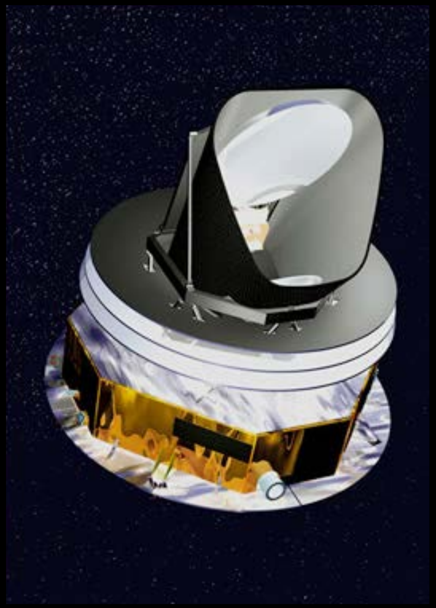
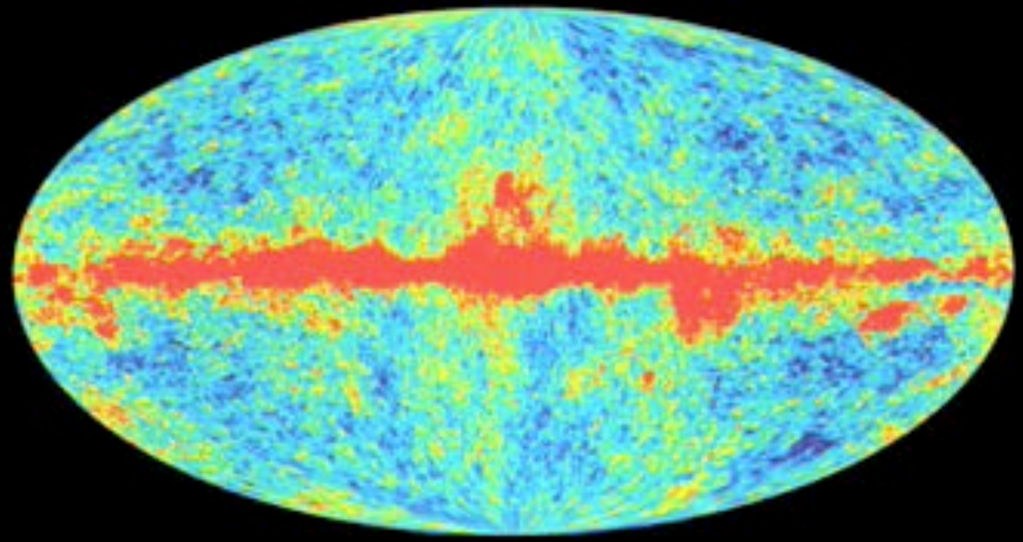
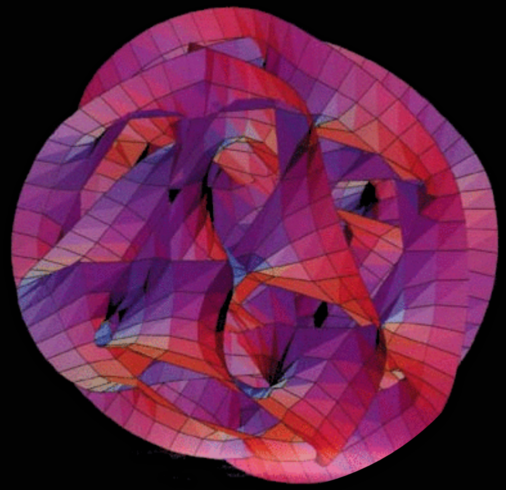


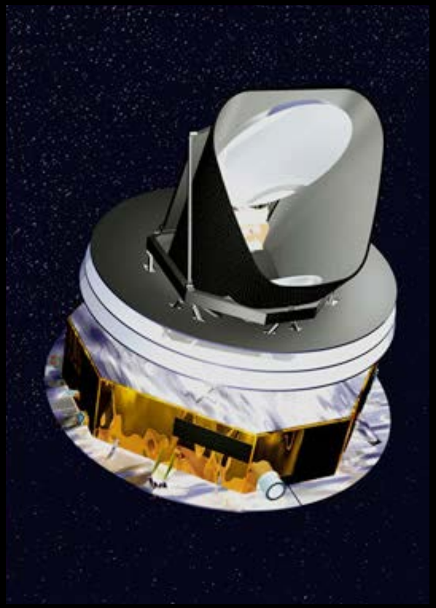


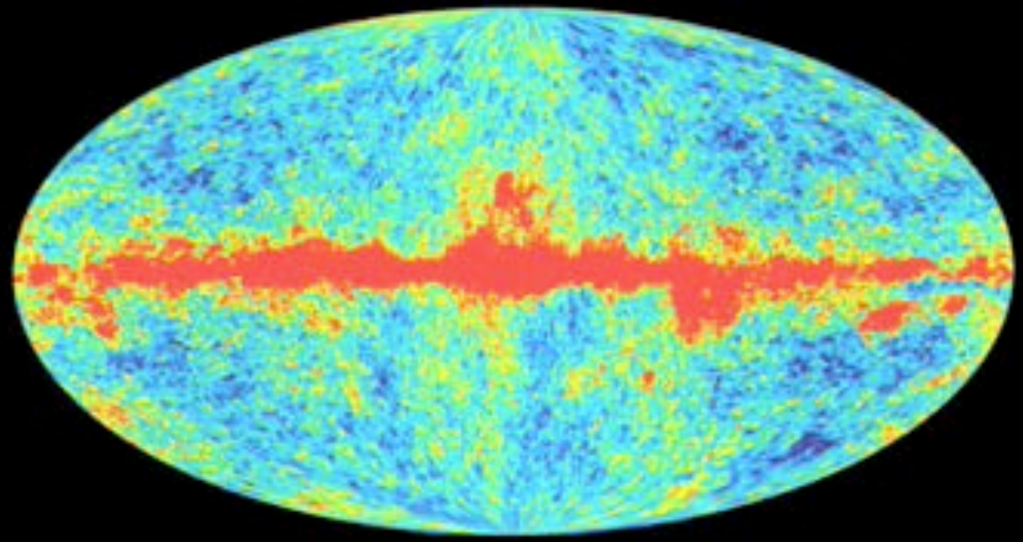


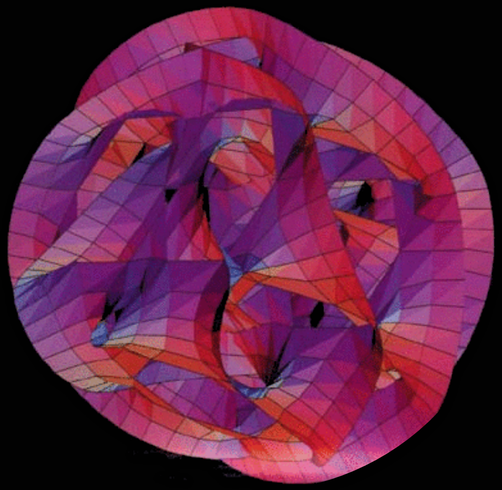
ULTRA-LIGHT AXIONS AND THE COSMIC MICROWAVE BACKGROUND

DANIEL GRIN
HAVERFORD COLLEGE

PICO WORKSHOP
5/1/2018







ULTRA-LIGHT AXIONS AND THE COSMIC MICROWAVE BACKGROUND

Daniel Grin
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PICO workshop
5/1/2018

Outline

- ✳ Ultra-light Axion (ULA) fundamentals
- ✳ Testing axion dark matter and dark energy using the CMB
- ✳ Future work

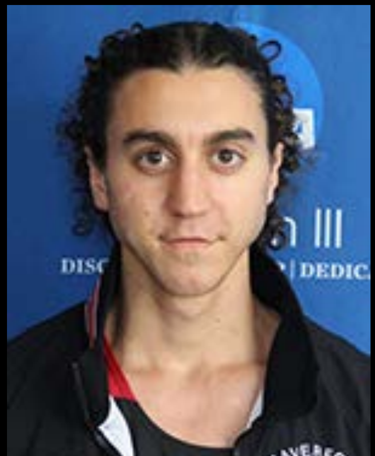
Collabs: R.Hložek, D.J. E. Marsh, P.Ferreira, J. Dunkley, E. Calabrese, R.Allison





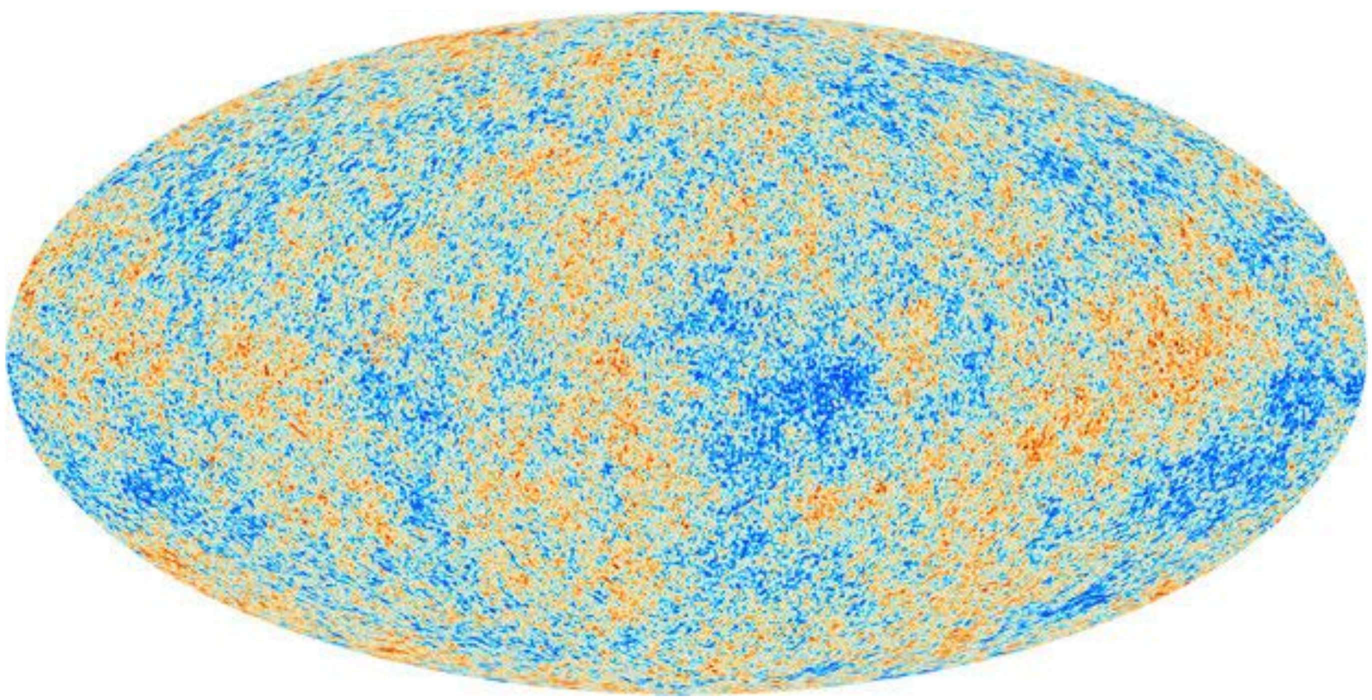

G. Given, E. Trott. D. Zegeye, S. Ditkovsky, J. Cookmeyer, M. Shea



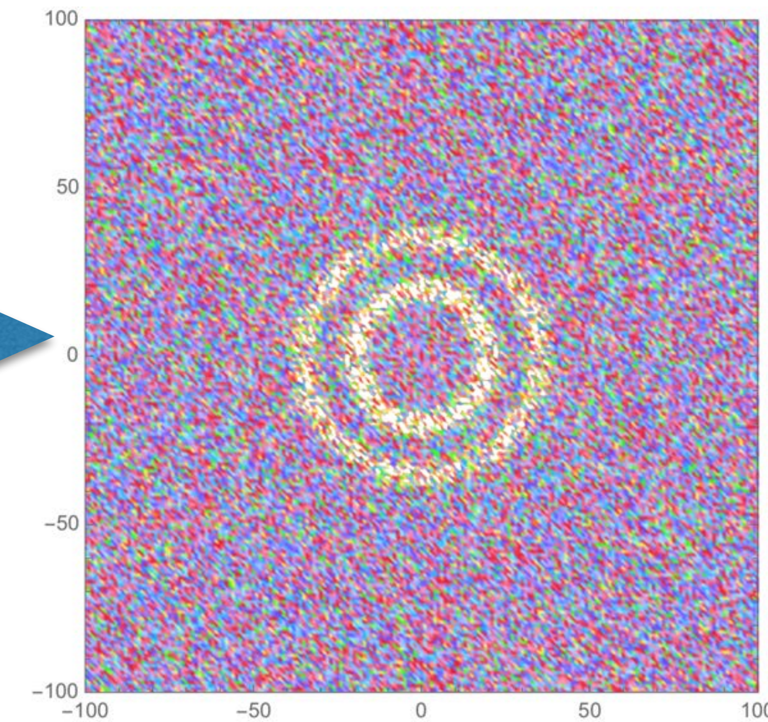



Fourier analysis of primordial sound

$$T(\vec{\theta})$$



$$a(\vec{k}) = \int T(\vec{\theta}) e^{i\vec{\theta}\cdot\vec{k}} d^2\theta$$



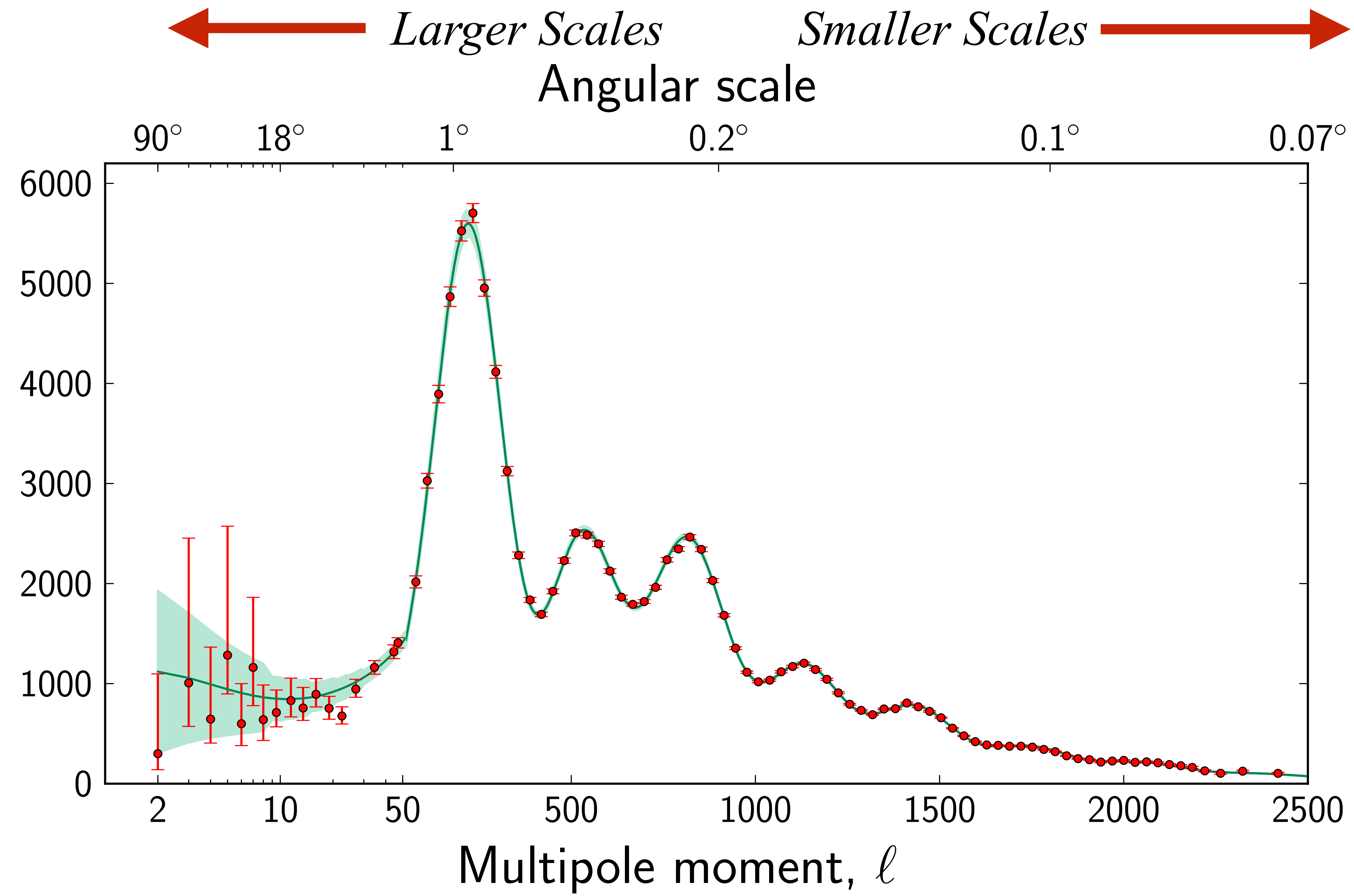
What can the CMB tell us about dark-matter and dark-energy particle physics?

Fourier analysis of primordial sound

Temperature variance

μK^2

$$\frac{l(l+1)C_l}{2\pi}$$



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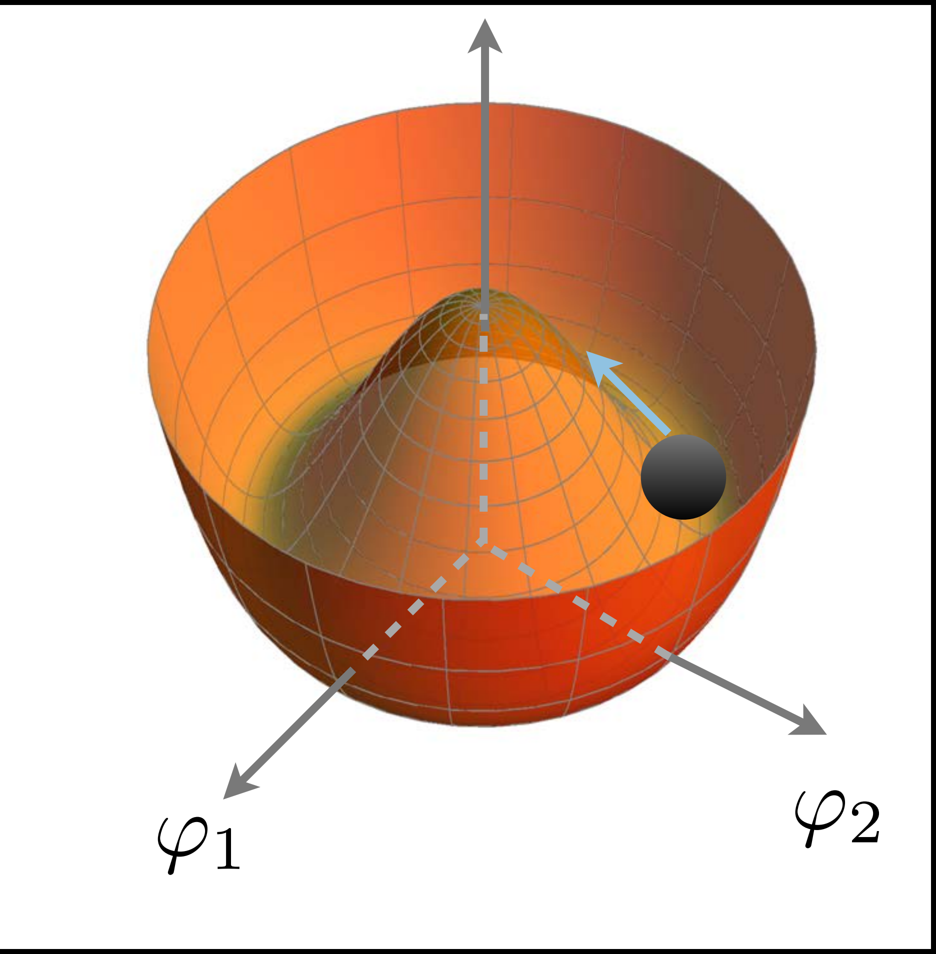
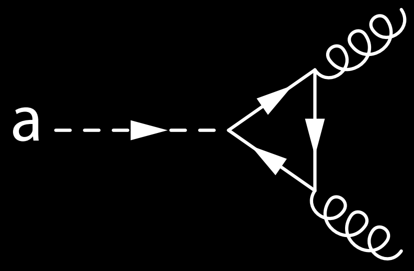
What are axions?



New scalar field with global U(1) symmetry!

$$\mathcal{L}_{\rm CPV} = \frac{\theta g^2}{32\pi^2} G\tilde{G} - \frac{a}{f_{\rm a}} g^2 G\tilde{G}$$



- Couples to SM gauge fields (via fermions)

- Dynamically erases QCD CP-violation

- Axion gets mass through non-perturbative QCD effects

$$m_a \sim \frac{\Lambda^2_{\rm QCD}}{f_a}$$

Peccei + Quinn (1977), Weinberg +Wilczek (1978), Kim (1979), Shifman et. al (1980), Zhitnitsky (1980), Dine et al. (1981), D.B. Kaplan (1985), A.E Nelson (1985,1990)

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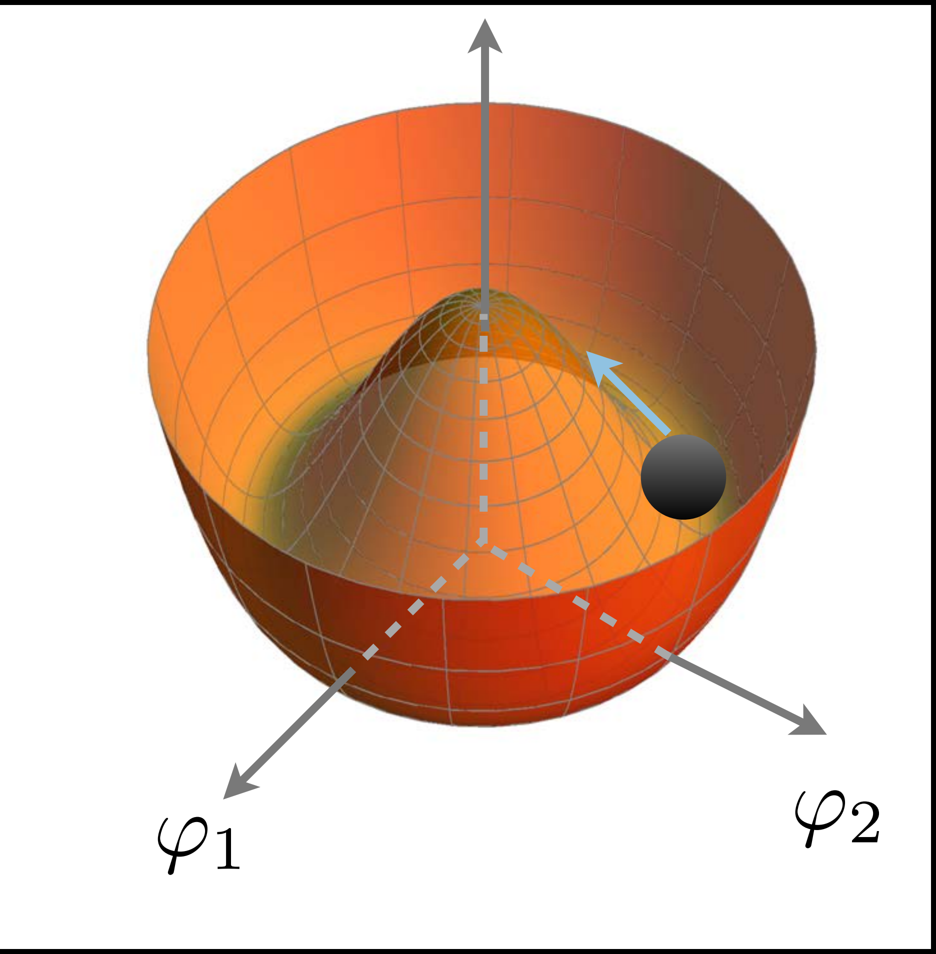

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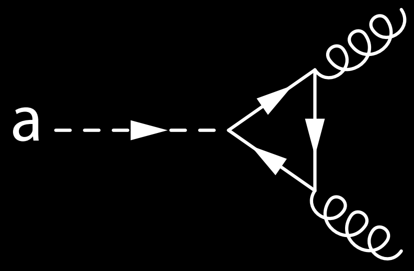

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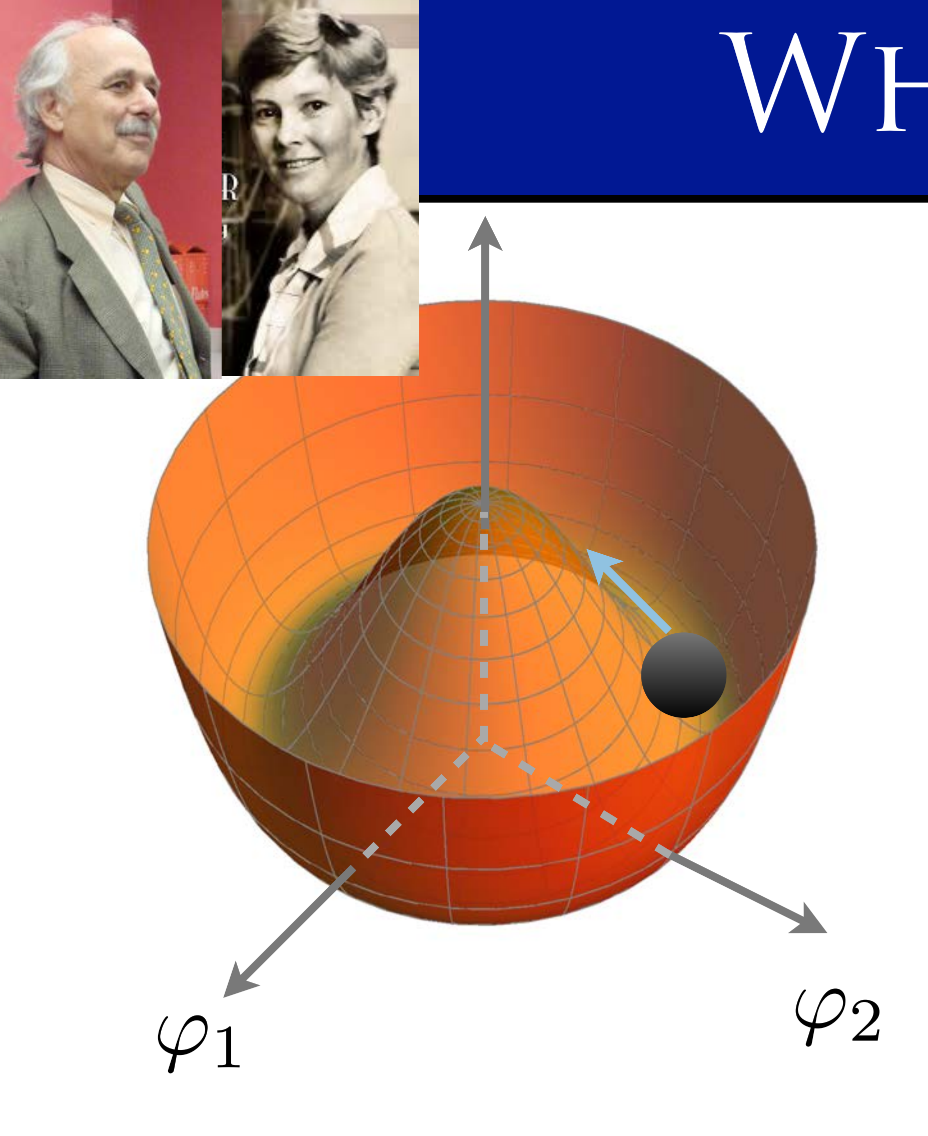

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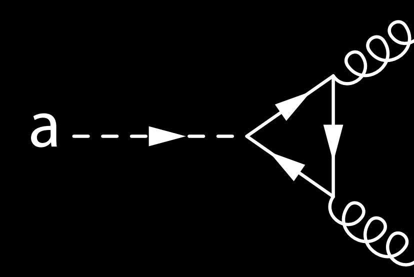

✳ Couples to SM gauge fields (via fermions)

$$\mathcal{L} \propto \frac{1}{f_{\rm a}} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

✳ Dynamically erases QCD CP-violation

✳ Axion gets mass through non-perturbative QCD effects

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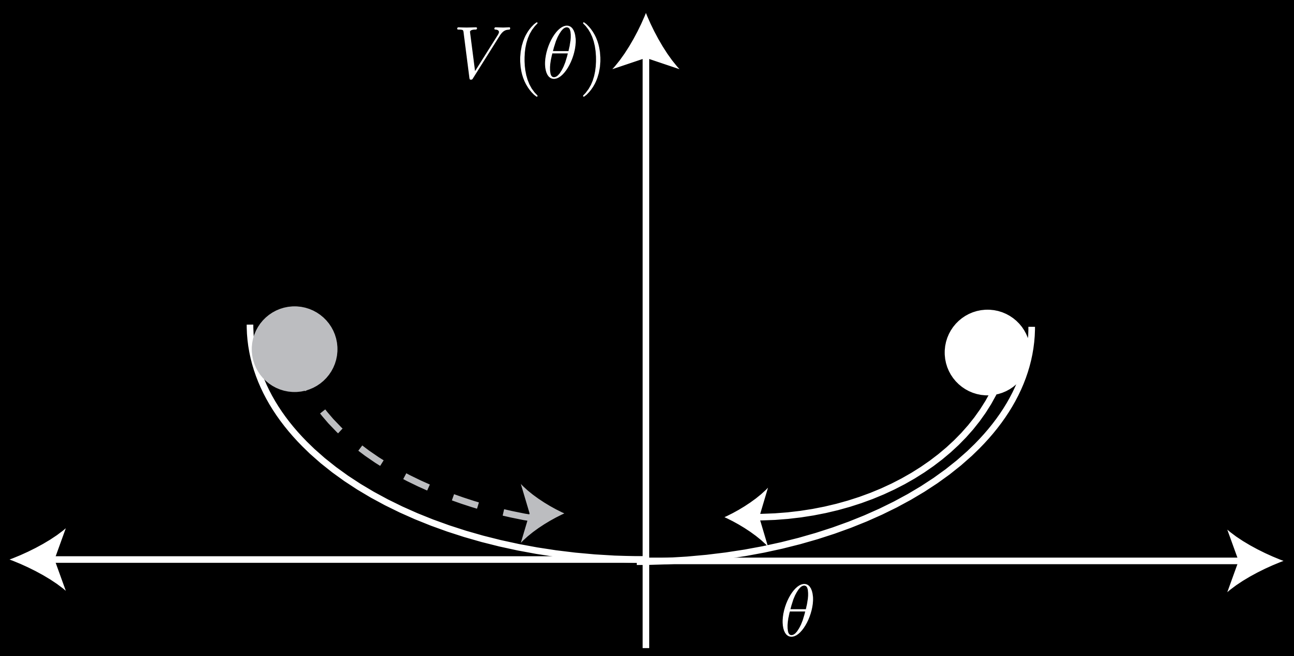
2 axion populations: Cold axions

$$m_a < 10^{-2}\ \mathrm{eV}$$



- Before PQ symmetry breaking, θ is generically displaced from vacuum value
- EOM: $\ddot{\bar{\theta}} + 3H\dot{\bar{\theta}} + m_{\mathrm{a}}^2(T)\,\bar{\theta} = 0 \qquad m_{\mathrm{a}}(T) \simeq 0.1 m_{\mathrm{a}}(T=0)\,(\Lambda_{\mathrm{QCD}}/T)^{3.7}$
- After $m_{\mathrm{a}}(T) \gtrsim 3H(T)$, coherent oscillations begin, leading to $n_{\mathrm{a}} \propto a^{-3}$
- Axions are cold $p \ll m_a c$

2 axion populations: Cold axions

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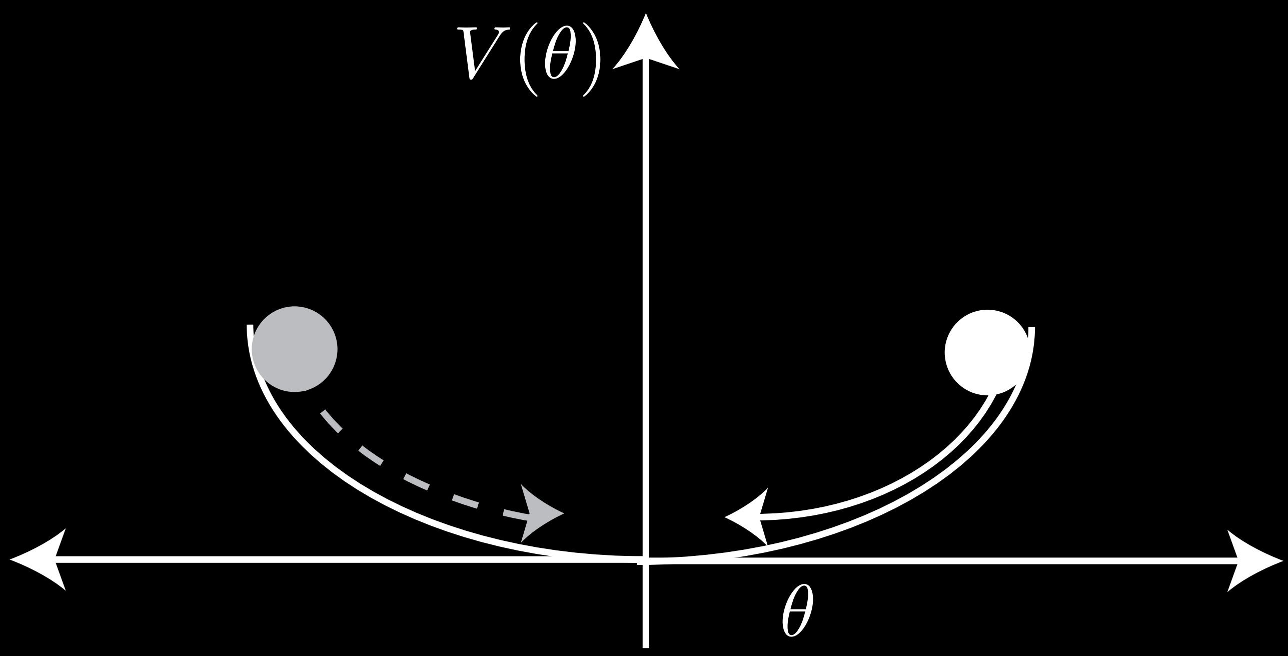

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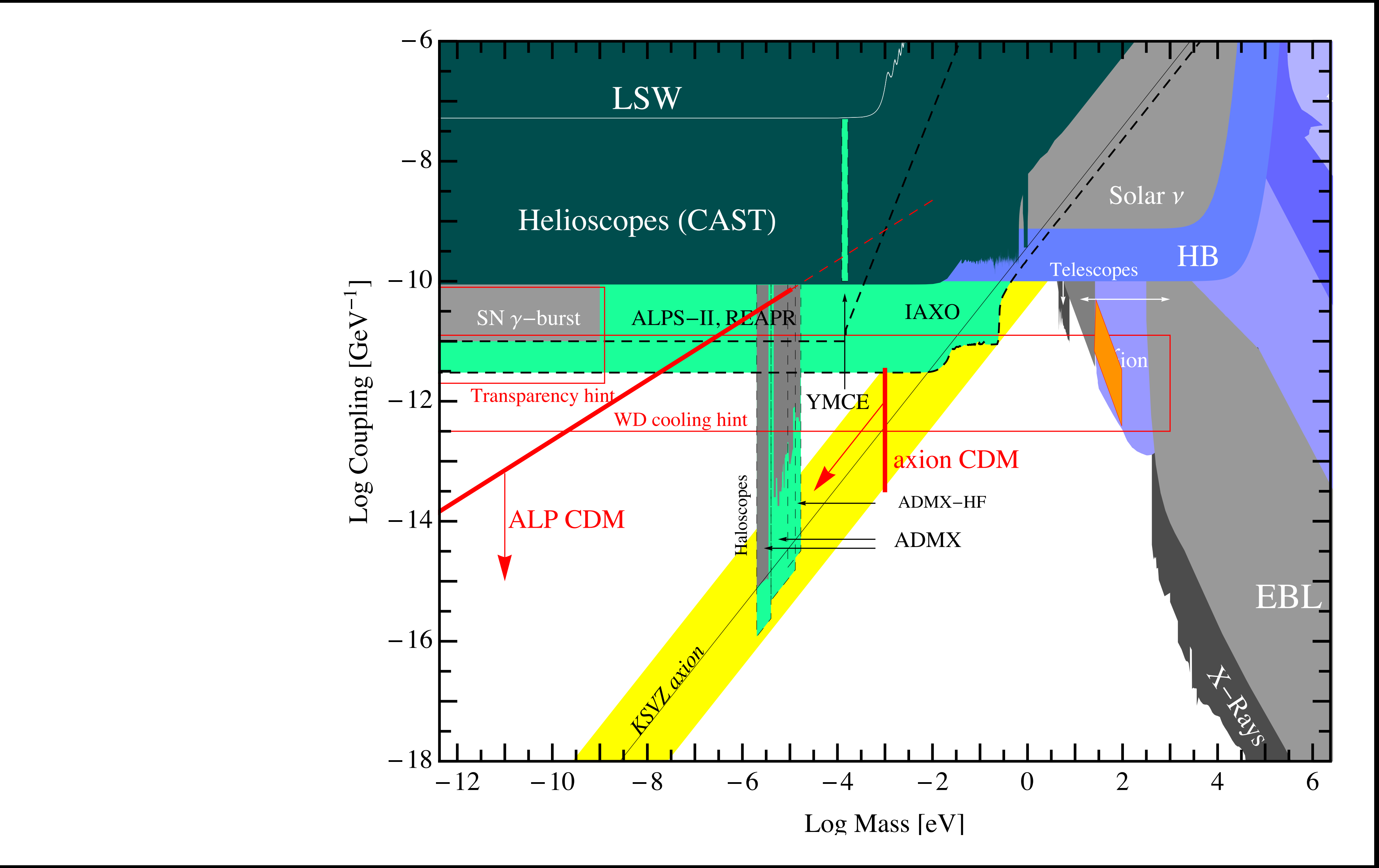
- After $m_{\mathrm{a}}(T) \gtrsim 3H(T)$, coherent oscillations begin, leading to $n_{\mathrm{a}} \propto a^{-3}$
- $$\Omega_{\mathrm{mis}} h^2 = 0.236\,\langle \theta_i^2 f(\theta_i) \rangle \left(\frac{m_a}{6.2\mu\mathrm{eV}} \right)^{-7/6}$$

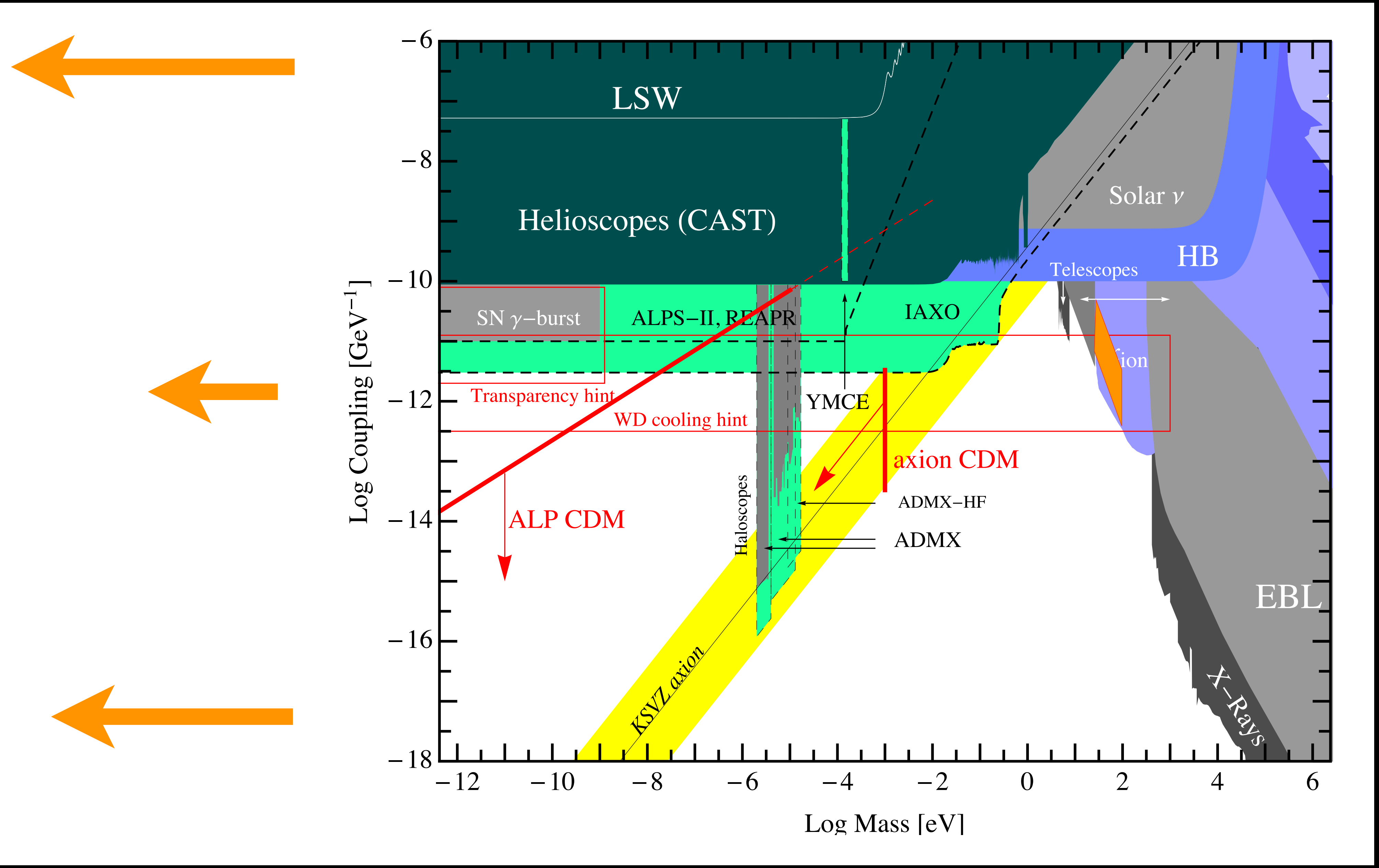
Experimental constraints
ULA and axion-like particles (ALPs)



$$\mathcal{L} \propto g_{a\gamma\gamma} \vec{E} \cdot \vec{B}$$

Experimental constraints
ULA and axion-like particles (ALPs)

Experimental desert: Gravitational constraints essential

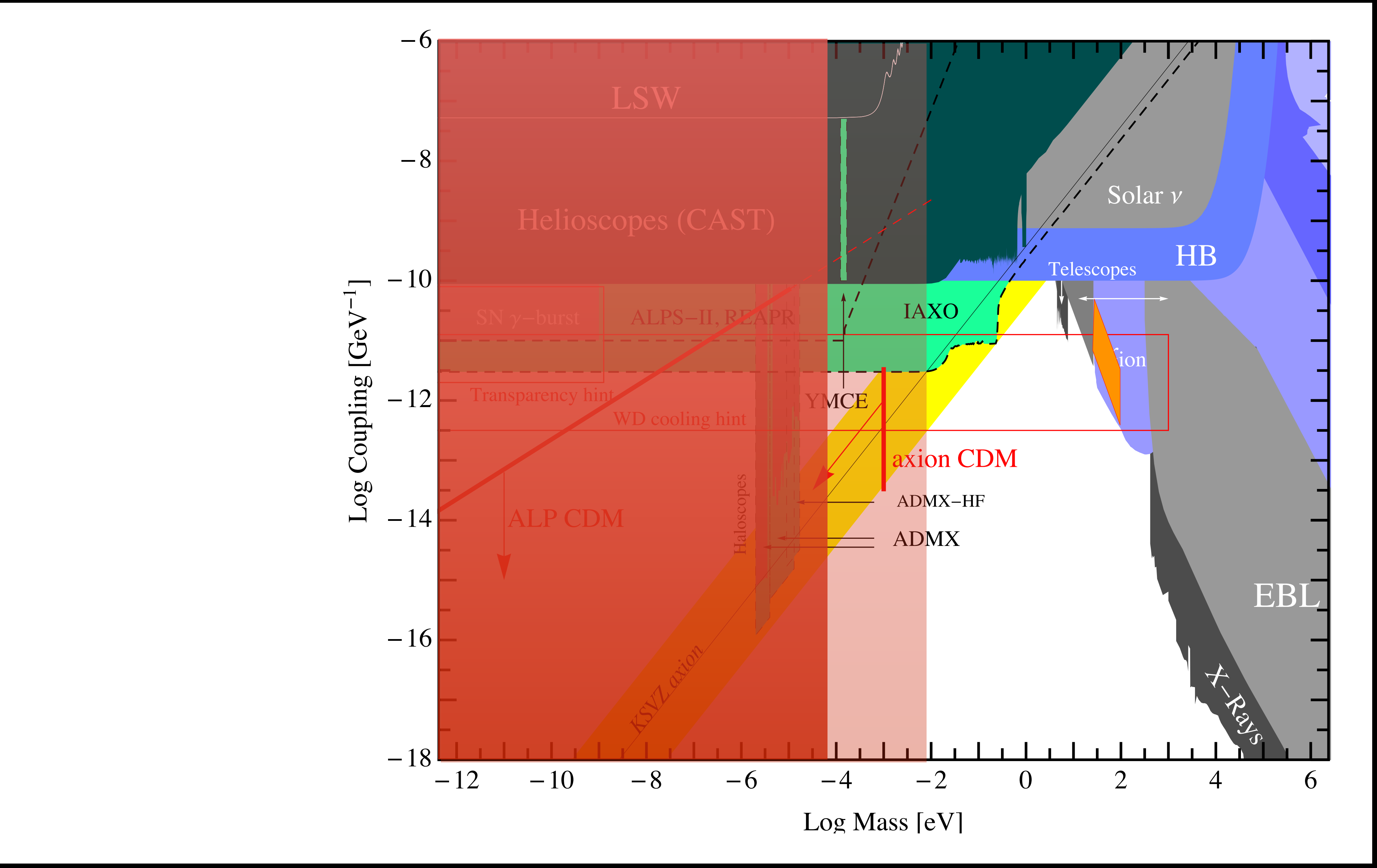


$$\mathcal{L} \propto g_{a\gamma\gamma} \vec{E} \cdot \vec{B}$$

From arXiv: 1205.2671

Experimental constraints
ULA and axion-like particles (ALPs)

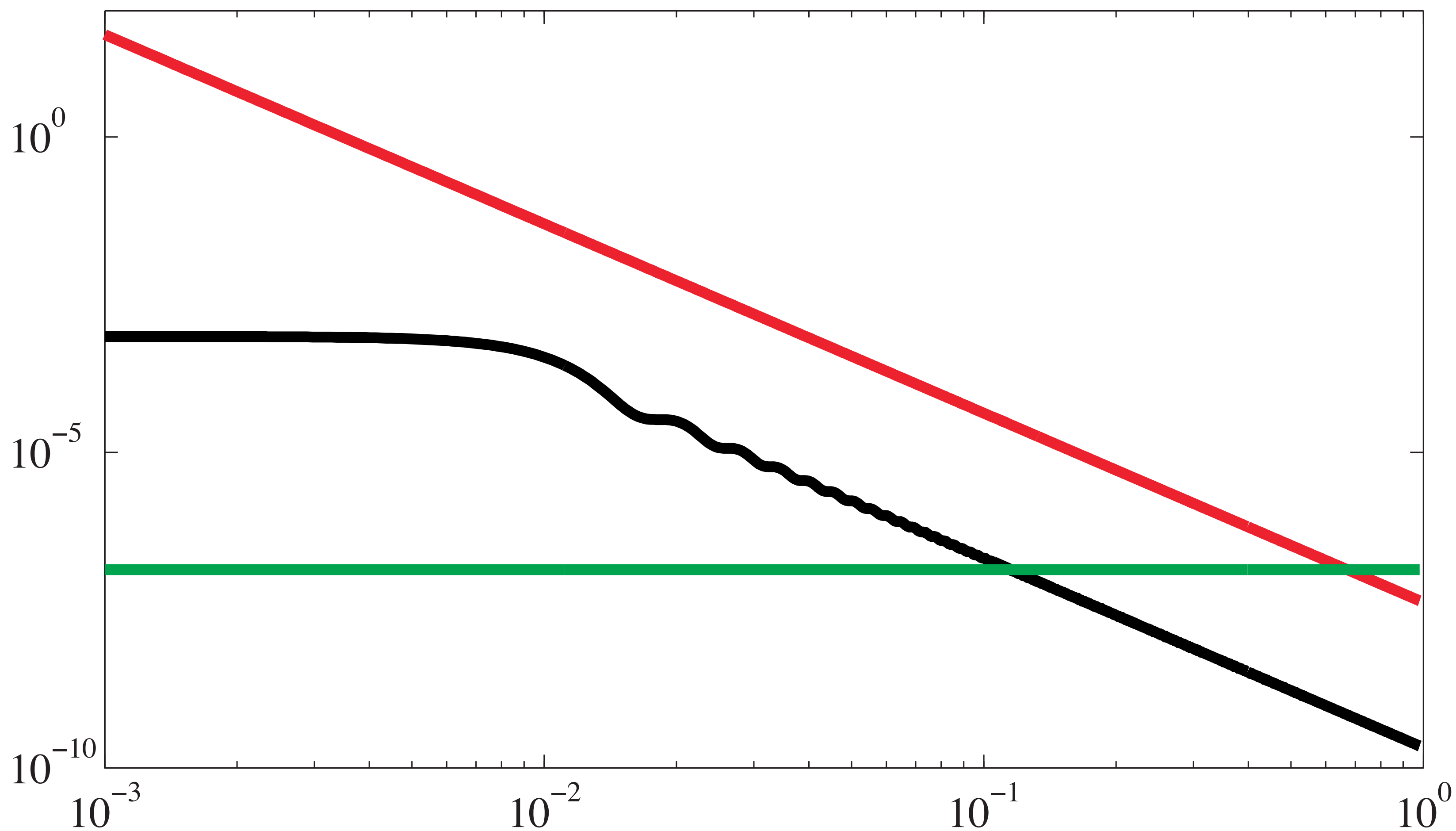
Cosmological abundance limits



$$\mathcal{L} \propto g_{a\gamma\gamma} \vec{E} \cdot \vec{B}$$

Cosmology of ultra-light axions: dark matter and dark energy candidates

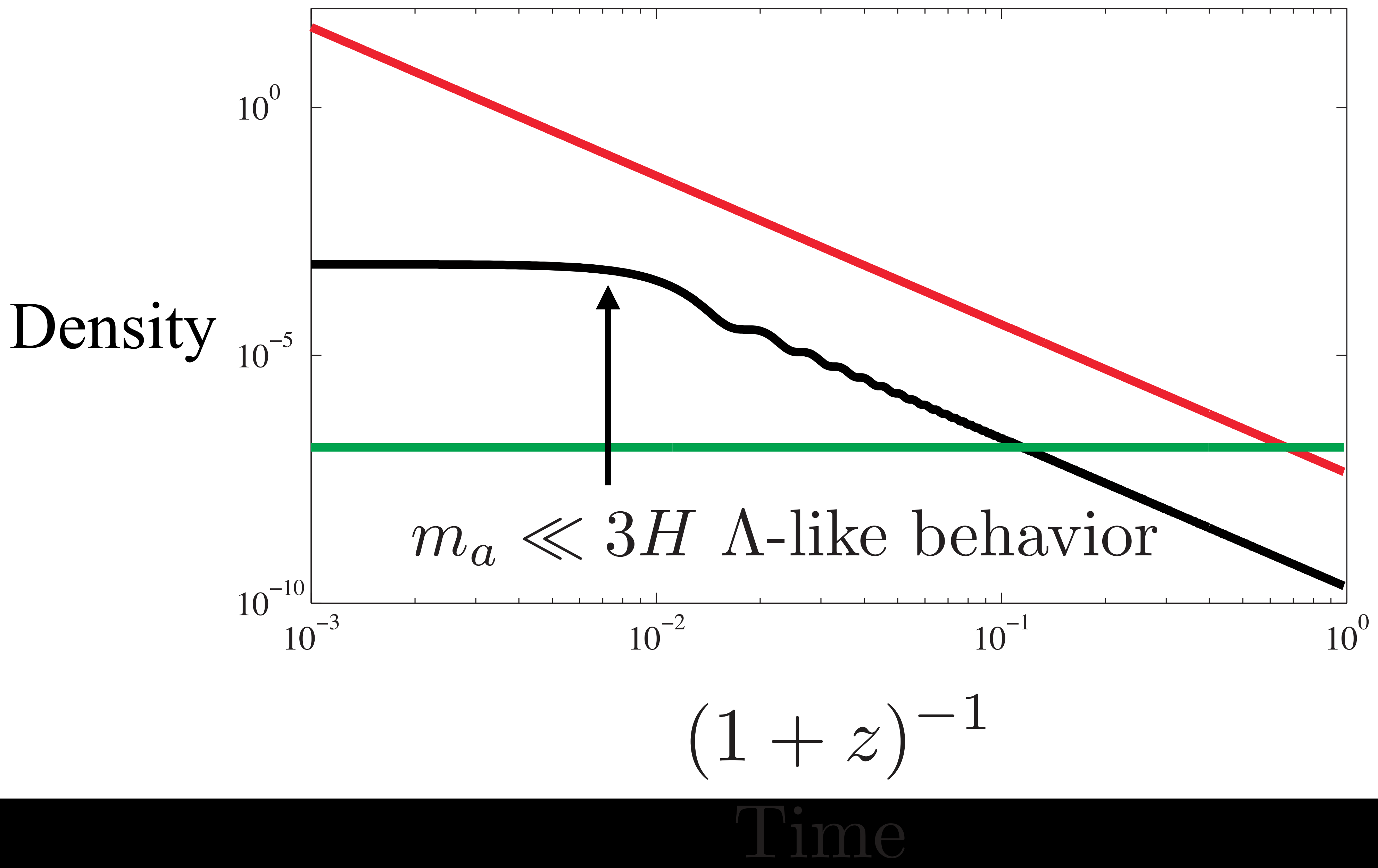
Density



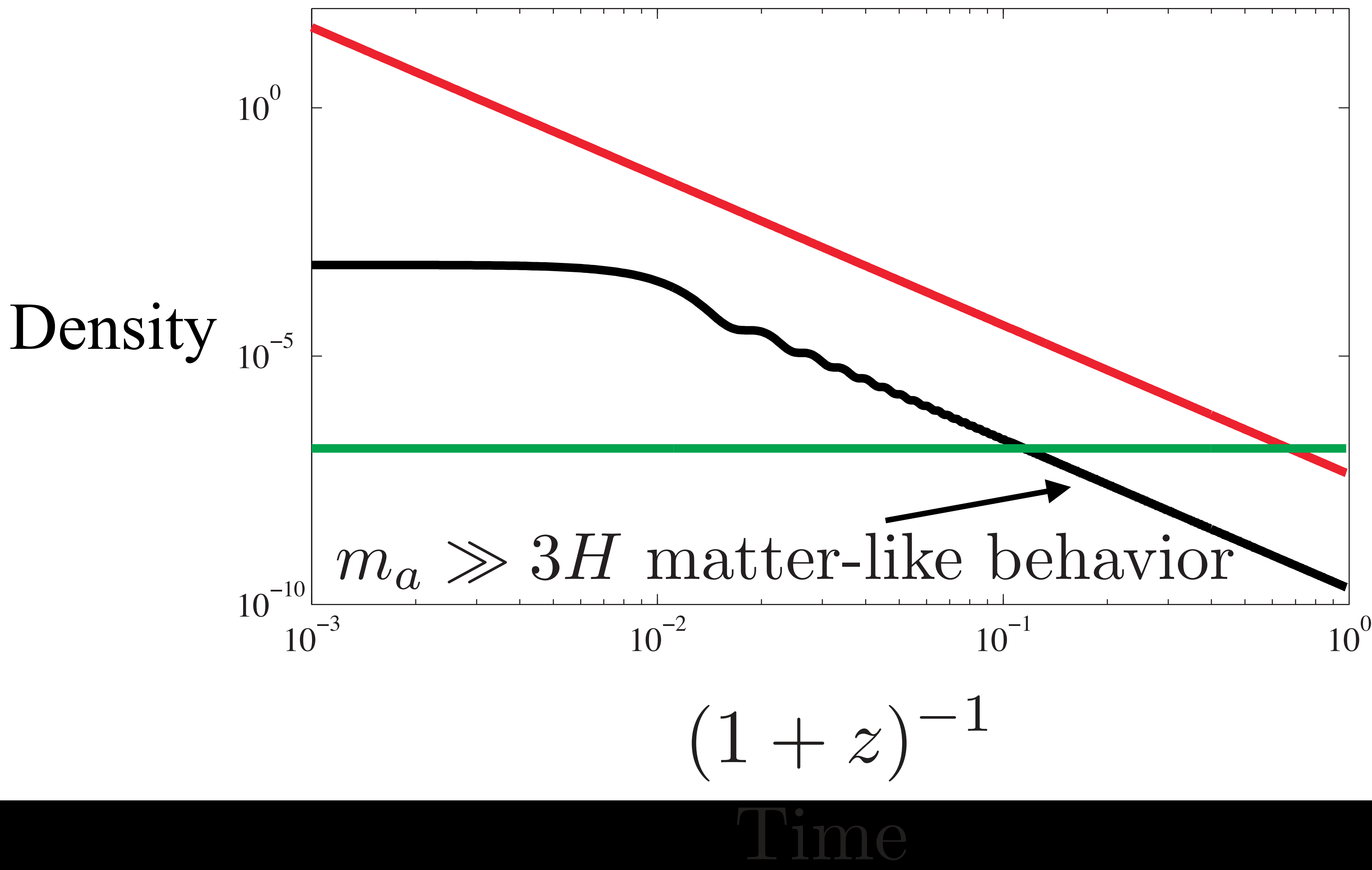
$(1+z)^{-1}$

Time

Cosmology of ultra-light axions: dark matter and dark energy candidates

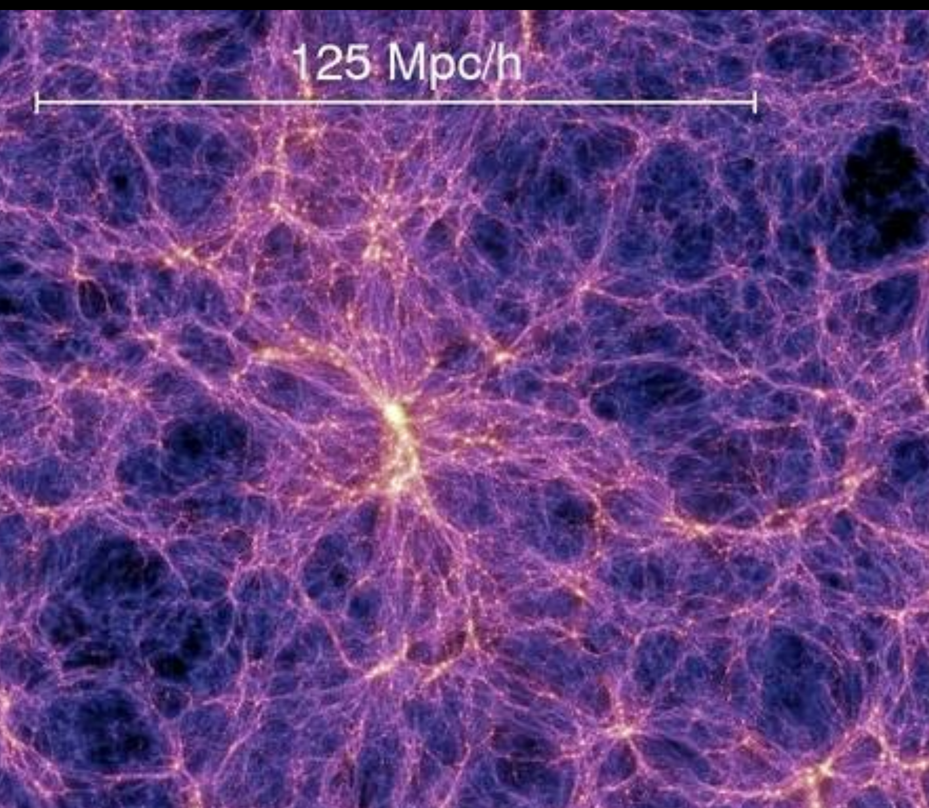


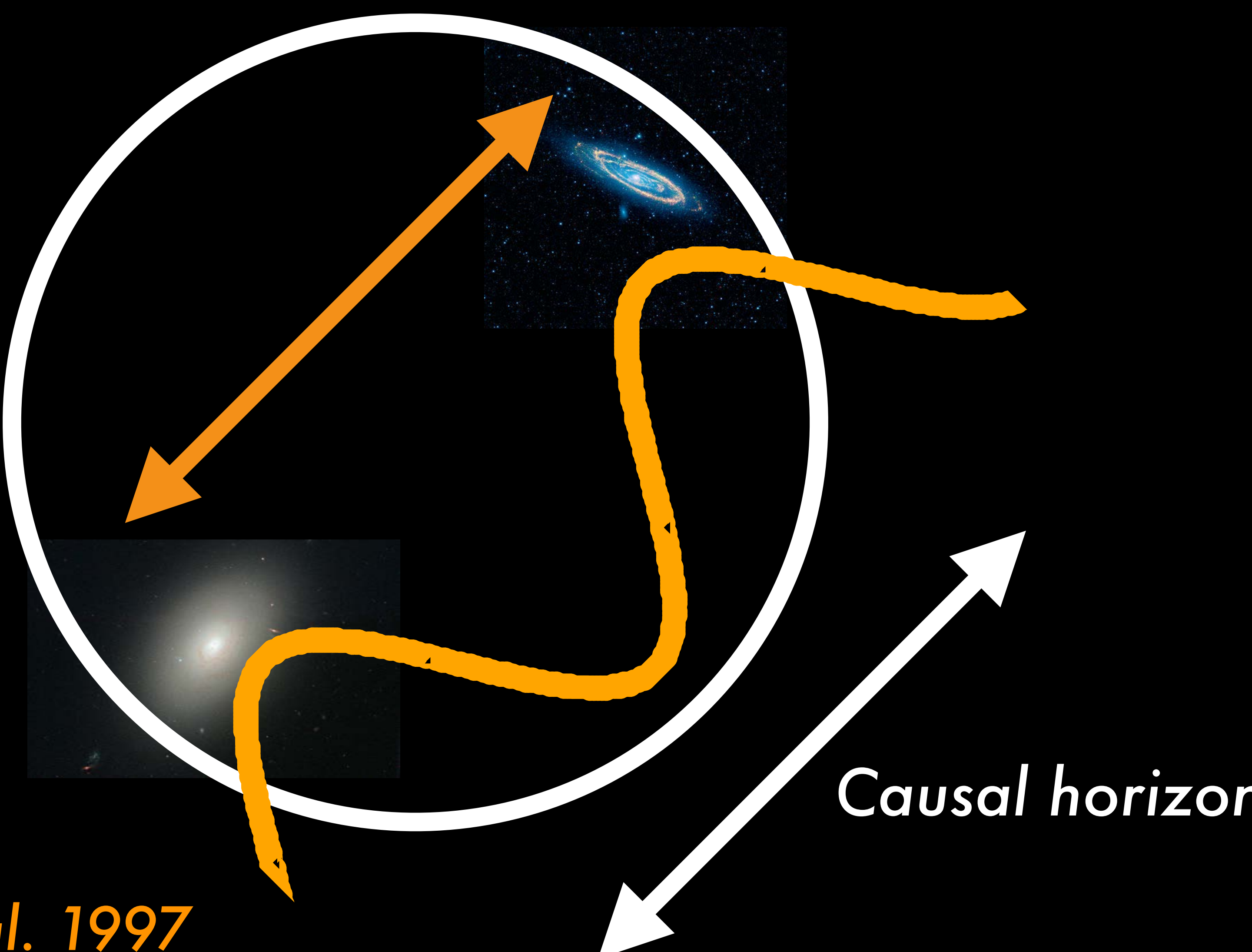
Cosmology of ultra-light axions: dark matter and dark energy candidates



Cosmology of ultra-light axions: dark matter and dark energy candidates

Scale corresponding to typical galaxy separation today





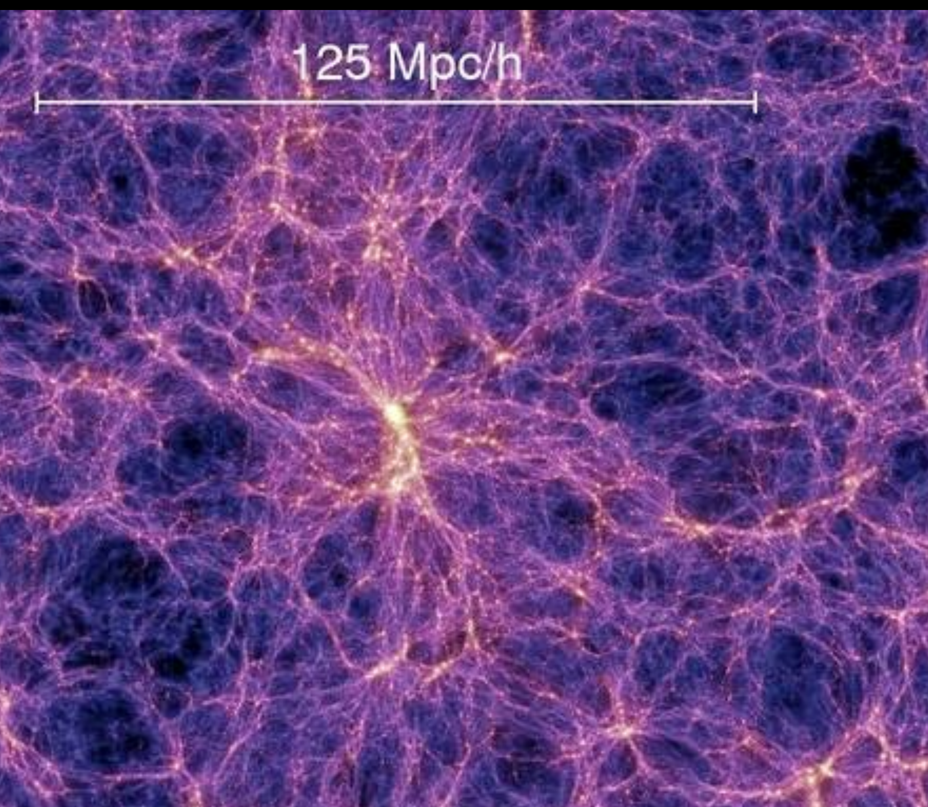
Frieman et al 1995, Coble et al. 1997

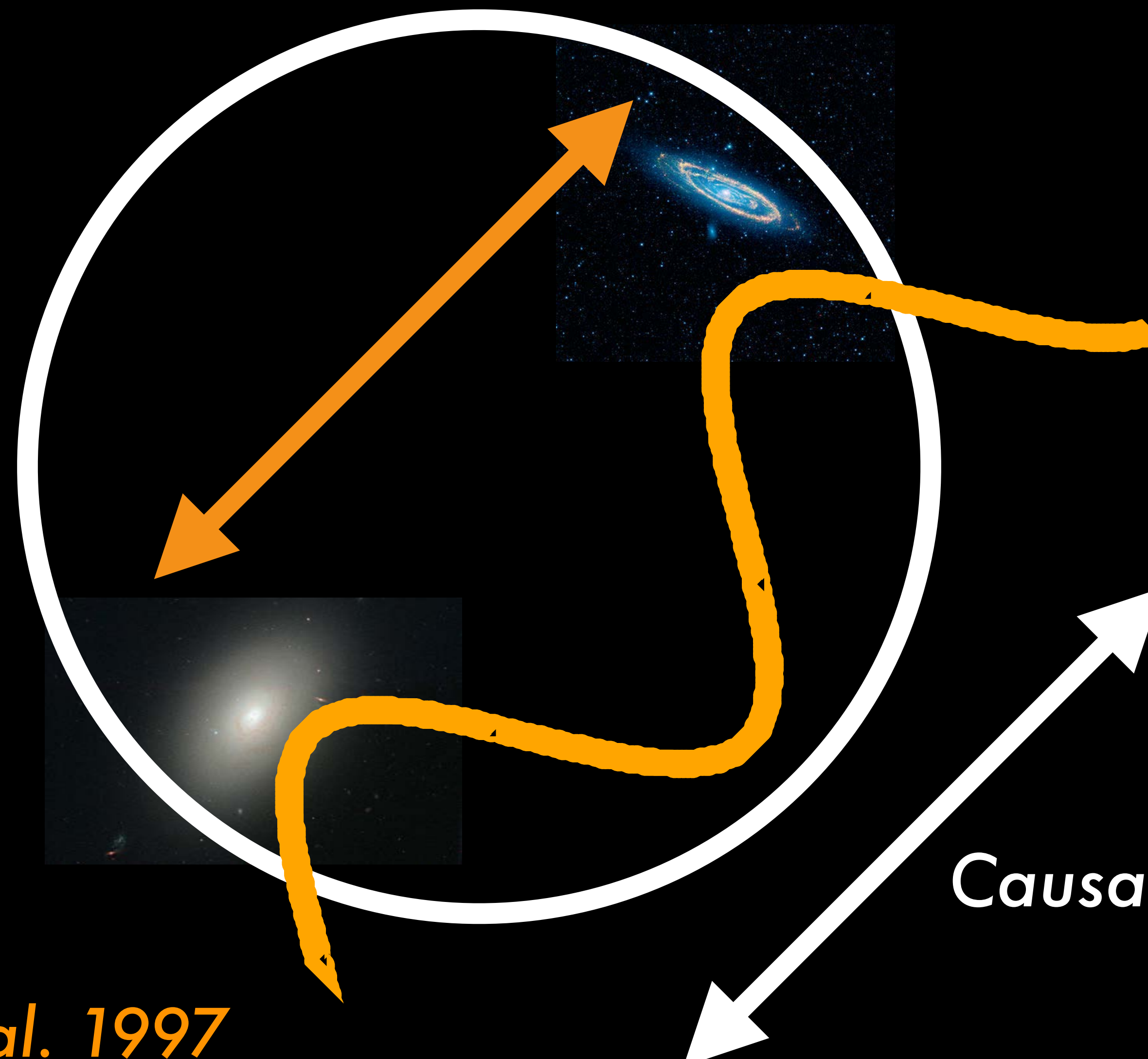
ULA as dark energy with specific w(z)

$m_a \lesssim 10^{-27}$ eV *ULA matter behavior starts too late for struct. formation*

Cosmology of ultra-light axions: dark matter and dark energy candidates

Scale corresponding to typical galaxy separation today





Causal horizon

Frieman et al 1995, Coble et al. 1997

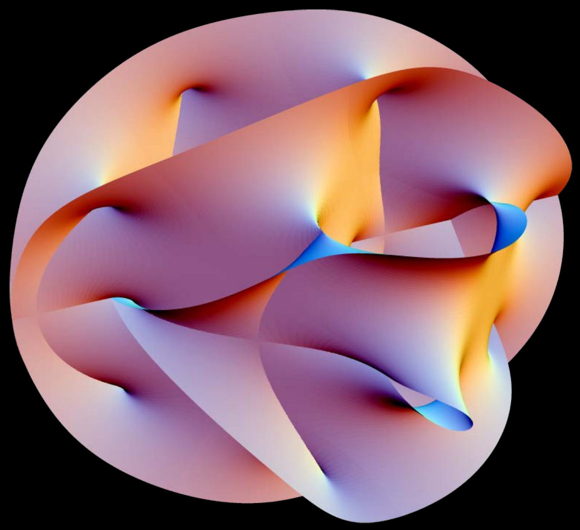
ULA as dark matter

$$m_a \gtrsim 10^{-27}\ \mathrm{eV}$$

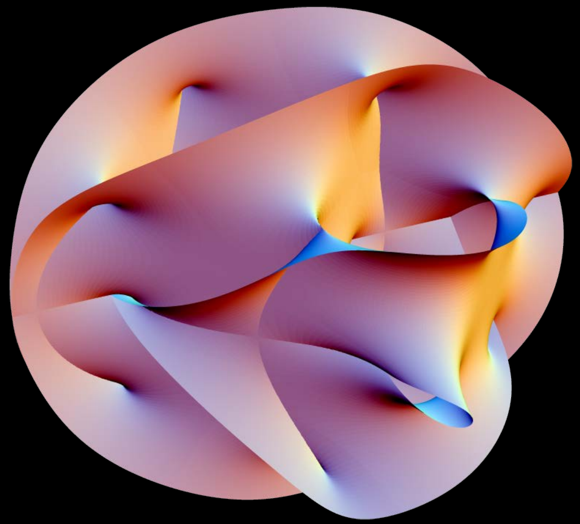
ULA matter behavior starts in time for struct. formation

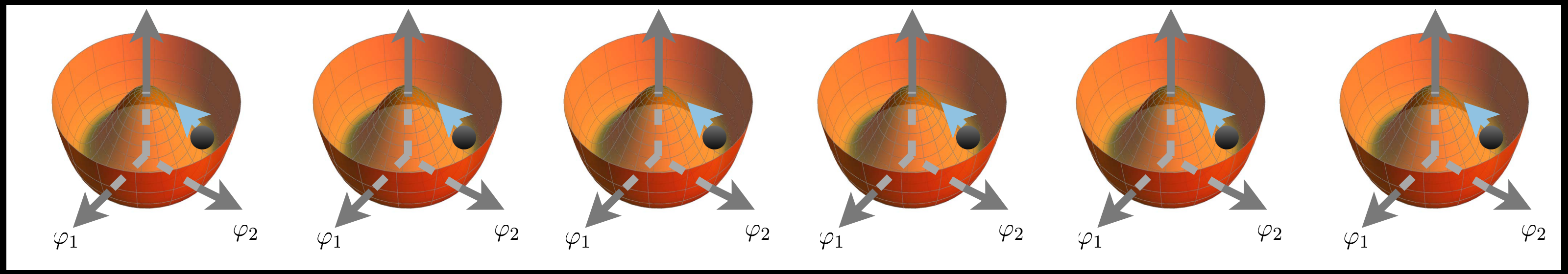
Ultra-light axions (ULAs) in string theory

- In string theory, extra dimensions compactified: Calabi-Yau manifolds



✳ In string theory, extra dimensions compactified: Calabi-Yau manifolds

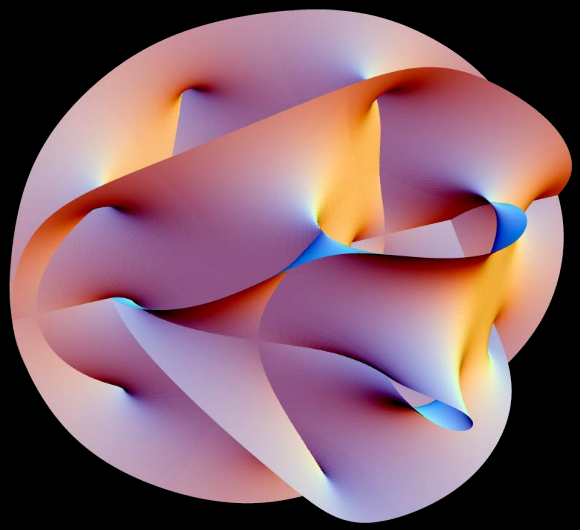


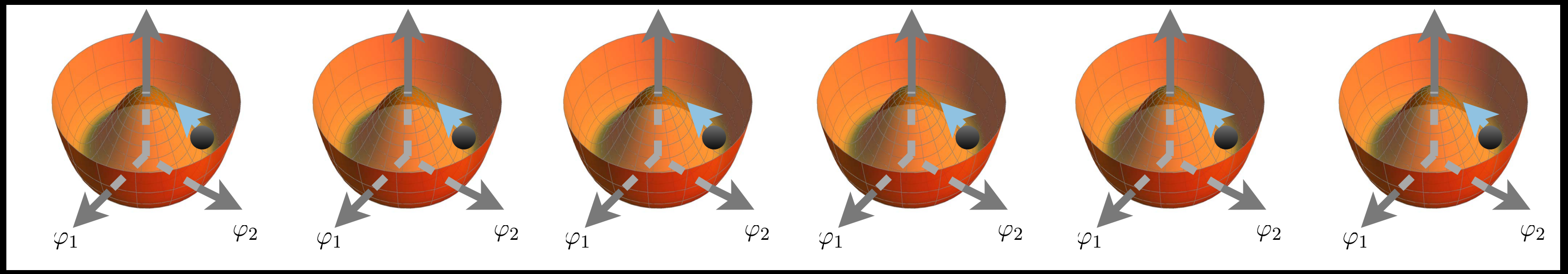


+....

Hundreds of scalars with approx shift symmetry

✳ In string theory, extra dimensions compactified: Calabi-Yau manifolds





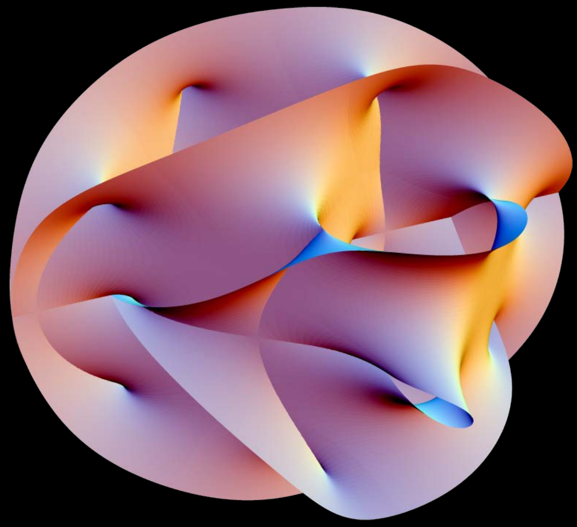
+....

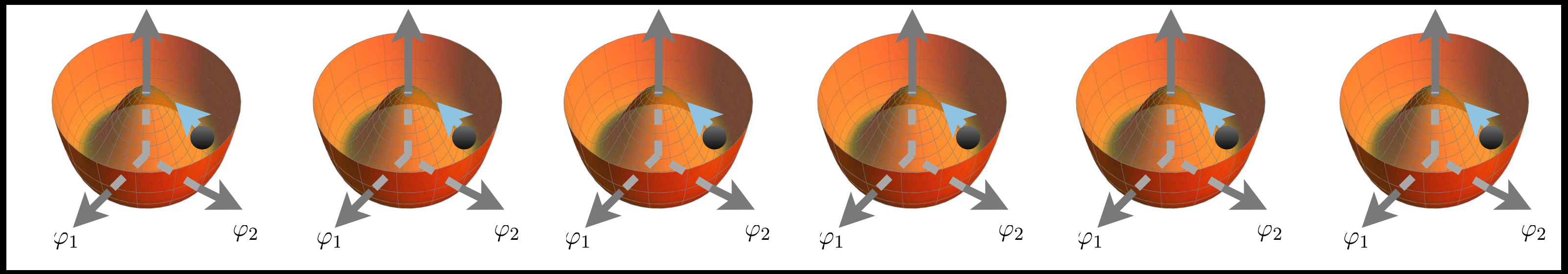
Hundreds of scalars with approx shift symmetry

↓

Many axions

✳ In string theory, extra dimensions compactified: Calabi-Yau manifolds





+....

Hundreds of scalars with approx shift symmetry

↓

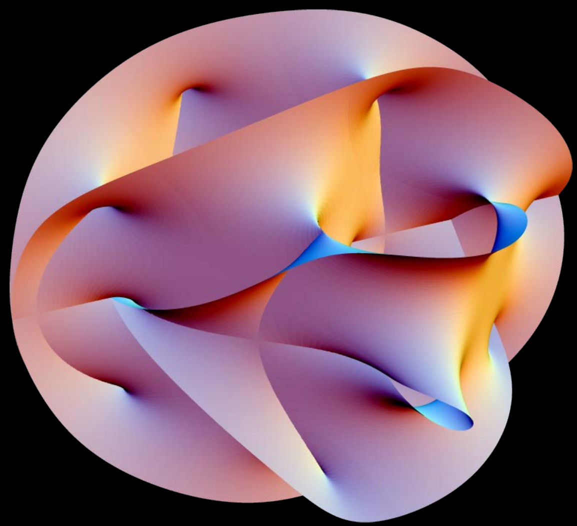
Many axions

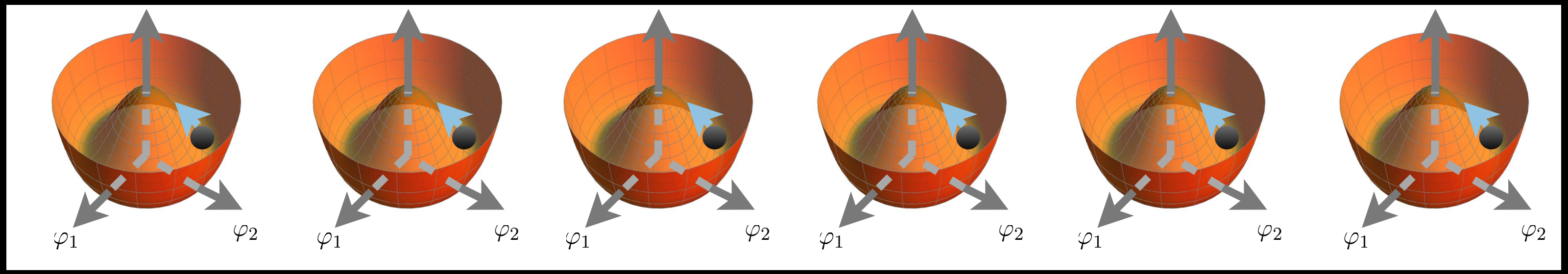
✳ Mass acquired non-perturbatively (instantons, D-Branes)

$$m_a^2 = \frac{\mu^4}{f_a^2} e^{-\text{Volume}}$$

ULTRA-LIGHT AXIONS (ULAS) IN STRING THEORY

- ✳ In string theory, extra dimensions compactified: Calabi-Yau manifolds





+....

Hundreds of scalars
with approx shift symmetry

↓

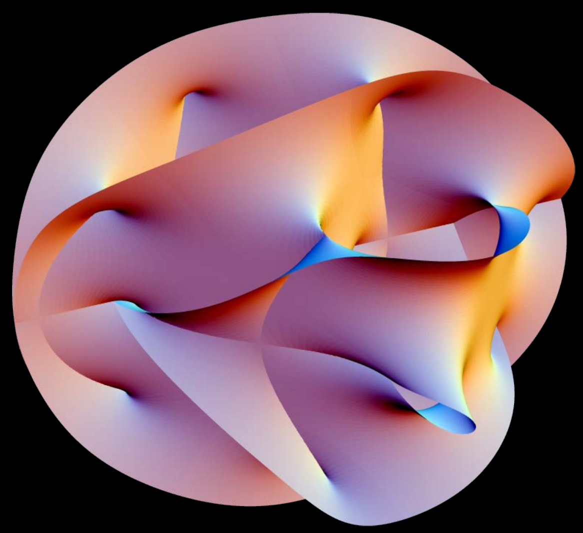
Many axions

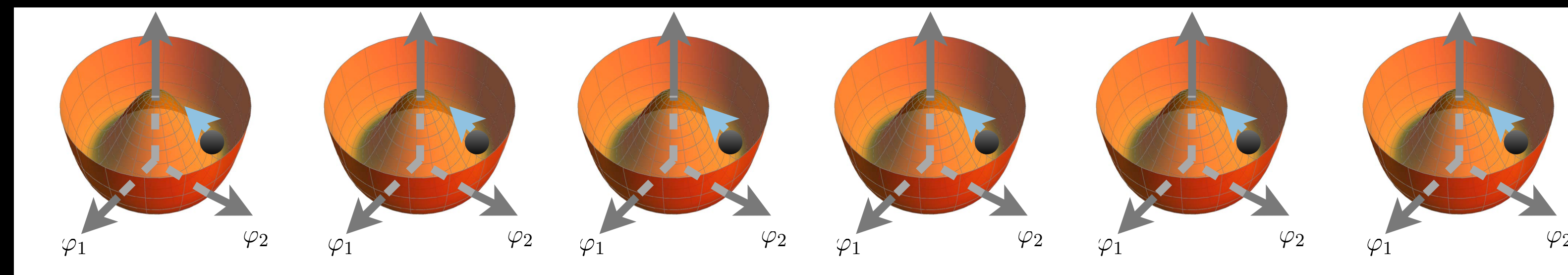
- ✳ Mass acquired non-perturbatively (instantons, D-Branes)

Scale of new
ultra-violet physics

$$m_a^2 = \frac{\mu^4}{f_a^2} e^{-\text{Volume}}$$

- In string theory, extra dimensions compactified: Calabi-Yau manifolds





+....

Hundreds of scalars with approx shift symmetry

↓

Many axions

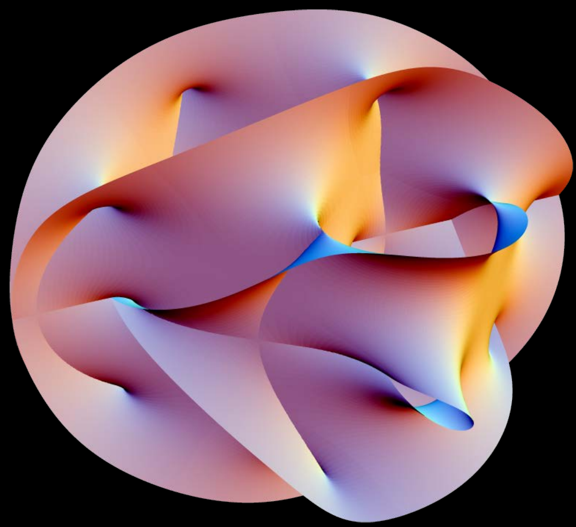
- Mass acquired non-perturbatively (instantons, D-Branes)

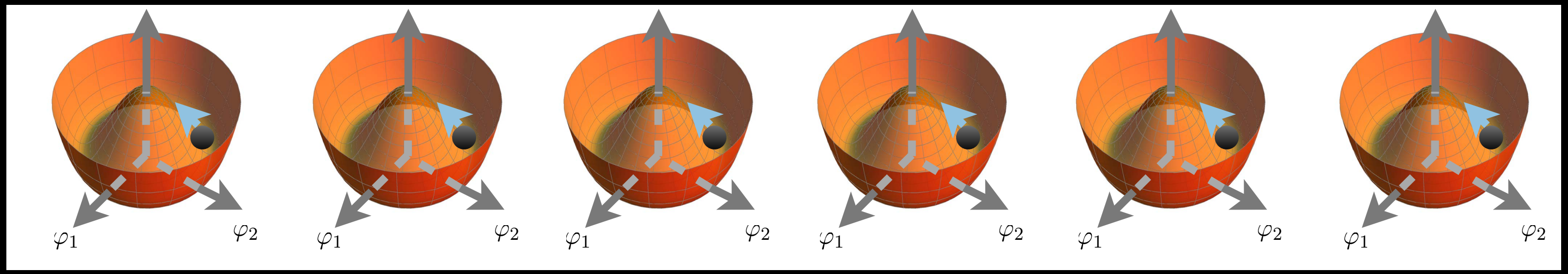
Scale of extra dimensions in Planck units

$$m_a^2 = \frac{\mu^4}{f_a^2} e^{-\text{Volume}}$$

ULTRA-LIGHT AXIONS (ULAS) IN STRING THEORY

* In string theory, extra dimensions compactified: Calabi-Yau manifolds

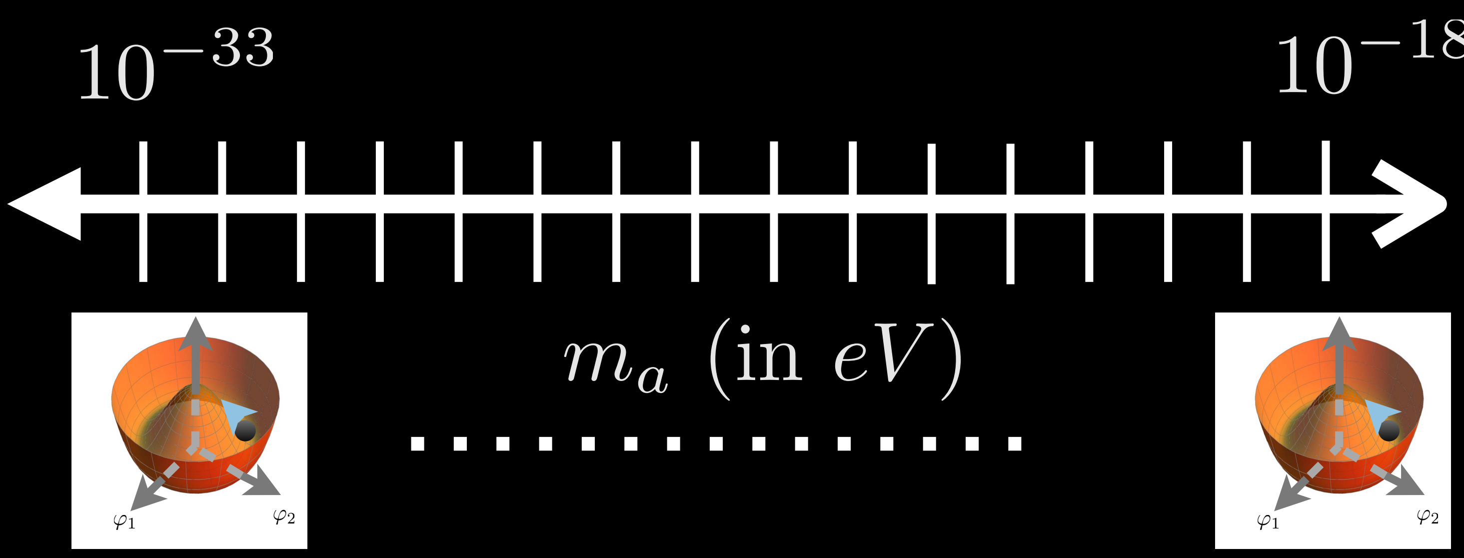




+....

Axiverse! *Arvanitaki+ 2009*

Witten and Srvcek (2006), Acharya et al. (2010), Cicoli (2012)



GROWTH OF ULA PERTURBATIONS

✳ Perturbed Klein-Gordon + Gravity

$k = 2\pi/\lambda$

$$\ddot{\delta\phi} + 2\mathcal{H}\dot{\delta\phi} + (k^2 + m_a^2 a^2)\delta\phi = 4\dot{\Psi}\dot{\phi}_0 - \Psi a^2 m_a^2 \phi_0$$

✳ Axionic Jeans Scale is macroscopic [in contrast to QCD axion]:

$$\lambda_J = 2.4 h^{-1/2} \left(\frac{m}{10^{-25}\ \mathrm{eV}}\right)^{-1/2} \mathrm{Mpc}$$

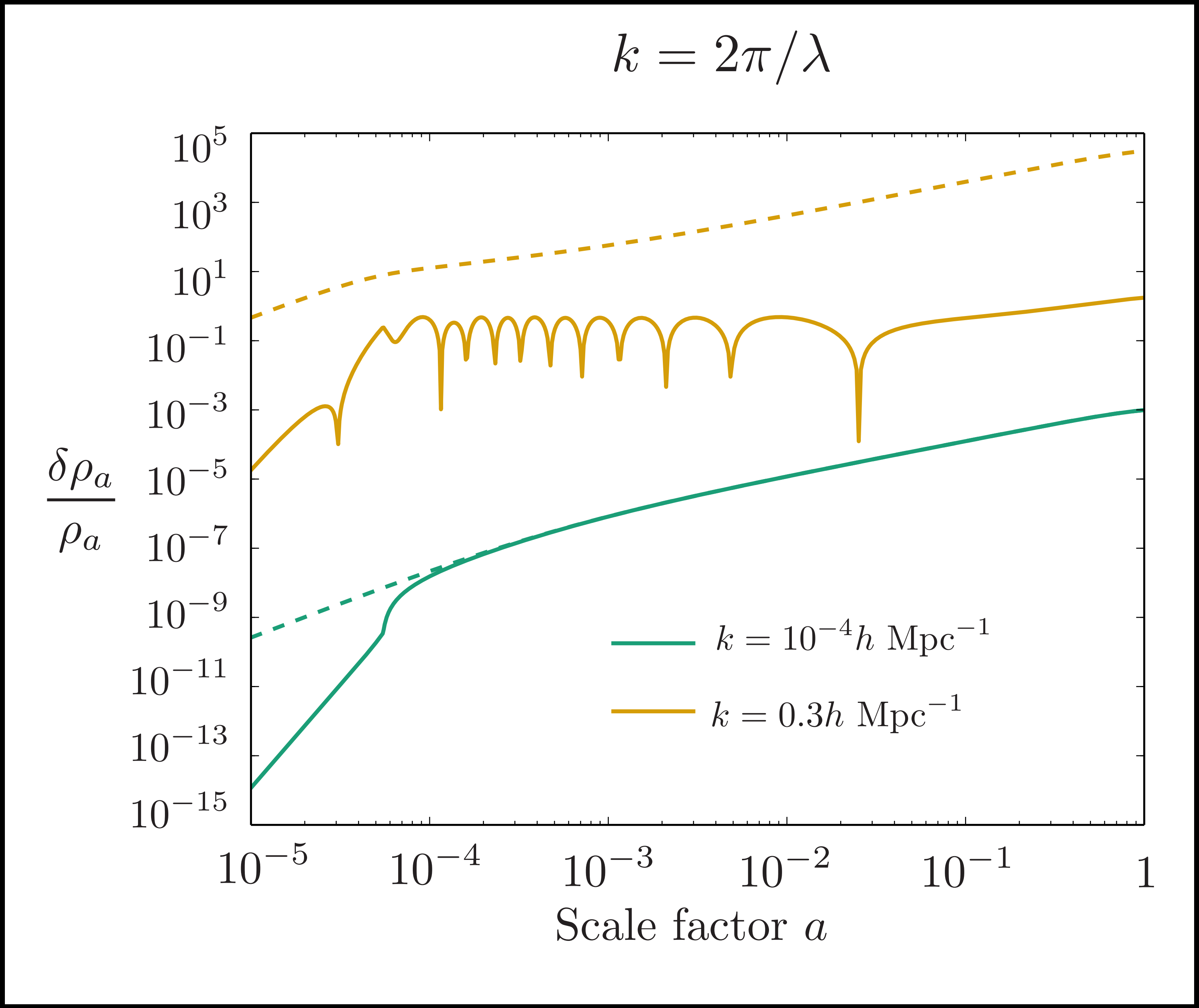
✳ Computing observables is expensive for $m \gg 3\mathcal{H}$:

- ✳ Coherent oscillation time scale $\Delta\eta \sim (ma)^{-1} \ll \Delta\eta_{\mathrm{CAMB}}$
- ✳ WKB approximation

$$\delta\phi = A_c \Delta_c(k,\eta)\cos(m\eta) + A_s \Delta(k,\eta)\sin(m\eta)$$

$$c_a^2 = \frac{\delta P}{\delta\rho} = \frac{k^2/(4m^2a^2)}{1 + k^2/(4m^2a^2)}$$

GROWTH OF ULA PERTURBATIONS

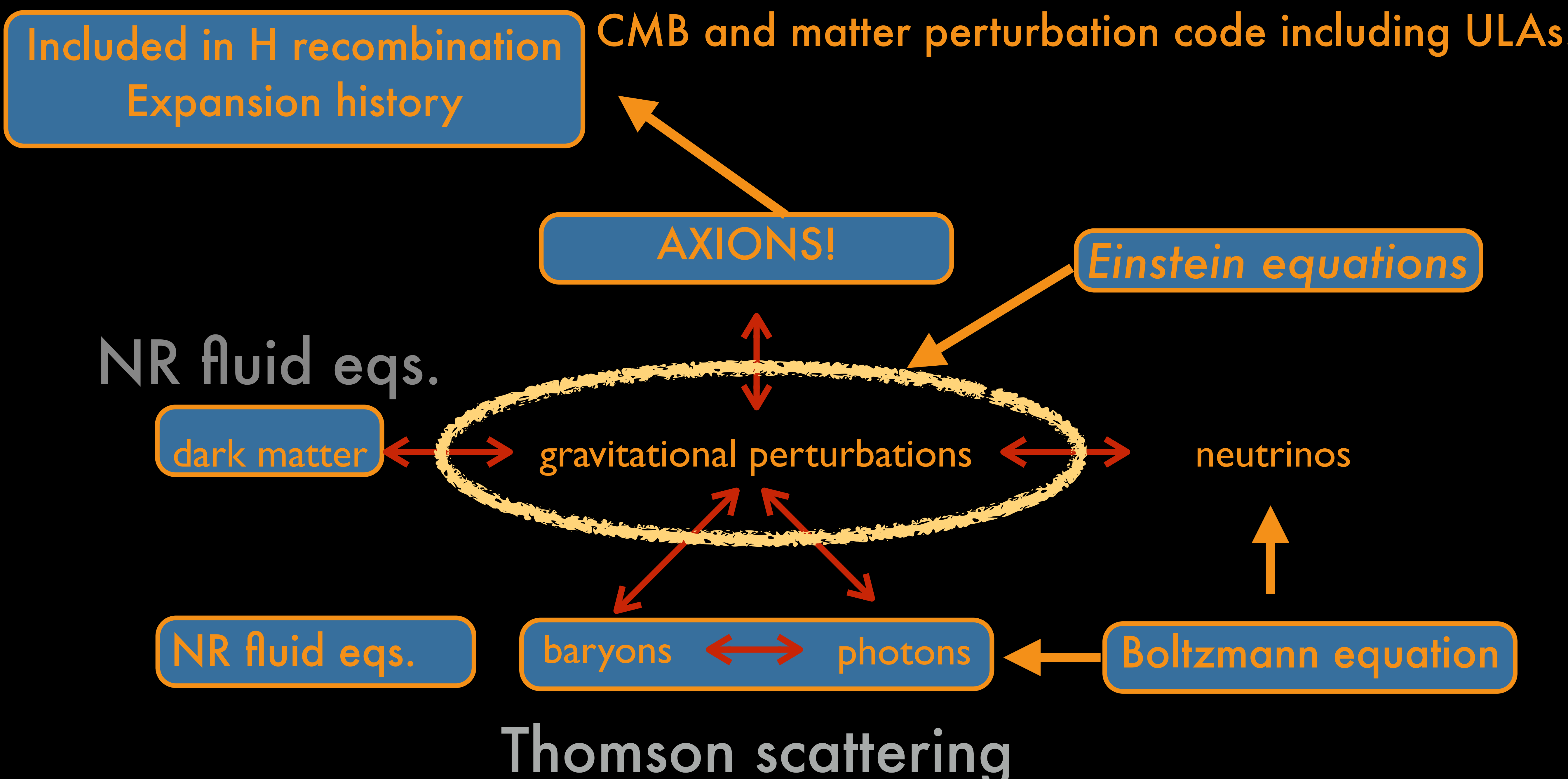


✳ Modes with $k \gg k_\mathrm{J} \sim \sqrt{m\mathcal{H}}$ oscillate instead of growing

AXIONCAMB

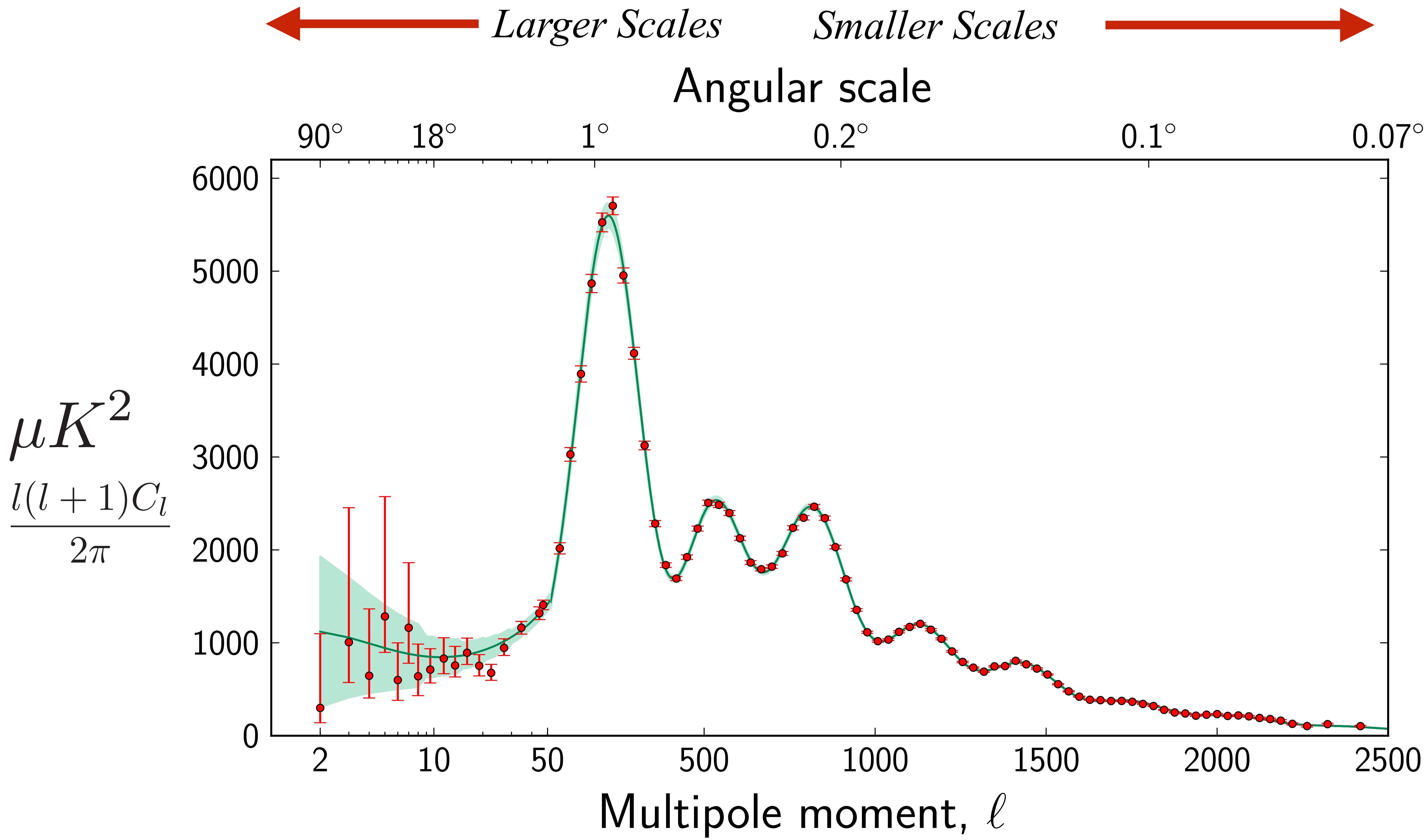
Code by Grin et al. 2013, based on CAMB (A. Lewis)

http://github.com/dgrin1/axionCAMB

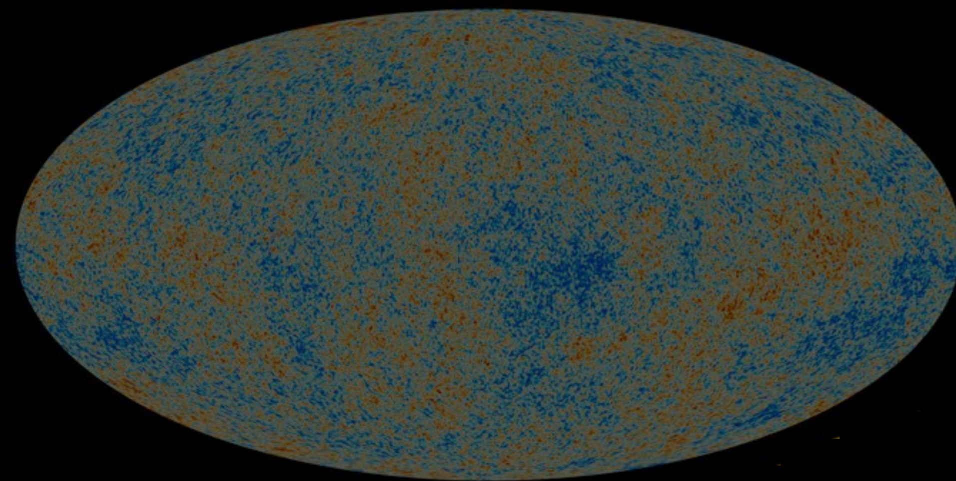


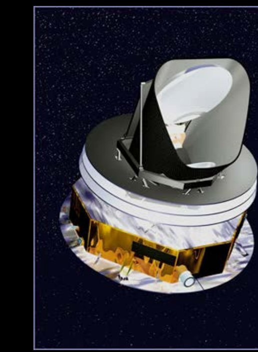
ULA of any mass is self-consistently followed from DE to DM regime

AXIONCAMB


Larger Scales
Smaller Scales
Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
μK^2
$\frac{l(l+1)C_l}{2\pi}$
2
10
50
500
1000
1500
2000
2500
Multipole moment, ℓ

Data + Analysis

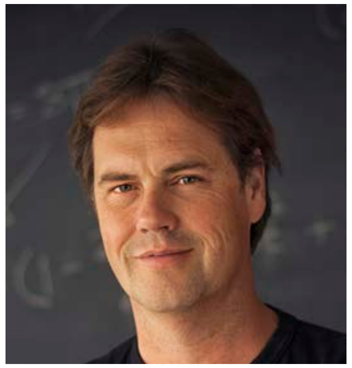


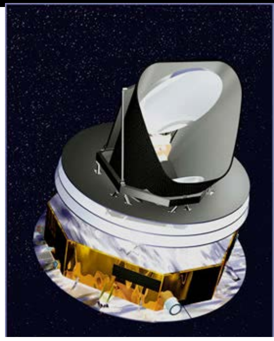


- Planck 2013 temperature anisotropy power spectra (+SPT+ACT)
  - Cosmic variance limited to $\ell \sim 1500$
- WiggleZ galaxy survey (linear scales only $k \lesssim 0.2h\ \mathrm{Mpc}^{-1}$)
  - 240,000 emission line galaxies at z<1
  - 3.9 m Anglo-Australian Telescope (AAT)
- Nested sampling, MCMC, vary $m_a, \Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\rm reion}$

CONSTRAINTS

Comparison with data





R.Hlozek, DG, D.J. E. Marsh, P.Ferreira

arXiv: 1708.05681, submitted to Phys. Rev. D

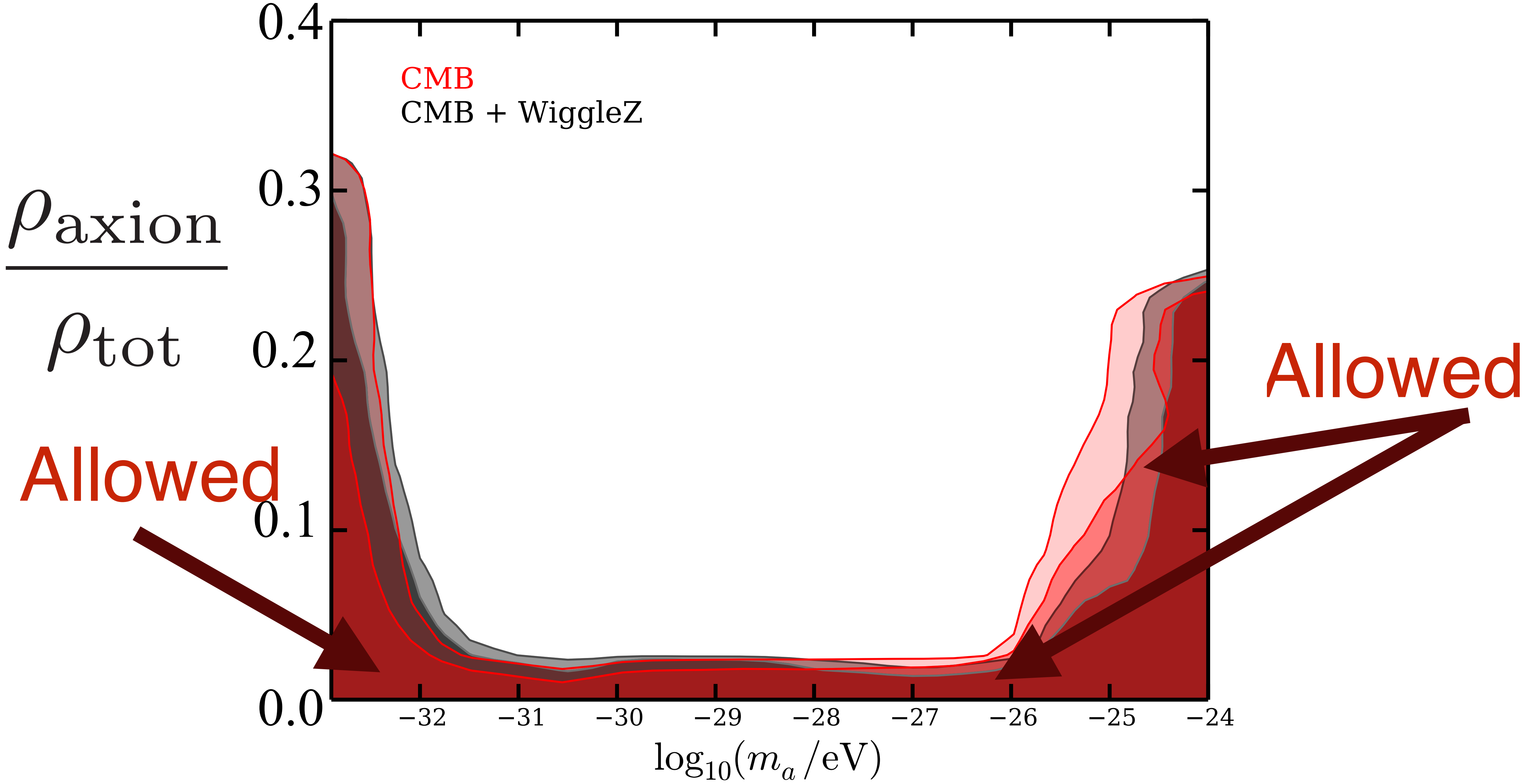
arXiv: 1607.08208, Phys. Rev. D 95, 123511 (2017).

arXiv:1410.2896, Phys. Rev. D 91, 103512 (2015)

arXiv:1403.4216, Phys. Rev. Lett. 113, 011801 (2014)

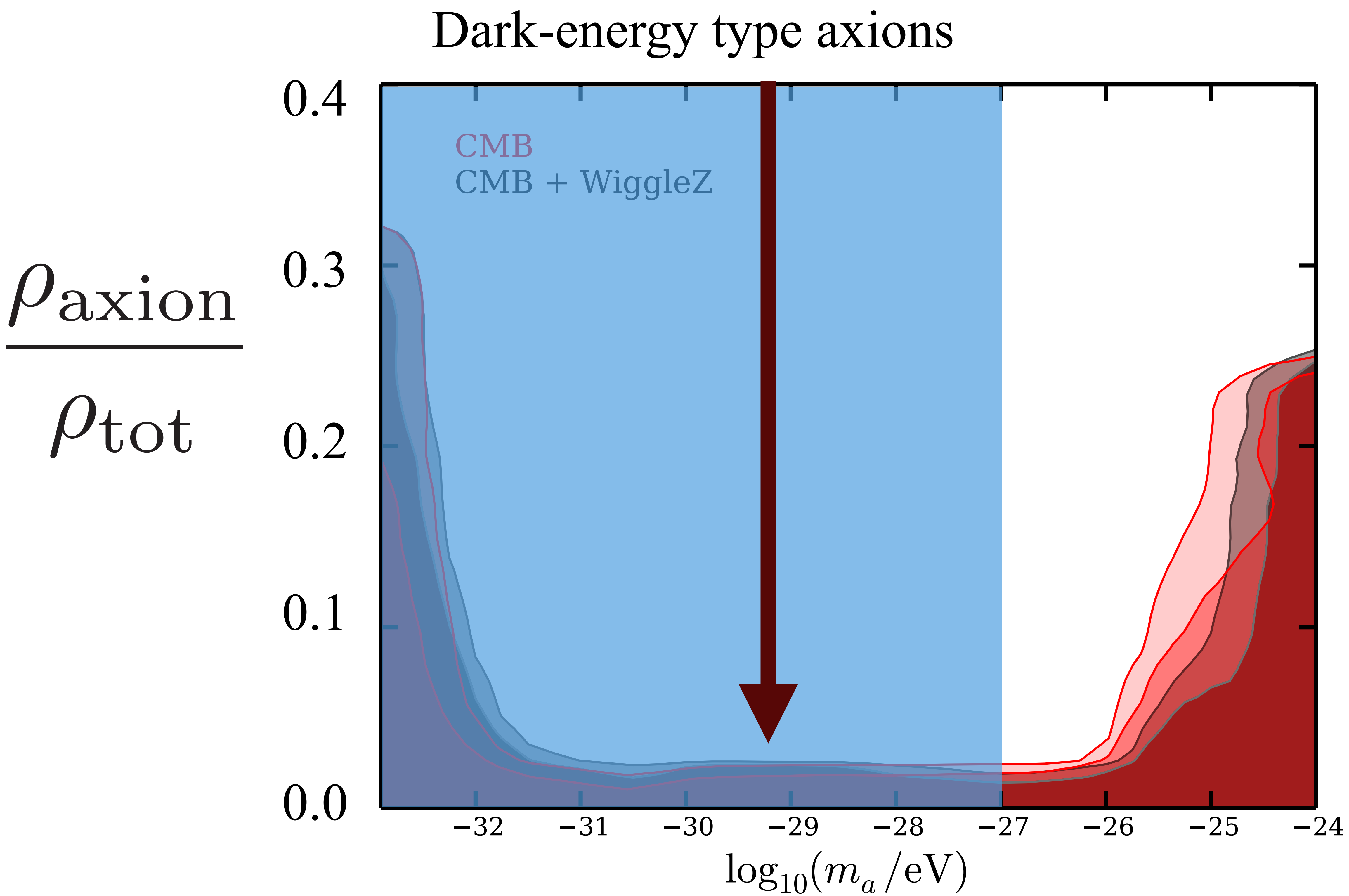
arXiv:1303.3008, Phys. Rev. D 87, 121701(R) (2013)

CONSTRAINTS



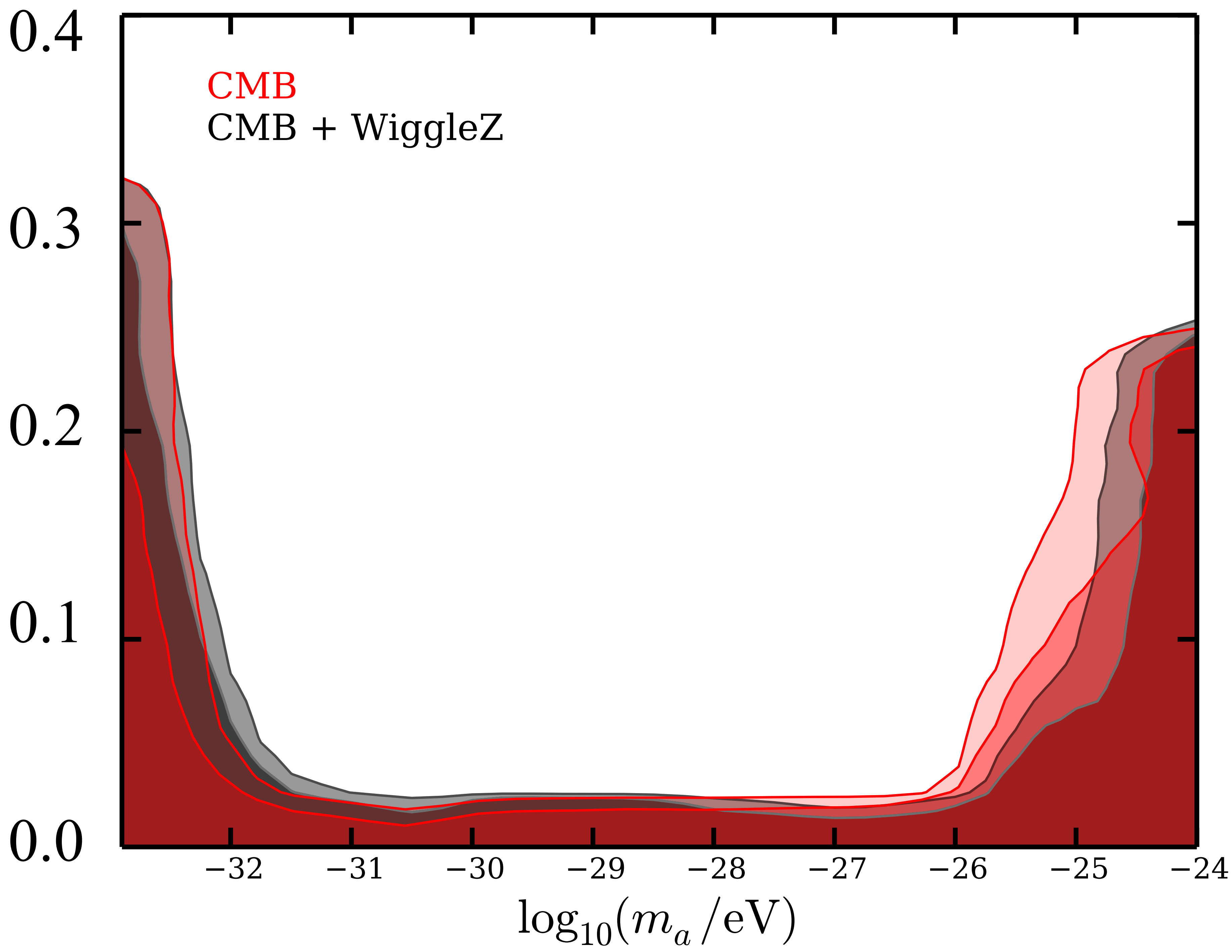
Thanks to AXIONCAMB and Planck

✴ULAs are viable DM/DE candidates in linear theory outside ``belly"

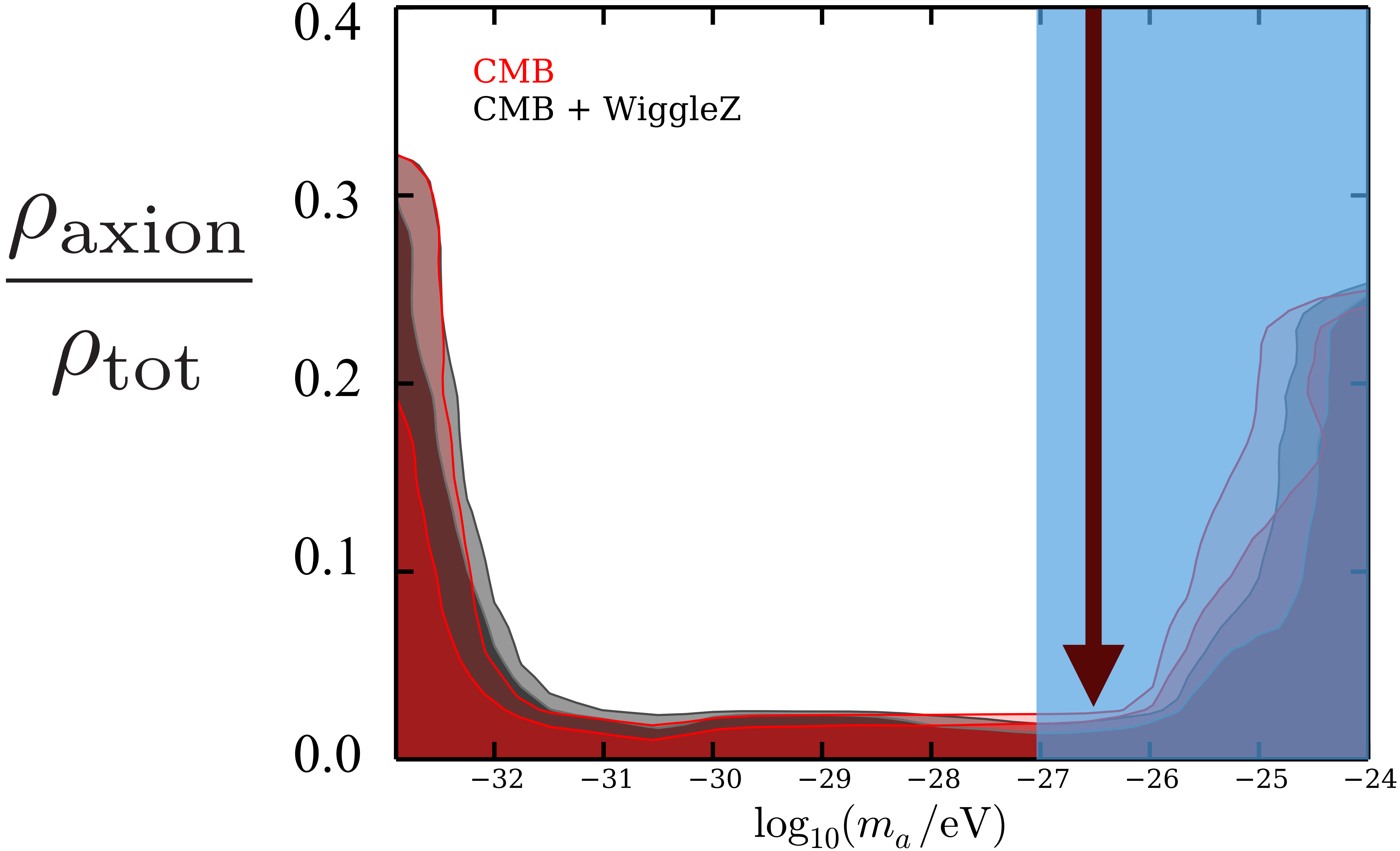


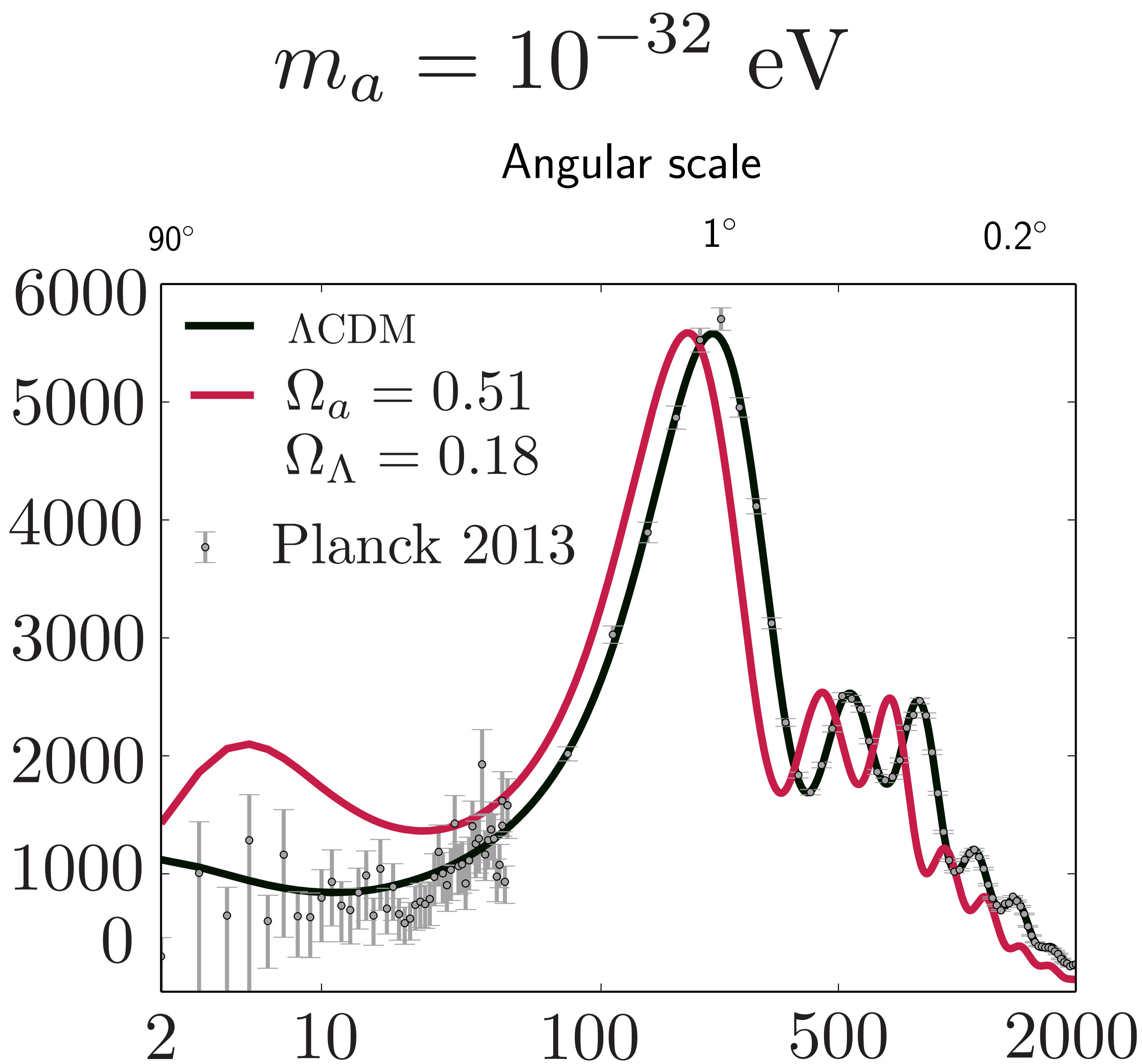
Dark-energy type axions
$\frac{\rho_{axion}}{\rho_{tot}}$
0.4
0.3
0.2
0.1
0.0
CMB
CMB + WiggleZ
−32
−31
−30
−29
−28
−27
−26
−25
−24
$\log_{10}(m_a/\mathrm{eV})$

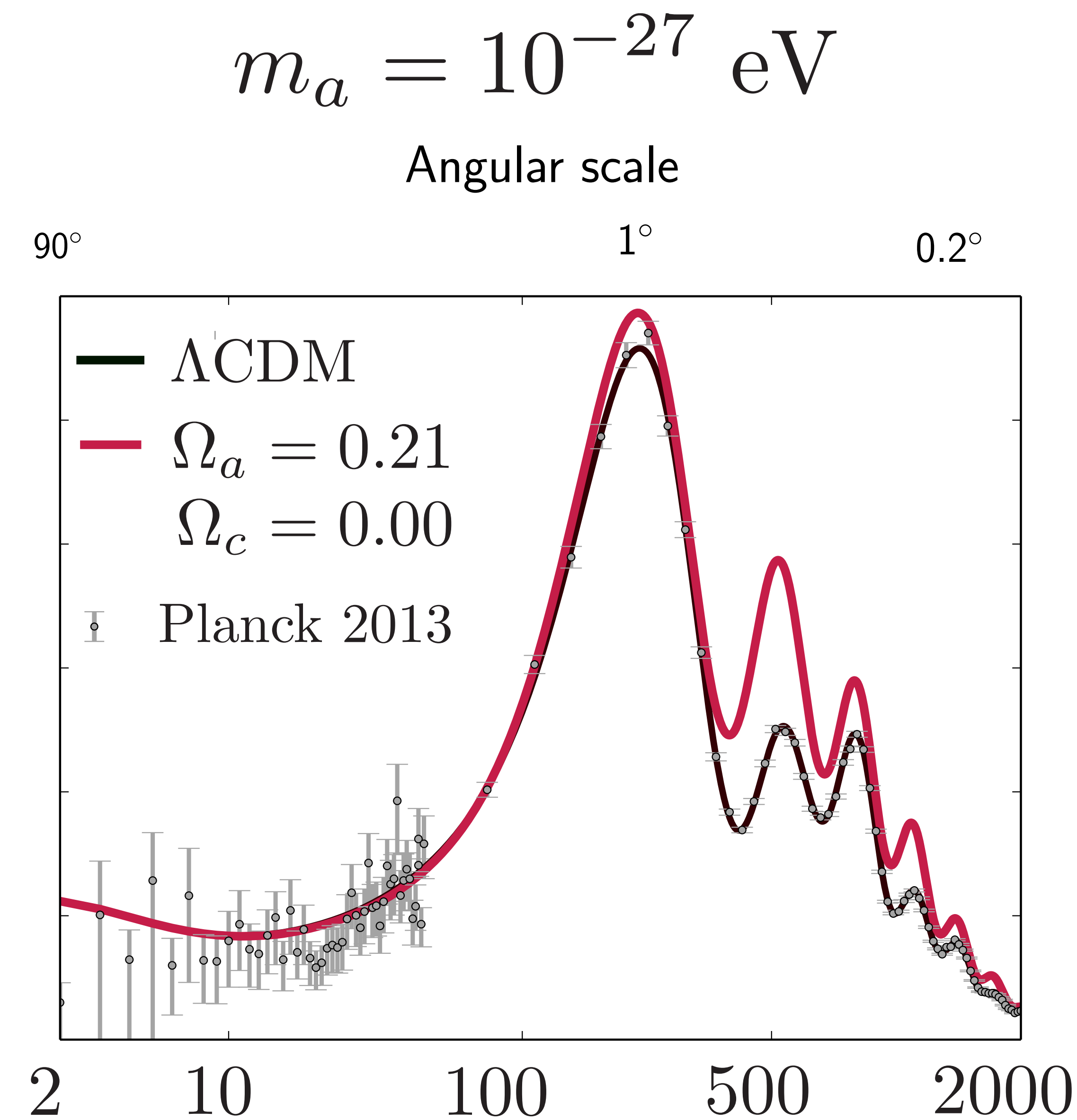
$$\frac{\rho_{\rm axion}}{\rho_{\rm tot}}$$



Dark-matter type axions

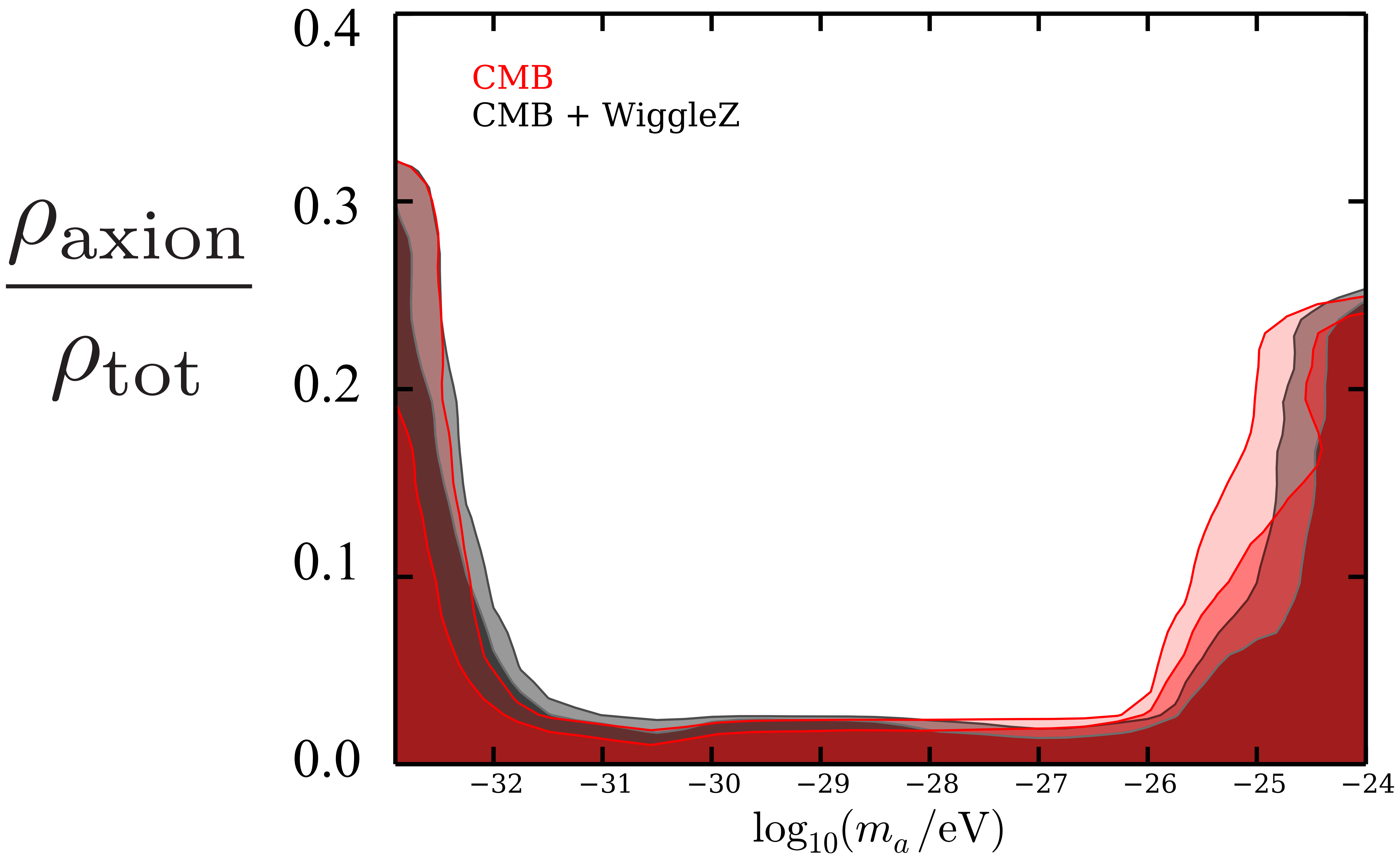


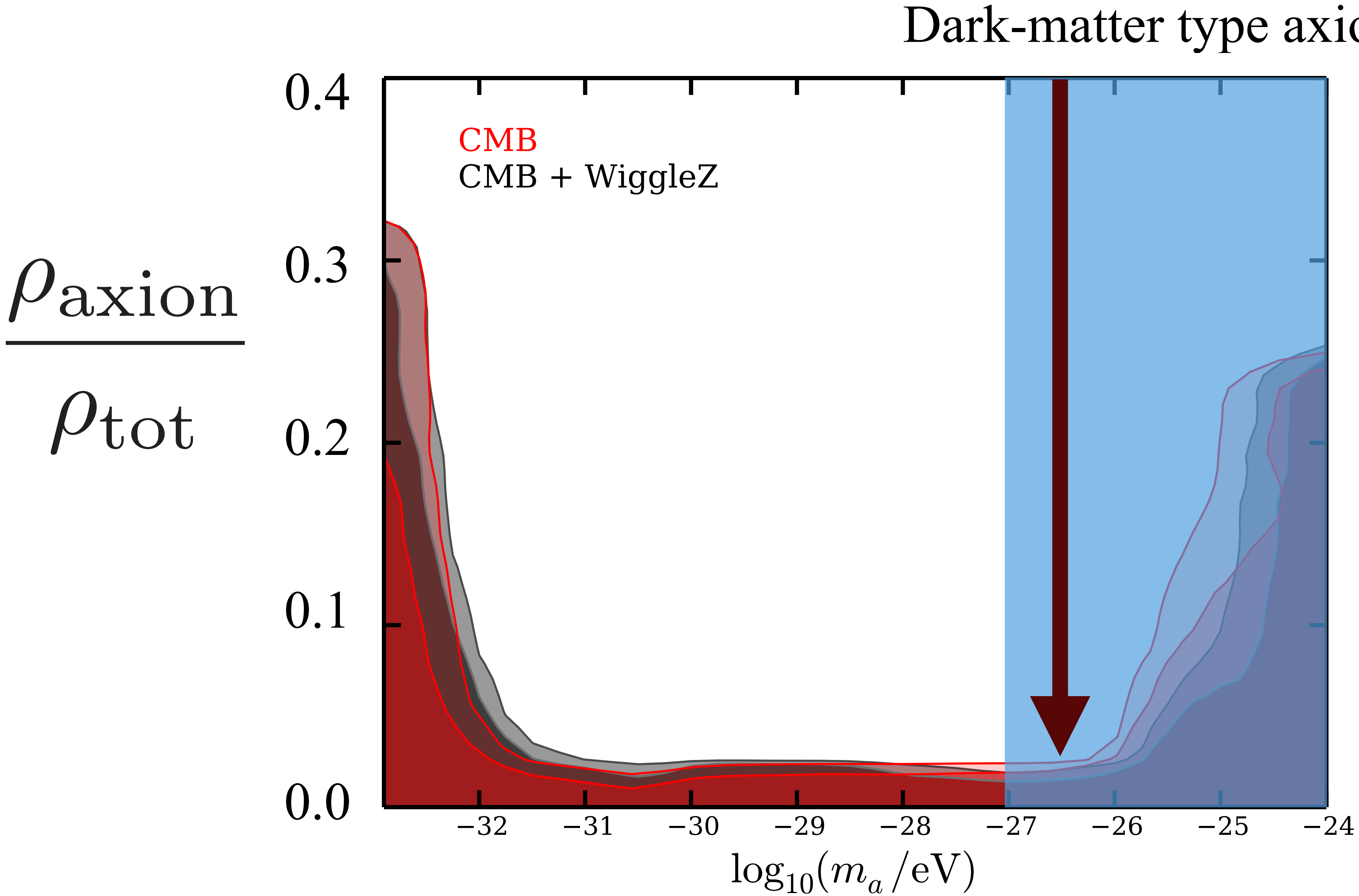




Dramatic changes to observables can result

CONSTRAINTS




Dark-matter type axions
$\frac{\rho_{\text{axion}}}{\rho_{\text{tot}}}$
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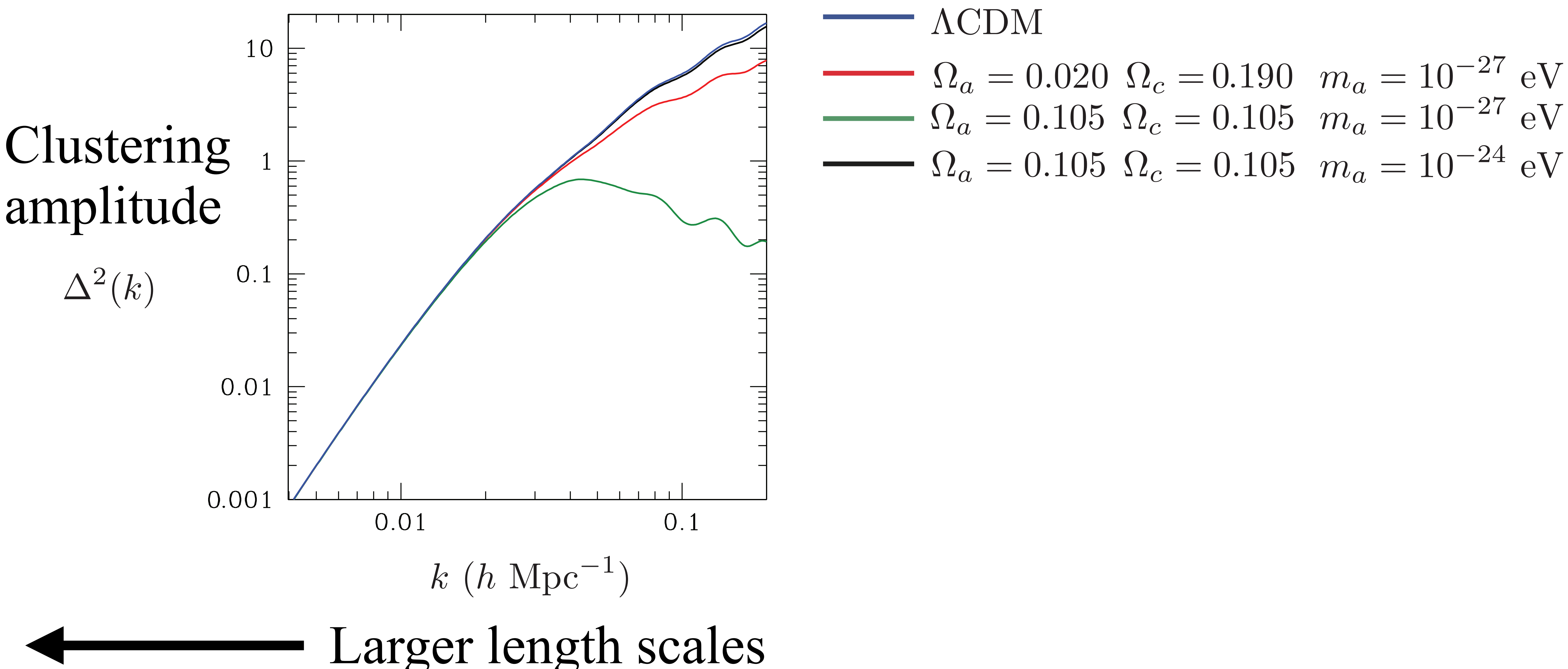
0.3
0.2
0.1
0.0
CMB
CMB + WiggleZ
−32
−31
−30
−29
−28
−27
−26
−25
−24
$\log_{10}(m_a/\text{eV})$

Matter clustering for ULA (in dark matter regime)

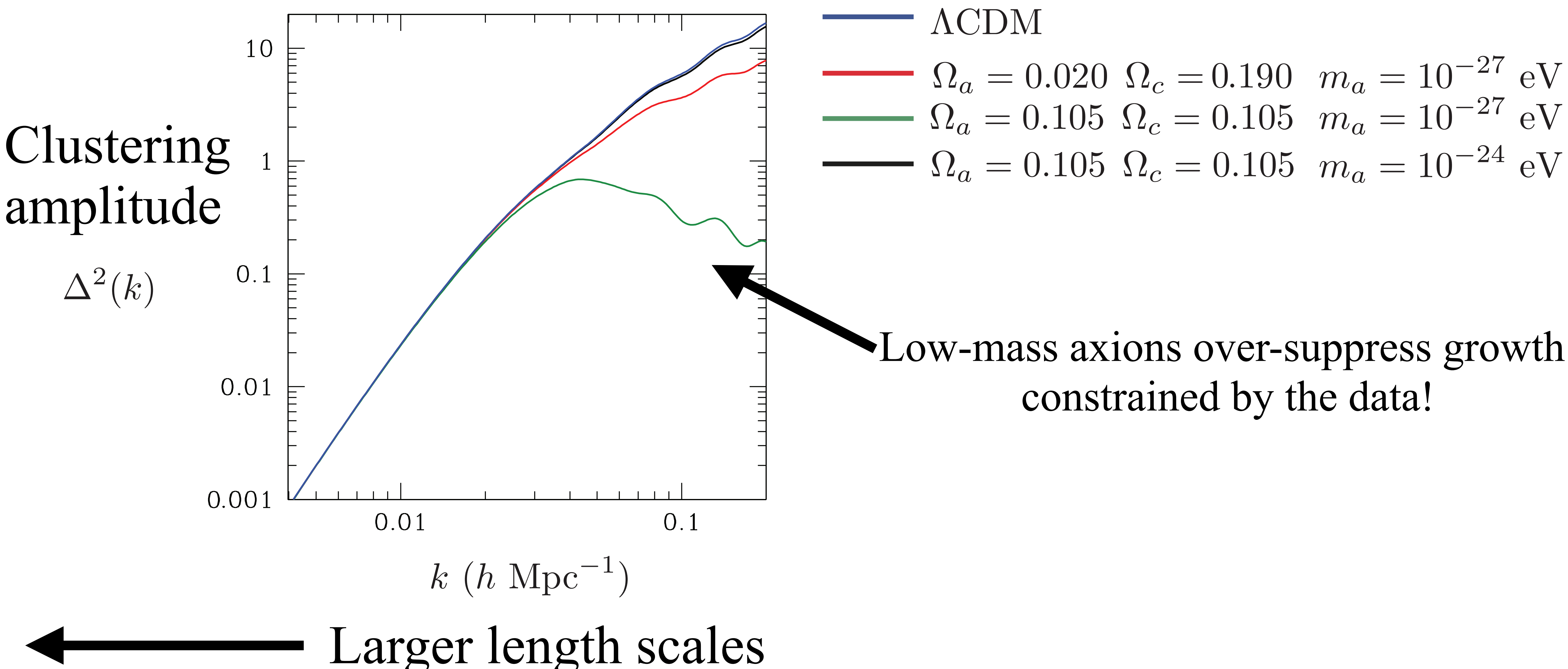
- Galaxies trace the matter in the universe

Matter clustering for ULA (in dark matter regime)



- DM structure growth severely suppressed on scales $k > k_J \simeq \sqrt{m\mathcal{H}}$
- Suppression grows $\propto -\dfrac{\Omega_a}{\Omega_a + \Omega_c}$

Matter clustering for ULA (in dark matter regime)



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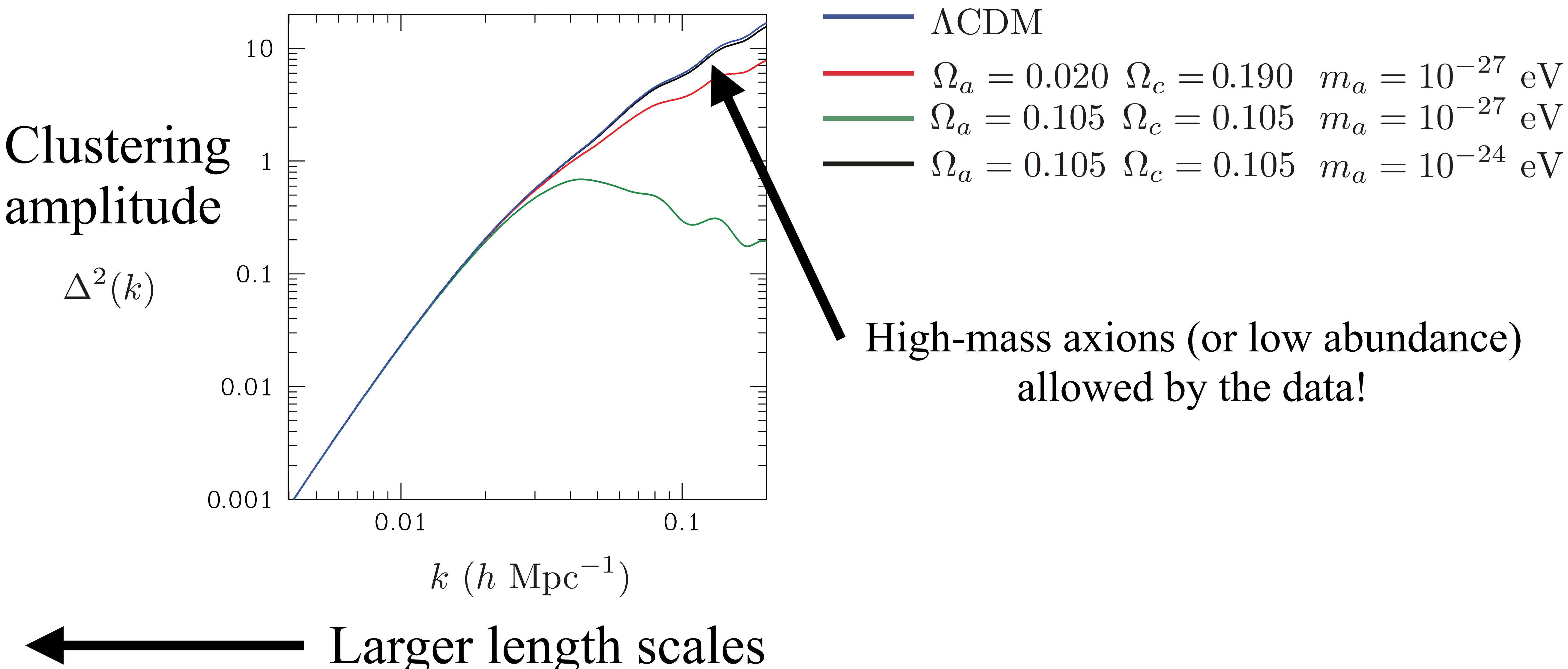
Matter clustering for ULA (in dark matter regime)



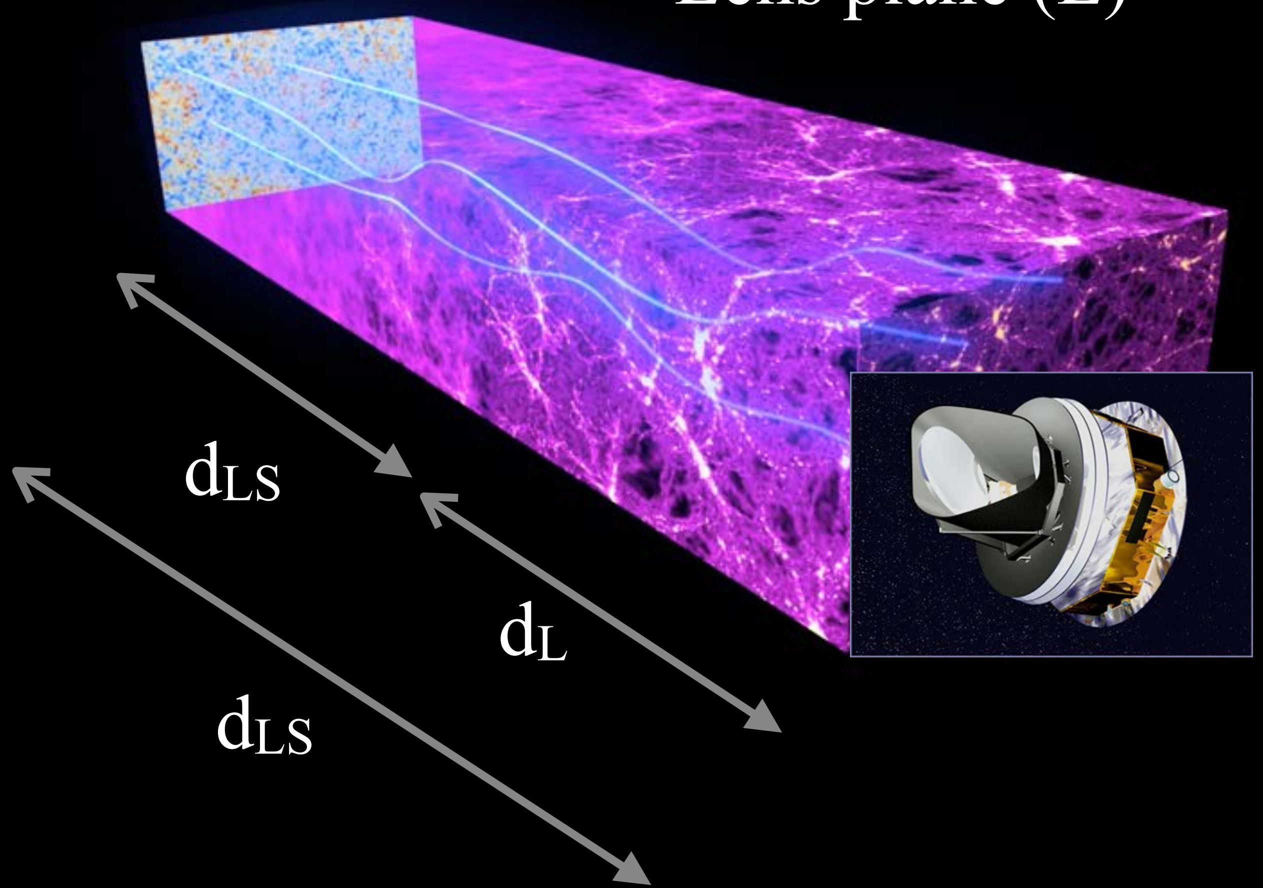
- DM structure growth severely suppressed on scales $k > k_J \simeq \sqrt{m\mathcal{H}}$
- Suppression grows $\propto -\dfrac{\Omega_a}{\Omega_a + \Omega_c}$

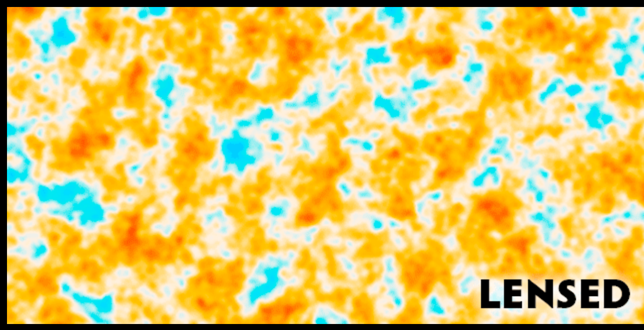
CMB LENSING

A slice of (dark matter) life at z~1

Source Plane (S)

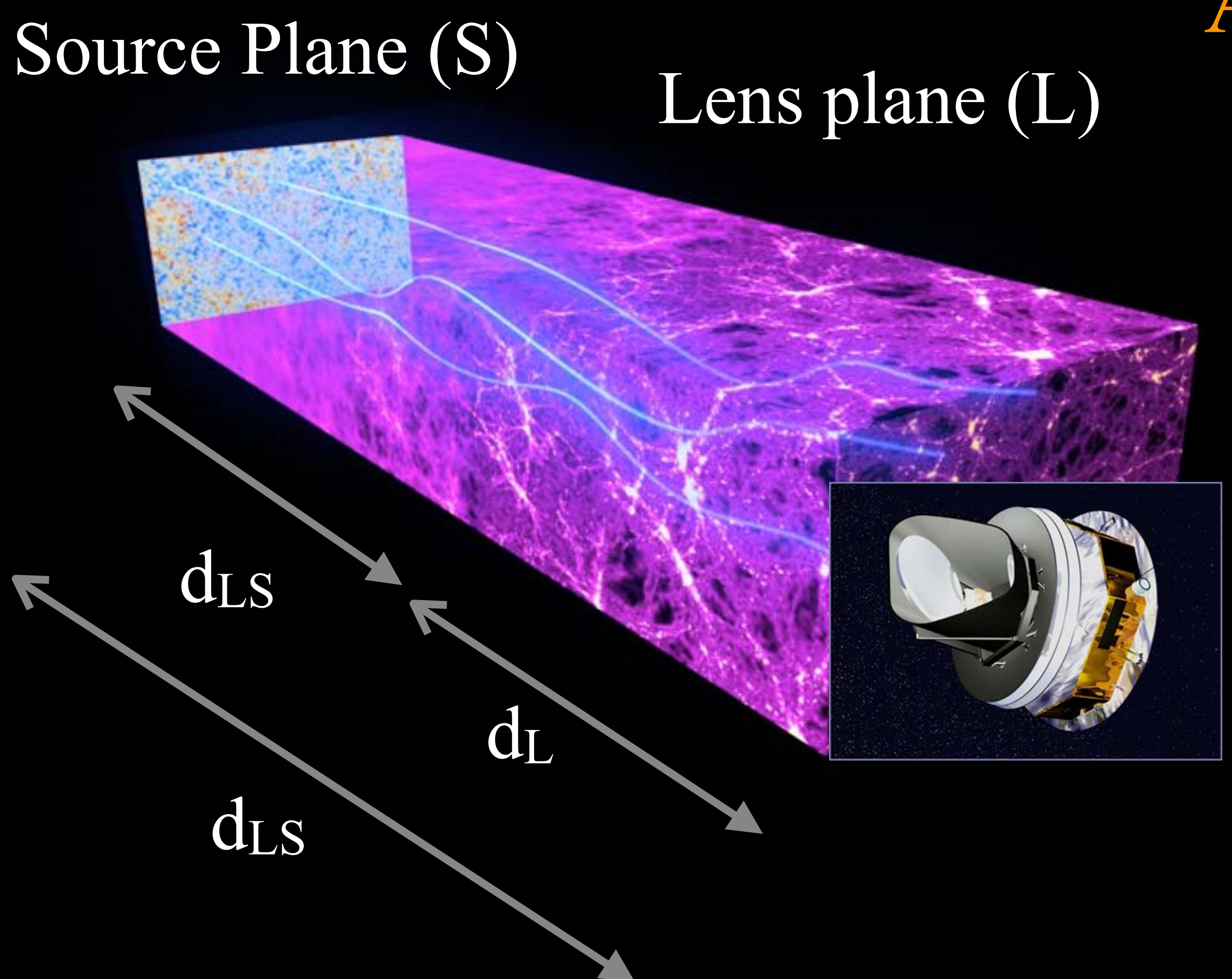
Lens plane (L)

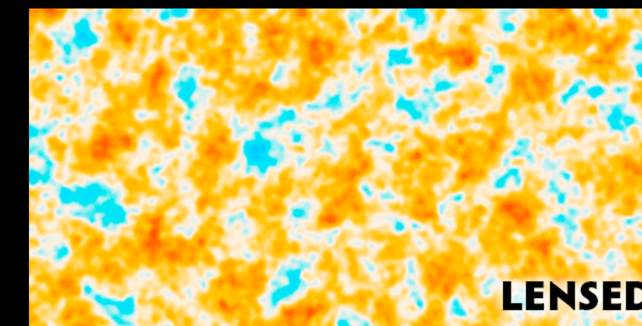




$$\vec{\alpha} = \nabla_{\vec{\theta}} \left\{ \int \left(\frac{d_{\rm LS}}{d_{\rm L} d_{\rm S}} \right) \Phi \left[d(\eta)\vec{\theta}, \eta \right] d\eta \right\}$$

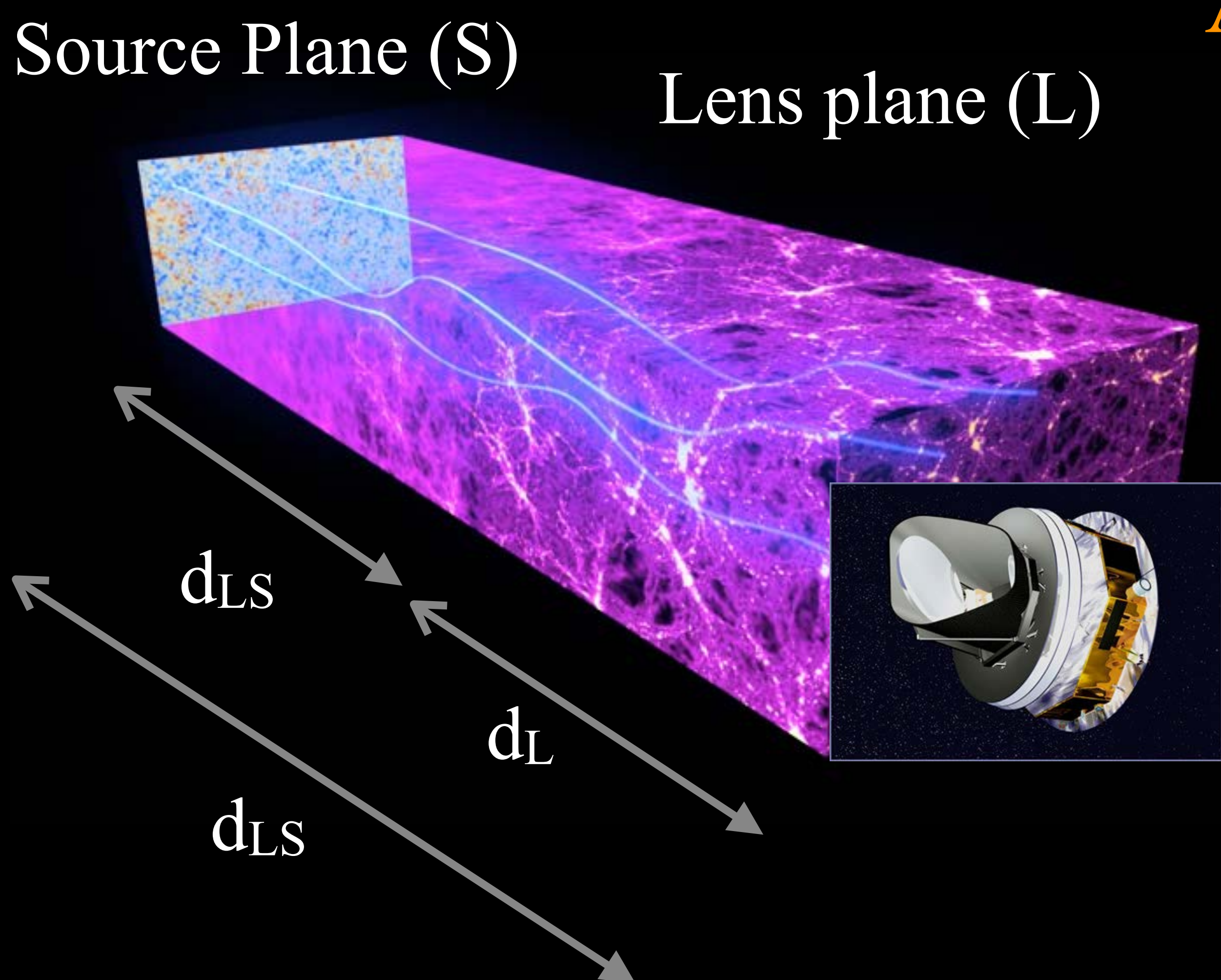
A slice of (dark matter) life at z~1

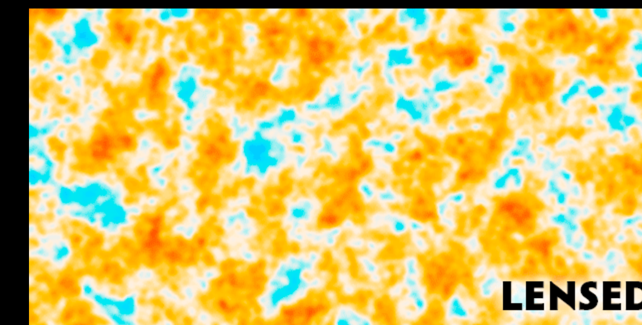




$$\vec{\alpha} = \nabla_{\vec{\theta}} \left\{ \int \left(\frac{d_{\rm LS}}{d_{\rm L} d_{\rm S}} \right) \Phi \left[d(\eta)\vec{\theta}, \eta \right] d\eta \right\}$$

A slice of (dark matter) life at z~1

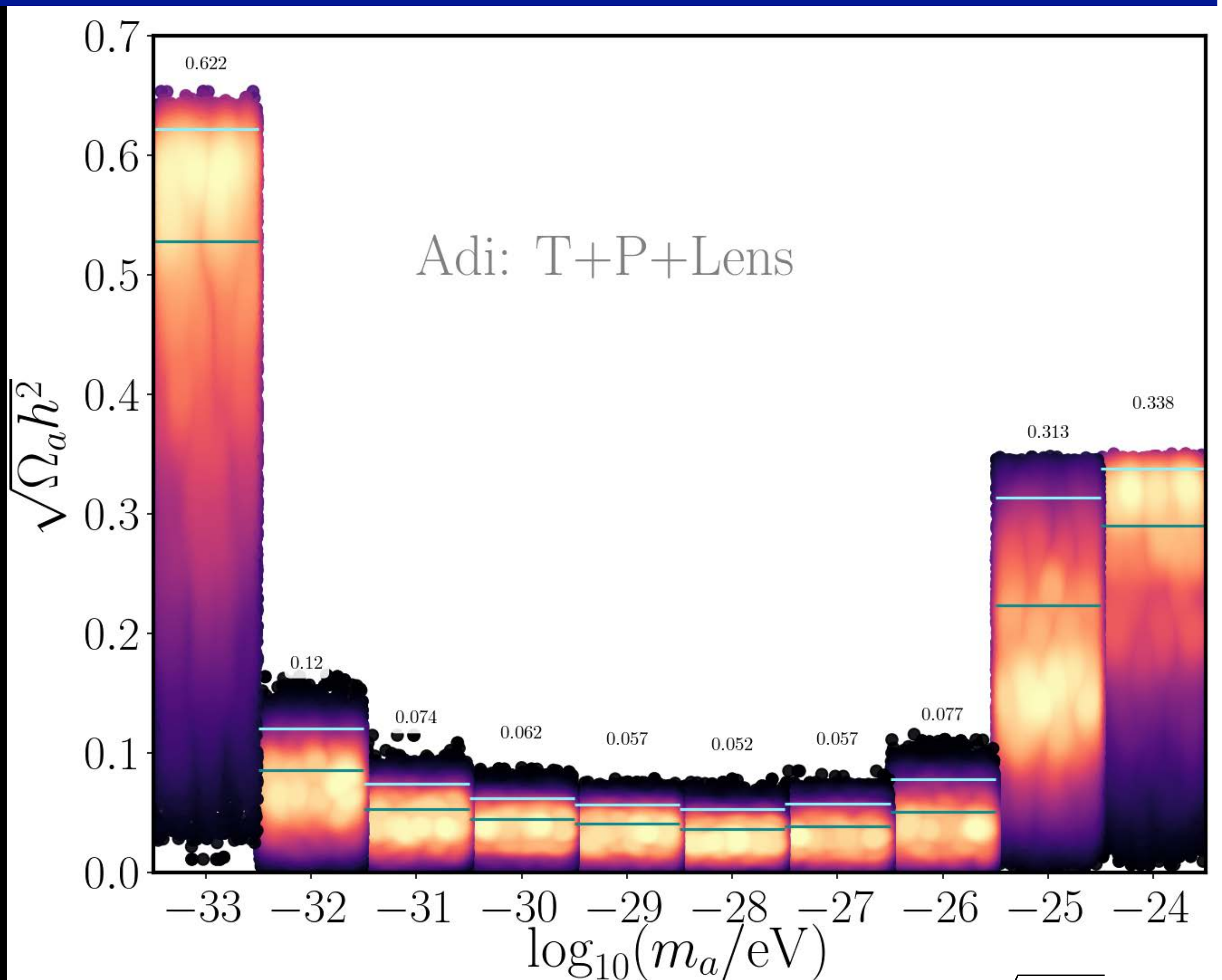


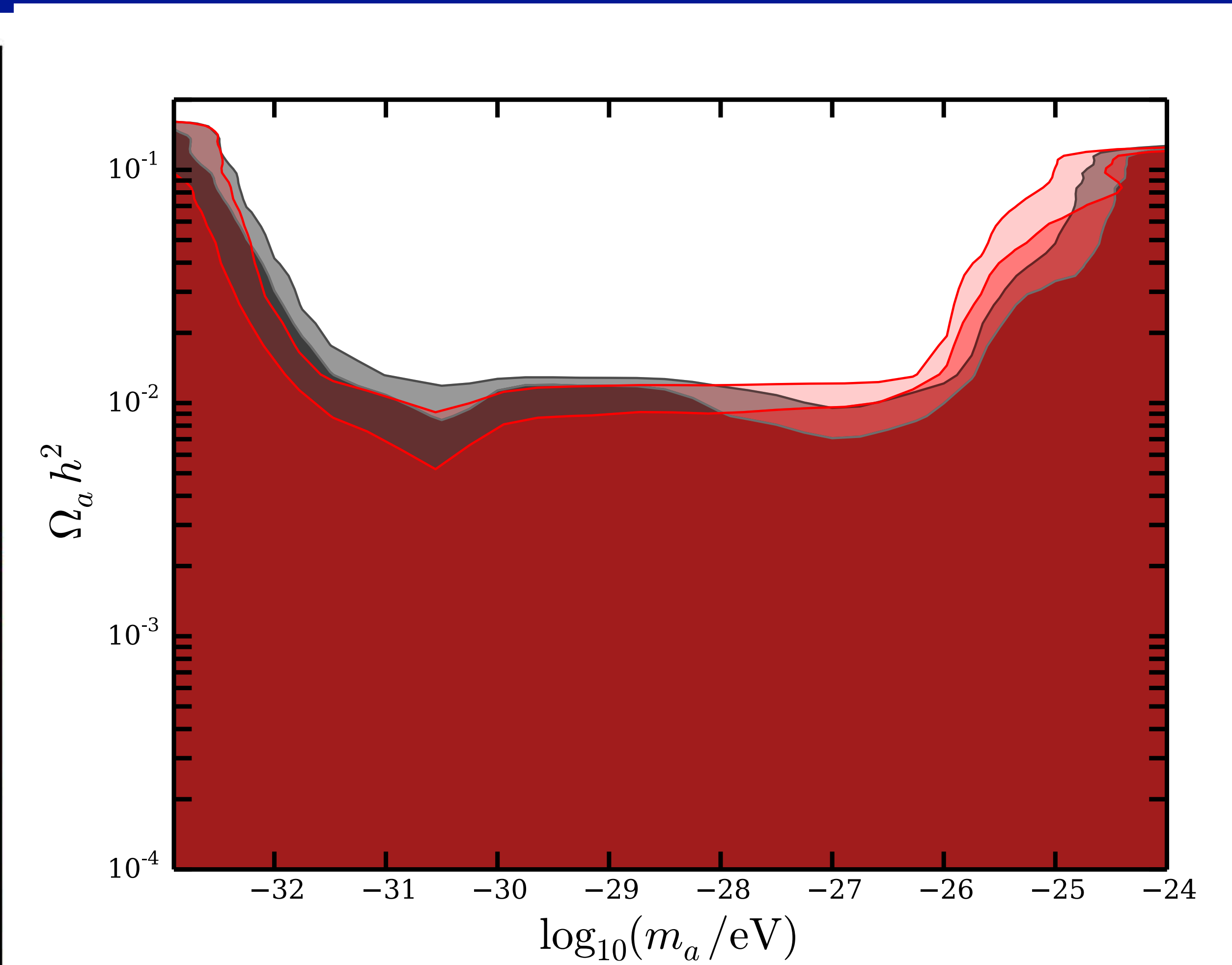


$$\vec{\alpha} = \nabla_{\vec{\theta}} \left\{ \int \left(\frac{d_{\mathrm{LS}}}{d_{\mathrm{L}} d_{\mathrm{S}}} \right) \Phi \left[d(\eta)\vec{\theta}, \eta \right] d\eta \right\}$$

ULAs change

CMB LENSING





https://arxiv.org/abs/1708.05681

Monthly Notices of the Royal Astronomical Society, Volume 476, Issue 3, 21 May 2018, Pages 3063–3085

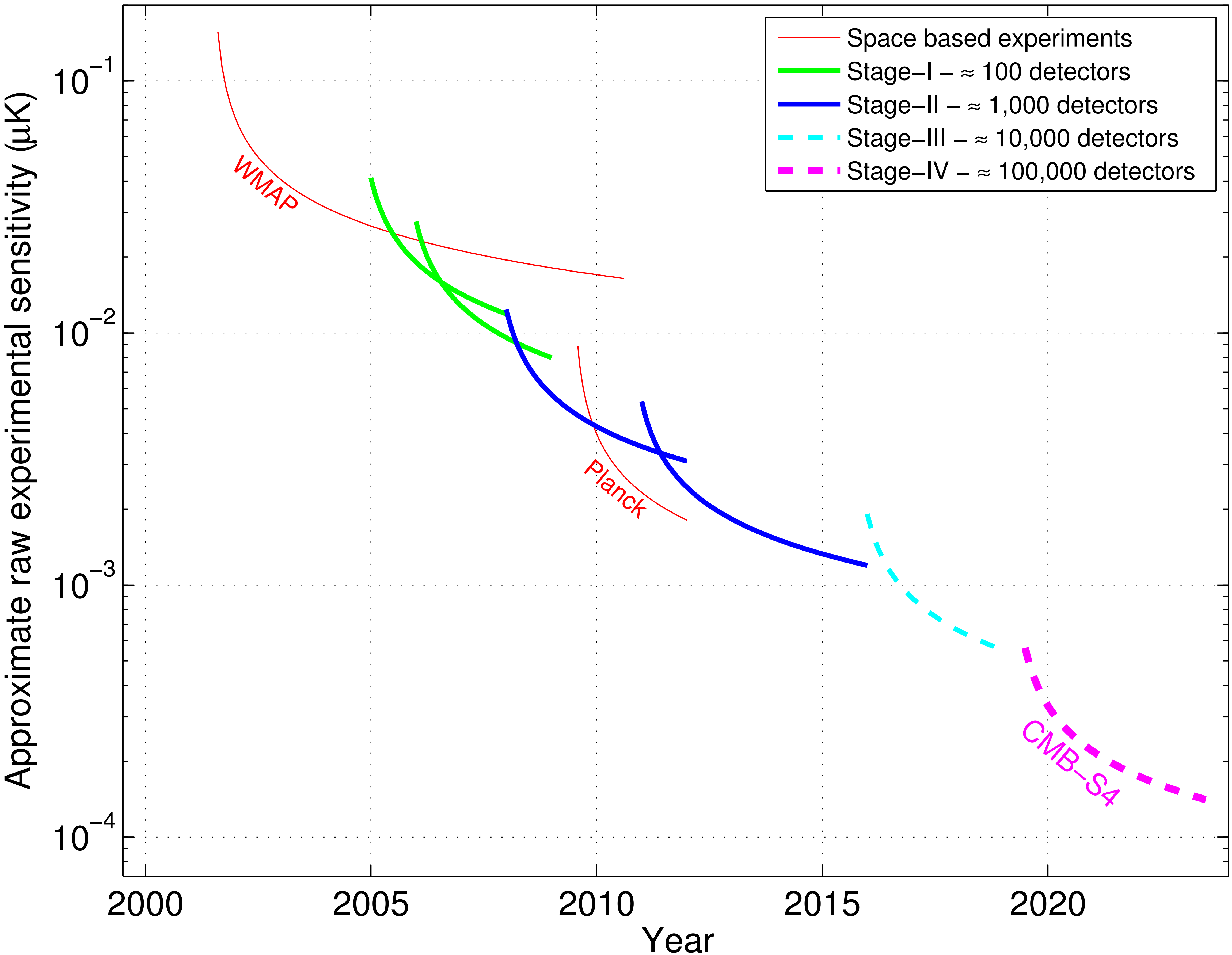
CMB-S4

CMB-S4
Next Generation CMB Experiment

- Next gen. CMB ground-based expt. concept
  - ~1 arcmin beam
  - 1 μK arcmin noise level
  - ~500,000 detectors
  - Location, sky coverage TBD

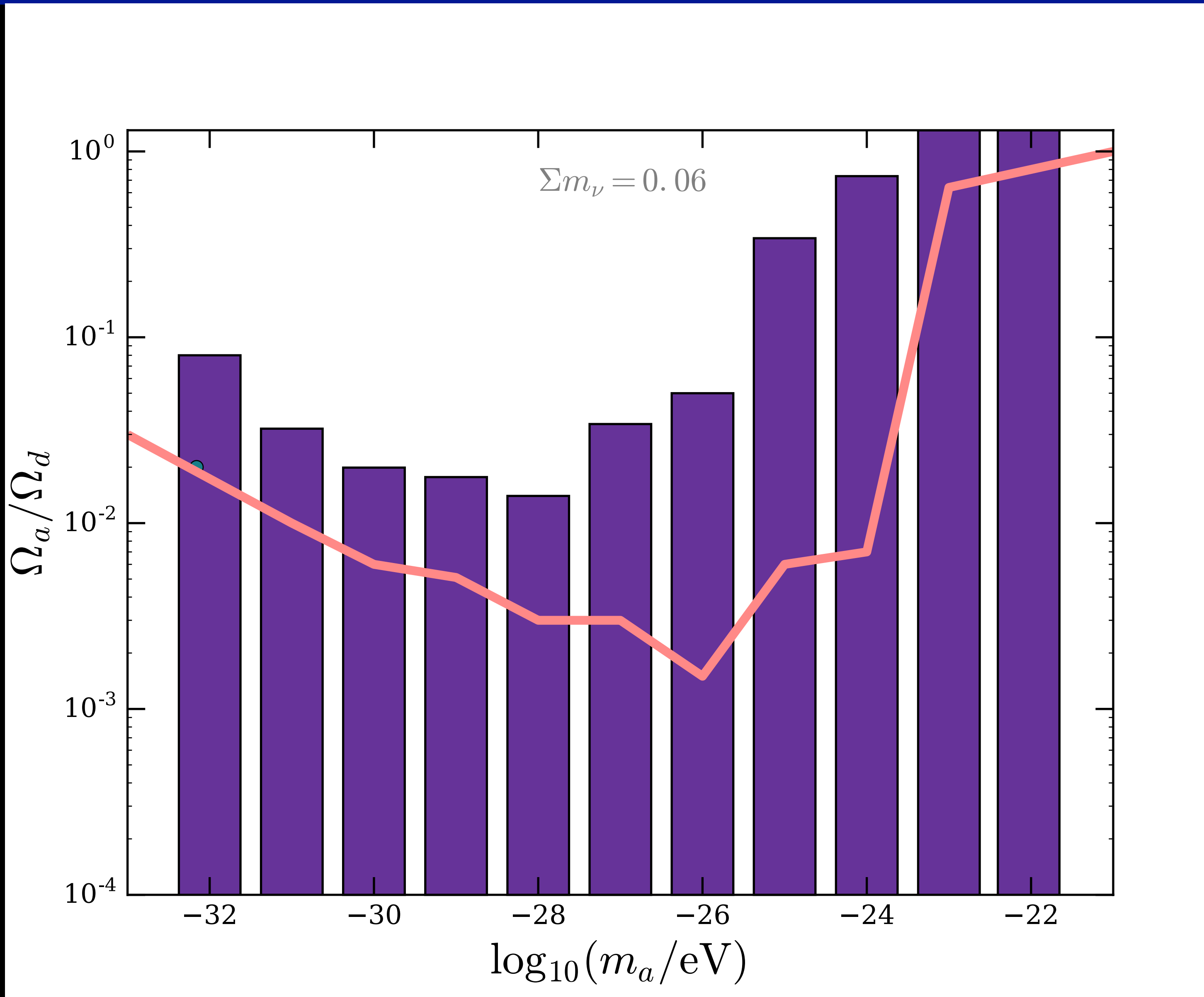
From CMB-S4 Science book…. arXiv: 1610.02743

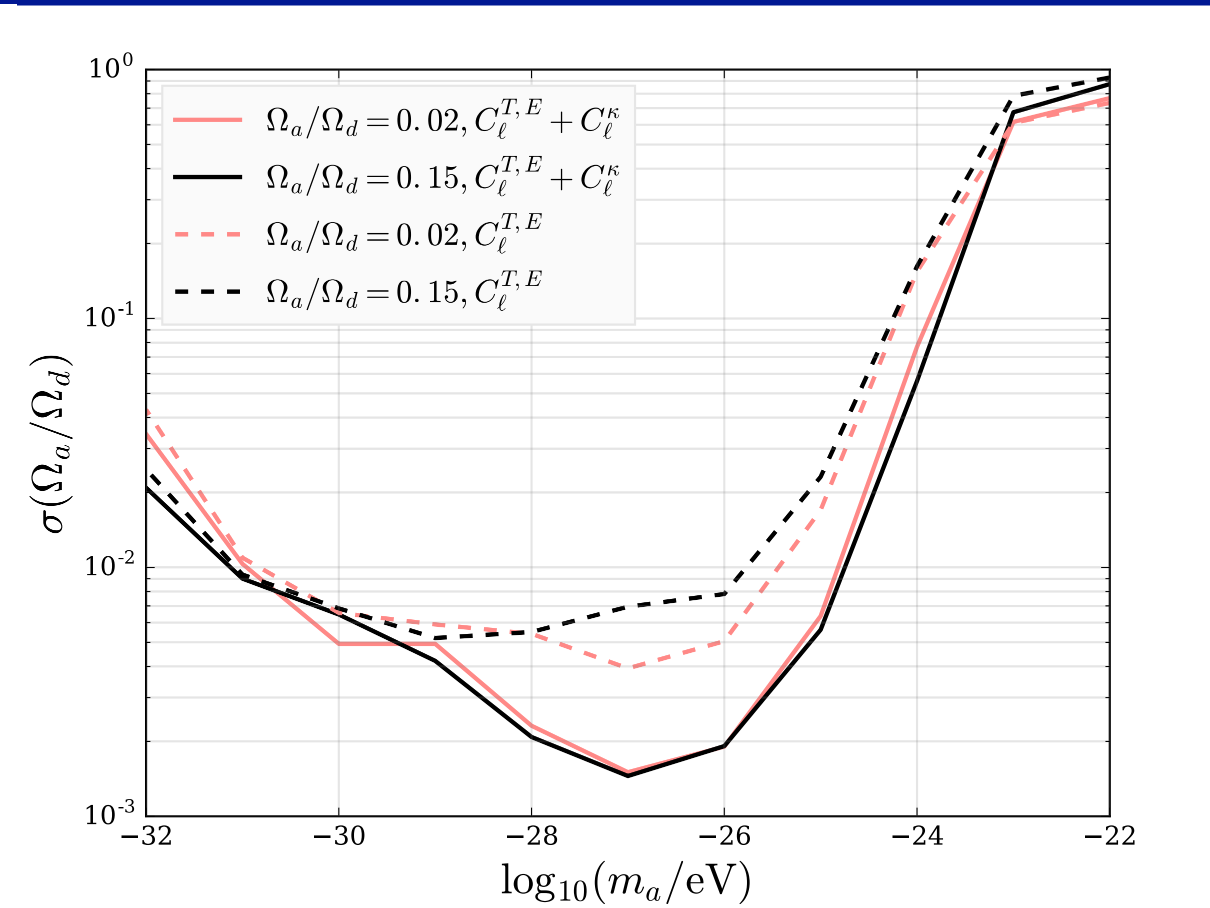
CMB-S4



Space based experiments
Stage−I − ≈ 100 detectors
Stage−II − ≈ 1,000 detectors
Stage−III − ≈ 10,000 detectors
Stage−IV − ≈ 100,000 detectors
WMAP
Planck
CMB−S4
Approximate raw experimental sensitivity (μK)
10−1
10−2
10−3
10−4
2000
2005
2010
2015
2020
Year

S4-CAST FOR LENSING AND ULAS





Fisher forecast using OXFISH code— OOM improvement driven by lensing

R.Hlozek, D.J.E. Marsh, D.G., J. Dunkley, R. Allison, E. Calabrese

arXiv: 1607.08208, Phys. Rev. D 95, 123511 (2017).

NON-LINEAR MATTERS

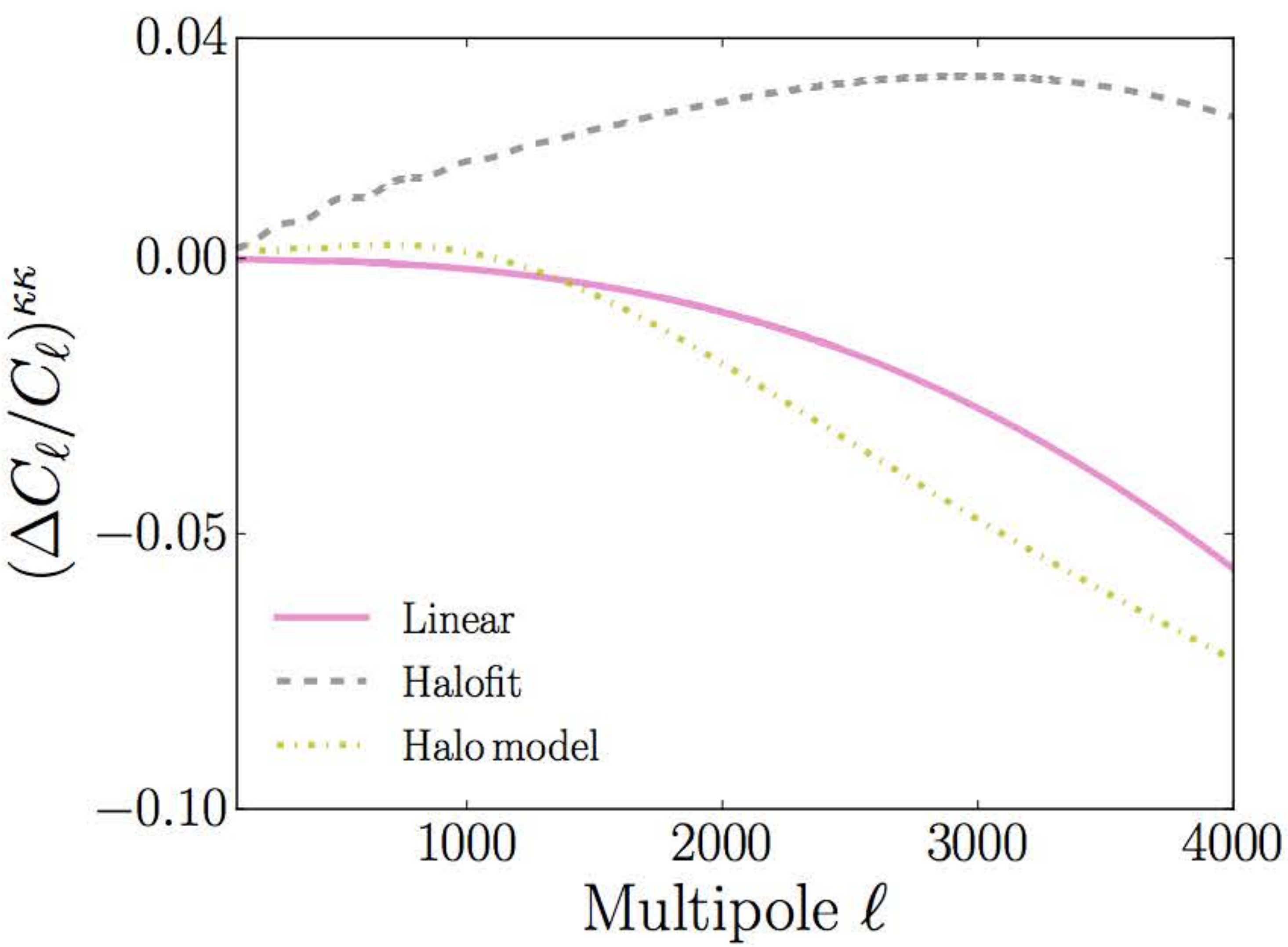


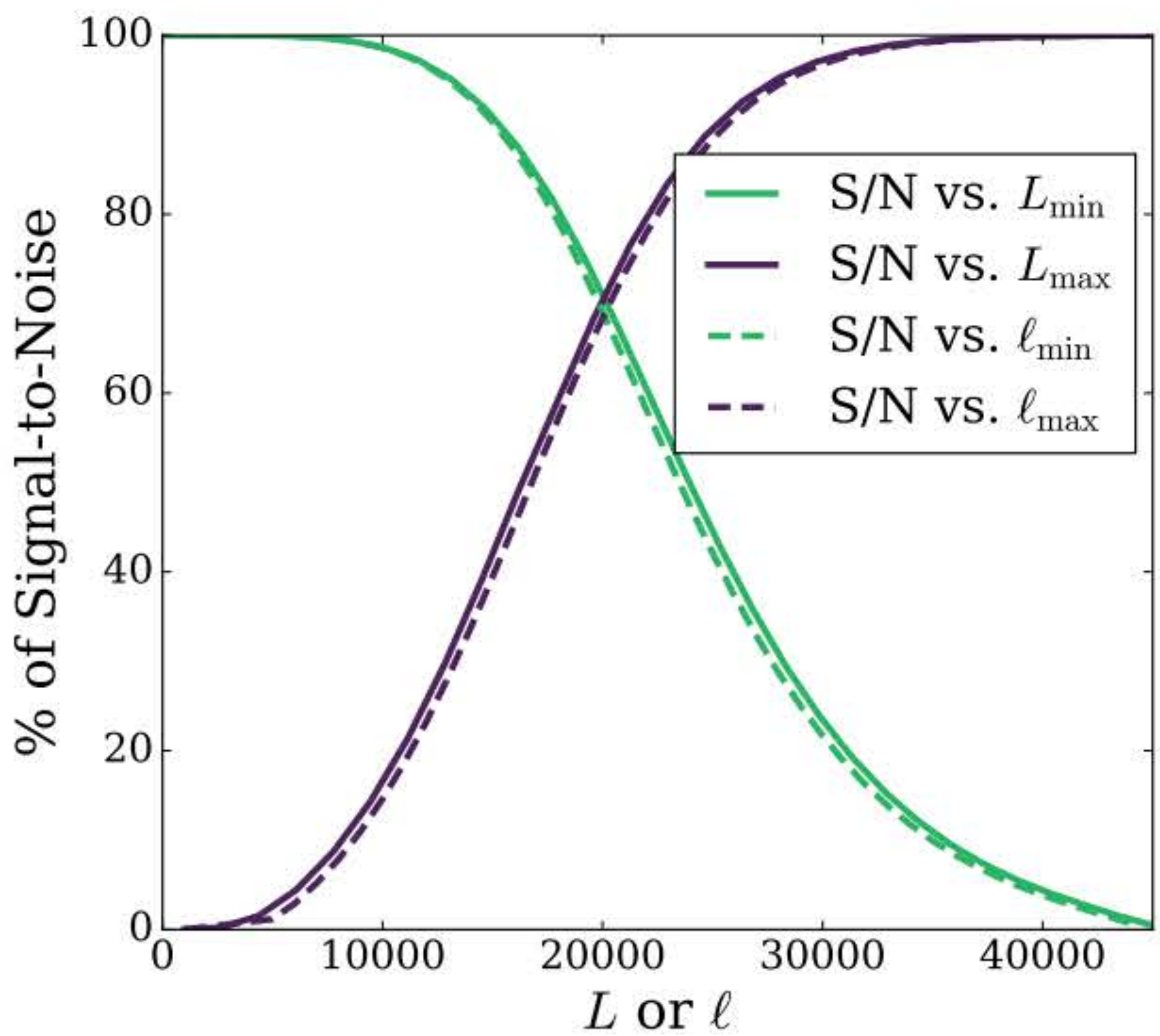
FIG. 3. **Comparison of ULAs to CDM in lensing deflection power for different models of non-linearities, where ULAs with $m_a = 10^{-23}$ eV constitute all the DM.** The unphysical power increase in the HALOFIT power for ULAs, seen in Figure 4, causes a similar unphysical increase in lensing power compared to the halo model. On the other hand, linear theory captures the sign and approximate magnitude of the effect seen in the halo model. Thus when forecasting constraints at high ULA mass we choose to use linear theory lensing as a reasonable approximation for the Fisher matrix derivative.

R.Hlozek, D.J.E. Marsh, D.G., J. Dunkley, R. Allison, E. Calabrese

arXiv: 1607.08208, Phys. Rev. D 95, 123511 (2017).

Non-linear matters

Nguyen, Sehgal, Madhavacheril, arXiv: 1710.03747

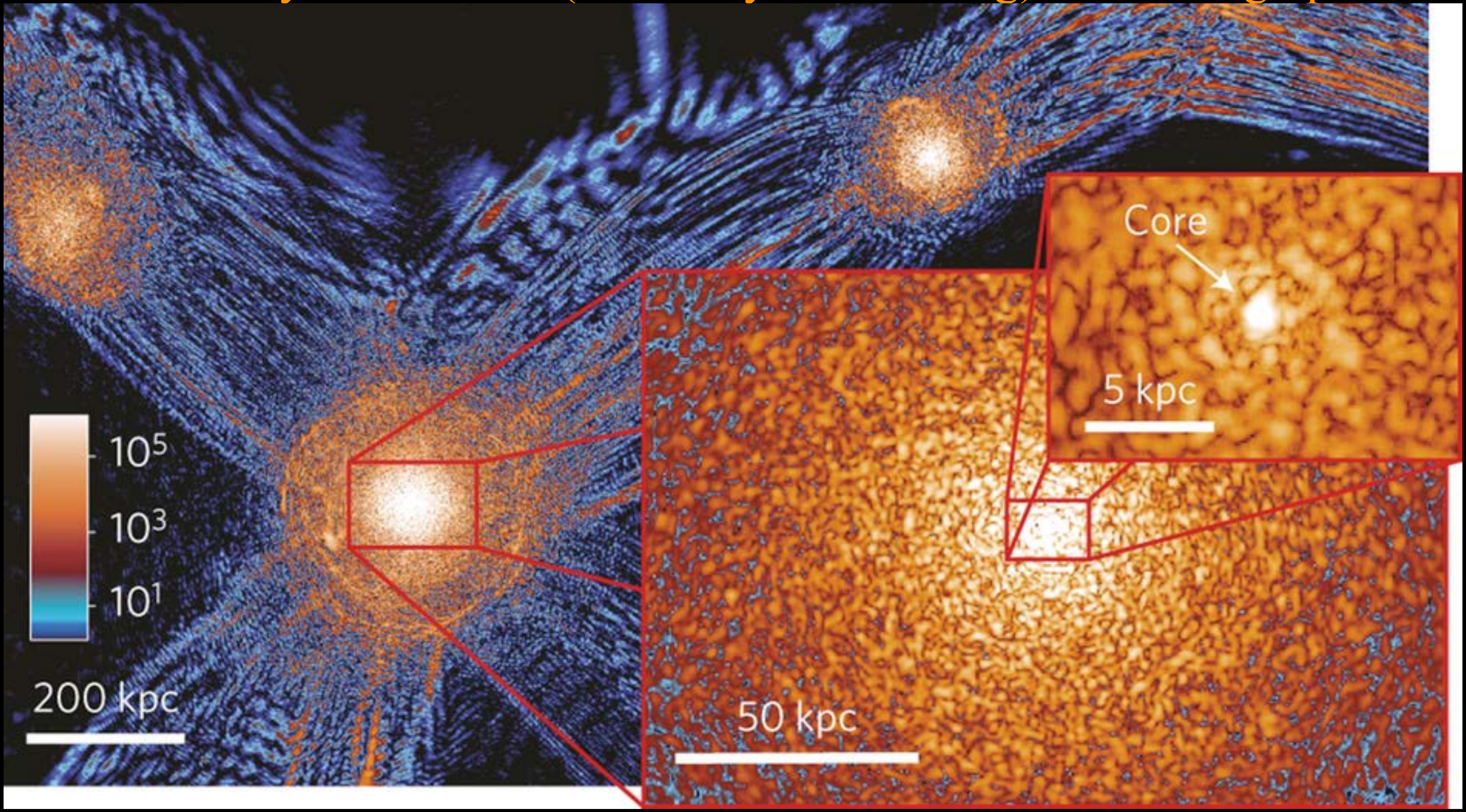


R.Hlozek, D.J.E. Marsh, D.G., J. Dunkley, R. Allison, E. Calabrese

arXiv: 1607.08208, Phys. Rev. D 95, 123511 (2017).

Non-linear matters

Fuzzy simulations (and analytic modeling) are heating up!



Cores! (Hu/Gruzinov/Barkana 2001, see also Marsh and Silk 2013, Marsh and Pop 2015, Matos 2012, Schive 2014, Vogelsberger 2017, and others)

Real Story

$$\frac{1}{R}\partial_t\left[R\partial_t a(\vec{x})\right] - (\nabla^2 - m_a^2 R^2)a(\vec{x},t) \propto \Psi$$

Work in progress, J. Cookmeyer HC 2017, now at Berkeley

Fluid Approximation

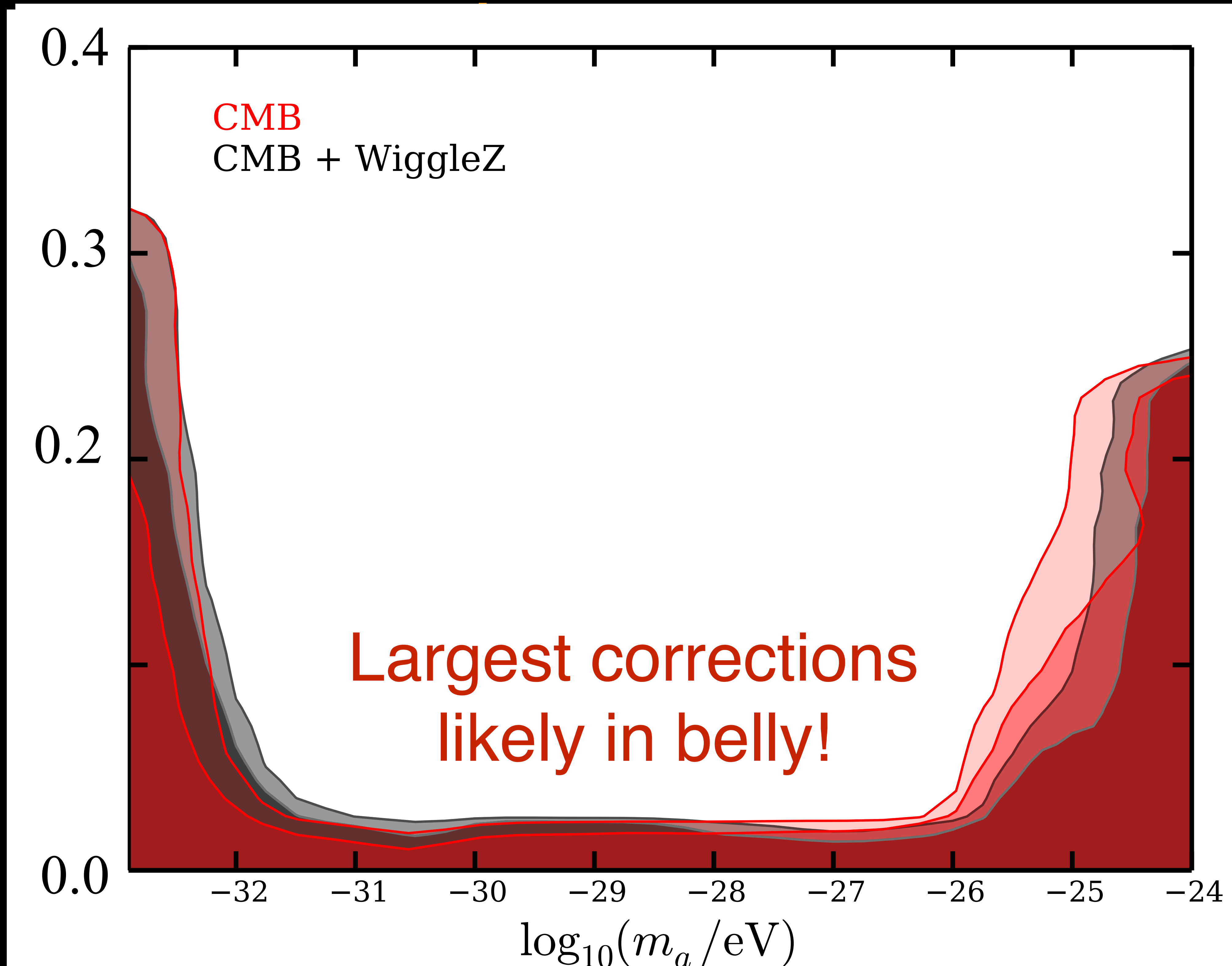
$$\delta\phi = A_c\Delta_c(k,\eta)\cos(m\eta) + A_s\Delta(k,\eta)\sin(m\eta)$$

$$c_s^2 = \frac{k^2/(4m_a^2a^2)}{1+k^2/(4m_a^2a^2)} + \left(\frac{\mathcal{H}}{m_a}\right)^2 g(k,\eta,m_a)$$

see also work by Urena-Lopez and Gonzalez-Morales, JCAP, arXiv: 1511.08195

IMPROVING THEORETICAL PREDICTIONS

Work in progress,
J. Cookmeyer
HC 2017, now
at Berkeley



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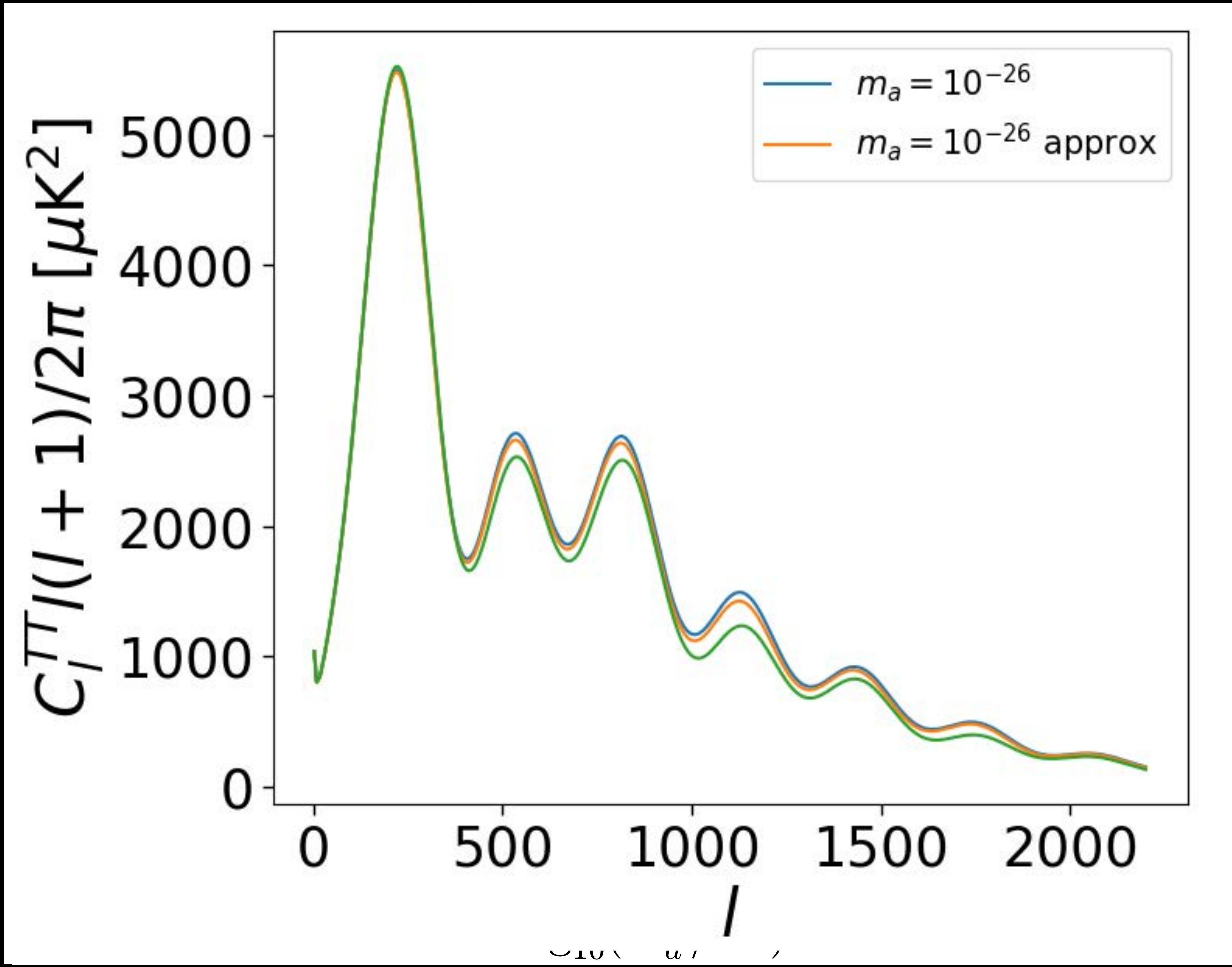
IMPROVING THEORETICAL PREDICTIONS

Work in progress, J. Cookmeyer HC 2017, now at Berkeley

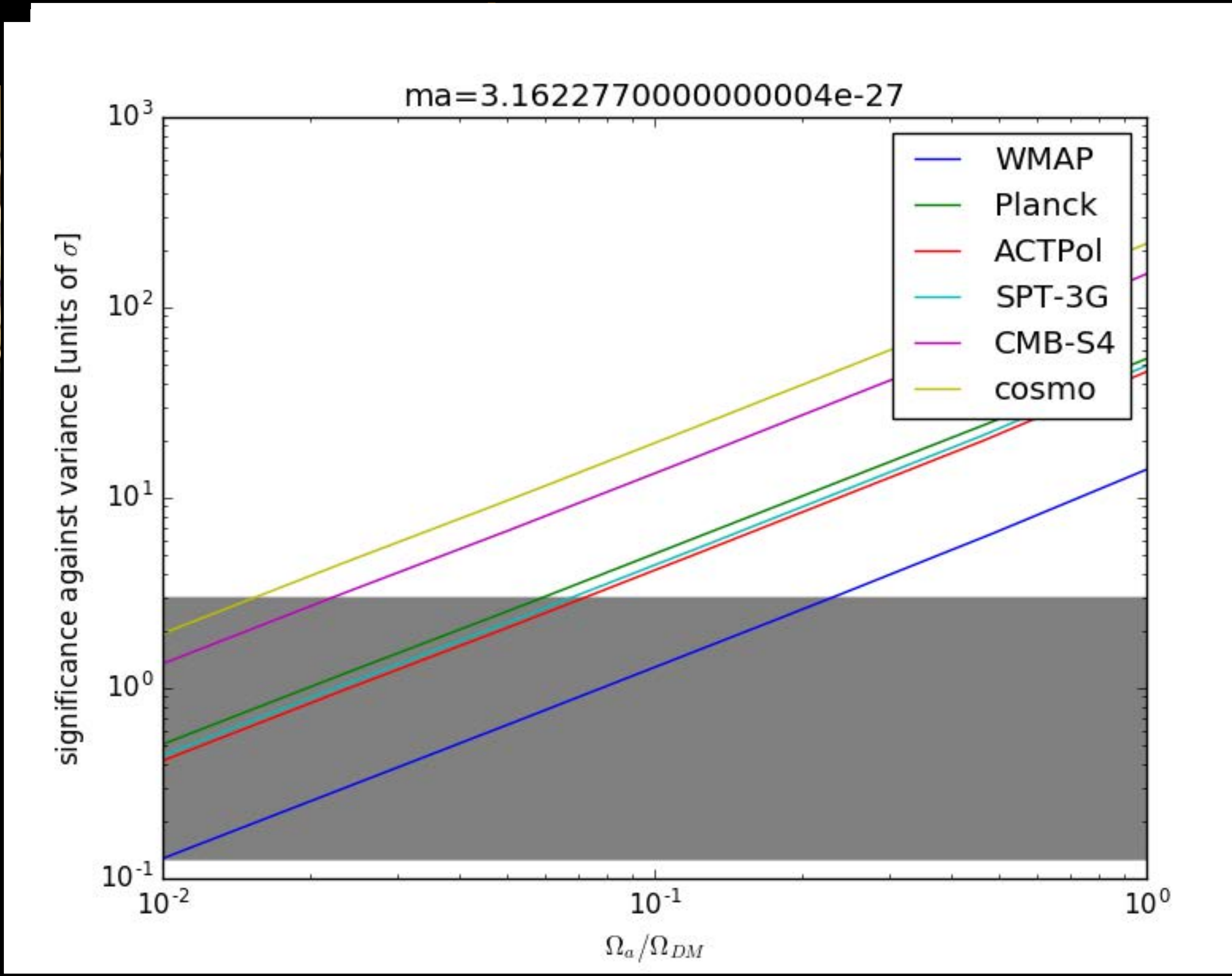


see also work by Urena-Lopez and Gonzalez-Morales, JCAP, arXiv: 1511.08195

Work in progress, J. Cookmeyer HC 2017, now at Berkeley

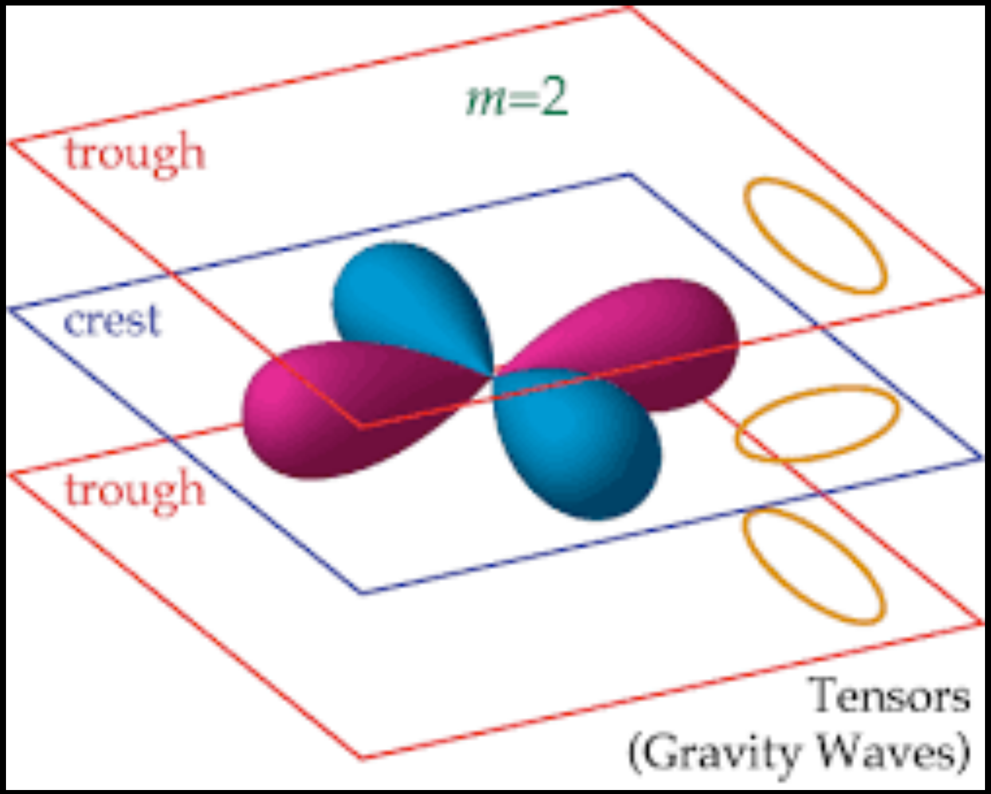
☐ SATISFACTORY

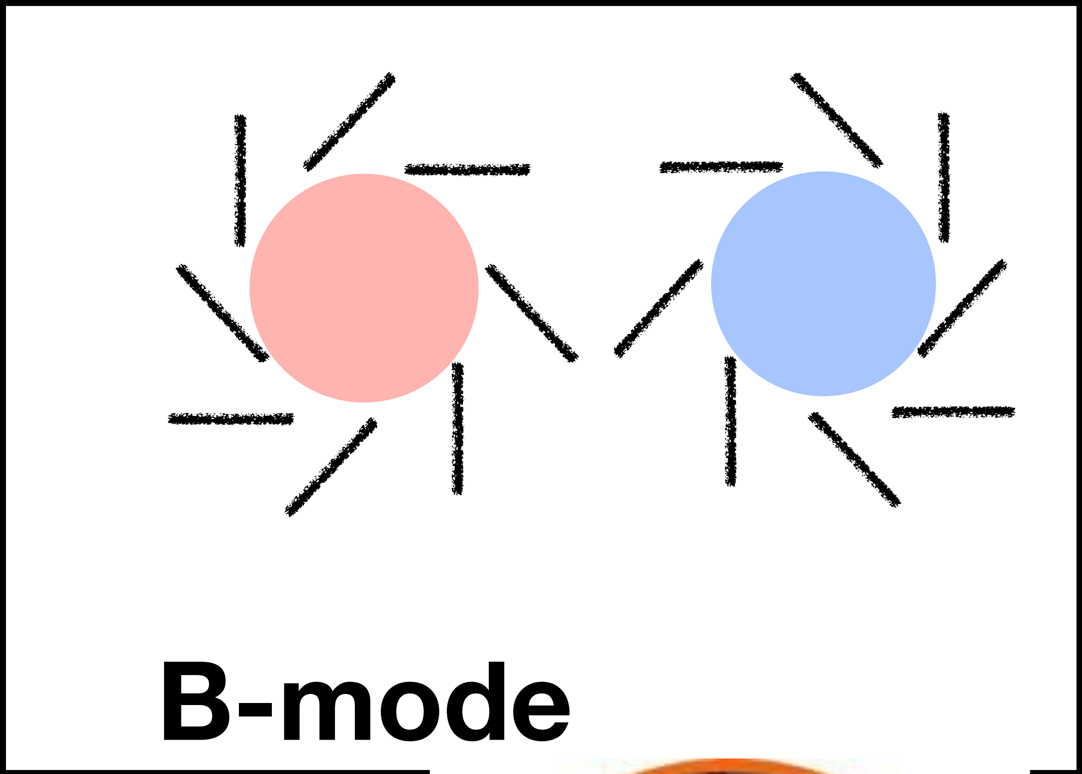
☑ NEEDS IMPROVEMENT



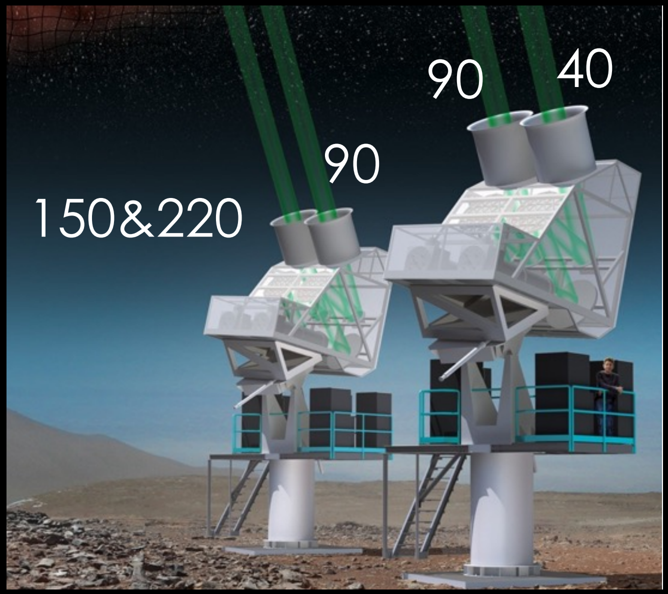
see also work by Urena-Lopez and Gonzalez-Morales, JCAP, arXiv: 1511.08195

ULAs as an inflationary probe





Spider SPT/BICEP2-3/KECK



CLASS

PICO

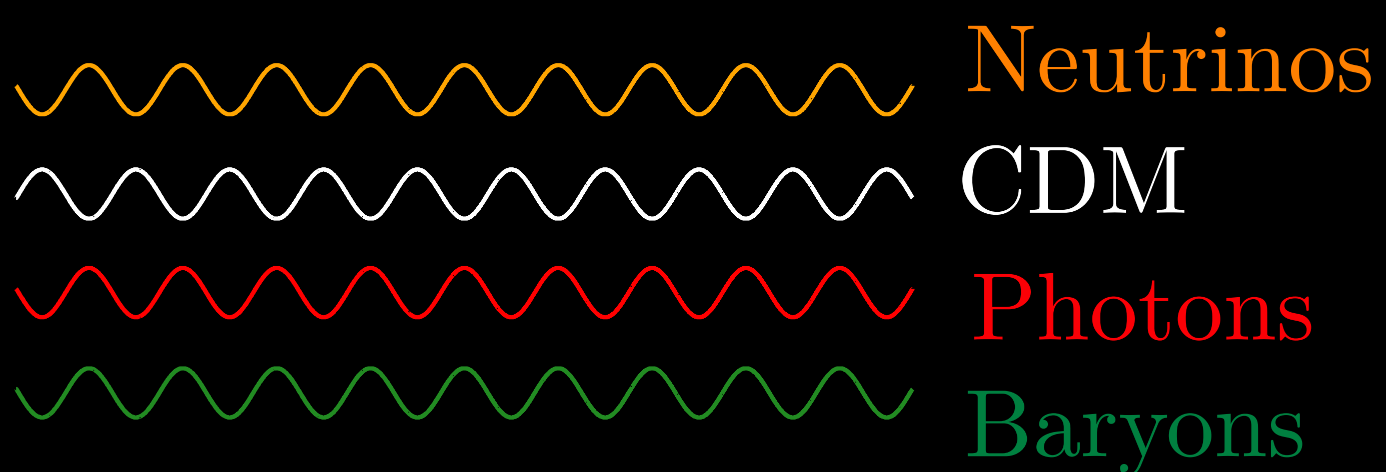
$$r = 16\varepsilon \approx 0.17 \left(\frac{2.1 \times 10^{-9}}{A_s}\right) \left(\frac{H_I}{10^{14}\ \mathrm{GeV}}\right)^2$$

Axions and isocurvature

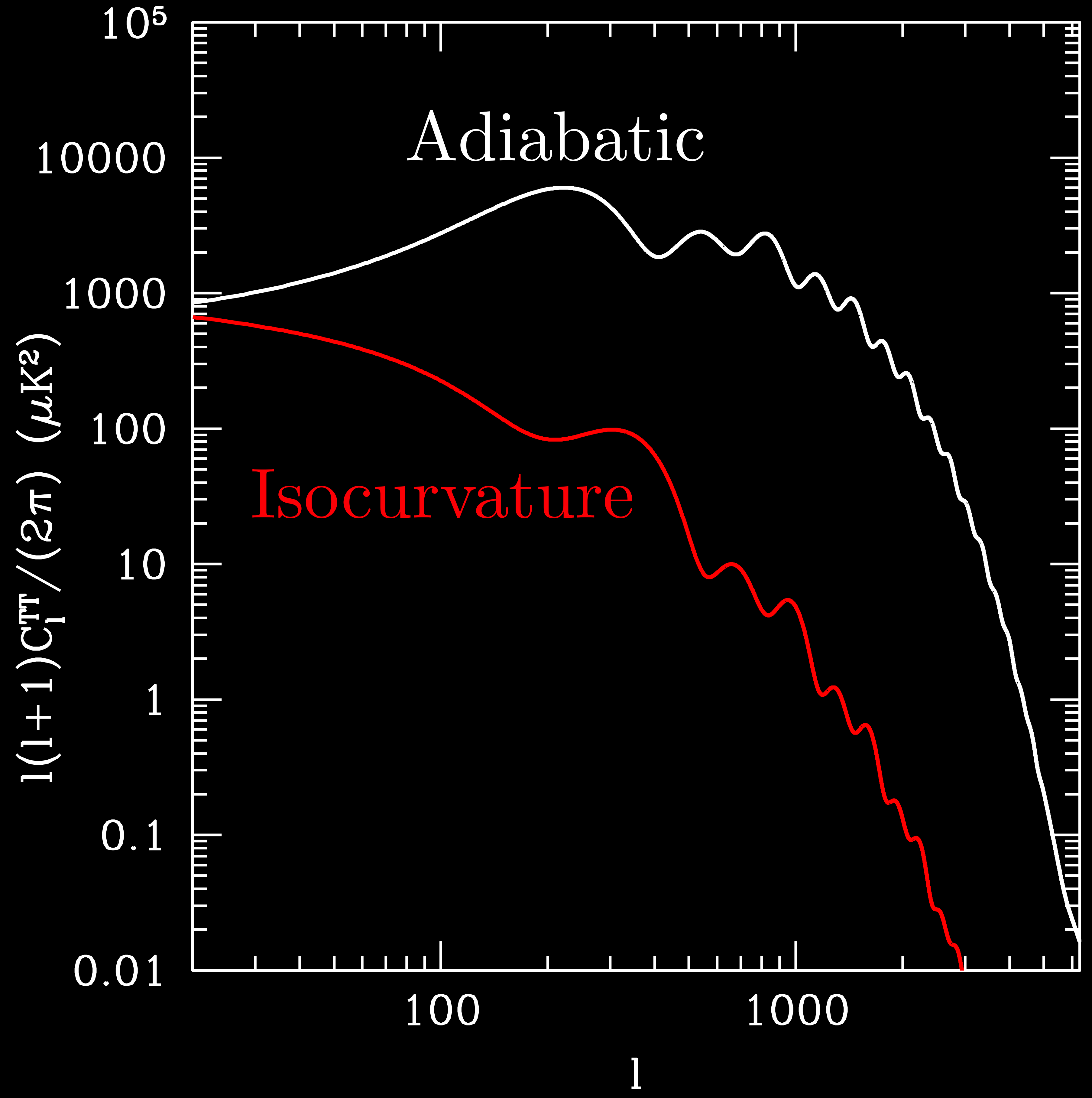
- ✳ Quantum zero-point flucts. in axion field

$$\sqrt{\langle a^2 \rangle} = \frac{H_{\rm I}}{2\pi}$$

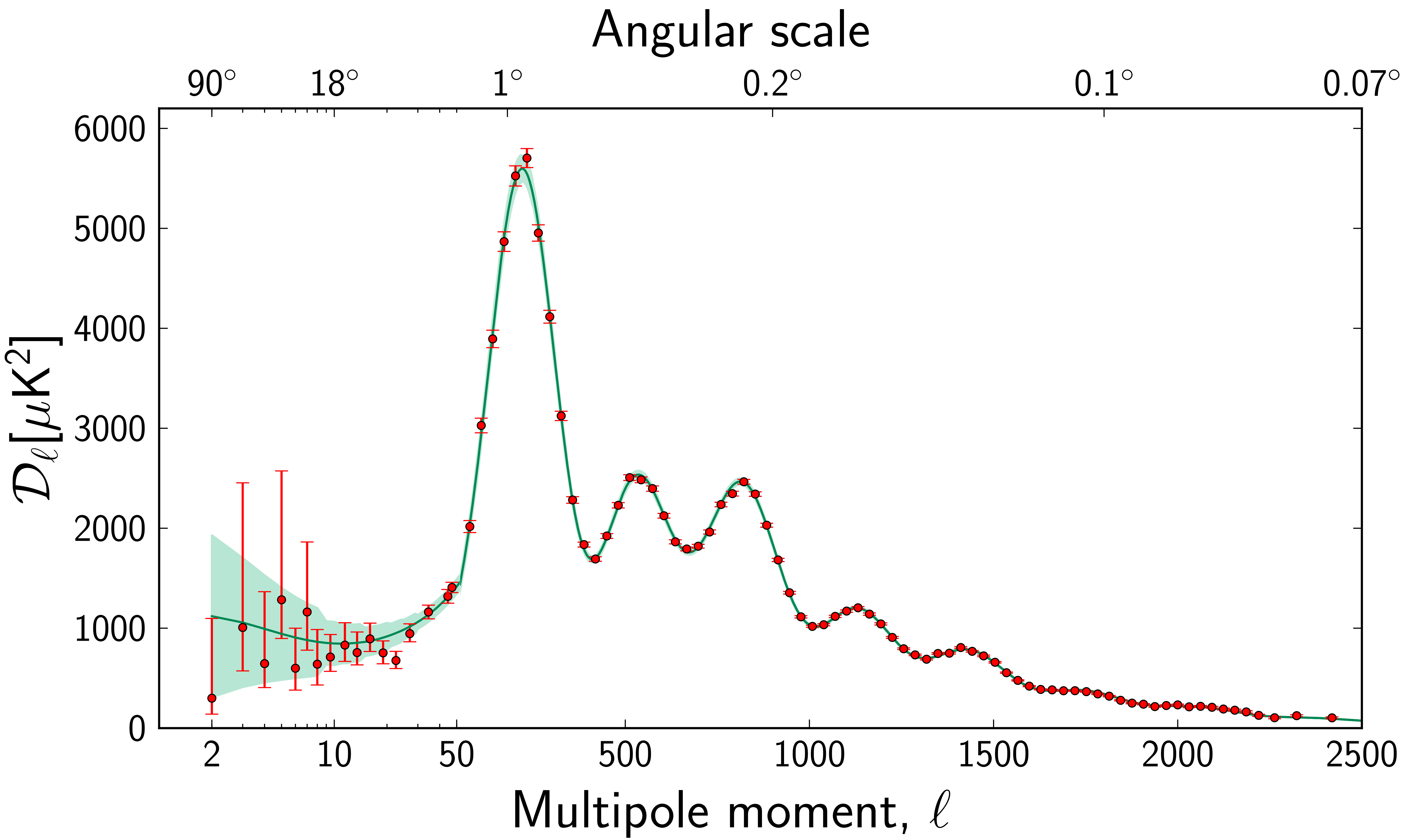
- ✳ Subdominant species seed isocurvature fluctuations



Axions and isocurvature



Axions and isocurvature



Forecast/future work: Tensors and ULAs

* Planck TT constraints

$$\frac{P_{\rm iso}}{P_{\rm tot}} \lesssim 1.6\times10^{-2}$$

$$\frac{H_I}{f_a\overline{\theta}}\frac{\Omega_a}{\Omega_{\rm d}} \lesssim 4\times10^{-5}$$

Also see Gondolo and Visinelli 2012

$$H_I \simeq 10^{14}\ \mathrm{GeV}$$

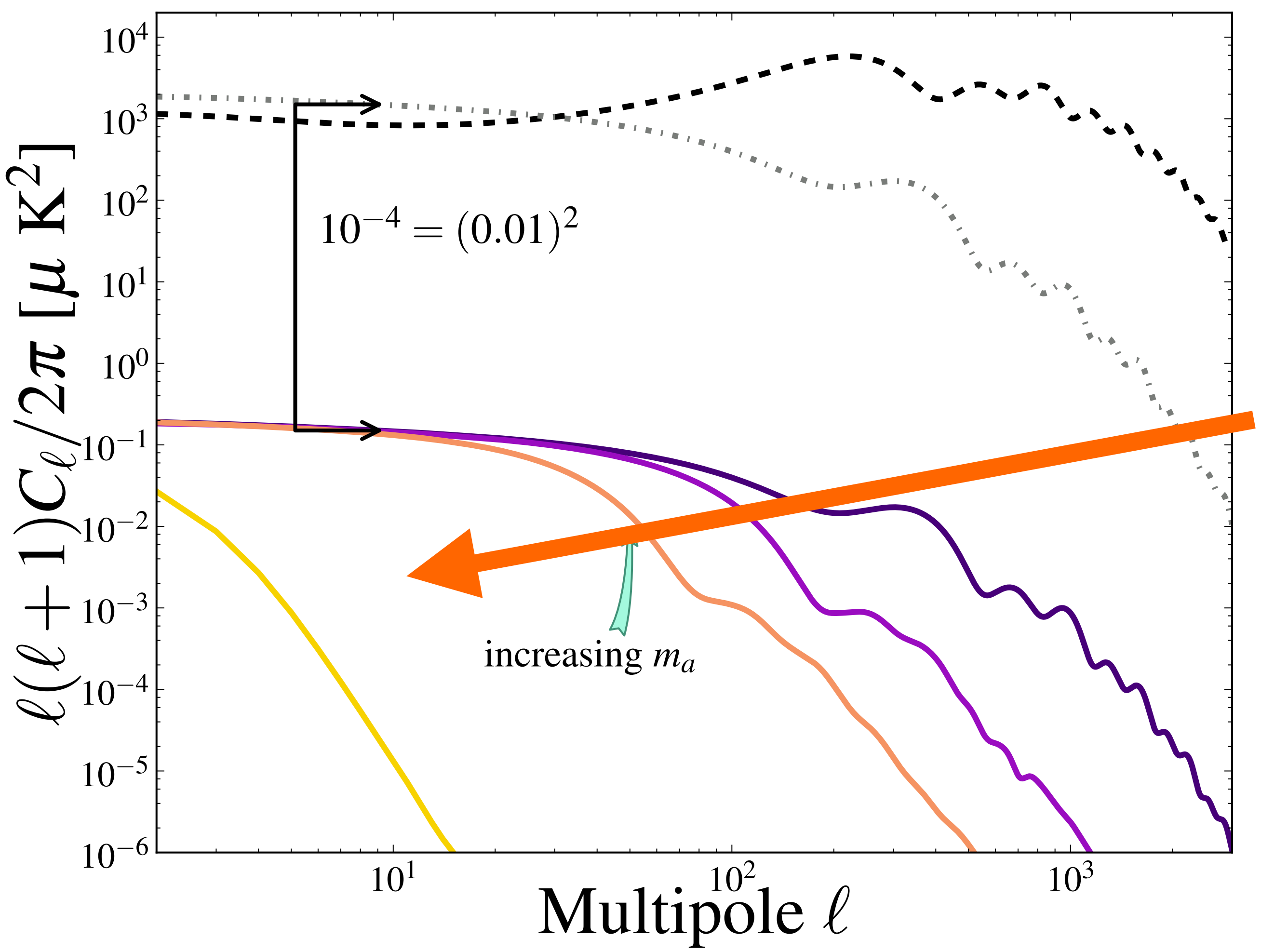
$$\frac{\Omega_a}{\Omega_a+\Omega_c} \lesssim 10^{-12}\left(\frac{0.2}{r}\right)^{7/2}$$

QCD axion

$$\frac{\Omega_a}{\Omega_a+\Omega_c} \lesssim 10^{-3}\left(\frac{0.2}{r}\right)$$

ULAs

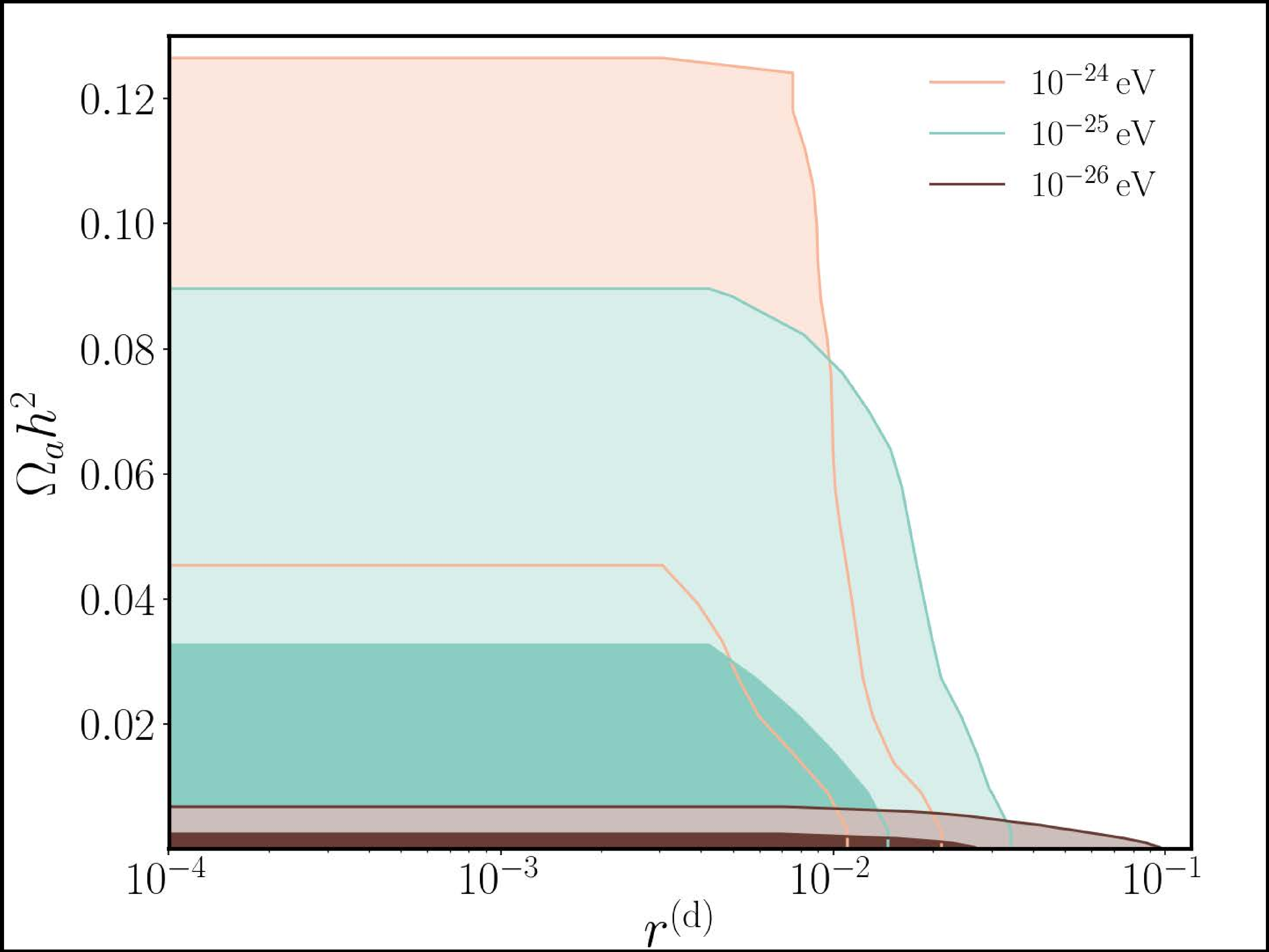
Forecast/future work: Tensors and ULAs



- ✳ Low-l plateau disappears
- ✳ Information lost
- ✳ Planck limits assume CDM isocurvature

✳ For $m_a \leq 10^{-27}$ eV, constraints cannot be simply remapped.

Tensors + isocurvature (RESULTS!) From arXiv: 1708.05681

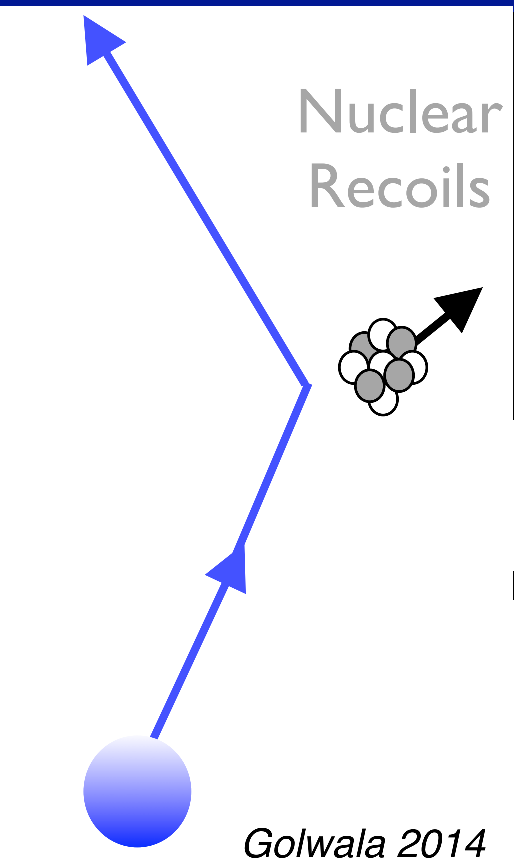


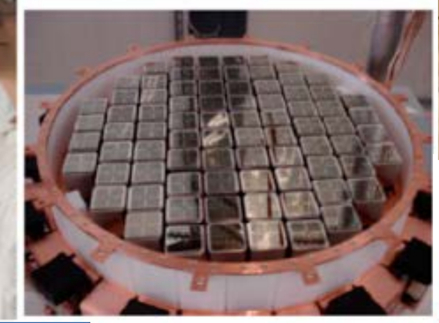
Conclusions

- ~5% level constraints on ultra-light axions from CMB
- CMB lensing can probe ultra-light axions:
  - 1% sensitivity with next-generation experiments
- Complementary constraints to inflationary energy scale

Most likely and desired overflow slides

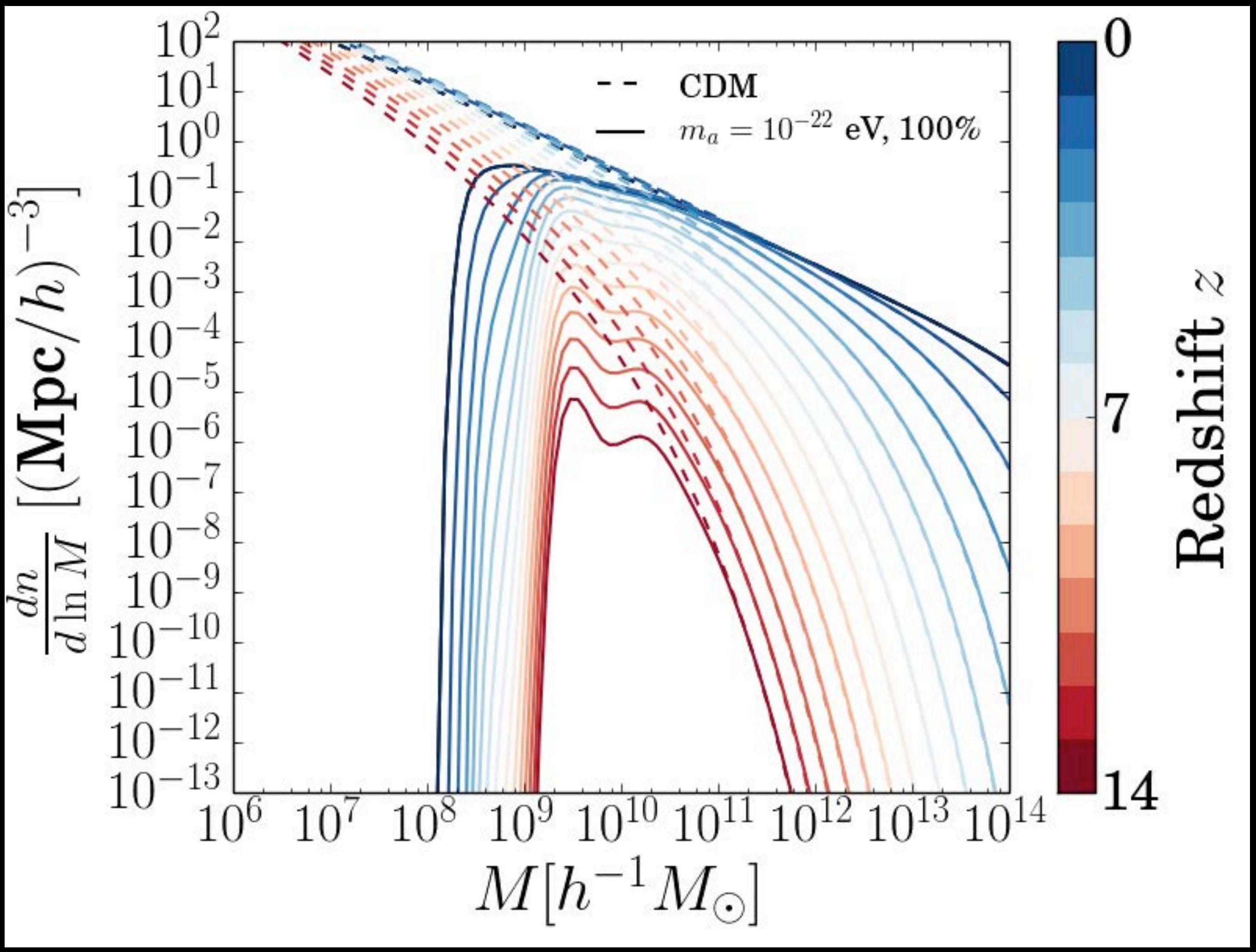
Dark matter: terrestrial experiment

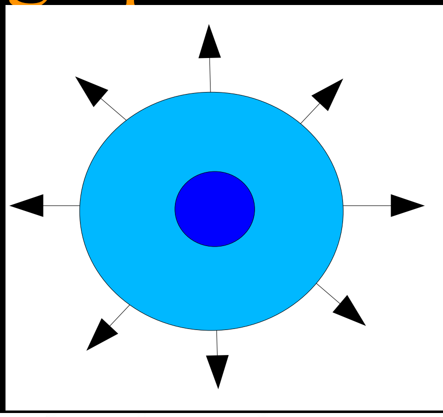


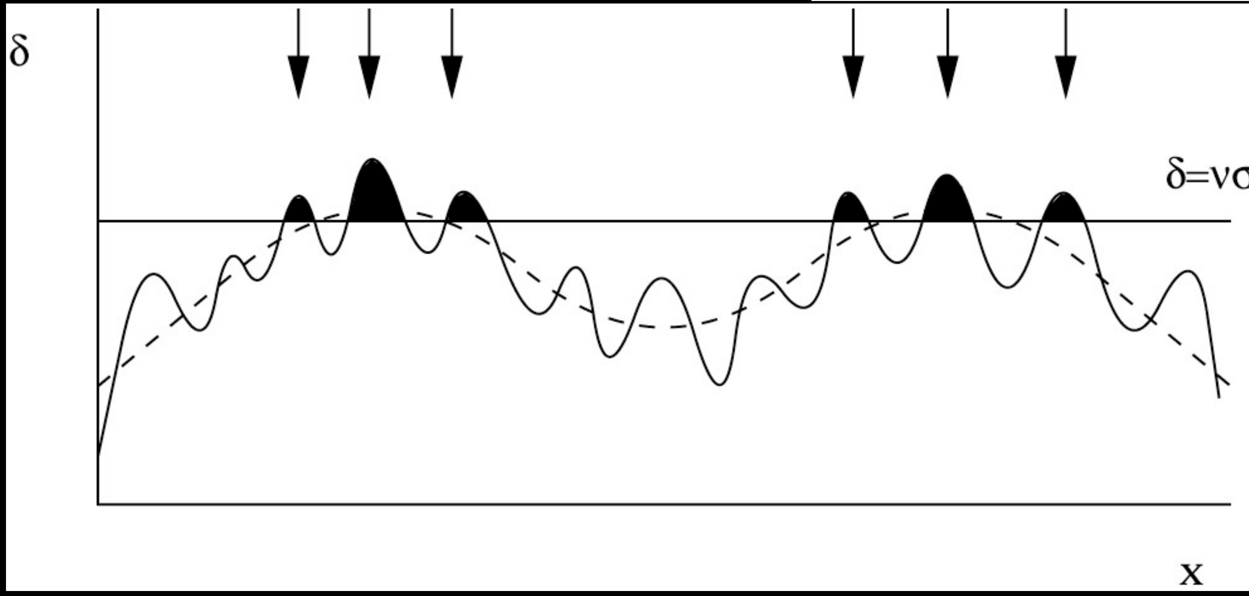


Search for WIMP (weakly interacting massive particle) with m~100 GeV: So far, no dice!

Fuzzy simulations (and analytic modeling) are heating up!







Cores! (Hu/Gruzinov/Barkana 2001, see also Marsh and Silk 2013, Marsh and Pop 2015, Matos 2012, Schive 2014, Vogelsberger 2017, and others)

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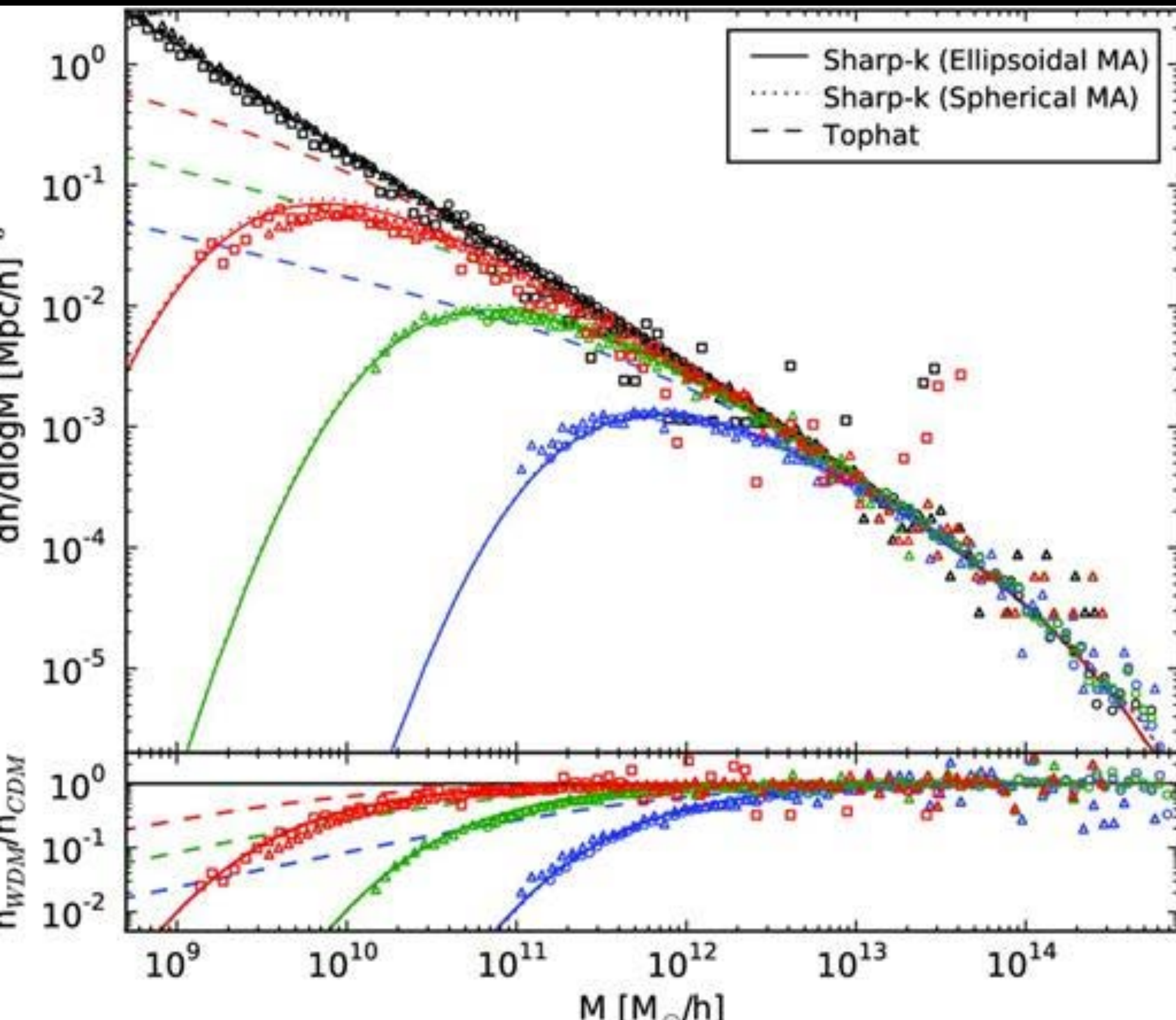
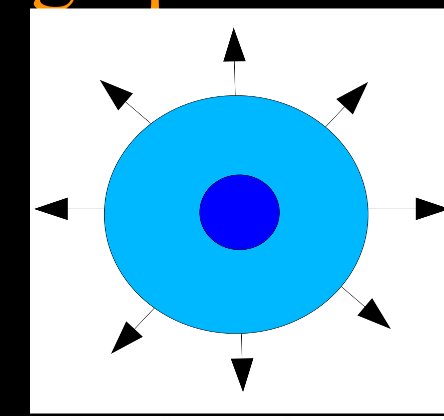
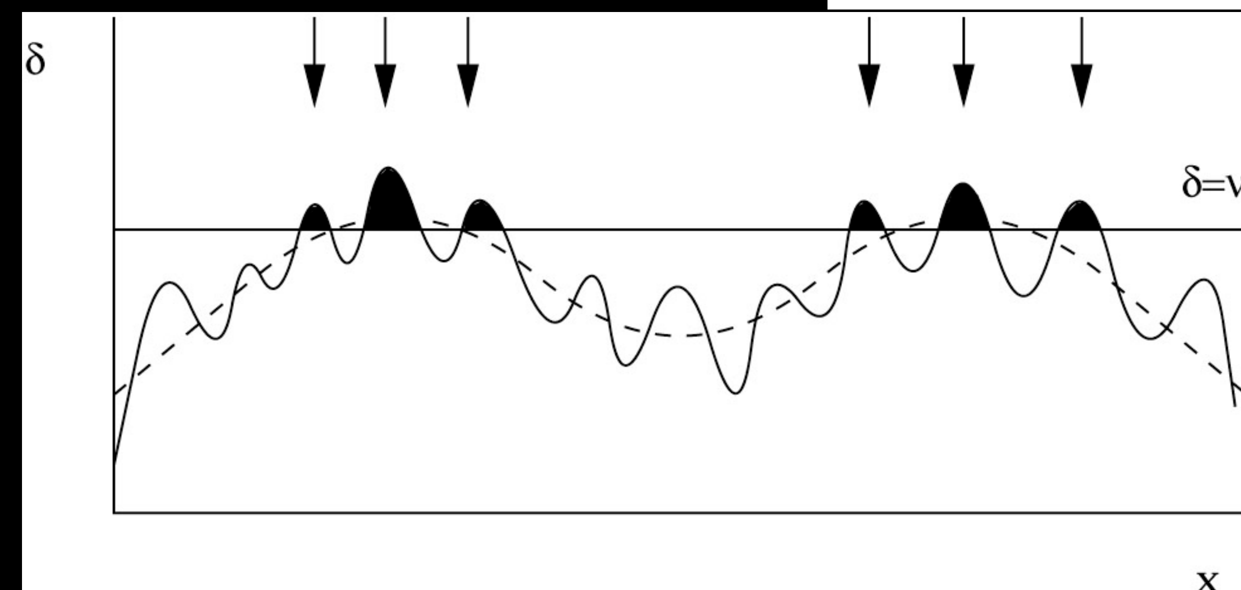






Schneider 2015

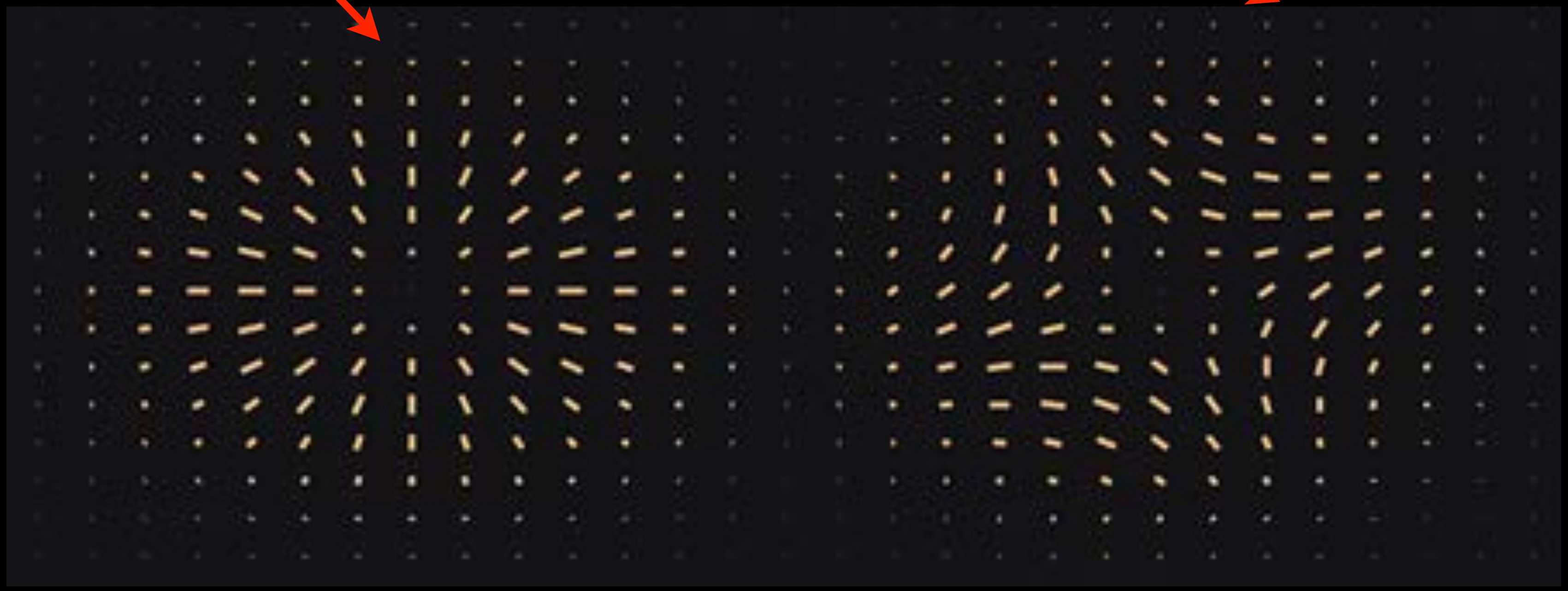
Cores! (Hu/Gruzinov/Barkana 2001, see also Marsh and Silk 2013, Marsh and Pop 2015, Matos 2012, Schive 2014, Vogelsberger 2017, and others)

Birefringence and B-modes

$$\mathcal{L} \sim \frac{a}{f_a} \vec{E} \cdot \vec{B}$$

- Funnels E modes to B modes

(μK^2)



Gluscevic et al., arXiv, 1104.1634, Phys. Rev. D.

Birefringence and B-modes

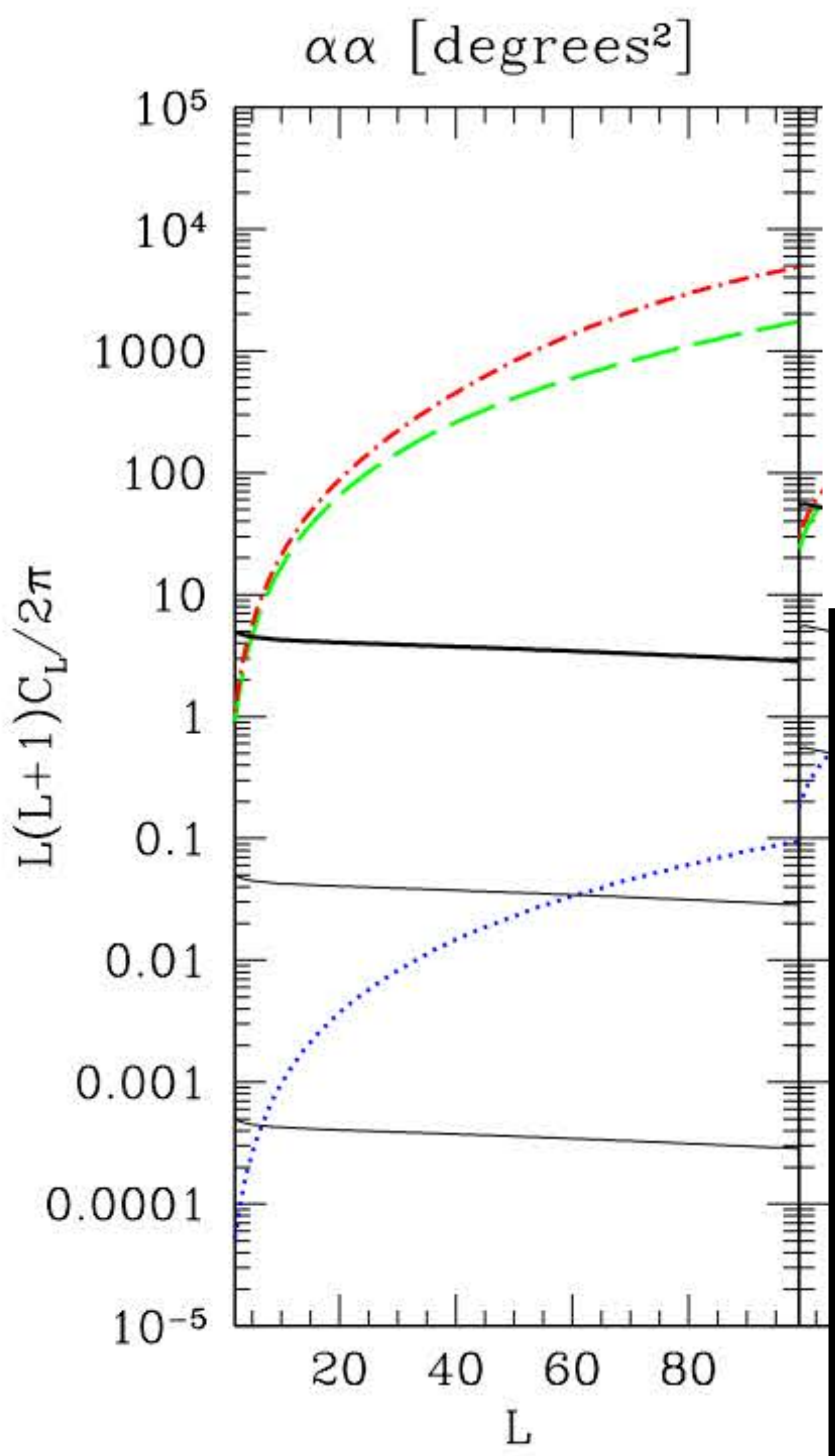
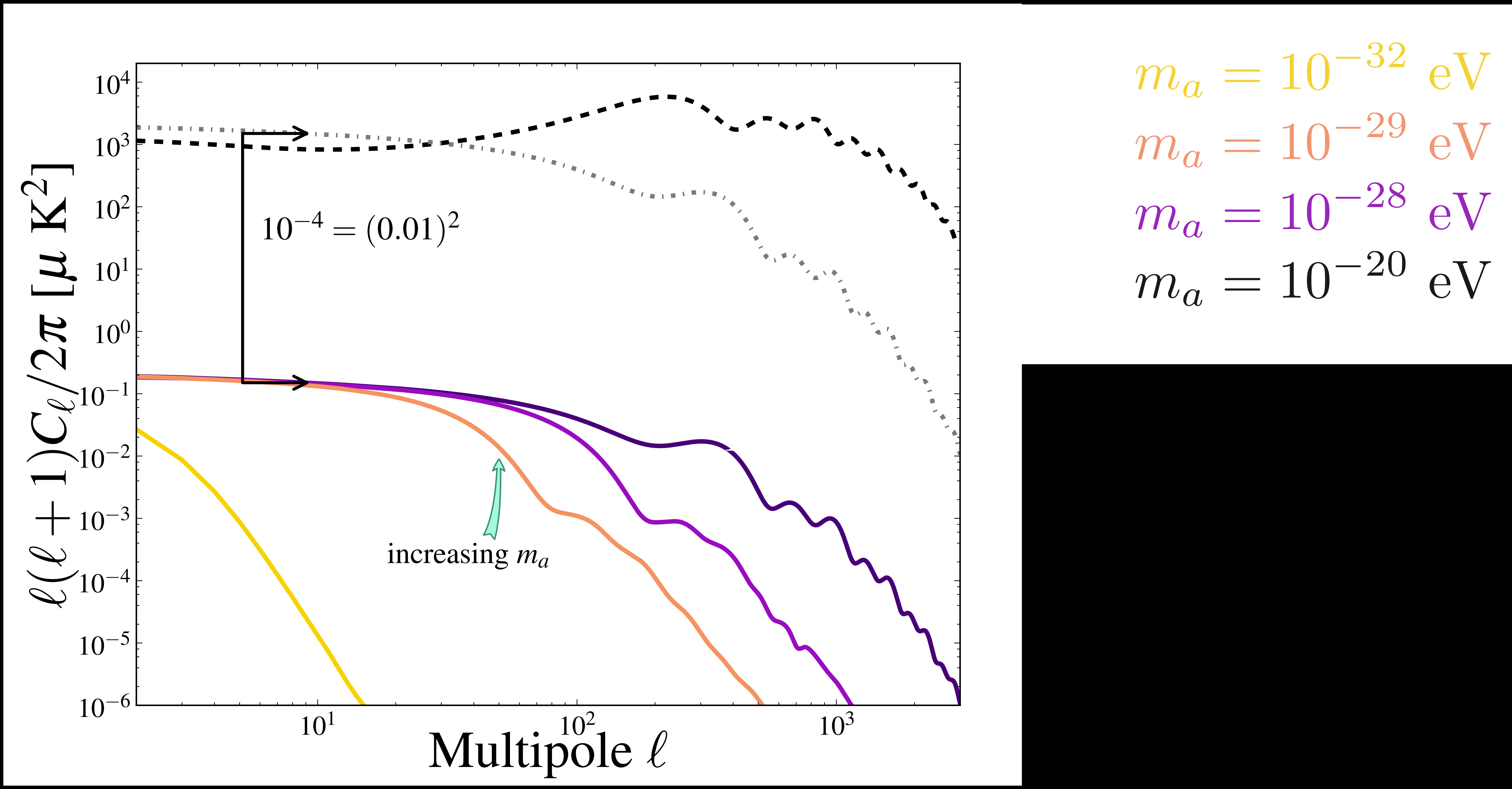


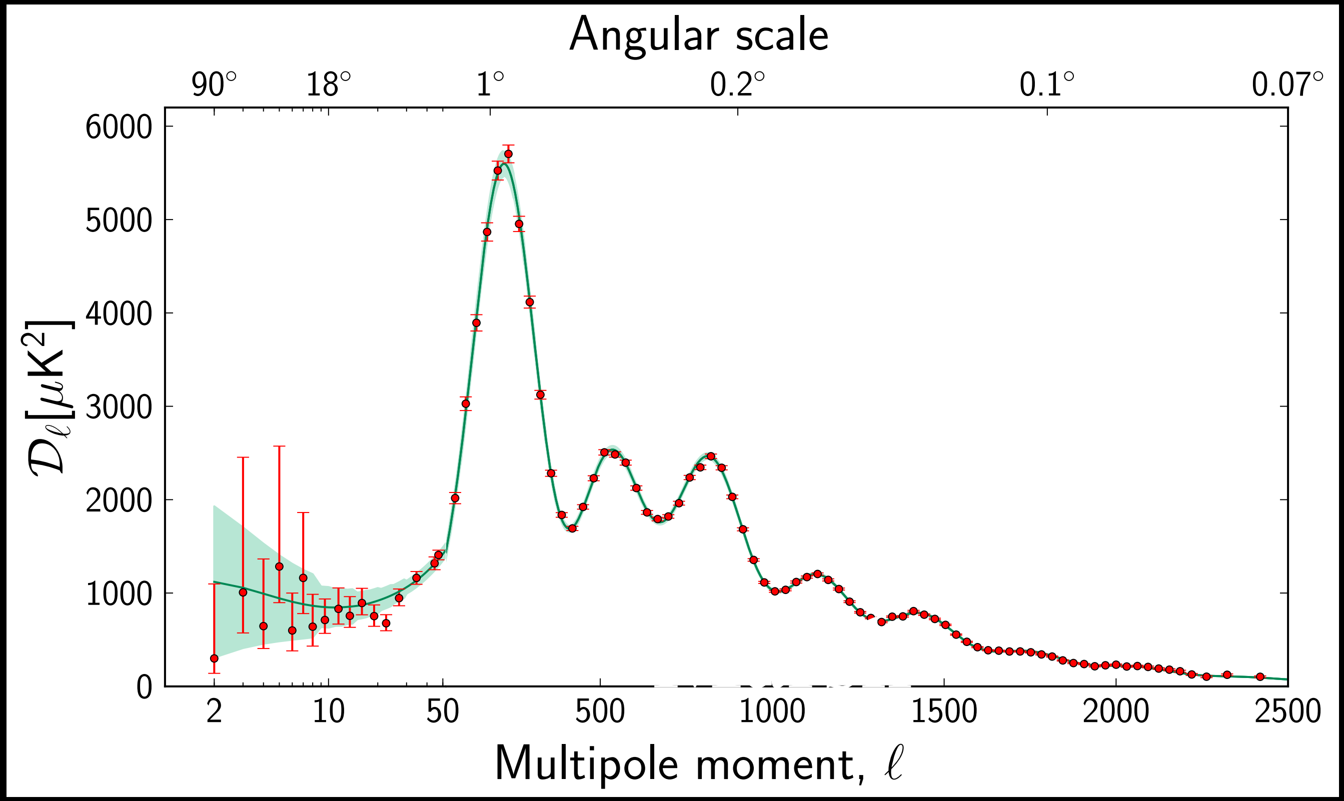
Figure 1: Shown are the power spectra for the cosmological-birefringence rotation angle $C_L^{\alpha\alpha}$ and its cross-correlation with the CMB temperature $C_L^{\alpha T}$ (logarithm of the absolute value), for a generic quintessence model in which the CB-angle fluctuations are due to scalar-field fluctuations at the LSS. The black solid curves are the theoretical prediction for (from top to bottom) $\alpha_4 = 1$, 0.1, and 0.01, where α_4 is the fluctuation amplitude for the CB angle in units of the maximum currently allowed amplitude [12]. We also show the noise power spectra anticipated for SPIDER (red, dot-dashed), Planck (green, dashed), and CMBPol (blue, dotted).

Gluscevic et al., arXiv, 1104.1634, Phys. Rev. D.



Spectra from AXICAMB using initial conditions obtained in DG+ (2015 in prep)

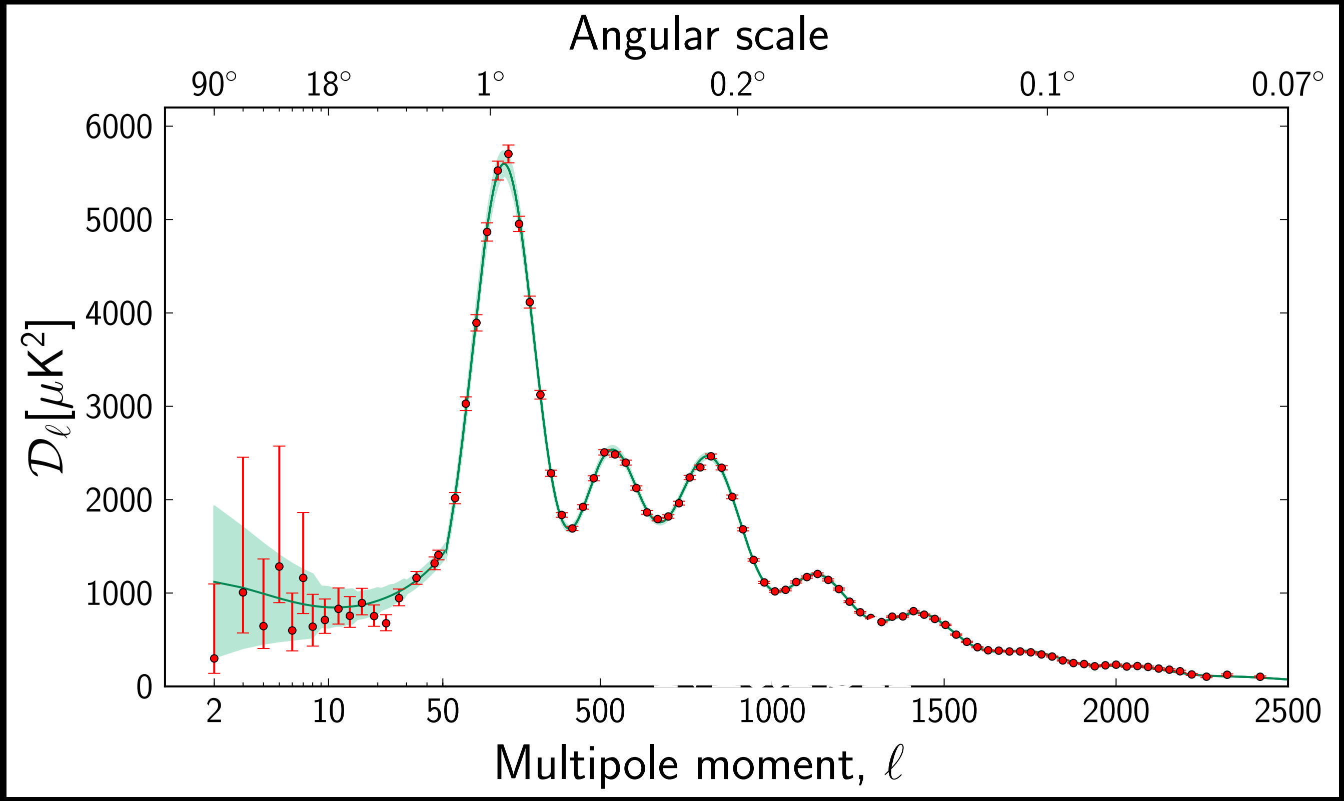
Planck 2013 TT



$$\alpha \equiv \frac{P_{S_{c\gamma}}(k)}{P_{S_{c\gamma}(k)} + P_{\mathcal{R}}(k)} \leq 0.039$$

ULAS AND ISOCURVATURE FLUCTUATIONS

Planck 2013 TT



QCD axion

$$\frac{\Omega_a}{\Omega_a + \Omega_c} \lesssim 10^{-12} \left(\frac{10^{14}\mathrm{GeV}}{H_I} \right)^{7/2}$$

ULAs

$$\frac{\Omega_a}{\Omega_a + \Omega_c} \lesssim 10^{-3} \left(\frac{10^{14}\mathrm{GeV}}{H_I} \right)$$

D.J.E. Marsh, DG +, arXiv:1403.4216, Phys. Rev. Lett. 113, 011801
D.J.E. Marsh, DG +, arXiv:1303.3008, Phys. Rev. D 87, 121701(R)

Axion isocurvature as an inflationary probe

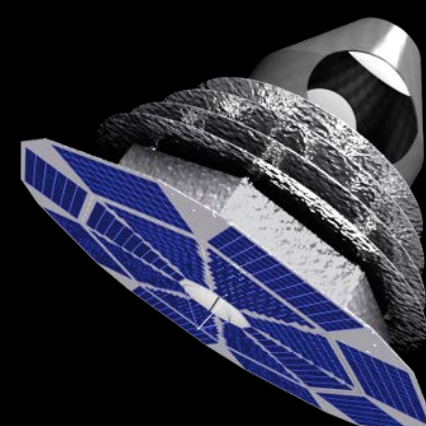
- Discovery of QCD axion/ULA dark matter → trouble for
  - GUT-scale inflation $H_I \sim 10^{14}$ GeV

QCD axion $H_I \sim 10$ GeV **ULA** $H_I \sim 10^5$ GeV

  - Null prediction for primordial B-mode searches

SPT/BICEP2-3/KECK/CMB-S4

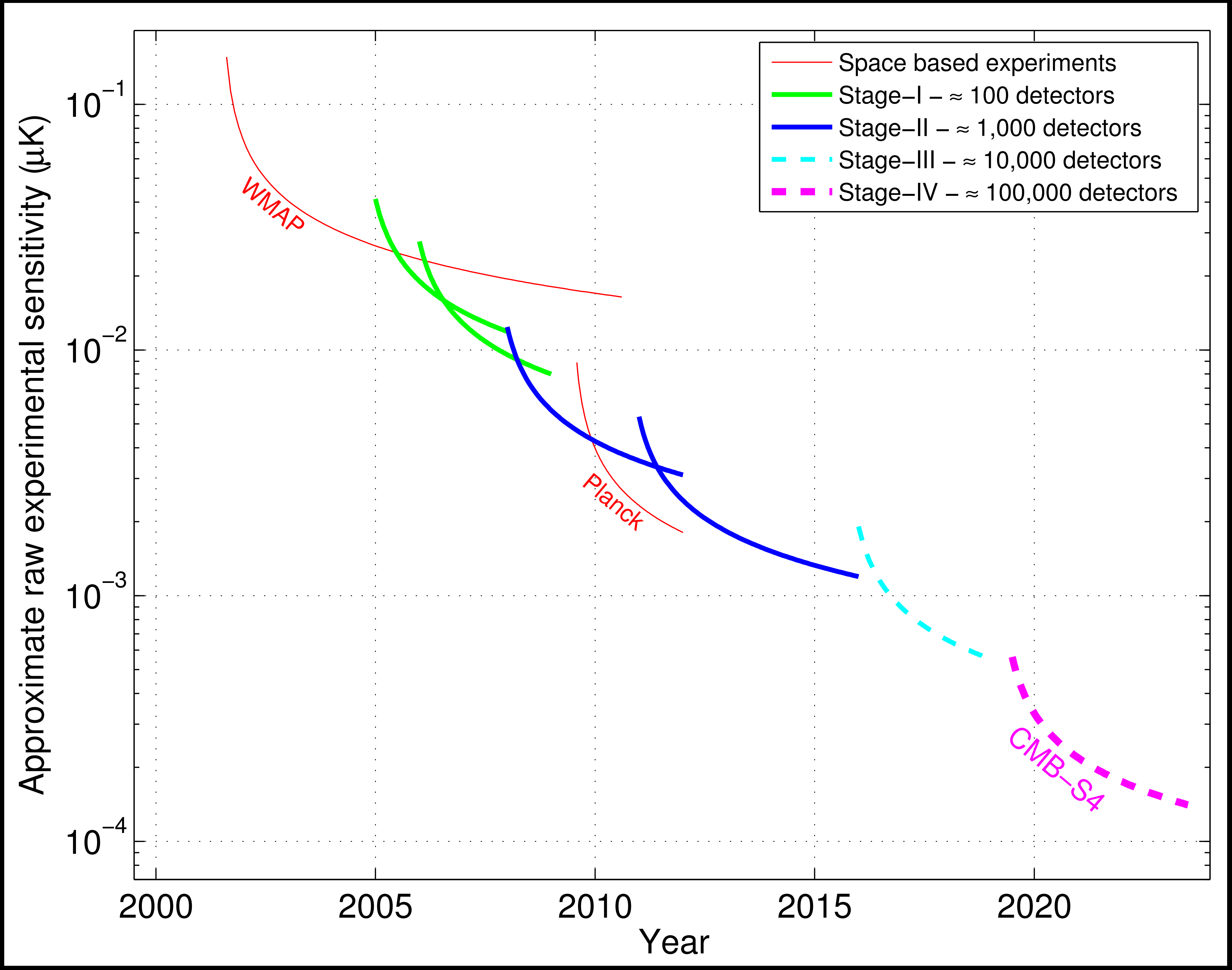
Spider



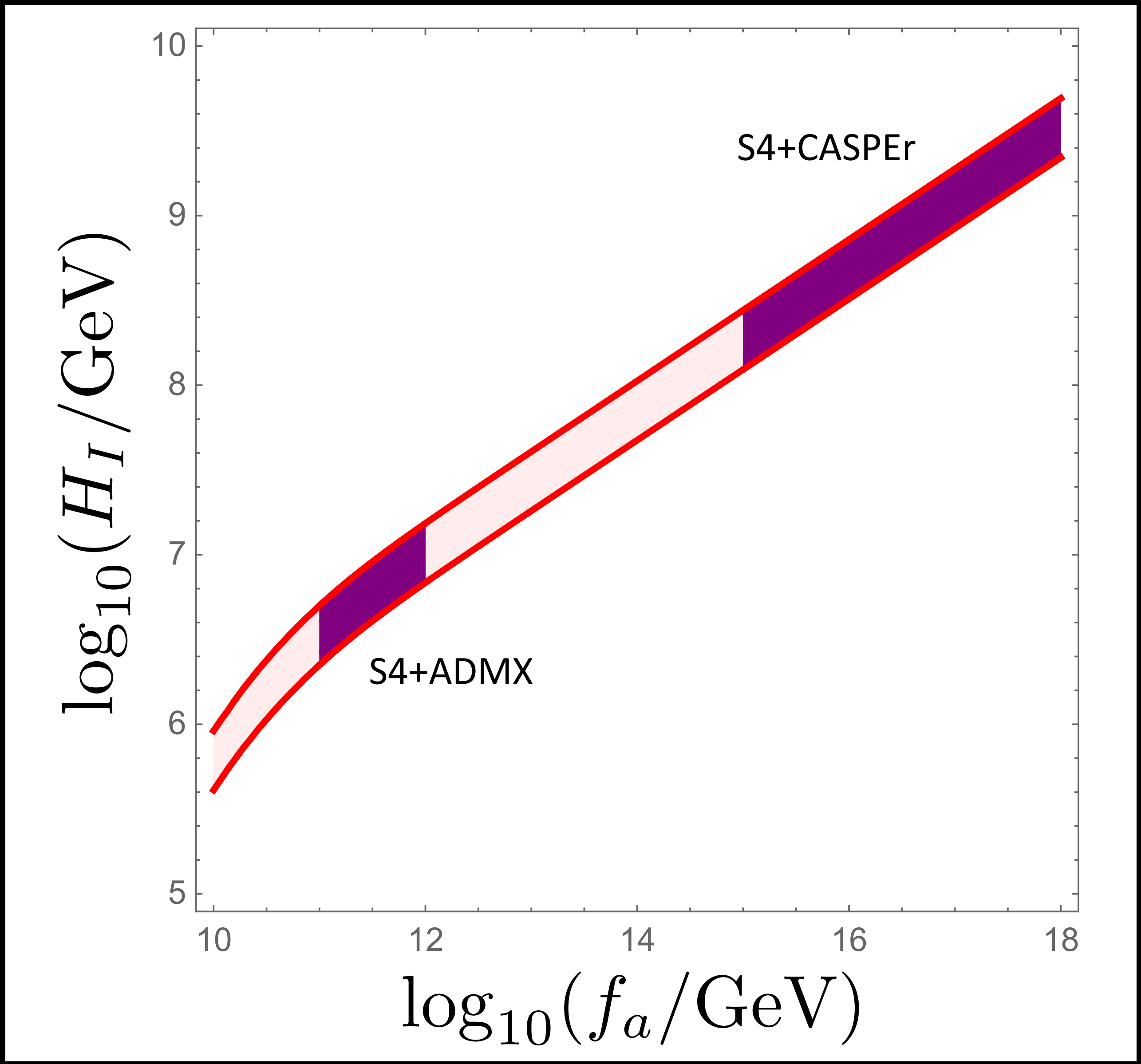
CORE

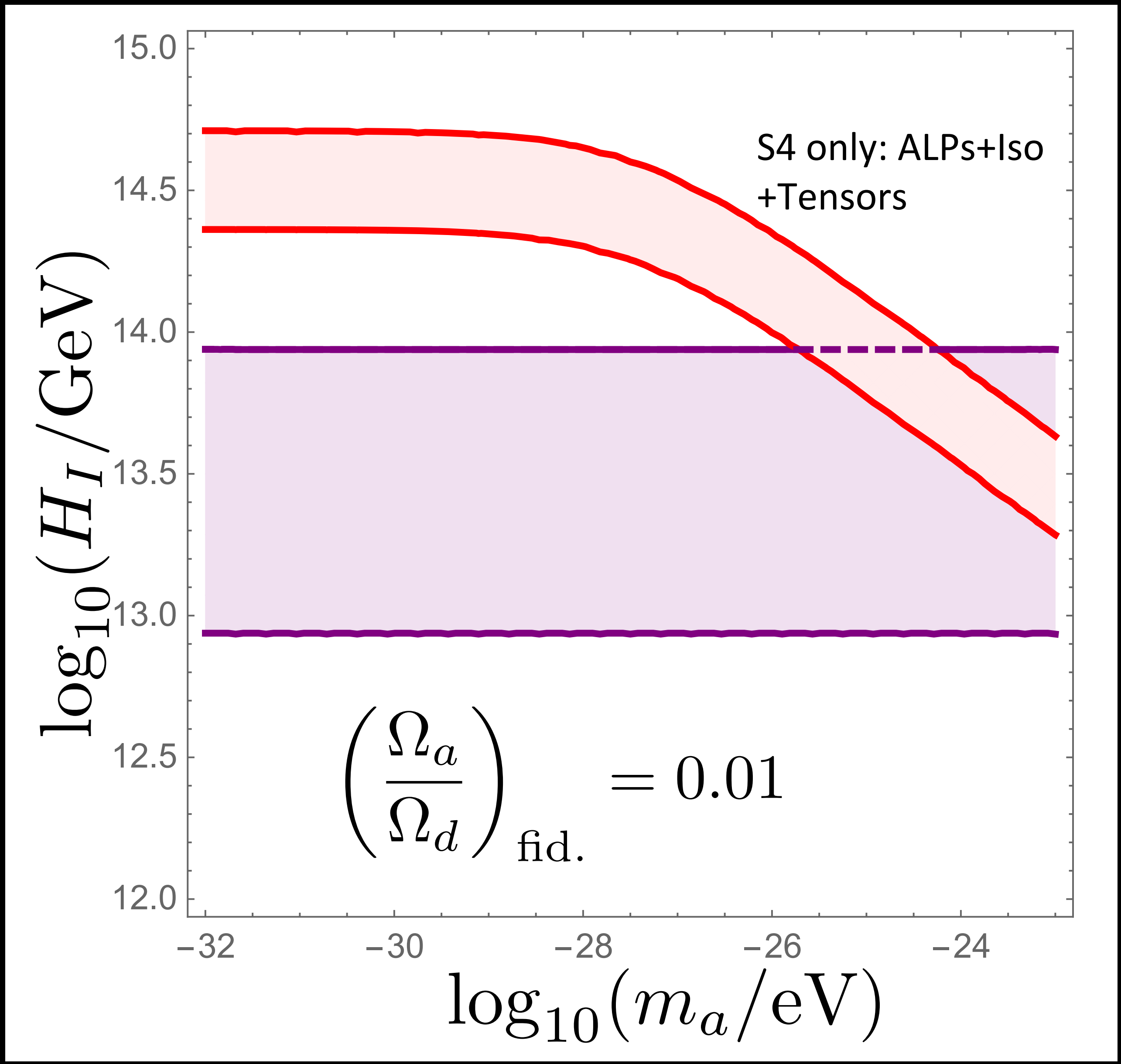
  - Avoidable with non-trivial thermal history/richer PQ symmetry breaking story

Axion isocurvature as an inflationary probe



HIGH-ENERGY COSMOLOGY WITH AXION ISOCURVATURE





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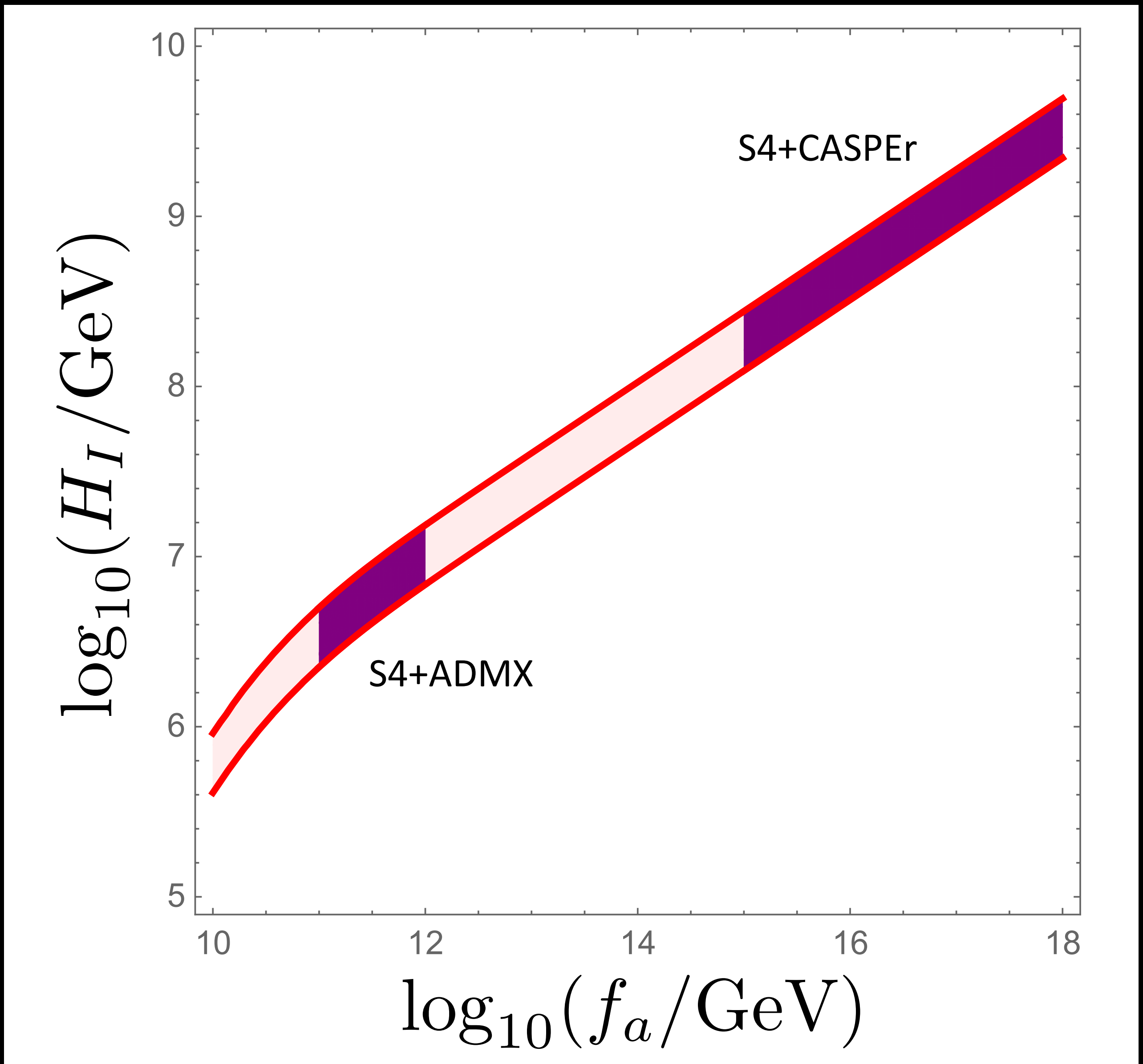
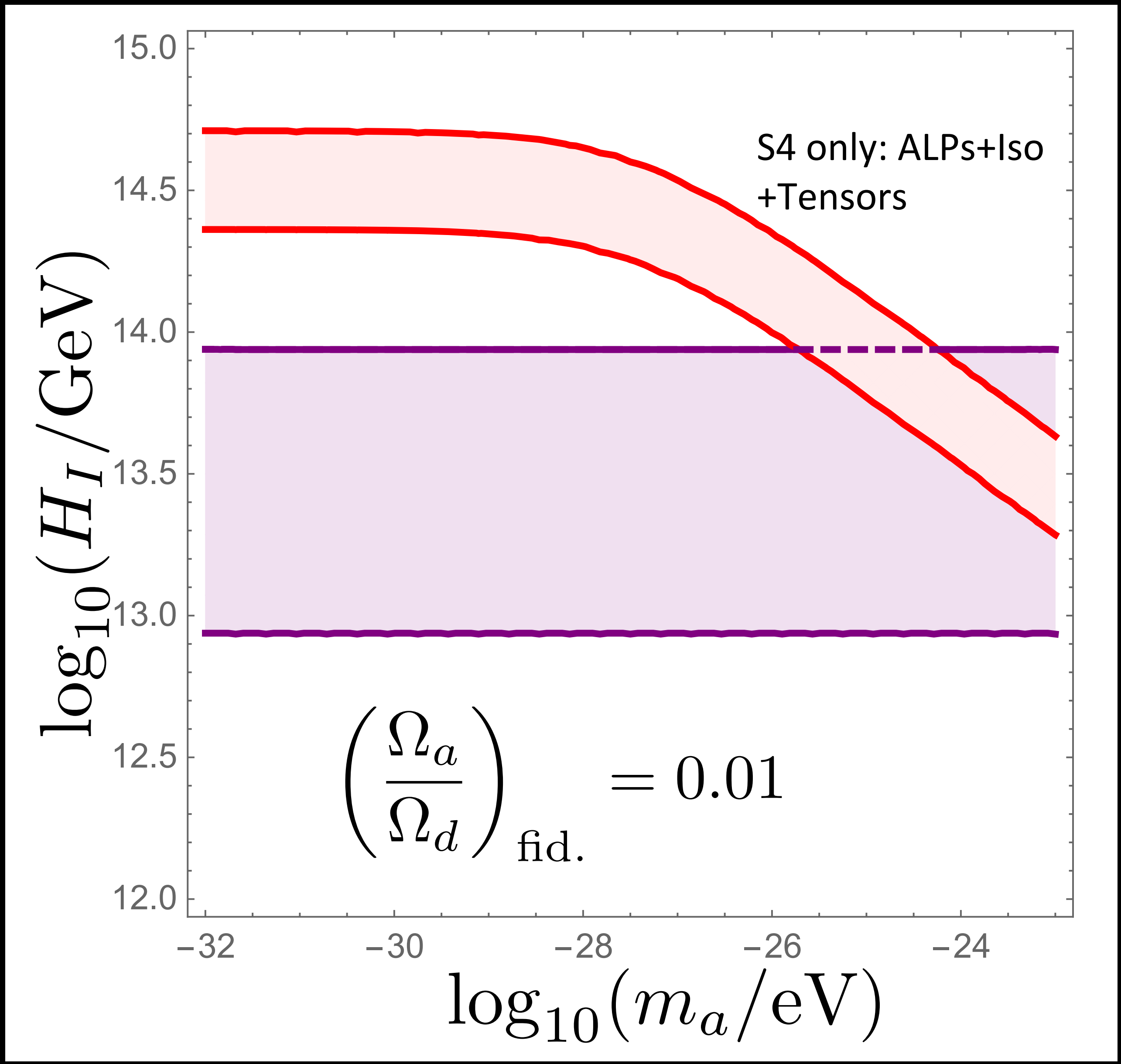
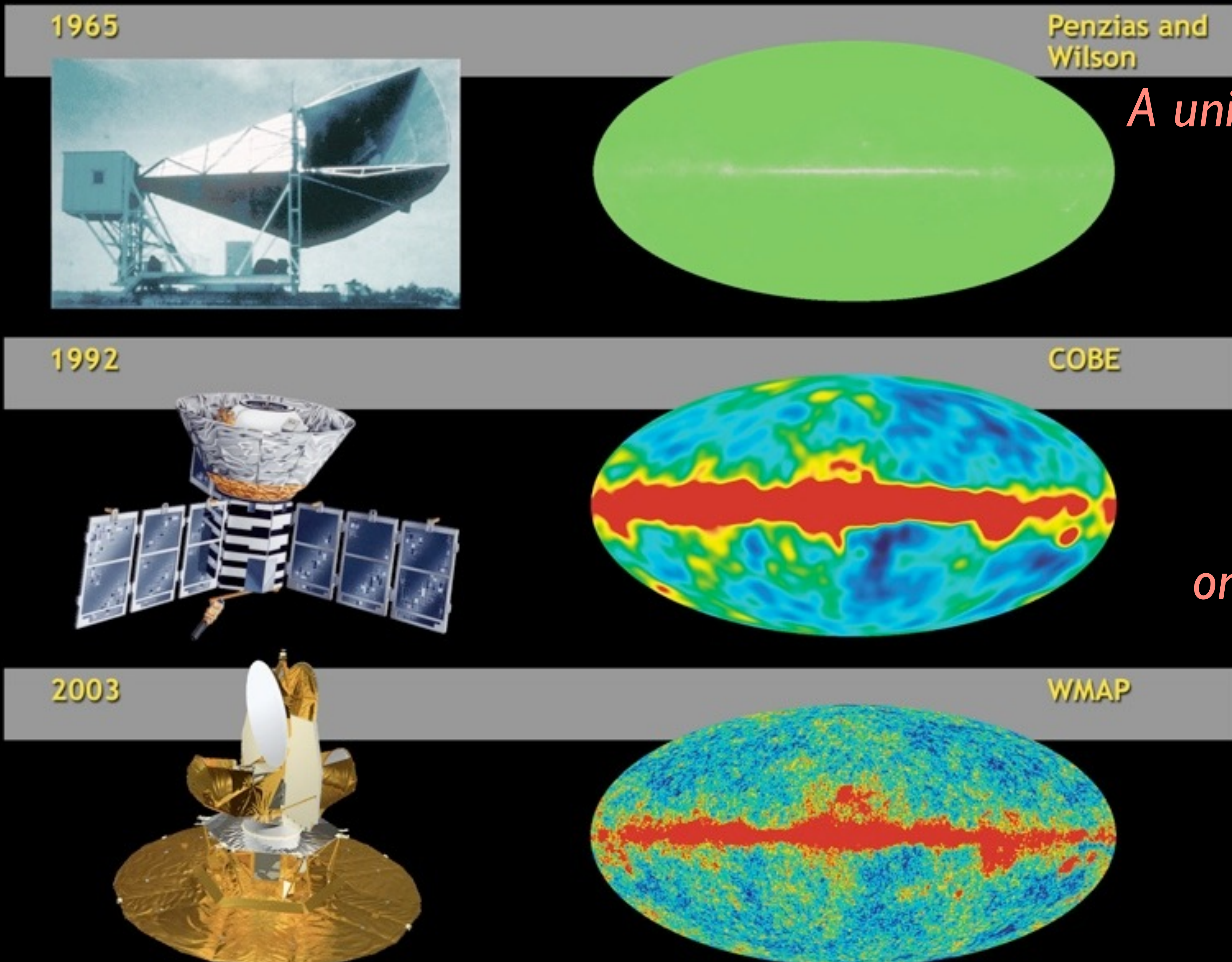




From forthcoming CMB-S4 Science book….

Backup slides

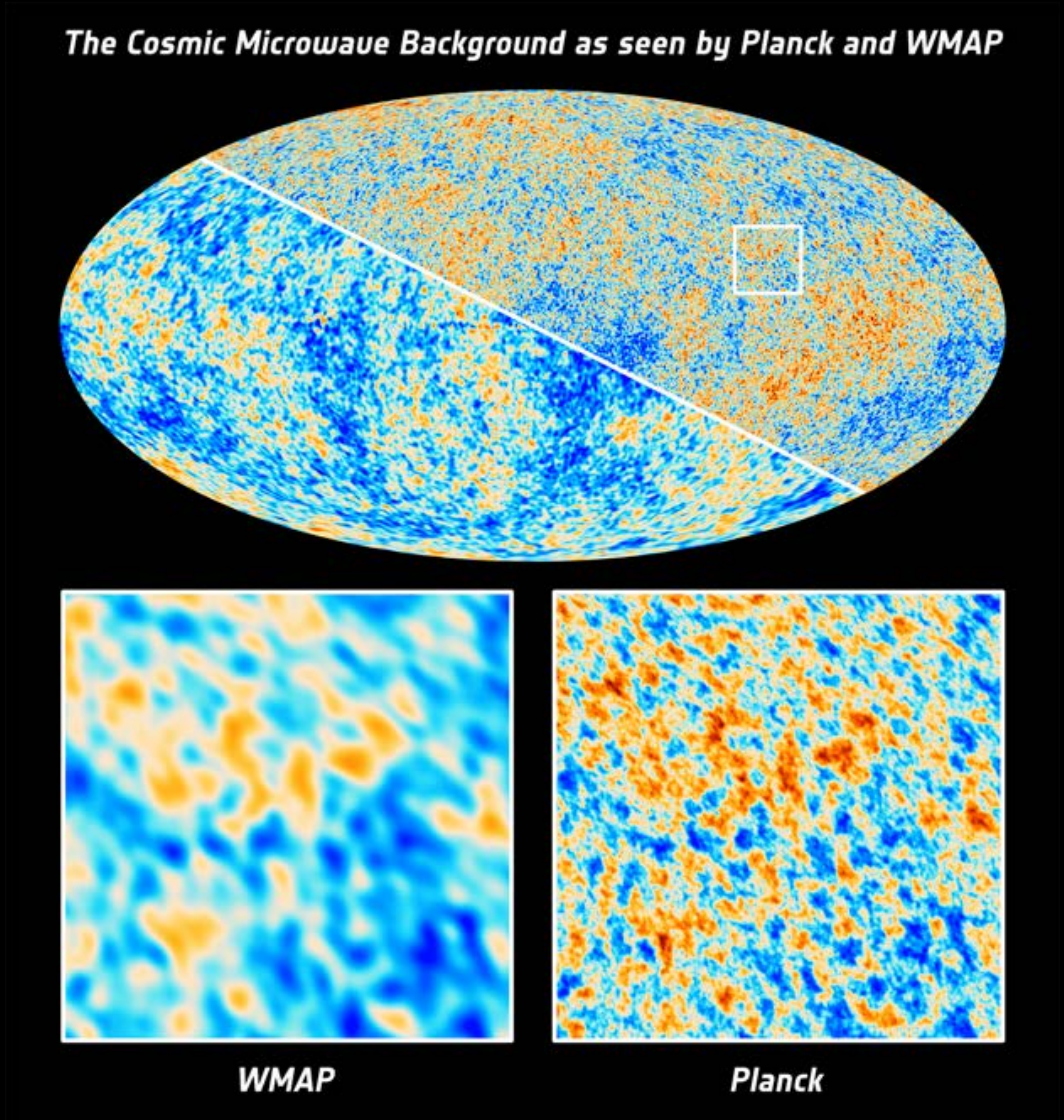
COSMIC MICROWAVE BACKGROUND (CMB): EXPERIMENTAL PROGRESS



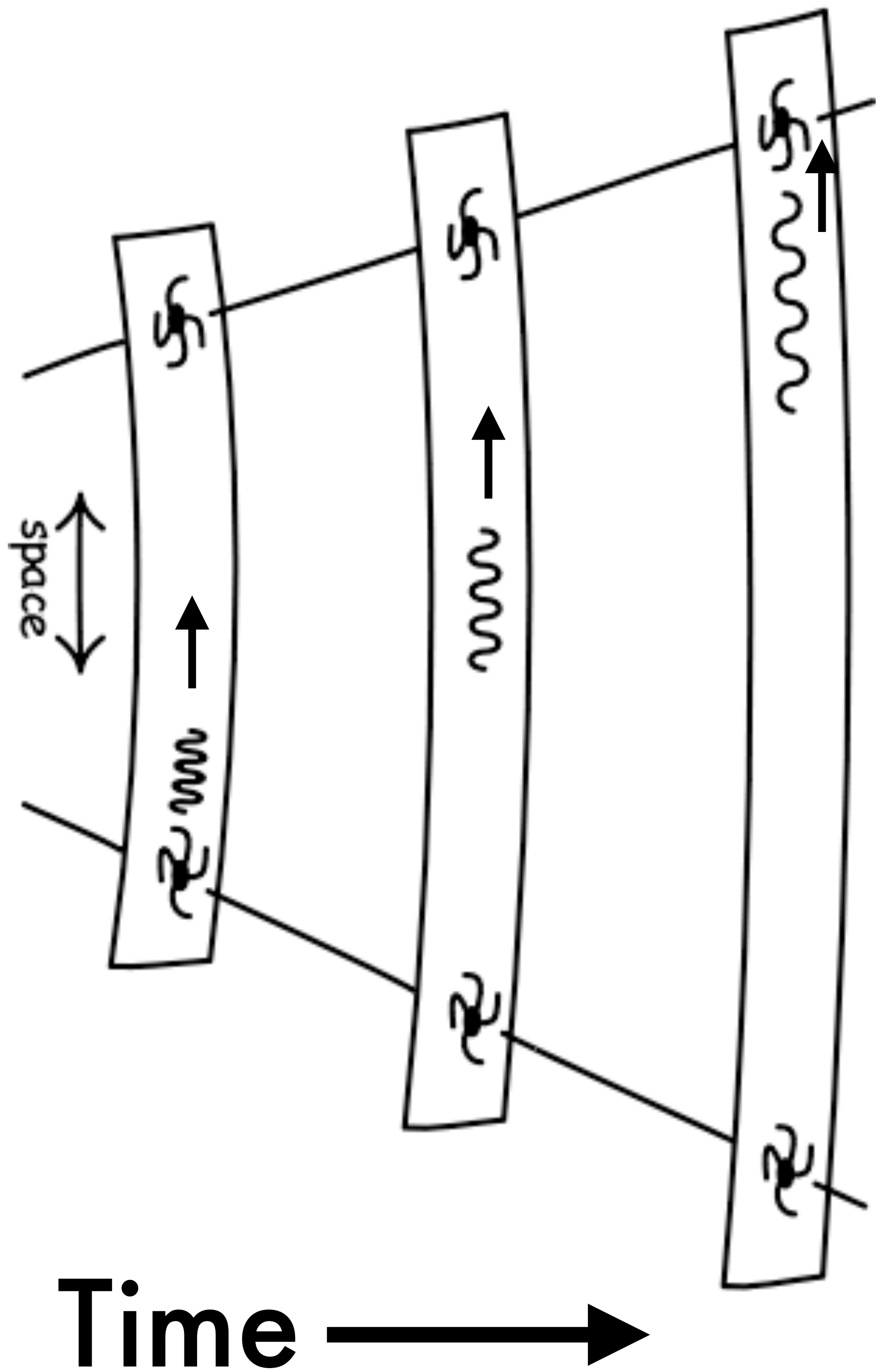
A uniform glow outside the Galactic Plane:
T = 2.7 Kelvin

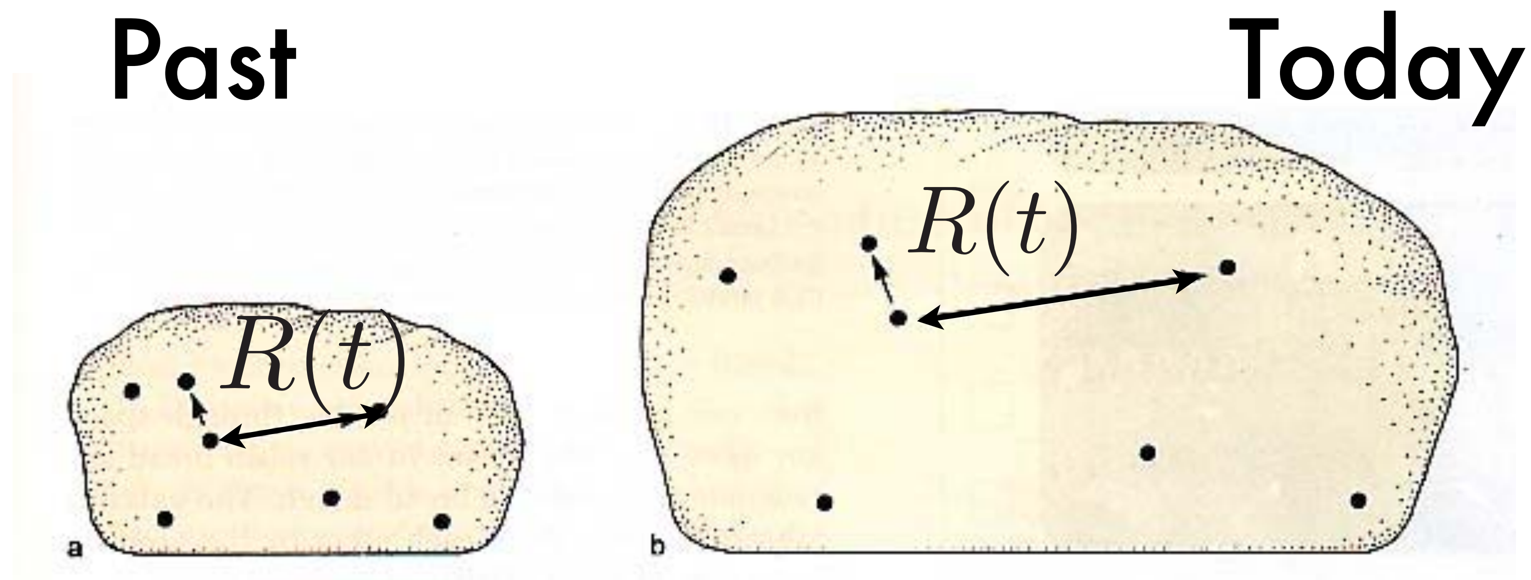
First detection of fluctuations:
one part in 100,000

COSMIC MICROWAVE BACKGROUND (CMB): EXPERIMENTAL PROGRESS



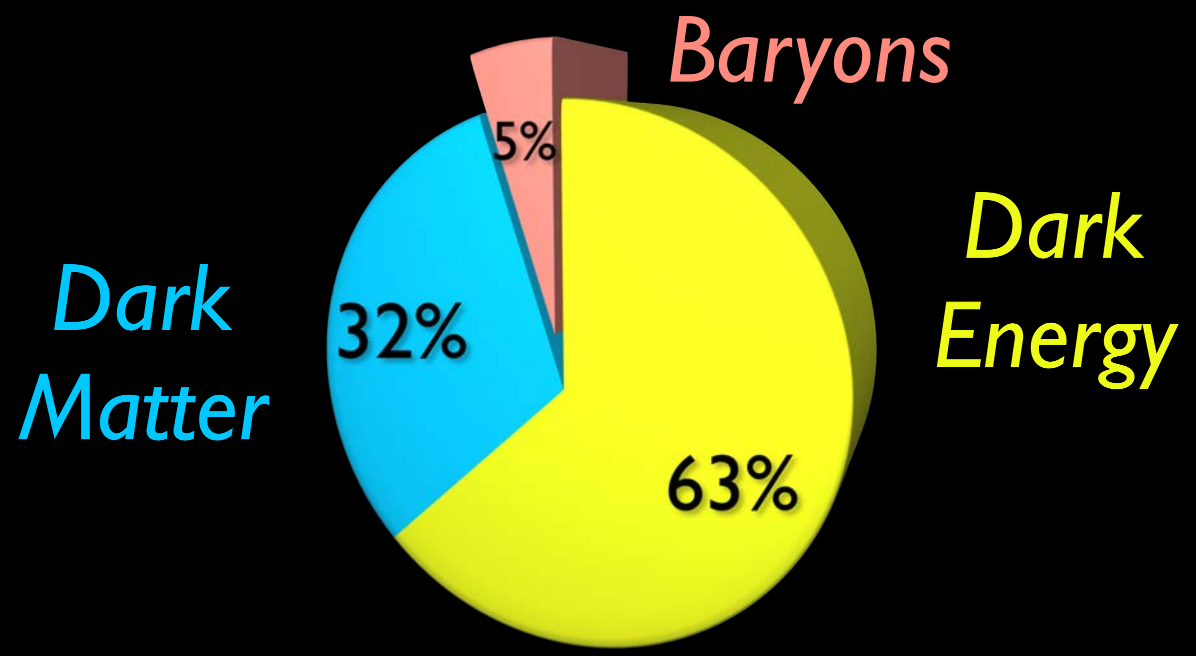
The expanding universe





With expansion

$$z = \frac{\lambda_{\text{observed}}}{\lambda_{\text{emitted}}} - 1$$



$\Omega_{\rm DE}$

5% baryonic matter: protons, electrons, atoms

- ✴"stuff we know"

32% cold dark matter (CDM)

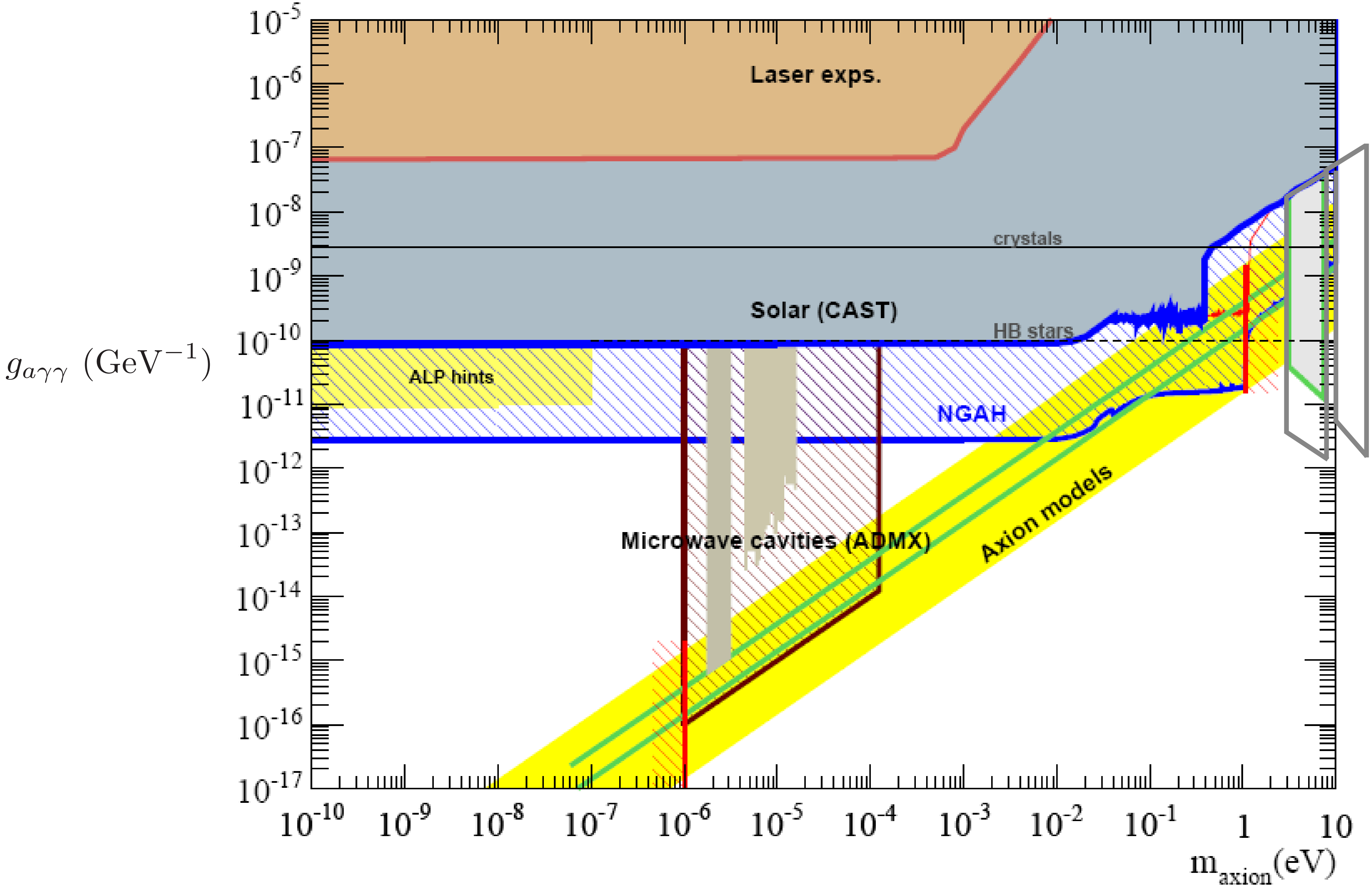
- ✴Stable, neutral, non-relativistic particle
- ✴Weak interactions with standard model

63% dark energy

Stuff we don't know!

Axion Fundamentals

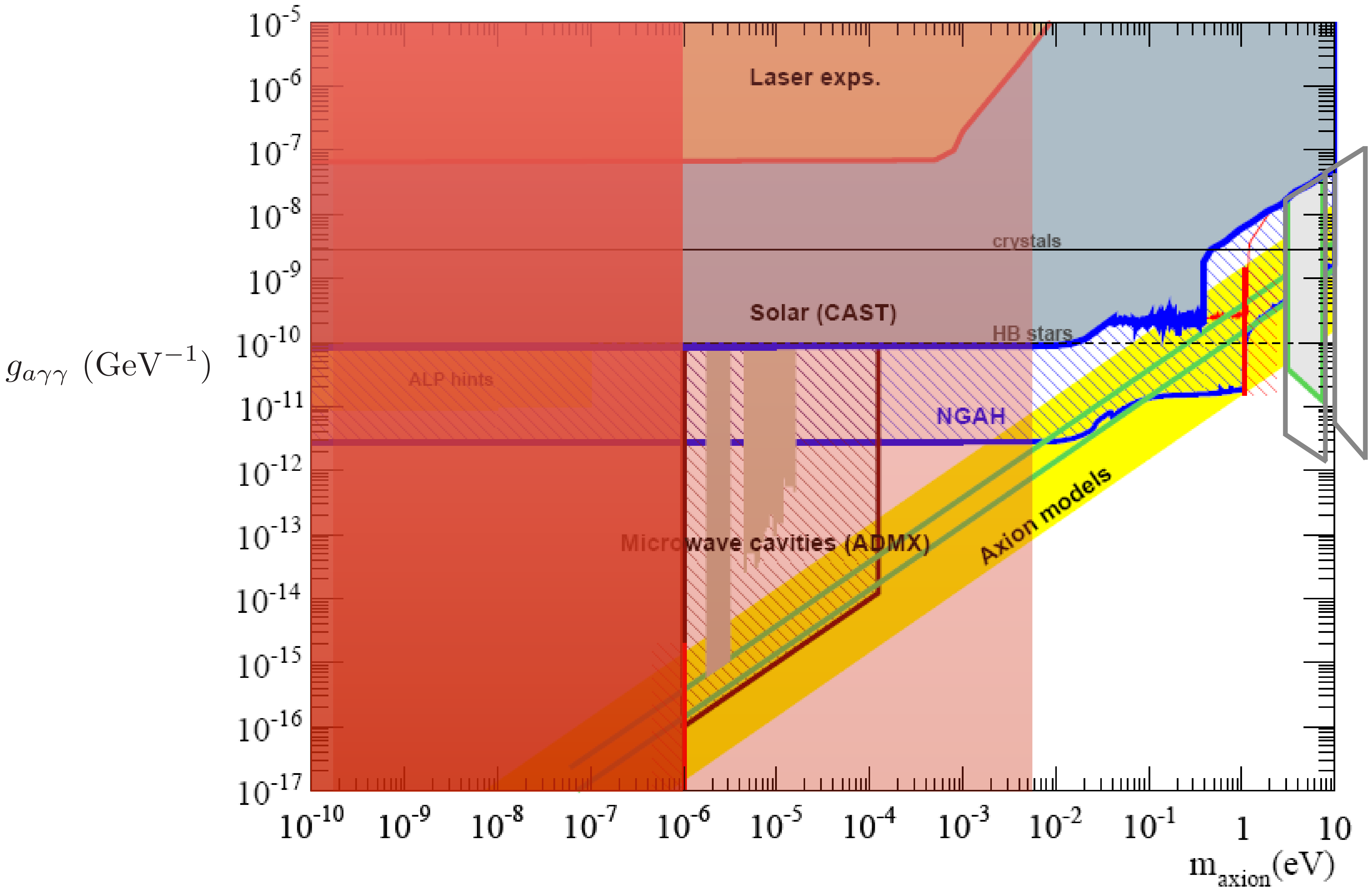
LIMITS



$g_{a\gamma\gamma}$ (GeV^{-1})
Laser exps.
crystals
Solar (CAST)
HB stars
ALP hints
NGAH
Microwave cavities (ADMX)
Axion models
m$_{axion}$(eV)

LIMITS

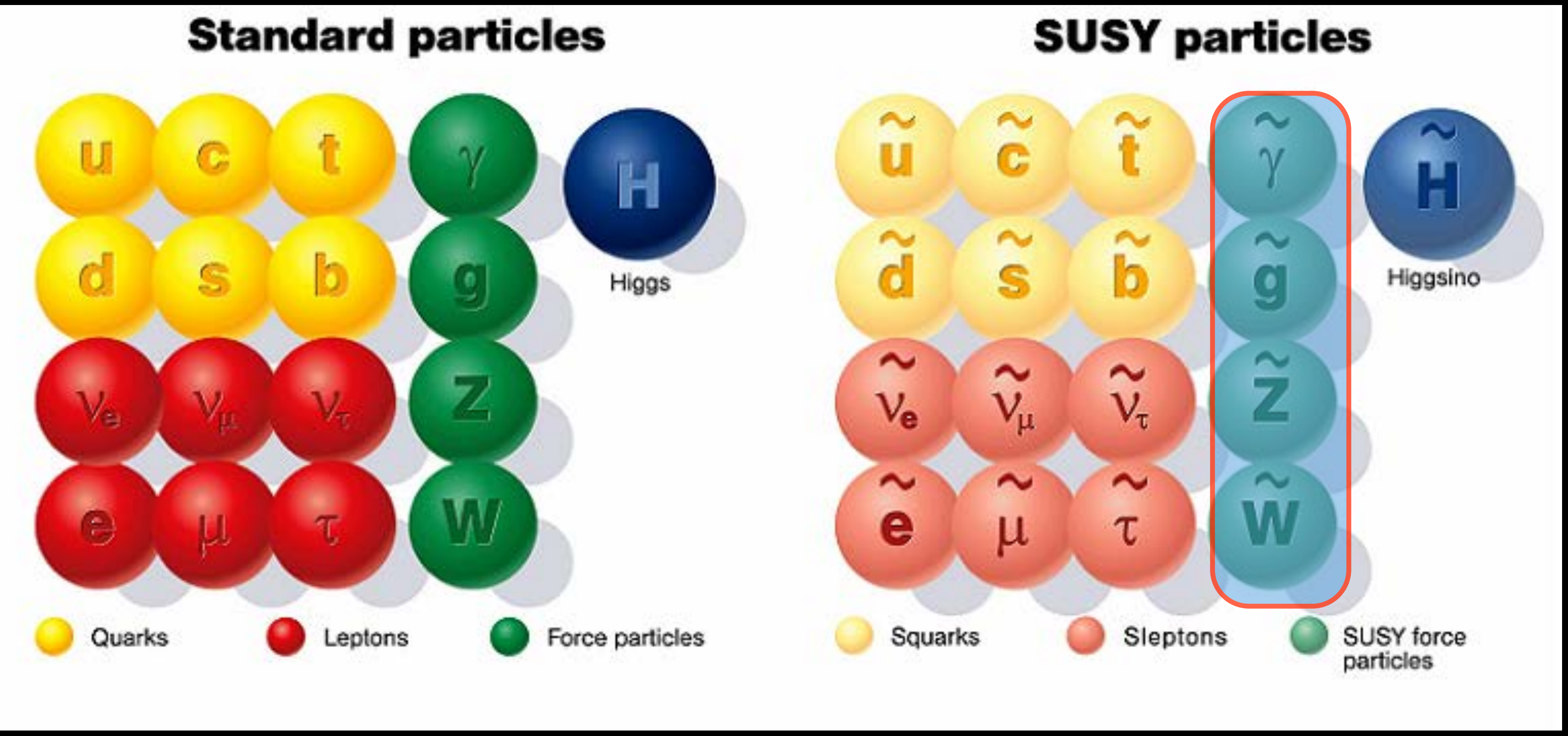
Cosmological dark matter



Supersymmetry theory

✳Solves many of SM's problems!

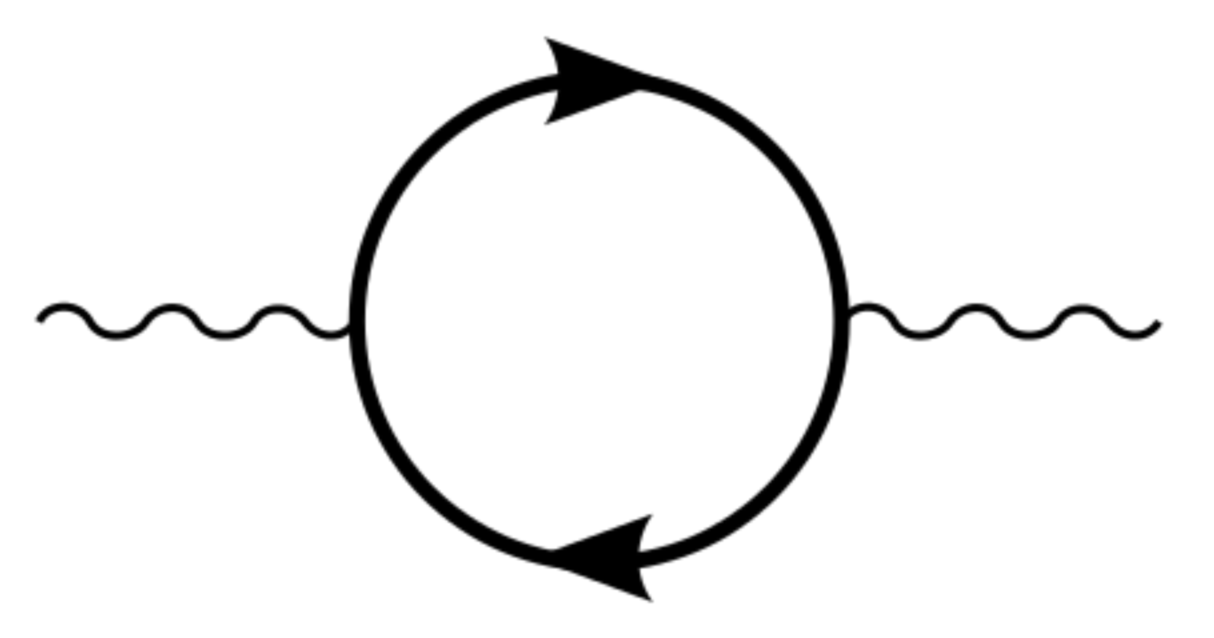
Dark matter?



✳Heavy! $m_{\text{dark matter}} \sim 10^2$ GeV vs $m_{\text{proton}} \sim 1$ GeV

✳Correct dark-matter abundance! 32% of cosmic mean density

DARK ENERGY: SM VACUUM ENERGY?



Crudely:

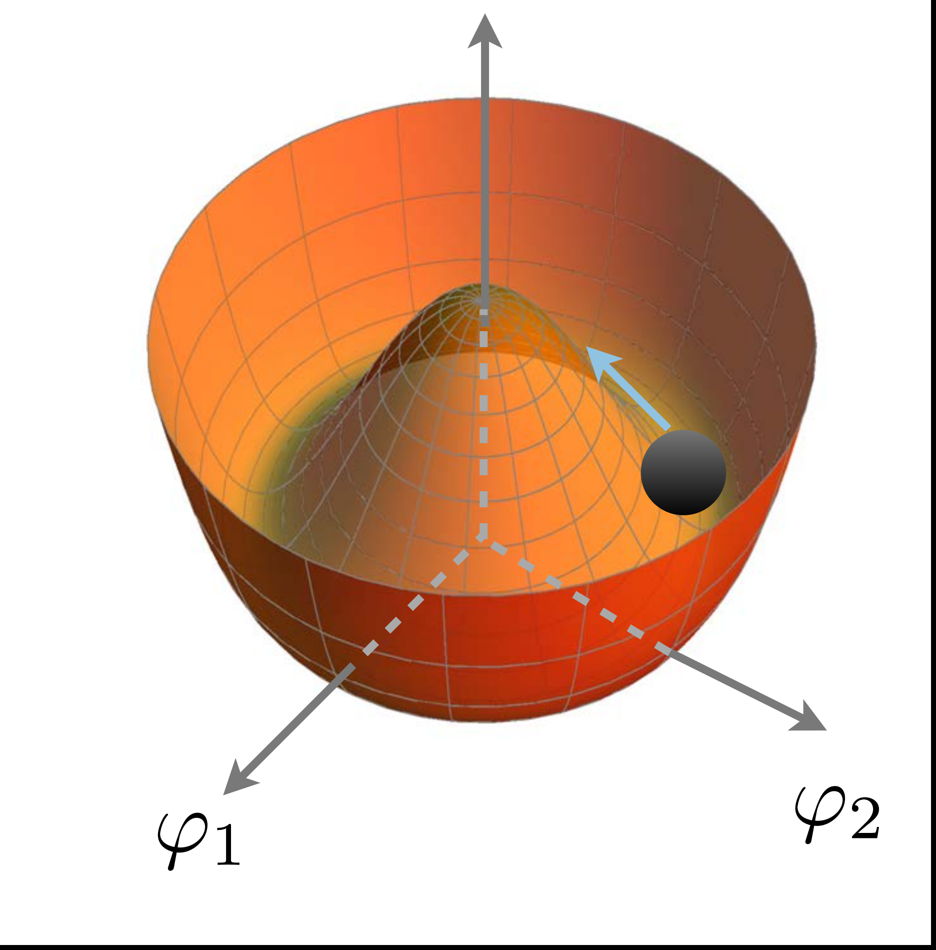
$$\Delta E \sim \frac{\hbar}{\Delta t}$$

Full standard model vacuum energy predicts….

$$\Omega_\Lambda \sim 10^{120} \quad \text{vs } \Omega_\Lambda \simeq 0.63$$

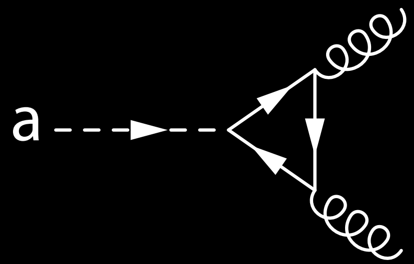
This is what you call a colossal failure

WHAT ARE AXIONS?



New scalar field with global U(1) symmetry!

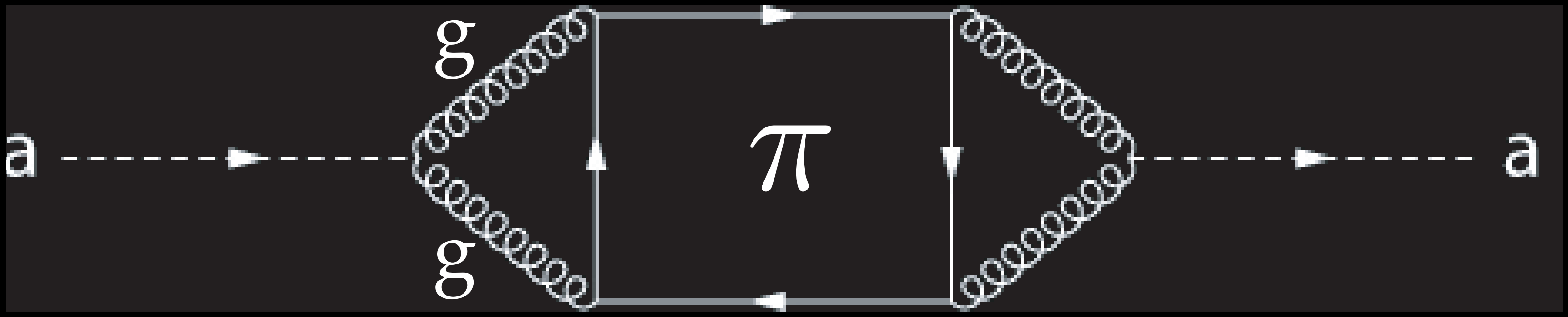
$$\mathcal{L}_{\rm CPV} = \frac{\theta g^2}{32\pi^2} G\tilde{G} - \frac{a}{f_{\rm a}} g^2 G\tilde{G}$$



✳ Couples to SM gauge fields (via fermions)

✳ Dynamically erases QCD CP-violation

✳ Mass through pion mixing



Peccei + Quinn (1977), Weinberg +Wilczek (1978), Kim (1979), Shifman et. al (1980), Zhitnitsky (1980), Dine et al. (1981), D.B. Kaplan (1985), A.E Nelson (1985,1990)

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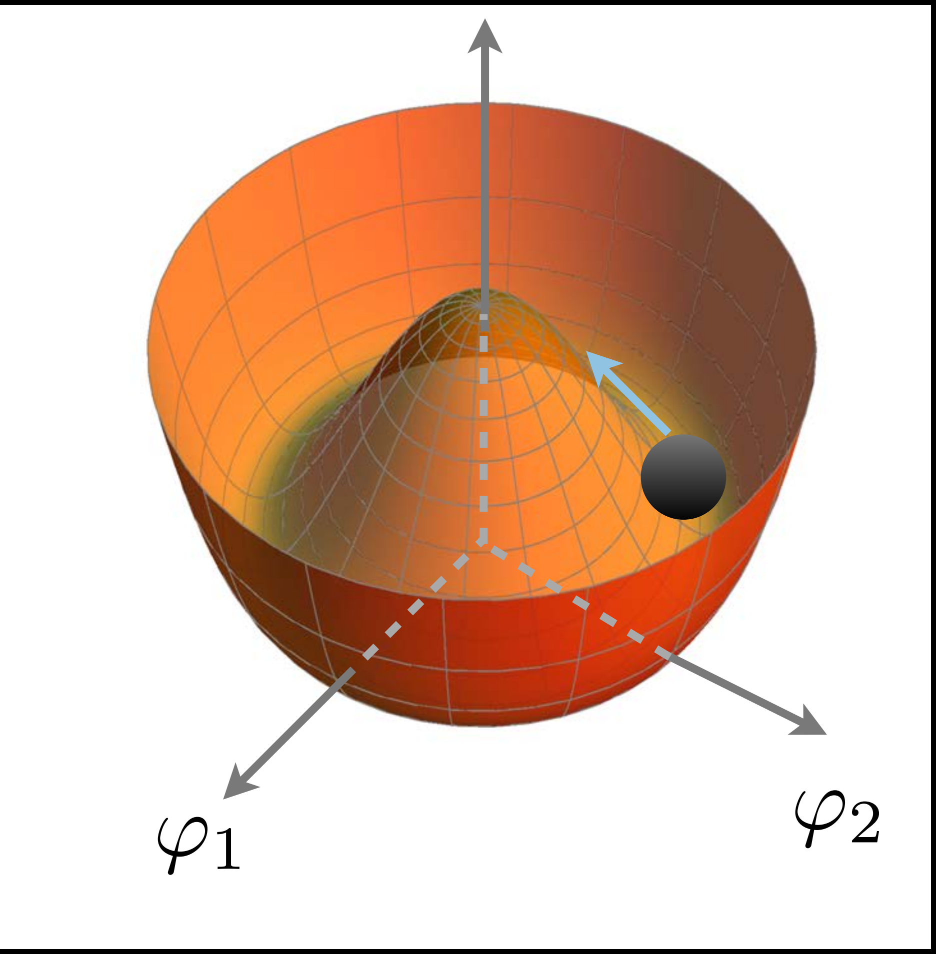

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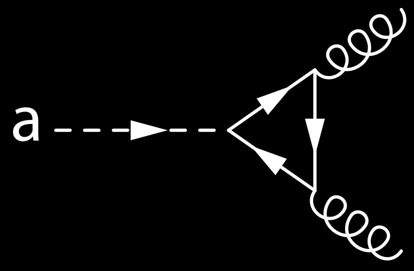

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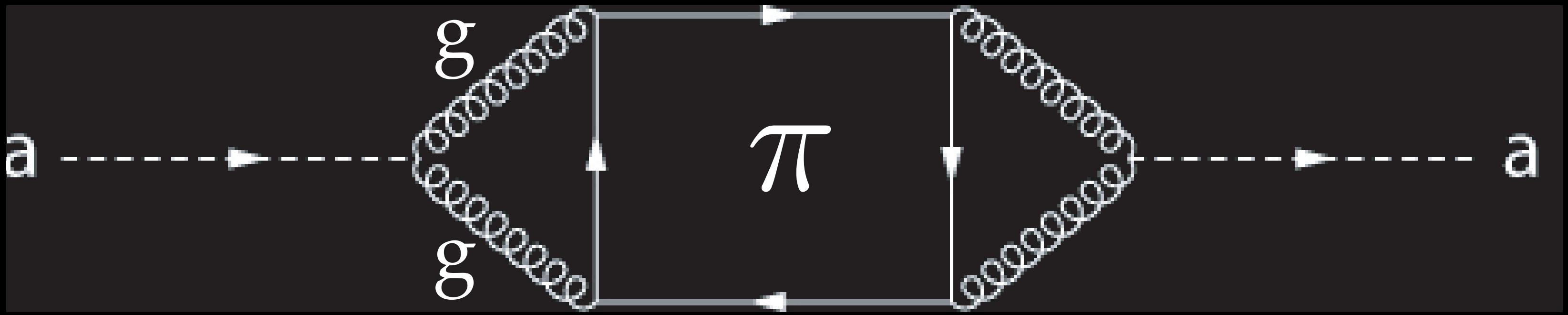

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- ✳ New field (axion) and U(1) symmetry dynamically drive net CP-violating term to 0

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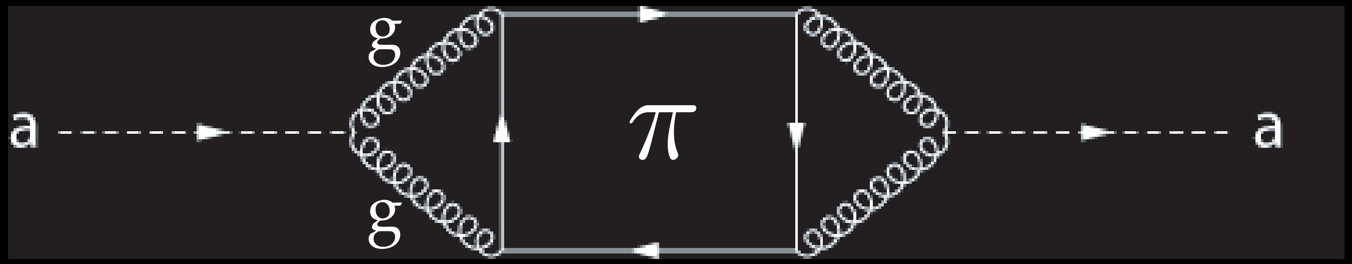
- ✳ Through coupling to pions, axions pick up a mass



$$m_a \simeq \frac{\Lambda_{\mathrm{QCD}}^2}{f_a}$$

$$\Lambda_{\mathrm{QCD}} \simeq 200 \ \mathrm{MeV}$$

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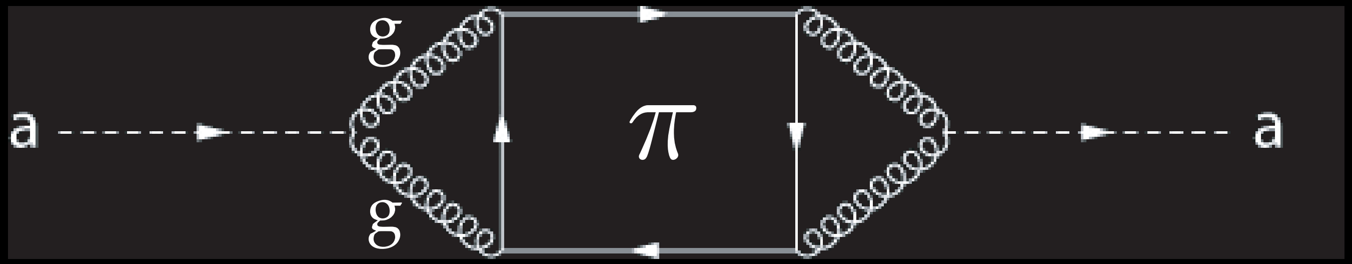


$$m_a = 6.2\mu\ \mathrm{eV} \left(\frac{10^{12}\ \mathrm{GeV}}{f_{\rm a}} \right)$$

Strong CP problem

- Strong interaction violates CP through θ -vacuum term

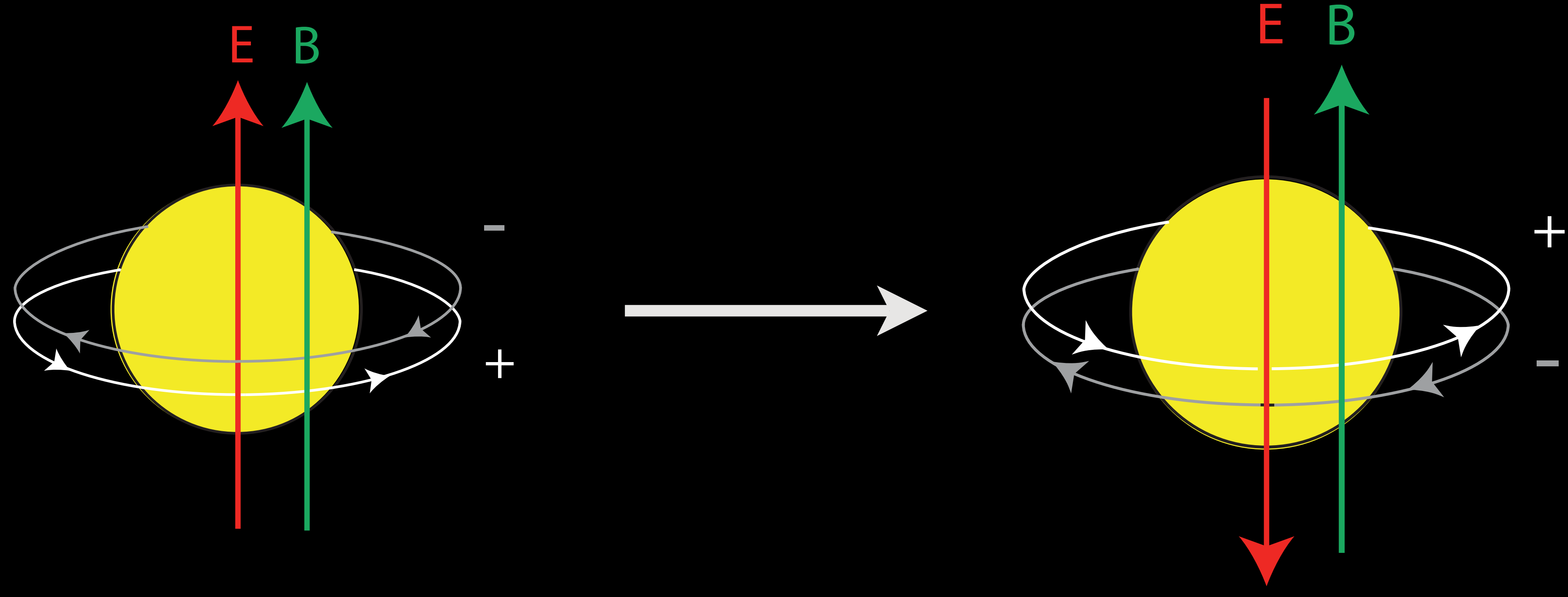
QCD strong-CP problem

$$\mathcal{L}_{\rm CPV} = \frac{\theta g^2}{32\pi^2} G\tilde{G}$$

- Limits on the neutron electric dipole moment are strong. Fine tuning?

$$d_n \simeq 10^{-16}\ \theta \text{ e cm}$$

$$\theta \lesssim 10^{-10},$$



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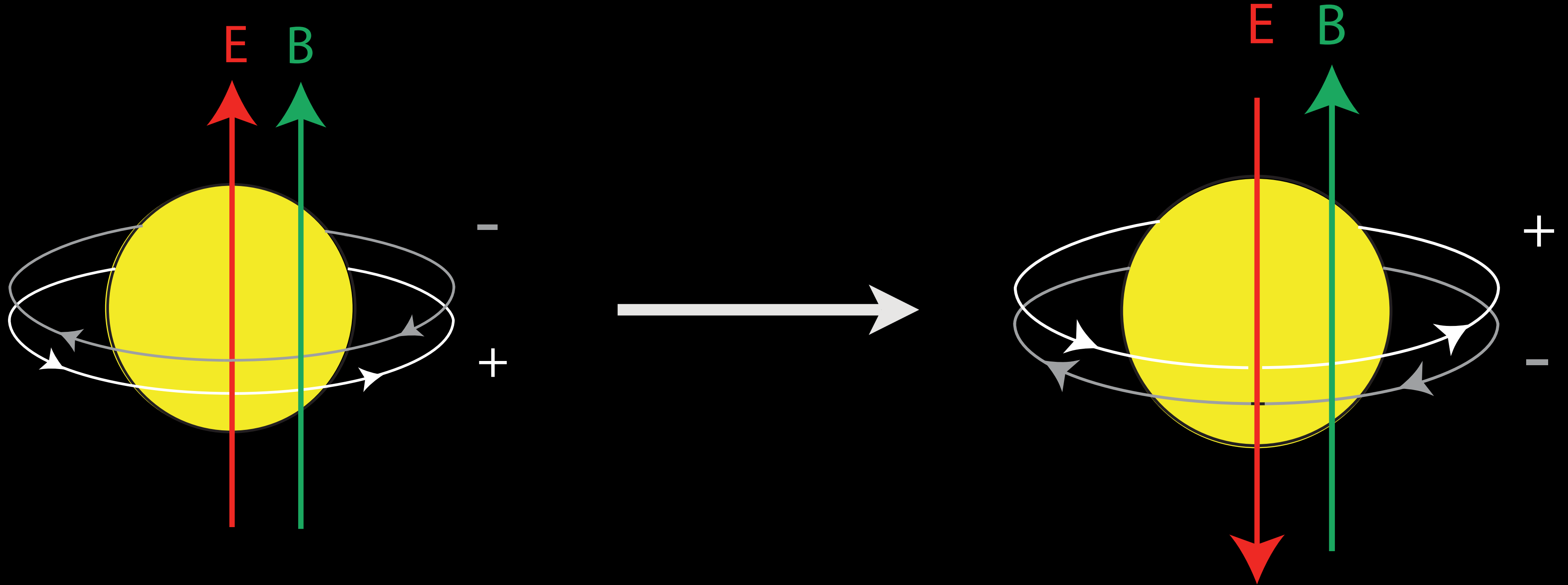

KEY QUESTIONS:

* ***Can the dark matter or dark energy be an ultra-light boson, like an axion?***
* What is the connection between the physics of inflation and the physics of the dark sector? Are initial fluctuations in different species spatially locked?
* What new probes of the dark sector could we soon have at our disposal?

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in collaboration with R. Hložek (Princeton), D. J. E. Marsh (Perimeter Institute), P. Ferreira (Oxford):

arXiv:1303.3008, Phys. Rev. D 87, 121701 (2013)
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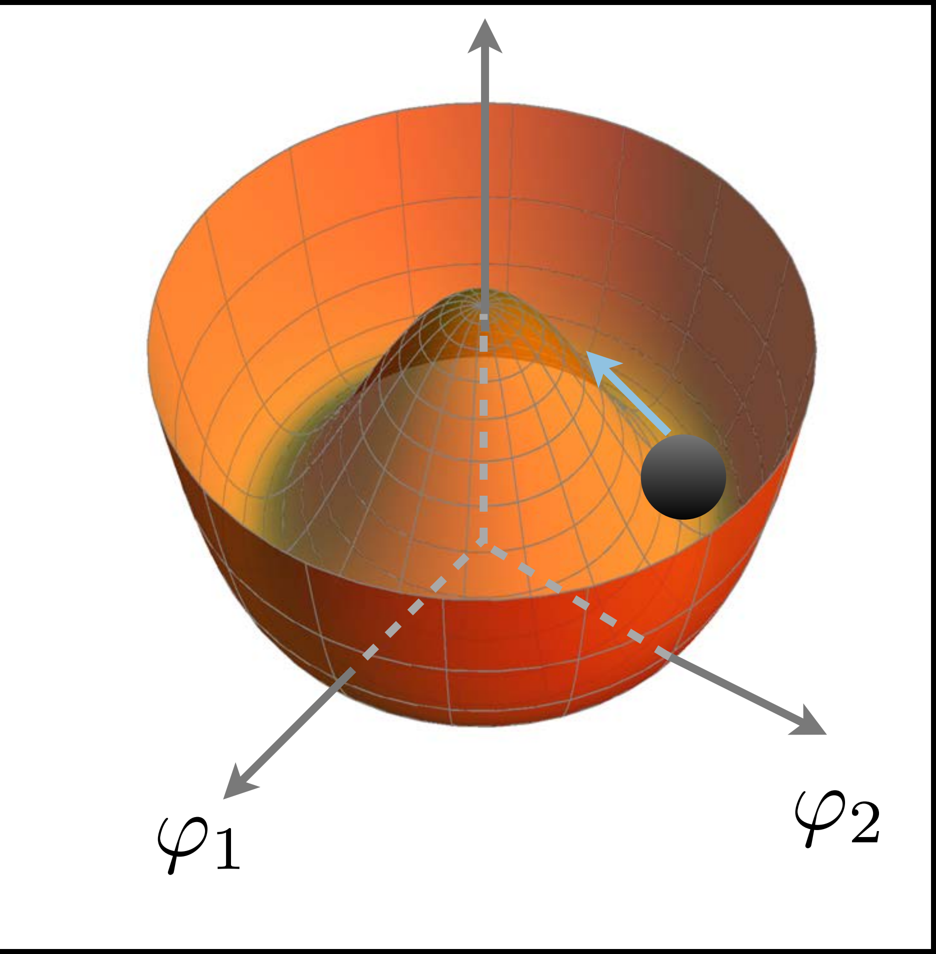

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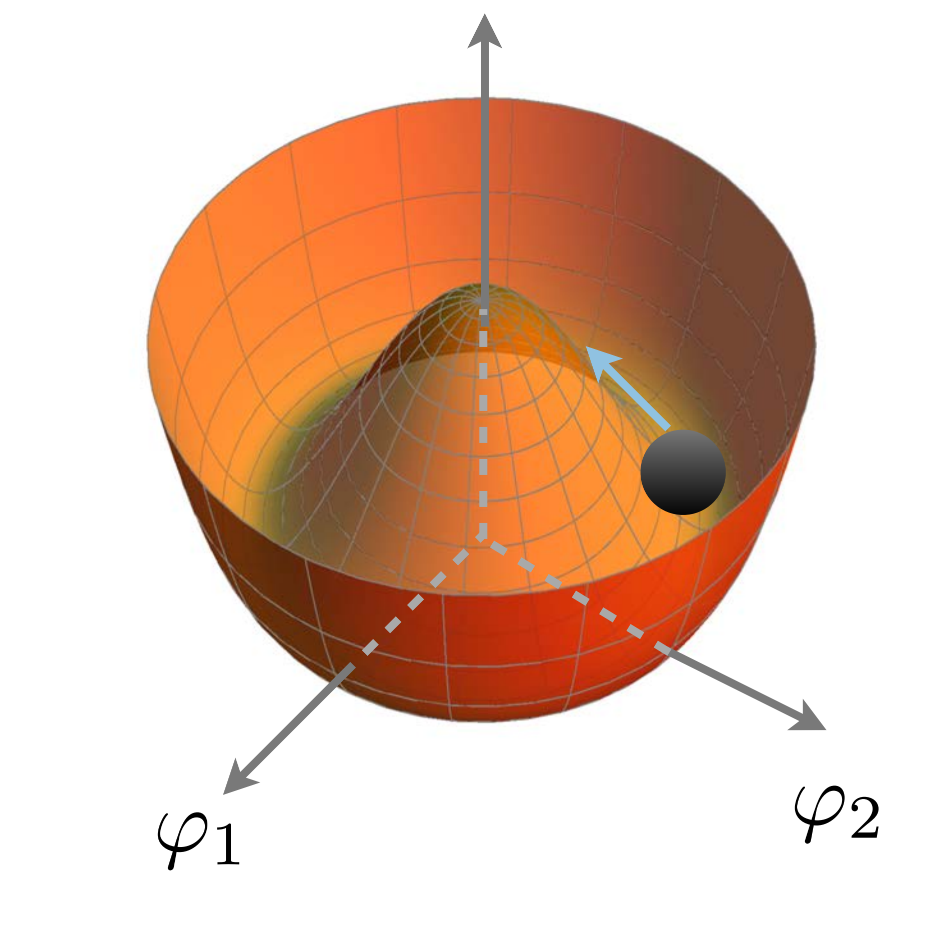

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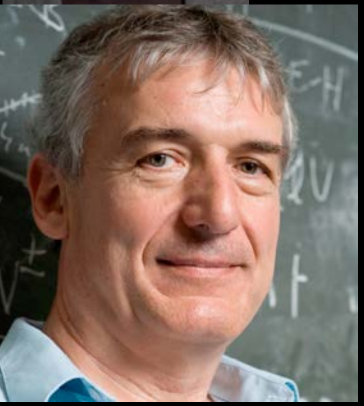
Cleaning up the dark matter mess?



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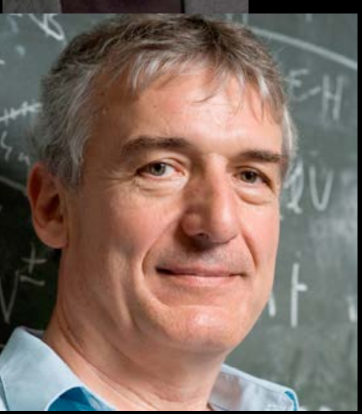
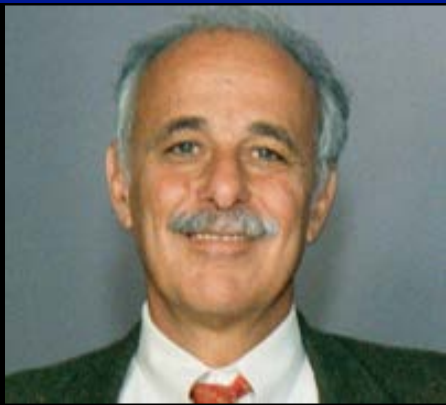
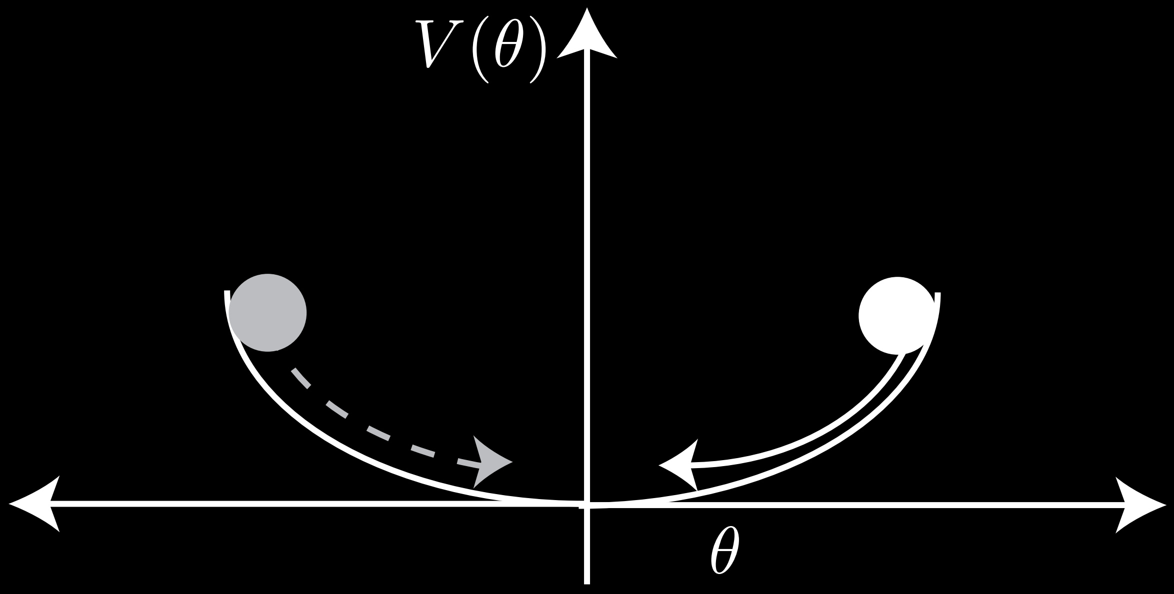


QCD axions are DM candidates

$m_a \lesssim 10^{-2}$ eV



- Field misaligned $m_a \gg 3H \rightarrow$ oscillation
- $\rho_a \propto (1+z)^3$ [as cold dark matter should]
- Axions **ARE** cold

  $v_a/c \lesssim 10^{-13}$ at CMB decoupling timescales

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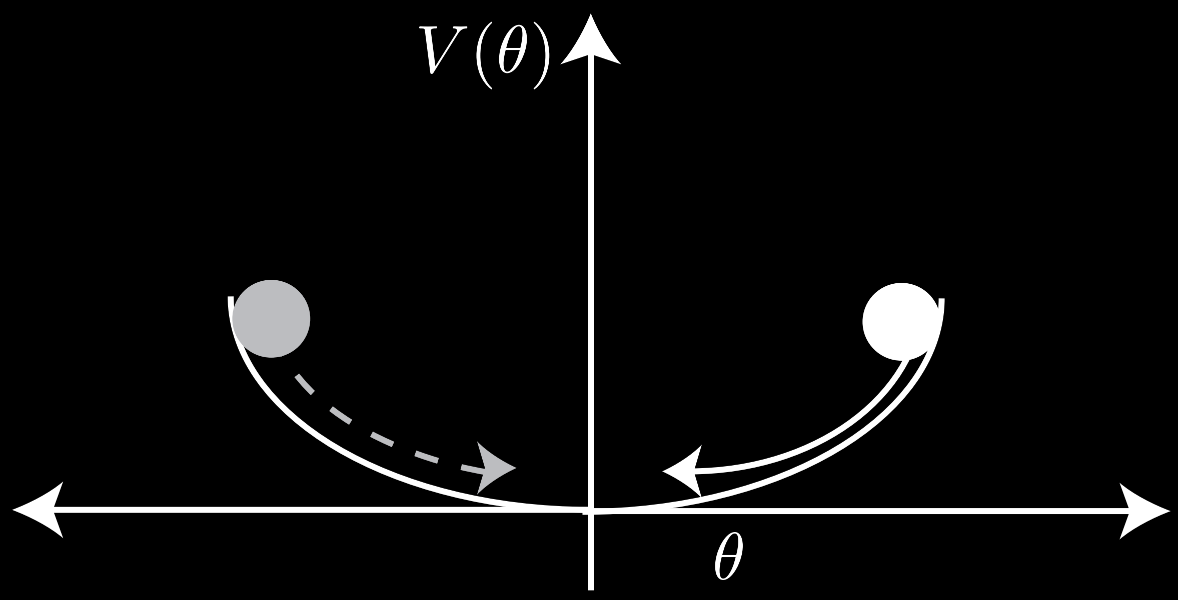

The QCD axion is a cold dark matter candidate

$$\Omega_{\rm mis} h^2 = 0.236 \left\langle \theta_i^2 f(\theta_i) \right\rangle \left(\frac{m_a}{6.2 \mu\text{eV}} \right)^{-7/6}$$

Solves a problem in particle physics:
Gives us a dark matter candidate for free!

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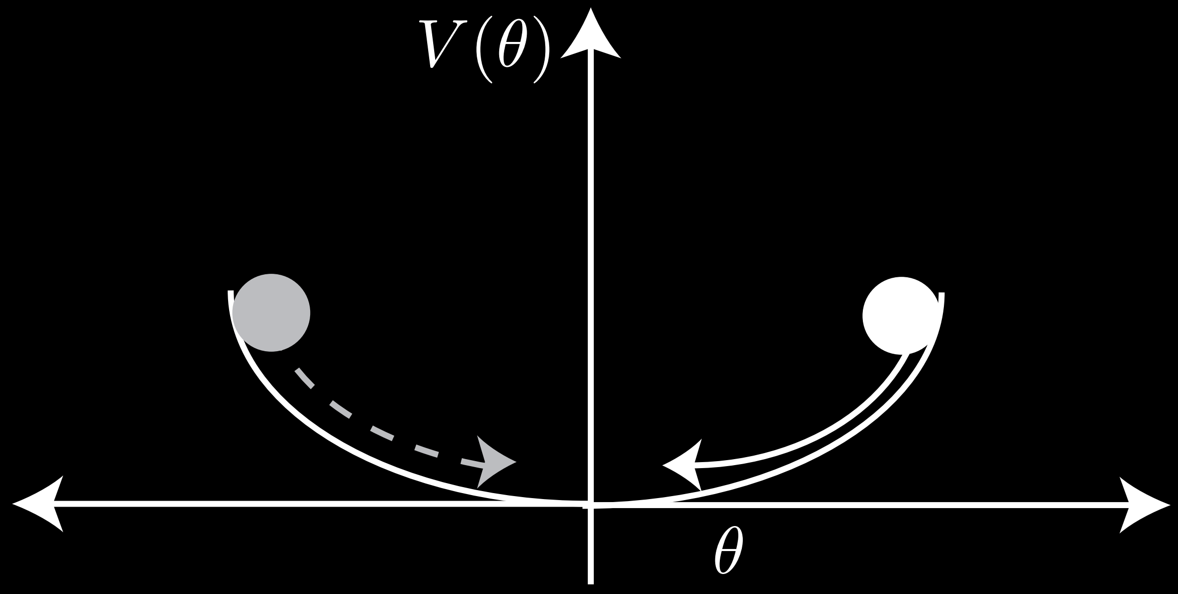

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QCD AXIONS ARE DM CANDIDATES

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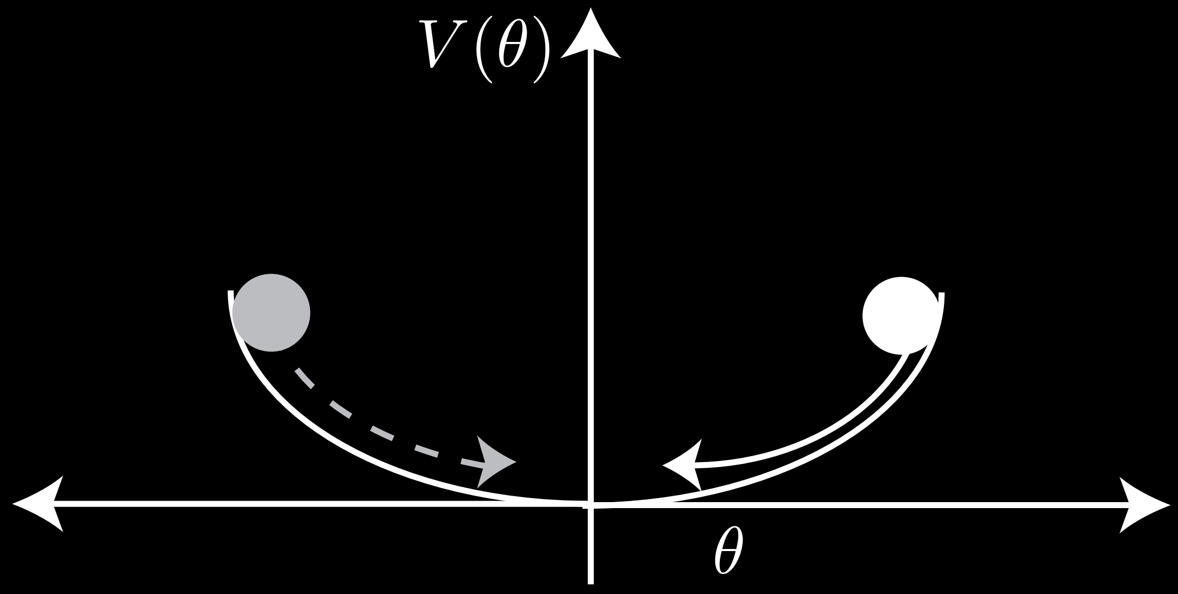

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Anthropic axion window: $f_a > \max\{T_{\rm RH}, H_{\rm I}\}$

- Axion field is relatively homogeneous

$$\langle \theta^2 \rangle = \overline{\theta}^2 + \left(\frac{H_I}{2\pi f_a} \right)^2$$

- Abundance

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Misalignment in our Hubble Patch

- Abundance

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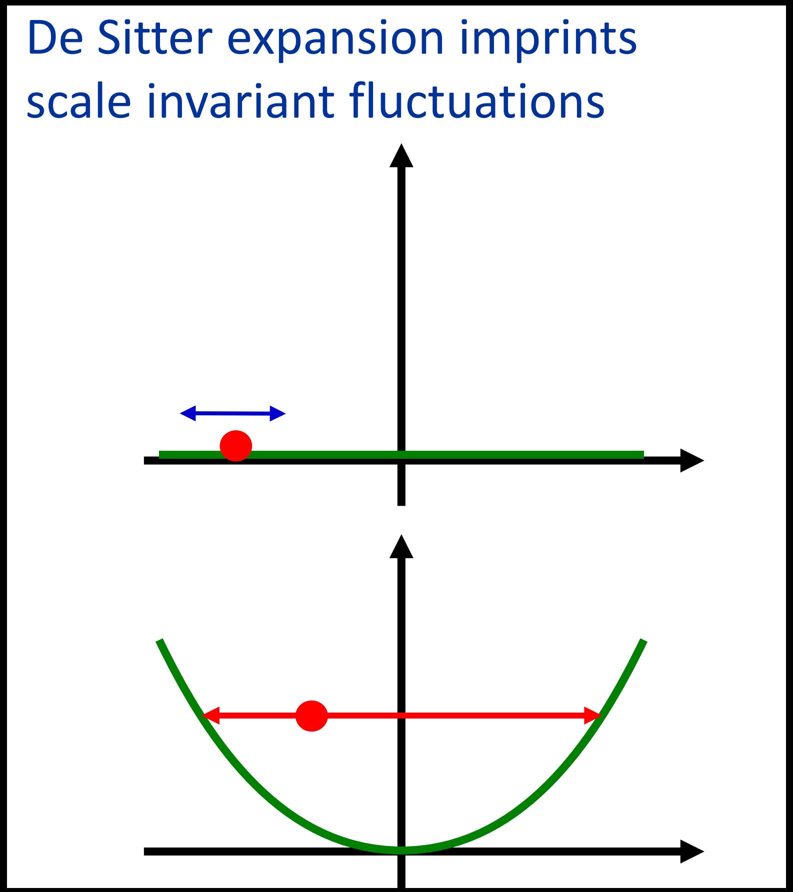
Vacuum fluctuations from inflation



From Raffelt 2012

- Abundance

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- Abundance

$$\Omega_a h^2 \simeq 0.43 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{7/6} \theta_i^2$$

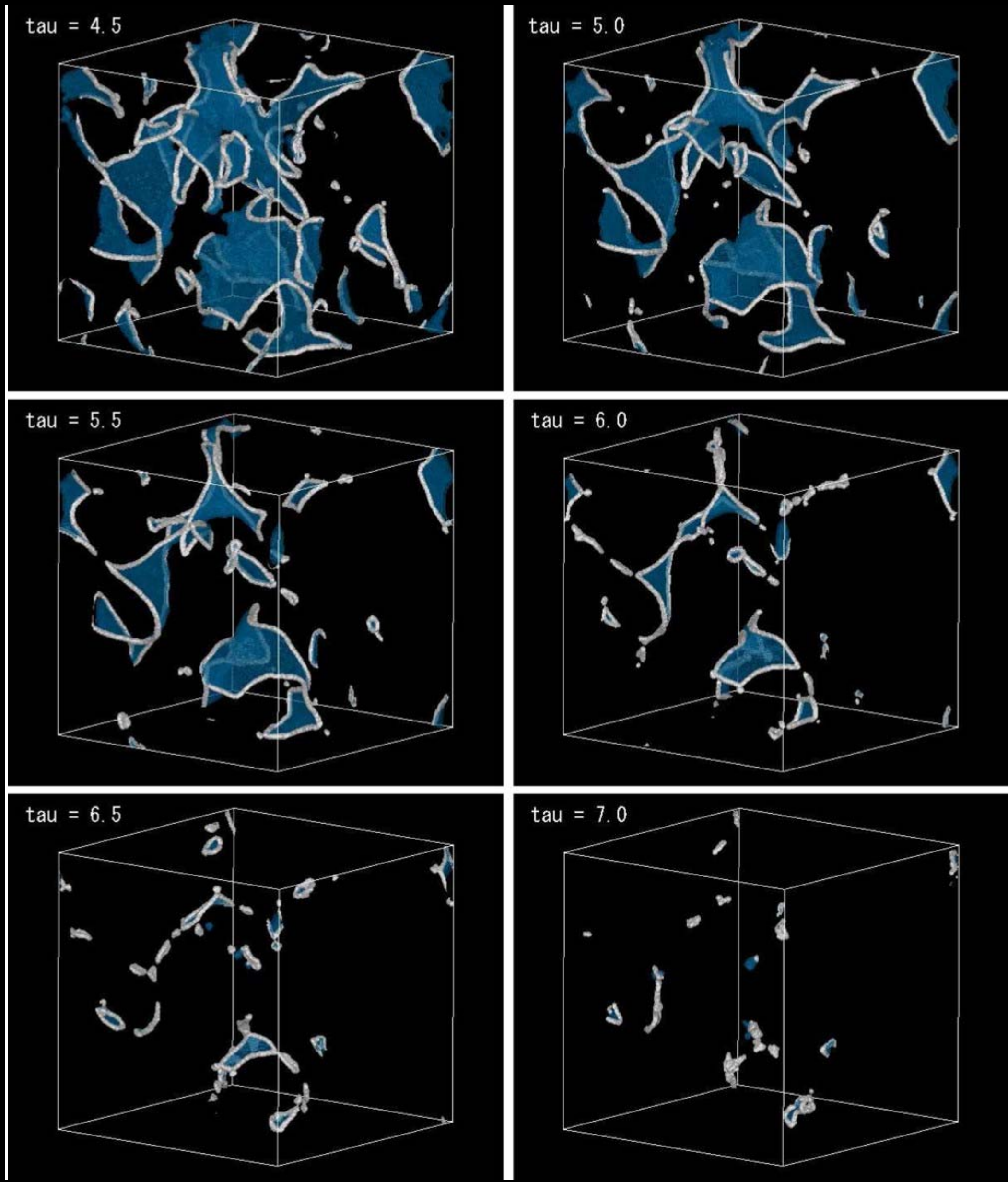
$$\Omega_a h^2 \simeq 0.005 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{3/2} \theta_i^2$$

- $\overline{\theta}$ can be tuned to get DM abundance for many axion masses

Classic axion window: $f_a < \max\{T_{\rm RH}, H_{\rm I}\}$

✴ Axion field is very inhomogeneous

$$\left\langle \bar{\theta}_i^2 \right\rangle = \frac{\pi^2}{6}$$



✴ Defects [domain walls, strings, etc..]

$$\mathcal{O}(1) \lesssim \alpha_{\rm defect} \lesssim \mathcal{O}(10^2)$$

✴ Abundance

$$\Omega_a h^2 \simeq 2.0\,\{1 + f_{\rm defect}\}\left(\frac{f_a}{10^{12}\ {\rm GeV}}\right)^{7/6}$$

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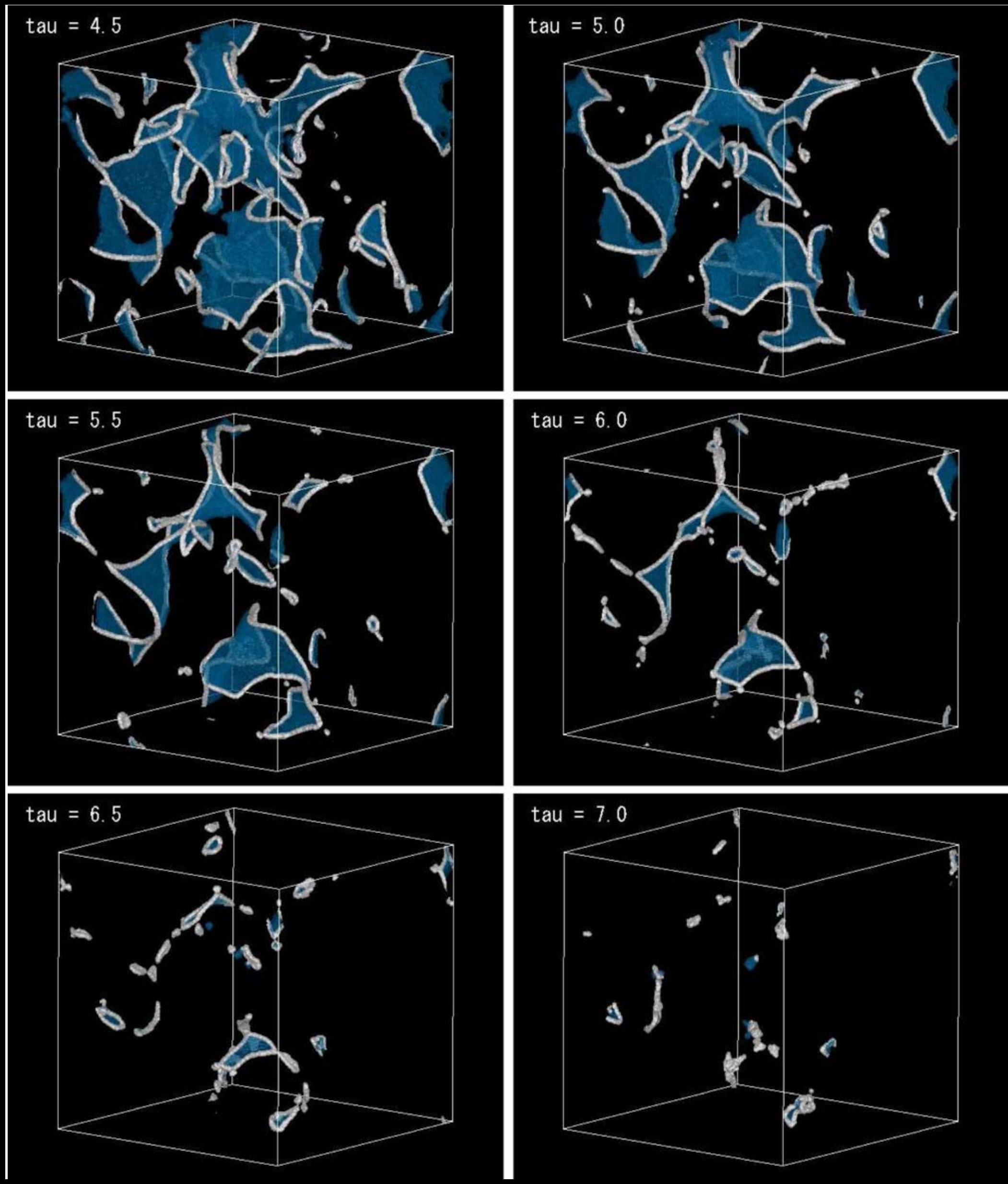

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CONTROVERSY!

- ✳ Abundance

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Dark matter axion abundance

- QCD axion couples to quarks/pions, temp-dependent mass
  - High-temp regime

$$m_{\rm a} = 0.02 m_{\rm a}^{(T=0)} \left(\frac{\Lambda_{\rm QCD}}{T}\right)^4 \ \text{if}\ T \gg \Lambda_{\rm QCD}$$

  - Low-temp regime $m_{\rm a} = m_{\rm a}^{(T=0)}$ if $T \lesssim \Lambda_{\rm QCD}$

$$\Omega_{\rm mis} h^2 = 0.236 \left\langle \theta_i^2 f(\theta_i) \right\rangle \left(\frac{f_a}{10^{12}\ \text{GeV}}\right)^{7/6} \quad \text{if}\ f_a \lesssim 10^{18}\ \text{GeV}$$

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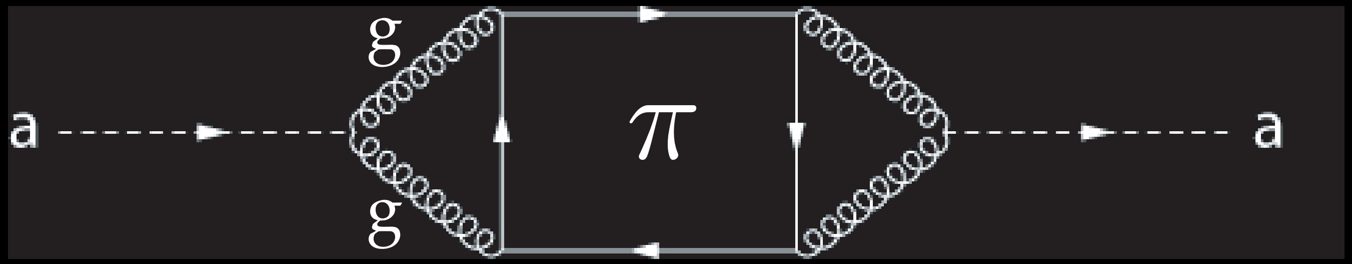
$$\mathcal{L}_{\rm CPV} = \frac{\theta g^2}{32\pi^2} G\tilde{G} - \frac{a}{f_{\rm a}} g^2 G\tilde{G}$$

- Through coupling to pions, axions pick up a mass

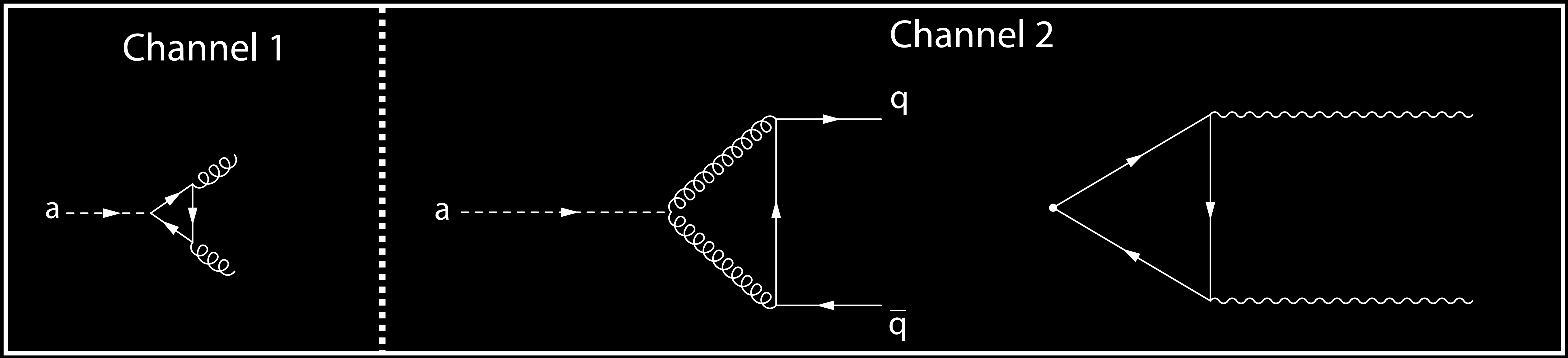


$$m_{\rm a} \simeq \frac{m_\pi f_\pi}{f_{\rm a}} \frac{\sqrt{r}}{1+r}$$

$$r \equiv m_{\rm u}/m_{\rm d}$$

$$m_a = 6.2\mu \text{ eV} \left(\frac{10^{12} \text{ GeV}}{f_{\rm a}} \right)$$

Two-photon coupling of axion

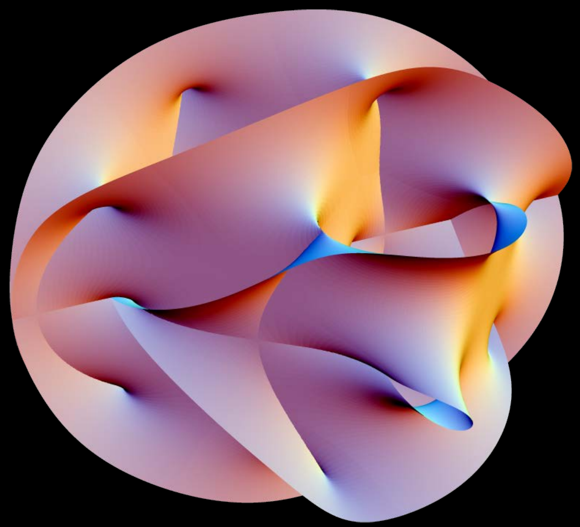


- Axions interact weakly with SM particles $\Gamma, \sigma \sim \alpha^2$
- Axions have a two-photon coupling

$$g_{\mathrm{a}\gamma\gamma} = -\frac{3\alpha}{8\pi f_{\mathrm{a}}}\xi$$

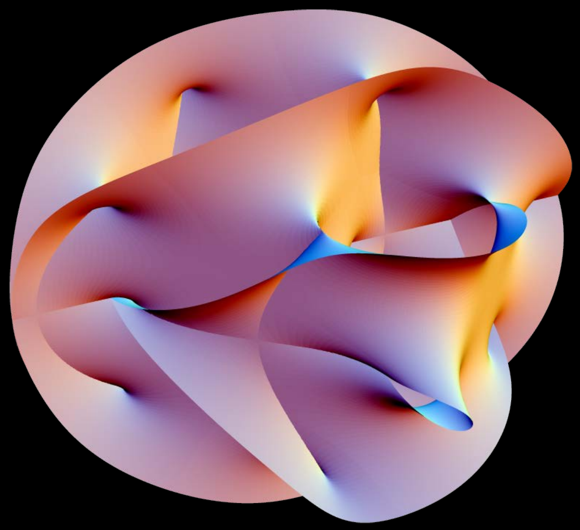
Ultra-light axions (ULAs) in string theory

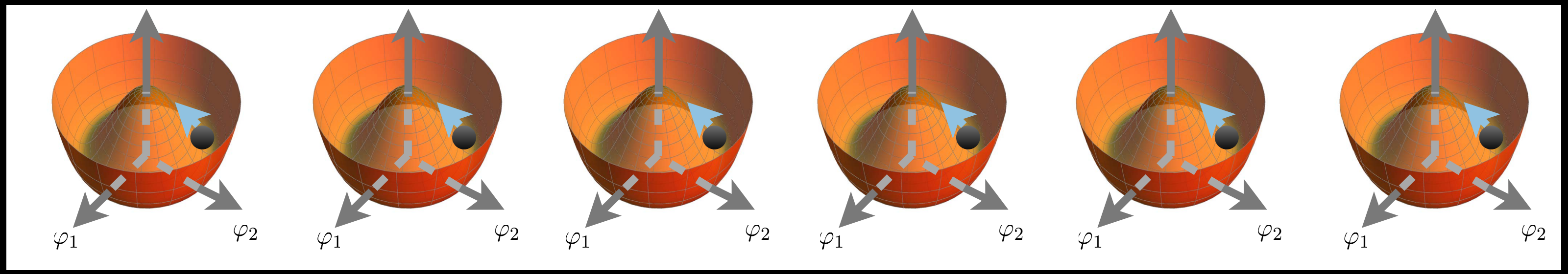
- In string theory, extra dimensions compactified: Calabi-Yau manifolds



ULTRA-LIGHT AXIONS (ULAS) IN STRING THEORY

✳ In string theory, extra dimensions compactified: Calabi-Yau manifolds





+....

Hundreds of scalars
with approx shift symmetry

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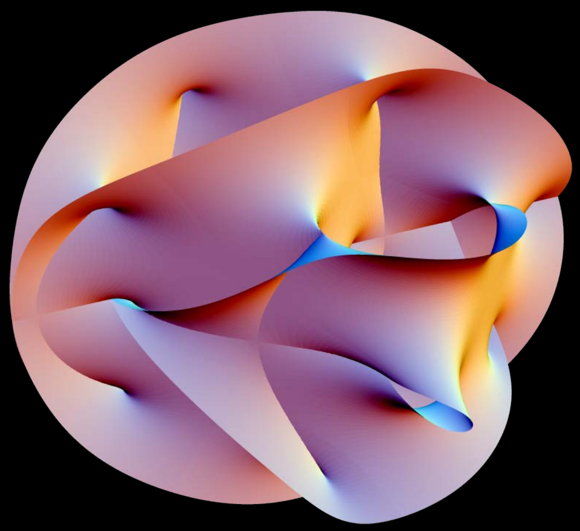

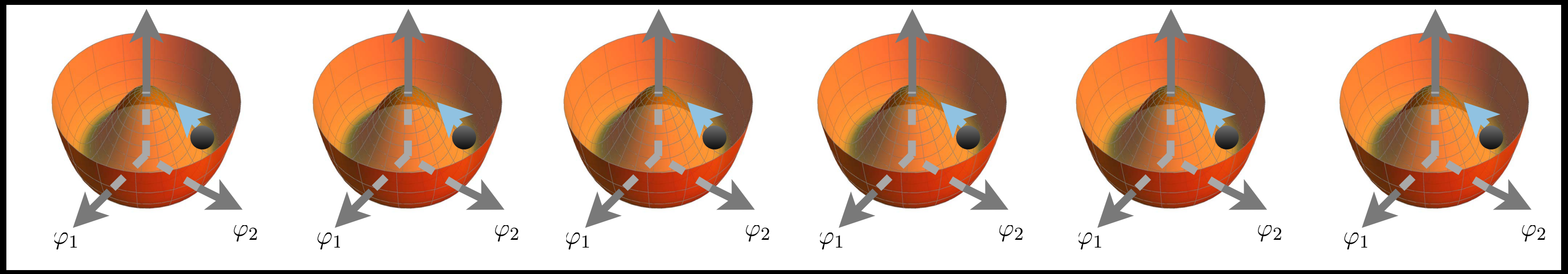

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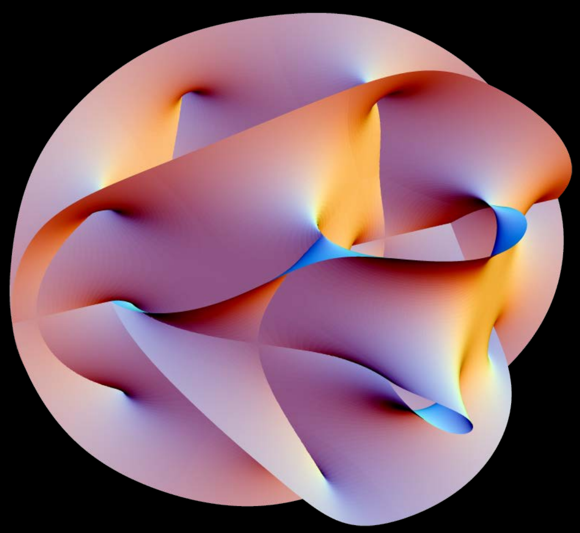

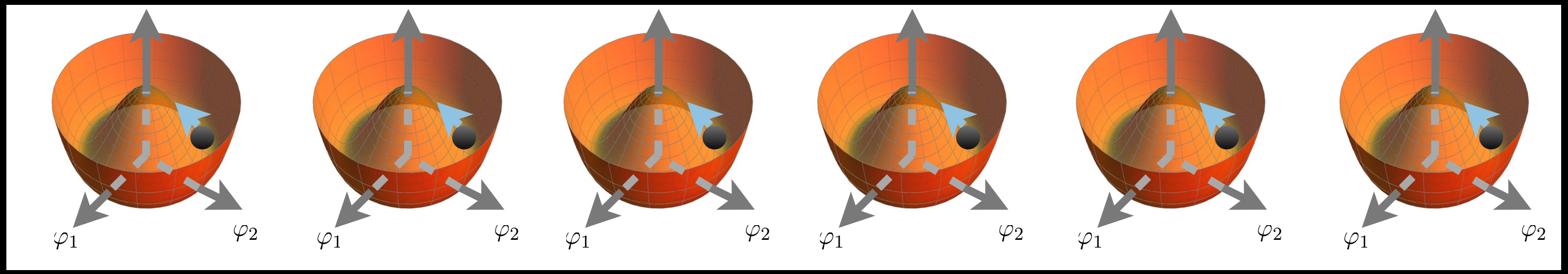

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Many axions

* Mass acquired non-perturbatively (instantons, D-Branes)

$$m_a^2 = \frac{\mu^4}{f_a^2} e^{-\text{Volume}}$$

ULTRA-LIGHT AXIONS (ULAS) IN STRING THEORY

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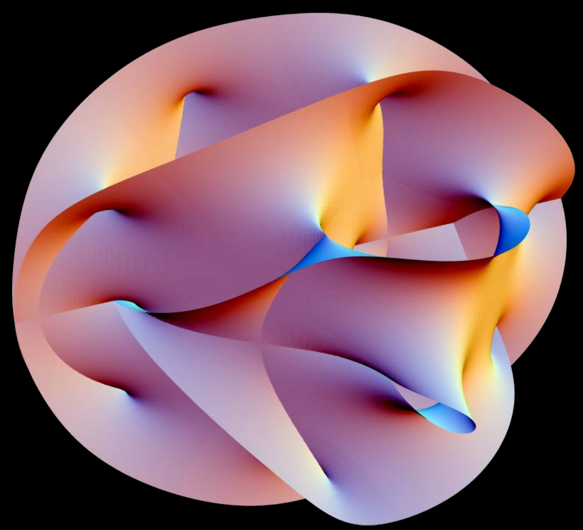

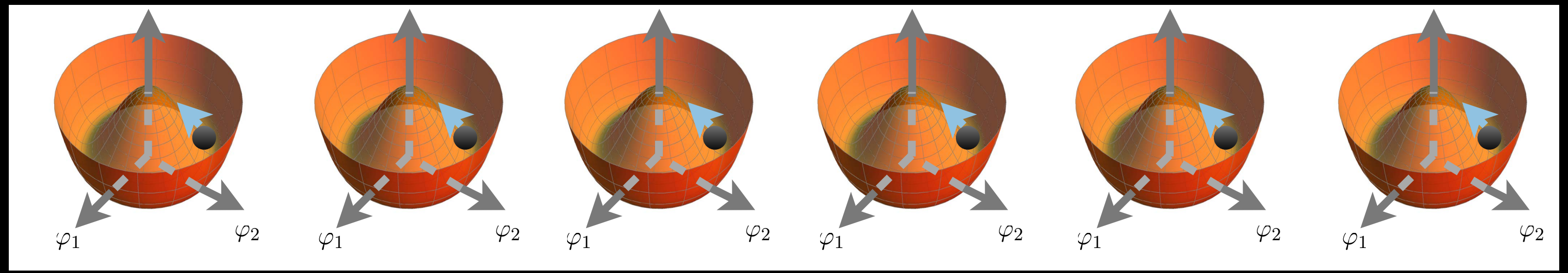

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Scale of new ultra-violet physics ←

$$m_a^2 = \frac{\mu^4}{f_a^2} e^{-\text{Volume}}$$

Ultra-light axions (ULAs) in string theory

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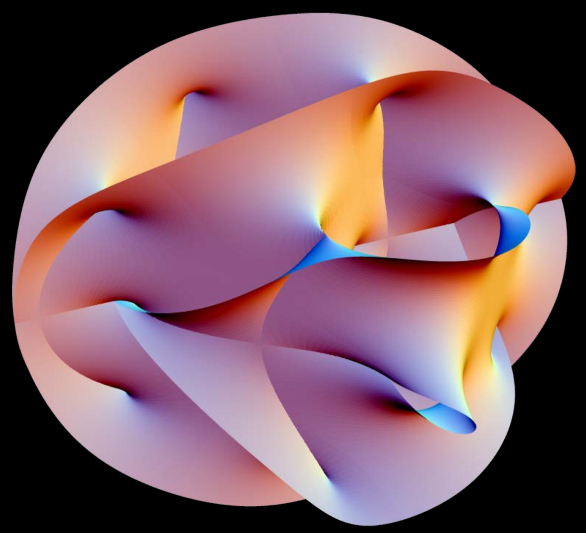

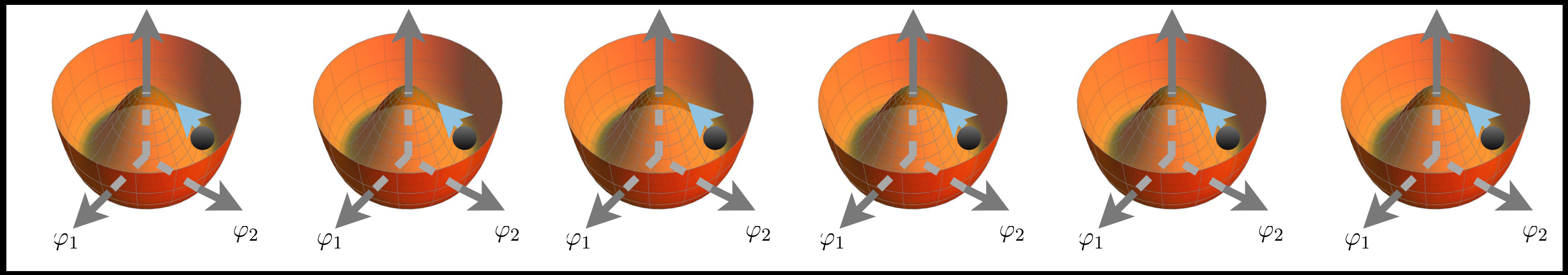

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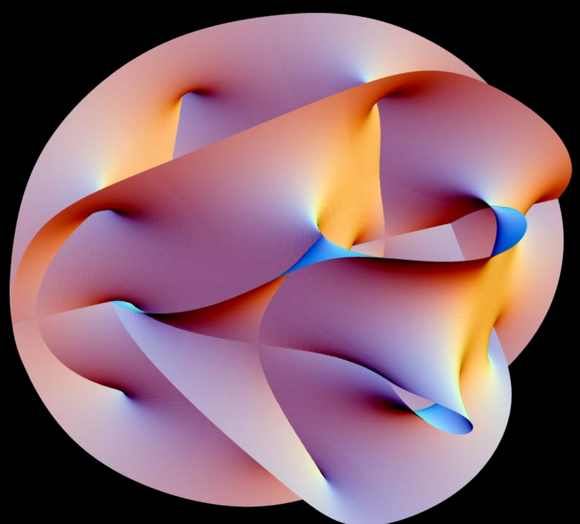
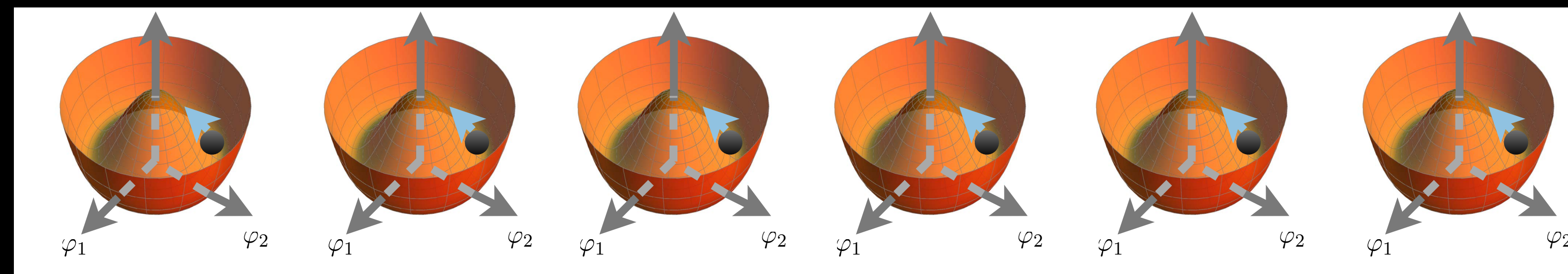
Scale of extra dimensions in Planck units

✳ In string theory, extra dimensions compactified: Calabi-Yau manifolds

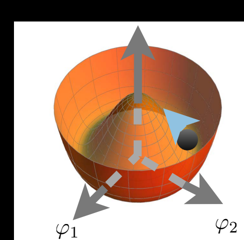




+....

Axiverse! ***Arvanitaki+ 2009***

Witten and Srvcek (2006), Acharya et al. (2010), Cicoli (2012)



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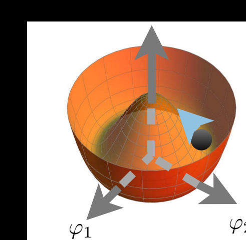


Ultra-light axions

- Interactions with standard model are very small!

$$g_{a\gamma\gamma} \propto m_a$$

- Inaccessible to terrestrial experimentation

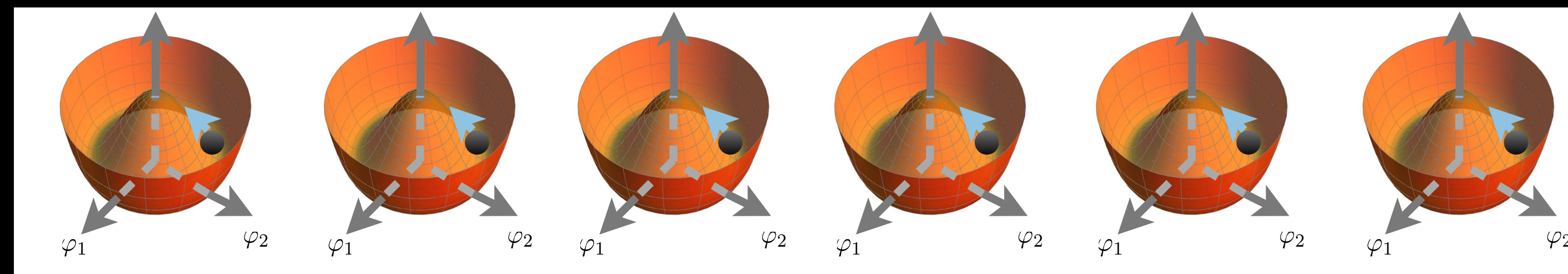
Ultra-light axions still gravitate!

Ultra-light axions (ULAs) in string theory

- Bosons moving in extra dimensions are axions in 4D!

Ultra-light axions (ULAs) in string theory

✳ Bosons moving in extra dimensions are axions in 4D!



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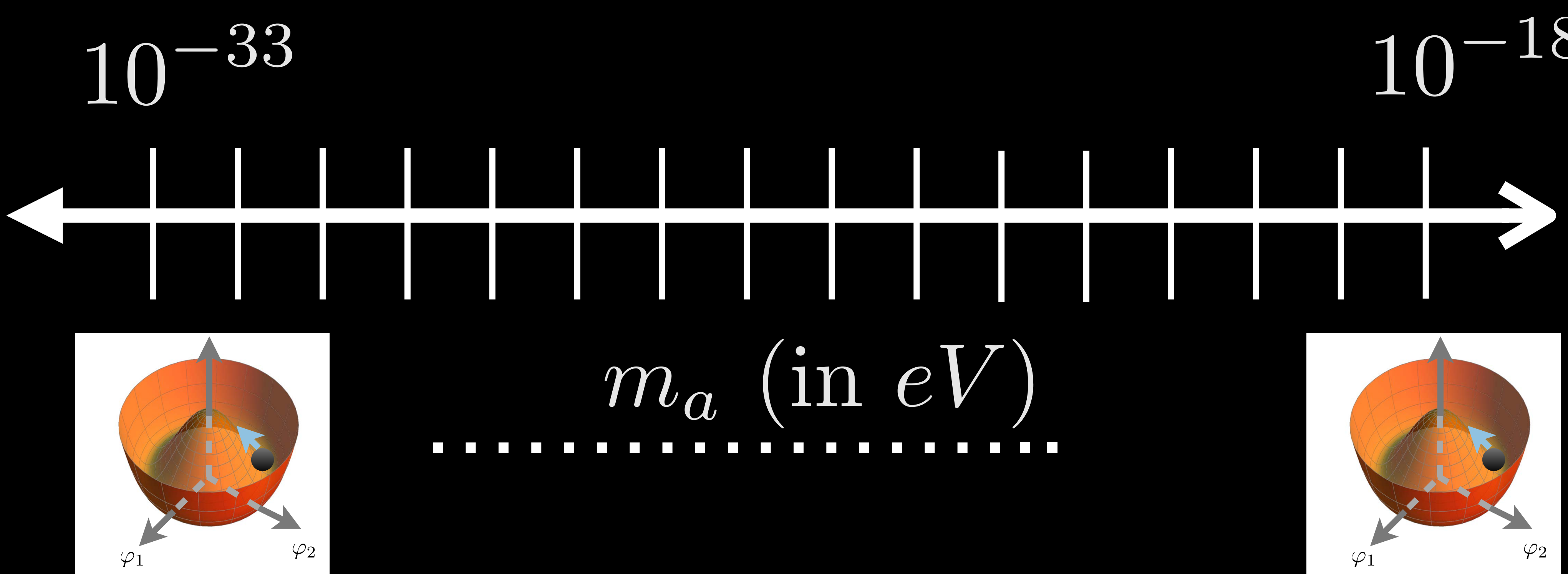

Ultra-light axions (ULAS) in string theory

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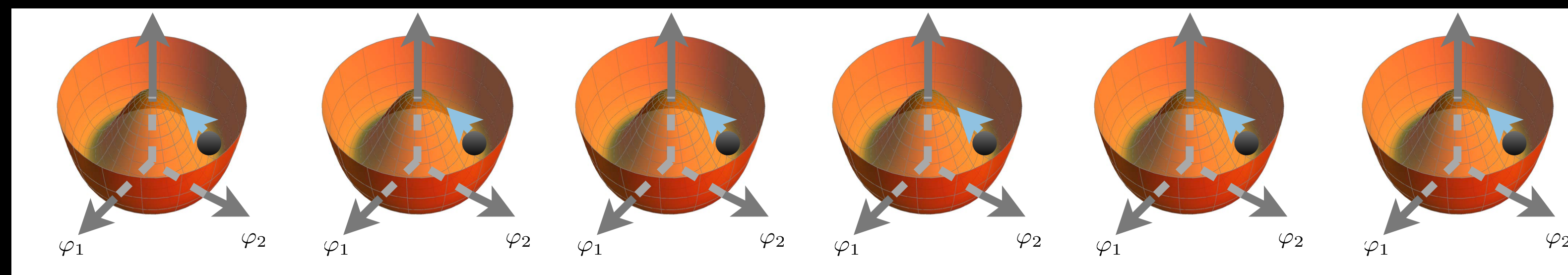

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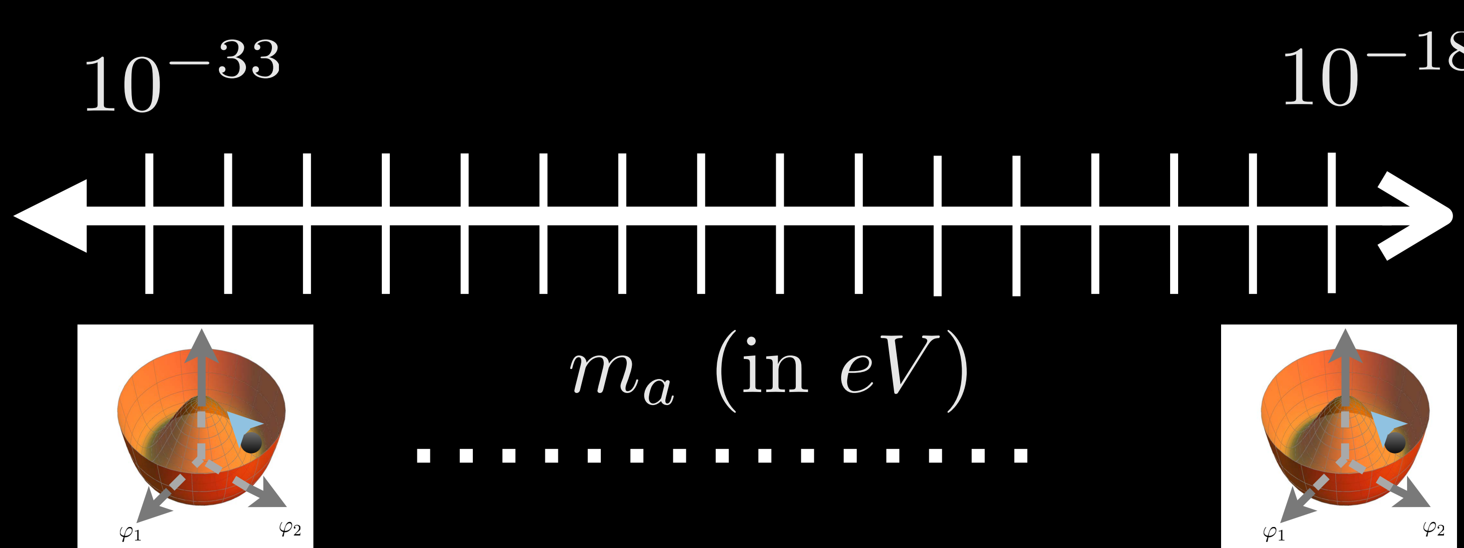
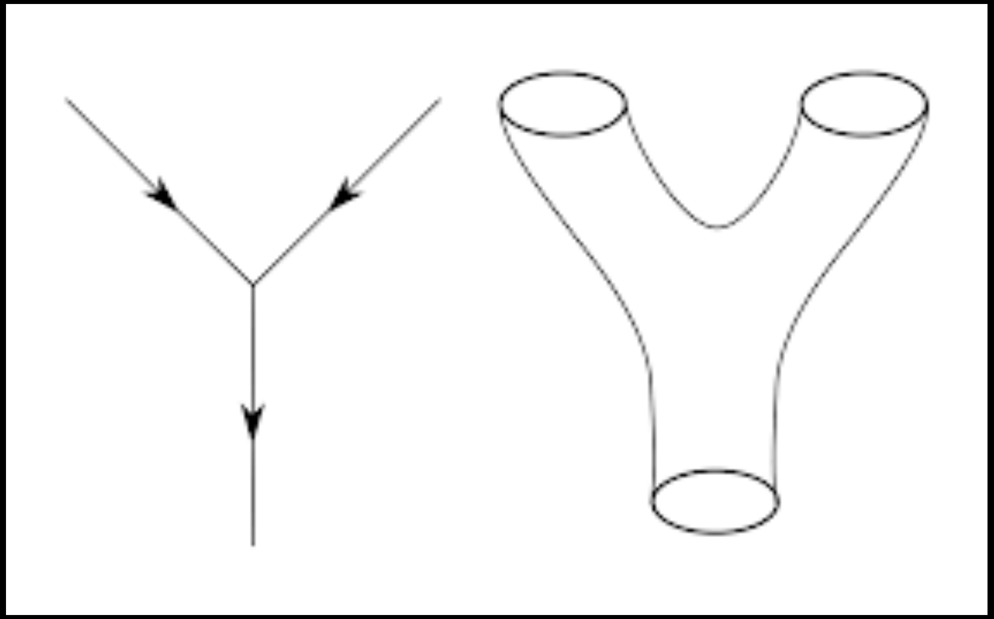


String theory

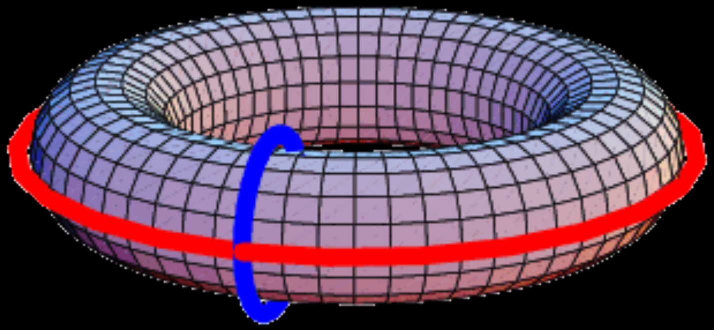
* One framework that solves SM problems is string theory

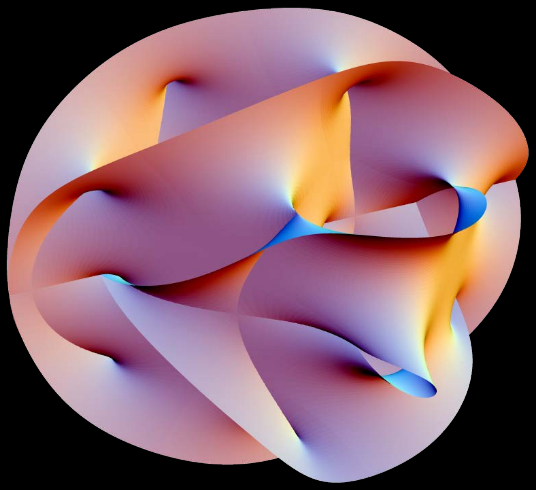


Replace point particles with extended objects

* String theory requires 6 extra dimensions that we don't see!

  Must be curled up/compactified





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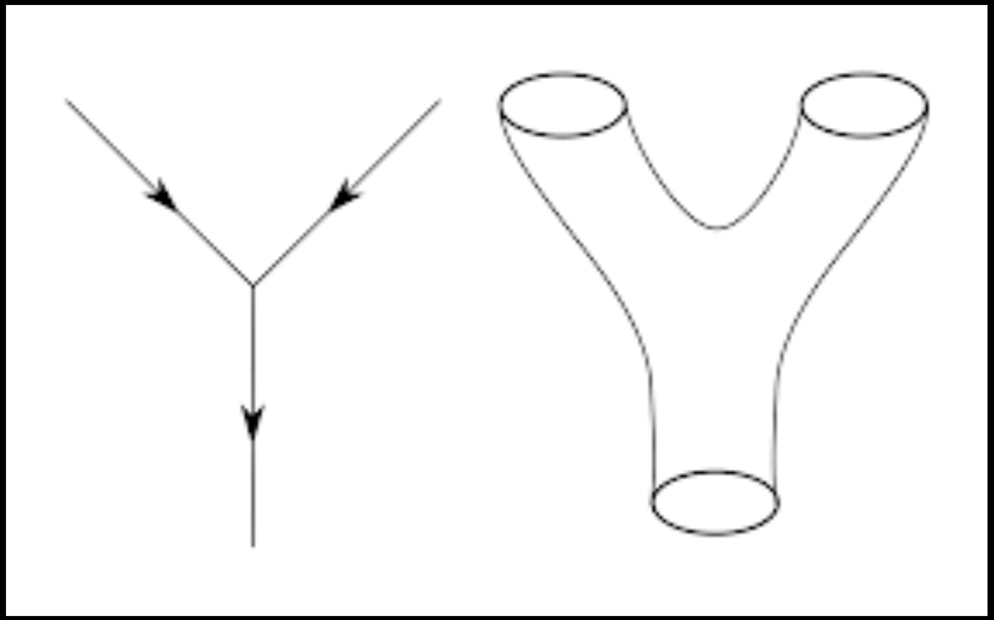

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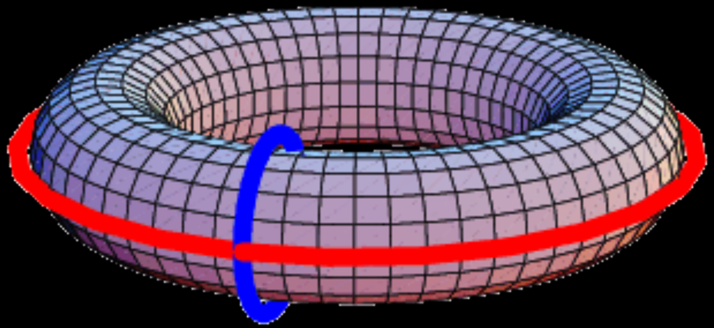
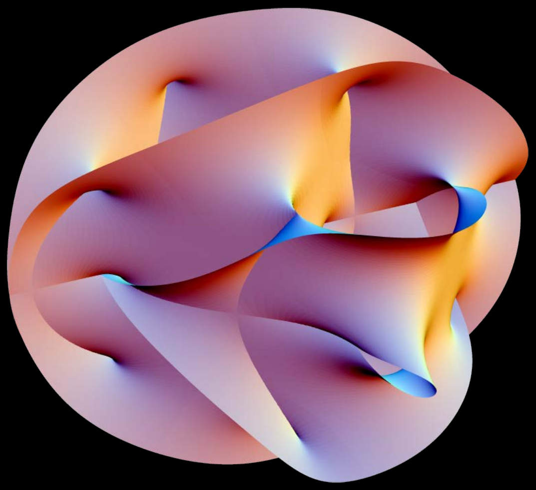
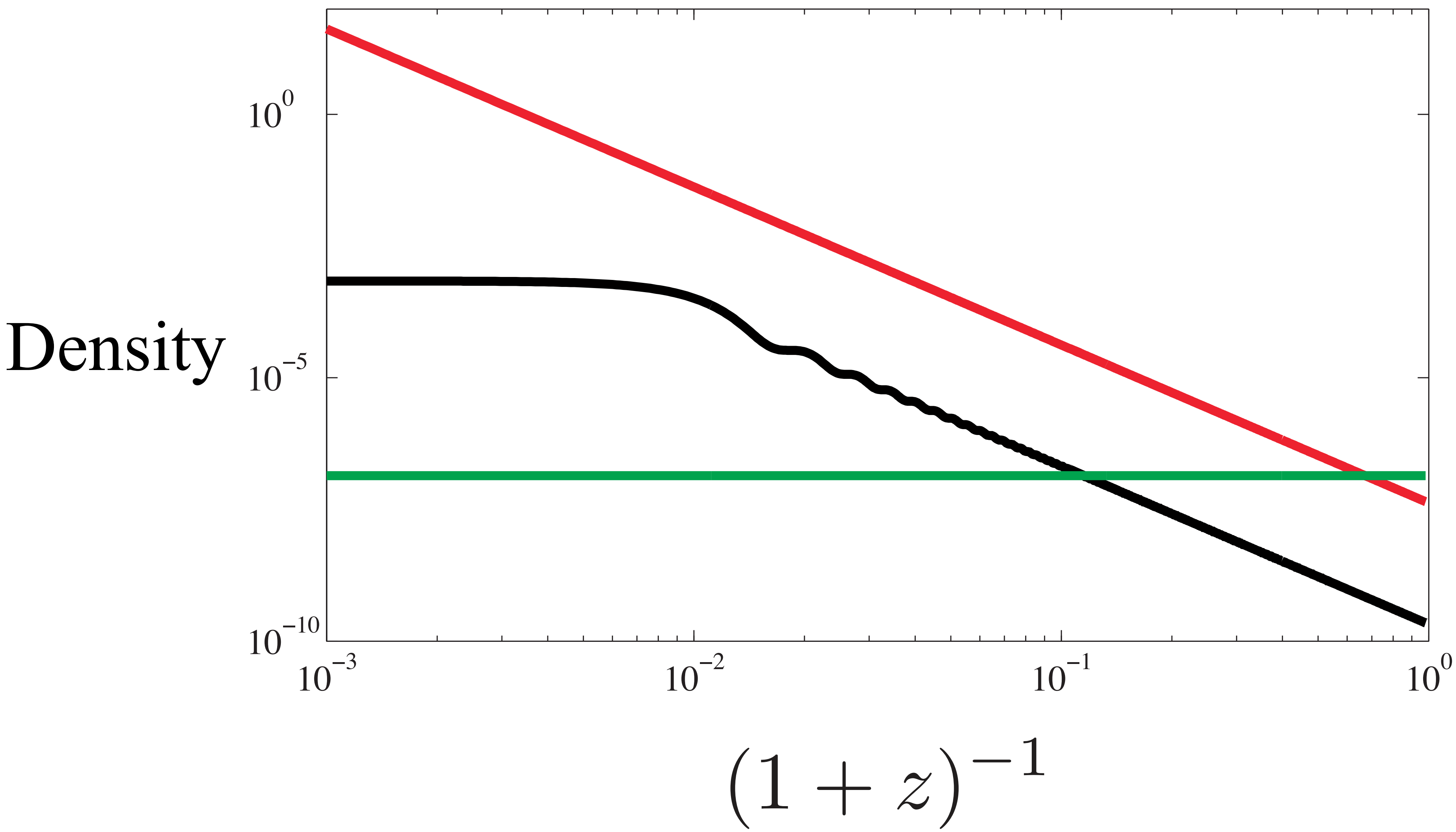




Cosmology of ultra-light axions: dark matter and dark energy candidates



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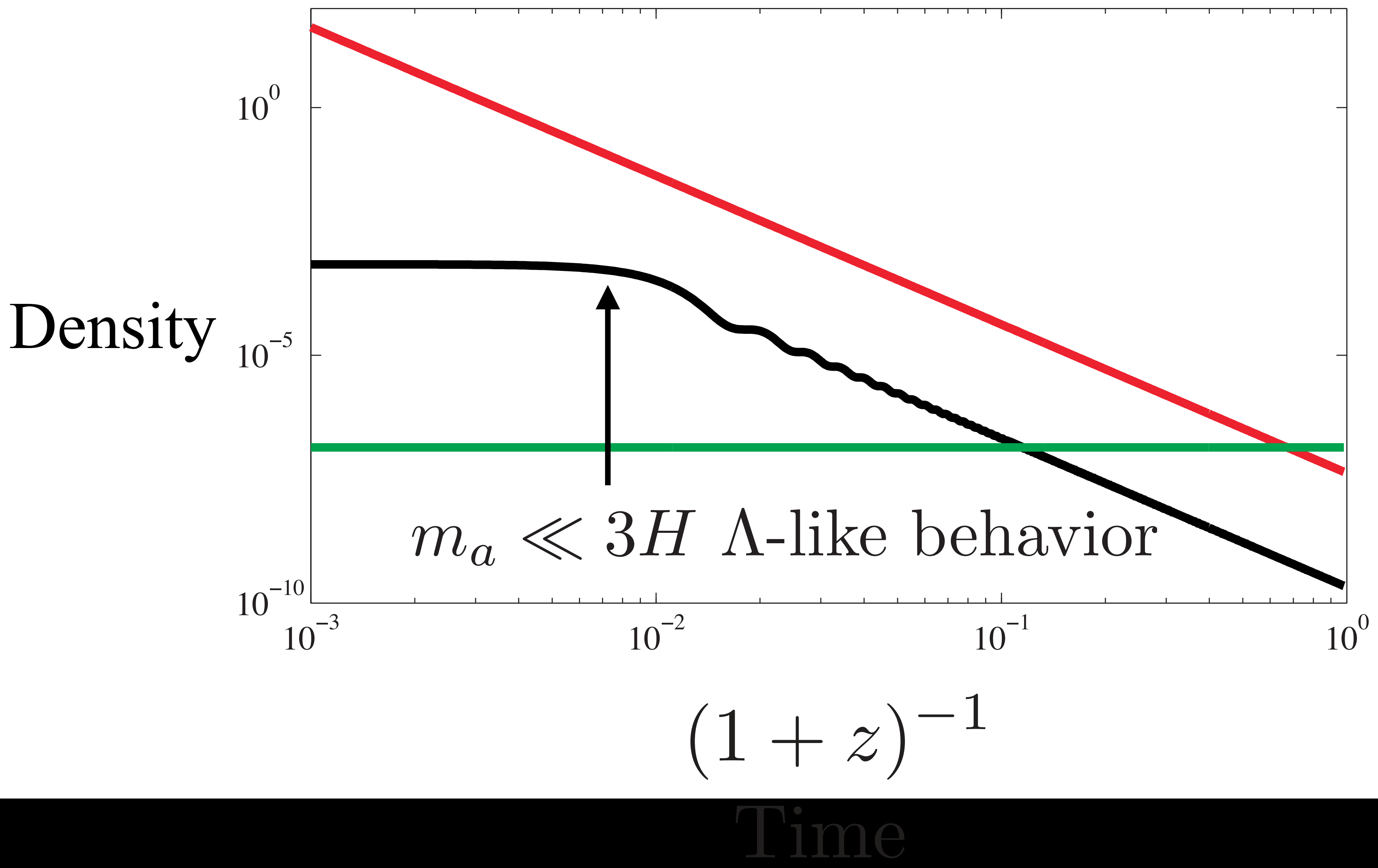

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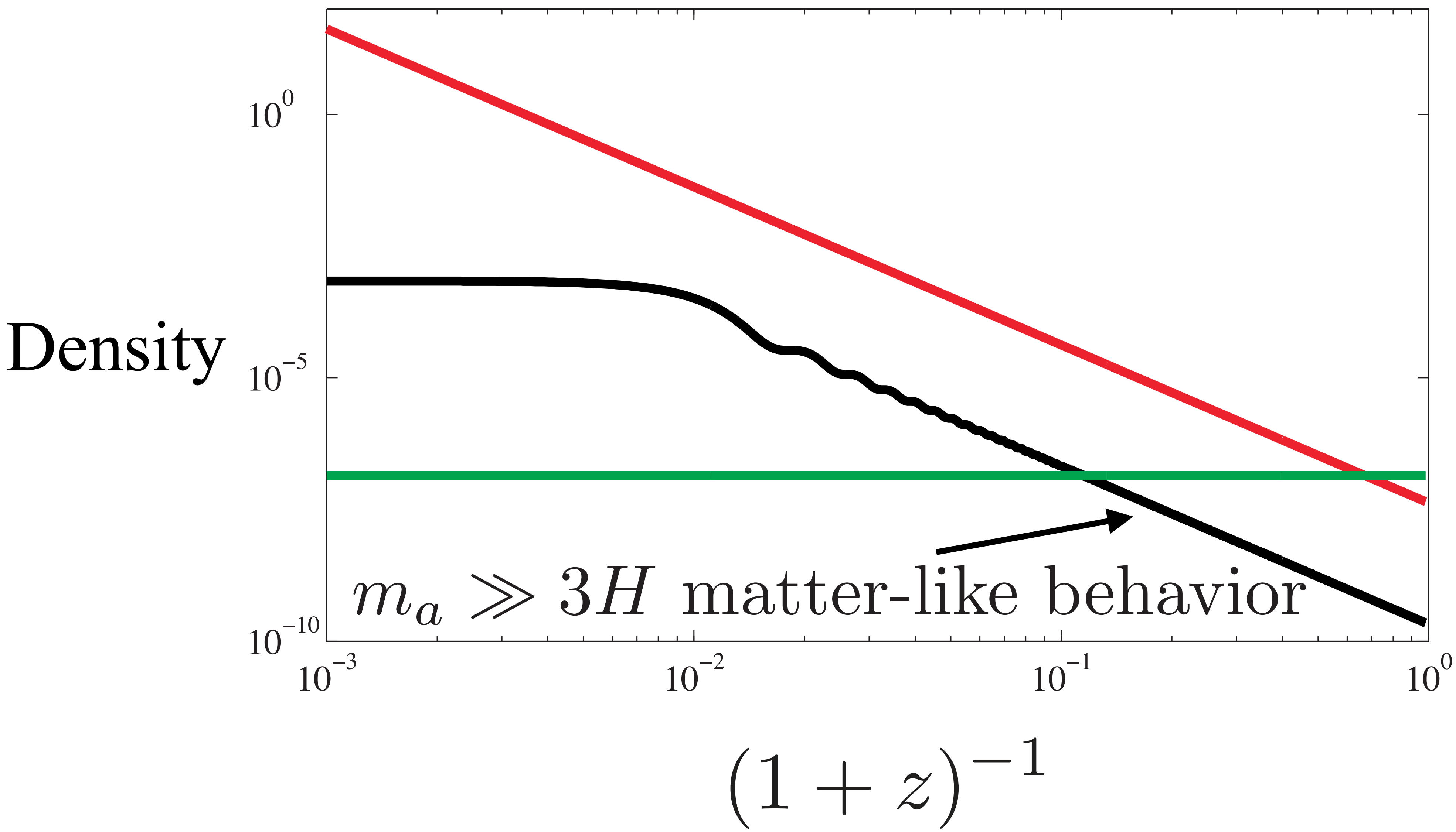

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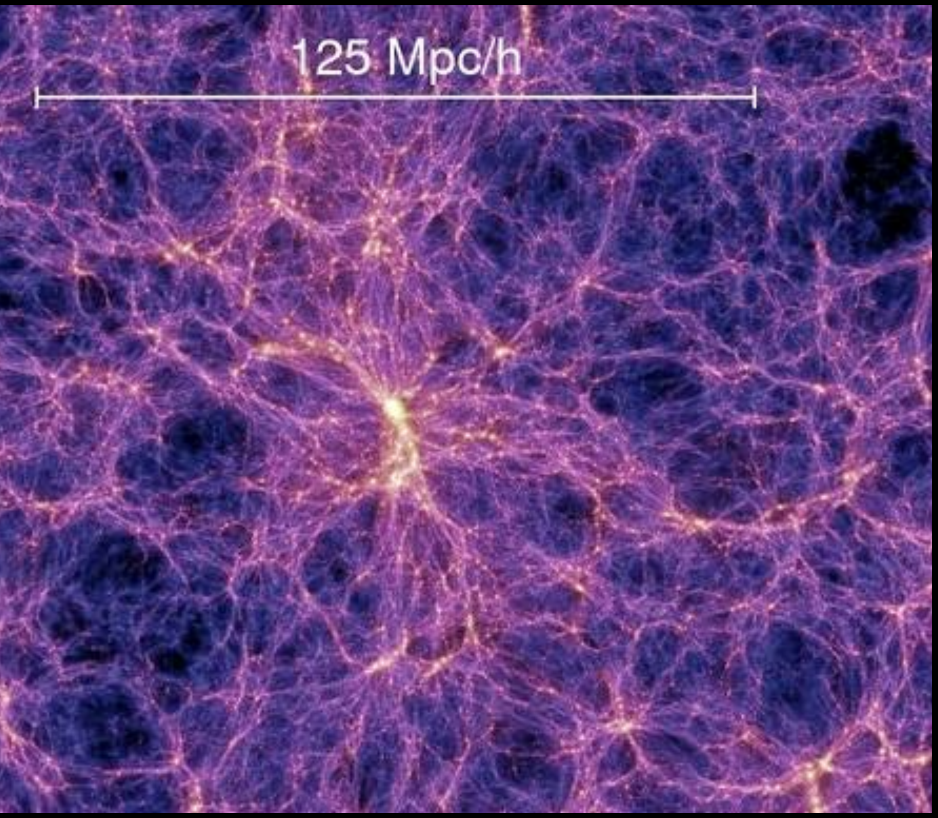
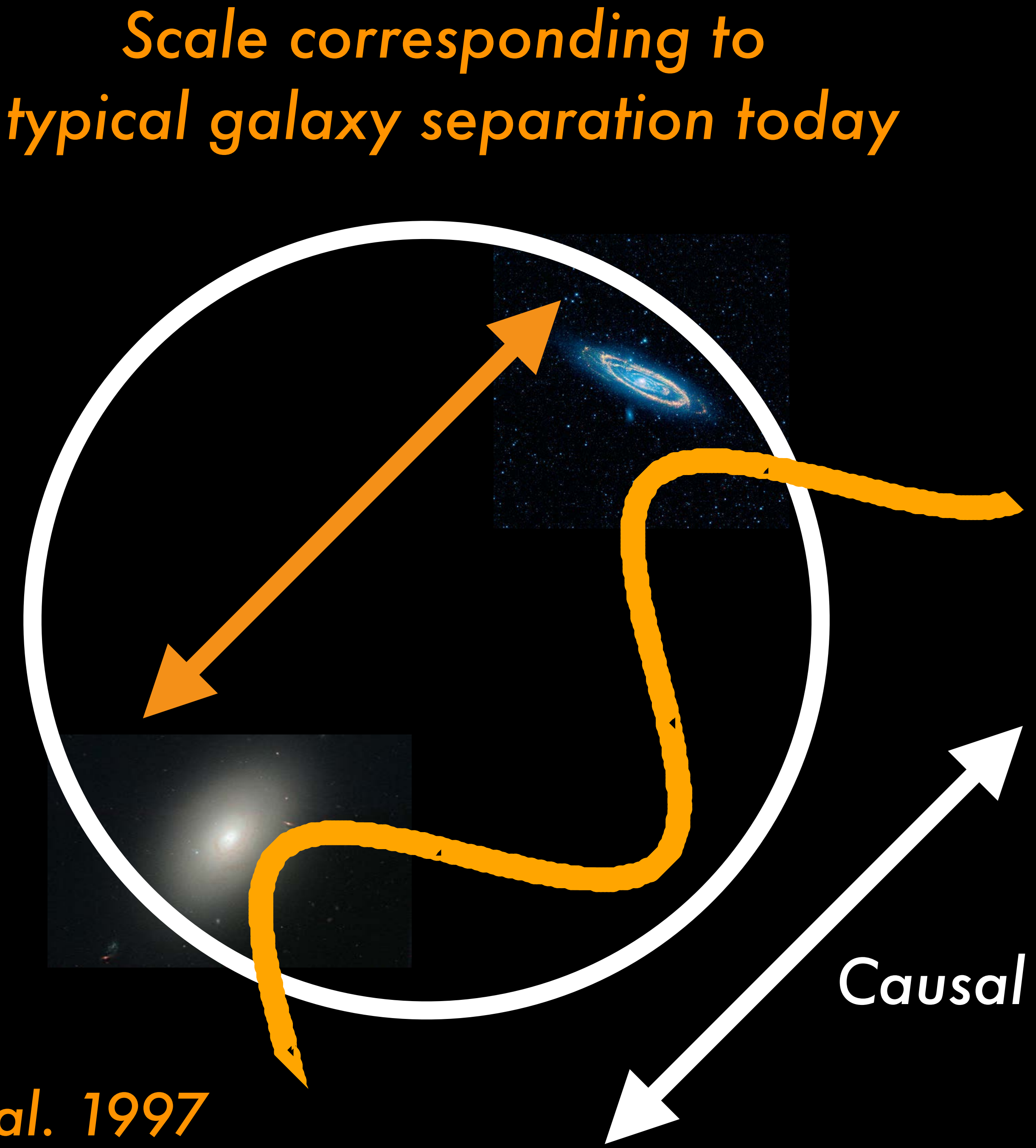


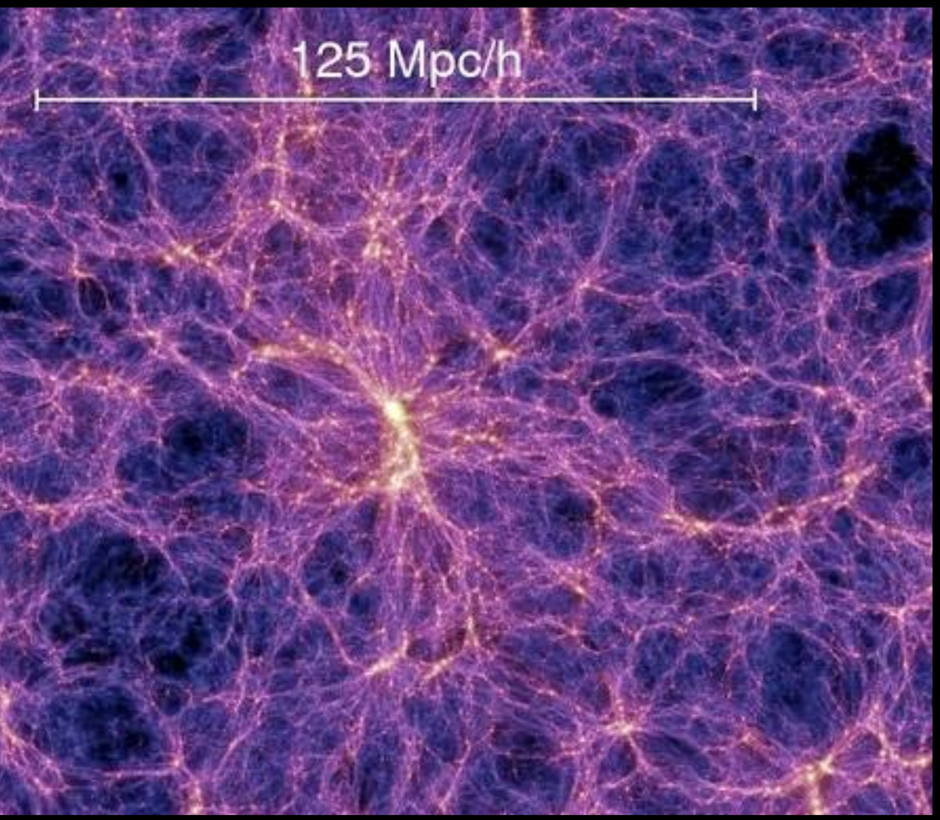


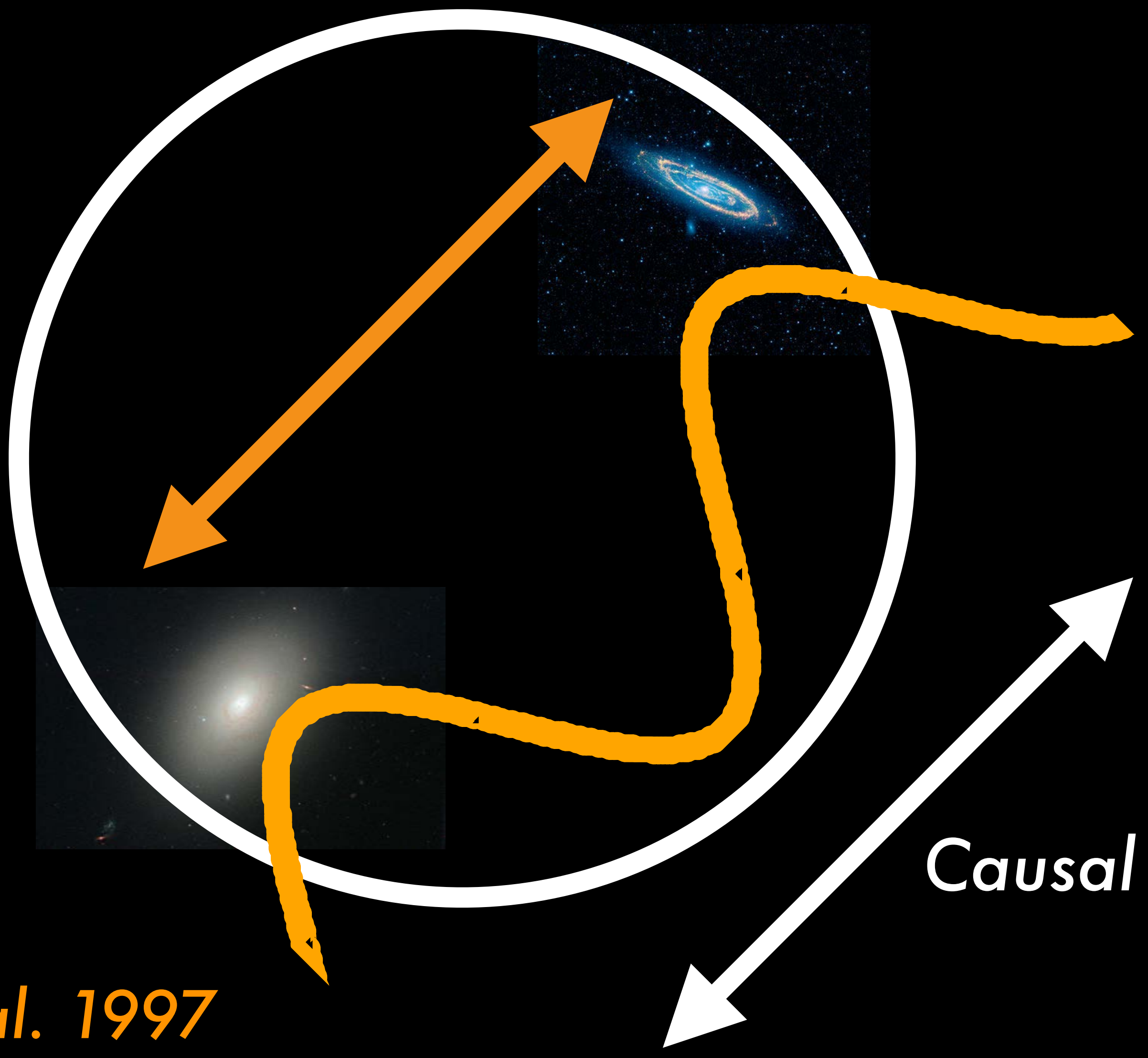
Frieman et al 1995, Coble et al. 1997

ULA as dark energy with specific w(z)

$m_a \lesssim 10^{-27}$ eV   ULA matter behavior starts too late for struct. formation

Cosmology of ultra-light axions: dark matter and dark energy candidates





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ULA matter behavior starts in time for struct. formation

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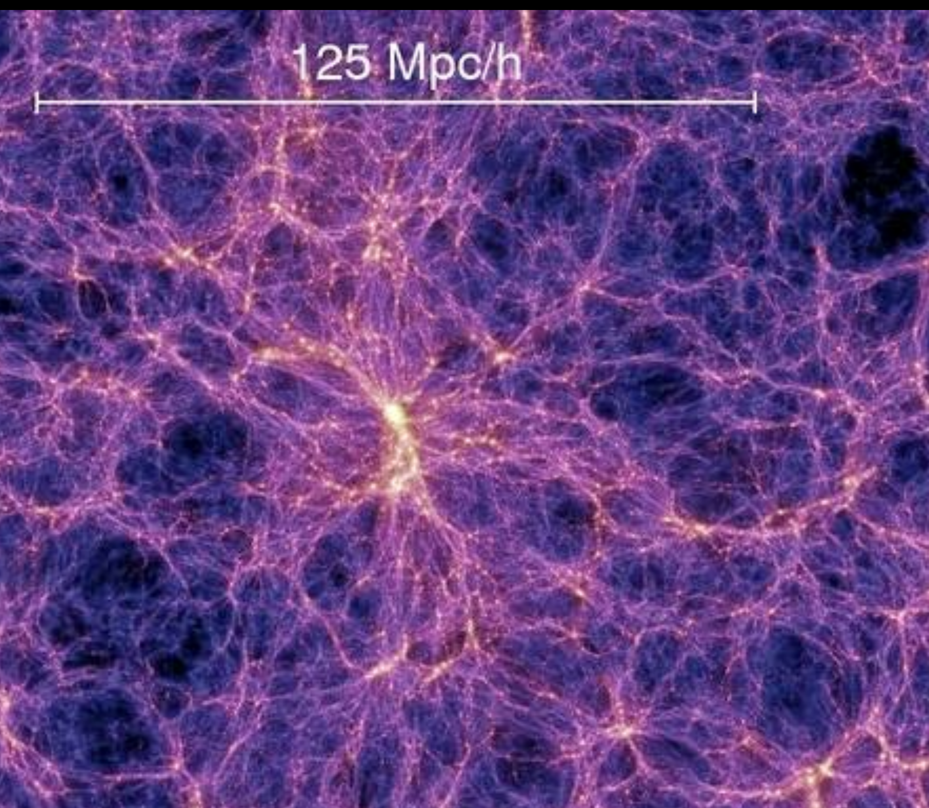
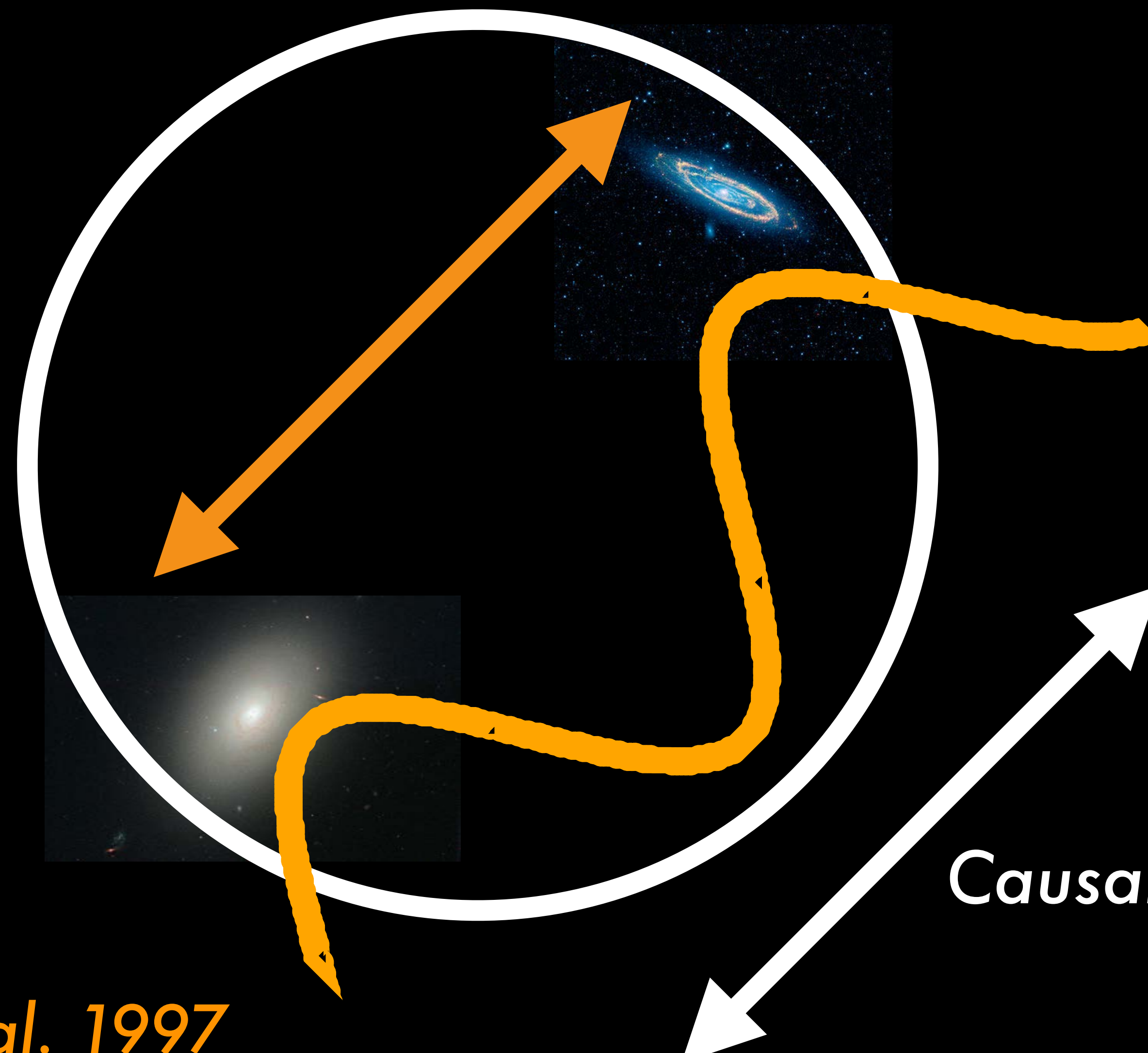


Scale corresponding to typical galaxy separation today



Causal horizon

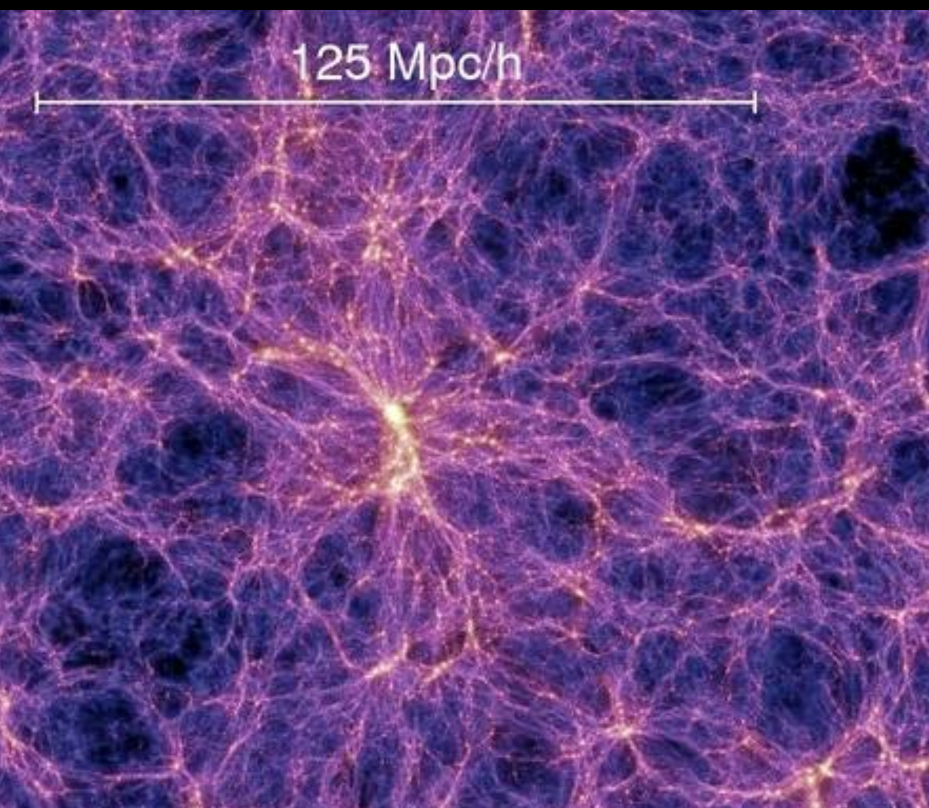
Frieman et al 1995, Coble et al. 1997

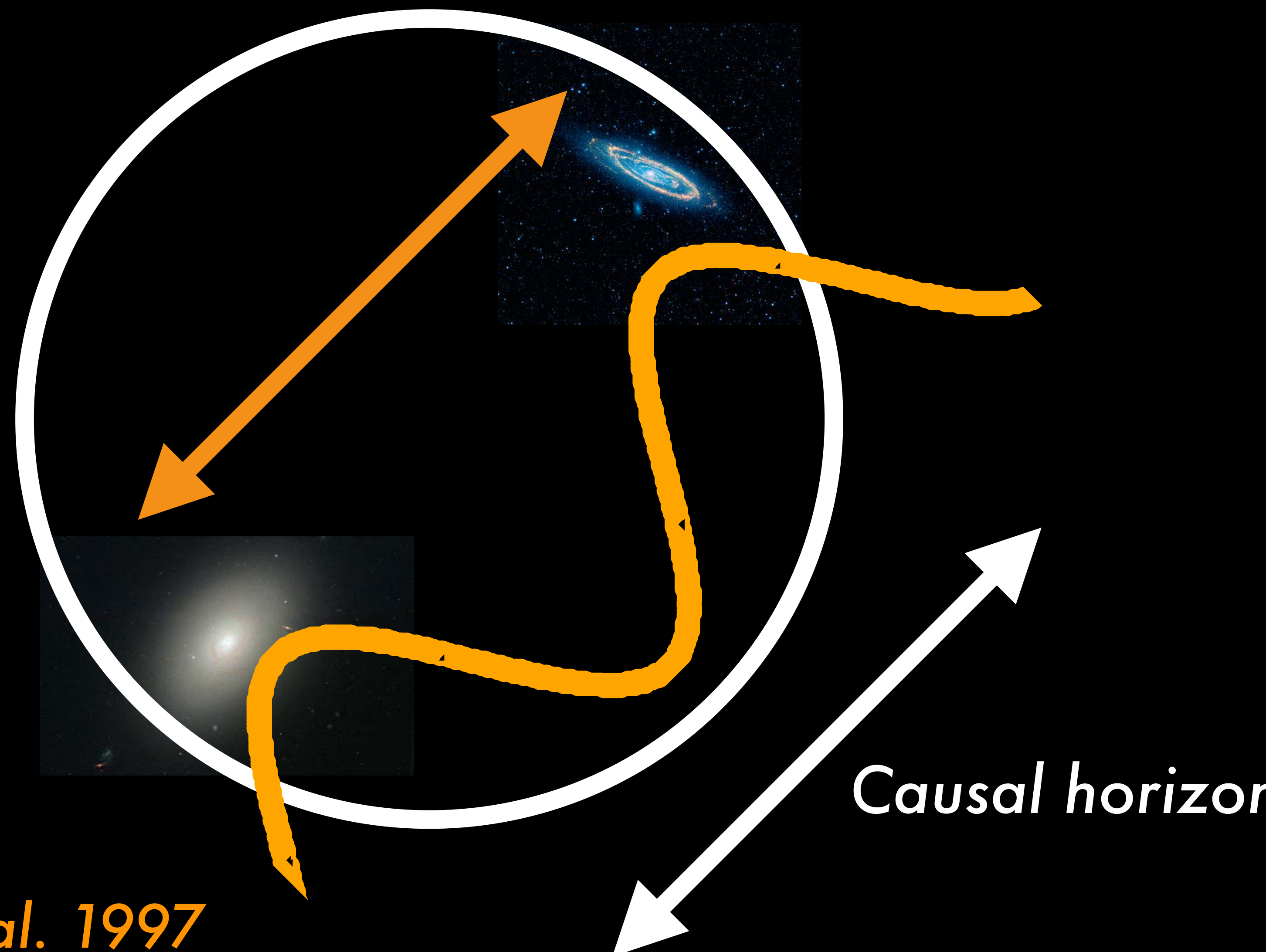
Corresponds to time of matter/radiation equality, when

$$\rho_m = \rho_\gamma + \rho_\nu$$

Cosmology of ultra-light axions: dark matter and dark energy candidates

Scale corresponding to typical galaxy separation today





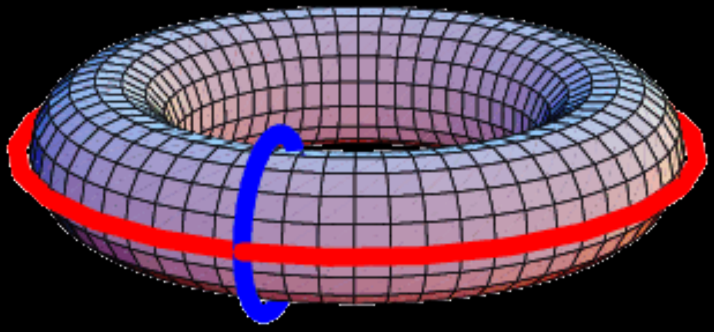
Frieman et al 1995, Coble et al. 1997

Simple relic density constraints:

$$10^{-33}\ \mathrm{eV} < m_a < 10^{-18}\ \mathrm{eV}$$

Light axions and string theory

- String theory has extra dimensions: *compactify (6)!*
- Form fields and gauge fields: `Axion' is KK zero-mode of form field



$$\mathcal{L} \propto \frac{aG\tilde{G}}{f_{\rm a}}$$

ULAs: gravitational constraints

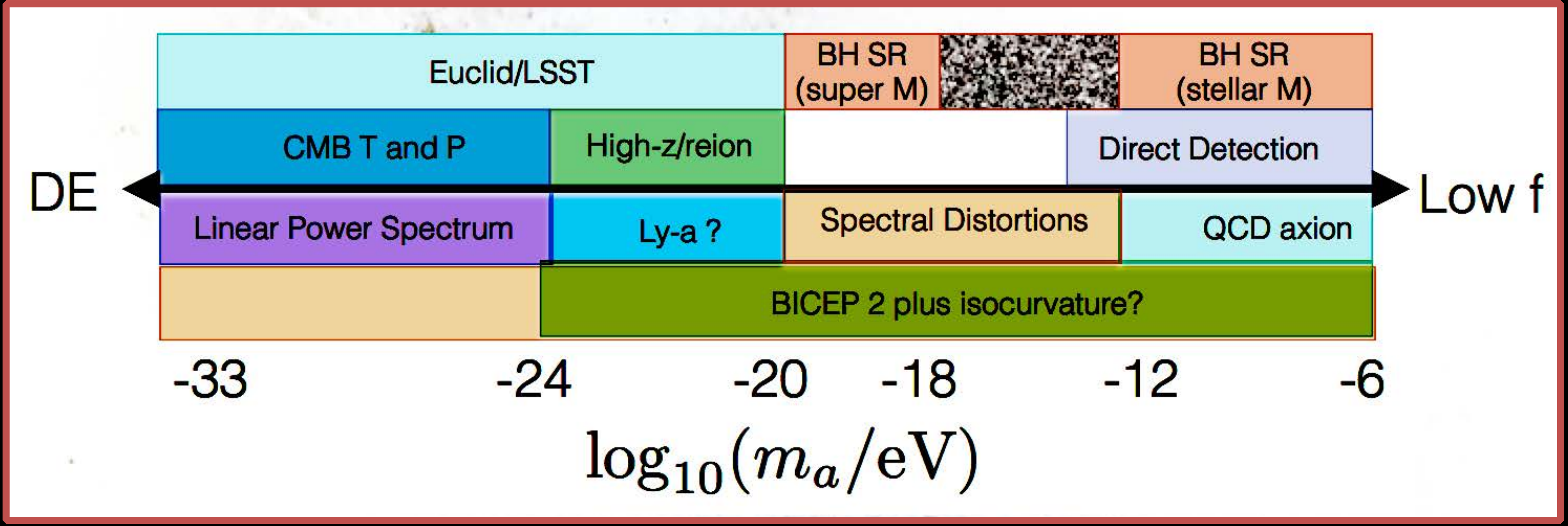


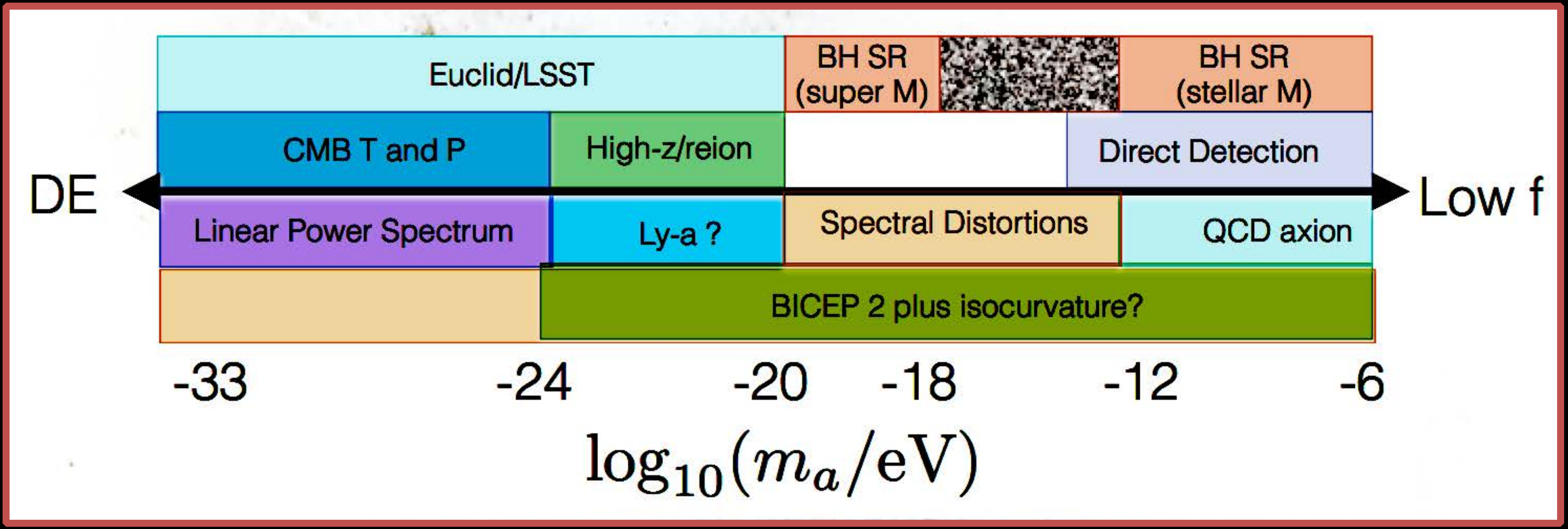
figure adapted from DJEM 2014

$$m_a^2 = \frac{\mu^4}{f_a^2} e^{-\mathrm{Volume}}$$

→ Flat logarithmic mass distribution: Very low axion masses natural!

ULAs: gravitational constraints

Independent of axion SM couplings: uncertainties astrophysical!



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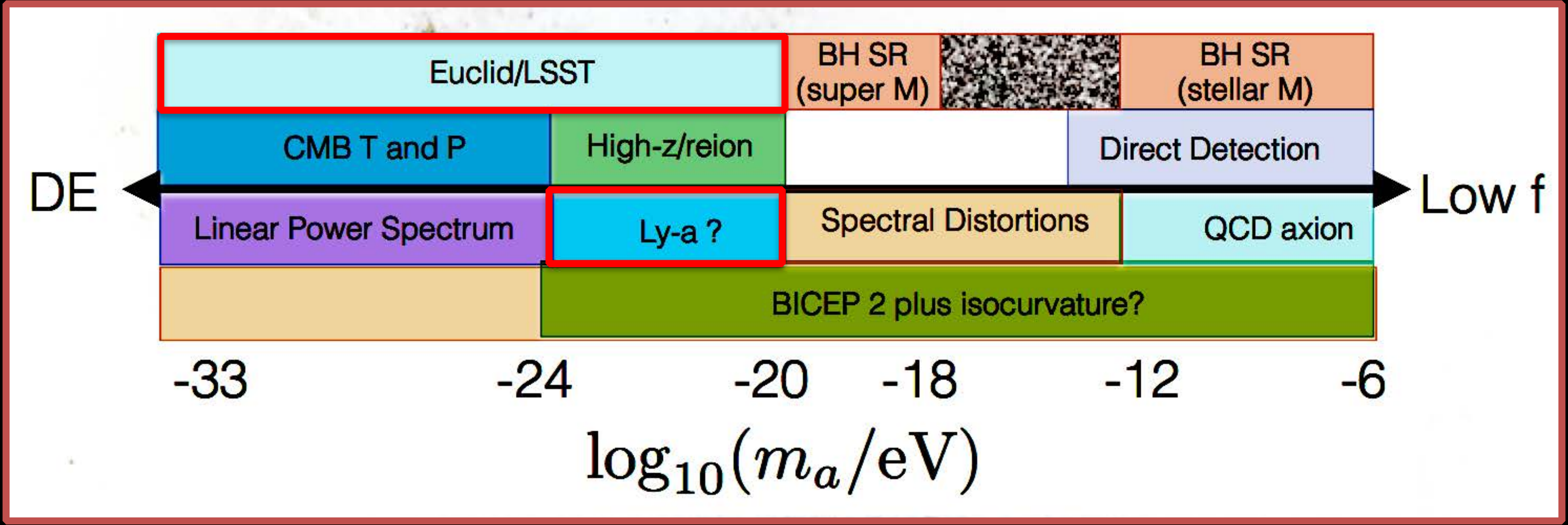
Forecast: uncertain scales



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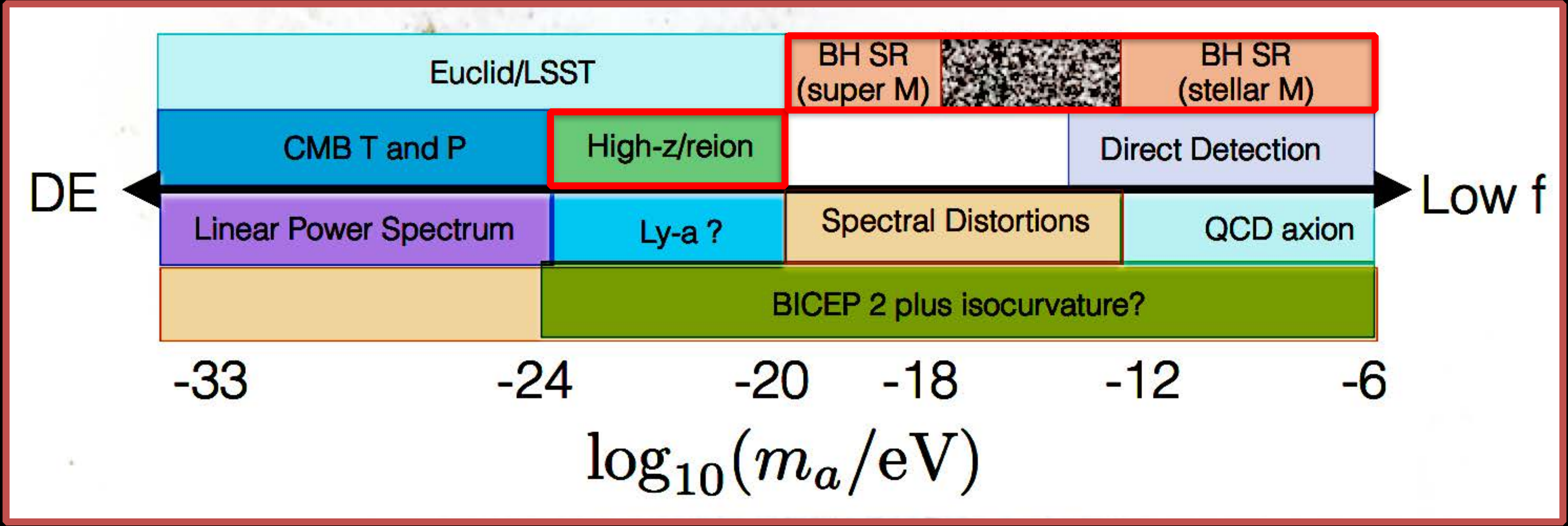
Constraint: astrophysical uncertainties



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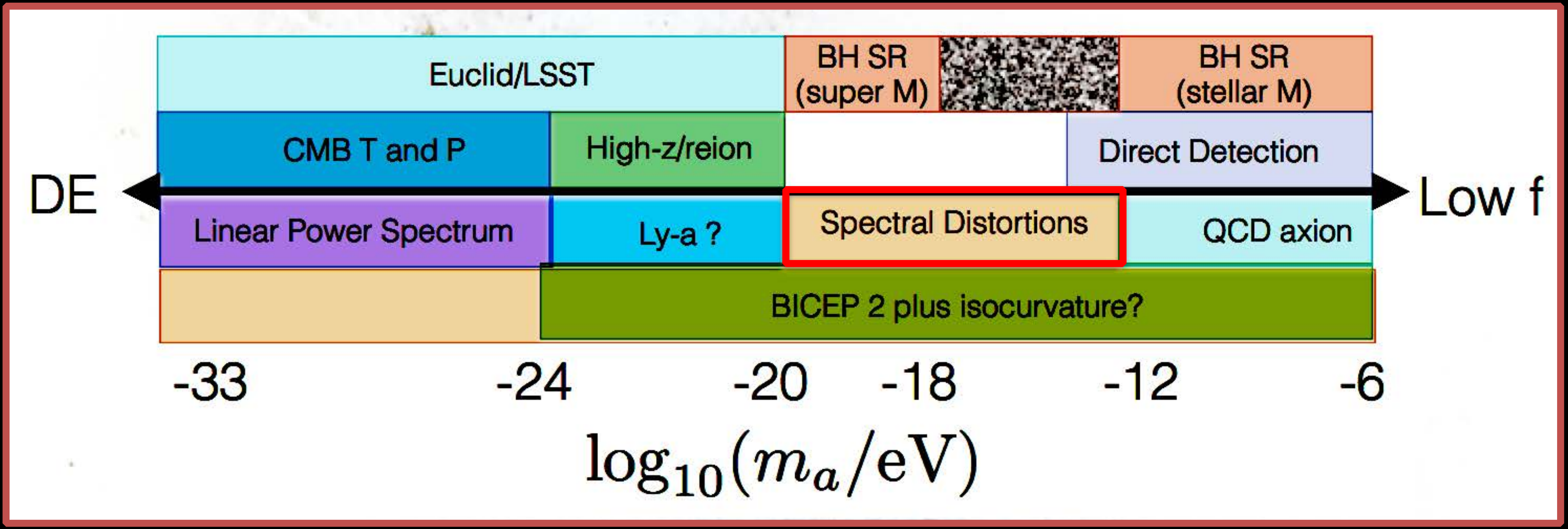

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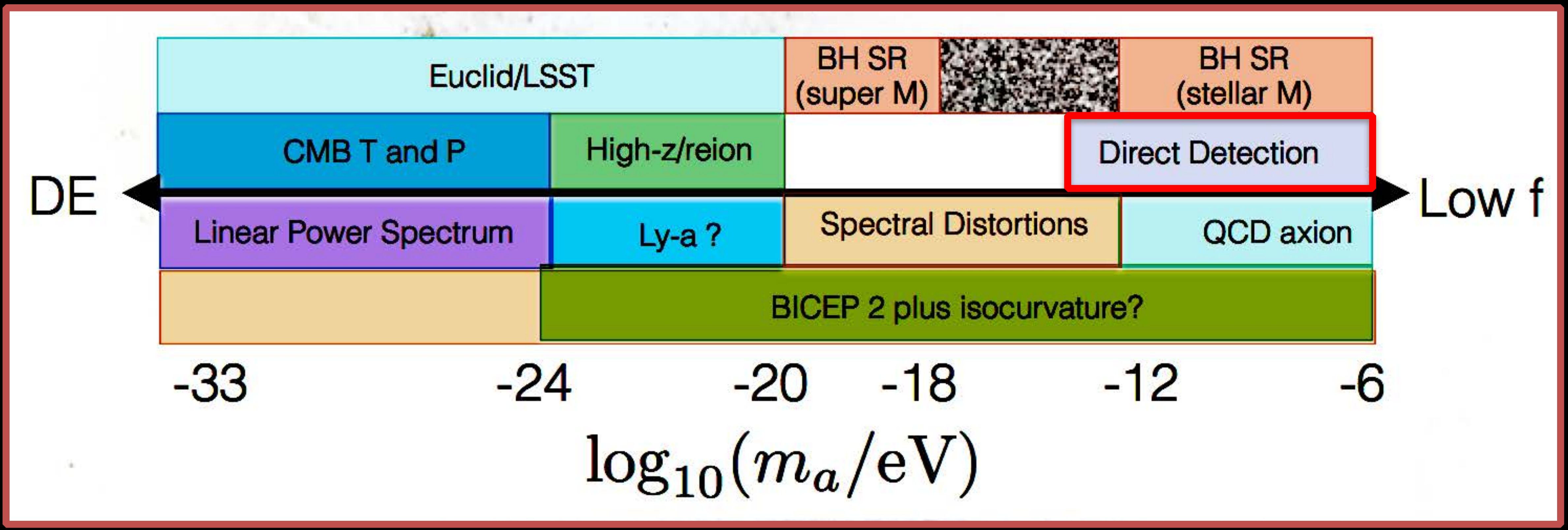
Underway



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ULAs: gravitational constraints

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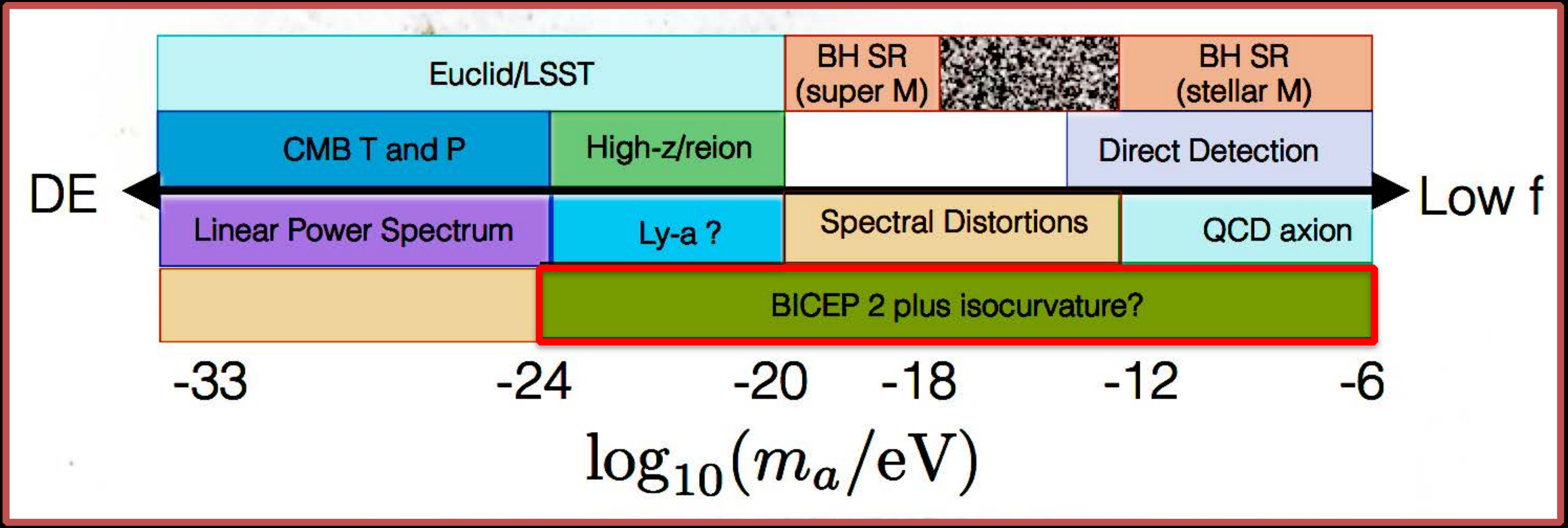
DUST!



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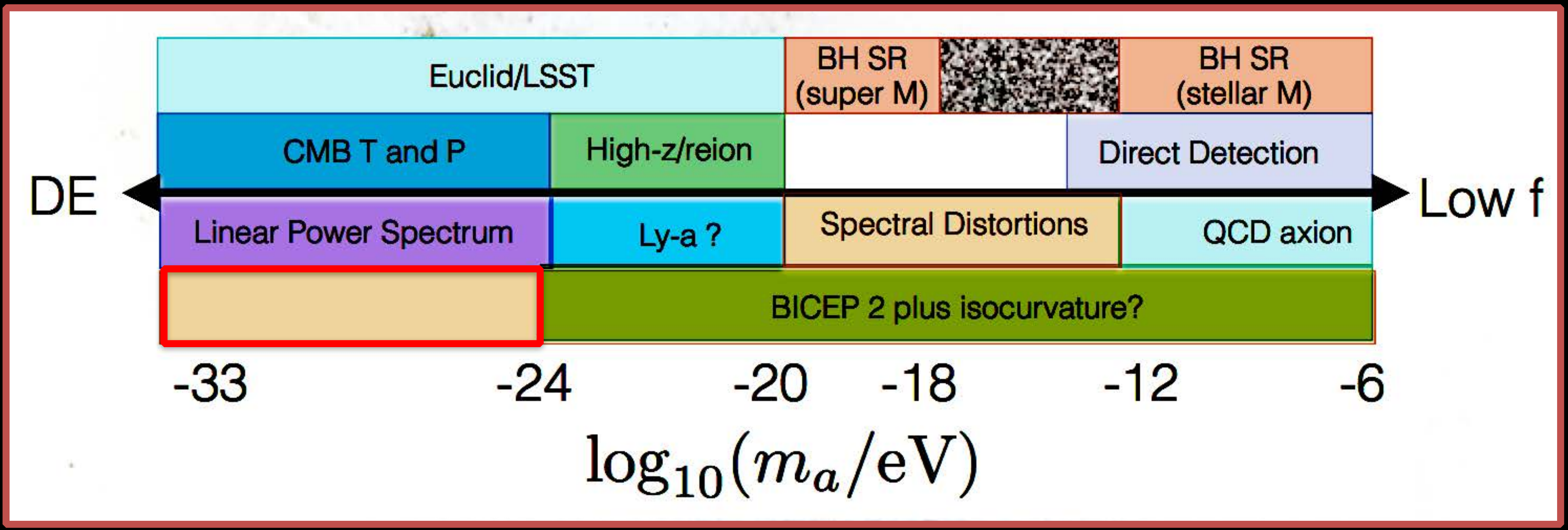
Rough forecast



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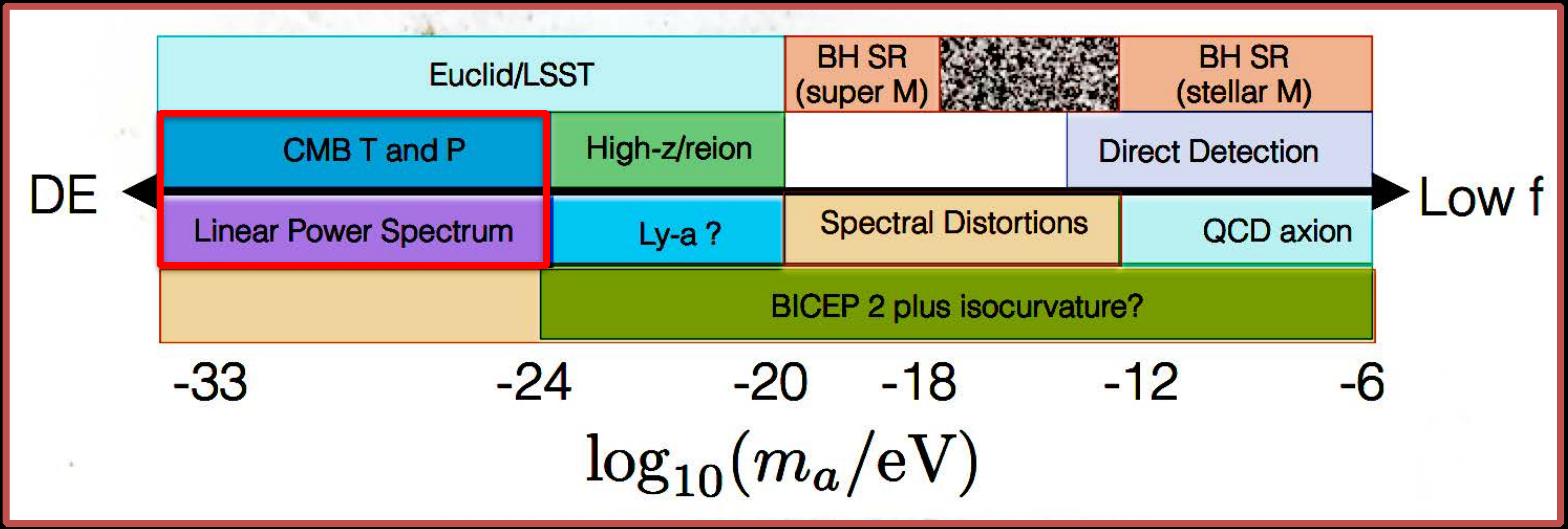
IRONCLAD: this work



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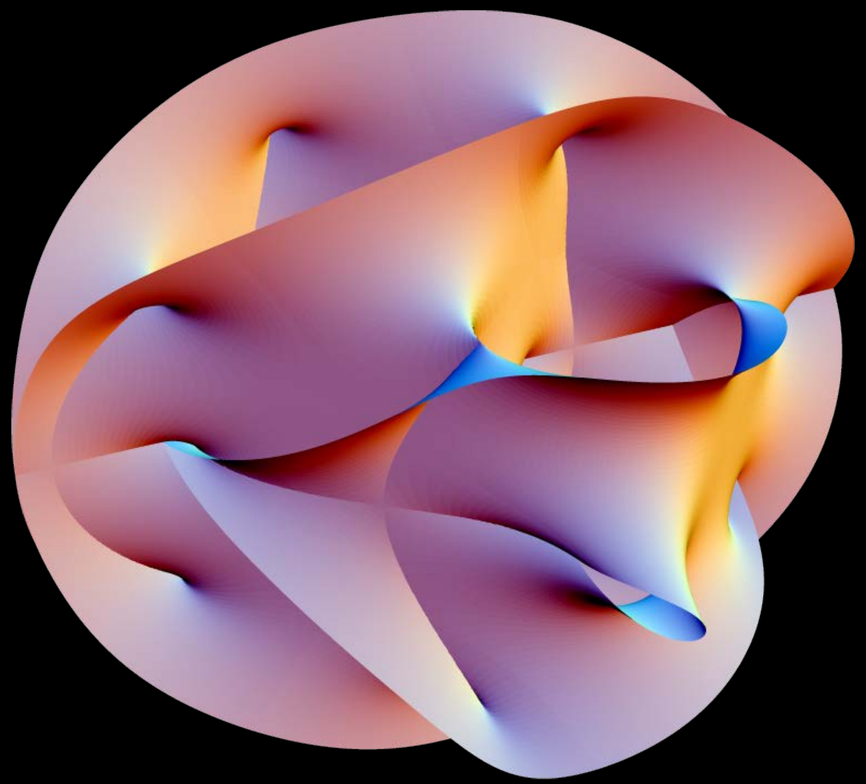
The axiverse: ultra-light axions (ULAs)

- Calabi-Yau manifolds

Many 2-cycles ⟶ Many axions

Hundreds!



- Mass from non-perturbative physics (instantons, D-branes)

$$m_a^2 = \frac{\mu^4}{f_a^2} e^{-\mathrm{Volume}}$$

$$f_a \propto \frac{M_{\mathrm{pl}}}{\mathrm{Volume}}$$

$$\mathcal{L} \propto g_{a\gamma\gamma} \vec{E}_{\mathrm{gauge}} \cdot \vec{B}_{\mathrm{gauge}}$$
$$g_{a\gamma\gamma} \propto \frac{1}{f_a}$$

Also Witten and Srvcek (2006), Acharya et al. (2010), Cicoli (2012)

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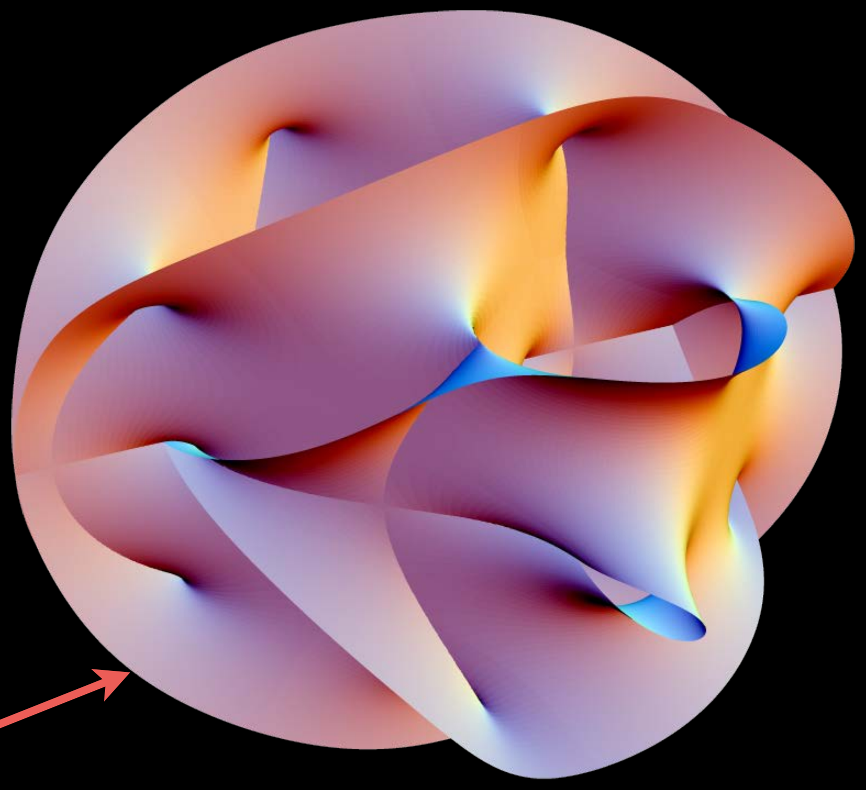

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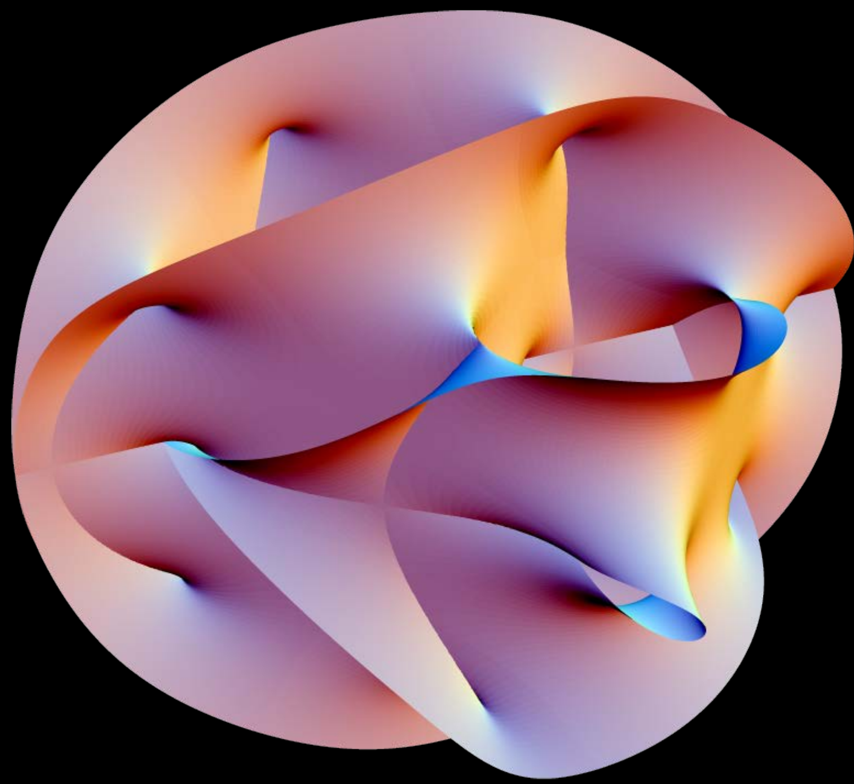

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New UV scale: not QCD scale

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THE AXIVERSE: ULTRA-LIGHT AXIONS (ULAS)

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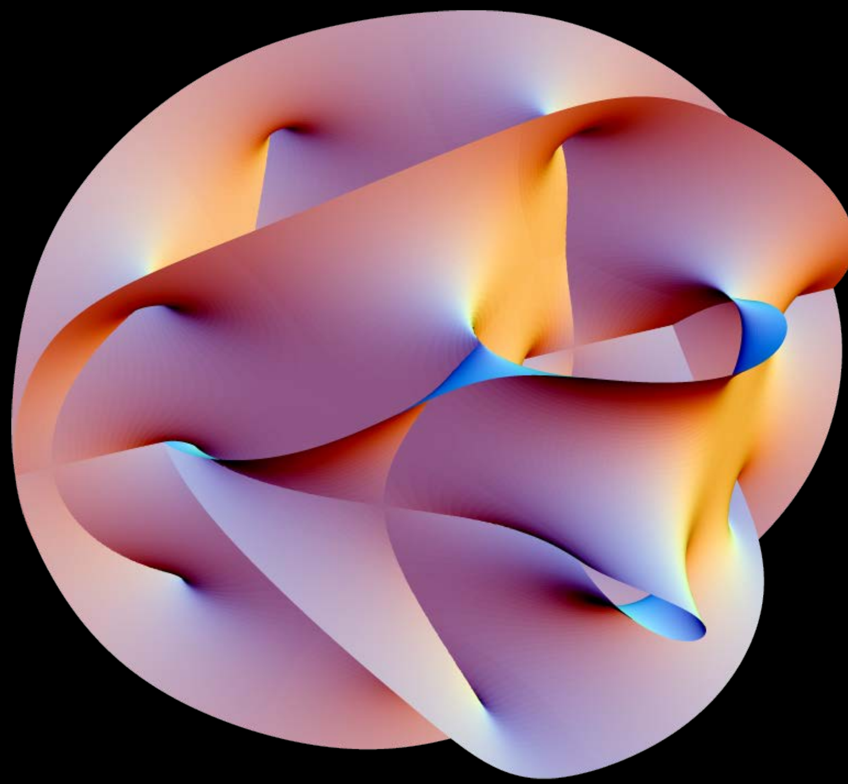
Many 2-cycles ⟶ Many axions

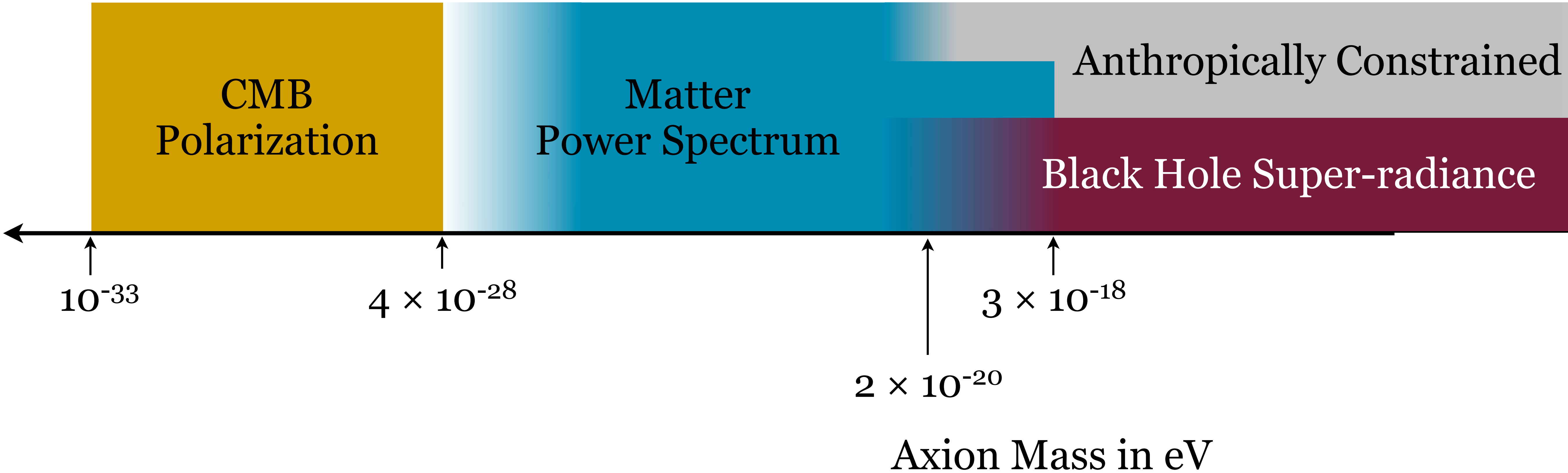
Hundreds!



Scalars with approximate shift symmetry ⟶ "Axion"

Also Witten and Srvcek (2006), Acharya et al. (2010), Cicoli (2012)

The axiverse: ultra-light axions (ULAs)



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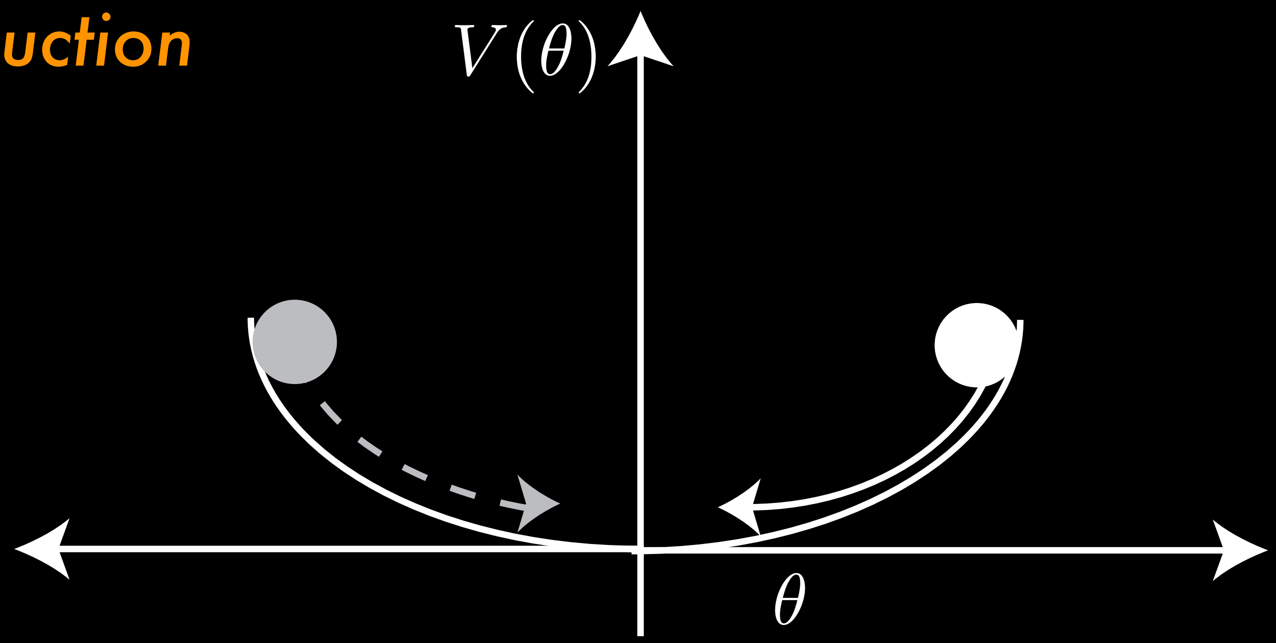
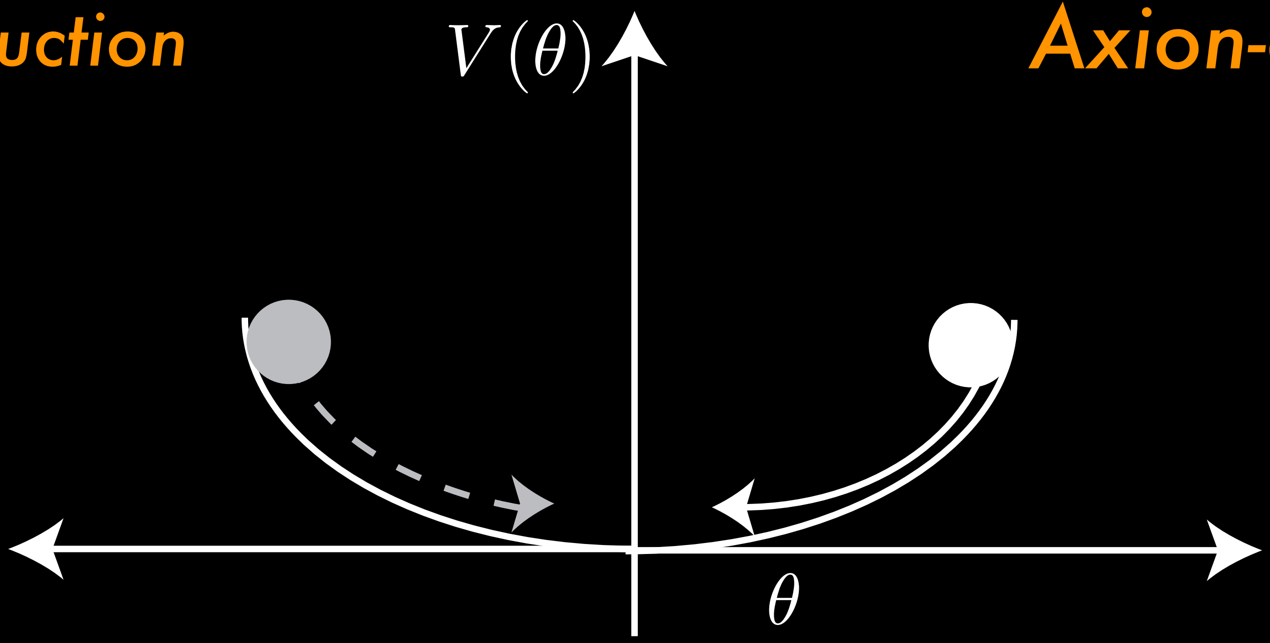
Misalignment production



Cosmological axion evolution

Misalignment production

Axion-driven acceleration



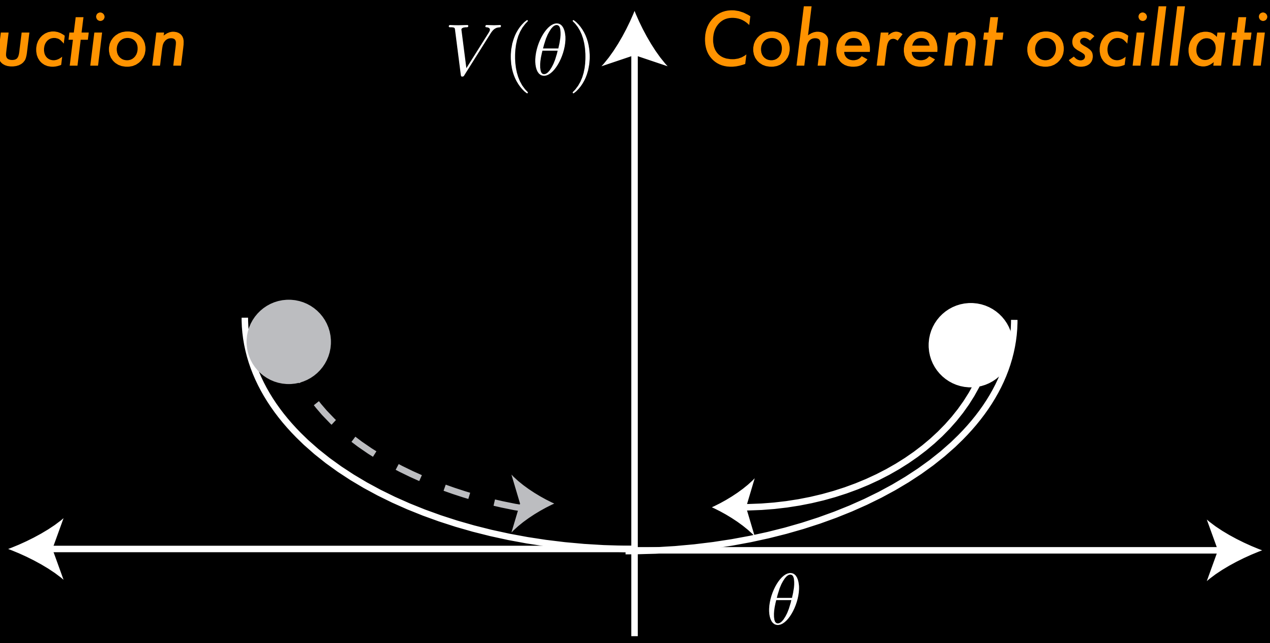
$$m \ll 3H \to n_a \propto \text{ const}, w_a \equiv \frac{P_a}{\rho_a}, w_a \simeq -1$$

$$m \gg 3H \to n_a \propto a^{-3}, \langle w_a \rangle_{T=2\pi/m_a} = 0$$

Cosmological axion evolution

Misalignment production

Coherent oscillation, Axions act like CDM



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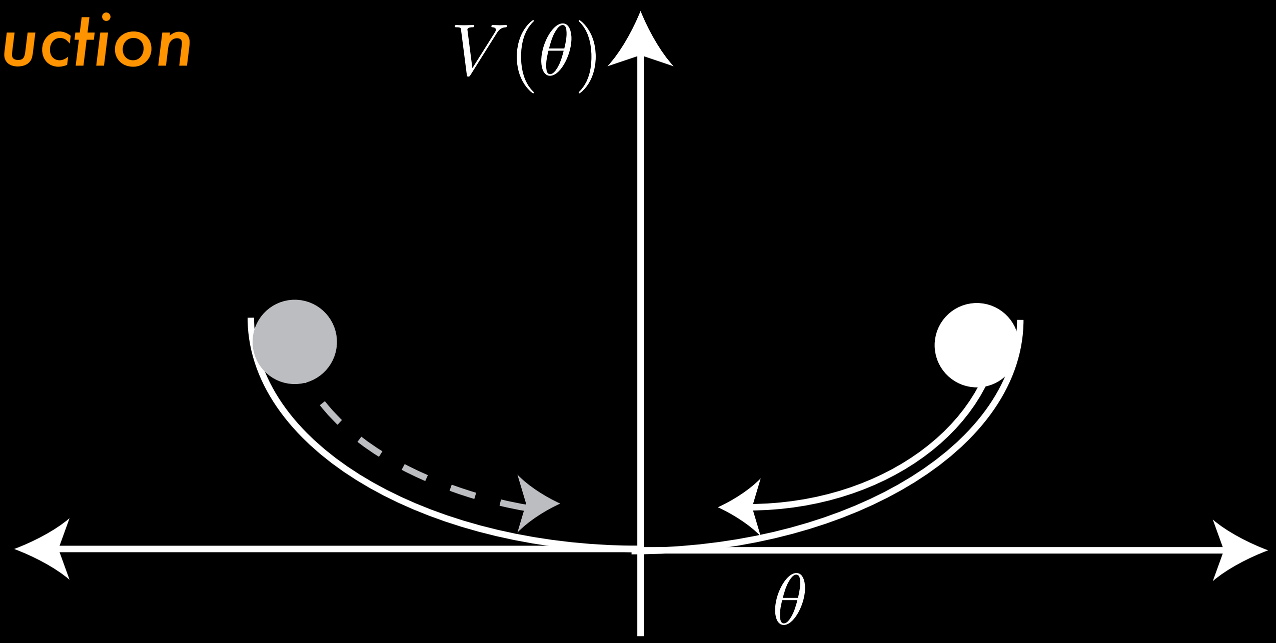
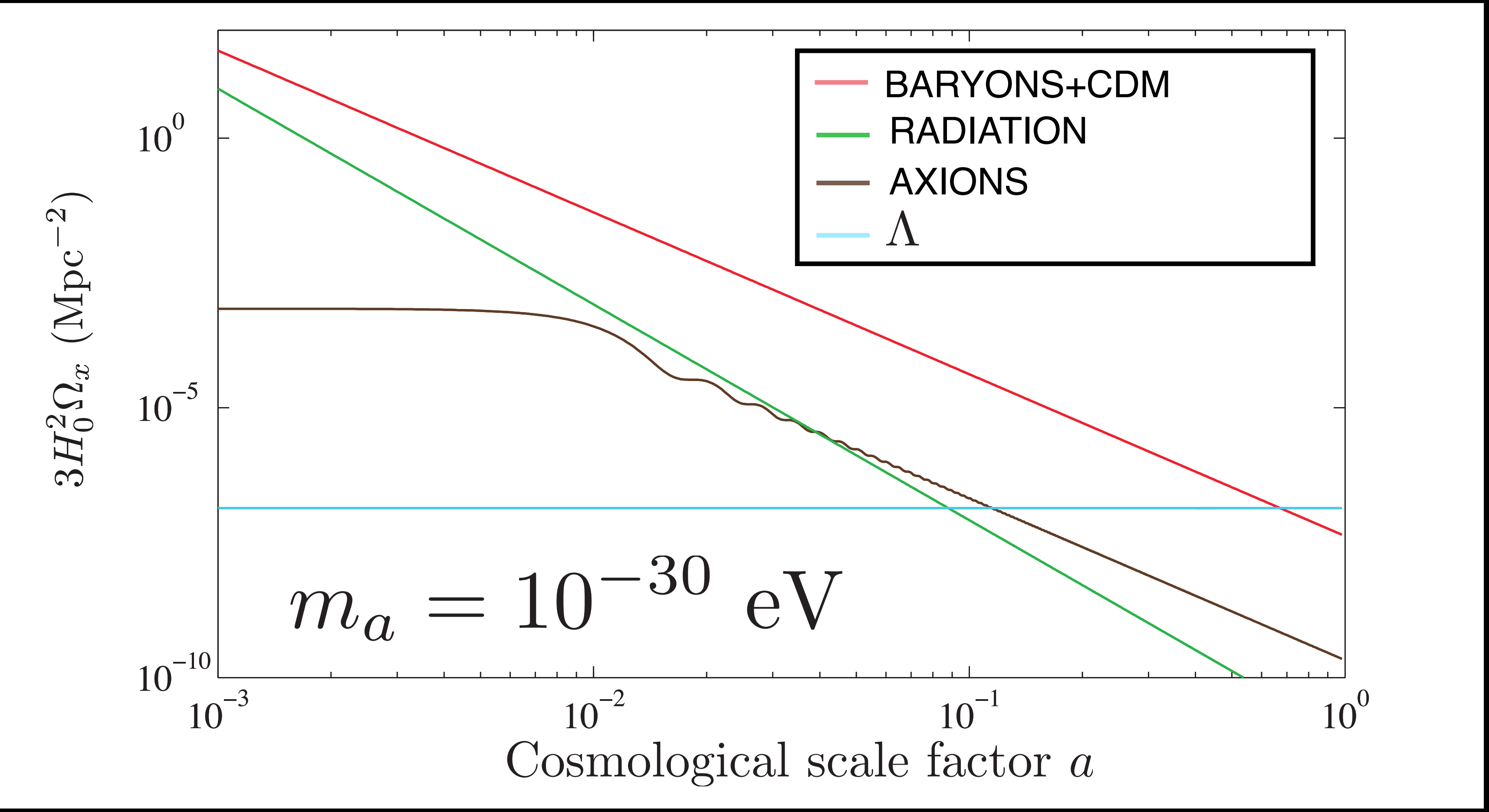


For QCD axion, we have a CDM candidate!

$$\Omega_{\rm mis}h^2 = 0.236\,\langle\theta_i^2 f(\theta_i)\rangle\left(\frac{m_a}{6.2\mu\text{eV}}\right)^{-7/6}$$

Cosmological axion evolution

Different parameter space for non-QCD axion(Frieman et al 1995, Coble et al. 2007)



10^{-33} eV $< m_a < 10^{-18}$ eV

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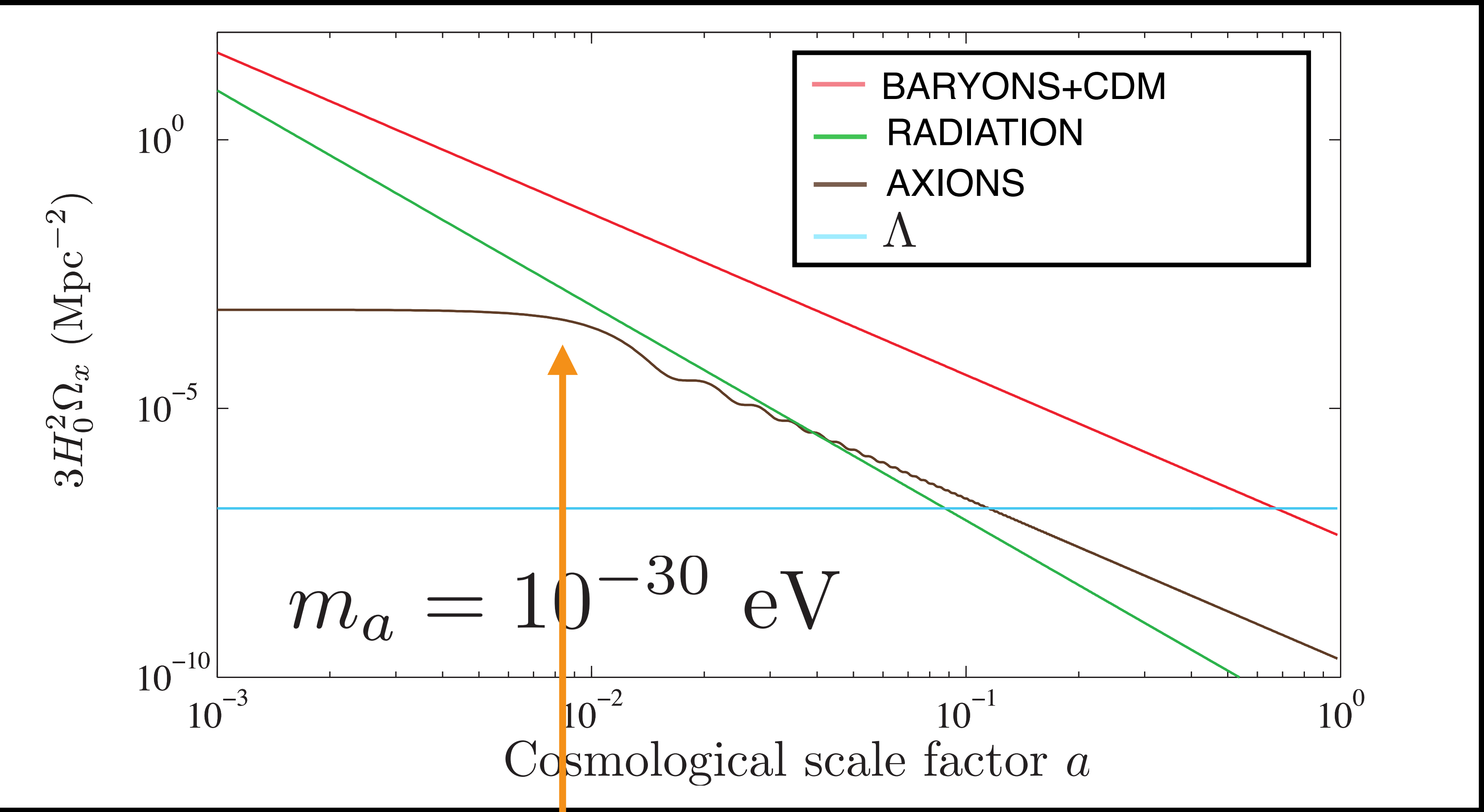

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$a \equiv a_{\rm osc} \quad m_a = 3H(a)$

Cosmological axion evolution

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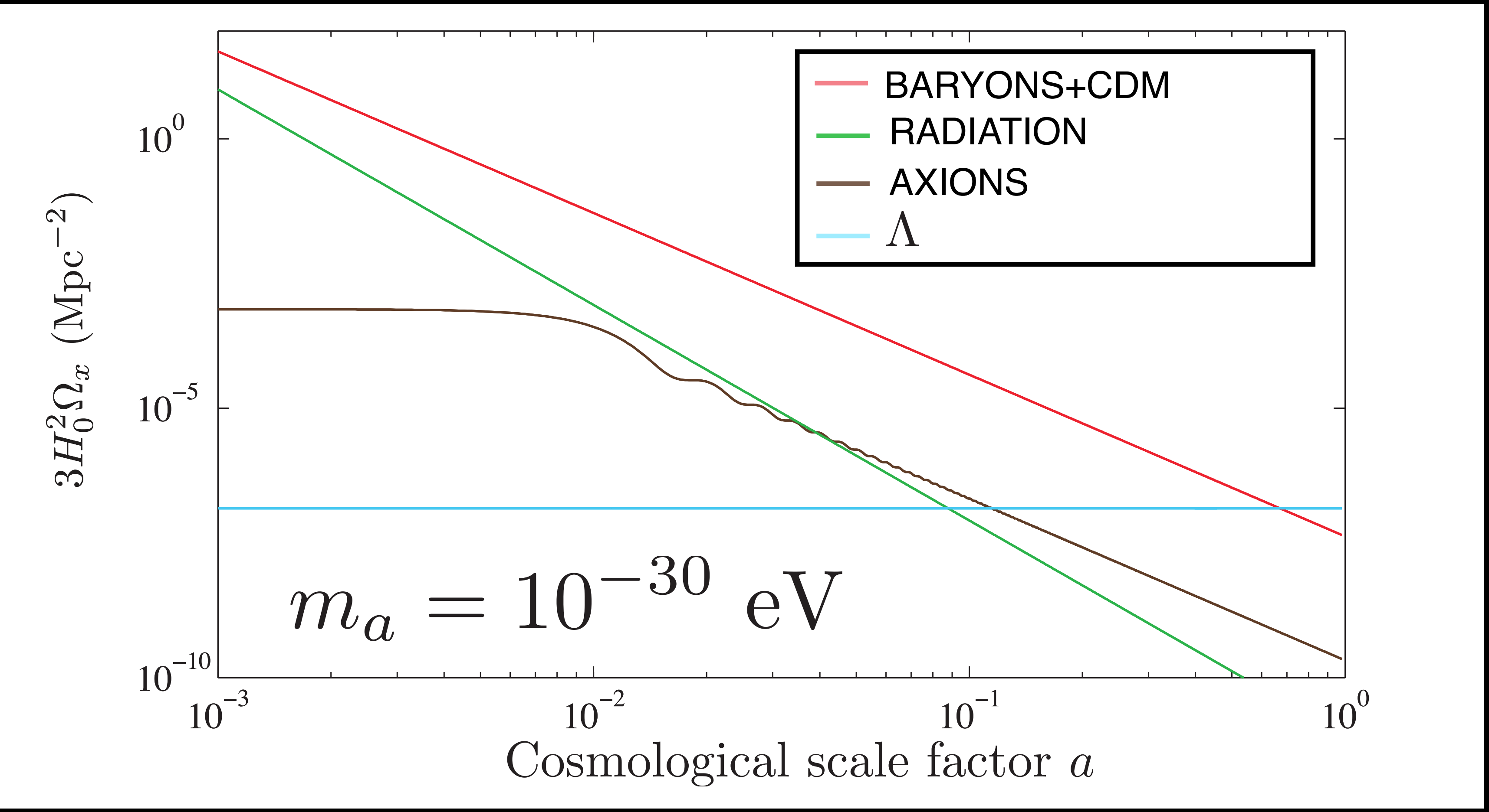
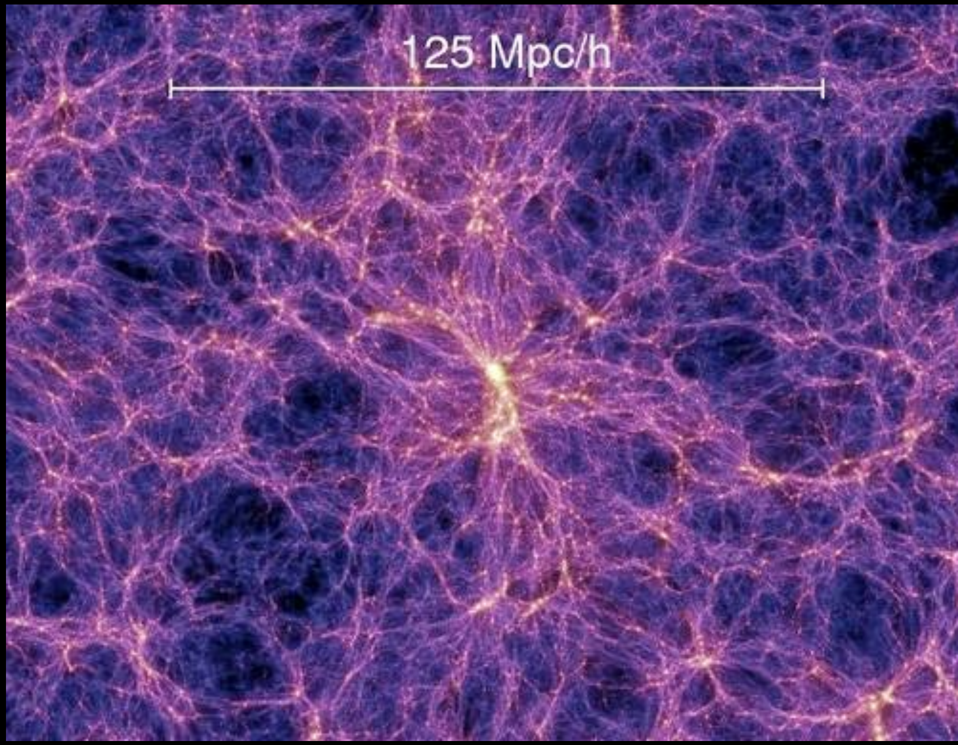


$$10^{-33}\ \text{eV} < m_a < 10^{-18}\ \text{eV}$$



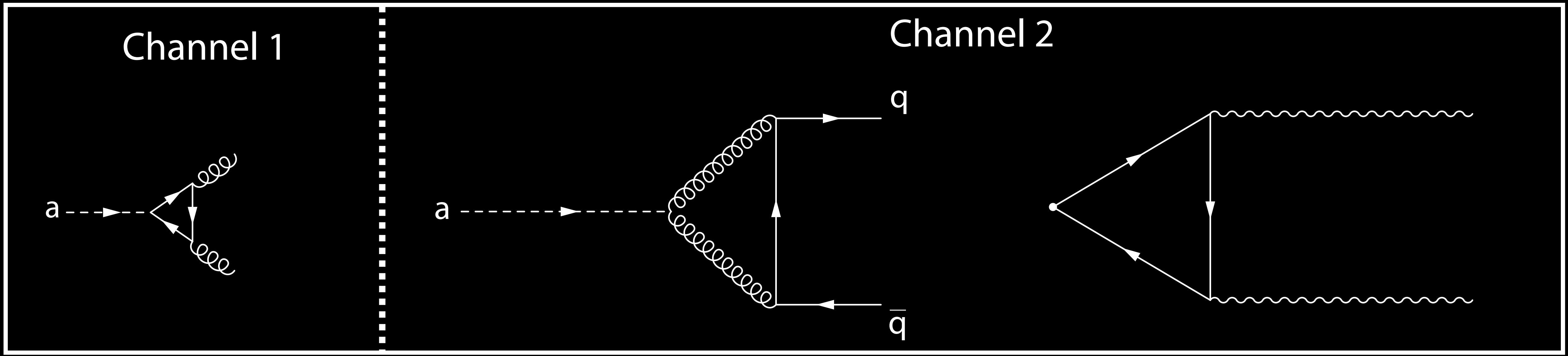
'DM' axions $\quad a_{\rm osc} < a_{\rm eq}$ *Oscillation starts in time for struct. formation*

$$m_a > 10^{-27}\ \text{eV}$$

DE axions $\quad a_{\rm osc} > a_{\rm eq}$ *Oscillation starts too late for struct. formation*

$$m_a < 10^{-27}\ \text{eV}$$

Two-photon coupling of axion



✳ Axions interact weakly with SM particles $\Gamma, \sigma \sim \alpha^2$

✳ Axions have a two-photon coupling

$$g_{a\gamma\gamma} = -\frac{3\alpha}{8\pi f_a}\xi \qquad \mathcal{L} \propto g_{a\gamma\gamma}\vec{E}\cdot\vec{B}$$

✳ Very little freedom once f_a specified

Axion Experiments/ Constraints

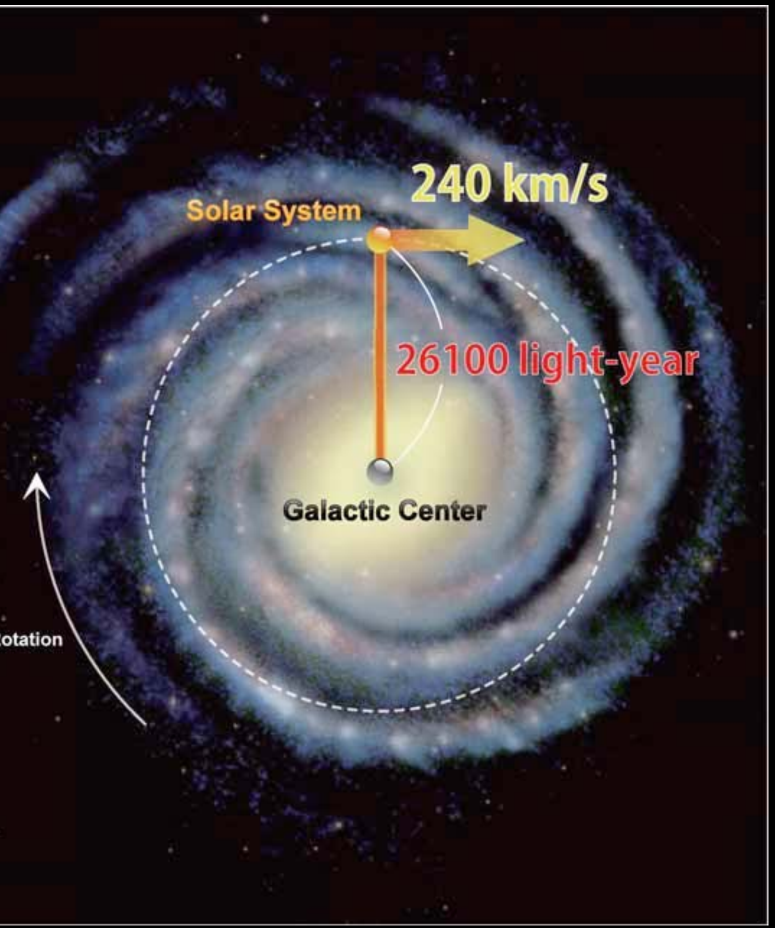
How to look for a QCD axion

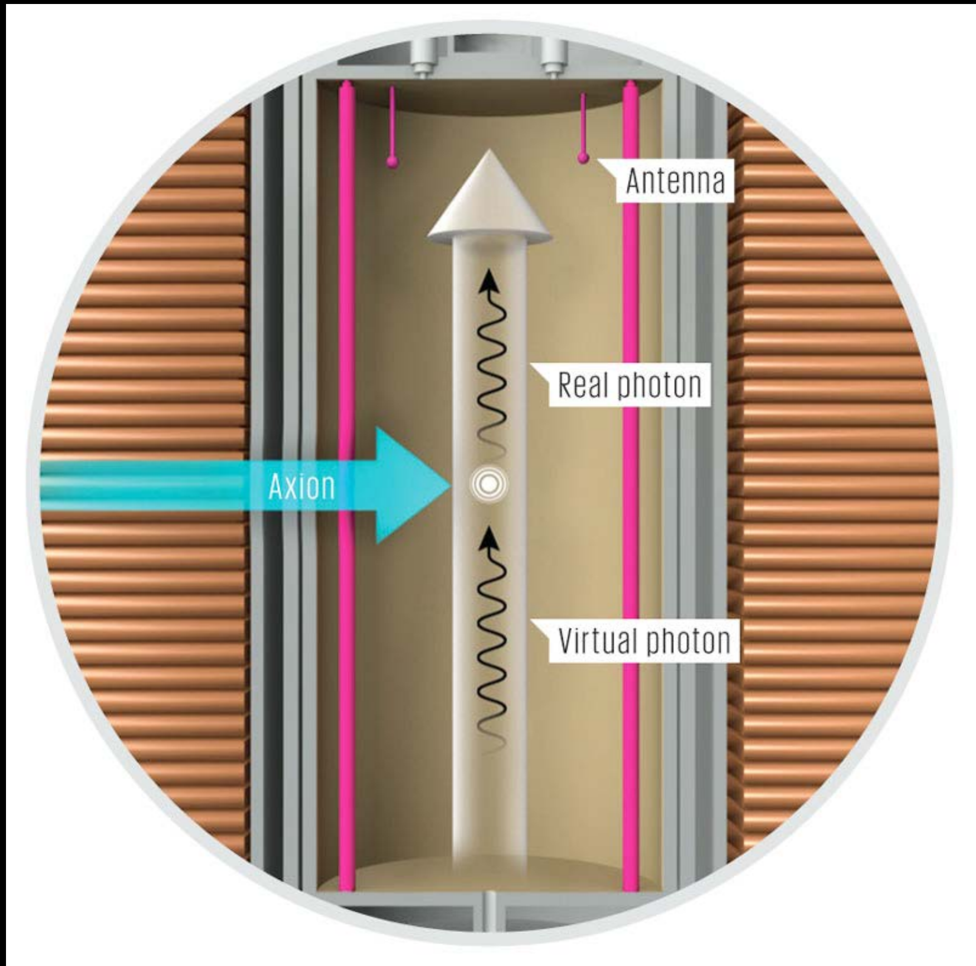
✳ ADMX: Use the DM axions the universe gives you

$$\mathcal{L} \propto g_{a\gamma\gamma} a \vec{E} \cdot \vec{B} \quad g_{a\gamma\gamma} \propto 1/f_a$$

P. Sikivie 1983

$E_\gamma = m_a c^2$ → *Excite cavity TEM modes*





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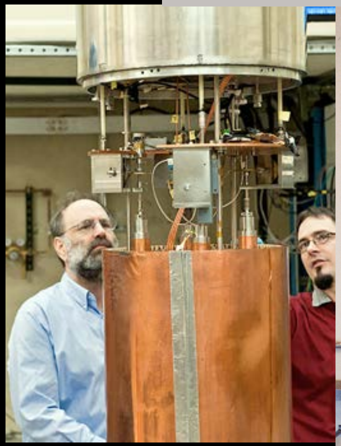
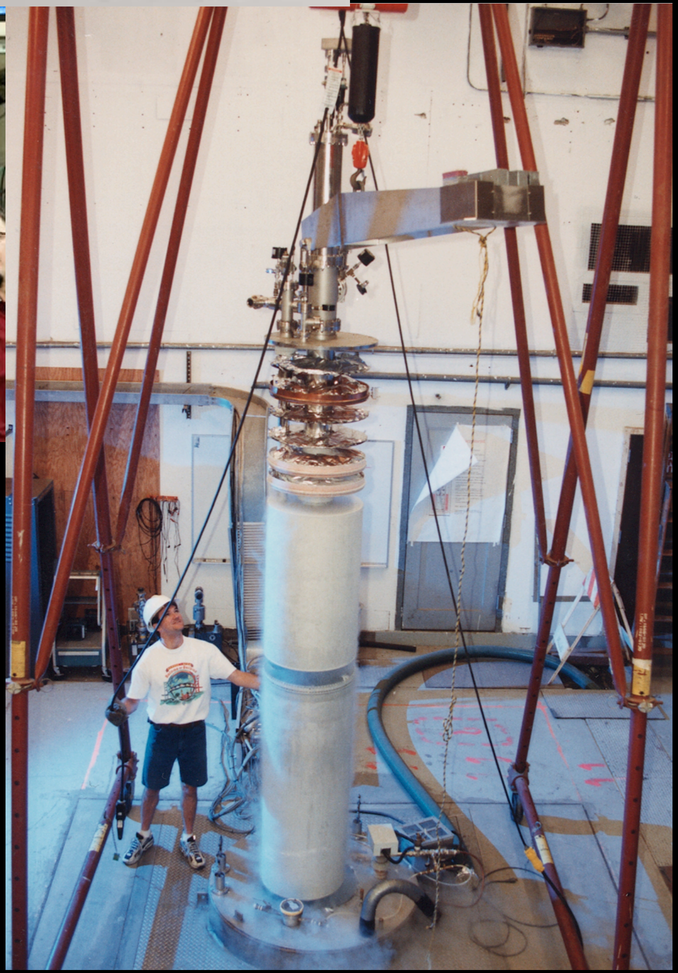
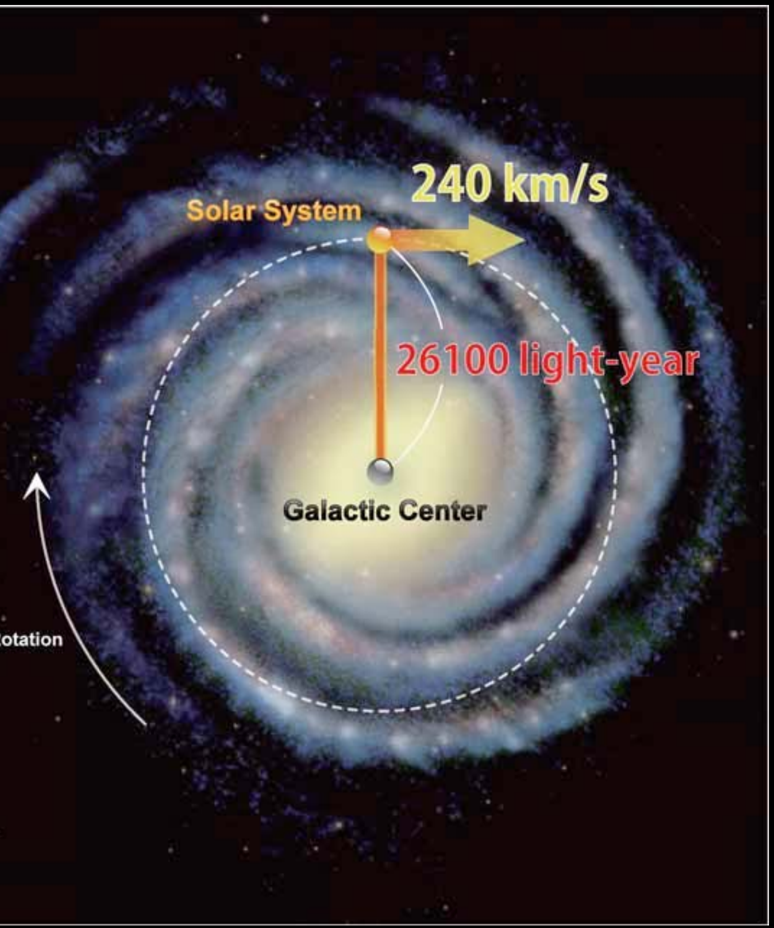
ADMX

L. Rosenberg and G. Rybka +....







How to look for axions

- ✳ By construction, axions interact with photons $g_{a\gamma\gamma} = -\frac{3\alpha\xi}{2\pi f_a}$

$g_{a\gamma\gamma}\ (\mathrm{GeV}^{-1})$

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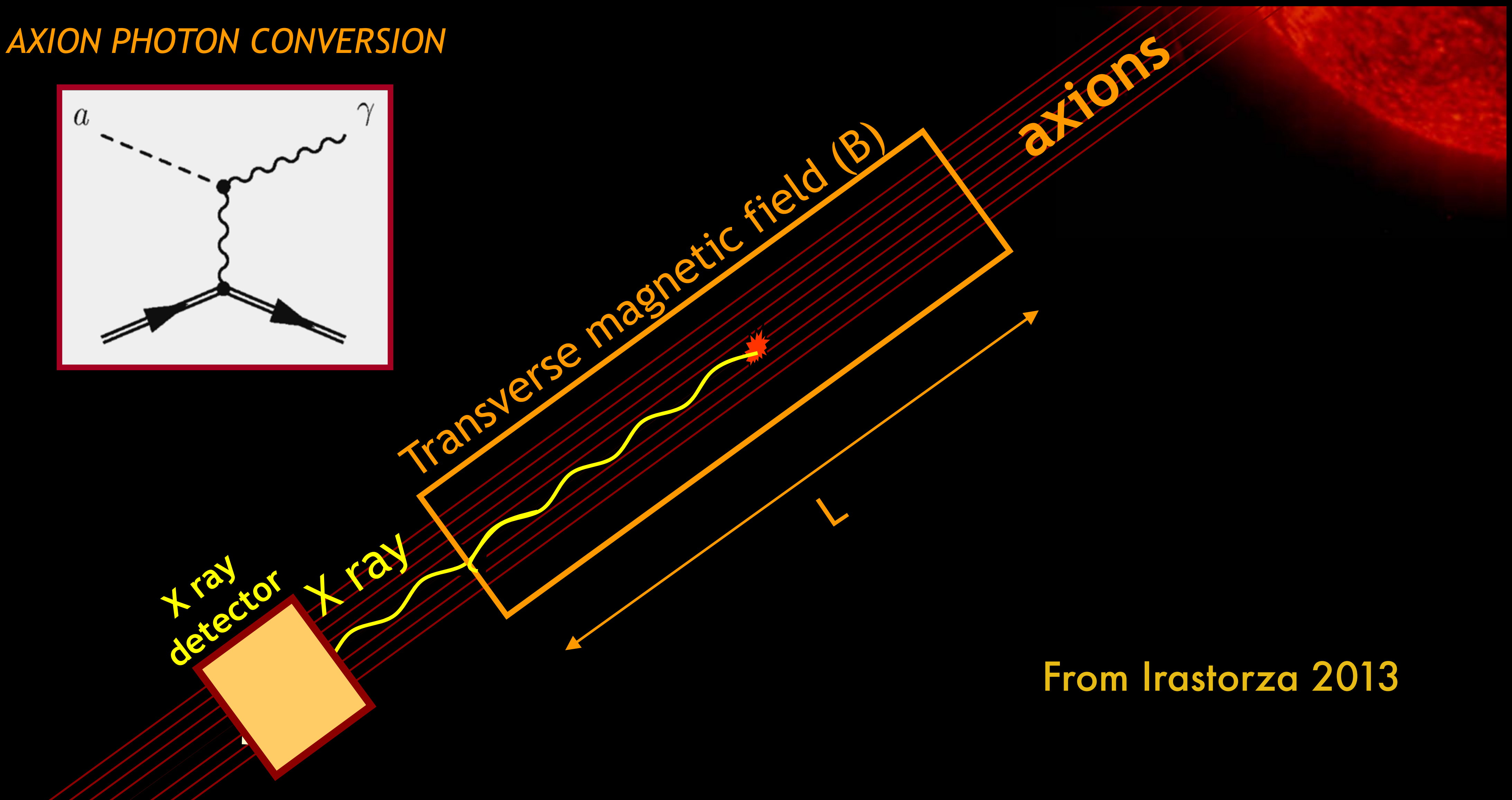

From Irastorza 2013

Make them in stars— Turn them back into photons on Earth!

CAST/IAXO experiments

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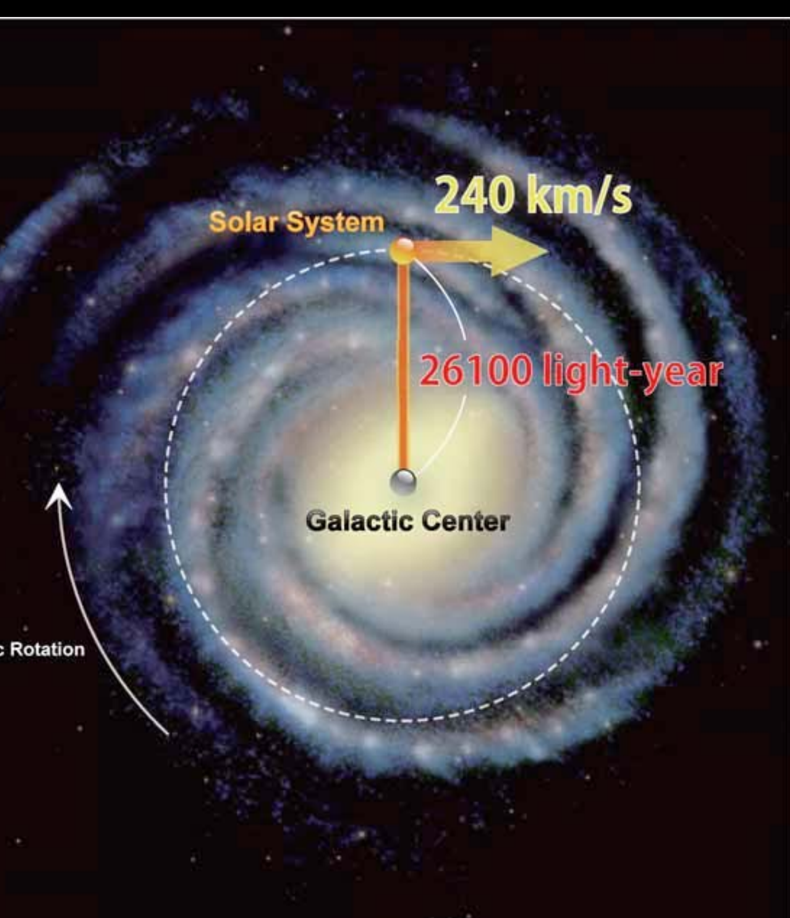
Pierre Sikivie

Use the dark matter in the universe!

$g_{a\gamma\gamma}$ (GeV^{-1})



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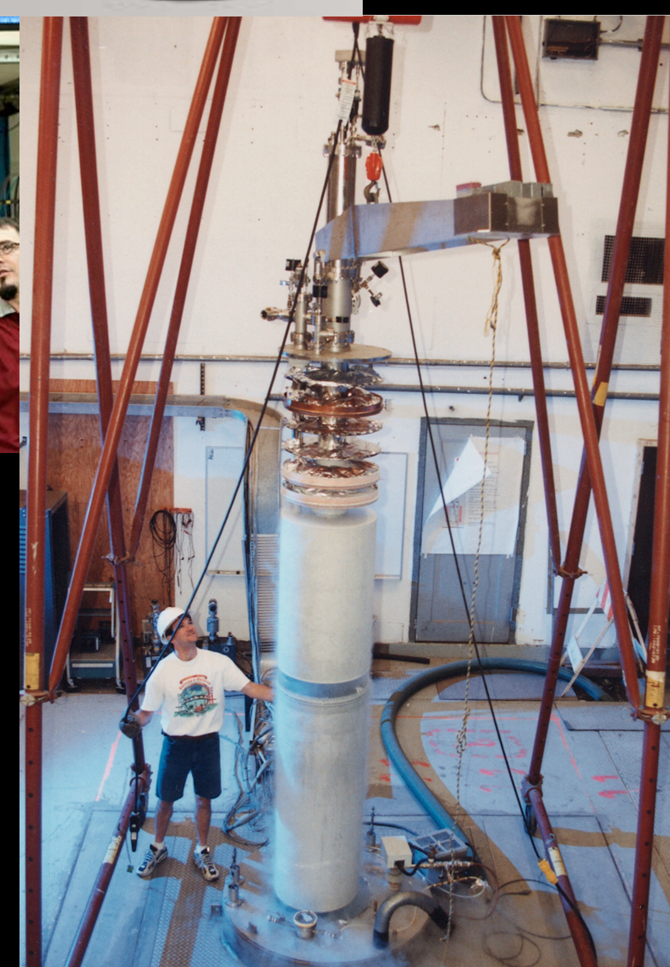

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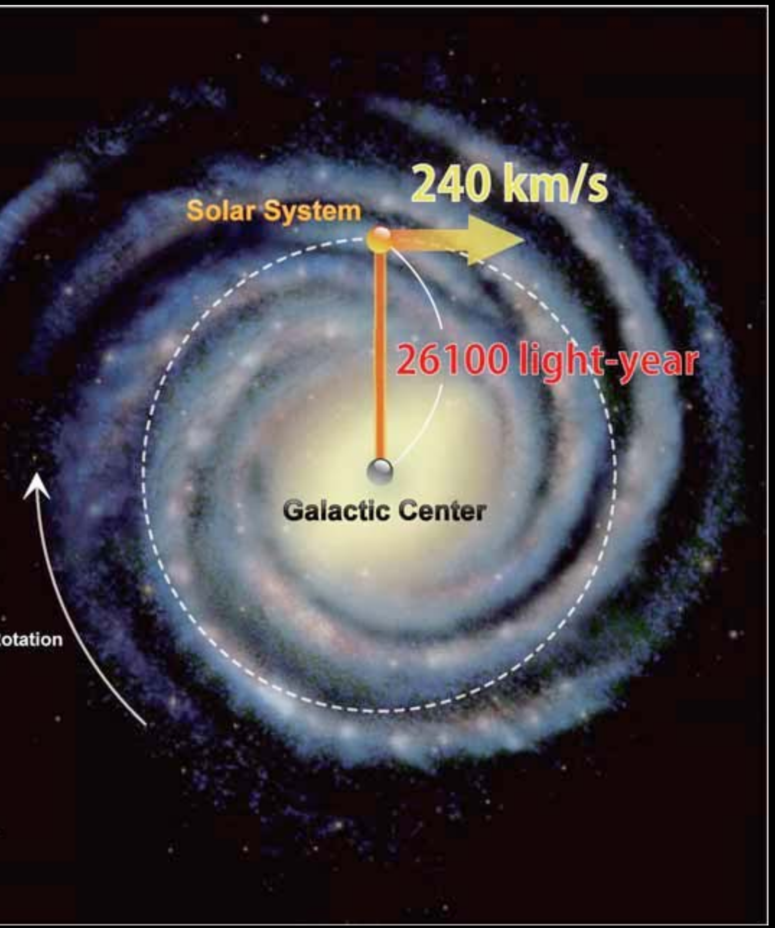

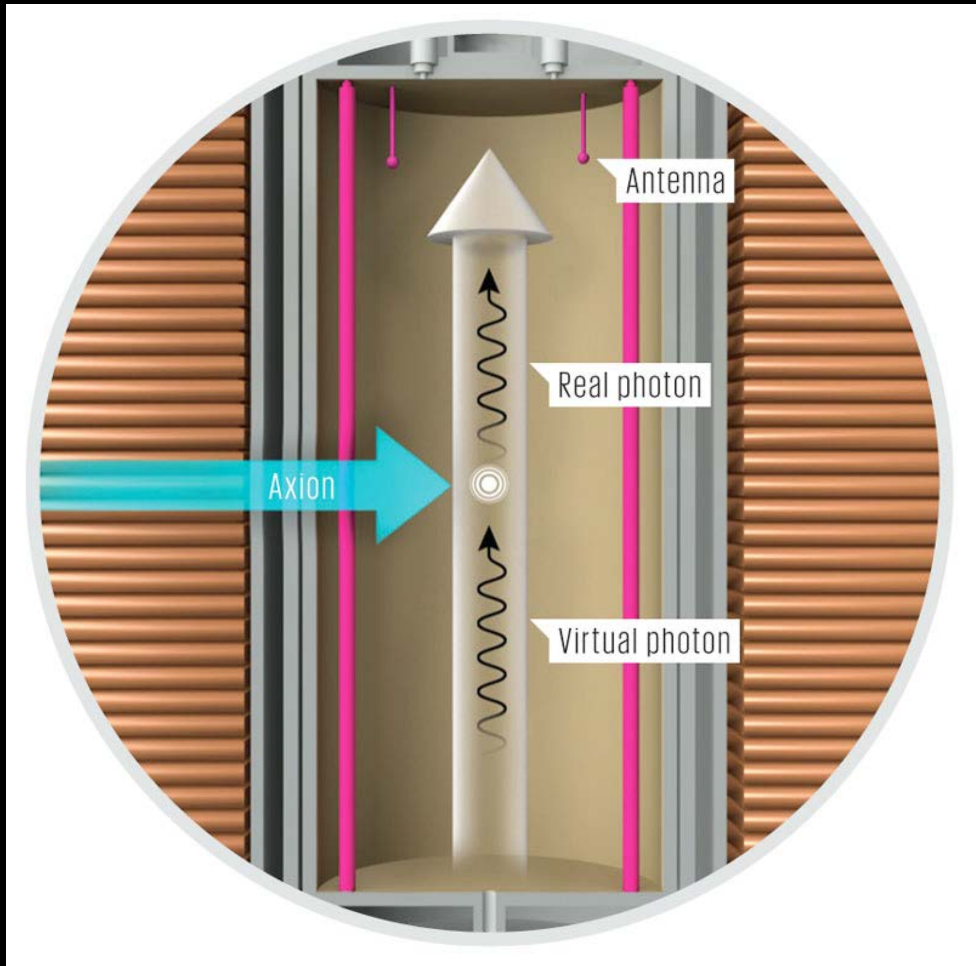

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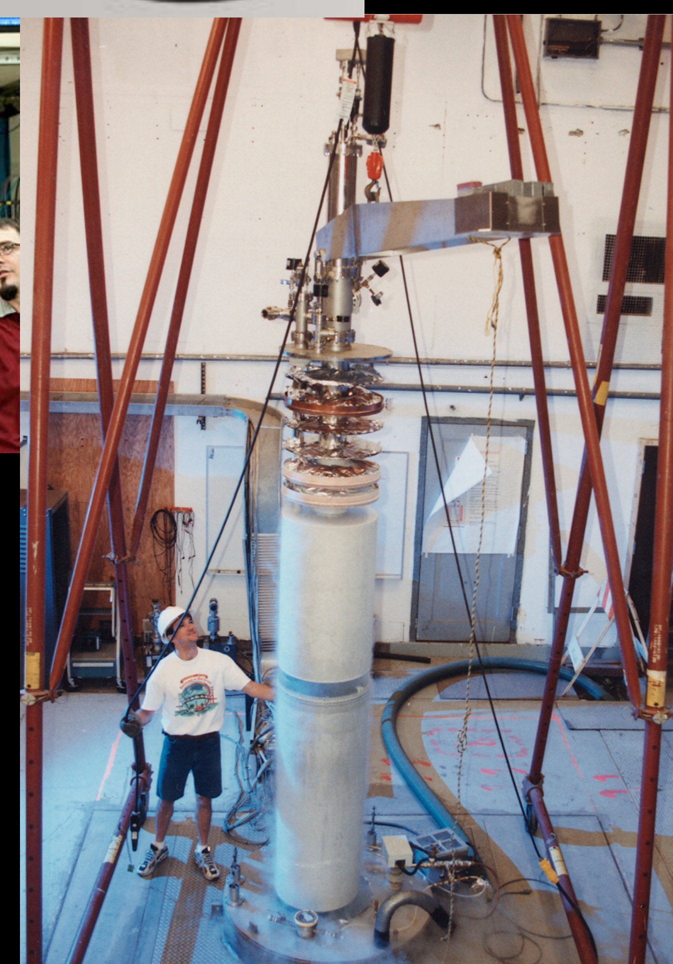

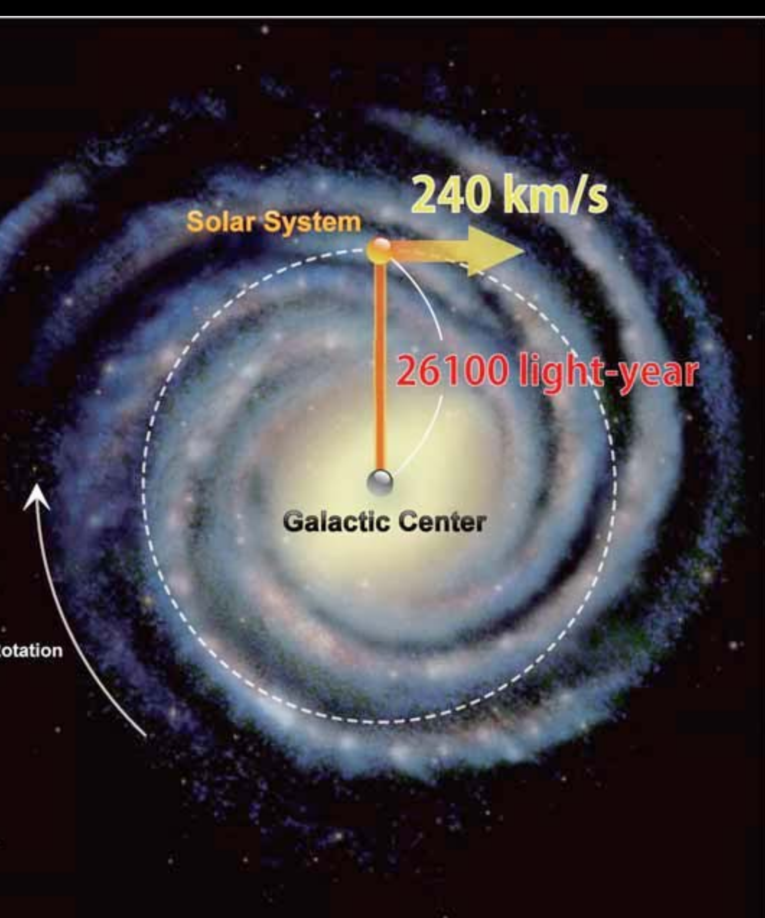

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$g_{a\gamma\gamma}$ (GeV^{-1})

How to look for axions

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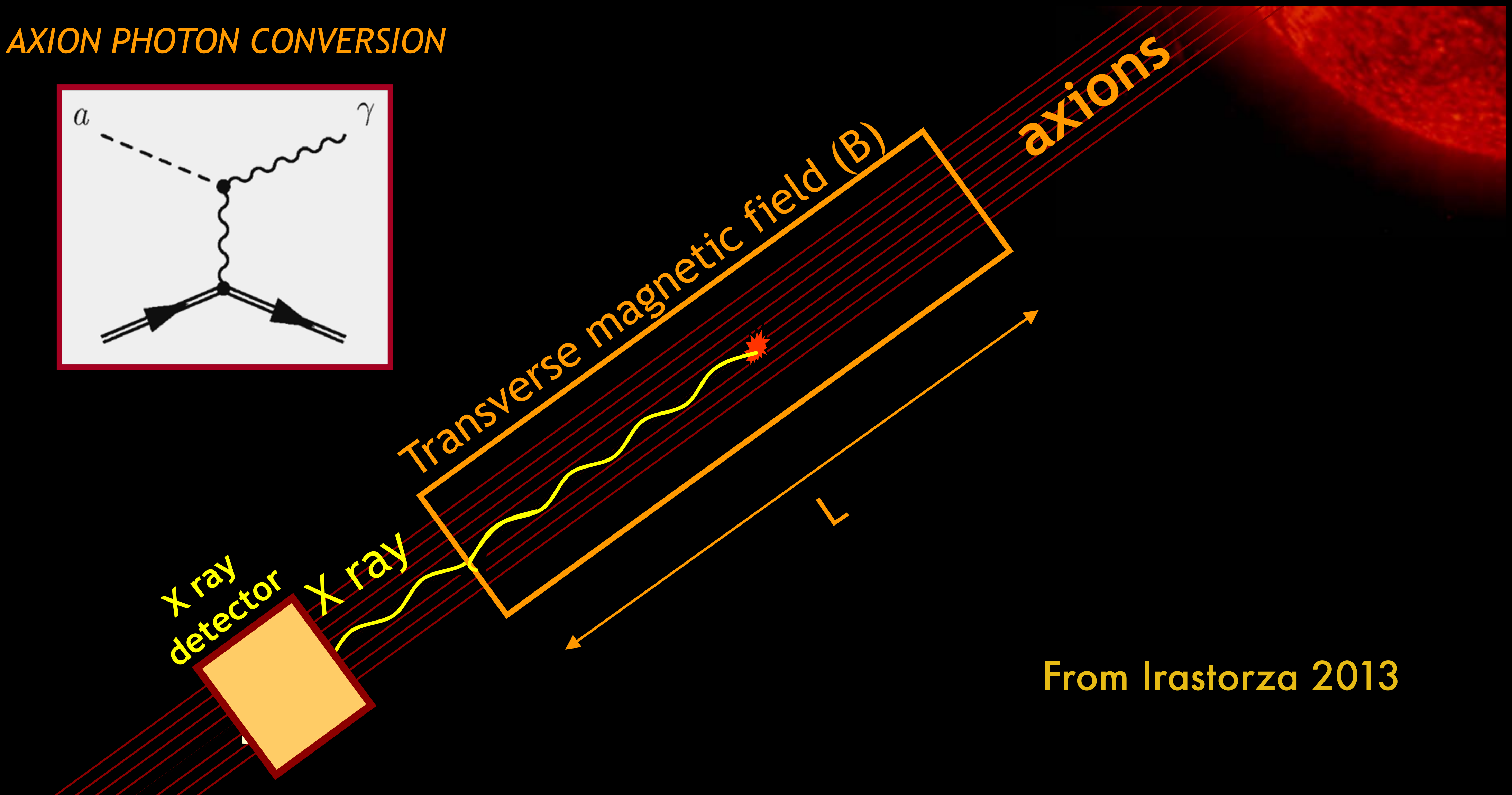

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Make them in stars— Turn them back into photons on Earth!

CAST/IAXO experiments

How to look for axions

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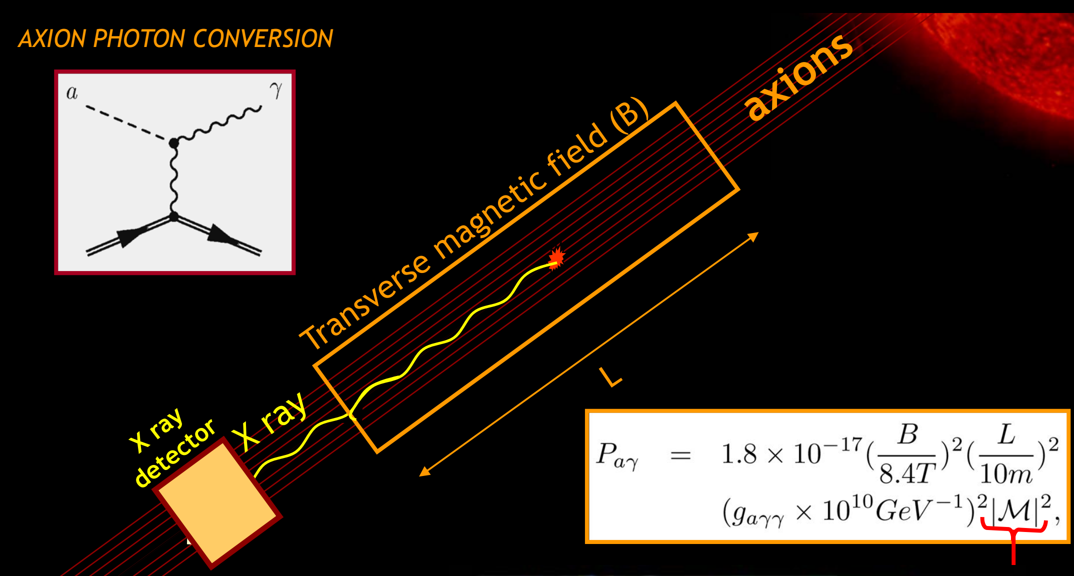
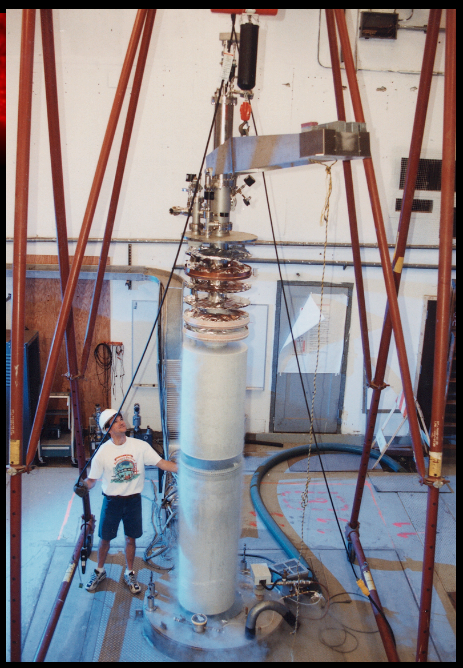
Make them in stars— Turn them back into photons on Earth!

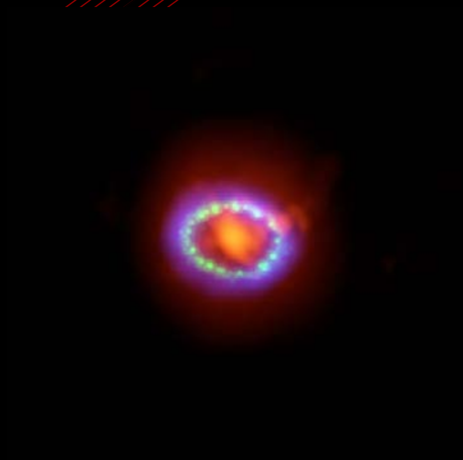
CAST/IAXO experiments

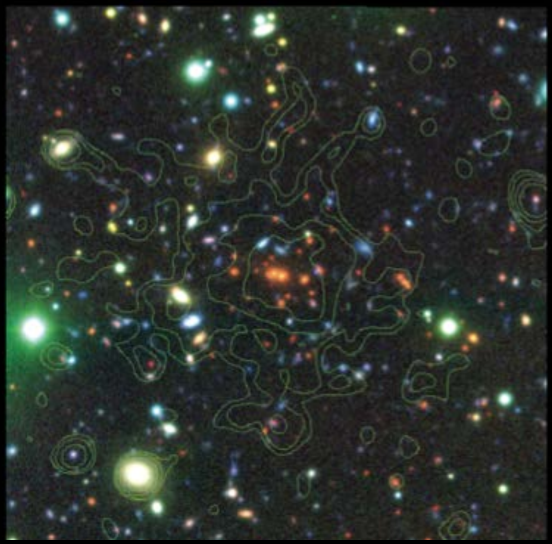
Limits and horizon



$$P_{a\gamma} = 1.8 \times 10^{-17} (\frac{B}{8.4T})^2 (\frac{L}{10m})^2 (g_{a\gamma\gamma} \times 10^{10} GeV^{-1})^2 |\mathcal{M}|^2,$$







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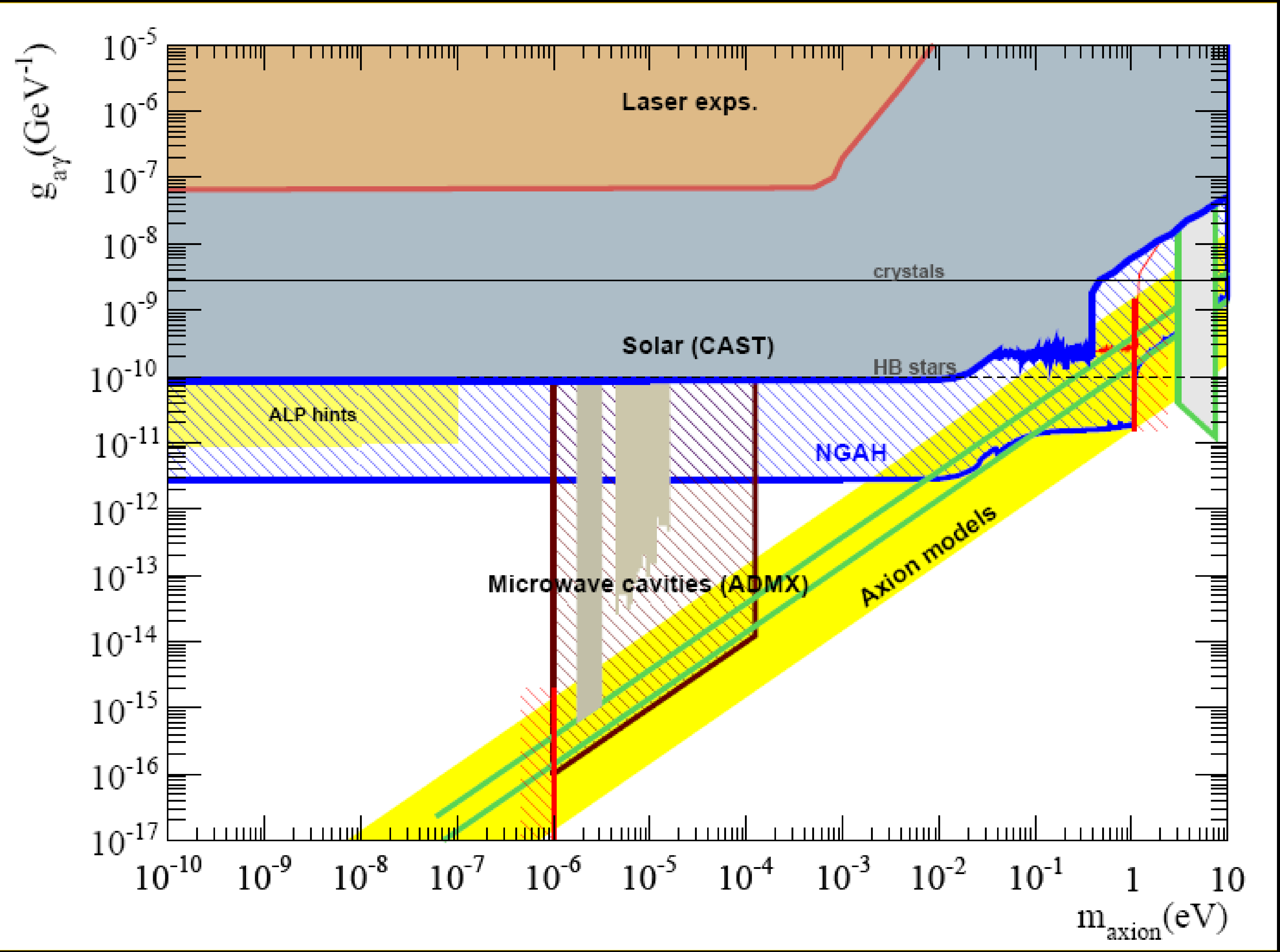
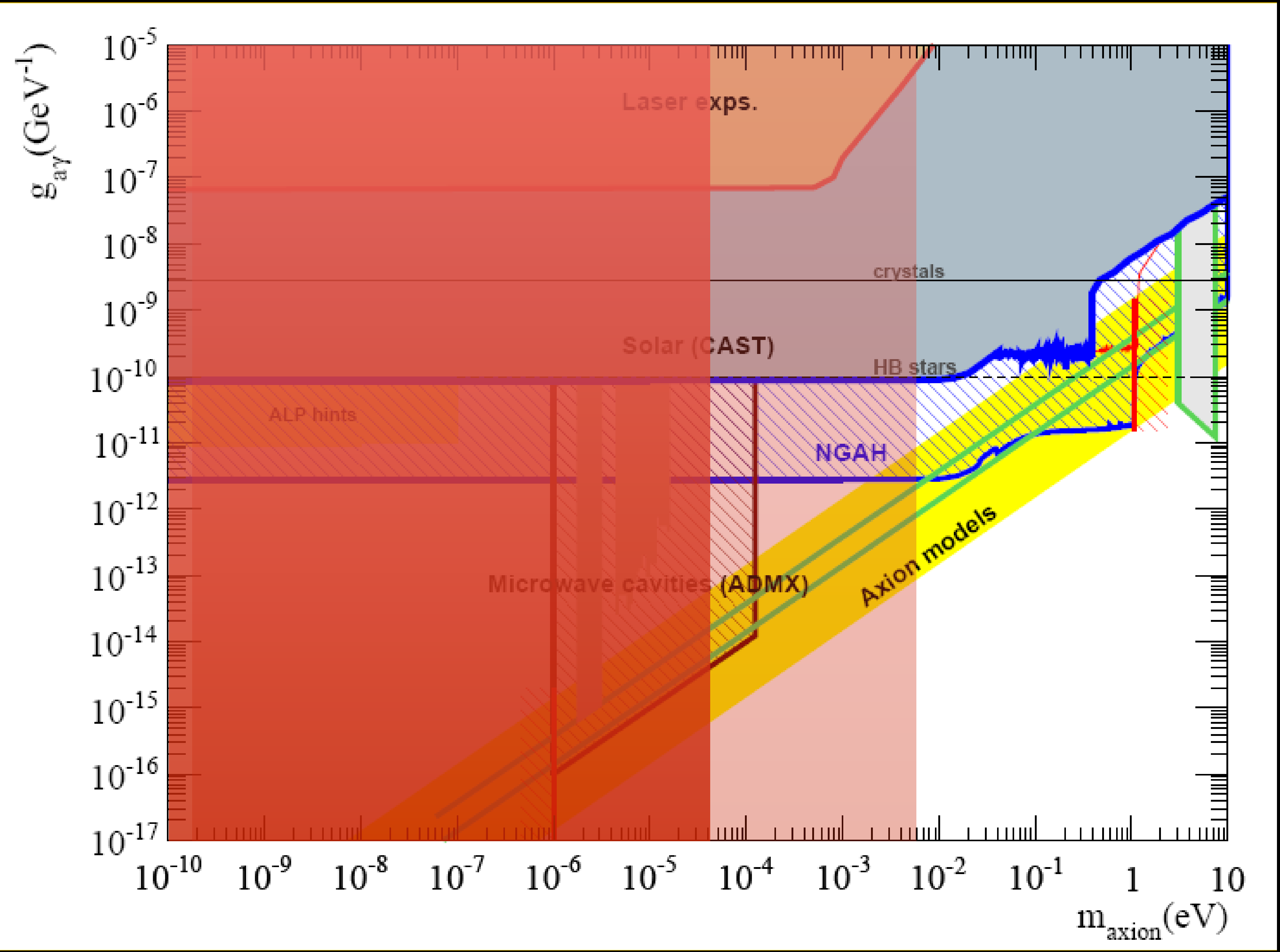
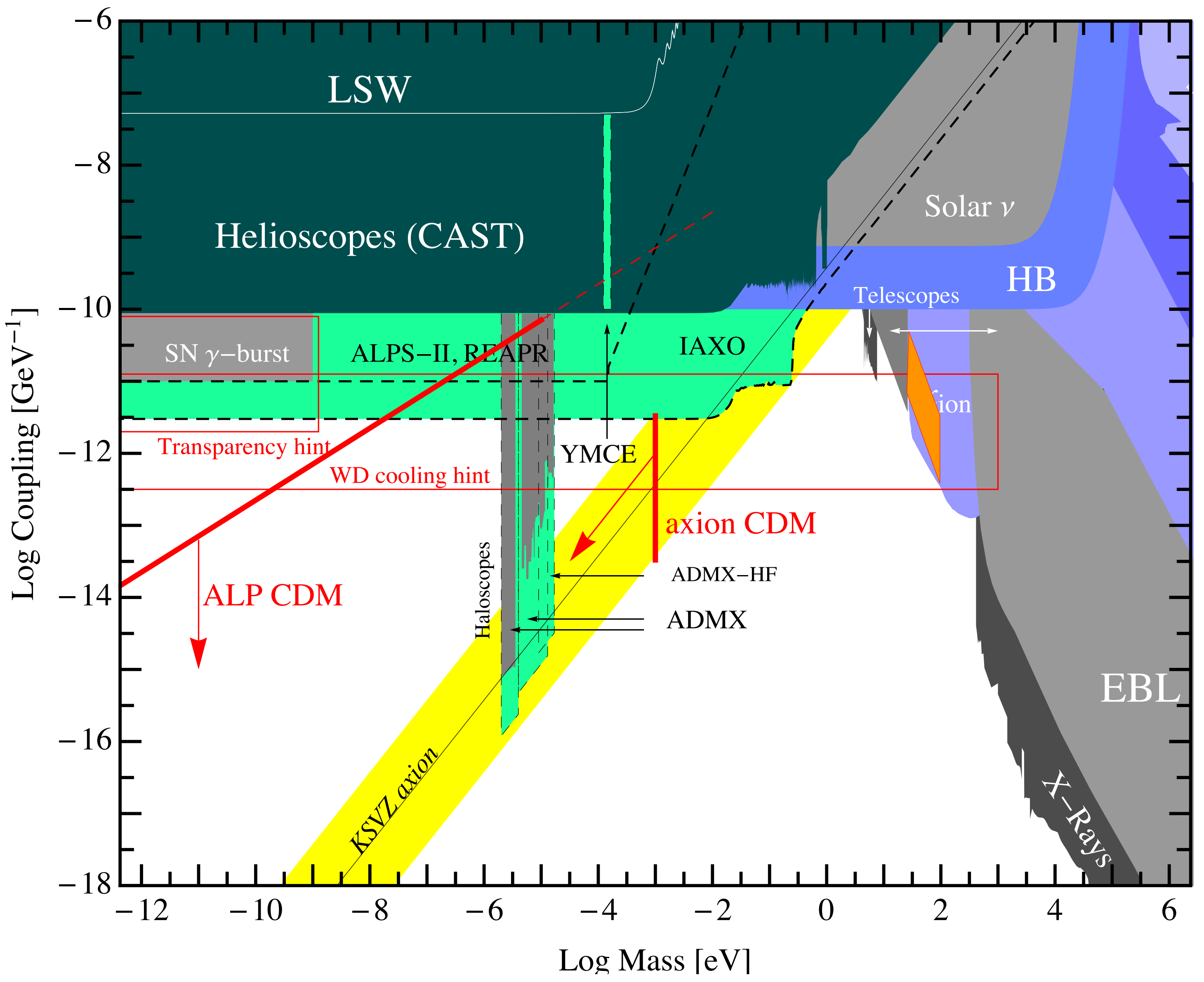


Limits and horizon

Cosmological abundance limits (more soon...)



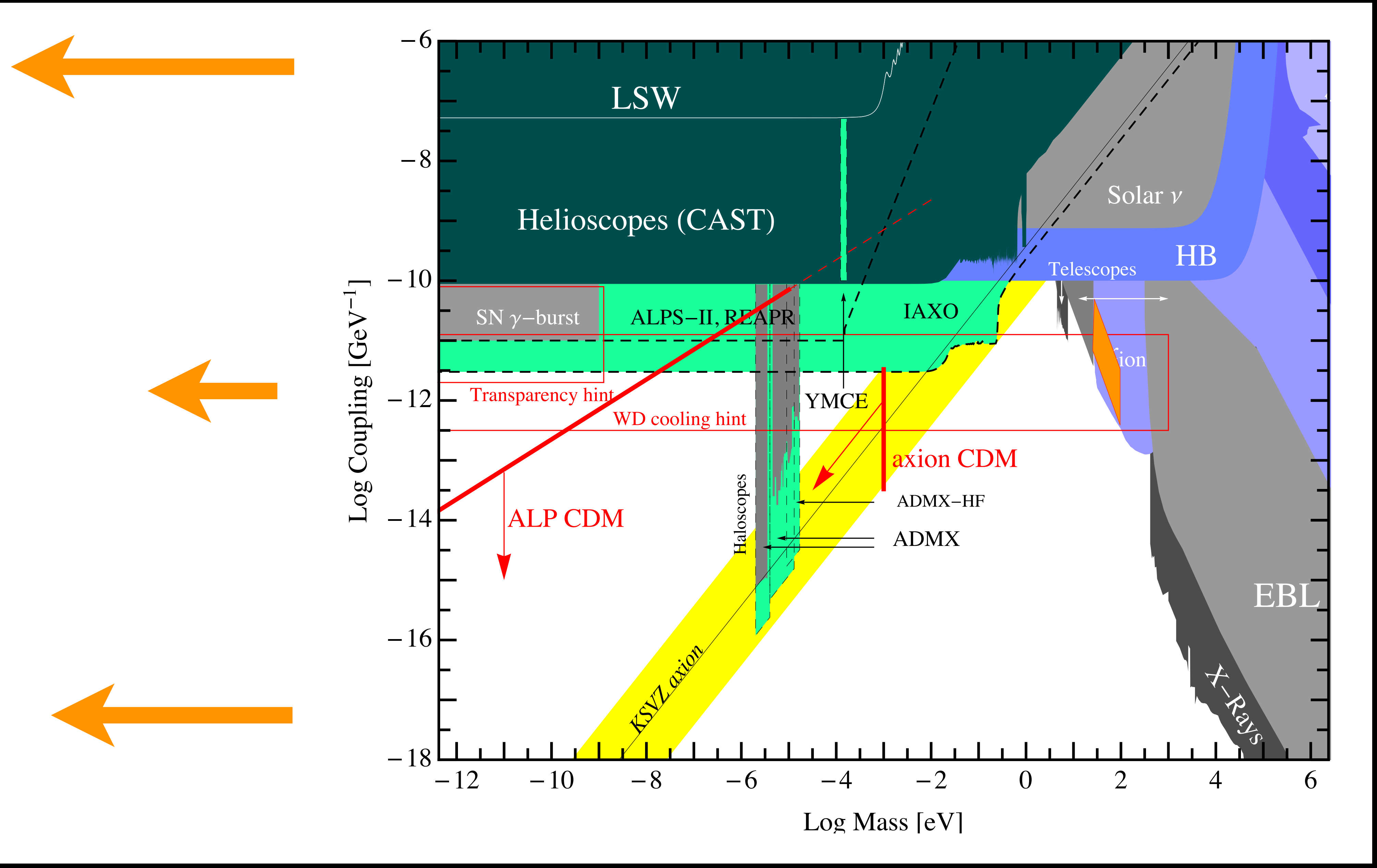
Experimental constraints
ULA and axion-like particles (ALPs)



$$\mathcal{L} \propto g_{a\gamma\gamma} \vec{E} \cdot \vec{B}$$

Experimental constraints
ULA and axion-like particles (ALPs)

Experimental desert: Gravitational constraints essential



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From arXiv: 1205.2671

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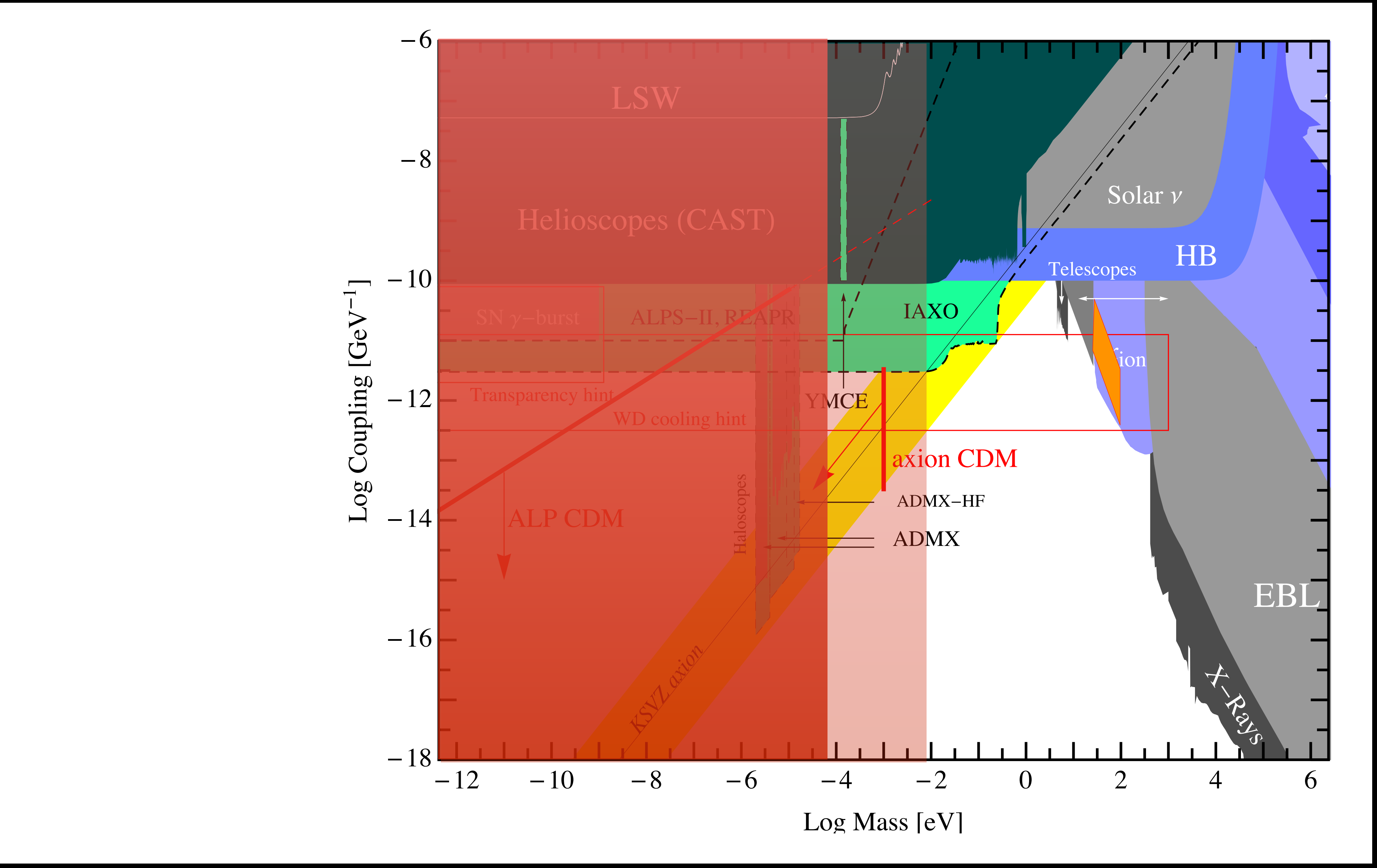

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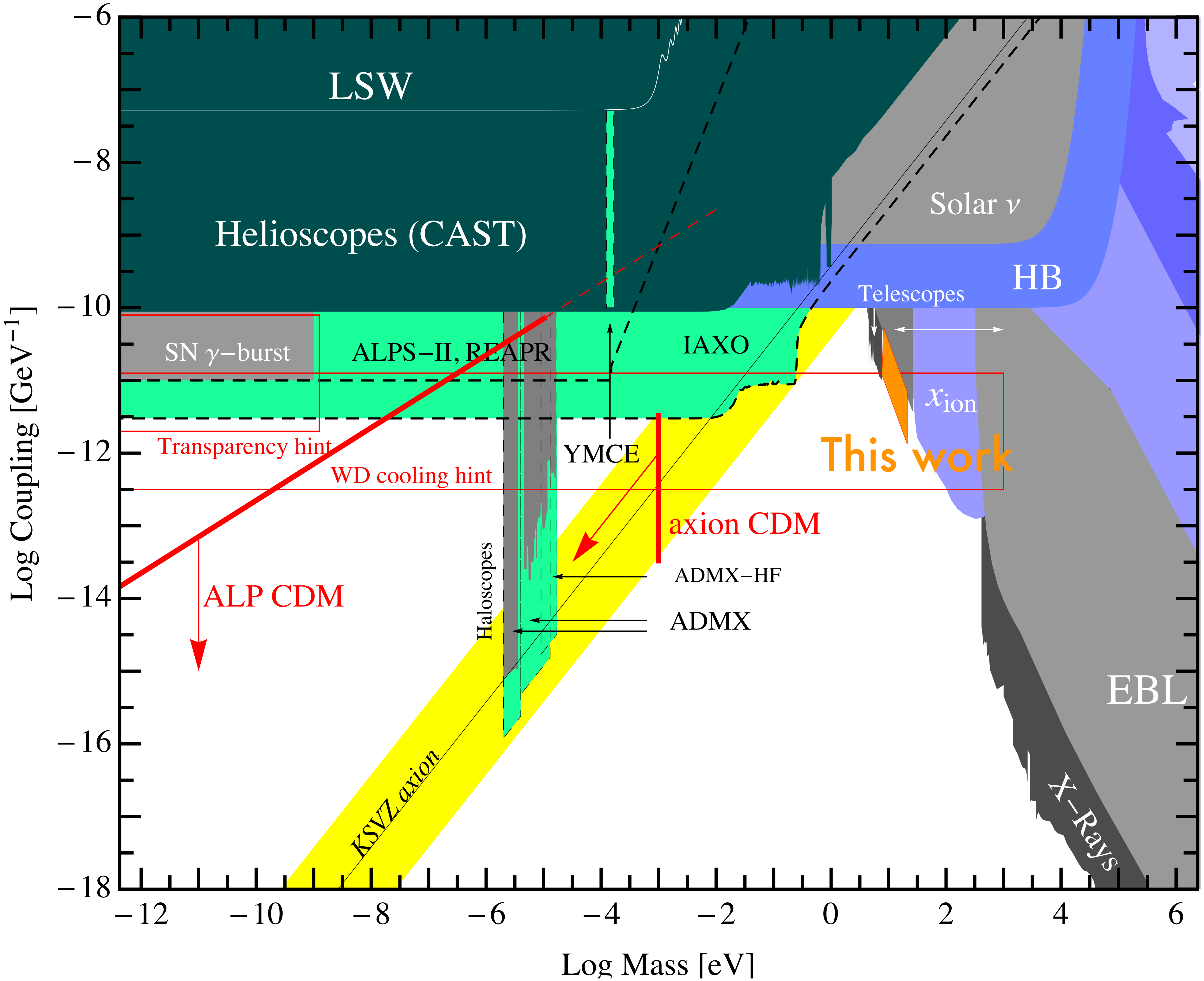
Lay of the land

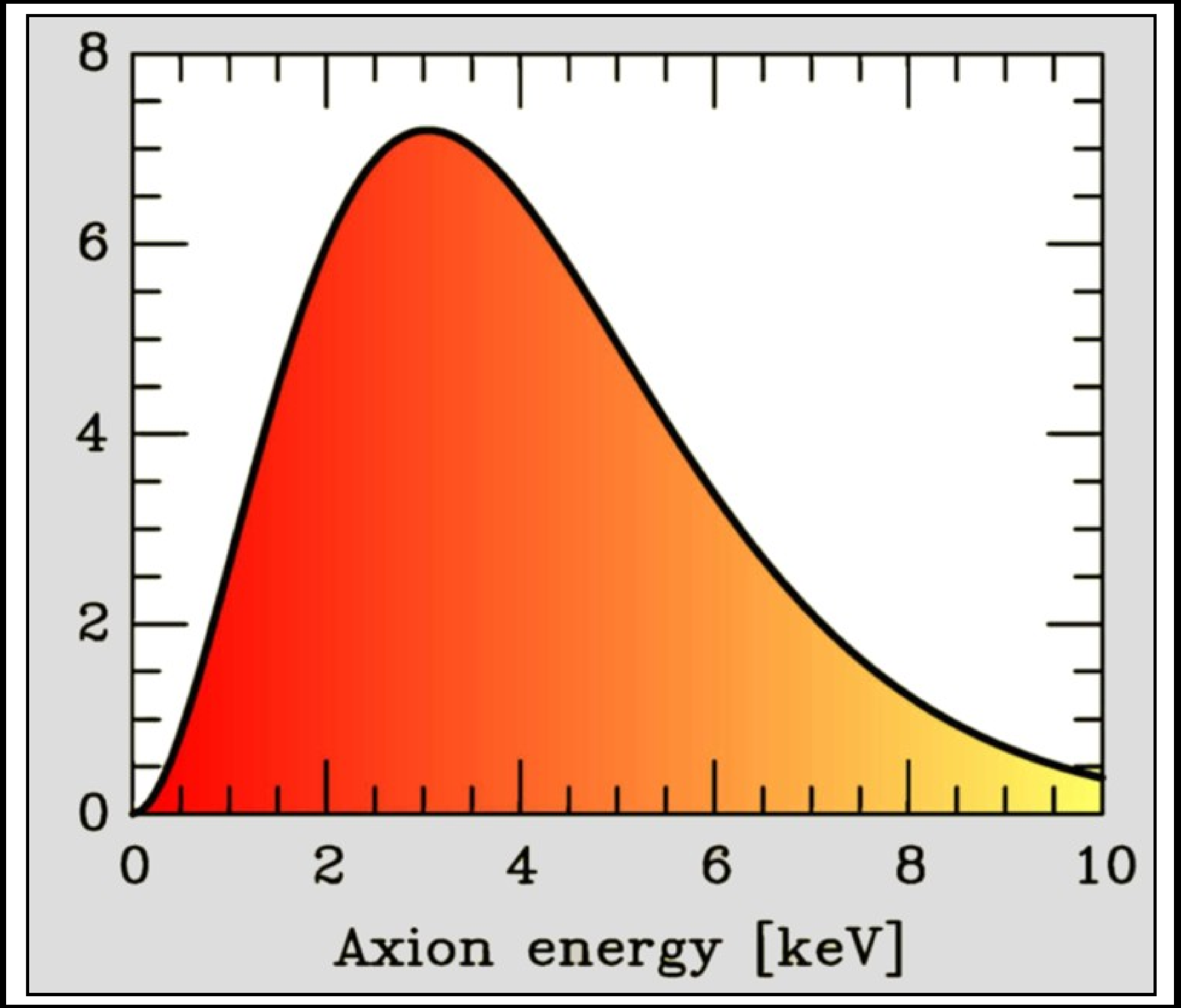


Axion helioscopes

- Resonance condition

$$qL < \pi \quad \Rightarrow \quad \sqrt{m_\gamma^2 - \frac{2\pi E_a}{L}} < m_a < \sqrt{m_\gamma^2 + \frac{2\pi E_a}{L}}$$

- Broad axion energy spectrum



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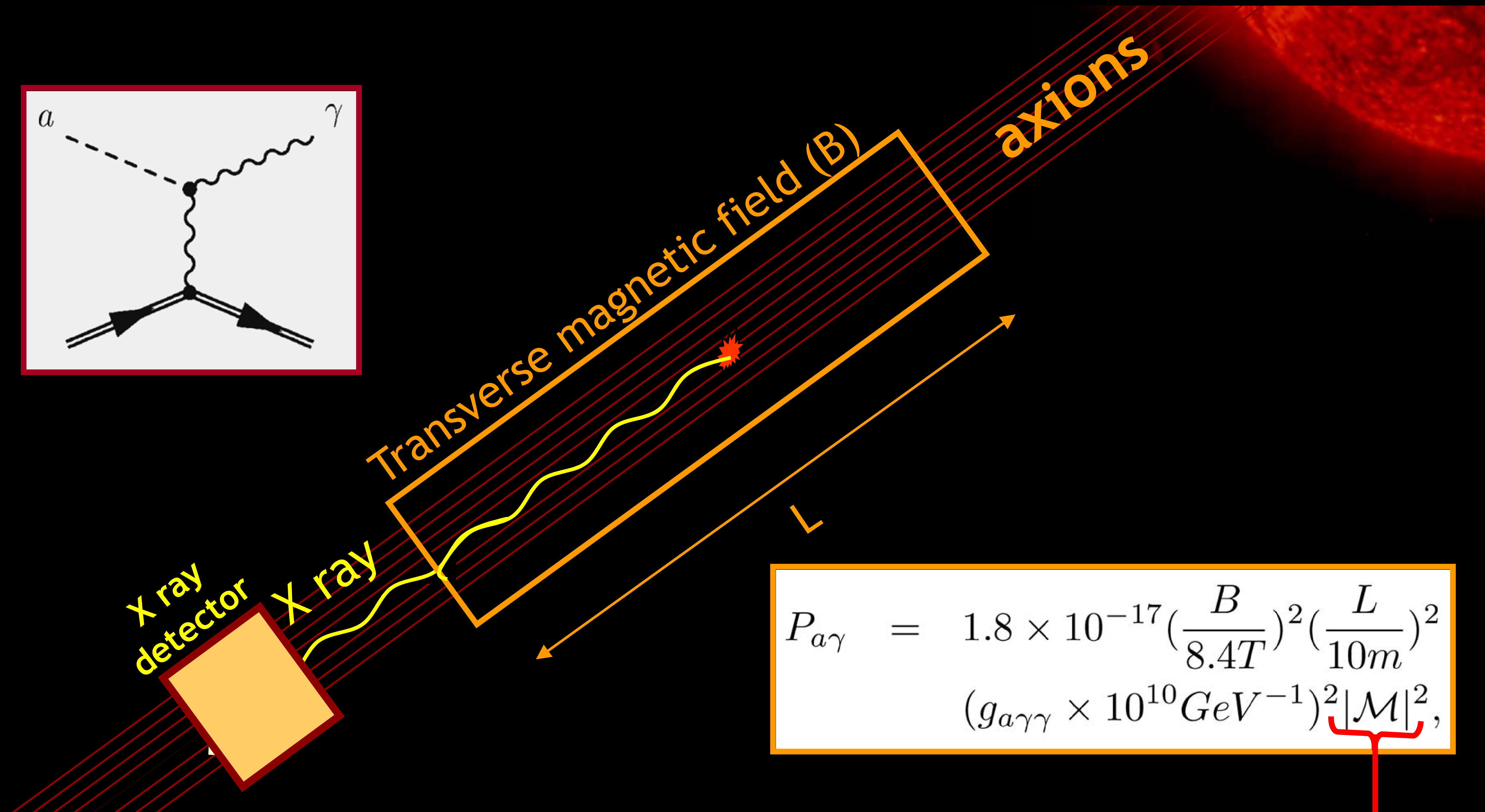
From Irastorza 2013



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CAST/IAXO

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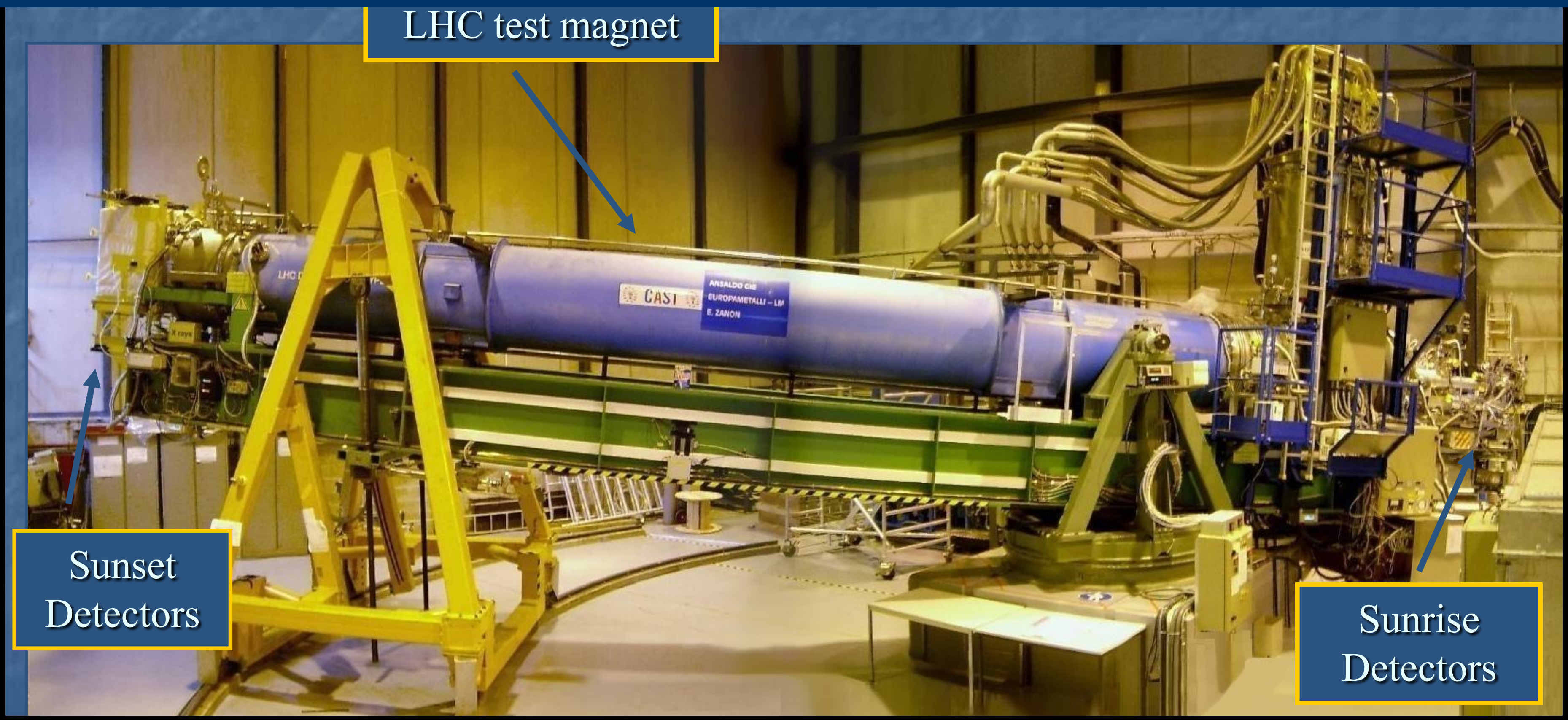
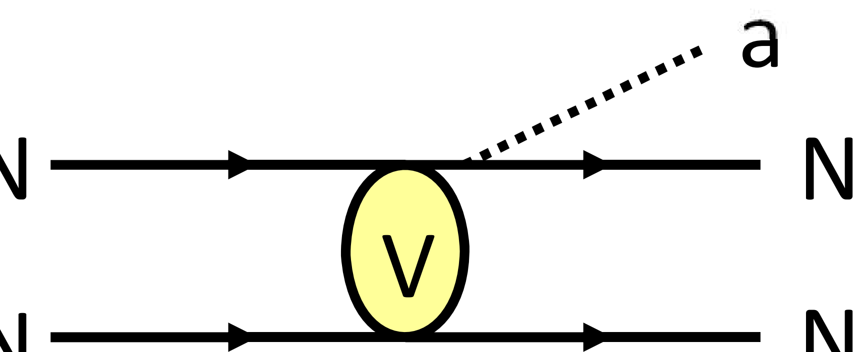


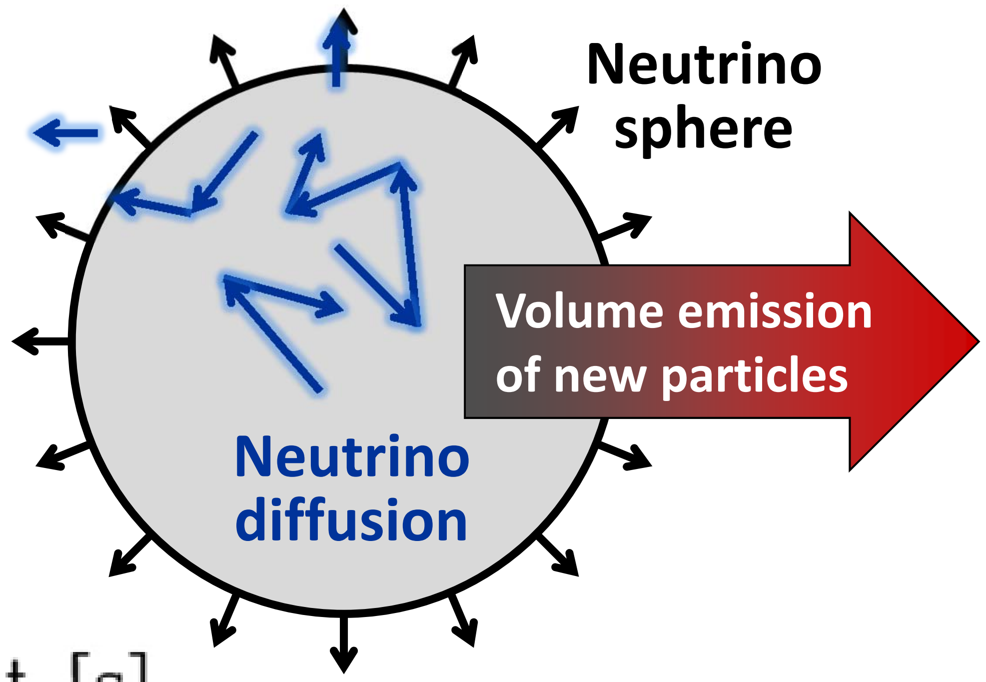
Lakic 2012

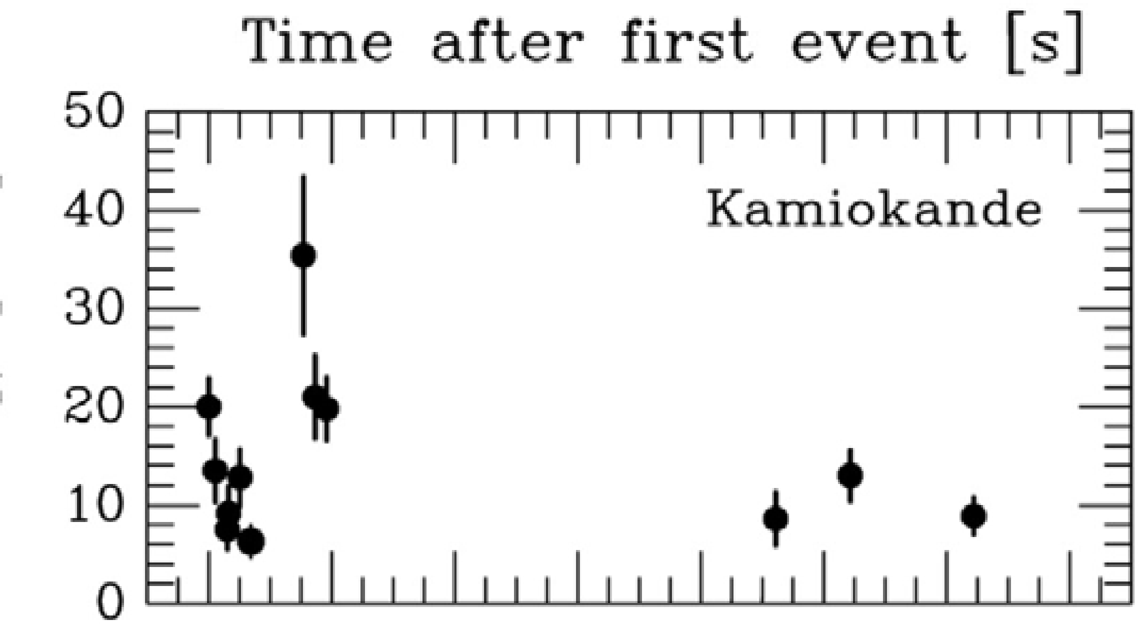
* IAXO proposal: 15-20m length magnet, optimized shape [not LHC DUD]

Making axions in (exploding) stars, III



Nucleon-Nucleon
Bremsstrahlung





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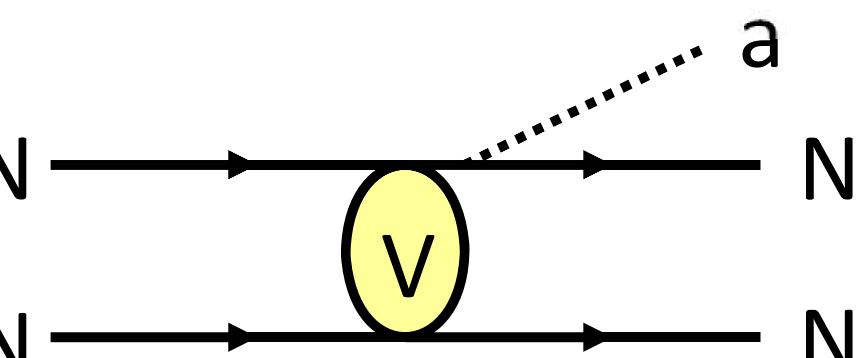

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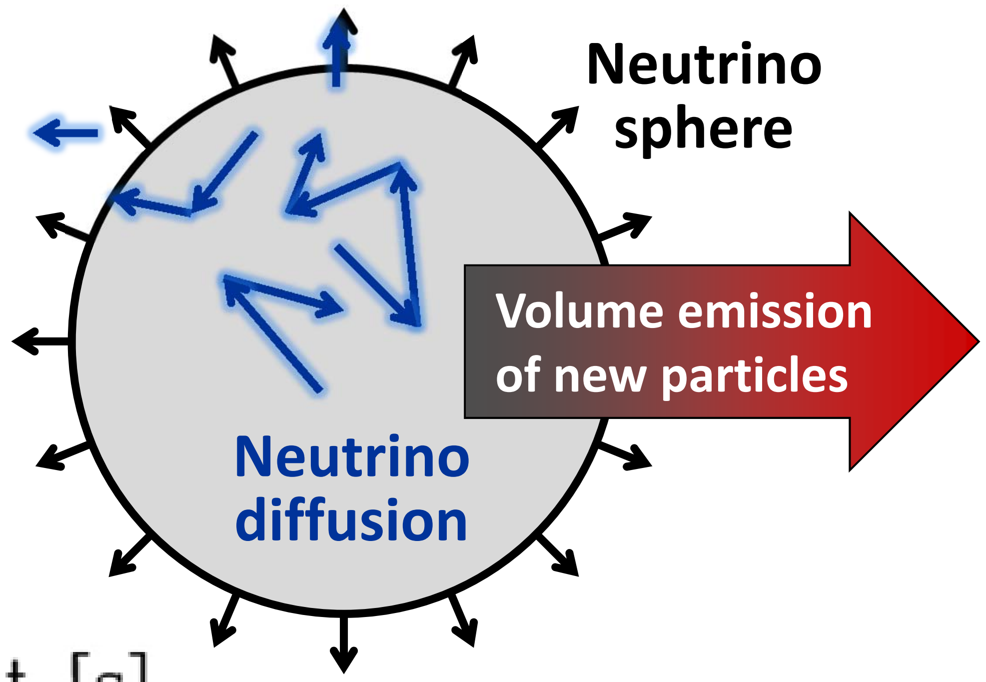

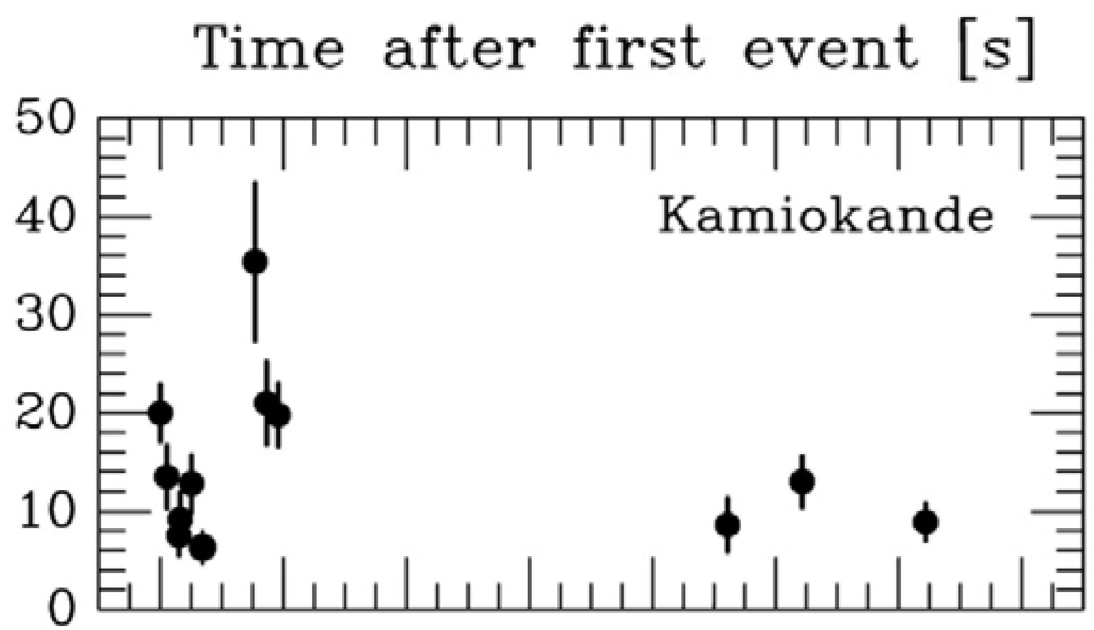

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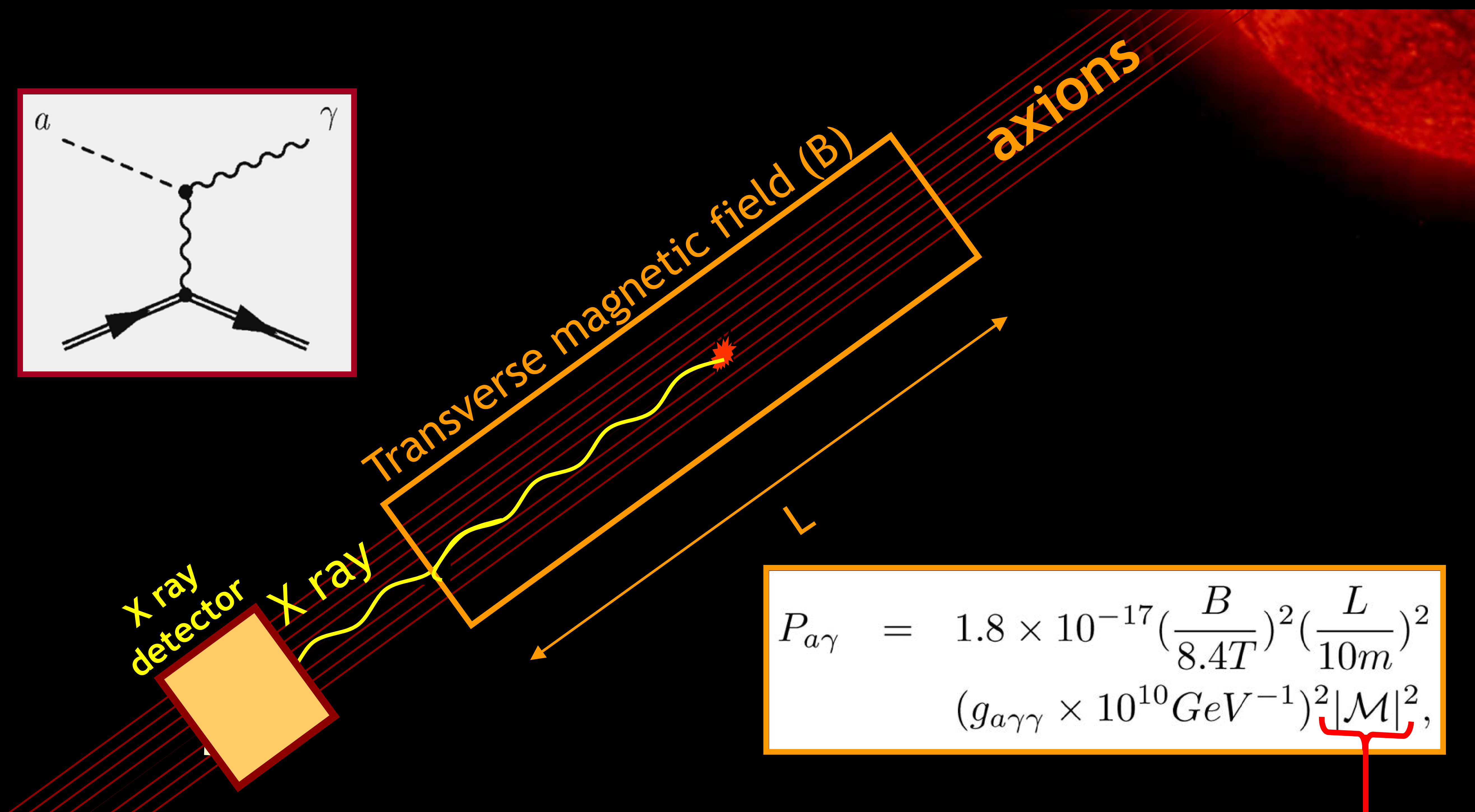

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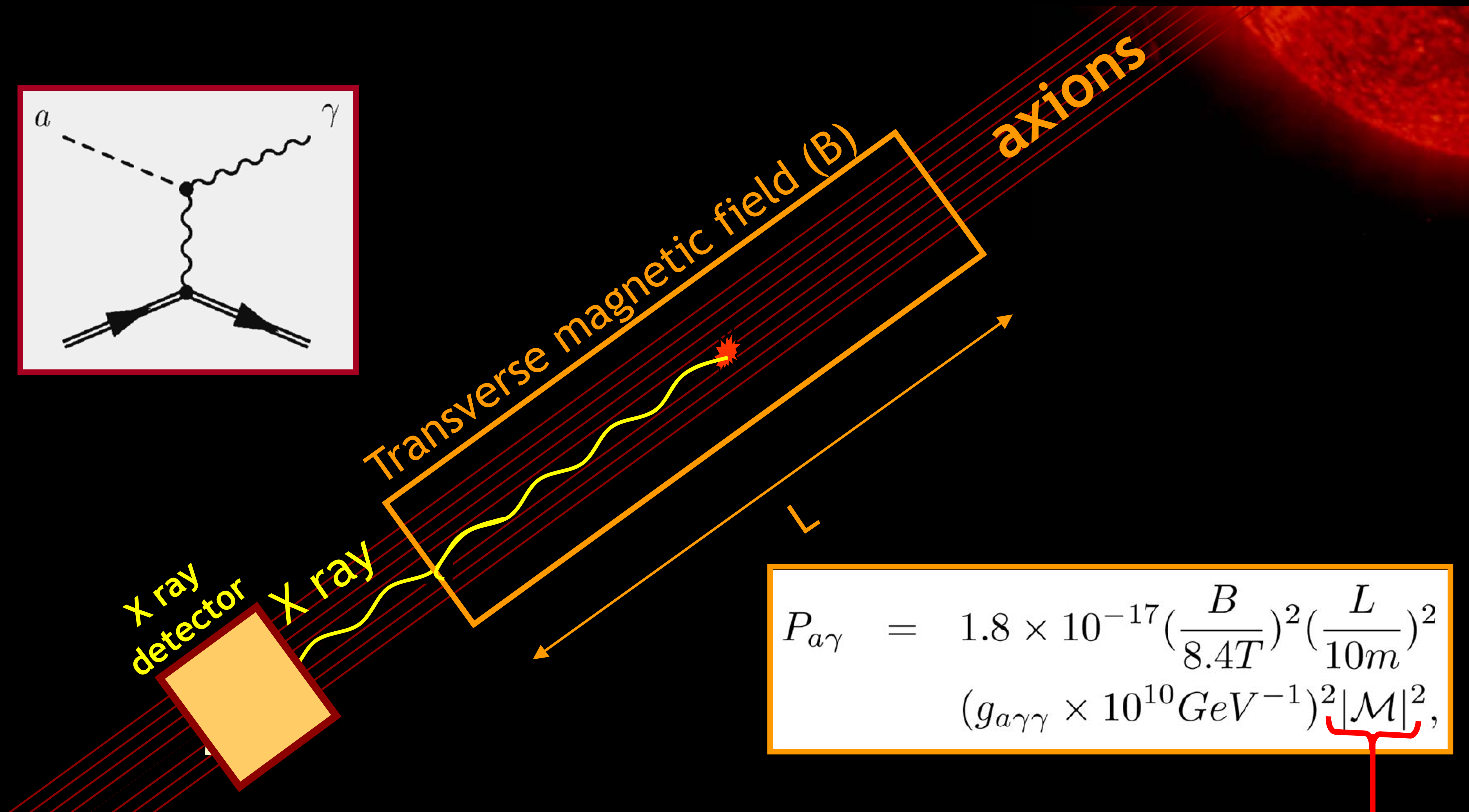

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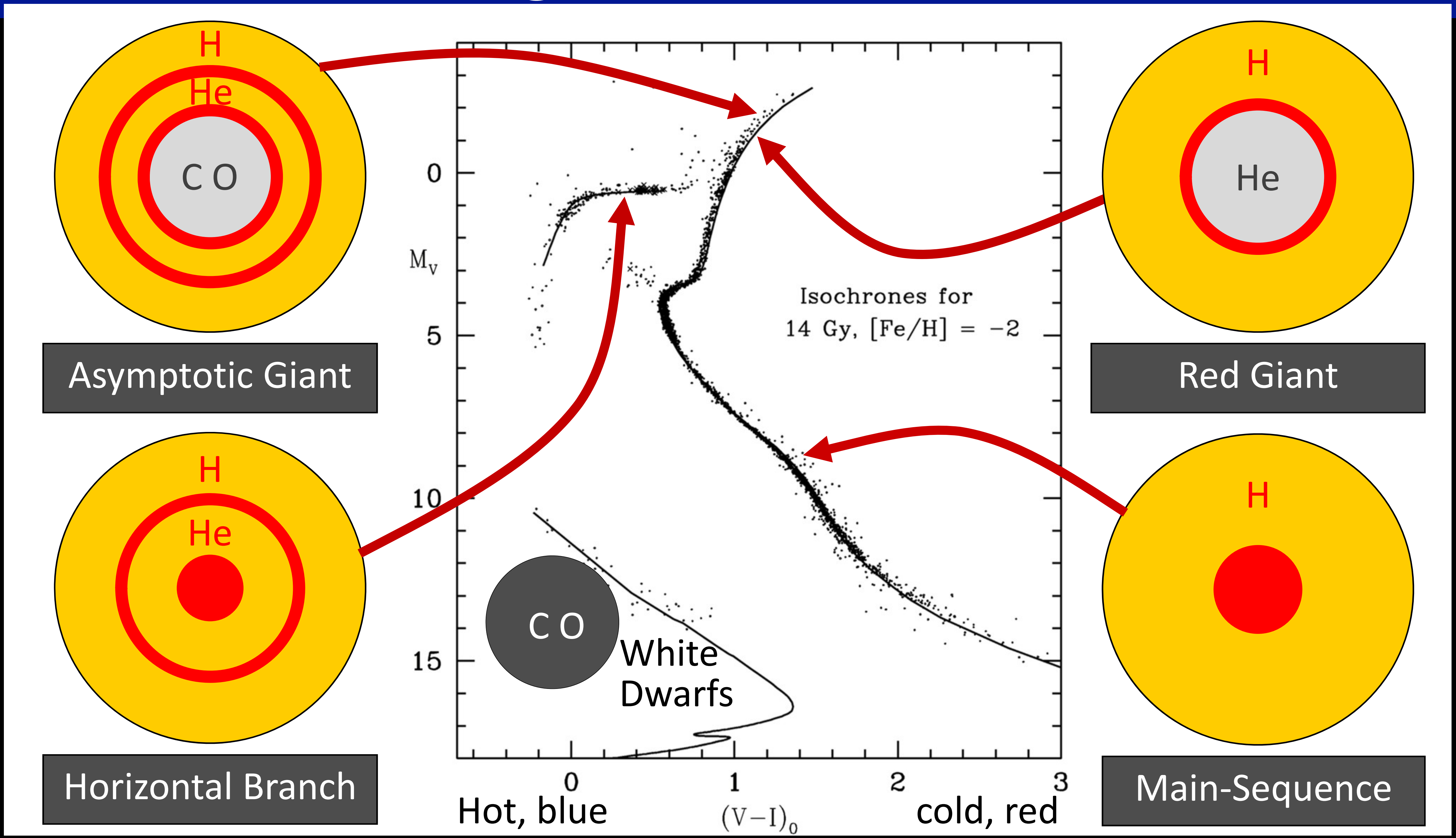
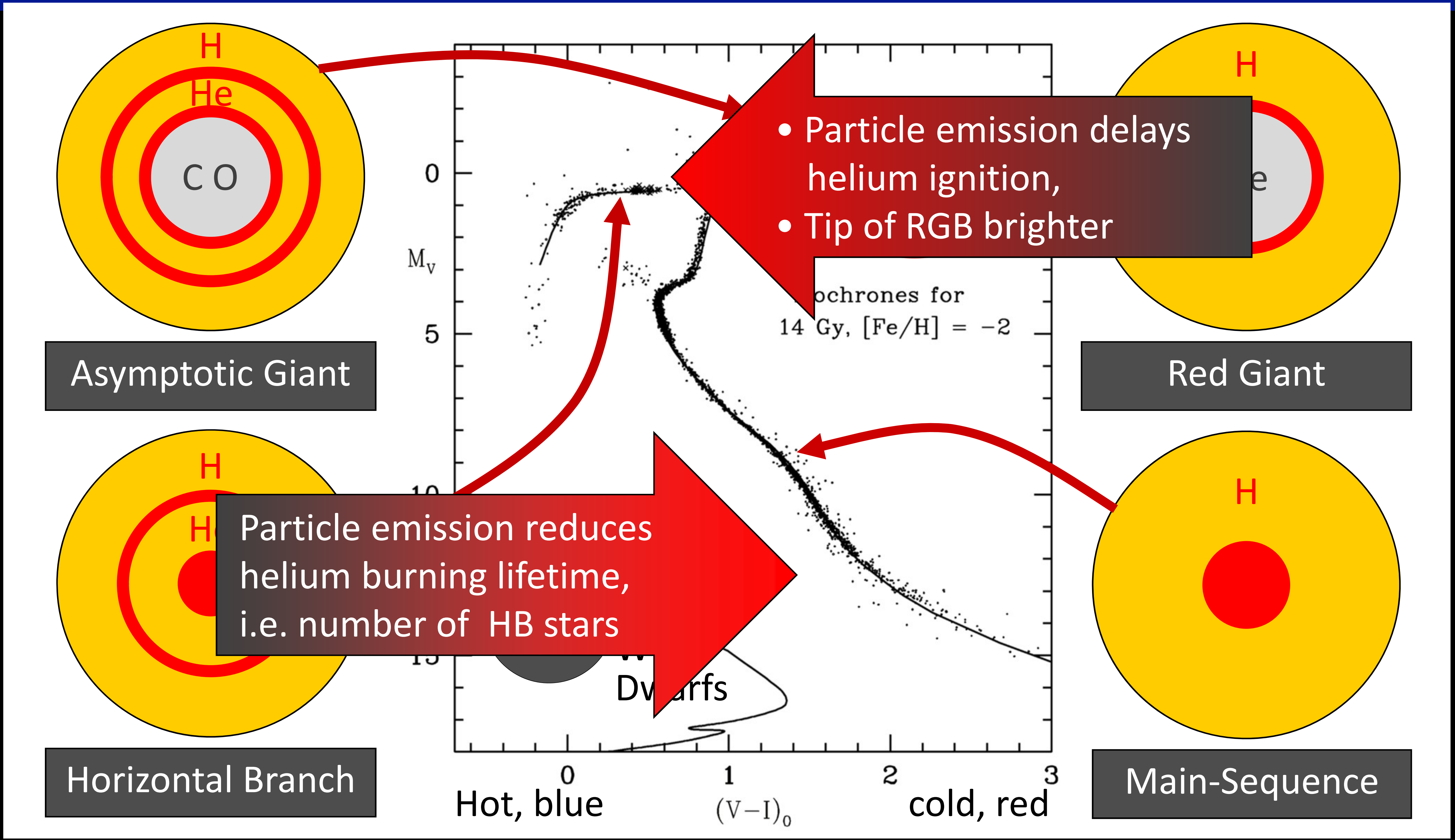
Making axions in stars, II



From Raffelt 2012

$$g_{a\gamma\gamma} \lesssim 10^{-10}\ \mathrm{GeV}^{-1}$$

Making axions in stars, II



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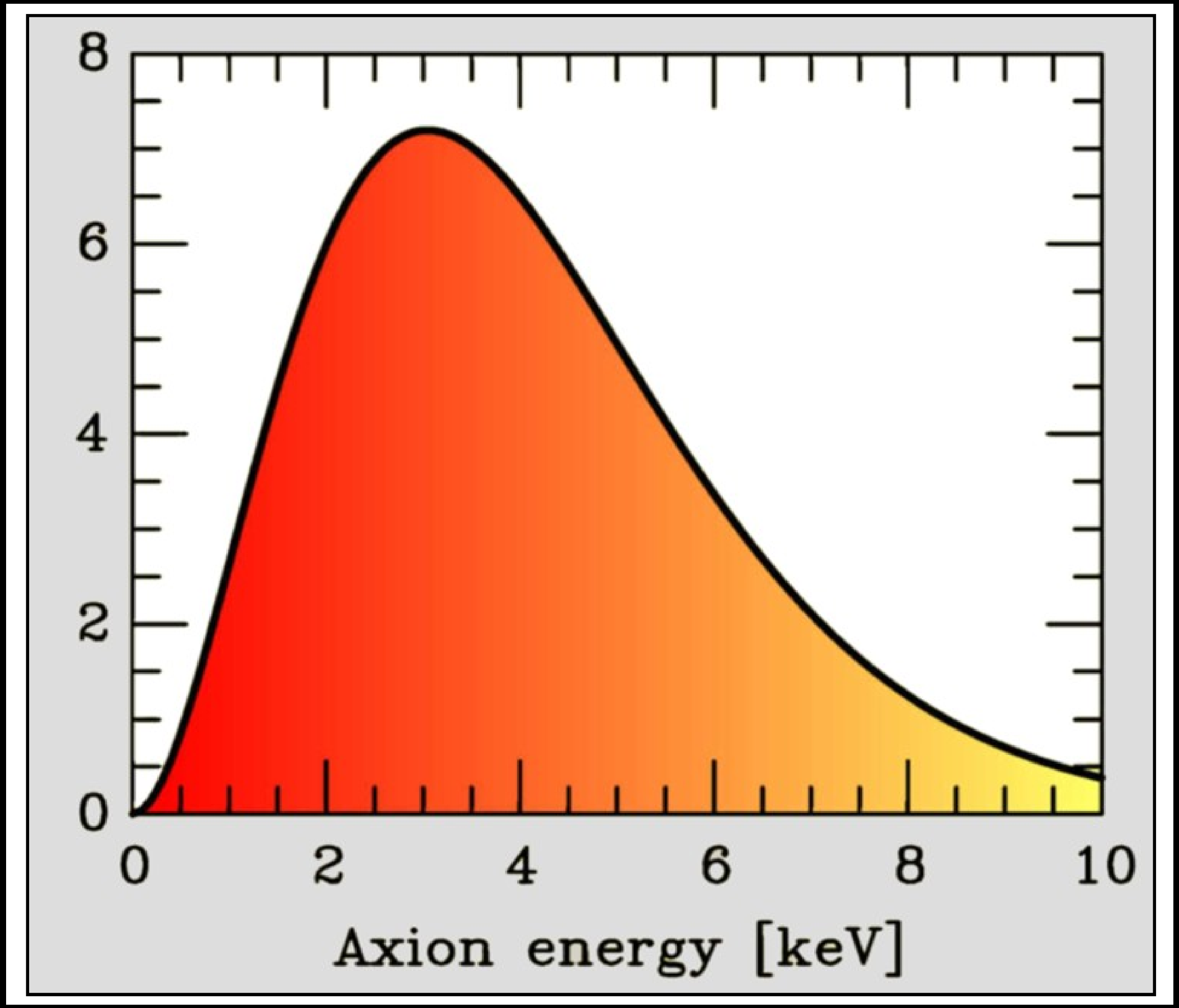

CAST/IAXO

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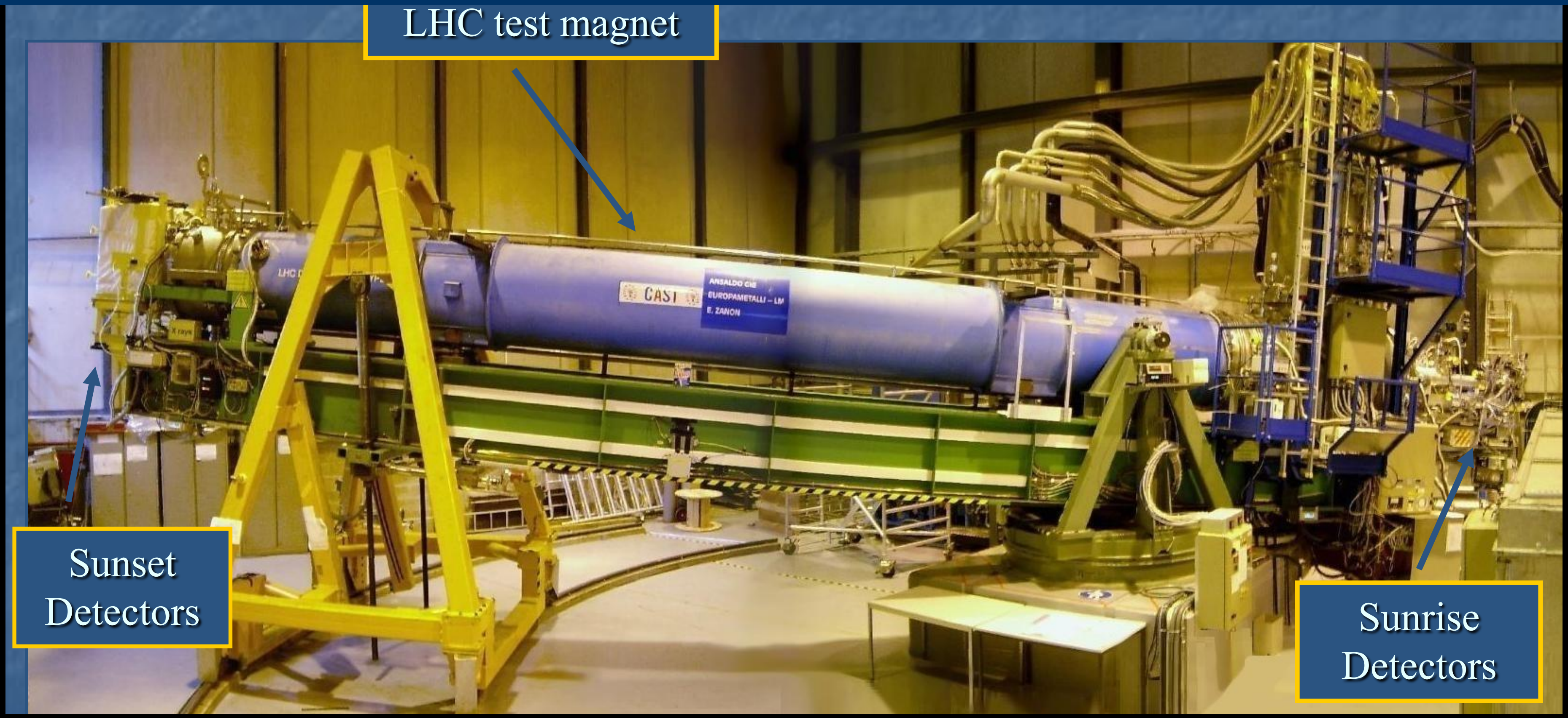

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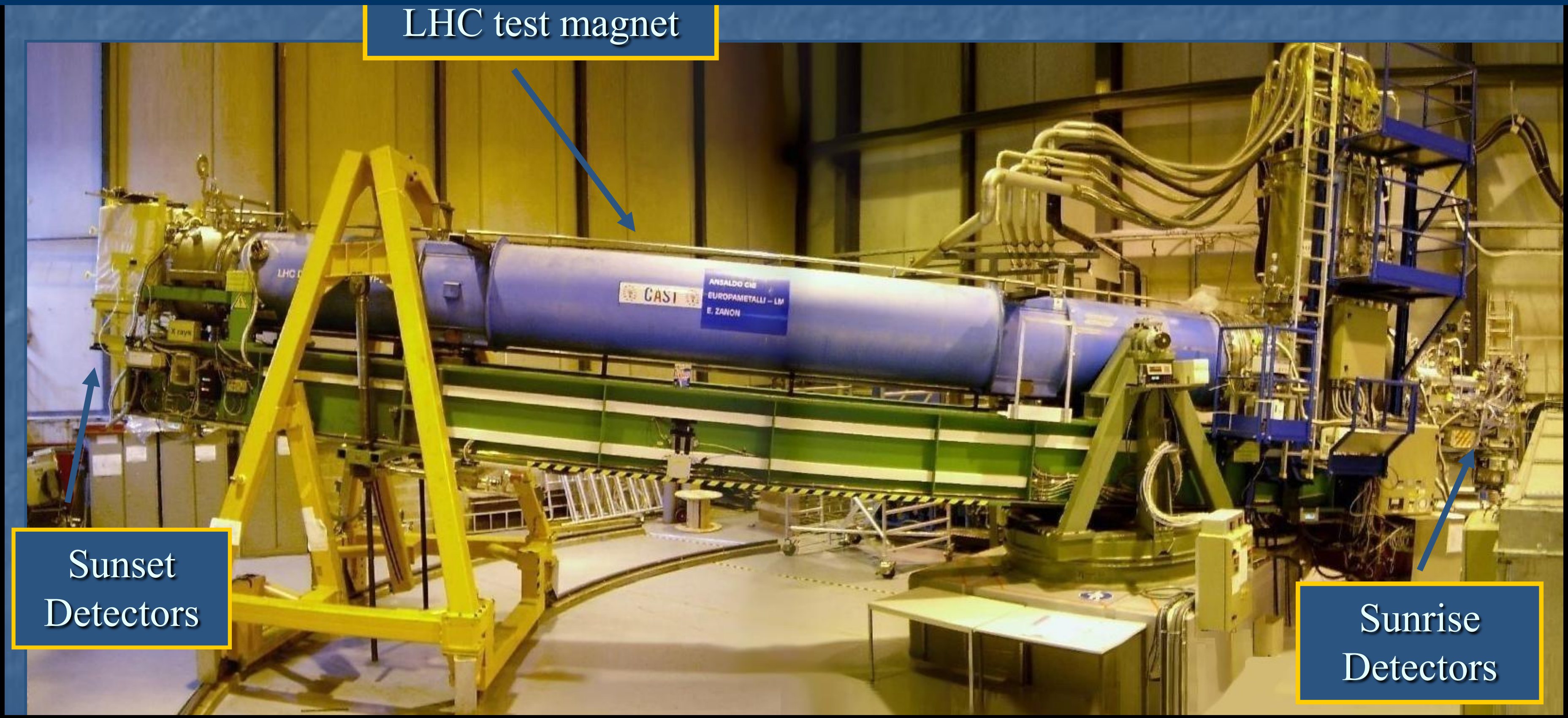

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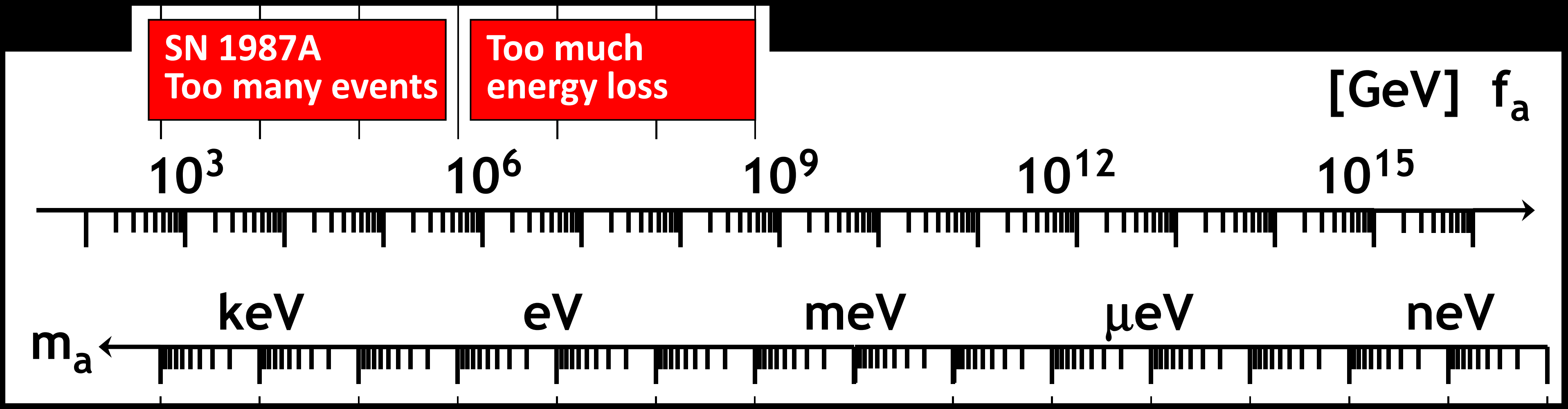
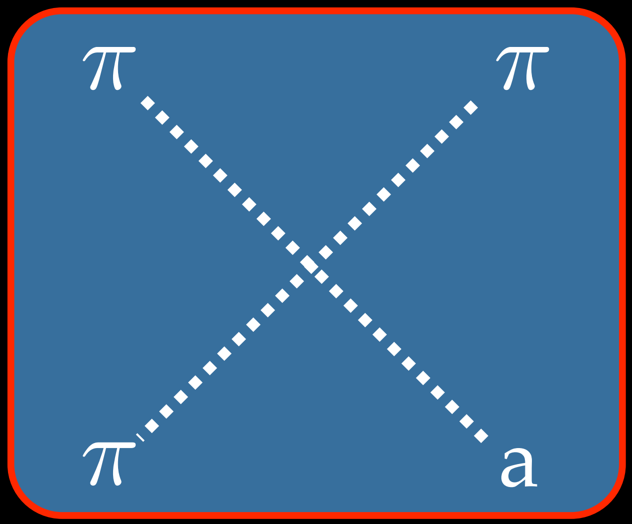
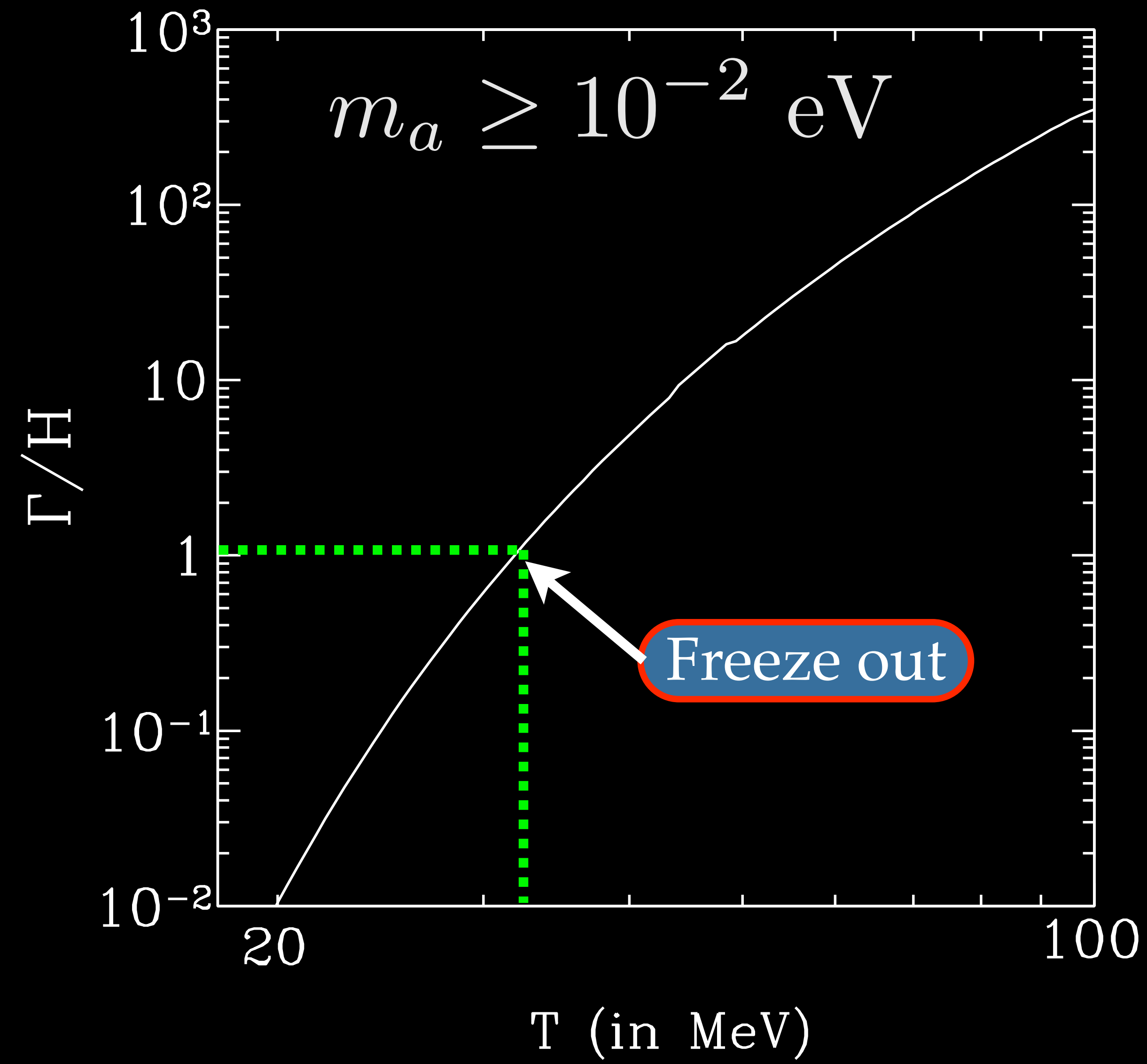


Hot axion production at early times

Axion Production:



$$\Omega_{\rm a} h^2 = \frac{m_{\rm a,eV}}{130}\left(\frac{10}{g_{*,\rm F}}\right)$$



- Axions produced through interactions between non-relativistic pions in chemical equilibrium with rate

Axion hot dark matter

- Axion free-streaming length

$$\lambda_{\rm fs} \simeq \frac{196\ \mathrm{Mpc}}{m_{\rm a,eV}}$$

- Entropy generation, e.g. modulus decay

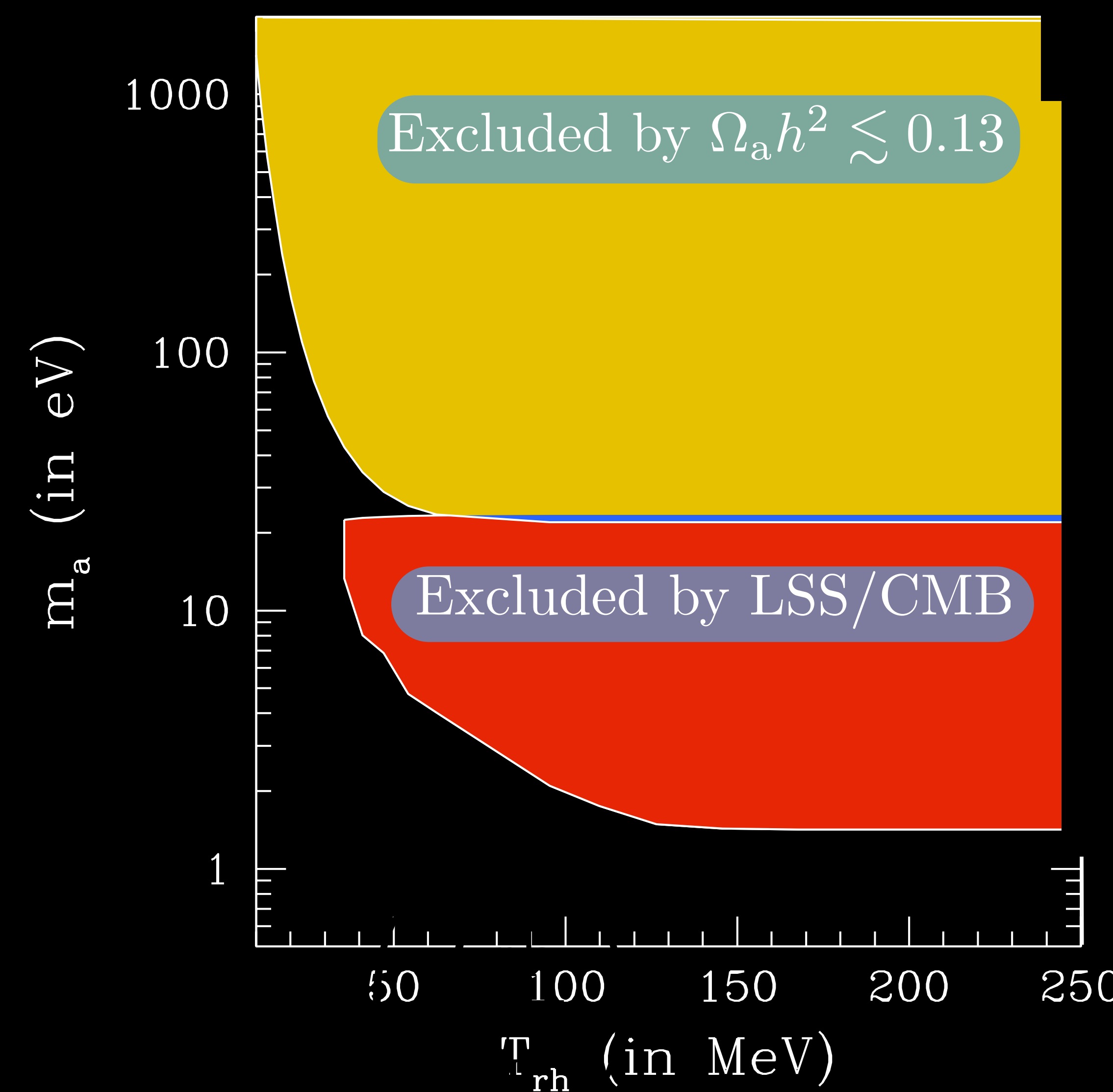
$$T_{\rm rh} \sim 10\ \mathrm{MeV} \left(\frac{m_\phi}{\mathrm{TeV}}\right)^{3/2}$$

- Axion temperature lowered

$$\frac{T_{\rm a}}{T_\nu} \propto \left(\frac{T_{\rm rh}}{T_{\rm F}}\right)^{5/3}$$

- Free streaming-length modified

$$\lambda_{\rm fs} \simeq \frac{196\ \mathrm{Mpc}}{m_{\rm a,eV}} \left(\frac{T_{\rm a}}{T_\nu}\right)$$



with T.L. Smith and M. Kamionkowski
Phys. Rev. D77 085020, 0711.1342

$$\Omega_a \to \Omega_a \left(\frac{T_{\rm rh}}{T_{\rm F}}\right)^5$$

A new telescope search for decaying relic axions

with K.Z. Khor, M. Kamionkowski, E.Jullo, G.Covone, J.P-Kneib

Axion HDM: Decay line

- Monochromatic emission line:

$$\lambda = \frac{c}{m_a c^2/2h} = 24800\mathring{A}\ \frac{(1+z_c)}{m_a/\ \mathrm{eV}}$$

- Axions decay:

$$\tau = 6.8 \times 10^{24} \xi^{-2} m_{a,\mathrm{eV}}^{-5}\ \mathrm{s}$$

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- Monochromatic emission line:

$$\lambda = \frac{c}{m_a c^2/2h} = 24800\mathring{A}\,\frac{(1+z_c)}{m_a/\text{ eV}}$$

Visible

- Axions decay:

$$\tau = 6.8 \times 10^{24} \xi^{-2} m_{a,\mathrm{eV}}^{-5} \text{ s}$$

Following in the footsteps of Ressell, Bershady, Turner 1991

Axion HDM: Galaxy clusters

✳ Galaxy clusters are huge axion reservoirs

$$N_{\rm ax} = 10^{80} m_{a,\rm eV}^{-1} \ !$$

✳ Reasonably wide line $\sigma_{1000} \sim 1$

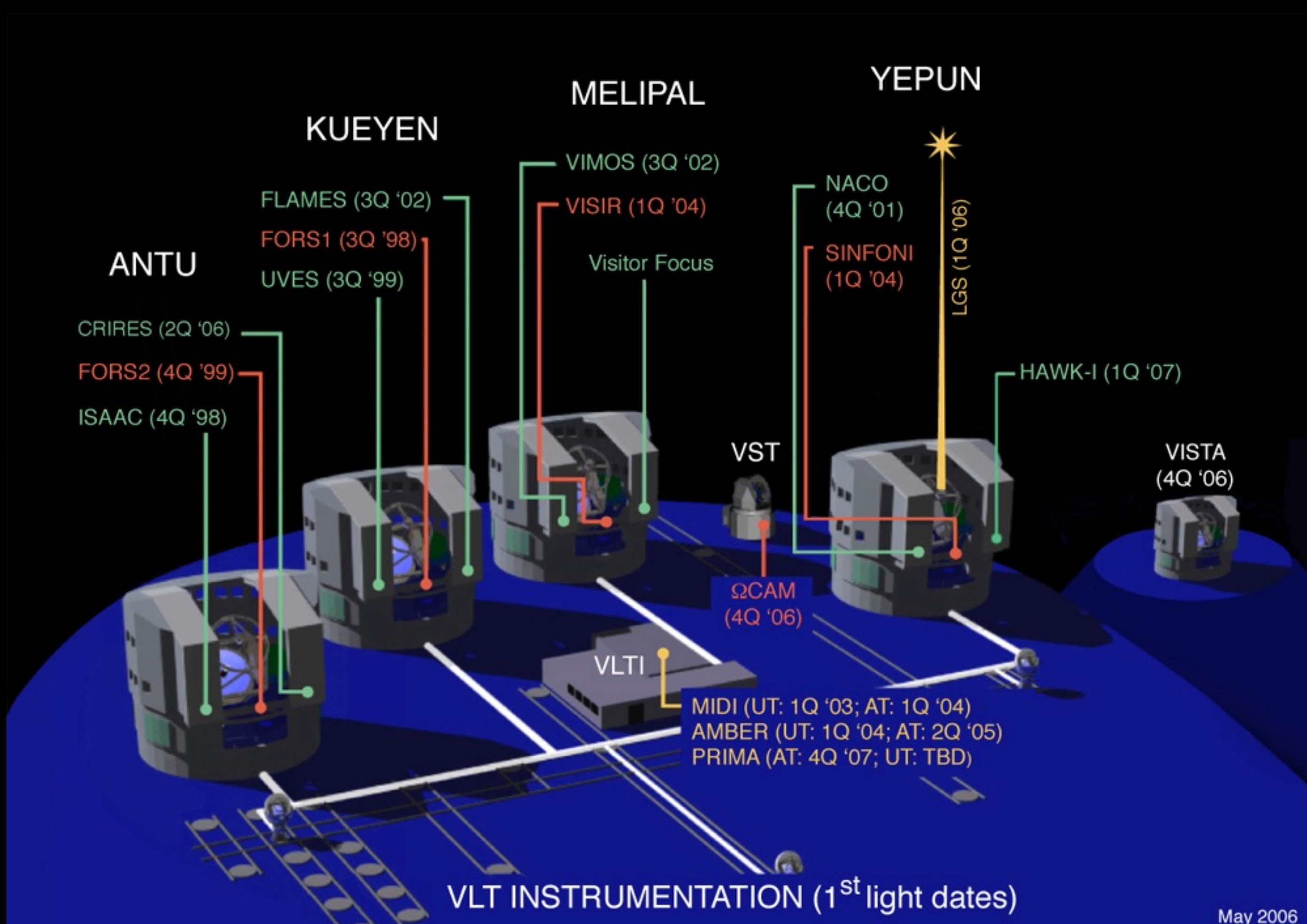
✳ Strong/weak gravitational lensing mass maps available

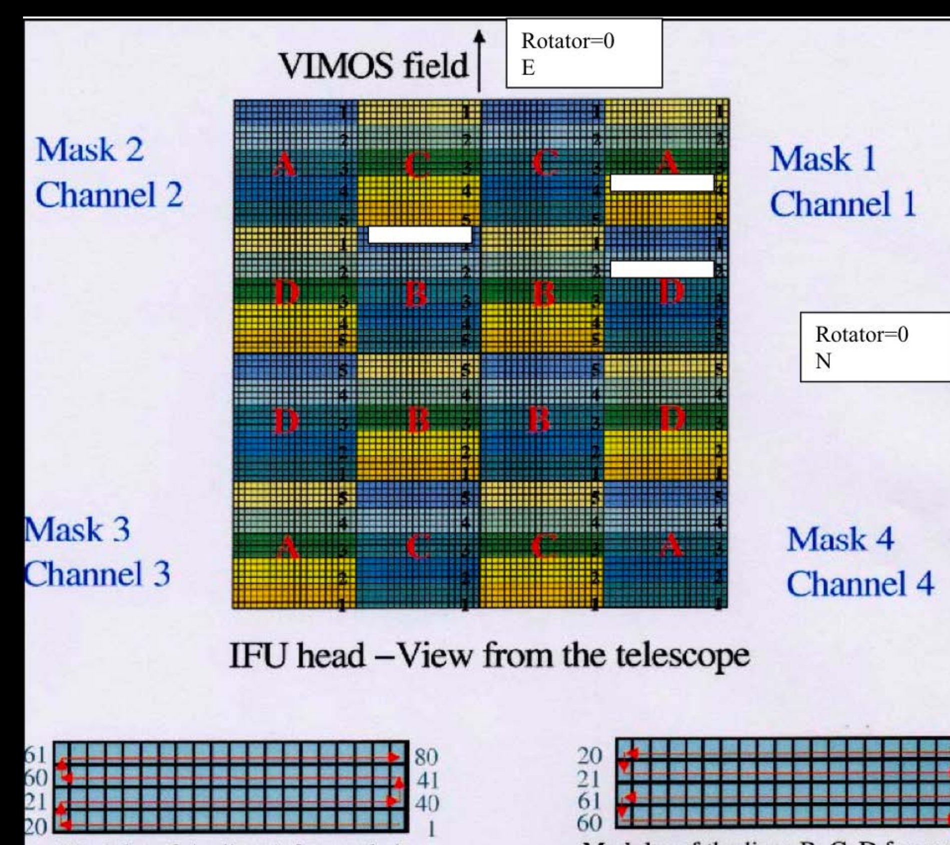
✳ Comparable to sky brightness

$$I_\lambda \simeq 10^{-18} \ \mathrm{cgs} \frac{\mathrm{m}_{\mathrm{a,eV}}^7 \xi^2}{(1+\mathrm{z_c})^4} \frac{\Sigma}{10^{12}\mathrm{M}_\odot \mathrm{pix}^{-2}}$$

Axion HDM: VIMOS IFU

- At VLT (Very Large Telescope) array of ~8 m instruments at Paranal, Chilé
- VIMOS IFU yields spatially resolved spectroscopy (6400 fibers in 1 arcmin²)





Axion HDM: Modern optical telescope searches

- RDCS 1252 is a $8 \times 10^{14} M_\odot$ cluster at $z = 1.237$
- Obtained 17 hrs of time for VIMOS IFU spectra using LR-Blue grism
- Publicly available weak-lensing mass maps (Lombardi et al. 2005) + single confirmed SL arc

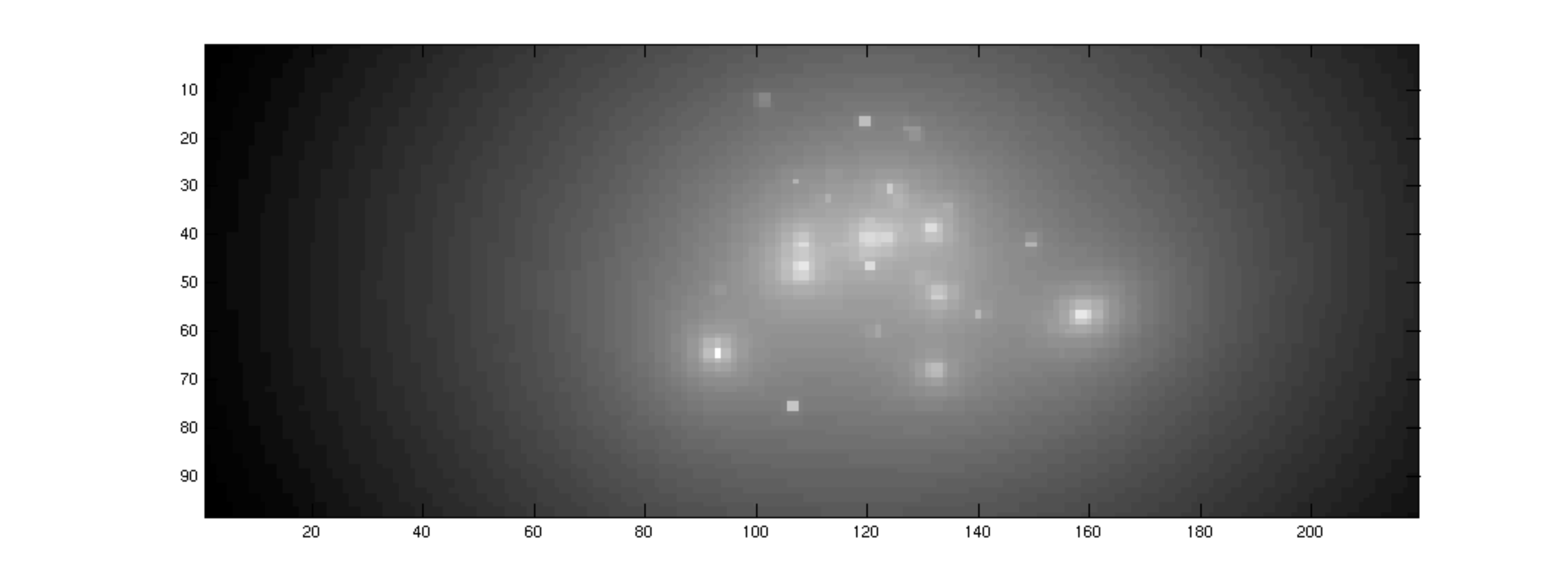
Axion HDM: Modern optical telescope searches

Axion HDM: Modern optical telescope searches

Grin et al. 2007: Abell 2667/2390 PRD, astro-ph/0611502

K.Z. Khor (Princeton Class of 2014)

Axion HDM: Cluster mass maps and



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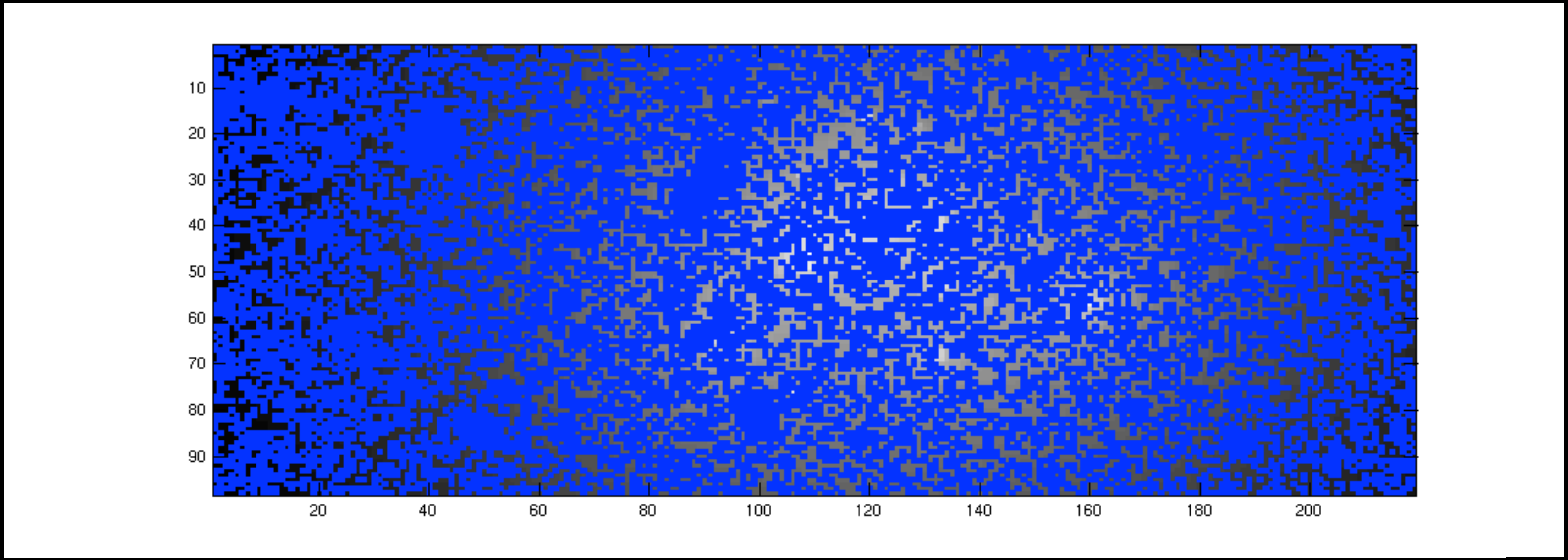

Axion HDM: RDCS 1252/A2667+A2390

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astro-ph/0611502, Phys.Rev.D75:105018,2007

+manuscript in progress

Axion HDM: RDCS 1252/A2667+A2390

astro-ph/0611502, Phys.Rev.D75:105018,2007

+manuscript in progress

Axion HDM: RDCS 1252/A2667+A2390

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astro-ph/0611502, Phys.Rev.D75:105018,2007

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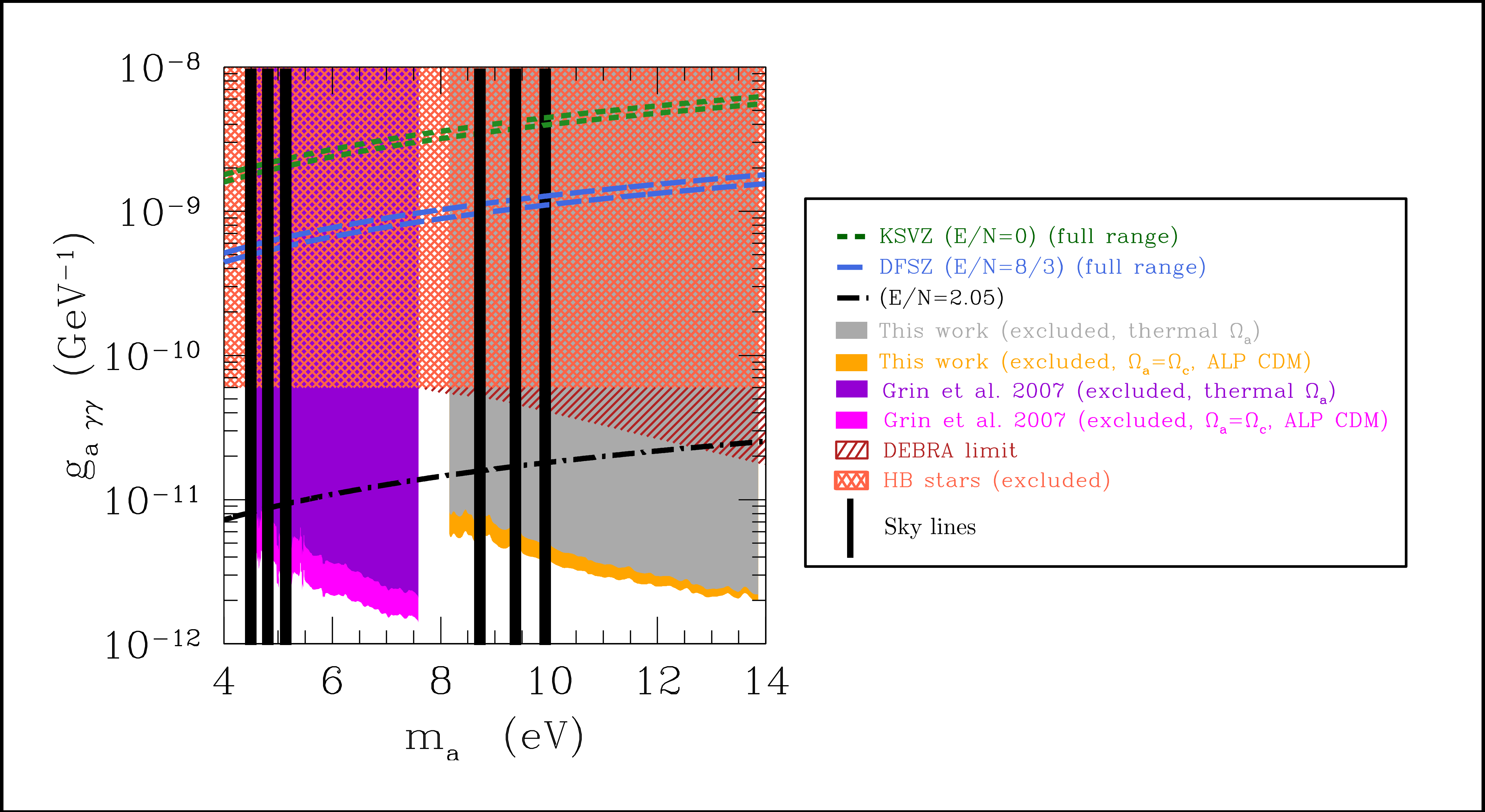
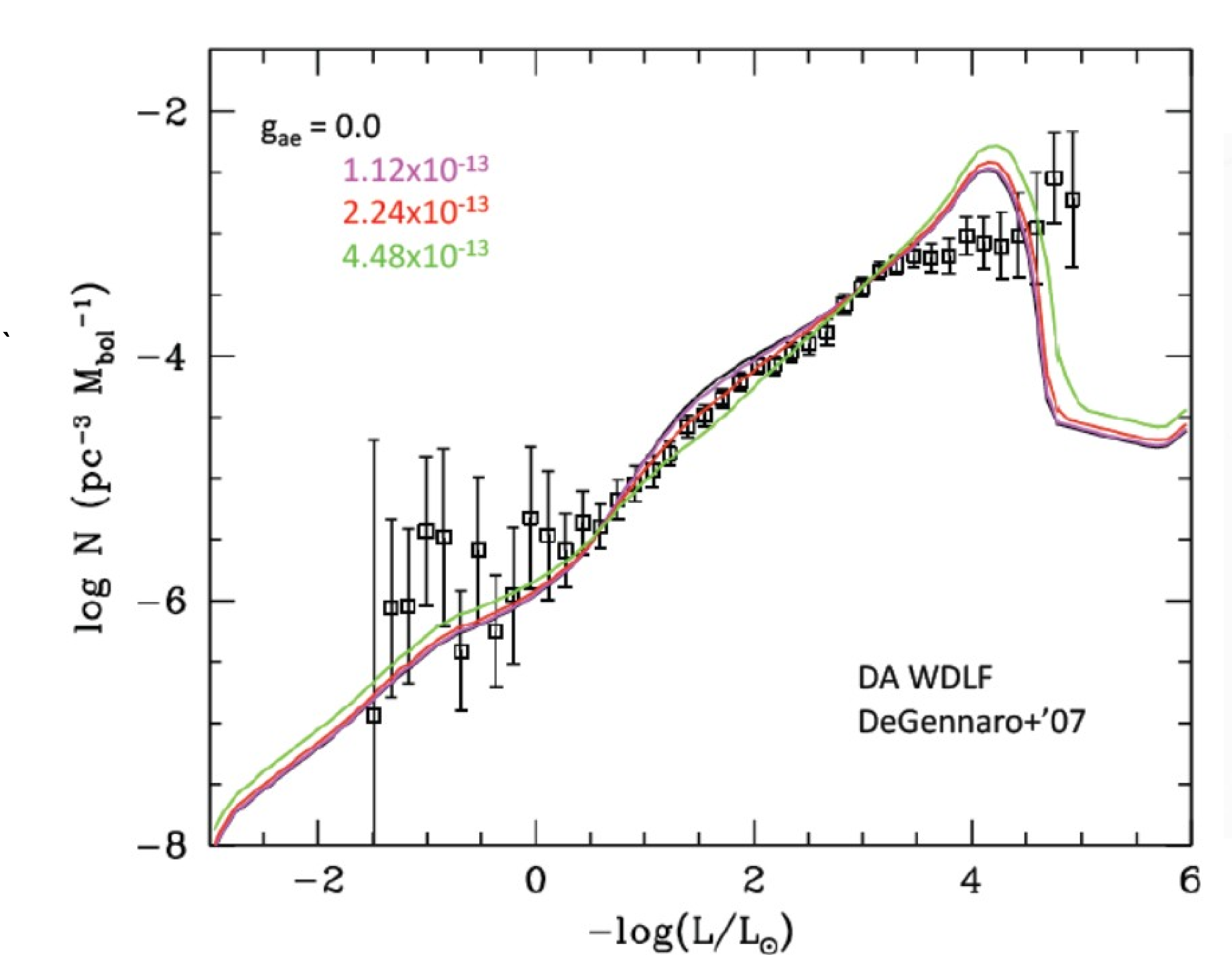


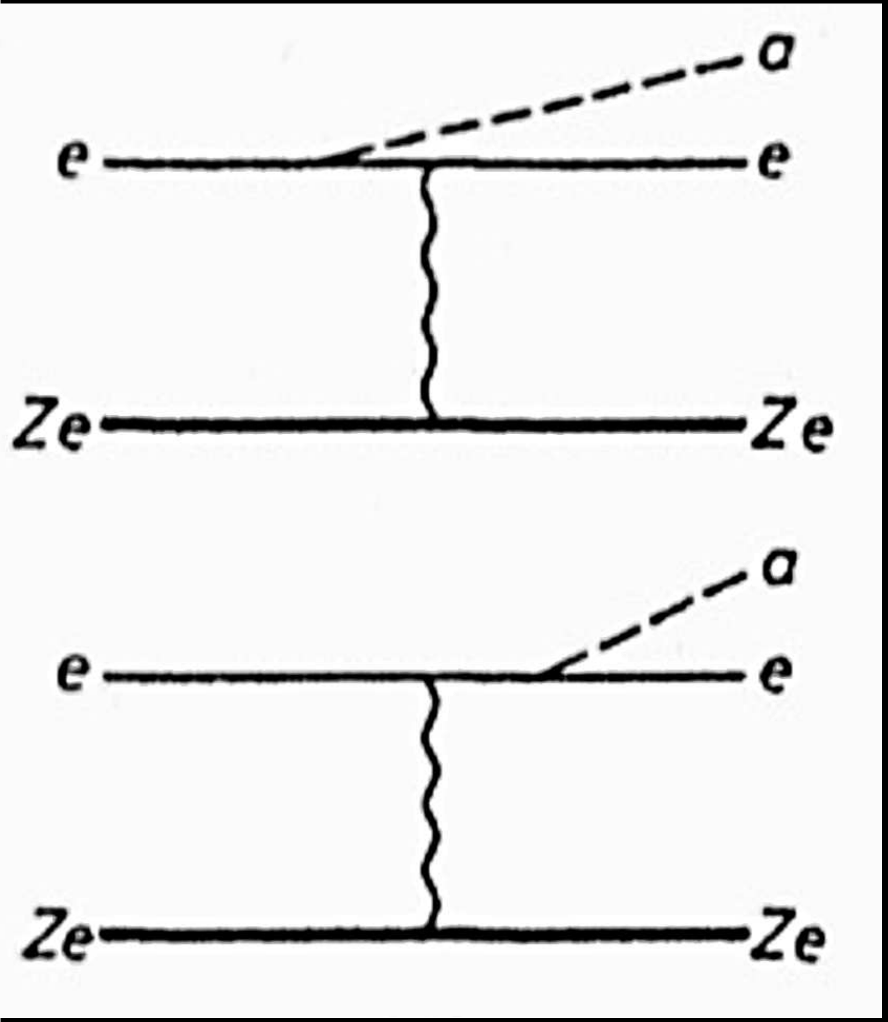
astro-ph/0611502, Phys.Rev.D75:105018,2007

+manuscript in progress

Making axions in degenerate stars, IV

- WDs are remnants of $1\ M_\odot$ main – sequence stars
- Axio-electric coupling provides additional cooling channel





Axion HDM: Decay line

- Monochromatic emission line:

$$\lambda = \frac{c}{m_a c^2/2h} = 24800\mathring{A}\ \frac{(1+z_c)}{m_a/\ \mathrm{eV}}$$

- Resolvable $\delta\lambda = 195\sigma_{1000} m_{a,\mathrm{eV}}^{-1} \mathring{A}$

- Axions decay:

$$\tau = 6.8 \times 10^{24} \xi^{-2} m_{a,\mathrm{eV}}^{-5}\ \mathrm{s}$$

- Axion thermal abundance

$$\Omega_{\mathrm{ax}} h^2 \simeq \frac{m_a}{130\ \mathrm{eV}}$$

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Following in the footsteps of Ressell, Bershady, Turner 1991

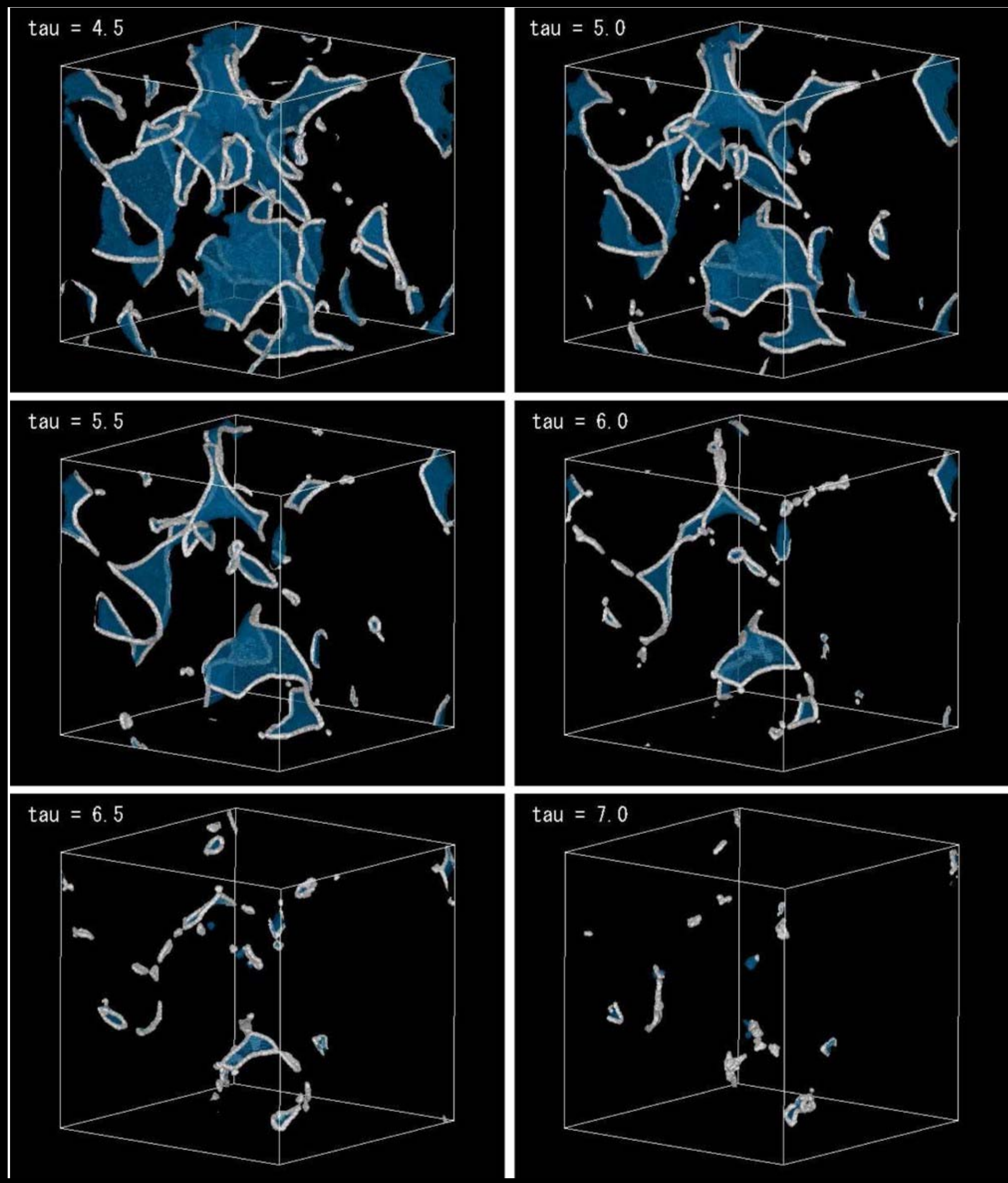
Classic axion window: $f_a < \max\{T_{\rm RH}, H_{\rm I}\}$

✳ Axion field is very inhomogeneous

$$\left\langle \overline{\theta}_i^2 \right\rangle = \frac{\pi^2}{6}$$

✳ Defects [domain walls, strings, etc..]

$$\mathcal{O}(1) \lesssim \alpha_{\rm defect} \lesssim \mathcal{O}(10^2)$$



✳ Abundance

$$\Omega_a h^2 \simeq 2.0\,\{1 + f_{\rm defect}\}\left(\frac{f_a}{10^{12}\ {\rm GeV}}\right)^{7/6}$$

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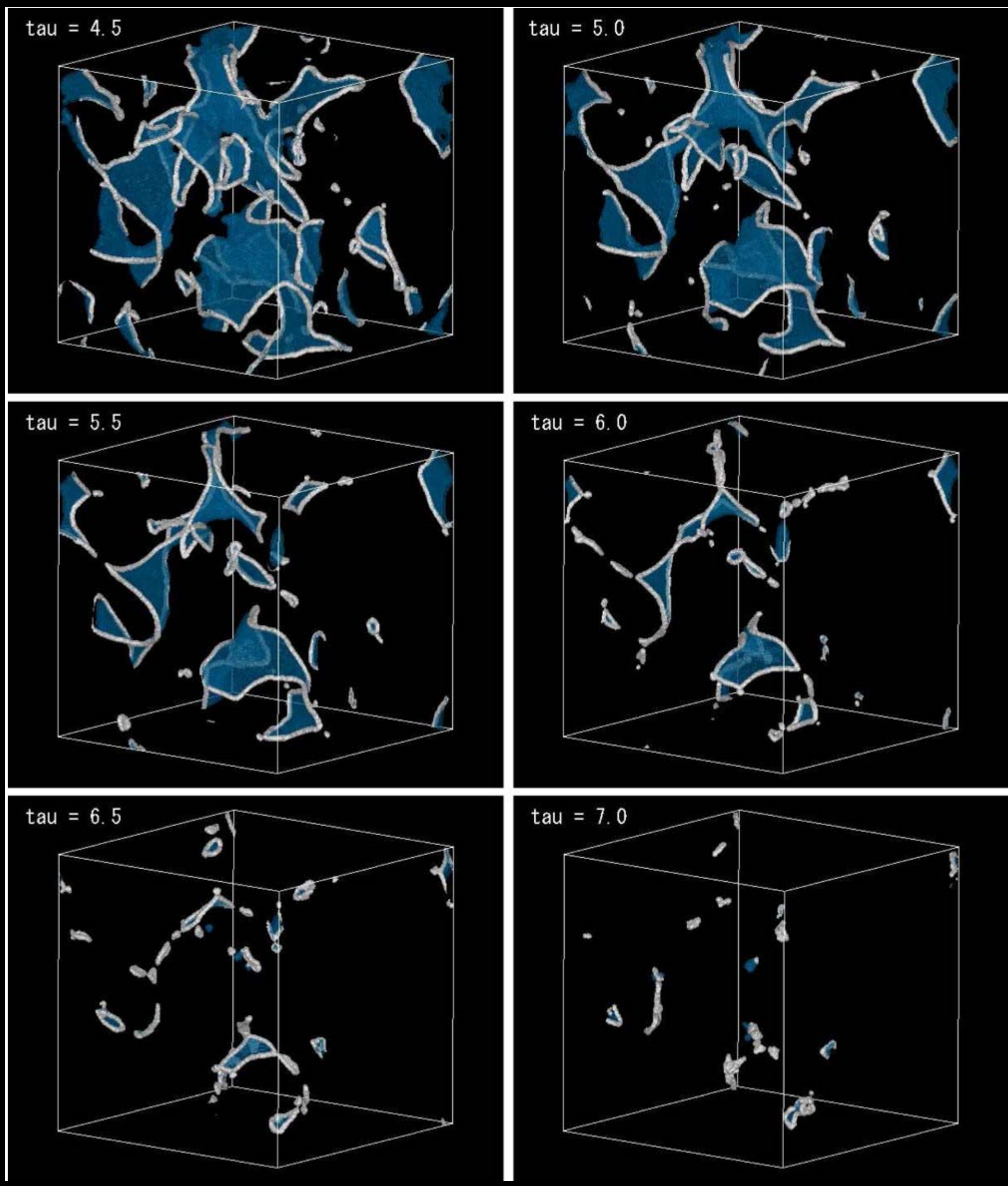
CONTROVERSY!



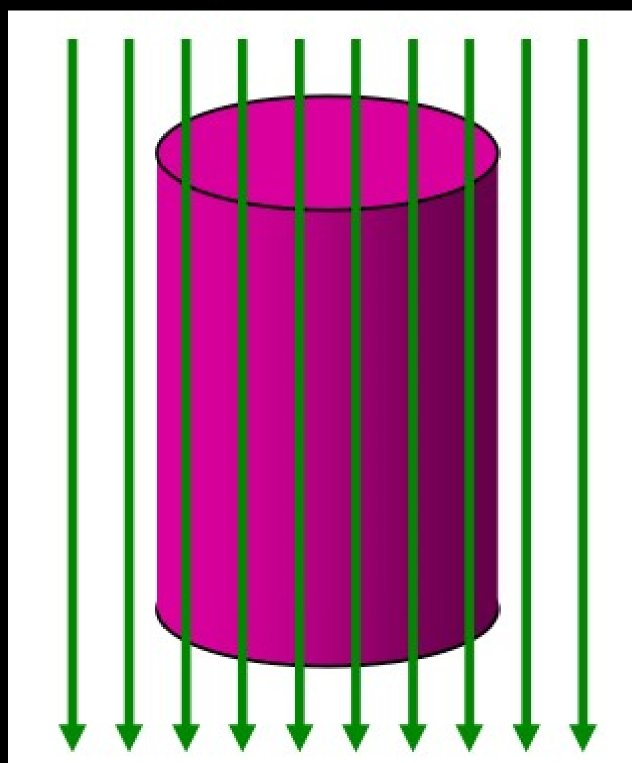
- ✳ Abundance

$$\Omega_a h^2 \simeq 2.0\,\{1 + f_{\mathrm{defect}}\}\left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{7/6}$$

Cavity searches [e.g. ADMX]

Images from Wong 2012

- Magnetized RF Cavity



- Axion excites cavity (TEM) modes [cavity must be tuned]

$$E_\gamma = m_\mathrm{a} c^2$$

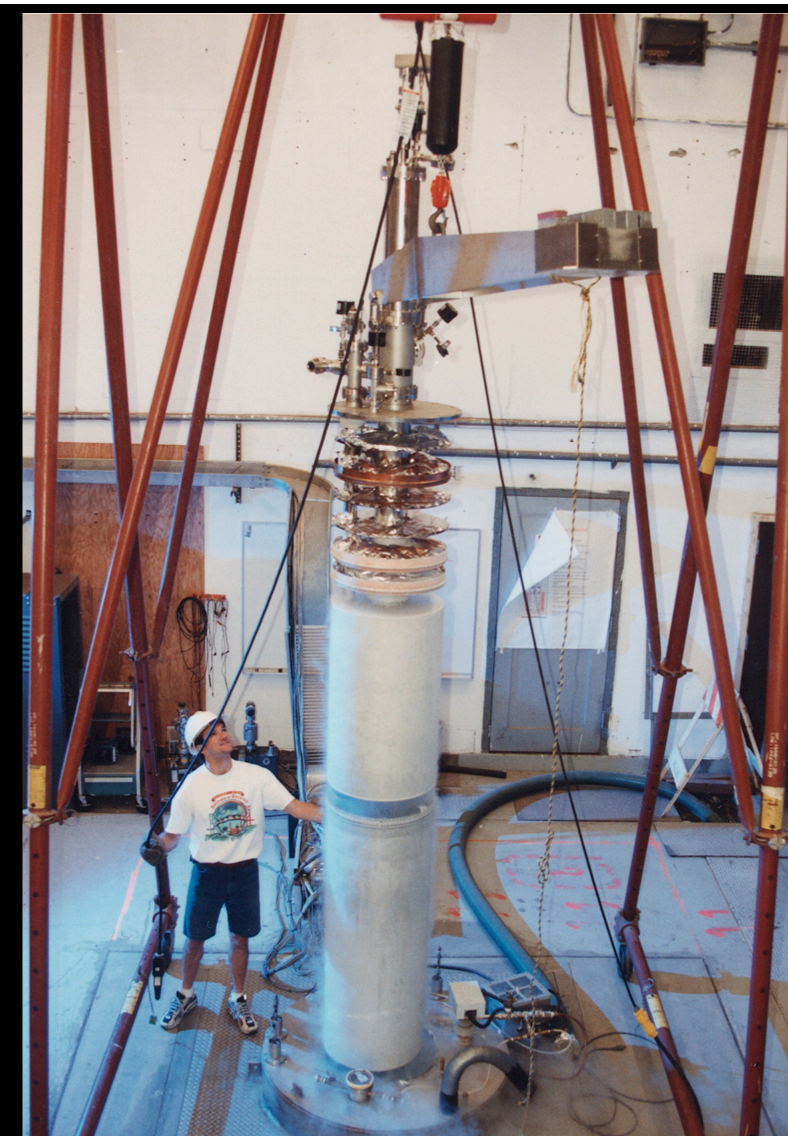
- Power

$$\mathrm{Power} = g_{a\gamma}^2 \frac{V B^2 \rho_a Q}{m_a} \sim 10^{-21}\ \mathrm{Watts}$$

Volume

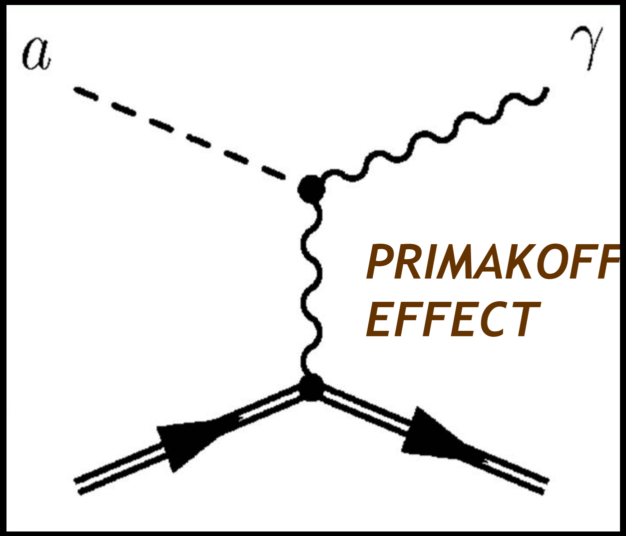
Quality factor

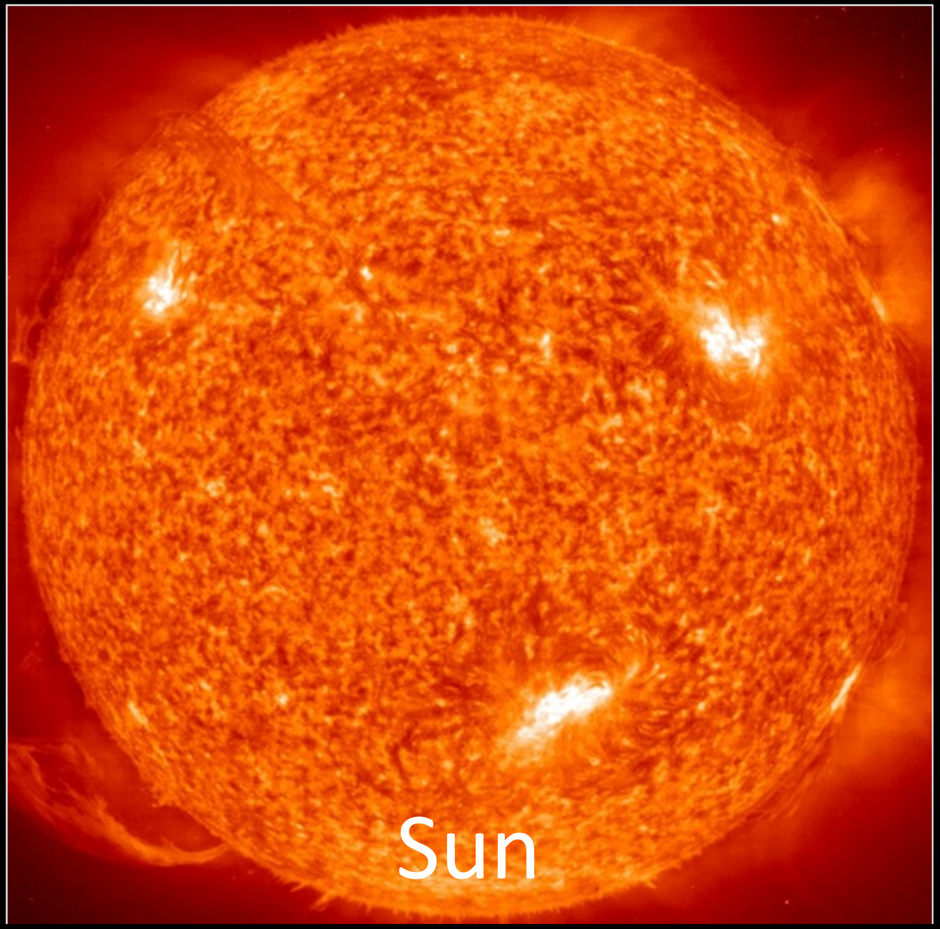
Axion energy density



Making axions in stars

- Primakoff process



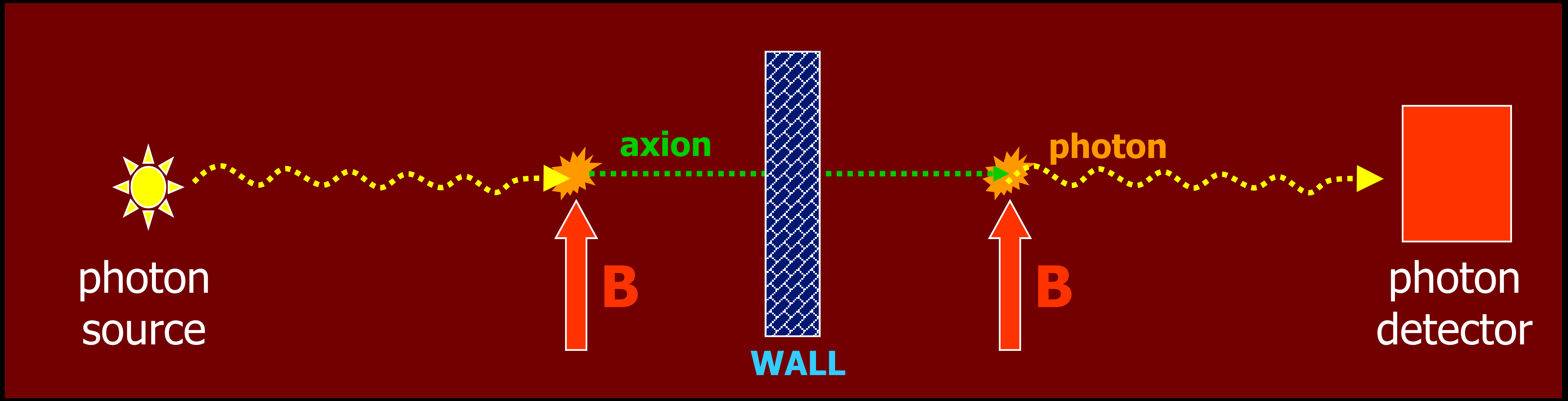


- Lifetime of our own sun/Solar luminosity/helioseismology impose constraint

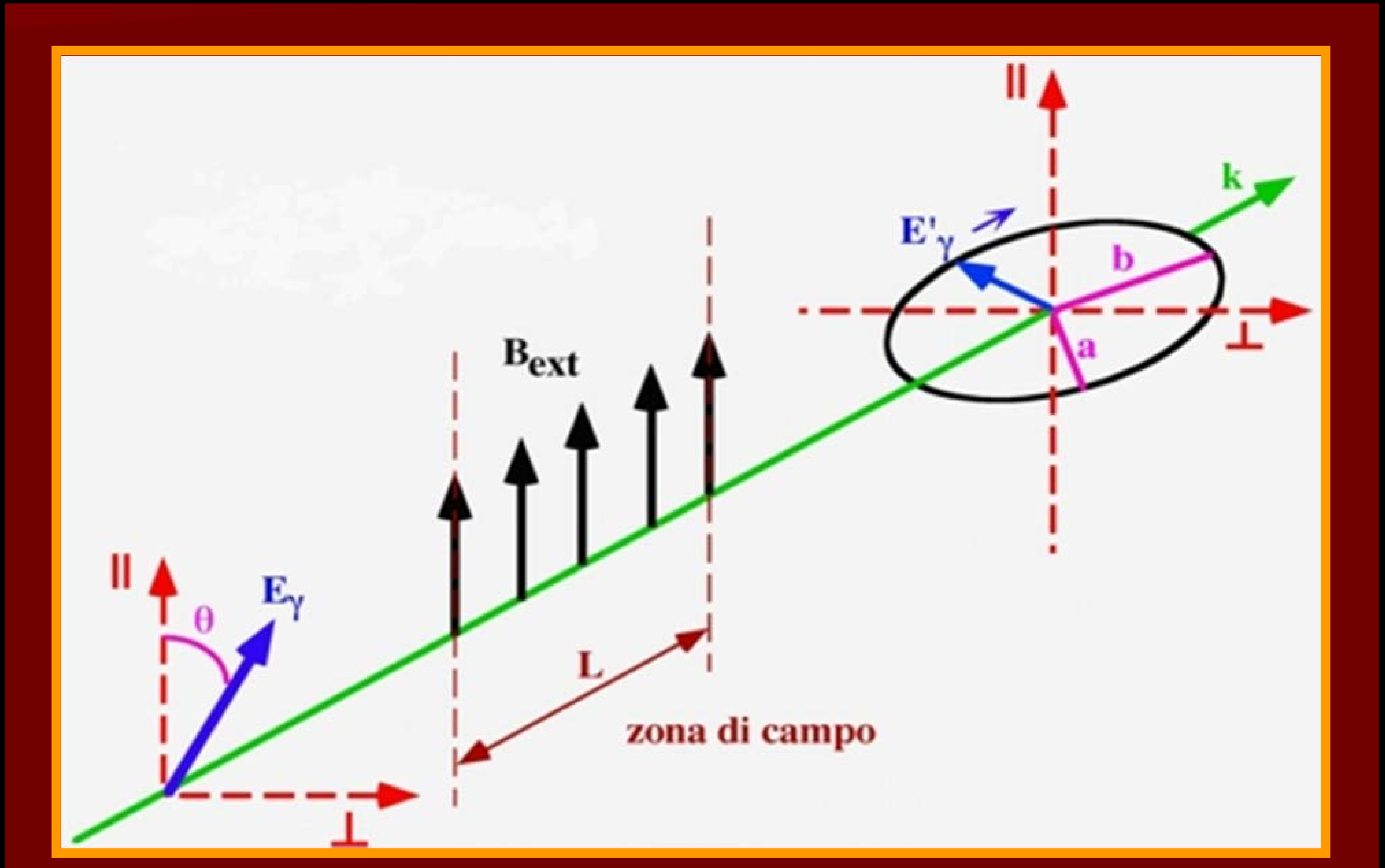
$$g_{a\gamma\gamma} \lesssim 1 - 3 \times 10^{-9}\ \mathrm{GeV}^{-1}$$

Laser experiments

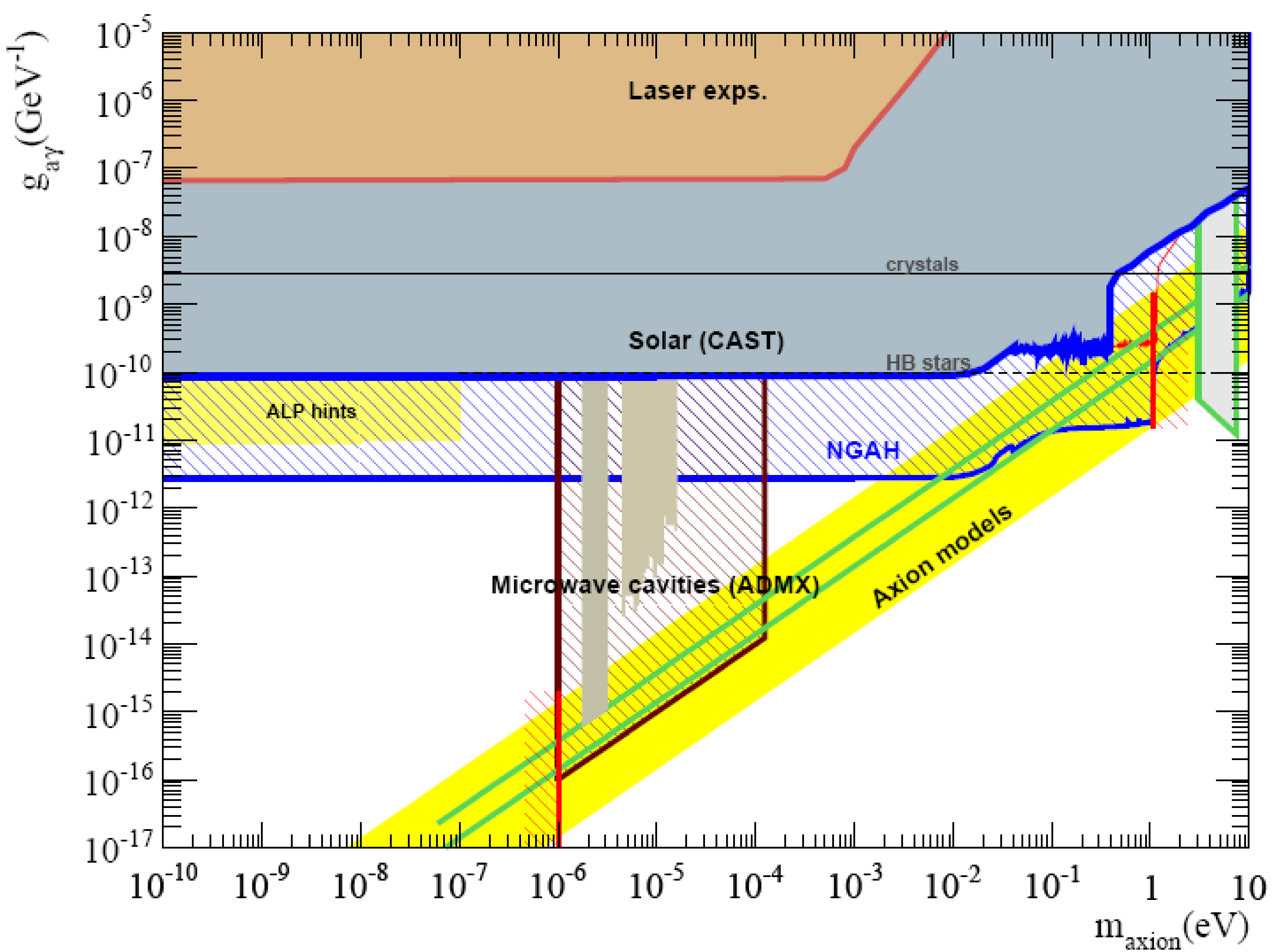
Light shining through walls (e.g. GammeV)



Polarization experiments (e.g. PVLAS)



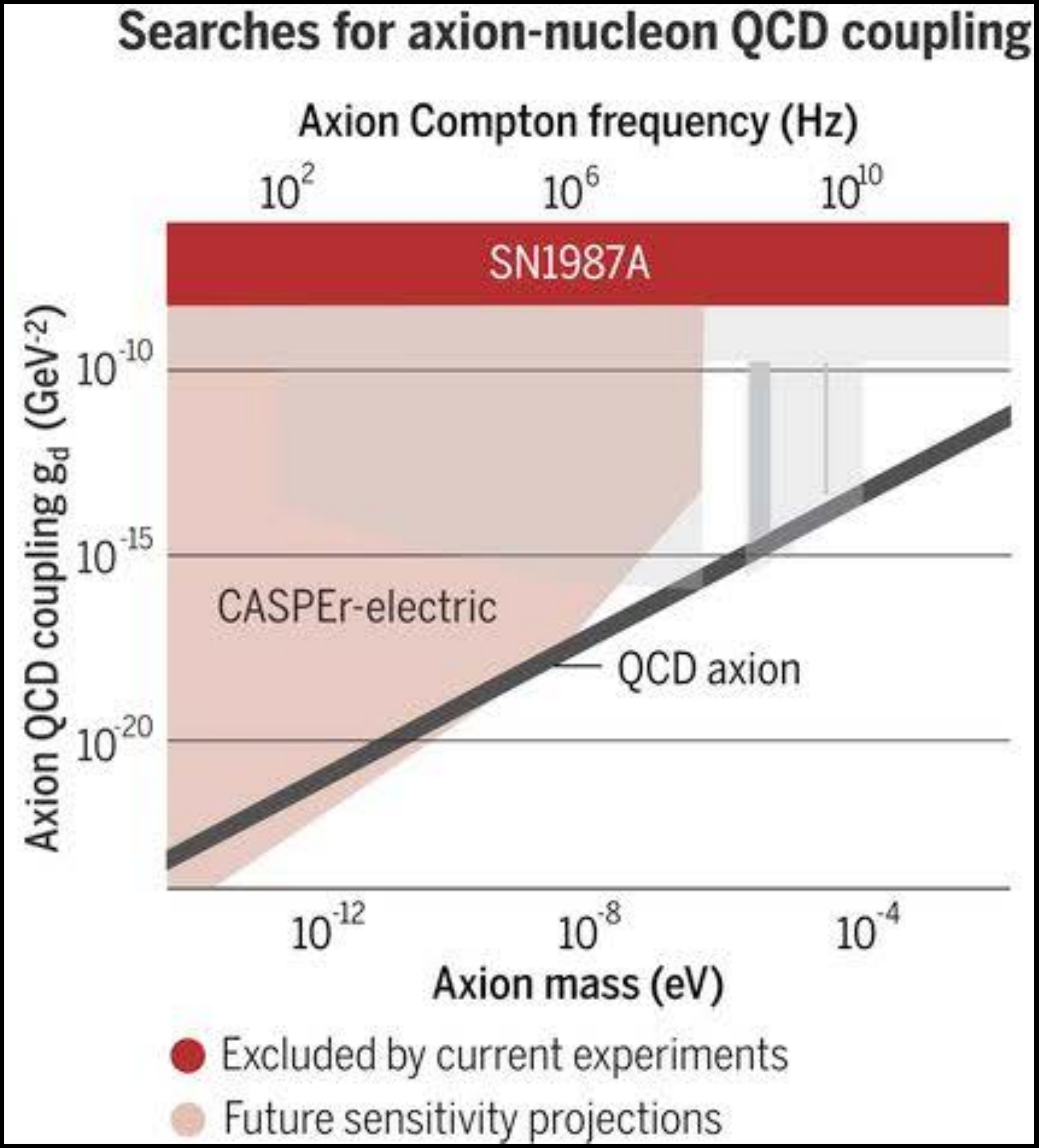
Limits and horizon

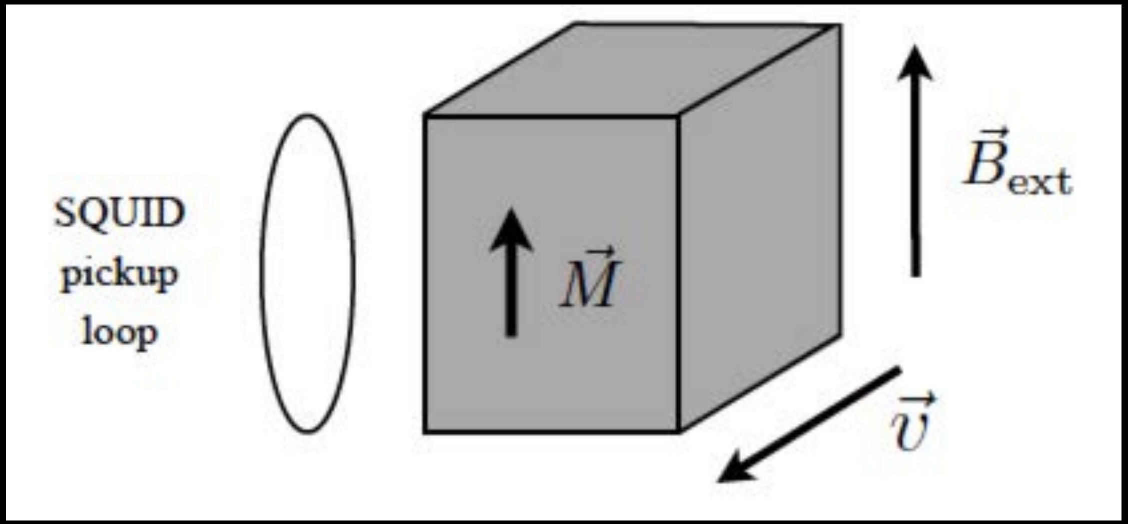


Other methods

- Spectra of magnetic white dwarves **[New]**
- Extragalactic background light
- Pulsating white dwarf seismology **[New]**
- Dimming of gamma-ray blazars **[New]**
- Two-photon decays in galaxy clusters
- Light degrees of freedom at BBN **[New]**
- Helioscope in space **[New]**
- Supernovae 1987a
- White dwarf luminosity function
- Oscillating electric dipole moments of nucleons **[NEW]**

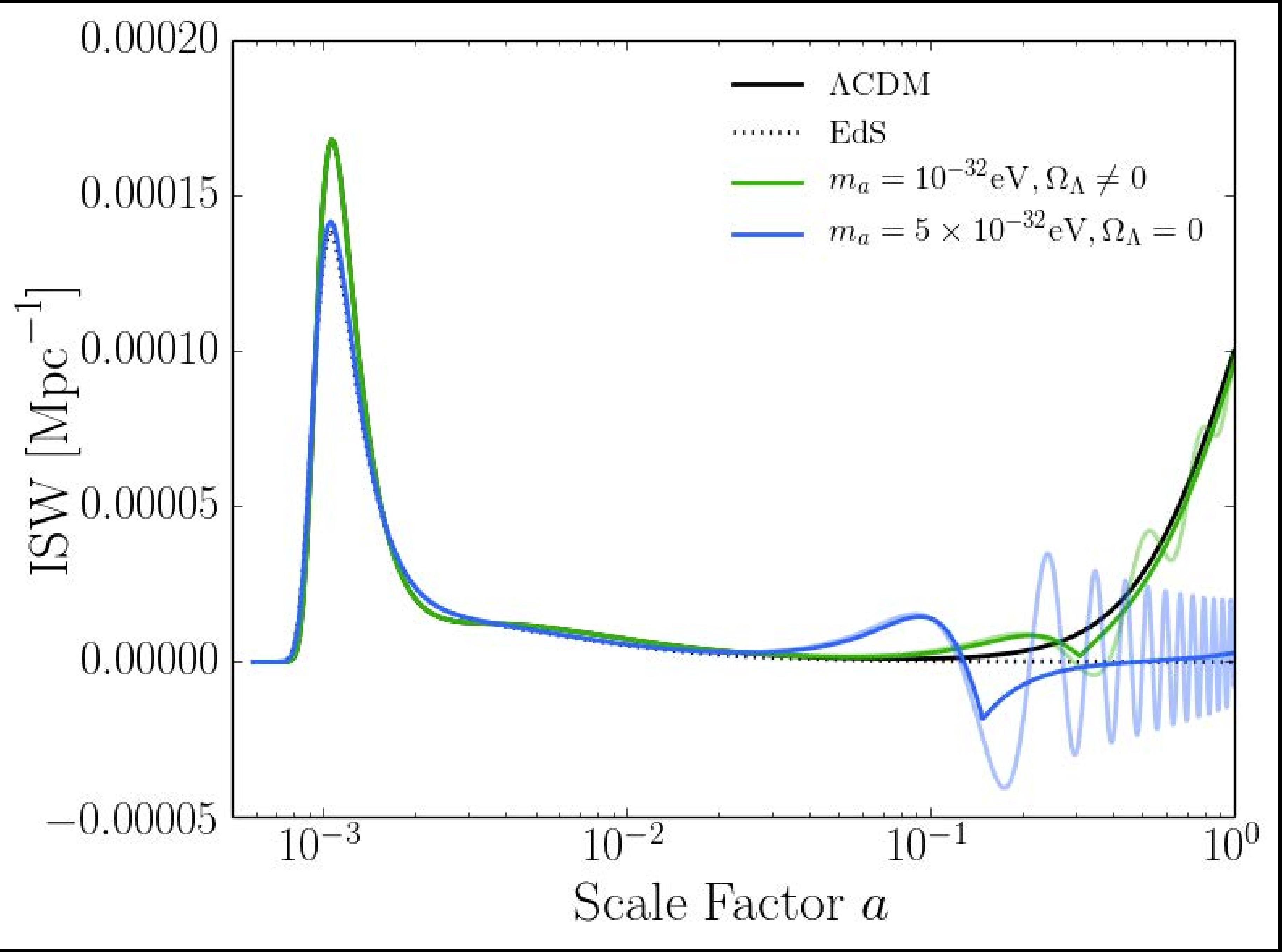
Demille, Doyle, Sushkov (Science 2017), idea of Graham and Rajendran (2014)





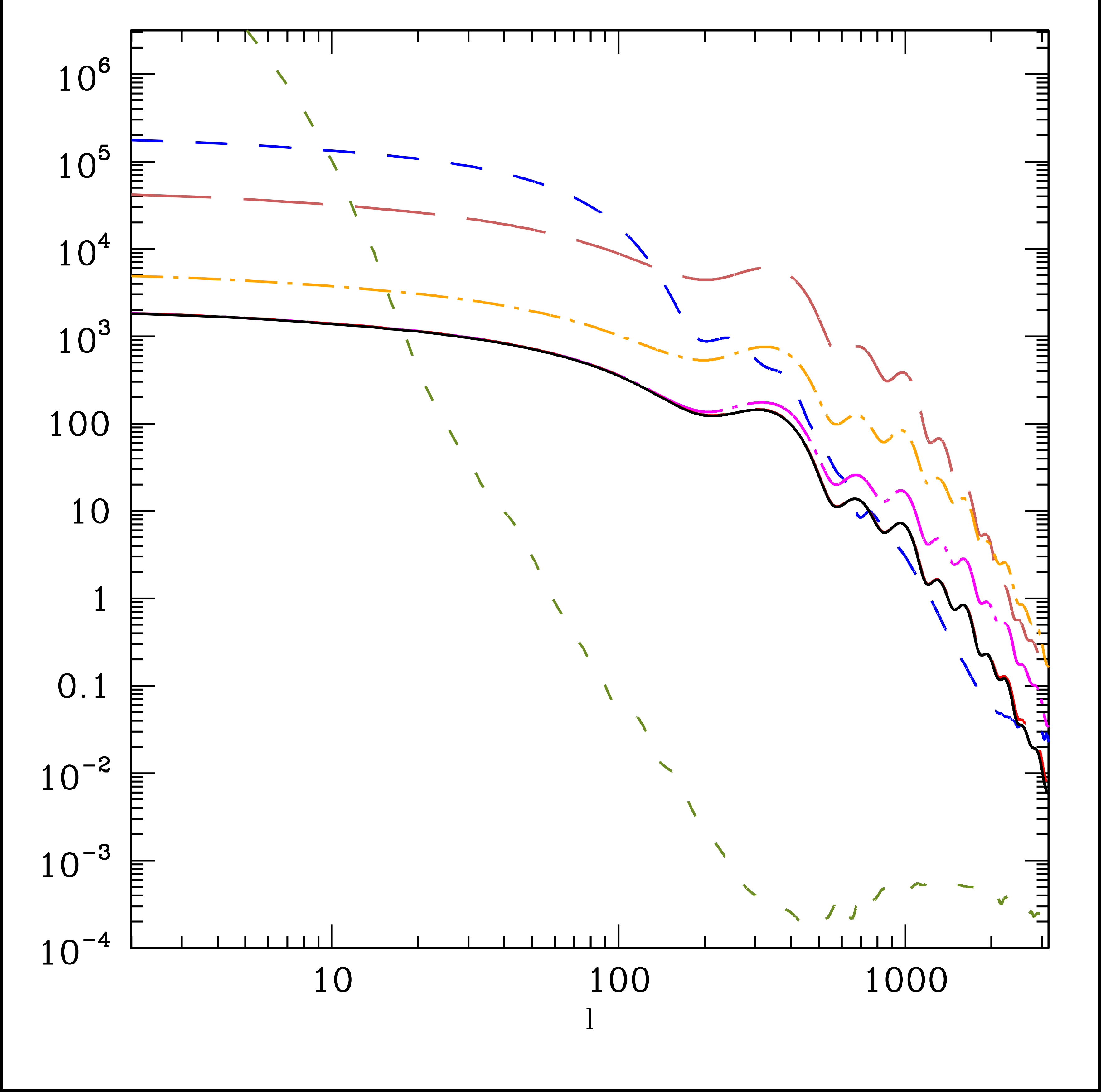
ULA Search Technical Details

ISW TEST



0.00020
0.00015
0.00010
0.00005
0.00000
−0.00005
ISW [Mpc^{-1}]
ΛCDM
EdS
$m_a = 10^{-32}\mathrm{eV}, \Omega_\Lambda \neq 0$
$m_a = 5 \times 10^{-32}\mathrm{eV}, \Omega_\Lambda = 0$
10^{-3}
10^{-2}
10^{-1}
10^{0}
Scale Factor a

Getting under the hood: The need for numerical care



Getting under the hood: The need for numerical care

$$\dot{\delta}_a = 3\mathcal{H}\left[w_a - 1\right]\delta_a - \left(1 + w_a\right)\left(kv_a + \dot{h}\right)$$

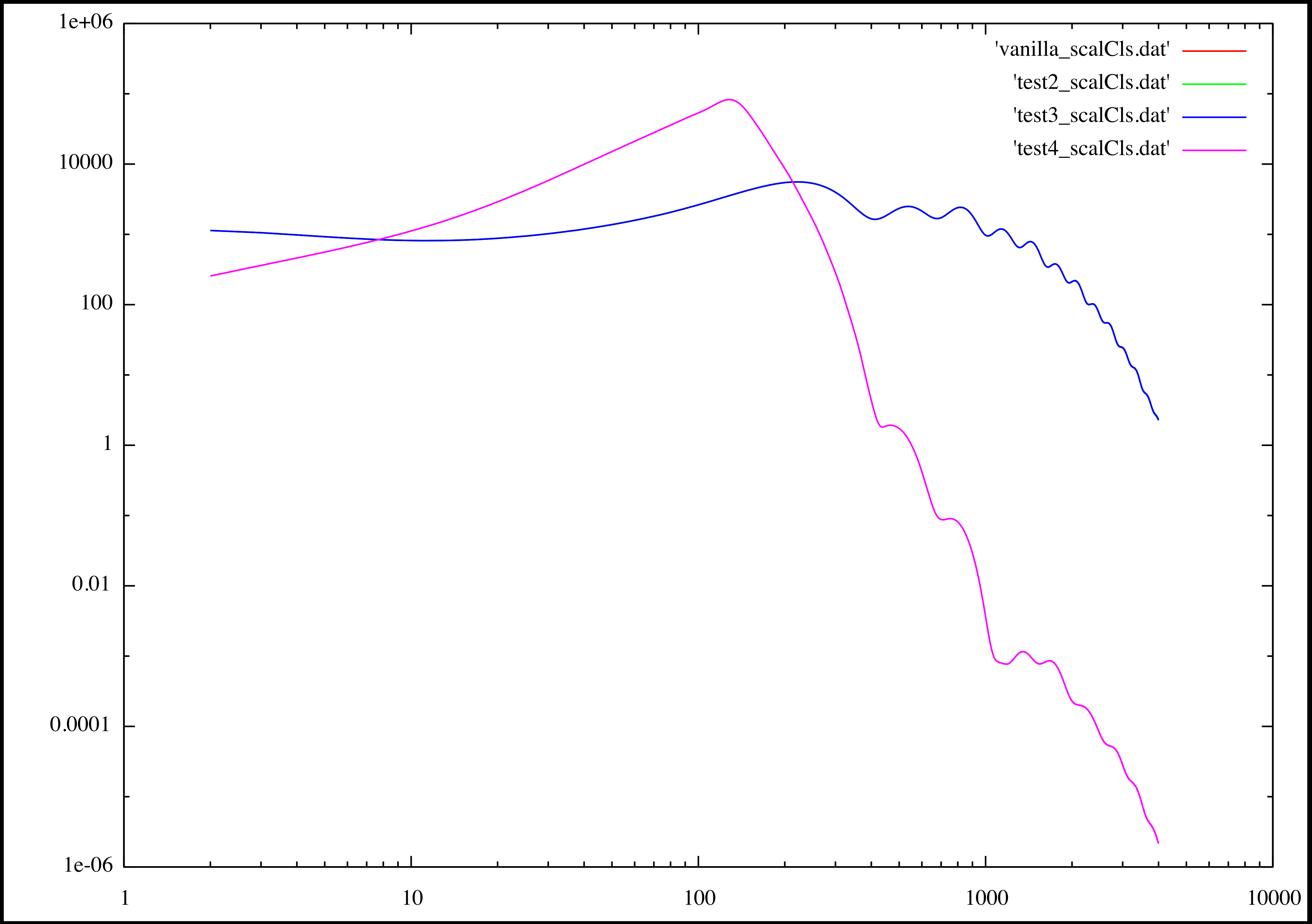
$$\dot{v}_a = -3\mathcal{H}\left[1 - 3w_a\right]v_a - \frac{\dot{w}_a}{\left(1 + w_w\right)}v_a + \frac{k\delta_a}{\left(1 + w_a\right)}$$

$$\dot{w}_a = -3\mathcal{H}\left(1 + w_a\right)\left[c_{\mathrm{ad}}^2 - w_a\right]$$

$$c_{\mathrm{ad}}^2 = \frac{\dot{P}_a}{\dot{\rho}_a} = -1 + \frac{2m_a a}{\mathcal{H}}\sqrt{\frac{\left(1 - w_a\right)}{\left(1 + w_a\right)}}$$

$$\dot{\rho}_a = -3\mathcal{H}\rho_a\left(1 + w_a\right)$$

Getting under the hood: The need for correct (super-horizon) initial conditions



Getting under the hood: The need for correct (super-horizon) initial conditions

Synchronous gauge 00-Einstein

$$\dot{h} \propto \eta \left[\frac{3\delta_{\rm R}}{a^2} + 3a^2 \mathcal{A} \delta_a \right]$$

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Perrotta and Baccigalupi, astro-ph/9811156

Getting under the hood: The need for correct (super-horizon) initial conditions

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Perrotta and Baccigalupi, astro-ph/9811156

$$\dot{\delta}_\gamma \simeq -\frac{\dot{h}}{2}$$

NOT KOSHER!

Getting under the hood: The need for correct (super-horizon) initial conditions

Synchronous gauge 00-Einstein

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Perrotta and Baccigalupi, astro-ph/9811156

$$\dot{\delta}_\gamma \simeq -\frac{\dot{h}}{2}$$

NOT KOSHER!

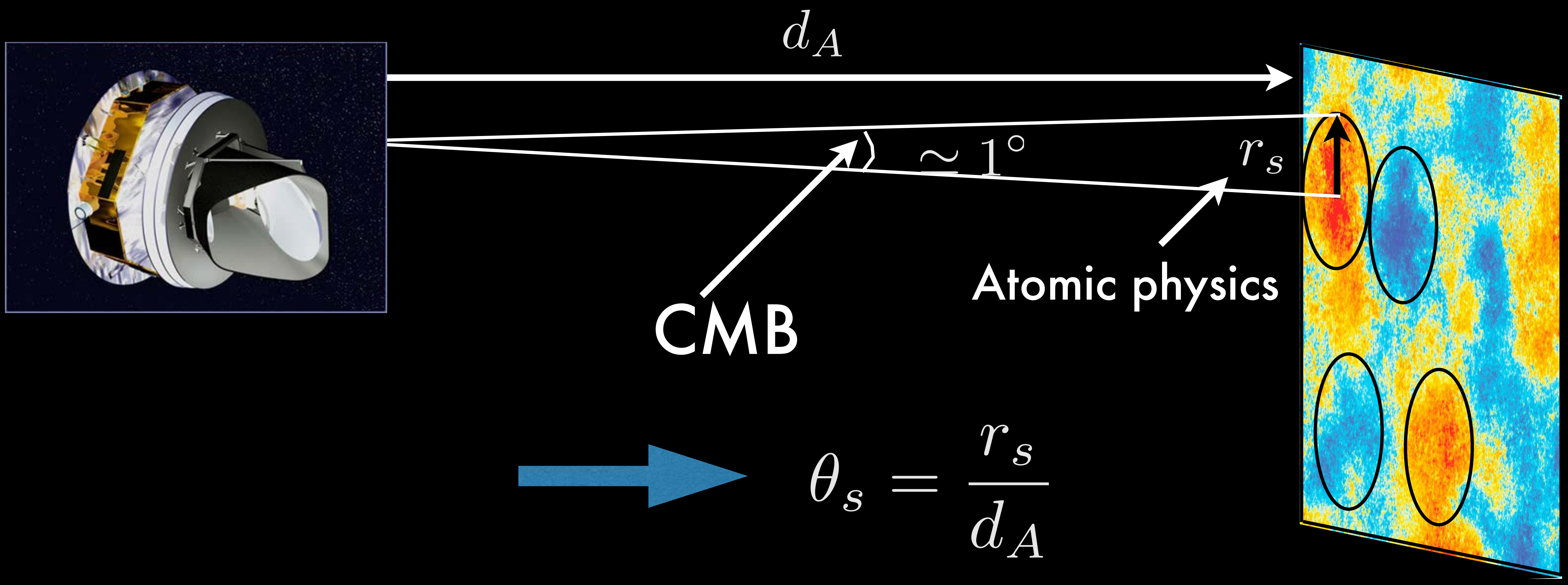
Solve Eigensystem and expand systematically

$$\frac{d\vec{U}_{\vec{k}}}{d\ln x} = \left(\underline{A}_0 + \underline{A}_1 x + \ldots \underline{A}_n x^n\right) \vec{U}_{\vec{k}}$$

Bucher, Moodley, and Turok, PRD62, 083508, sol'ns can be obtained using this technique, outlined in Doran et al. , astro-ph/0304212

ULAs and the angular sound horizon

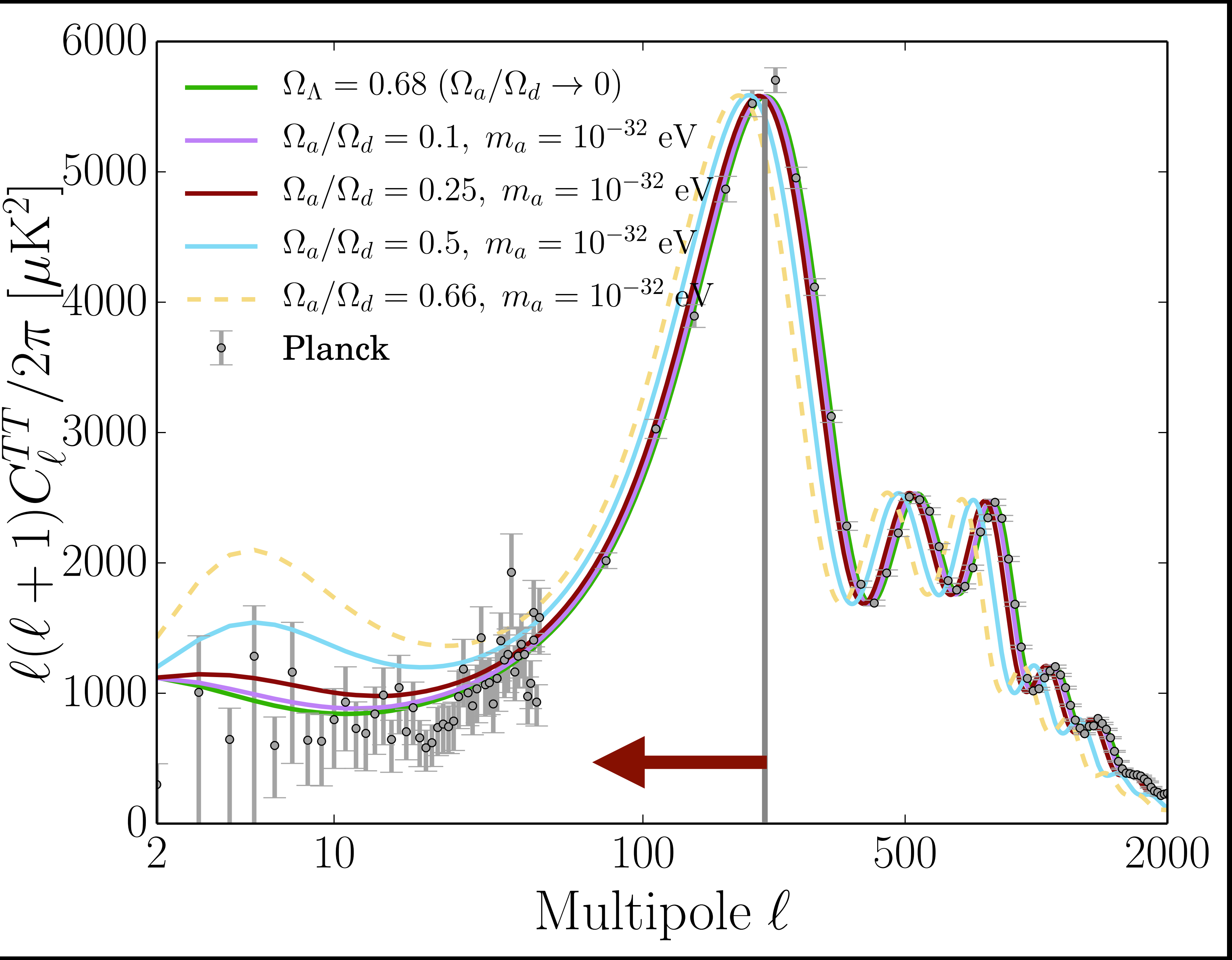
$$\theta_s \equiv \frac{r_s}{d_\mathrm{A}(z=1100)} = \left(l_\mathrm{CMB}^\mathrm{peak}\right)^{-1}$$



$$\theta_s = \frac{r_s}{d_A}$$

Diagram by T. Smith (used with permission)

ULAs and the angular sound horizon



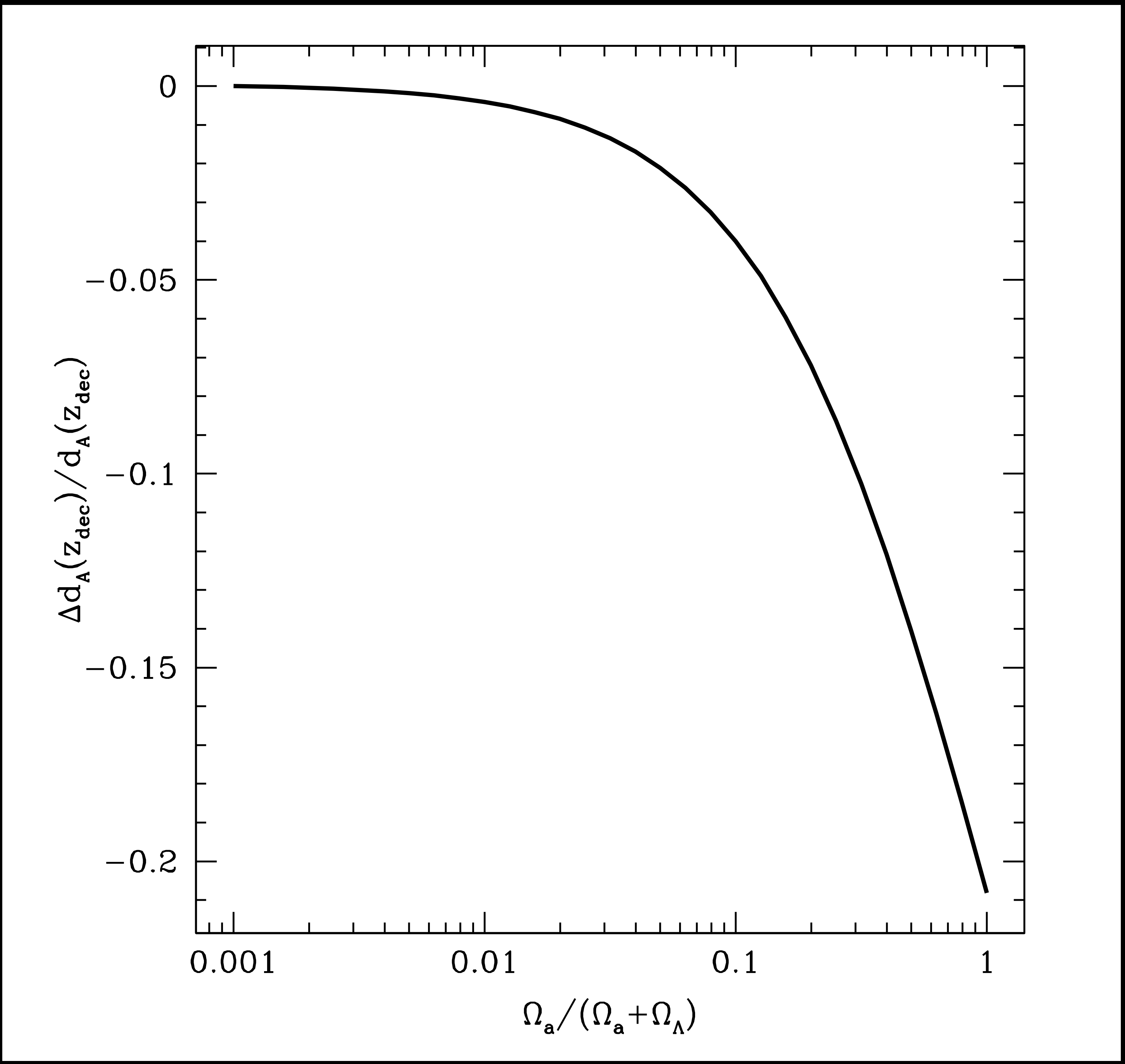
$$\theta_s \equiv \frac{r_s}{d_A(z=1100)} = \left(l_{\rm CMB}^{\rm peak}\right)^{-1}$$

$$d_A \propto \int \frac{dz}{H(z)}$$

$$H(z) = H_0 \left\{ \frac{\Omega_m}{a^3} + \frac{\Omega_{\rm axion}}{a^{3\int[1+w(\eta)]d\eta}} \right\}^{1/2}$$

Faster early expansion brings LSS closer

ULAs and the angular sound horizon



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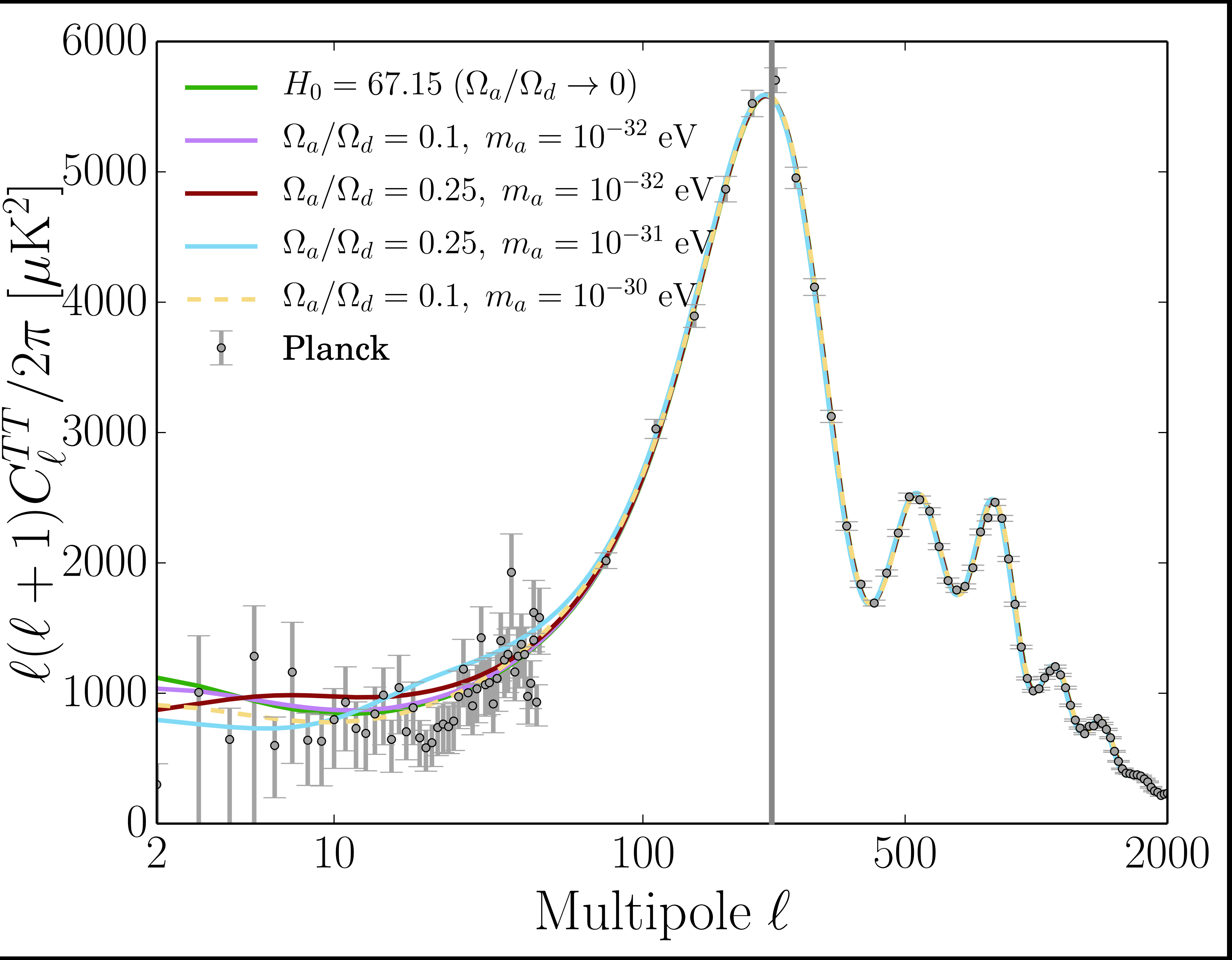
ULAs and the angular sound horizon



$$\theta_s \equiv \frac{r_s}{d_A(z=1100)} = \left(l_{\rm CMB}^{\rm peak}\right)^{-1}$$

$$d_A \propto \int \frac{dz}{H(z)}$$

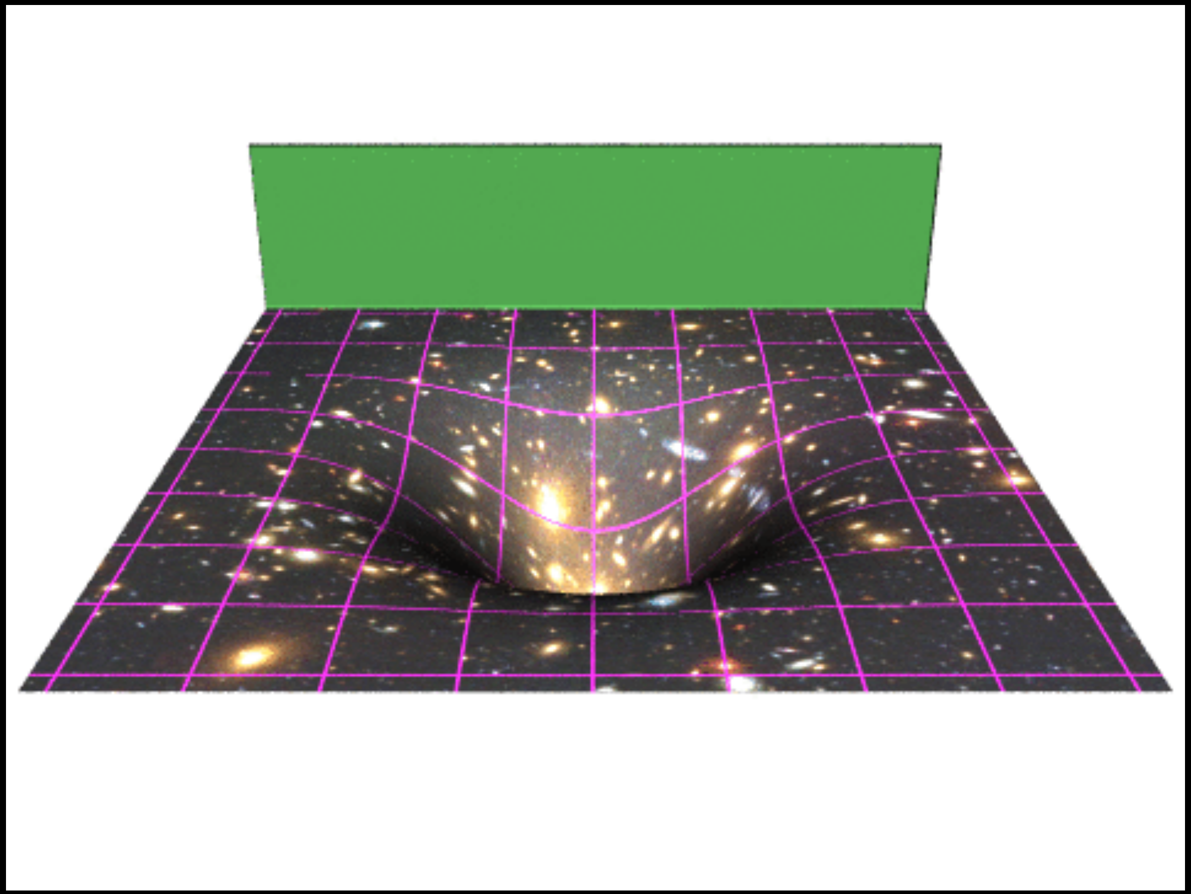
Absorb and lock onto usual peaks by lowering H_0

$$H(z) = H_0 \left\{ \frac{\Omega_m}{a^3} + \frac{\Omega_{\rm axion}}{a^{3\int[1+w(\eta)]d\eta}} \right\}^{1/2}$$

Faster early expansion brings LSS closer

ULAs and the CMB: high mass and early ISW

Higher mass (DM-like) case: high-l ISW



CMB temperature anisotropies from potential decay

$$\Delta T_{\rm ISW} = -2\int_0^{\eta_{\rm dec}} d\eta \dot{\Phi}(\eta, \hat{n}\eta)$$

$$\Phi \propto \frac{1}{k^2}\left\{\frac{\Omega_m\delta_m\left(1-\frac{\Omega_a}{\Omega_m}\right)}{a^3}+\frac{\delta_R\Omega_R}{a^4}\right\}$$

ULAs and the CMB: high mass and early ISW

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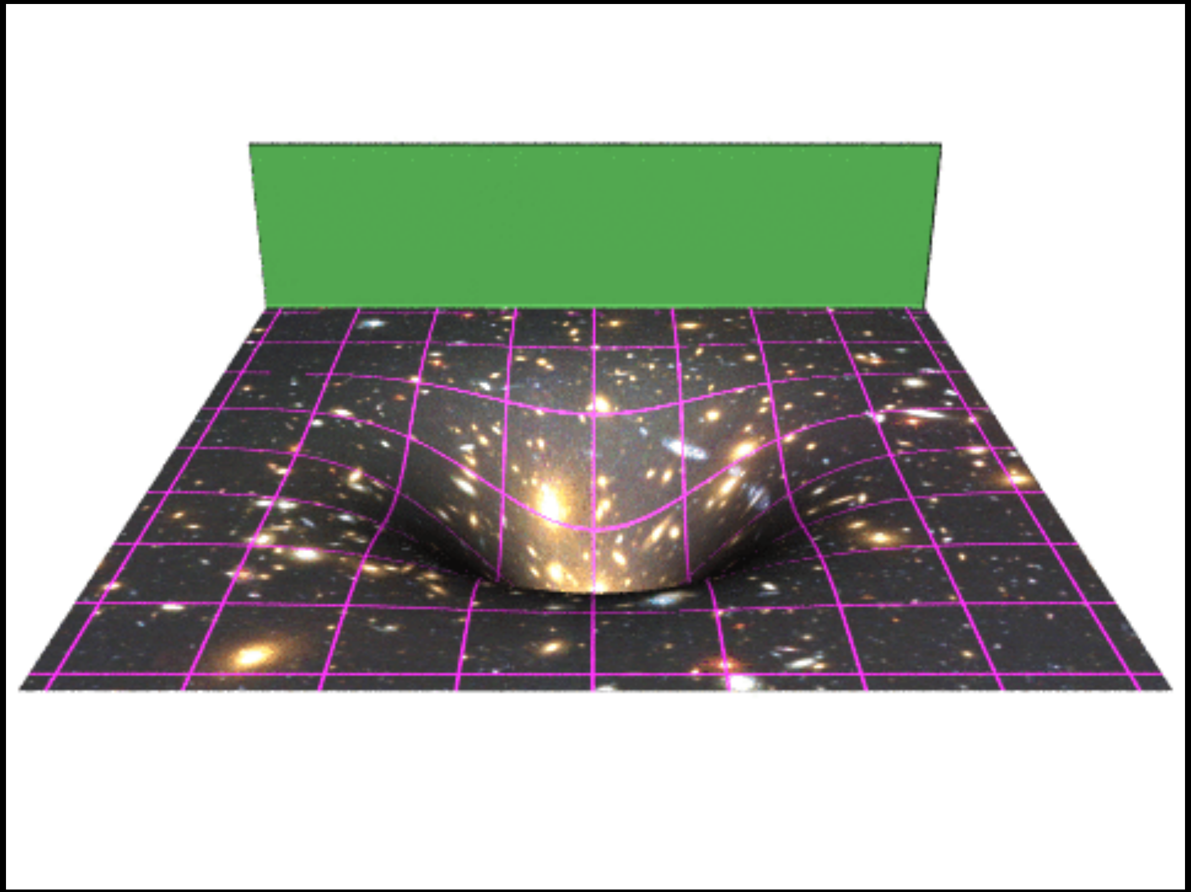

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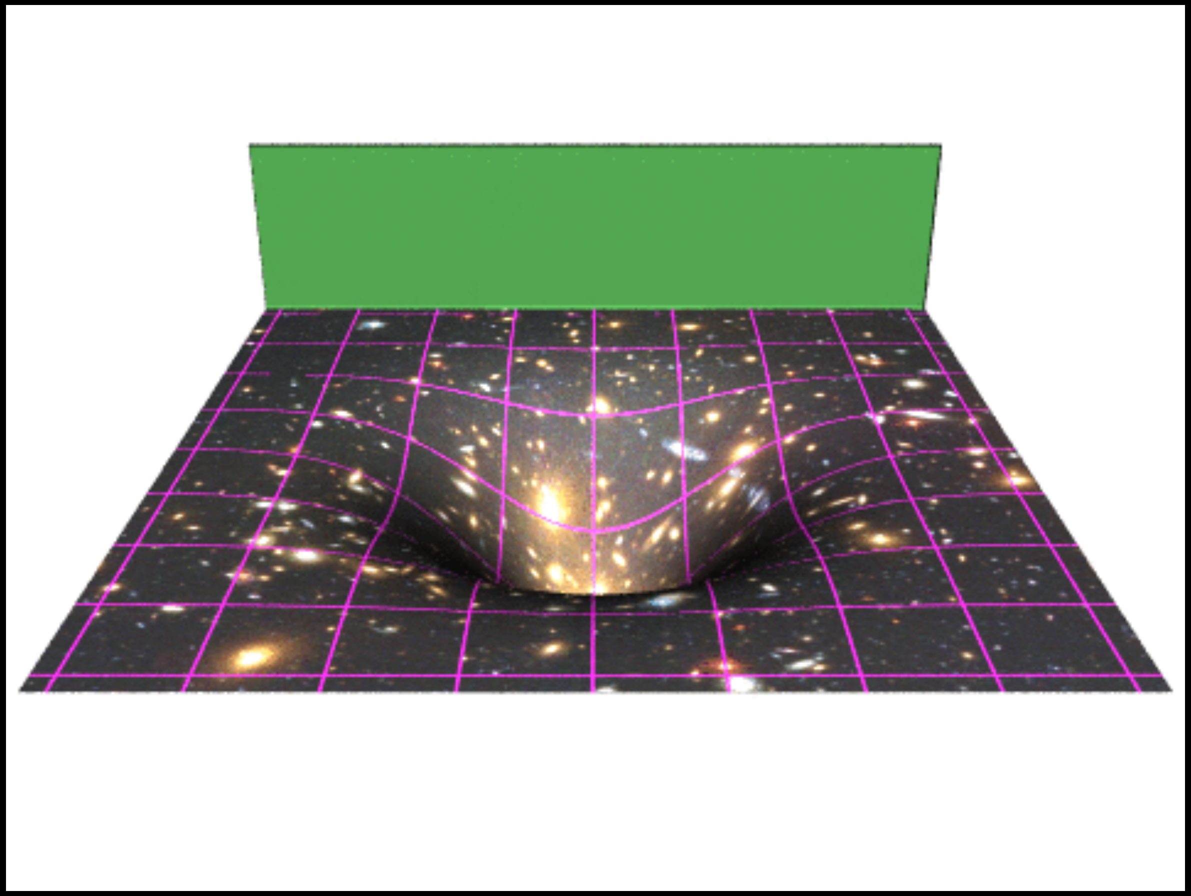
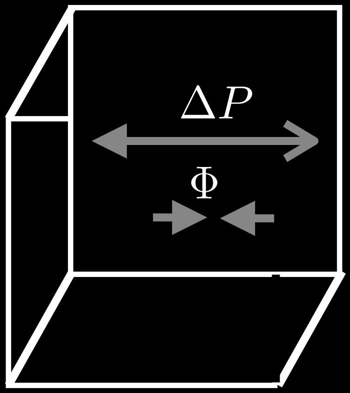


Radiation pressure causes potential decay

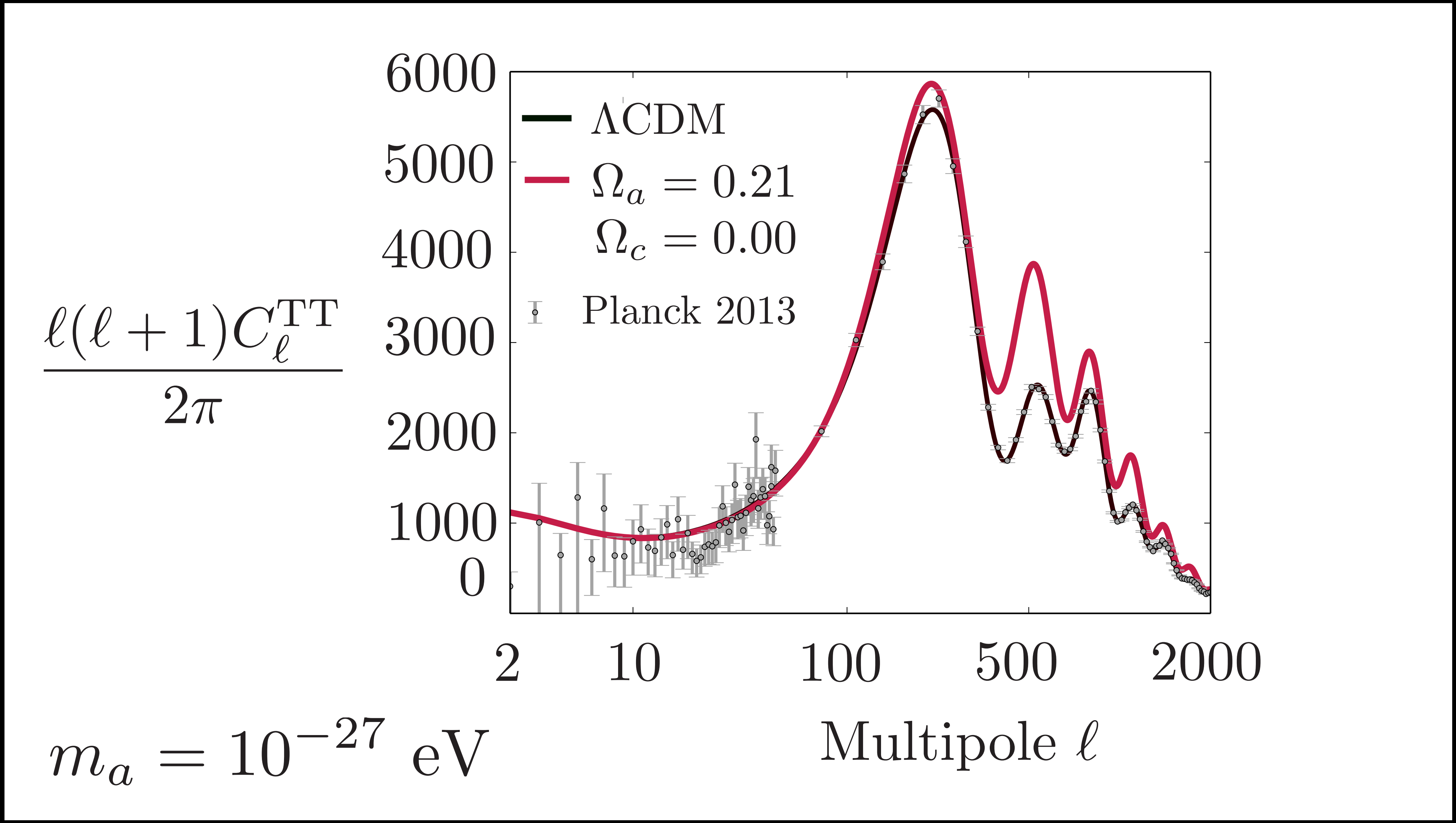


$$\Phi \propto \frac{1}{k^2}\left\{\frac{\Omega_m \delta_m \left(1-\frac{\Omega_a}{\Omega_m}\right)}{a^3}+\frac{\delta_R \Omega_R}{a^4}\right\}$$

$$\Delta P \Delta A > \rho \delta V \nabla \Phi$$

ULAs and the CMB: high mass and early ISW

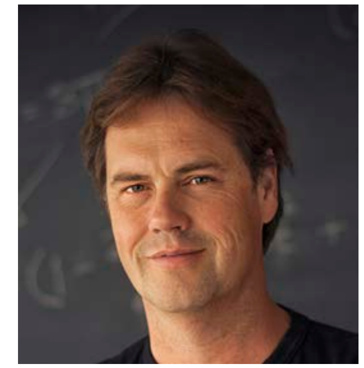
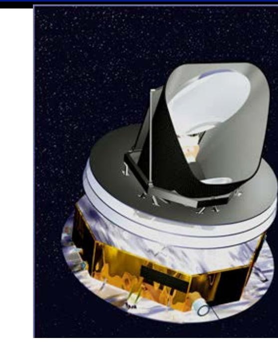
Higher mass (DM-like) case: high-l ISW



CONSTRAINTS

Comparison with data

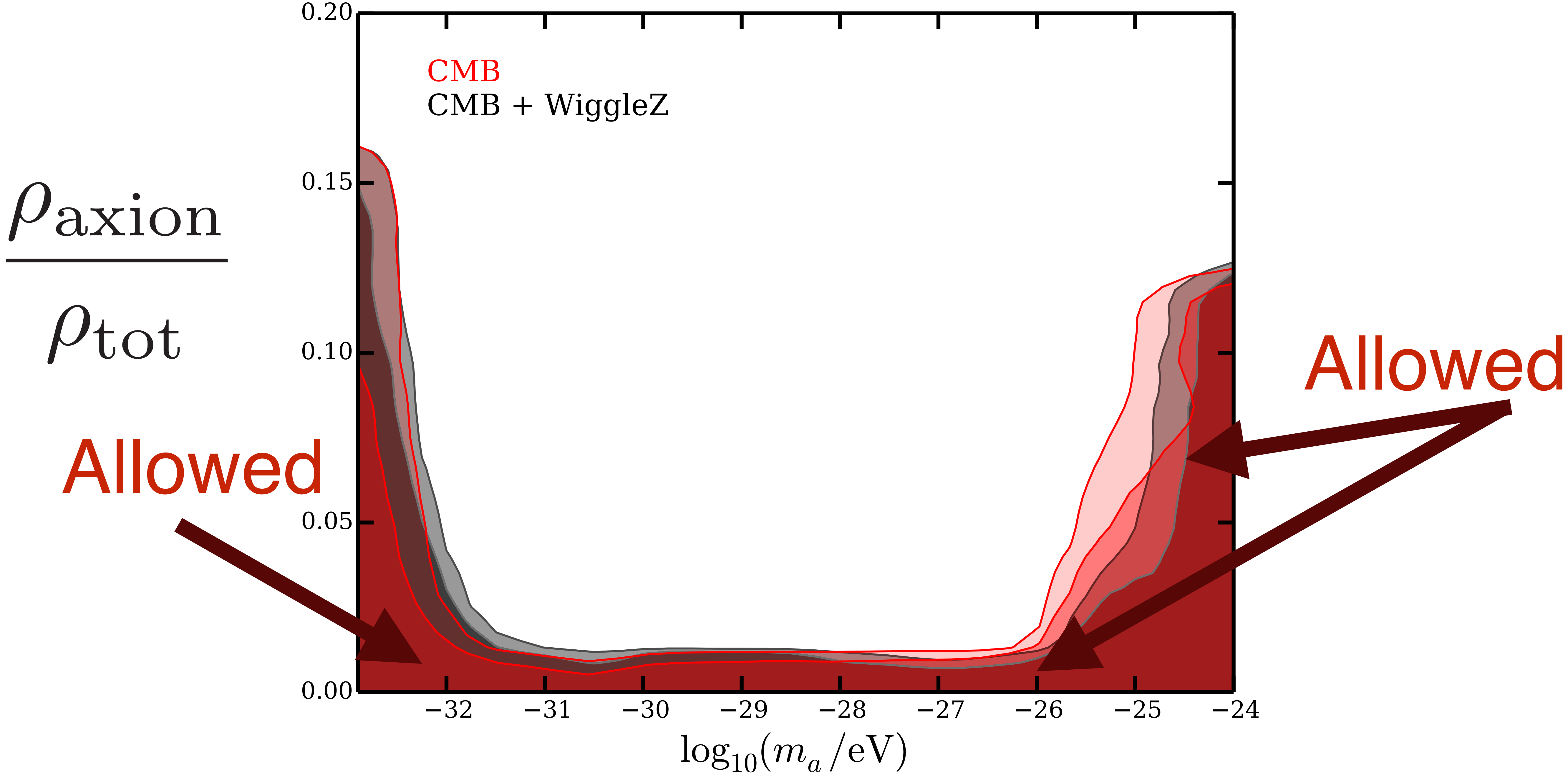


R.Hlozek, DG, D.J. E. Marsh, P.Ferreira

arXiv:1410.2896, Phys. Rev. D 91, 103512 (2015)
arXiv:1403.4216, Phys. Rev. Lett. 113, 011801 (2014)
arXiv:1303.3008, Phys. Rev. D 87, 121701(R) (2013)

CONSTRAINTS



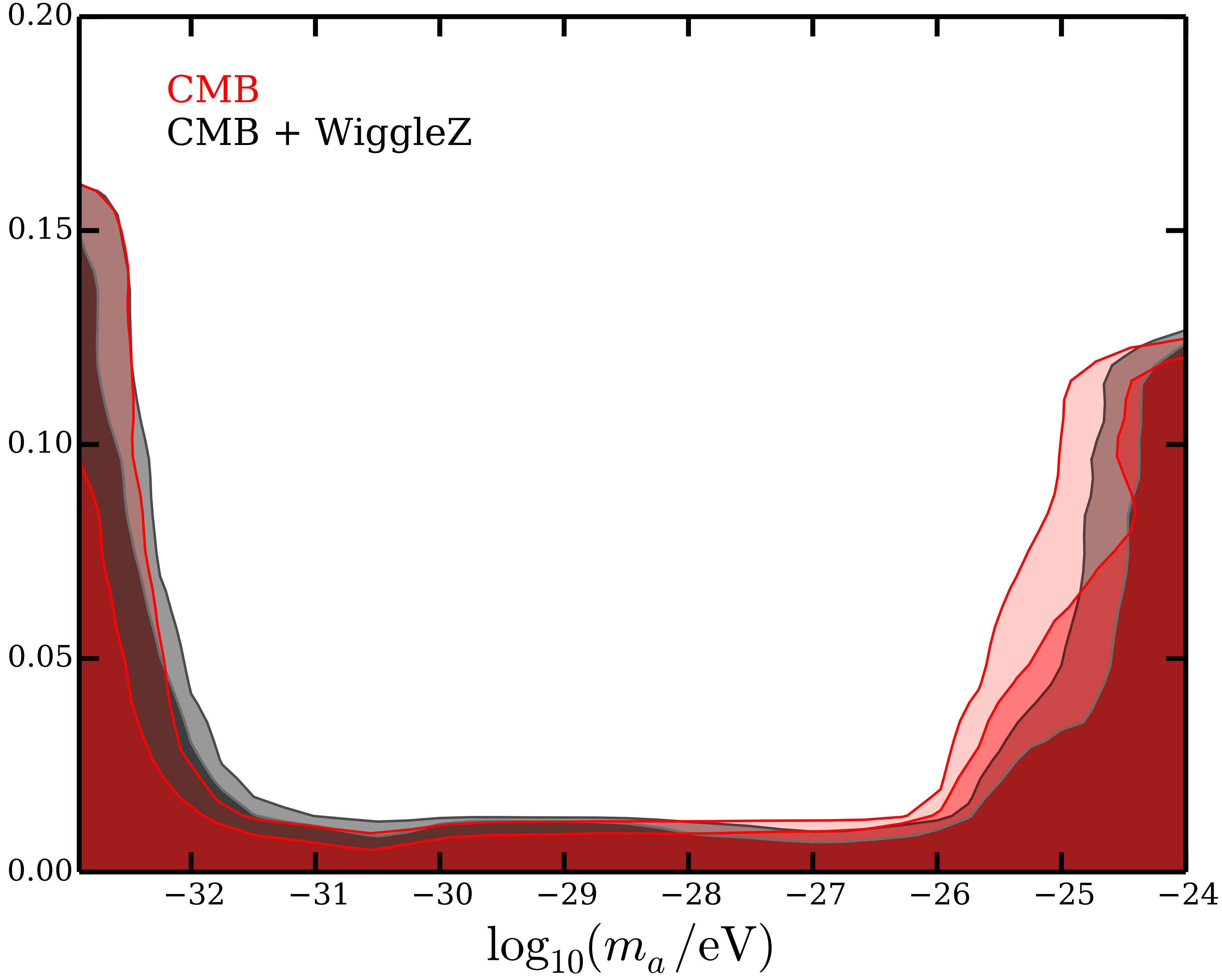
✳Tight constraints over 7 orders of magnitude in mass:

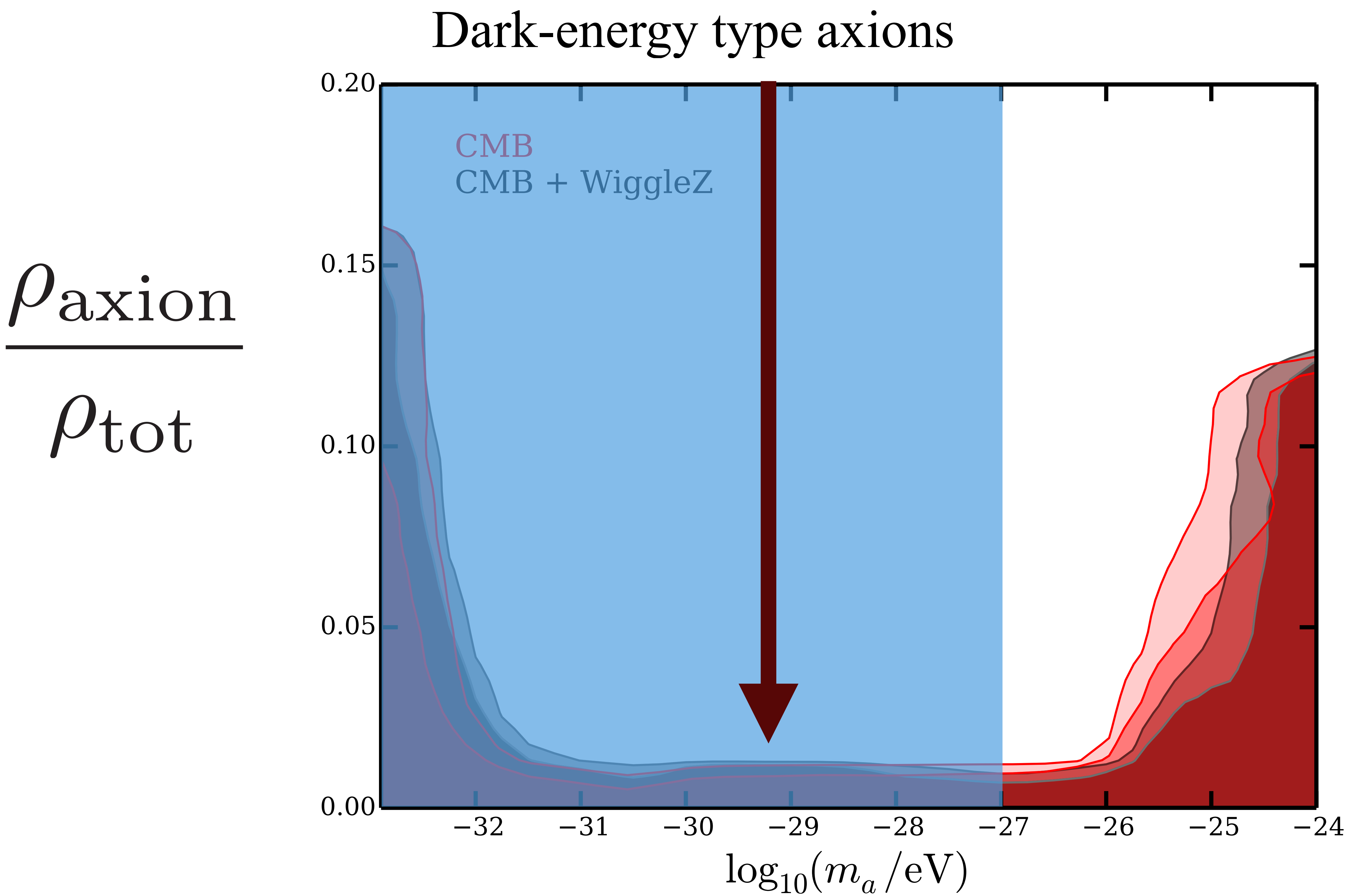
Thanks to AxiCamb and Planck

✳ULAs are viable DM/DE candidates in linear theory outside ``belly”

Physics behind the constraints

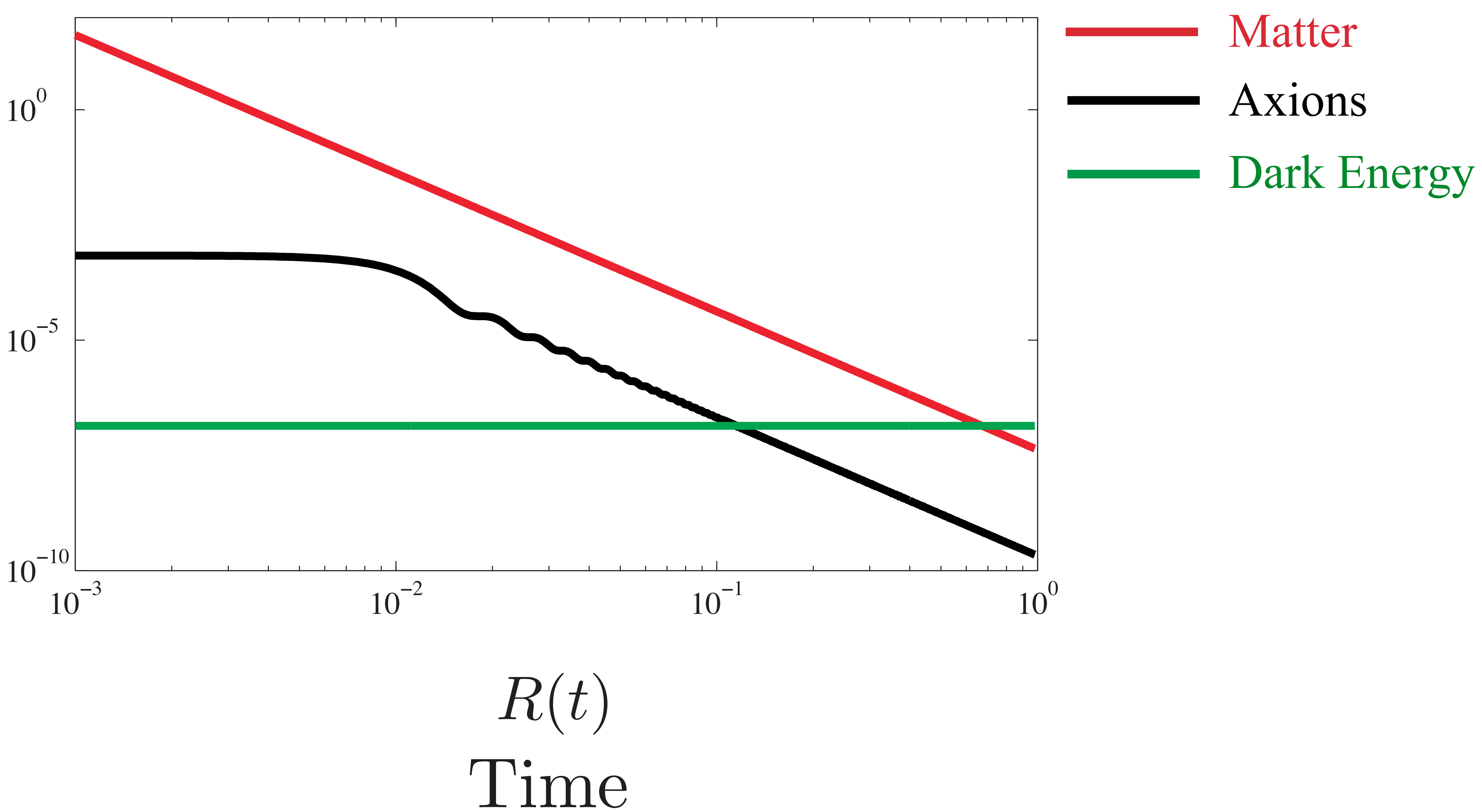
$$\frac{\rho_{\mathrm{axion}}}{\rho_{\mathrm{tot}}}$$




Dark-energy type axions
CMB
CMB + WiggleZ
0.20
0.15
0.10
0.05
0.00
−32
−31
−30
−29
−28
−27
−26
−25
−24
$\log_{10}(m_a/\mathrm{eV})$
$\frac{\rho_{\text{axion}}}{\rho_{\text{tot}}}$

CMB Constraints at low masses

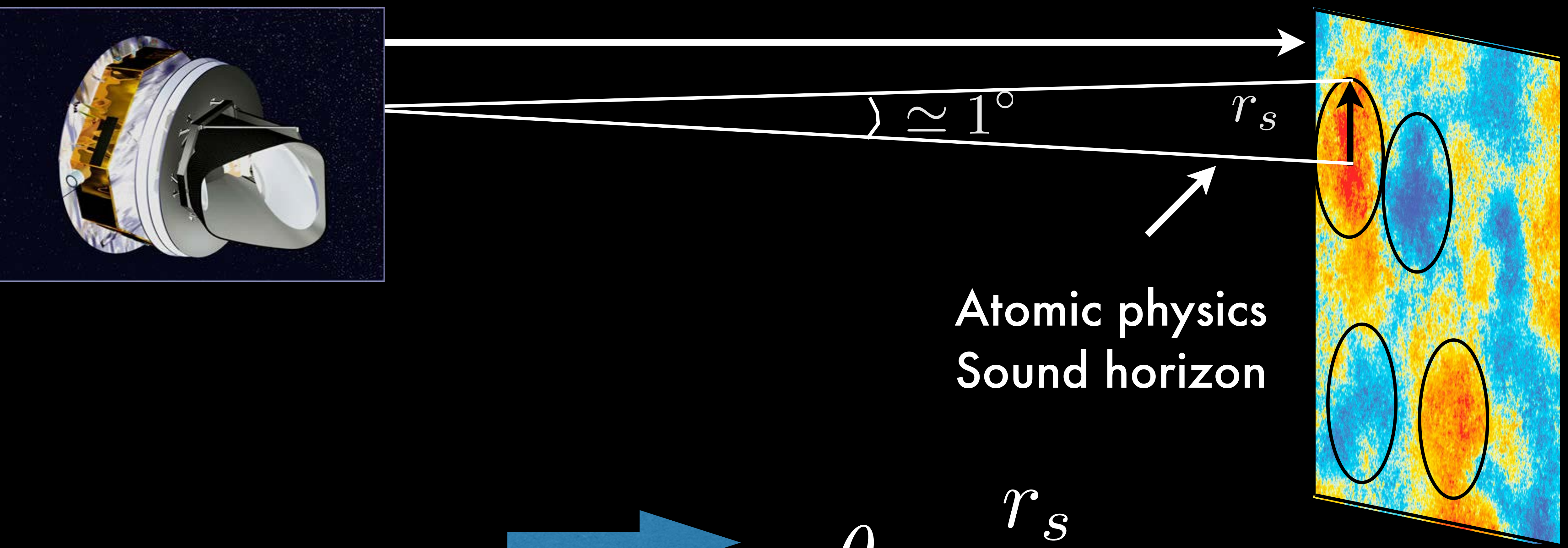
✳Axion energy density behaves unusually



Faster early expansion brings CMB emission surface closer

CMB Constraints at low masses and the angular sound horizon

D (sensitive to any energy source)



$$\theta = \frac{r_s}{D}$$

Fig. modified from T. Smith with permission

Faster early expansion brings CMB emission surface closer

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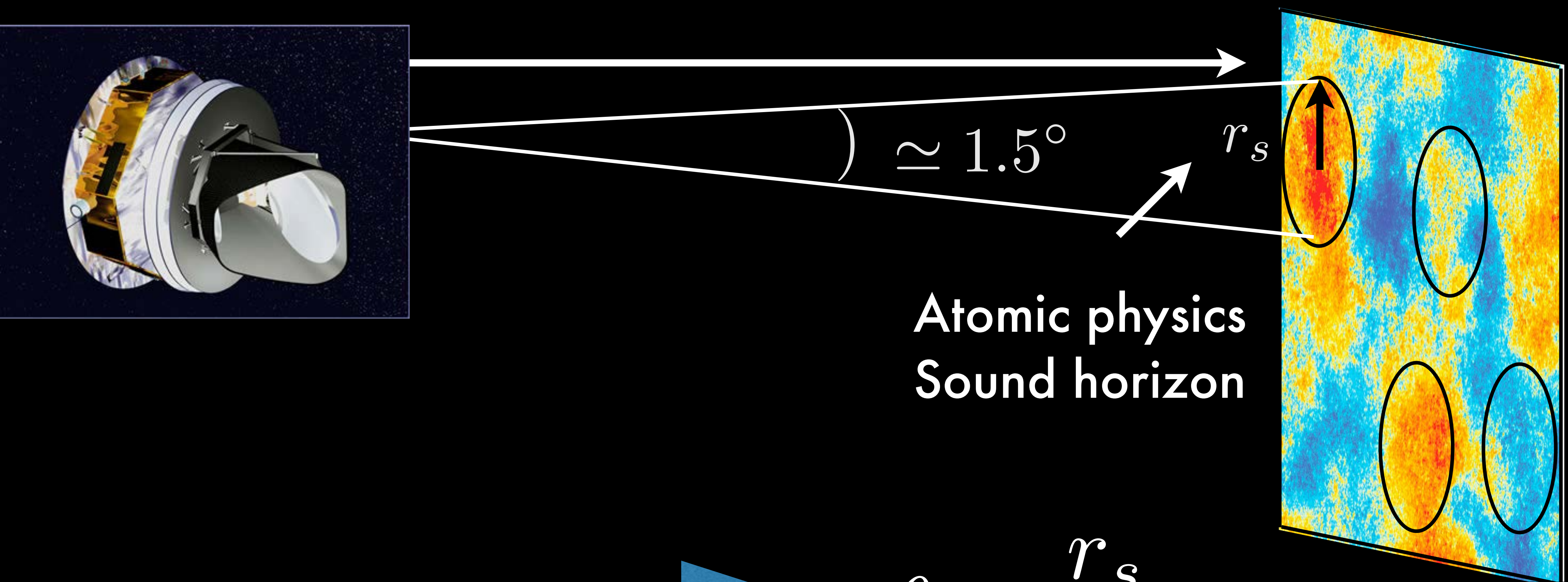


$$\theta = \frac{r_s}{D}$$

Fig. modified from T. Smith with permission

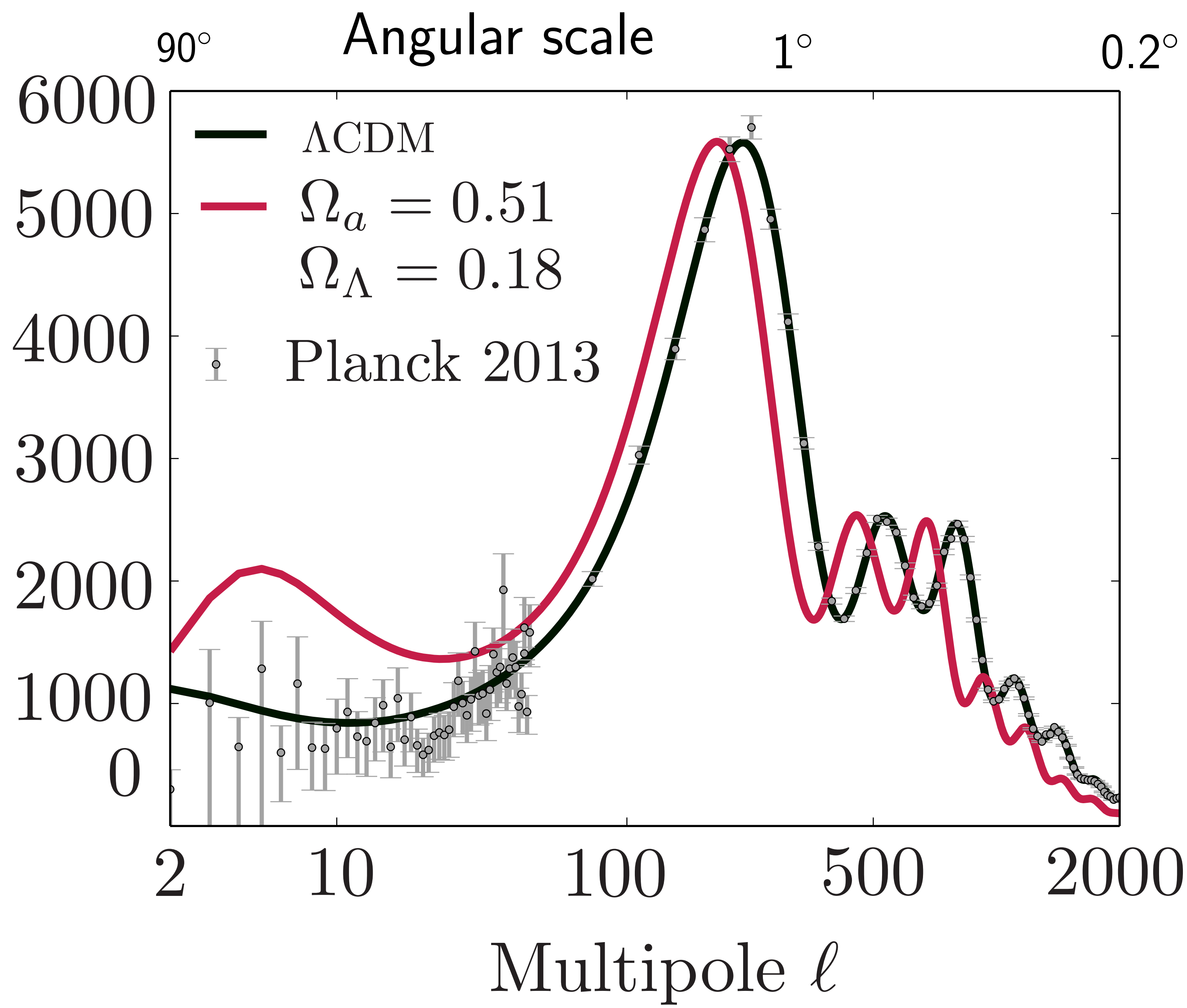
Faster early expansion brings CMB emission surface closer

CMB Constraints at low masses

$m_a = 10^{-32}$ eV

Temperature Variance

$$\mu\text{K}^2 \quad \frac{\ell(\ell+1)C_\ell^{TT}}{2\pi}$$



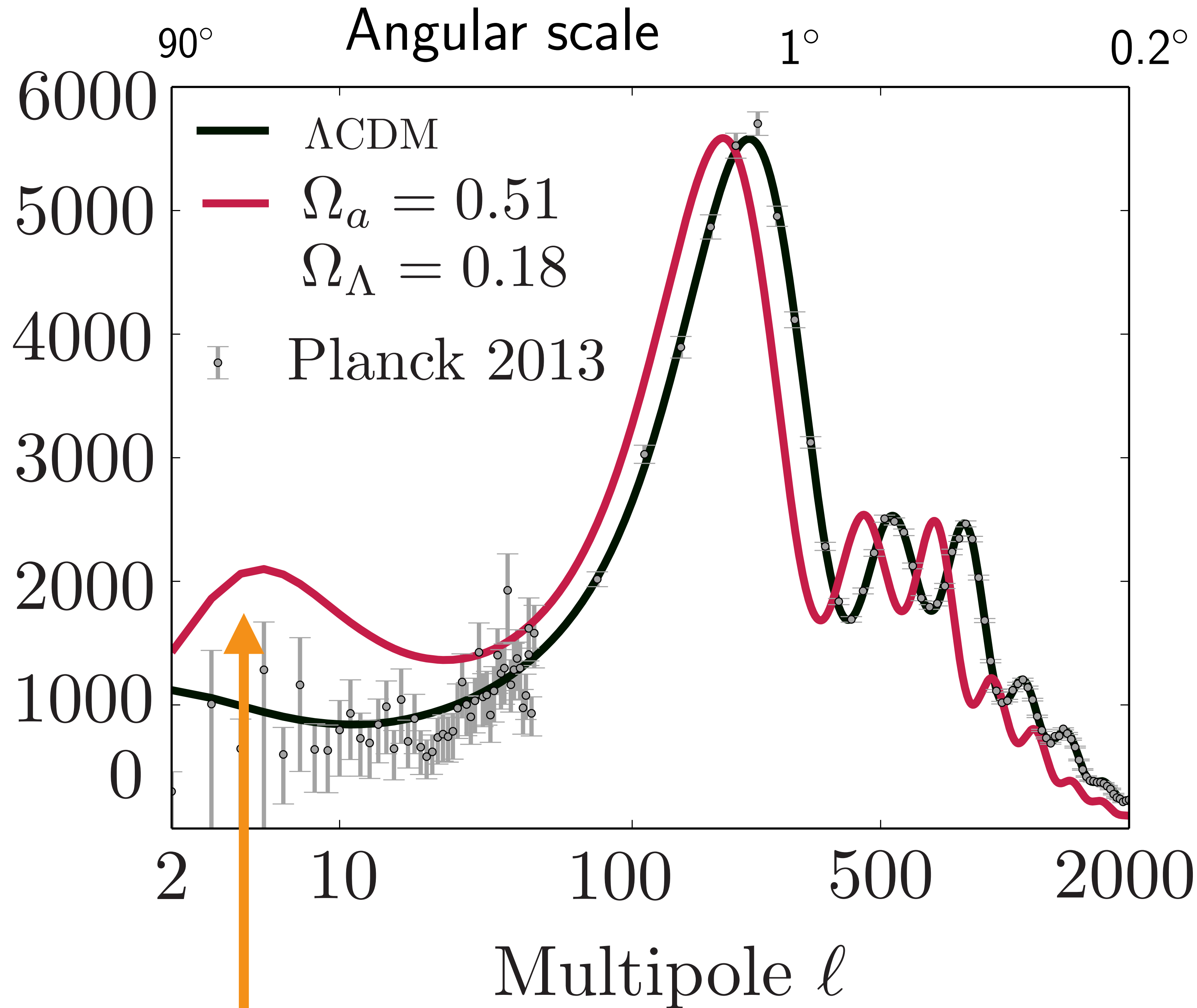
Acoustic features shift!

CMB CONSTRAINTS AT LOW MASSES

$m_a = 10^{-32}$ eV

Temperature Variance

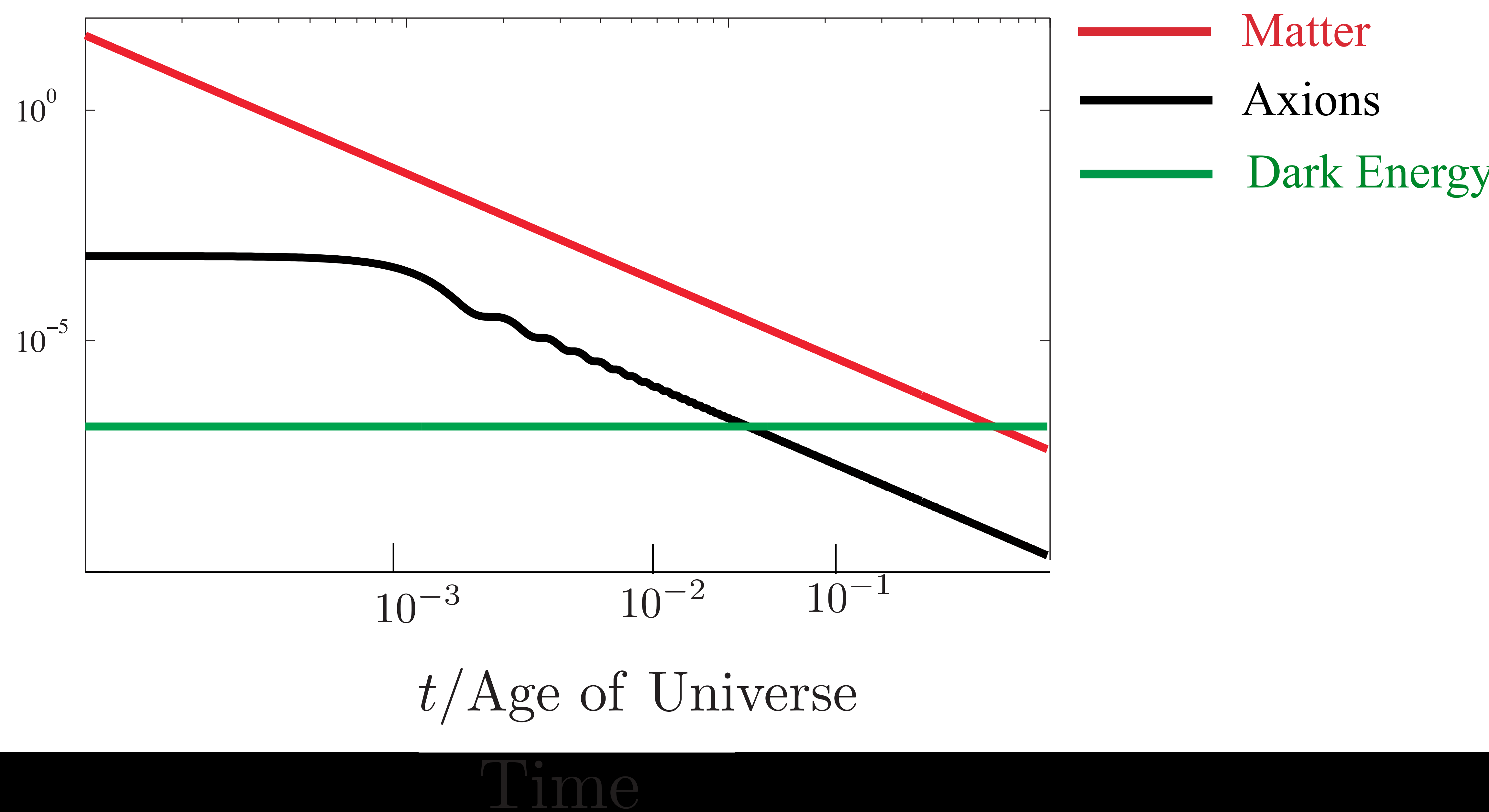
$$\mu\text{K}^2 \quad \frac{\ell(\ell+1)C_\ell^{TT}}{2\pi}$$



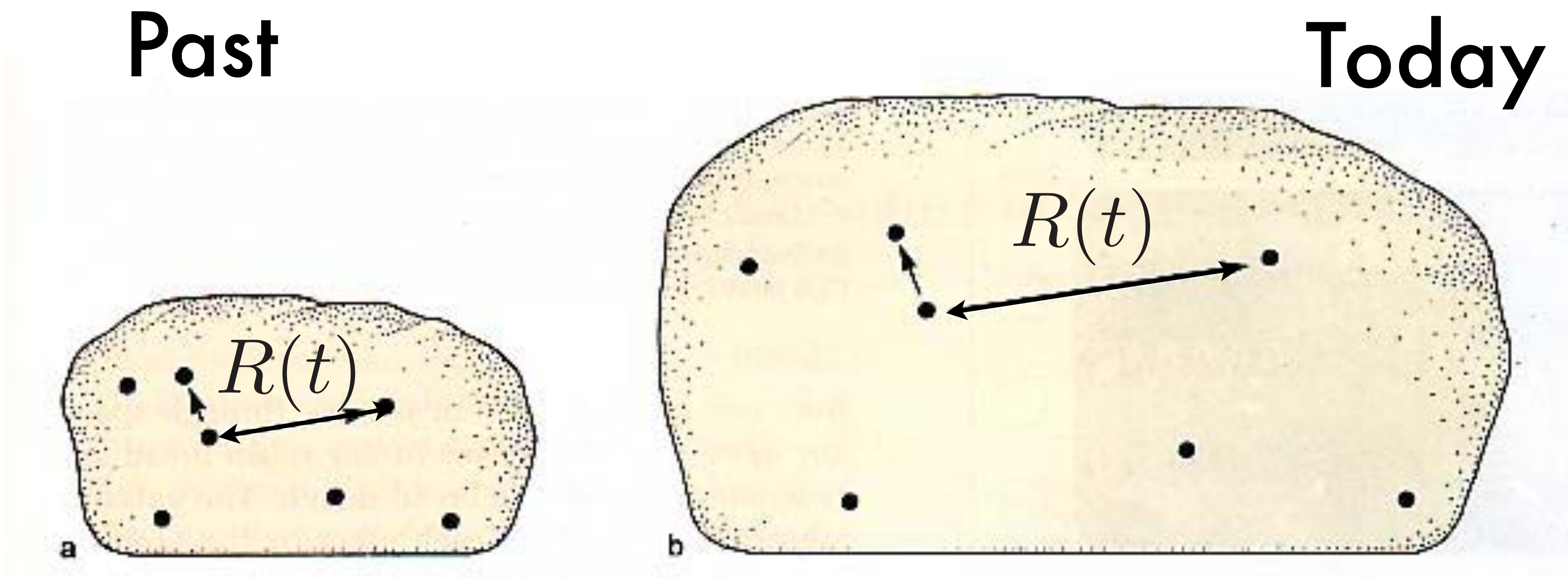
What about this bump?

Axions imprint on cosmology

- ✳Axion energy density behaves unusually



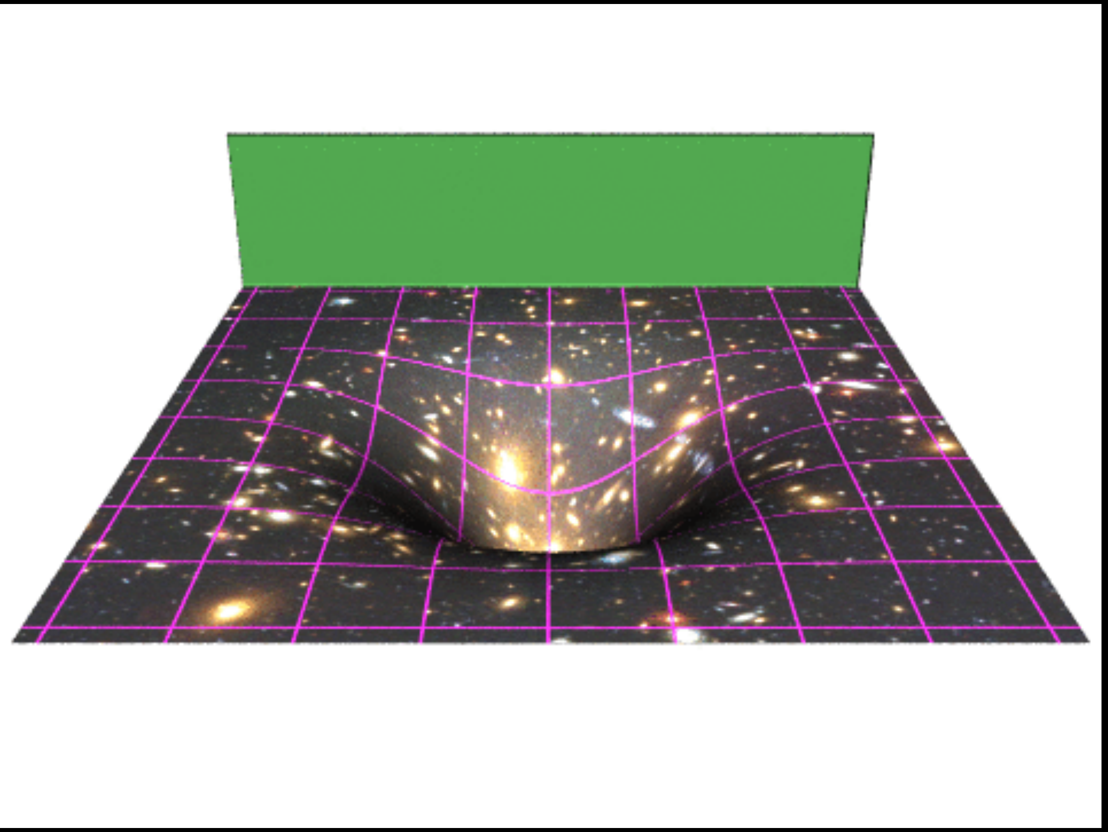
✶Axion alters cosmic expansion history



$$\left[\frac{\dot{R}(t)}{R(t)}\right]^2 = \frac{8\pi G\rho}{3}$$

Energy content (incuding axions) determines expansion history

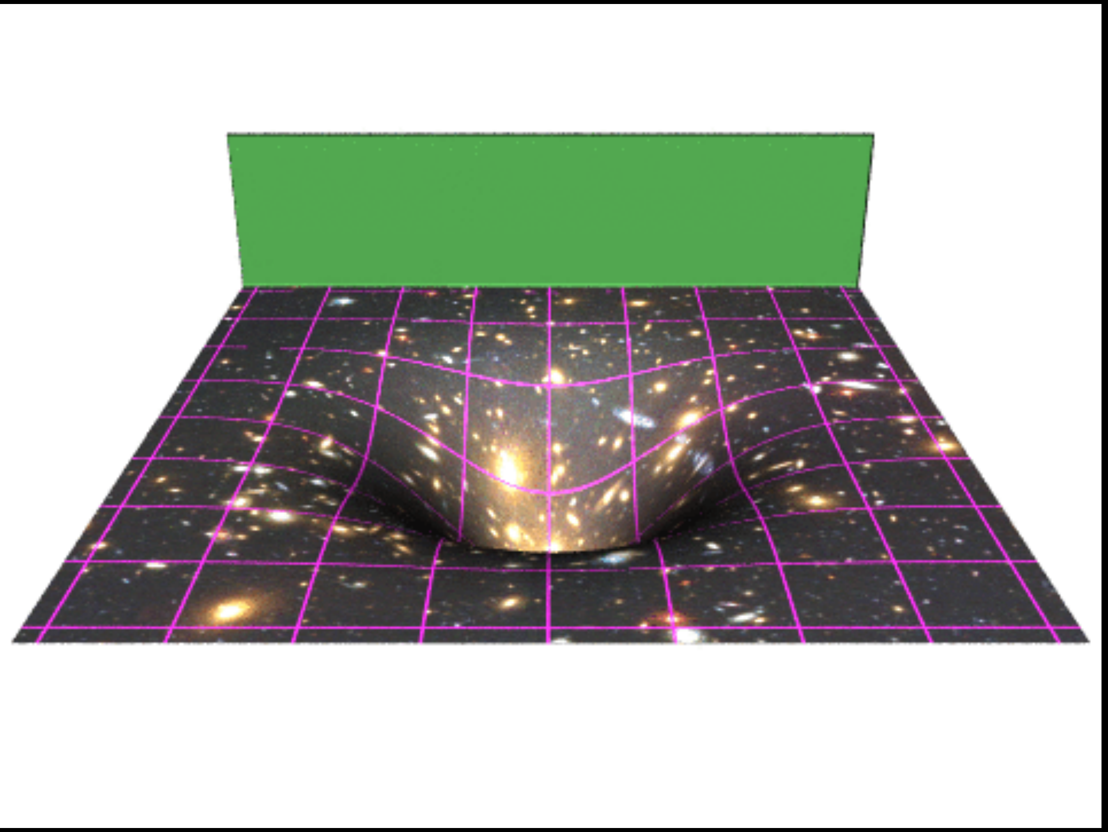
Low mass (DE-like) case:
late Integrated Sachs-Wolfe Effect



CMB temperature anisotropies from potential decay

$$\Delta T_{\rm ISW} = -2\int_0^{\eta_{\rm dec}} d\eta \dot{\Phi}(\eta, \hat{n}\eta)$$

Low mass (DE-like) case:
late Integrated Sachs-Wolfe Effect



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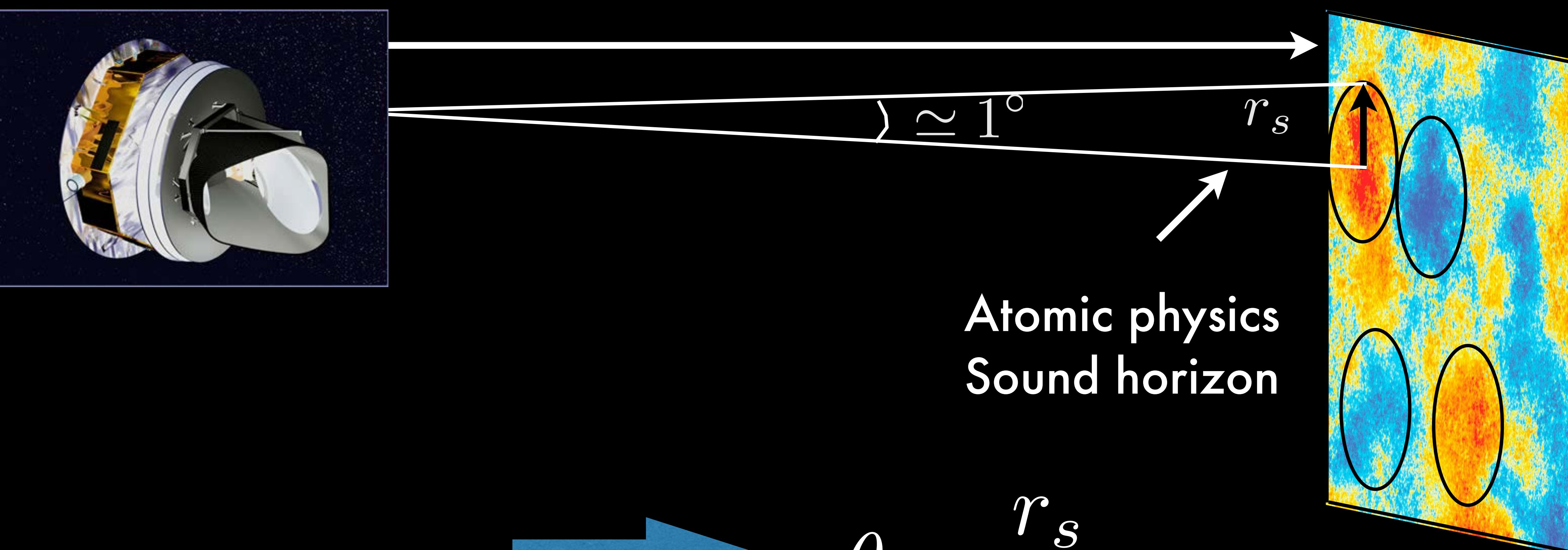
ULAs as dark energy and the angular sound horizon

D (sensitive to any energy source)



$$\theta = \frac{r_s}{D}$$

Fig. modified from T. Smith with permission

Faster early expansion brings LSS closer

ULAs as dark energy and the angular sound horizon

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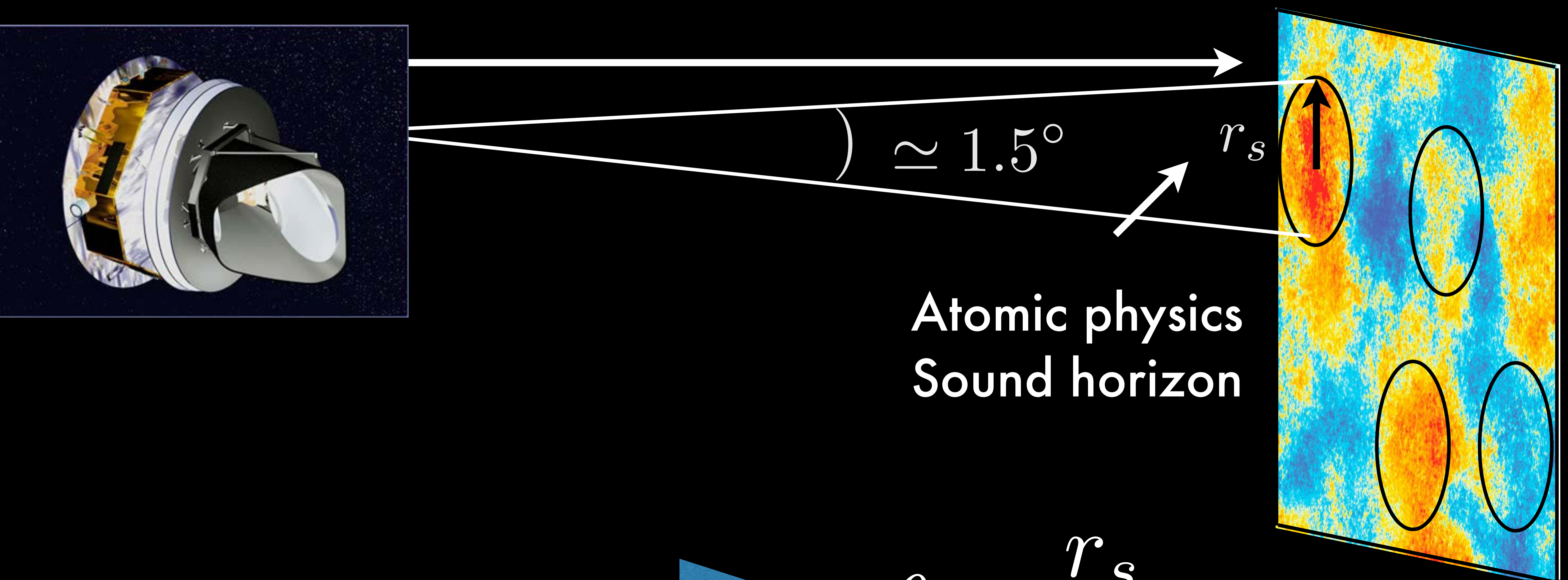

$$\theta = \frac{r_s}{D}$$

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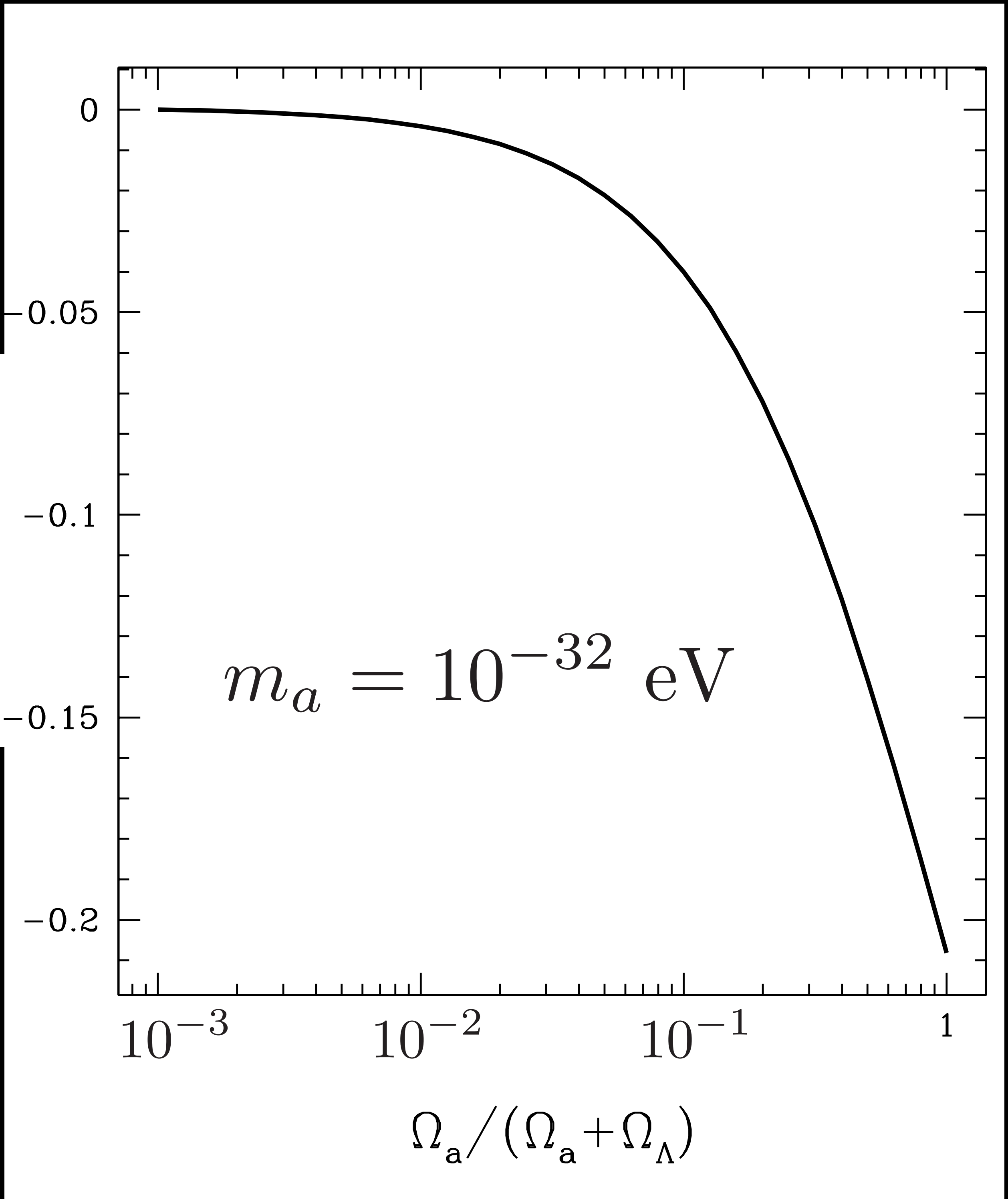
Faster early expansion brings LSS closer

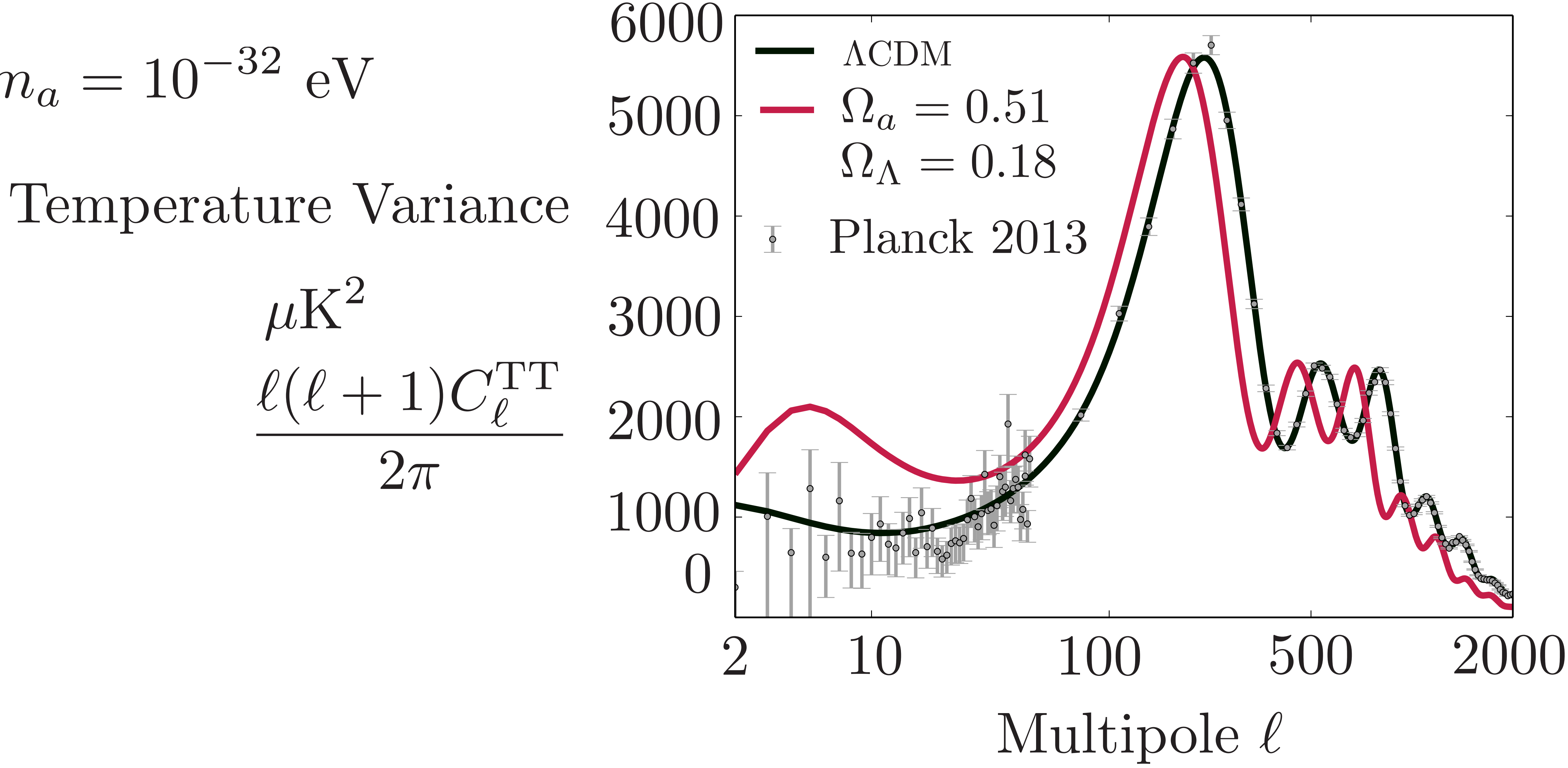
ULAs as dark energy and the angular sound horizon

$$\frac{D(z_{\rm decoupling}) - D^{\rm axion}(z^{\rm axion}_{\rm decoupling})}{D(z_{\rm decoupling})}$$



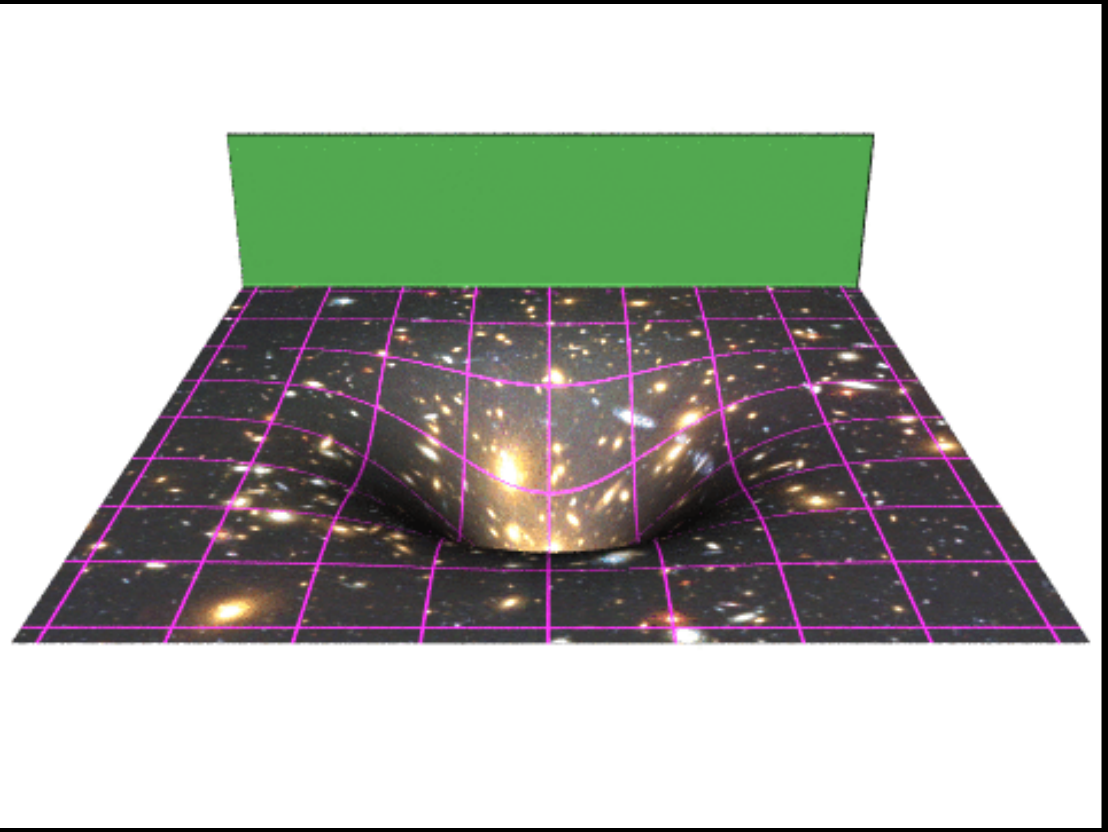
Faster early expansion brings LSS closer

$m_a = 10^{-32}$ eV


Temperature Variance
μK^2
$\frac{\ell(\ell+1)C_\ell^{TT}}{2\pi}$
6000
5000
4000
3000
2000
1000
0
ΛCDM
$\Omega_a = 0.51$
$\Omega_\Lambda = 0.18$
Planck 2013
2
10
100
500
2000
Multipole ℓ

ULAs as dark energy and perturbations in other fluids

Low mass (DE-like) case: late Integrated Sachs-Wolfe Effect



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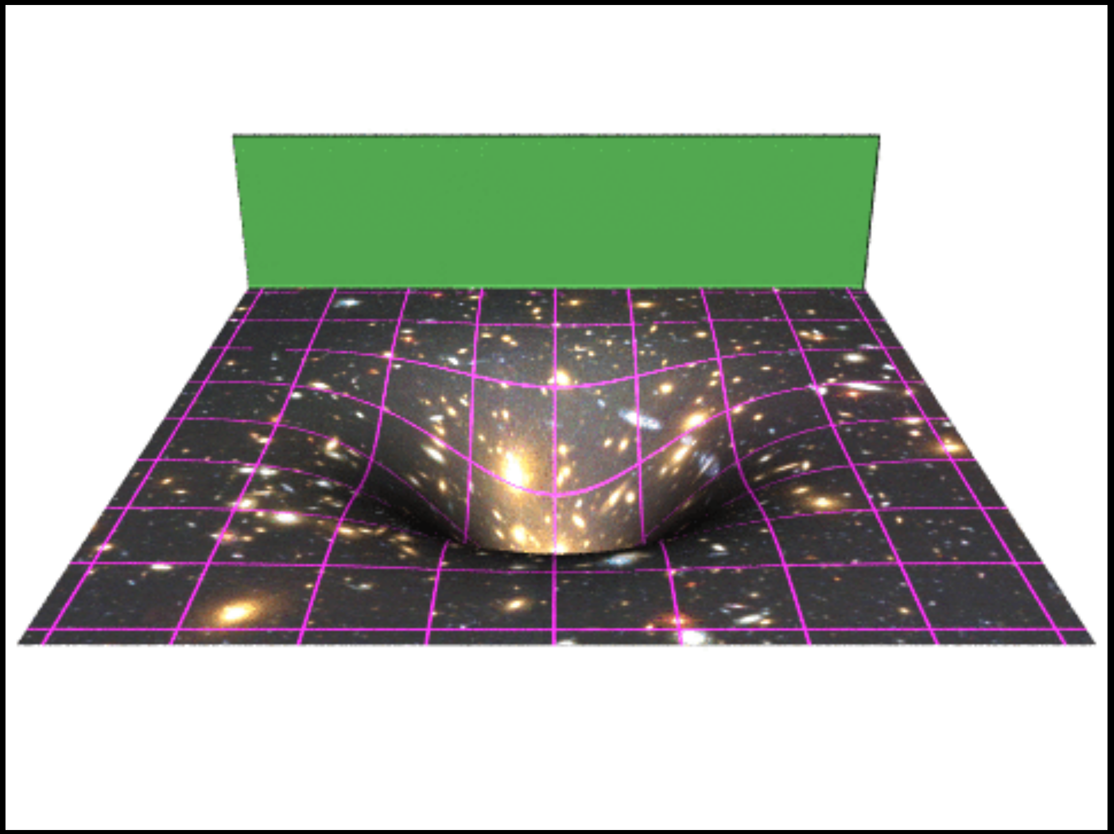

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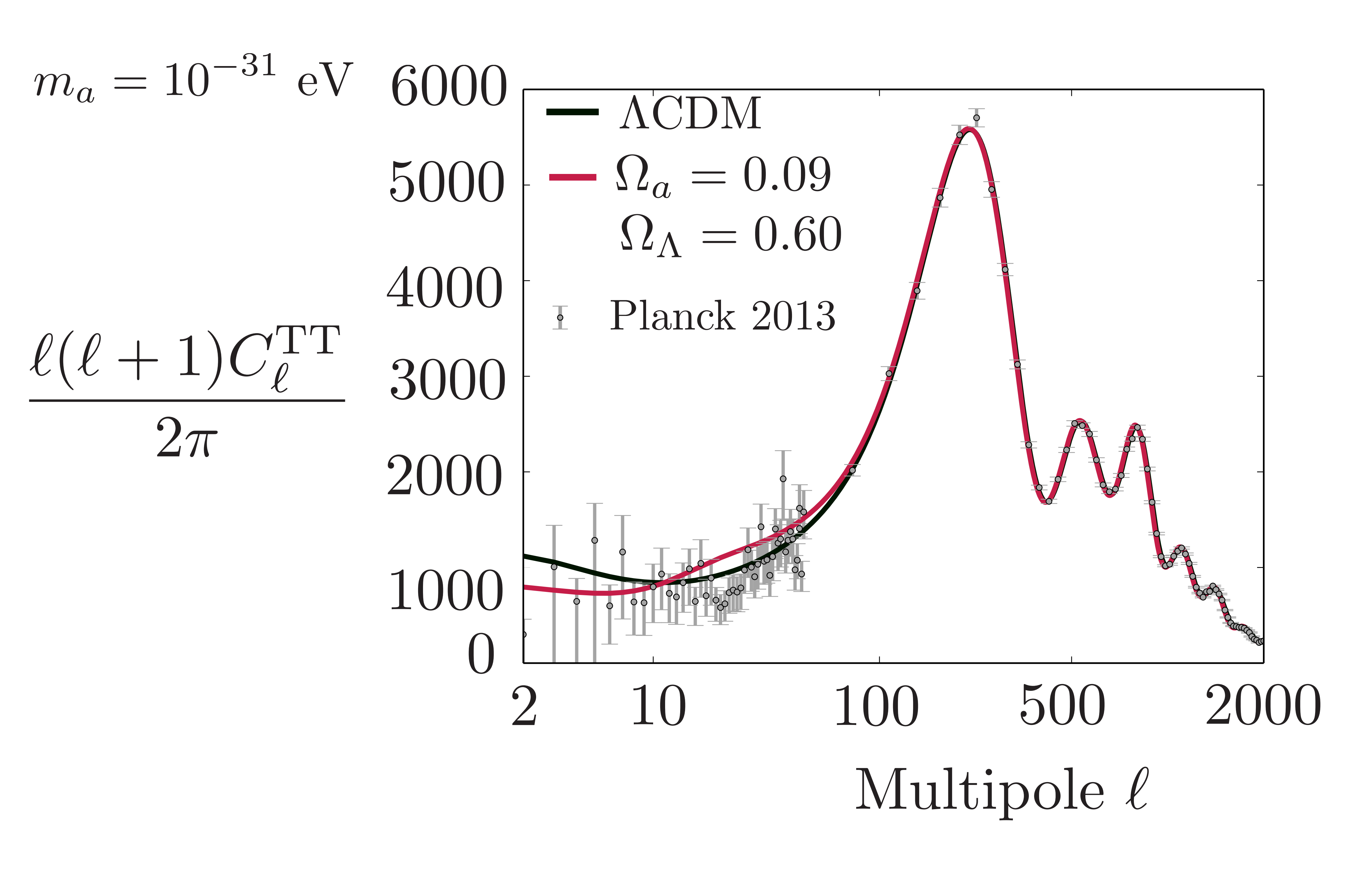
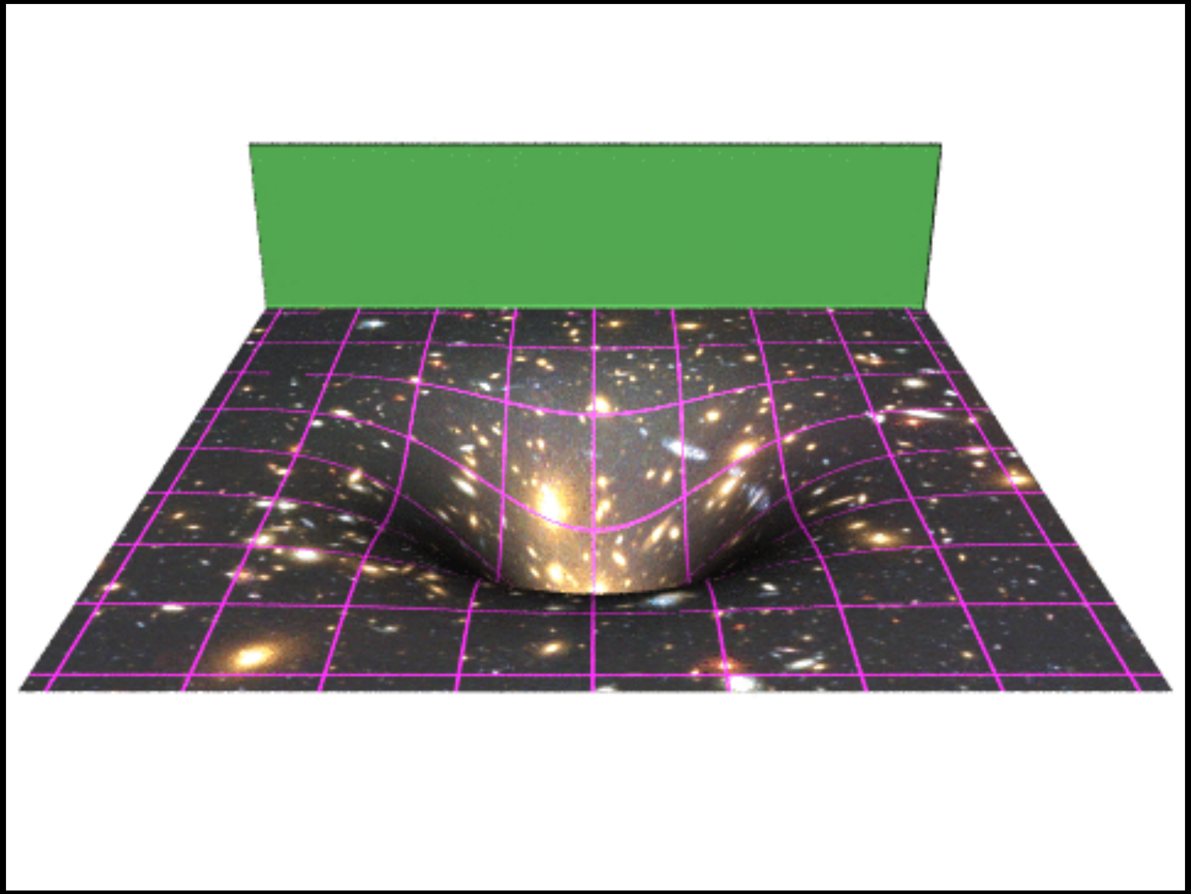


ULAs and the CMB: high mass and early ISW

Higher mass (DM-like) case: high-l ISW



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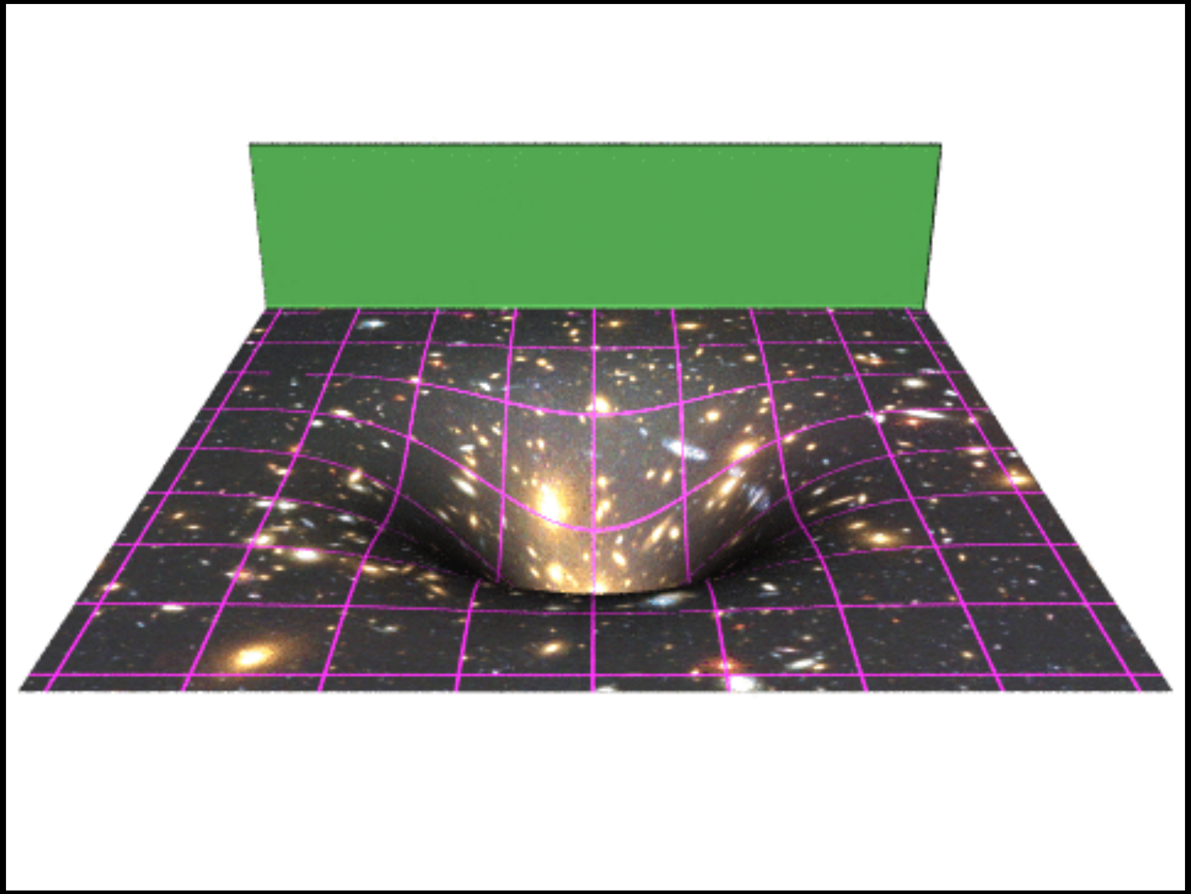

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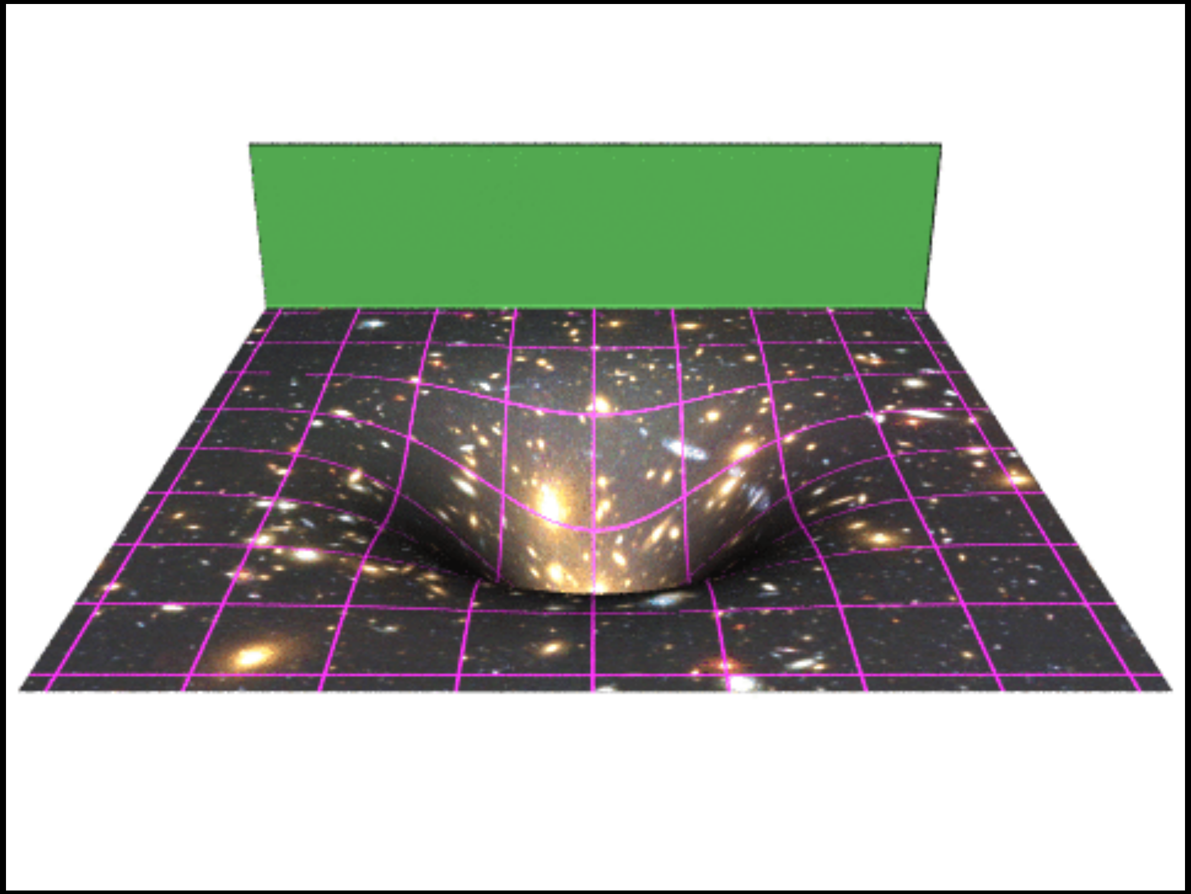
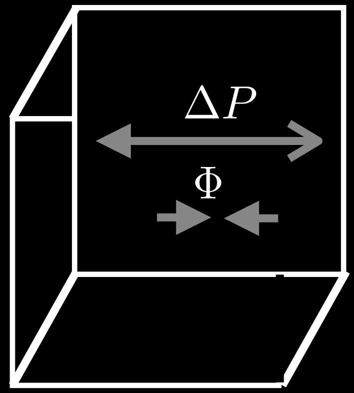


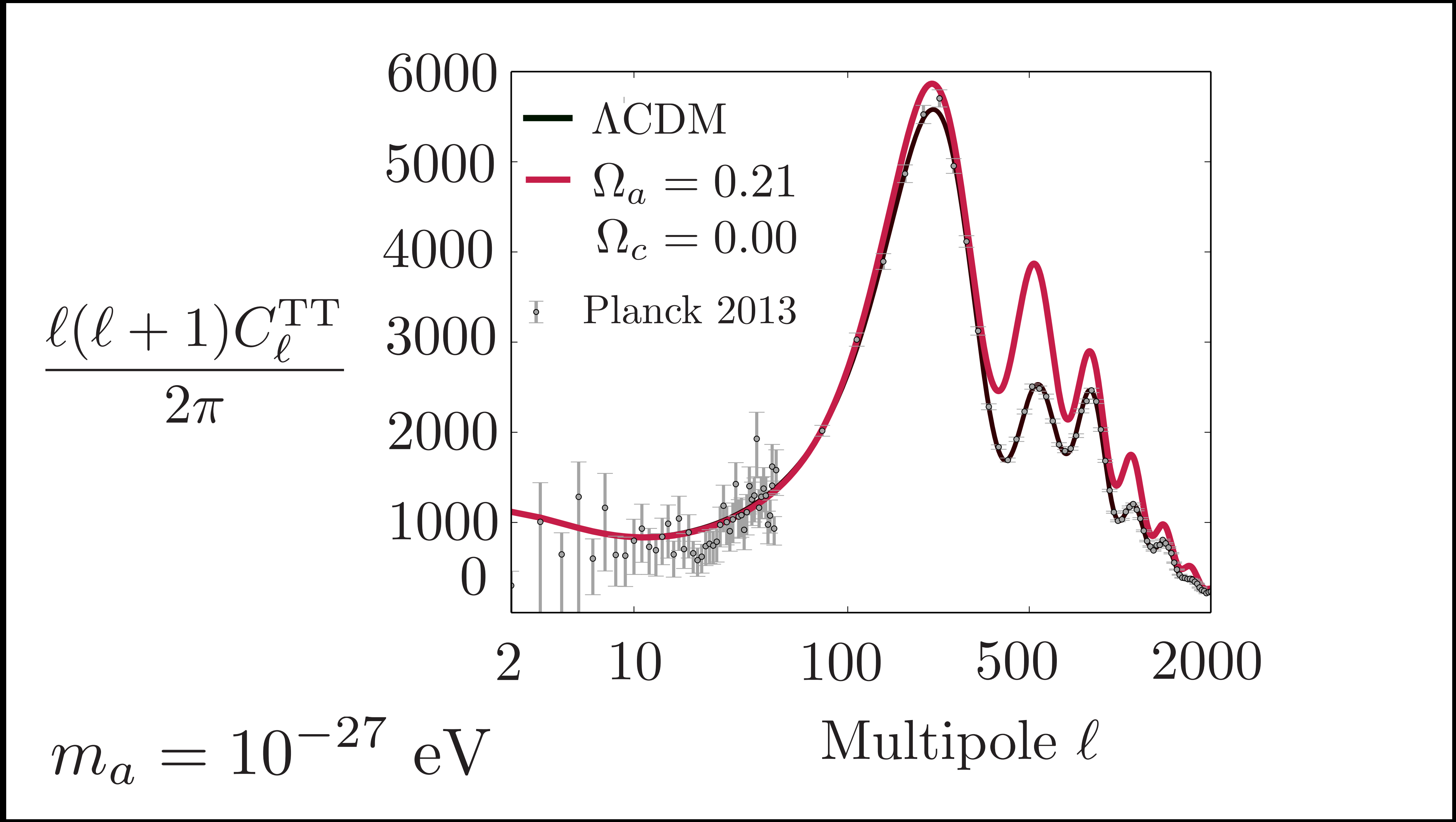
Radiation pressure causes potential decay



$$\Delta P \Delta A > \rho \delta V \nabla \Phi$$

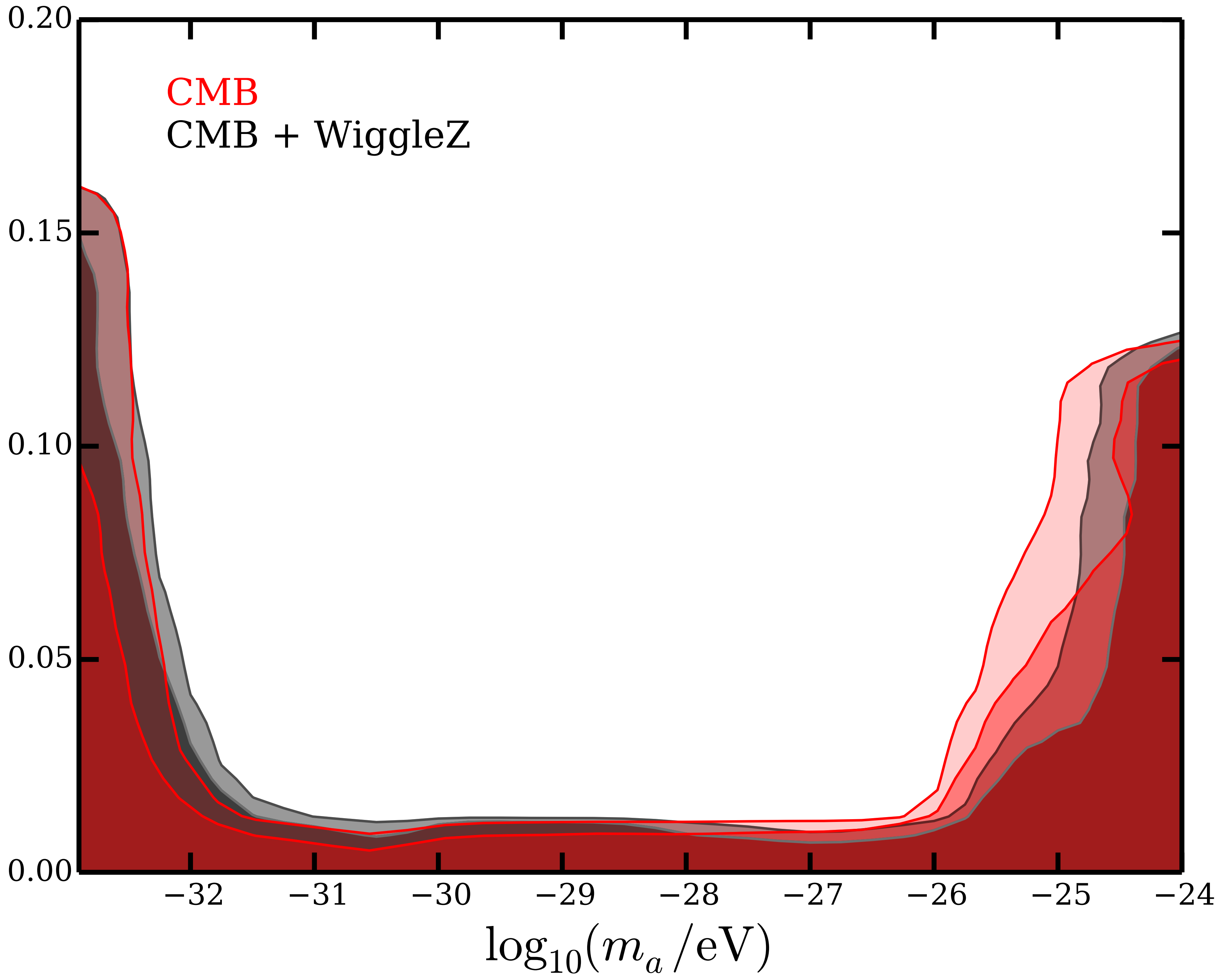
ULAs and the CMB: high mass and early ISW

Higher mass (DM-like) case: high-l ISW



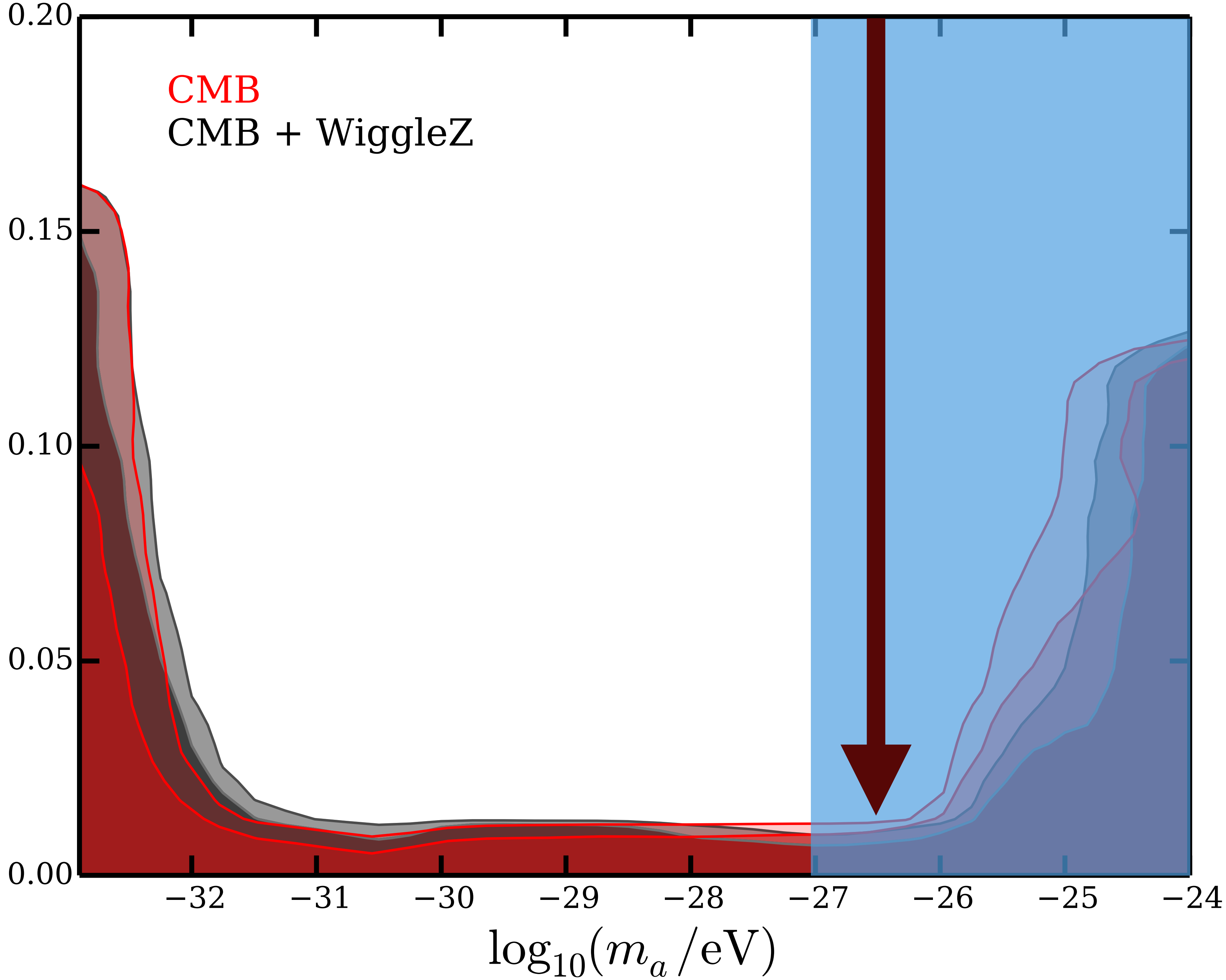
Physics behind the constraints

$$\frac{\rho_{\rm axion}}{\rho_{\rm tot}}$$



Dark-matter type axions

$$\frac{\rho_{\text{axion}}}{\rho_{\text{tot}}}$$



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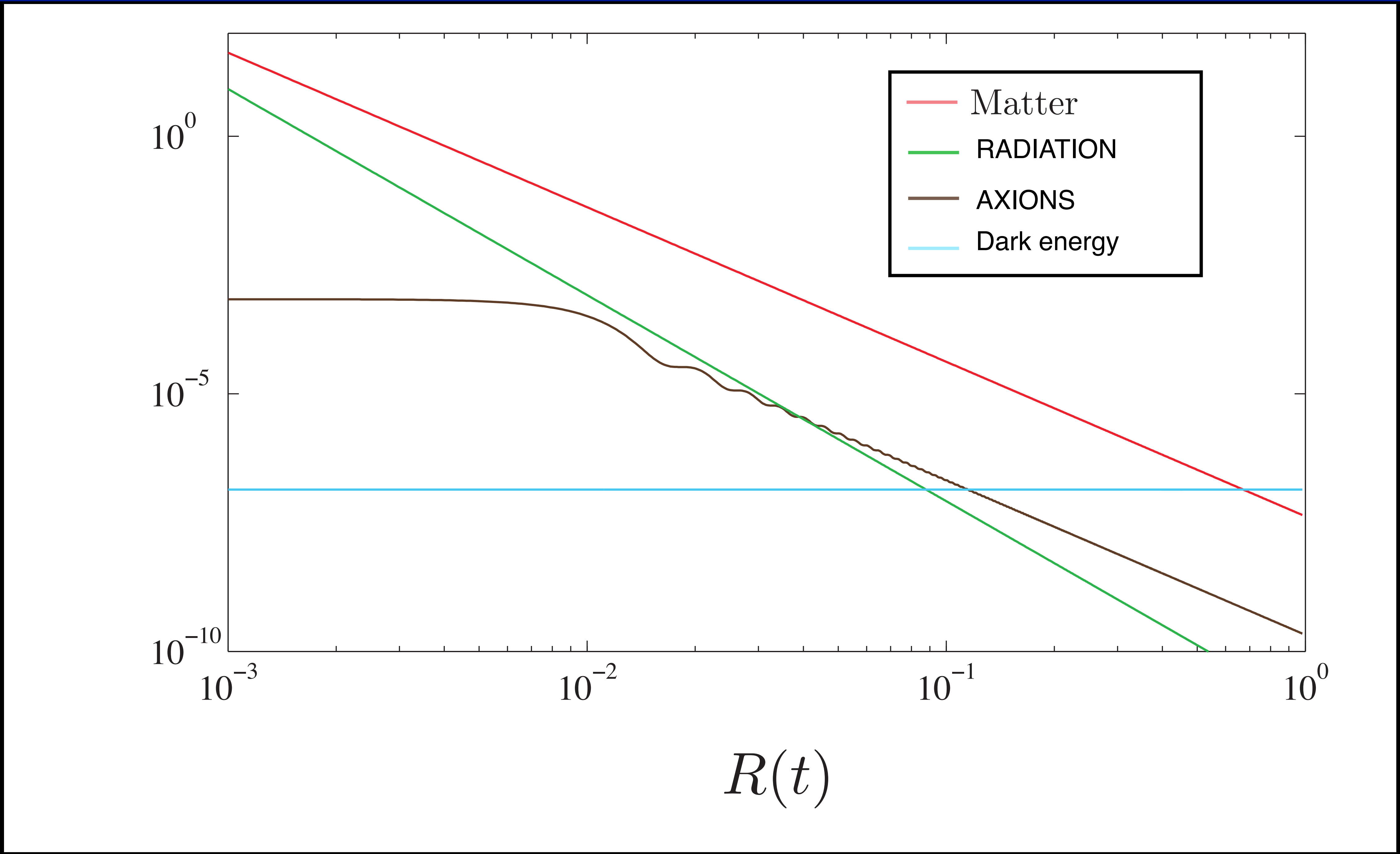
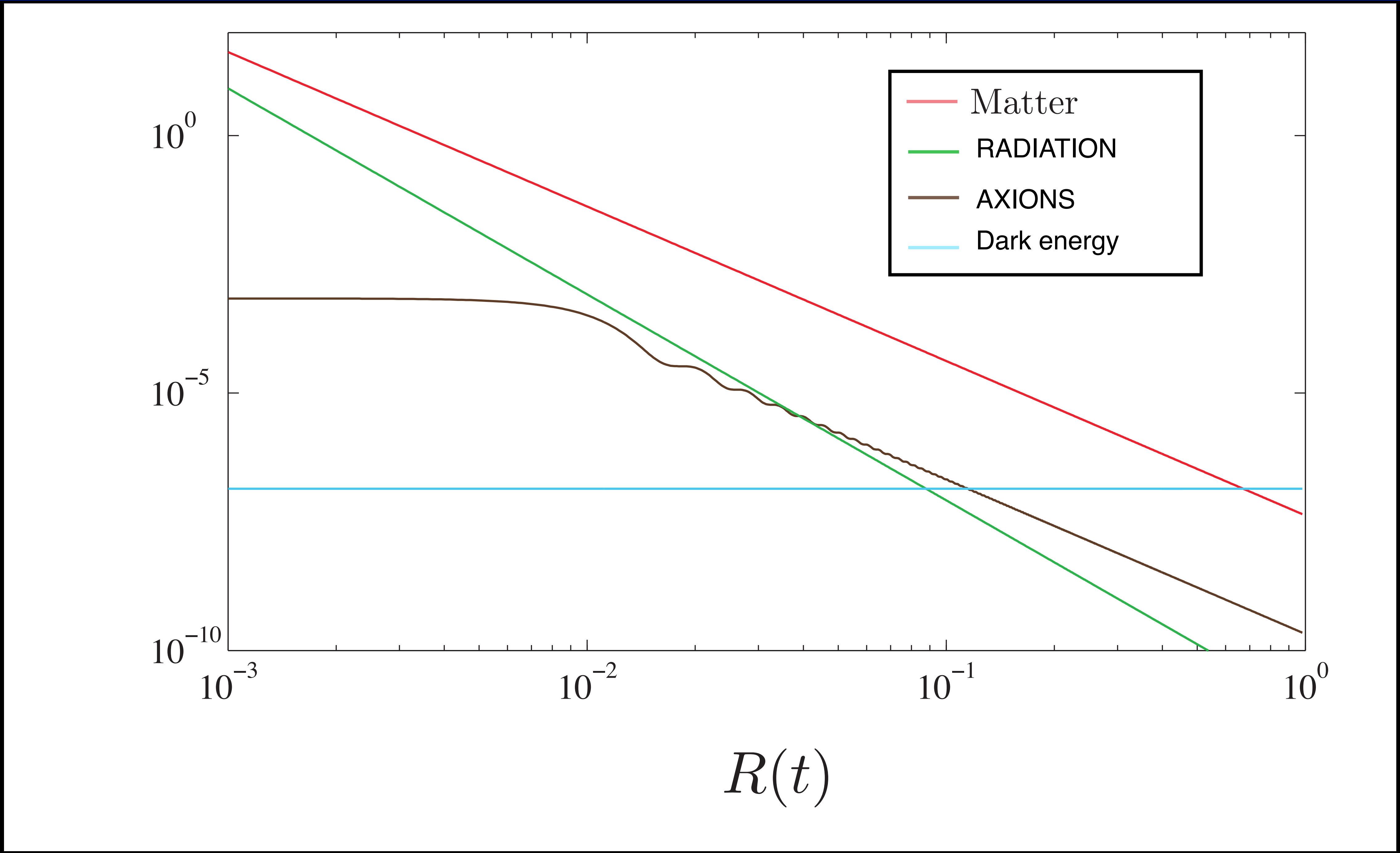


Matter-radiation balance changed at z~3400

ULAs and the CMB: high mass and early ISW



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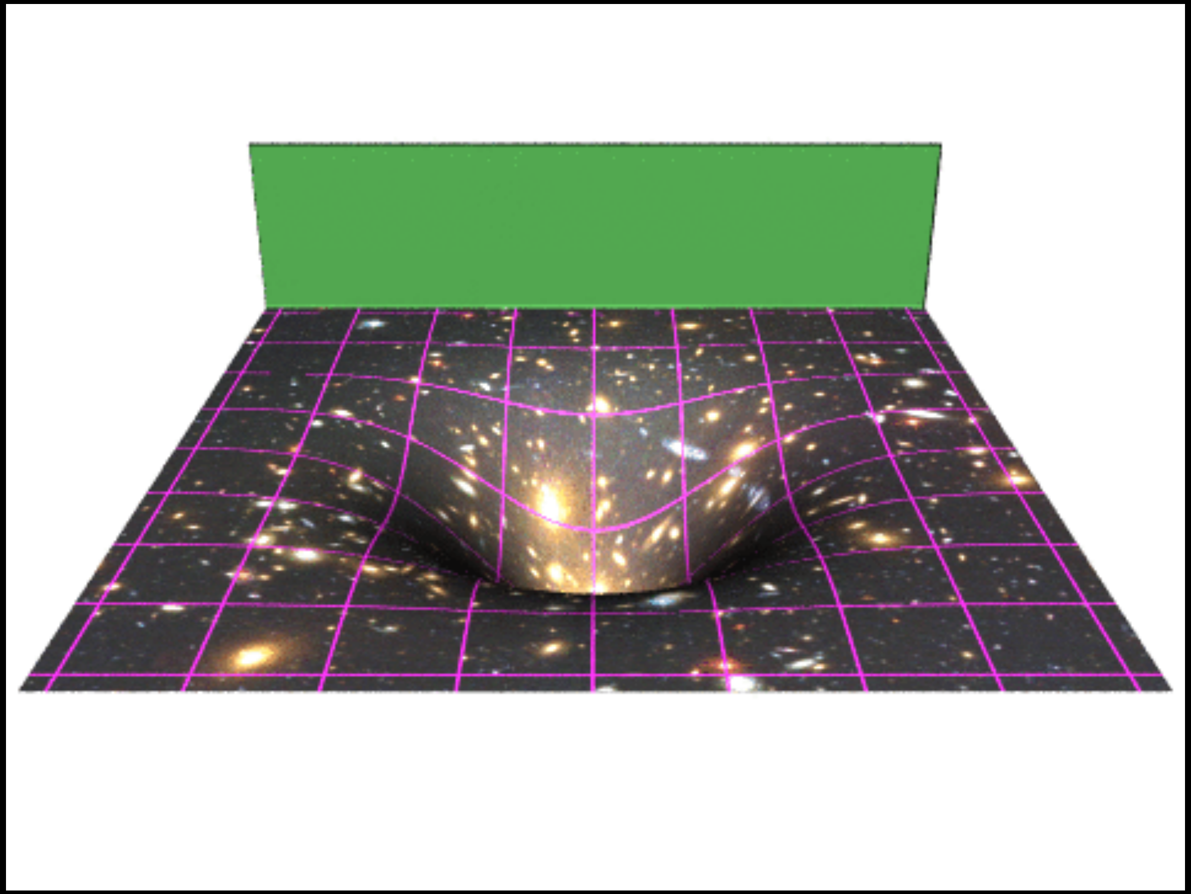

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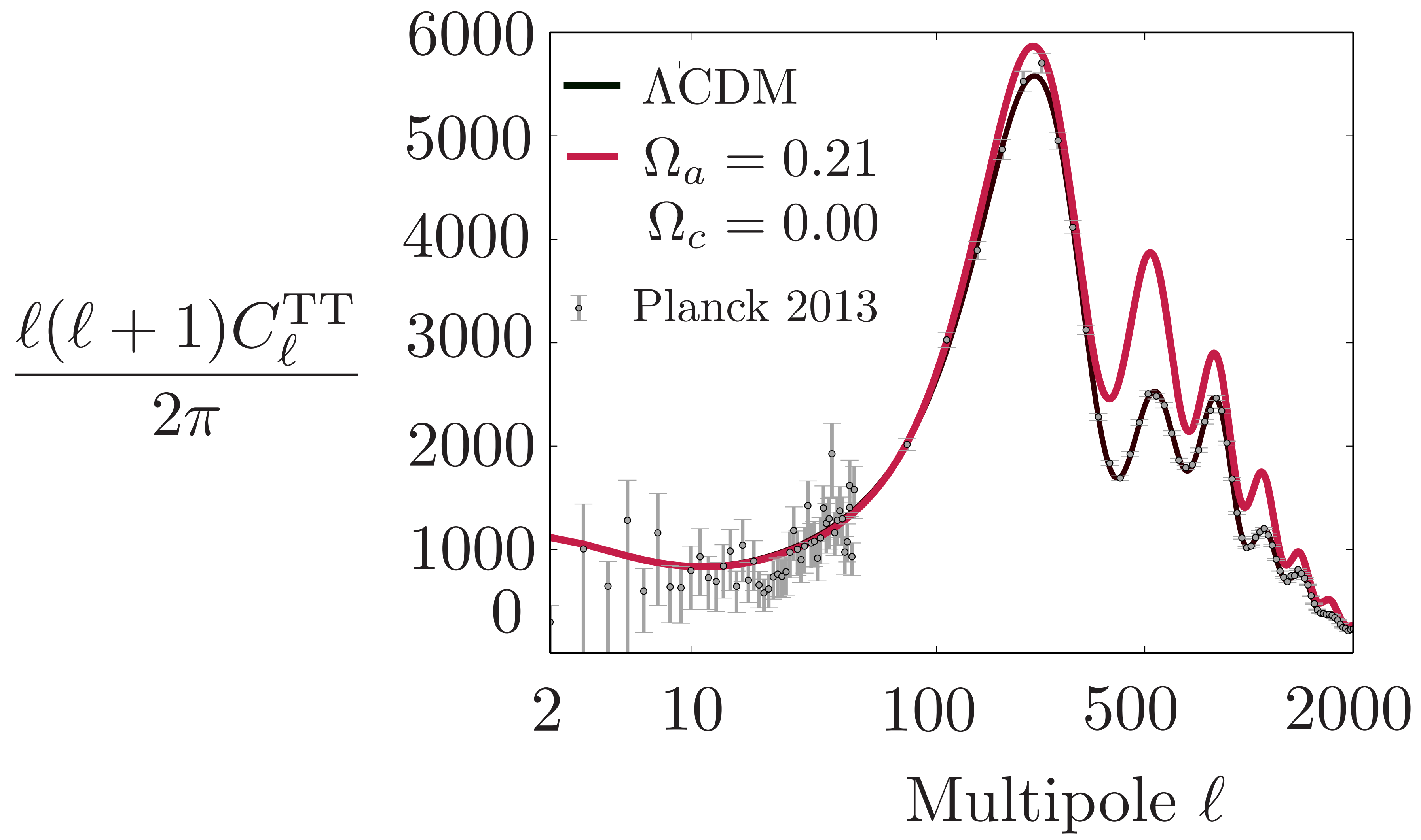
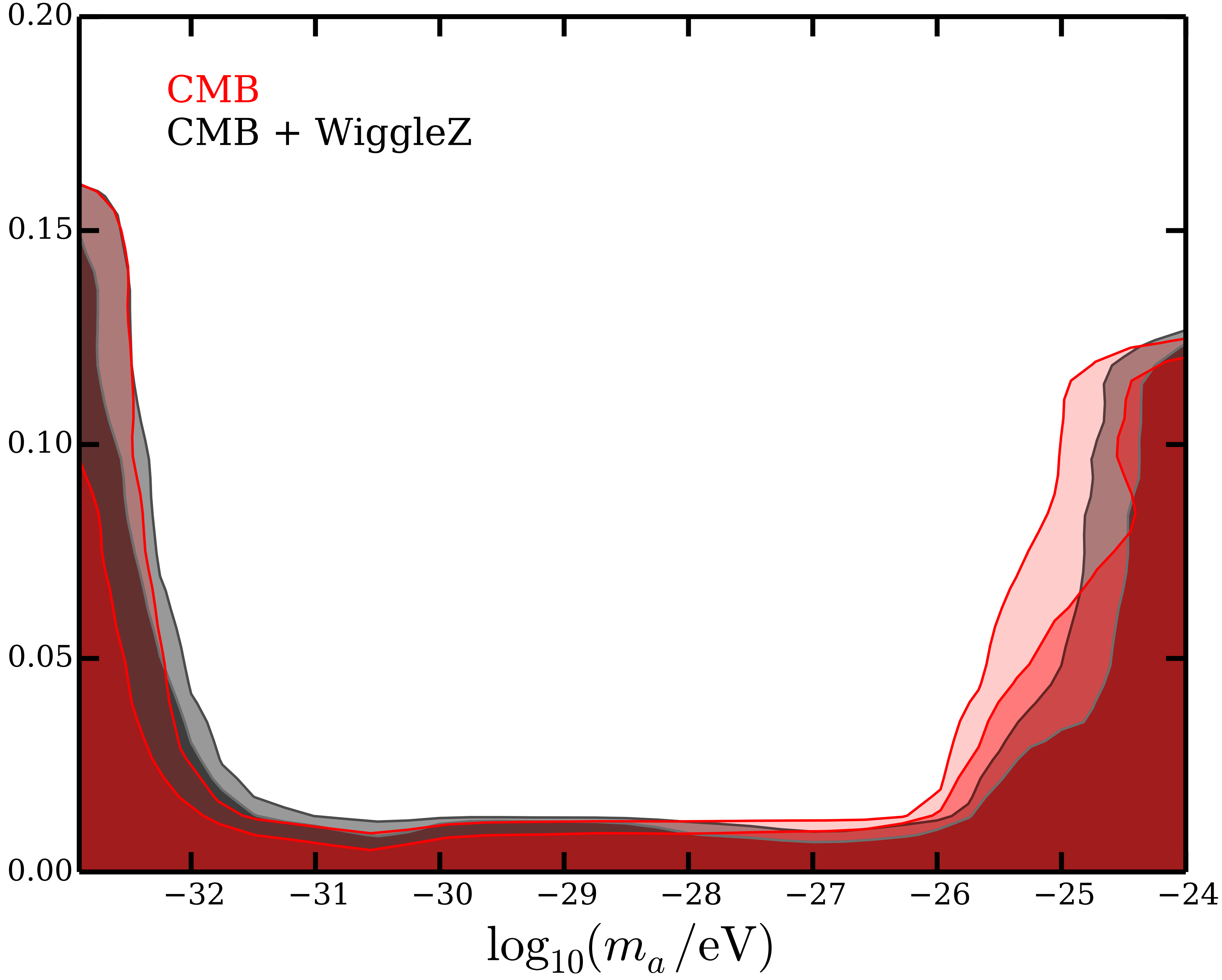


PHYSICS BEHIND THE CONSTRAINTS

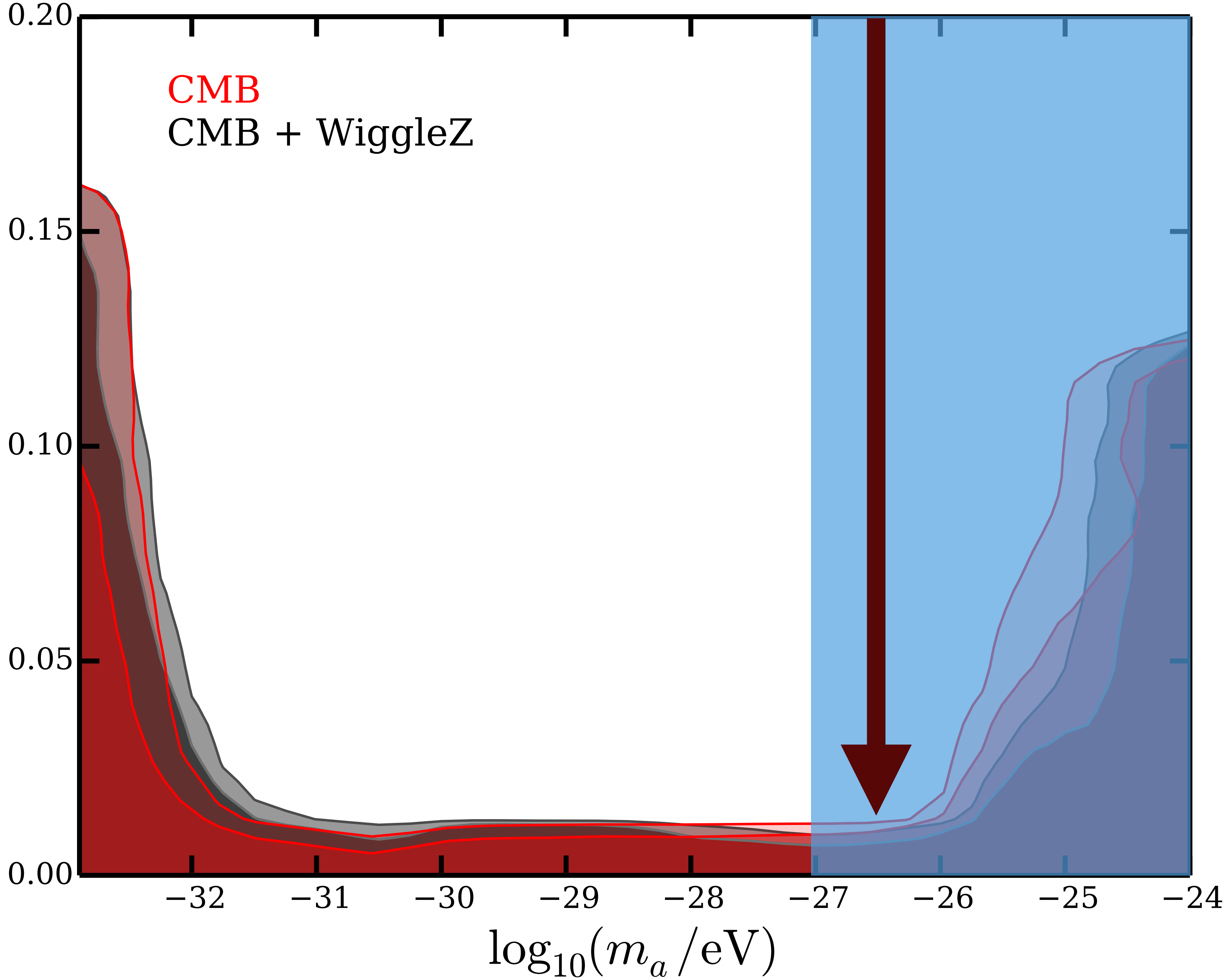
$$\frac{\rho_{\rm axion}}{\rho_{\rm tot}}$$



Physics behind the constraints

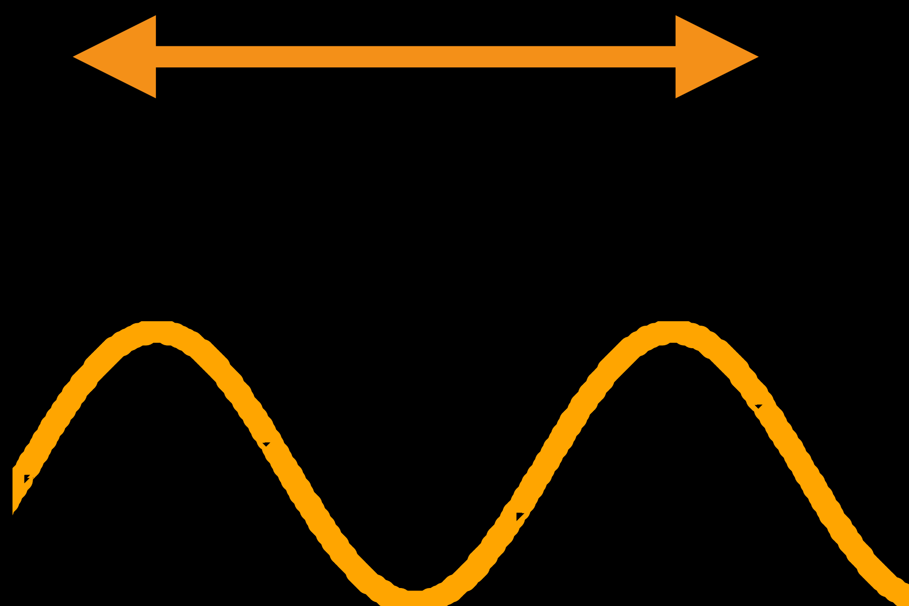
Dark-matter type axions

$$\frac{\rho_{\rm axion}}{\rho_{\rm tot}}$$

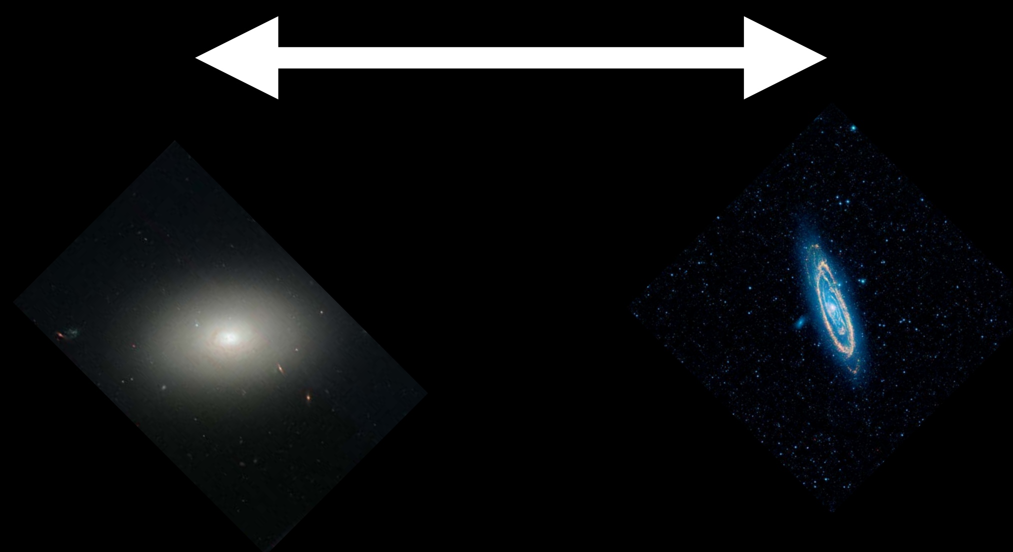


Look for ultra-light axions in the cosmos

Axion deBroglie wavelength



Astronomical length scale
kilo-lightyear – giga-lightyear!



GROWTH OF ULA PERTURBATIONS

- Perturbed Klein-Gordon + Gravity

$$\delta\ddot{\phi} + 2\mathcal{H}\delta\dot{\phi} + (k^2 + m_a^2 a^2)\delta\phi = 4\dot{\Psi}\dot{\phi}_0 - \Psi a^2 m_a^2 \phi_0$$

- Axionic Jeans Scale is macroscopic [in contrast to QCD axion]:

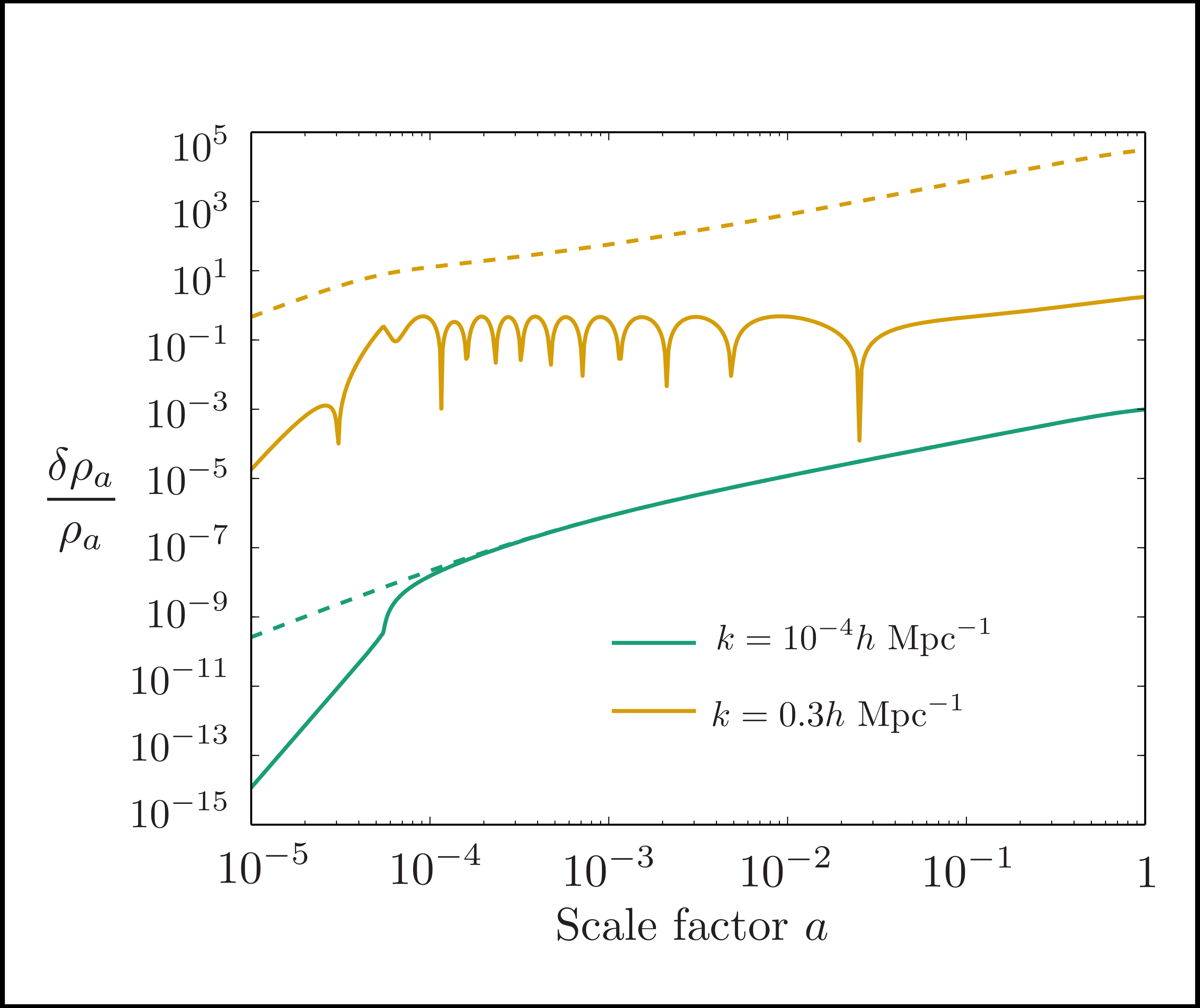
$$\lambda_J = 2.4 h^{-1/2} \left(\frac{m}{10^{-25}\ \mathrm{eV}}\right)^{-1/2} \mathrm{Mpc}$$

- Computing observables is expensive for $m \gg 3\mathcal{H}$:
  - Coherent oscillation time scale $\Delta\eta \sim (ma)^{-1} \ll \Delta\eta_{\mathrm{CAMB}}$
  - WKB approximation

$$\delta\phi = A_c \Delta_c(k,\eta)\cos(m\eta) + A_s \Delta(k,\eta)\sin(m\eta)$$

$$c_a^2 = \frac{\delta P}{\delta\rho} = \frac{k^2/(4m^2a^2)}{1 + k^2/(4m^2a^2)}$$

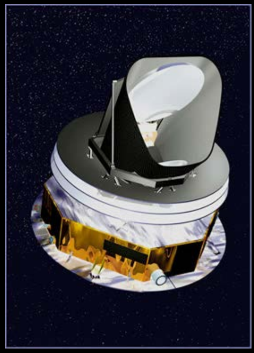
Growth of ULA perturbations

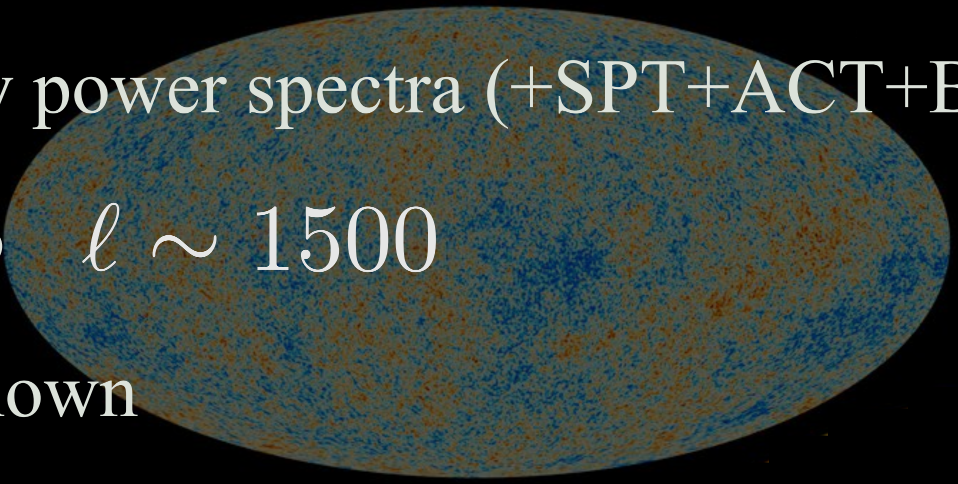


✳ Modes with $k \gg k_J \sim \sqrt{m\mathcal{H}}$ oscillate instead of growing

✳ "Pressure" stabilization

DATA

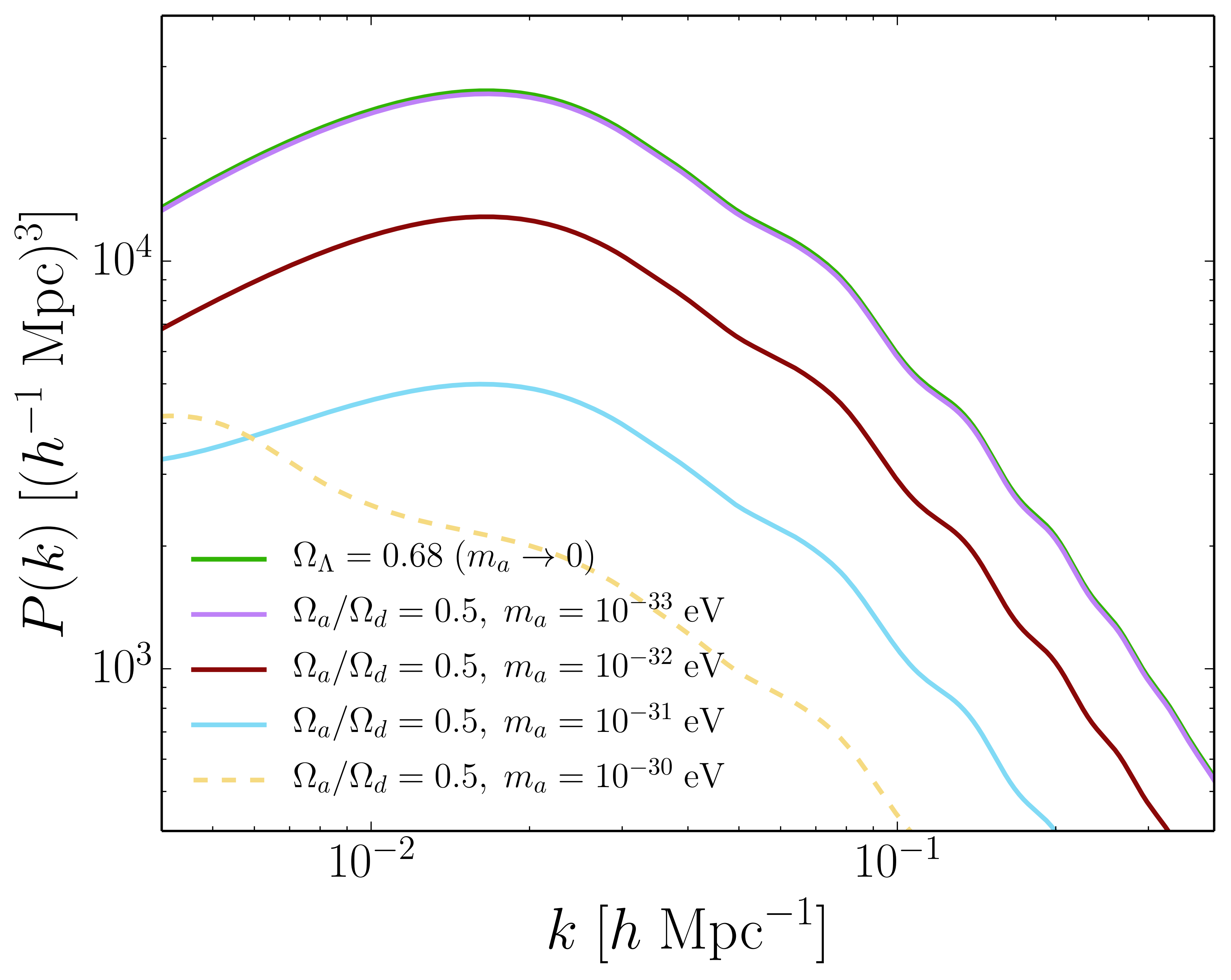




- Planck 2013 temperature anisotropy power spectra (+SPT+ACT+BAO)
  - Cosmic variance limited to $\ell \sim 1500$
  - Power spectrum already shown

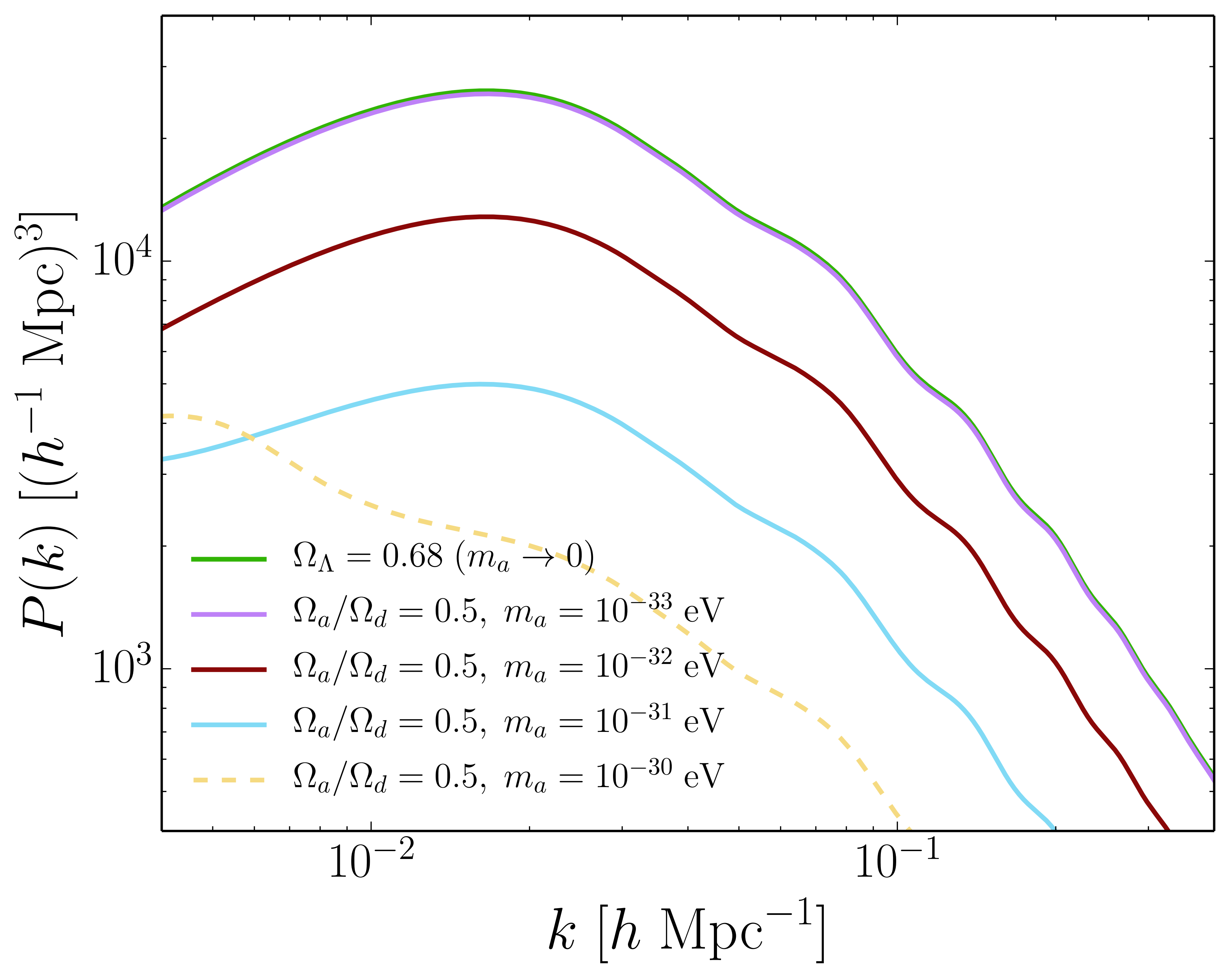
- WiggleZ galaxy survey (linear scales only $k \lesssim 0.2h\ \mathrm{Mpc}^{-1}$)
  - Galaxy bias marginalized over
  - Theory P(k) convolved with survey window function
  - 240,000 emission line galaxies at z<1
  - 3.9 m Anglo-Australian Telescope (AAT)

Matter power spectrum for ULA (in DE regime)



θ_s

Matter power spectrum for ULA (in DE regime)



θ_s fixed to lock CMB

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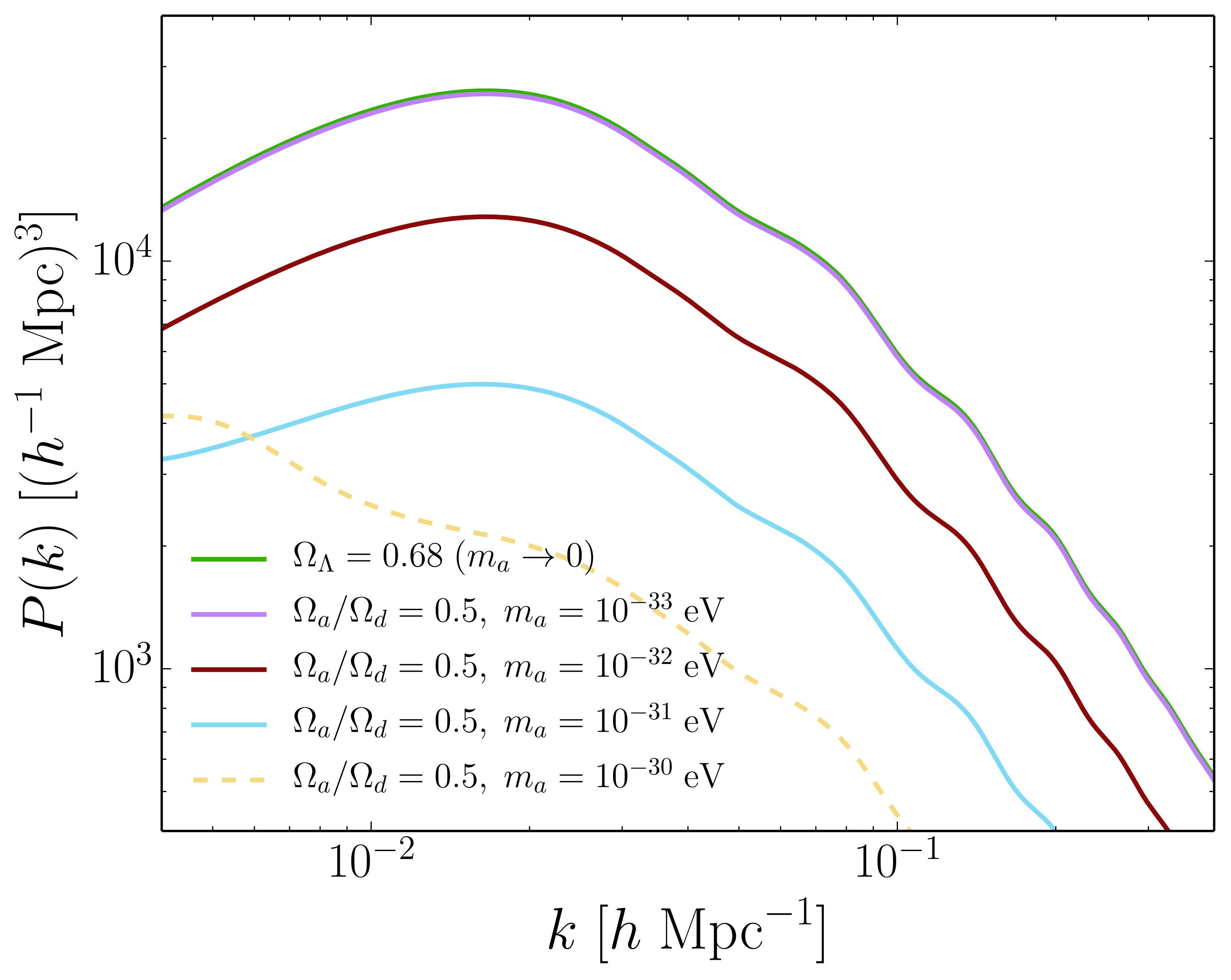


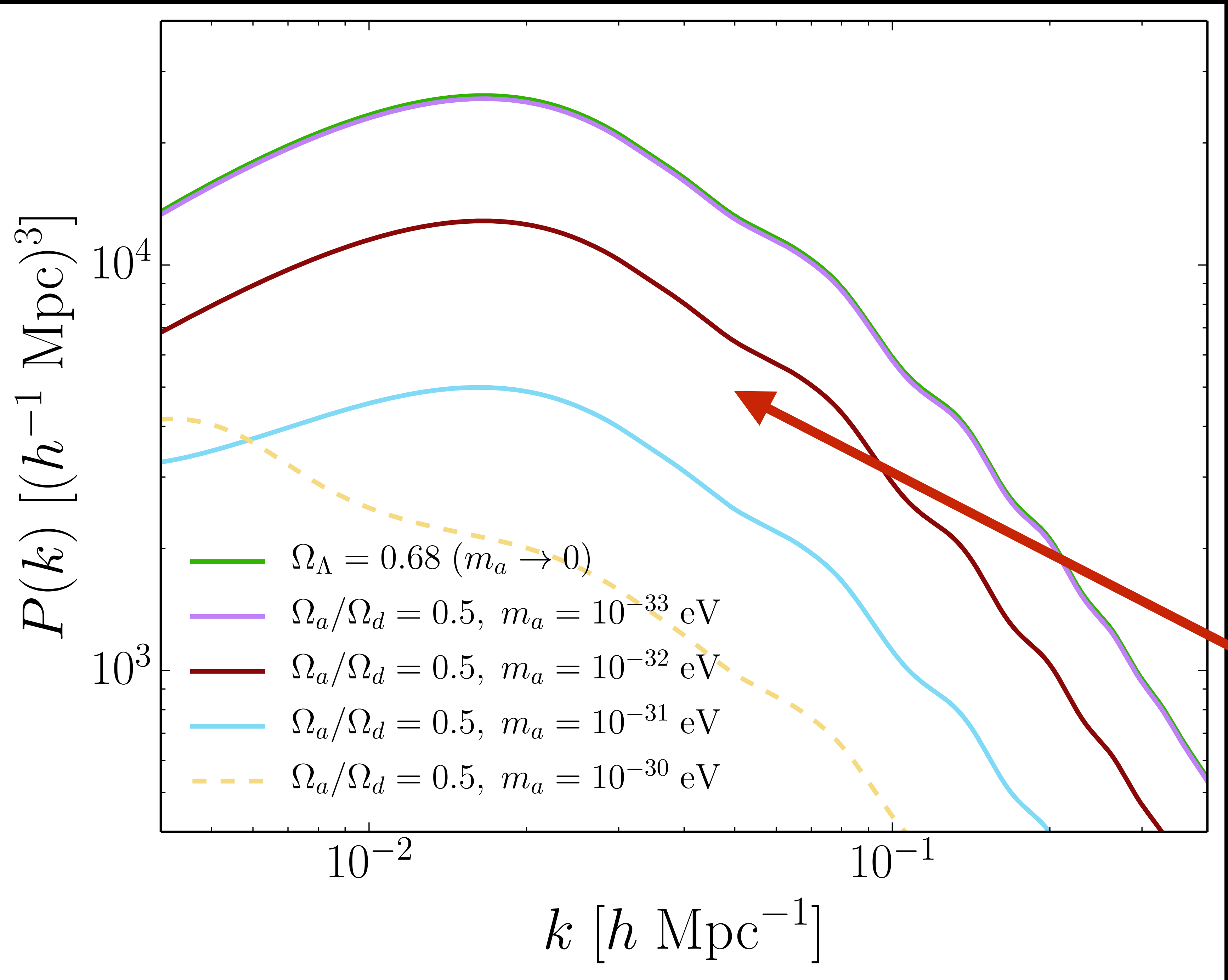
θ_s fixed to lock CMB

H_0 ↓

$$1 + z_{eq} = \frac{\Omega_m h^2}{\rho_{\rm rad}}$$

Matter-radiation equality delayed

Matter power spectrum for ULA (in DE regime)



θ_s fixed to lock CMB

H_0 ↓

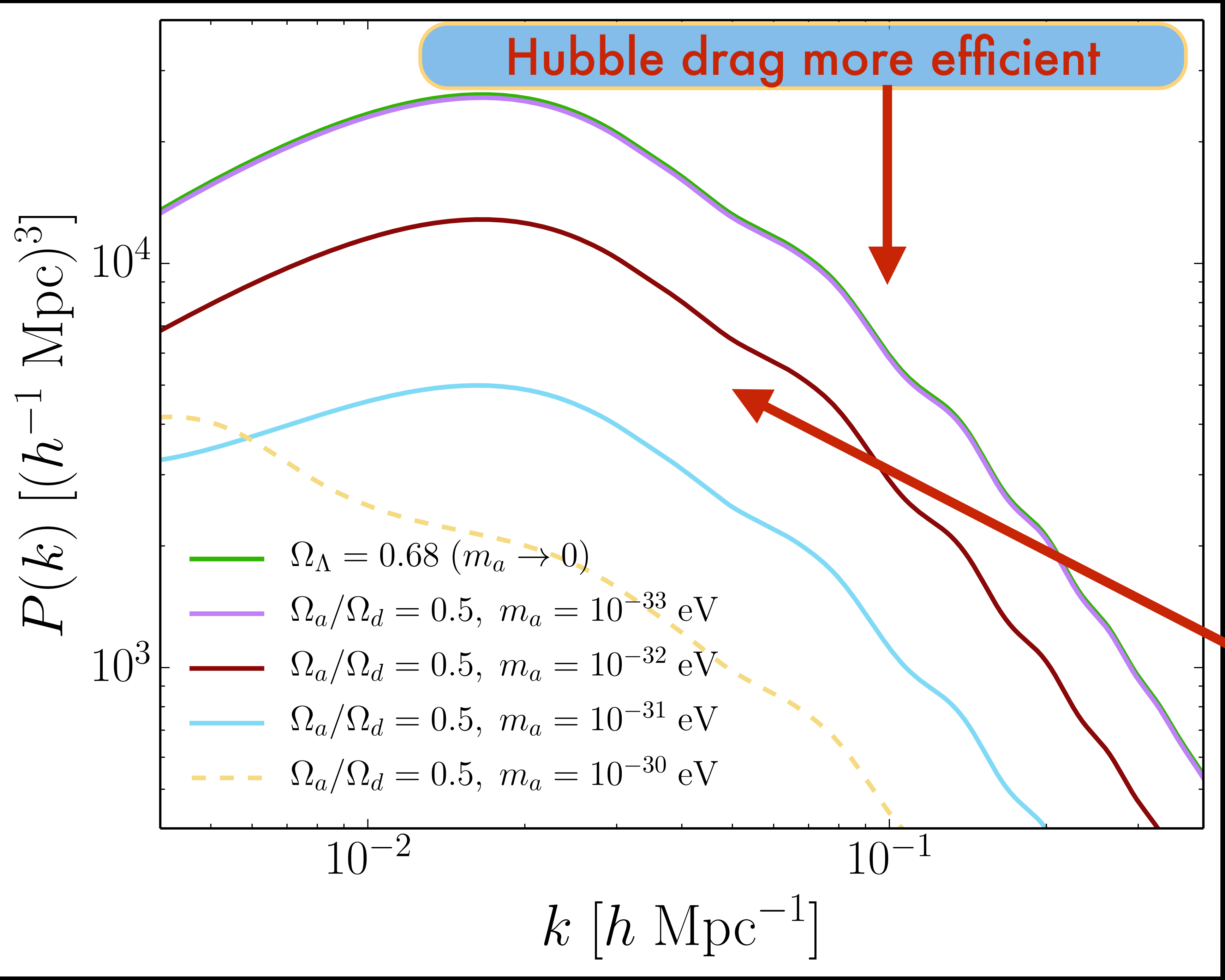
$k_{eq} = \lambda^{-1}_{\mathrm{horizon,eq}}$ ↓

Peak of P(k) to lower k

$$1 + z_{eq} = \frac{\Omega_m h^2}{\rho_{\mathrm{rad}}}$$

Matter-radiation equality delayed

Matter power spectrum for ULA (in DE regime)



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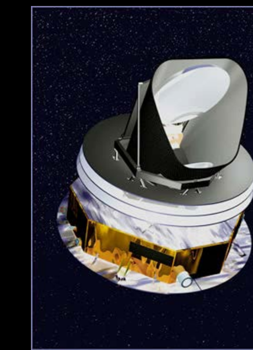
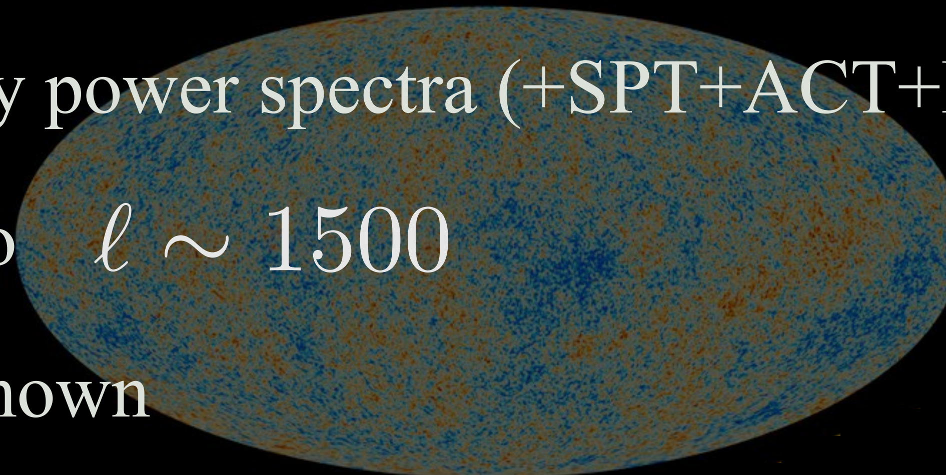
Data





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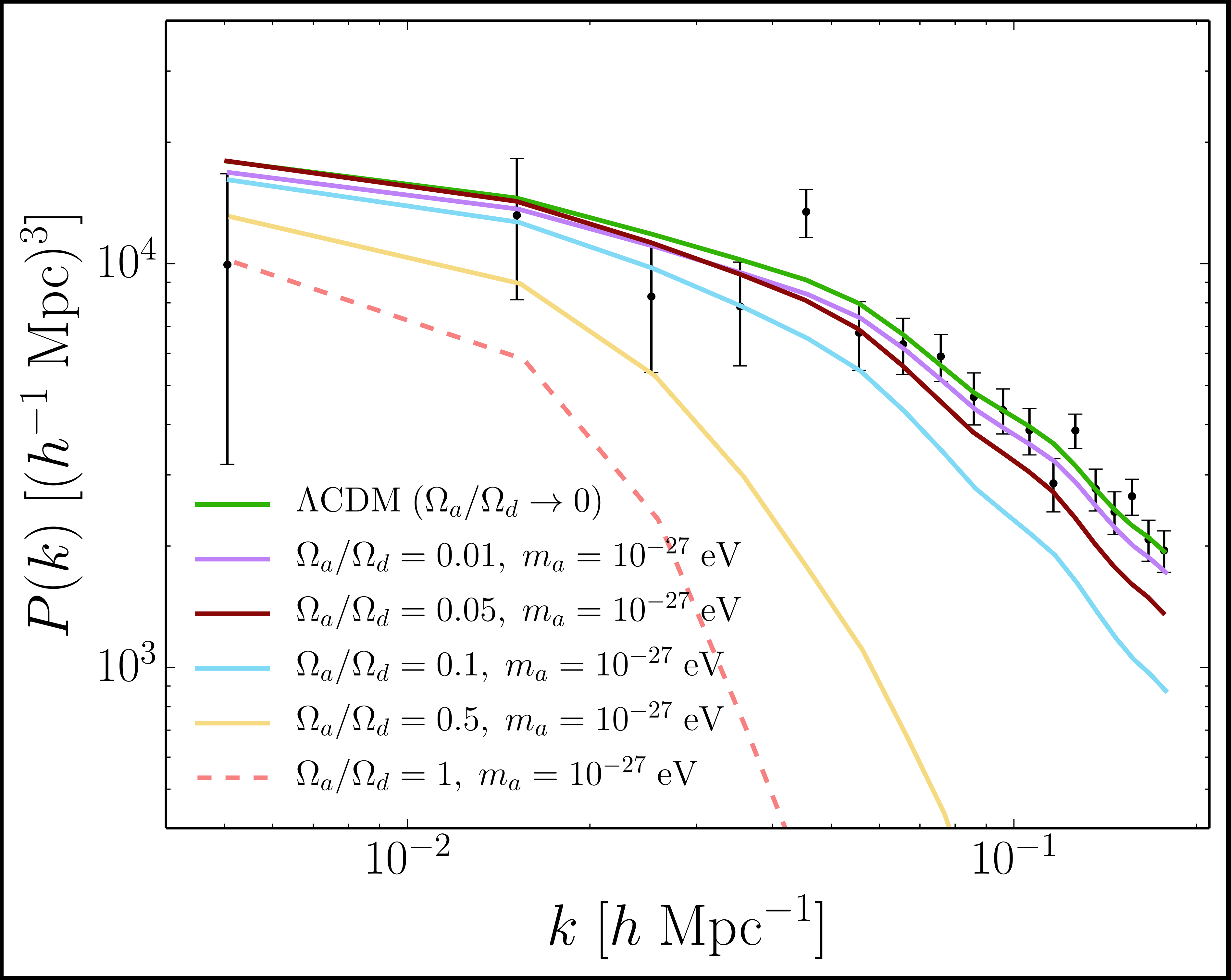
Data



$P(k)\ [(h^{-1}\ \mathrm{Mpc})^3]$
10^4
10^3
10^{-2}
10^{-1}
$k\ [h\ \mathrm{Mpc}^{-1}]$
ΛCDM $(\Omega_a/\Omega_d \to 0)$
$\Omega_a/\Omega_d = 0.01,\ m_a = 10^{-27}$ eV
$\Omega_a/\Omega_d = 0.05,\ m_a = 10^{-27}$ eV
$\Omega_a/\Omega_d = 0.1,\ m_a = 10^{-27}$ eV
$\Omega_a/\Omega_d = 0.5,\ m_a = 10^{-27}$ eV
$\Omega_a/\Omega_d = 1,\ m_a = 10^{-27}$ eV

Difficult parameter space

$$m_a, \Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\rm reion}$$

Difficult parameter space

$$m_a, \Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\text{reion}}$$

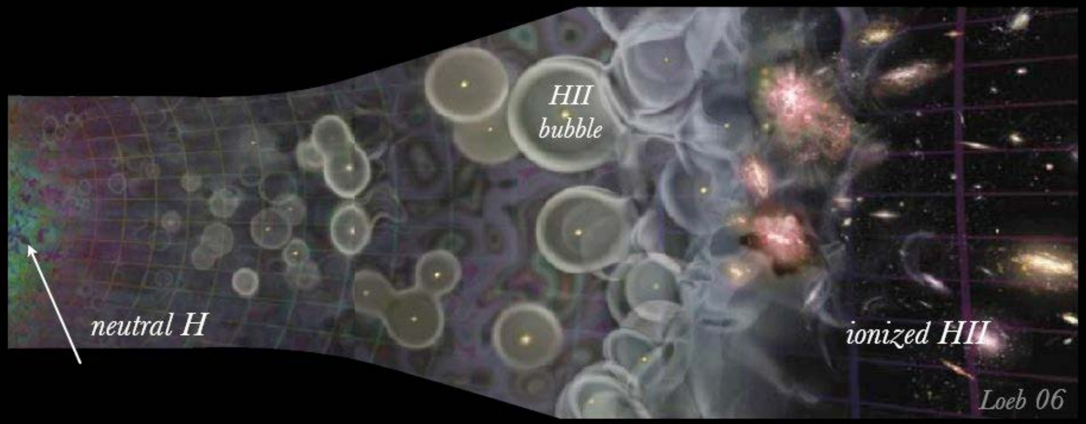
$$\Delta^2_{\mathcal{R}}(k) \equiv A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

Initial conditions

Difficult parameter space

$$m_a, \Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\rm reion}$$

$$\tau_{\rm reion} = \int dl n_e \sigma_T$$



Difficult parameter space

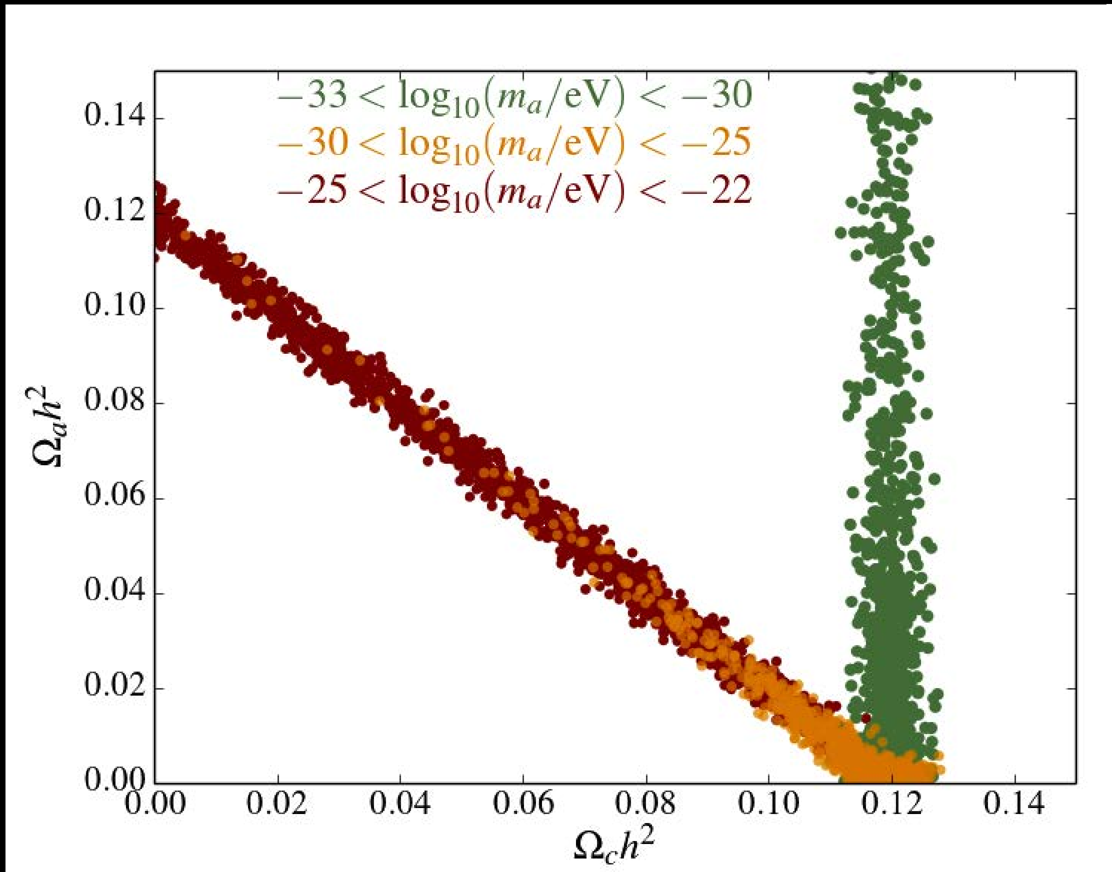
$$m_a, \Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\rm reion}$$

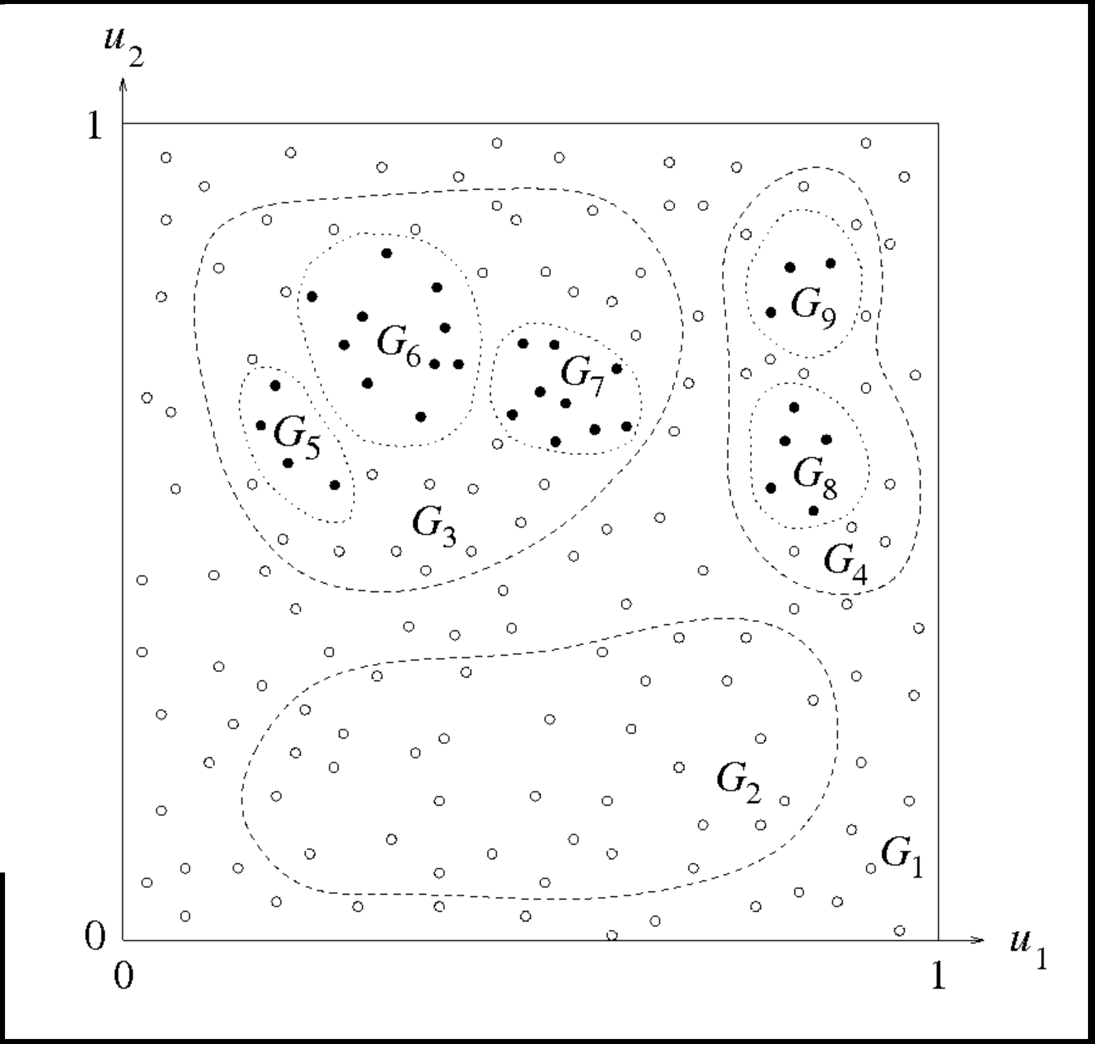
AxiCAMB

Compare with data
Explore posterior using Monte Carlo
Markov Chain (MCMC)

Difficult parameter space

$$m_a, \Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\rm reion}$$





Addressed using nested sampling

MULTINEST (Hobson, Feroz, others 2008)

Parameter space

$$m_a, \Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\rm reion}$$

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ULA parameters

Parameter space

$$m_a, \Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\rm reion}$$

Densities of standard species

Parameter space

$$m_a, \Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\rm reion}$$

$$\Delta^2_{\mathcal{R}}(k) \equiv A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

Initial conditions

Parameter space

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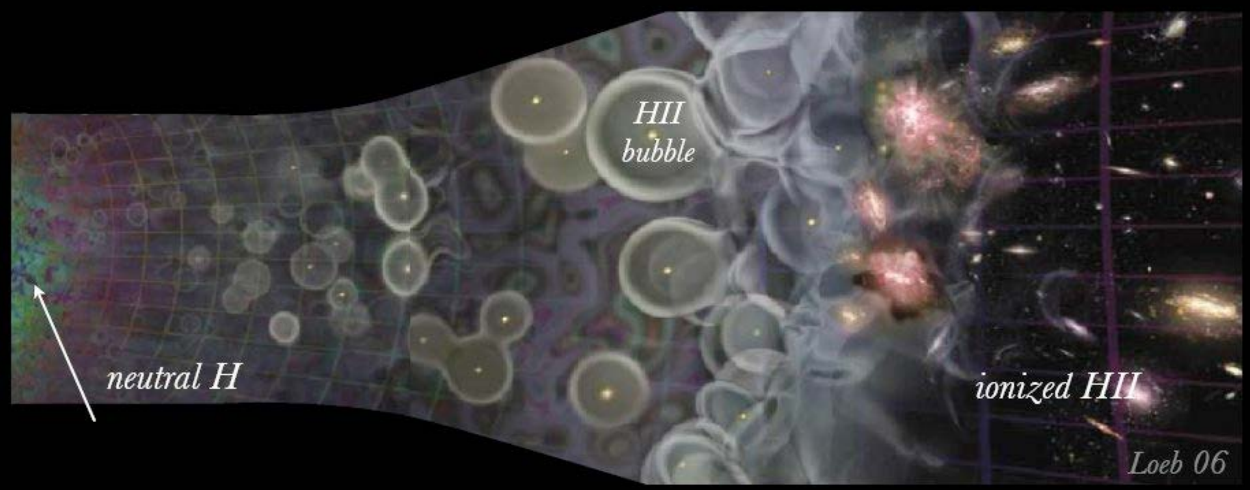

Parameter space

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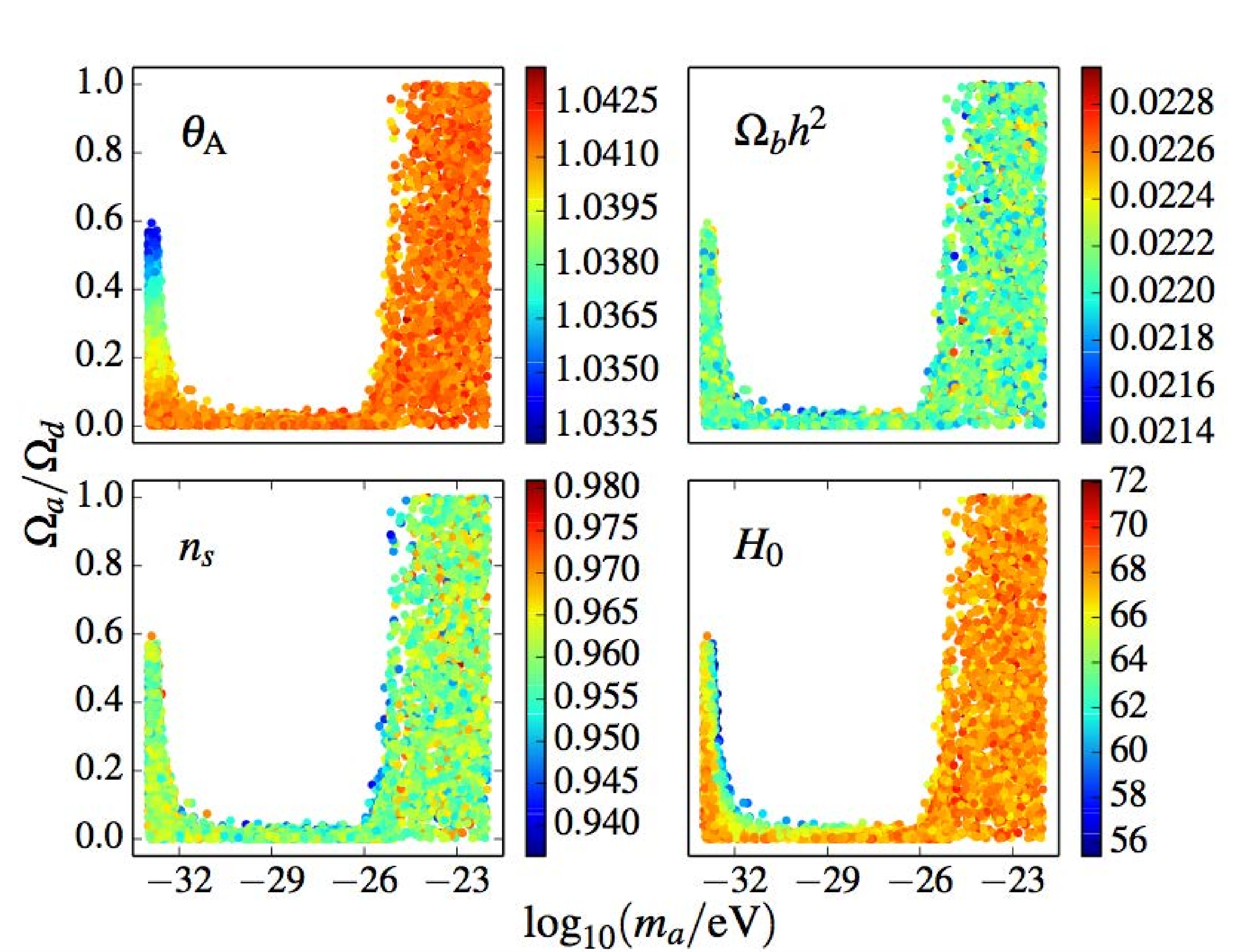
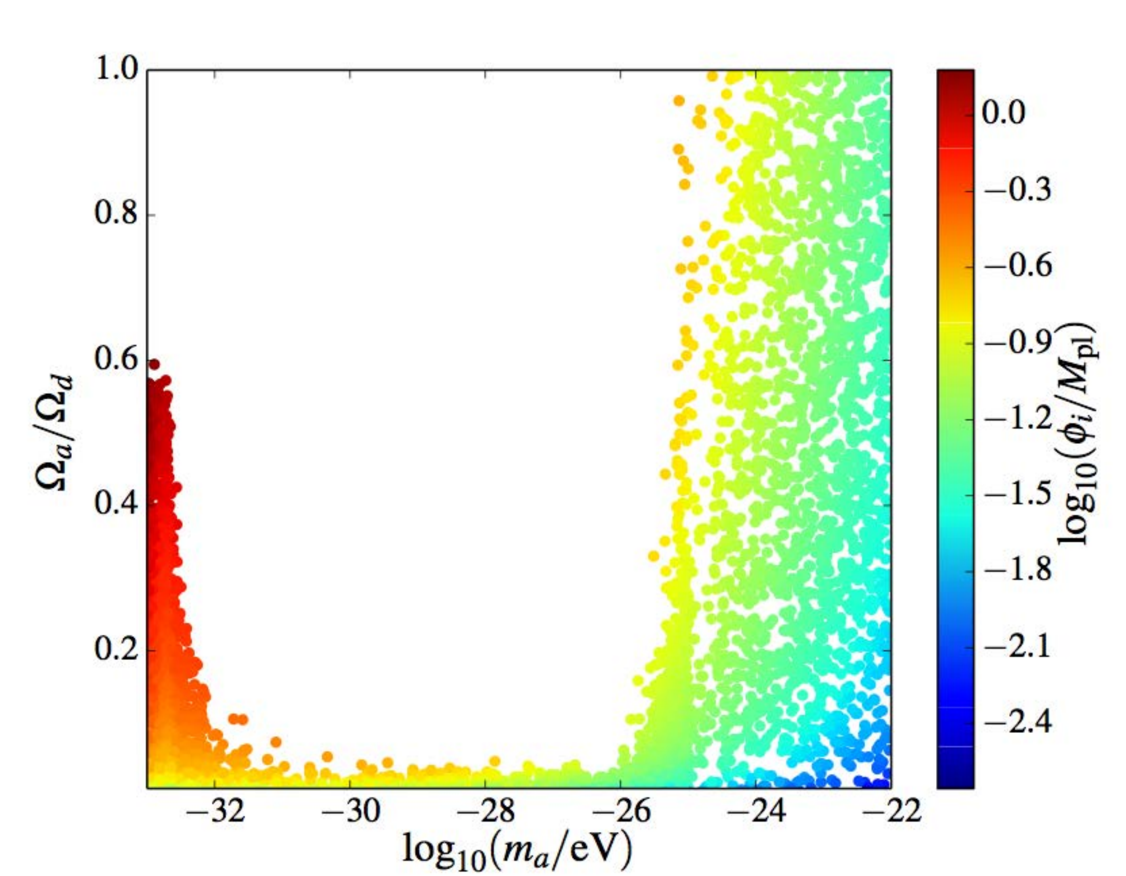
AxionCAMB

Compare with data

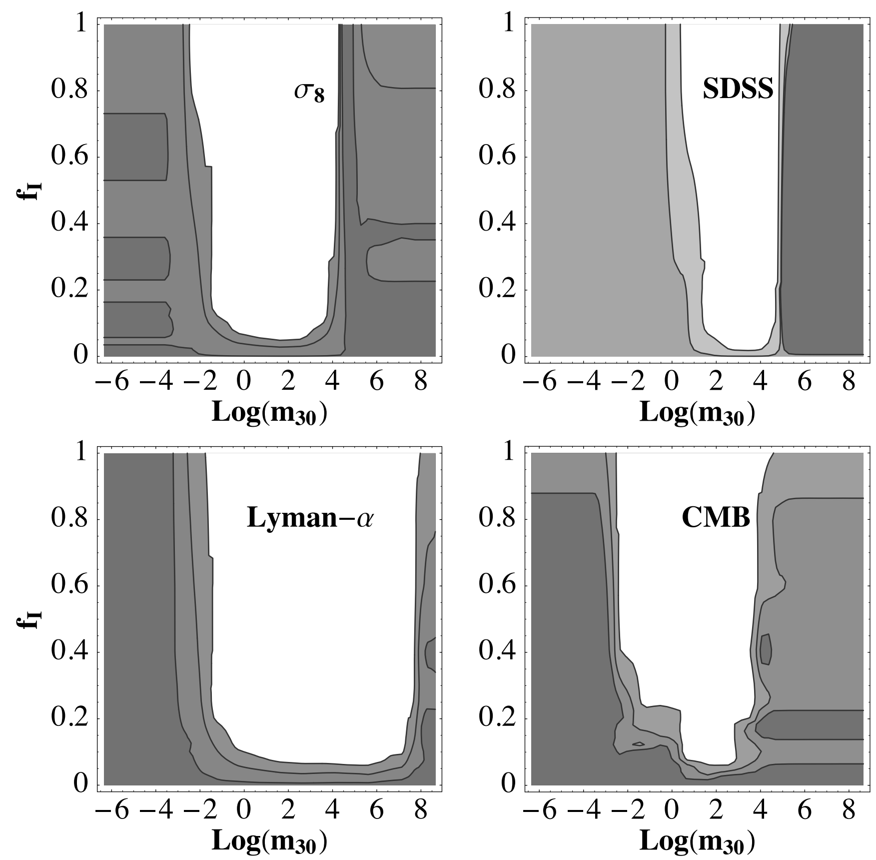
Explore posterior using Nested sampling

Degeneracies/Weak gravity conjecture





Amendola and Barbieri



Old power spectrum constraints from Amendola and Barbieri, arXiv:hep-ph/0509257

1) Grid search

2) No isocurvature

3) No marginalization over foregrounds

4) No lensing, no polarization

5) No real Boltzmann code [step in power spectrum, or unclustered DE at low m]

Difficult parameter space

$$m_a, \Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\text{reion}}$$

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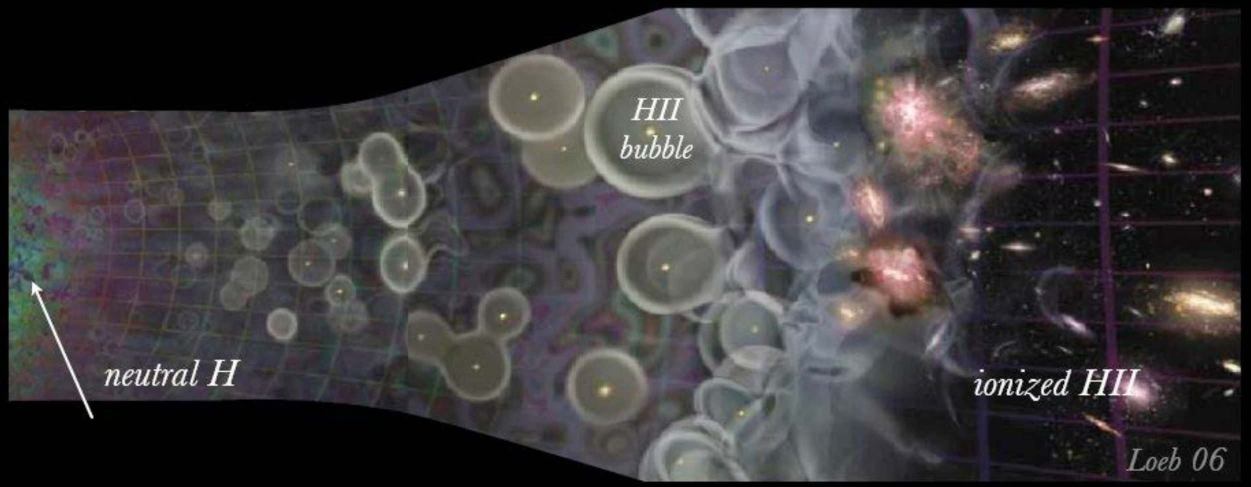
Initial conditions

Difficult parameter space

$$m_a, \Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\rm reion}$$

$$\tau_{\rm reion} = \int dl n_e \sigma_T$$



Difficult parameter space

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AxiCAMB

Compare with data
Explore posterior using Monte Carlo Markov Chain (MCMC)

Difficult parameter space

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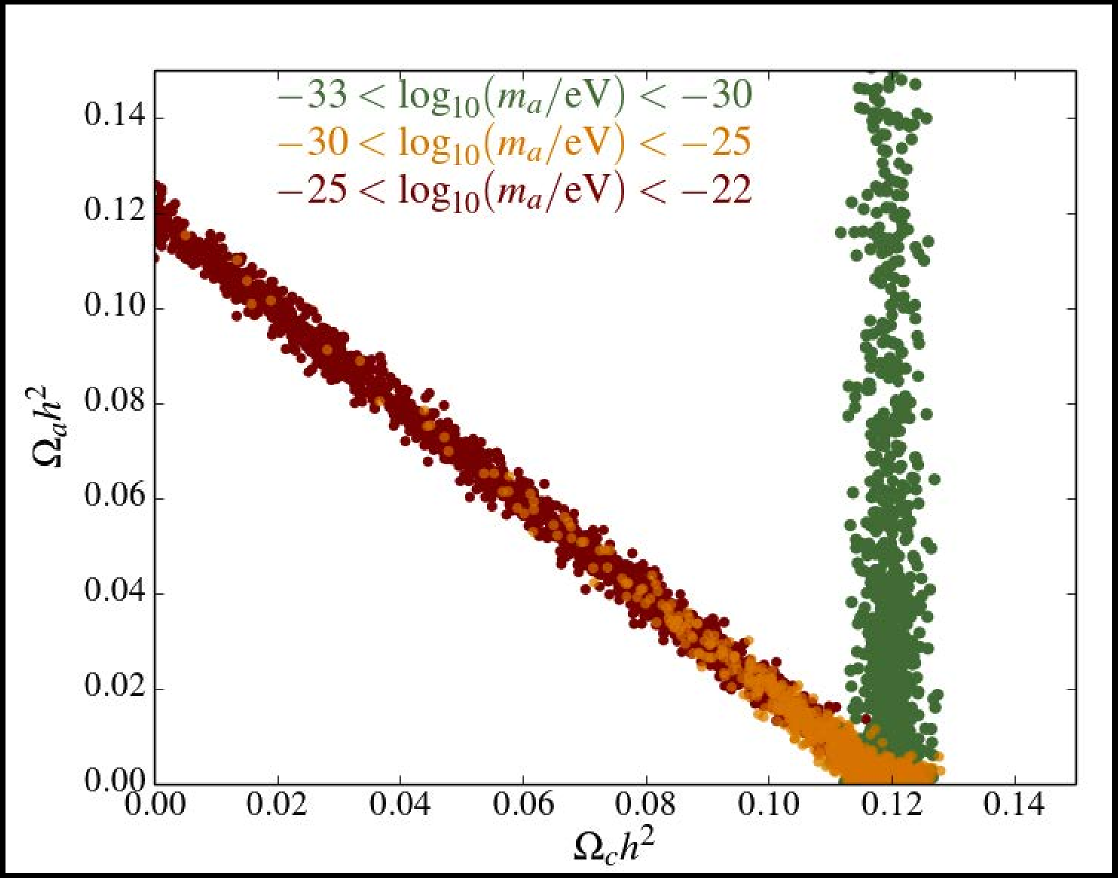
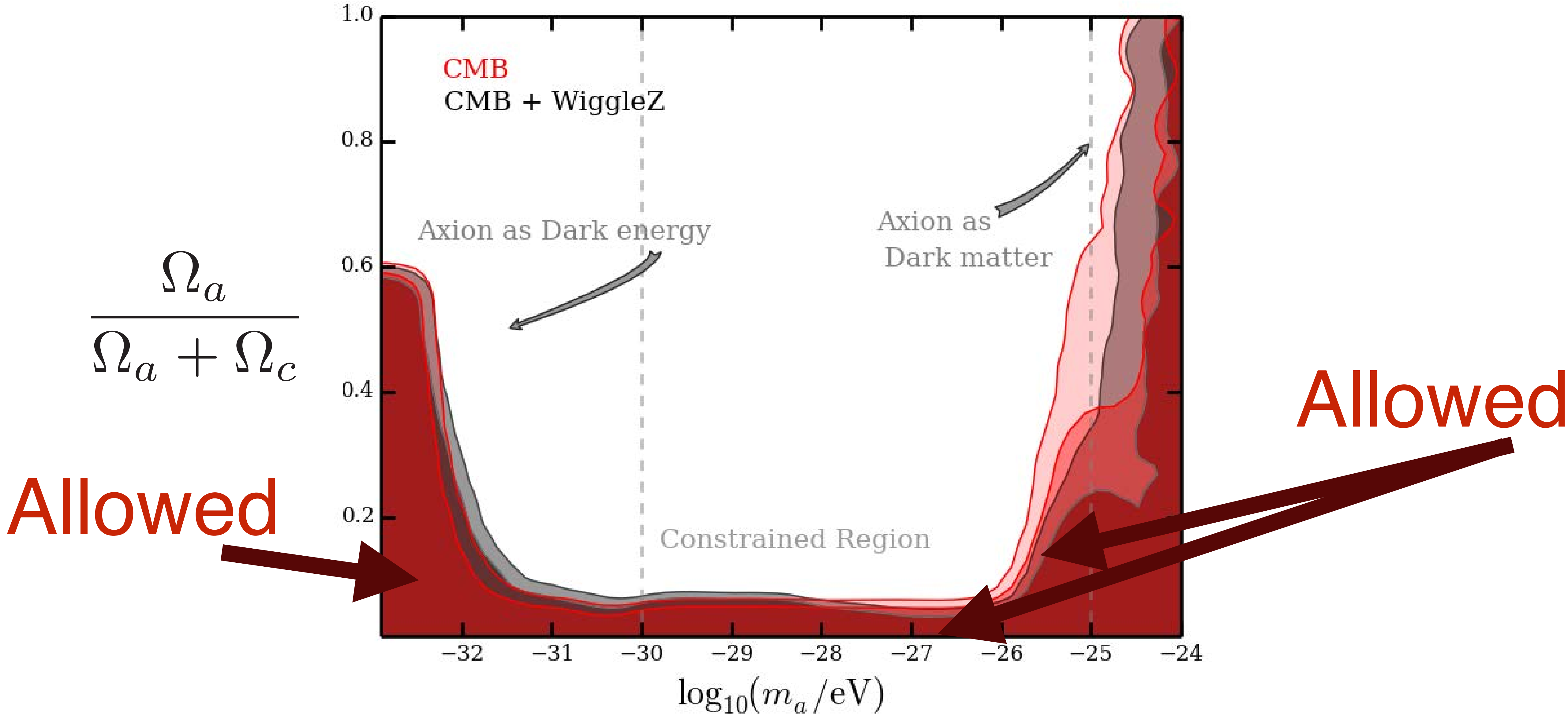


Addressed using nested sampling

MULTINEST (Hobson, Feroz, others 2008)

CONSTRAINTS



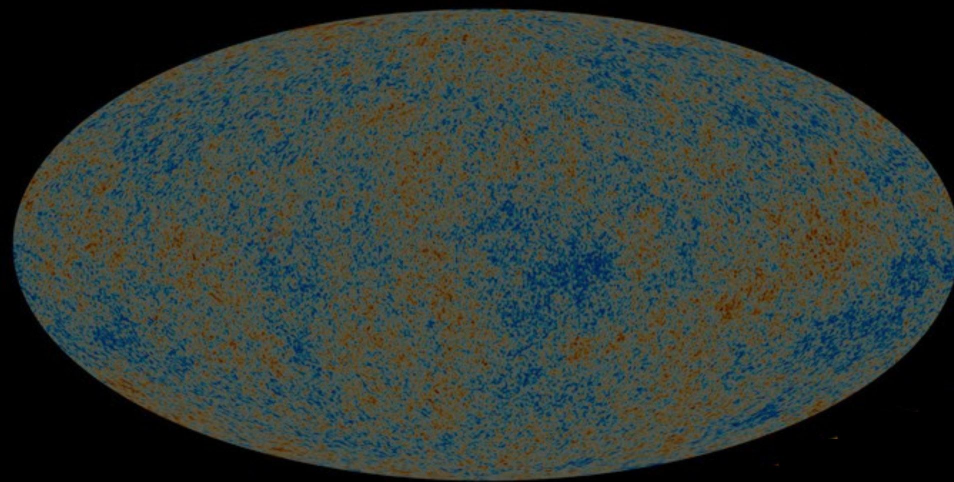
✳Interesting constraints over 7 orders of magnitude in mass:

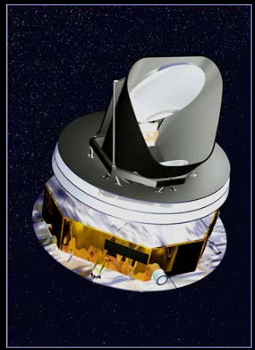
Thanks to AxiCAMB and MultiNest

✳ULAs highly constrained if 10^{-32} eV $\lesssim m_a \lesssim 10^{-25.5}$ eV

✳ULAs are viable DM/DE candidates in linear theory outside ``belly"

DATA + ANALYSIS



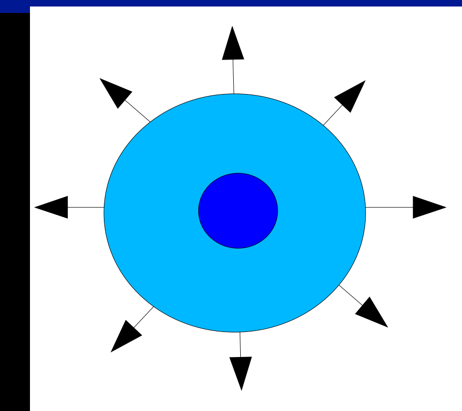


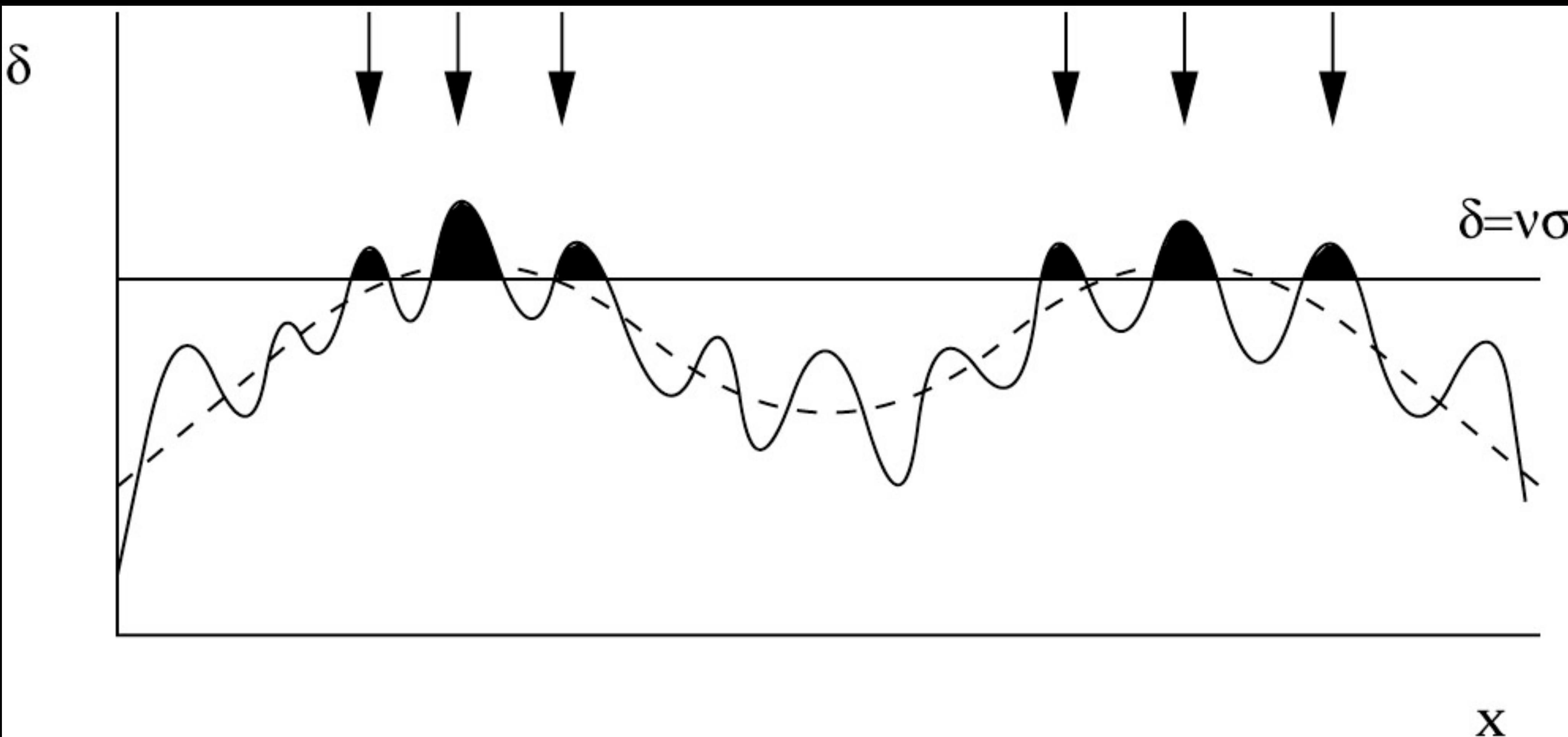
- Planck 2013 temperature anisotropy power spectra (+SPT+ACT)
  - Cosmic variance limited to $\ell \sim 1500$

- Nested sampling, MCMC, vary $m_a, \Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\rm reion}$

Future work: ULAs and galaxies

Collapse threshold for ULA DM unknown





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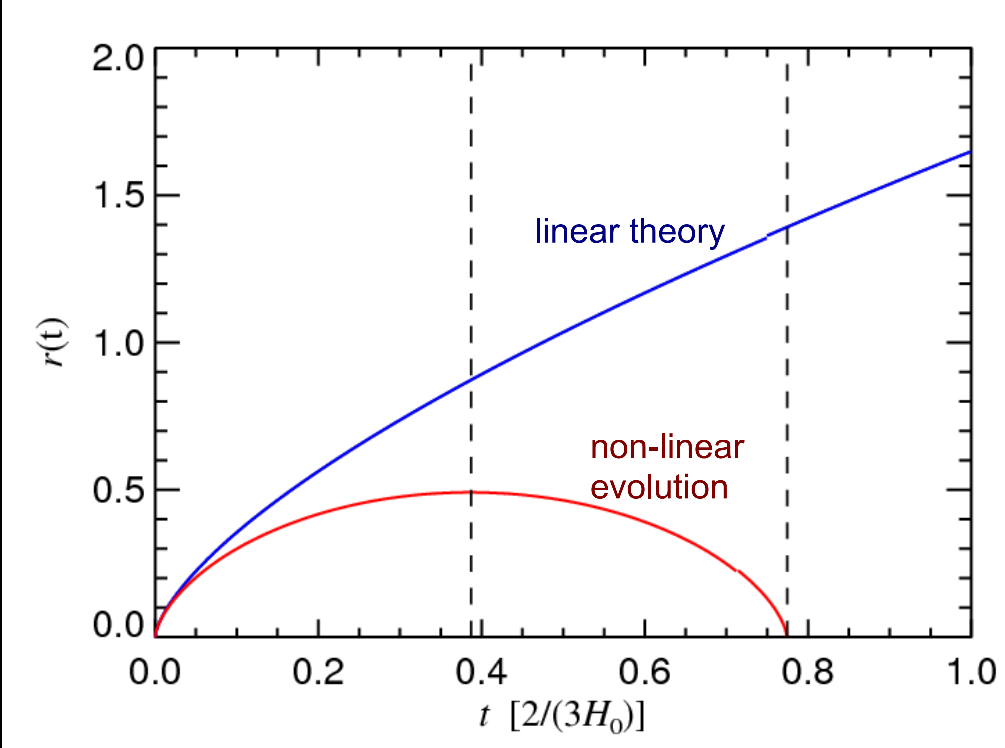
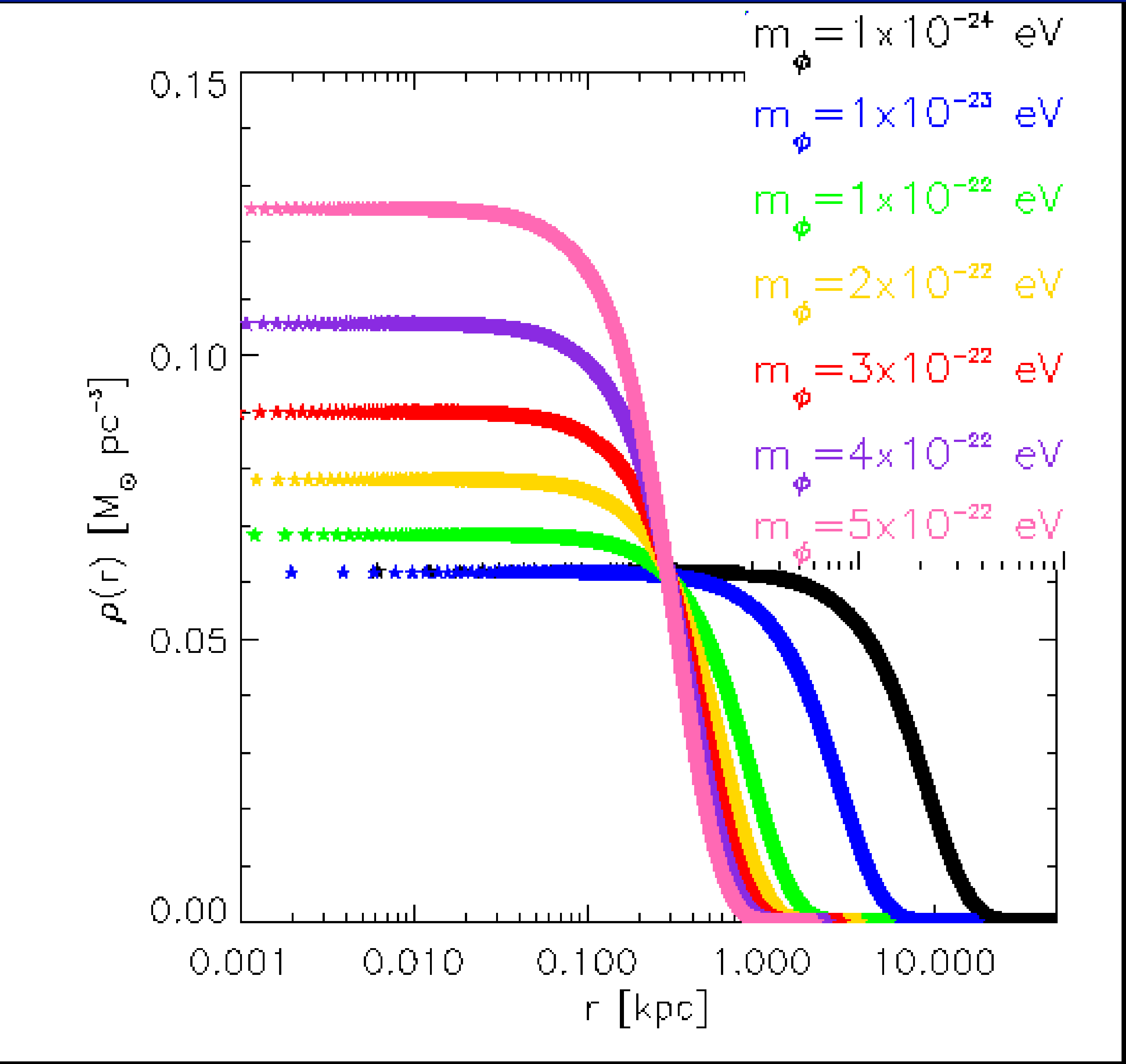


FUTURE WORK: ULAS CORES + CUSPS?



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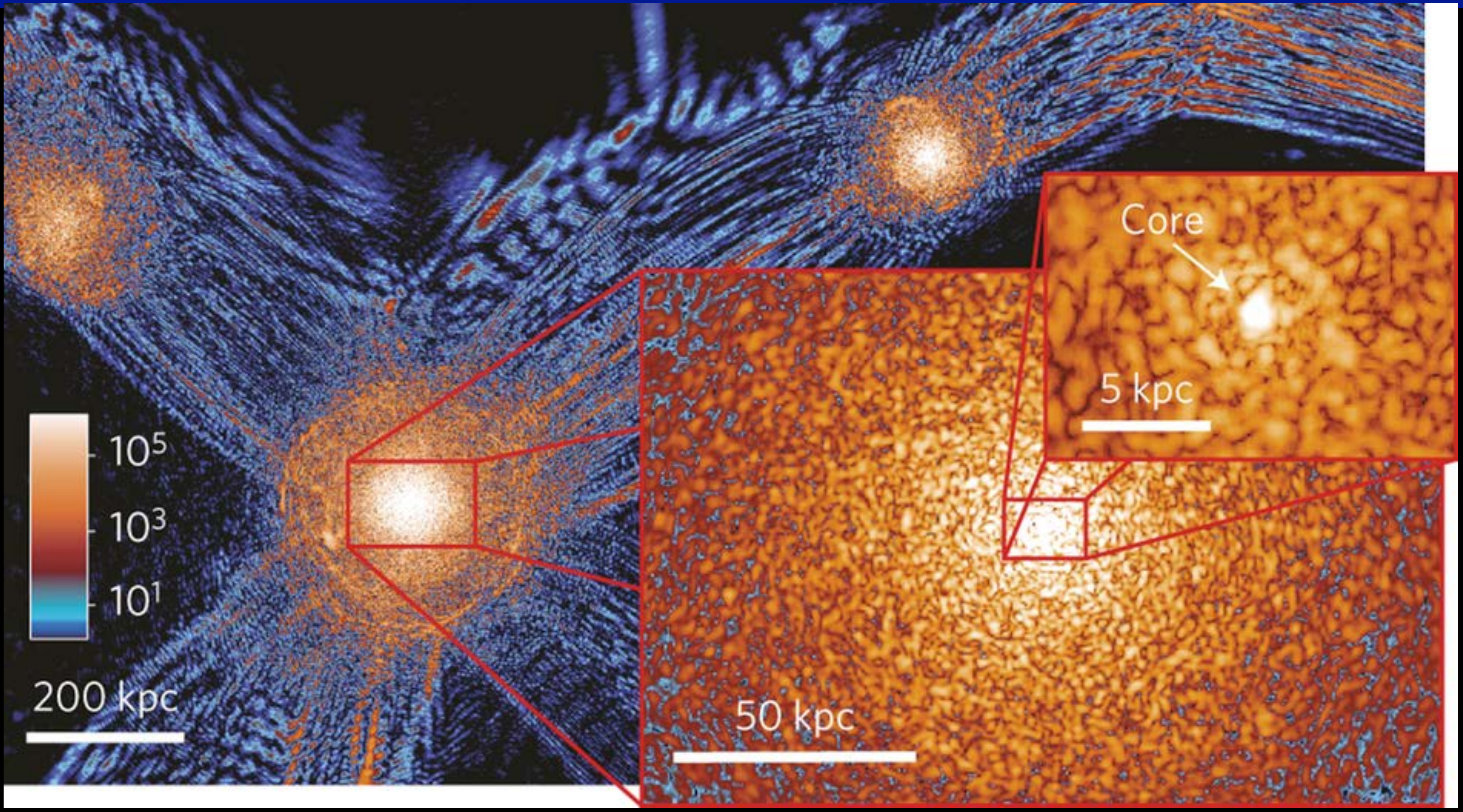
Future work: ULAs cores + cusps?



From Schive et al., more cosmological volume needed for statistics, baryons, etc...

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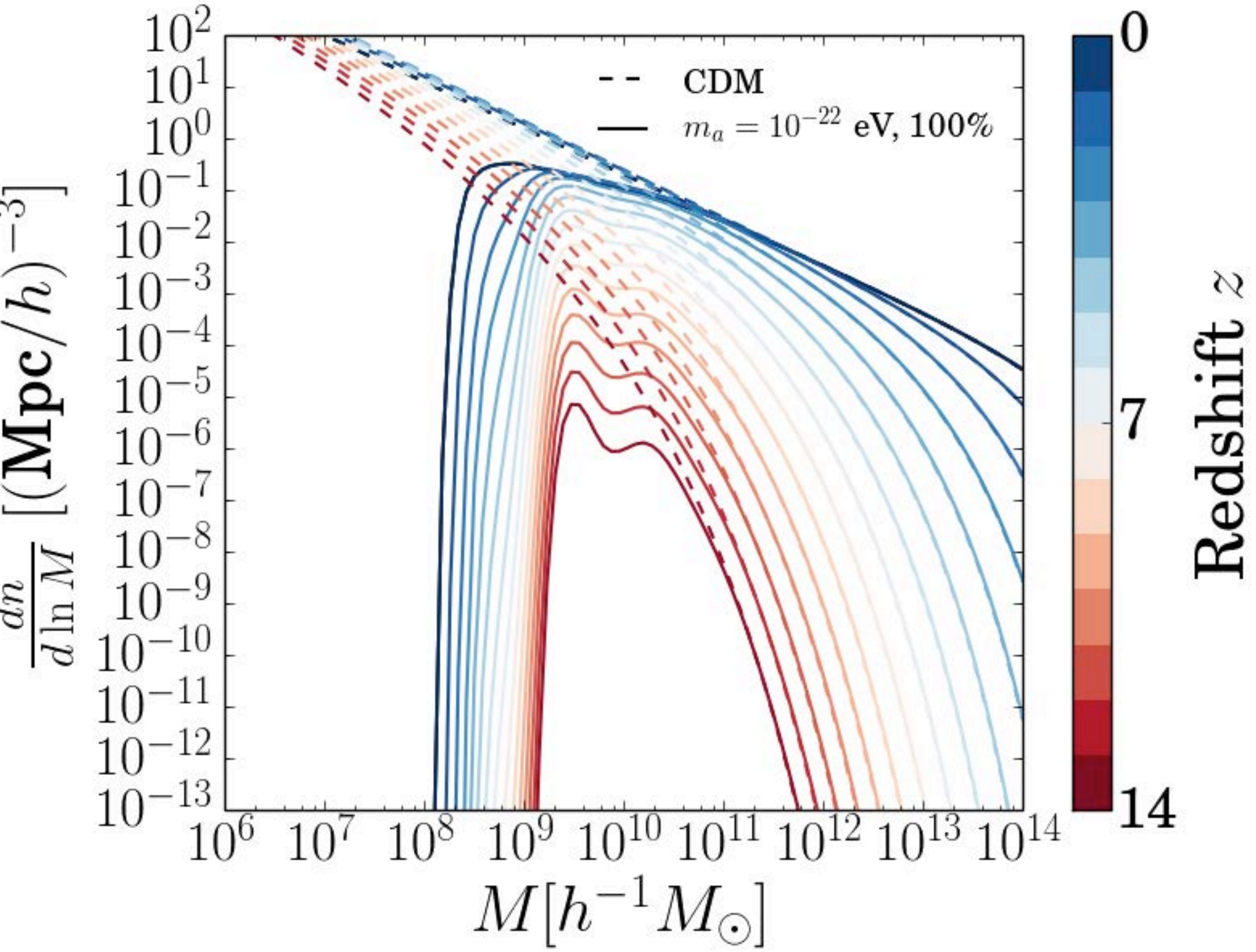
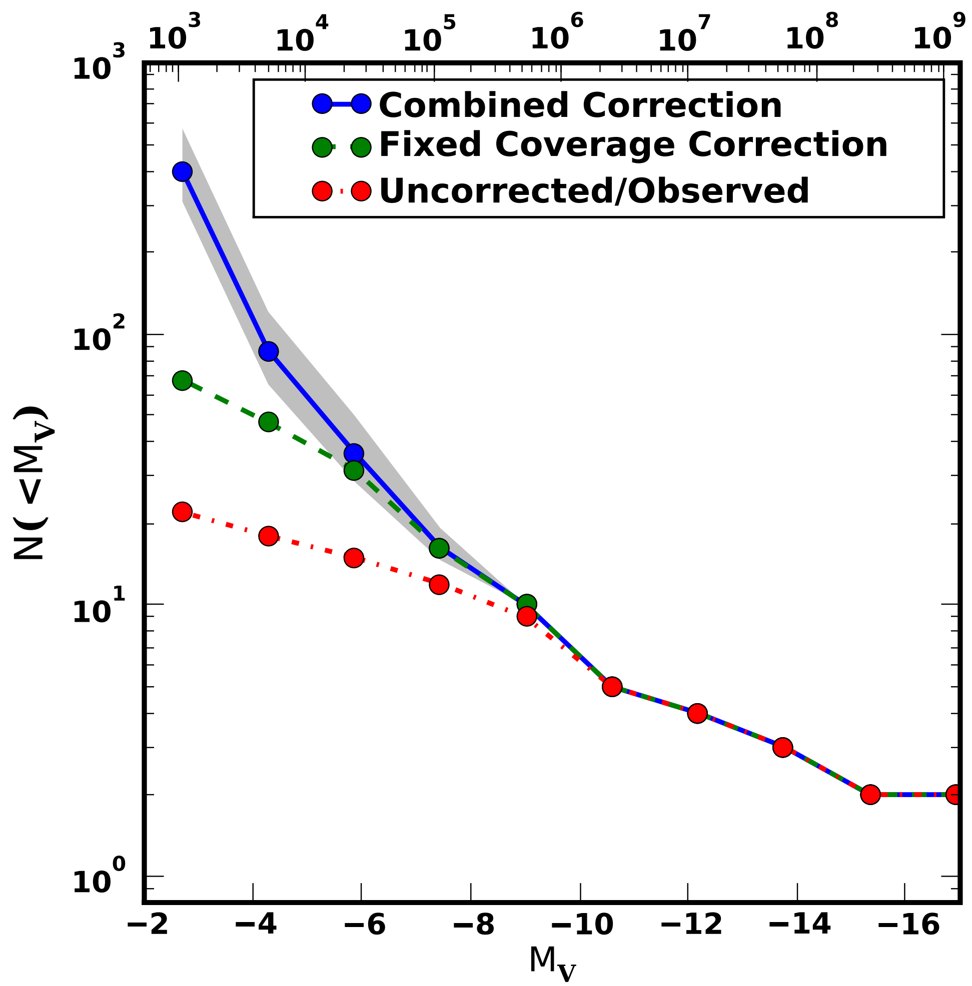
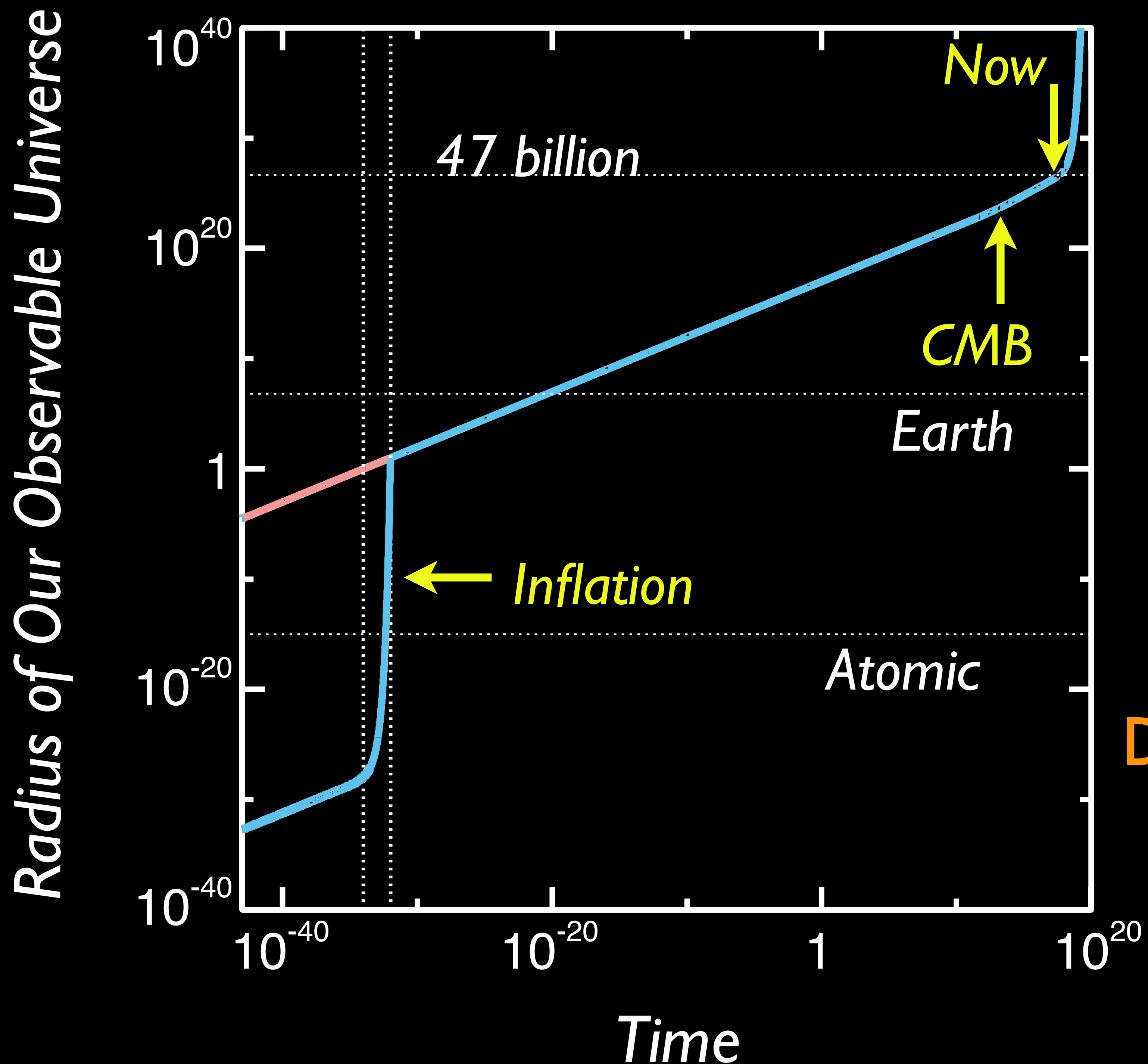




Marsh et al 2014, Klypin 1999, Bullock 2010

Dynamical friction, tidal disruption, substructure, halo model, spherical collapse, better simulations (much work to be done!)

✳ Inflation is an early epoch of accelerated expansion



Hubble parameter

$H_I = ?????$

Determined by energy scale

Axions and isocurvature fluctuations

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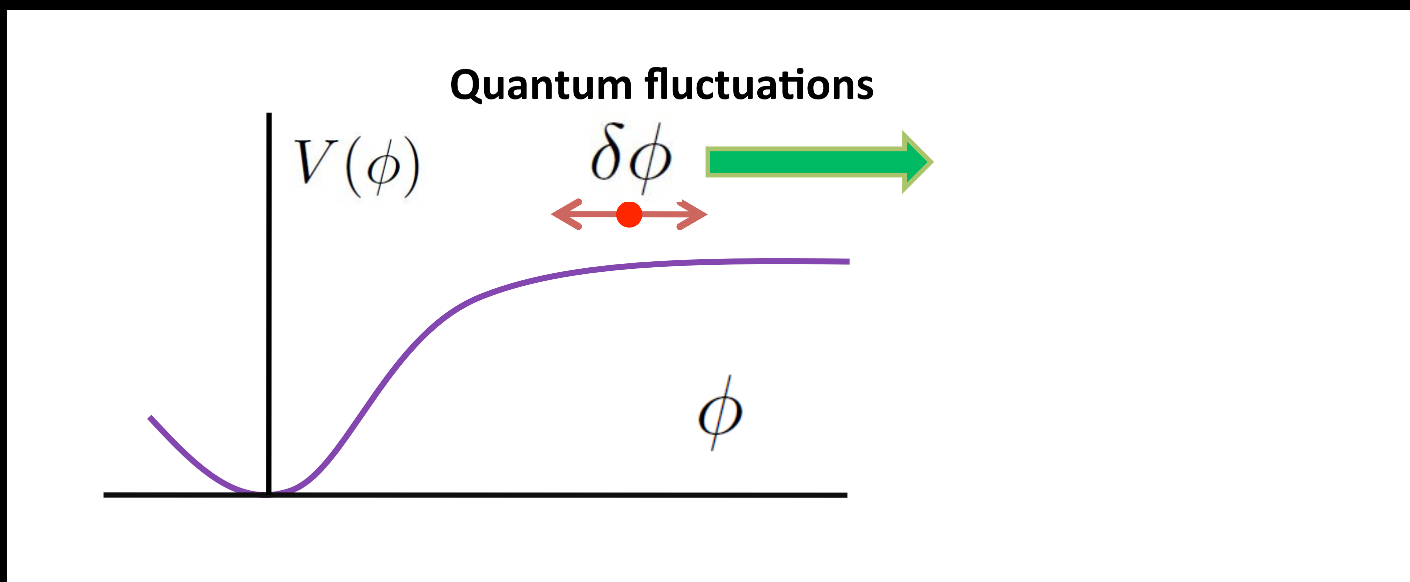
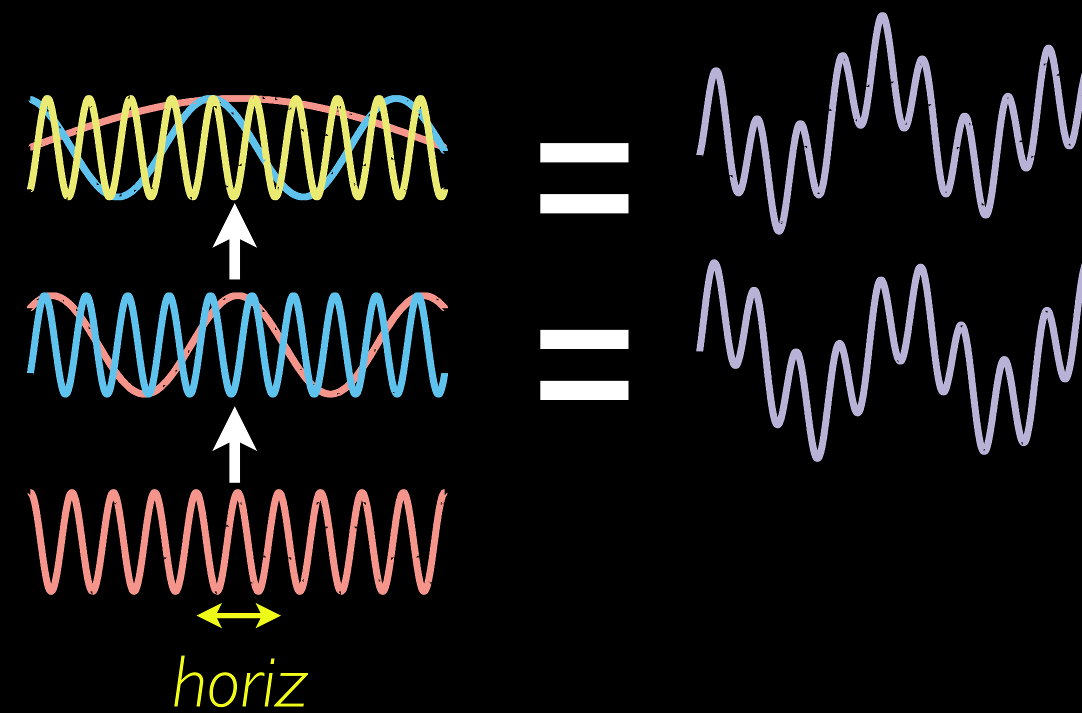
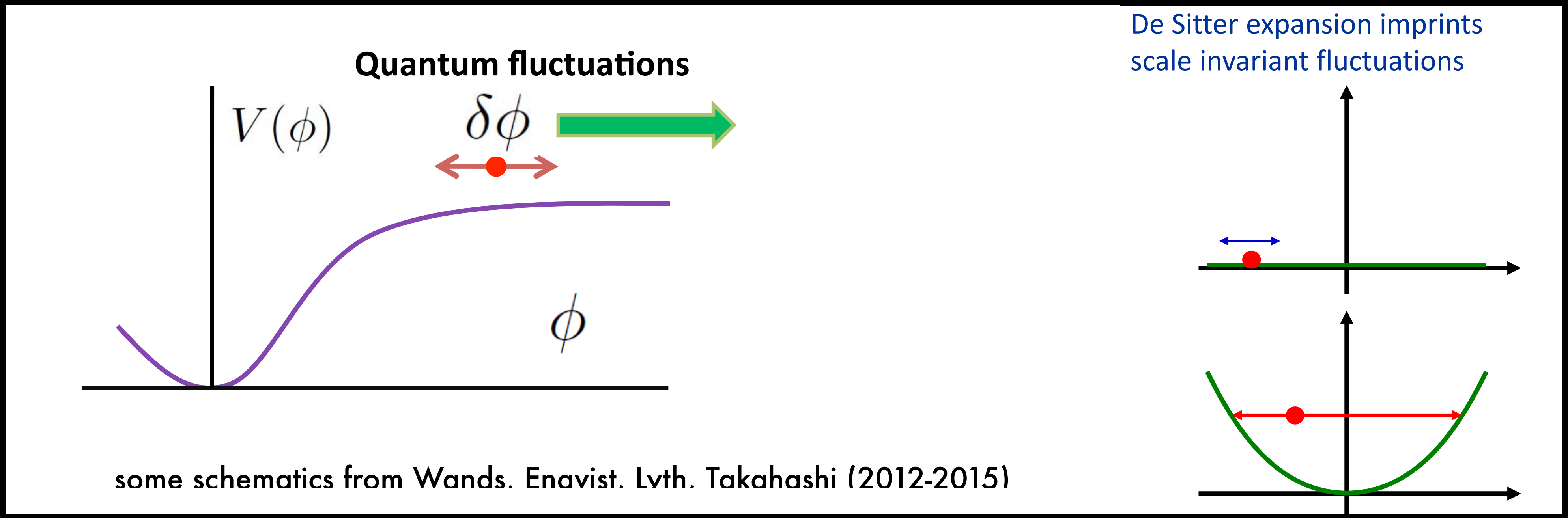


some schematics from Wands, Engvist, Lyth, Takahashi (2012-2015)



Sets A_s and n_s

✳ If $f_a > H_I$



$$\sqrt{\langle a^2 \rangle} = \frac{H_\mathrm{I}}{2\pi}$$

Quantum zero-point fluctuations!

$$\rho_a \ll \rho_{\mathrm{tot}} \rightarrow \Phi_a \ll 10^{-5}$$

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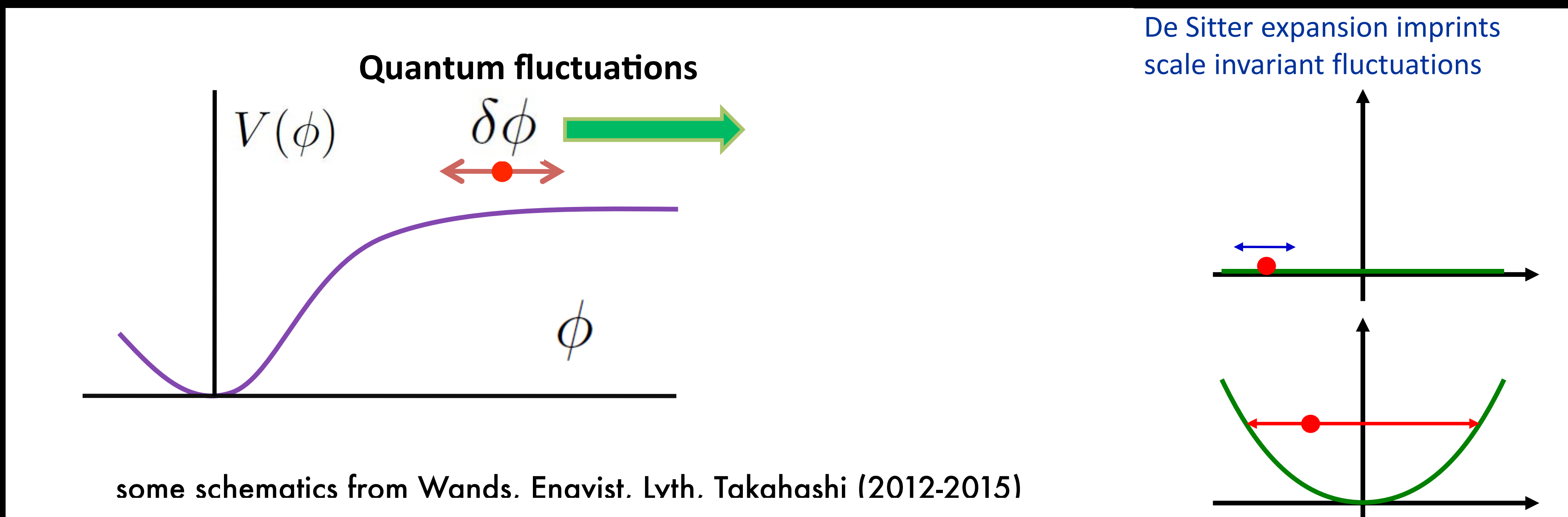

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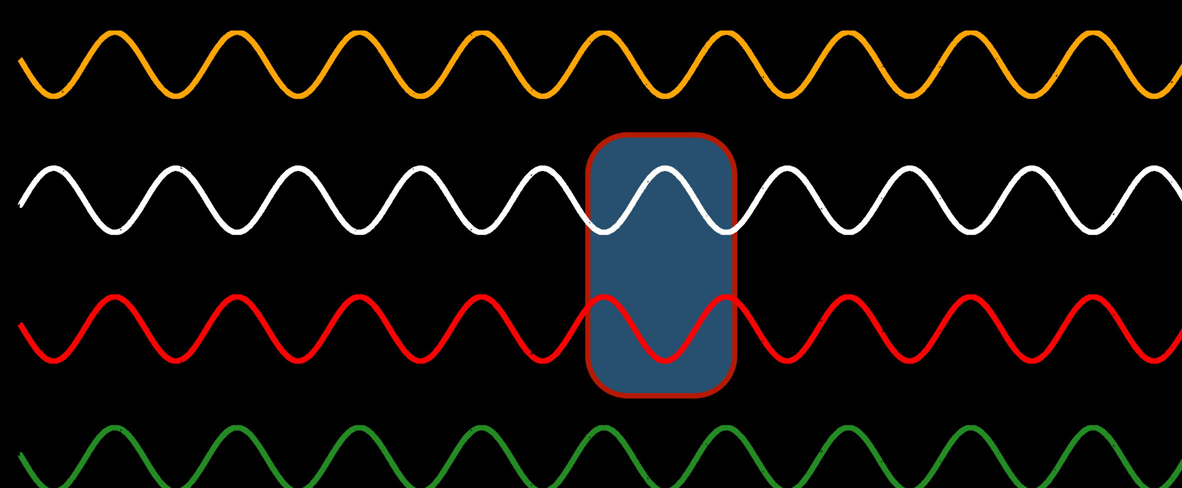
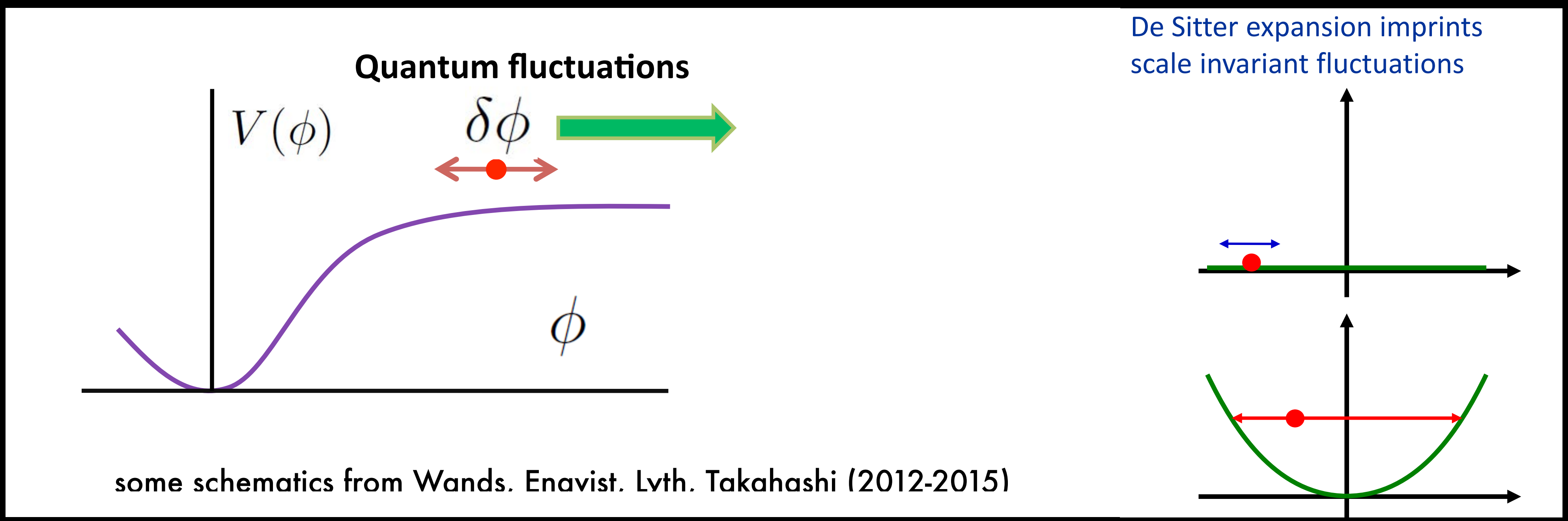
CDM
socurvature

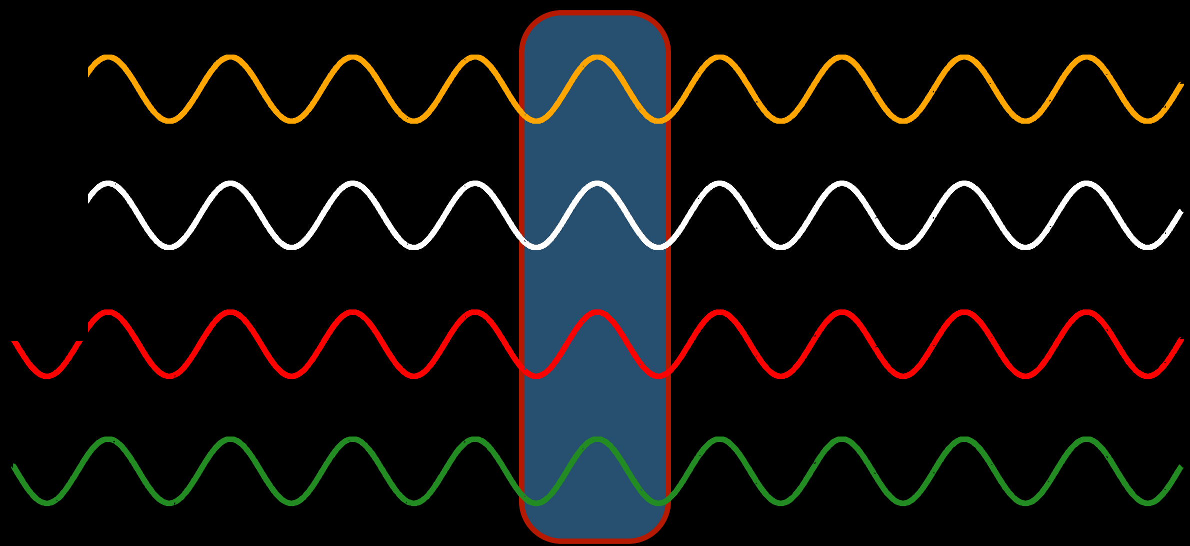


Neutrinos
CDM
Photons
Baryons

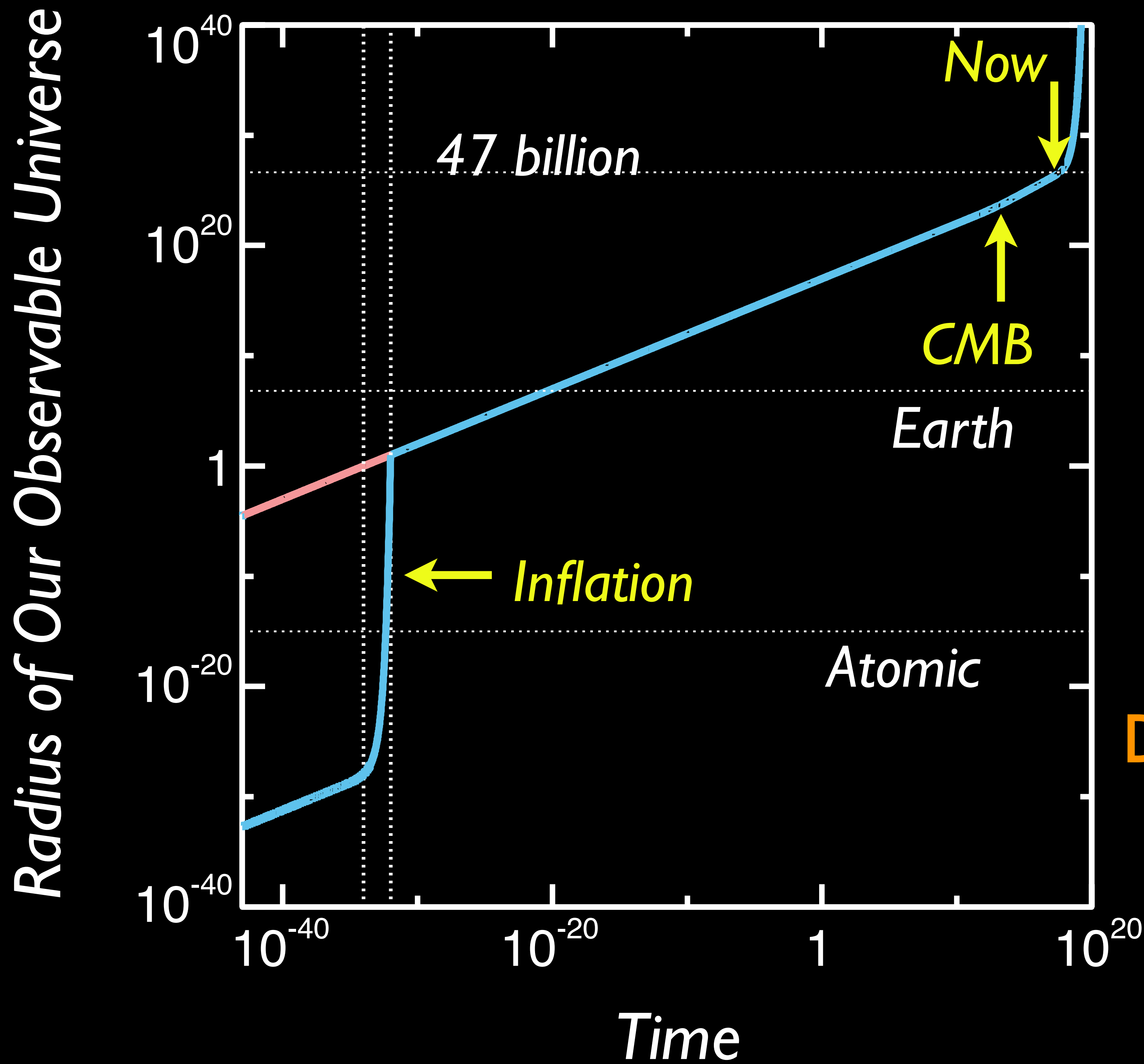
✴ If $f_a > H_I$



Total density fluctuation



* Inflation is an early epoch of accelerated expansion



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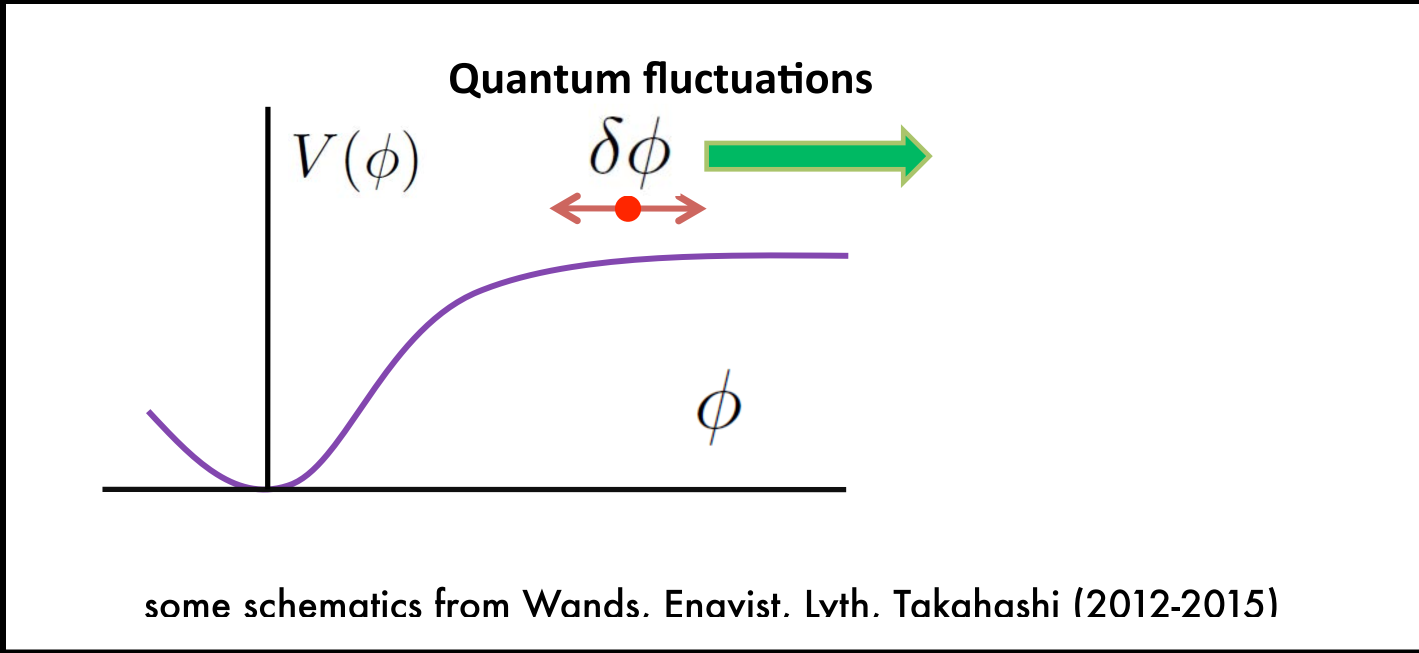

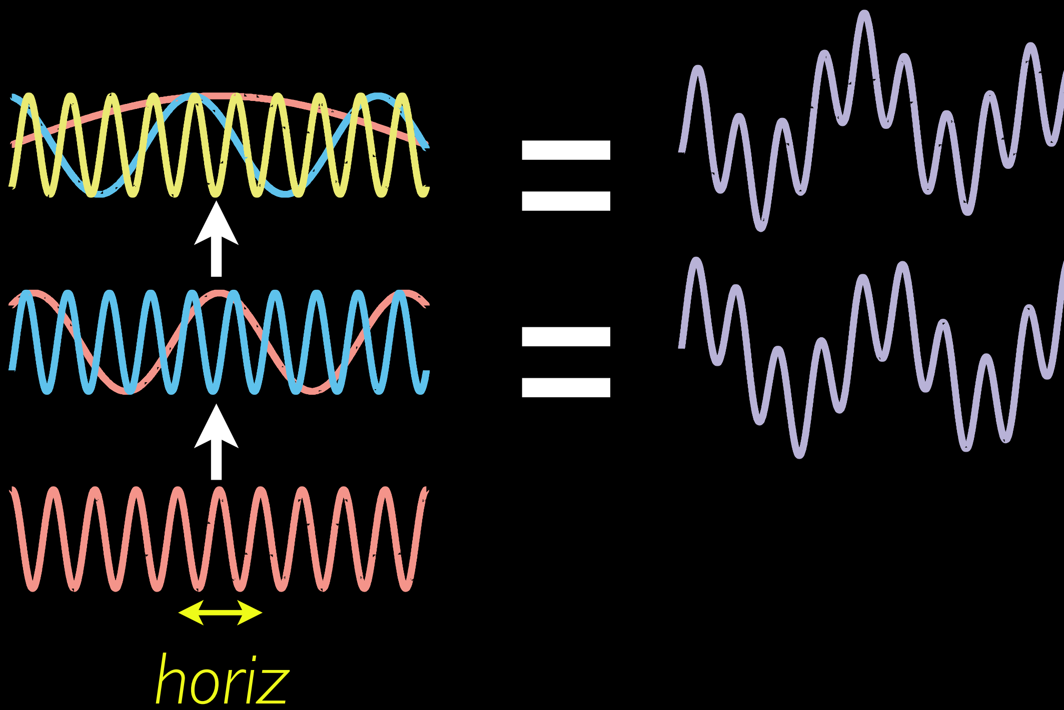

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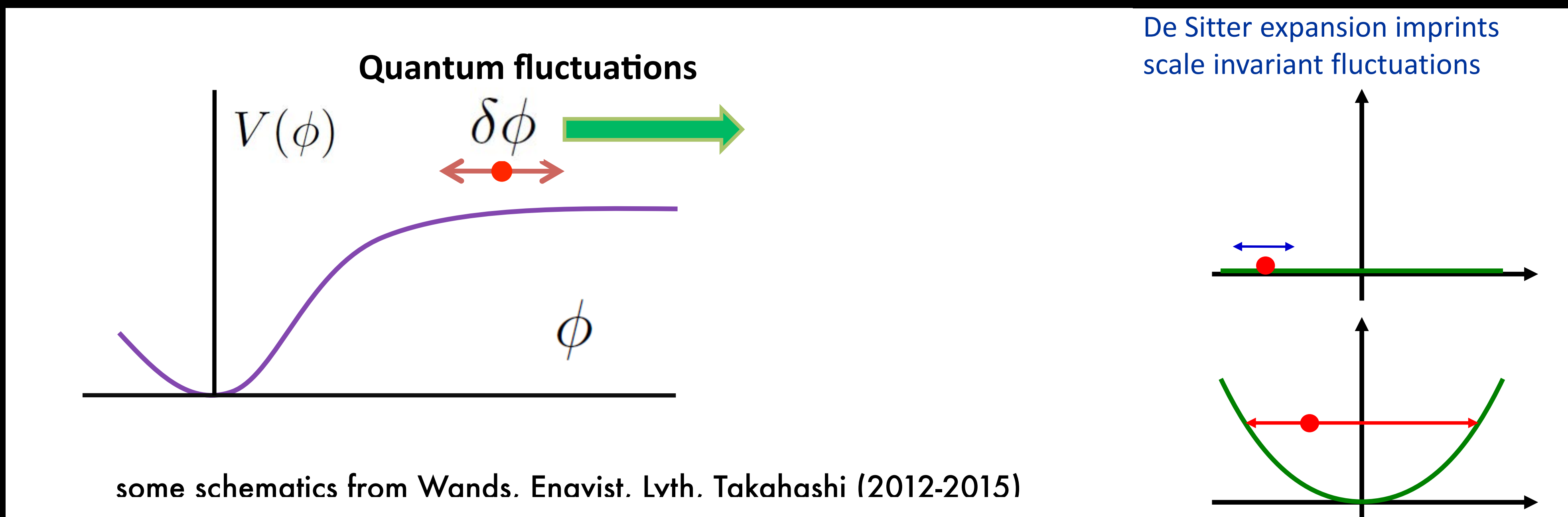

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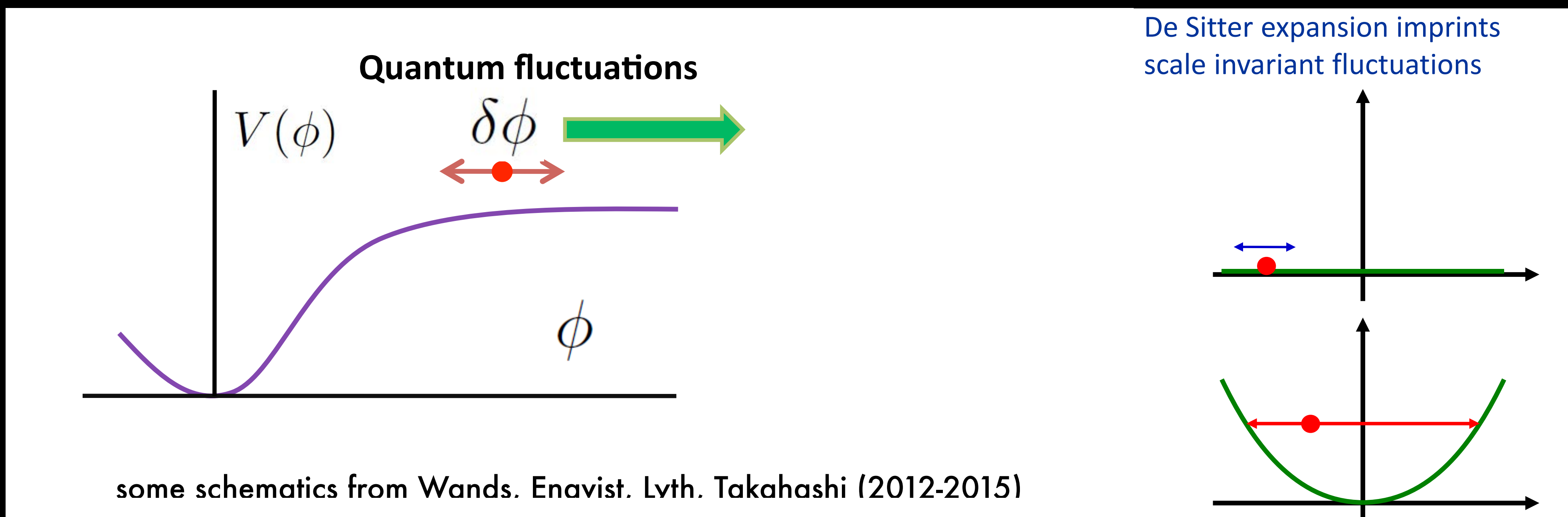
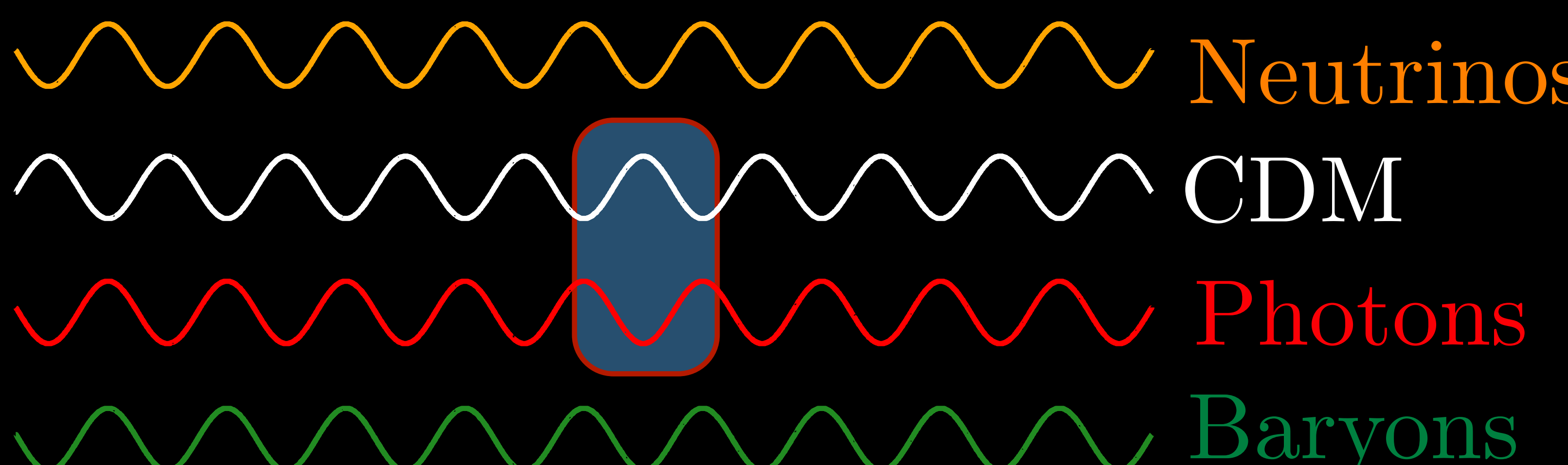


CDM isocurvature



Axions and isocurvature fluctuations

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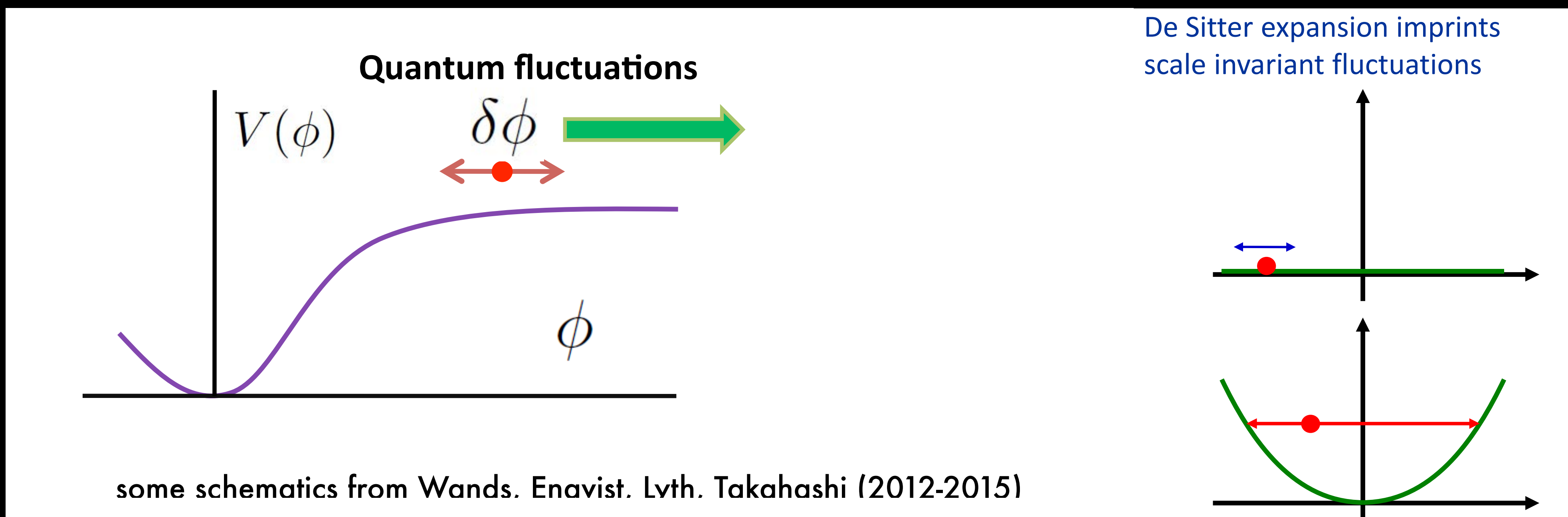
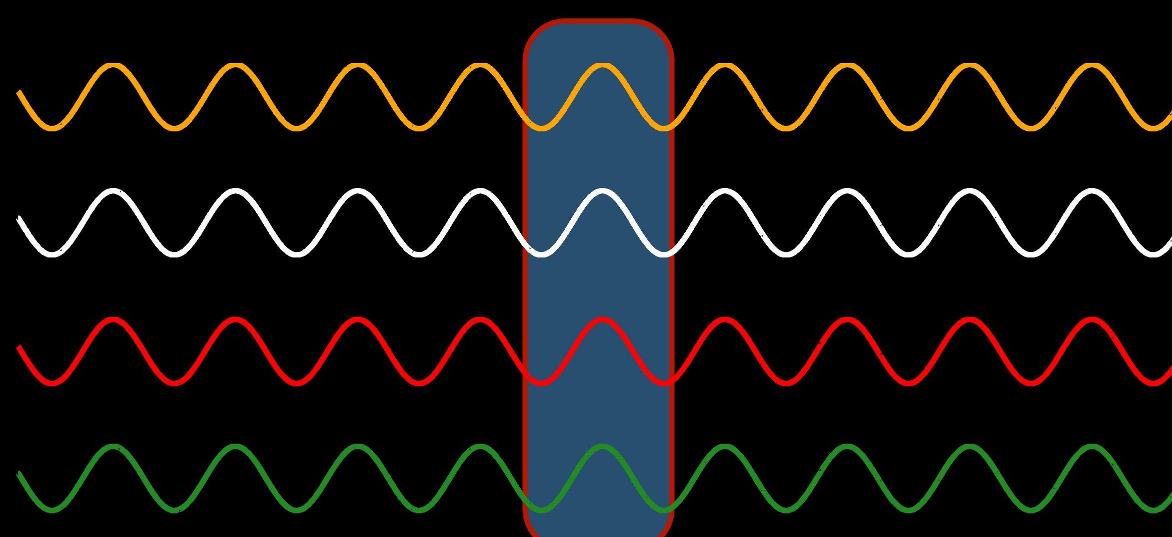


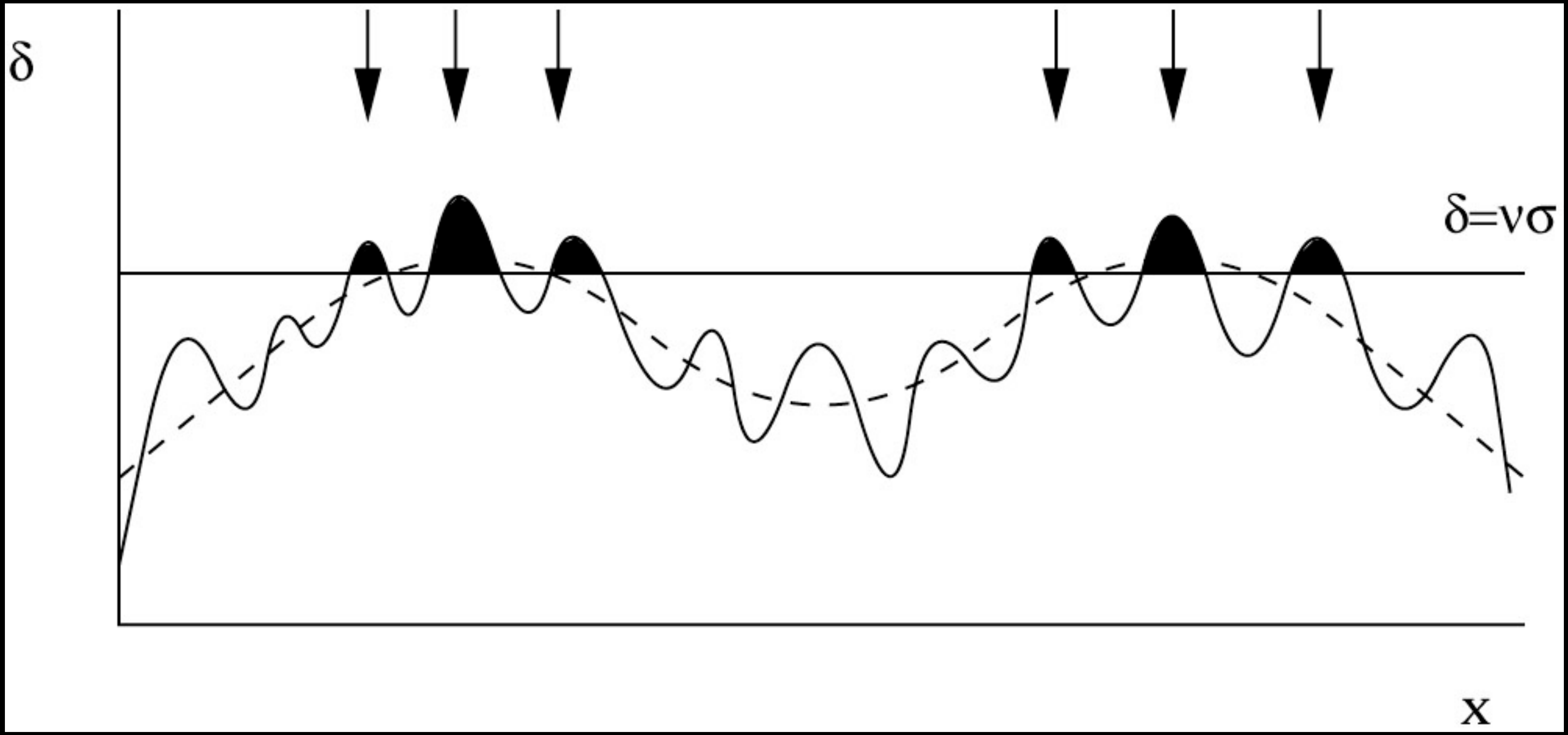
Adiabatic
Total density
fluctuation



Additional slides:
ULAs and galaxies

Future work: ULAs and galaxies

✳ Galaxies are biased tracers



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$$\delta_g = b\left(\frac{\delta\rho_m}{\rho_m}\right) \quad \textbf{vs.} \quad \delta_g = b\left(\frac{\delta\rho_m + \delta\rho_a}{\rho_m + \rho_a}\right)$$

Unfair penalty on scales where axions don't cluster

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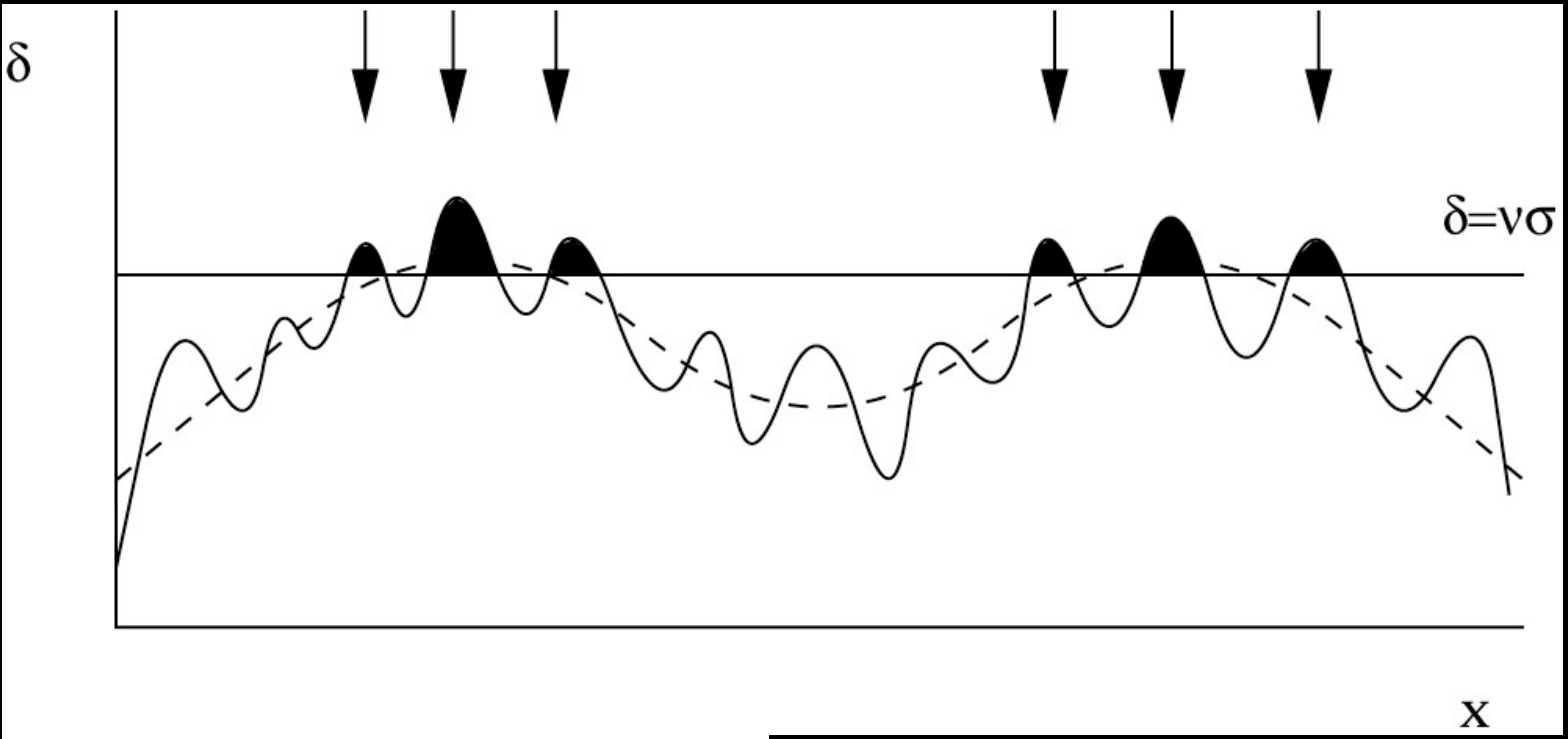

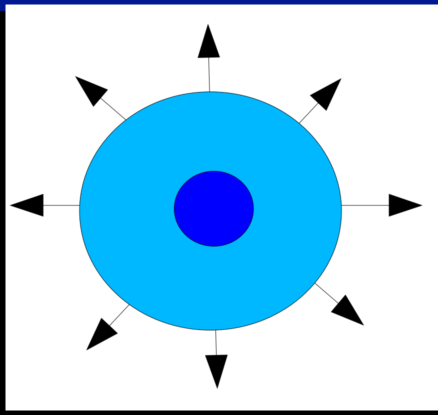

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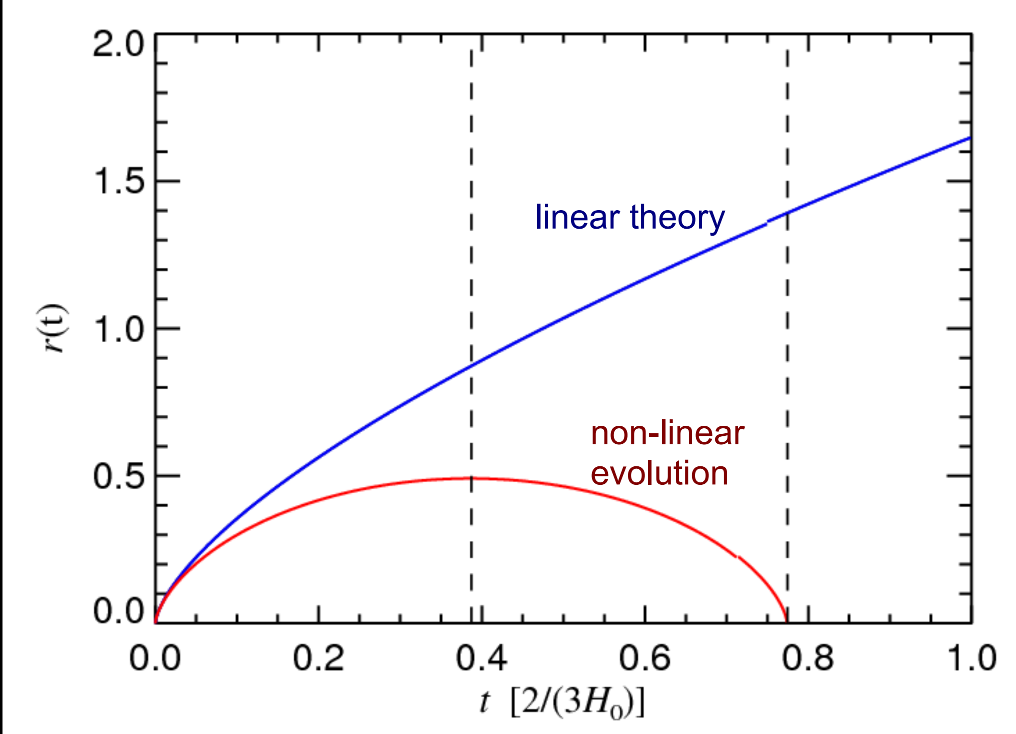
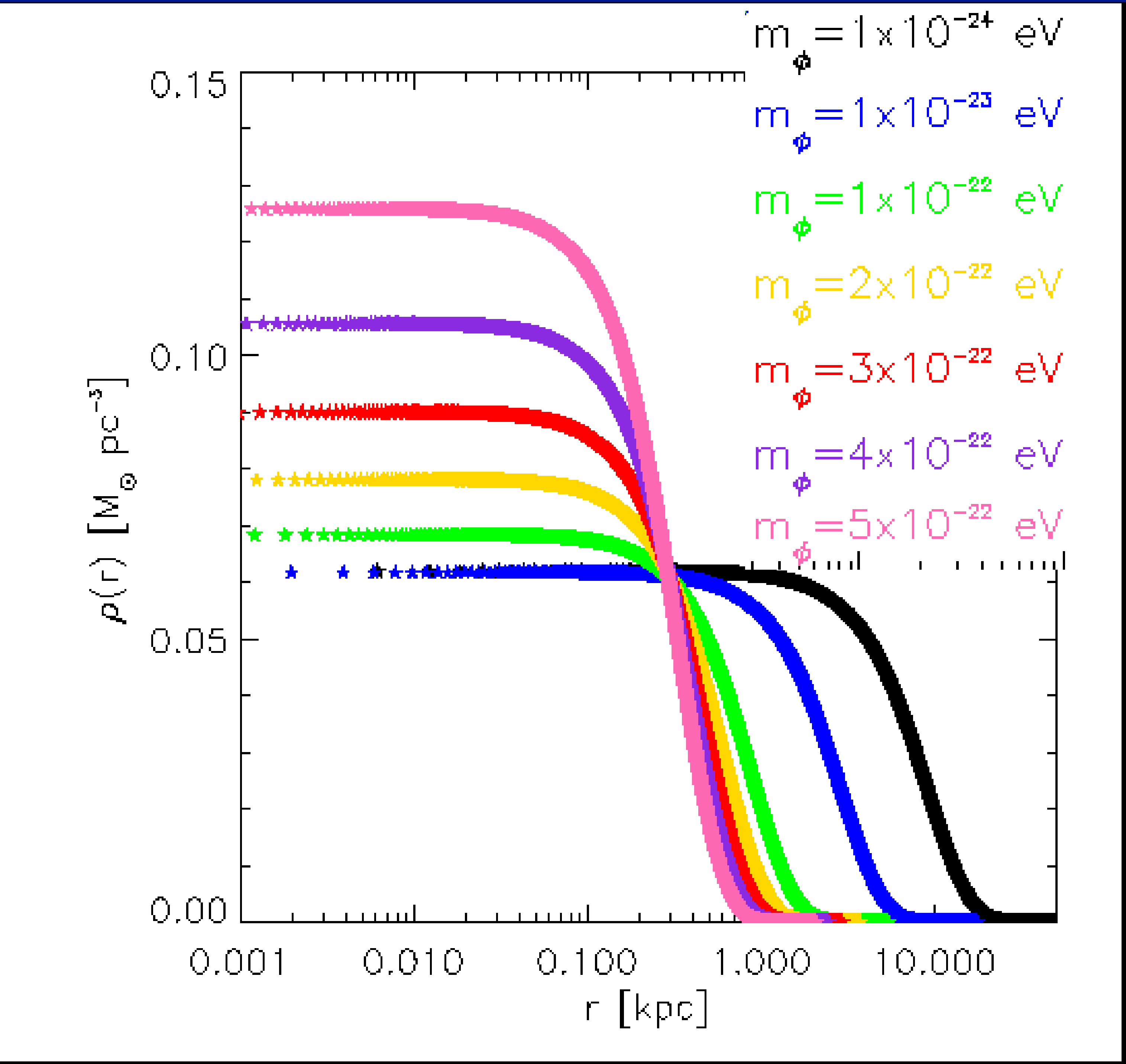


Future work: ULAs cores + cusps?



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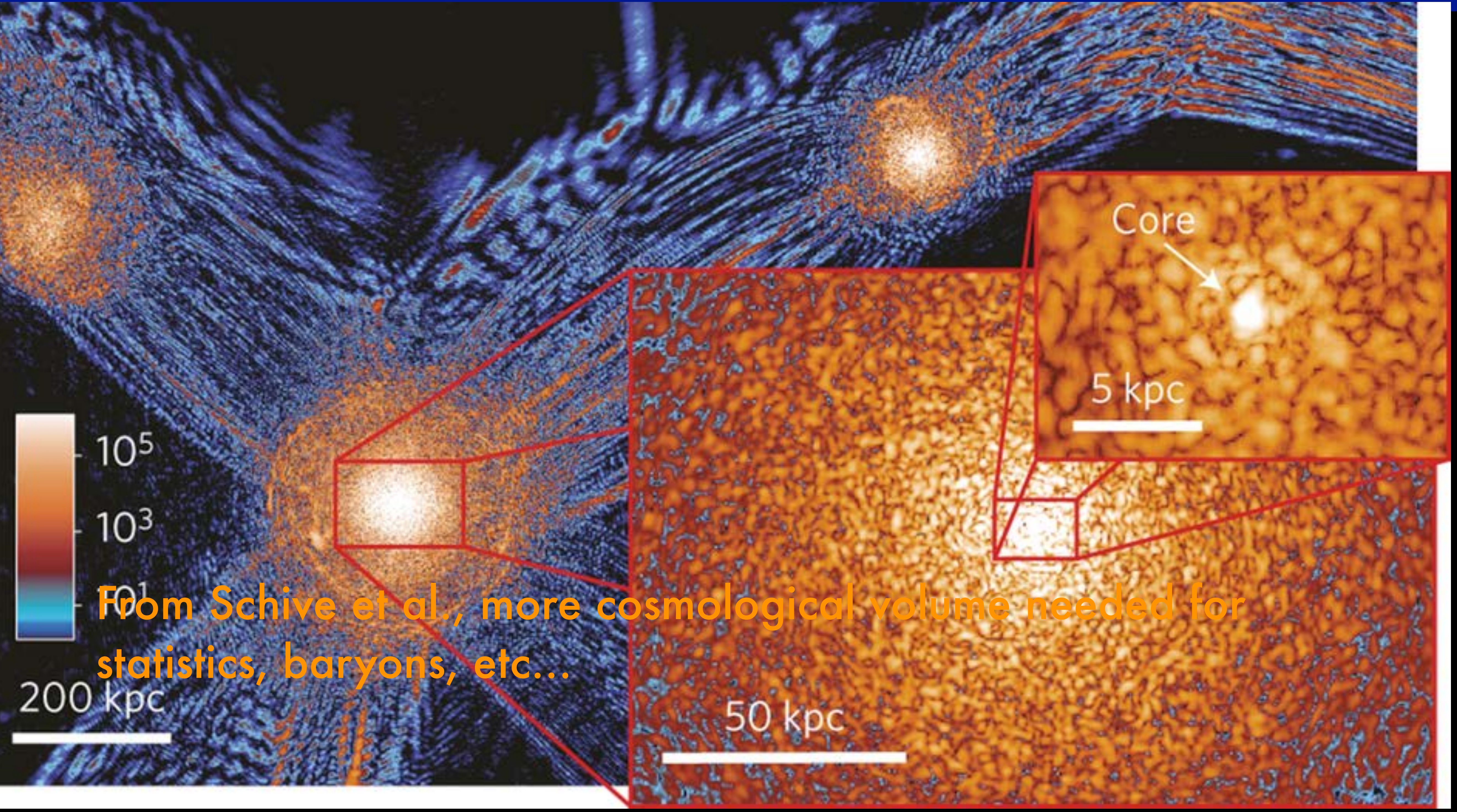

From Schive et al., more cosmological volume needed for statistics, baryons, etc...

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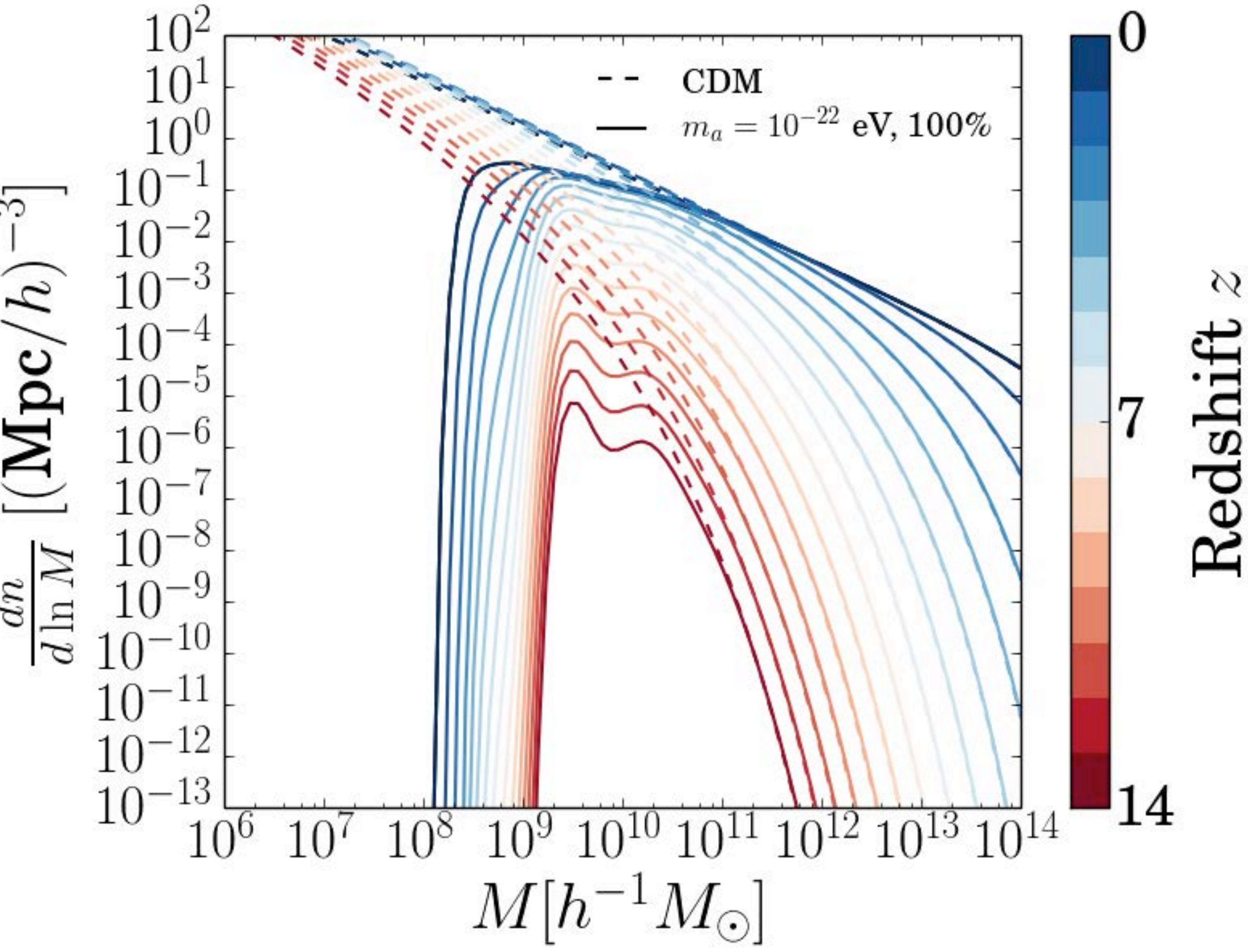

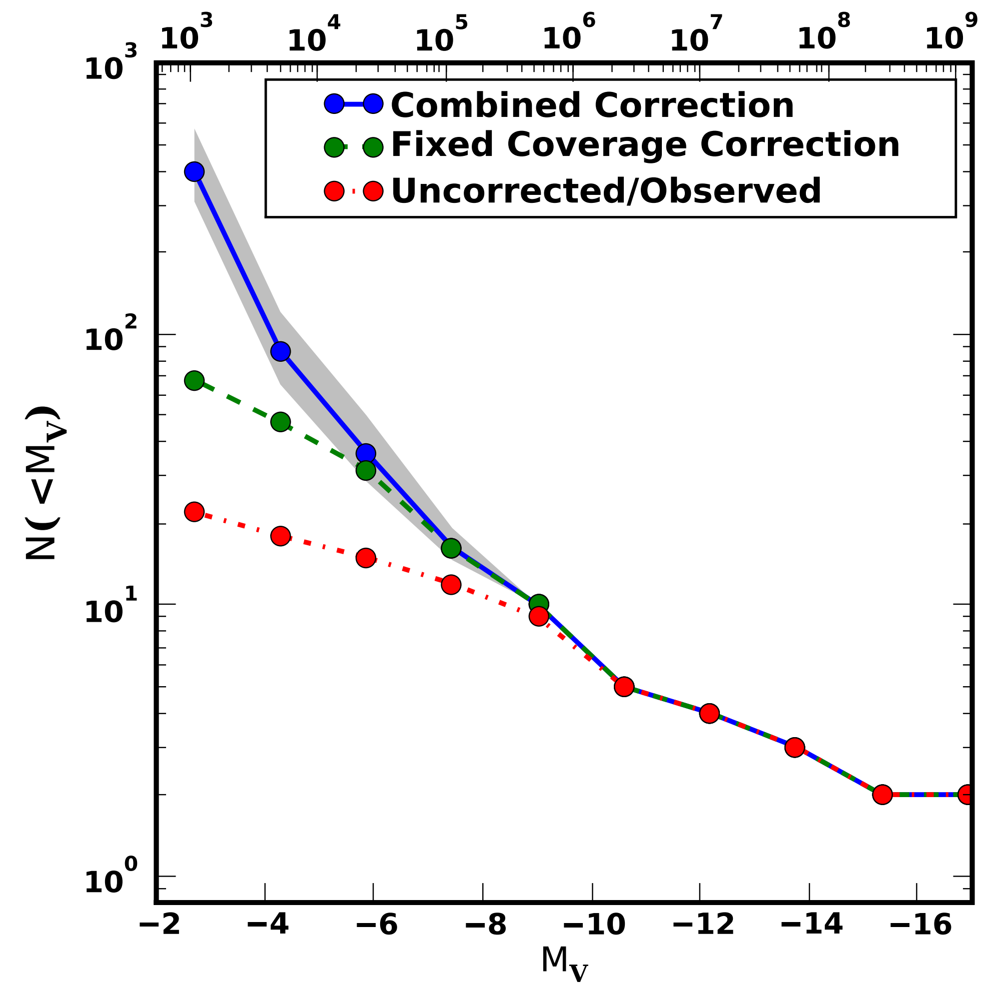

Marsh et al 2014, Klypin 1999, Bullock 2010

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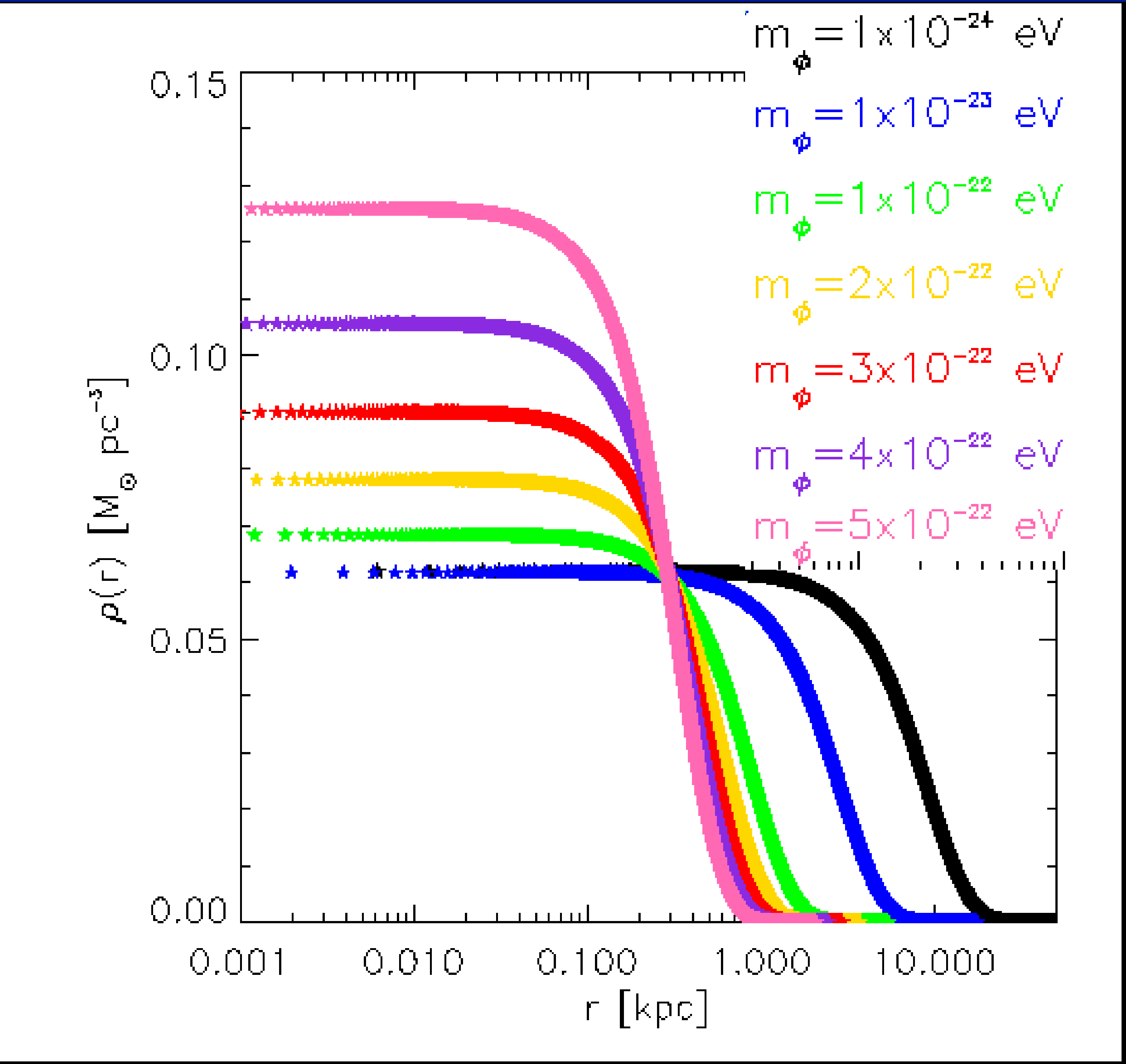

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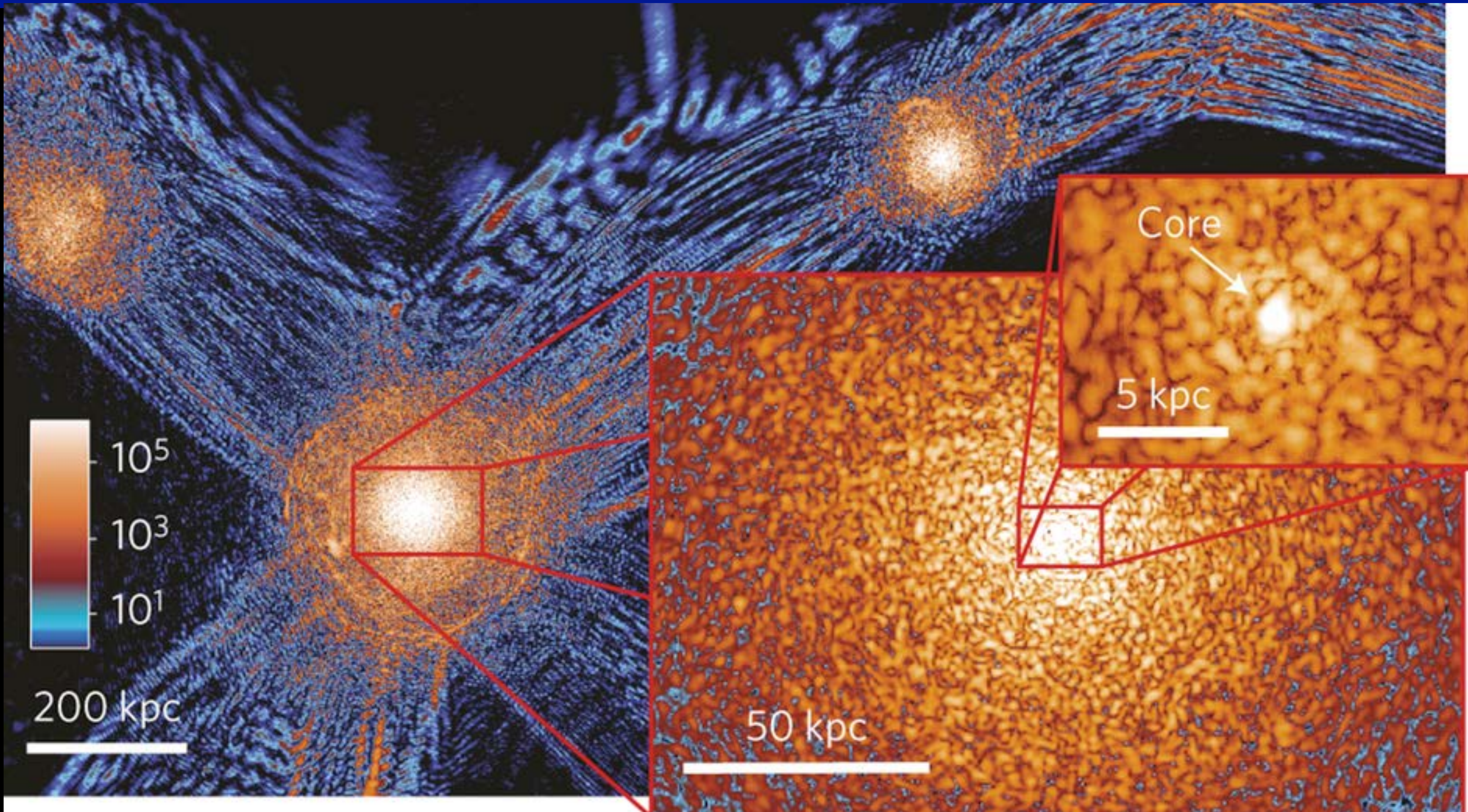

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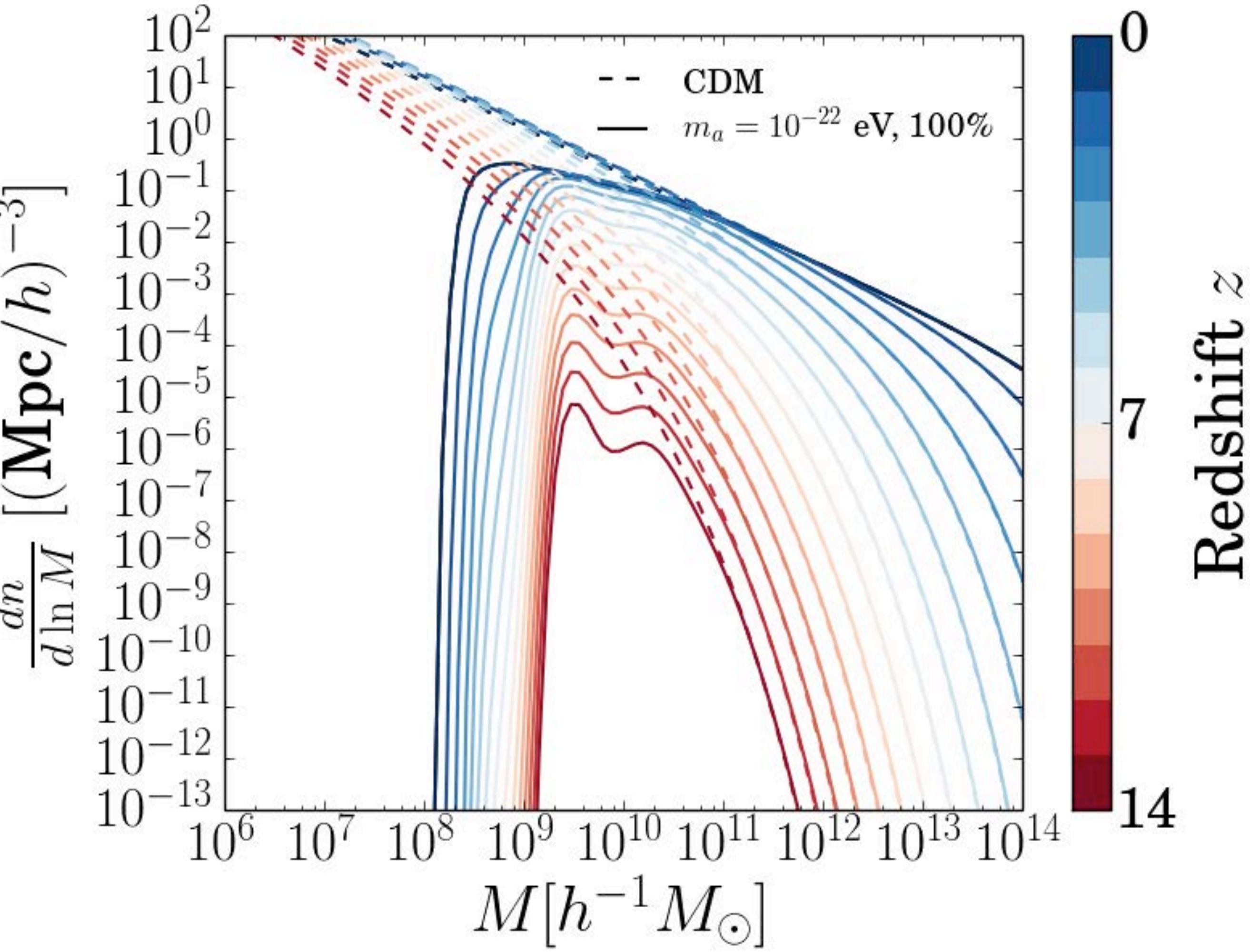

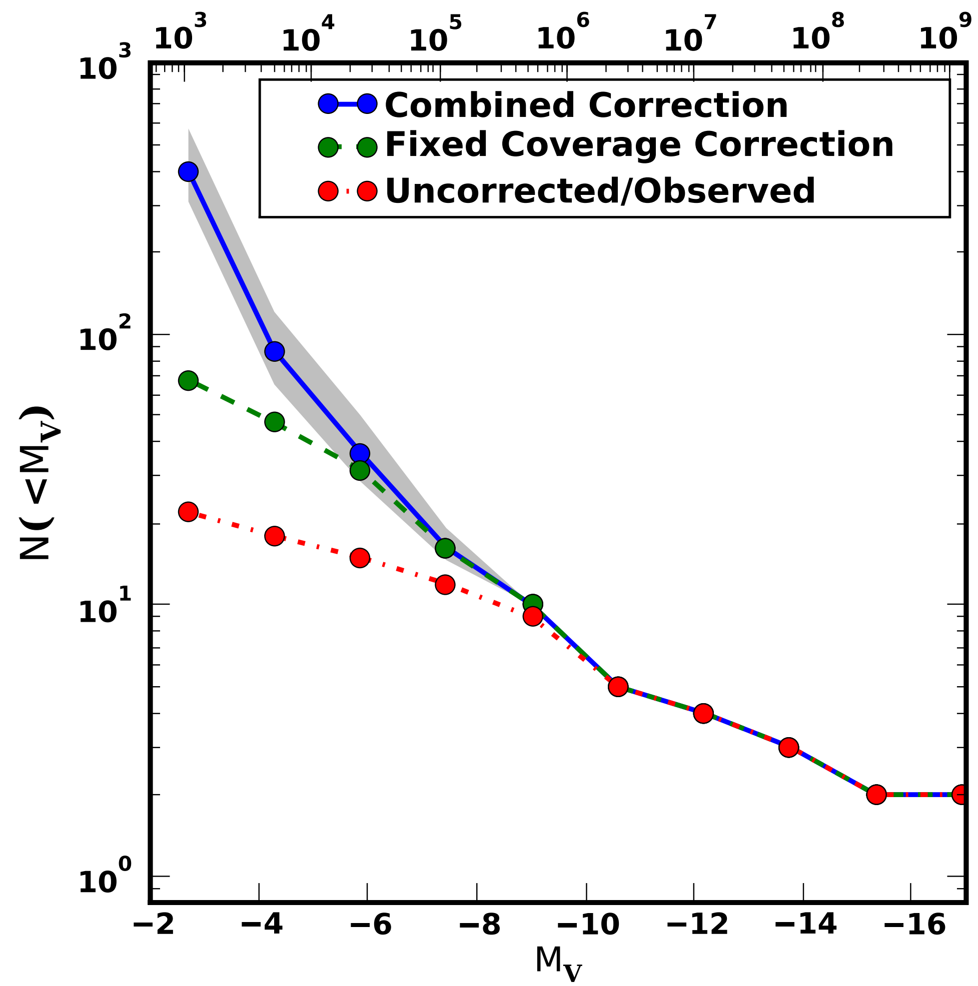

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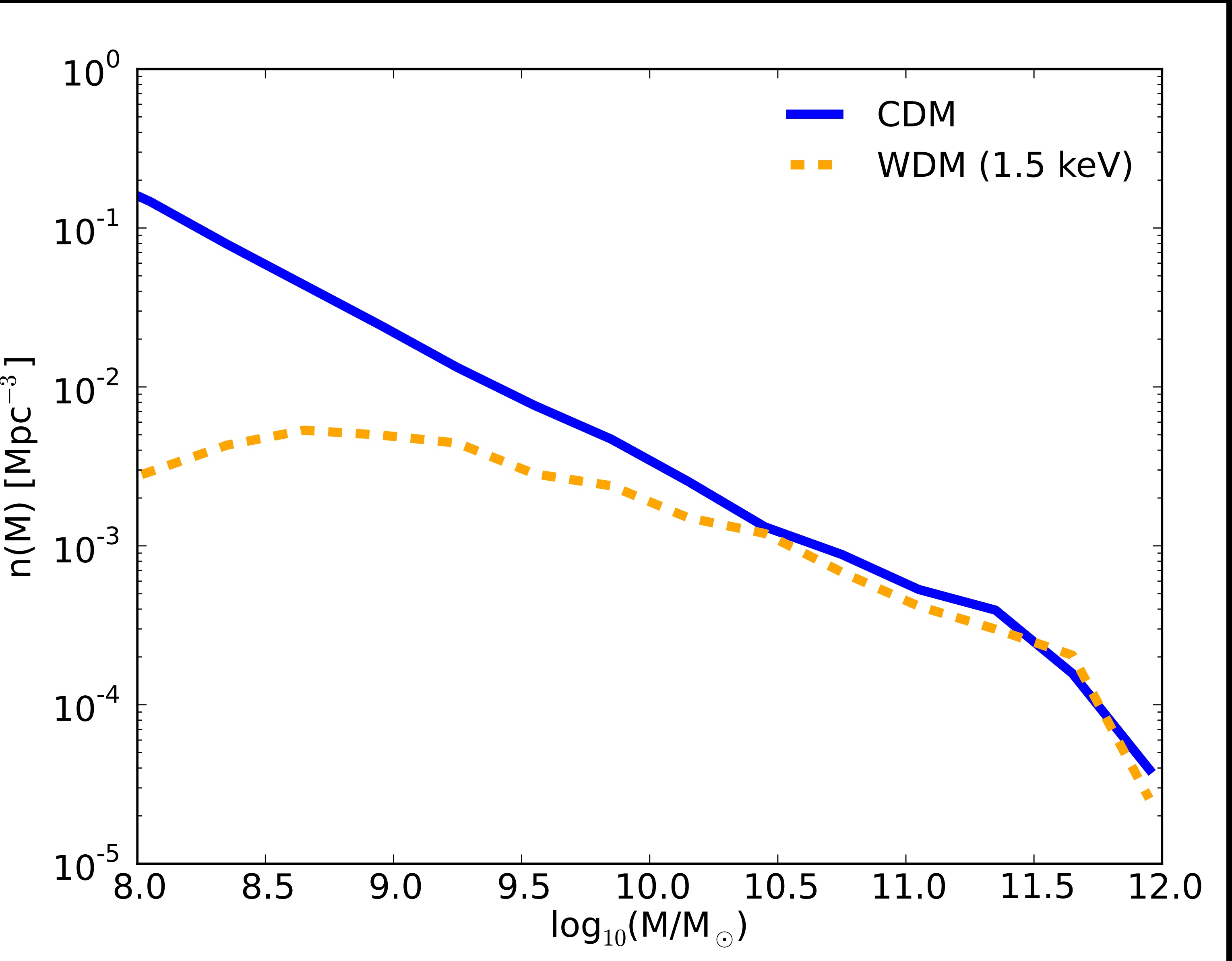
Dynamical friction, tidal distruption, substructure, halo model, spherical collapse, better simulations (much work to be done!)

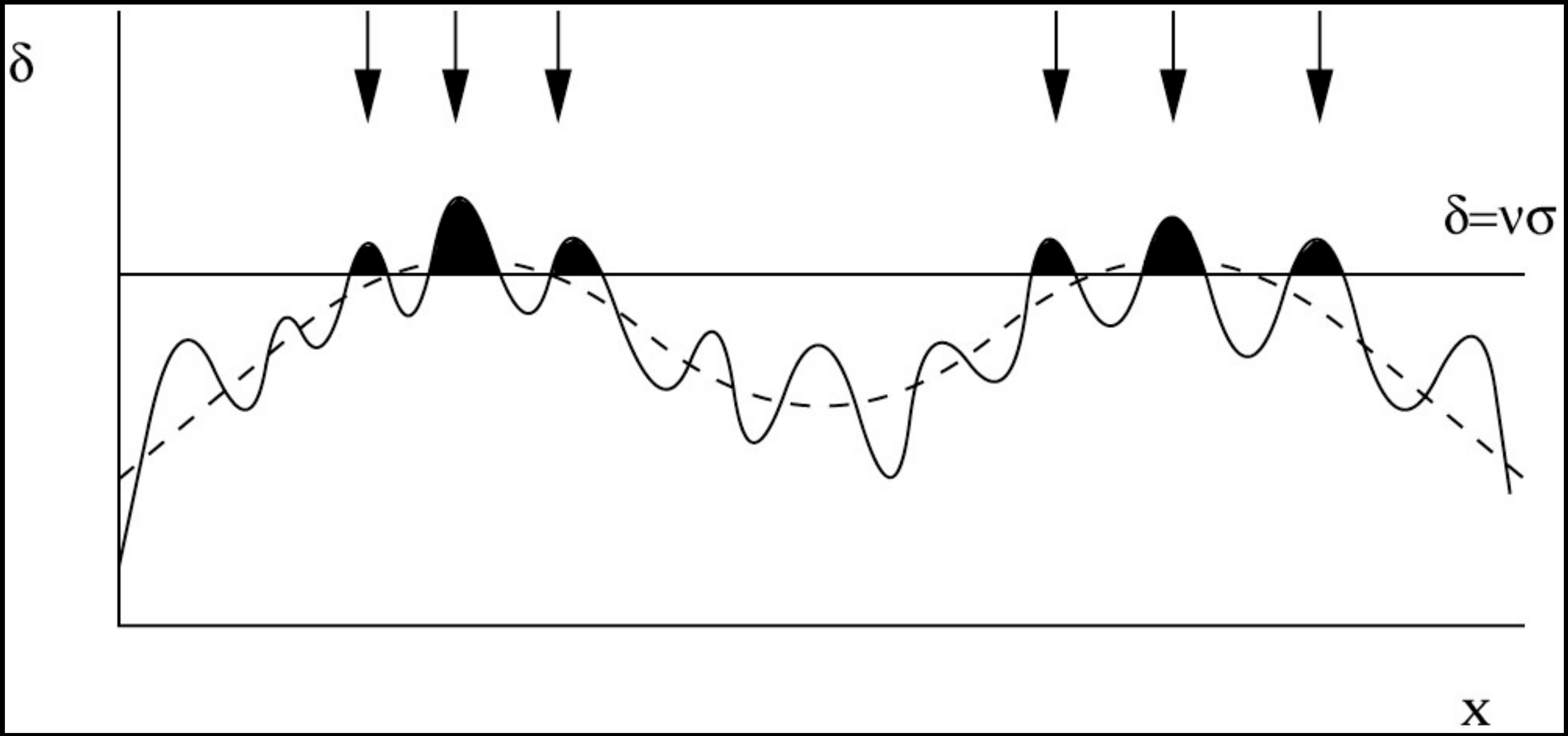
FUTURE WORK: ULAS AND GALAXIES

- ✳ Galaxy correlation function (counts, bias)
- ✳ Galaxy lensing
- ✳ Substructure in halos [flux ratio anomalies in multiply lensed]

ULA substructure?



- Galaxies are biased tracers



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✴ We use hard switch at $k_{osc} = k_{eq}; k_{\rm osc} \equiv a_{\rm osc} H_{\rm osc}$

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Doesn't include ULAs as matter component on scales where they cluster

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✳Realistic [smooth] treatment of scale-dependent bias needed (incorporating physics of ULA formation in halos)

- ✳Often neglected (but shouldn't be) for neutrinos (LoVerde 2013)