Probing the nature of DM with CMB observations

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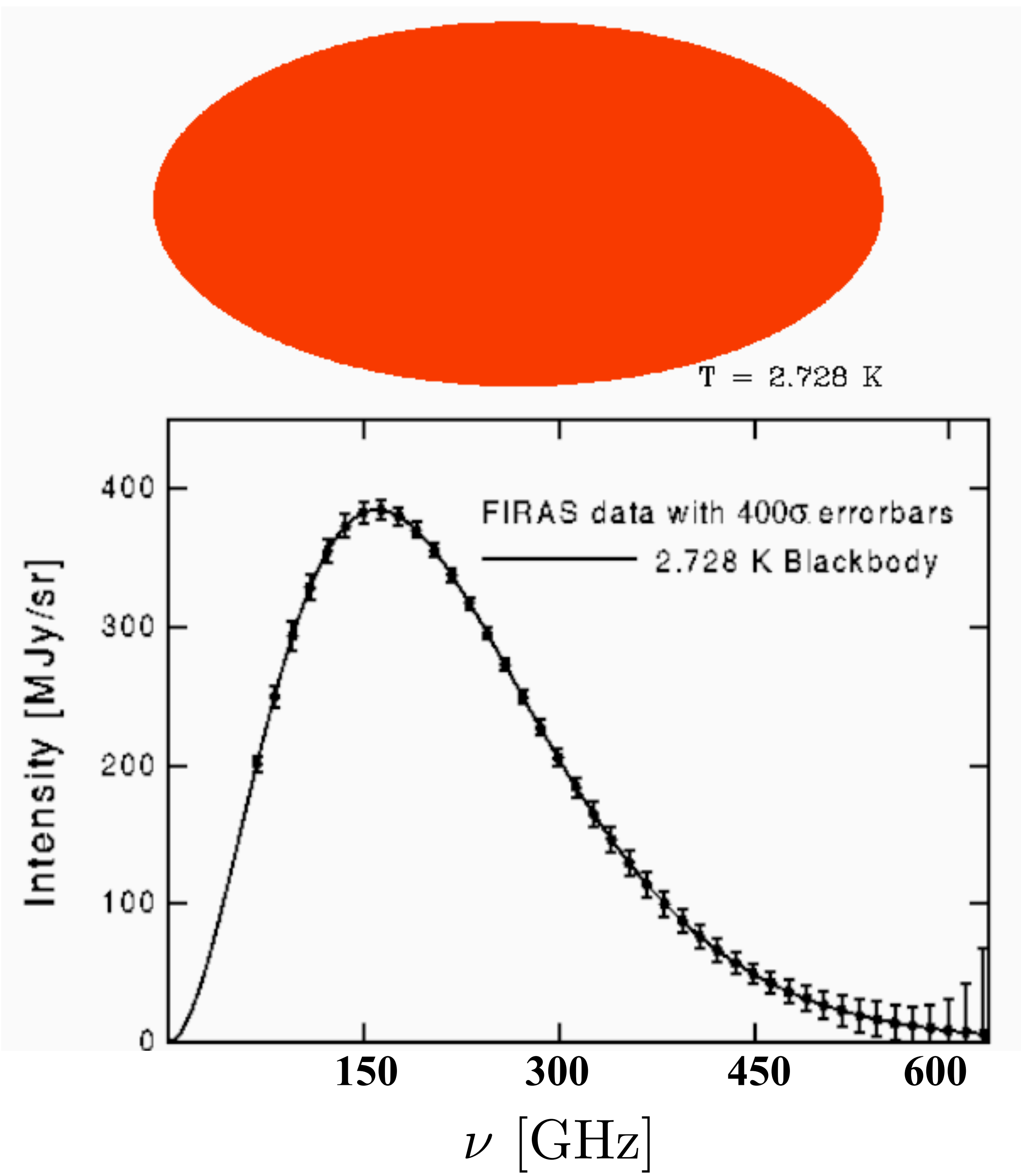
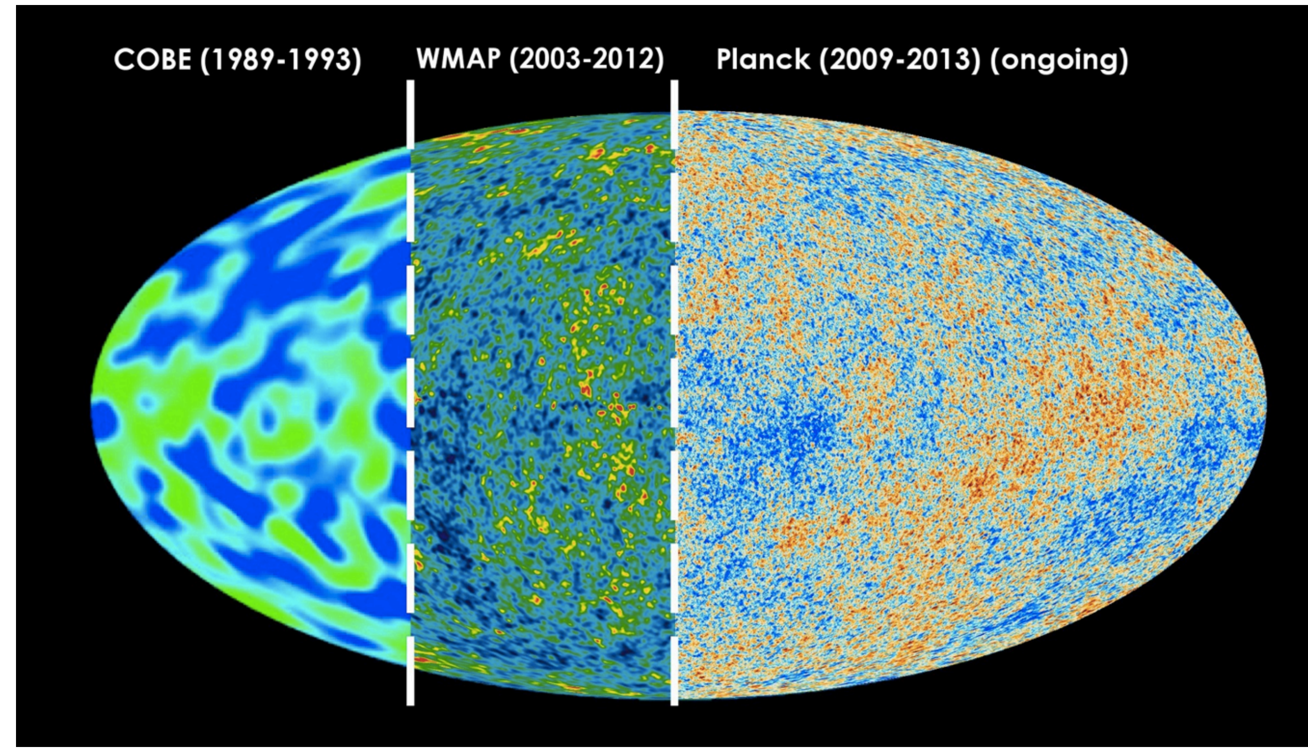
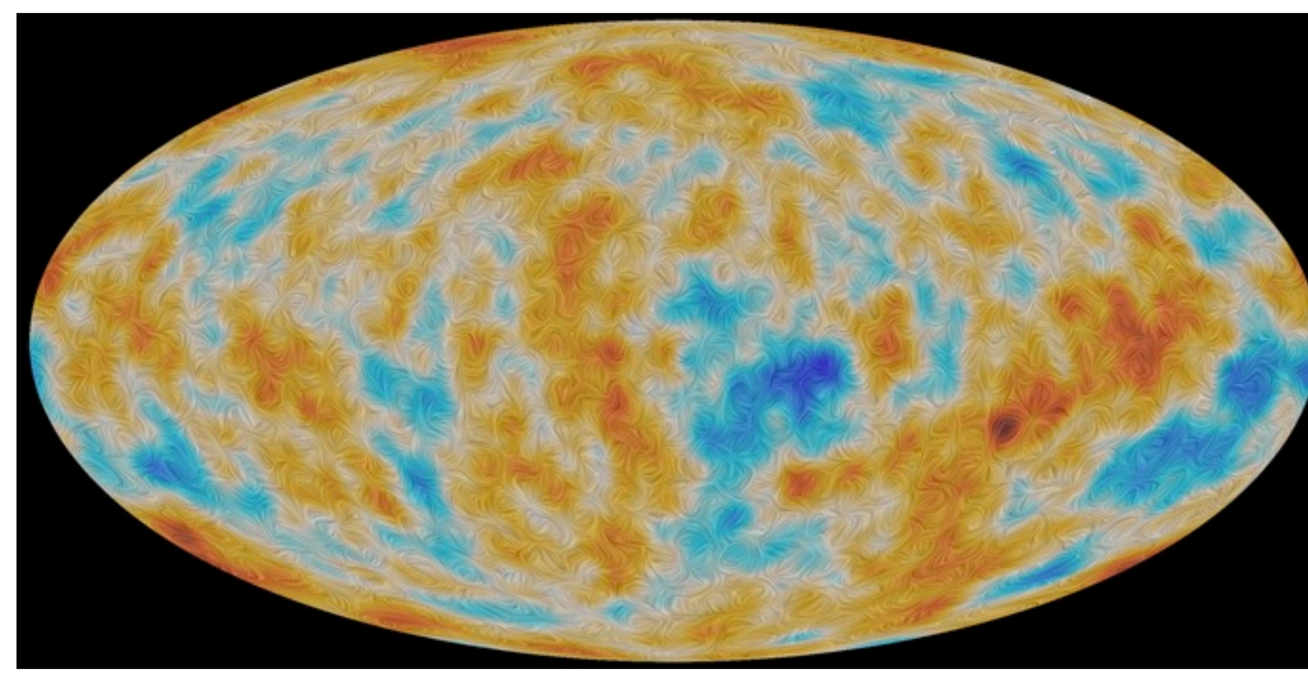
The CMB brightness is 2-dimensional function: frequency and direction

$$T(\nu, \hat{n}) = T_0 \ + \Delta T_{\rm spec}(\nu) + \Delta T_{\rm anis}(\hat{n}) + \delta T(\nu, \hat{n})$$





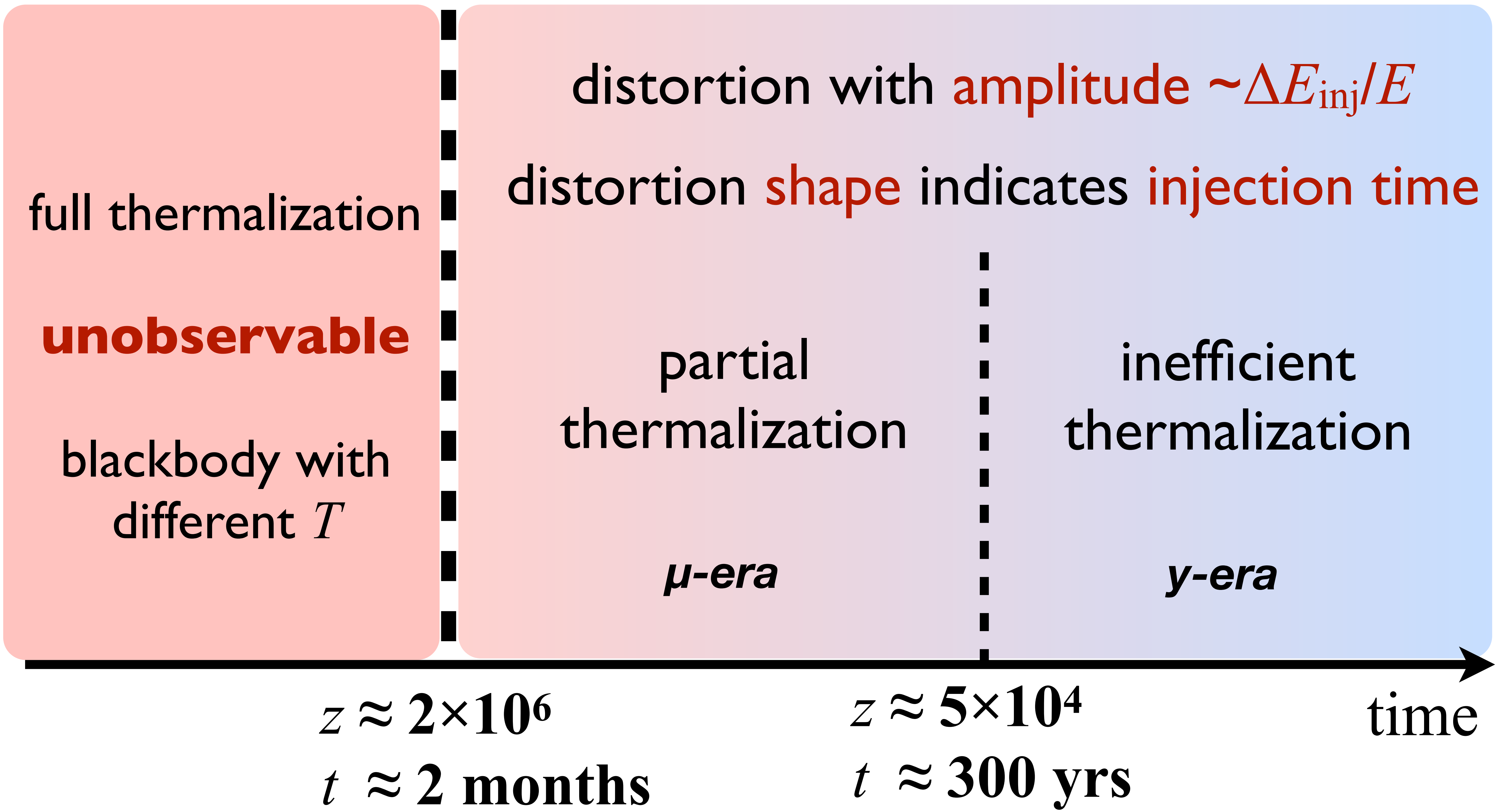


Planck polarization

Distortions tell us about thermal history

See e.g. Hu & Silk 1993, Chluba & Sunyaev 2012

Effect of heat injection as a function of time:



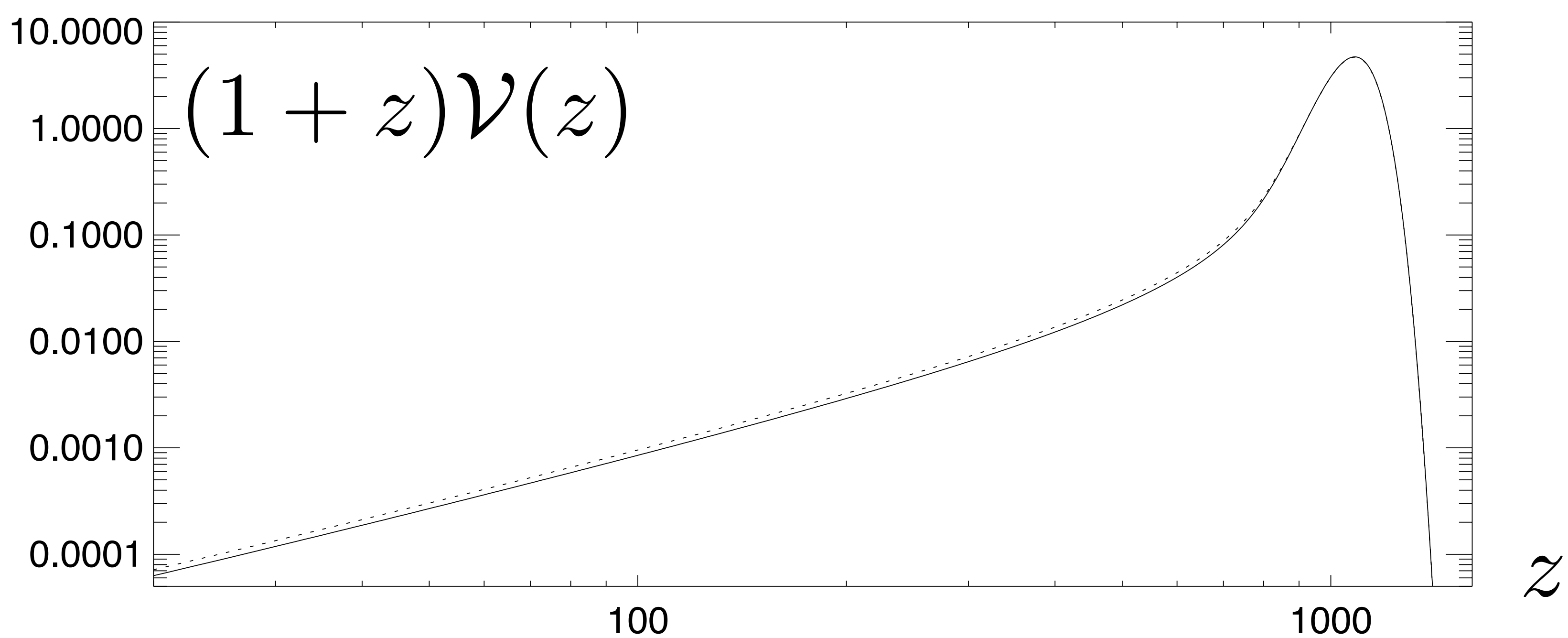
Anisotropies tell us about initial conditions + dynamics of perturbations + ionization history

$$\frac{\Delta T}{T}(z=0,\hat{n}) = \int dz\, \boxed{\mathcal{V}(z)}\, \boxed{\mathcal{T}(z, r(z)\hat{n})}\, \zeta_{\rm init} \quad [\ + \ \ (\mathrm{I})\mathrm{SW}]$$

Transfer function (mostly photon monopole + dipole for temperature, quadrupole for polarization): result of linear evolution of photon + neutrino + baryon + DM.

Visibility function: probability of last Thomson scattering between z and z + dz.

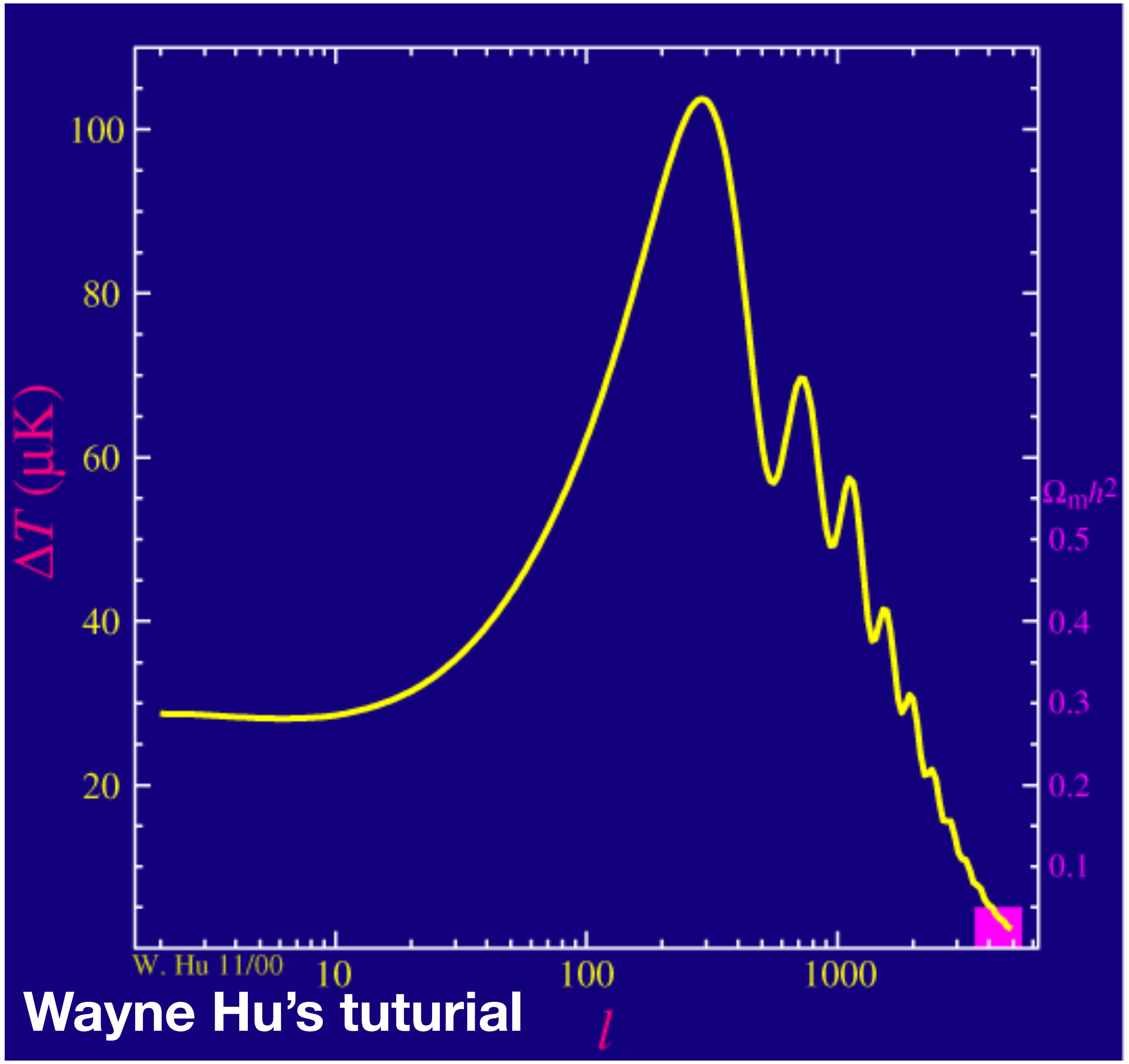
$$\mathcal{V}(z) = n_{\rm H} x_e \sigma_{\rm T} \frac{dt}{dz} \times \exp\left[-\int_0^z dz' \left(n_{\rm H} x_e \sigma_{\rm T} \frac{dt}{dz}\right)_{z'}\right]$$



0-th order measurement: total abundance of cold, collisionless dark matter

$$\Omega_c h^2 = 0.1199 \pm 0.0022$$

[Planck collaboration 2015]



What can the CMB tell us about the nature of DM?

Testing the vanilla WIMP with the CMB

``WIMP miracle": DM abundance results from annihilation cross section

$$\langle \sigma v \rangle_{\rm relic} \sim 10^{-26} {\rm cm}^3 {\rm s}^{-1}$$

Step 0: DM annihilations inject energy with volumetric rate

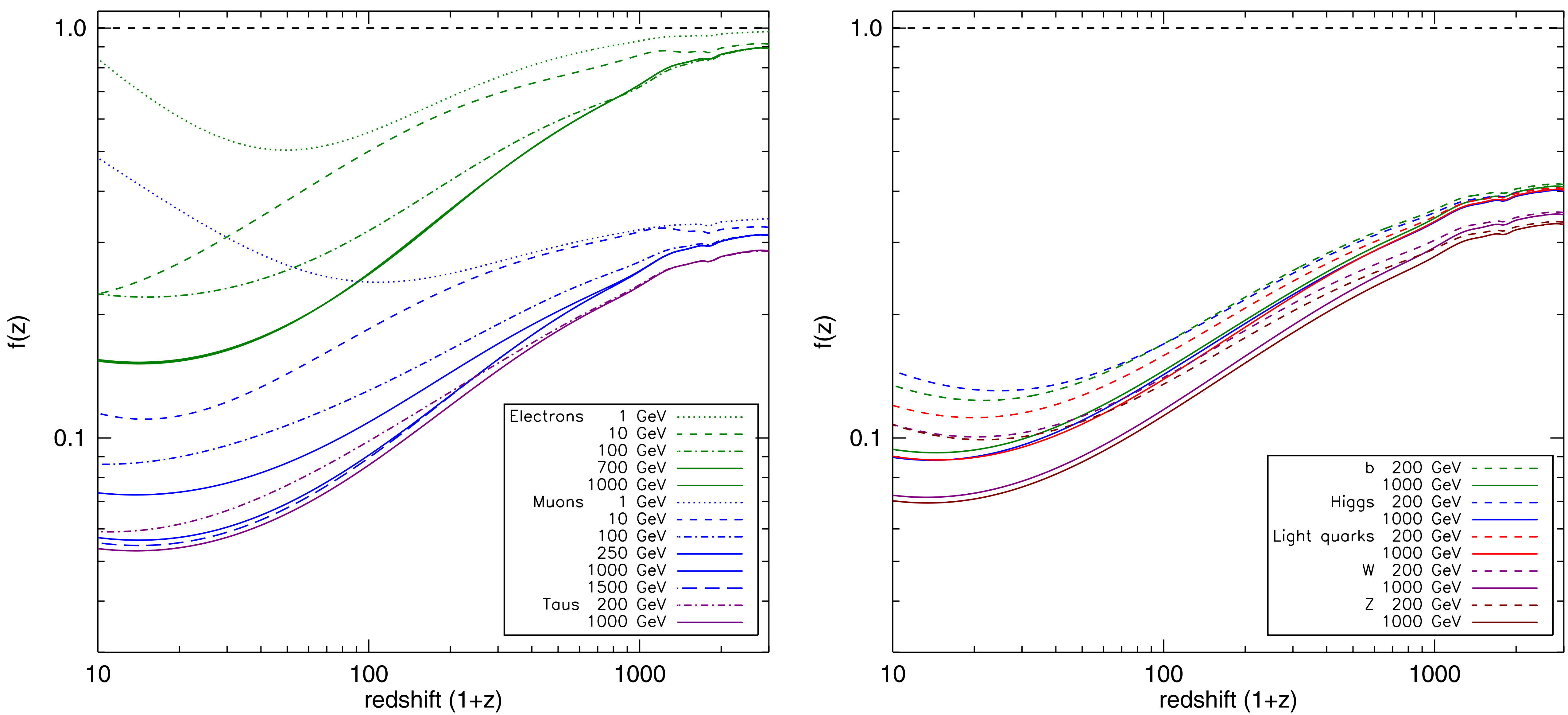
$$\dot{\rho}_{\rm inj} = \frac{1}{2} \left(\frac{\rho_c}{m_\chi} \right)^2 \langle \sigma v \rangle m_\chi = \frac{1}{2} \frac{\langle \sigma v \rangle}{m_\chi} \rho_c^2$$

=> CMB is mostly sensitive to $p_{\rm ann} = \frac{\langle \sigma v \rangle}{m_\chi}$

Step 1: compute energy deposited into the plasma

$$\dot{\rho}_{\rm dep}(z) = f(z)\ \dot{\rho}_{\rm inj}$$

Depends on the nature and spectrum of particles produced in annihilation, e.g. if the DM annihilates entirely to neutrinos, *f* = 0



***f*(z) from Slatyer, Padmanabhan & Finkbeiner 09 for different models**

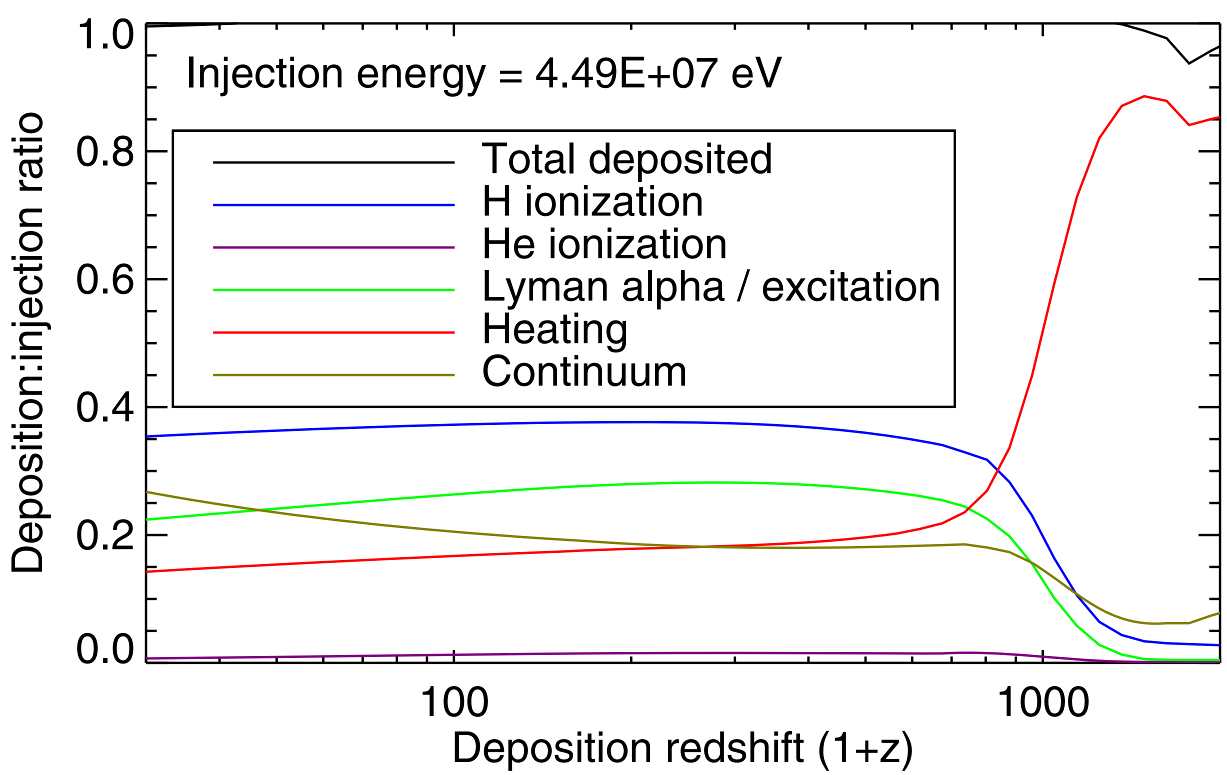
Step 2: channel of energy deposition: heat / ionizations / excitations

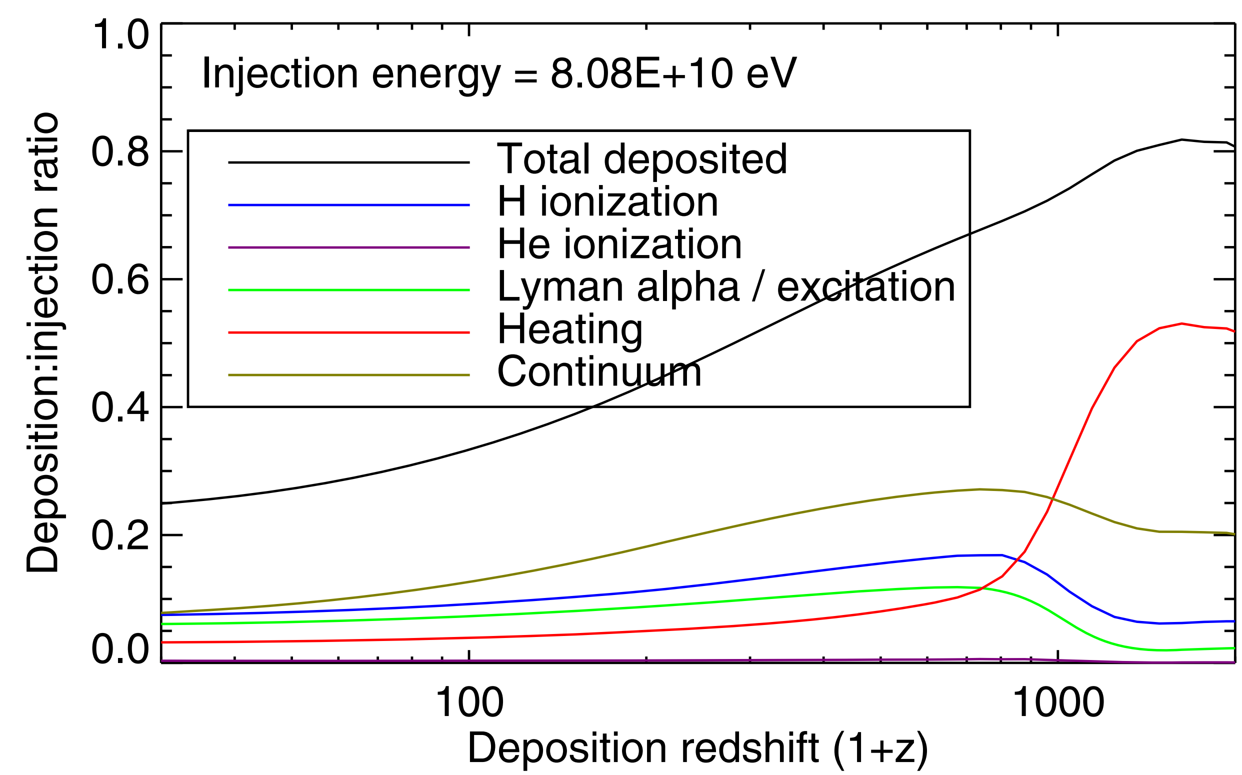
Simple estimate of Chen & Kamionkowski 04 (based on numerical studies of Shull & Van Steenberg 85):

fraction in heat, ionization, excitation ~ $$\left[\frac{1+2x_e}{3}, \frac{1-x_e}{3}, \frac{1-x_e}{3}\right]$$

In practice, depends on detailed injection spectrum

Slatyer 16, for e$^-$ e$^+$ pairs





Step 3: effect on CMB observables

- **spectral distortions:**

$$\frac{\Delta I_\nu}{I_\nu^{\rm BB}} \sim \int dt\ f_{\rm heat} \frac{\dot\rho_{\rm dep}}{\rho_\gamma}$$

typically much less sensitive to DM annihilation than anisotorpies

- **recombination history:**

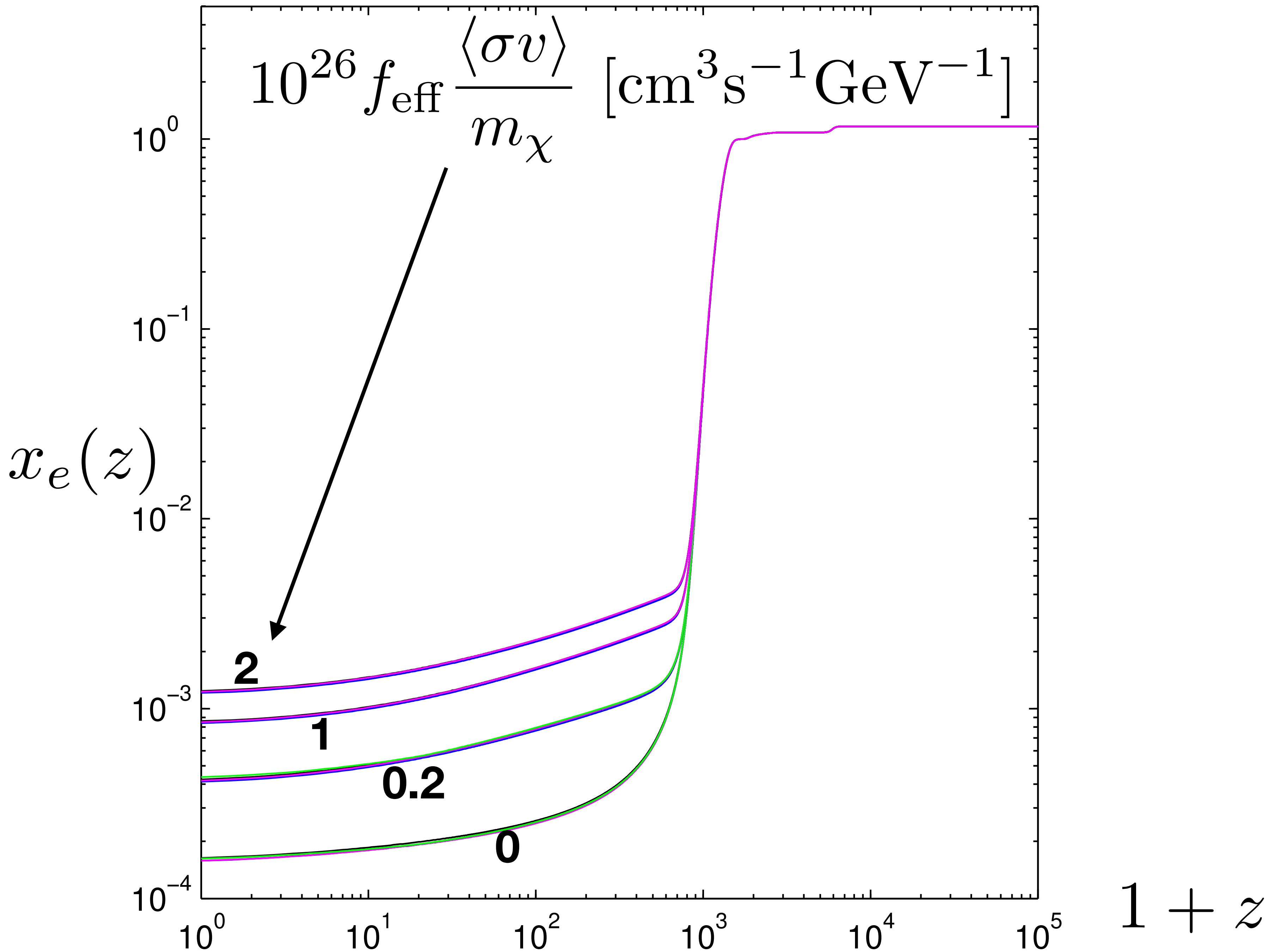
$$\dot x_e^{\rm direct} = \dot x_e^{\rm std} + f_{\rm ion} \frac{\dot\rho_{\rm dep}}{n_{\rm H} \times 13.6\ {\rm eV}}$$

$$\dot x_2 = \dot x_2^{\rm std} + f_{\rm exc} \frac{\dot\rho_{\rm dep}}{n_{\rm H} \times 10.2\ {\rm eV}}$$

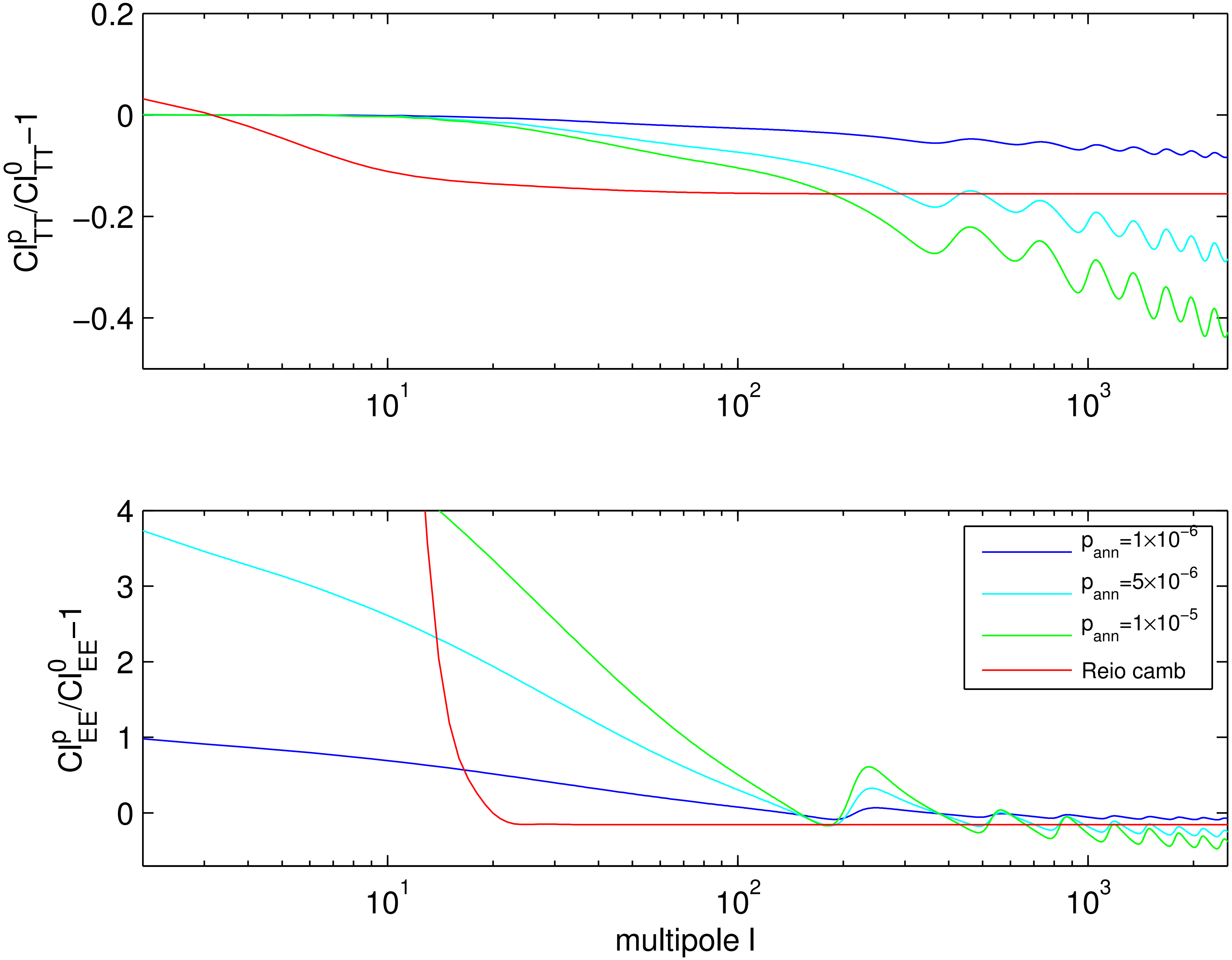
$$\dot T_{\rm gas} = \dot T_{\rm gas}^{\rm std} + \frac{2}{3 n_{\rm gas}} f_{\rm heat}\ \dot\rho_{\rm dep}$$

Requires highly accurate standard recombination theory
[YAH & Hirata 10, 11, Chluba ++ 11]

Implemented by several authors, e.g. Galli ++ 09, Slatyer ++09, Finkbeiner ++12, Green, Meerburg & Meyers 18

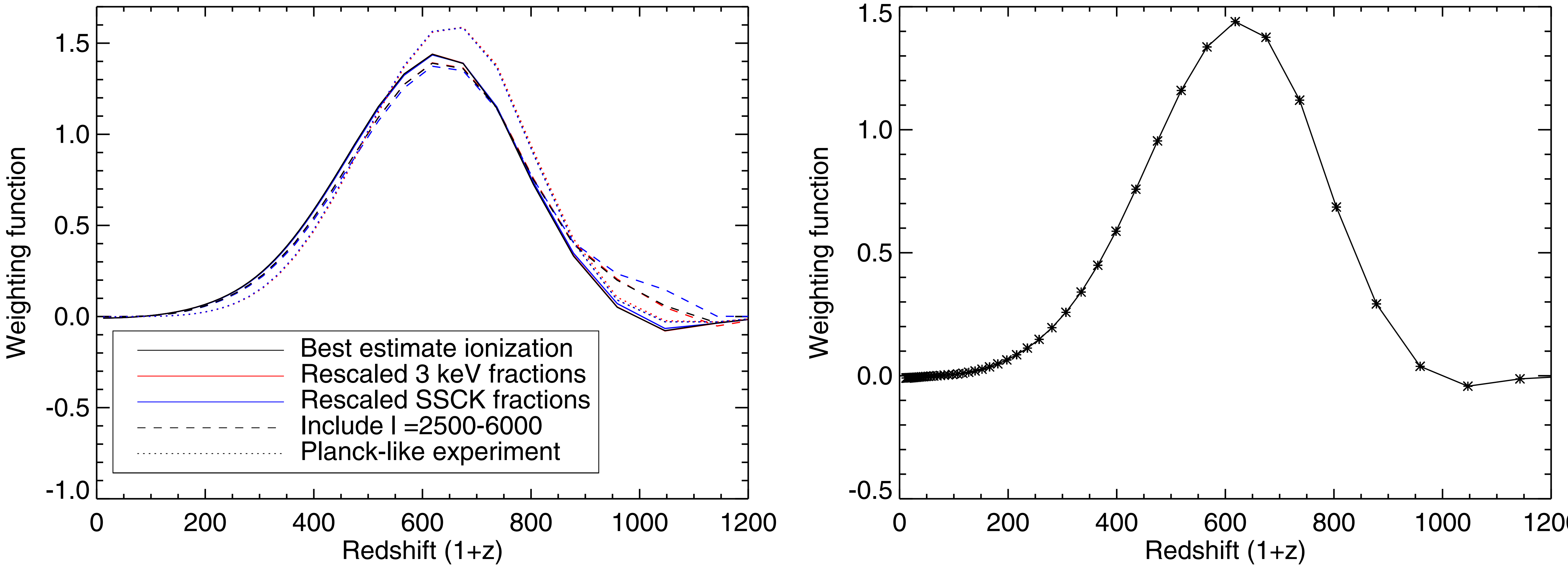


Giesen, Lesgourgues, Audren & YAH 12, computed with HyRec [YAH & Hirata, 2010, 2011]



Giesen, Lesgourgues, Audren & YAH 12,
computed with HyRec + CLASS [Lesgourgues 2011]

Anisotropies are mostly sensitive to DM annihilation around z~400-800



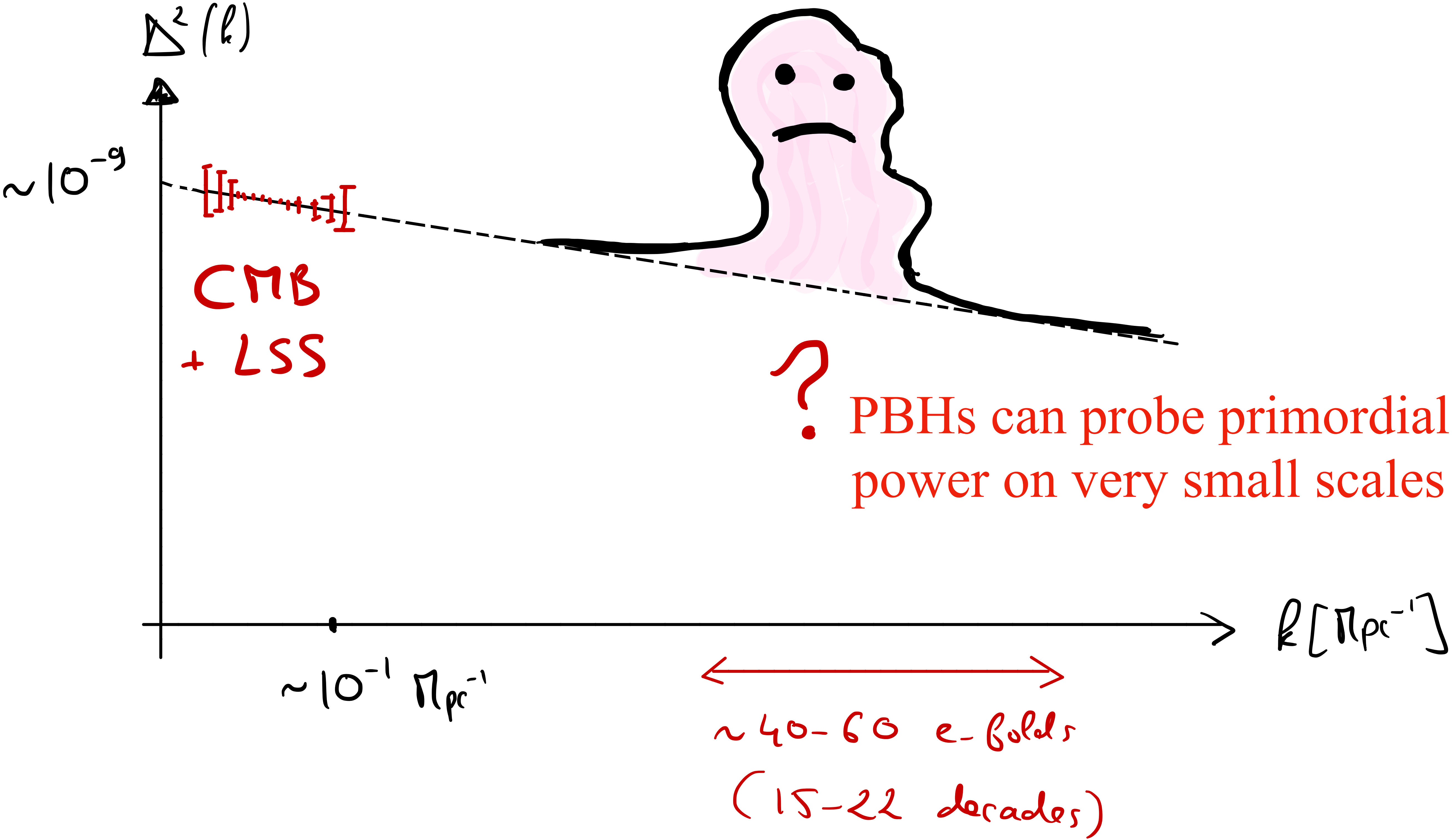
weighing function f(z) derived by PCA [Slatyer 2016]

Same general picture holds to test any DM model injecting energy into the photon-baryon plasma (e.g. decaying DM):

energy injection -> energy deposition -> heat + ionizations

CMB constraints on primordial black holes

We have only measured the primordial curvature perturbation on 2-3 decades



PBHs can probe primordial power on very small scales

CMB constraints on primordial black holes

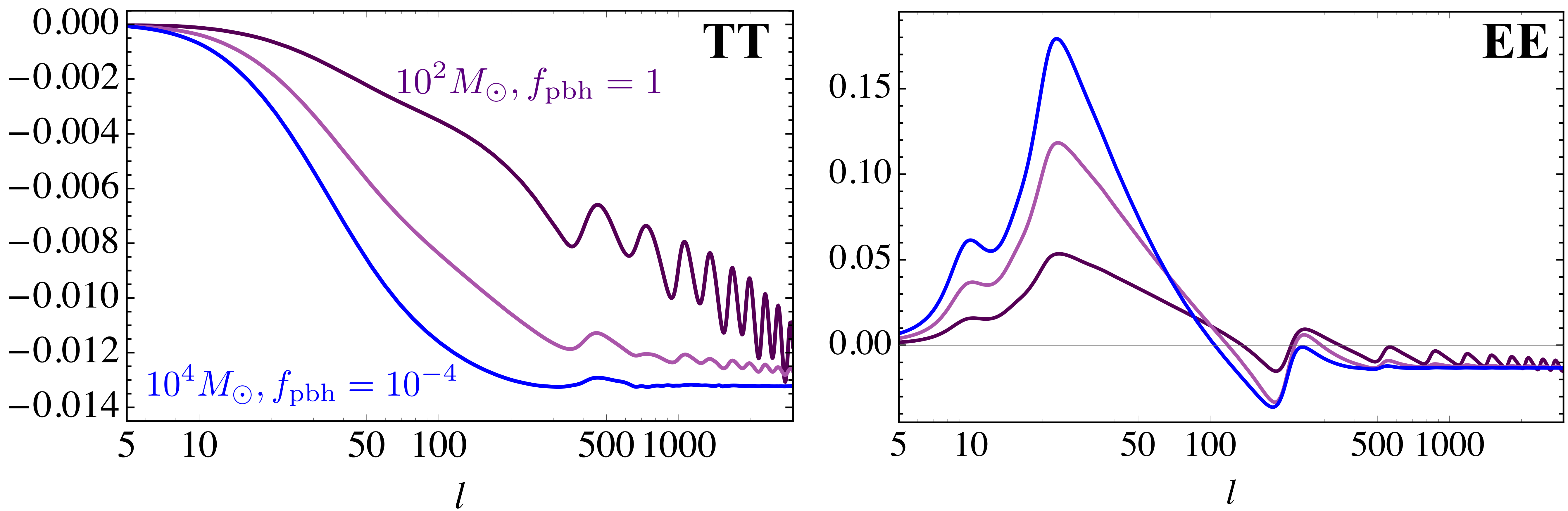
Ricotti, Ostriker & Mack 08, YAH & Kamionkowski 2017

Same idea: energy injection -> energy deposition -> heat + ionizations

accretion rate and radiative efficiency

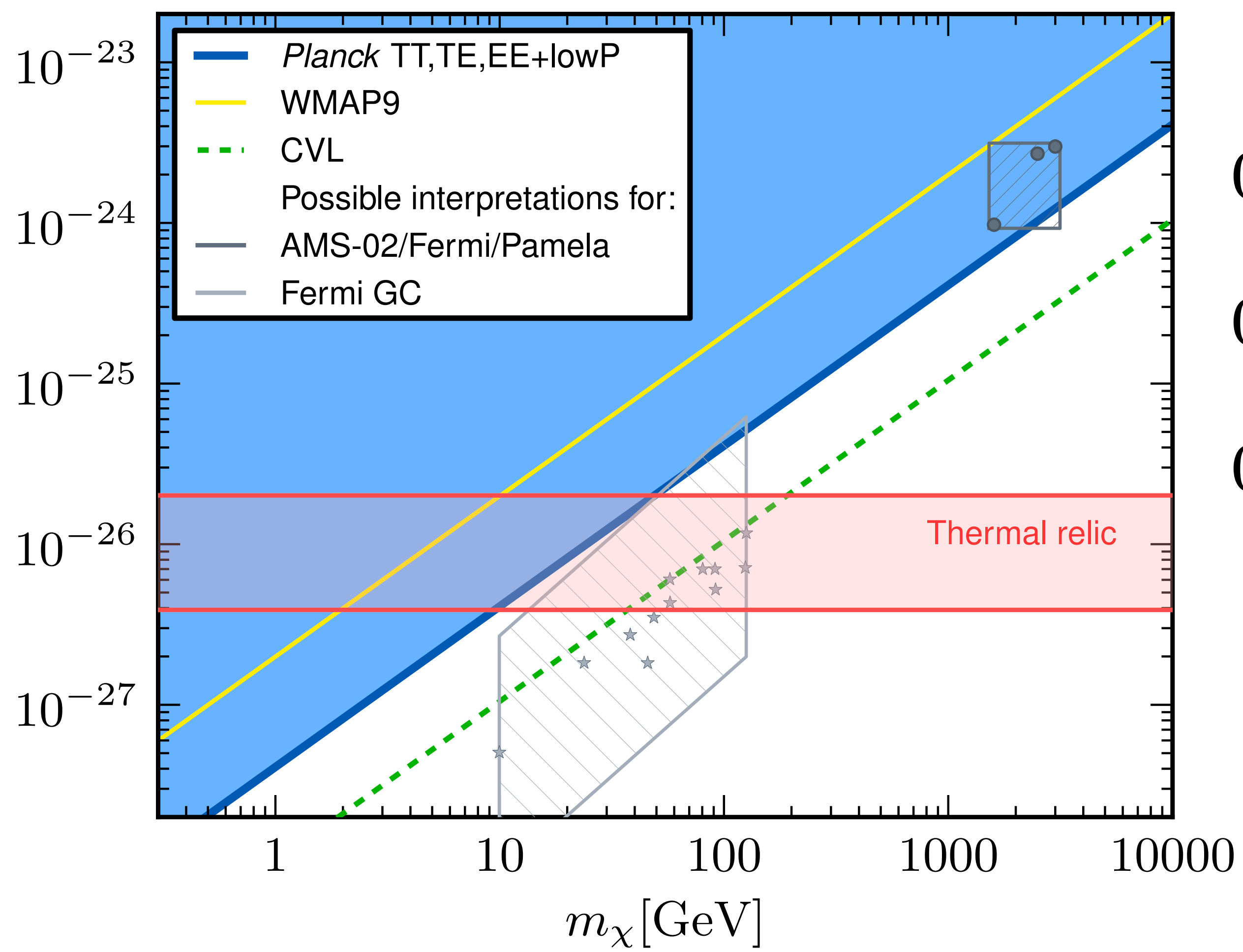
mostly through Compton scattering of ~MeV photons

$\frac{\Delta C_\ell}{C_\ell}$ Computed with modified HYREC + CLASS



Bounds to DM through effect on recombination history

$$\max\left(f_{\rm eff}\frac{\langle\sigma v\rangle}{m_\chi}\right)\quad[\mathrm{cm}^3\mathrm{s}^{-1}]$$



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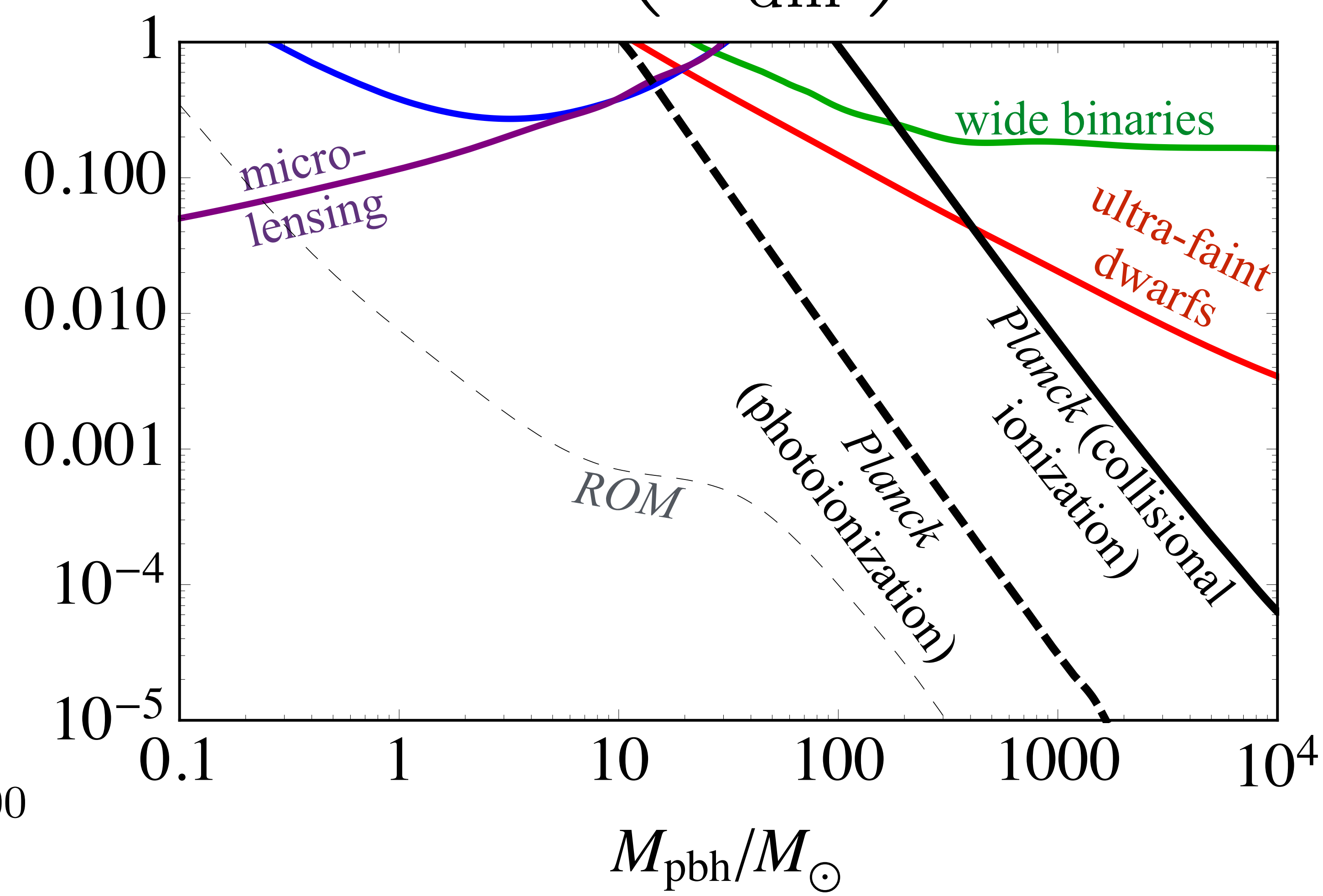
$$\max\left(\frac{\Omega_{\rm pbh}}{\Omega_{\rm dm}}\right)$$



YAH & Kamionkowski 17

CMB as a direct detection experiment: testing dark matter scattering

suppose the DM elastically scatters with baryons / electrons / photons.

=> exchanges momentum with the photon-baryon plasma

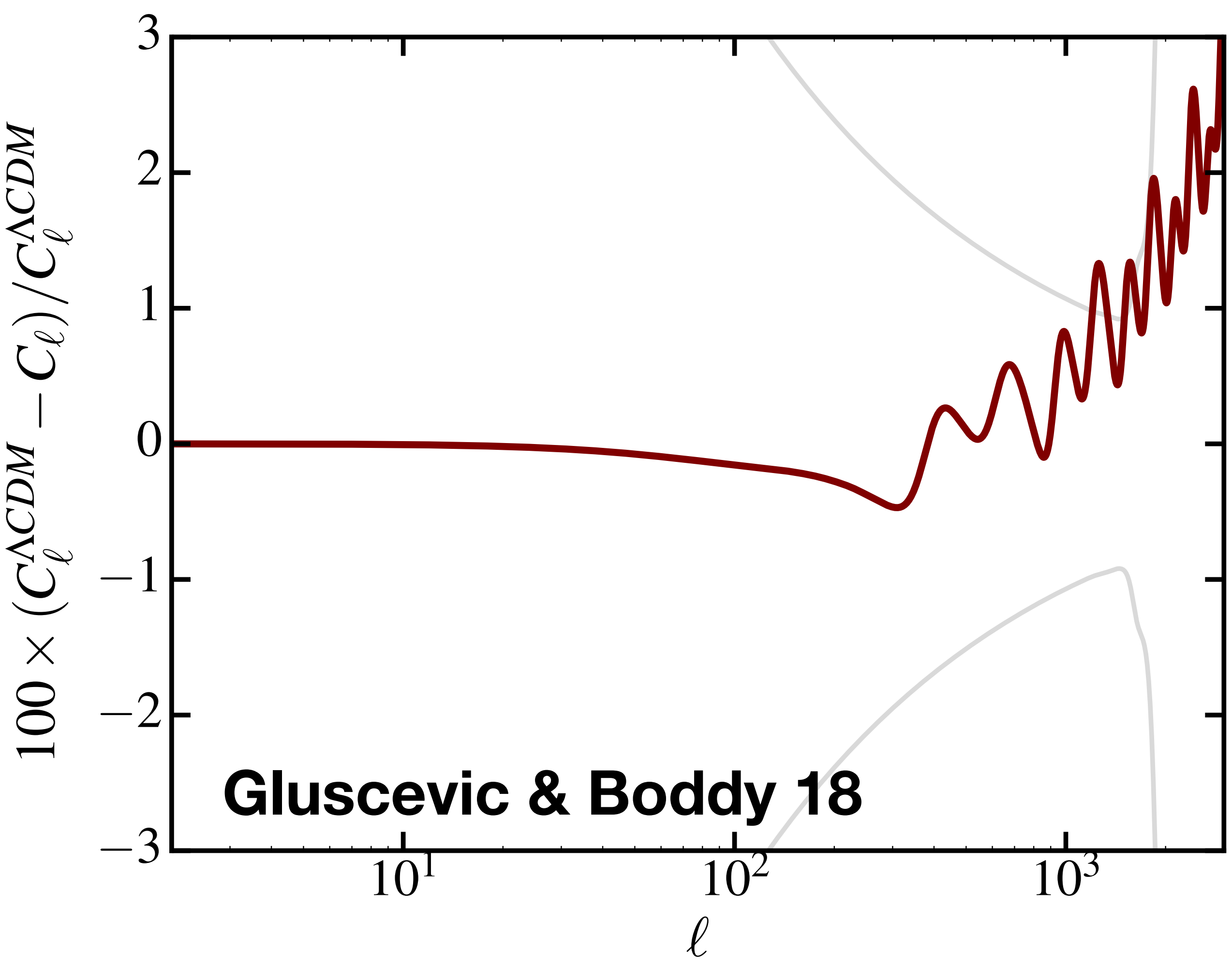
=> affects the linear evolution of perturbations
[Chen ++ 02, Sigurdson ++ 04, Dvorkin ++ 14, Boddy & Gluscevic 18]

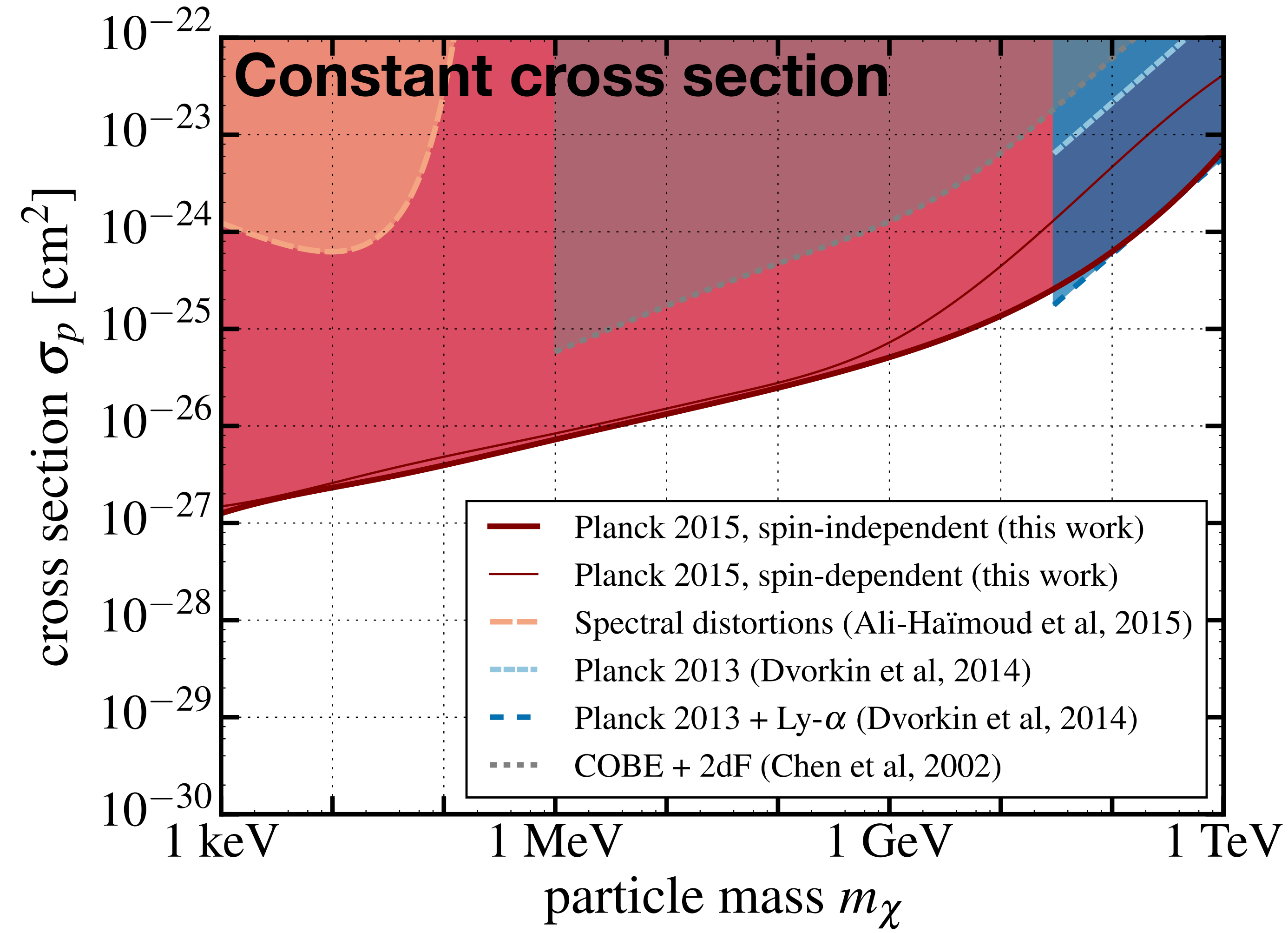
$$a^{-1}\frac{d}{dt}(a\vec{v}_b) = -\vec{\nabla}\phi + \Gamma_{\mathrm{Compt}}(\vec{v}_\gamma - \vec{v}_b) + \Gamma_{\chi b}(\vec{v}_\chi - \vec{v}_b)$$

$$a^{-1}\frac{d}{dt}(a\vec{v}_\chi) = -\vec{\nabla}\phi + \frac{\rho_b}{\rho_\chi}\Gamma_{\chi b}(\vec{v}_b - \vec{v}_\chi)$$

$$\Gamma_{\chi b} \sim \frac{\rho_\chi}{m_b + m_\chi}\langle \sigma v_{\mathrm{rel}} \rangle$$

Effect on CMB anisotropies





See also Boddy & Gluscevic 18 for constraints to general operators.

Bounds appear weaker than direct detection limits but

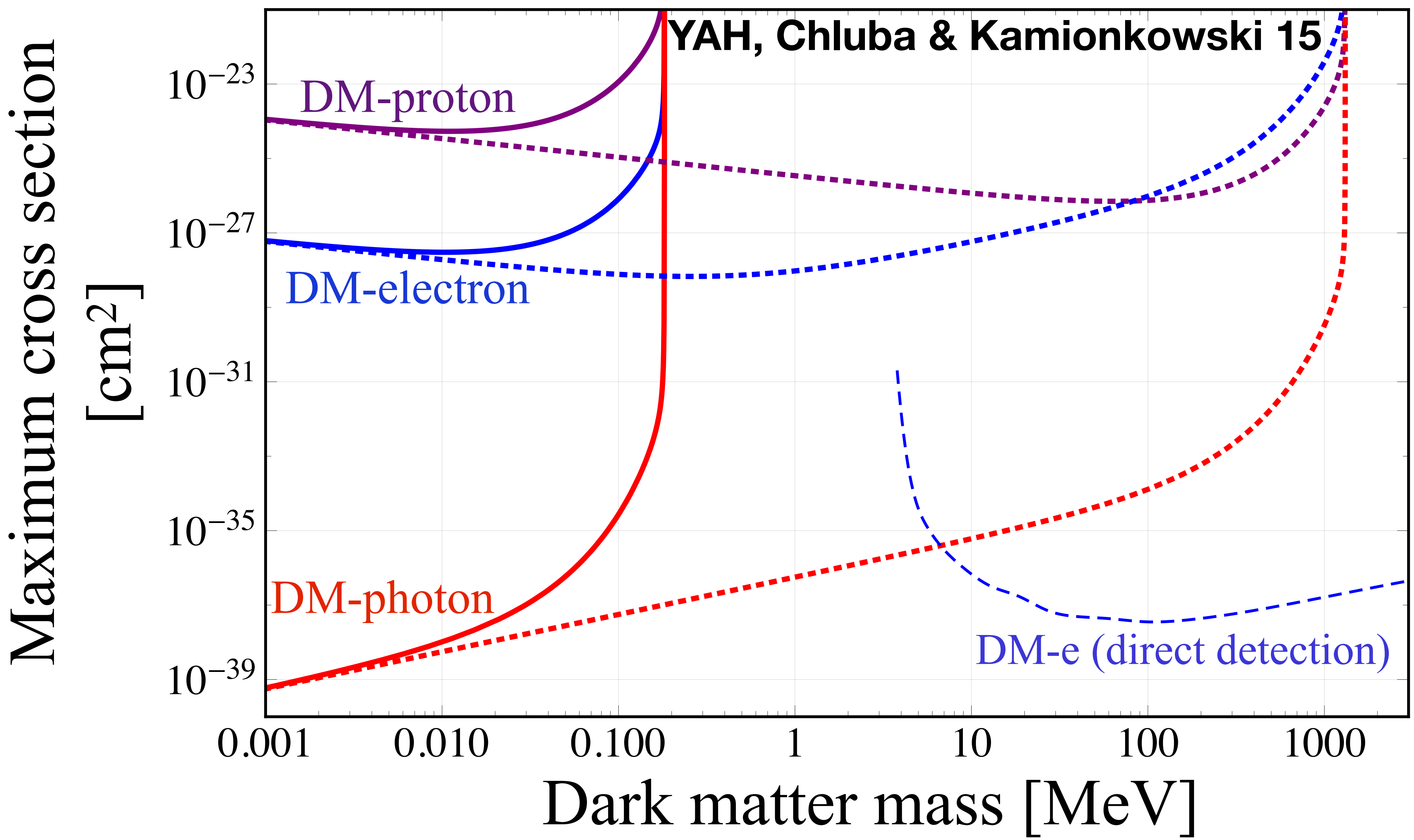
(i) can probe masses < GeV

(ii) shielding puts a ceiling to detectable cross sections

Constraints from spectral distortions

If non-relativistic, scattering DM extracts heat from the photon-baryon plasma

In progress: detailed study of thermal decoupling of DM and resulting spectral distortion bounds.



Summary

- CMB anisotropies and spectral distortions can constrain DM annihilation, or in general energy injection in the plasma, e.g. PBHs.
- The CMB can also probe scattering DM through its cooling effect and momentum exchange.
- How much can bounds be improved?

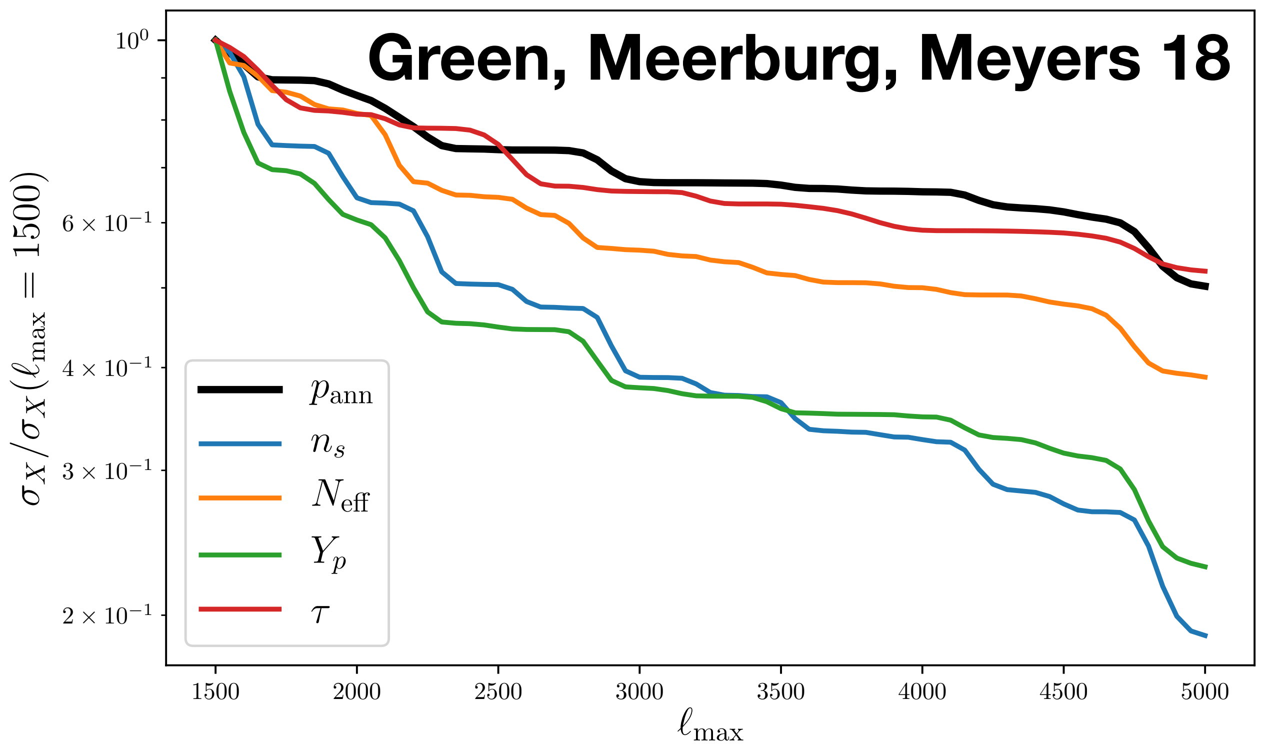


Figure 4. Improvement on forecasted constraints for a cosmic-variance-limited temperature-only CMB experiment up to a given $\ell_{\max}$ relative to that with $\ell_{\max} = 1500$.