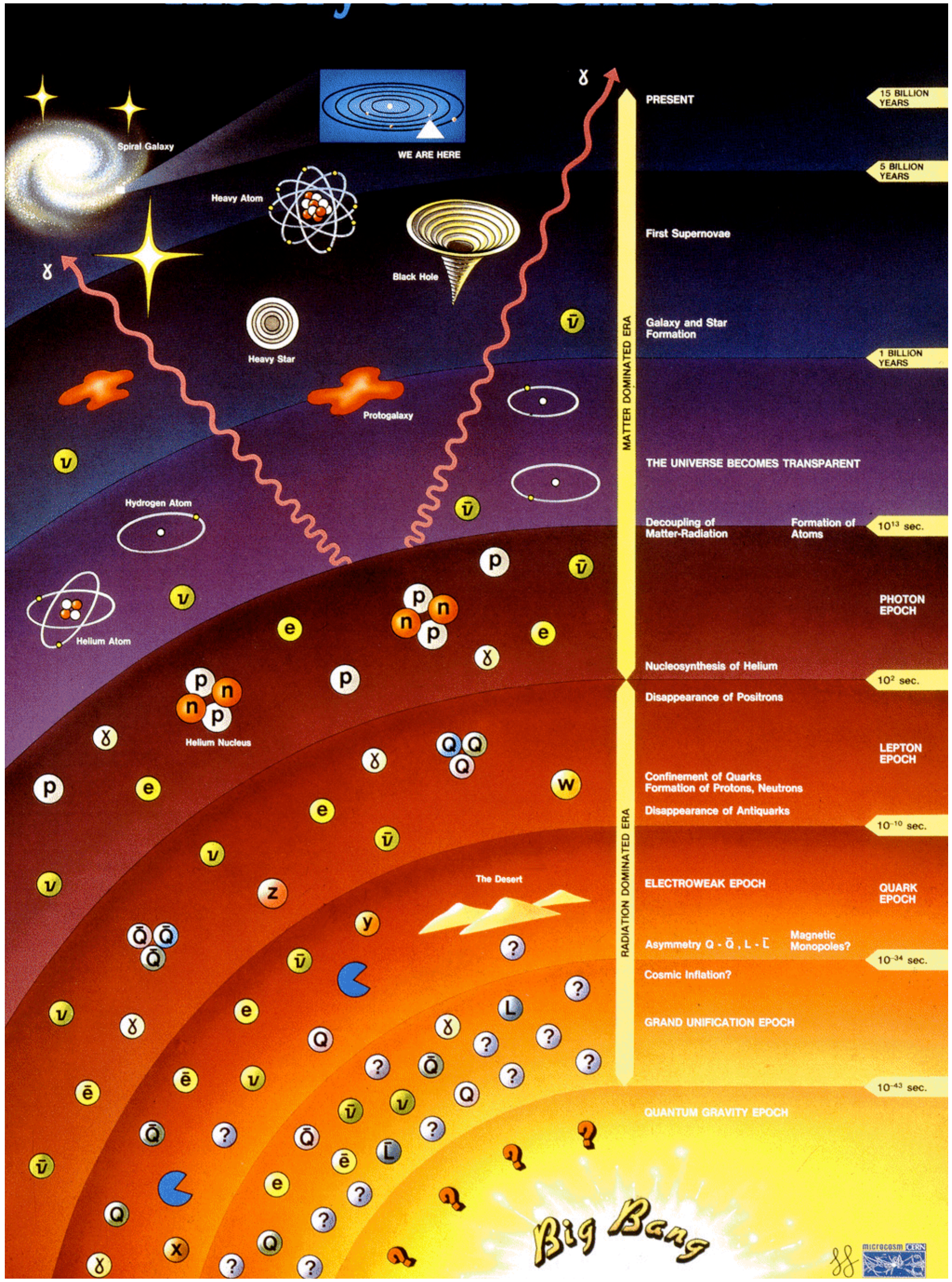


Spiral Galaxy
WE ARE HERE
Heavy Atom
Black Hole
Heavy Star
Protogalaxy
Hydrogen Atom
Helium Atom
Helium Nucleus
The Desert
PRESENT
15 BILLION YEARS
5 BILLION YEARS
First Supernovae
Galaxy and Star Formation
1 BILLION YEARS
MATTER DOMINATED ERA
THE UNIVERSE BECOMES TRANSPARENT
Decoupling of Matter-Radiation
Formation of Atoms
10¹³ sec.
PHOTON EPOCH
Nucleosynthesis of Helium
10² sec.
Disappearance of Positrons
LEPTON EPOCH
Confinement of Quarks
Formation of Protons, Neutrons
Disappearance of Antiquarks
10⁻¹⁰ sec.
RADIATION DOMINATED ERA
ELECTROWEAK EPOCH
QUARK EPOCH
Asymmetry Q - Q̄ , L - L̄
Magnetic Monopoles?
10⁻³⁴ sec.
Cosmic Inflation?
GRAND UNIFICATION EPOCH
10⁻⁴³ sec.
QUANTUM GRAVITY EPOCH
Big Bang
microcosm CERN

Theoretical cosmology/astrophysics

Alexander Heger: Stellar evolution, nucleosynthesis, first stars

Keith Olive: Nucleosynthesis, Supersymmetry (Dark matter), Inflation, first stars

Yong-Zhong Qian: Nucleosynthesis, supernovae neutrinos, first stars

Lilya Williams: Distribution of dark matter, structure formation, gravitational lensing

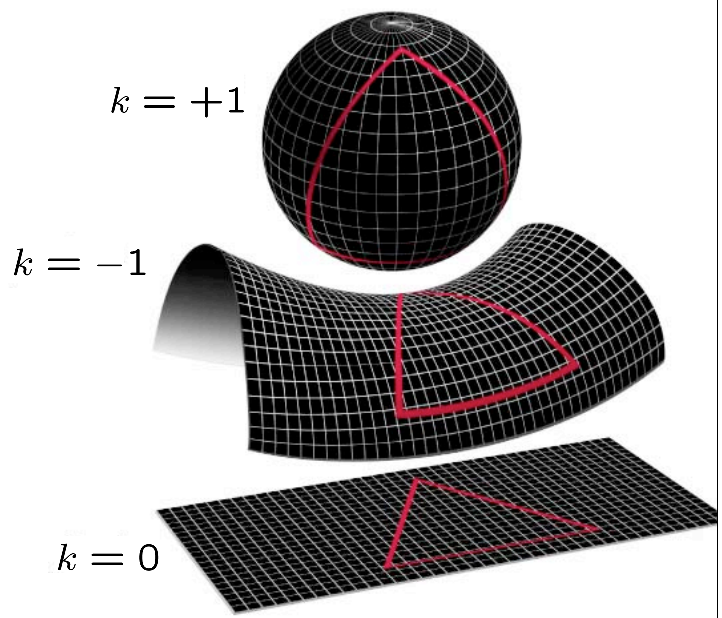
Observational cosmology/astrophysics

Prisca Cushman: Dark matter detection

Shaul Hanany: CMB

Vuk Mandic: Gravitational waves (LIGO)

It is remarkable how well we know the evolution of the universe. Homogeneity and isotropy + GR give



Physical distances $\propto a(t)$

$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{8\pi}{3M_p^2}\rho - \frac{k}{a^2}$$

$$\rho = \frac{\rho_R}{a^4} + \frac{\rho_M}{a^3} + \rho_\Lambda$$

Big-Bang Nucleosynthesis
1 sec - 3 min

Structure formation
galaxies, clusters

Present acceleration
$a_{\rm acc} \simeq 0.5\, a_0$

What is even more remarkable is the fact that the universe is so homogeneous and isotropic

Guth '81

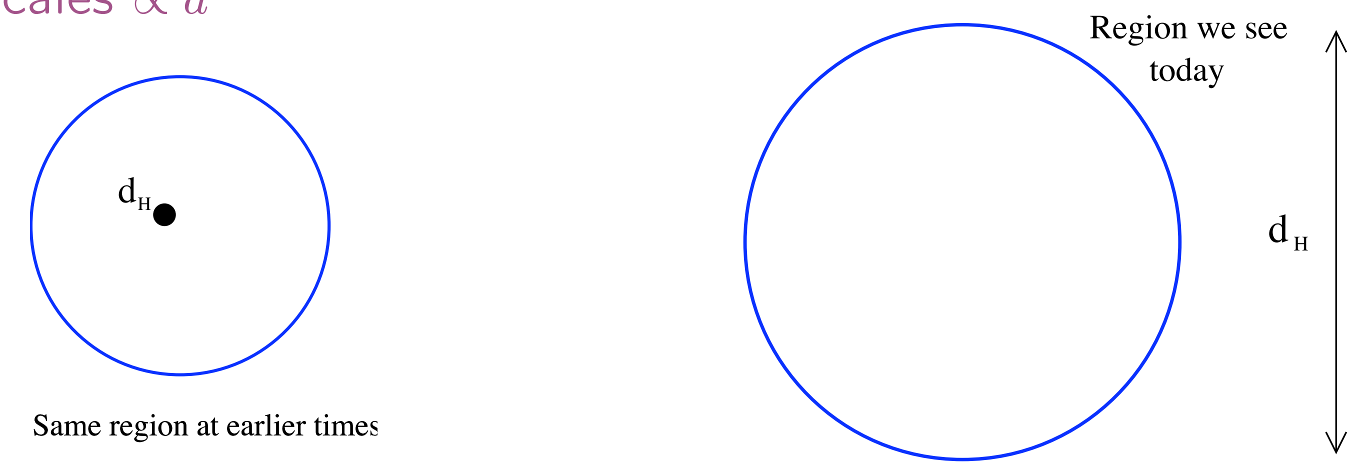
Horizon problem

- Light travels finite distance in finite time

  Scales $> d_H(t)$ cannot be causally connected

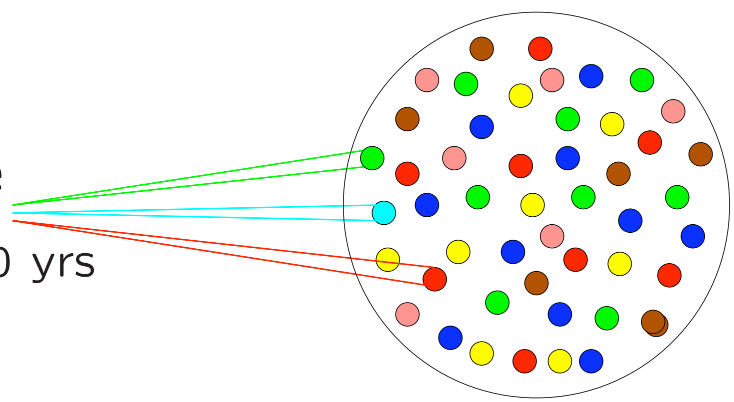
$$d_H(t) = a(t) \int_0^t \frac{dt'}{a(t')} \sim H^{-1}$$

In a matter + radiation universe, horizon $\propto H^{-1}$ grows faster than physical scales $\propto a$



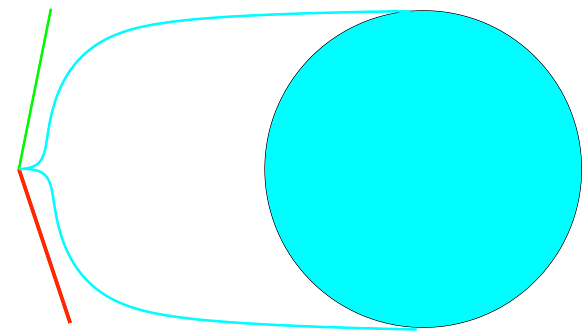
Earlier time

$t_{\rm CMB} \simeq 380,000$ yrs



Sharp contrast with the observed $T_0 \simeq 2.73$K everywhere

Solved if which physical scales (a) grow faster than horizon ($a/\dot{a}$)



Need $\ddot{a} > 0$, acceleration $\equiv$ inflation

Flatness problem

$$\frac{\dot{a}^2}{a^2} = \frac{8\pi}{3M_p^2}\left[\frac{\rho_M}{a^3} + \frac{\rho_R}{a^4}\right] - \frac{k}{a^2} + \frac{\rho_X}{a^\gamma}$$

Curvature $\leq 1\%$ today. Must have been $\leq 10^{-18}$ at BBN.

Requires ρ_X which "flattens the universe" at earlier times.

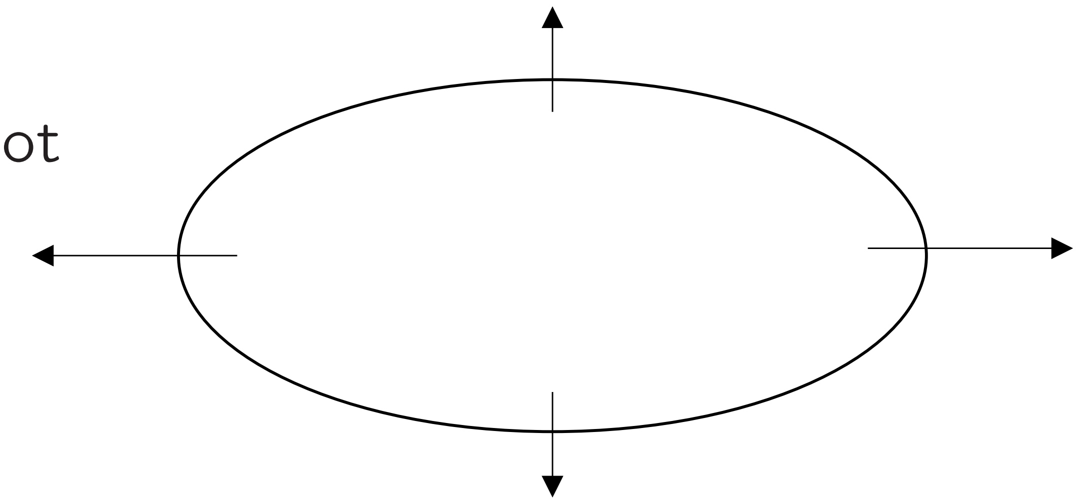
Idea: ρ_X dominates at very early times; then, it decays into matter / radiation. To dominate over curvature, $\gamma < 2$

But $\gamma < 2$ leads to increasing $\dot{a}$ $\Rightarrow$ inflation

Isotropy problem

Why identical expansion rates ($H = \dot{a}/a$) in all directions ?

Why not



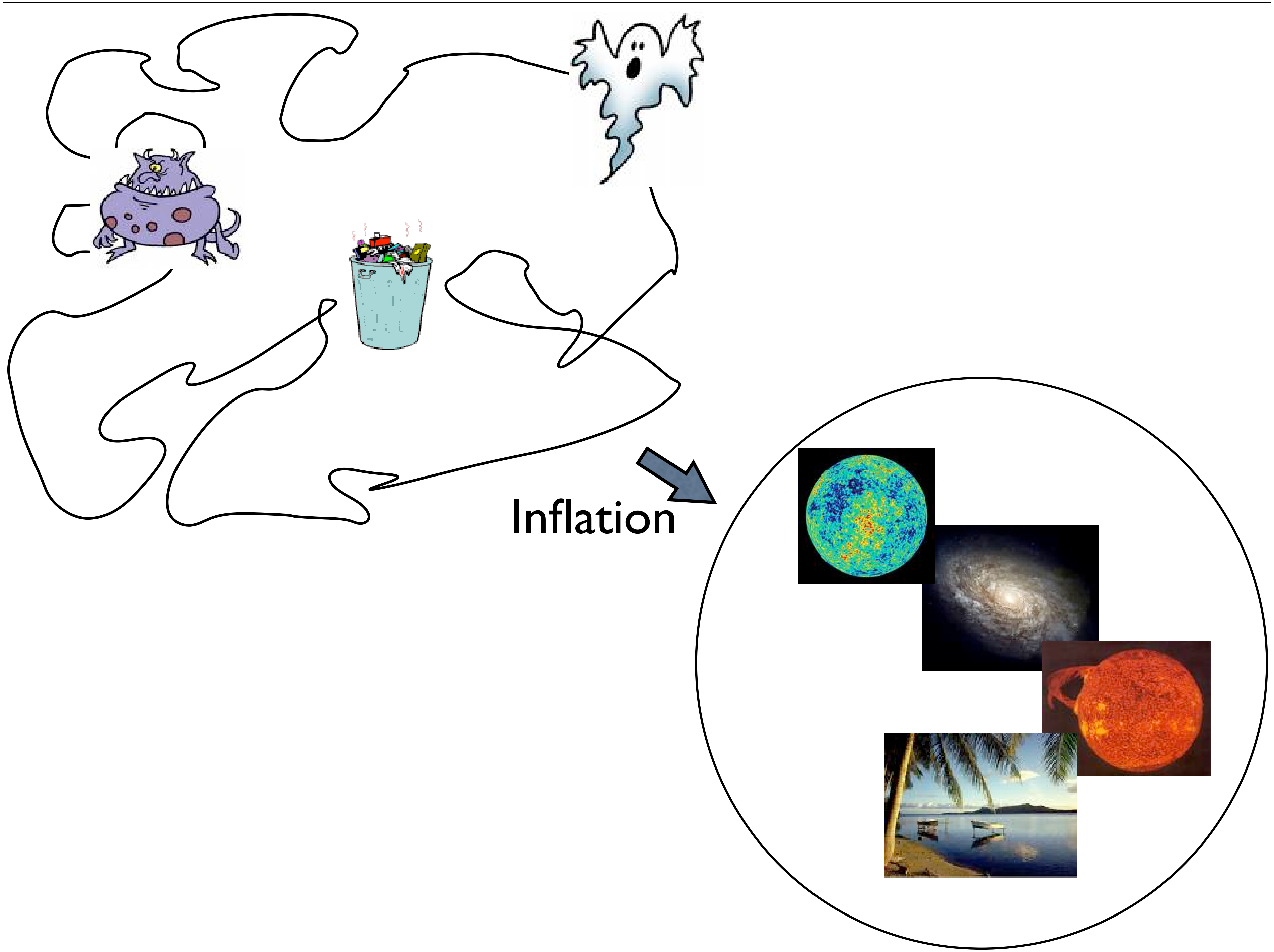
?

Imagine universe started out not perfectly isotropic

non accelerated expansion $\Rightarrow$ anisotropy grows

accelerated expansion $\Rightarrow$ anisotropy $\rightarrow 0$

Homogeneity, gravitino, monopole, . . . problems


Inflation

Inflation $\equiv$ accelerated expansion, $\ddot{a} > 0$

Einstein eqs.: $$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

ρ: energy density; p: pressure

Need $w \equiv \frac{p}{\rho} < -\frac{1}{3}$

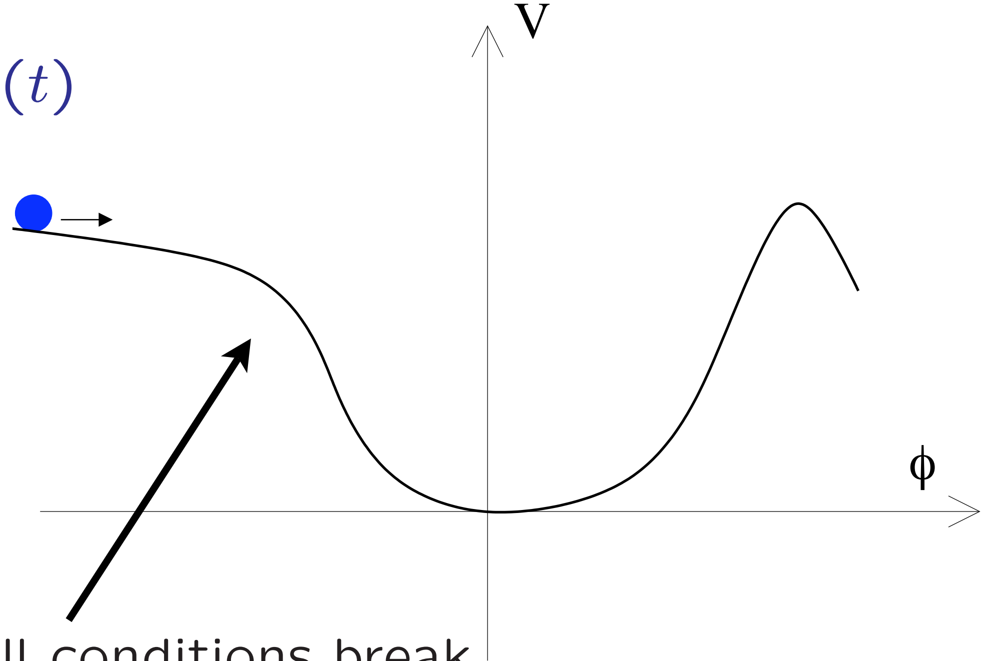
Won't work for matter ($w = 0$) or radiation ($w = 1/3$)

Homogeneous scalar field $\phi(t)$

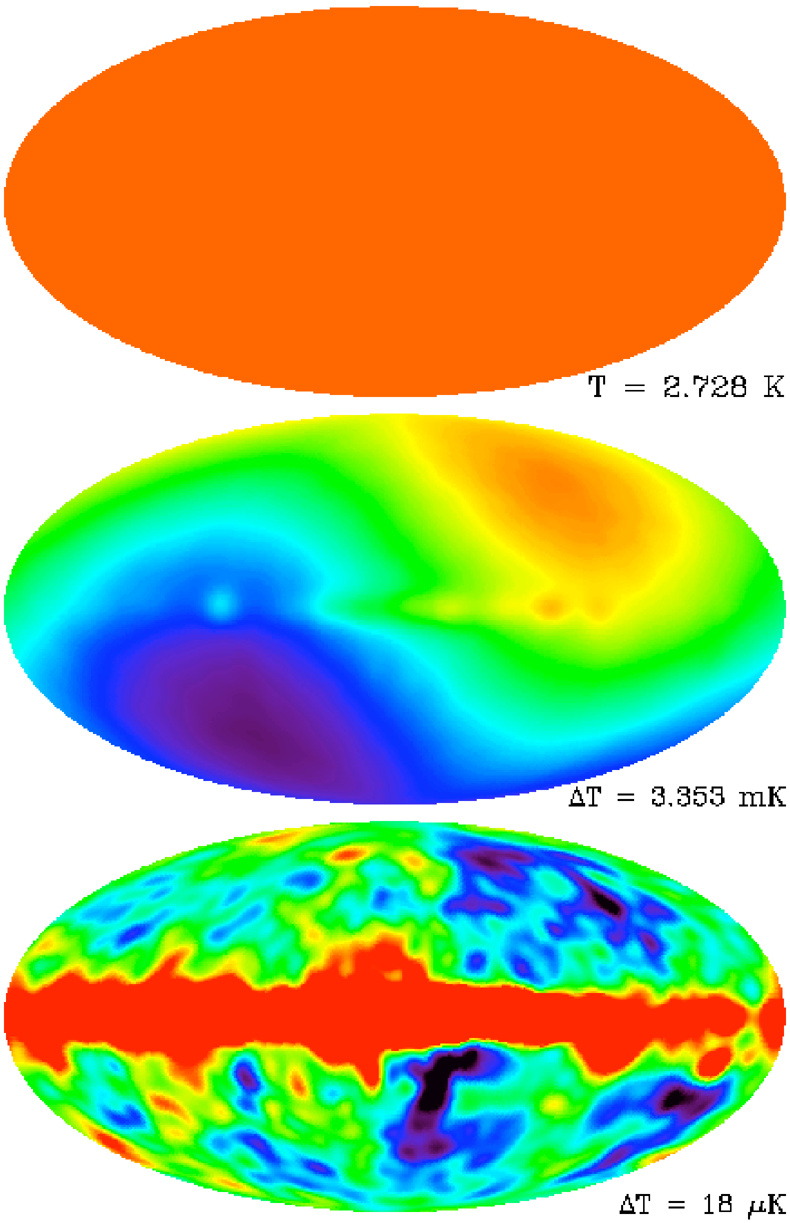
in potential V

$$w = \frac{\dot{\phi}^2/2 - V}{\dot{\phi}^2/2 + V}$$

$w \simeq -1$ if $\dot{\phi}^2 \ll V$ Slow roll



Inflation terminates when slow roll conditions break



Inflaton (quantum) perturbations

↓

cosmological perturbations

$$\frac{\delta\rho}{\rho} \sim \frac{\Delta T}{T} \sim 10^{-5}$$

We don't know $V(\phi)$

If $V = V_0 + \frac{1}{2}m^2\phi^2 + \ldots$

correct amplitude fluctualtions

for $m \sim 10^{13}\,\mathrm{GeV}/c^2$

Inflation → REHEATING → Hot big-bang cosmology

Unknowns:

Scale of inflation

Inflaton ϕ

Coupling to matter

Require:

$T >$ MeV, for Nucleosynthesis

No gravitinos, $T < 10^9$ GeV

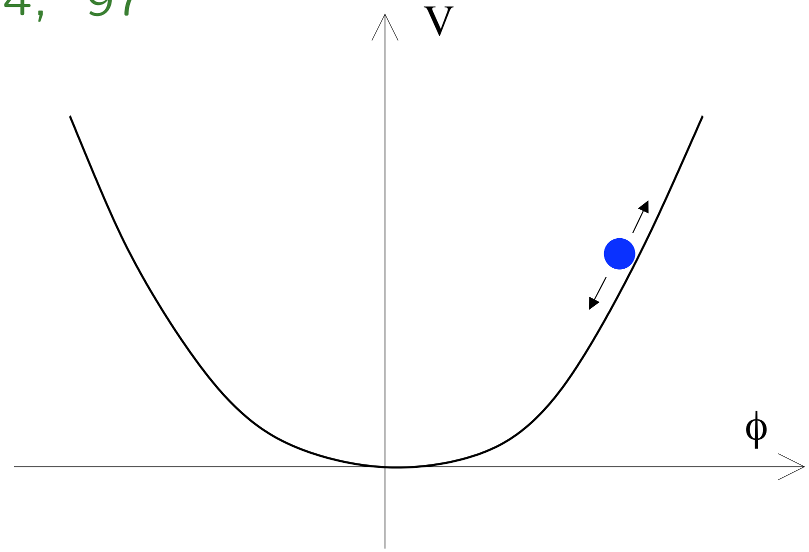
Matter / anti–matter asymmetry

1 "Slow" (perturbative) decay; quick thermalization

2 Fast decay, slow (?) thermalization

Nonperturbative inflaton decay

Preheating: Kofman, Linde, Starobinsky '94; '97



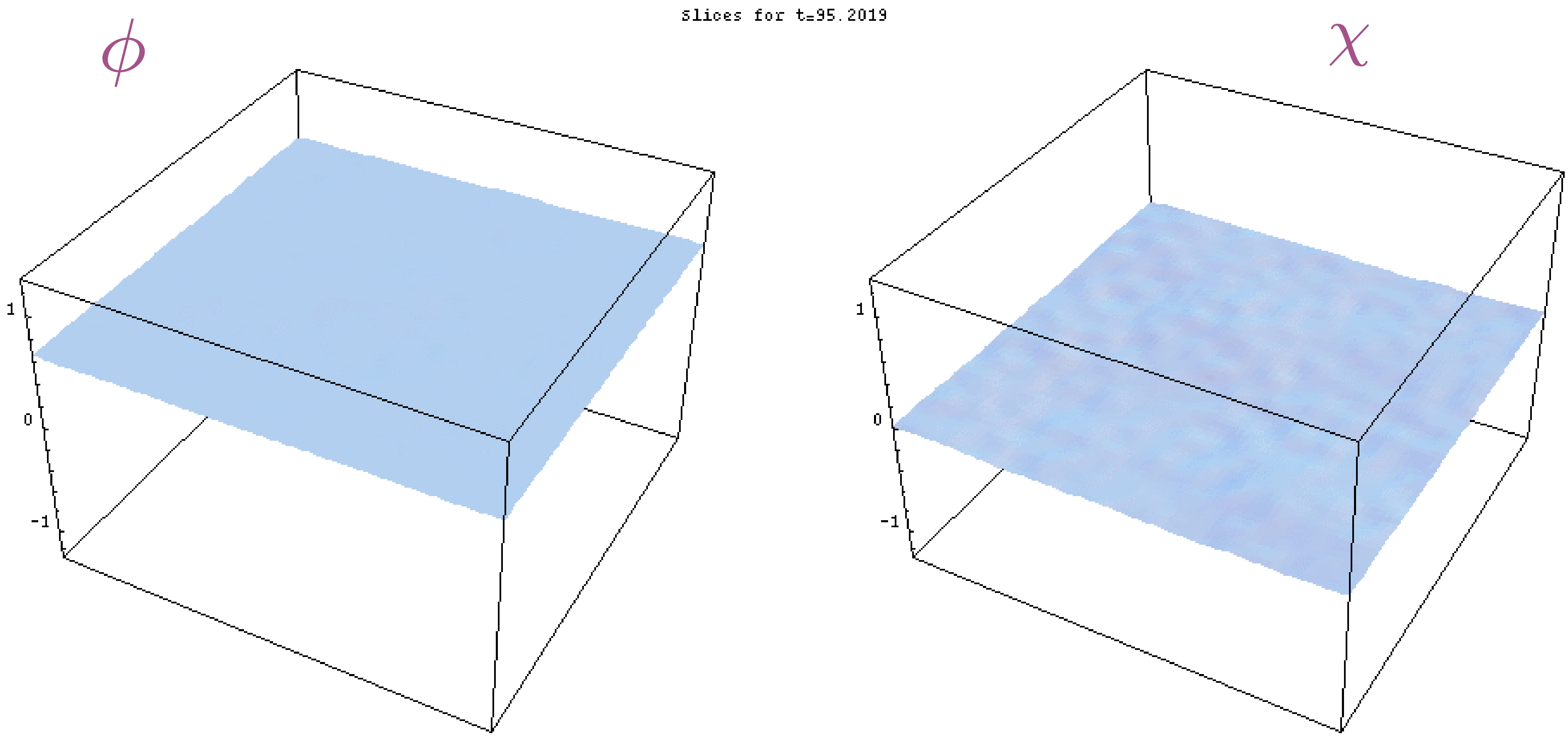
Resonant particle production due to coherent inflaton oscillations

$$V = \frac{1}{2}m^2\phi^2 + \frac{g^2}{2}\phi^2\chi^2 \;\Rightarrow\; \omega_\chi^2 = (k/a)^2 + g^2\phi(t)^2$$

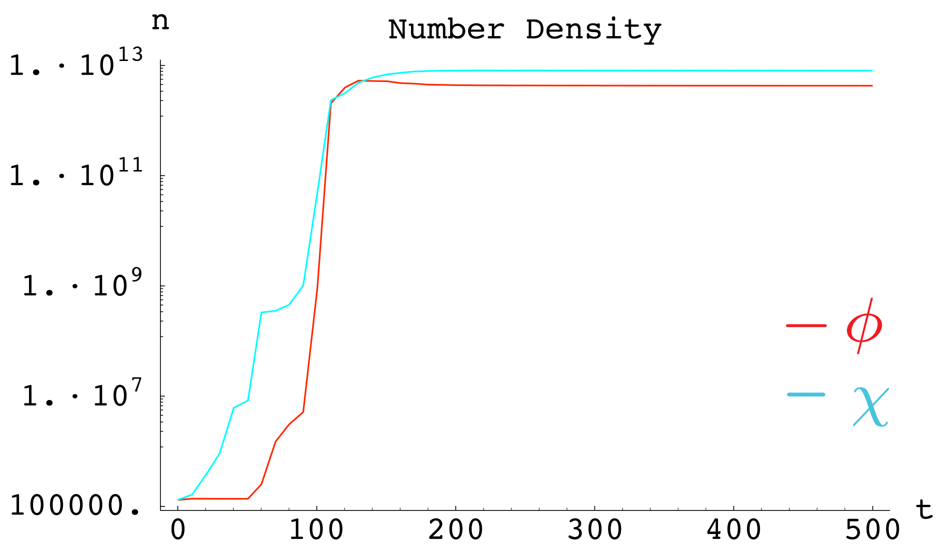
- Excitation when $\omega'_\chi > \omega_\chi^2$
- Periodic "driving force" $\rightarrow$ resonant instability bands

Strong instability for $g^2 \gtrsim \dfrac{m^2}{\phi^2} \sim 10^{-10}$

$$V = \frac{1}{2}m^2\phi^2 + \frac{g^2}{2}\phi^2\chi^2$$



G. Felder, I. Tkachev



(1) Preheating: Stimulated particle production

(2) Rescattering: Produced quanta scatter against the zero mode of ϕ

Destroys coherence & terminates production. Classical lattice simulations

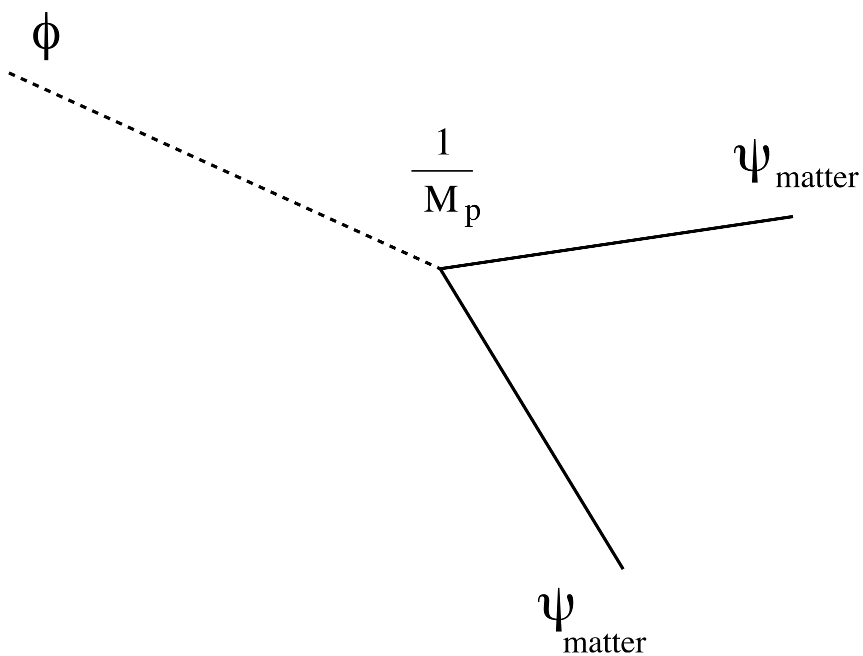
(3) Thermalization: Very slow evolution towards thermal equilibrium

$k_* \simeq 10\, m_\phi \ll N^{1/3} \;\Rightarrow$ particle fusion. Kolmogorov turbulence

Weakest possible coupling

Gravity

Inflationary sector ⟷ Observable sector: Standard model, MSSM ?



$$\Gamma \simeq \frac{m_\phi^3}{M_p^2}$$

$$\tau = \frac{h}{\Gamma c^2} \sim 10^{-25}\,\mathrm{s}$$

Instantaneous thermalization of the decay products

SUSY flat directions

Many scalar fields (one per particle). Complicated potential

Flat directions: E.g. $V = m_1^2\,\psi_1^2 + m_2^2\,\psi_2^2 + (\psi_1 - \psi_2)^4$

↖ ↗ $10^2 - 10^3$ GeV

↖ ↗ $M_{\text{GUT}} - M_p$

- Low cost: We expect them to be excited during inflation
- ψ's carry baryon number. Baryogenesis, Affleck, Dine '85

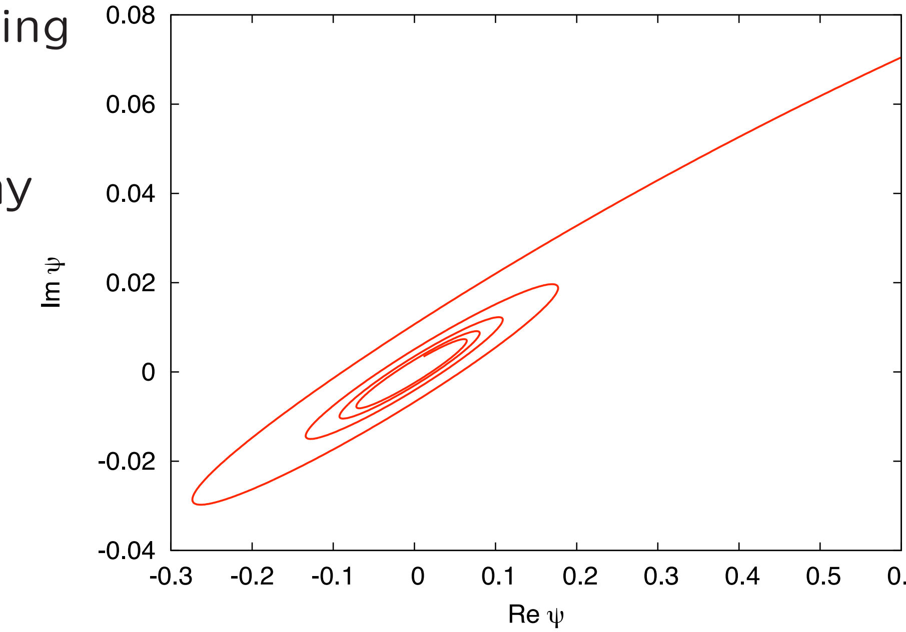
How do particles get mass ? $g\,H\,\bar{t}\,t$, $\langle H\rangle \sim 250\,$GeV

- Now $m \sim \langle\psi\rangle \sim 10^{15} - 10^{19}\,$GeV. Slows down thermalization

Allahverdi, Mazumdar '05

Complex: rotations with slowly decreasing amplitude (expansion)

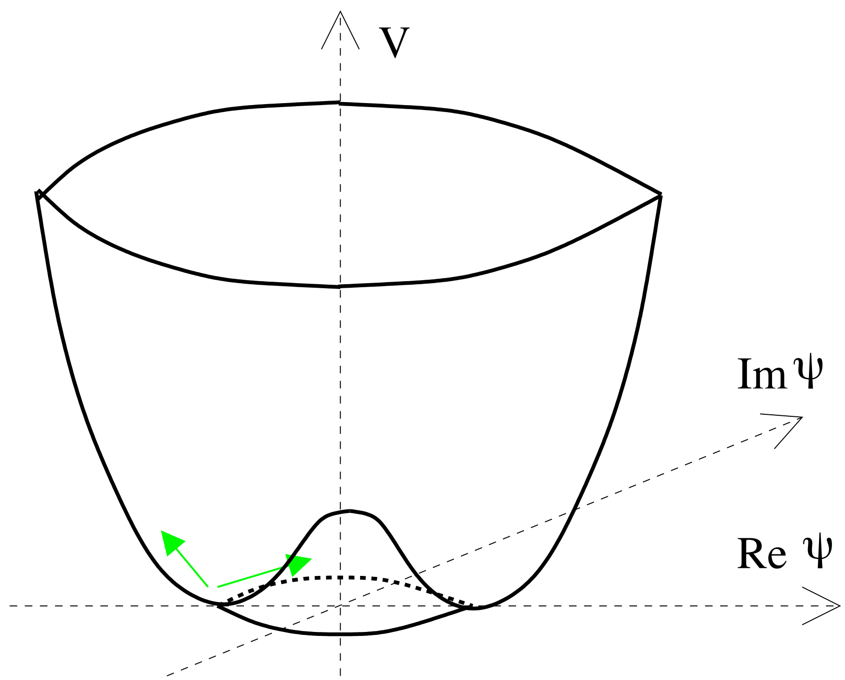
$N_{\rm rot} \sim 10^{11}$ before perturbative decay



Nonperturbative effects ?

Expand $\psi(t) + \delta\psi$

Fields on a $t-$evolving background



(Nearly) constant eigenmasses

Quick variation of eigenstates

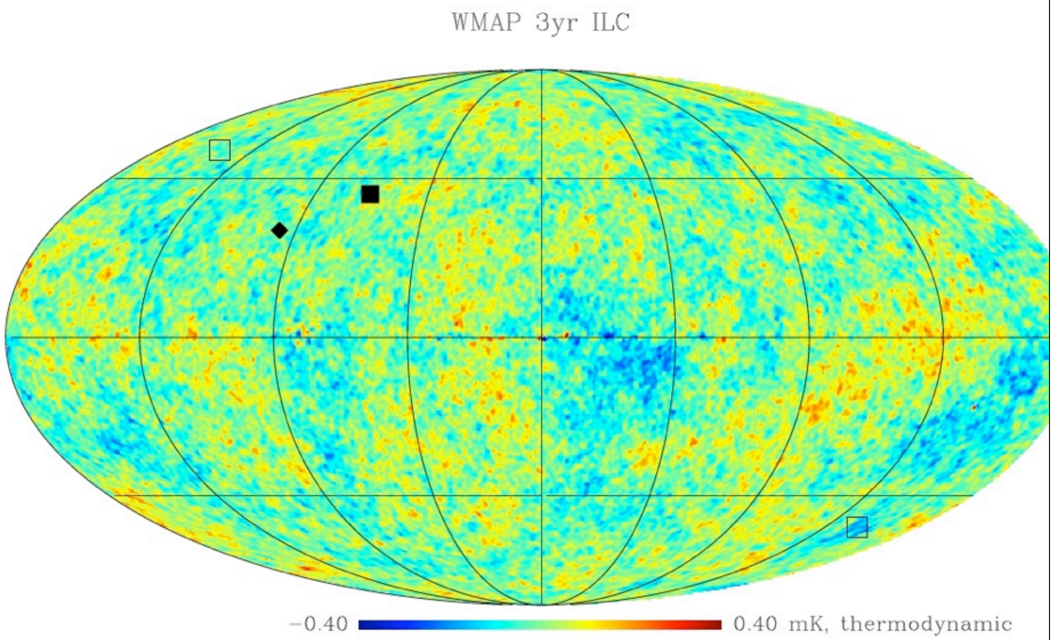
⇓

Decay in $N_{\rm rot} \sim 10$

Olive, MP '06

Gumrukcuoglu, Olive, MP, Sexton

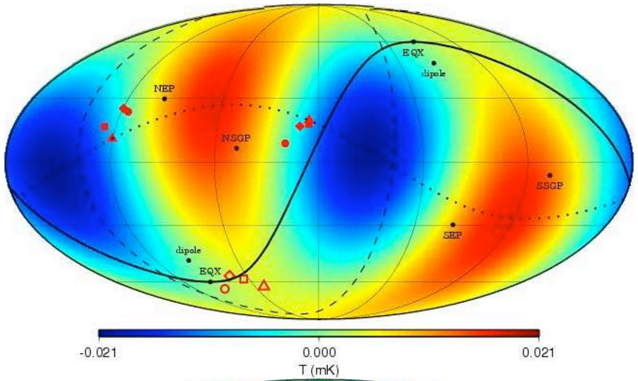
North–south asymmetry

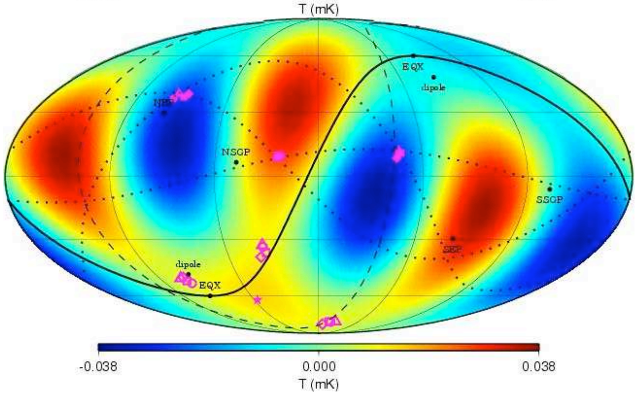


S $>$ N for $l = 5 - 40$ ($\sim$ 1 in 100)

Eriksen et al. '04, '07

$$\theta = 180^0 / l$$





Quadrupole-octupole

planarity & alignment ($\sim$ 1 in 50)

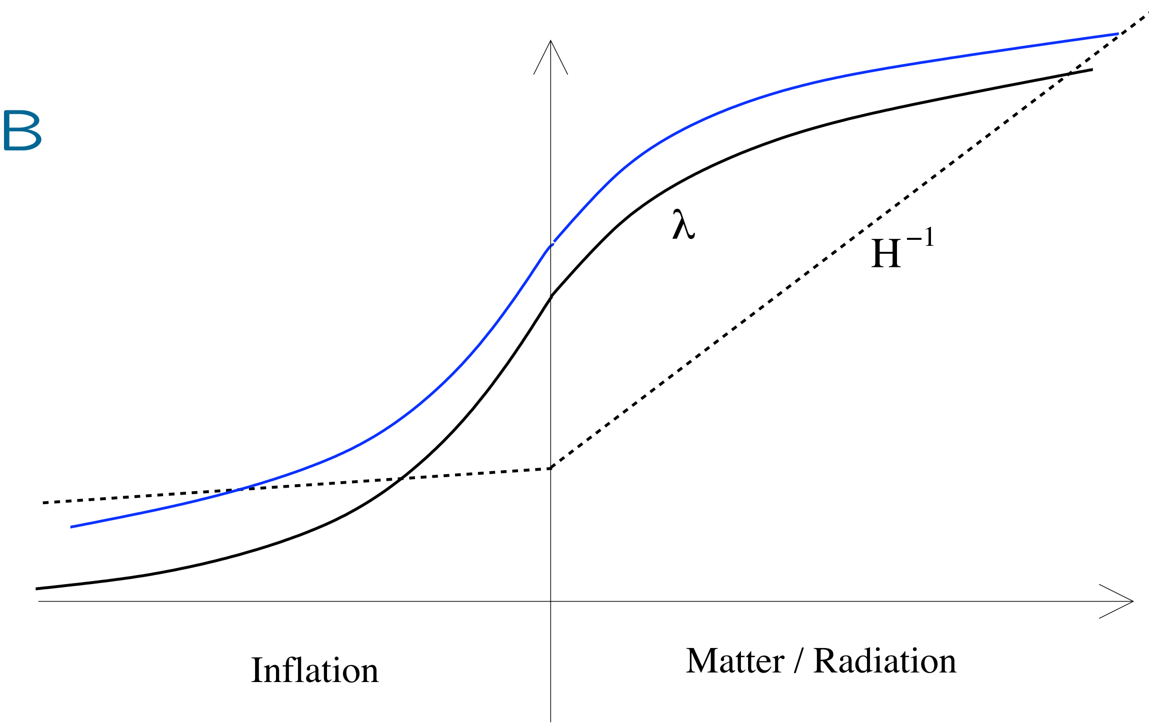
de Oliveira-Costa et al. '03 ; ... ; Copi et al. '06

alignm. for $l = 2 - 5$ ($\sim$ 1 in 1000)

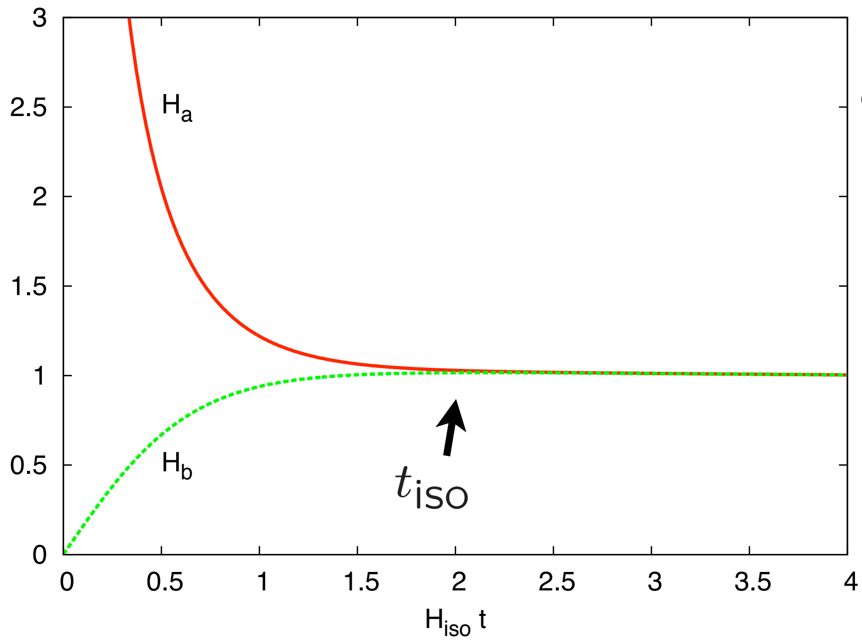
Axis of evil ! Land, Magueijo '05, '06

Primordial perturbations

$\delta g_{\mu\nu}\ ,\ \ \delta\phi \longrightarrow$ CMB



Larger modes leave the horizon earlier (probe earlier inflation)



$$ds^2 = dt^2 - a(t)^2 dx^2 - b(t)^2 \left[dy^2 + dz^2\right]$$

$$H_a = \frac{\dot{a}}{a}\,, \quad H_b = \frac{\dot{b}}{b}$$

Very rapid isotropization

(one Hubble time, $t_{\rm iso} \sim 10^{-38}\,$s)

- Developed formalism for computing CMB anisotropies
- Initial singularity $\rightarrow$ nonlinearities in perturbations

Gumrukcuoglu, Contaldi, Peloso '07

- Better background (anisotrpy driven by a vector field)

Contaldi, Himmetoglu, MP, in progress

Open Problems

- What is the inflaton ?

  Fundamental scalar

  Brane-antibrane distance

  Component gauge field in extra dim.

- What is the maximal T reached at reheating ?

  Fast / slow decay ?

  Fast / slow thermalization ?

  Can produce only particles with $m < T$

- How was the universe before inflation ?

  Inflation erases informations

  Maybe some signal left in CMB

  Anomalies at large scales ?