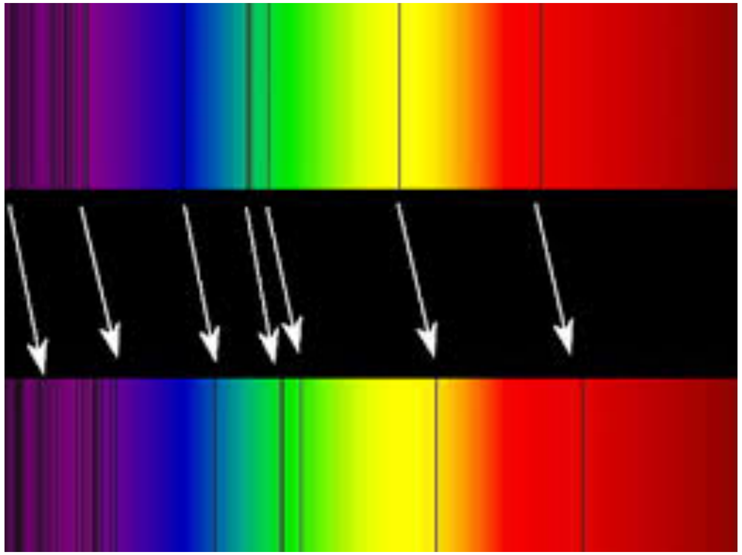
Paolo Creminelli, ICTP (Trieste)

The quest for the beginning

Nikhef - November 20th 2015

A dynamical universe



Spectral lines from faraway galaxies are redshifted: Doppler effect

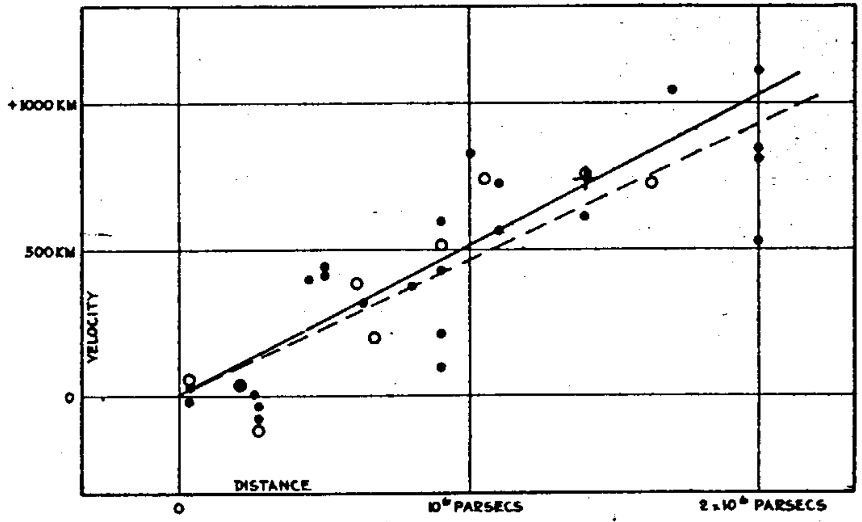


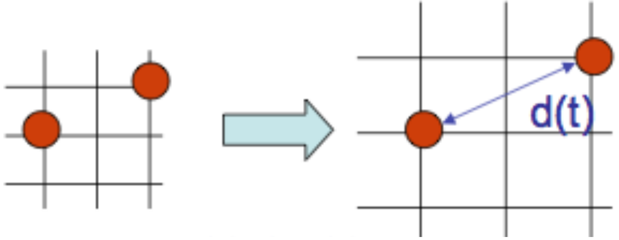
FIGURE 1

Galaxies get away from each other

Velocity proportional to distance

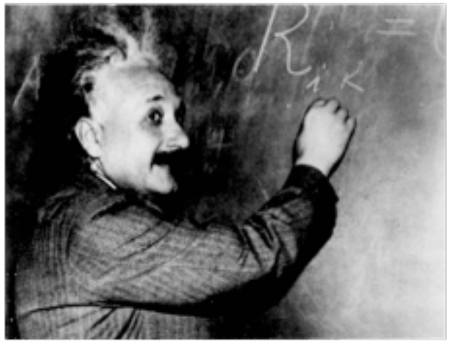
Expanding space

The distance between observers “at rest” is increasing in time:



$$d(t) \propto a(t)$$

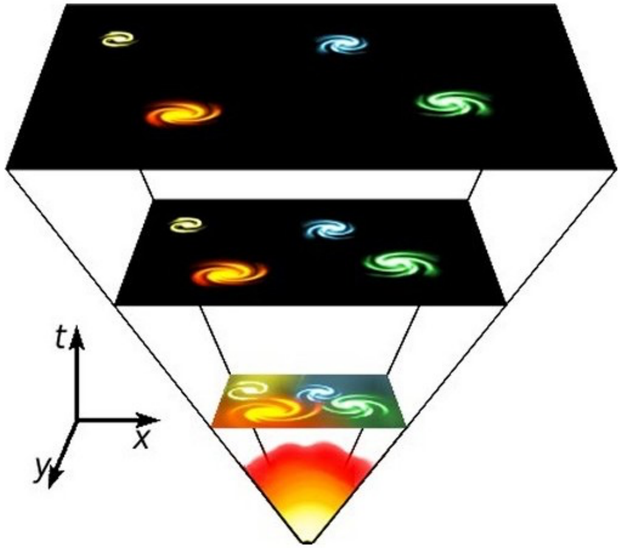
Space(time) dynamics described by General Relativity. Depends on matter:



$$\left(\frac{da}{dt}\right)^2 = \frac{8\pi G}{3}\rho a^2 + K$$

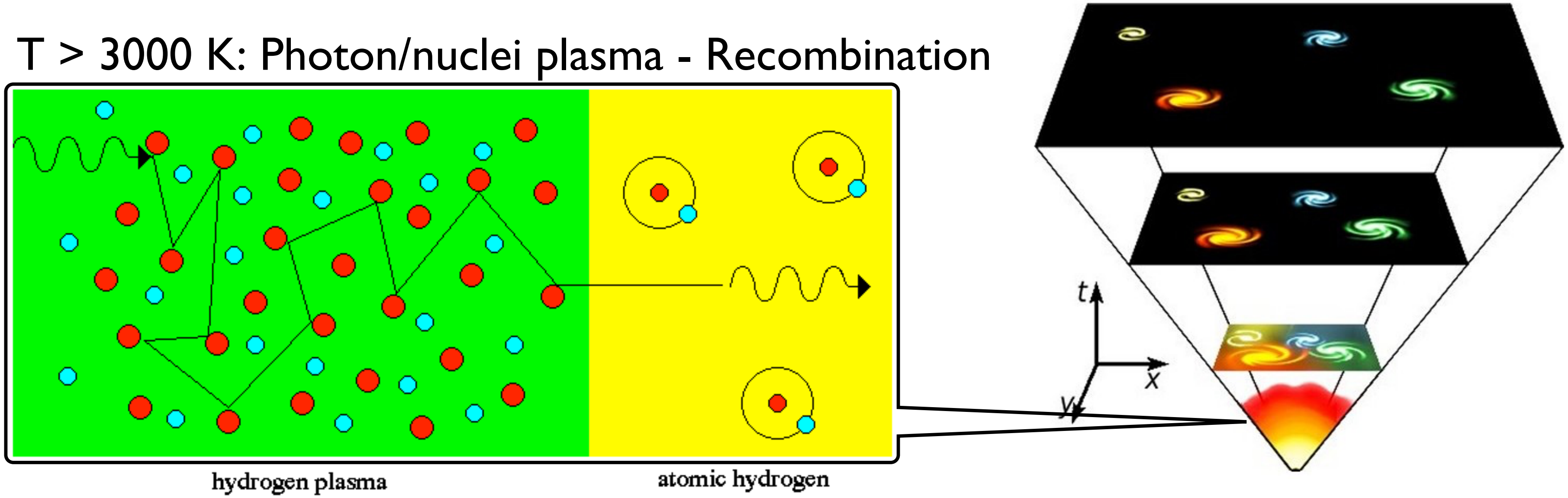
Back in the past everything was denser and hotter

Speed of expansion much faster back then

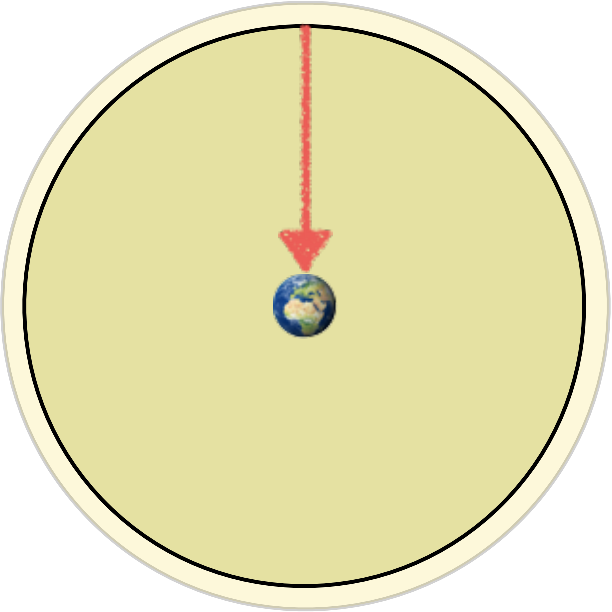


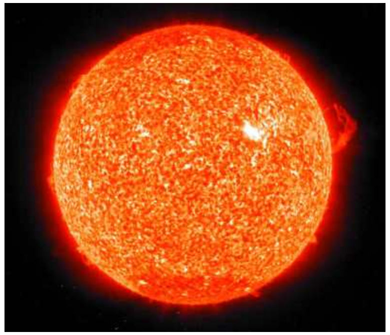
Cosmic Microwave Background

T > 3000 K: Photon/nuclei plasma - Recombination



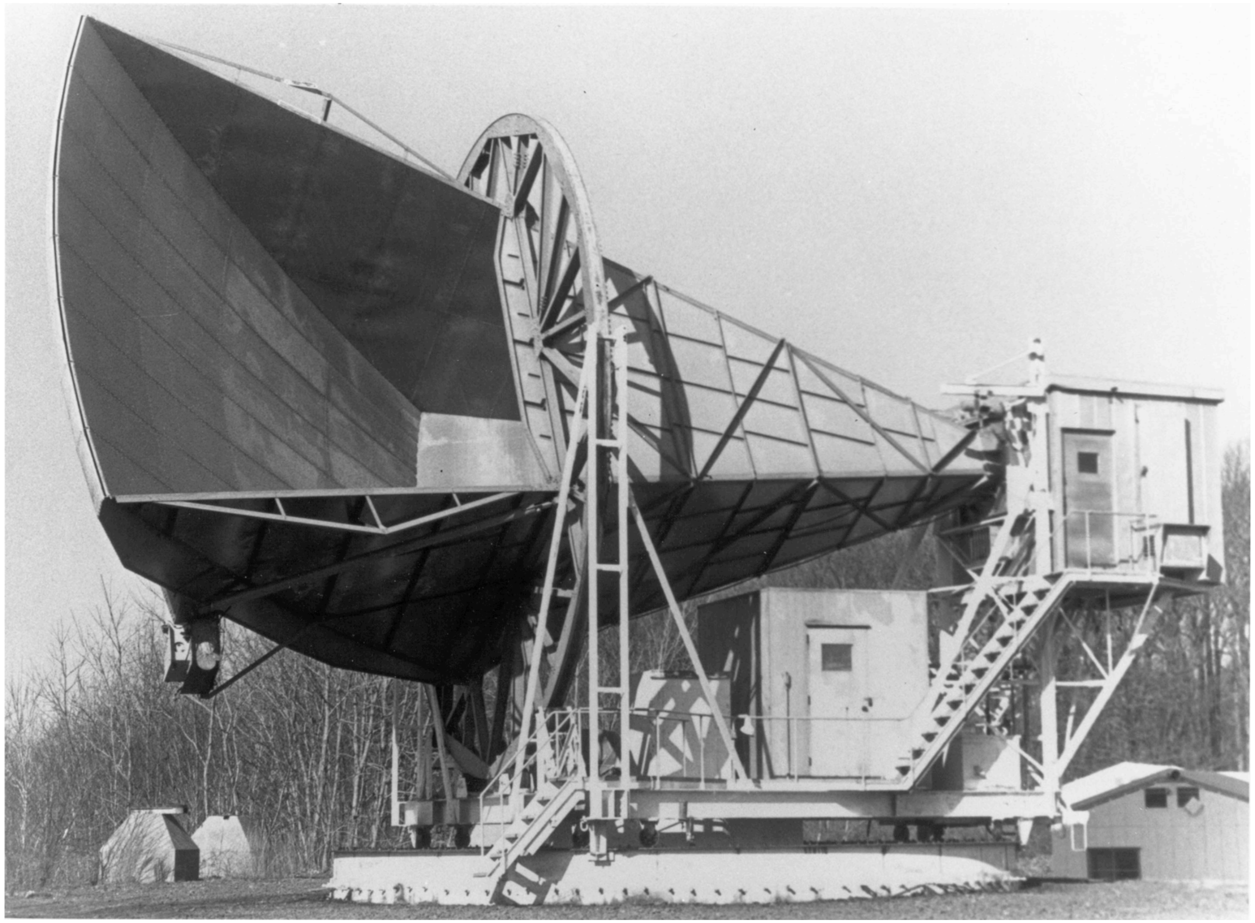
Last scattering
surface:



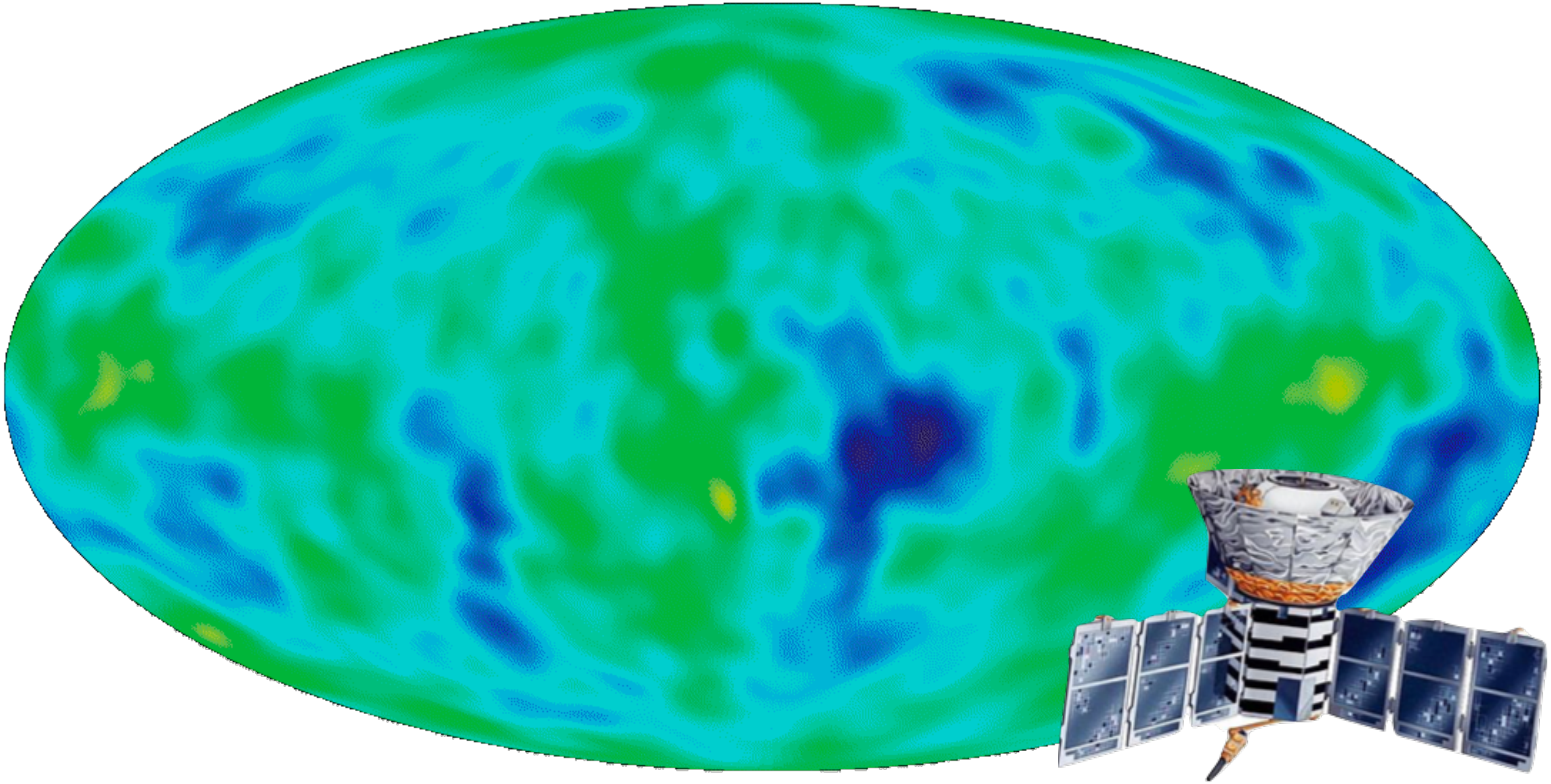


First detection

Penzias and Wilson 1965: T ~ 3 K



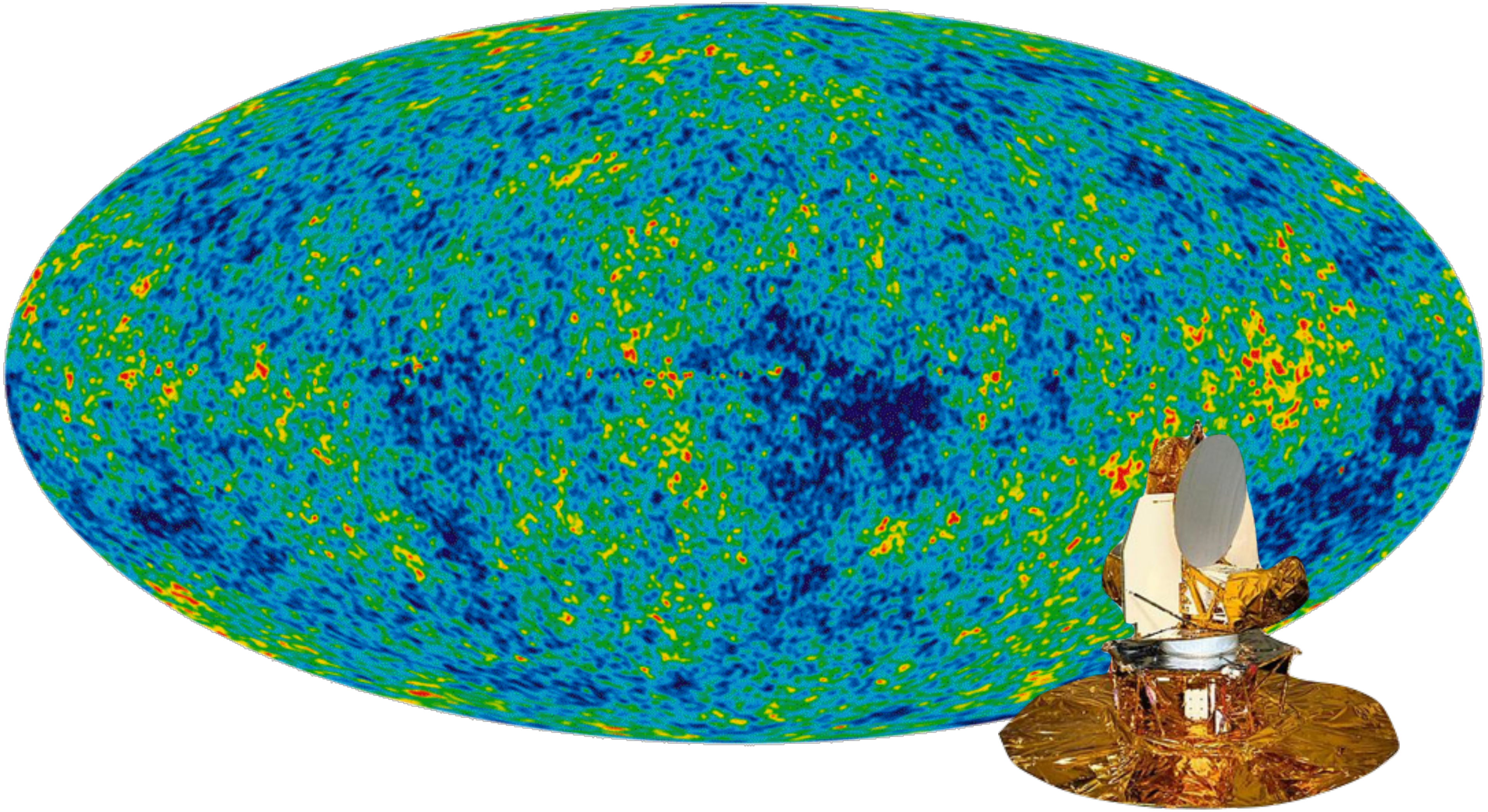
COBE (1992)



$$\Delta T \sim 3K \times 10^{-5}$$

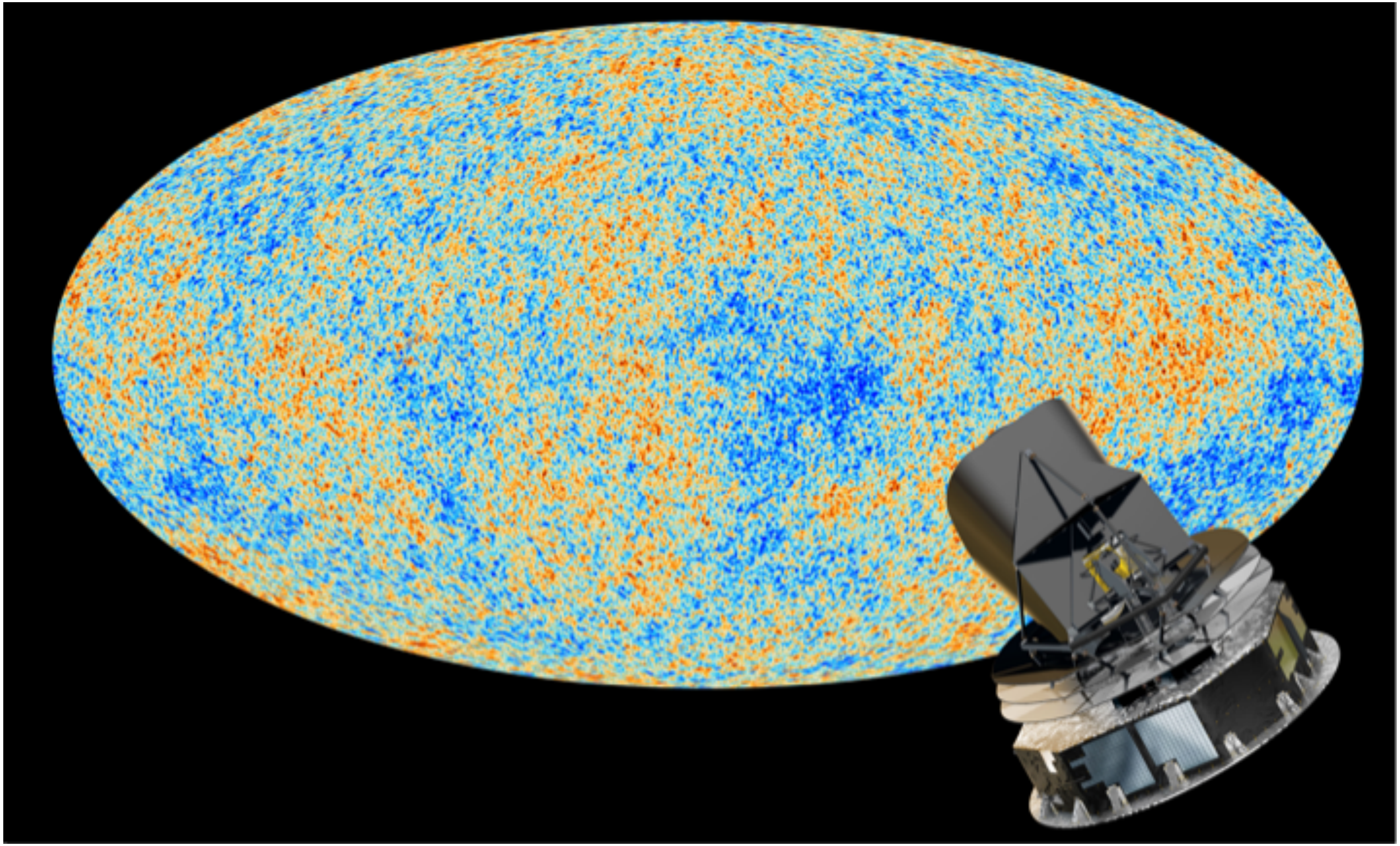

NYKO

WMAP (2009)

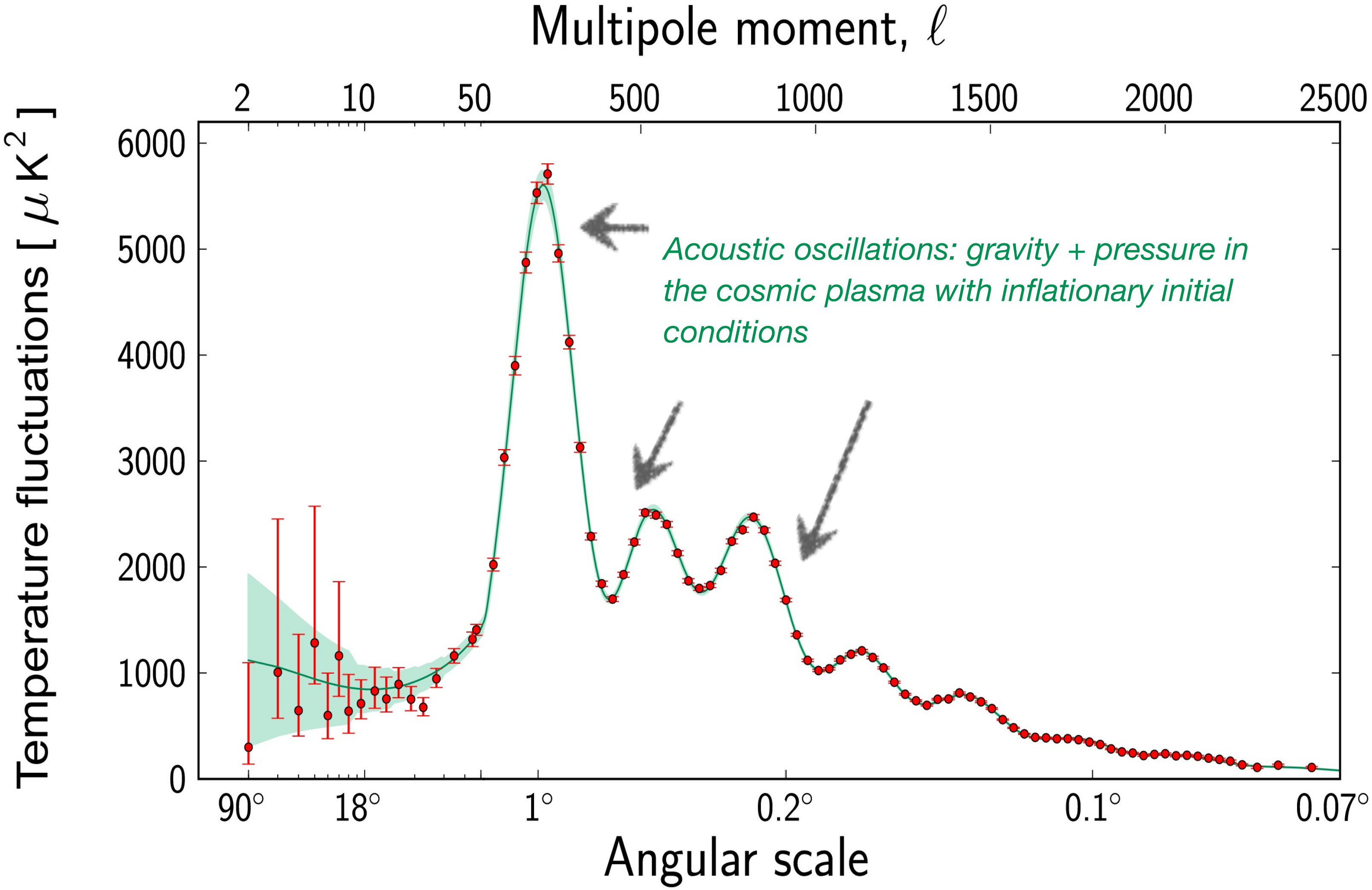



NYKO

Planck (2013)



Acoustic oscillations

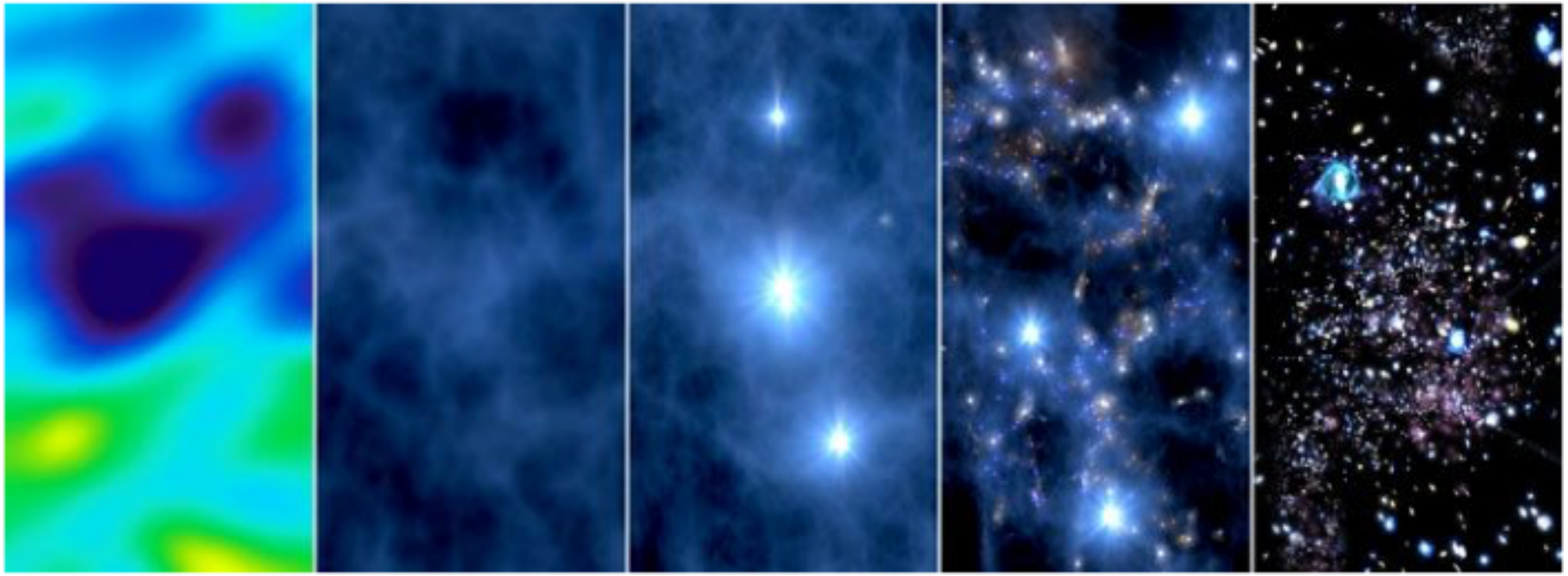


Acoustic oscillations: gravity + pressure in the cosmic plasma with inflationary initial conditions

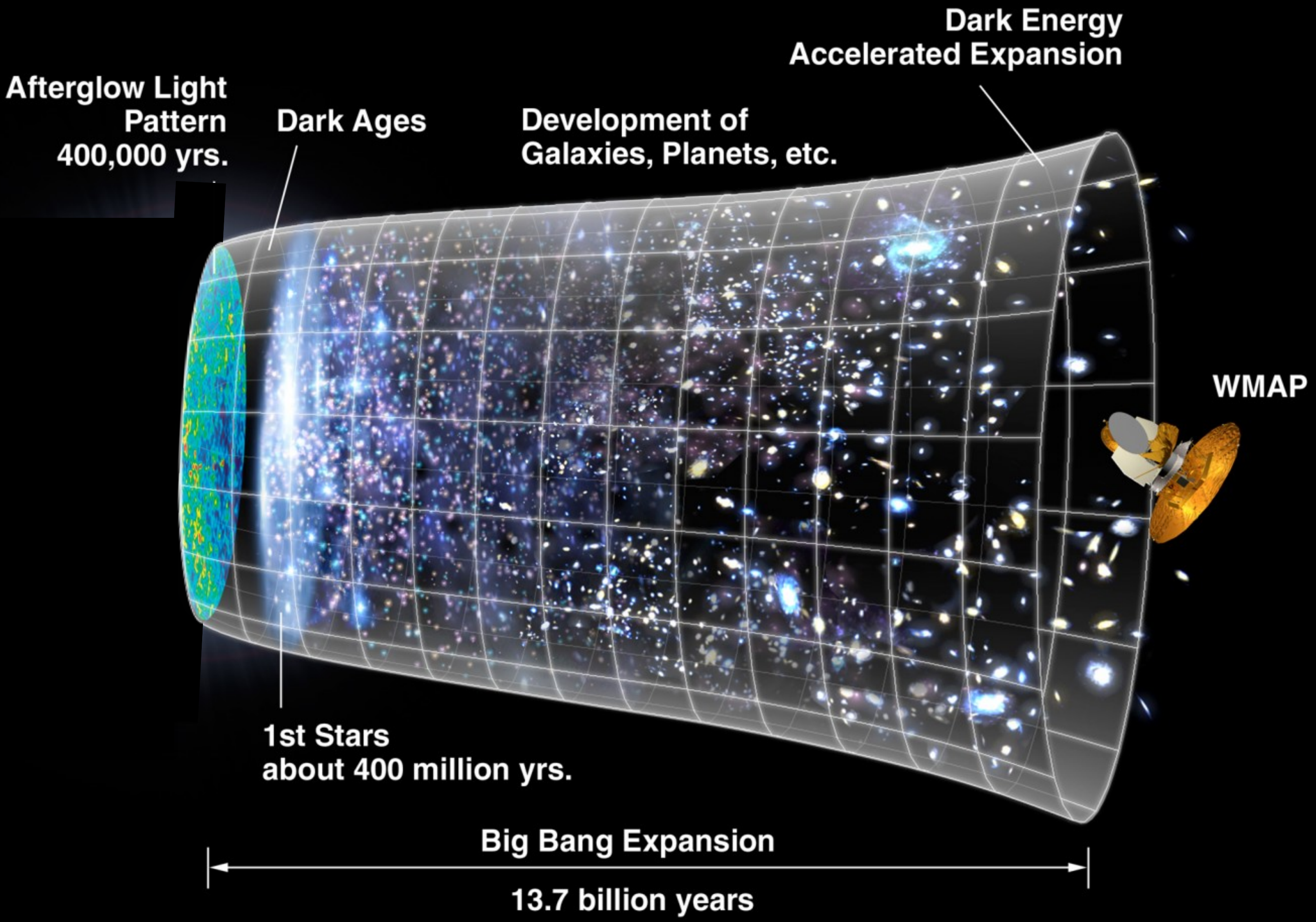
Initial seeds

Inhomogeneities are acoustic oscillation due to some initial (primordial) seeds

Homogeneities then grow to give rise to all the structures we see



Chronology of the universe



What is the origin of these primordial seeds ?

The Cauchy problem of the Universe

The Universe appears to have very finely tuned initial conditions

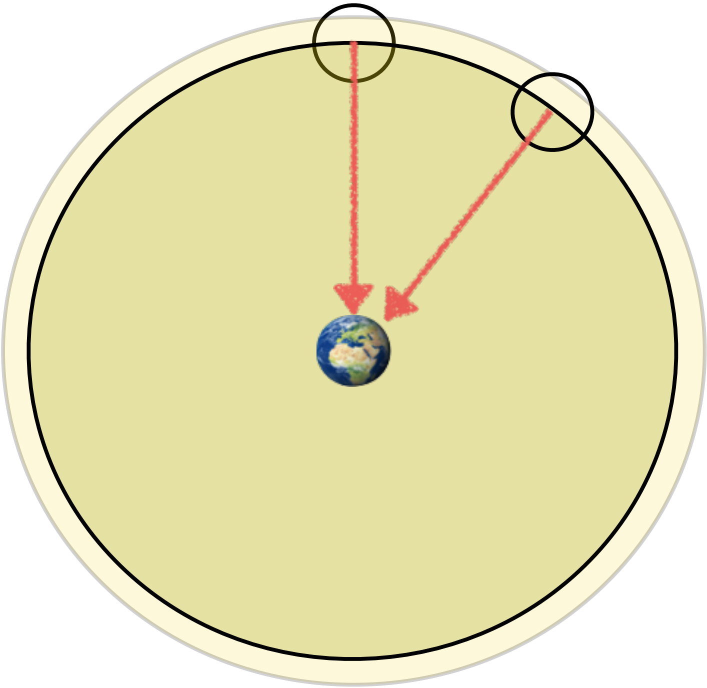
- Initial homogeneity: $r(\mathbf{x})$ and $p(\mathbf{x})$ are remarkably homogeneous in the past and later amplified by gravity.

Why did it start so homogenoeus?

- Initial velocities: tuned choice of initial velocity to avoid immediate recollapse or dilution

Why did it last so long?

Horizon and flatness problems



How comes unrelated spots are so much correlated ?

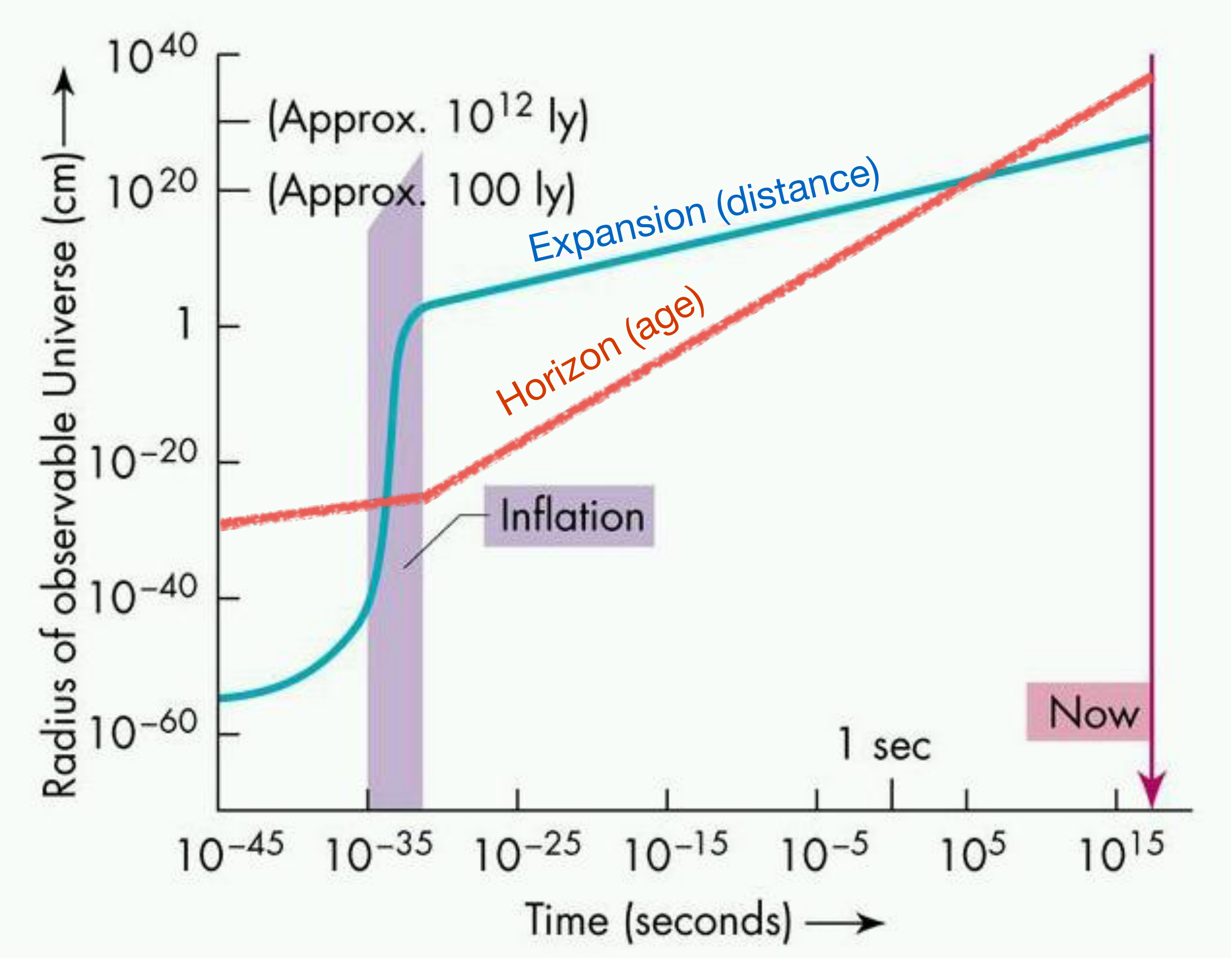
$$\left(\frac{da}{dt}\right)^2 = \frac{8\pi G}{3}\rho a^2 + K$$

Why K is so small ?

Cosmic inflation: $\ddot{a} > 0$

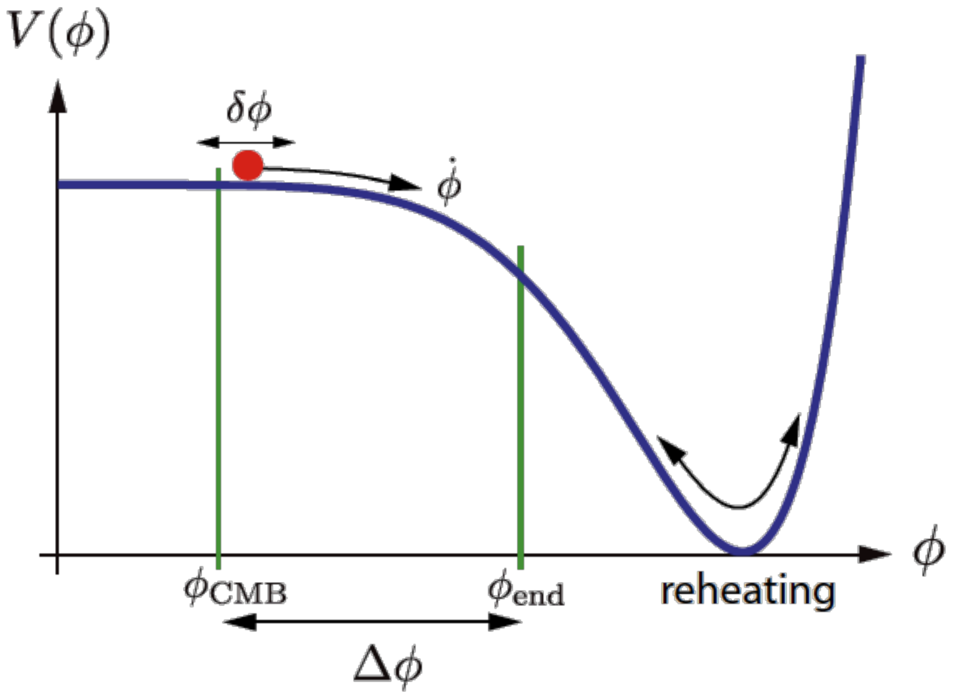
Starobinsky 80; Guth 81;

Linde 82, 83; Albrecht, Steinhardt 82



(Slow-roll) inflation

$$S = \int d^4x\sqrt{-g}\left[\frac{M_p^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right]$$



$$\ddot{\phi} + \underline{3H\dot{\phi}} + V'(\phi) = 0$$

friction is dominant

$$\epsilon = \frac{1}{2}M_P^2\left(\frac{V'}{V}\right)^2$$

$$\eta = M_P^2\frac{V''}{V}$$

$$\epsilon, \eta, \ldots \ll 1$$

$$\dot{a}^2 = \frac{\Lambda(t)}{3}a^2$$

$$H \equiv \frac{\dot{a}}{a}$$

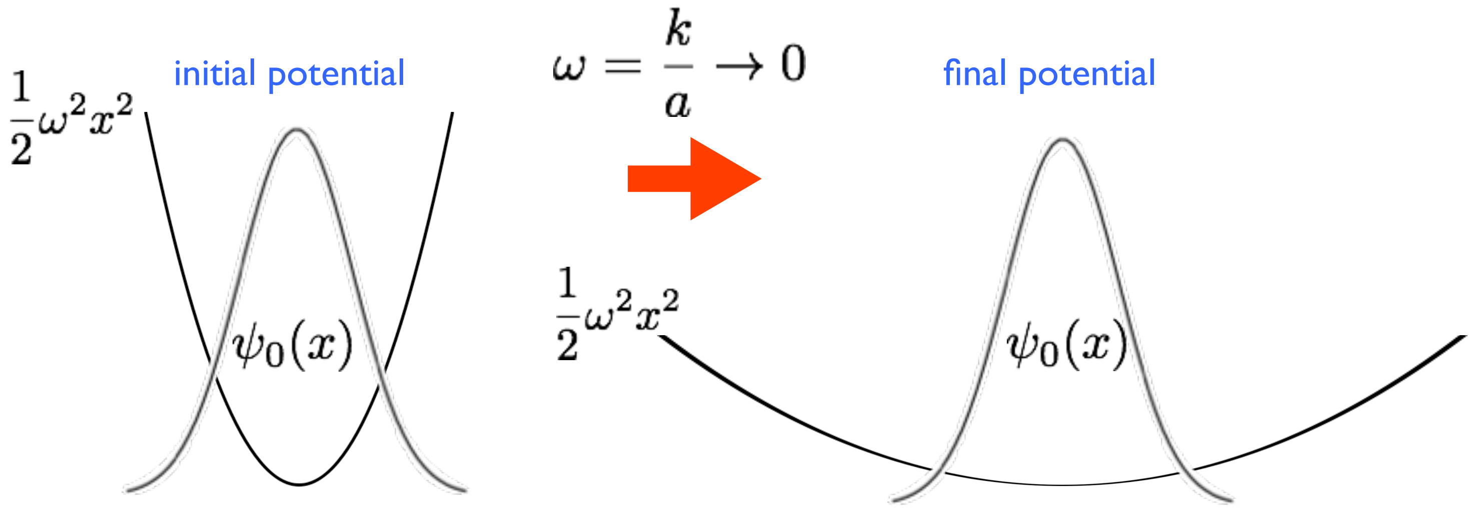
Hubble rate

$$\epsilon \equiv -\frac{\dot{H}}{H^2} \ll 1$$

$\hbar \neq 0$

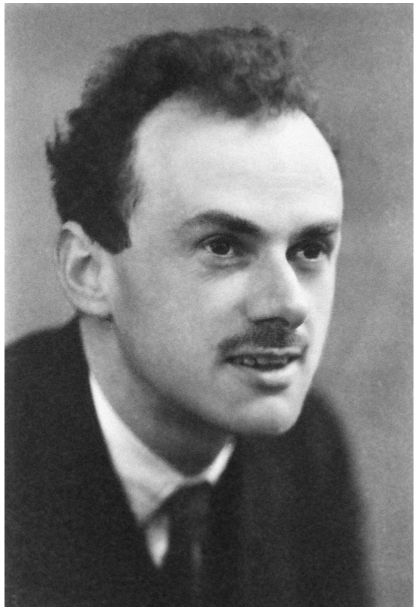
Inflation as slowly decreasing vacuum energy, which knows when to end: a clock

This clock has quantum fluctuations that behave as harmonic oscillators



We believe QM sets up the initial conditions of the Universe

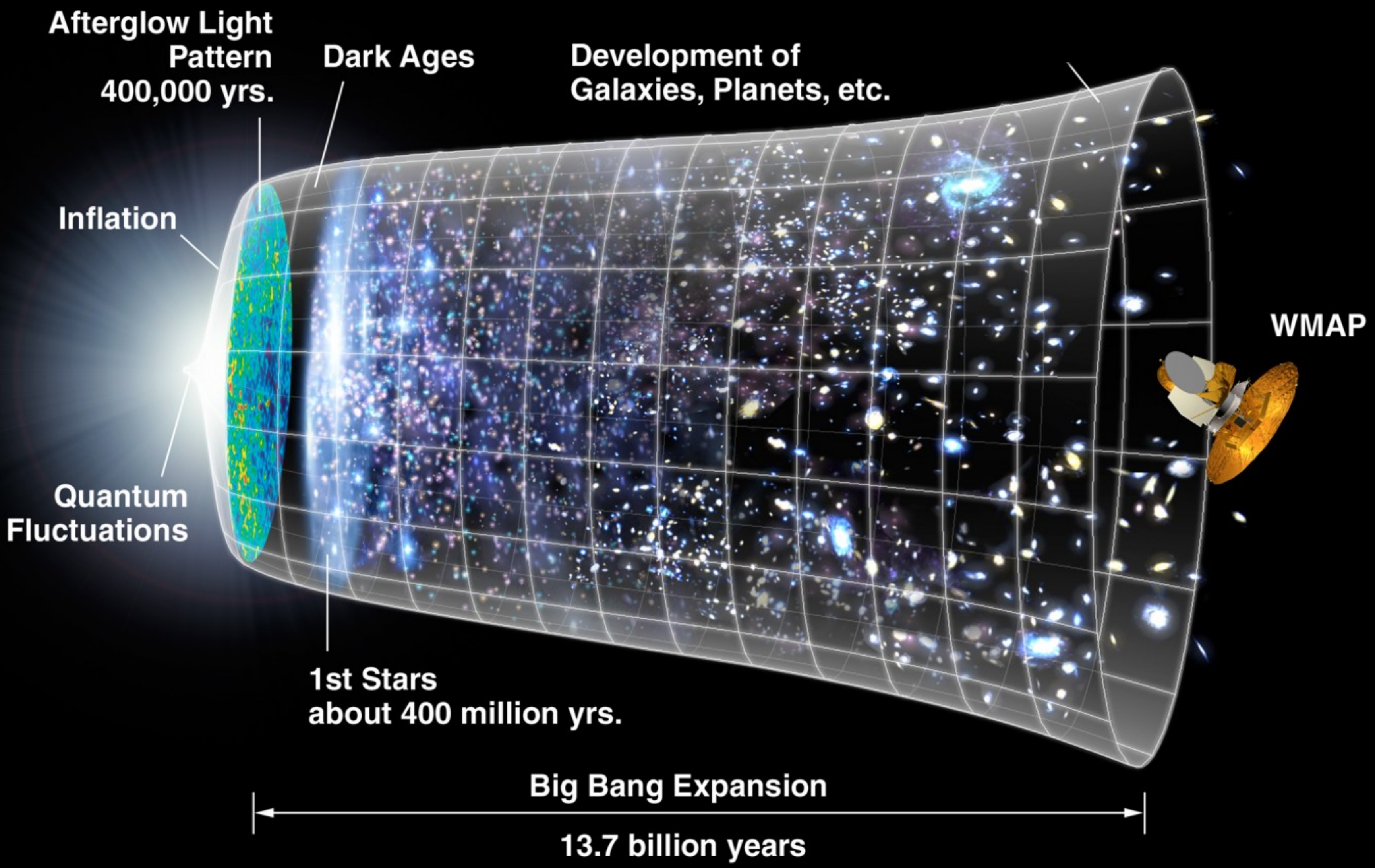
An old idea



With the new cosmology the universe must have started off in some very simple way. What, then, becomes of the **initial conditions required by dynamical theory**? Plainly there cannot be any, or they must be trivial. We are left in a situation which would be untenable with the old mechanics. If the universe were simply the motion which follow from a given scheme of equations of motion with trivial initial conditions, it could not contain the complexity we observe. **Quantum mechanics provides an escape from the difficulty. It enables us to ascribe the complexity to the quantum jumps, lying outside the scheme of equations of motion.**

P.A.M. Dirac 1939

New chronology of the universe



Standard model

Background:

0. Composition of the universe: $\Omega_{\rm b}$, $\Omega_{\rm CDM}$, H_0 (1% level)

Standard model

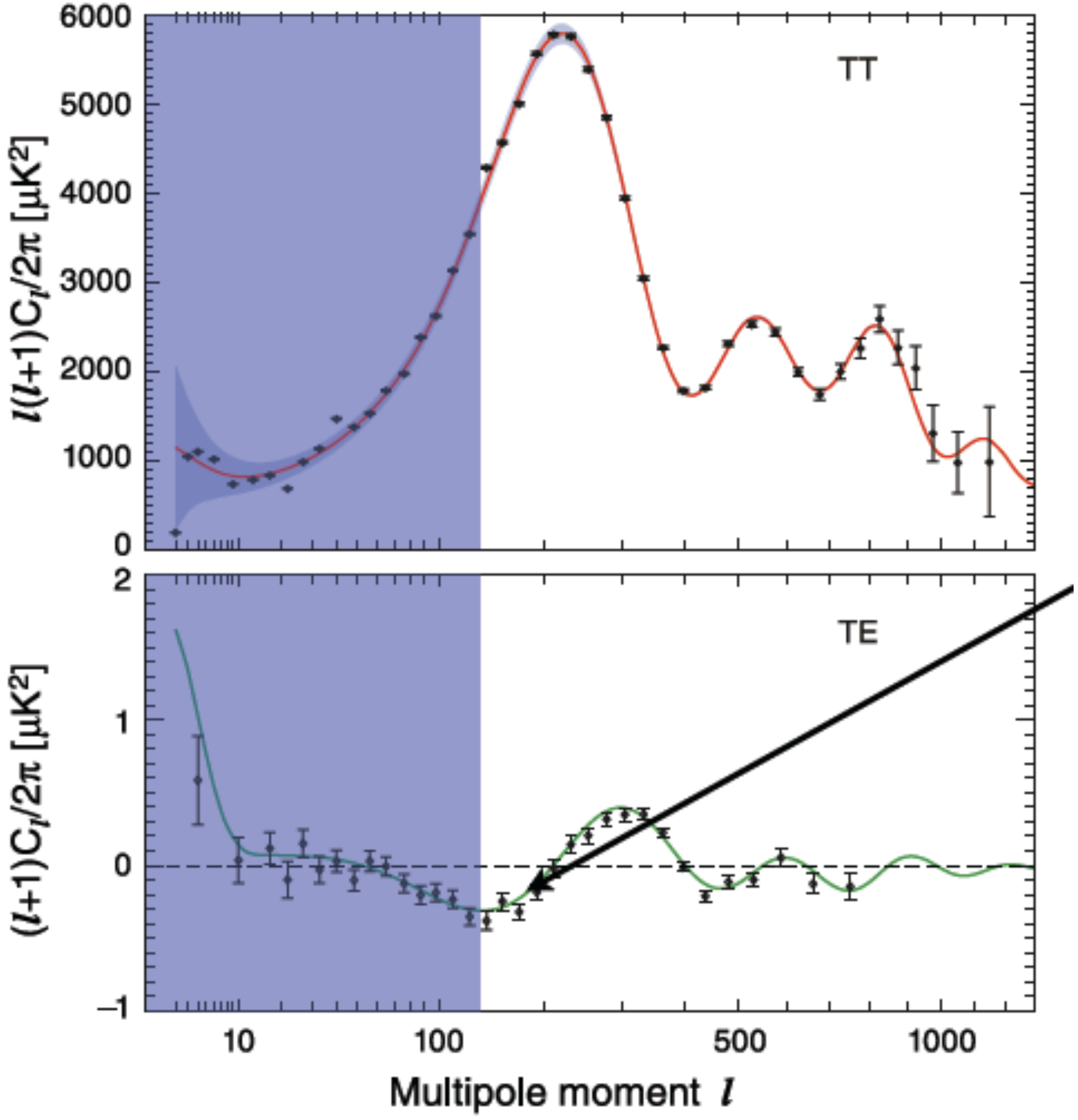
Background:

0. Composition of the universe: $\Omega_{\rm b}\ ,\quad \Omega_{\rm CDM}\ ,\quad H_0$ (1% level)

Perturbations; what we see:

1. Initial fluctuations are primordial

Causality → Primordial



Correlation outside horizon at recombination

Polarization cannot be generated afterwards

Spergel, Zaldarriaga 97

Standard model

Background:

0. Composition of the universe: $\Omega_{\rm b}$, $\Omega_{\rm CDM}$, H_0 (1% level)

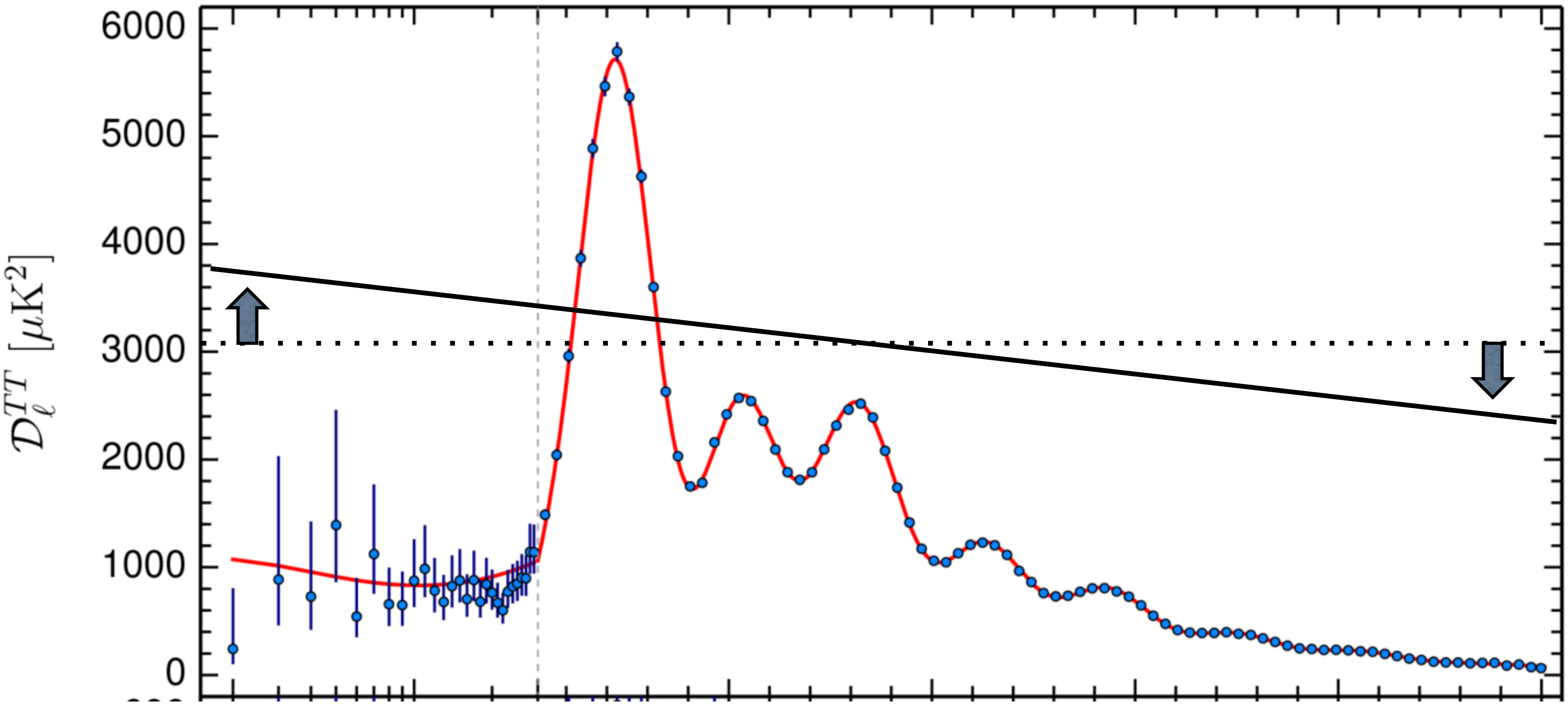
Perturbations; what we see:

1. Initial fluctuations are primordial

2. Amplitude $A_s = (2.14 \pm 0.05) \times 10^{-9}$

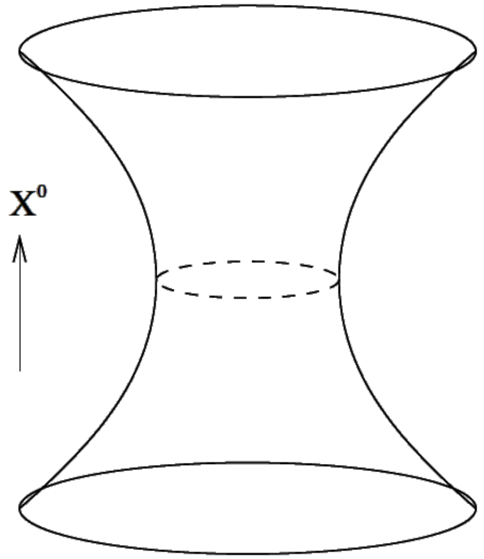
3. Tilt $n_s - 1 = -0.0348 \pm 0.0047 \quad (\gtrsim 7\sigma)$

Spectral tilt



More power on large scales

de Sitter SO(4,1)



Inflation takes place in ~ dS

$$ds^2 = \frac{1}{H^2\eta^2}(-d\eta^2 + d\vec{x}^2)$$

- Translations, rotations

- Dilations $\eta \to \lambda\eta,\ \vec{x} \to \lambda\vec{x}$

→ scale-invariance

$$\varphi_{\vec{k}} \to \lambda^3 \varphi_{\vec{k}/\lambda} \qquad \langle \varphi_{\vec{k}_1}\varphi_{\vec{k}_2}\rangle = (2\pi)^3\delta(\vec{k}_1 + \vec{k}_2)\frac{1}{k_1^3}F(k_1\eta)$$

(assuming approximate $\phi \to \phi + c$)

Standard model

Background:

0. Composition of the universe: Ω_{b} , Ω_{CDM} , H_0 (1% level)

Perturbations; what we see:

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3. Tilt $n_s - 1 = -0.0348 \pm 0.0047 \quad (\gtrsim 7\sigma)$

Perturbations; what we do not see:

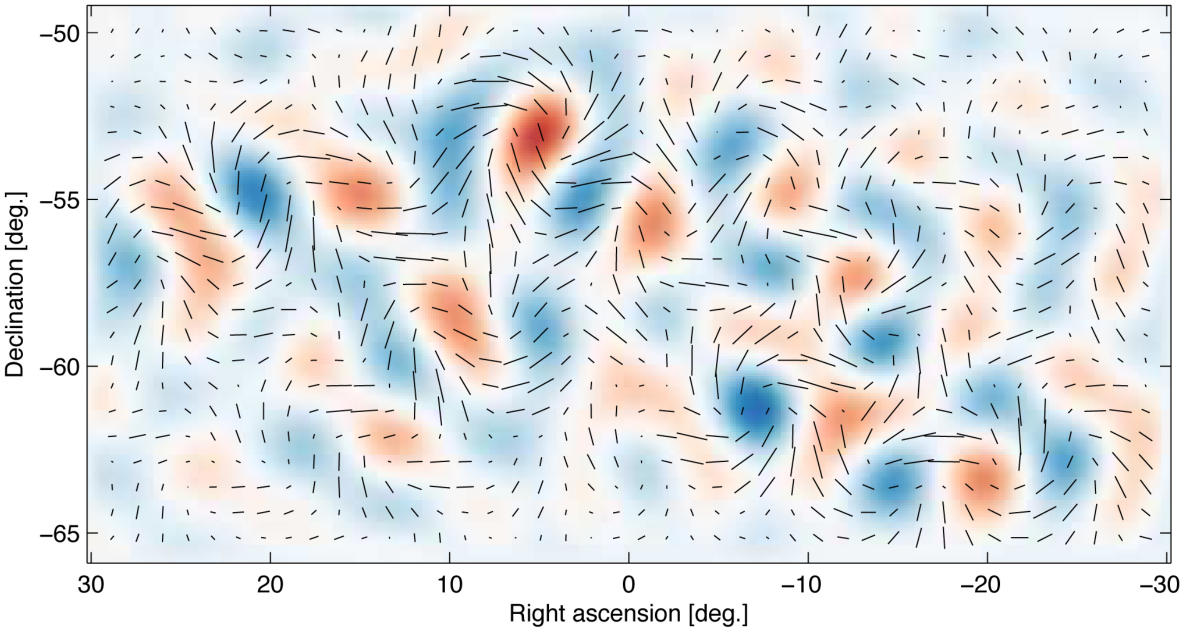
4. No fluctuations in composition: < 1%

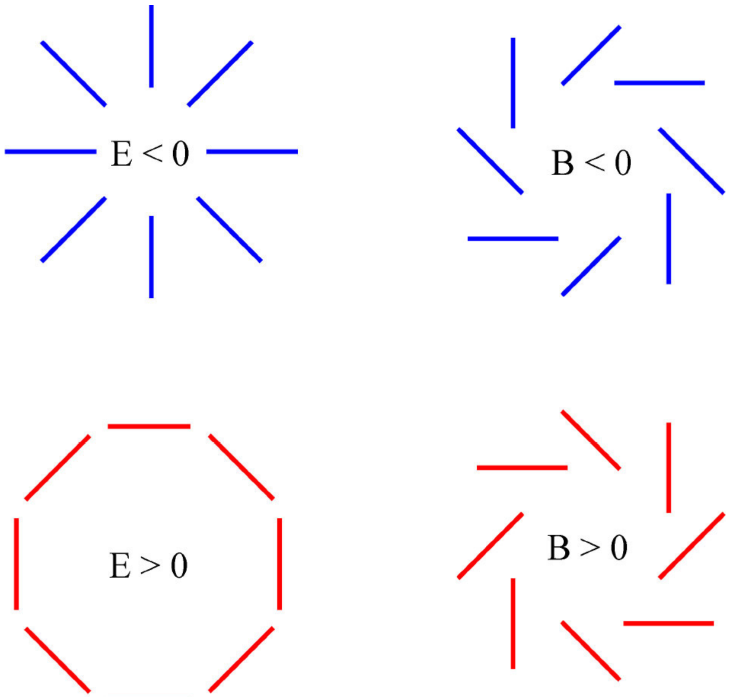
5. No gravitational waves: < 10%

E and B - modes

At each point
polarization of CMB is I_{ij}

Stokes parameters
$Q = (I_{11}-I_{22})/4$
$U = I_{12}/2$



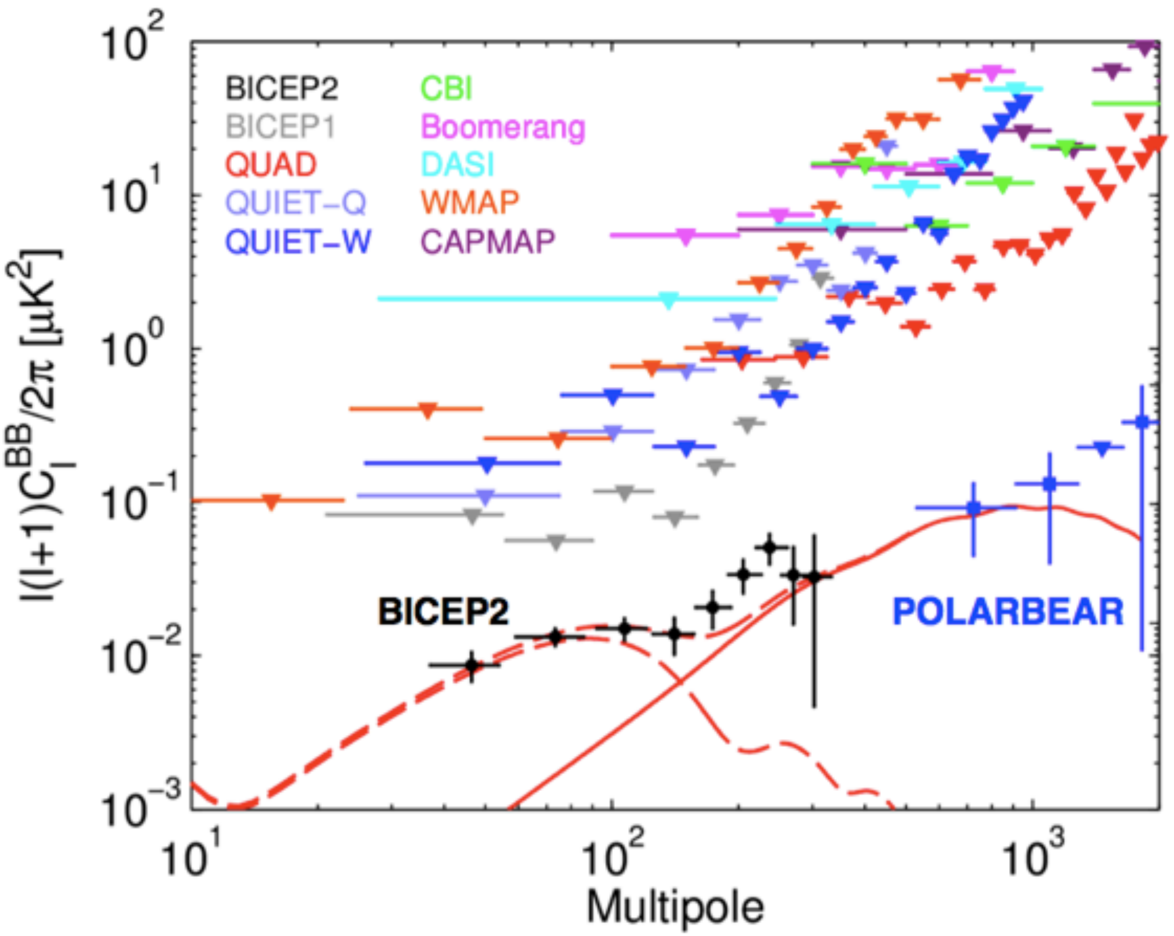


Equivalently info is encoded in E
(scalar) and B (pseudoscalar)

B-modes are not generated by
scalar perturbations:
smoking gun of GWs

Kamionkowski etal 97 Seljak, Zaldarriaga 97

The new era of B-modes

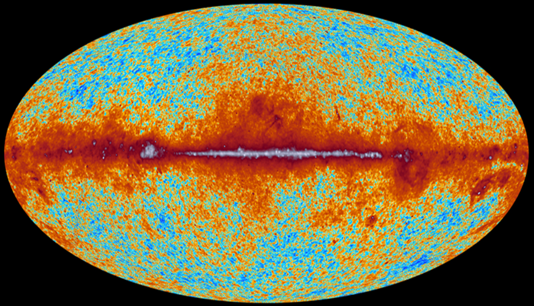


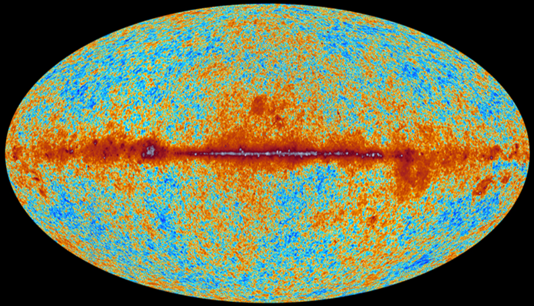
- Amazing improvement in exp sensitivity

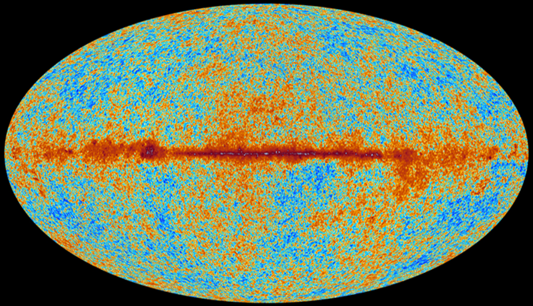
ΔP ~ 3 μK arcmin
(Planck ΔP ~ 45 μK arcmin)

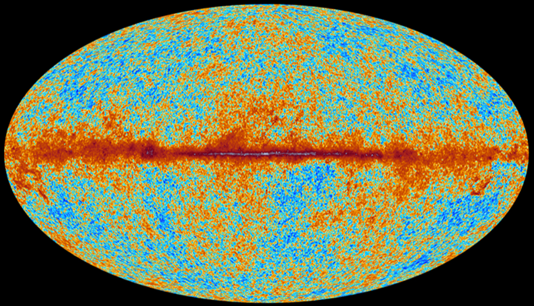
- Theoretically motivated region

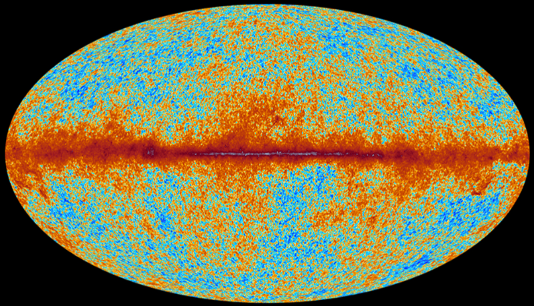
The sky as seen by Planck

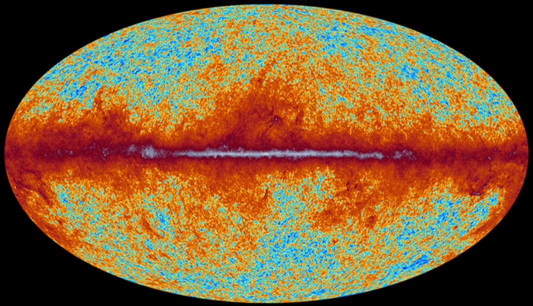

30 GHz

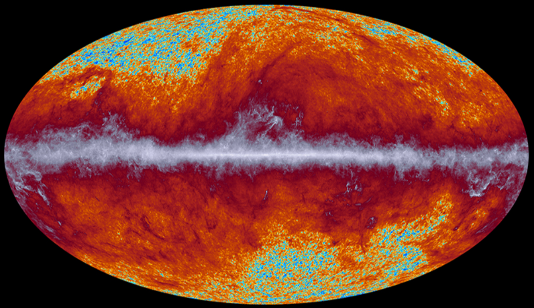

44 GHz

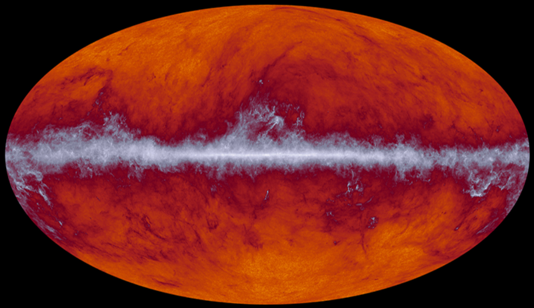

70 GHz

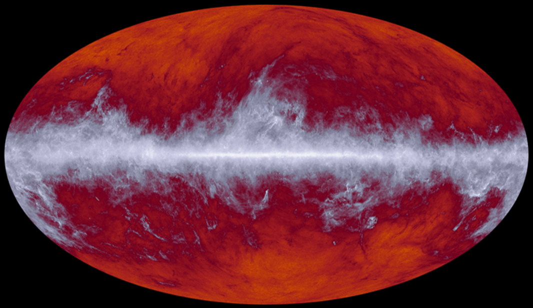

100 GHz


143 GHz

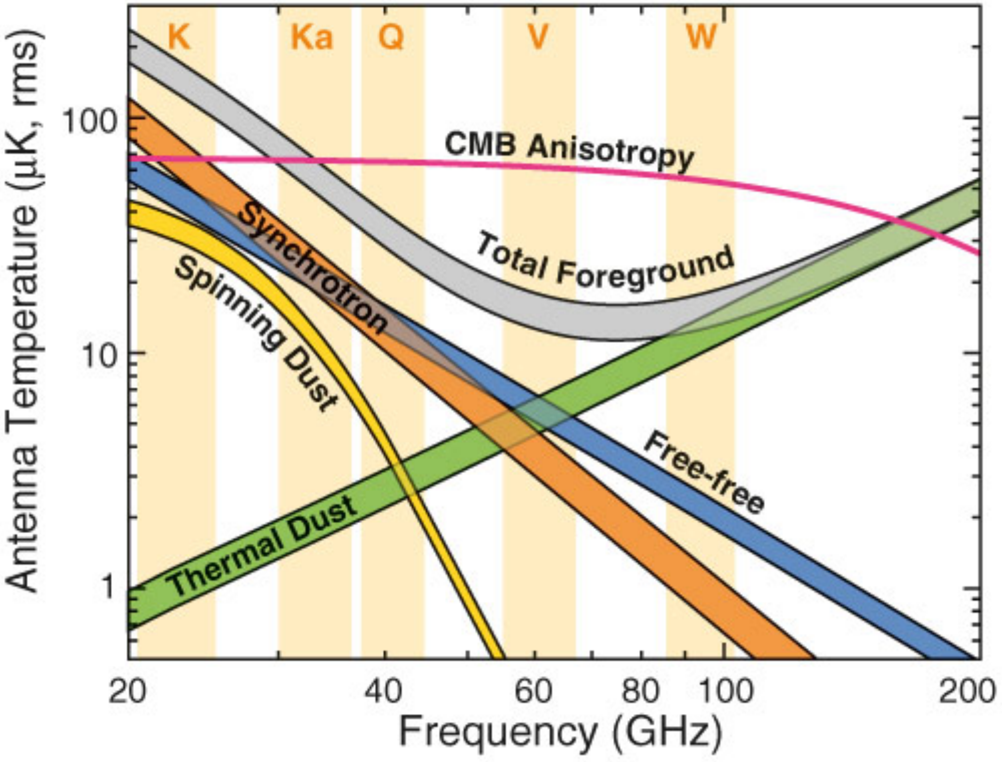

217 GHz


353 GHz

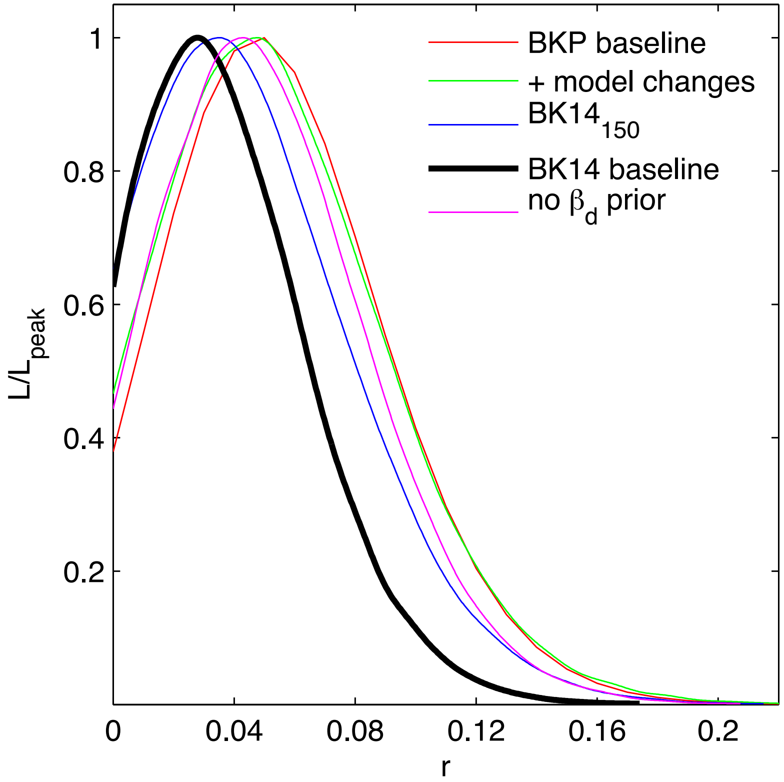

545 GHz


857 GHz

Dust under the carpet



BICEP2/Keck + Planck:
signal is compatible with being only dust




GRAVITATIONAL
WAVES

Huge experimental effort

B-modes search is ongoing by many experiments:

- Ground based telescopes: ACTpol/AdvACT, CLASS, Keck/BICEP3, Qubic, Quijote, Polarbear, Simons Array, Spud, SPTpol/-3G;
- Balloon experiments: EBEX, Lspe, SPIDER, PIPER;
- Future satellite missions: CMBPol, Pixie (NASA), EPIC (NASA), LiteBIRD (KEK), CoRE+ (ESA).

$r = 0.001$ achievable even with ground-based and baloon borne experiments

(100 smaller than than background)

Tensor to scalar ratio

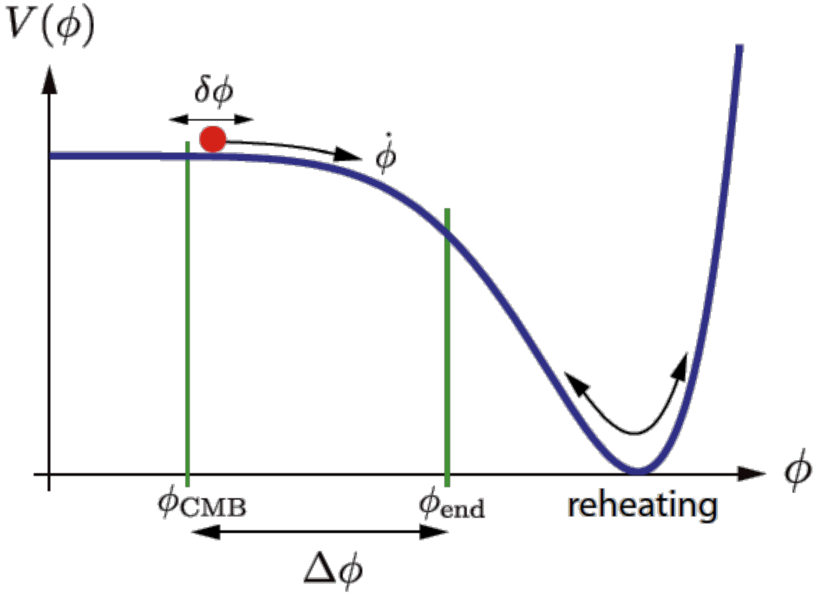
Tensors: $S = \frac{M_{\rm Pl}^2}{8}\int dt d^3x \left[a^3(\dot{h}_{ij})^2 - a(\partial_l h_{ij})^2\right]$

$$\Delta_{\rm t}^2(k) \equiv 2\Delta_h^2(k) = \frac{2}{\pi^2}\frac{H^2}{M_{\rm pl}^2}$$

Scalar: $S = \frac{1}{2}\int dt d^3x \frac{\dot{\phi}^2}{H^2}\left[a^3\dot{\zeta}^2 - a(\partial\zeta)^2\right]$

$$\Delta_{\rm s}^2(k) \equiv \Delta_{\mathcal{R}}^2(k) = \frac{1}{8\pi^2}\frac{H^2}{M_{\rm pl}^2}\frac{1}{\varepsilon}$$

$$\varepsilon = \frac{1}{2}M_{\rm Pl}\left(\frac{V'}{V}\right)^2 \ll 1$$



Tensors are suppressed wrt to scalars $r = 16\varepsilon$

BICEP2/Keck/Planck: $r < 0.07 \quad 95\%$ C.L.

Robust signature

- It is easy to play with scalar perturbations:

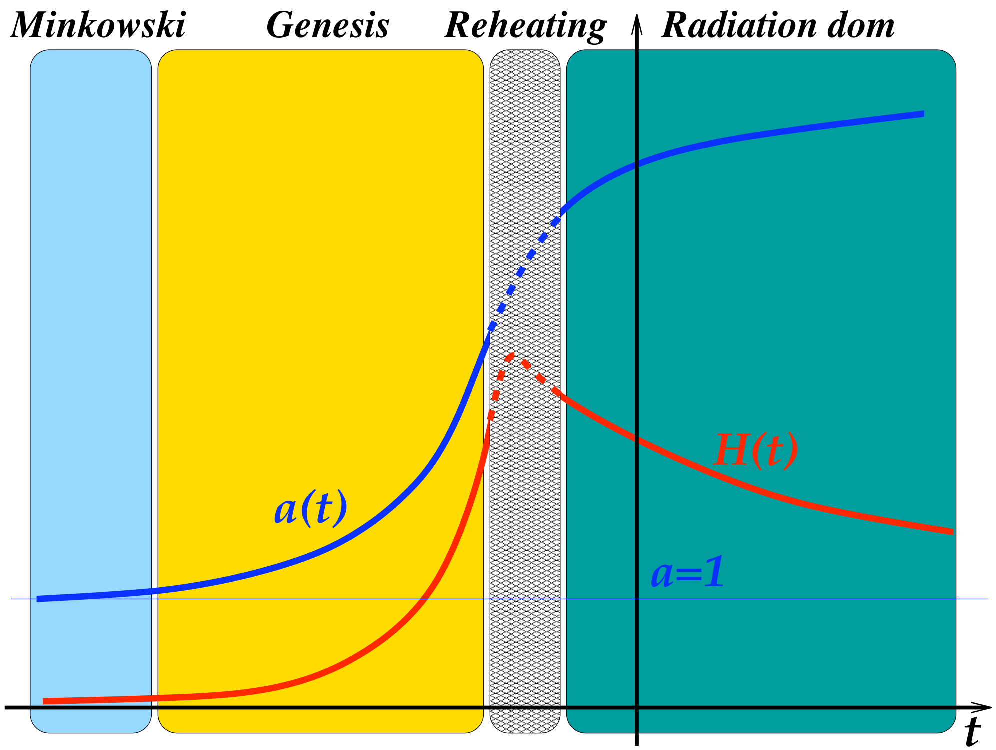
1. choice of potential
2. many scalars (effects on late Universe)
3. speed of propagation c_S

- It is not easy to play with gravity ! GWs are direct probes of H

A proof of inflation?

Galilean Genesis

PC, Nicolis, Trincherini 10



SO(4,2) → SO(4,1) Scale invariant scalar perturbations

No gravitational waves!

Touching the sky

- Energy scale of inflation

$$V^{1/4} \sim \left(\frac{r}{0.01}\right)^{1/4} 10^{16}\,\mathrm{GeV}$$

Observable GWs ($r > 0.001$) require GUT-scale energies

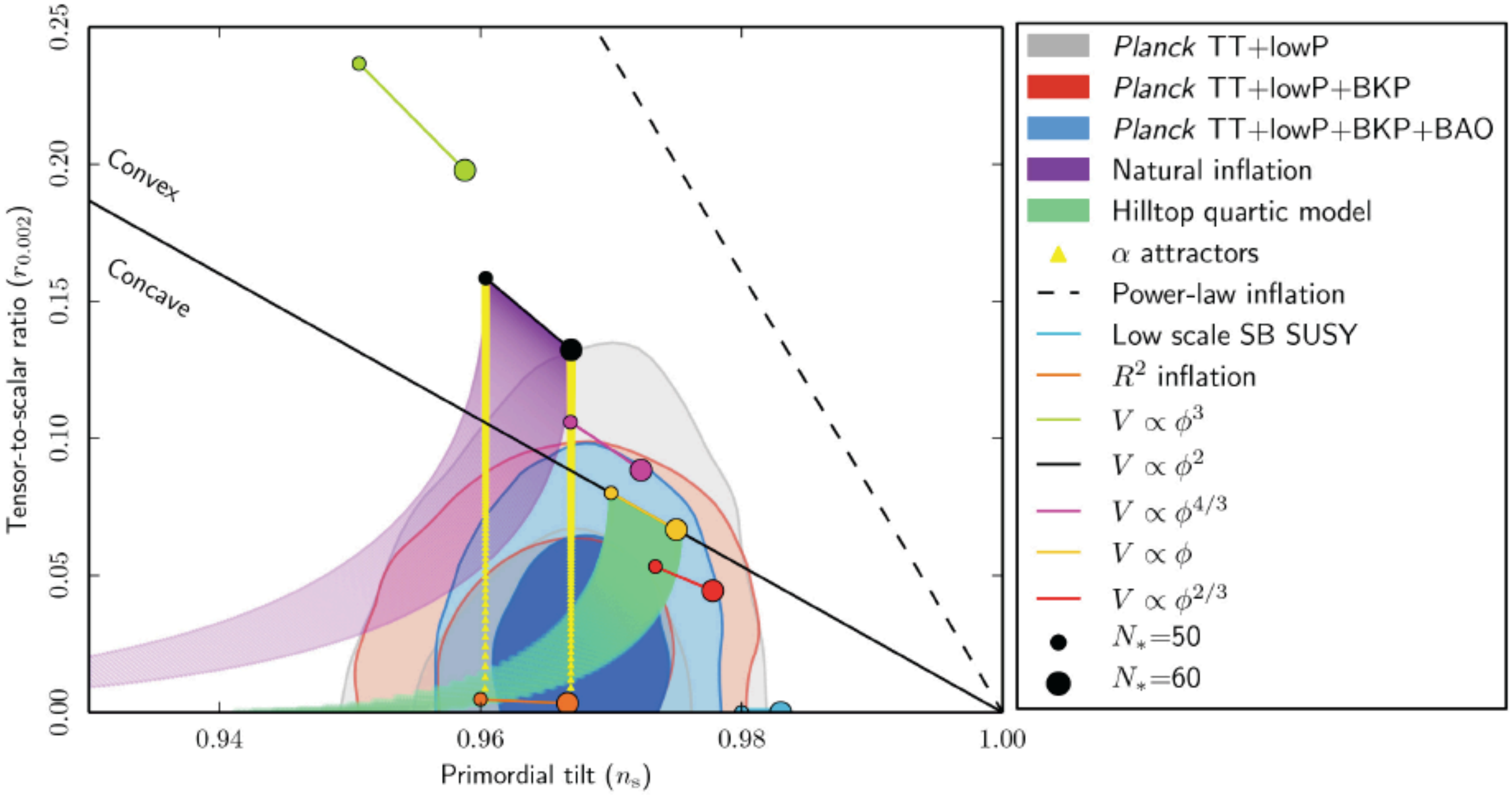
- Lyth's bound : $\frac{\Delta\phi}{M_{\rm pl}} = \int_{N_{\rm end}}^{N_{\rm cmb}} \mathrm{d}N \sqrt{\frac{r}{8}}$ $\qquad$ $\Delta\phi \gtrsim 5\; M_{\rm Pl} \times \left(\frac{r}{0.2}\right)^{1/2}$

Lyth 96

Observable GWs implies Transplanckian displacement

➡ UV sensitivity, connection with Gravity UV completion

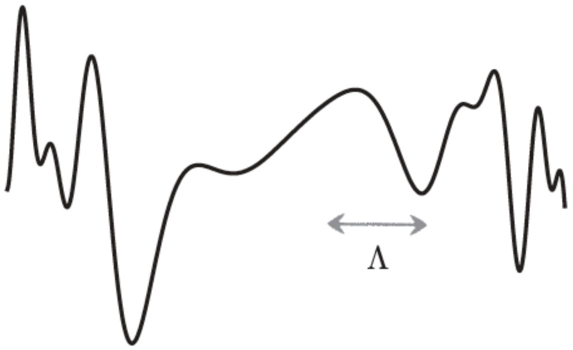
The plane



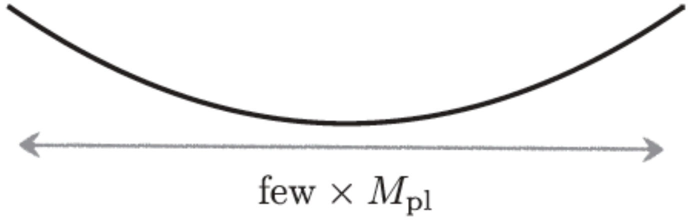
Tensor-to-scalar ratio ($r_{0.002}$)
Primordial tilt (n_s)
0.00
0.05
0.10
0.15
0.20
0.25
0.94
0.96
0.98
1.00
Convex
Concave
Planck TT+lowP
Planck TT+lowP+BKP
Planck TT+lowP+BKP+BAO
Natural inflation
Hilltop quartic model
α attractors
Power-law inflation
Low scale SB SUSY
R^2 inflation
$V \propto \phi^3$
$V \propto \phi^2$
$V \propto \phi^{4/3}$
$V \propto \phi$
$V \propto \phi^{2/3}$
N_*=50
N_*=60

Mountains or hills ?

Landscape:



Around a minimum
all functions look
the same…



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

This is now ruled out experimentally

Standard model

Background:

0. Composition of the universe: $\Omega_{\rm b}$, $\Omega_{\rm CDM}$, H_0 (1% level)

Perturbations; what we see:

1. Initial fluctuations are primordial

2. Amplitude $A_s = (2.14 \pm 0.05) \times 10^{-9}$

3. Tilt $n_s - 1 = -0.0348 \pm 0.0047 \quad (\gtrsim 7\sigma)$

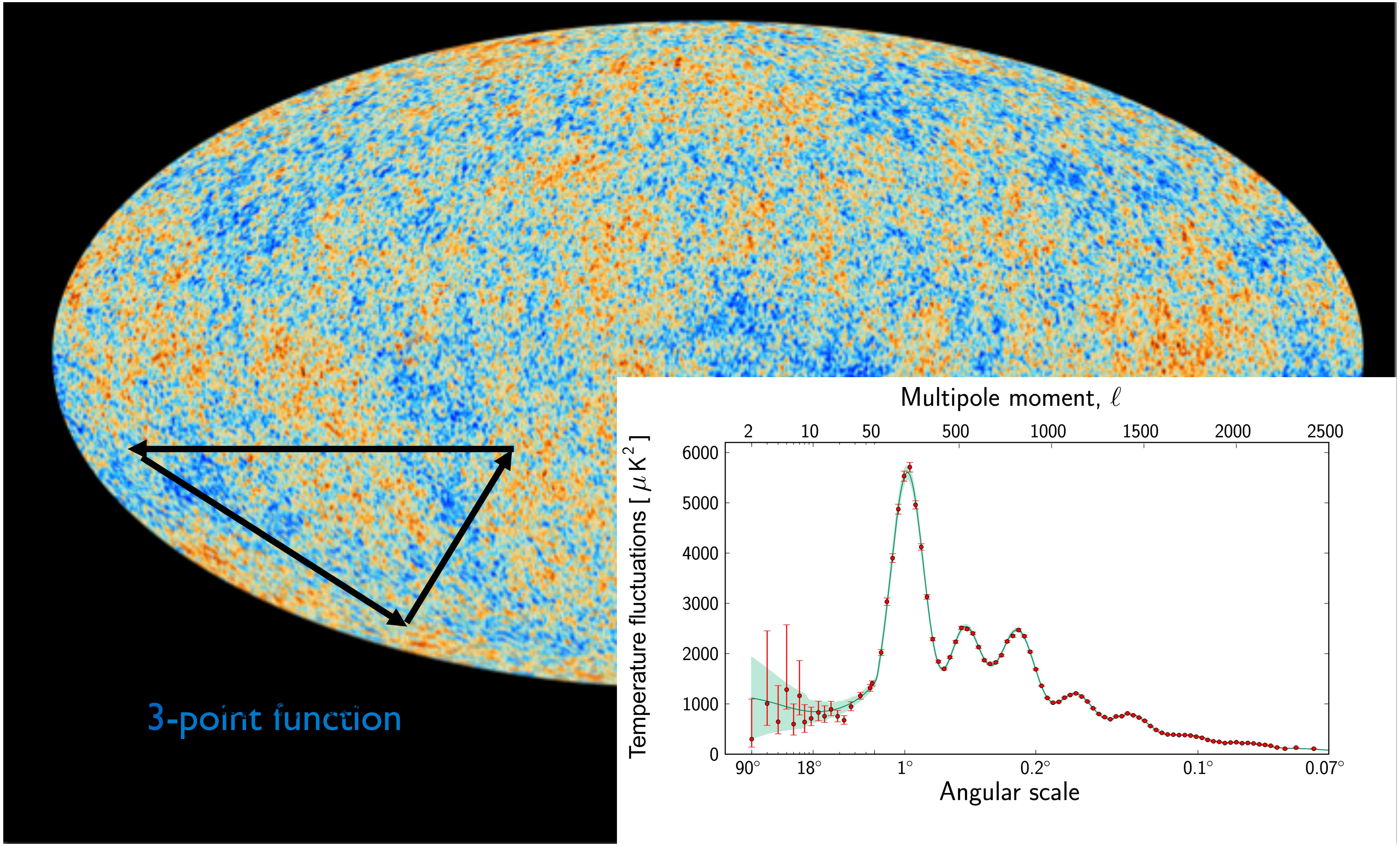
Perturbations; what we do not see:

4. No fluctuations in composition: < 1%

5. No gravitational waves: < 10%

6. No departures from Gaussianity: < 0.1-0.01%

Non-Gaussianity

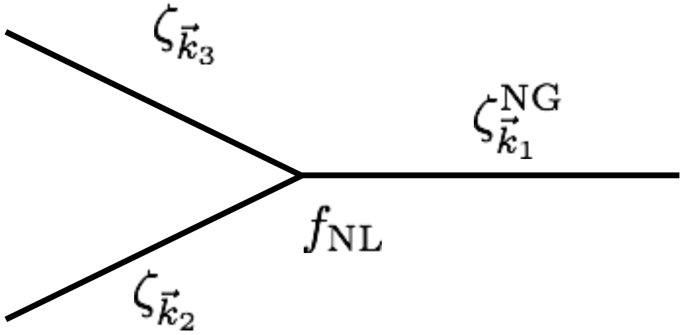


3-point function

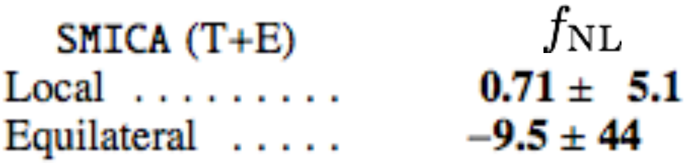
Non-Gaussianity = interactions

Quantum harmonic oscillator ⇒ Gaussian fluctuations

Probe of interactions during inflation:



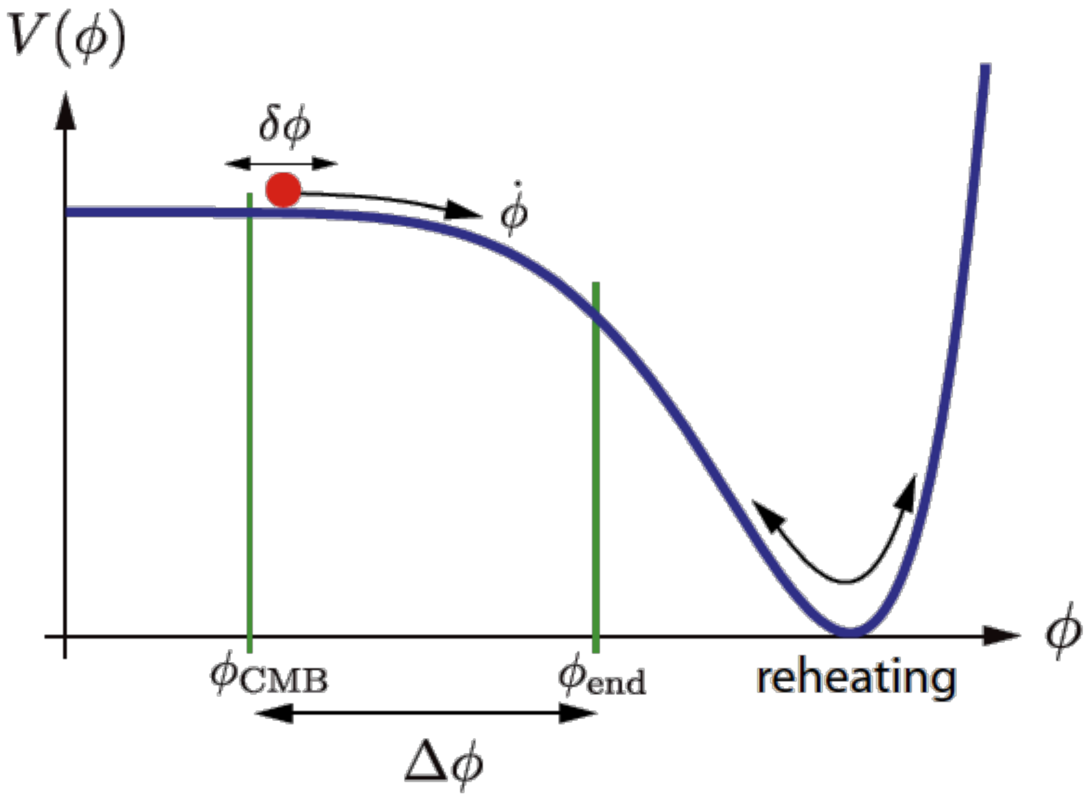
Current constraints (Planck 2015):



SMICA (T+E)	f_{NL}
Local	**0.71 ± 5.1**
Equilateral	**−9.5 ± 44**

$$\frac{\langle\zeta\zeta\zeta\rangle}{\langle\zeta\zeta\rangle^{3/2}} \sim f_{\mathrm{NL}}\langle\zeta\zeta\rangle^{1/2} \lesssim 10^{-3} \div 10^{-4}$$

Slow-roll = weak coupling = Gaussian



$$\epsilon = \frac{1}{2}M_P^2\left(\frac{V'}{V}\right)^2$$

$$\eta = M_P^2\frac{V''}{V}$$

$$\epsilon, \eta, \ldots \ll 1$$

$$\lambda \equiv V^{(4)} \lesssim \mathcal{O}(\epsilon^3, \eta^3)(10^{-5})^2$$

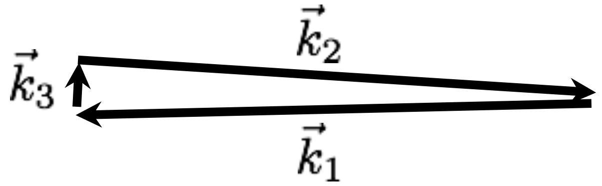
Compare with Higgs!

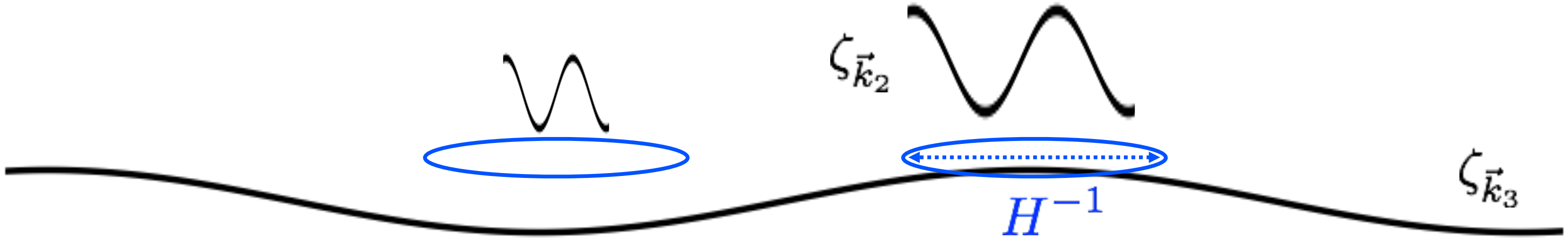
$$f_{\rm NL} \sim \epsilon$$

Single - field

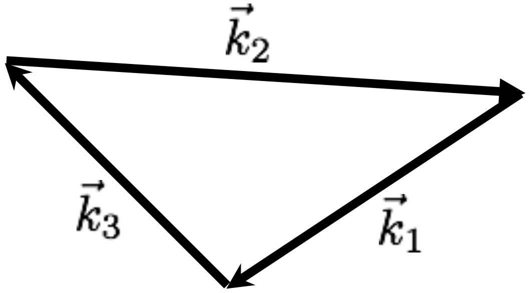
- Derivative interactions may be relevant (~ Goldstone). E.g. $\frac{(\partial\phi)^4}{\Lambda^4}$

- General result: absence of NG in the squeezed limit





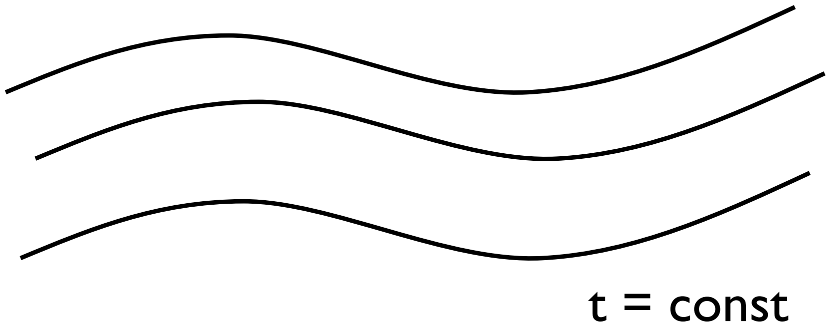
- Equilateral NG: f_{NL}^{eq}



Effective Field Theory of Inflation

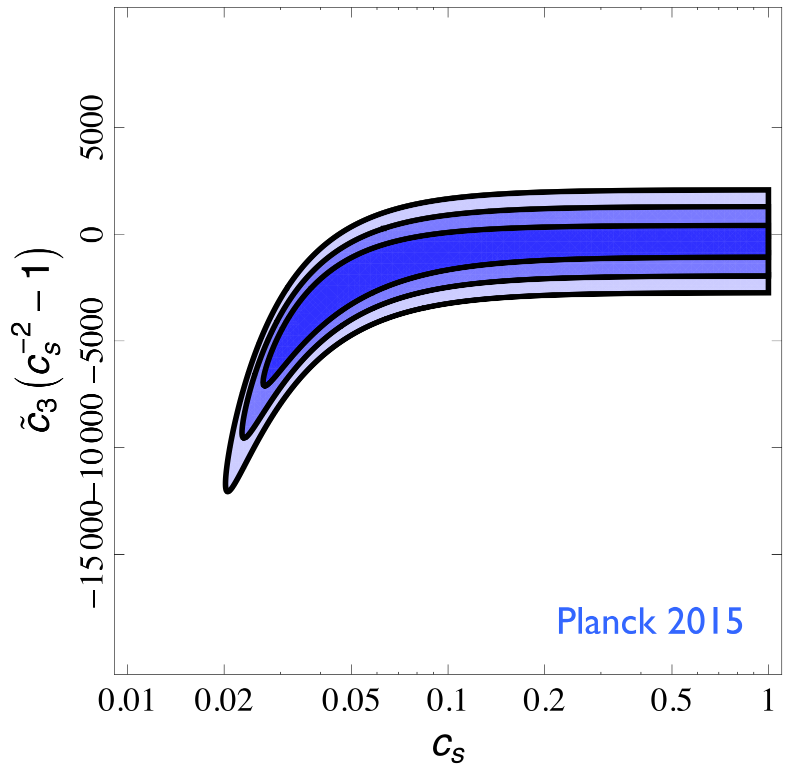
Cheung, PC, Fitzpatrick, Kaplan, Senatore 07

Parametrizes the most general dynamics
compatible with symmetries



$$S = \int d^4x\,\sqrt{-g}\left[-\frac{M_{\rm Pl}^2\dot{H}}{c_{\rm s}^2}\left(\dot{\pi}^2 - c_{\rm s}^2\frac{(\partial_i\pi)^2}{a^2}\right)\right.$$

$$\left. - \; M_{\rm Pl}^2\dot{H}(1-c_{\rm s}^{-2})\dot{\pi}\frac{(\partial_i\pi)^2}{a^2} + \left(M_{\rm Pl}^2\dot{H}(1-c_{\rm s}^{-2}) - \frac{4}{3}M_3^4\right)\dot{\pi}^3\right]$$

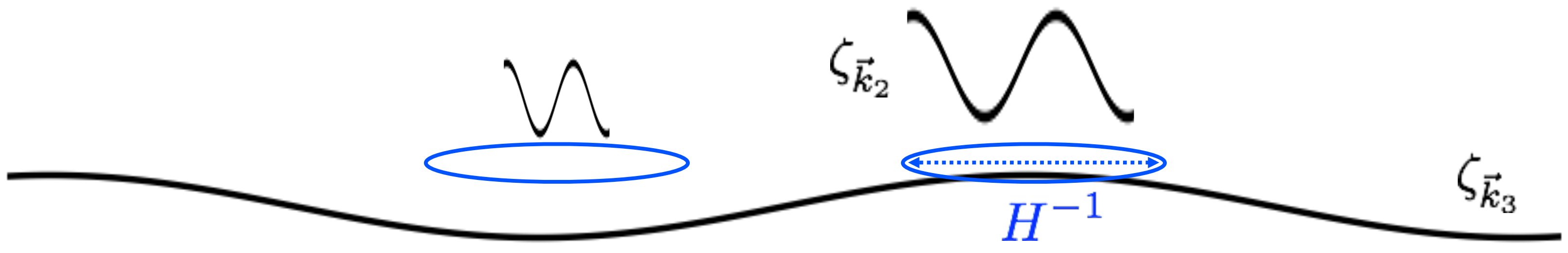


Relevant target: $f_{NL}^{EQ} \sim 1$ $c_s \sim 1$

Lorentz invariant limit: $\Lambda \sim \dot{\phi}^{1/2}$

Multi - field

- Squeezed limit non-vanishing (local non-Gaussianity)



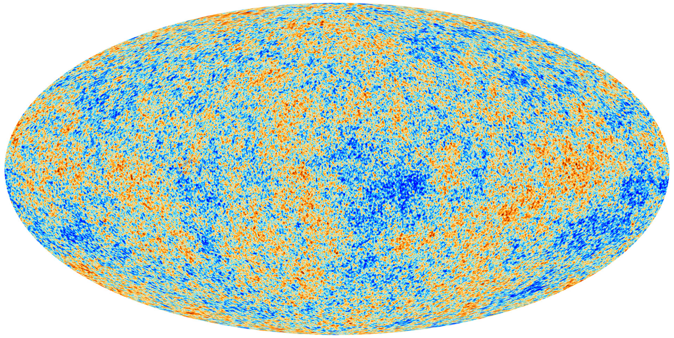
- Observables sensitive to this limit only (scale-dependent bias)

- Models where the source of perturbations is not the inflaton: $f_{NL}^{loc} > 1$

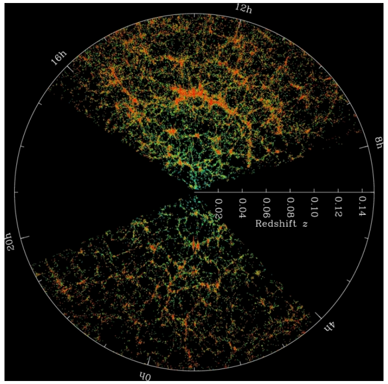
The future

Constraints are statistical in nature:

$$\Delta f_{\rm NL} \sim \frac{10^4}{N_{\rm modes}^{1/2}}$$

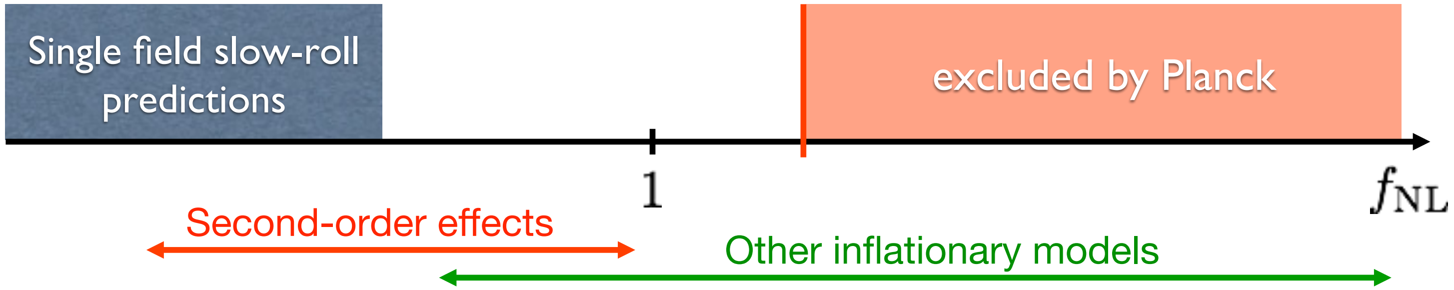


+



Future experimental target, reachable (?) by CMB + LSS: $f_{\rm NL}^{\rm loc} \lesssim 1$

$f_{\rm NL}^{\rm eq} \lesssim 1$



Single field slow-roll predictions

excluded by Planck

Second-order effects

Other inflationary models

Conclusions

1. We believe inflation sets up our initial conditions:
   strong support (e.g. tilt) but room to doubt.

2. We entered the B-mode era. Primordial gravity waves predictions extremely robust. Window on the highest energies and probe of early acceleration.

3. Large non-Gaussianity would rule out all single-field slow-roll models. Probe of new early universe physics: multi-field models and self-interactions. Future experiments are very close to targets $f_{\rm NL} \sim \mathcal{O}(1)$.

Backup slides