Title: Cosmology Theory: Inflation

Date: Jul 09, 2015 10:15 AM

URL: http://pirsa.org/15070027

Abstract:

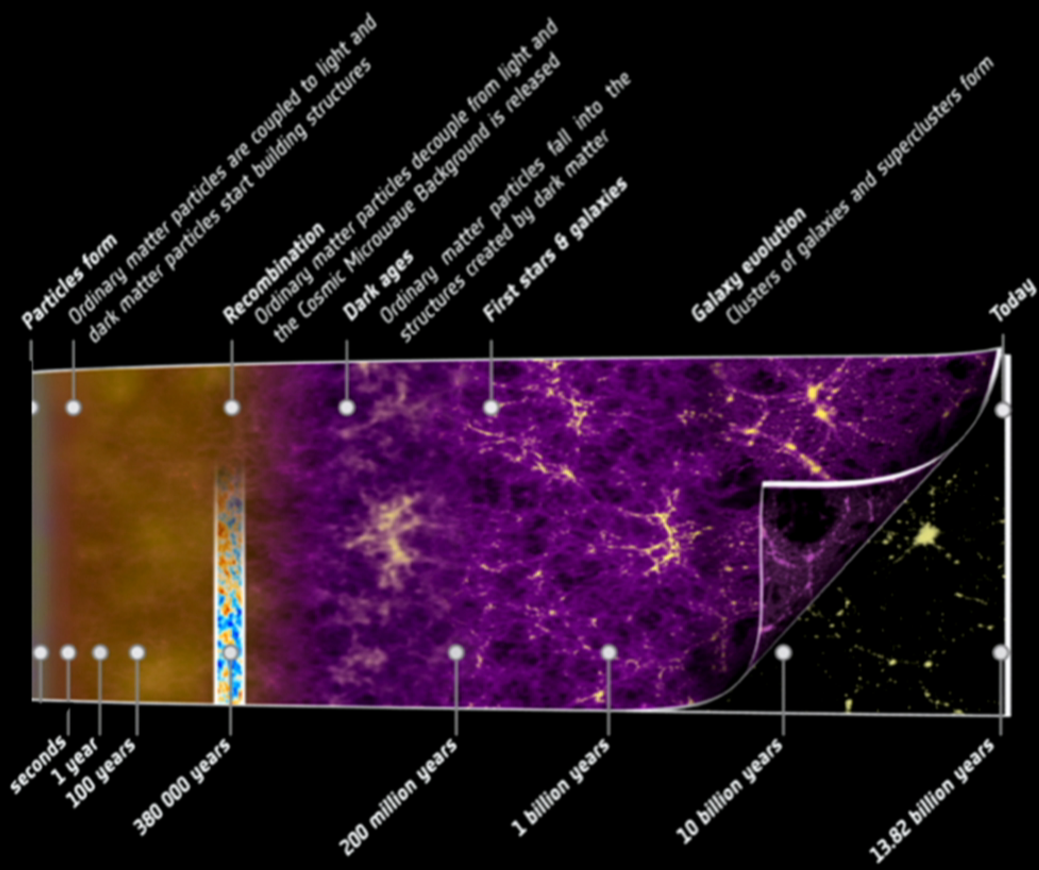
Inflation

Large Scale Structure

July 2015


$(m_N/\mathrm{GeV})^{1/2}$

We live in the aftermath of a Big Bang



FRW Background

$$ds^2 = a^2(\tau)[-d\tau^2 + dx^2] \qquad a d\tau = dt$$

$$\mathcal{H}^2 = (\frac{\dot{a}}{a})^2 = \frac{8\pi G a^2}{3}\rho$$

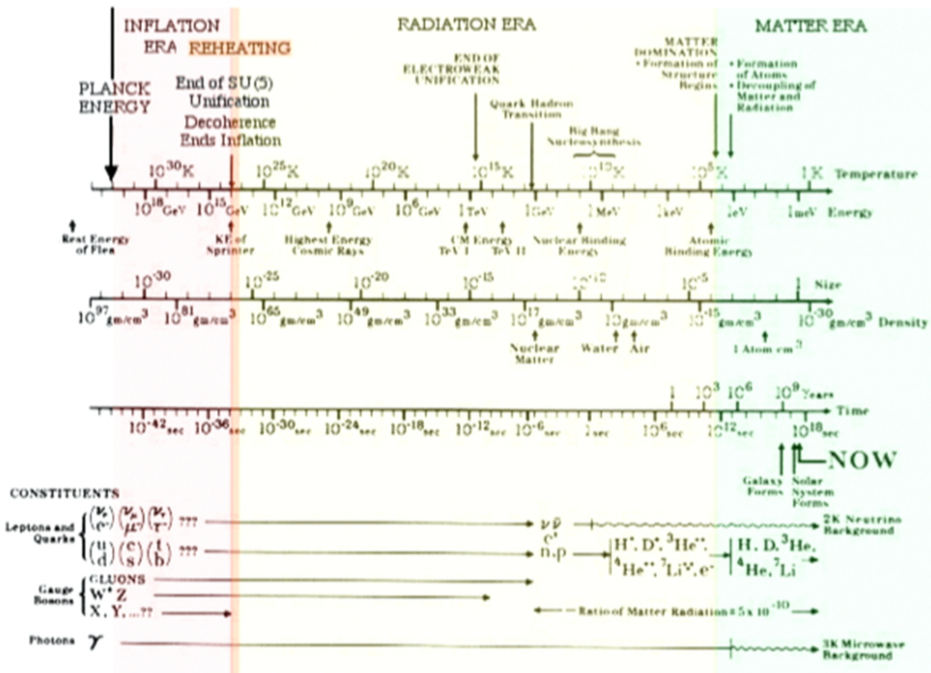
$$\dot{\rho} = 3\mathcal{H}(\rho + p)$$

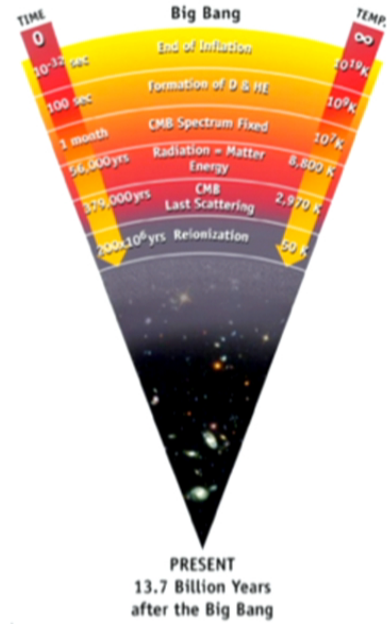
$$\Omega = \frac{8\pi G}{3H^2}\rho \equiv \frac{\rho}{\rho_{\rm crit}} \qquad \rho \propto \Omega h^2 \equiv \omega \propto \frac{\rho}{\rho_\gamma}$$

$$a(\tau) \propto \tau \quad \text{(Radiation era)}$$

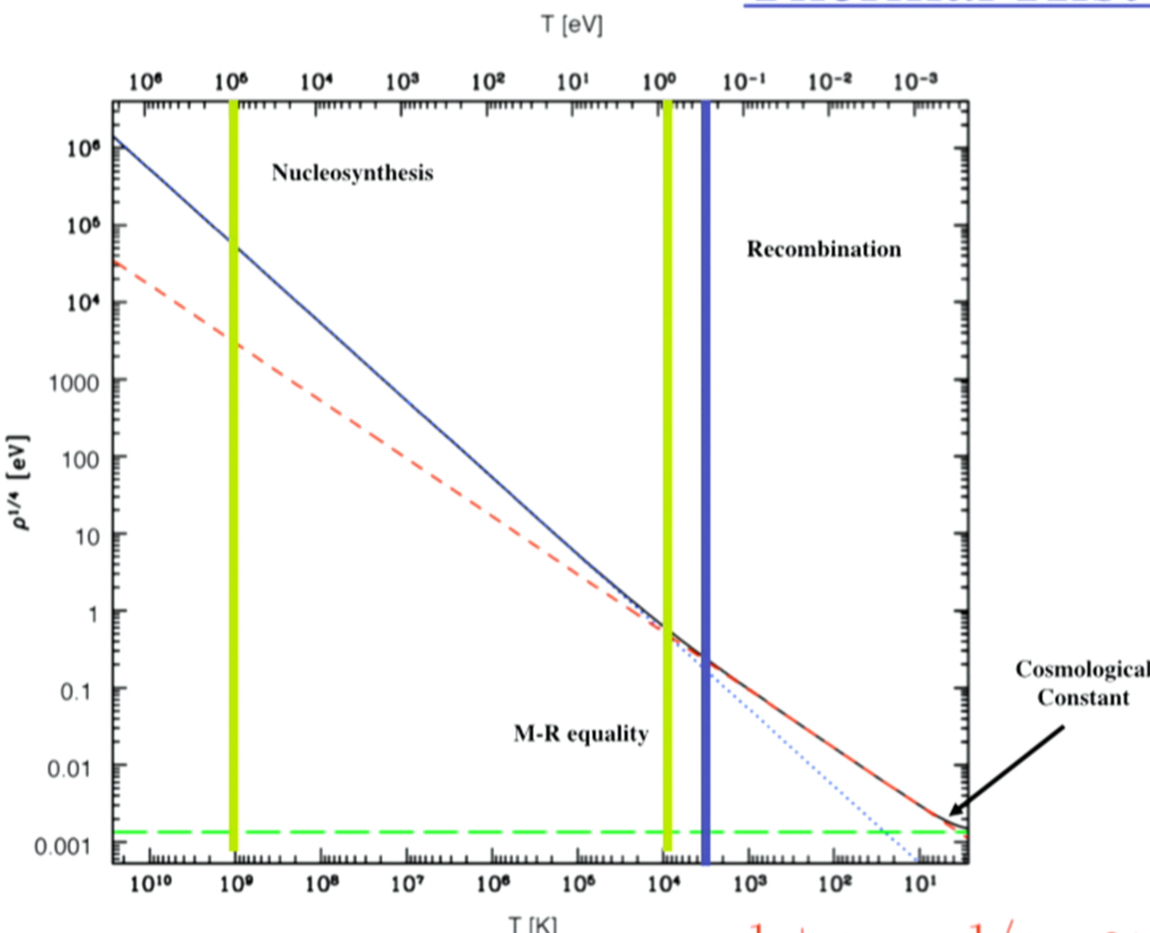
$$a(\tau) \propto \tau^2 \quad \text{(Matter era)}$$

????


INFLATION ERA
REHEATING
RADIATION ERA
MATTER ERA
PLANCK ENERGY
End of SU(5) Unification
Decoherence Ends Inflation
END OF ELECTROWEAK UNIFICATION
Quark Hadron Transition
Big Bang Nucleosynthesis
MATTER DOMINATION
Temperature
Energy
Size
Density
Time
NOW
CONSTITUENTS
Leptons and Quarks
Gauge Bosons
GLUONS
Photons
2K Neutrino Background
3K Microwave Background


TIME
Big Bang
TEMP.
End of Inflation
Formation of D & HE
CMB Spectrum Fixed
Radiation = Matter Energy
CMB Last Scattering
Reionization
PRESENT
13.7 Billion Years
after the Big Bang

Thermal History



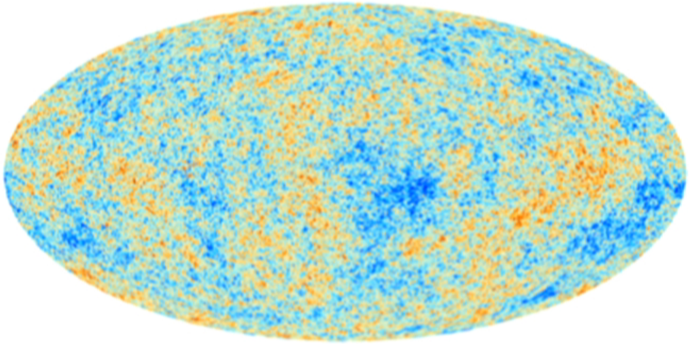
$$1 + z_{eq} = 1/a_{eq} \approx 3600$$

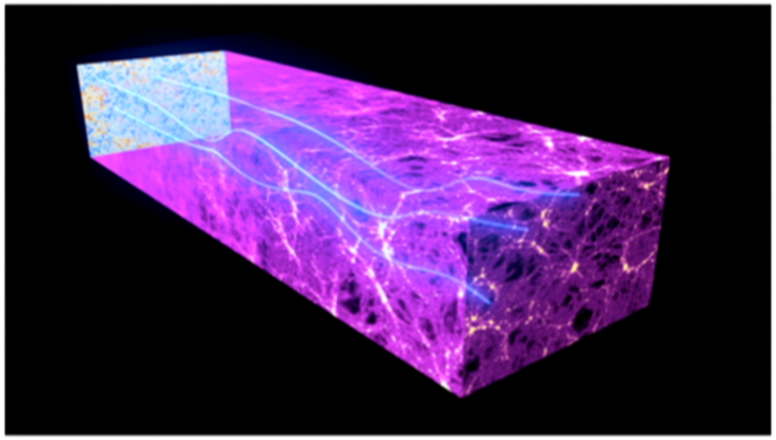
$$\Omega_m = 0.3 \; ; \; \Omega_v = 0.7$$

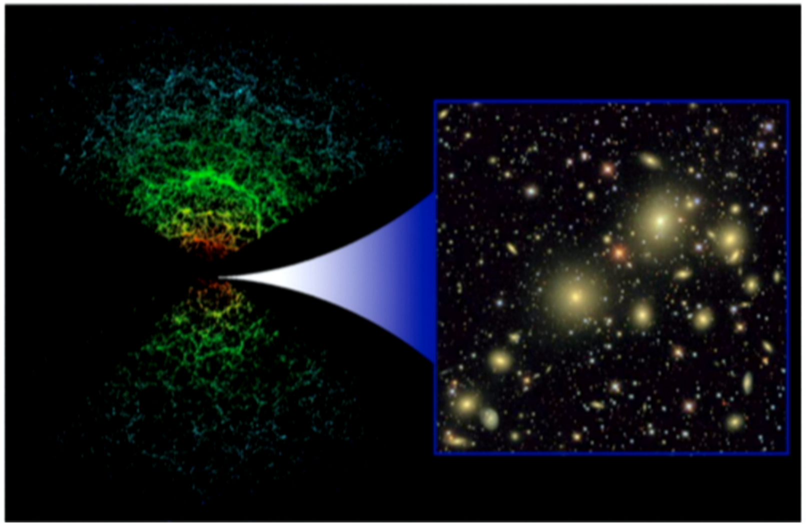
Relics from the early stages of the HBB

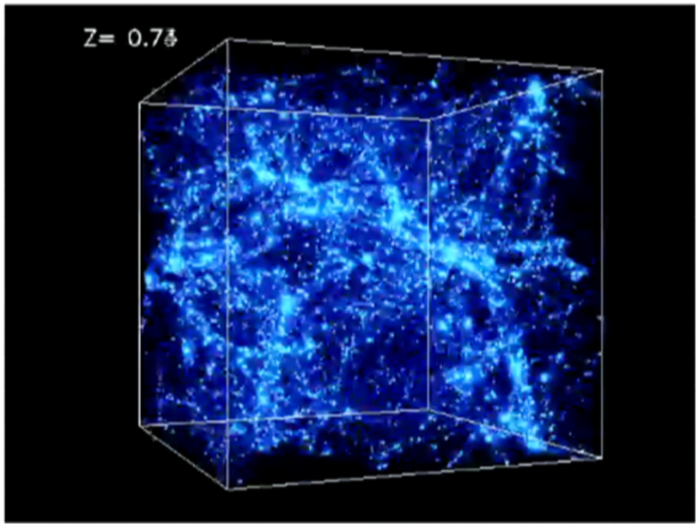
1. BBN Nuclei
2. Cosmic Neutrino Background
3. CMB BB spectrum
4. Dark matter
5. Baryons
6. Others

The growth of structure

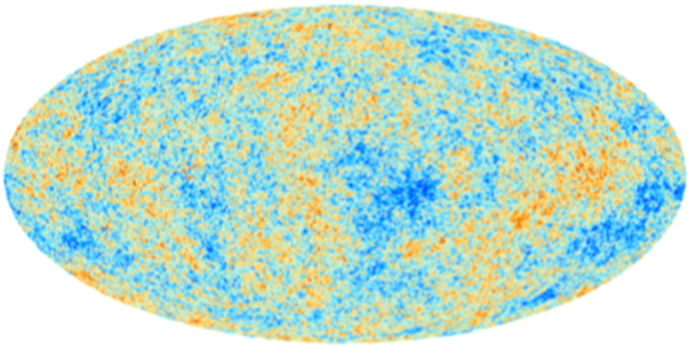


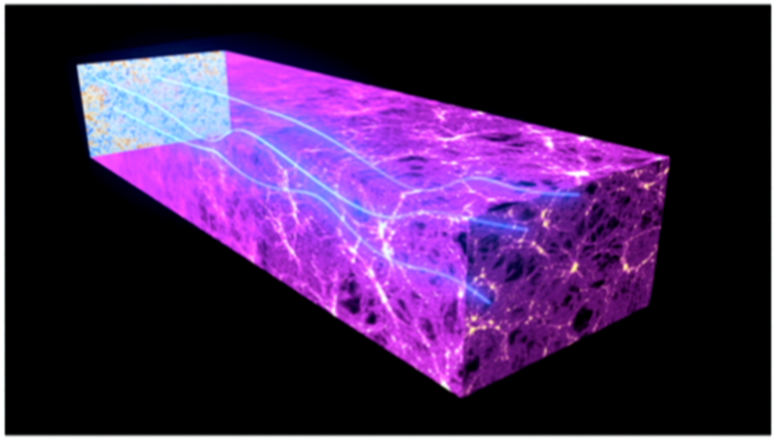


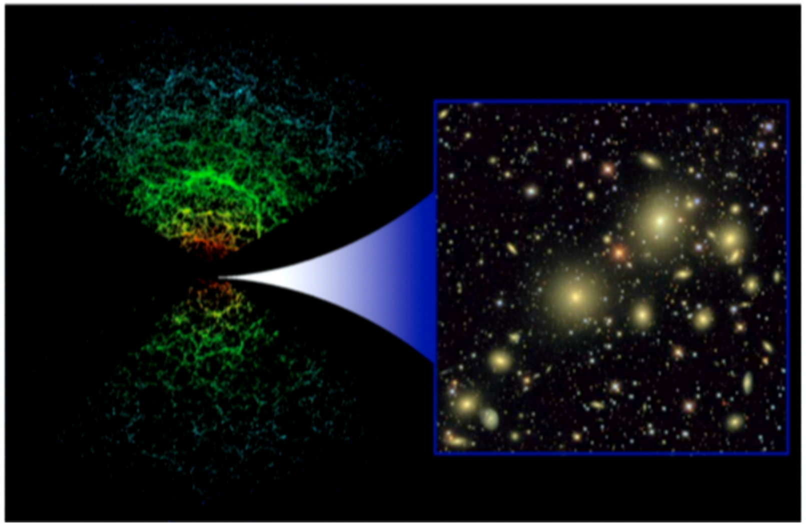


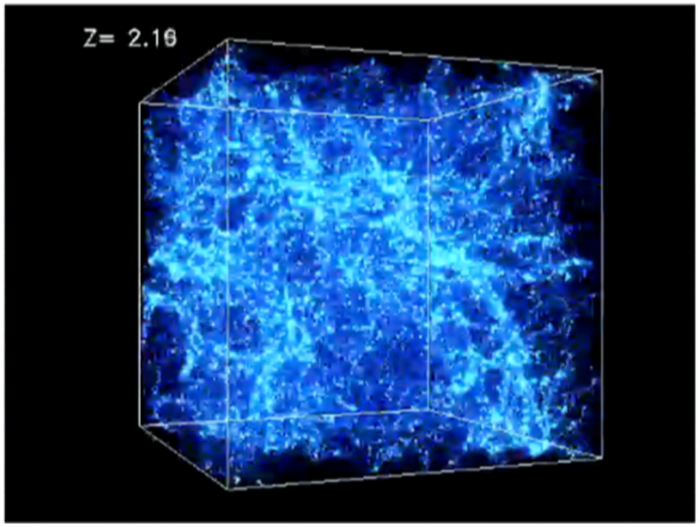


The growth of structure

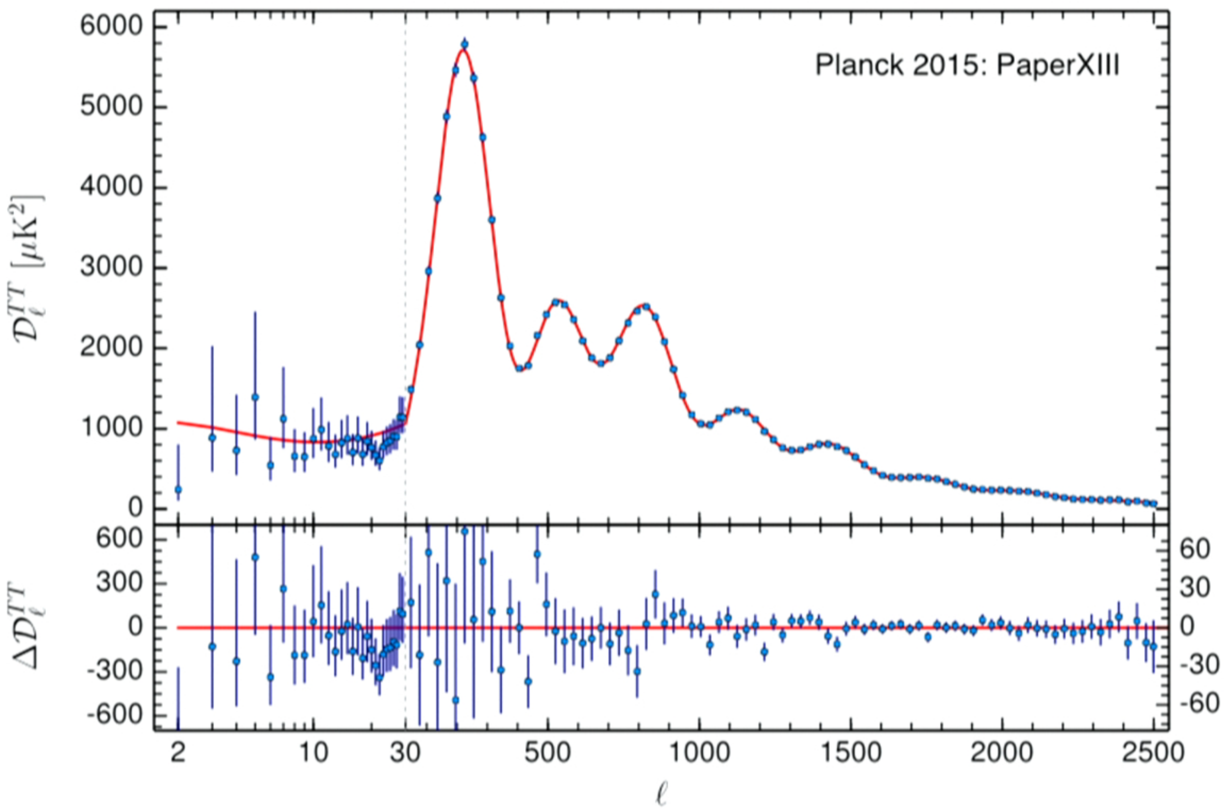


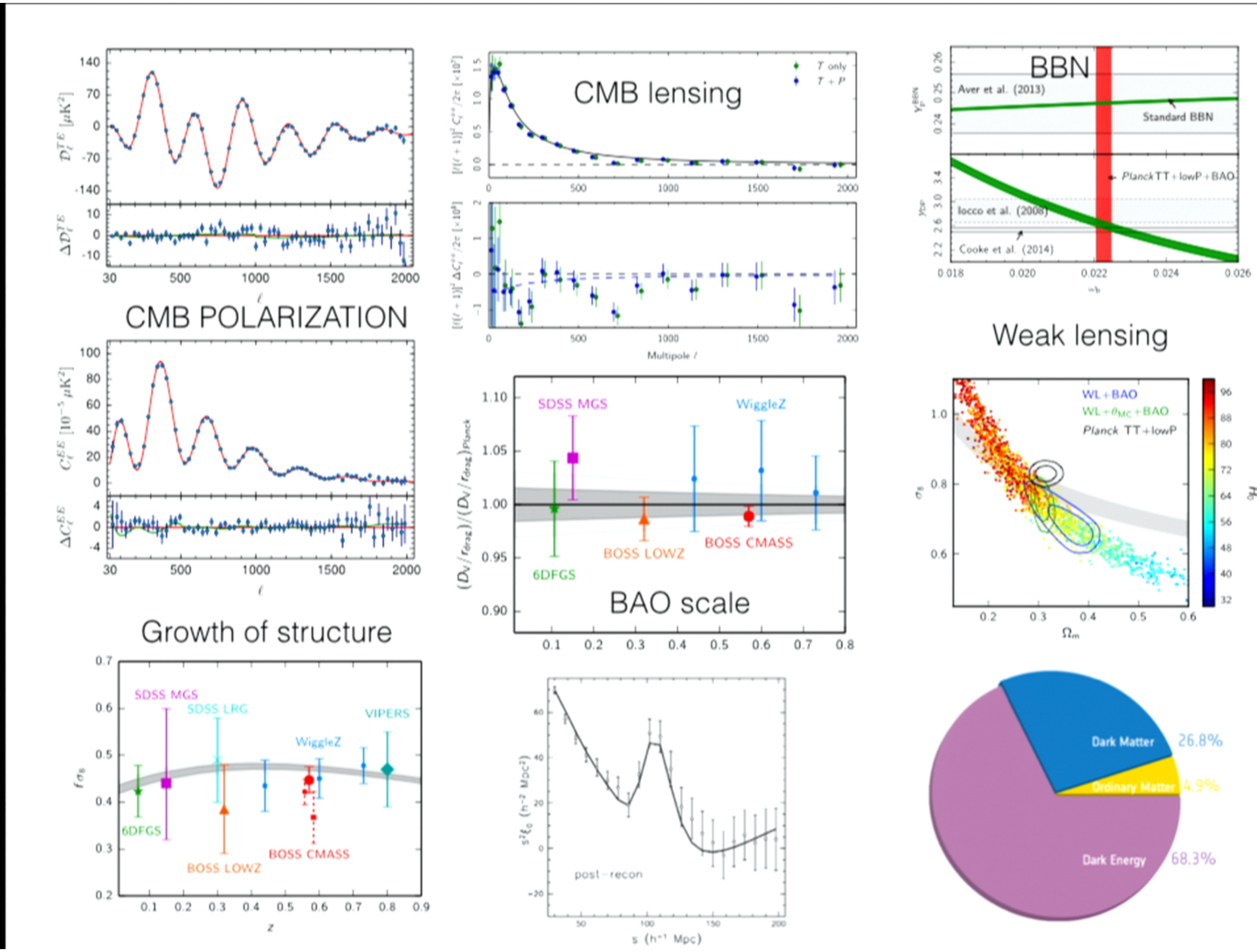




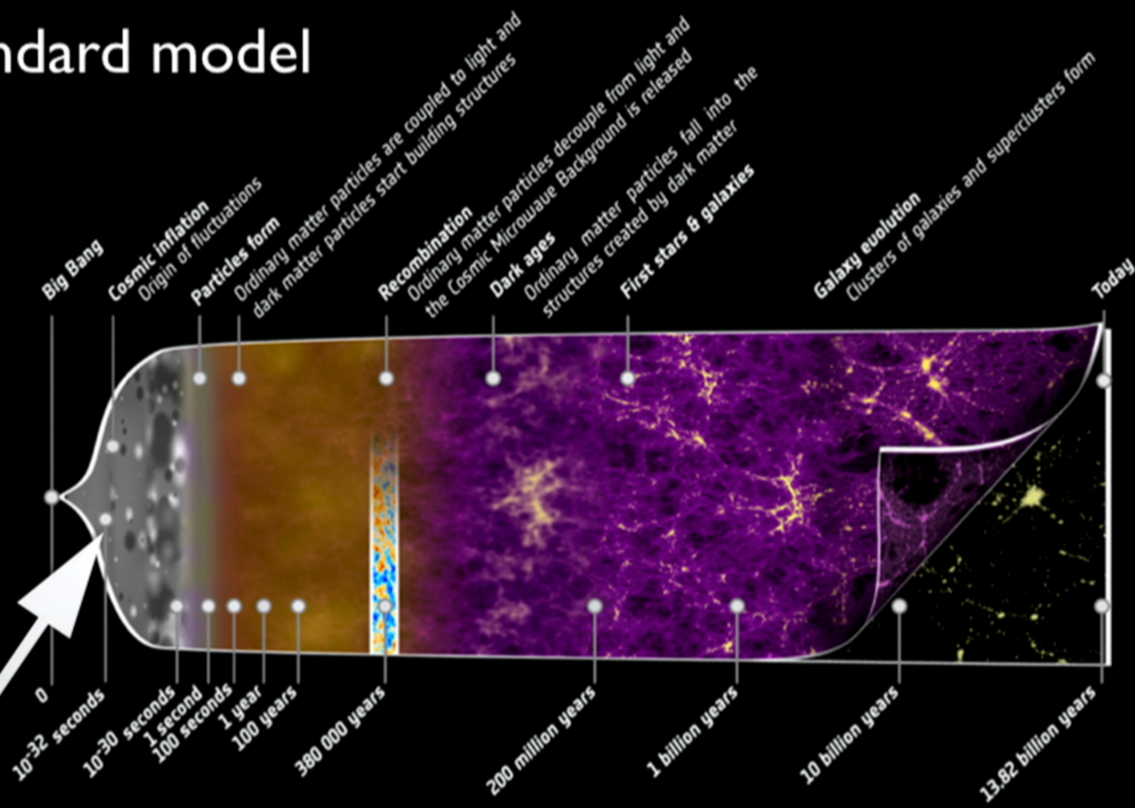


Agreement between theory and data




CMB POLARIZATION
CMB lensing
T only
T + P
Multipole ℓ
BBN
Aver et al. (2013)
Standard BBN
Planck TT+lowP+BAO
Iocco et al. (2008)
Cooke et al. (2014)
Weak lensing
WL+BAO
Planck TT+lowP
BAO scale
SDSS MGS
WiggleZ
6DFGS
BOSS LOWZ
BOSS CMASS
Growth of structure
SDSS LRG
VIPERS
post-recon
Dark Matter
26.8%
Ordinary Matter
4.9%
Dark Energy
68.3%

The standard model



Why is the Universe so old/big? Attractor solution.
Seeds for structure formation are quantum fluctuations of the clock.

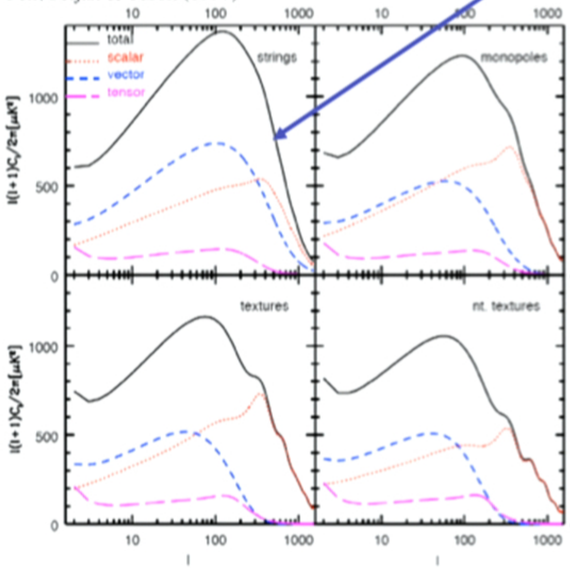
Fluctuations are primordial

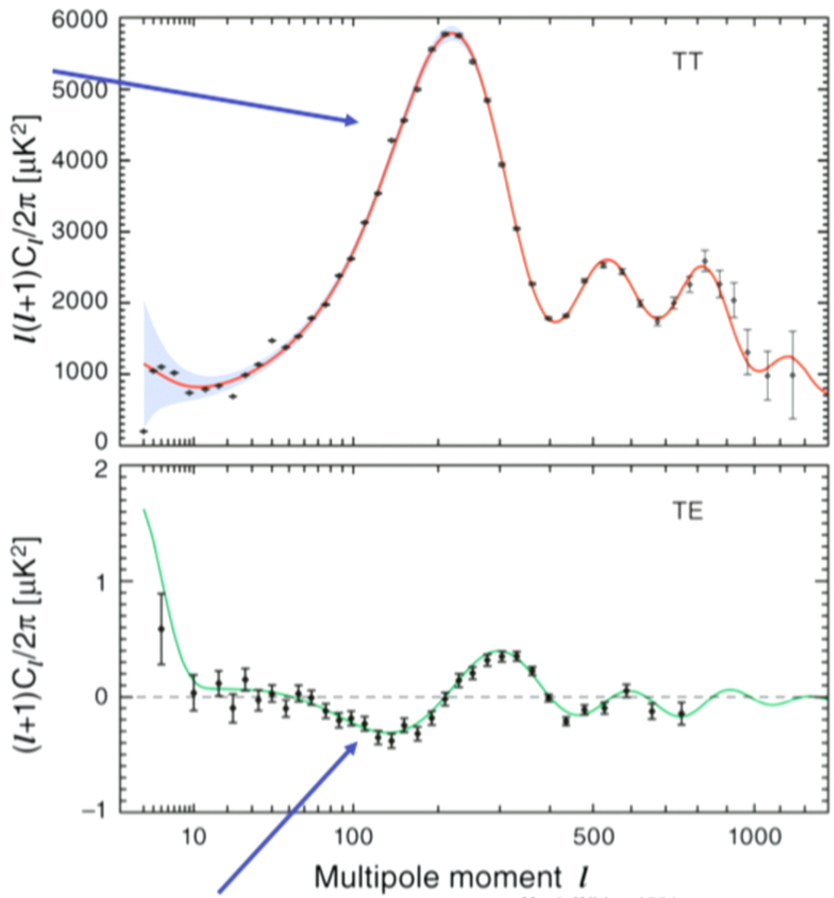
WMAP 7yrs

Causal Seeds

Sharp acoustic peaks are difficult to create without inflation

Pen, Seljak & Turok (1997)



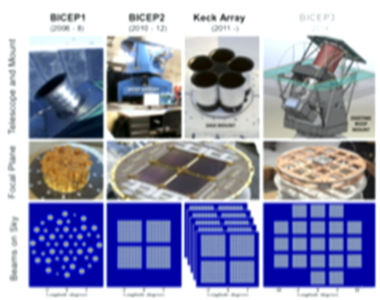


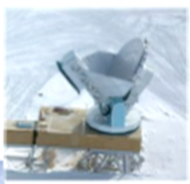
Fluctuations are put in place before the Hot Big Bang starts. Although the theory for the origin of the fluctuations is bound to be speculative this fact is robust.

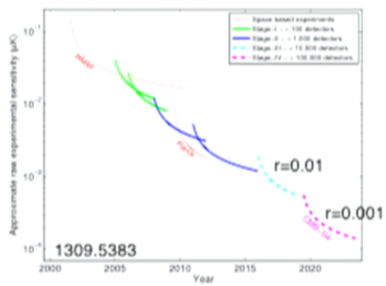
Negative peak imply fluctuations come from outside horizon

Hu & White (1996)
Spergel & MZ (1997)
Pieris et al WMAP (2003)

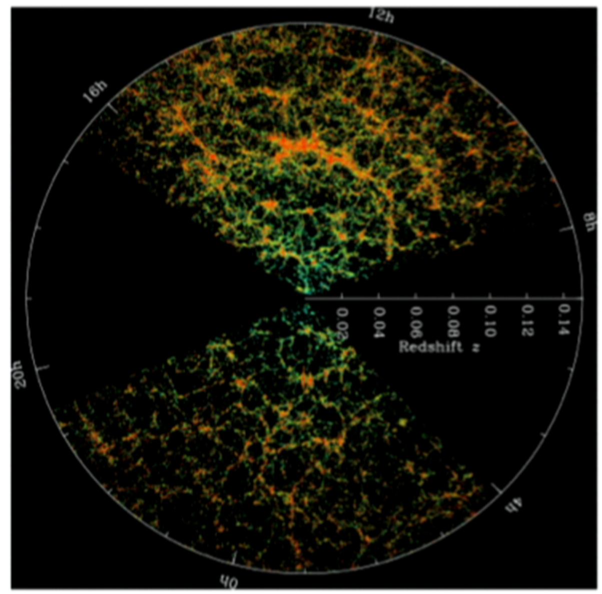
Can we get a second fossil?







Can we learn more about the scalar fluctuations?



What we have learned so far

0. No curvature (1/2 percent level)

1. The seeds are primordial

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2. Amplitude: $\ln A_s = -19.932 \pm 0.034$

3. Slope: $1 - n_s = 0.0355 \pm 0.0049$

---

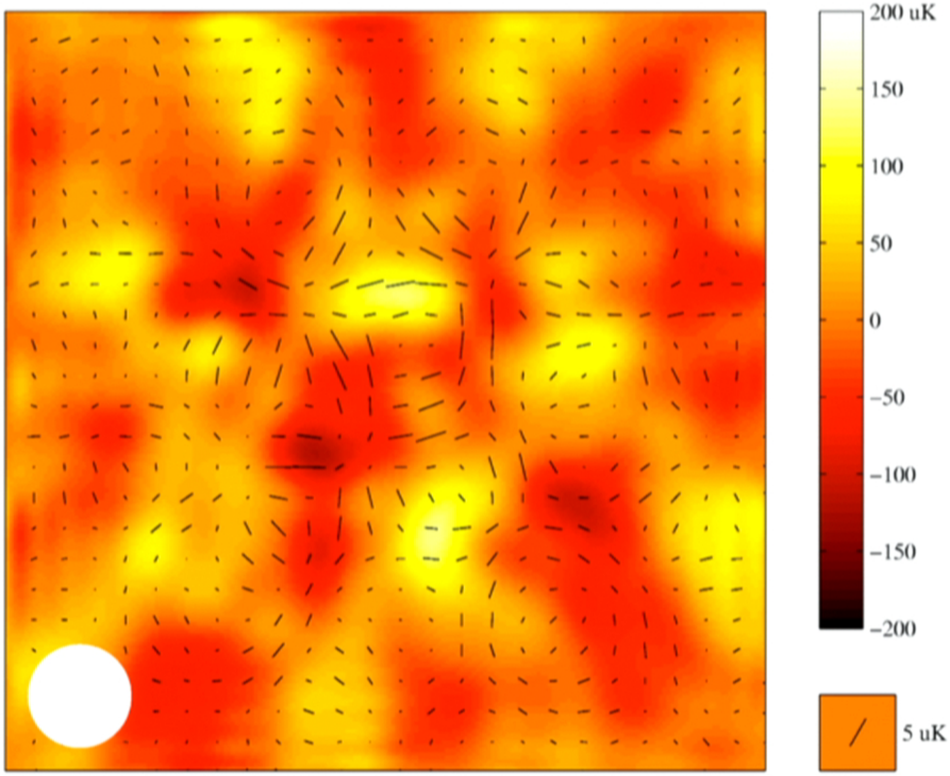
4. No gravitational waves (10 percent level)

5. No fluctuation in composition (percent level)

6. No departures from Gaussianity $\frac{\mathrm{Non-Gaussian}}{\mathrm{Gaussian}} < 10^{-3} - 10^{-4}$

The Anisotropies are polarized

DASI

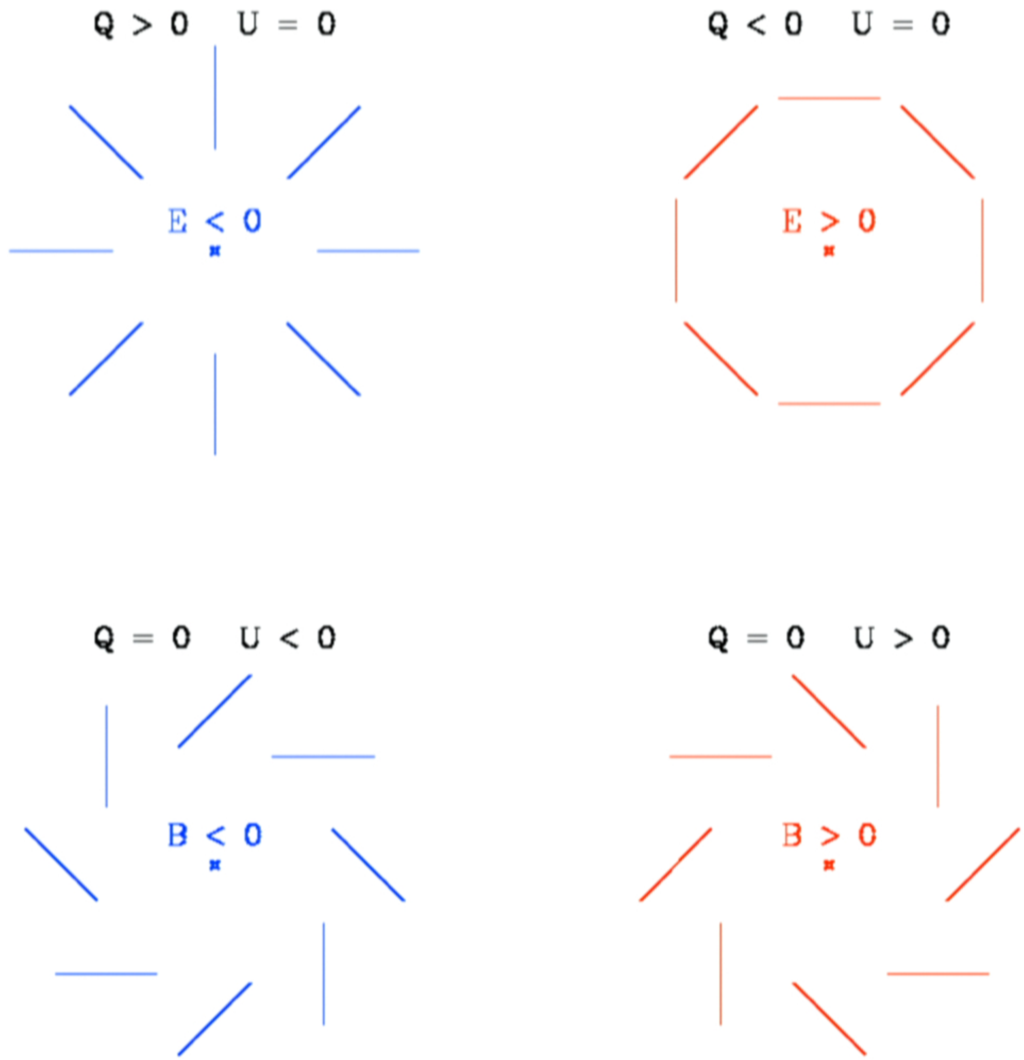


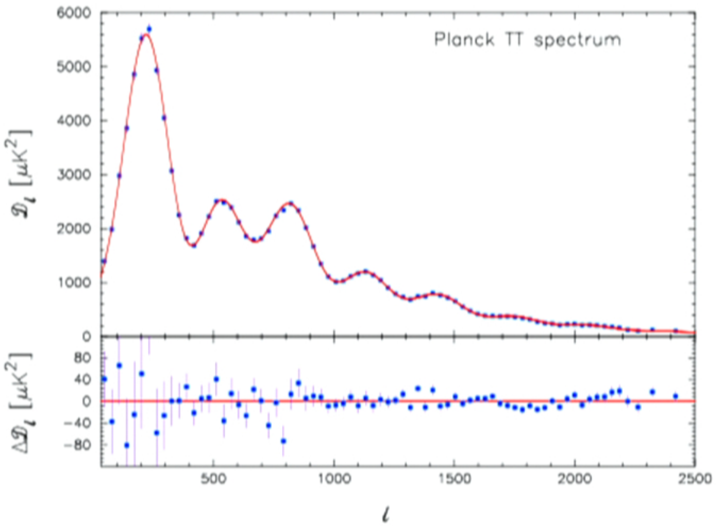
Map is 5 degrees square

Kovac et al.
astro-ph/0209478

Density pert.
&
Gravity Waves

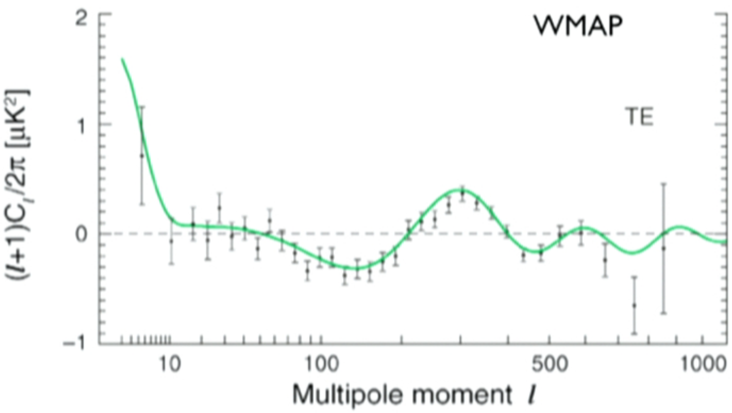
Gravity
Waves

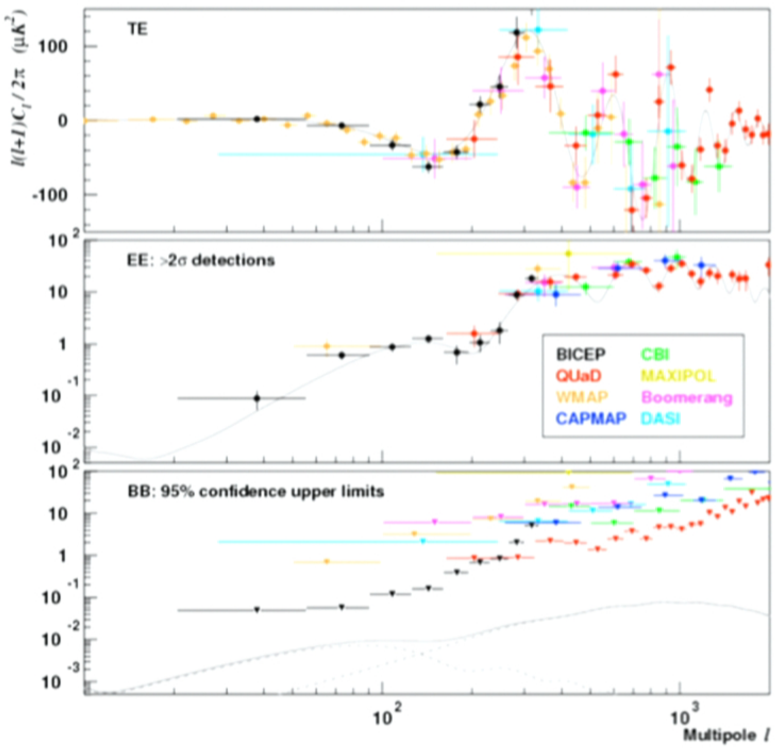


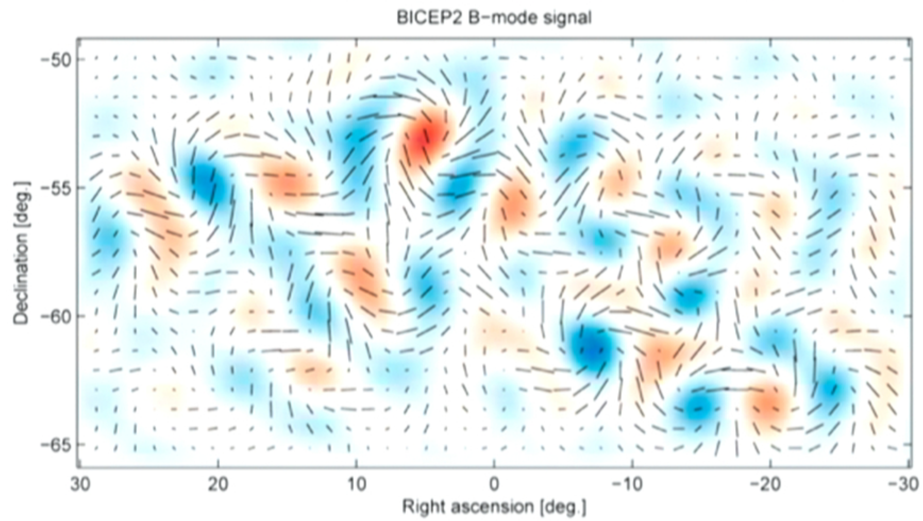


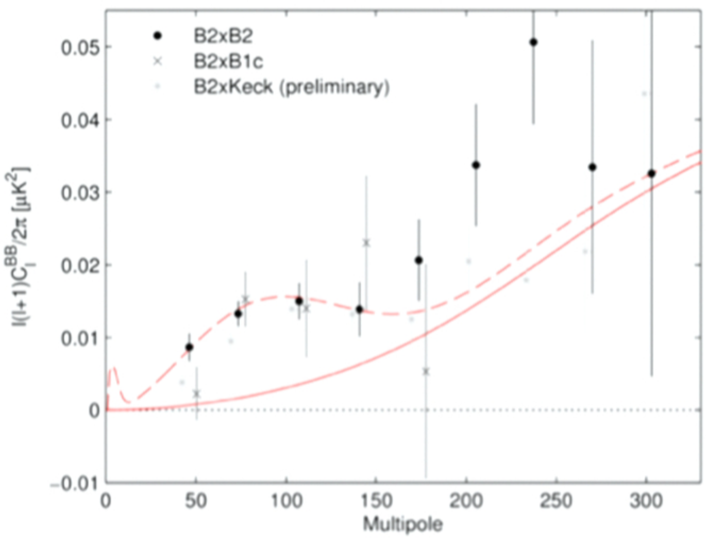
State of the art prior to BICEP2

$$T \sim 10 \text{ to } 70\ \mu K$$
$$E \sim 1 \text{ to } 5\ \mu K$$

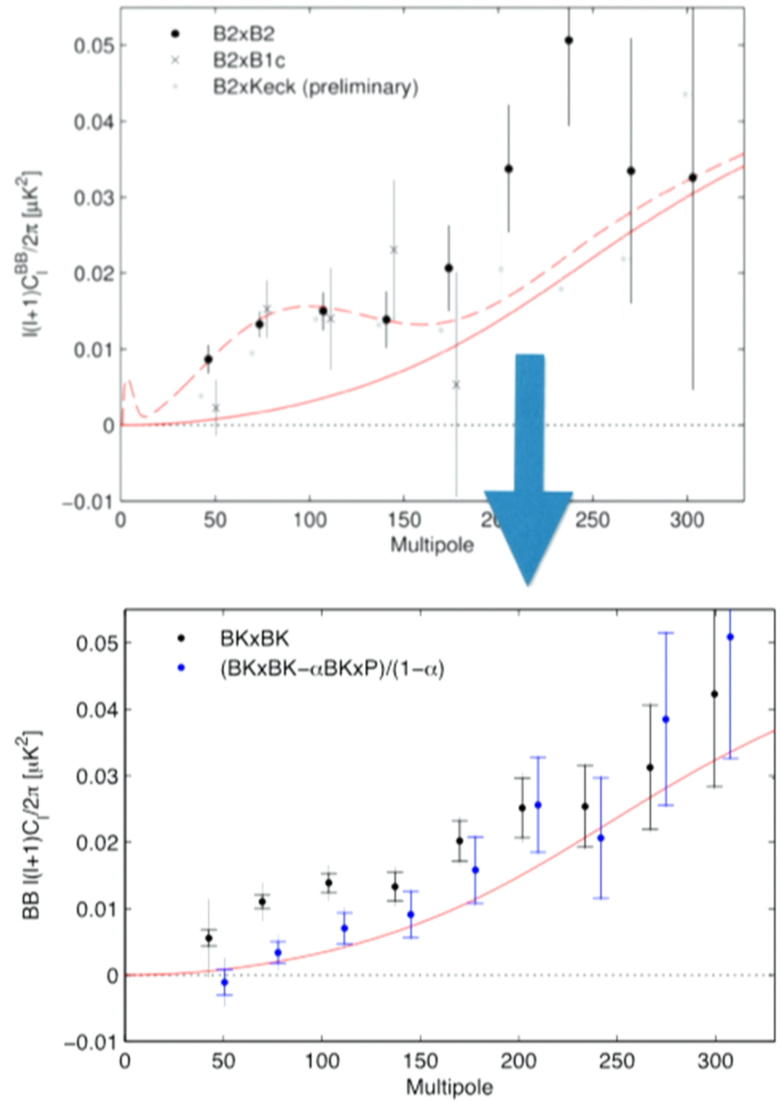








BICEP 2: Evidence for Cosmic Inflation


B2xB2
B2xB1c
B2xKeck (preliminary)
$l(l+1)C_l^{BB}/2\pi$ [μK^2]
Multipole
BKxBK
(BKxBK−αBKxP)/(1−α)
BB $l(l+1)C_l/2\pi$ [μK^2]
Multipole

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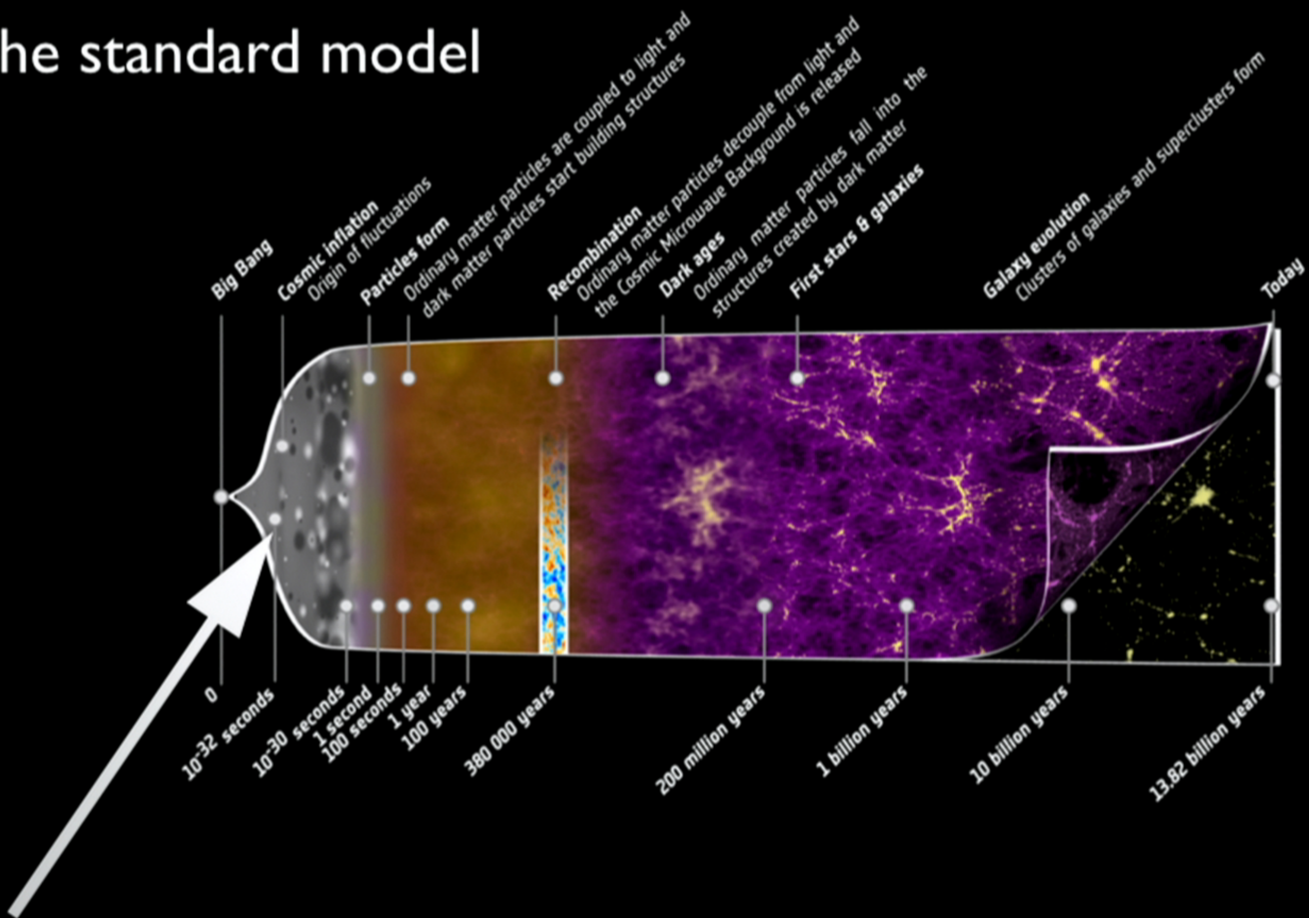
21

The standard model



Why is the Universe so old/big? Attractor solution.
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Inflationary dynamics

$$ds^2 = -dt^2 + a^2(t)dx^2$$

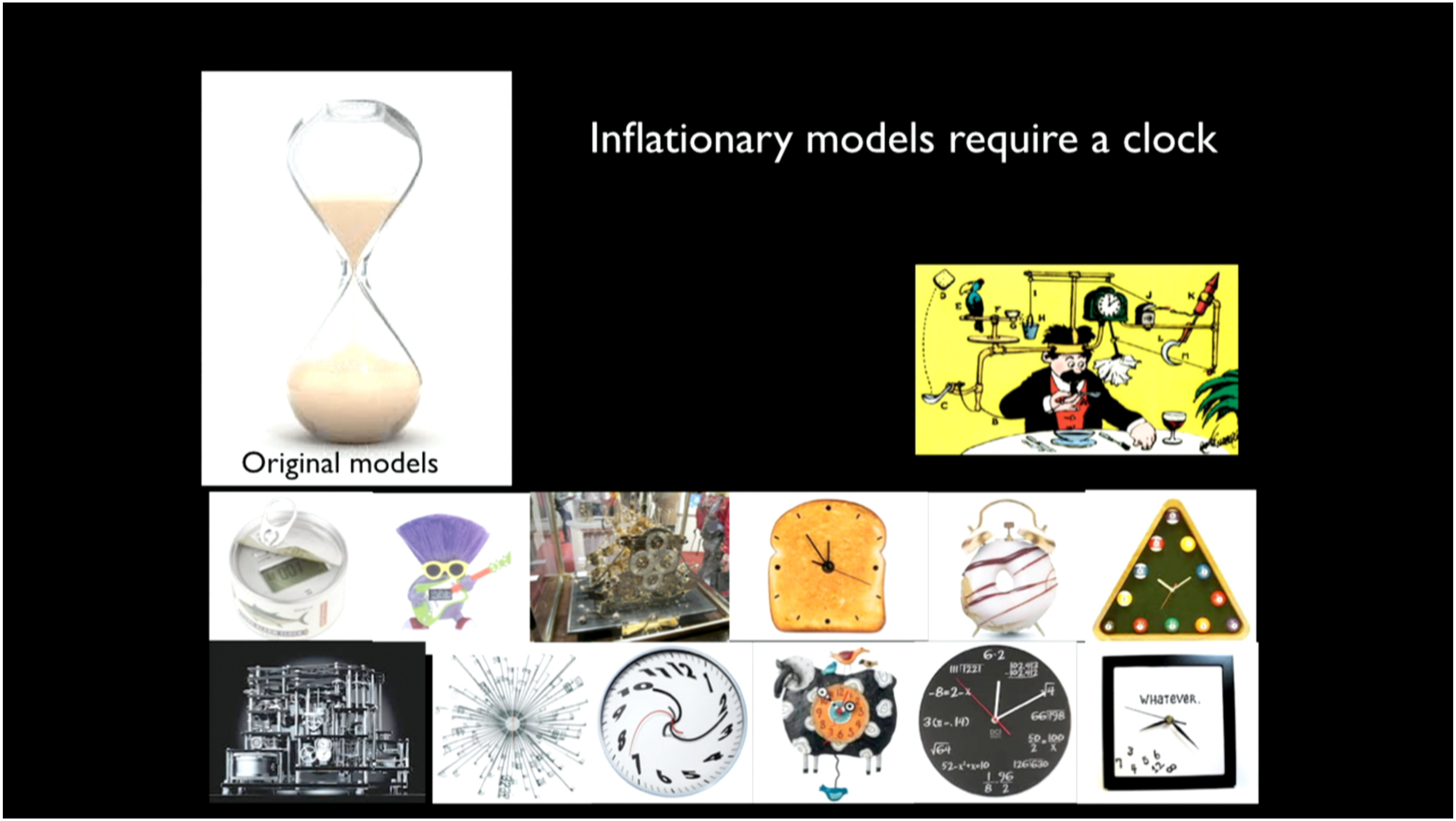
Almost exponential expansion
Only small departures from
Cosmological Constant because
Inflation has to end

$$H = \frac{\dot{a}}{a} \qquad H^2 = \frac{V}{M_{pl}^2}$$

$$p = w\rho = (-1+\epsilon)\rho \qquad \epsilon = -\frac{\dot{H}}{H^2}$$

During this period the Universe must have expanded by roughly 60 enfolds

$$N = \ln(a_{\mathrm{final}}/a_\star) \approx 60$$


Inflationary models require a clock
Original models
WHATEVER.

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21

Big success of inflation

Quantum mechanics implies that the clock must fluctuate.

The Universe cannot be perfectly homogeneous.

Properties of the fluctuations are consistent with our best observations.

Potentially there is an additional fossil, a stochastic background of gravitational waves.

Calculations are under control.

The origin of fluctuations

The clock fluctuations are "frozen" at horizon crossing (frequency of order H). *We are probing the theory at an energy H which is roughly constant in time*. What we observe is the fluctuations in the expansion of one region relative to the other due to the clock fluctuations.

Amplitude of scalar and tensor fluctuations as a function of scale are determined by the expansion history during inflation.

wavenumber of fluctuations

Frequency is of order Hubble

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

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

$$\epsilon = -\frac{\dot{H}}{H^2}$$

Tensor to scalar ratio

$$r \equiv \frac{\Delta_{\rm t}^2}{\Delta_{\rm s}^2} = 16\,\varepsilon_\star\,.$$

Scale dependence of fluctuations

$$\Delta_s^2(k) = \Delta_s^2(k_\star)(\frac{k}{k_\star})^{n_s-1}$$

$$n_s - 1 = \frac{1}{H}(2\dot{H}/H - \dot{\epsilon}/\epsilon)$$

Slope: $1 - n_s = 0.0355 \pm 0.0049$ → ???? $(n_s - 1) \propto \frac{1}{N}$

$$\Delta \propto \frac{H^2}{M_{pl}^2 \epsilon} \qquad \epsilon = -\frac{\dot{H}}{H^2} = -\frac{d \ln H}{dN}$$

$$(n_s - 1) = \frac{d \ln \Delta}{d ln k} = -2\epsilon - \frac{d \ln \epsilon}{dN}$$

$$\Delta_h \propto \frac{H^2}{M_{pl}^2} \qquad r = 16\epsilon$$

What we have learned so far

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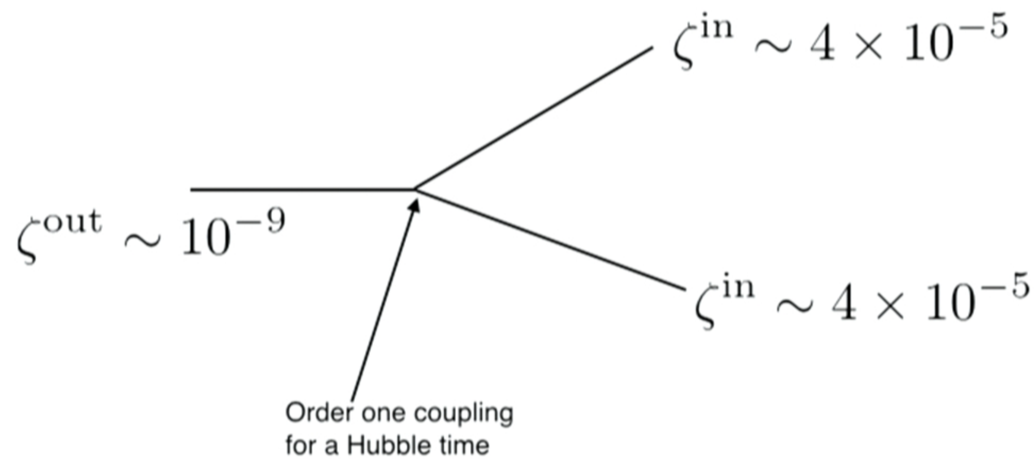
31

$$\ln A_s = -19.932 \pm 0.034$$

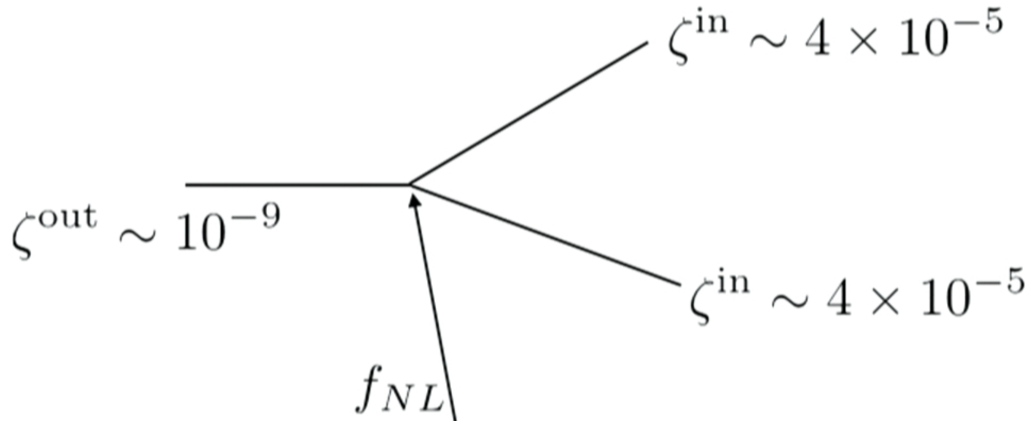
Higher order moments



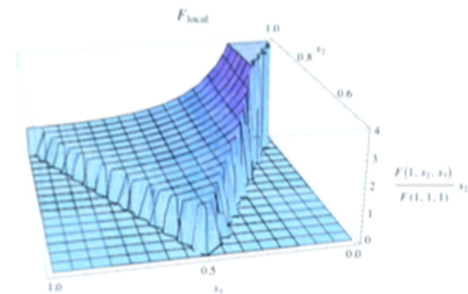
Interactions produce a 4×10^{-5} corrections to what was already there.
Detection requires 10^9 modes

Higher order moments

$$\ln A_s = -19.932 \pm 0.034$$



	Independent KSW	ISW-lensing subtracted KSW
SMICA		
Local	9.8 ± 5.8	**2.7 ± 5.8**
Equilateral	−37 ± 75	**−42 ± 75**
Orthogonal	−46 ± 39	**−25 ± 39**

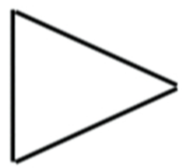


33

Three point-function in single field slow roll inflation

$$ds^2 = -dt^2 + a^2(t)e^{2\zeta(x,t)}dx^2$$

$\langle \zeta_{\vec{k}_1}\zeta_{\vec{k}_2}\zeta_{\vec{k}_3}\rangle$



$$F_{\rm stand}(\vec{k}_1,\vec{k}_2,\vec{k}_3) = \frac{1}{8}(2\pi)^4 P_{\mathcal{R}}^2 \cdot \frac{1}{\prod k_i^3}\left[(3\epsilon-2\eta)\sum_i k_i^3 + \epsilon\sum_{i\neq j} k_i k_j^2 + 8\epsilon\frac{\sum_{i>j}k_i^2 k_j^2}{k_t}\right]$$

suppressed in the squeezed limit

Local piece

$k_3 \ll k_2, k_1$

Is the small scale power modulated in a way that correlates with the long wavelength modes ?

The small scale power is independent of the amplitude of the long mode.

This is a consequence of the "sequential hiding" of modes and attractor solution.

Local non-Gaussianity is analog to a fluctuation in composition but in something that is conserved.

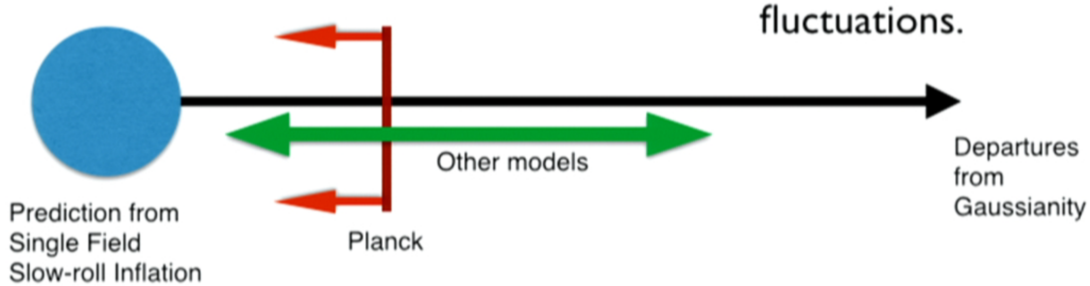
Planck 2015

	f_{NL}(KSW)	
Shape and method	Independent	ISW-lensing subtracted
SMICA (*T*)		
Local	10.2 ± 5.7	**2.5** ± **5.7**
Equilateral	−13 ± 70	**−16** ± **70**
Orthogonal	−56 ± 33	**−34** ± **33**
SMICA (*T*+*E*)		
Local	6.5 ± 5.0	**0.8** ± **5.0**
Equilateral	3 ± 43	**−4** ± **43**
Orthogonal	−36 ± 21	**−26** ± **21**

Target

$f_{NL}^{local} \leq 1$ Single field Inflation

$f_{NL}^{eq} \leq 1$ Slow-Roll single field Inflation



In the Standard story:

Local non-Gaussianity is zero because of attractor nature of inflation. Can only be true for clock.

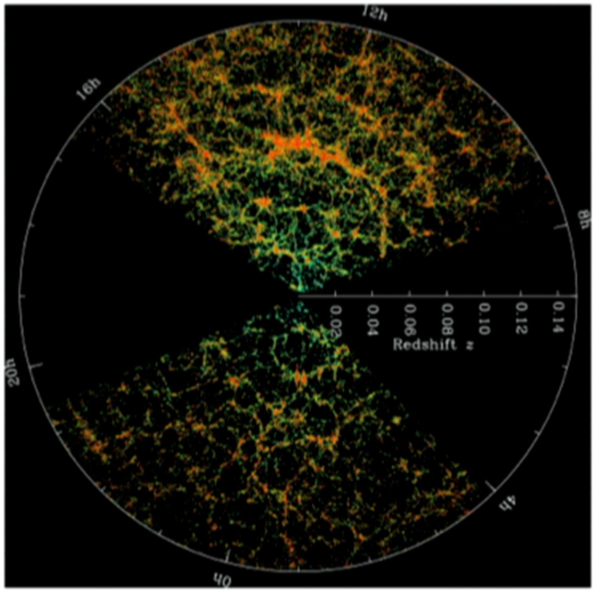
If the theory for the perturbations can also describe the background then equilateral non-G are small.

Equilateral part can be really tiny because we are looking at time delay fluctuations, actual change in the space-time is down by epsilon.

“Collapsed” non-Gaussianities are very small because we are seeing vacuum fluctuations.

Can we improve over CMB?

We either constrain a different period during inflation to test if indeed things were approximately time translation invariant or we have to surpass the statical precision of the CMB.

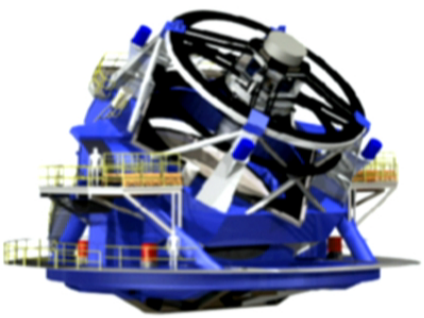


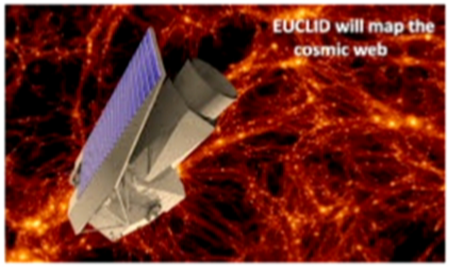
Constraints are statistical in nature, they scale as

$$1/N_{modes}^{-1/2}$$

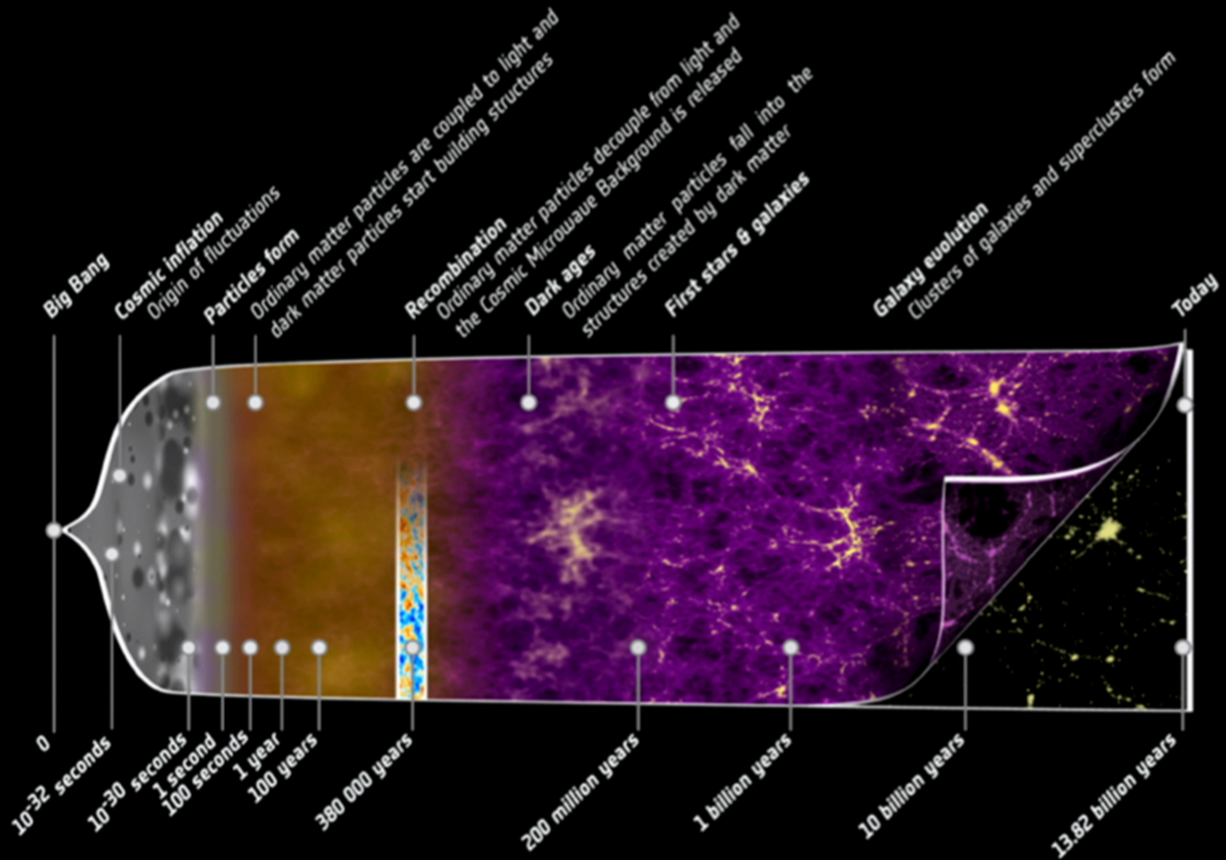
	LSST	DESI	Euclid	SPHEREx	CHIME
Survey type	photo	spectro	photo+spectro	low-res spectro	21-cm
Ground or space	ground	ground	space	space	ground
Previous surveys	CFHTLS, DES, HSC	BOSS, eBOSS, PFS	no direct precursor	PRIMUS, COMBO-17, COSMOS	GBT HIM
Survey start	2020	2020	2018	2020	2016
Redshift-range	$z < 3$ (1% sources above 3)	$z < 1.4$, $2 < z < 3.5$ (Lya)	$z < 3$	$z < 1.5$	$0.75 < z < 2.5$
Survey area [$\deg^2$]	20k	14k	15k	40k	20k
Approximate number of objects	2×10^9 (WL sources)	22×10^6 gal., $\sim 2.4 \times 10^5$ QSOs	40×10^6 redshifts, 1.5×10^9 photo-zs	15×10^9 pixels	10^7 pixels
Galaxy clustering	✓✓$^\diamond$	✓	✓	✓	✓
Weak lensing	✓		✓		✓
RSD		✓	✓	✓✓	✓✓
Multi-tracer	✓✓	✓✓	✓✓	✓	

Table 2. A selection of currently funded or planned surveys. Other important surveys not included in the table are PFS, JPAS, PAU, EMU. Relevant survey links [LSST],[DESI],[Euclid], [UBC],[PFS], [JPAS],[PAU], [EMU]. $^\diamond$Galaxy clustering is possible, but very strong radial degradation.

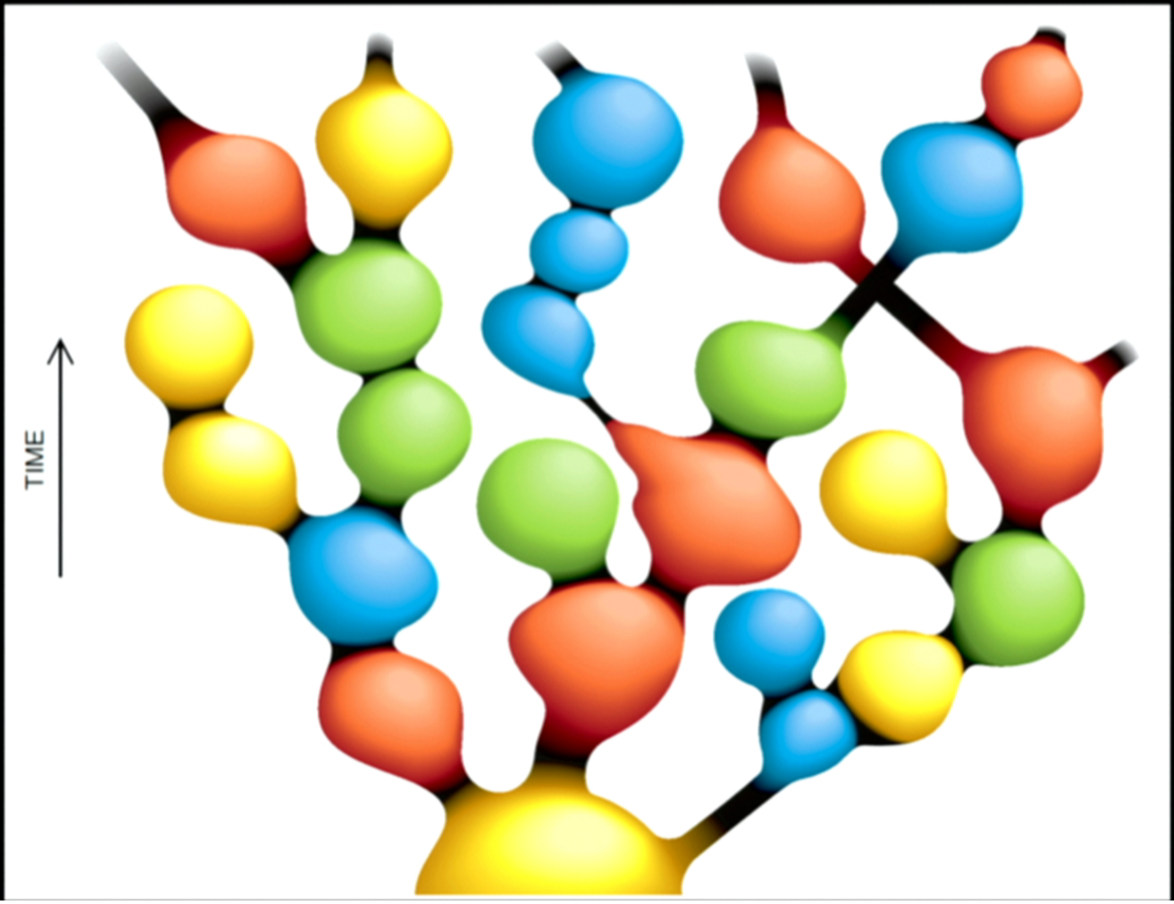


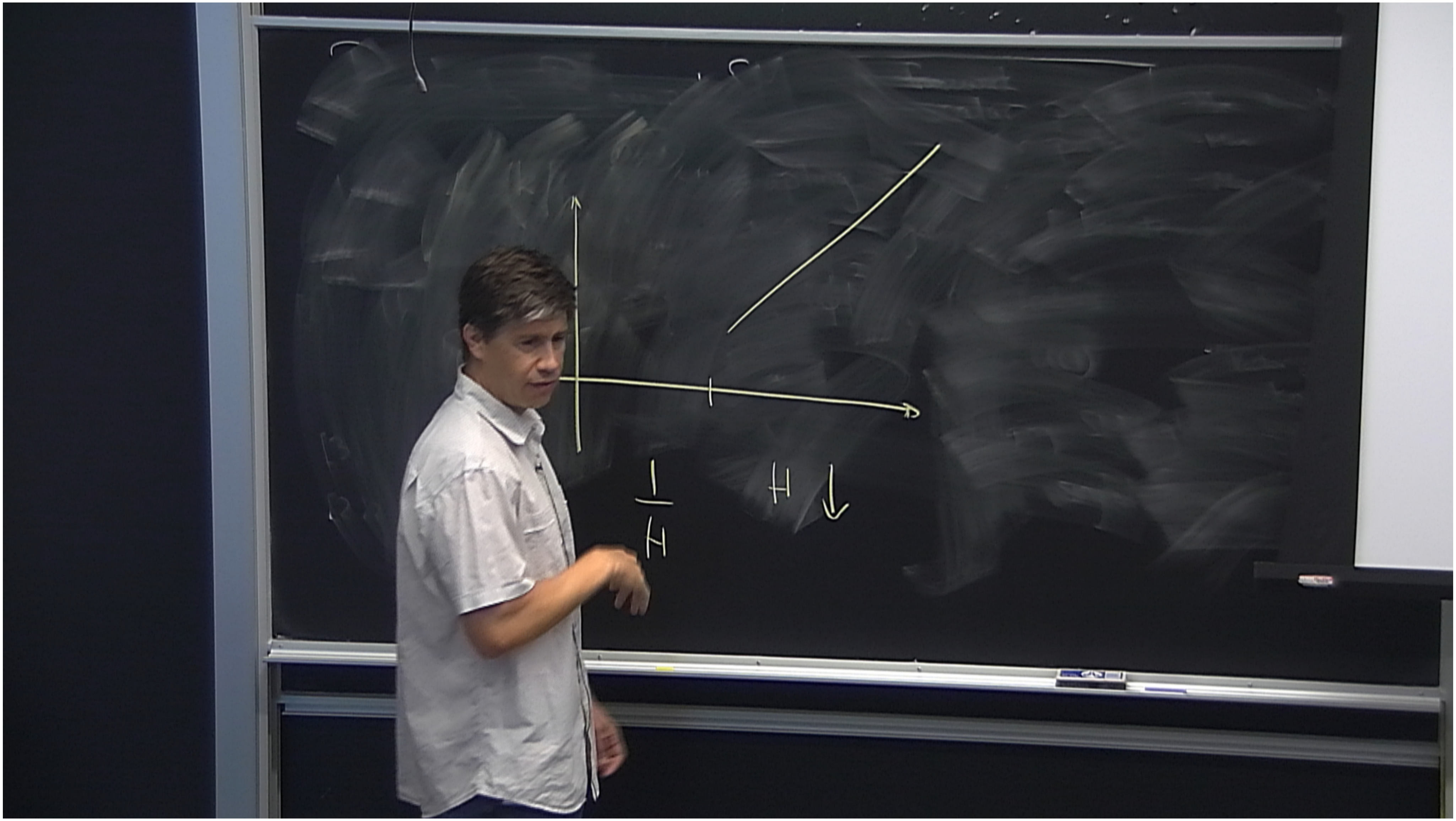


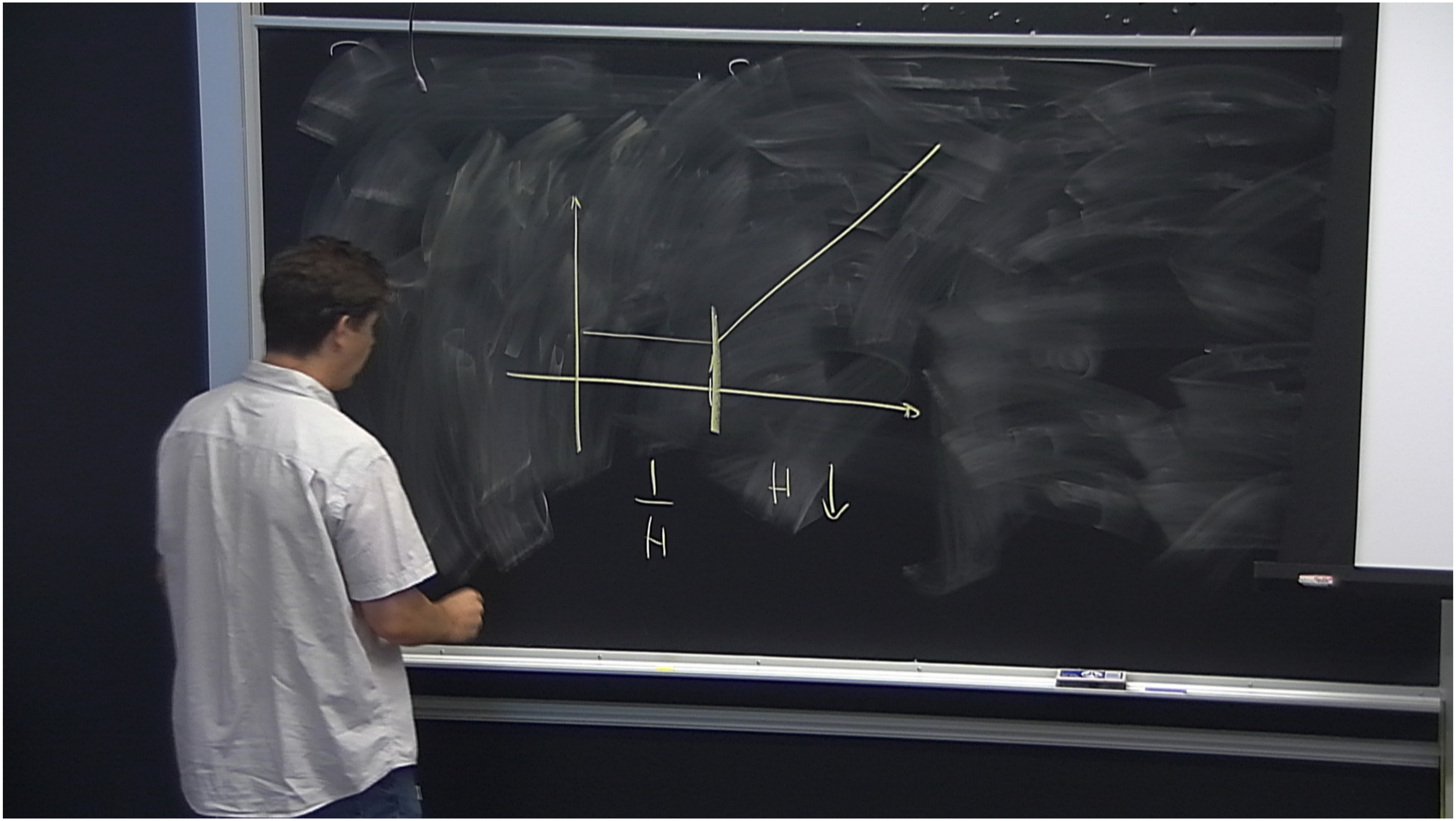
Is inflation the final theory ?

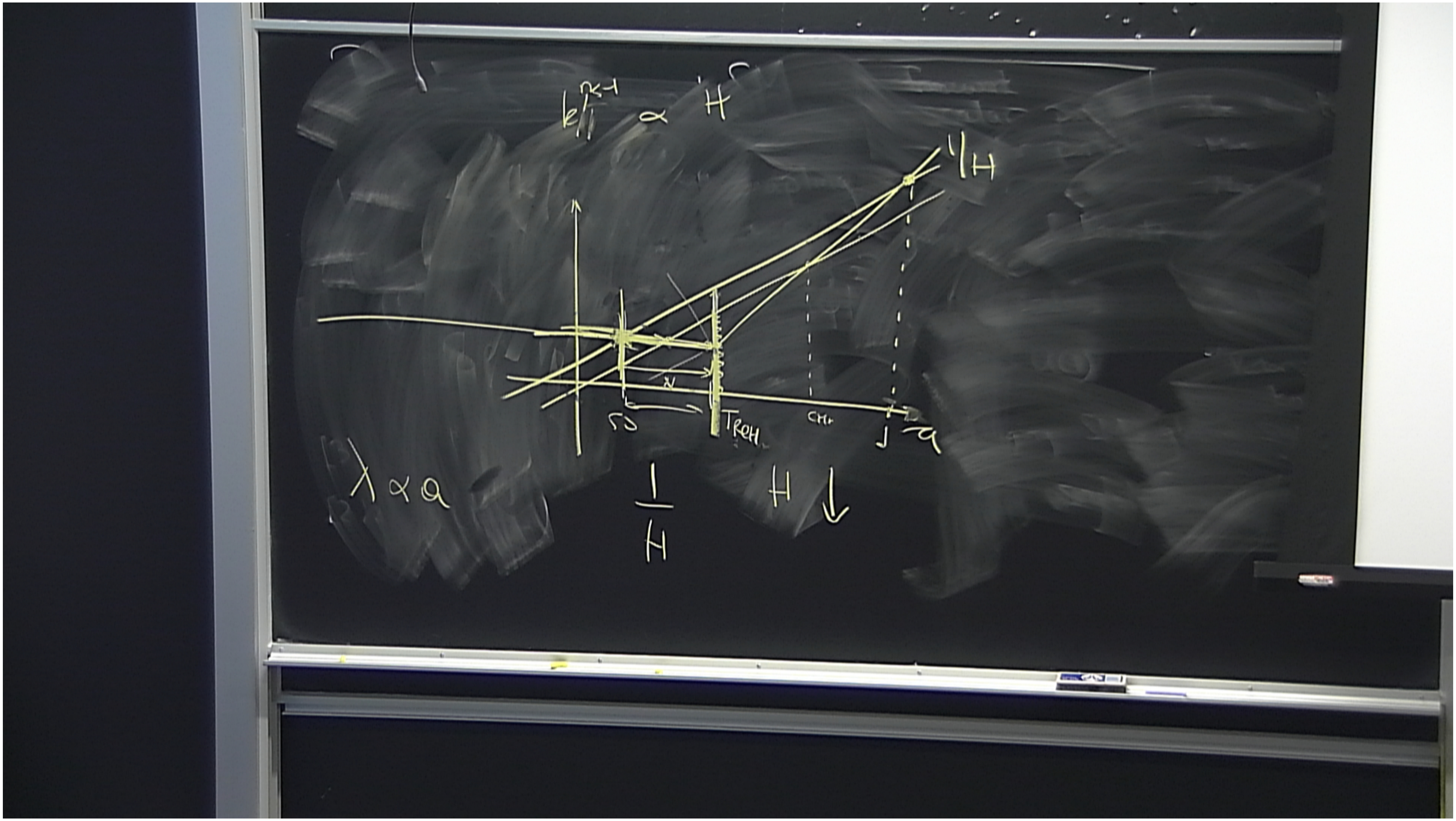


A "multiverse" is an alternative




1
H
H ↓


$\frac{1}{H}$
H ↓



1/H
H
T_{REH}
$\lambda \propto a$
$\frac{1}{H}$
H ↓