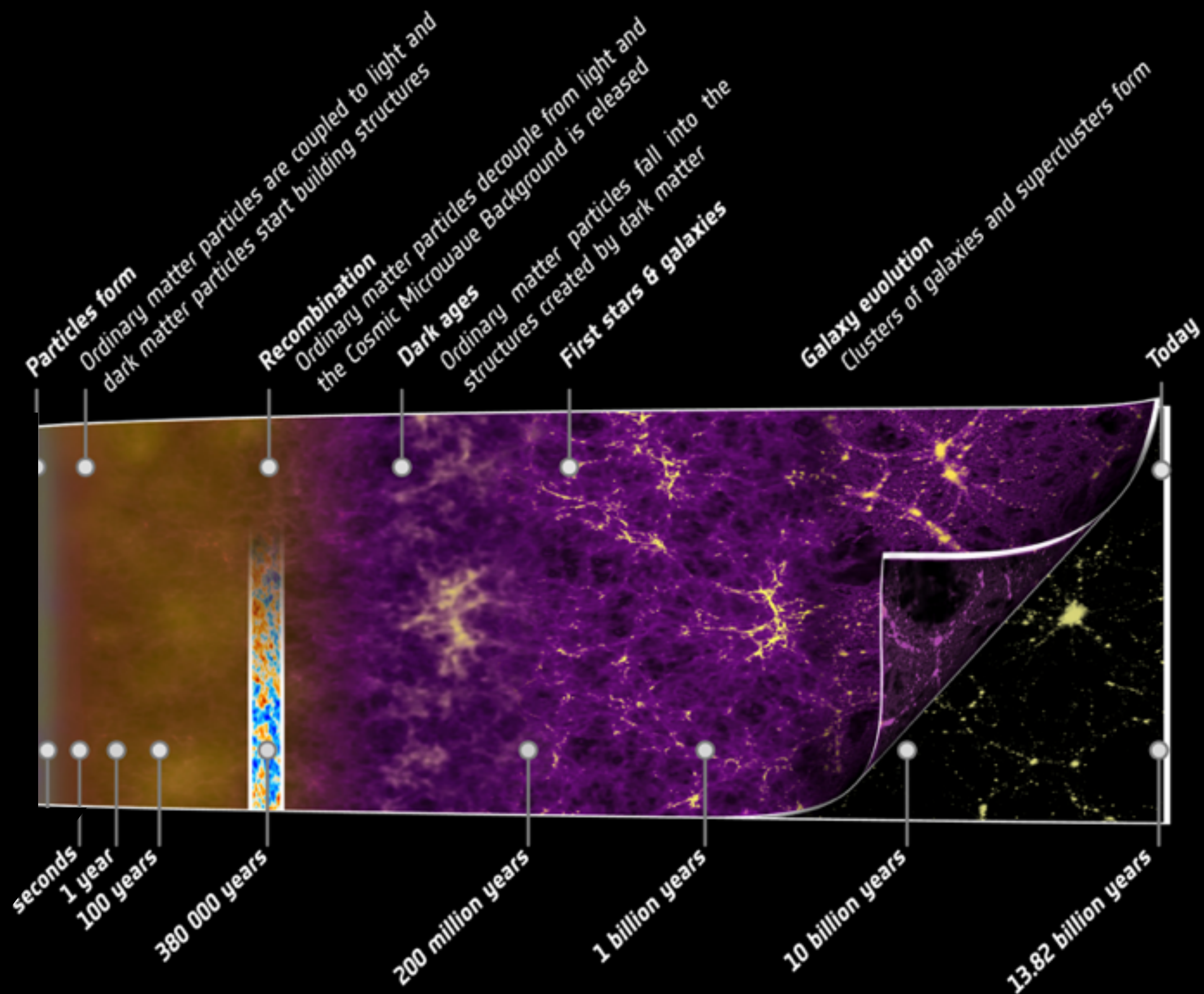
The Early Universe
&
Inflation

April 2018

We live in the aftermath of a Big Bang



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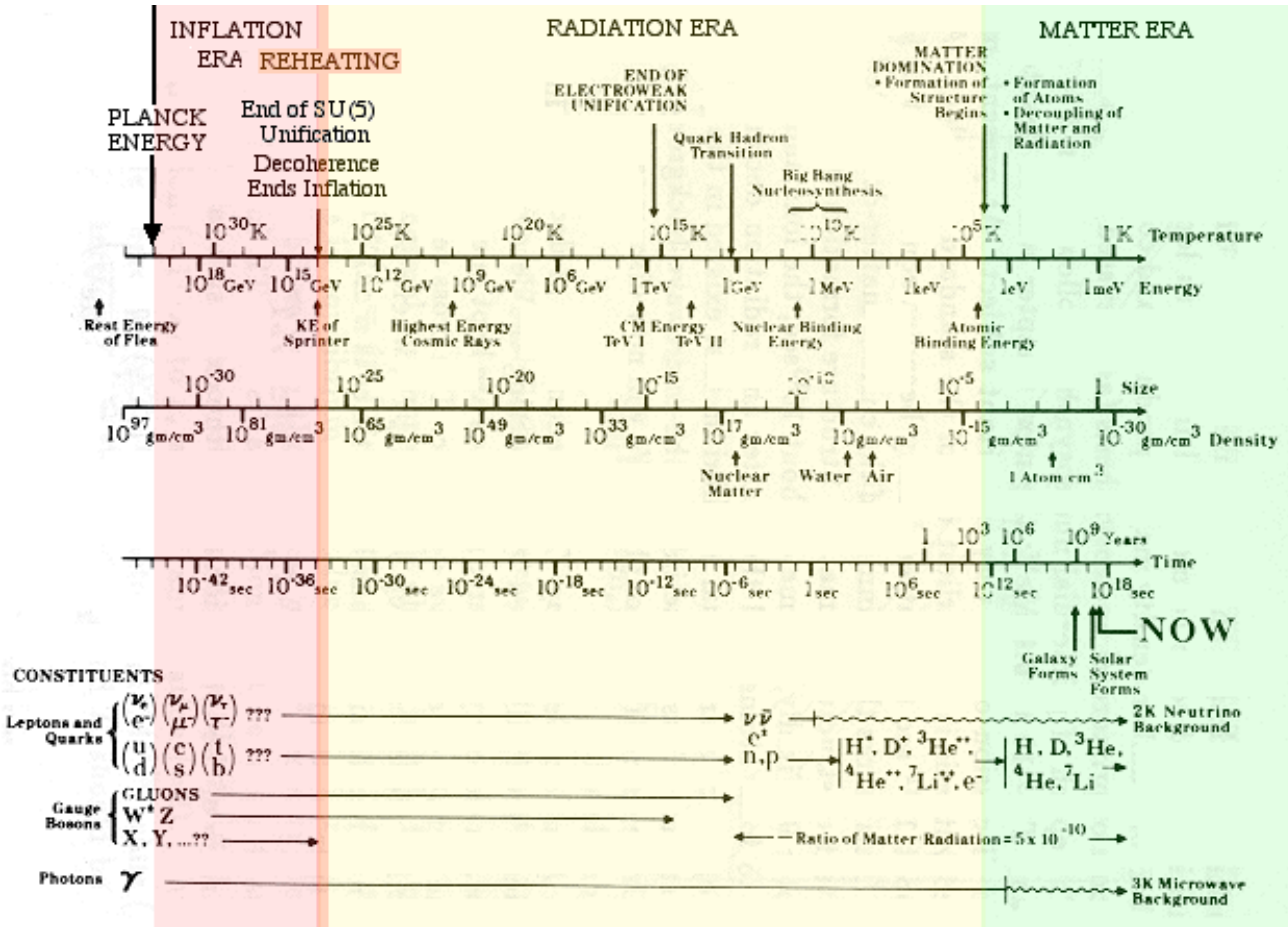
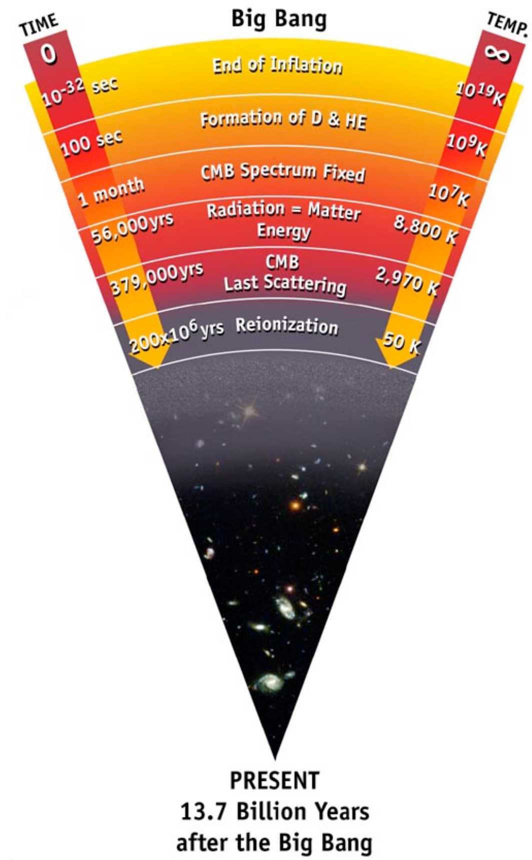


INFLATION ERA
REHEATING
RADIATION ERA
MATTER ERA
PLANCK ENERGY
End of SU(5) Unification
Decoherence Ends Inflation
END OF ELECTROWEAK UNIFICATION
Quark Hadron Transition
Big Bang Nucleosynthesis
MATTER DOMINATION
• Formation of Structure Begins
• Formation of Atoms
• Decoupling of Matter and Radiation
Temperature
Energy
Rest Energy of Flea
KE of Sprinter
Highest Energy Cosmic Rays
CM Energy TeV I TeV II
Nuclear Binding Energy
Atomic Binding Energy
Size
Density
Nuclear Matter
Water
Air
1 Atom cm⁻³
Time
Years
NOW
Galaxy Forms
Solar System Forms
CONSTITUENTS
Leptons and Quarks
Gauge Bosons
GLUONS
Photons
2K Neutrino Background
Ratio of Matter Radiation = 5 x 10⁻¹⁰
3K Microwave Background

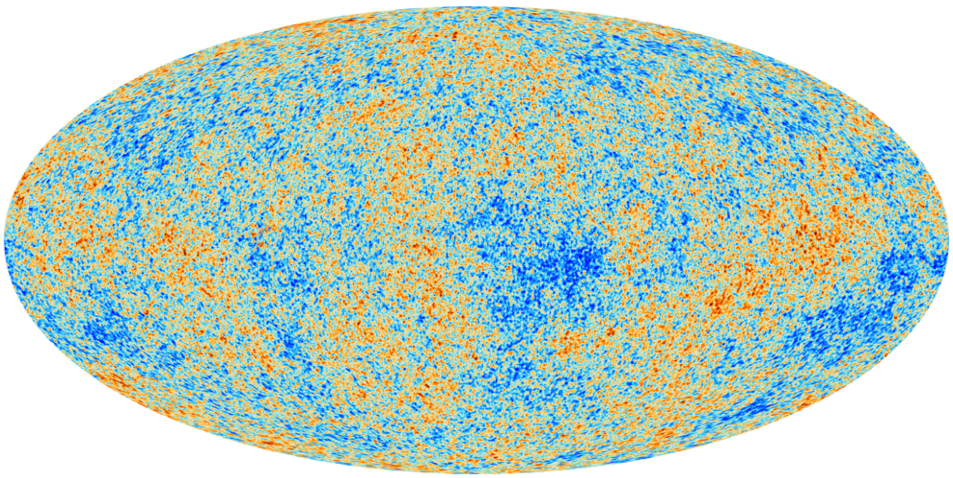


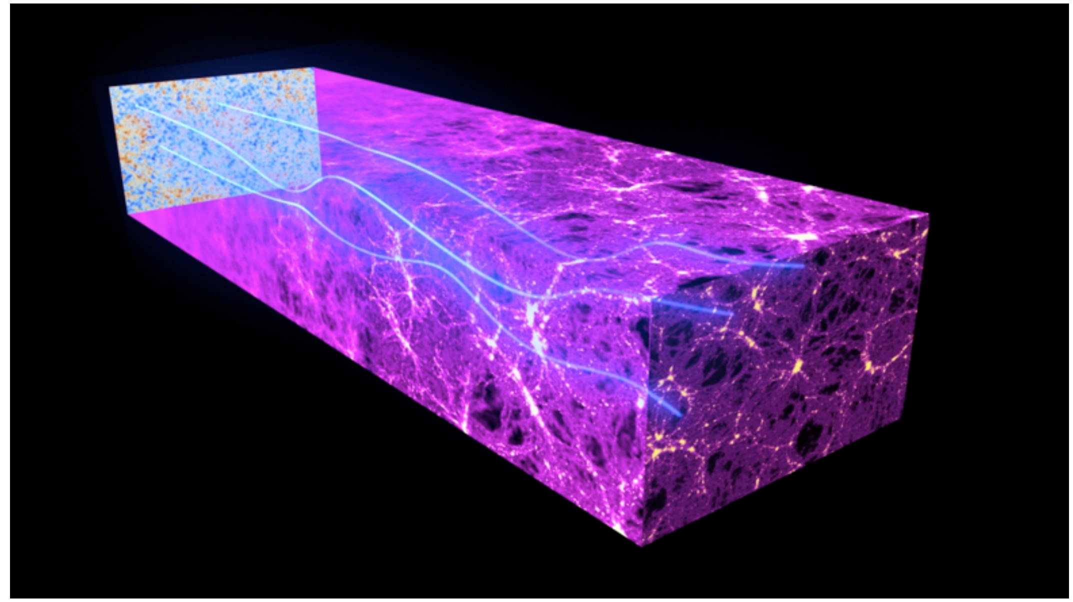
TIME
TEMP.
Big Bang
End of Inflation
Formation of D & HE
CMB Spectrum Fixed
Radiation = Matter Energy
CMB Last Scattering
Reionization
100 sec
1 month
56,000yrs
379,000yrs
8,800 K
2,970 K
50 K
PRESENT
13.7 Billion Years
after the Big Bang

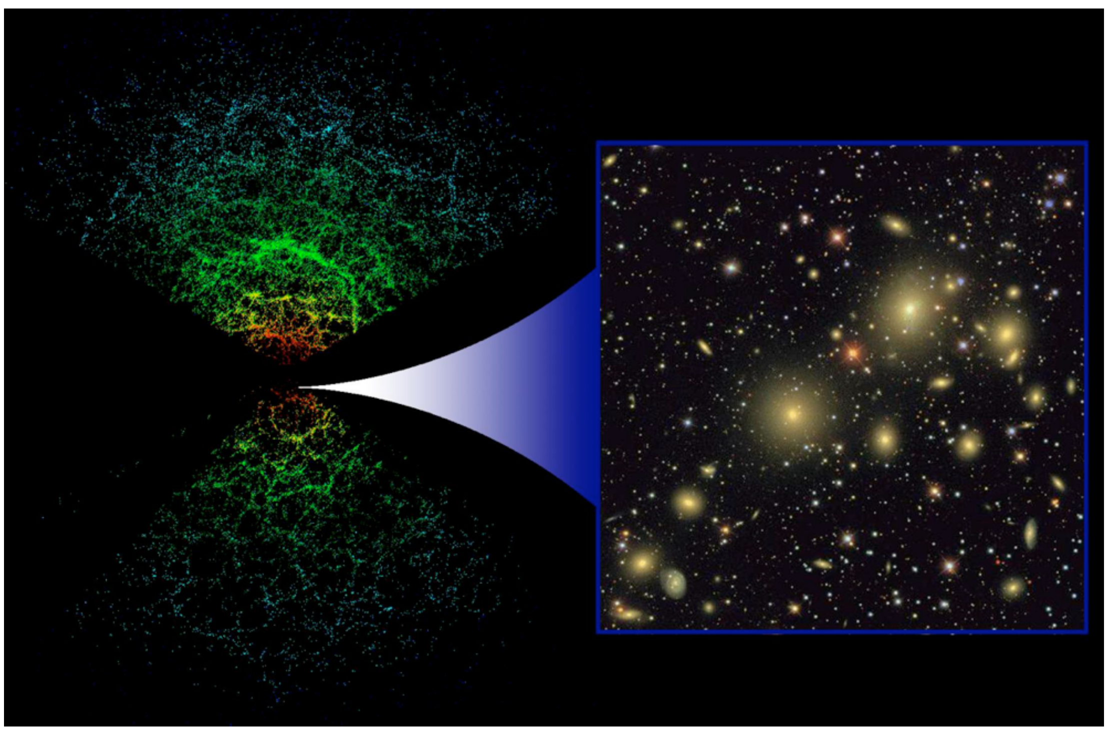
Relics from the early stages of the HBB

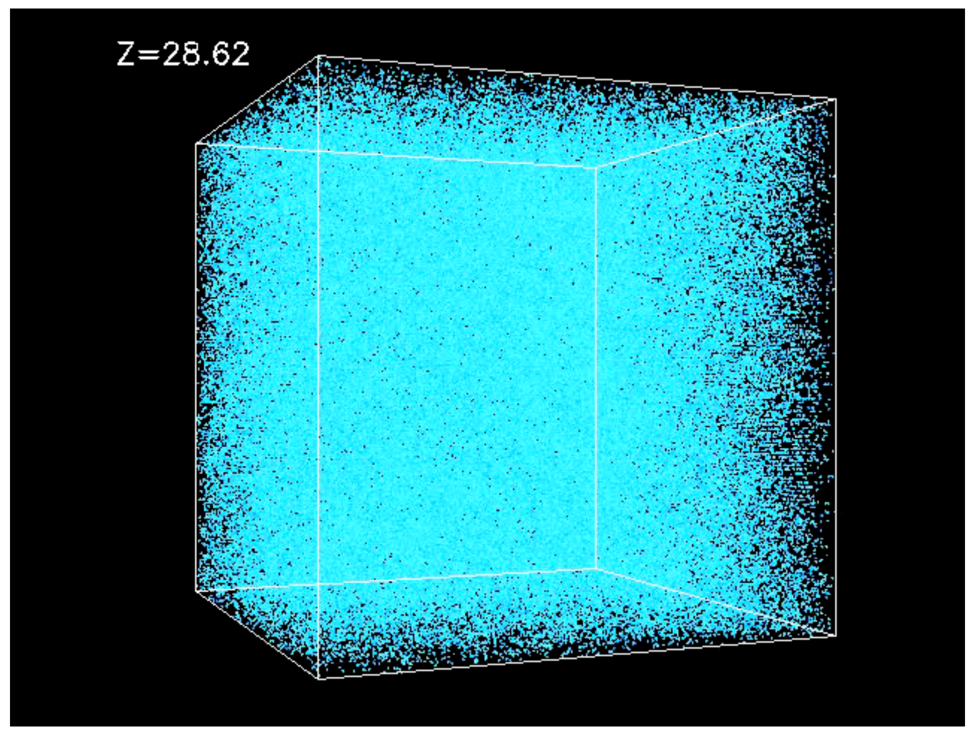
1. BBN Nuclei
2. Cosmic Neutrino Background
3. CMB BB spectrum
4. Dark matter
5. Baryons
6. Others

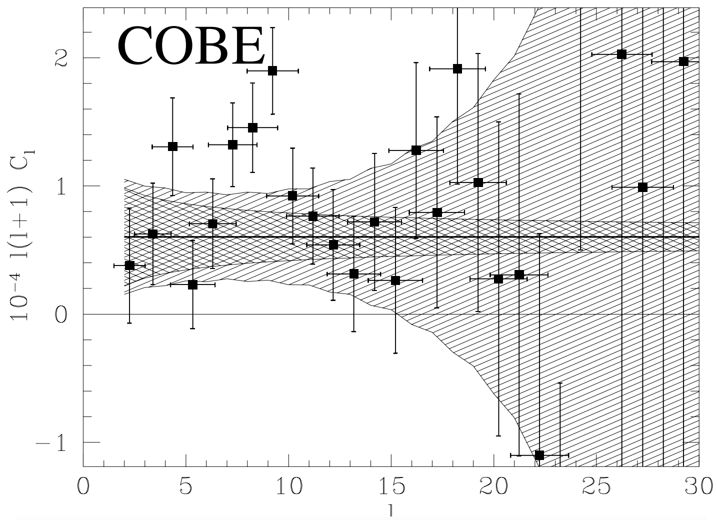
The growth of structure



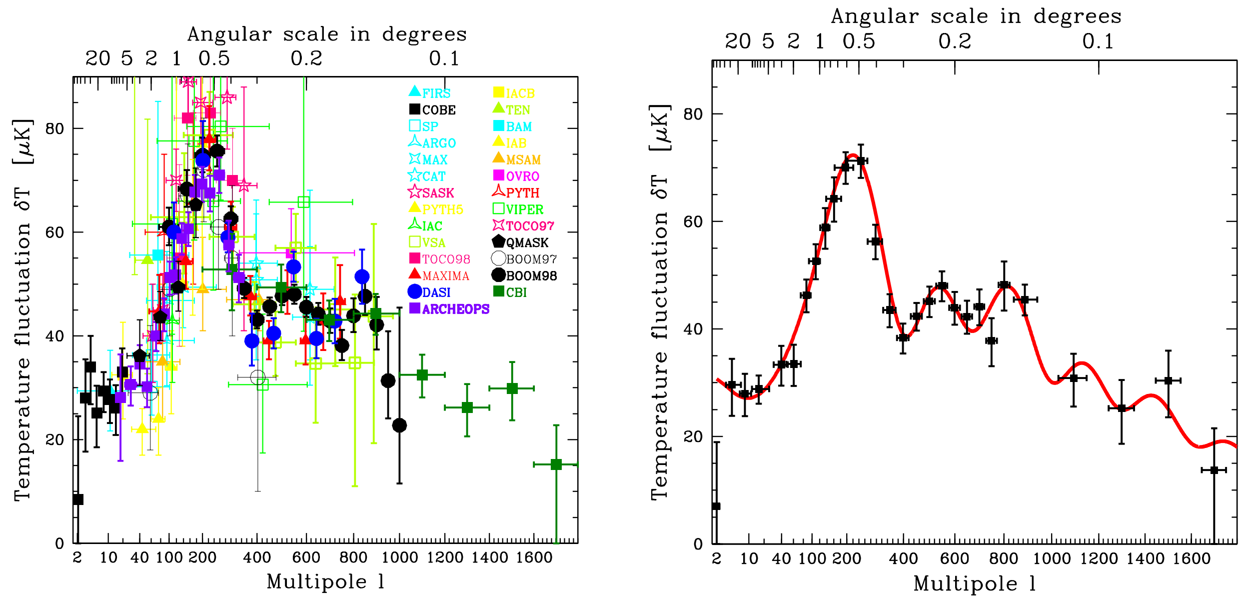


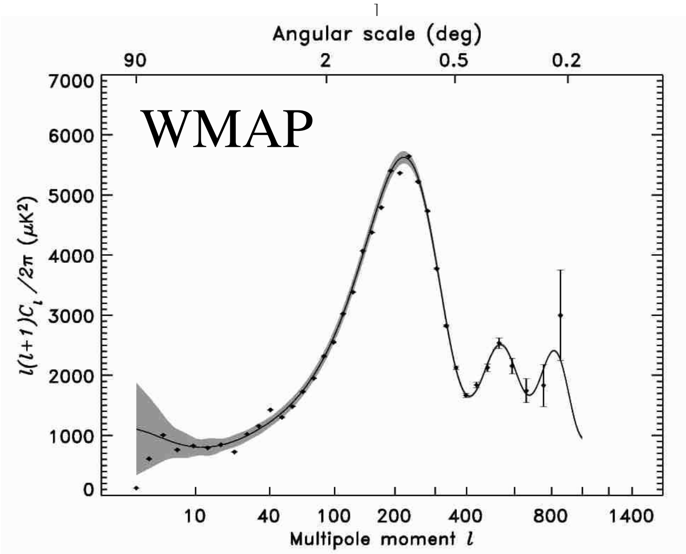


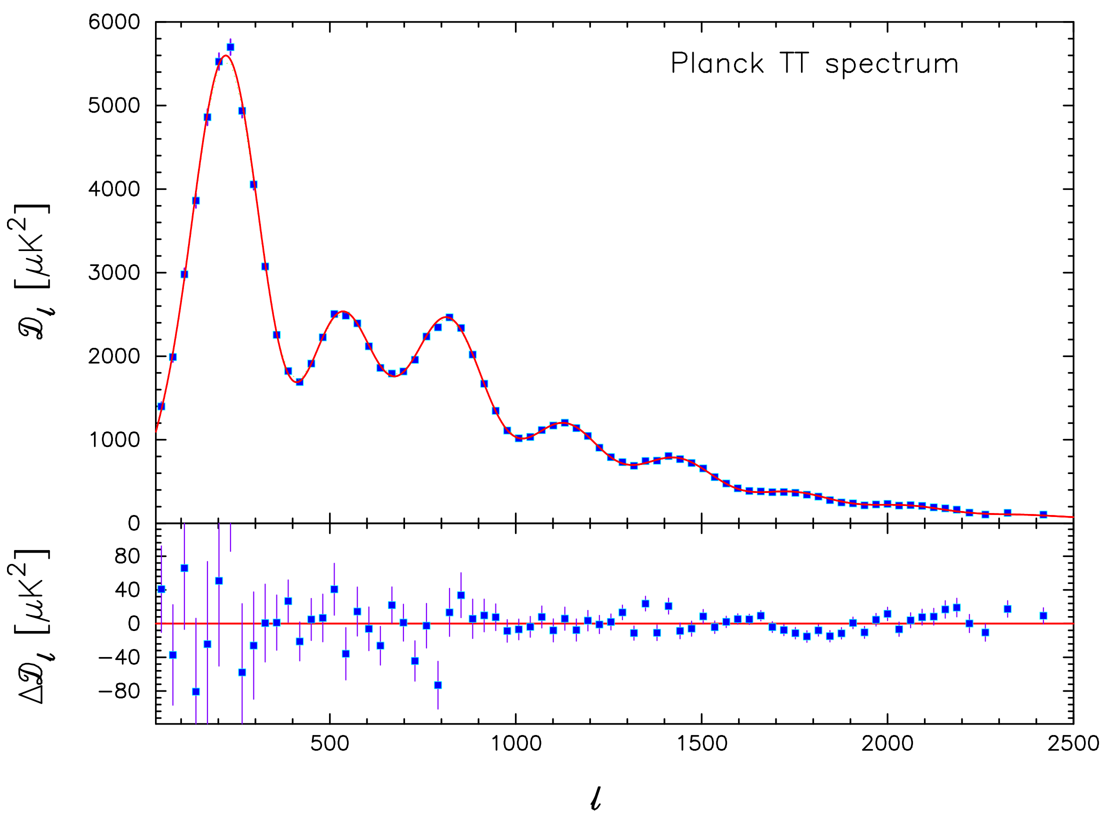


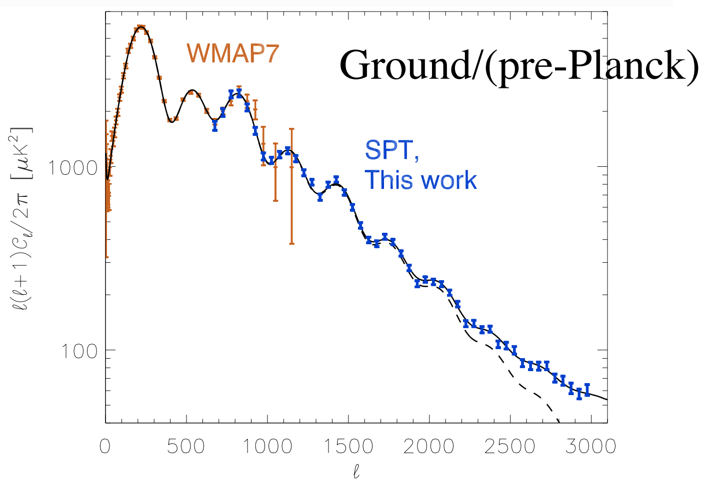


Ground/Balloon (pre-WMAP)

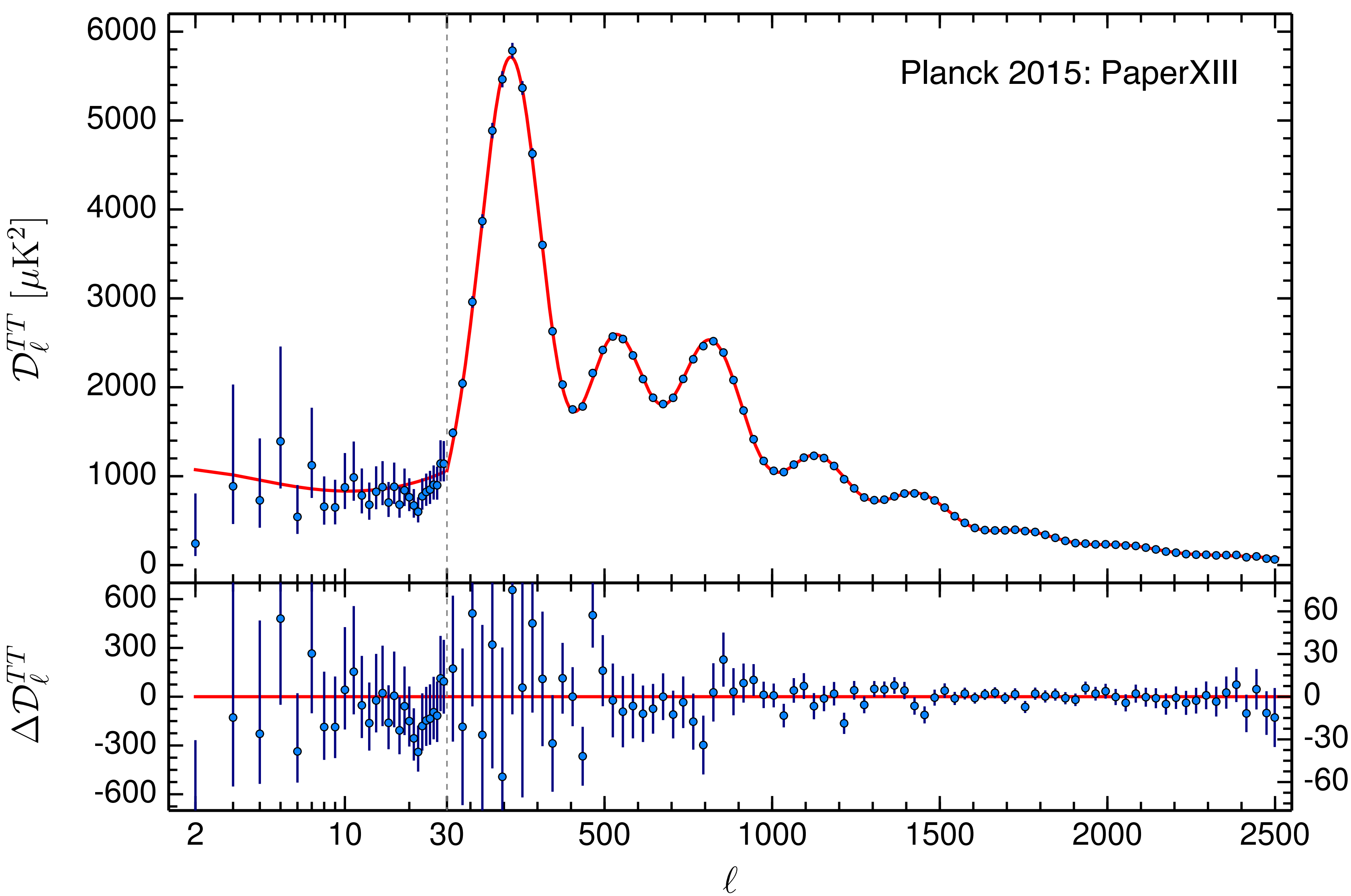


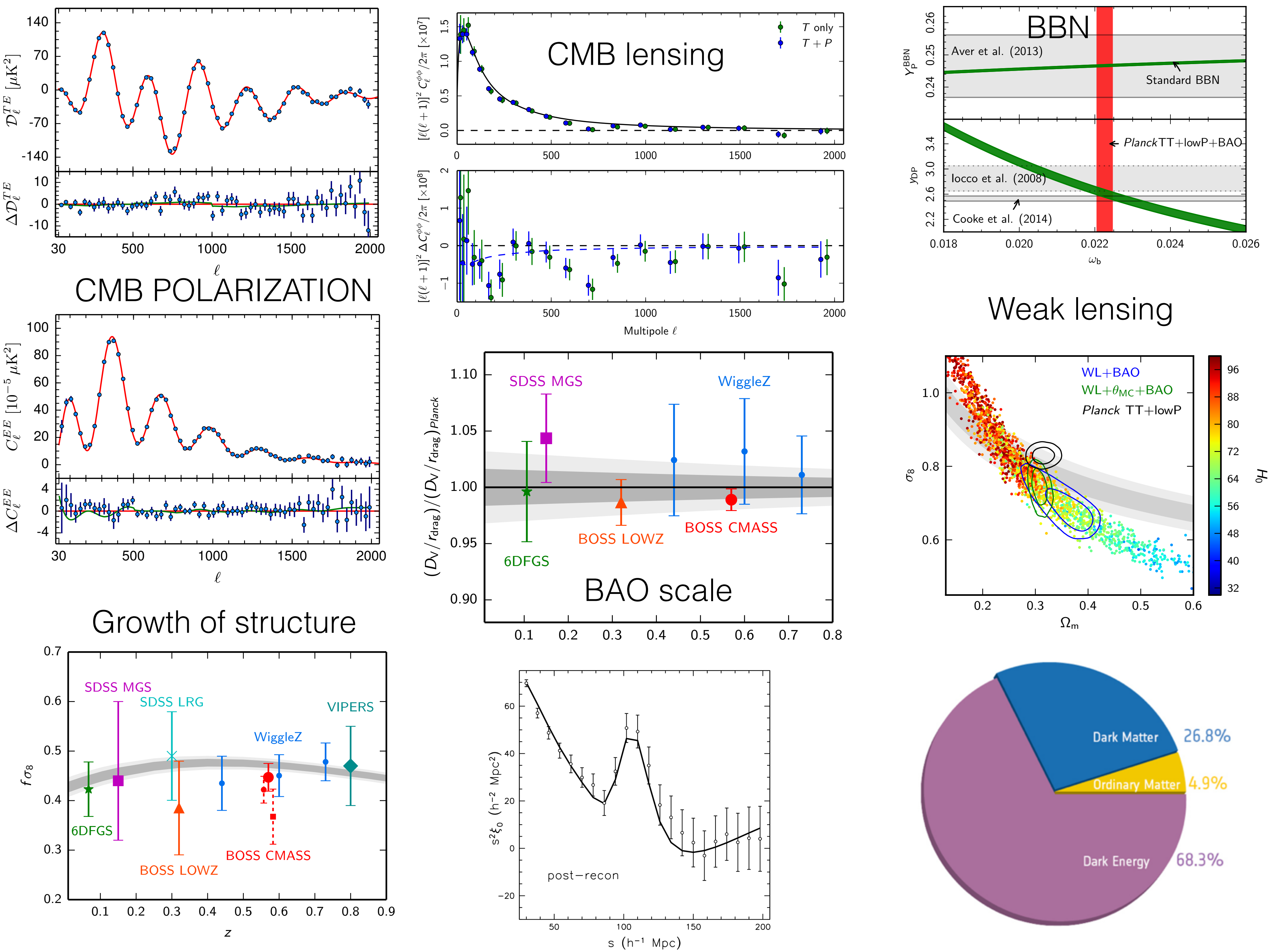






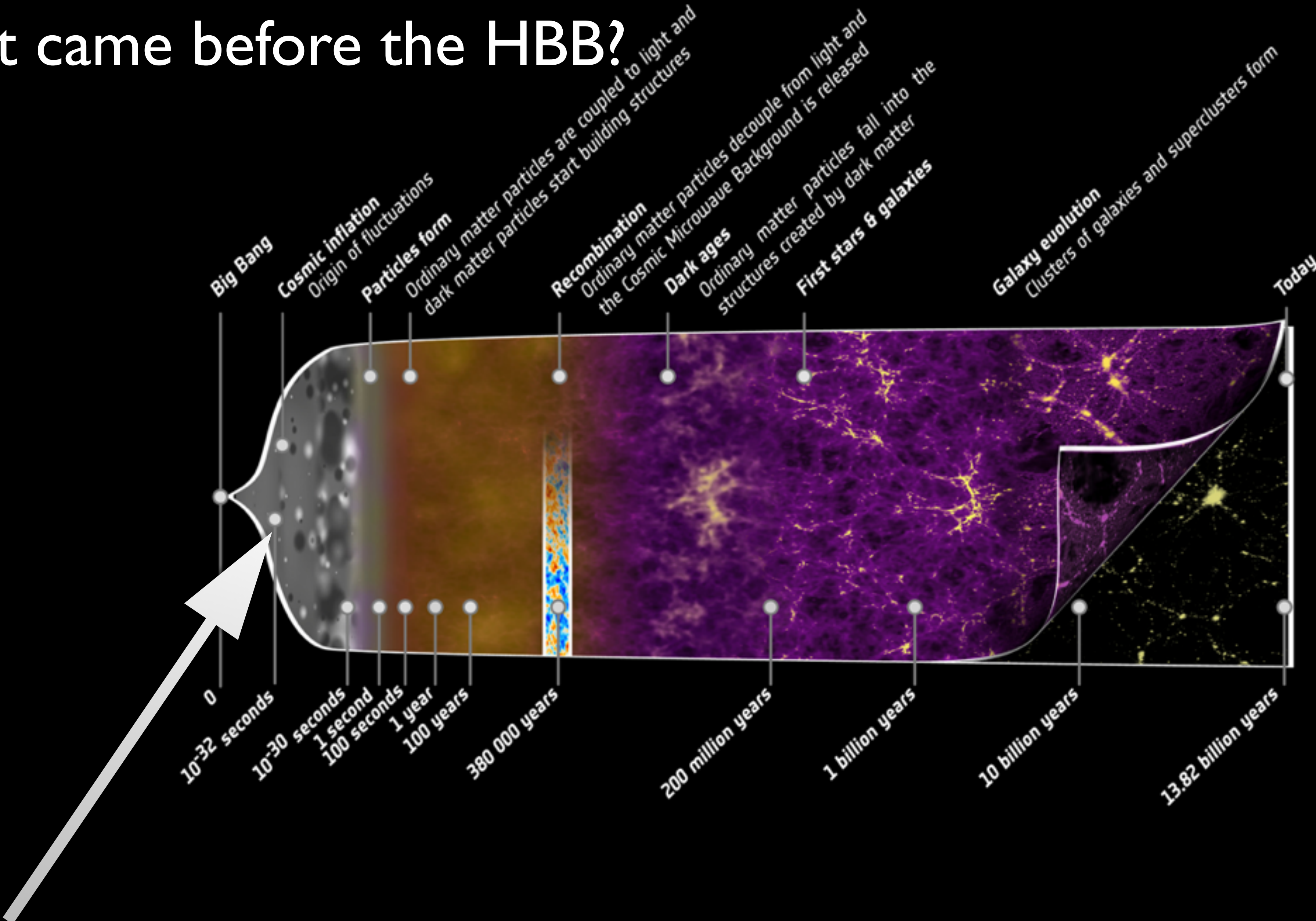
Agreement between theory and data





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
WL+θMC+BAO
Planck TT+lowP
BAO scale
SDSS MGS
WiggleZ
6DFGS
BOSS LOWZ
BOSS CMASS
Growth of structure
SDSS MGS
SDSS LRG
VIPERS
WiggleZ
6DFGS
BOSS CMASS
BOSS LOWZ
post−recon
s (h⁻¹ Mpc)
Dark Matter 26.8%
Ordinary Matter 4.9%
Dark Energy 68.3%

What came before the HBB?



We need fossils to sort this out.

FRW Background

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

$$a d\tau = dt$$

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

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

$$\Omega = \frac{8\pi G}{3H^2}\rho \equiv \frac{\rho}{\rho_{\rm crit}}$$

$$\rho \propto \Omega h^2 \equiv \omega \propto \frac{\rho}{\rho_\gamma}$$

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

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

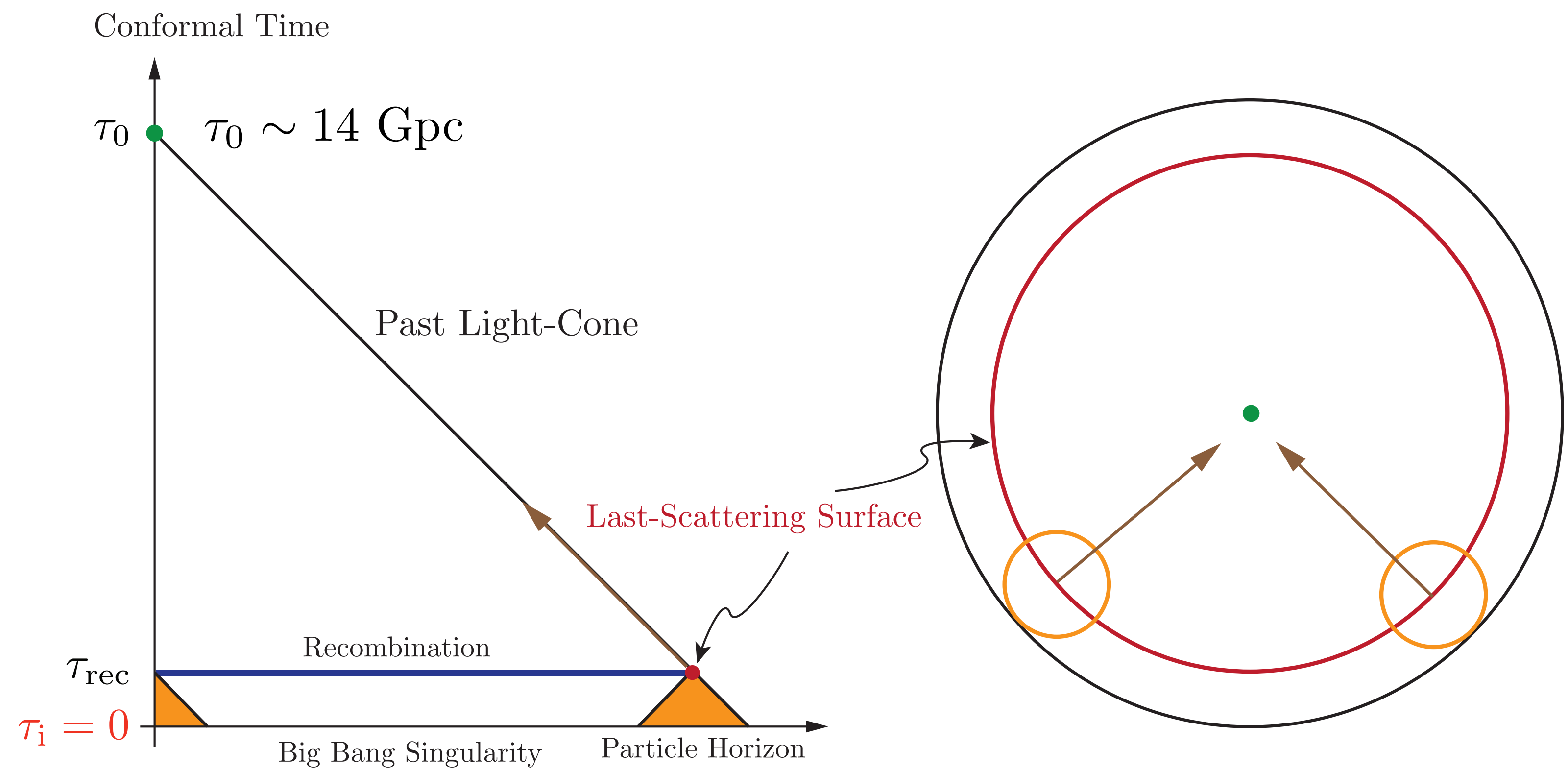


Figure 8: Conformal diagram of Big Bang cosmology. The CMB at last-scattering (recombination) consists of 10^5 causally disconnected regions!

Daniel Baumann 0907.5424

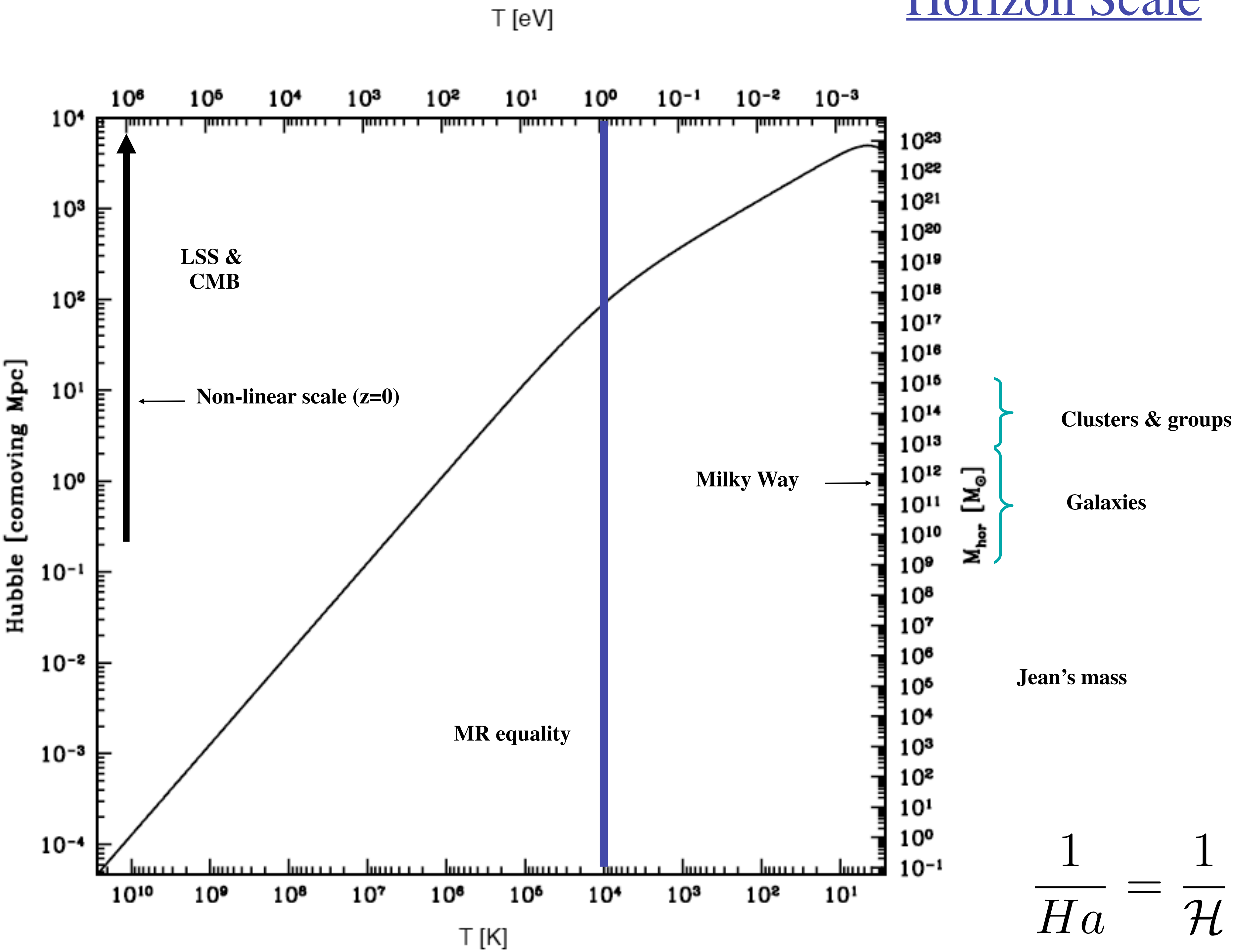
$$\tau_{rec} \sim 300 \text{ Mpc}$$

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

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

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

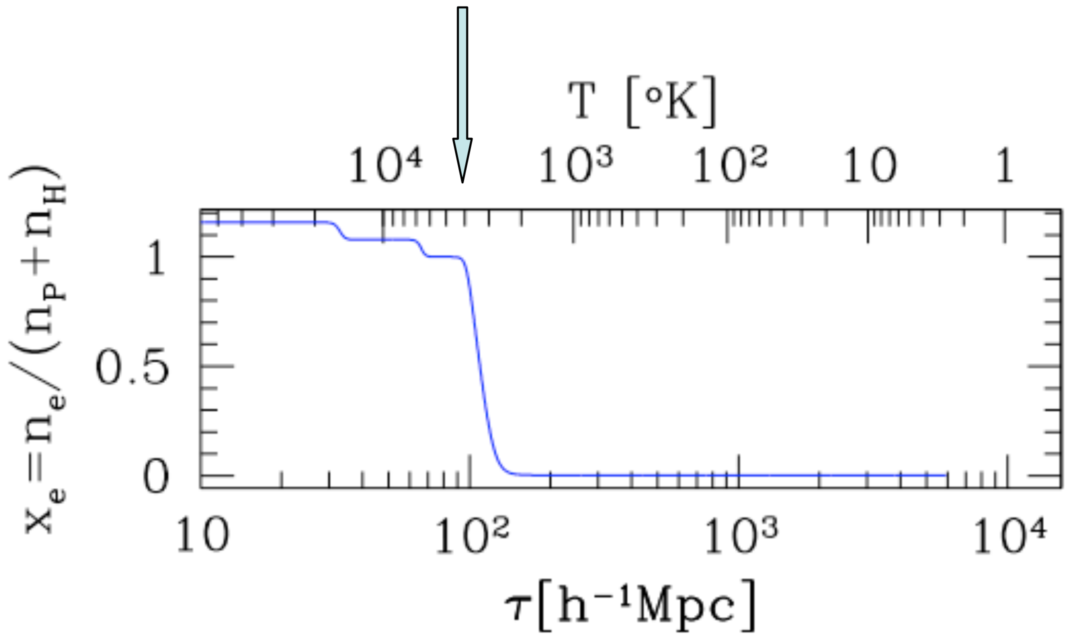
Horizon Scale



$$\frac{1}{Ha} = \frac{1}{\mathcal{H}}$$

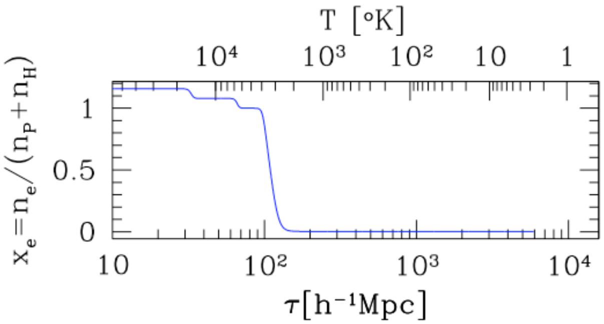
Recombination

$T = 0.3 \text{ eV} \ll m_e c^2$



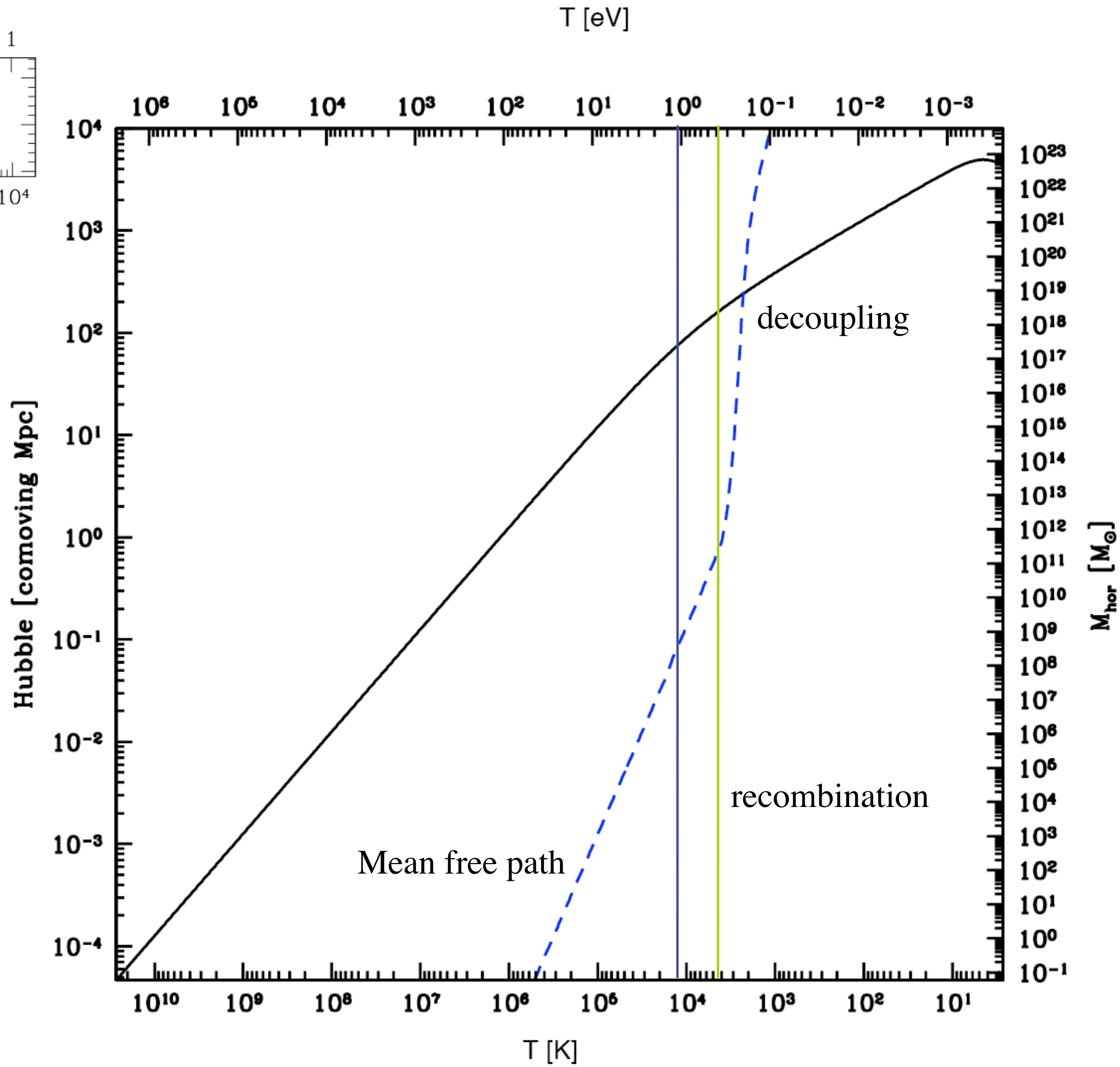
Hydrogen is ionized **Hydrogen is neutral**

Thomson Scattering



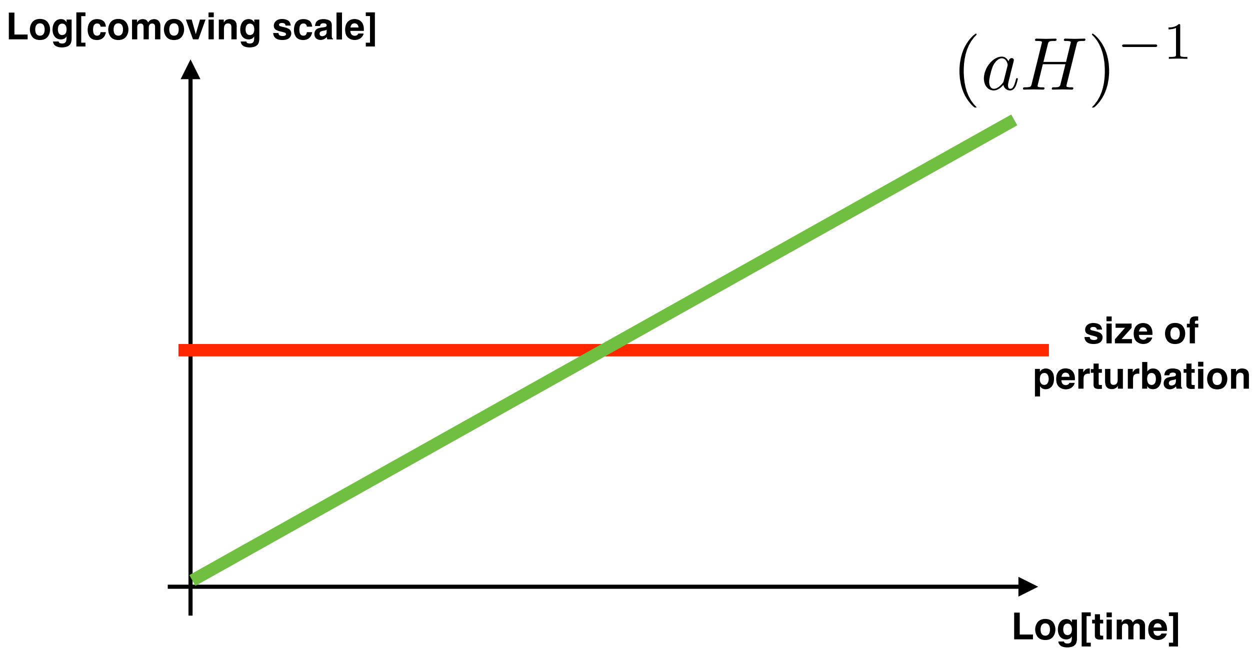
$$\tau_c = \frac{1}{a n_e \sigma_T}$$

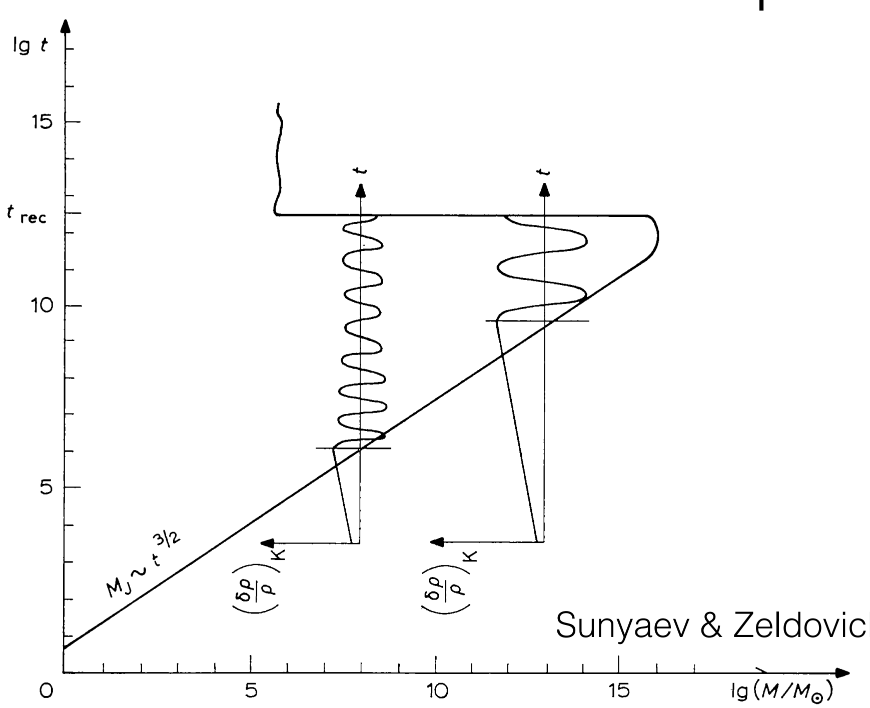
There is a big difference in the dynamics of perturbations depending on the ratio between their wavelength and the Hubble scale.



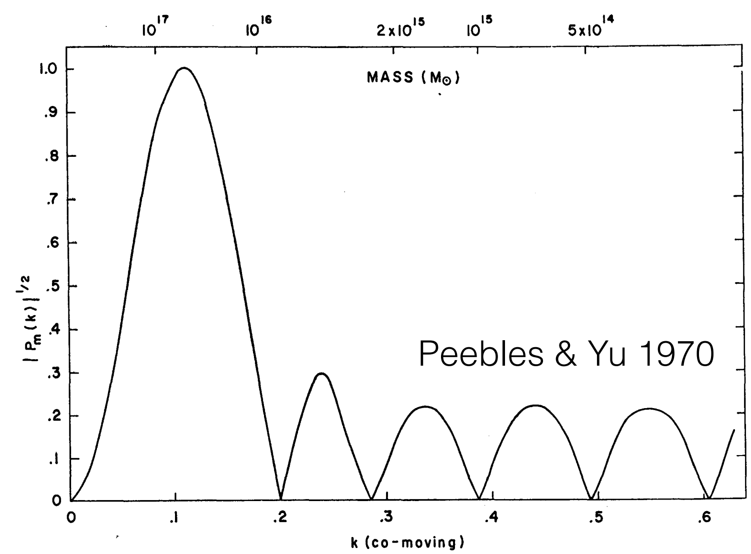
We need to follow dynamics across horizon crossing

Perturbations already present at the beginning of the hot big bang phase need to be tracked while they are larger than the horizon and as they enter the horizon.





Sunyaev & Zeldovich 1970



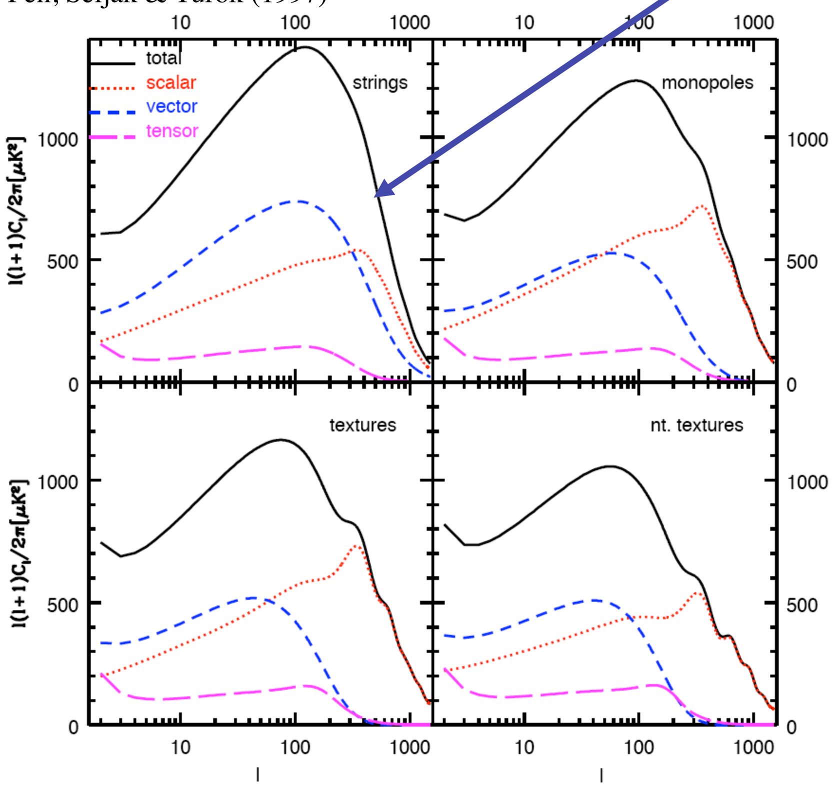
Peebles & Yu 1970

Fluctuations are primordial

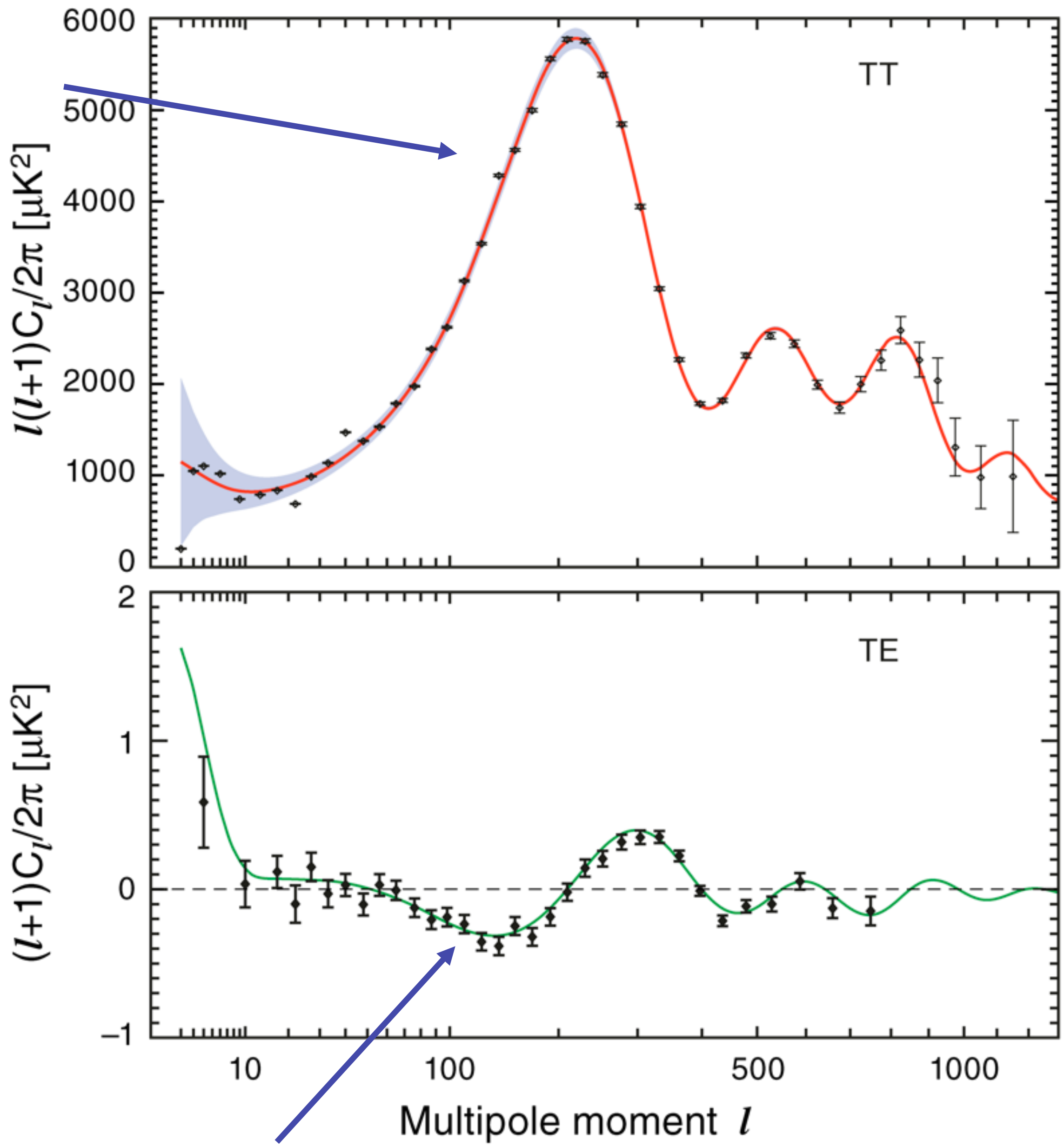
Causal Seeds

Pen, Seljak & Turok (1997)

Sharp acoustic peaks are difficult to create without inflation



WMAP 7yrs



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)

Fossils from before the Hot Big Bang

1. The seeds are primordial

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

3. Slope: $1 - n_s = 0.0355 \pm 0.0049$ (Departure from scale-invariance)

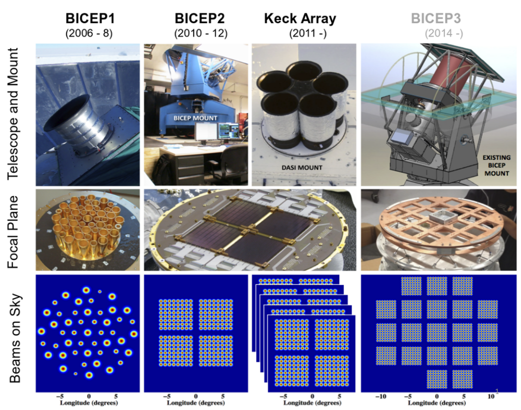
4. No gravitational waves (10 percent level)

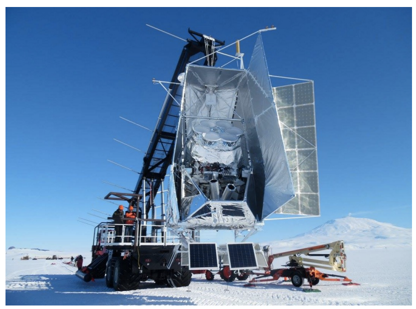
5. No fluctuation in composition (percent level)

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

$$f_{\rm NL}^{\rm loc.} = 0.8 \pm 5.0\ , \quad f_{\rm NL}^{\rm eq.} = -4 \pm 43\ , \quad (68\%\ \mathrm{CL})\ .$$

Can we get a second fossil?





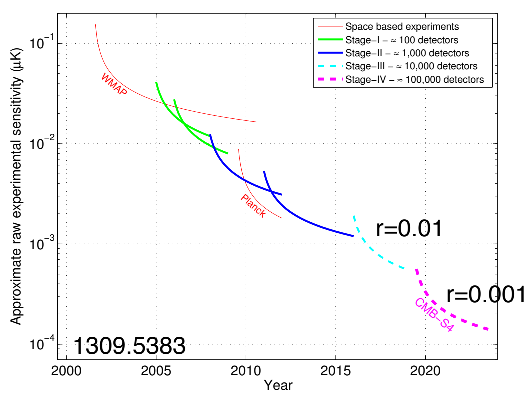
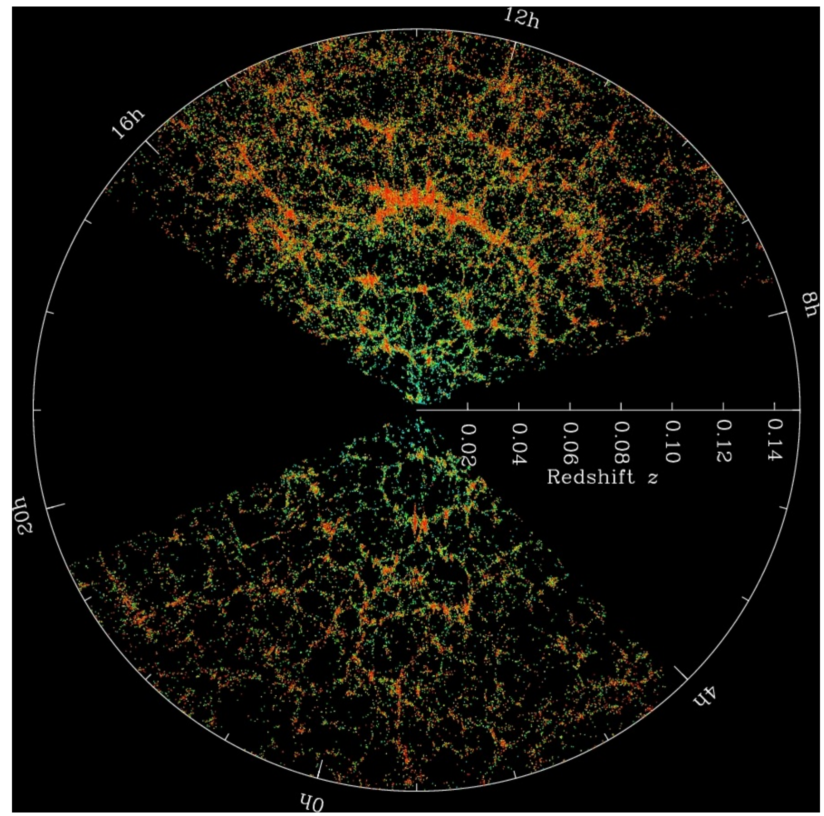


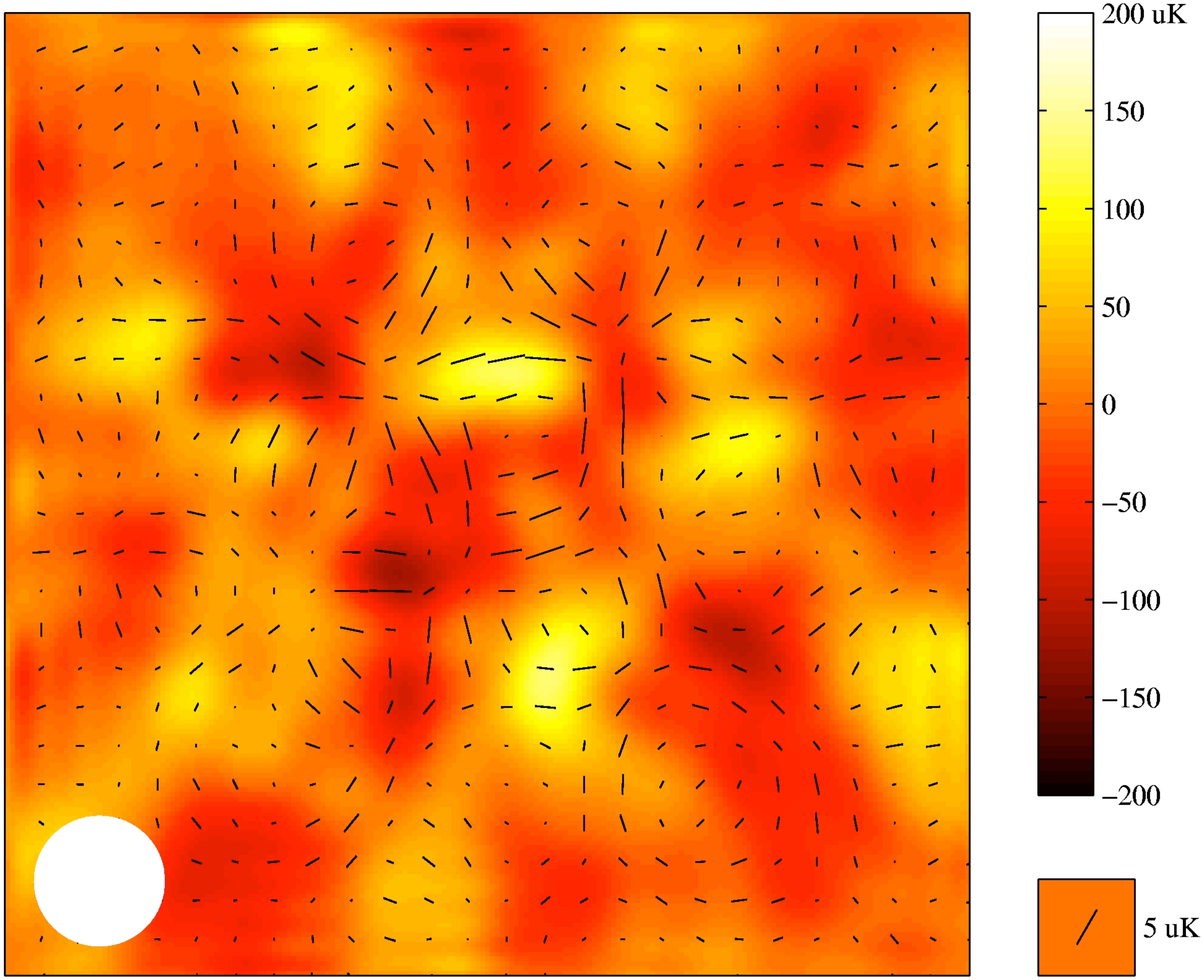
Figure 6. *Plot illustrating the evolution of the raw sensitivity of CMB experiments, which scales as the total number of bolometers. Ground-based CMB experiments are classified into Stages with Stage II experiments having O(1000) detectors, Stage III experiments having O(10,000) detectors, and a Stage IV experiment (such as CMB-S4) having O(100,000) detectors.*

Can we learn more about the scalar fluctuations?



The Anisotropies are polarized

DASI

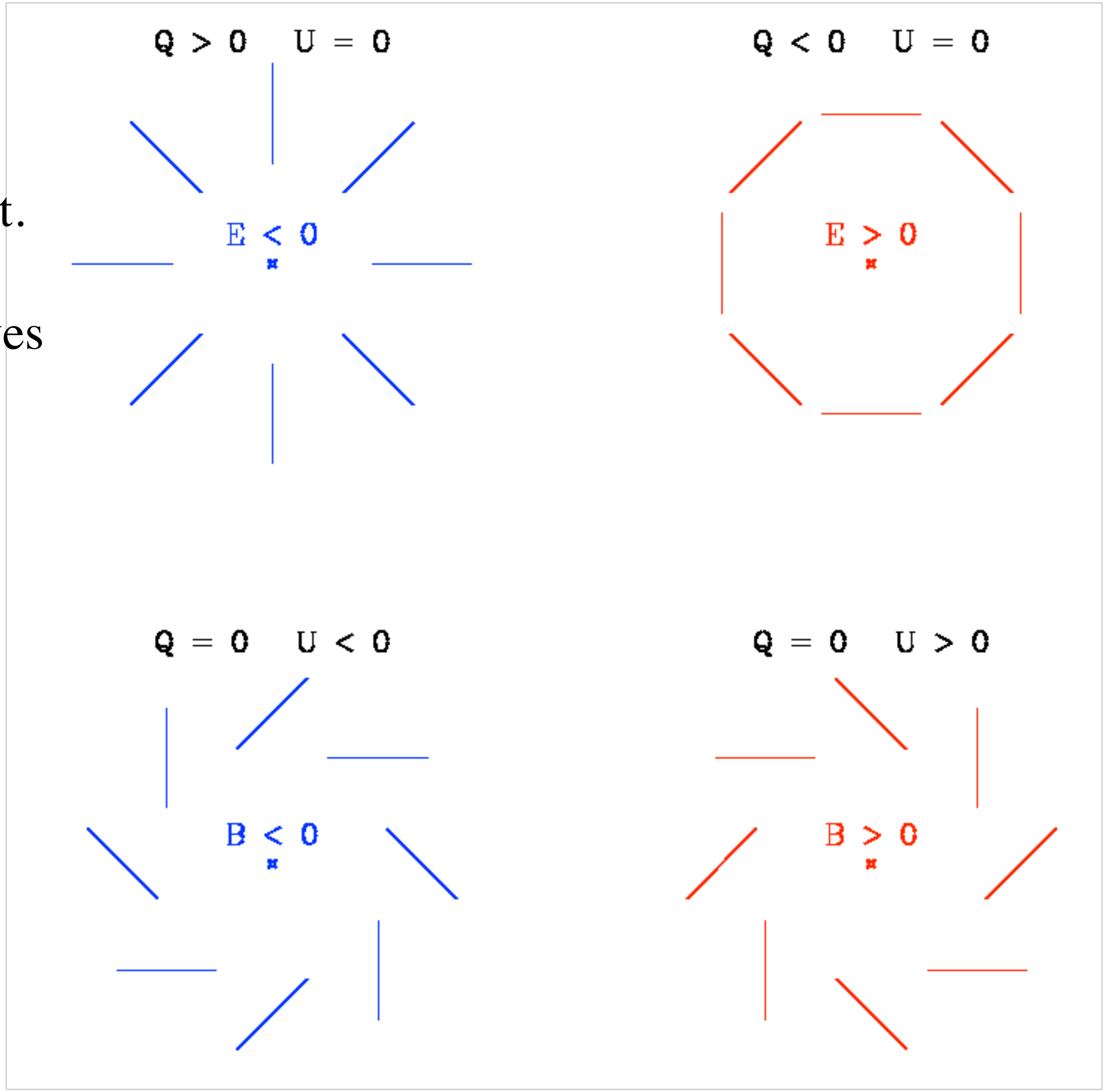


Map is 5 degrees square

Kovac et al.
astro-ph/0209478

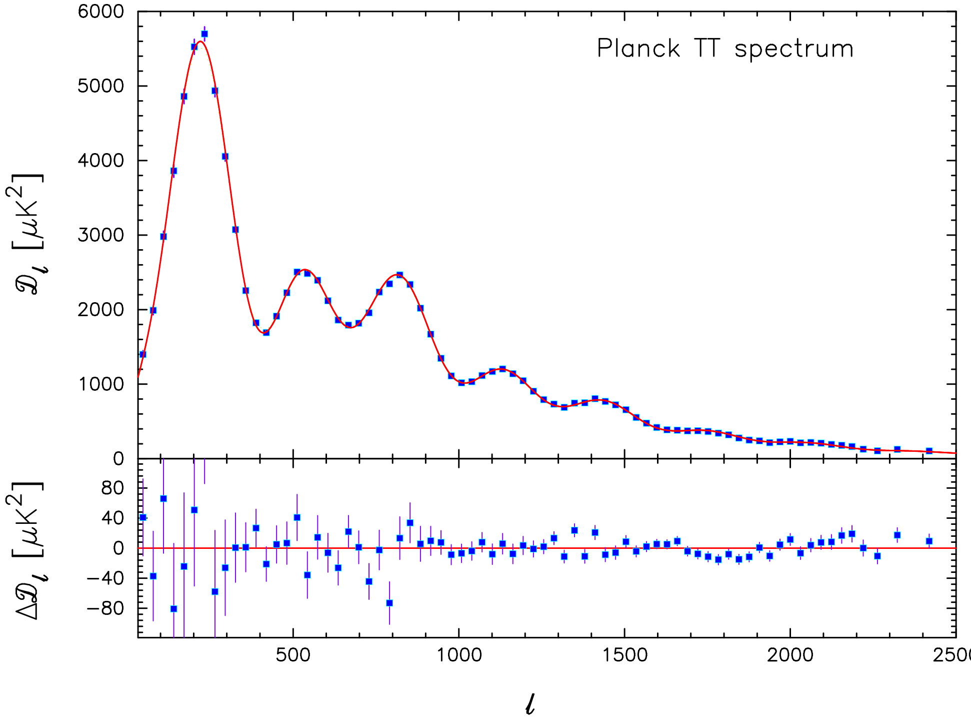
Density pert.
&
Gravity Waves

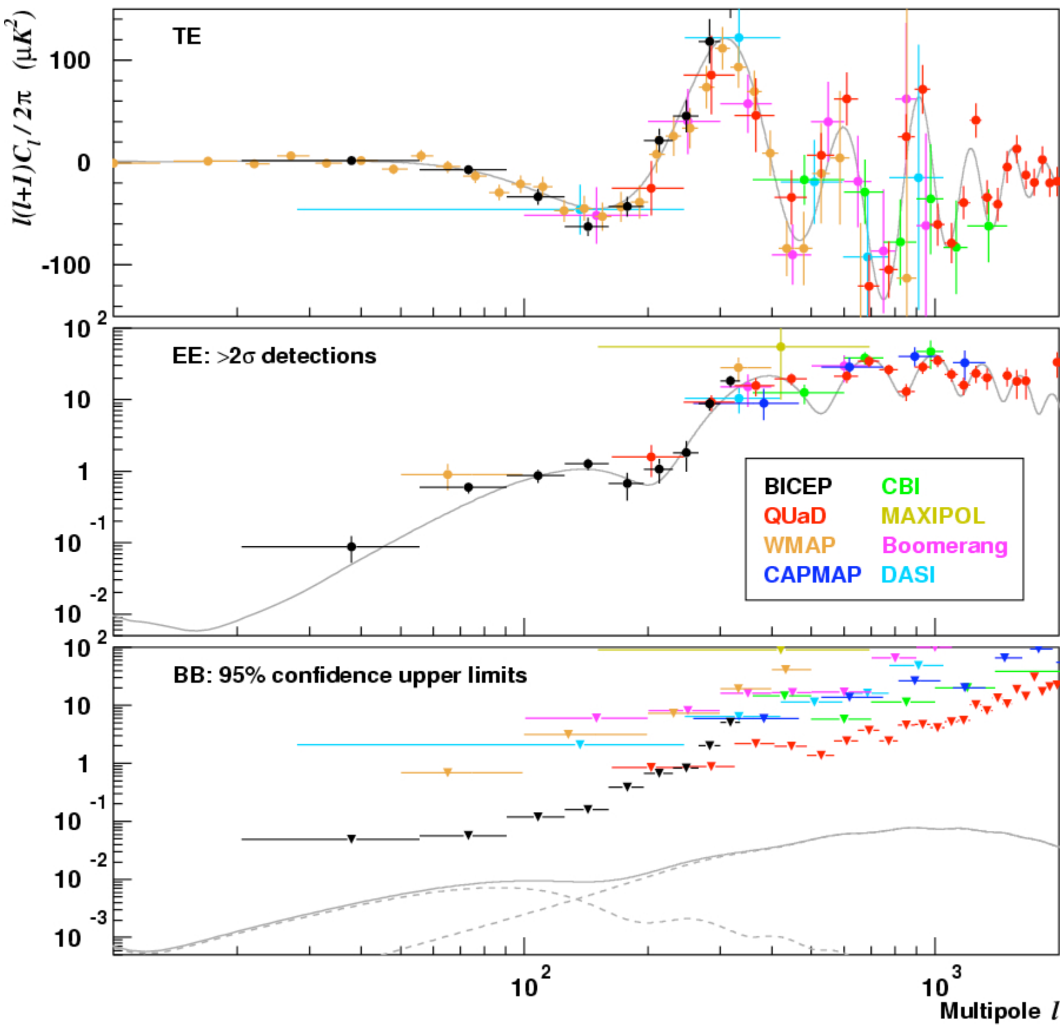
Gravity
Waves

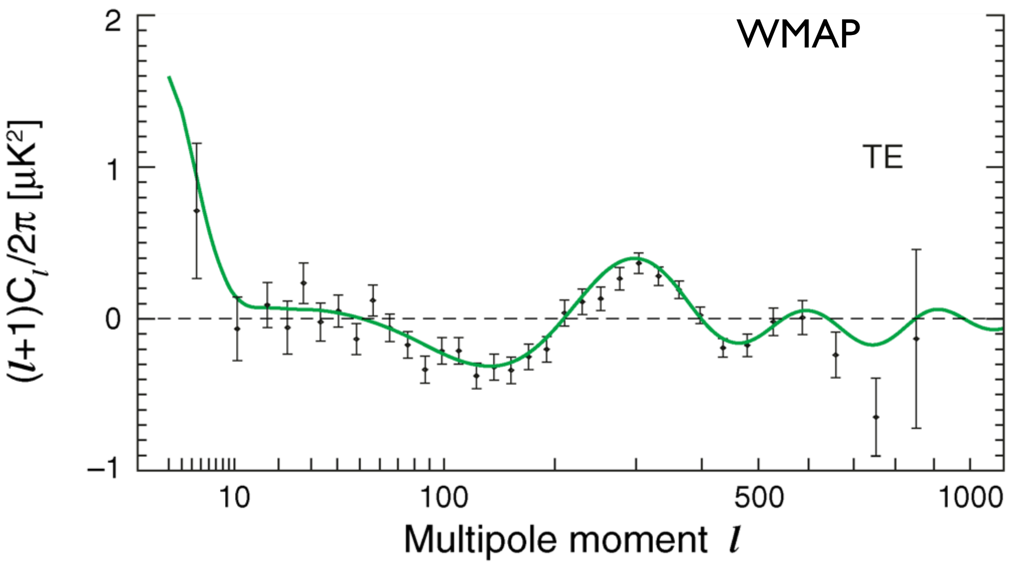


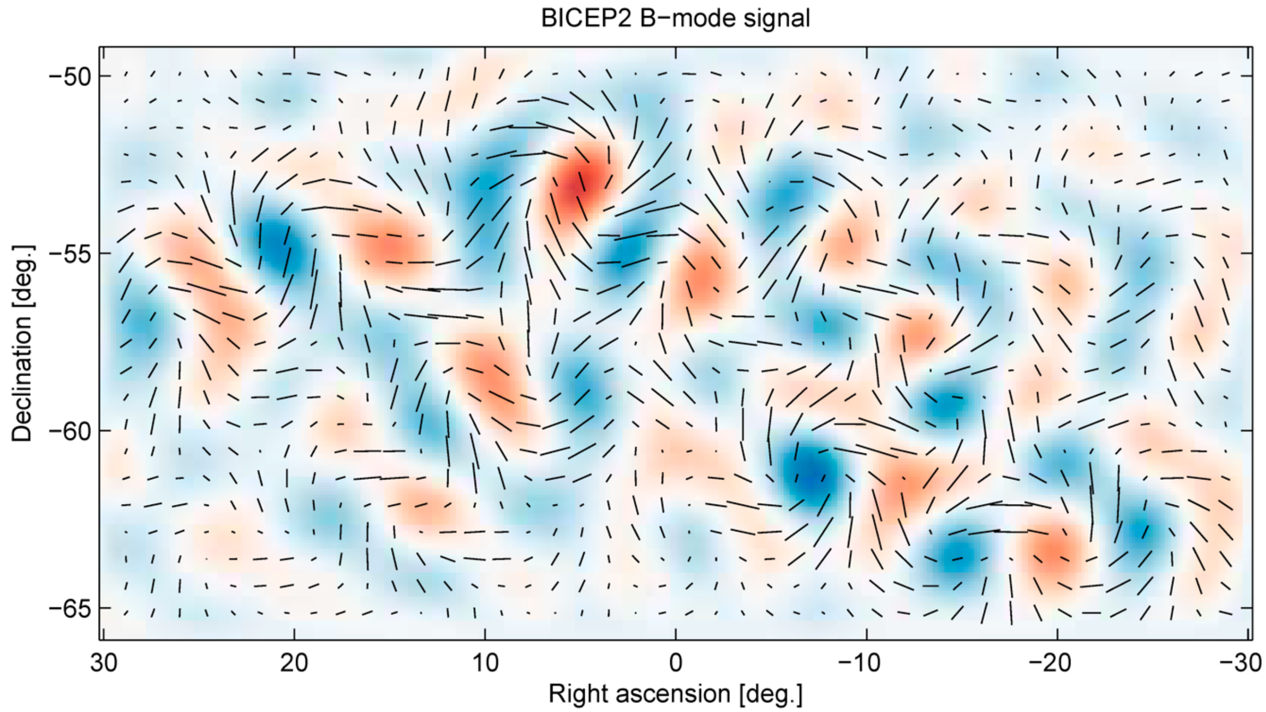
State of the art prior to BICEP2

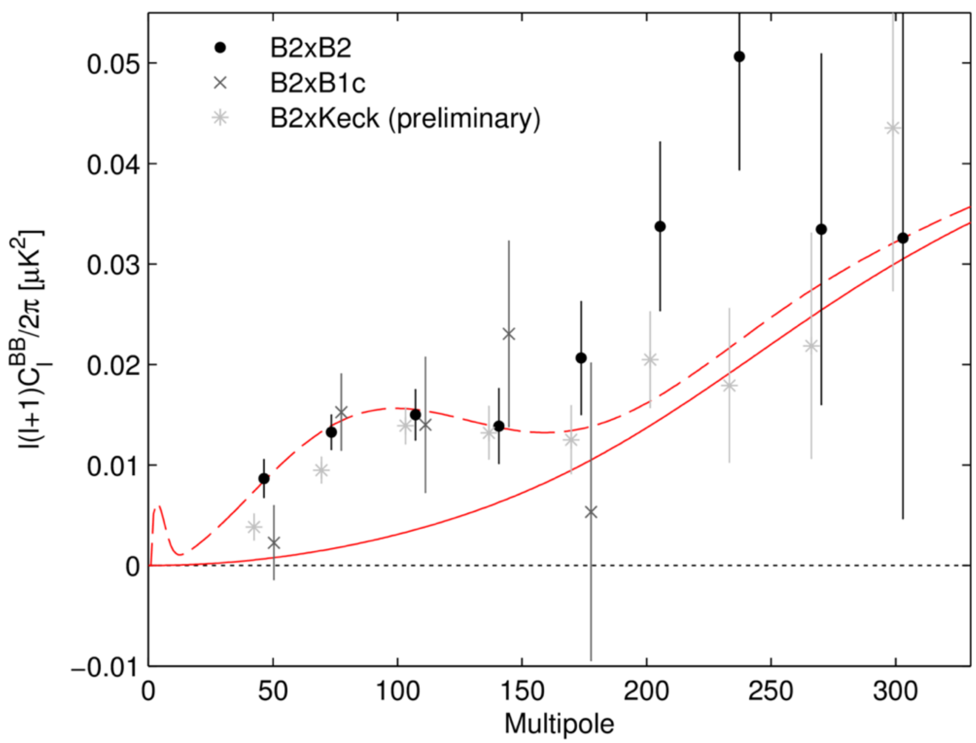
$$T \sim 10 \text{ to } 70\ \mu K$$
$$E \sim 1 \text{ to } 5\ \mu K$$



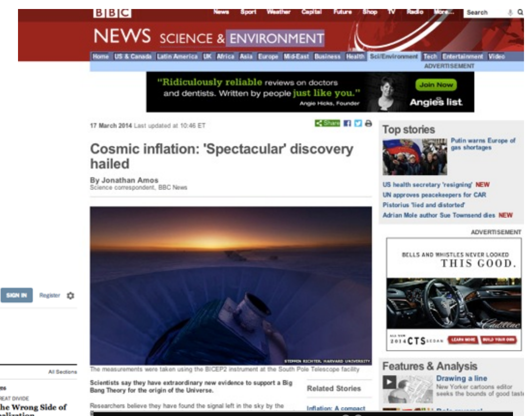


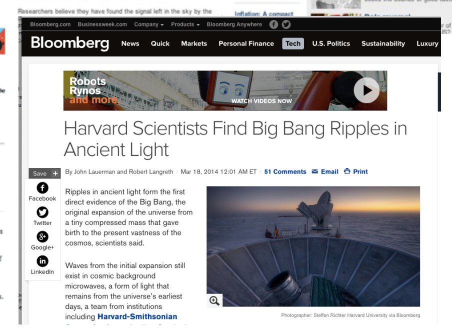


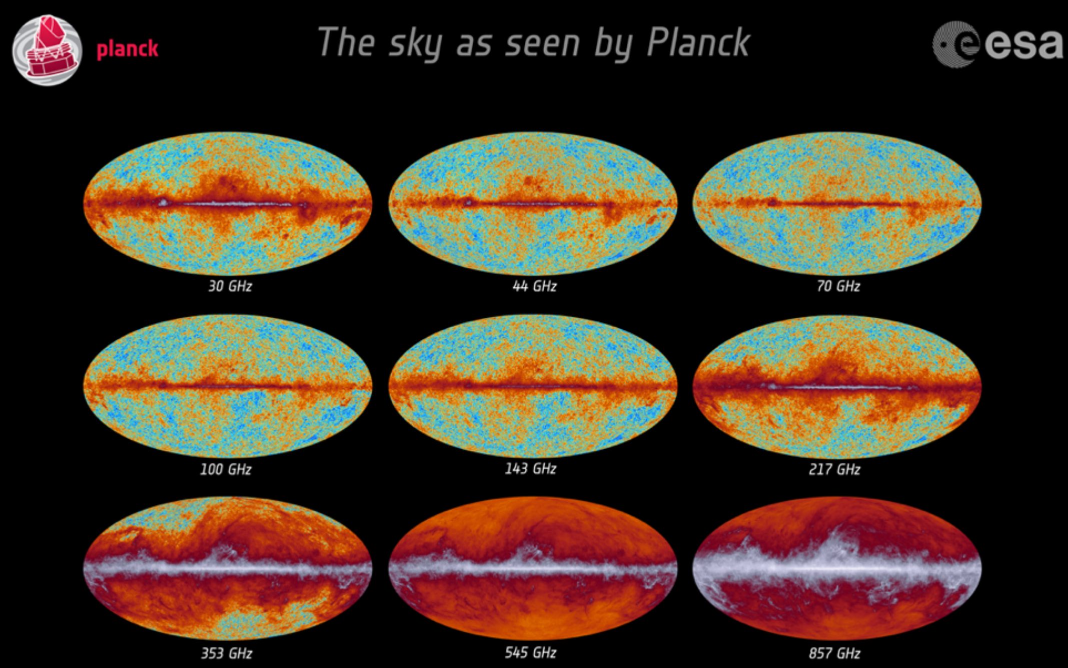


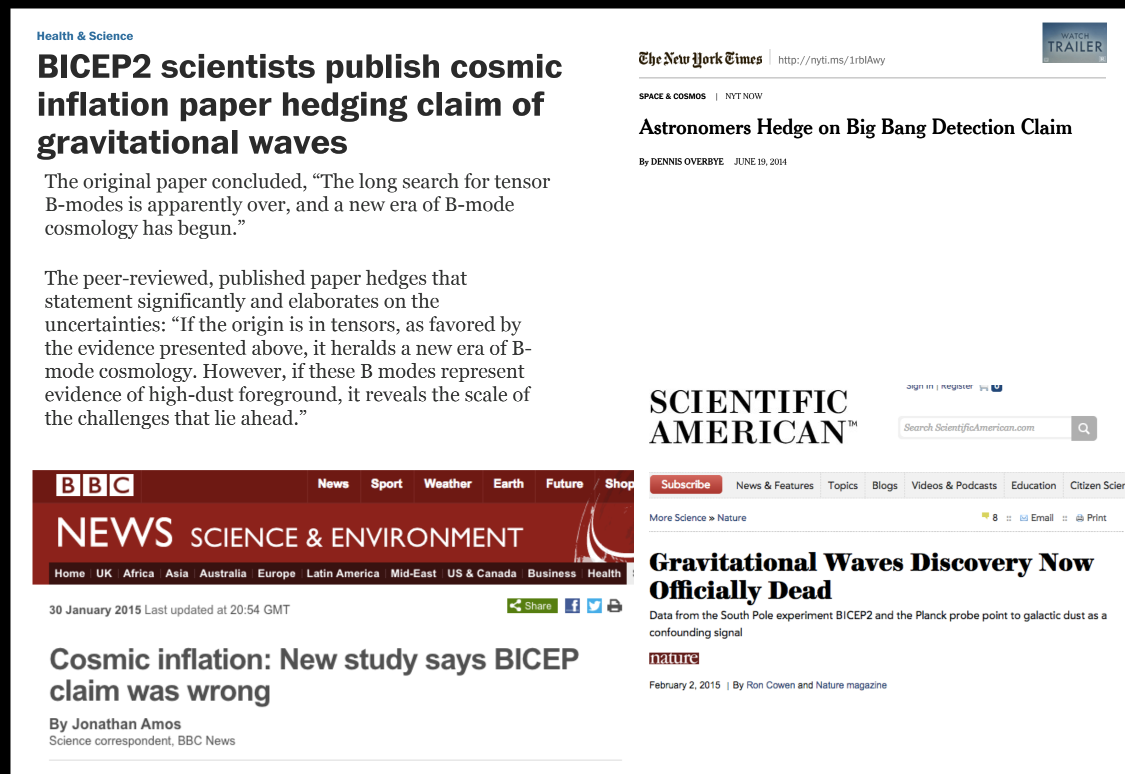


BICEP 2: Evidence for Cosmic Inflation









Health & Science

BICEP2 scientists publish cosmic inflation paper hedging claim of gravitational waves

The original paper concluded, "The long search for tensor B-modes is apparently over, and a new era of B-mode cosmology has begun."

The peer-reviewed, published paper hedges that statement significantly and elaborates on the uncertainties: "If the origin is in tensors, as favored by the evidence presented above, it heralds a new era of B-mode cosmology. However, if these B modes represent evidence of high-dust foreground, it reveals the scale of the challenges that lie ahead."

The New York Times | http://nyti.ms/1rblAwy

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Astronomers Hedge on Big Bang Detection Claim

By DENNIS OVERBYE JUNE 19, 2014

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30 January 2015 Last updated at 20:54 GMT

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Cosmic inflation: New study says BICEP claim was wrong

By Jonathan Amos
Science correspondent, BBC News

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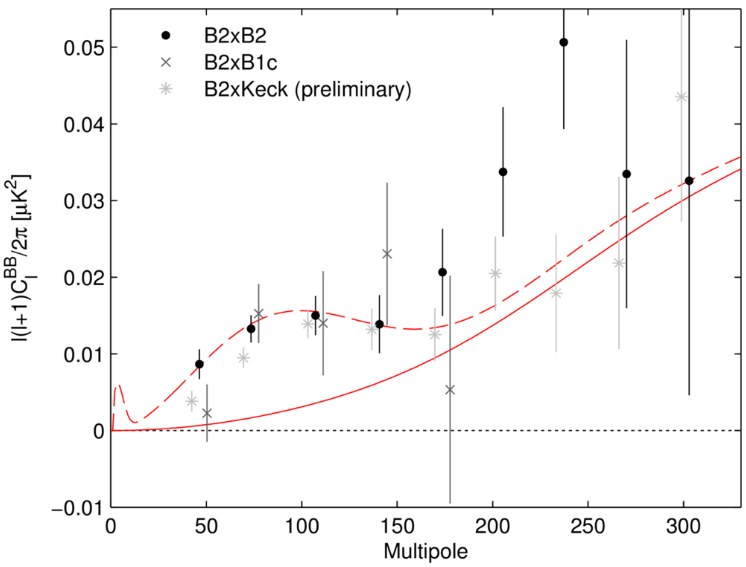
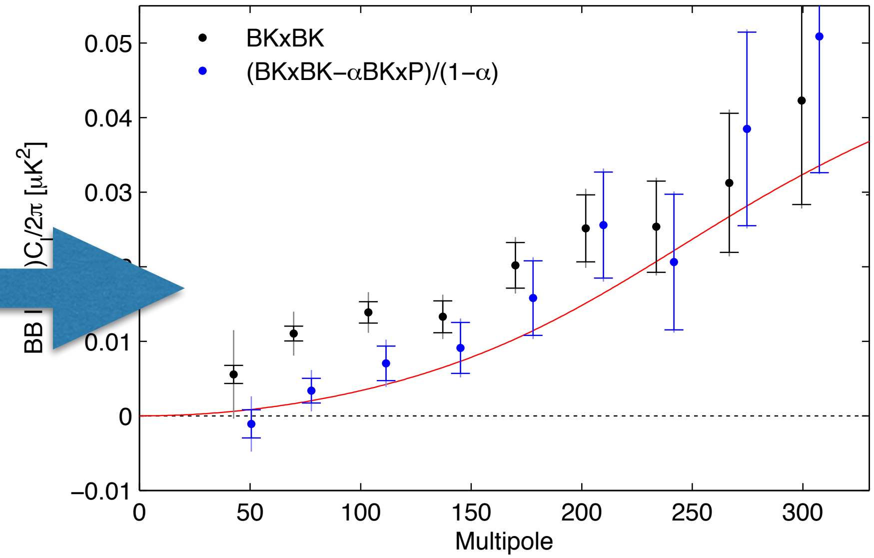
Gravitational Waves Discovery Now Officially Dead

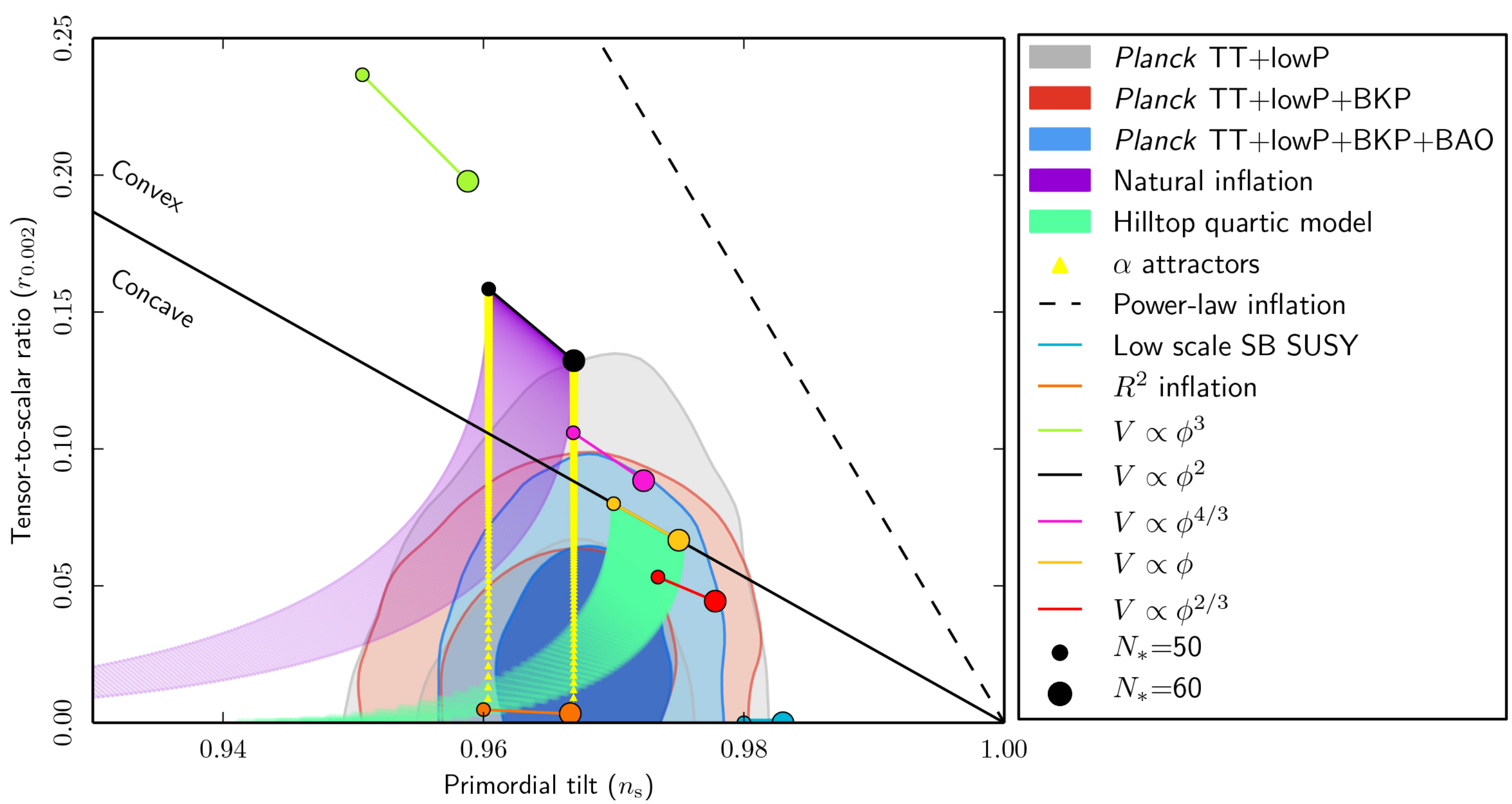
Data from the South Pole experiment BICEP2 and the Planck probe point to galactic dust as a confounding signal

nature

February 2, 2015 | By Ron Cowen and Nature magazine


B2xB2
B2xB1c
B2xKeck (preliminary)
l(l+1)C_l^BB/2π [μK²]
Multipole


BKxBK
(BKxBK−αBKxP)/(1−α)
Multipole


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
R² inflation
V ∝ φ³
V ∝ φ²
V ∝ φ^{4/3}
V ∝ φ
V ∝ φ^{2/3}
N*=50
N*=60
Tensor-to-scalar ratio (r_0.002)
Primordial tilt (n_s)

Fossils from before the Hot Big Bang

1. The seeds are primordial

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3. Slope: $1 - n_s = 0.0355 \pm 0.0049$ (Departure from scale-invariance)

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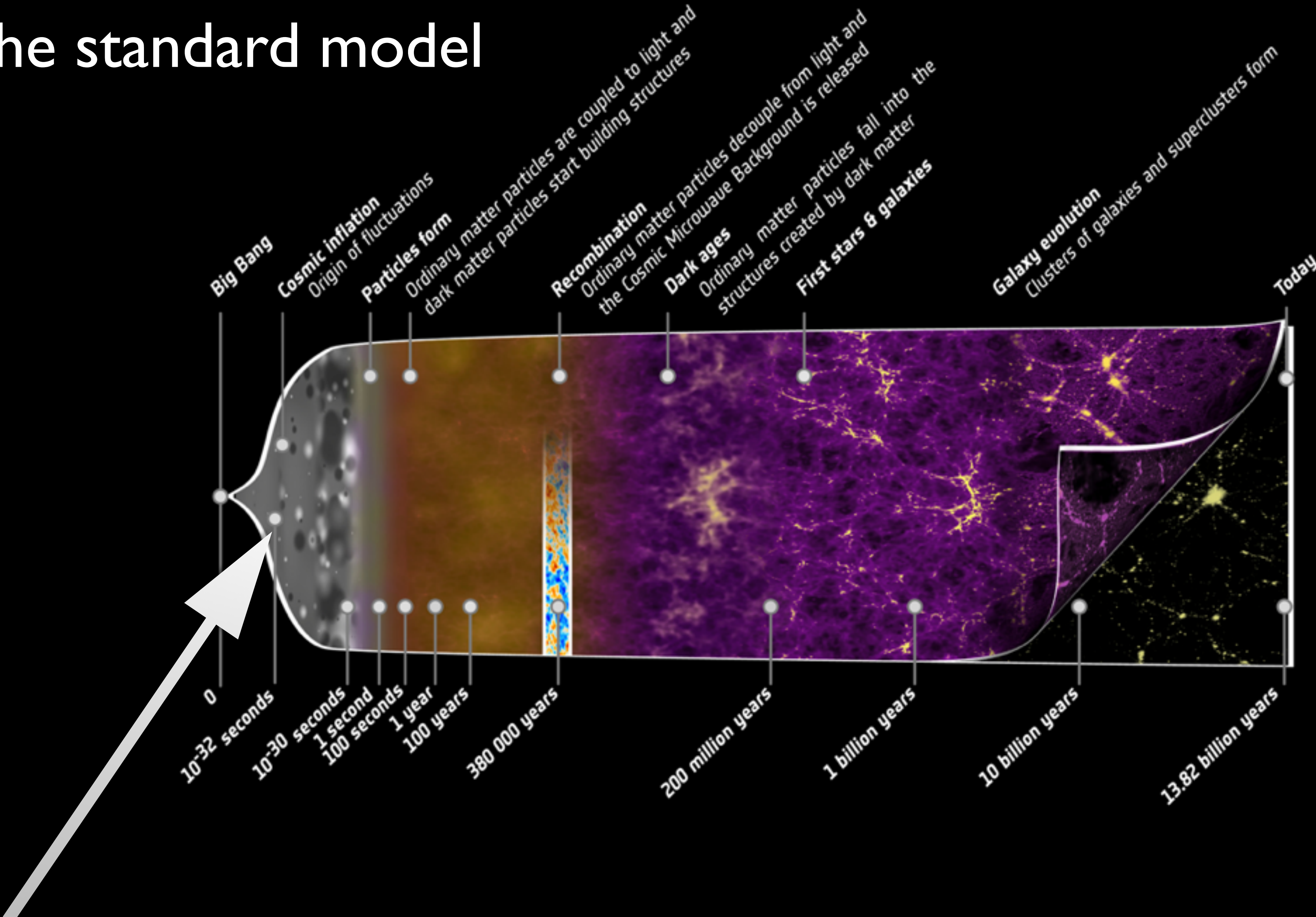
$$f_{\mathrm{NL}}^{\mathrm{loc.}} = 0.8 \pm 5.0 \,, \quad f_{\mathrm{NL}}^{\mathrm{eq.}} = -4 \pm 43 \,, \quad (68\% \ \mathrm{CL}) \,.$$

The standard model



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

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

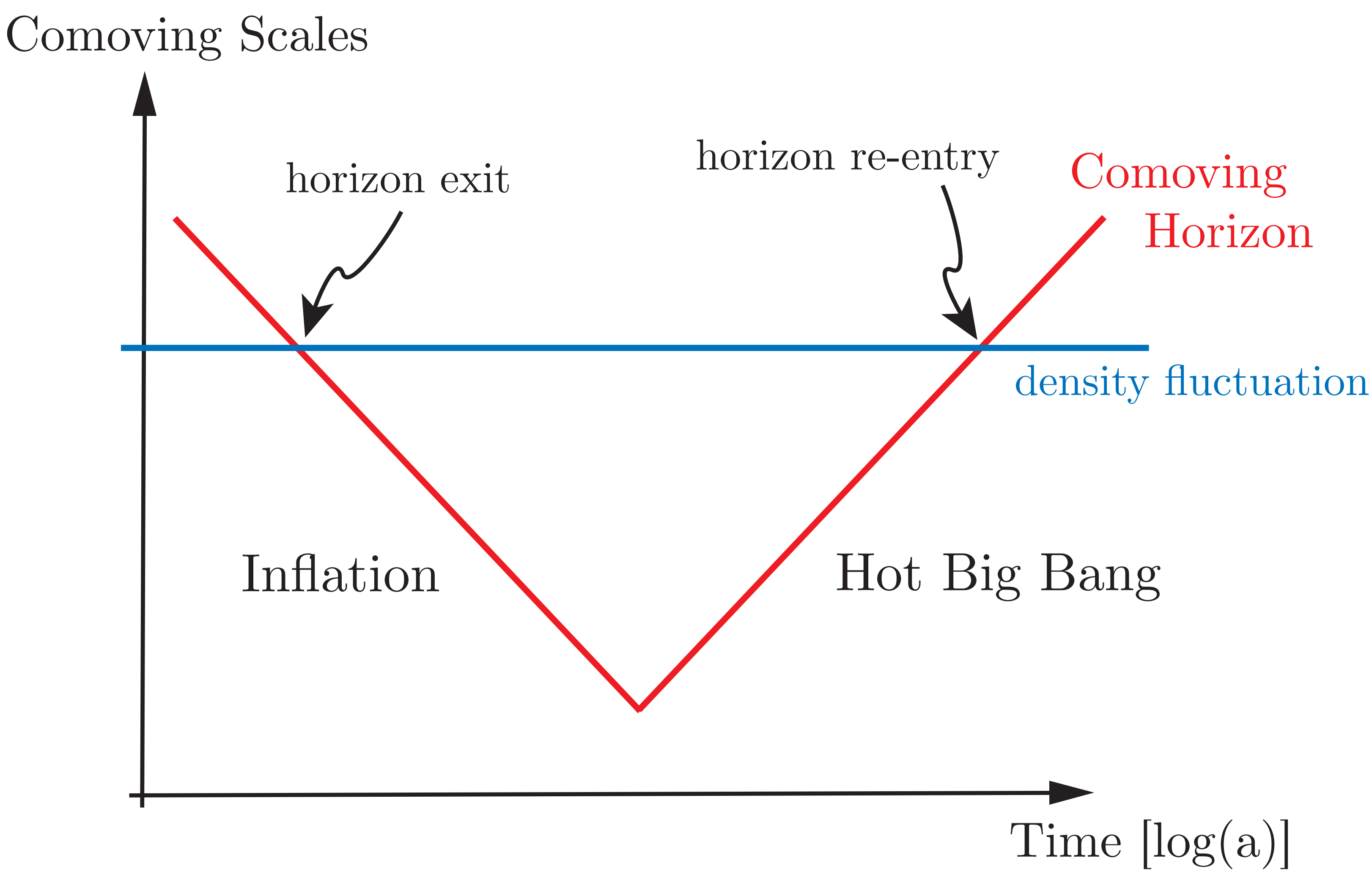
$$H = \frac{\dot{a}}{a} \qquad H^2 = \frac{V}{M_{pl}^2}$$

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

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

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

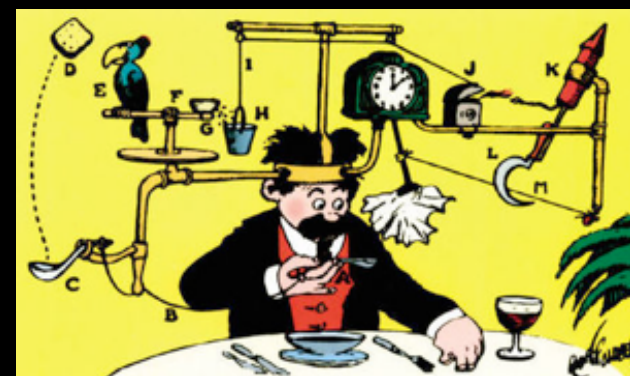
Horizon scale

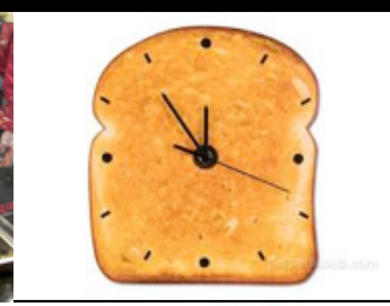


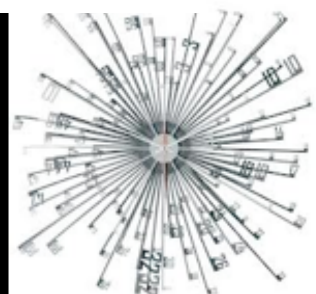
Daniel Baumann
0907.5424

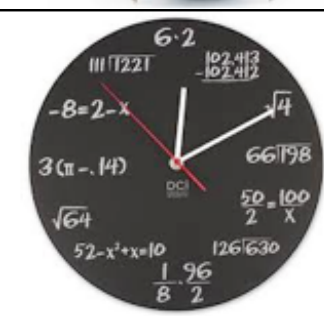
Inflationary models require a clock

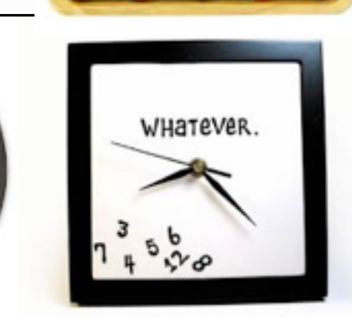

Original models



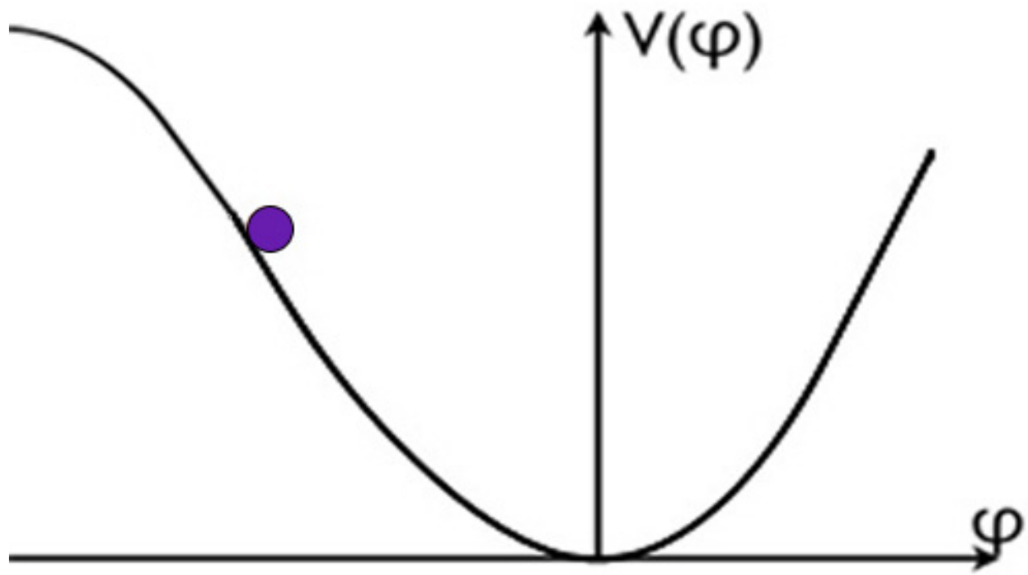








Example of a "clock"



$$\frac{1}{2}(\partial\phi)^2 - V(\phi)$$

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.

Effective theory of inflation: Chung, Creminelli, Fitzpatrick, Kaplan & Senatore. 0709.0293

Use the measured time in the clock as the time coordinate.
The clock disappears from the action, everything is in the metric.
Can still make time dependent transformations of the spatial coordinates but time has been fixed. Terms must respect the residual symmetry.

$$S_{\text{E.H. + S.F.}} = \int d^4x \,\sqrt{-g}\Big[\frac{1}{2}M_{\rm Pl}^2 R + M_{\rm Pl}^2 \dot{H} g^{00} - M_{\rm Pl}^2(3H^2+\dot{H}) + \\ +\frac{1}{2!}M_2(t)^4(g^{00}+1)^2 + \frac{1}{3!}M_3(t)^4(g^{00}+1)^3 + \\ -\frac{\bar{M}_1(t)^3}{2}(g^{00}+1)\delta K^\mu{}_\mu - \frac{\bar{M}_2(t)^2}{2}\delta K^\mu{}_\mu{}^2 - \frac{\bar{M}_3(t)^2}{2}\delta K^\mu{}_\nu \delta K^\nu{}_\mu + \ldots\Big]$$

$\delta K_{\mu\nu}$ the variation of the extrinsic curvature of constant time surfaces

Has one more derivative.
Expansion in fluctuations and in derivatives. Coefficients in the first line are such that the action starts quadratic.

This Lagrangian is both general and unique. It describes 3 degrees of freedom.

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

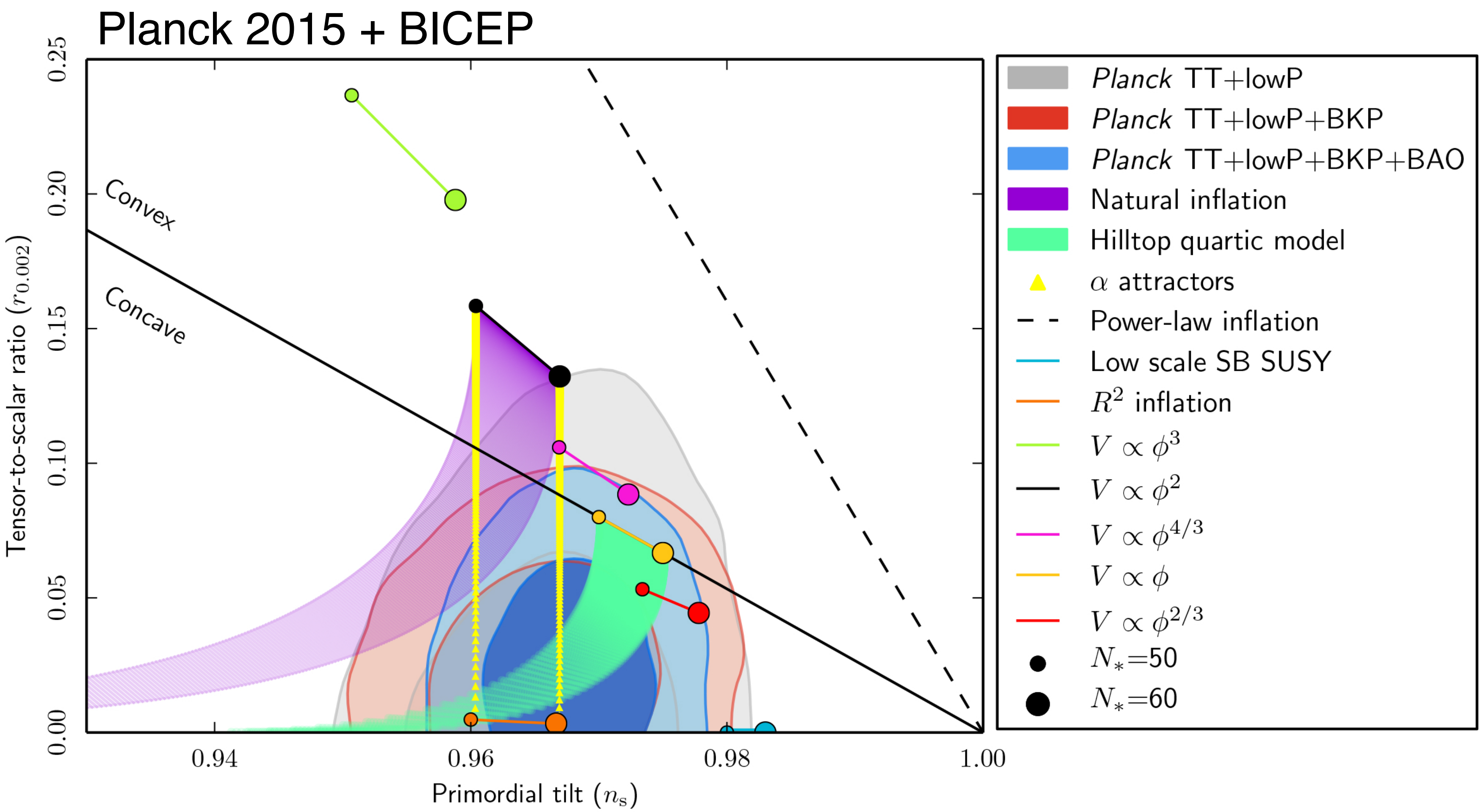
$$r \equiv \frac{\Delta_{\rm t}^2}{\Delta_{\rm s}^2} = 16\,\varepsilon_\star\,.$$

Scale dependence of fluctuations

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

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

Tensors from Planck + BICEP



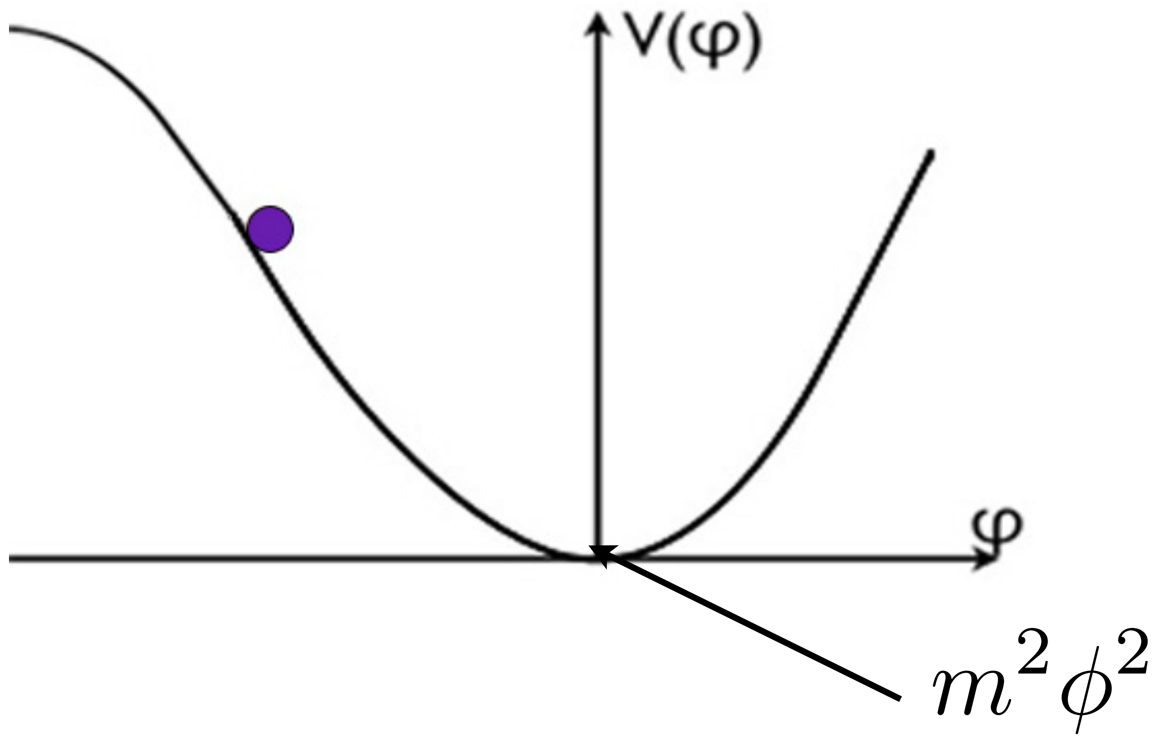
$$V^{1/4} \sim \left(\frac{r}{0.01}\right)^{1/4} 10^{16}\,\mathrm{GeV} \,.$$

Observable gravity waves imply inflation happened around the GUT scale.

$$\Delta\phi \sim \left(\frac{r}{0.002}\right)^{1/2} \left(\frac{N_\star}{60}\right) \; M_{pl}$$

Observable gravity waves imply super-Planckian field excursions.

Can we extrapolate from the small period we have access to all the way to the end of inflation?



Brook Taylor

1685-1731

What is the relevant scale for the Taylor expansion? How far away from the minimum we have to be so the potential is no-longer a parabola?

$\frac{\phi}{M_{pl}}$ Seems to be the relevant expansion and the potential seem to become shallower

The robust thing we are learning is if we can extrapolate from what we are measuring 60 e-folds before the end of inflation to what happens at the end of inflation.

$m^2\phi^2$ is out. We can conclude that there is some other piece of physics playing a role between the minimum of the potential and 60 e-folds before the end. This seems a very interesting statement to be able to make.

If tensors are well below this $m^2\phi^2$ we could eventually conclude that there is something more dramatic like a phase transition in between the observable window and reheating. Although this boundary is not so sharp.

UV sensitivity

$$\frac{\Delta\phi}{M_{\rm pl}} \approx \frac{1}{\sqrt{8}}\int_0^N {\rm d}N\,\sqrt{r}$$

$$\boxed{\frac{\Delta\phi}{M_{\rm pl}} = \mathcal{O}(1) \times \left(\frac{r}{0.01}\right)^{1/2}}$$

$$\boxed{\mathcal{L}_{\rm eff}(\phi) = -\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{1}{4}\lambda\phi^4 - \sum_{p=1}^{\infty}\left[\lambda_p\phi^4 + \nu_p(\partial\phi)^2\right]\left(\frac{\phi}{M_{\rm pl}}\right)^{2p} + \cdots}$$

Shift symmetry forbids these terms $\phi \to \phi + const.$

Symmetry needs to be respected by quantum gravity
For a while there were no example in ST so it was conjectured that you could not get gravity waves.
Now there is a counter example: axion monodromy

Single time scale histories

Changes over one e-fold

$$\epsilon_X = |\frac{\dot{X}}{HX}|$$

$$\epsilon_H = |\frac{\dot{H}}{HH}|$$

If both are of the same size then the gravitational wave contribution is substantial.

$$\epsilon_{\dot{H}} = |\frac{\ddot{H}}{H\dot{H}}|$$

$$r = 16\epsilon_H$$
$$n_s - 1 = -2\epsilon_H + \epsilon_{\dot{H}}$$

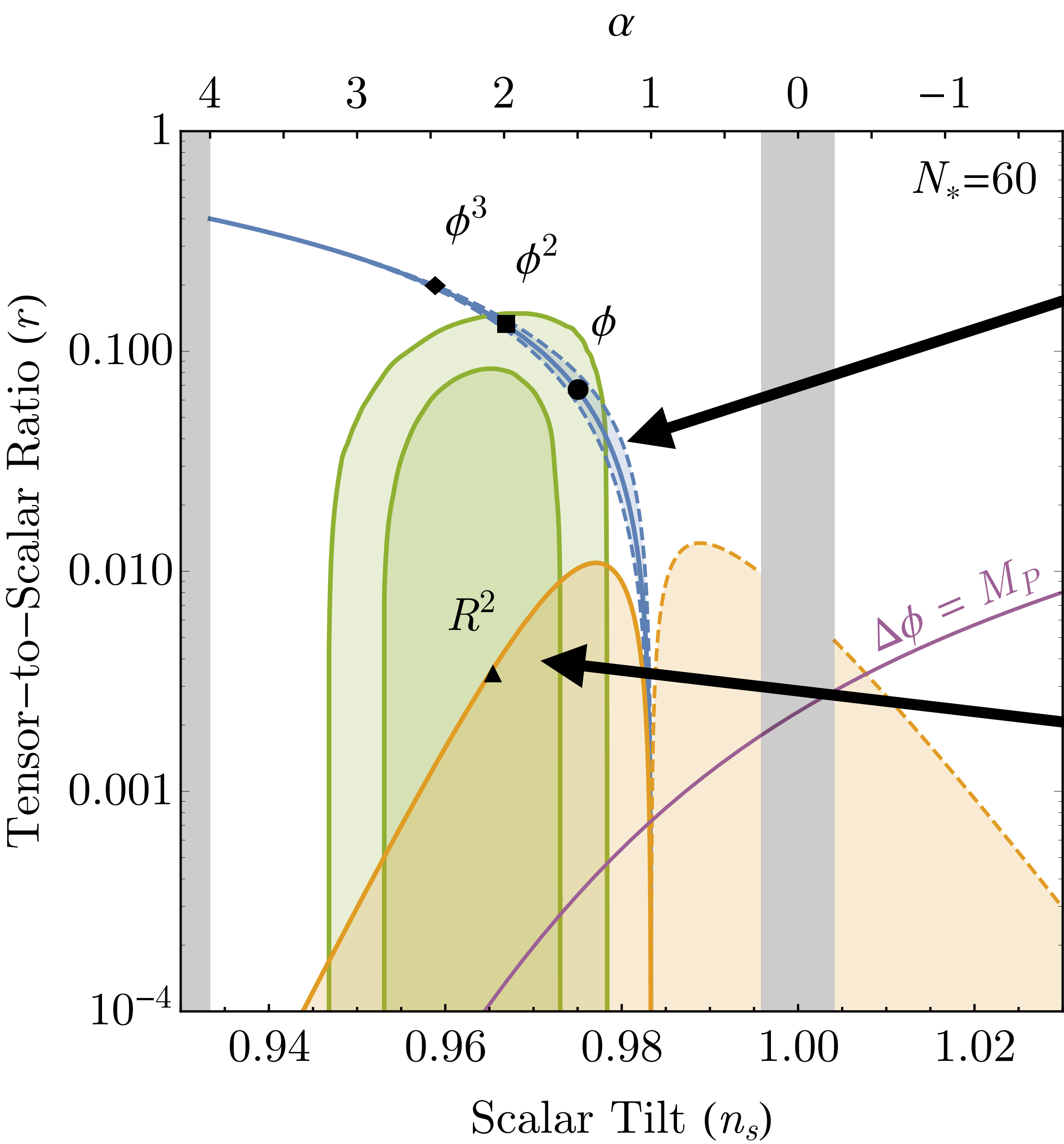
Of course it is easy to open a hierarchy between these two parameters.

$$H(t) = H_\star + \Delta H(t/t_\star)$$

$$\frac{\epsilon_H}{\epsilon_{\dot{H}}} \sim \frac{\Delta H}{H_\star}$$

$$\Delta H \sim 1/t_\star \rightarrow \epsilon_H \sim \epsilon_{\dot{H}}^2$$

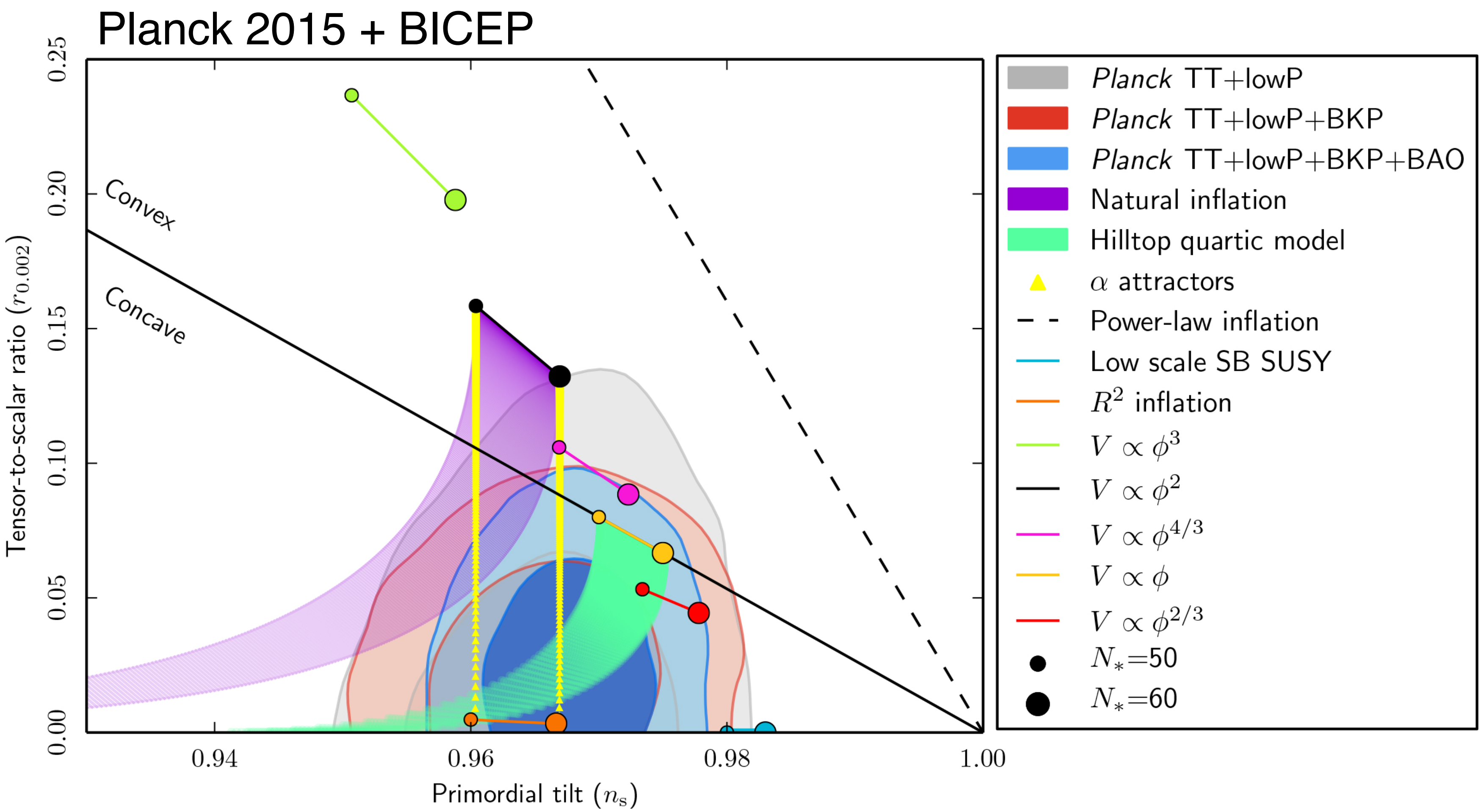
Consequences of $n_s - 1 = -\dfrac{\alpha}{N}$ $r = 16\epsilon$



$$\epsilon(N) = \frac{(\alpha - 1)}{2N}$$

$$\epsilon(N) = \frac{1}{AN^{\alpha}}$$

Tensors from Planck + BICEP



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Observable gravity waves imply super-Planckian field excursions.

Tensor modes

Experiments are testing very interesting values.

We can expect important progress in the relatively near future.

If we do not see tensor modes in this range we will effectively loose the connection between ns and the number of e-folds.

Fossils from before the Hot Big Bang

1. The seeds are primordial

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

3. Slope: $1 - n_s = 0.0355 \pm 0.0049$ (Departure from scale-invariance)

4. No gravitational waves (10 percent level)

5. No fluctuation in composition (percent level)

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

$$f_{\rm NL}^{\rm loc.} = 0.8 \pm 5.0 \ , \quad f_{\rm NL}^{\rm eq.} = -4 \pm 43 \ , \quad (68\% \ {\rm CL}) \ .$$

Non-Gaussianities

$$
\begin{aligned}
S_{\text{E.H. + S.F.}} = \int d^4x \, \sqrt{-g} \Big[& \frac{1}{2} M_{\rm Pl}^2 R + M_{\rm Pl}^2 \dot{H} g^{00} - M_{\rm Pl}^2 (3H^2 + \dot{H}) + \\
& + \frac{1}{2!} M_2(t)^4 (g^{00}+1)^2 + \frac{1}{3!} M_3(t)^4 (g^{00}+1)^3 + \\
& - \frac{\bar{M}_1(t)^3}{2} (g^{00}+1) \delta K^\mu{}_\mu - \frac{\bar{M}_2(t)^2}{2} \delta K^\mu{}_\mu{}^2 - \frac{\bar{M}_3(t)^2}{2} \delta K^\mu{}_\nu \delta K^\nu{}_\mu + \ldots \Big]
\end{aligned}
$$

This Lagrangian is not quadratic, there are interactions.

There is a minimum level of interactions coming from the terms that are fixed by the cosmic history. This level is small but not minuscule.

Probability distribution for the primordial seeds

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

Wave function

$$\Psi[\{\zeta_k\}, \tau] \to P[\{\zeta_k\}, \tau] = |\Psi[\{\zeta_k\}, \tau]|^2$$

Wave vector of mode

Gaussian probability distribution. Almost scale invariant amplitude.

$$k^3\langle\zeta_k\zeta_k\rangle' = \frac{1}{8\pi^2}\frac{H^2}{M_{pl}^2\epsilon} \propto k^{n_s-1} \quad \epsilon = -\frac{\dot{H}}{H^2}$$

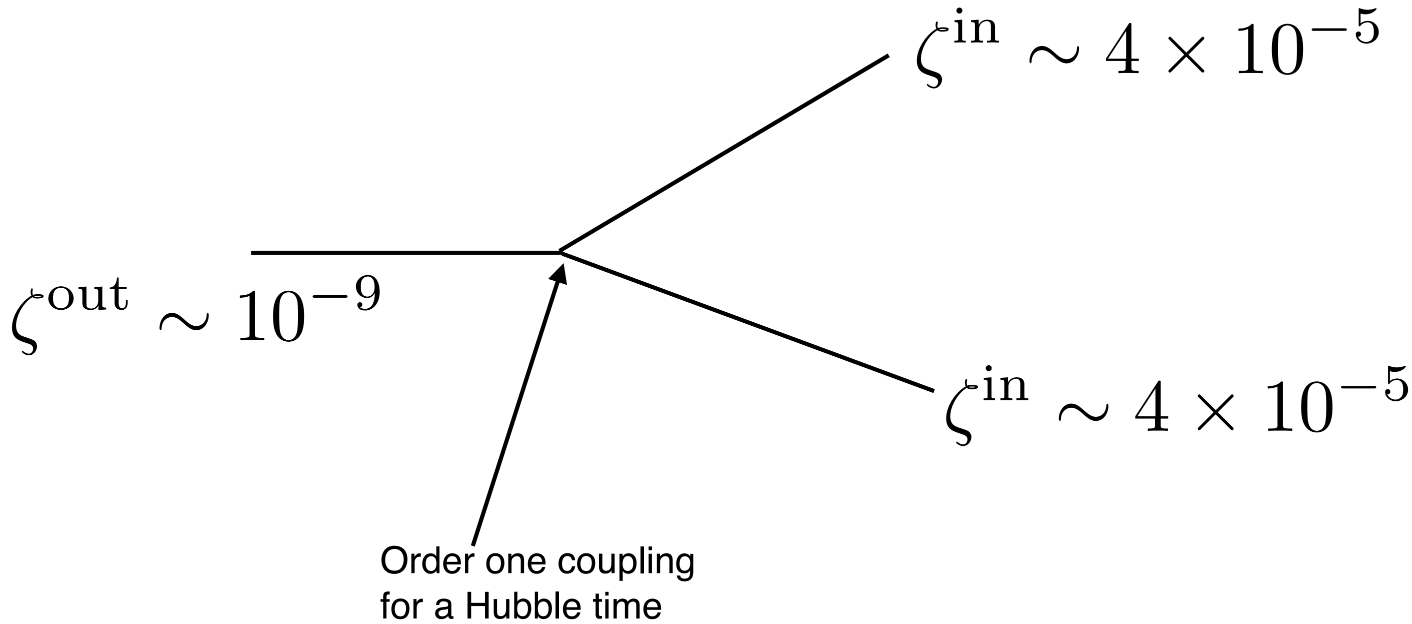
$$1 - n_s = 0.0355 \pm 0.0049$$

Planck: $\dfrac{\mathrm{Non-Gaussian}}{\mathrm{Gaussian}} < 10^{-3} - 10^{-4}$

No fluctuations in composition (percent level)

Higher order moments

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

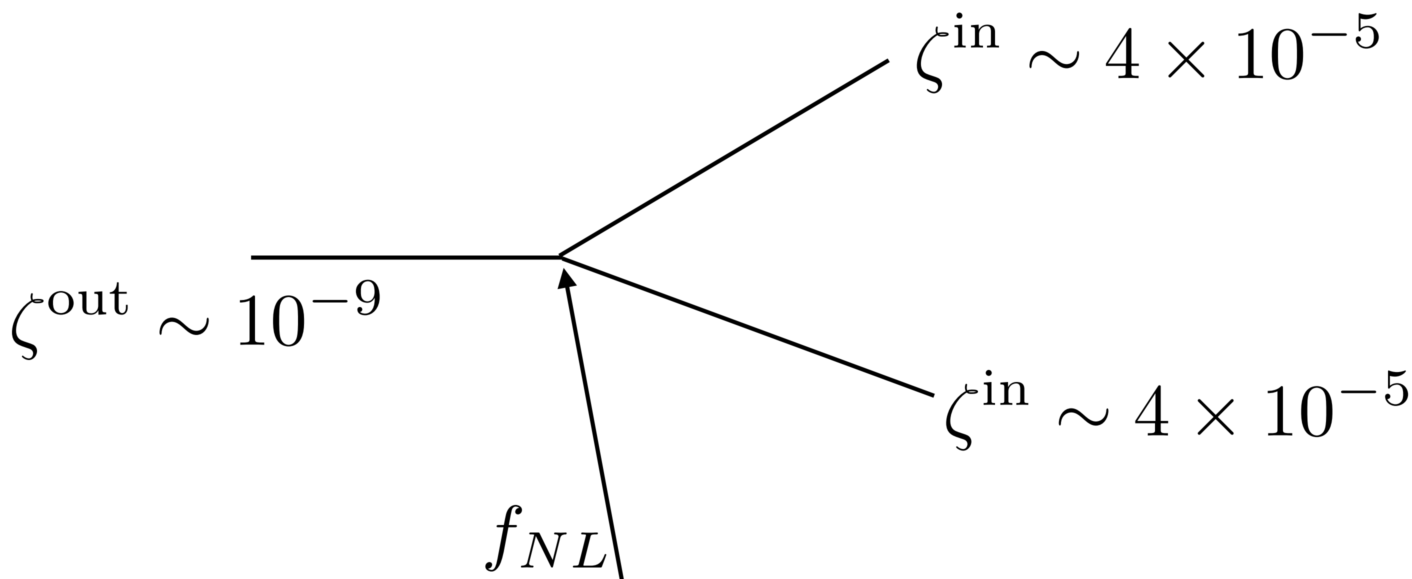


Interactions produce a 4 x 10^{-5} corrections to what was already there.
Detection requires 10^{9} modes

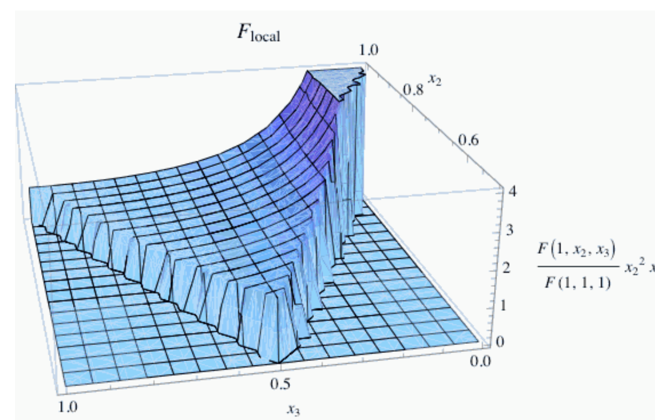
$$ds^2 = -dt^2 + a^2(t)e^{2\zeta(x,t)}dx^2$$

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**



The origin of the seeds of structure

The fact that the seeds for structure formation are primordial in well established. After such impressive data, the idea that the fluctuations were generated during a period of de-Sitter like expansion has survived impressive tests. The firm detection of a non-zero slope for the power spectrum is a stunning success of both the idea and the experiments.*

The idea that the source of fluctuations are vacuum fluctuations of a slowly rolling scalar field which served as the clock that determined when inflation ends (ie slow-roll inflation) is much less well established. It is **only** tested through our study of non-Gaussianities. In this area Planck has made tremendous progress. After Planck we can say that this idea has survived non-trivial tests. However a significant fraction of parameter space is still unexplored.

* What about the "anomalies"? And what should I make of the Bianchi VII stuff?

Were fluctuations converted into curvature fluctuations at the beginning/during the hot big bang?

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

$$\zeta \ll 10^{-5} \to \zeta \sim 10^{-5}$$

$$H^2 = \frac{\rho}{M_{pl}^2}$$

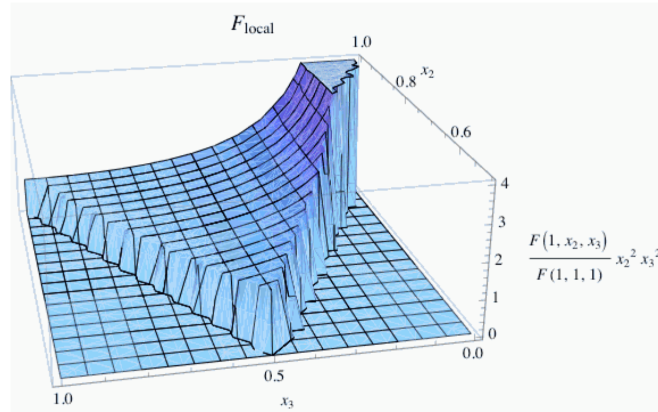
$$\zeta \leftrightarrow \delta \log a$$

$$\dot{H} = -\frac{3}{2}\frac{\rho + p}{M_{pl}^2}$$

Did super-horizon modes ever produce locally observable differences that modulate the equation of state?

Robust signature: Local non-Gaussianty

Modulate the equation of state:



$$p(\rho) = \bar{p}(\rho) + \delta p(\sigma)$$

The conversion into curvature perturbations happens outside the horizon. Gradients are negligible and thus it leads to local type of non-Gaussianity.

$$\zeta(x) = f(\sigma(x)) = \epsilon(\sigma + \alpha\sigma^2 + \cdots) \qquad f_{NL}^{local} \sim \frac{1}{\epsilon}$$

There are many contributions to the non-linearities. Friedman equation, relation between field and the change in the equation of state, etc.

Only part of the pressure is modulated. Mechanism need not be perfectly efficient.

Examples, translation between decay rate and expansion or fractional contribution to the energy density by the curvaton.

$$r_{\mathrm{D}} = [3\rho_{\mathrm{curvaton}}/(3\rho_{\mathrm{curvaton}} + 4\rho_{\mathrm{radiation}})]_{\mathrm{D}}$$

$$r_{\mathrm{D}} \geq 0.15 \qquad 95\%\ \mathrm{CL}\,.$$

$$\zeta(x) = \frac{1}{6}\frac{\delta\Gamma}{\Gamma}$$

Time delay fluctuations

Attractor solution sequentially hides perturbations

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

Curvature

$$\frac{\dot{\zeta}}{H} \qquad \frac{\nabla^2\zeta}{a^2H^2} \longrightarrow (\frac{k_L}{k_S})^2$$

Locally observable effect are very small. Signal suppressed by $(\frac{k_L}{k_S})^2$

Actual result $\quad f_{NL}^{equil} \sim \epsilon$

We are actually seeing time delay fluctuations

What to conclude

"Probably" fluctuations were not converted into curvature at the beginning of the HBB but the window is not completely closed. How do we close it?

This is particularly interesting because only inflationary backgrounds gives us scale invariant curvature perturbations. One can tune the two point function to be scale invariant around other backgrounds but interactions (higher order moments) are not scale invariant. In inflation, time translational is the origin of scale invariance and thus it is a very robust outcome, irrespective of the details of how the perturbations are generated or interact.

To get scale invariant perturbations around other backgrounds people have to invoke a second field that converts later.

Furthermore building a theory for some of the anomalies requires a second field so not seeing local non-G provides an interesting constrain.

We are led to think about the adiabatic fluctuations during inflation.

The theory of the adiabatic fluctuations

- There is always the "adiabatic fluctuations"
- Dynamics of the fluctuations of the clock are very constrained by symmetries, "EFT of inflation"
- One can use time diffs to make the clock look unperturbed and thus all the dynamics is in the metric

$$
\begin{aligned}
S = \int d^4x\,\sqrt{-g}\ \Big[\ & \frac{1}{2}M_{\rm Pl}^2 R + M_{\rm Pl}^2 \dot{H} g^{00} - M_{\rm Pl}^2 (3H^2 + \dot{H}) + \\
& + \frac{1}{2!} M_2(t)^4 (g^{00}+1)^2 + \frac{1}{3!} M_3(t)^4 (g^{00}+1)^3 + \\
& - \frac{\bar{M}_1(t)^3}{2} (g^{00}+1)\delta K^\mu{}_\mu - \frac{\bar{M}_2(t)^2}{2} \delta K^\mu{}_\mu{}^2 - \frac{\bar{M}_3(t)^2}{2} \delta K^\mu{}_\nu \delta K^\nu{}_\mu + \ldots \Big]
\end{aligned}
$$

Change the dispersion relation of the fluctuations

All single field models fall in this framework but this is more general.

The connection between sound speed and non-Gaussianity

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

In the decoupling limit: $\zeta = H\pi$

$$S = \int d^4x \sqrt{-g}\left[-\frac{M_{\rm Pl}^2 \dot{H}}{c_s^2}\left(\dot{\pi}^2 - c_s^2\frac{(\partial_i \pi)^2}{a^2}\right) + (M_{\rm Pl}^2 \dot{H})\frac{1-c_s^2}{c_s^2}\left(\frac{\dot{\pi}(\partial_i\pi)^2}{a^2} + \frac{A}{c_s^2}\dot{\pi}^3\right) + \cdots\right]$$

$$A = -(c_{\rm s}^2 + (2/3)\tilde{c}_3),$$

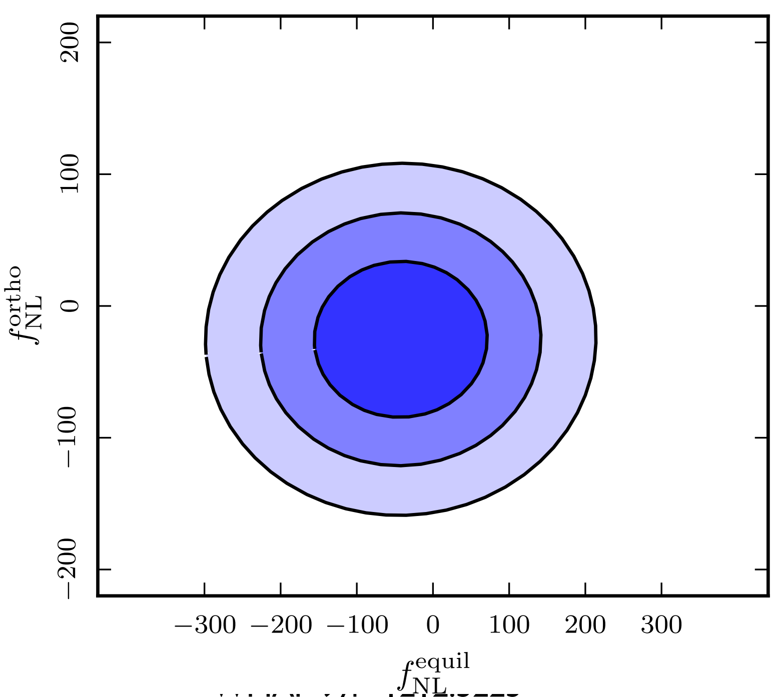


Fig. 22. 68%, 95%, and 99.7% confidence regions in the parameter space ($f_{\rm NL}^{\rm equil}$, $f_{\rm NL}^{\rm ortho}$), defined by thresholding χ^2 as described

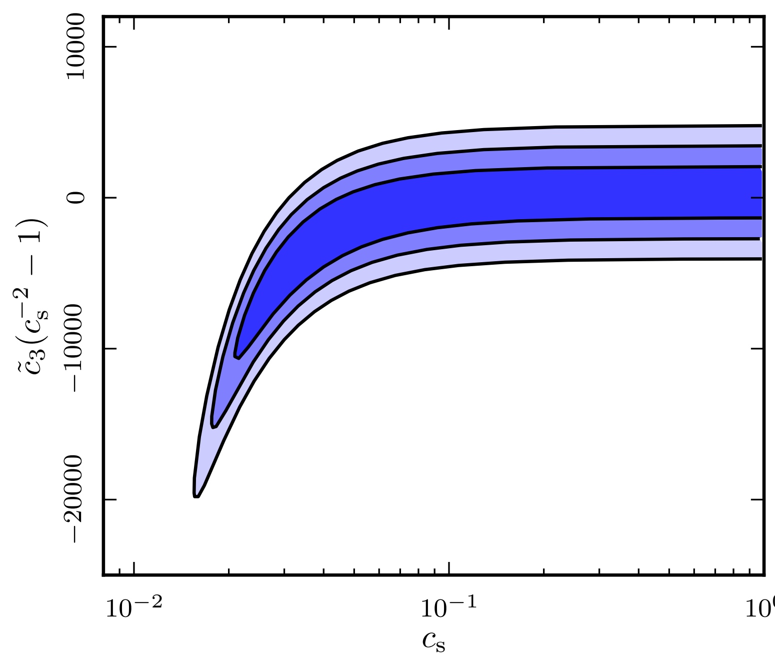


Fig. 23. 68%, 95%, and 99.7% confidence regions in the single-field inflation parameter space ($c_{\rm s}$, $\tilde{c}_3$), obtained from Fig. 22 via the change of variables in Eq. (98).

Large self-interactions

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 + \frac{1}{8}\frac{(\partial\phi)^4}{M^4} \longrightarrow f_{NL}^{eq} \sim \frac{\dot{\phi}^2}{M^4}$$

In non-Gaussianities are large, then field is not slowly rolling in the background solution.

The theory of the perturbations cannot be extrapolated to the energy scale relevant for the background solution. (This is always the case for small sound speeds)

Example: DBI

$$\mathcal{L} = -M^4\sqrt{1 - \frac{(\partial\phi)^2}{M^4}}$$

The connection between sound speed and non-Gaussianity: Simple reason

$$\left(\frac{\partial v}{\partial t} + v \cdot \nabla v\right) = -\frac{\nabla p}{(\rho + p)}$$

$$NG \sim \frac{kv}{\omega} \sim \frac{v}{c_s}$$ (at Freeze out)

$$v \sim \frac{c^2}{aH}\partial_i \zeta \longrightarrow NG \sim \frac{c^2}{c_s^2}\zeta$$

Not related to QM or any detail of the dynamics, just Lorentz invariance

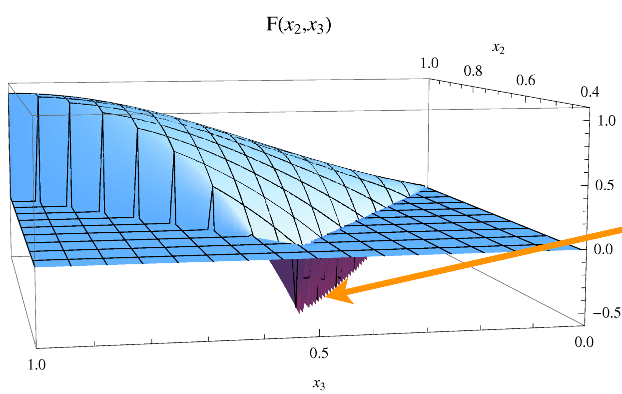
Cases with dissipation (fluctuations are not QM vacuum fluctuations)

$$S_2^{\mathcal{O}} = -\int d^4x \sqrt{-g}\ \{ f_2(t)\delta g^{00}\mathcal{O}_2 + f_3(t)(\delta g^{00})^2\mathcal{O}_3 + f_4(t)(\delta g^{00})^3\mathcal{O}_4 + \ldots \}$$

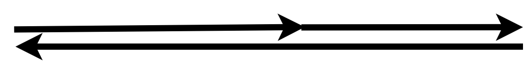
γ Rate at which waves loose energy

$$\gamma\dot{\pi} \to \gamma(\partial_i\pi)^2$$

$$\frac{\gamma(\partial_i\pi)^2}{c_s^2\partial_i^2\pi} \sim f_{\rm NL}\zeta \to |f_{\rm NL}| \simeq \frac{\gamma}{c_s^2 H}$$



Folded Triangles



$$\omega_1 = \omega_2 + \omega_3$$

Non-Gaussianities in Adiabatic fluctuations

They are directly related to basic questions about the properties of fluctuations when they were generated.

They directly tell us about the dispersion relation of fluctuations.

$$\omega^2 - i\gamma\omega - c_s^2 k^2 = 0$$

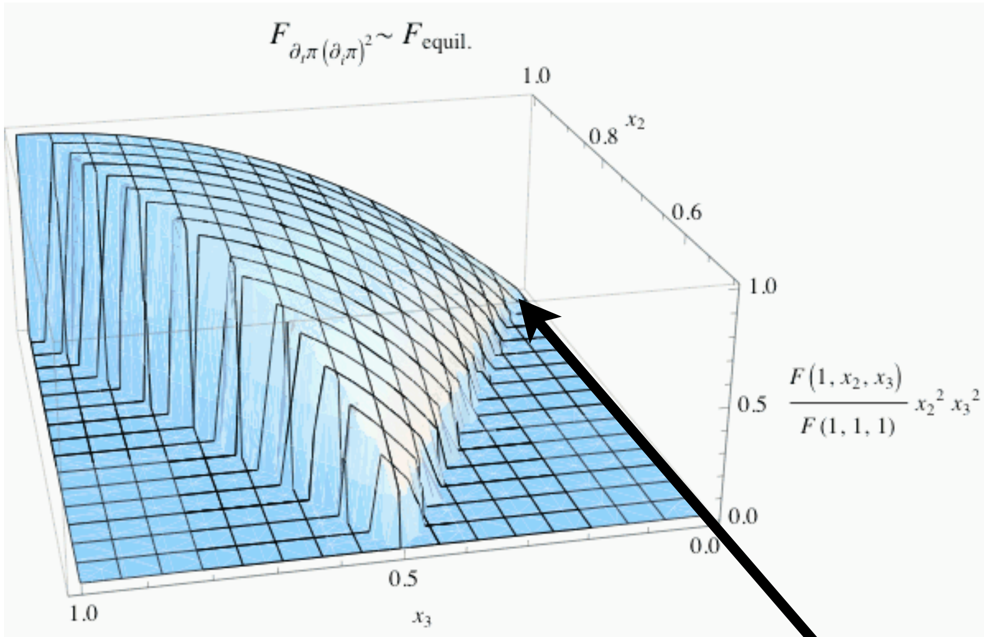
If we change the dispersion relation of the waves NG must be there just by Lorentz invariance.

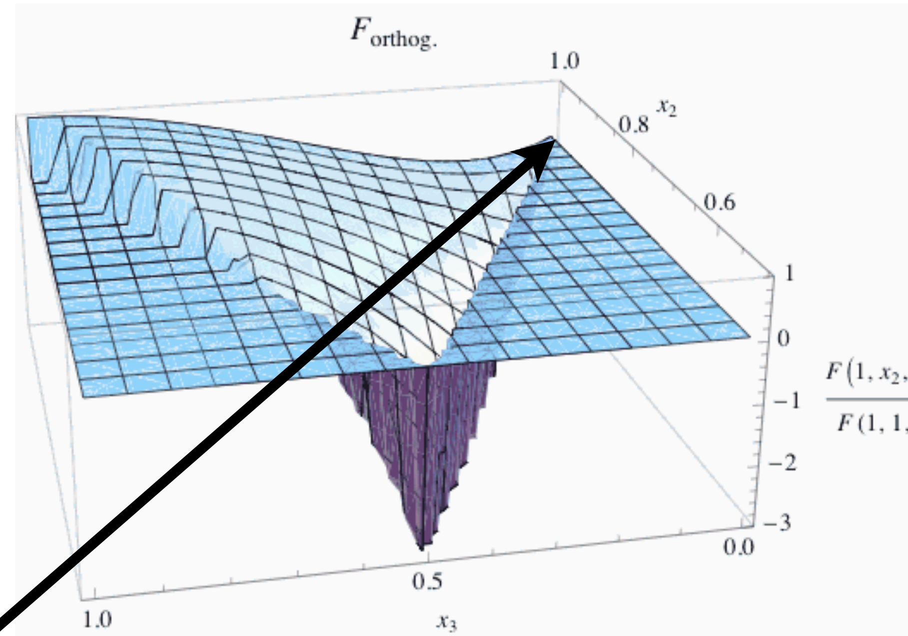
When the relevant dynamics happens well inside the horizon, velocities are larger and thus the NG effects are enhanced and eventually ruled out by Planck.

Slow roll has passed a very non-trivial test. But we have not closed the window. Should we declare victory?

$$c_s > 0.05 \qquad\qquad \frac{\gamma}{c_s^2 H} < 400$$

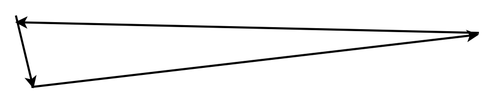
Shape and attractor solution





Squeezed limit

$$k_3 \ll k_2, k_1$$

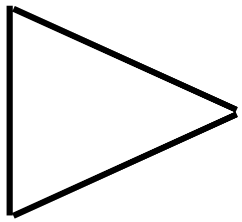


The vanishing amplitude in this limit is a direct reflection of the attractor nature of the inflationary solution.

Three point-function in single field slow roll inflation

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

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

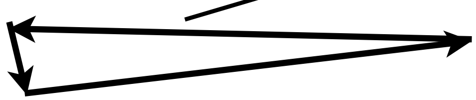


$$F_{\text{stand}}(\vec{k}_1,\vec{k}_2,\vec{k}_3) = \frac{1}{8}(2\pi)^4 P_{\mathcal{R}}^2 \cdot \frac{1}{\prod k_i^3}\left[(3\epsilon - 2\eta)\sum_i k_i^3 + \epsilon \sum_{i\neq j} k_i k_j^2 + 8\epsilon \frac{\sum_{i>j} k_i^2 k_j^2}{k_t}\right]$$

Local piece

suppressed in the squeezed limit

$k_3 \ll k_2, k_1$



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.

Only background that gives scale invariant Gaussian perturbations for the adiabatic mode is de Sitter.

Thus in other scenarios you are forced to get the fluctuations in the curvature from a conversion from another field.

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

Modes are all super-horizon during conversion.
They are all observable at the same time as they are all changing the equation of state at the same time. There is no suppression in the squeezed limit.

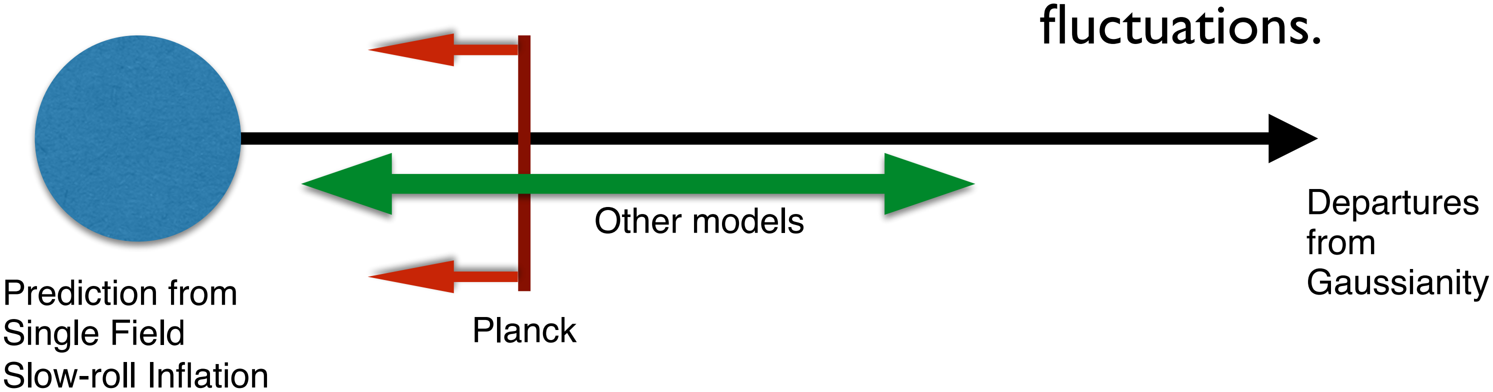
Planck 2015

Shape and method	f_{NL}(KSW) 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:

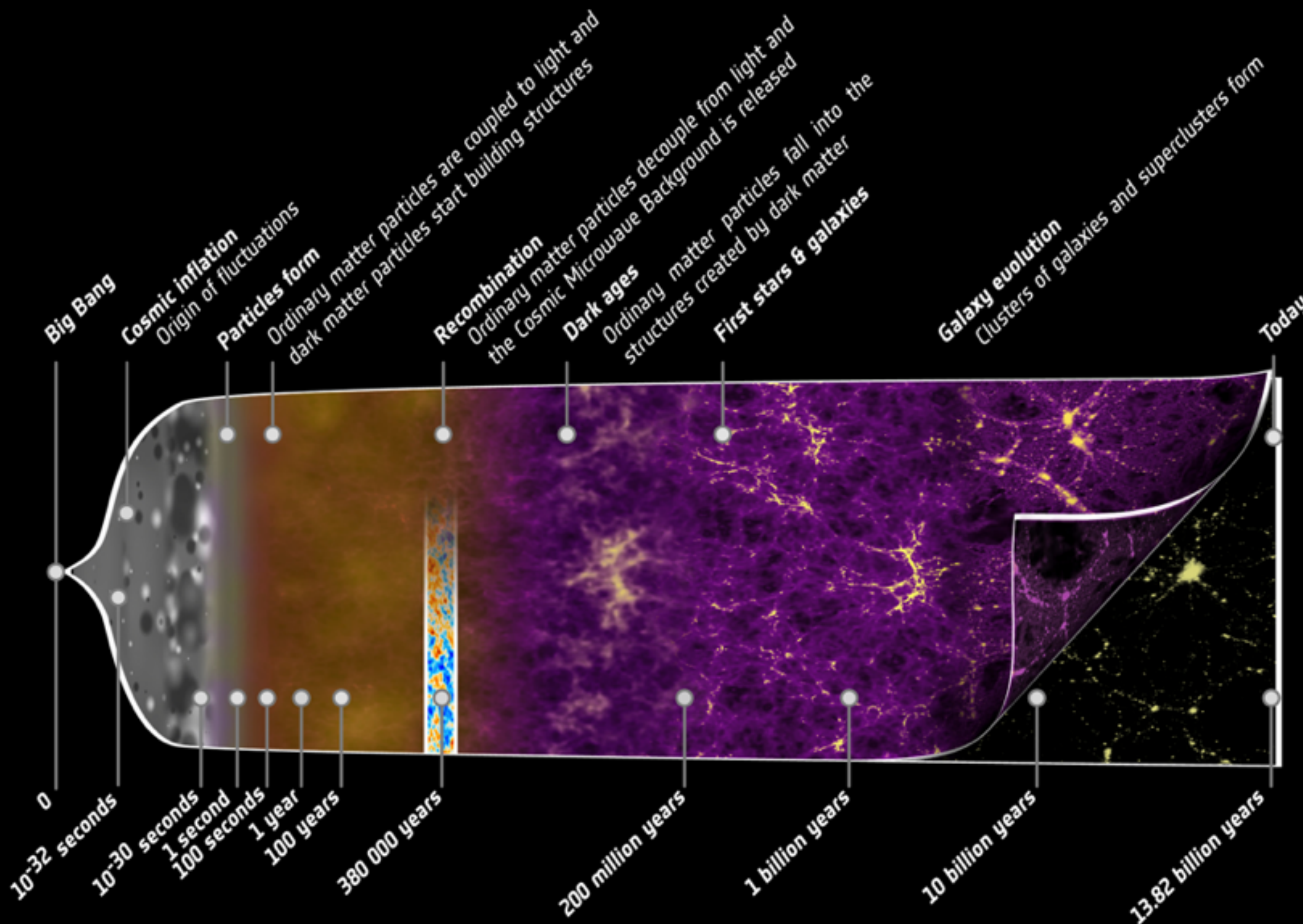
Local non-Gaussianity is zero because of attractor nature of inflation. Can only be true for clock.

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.

Is inflation the final theory ?



Could we ever get to a final theory?

Occam's razor vs Hickam's dictum

William of Ockham (*c*. 1285–1349) is remembered as an influential medieval philosopher and nominalist, though his popular fame as a great logician rests chiefly on the maxim attributed to him and known as Ockham's razor. The term *razor* refers to distinguishing between two hypotheses either by "shaving away" unnecessary assumptions or cutting apart two similar conclusions.

This maxim seems to represent the general tendency of Occam's philosophy, but it has not been found in any of his writings.[17] His nearest pronouncement seems to be *Numquam ponenda est pluralitas sine necessitate* [**Plurality must never be posited without necessity**], which occurs in his theological work on the 'Sentences of Peter Lombard' (*Quaestiones et decisiones in quattuor libros Sententiarum Petri Lombardi* (ed. Lugd., 1495), i, dist. 27, qu. 2, K).

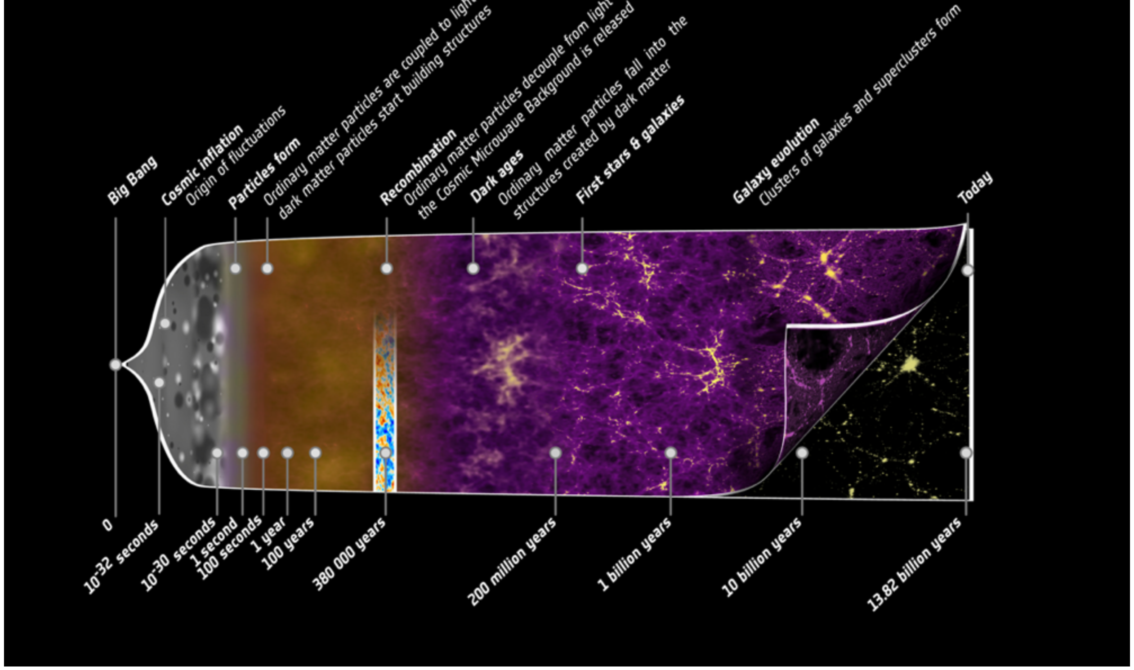
<u>Occam's razor vs Hickam's dictum</u>

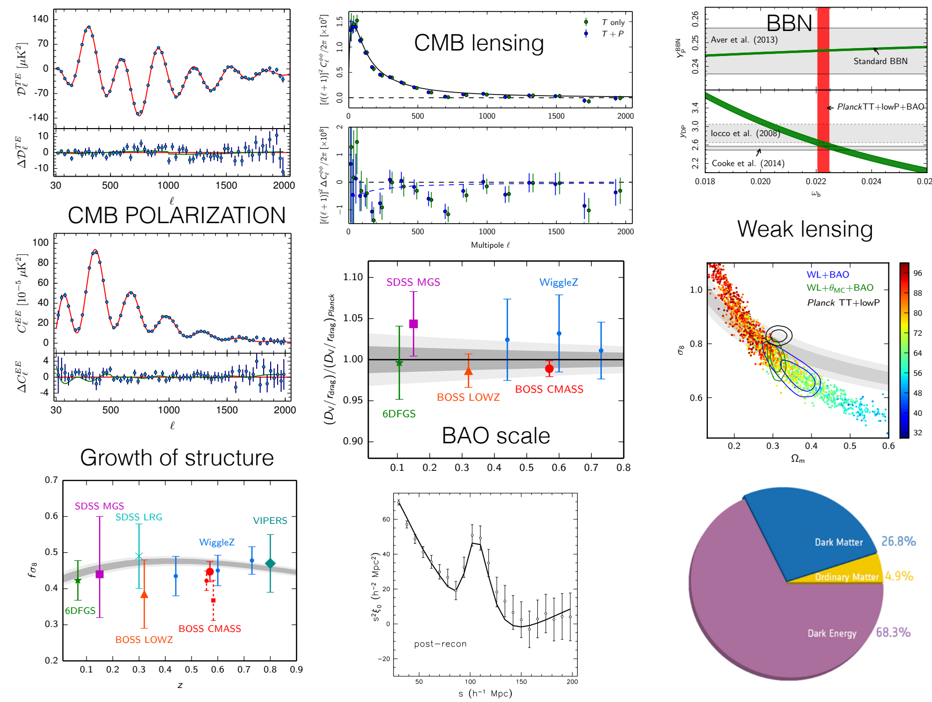
William of Ockham (*c*. 1285–1349) is remembered as an influential medieval philosopher and nominalist, though his popular fame as a great logician rests chiefly on the maxim attributed to him and known as Ockham's razor. The term *razor* refers to distinguishing between two hypotheses either by "shaving away" unnecessary assumptions or cutting apart two similar conclusions.

This maxim seems to represent the general tendency of Occam's philosophy, but it has not been found in any of his writings.[17] His nearest pronouncement seems to be *Numquam ponenda est pluralitas sine necessitate* [**Plurality must never be posited without necessity**], which occurs in his theological work on the 'Sentences of Peter Lombard' (*Quaestiones et decisiones in quattuor libros Sententiarum Petri Lombardi* (ed. Lugd., 1495), i, dist. 27, qu. 2, K).

Hickam's dictum is a counterargument to the use of Occam's razor in the medical profession.[1] The principle is commonly stated: **"Patients can have as many diseases as they damn well please"**. The principle is attributed to John Hickam, MD. Hickam was a faculty member at Duke University in the 1950s, and was later chairman of medicine at Indiana University.[2]

Summary





1. The seeds are primordial

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

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

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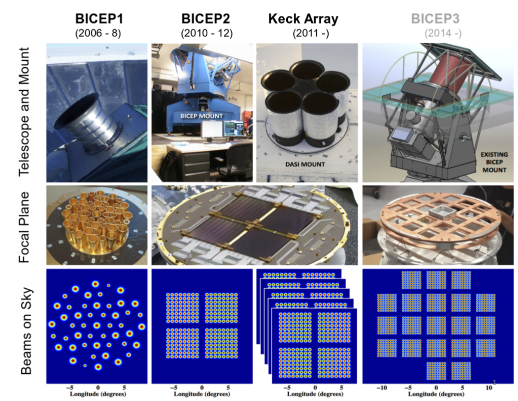
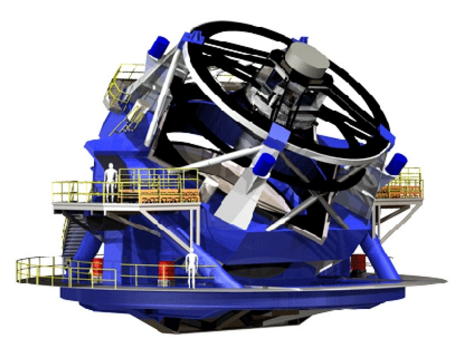
4. No gravitational waves (10 percent level)

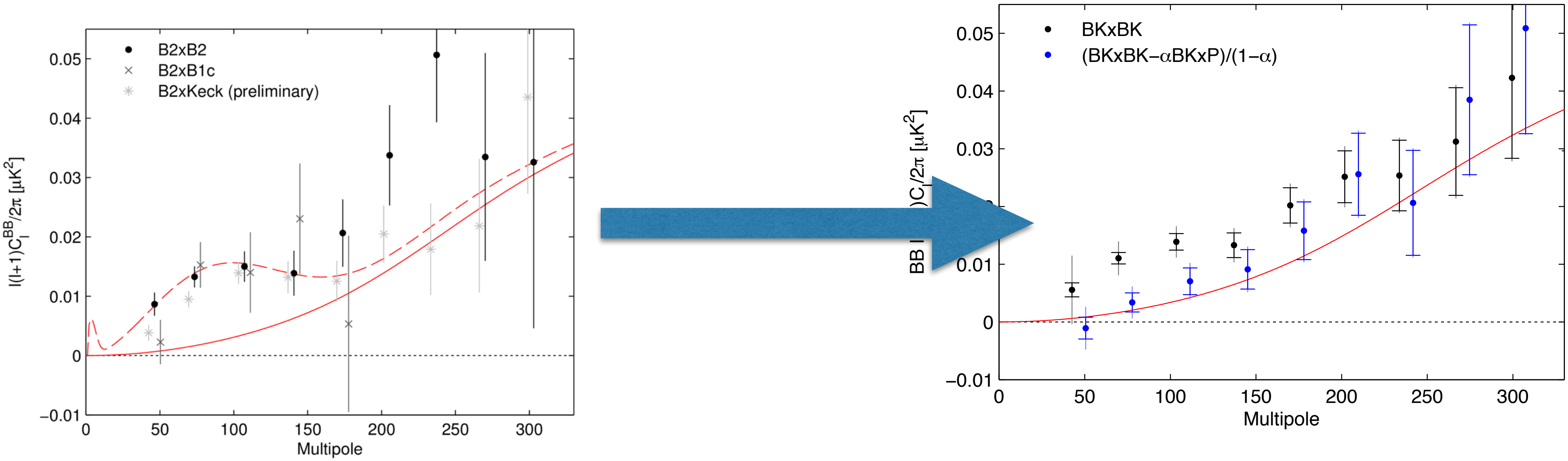
5. No fluctuation in composition (percent level)

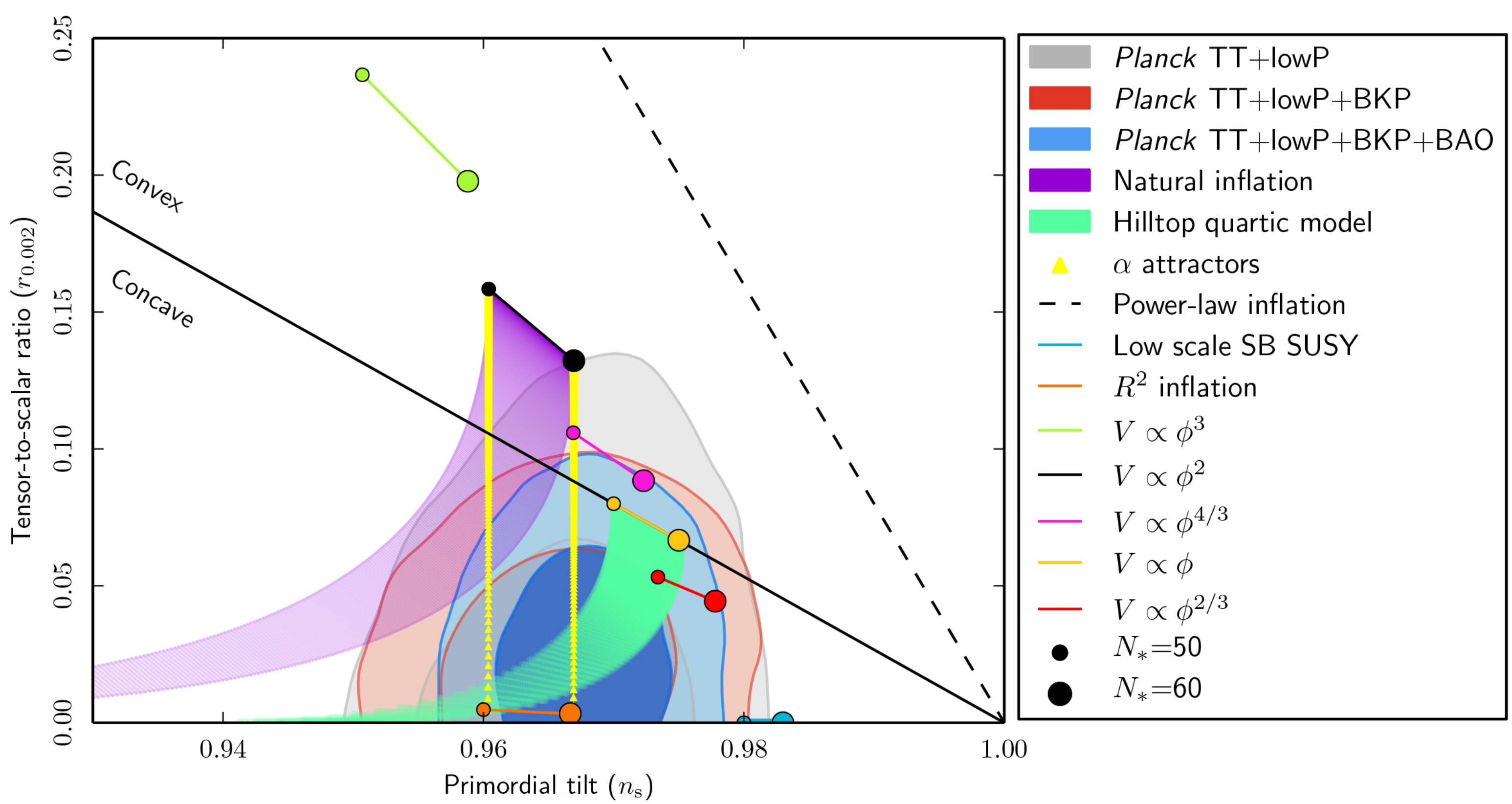
6. No departures from Gaussianity $\frac{\mathrm{Non-Gaussian}}{\mathrm{Gaussian}} < 10^{-3} - 10^{-4}$



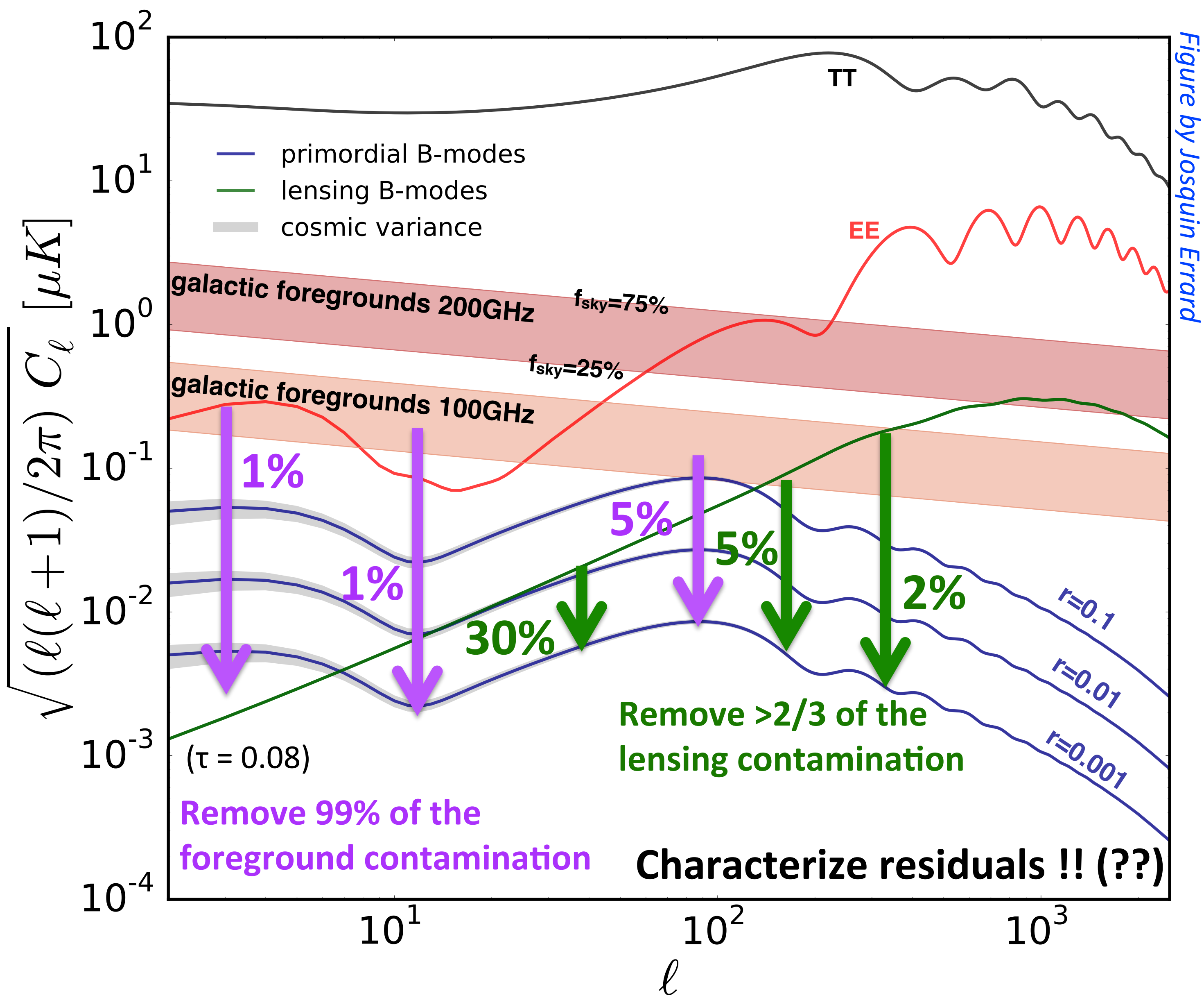


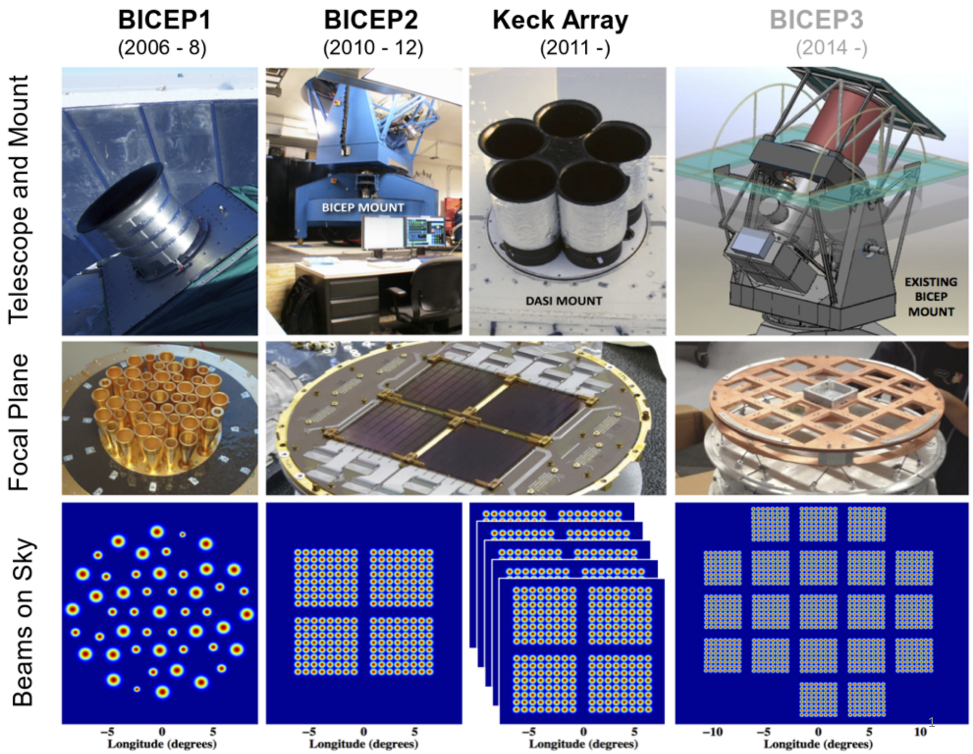
Future observatories


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


Convex
Concave
Tensor-to-scalar ratio ($r_{0.002}$)
Primordial tilt (n_s)
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

Understanding foregrounds is crucial





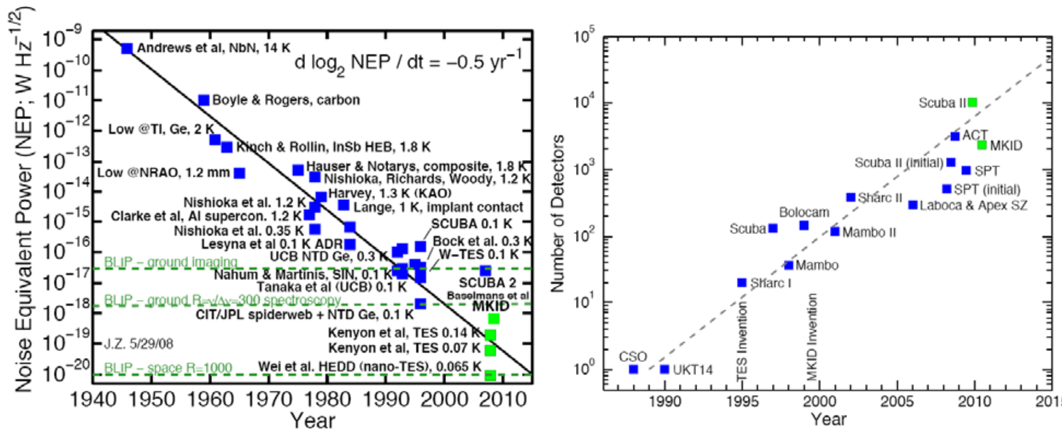
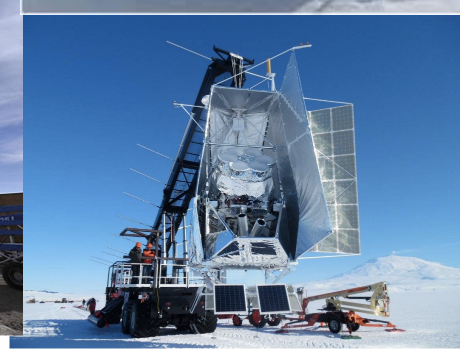


Fig. 1. Detector sensitivity **(left)** has historically doubled every 2 years over the past 70 years. Detector arrays **(right)** have doubled in format every 20 months over the past 10 years.



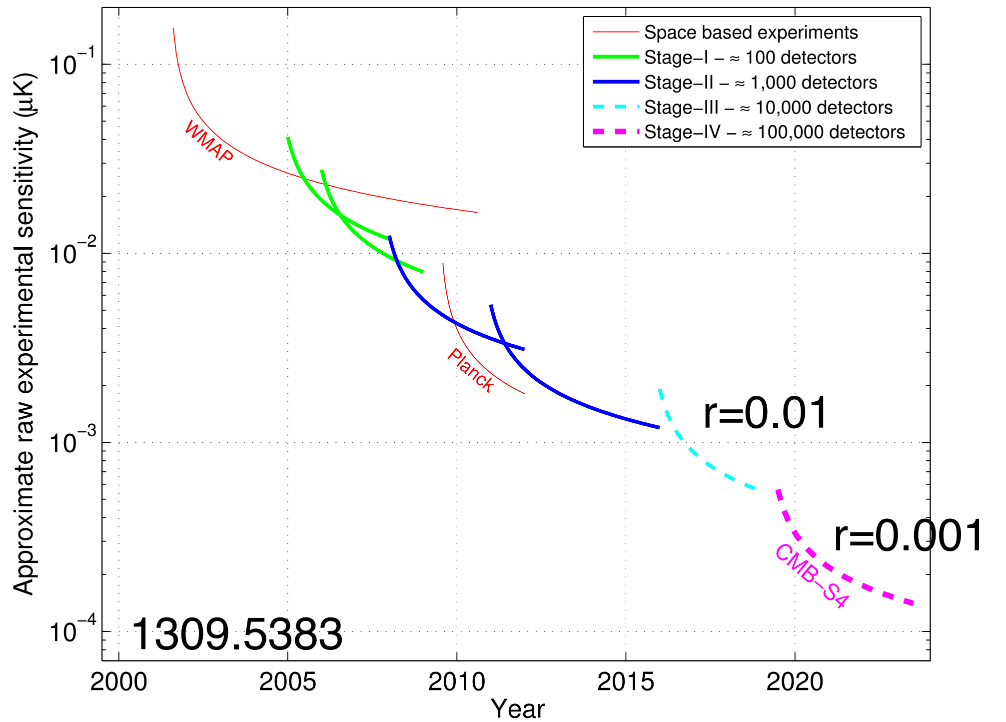


Figure 6. *Plot illustrating the evolution of the raw sensitivity of CMB experiments, which scales as the total number of bolometers. Ground-based CMB experiments are classified into Stages with Stage II experiments having O(1000) detectors, Stage III experiments having O(10,000) detectors, and a Stage IV experiment (such as CMB-S4) having O(100,000) detectors.*

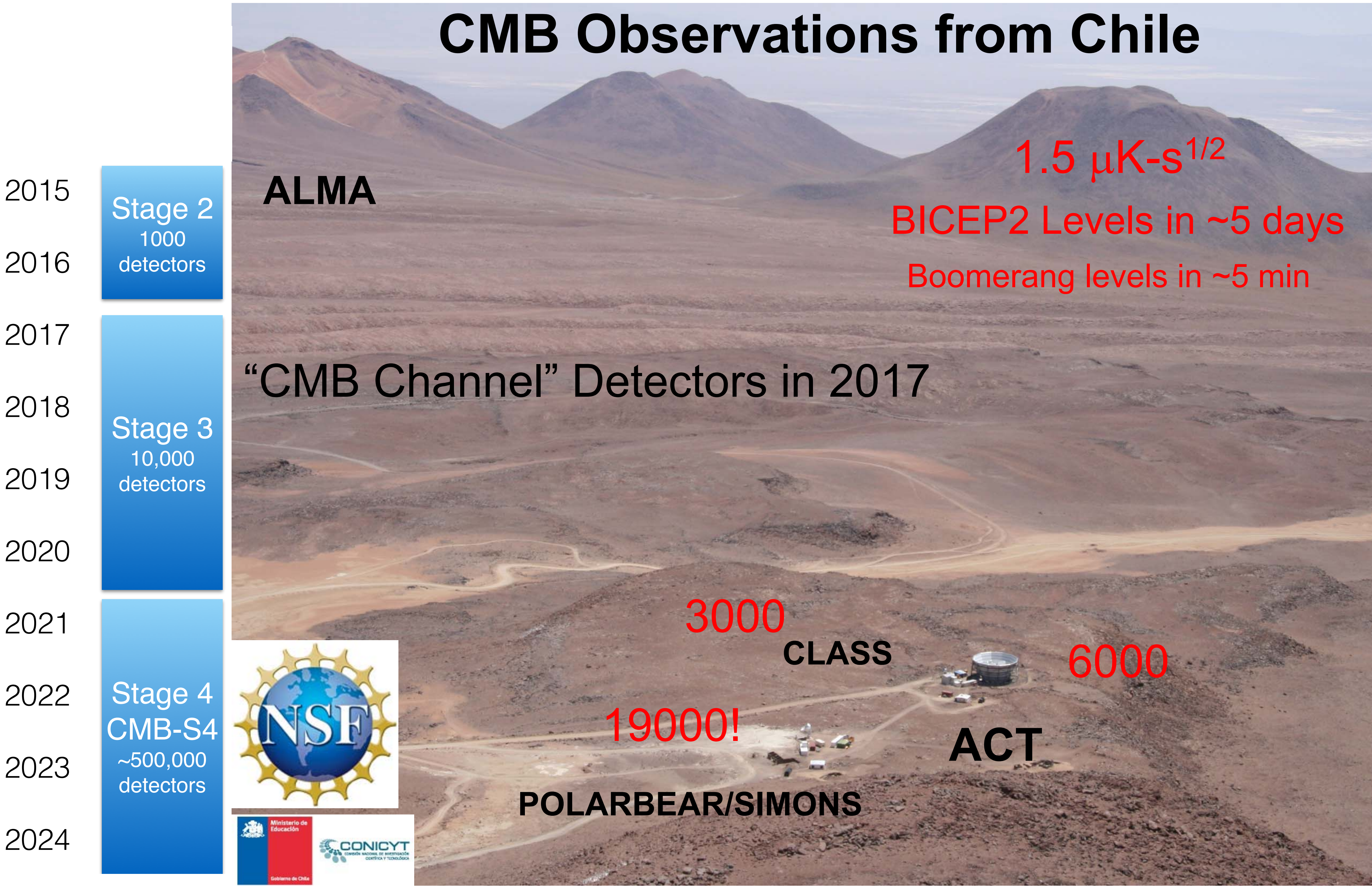


Figure 2. *Schematic timeline of evolution of Stage 3 and CMB-S4 sensitivity in μK^2 and the expected improvement in a few of the key cosmological parameters.*

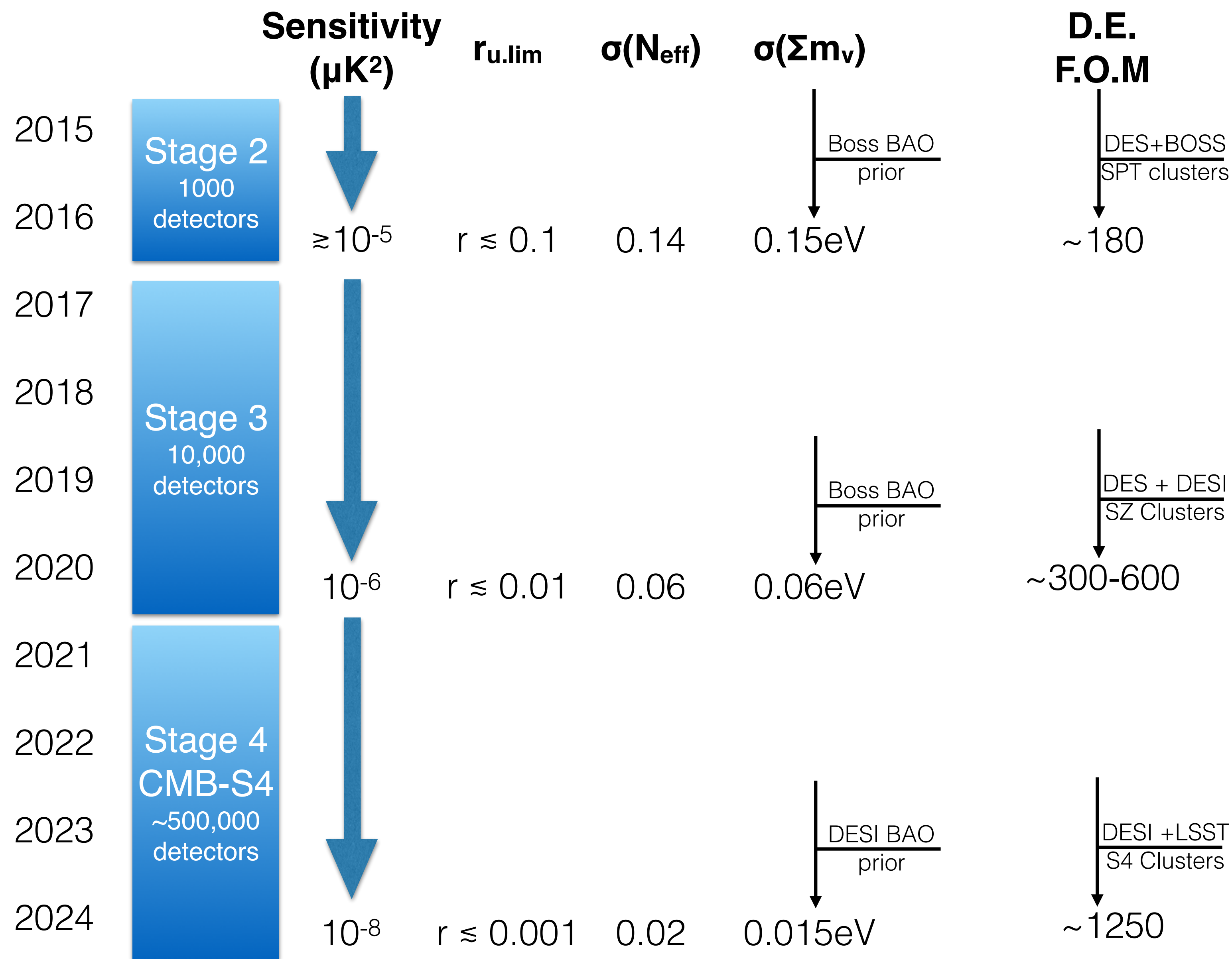
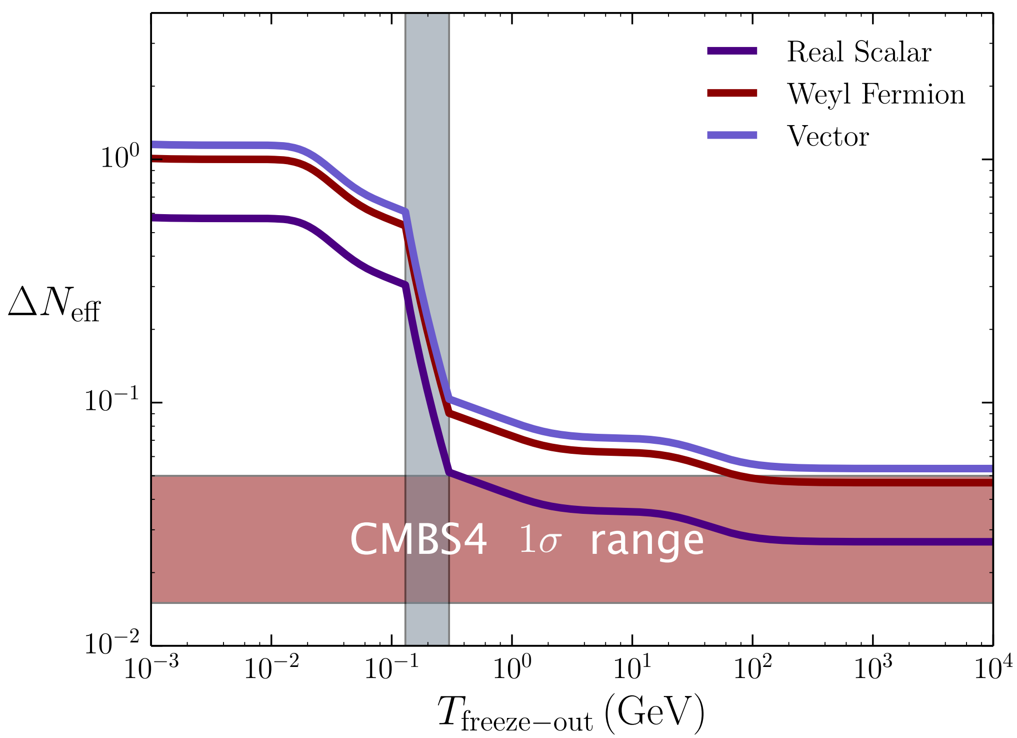
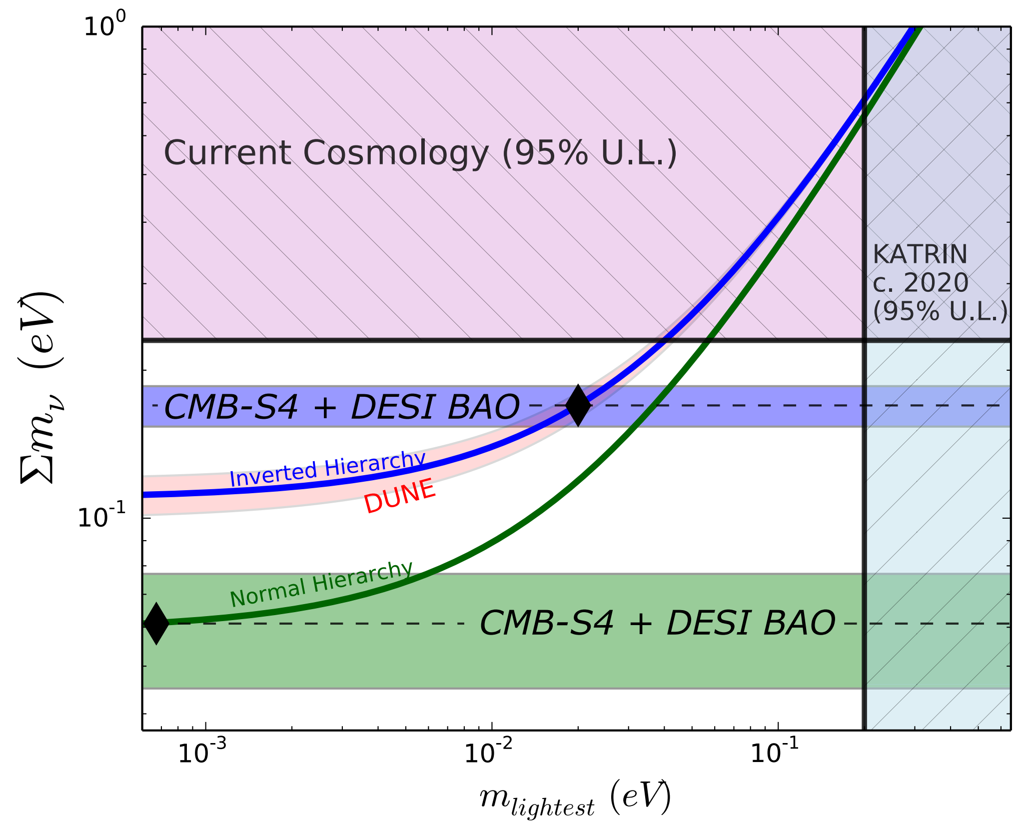


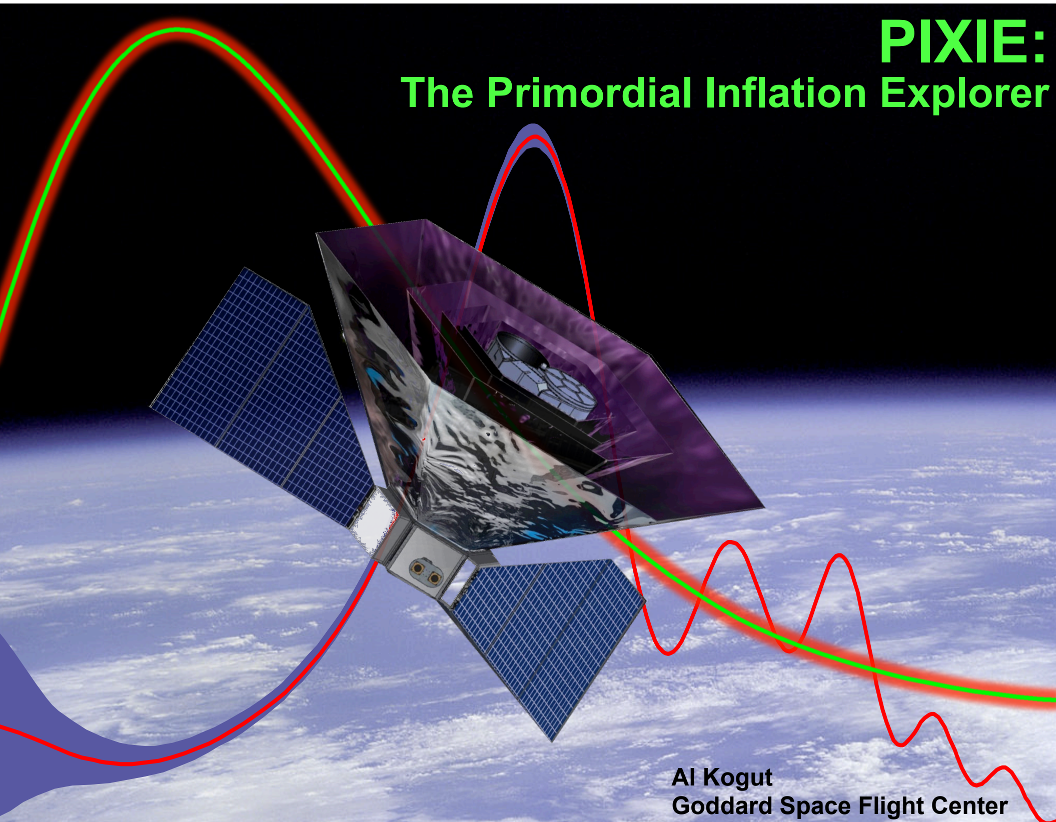
Figure 2. *Schematic timeline of evolution of Stage 3 and CMB-S4 sensitivity in μK^2 and the expected improvement in a few of the key cosmological parameters.*

Additional relativistic species through detailed study of the acoustic peaks



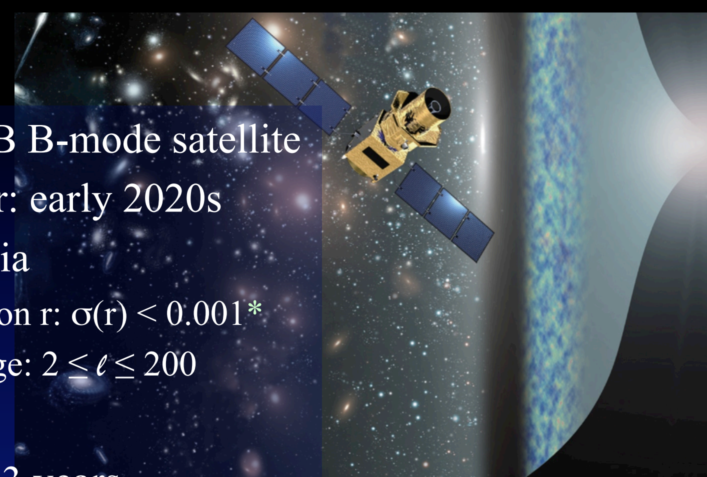
Neutrino masses through lensing





LiteBIRD

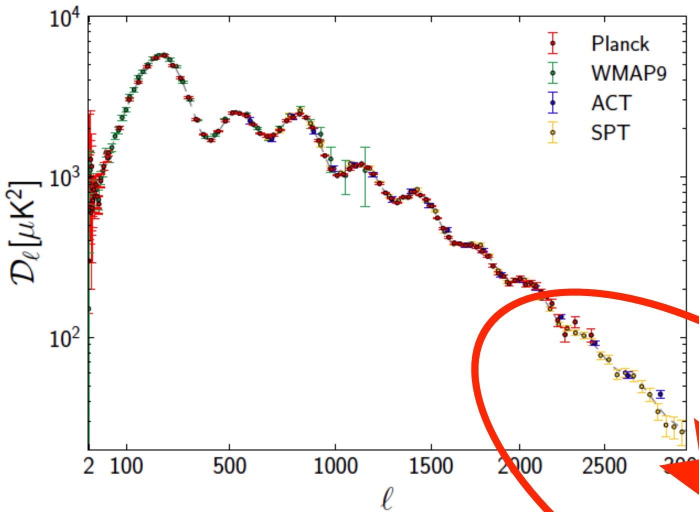
Lite (Light) Satellite for the Studies of B-mode Polarization and Inflation from Cosmic Background Radiation Detection



- JAXA-based CMB B-mode satellite
- Target launch year: early 2020s
- Full success criteria
  - Total uncertainty on r: $\sigma(r) < 0.001$*
  - Multipole coverage: $2 \leq \ell \leq 200$
- Orbit: L2
- Observing time: ≥3 years

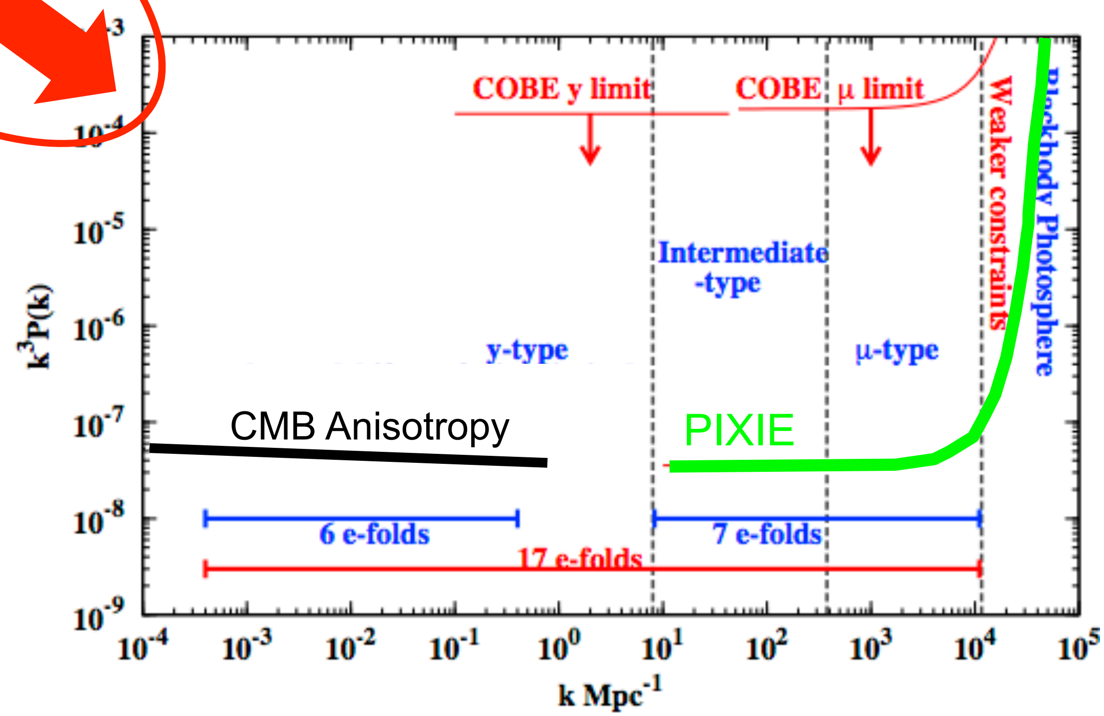
*Studies with our current design indicate better performance

Beyond the Power Spectrum



Spectral distortions extend tests of inflation by 4 orders of magnitude in physical scale

- Scalar index and running
- Non-Gaussian f_{NL}
- Tensor index and running

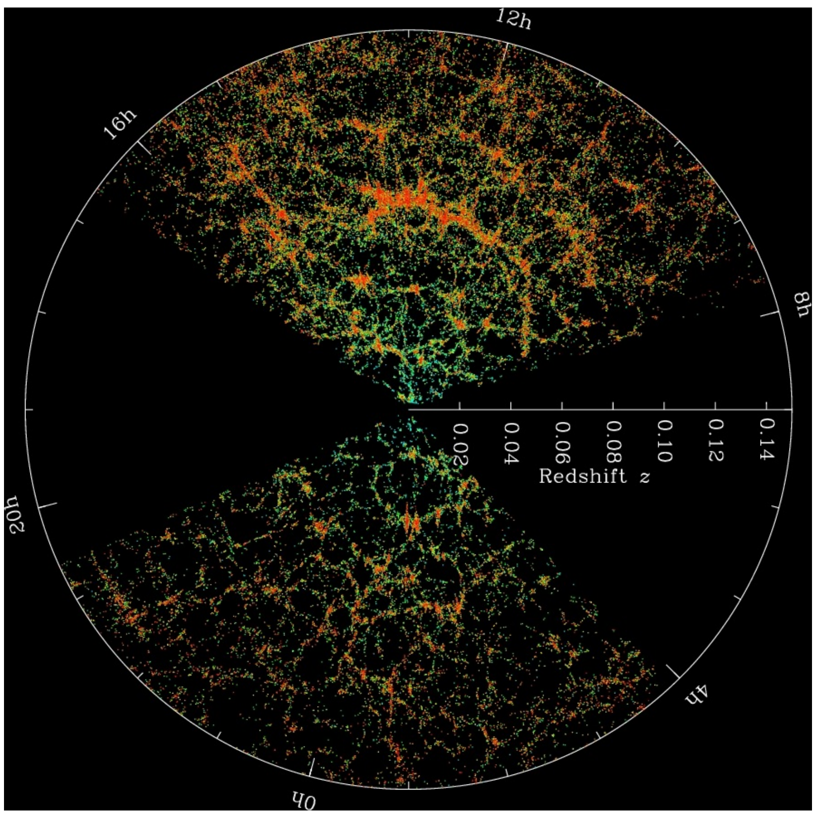


Complementary to both CMB anisotropy and polarization

Sunyaev & Khatri 2013

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.



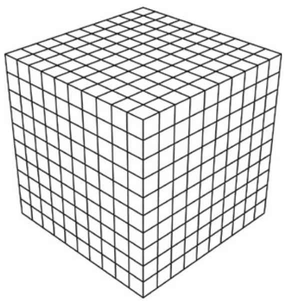
Constraints are statistical in nature, they scale as

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

Statistical vs theoretical errors

Planck 10^6 modes

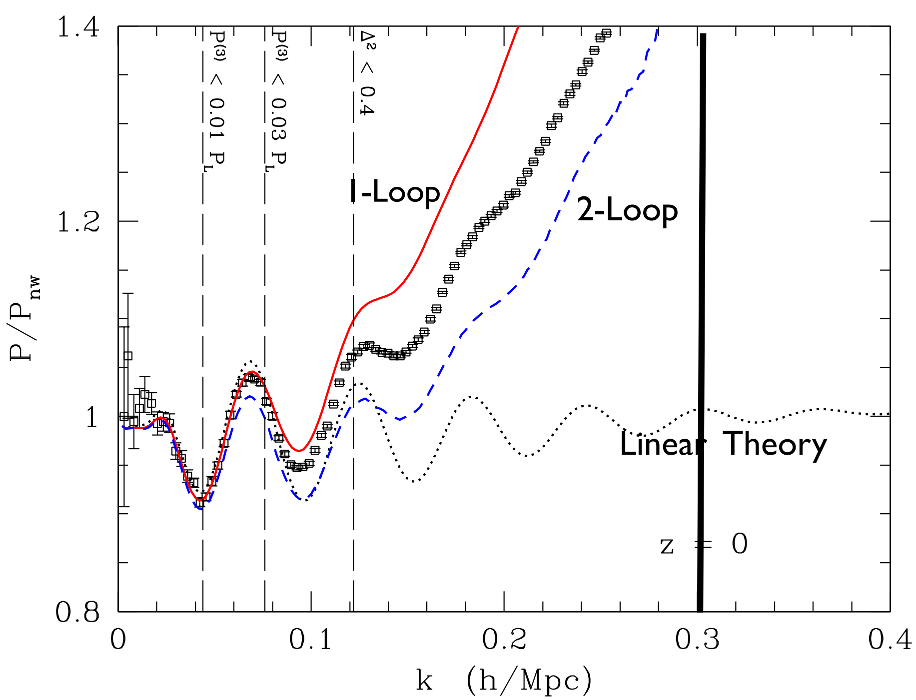
Statistical errors decrease as: $$N_{\mathrm{modes}}^{-1/2}$$



$$k_{\max} = \frac{\pi}{l}$$

$$N_{\mathrm{modes}} = (\frac{L}{l})^3 = \frac{V k_{\max}^3}{\pi^3}$$

redshift range	Volume Gpc^3	kmax h Mpc^{-1} (Planck x 10)
0-1	50	0.4
1-2	140	0.3
2-3	160	0.3



Nonlinear corrections grow rapidly with k

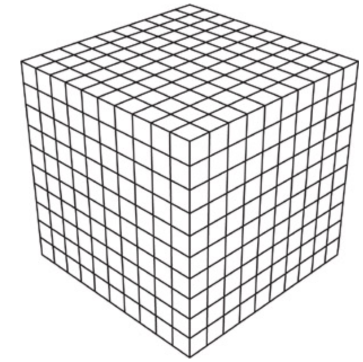
<u>Where will the constrains come from?</u>

Recent results using the EFT of LSS

Assasi, Baldauf, Mercolli, Mirbabayi, Schaan, Schmitfull, Senatore, Simonovic

EFT of LSS

Describe the dynamics on large scales, after integrating out the short scale modes.



$$\partial_\tau \delta + \partial_i[(1+\delta)v^i] = \partial_i u^i \ ,$$

$$\partial_\tau v^i + \mathcal{H}v^i + \partial^i\phi + v^j\partial_j v^i = -\frac{1}{a\rho}\partial_j\tau^{ij}$$

$$\triangle\phi = \frac{3}{2}\mathcal{H}^2\Omega_{\rm m}\delta \ .$$

$$\delta = \delta_{(1)} + \delta_{(2)} + \delta_{(3)} + \delta_{(4)} + \delta_{(5)} + \cdots$$

$$\tau_\theta \equiv -\partial_i\left[\frac{1}{a\rho}\partial_j\tau^j\right] = \tau_\theta^{\rm det} + \tau_\theta^{\rm stoch}$$

$$\tau_\theta^{\rm det} = \tau_\theta^{\rm det}[\partial_i\partial_j\bar{\phi}].$$

$$\tau_\theta^{\rm det}\big|_{\rm LO} = -d^2\triangle\delta_{(1)} = -d^2\triangle\triangle\bar{\phi}_{(1)}$$

$$\tau_\theta^{\rm det}\big|_{\rm NLO} = -d^2\triangle[\delta_{(1)} + \delta_{(2)}] - e_1\triangle\delta_{(1)}^2 - e_2\triangle(s_{ij(1)}s^{ij}_{(1)}) - e_3\partial_i s^{ij}_{(1)}\partial_j\delta_{(1)},$$

$$s_{ij} = \left(\partial_i\partial_j - \frac{1}{3}\delta^{(\rm K)}_{ij}\triangle\right)\bar{\phi}.$$

EFT of LSS

- Study regime of small corrections
- Characterize terms
- Calculable vs non-calculable (counter terms)
- How many terms to achieve a desired accuracy?
- What is the relation between results for different statistics

EFT terms

- Write all terms consistent with symmetries: Mass & momentum conservation, equivalence principle
- Non-locality in time

Examples:

$\delta_0(\boldsymbol{k})$ Initial conditions

$$\delta^{(2)}(\boldsymbol{k}) = \int_p \left[\frac{3}{14}\left(1 - \frac{(\boldsymbol{p}_1\cdot\boldsymbol{p}_2)^2}{\boldsymbol{p}_1^2\boldsymbol{p}_2^2}\right) + \frac{1}{2}\frac{\boldsymbol{k}\cdot\boldsymbol{p}_2}{\boldsymbol{p}_1^2}\frac{\boldsymbol{k}\cdot\boldsymbol{p}_2}{\boldsymbol{p}_2^2}\right]\delta_0(\boldsymbol{p}_1)\delta_0(\boldsymbol{p}_2)$$

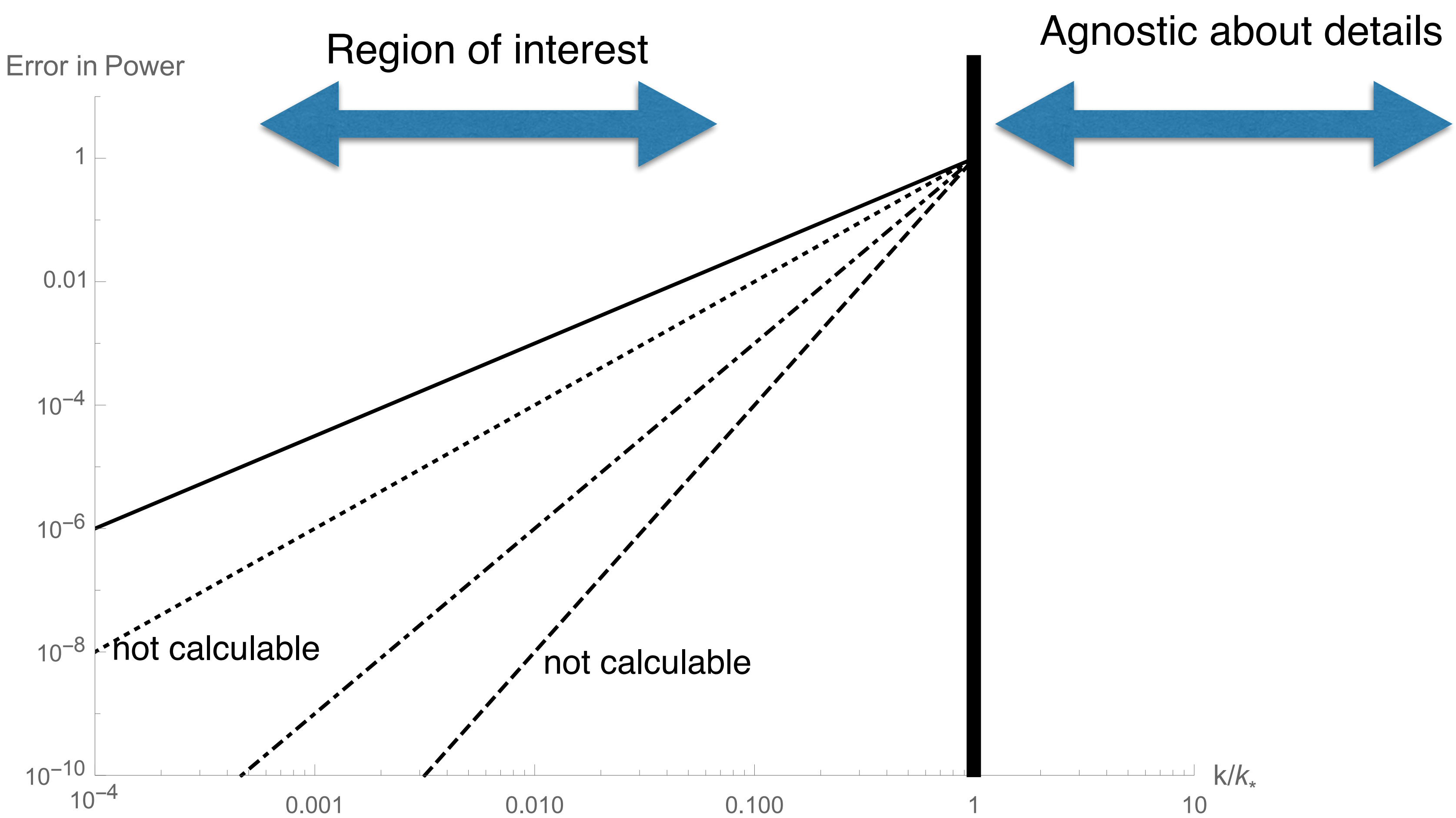
First correction

$$\delta^{ct(1)}(\boldsymbol{k}) = l_1^2\boldsymbol{k}^2\delta_0(\boldsymbol{k}) + l_1^2\int_p \frac{\boldsymbol{k}\cdot\boldsymbol{p}_1}{\boldsymbol{p}_1^2}\frac{\boldsymbol{k}\cdot\boldsymbol{p}_2}{\boldsymbol{p}_2^2}\boldsymbol{p}_1^2\delta_0(\boldsymbol{p}_1)\delta_0(\boldsymbol{p}_2)$$

first “un-calculable” piece (starts linear)

$$\delta^{ct(2)}(\boldsymbol{k}) = \int_p \left[l_{21}^2\boldsymbol{k}^2 + l_{22}^2\boldsymbol{k}^2(1 - \frac{(\boldsymbol{p}_1\cdot\boldsymbol{p}_2)^2}{\boldsymbol{p}_1^2\boldsymbol{p}_2^2}) + l_{23}^2\frac{\boldsymbol{k}\cdot\boldsymbol{p}_1\ \boldsymbol{k}\cdot\boldsymbol{p}_2\ \boldsymbol{p}_1\cdot\boldsymbol{p}_2}{\boldsymbol{p}_1^2\boldsymbol{p}_2^2}\right]\delta_0(\boldsymbol{p}_1)\delta_0(\boldsymbol{p}_2)$$

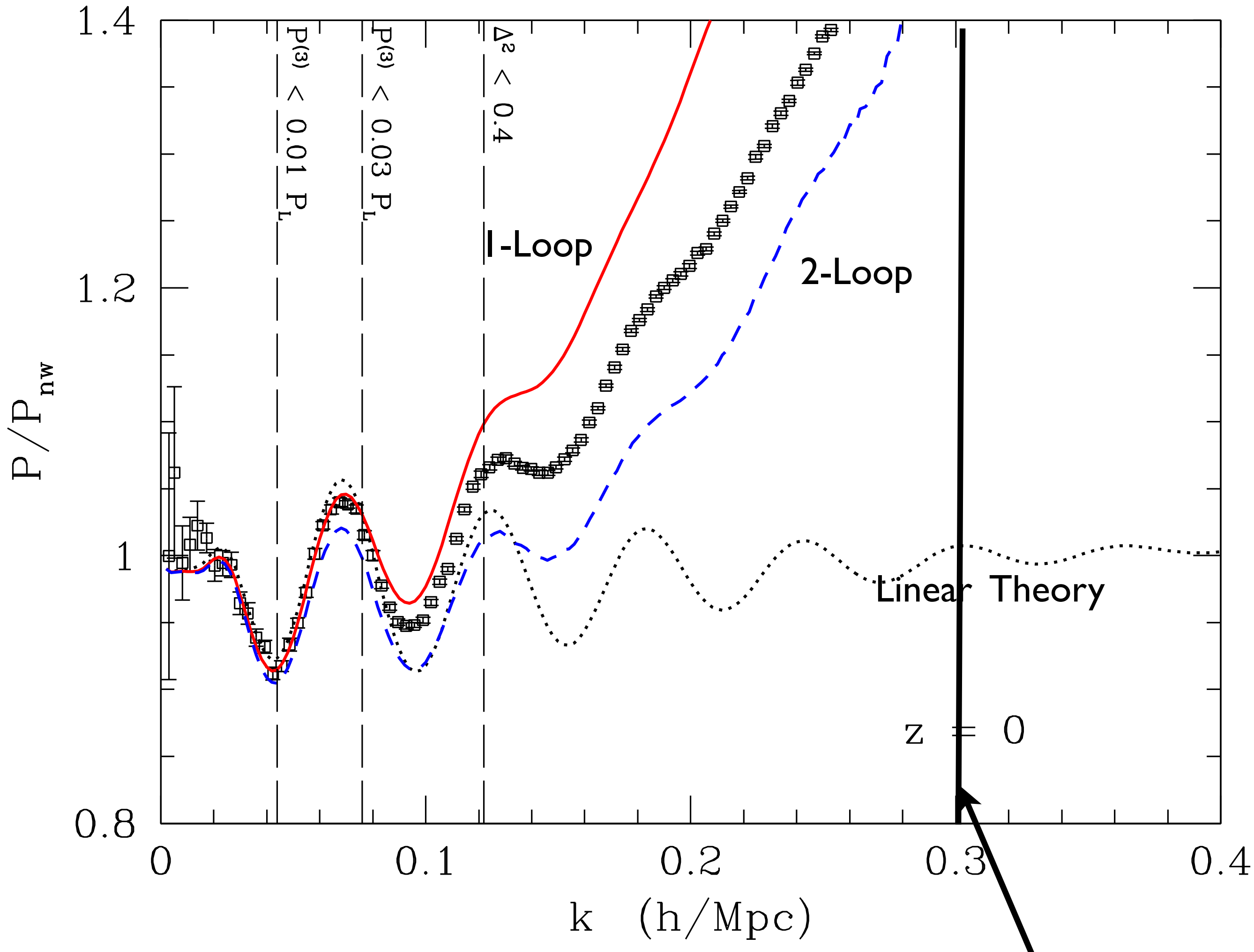
“un-calculable” pieces
that starts quadratic



There are contributions whose size cannot be computed within the large scale theory, they depend on the details of the small scale dynamics. However there k dependence is known.

$$\delta^{ct(1)}(\boldsymbol{k}) = l_1^2 \boldsymbol{k}^2 \delta_0(\boldsymbol{k}) + l_1^2 \int_p \frac{\boldsymbol{k}\cdot\boldsymbol{p}_1}{\boldsymbol{p}_1^2} \frac{\boldsymbol{k}\cdot\boldsymbol{p}_2}{\boldsymbol{p}_2^2} \boldsymbol{p}_1^2 \delta_0(\boldsymbol{p}_1)\delta_0(\boldsymbol{p}_2)$$

Standard Perturbation Theory

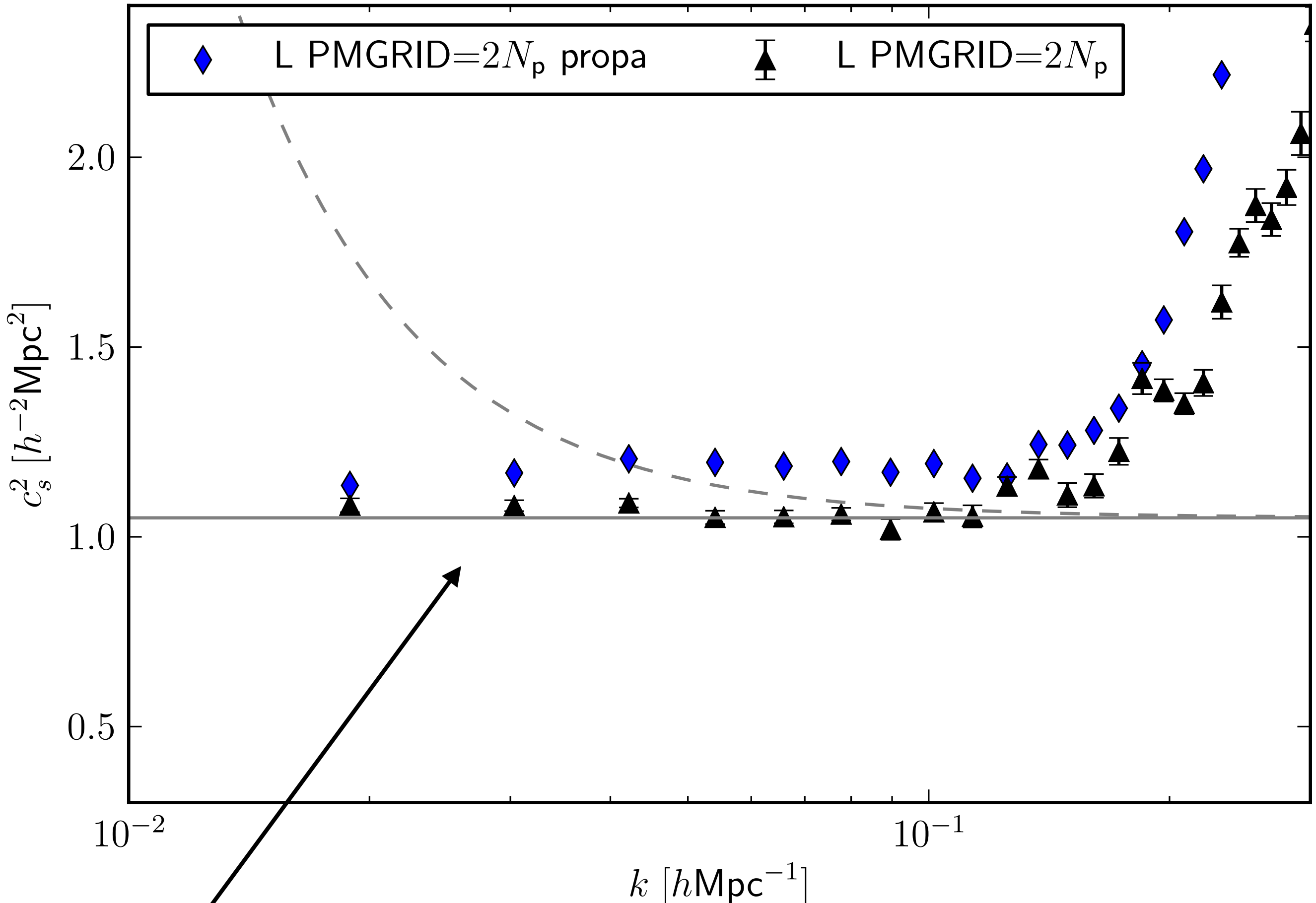


At this scale the 2-loop EFT is good to 1 %

Carlson et al 0905.0479

Amplitude of the first non-calculabe term:

l_1^2

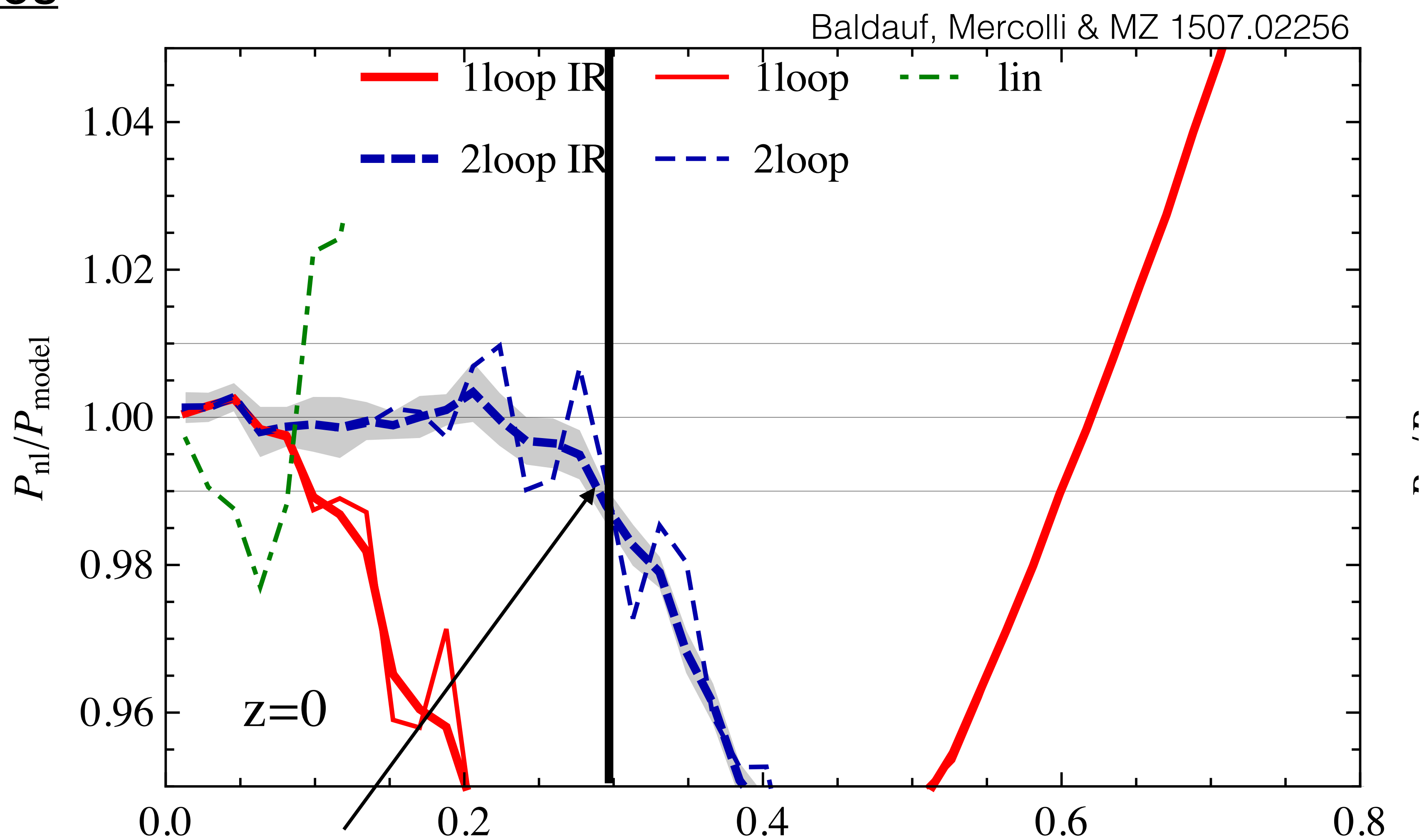


$$\delta^{ct(1)}(\boldsymbol{k}) = l_1^2 \boldsymbol{k}^2 \delta_0(\boldsymbol{k}) + l_1^2 \int_p \frac{\boldsymbol{k}\cdot\boldsymbol{p}_1}{\boldsymbol{p}_1^2}\frac{\boldsymbol{k}\cdot\boldsymbol{p}_2}{\boldsymbol{p}_2^2}\boldsymbol{p}_1^2 \delta_0(\boldsymbol{p}_1)\delta_0(\boldsymbol{p}_2)$$

Measured on large scales

Baldauf, Mercolli & MZ 1507.02256

Comparison with sims once non-calculable term measured on large scales



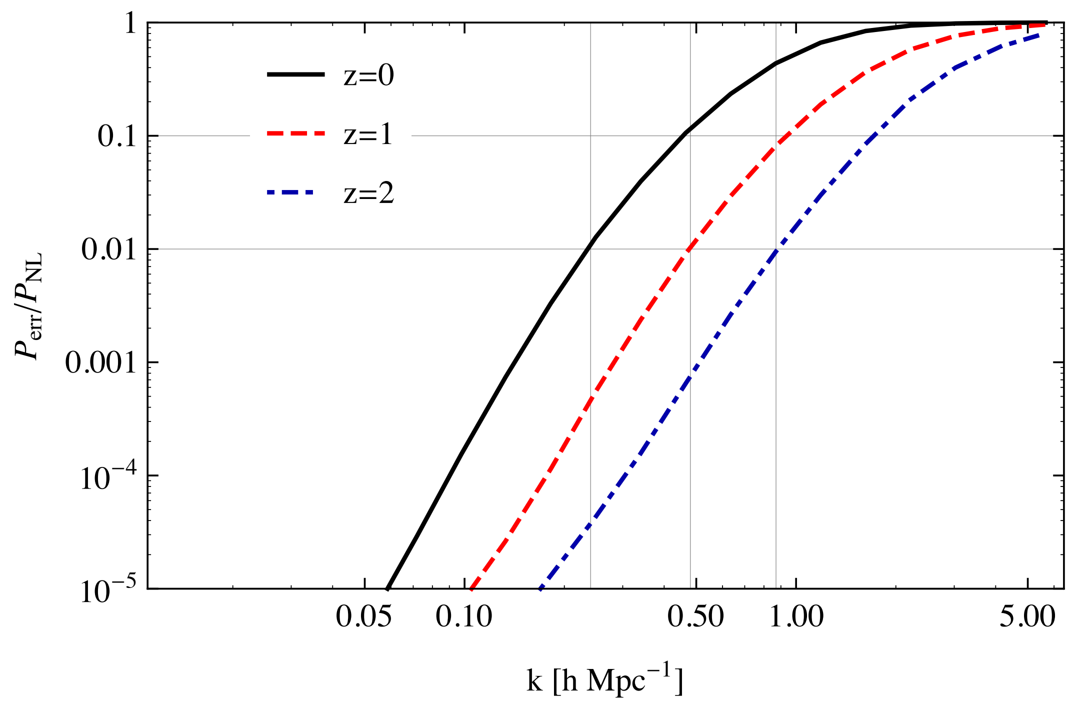
Improvements in the mildly non-linear regime

$$\delta^{ct(1)}(\boldsymbol{k}) = l_1^2 \boldsymbol{k}^2 \delta_0(\boldsymbol{k}) + l_1^2 \int_p \frac{\boldsymbol{k}\cdot\boldsymbol{p}_1}{\boldsymbol{p}_1^2}\frac{\boldsymbol{k}\cdot\boldsymbol{p}_2}{\boldsymbol{p}_2^2}\boldsymbol{p}_1^2 \delta_0(\boldsymbol{p}_1)\delta_0(\boldsymbol{p}_2)$$

Amplitude determined at k=0.02, shape known theoretically improvement at k=0.3

Comparison realization by realization

Baldauf, Schaan & MZ 1505.07098, 1507.02255



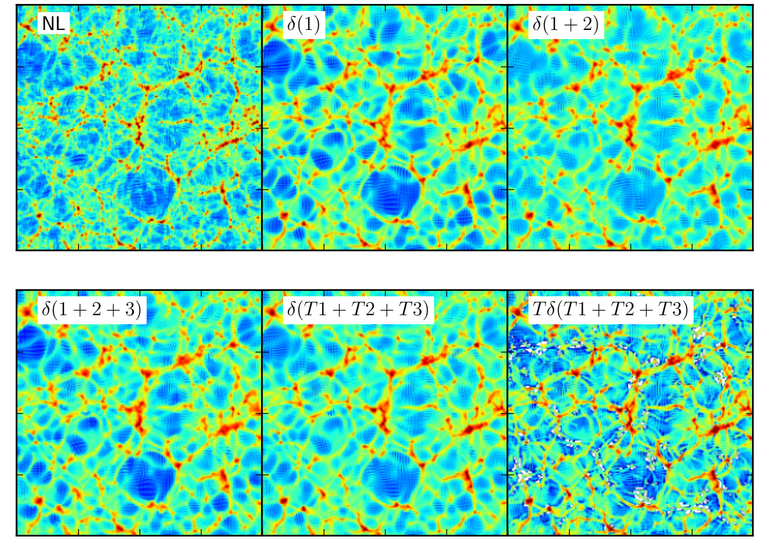
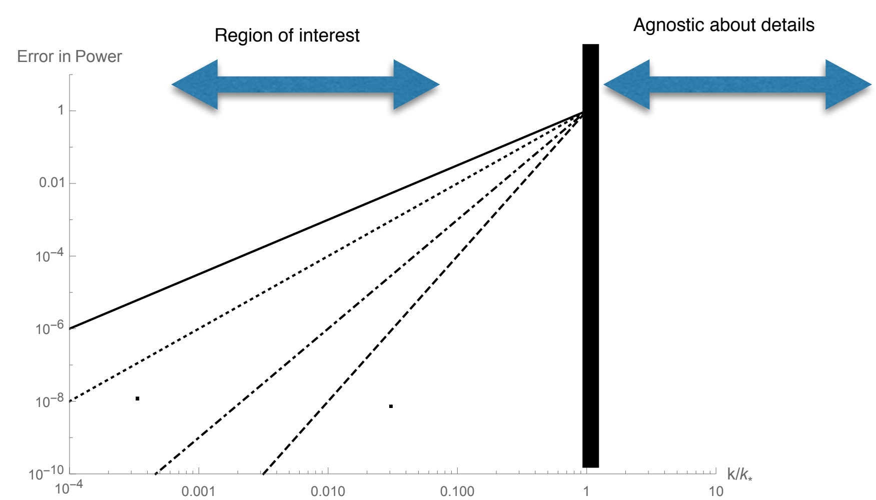


Figure 7. Non linear transformation of the density field in a patch of 300 h^{-1}Mpc length and 15 h^{-1}Mpc depth.



Note: no cosmic variance
When you consider biased tracers shot noise will be larger, so this accuracy for the dark matter is more than sufficient.

General lessons from EFT

- The small scale dynamics that is not captured by perturbation theory introduces a small number of free parameters that need to be fitted from simulation or data
- We understand the structure of these new terms, their dependence with scale is fixed.
- Calculations come with theoretical error bars.
- We are not strangers to these type of things, bias, higher dimension operators in particle physics.

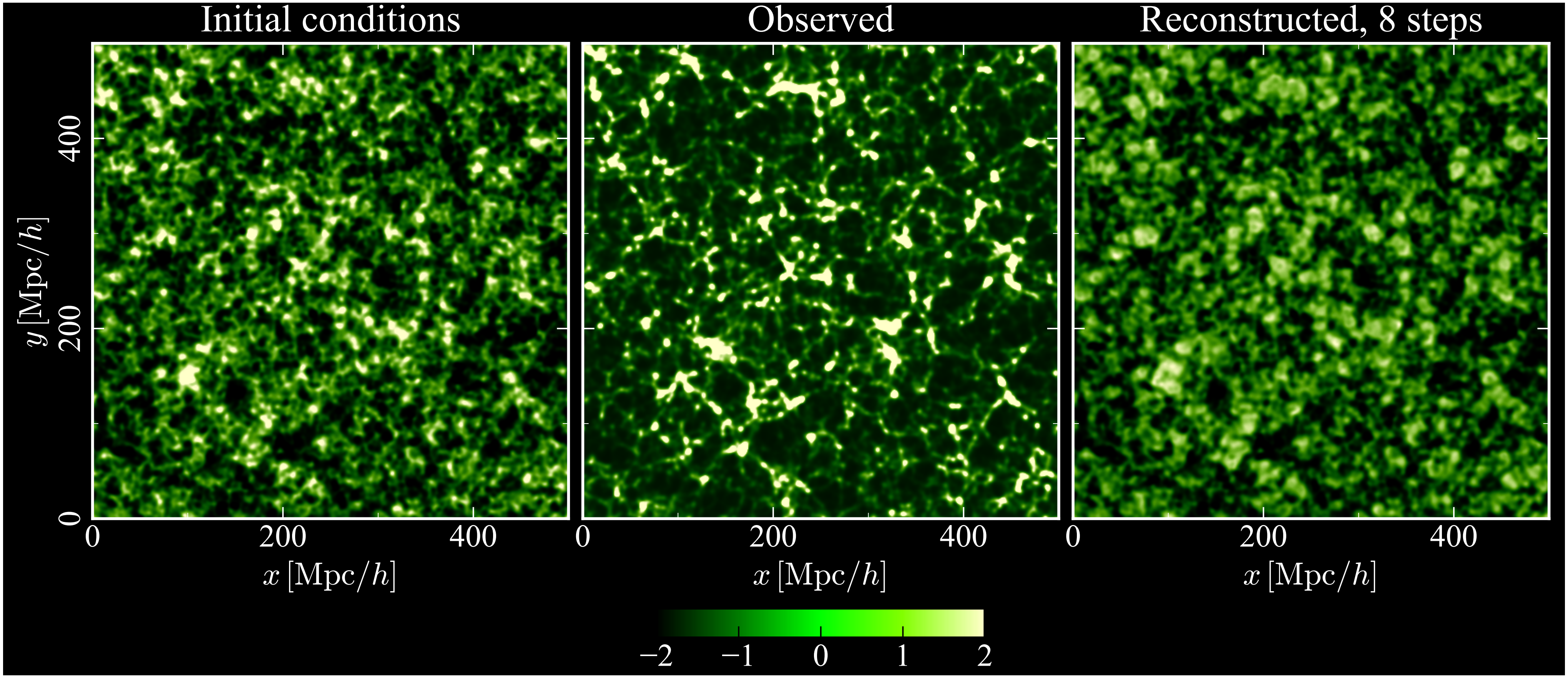
Interesting conceptual differences to standard QFT set up

- Non-locality in time
- Prevalence of composite operators

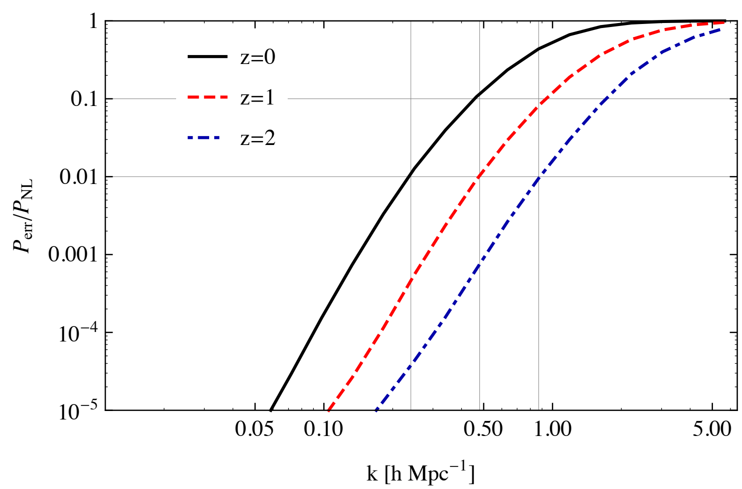
Additional things to consider

- Biased tracers, redshift space distortions, bispectrum
- Better comparison with simulations to cross the percent level accuracy
- Where is the information on parameters of interest?

Backward modeling/reconstruction



$$\delta_{NL} = \delta_{PT}[\delta_{lin}] + \mathrm{error}$$



Filter the non-linear density and solve for the linear density