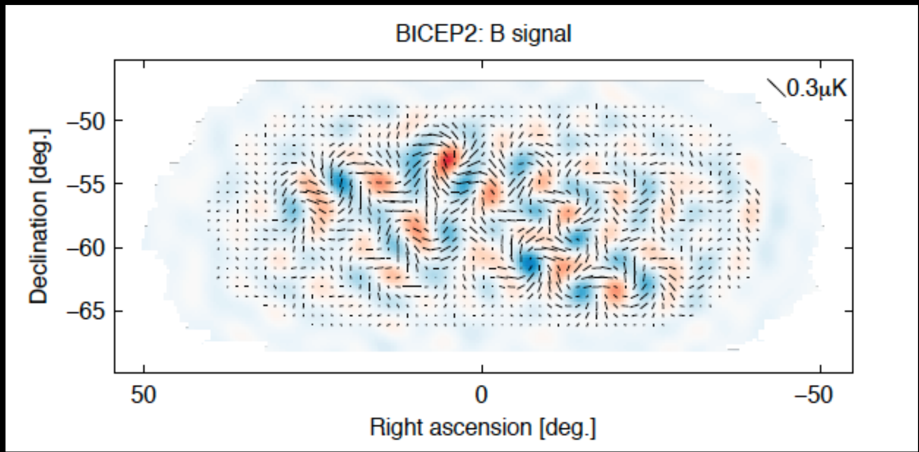
Implications of the Bicep2 Results
(if the interpretation is correct)



Antonio Riotto
Geneva University & CAP

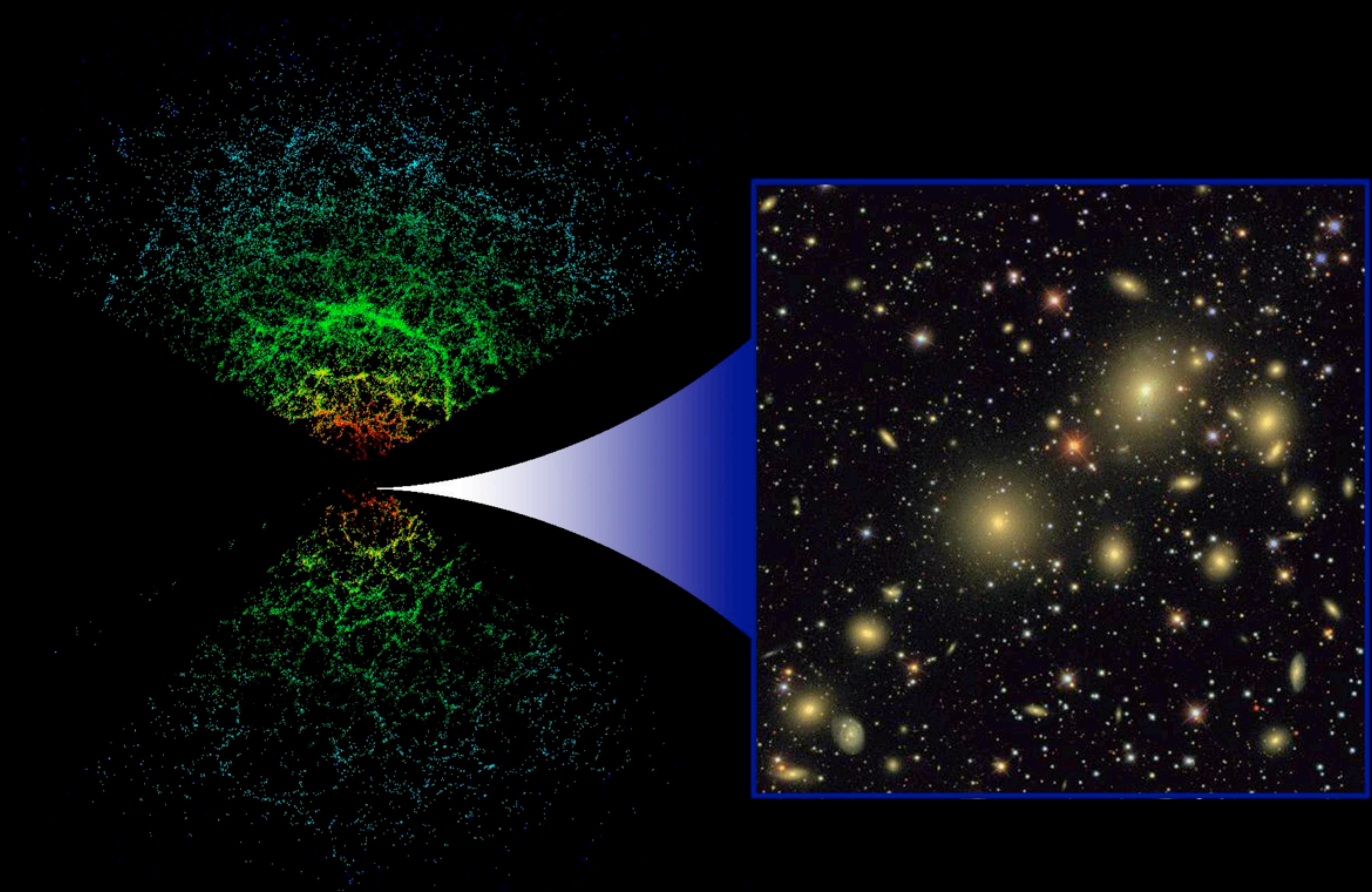
Center for Astroparticle Physics
GENEVA

La Sapienza, Roma, 12/6/2014

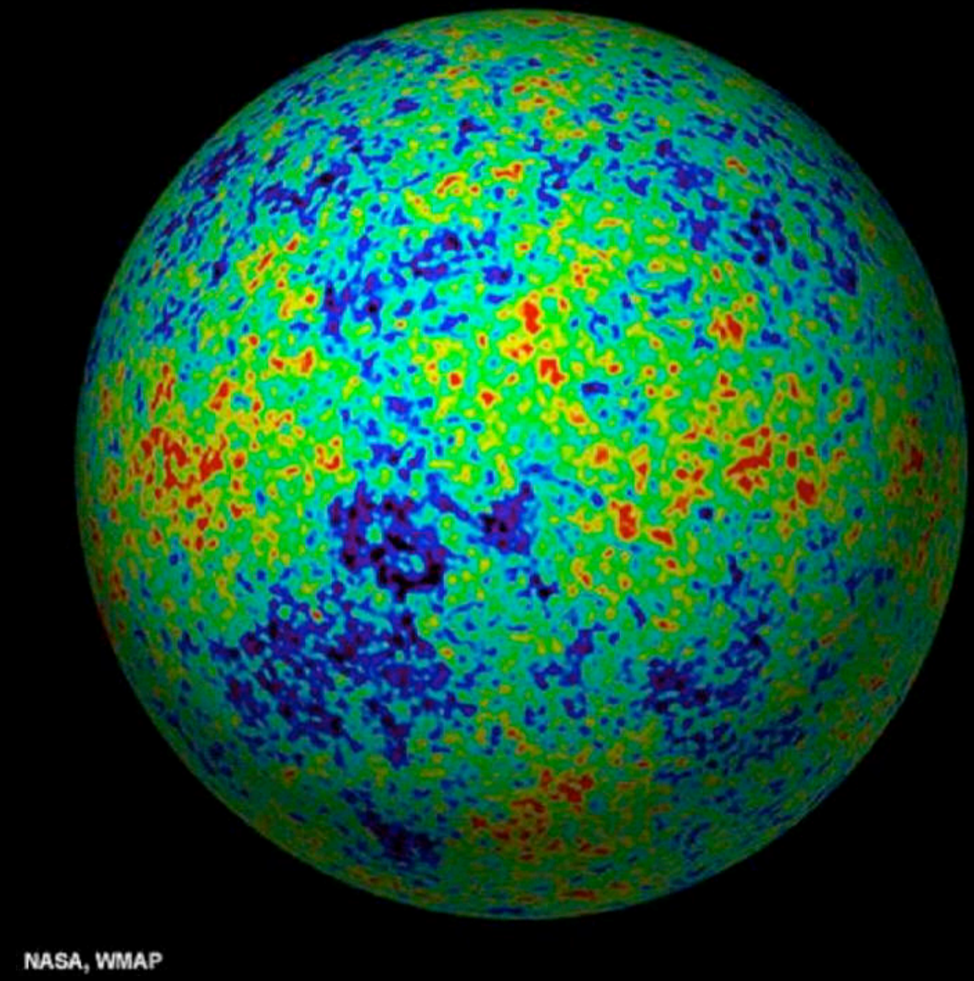
Plan of the talk

- Short introduction to cosmological perturbations from inflation
- BICEP2 and its implications for HEP and cosmology

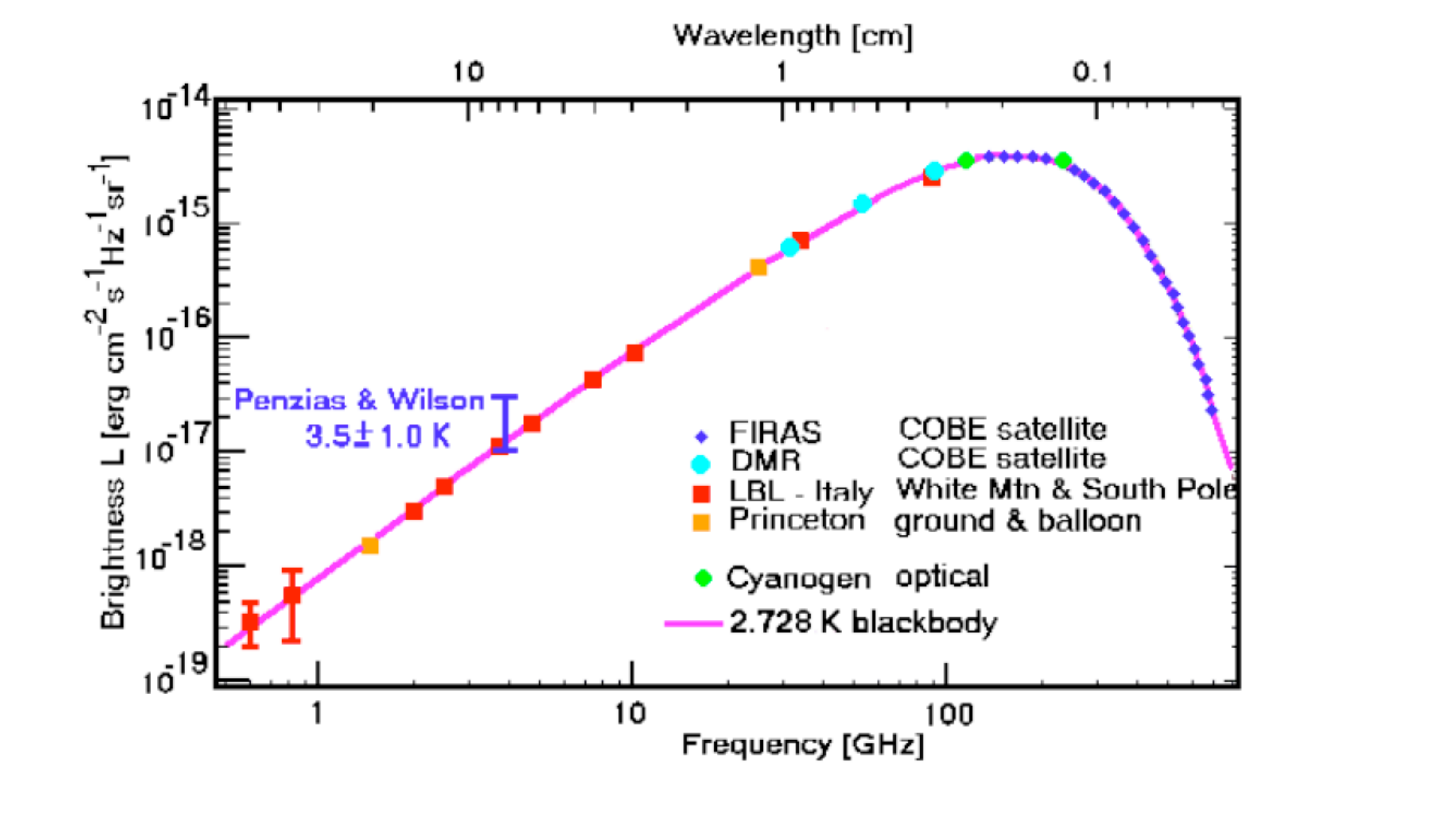
The Universe is homogeneous and isotropic on sufficiently large scales, but has structure



The Universe has structure in the Cosmic Microwave Background

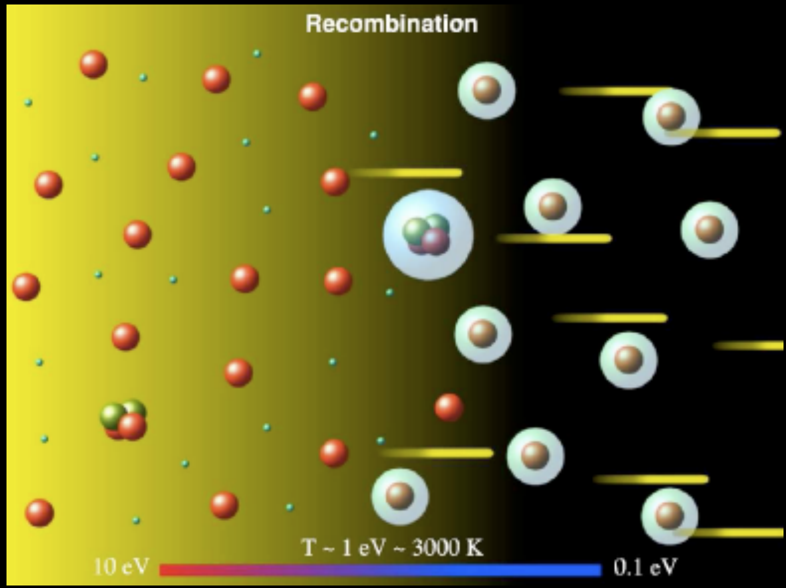


CMB



Wavelength [cm]
10
1
0.1
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
Brightness L [erg cm^{-2}s^{-1}Hz^{-1}sr^{-1}]
Penzias & Wilson
3.5±1.0 K
FIRAS COBE satellite
DMR COBE satellite
LBL - Italy White Mtn & South Pole
Princeton ground & balloon
Cyanogen optical
2.728 K blackbody
1
10
100
Frequency [GHz]

Hydrogen Recombination & Last Scattering Surface



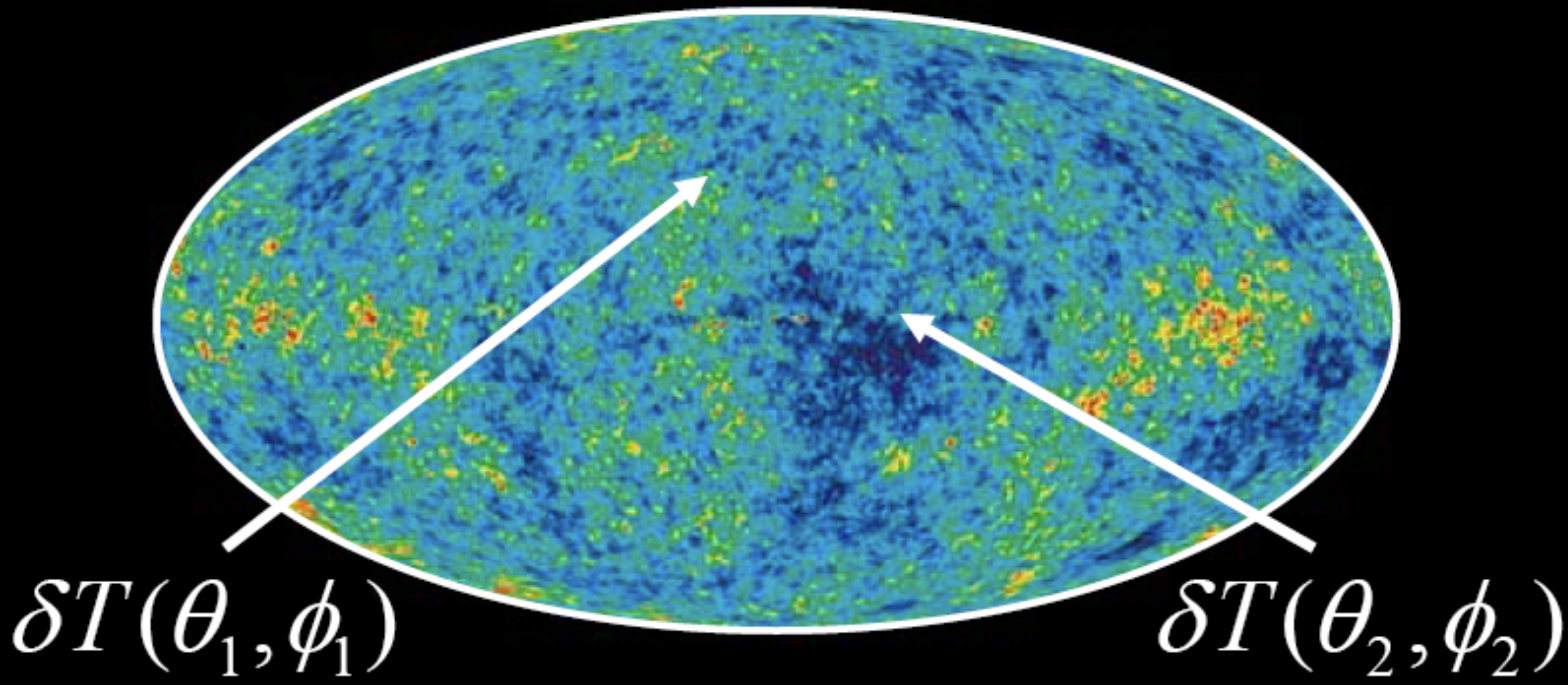
Matter is ionized at temperatures higher than the hydrogen ionization energy of 13.6 eV

$$\frac{n_e n_p}{n_H} = \left(\frac{m_e T}{2\pi}\right)^{3/2} e^{-E_{\rm ion}/T}$$

The Universe becomes transparent to photons when

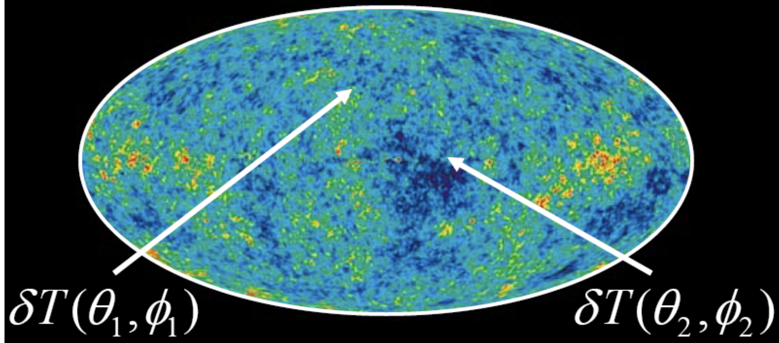
$$(\sigma_{e\gamma} n_e)^{-1} \sim t,\ \ \sigma_{e\gamma} = 8\pi\alpha^2/3m_e^2,\ \ T_{\rm LS} \simeq 0.26\ {\rm eV}$$

CMB anisotropy

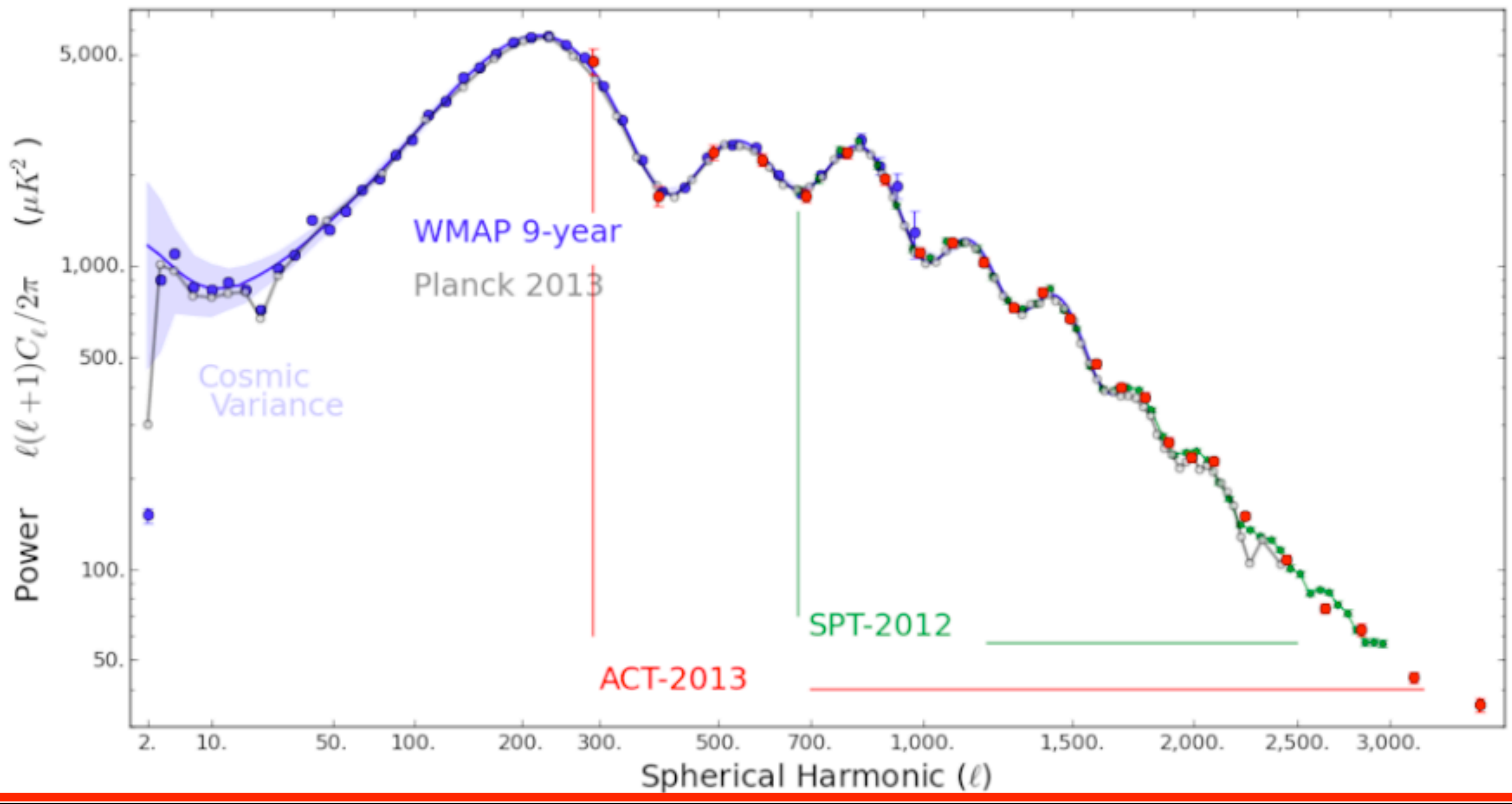


$$
\begin{aligned}
\frac{\Delta T}{T}(x_0, \tau_0, \mathbf{n}) &= \sum_{\ell m} a_{\ell m}(x_0) Y_{\ell m}(\mathbf{n}) \\
\langle a_{\ell m} a_{\ell' m'} \rangle &= \delta_{\ell \ell'} \delta_{m m'} C_\ell \\
\left\langle \frac{\Delta T}{T}(\mathbf{n}) \frac{\Delta T}{T}(\mathbf{n}') \right\rangle &= \sum_{\ell} \frac{(2\ell + 1)}{4\pi} C_\ell P_\ell(\mathbf{n} \cdot \mathbf{n}')
\end{aligned}
$$

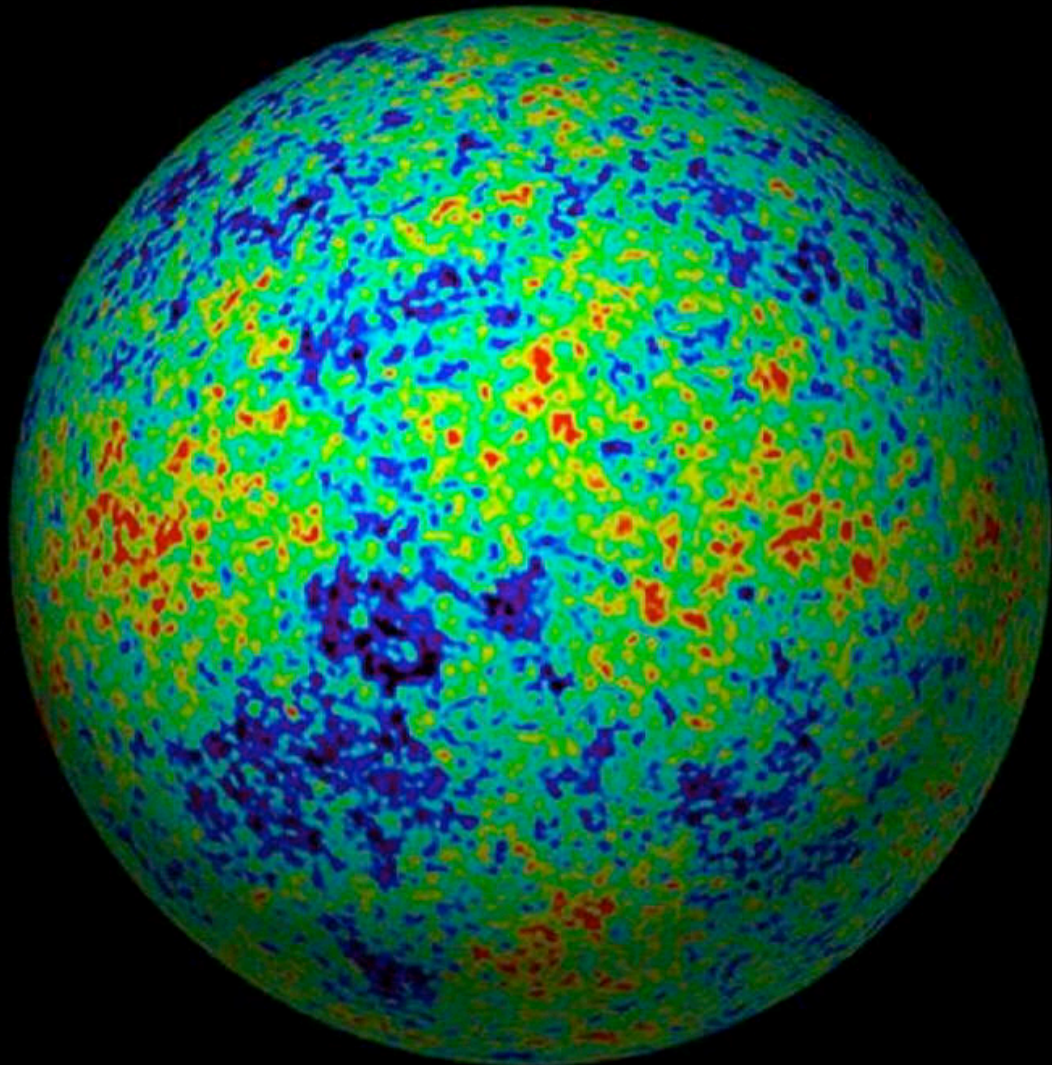
CMB anisotropy



Courtesy of M. Halpern

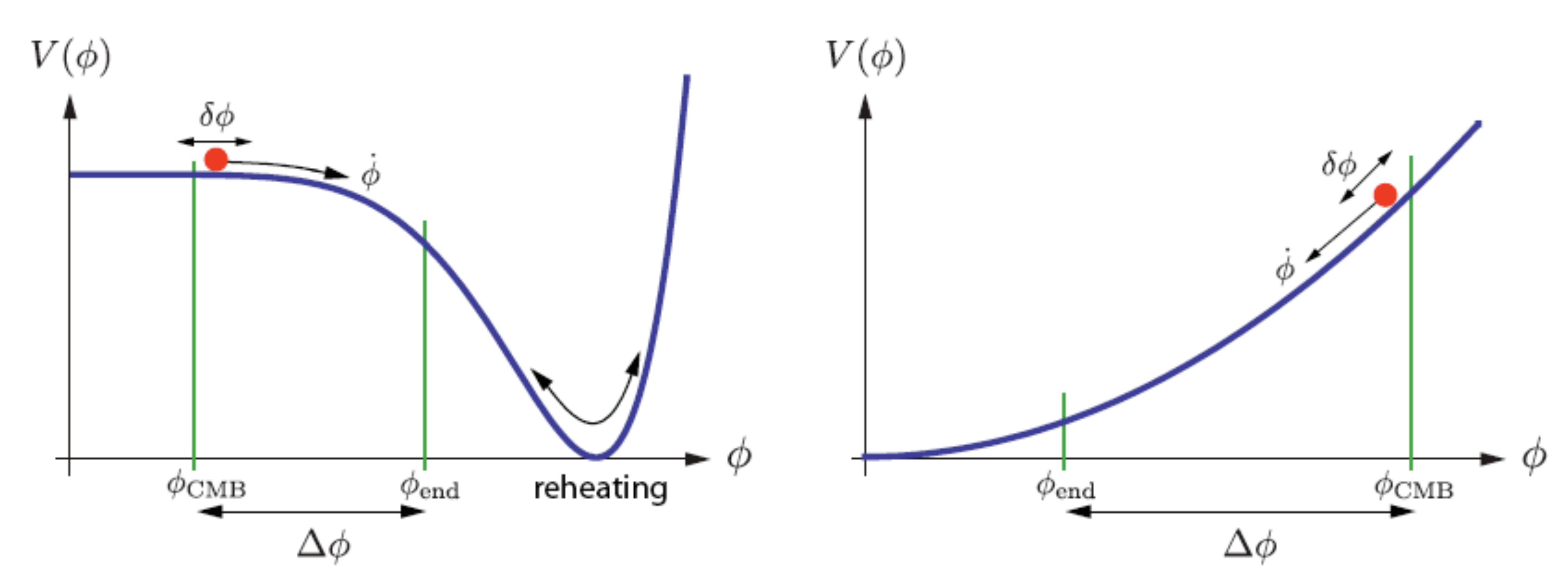


Where is this structure coming from ?



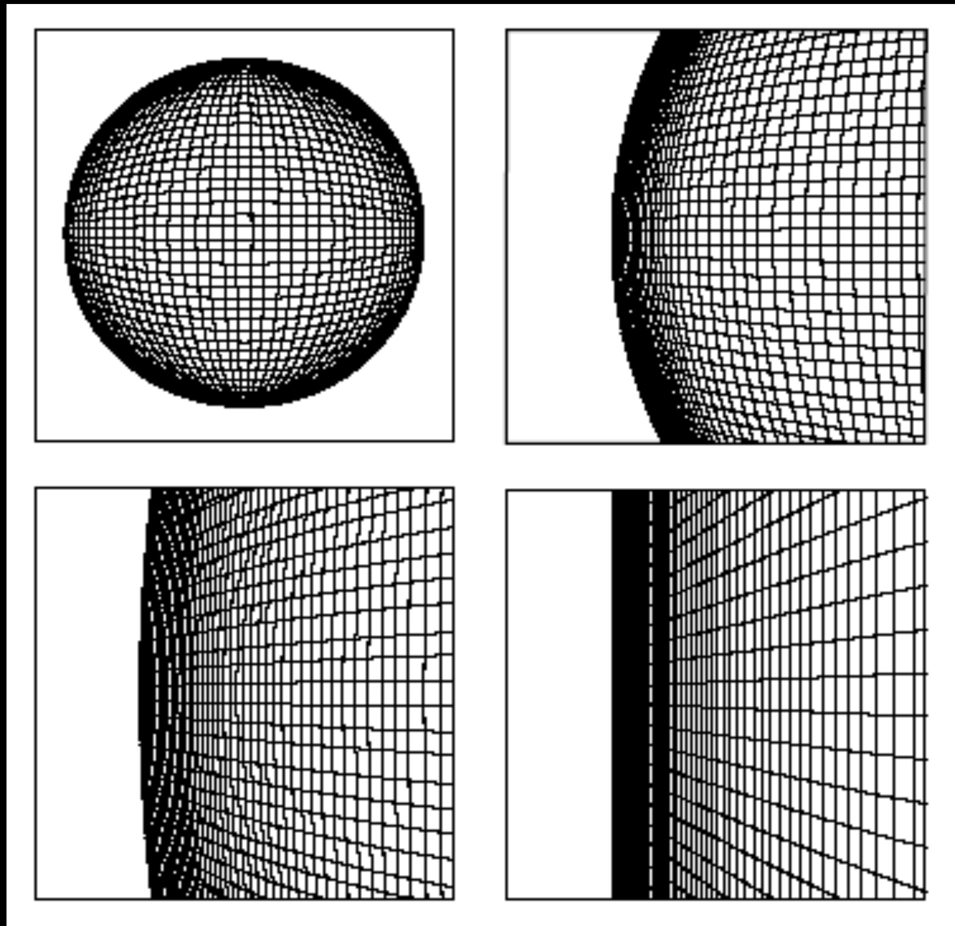

Inflation

The Inflationary Cosmology

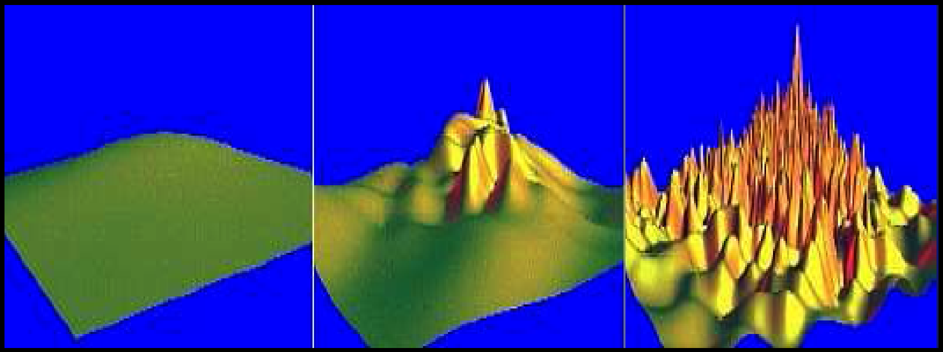


$$a(t) \sim e^{Ht}$$

Inflation makes locally the Universe flat

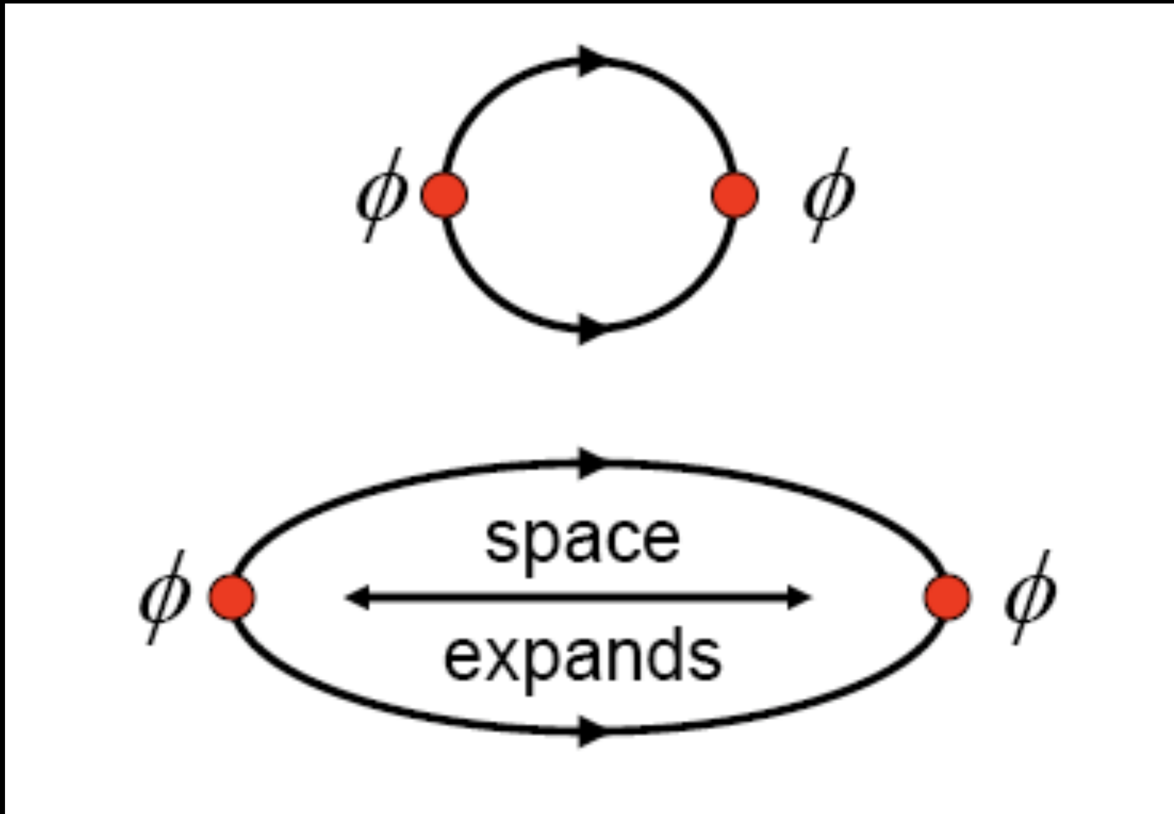


$$a(t) \sim e^{Ht}$$



From Quantum Fluctuations to the Large Scale Structure

Particle production in an expanding Universe



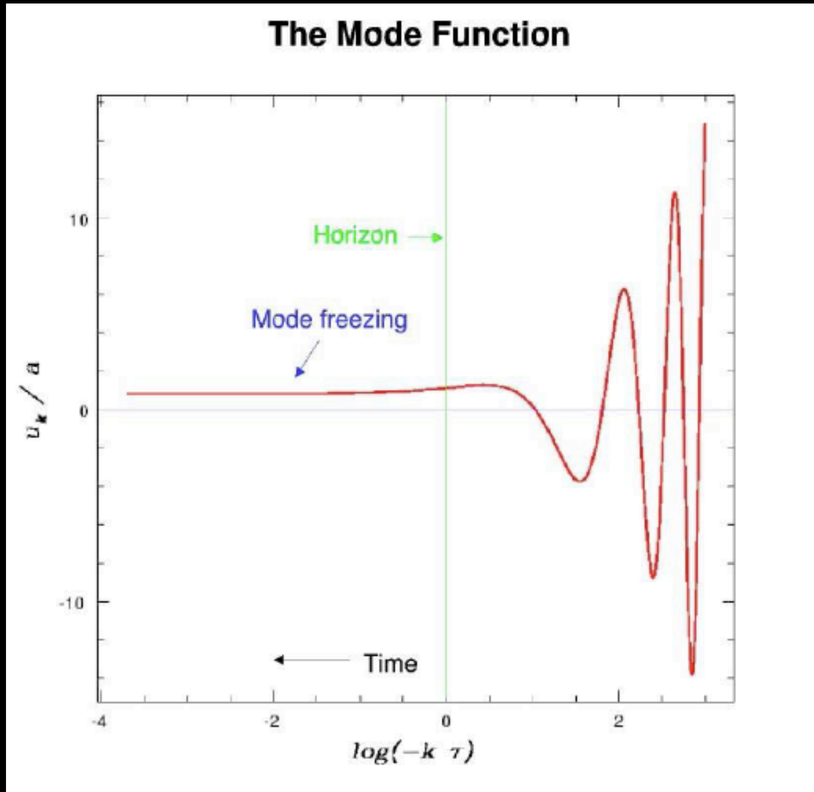
All massless scalar fields are quantum-mechanically excited during Inflation

$$\begin{aligned}
\sigma(\mathbf{x},\tau) &= \sigma_0(\tau) + \delta\sigma(\mathbf{x},\tau), \\
u_k(\tau) &= a(\tau)\delta\sigma_k(\tau), \\
\mathrm{d}\tau &= \frac{\mathrm{d}t}{a}
\end{aligned}$$

$$\boxed{u_k'' + \left(k^2 - \frac{a''}{a}\right)u_k = 0}$$

Oscillator with time-dependent frequency

Any light scalar field is quantum mechanically excited during inflation with a scale-invariant power spectrum



$$\mathcal{P}_\sigma = \frac{k^3}{2\pi^2}\left|\delta\sigma_k\right|^2 = \left(\frac{H}{2\pi}\right)^2\left(\frac{k}{aH}\right)^{n-1}$$

$$n \simeq 1 + \mathcal{O}(10^{-2})$$

The perturbations have a
scale invariant spectrum because of scale invariance

$$\mathrm{d}s^2 = \frac{1}{H^2\tau^2}(\mathrm{d}\tau^2 - \mathrm{d}\vec{x}^2)$$

The metric is invariant under

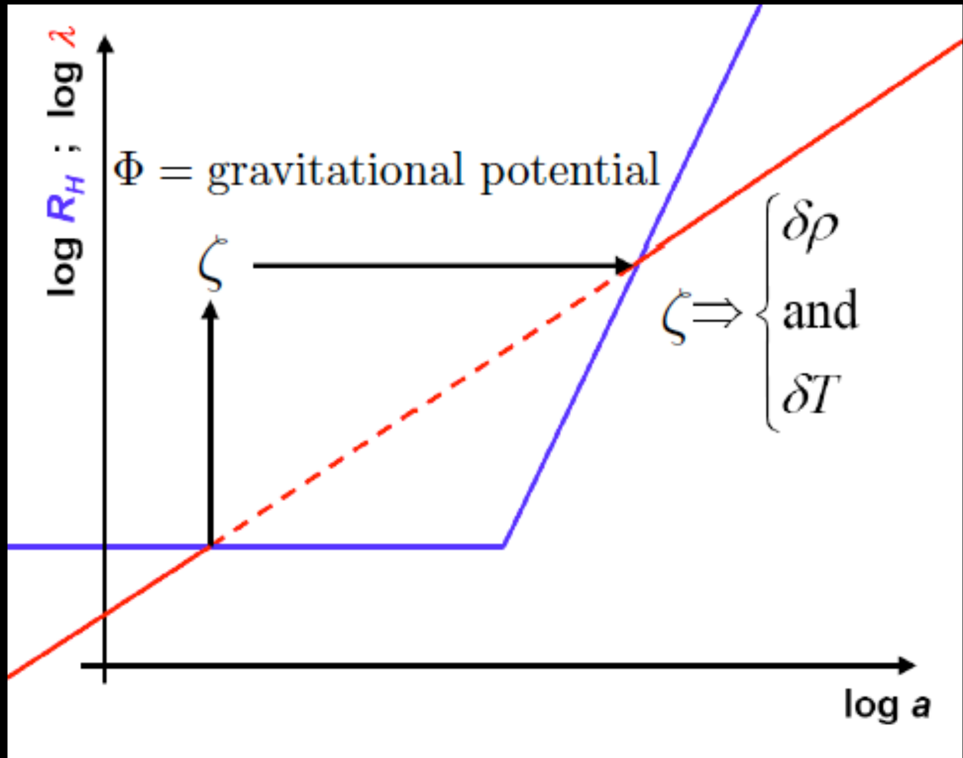
$\tau \to \lambda\tau$ and $\vec{x} \to \lambda\vec{x}$

$$-\dot{H} \ll H^2$$

In the high-energy physics language,
the approximate time-translational invariance is
associated to a pseudo-Goldstone boson
representing fluctuations in the clock

$$\zeta \sim \frac{\delta a}{a} \sim H\delta t \sim H\frac{\delta\phi}{\dot{\phi}}$$

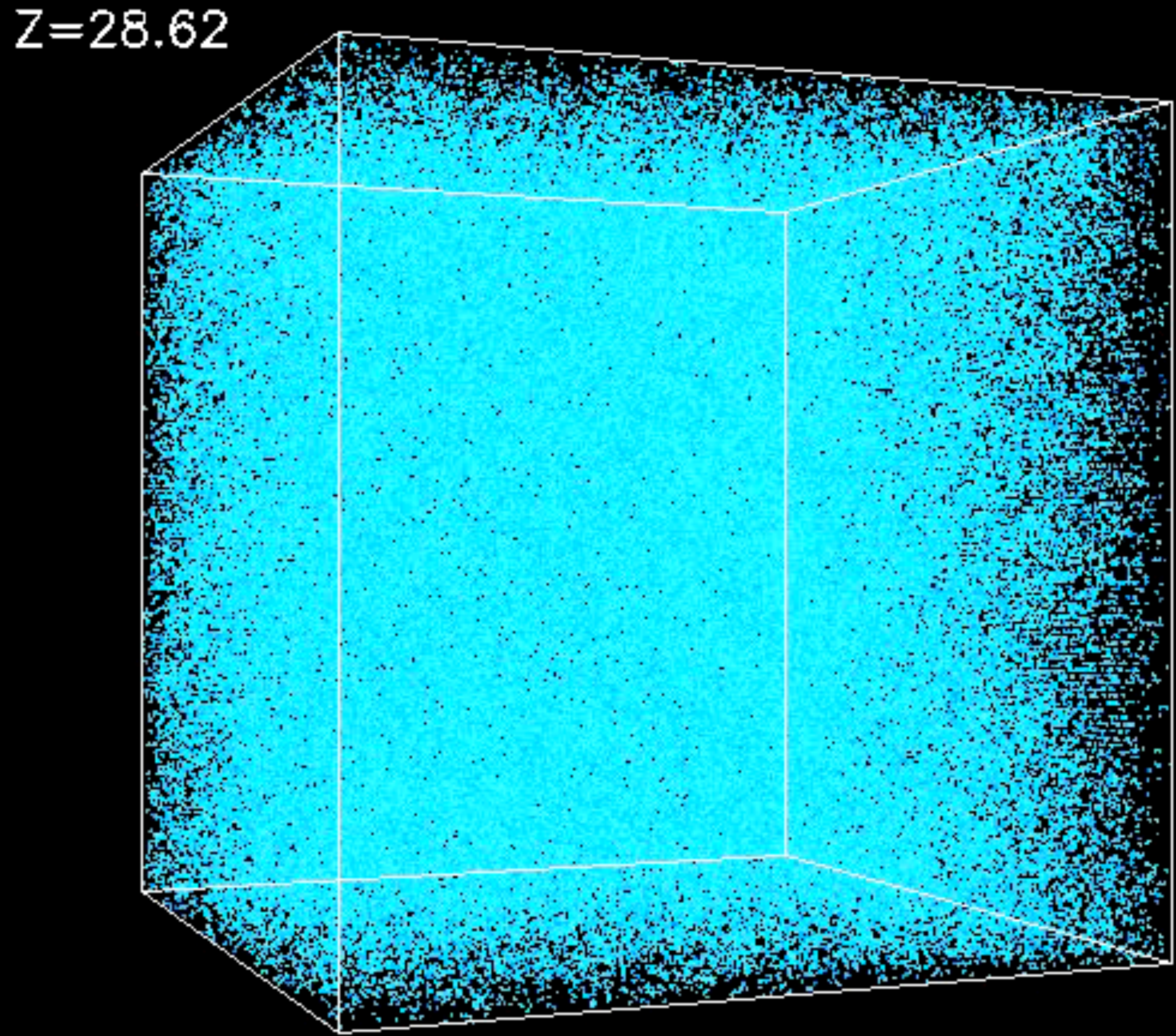
Standard single-field models



$$\mathcal{P}_\zeta = \frac{1}{2}\left(\frac{H}{2\pi M_{\rm Pl}\epsilon^{1/2}}\right)^2\left(\frac{k}{aH}\right)^{n_\zeta - 1}$$

$$n_\zeta = 1 + 2\eta - 6\epsilon$$

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



The Millenium Simulation Project:
http://www.mpa-garching.mpg.de/galform/virgo/millennium/

Tensor perturbations

$$ds^2 = dt^2 - a^2(\delta_{ij} + h_{ij})dx^i dx^j$$

$$\begin{aligned} v_k &= \frac{aM_{\rm Pl}}{\sqrt{2}} h_k \\ v_k'' &+ \left(k^2 - \frac{a''}{a}\right) v_k = 0 \end{aligned}$$

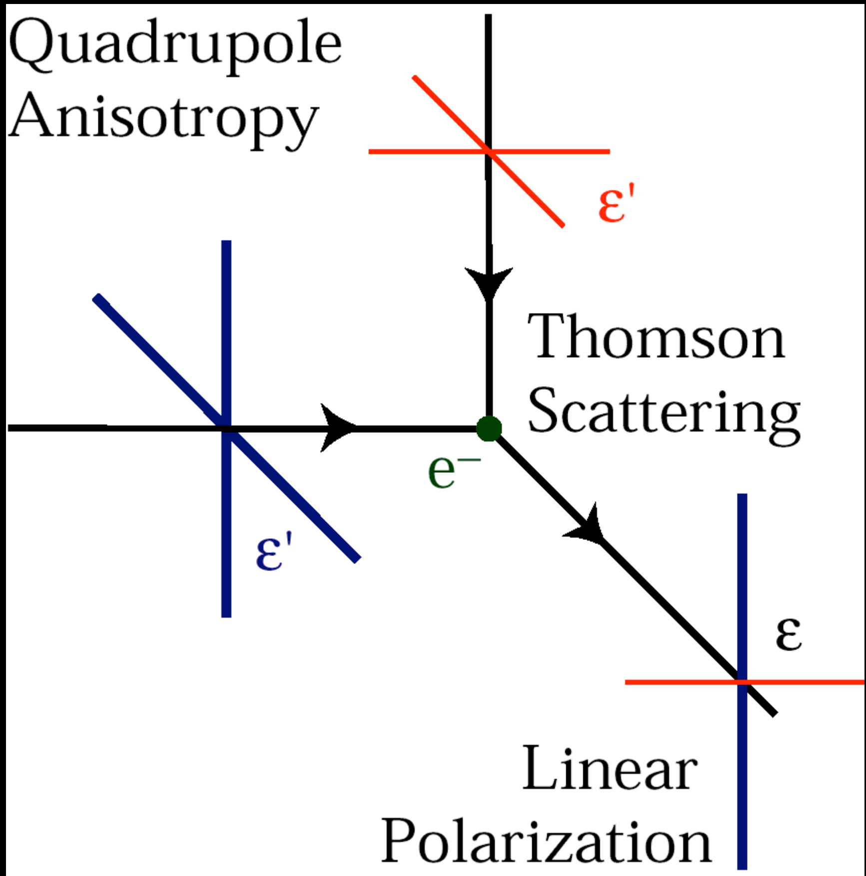
$$\mathcal{P}_T(k) \simeq \frac{8}{M_{\rm Pl}^2}\left(\frac{H}{2\pi}\right)^2 \left(\frac{k}{aH}\right)^{n_T}$$

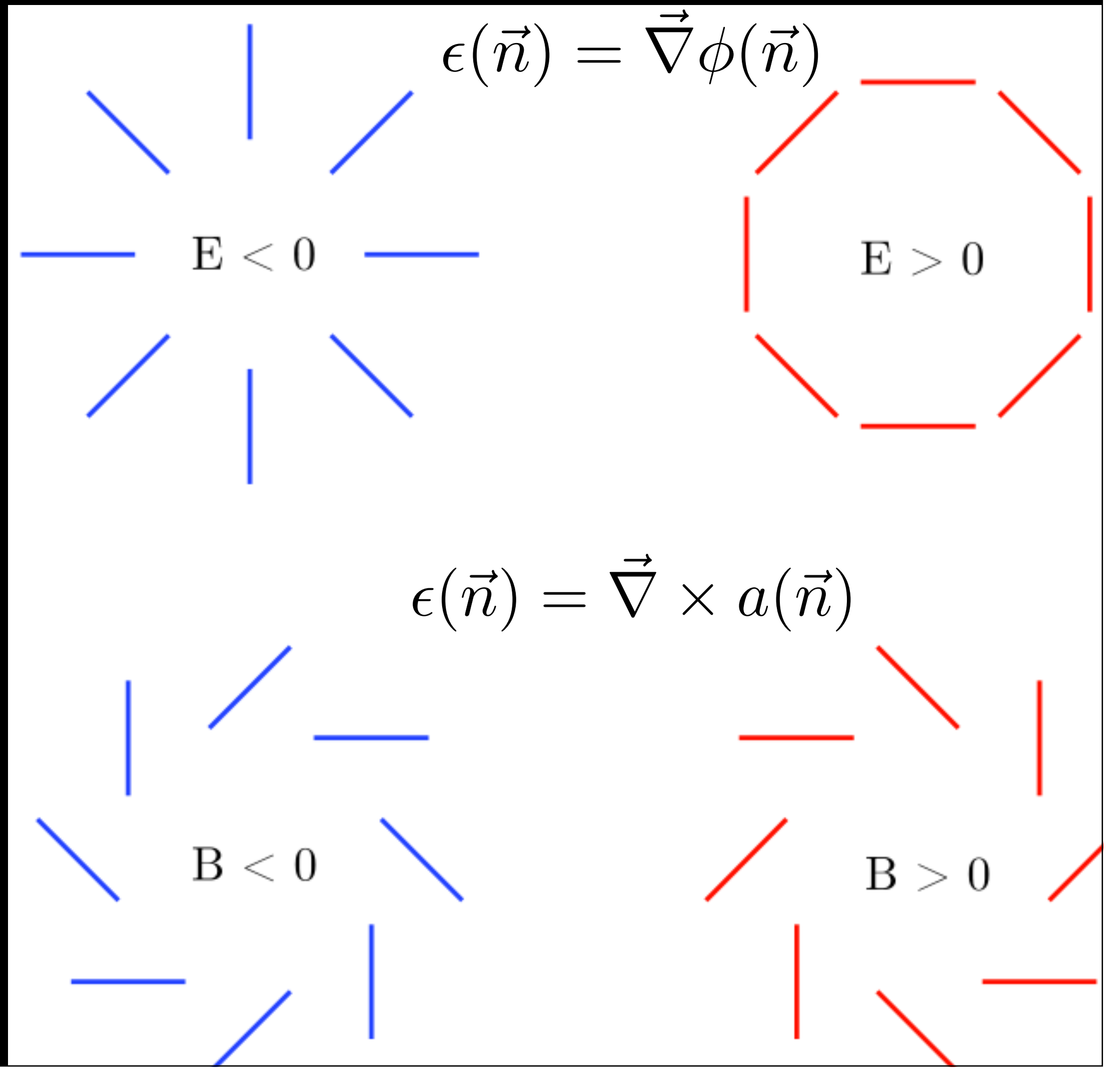
$$H^2 \simeq E_{\rm inf}^4 / M_{\rm Pl}^2 \qquad n_T = -2\epsilon$$

Measuring the
energy scale of inflation
implies detecting
tensor modes from inflation

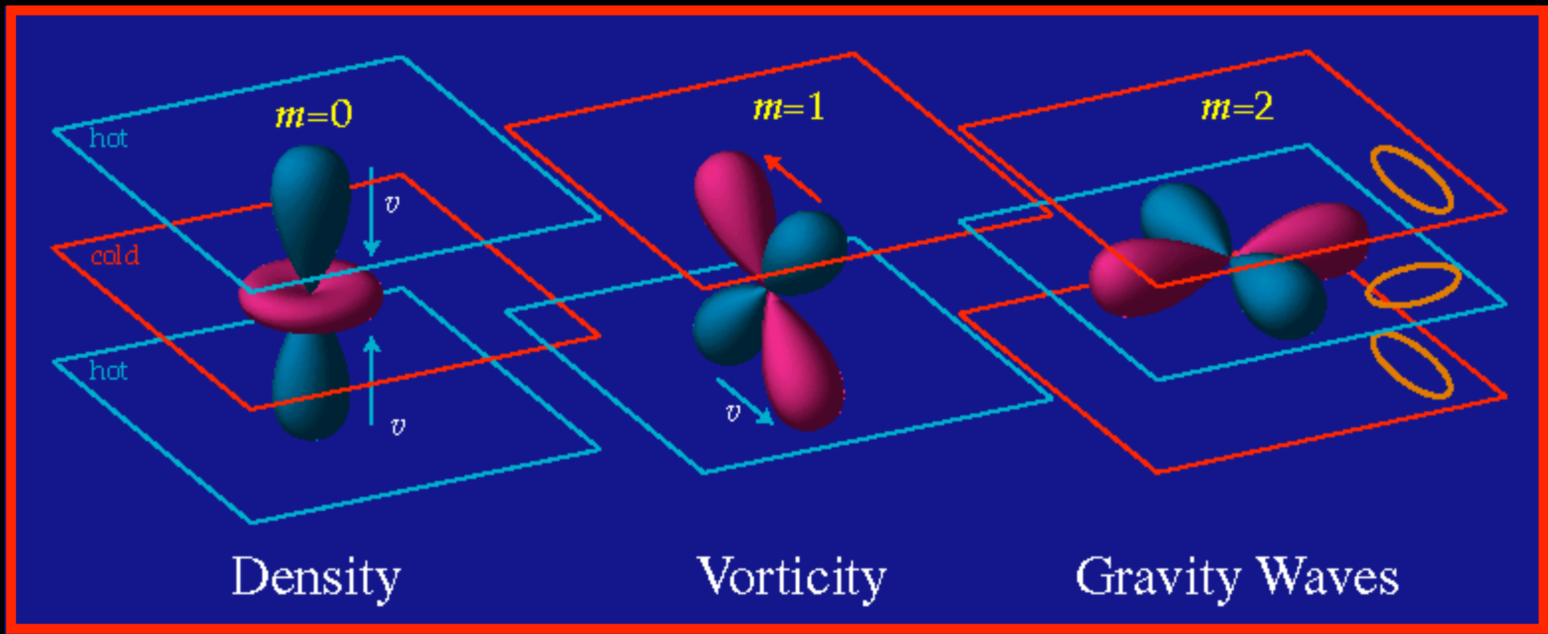
$$H \simeq \frac{E_{\rm inf}^2}{M_{\rm Pl}}$$

The CMB anisotropy is polarized





Tensor modes induce B-mode polarization



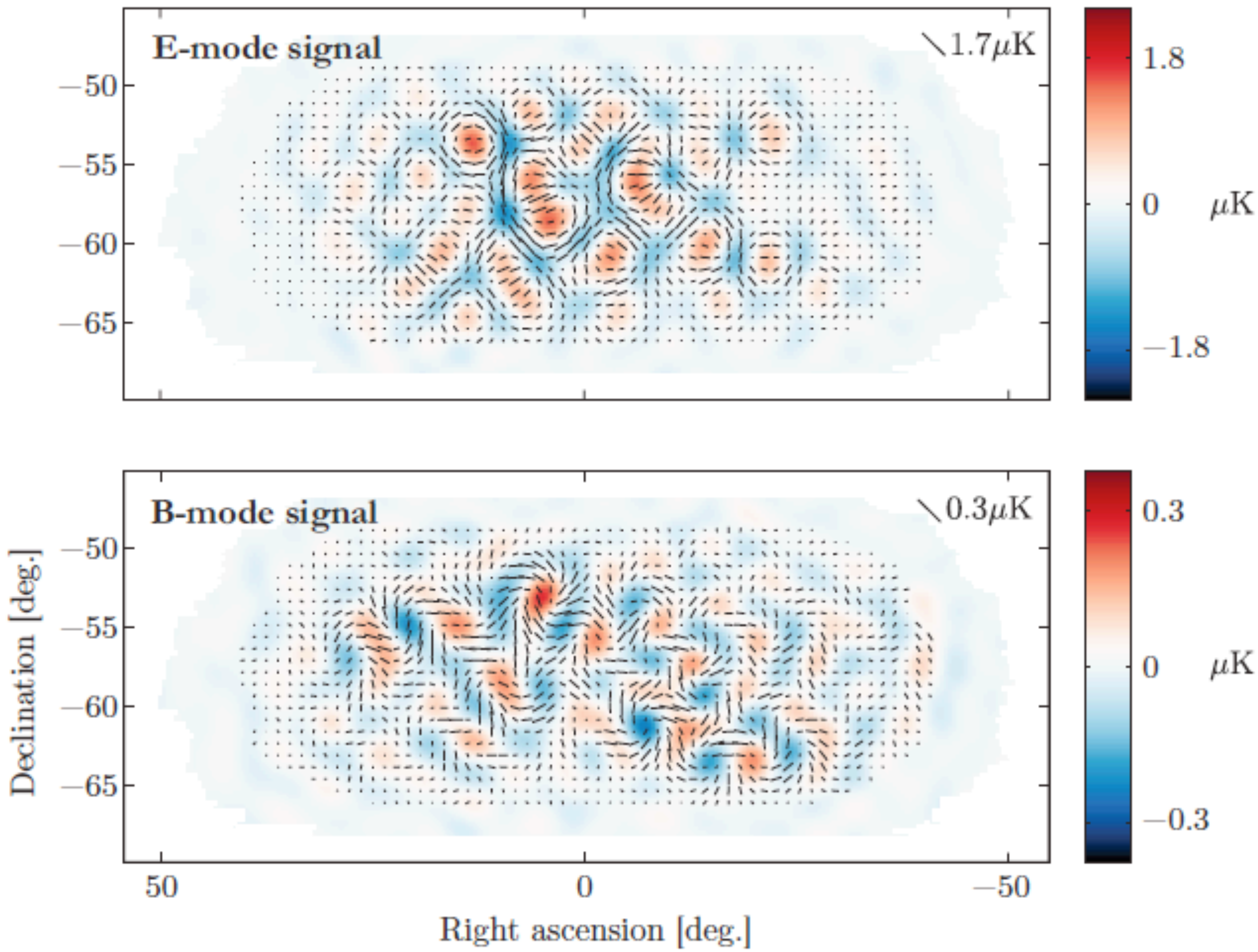
IF

B-mode polarization comes from inflation

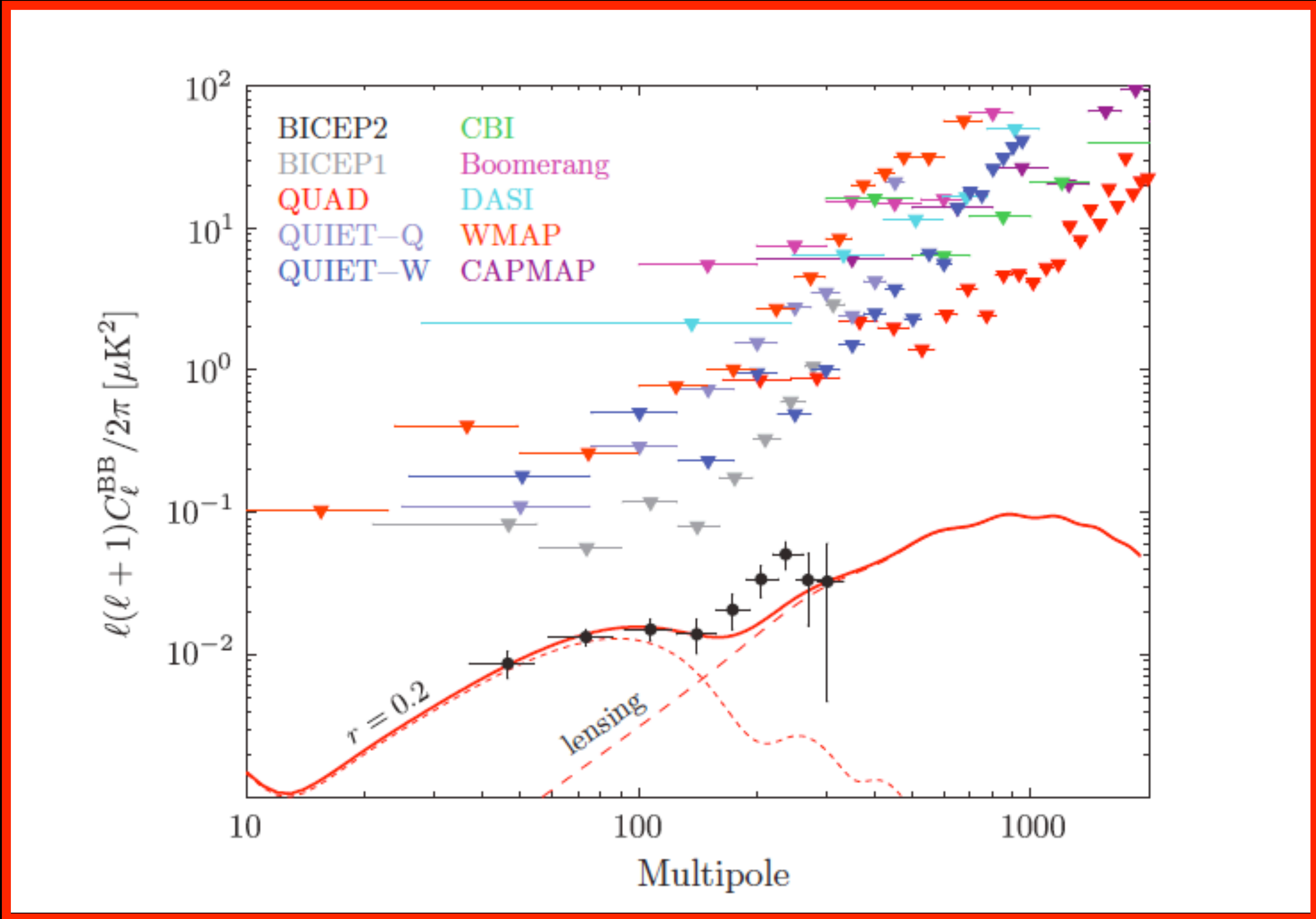
THEN

$$r = \frac{\mathcal{P}_T}{\mathcal{P}_\zeta} = 16\epsilon = -8n_T$$


Bicep2


E-mode signal
1.7μK
1.8
0
μK
−1.8
B-mode signal
0.3μK
0.3
0
μK
−0.3
Declination [deg.]
−50
−55
−60
−65
50
0
−50
Right ascension [deg.]

Bicep2



$$r = 0.2^{+0.07}_{-0.05}$$

$$[\ell(\ell+1)C_{B\ell}/2\pi]^{1/2} \simeq 0.024(E_{\rm inf}/10^{16}\,{\rm GeV})\,\mu{\rm K}$$

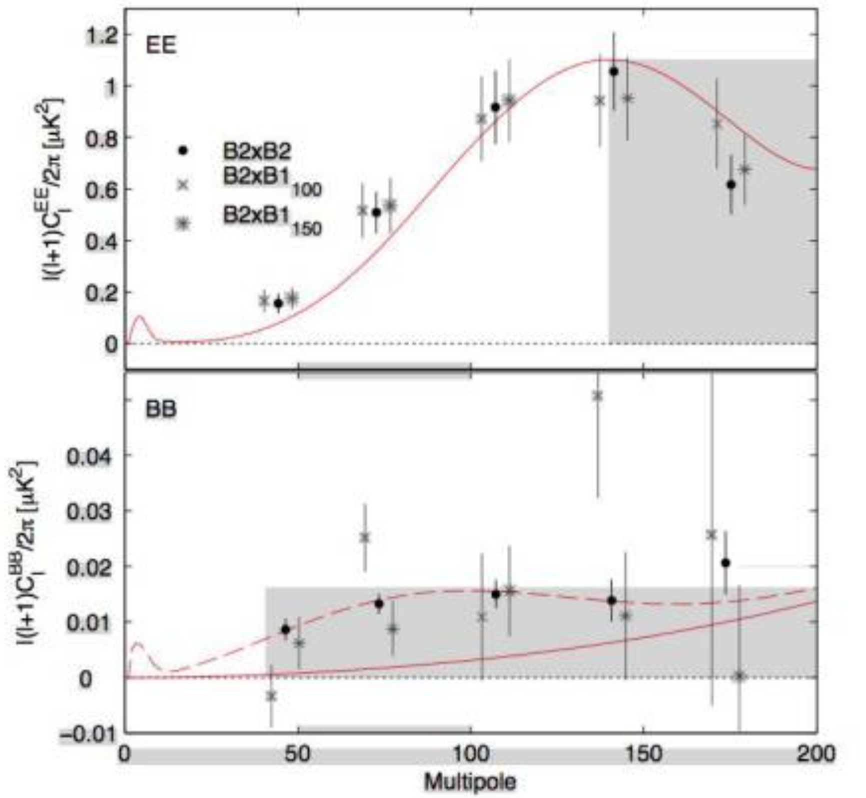
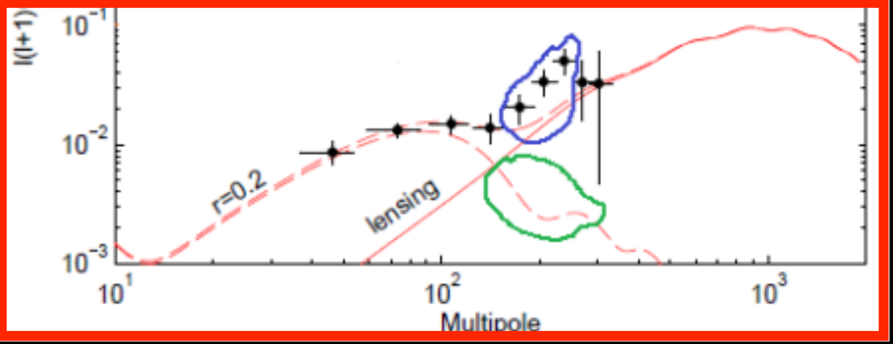


FIG. 7.— The BICEP2 *EE* and *BB* auto spectra (as shown in Figure 2) compared to cross spectra between BICEP2 and the 100 and 150 GHz maps from BICEP1. The cross spectrum points are offset horizontally for clarity.

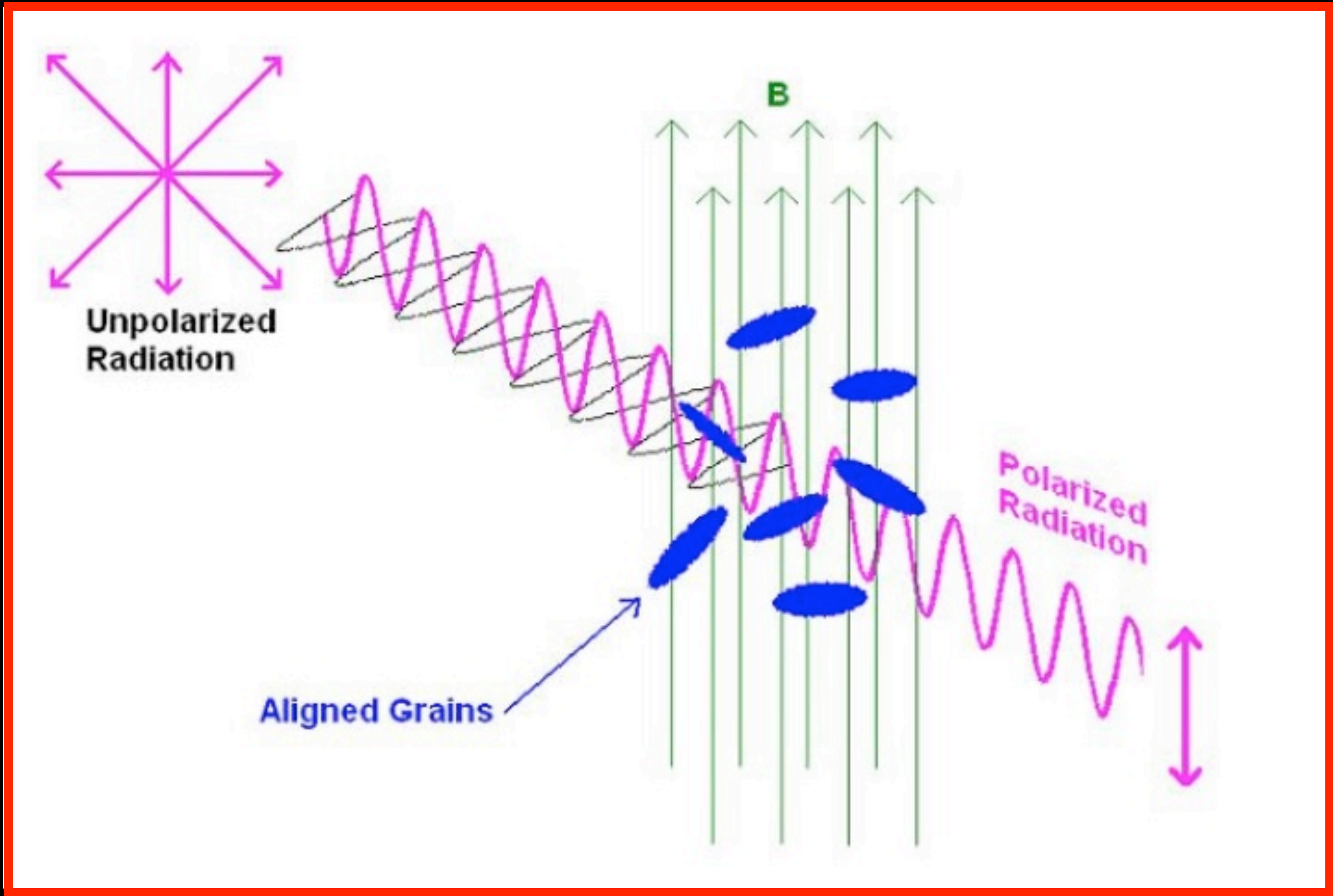


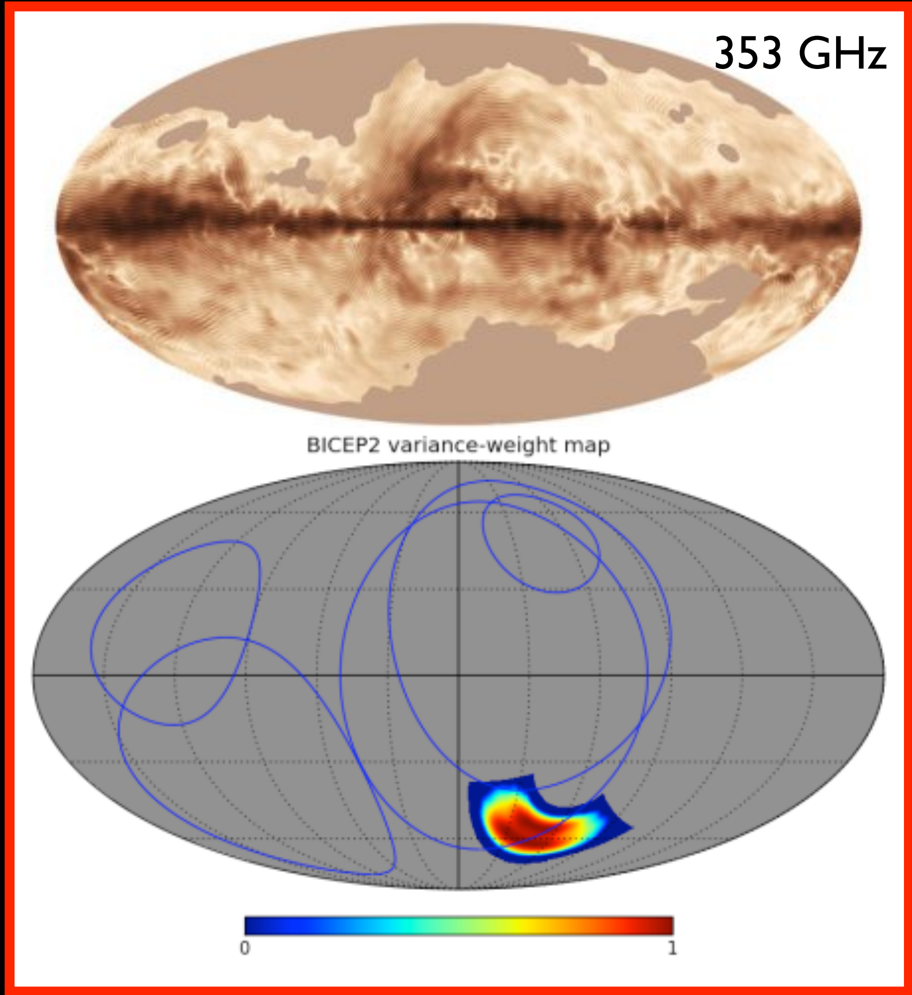
Systematics at high multipoles?

Leakage between E- and B-modes in the spherical harmonic decomposition?

Different frequency check?

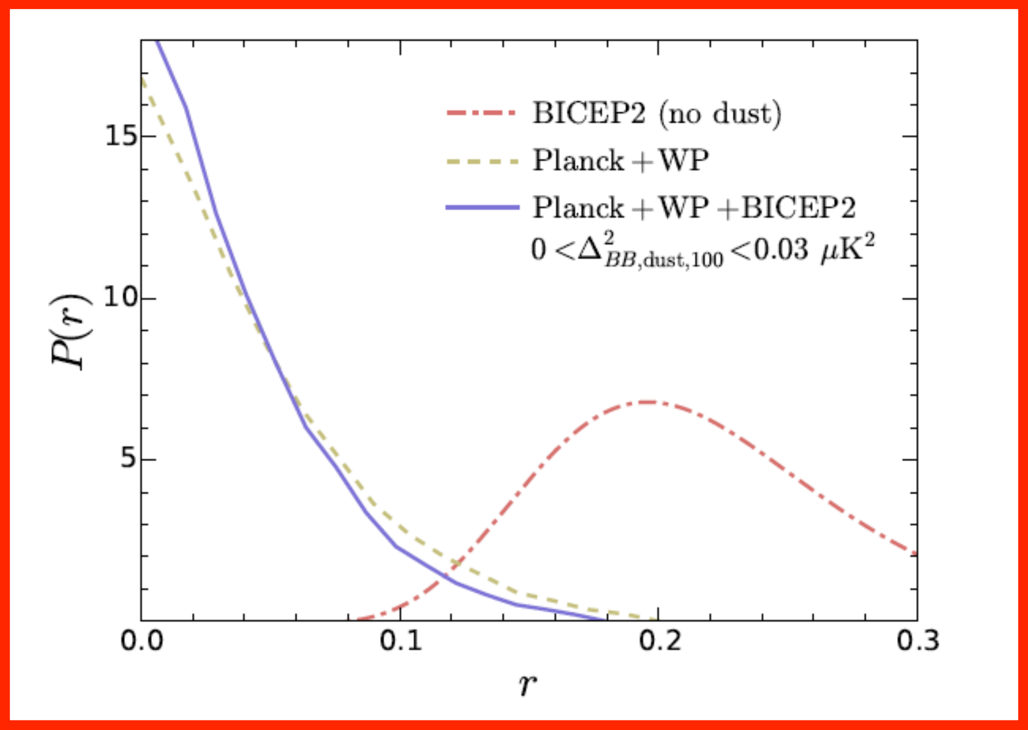
Dust induced polarization



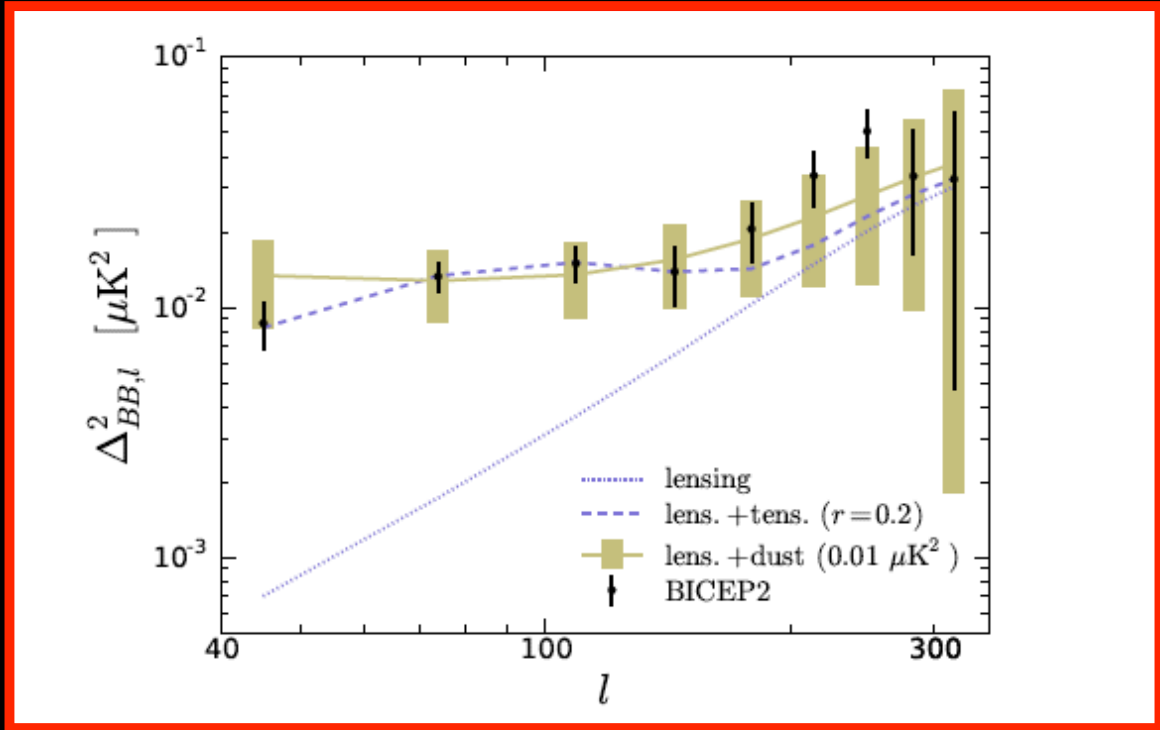


Planck collaboration (2014)

Galactic dust emission increases with frequency so one would expect more of an effect in the Planck map than in BICEP2, but the fact that polarized foreground emission is so strong at these frequencies does give one pause for thought.



M.J. Mortonson and U. Seljak, (May 2014)

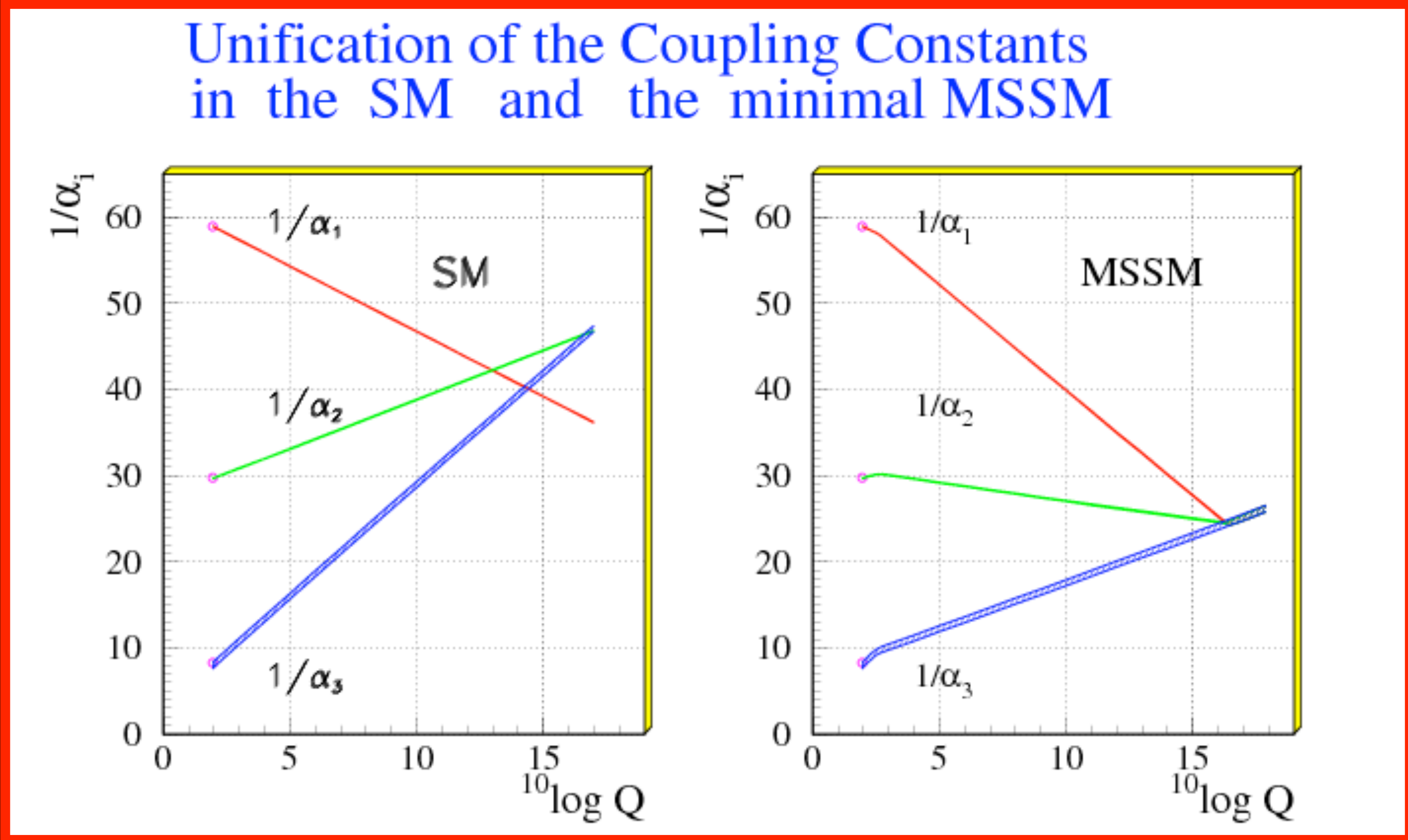


A tale of Two Cities, Charles Dickens (1859)

It was the best of times, it was the worst of times,
it was the age of wisdom, it was the age of foolishness,
it was the epoch of belief, it was the epoch of incredulity,
it was the season of Light, it was the season of Darkness,
it was the spring of hope, it was the winter of despair....

Implication 1

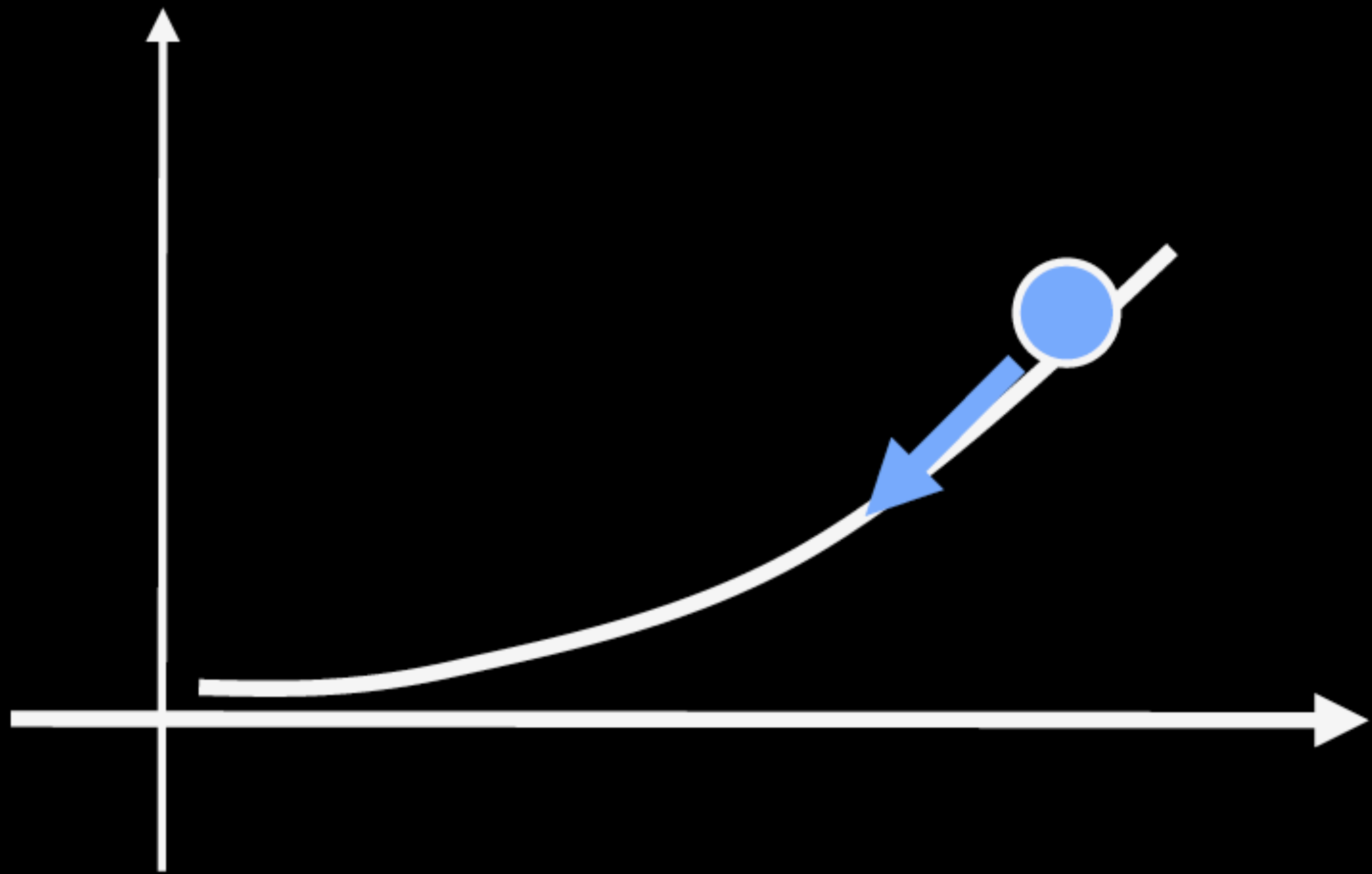
$$E_{\text{Bicep2}} \simeq 2 \cdot 10^{16}\,\text{GeV}$$



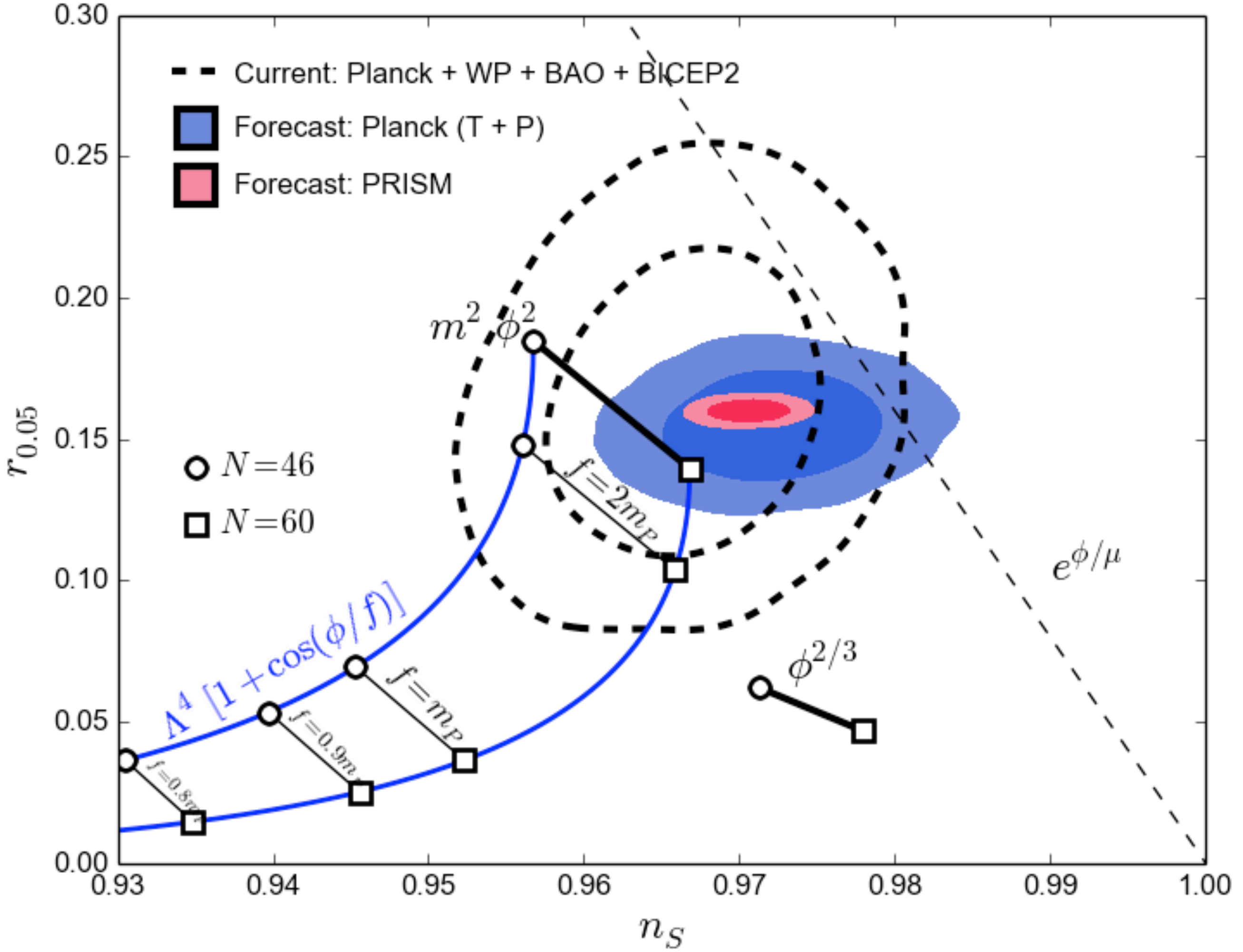
Coincidence? Problem?

Implication 2

Who is the inflaton?

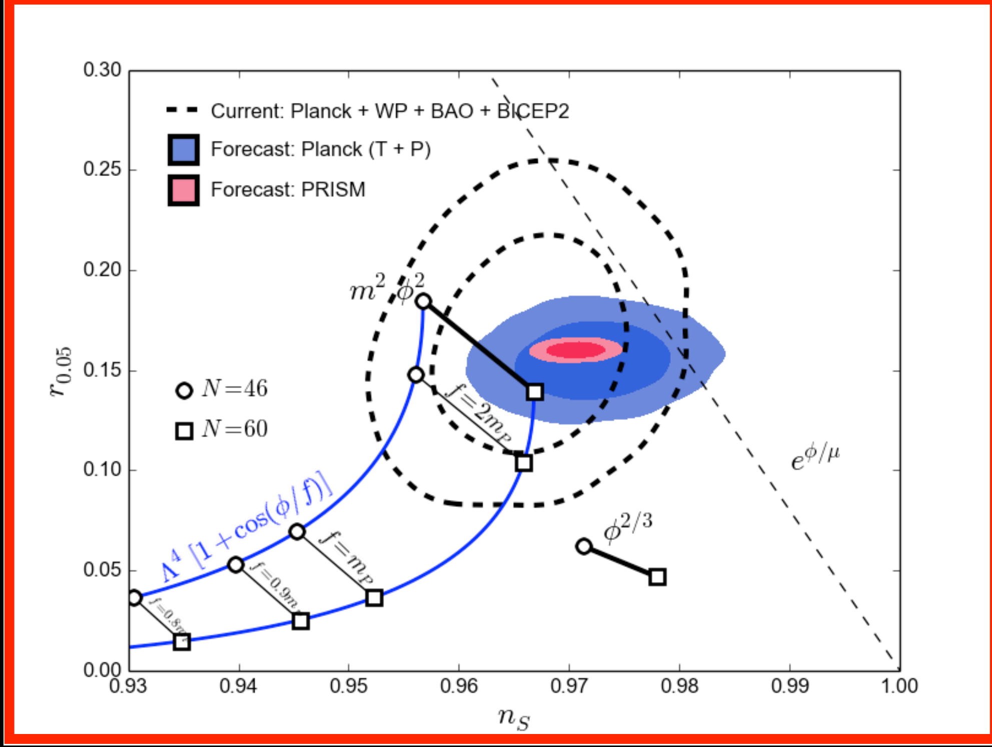


Universe of maximum theoretical bliss?



W.H. Kinney et al., in preparation

Universe of maximum theoretical bliss?

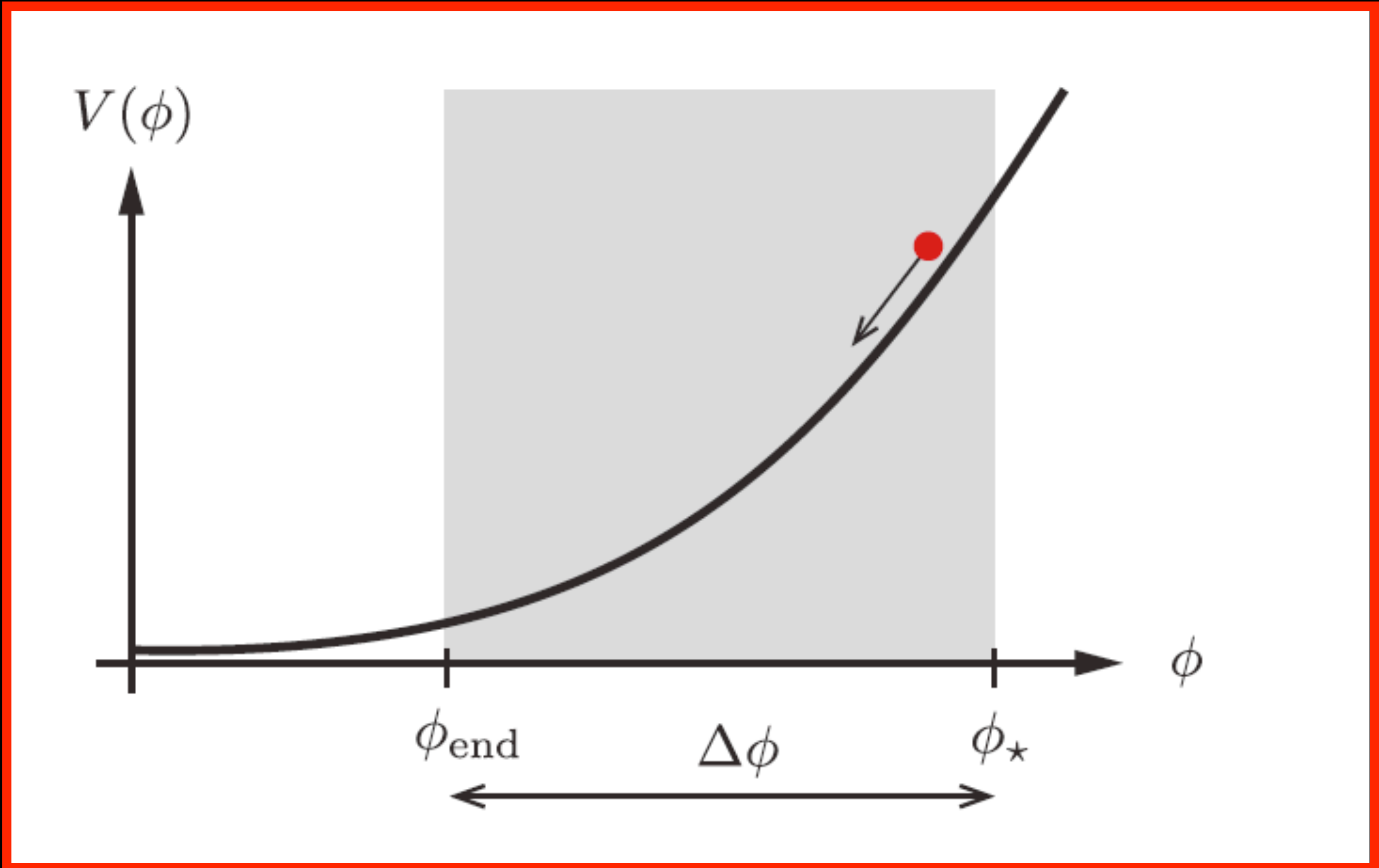


$$V(\phi) = \frac{1}{2}m^2\phi^2 : \epsilon = \eta = \frac{1}{2N}$$

$$n_\zeta - 1 = -\frac{2}{N} \simeq 0.96, \;\; r = \frac{8}{N} \simeq 0.16$$

Implication 3

Observation of tensor modes imply Planckian field excursions



$$r = 8\left(\frac{1}{M_{\rm Pl}}\frac{{\rm d}\phi}{{\rm d}N}\right)^2 \Rightarrow \frac{\Delta\phi}{M_{\rm Pl}} \simeq 1.1\left(\frac{r}{0.2}\right)^{1/2}$$

Invalidity of EFT?

$$\mathcal{L} \supset \sum_p \lambda_p \frac{\phi^{4+p}}{M_{\text{Pl}}^p}$$

1. What is wrong with Planckian excursions? Are they physical (observable)? Usually not, when they are (e.g. radius of extra dimension) problems arise

2. What happens when other d.o.f. get a mass larger than the Planckian scale? Are non-renormalizable operators suppressed because of black hole arguments?

3. Shift symmetry: $\phi \to \phi + c \Rightarrow \lambda_p \sim (V/M_{\text{Pl}})^p$

Implication 4

Extra-dimensions

Large extra-dimensional models where the fundamental gravity mass is small are highly disfavoured

$$S_{\rm g} = M_*^{2+n} \int \mathrm{d}^{4+n}x\, R_{4+n} = M_{\rm Pl}^2 \int \mathrm{d}^4 x\, R_4$$

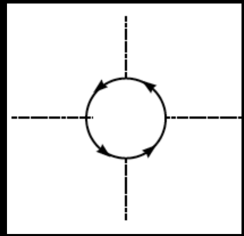
$$M_{\rm Pl}^2 = R^n M_*^{2+n}$$

$$\boxed{M_* \gg E_{\rm Bicep2}}$$

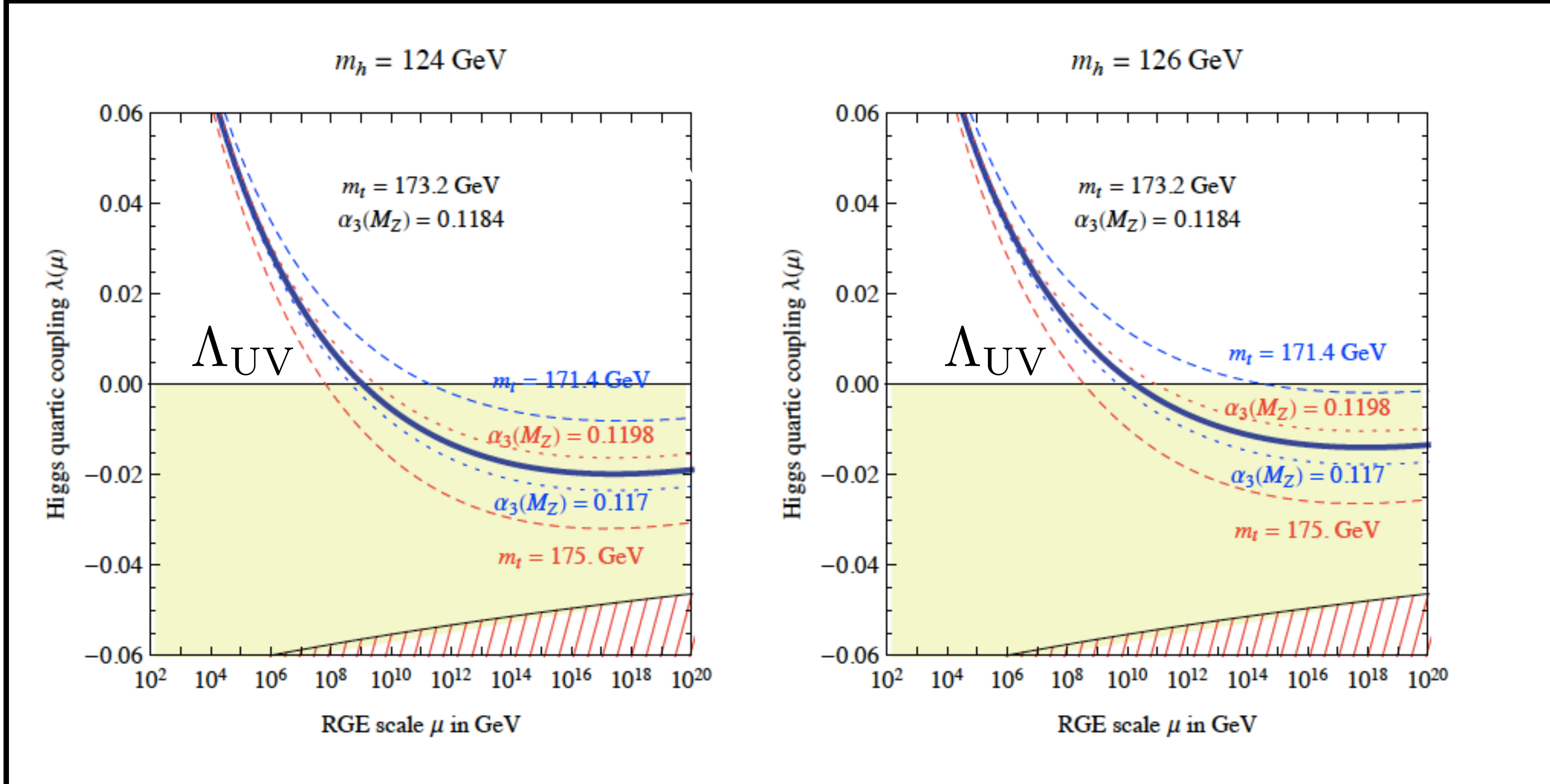
TeV-scale gravity ruled out

Implication 5

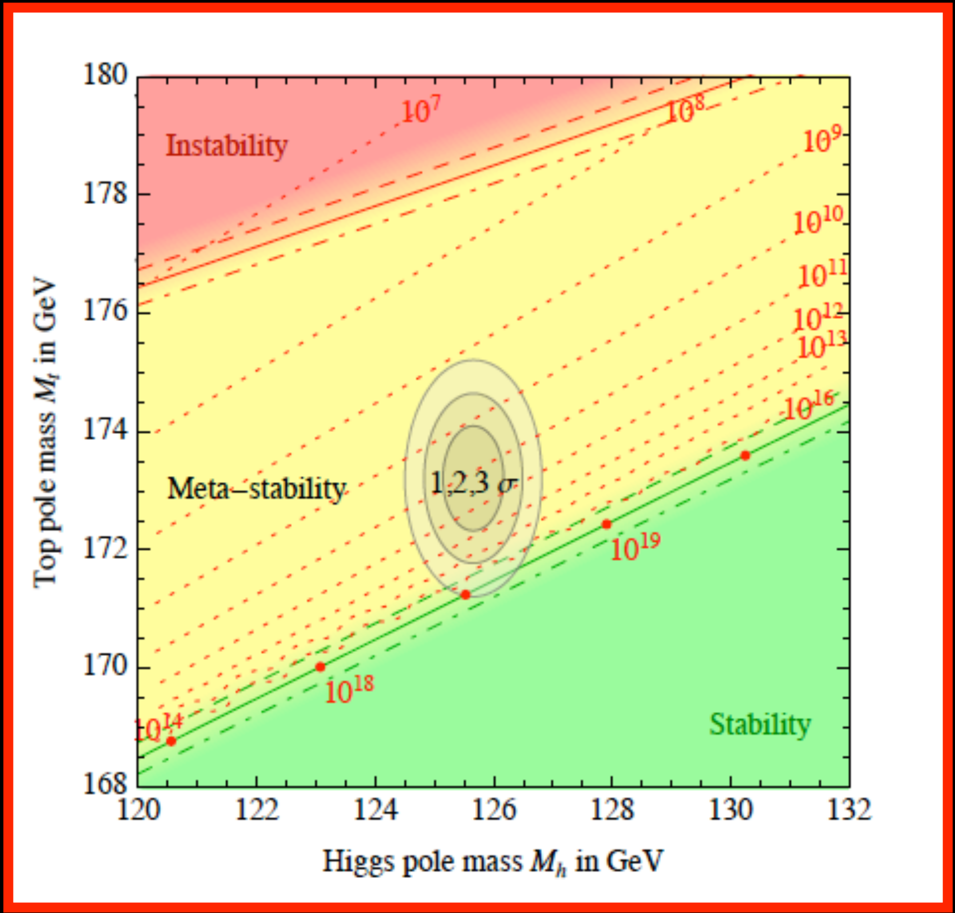
SM Higgs



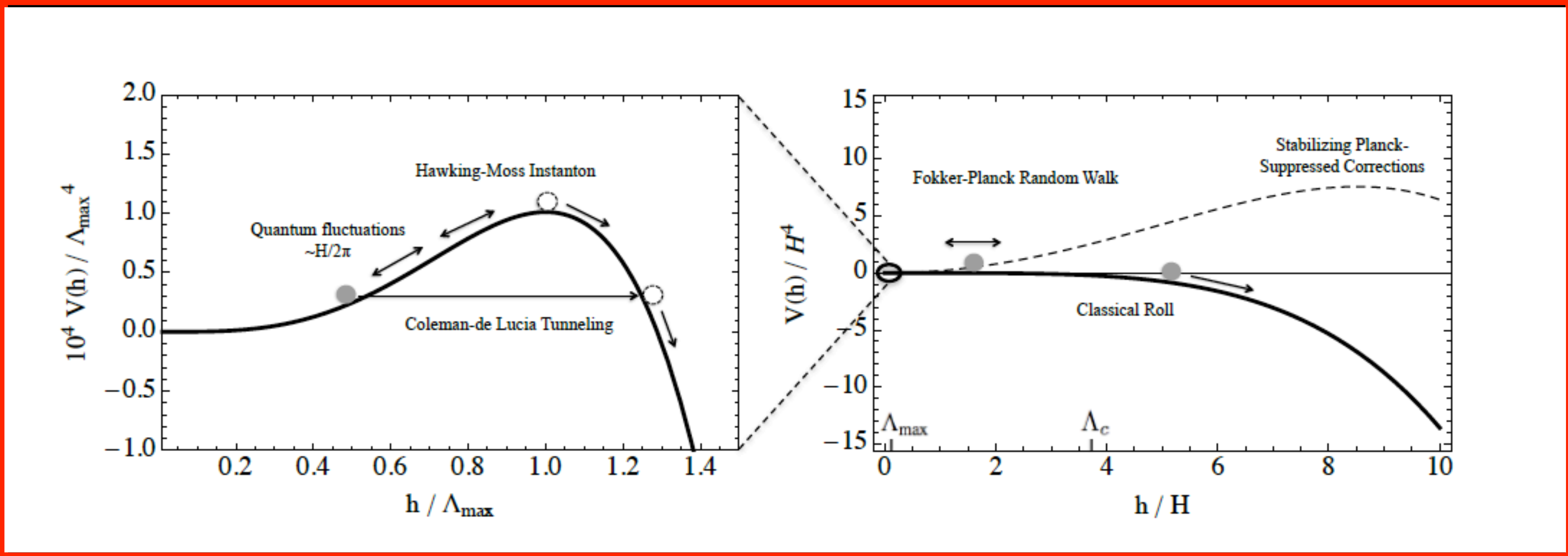
$$\frac{\mathrm{d}\lambda}{\mathrm{d}\ln\mu} = -\frac{6}{16\pi^2}h_t^4 + \cdots$$



J. Elias-Miro, J.R. Espinosa, G.F. Giudice, G. Isidori, A.R. and A. Strumia (2012)



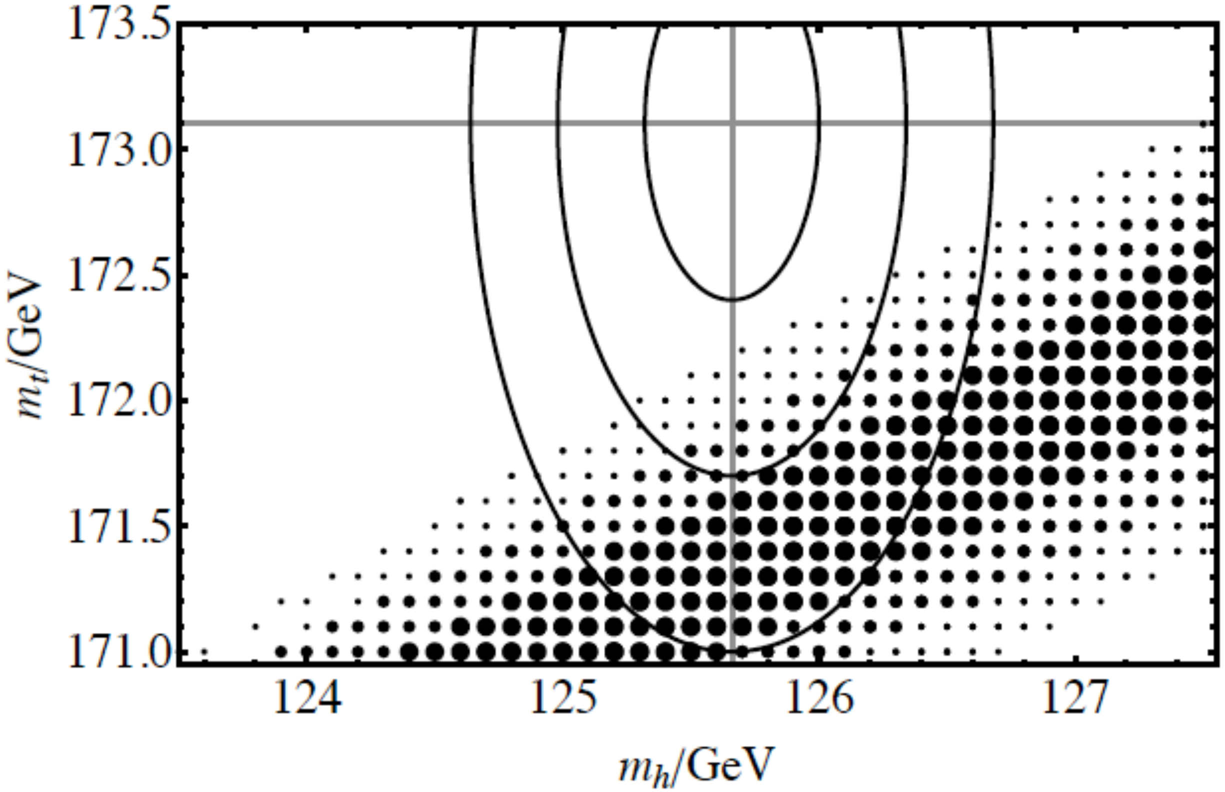
D. Buttazzo et al. (2014)



$$\langle h^2 \rangle \simeq \left(\frac{H}{2\pi} \right)^2$$

$$P_{\rm surv} \sim \exp\left(-H^3 t / 32\pi\Lambda_{\rm UV}^2\right)$$

J.R. Espinosa, G.F. Giudice and A.R. (2007)



K. Enqvist and S. Nurmi (2014)

$$H_{\rm Bicep2} \simeq 1.1 \cdot 10^{14}\,{\rm GeV} \gg \Lambda_{\rm UV}$$

During inflation, quantum fluctuations drive the Higgs field towards the instability region

The SM Higgs must be coupled to either the inflaton or to gravity to avoid this catastrophe

$$\mathcal{L} \supset -Rh^2 = 12H^2h^2$$

Implication 6

SM Higgs Inflation

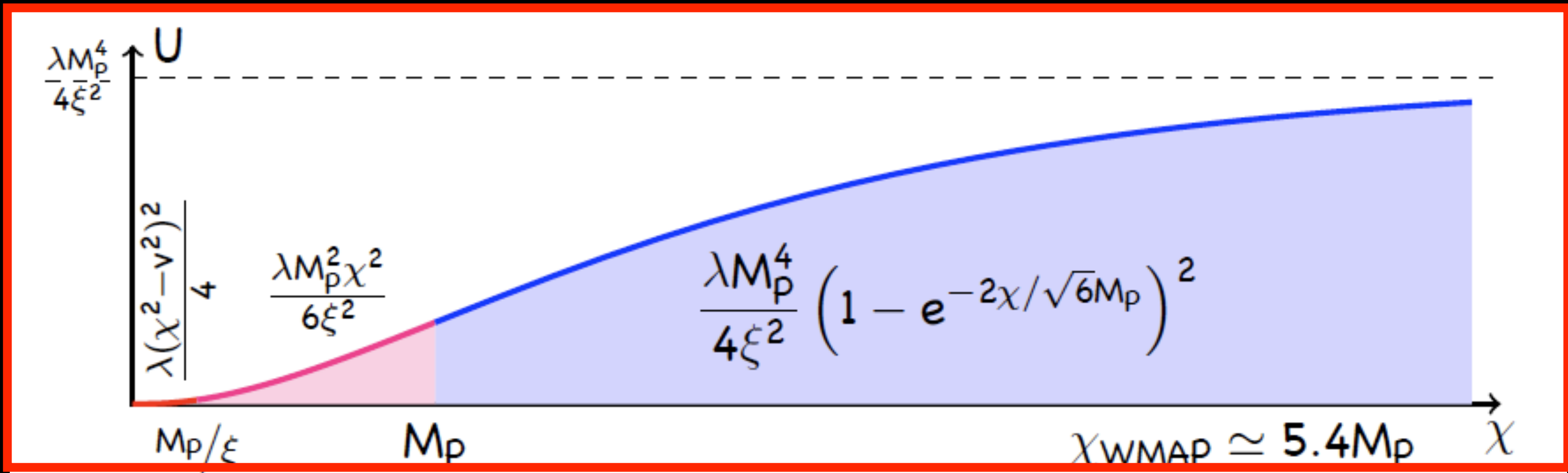
Jordan frame:

$$\mathcal{L} = \mathcal{L}_{\rm EH} + \mathcal{L}_{\rm SM} - \int {\rm d}^4x\sqrt{-g}\frac{\xi}{2}\mathcal{R}h^2$$

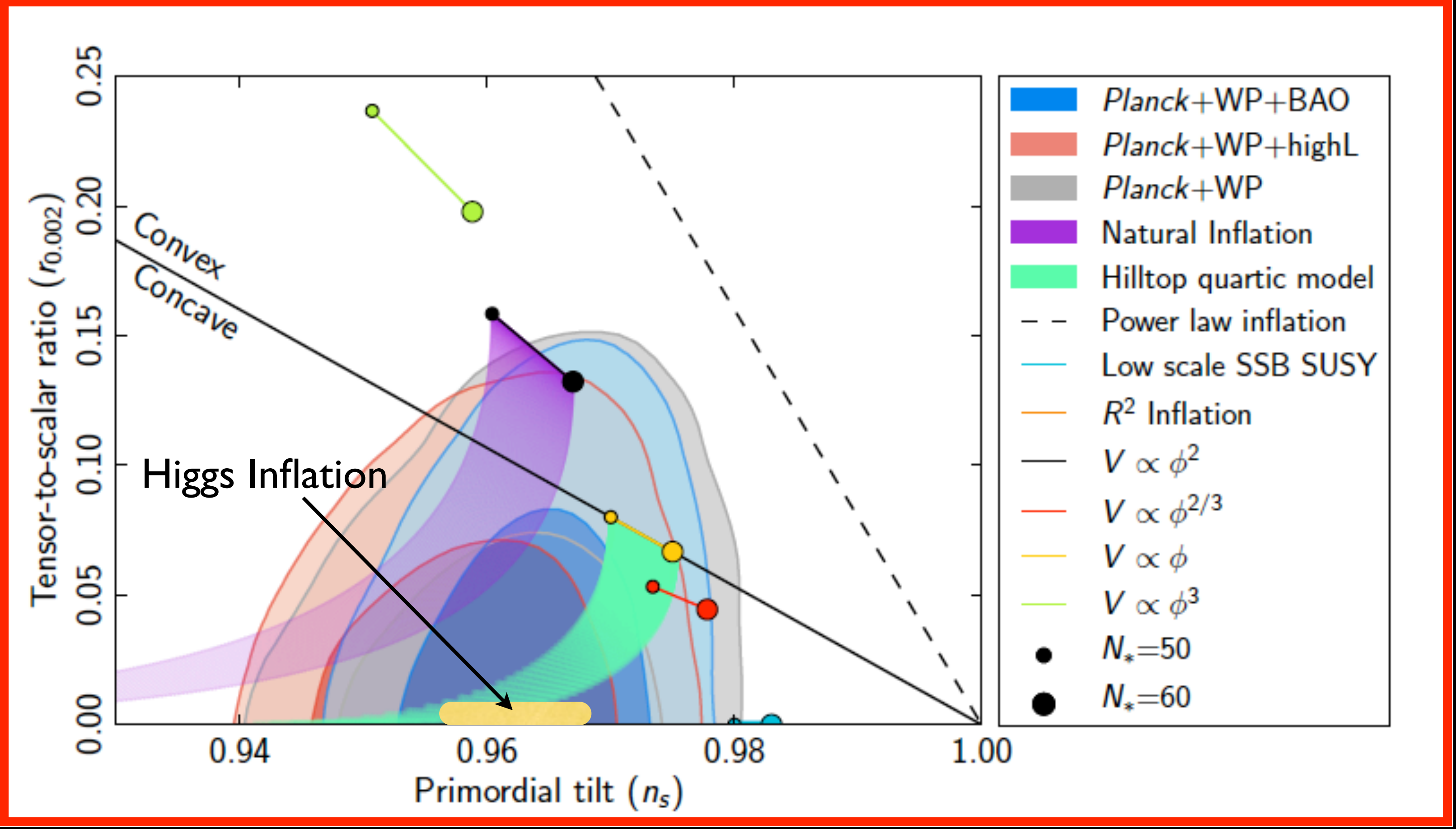
Einstein frame:

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{M_{\rm Pl}^2}{2}\int {\rm d}^4x\sqrt{-\bar{g}}\bar{\mathcal{R}} + \frac{1}{2}(\partial\chi)^2 - \frac{\lambda}{4}\frac{h^4(\chi)}{\Omega^4(\chi)}$$

$$\bar{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}, \quad \Omega^2 = 1 + \frac{\xi h^2}{M_{\rm Pl}^2}$$

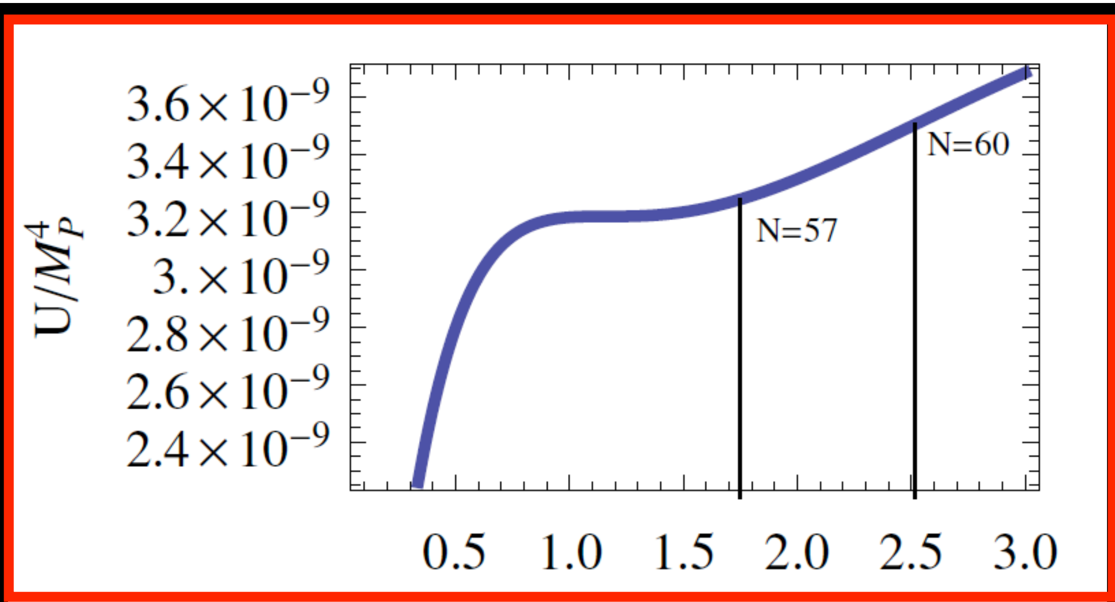


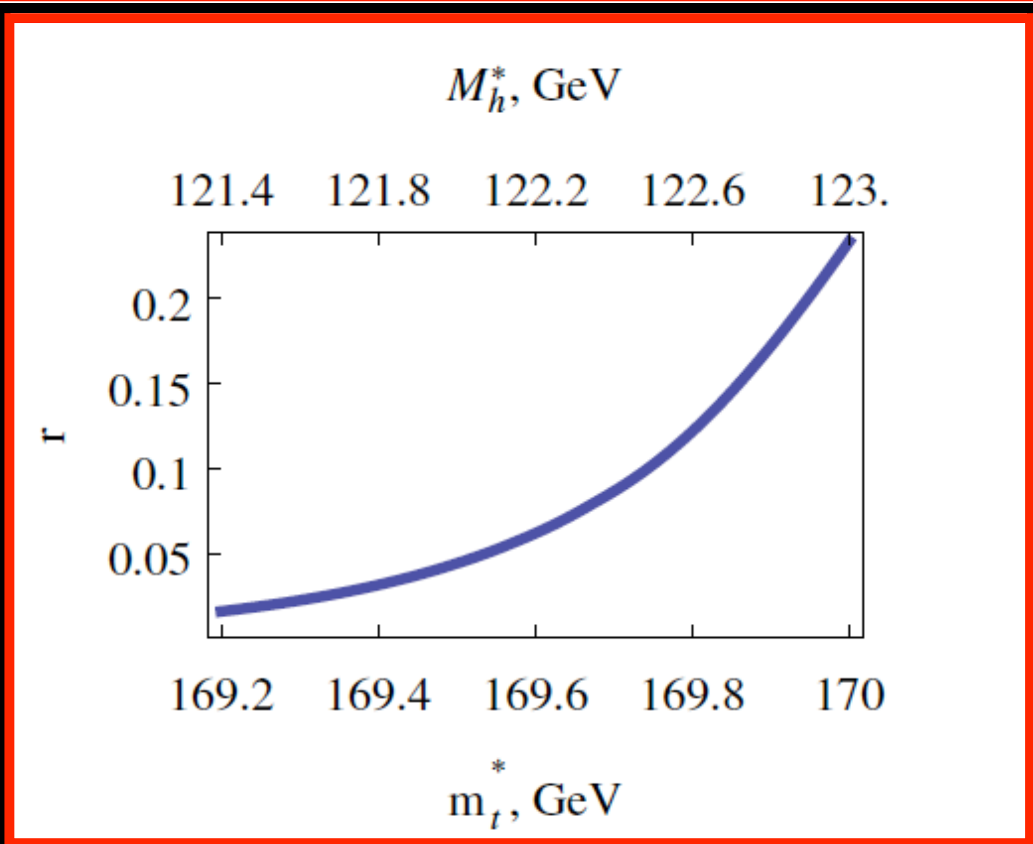
Zee (1978), Salopek, Bond and Bardeen (1979), F. Bezrukov et al. (2008+)



$$\xi \sim 10^3$$

$$M_h > M_c = \left[129.6 + \frac{h_t(173.2\,\mathrm{GeV}) - 0.9361}{0.0058} \times 2 - \frac{\alpha_s - 0.1184}{0.0007} \times 0.5\right] \mathrm{GeV}$$





$$\xi \sim 1$$

F. Bezrukov and M. Shaposhnikov (2014)

Implication 7

SUSY

Flat directions are a generic property of supersymmetry

$$\phi = \widetilde{u}_1 = \widetilde{d}_2 = \widetilde{d}_3$$

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

$$\boxed{\mu \frac{\mathrm{d}m^2}{\mathrm{d}\mu} \simeq \frac{1}{8\pi^2} \left(-16 g_3^2 M_3^2 - \frac{8}{3} g_1^2 M_1^2 \right)}$$

The flat direction is unbounded from below
and destabilzed during inflation unless
scalar masses are typically larger than gaugino masses

Conclusions

- BICEP2 results under scrutiny

If true

- High energy scale of inflation, possibly supporting GUTs
- The high energy scale of inflation dangerous for the SM Higgs, needs extra coupling; same true for the MSSM flat directions
- Large extra-dimensions rule out
- Window to Planckian physics