Implications of BICEP2 for Cosmology and Particle Physics

16th April 2014
@ICEPP

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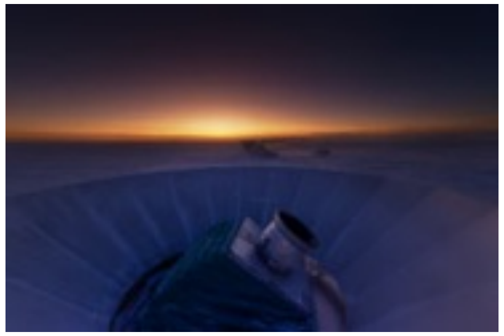
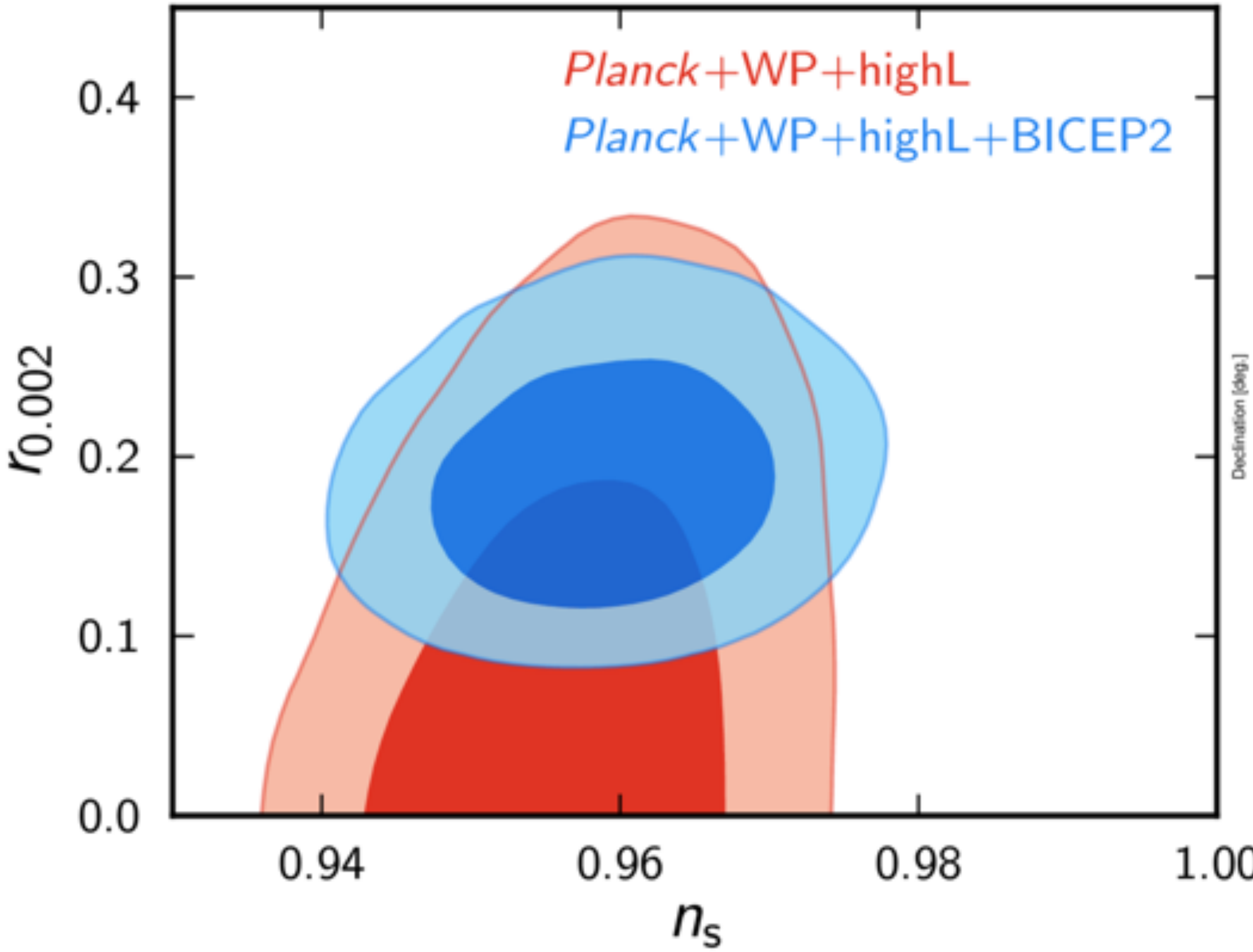
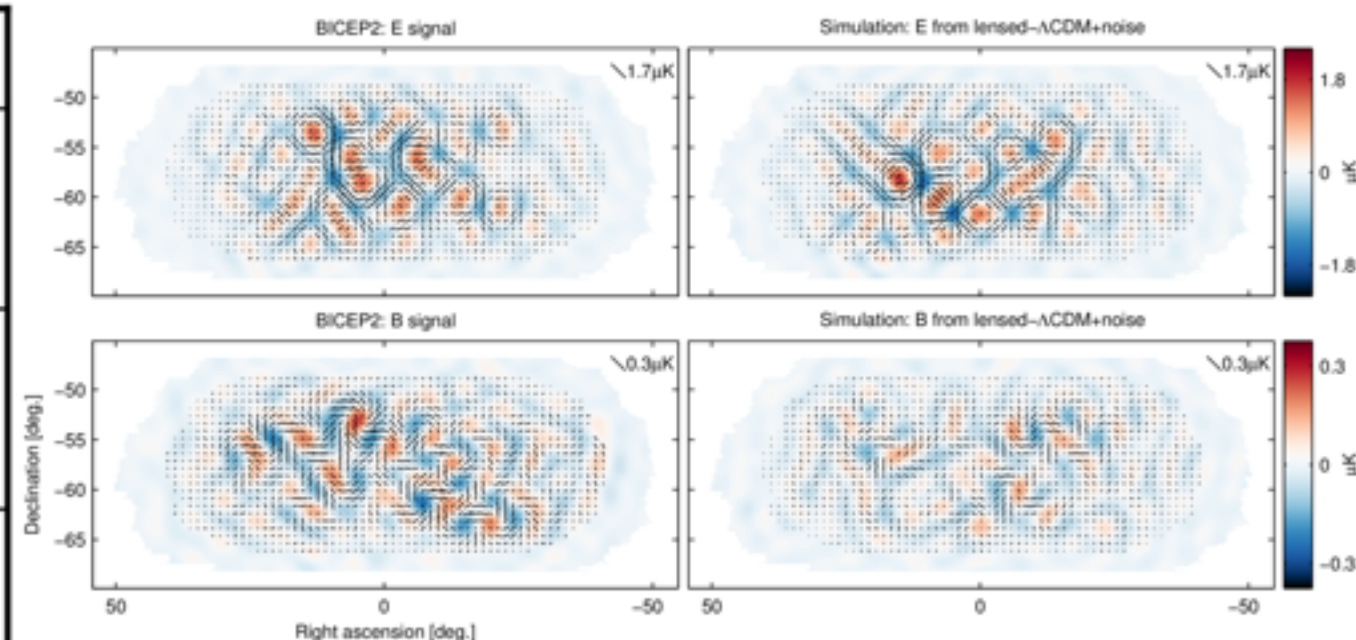
[Caveat: I assume BICEP2 is basically correct.]

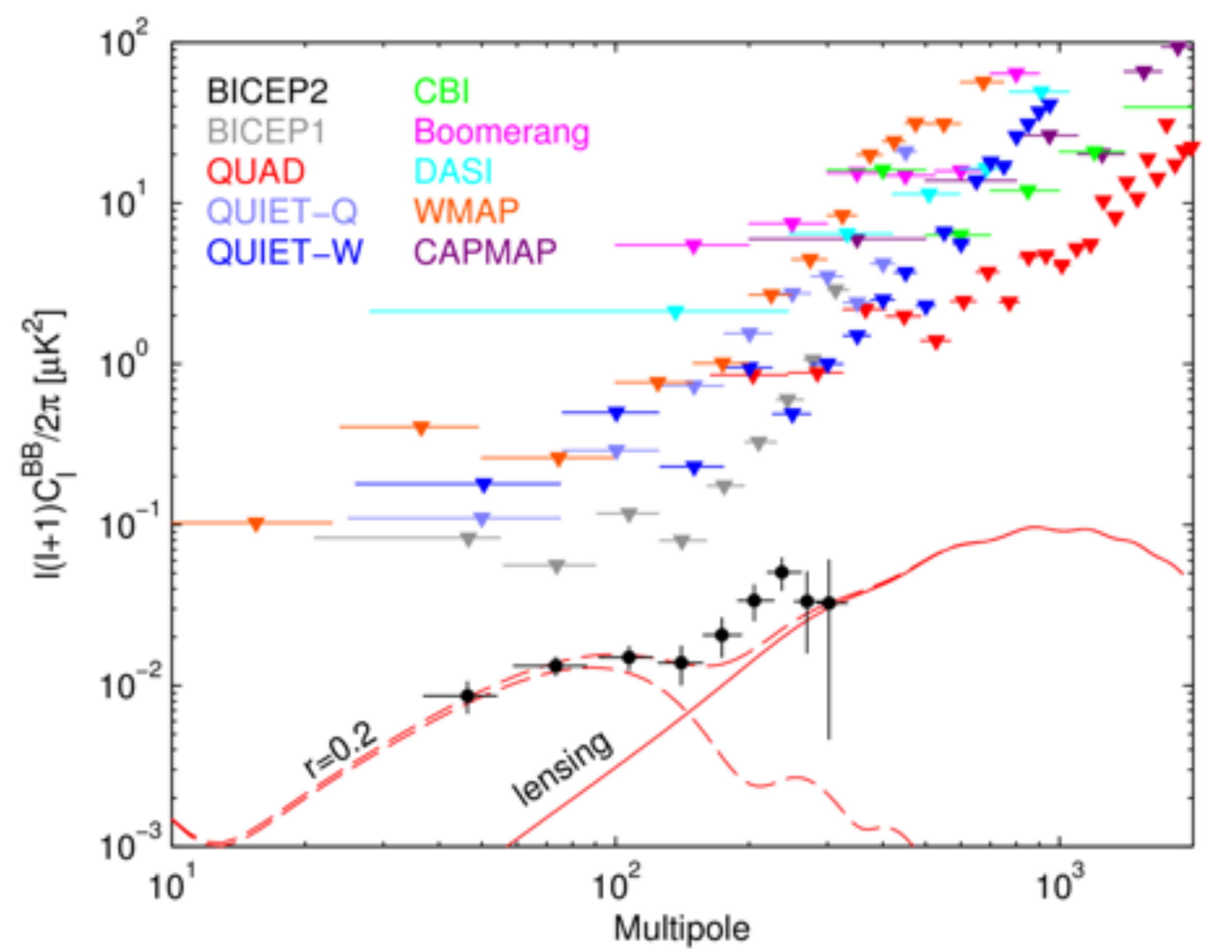


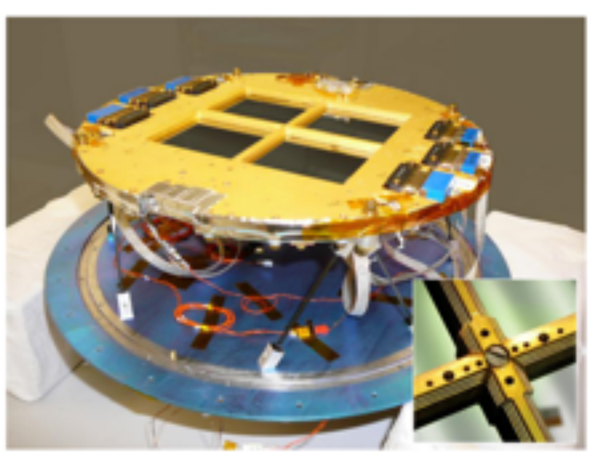
BICEP2

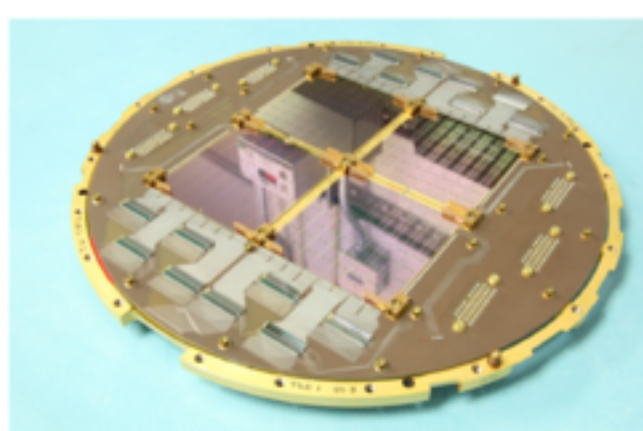
1403.3985







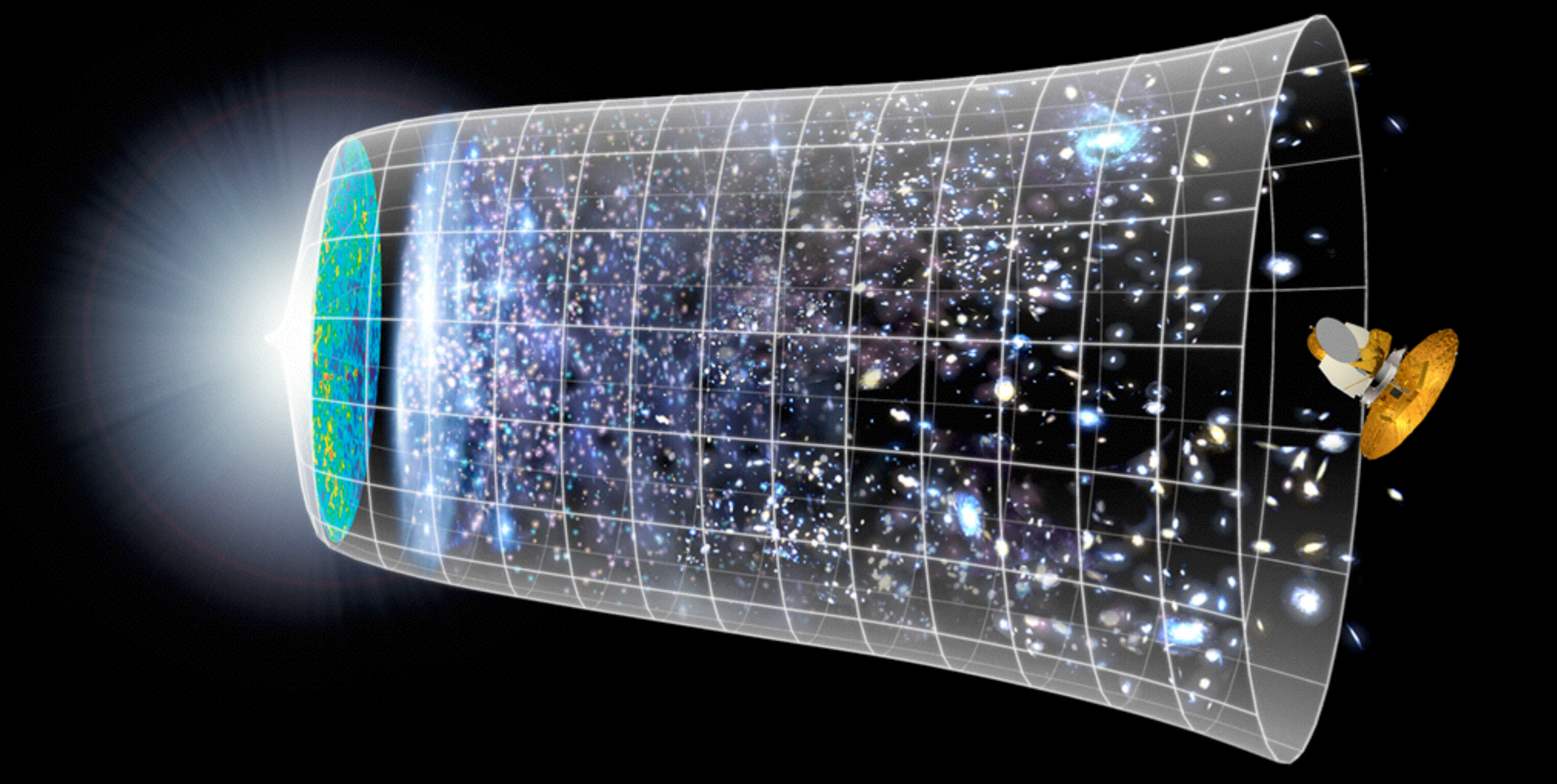




Talk Plan

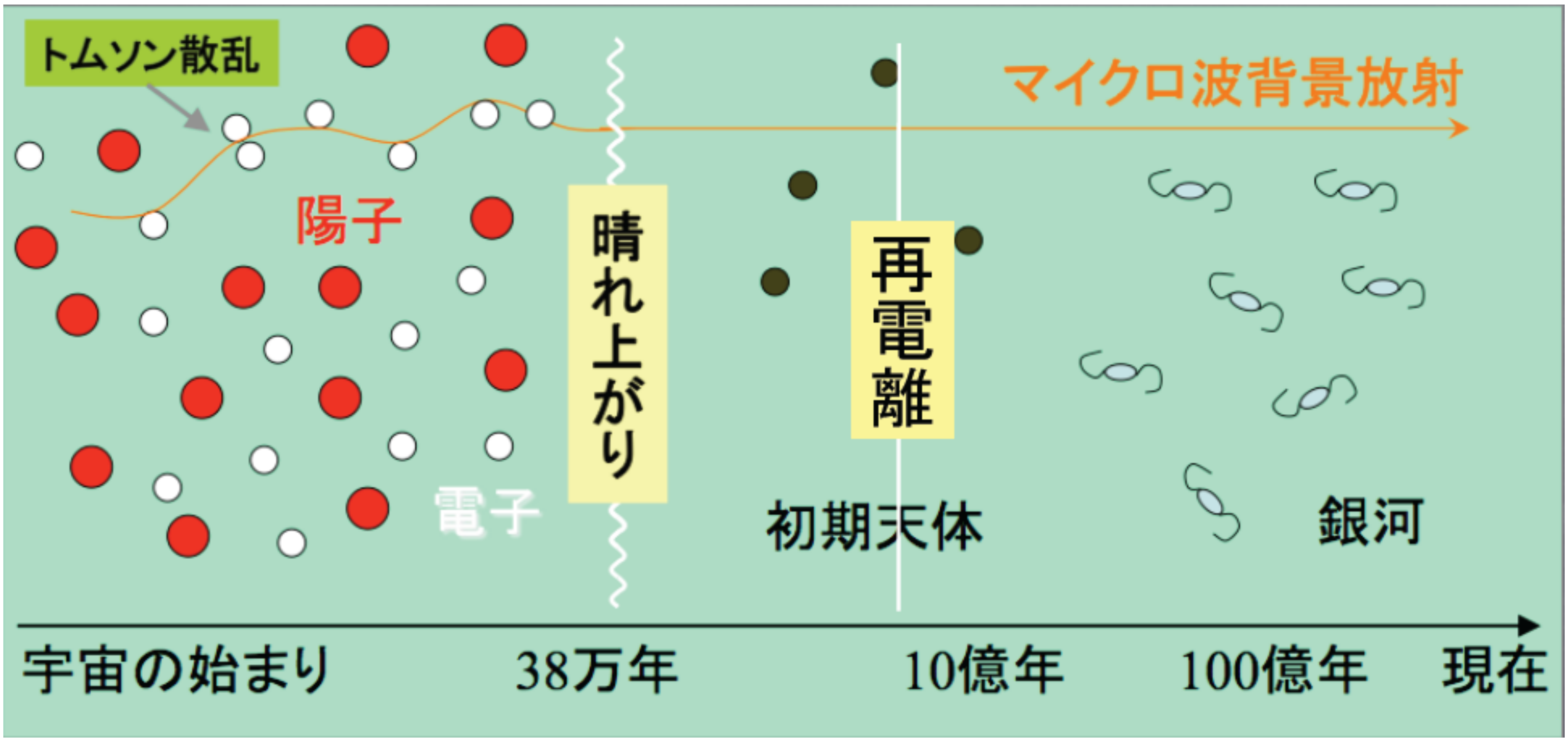
1. What did BICEP2 find? What is B-mode? How can we explain it?
2. Inflation does the job!
3. Implications of BICEP2
    1. For particle physics
    2. For cosmology
4. Conclusions

What did BICEP2 find?

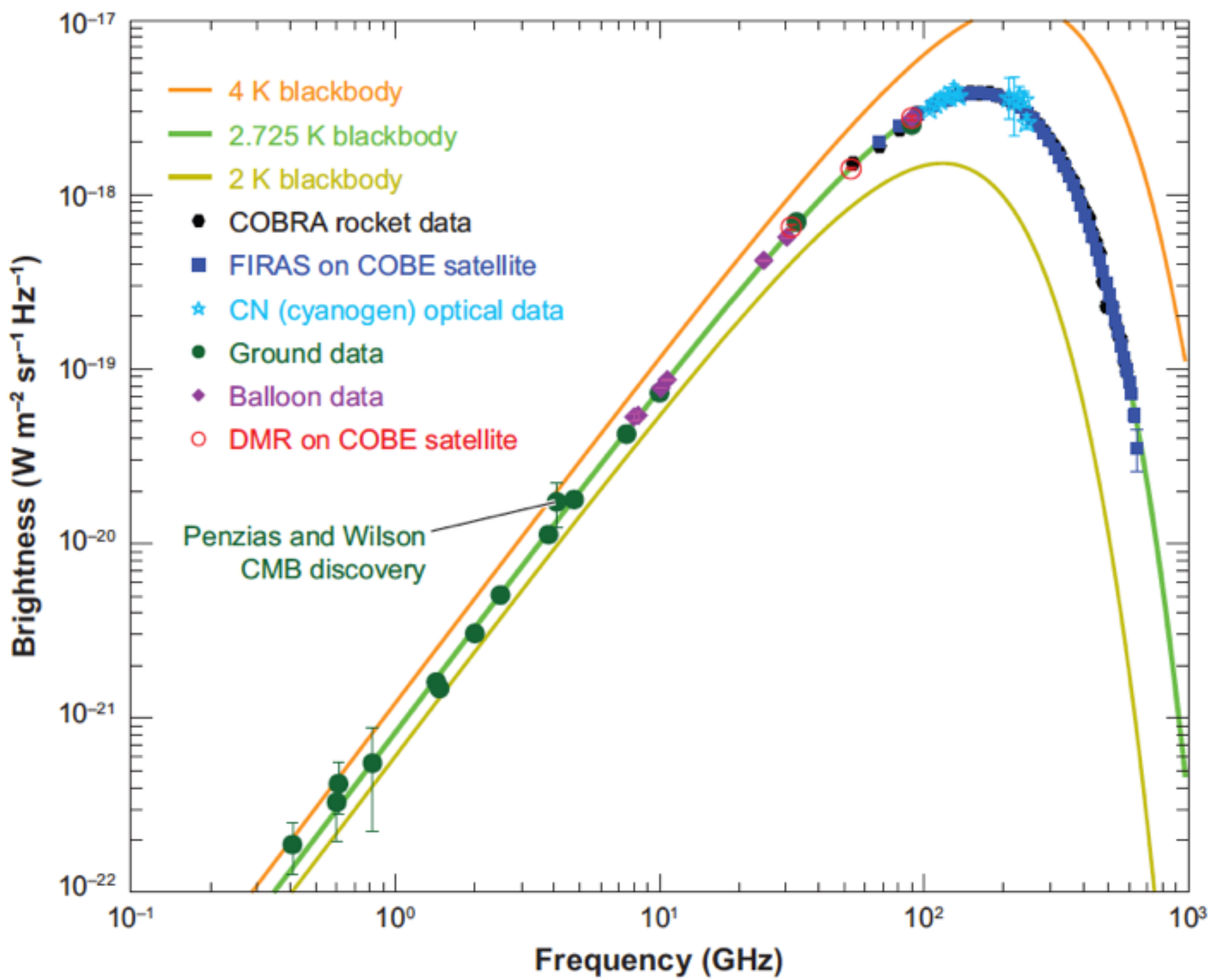


NASA/WMAP Science Team

宇宙マイクロ波背景放射(CMB)



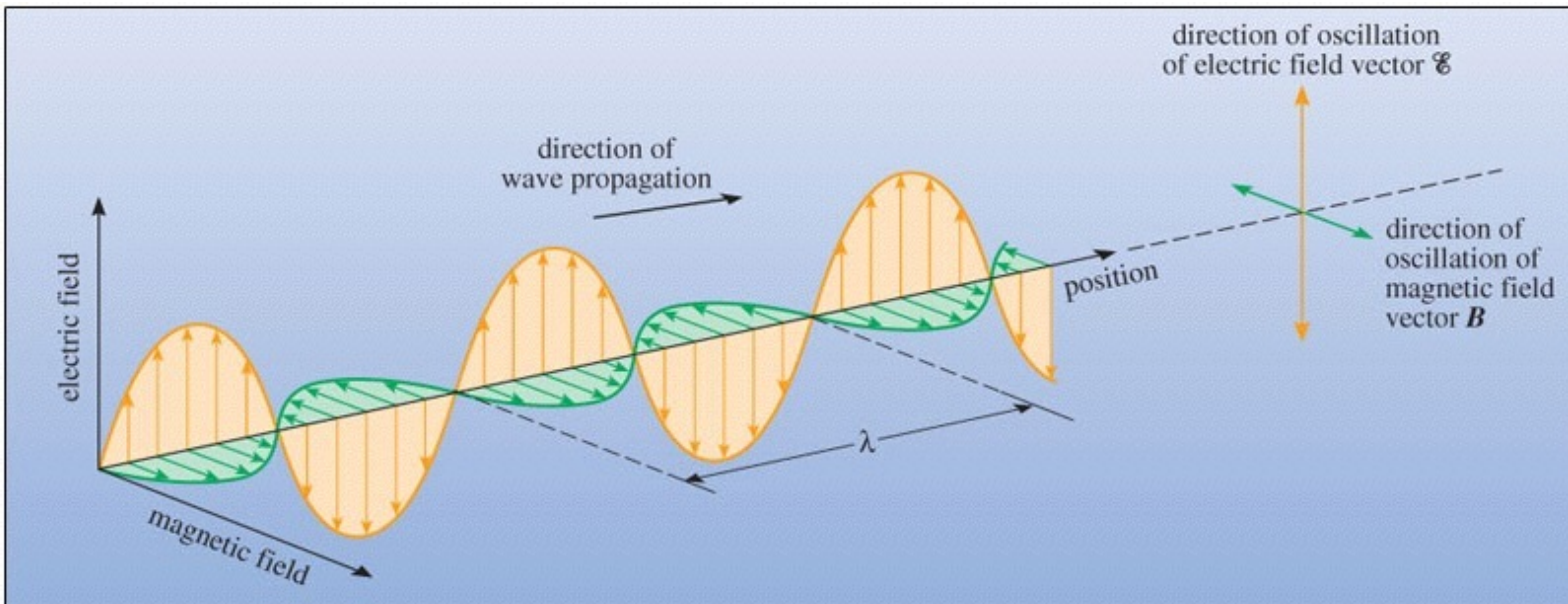
Planck distribution of CMB



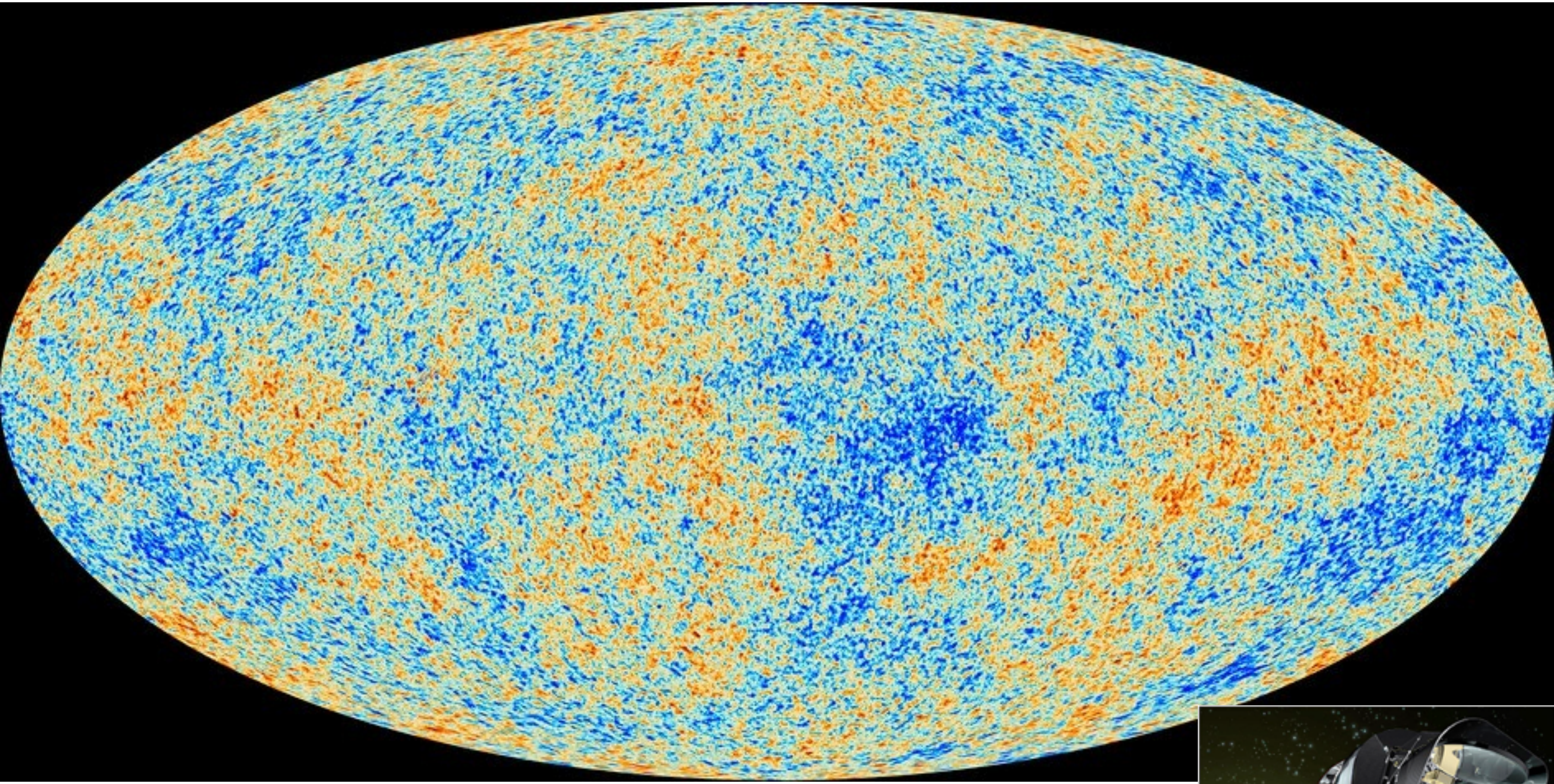
Our Universe was in equilibrium.

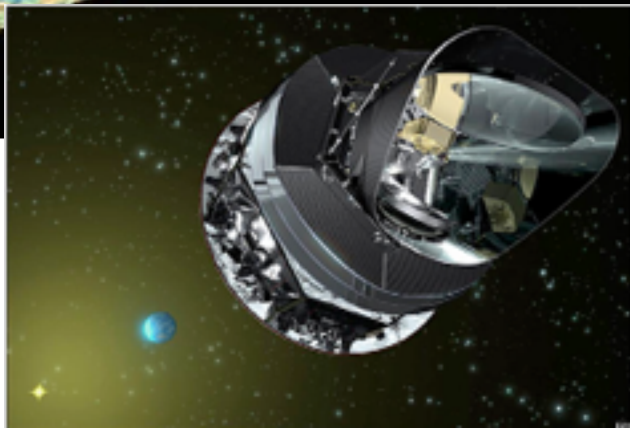
CMB photons are characterized by

1. Energy (or temperature) **scalar**
2. Polarization **vector**

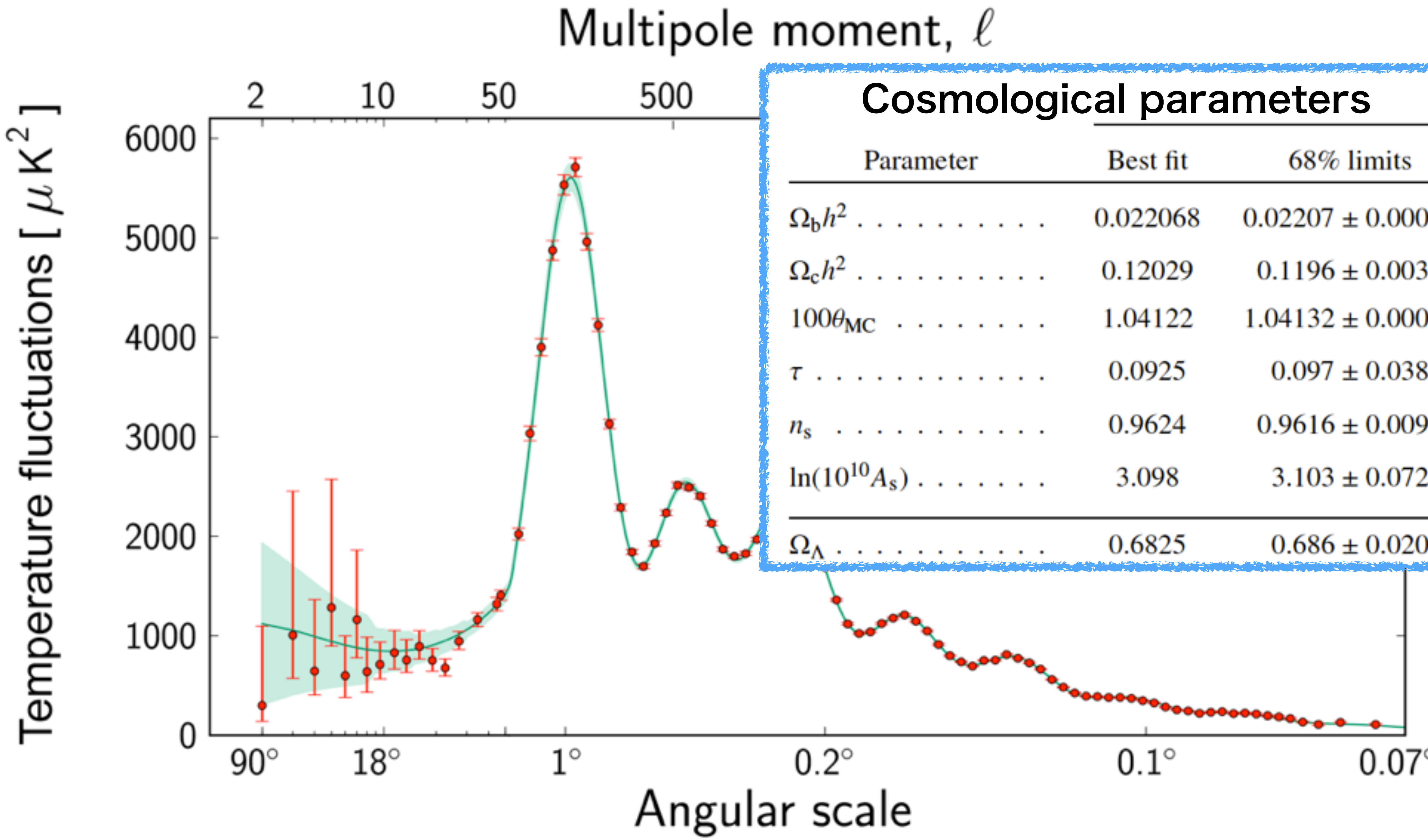


CMB temperature sky map





CMB anisotropy angular power spectrum

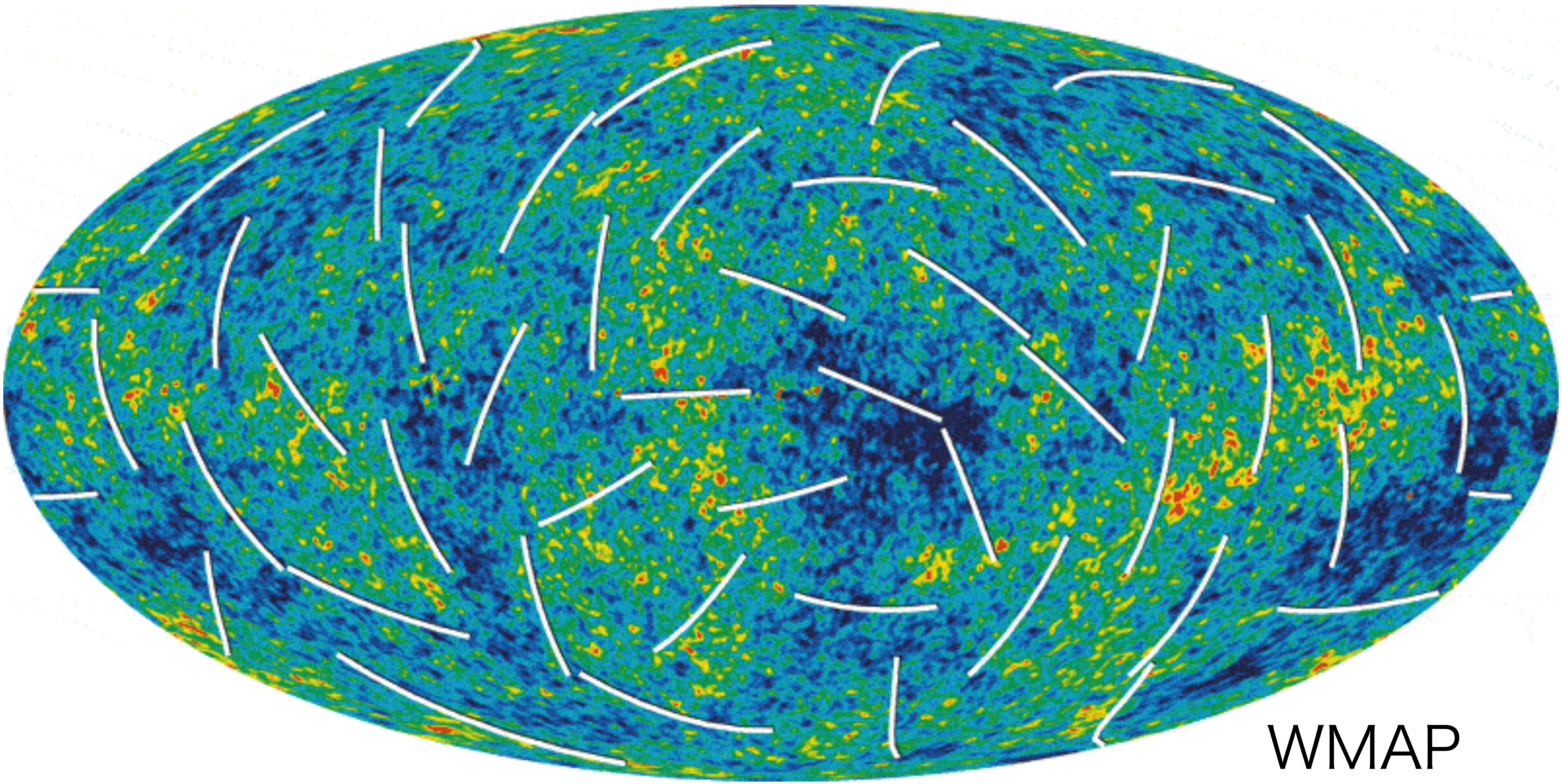


Cosmological parameters

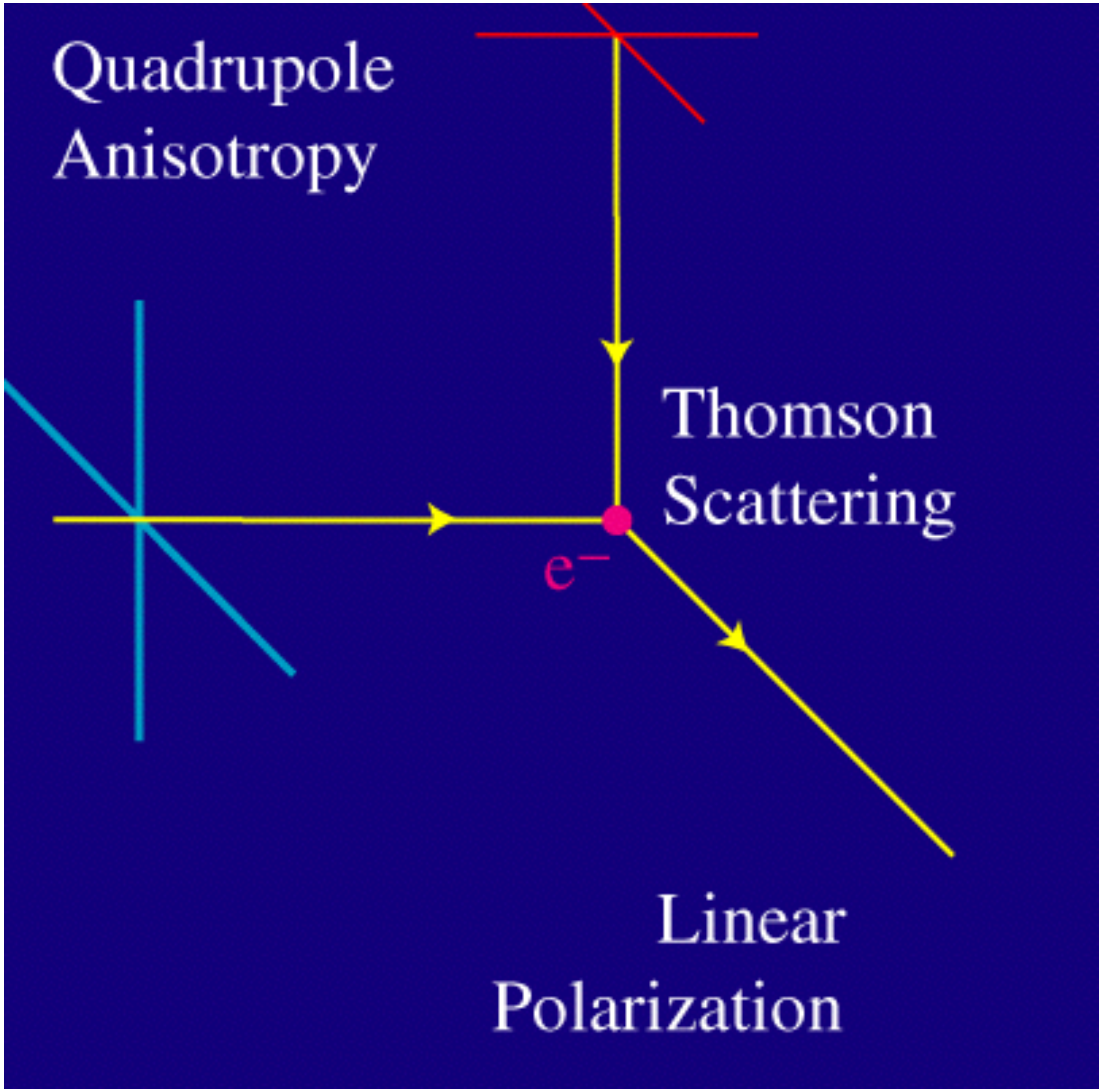
Parameter	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068
τ	0.0925	0.097 ± 0.038
n_s	0.9624	0.9616 ± 0.0094
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072
Ω_Λ	0.6825	0.686 ± 0.020

CMB polarization

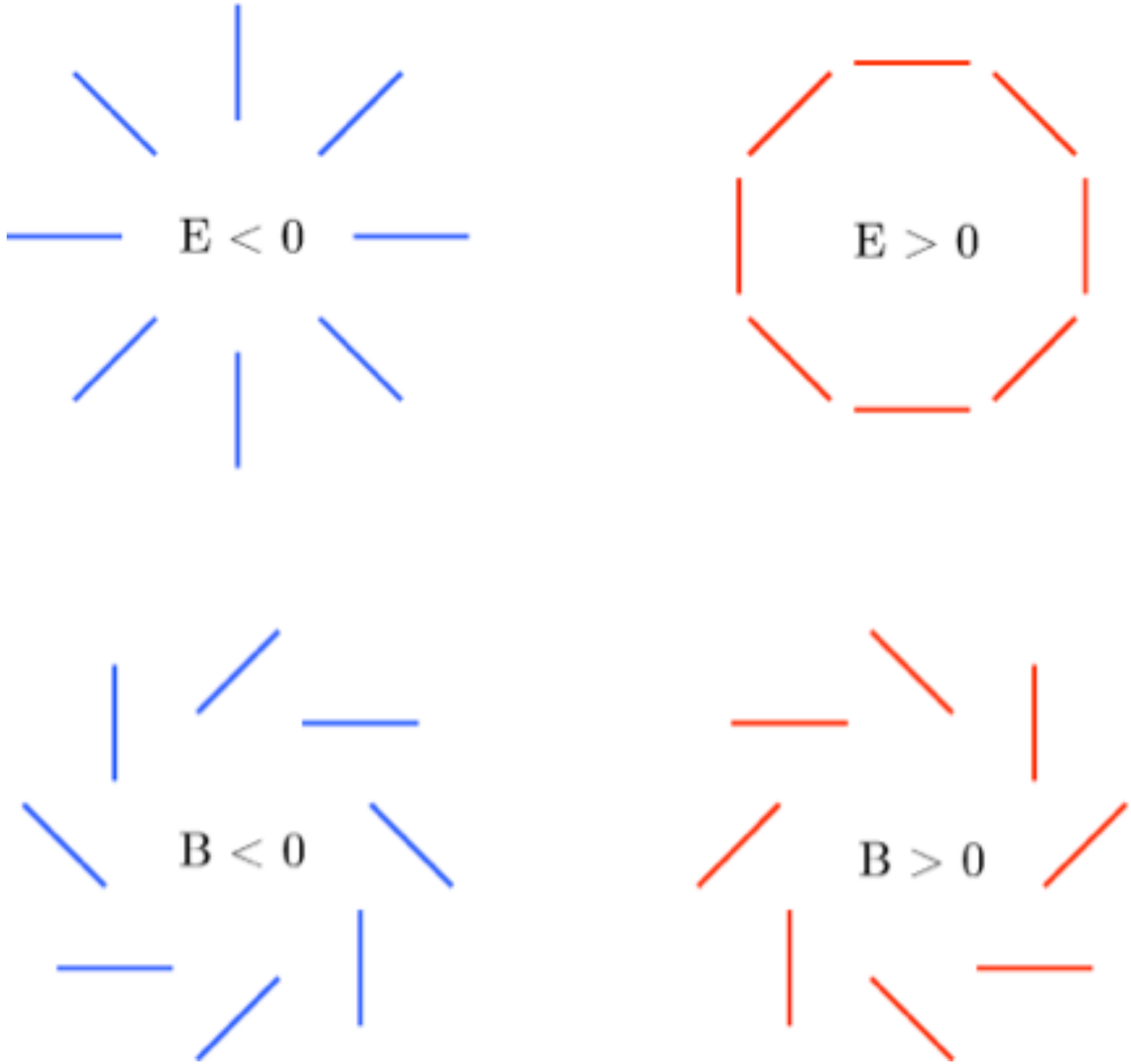
CMB photons are polarized!!



Polarization is due to quadrupole anisotropy around electrons.



(Taken from W. Hu's webpage)



E-mode and B-mode are exchanged by rotating the polarization vector by 45 degrees.

Perturbations of spacetime

Flat FRW Universe:

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

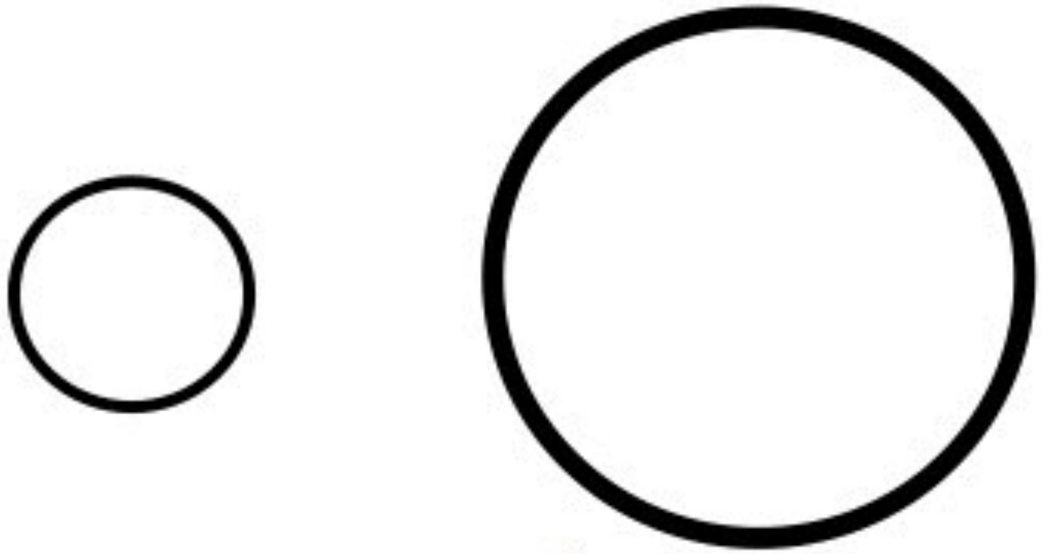
+ small perturbations

$$ds^2 = -(1+2A)dt^2 - 2aB_i dt dx^i + a^2 \left(\delta_{ij} + 2H_L \delta_{ij} + 2H_{Tij}\right) dx^i dx^j$$

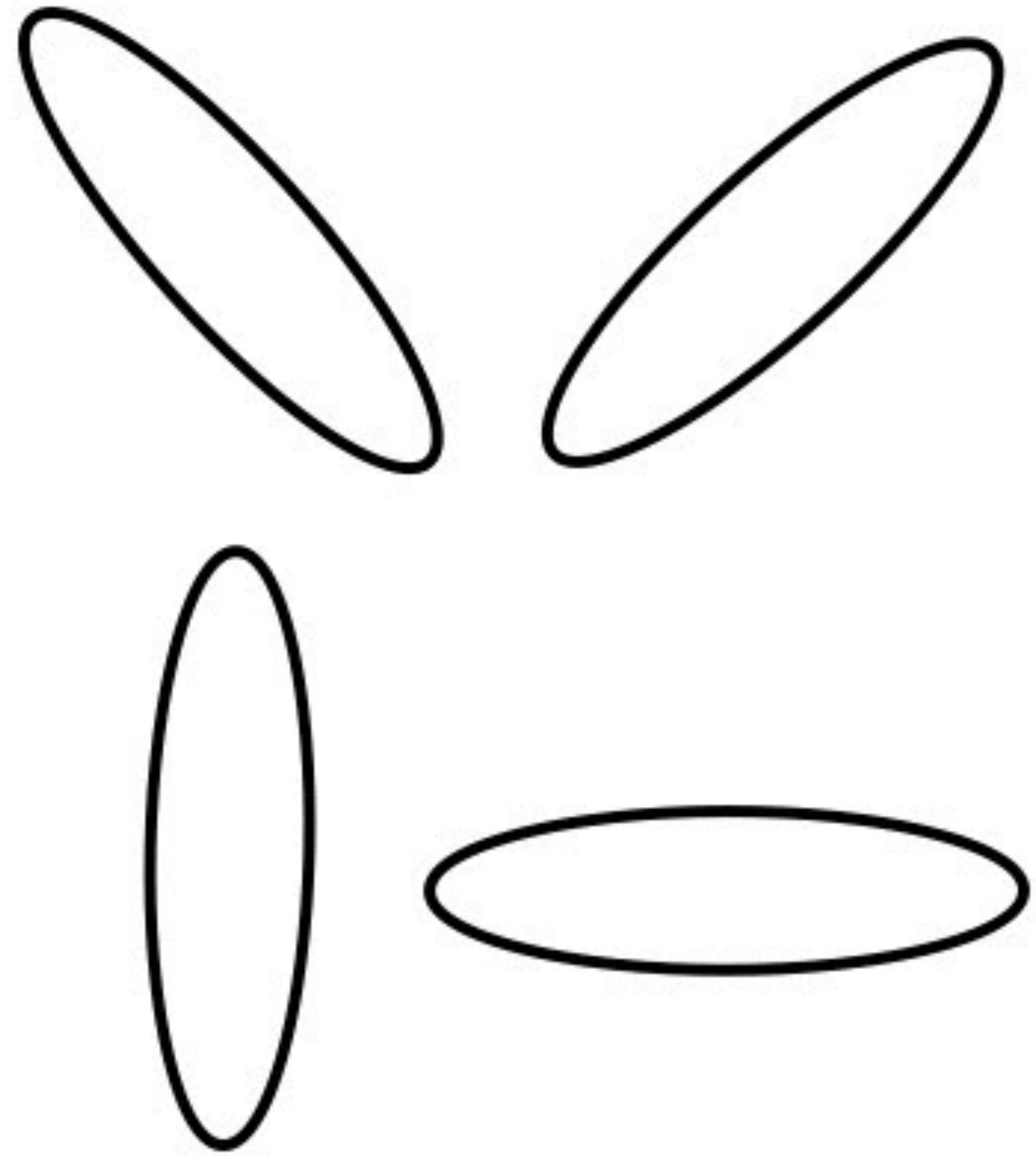
The perturbations can be decomposed into three types.

1. Scalar $ds^2 = -(1+2\Phi)dt^2 + a^2(1+2\Psi)d\mathbf{x}^2$ inflaton
2. Vector
3. Tensor $ds^2 = -dt^2 + a^2 \left(\delta_{ij} + h_{ij}\right) dx^i dx^j$ GW

Scalar perturbations



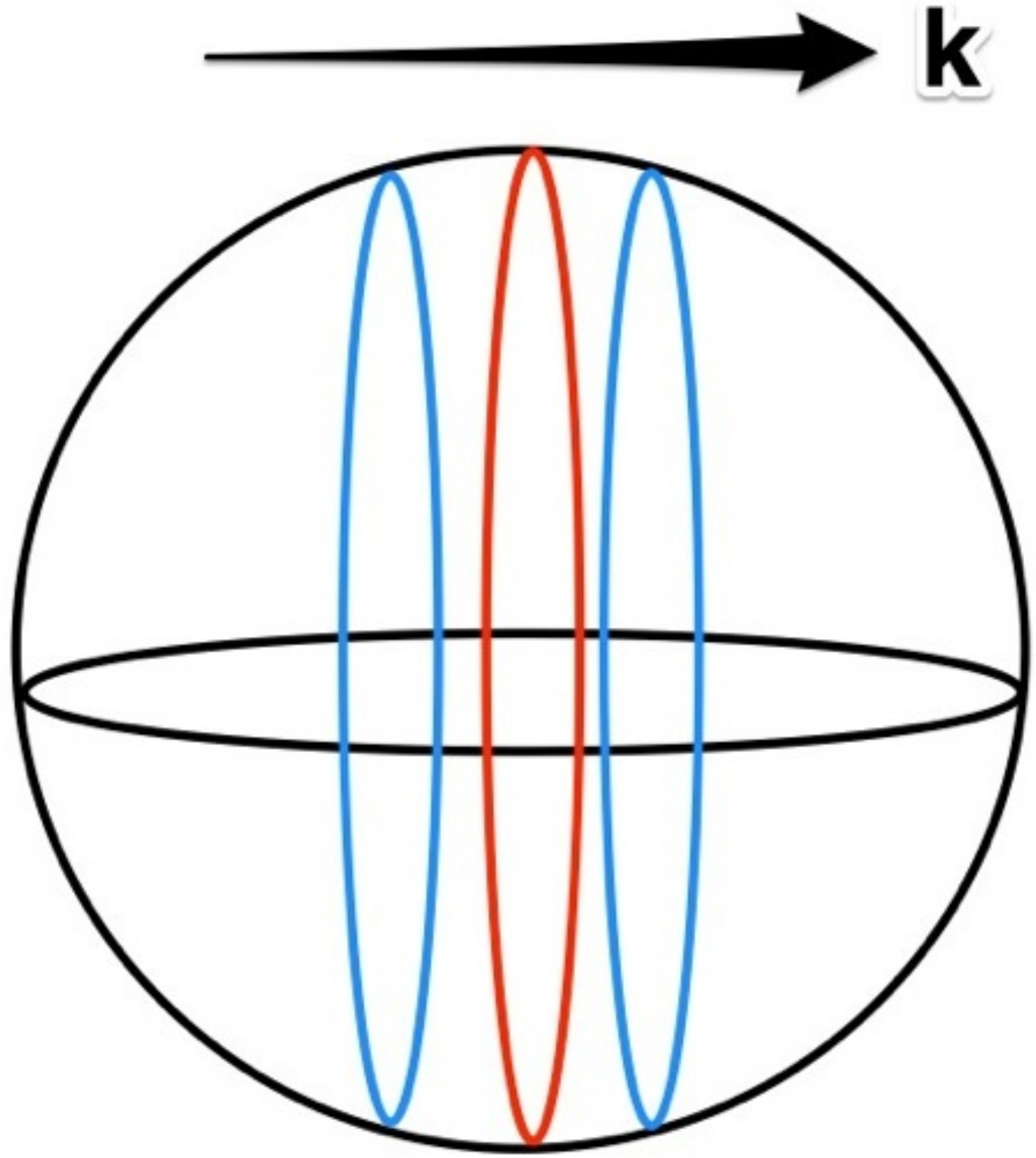
Tensor perturbations



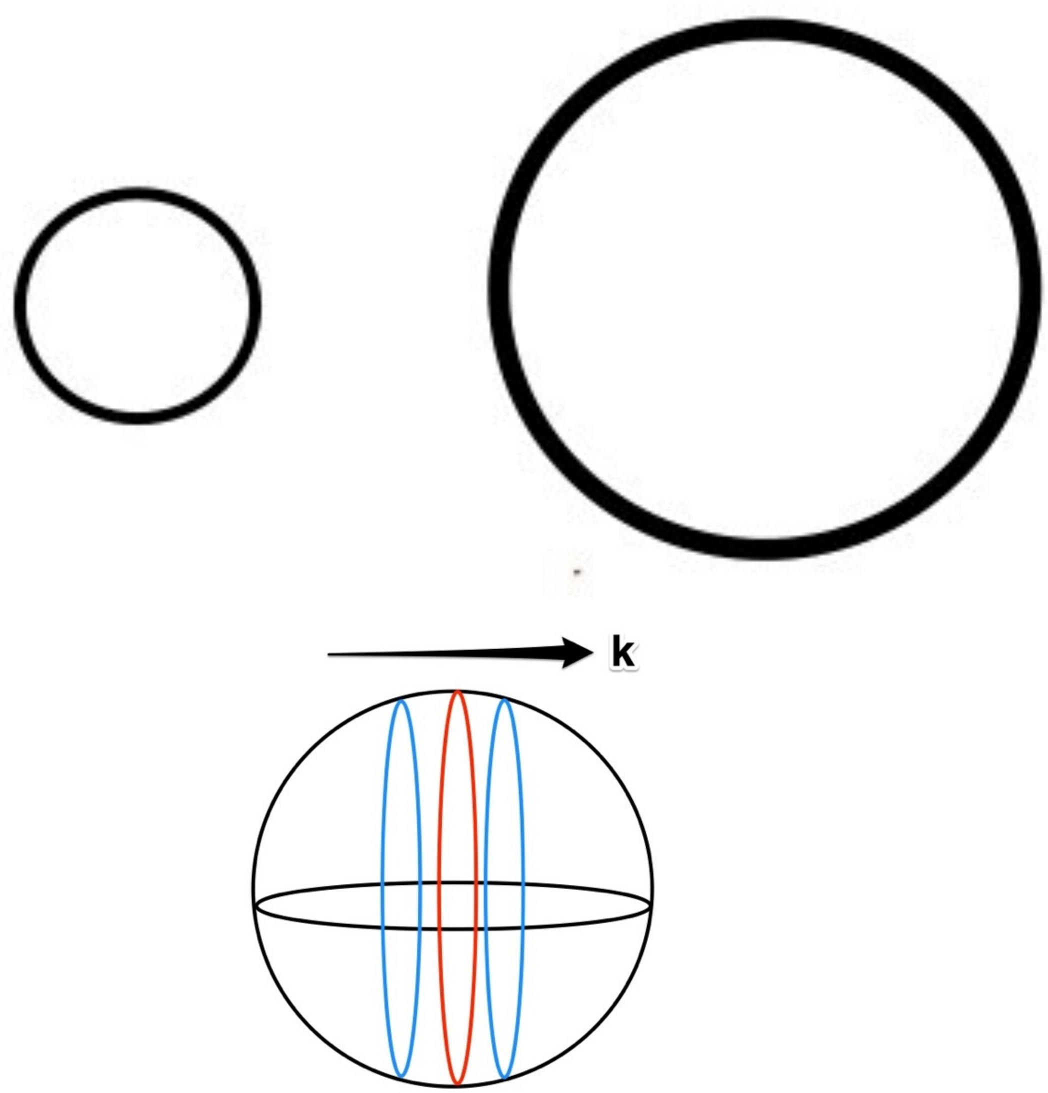
E-mode ONLY

BOTH E-mode and B-mode

Density (scalar) perturbations generate only E-mode.

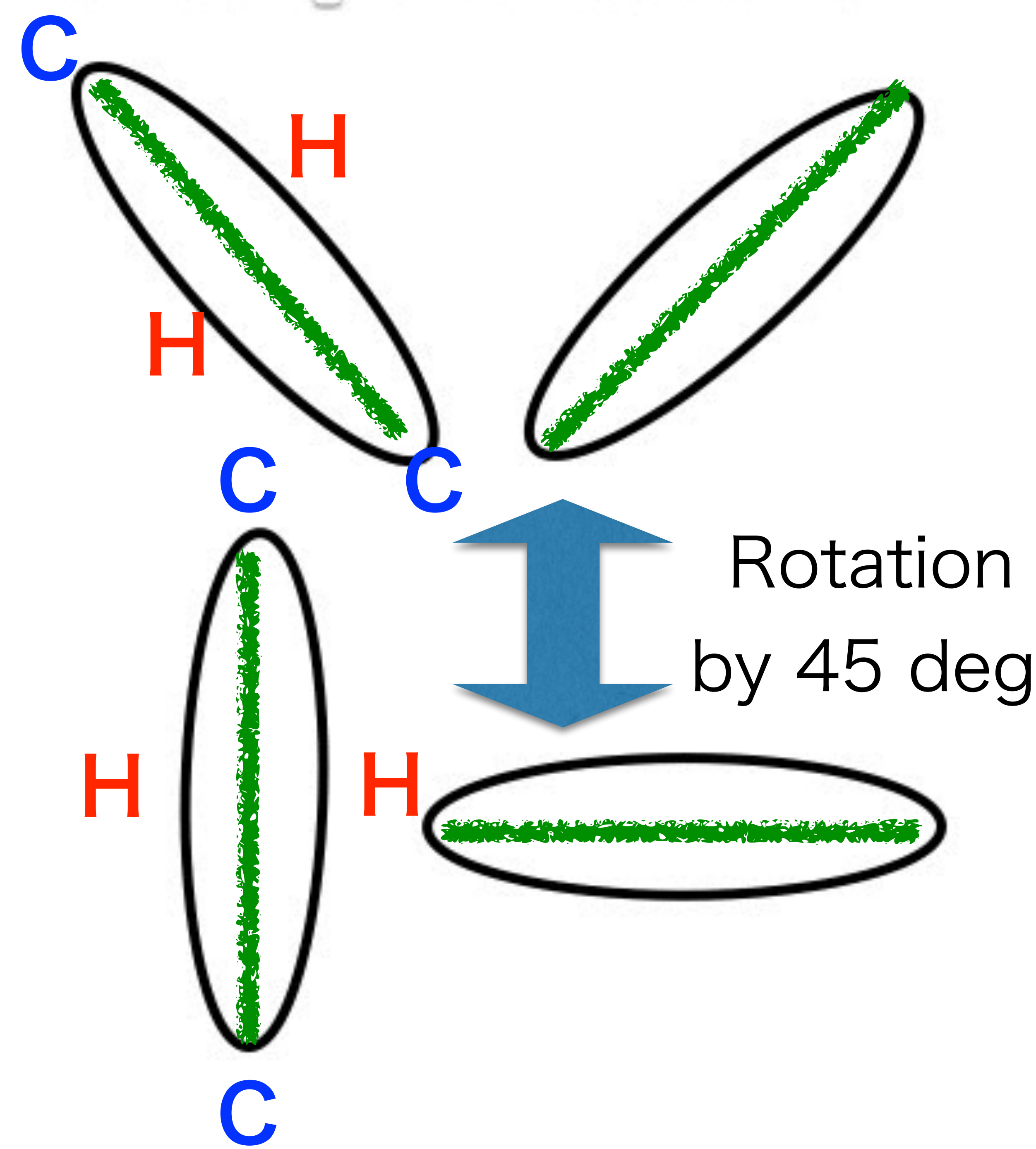


Scalar perturbations



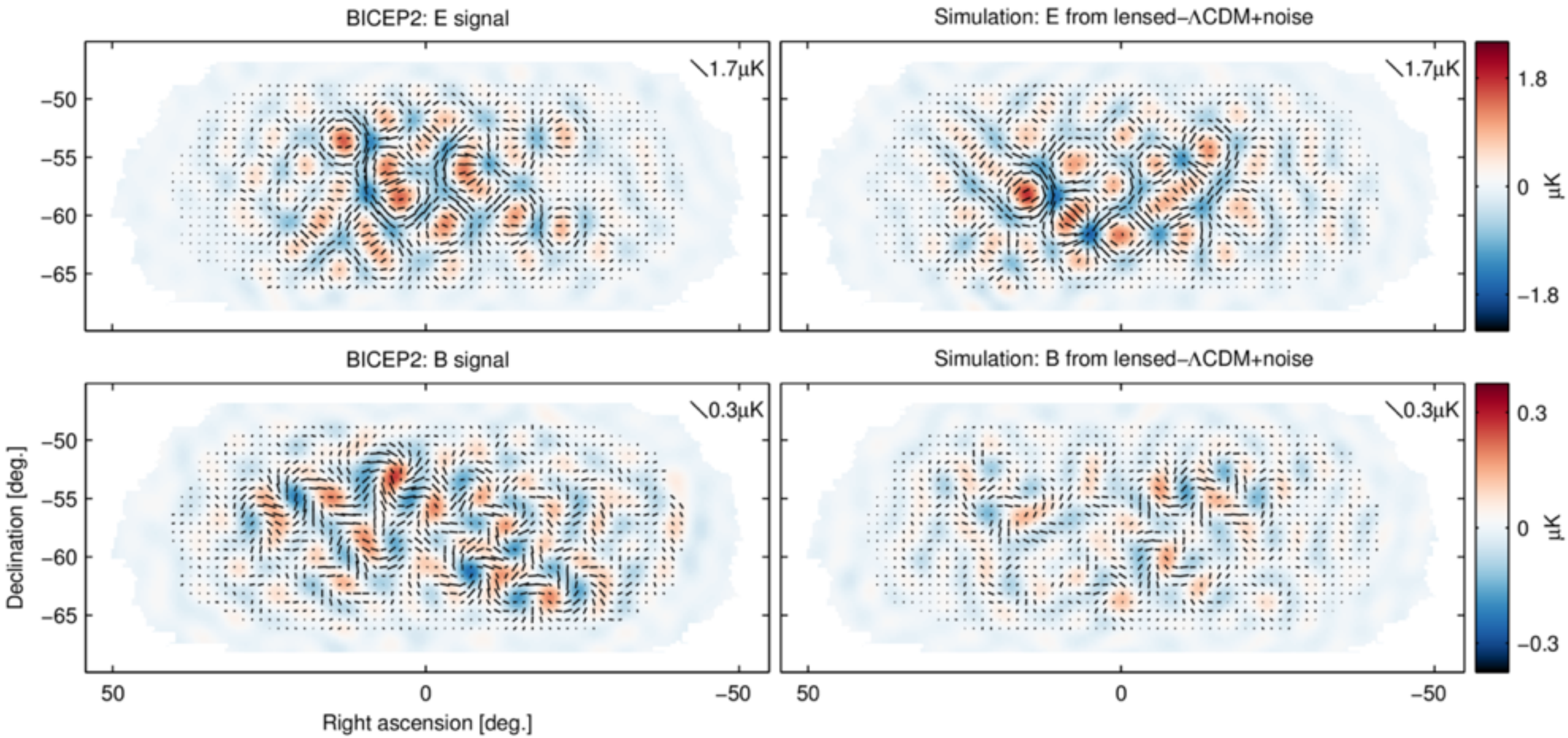
E-mode ONLY

Tensor perturbations



BOTH E-mode and B-mode

B-mode, B-mode, and B-mode!!!!!!

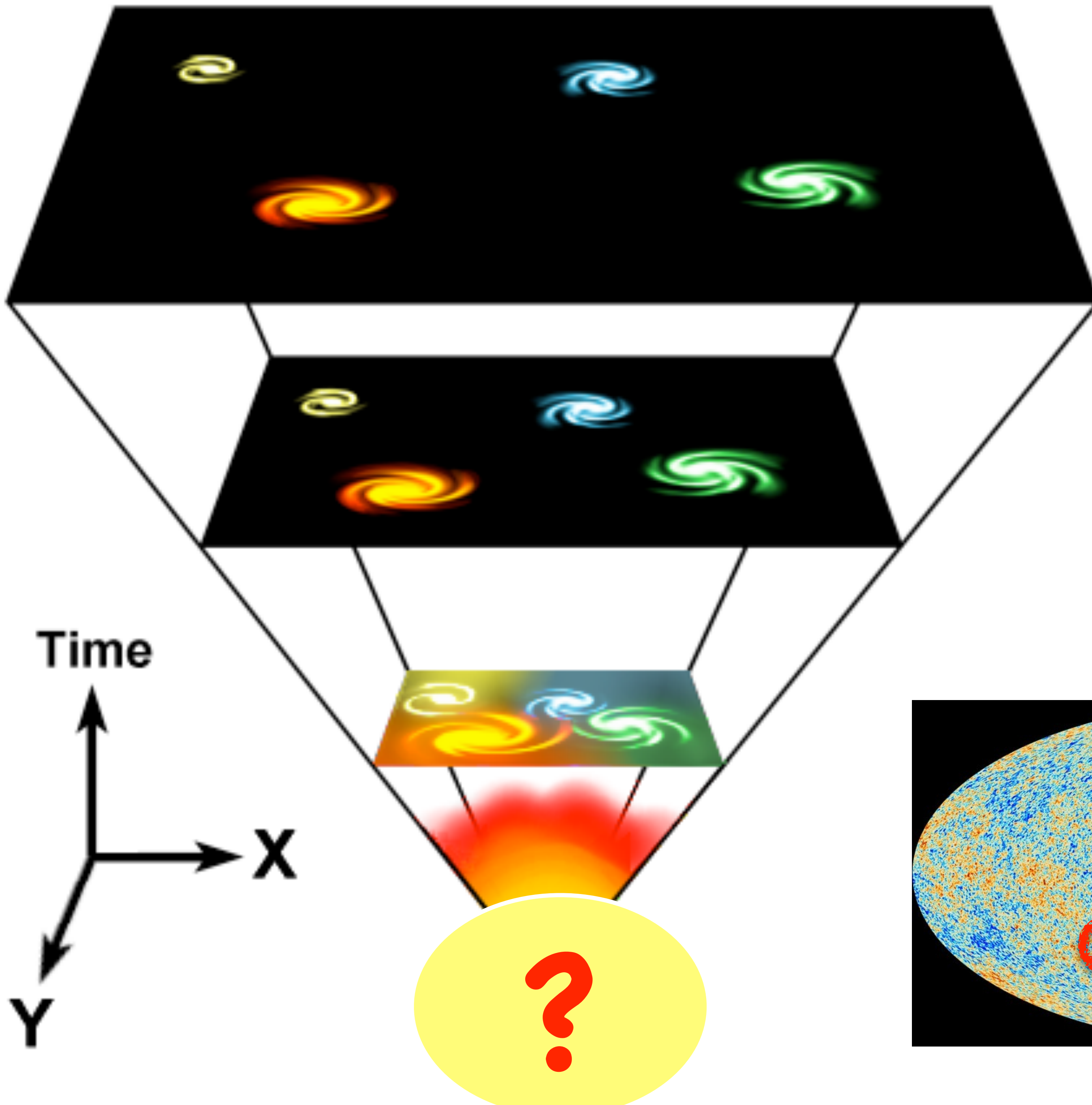


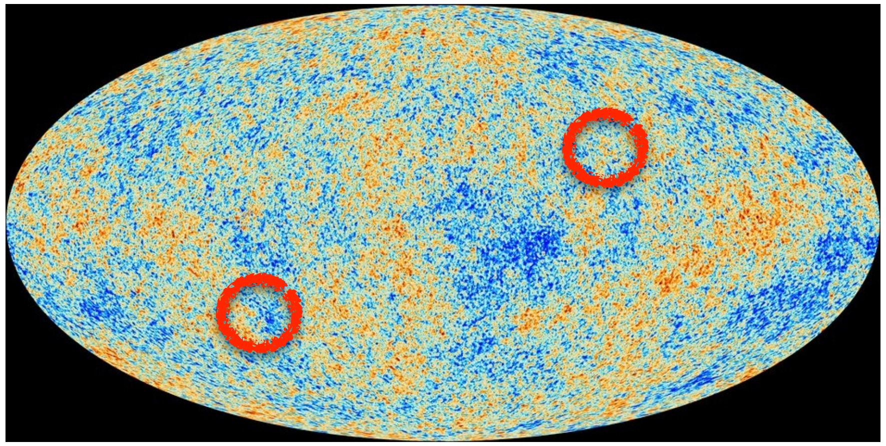
BICEP2, 1403.3985

OK, B-mode. So what?

Inflation is by far the most plausible explanation for the observed primordial B-mode polarization, **if true.**

Can we extrapolate the decelerated expansion back to the very beginning of the Universe?



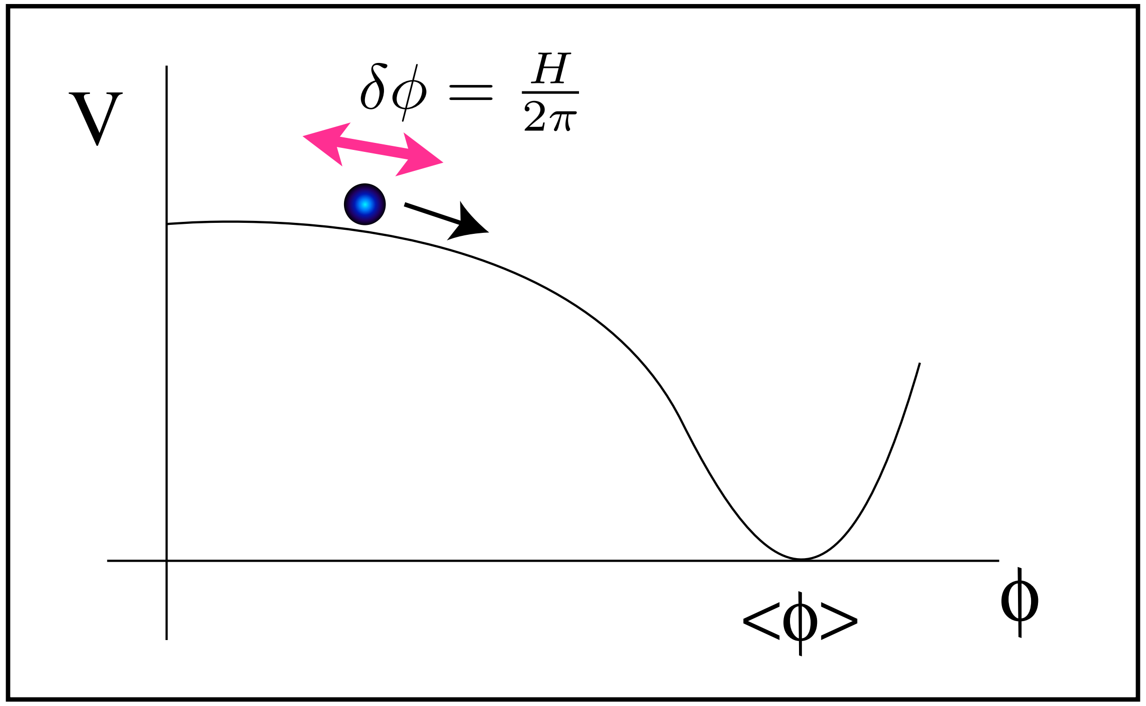


Inflation

: a phase of the exponential expansion.

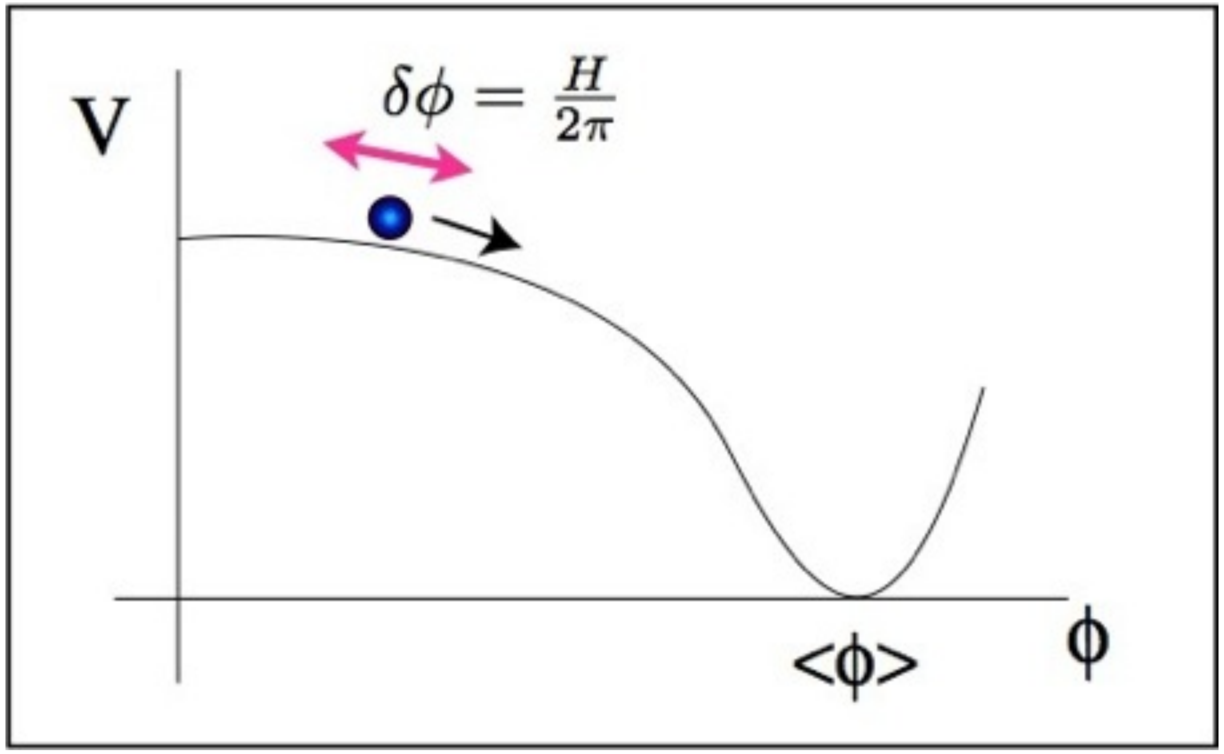
➡ Inflation can solve the horizon and flatness problems.

One way to realize the inflation is the slow-roll inflation.



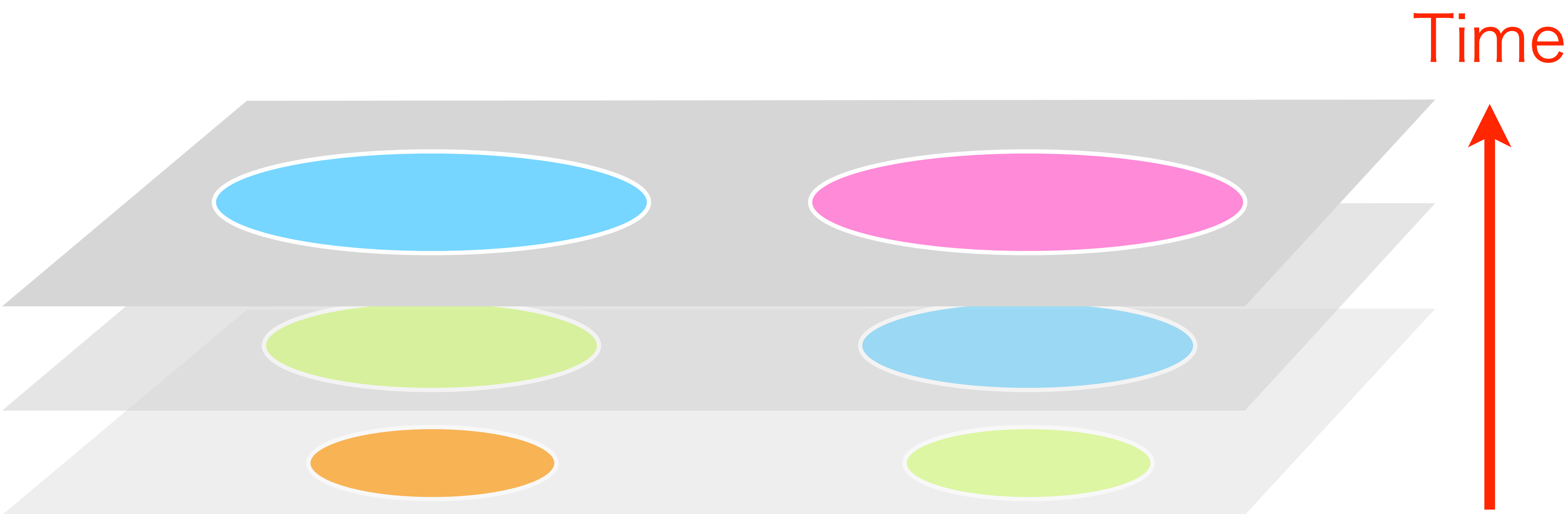
Scalar mode

$$ds^2 = -(1+2\Phi)dt^2 + a^2(1+2\Psi)d\mathbf{x}^2$$



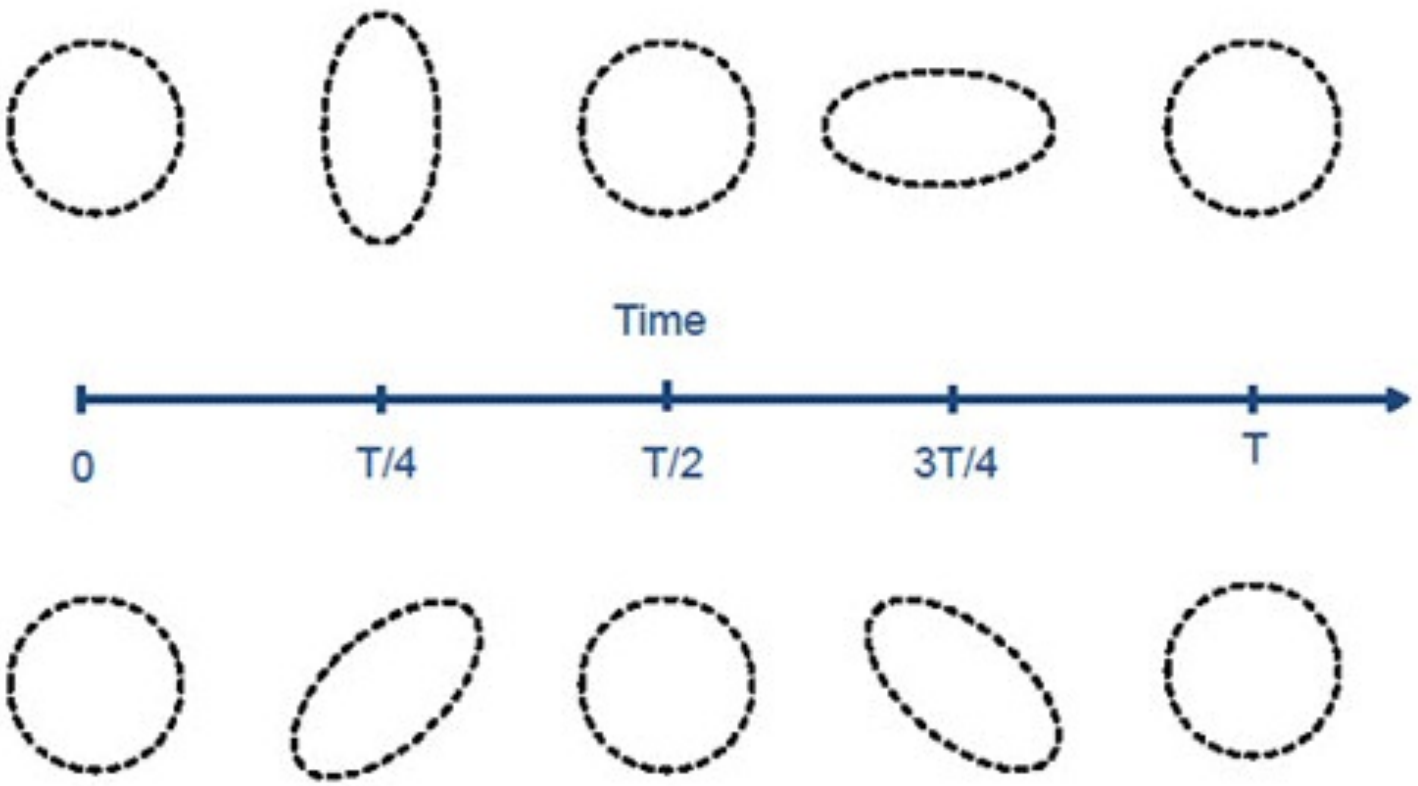
It is due to **fluctuations in time** induced by the inflaton's quantum fluctuation.

$$\Phi \sim \frac{\delta\rho}{\rho} \sim H\delta t \sim H_{\rm inf}\frac{\delta\phi}{\dot{\phi}} \sim \left|\frac{V^{3/2}}{V' M_P^3}\right|$$



Tensor mode

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



It is due to **fluctuations of graviton itself.**

$$h_{ij} \sim \frac{H_{\rm inf}}{M_P}$$

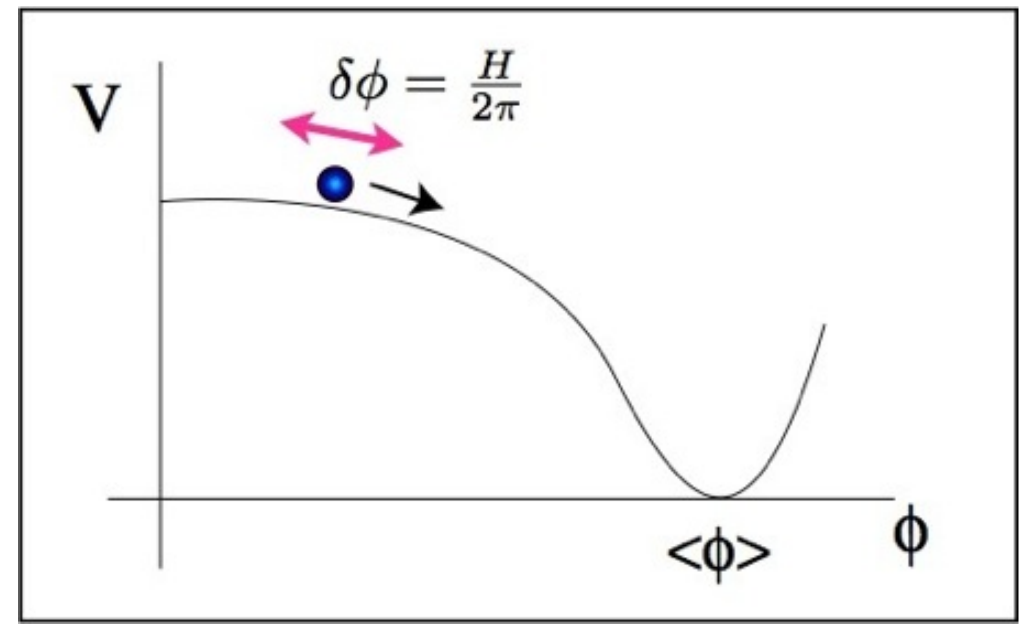
Observation vs Theory

Scalar mode

$$P_{\mathcal{R}} = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

Tensor mode

$$P_t = A_t \left(\frac{k}{k_0}\right)^{n_t}$$



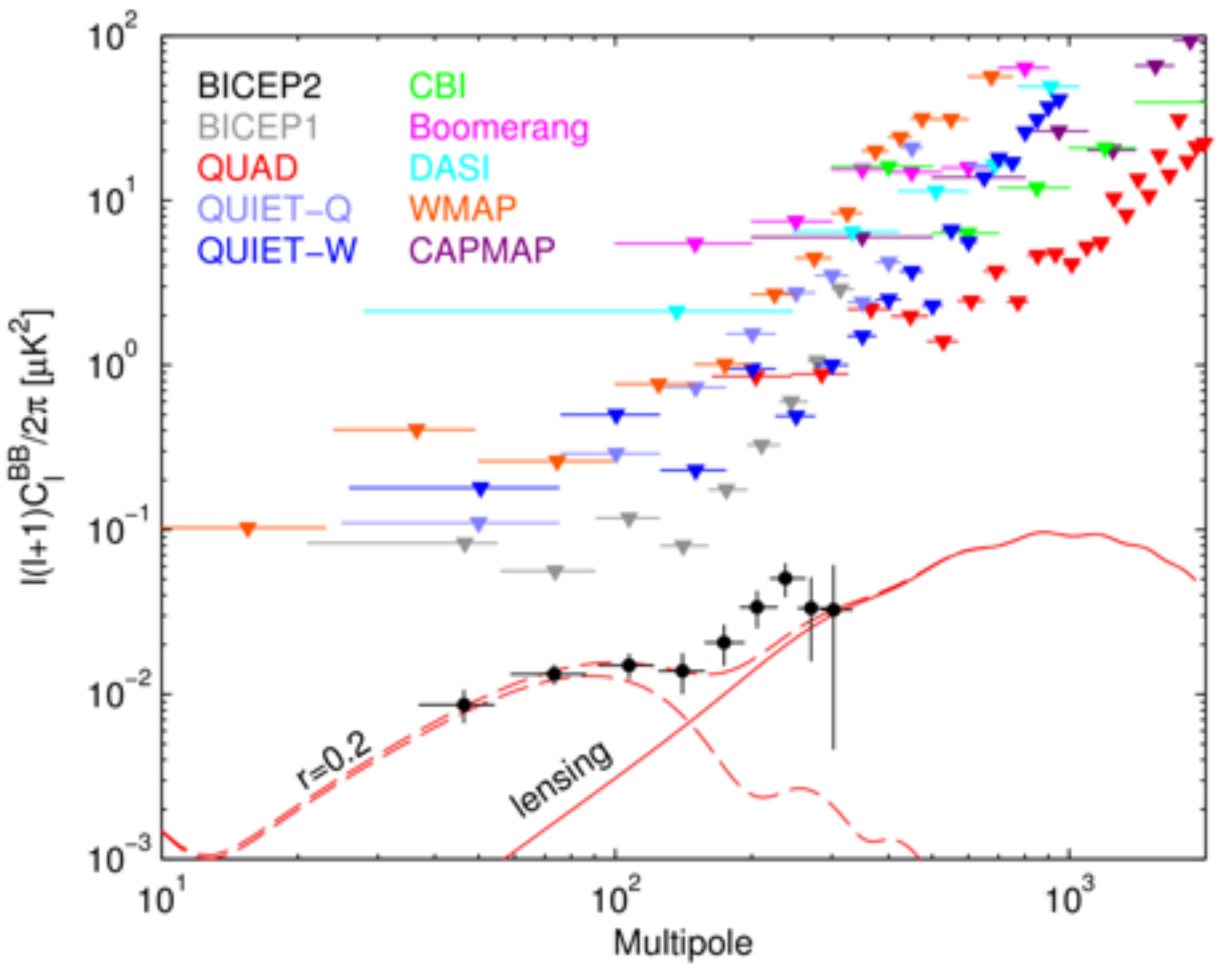
$$A_s, \ n_s, \ r \equiv \frac{A_t}{A_s}$$

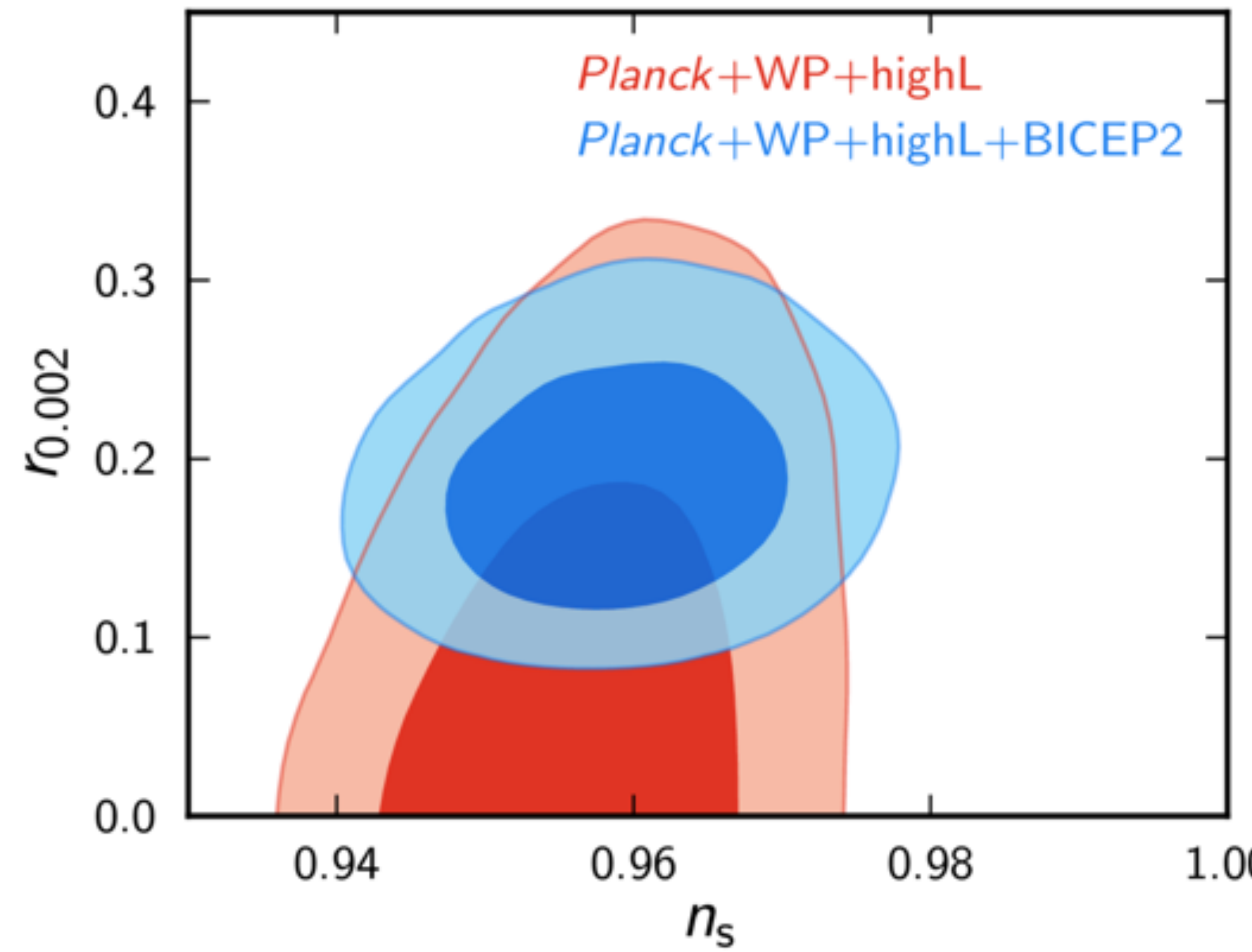
⟷

$$V, \ V', V''$$

BICEP2

BICEP2, 1403.3985





(Running n_s is assumed [later])

$$r = 0.20^{+0.07}_{-0.05}$$

What can we say about inflation?

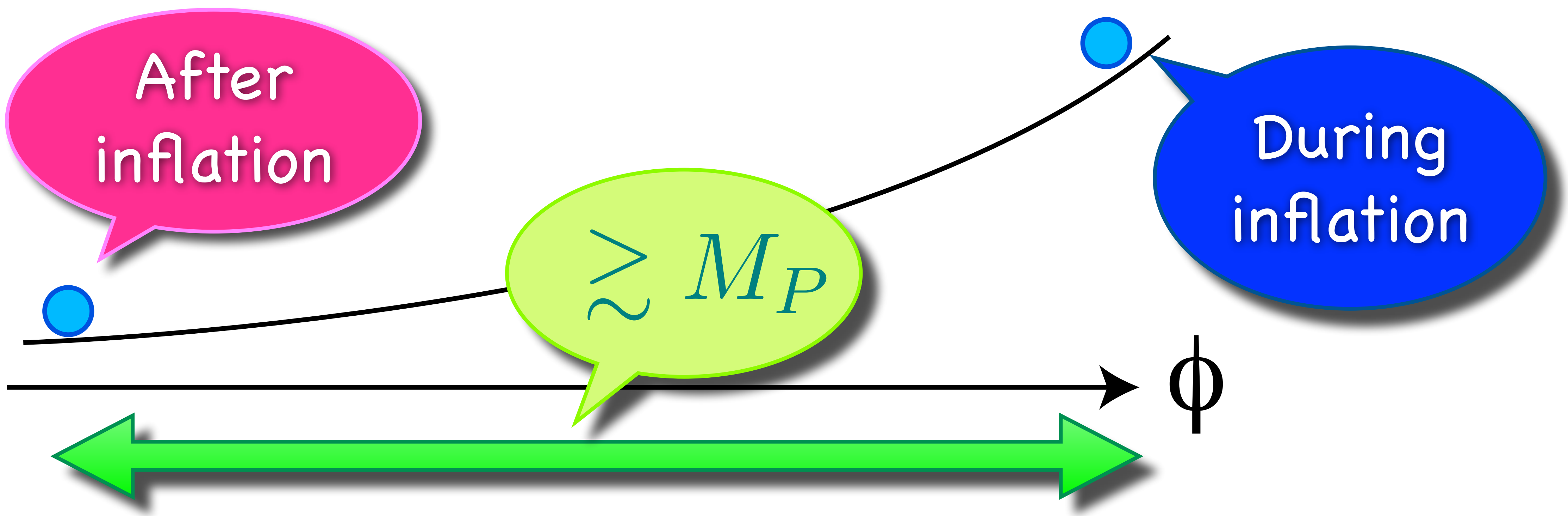
It's GUT-scale inflation!

$$V_{\rm inf} \simeq (2.1 \times 10^{16}\,{\rm GeV})^4 \left(\frac{r}{0.16}\right)$$

$$H_{\rm inf} \simeq 1.0 \times 10^{14}\,{\rm GeV} \left(\frac{r}{0.16}\right)^{\frac{1}{2}},$$

It's large-field inflation!

The inflaton excursion exceeds the Planck scale!



Lyth bound: $\Delta\phi \gtrsim 8M_P \left(\frac{r}{0.2}\right)^{\frac{1}{2}} \left(\frac{N}{50}\right)$

Lyth 1997

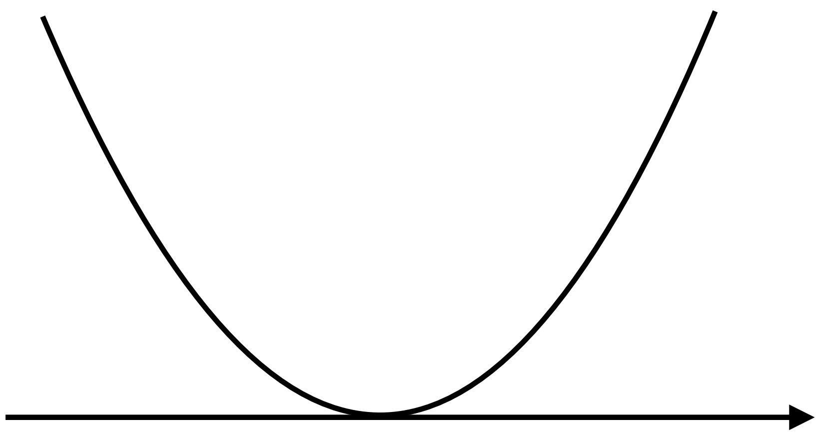
Various large-field inflation models

Quadratic chaotic inflation

Linde `83

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

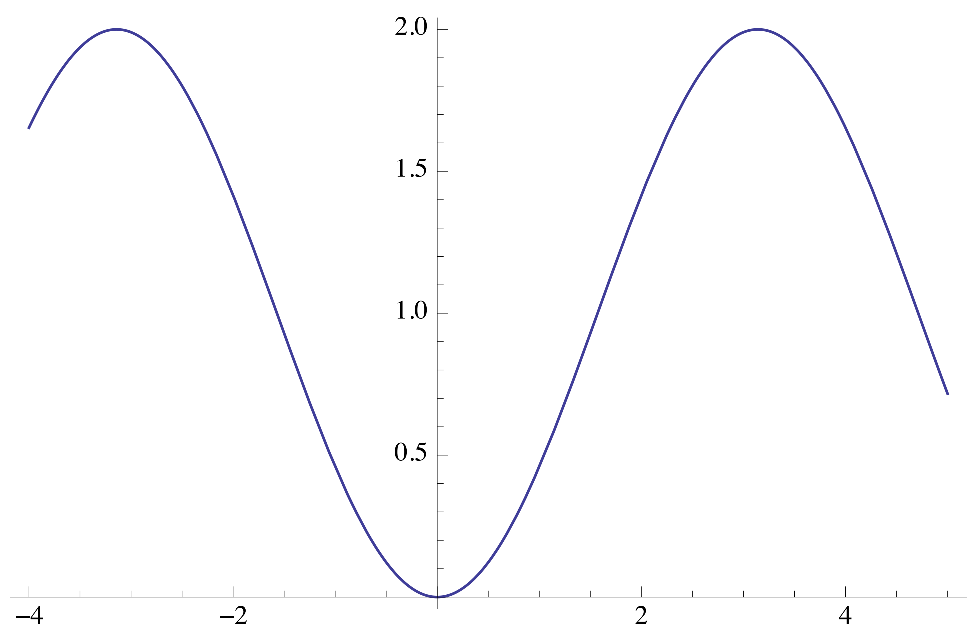
$m \simeq 2 \times 10^{13}\,\mathrm{GeV}$ $\quad \phi_{60} \sim 16 M_P$



Natural inflation

Freese et al, `90

$$V = \Lambda^4\left(1 - \cos\left(\frac{\phi}{f}\right)\right)$$

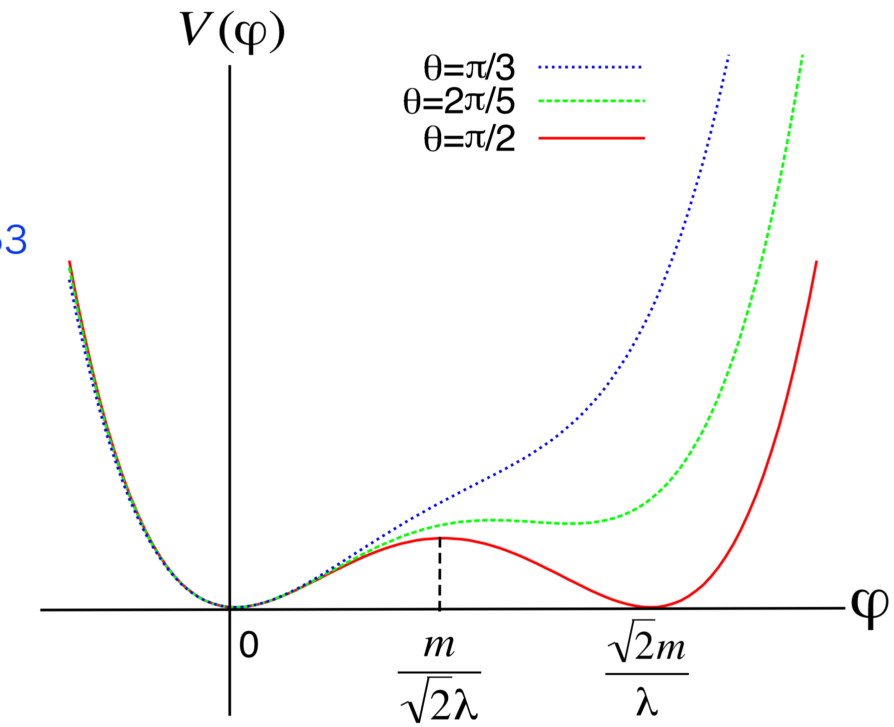


Various large-field inflation models

Polynomial chaotic inflation

Nakayama, FT, Yanagida 1303.7315
cf. Croon, Ellis, Mavromatos 1303.6253

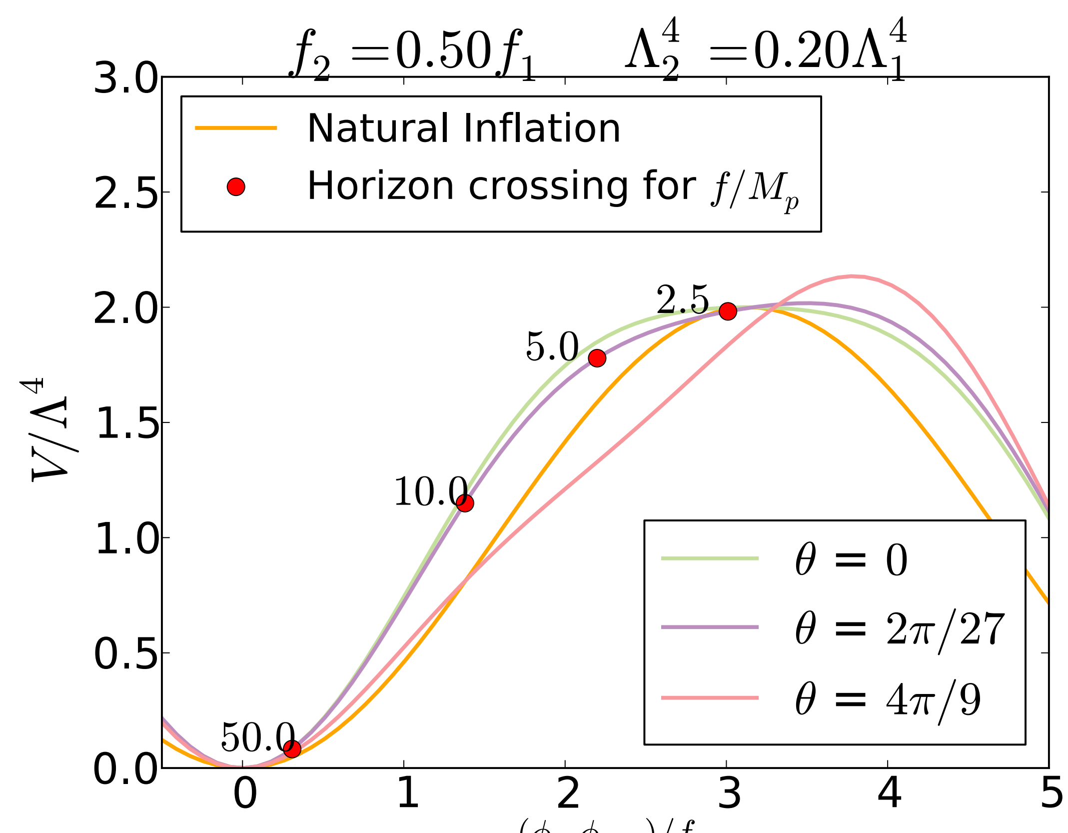
$$V = \frac{1}{2}m^2\phi^2 + \frac{\kappa}{3}\phi^3 + \frac{\lambda}{4}\phi^4 + \cdots$$



Multi-Natural inflation

Czerny, FT 1401.5212
Czerny, Higaki FT 1403.0410, 1403.5883

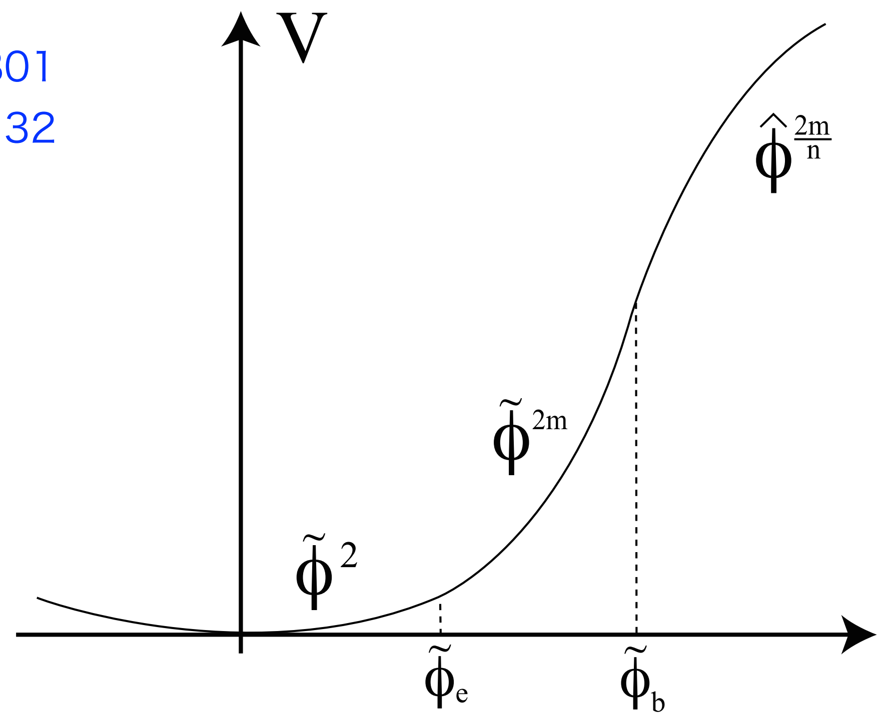
$$V(\phi) = C - \Lambda_1^4\cos(\phi/f_1) - \Lambda_2^4\cos(\phi/f_2 + \theta),$$



Various large-field inflation models

Running kinetic inflation

FT 1006.2801
Nakayama, FT 1008.2956, 1008.4467, 1403.4132



$$V = (1 + \xi\phi^2)(\partial\phi)^2 - V(\phi)$$

Higgs chaotic inflation is possible.

$$\mathcal{L} = \frac{1}{2}\left(1 + \xi h^2\right)(\partial h)^2 - \frac{\lambda}{4}\left(h^2 - v^2\right)^2,$$

$$\Rightarrow \quad \mathcal{L} \simeq \frac{1}{2}(\partial\hat{h})^2 - \lambda\hat{h}^2, \quad \hat{h} \equiv h^2/2$$

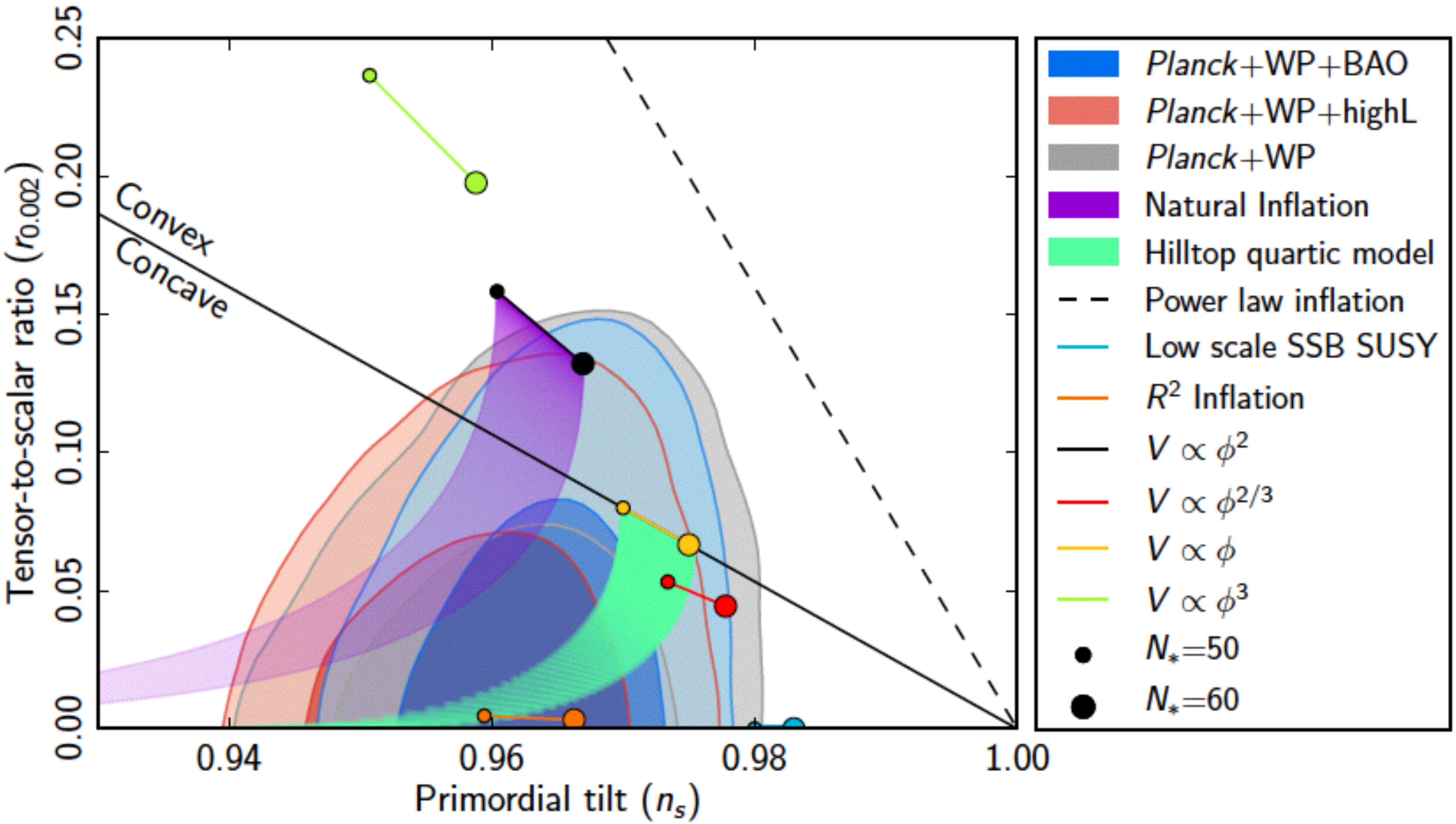
The transition takes place at the intermediate scale.

Axion monodromy inflation

Silverstein, Westphal, 0803.3085
McAllister, Silverstein, Westphal, 0808.0706

$$V = \mu^3\phi + \Lambda^4 \cos\left(\frac{\phi}{f_a}\right)$$

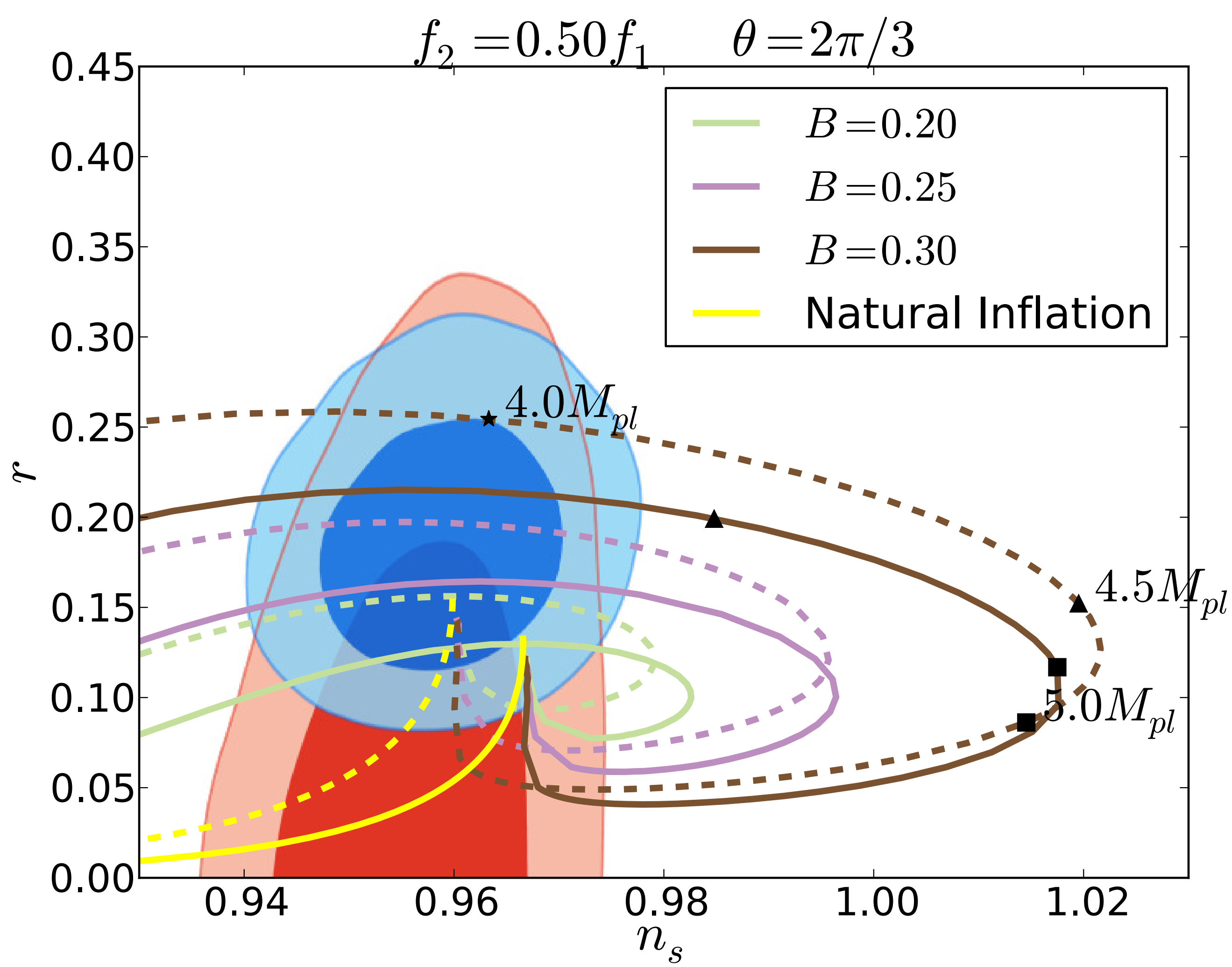
Predicted values of (n_s, r)

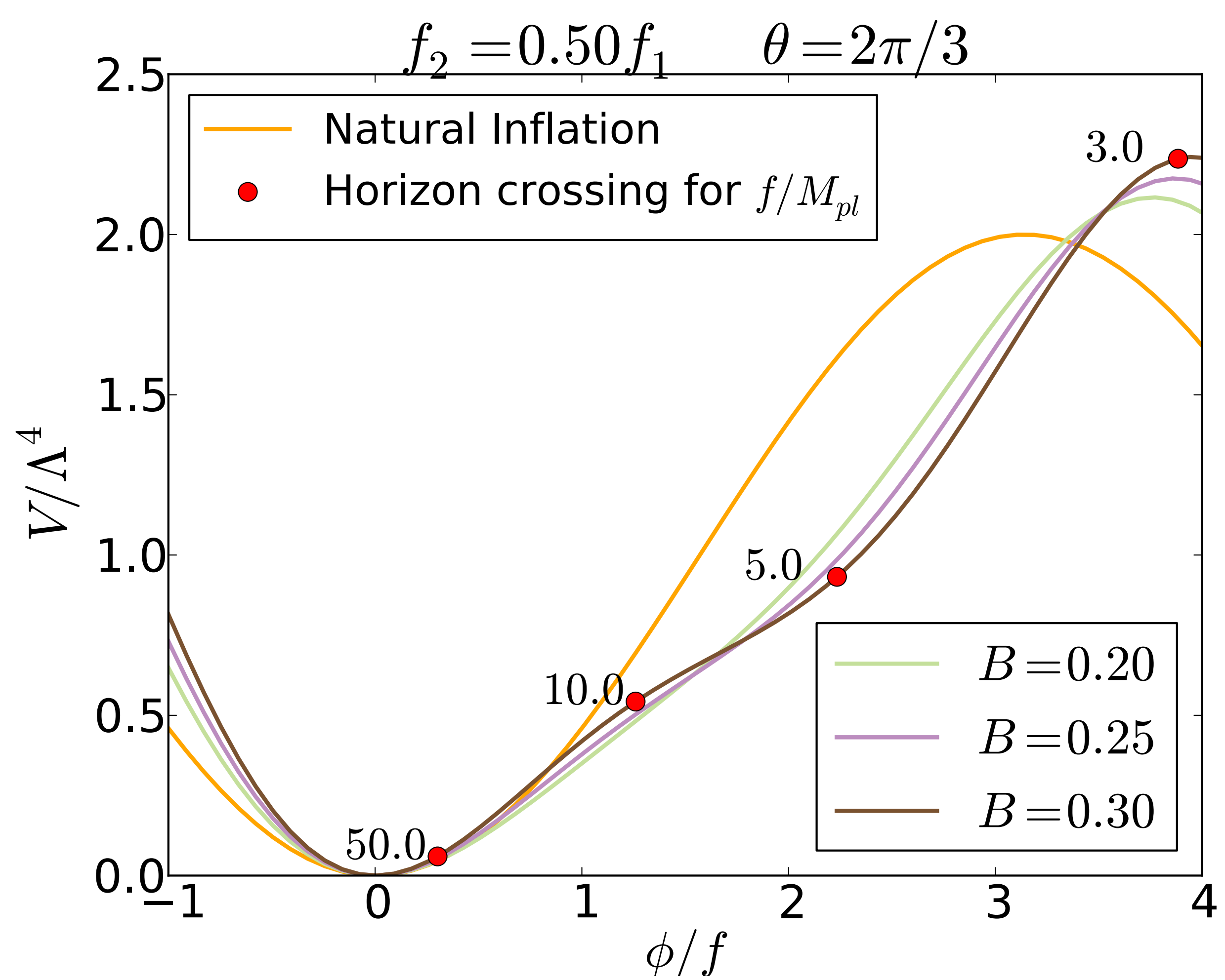


Planck, 1303.5802

Various values of (n_s, r) are also possible.

e.g. Multi-natural inflation

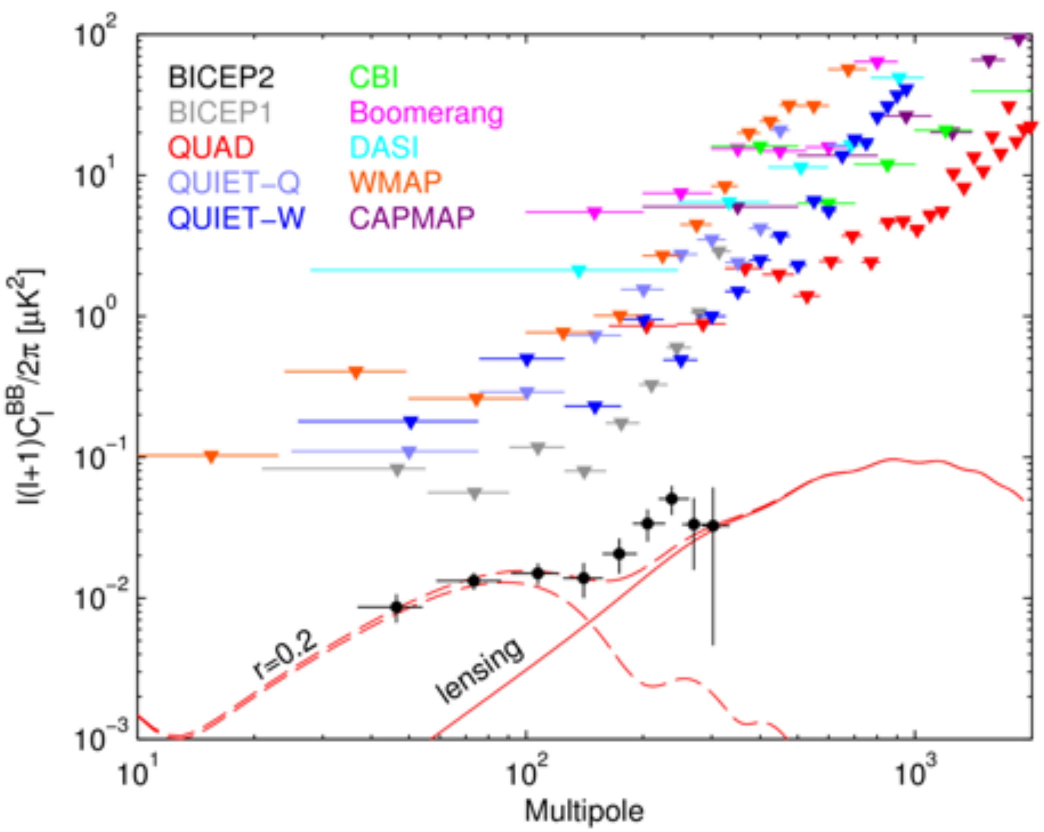




Czerny, Higaki FT 1403.5883

Tension between BICEP2 and Planck

(Polarization) (Temperature)



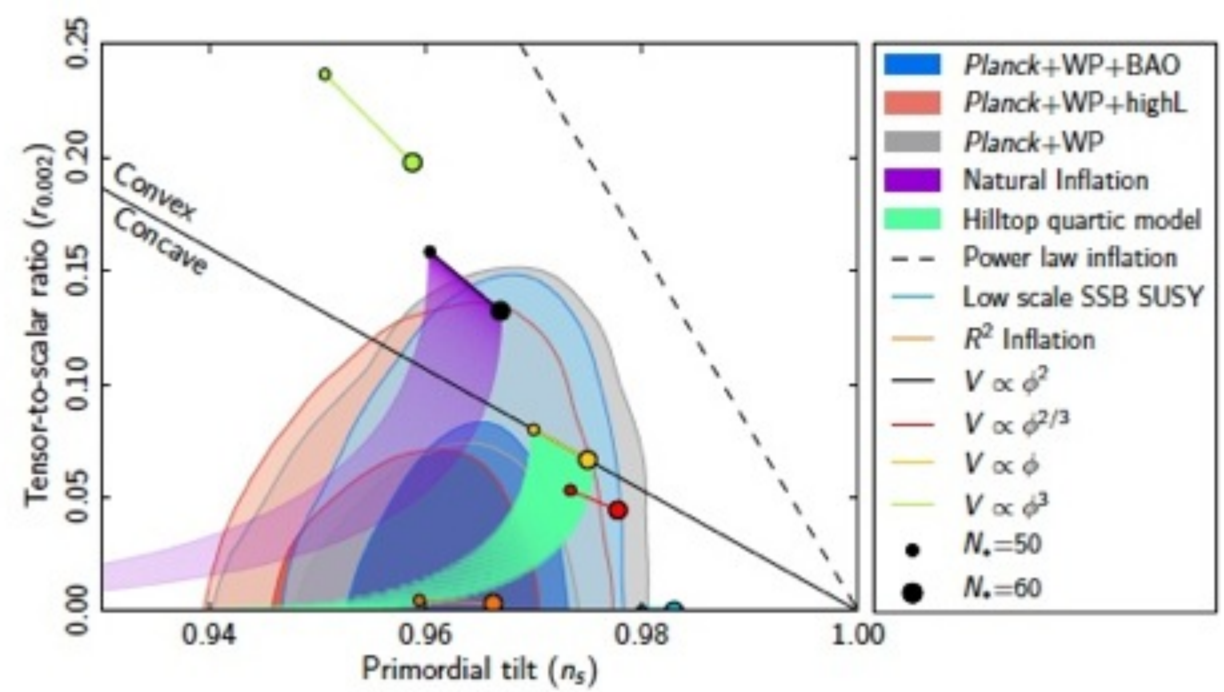


Fig. 1. Marginalized joint 68% and 95% CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets compared to the theoretical predictions of selected inflationary models.

$$r = 0.20^{+0.07}_{-0.05}$$

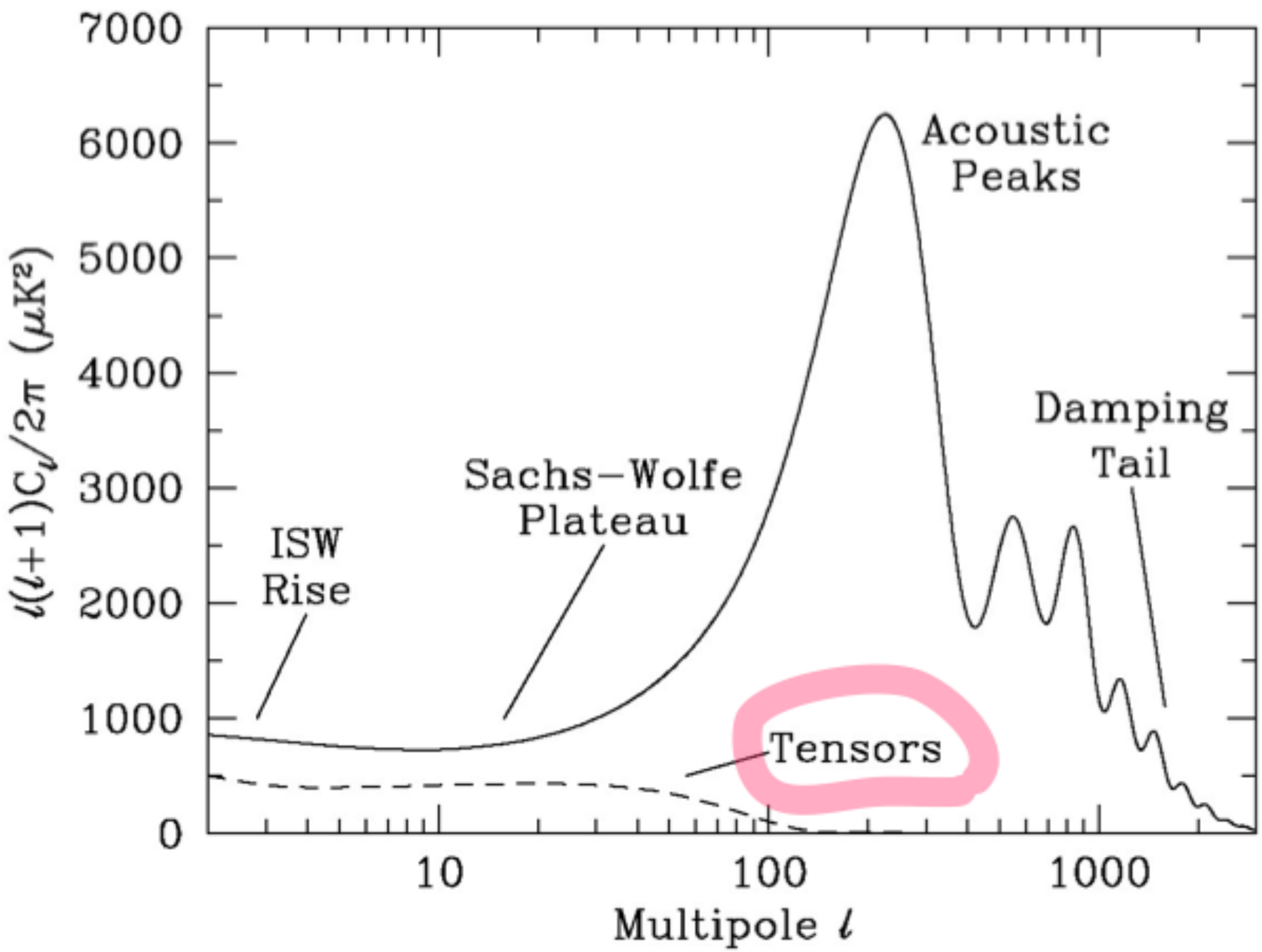
BICEP2, 1403.3985

$$r < 0.11 \quad (95\%\mathrm{CL})$$

Planck, 1303.5802

Tension between BICEP2 and Planck

(Polarization) (Temperature)



The tensor mode also contributes to the temperature fluctuations at large scales.

Implications of BICEP2

Implications of BICEP2

If true, the BICEP2 results have SIGNIFICANT impacts on particle physics and cosmology.

They can be broadly classified into the two categories.

1. GUT-scale large-field inflation

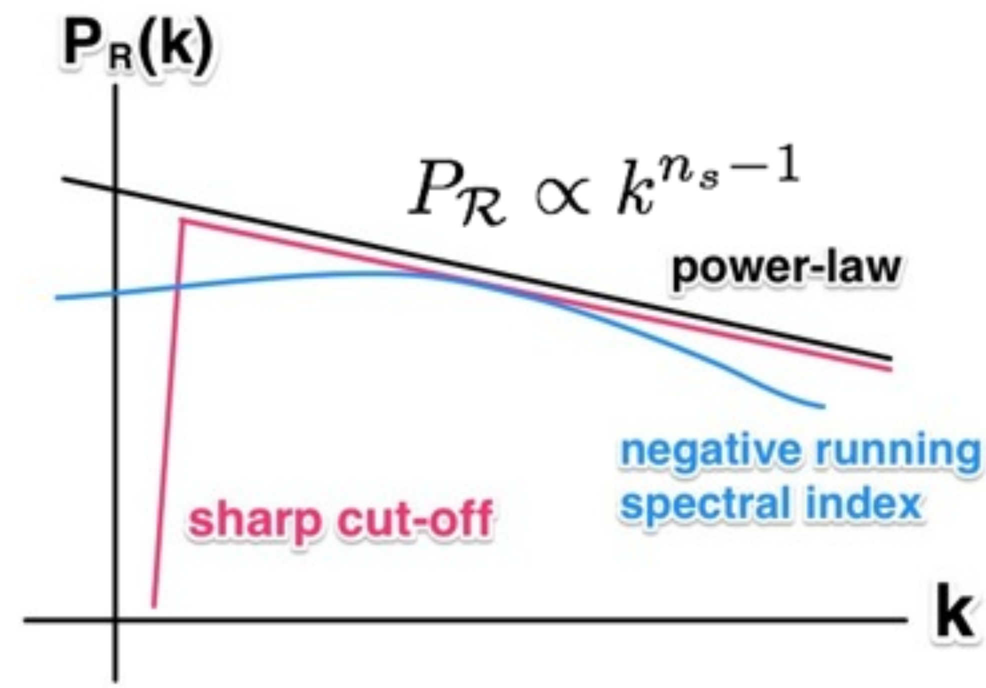
2. Tension with Planck and others

GUT-scale, large-field inflation

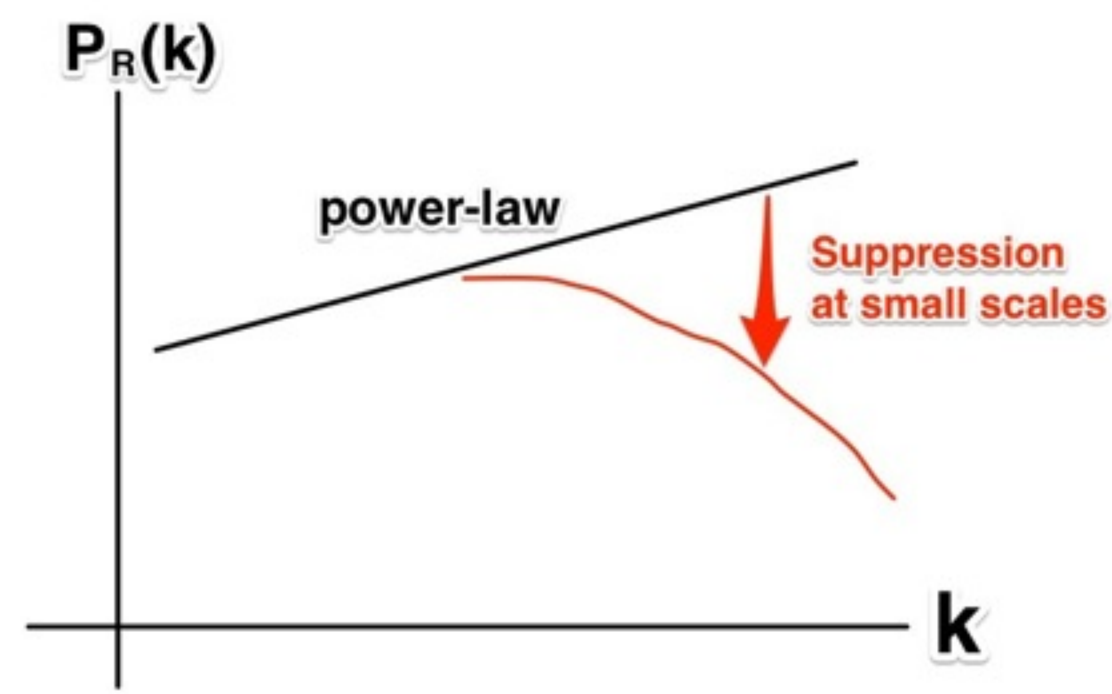
- **Inflation model building in sugra/string**
  - Shift symmetry is likely. String axion? Higgs? RH sneutrino?
- **High reheating temperature:** $T_R \gtrsim 10^9\,\mathrm{GeV}$
  - Thermal leptogenesis more likely than before.
  - Baryogenesis, dark matter, unwanted relics
  - Symmetry restoration is probable.
- **The inflaton mass is about** $m \sim 10^{13}\,\mathrm{GeV}$.
  - Related to SUSY breaking scale or RH neutrino mass?
- **Too large isocurvature perturbations.**
  - The QCD axion less likely? PQ symmetry restoration?

Tension between BICEP2 and Planck

- **Deviation from power-law density perturbations**
  - Running of spectral index
  - Sharp cut-off at large scales.
    - Fast roll
    - False vacuum decay



- **Suppression at small scales**
  - Dark radiation,
  - hot dark matter,
  - neutrino mass.



- **Anti-correlation between tensor and scalar**

Implications for particle physics

Let me start with general observations, and then go to more model-dependent issues.

Because the inflation scale is high,

- T_R is also high. $T_R \gtrsim 10^9\,\mathrm{GeV}$

  e.g. $\frac{\phi}{M_P} F_{\mu\nu} F^{\mu\nu}$ ➡ $\Gamma \sim \frac{m_\phi^3}{M_P^2} \sim \mathcal{O}(1-100)\,\mathrm{GeV}$

  $T_R \sim 10^{9-10}\,\mathrm{GeV}$

Thermal leptogenesis is likely.

Implications for particle physics

Let me start with general observations, and then go to more model-dependent issues.

Because the inflation scale is high,

- T_R is also high. $T_R \gtrsim 10^9\,\mathrm{GeV}$
- unwanted relics can be copiously produced.

  (a) gravitinos can be produced thermally and non-thermally.
  (b) the inflaton may decay into hidden sector.
  (c) topological defects associated with SSB.

Implications for particle physics

Let me start with general observations, and then go to more model-dependent issues.

Because the inflation scale is high,

- T_R is also high. $T_R \gtrsim 10^9\,\mathrm{GeV}$
- unwanted relics can be copiously produced.
- large isocurvature perturbations are generated. e.g. QCD axion

Higaki, Jeong, FT, 1403.4186, Marsh et al, 1403.4216, Visinelli, Gondolo, 1403.4594

What can we say about SUSY breaking from BICEP2?

In any case, there appears a new mass scale

$$m_{\rm inf} = 10^{13}\,{\rm GeV}$$

So question is whether

$$m_{3/2} \gtrsim 10^{13}\,{\rm GeV}$$

or

$$m_{3/2} \lesssim 10^{13}\,{\rm GeV}$$

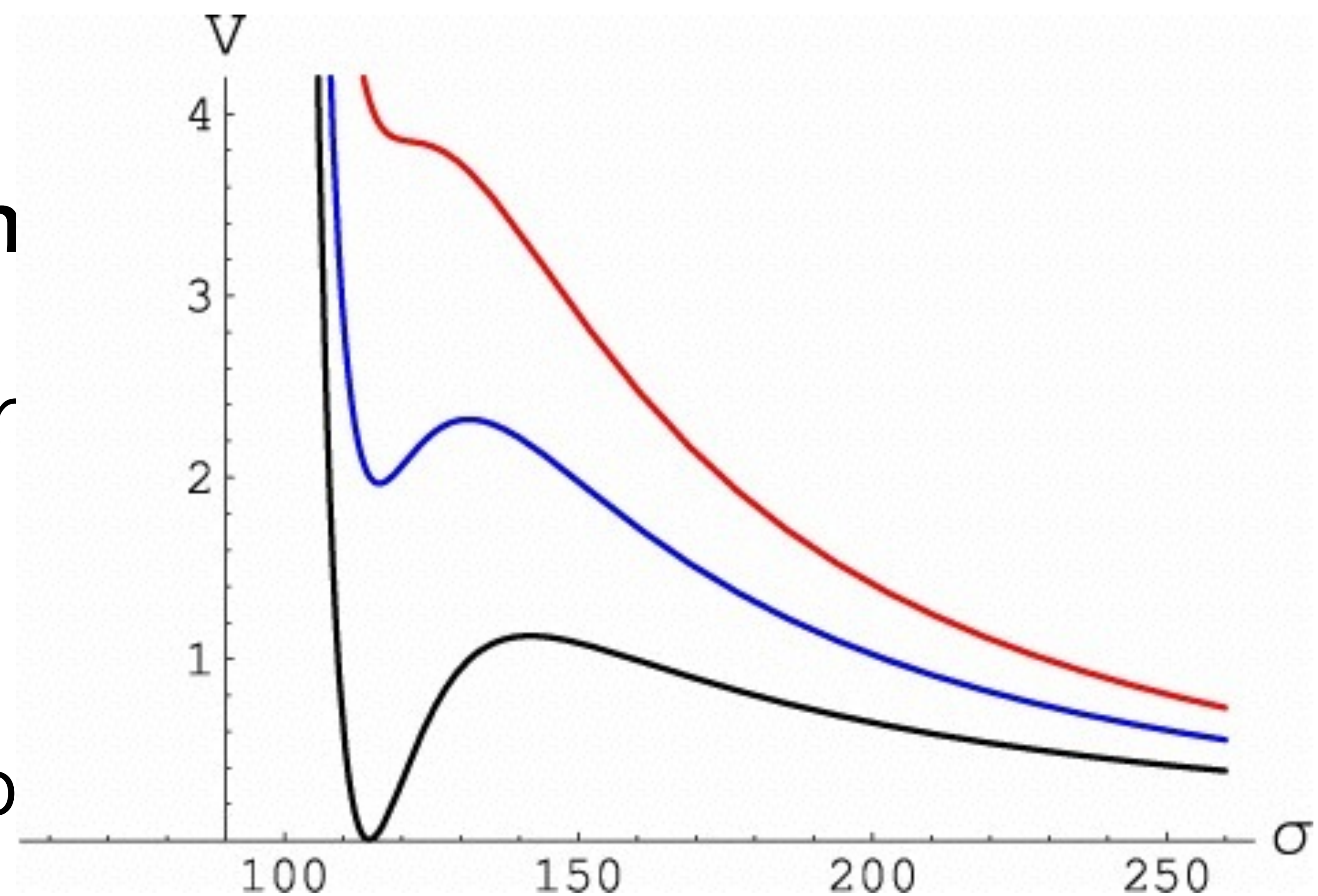
There appeared papers which argue for SUSY around the inflaton mass scale ~ 10^{13}GeV or below.

Ibanez and Valenzuela 1403.6081, Hall, Nomura, Shirai 1403.8138, Fan, Jain Ozsoy 1404.1914

- 126 GeV Higgs mass OK
- Gauge coupling unification OK

Is it good for anyth

- Moduli stabilizatior
- If moduli=inflaton, inflaton.
- Stable moduli stab



What if $m_{3/2} \lesssim 10^{13}\,\mathrm{GeV}$?

Chaotic inflation in SUGRA

Kawasaki, Yamaguchi, Yanagida, hep-ph/0004243 ,hep-ph/0011104

To have a good control over the inflaton field values greater than the Planck scale, we impose a shift symmetry;

$$\phi \to \phi + iC,$$

which is explicitly broken by the superpotential.

$$K_{\rm inf} = c(\phi + \phi^\dagger) + \frac{1}{2}(\phi + \phi^\dagger)^2 + |X|^2 - k|X|^4 + \cdots$$

$$W_{\rm inf} = mX\phi,$$

$$V_{\rm sugra} = e^K \left((D_i W) K^{i\bar{j}} (D_j W)^* - 3|W|^2 \right).$$

$$V \simeq \frac{1}{2} m^2 \varphi^2$$

$$\varphi \equiv \sqrt{2}{\rm Im}[\phi]$$

even for $\varphi \gg M_p$

Z_2 or not Z_2?

One can impose a Z_2 symmetry on the inflaton and X.

$$Z_2: \quad \phi \to -\phi \qquad X \to -X$$

$$K_{\rm inf} = \cancel{c(\phi + \phi^\dagger)} + \frac{1}{2}(\phi + \phi^\dagger)^2 + |X|^2 - k|X|^4 + \cdots$$
$$W_{\rm inf} = mX\phi,$$

The Z_2 symmetry affects the inflaton decays, while it hardly affects the inflaton dynamics.

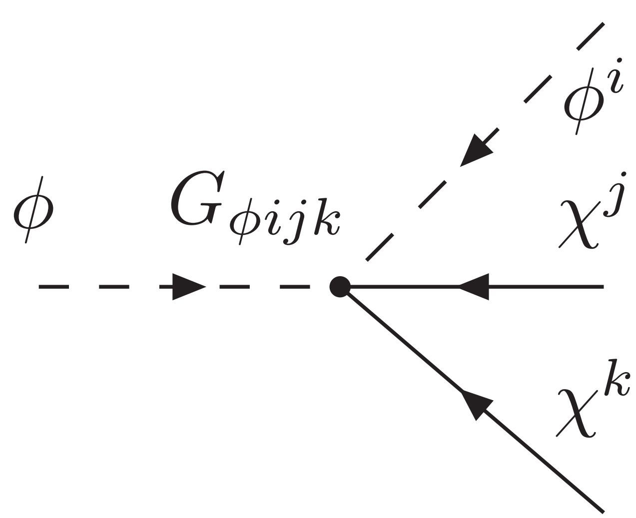
Chaotic inflation w/o Z2

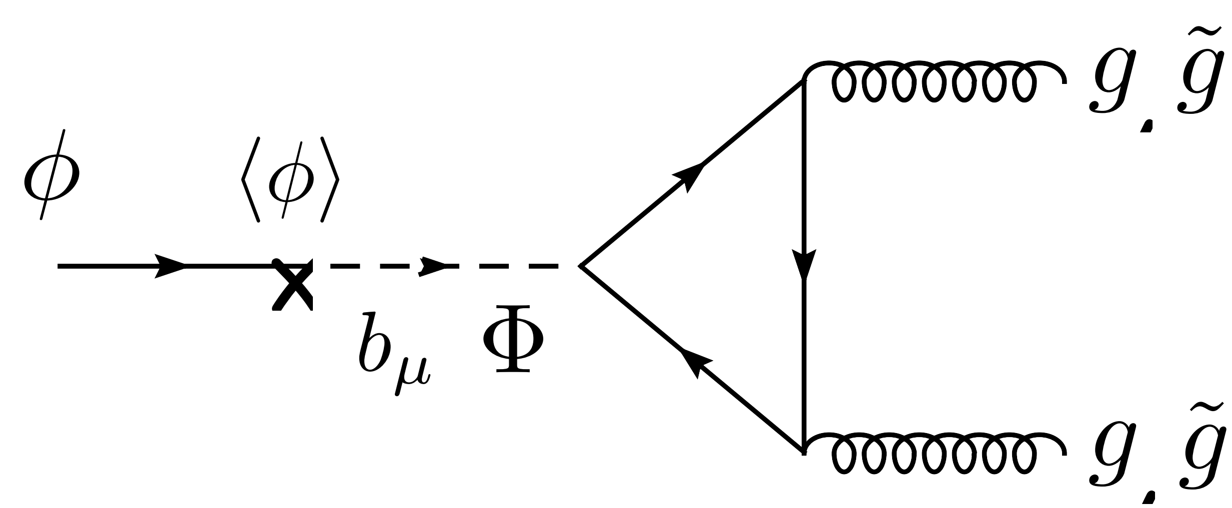
$$K = c(\phi + \phi^\dagger) + \cdots \quad \Rightarrow \quad \langle K_\phi \rangle = c = \mathcal{O}(1)$$

- **Pro**

  The inflaton automatically decays into the visible sector w/o introducing ad hoc couplings.

Endo, Kawasaki, FT, Yanagida, hep-ph/0607170
Endo, FT, Yanagida,hep-ph/0701042





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  Endo, FT, Yanagida,hep-ph/0701042

$$\Gamma \sim \frac{m^3}{M_P^2}, \quad T_R \sim 10^9\,\mathrm{GeV}$$

  high enough for thermal leptogenesis

- **Con**

  The inflaton decays into hidden sectors, producing too many gravitinos.

  Endo, Hamaguchi, FT, \`06
  Nakamura, Yamaguchi, \`06
  Kawasaki, FT, Yanagida,\`06
  Dine, Kitano, Morisse, Shirman,\`06
  Endo, FT, Yanagida,\`06,\`07

$$\Gamma(\phi \to 2\psi_{3/2}) \sim \frac{m^3}{M_P^2}$$

Gravitino production in chaotic inflation w/o Z_2

Nakayama, FT, Yanagida,1404.2472

Let us add a SUSY breaking field z;

$$K = K_{\rm inf} + |z|^2 - \frac{|z|^4}{\Lambda^2},$$
$$W = W_{\rm inf} + \mu^2 z + W_0,$$

$$m_z^2 \simeq \frac{12 m_{3/2}^2}{\Lambda^2}.$$

$$\langle z \rangle \simeq 2\sqrt{3}\left(\frac{m_{3/2}}{m_z}\right)^2 \simeq \frac{m_{3/2}}{m_z}\Lambda.$$

There are various sources for gravitino production;

- Thermal production
- Non-thermal production
  - Inflaton decays into gravitinos
  - Inflaton decays into z.
  - The z coherent oscillations.

Gravitino production in chaotic inflation w/o Z_2

Nakayama, FT, Yanagida,1404.2472

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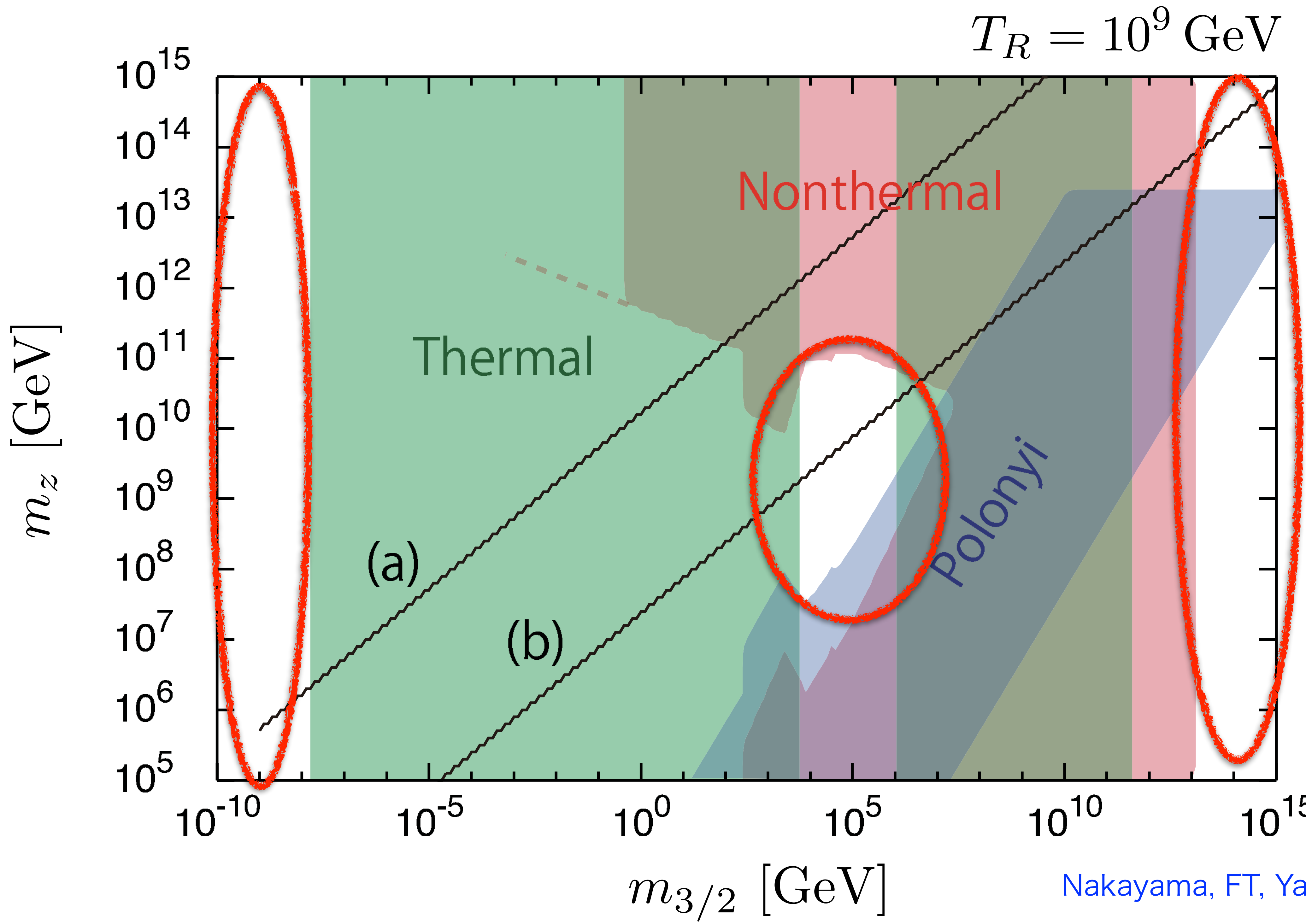
$$W = W_{\rm inf} + \mu^2 z + W_0, \qquad \langle z \rangle \simeq 2\sqrt{3}\left(\frac{m_{3/2}}{m_z}\right)^2 \simeq \frac{m_{3/2}}{m_z}\Lambda.$$

There are various sources for gravitino production;

$$Y_{3/2} = Y_{3/2}^{(\rm th)} + Y_{3/2}^{(\phi)} + Y_{3/2}^{(z)}.$$

$$Y_{3/2}^{(\rm th)} \simeq \begin{cases} \min\left[2\times 10^{-12}\left(1+\frac{m_{\tilde g}^2}{3m_{3/2}^2}\right)\left(\frac{T_{\rm R}}{10^{10}\,{\rm GeV}}\right),\ \frac{0.42}{g_{*s}(T_{3/2})}\right] & \text{for } T_{\rm R} \gtrsim m_{\rm SUSY}, \\ 0 & \text{for } T_{\rm R} \lesssim m_{\rm SUSY}, \end{cases}$$

$$Y_{3/2}^{(\phi)} = \frac{3T_{\rm R}}{4m}\frac{2\Gamma(\Phi\to\tilde z\tilde z) + 4\Gamma(\Phi\to z z^\dagger)}{\Gamma_{\rm tot}}, \qquad Y_{3/2}^{(z)} \simeq \frac{2}{m_z}\frac{\rho_z}{s}.$$



$\Lambda = (4\pi/\lambda^2)\Lambda_{\rm dyn}$

$(a)\lambda = 4\pi$

$(b)\lambda = 1$

Nakayama, FT, Yanagida,1404.2472

3 allowed regions:

(i) $m_{3/2} \lesssim 16\text{eV}$

(ii) $m_{3/2} = 10 - 1000\text{TeV}$

(iii) $m_{3/2} \gtrsim 10^{13}\ \text{GeV}$

consistent with 126 GeV Higgs.

Chaotic inflation with Z_2

$$K = \frac{1}{2}(\phi + \phi^\dagger)^2 + \cdots \quad \Rightarrow \quad \langle K_\phi \rangle = 0$$

- **Pro**

  Non-thermal gravitino production is forbidden.

- **Con(?)**

  Reheating the visible sector is non-trivial.

  If Z_2 symmetry is unbroken, one needs to assign the Z_2 charge on the SM and their SUSY partners; otherwise the inflaton will be stable.
  Or, Z_2 must be broken.

What is the Z_2 symmetry, under which SM particles are charged?

It could be the matter parity!

Then, the inflaton is one of the matter fields of mass about 10^{13}GeV….

It's right-handed sneutrino!

$$W = \underset{(-)}{\Phi}\,\underset{(-)}{L}H_u$$ is then allowed.

$$\mathcal{L} \sim \frac{(LH_u)^2}{M}$$

Neutrino mass is a low-E consequence of the inflaton!

Sneutrino Chaotic inflation

Murayama, Nakayama, FT, Yanagida,1404.3857

We impose an approximate shift symmetry on one of N_i

$$K = |N_1|^2 + |N_2|^2 + \frac{1}{2}(N_3 + N_3^\dagger)^2 + \cdots$$

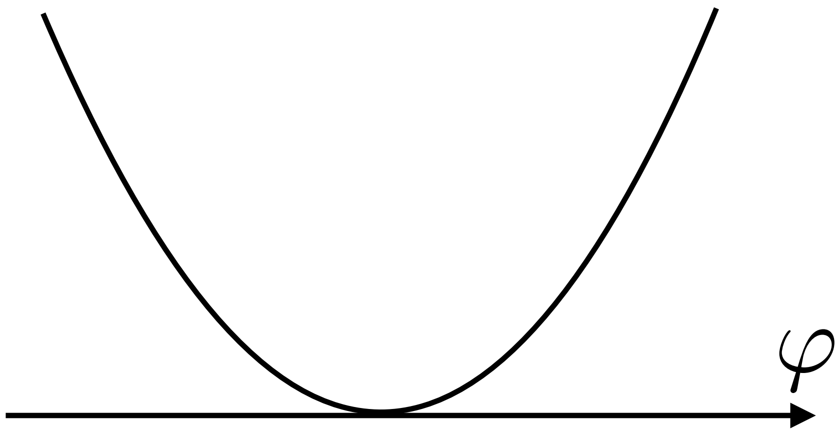
$$W = \frac{1}{2}M_{ij}N_iN_j + h_{i\alpha}N_iL_\alpha H_u$$

with

$$M_{ij} = \begin{pmatrix} m & 0 & 0 \\ 0 & 0 & M \\ 0 & M & 0 \end{pmatrix}$$

The inflaton is $\varphi = \sqrt{2}\mathrm{Im}N_3$

$$V = \frac{1}{2}M^2\varphi^2$$



All the other directions can be stabilized during inflation.

- The model explains why the inflaton mass is about 10^{13}GeV; it is the RH neutrino scale.

- The seesaw mechanism for light neutrino masses works.

- High reheating temperature.

$$\Gamma \sim \frac{h^2}{8\pi} M \qquad T_R \sim g_*^{-\frac{1}{4}} \sqrt{\Gamma M_P} \sim 10^{13}\,\mathrm{GeV}$$

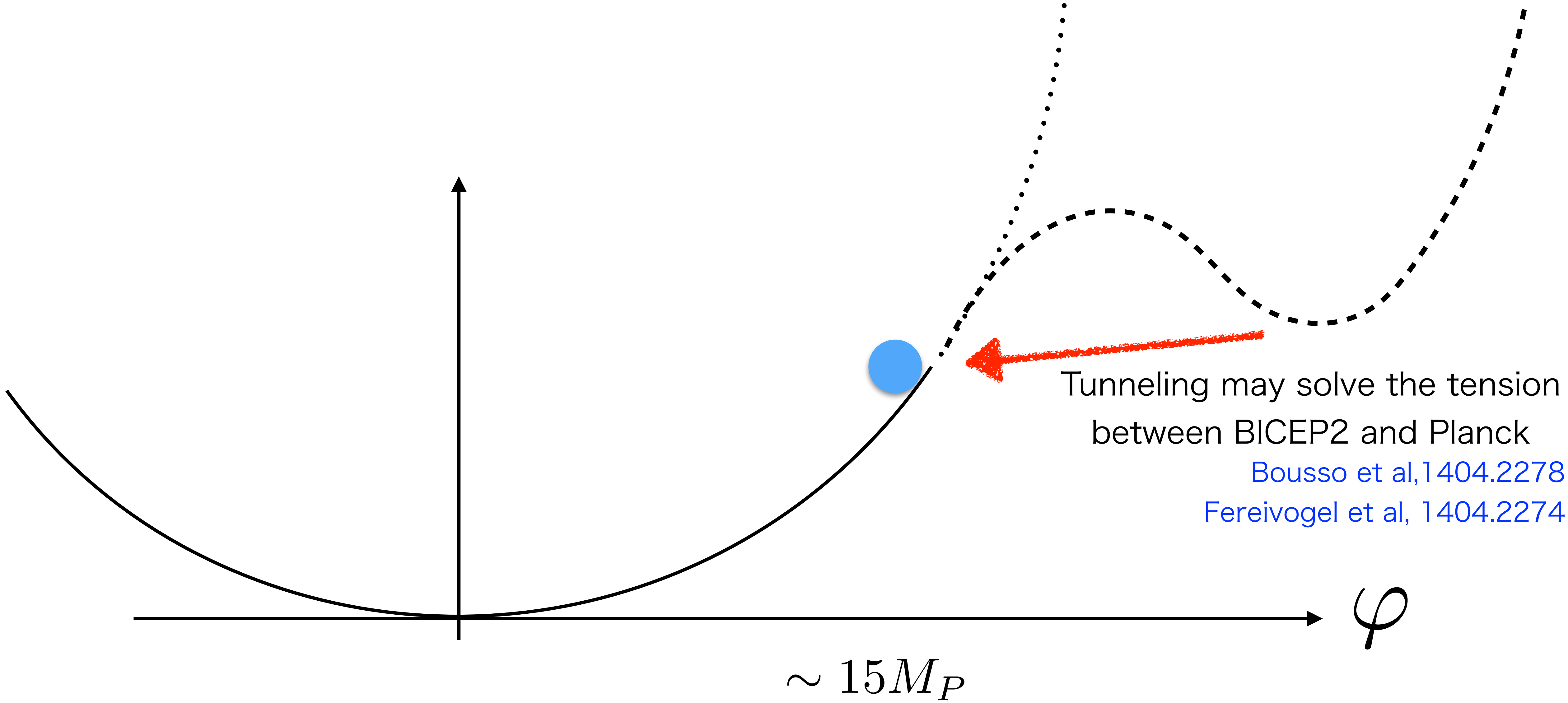
- Thermal leptogenesis by N_1 works successfully.

- No non-thermal gravitino production, but many gravitinos from thermal scatterings.

R-parity (matter parity) violation for $m_{3/2} > 30$TeV
or light gravitinos with mild entropy production, or $m_{3/2} < 16$eV.

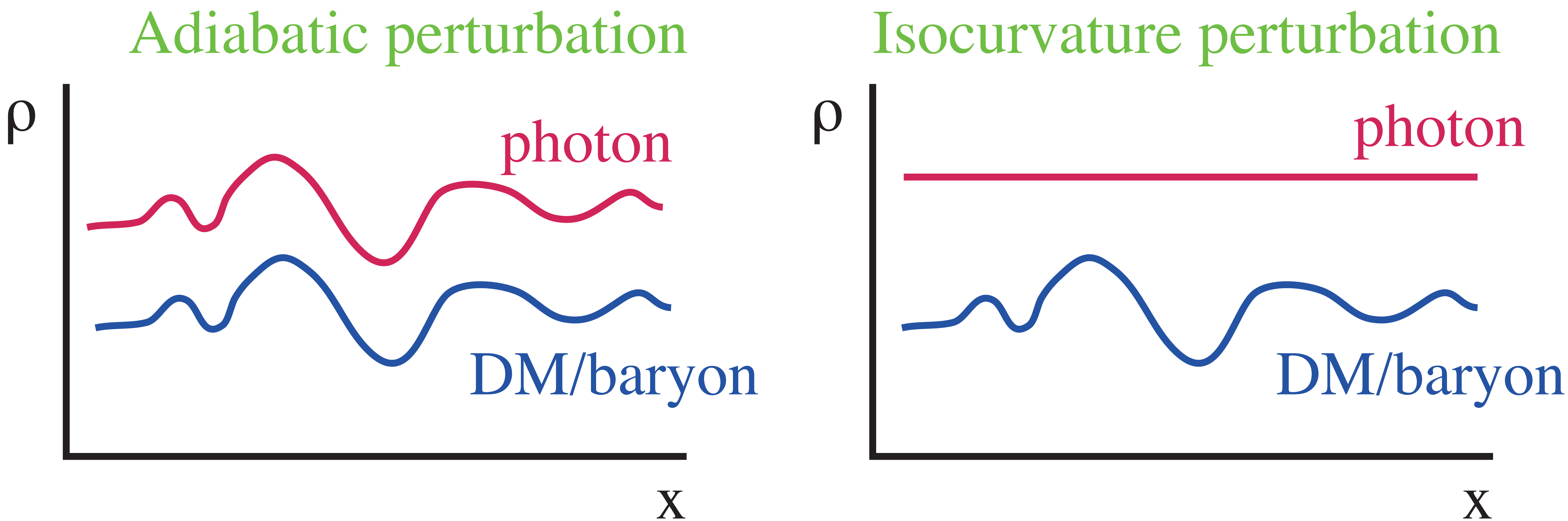
The shift symmetry must be broken by the neutrino Yukawa couplings for successful inflation, and $h_{3\alpha} \sim 0.1$ is suggested by the neutrino mass & seesaw.

$$W \supset N_2 \left(\frac{1}{2} M N_3 + h_{2\alpha} L_\alpha H_u \right) + h_{3\alpha} N_3 L_\alpha H_u$$



Sneutrino as a portal to the mother Universe.

Axion isocurvature perturbations

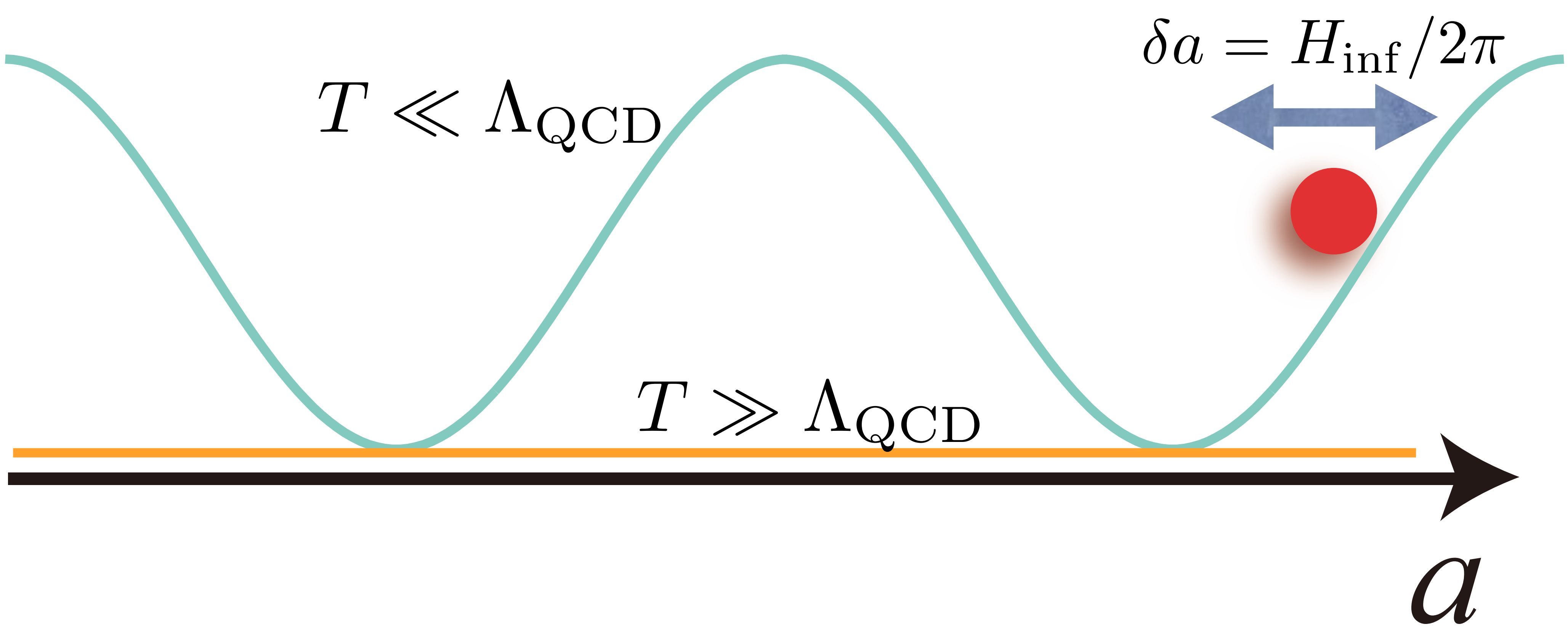


$$\alpha \equiv \frac{P_S}{P_{\mathcal{R}}} \lesssim 0.041 \quad (95\%\text{CL})$$

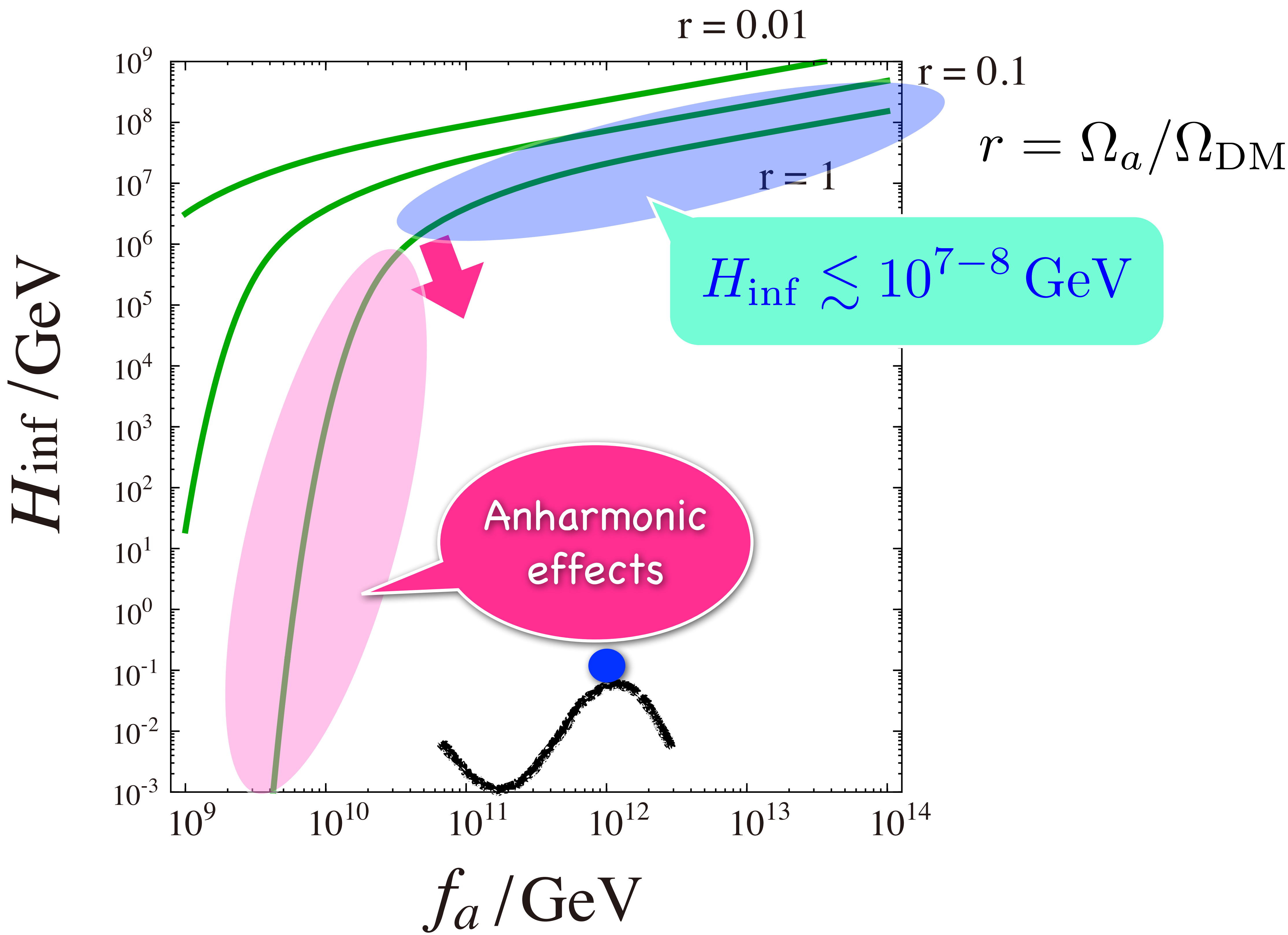
(Planck+WMAP polarization)

The QCD axion is a plausible candidate for DM with isocurvature perturbations.

$$\mathcal{L} = \left(\theta + \frac{a}{f_a}\right) \frac{g_s^2}{32\pi^2} G^{\mu\nu} \tilde{G}_{\mu\nu}$$



Isocurvature constraint on H_{inf}

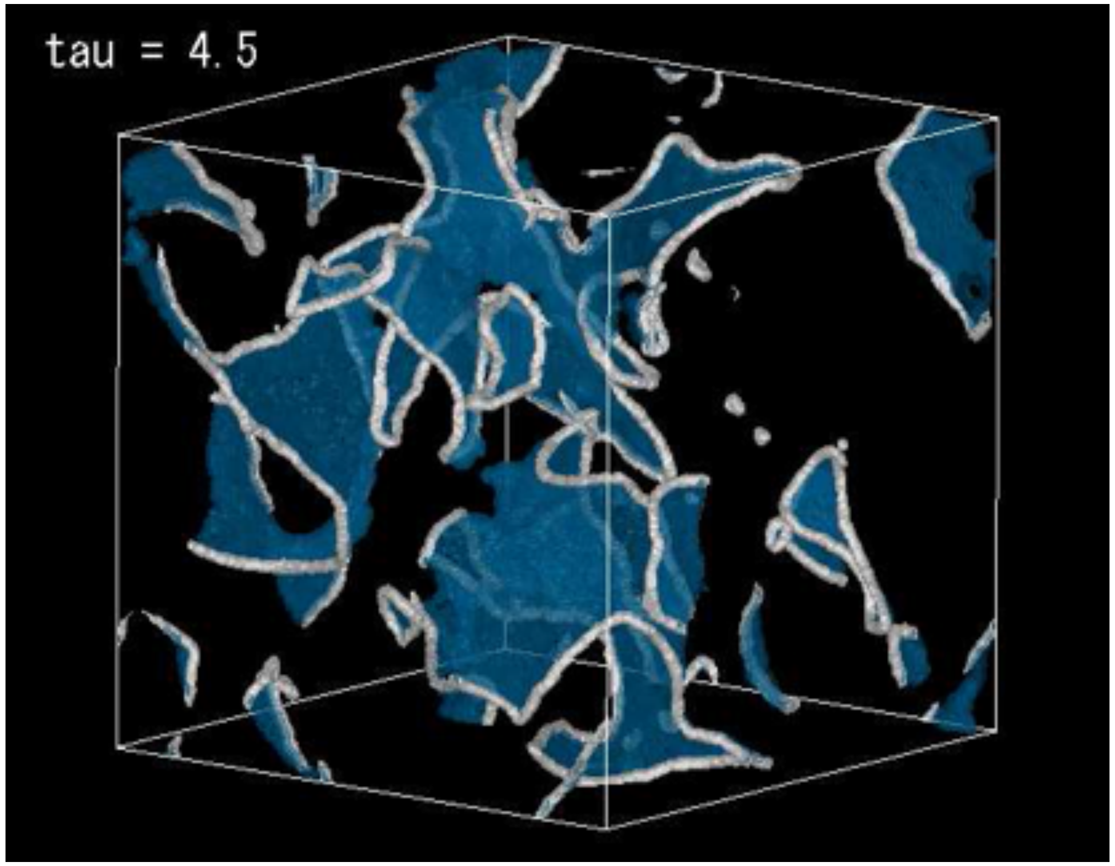


Kobayashi, Kurematsu, FT, 1304.0922

Solutions

- Restoration of Peccei-Quinn symmetry during inflation.
  - Axions are produced from domain walls and axion DM is possible for $f_a = 10^{10}$GeV.

Hiramatsu, Kawasaki, Saikawa and Sekiguchi, 1202.5851,1207.3166



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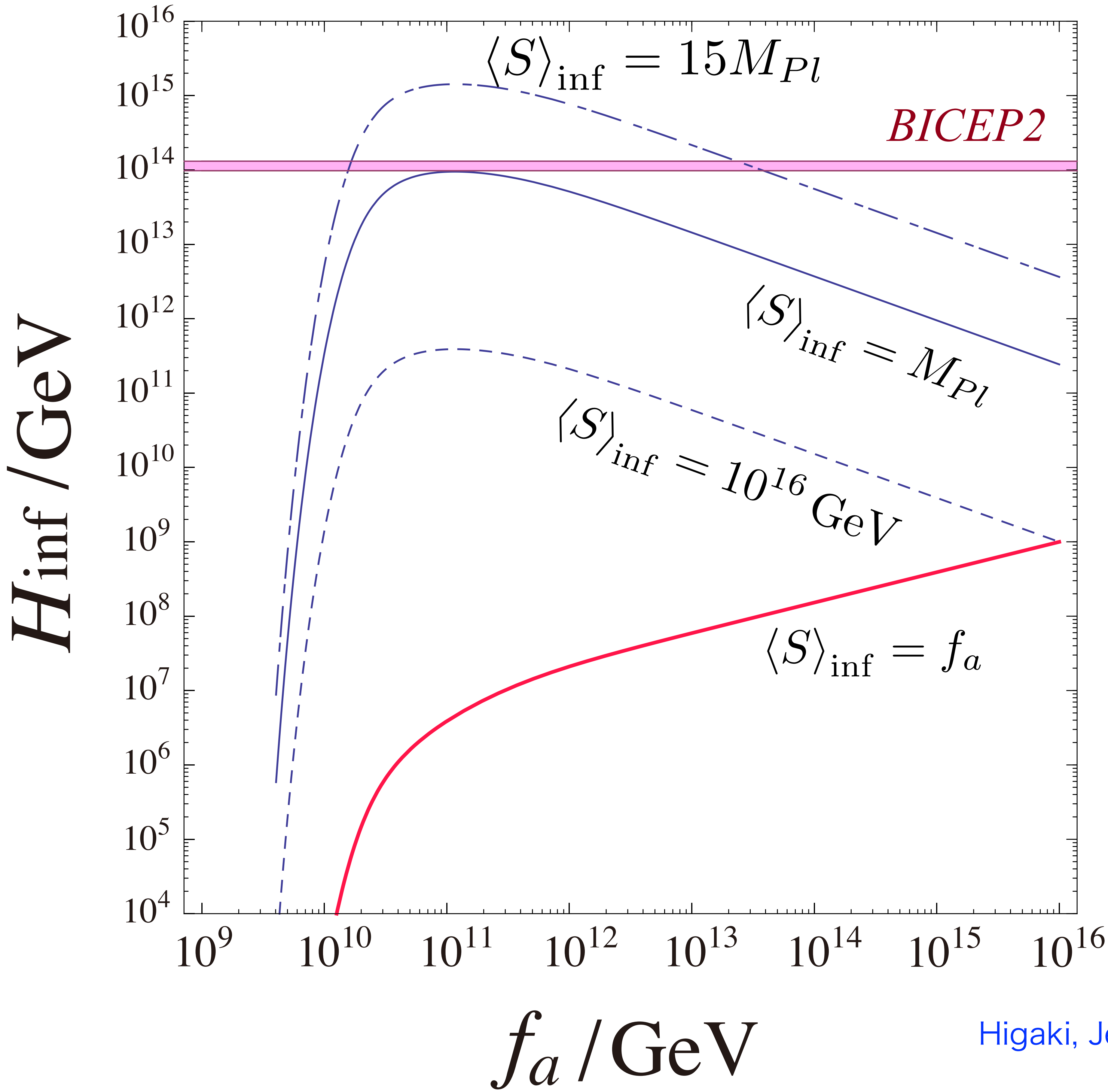
Hiramatsu, Kawasaki, Saikawa and Sekiguchi, 1202.5851,1207.3166

- Super-Planckian saxion field value during inflation. (Saxion could be the inflaton)



Higaki, Jeong, FT, 1403.4186

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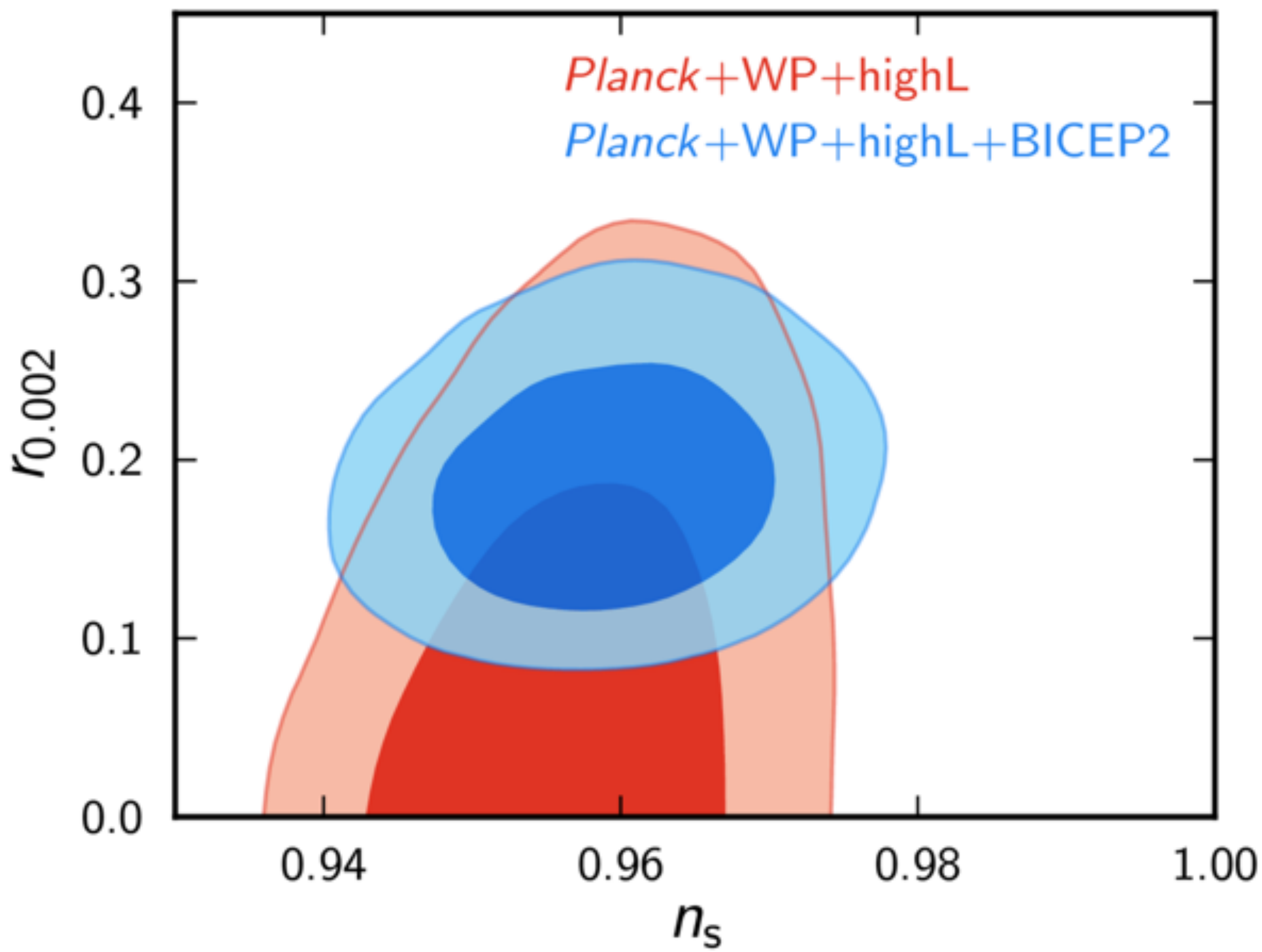
Hiramatsu, Kawasaki, Saikawa and Sekiguchi, 1202.5851,1207.3166

- Super-Planckian saxion field value during inflation. (Saxion could be the inflaton)
- Heavy axions during inflation. $m_a^2 \gtrsim H_{\rm inf}^2$
  - Stronger QCD during inflation Jeong, FT 1304.8131
  - Enhanced explicit PQ breaking Higaki, Jeong, FT, 1403.4186

Implications for cosmology



In this figure, **running of n_s** is assumed.

Why?

Because there is a tension, otherwise.

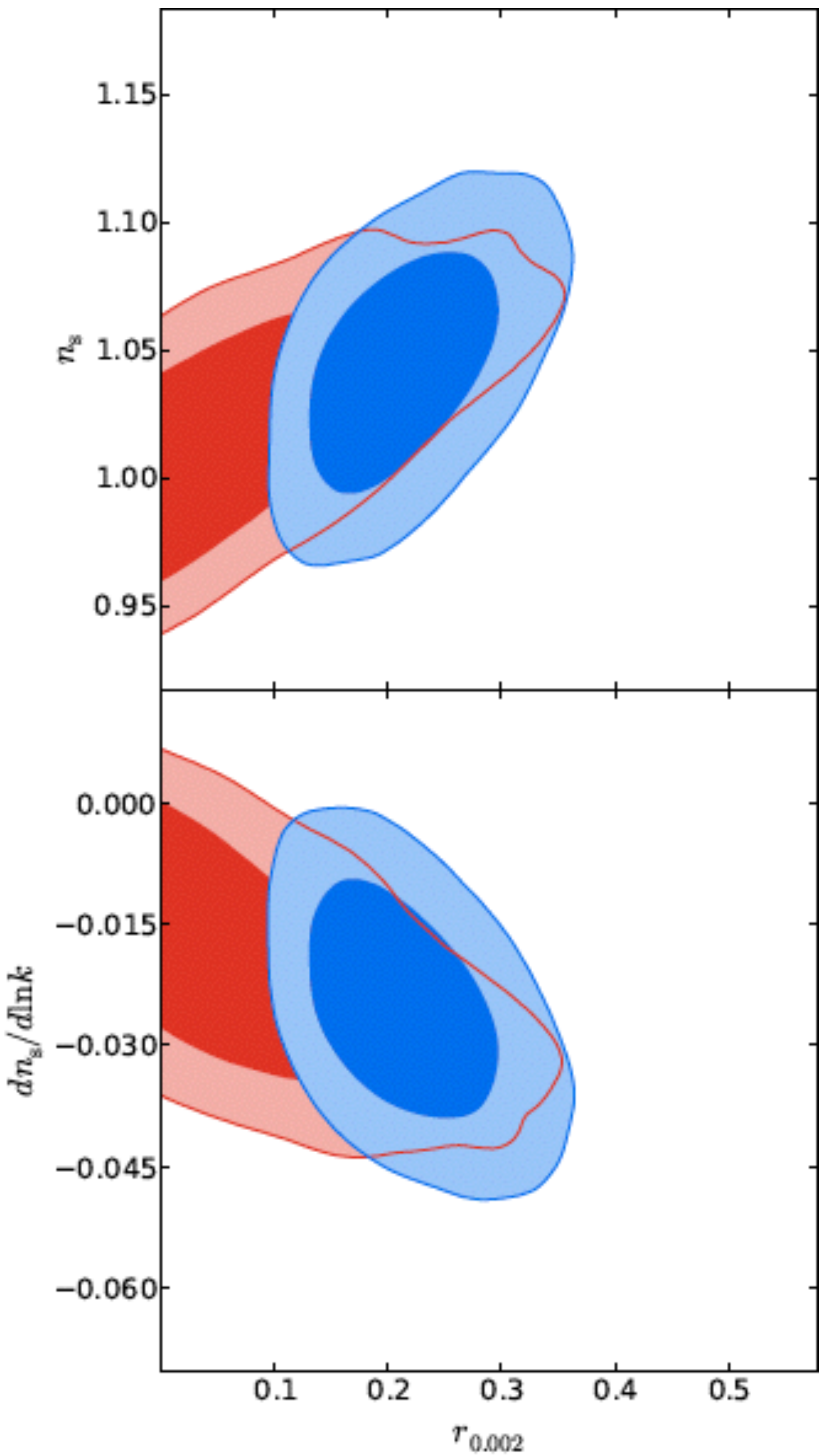
Running spectral index

If the spectral index depends on scales, the tension can be relaxed. But it is difficult to generate a large running.

Spectral index
$$n_s - 1 = \frac{d \ln P_\zeta}{d \ln k} \simeq 2\eta - 6\epsilon$$

Running of spectral index
$$\frac{dn_s}{d \ln k} = -24\epsilon^2 + 16\epsilon\eta - 2\xi$$

$$\epsilon \equiv \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2, \; \eta \equiv M_p^2 \frac{V''}{V}, \; \xi \equiv M_p^4 \frac{V'V'''}{V^2}.$$



Chen, Huang, Zhao, 1404.3467

$$n_s \sim 1$$

$$\frac{dn_s}{d\ln k} = -0.02 \sim -0.03$$

are needed to reconcile the tension.

But, then inflation ends soon and in general $N_e < 30$.

Easther and Peiris, astro-ph/0604214

(a constant running is assumed)

Large-field inflation with modulations

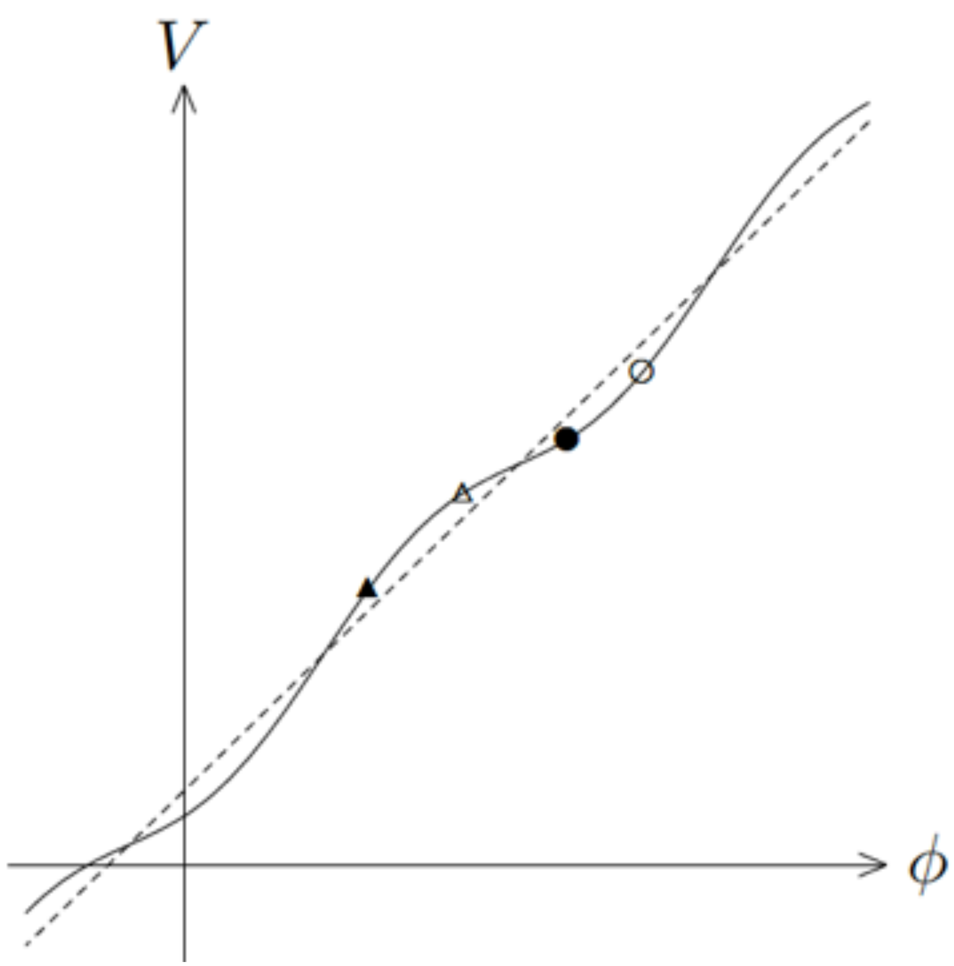
Kobayashi, FT, 1011.3988
Czerny, Kobayashi, FT, 1403.4589

Let us add small modulations to the inflaton potential.

$$V(\phi) = V_0(\phi) + V_{mod}(\phi),$$

satisfying

$$\begin{aligned} |V_0(\phi)| &\gg |V_{mod}(\phi)|, \\ |V_0'(\phi)| &> |V_{mod}'(\phi)|. \\ |V_0''(\phi)| &\lesssim |V_{mod}''(\phi)|, \\ |V_0'''(\phi)| &\ll |V_{mod}'''(\phi)|. \end{aligned}$$



Then the spectral index and its running are significantly affected by modulations, while the inflaton dynamics and the normalization of density perturbations are hardly affected.

Large-field inflation with modulations

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Czerny, Kobayashi, FT, 1403.4589

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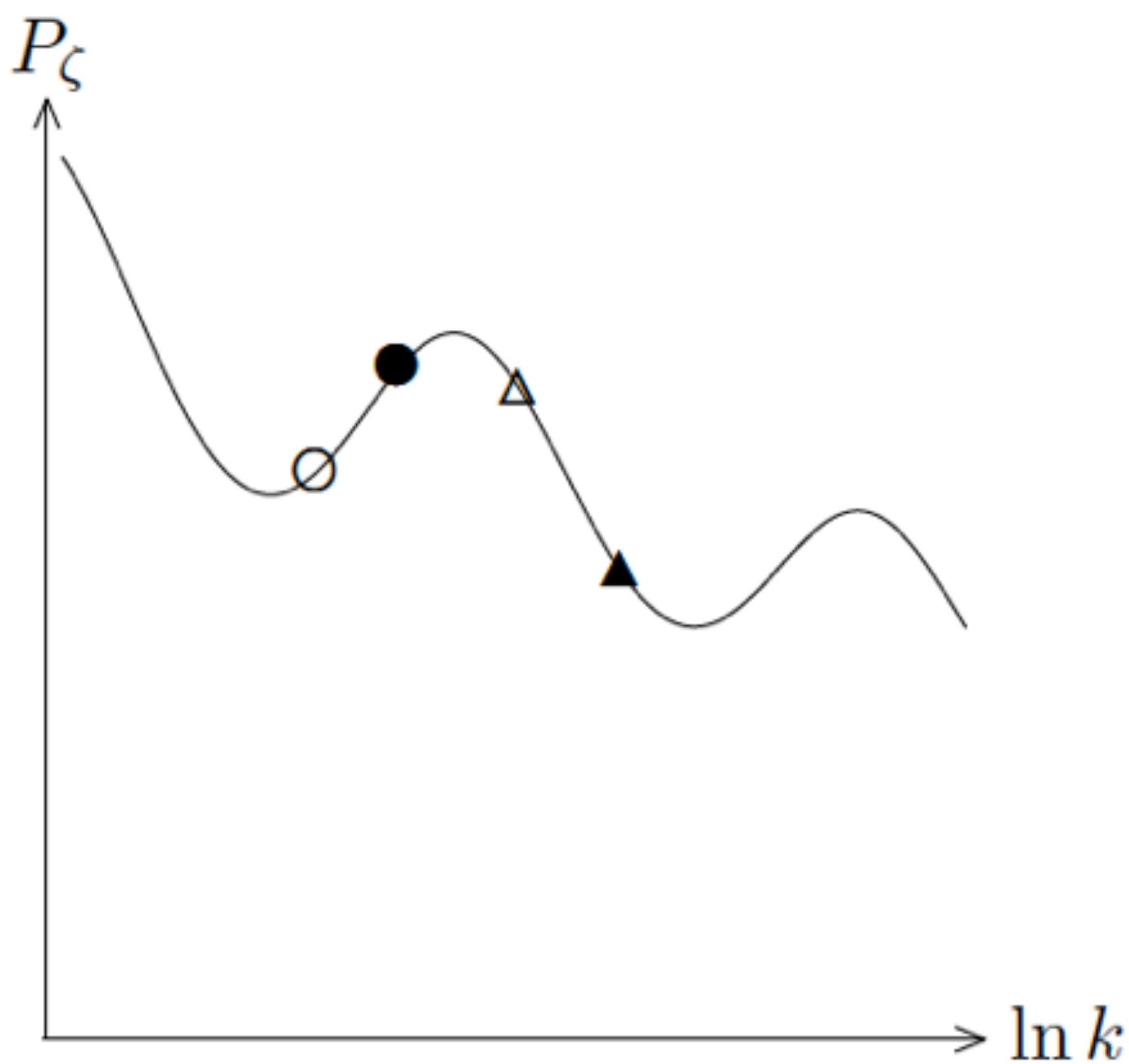

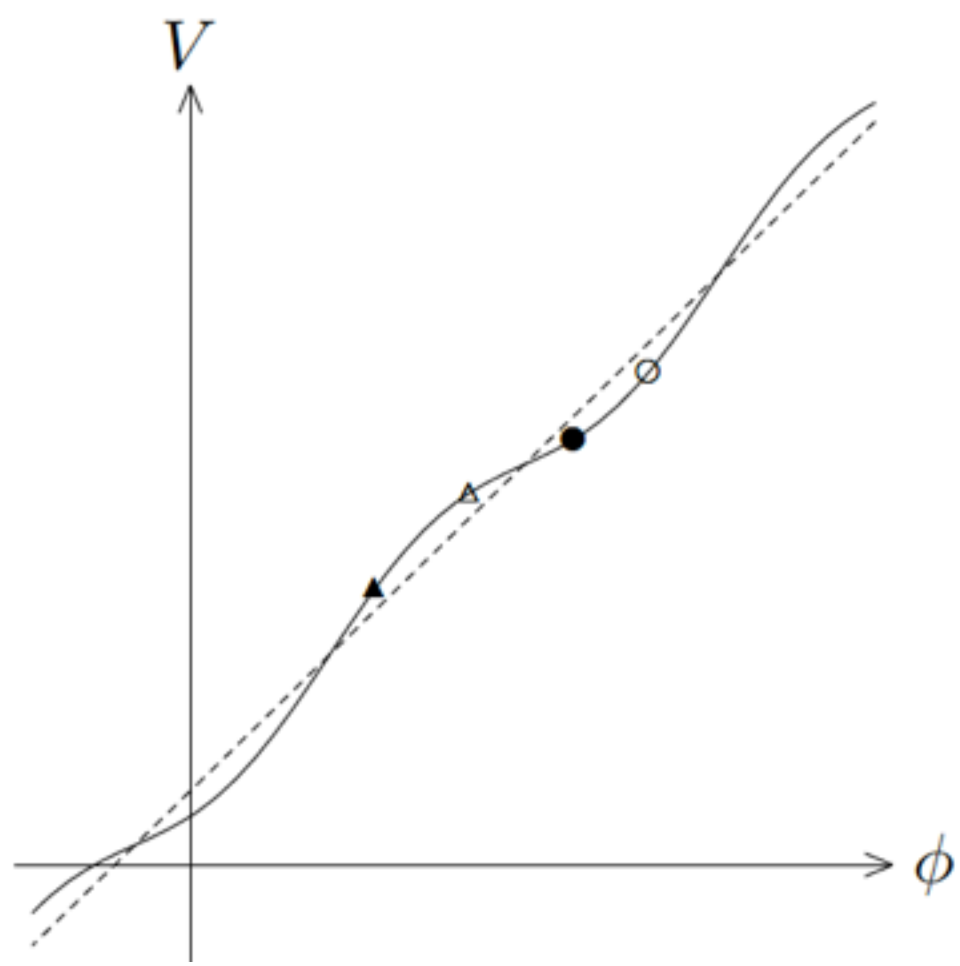

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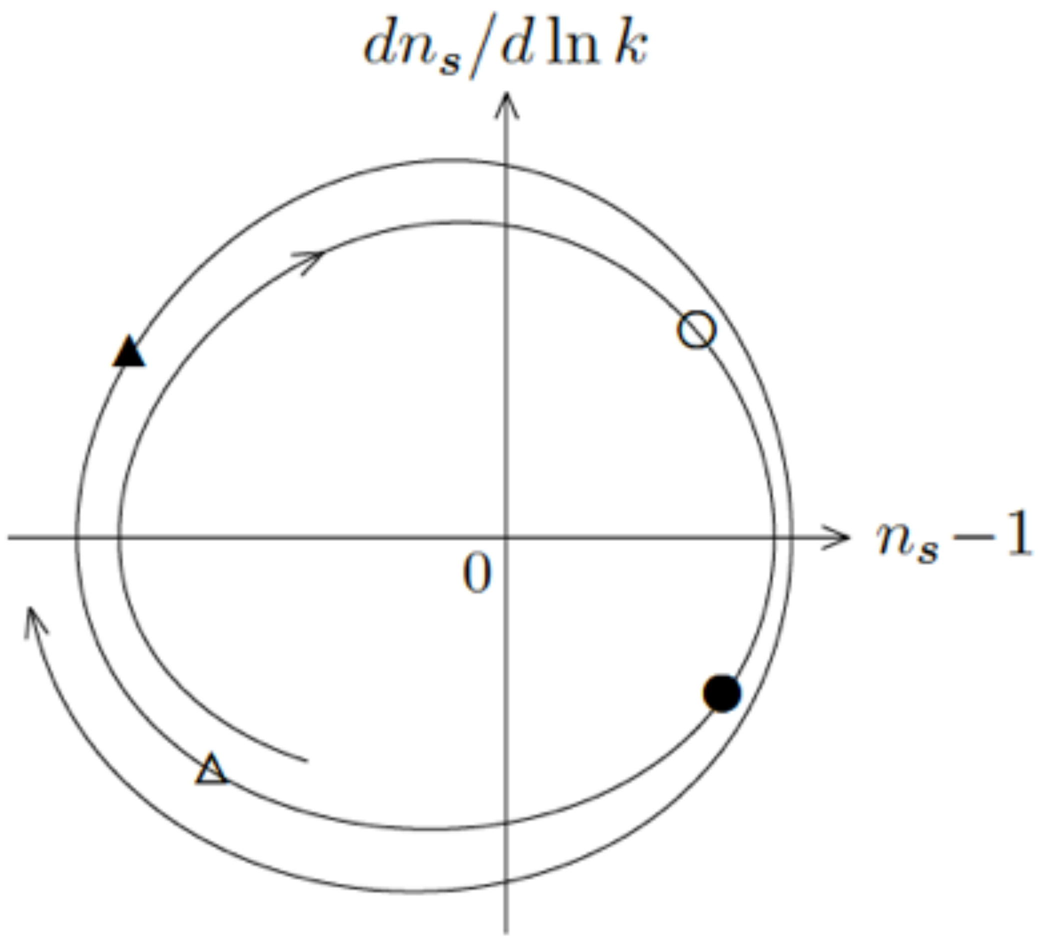
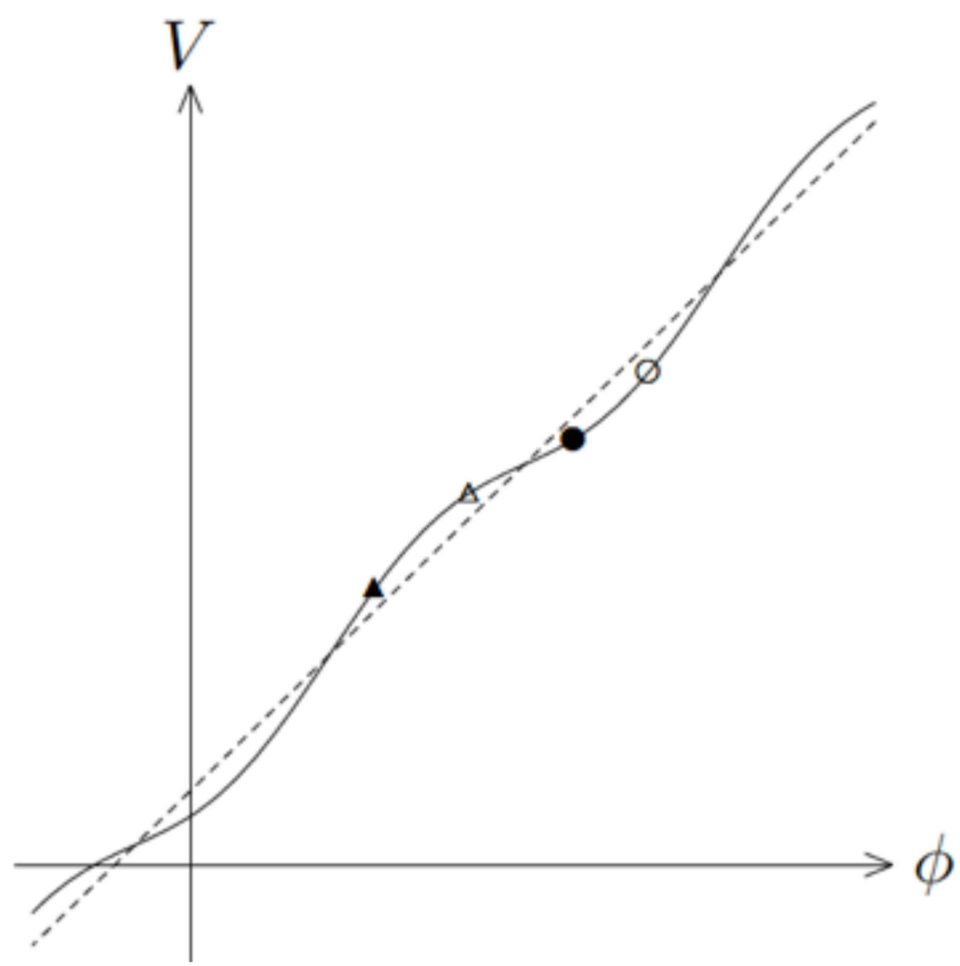


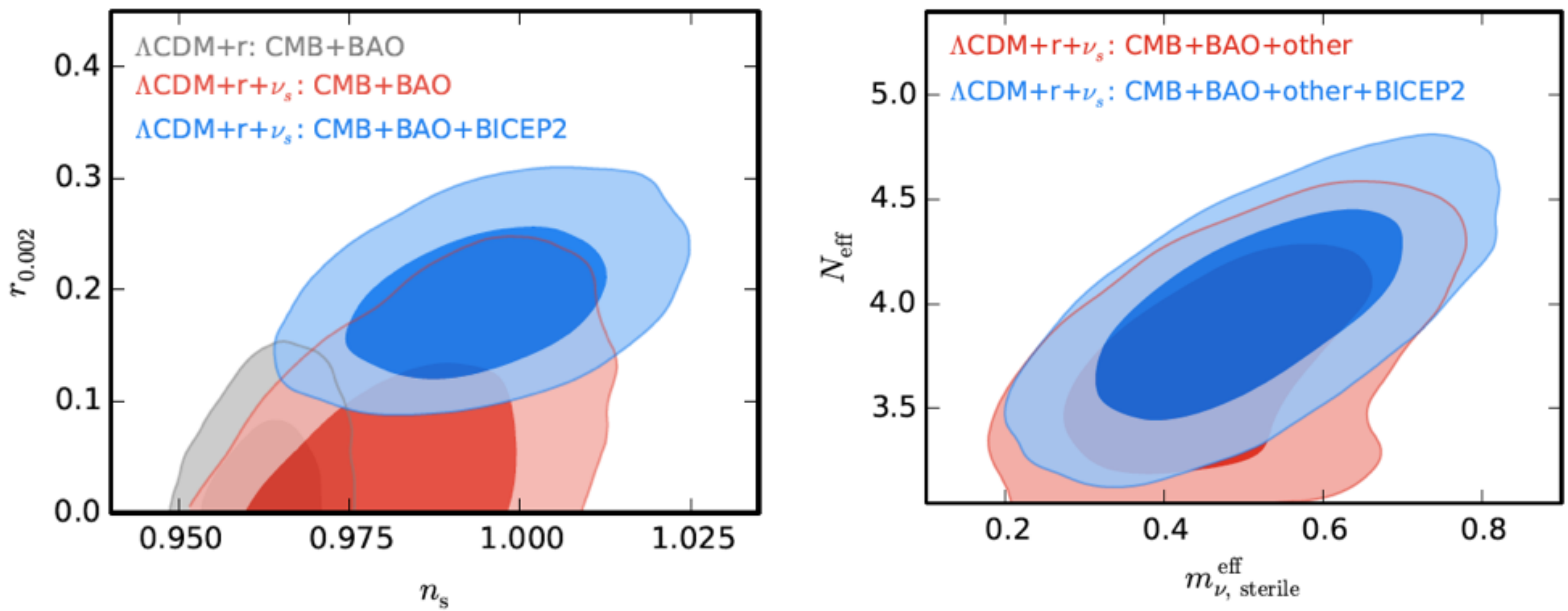


Such small modulations are built-in feature of the multi-natural inflation model.

Sterile neutrinos/HDM/dark radiation

LambdaCDM + Sterile neutrino

$$m_{\nu_s} \sim 1\,\mathrm{eV}, \quad N_{\mathrm{eff}} \sim 1$$



Zhang, Li, Zhang, 1403.7028

Conclusions

- If true, the BICEP2 results have SIGNIFICANT impacts on particle physics and cosmology.
- **GUT-scale inflation with super-Planckian field values**
  - What is the inflaton? How can we keep the potential form?
  - Reheating, baryogenesis, dark matter.
  - Too large isocurvature of QCD axion.
  - Symmetry restoration?
- **Tension between BICEP2 and Planck.**
  - Unusual features in the density perturbations?
  - Dark radiation, hot dark matter, neutrino mass?
  - Initial condition for the inflation?
    - False vacuum decay, fast roll, etc.