Precision
Cosmology meets particle physics

@ Kyoto University
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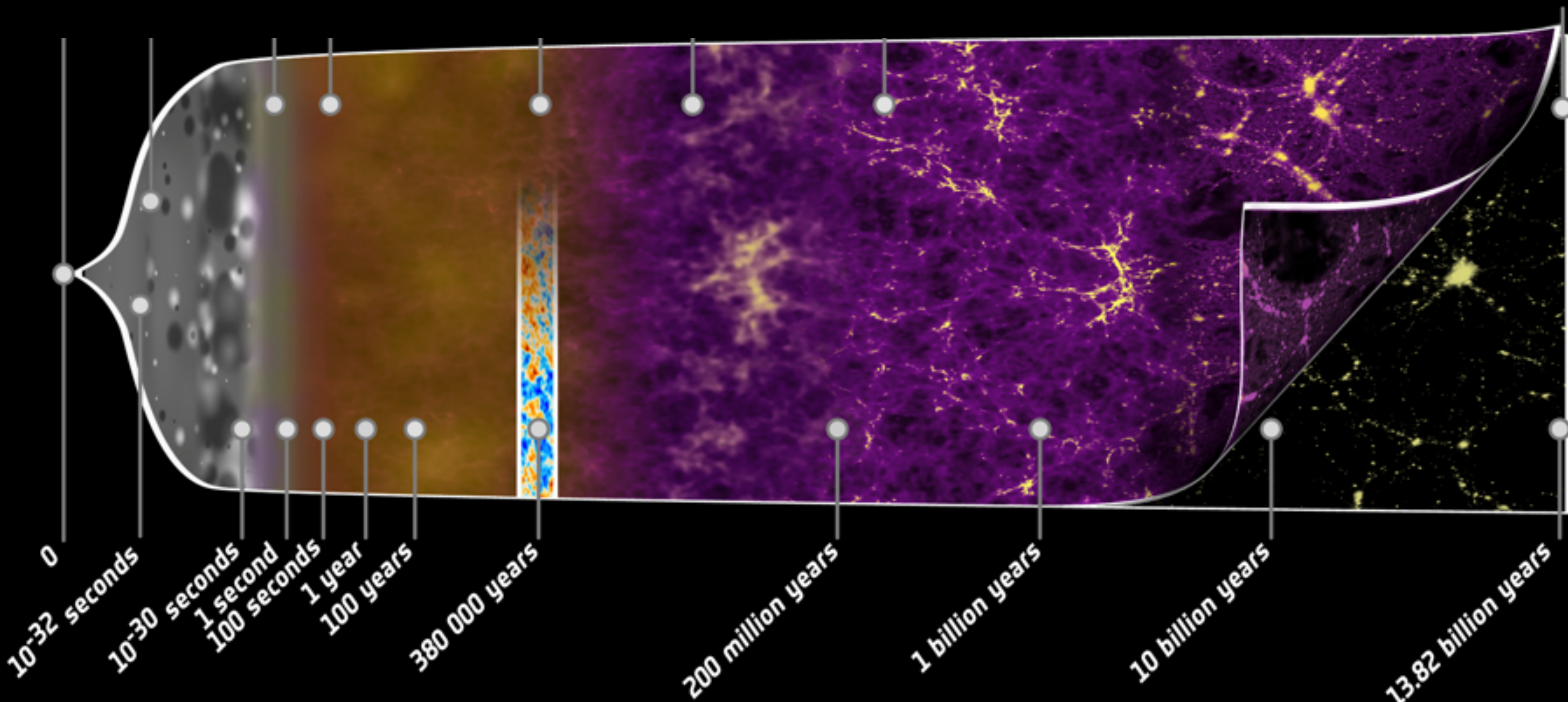
(Tohoku University)

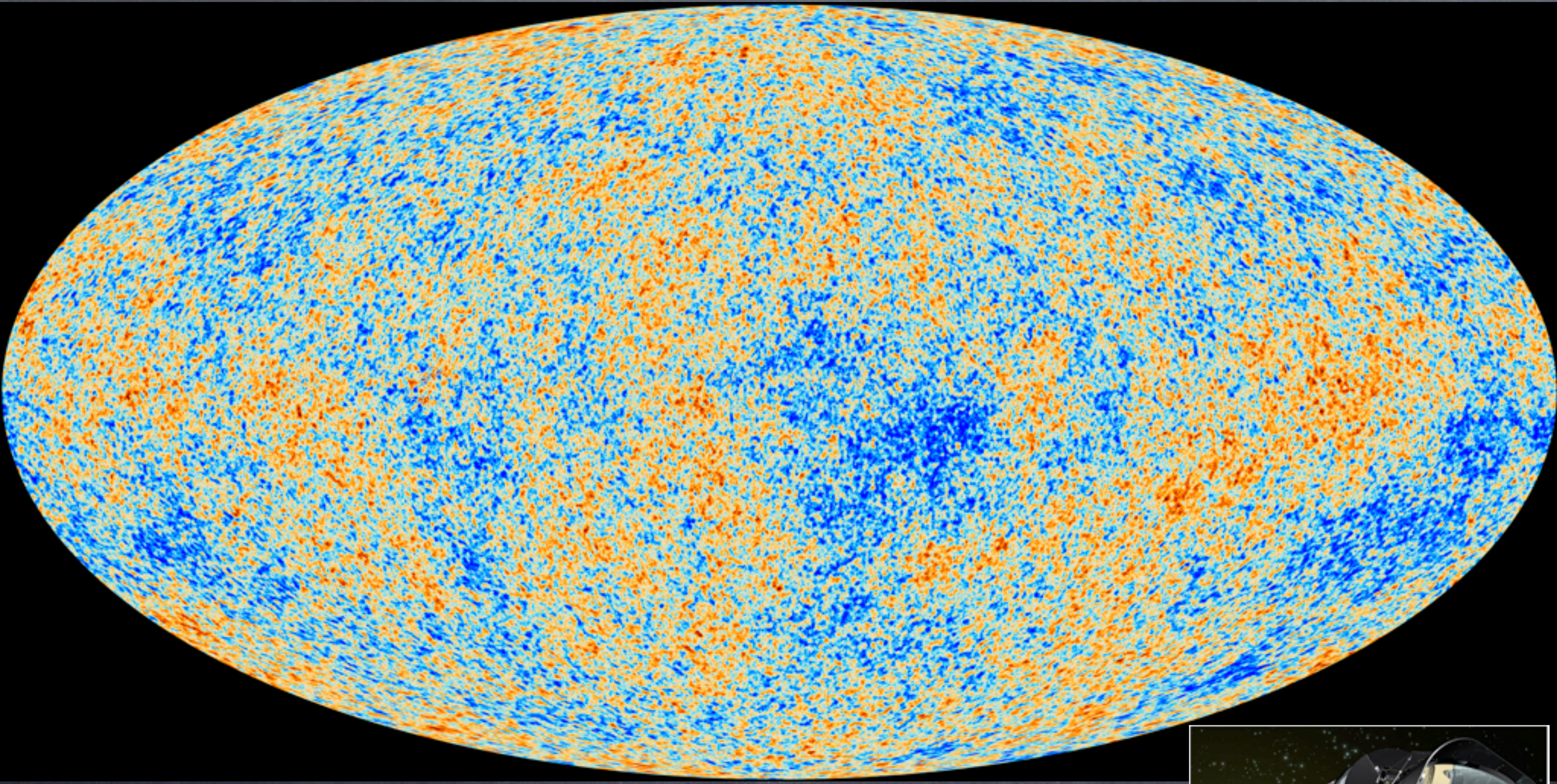
based on the works with K-S Jeong, T. Higaki, K. Nakayama, T. Yanagida, T. Koboyashi, R. Kurematsu

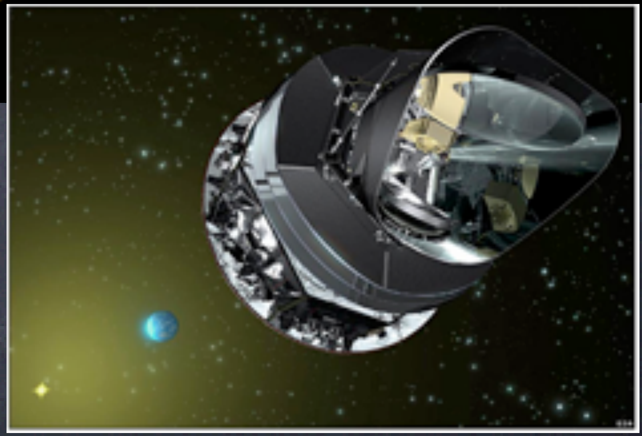
Why cosmology?

Particle physics and cosmology are connected in the expanding Universe.



Cosmology is now a precision science.





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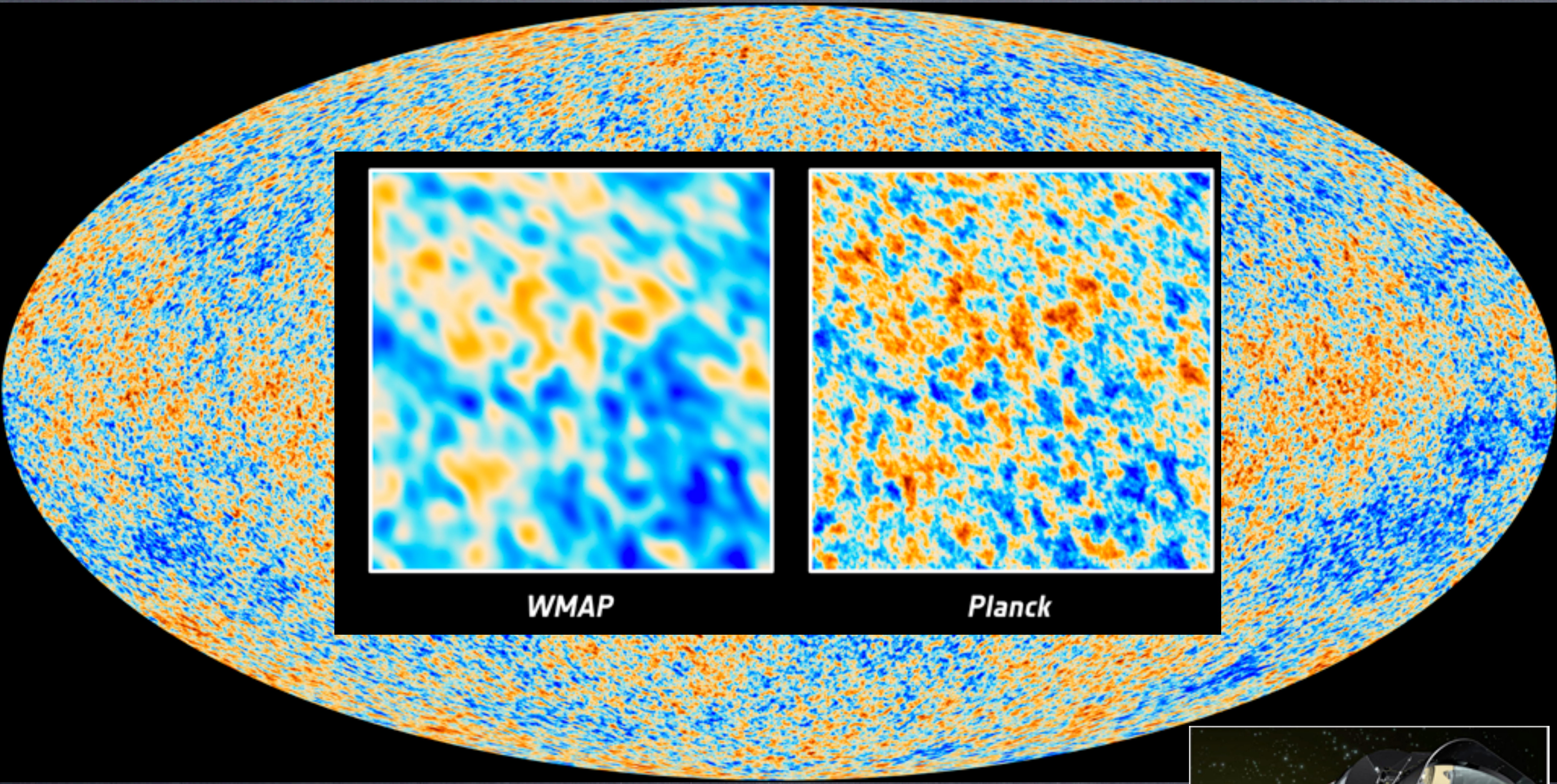

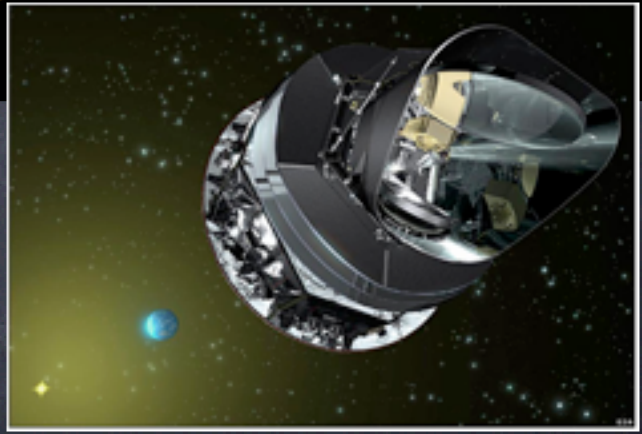

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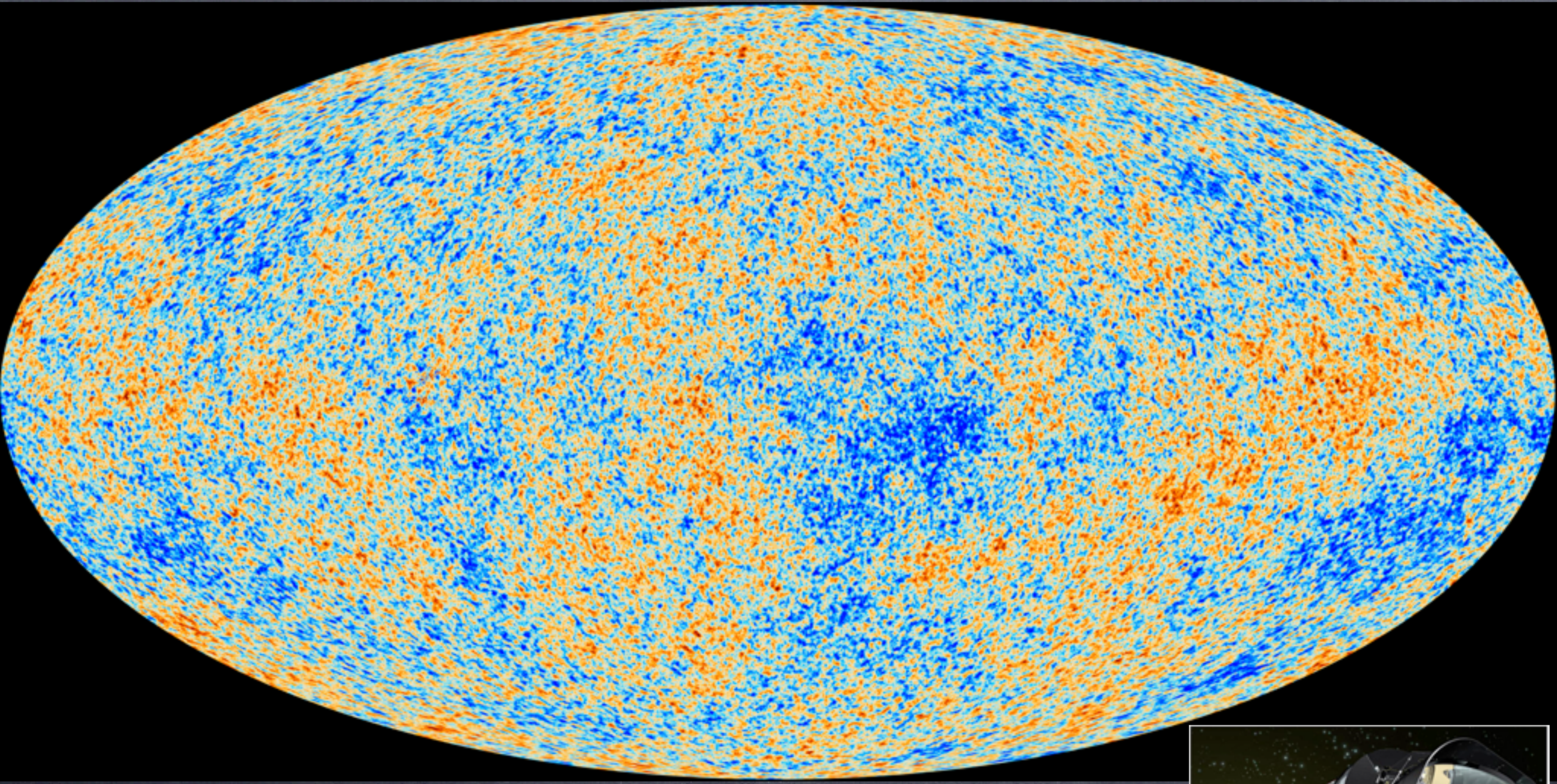

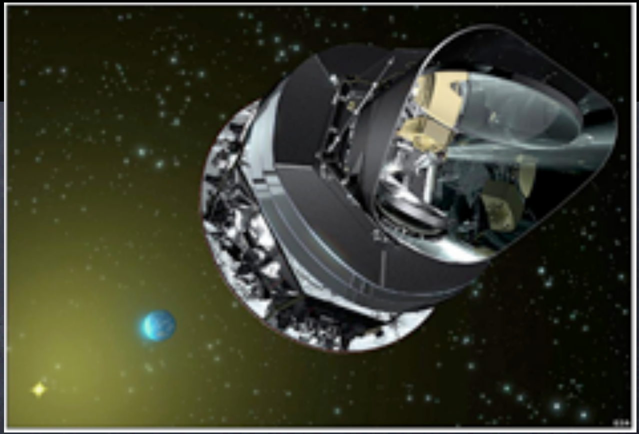

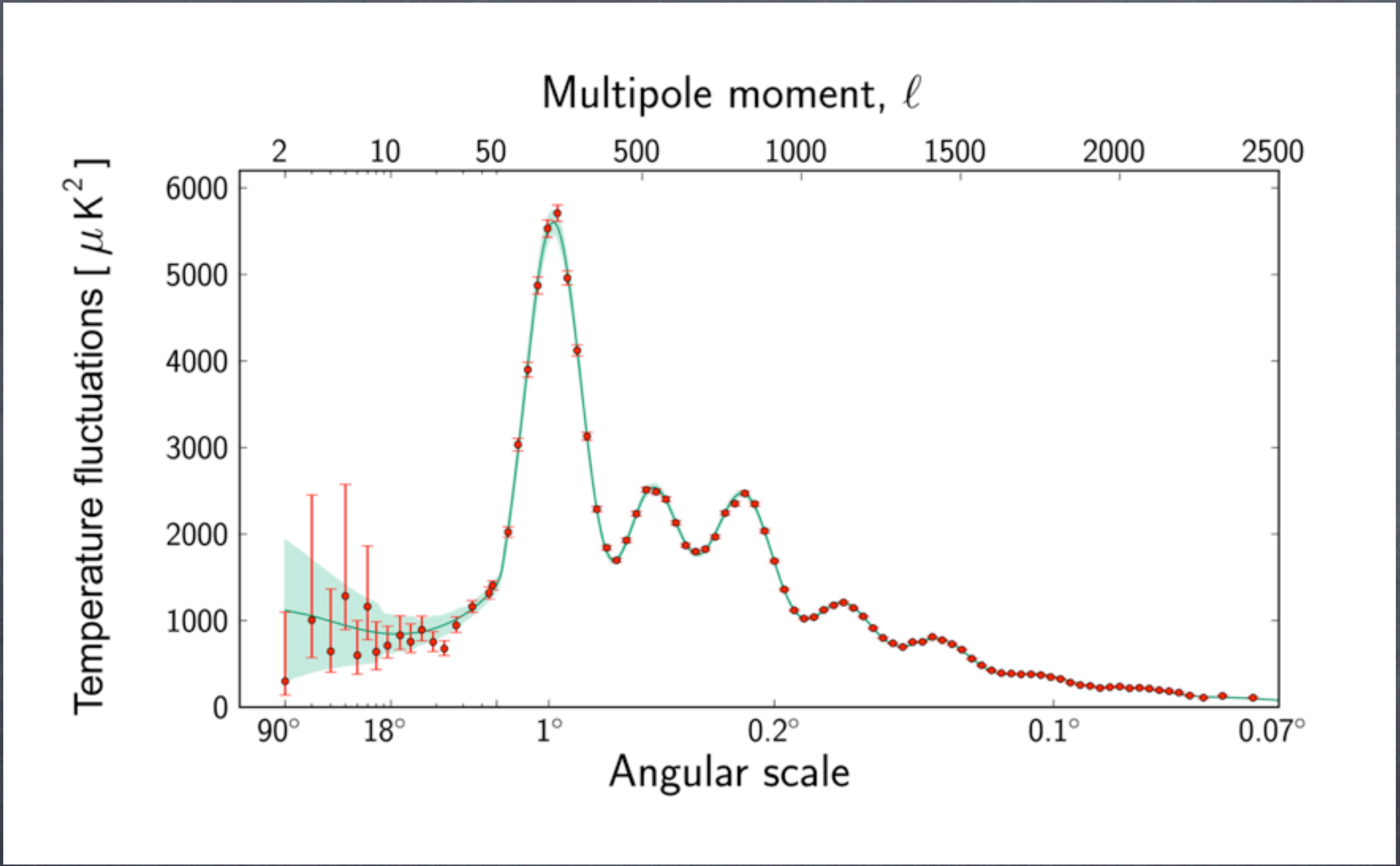

Perfect agreement with the standard LCDM model with 6 parameters. $(\Omega_b h^2, \Omega_c h^2, \theta_{\rm MC}, \tau, n_s, \ln(A_s))$

What did we learn from Planck?

- ✓ Adiabatic and gaussian density perturbations at super-horizon scales strongly support for a simple class of inflation.

- ✓ Cosmological parameters are determined with a greater accuracy.

$$\Omega_c h^2 = 0.1199 \pm 0.0027$$
$$\Omega_b h^2 = 0.02205 \pm 0.00028$$

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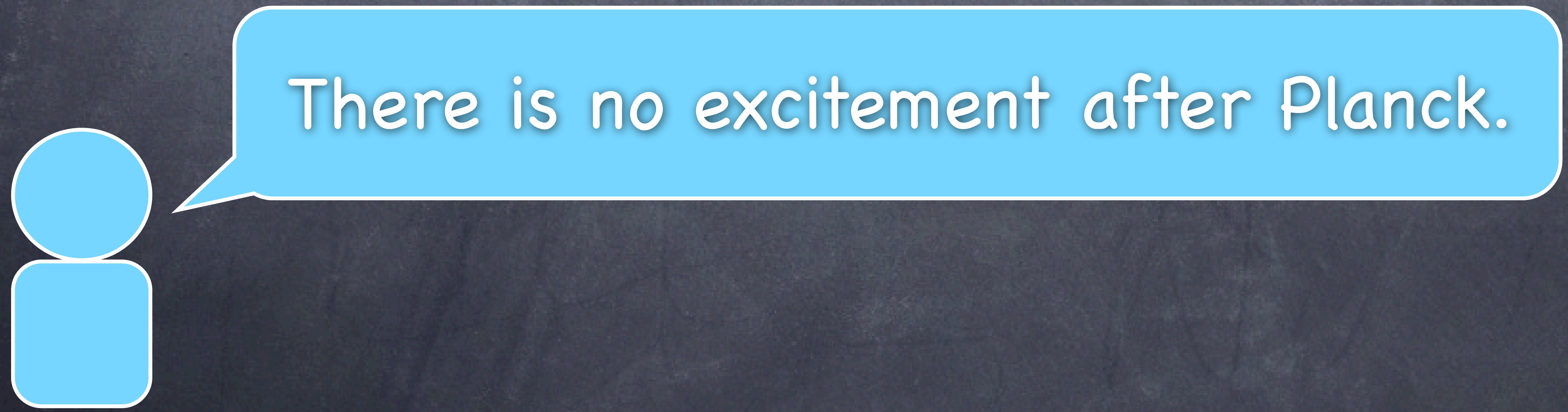

Theorist

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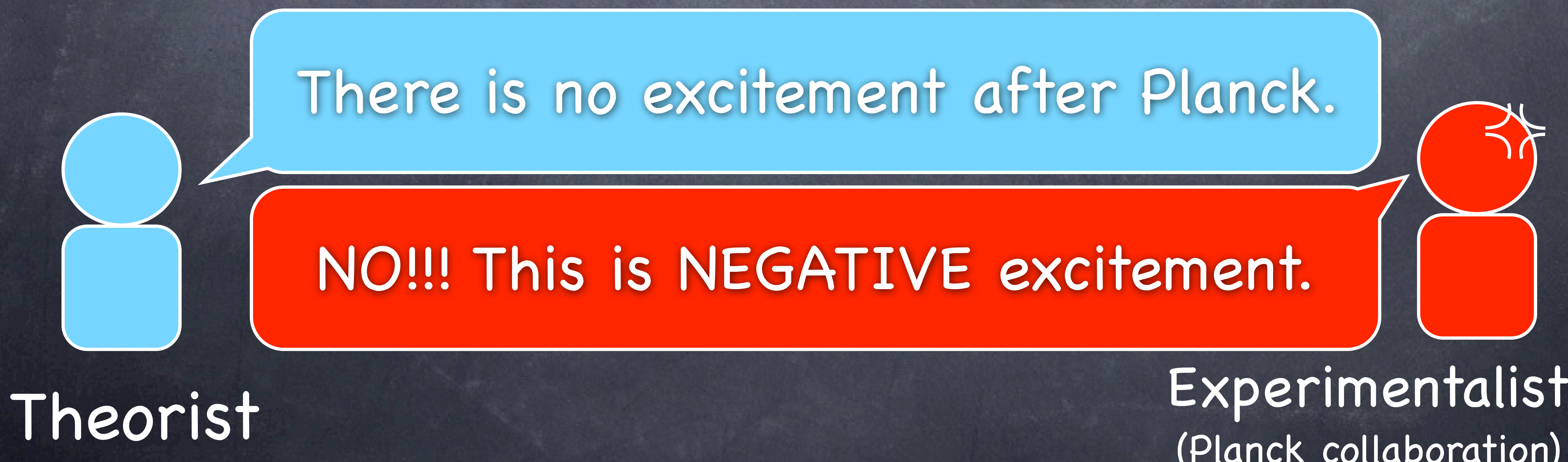

The rationale for precision measurements

"The whole history of physics proves that a new discovery is quite likely lurking at the next decimal place."

F.k. Richtmeyer (1931)

"A precision experiment is justified if it can reveal a flaw in our theory or observe a previously unseen phenomenon, not simply because the experiment happens to be feasible..."

S. L. Glashow, 1305.5482

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S. L. Glashow, 1305.5482

I think there is no point in measuring the dark matter or baryon abundance more precisely.

Then where to look for?

Here I list three possible extensions to the std. LCDM model.

- ✓ **Tensor mode (or B-mode polarization)**

  The inflation near the GUT scale.

- ✓ **Isocurvature perturbations**

  Light degrees of freedom during inflation, which affected the DM or B abundance.

- ✓ **Dark radiation**

  Ultra-light relativistic degrees of freedom at the recombination epoch.

If discovered, it will have a big impact not only on cosmology but also on particle physics!

1. Tensor mode

Density perturbations are induced by distortion of space;

$$ds^2 = -dt^2 + a^2(t)\left(1 + 2\zeta(x,t) + \cdots\right)\left(\delta_{ij} + h_{ij}(x,t) + \cdots\right)dx^i dx^j$$

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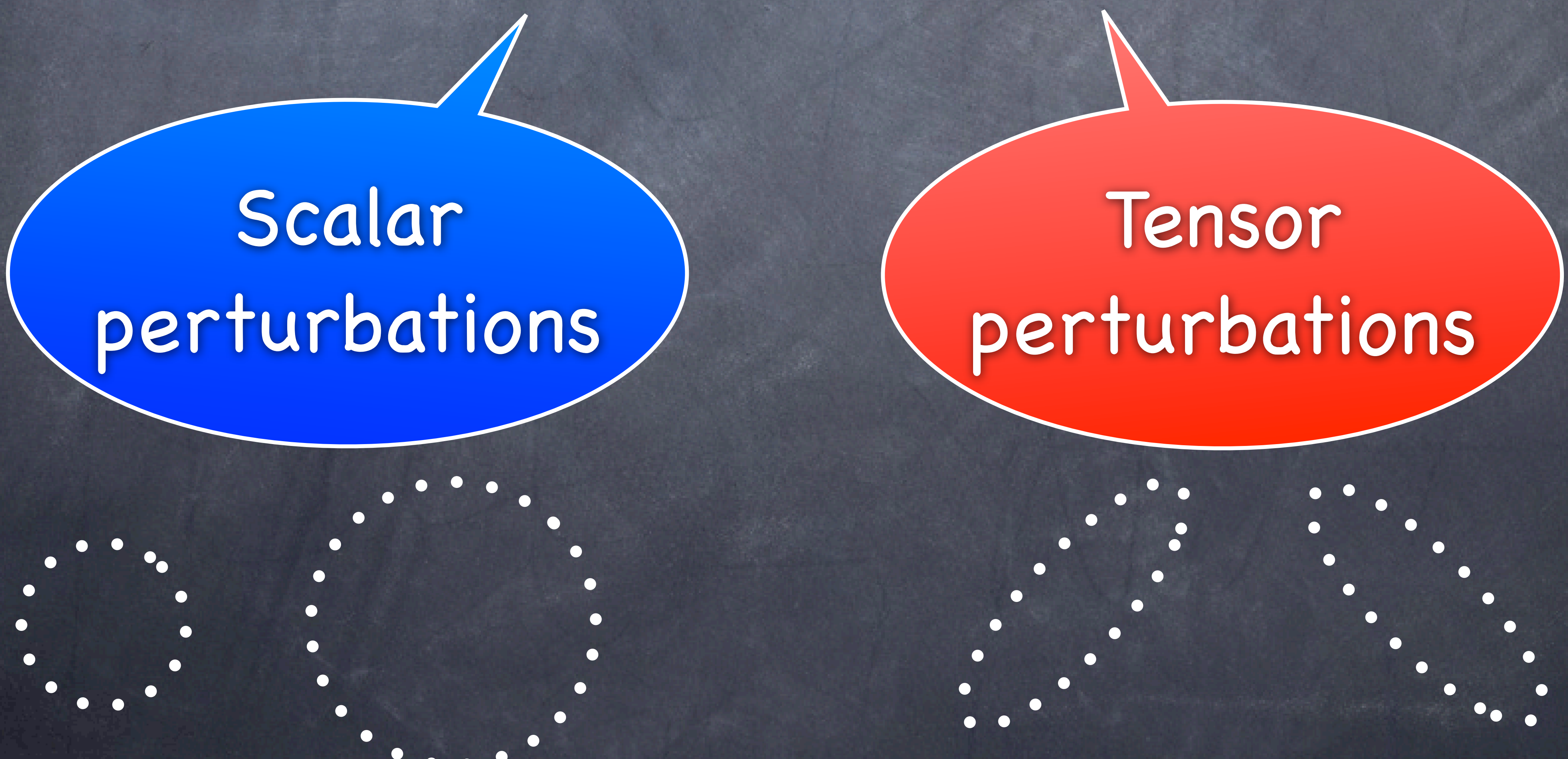


1. Tensor mode

$$k_0 = 0.05\,\mathrm{Mpc}^{-1}$$

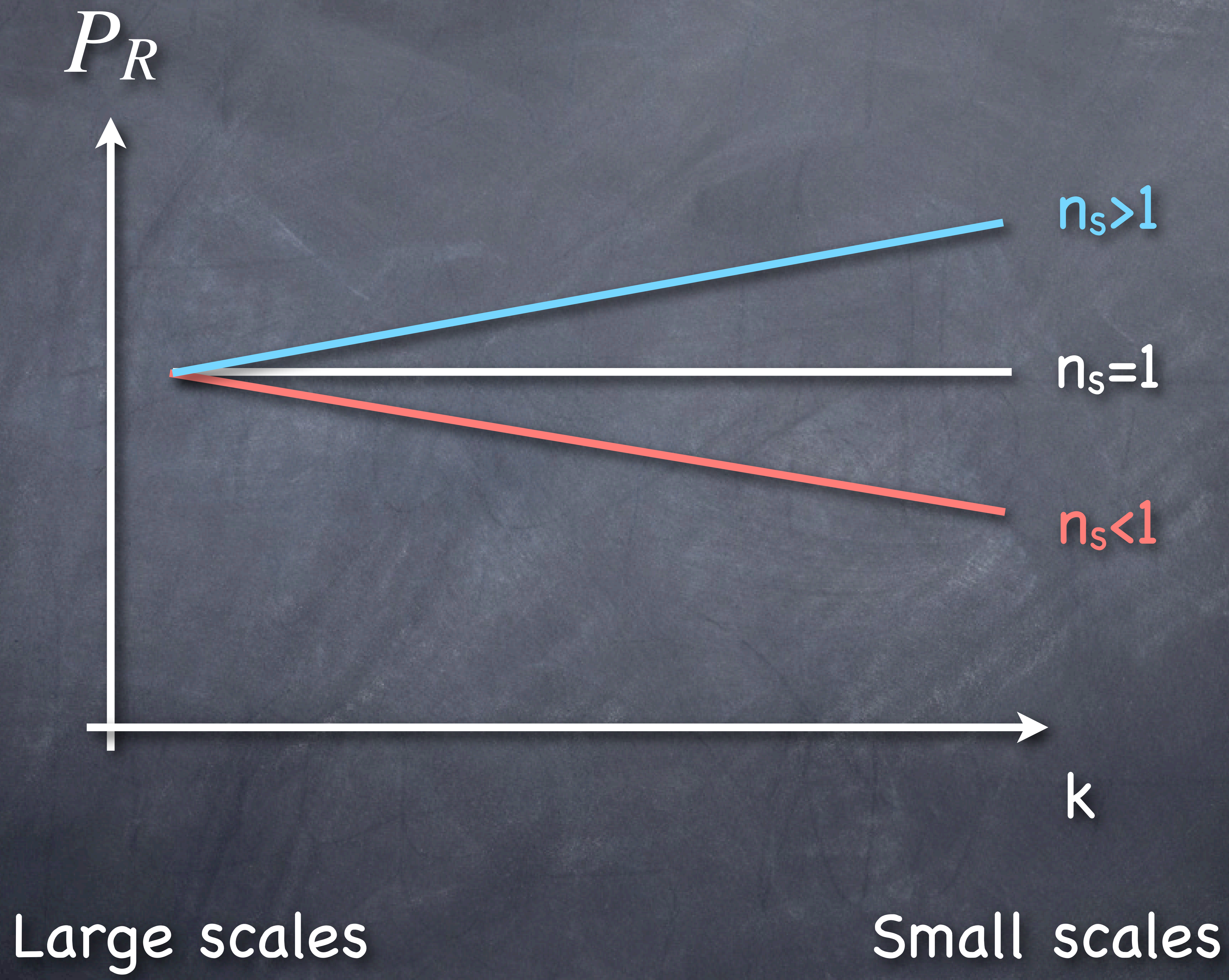
Curvature perturbations: $\mathcal{P}_{\mathcal{R}} = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$

Tensor mode (gravitational waves): $\mathcal{P}_t = A_t \left(\frac{k}{k_0}\right)^{n_t}$

The spectral index: n_s

The tensor-to-scalar ratio

$$r = \frac{A_t}{A_s} \simeq 0.15 \left(\frac{H_{\mathrm{inf}}}{10^{14}\,\mathrm{GeV}}\right)^2$$


P_R
$n_s>1$
$n_s=1$
$n_s<1$
k
Large scales
Small scales

(n_s, r)

$$n_s = 1 + 2\frac{V''}{V} - 3\left(\frac{V'}{V}\right)^2$$

$$r = 8\left(\frac{V'}{V}\right)^2$$

V: the inflaton potential.

They can be used to distinguish between different inflation models.

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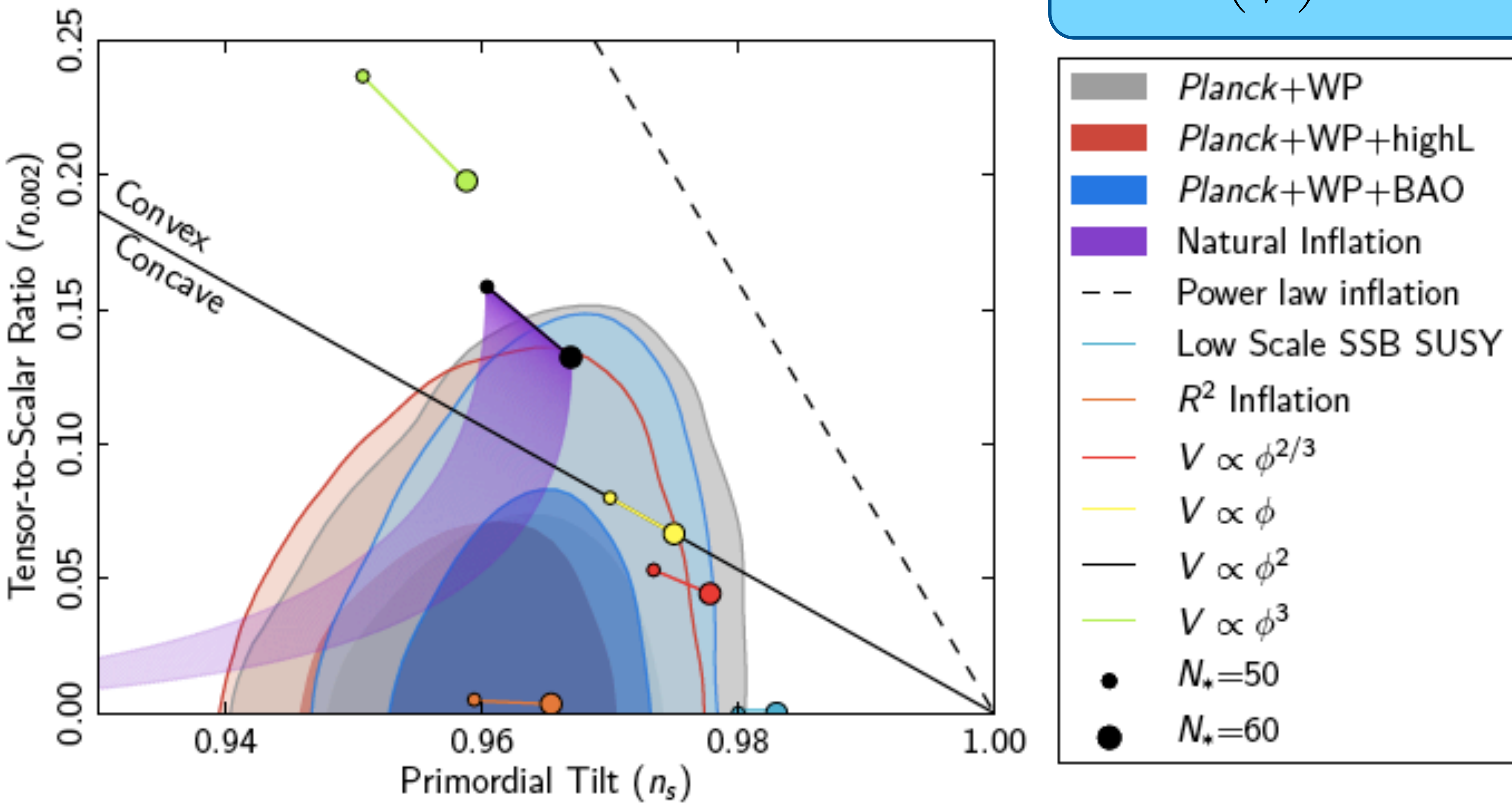

Fig. 1. Marginalized joint 68% and 95% CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets compared to the theoretical predictions of selected inflationary models.

Planck collaborations, 1303.5082

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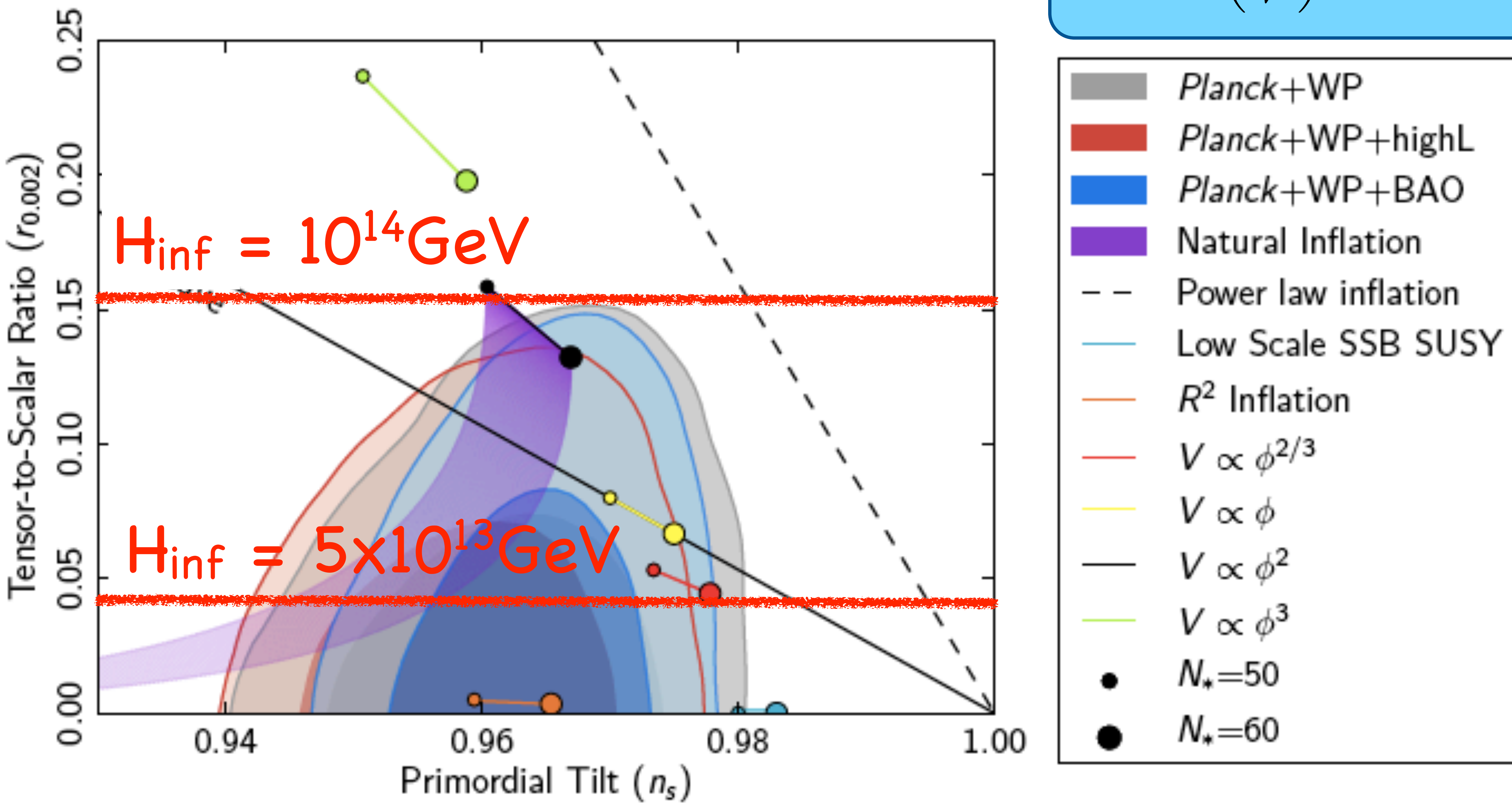

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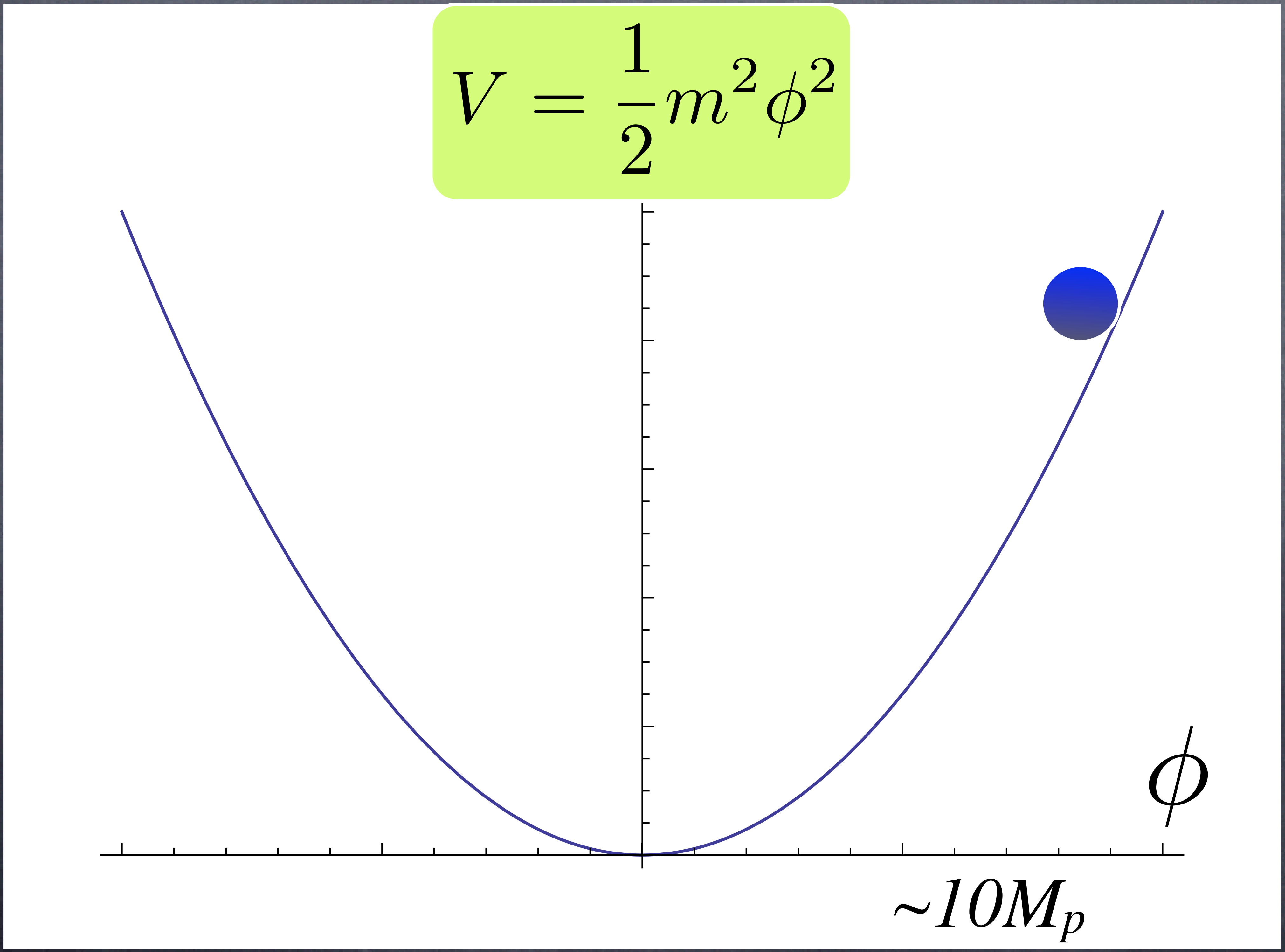

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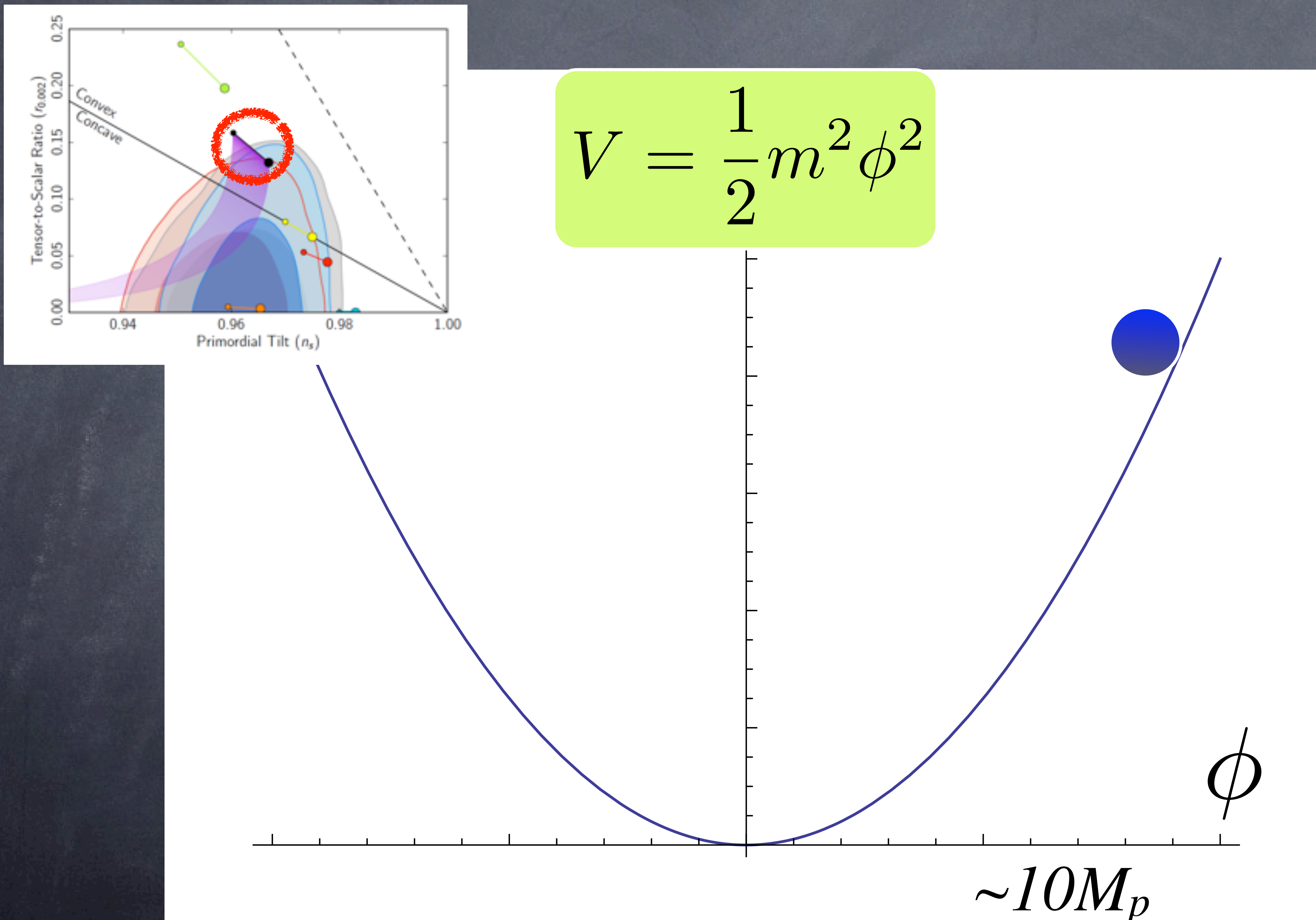

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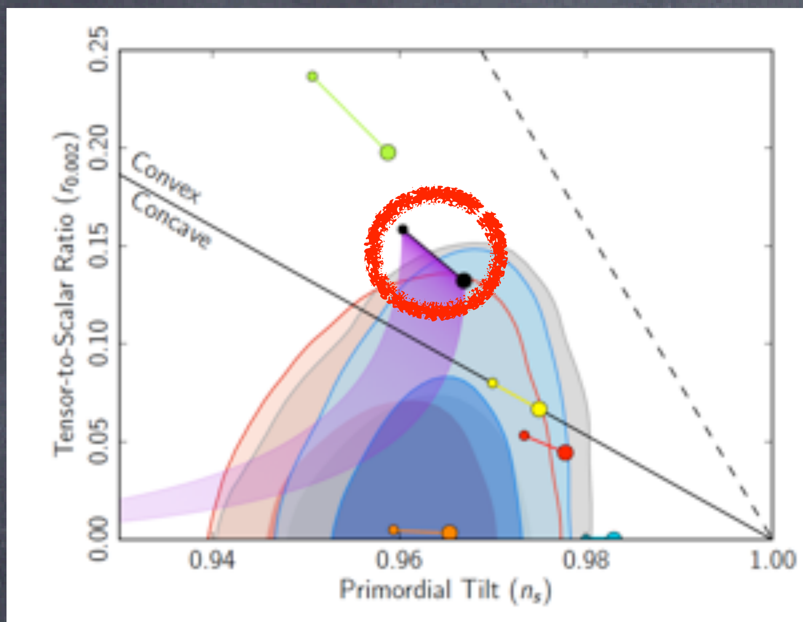

$$V = \frac{1}{2} m^2 \phi^2$$

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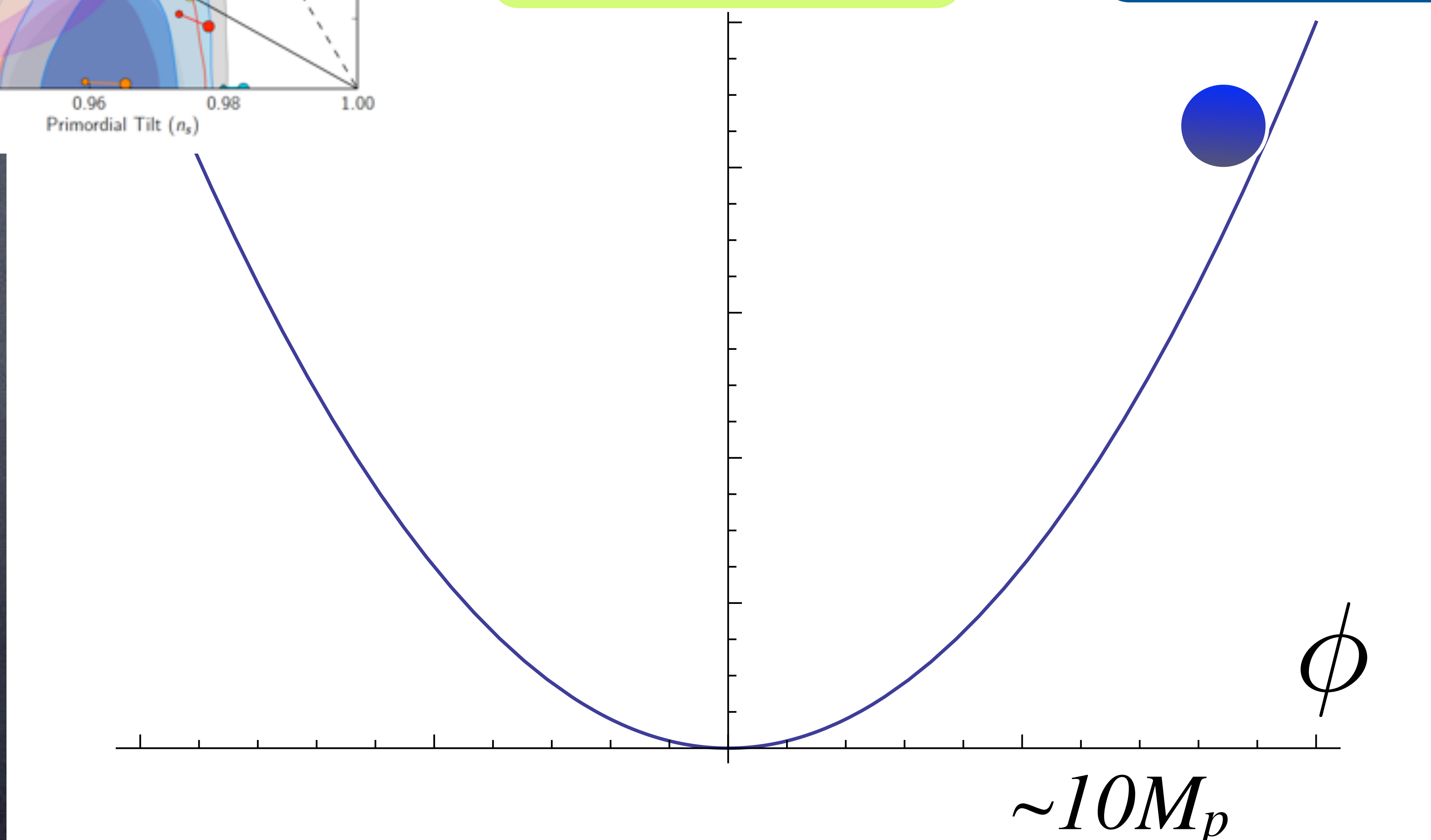

- It is possible to reduce only r, if the potential is flatter and has a small (even negative) curvature.

$$V \sim \frac{1}{2} m^2 \phi^2 \left(1 - \phi + \phi^2\right)$$

$$n_s = 1 + 2\frac{V''}{V} - 3\left(\frac{V'}{V}\right)^2$$

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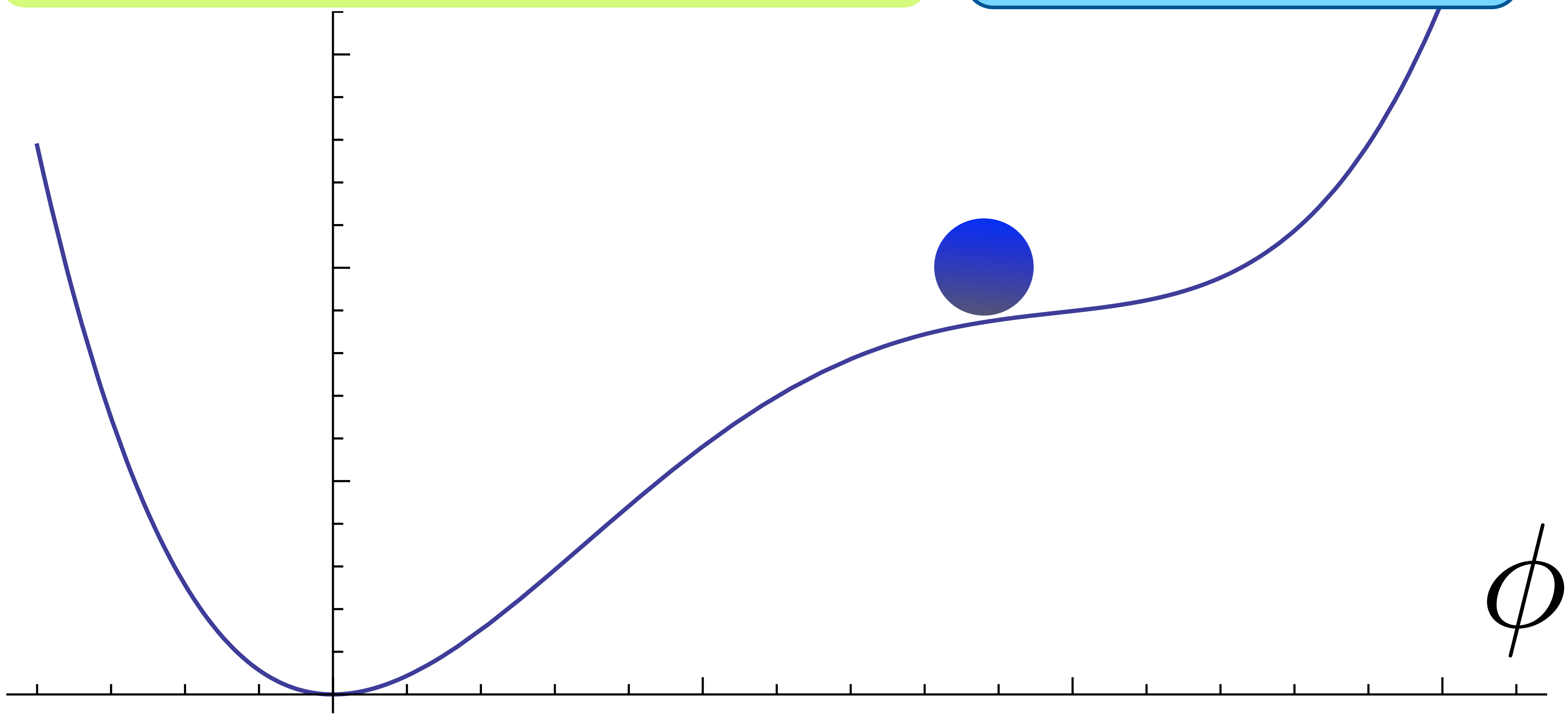
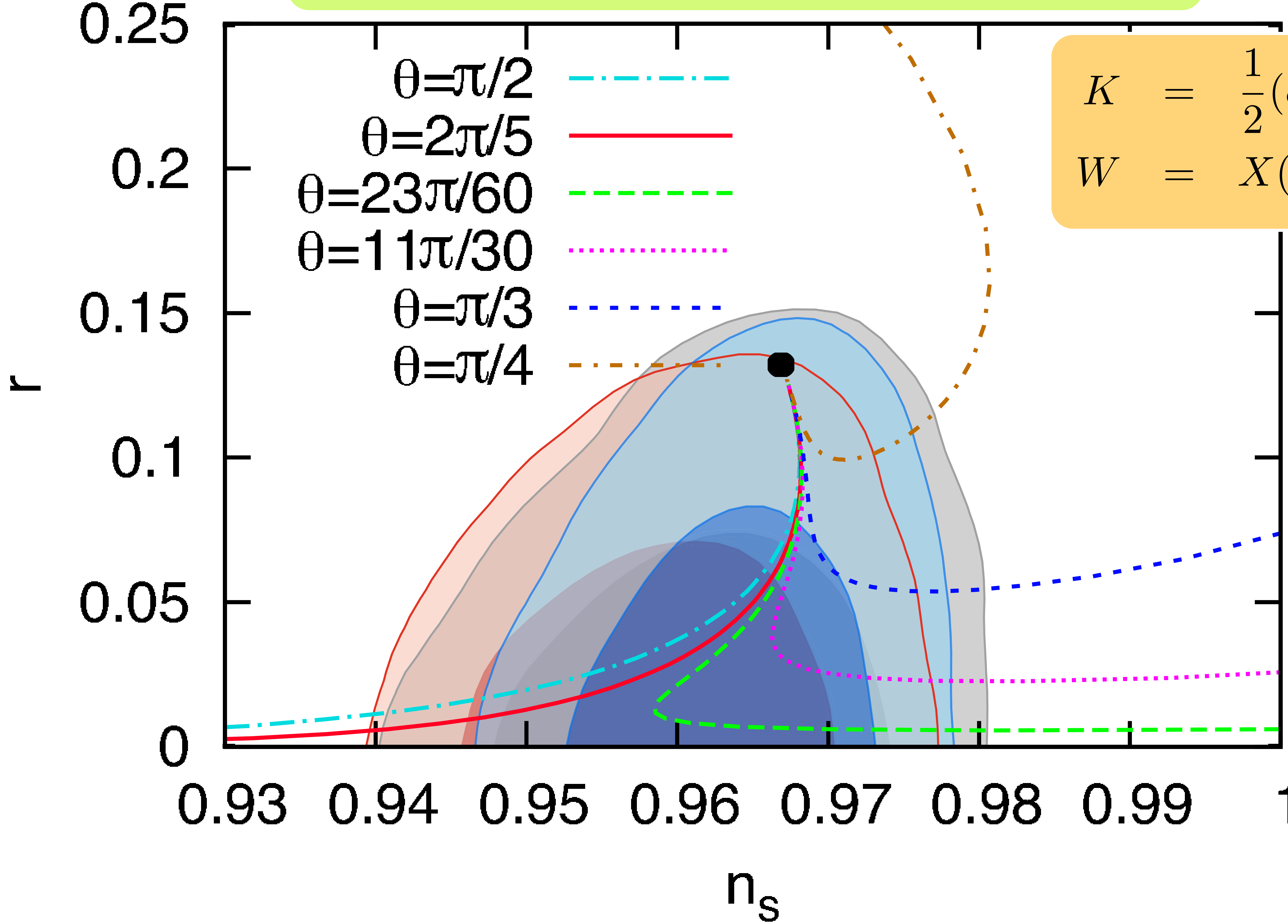


$$V \simeq \frac{1}{2}\varphi^2\left(m^2 - \sqrt{2}m\lambda\sin\theta\,\varphi + \frac{\lambda^2}{2}\varphi^2\right).$$

$$K = \frac{1}{2}(\phi + \phi^\dagger)^2$$
$$W = X(m\phi + \lambda\phi^2)$$



Nakayama, FT, Yanagida, 1303.7315, 1303.5099

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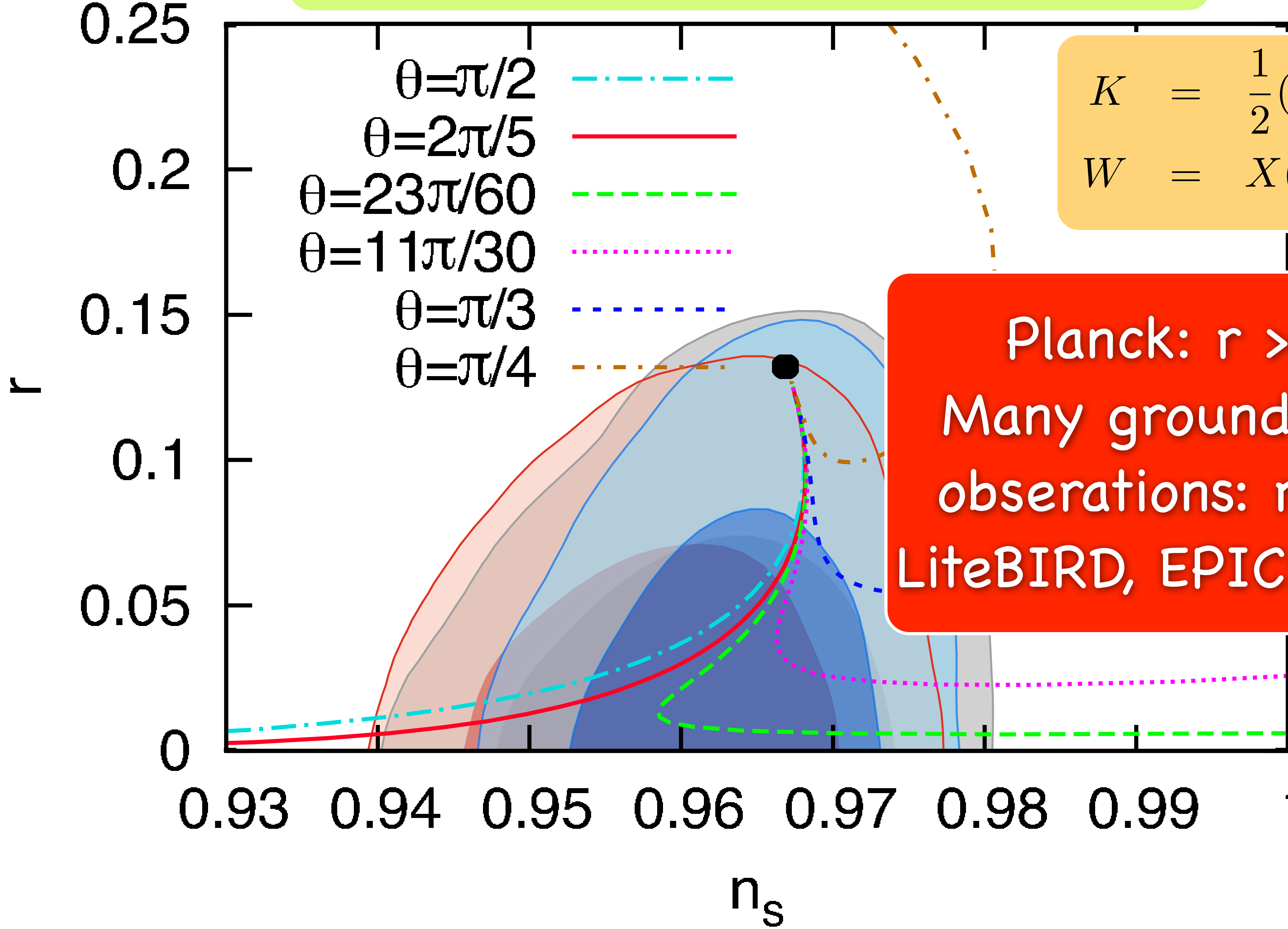


Planck: r >0.05
Many ground-based observations: r > 0.01
LiteBIRD, EPIC: r > 10^{-3}

Nakayama, FT, Yanagida, 1303.7315, 1303.5099

What if no tensor mode is detected?

- There are many low-scale inflation models (such as hybrid inflation, new inflation, etc.) and so, inflation is not excluded.
- In some case, the inflation scale can be related to the B-L breaking scale (or neutrino mass thru seesaw) and SUSY breaking scale.

B-L new inflation model

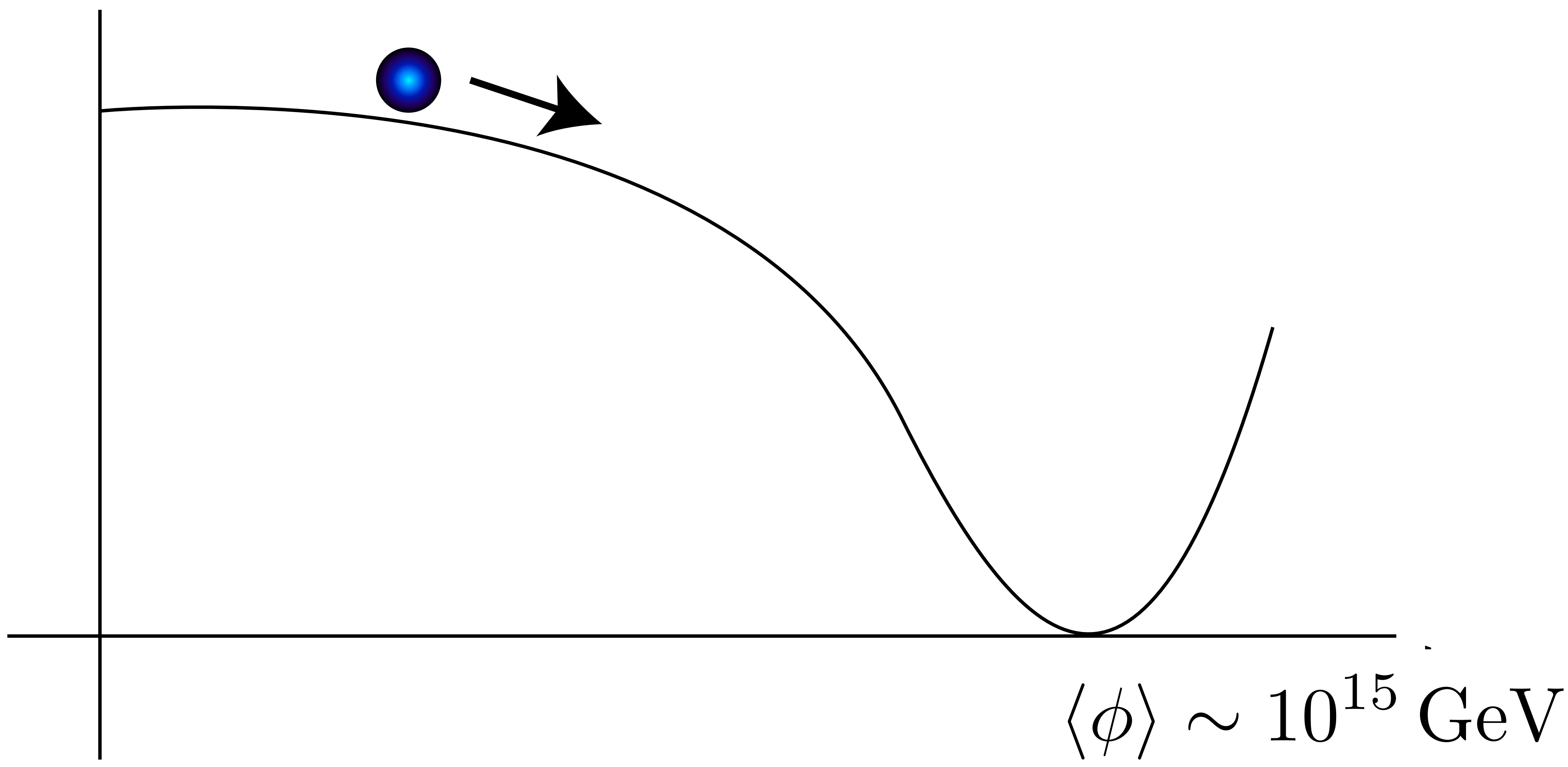
Nakayama and FT `11, `12.

$$K = |\Phi|^2 + |\bar{\Phi}|^2 + |\chi|^2 + k_3|\Phi|^2|\chi|^2 + k_4|\bar{\Phi}|^2|\chi|^2 + \cdots,$$

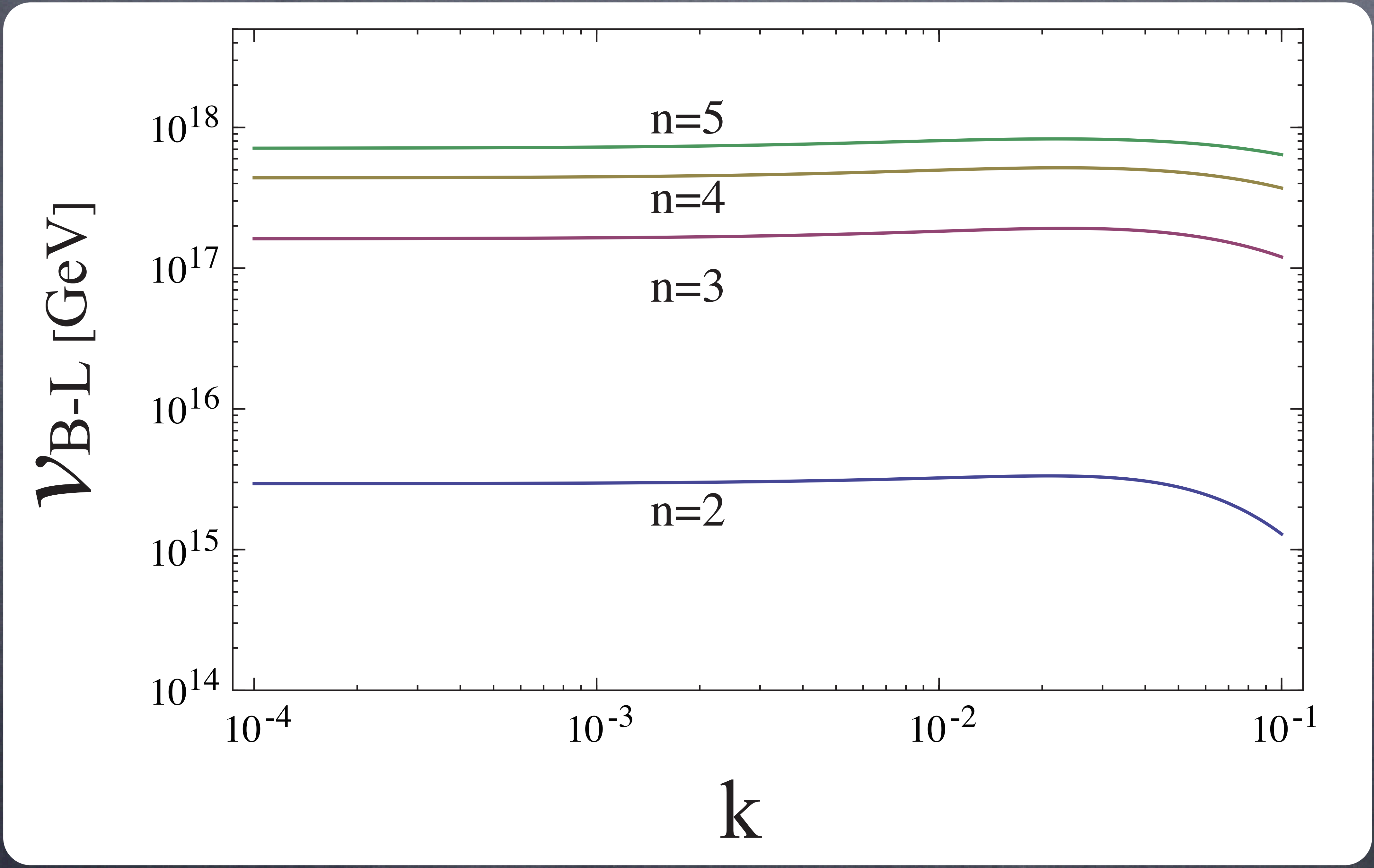
$$W = \chi\left(v^2 - g(\Phi\bar{\Phi})^n\right), \quad \phi^2 \equiv \Phi\bar{\Phi}$$

Asaka et al `99
Senoguz and Shafi, `04

$$V(\sigma) \simeq v^4 - \frac{1}{2}kv^4\sigma^2 - \frac{g}{2^{2n-1}}v^2\sigma^{2n} + \frac{g^2}{2^{4n}}\sigma^{4n}.$$



B-L breaking scale (inflaton VEV) is fixed by the COBE normalization.



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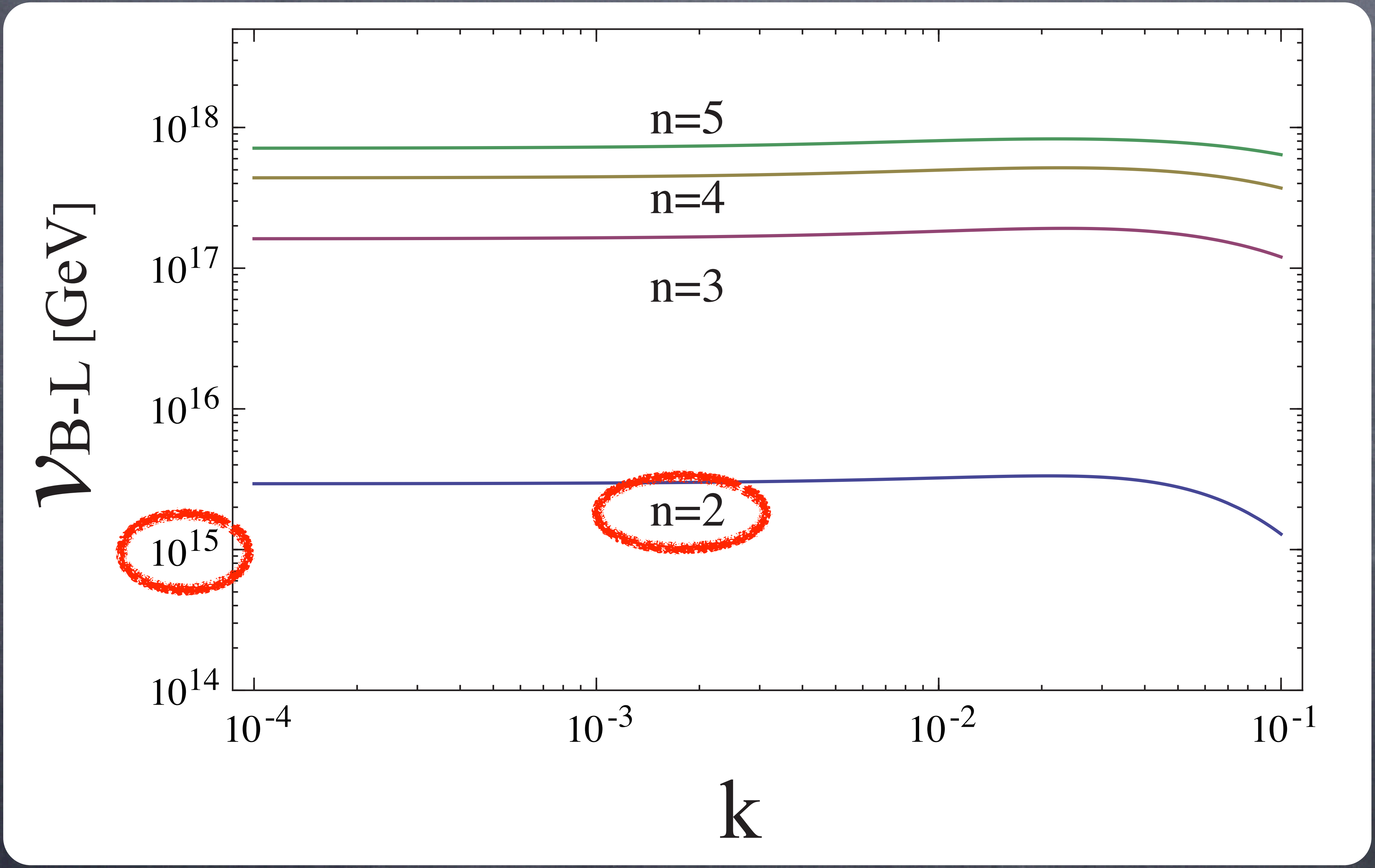

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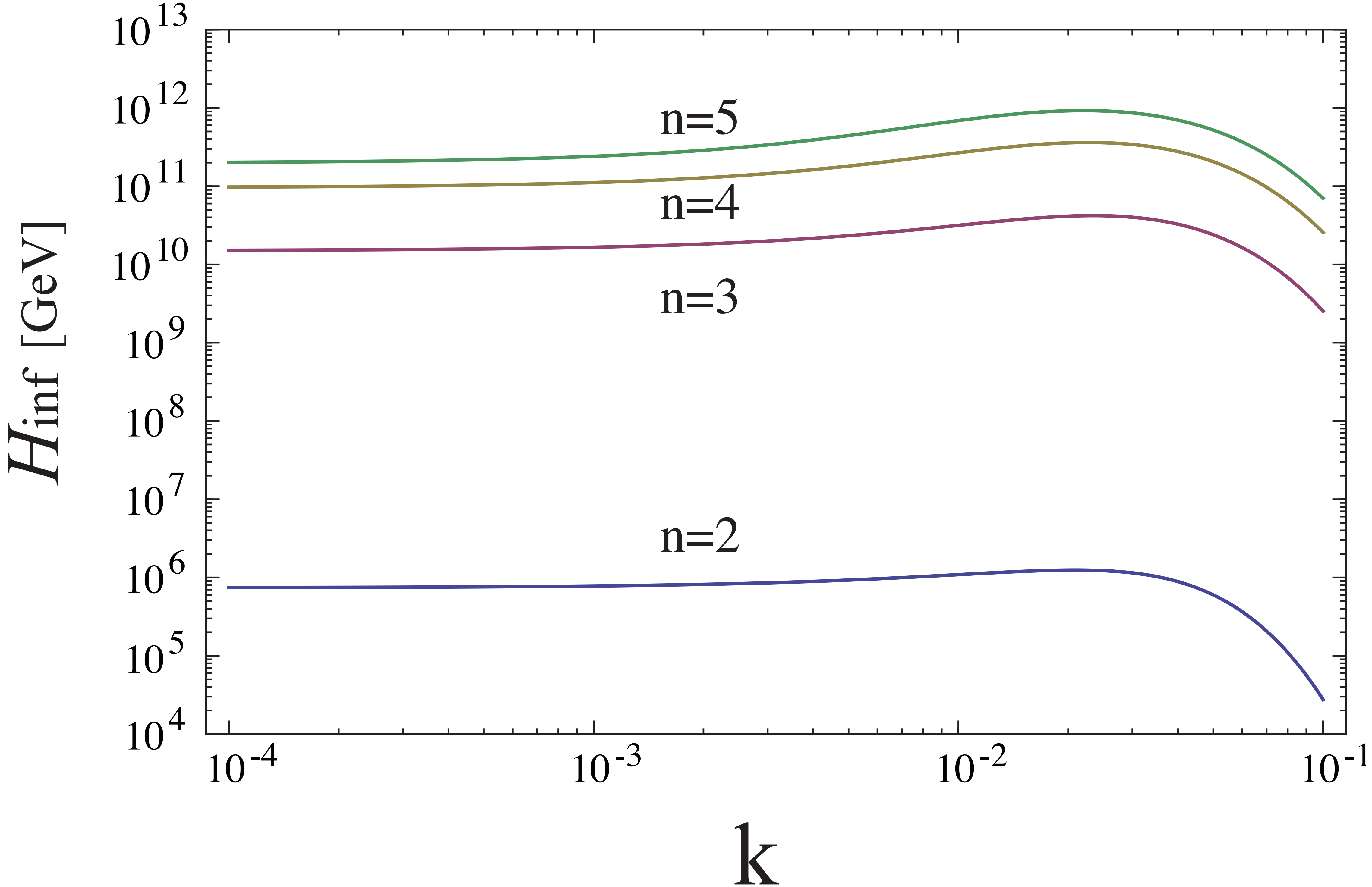
Inflation scale



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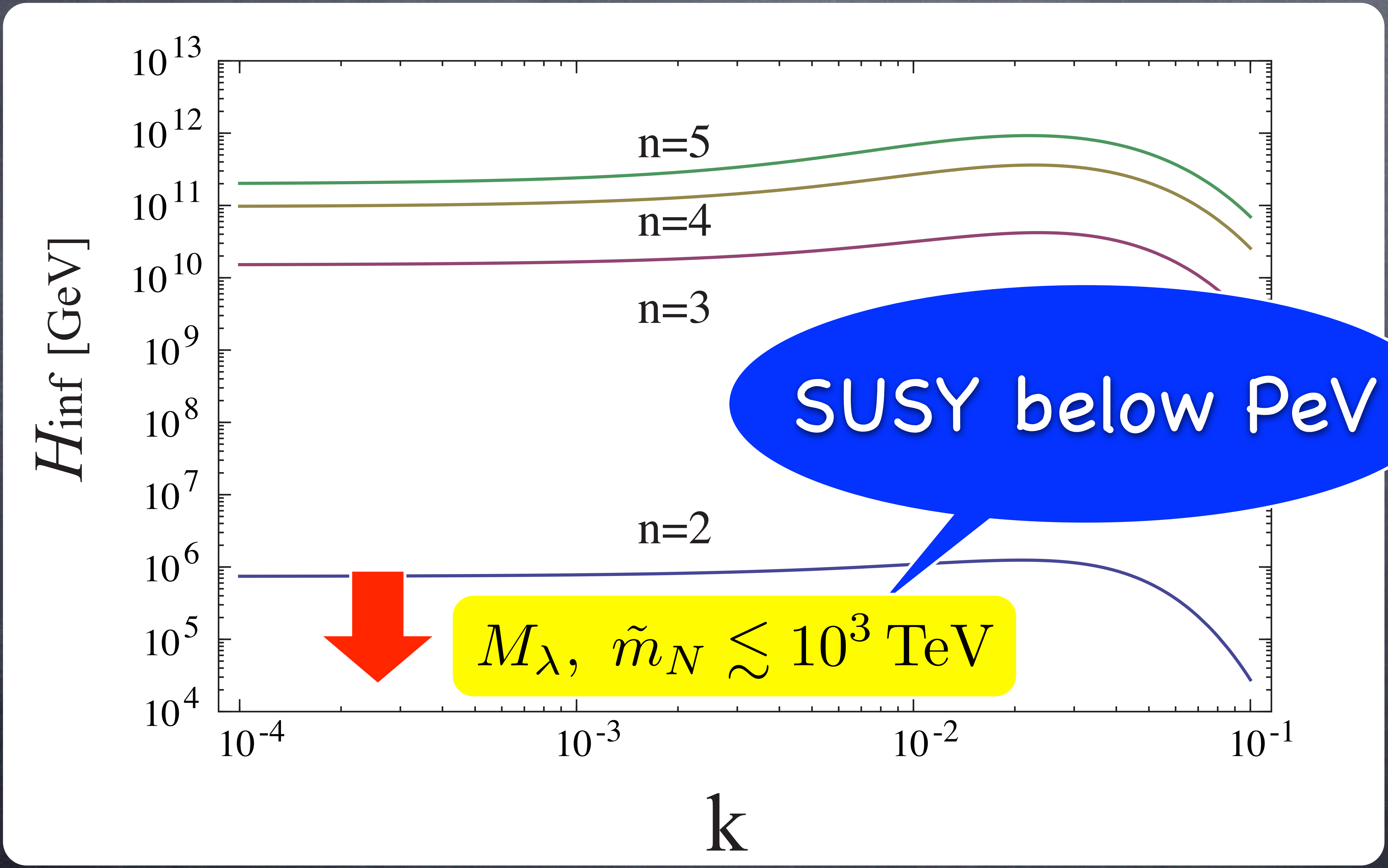
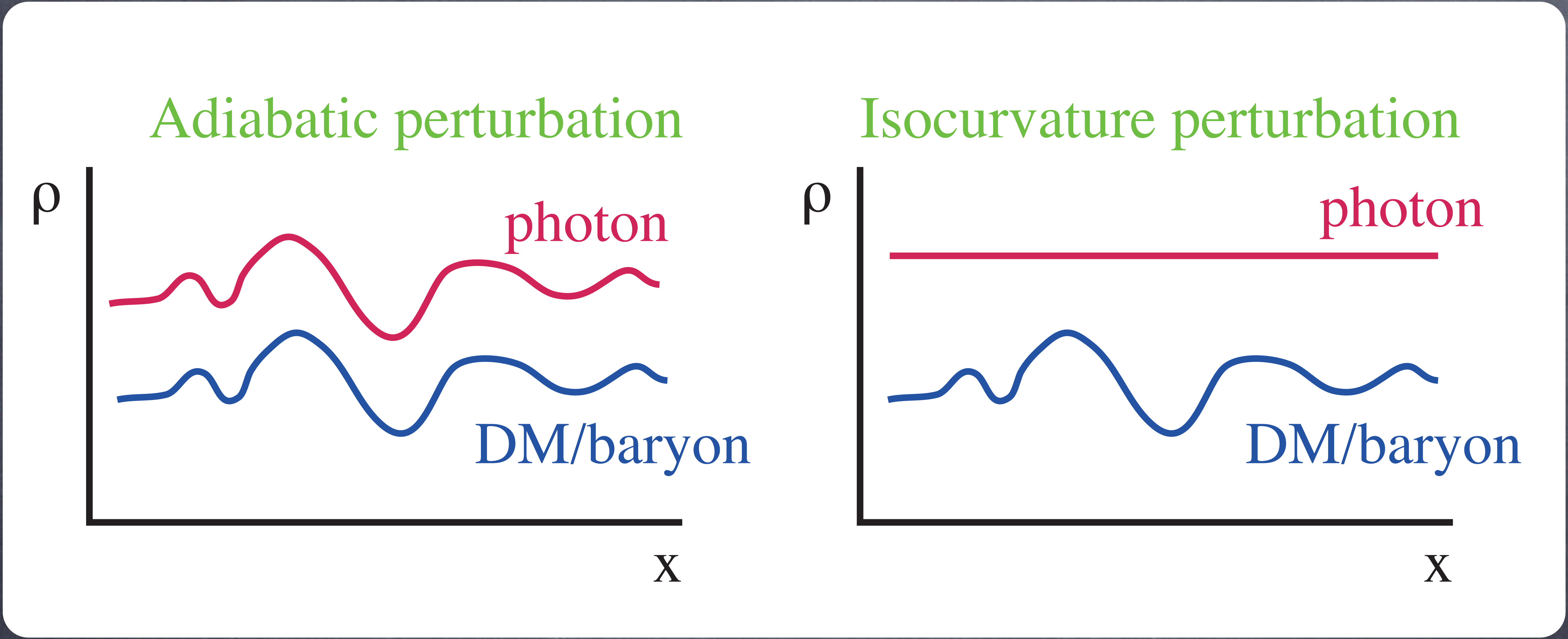


Nakayama and FT `11, `12.

2. Isocurvature perturbations

There are actually two kinds of scalar perturbations.

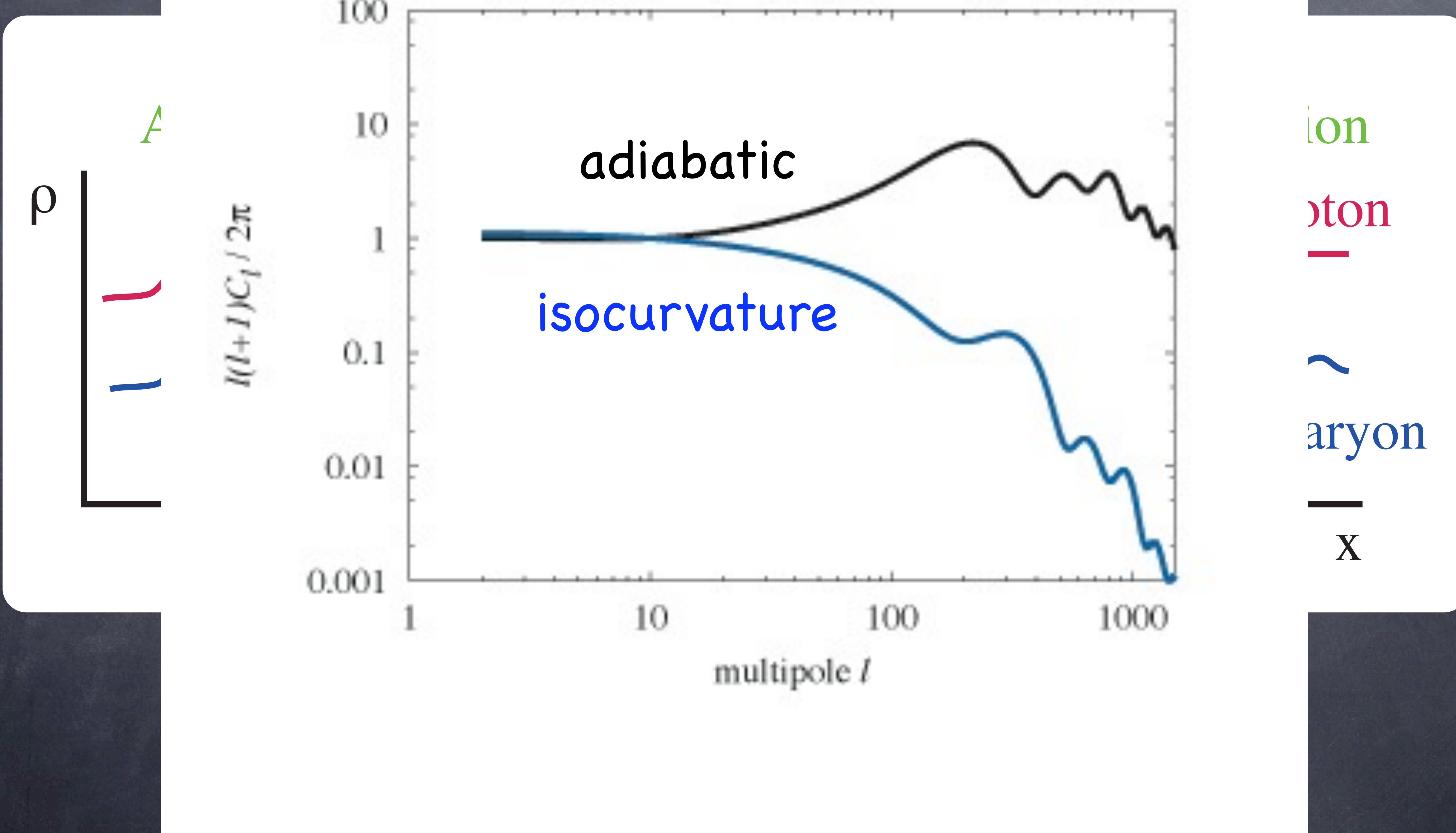


ζ $\qquad$ S

Curvature perturbation $\qquad$ Isocurv. perturbation

2. Isocurvature perturbations

Th… …ns.



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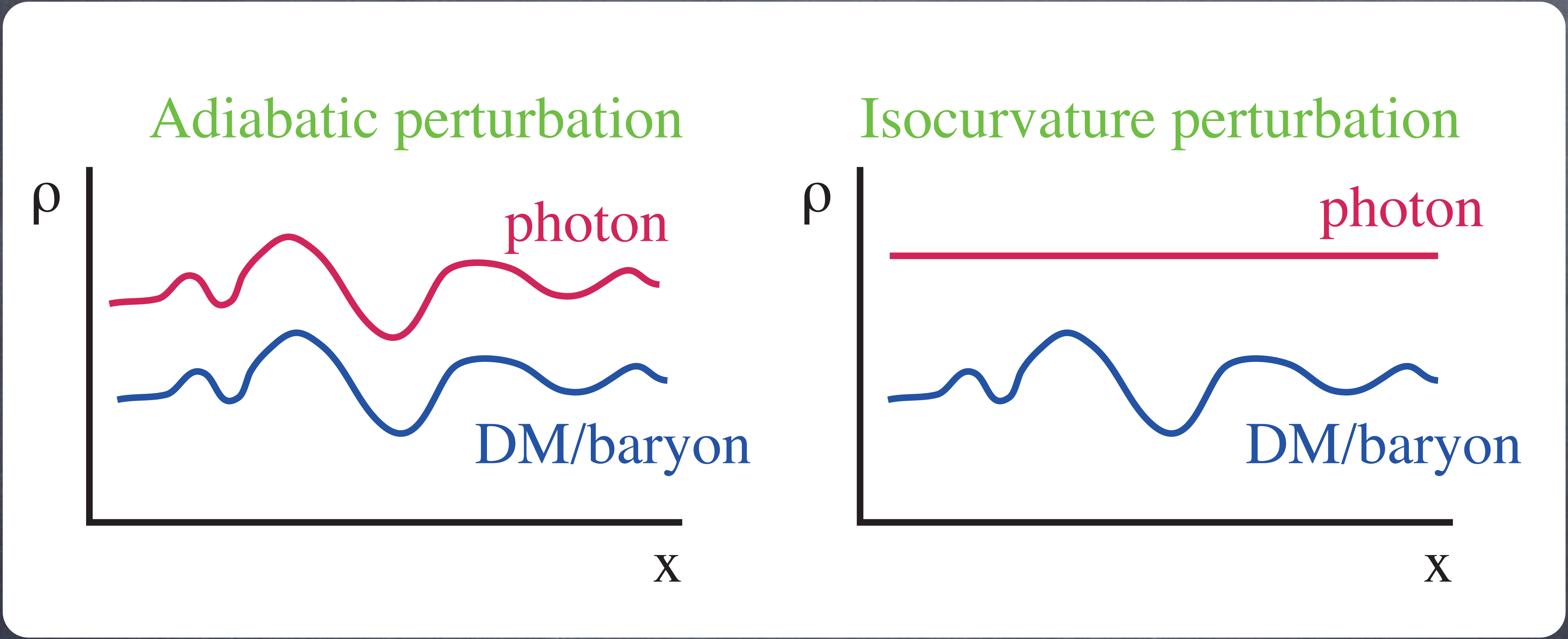

$$\zeta \qquad\qquad S$$

Curvature perturbation   Isocurv. perturbation

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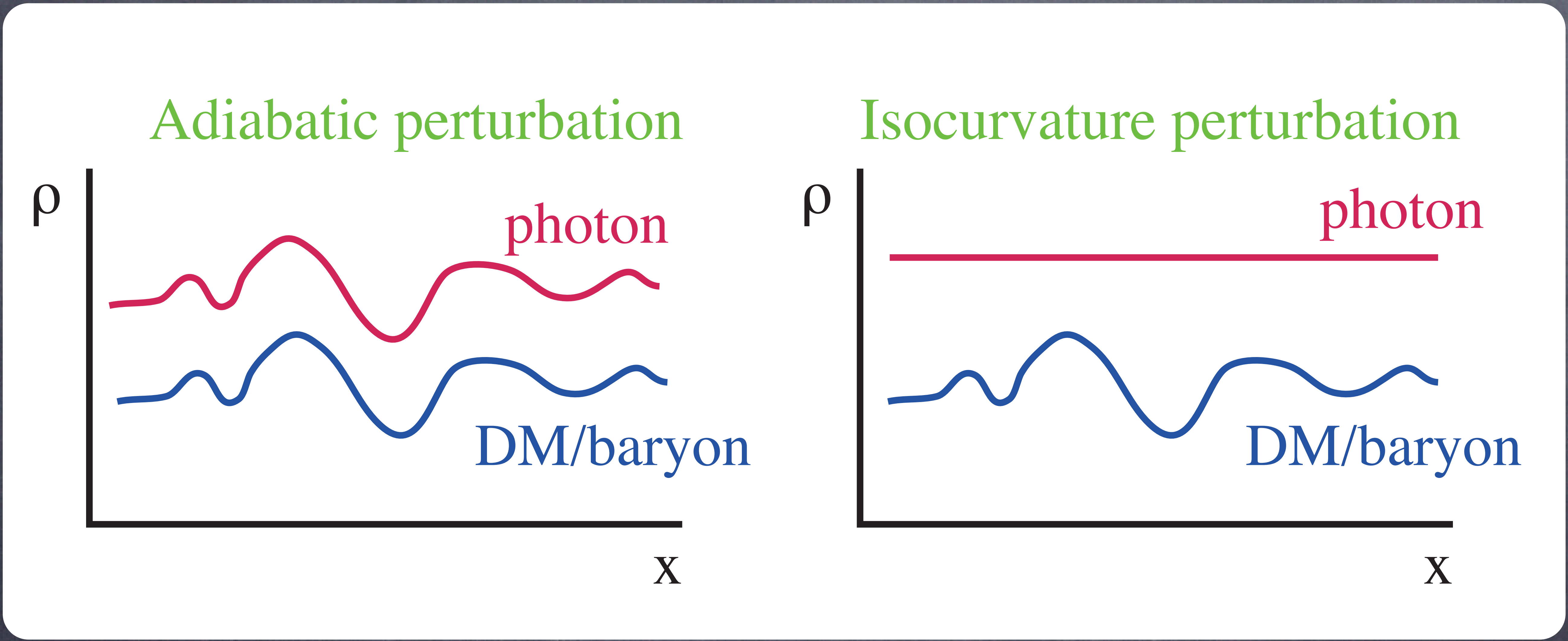
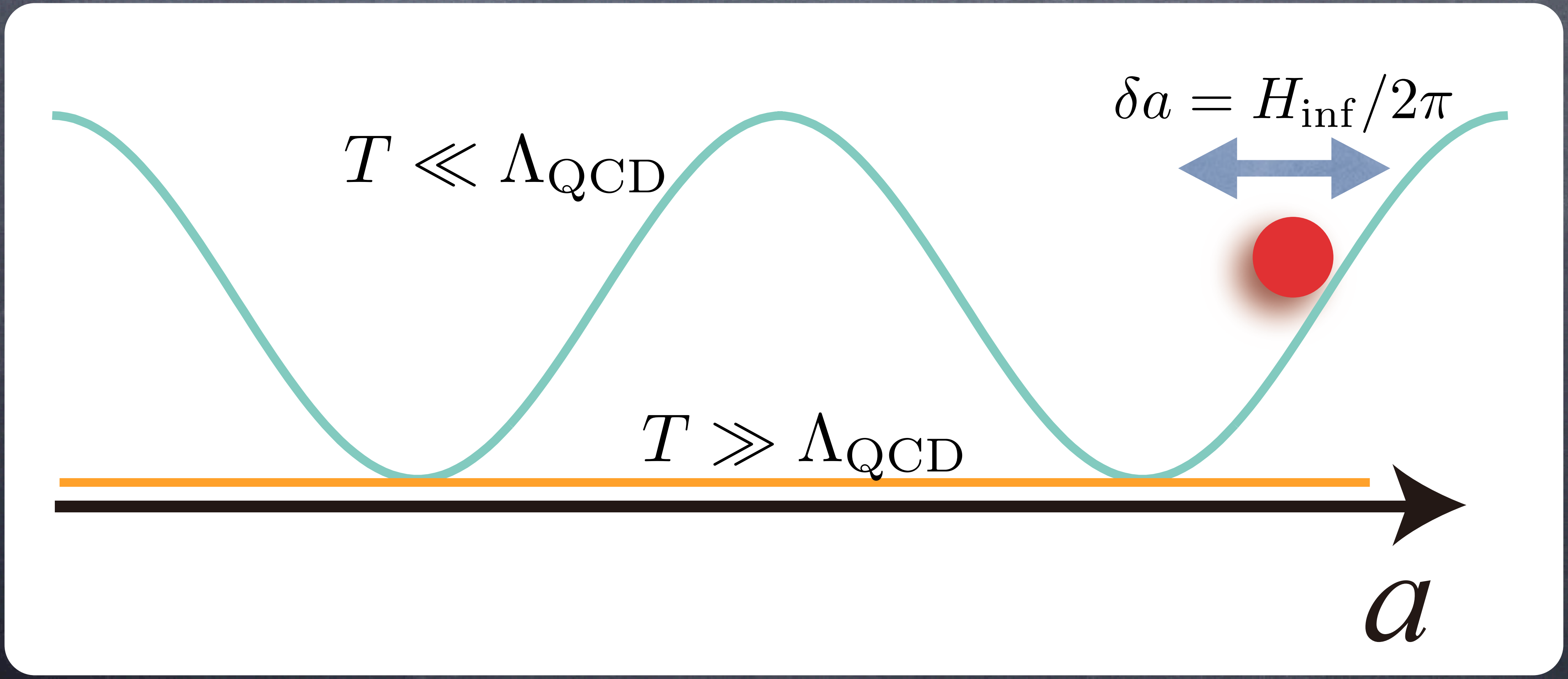


$$\alpha \equiv \frac{P_S}{P_\zeta} \lesssim 0.041 \quad (95\%\,\mathrm{C.L.})$$

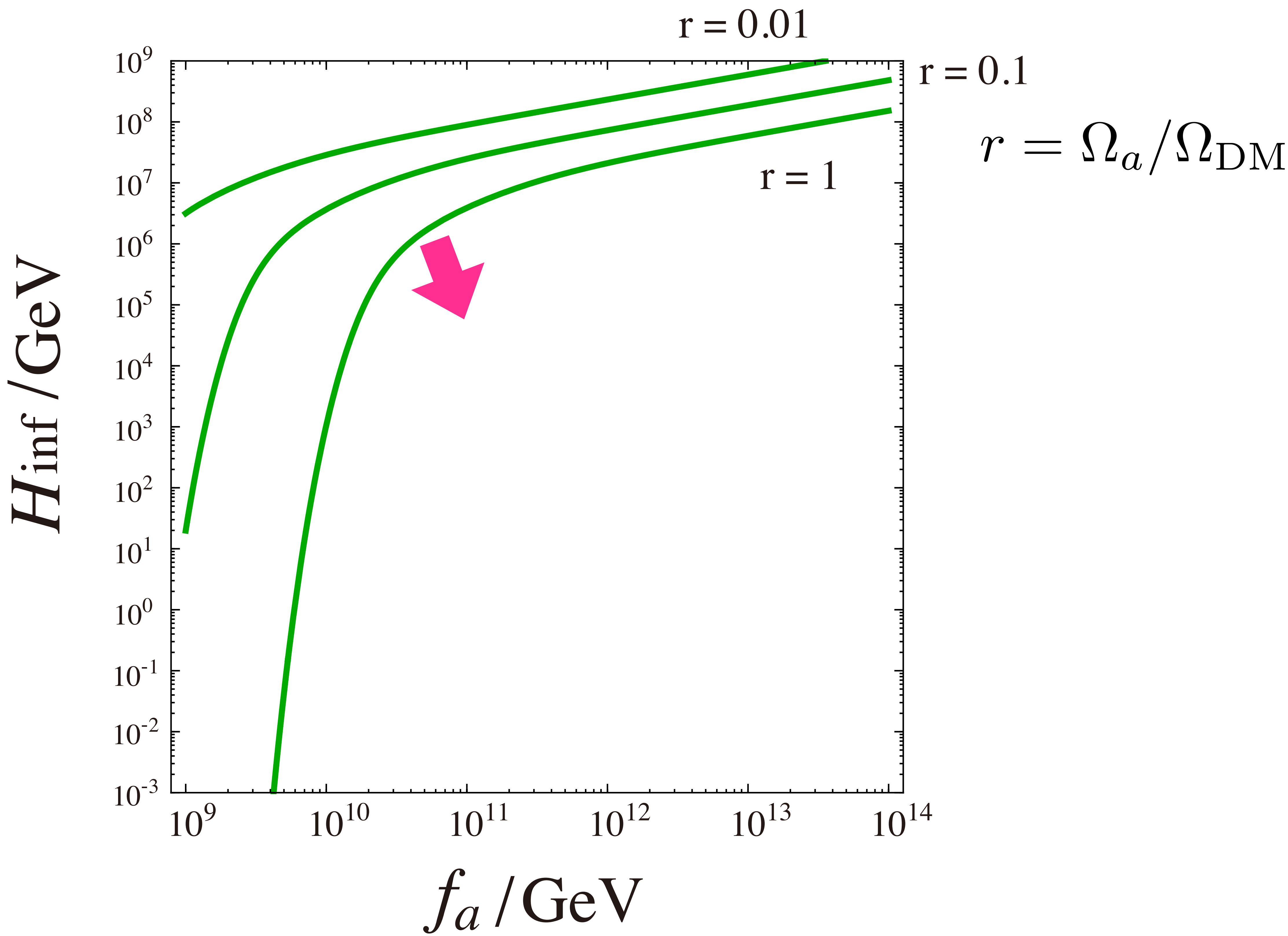
Planck +WMAP pol.

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

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



Isocurvature constraint on H_{inf}



Kobayashi, Kurematsu, FT, 1304.0922

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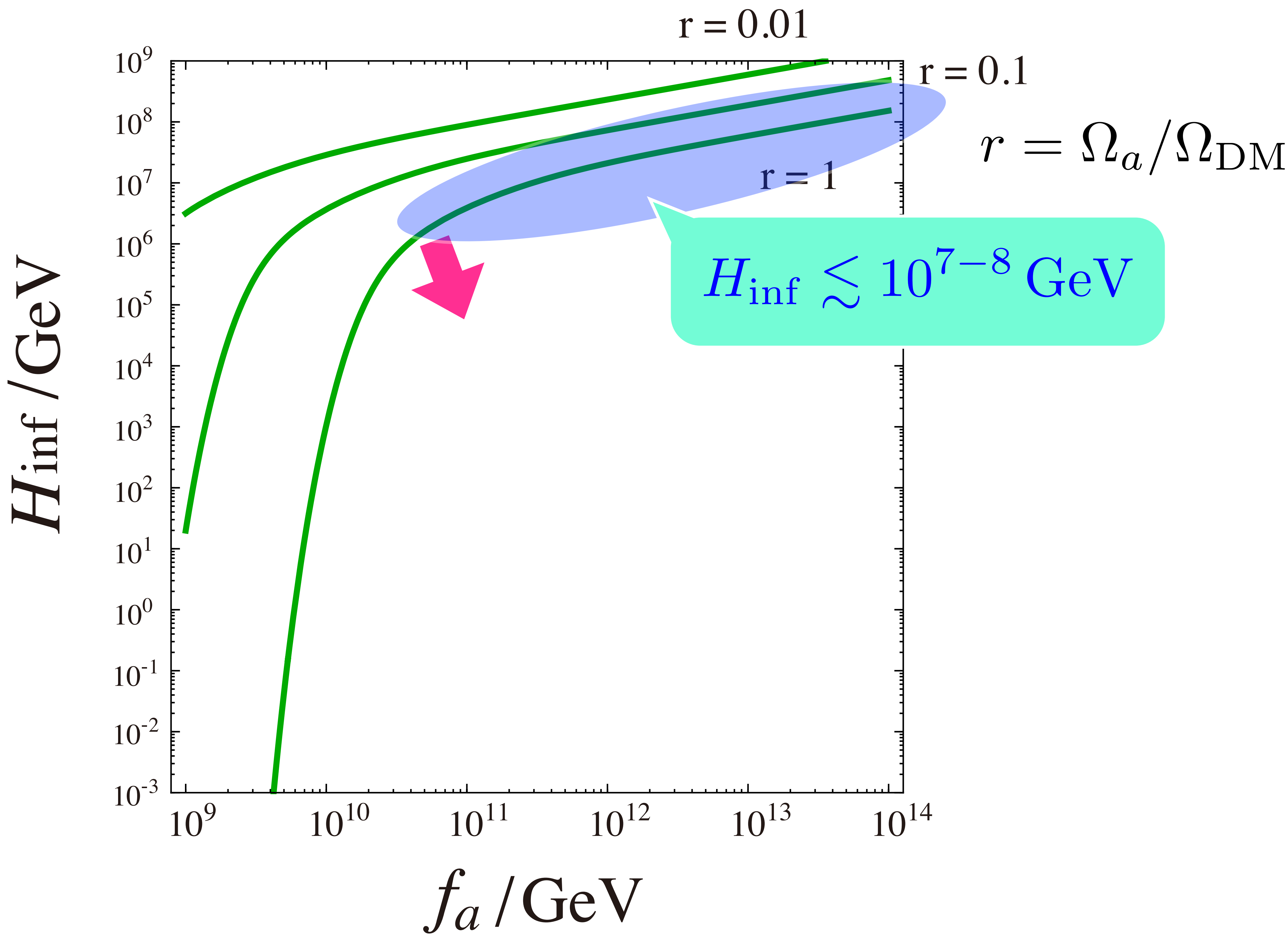

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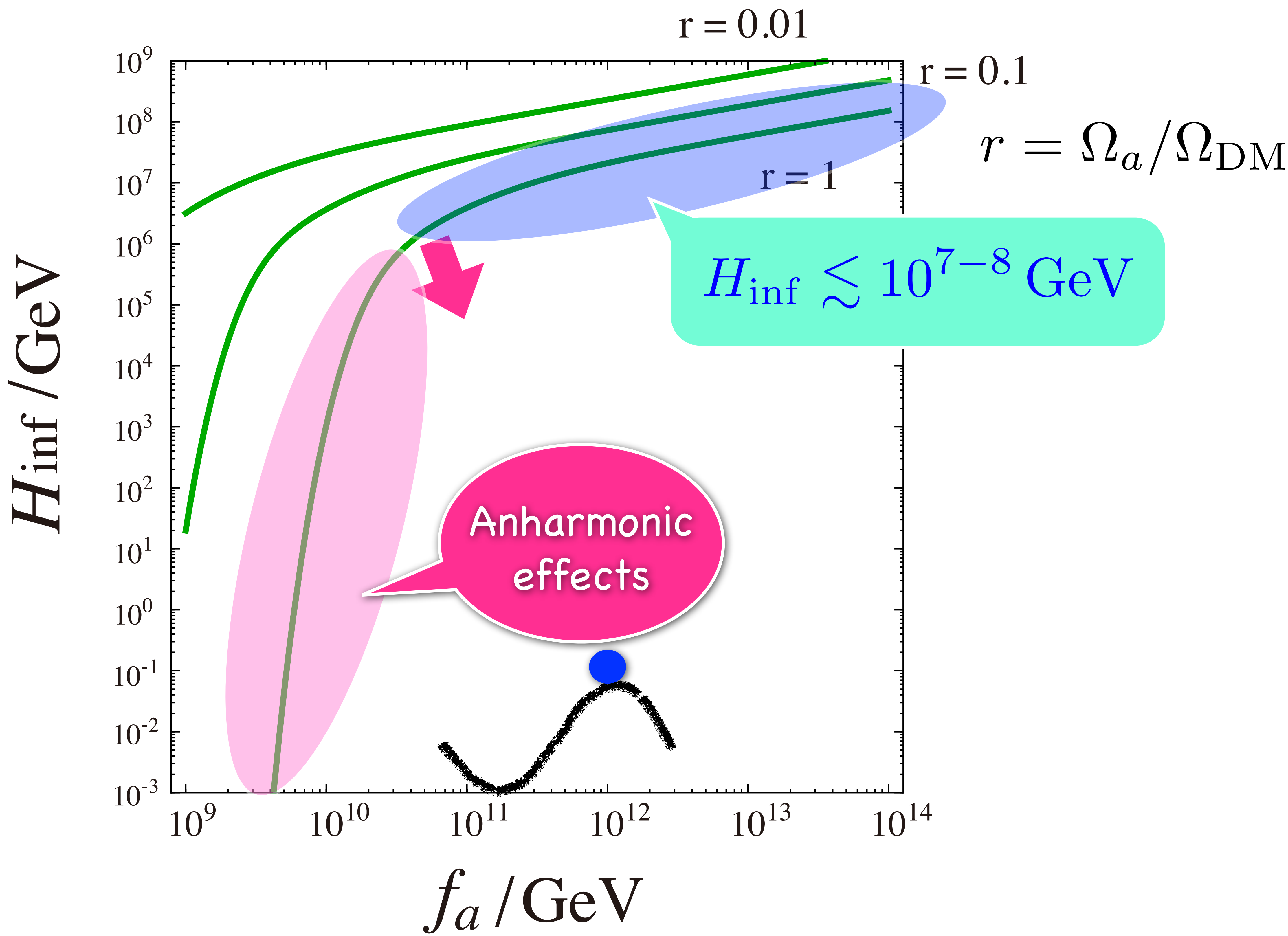
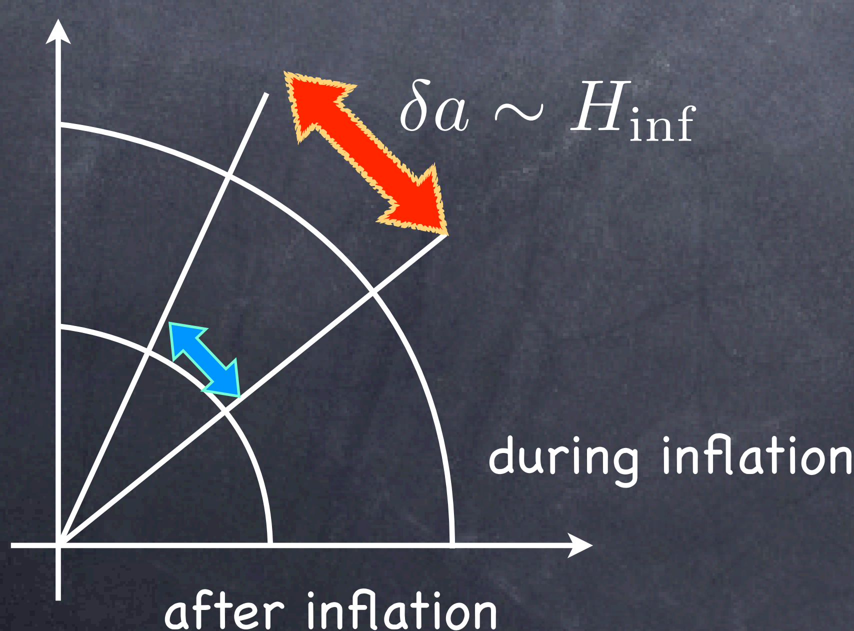


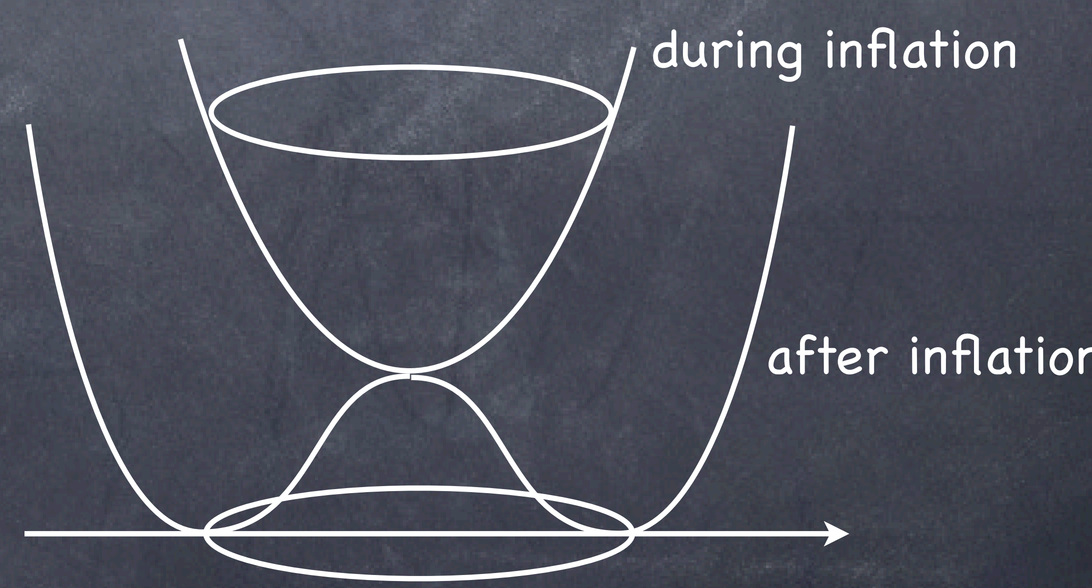
Kobayashi, Kurematsu, FT, 1304.0922

If the tensor mode is discovered (i.e. $H_{inf} = 10^{13-14}$GeV), the axion DM is excluded?

There are a couple of ways to avoid the bound.

1. Large VEV of the PQ scalar during inflation.
   Linde, Lyth (1990) Linde (1991)
2. The restoration of PQ symmetry.
   Linde, Lyth (1990) Lyth, Stewart (1992)
3. Stronger QCD in the early Universe.
   K-S. Jeong, FT, 1304.8131





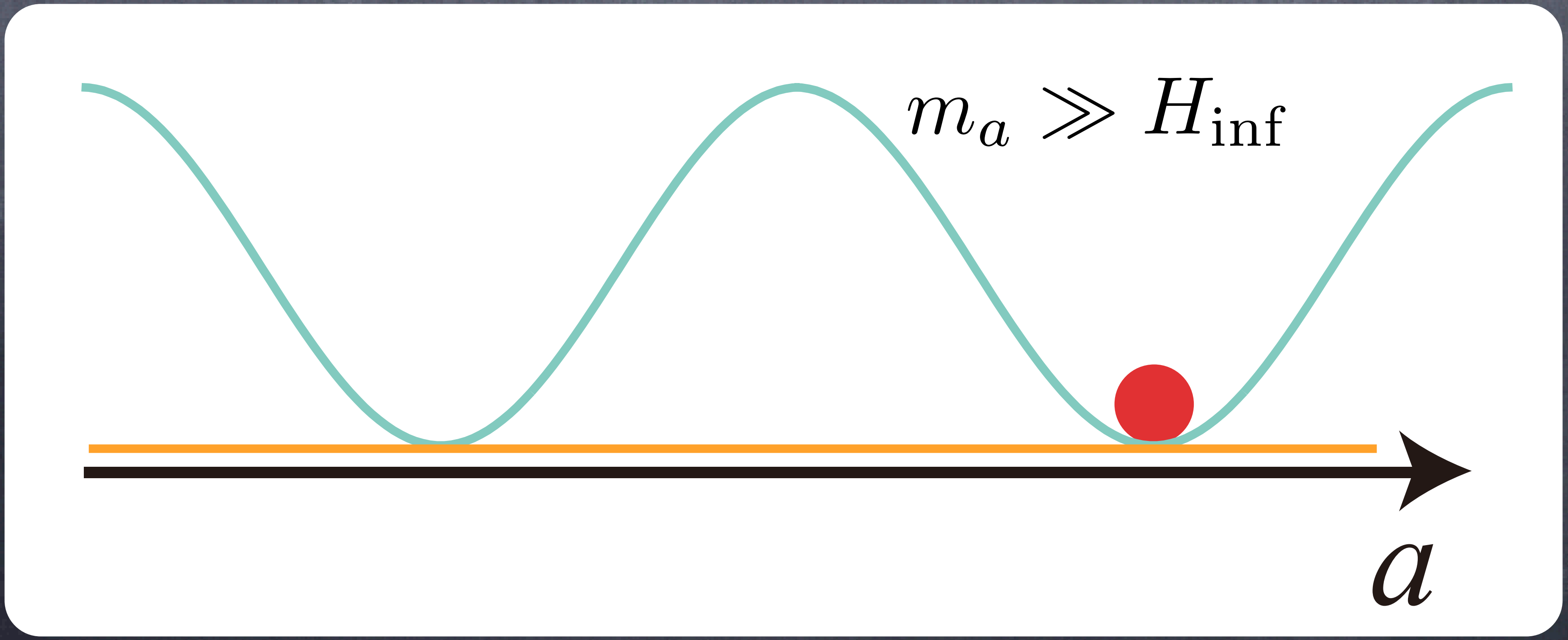
Stronger QCD in the early Universe

K-S. Jeong, FT, 1304.8131

If the QCD interactions are strong during inflation, the axion is more massive than at present.

cf. Dvali `95, K. Choi, H. B. Kim and J. E. Kim `96, Banks and Dine `96

If $m_a > H_{\rm inf}$, it does not acquire sizable quantum fluctuations at super-horizon scales, suppressing axion isocurvature perturbations.



Suppose that the H_uH_d flat direction of SUSY SM has a negative Hubble-induced mass and stabilized at around the GUT scale (or larger).

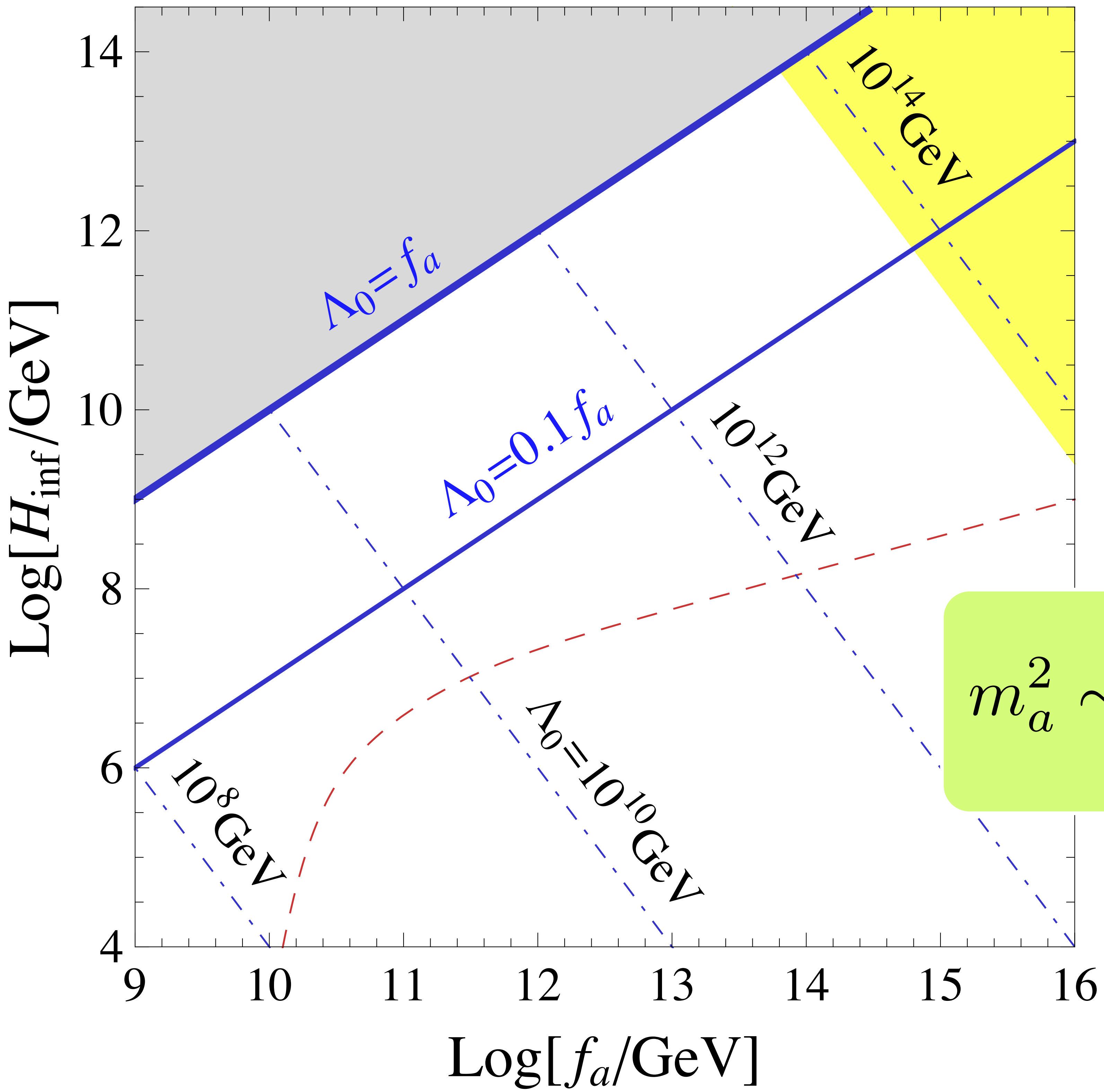
$$W = \frac{\phi^4}{M} \qquad \phi^2 = H_u H_d$$

If the effective QCD scale Λ_h is higher than the inflation scale $H_{\rm inf}$, the gluino condensation is formed;

$$W_{\rm np} = N_c \Lambda_0^3 \propto e^{-8\pi^2 f_h/N_c},$$

where the gauge kinetic function for SU(3)c:

$$f_h = ({\rm constant}) - \frac{n}{8\pi^2}\ln S - \frac{N_f}{8\pi^2}\ln\phi,$$
$$N_c = 3, \quad N_f = 6$$

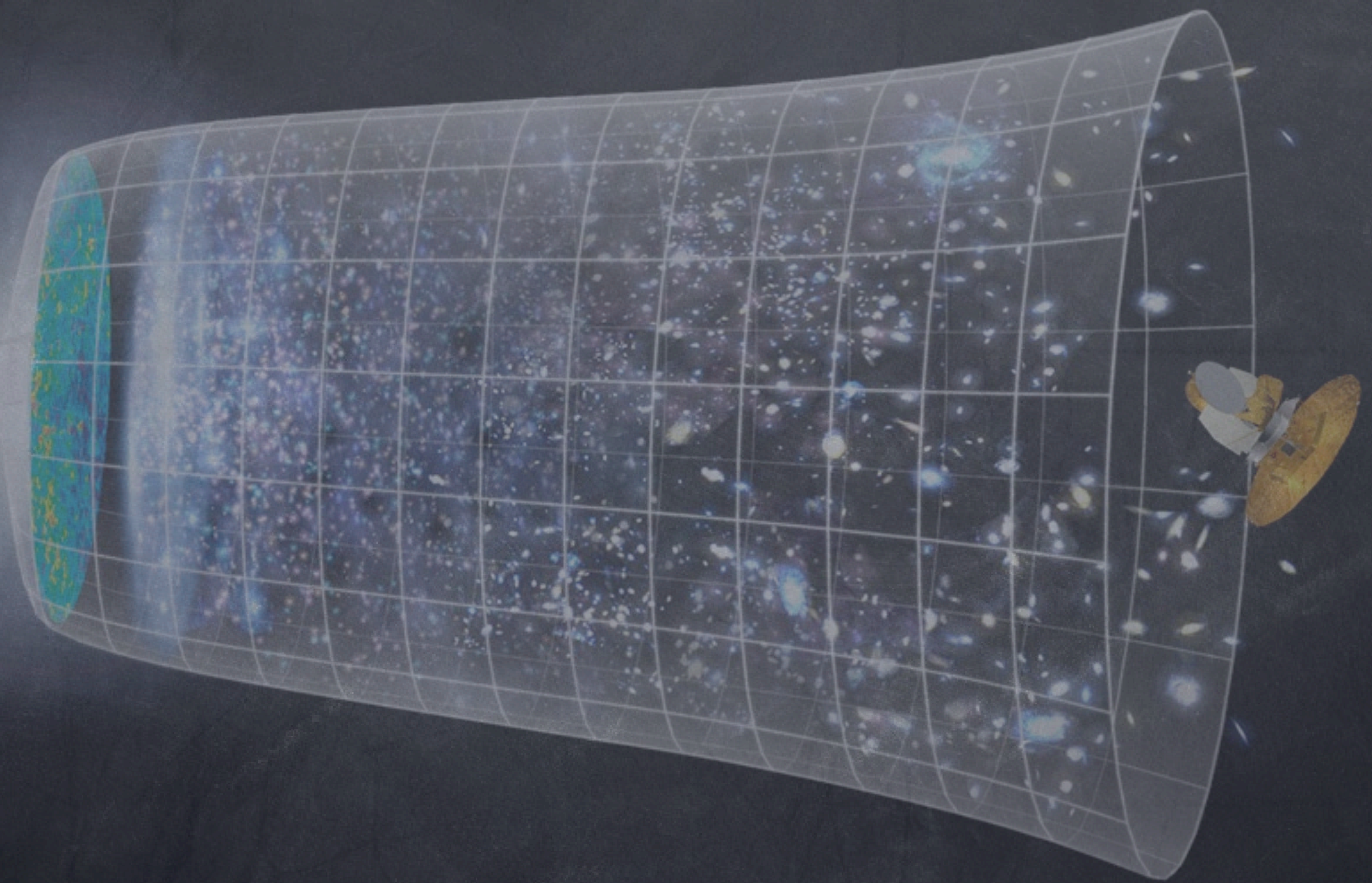


$$m_a^2 \sim \frac{H_{\rm inf}\Lambda_0^3}{f_a^2}$$

3. Dark radiation

Dark radiation = Extra relativistic degrees of freedom

Cosmic pie chart

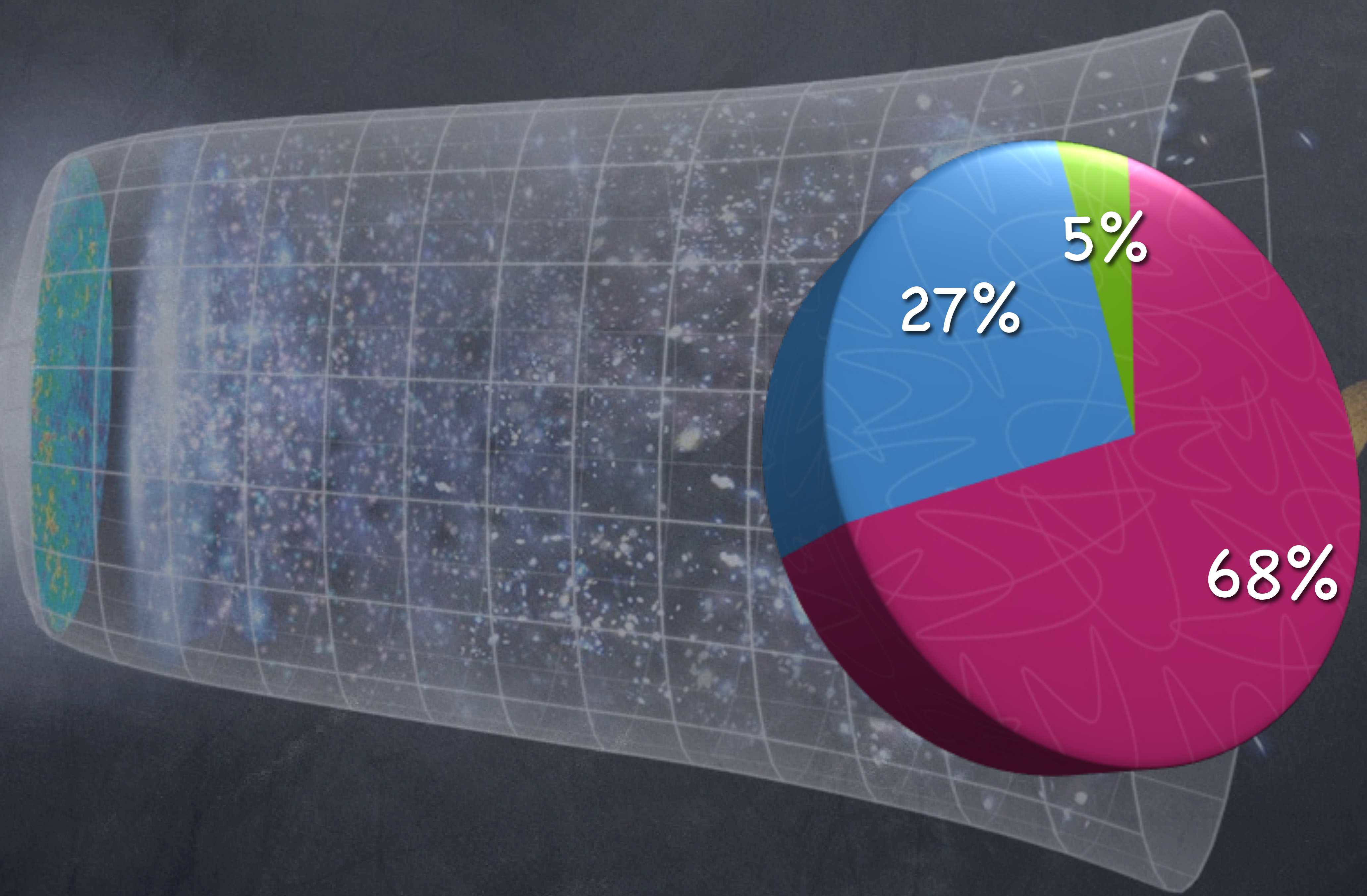


13.7billion years ago
(Universe 380,000 years old)

Today

NASA/WMAP Science Team

Cosmic pie chart



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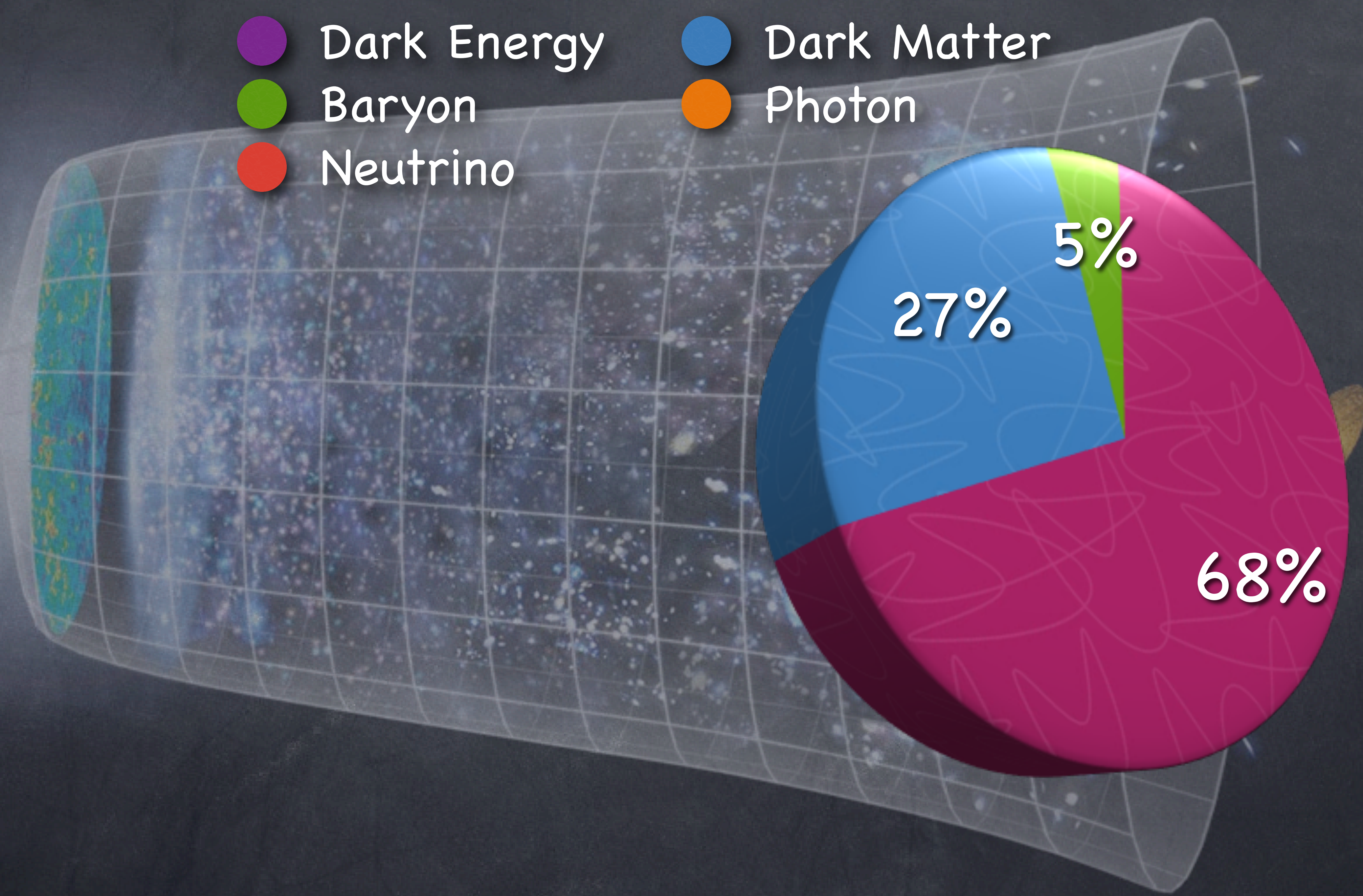

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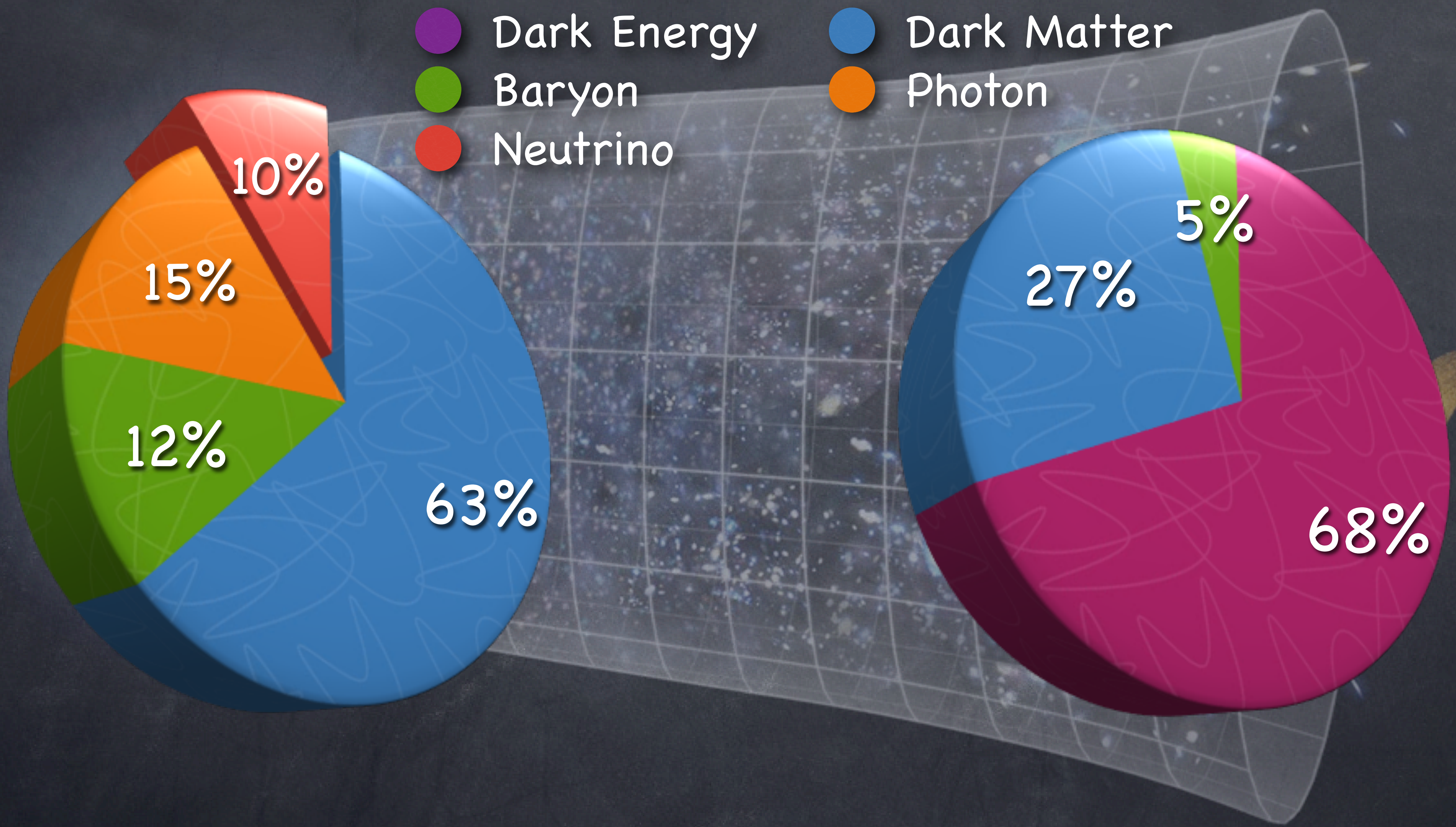

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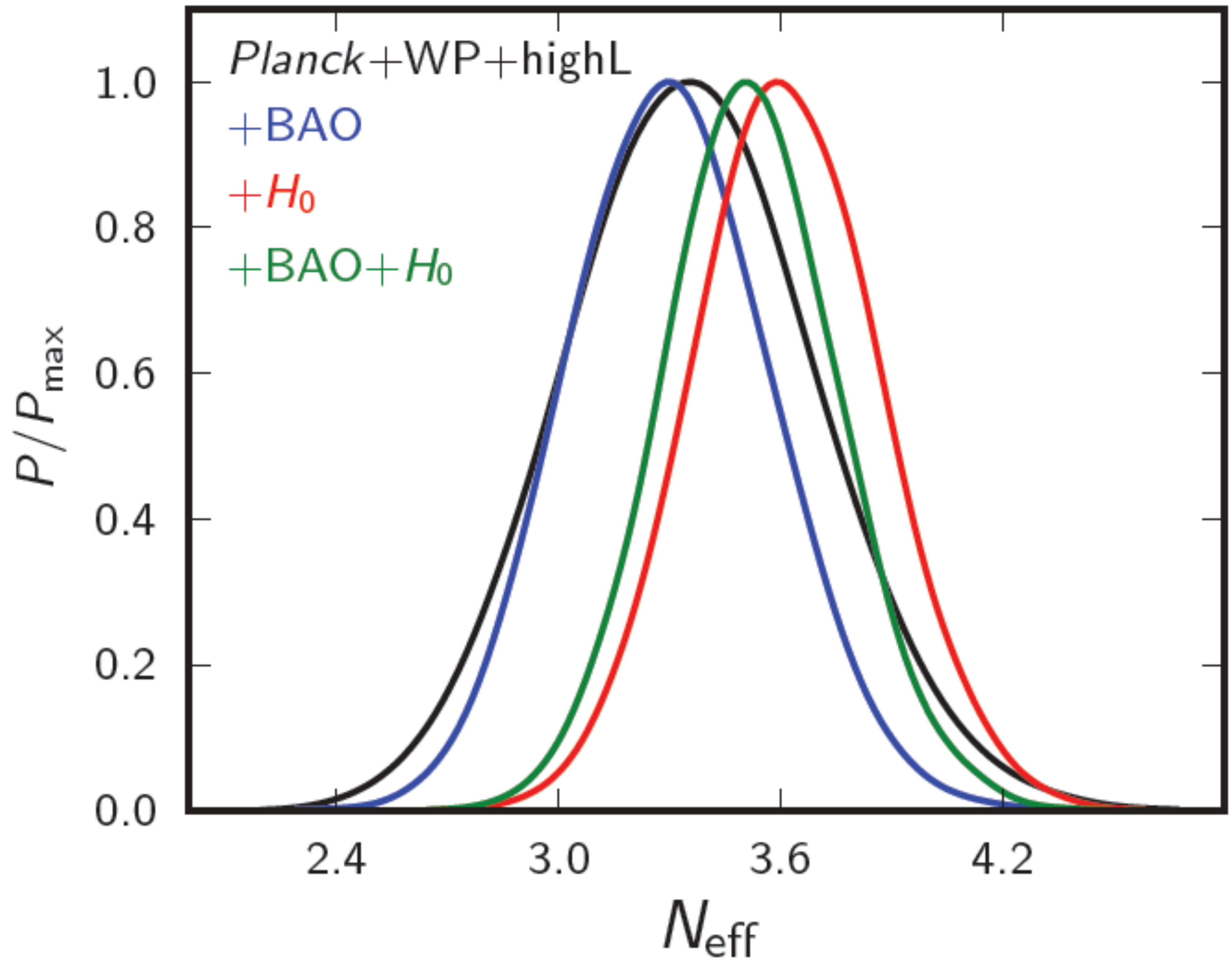
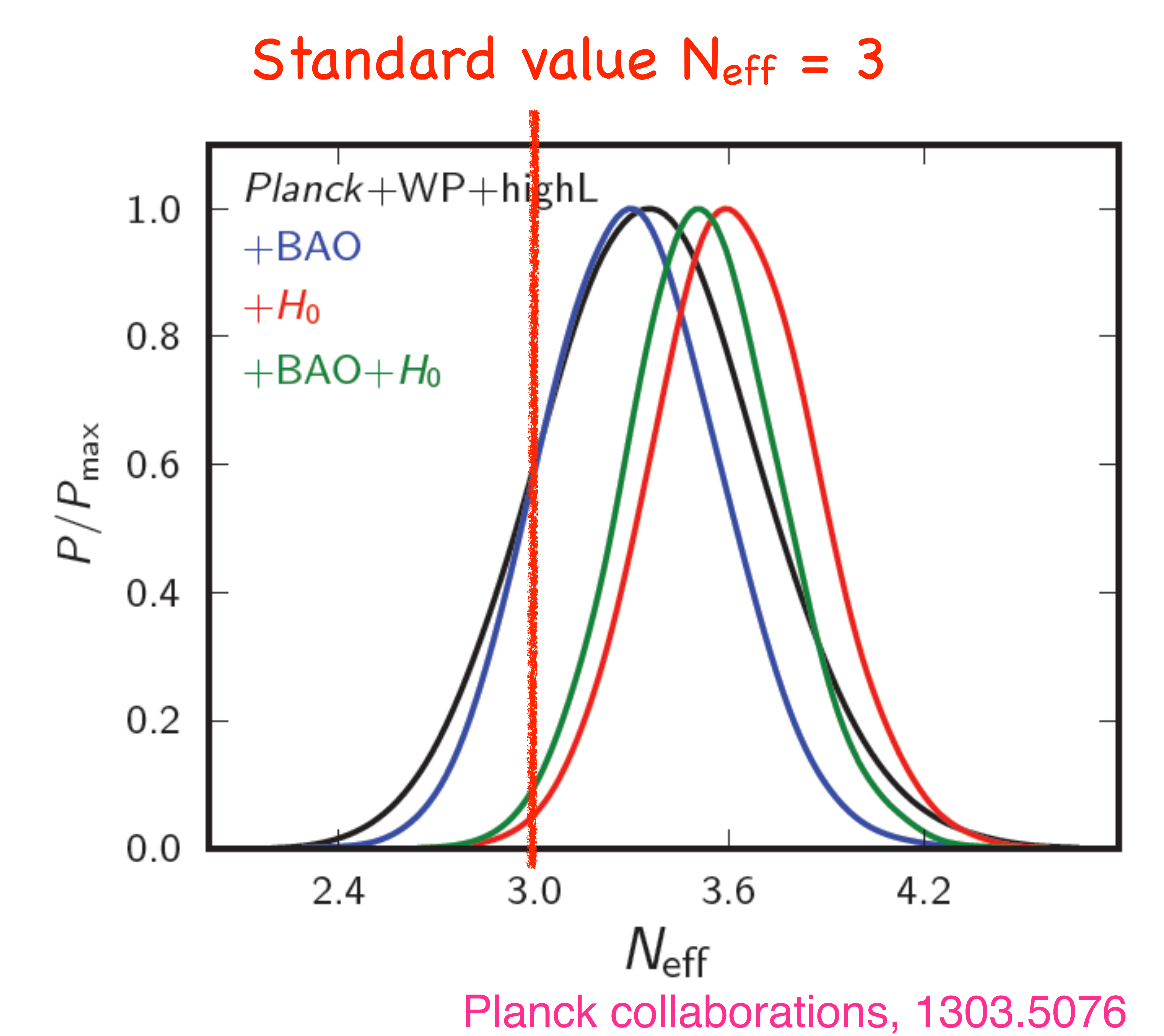
DR contributes to the effective number of neutrino species

$$N_{\rm eff} = 3.046 + \Delta N_{\rm eff}$$

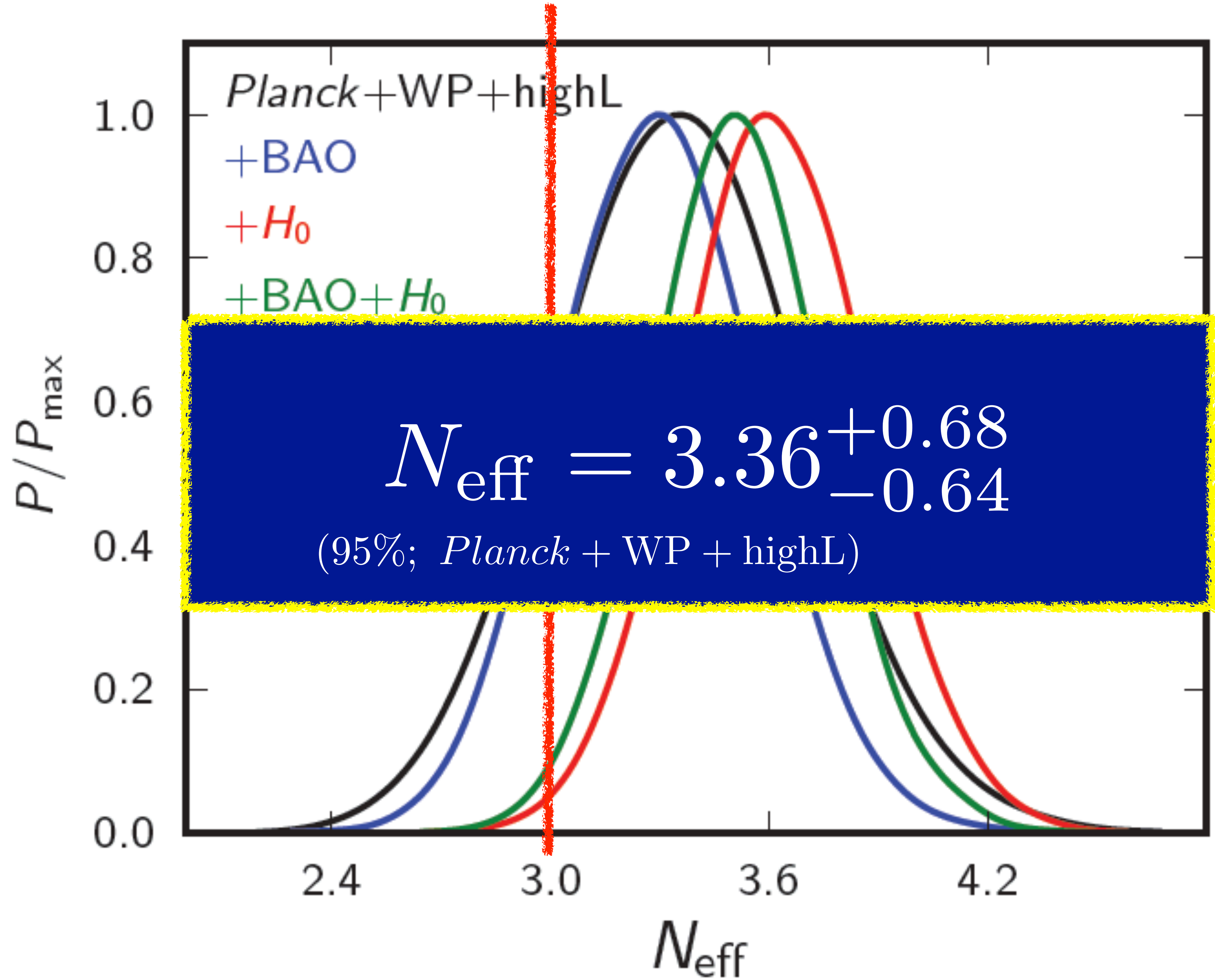


Planck collaborations, 1303.5076



Standard value N_{eff} = 3
Planck+WP+highL
+BAO
+H_0
+BAO+H_0
1.0
0.8
0.6
0.4
0.2
0.0
P/P_{max}
2.4
3.0
3.6
4.2
N_{eff}
Planck collaborations, 1303.5076

Standard value $N_{eff} = 3$



$$N_{\rm eff} = 3.36^{+0.68}_{-0.64}$$

(95%; *Planck* + WP + highL)

Planck collaborations, 1303.5076

Let us introduce new light degrees of freedom to account for dark radiation. Then there are two questions that immediately arise.

1. Why relativistic at the recombination epoch?
2. Why $\Delta N_{\rm eff} \sim 0.3$?

Thermal production

Nakayama, FT, Yanagida (2010)
S. Weinberg (2013) K-S. Jeong, FT (2013)

✓ $m \lesssim 0.1\,\mathrm{eV}$ ⟶ Symmetry forbidding the mass.

(i) Gauge symmetry, (ii) Chiral symmetry, (iii) Shift symmetry

gauge bosons chiral fermions NG bosons

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✓ $\Delta N_{\mathrm{eff}} = \mathcal{O}(0.1 - 1)$ is natural.

$$\Delta N_{\mathrm{eff}} = \left(\frac{8}{7} N_g + N_f + \frac{4}{7} N_{\mathrm{GB}}\right) \left(\frac{g_{*\nu}}{g_{*\mathrm{dec}}}\right)^{4/3},$$

$$g_{*\nu} = 10.75 \qquad g_{*\mathrm{dec}} = 10.75 \sim 106.75$$

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✓ Relatively strong coupling with the SM sector.

Non-thermal production

Ichikawa et al `07, many others.

- ✓ Decay of heavy fields like inflaton, moduli (saxion), gravitino.

- ✓ Non-trivial to explain the abundance.
  Often overproduced.

“Moduli-induced axion problem”
Higaki, Nakayama, FT 1304.7987

- ✓ Almost decoupled from the SM. Difficult to probe?

See Conlon and Marsh
1304.1804, 1305.3603

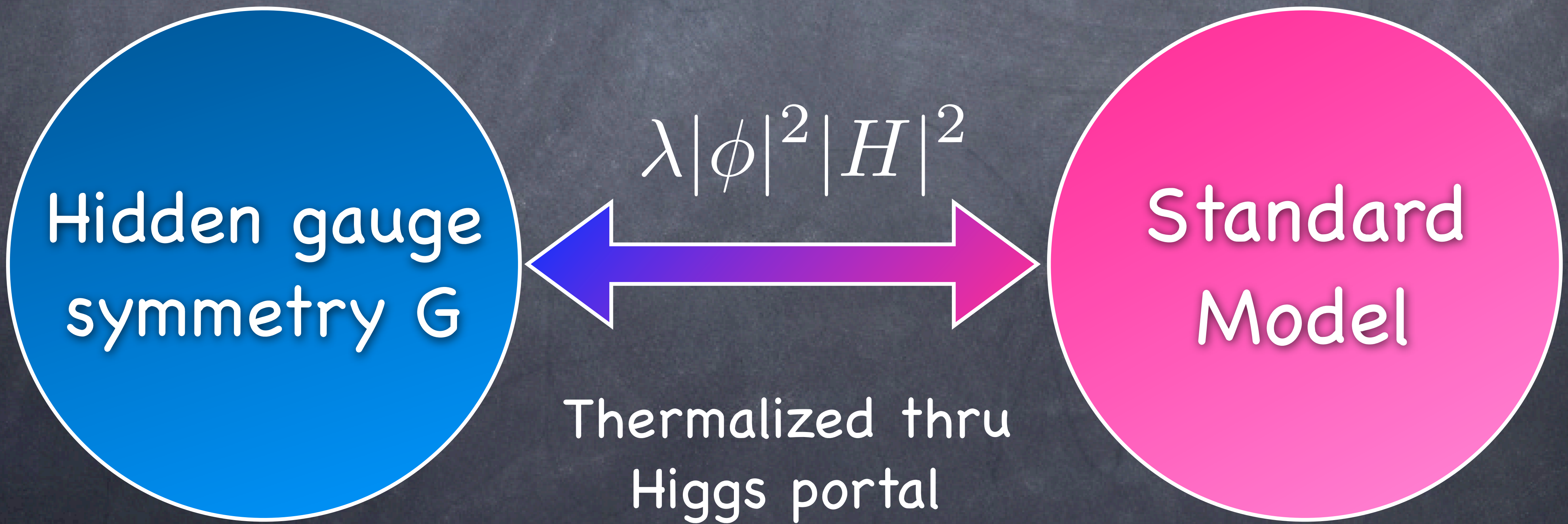
Consider an unbroken hidden gauge symmetry G ;

$$\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + |D\phi|^2 + \frac{\lambda}{4}|\phi|^2|H|^2 + \mathcal{L}_{\rm SM}$$

ϕ : scalar charged under G

G=U(1), SU(2), etc.

H : SM Higgs doublet



K-S. Jeong, FT `13

The hidden sector remains coupled to the SM sector at temperatures below the mass of ϕ .

$$\mathcal{L}_{\rm eff} = \frac{1}{\Lambda_\phi^2} F'_{\mu\nu} F'^{\mu\nu} |H|^2, \quad \text{for} \ \ m_h < T < m_\phi$$

cf. Higgs decays into hidden sector after EW breaking.

$$\Lambda_\phi \sim \left(\frac{\lambda g'^2}{8\pi^2}\right)^{-1/2} m_\phi,$$

$$\mathcal{L}_{\rm eff} = \frac{1}{\Lambda_\phi^2} \frac{m_f}{m_h^2} F'_{\mu\nu} F'^{\mu\nu} \bar{f} f, \quad \text{for} \ \ T < m_h$$

f: SM quarks, leptons

The hidden sector is decoupled when the interaction rate becomes equal to the Hubble parameter.

- Consider G=U(1). We may add N_f chiral fermions; their number and charges are constrained to satisfy the anomaly-free conditions;

$$\sum_i q_i^3 = 0 \qquad \sum_i q_i = 0$$

- N_f is bounded below; $N_f \geq 5$

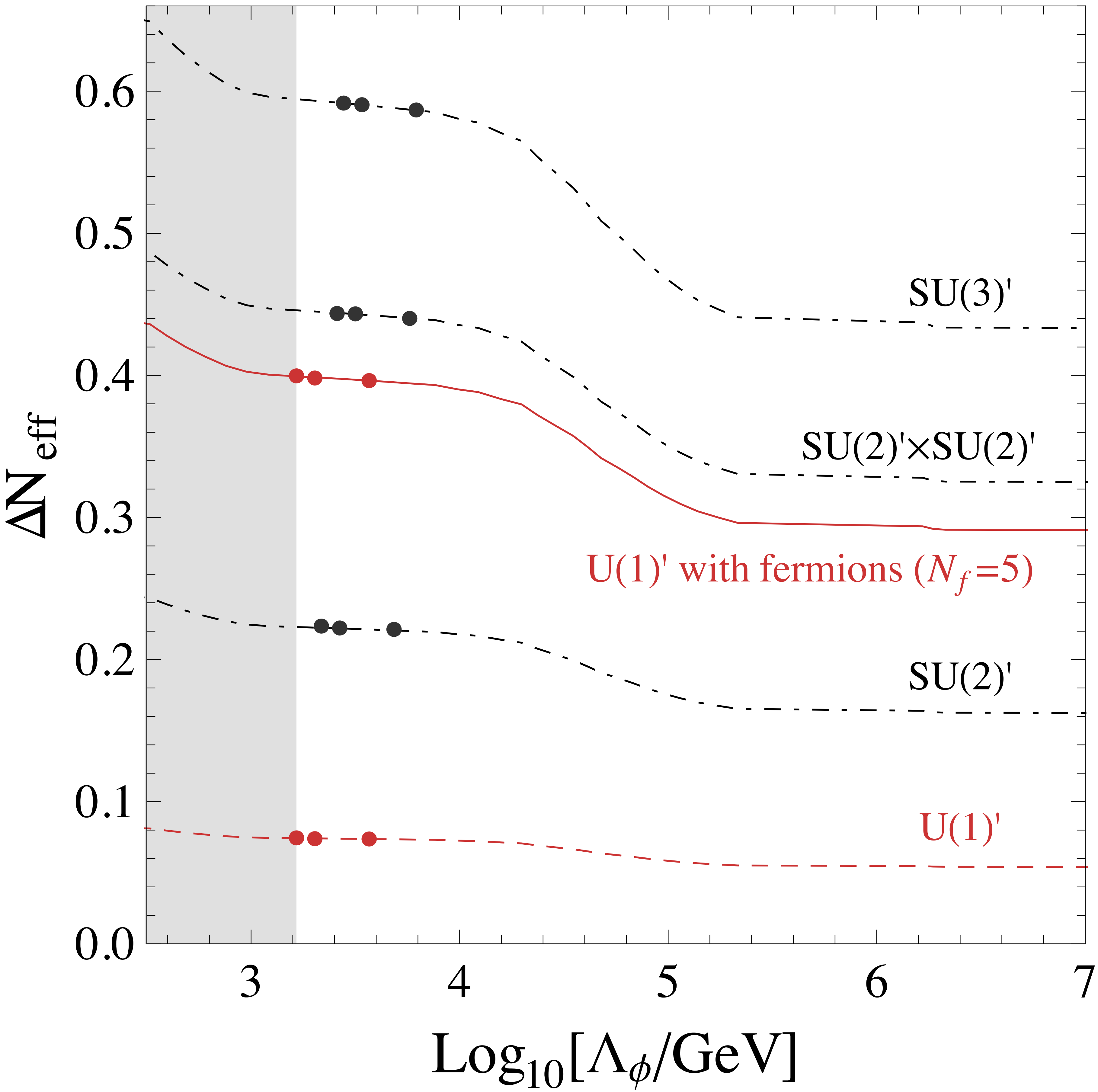
  Batra, Dobrescu and Spivak (2006)
  Nakayama, FT, Yanagida (2011)

  e.g. (1,5,-7,-8,9)

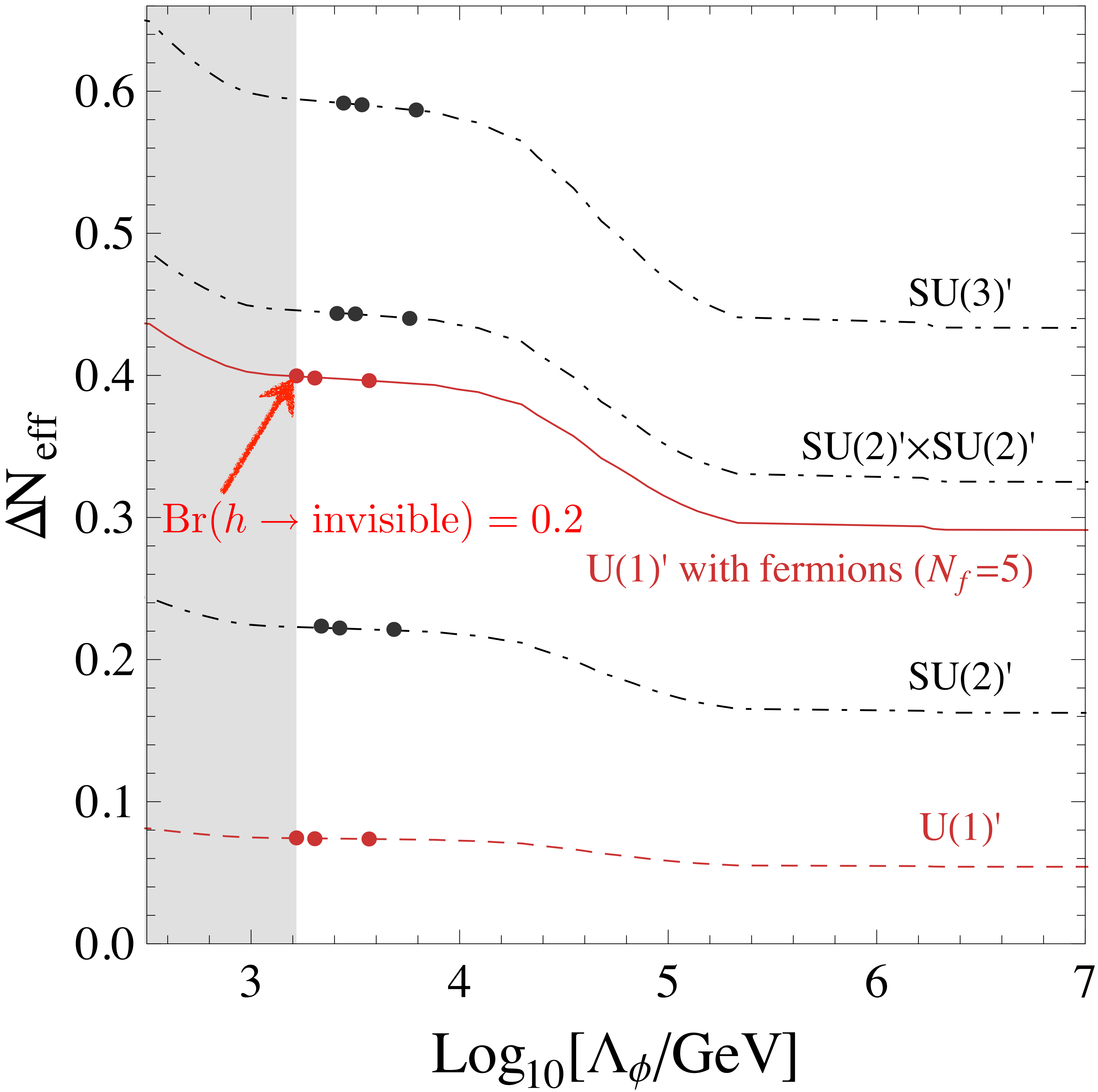
- Gauge boson and chiral fermions remain in equilibrium due to the hidden gauge interactions.

"Self-interacting dark radiation"

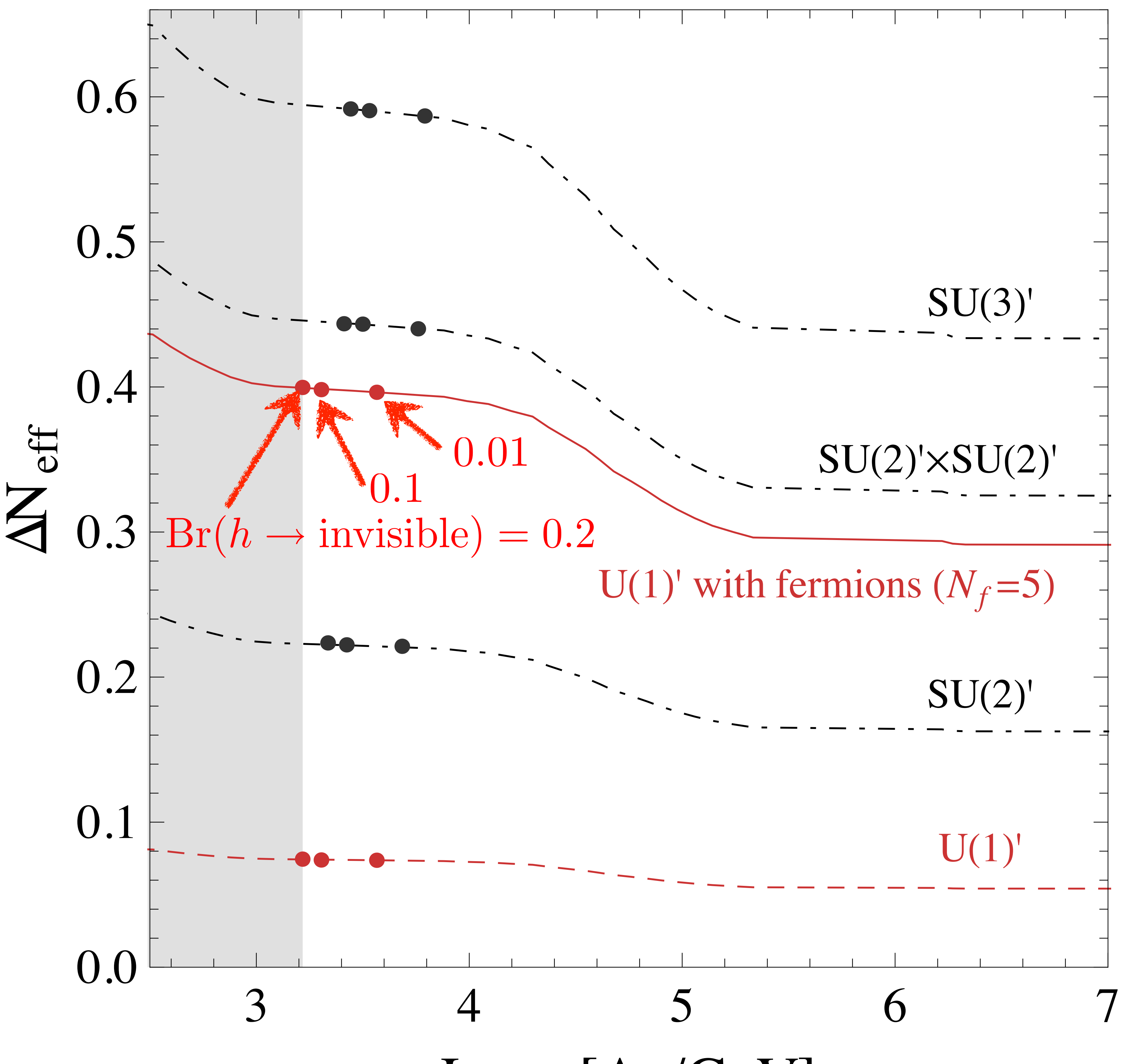
K-S. Jeong, FT (2013)



0.6
0.5
0.4
0.3
0.2
0.1
0.0
$\Delta N_{\rm eff}$
3
4
5
6
7
$\mathrm{Log}_{10}[\Lambda_\phi/\mathrm{GeV}]$
SU(3)'
SU(2)'×SU(2)'
U(1)' with fermions (N_f=5)
SU(2)'
U(1)'



0.6
0.5
0.4
0.3
0.2
0.1
0.0
3
4
5
6
7
ΔN_{eff}
$Log_{10}[\Lambda_\phi/GeV]$
SU(3)'
SU(2)'×SU(2)'
Br($h \to$ invisible) = 0.2
U(1)' with fermions (N_f=5)
SU(2)'
U(1)'



0.0
0.1
0.2
0.3
0.4
0.5
0.6
3
4
5
6
7
ΔN_eff
Log10[Λ_φ/GeV]
SU(3)'
SU(2)'×SU(2)'
SU(2)'
U(1)' with fermions (N_f=5)
U(1)'
0.01
0.1
Br($h \to$ invisible) = 0.2

Conclusions

- Precision cosmology will provide important inputs, constraints, and implications for particle physics.
- Tensor mode, isocurvature perturbations, and dark radiation are worth measuring with a greater accuracy. (The precision will be improved by a factor of 10^2, 5 and 10 in the planned experiments).
- Hidden gauge symmetry is a plausible candidate for dark radiation, which may be probed by the invisible Higgs decay.