Planck implications for high energy physics

@String Pheno 2013
18th July

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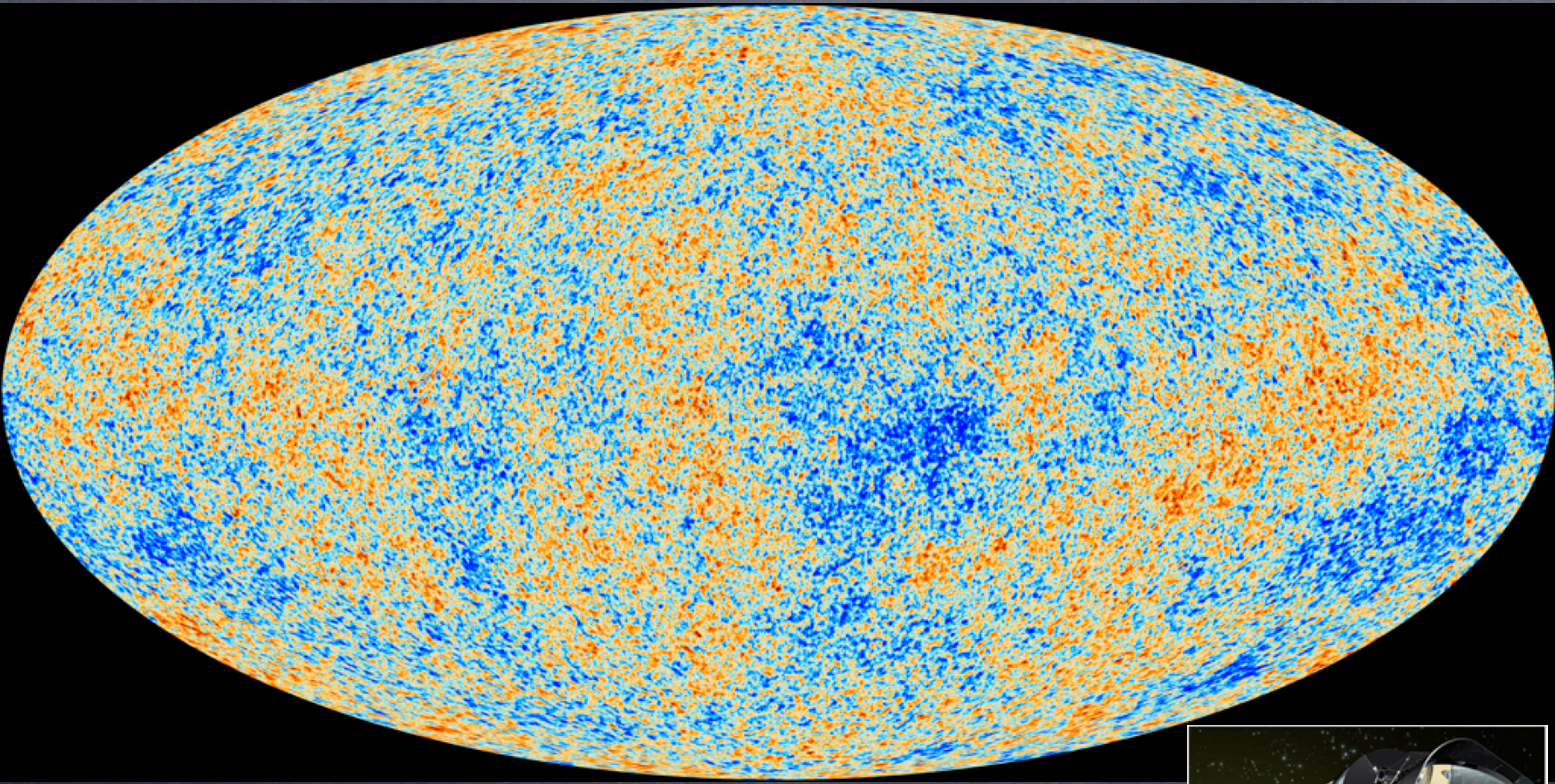
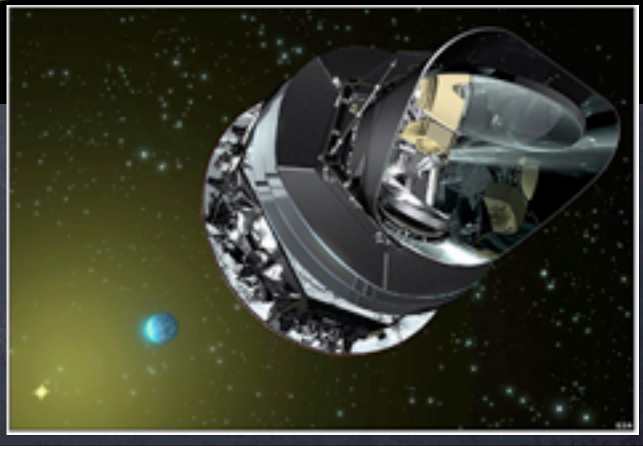
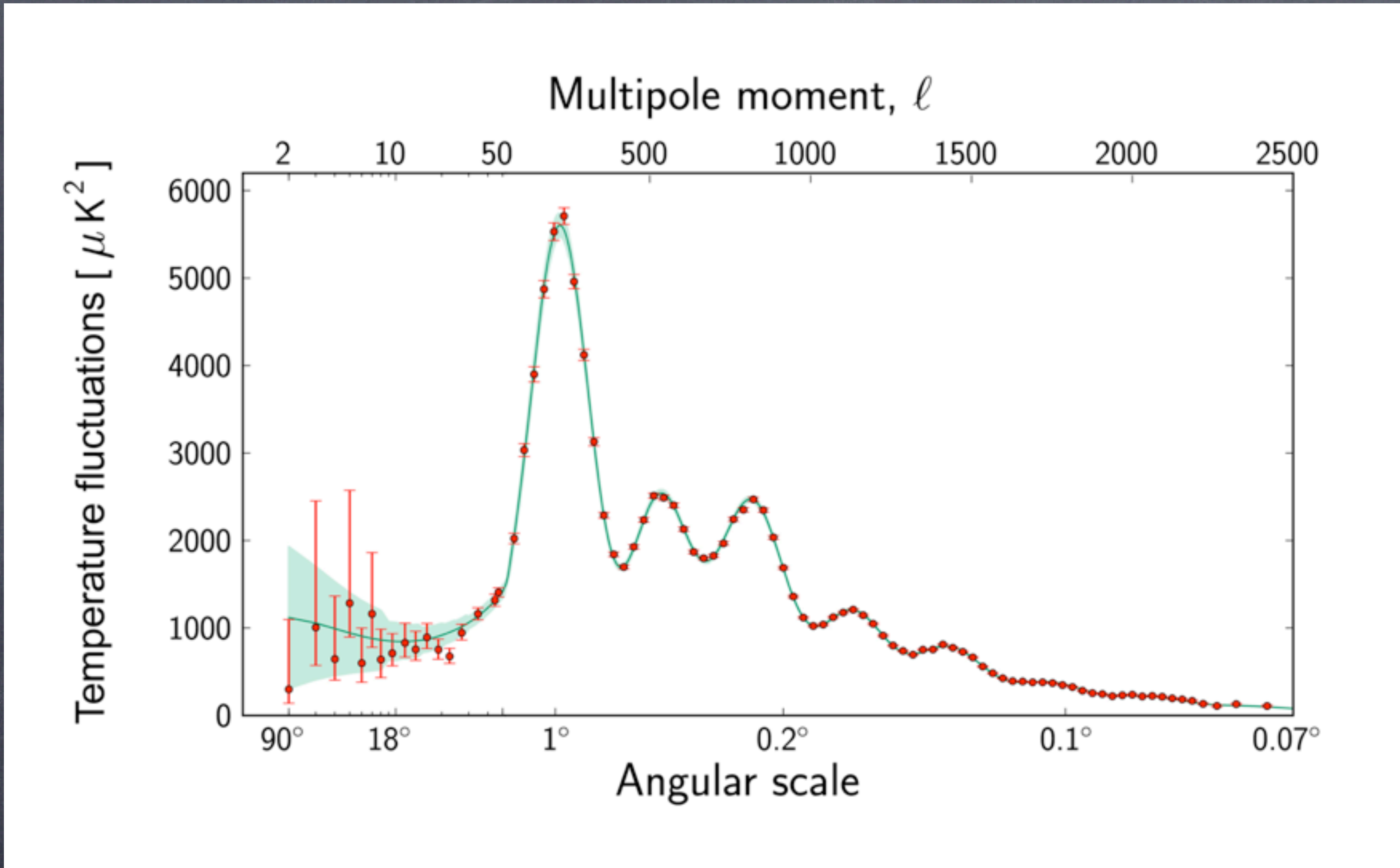
(Tohoku University)

1303.7315, 1305.5099 with K. Nakayama, T. Yanagida
1305.6521 with K-S Jeong
1304.7987, 1306.6518 with T. Higaki and K. Nakayama

Cosmology is now a precision science.







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

What did we learn from Planck?

- ✓ Cosmological parameters are determined with a greater accuracy.

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

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

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Great! Now the time for precision measurements. New physics is about to be revealed!

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

Then where to look for?

In this talk I focus on two possible extensions to the std. LCDM model.

- ✓ Tensor mode (or B-mode polarization)

  The inflation near the GUT scale.

- ✓ Dark radiation

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

There are many other extensions such as isocurvature perturbations, non-Gaussianity, curvature, dark energy, etc.

cf. ``Suppressing Isocurvature Perturbations of QCD Axion DM" 1304.8131, K-S. Jeong, FT

Tensor mode

Density perturbations are induced by distortion of space;

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

Tensor mode

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Scalar perturbations

Tensor mode

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Scalar perturbations

Tensor perturbations

Tensor mode

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

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

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

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

(n_s, r)

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

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

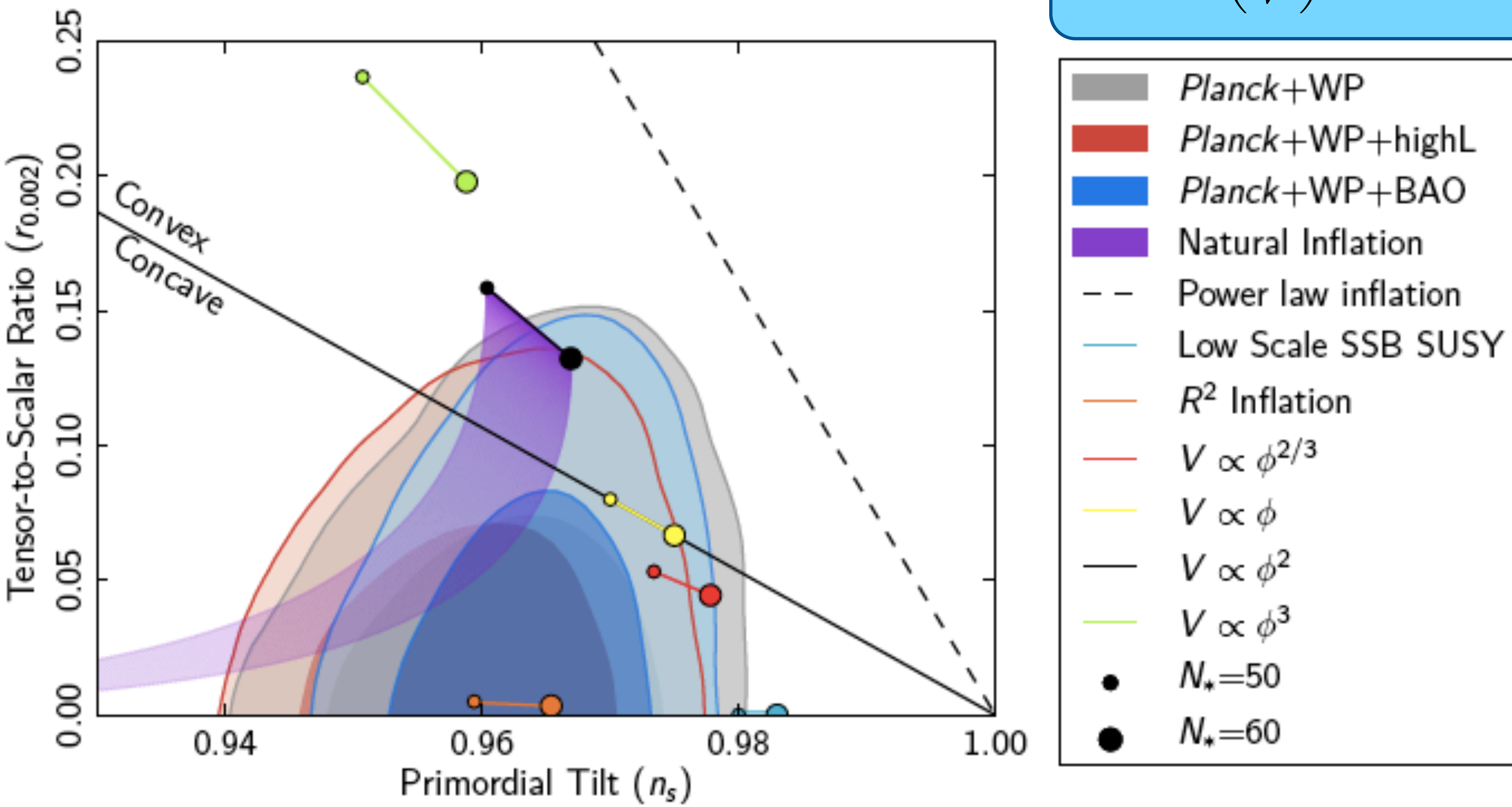
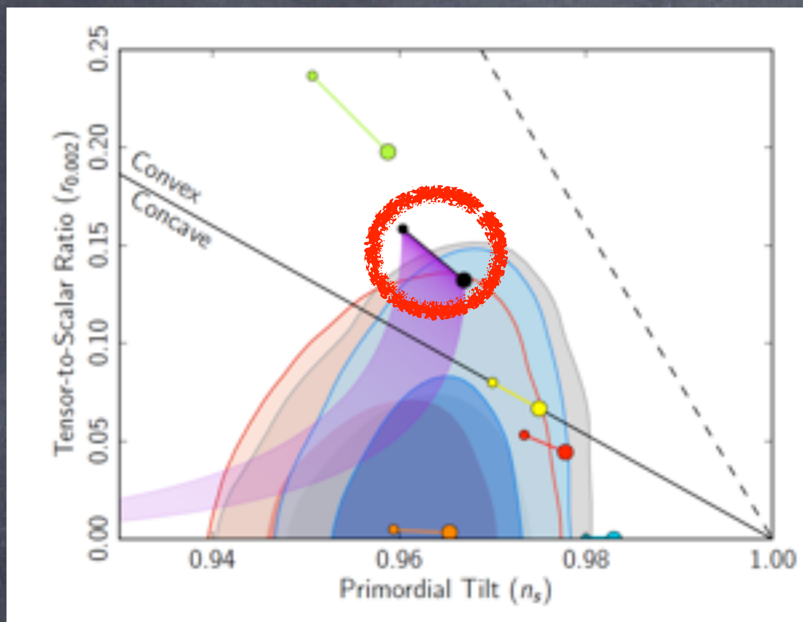


Fig. 1. Marginalized joint 68% and 95% CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets compared to the theoretical predictions of selected inflationary models.

Planck collaborations, 1303.5082

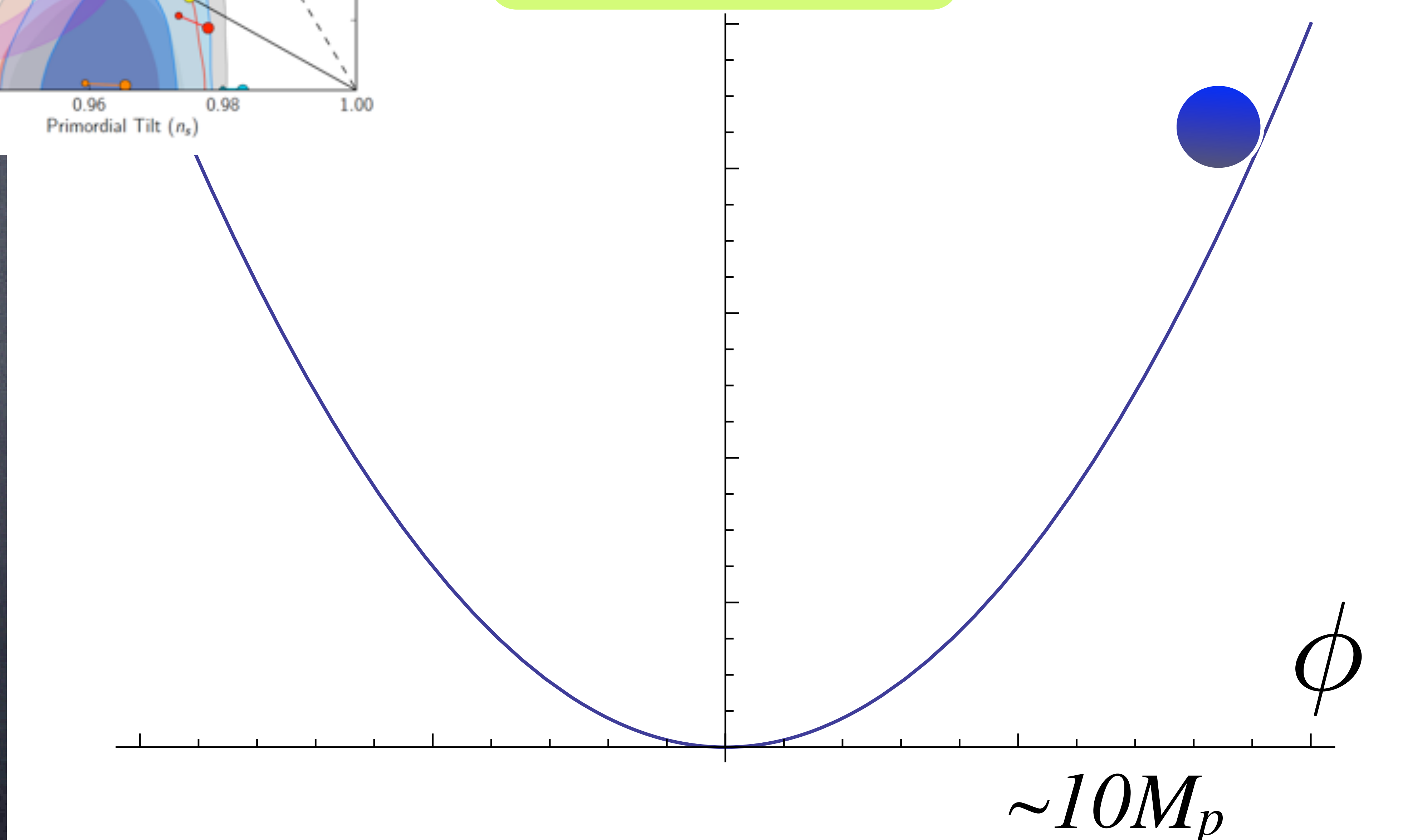
- Chaotic inflation models based on the monomial potential are outside the 1 sigma allowed region.



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

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

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



- 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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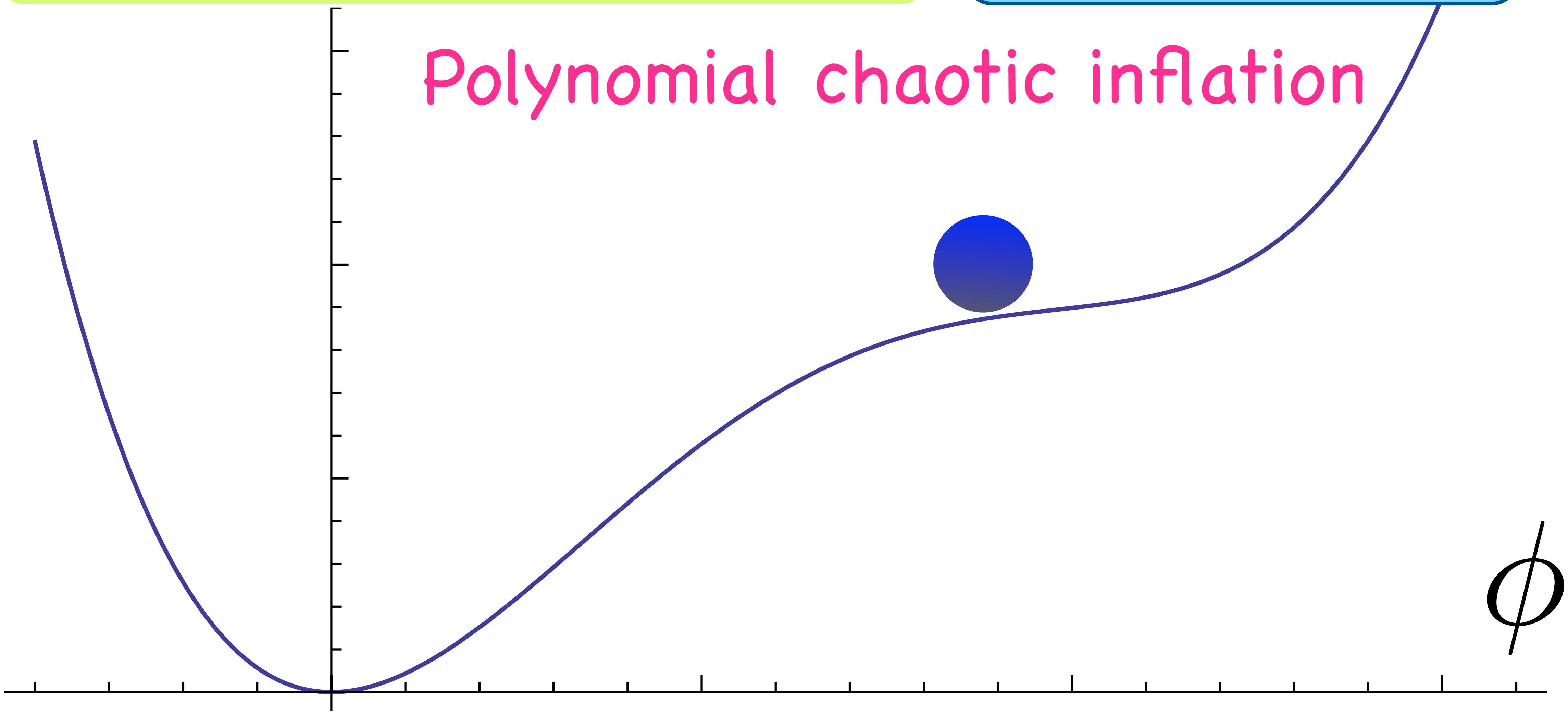


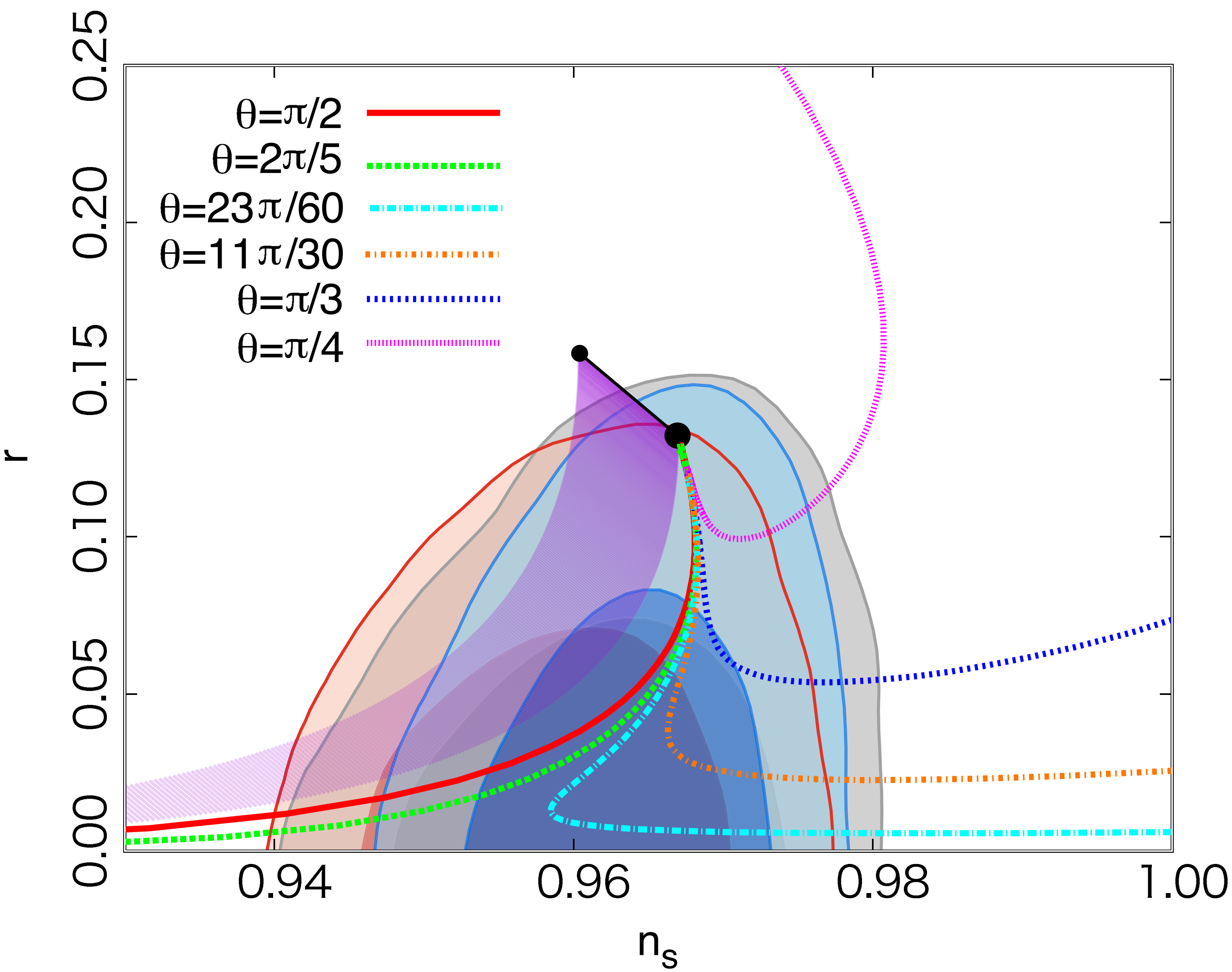
Polynomial chaotic inflation

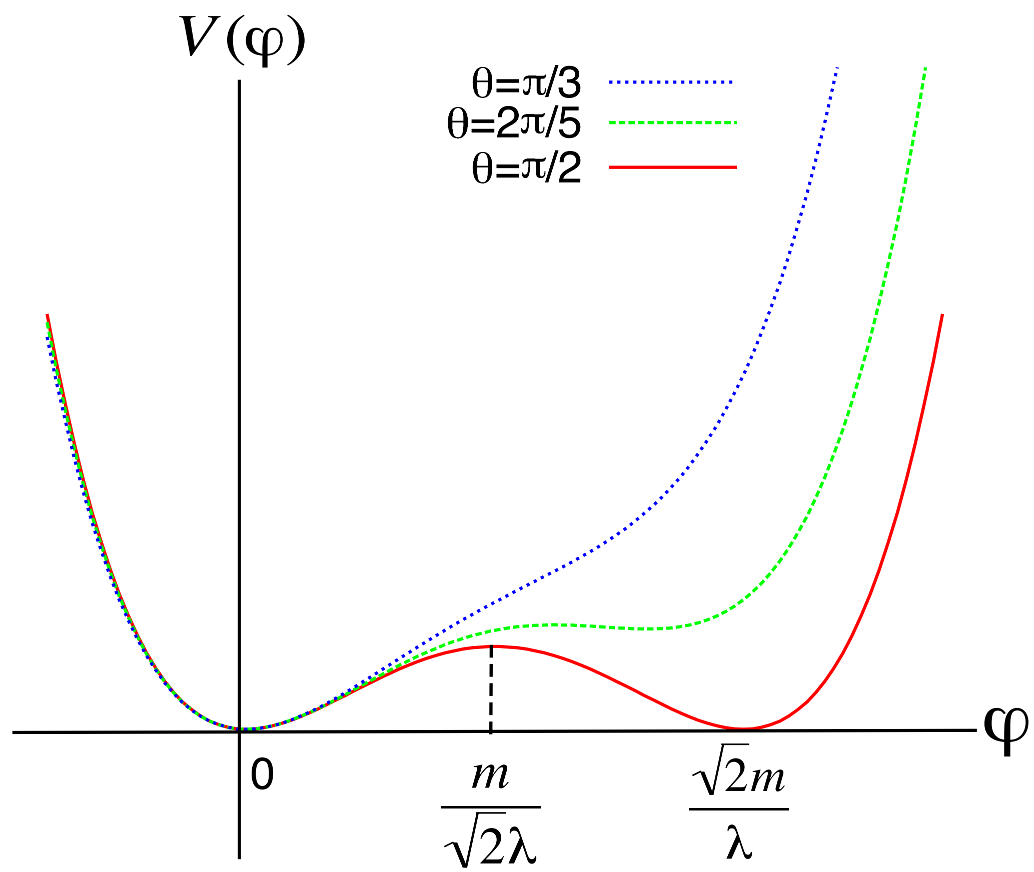
Nakayama, FT, Yanagida, 1303.7315, 1303.5099

cf. Destri, Vega, Sanchez (2007) for non-susy case.

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

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





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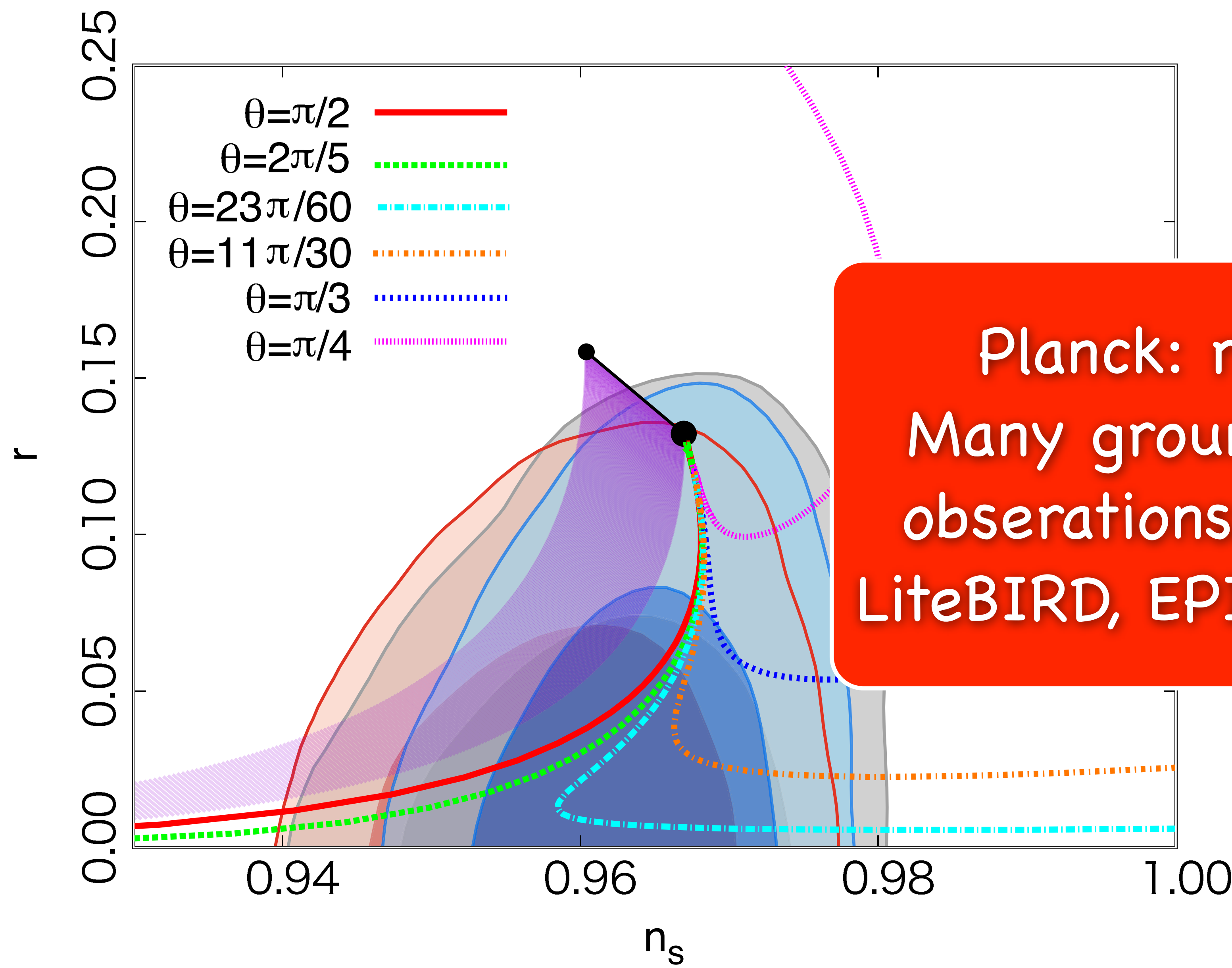
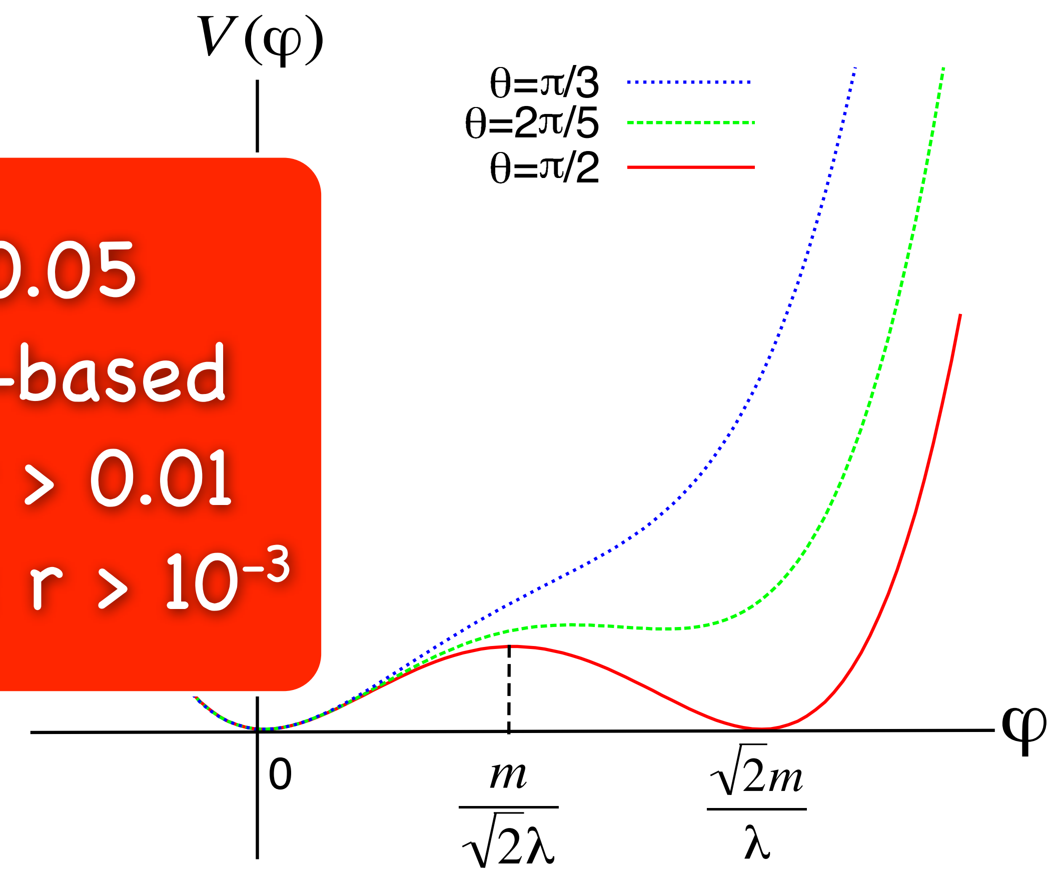


Planck: r >0.05

Many ground-based observations: r > 0.01

LiteBIRD, EPIC: r > 10^{-3}

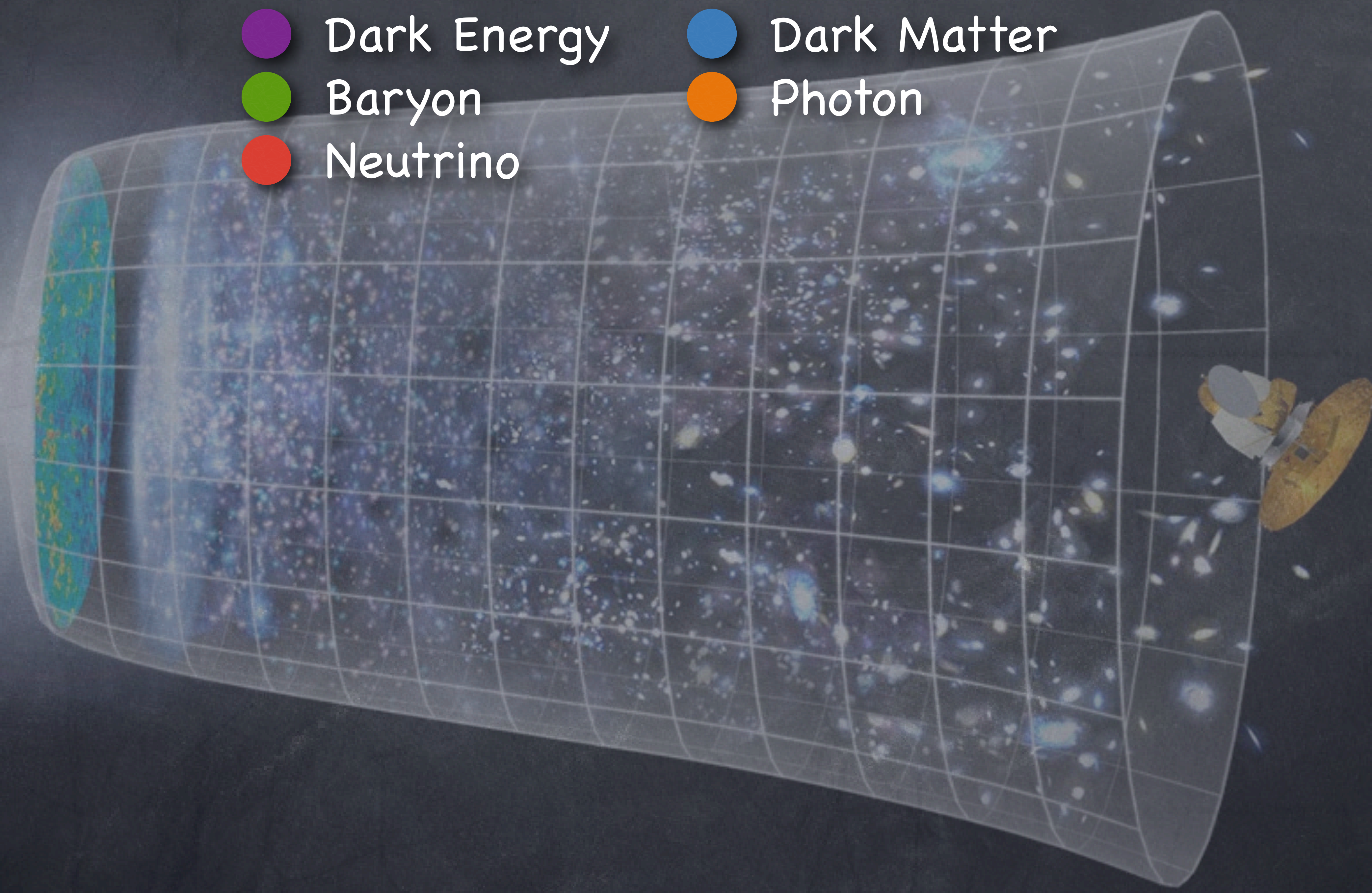


Dark radiation

Dark radiation = Extra relativistic degrees of freedom

Cosmic pie chart

- Dark Energy
- Dark Matter
- Baryon
- Photon
- Neutrino

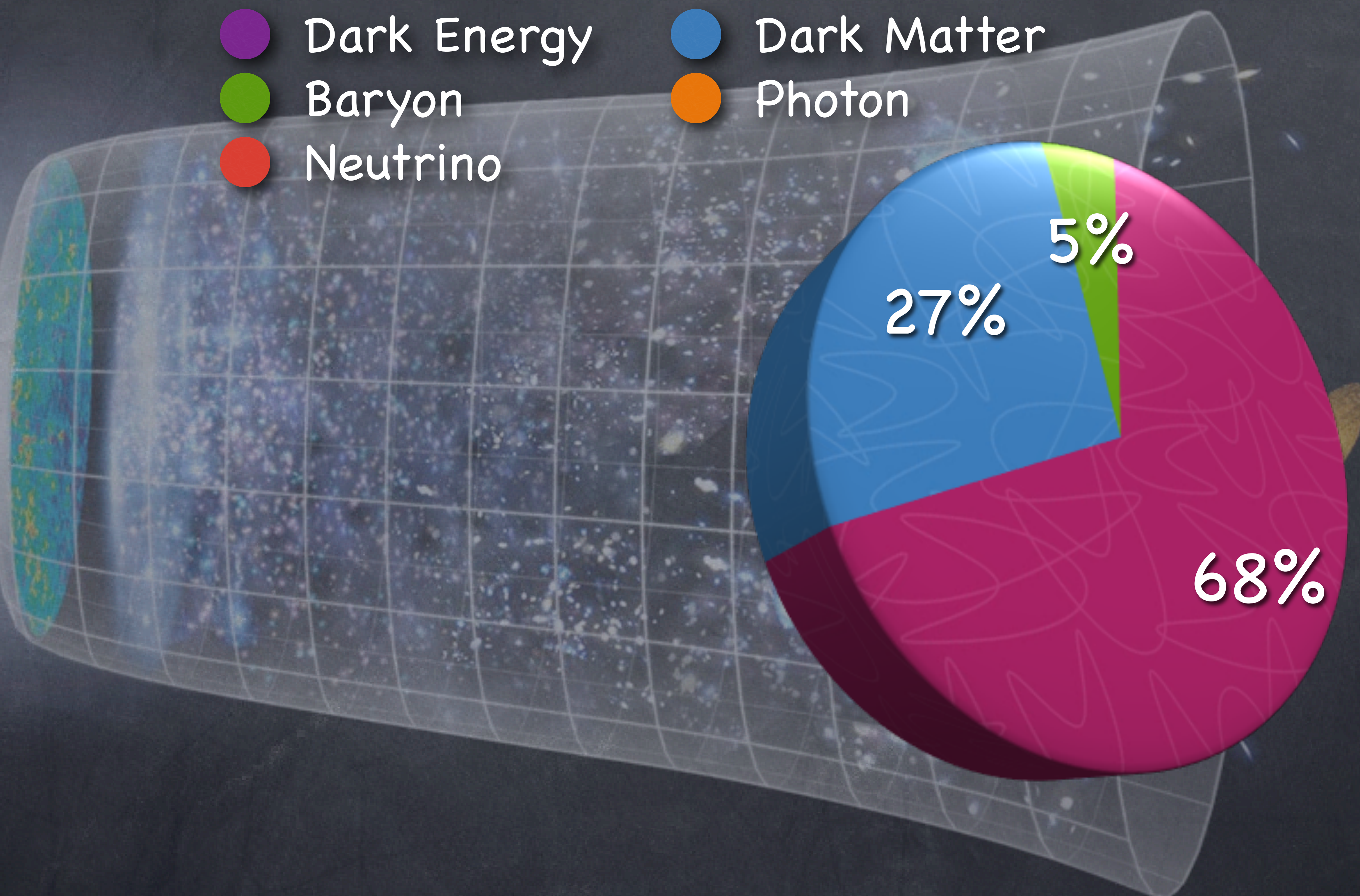


13.7billion years ago
(Universe 380,000 years old)

Today

NASA/WMAP Science Team

Cosmic pie chart



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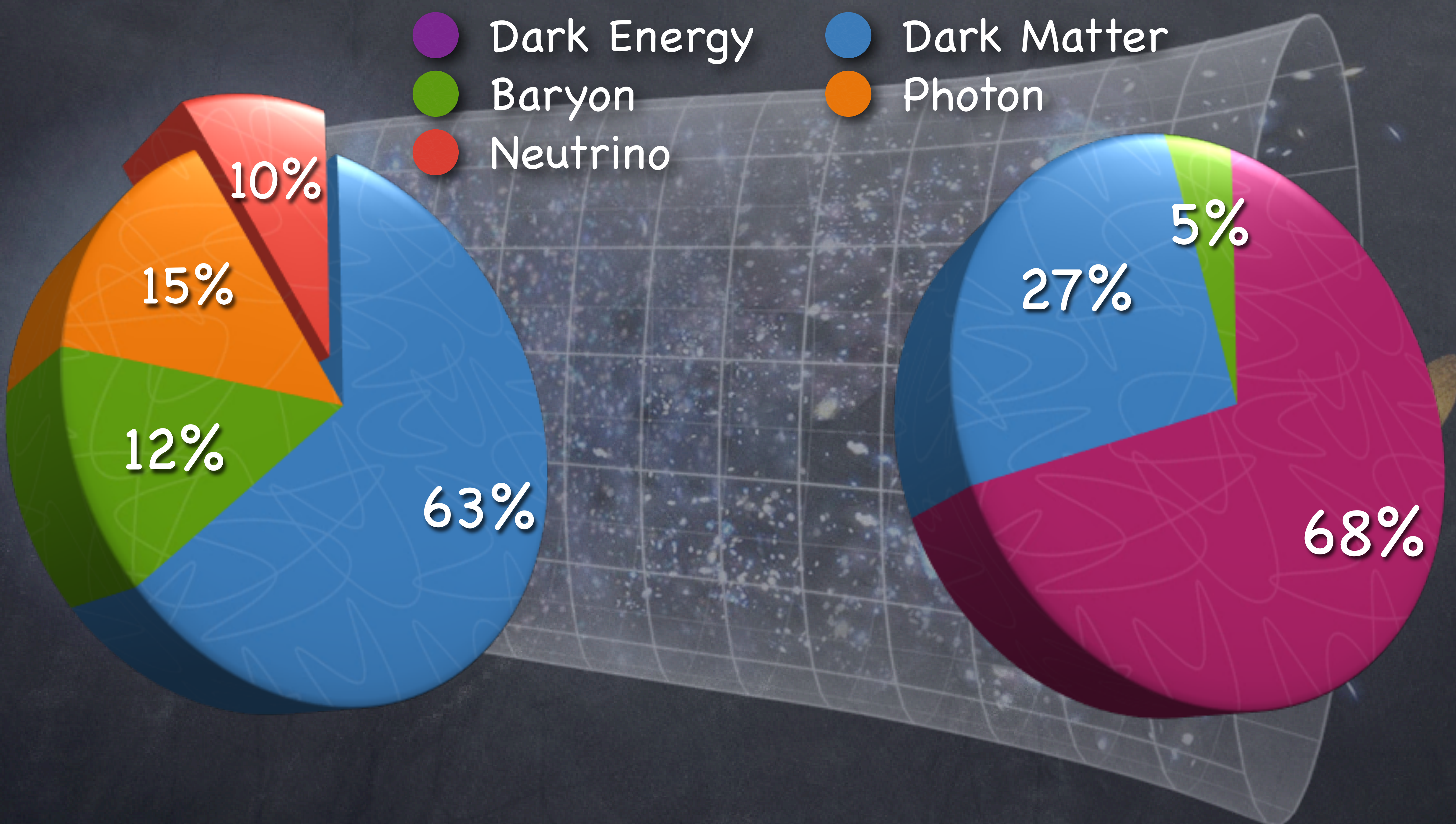

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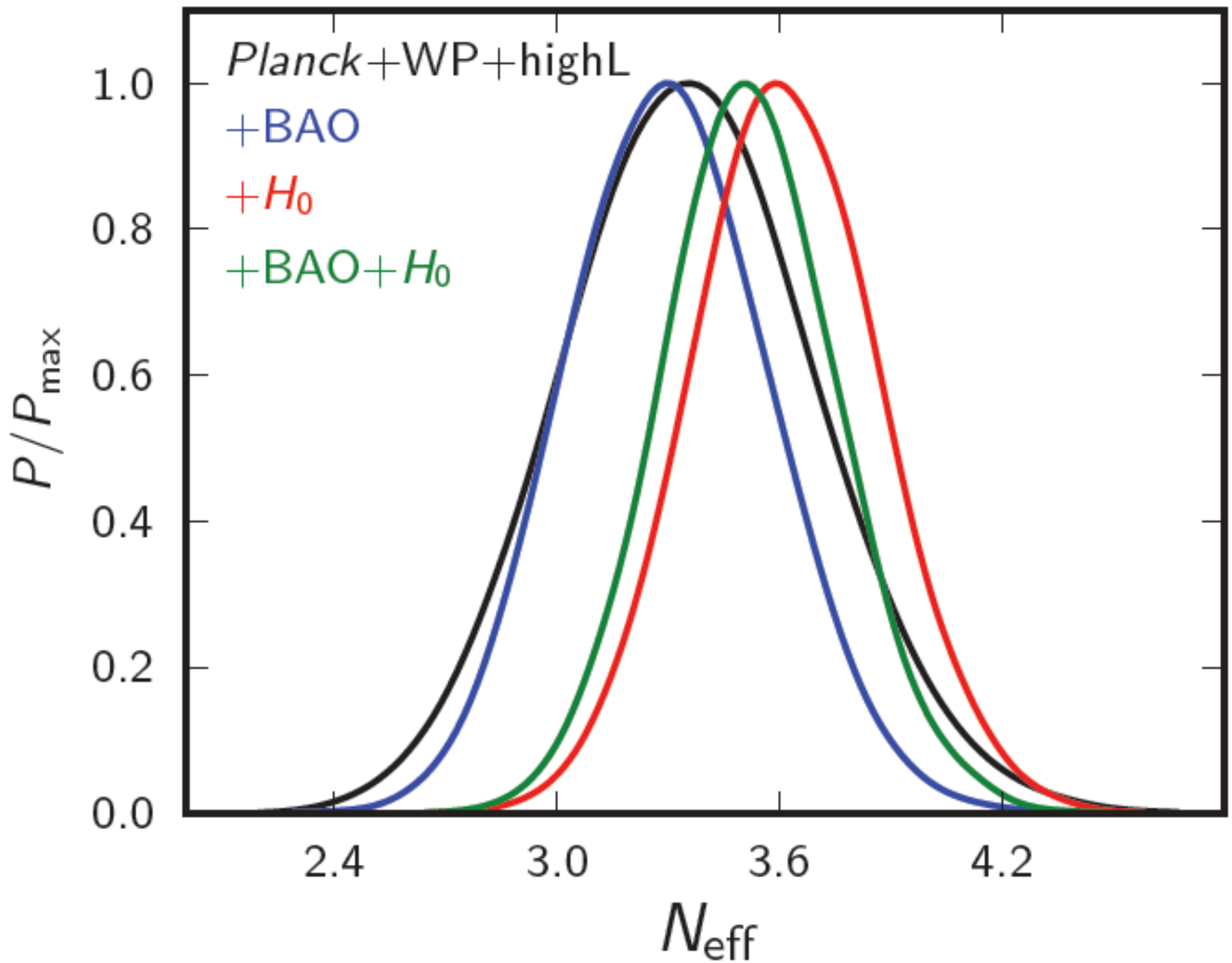
Today

Dark radiation

Dark radiation (DR) = Extra relativistic degrees of freedom

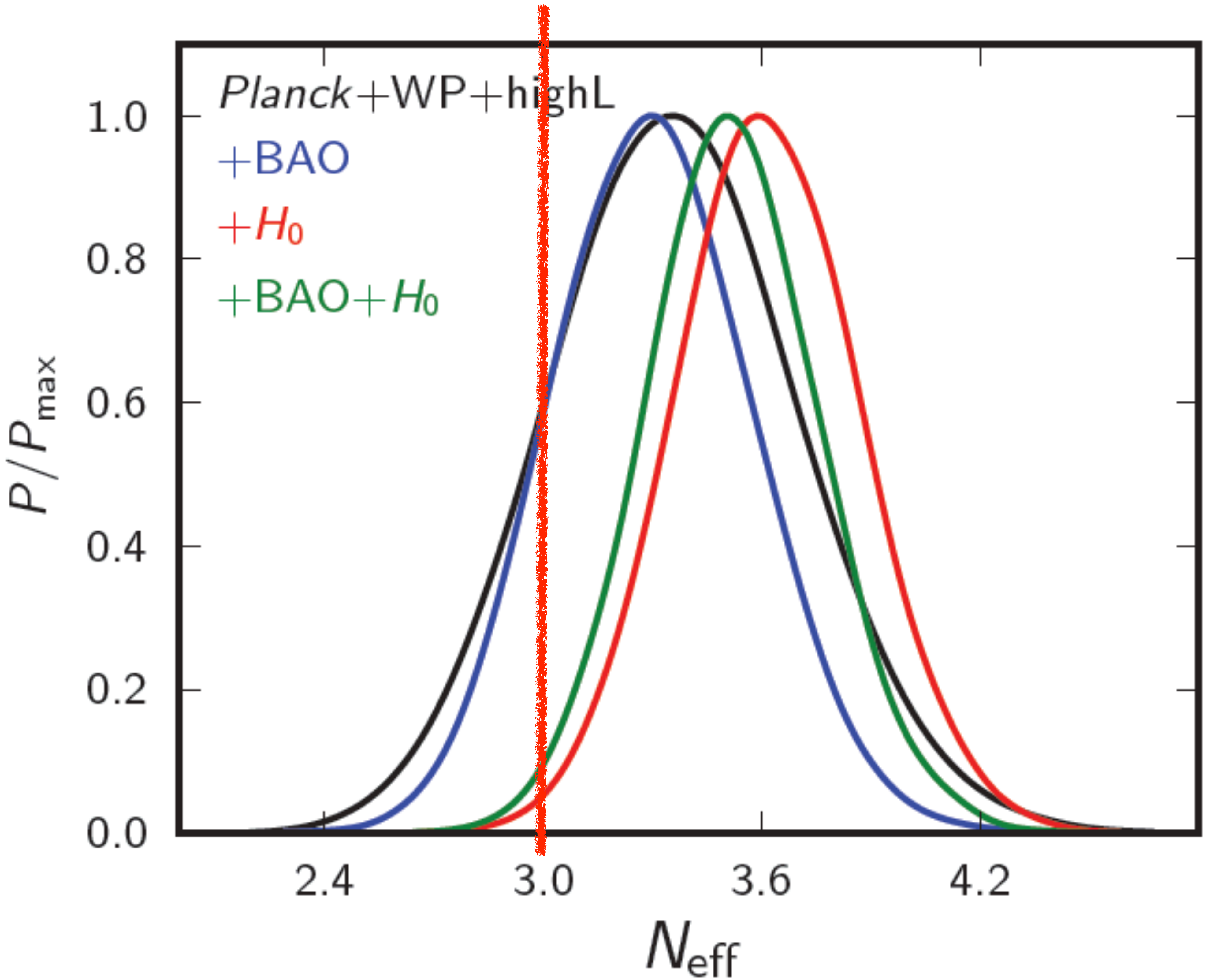
DR contributes to the effective number of neutrino species

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



Planck collaborations, 1303.5076

Standard value N_{eff} = 3



Planck collaborations, 1303.5076

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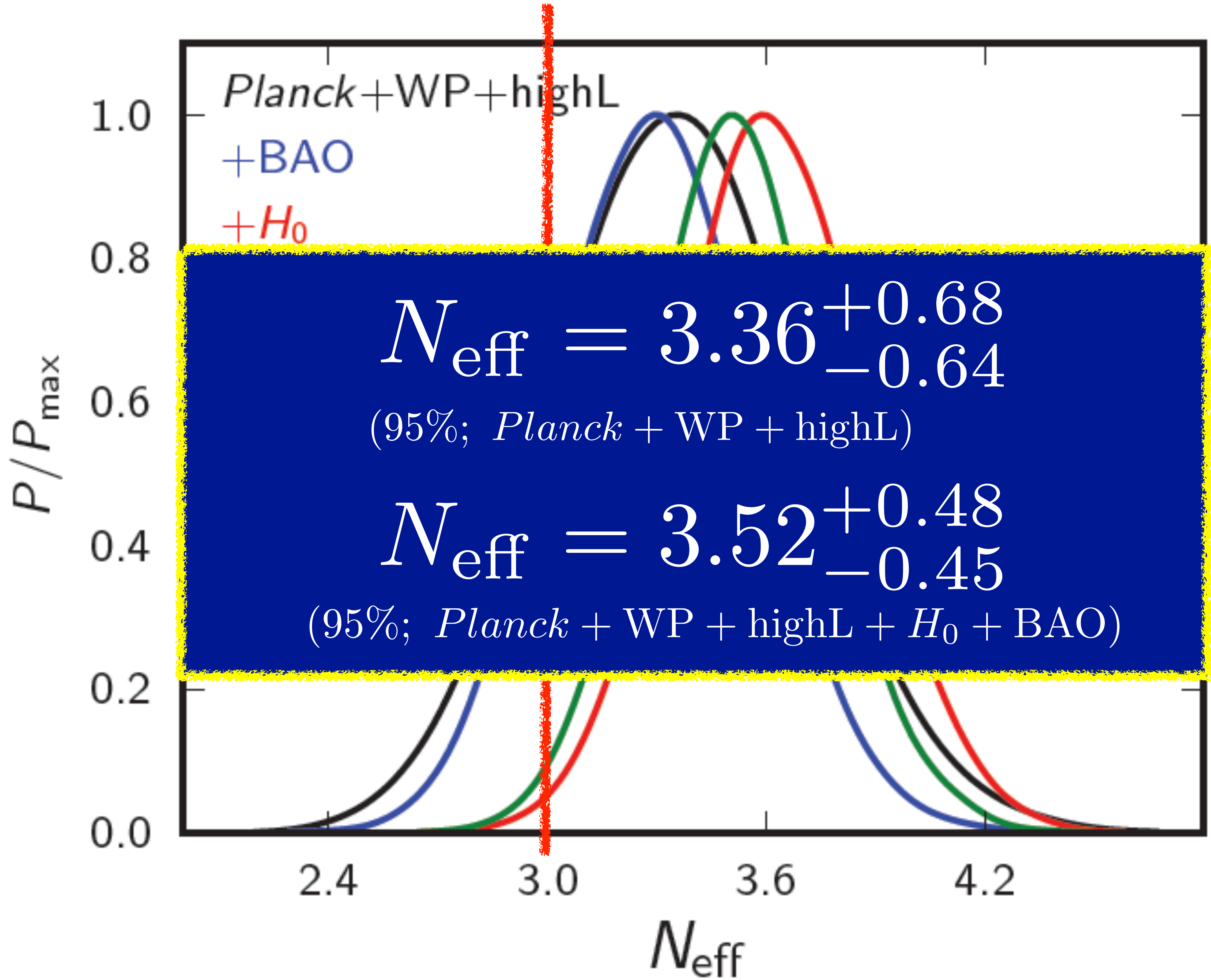

$$N_{\rm eff} = 3.36^{+0.68}_{-0.64}$$

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

$$N_{\rm eff} = 3.52^{+0.48}_{-0.45}$$

(95%; *Planck* + WP + highL + H_0 + BAO)

Planck collaborations, 1303.5076

If we introduce light degrees of freedom to explain DR, the following questions immediately arise.

1. Why still relativistic at late time?
2. Why $\Delta N_{\rm eff} \sim \mathcal{O}(0.1)$?
3. How to distinguish between different models?

The DR models are broadly classified into thermal and non-thermal production.

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

Thermal production

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Gauge bosons   Chiral fermions   NG bosons

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

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

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

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✓ Relatively strong coupling with the SM sector.

Consider an unbroken hidden gauge symmetry G, which is thermalized thru Higgs portal.

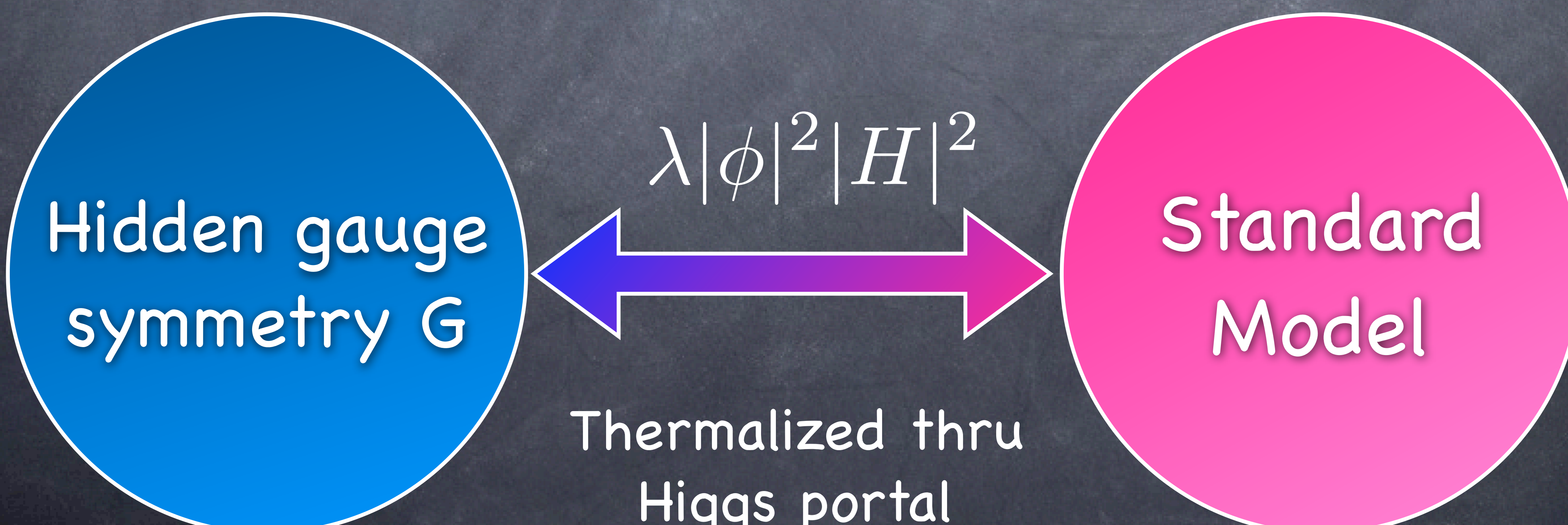
K-S. Jeong, FT 1305.6521

Hamada, Kobayashi, Jeong and FT, in preparation.

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

ϕ : scalar charged under G G=U(1), SU(N), etc.

H : SM Higgs doublet



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

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

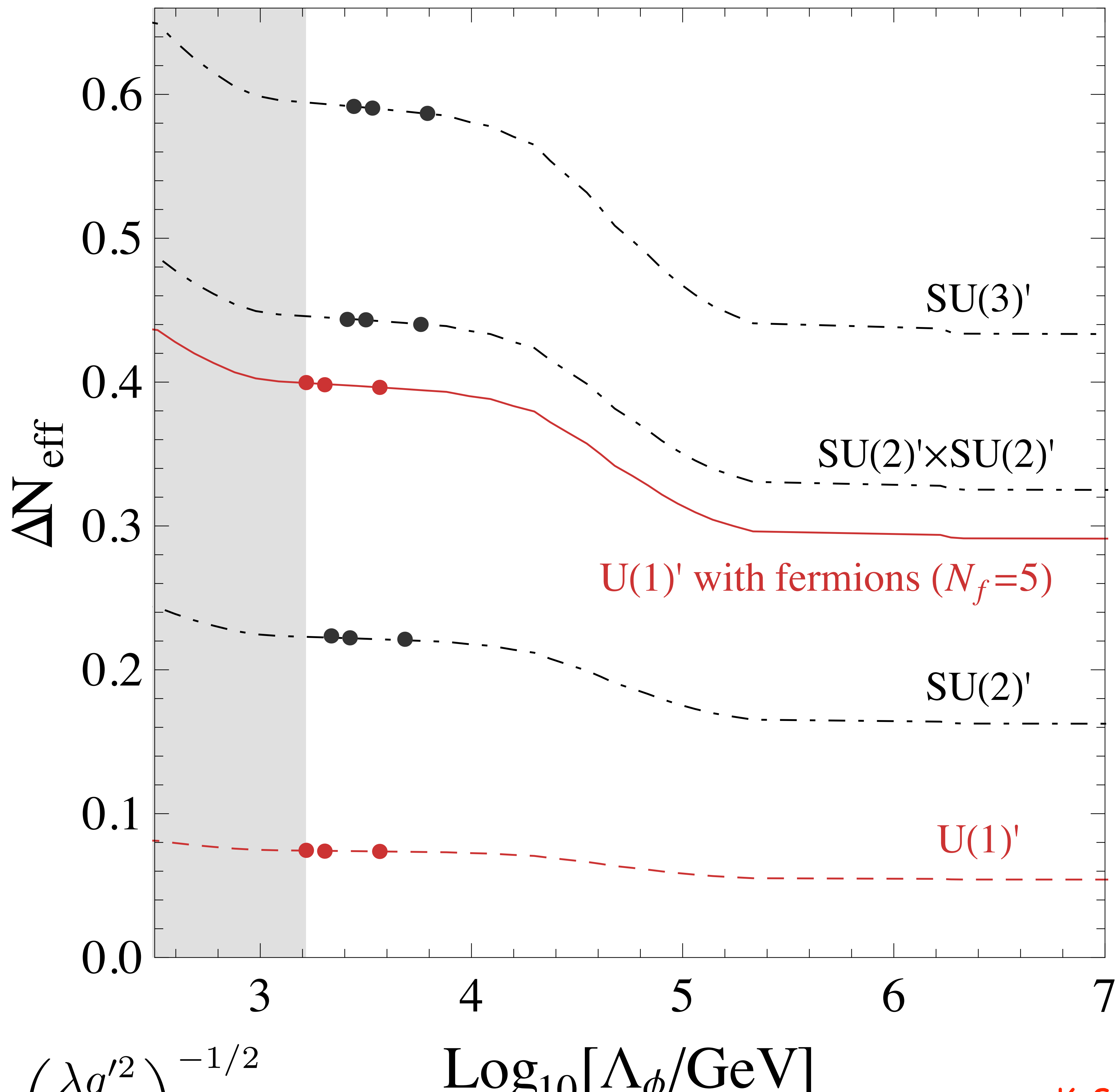
cf. Higgs decays into hidden sector after EW breaking.

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

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

f: SM quarks, leptons

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



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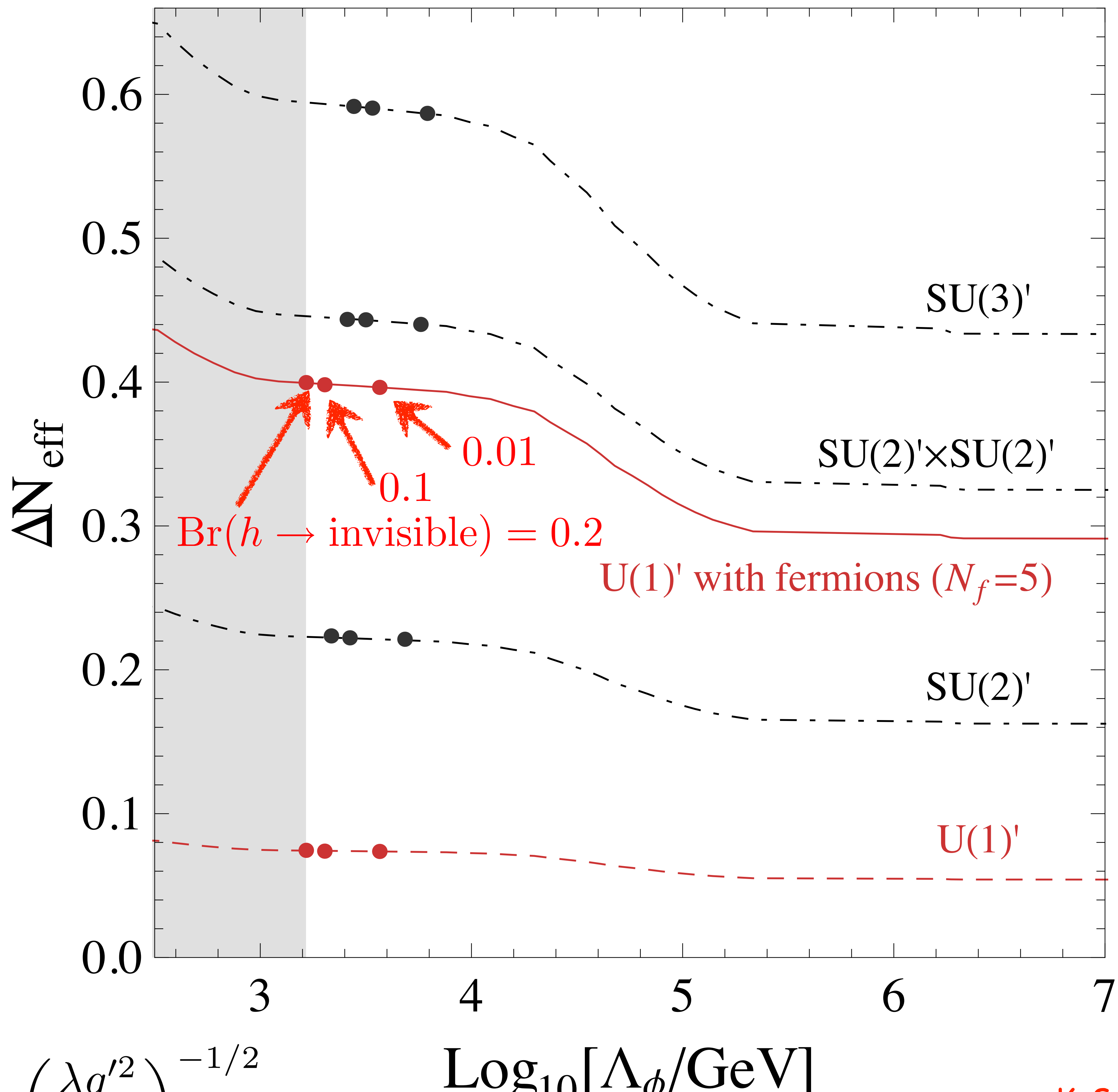

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Non-thermal production

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

Ichikawa et al `07, Hasenkamp `11, Menestrina and Scherrer `11, Higaki, Kamada, FT `12, Cicoli, Conlon and Quevedo `12, Higaki FT `12, and many others.

✓ Non-trivial to explain the abundance.
Often overproduced → constraints on microscopic theory.

✓ Almost decoupled from the SM. Difficult to probe?

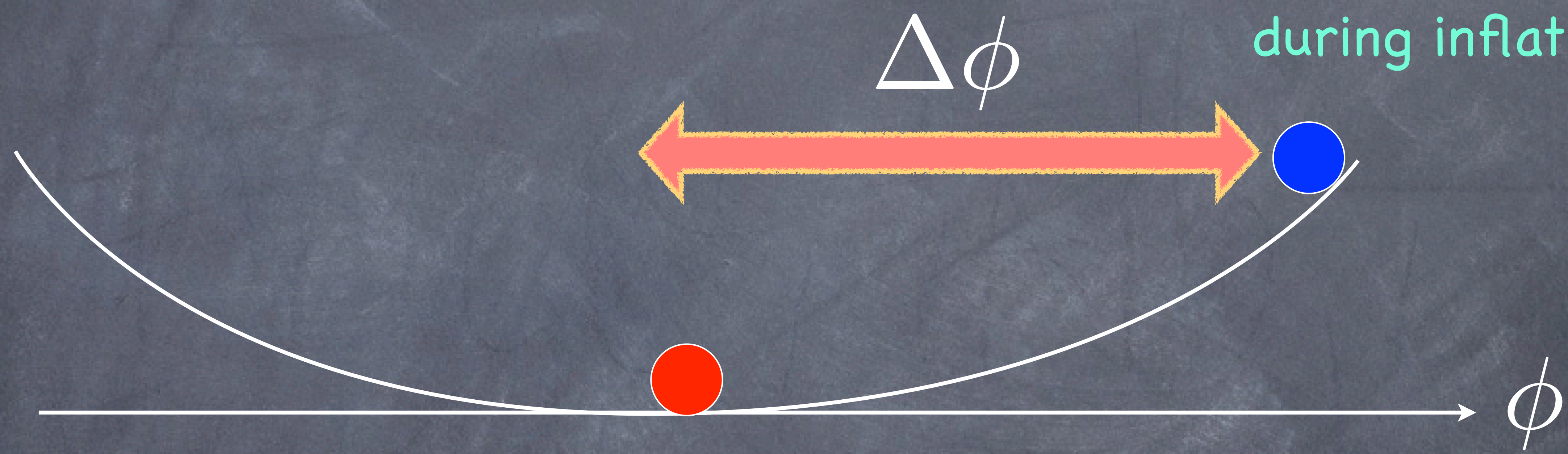
I will consider the moduli decays as a source of DR.

See talks by Angus, Higaki, and Conlon

Cosmological moduli problem

G. D. Coughlan et al (1983)

ϕ : moduli



The moduli dominate the Universe and decay after BBN unless they are very heavy, thus altering the light element abundances in contradiction with observations.

The simplest solution is to make the modulus heavier than O(10)TeV so that it decays before BBN.

The simplest solution is to make the modulus heavier than O(10)TeV so that it decays before BBN.

Note however that one needs to make sure if the modulus decay does not produce any unwanted relics.

This depends on microscopic details of the moduli, especially how they are stabilized.

Moduli decays

✓ SUSY moduli

- has a SUSY mass heavier than $m_{3/2}$.
- e.g. KKLT
- decays into gravitinos and gauginos/Higgsinos.

"Moduli-induced gravitino/LSP problem"

Endo, Hamaguchi, FT \`06, Nakamura, Yamaguchi \`06
Dine, Kitano, Morisse, and Shirman \`06.

$$\mathrm{Br}(\phi \to 2\psi_{3/2}) = O(0.1)$$
$$\Gamma(\phi \to AA) = \Gamma(\phi \to \lambda\lambda)$$

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✓ Non-SUSY moduli

- has a SUSY breaking mass of order (or lighter than) $m_{3/2}$ from Kahler potential.
- e.g. QCD saxion, overall volume modulus in LVS.
- decays into axion pairs.

"Moduli-induced axion problem"
Higaki, Nakayama, FT 1304.7987

cf. Chun, Lukas `95, Hashimoto, Izawa, Yamaguchi and Yanagida `98
See also Cicoli, Conlon and Quevedo `12, Higaki and FT `12 for the LVS case.

Moduli-induced axion problem

Talk by Higaki

$K = K(T + T^\dagger)$ respects a shift symmetry $T \to T + i\alpha$

The axion component a remains ultralight. $T - \langle T \rangle = \dfrac{\tau + ia}{\sqrt{2K_{TT}}}$

Moduli τ

Γ_a

$$\Gamma_a(\tau \to aa) = \frac{1}{64\pi}\frac{K_{TTT}^3}{K_{TT}^3} m_\tau^3$$

via the kinetic term

Axion pairs (DR)

Moduli-induced axion problem

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Moduli $\mathcal{T}$

$$\Gamma_a(\tau \to aa) = \frac{1}{64\pi}\frac{K_{TTT}^3}{K_{TT}^3} m_\tau^3$$

via the kinetic term

Γ_a $\Gamma_{\rm SM}$

$$K = g(T + T^\dagger) H_u H_d$$

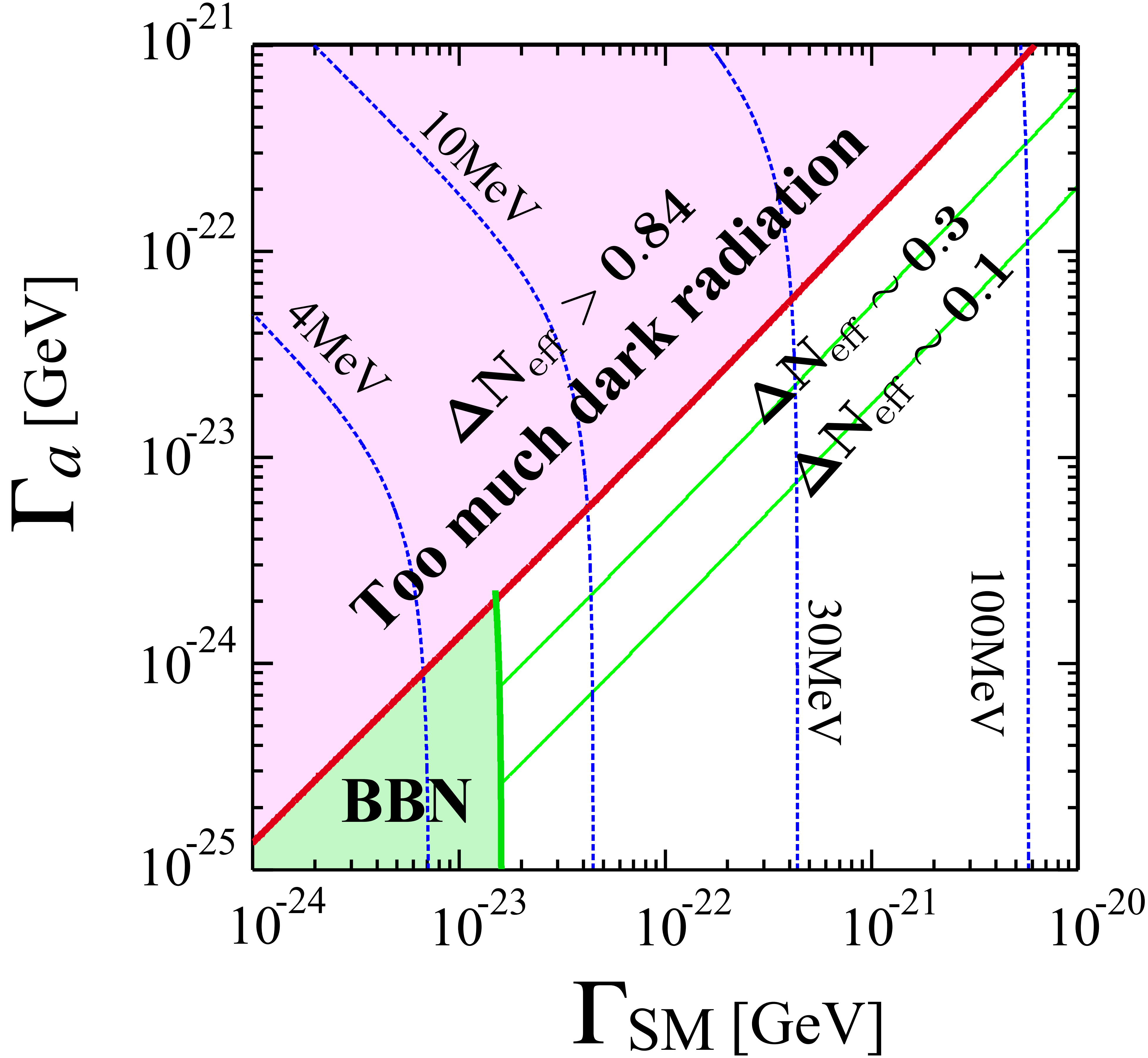
$$\Gamma(\tau \to HH) \simeq \frac{g_T^2}{8\pi K_{TT}} m_\tau^3$$

$$\Gamma(\tau \to AA) \simeq \frac{N_g}{128\pi}\frac{|\partial_T f_{\rm vis}|^2}{({\rm Re} f_{\rm vis})^2}\frac{m_\tau^3}{K_{TT}}$$

thru Higgs/gauge bosons

Axion pairs (DR)

Standard Model



Higaki, Nakayama, FT 1304.7987

Axion-photon conversion

Sikivie `83

$$\mathcal{L} = -\frac{1}{4} g_a a F_{\mu\nu} \tilde{F}^{\mu\nu} = g_a a \vec{E} \, \vec{B}$$

Axions mix with photons in the presence of magnetic field.

$$\begin{array}{cccc} & \gamma & a & \\ M_{ij}^2 = & \left(\begin{array}{cc} \omega_p^2 & -g_a B E \\ -g_a B E & m_a^2 \end{array} \right) & & \begin{array}{c} \gamma \\ a \end{array} \end{array}$$

$$\omega_p = \sqrt{\frac{4\pi\alpha n_e}{m_e}} \simeq 2 \times 10^{-14}\,\mathrm{eV}\,(1+z)^{3/2} X_e^{1/2}$$: Plasma frequency

E : Axion energy

Axion-photon mixing in the early U: Higaki, Nakayama and FT, 1306.6518

Axion-photon mixing in cluster: Conlon and Marsh 1305.3603

Talk by Conlon

(cf. Scattering with matter considered in Conlon and Marsh 1304.1804)

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E : Axion energy

Resonant and non-resonant conversion take place.

Yanagida and Yoshimura `88, Sikivie `83

The conversion rate depends on B_0.

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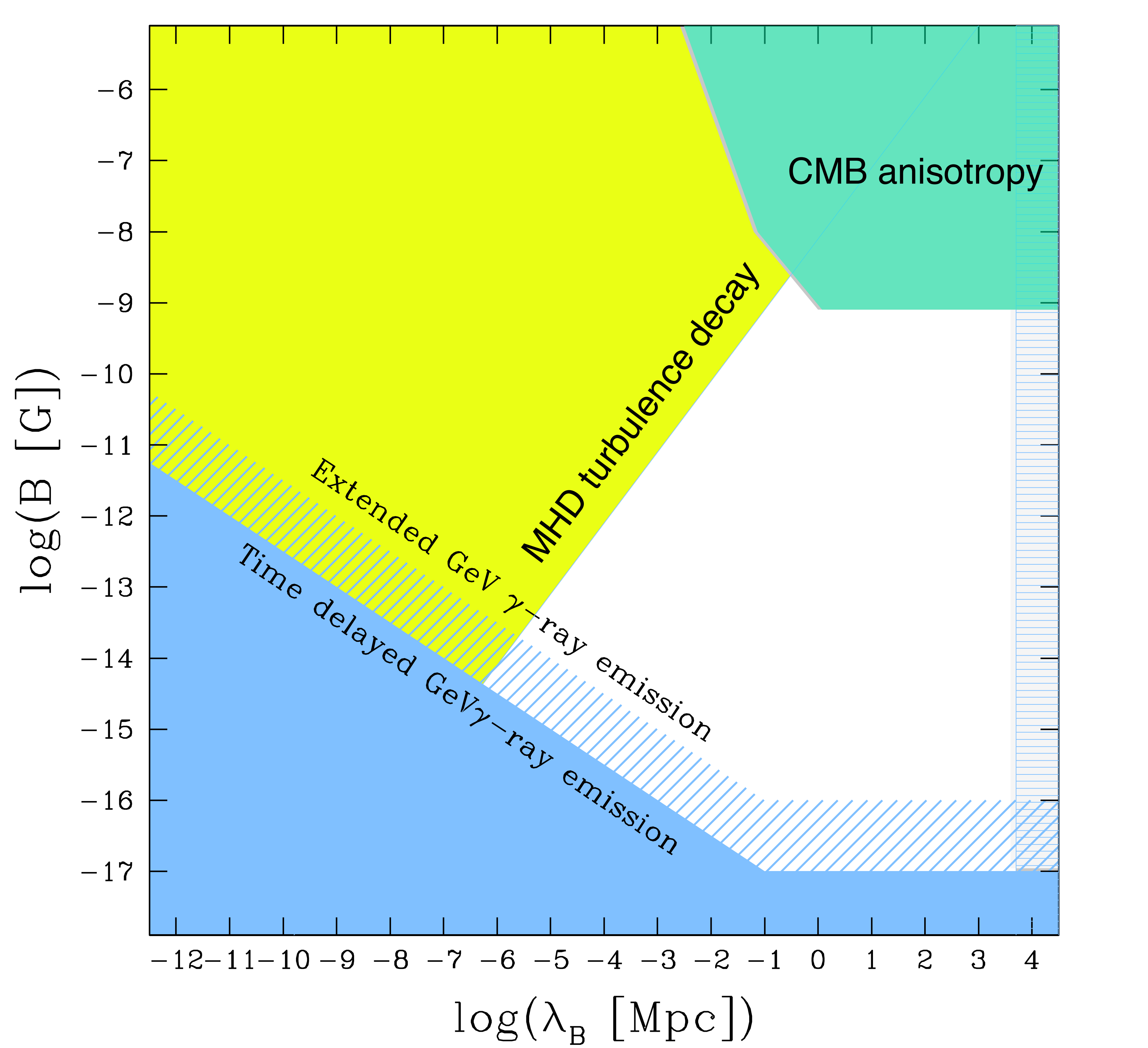
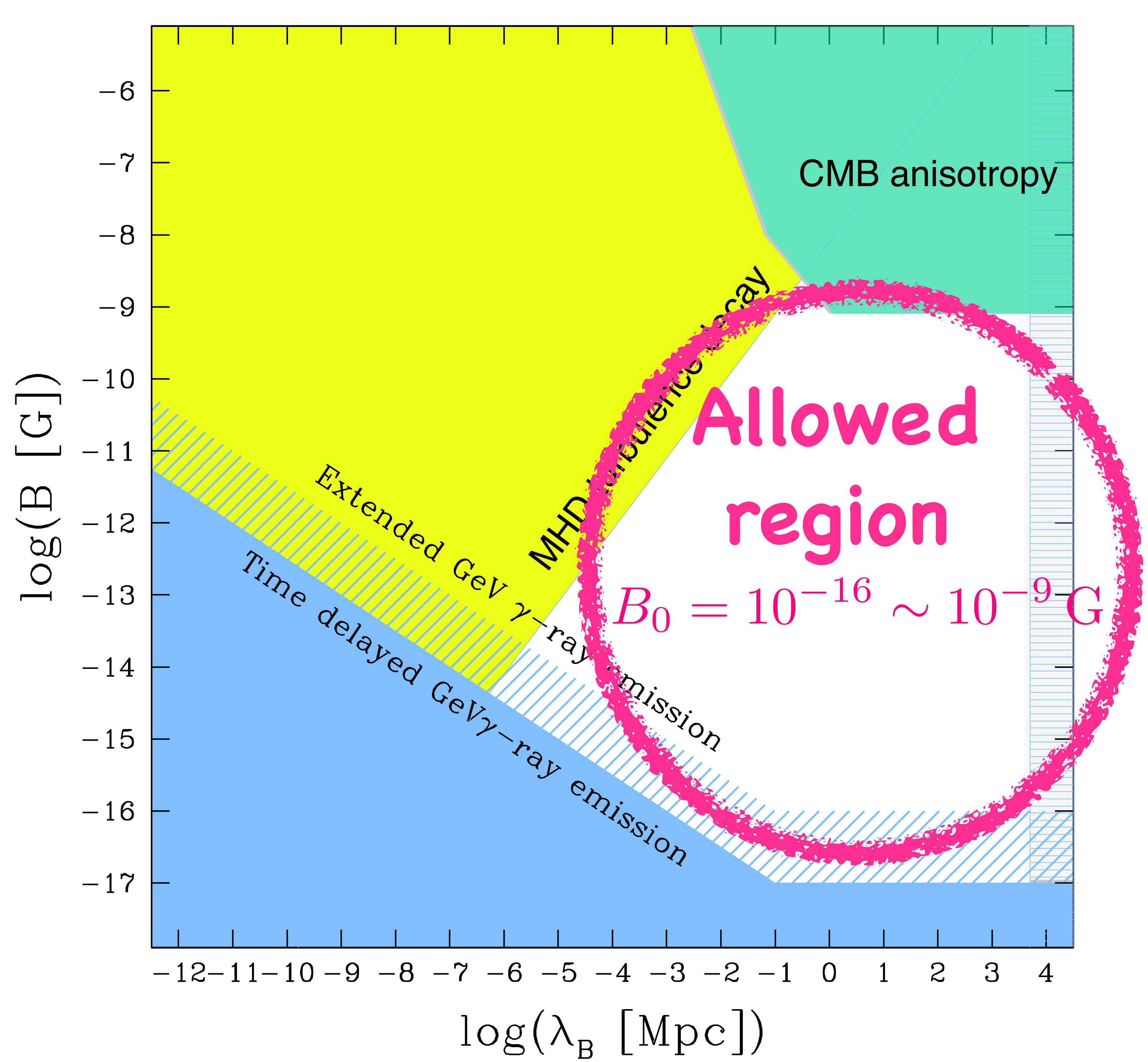
Intergalactic magnetic field



Durrer and Neronov 1303.7121

2013年7月22日月曜日

Intergalactic magnetic field



Durrer and Neronov 1303.7121

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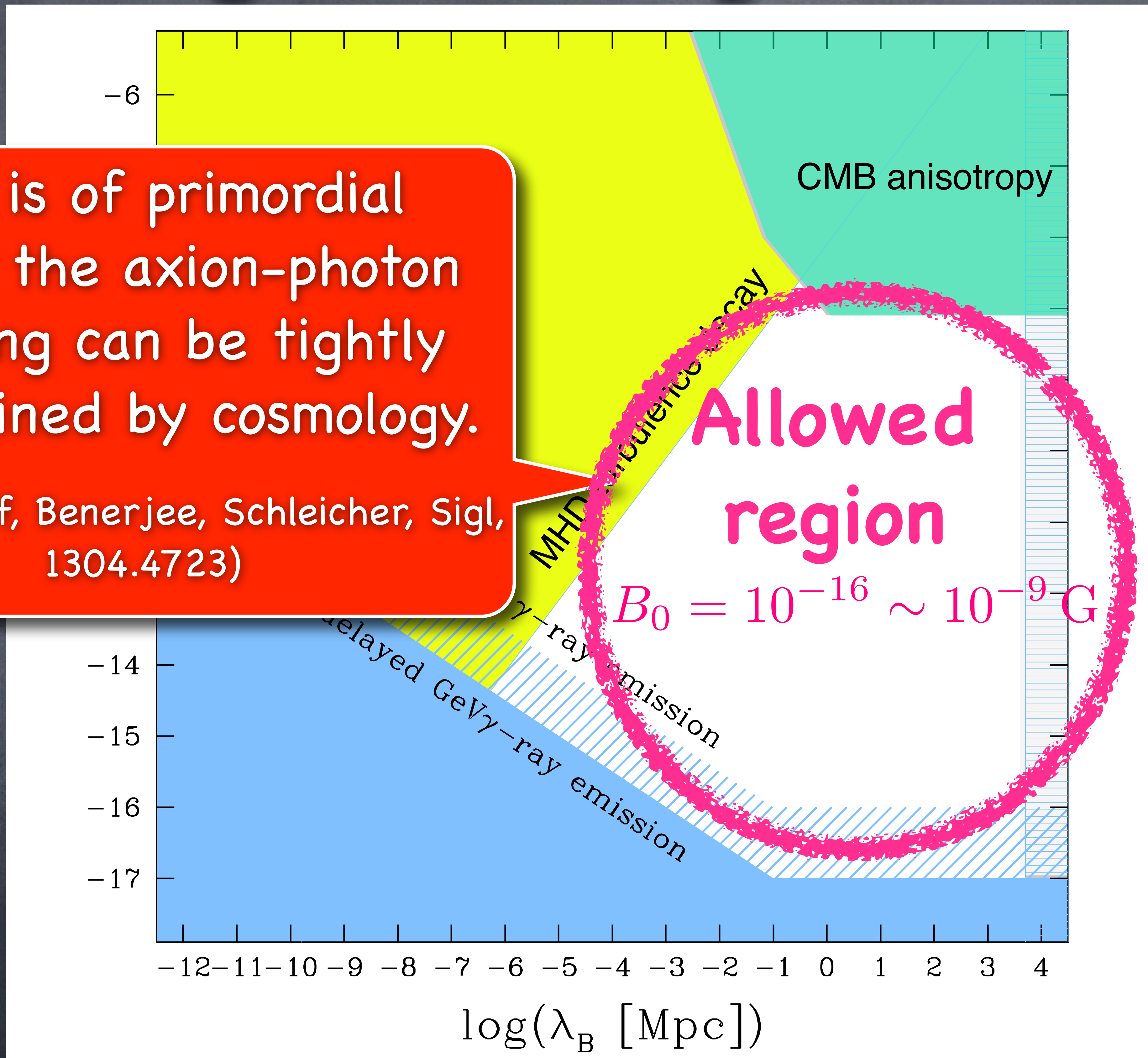
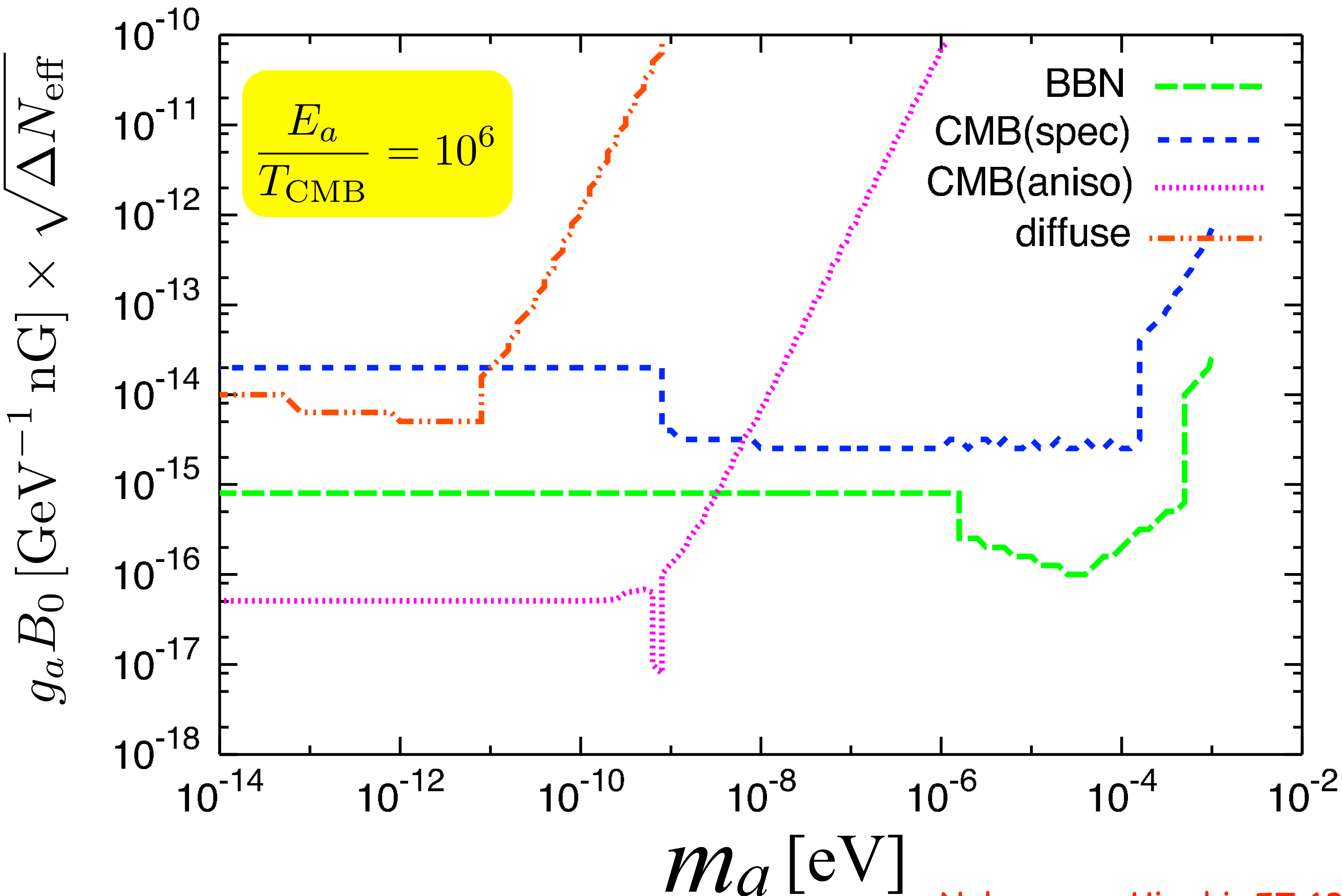
Intergalactic magnetic field

If B is of primordial origin, the axion-photon coupling can be tightly constrained by cosmology.

(cf. Wagstaff, Benerjee, Schleicher, Sigl, 1304.4723)



Durrer and Neronov 1303.7121



Nakayama, Higaki, FT 1306.6518

Typically, $g_a \lesssim 10^{-16}\,\mathrm{GeV}^{-1}\left(\frac{B_0}{1\,\mathrm{nG}}\right)^{-1}$

for $\Delta N_{\rm eff} = \mathcal{O}(0.1)$

Conclusions

- Precision cosmology will hopefully provide insight into fundamental physics such as strings. Tensor modes, DR, isocurvature, non-Gaussianity, etc.

✓ Tensor mode:

- Polynomial chaotic inflation can lead to n_s and r within 1 sigma allowed region.

✓ Dark radiation:

- Hidden gauge boson thermalized thru Higgs portal can be probed by invisible Higgs decay.
- Axion DR produced by moduli decays may be probed by the axion-photon conversion.