New constraints on small-scale primordial magnetic fields from Magnetic Reheating

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Based on

S.S, H.Tashiro, and S.Yokoyama [MNRAS 475 L52(2018)]

S.S, A.Ota, H.Tashiro, and S.Yokoyama in prep.

Outline

1. Introduction to PMFs
2. Reheating of the CMB photon
3. Magnetic Reheating
4. Summary

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1. Introduction to PMFs

Primordial Magnetic Fields(PMFs)

generated by cosmological phenomena in the early universe

Why we consider PMFs?

Observed (large-scale) magnetic fields

- Galaxy(~ kpc) ~ 10^{-5} - 10^{-6} Gauss
- Cluster(~ Mpc) ~ 10^{-6} Gauss
- Intergalactic(void) > 10^{-16} - 10^{-21} Gauss

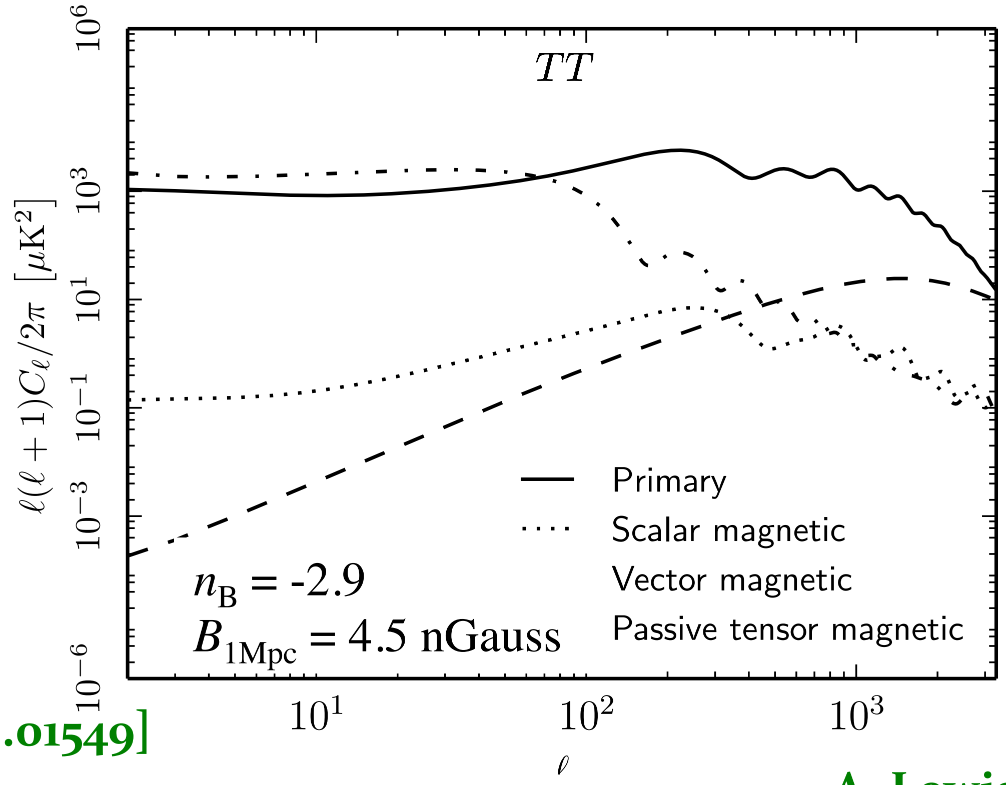
Setting seed fields in the early universe and amplifying

Cosmological constraint on PMFs

- CMB anisotropy
- CMB distortion
- Big Bang Nucleosynthesis (BBN)

1.1 Example(1) CMB anisotropy

PMFs generate CMB temperature and polarization anisotropies.



Planck 2015 [1502.01549]

A. Lewis [astro-ph/0406096]

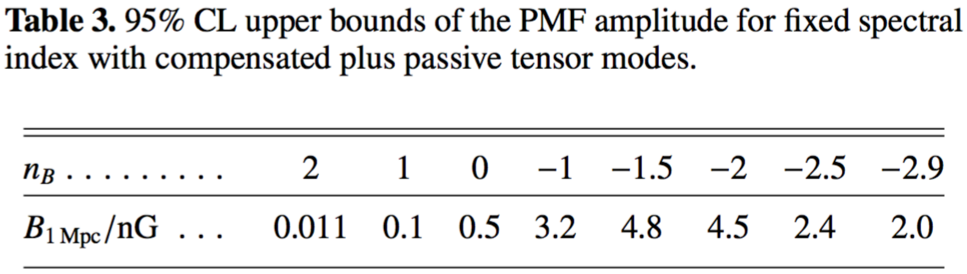


Table 3. 95% CL upper bounds of the PMF amplitude for fixed spectral index with compensated plus passive tensor modes.

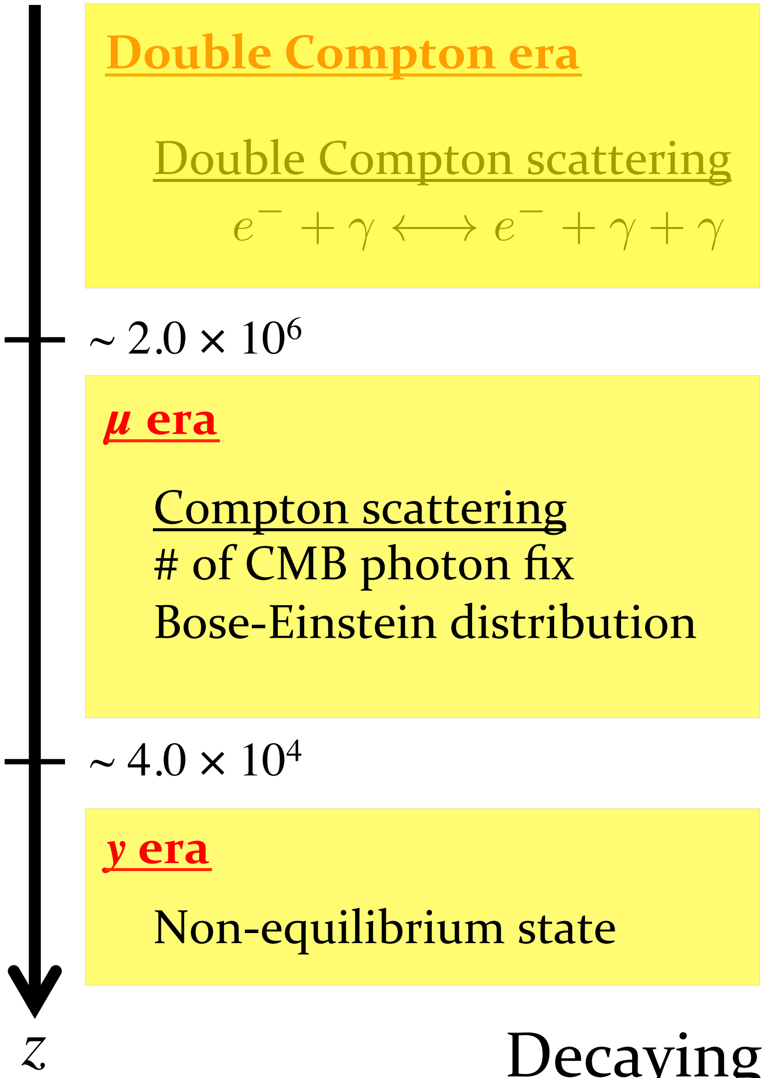
n_B	2	1	0	−1	−1.5	−2	−2.5	−2.9
$B_{1\,\mathrm{Mpc}}/\mathrm{nG}$ . . .	0.011	0.1	0.5	3.2	4.8	4.5	2.4	2.0

$$P_B(k) \propto k^{n_B}$$

~ O(nGauss)

1.2 Example(2) CMB distortion

J. Ganc and M. S. Sloth [1404.5957]
K. K. Kunze and E. Komatsu [1309.7994]



Double Compton era

Double Compton scattering

$$e^- + \gamma \longleftrightarrow e^- + \gamma + \gamma$$

~ 2.0×10^6

***μ* era**

Compton scattering
# of CMB photon fix
Bose-Einstein distribution

~ 4.0×10^4

***y* era**

Non-equilibrium state

z

Chemical potential

$$f(\epsilon) = \left[\exp\left(\frac{\epsilon - \mu}{k_{\mathrm{B}}T}\right) - 1\right]^{-1}$$

y-parameter

$$y = \frac{1}{12}\int \mathrm{d}z \frac{1}{\rho_\gamma}\frac{\mathrm{d}Q}{\mathrm{d}z}$$

Decaying of PMFs generates μ and y distortion
➔ From the observation of COBE, $B < O(\mathrm{nG})$.

1.3 Constraint on PMFs

In the cosmological observations,

n Gauss PMFs on Large Scale ($\gtrsim$ **Mpc)**

PMFs on **much smaller scales** ?

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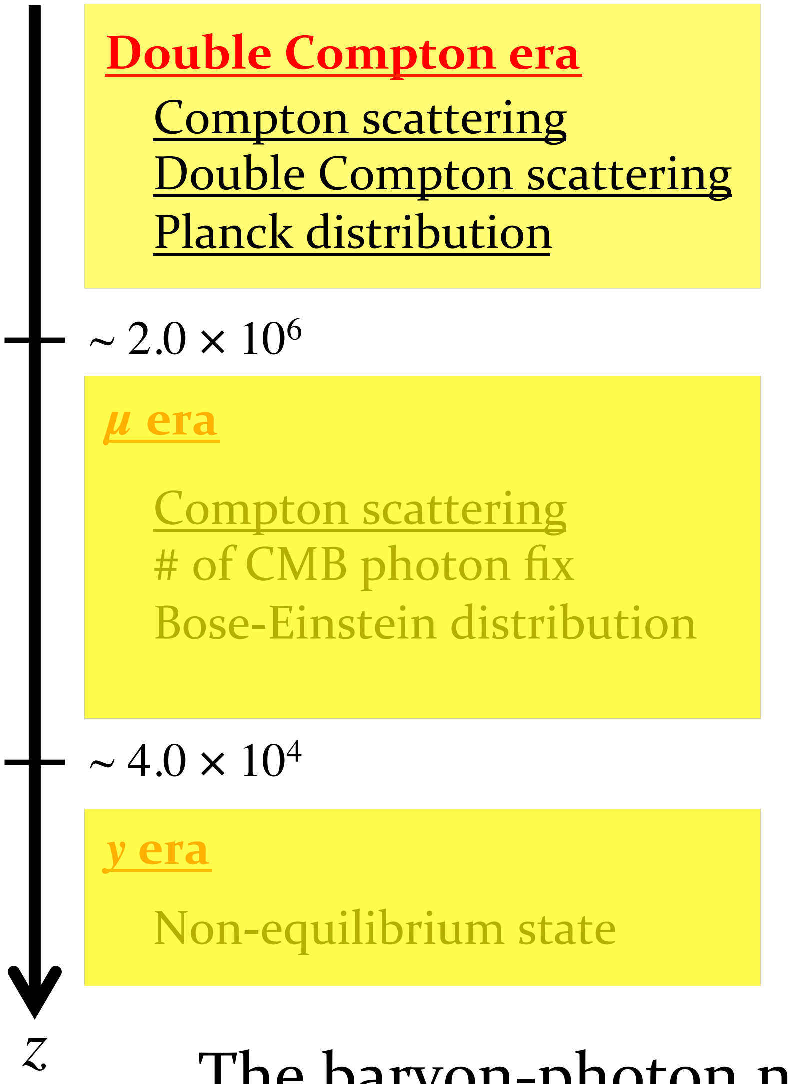
2. Reheating of the CMB photon



Double Compton era

Compton scattering
Double Compton scattering
Planck distribution

~ 2.0 × 10^6

***μ* era**

Compton scattering
# of CMB photon fix
Bose-Einstein distribution

~ 4.0 × 10^4

***y* era**

Non-equilibrium state

z

Before μ era, i.e., $\mathbf{2.0 \times 10^6 \lesssim 1 + z}$,

Double Compton scattering is efficient.

- Thermal equilibrium
- Planck distribution

An energy injection
increases # of CMB photons
while # of baryons does not change.

The baryon-photon number ratio η decreases. $\eta = \dfrac{n_{\rm b}}{n_\gamma}$

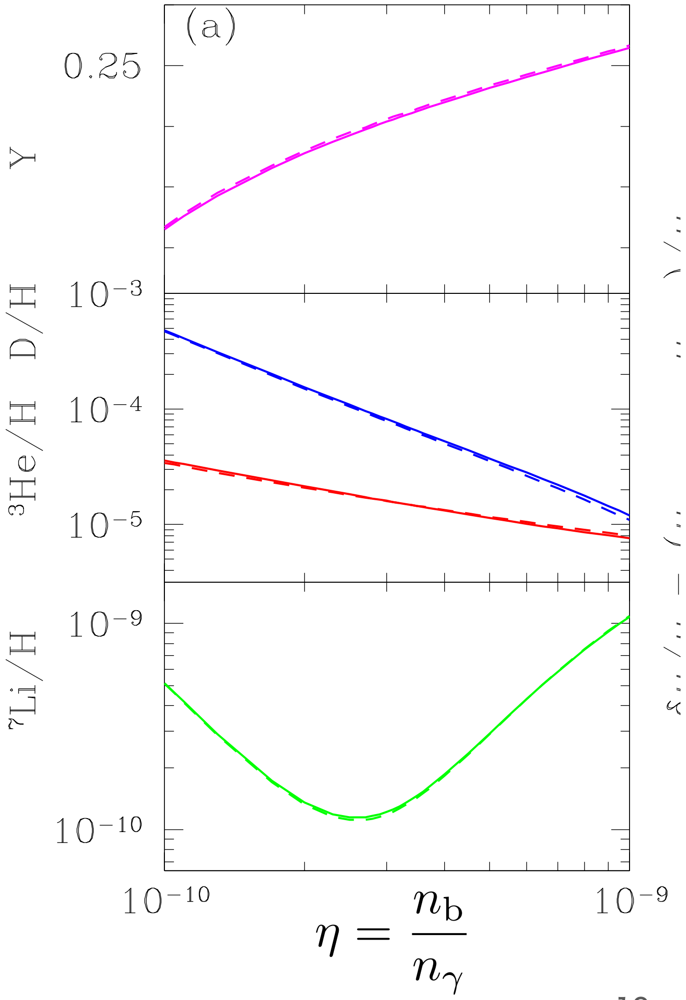
2.1 Baryon-photon ratio η

Baryon-photon ratio is independently constrained by BBN and CMB. **R.H.Cyburt, B.D.Fields, and K.A.Olive [astro-ph/0503065]**

η determines

➔ photon dissociation rate, reaction rate, and so on.

➔ abundance of light element generated in BBN era



Constrained value by BBN

$$\eta_{\mathrm{BBN}} = (6.19 \pm 0.21) \times 10^{-10}$$

K.M.Nollet and G.Steigman [1312.5725]

2.2 Baryon-photon ratio η

Baryon-photon ratio is determined independently by BBN and CMB.

From CMB observations,

- Temperature of CMB photons: T_{CMB}
- Density of baryons: Ω_{b0}

We can directly determine η

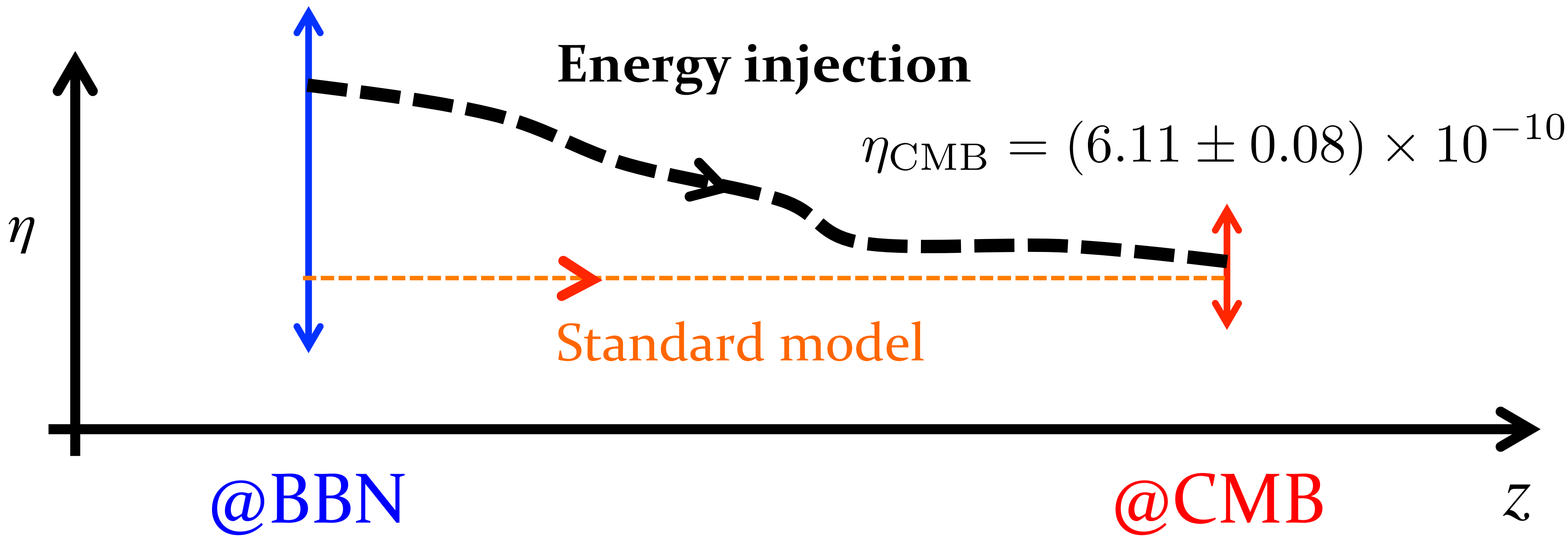
Constrained value by CMB (after the onset of the μ-era)

$$\eta_{\mathrm{CMB}} = (6.11 \pm 0.08) \times 10^{-10}$$

Planck 2013 [1303.5076]

2.3 Baryon-photon ratio *η*

$$\eta_{\mathrm{BBN}} = (6.19 \pm 0.21) \times 10^{-10}$$



Energy injection

$$\eta_{\mathrm{CMB}} = (6.11 \pm 0.08) \times 10^{-10}$$

Standard model

@BBN

@CMB

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3 Magnetic Reheating

Energy injection source = Diffusion of PMFs

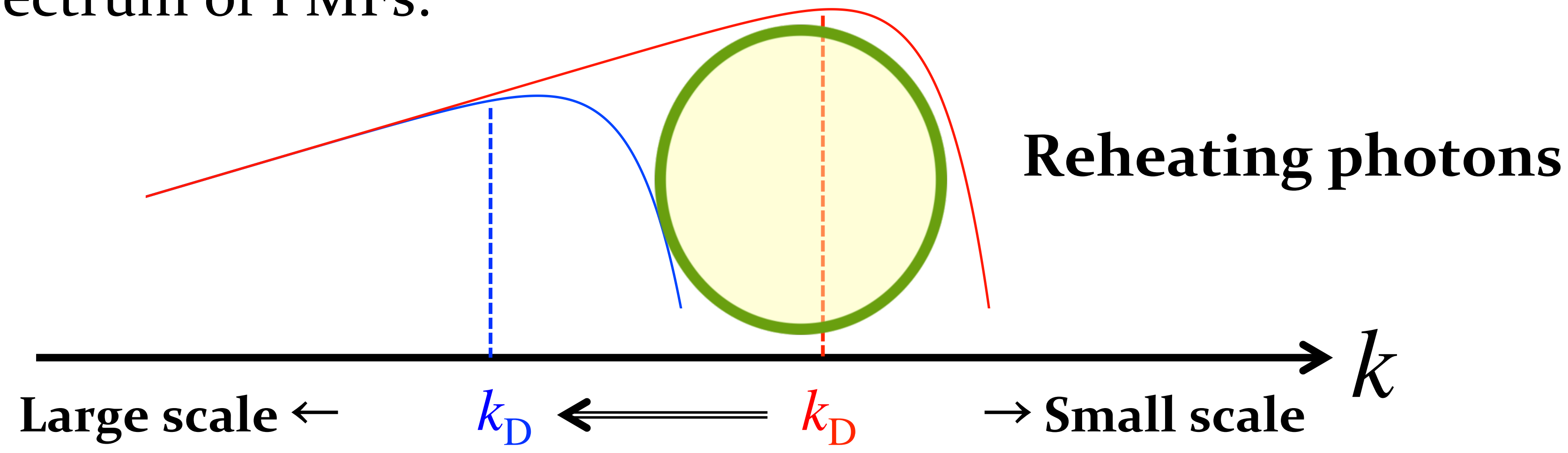
→ increasing n_γ (i.e., reheating)

MHD mode analysis

Example: Fast-magnetosonic mode

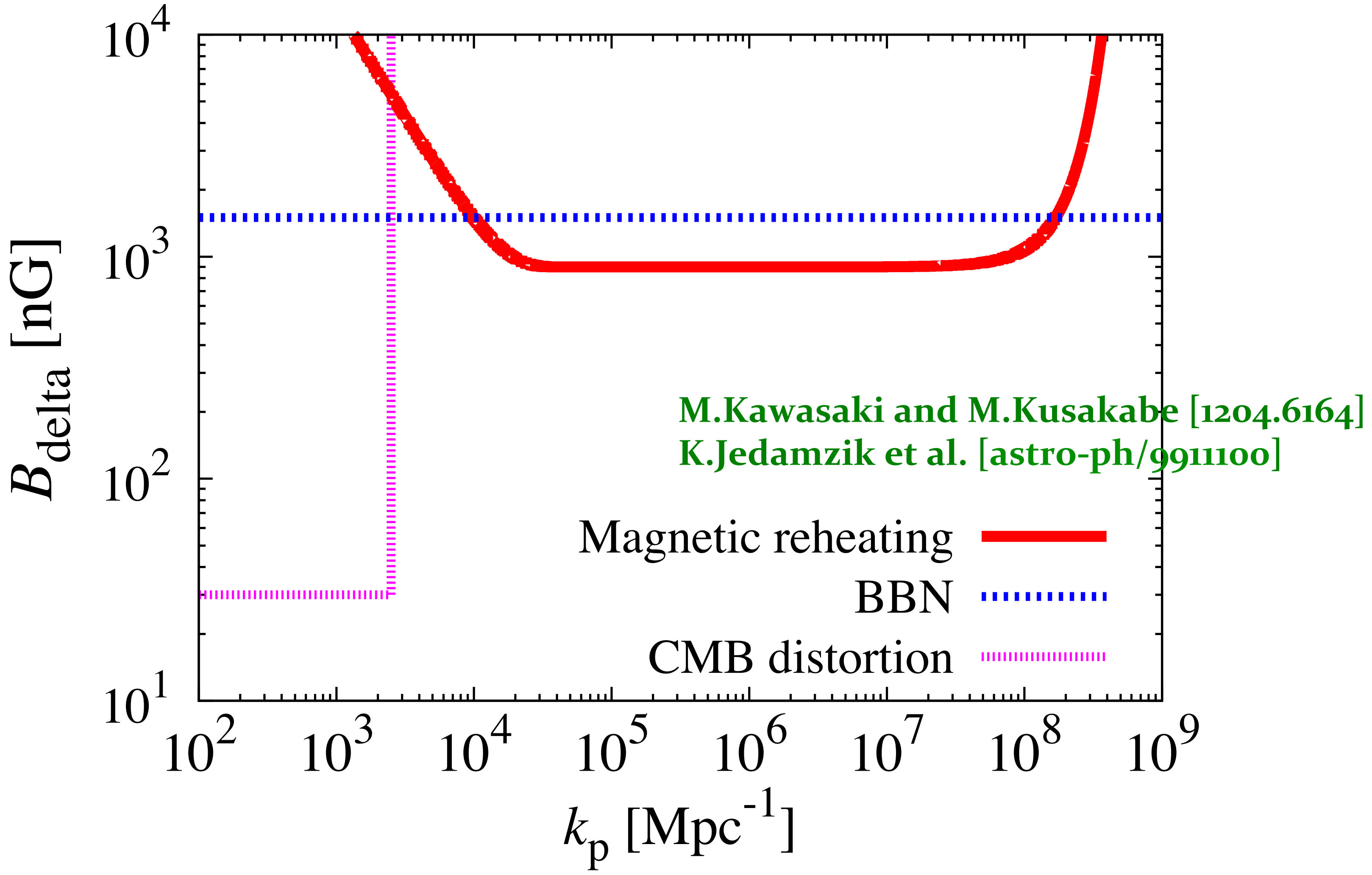
$$k_{\rm D}(z) \approx 7.44 \times 10^{-6} \underline{(1+z)^{3/2}}\ {\rm Mpc}^{-1} \sim k_{\rm Silk}(z)$$

Spectrum of PMFs:



3.1 Delta-function type

$$\mathcal{P}_B(k) = \underline{\mathcal{B}^2_{\rm delta}}\,\delta_{\rm D}(\ln(k/\underline{k_{\rm p}}))$$



M.Kawasaki and M.Kusakabe [1204.6164]
K.Jedamzik et al. [astro-ph/9911100]

3.2 Power-law type (Upper bound)

$$\mathcal{P}_B(k) = \underline{\mathcal{B}^2}\left(\frac{k}{k_0}\right)^{\underline{n_B}+3} \qquad k_0 = 1\ \mathrm{Mpc}^{-1}$$

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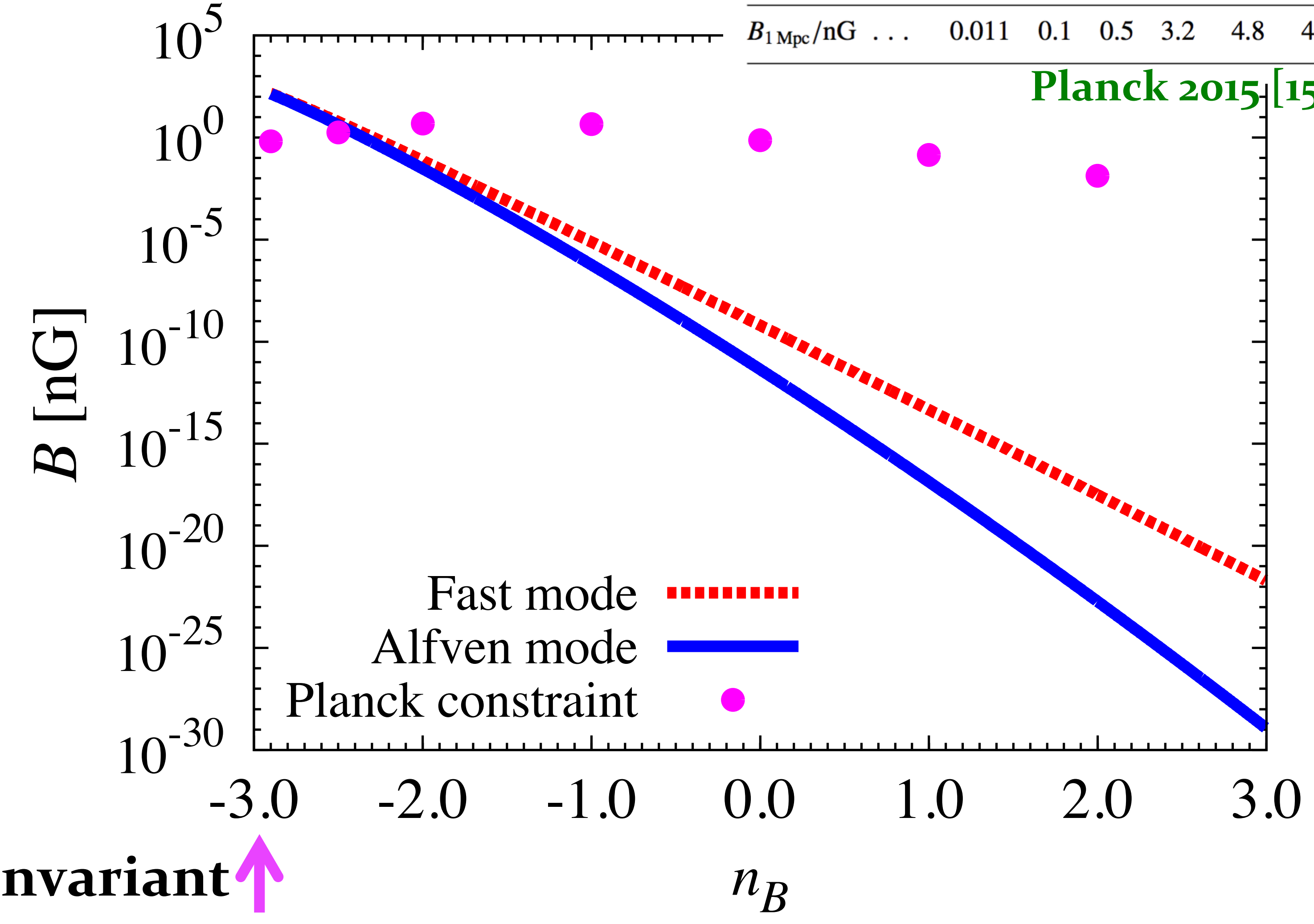
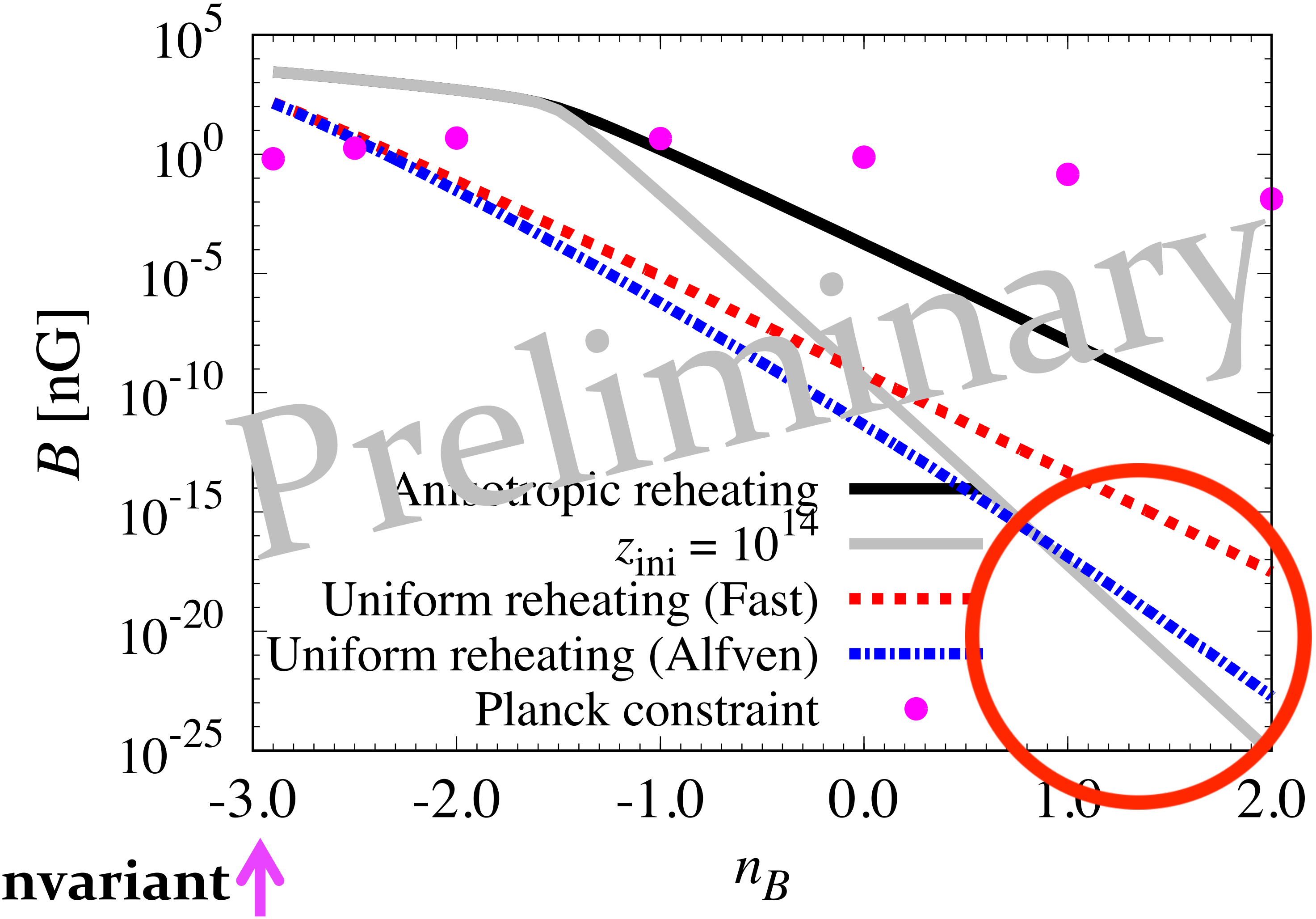


Scale-invariant ↑

3.3 Anisotropic reheating(Preliminary)

$$\mathcal{P}_B(k) = \mathcal{B}^2 \left(\frac{k}{k_0}\right)^{n_B+3} \qquad k_0 = 1\ \mathrm{Mpc}^{-1}$$



Scale-invariant ↑

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Magnetic Reheating is the novel mechanism to explore **small-scale PMFs**.

In the case of power-law type spectrum, bluer tilt is strongly constrained:

for example,

$$B \lesssim 10^{-17}\,\mathrm{nG} \quad \mathrm{for} \quad n_{\mathrm{B}} = 1.0$$

$$10^{-23}\,\mathrm{nG} \quad \mathrm{for} \quad n_{\mathrm{B}} = 2.0$$

⇔ Planck ~ O(1.0 nG) !!!

+ Magnetic anisotropic reheating?