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

Shohei Saga (YITP, Kyoto University)

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with Hiroyuki Tashiro (Nagoya U.) and Shuichiro Yokoyama (Rikkyo U.)

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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 (before recombination)

Vachaspati's talk

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

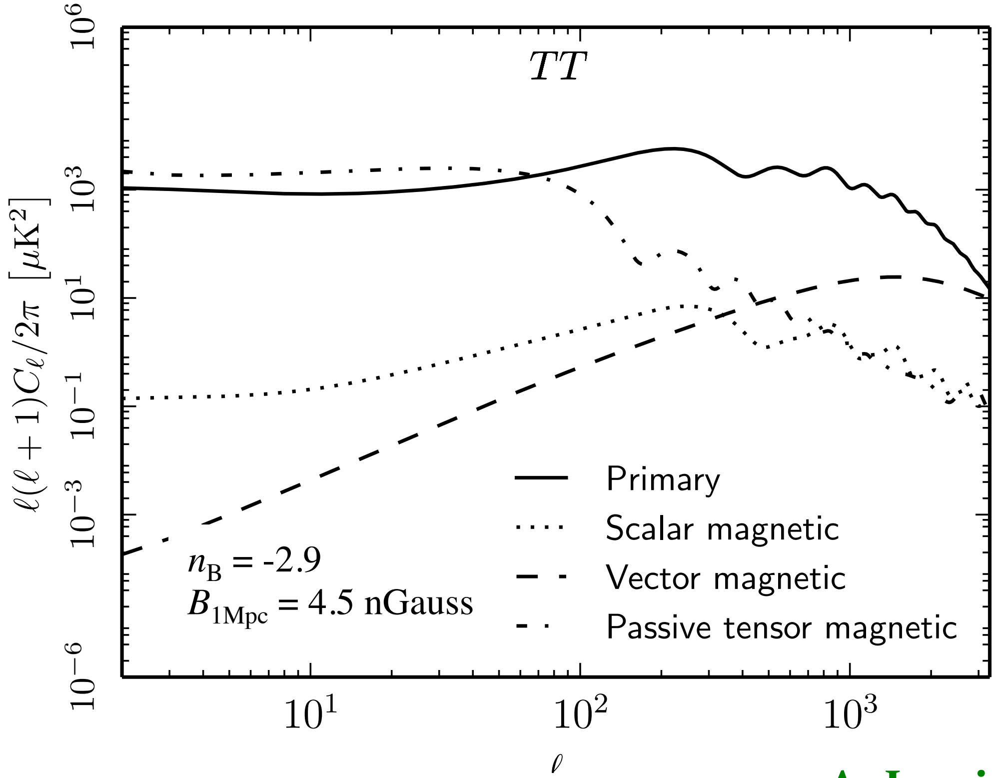
Setting seed fields in the early universe and amplifying

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.



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
$B_{1\,\mathrm{Mpc}}$/nG . . .	0.011	0.1	0.5	3.2	4.8	4.5	2.4	2.0

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

Planck 2015 [1502.01549]

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

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

$\sim 2.0 \times 10^6$

***μ* era**

Compton scattering
# of CMB photon fix
Bose-Einstein distribution

$\sim 4.0 \times 10^4$

***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 (> 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

During the Double Compton era, i.e., $\mathbf{2.0 \times 10^6 < 1 + z}$,

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. $\eta = \frac{n_b}{n_\gamma}$

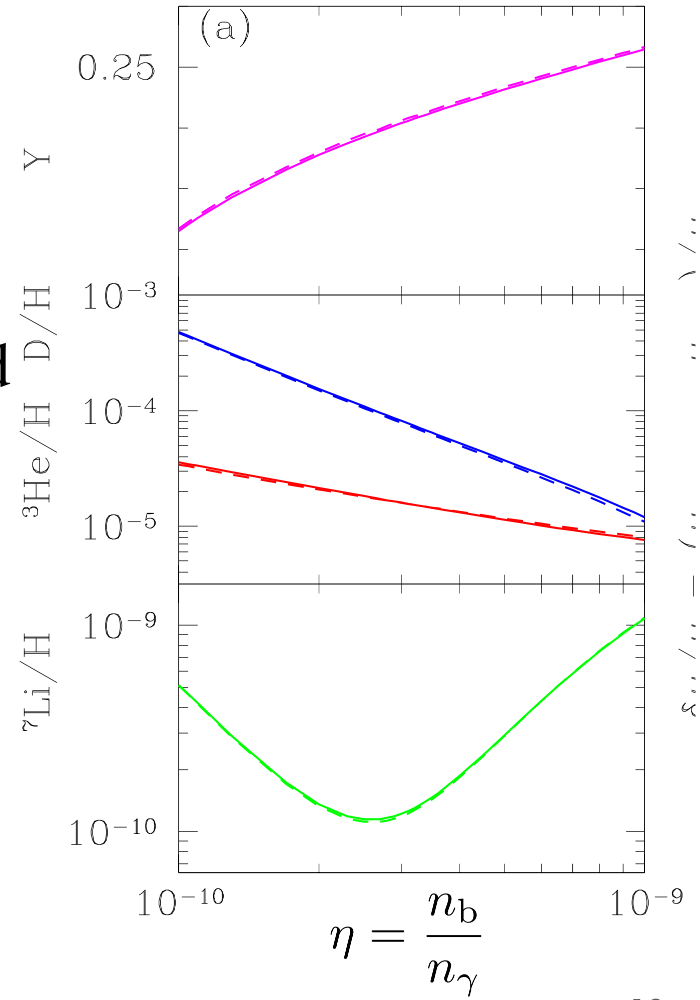
2.1 Baryon-photon ratio η

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



<u>BBN constrained value</u>

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

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

2.2 Baryon-photon ratio η

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

By CMB observations,

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

We can directly determine η

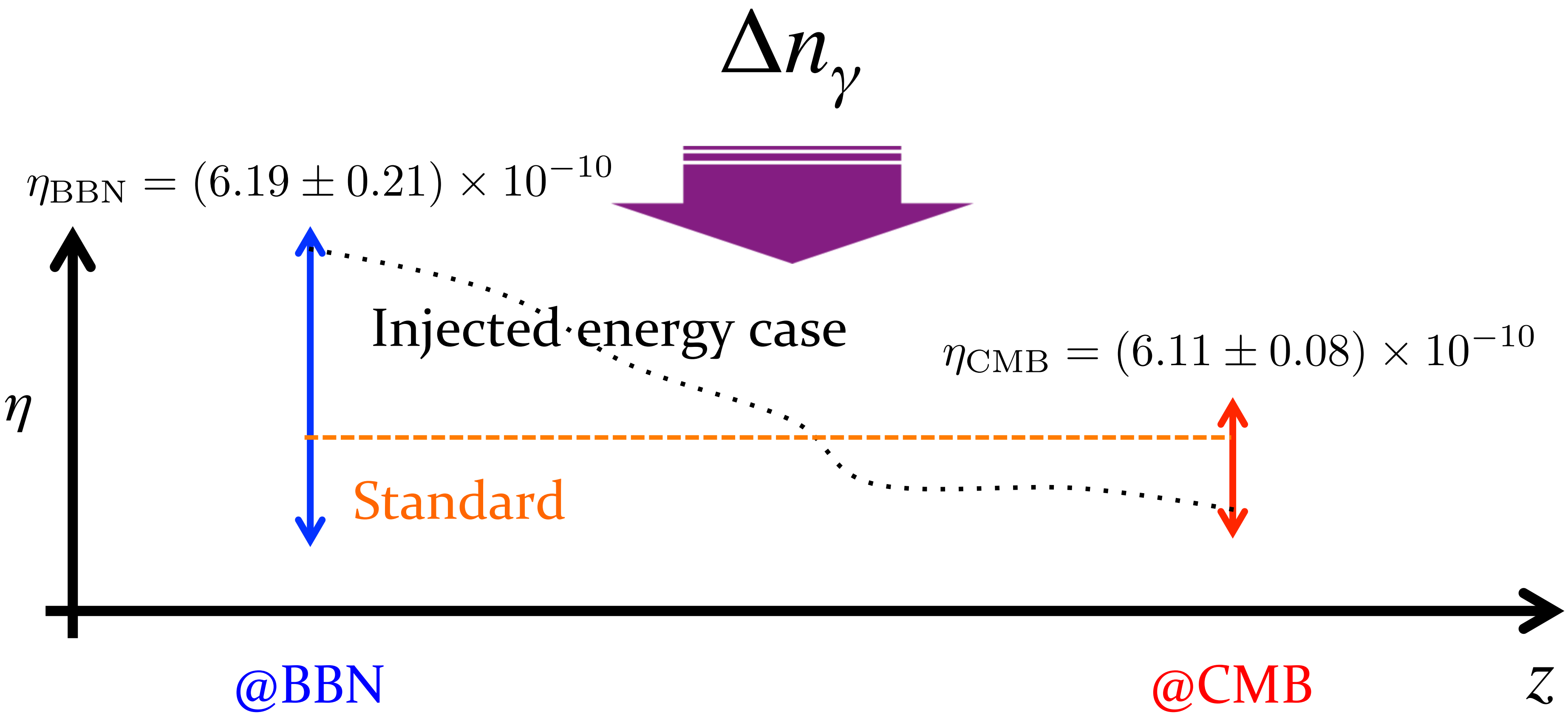
CMB (after the onset of the μ-era) constrained value

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

Planck 2013 [1303.5076]

2.3 Baryon-photon ratio η

Energy injection ⇔ increasing n_γ (“reheating”)
⇔ decreasing η



2.4 Baryon-photon ratio η

We assume increasing photon number density Δn_γ,

$$\frac{\eta_{\rm CMB}}{\eta_{\rm BBN}} = \frac{n_{\gamma\rm BBN}}{n_{\gamma\rm CMB}} = \left(1 - \frac{3}{4}\frac{\Delta\rho_\gamma}{\rho_\gamma}\right) > \frac{\eta^{\rm obs}_{\rm CMB}}{\eta^{\rm obs}_{\rm BBN}} = \frac{(6.11 - 0.08)\times 10^{-10}}{(6.19 + 0.21)\times 10^{-10}}$$

⇩

Allowed energy injection in terms of photon's energy density:

$$\frac{\Delta\rho_\gamma}{\rho_\gamma} < 7.71 \times 10^{-2}$$

Arbitrary energy injection into the CMB photon:

$$\frac{\Delta\rho_\gamma}{\rho_\gamma} = \int_{z_{\rm f}}^{z_{\rm i}} \frac{1}{a^4\rho_\gamma}\frac{{\rm d}\left(a^4 Q_{\rm in}\right)}{{\rm d}z}{\rm d}z$$

Q_{in} = **Diffusion of PMFs ➔ Magnetic Reheating**

c.f., Q_{in} = Diffusion of density perturbations ➔ Acoustic Reheating

D.jeong, J.Pradler, J.Chluba, and M.Kamionkowski [1403.3697]
T.Nakama, T.Suyama, and J.Yokoyama [1403.5407]

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3 Results: Magnetic Reheating

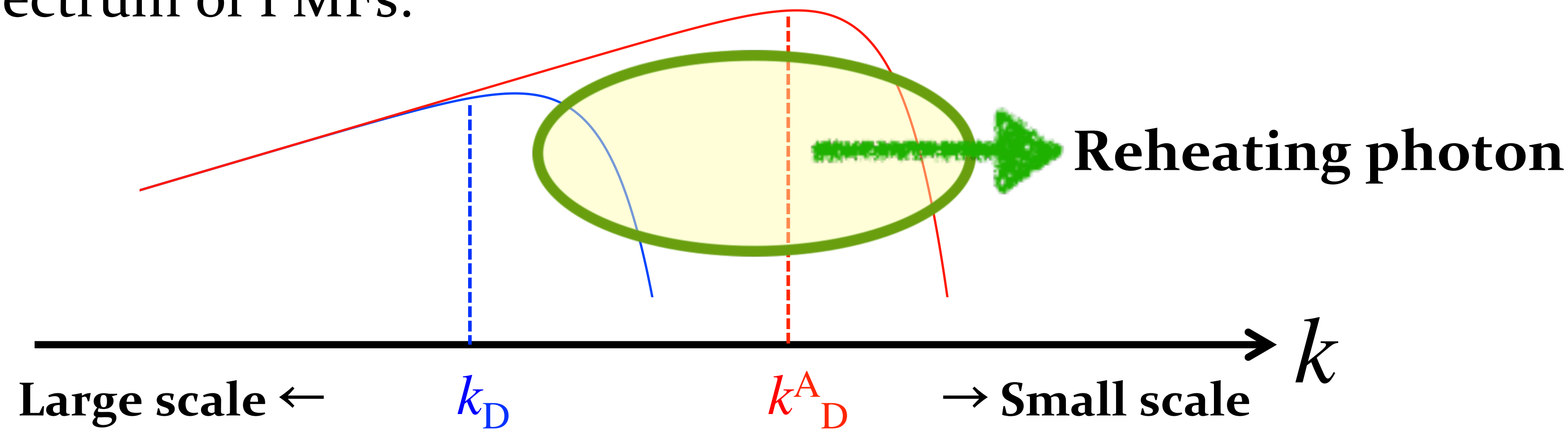
MHD mode analysis: Fast-magnetosonic mode

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

Slow-magnetosonic and Alfven modes

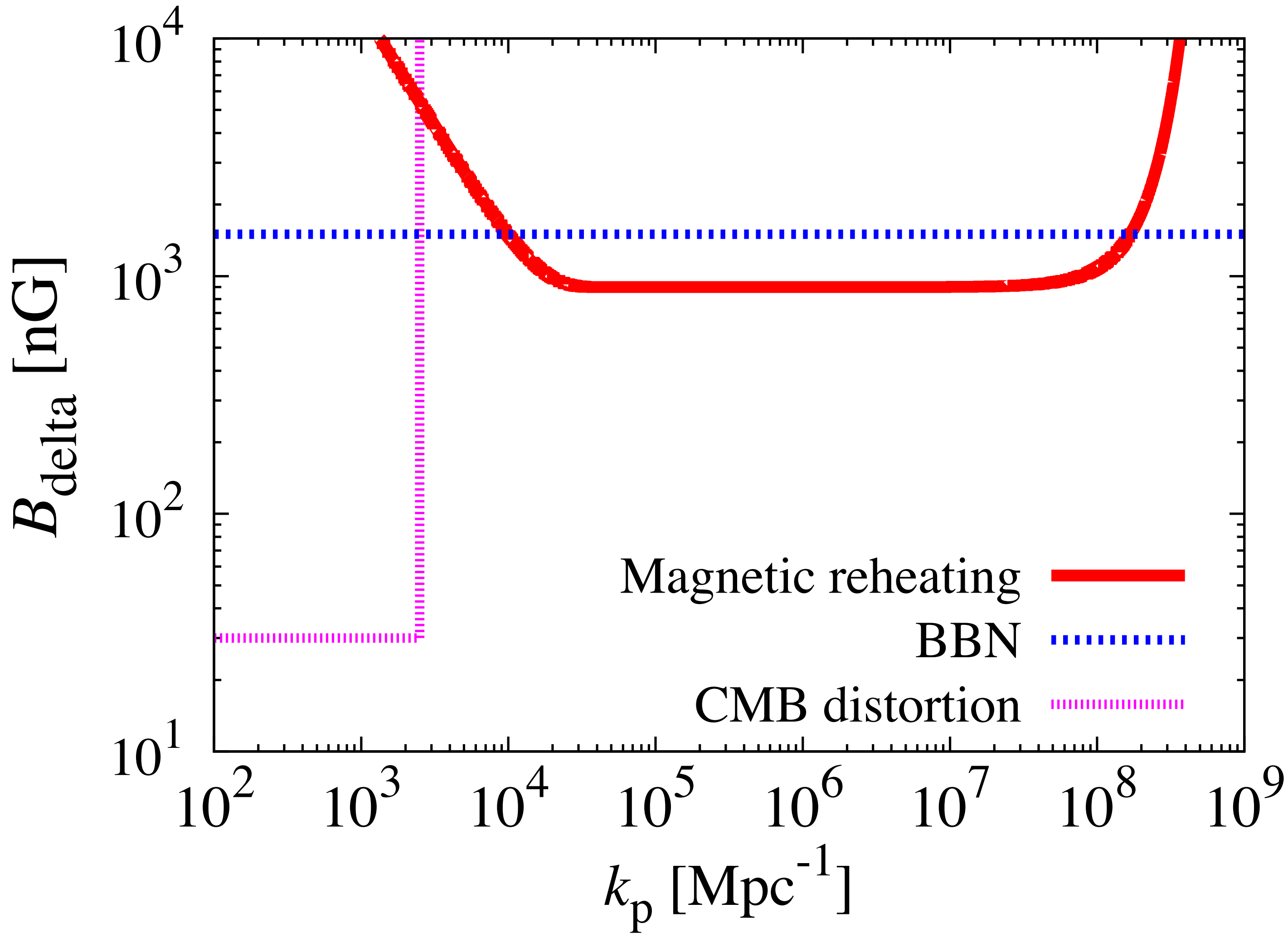
$$k_{\rm D}^{\rm A}(z) \approx k_{\rm D}(z)/V_{\rm A}(z)$$

Spectrum of PMFs:



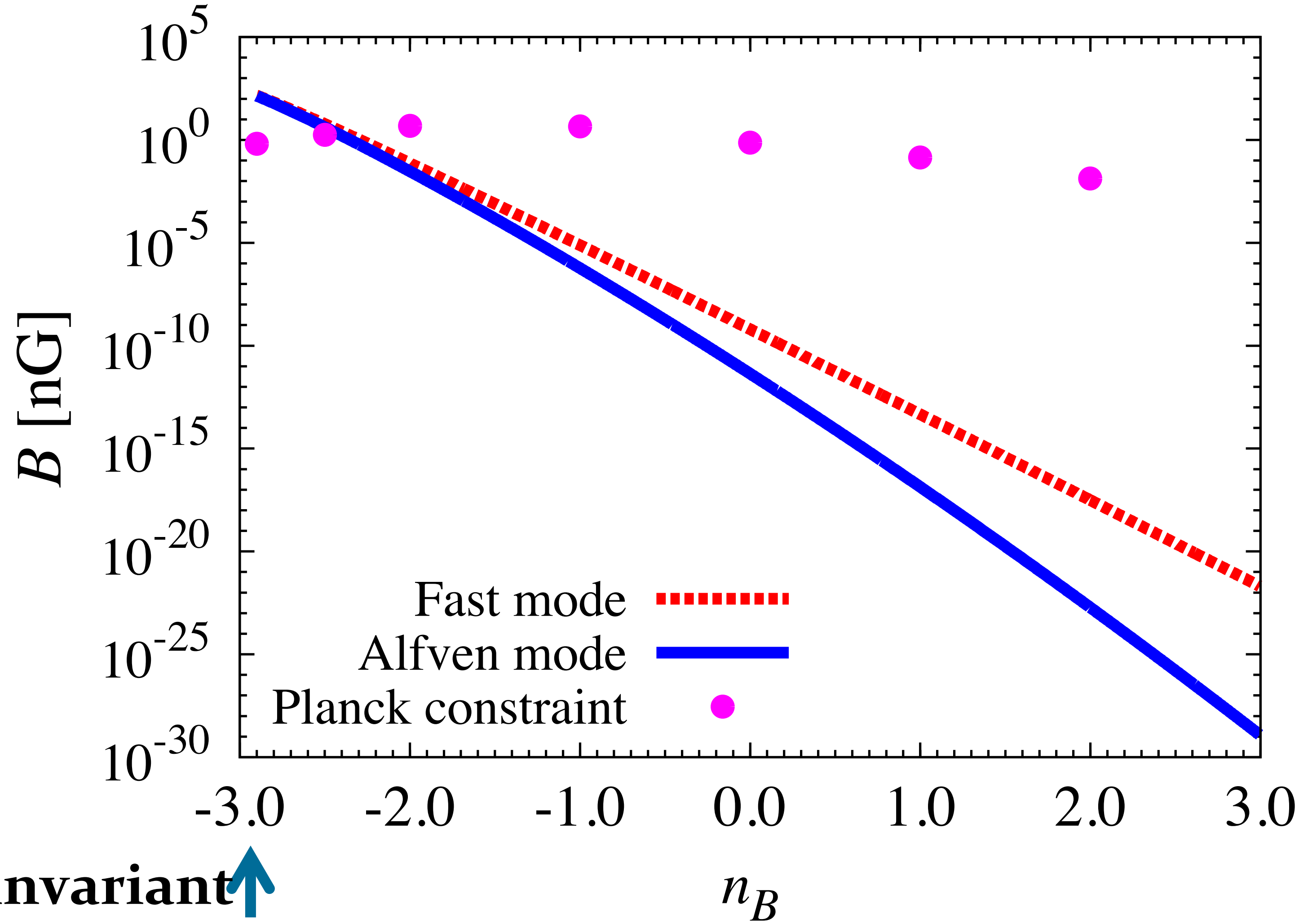
3.1 Delta-function type

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



3.2 Power-law type (Upper bound)

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



Scale-invariant

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

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

for example,

$$B \lesssim 10^{-17}\ \mathrm{nG}\ \text{for}\ n_{\mathrm{B}} = 1.0$$
$$10^{-23}\ \mathrm{nG}\ \text{for}\ n_{\mathrm{B}} = 2.0$$
$$10^{-29}\ \mathrm{nG}\ \text{for}\ n_{\mathrm{B}} = 3.0$$

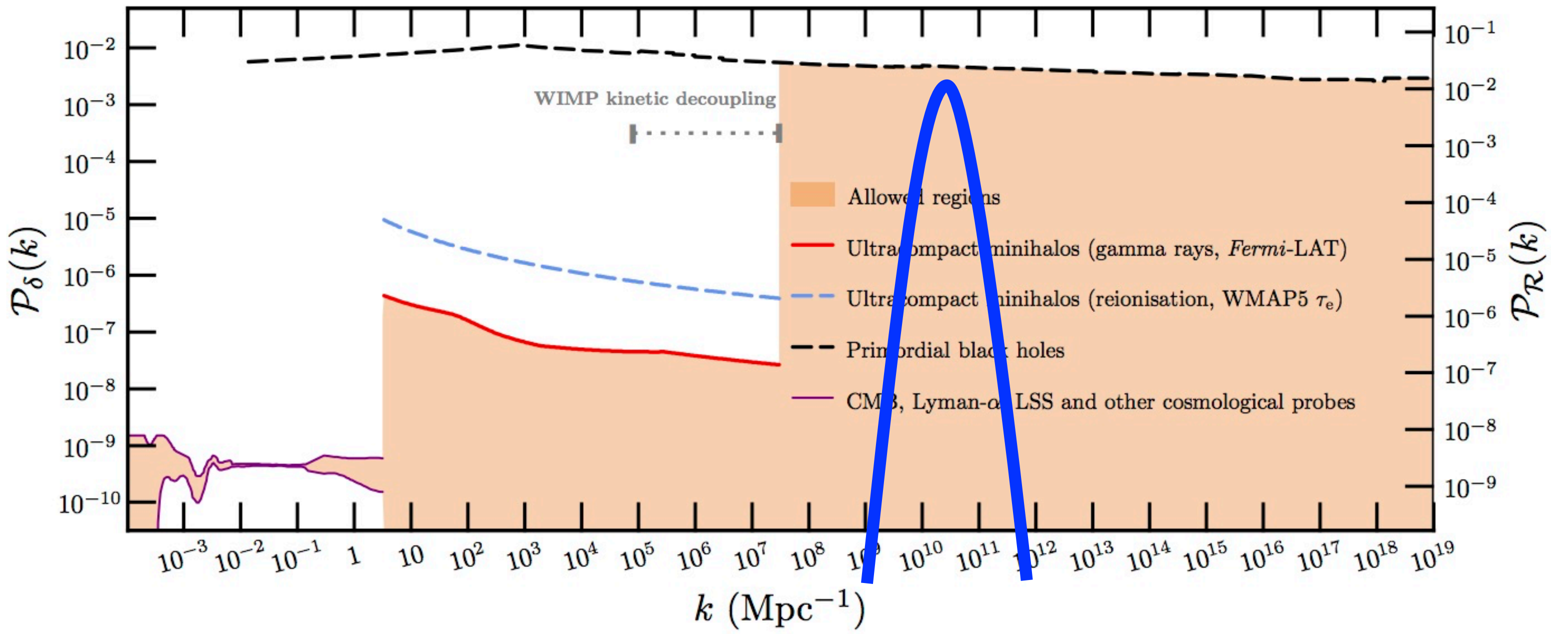
⇔ Planck ~ O(1.0 nG) !!!

2.5 Acoustic Reheating

$$\frac{\Delta\rho_\gamma}{\rho_\gamma} < 7.71 \times 10^{-2} \qquad \frac{\Delta\rho_\gamma}{\rho_\gamma} = \int_{z_\mathrm{f}}^{z_\mathrm{i}} \frac{1}{a^4\rho_\gamma}\frac{\mathrm{d}\left(a^4 Q_\mathrm{in}\right)}{\mathrm{d}z}\mathrm{d}z$$

This limit can be rewritten in the amplitude of the primordial power spectrum:

Scale-invariant power spectrum gives **negligible reheating**.



T.Bringmann et al.[1110.2484]

2.6 Acoustic Reheating

$$\frac{\Delta\rho_\gamma}{\rho_\gamma} < 7.71 \times 10^{-2} \qquad \frac{\Delta\rho_\gamma}{\rho_\gamma} = \int_{z_\mathrm{f}}^{z_\mathrm{i}} \frac{1}{a^4\rho_\gamma} \frac{\mathrm{d}\left(a^4 Q_\mathrm{in}\right)}{\mathrm{d}z} \mathrm{d}z$$

Silk damping case:

$$\frac{1}{a^4\rho_\gamma} \frac{\mathrm{d}(a^4 Q_\mathrm{Silk})}{\mathrm{d}z} \sim 9.4a \int \frac{k\mathrm{d}k}{k_\mathrm{D}^2(z)} \mathcal{P}_\mathcal{R}(k) 2\sin^2(kr_\mathrm{s}) e^{-2k^2/k_\mathrm{D}^2(z)}$$

➔ Large amplitude on small scales

$$\Delta_\mathcal{R}^2 < 0.3 \text{ at } k \sim 10^{20-25}\ \mathrm{Mpc}^{-1}$$

T.Nakama, T.Suyama, and J.Yokoyama [1403.5407]

$$\Delta_\mathcal{R}^2 < 0.007 \text{ at } k \sim 10^{4-5}\ \mathrm{Mpc}^{-1}$$

D.jeong, J.Pradler, J.Chluba, and M.Kamionkowski [1403.3697]

Q_in = **Diffusion of PMFs ➔ Magnetic Reheating**

3.2 Diffusion of PMFs

In the damping PMF case,

$$\frac{\Delta\rho_\gamma}{\rho_\gamma} = -\int_{z_\mathrm{f}}^{z_\mathrm{i}} \mathrm{d}z \left[-\frac{1}{\rho_\gamma(z)} \frac{1}{8\pi a^4} \frac{\mathrm{d}}{\mathrm{d}z} \left\langle |\boldsymbol{b}(z,\boldsymbol{x})|^2 \right\rangle \right]$$

Injection energy due to PMFs is given as

$$\left\langle |\boldsymbol{b}(z,\boldsymbol{x})|^2 \right\rangle = \int \frac{\mathrm{d}k}{k} \mathcal{P}_B(k) e^{-2\left(\frac{k}{k_\mathrm{D}(z)}\right)^2}$$

Power spectrum: $\left\langle \tilde{b}_i(\boldsymbol{k}) \tilde{b}_j(\boldsymbol{k'}) \right\rangle = (2\pi)^3 \delta_\mathrm{D}^3(\boldsymbol{k}+\boldsymbol{k'}) \frac{2\pi^2}{k^3} \frac{\delta_{ij} - \hat{k}_i \hat{k}_j}{2} \mathcal{P}_B(k)$

c.f.) Silk damping $\frac{1}{a^4\rho_\gamma} \frac{\mathrm{d}(a^4 Q_\mathrm{Silk})}{\mathrm{d}z} \sim 9.4a \int \frac{k\mathrm{d}k}{k_\mathrm{D}^2(z)} \mathcal{P}_\mathcal{R}(k) 2\sin^2(kr_\mathrm{s}) e^{-2k^2/k_\mathrm{D}^2(z)}$

D.jeong, J.Pradler, J.Chluba, and M.Kamionkowski [1403.3697]
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3. Magnetic Reheating

PMFs lose their amplitude on small scales through the dissipation process due to the photon viscosity.

Solution of the MHD mode: $$\omega \sim v_{\rm A}\left(\frac{k}{a}\right) + i l_\gamma \left(\frac{k}{a}\right)^2$$

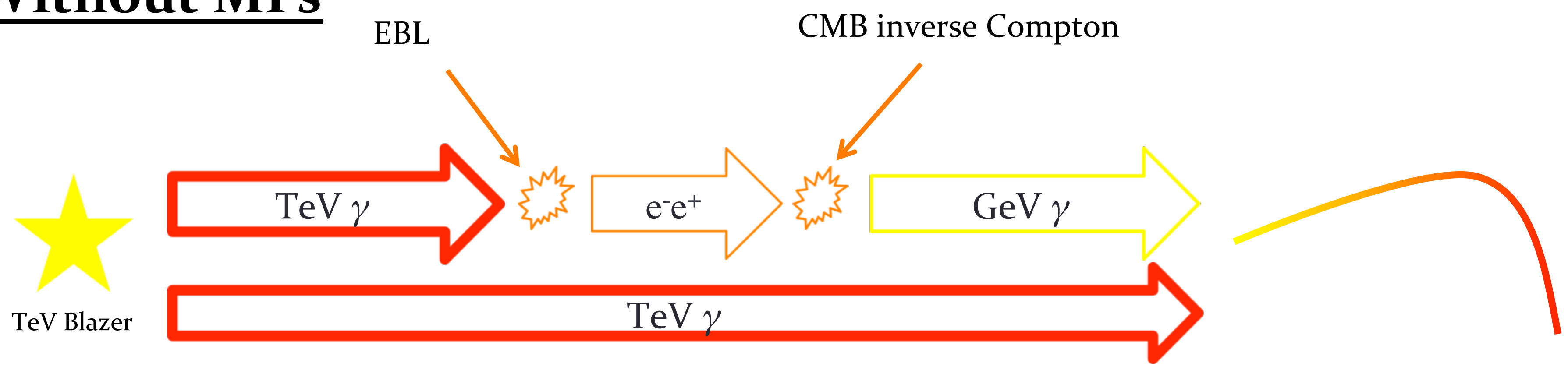
Oscillation Diffusion

Diffusion of PMFs: $$\boldsymbol{b}(z, \boldsymbol{k}) = \tilde{\boldsymbol{b}}(\boldsymbol{k}) \exp\left[-\left(\frac{k}{k_{\rm D}(z)}\right)^2\right]$$

Diffusion scale is very small (~Silk scale) ➔ Small-scale PMFs

Blazer observation

Without MFs



With MFs