A constraint on primordial magnetic fields from 21-cm line observation

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Today's Outline

1. Introduction
   - Primordial Magnetic Fields (PMFs)
   - 21-cm global signal
   - IGM thermal history in Dark Age

2. Theory and Methods
   - Statistical property of PMFs
   - MHD dissipation and heating IGM

3. Results
   - IGM thermal history with PMFs
   - A constraint on the PMFs

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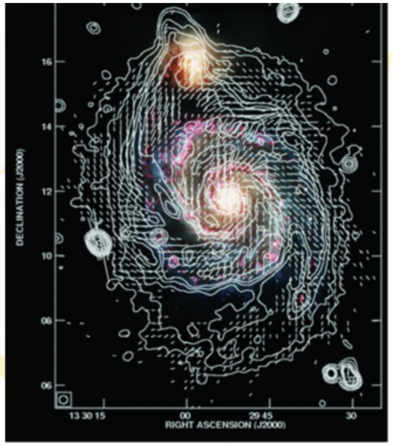
Primordial Magnetic Fields

Various structures in the universe is magnetized.

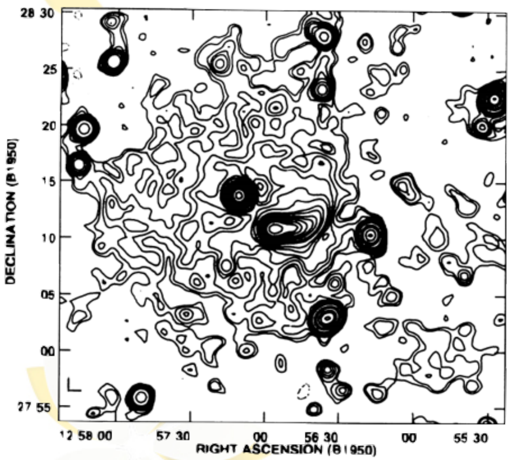
✓Galaxies ~ 1-100 μG
✓Galaxy Clusters ~ 0.1-10 μG

✓Voids (Intergalactic region)
~ $10^{-15} - 10^{-20}$ G

Recently, existence of magnetic fields in low-density region is suggested by gamma-ray from TeV blazars
(Ando & Kusenko 2010; Neronov & Vovk 2010)



M51 galaxy [visible & radio]
VLA/Effelsberg 20cm, HST
(Fletcher+, 2011, MNRAS, 412)



Coma cluster [radio] WSRT, 90cm
(Giovannini+, 1993, ApJ, 406)

These large-scale magnetic fields can be generated in the early universe.
(inflation, phase transition, topological defects, Harrison mechanism, …)

= Primordial Magnetic Fields (PMFs)

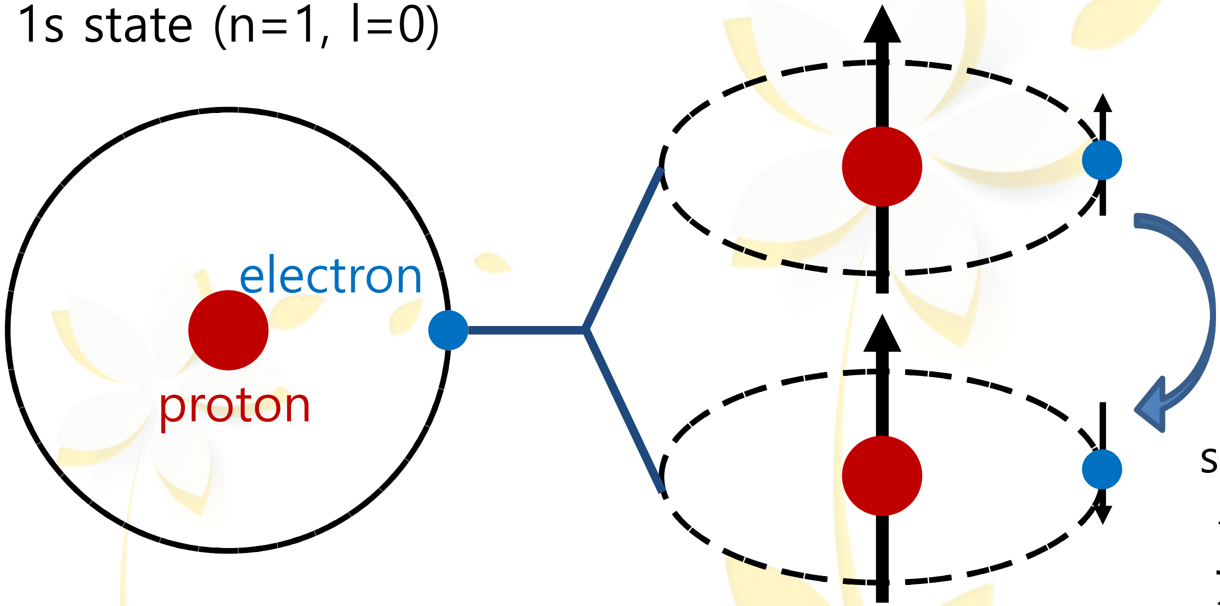
(Kandus+ 2011; Subramanian 2016)

What is 21-cm line?

A radio wave due to hyperfine structure of neutral hydrogen HI

A neutral hydrogen
1s state (n=1, l=0)

Hyperfine structure



$$\Delta E = 5.87\ \mu\text{eV}$$
$$\nu \approx 1.42\ \text{GHz}$$
$$\lambda \approx 21.1\ \text{cm}$$

21-cm line

spin temperature T_{spin} $(\neq T_{\text{K}})$

$$\frac{n_1}{n_0} = 3\exp\left(-\frac{\Delta E}{k_{\text{B}} T_{\text{spin}}}\right)$$

large radio telescopes (SKA, MWA, LOFAR, …)
=> the distribution of neutral hydrogen atoms in high redshifts
=> matter density field, IGM thermal history, epoch of reionization, …

21-cm line global signal

Redshift dependence of 21-cm global signal (sky averaged signal)

Roughly speaking, $T_{\rm spin}$ is coupled with either $T_{\rm K}$ or $T_{\rm CMB}$

$$T_{\rm spin} = \frac{T_{\rm CMB} + (y_{\rm coll} + y_\alpha) T_{\rm K}}{1 + y_{\rm coll} + y_\alpha}$$

($y_{\rm coll}$, y_α: positive coefficient)

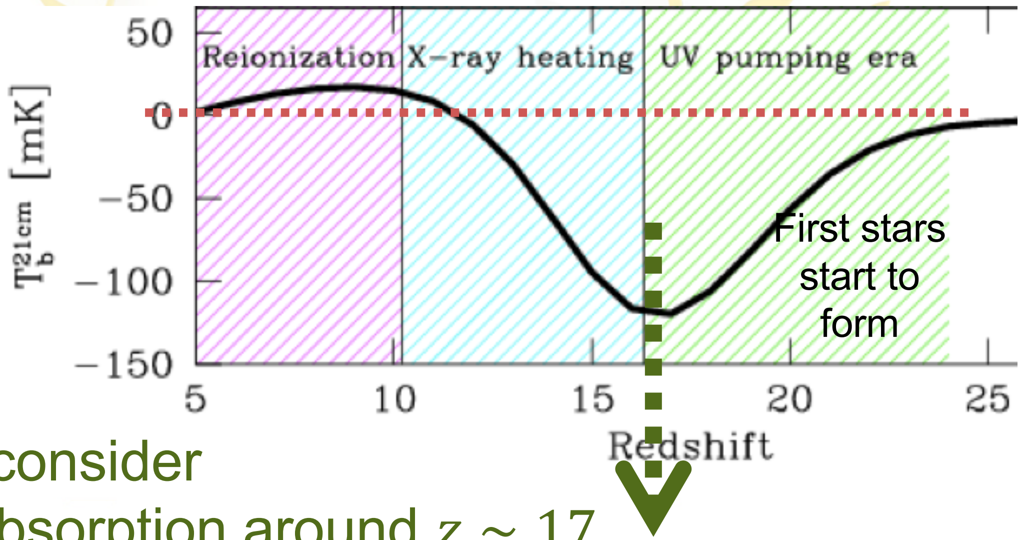
21-cm line signal is observed as

emission when

$$T_{\rm K} \geq T_{\rm spin} \geq T_{\rm CMB} ,$$

or absorption when

$$T_{\rm K} \leq T_{\rm spin} \leq T_{\rm CMB}$$

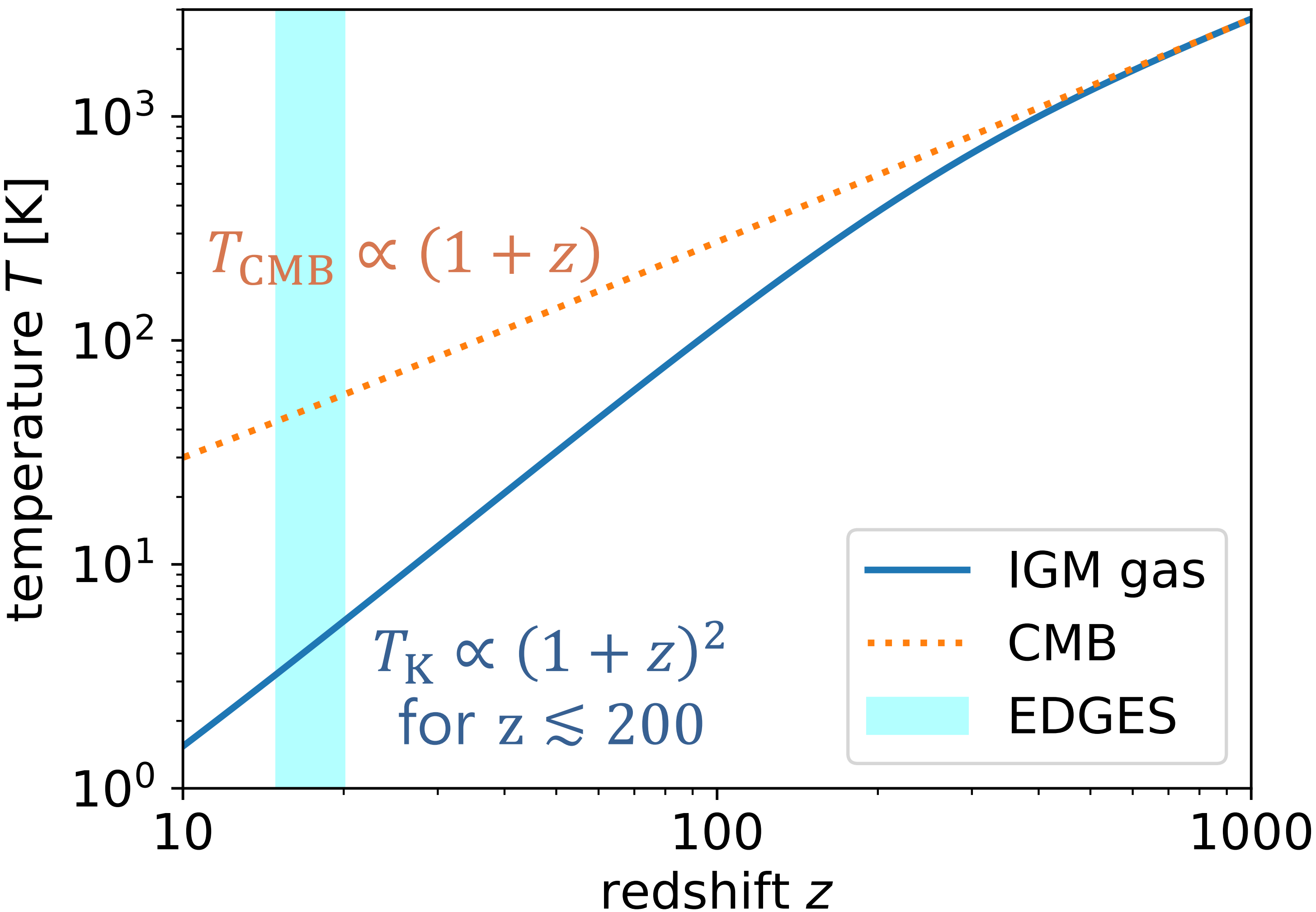


In this work, we consider a strong absorption around $z \sim 17$

(McQuinn & O'Leary, 2012)

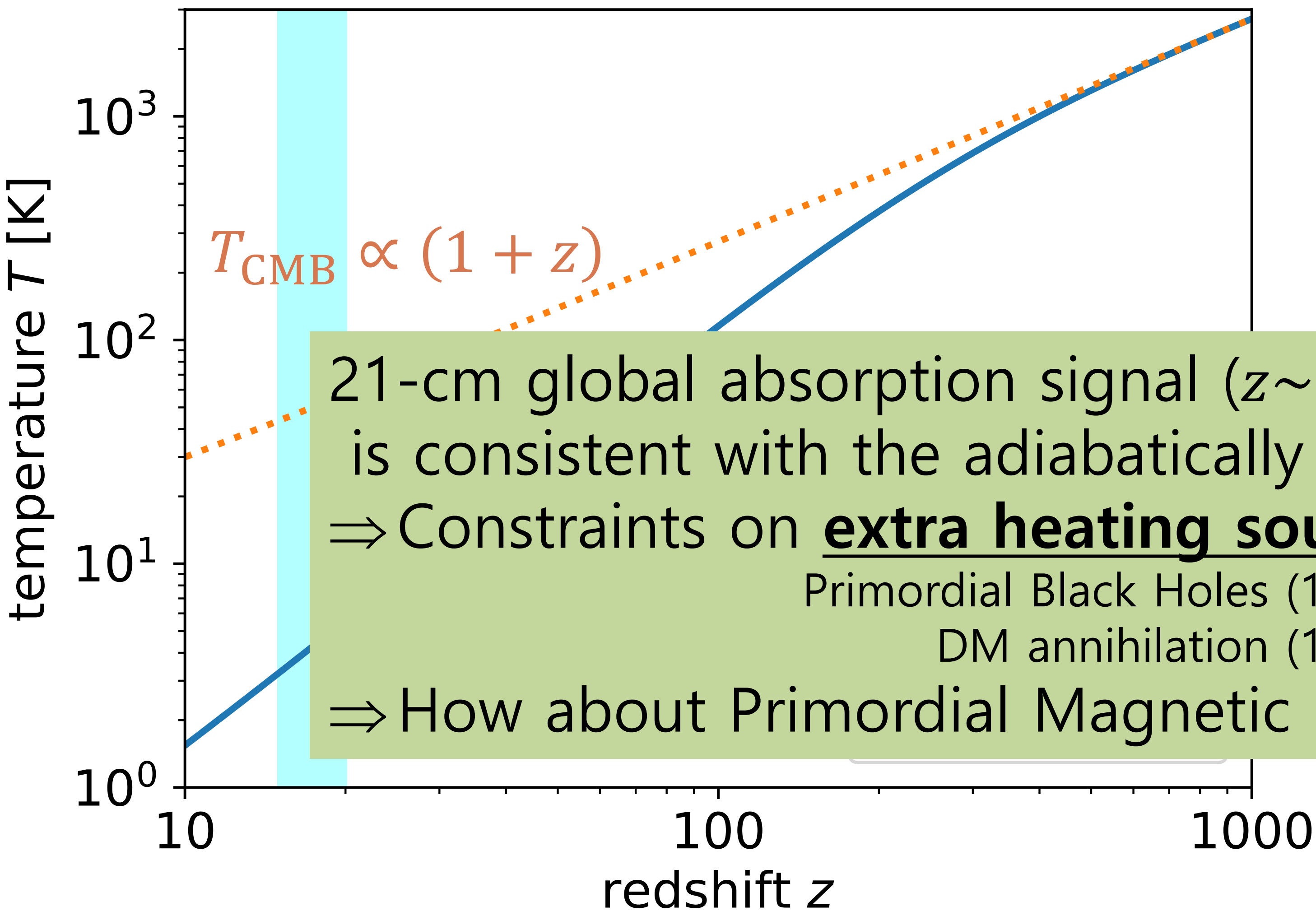
IGM thermal history (without PMFs)

Adiabatic thermal history predict absorption ($T_{\rm CMB} > T_{\rm K}$) at $z\sim 17$



IGM thermal history (without PMFs)

Adiabatic thermal history predict absorption ($T_{\mathrm{CMB}} > T_{\mathrm{K}}$) at $z \sim 17$



21-cm global absorption signal ($z \sim 17$) is consistent with the adiabatically cooling.

$\Rightarrow$ Constraints on **<u>extra heating sources</u>**

Primordial Black Holes (1803.09390)

DM annihilation (1803.03629)

$\Rightarrow$ How about Primordial Magnetic Fields?

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stochastic PMF formalism

Assuming scale-dependent magnetic field strength

scale dependence

$$B_\lambda = 0 \qquad (\text{for } \lambda < \lambda_{\rm cut})$$

$$B_\lambda = B_{1\,\rm Mpc}\left(\frac{\lambda}{1\ \rm Mpc}\right)^{-(n_B+3)/2} \qquad (\text{for } \lambda \geq \lambda_{\rm cut})$$

PMF strength smoothed on 1Mpc

$\left(B_{1\,\rm Mpc}, n_B\right)$ determine the statistical property of PMFs (and cut-off length).

cut-off in UV region

Before the recombination epoch, radiative viscosity damps PMFs on scales ~photons' mean free path.

$$\lambda_{\rm cut} = \left(\frac{B_{\rm cut}^2}{4\pi\rho_{\rm CMB}\sigma_{\rm T}}\int_0^{t_{\rm rec}}\frac{c\,dt}{a^2\,n_e}\right)^{\frac{1}{2}} \simeq \left[7.2\times10^{-4}\times\left(\frac{B_{1\,\rm Mpc}}{1\ \rm nG}\right)^2\right]^{\frac{1}{n_B+5}} \quad [\rm Mpc]$$

*(Jedamzik+ 1998; Subramanian & Barrow 1998)

PMFs as an IGM heating source

- **Ambipolar Diffusion**
  - PMFs dissipate due to the friction between electrical charged particles and the neutral particles.
  - Heating rate is proportional to the Lorentz force.

$$\dot{Q}_{\mathrm{AD}} \propto |(\boldsymbol{\nabla}\times\boldsymbol{B})\times\boldsymbol{B}|^2$$

- **Decaying Turbulence**
  - Kolmogorov-like turbulence cause small-scale eddies, which is thermalized due to Ohmic dissipation.
  - Heating rate is proportional to the PMF energy density.

$$\dot{Q}_{\mathrm{DT}} \propto |\boldsymbol{B}|^2$$

Evolutionary equations for IGM

- kinetic temperature

$$\frac{dT_{\rm K}}{dt} = -2HT_{\rm K} + \frac{x_e}{1+x_e}\frac{8\rho_{\rm CMB}\sigma_{\rm T}}{3m_e c}(T_{\rm CMB} - T_{\rm K}) + \frac{\dot{Q}_{\rm AD} + \dot{Q}_{\rm DT}}{1.5k_{\rm B}n_{\rm b}}$$

cosmic expansion

Compton heating (cooling)

magnetic heating

- ionization fraction

$$\frac{dx_e}{dt} = \gamma_e n_{\rm b} x_e$$

collisional ionization

$$+\left[-\alpha_e n_{\rm b} x_e^2 + \beta_e(1-x_e)\exp\left(-\frac{3E_{\rm ion}}{4k_{\rm B}T_{\rm CMB}}\right)\right] \times \frac{1+K_\alpha \Lambda n_{\rm b}(1-x_e)}{1+K_\alpha(\Lambda+\beta_e)\,n_{\rm b}(1-x_e)}$$

recombination

photo-ionization by CMB

- magnetic energy

$$\frac{d}{dt}\left(\frac{|\boldsymbol{B}|^2}{8\pi}\right) = -4H\frac{|\boldsymbol{B}|^2}{8\pi} - (\dot{Q}_{\rm AD} + \dot{Q}_{\rm DT})$$

cosmic expansion

magnetic dissipation

RECFAST code (astro-ph/9909275) + our modification

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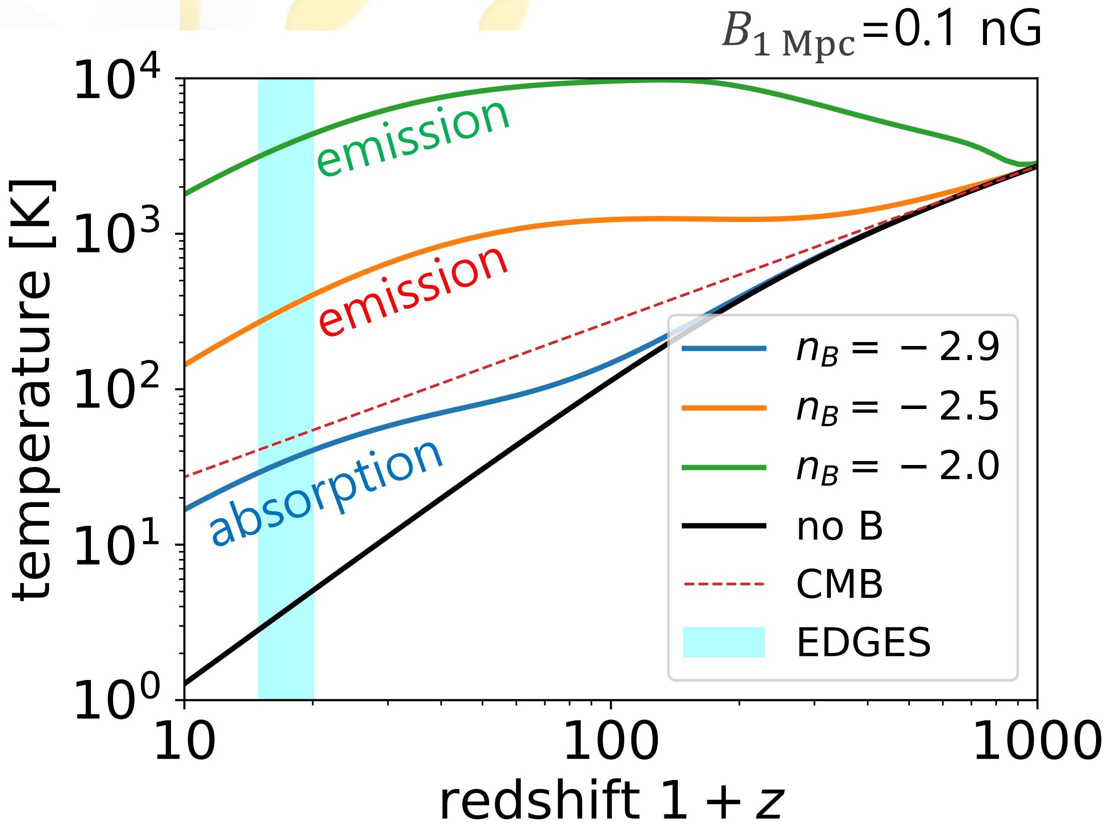
IGM thermal history (with PMFs)

$$B_\lambda = B_{1\,\mathrm{Mpc}} \left(\frac{\lambda}{1\,\mathrm{Mpc}}\right)^{-(n_B+3)/2}$$

$$\frac{dT_\mathrm{K}}{dt} = \frac{x_e}{1+x_e}\frac{8\rho_\mathrm{CMB}\sigma_T}{3m_e c}\left(T_\mathrm{CMB} - T_\mathrm{K}\right) - 2HT_\mathrm{K}$$

$$+ \frac{\dot{Q}_\mathrm{AD} + \dot{Q}_\mathrm{DT}}{1.5k_B n_b}$$

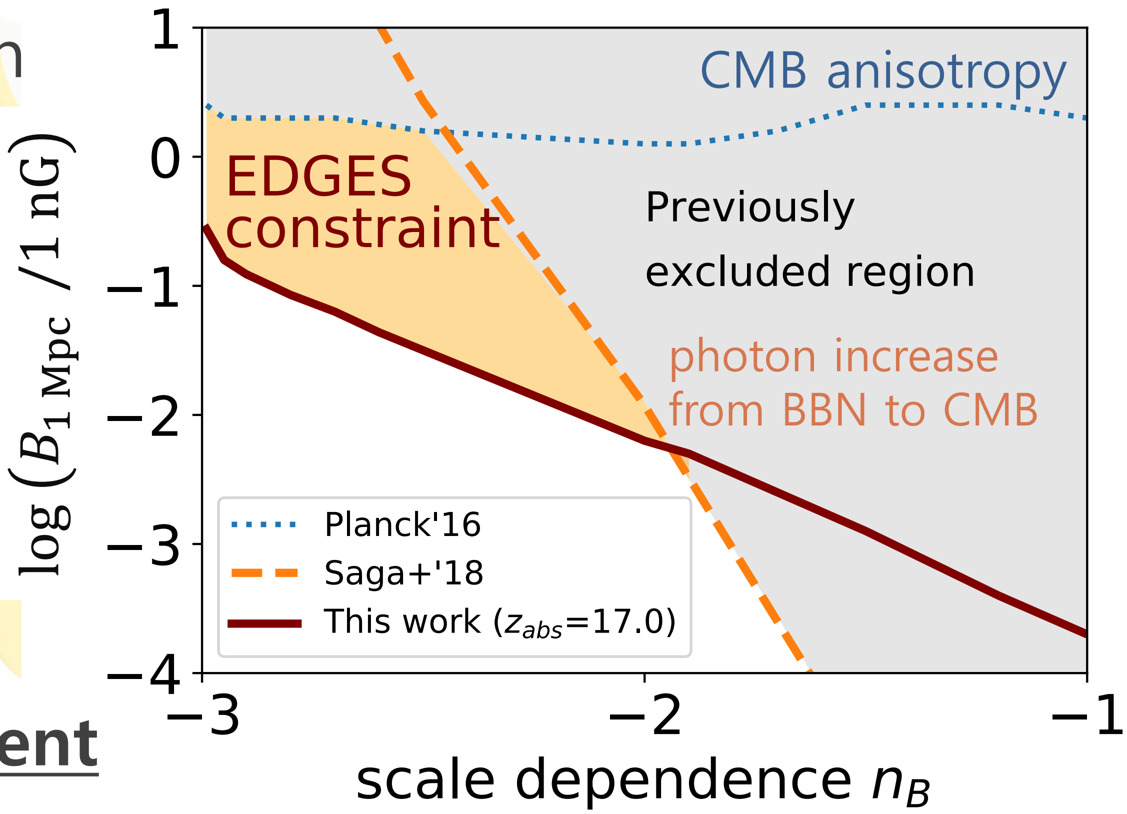
+ ionization fraction
+ magnetic fields



A constraint on PMFs

- Calculate T_{K} with various PMF model parameters $(B_{1\,\mathrm{Mpc}}, n_B)$
- With 21-cm absorption condition as $\boldsymbol{T_{\mathrm{K}} < T_{\mathrm{CMB}}}$ for $z \sim 17$, put the upper limit of PMFs.

=> $B_{1\,\mathrm{Mpc}} \lesssim 0.1$ nG



<u>One of the most stringent constraints on PMFs</u>

Summary

- PMFs are possible origin of the cosmic magnetic fields
- We assume the power-law scale-dependence of PMFs
- Calculate T_{K} with various PMF model parameters $(B_{1\ \mathrm{Mpc}}, n_B)$
- From 21-cm global absorption signal observation, $T_{\mathrm{K}} < T_{\mathrm{CMB}}$ for $z \sim 17$
- We derive the tightest upper bound on the PMFs as $B_{1\ \mathrm{Mpc}} \lesssim 0.1$ nG

Thank you for listening!