The limit on the primordial magnetic fields from the EDGES observation

Teppei Minoda, H. Tashiro (Nagoya-U),
Tomo Takahashi (Saga-U)

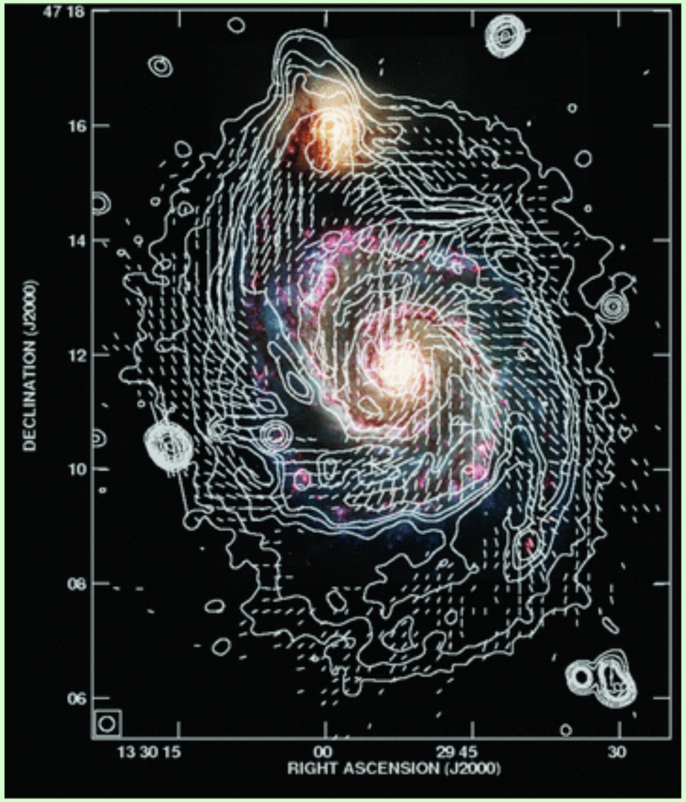
Science at Low Frequencies V at Nagoya, Japan

The Contents

1. Introduction
   - Primordial Magnetic Fields & Its constraint
2. Theory
   - Energy dissipation of the PMFs
   - 21-cm line global signal
3. Methods
4. Results
   - Cosmological history of the IGM temperature
   - The constraint on the PMF from EDGES

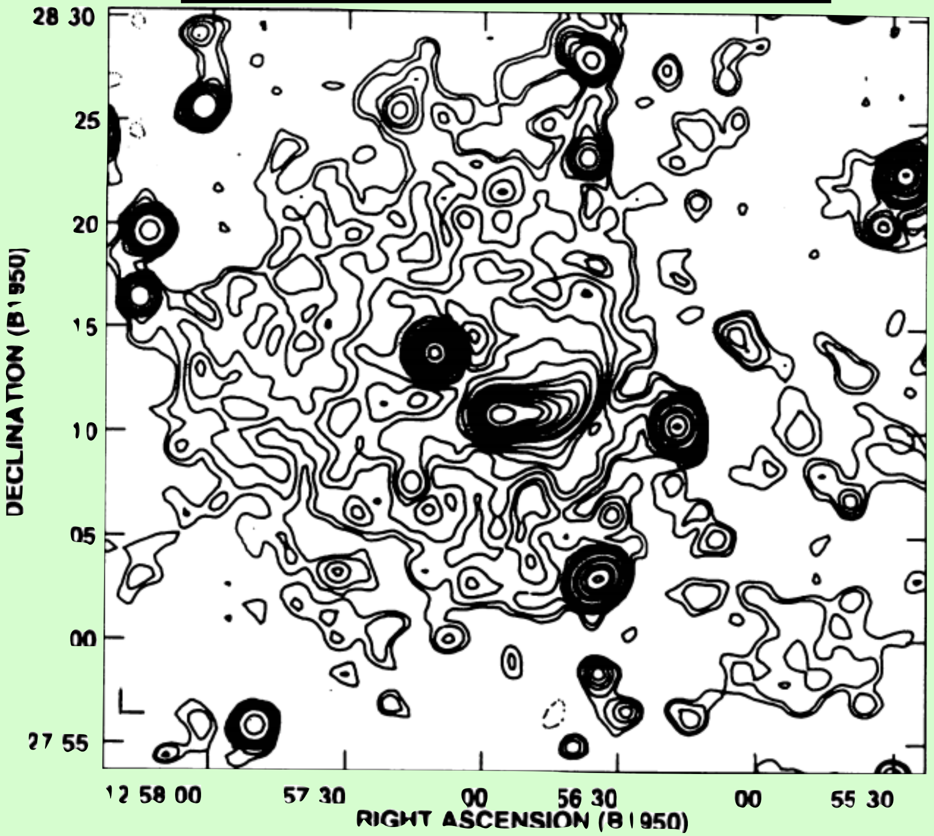
Cosmic Magnetic Fields

galaxy B ~10^{-5} G



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

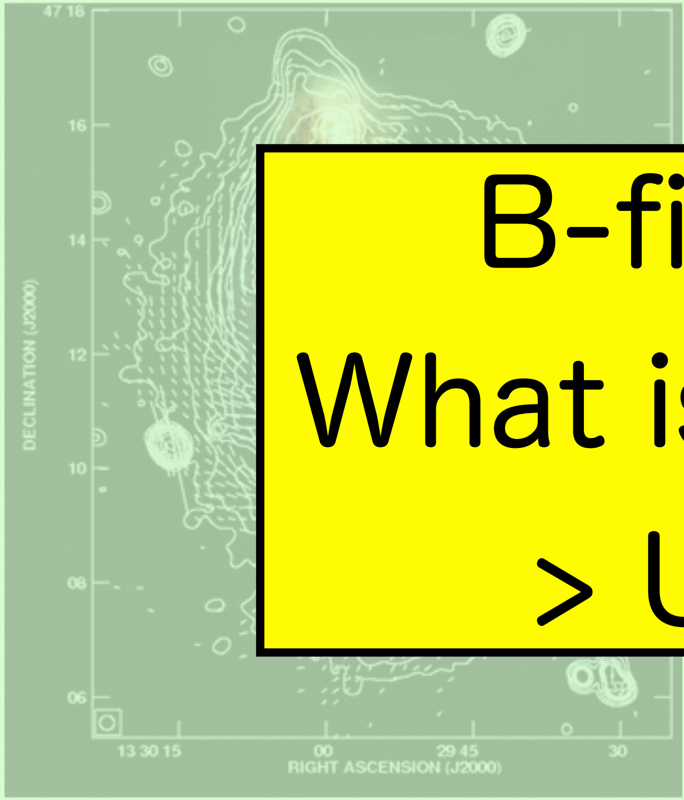
cluster B~10^{-6} G



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

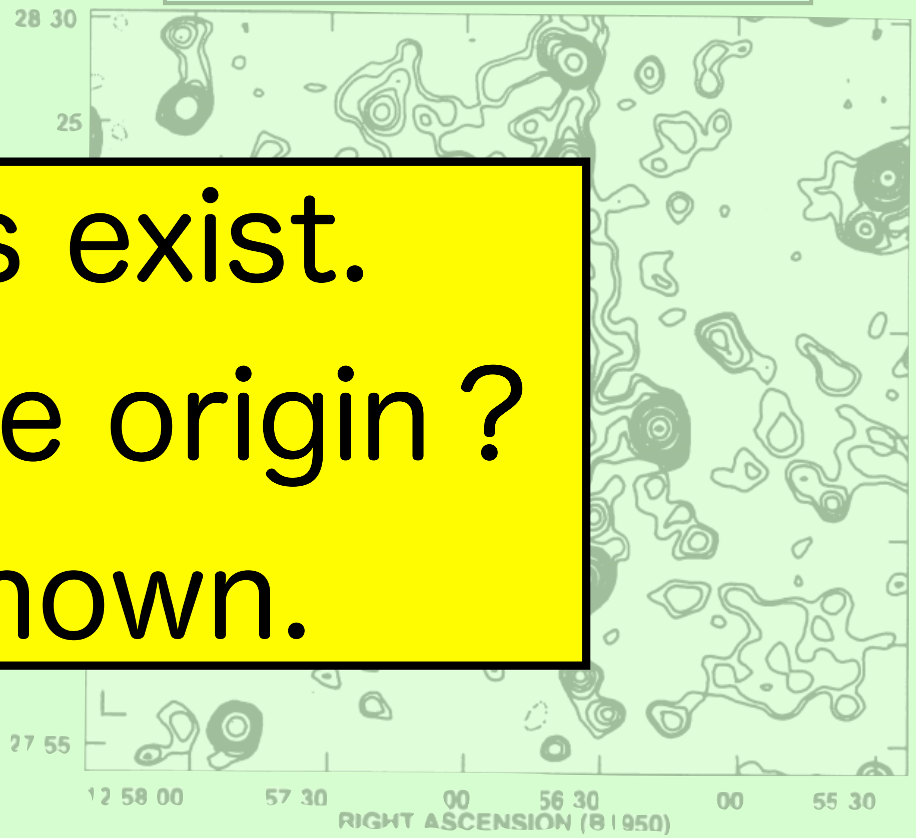
Cosmic Magnetic Fields

galaxy B ~10^{-5} G



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

cluster B~10^{-6} G



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

B-fields exist.
What is the origin ?
> Unknown.

The origin of B-fields

Cosmological origin ?

- Inflation
- Phase transition
- New physics

Various models are considered

Strong dependence
on assuming models

Difficult for observational test

Astrophysical origin ?

- Shock wave
- Turbulent motion
- Plasma physics

Highly non-linear effect

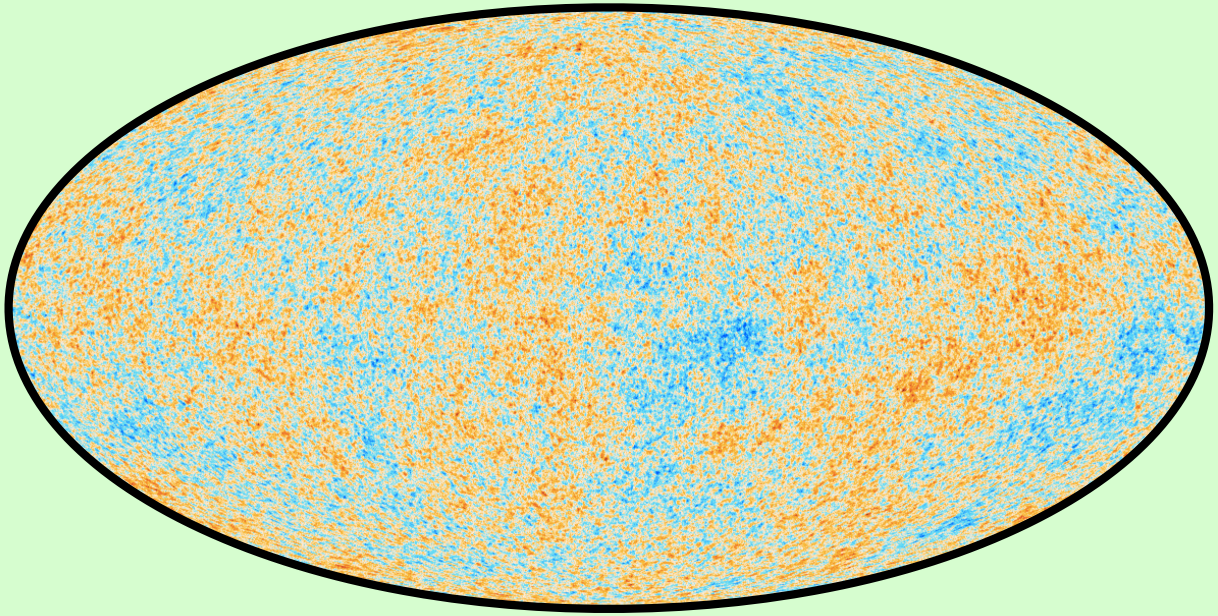
Too small scale to investigate
in the cosmological scale

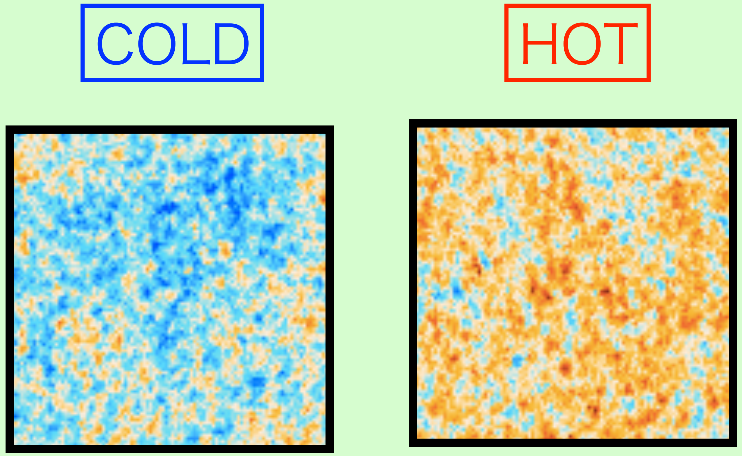
Difficult to explain IGMF?

Is there an observational signal for the Primordial Magnetic Fields (PMFs)?

Constraint from CMB

Cosmic Microwave Background (CMB)





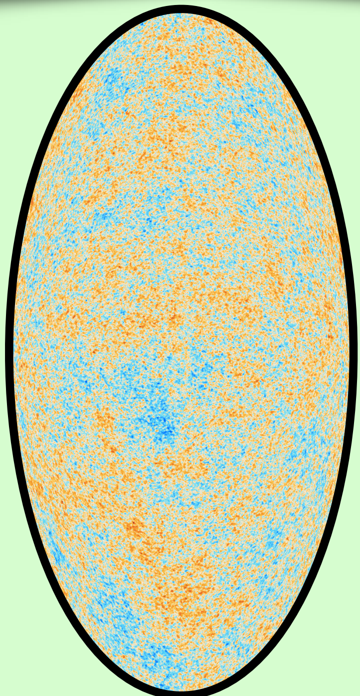
(Planck Collaboration, 2016, A&A, 594)

Anisotropy on T~2.7255 K has an order of 10^{-5}
→ Metric perturbation at the recombination epoch
To constrain the stress-energy tensor of the PMFs
Planck 2015 result gives $B_{1\,\mathrm{Mpc}} \lesssim 4\ \mathrm{nG}$

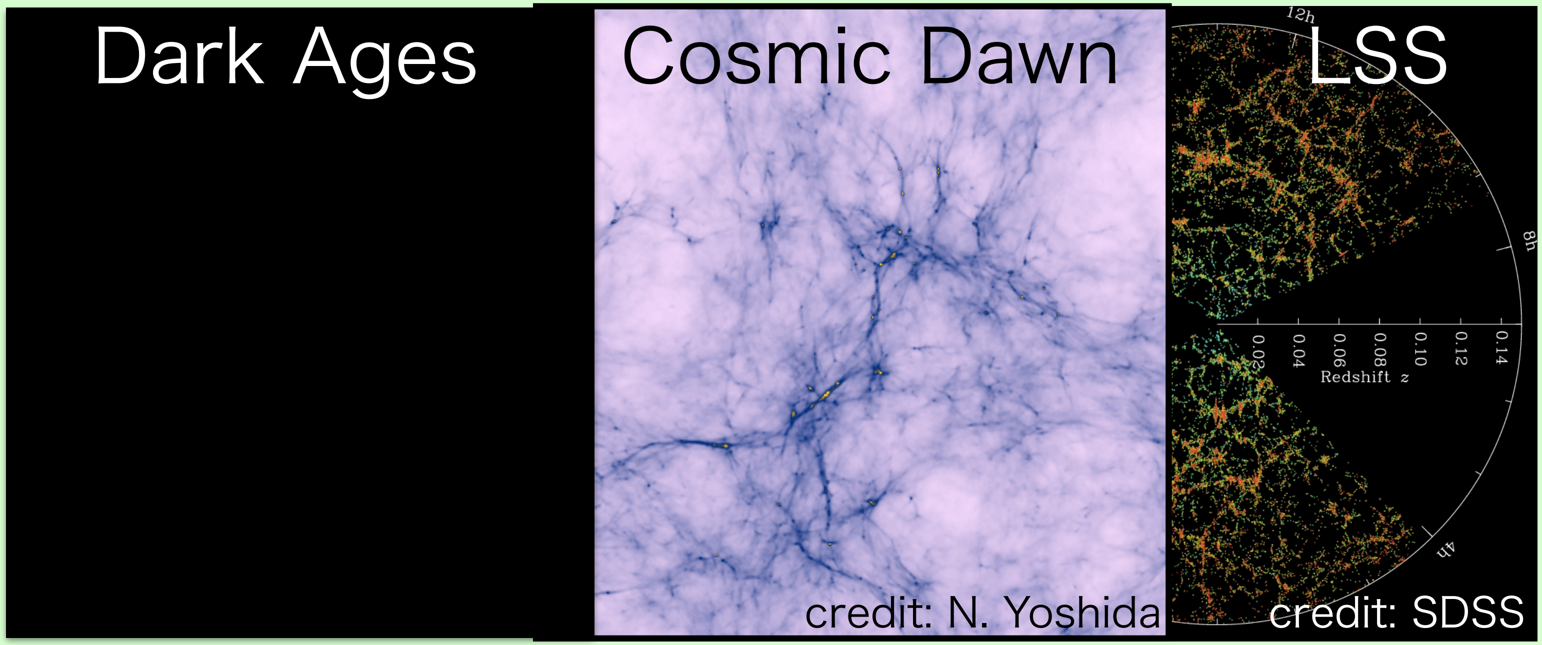
Motivation

$B_{1\ \mathrm{Mpc}} \lesssim 4\ \mathrm{nG}$

PMFs affect other observations?



credit: *Planck*



recombination

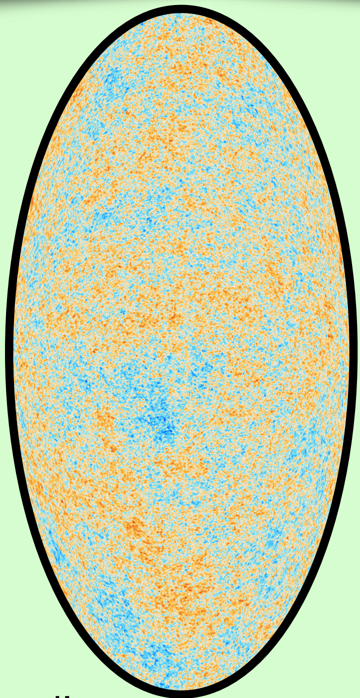
~380 K yrs

time

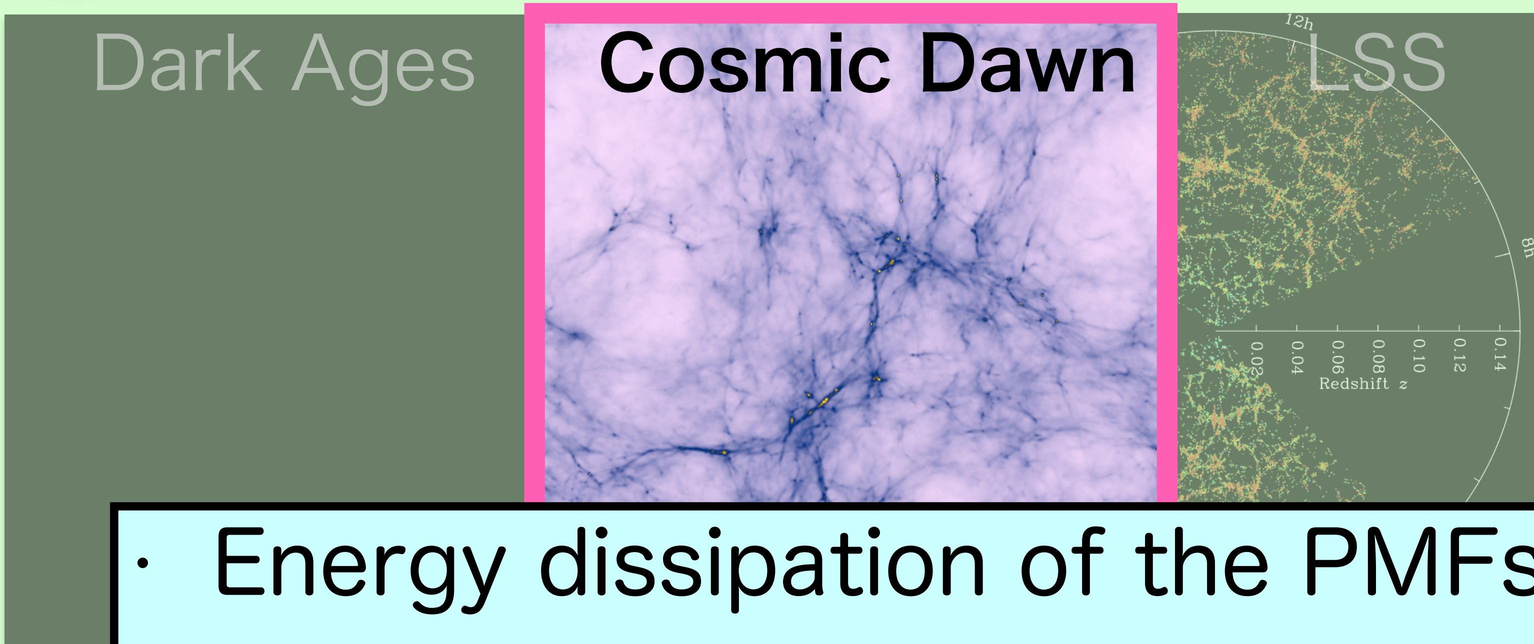
Motivation

$B_{1\ \mathrm{Mpc}} \lesssim 4\ \mathrm{nG}$

PMFs affect other observations?



credit: *Planck*



- Energy dissipation of the PMFs
- IGM during the cosmic dawn
- 21cm line global signal

recombination

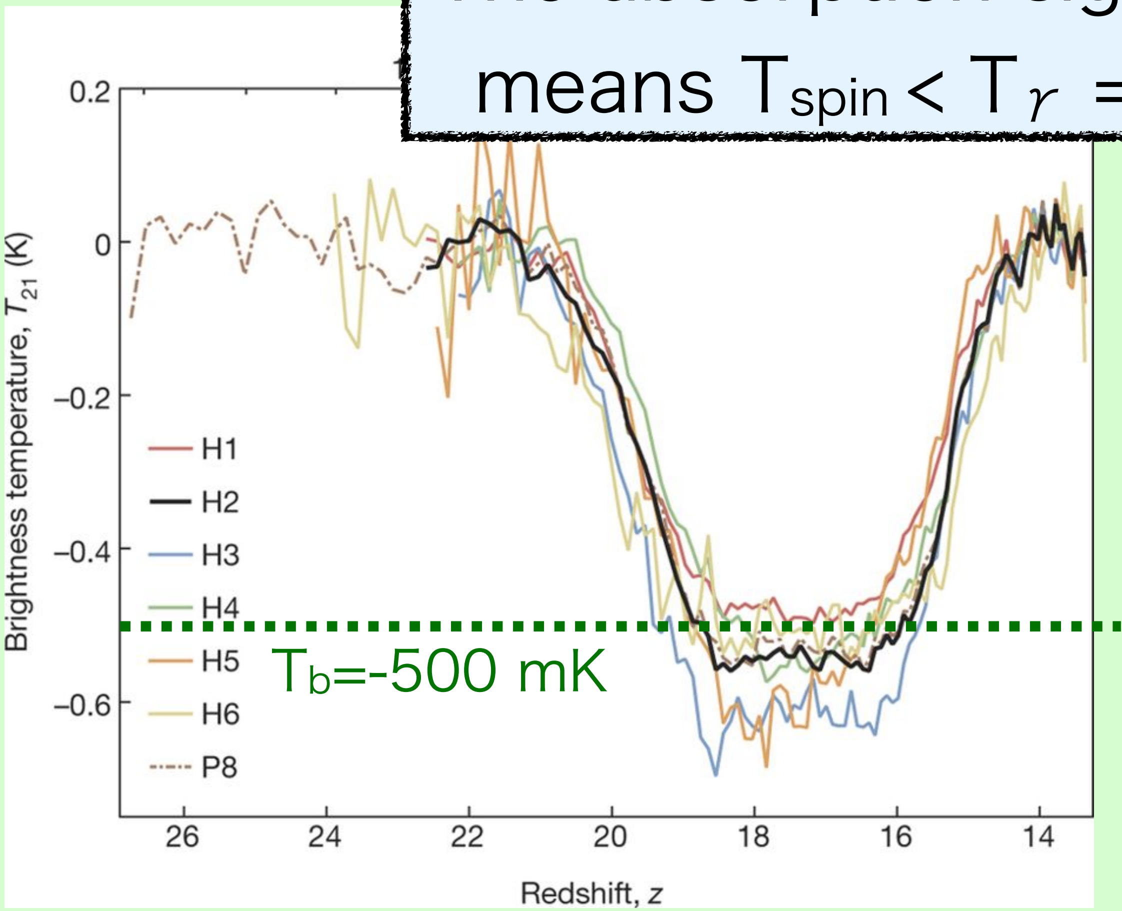
~380 K yrs

time

21cm global signal

$$\delta T_b(z) \simeq 27 x_{\rm HI}(z)\left[1-\frac{T_\gamma(z)}{T_{\rm spin}(z)}\right]\times\left(\frac{\Omega_{\rm b} h^2}{0.02}\right)\left(\frac{0.15}{\Omega_{\rm m} h^2}\right)^{1/2}\left(\frac{1+z}{10}\right)^{1/2}[\mathrm{mK}]$$

The absorption signal at $\lambda = 21(1+z_{abs})$ [cm] means $T_{spin} < T_\gamma$ => "**$T_{gas} < T_\gamma$** for **$z=z_{abs}$**".



- absorption at z ~ 17
  > agree w/ LCDM

We use this condition to constrain the PMFs.

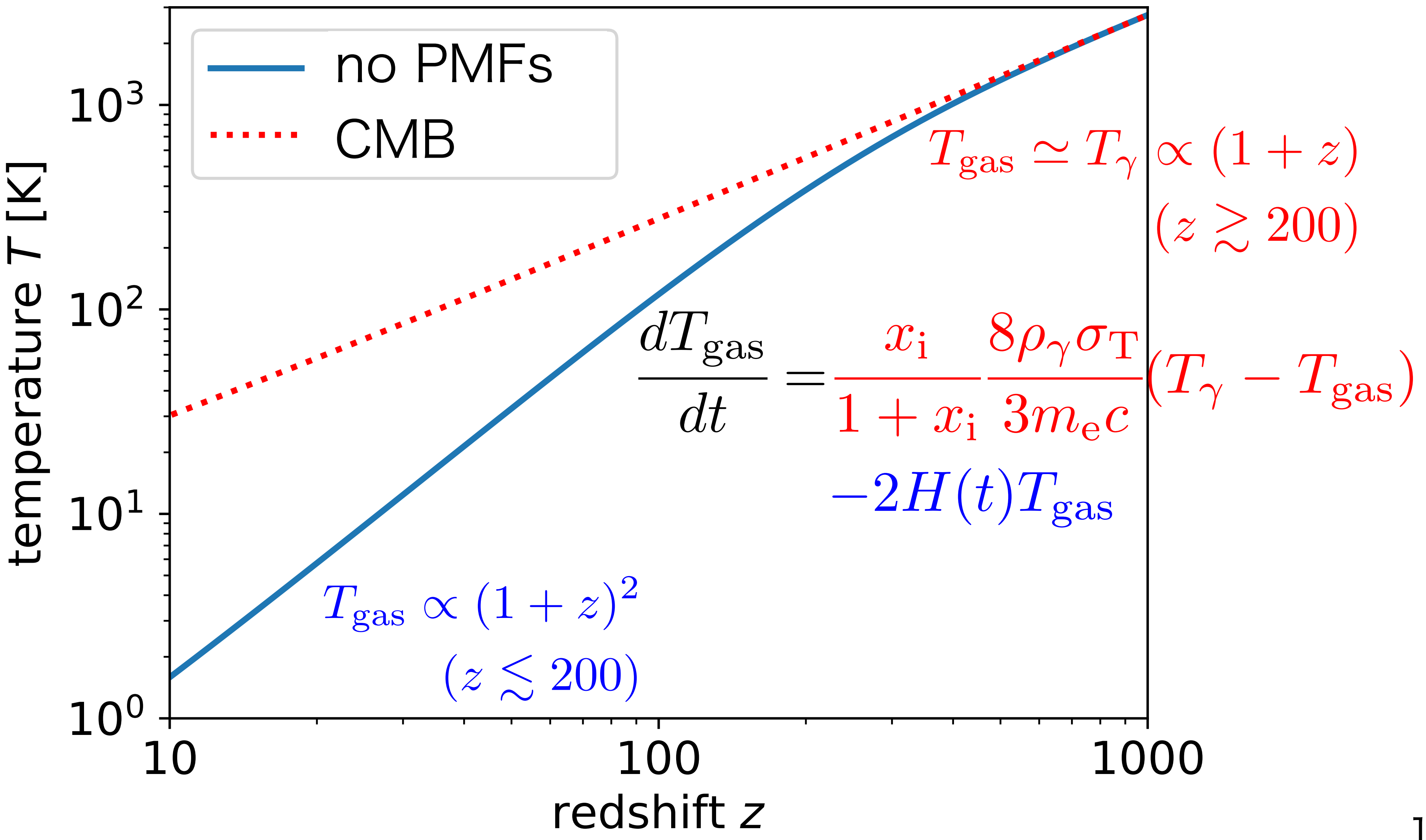
~~(Too strong absorption)~~

EDGES observation

(Bowman+, 2018, Nature 555, 67)

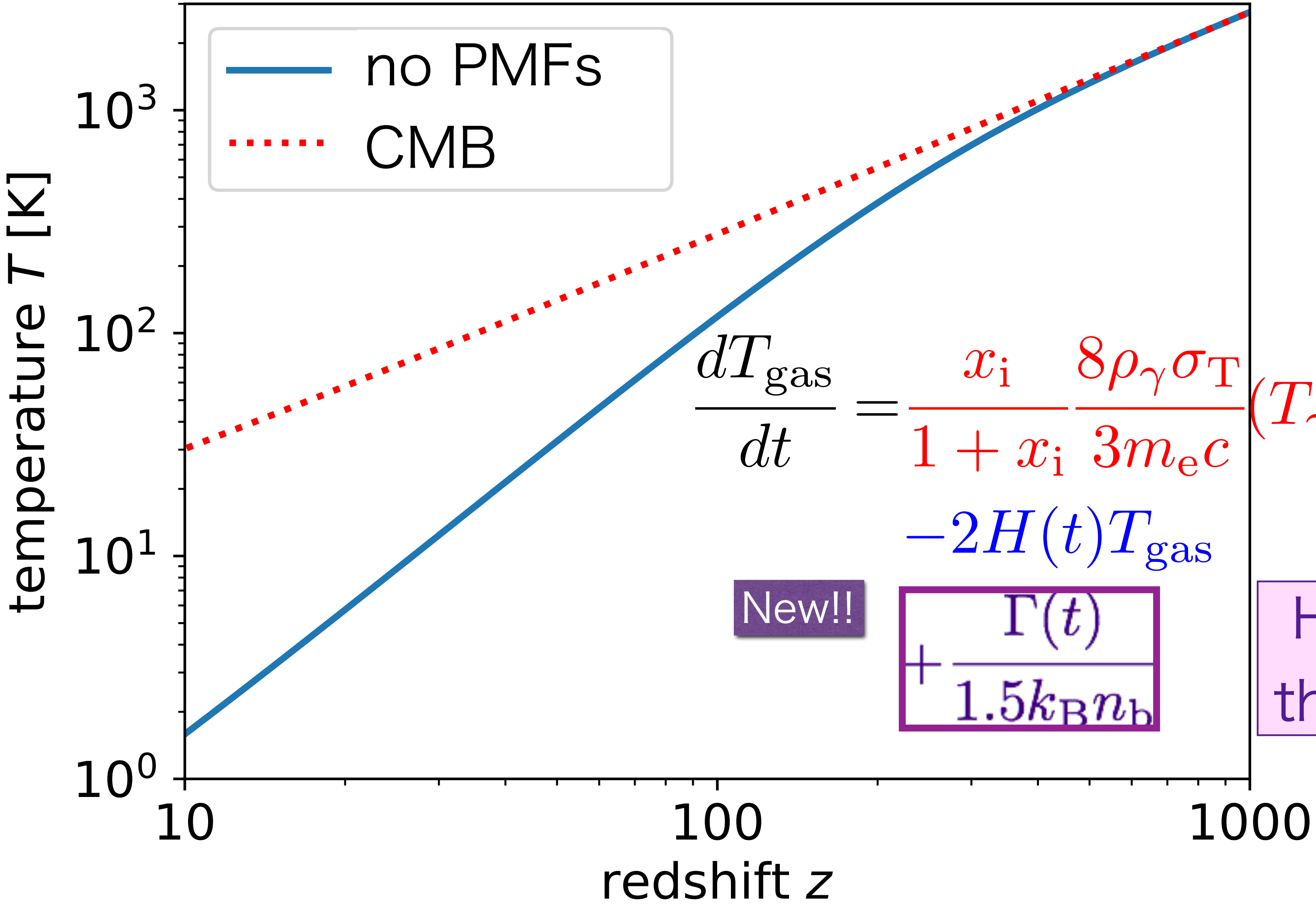
Methods

IGM gas temperature



Methods

IGM gas temperature



$$\frac{dT_{\rm gas}}{dt} = \frac{x_{\rm i}}{1+x_{\rm i}}\frac{8\rho_\gamma \sigma_{\rm T}}{3m_{\rm e}c}(T_\gamma - T_{\rm gas}) - 2H(t)T_{\rm gas} + \frac{\Gamma(t)}{1.5k_{\rm B}n_{\rm b}}$$

New!!

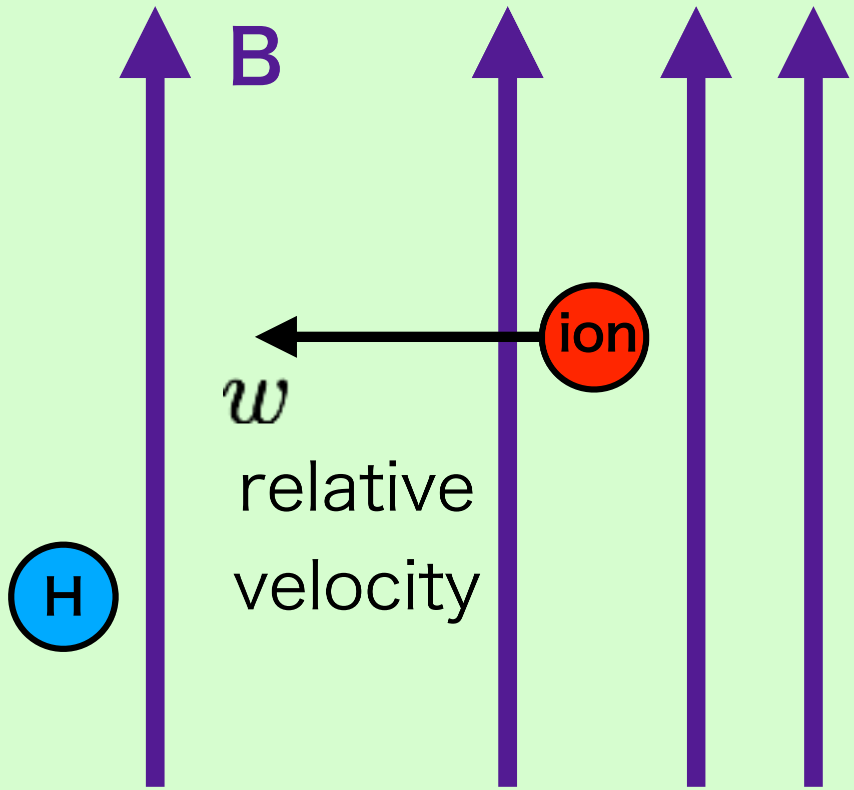
How does this affect?

PMF dissipation

(Sethi & Subramanian, 2005, MNRAS, 356)

The PMFs dissipate their energy and heat the IGM via

1. **Ambipolar Diffusion**: collision between the neutral and ionized medium
2. **Decaying Turbulence**: small-scale eddies from turbulent cascade



Ambipolar Diffusion's schematic picture

PMF dissipation

(Sethi & Subramanian, 2005, MNRAS, 356)

Ambipolar Diffusion (AD)

Neutral bulk motion

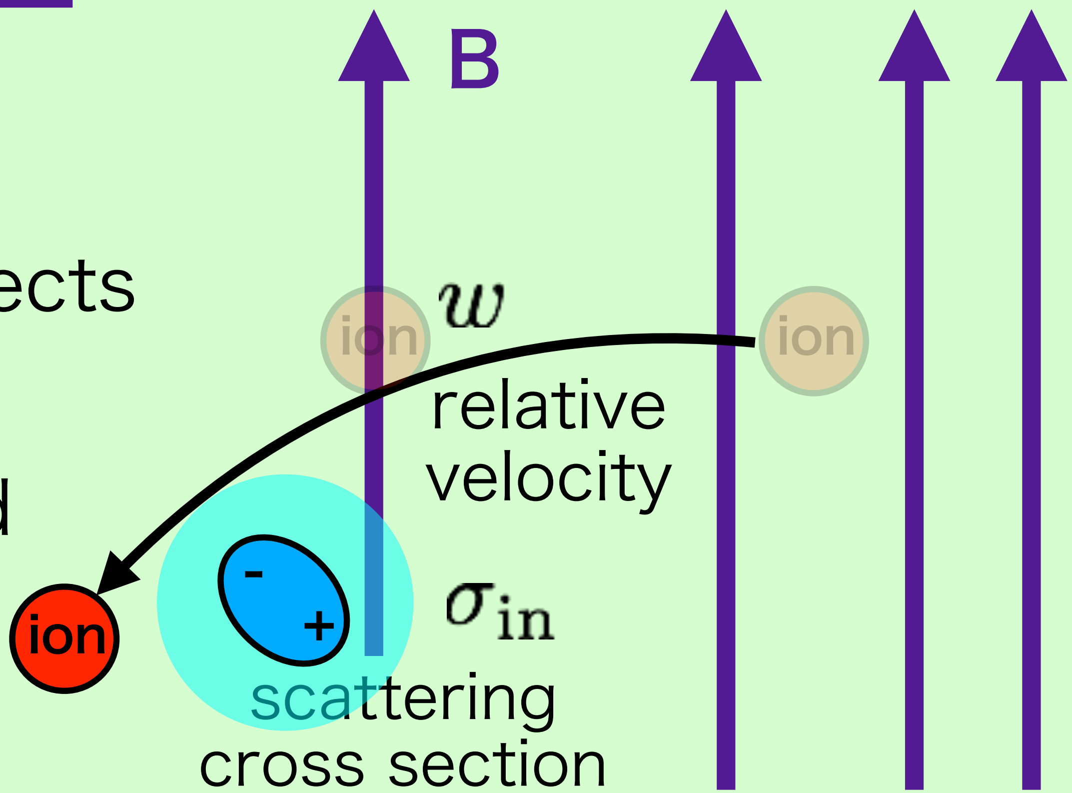
Ionized bulk motion

+ magnetic effects

> the relative motion
b/w neutral and ionized

> electric dipole moment
of the neutral particle

> thermalize the relative motion
from B-fields



Ambipolar Diffusion's schematic picture

PMF dissipation

(Sethi & Subramanian, 2005, MNRAS, 356)

Heating Rate from AD

$$\Gamma = \frac{|(\nabla \times \mathbf{B}) \times \mathbf{B}|^2}{16\pi^2 \xi \rho_b^2} \frac{(1 - x_i)}{x_i}$$

ρ_b: baryon mass density

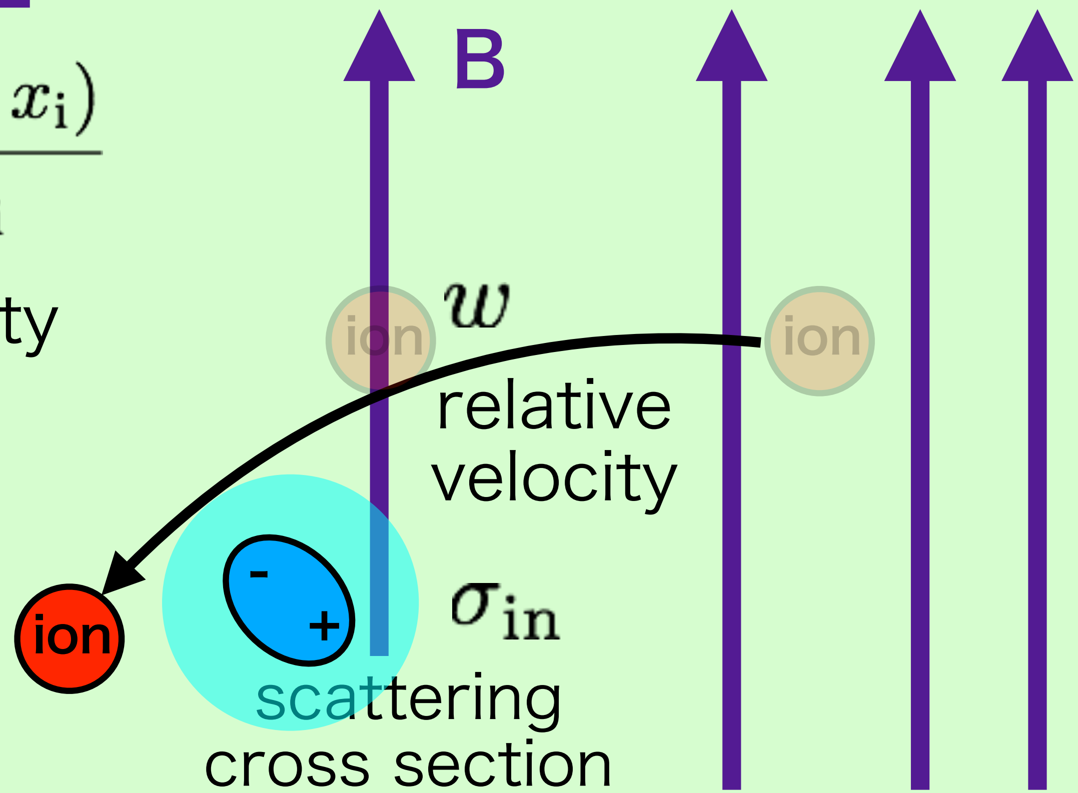
x_i : ionization fraction

drag coefficient

$$\xi = \frac{\langle w \sigma_{in} \rangle}{m_i + m_n}$$

$$\simeq 1.9 \times 10^{14} \ (T_{gas}/1 \text{ K})^{0.375}$$

$$[\text{cm}^3/\text{g}/\text{s}]$$



Ambipolar Diffusion's schematic picture

Methods

(Planck Collaboration, 2016, A&A, 594)

2 point correlation

Power spectrum

$$\langle B_i^*(\mathbf{k}) B_j(\mathbf{k}')\rangle = \frac{(2\pi)^3}{2}\delta(\mathbf{k}-\mathbf{k}')\left(\delta_{ij}-\hat{k}_i\hat{k}_j\right)P_B(k)$$

$$P_B(k) = \begin{cases} A_B k^{n_B} & (k < k_c) \\ 0 & (k \geq k_c) \end{cases}$$

$$A_B = \frac{(2\pi)^{n_B+5}}{\Gamma\left(\frac{n_B+3}{2}\right)} k_n^{-(n_B+3)} B_n^2$$

cut off scale for the PMF

Each (Bn, nB) for a PMF model

$$B_\lambda^2 = \frac{1}{2\pi^2}\int_0^{k_\lambda} k^2 dk P_B(k) = B_n^2 \left(\frac{k_\lambda}{k_n}\right)^{n_B+3}$$

Methods

Ambipolar Diffusion (AD)

(Cowling, 1956, MNRAS , 116)
(Brandenburg+, 1996, PRD, 54)

$$\Gamma_{\rm AD} = \frac{|(\nabla \times \mathbf{B}) \times \mathbf{B}|^2}{16\pi^2 \xi \rho_{\rm b}^2} \frac{1 - x_{\rm i}}{x_{\rm i}}$$

$$|(\nabla \times \mathbf{B}) \times \mathbf{B}|^2 = \int \left(\frac{dk_1}{2\pi}\right)^3 \int \left(\frac{dk_2}{2\pi}\right)^3 k_1^2 P_B(k_1) P_B(k_2) (1+z)^{10} f^2(t)$$

Decaying Turbulence (DT)

$$\Gamma_{\rm DT} = \frac{3w_B}{2} H \frac{|\mathbf{B}|^2}{8\pi} a^4 \frac{[\ln(1 + t_{\rm d}/t_{\rm red})]^{w_B}}{[\ln(1 + t_{\rm d}/t_{\rm red}) + \ln(t/t_{\rm red})]^{1+w_B}}$$

$$|\mathbf{B}|^2 = \int \left(\frac{dk}{2\pi}\right)^3 P_B(k) (1+z)^4 f(t)$$

Methods

(Schleicher+, 2008, PRD, 78)
(Minoda+, 2017, PRD, 96)

IGM ionization fraction

$$\frac{dx_{\rm i}}{dt} = \left[-\alpha_e n_{\rm b} x_{\rm i}^2 + \beta_e (1 - x_{\rm i}) \exp\left(-\frac{E_{12}}{k_{\rm B} T_\gamma}\right)\right] D + \gamma_e n_{\rm b} (1 - x_{\rm i}) x_{\rm i}$$

recombination

photoionization from CMB

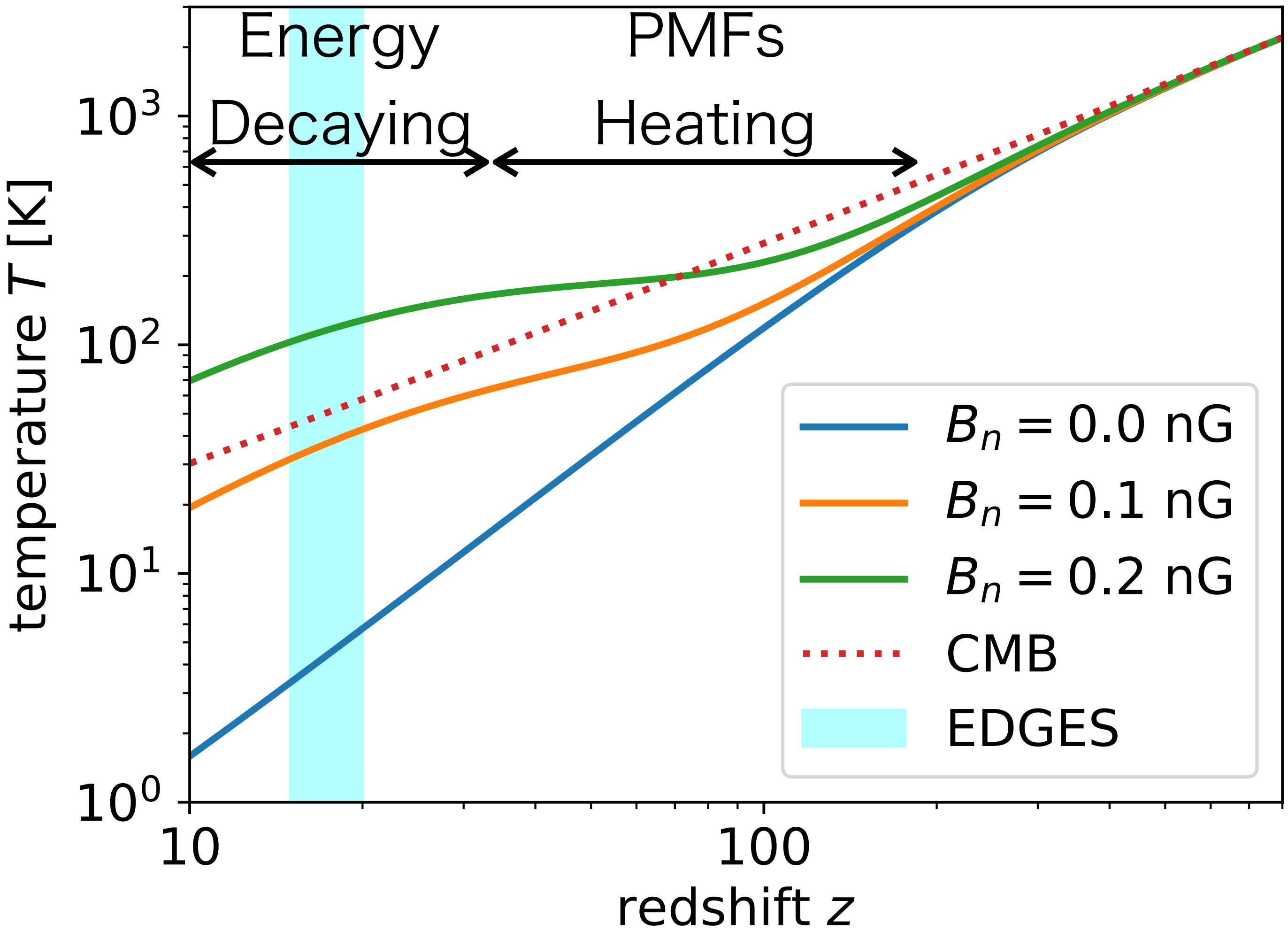
collisional ionization

PMFs energy

$$\frac{d}{dt}\left(\frac{|\mathbf{B}|^2}{8\pi}\right) = -4H\frac{|\mathbf{B}|^2}{8\pi} - \Gamma_{\rm AD} - \Gamma_{\rm DT}$$

Results

Thermal history of the IGM gas (n_B=-2.9)



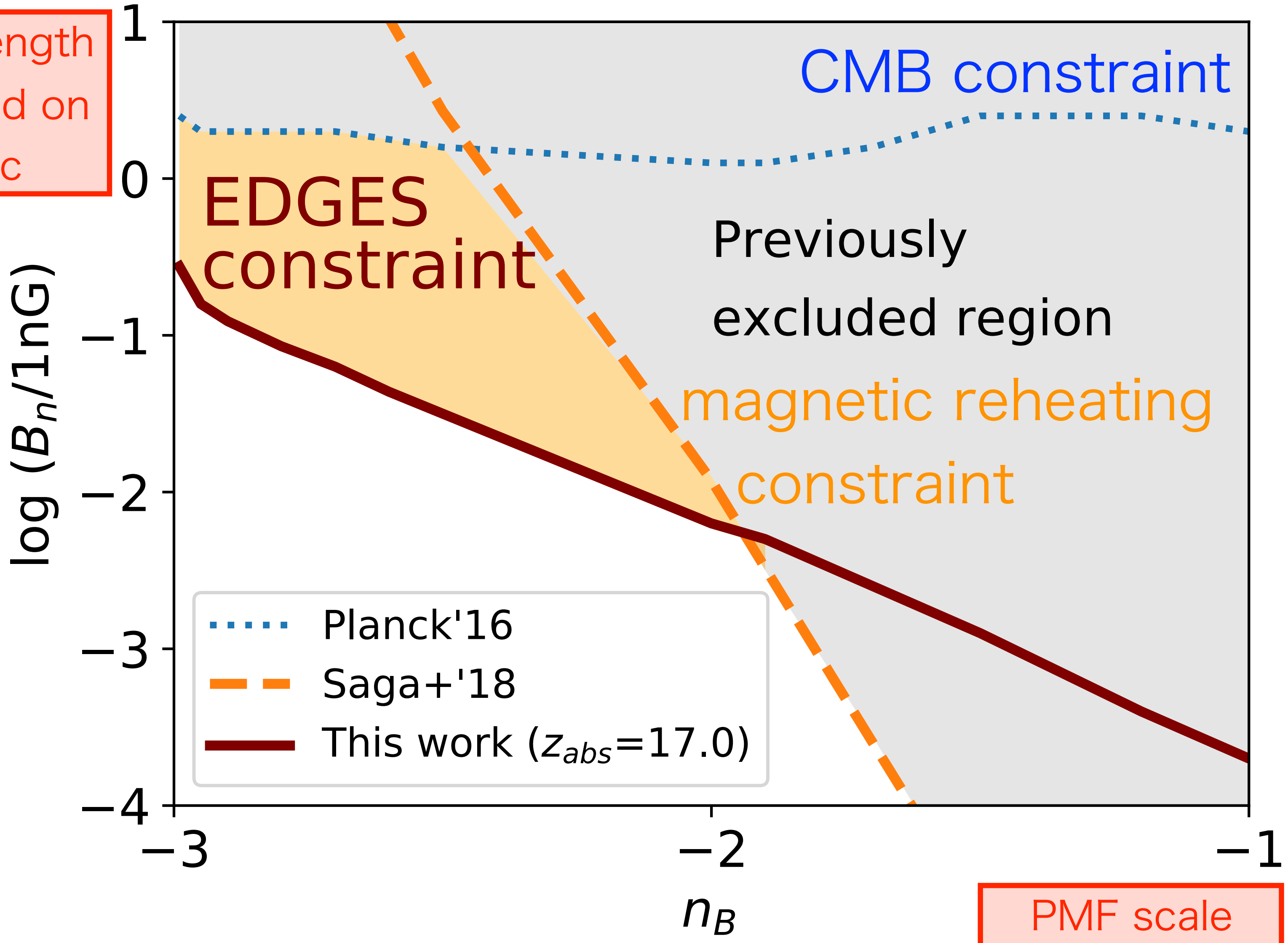
scale dependence

PMF strength smoothed on 1 Mpc

(Minoda+, 2018, arXiv:1812.00730)

Results

PMF strength smoothed on 1 Mpc



PMF scale dependence

(Minoda+, 2018, arXiv:1812.00730)

Summary

- We focus on the **PMFs** and the 21-cm signal.
- The impact of PMFs with B_{1Mpc} < 1nG on IGM thermal history in **Dark Age**
- Calculate IGM **temperature** and **ionization fraction** to compare T_{gas} and T_{CMB}
- The absorption signal at z_{abs}~17 (from EDGES) constrains the PMFs as B_{1Mpc} < 0.1nG (**The most stringent for nB<-2, white spectrum**)