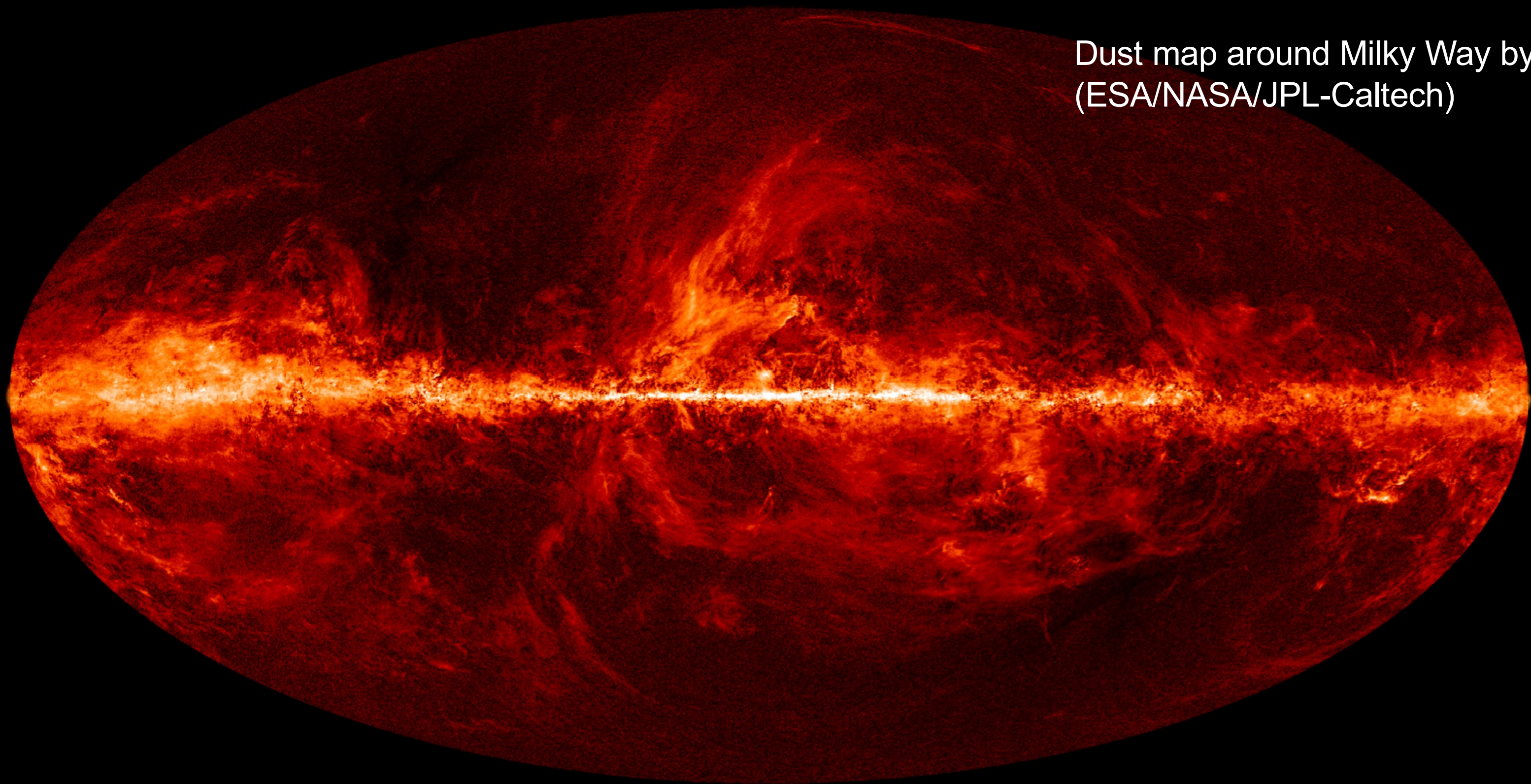
Hongo 21cm workshop at University of Tokyo, 4th Oct. 2024

Signatures of the primordial magnetic fields in the CD/EoR 21-cm signal

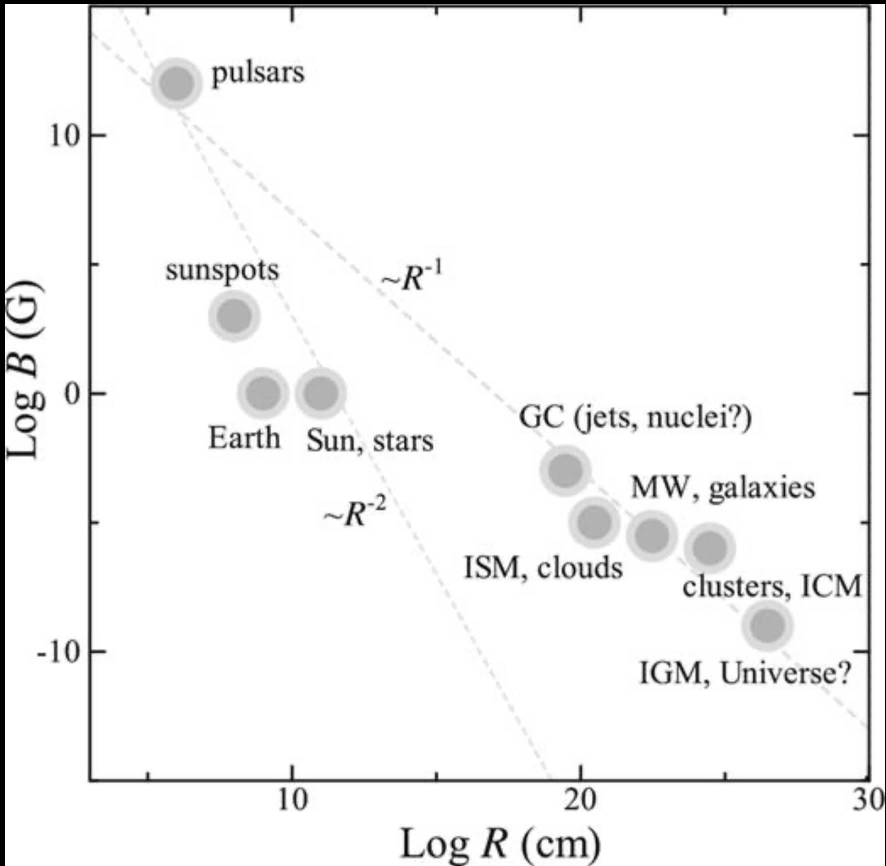


Dust map around Milky Way by Planck
(ESA/NASA/JPL-Caltech)

清華大學天文系
Department of Astronomy, Tsinghua University

Teppei Minoda (Tsinghua University)

Cosmic magnetic fields on various scales

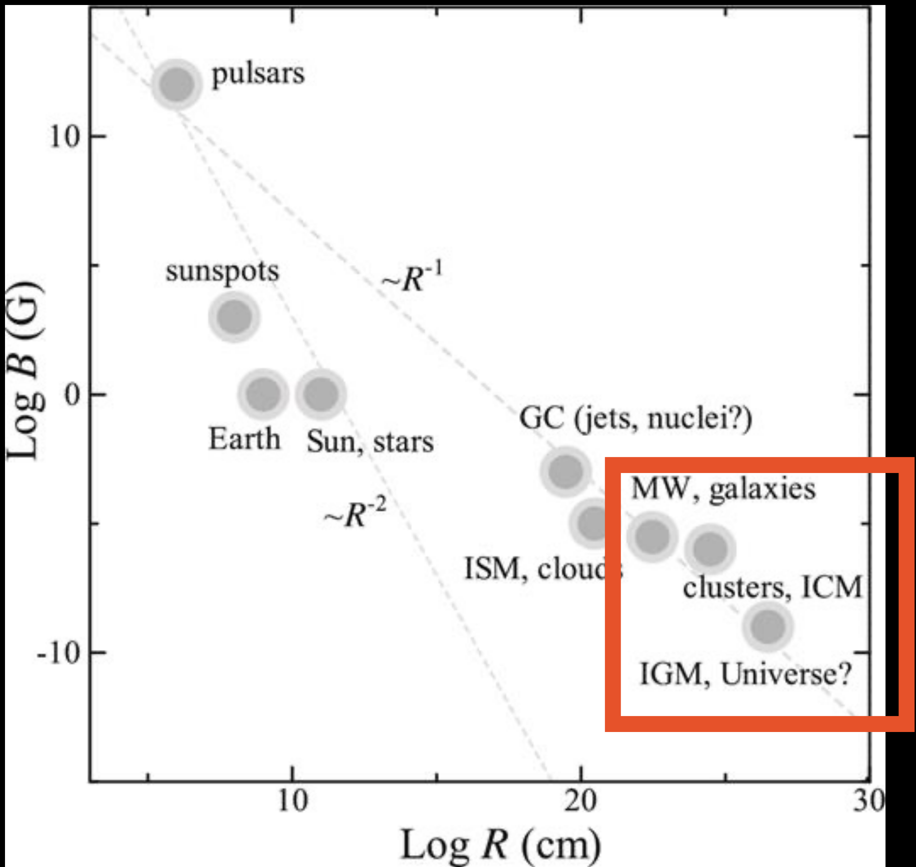


Size of various objects and magnetic field strength

- Magnetic fields exist on various scales
- Origin and evolutions are open questions

(Akahori et al. 2018)

Cosmic magnetic fields on various scales



Size of various objects and magnetic field strength

- Magnetic fields exist on various scales
- Origin and evolutions are open questions
- Particularly large-scale magnetic fields ($\gtrsim$ Mpc) can be related to cosmology and astrophysics

(Akahori et al. 2018)

Magnetogenesis

Generation mechanisms and PMF strength

- Inflation ~10^{-15} G (scale-invariant, helical)
- Phase transition ~10^{-9} G on 50 kpc or 10^{-10} G on 0.3 kpc,
- Topological defects ~10^{-17} G on 6 Mpc
- Baryon-photon streaming ~5×10^{-24} G on 20 Mpc

✓ Small strength, but expected as the seed field of galactic, or intergalactic magnetic fields?

✓ Conflict with the current cosmological observations?
=> **Observational constraint**

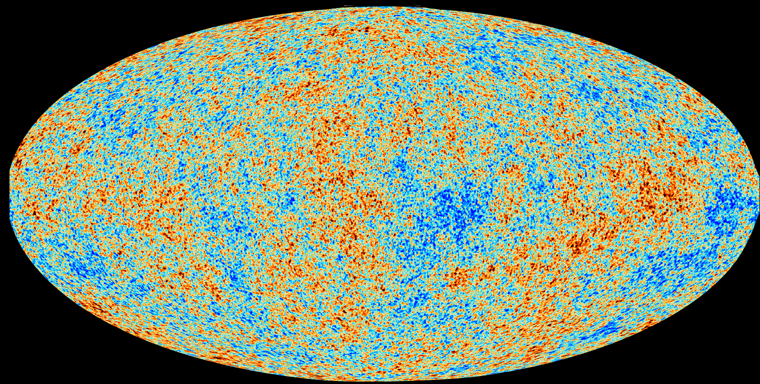
(Fujita & Durrer 2019; Kahniashvili et al. 2013; Horiguchi et al. 2015, 2016; Saga et al. 2015; Subramanian 2016)

Previous constraints on PMFs

- Constraint with CMB anisotropy

Cosmic Microwave Background (CMB):

- Nearly isotropic temperature ~2.7 K
- Small anisotropy $\delta T/T \sim 10^{-5}$
- (due to the inflationary primordial curvature perturbations)



Einstein field equation:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Geometrical curvature

Matter (energy)

If PMFs exist,

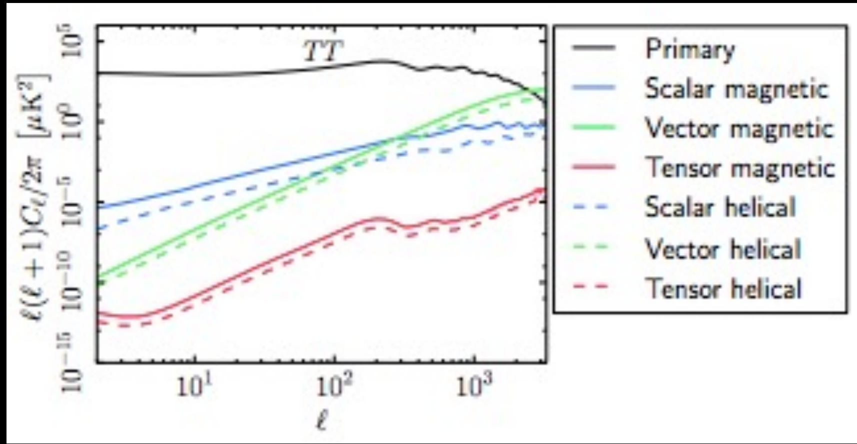
Magnetic energy tensor also induce the curvature perturbations

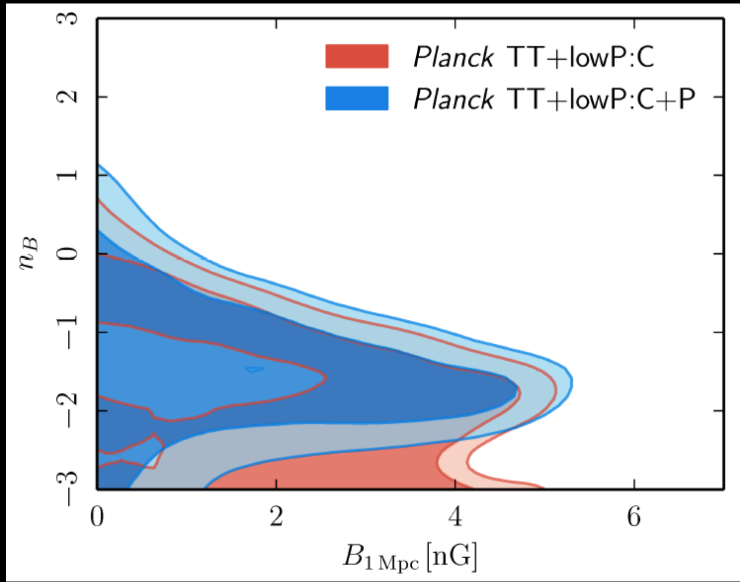
Previous constraints on PMFs

- Constraint with CMB anisotropy
  - Stress-energy tensor of PMFs induce curvature fluctuations
  - Stronger B-fields conflict with the observed CMB temperature anisotropies (and/or polarization, spectral distortion)

$$B_{1\,\mathrm{Mpc}} < 4.5\times10^{-9}\ \mathrm{G}$$

PMF strength smoothed on 1Mpc





(Planck 2015 results. XIX. Constraints on primordial magnetic fields)

Model of PMFs

- Assumption: statistical homogeneity and isotropy, no helicity, no electric fields
- PMF 2-point correlation function

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

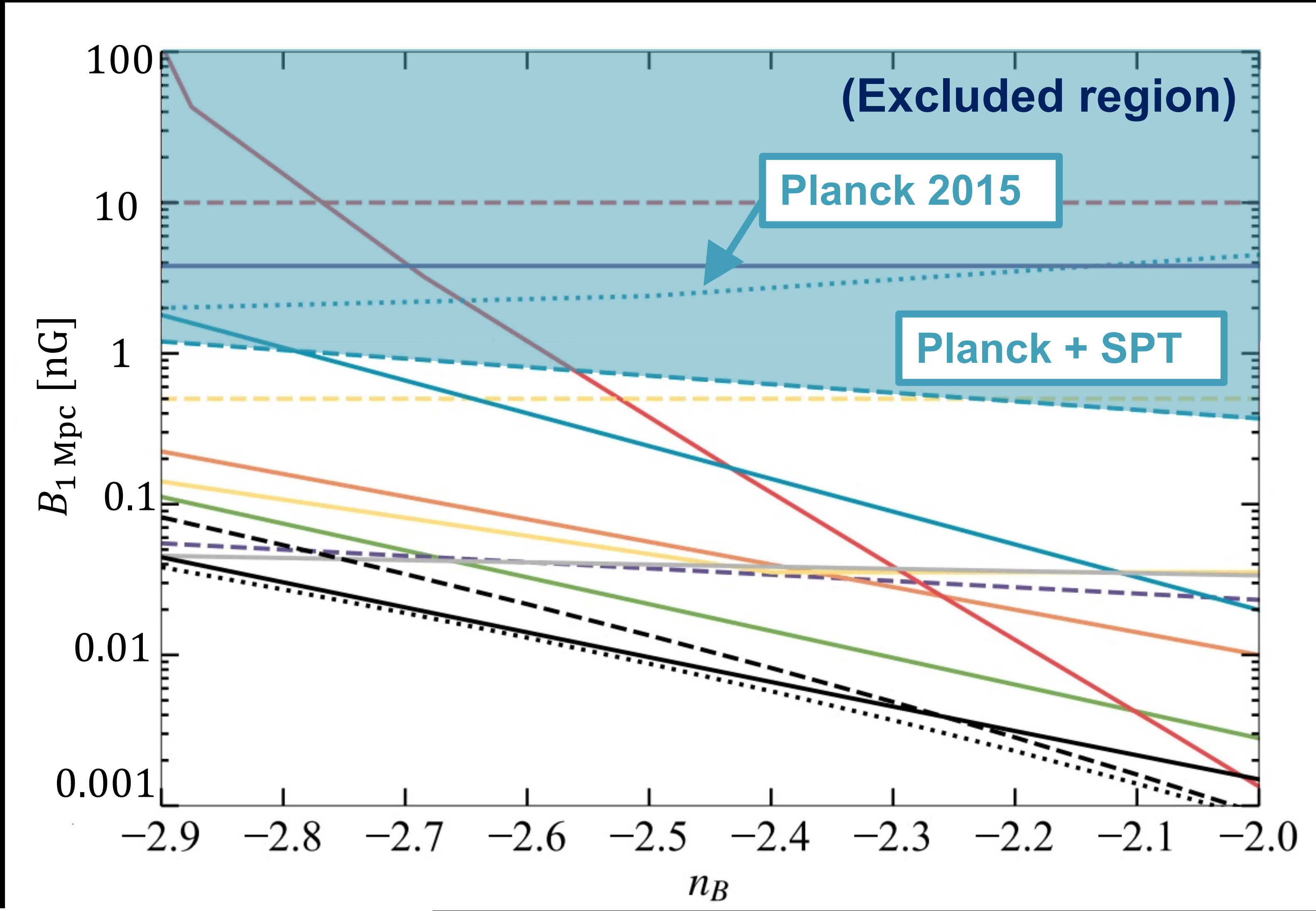
Single power-law power spectrum

$$P_B(k) \propto B_{1\mathrm{Mpc}}^2 \, k^{n_B}$$

$B_{1\mathrm{Mpc}}^2$ → normalizing amplitude

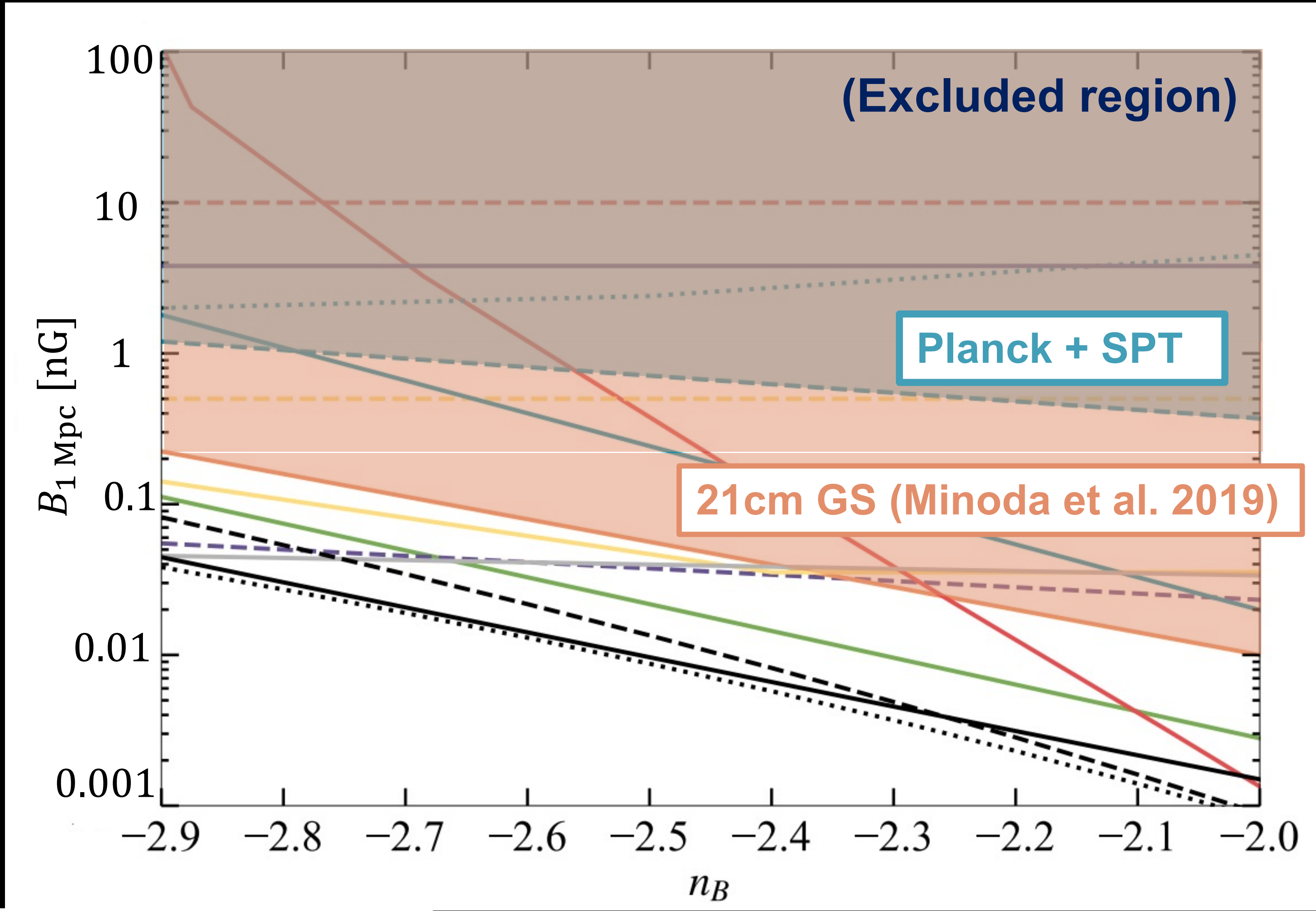
k^{n_B} → scale dependence

Recent Update



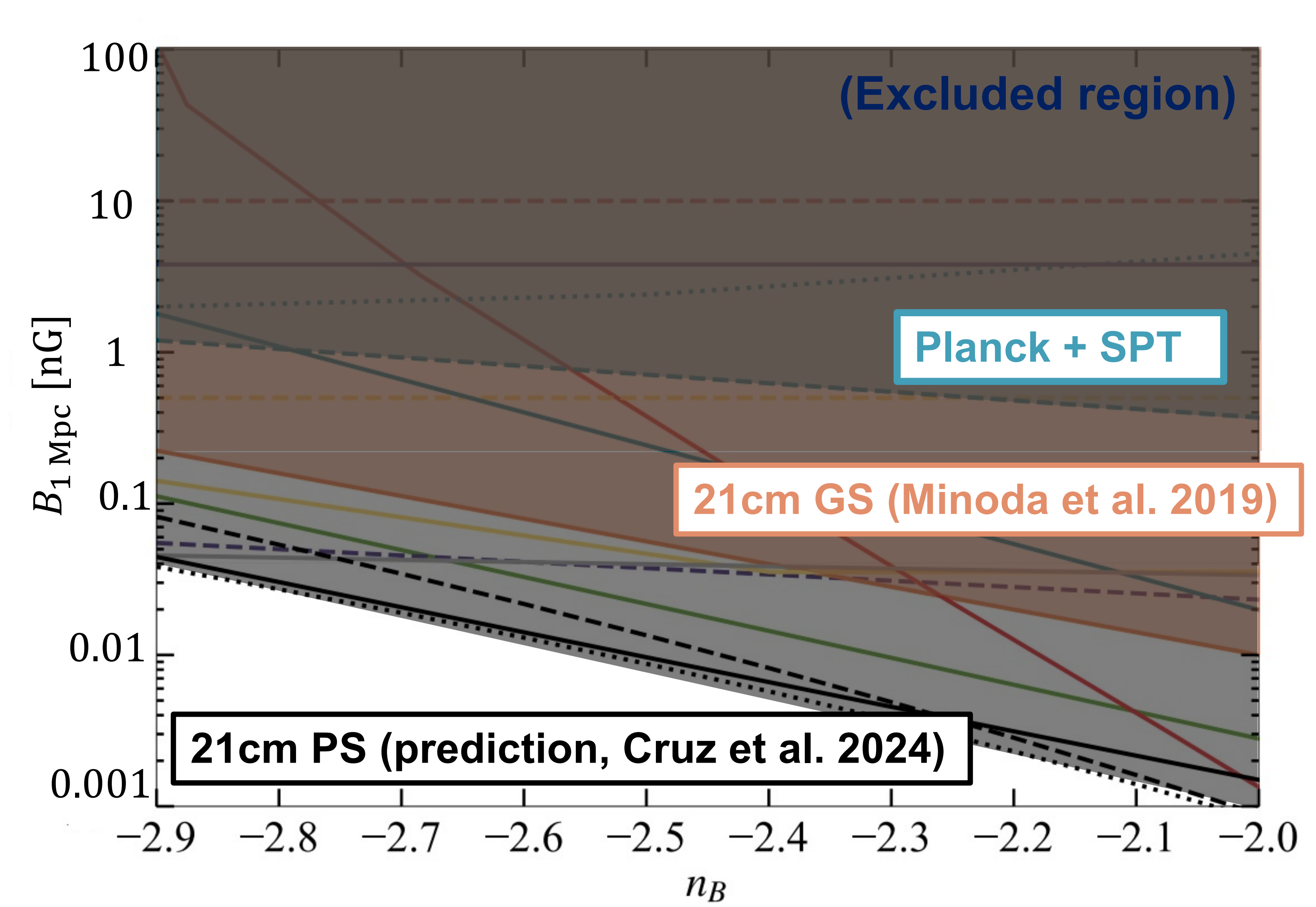
(Cruz et al. 2024)

Recent Update



(Cruz et al. 2024)

Recent Update



(Cruz et al. 2024)

2 types of Constraint on PMFs

- Gas heating from MHD dissipation

  Ex. 21cm global signal, magnetic reheating, CMB optical depth

- Density perturbations from Lorentz force

  Ex. 21cm power spectrum, galaxy number count, CMB anisotropy and optical depth

(Minoda et al. 2019; Saga et al. 2018; Cruz et al. 2024; Sanati et al. 2020; Safarzadeh and Loeb 2019; Galli et al. 2022;)

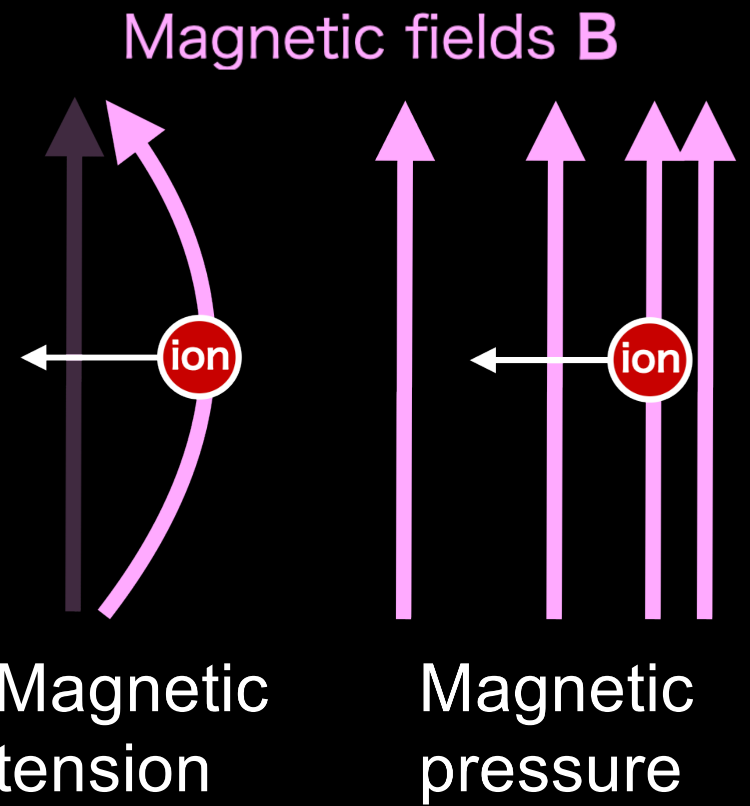
PMFs on the baryon dynamics

Lorentz force on electrically charged particles:

$$f_{\mathrm{Lorentz}} = \frac{(\nabla \times B) \times B}{4\pi} = \frac{(B \cdot \nabla)B}{4\pi} - \nabla\left(\frac{B^2}{8\pi}\right)$$

Lorentz force affect the baryon gas dynamics and structure formation

- To calculate the Lorentz force, spatial distribution of the PMF must be known



Ambipolar diffusion

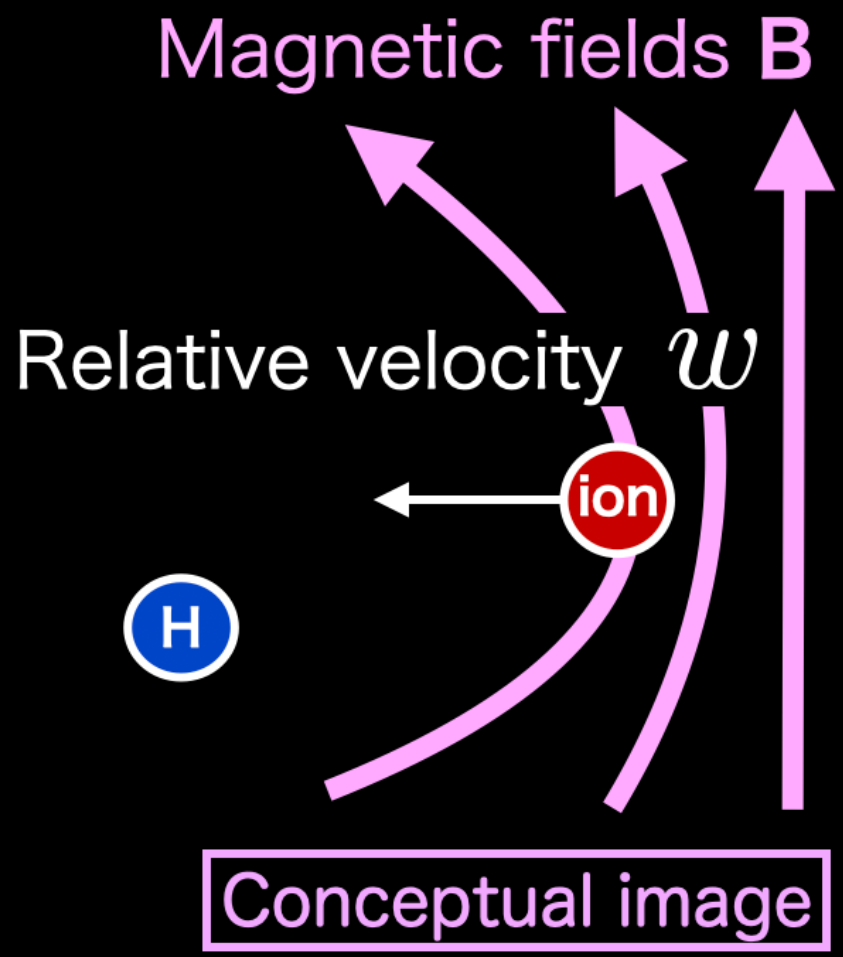
Neutral particles

– Only bulk motion

Charged particles

– Bulk + Magnetic fields

> Streaming motion occurs



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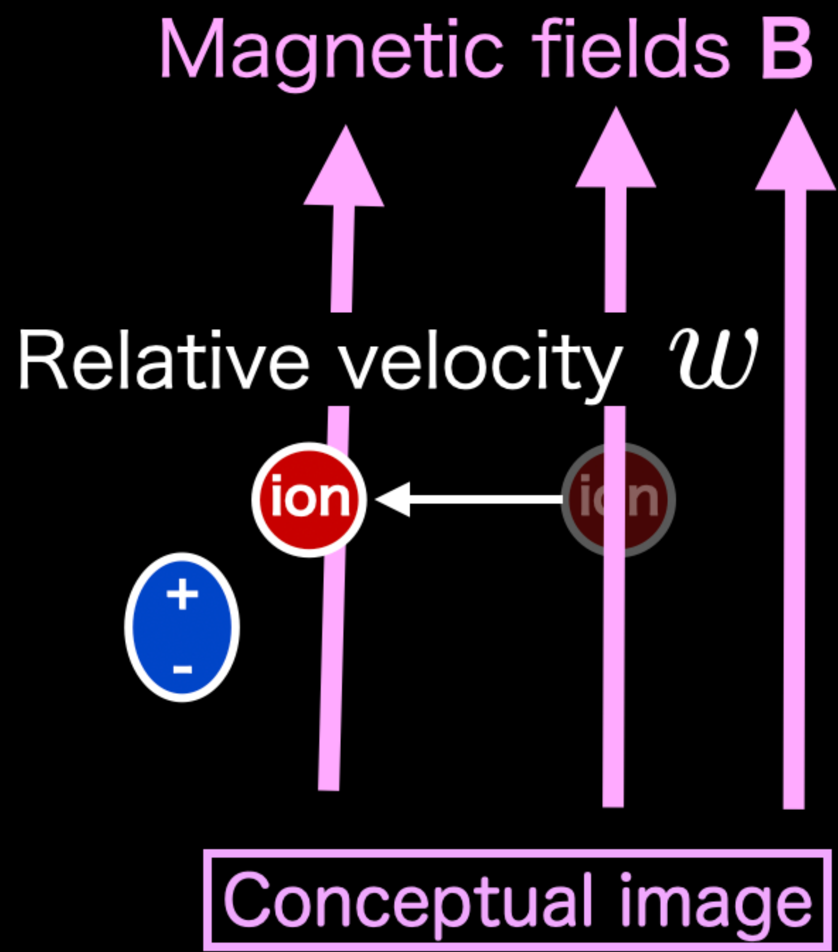
> Electric dipole moment of the neutral particle is generated



Ambipolar diffusion

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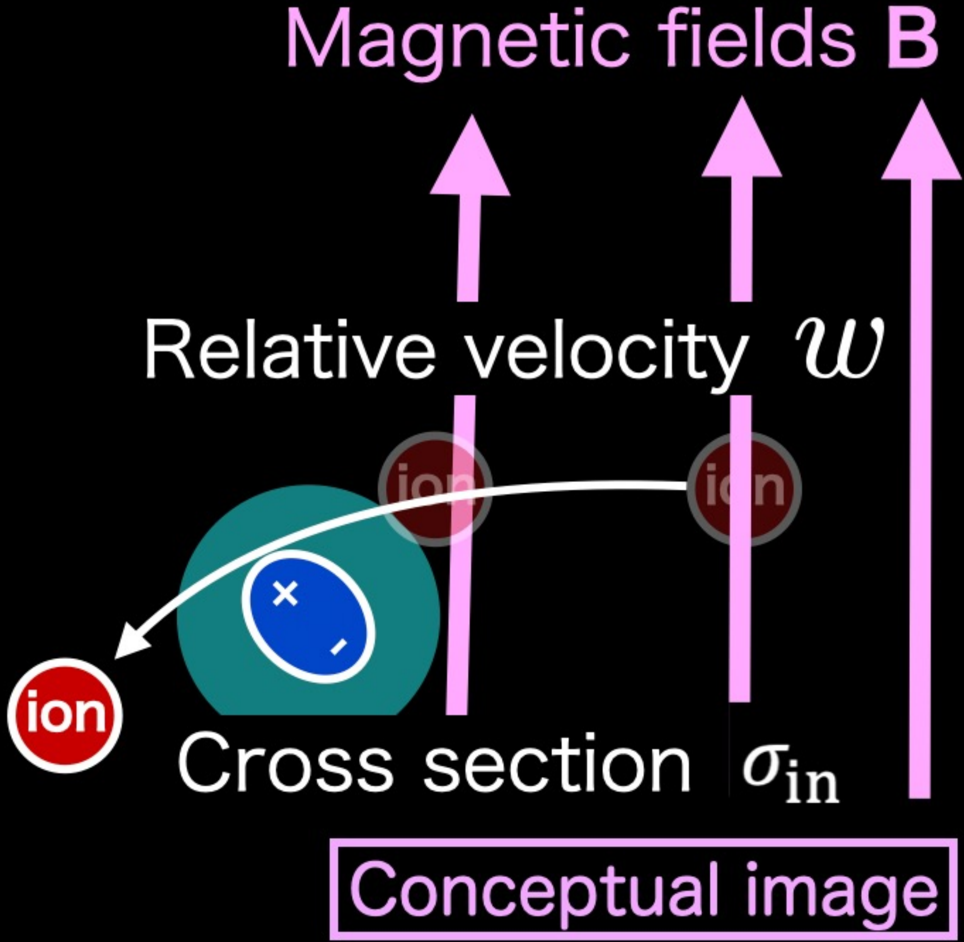


> Streaming motion occurs

> Electric dipole moment of the neutral particle is generated

> Streaming motion is thermalized due to the Coulomb scattering

Ambipolar diffusion

Heating rate due to ambipolar diffusion

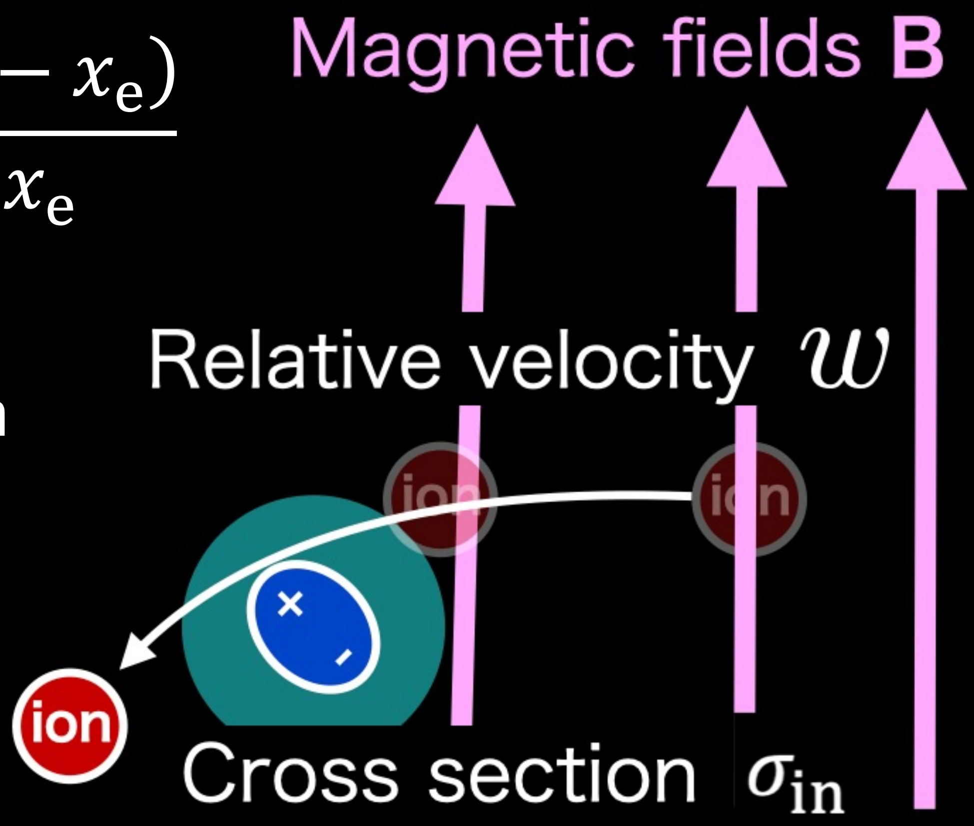
$$\dot{Q}_{\rm AD} = \frac{|(\boldsymbol{\nabla}\times\boldsymbol{B})\times\boldsymbol{B}|^2}{16\pi^2\xi\rho_{\rm b}^2}\frac{(1-x_{\rm e})}{x_{\rm e}}$$

$\rho_{\rm b}$: baryon density
$x_{\rm e}$: free electron fraction

Collision rate:

$$\xi = \frac{\langle w\sigma_{\rm in}\rangle}{m_{\rm e}+m_{\rm n}} \simeq 3.5\times10^{13}\ [\mathrm{cm^3/g/s}]$$

(Draine+, 1983, ApJ, 270)



Conceptual image

(Sethi & Subramanian 2005)

21-cm line global signal

Observable: $\delta T_b \cong 27\, x_{\rm HI} \left(1 - \frac{T_\gamma}{T_{\rm spin}}\right) \left(\frac{1+z}{10}\right)^{1/2}$ [mK]

Roughly speaking,

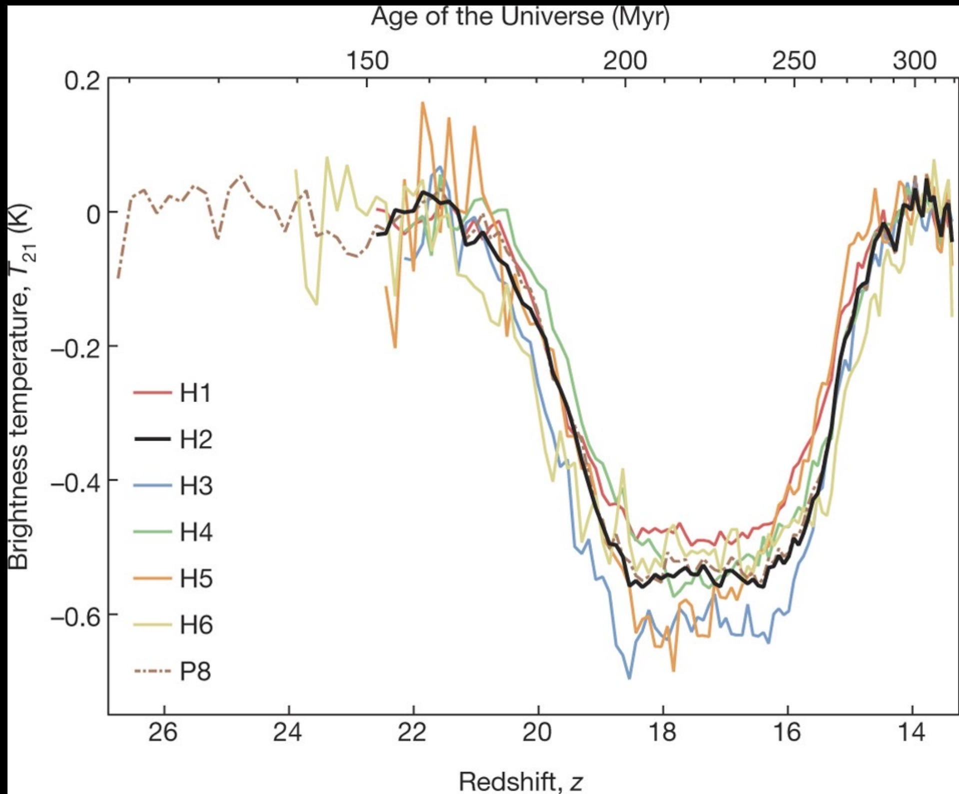
Emission:

$$T_{\rm K} \geq T_{\rm spin} \geq T_\gamma$$

Absorption:

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

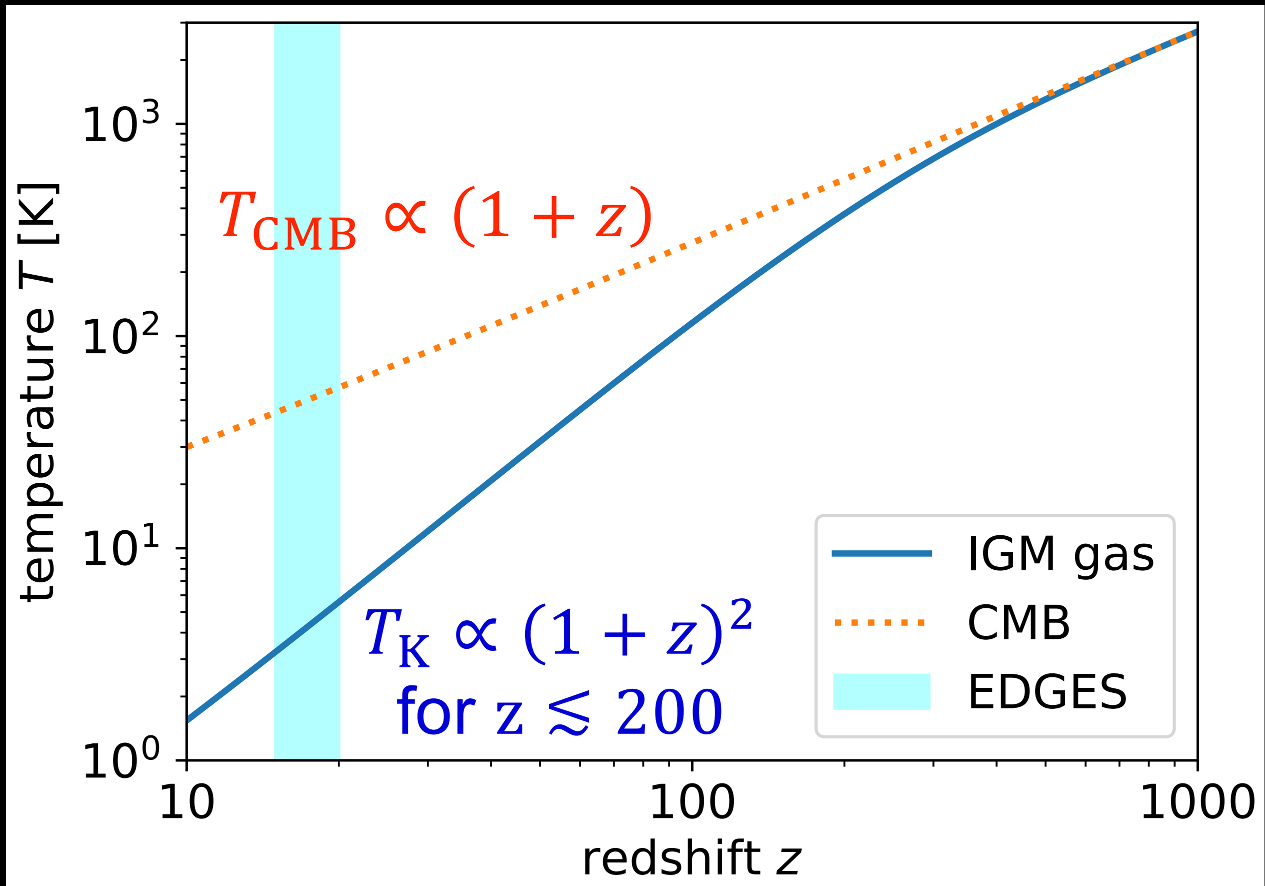
EDGES results:
NO EMISSION at z~17



(Bowman et al. 2018)

thermal history in dark ages

ΛCDM predicts $T_{\mathrm{CMB}} > T_{\mathrm{K}}$ (absorption signal) at $z \sim 17$



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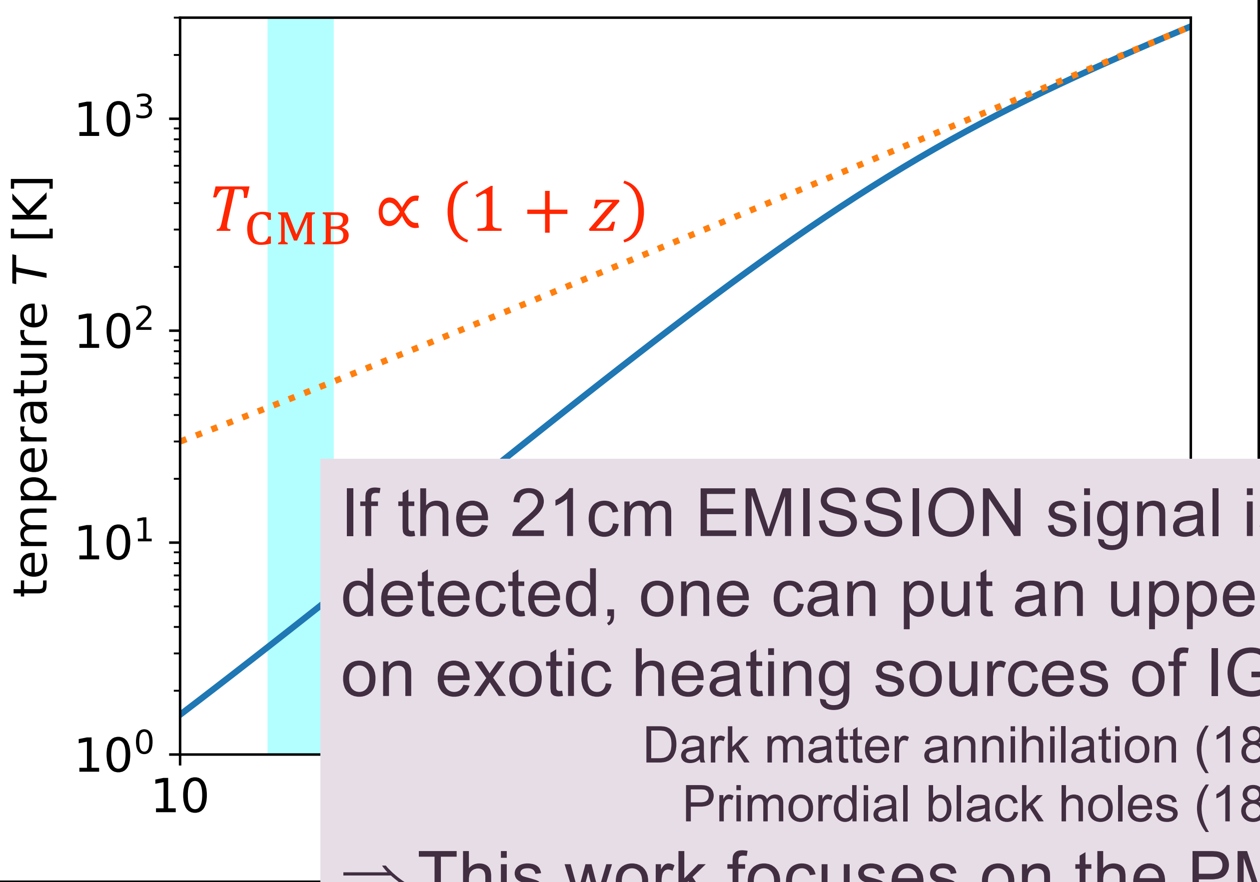


If the 21cm EMISSION signal is NOT detected, one can put an upper limit on exotic heating sources of IGM

Dark matter annihilation (1803.03629)

Primordial black holes (1803.09390)

⇒ This work focuses on the PMFs

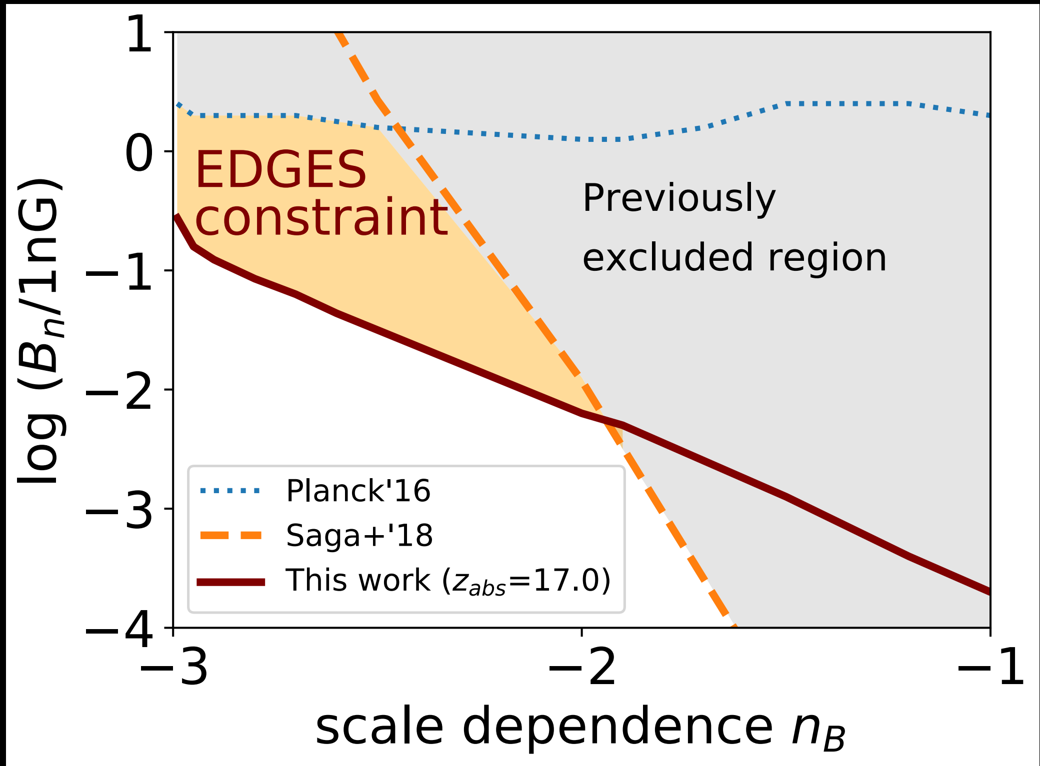
A new constraint on PMFs

Calculate time evolution of T_{K} with various combinations (B_n, n_B)

Put an upper limit on PMFs to satisfy the 21-cm line absorption condition:

$$T_{\mathrm{K}} < T_{\mathrm{CMB}} \quad \text{(at } z\sim17\text{)}$$

$$B_{1\ \mathrm{Mpc}} \lesssim 0.1\ \mathrm{nG}$$



First time to compare with other observational constraints

(Minoda et al. 2019)

Density perturbations from PMFs

Continuity equation and EoM

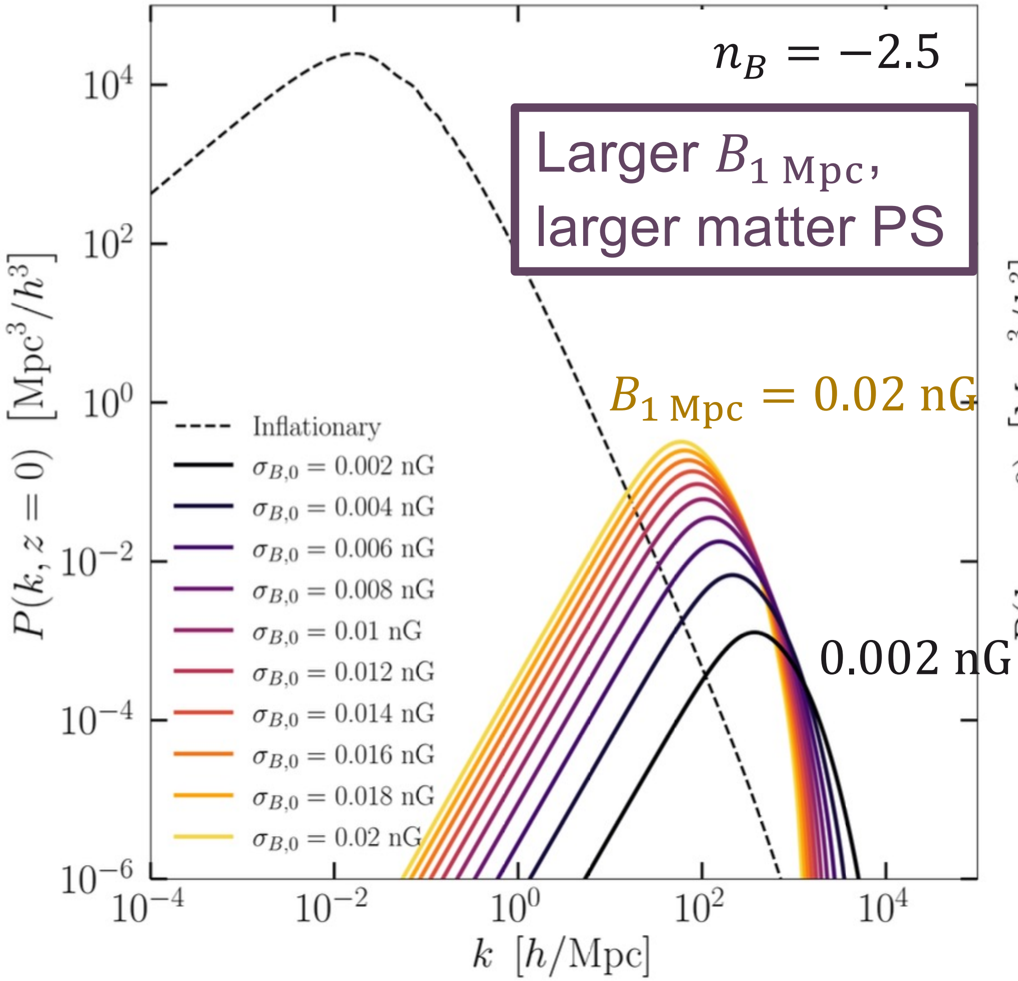
$$\begin{cases} \dfrac{\partial \rho_{\rm b}}{\partial t} + \nabla \cdot (\rho_{\rm b} \boldsymbol{v}_{\rm b}) = 0 \\ \dfrac{\partial \boldsymbol{v}_{\rm b}}{\partial t} + (\boldsymbol{v}_{\rm b} \cdot \nabla) \boldsymbol{v}_{\rm b} = -\dfrac{\nabla p}{\rho_{\rm b}} + \dfrac{\boldsymbol{f}_{\rm Lorentz}}{\rho_{\rm b}} - \nabla \Phi \end{cases}$$

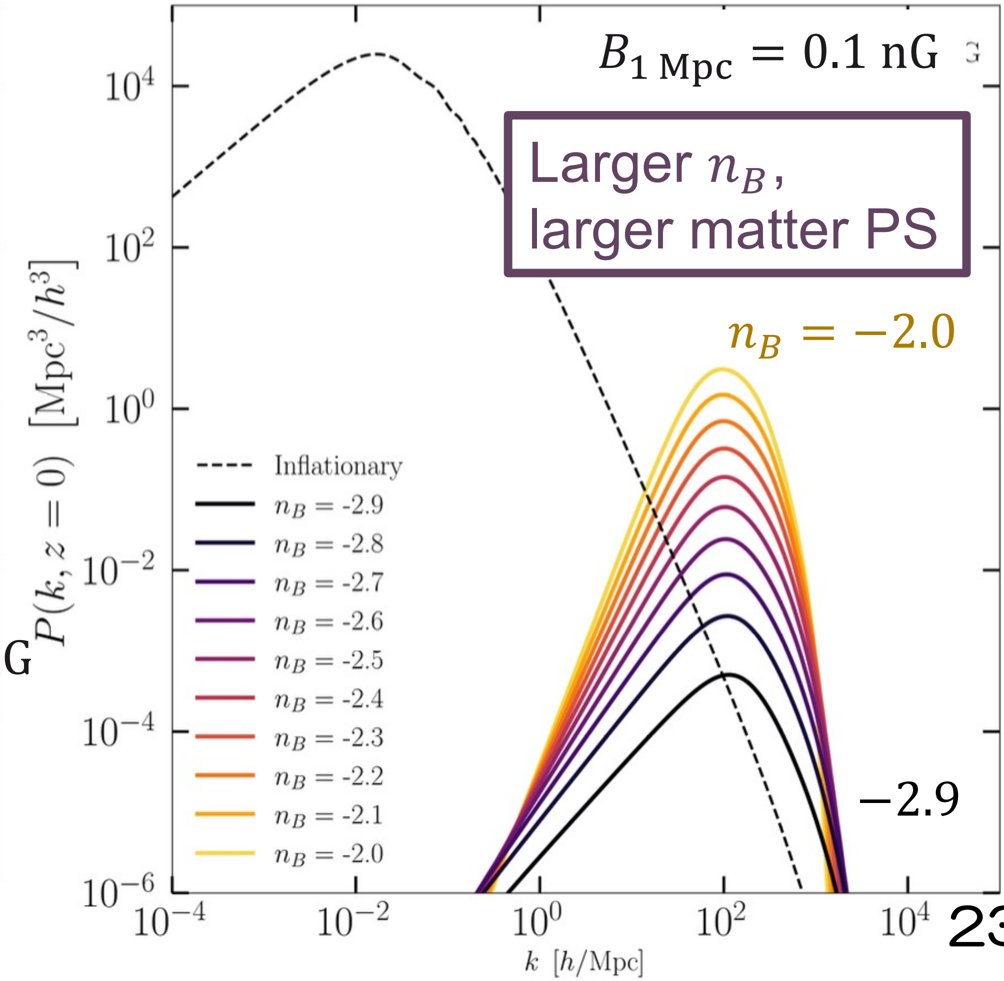
Density contrast: $\rho_{\rm b} = \bar{\rho}_{\rm b}(1 + \delta_{\rm b})$

(Linear approximation, $\delta_{\rm b} \ll 1$)

$$\ddot{\delta}_{\rm b} + 2\frac{\dot{a}}{a}\dot{\delta}_{\rm b} - 4\pi G[\bar{\rho}_{\rm c}\delta_{\rm c} + \bar{\rho}_{\rm b}\delta_{\rm b}] = \frac{\nabla \cdot \boldsymbol{f}_{\rm Lorentz}}{\bar{\rho}_{\rm b}}$$

Matter power spectrum



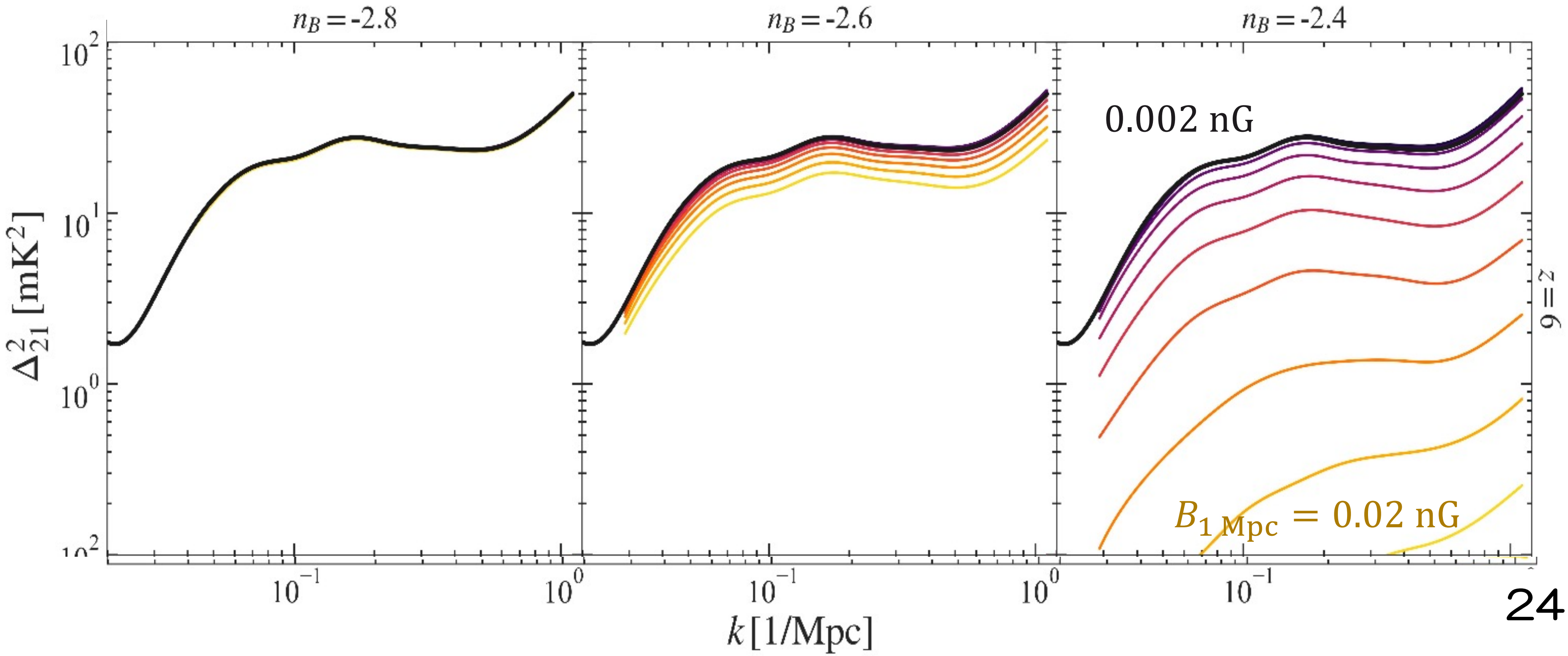


Calculate 21cm signal with PMFs (21cmFAST)

(Cruz et al. 2024)

21cm power spectrum (z=6)

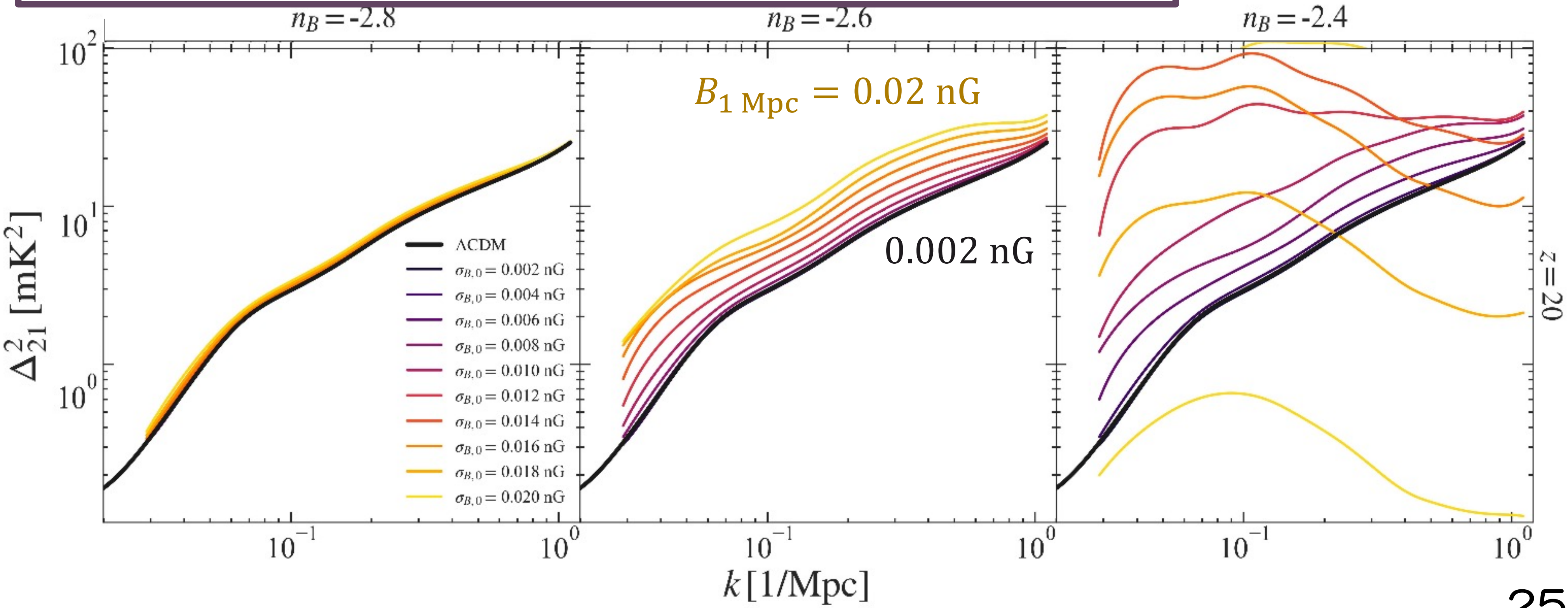
Larger $B_{1\ \mathrm{Mpc}}$ and n_B, earlier reionization ends.
Smaller amplitude 21cm PS



(Cruz et al. 2024)

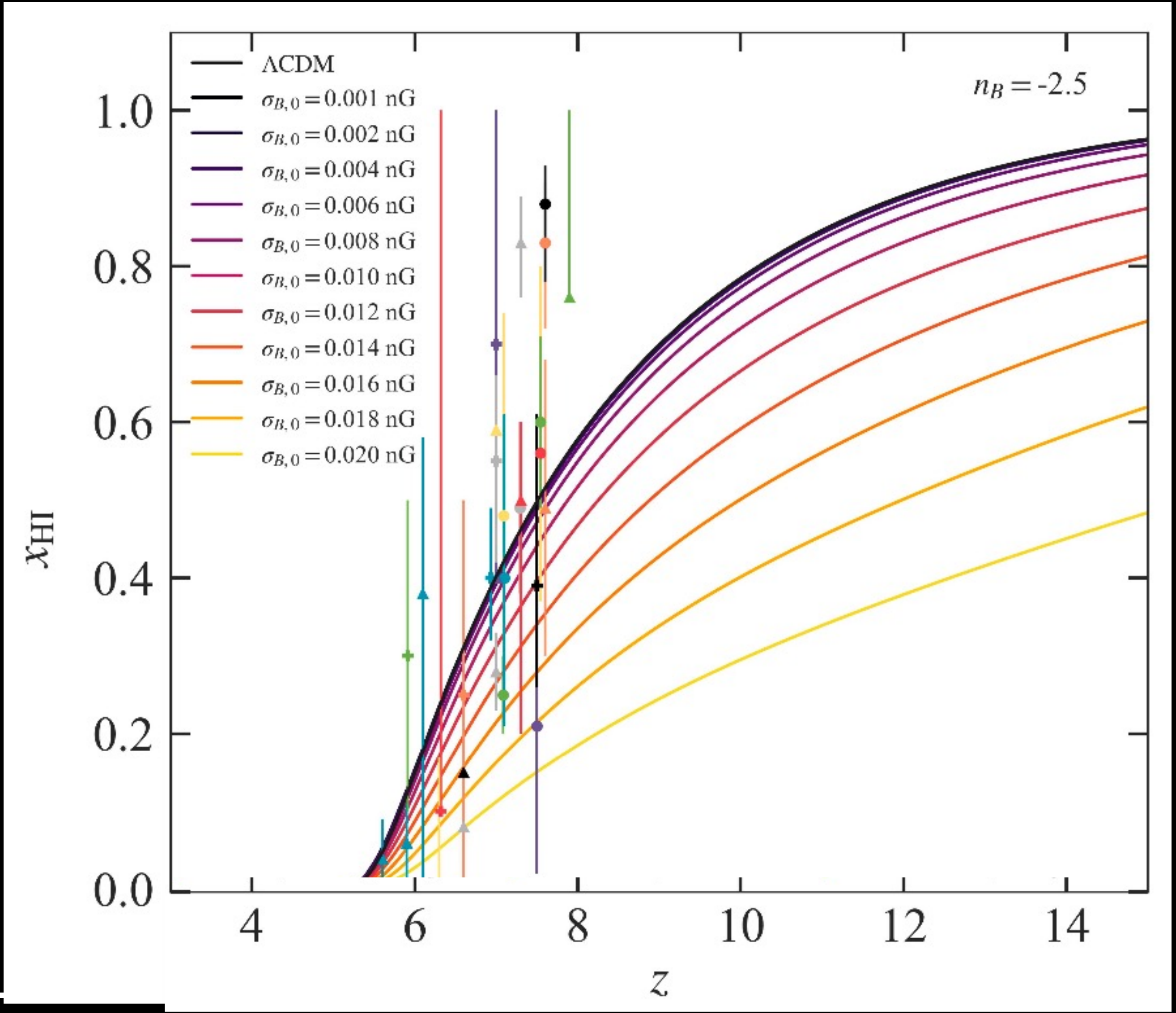
21-cm power spectrum (z=20)

Larger $B_{1\ \mathrm{Mpc}}$ and n_B, earlier structure formation starts.
Larger amplitude in the Dark Ages
Too strong PMF cases, reionization ends even at z=20



(Cruz et al. 2024)

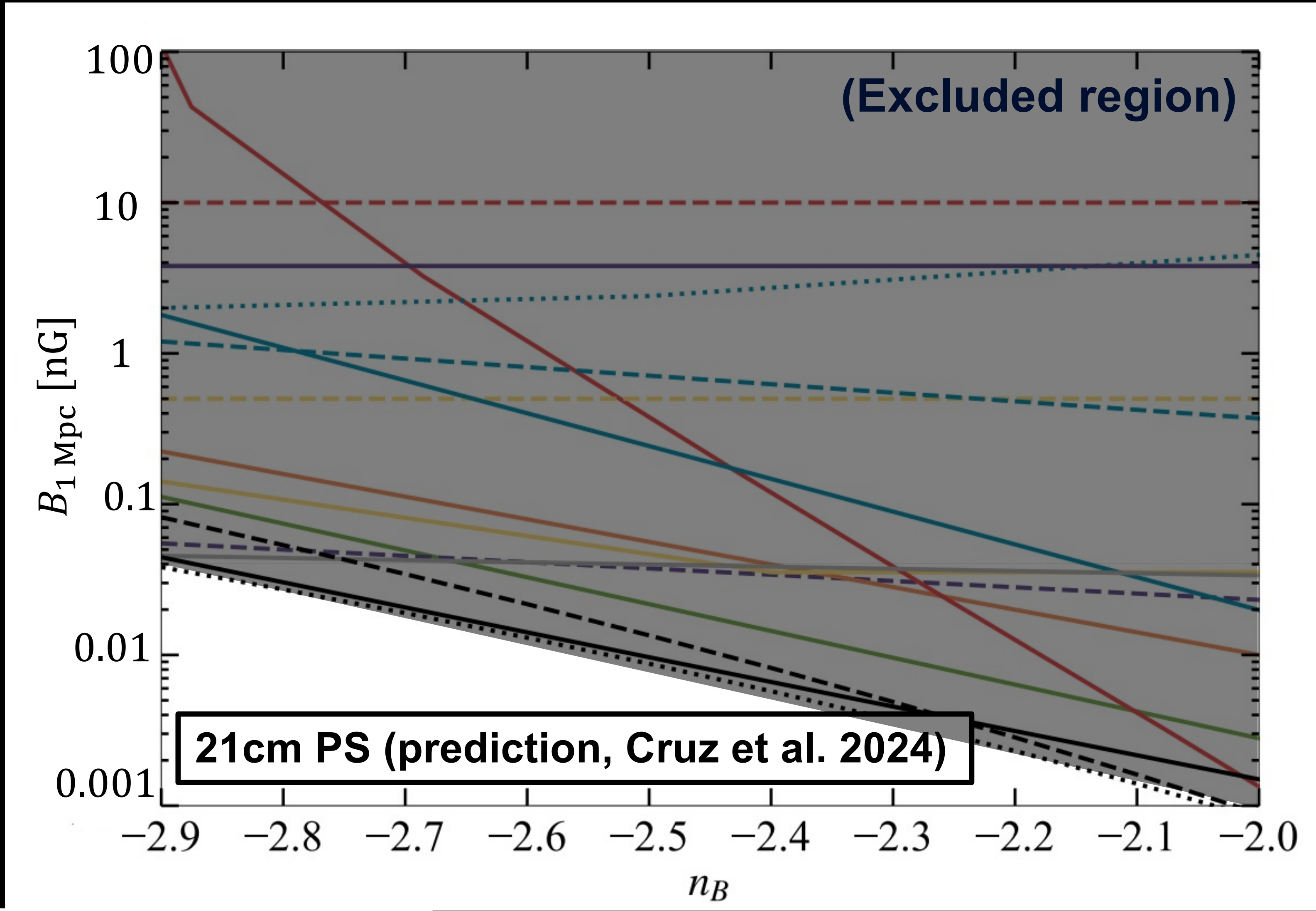
Reionization history



(Data points):
quasors Lyman alpha,
quasor damping wings,
Lyman break galaxies,
Lyman alpha emitters,
GRB damping wings,
Dark fractions

(Cruz et al. 2024)

Results



(Cruz et al. 2024)

Summary

- ✓ Review recent constraints on the PMFs
- ✓ (1) PMF dissipation heat up the IGM gas
- ✓ (2) Lorentz force induce density perturbations
- ✓ Future prospects:
  non-Gaussianity of perturbations?
  Halo formation condition?

Thank you very much!