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Thermal Sunyaev-Zel'dovich effect in the IGM due to the primordial magnetic fields

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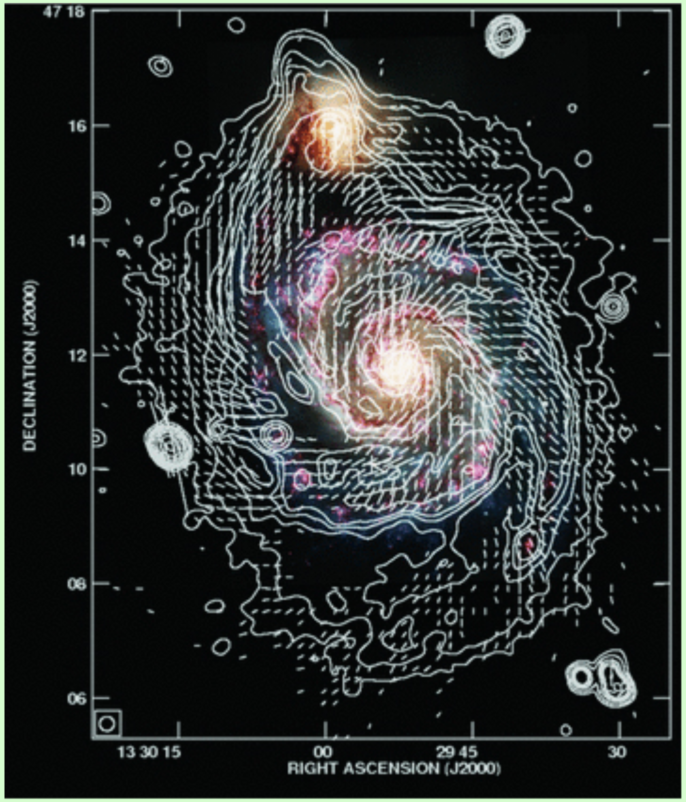
Today's Contents

1. Introduction
    - Primordial Magnetic Fields & Its Constraint
2. Theory
    - Gas dynamics with the PMFs (previous work)
    - Thermal Sunyaev-Zel'dovich effect
3. Methods
4. Results
    - Evolution of the gas density & temperature
    - CMB temperature anisotropy

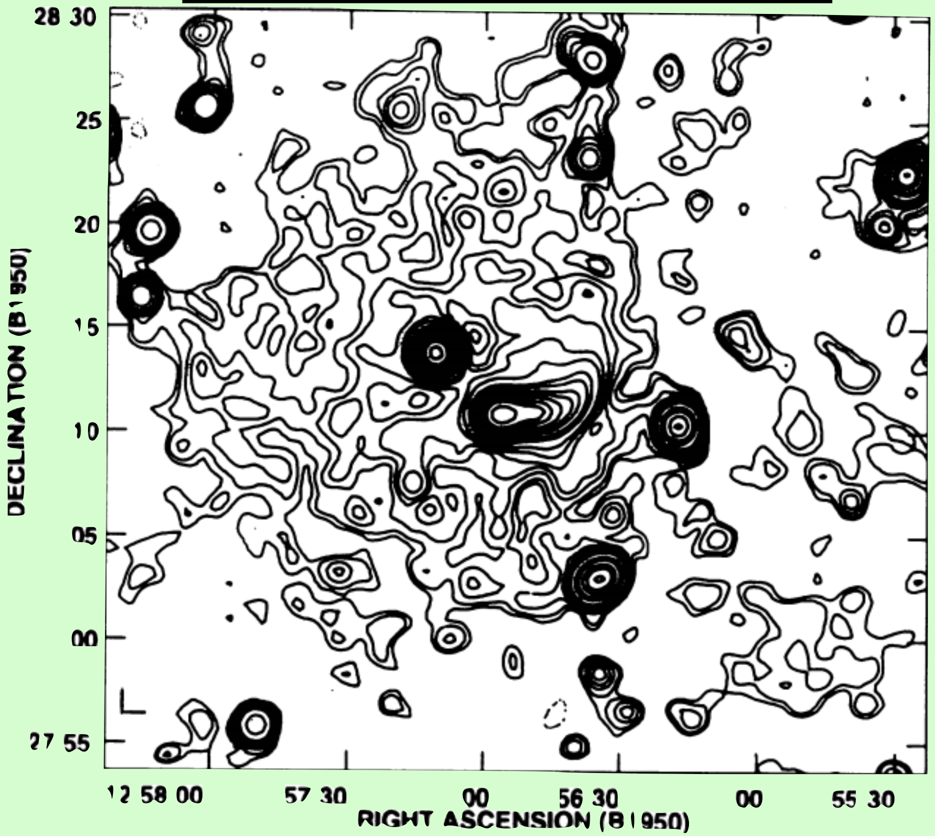
Cosmic Magnetic Fields

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

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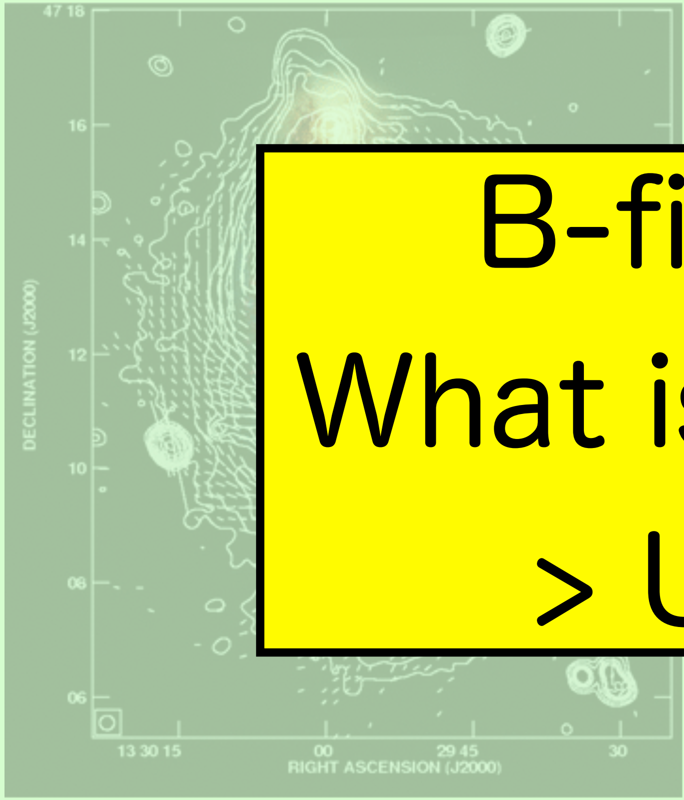

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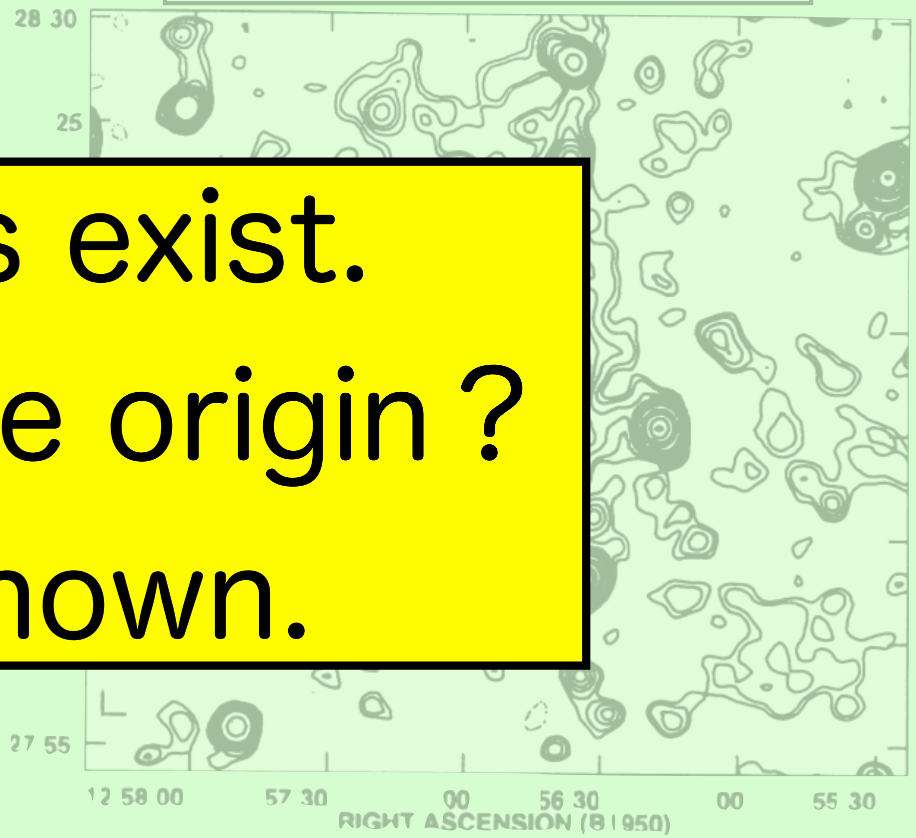

Coma Cluster [radio] WSRT, 90cm
(Giovannini+, 1993, ApJ, 406)

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

The origin of B-fields

Cosmological origin ?
(e.g. Jennifer's talk)

- Inflation
- Phase transition
- New physics

Small strength compared to the observed value
Difficult for observational test

Astrophysical origin ?
(e.g. Julius' talk)

- Shock wave
- Turbulent motion
- Plasma physics

Too small scale to calculate cosmological evolution
Difficult to explain IGMF?

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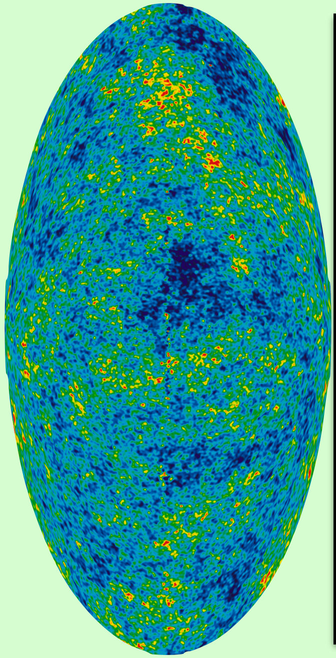
Difficult to explain IGMF?

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

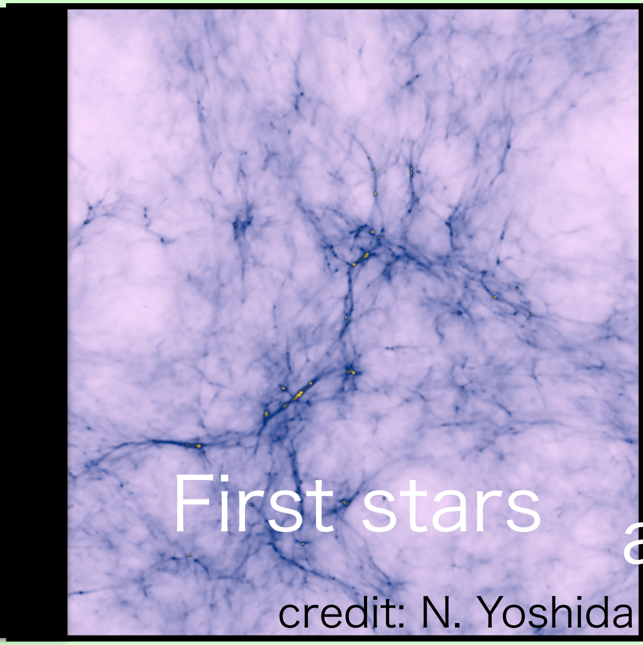
The origin of B-fields

constraint on the PMFs from the CMB anisotropy

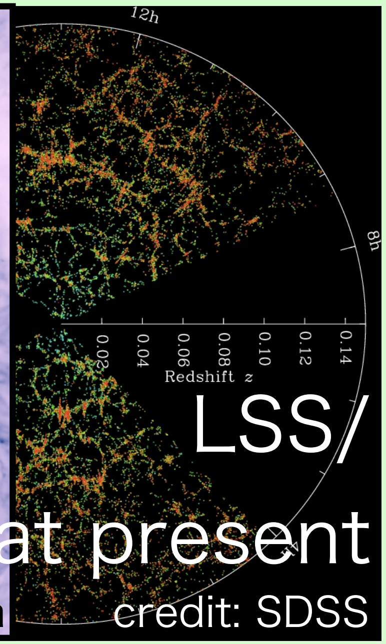


credit: *Planck*

Dark Age



credit: N. Yoshida



credit: SDSS

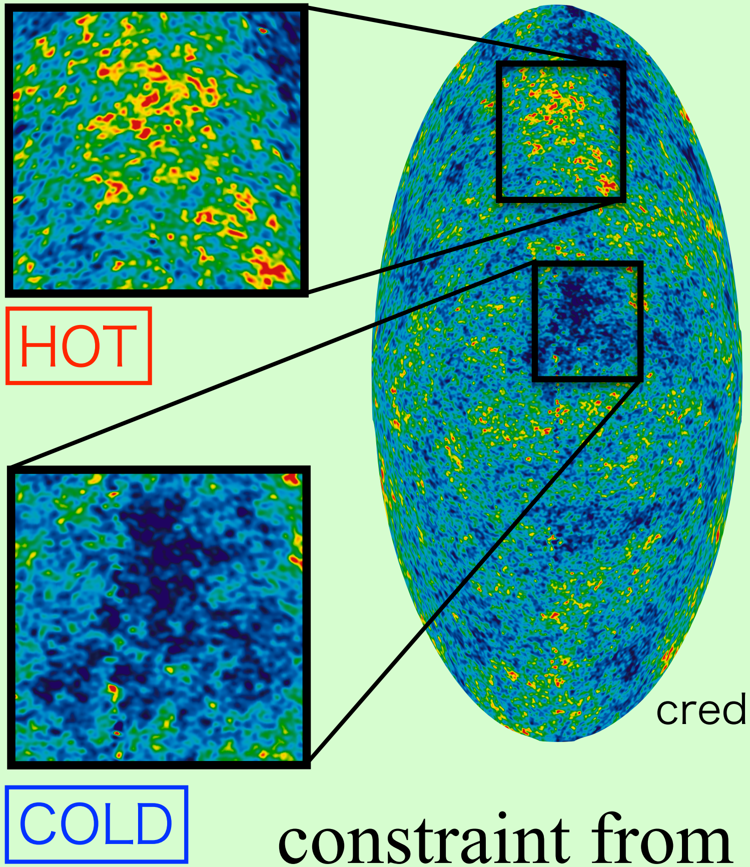
$B_{1\ \mathrm{Mpc}} \lesssim 4\ \mathrm{nG}$

time

z~1100

Constraint from CMB

Cosmic Microwave Background (CMB)



Radiation with T~2.725 K
Actually there is some fluctuation
→ Metric perturbation
To constrain the stress-energy tensor of the PMFs

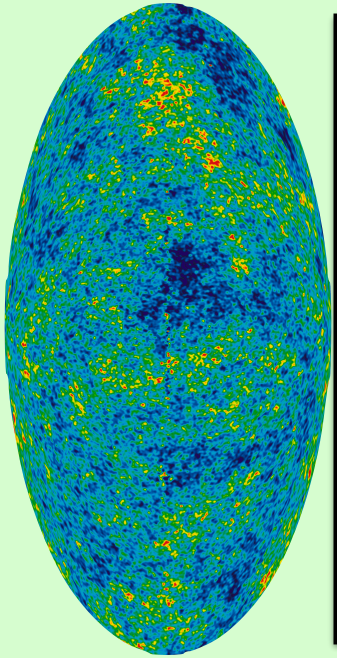
constraint from *Planck* 2015 $B_{1\ \mathrm{Mpc}} \lesssim 4\ \mathrm{nG}$

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

Motivation

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

Can the PMFs affect the universe after the recombination epoch ?



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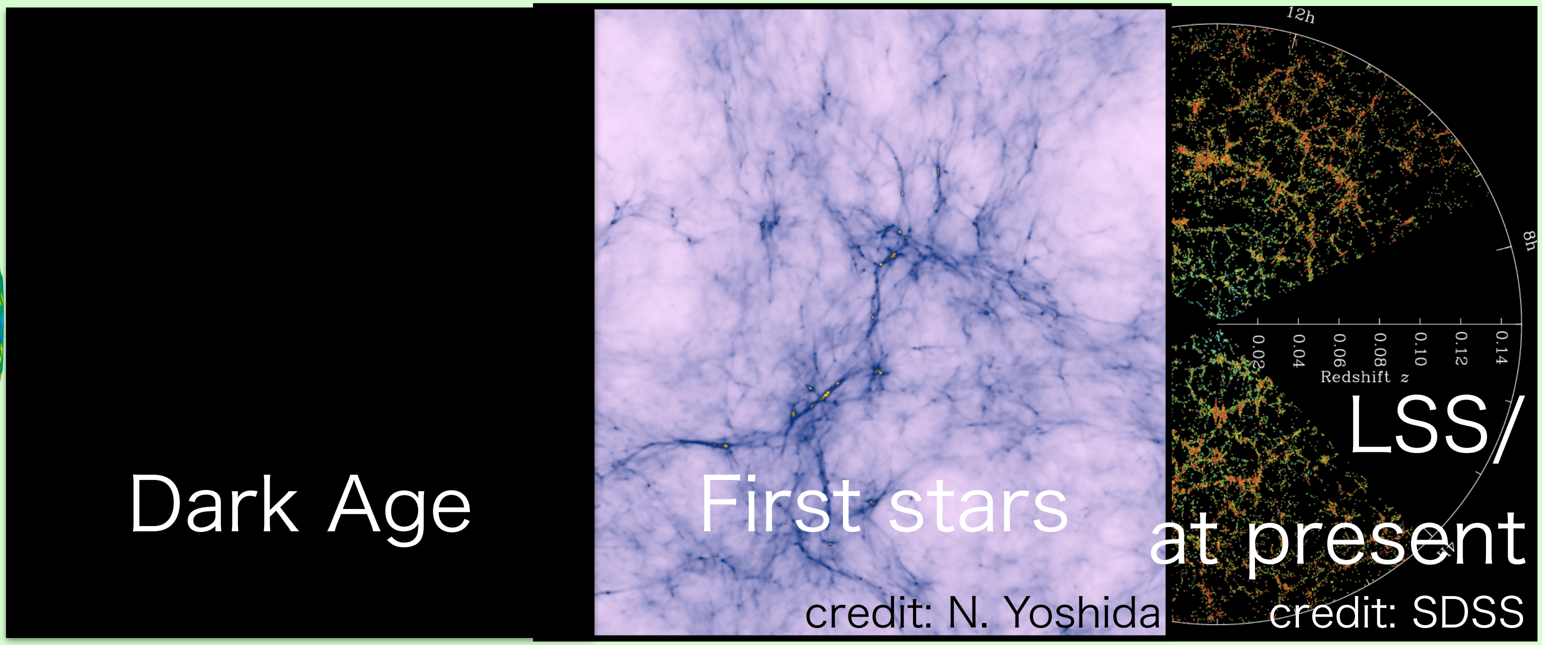

the recombination

time

z~1100

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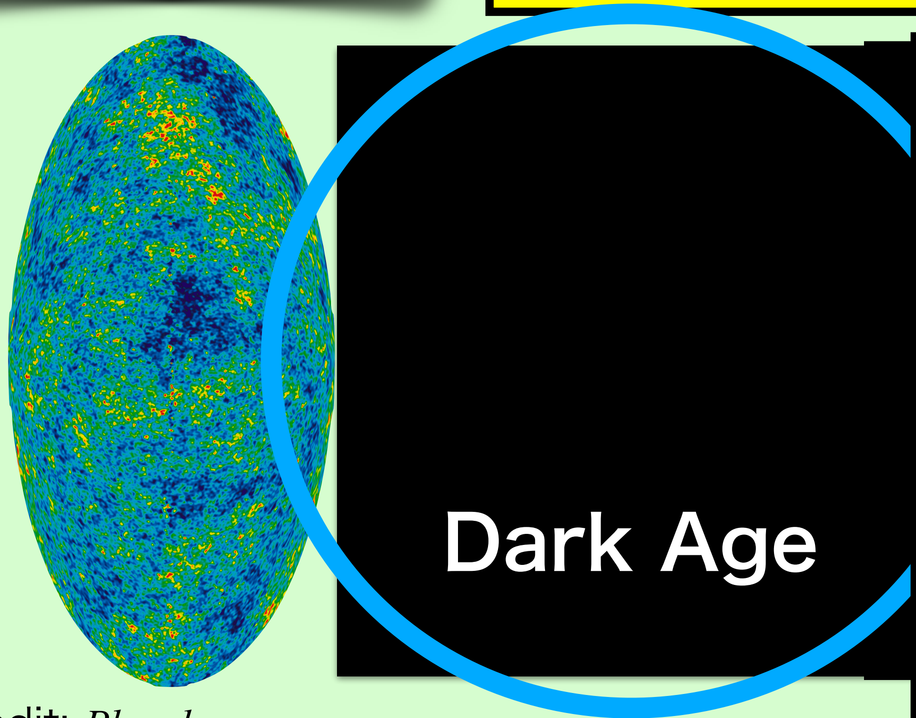


credit: *Planck*

Focus on the PMFs and gas dynamics in the Dark Age

(T_{gas} and n_{gas} time evolution)

[Reasons]

- Little ambiguity of the theory
- No astronomical objects

the recombination

z~1100

time

Methods

GOAL：To consider the effects of the PMFs on gas dynamics in the dark age and CMB temperature anisotropy

[Our work]

① Calculate evolution T_{gas} and n_{gas} with PMFs in the dark age

② Estimate CMB anisotropy generated by tSZ effect

Thermal history with PMFs

(Sethi & Subramanian, 2005, MNRAS, 356)

[Abstract of SS 2005]

- PMFs could heat the baryon gas through **ambipolar diffusion**
- PMFs with B~3 [nG] can heat up the gas temperature to T~10^4 [K] after the recombination.

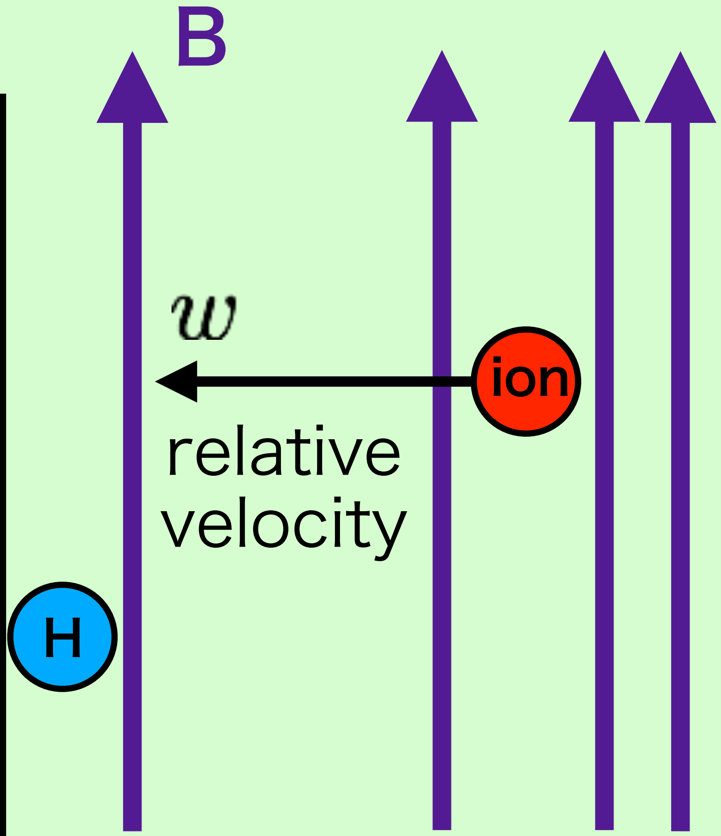


Illustration of ambipolar diffusion

Thermal history with PMFs

(Sethi & Subramanian, 2005, MNRAS, 356)

What is ambipolar diffusion ?

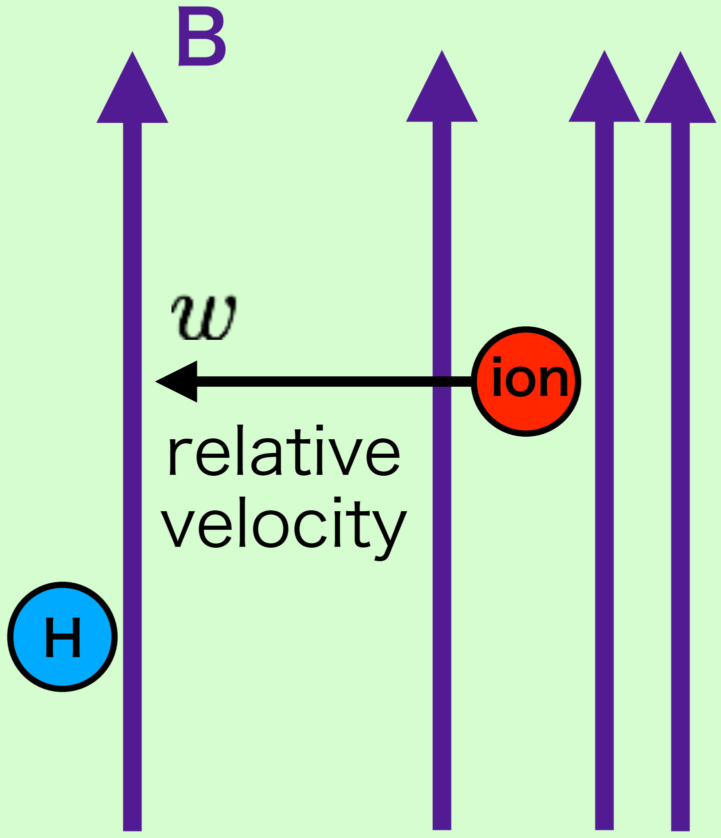
Neutral bulk motion

Charged bulk motion

+ magnetic effects

> occurrence of

the relative motion



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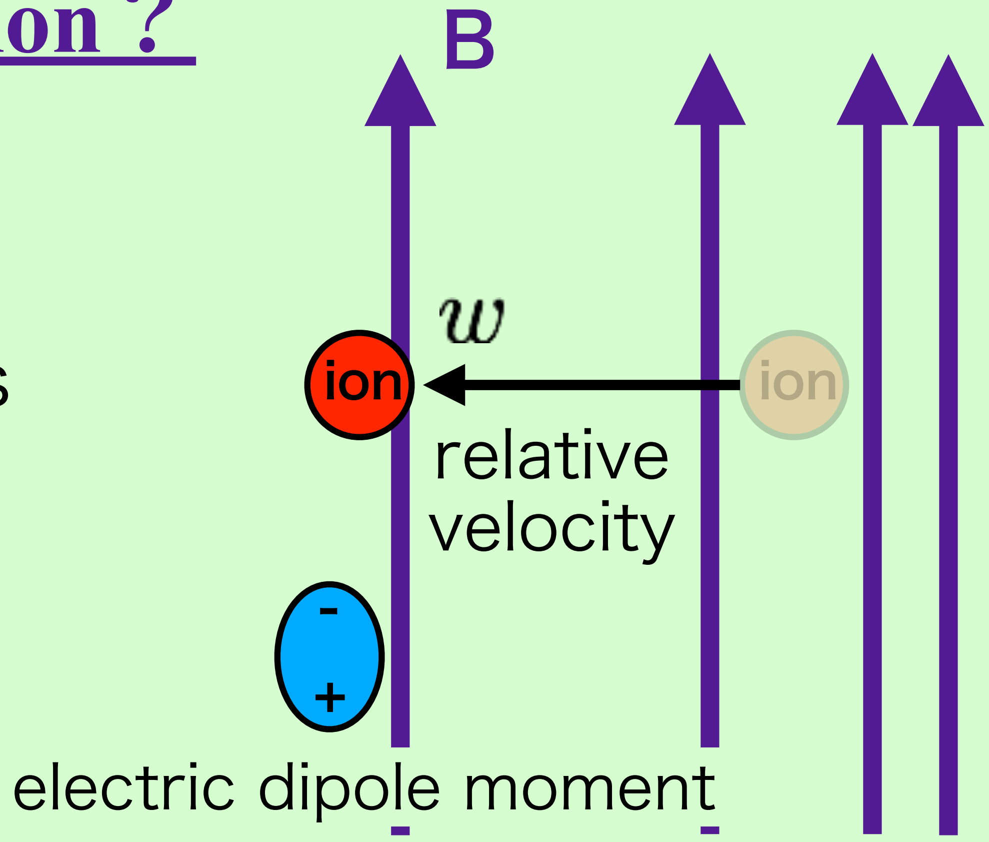
> induce electric dipole moment to the neutrals



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What is ambipolar diffusion ?

Neutral bulk motion

Charged bulk motion

+ magnetic effects

> occurrence of the relative motion

> induce electric dipole moment to the neutrals

> thermalize the relative motion from B-fields

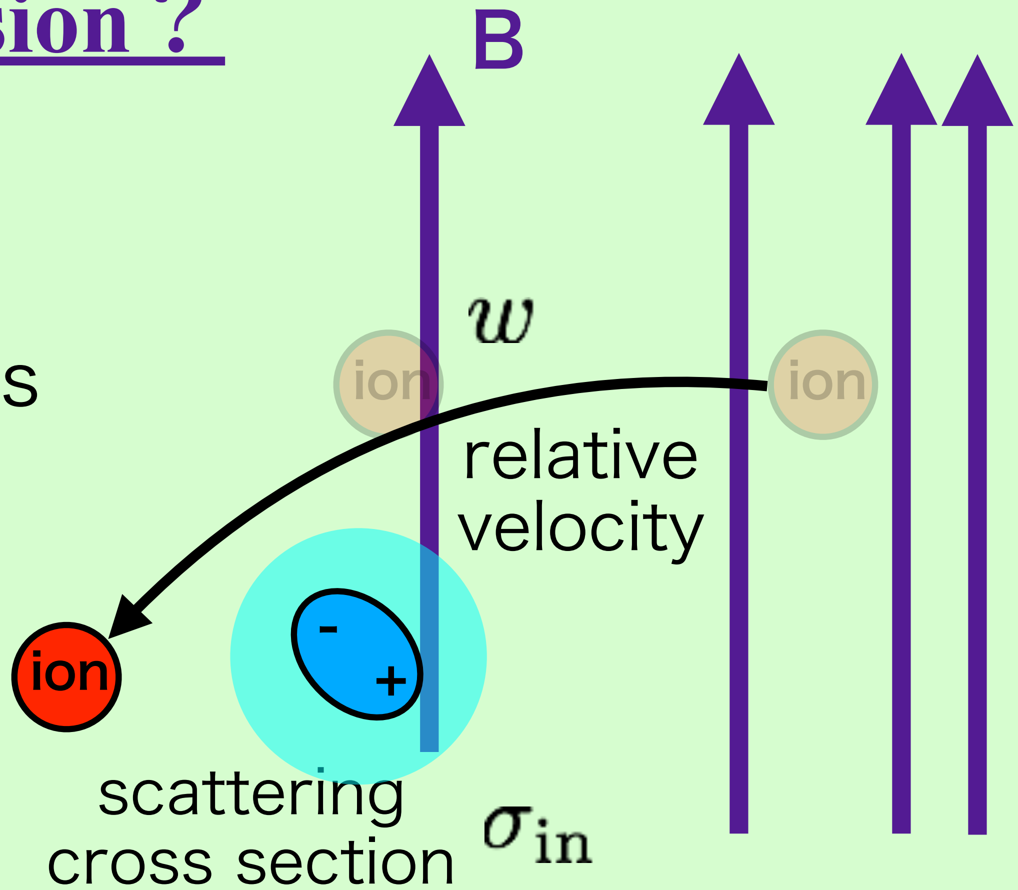


Illustration of ambipolar diffusion

Thermal history with PMFs

(Sethi & Subramanian, 2005, MNRAS, 356)

Heating rate with ambipolar diffusion

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

baryon mass density : ρ_b

baryon ionization fraction : x_i

collisional coefficient :

$$\xi = \frac{\langle w \sigma_{in} \rangle}{m_i + m_n} \simeq 3.5 \times 10^{13}\ [\mathrm{cm}^3/\mathrm{g/s}]$$

(Draine+, 1983, ApJ, 270)

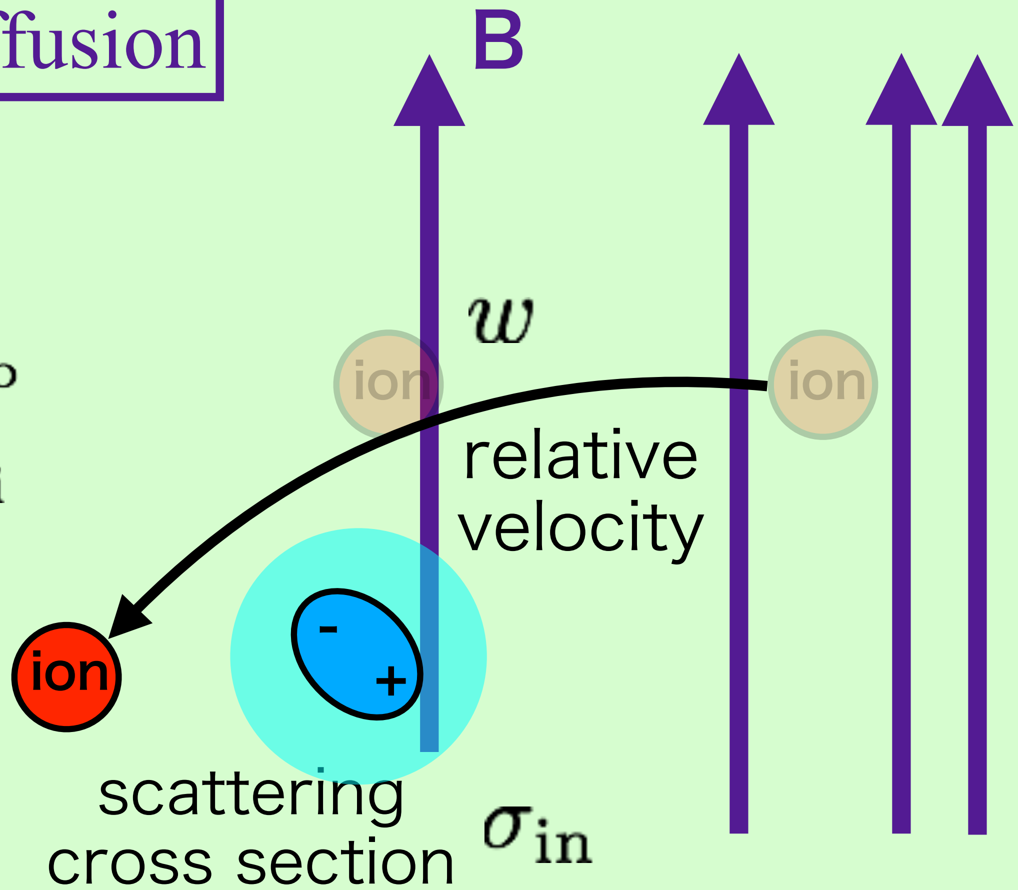


Illustration of ambipolar diffusion

Thermal history with PMFs

(Sethi & Subramanian, 2005, MNRAS, 356)

$$\frac{dT_{\rm gas}}{dt} = -2H(t)T_{\rm gas}$$

adiabatic cooling from the cosmic expansion

$$+\frac{x_{\rm i}}{1+x_{\rm i}}\frac{8\rho_\gamma\sigma_{\rm T}}{3m_{\rm e}c}(T_\gamma - T_{\rm gas})$$

Compton scattering with CMB photons

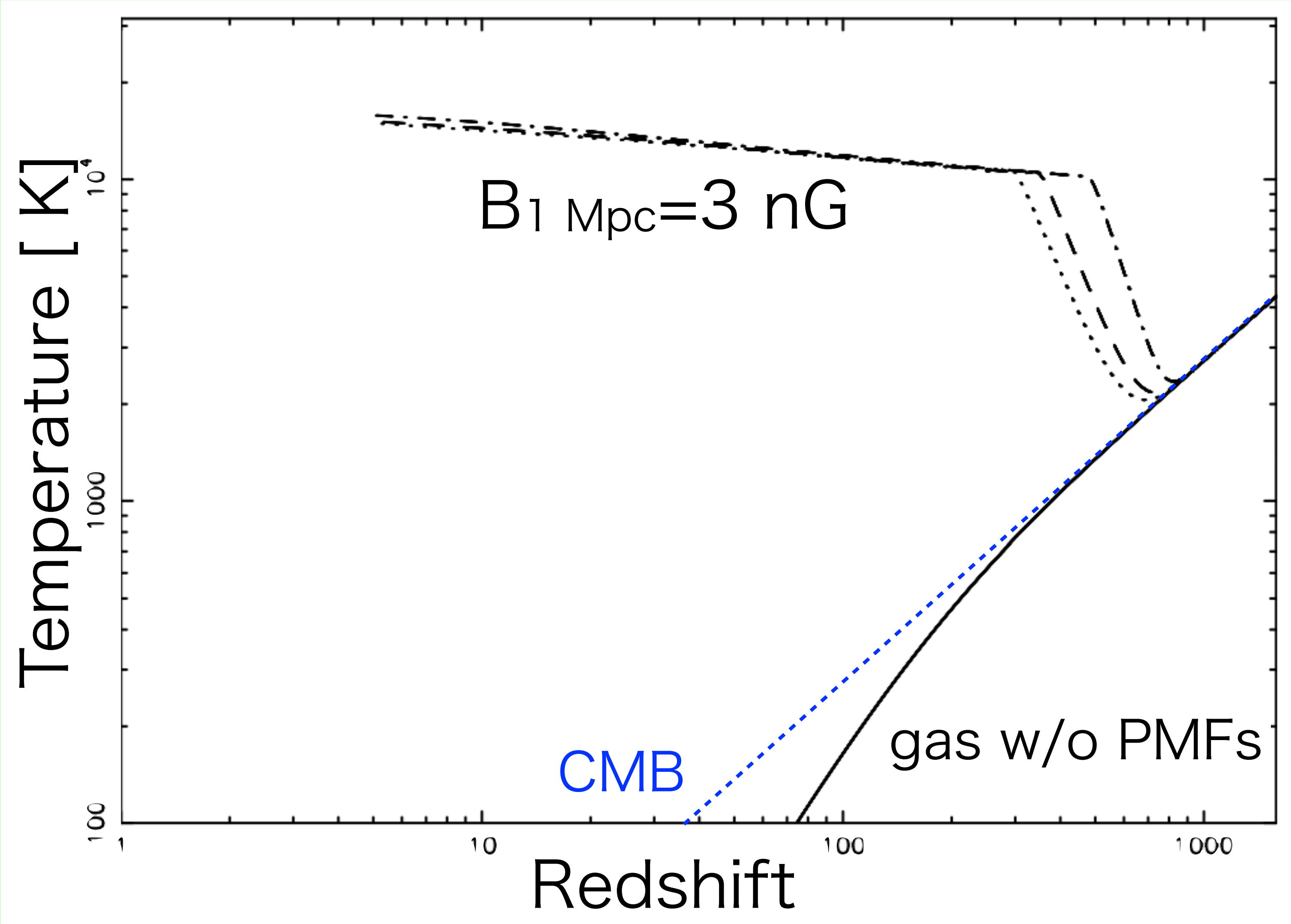
$$+\frac{\Gamma(t)}{1.5k_{\rm B}n_{\rm b}}$$

Ambipolar diffusion from PMFs

$T_{\rm gas}$	: gas temperature	ρ_γ	: CMB energy density
T_γ	: CMB temperature	$\sigma_{\rm T}$	: cross-section of Thomson scattering
H	: Hubble parameter		

Thermal history with PMFs

(Sethi & Subramanian, 2005, MNRAS, 356)



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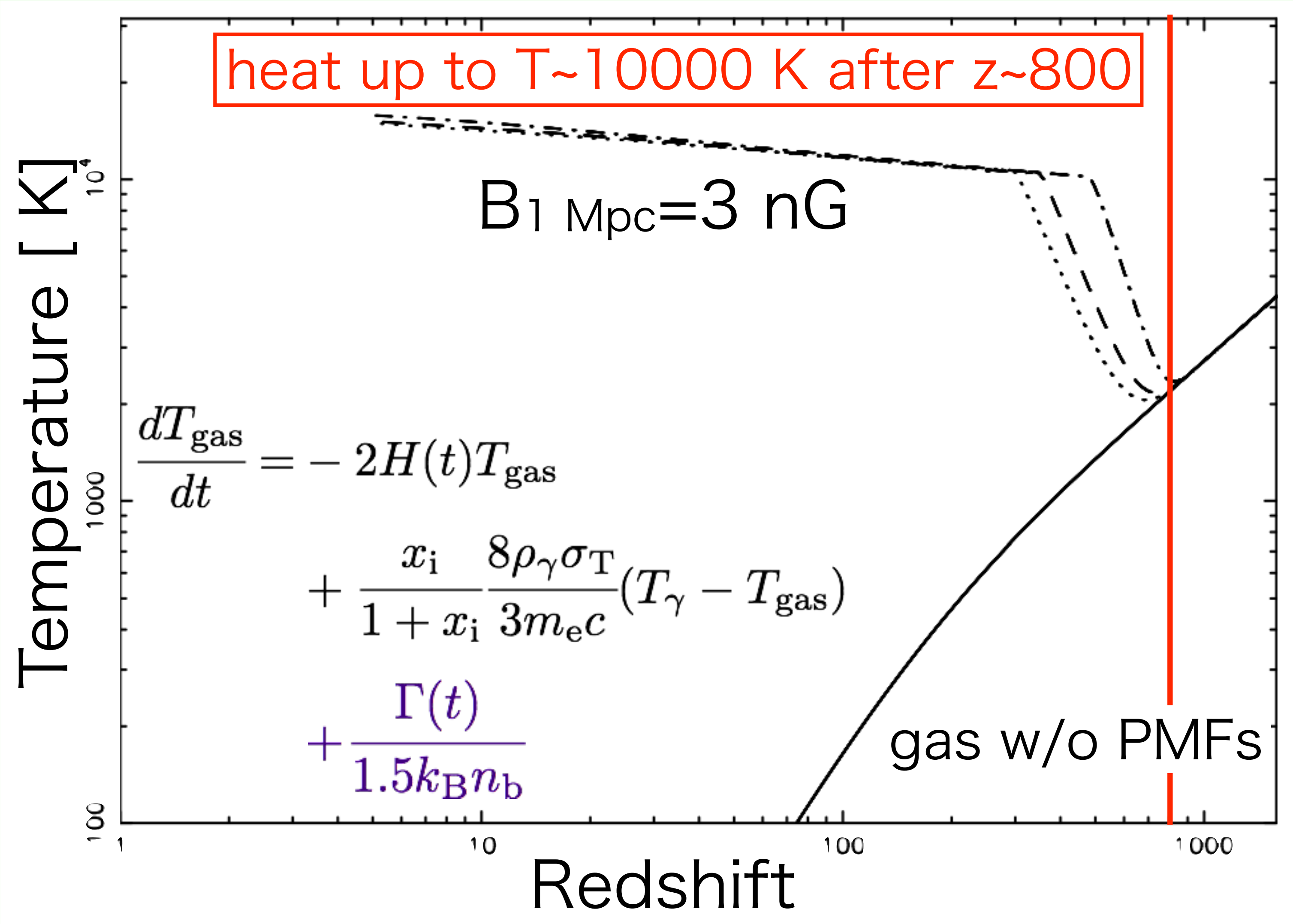
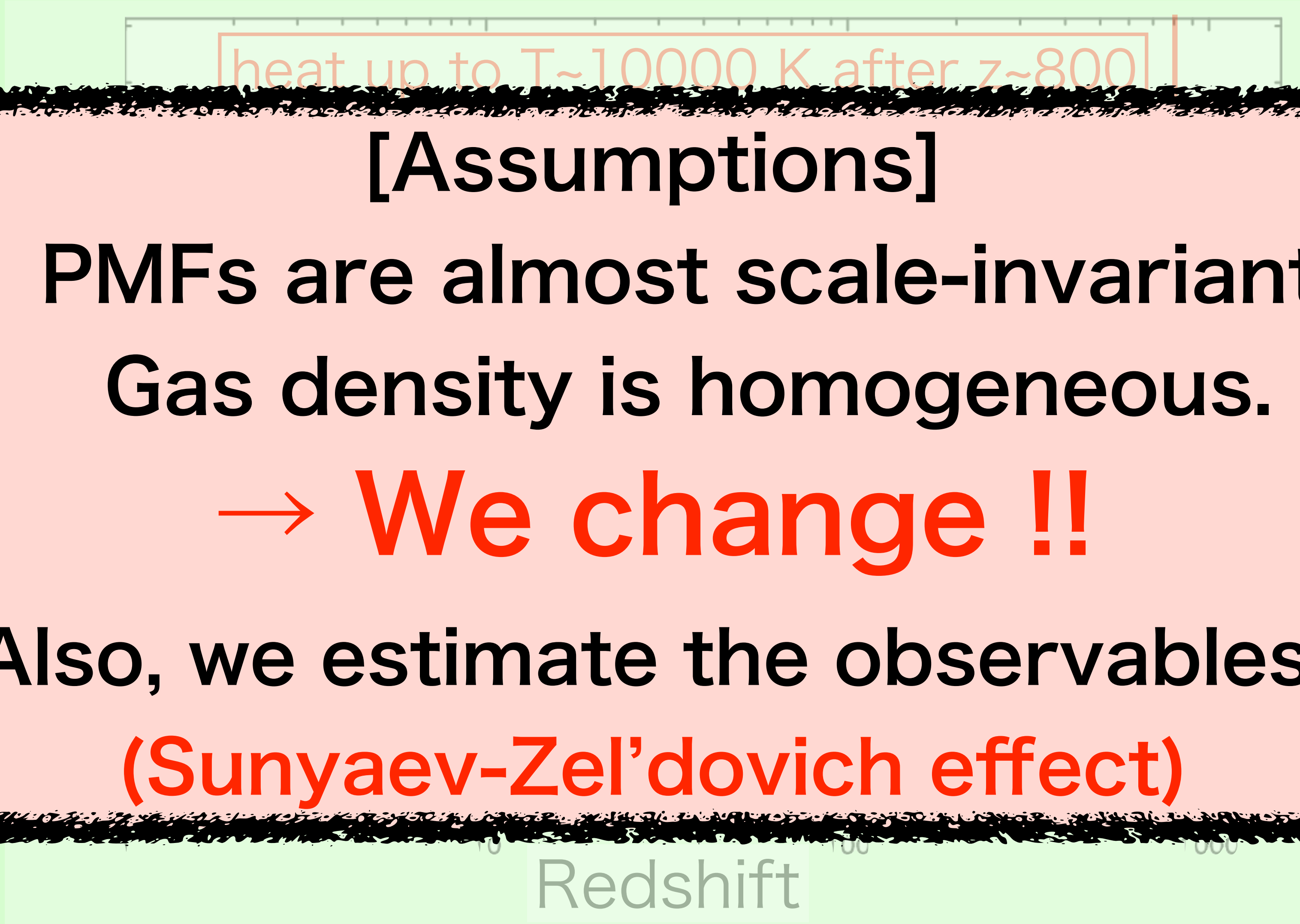


$$\frac{dT_{\rm gas}}{dt} = -2H(t)T_{\rm gas} + \frac{x_{\rm i}}{1+x_{\rm i}}\frac{8\rho_\gamma\sigma_{\rm T}}{3m_{\rm e}c}(T_\gamma - T_{\rm gas}) + \frac{\Gamma(t)}{1.5k_{\rm B}n_{\rm b}}$$

Thermal history with PMFs

(Sethi & Subramanian, 2005, MNRAS, 356)



[Assumptions]

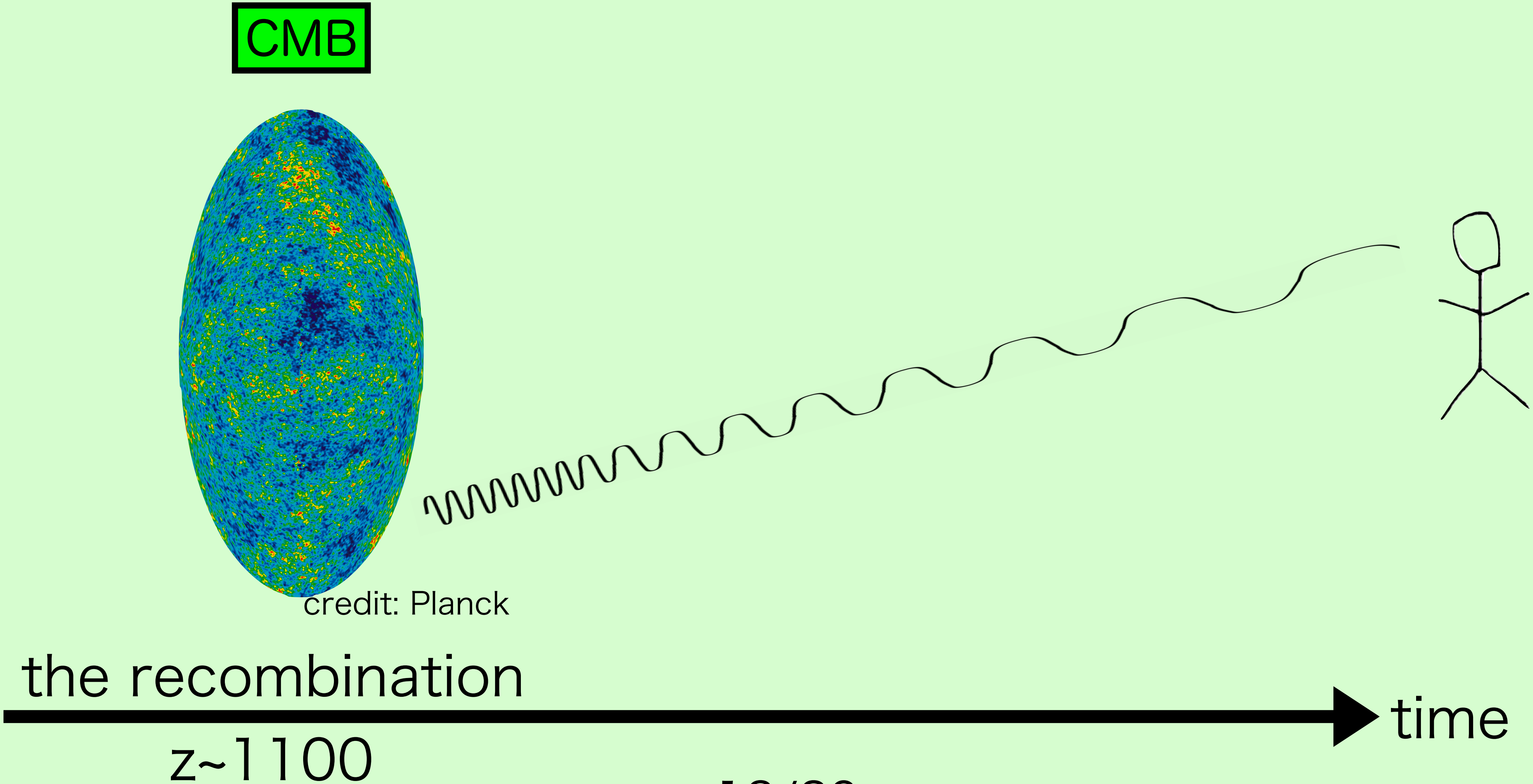
- PMFs are almost scale-invariant.
- Gas density is homogeneous.

→ We change !!

Also, we estimate the observables.

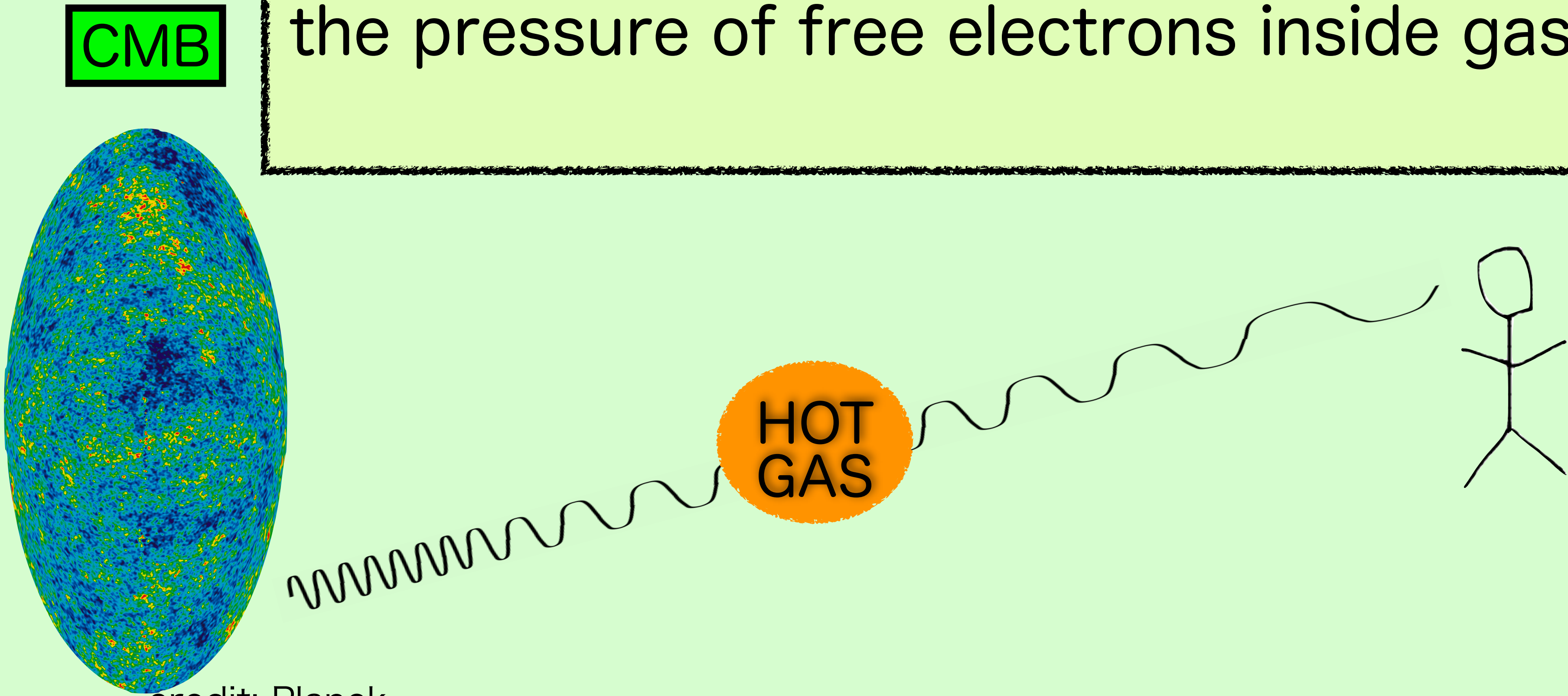
(Sunyaev-Zel'dovich effect)

Sunyaev-Zel'dovich effect



Sunyaev-Zel'dovich effect

Increase of CMB temperature due to the pressure of free electrons inside gas



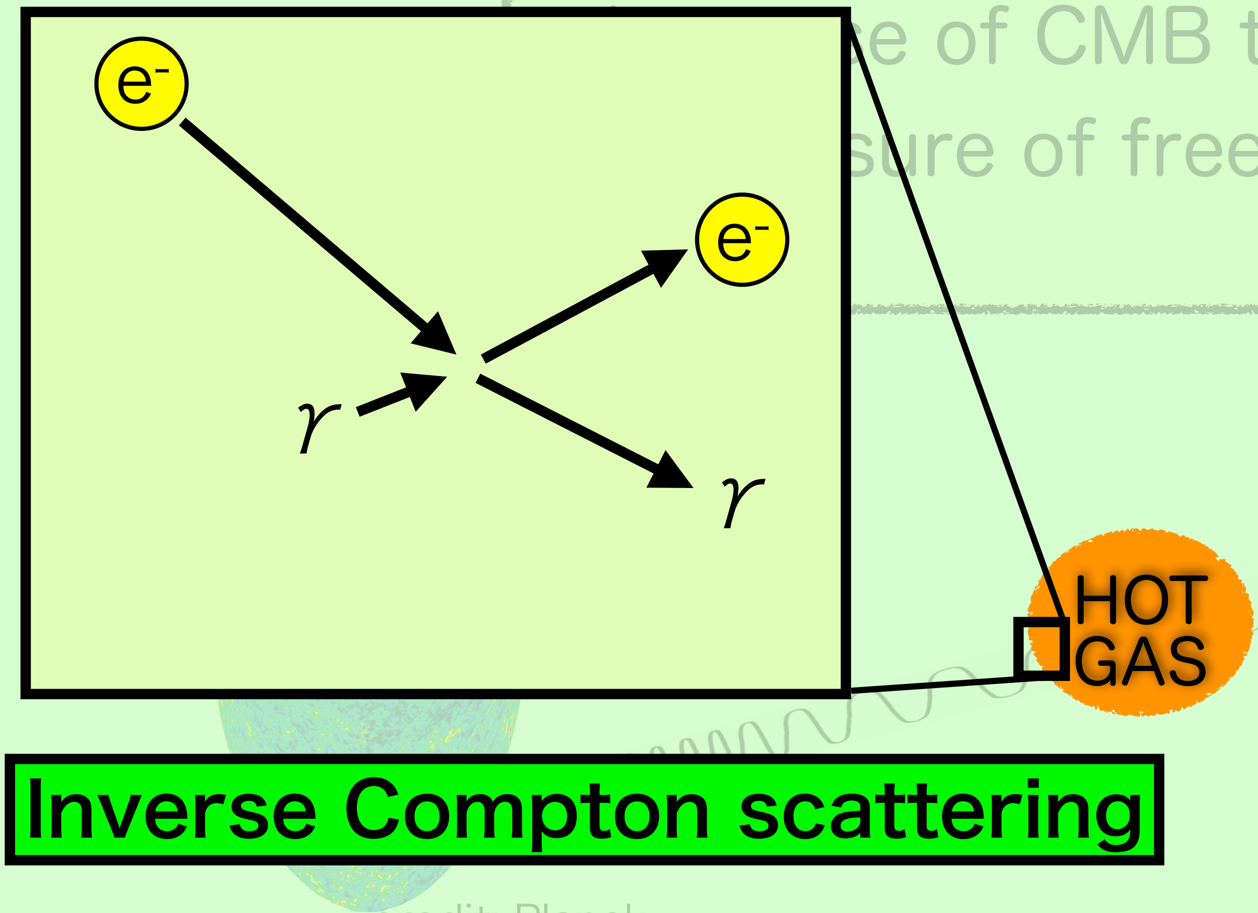
credit: Planck

the recombination

time

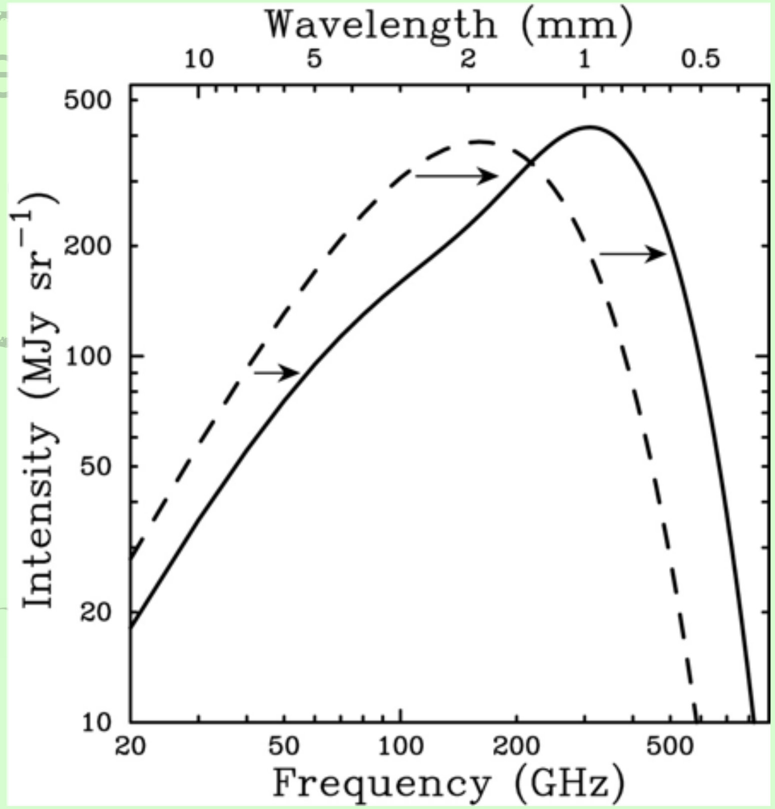
z~1100

Sunyaev-Zel’dovich effect



Inverse Compton scattering

credit: Planck



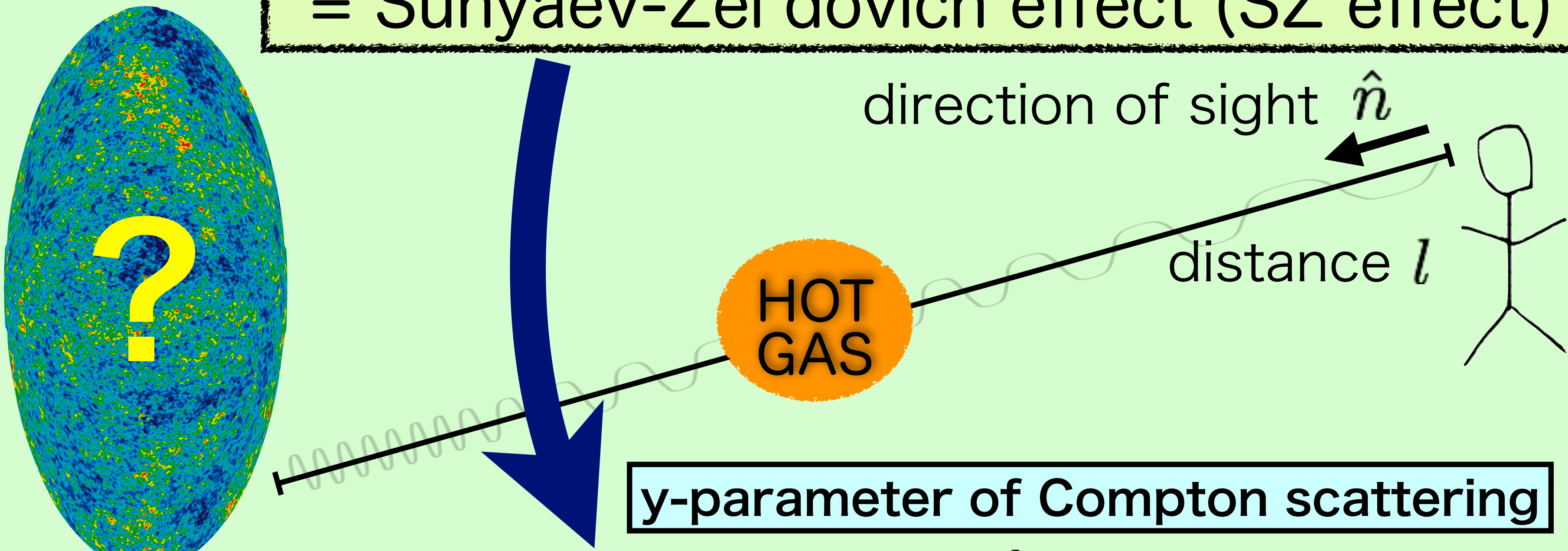
Carlstrom+, 2002
ARA&A, **40**

CMB photons gain their energy (spectral distortion)

Sunyaev-Zel'dovich effect

Increase of CMB temperature due to the pressure of free electrons inside gas = Sunyaev-Zel'dovich effect (SZ effect)

CMB



y-parameter of Compton scattering

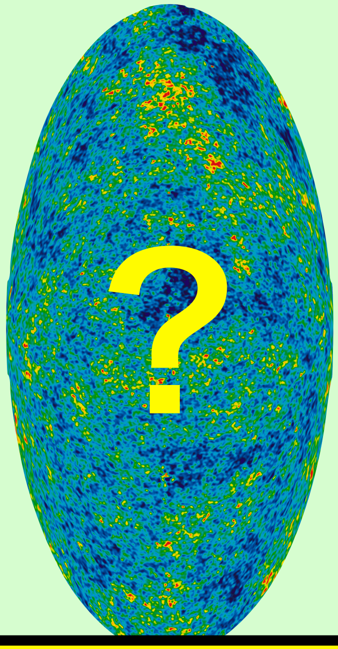
$$y(\hat{n}, l) \equiv \frac{k_{\rm B}\sigma_{\rm T}}{m_{\rm e}c^2}\int_0^l n_{\rm e}(\hat{n}, l')T_{\rm e}(\hat{n}, l')\ dl'$$

Density Temperature

Fluctuations of gas create fluctuations of CMB temperature

Sunyaev-Zel'dovich effect

CMB



Fluctuations of gas create fluctuations of CMB temperature

The fluctuations of T_{gas}, n_{gas}, B is significant !!

y-parameter of Compton scattering

$$y(\hat{n}, l) \equiv \frac{k_B \sigma_T}{m_e c^2} \int_0^l n_e(\hat{n}, l') T_e(\hat{n}, l')\, dl'$$

Density Temperature

Our work

① Numerical realization of the 3d PMFs

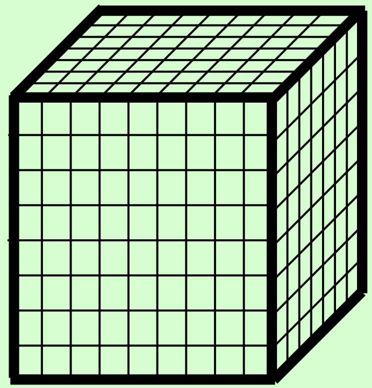
Vector potential $\mathbf{A}$

B fields $\mathbf{B} = \nabla \times \mathbf{A}$

Lorentz force

$$\mathbf{L} = \frac{(\nabla \times \mathbf{B}) \times \mathbf{B}}{4\pi}$$

※assume that MFs evolve adiabatically



② calculate T_{gas} & n_{gas} at each time & place

1000 > z > 10

Source terms:

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

$$S(t) = \frac{\nabla \cdot (\nabla \times \mathbf{B}_0) \times \mathbf{B}_0}{4\pi \bar{\rho}_{\rm b,0} a^3(t)}$$

Our work

Basic equations of baryon fluid

$$\begin{cases} \dfrac{\partial \rho_{\rm b}}{\partial t} + \nabla \cdot (\rho_{\rm b} \mathbf{u}_{\rm b}) = 0 \\ \dfrac{\partial \mathbf{u}_{\rm b}}{\partial t} + (\mathbf{u}_{\rm b} \cdot \nabla)\mathbf{u}_{\rm b} = -\dfrac{\nabla p}{\rho_{\rm b}} + \dfrac{(\nabla \times \mathbf{B}_0) \times \mathbf{B}_0}{4\pi \rho_{\rm b}} - \nabla \Phi \end{cases}$$

Lorentz force of PMFs

pressure

gravity

density fluctuation from the background value

$$\rho_{\rm b} = \bar{\rho_{\rm b}}(1 + \delta_{\rm b})$$

linear approximation ($\delta_{\rm b} \ll 1$) + cosmic expansion

baryon density evolution

$$\ddot{\delta}_{\rm b} + 2\frac{\dot{a}}{a}\dot{\delta}_{\rm b} - 4\pi G[\bar{\rho}_{\rm c}\delta_{\rm c} + \bar{\rho}_{\rm b}\delta_{\rm b}] = \frac{\nabla \cdot (\nabla \times \mathbf{B}_0) \times \mathbf{B}_0}{4\pi \bar{\rho}_{\rm b,0} a^3}$$

Our work

baryon density fluctuation due to the PMFs

$\eta = t/t_{\rm rec}$

$$\delta_{\rm b}(t) = \frac{2}{15H^2}\frac{\nabla\cdot(\nabla\times\mathbf{B}_0)\times\mathbf{B}_0}{4\pi\bar{\rho}_{\rm b,0}a^3(t)}\left[(3\eta+2\eta^{-\frac{3}{2}}-15\ln\eta)\frac{\Omega_{\rm b}}{\Omega_{\rm m}}+15\ln\eta\right.$$
$$\left.+30\left(1-\frac{\Omega_{\rm b}}{\Omega_{\rm m}}\right)\eta^{-\frac{1}{2}}-\left(30-25\frac{\Omega_{\rm b}}{\Omega_{\rm m}}\right)\right]$$

$T_{\rm gas}$ time evolution

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

effect of local density fluctuations

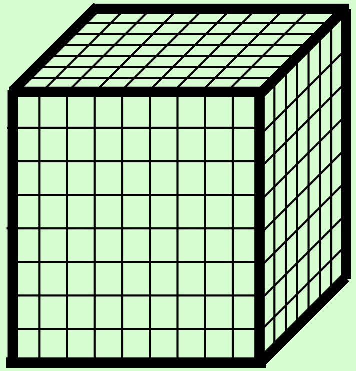
$$-\frac{x_{\rm i}n_{\rm b}}{1.5k_{\rm B}}[\Theta x_{\rm i}+\Psi(1-x_{\rm i})+\eta x_{\rm i}+\zeta(1-x_{\rm i})]$$

bremsstrahl.
collis.-excit.
recombinat.
collis.-ioniz.

Cooling due to atomic state-trans.

Our work

③ Estimate of the T_{CMB} anisotropy from the 3D y-parameter map.



64^3 grids

Box size 2 Mpc

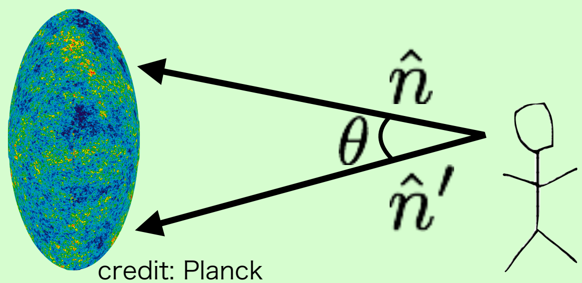
y-parameter of Compton scattering

$$y(\hat{n}, l) \equiv \frac{k_B \sigma_T}{m_e c^2} \int_0^l n_e(\hat{n}, l') T_e(\hat{n}, l') \, dl'$$

density temperature

Integrate y-parameter in 1000 > z > 10

CMB temperature angular power spectrum



credit: Planck

$$C_\ell = \frac{(g_\nu T_\gamma)^2}{4\pi} \int P_\ell(\cos\theta) \langle y(\hat{n}) y(\hat{n}') \rangle \, d^2\hat{n} \, d^2\hat{n}'$$

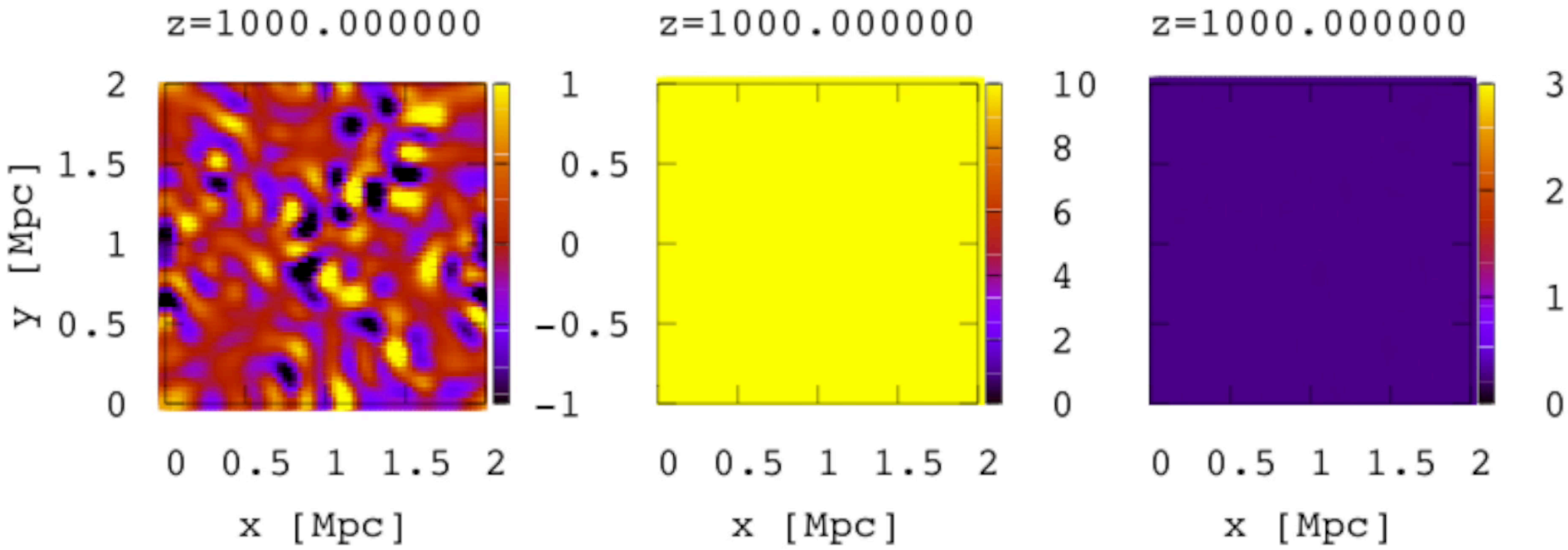
↑ (Legendre polynomials)

multipole $\ell \sim \frac{\pi}{\theta}$

Results

Evolution from z=1000 to 10

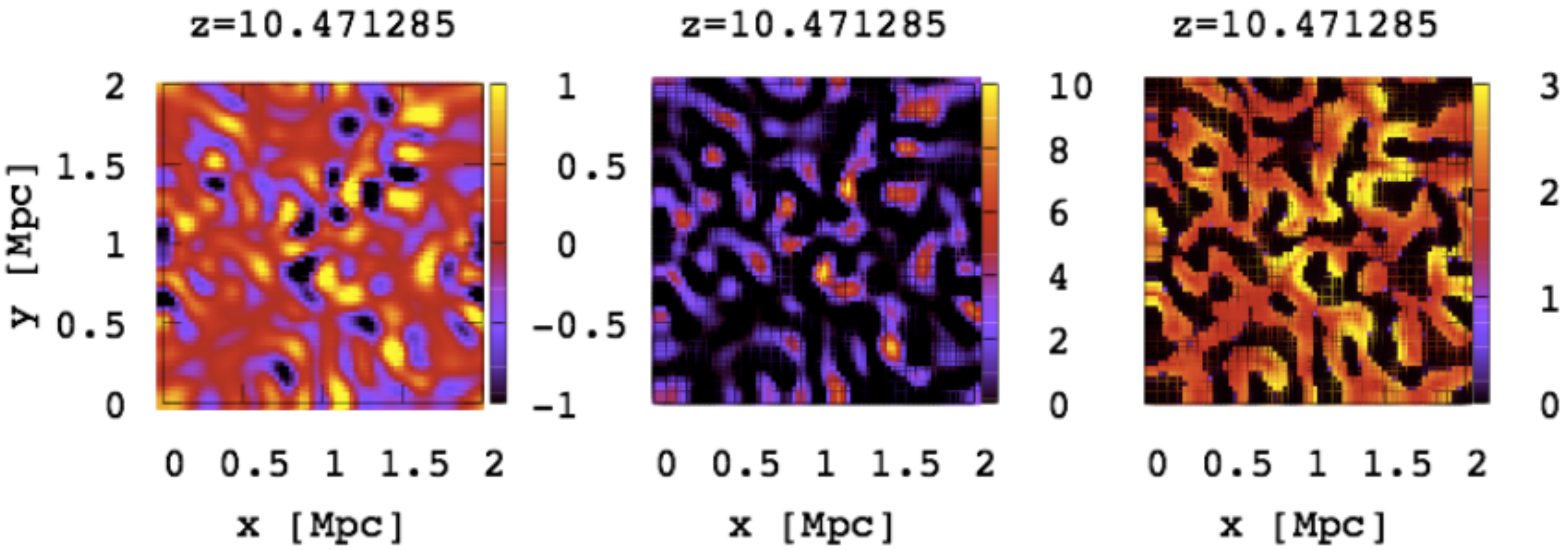
Lorentz force [x10^5 nG^2 Mpc^{-2}] | gas # density [cm^{-3}] | gas temperature [x10^4 K]



Results

Evolution from z=1000 to 10

Lorentz force $[\times 10^5 \, nG^2 \, Mpc^{-2}]$ | gas # density $[cm^{-3}]$ | gas temperature $[\times 10^4 \, K]$



Results

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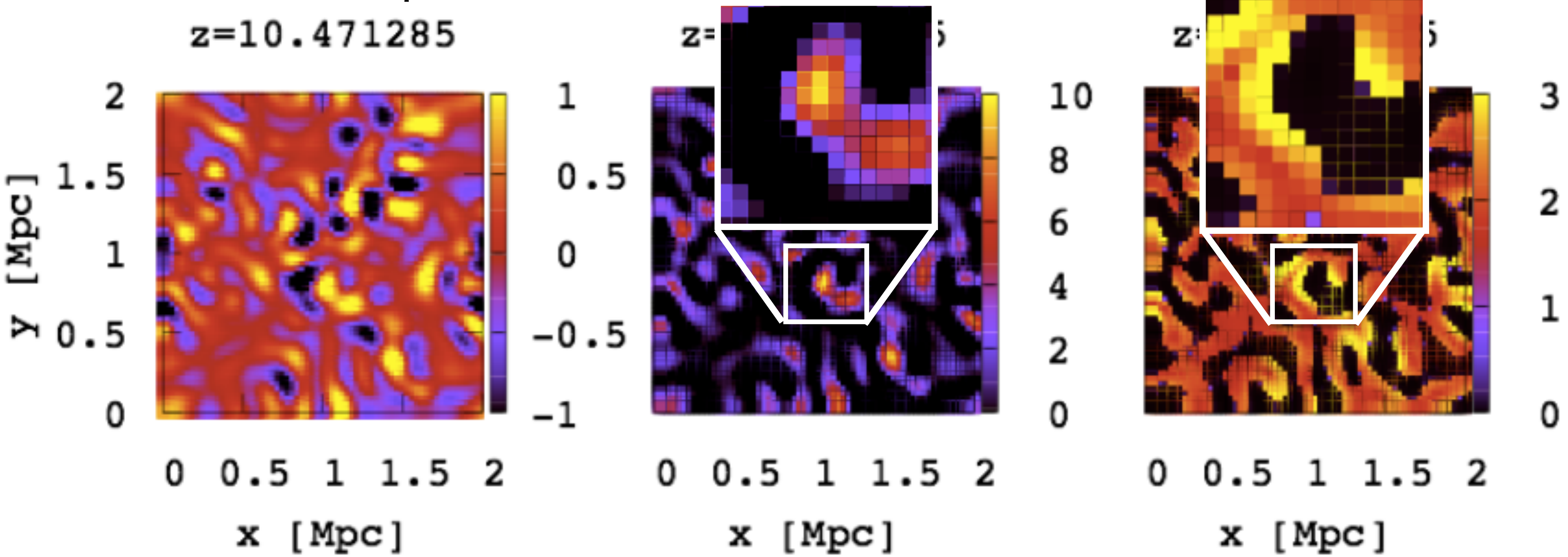
Lorentz force	gas # density	gas temperature
[x10^5 nG^2 Mpc^{-2}]	[cm^{-3}]	[x10^4 K]



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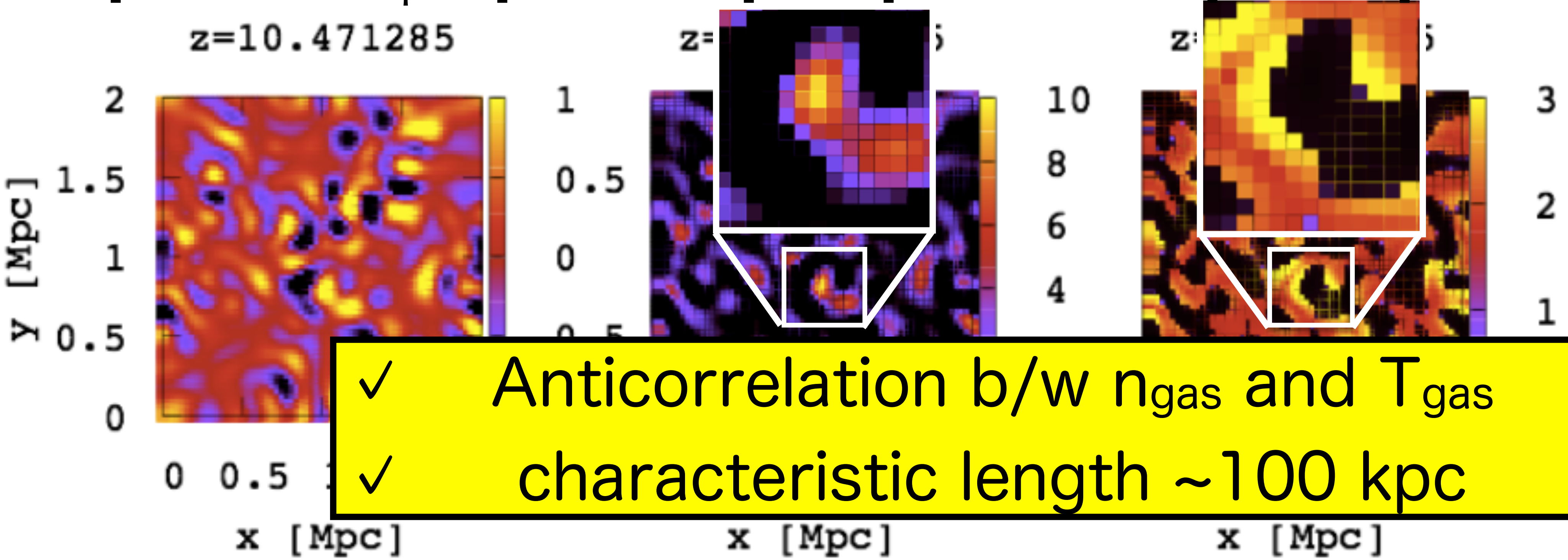
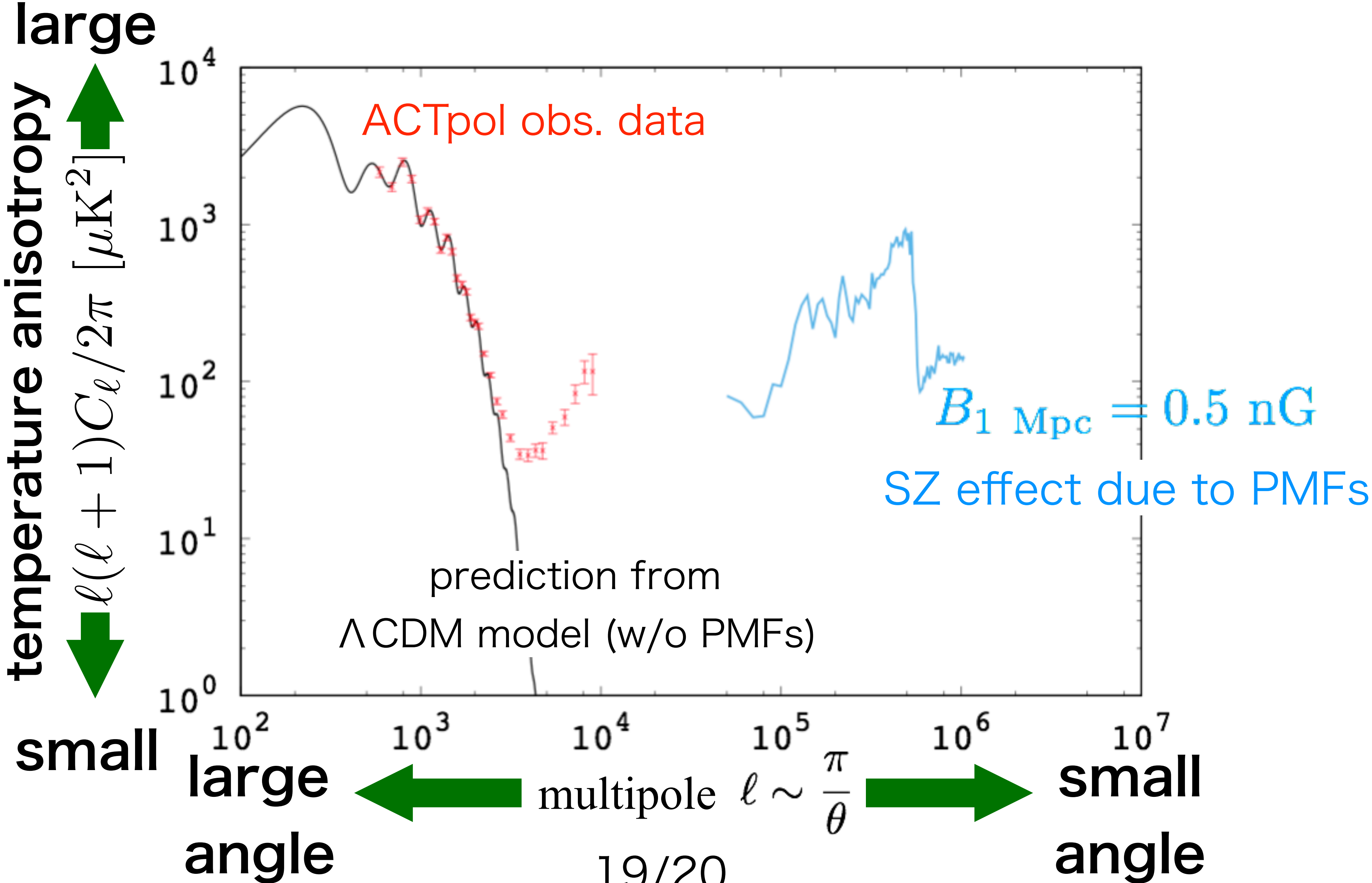


✓ Anticorrelation b/w n_{gas} and T_{gas}

✓ characteristic length ~100 kpc

CMB anisotropies



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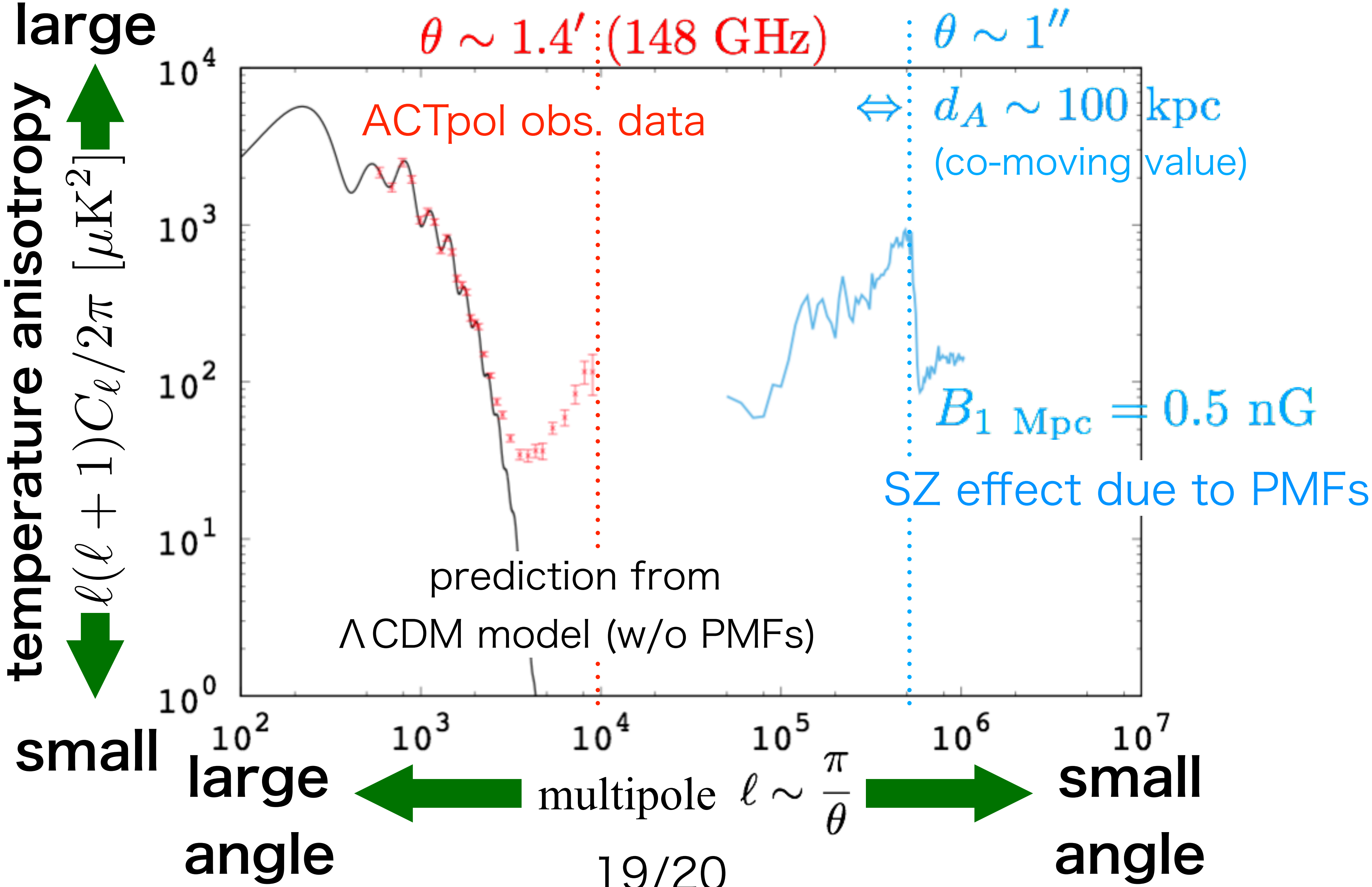

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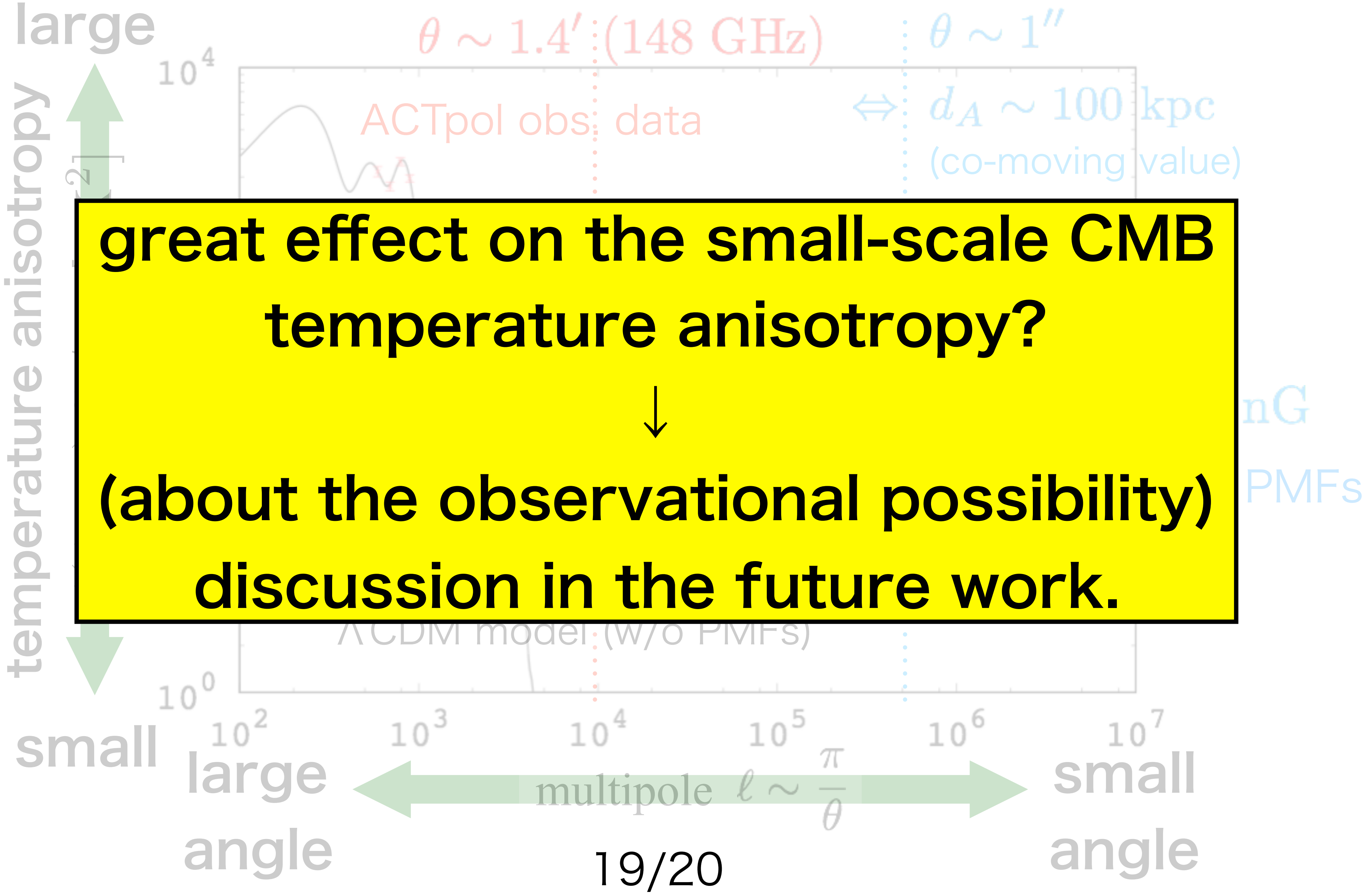

great effect on the small-scale CMB temperature anisotropy?

↓

(about the observational possibility) discussion in the future work.

Summary

- Focus on the **PMFs** and observables
- The effect of B_{1Mpc}~0.5 nG PMFs on structure formation in the cosmic **Dark Age.**
- calculated **Density** and **Temperature** of baryon gas, and found their **anti-correlation**
- estimate the **CMB temperature anisotropy** from thermal Sunyaev-Zel'dovich effect