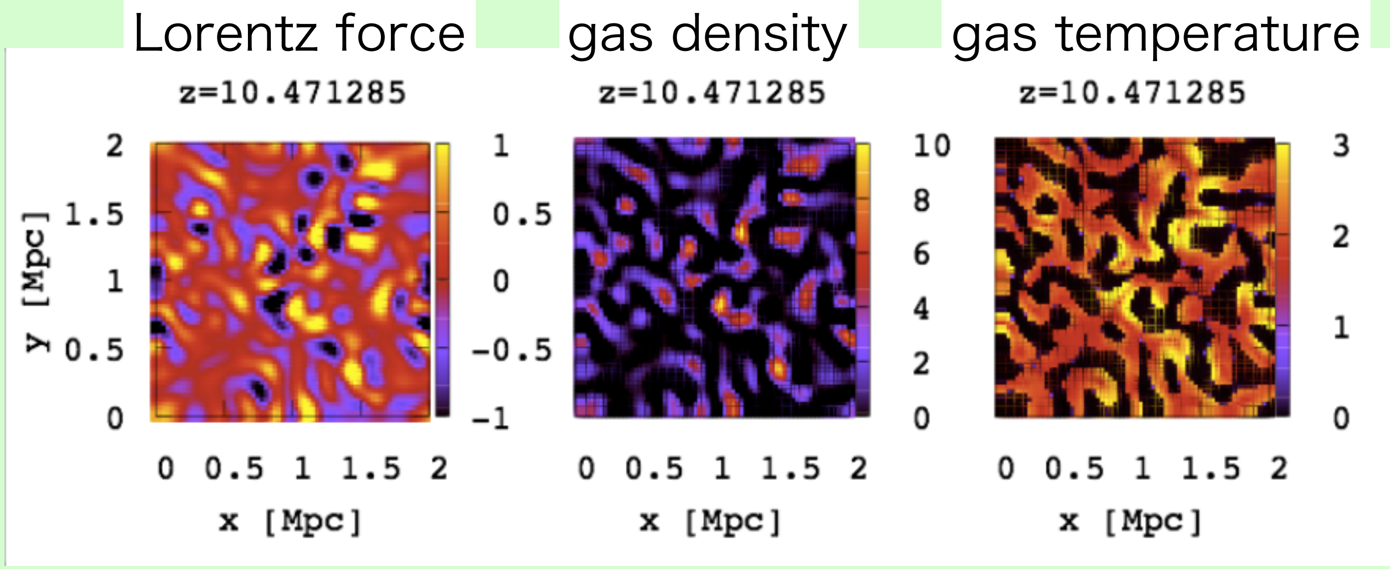
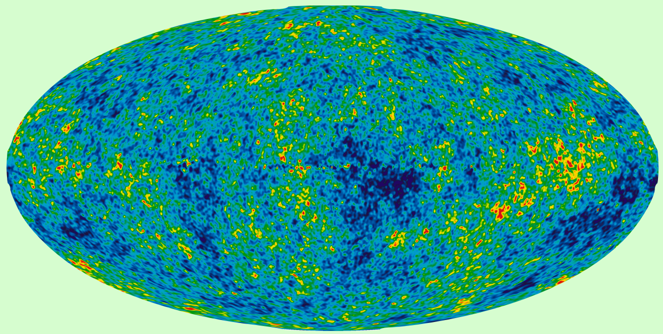
The effect of the primordial magnetic fields on the CMB anisotropy

Teppei MINODA, K. Hasegawa, H. Tashiro, K. Ichiki, & N. Sugiyama (Cosmology group, Nagoya University)





credit: *Planck*

Primordial B-fields > Gas physics > CMB anisotropy

National Astronomical Observatory of Japan

NAGOYA UNIVERSITY

Nagoya University Cosmology Group Department of Physics

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Self Introduction

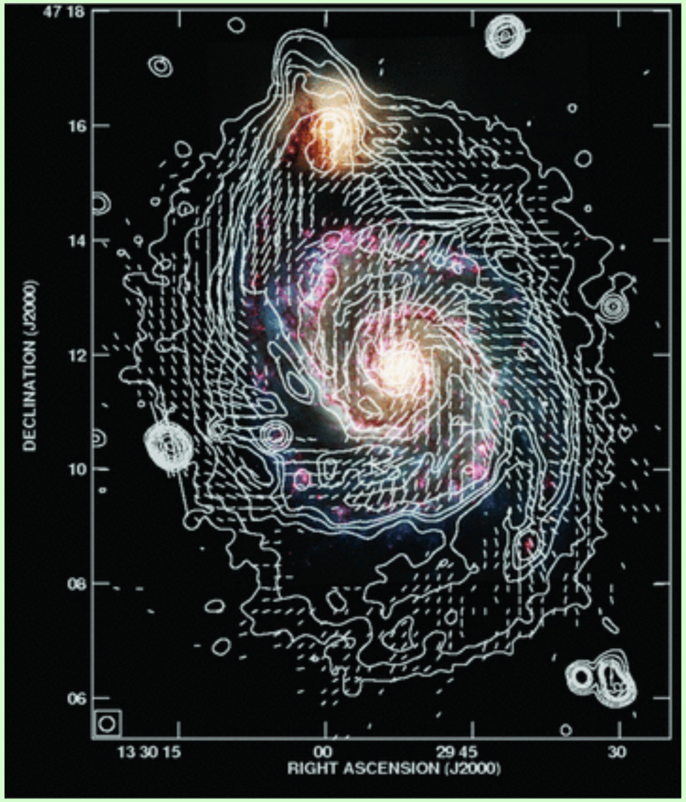
1. Name
   - Teppei MINODA, D1, Nagoya University
2. Supervisor
   - Naoshi Sugiyama (Tashiro, Ichiki, Hasegawa)
3. Birthplace
   - Ishigaki island, OKINAWA prefecture.
4. Curriculum
   - Bachelor at Sophia University (Relativ. Fluid)
   - Master at Nagoya University (Today’s talk)

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

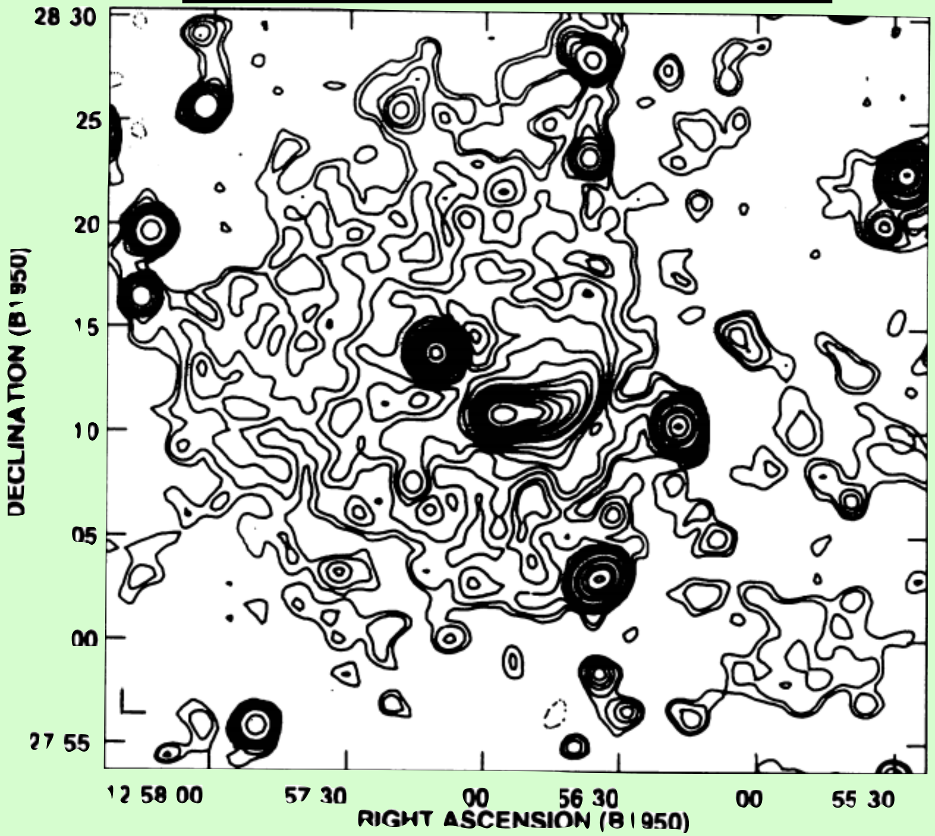
Cosmic Magnetic Fields

galaxy B ~10^{-5} G



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

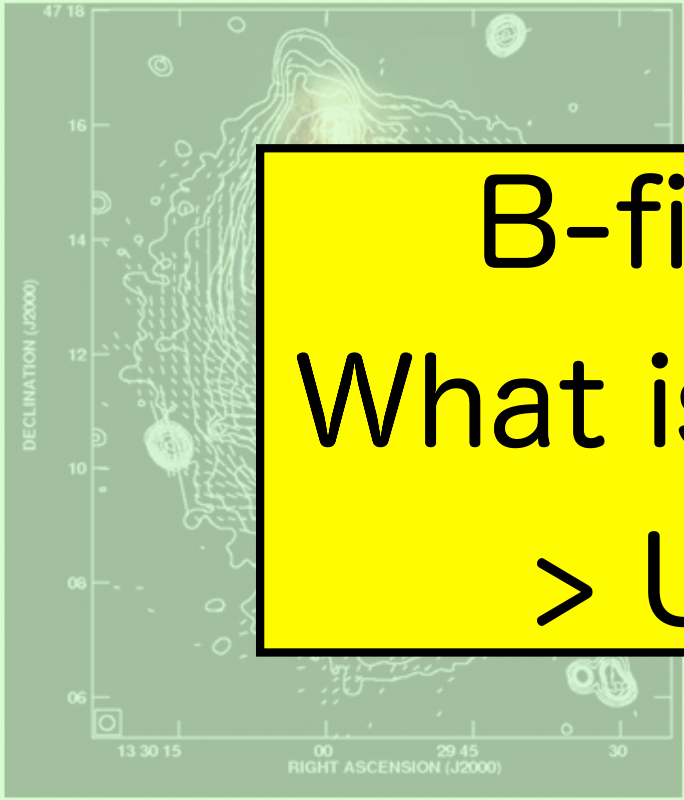
cluster B~10^{-6} G



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

Cosmic Magnetic Fields

galaxy B ~10^{-5} G



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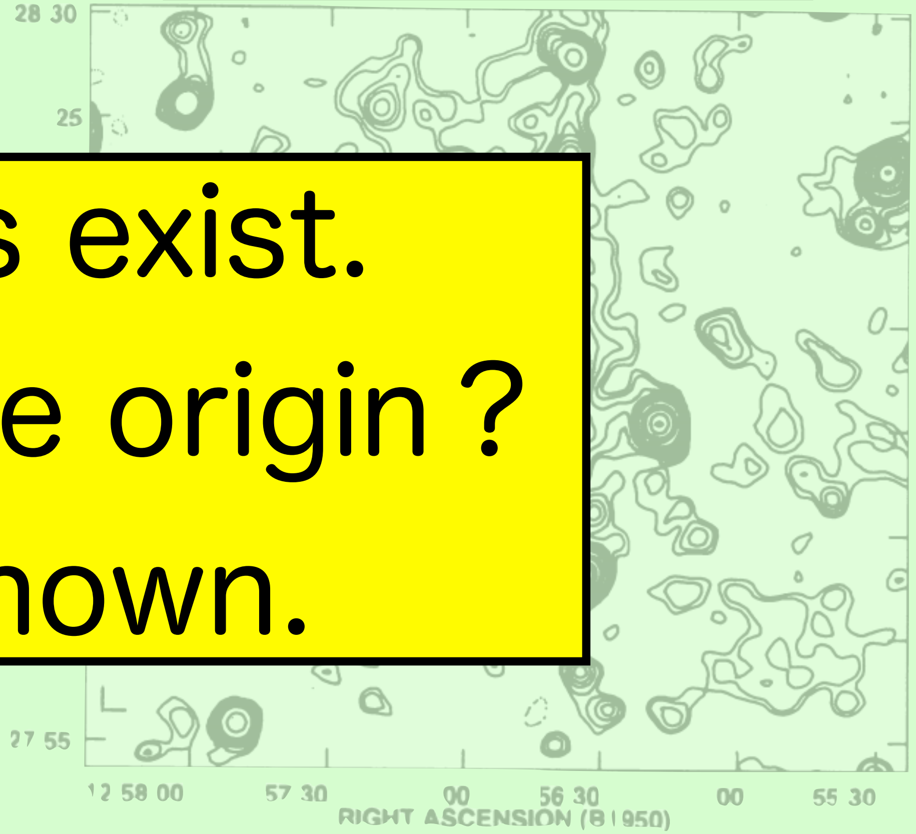

Coma Cluster [radio] WSRT, 90cm
(Giovannini+, 1993, ApJ, 406)

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

The origin of B-fields

Cosmological origin ?

- Inflation
- Phase transition
- New physics

Small strength compared to the observed value

Difficult for observational test

Astrophysical origin ?

- Shock wave
- Turbulent motion
- Plasma physics

Too small scale to calculate cosmological evolution

Difficult to explain IGMF?

The origin of B-fields

Cosmological origin ?
- Inflation
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Small strength compared to the observed value

Difficult for observational test

Astrophysical origin ?
- Shock wave
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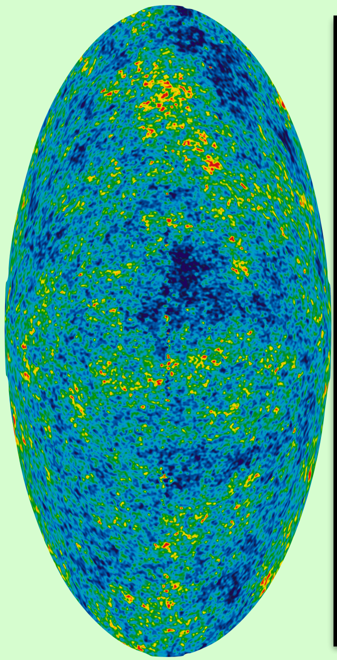
Too small scale to calculate cosmological evolution

Difficult to explain IGMF?

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

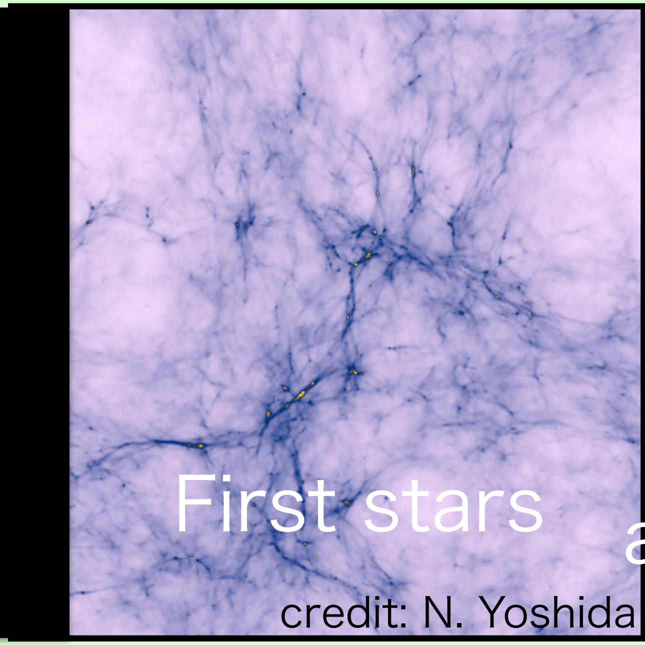
The origin of B-fields

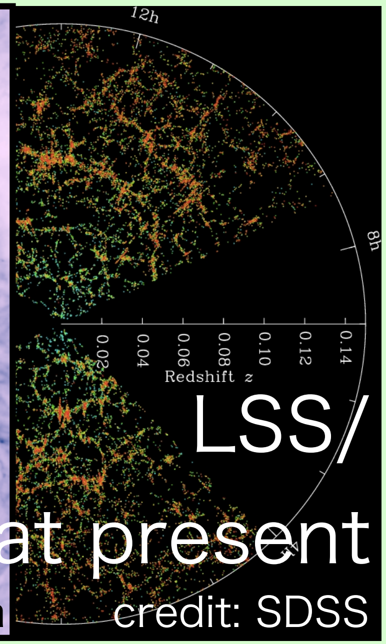
constraint on the PMFs from the CMB anisotropy



credit: *Planck*

Dark Age



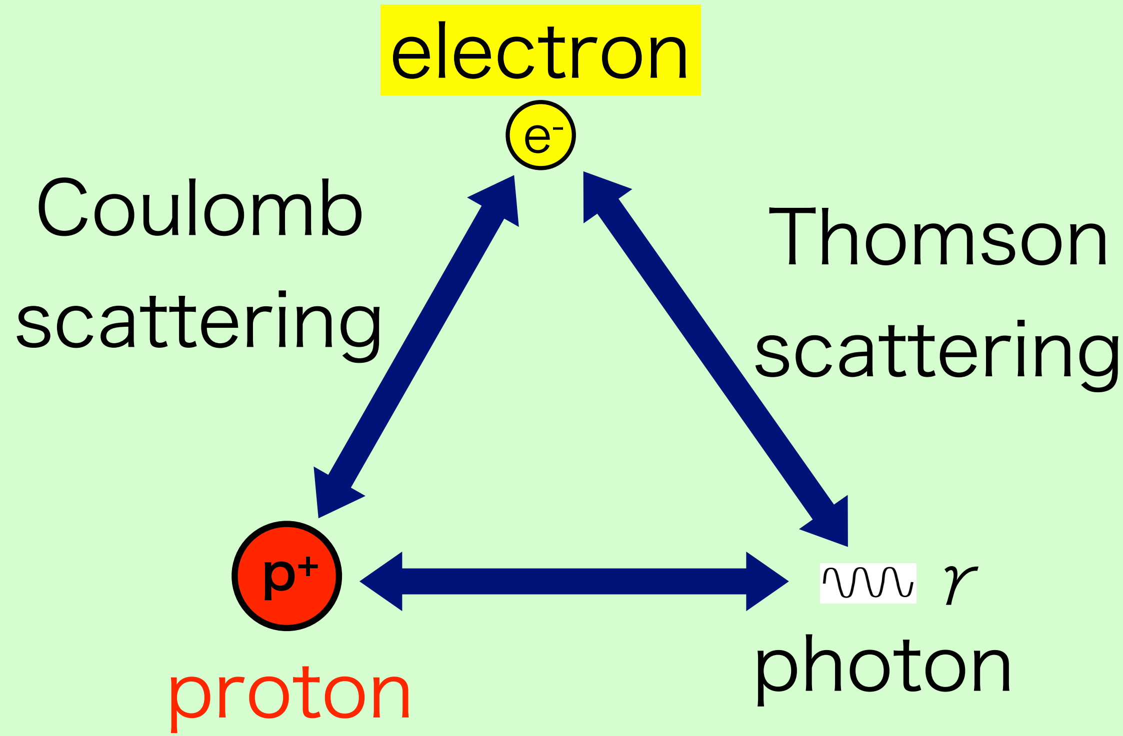


$B_{1\ \mathrm{Mpc}} \lesssim 4\ \mathrm{nG}$

time

z~1100

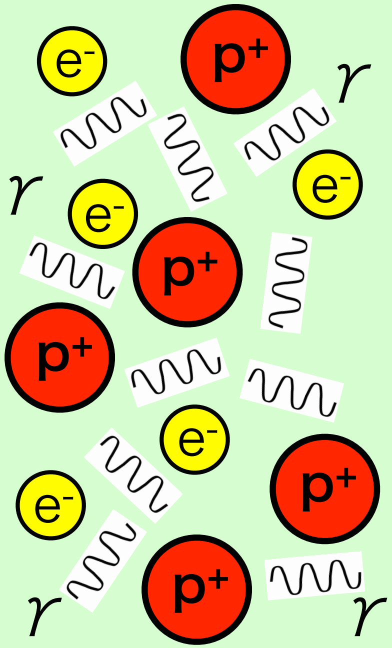
Cosmic recombination

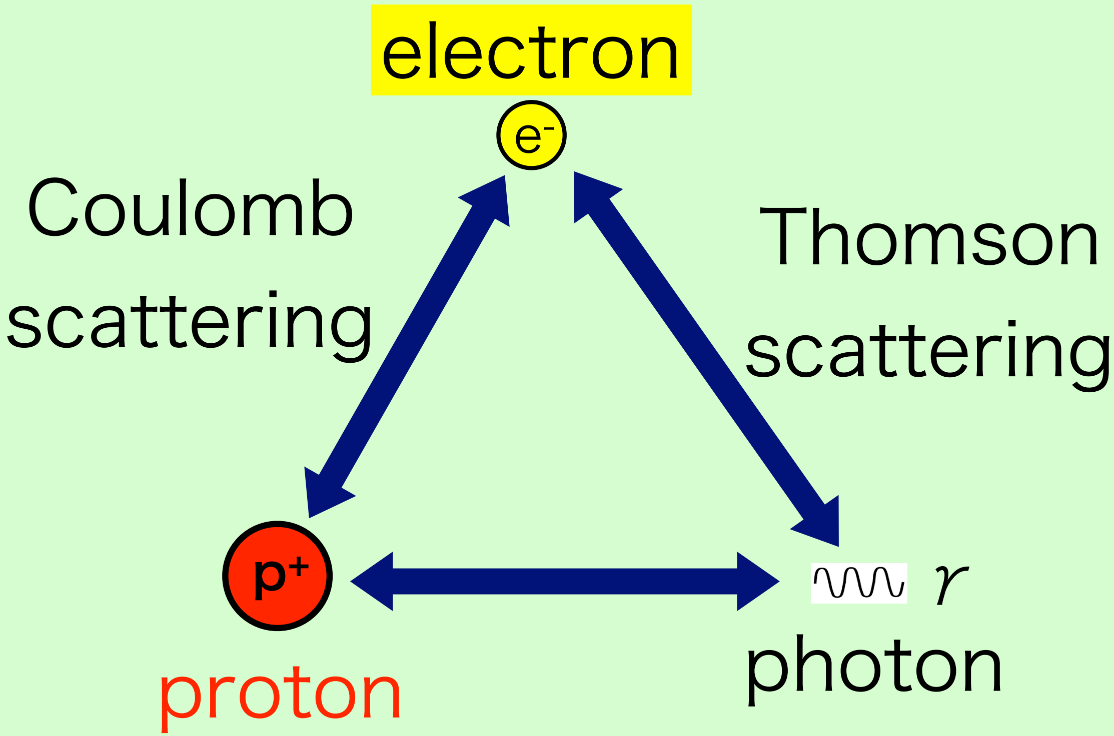


In the early universe, protons, electrons, and photons behave like one-component fluid (= photon-baryon plasma)

Cosmic recombination

photon-baryon plasma





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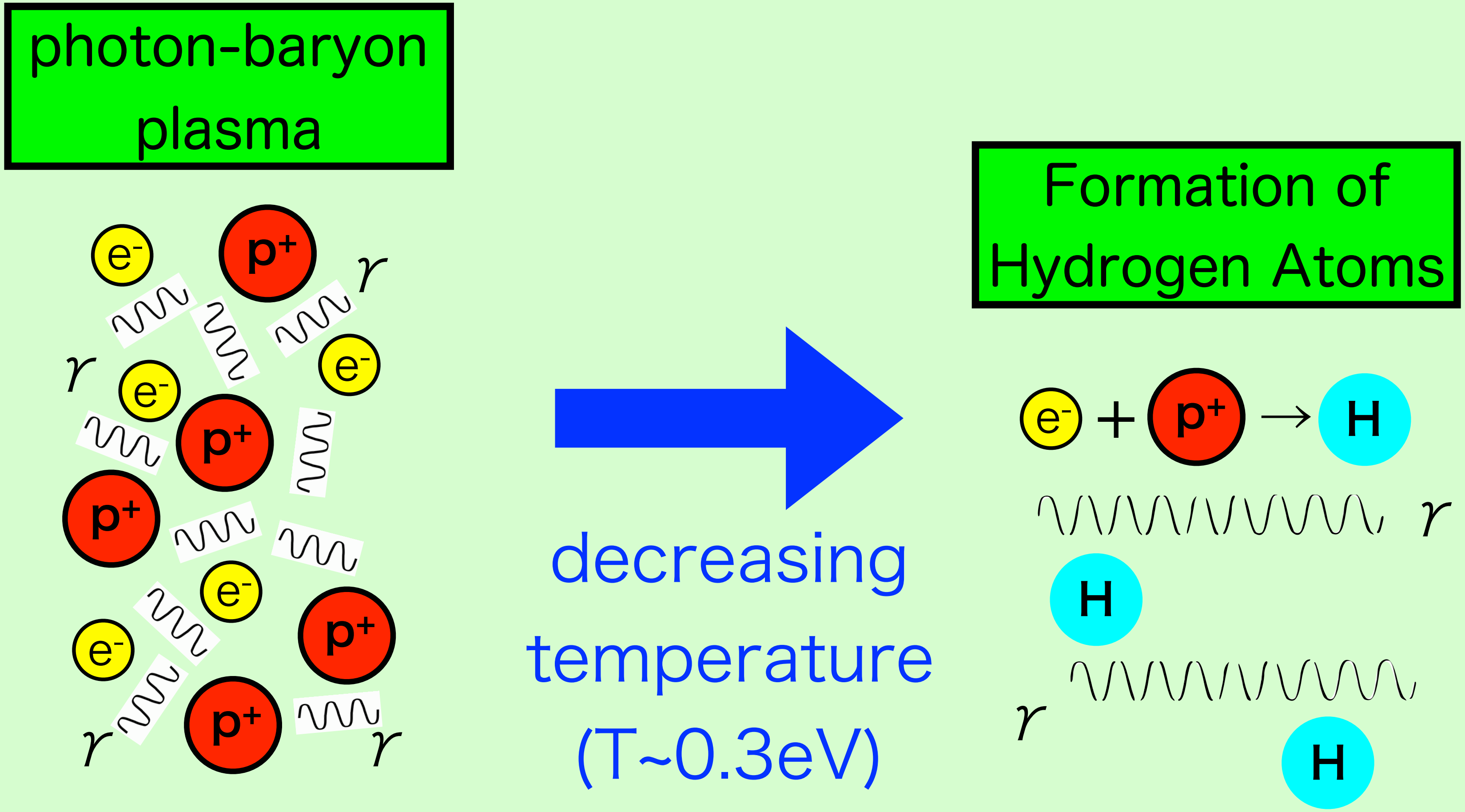
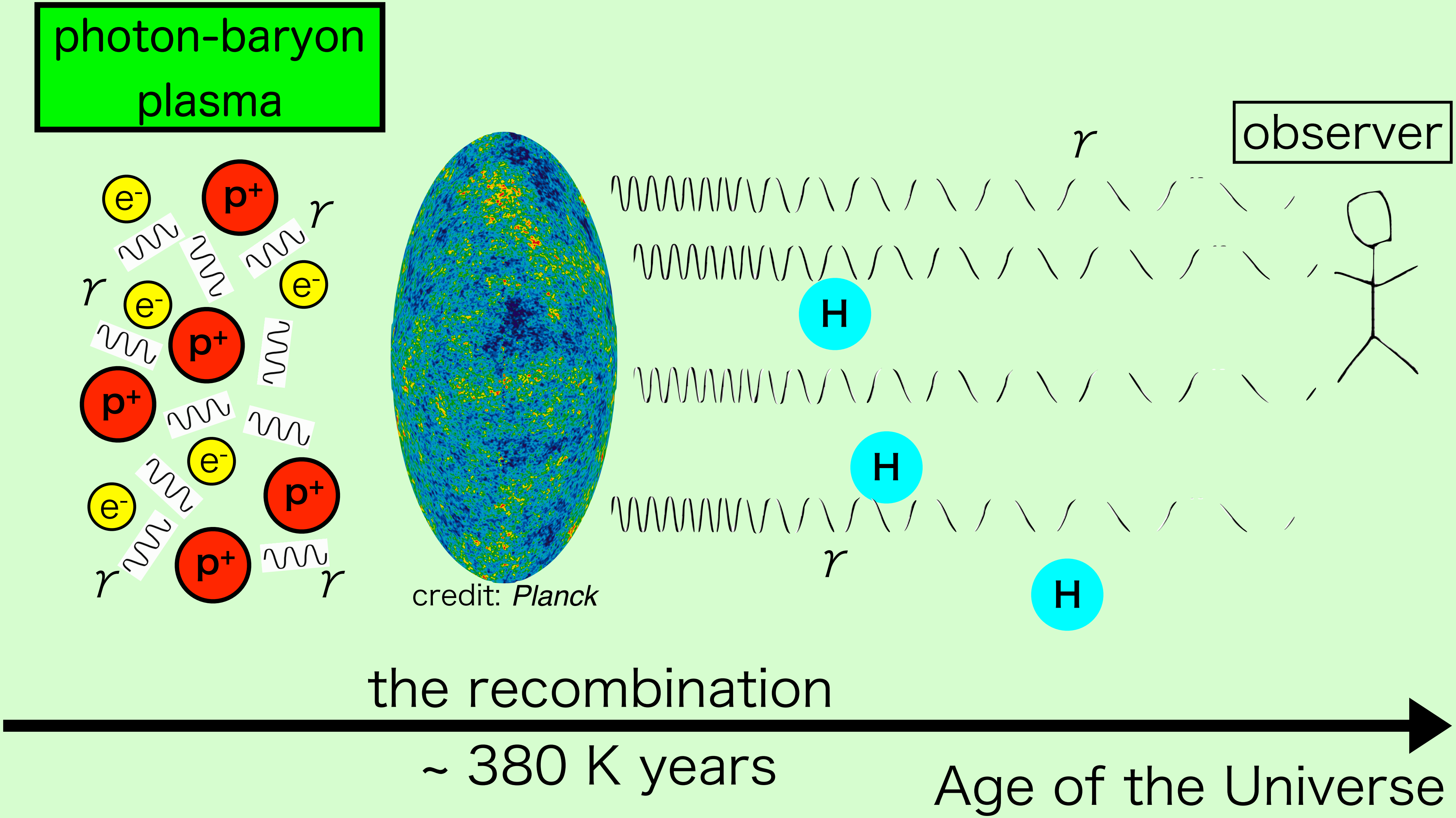
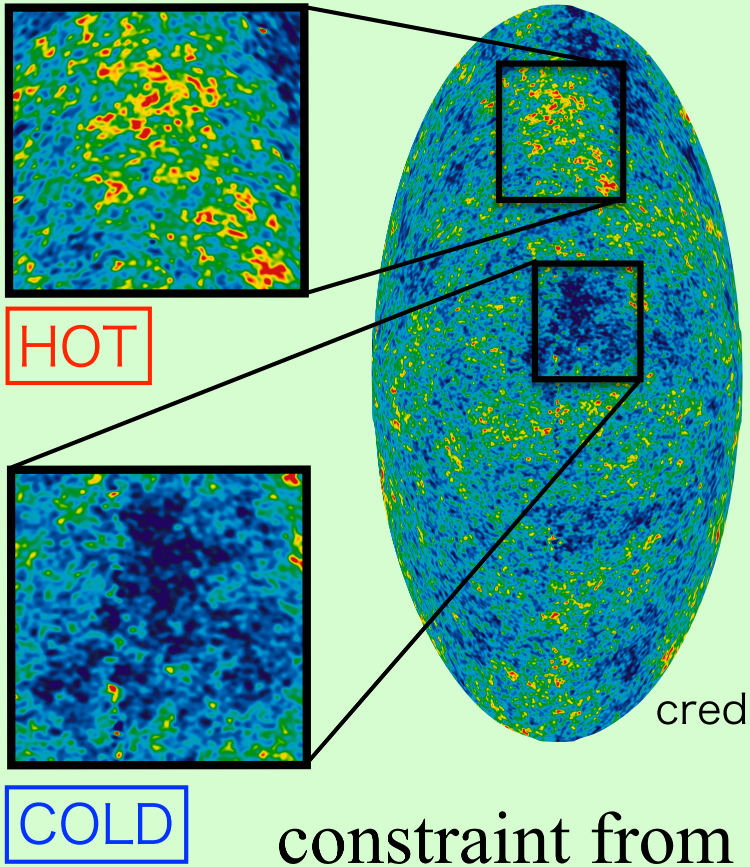


Cosmic recombination



Constraint from CMB

Cosmic Microwave Background (CMB)



credit: *Planck*

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

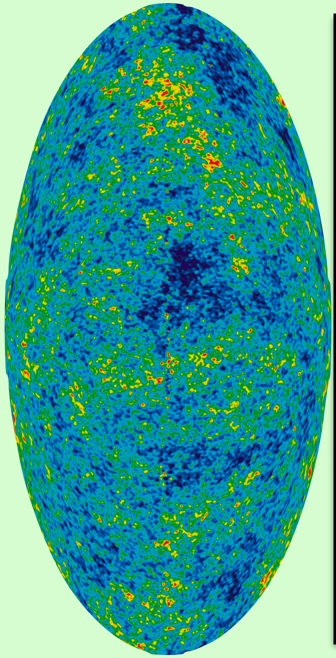
constraint from *Planck* 2015 $B_{1\ \mathrm{Mpc}} \lesssim 4\ \mathrm{nG}$

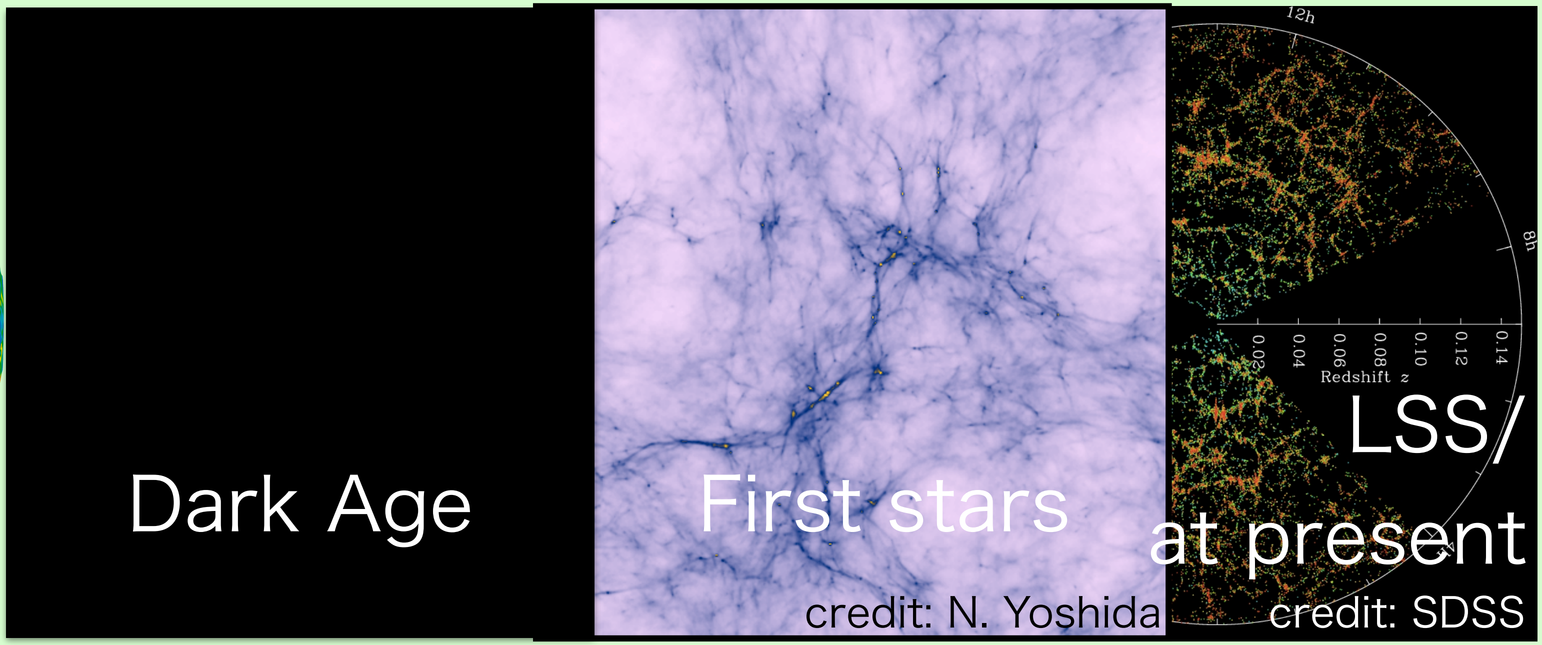
(Planck Collaboration, 2016, A&A, 594)

Motivation

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

Can the PMFs affect the universe after the recombination epoch ?





the recombination

z~1100

time

Motivation

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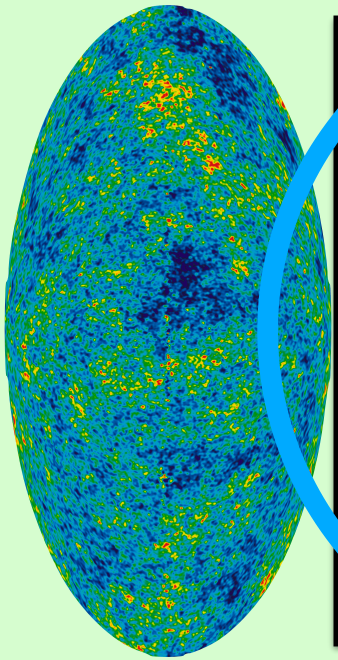
Can the PMFs affect the universe after the recombination epoch ?



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

Model of PMFs

2PCF of PMFs

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

Power spectrum

$$P_B(k) = \begin{cases} A_B k^{n_B} & (k < k_c) \\ 0 & (k \geq k_c) \end{cases} \qquad A_B = \frac{n_B + 3}{2} \frac{(2\pi)^2 B_n^2}{k_n^{n_B+3}}$$

cut-off scale of the PMFs

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

2 parameters give the model

Model of PMFs

$$B_n = 0.01 \text{ [nG]},$$
$$n_B = 1.0$$

$$k_c \simeq 200 \text{ [kpc]}$$

Power spectrum

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

cut-off scale of the PMFs

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

2 parameters give the model

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.

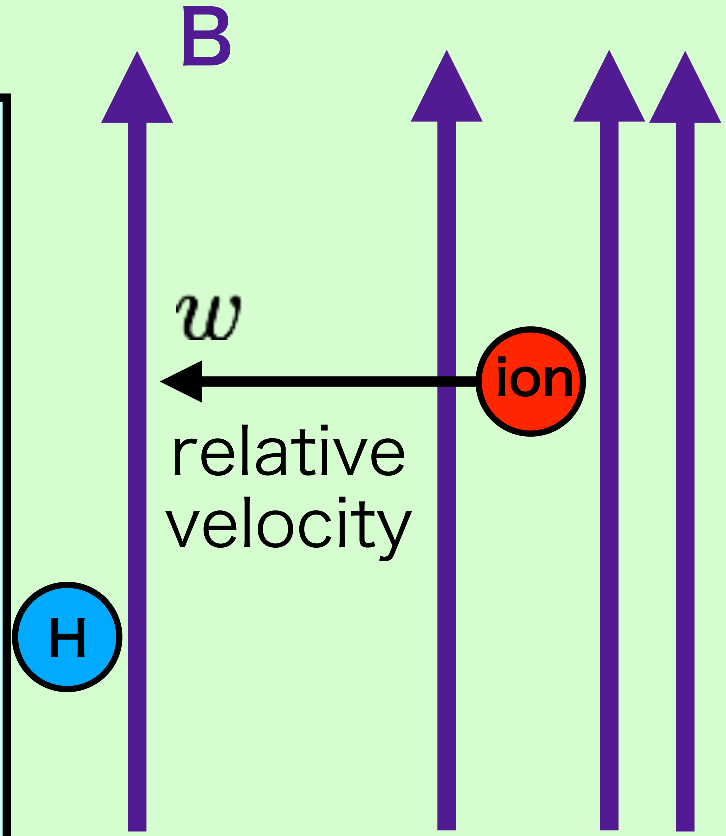


Illustration of ambipolar diffusion

Thermal history with PMFs

What is ambipolar diffusion ?

Neutral bulk motion

Charged bulk motion

+ magnetic effects

> occurrence of

the relative motion

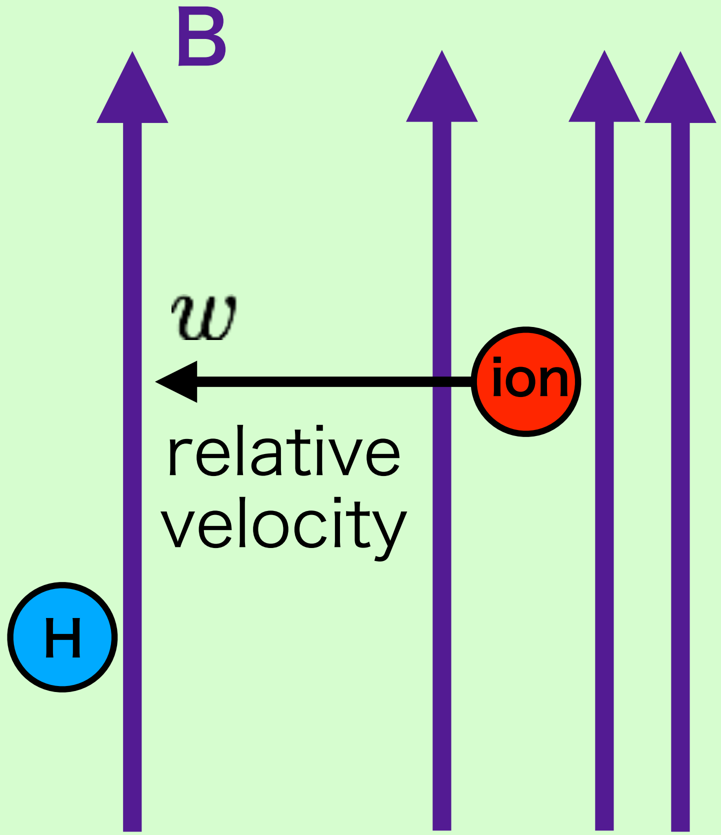


Illustration of
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What is ambipolar diffusion ?

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> occurrence of
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> induce electric dipole
moment to the neutrals

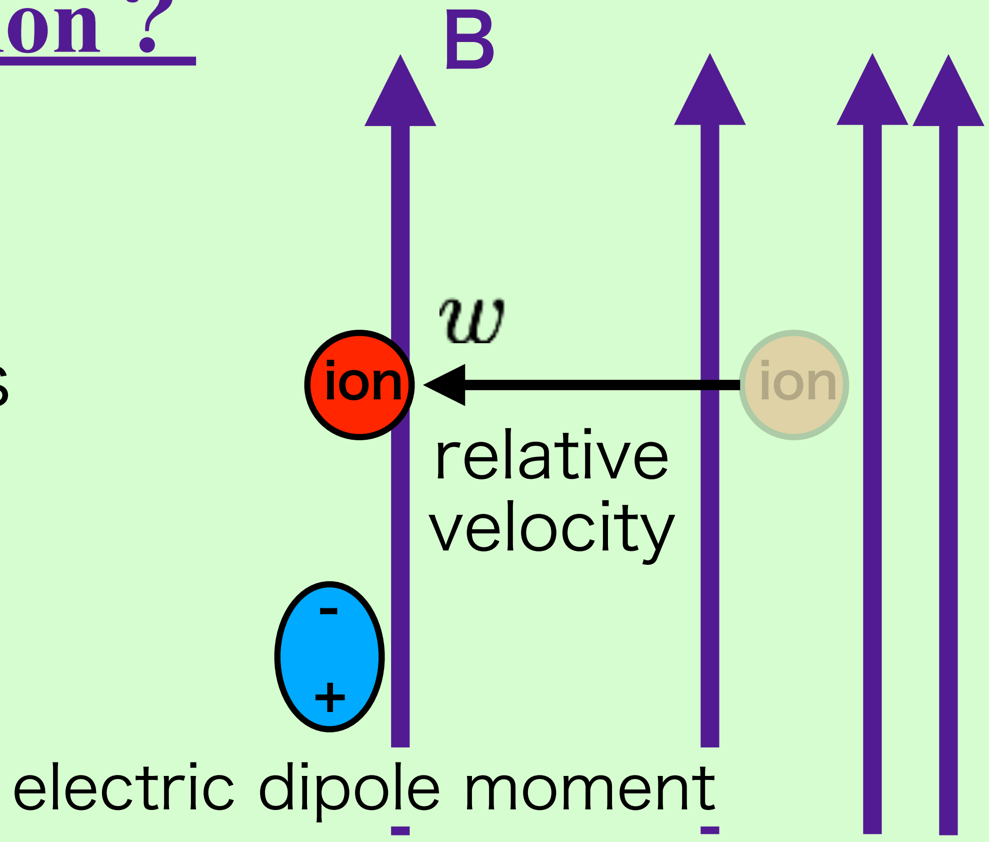


Illustration of
ambipolar diffusion

Thermal history with PMFs

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

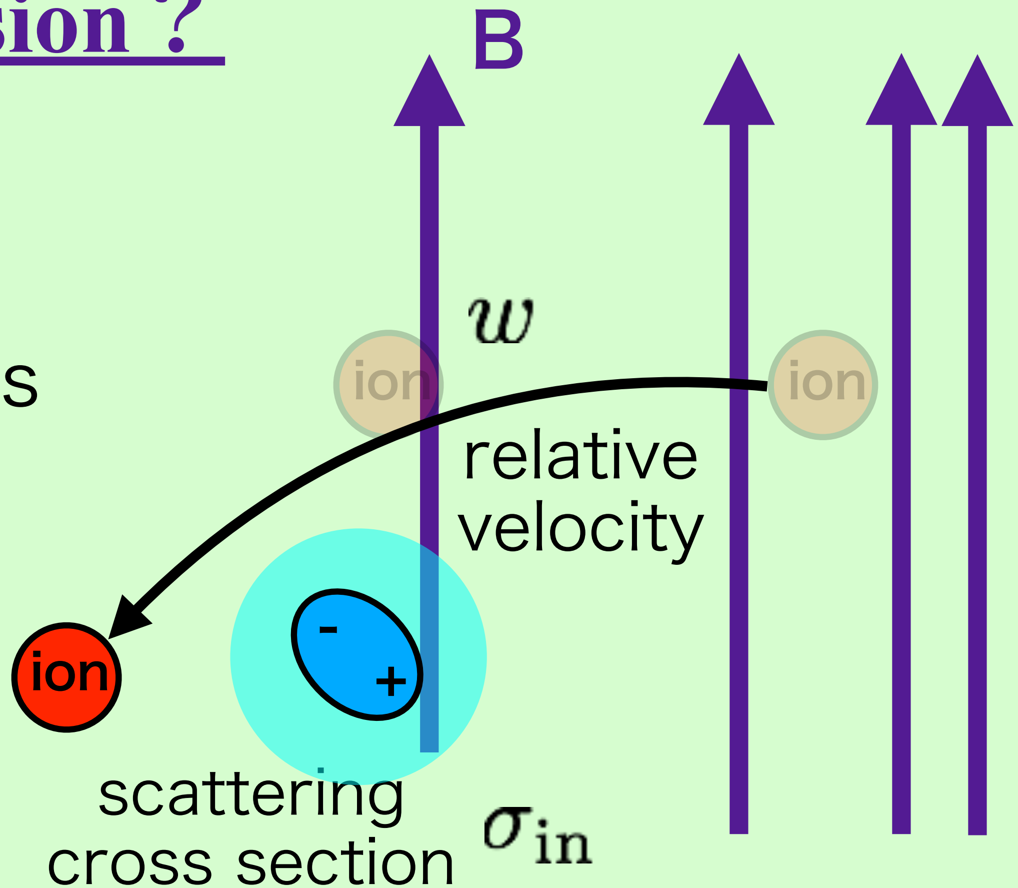


Illustration of
ambipolar diffusion

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)

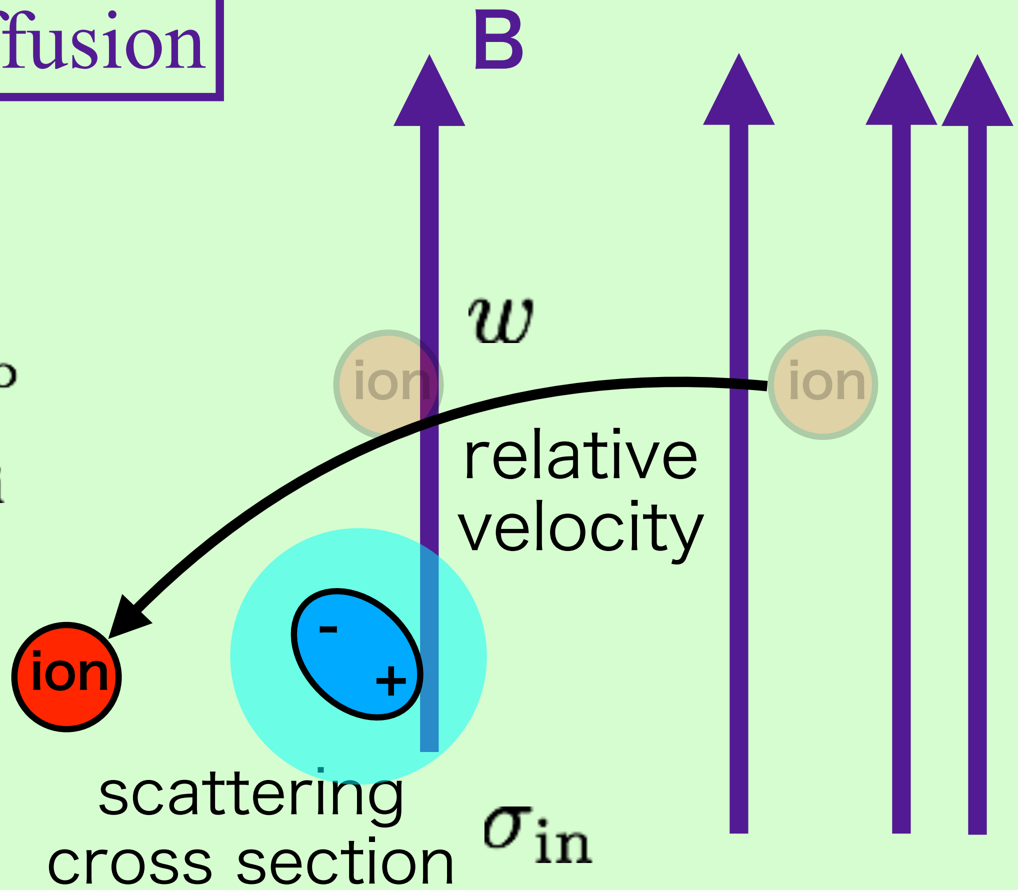


Illustration of ambipolar diffusion

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

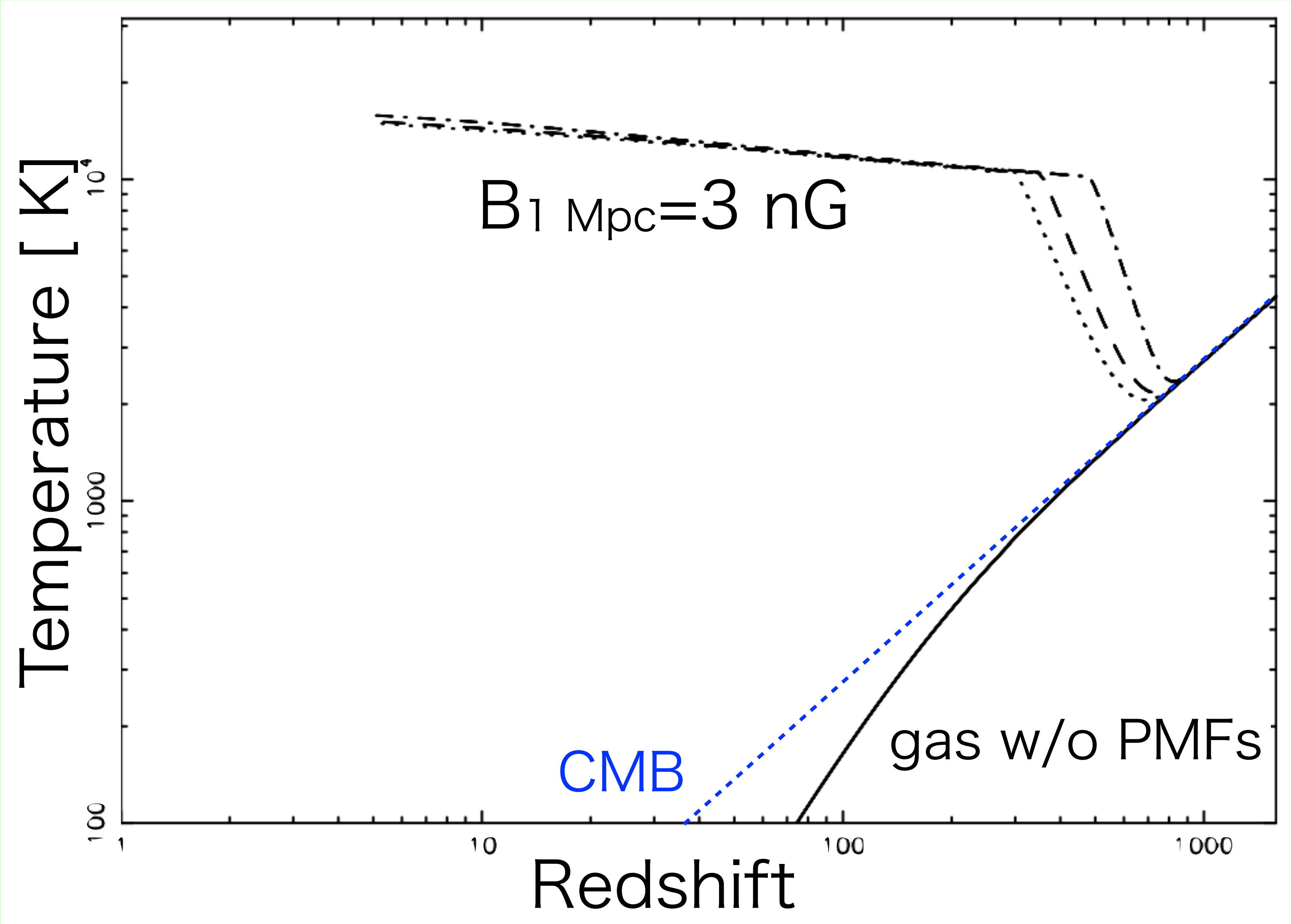
$$+\frac{\Gamma(t)}{1.5k_{\rm B}n_{\rm b}}$$

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		

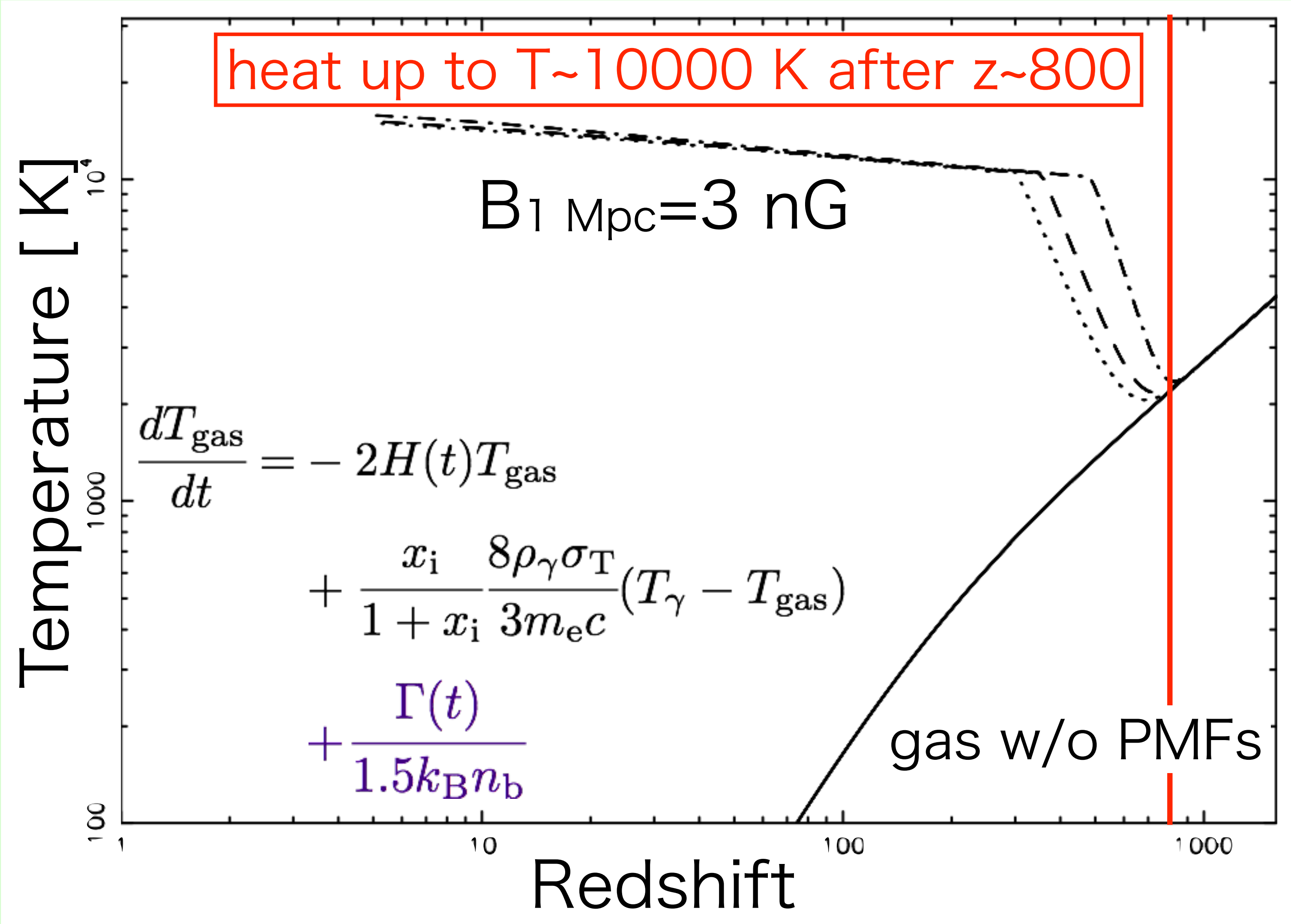
Thermal history with PMFs

(Sethi & Subramanian, 2005, MNRAS, 356)

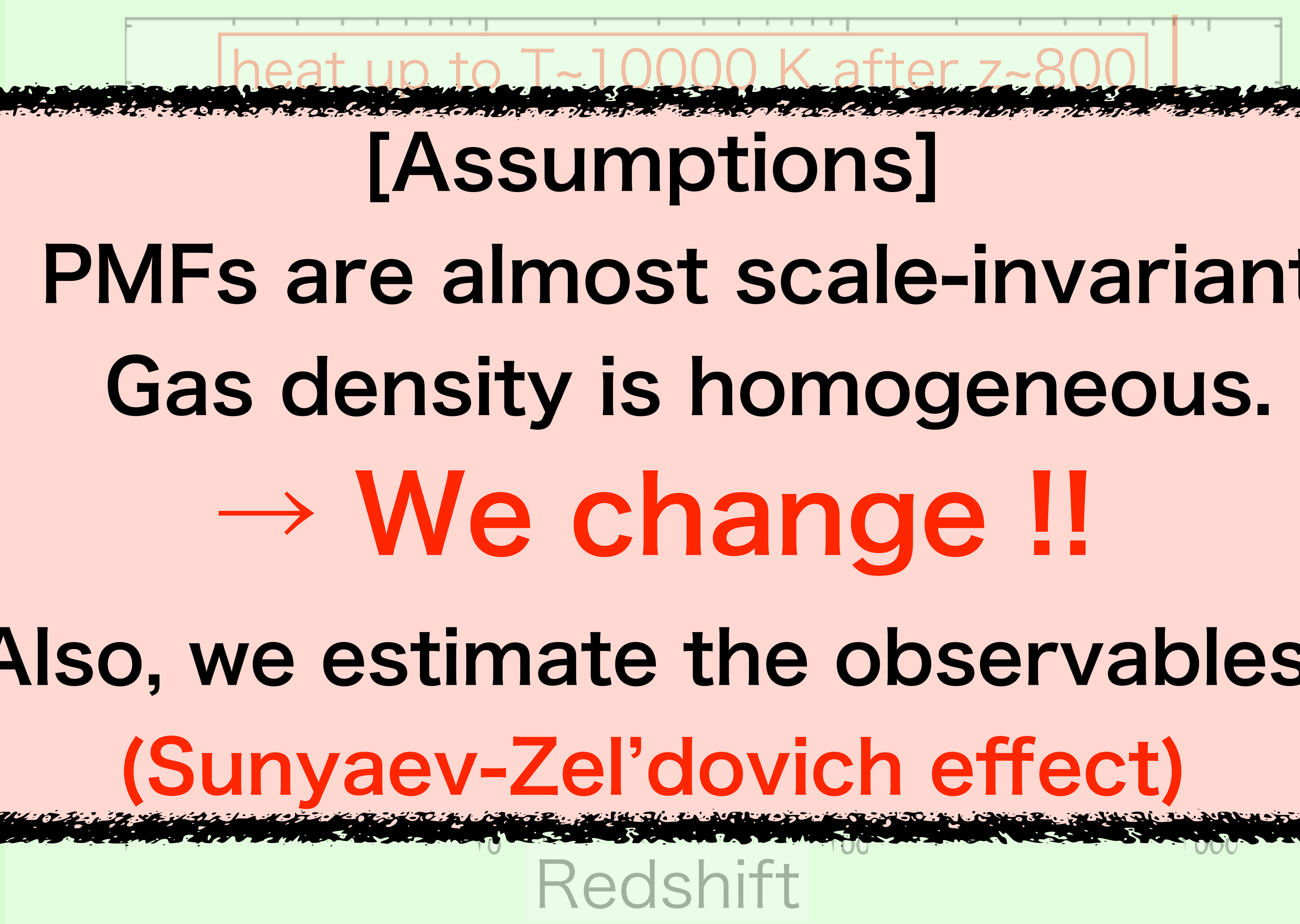


Thermal history with PMFs

(Sethi & Subramanian, 2005, MNRAS, 356)



Thermal history with PMFs



[Assumptions]

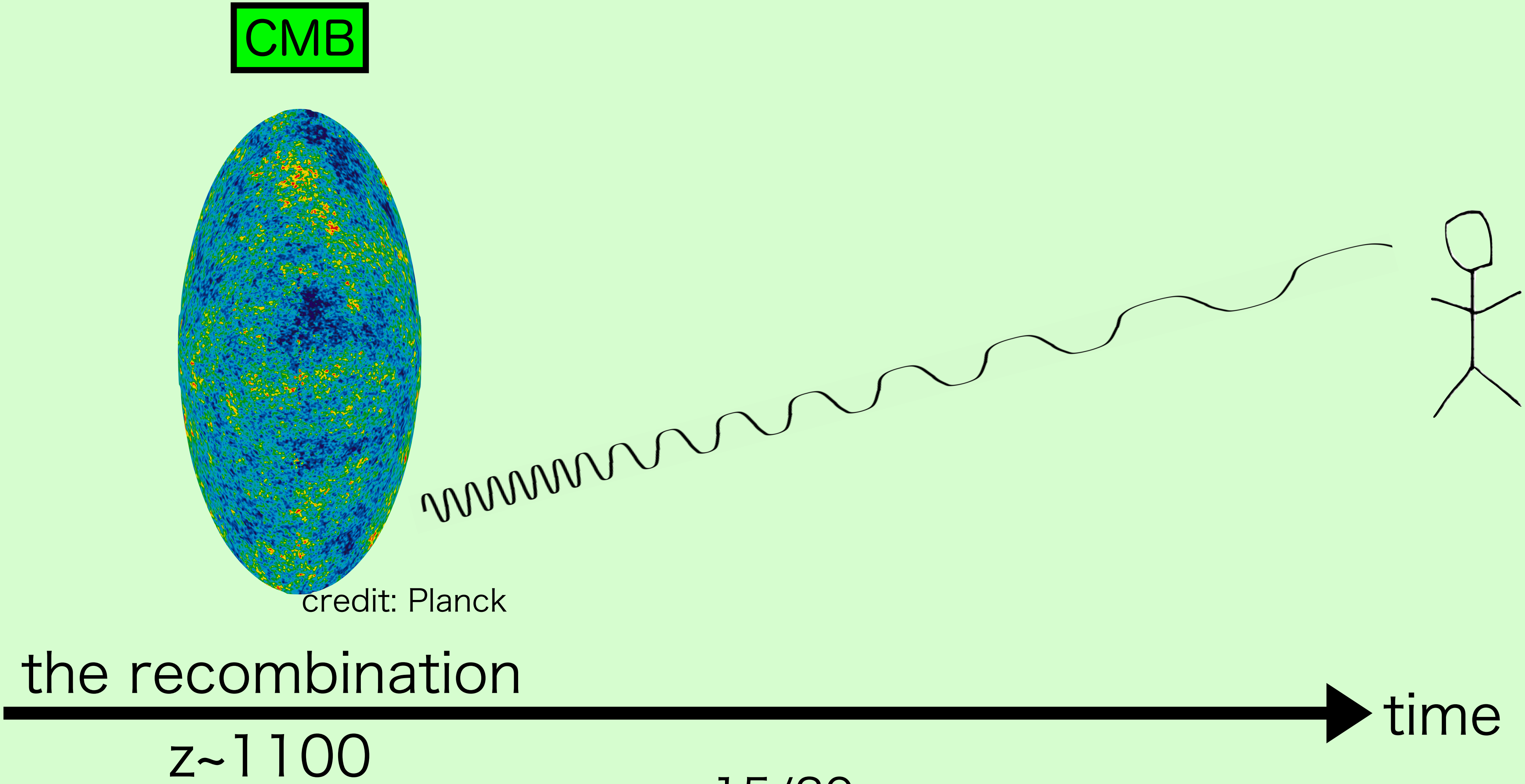
- PMFs are almost scale-invariant.
- Gas density is homogeneous.

→ We change !!

Also, we estimate the observables.

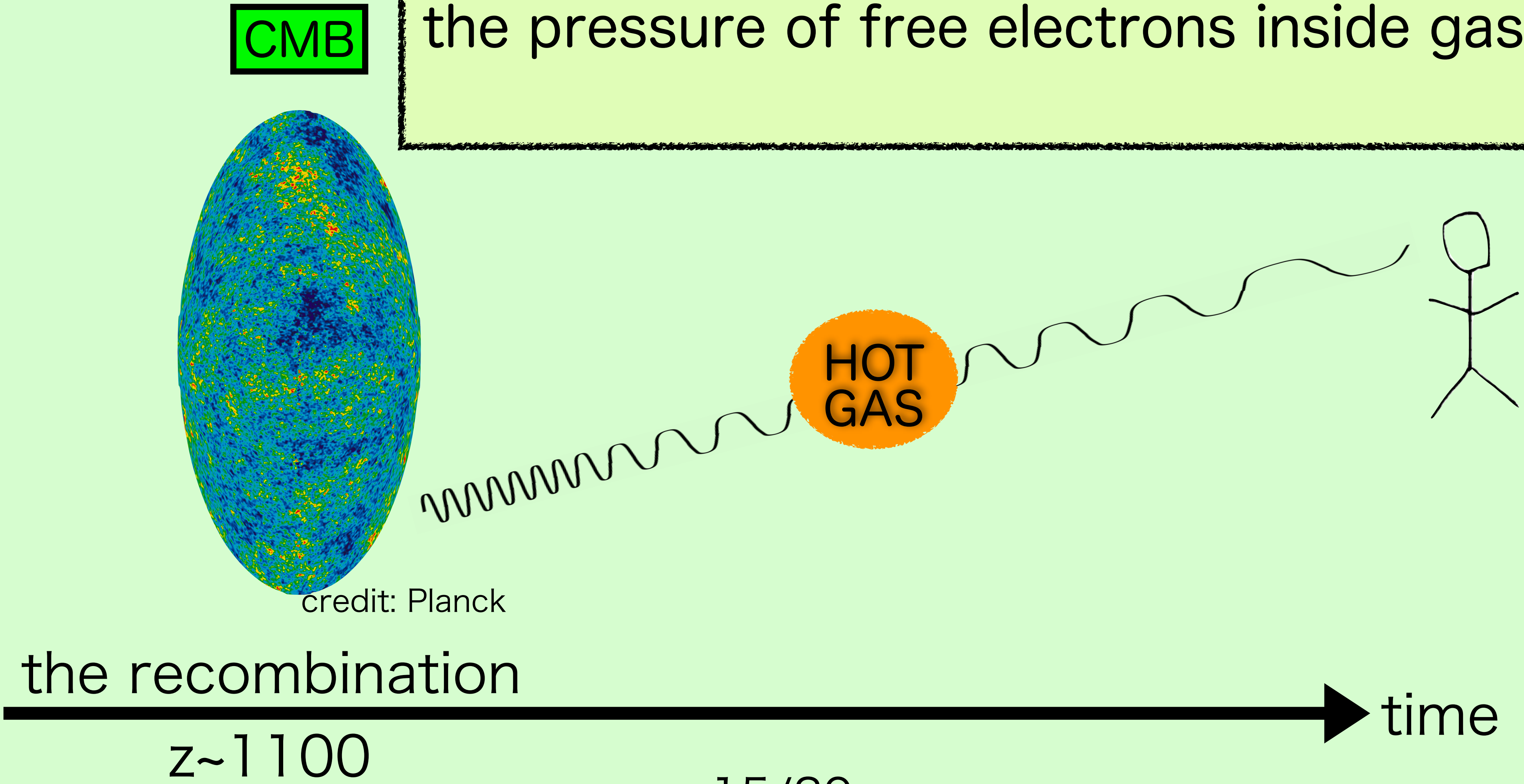
(Sunyaev-Zel'dovich effect)

Sunyaev-Zel'dovich effect

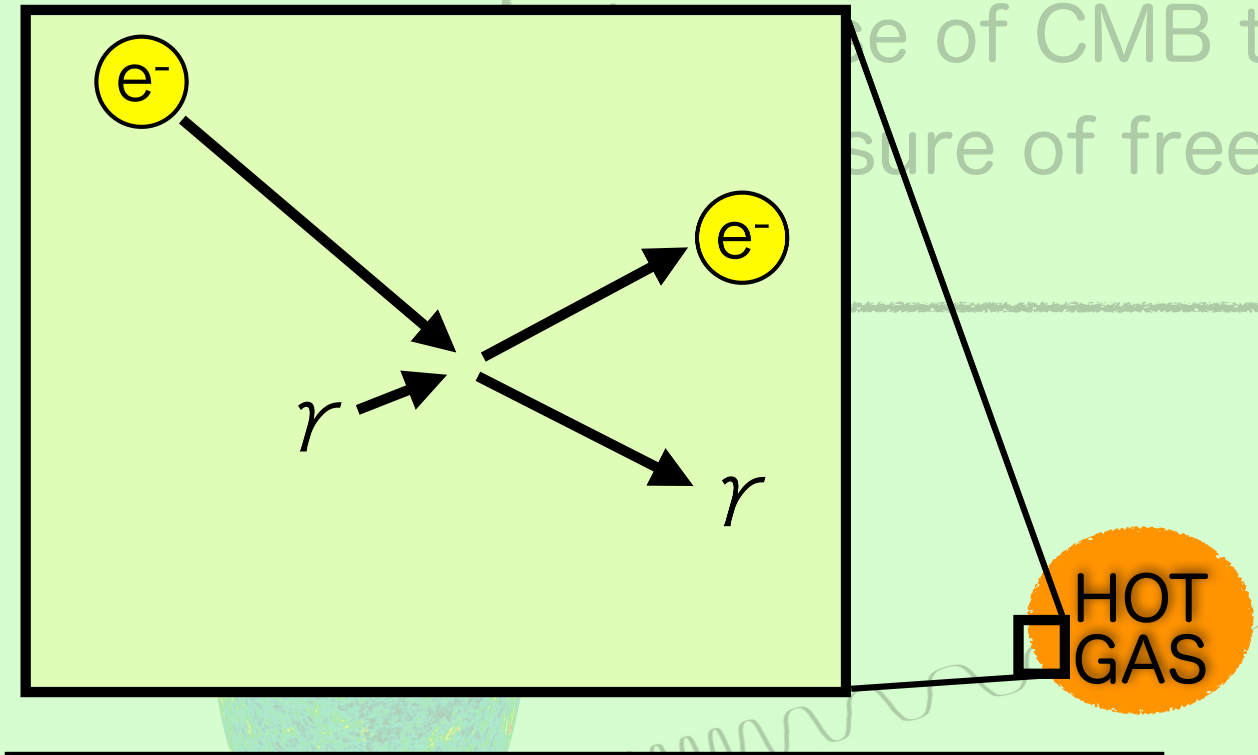


Sunyaev-Zel'dovich effect

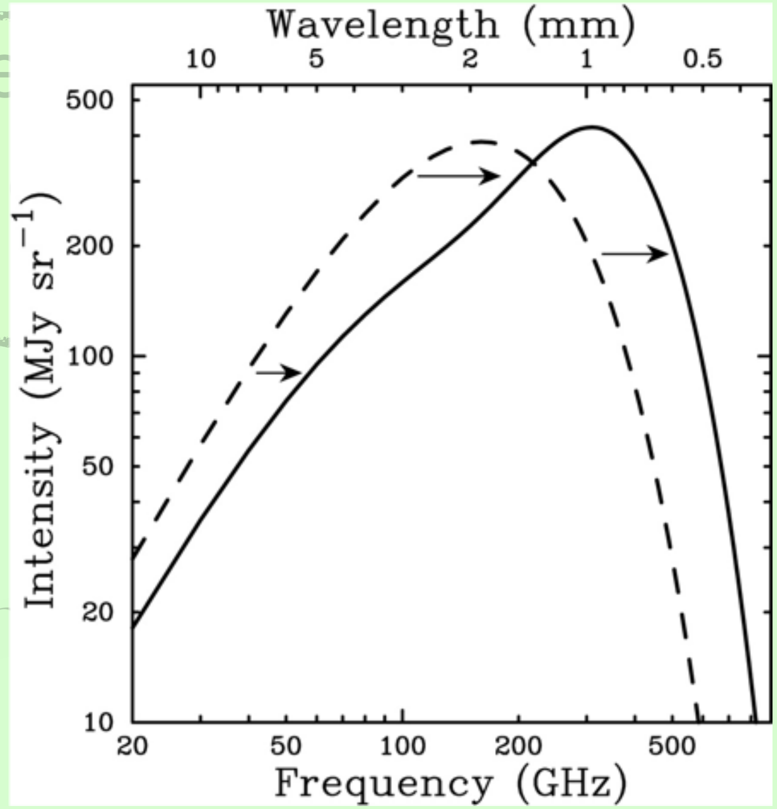
Increase of CMB temperature due to the pressure of free electrons inside gas



Sunyaev-Zel'dovich effect



Inverse Compton scattering

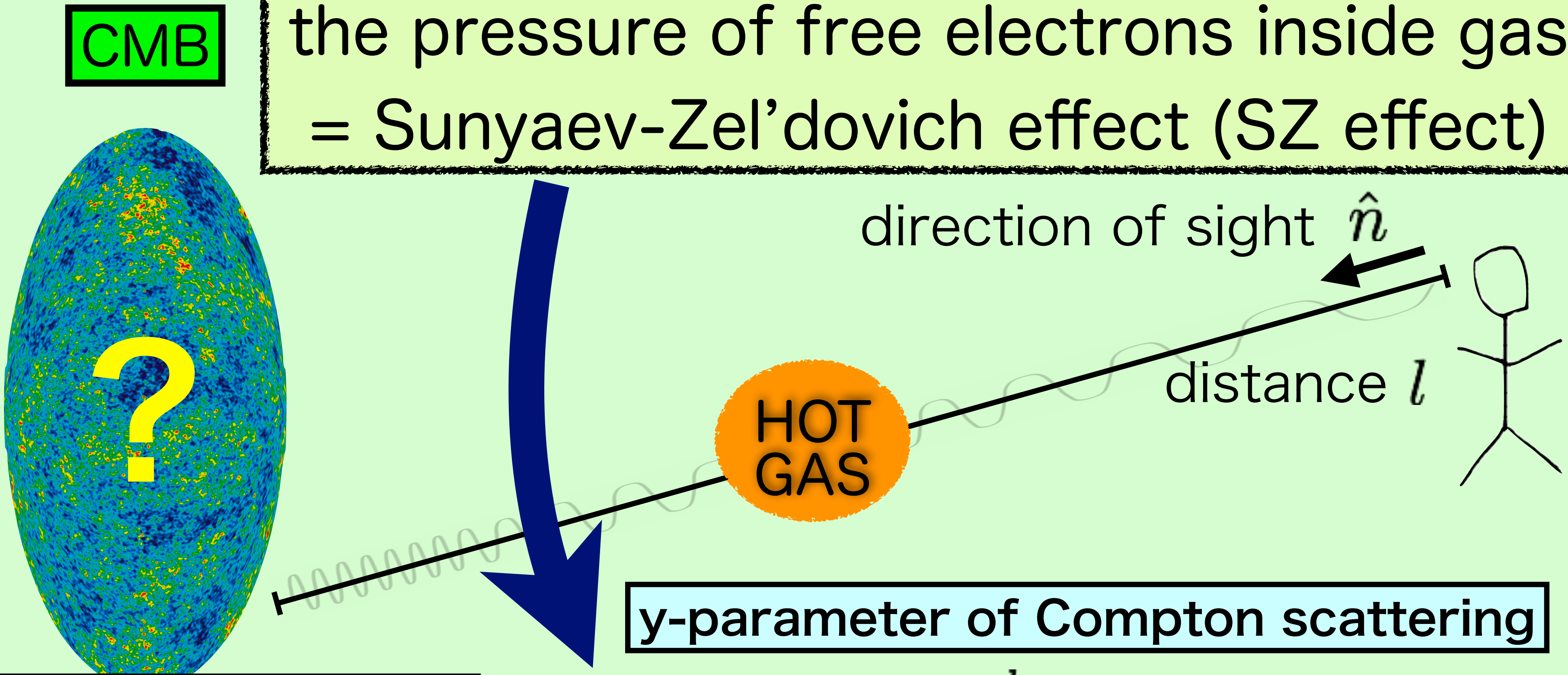


Carlstrom+, 2002
ARA&A, **40**

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)



Fluctuations of gas create fluctuations of CMB temperature

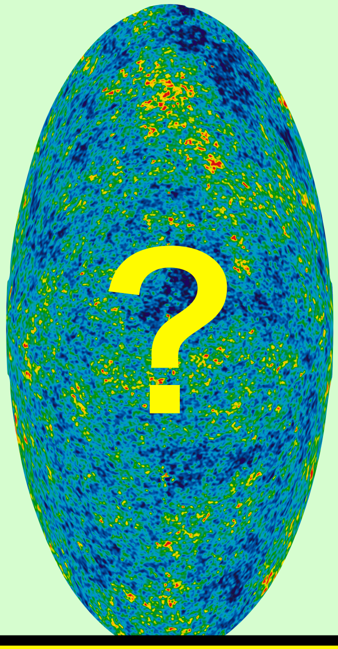
y-parameter of Compton scattering

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

Density Temperature

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

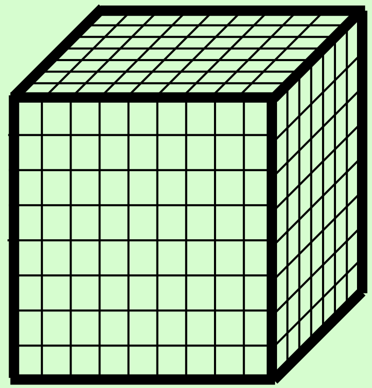
Vector potential $\mathbf{A}$

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

Lorentz force

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

※Assumption: B-fields adiabatically evolve.



64^3 grids

Box Size 2 Mpc
(co-moving coordinate)

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

$1000 > z > 10$

Source terms:

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

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

Our work

Basic equations of baryon fluid

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

Lorentz force of PMFs

pressure

gravity

density fluctuation from the background value

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

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

baryon density evolution

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

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

$$T_n = T_{\rm gas}\ [K] \times 10^{-n}$$

bremsstrahlung

$$\Theta = 1.42 \times 10^{-27} T_{\rm gas}^{0.5} \quad [\rm erg\ cm^3\ s^{-1}]$$

collisional excitation

$$\Psi = 7.5 \times 10^{-19} \left(1 + T_5^{0.5}\right)^{-1} \exp\left(-\frac{1.18}{T_5}\right) \quad [\rm erg\ cm^3\ s^{-1}]$$

recombination

$$\eta = 6.50 \times 10^{-27} \frac{T_{\rm gas}^{0.5}}{T_3(1+T_6)} \quad [\rm erg\ cm^3\ s^{-1}]$$

collisional ionization

$$\zeta = 1.27 \times 10^{-21} \frac{T_{\rm gas}^{0.5}}{1+T_5^{0.5}} \exp\left(-\frac{1.58}{T_5}\right) \quad [\rm erg\ cm^3\ s^{-1}]$$

(Fukugita & Kawasaki, 1994, MNRAS, 269)

Our work

x_{ion} time evolution

collisional ionization

recombination

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

photoionization (CMB)

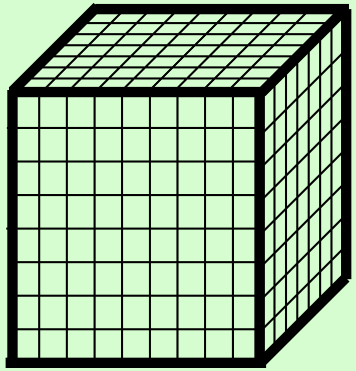
$$\alpha_e = 1.14 \times 10^{-13} \times \frac{4.309\, T_4^{-0.6166}}{1 + 0.6703\, T_4^{0.5300}} \quad [{\rm cm}^3\ {\rm s}^{-1}]$$

$$\beta_e = \alpha_e \left(\frac{2\pi m_{\rm e} k_{\rm B} T_\gamma}{h_{\rm Pl}^2} \right)^{\frac{3}{2}} \exp\left(\frac{E_{2s}}{k_{\rm B} T_\gamma} \right) \quad [{\rm s}^{-1}]$$

$$\gamma_e = 0.291 \times 10^{-7} \times U^{0.39} \frac{\exp(-U)}{0.232 + U} \quad [{\rm cm}^3 {\rm s}^{-1}]$$

Our work

③ Estimate the $T_{\rm CMB}$ anisotropy from the 3D y-parameter map.



64^3 grids

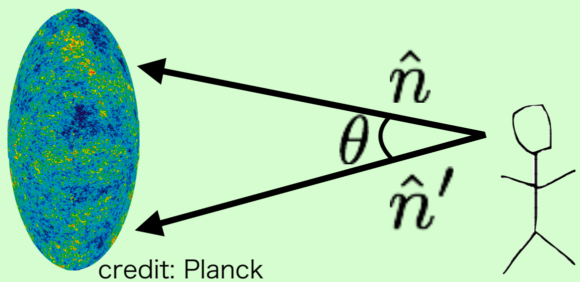
Box size 2 Mpc

y-parameter of Compton scattering

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

density temperature

Integrate y-parameter in 1000 > z > 10



$$\mathcal{D}_\ell = \frac{\ell(\ell+1)}{2\pi}\frac{(g_\nu T_\gamma)^2}{4\pi}\int P_\ell(\cos\theta)\langle y(\hat{n})y(\hat{n}')\rangle\ d^2\hat{n}\ d^2\hat{n}'\ ,$$

(Legendre polynomials)

CMB angular power spectrum

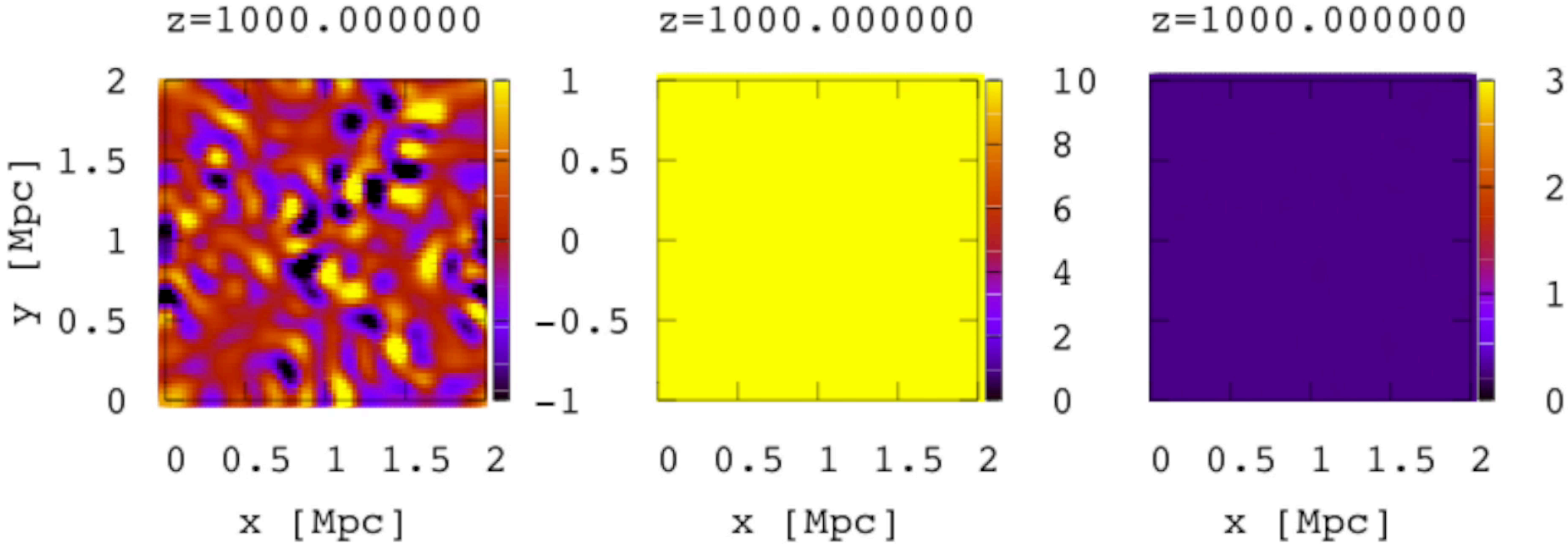
$$\frac{\langle \delta T_{\rm CMB}^2\rangle}{T_{\rm CMB}^2} \approx \int d\log\ell\ \mathcal{D}_\ell$$

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

Results

Evolution from z=1000 to 10

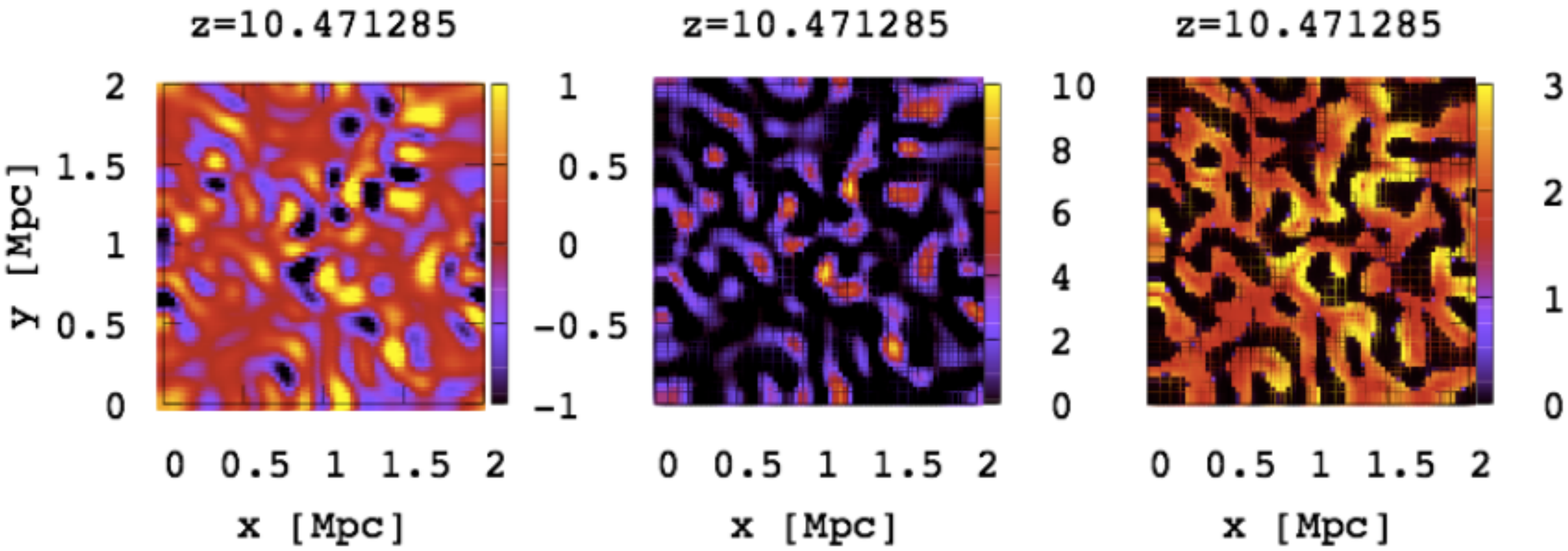
Lorentz force	gas # density	gas temperature
[x10^5 nG^2 Mpc^{-2}]	[cm^{-3}]	[x10^4 K]



Results

Evolution from z=1000 to 10

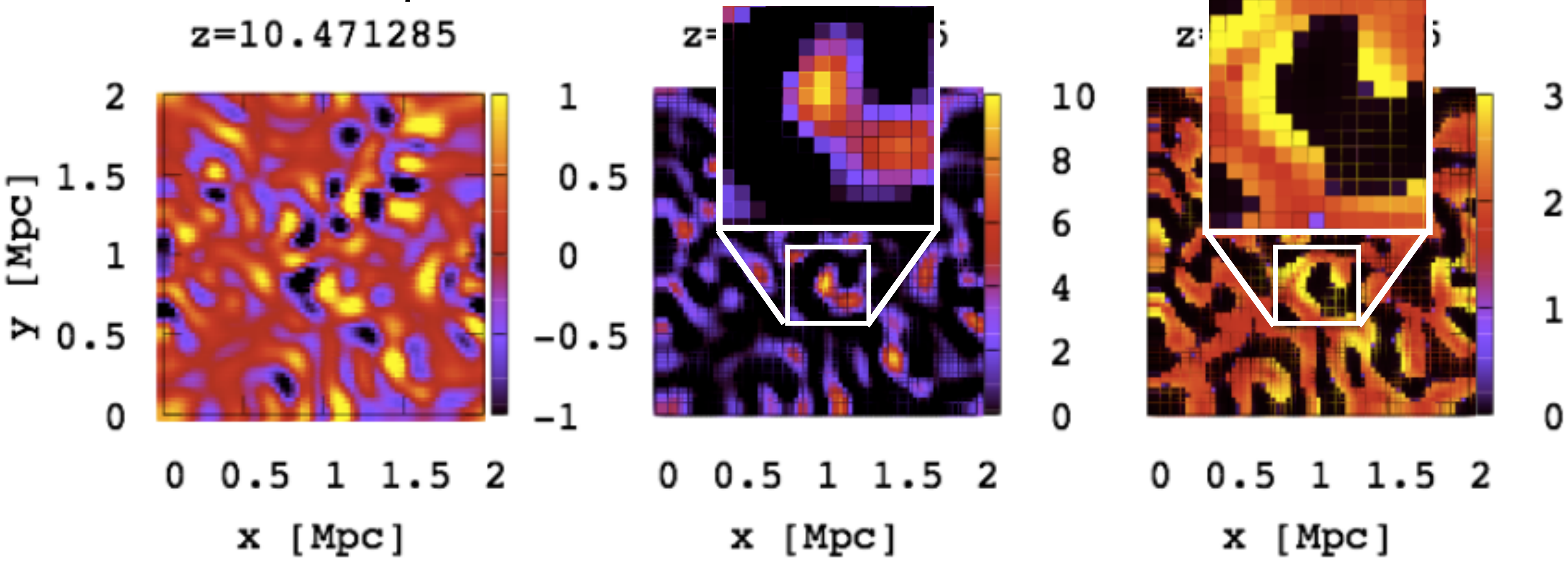
Lorentz force $[\times 10^5\ nG^2\ Mpc^{-2}]$ | gas # density $[cm^{-3}]$ | gas temperature $[\times 10^4\ K]$



Results

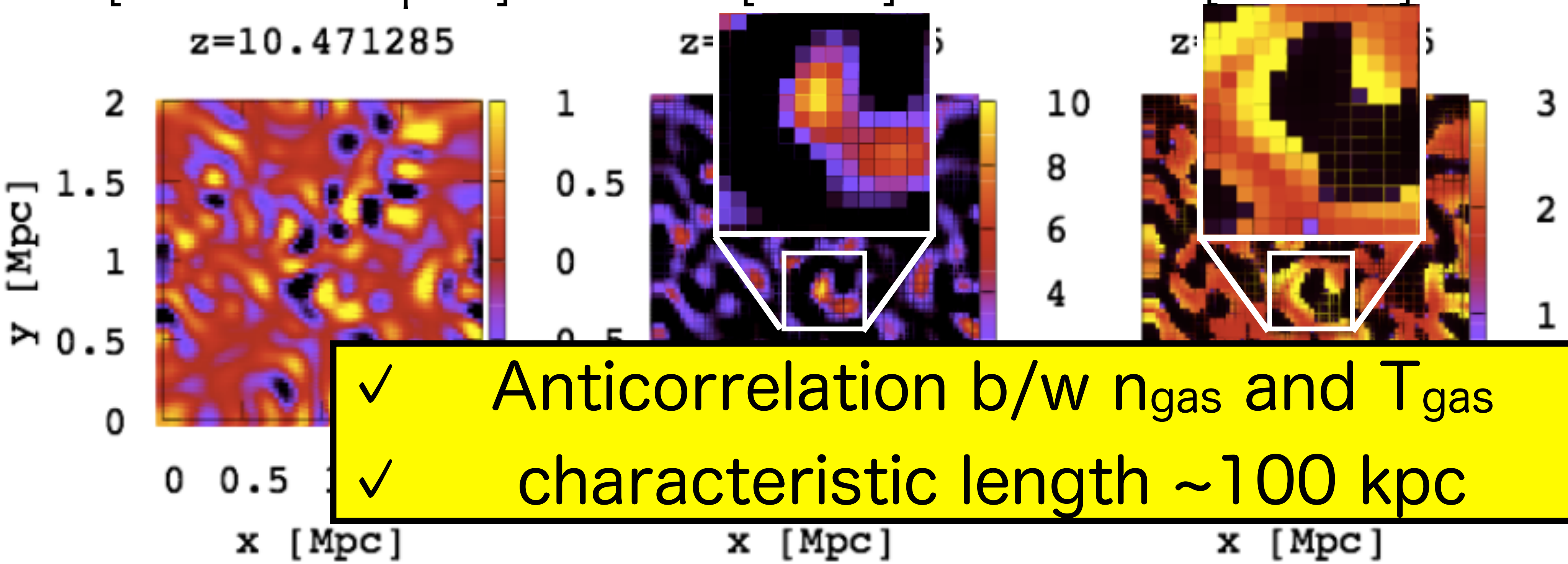
Evolution from z=1000 to 10

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



Results

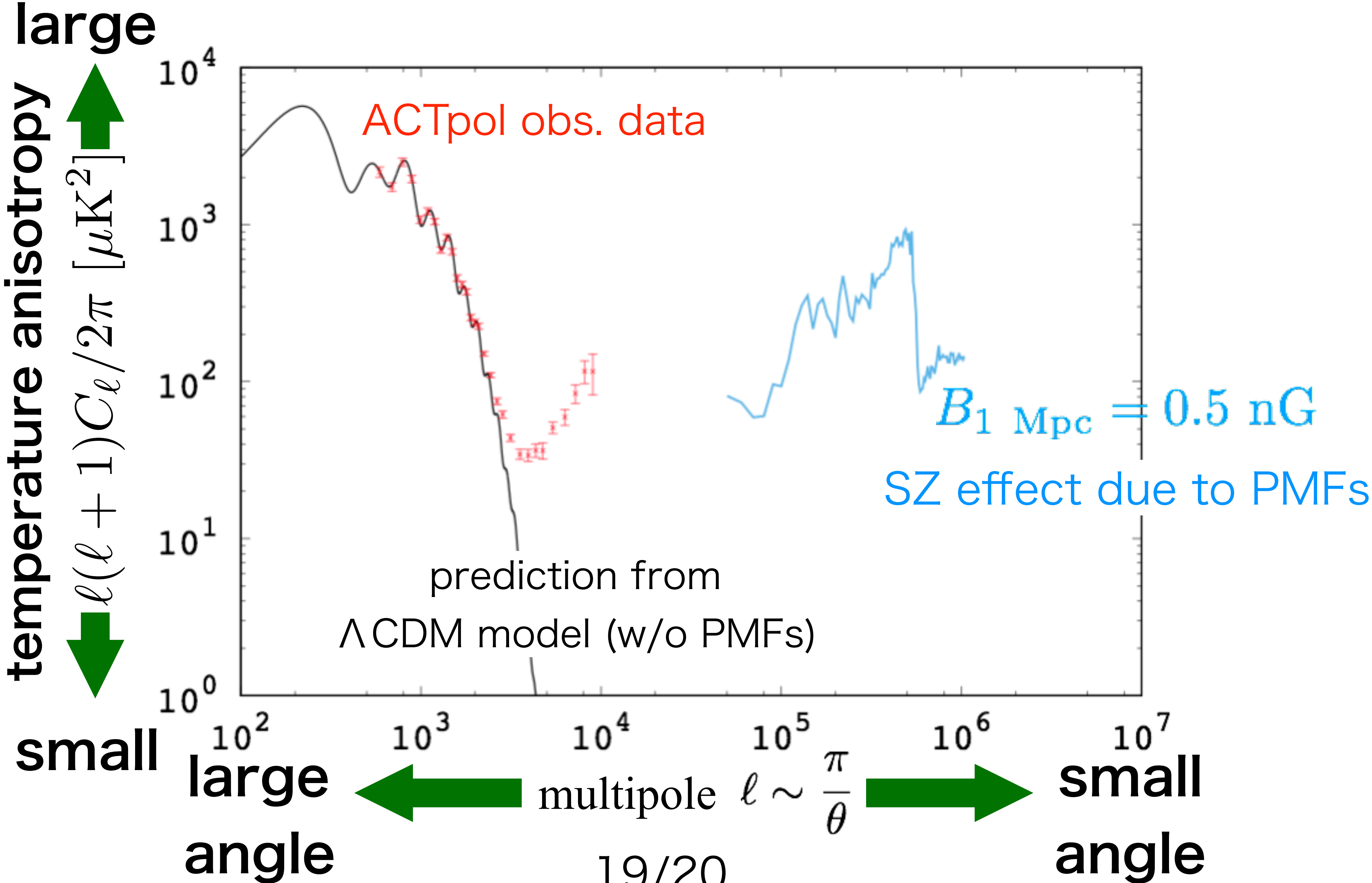
Evolution from z=1000 to 10



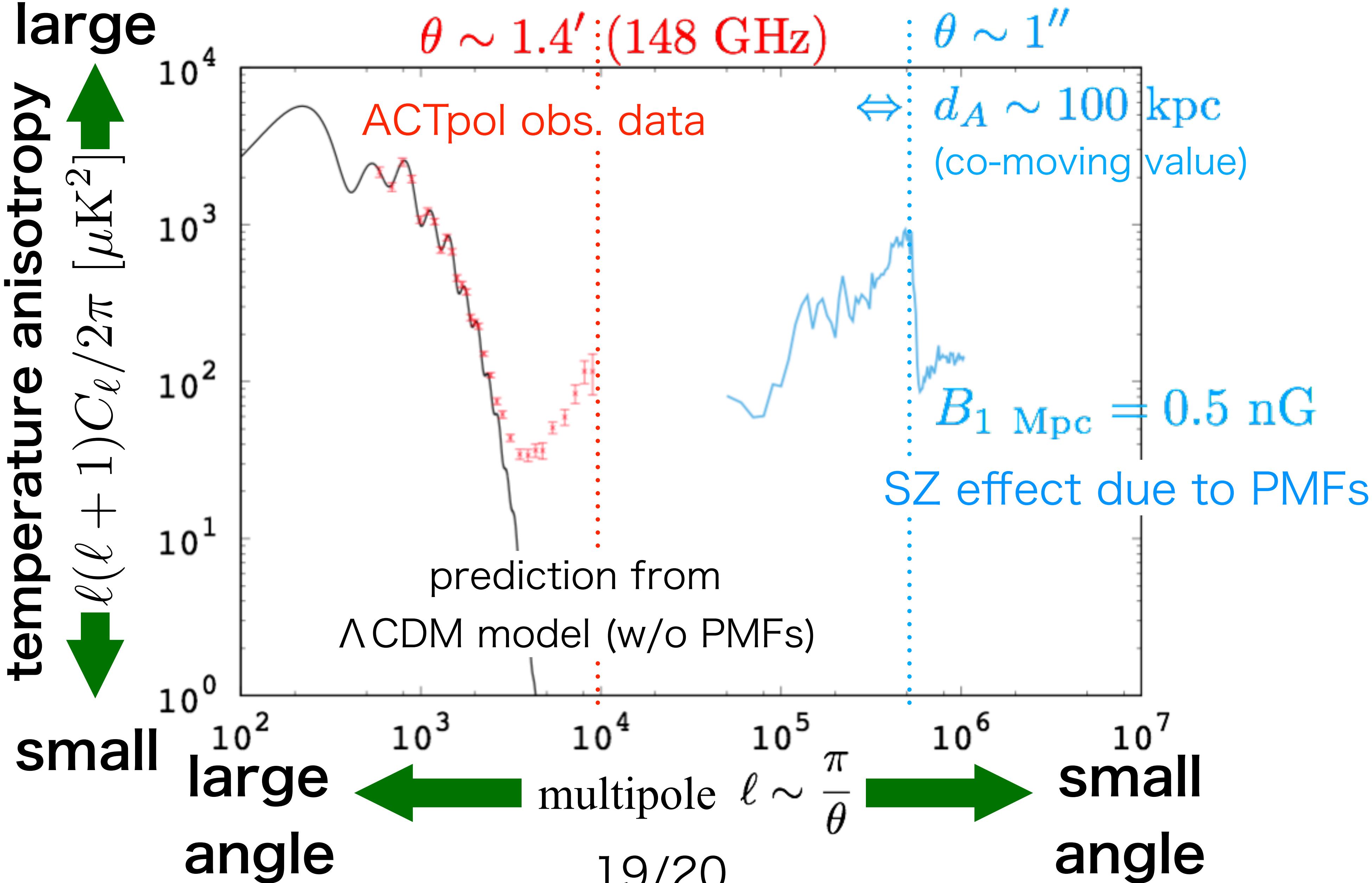
✓ Anticorrelation b/w n_{gas} and T_{gas}

✓ characteristic length ~100 kpc

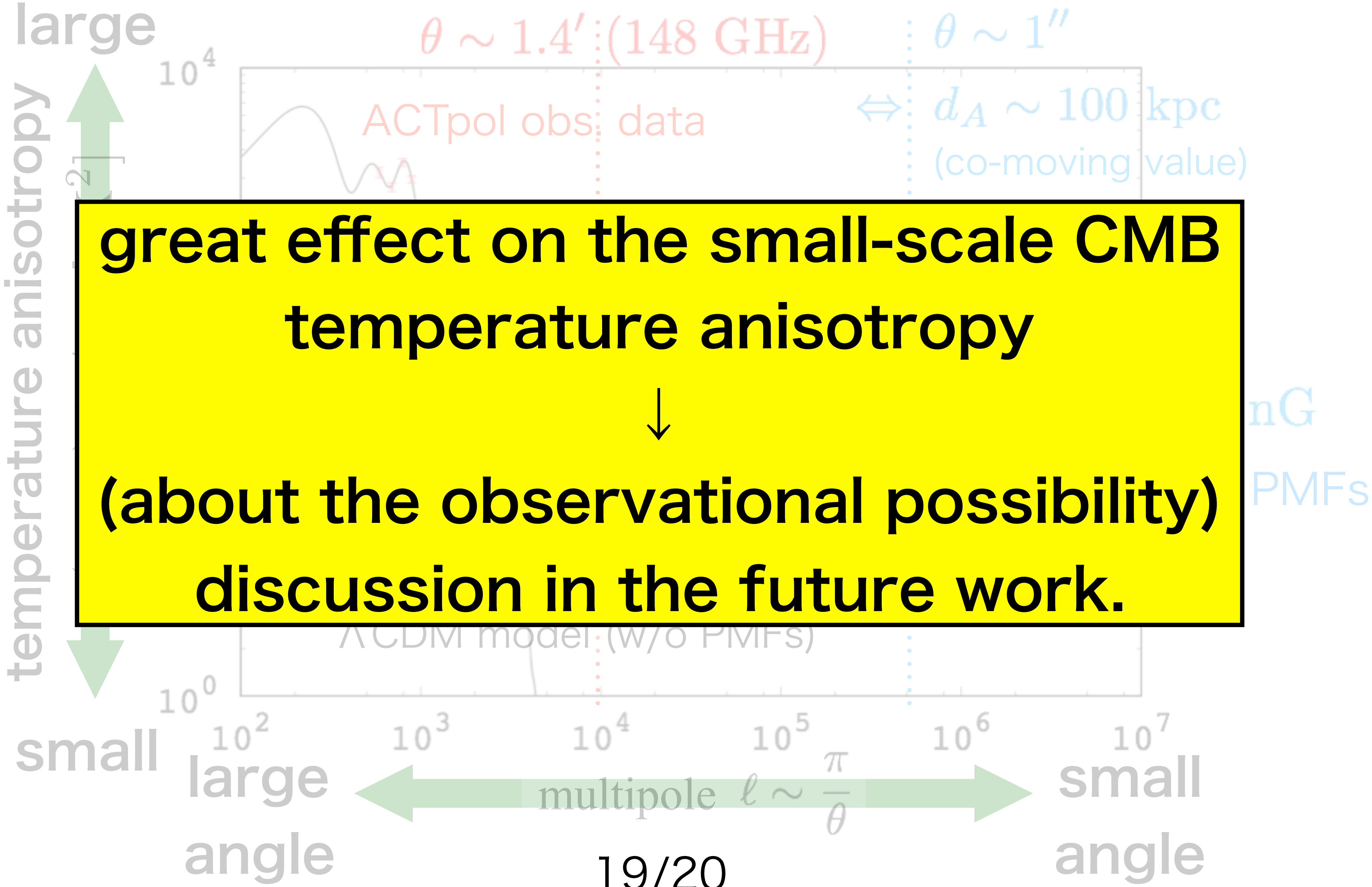
CMB anisotropies



CMB anisotropies



CMB anisotropies



great effect on the small-scale CMB temperature anisotropy

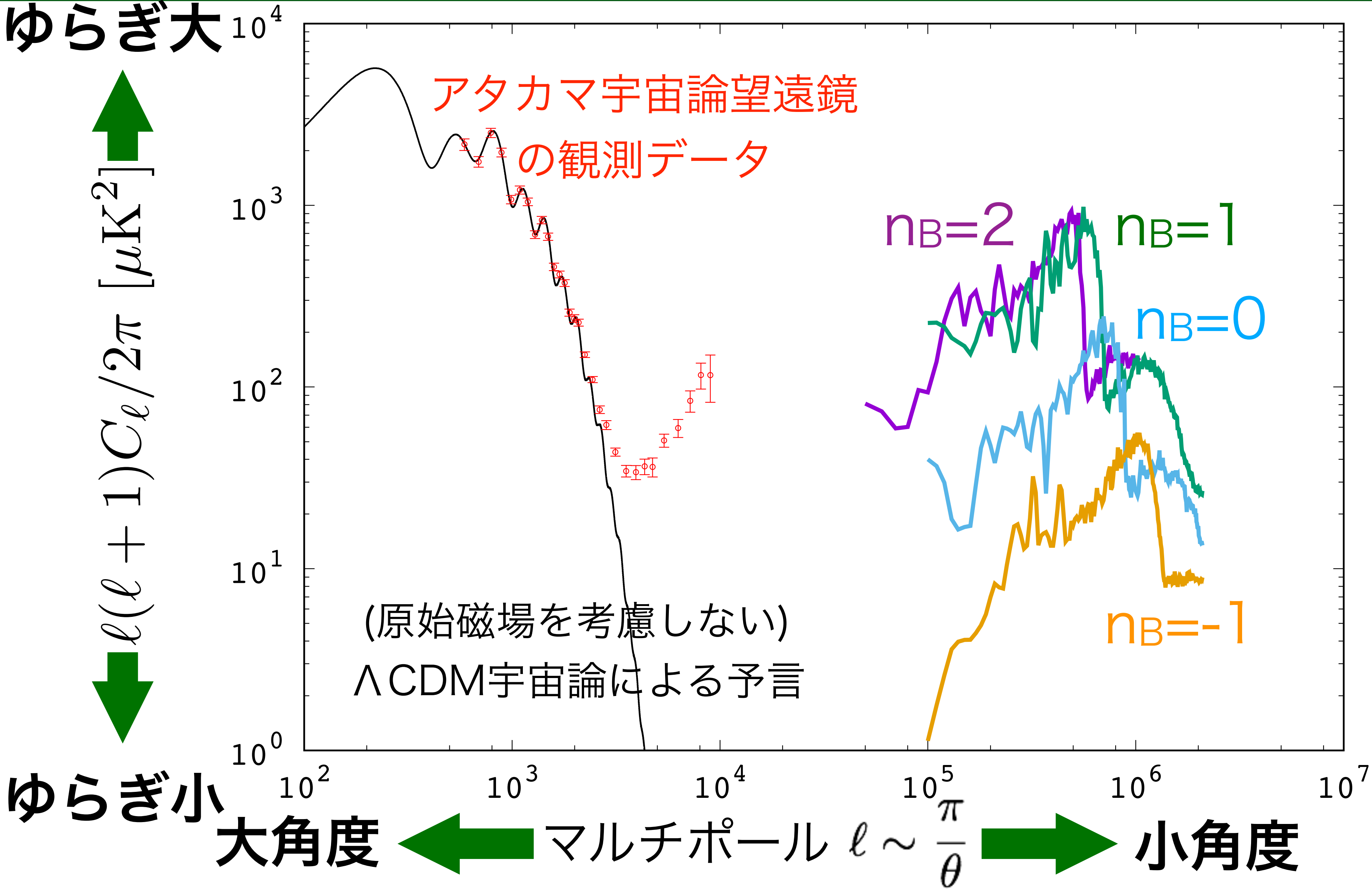
↓

(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

CMBの温度ゆらぎ



ゆらぎ大
ゆらぎ小
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
10^4
10^3
10^2
10^1
10^0
10^2
10^3
10^4
10^5
10^6
10^7
アタカマ宇宙論望遠鏡
の観測データ
nB=2
nB=1
nB=0
nB=-1
(原始磁場を考慮しない)
ΛCDM宇宙論による予言
大角度
マルチポール $\ell \sim \frac{\pi}{\theta}$
小角度