原始磁場が引き起こす CMB の小スケールゆらぎ

2017年10月24日

箕田鉄兵

（共同研究者）

長谷川賢二・田代寛之・市來淨與・杉山直

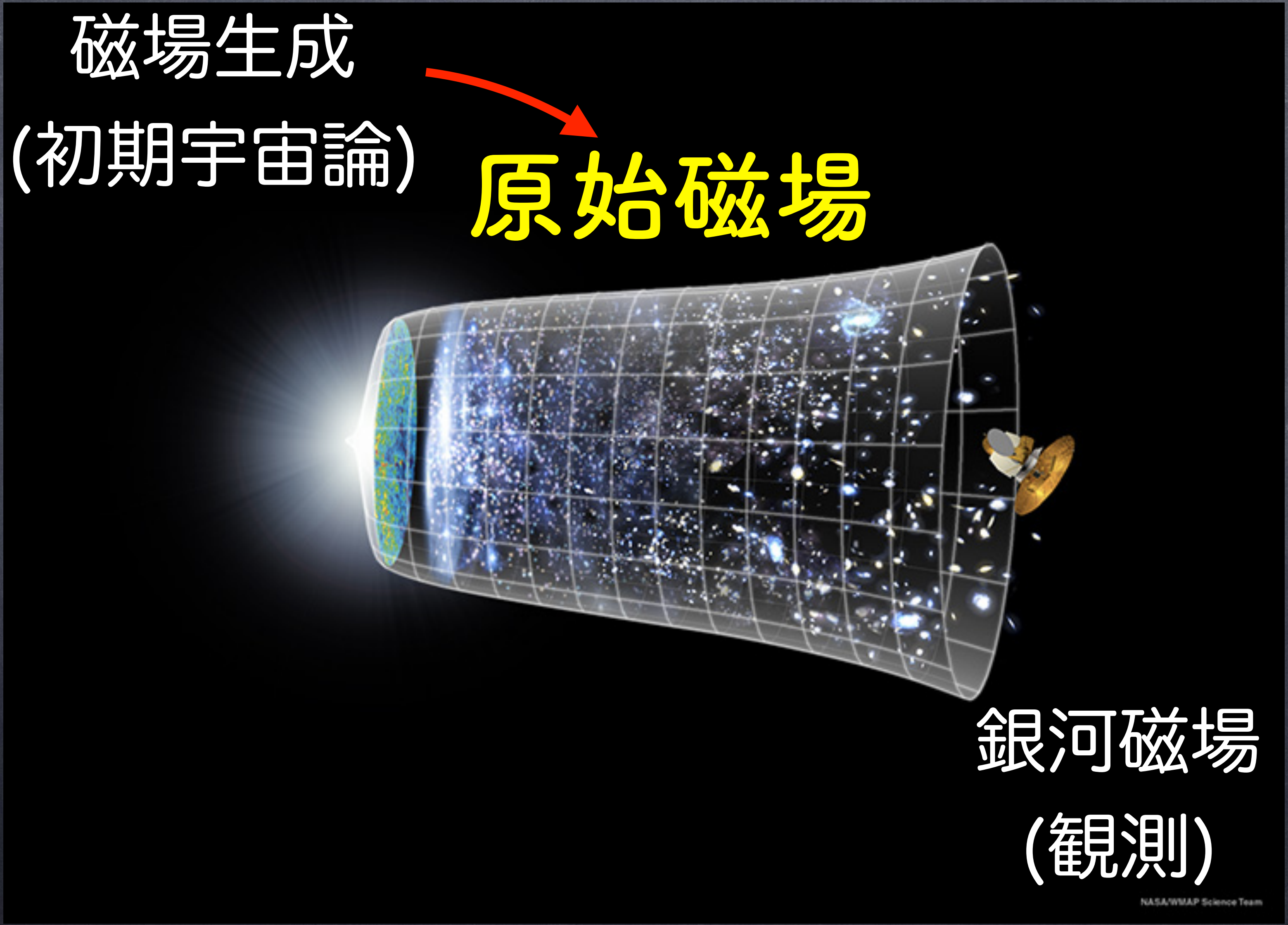
T. Minoda et al., (2017) arXiv:1705.10054

Contents

- Introduction
- Calculation Methods
- Results/Discussion
- Summary

Contents

Introduction



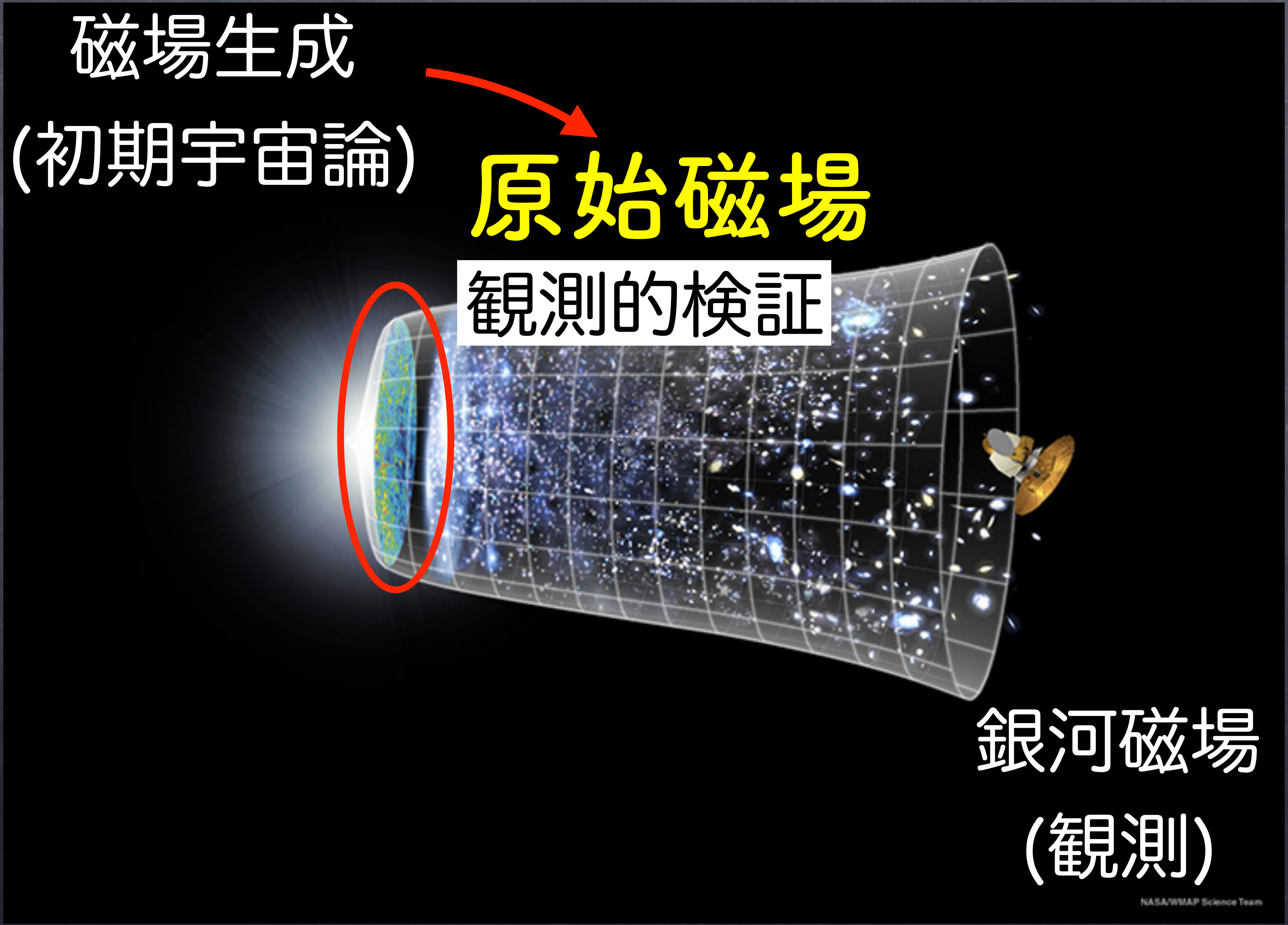
磁場生成
(初期宇宙論)

原始磁場

銀河磁場
(観測)

NASA/WMAP Science Team

Introduction



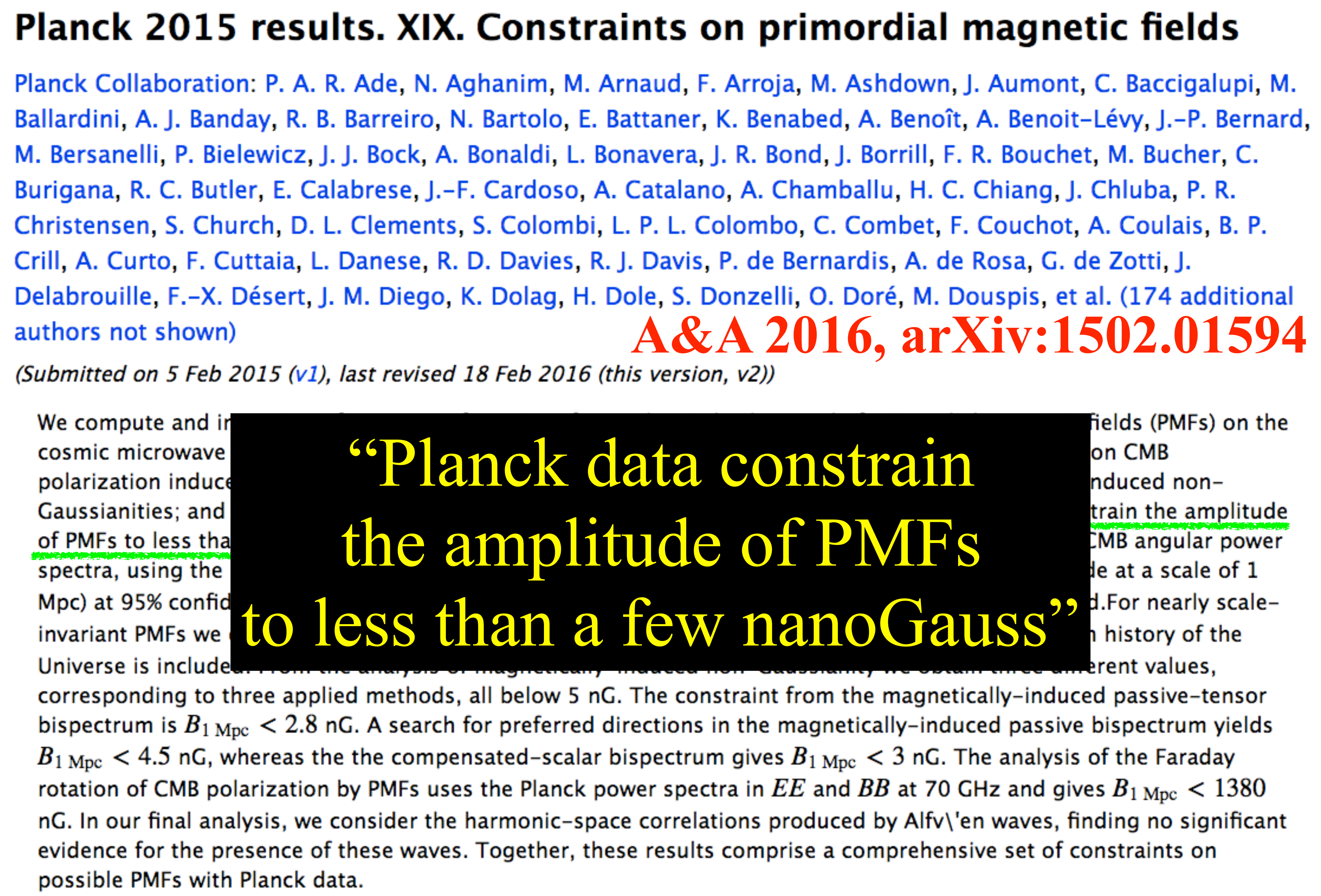
磁場生成
(初期宇宙論)

原始磁場

観測的検証

銀河磁場
(観測)

NASA/WMAP Science Team



Planck 2015 results. XIX. Constraints on primordial magnetic fields

Planck Collaboration: P. A. R. Ade, N. Aghanim, M. Arnaud, F. Arroja, M. Ashdown, J. Aumont, C. Baccigalupi, M. Ballardini, A. J. Banday, R. B. Barreiro, N. Bartolo, E. Battaner, K. Benabed, A. Benoît, A. Benoit-Lévy, J.-P. Bernard, M. Bersanelli, P. Bielewicz, J. J. Bock, A. Bonaldi, L. Bonavera, J. R. Bond, J. Borrill, F. R. Bouchet, M. Bucher, C. Burigana, R. C. Butler, E. Calabrese, J.-F. Cardoso, A. Catalano, A. Chamballu, H. C. Chiang, J. Chluba, P. R. Christensen, S. Church, D. L. Clements, S. Colombi, L. P. L. Colombo, C. Combet, F. Couchot, A. Coulais, B. P. Crill, A. Curto, F. Cuttaia, L. Danese, R. D. Davies, R. J. Davis, P. de Bernardis, A. de Rosa, G. de Zotti, J. Delabrouille, F.-X. Désert, J. M. Diego, K. Dolag, H. Dole, S. Donzelli, O. Doré, M. Douspis, et al. (174 additional authors not shown)

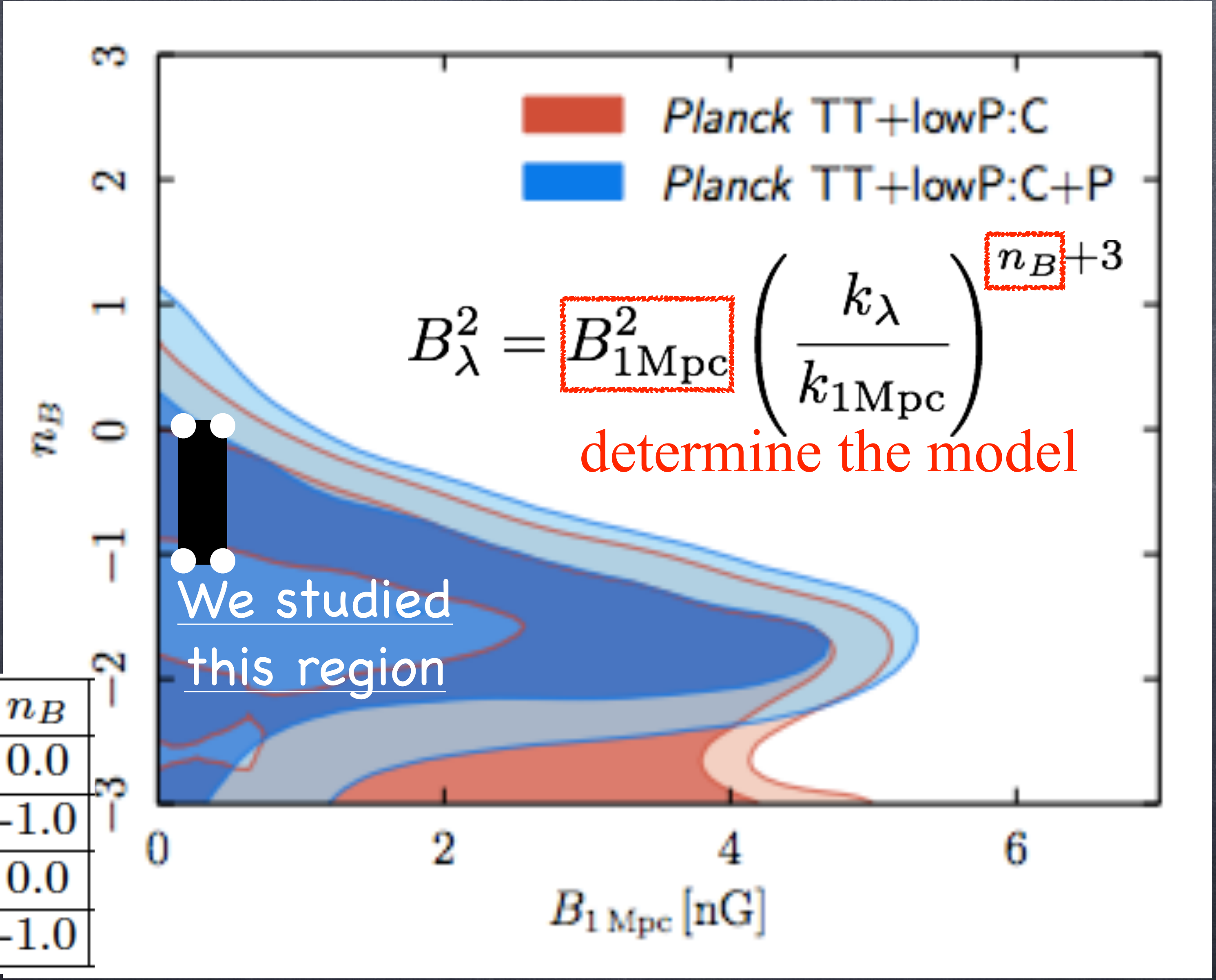
A&A 2016, arXiv:1502.01594

(Submitted on 5 Feb 2015 (v1), last revised 18 Feb 2016 (this version, v2))

We compute and i … fields (PMFs) on the
cosmic microwave … on CMB
polarization induce … nduced non–
Gaussianities; and … train the amplitude
of PMFs to less tha … CMB angular power
spectra, using the … de at a scale of 1
Mpc) at 95% confid … d.For nearly scale–
invariant PMFs we … history of the
Universe is include … erent values,
corresponding to three applied methods, all below 5 nG. The constraint from the magnetically–induced passive–tensor bispectrum is $B_{1\,\mathrm{Mpc}} < 2.8$ nG. A search for preferred directions in the magnetically–induced passive bispectrum yields $B_{1\,\mathrm{Mpc}} < 4.5$ nG, whereas the the compensated–scalar bispectrum gives $B_{1\,\mathrm{Mpc}} < 3$ nG. The analysis of the Faraday rotation of CMB polarization by PMFs uses the Planck power spectra in EE and BB at 70 GHz and gives $B_{1\,\mathrm{Mpc}} < 1380$ nG. In our final analysis, we consider the harmonic–space correlations produced by Alfv\'en waves, finding no significant evidence for the presence of these waves. Together, these results comprise a comprehensive set of constraints on possible PMFs with Planck data.

“Planck data constrain the amplitude of PMFs to less than a few nanoGauss”

Models of the PMF



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

determine the model

We studied this region

$B_{1\mathrm{Mpc}}$ [nG]	n_B
0.5	0.0
0.5	-1.0
0.1	0.0
0.1	-1.0

A&A 2016, arXiv:1502.01594

Contents

- Introduction
- Calculation Methods
- Results/Discussion
- Summary

Calculation Methods

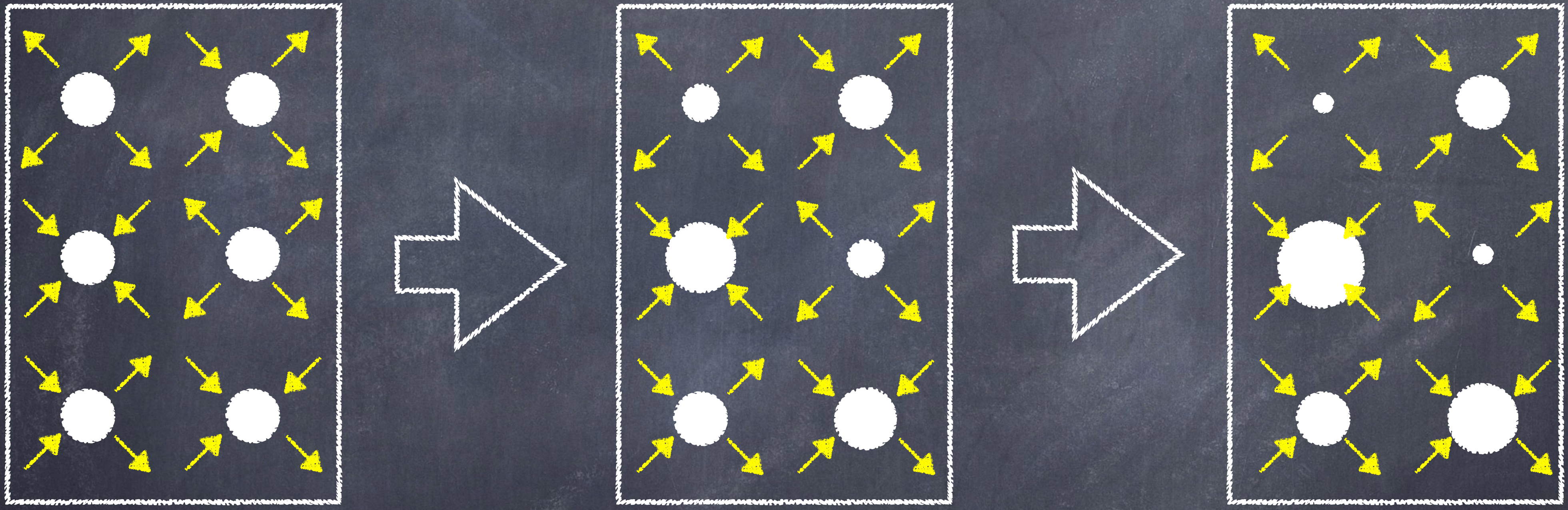
- 最終散乱面でのCMB温度揺らぎへの影響

＞　Planckの制限などで考察済み

- 晴れ上がり以降はCMBに影響？
- ガスの密度・温度・電離度の進化を変更
- 間接的にCMBで観測可能？

Density evolution

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



物質：　一様

ローレンツ力：非一様

原始磁場によって
密度揺らぎが生成

(Wasserman 1978)

inhomogeneity from PMFs

(CDM):
$$\frac{\partial^2\delta_{\mathrm{c}}}{\partial t^2}+2H(t)\frac{\partial\delta_{\mathrm{c}}}{\partial t}-4\pi G(\rho_{\mathrm{c}}\delta_{\mathrm{c}}+\rho_{\mathrm{b}}\delta_{\mathrm{b}})=0\ ,$$

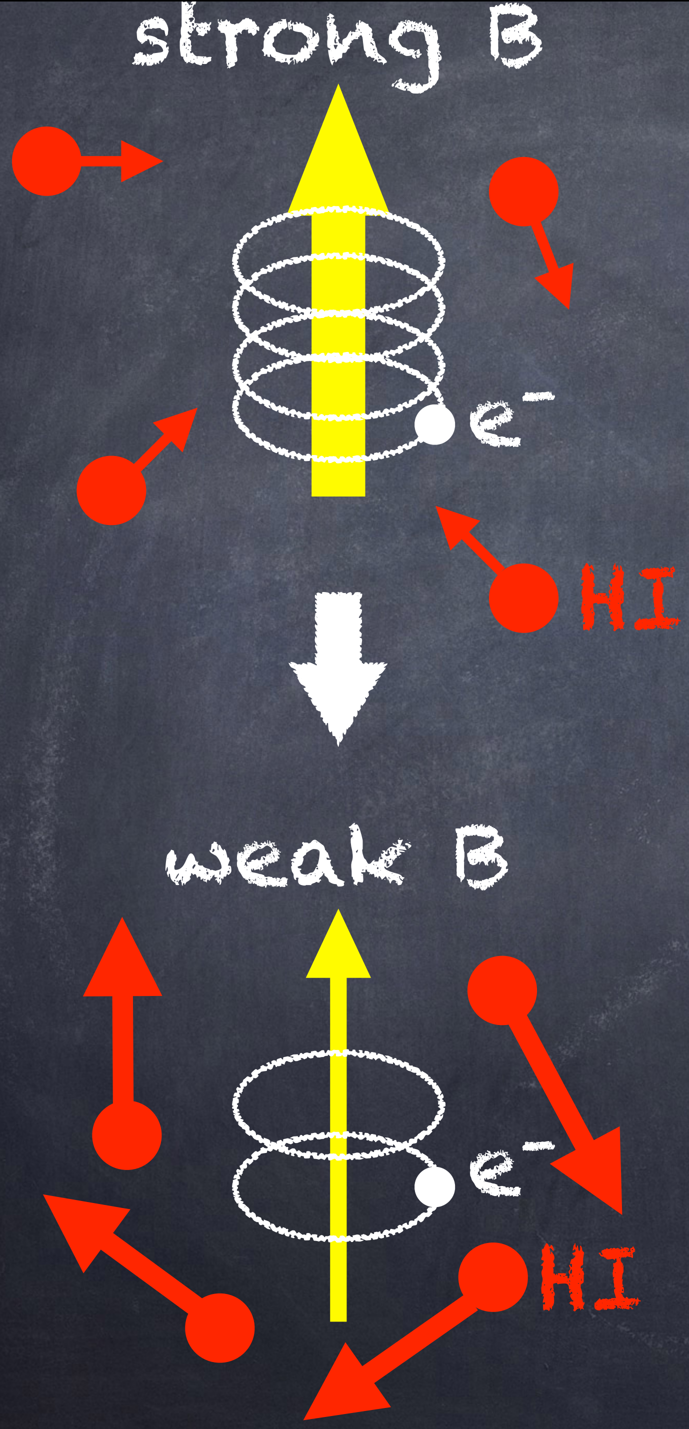
(Baryon):
$$\frac{\partial^2\delta_{\mathrm{b}}}{\partial t^2}+2H(t)\frac{\partial\delta_{\mathrm{b}}}{\partial t}-4\pi G(\rho_{\mathrm{c}}\delta_{\mathrm{c}}+\rho_{\mathrm{b}}\delta_{\mathrm{b}})=S(t)\ ,$$

$$S(t)=\frac{\nabla\cdot(\nabla\times\mathbf{B}(t,\mathbf{x}))\times\mathbf{B}(t,\mathbf{x})}{4\pi\rho_{\mathrm{b}}(t)a^2(t)}\ ,$$

$$\begin{aligned}\delta_{\mathrm{b}}=\frac{2S(t)}{15H^2(t)}\Bigg[&\left\{3\left(\frac{a}{a_{\mathrm{rec}}}\right)+2\left(\frac{a}{a_{\mathrm{rec}}}\right)^{-\frac{3}{2}}-15\ln\left(\frac{a}{a_{\mathrm{rec}}}\right)\right\}\frac{\Omega_{\mathrm{b}}}{\Omega_{\mathrm{m}}}\\&+15\ln\left(\frac{a}{a_{\mathrm{rec}}}\right)+30\left(1-\frac{\Omega_{\mathrm{b}}}{\Omega_{\mathrm{m}}}\right)\left(\frac{a}{a_{\mathrm{rec}}}\right)^{-\frac{1}{2}}-\left(30-25\frac{\Omega_{\mathrm{b}}}{\Omega_{\mathrm{m}}}\right)\Bigg]\ ,\end{aligned}$$

(Wasserman 1978)

Ambipolar diffusion



$$E_{mag} \gg E_{th}$$

$$\Downarrow$$

$$E_{mag} - \Delta E \gg E_{th} + \Delta E$$

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

ξ : drag coefficient

(Sethi & Subramanian, 2005)

Thermal history

（ガスの温度変化）

＝（宇宙膨張による断熱冷却）

＋（CMBとのCompton散乱）

＋（磁場による加熱：ambipolar diffusion）

(Sethi & Subramanian, 2005)

＋（密度揺らぎによるlocalな断熱膨張・圧縮）

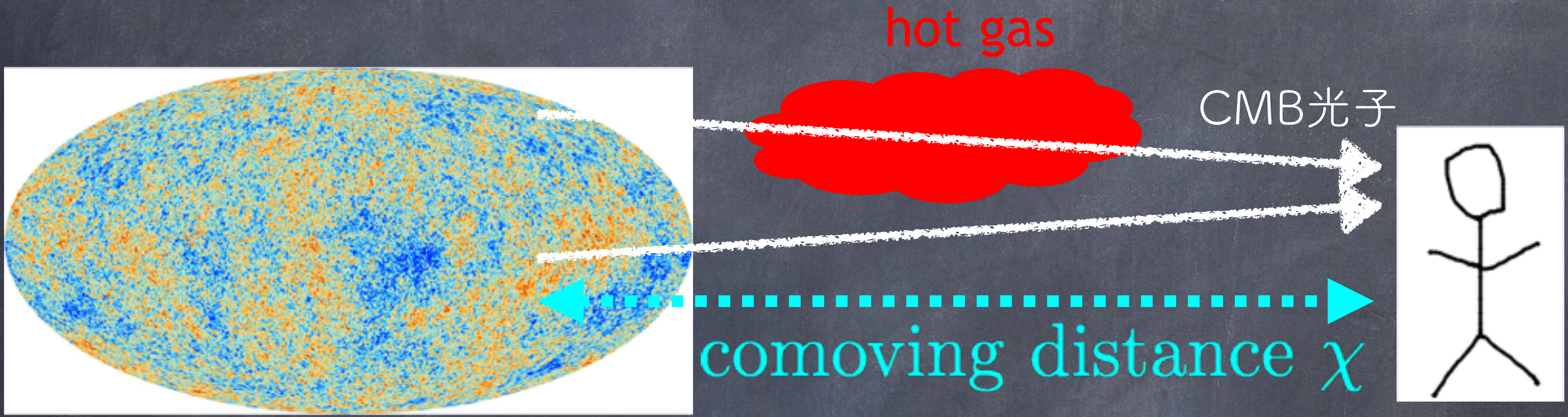
＋（free-free，衝突励起，再結合，衝突電離)

(Fukugita & Kawasaki, 1994)

Observation

- 原始磁場の存在を考慮して熱史・密度史を同時に計算　> OK.
- 観測で検証できるか?　> 熱的SZ効果

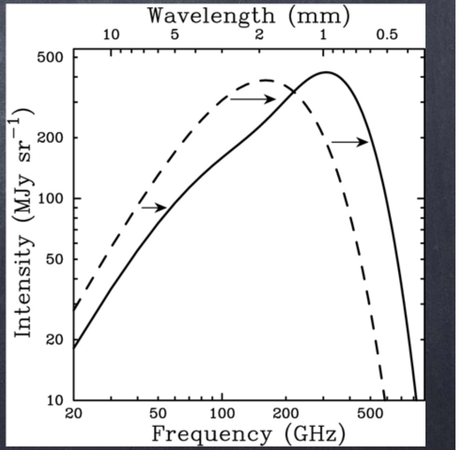
Thermal SZ effect



hot gas

CMB光子

comoving distance χ



$$y(\hat{n}) \equiv \frac{\sigma_T k_B}{m_e c^2} \int d\chi \; n_b x_{\rm ion} (T_{\rm gas} - T_\gamma)$$

$10 \lesssim z \lesssim 1100$ で $(1\ {\rm cMpc})^3$ のy-mapを作成

Calculation Methods

$$S(t) = \frac{\nabla \cdot [(\nabla \times \mathbf{B}) \times \mathbf{B}]}{4\pi \rho_b(t) a^2(t)}, \quad \Gamma(t) = \frac{|(\nabla \times \mathbf{B}) \times \mathbf{B}|^2}{16\pi^2 \xi \rho_b^2(t)} \frac{(1 - x_{\rm ion})}{x_{\rm ion}}$$

1. 数値的に原始磁場を生成
2. バリオンガスの物理量を計算
3. tSZ power spectrumを推定

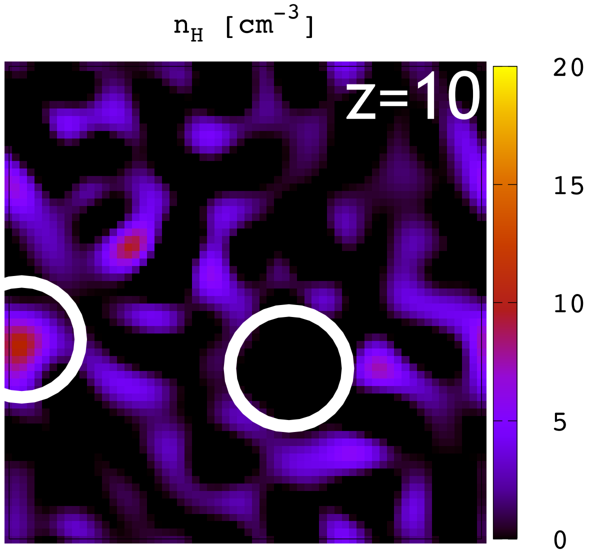
$$\left\{ \begin{array}{l} x_{\rm ion} \\ T_{\rm gas} \\ n_{\rm H} \end{array} \right.$$

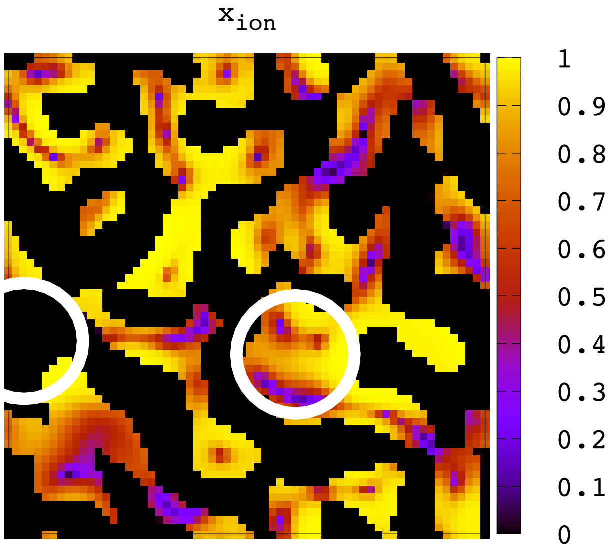
$$y(\hat{n}) \equiv \frac{\sigma_T k_B}{m_e c^2} \int d\chi \; n_b x_{\rm ion} (T_{\rm gas} - T_\gamma)$$

Contents

- Introduction
- Calculation Methods
- Results/Discussion
- Summary

Results



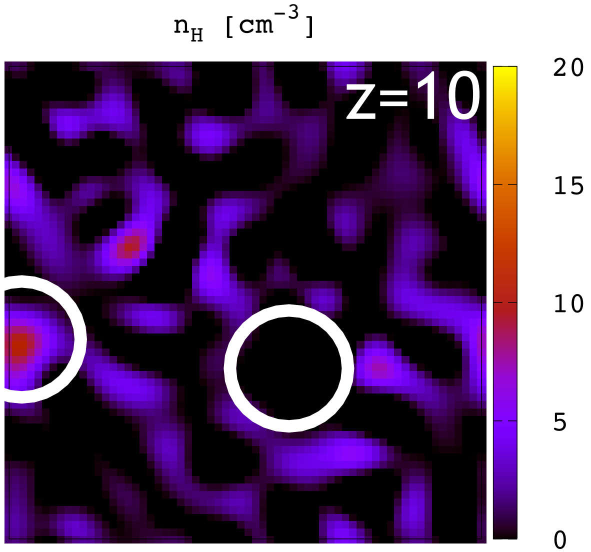


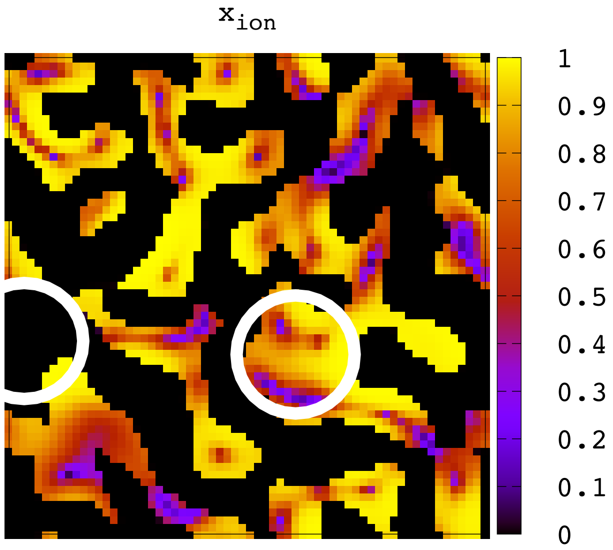
B_{1Mpc}=0.5nG, n_B=0.0
(上) バリオン数密度 [/cc], (下) 電離度

高密度＞低温度・低電離度

低密度＞高温度・高電離度

Results





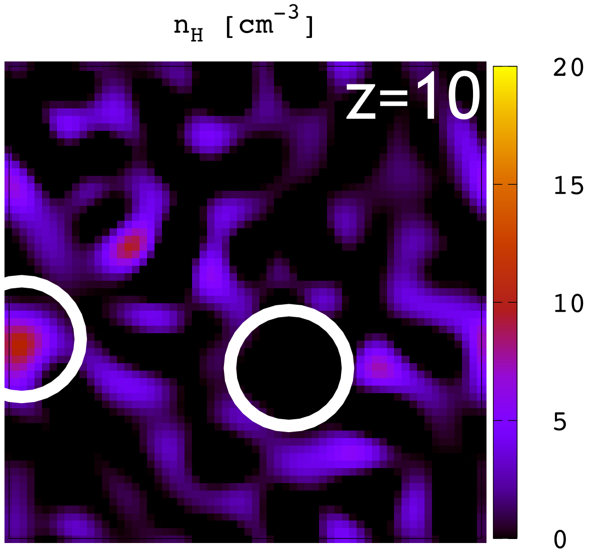
B_{1Mpc}=0.5nG, n_B=0.0
(上) バリオン数密度 [/cc], (下) 電離度

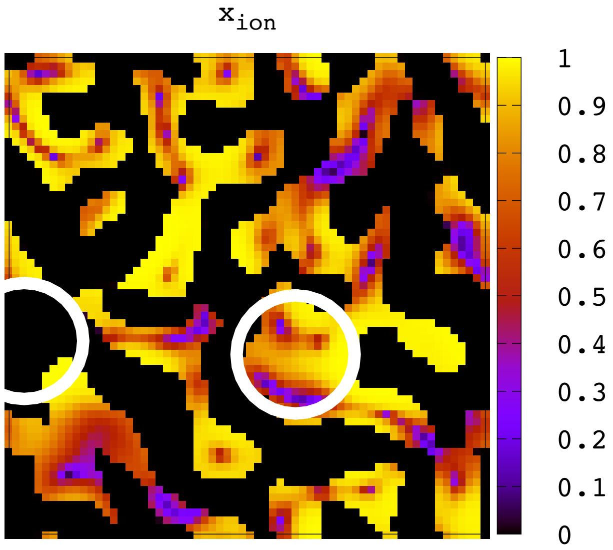
高密度＞低温度・低電離度

低密度＞高温度・高電離度

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

Results





B_{1Mpc}=0.5nG, n_B=0.0
(上) バリオン数密度 [/cc], (下) 電離度

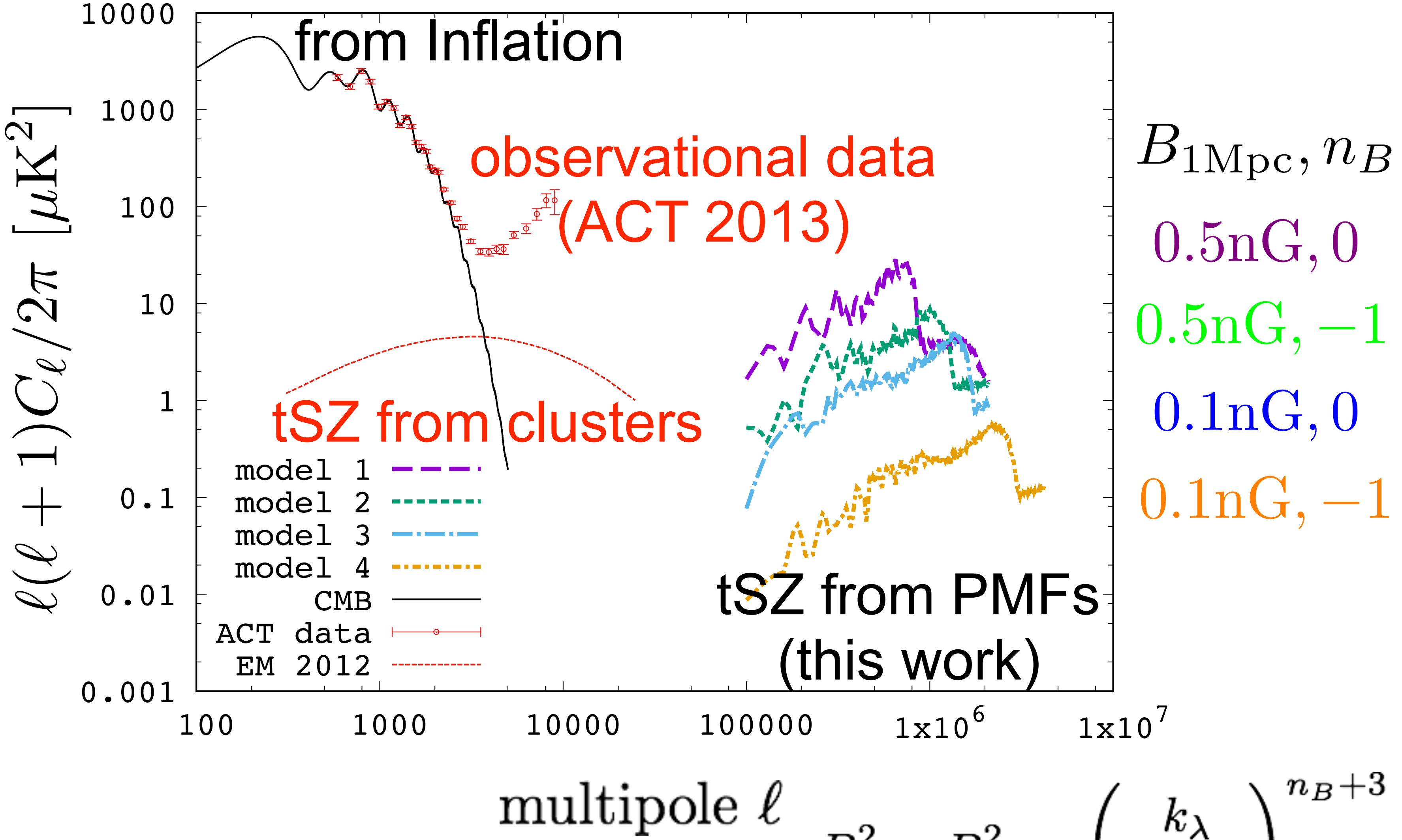
高密度＞低温度・低電離度

低密度＞高温度・高電離度

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

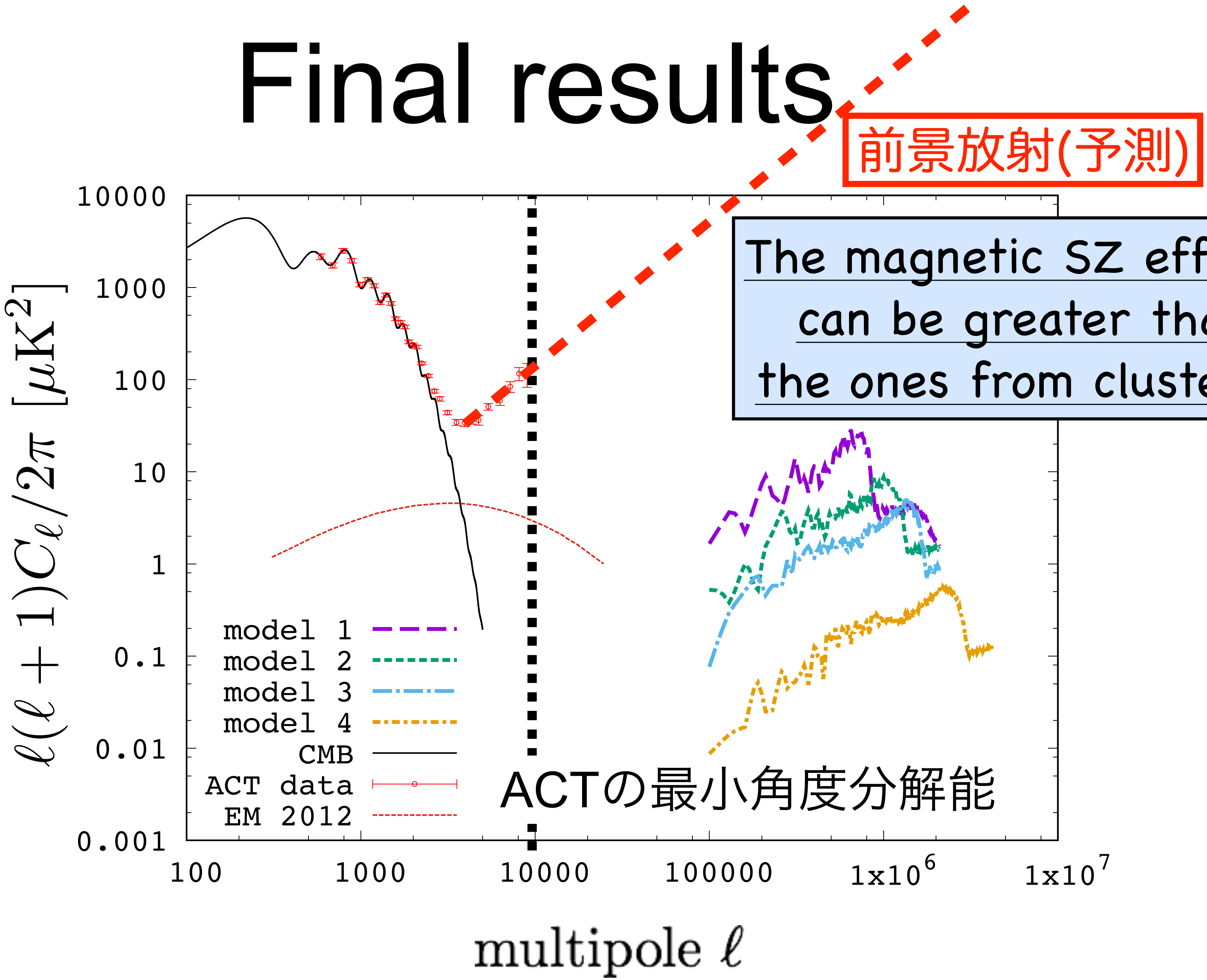
ボイド領域におけるSZ効果

Final results



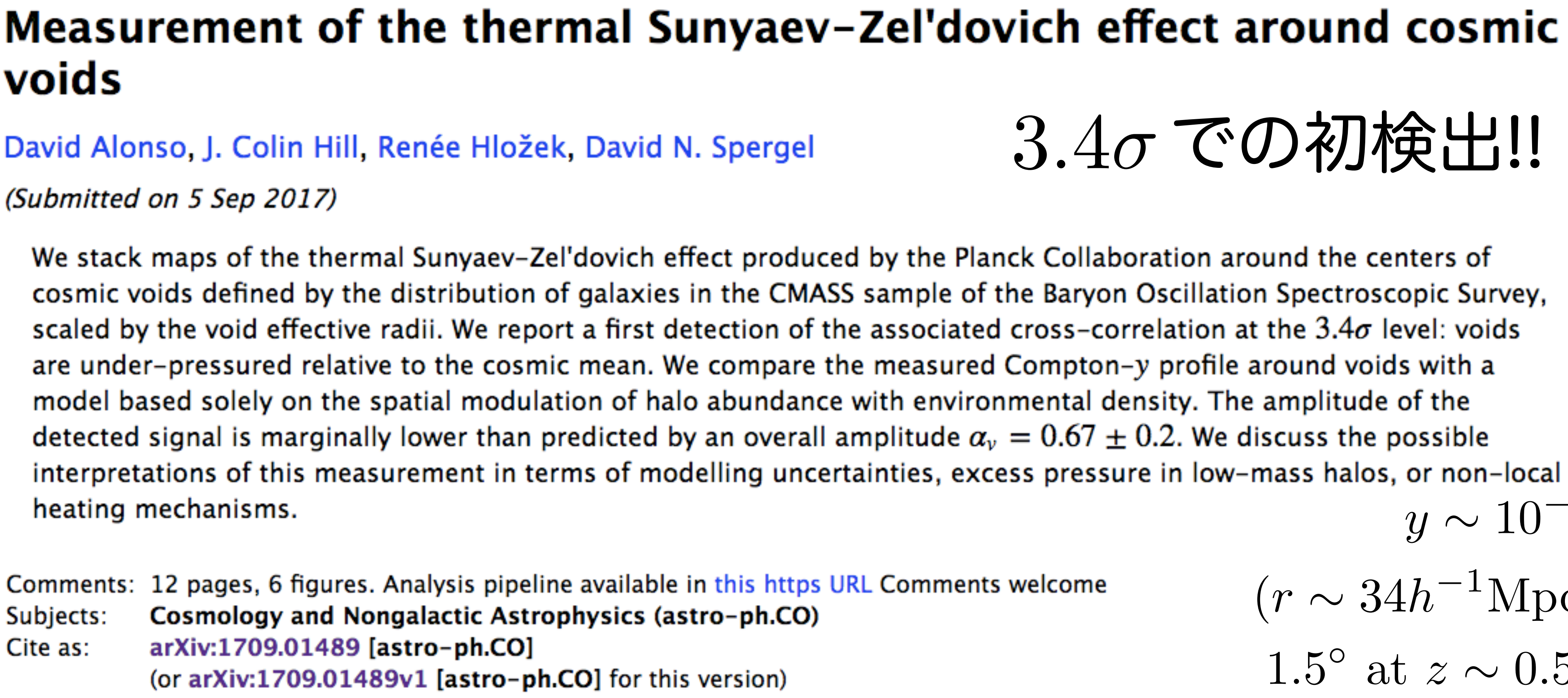
$$B_\lambda^2 = B_{1\mathrm{Mpc}}^2 \left(\frac{k_\lambda}{k_{1\mathrm{Mpc}}}\right)^{n_B+3}$$

Final results



The magnetic SZ effects
can be greater than
the ones from clusters!!

Suggestion for Our Theory??



Measurement of the thermal Sunyaev-Zel'dovich effect around cosmic voids

David Alonso, J. Colin Hill, Renée Hložek, David N. Spergel

(Submitted on 5 Sep 2017)

We stack maps of the thermal Sunyaev-Zel'dovich effect produced by the Planck Collaboration around the centers of cosmic voids defined by the distribution of galaxies in the CMASS sample of the Baryon Oscillation Spectroscopic Survey, scaled by the void effective radii. We report a first detection of the associated cross-correlation at the 3.4σ level: voids are under-pressured relative to the cosmic mean. We compare the measured Compton-y profile around voids with a model based solely on the spatial modulation of halo abundance with environmental density. The amplitude of the detected signal is marginally lower than predicted by an overall amplitude $\alpha_v = 0.67 \pm 0.2$. We discuss the possible interpretations of this measurement in terms of modelling uncertainties, excess pressure in low-mass halos, or non-local heating mechanisms.

Comments: 12 pages, 6 figures. Analysis pipeline available in this https URL Comments welcome
Subjects: **Cosmology and Nongalactic Astrophysics (astro-ph.CO)**
Cite as: **arXiv:1709.01489 [astro-ph.CO]**
(or **arXiv:1709.01489v1 [astro-ph.CO]** for this version)

3.4σ での初検出!!

$y \sim 10^{-8}$

$(r \sim 34h^{-1}\mathrm{Mpc},$
1.5° at $z \sim 0.5)$

Summary

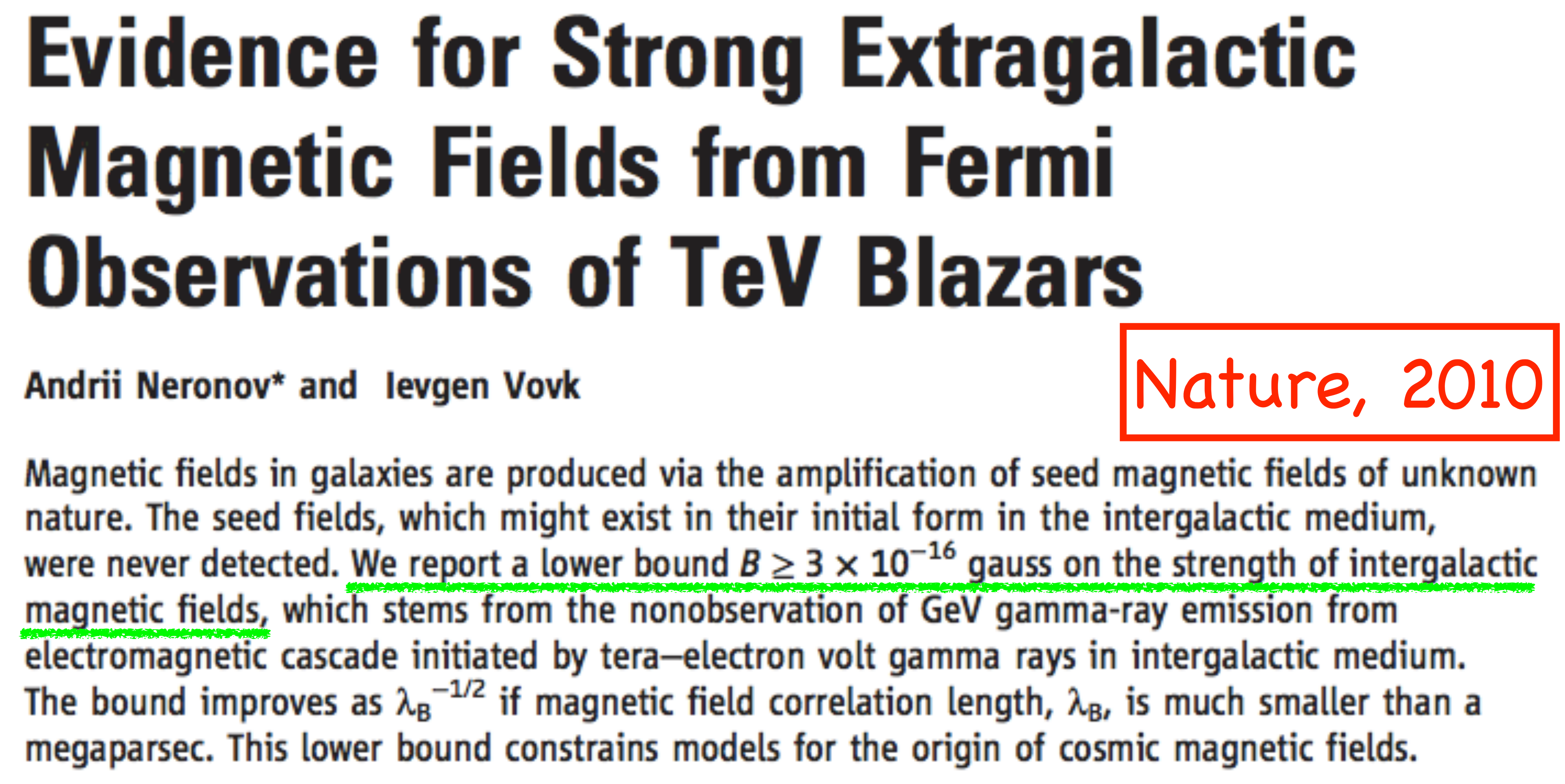
- 単一べきの原始磁場による暗黒時代のガス密度・温度・電離度への影響を計算
- 高赤方偏移(z~200)において銀河サイズのIGMが熱的SZ効果を誘発
- Planckで棄却されていないsub-nG程度の原始磁場を検証可能

T. Minoda et al., (2017) arXiv:1705.10054

END

Thank you for listening !

existence of extragalactic magnetic fields ?



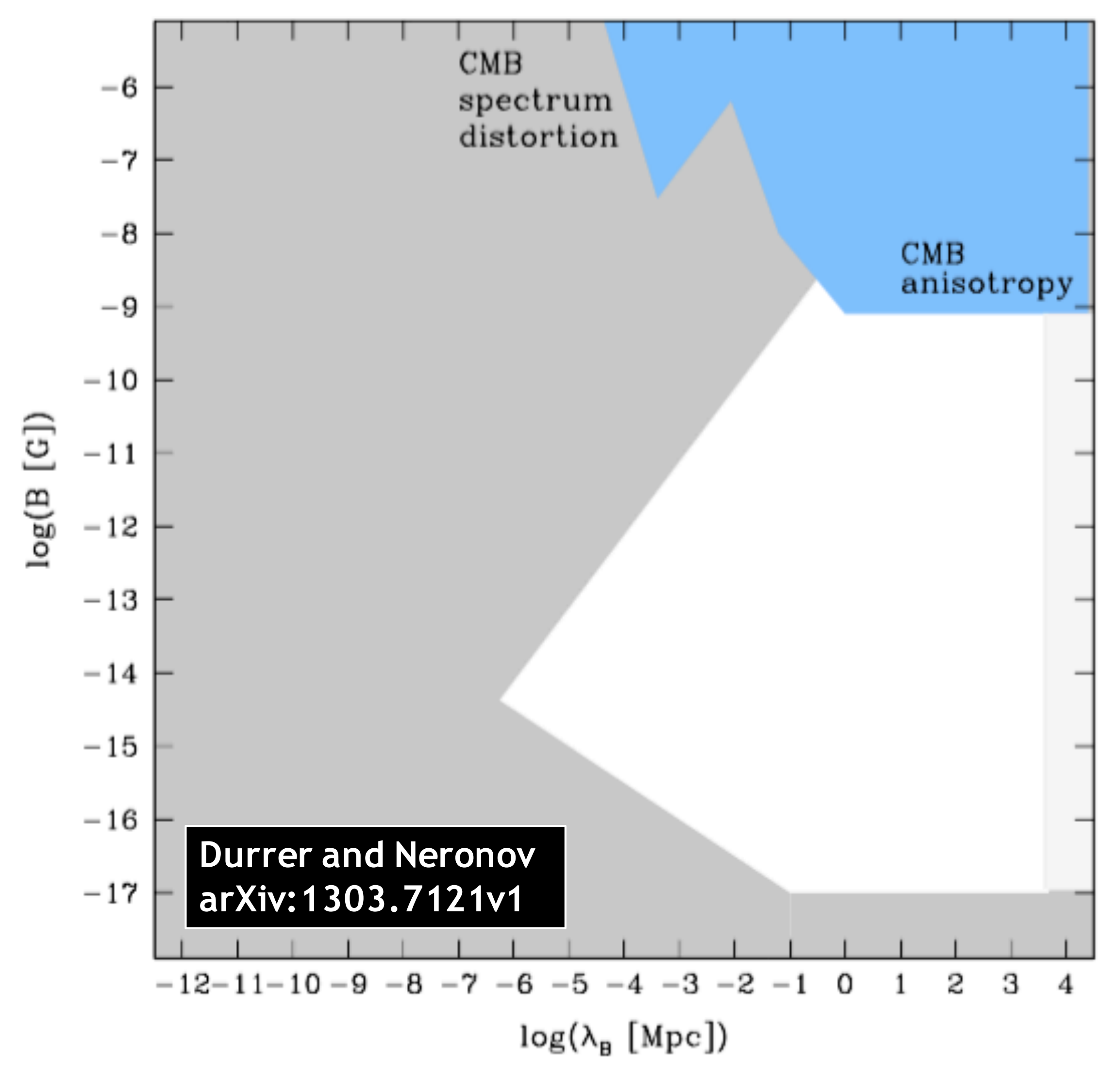
Evidence for Strong Extragalactic Magnetic Fields from Fermi Observations of TeV Blazars

Andrii Neronov* and Ievgen Vovk

Nature, 2010

Magnetic fields in galaxies are produced via the amplification of seed magnetic fields of unknown nature. The seed fields, which might exist in their initial form in the intergalactic medium, were never detected. We report a lower bound $B \geq 3 \times 10^{-16}$ gauss on the strength of intergalactic magnetic fields, which stems from the nonobservation of GeV gamma-ray emission from electromagnetic cascade initiated by tera–electron volt gamma rays in intergalactic medium. The bound improves as $\lambda_B^{-1/2}$ if magnetic field correlation length, λ_B, is much smaller than a megaparsec. This lower bound constrains models for the origin of cosmic magnetic fields.

Constraint on PMFs



Durrer and Neronov
arXiv:1303.7121v1

cut-off of PMFs

the smallest (cut-off) scale of PMFs is due to the photon dissipation before the recombination.

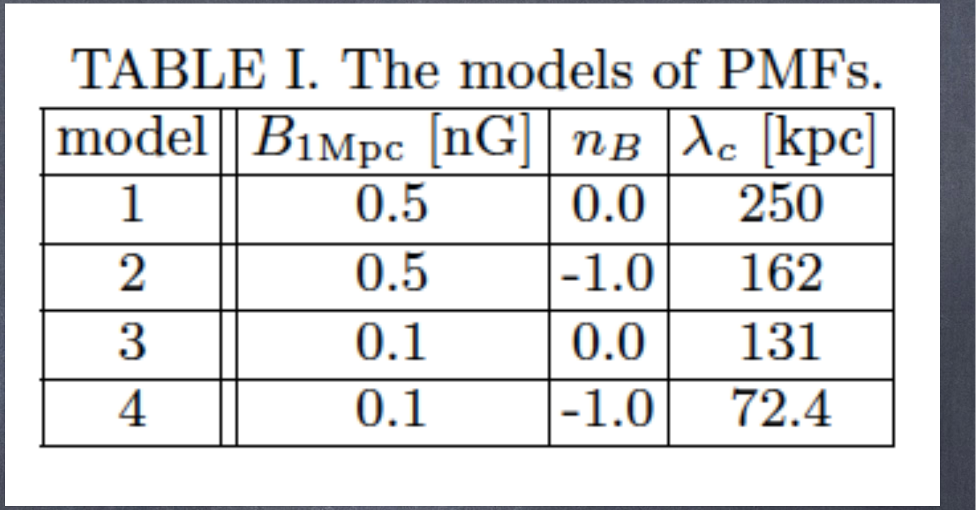


TABLE I. The models of PMFs.

model	$B_{1\mathrm{Mpc}}$ [nG]	n_B	λ_c [kpc]
1	0.5	0.0	250
2	0.5	-1.0	162
3	0.1	0.0	131
4	0.1	-1.0	72.4

$$k_{\max}^{-2} = \left(\frac{\lambda_{\max}}{2\pi}\right)^2 = V_A^2 \int_0^{t_r} \frac{l_\gamma(t)}{a^2(t)} dt$$

inhomogeneity from PMFs

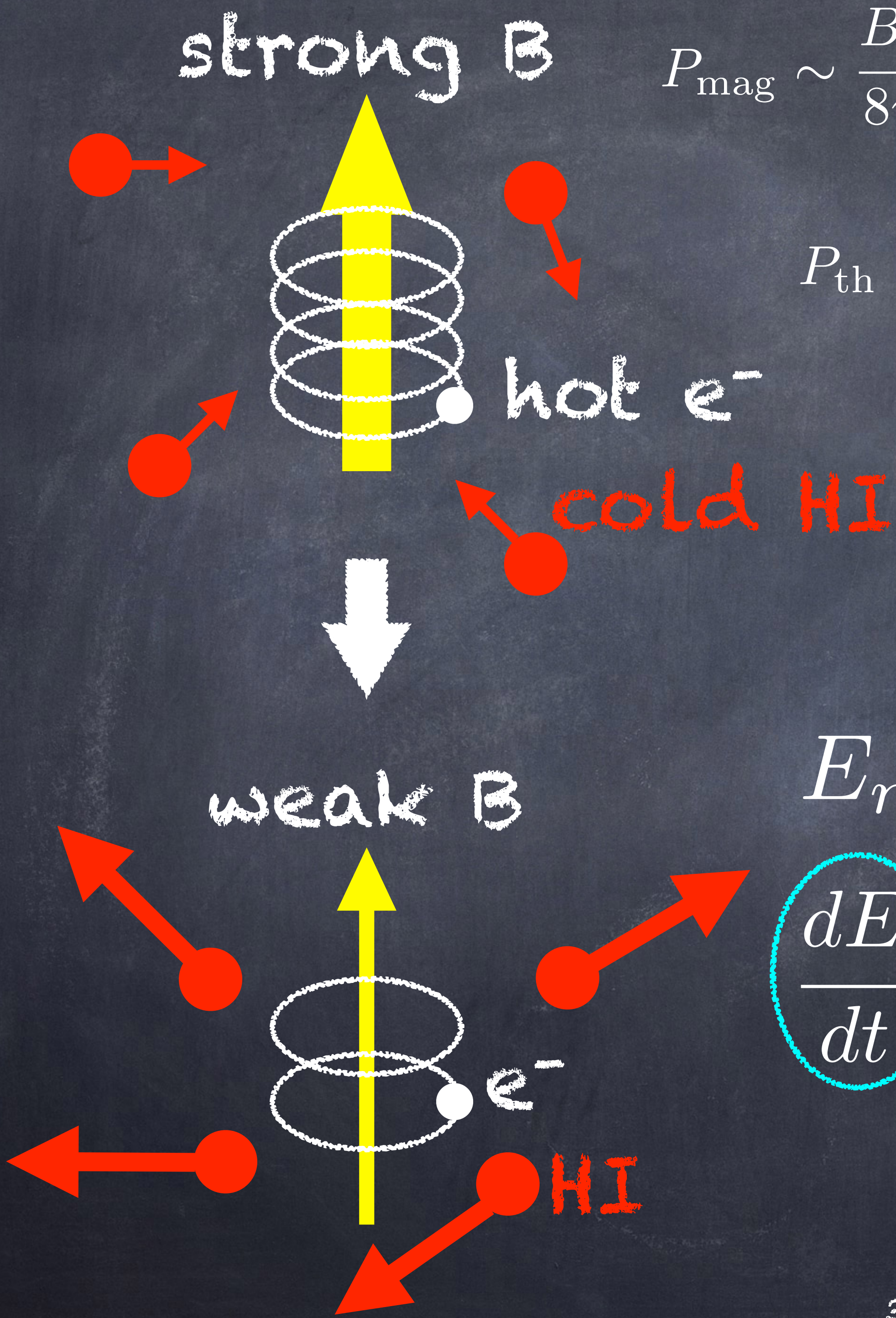
(CDM): $$\frac{\partial^2 \delta_{\rm c}}{\partial t^2} + 2H(t)\frac{\partial \delta_{\rm c}}{\partial t} - 4\pi G(\rho_{\rm c}\delta_{\rm c} + \rho_{\rm b}\delta_{\rm b}) = 0\ ,$$

(Baryon): $$\frac{\partial^2 \delta_{\rm b}}{\partial t^2} + 2H(t)\frac{\partial \delta_{\rm b}}{\partial t} - 4\pi G(\rho_{\rm c}\delta_{\rm c} + \rho_{\rm b}\delta_{\rm b}) = S(t)\ ,$$

$$S(t) = \frac{\nabla\cdot(\nabla\times\mathbf{B}(t,\mathbf{x}))\times\mathbf{B}(t,\mathbf{x})}{4\pi\rho_{\rm b}(t)a^2(t)}\ ,$$

$$\delta_{\rm b} = \frac{2S(t)}{15H^2(t)}\left[\left\{3\left(\frac{a}{a_{\rm rec}}\right) + 2\left(\frac{a}{a_{\rm rec}}\right)^{-\frac{3}{2}} - 15\ln\left(\frac{a}{a_{\rm rec}}\right)\right\}\frac{\Omega_{\rm b}}{\Omega_{\rm m}} \right.$$
$$\left. + 15\ln\left(\frac{a}{a_{\rm rec}}\right) + 30\left(1-\frac{\Omega_{\rm b}}{\Omega_{\rm m}}\right)\left(\frac{a}{a_{\rm rec}}\right)^{-\frac{1}{2}} - \left(30 - 25\frac{\Omega_{\rm b}}{\Omega_{\rm m}}\right)\right]\ ,$$

(Wasserman 1978)



$$P_{\rm mag} \sim \frac{B^2}{8\pi} \sim 10^{-7}\left(\frac{B}{1.0{\rm nG}}\right)^2\left(\frac{1+z}{1000}\right)^4 \ [{\rm erg/cc}]$$

$$P_{\rm th} \sim n_{\rm H} k_{\rm B} T_{\rm gas} \sim 10^{-10}\left(\frac{1+z}{1000}\right)^4 \ [{\rm erg/cc}]$$

$$E_{mag} \gg E_{th}$$

$$\Big\downarrow$$

$$E_{mag} - \boxed{\Delta E} \gg E_{th} + \boxed{\Delta E}$$

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

ξ : drag coefficient

(Sethi & Subramanian, 2005)

Thermal history

cosmic expansion

local expansion/compression

magnetic heating

Compton scattering

$$\frac{dT_{\rm gas}}{dt} = -2H(t)T_{\rm gas} + \frac{\dot{\delta}_{\rm b}}{1+\delta_{\rm b}}T_{\rm gas} + \frac{x_{\rm i}}{1+x_{\rm i}}\frac{8\rho_\gamma\sigma_{\rm T}}{3m_{\rm e}c}(T_\gamma - T_{\rm gas}) + \frac{\Gamma(t)}{1.5k_{\rm B}n_{\rm b}} - \frac{x_{\rm i}n_{\rm b}}{1.5k_{\rm B}}[\Theta x_{\rm i} + \Psi(1-x_{\rm i}) + \eta x_{\rm i} + \zeta(1-x_{\rm i})] \ ,$$

free-free

recombination

collisional excitation

collisional ionization

(Sethi & Subramanian, 2005)

+ (Fukugita & Kawasaki, 1994)

recombination photo-ionization

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

collisional ionization

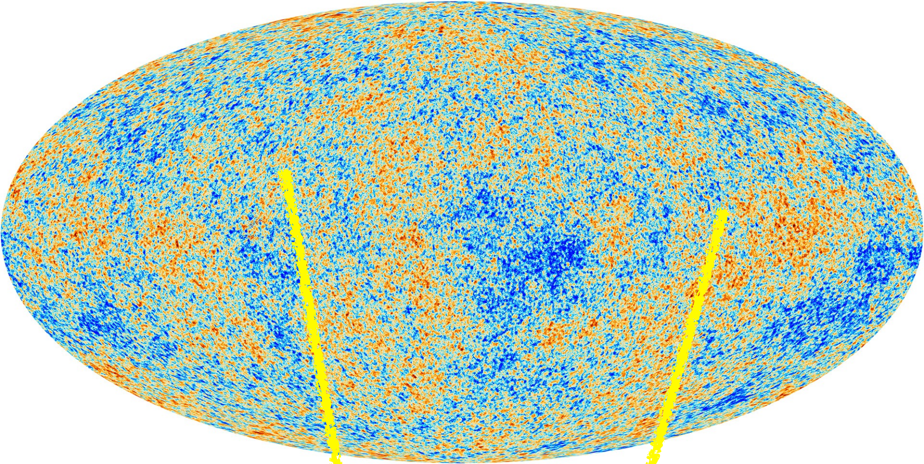
$$D = \frac{1 + K \Lambda n_{\rm b} (1 - x_{\rm i})}{1 + K \Lambda n_{\rm b} (1 - x_{\rm i}) + K \beta_e (1 - x_{\rm i})} \ ,$$

K = Lyαの赤方偏移率

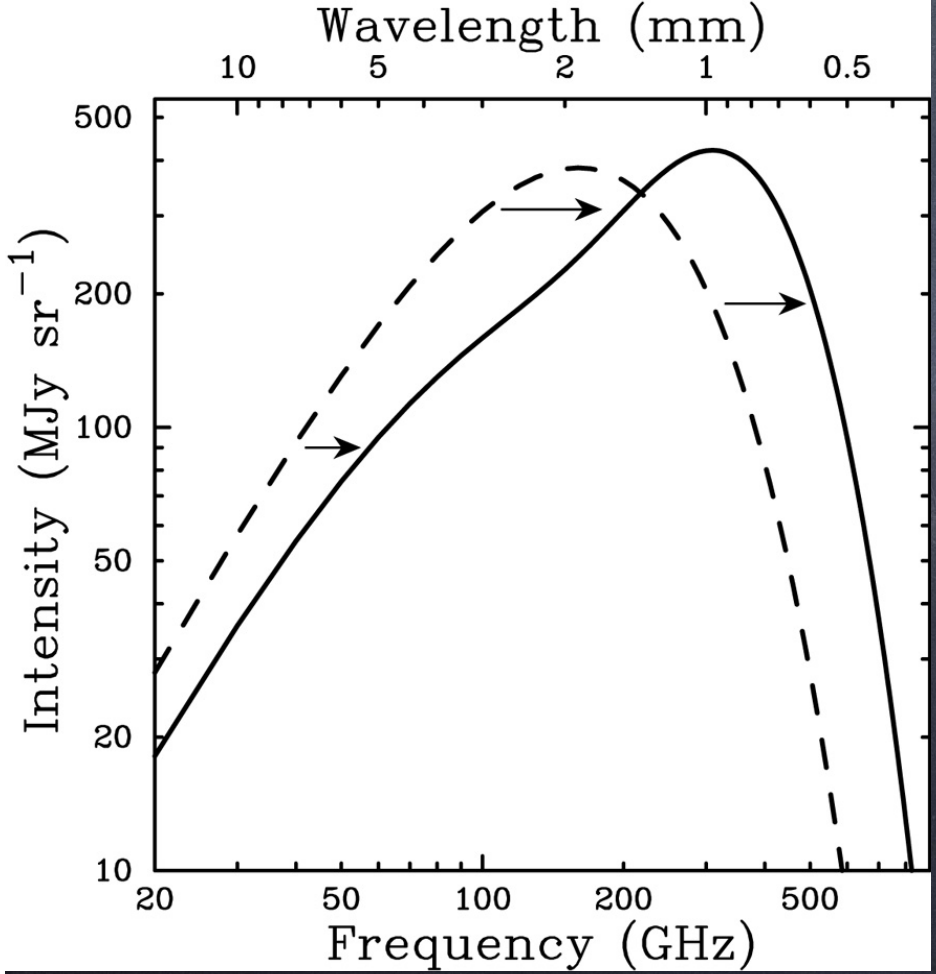
Λ = 二光子放射係数

(Sethi & Subramanian, 2005)

(c) ESA and the Planck Collaboration



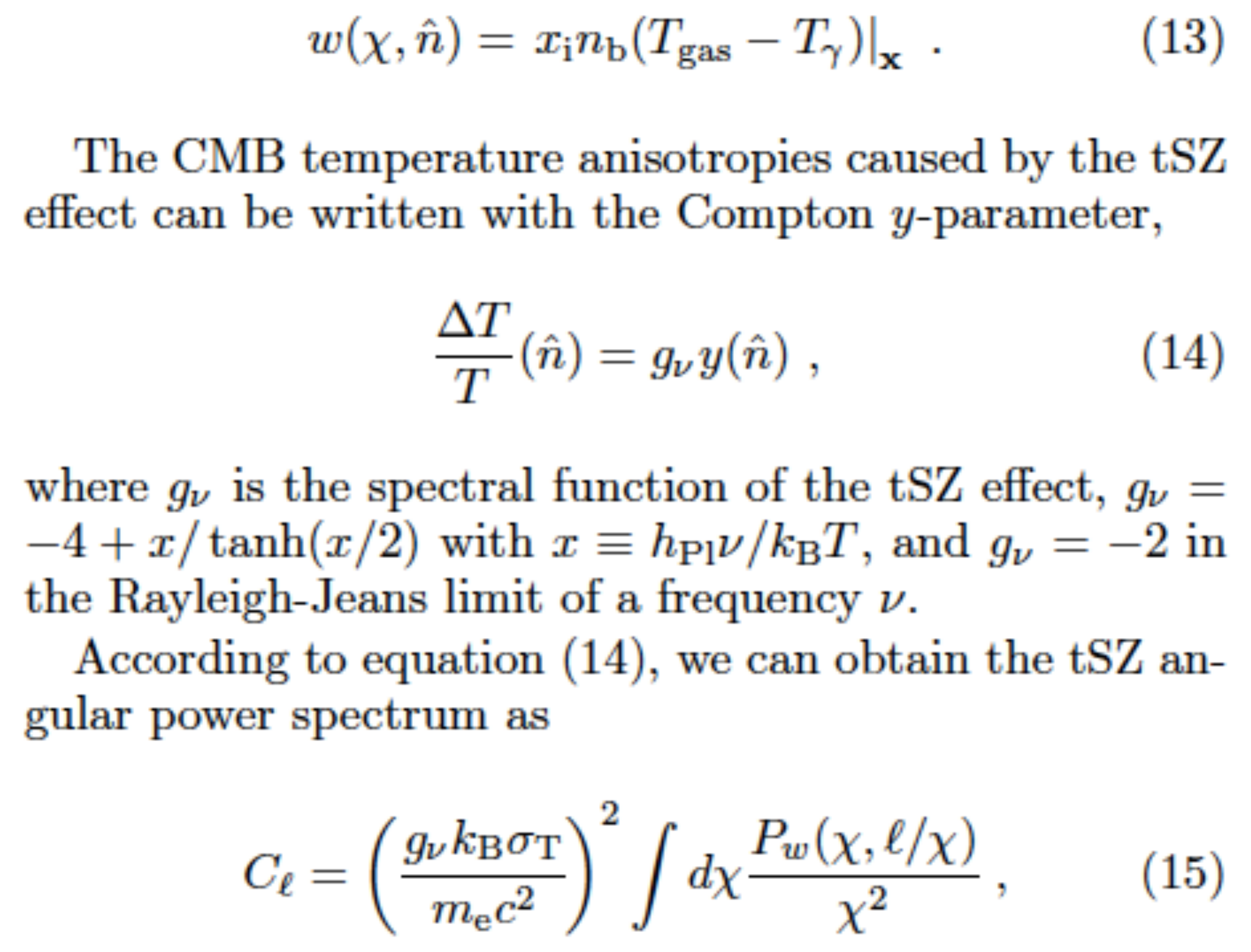
(c) Carlstrom et al., 2002



thermal SZ effect

The spectrum of CMB photons is distorted by inverse-Compton scattering

tSZ angular power spectrum



$$w(\chi, \hat{n}) = x_{\mathrm{i}} n_{\mathrm{b}} (T_{\mathrm{gas}} - T_{\gamma})|_{\mathbf{x}} \ . \tag{13}$$

The CMB temperature anisotropies caused by the tSZ effect can be written with the Compton y-parameter,

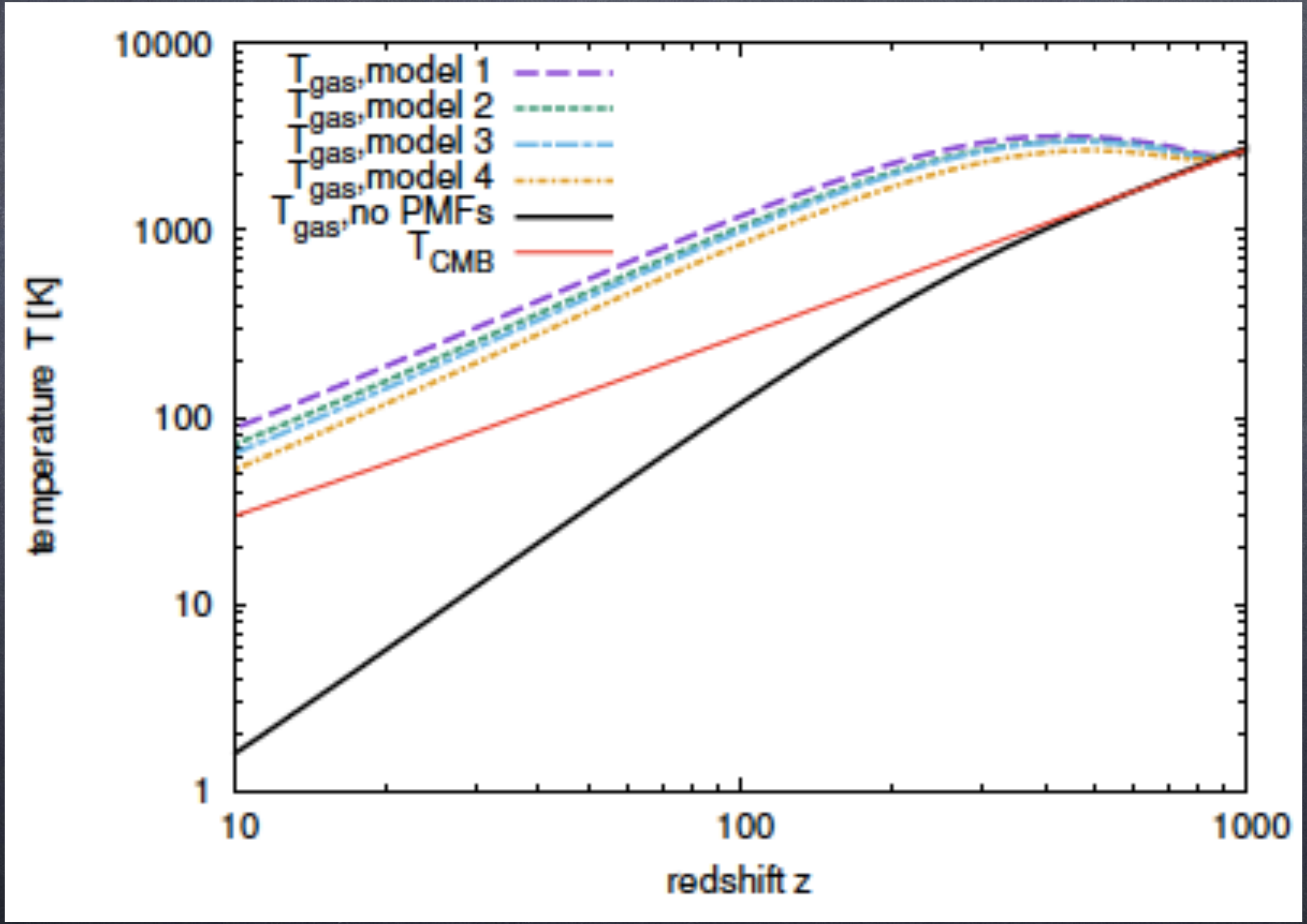
$$\frac{\Delta T}{T}(\hat{n}) = g_{\nu} y(\hat{n}) \ , \tag{14}$$

where g_ν is the spectral function of the tSZ effect, $g_\nu = -4 + x/\tanh(x/2)$ with $x \equiv h_{\mathrm{Pl}}\nu/k_{\mathrm{B}}T$, and $g_\nu = -2$ in the Rayleigh-Jeans limit of a frequency ν.

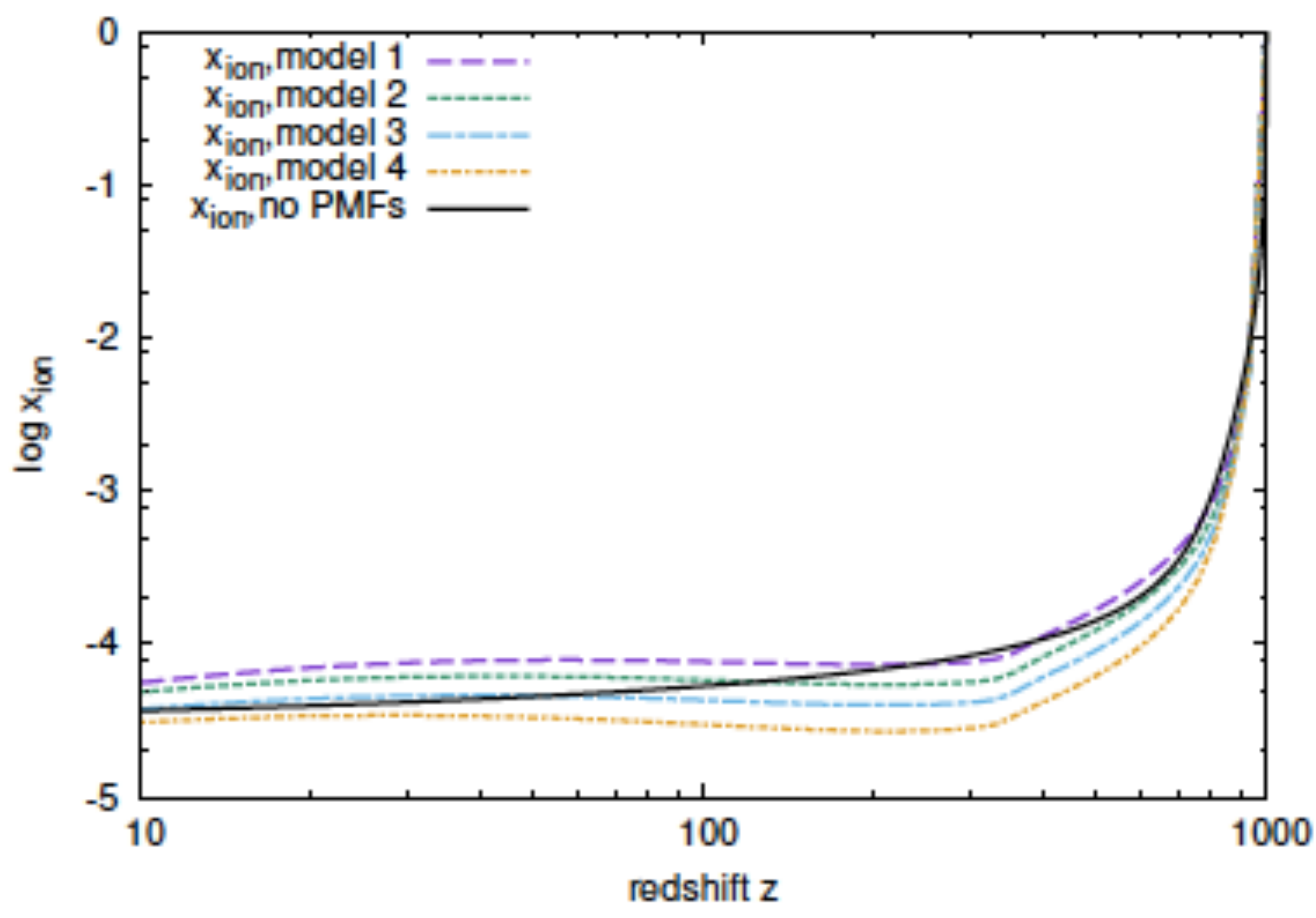
According to equation (14), we can obtain the tSZ angular power spectrum as

$$C_{\ell} = \left(\frac{g_{\nu} k_{\mathrm{B}} \sigma_{\mathrm{T}}}{m_{\mathrm{e}} c^2}\right)^2 \int d\chi \frac{P_w(\chi, \ell/\chi)}{\chi^2} \ , \tag{15}$$

T_gas averaged by unit mass



x_ion averaged by unit mass



Future prospects

- calculate density and temperature in detail (non linear evolution)
- back reaction to magnetic fields
- => MHD simulation (with RAMSES)
- energy-conservation problem