4th Korea-Japan joint workshop on Dark Energy at KMI

# Thermal SZ effect in the IGM from the primordial magnetic fields

29th. Aug. 2017,

Teppei Minoda

(collaborators)

K. Hasegawa, H. Tashiro, K. Ichiki, & N. Sugiyama

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- Introduction
- Calculation Methods
- Results/Discussion
- Summary

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

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# Introduction

## What is the origin of the cosmic magnetic fields?

- the primordial magnetic fields?

**NEED OBSERVATIONAL TESTS.**

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

# 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)

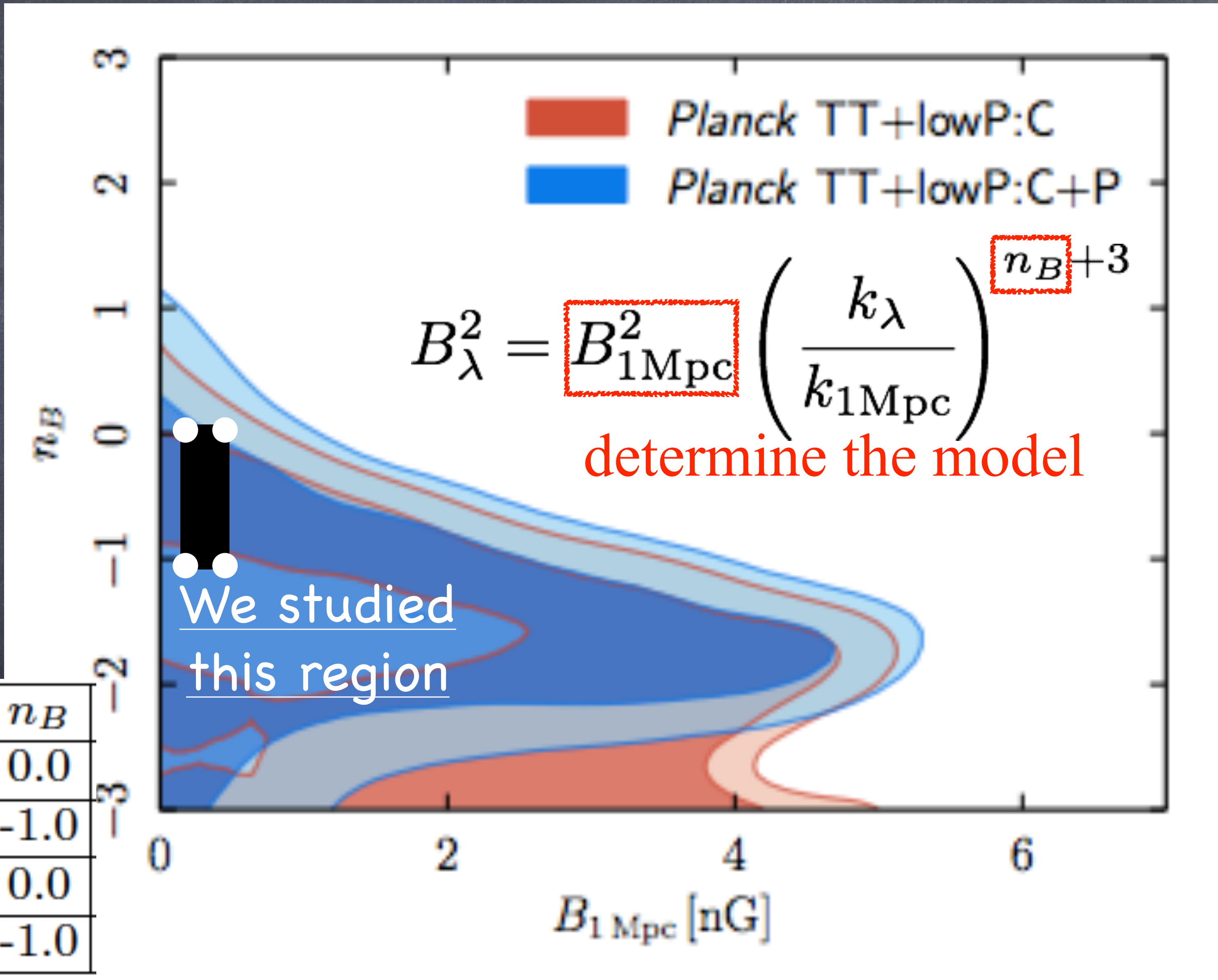
**A&A 2016, arXiv:1502.01594**

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

**"Planck data constrain the amplitude of PMFs to less than a few nanogauss"**

We compute and in … fields (PMFs) on the
cosmic microwave … on CMB
polarization induce… induced non-
Gaussianities; and … strain the amplitude
of PMFs to less than … CMB angular power
spectra, using the P… de at a scale of 1
Mpc) at 95% confide… ld.For nearly scale-
invariant PMFs we … n history of the
Universe is included… 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.

# Models of the PMF




| $B_{1\mathrm{Mpc}}$ [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

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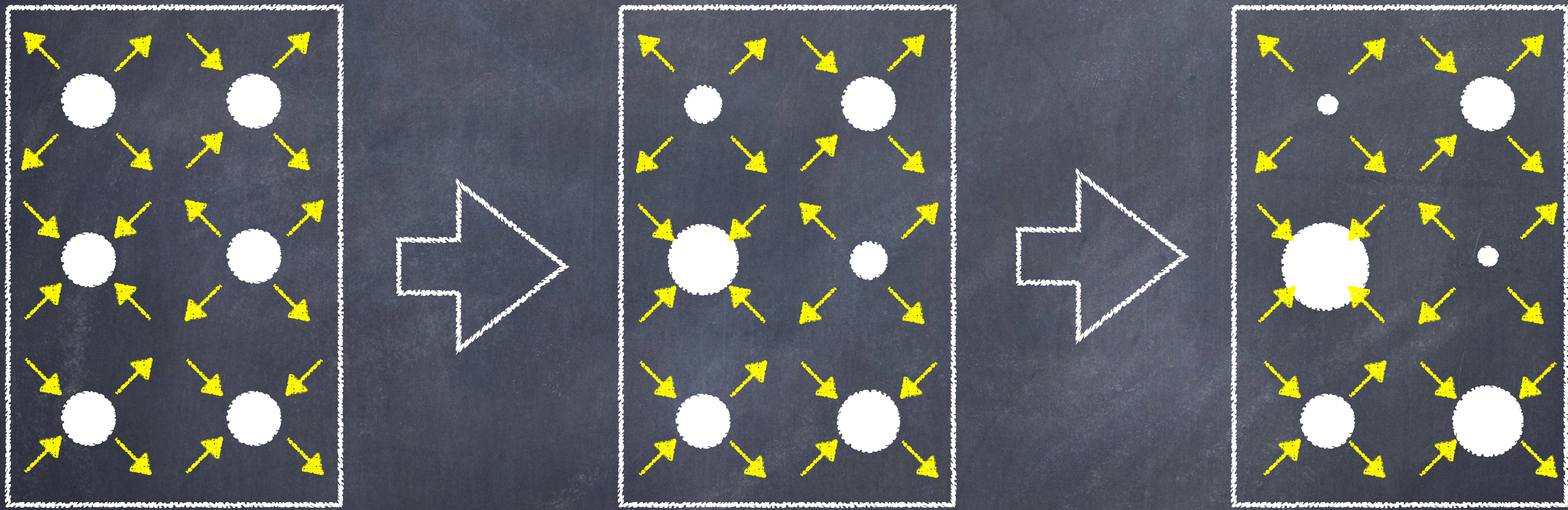
# Density evolution

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



matter:

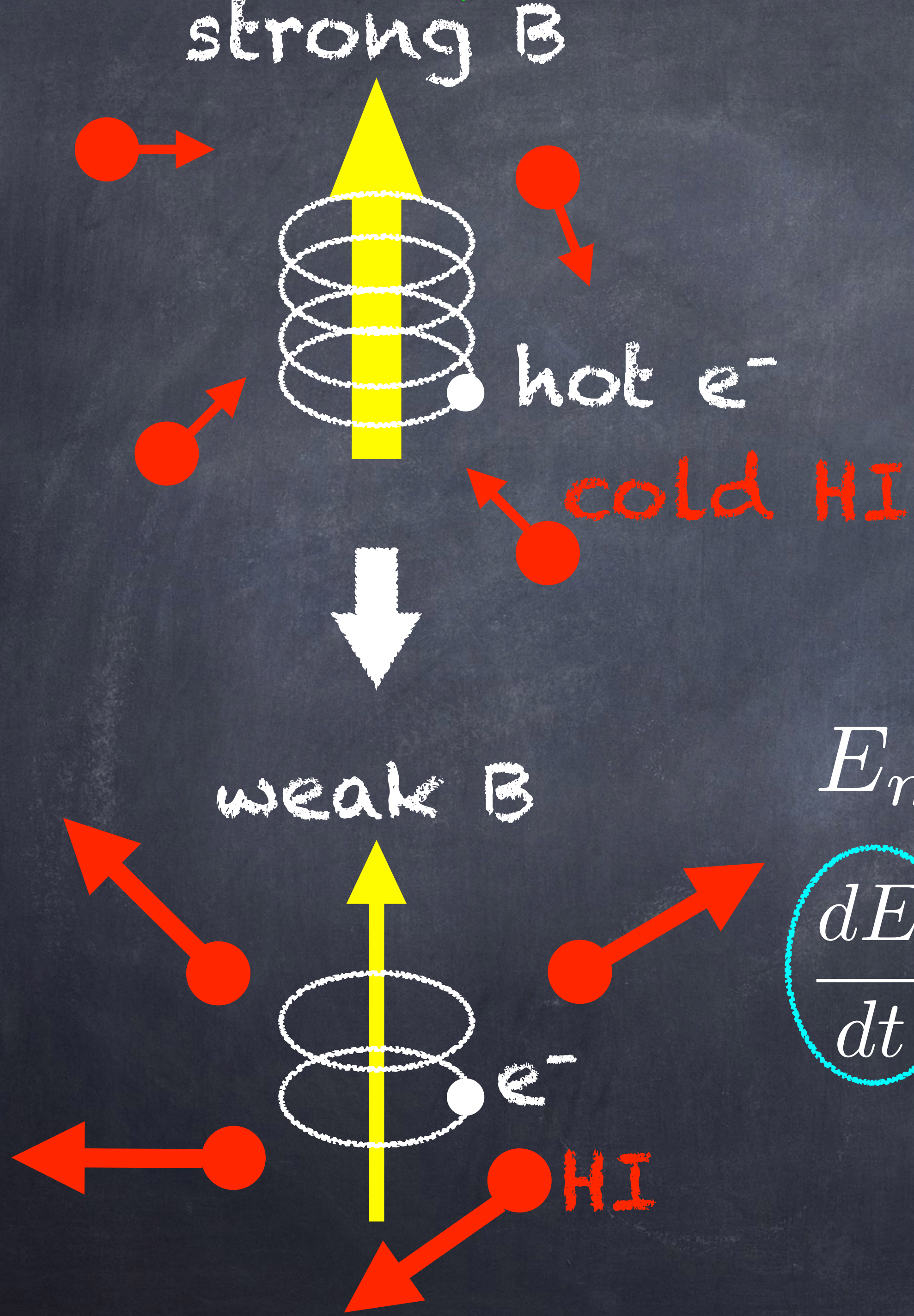
uniform

Lorentz force:

inhomogeneous

density fluctuations
are generated by PMFs !

(Wasserman 1978)




# Ambipolar diffusion

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

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

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

$\xi$ : drag coefficient

(Sethi & Subramanian, 2005)

# Thermal history

(variation of the gas temperature)

= (cosmic expansion)

+ (Compton scattering with CMB)

+ (magnetic heating via ambipolar diffusion)

**Sethi & Subramanian, 2005**

+ (local expansion/compression)

+ (free-free, collisional excitation,
  recombination, and collisional ionization)

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

# Observation

We consistently calculated

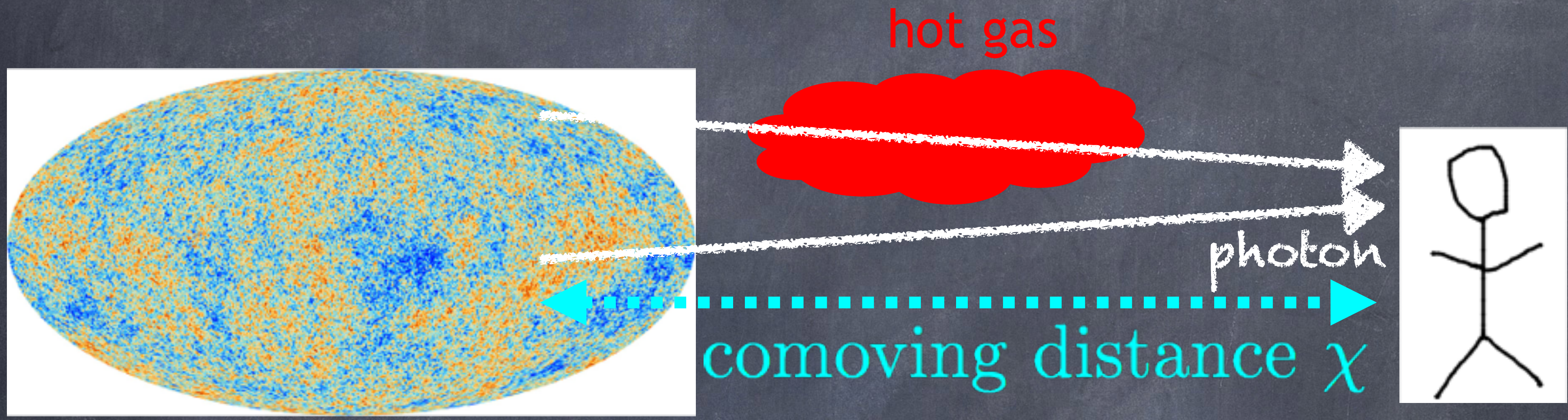
thermal history & density evolution

- Can we observe these effects?

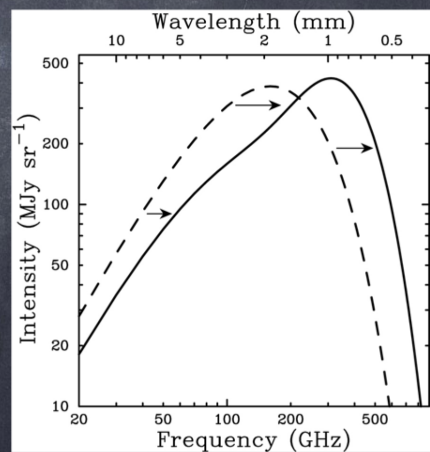
  > thermal SZ effect

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

# Thermal SZ effect




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

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# 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. Numerically generate PMFs
2. Calculate the physical quantities $\begin{cases} x_{\rm ion} \\ T_{\rm gas} \\ n_{\rm H} \end{cases}$
3. Estimate the tSZ power spectrum

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

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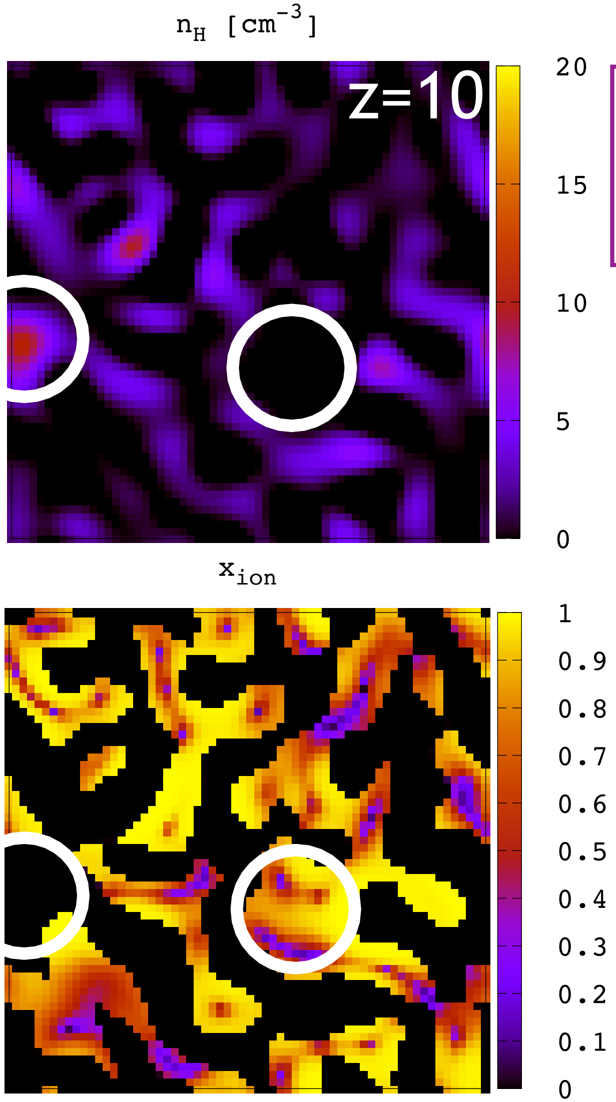
# Result



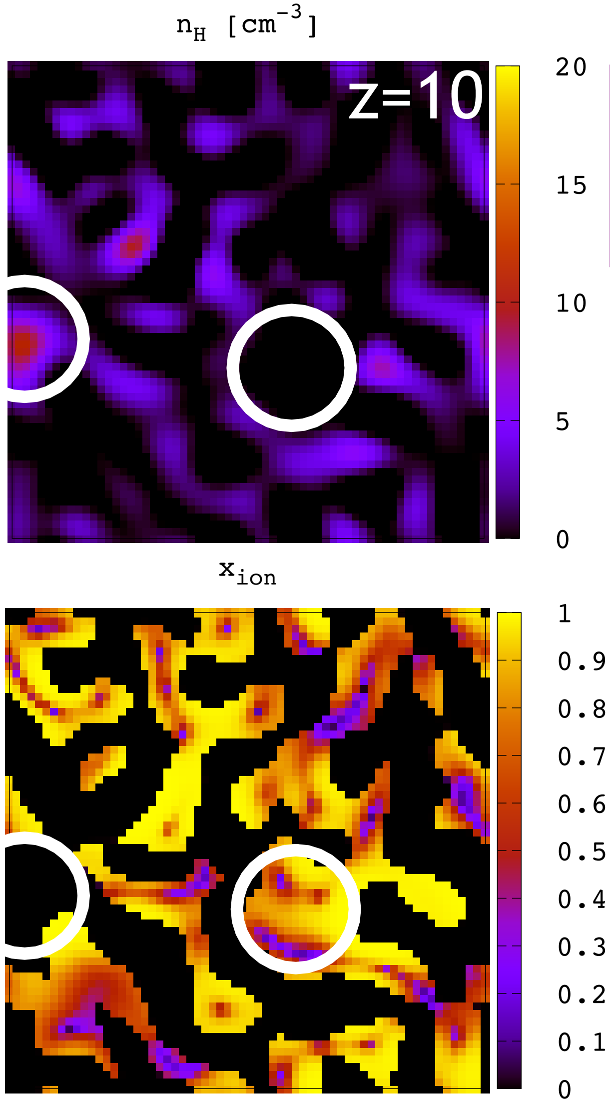

B_{1Mpc}=0.5nG, n_B=0.0
(t) baryon number density [/cc], (b) ion rate

large $n_{\rm H}$ > small $T_{\rm gas}$ and $x_{\rm ion}$

small $n_{\rm H}$ > large $T_{\rm gas}$ and $x_{\rm ion}$

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

# Result




B_{1Mpc}=0.5nG, n_B=0.0

(t) baryon number density [/cc], (b) ion rate

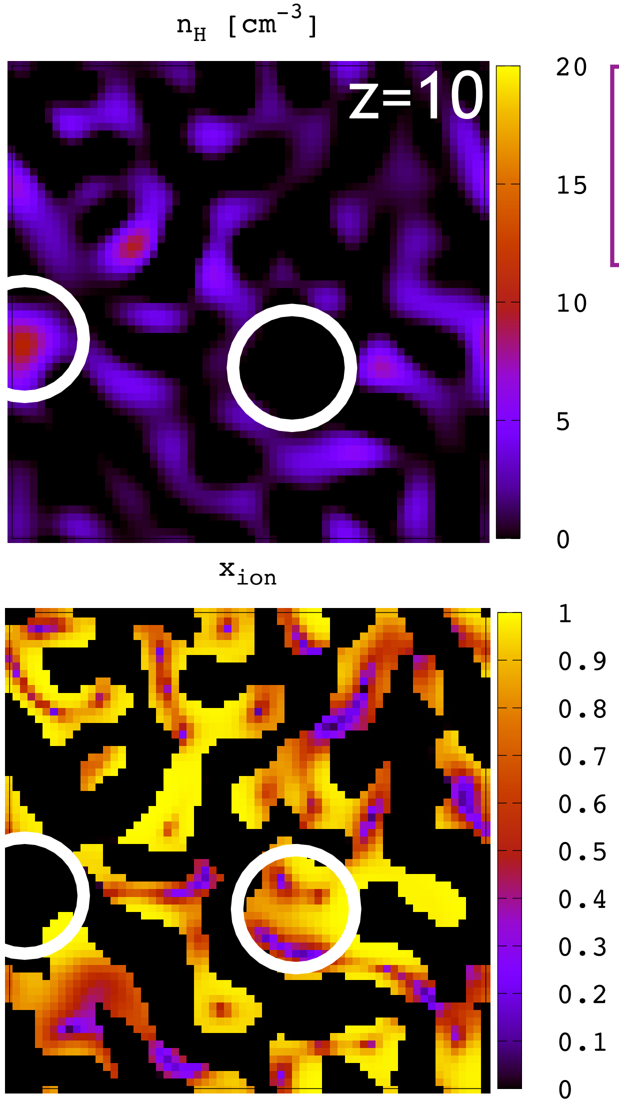
$$\text{large } n_{\rm H} > \text{small } T_{\rm gas} \text{ and } x_{\rm ion}$$

$$\text{small } n_{\rm H} > \text{large } T_{\rm gas} \text{ and } x_{\rm ion}$$

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

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

# Result




B_{1Mpc}=0.5nG, n_B=0.0
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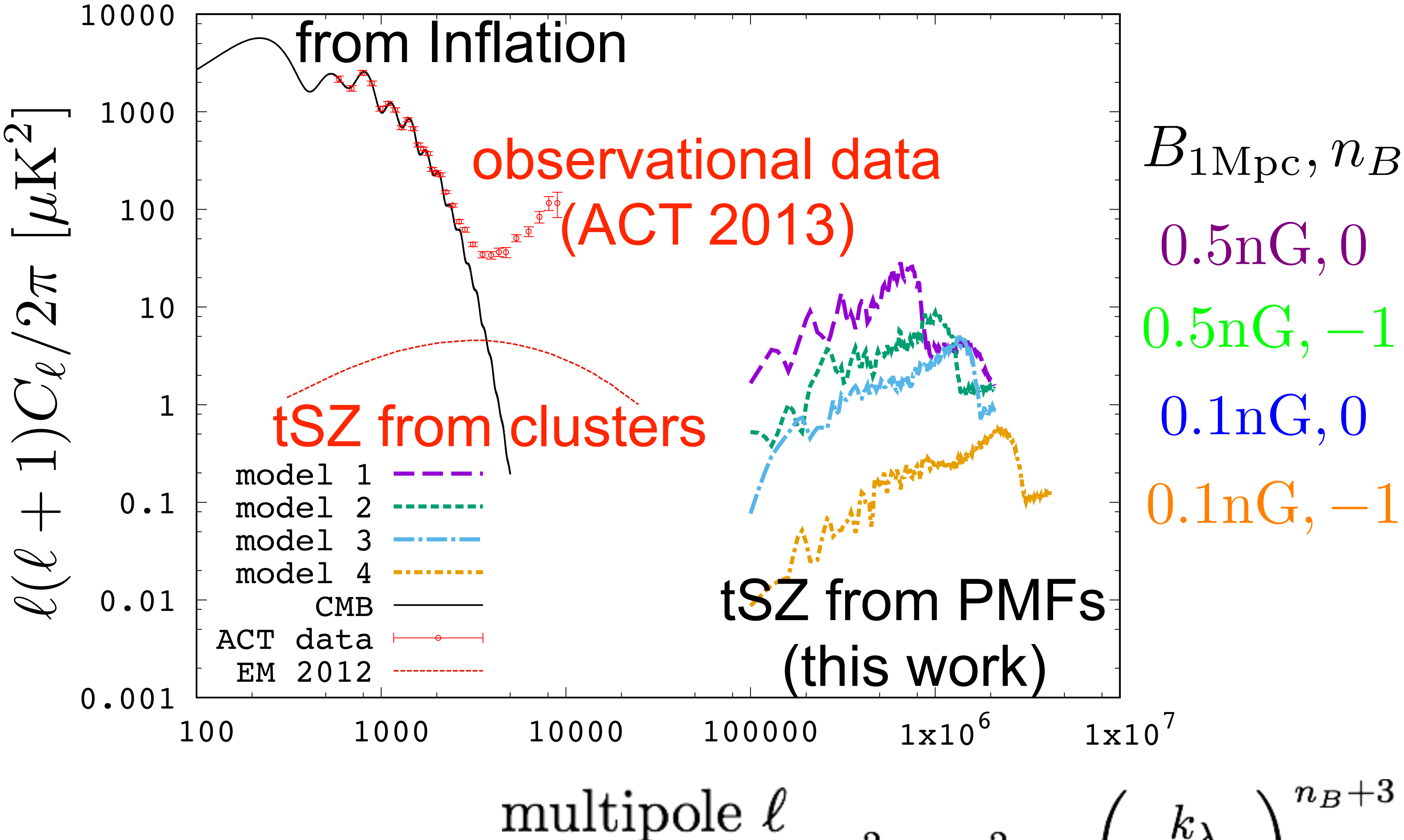
$$\Gamma(t) = \frac{|(\nabla \times \mathbf{B}) \times \mathbf{B}|^2}{16\pi^2 \xi \rho_{\rm b}^2(t)} \frac{(1 - x_{\rm i})}{x_{\rm i}}$$

<u>PMFs generate tSZ</u>

<u>in the VOID region!!</u>

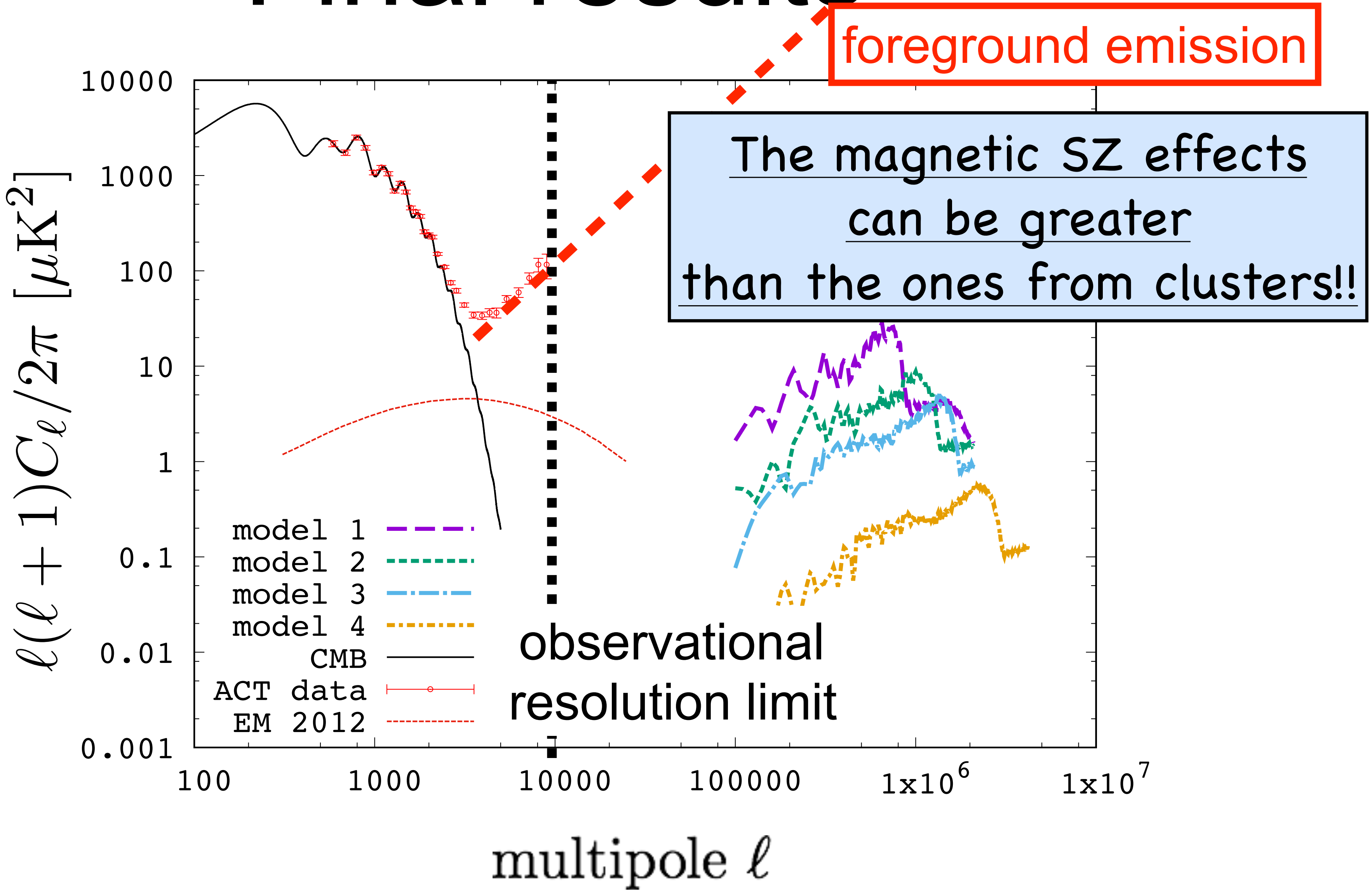
T. Minoda et al., (2017) arXiv:1705.10054

# Final results




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

# Final results



# Summary

- The origin of the cosmic magnetic fields is unknown
- If exist, PMFs have an influence on gas density, temperature, ionization rate
- We show the tSZ from PMFs is stronger than that from clusters, but hard to detect this signal (too small scale).

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

# END

Thank you for listening !

# existence of extragalactic magnetic fields ?

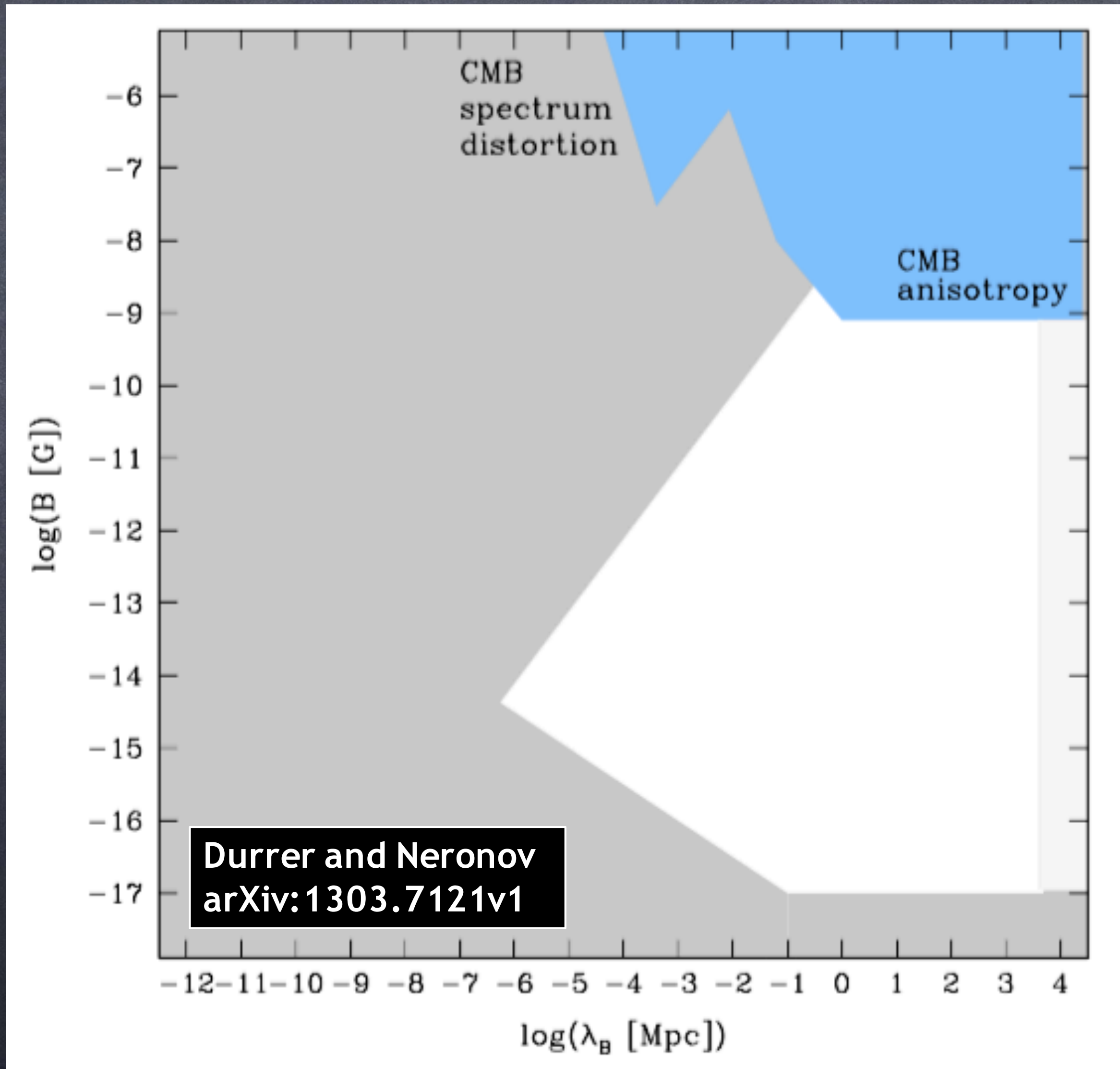
## Evidence for Strong Extragalactic Magnetic Fields from Fermi Observations of TeV Blazars

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, $\lambda_B$, is much smaller than a megaparsec. This lower bound constrains models for the origin of cosmic magnetic fields.

# Constraint on PMFs



# 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] | $n_B$ | $\lambda_c$ [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

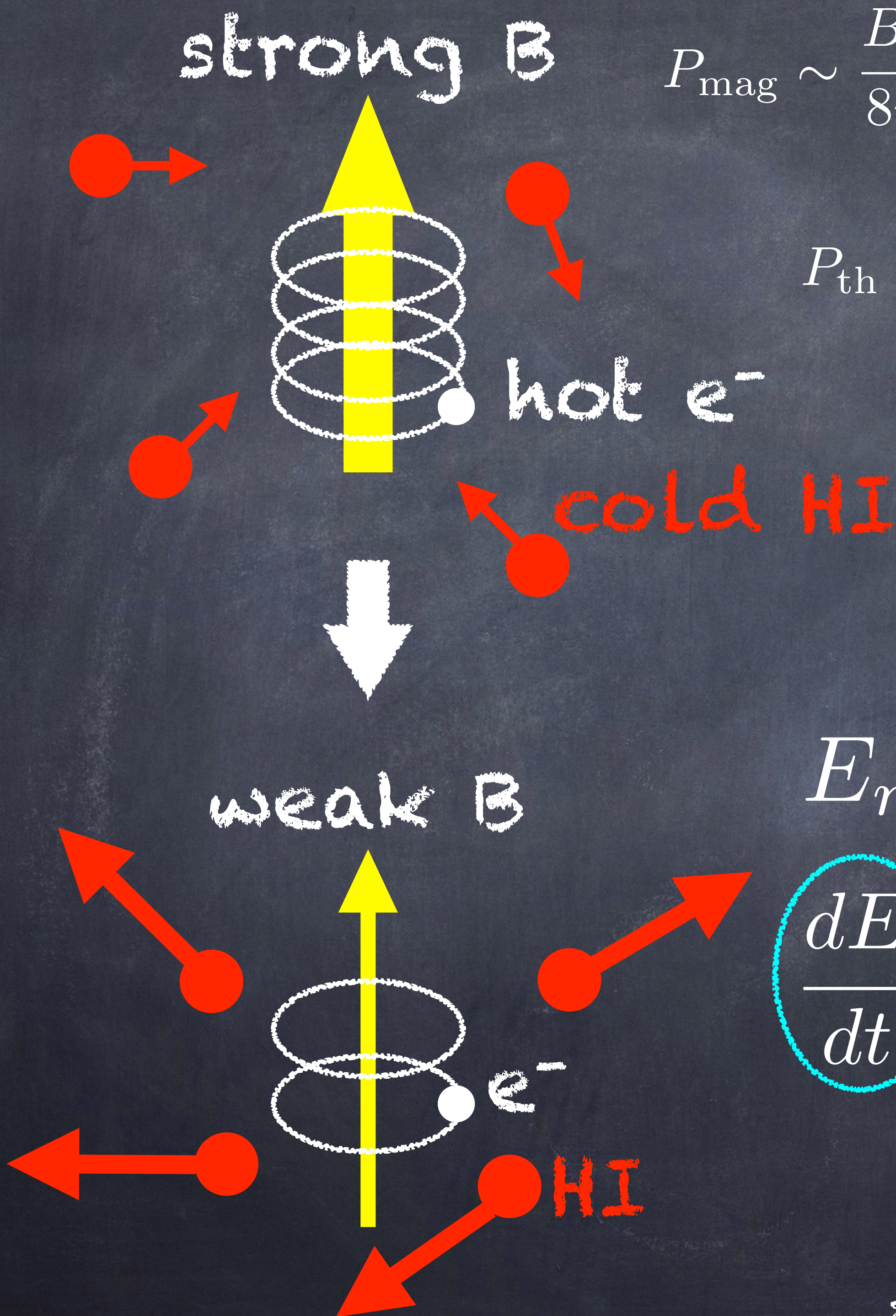
(CDM): $$\frac{\partial^2 \delta_c}{\partial t^2} + 2H(t)\frac{\partial \delta_c}{\partial t} - 4\pi G(\rho_c \delta_c + \rho_b \delta_b) = 0 \ ,$$

(Baryon): $$\frac{\partial^2 \delta_b}{\partial t^2} + 2H(t)\frac{\partial \delta_b}{\partial t} - 4\pi G(\rho_c \delta_c + \rho_b \delta_b) = S(t) \ ,$$

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

$$\delta_b = \frac{2S(t)}{15H^2(t)}\left[\left\{3\left(\frac{a}{a_{\rm rec}}\right) + 2\left(\frac{a}{a_{\rm rec}}\right)^{-\frac{3}{2}} - 15\ln\left(\frac{a}{a_{\rm rec}}\right)\right\}\frac{\Omega_b}{\Omega_m} + 15\ln\left(\frac{a}{a_{\rm rec}}\right) + 30\left(1-\frac{\Omega_b}{\Omega_m}\right)\left(\frac{a}{a_{\rm rec}}\right)^{-\frac{1}{2}} - \left(30 - 25\frac{\Omega_b}{\Omega_m}\right)\right] \ ,$$

(Wasserman 1978)




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

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

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

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

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

$\xi$ : drag coefficient

(Sethi & Subramanian, 2005)

# Thermal history (S&S 2005)

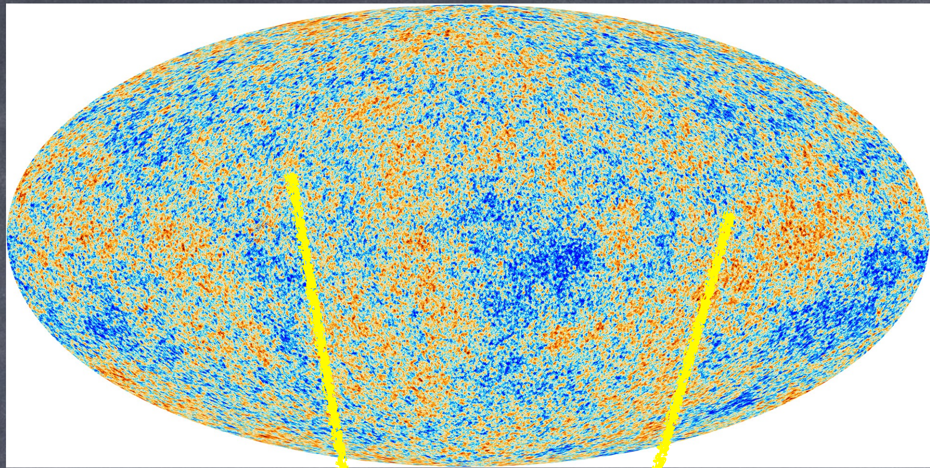
cosmic expansion — Compton scattering — magnetic heating

$$\dot{T}_{\rm e} = -2\frac{\dot{a}}{a}T_{\rm e} + \frac{x_{\rm e}}{1+x_{\rm e}}\frac{8\rho_\gamma\sigma_{\rm t}}{3m_{\rm e}c}(T_\gamma - T_{\rm e}) + \frac{\Gamma_{\rm e}}{(1.5k_{\rm B}n_{\rm e})}$$

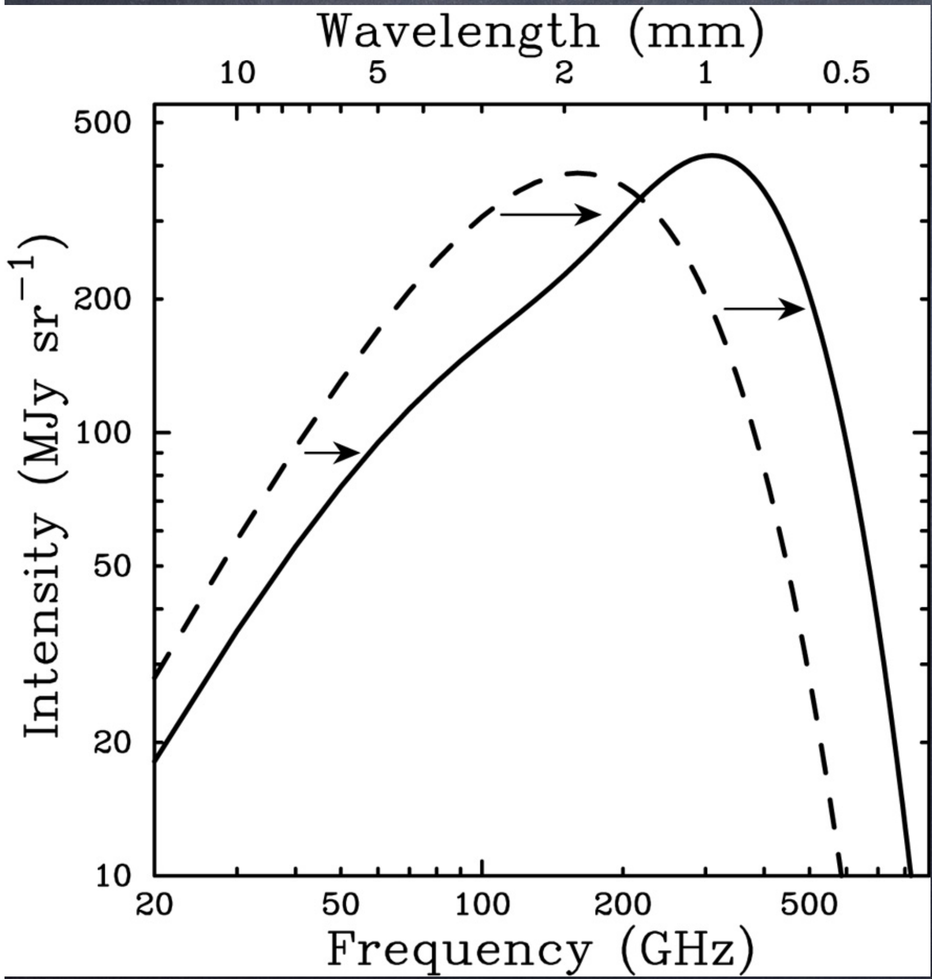
$$\dot{x}_{\rm e} = \left\{\beta_{\rm e}(1-x_{\rm e})\exp\left[-h\nu_\alpha/(k_{\rm B}T_{\rm cbr})\right] - \alpha_{\rm e}n_{\rm b}x_{\rm e}^2\right\}C + \gamma_{\rm e}n_{\rm b}(1-x_{\rm e})x_{\rm e}.$$

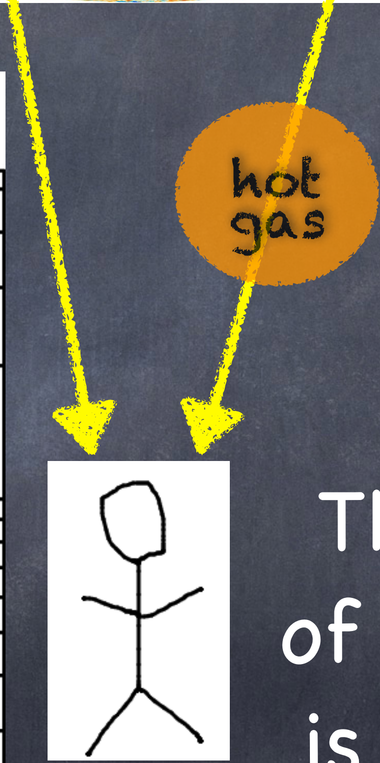
collisional ionization — photo-ionization — collisional recombination

(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

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

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

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

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

# Future prospects

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