International Symposium on Cosmology and Particle Astrophysics:
CosPA 2017

Thermal SZ effect in the IGM with Primordial Magnetic Fields

14th. Dec. 2017,

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- Introduction
- Calculation Methods
- Results/Discussion
- Summary

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

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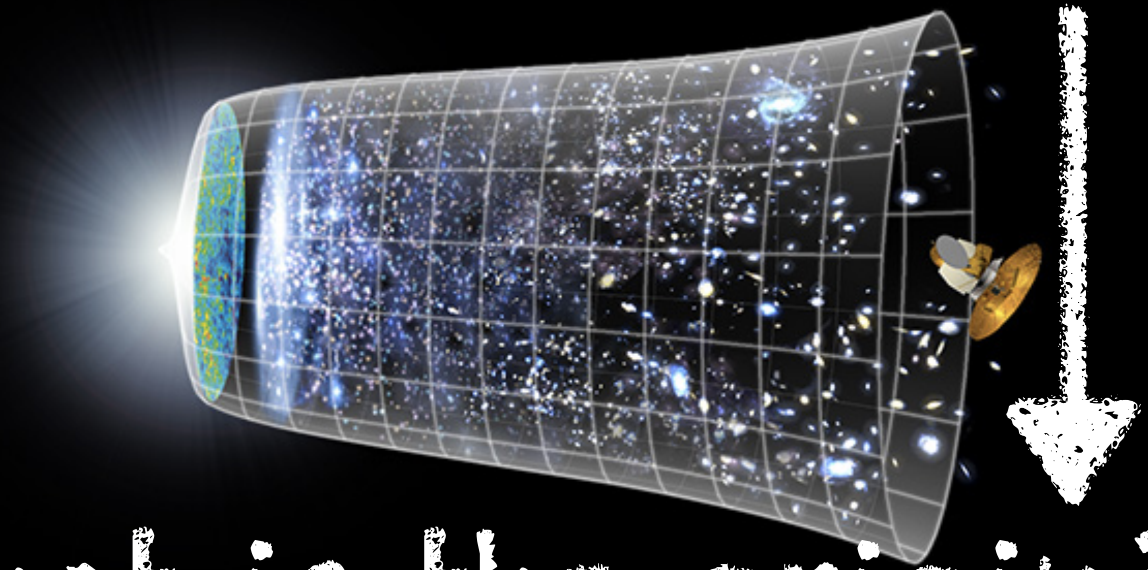
Introduction

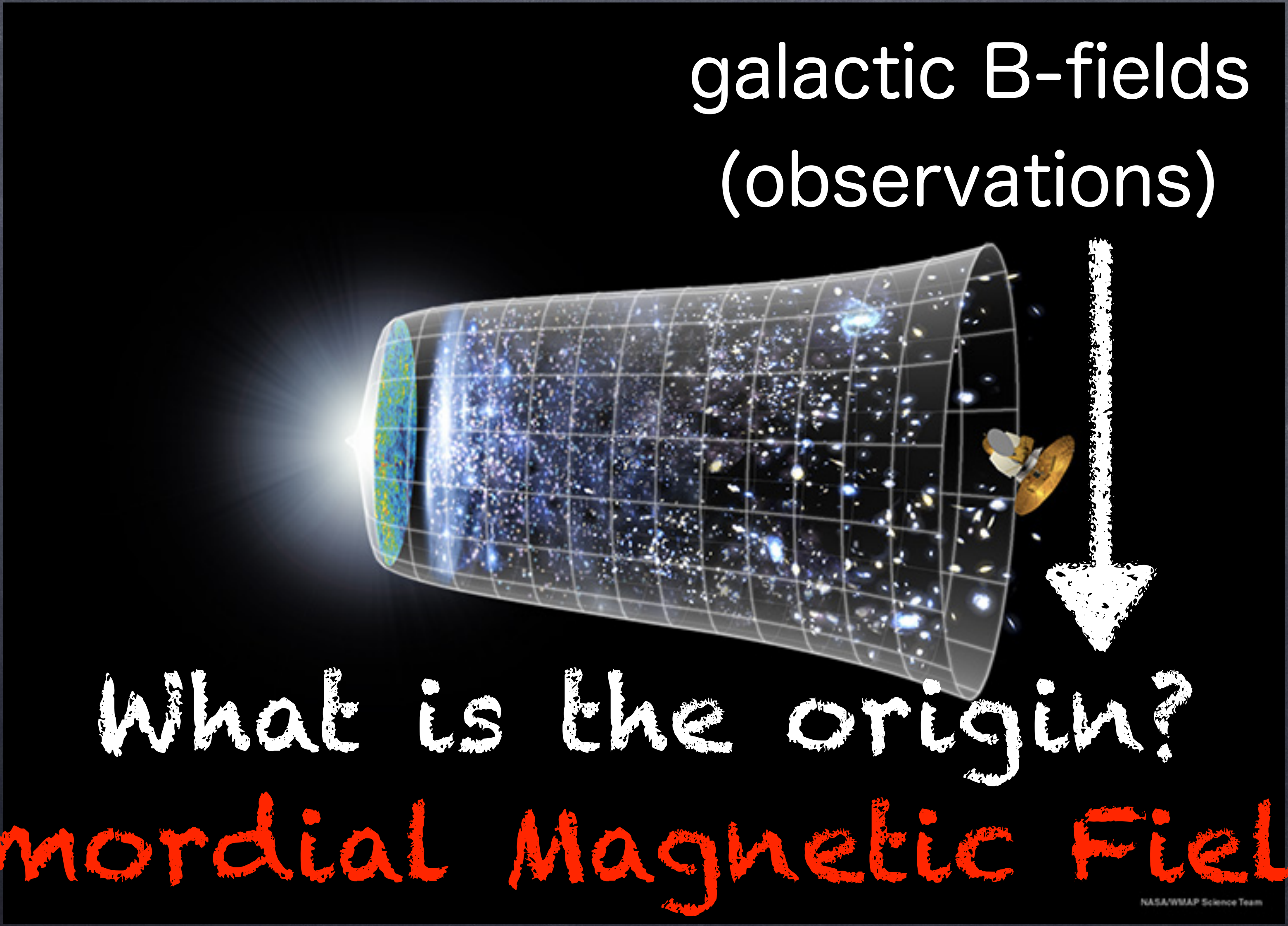
galactic B-fields
(observations)



What is the origin?

NASA/WMAP Science Team

Introduction



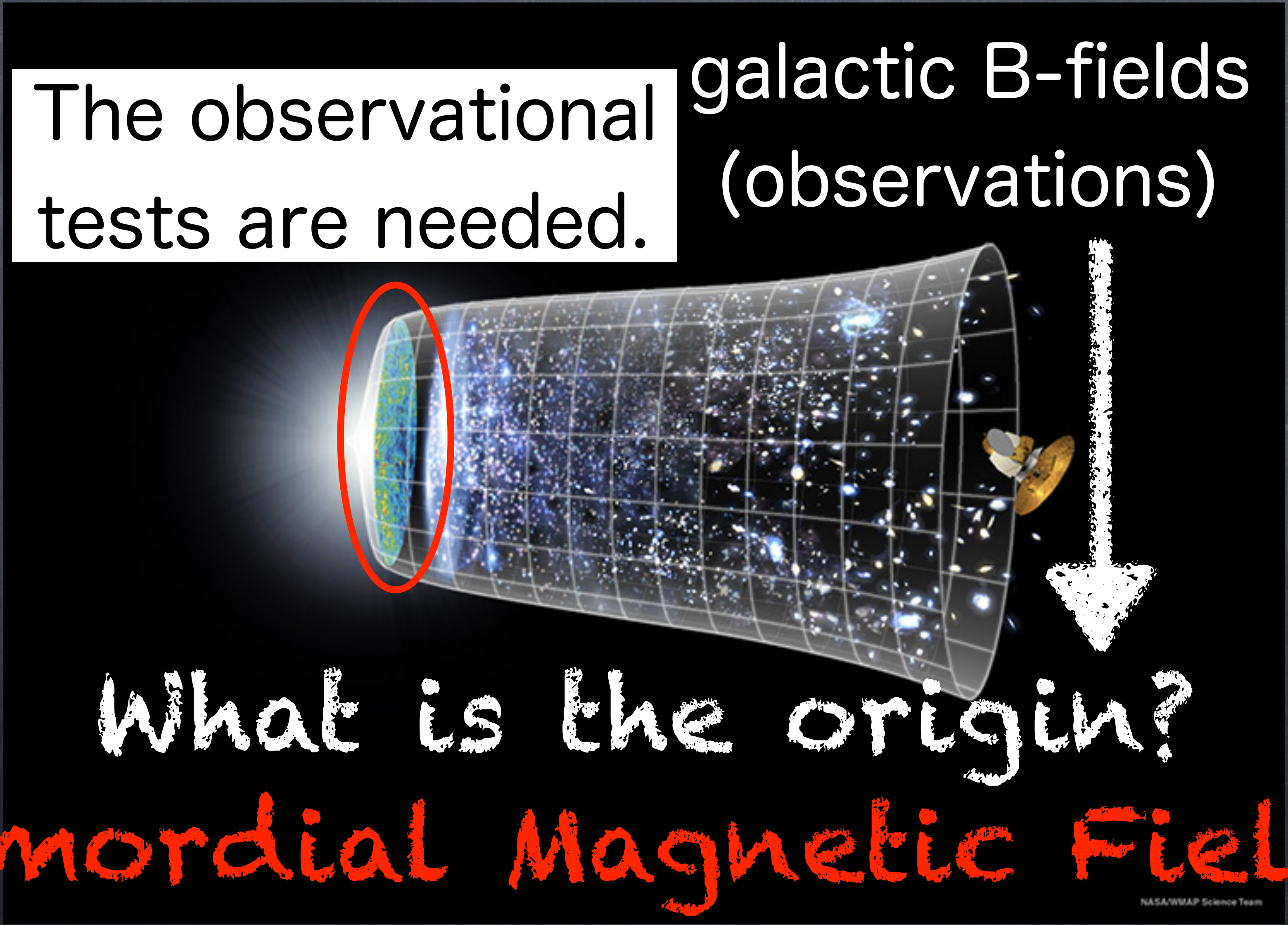
galactic B-fields
(observations)

What is the origin?

Primordial Magnetic Fields?

NASA/WMAP Science Team

Introduction



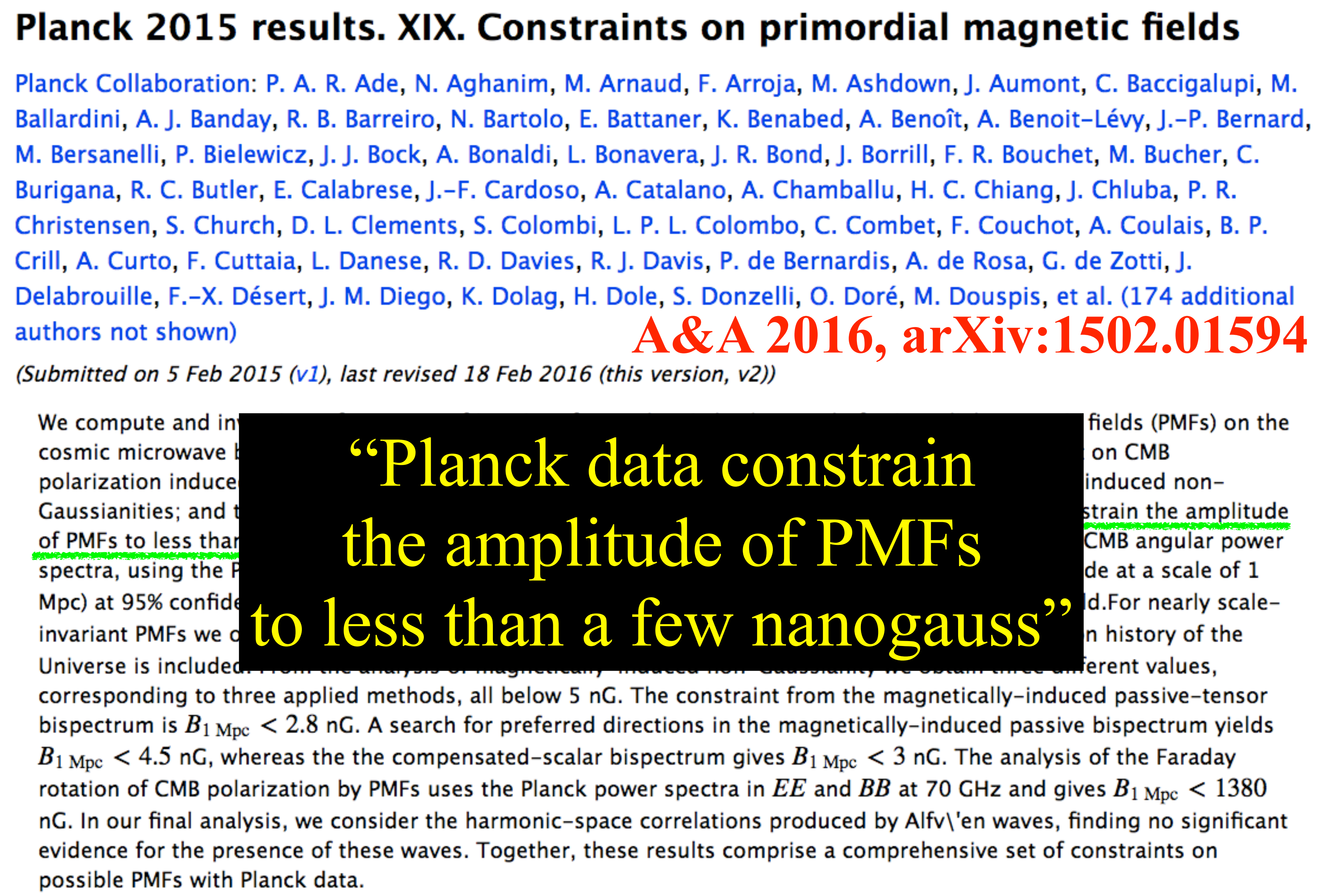
The observational tests are needed.

galactic B-fields (observations)

What is the origin?

Primordial Magnetic Fields?

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)

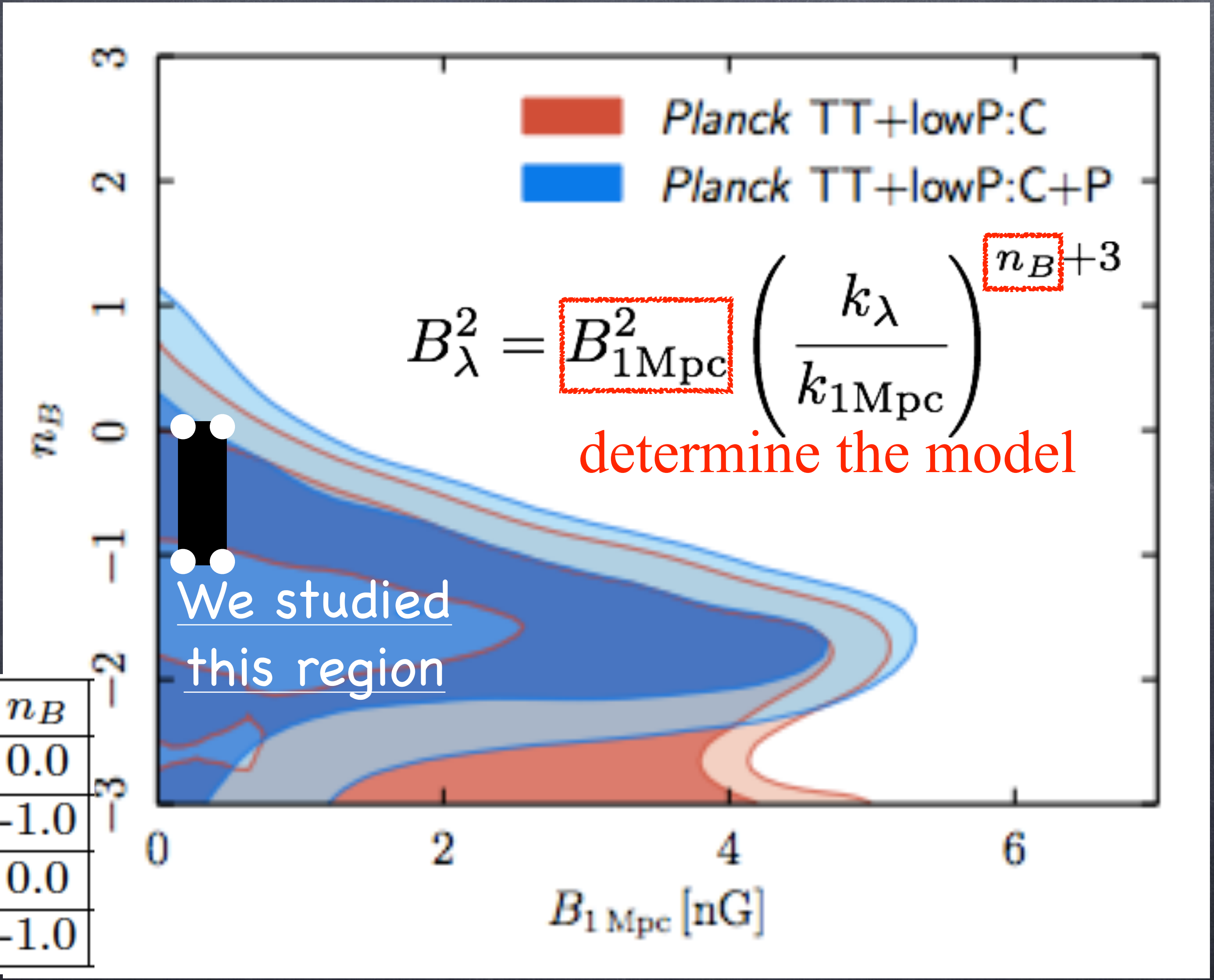
A&A 2016, arXiv:1502.01594

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

We compute and in fields (PMFs) on the
cosmic microwave b on CMB
polarization induce induced non-
Gaussianities; and t 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 o n history of the
Universe is included ferent 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



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

determine the model

We studied this region

$B_{1\rm Mpc}$ [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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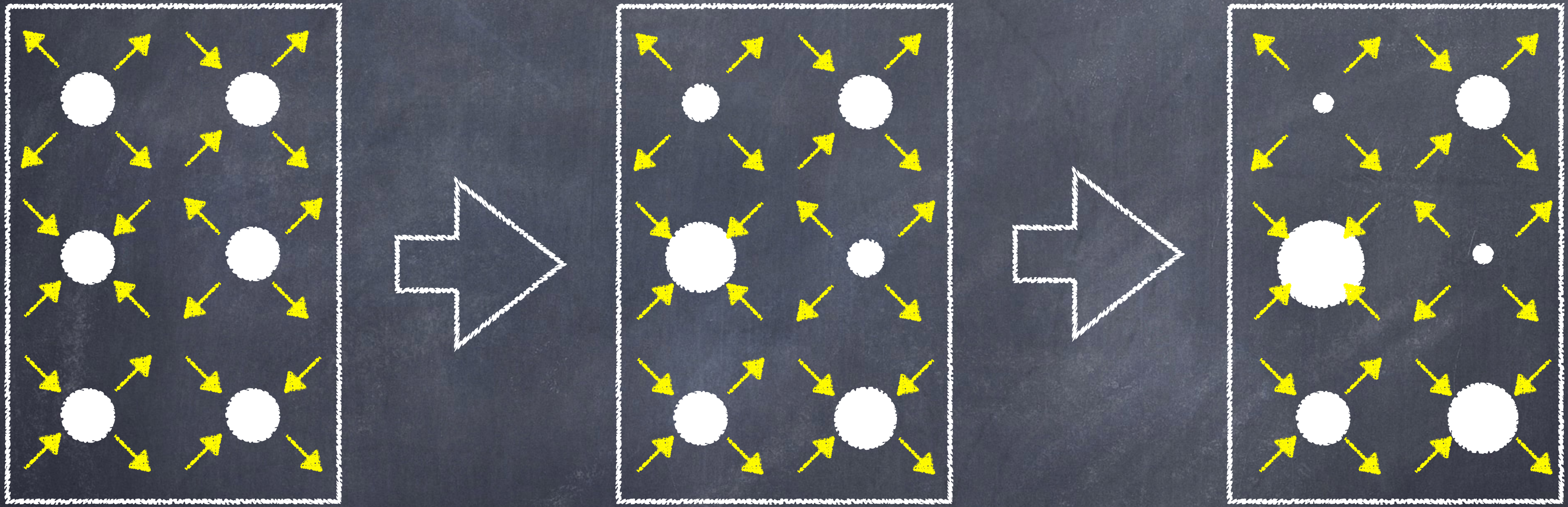
Density evolution

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



matter:

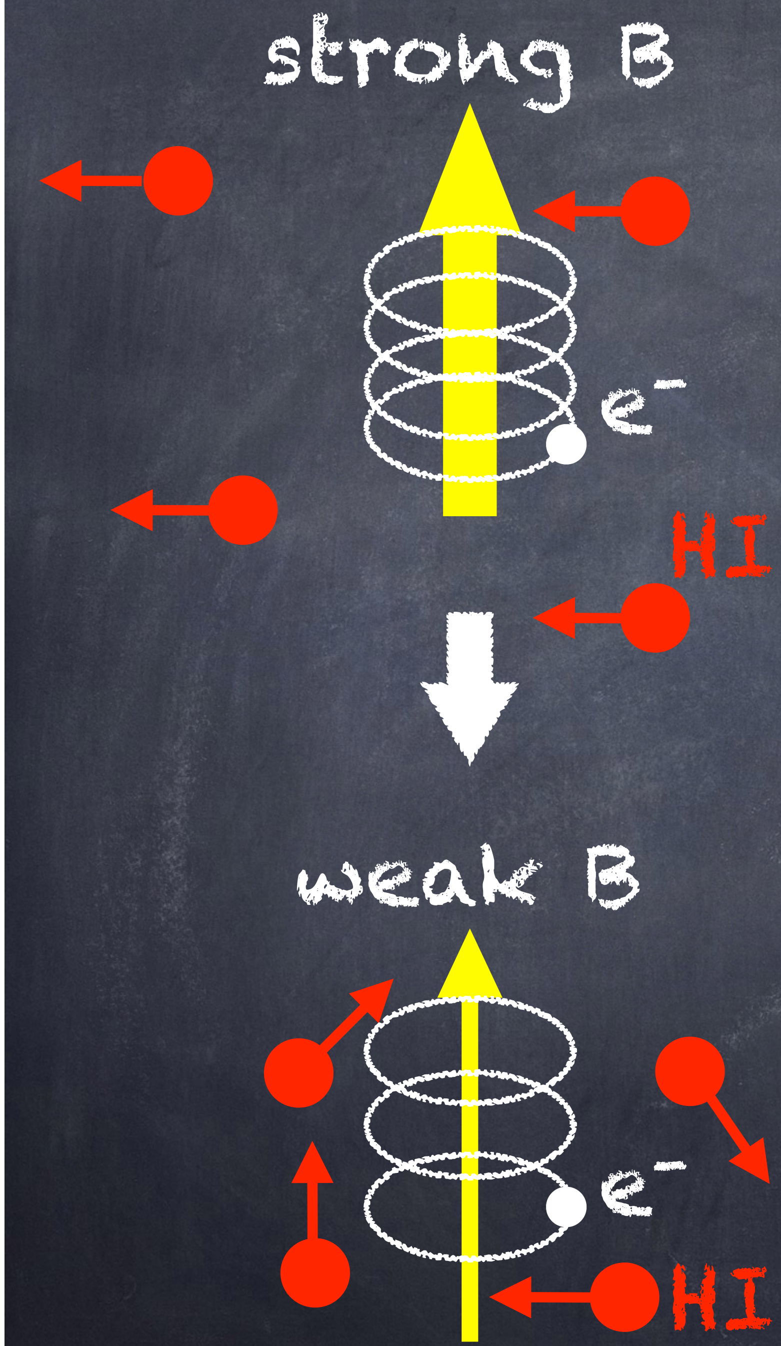
uniform

Lorentz force:

inhomogeneous

density fluctuations are generated by PMFs !

(Wasserman 1978)



Ambipolar diffusion

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

$$\Downarrow$$

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

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

ξ : drag coefficient

(Sethi & Subramanian, 2005)

Thermal history

(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)

Fukugita & Kawasaki, 1994

Observation

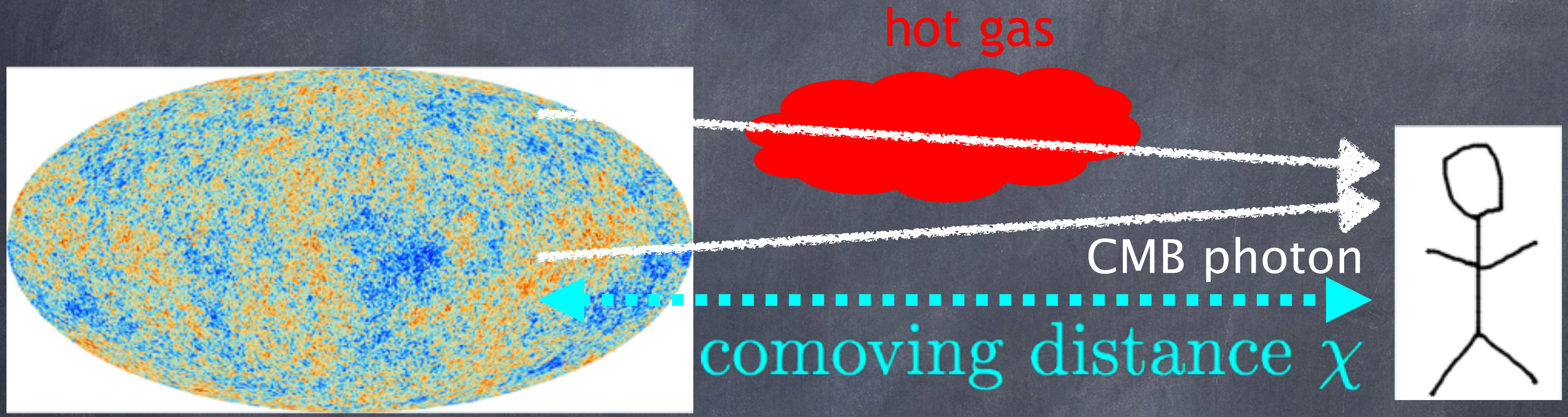
We consistently calculated

density evolution & thermal history

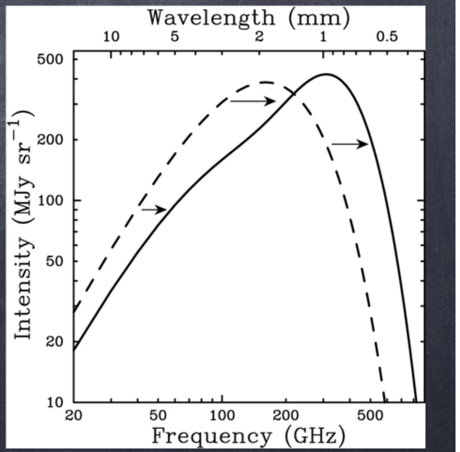
- Can we observe these effects?
  > thermal Sunyaev-Zel'dovich (tSZ) effect

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

Thermal SZ effect



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



3D y-map with $(1\ {\rm cMpc})^3,\ 10 \lesssim z \lesssim 1100$

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

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. Numerical generation of PMFs
2. Calculation of physical quantities $\begin{cases} x_{\rm ion} \\ T_{\rm gas} \\ n_{\rm H} \end{cases}$
3. Estimate the tSZ power spectrum

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

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

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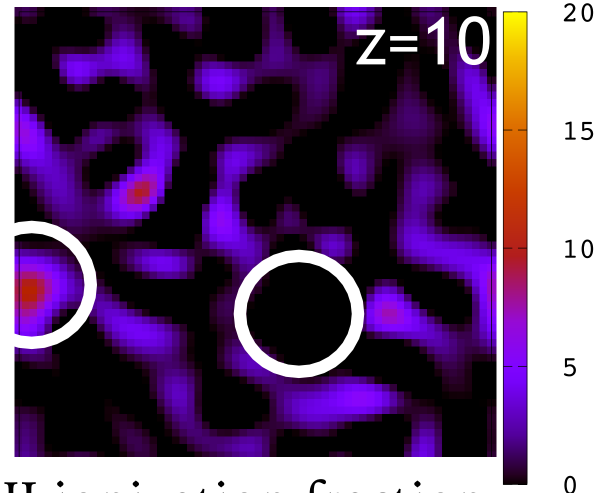
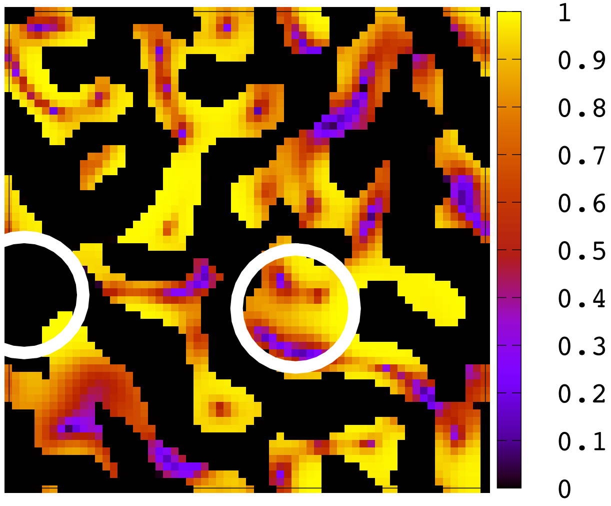
Result

HI number density [/cm^3]



HI ionization fraction



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

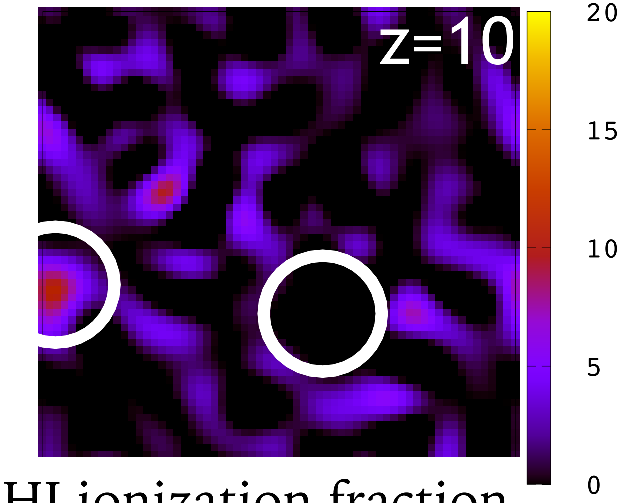
$$\text{large } n_{\rm H} > \text{small } T_{\rm gas} \text{ and } x_{\rm ion}$$

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

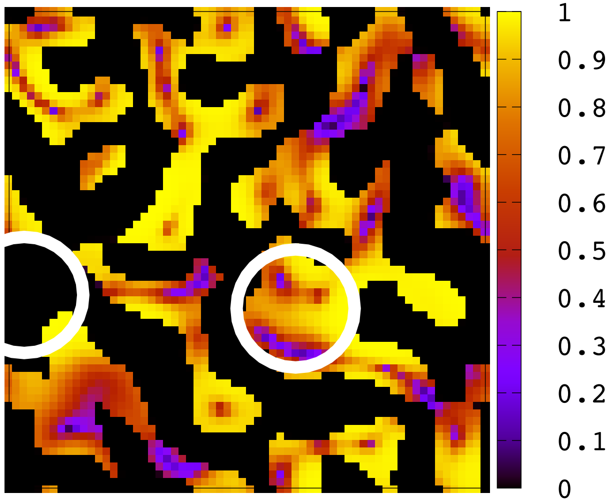
T. Minoda et al., (2017) arXiv:1705.10054

Result

HI number density [/cm^3]



HI ionization fraction



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

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

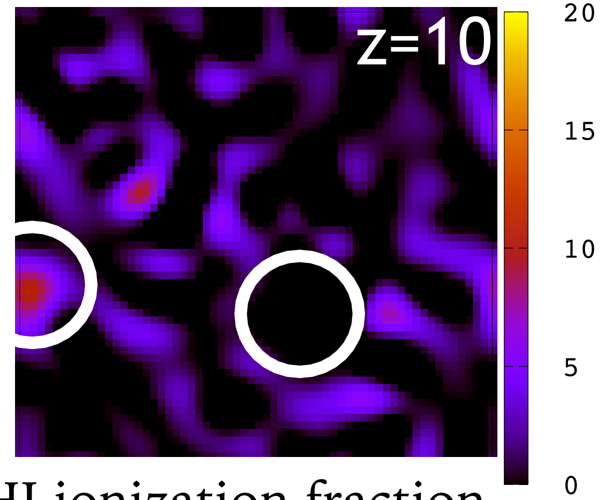
small n_{H} > large T_{gas} and x_{ion}

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

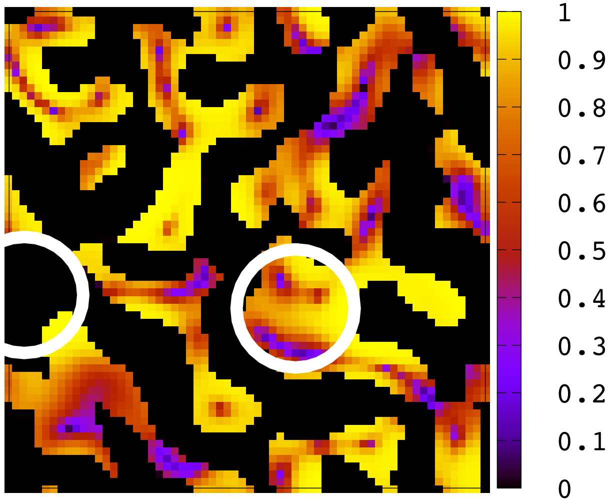
T. Minoda et al., (2017) arXiv:1705.10054

Result

HI number density [/cm^3]



HI ionization fraction



B_{1Mpc}=0.5nG, n_B=0.0
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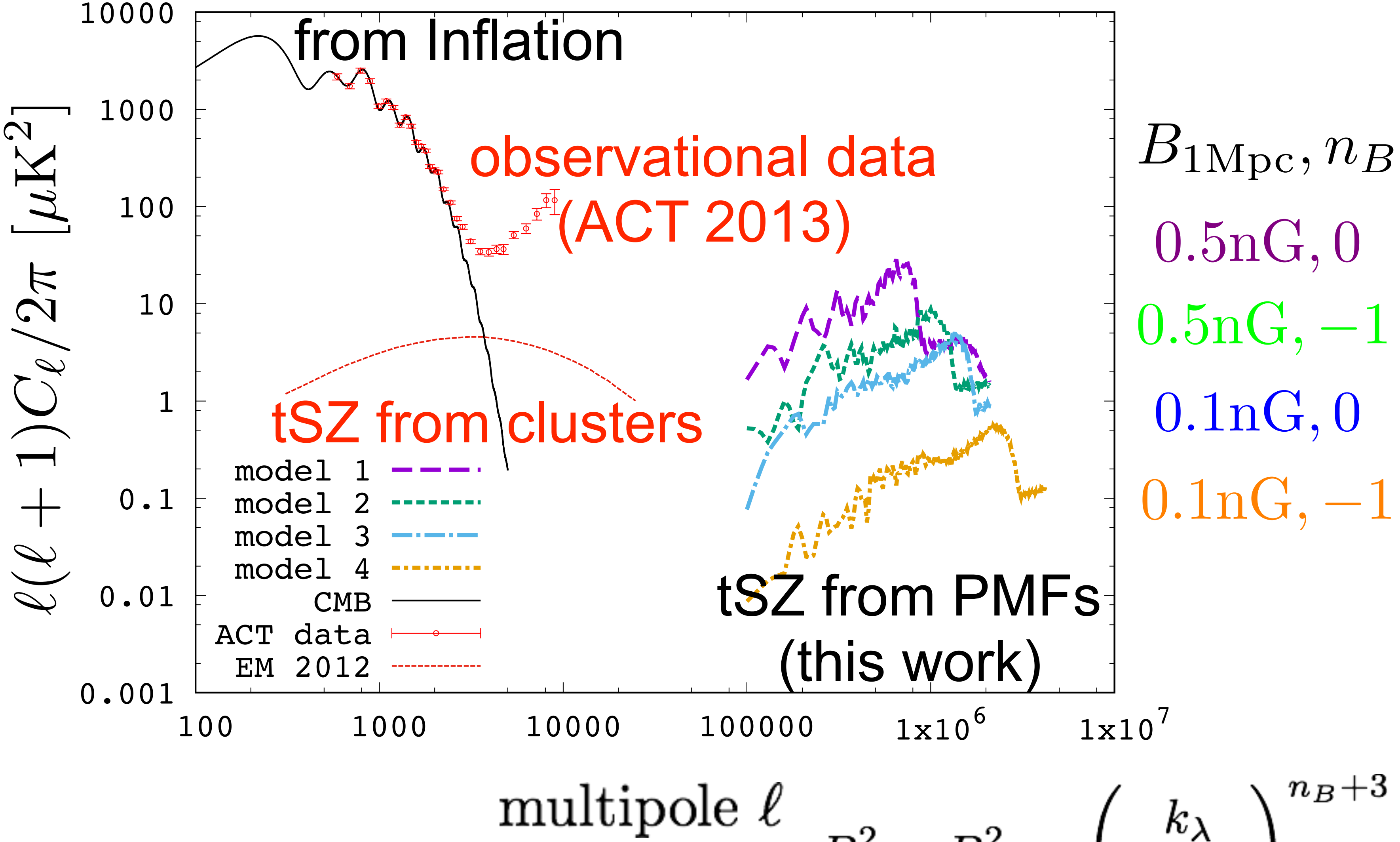
$$\text{small } n_{\rm H} > \text{large } T_{\rm gas} \text{ and } x_{\rm ion}$$

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

PMFs generate tSZ
in the VOID region!!

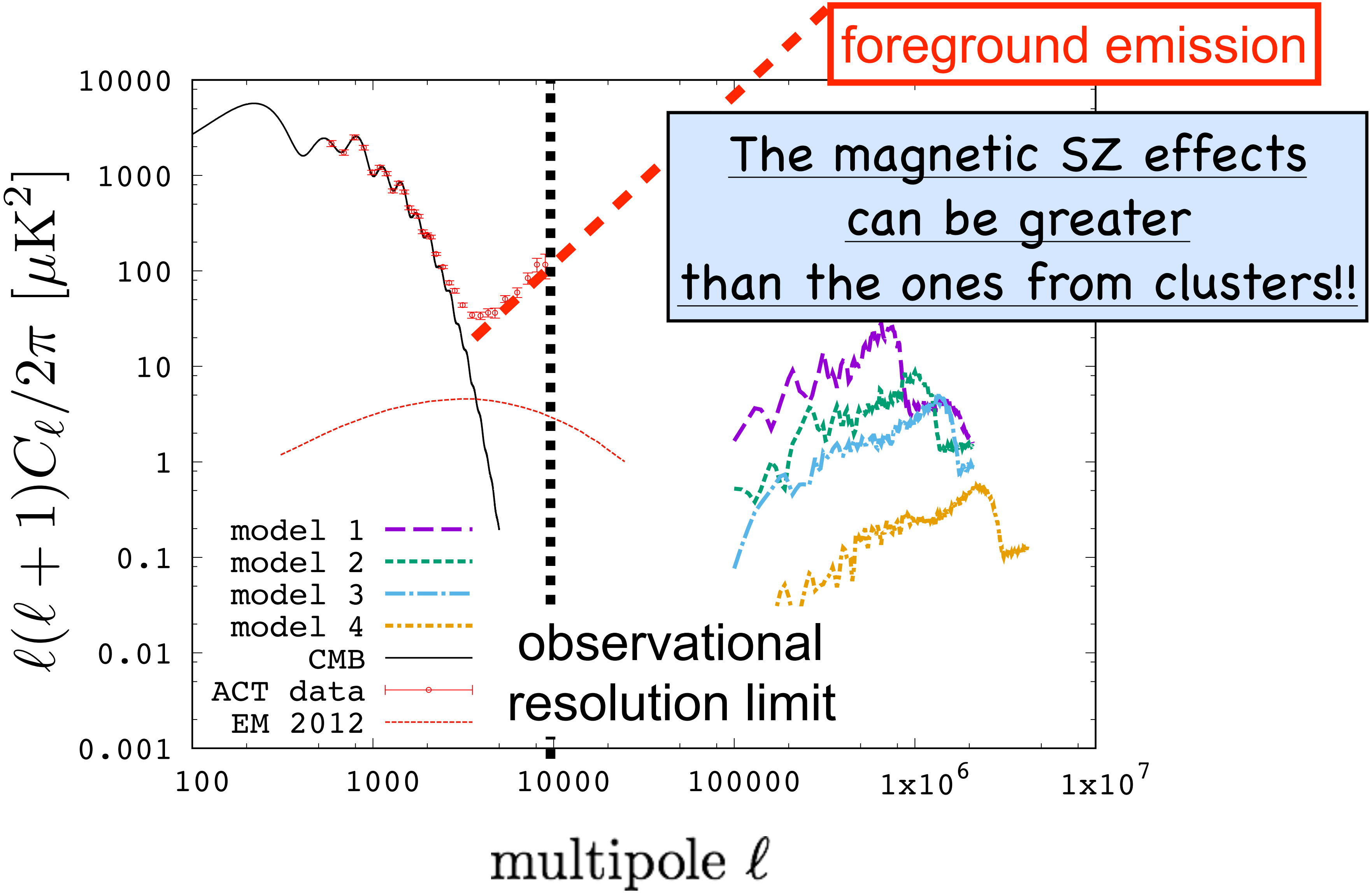
T. Minoda et al., (2017) arXiv:1705.10054

Final results



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

Final results



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

Summary

- We consistently calculate the evolution of gas density, temperature, ionization rate with PMFs for the first time.
- We show that the 10 kpc size IGM at z~200 can induce tSZ effect.
- Consideration of non-linear evolution

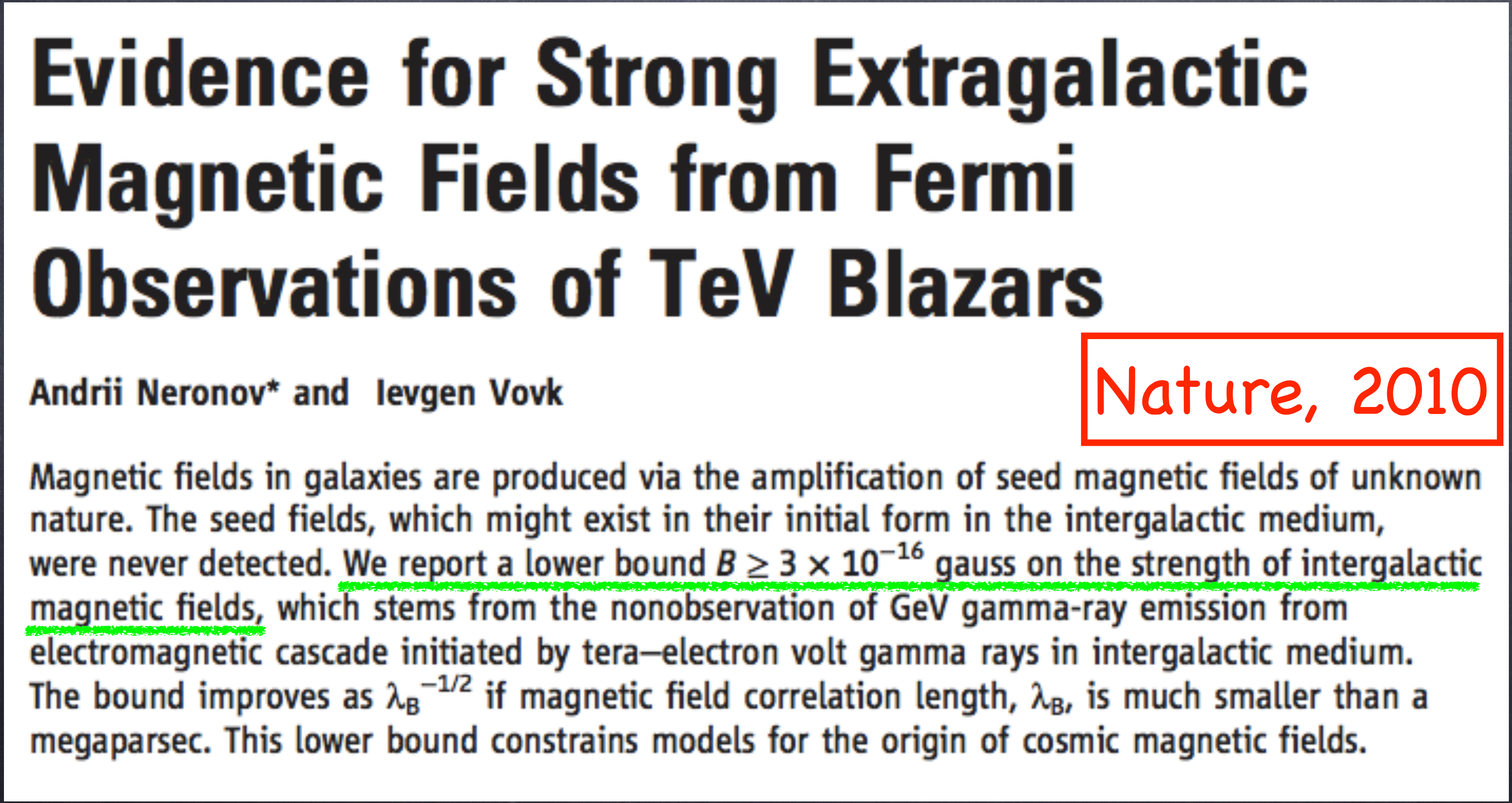
  > Future works!!

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

END

Thank you for listening !

existence of extragalactic magnetic fields ?



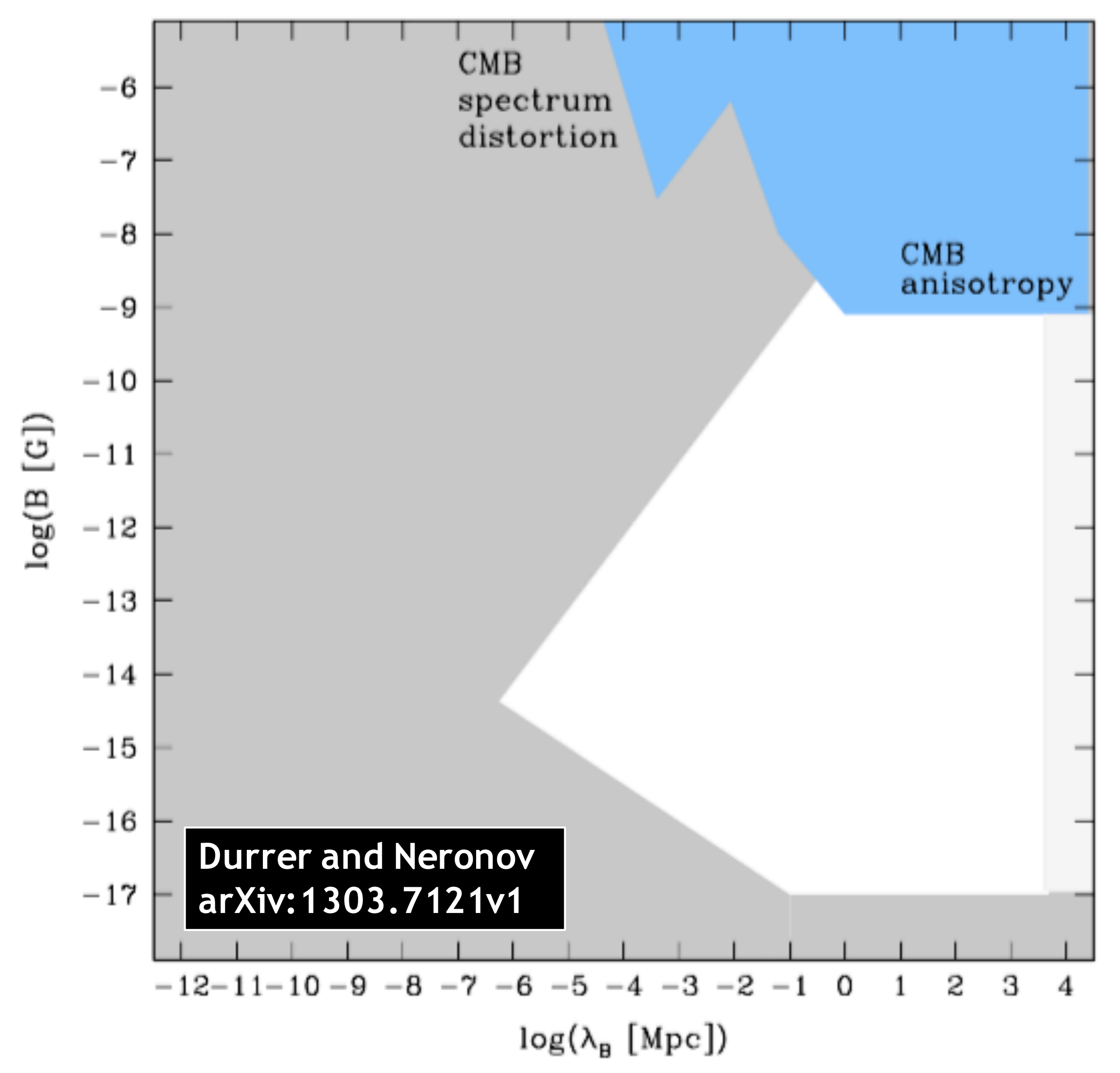
Evidence for Strong Extragalactic Magnetic Fields from Fermi Observations of TeV Blazars

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.

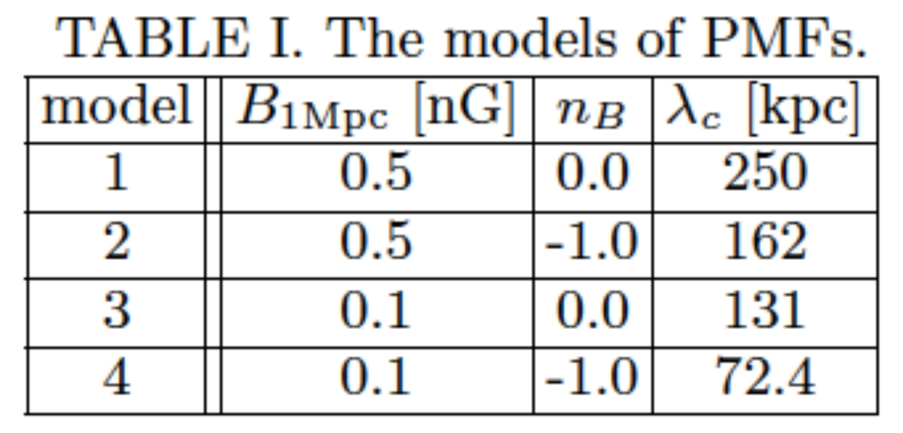


TABLE I. The models of PMFs.

model	$B_{1\text{Mpc}}$ [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

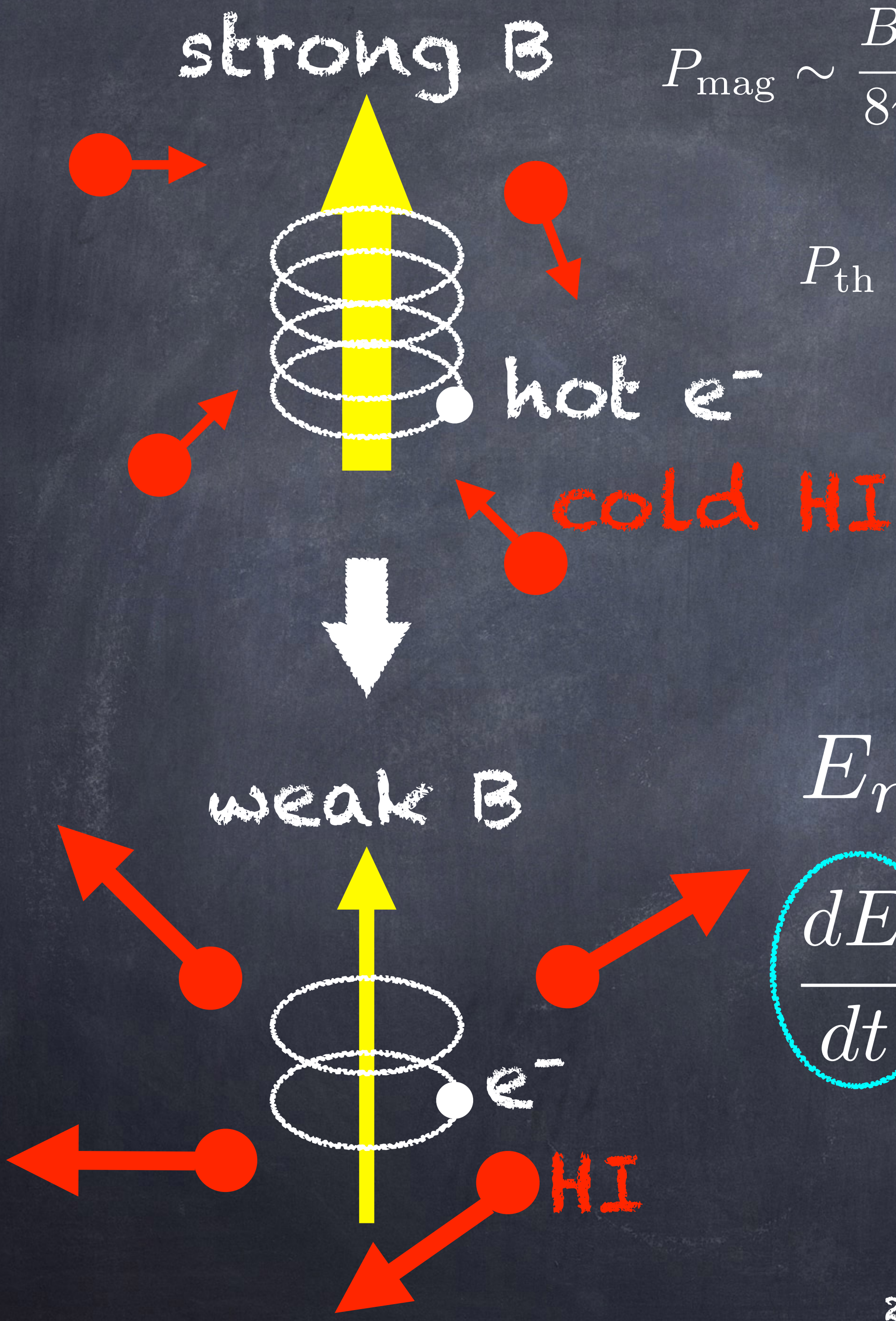
(CDM):
$$\frac{\partial^2 \delta_{\rm c}}{\partial t^2} + 2H(t)\frac{\partial \delta_{\rm c}}{\partial t} - 4\pi G(\rho_{\rm c}\delta_{\rm c} + \rho_{\rm b}\delta_{\rm b}) = 0 \ ,$$

(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)



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

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

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

$$\Downarrow$$

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

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

ξ : drag coefficient

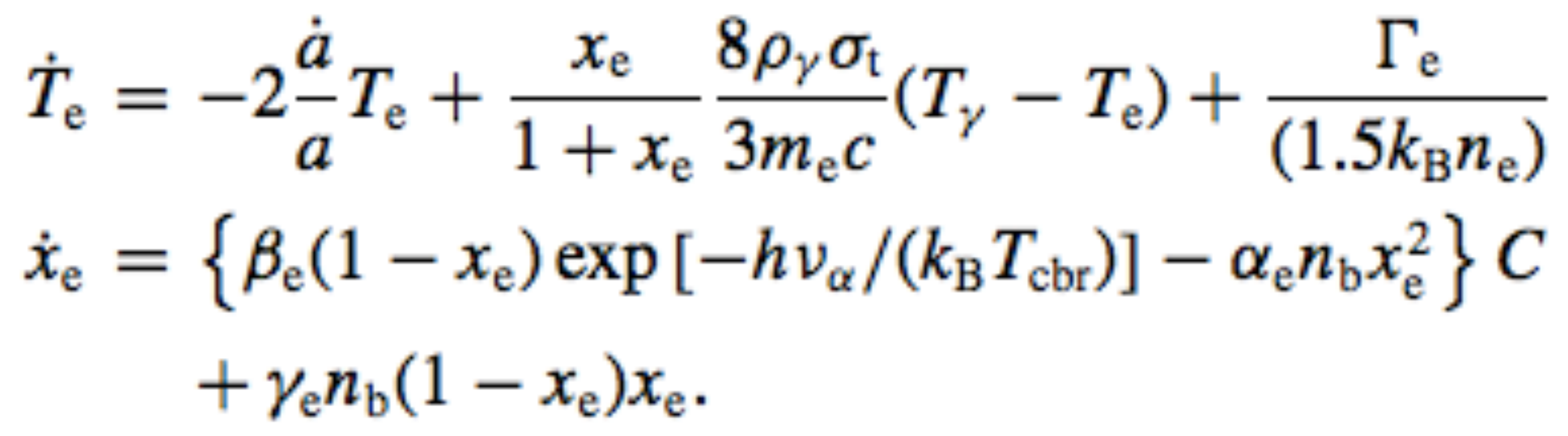
(Sethi & Subramanian, 2005)

Thermal history (S&S 2005)

cosmic expansion

Compton scattering

magnetic heating



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

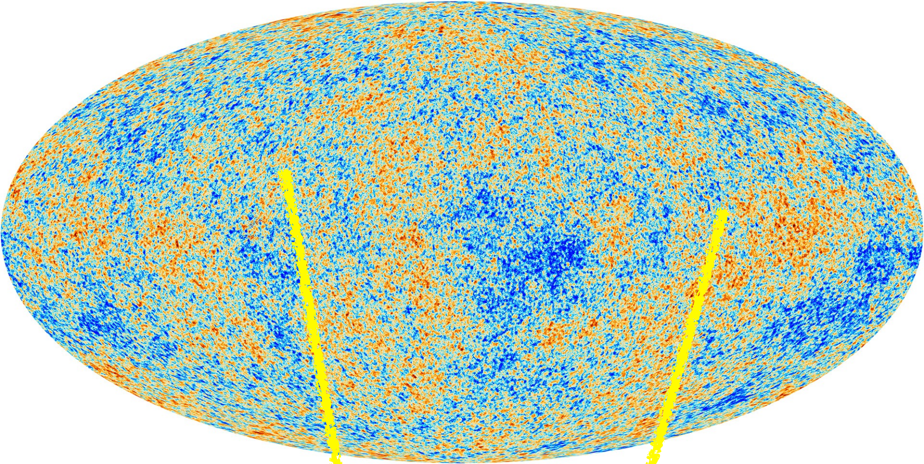
$$\begin{aligned}\dot{x}_{\rm e} = &\left\{\beta_{\rm e}(1-x_{\rm e})\exp\left[-h\nu_\alpha/(k_{\rm B}T_{\rm cbr})\right] - \alpha_{\rm e}n_{\rm b}x_{\rm e}^2\right\}C\\ &+\gamma_{\rm e}n_{\rm b}(1-x_{\rm e})x_{\rm e}.\end{aligned}$$

collisional ionization

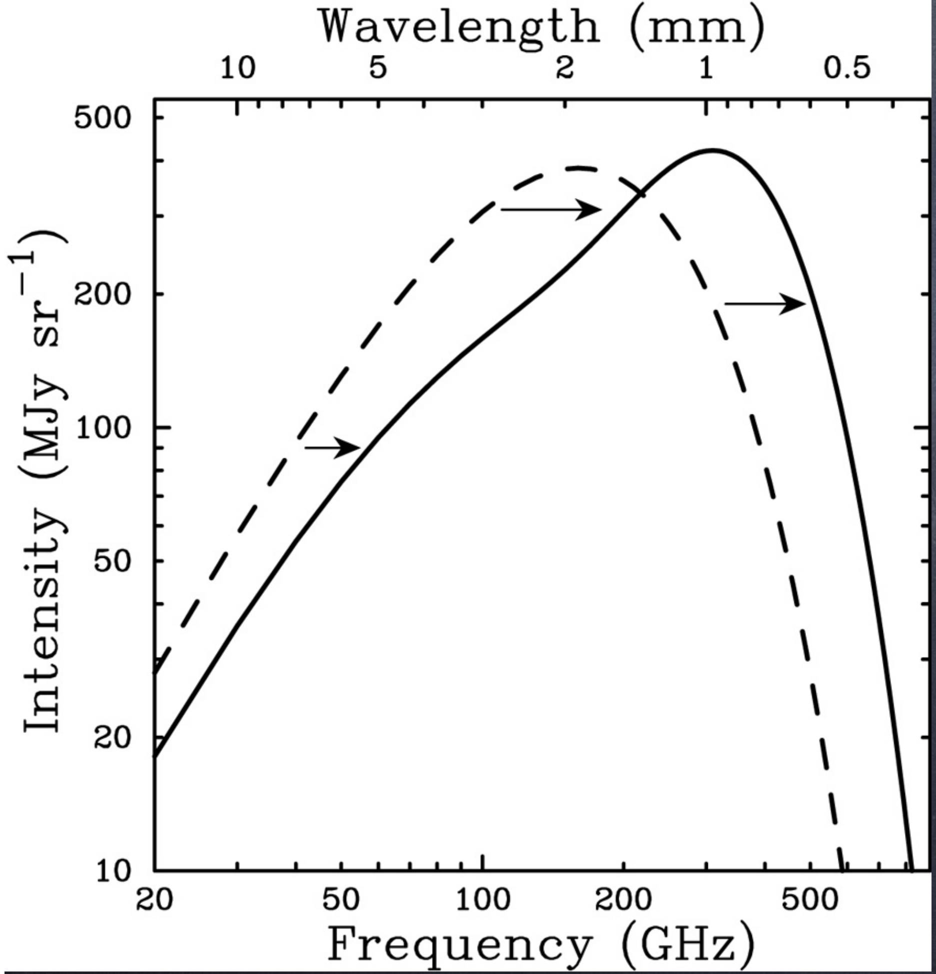
photo-ionization

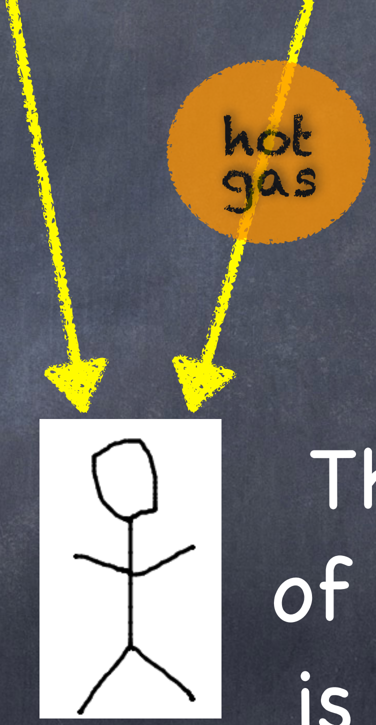
collisional recombination

(c) ESA and the Planck Collaboration



(c) Carlstrom et al., 2002

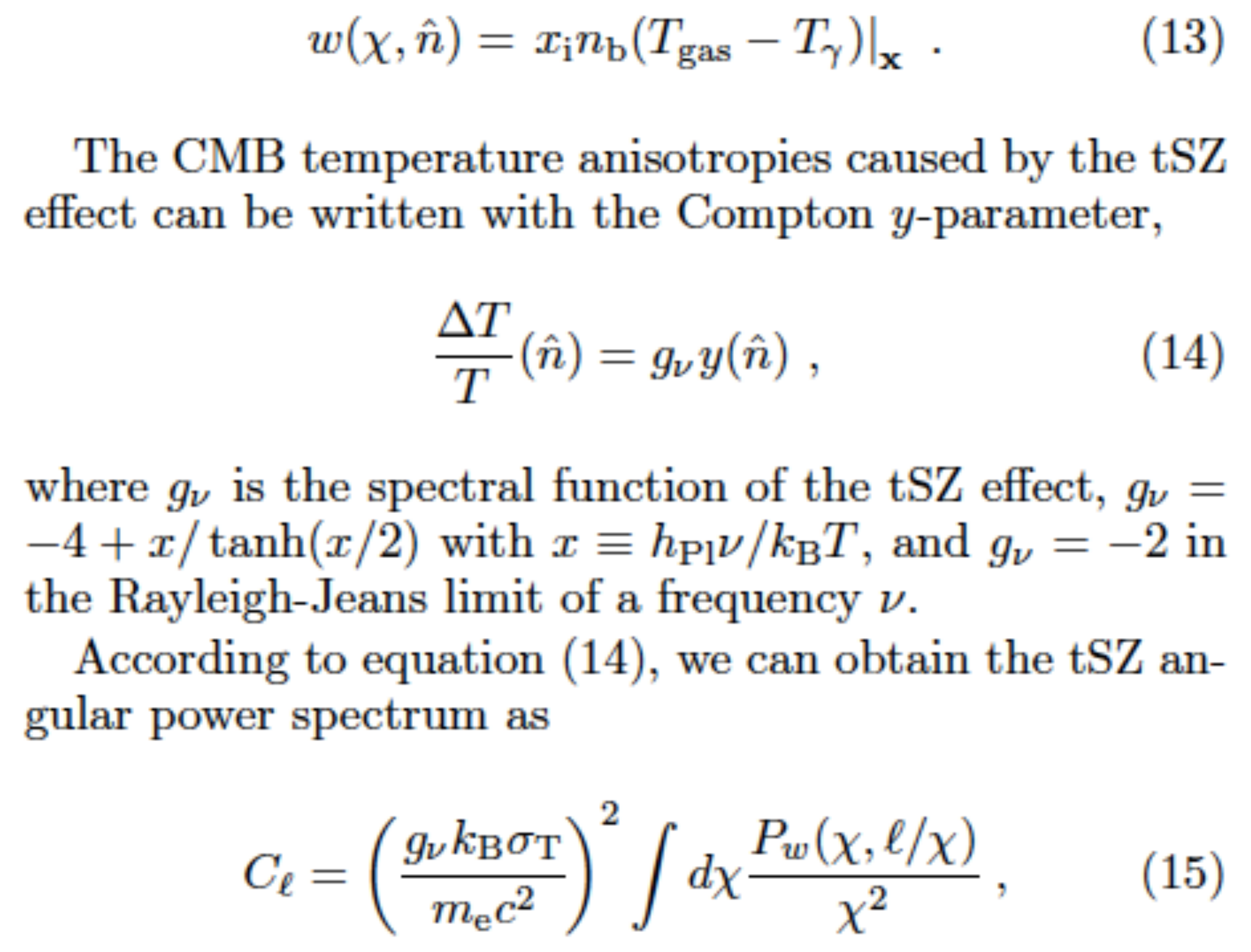




thermal SZ effect

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

tSZ angular power spectrum



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

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

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

where g_ν 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 ν.

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

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

Frank Shu (1992) vs. Sethi Subramanian (2005)

- Shu (1992) Eq. (27.19)

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

only true with slightly ionized medium

- SS (2005) Eq. (9).

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

- This is based on the result of Cowling (1956) Eq. (27), and can be applied for an arbitrary ionized medium. > WE ADOPTED THIS!!

Future prospects

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