Generation of Magnetic fields during pre-recombination

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Cosmology at Interface, SINP, Kolkata   29 January 2015

Overview

- Observation of Magnetic fields
  Current upper and lower bounds
- Generation of seed Magnetic fields
  Current theoretical models
- Our Model
  - Vorticity generation — Thomson scattering
  - From Vorticity to Magnetic fields — Coulomb scattering
  - Comparison with the current observations
- Conclusions and Future work

Observations of magnetic fields

Magnetic fields in the Universe

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- Range of field strength $1\ G = 10^{-4}\ T$

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The Earth	10^{-1} G
Star	$1 - 10^{15}$ G
Molecular cloud	10^{-3} G
Interstellar medium	10^{-6} G
Cluster of galaxies	$10^{-7} - 10^{-6}$ G
Void	10^{-16} G (10 Mpc)

Stronger field ↑

Larger scale ↓

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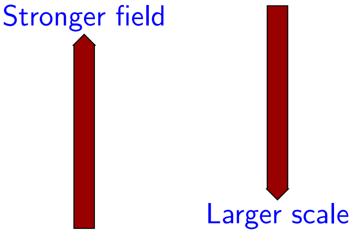
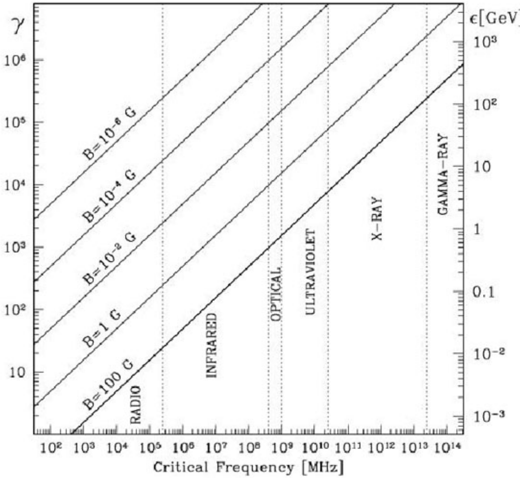


Detection methods

Synchrotron emission

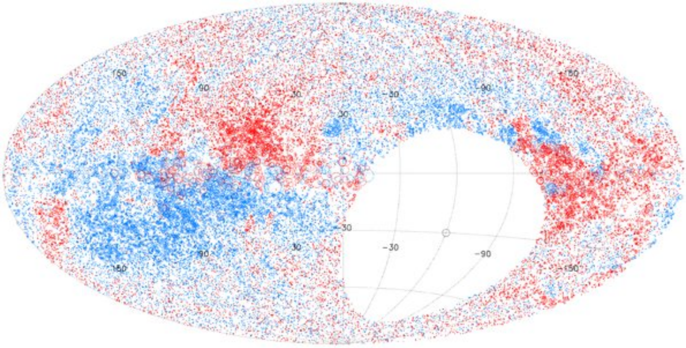
- produced by the spiraling motion of relativistic electrons in $\vec{B}$
- total emission provides an estimate of $|\vec{B}|$ $\langle n_e \vec{B}^2 \rangle$
- degree of polarization provides uniformity and structure
- $B_{\rm galaxy} \approx 10^{-6}$ G
  coherence length $1 - 10$ kpc



Credit: Govoni & Ferriti (2004)

Detection methods

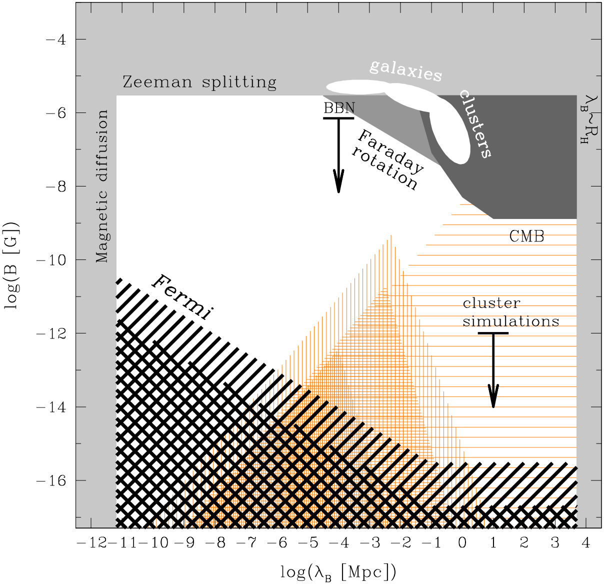
Faraday rotation



Taylor et al (2010)

- polarized radiation from a distant object passes through $\vec{B}$ of an intervening object and is altered $\sim \int n_e \vec{B} \cdot d\vec{l}$
- $B_{\rm galaxy} \approx 0.1\mu$ G
  coherence length 10 kpc

Cosmological Magnetic fields: Limits



Upper bound

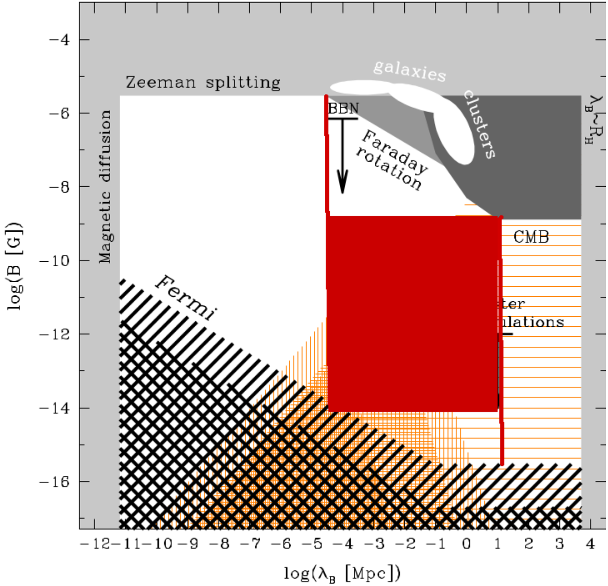
- BBN $\sim 0.1\ \mu$G
  [Grasso & Rubinstein '01]
- CMBR $\sim$ nG
  [Yamazaki et al '10]
- Reionization $\sim$ nG
  [Schleicher & Miniati '11]

Lower bound

- TeV Blazar/FERMI
  $\sim 10^{-6}$ nG
  [Tavechio et al '11]

Neronov & Vovk (2010)

Cosmological Magnetic fields: Limits



What is the origin of these large scale magnetic fields?

Neronov & Vovk (2010)

Generation of magnetic fields

Generation of magnetic fields

Grasso & Rubinstein '01, Widrow '02

Late times ($z \sim 20$)

- fields generated in proto galaxies; spilled to IGM
- Experimental Constraints $\Longrightarrow$ fields of $10^{-15}G$ are in every void
- difficult to produce fields with such coherence length ($10\ \mathrm{Kpc}$)

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- Inflation; breaking of conformal invariance
- QCD or EW phase transition
- causal process of large scale generation;
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☛ Talk will focus on new mechanism that generates in intermediate scales

Evolution of magnetic field and matching with observations

Model

pre-decoupling era
$z > 1000$

- freezing of magnetic flux; high conductivity of the medium
- $B \propto a^{-2}$
- $B_1 = 10^{-2} \times B_{\mathrm{seed}}$

Dark ages
$1000 < z < 10$

- matter collapse; adiabatic compression
- formation of first structures
- $B_2 = 10^4 \times B_1 = 10^2 \times B_{\mathrm{seed}}$

Galaxy formation
$z < 10$

- Galactic or inter-galactic dynamo mechanism (uncertainty)
- easier to have amplification in dense regions
- Amplification factor $\mathcal{A} = [10^7, 10^{28}]$
- $B_{\mathrm{obs}} = \mathcal{A} \times B_2 = \mathcal{A} \times 10^2 \times B_{seed}$

Current Measurements

Model and its predictions

Model and assumptions

Features $1eV \sim 10^4 K$

- Before recombination; energy range $20 < T < 100$ eV
- No new physics
- Generation of the Vorticity through the mechanism introduced by Berezhiani and Dolgov (2003)

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Ingredients

- Universe = hot, dense plasma
- protons + electrons + photons + dark matter
- n_e: number density of electrons
- n_p: number density of protons
- n_γ: number density of photons
- charge neutrality $\Longrightarrow \quad n_e = n_p$
- Radiation dominated $\Longrightarrow \beta = n_e/n_\gamma = 6 \times 10^{-10}$ (CMBR)

Interactions

- Thomson scattering of photons on free electrons :

  $e^- + \gamma \Rightarrow e^- + \gamma$ Responsible for vorticity generation

- Coulomb scattering of electrons on protons:

  $p + e^- \Rightarrow p + e^-$ Responsible for magnetic field generation

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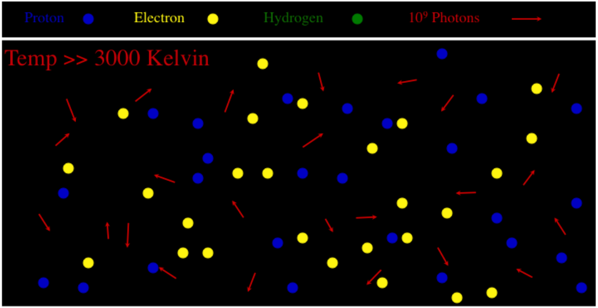
- $v_p << v_{e^-} << v_\gamma$
- $v_p << v_{e^-}$: induced current $\vec{J}$ leading to seed magnetic field $\vec{B}_{\mathrm{seed}}$
- $v_{e^-} << v_\gamma$: plasma velocity $v \approx v_\gamma$

Vorticity generation

- Plasma has low Reynold's number.



Electrons scatter of Photons efficiently.

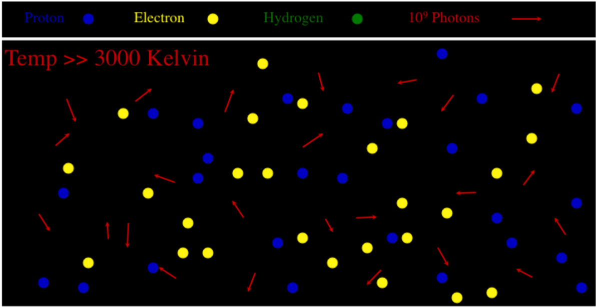
Uniform distribution of Photons do not generate any Vorticity.

- Boltzmann equation for f_γ

$$\left(\partial_t + \vec{V}.\nabla\right) \boldsymbol{f}_\gamma(t, \vec{x}, E, \vec{p}) = I_{\text{coll}}[f_i] \propto \Gamma_{\text{Th}}$$

- $\vec{V}$ is particle velocity (for photons, electrons) and not macroscopic fluid velocity $\vec{v}$
- $f_\gamma \approx f_\gamma^{(0)} = e^{-E/T}$

Vorticity generation



primordial perturbations reenter producing changes in the photon distribution

Electrons are not uniformly scattered everywhere resulting in small vorticity generation.

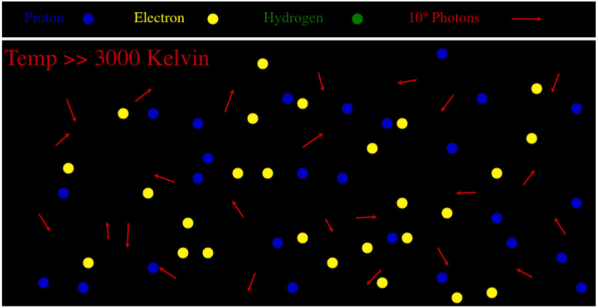
- $f_\gamma = f_\gamma^{(0)}(t) + f_\gamma^{(1)}(t, \mathbf{x}) + f_\gamma^{(2)}(t, \mathbf{x})$

$$\mathcal{K} = \partial_t + \vec{V}.\nabla - H\vec{p}.\partial_{\vec{p}} + \vec{F}.\partial_{\vec{p}}$$

$$f_\gamma^{(1)} = -\left(\frac{1}{\Gamma_{\rm Th}}\mathcal{K}f_\gamma^{(0)} - \frac{1}{\Gamma_{\rm Th}^2}(\partial_t + V_j\partial_j)\mathcal{K}f_\gamma^{(0)} + \frac{3}{\Gamma_{\rm Th}^2}\left[\frac{\partial_t T}{T} + V_i\frac{\partial_i T}{T}\right]\mathcal{K}f_\gamma^{(0)}\right)$$

$$f_\gamma^{(2)} = -\int_0^t \mathrm{d}\tau_1 \exp\left[-\int_0^{\tau_1}\mathrm{d}\tau_2\Gamma_{\rm Th}(t-\tau_2, \vec{x}-\vec{v}\tau_2)\right]\mathcal{K}f_\gamma^{(1)}(t-\tau_1, \vec{x}-\vec{v}\tau_1)$$

Vorticity generation



Changes in the Photon distribution function induces macroscopic changes in the plasma fluid, specifically non-zero vorticity.

- Average macroscopic velocity of the plasma $\vec{v}$

$$v_k = \frac{1}{\int \mathrm{d}^3\vec{p}\ f_\gamma^{(0)}} \int \mathrm{d}^3\vec{p}\ V_k f_\gamma$$

- Vorticity $(\vec{\Omega} = \vec{\nabla} \times \vec{v})$ is $\quad \Omega \approx 12 \times 10^3 \times c \frac{\ell_\gamma^3}{\lambda^4} \left(\frac{\delta T}{T}\right)^2$

From Vorticity to Magnetic fields

MHD equation for a conductive fluid:

$$\partial_t \vec{B}_{\rm seed} = \vec{\nabla} \times (\vec{v} \times \vec{B}_{\rm seed}) + \frac{e\, n_e}{\kappa} \vec{\Omega}$$

- Seed magnetic field $\vec{B}_{\rm seed}$
- Fluid velocity $\vec{v}$
- Conductivity due to interactions κ
- Vorticity $\vec{\Omega} = \vec{\nabla} \times \vec{v}$

$$B_{\rm seed} \approx \boldsymbol{t} \times e \times n_e \frac{\Omega}{\boldsymbol{\kappa}}$$

$B_{\rm seed} \propto \kappa^{-1} \quad \Longrightarrow \quad$ process with lowest κ lead to maximum contribution

Conductivity of the processes

- Conductivity

$$\kappa = J/E = e^2 n_e \Delta t / m_e \qquad \Delta t \text{ time between 2 collisions}$$

- $\kappa_{\mathrm{Coul}}(\kappa_{\mathrm{Th}})$ conductivity due to Coulomb (Thomson) scattering
- Ratio of conductivities

$$\frac{\kappa_{\mathrm{Th}}}{\kappa_{\mathrm{Coul}}} = \frac{\beta \ln(\Lambda)}{\sqrt{\pi}} \left(\frac{m_e c^2}{k_B T}\right)^{5/2} \approx 10^{-9} \times \frac{1}{(T_{\mathrm{MeV}})^{5/2}}$$

- For $1 < T < 100$ eV,

$$\frac{1}{\kappa_{\mathrm{Coul}}} \gg \frac{1}{\kappa_{\mathrm{Th}}} \qquad \Longrightarrow \qquad \frac{1}{\kappa} \approx \frac{1}{\kappa_{\mathrm{Coul}}}$$

Seed Magnetic field

- $B_{\rm seed}$

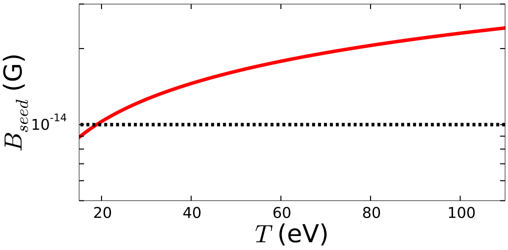
$$\frac{\boldsymbol{B}_{\mathbf{seed}}}{(k_B T)^2}\left(\epsilon_0 \hbar^3 c^5\right)^{1/2} \approx 2.4 \times \left(\frac{m_e c^2}{k_B T}\right)^{1/2} \times \beta \ln(\Lambda) \times \frac{ct\ell_\gamma^3}{\lambda^4}\left(\frac{\delta T}{T}\right)^2$$

- Let us consider fluctuations entering the Hubble horizon at $T >> 1\ {\rm eV}$ during the radiation-domination era.
- $\lambda_M = \lambda_0 / 1\ {\rm Mpc}$: actual coherence length $\boldsymbol{B}_{\mathbf{seed}}$, where $\boldsymbol{\lambda_0}$ is the actual size of the fluctuations

$$\frac{T}{1\ {\rm eV}} = 1.64 \times \lambda_M^{-2/3}$$

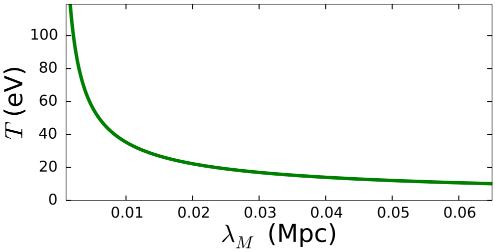
$$\lambda_M = 2.1 \times \left(\frac{T}{1\ {\rm eV}}\right)^{-3/2}$$

Magnetic field generated



$$\frac{B_{\rm seed}}{1\ {\rm G}} = 3 \times 10^{-15} \times \lambda_M^{-1/3}$$

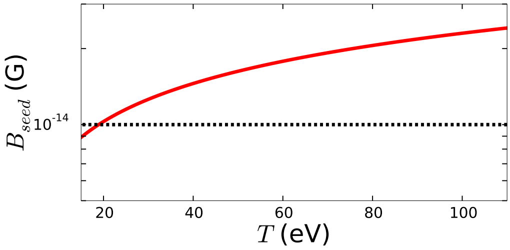
$$\frac{B_{\rm seed}}{1\ {\rm G}} = 2.3 \times 10^{-15} \times \left[\frac{T}{1\ {\rm eV}}\right]^{1/2}$$



For galactic scales $\approx 10\ {\rm kpc}$

$B_{\rm seed} \approx 10^{-14}\ {\rm G}$

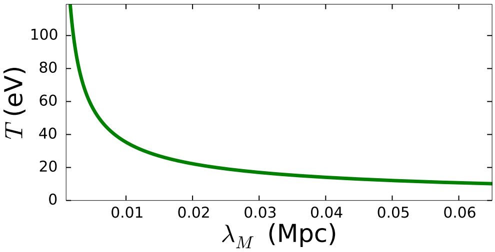
Magnetic field generated



Back

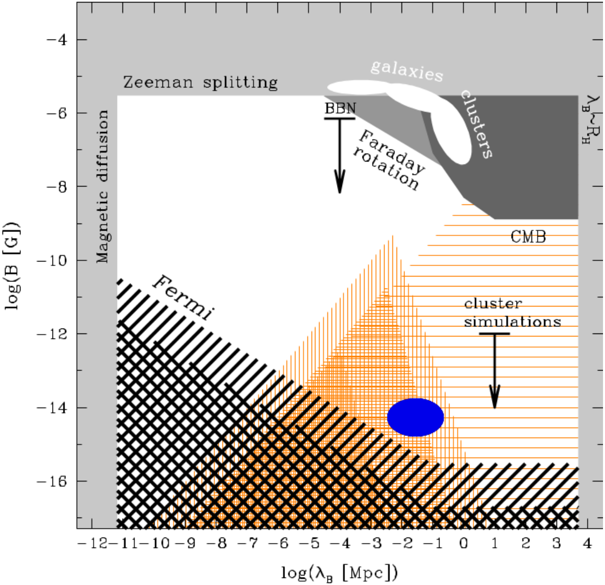
$$B^{(\mathrm{gal})} = 10^2 \times \mathcal{A}_{\mathrm{gal}} \times \boldsymbol{B}^{(\mathbf{gal})}_{\mathbf{seed}}$$

$$B^{(\mathrm{gal})} = 10^{-6}\ \mathrm{G}$$
$$\Longrightarrow \mathcal{A}_{\mathrm{gal}} = 10^6$$



New mechanism allows us to generate galactic scale magnetic fields compatible with low dynamo amplification.

Constraints on B and λ_B



- Grey: known observational bounds on extra-galactic B
- BBN constraints
- Black hatched region: lower bound on extra-galactic B derived from *Fermi*
- Orange hatched regions: constraints on seed fields generated.
- Our model predicts

$$B \simeq 10^{-14} G$$
$$\lambda_M \sim 10 kPc$$

Neronov & Vovk (2010)

Conclusion and perspectives

Conclusion

- Intermediate scale, mechanism to generate large-scale magnetic fields
- Based of the known physics of the cosmological plasma just before recombination
- With low galactic dynamo amplification, recover galactic $\vec{B}$ fields detected strength

Perspectives

- More accurate evaluation of Coulomb and Thomson contributions in the Boltzmann equation
- Imprints of these $\vec{B}$ fields on the Cosmic Microwave Background (CMB), especially on its E and B-modes

Thank you for your attention