Magnetic Field Generation Induced by Streaming Cosmic Rays

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Web page

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1. Introduction

- Cosmic Rays (CRs) and magnetic fields are important constituents in the current universe.

  -> How about in the early universe?

- Magnetic fields are observed in various length scales.

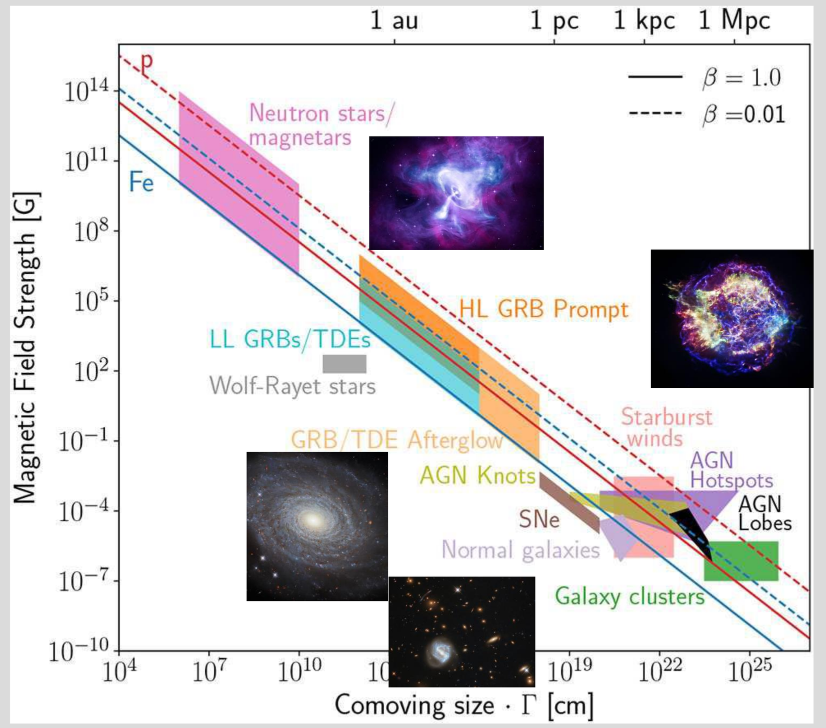
- A lower bound on the magnetic field strength in the cosmic void is given by **γ-ray observations** of TeV blazers (Neronov & Vovk, 2010).

  -> What is the origin of magnetic fields?

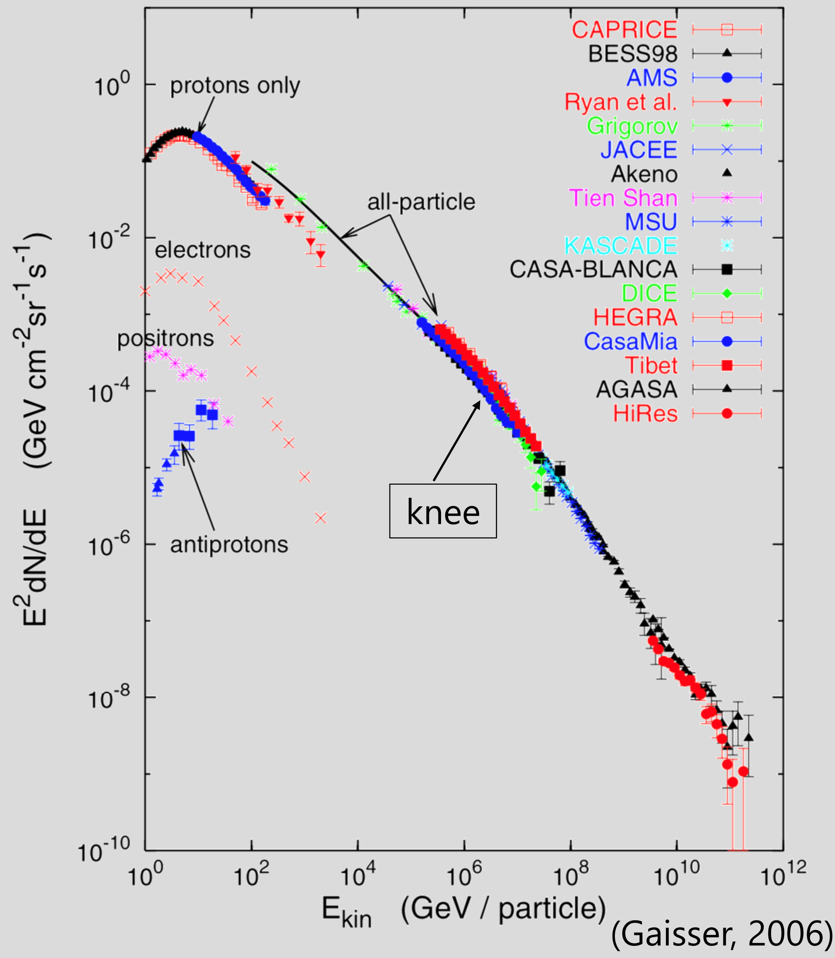
Energy density in the local interstellar medium

Component	Energy density
Starlight	0.54 eV cm^{-3}
Thermal kinetic energy	0.49 eV cm^{-3}
Turbulence	0.22 eV cm^{-3}
Magnetic field	0.89 eV cm^{-3}
Cosmic rays	1.39 eV cm^{-3}

(Draine, 2011)



(Alves Batista, 2019 & NASA)

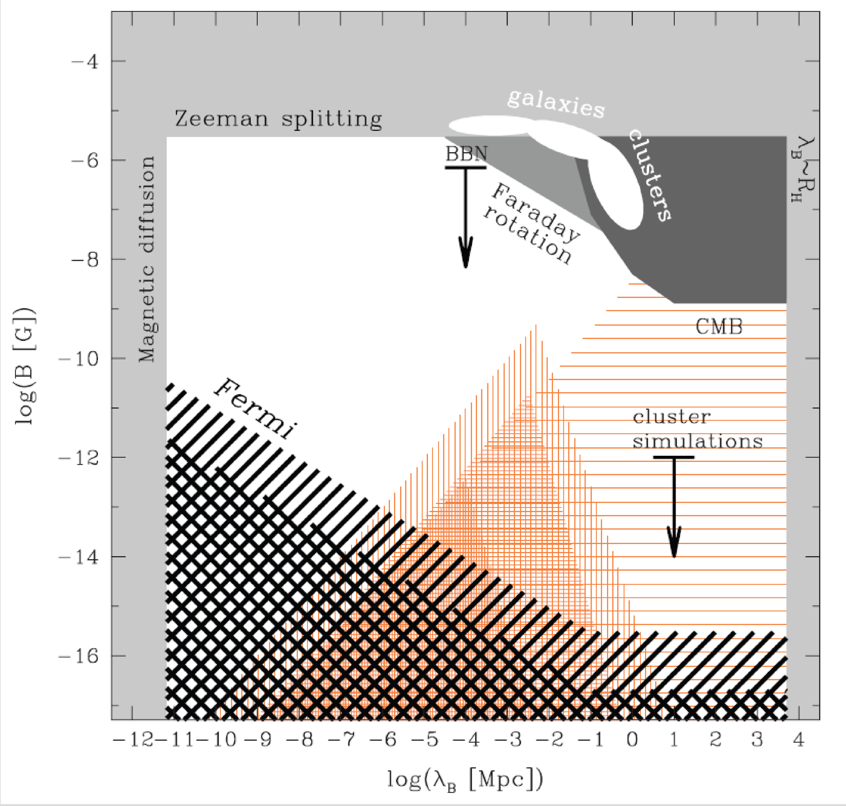


(Gaisser, 2006)

- There are two classes of magnetogenesis in the early universe (e.g. Subramanian, 2016):
  - ✓ **Primordial origin** (e.g. inflation, electroweak or QCD phase transition)
  - ✓ **Astrophysical origin** (e.g. Biermann battery around forming galaxies)

- CRs are accelerated in shocks of supernova remnants of the first stars (Ohira & Murase, 2019).

  -> We investigate astrophysical **magnetogenesis induced by CRs.**



(Neronov & Vovk, 2011)

2. Generation Mechanism

- Generalized Ohm's law

$$\boldsymbol{E} = -\frac{\boldsymbol{V}_e}{c}\times\boldsymbol{B} + \frac{m_e}{n_e e^2}\nabla\cdot\left(\sum_s q_s n_s \boldsymbol{V}_s\boldsymbol{V}_s\right) - \frac{\nabla P_e}{n_e e} + \eta \boldsymbol{J}_t$$

- The second term in the RHS is relevant for the generation mechanism proposed by Ohira, 2021 (hereafter, O21).
- Applying Faraday's law and keeping the relevant terms for our purpose,

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla\times(\boldsymbol{V}_e\times\boldsymbol{B}) + \frac{c^2\eta}{4\pi}\nabla^2\boldsymbol{B} - \frac{c}{n_e e^2}\nabla n_e\times\nabla P_e + c\nabla\times(\eta \boldsymbol{J}_{CR})$$

- The last term in the RHS is relevant for the generation mechanism proposed by Miniati & Bell, 2011 (hereafter, MB11).
- CRs also induce **resistive heating** (MB11).

$$\frac{d}{dt}\left(\frac{3}{2}nk_BT\right) = \eta J_{CR}^2, \qquad \eta = 7.23\times10^{-9}\log\Lambda\left(\frac{T}{1\ \mathrm{K}}\right)^{-3/2}\ \mathrm{sec}$$

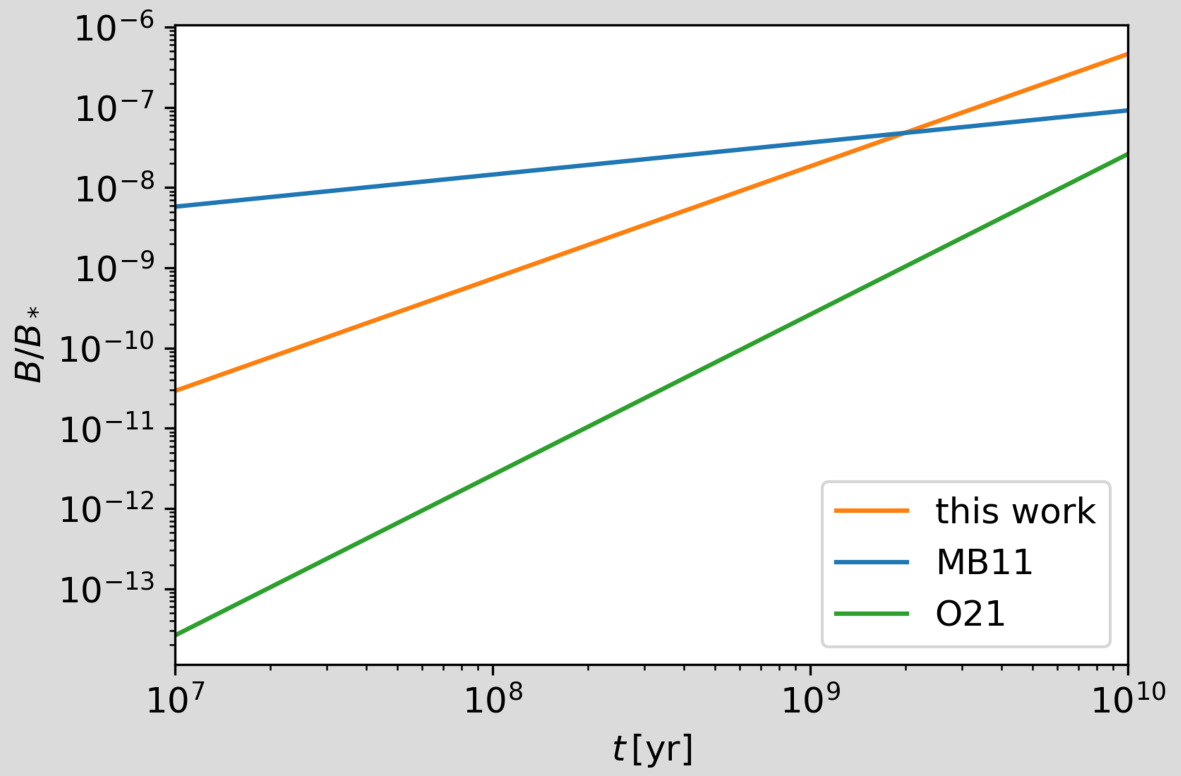
- If CRs propagate inhomogeneously, plasmas are also heated inhomogeneously and produces ∇T which is misaligned with ∇n_e.

  -> CR streaming induces the Biermann battery $\nabla n_e \times \nabla P_e$.

  : **New driving mechanism** of the Biermann battery!

- Exploiting some simplifying assumptions, we can solve these equations analytically.

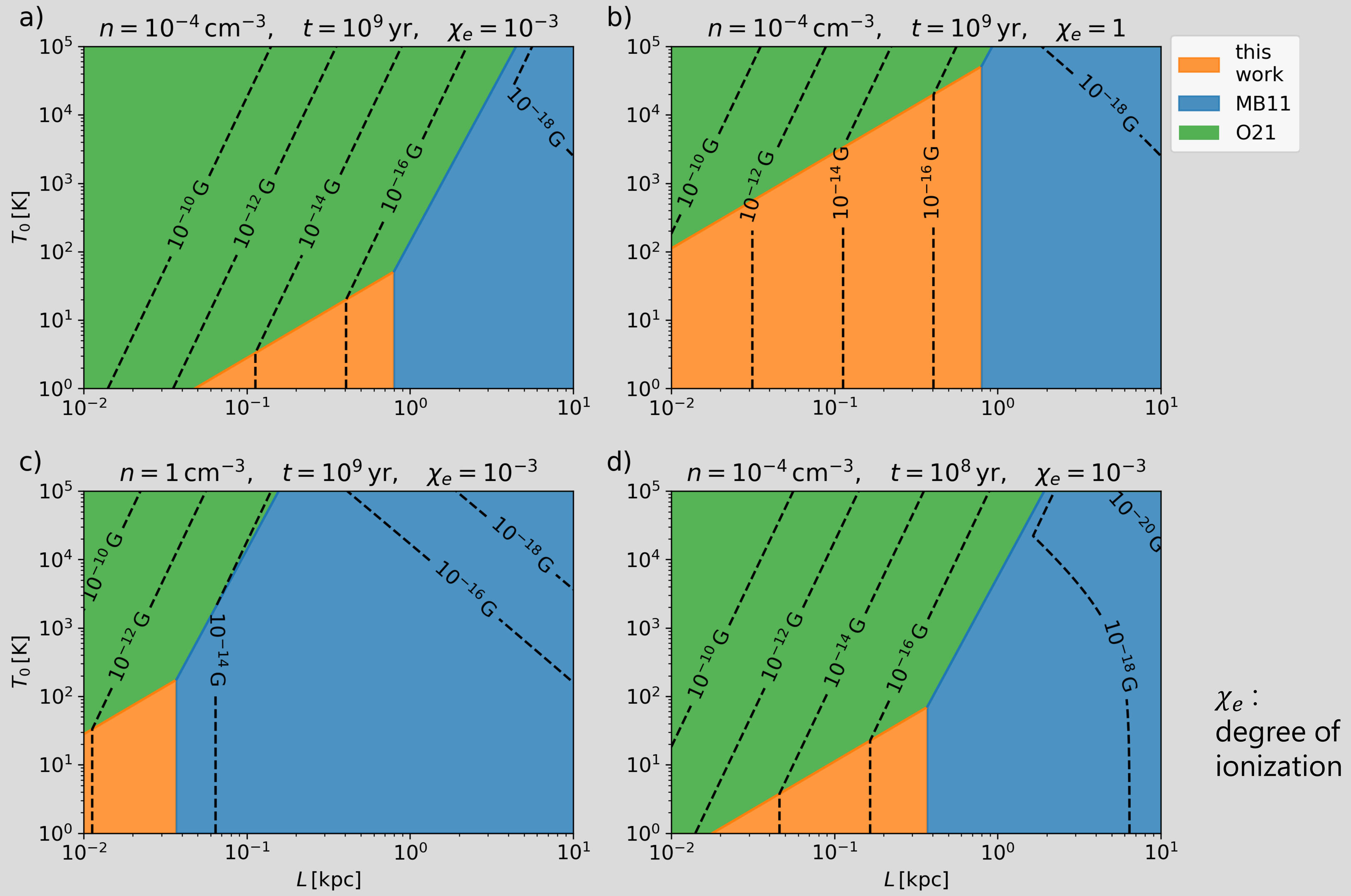
$$B \simeq 3.9\times10^{-18}\ \mathrm{G}\left(\frac{n}{10^{-4}\ \mathrm{cm}^{-3}}\right)^{-2/5} \cdot \left(\frac{L}{1\ \mathrm{kpc}}\right)^{-2}\left(\frac{n_{CR}V_{CR}}{10\ \mathrm{cm}^{-2}\mathrm{s}^{-1}}\right)^{4/5}\left(\frac{t}{1\ \mathrm{Gyr}}\right)^{7/5}$$



$B_* = 2.1\times10^{-10}$ G

3. Comparison with other mechanisms

- We compare our new mechanism with the previously proposed mechanisms of magnetogenesis induced by CRs (Miniati & Bell, 2011 and Ohira, 2021).
- Our new mechanism dominates in relatively small-scale, low-temperature, and strongly-ionized plasmas



χ_e : degree of ionization

4. Summary

- We found a **new driving mechanism of the Biermann battery**, that is, inhomogeneous **resistive heating induced by streaming CRs**.
- The strength achieved by this mechanism is sufficient for the seed of galactic magnetic fields found in the current universe.
- Our mechanism dominates over the previously proposed ones in relatively small-scale, low-temperature, and strongly-ionized regions.

5. Future works (Remained questions)

- Evolution of seed magnetic fields to the galactic fields.

  -> simulations including both generation of seed magnetic fields and their subsequent dynamo amplification.

- Other influence of the first CRs on the evolution of early universe (e.g. ionization, gas heating).