Dark Matter at the origin of the Galactic Magnetic Fields

University of Pisa, 24th June 2019

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Outline

- Introduction to Galactic Magnetic Fields
- What is their origin? Possible models that explain the origin of Galactic Magnetic Fields
    - CMB
    - Dark Matter
- Summary

Introduction

Galactic magnetic fields → very important component of the galactic dynamics

- Relevant for the compression of gas clouds and formation of spiral arms
- Influence the star formation process and the evolution of the galaxies
- Determine the spectrum of the galactic cosmic rays

Measurement of galactic magnetic fields

↓

Radiotelescopes

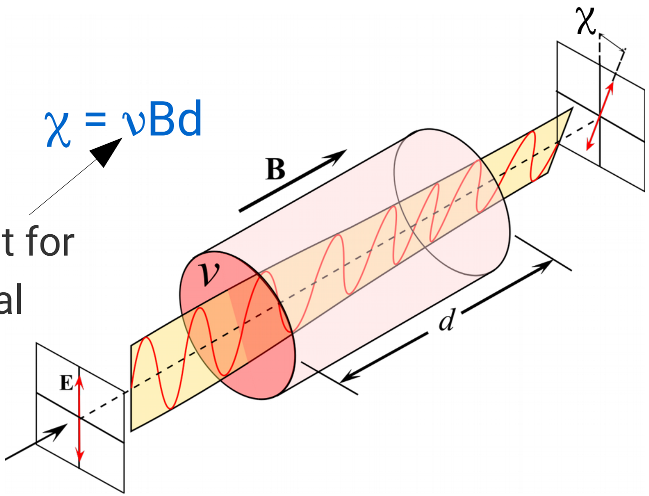

Very Large Array, Socorro, USA

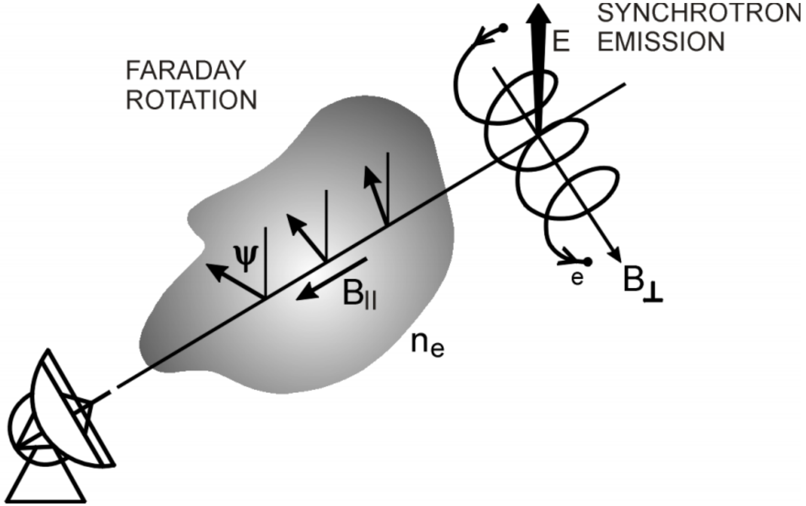
Notes on the measurement of Galactic Magnetic Fields

Measurements of light polarization → Faraday Rotation

$\chi = \nu B d$

ν: constant for the material crossed





$$RM = k\int_0^L n_e \mathbf{B}\cdot ds$$

RM: Faraday rotation measure
L: distance (pc = $3\cdot 10^{18}$ cm)
n_e: electron density (cm^{-3})
B: magnetic field (G)
k: constant

$$RM = \frac{\chi(\lambda_1) - \chi(\lambda_2)}{\lambda_1^2 - \lambda_2^2}$$

$\chi(\lambda)$ is the polarization angle associated to the wavelenght λ

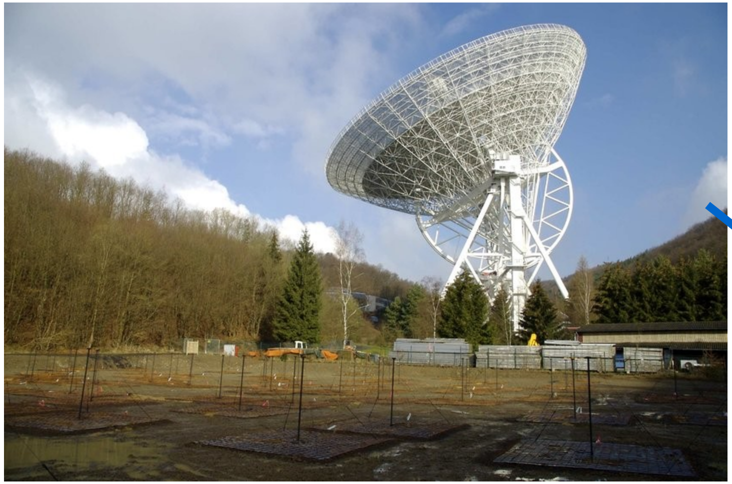
Set of measurements (λ_i, $\chi(\lambda_i)$)

$$\chi(\lambda) = \mathrm{constant} + \mathrm{RM}\cdot\lambda^2$$

Extract *RM* from a fit

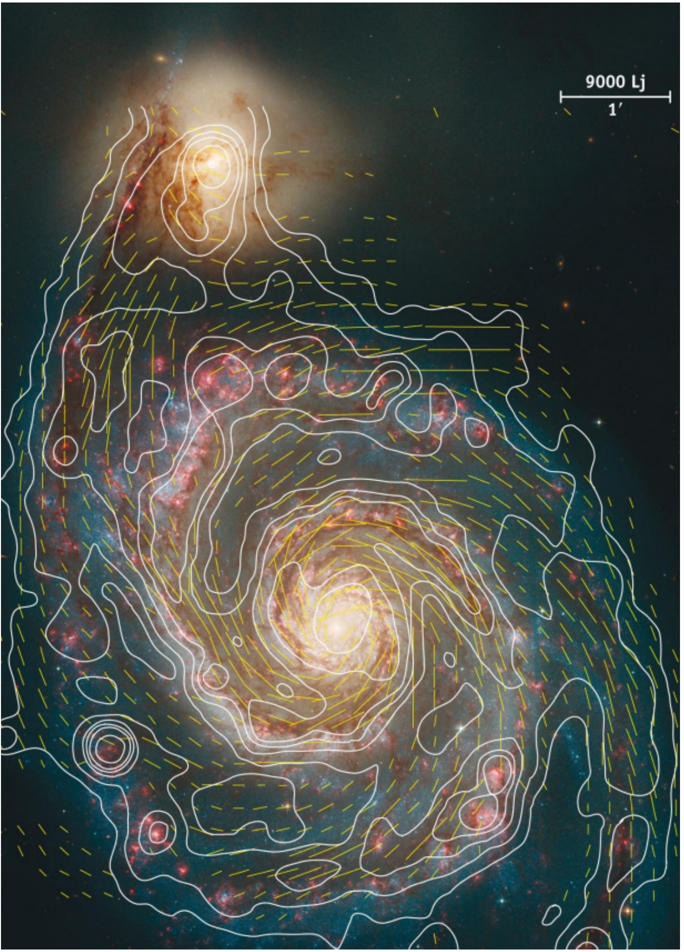
Observations of galactic magnetic fields

Effelsberg Telescope, Germany



Very Large Array, Socorro, USA

Spiral Galaxy M51 (HST)



HST = Hubble Space Telescope

Total radio emission (contours) and magnetic field vectors at 4.8 GHz

Galactic Magnetic Fields characteristics

- Galatic Magnetic Fields ~ μG
  - Milky Way ~ 6 μG near the sun and ~ 20 / 40 μG in the center (Earth's Magnetic Field ~ 0.1 G)
- Magnetic fields observed are enhanced by galactic dynamo effect → combined effect of differential rotation and helical turbulence
- The dynamo effect can amplify magnetic fields up to the values observed today but it works if a magnetic field was already present → B_{seed}
- What is the origin of the magnetic fields?
- ...we will try to find an answer to this question!

Estimate of the initial Magnetic Field needed

- Dynamo mechanism can lead to an exponential increase of the galactic magnetic fields till $B_{eq} = B \sim \mu G$ starting from very small B_{seed}

- In order to reach the B_{eq} the seed must satisfy $B_{seed} > B_{eq} e^{-\frac{t-t_{gal}}{\tau_{dyn}}}$
  - t_{gal}: time of galaxy formation
  - τ_{dyn}: action time of the dynamo ~0.2 – 0.5 Gyr (depends on the characteristics of the plasma in the protogalaxy)

- If t = 14 Gyr → $B \sim \mu G$ with $B_{seed} < 10^{-20}$ G, it seems to work! The problem is that also galaxies at cosmological redshift z = 1 or 2 (t ~ 4.4 Gyr) show $B \sim \mu G$
  - too young for an efficient dynamo effect → higher B_{seed} needed

It can be shown that at least $B_{seed} \sim 10^{-15}$ G is required

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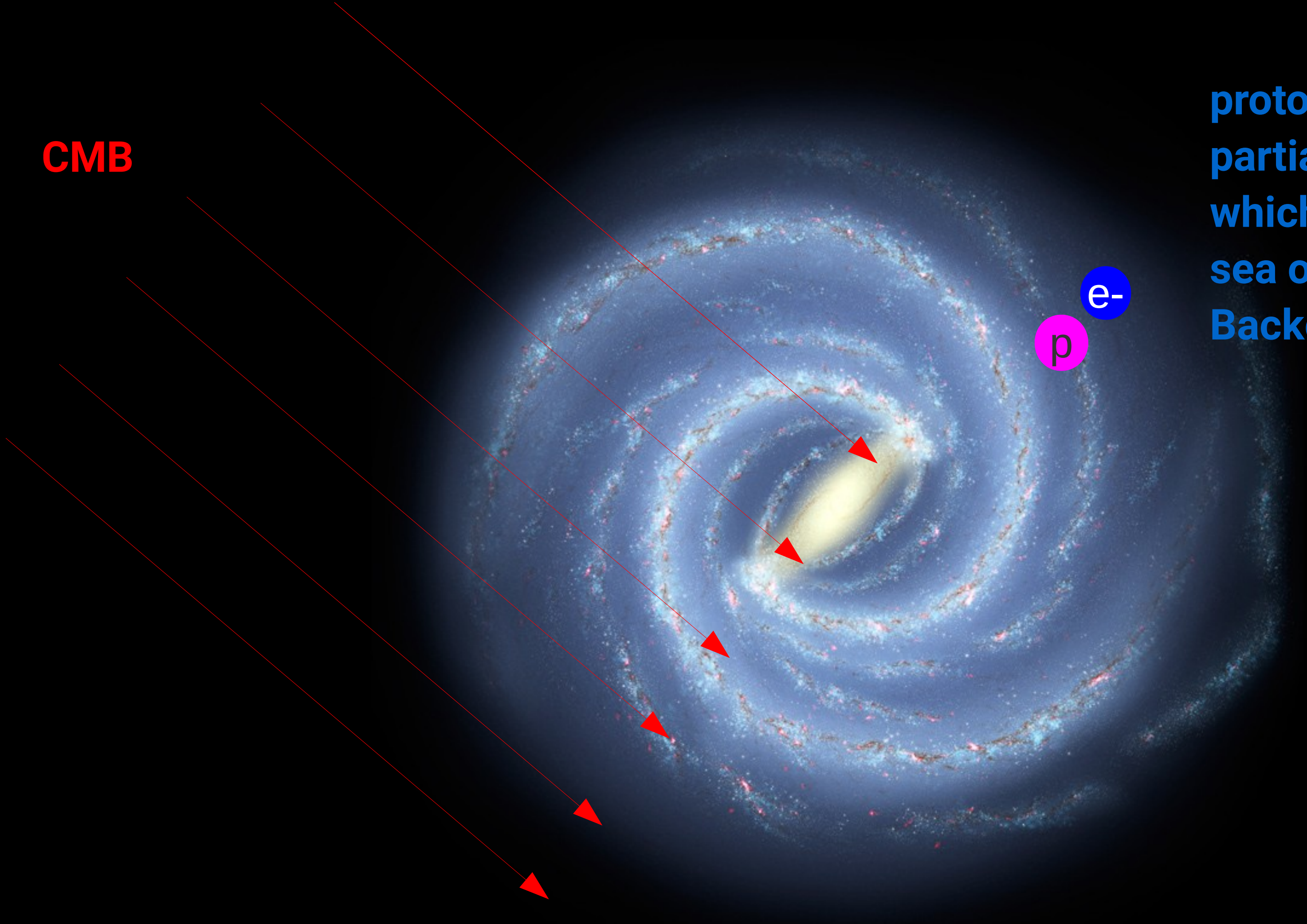
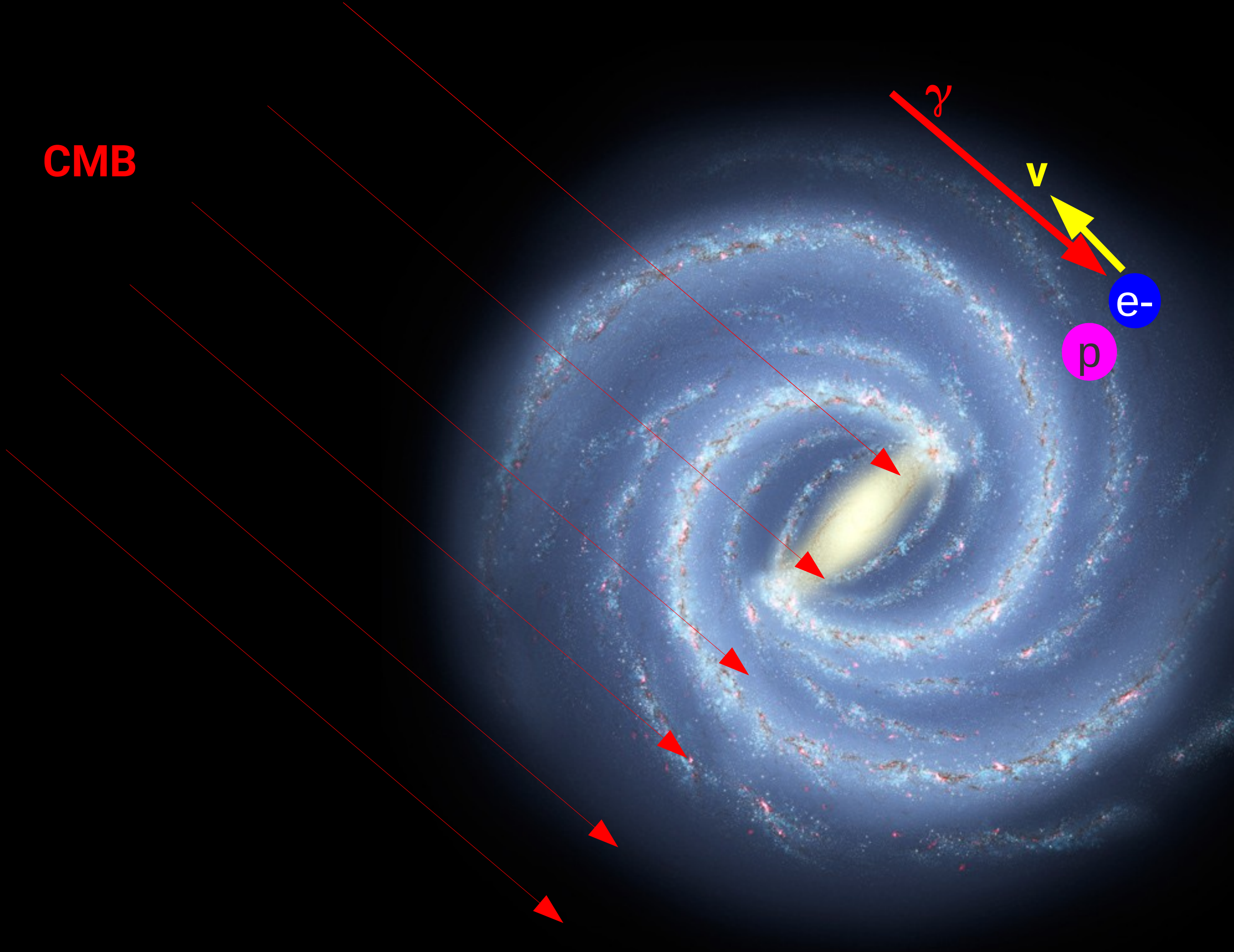
CMB at the origin of Galactic Magnetic Fields



protogalaxy: cloud of partially ionized matter which rotates in the isotropic sea of Cosmic Microwave Background (CMB) photons

CMB at the origin of Galactic Magnetic Fields



Photons interact with electrons with the Thomson cross-section $\sigma_{e\gamma}$

v: local flow velocity of electrons in plasma

Drag force induced:

$F = evB_F$

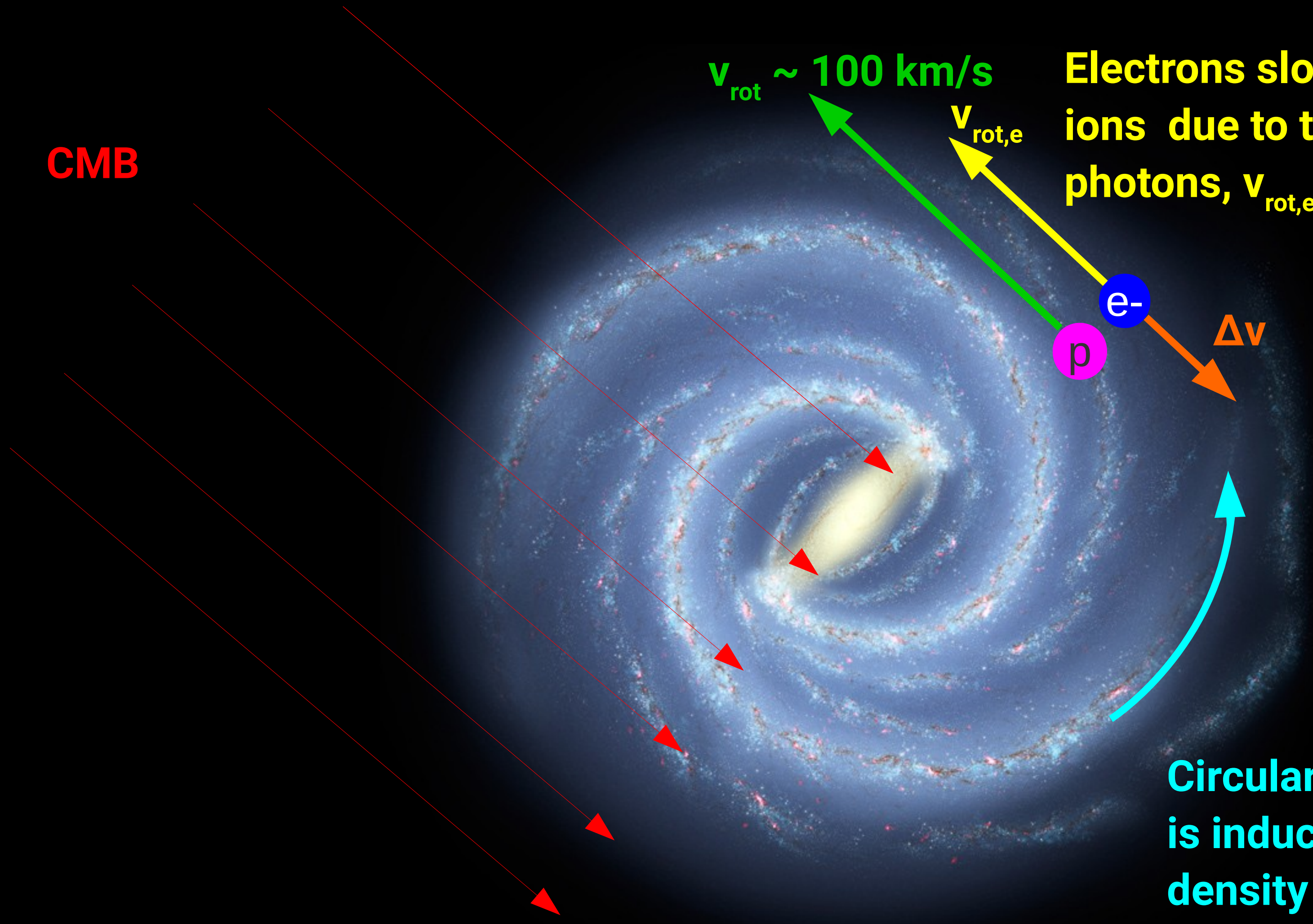
$B_F = \sigma_{e\gamma} n_\gamma \omega_\gamma / e$

n_γ: number density of the CMB photons

ω_γ: mean energy of the CMB photons

CMB pressure on protons is negligible: $\sigma_{p\gamma}/\sigma_{e\gamma} \sim (m_e/m_p)^2$

CMB at the origin of Galactic Magnetic Fields



Electrons slow down with respect ions due to the interaction with photons, $v_{rot,e} < v_{rot}$

CMB pressure causes a relative drag of electrons in the direction opposite to the galaxy rotation

Circular current is induced, density $j = en_e\Delta v$

B_{seed} generated by the CMB action

- $j = en_e \Delta v = \sigma F/e$ → F is the drag force applied by the CMB, σ is the electric conductivity of the plasma → it depends on the time of interaction between e-p

- Magnetic Hydrodynamics (MHD) Maxwell equation → external force F acting on electrons

density current vector

local flow velocity of electrons

$$\mathbf{J} = \sigma(\mathbf{E} + \mathbf{v} \times \mathbf{B} + \mathbf{F}/e)$$

conductivity of plasma

drag force

- Solving the MHD Maxwell equations → Source term B_F inducing a nonzero magnetic seed field in $B(t)$

- Considering that the highest B_{seed} can be obtained around the decoupling epoch (z ~ 1000 → t ~ 500 kyr); at earlier times the plasma is strongly coupled and Δv is negligible

Highest $B_{seed} < 10^{-20}$ G, CMB is not enough (required $B_{seed} \sim 10^{-15}$ G)

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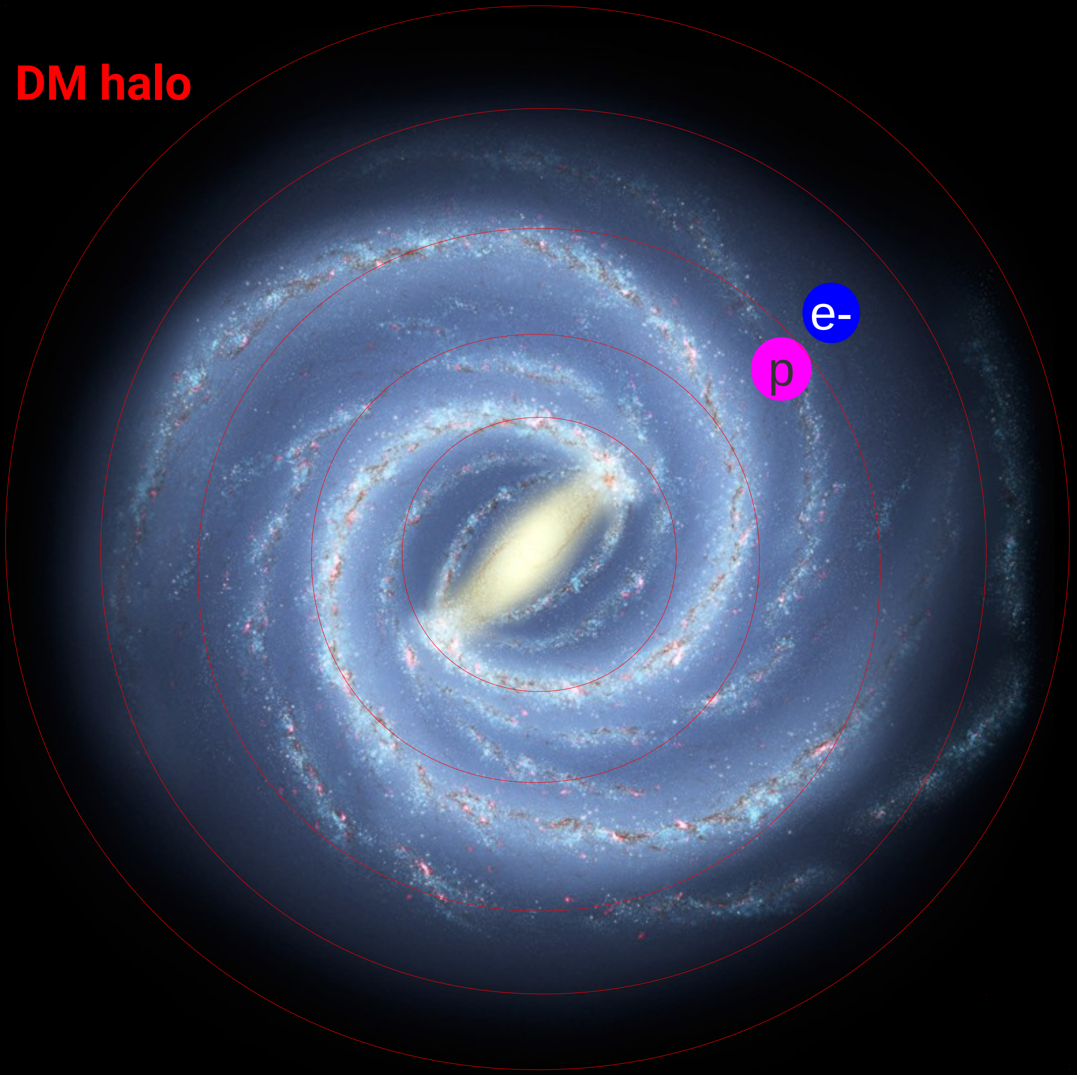
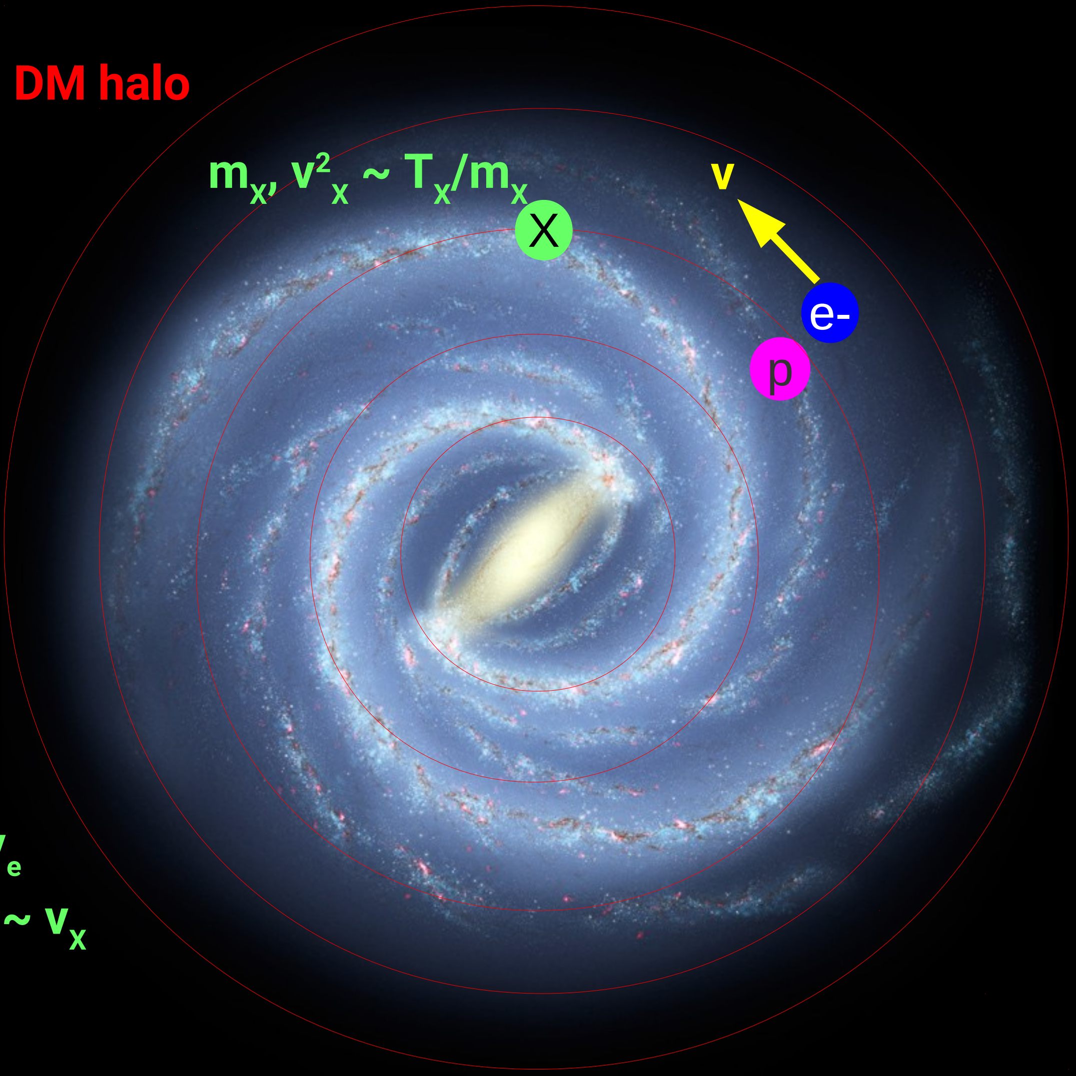


protogalaxy: cloud of partially ionized matter which rotates immersed in the Dark Matter (DM) halo

Dark Matter at the origin of Galactic Magnetic Fields



DM particles X interact with electrons with the elastic scattering cross-section σ_{eX}

v: local flow velocity of electrons in plasma

Drag force induced:

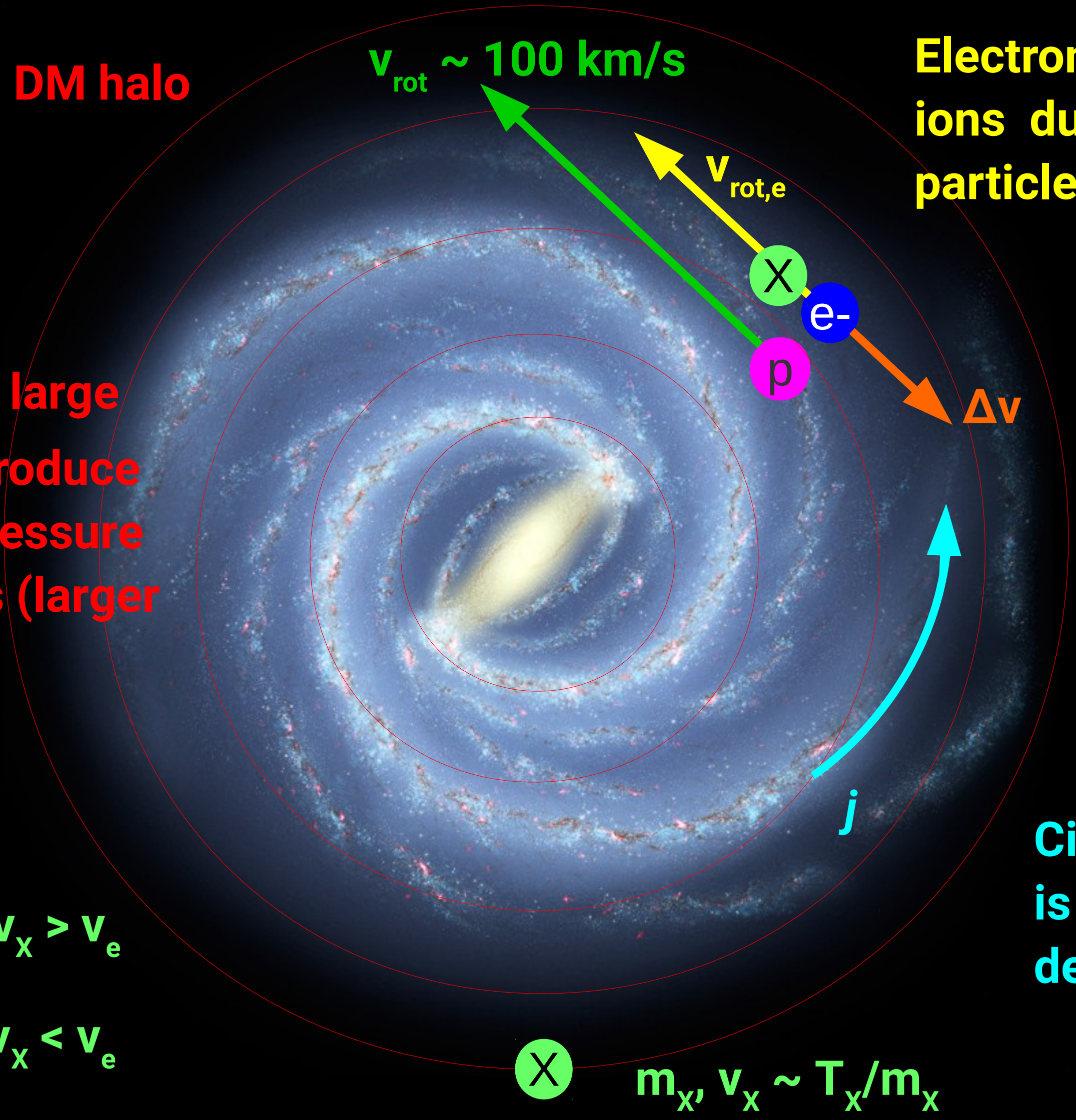
$$F = evB_F$$

$$B_F = \sigma_{eX} n_X m_X v_{rel} / e$$

n_X: number density of X particles in the halo
m_X: mass of X particles
v_{rel}: relative velocity between the electrons and X particles

- **if $v_X >> v_e$ than $v_{rel} \sim v_X$**

Dark Matter at the origin of Galactic Magnetic Fields



Electrons slow down with respect ions due to the interaction with DM particles X, $v_{rot,e} < v_{rot}$

σ_{eX} must be large enough to produce sufficient pressure on electrons (larger than CMB)

DM pressure causes a relative drag of electrons in the direction opposite to the galaxy rotation

Circular current is induced, density $j = en_e\Delta v$

- **$m_X < m_e$, $v_X > v_e$**
- **$m_X > m_e$, $v_X < v_e$**

B_{seed} generated by DM action, $m_X < m_e$

- m_X = 10 keV with a feeble coupling to standard matter
- In the case of CMB we considered that the protogalactic matter rotates while the CMB photons do not
- The same assumption is valid for DM at the epoch of reionization ($z \sim 6 \rightarrow t \sim 1$Gyr) when $\tau_{eX} > t \rightarrow$ the motion of DM component is independent from that of standard matter
- For later epochs ($z < 6$) $\tau_{eX} < t$, so the X particles would be dragged by the rotation of standard matter
- At $z < 6$ ($t > 1$ Gyr) the Universe was completely reionized so the interactions between X and standard matter increase and v_{rel} decreases → B_F is negligible
- Highest B_{seed} can be obtained at the epoch of reionization ($z = 6$)

m_X = 10 keV, $B_{seed} < 10^{-15}$ G, what it is needed

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- Highest B_{seed} can be obtained at the epoch of reionization ($z = 6$)

m_X = 10 keV, $B_{seed} < 10^{-15}$ G (required $B_{seed} \sim 10^{-15}$ G)

B_{seed} generated by DM action, $m_X > m_e$

- A particle of mass $m_X > m_e$ with a feeble coupling to standard matter
- X particles are decoupled from standard matter also for epochs after the complete reionization ($z < 6$)
- The effect of the source B_F can be calculated for later epochs
- Considering for example ($t \sim 2$ Gyr)

- **m_X = 1 MeV, $B_{seed} \sim 10^{-15}$ G**
- **m_X = 1 GeV, $B_{seed} \sim 10^{-12}$ G**

DM with a feeble coupling with standard matter could explain the origin of Galactic Magnetic Fields!

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● $m_X = 1$ MeV, $B_{seed} \sim 10^{-15}$ G

● $m_X = 1$ GeV, $B_{seed} \sim 10^{-12}$ G

DM with a feeble coupling with standard matter could explain the origin of Galactic Magnetic Fields!

Summary

- The galactic magnetic fields are a very important component of the galactic dynamics

- Thanks to radiotelescopes it is possible to measure their intensity (~ μG), study their characteristics and their effects on the life of galaxies, however their origin is still a mistery

- Galactic magnetic fields can be enhanced up to the current observed intensities thanks to the dynamo effect if a magnetic fields $B_{seed} \sim 10^{-15}$ G was alredy present in galaxies

Summary

- The origin of Galatic Magnetic Fields is not explained by CMB pressure on electrons in protogalaxies → $B_{\text{seed}} \sim 10^{-20}$ G is not enough

- In rotating protogalaxies circular currents can be generated by the interaction of free electrons with DM particles → $B_{\text{seed}} < 10^{-15}$ G (depending on the mass of DM particles and on the strenght of the coupling between DM and standard matter)

- Existence of DM with a feeble coupling with standard matter → origin of Galactic Magnetic Fields

Thank you!

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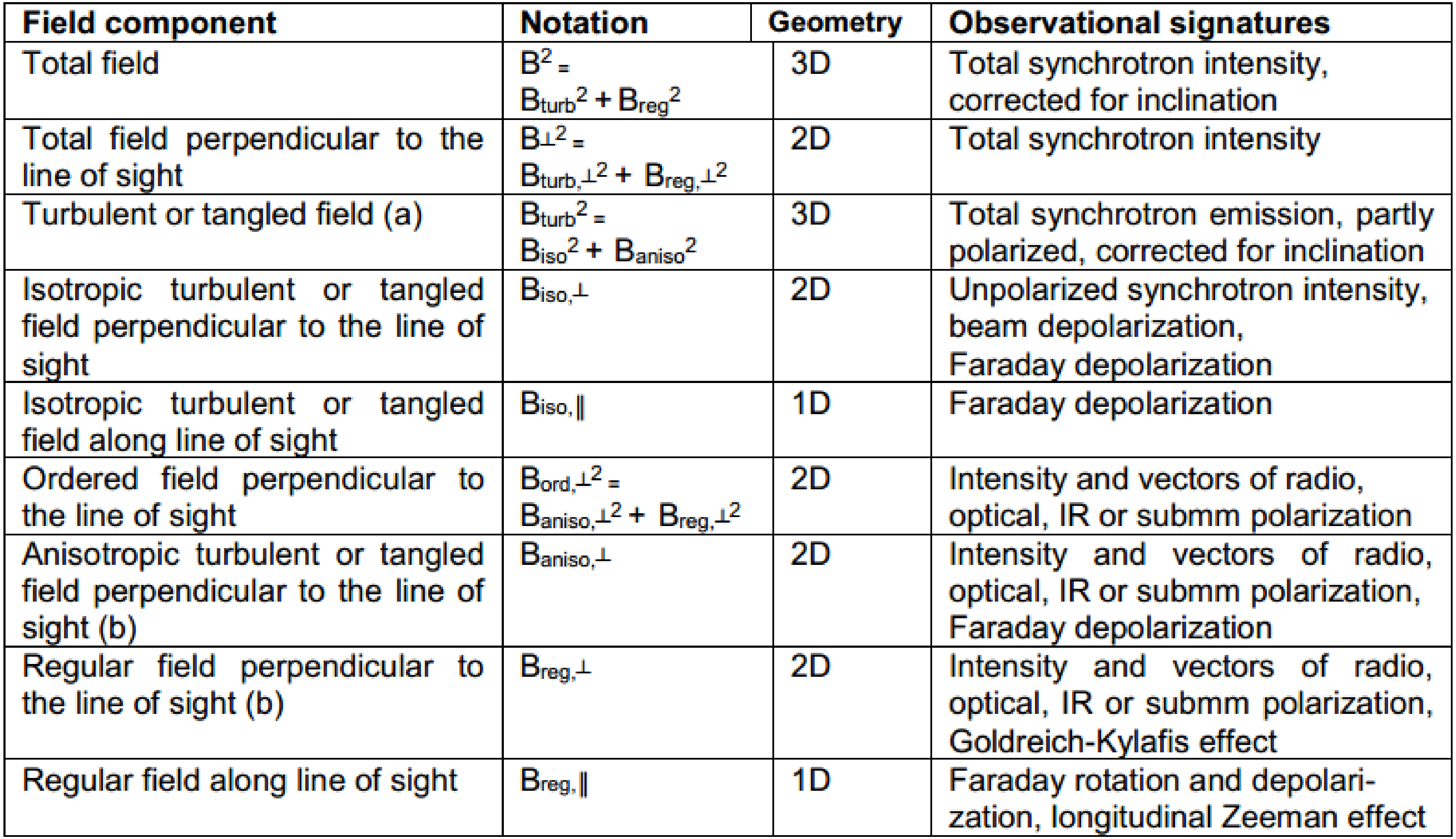
References

- Zurab Berezhiani, A.D. Dolgov and I.I. Tkachev, "*Dark matter and generation of galactic magnetic fields*", *Eur. Phys. J. C* **73**, *2620 (2013) [arXiv:1307.6953* [astro-ph.CO]]

- R. Beck and R. Wielebinski, *"Magnetic Fields in the Milky Way and in Galaxies"* [arXiv:1302.5663 [astro-ph.GA]]

- R. Beck, "*Galactic and Extragalactic Magnetic Fields*", AIP Conf. Proc. **1085**, n°. 1, 83 (2009) [arXiv:0810.2923 [astro-ph]]

Magnetic field components and their observational signatures



Field component	**Notation**	**Geometry**	**Observational signatures**
Total field	$B^2 = B_{turb}^2 + B_{reg}^2$	3D	Total synchrotron intensity, corrected for inclination
Total field perpendicular to the line of sight	$B_\perp^2 = B_{turb,\perp}^2 + B_{reg,\perp}^2$	2D	Total synchrotron intensity
Turbulent or tangled field (a)	$B_{turb}^2 = B_{iso}^2 + B_{aniso}^2$	3D	Total synchrotron emission, partly polarized, corrected for inclination
Isotropic turbulent or tangled field perpendicular to the line of sight	$B_{iso,\perp}$	2D	Unpolarized synchrotron intensity, beam depolarization, Faraday depolarization
Isotropic turbulent or tangled field along line of sight	$B_{iso,\parallel}$	1D	Faraday depolarization
Ordered field perpendicular to the line of sight	$B_{ord,\perp}^2 = B_{aniso,\perp}^2 + B_{reg,\perp}^2$	2D	Intensity and vectors of radio, optical, IR or submm polarization
Anisotropic turbulent or tangled field perpendicular to the line of sight (b)	$B_{aniso,\perp}$	2D	Intensity and vectors of radio, optical, IR or submm polarization, Faraday depolarization
Regular field perpendicular to the line of sight (b)	$B_{reg,\perp}$	2D	Intensity and vectors of radio, optical, IR or submm polarization, Goldreich-Kylafis effect
Regular field along line of sight	$B_{reg,\parallel}$	1D	Faraday rotation and depolarization, longitudinal Zeeman effect