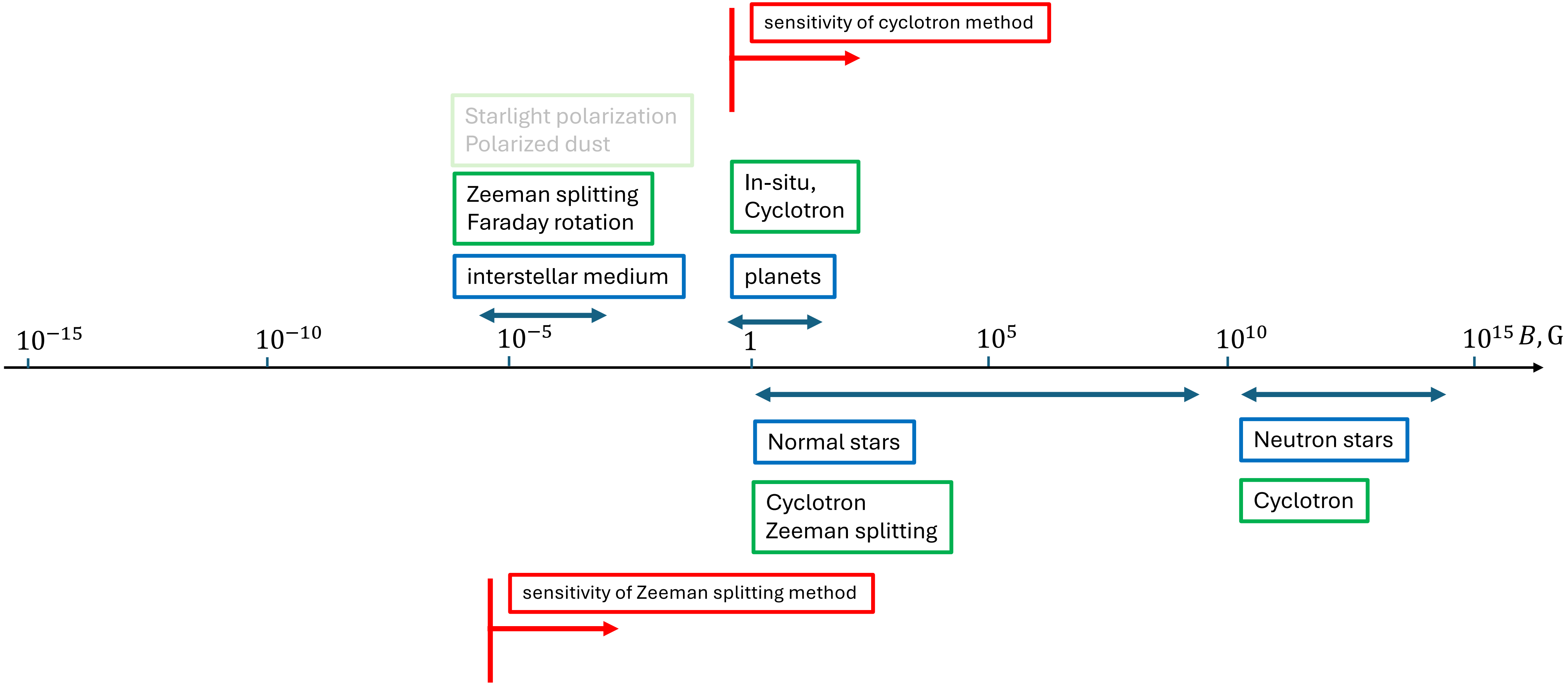
Summary lecture 2



Cosmological magnetic field observations
Lecture 3
Magnetic fields in the present-day Universe

Magnetic field of the Milky Way

- Synchrotron emission from interstellar medium
- Cosmic rays
- Global models of the Milky Way magnetic field

Magnetic fields of distant galaxies galaxy groups and clusters

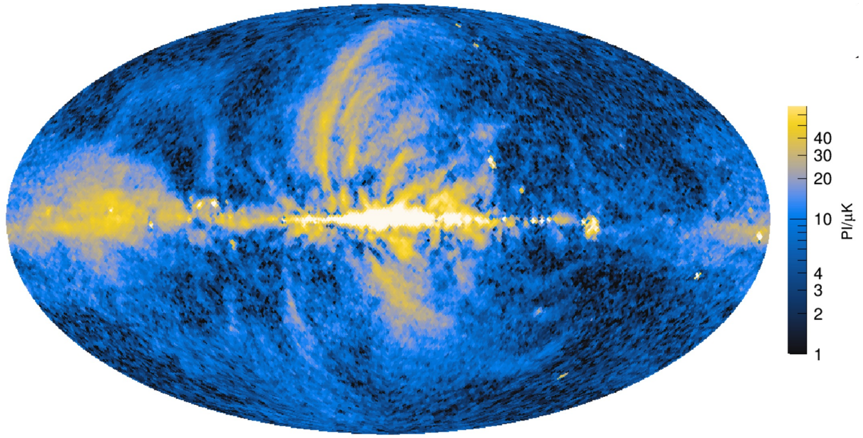
- Synchrotron emission from other galaxies
- Polarized dust emission from distant galaxies
- Magnetized outflows from galaxies
- Magnetic fields in galaxy groups and galaxy clusters

Magnetic fields of galaxy in filaments and voids of the Large Scale Structure

- Measurement of field in filaments
- Upper bounds on the void field from Faraday rotation and ultra-high-energy cosmic rays

Synchrotron radiation

WMAP+Planck polarized intensity



Reminder: dipole radiation from relativistic charge moving along a circle

$$I = \frac{2}{3}\frac{e^2\gamma^4 v^4}{R^2}$$

$$\omega \sim \Delta t^{-1} \sim \frac{\gamma^3}{R}$$

If the gyration is due to magnetic field B, the gyroradius is $R = E/eB$ (E is particle energy). The radiation mechanism is called synchrotron in this case. The emission spectrum is peaked at the energy / frequency

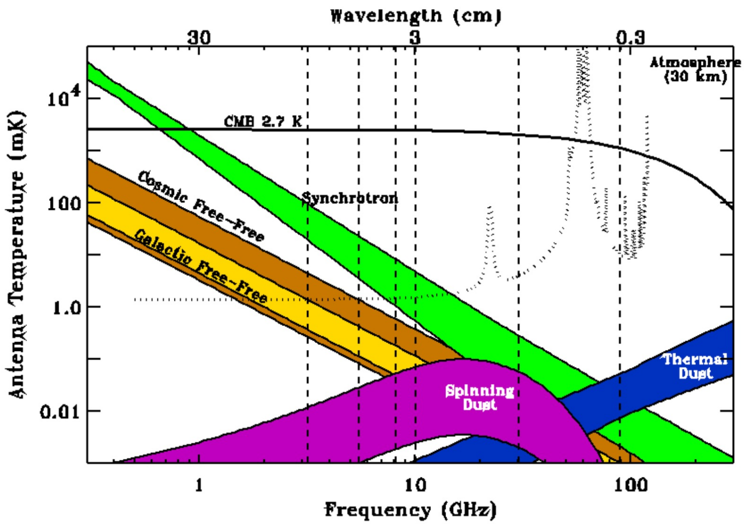
$$\omega_s = \frac{eBE^2}{m_e^3} \simeq 5\times10^{-5}\left[\frac{E}{10^{10}\ \mathrm{eV}}\right]^2\left[\frac{B}{10\ \mu\mathrm{G}}\right]\ \mathrm{eV}$$

With intensity

$$I = \frac{2}{3}\frac{e^4 E^2 B^2}{m_e^4}$$

Synchrotron radiation is up to 70% polarized.

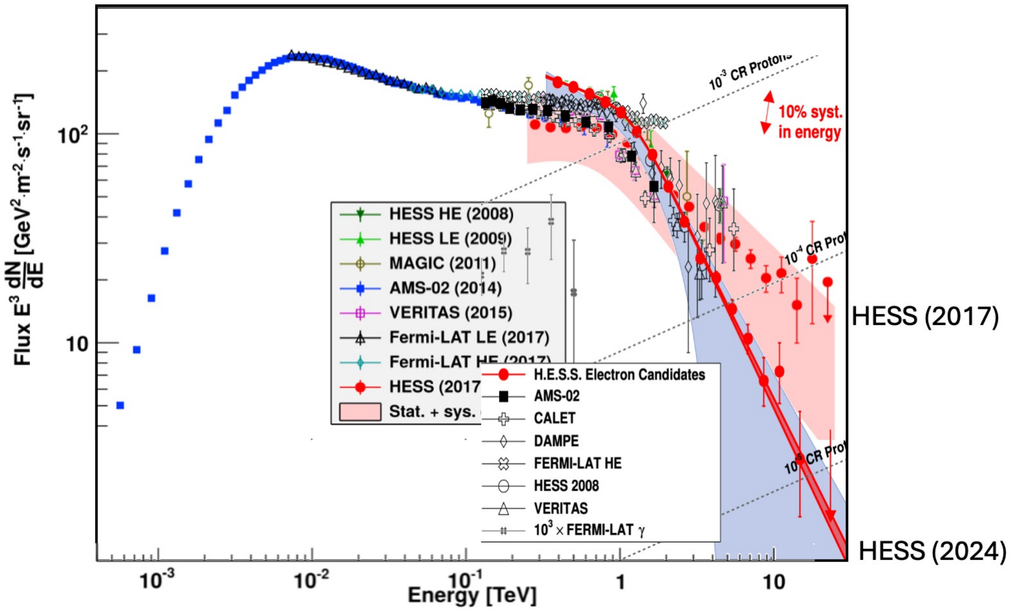
Synchrotron radiation per se does not provide a measurement of magnetic field, if the energy distribution of relativistic electrons is not known a-priori.



High-energy electrons in Milky Way

We measure (with some uncertainty, see picture) the local cosmic ray electron spectrum at the position of the Solar system. We don't control much the spectrum in other parts of the Galaxy.

Instead, numerical modelling is conventionally used to infer distribution of high-energy electrons in and around the Milky Way disk.



https://arxiv.org/pdf/2411.08189

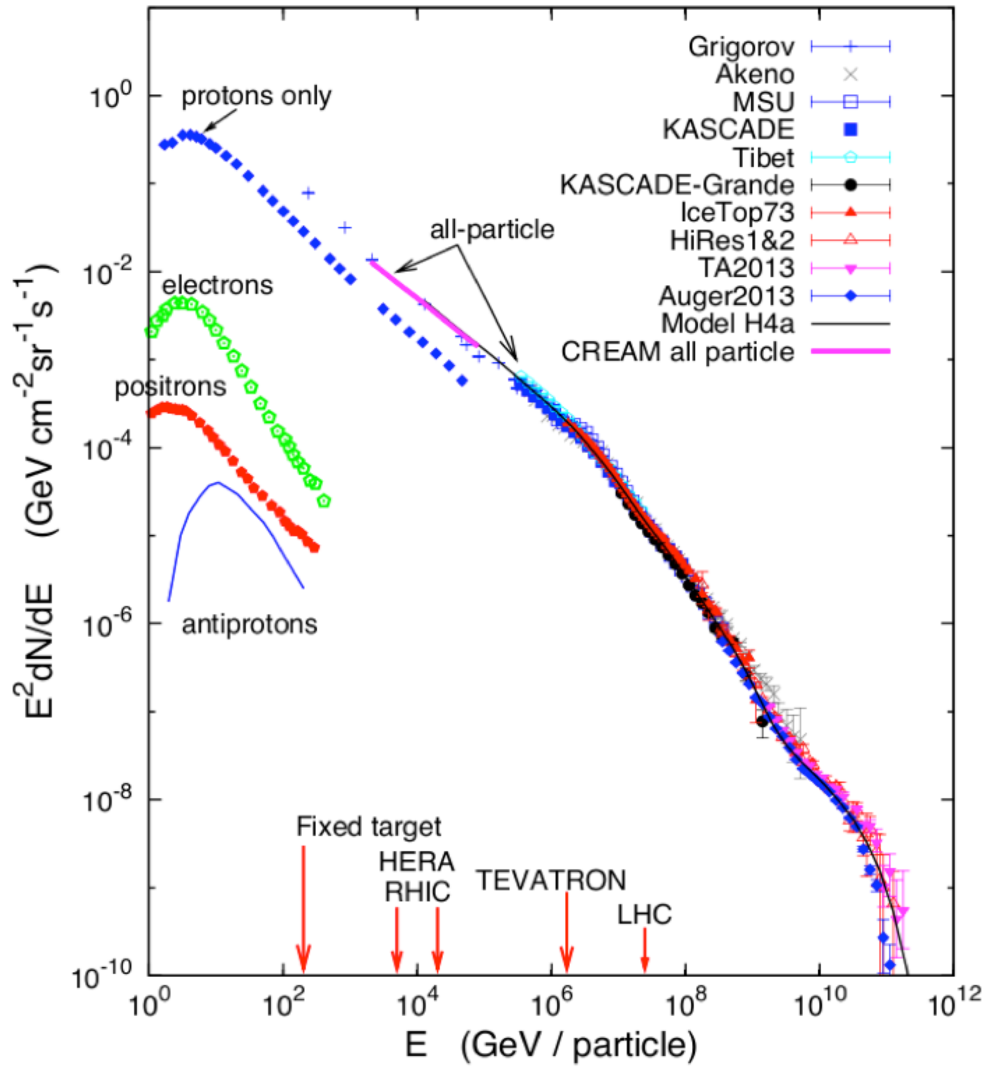
Cosmic rays in Milky Way

Cosmic ray electron flux is a sub-dominant component of the overall flux of cosmic rays: charged high-energy particles penetrating the Earth atmosphere and mostly coming from outside the solar system.

Cosmic ray spectrum is a broken powerlaw extending up to 10^{20} eV. Galactic cosmic rays, presumably injected by phenomena related to supernova in the Galactic disk. They escape from the disk into a broader halo and ultimately into intergalactic medium along Galactic magnetic field lines. The escape rate is regulated by scattering on inhomogeneities of turbulent Galactic magnetic field.

Primary cosmic rays from supernovae interact with interstellar gas producing γ-ray and neutrino glow of the Galaxy and generating secondary cosmic rays. Observations of γ-rays and neutrinos and measurements of abundances of secondary cosmic rays can be used to constrain the details of cosmic ray diffusion

...... and hence to constrain the Galactic magnetic field.



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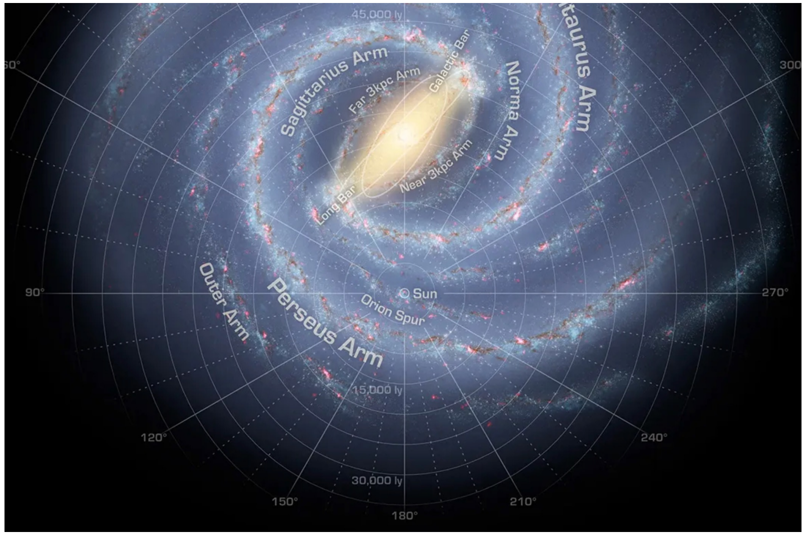
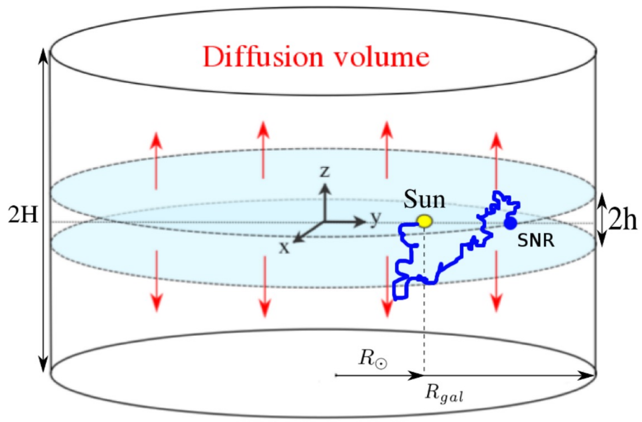
Numerical models of cosmic ray population in the galaxy do not yet include the detailed Galactic magnetic field structure. The adopt simplistic Milky Way model of “leaky box” model of height H, with particles diffusing out of the box with phenomenological diffusion coefficient $D(E) \propto E^{\kappa}$, within the escape time $t_{esc} = H^2/D$





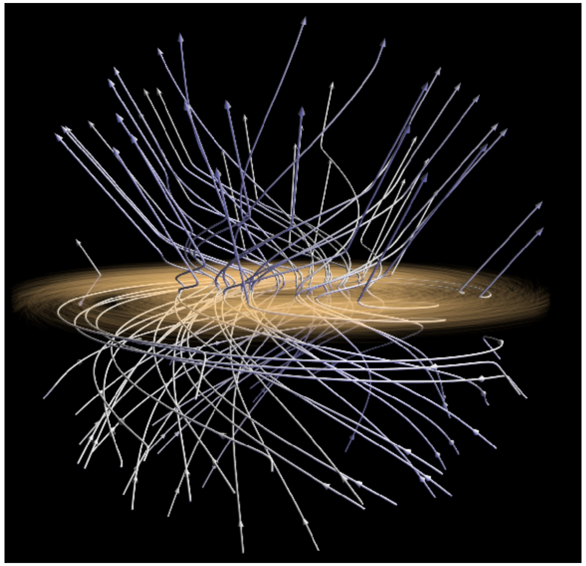
Global galactic magnetic field model from RM+DM+Synchrotron

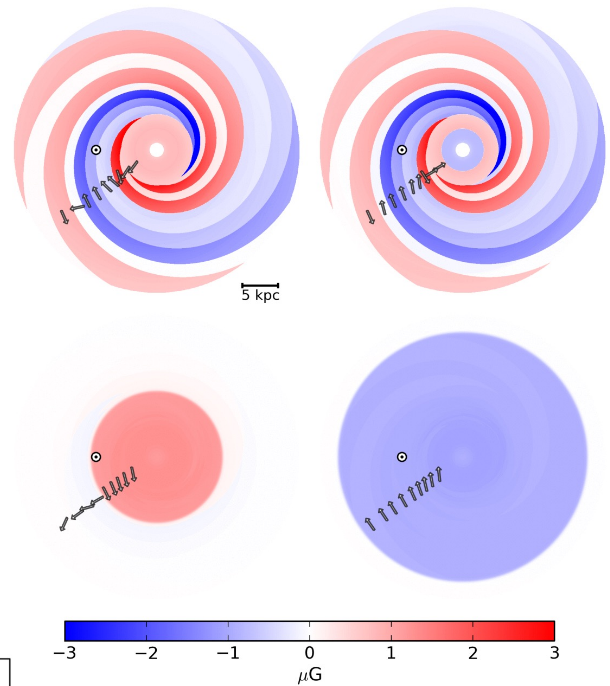
Ideally, modelling of cosmic ray escape from the Galaxy should be based on knowledge of geometry of the ordered magnetic field of the Milky Way and of the structure of the turbulent field.

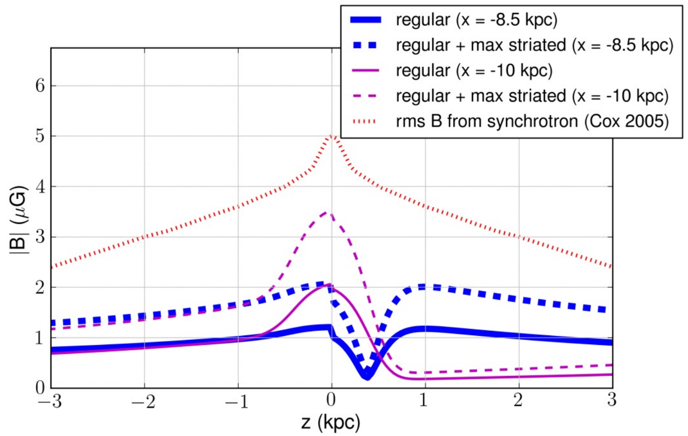
Global structure of Milky Way magnetic field can be guessed based on a combination of RM+DM and synchrotron data.

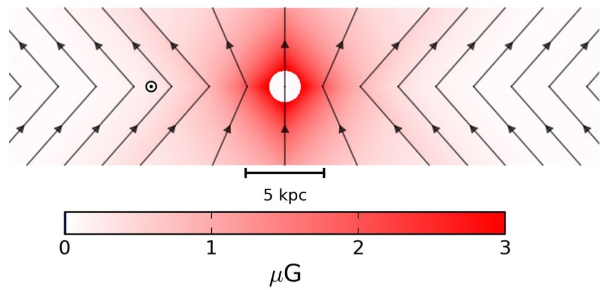
The modelling starts from an analytical model of global field geometry, with tens of parameters. The model predictions are fitted to pixelized RM+DM+synchrotron data.

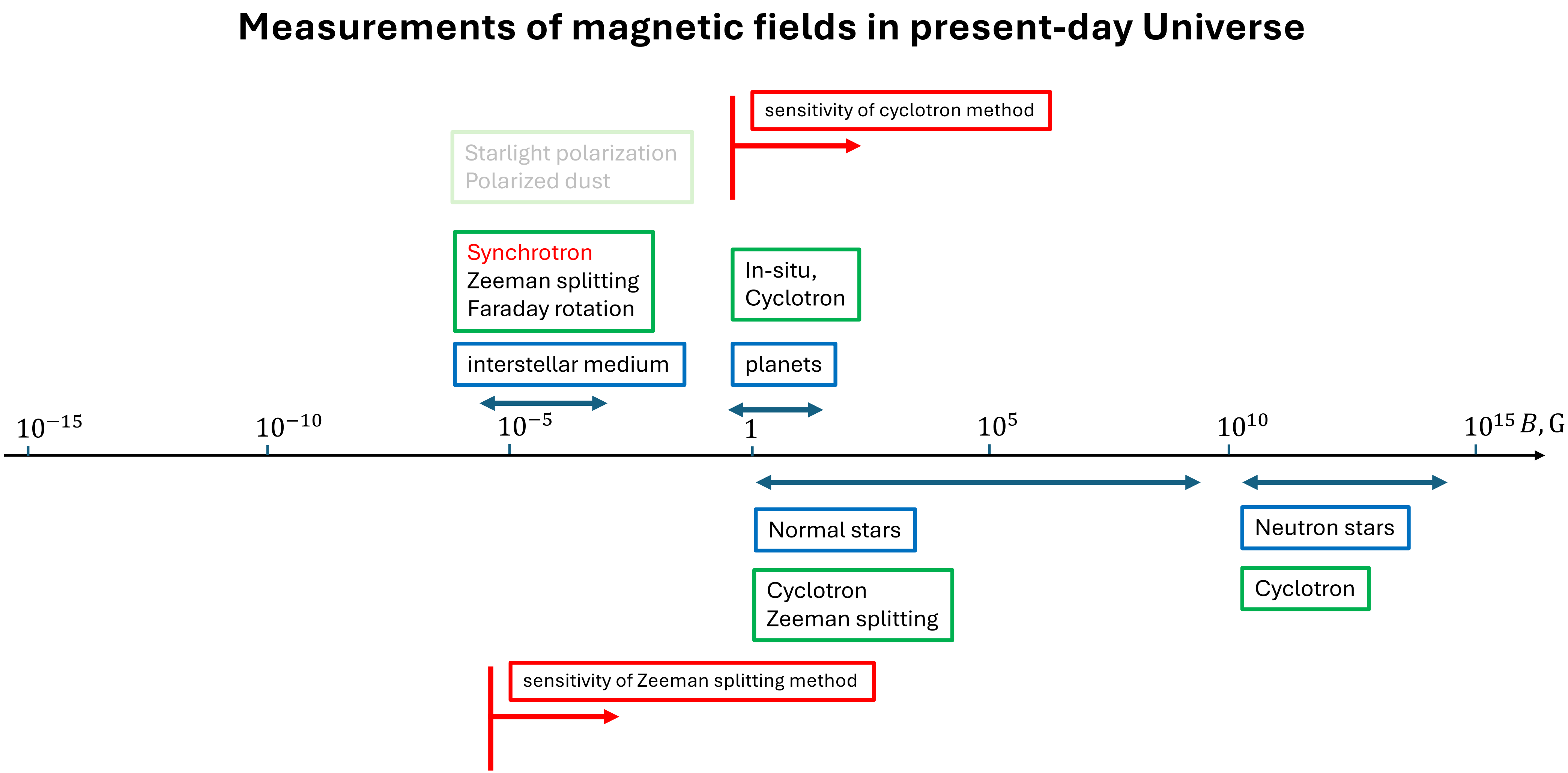
Jansson, Farrar https://arxiv.org/pdf/1204.3662
Korochkin et al. https://arxiv.org/abs/2407.02148



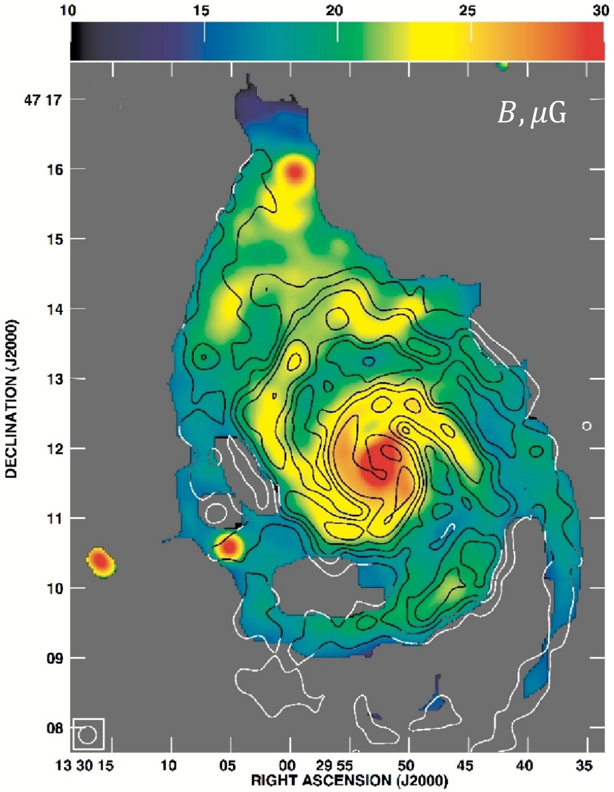


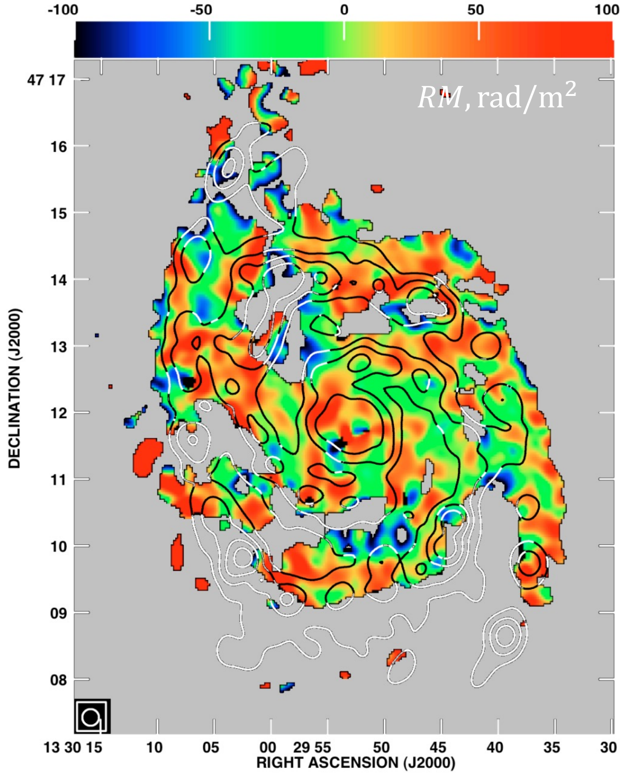





Measurements of magnetic fields in present-day Universe
sensitivity of cyclotron method
Starlight polarization
Polarized dust
Synchrotron
Zeeman splitting
Faraday rotation
In-situ,
Cyclotron
interstellar medium
planets
10^{-15}
10^{-10}
10^{-5}
1
10^{5}
10^{10}
10^{15} B, G
Normal stars
Neutron stars
Cyclotron
Zeeman splitting
Cyclotron
sensitivity of Zeeman splitting method

Magnetic fields in other galaxies





https://arxiv.org/pdf/1001.5230

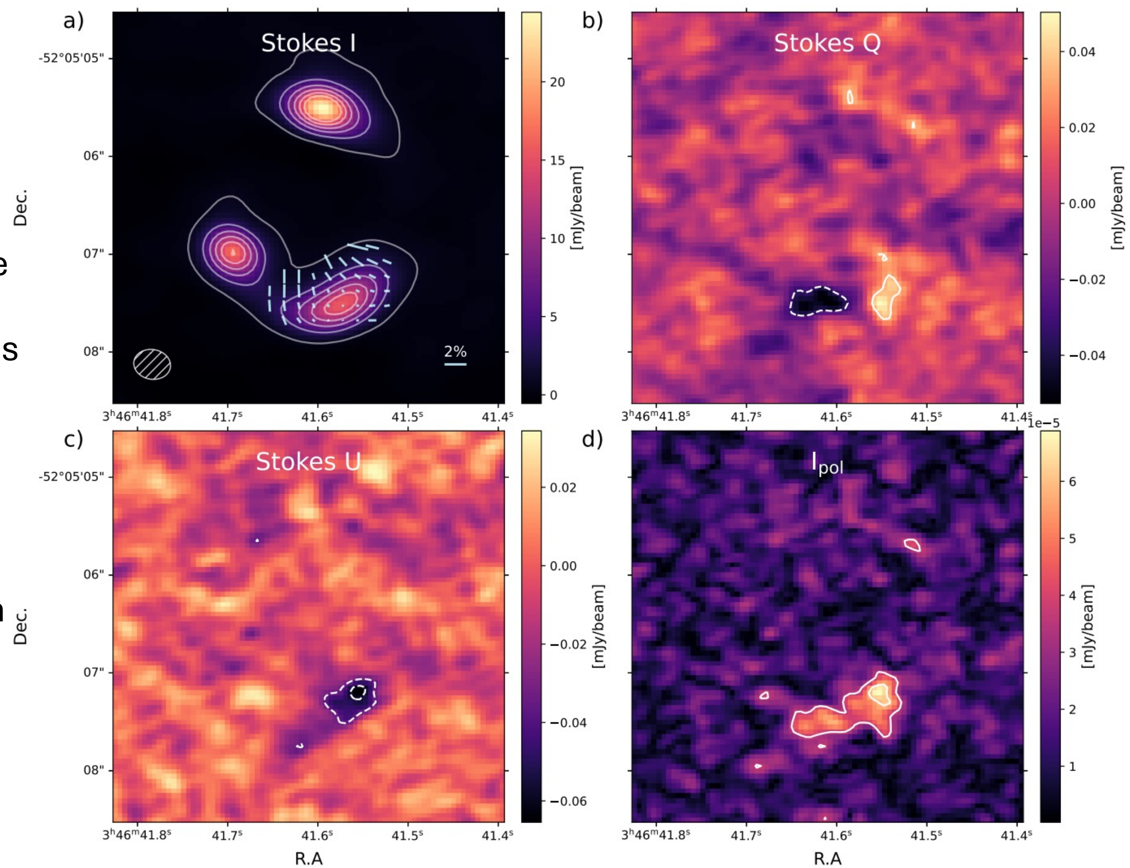
Observations of synchrotron emission are commonly used to infer magnetic fields in other galaxies. Similar to the Milky Way, The synchrotron emission is polarized and is subject to Faraday rotation.

Exercise 1. "Minimal energy argument". Consider a source of size R providing synchroton luminosity L_s at frequency $\nu_s = \omega_s/2\pi$. Find an estimate of magnetic field that minimizes the total energy needed to provide the observed luminosity (energy in magnetic field plus energy in relativistic electrons).

Magnetic fields in high redshift galaxies

Faraday rotation can also be used to statistically infer the existence of magnetic fields in galaxies at high redshifts. Bernet et al. https://arxiv.org/pdf/0807.3347 have dound that the RM aoong lines of sight passing through regions with MgII absorption lines at median redshift $z \sim 1$ (i.e. "metals", i.e. LoS crossing a galaxy) are systematically higher compared to randomly selected lines-of-sight.

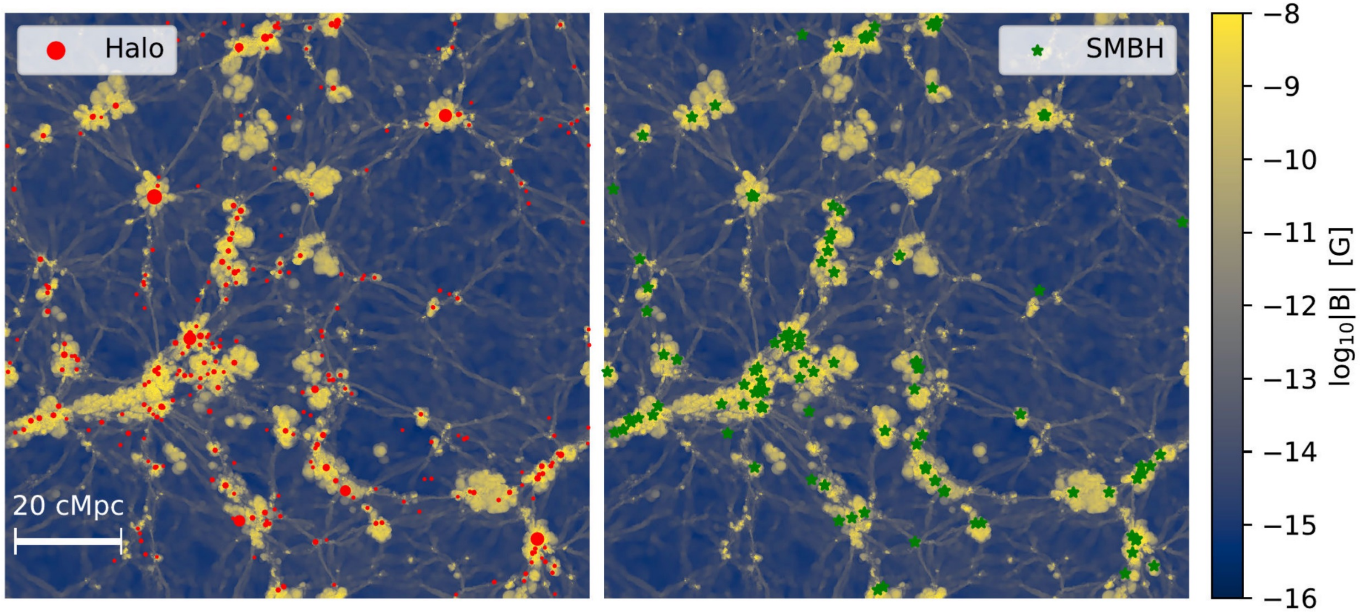
Apart from Faraday rotation, polarized dust emission is observed in high redshift galaxies. Example on the right: galaxy SPT0346−52 at redshift $z = 5.6$ (!) has ordered magnetic field on kpc scales.



https://arxiv.org/pdf/2407.14596

Magnetized bubbles around galaxies?

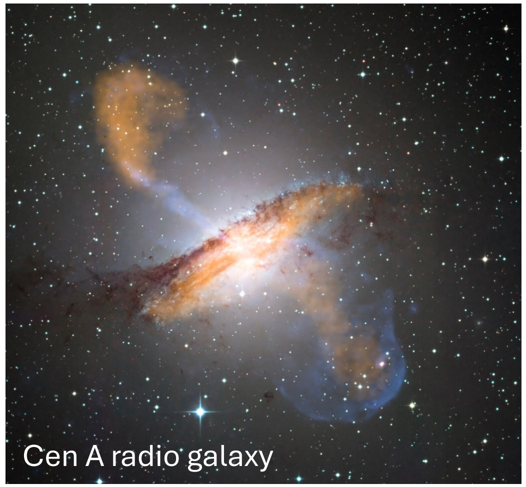
https://arxiv.org/abs/2011.11581



Star formation activity and active galactic nuclei in galaxies are known to drive outflows in the form of non-relativistic winds and relativistic jets.

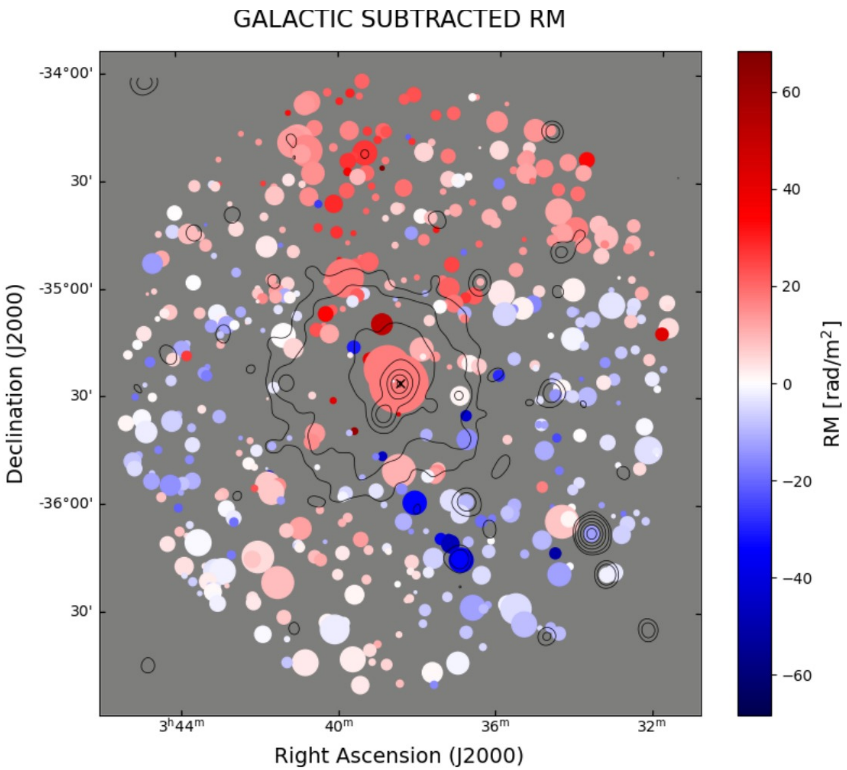
These spread matter and magnetic fields into circumgalactic medium. Cosmological simulations (like Illustris-TNG) show that magnetized bubbles are forming around galaxies in result of this process.

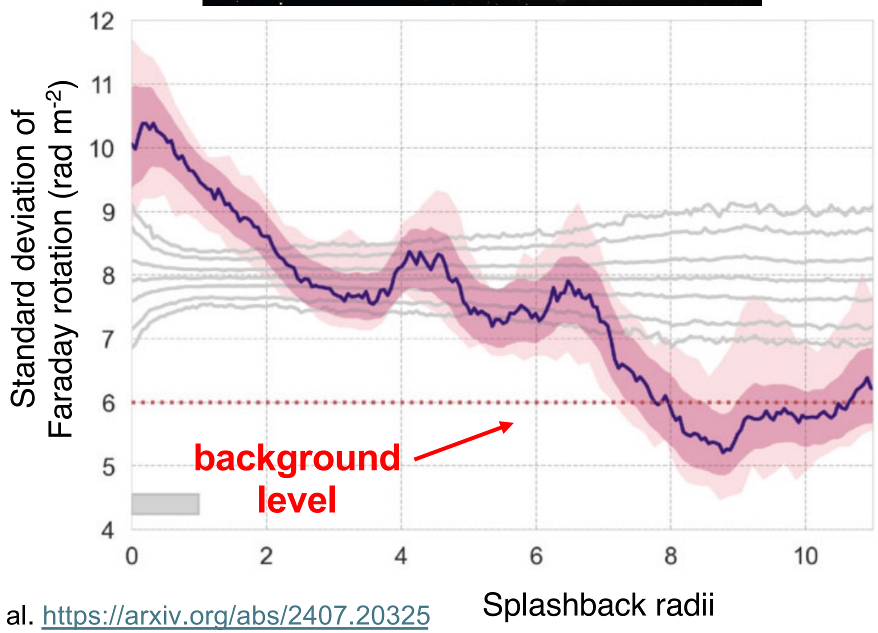
Such magnetized bubbles have not yet been observed and their extent has not been measured.



Galaxy groups and galaxy clusters

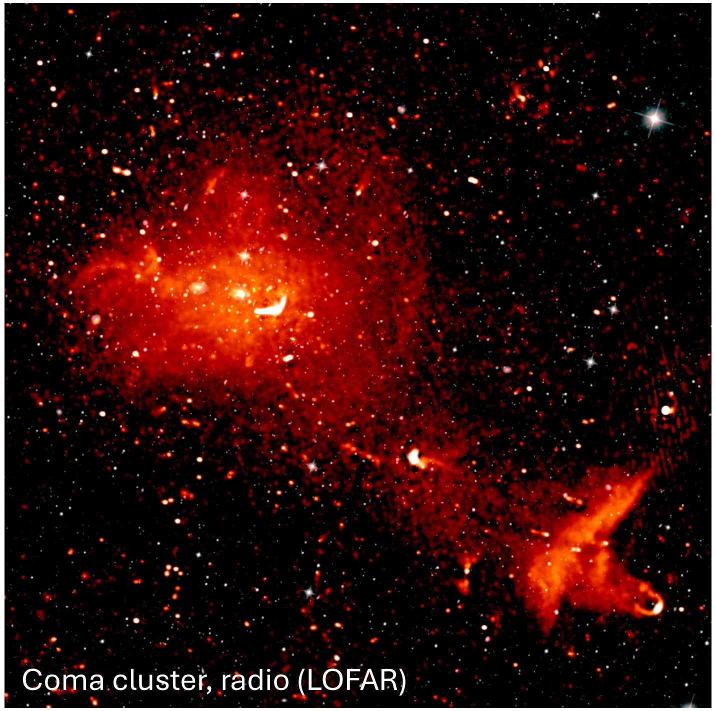
POSSUM survey provides dense enough Rotation Measure ”grid” on the sky, to enable measurements of magnetic fields on galaxy group and galaxy cluster scales.



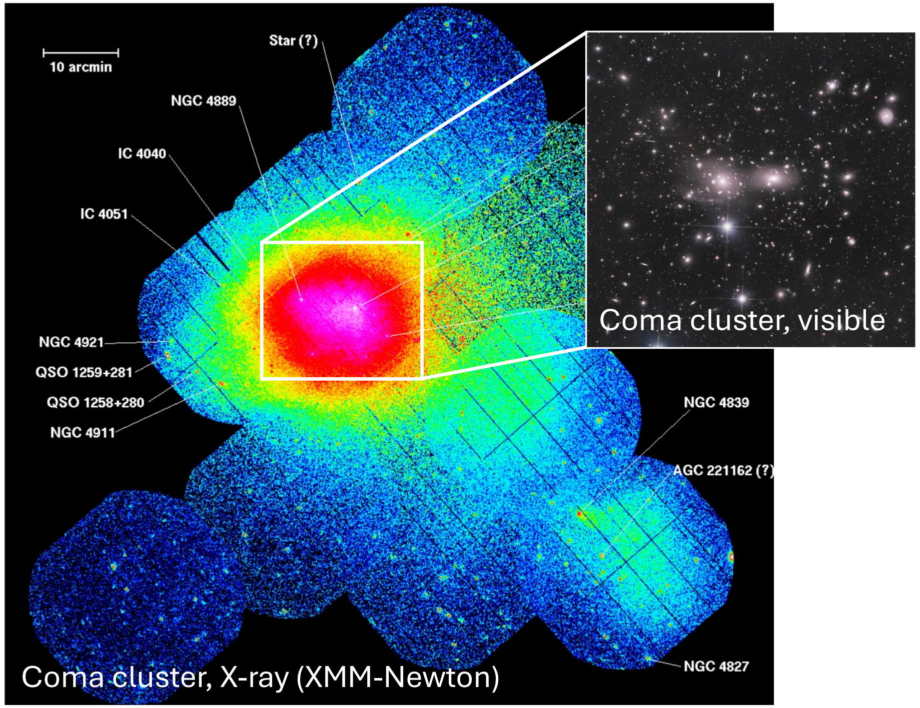


Anderson, et al. https://arxiv.org/abs/2407.20325

Faraday rotation and synchrotron emission in galaxy clusters


Coma cluster, radio (LOFAR)

https://arxiv.org/abs/2203.01958



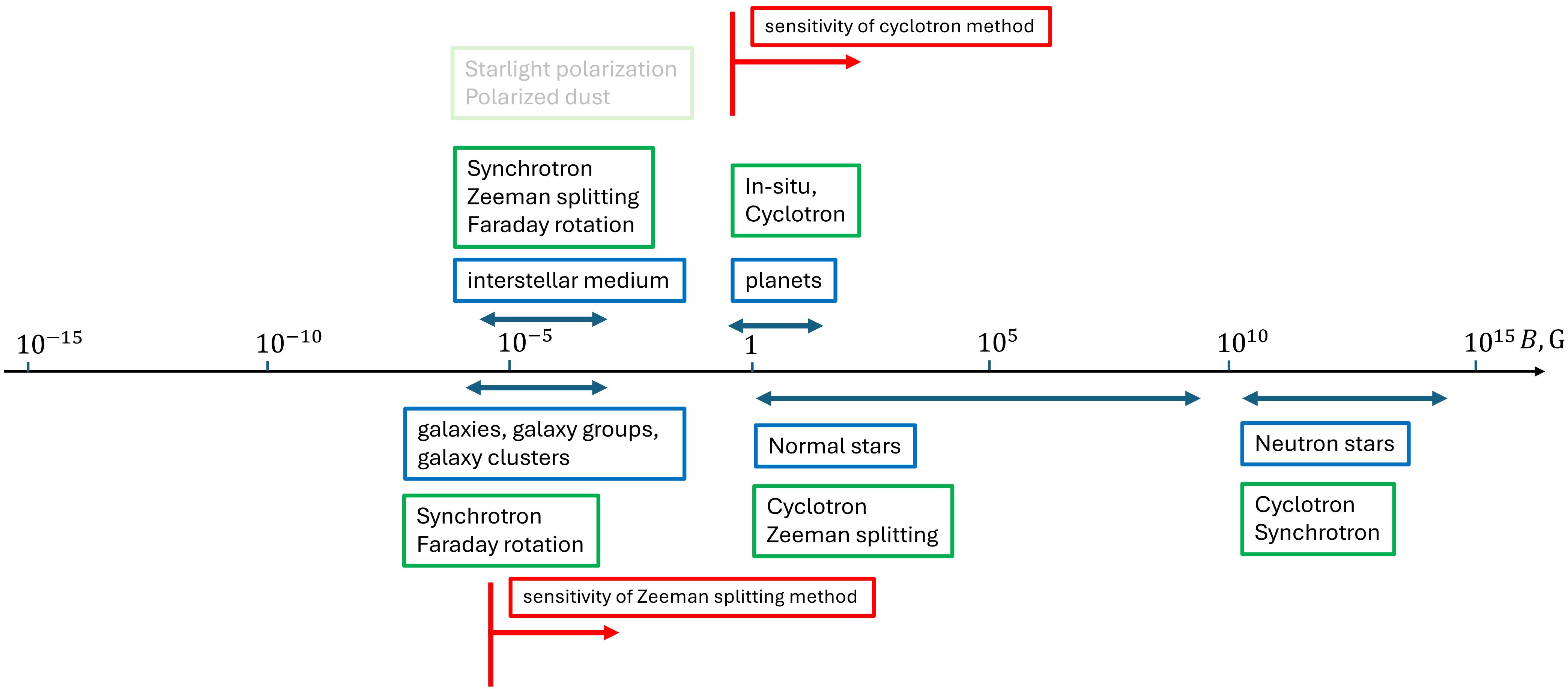
Coma cluster, X-ray (XMM-Newton)

Coma cluster, visible

https://arxiv.org/abs/astro-ph/0011323

Galaxy clusters are sources of polarized radio synchrotron emission on their own (radio halos and radio relics). Properties of the synchrotron signal (minimal energy argument?) and Faraday rotation can be used to infer strength and spatial structure of magnetic field.

Measurements of magnetic fields in present-day Universe



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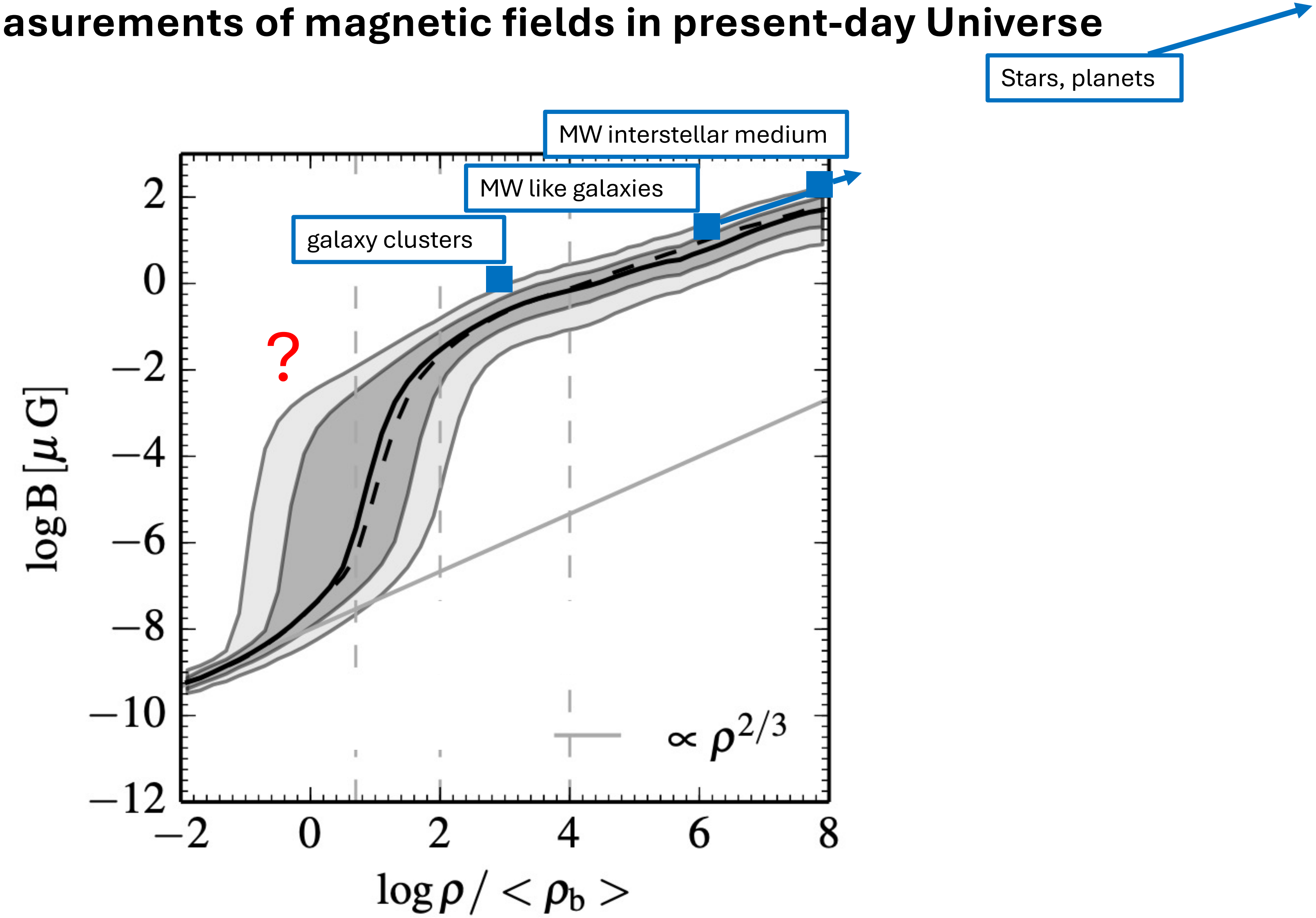
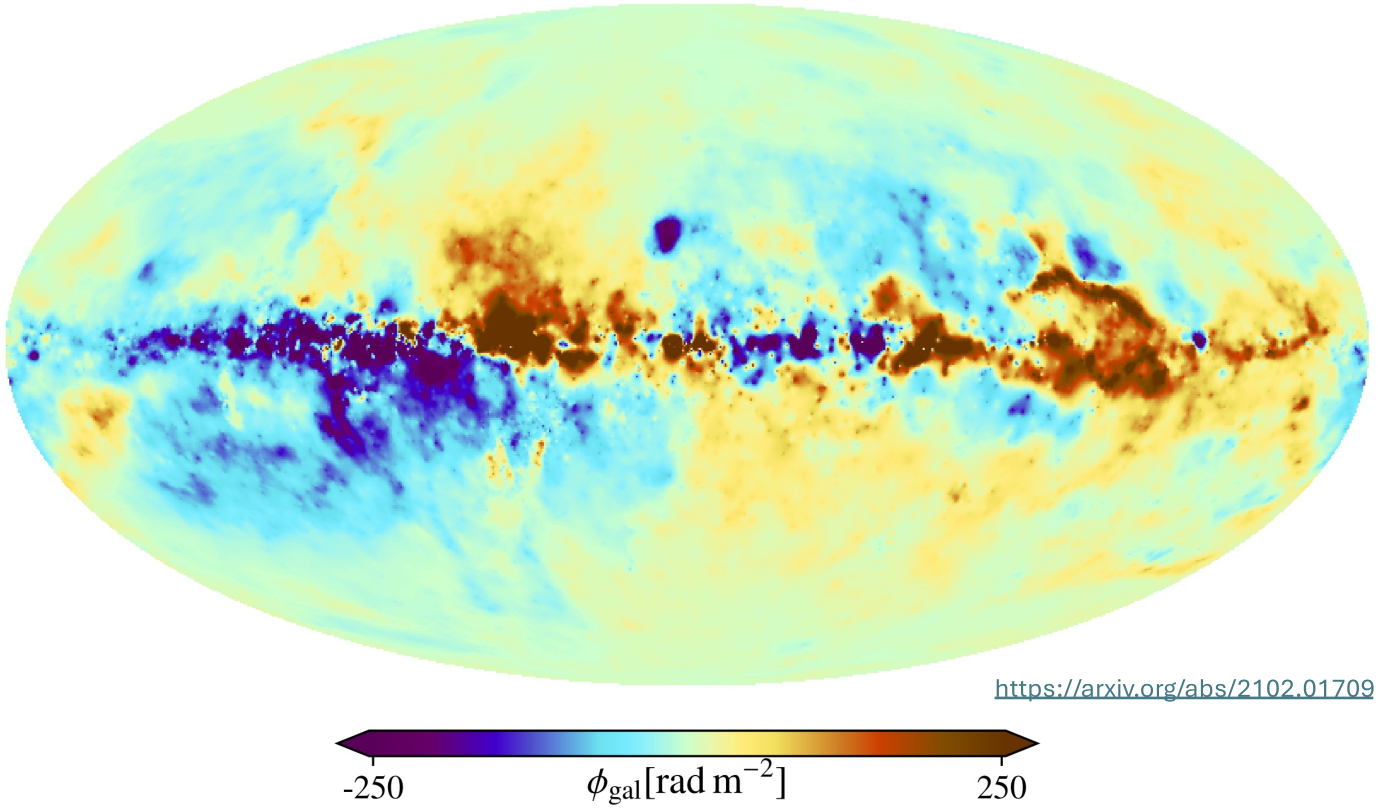


Residual Rotation Measure



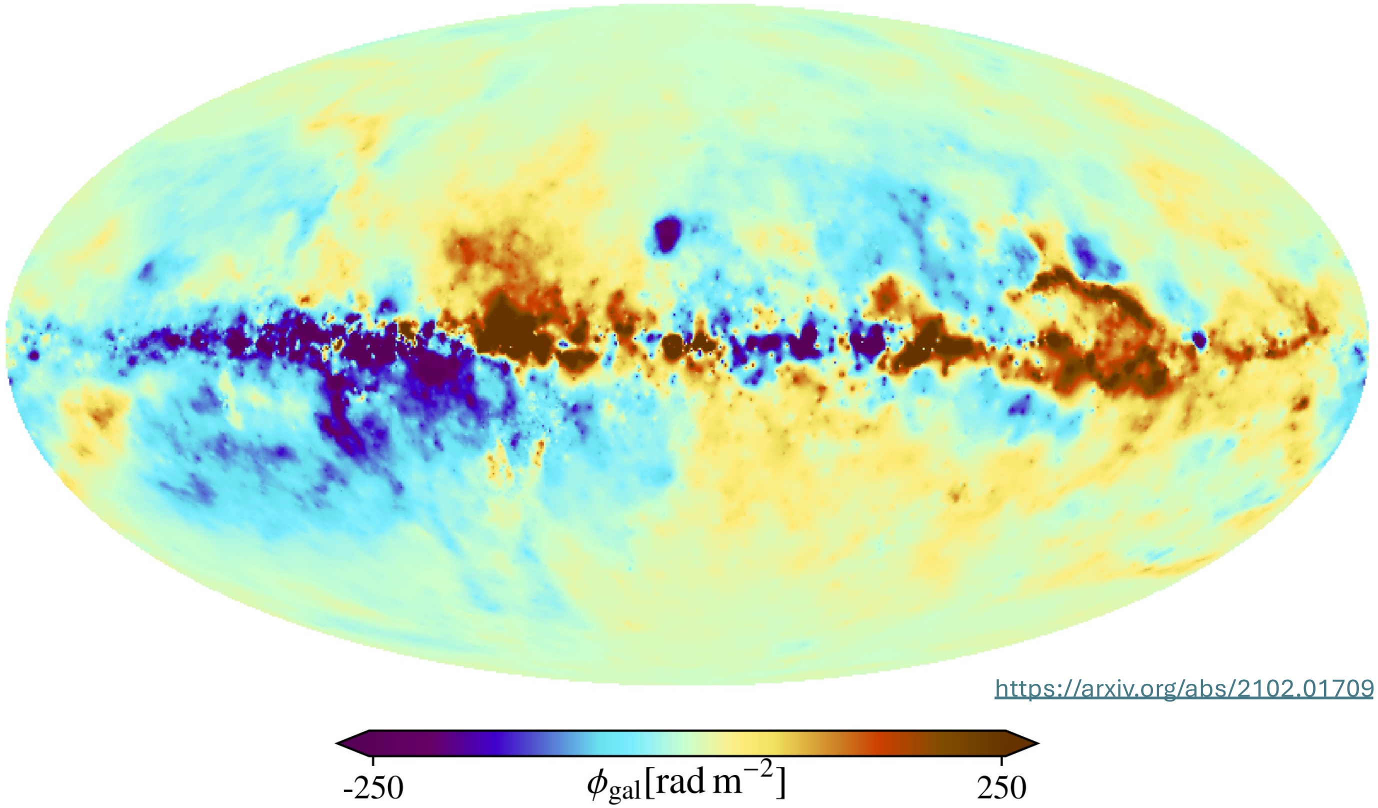
https://arxiv.org/abs/2102.01709

The RM integral

$$RM = \frac{e^3}{2\pi\, m_e^2\, c^4} \int n_e B dl$$

is composed of several parts from propagation of the signal inside the source and source host galaxy (intrinsic RM), intergalactic medium, the Milky Way interstellar medium, $RM = RM_{intr} + RM_{IGM} + RM_{MW}$. Subtracting the Galactic contribution, one finds the "residual" RM, $RRM = RM - RM_{MW}$. The Milky Way contribution can be either estimated from the analytical model of from averaging of the RM over certain sky regions around the direction of interest (as picture above).

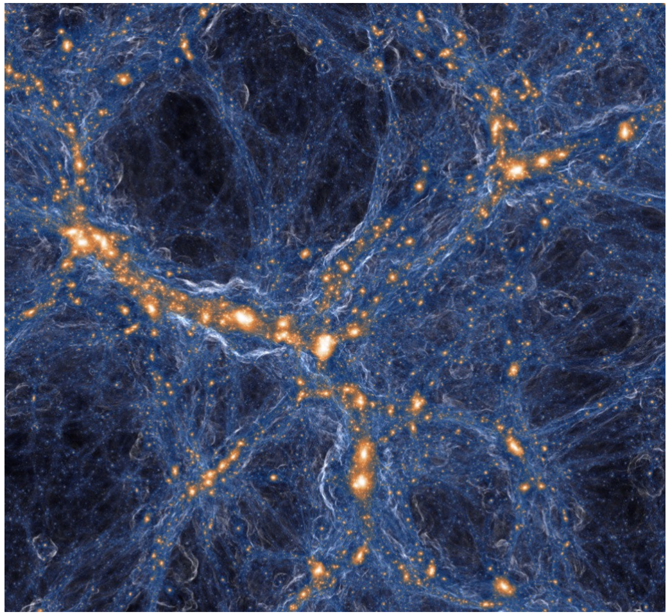
Residual Rotation Measure



https://arxiv.org/abs/2102.01709

Exercise 2. Download the Galactic Rotation Measure model shown in this figure, https://wwwmpa.mpa-garching.mpg.de/~ensslin/research/data/faraday2020.html , and apply it to the RM dataset studied in exercise 5 of Lecture 2 to obtain the RRM dataset. Calculate the mean and the root mean square spread of the RRM values.

Rotation measure of intergalactic space



The radio signal from sources at non-zero redshift propagates through expanding Universe. The rotation of polarization angle accumulated during signal propagation between redshift $z + dz$ and z is

$$d\Psi = (dRM)\big(\lambda(z)\big)^2 dl(z), \qquad \lambda(z) = a\lambda_{obs} = \frac{\lambda_{obs}}{1+z}, \qquad dRM = \frac{e^2}{2\pi m_e^2} n_e(z)B(z),$$

The distance increment between and z $z - dz$ or between $a = (1+z)^{-1}$ and $a - da,\ da = a^2 dz$ is $dl = dt = \frac{da}{\dot{a}} = \frac{da}{Ha} = \frac{adz}{H} = \frac{dz}{(1+z)H}$. The density of the Universe today, ρ_0, has a contribution by non-relativistic matter, $\Omega_m \rho_0$, with equation of state $w = 0$ and dark energy with density $\Omega_\Lambda \rho_0$ and with $w = -1$. The matter density scales as $a^{-3} = (1+z)^3$ while the dark energy density is independent of a. The Friedman equation reads

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3M_{Pl}^2}\rho_0(\Omega_m(1+z)^3 + \Omega_\Lambda) = H_0^2(\Omega_m(1+z)^3 + \Omega_\Lambda)$$

$$dl = \frac{dz}{H_0(1+z)\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}}$$

Integrating over the distance to the source one finds

$$RM = \frac{e^2}{2\pi m_e^2}\int \frac{n_e(z)B(z)}{(1+z)^2}\,\frac{dz}{H_0(1+z)\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}}$$

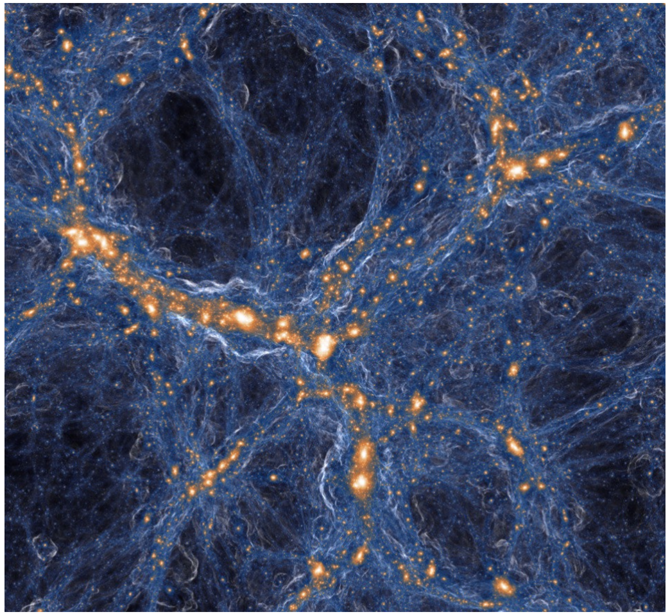
Rotation measure of intergalactic space

Integrating over the distance to the source one finds

$$RM = \frac{e^2}{2\pi m_e^2} \int \frac{n_e(z)B(z)}{(1+z)^2} \frac{dz}{H_0(1+z)\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}}$$

In the simple case of homogeneous electron density diluted by the Universe expansion and non-evolving comoving magnetic field, $n_e(z) = \frac{n_{e,0}}{a^3} = (1+z)^3 n_{e,0}$, $B(z) = \frac{B_0}{a^2} = (1+z)^2 B_0$. In this case RM grows at $z > 1$ as

$$RM \propto \int z^{\frac{1}{2}}\, dz \propto z^{\frac{3}{2}}$$

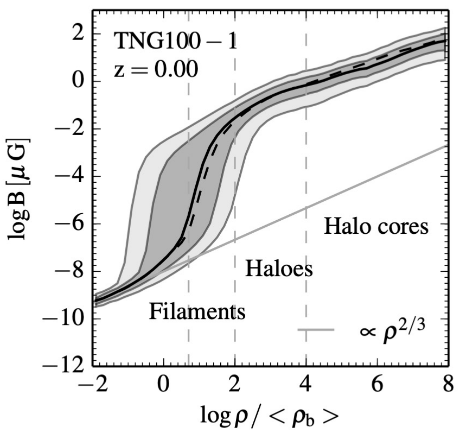


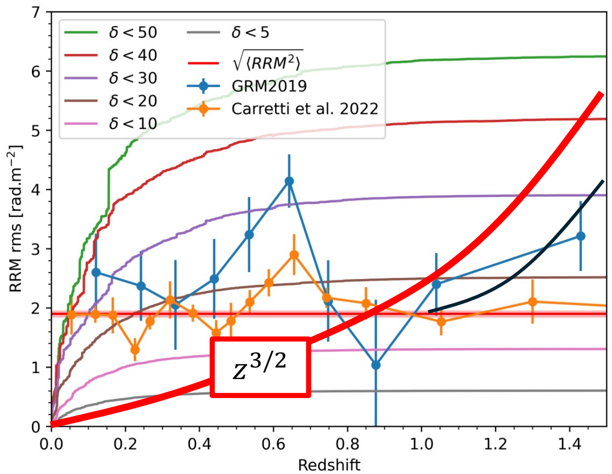
This simple "toy model" does not work because of the presence of LSS: both n_e and B scale with (over)density of the LSS, cosmological simulations need to be used:

– if $B \propto \rho^{2/3}$, $n_e \propto \rho$, $L \propto \rho^{-1/3}$, overdensities give enhanced contributions to RM

$$\delta RM \propto B n_e L \propto \rho^{4/3}$$

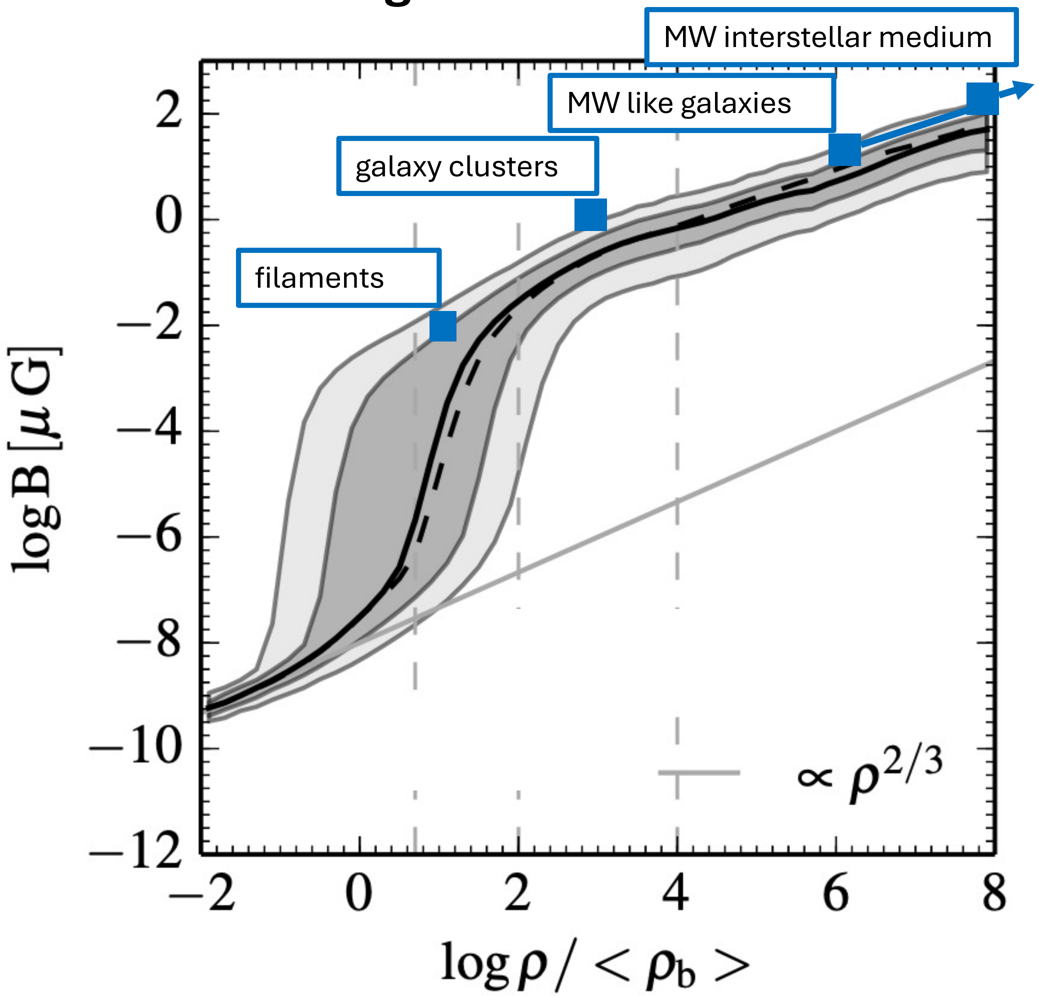
– outflows from galaxies magnetize intergalactic medium beyond the magnetization by the compressed relic cosmological field.

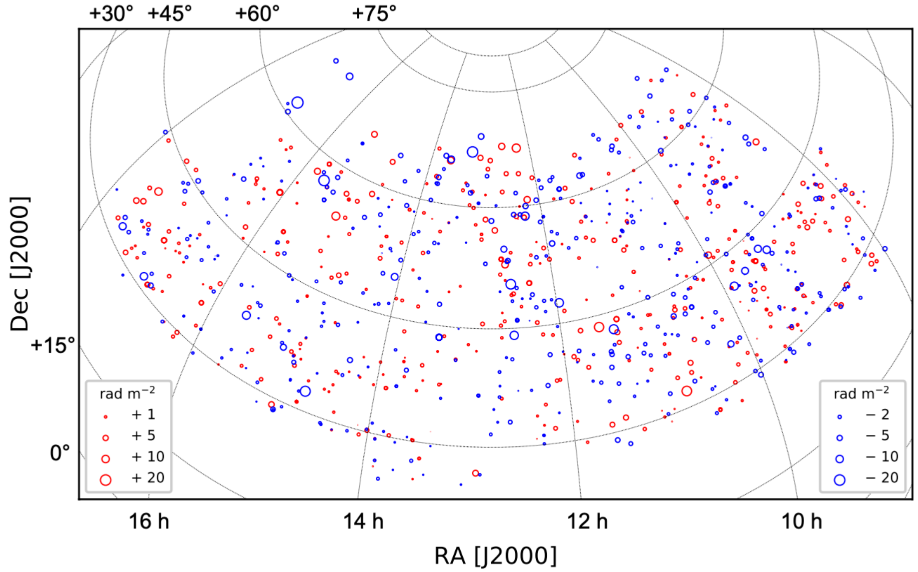


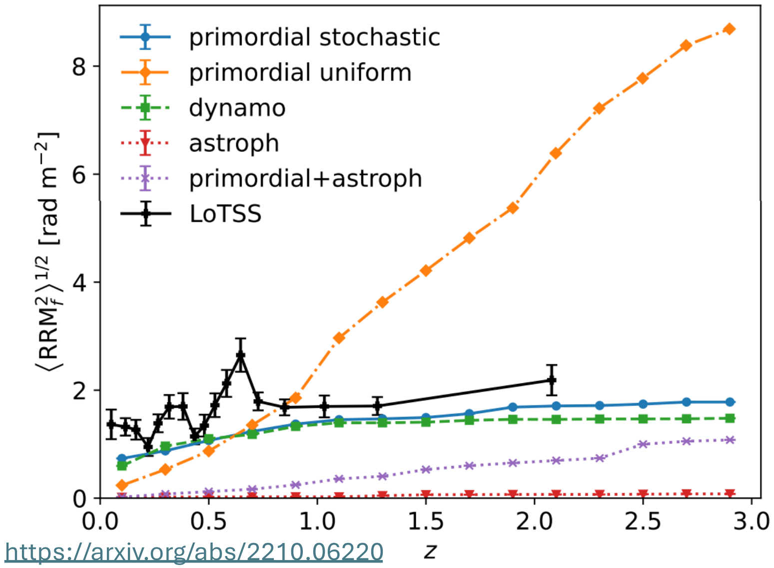


https://arxiv.org/abs/2403.13418

Magnetic field in filaments of the Large Scale Structure



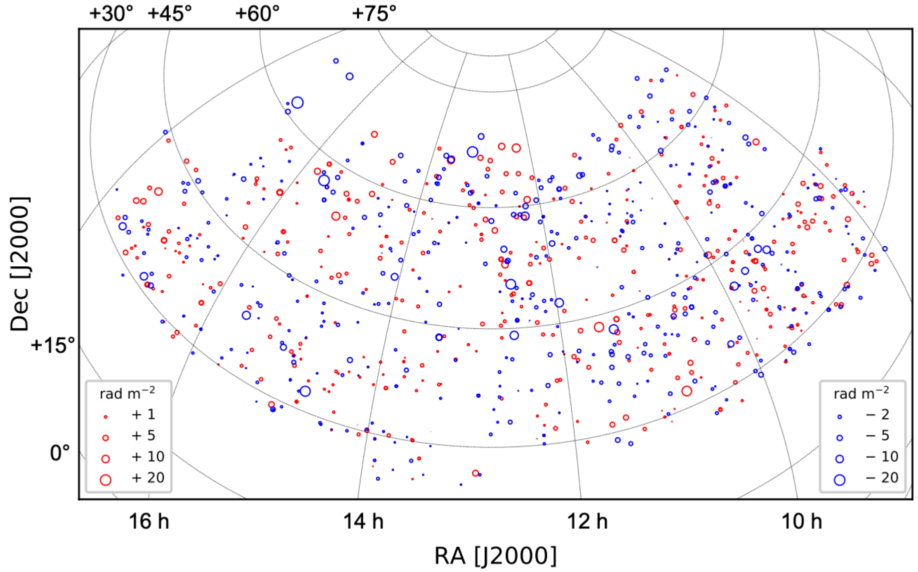




https://arxiv.org/abs/2210.06220

LOFAR RRM data can be fit with LSS models in which magnetic field in the filaments is of the order of $B \sim 10$ nG for filaments with overdensities $\delta\rho/\rho \simeq 10$.

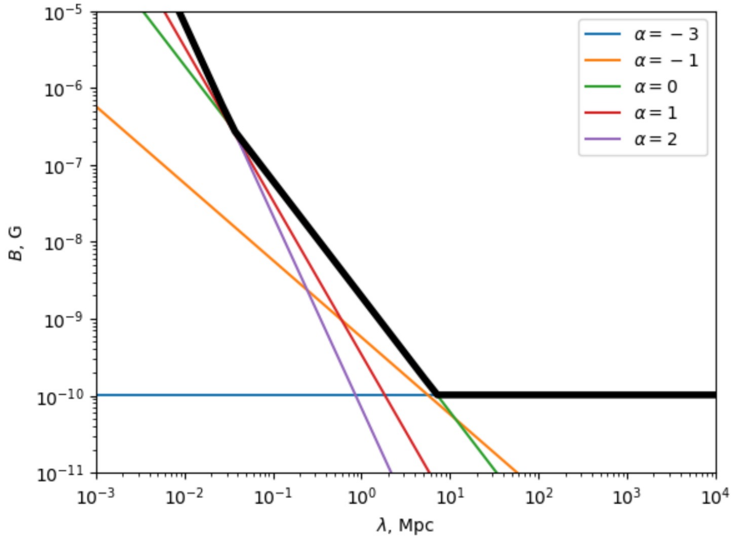
Rotation measure limit on the void fields



LOFAR RRM data also impose an upper bound on the field in voids (oversensities $\delta\rho/\rho \le 0$).

The void field is mostly not processed by structure formation and it may be the relic cosmological magnetic field, statistically homogeneous and isotropic, characterized by power spectrum with the slope $n_s (\equiv \alpha$ in the figure on the right).

The bound depends on the slope of the field power spectrum.



https://arxiv.org/abs/2412.14825

Rotation measure limit on the void fields

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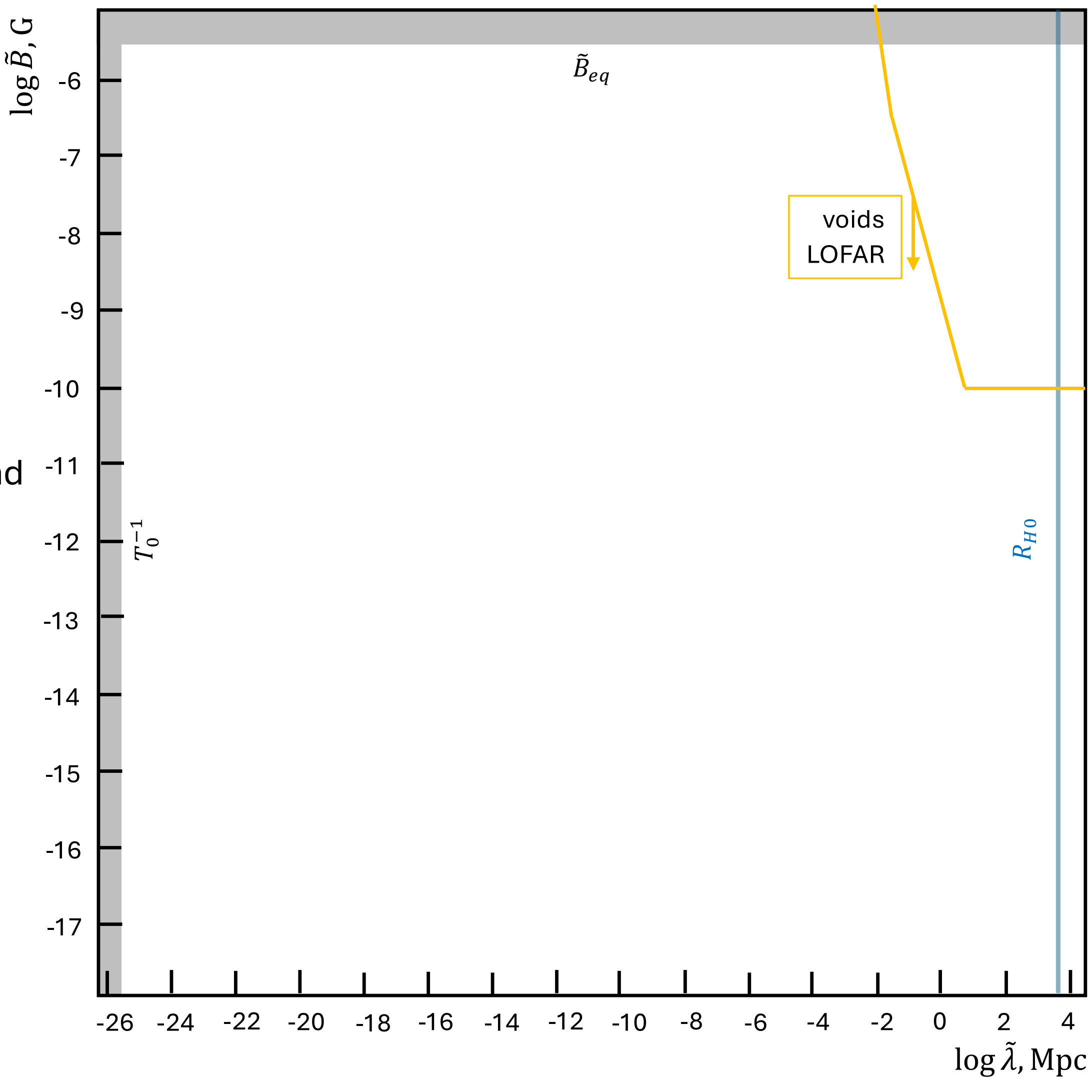

Measurements of magnetic fields in present-day Universe