Cosmological magnetic field observations
Lecture 2
Methods of measurement of cosmic magnetic fields

Magnetic field parameters across cosmological epochs
- Recap lecture 1: cosmological epochs
- Magnetic field strength and correlation length constraints for different epochs

Measurements of magnetic fields in the present-day Universe
- Cyclotron emission / absorption
- Zeeman splitting
- Polarized dust emission and starlight polarization
- Faraday rotation

Summary of Lecture 1

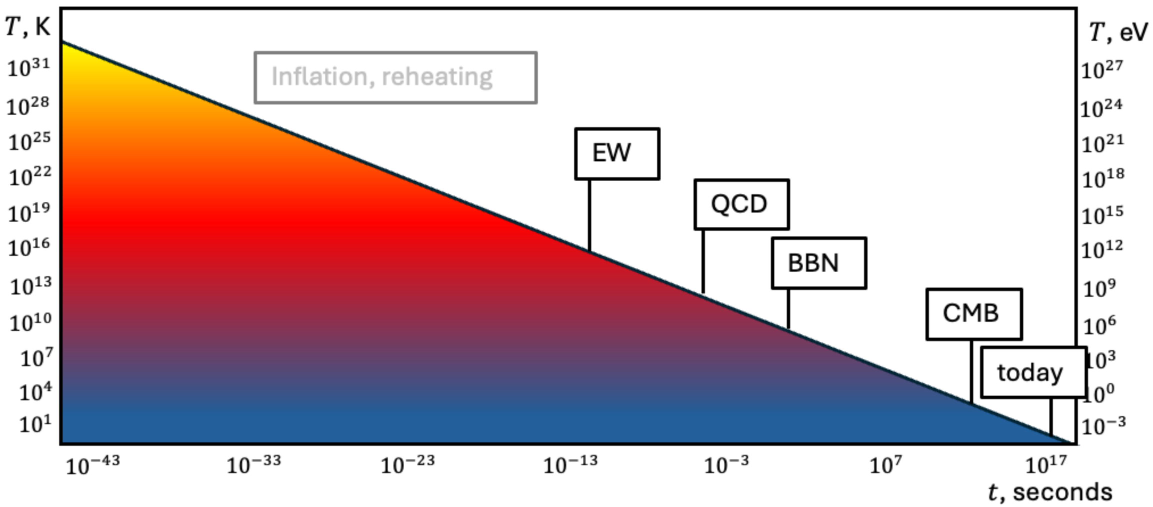
Notation conventions and units

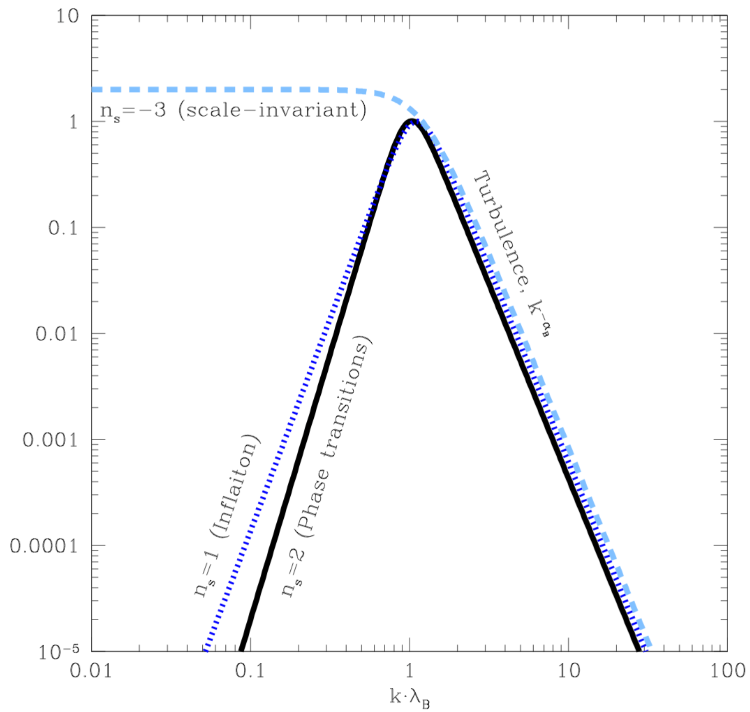
Introduction and motivations

- Cosmological epochs
- Cosmological observables
- Existing cosmological probes
- Magnetic field as a cosmological observable?

Cosmological magnetic field description

- Maxwell equations in curved space-time
- "locally measured" and "comoving" electric and magnetic fields
- Stochastic magnetic fields: power spectrum, strength, correlation length



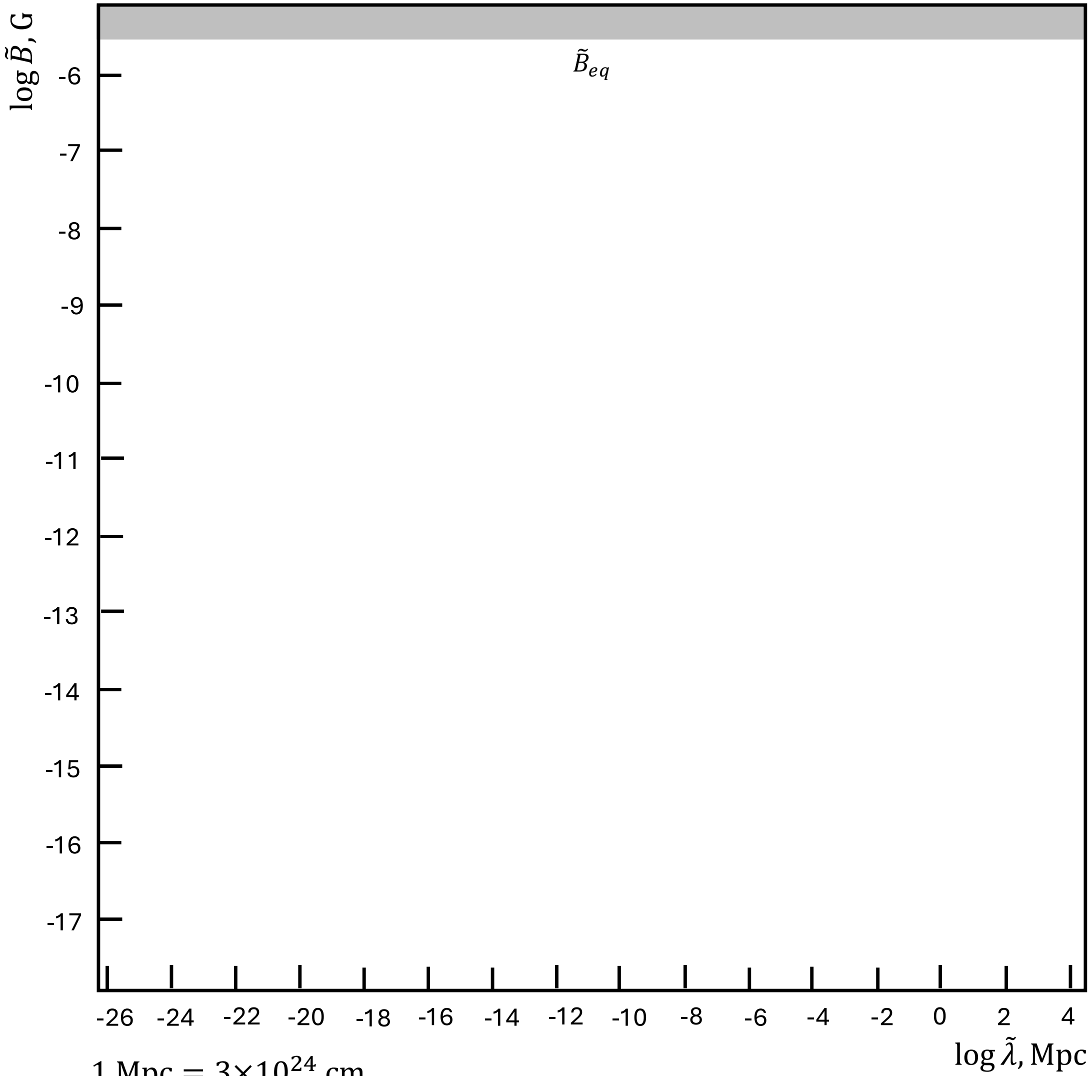


Magnetic field parameter space

$\langle\tilde{B}\rangle$, $\tilde{\lambda}_B$, the characteristic strength and variability distance scale of magnetic field, are two basic parameters of interest for characterisation of magnetic field at any cosmological epoch.

$\langle\tilde{B}\rangle$ is naturally limited from above by the requirement that the magnetic field energy density should not be too high, so that it does not alter the dynamics of the Universe.

$$\langle\tilde{B}\rangle \ll \tilde{B}_{eq} \simeq 4\times10^{-6}\left[\frac{g_*}{4}\right]^{-1/6}\,\mathrm{G}$$



1 Mpc = 3×10^{24} cm

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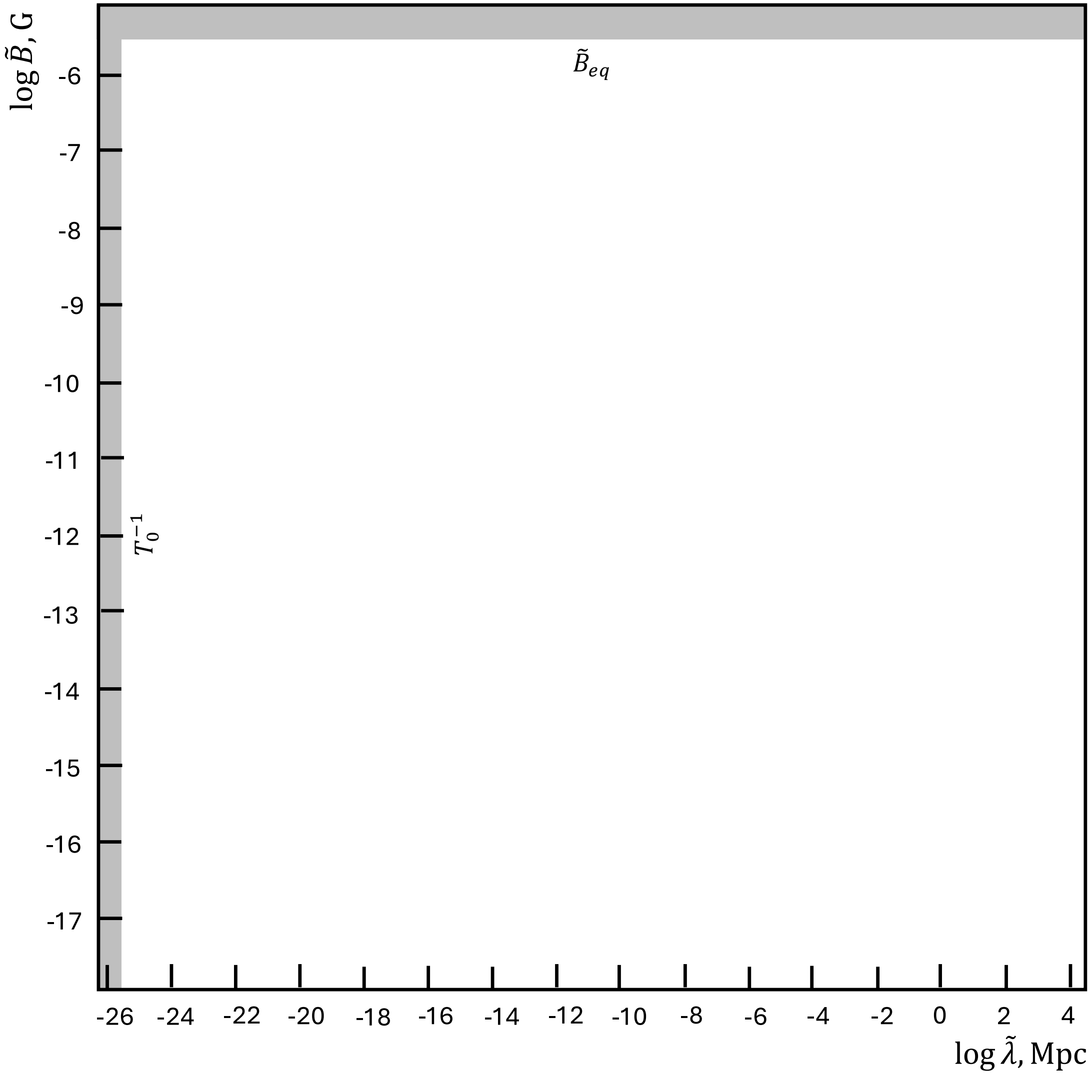
$$\langle\tilde{B}\rangle \ll \tilde{B}_{eq} \simeq 4\times10^{-6}\left[\frac{g_*}{4}\right]^{-1/6}\mathrm{G}$$

The shortest possible correlation length at any moment in time is that of thermal fluctuations of electromagnetic field,

$$\tilde{\lambda}_B \geq \frac{T^{-1}}{a} \simeq \left[\frac{g_*}{4}\right]^{\frac{1}{3}} T_0^{-1} \simeq 0.1\left[\frac{g_*}{4}\right]^{\frac{1}{3}}\mathrm{cm} \simeq 3\times10^{-26}\left[\frac{g_*}{4}\right]^{\frac{1}{3}}\mathrm{Mpc}$$

where we have used

$$a = \left[\frac{g_*}{4}\right]^{-\frac{1}{3}}\left[\frac{T}{T_0}\right]^{-1}$$



Magnetic field parameter space

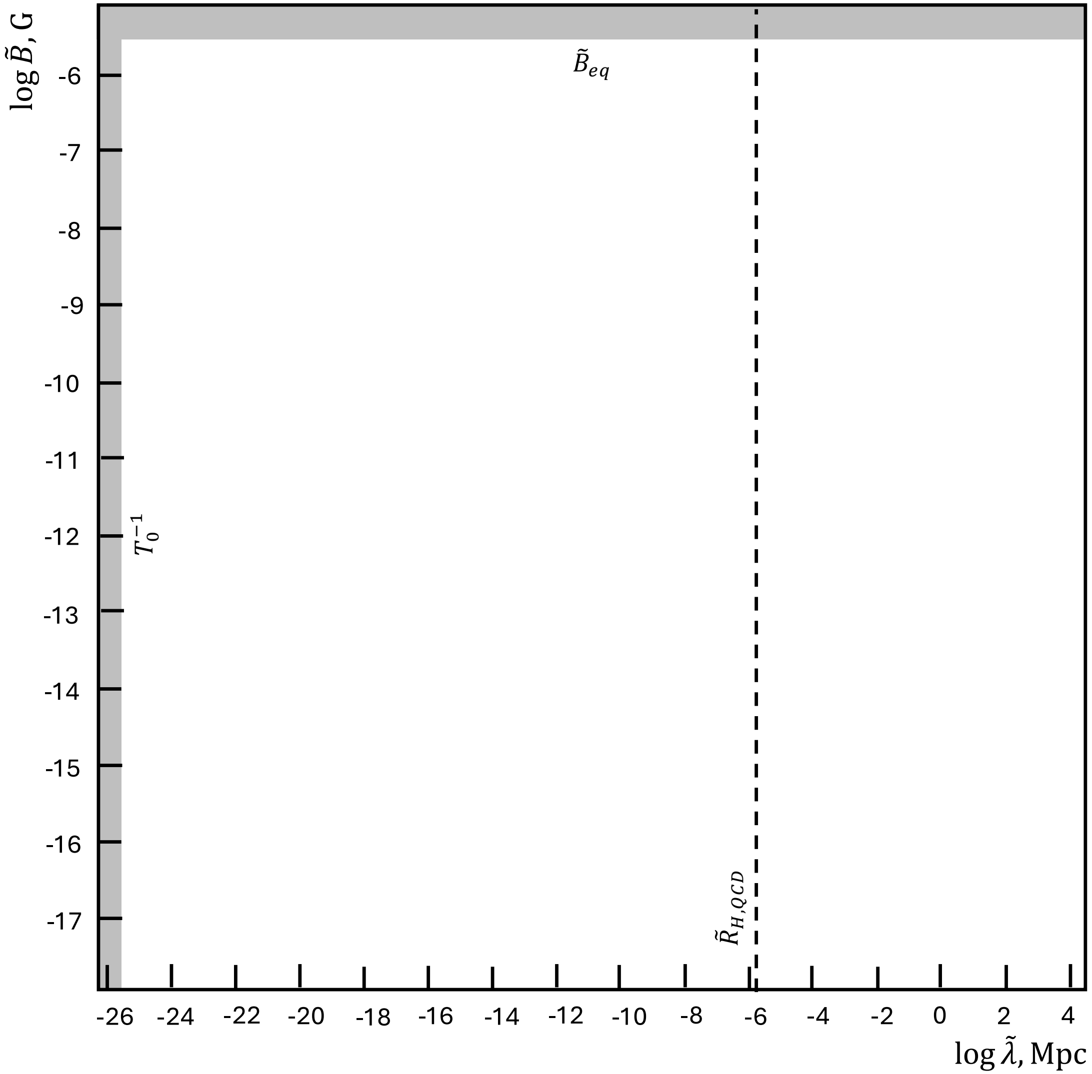
If magnetic field has been generated at certain cosmological epoch at temperature T, its correlation length cannot exceed the Hubble radius at this epoch

$$\tilde{\lambda}_B \leq \frac{1}{Ha} \simeq \sqrt{\frac{3M_{Pl}^2}{8\pi}\left(\frac{30}{\pi^2 g_* T^4}\right)}\left[\frac{g_*}{4}\right]^{\frac{1}{3}}\left[\frac{T}{T_0}\right]^1 = \sqrt{\frac{90}{2\pi^3}}\left[\frac{g_*}{4}\right]^{-\frac{1}{6}}\frac{M_{Pl}}{TT_0}$$

$$\simeq 4\times10^2\left[\frac{g_*}{4}\right]^{-\frac{1}{6}}\left[\frac{T}{1\text{ eV}}\right]^{-1}\text{Mpc}$$

This gives

$$\tilde{\lambda}_B < \tilde{R}_{H,QCD} \simeq 2\left[\frac{g_*}{50}\right]^{-\frac{1}{6}}\left[\frac{T}{150\text{ MeV}}\right]^{-1}\text{pc} \quad @\text{ QCD epoch}$$



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$$\simeq 4\times 10^2 \left[\frac{g_*}{4}\right]^{-\frac{1}{6}}\left[\frac{T}{1\ \mathrm{eV}}\right]^{-1} \mathrm{Mpc}$$

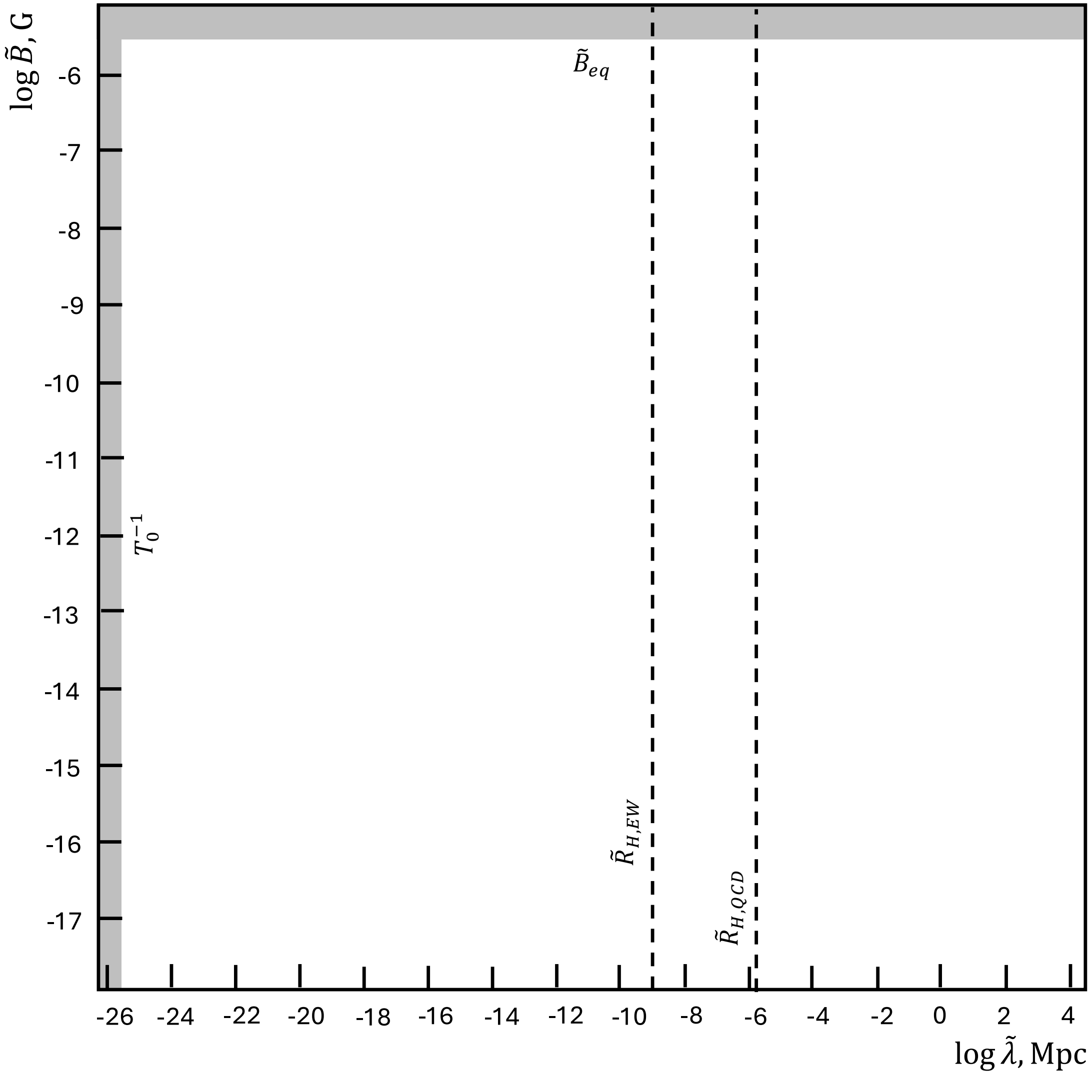
This gives

$$\tilde{\lambda}_B < \tilde{R}_{H,QCD} \simeq 2\left[\frac{g_*}{50}\right]^{-\frac{1}{6}}\left[\frac{T}{150\ \mathrm{MeV}}\right]^{-1} \mathrm{pc} \quad @\ \mathrm{QCD\ epoch}$$

or

$$\tilde{\lambda}_B < \tilde{R}_{H,EW} \simeq 10^{-9}\left[\frac{g_*}{10^2}\right]^{-\frac{1}{6}}\left[\frac{T}{170\ \mathrm{GeV}}\right]^{-1} \mathrm{pc} \quad @\ \mathrm{EW\ epoch}$$

There is formally no constraint on the correlation length of magnetic field originating from Inflation.



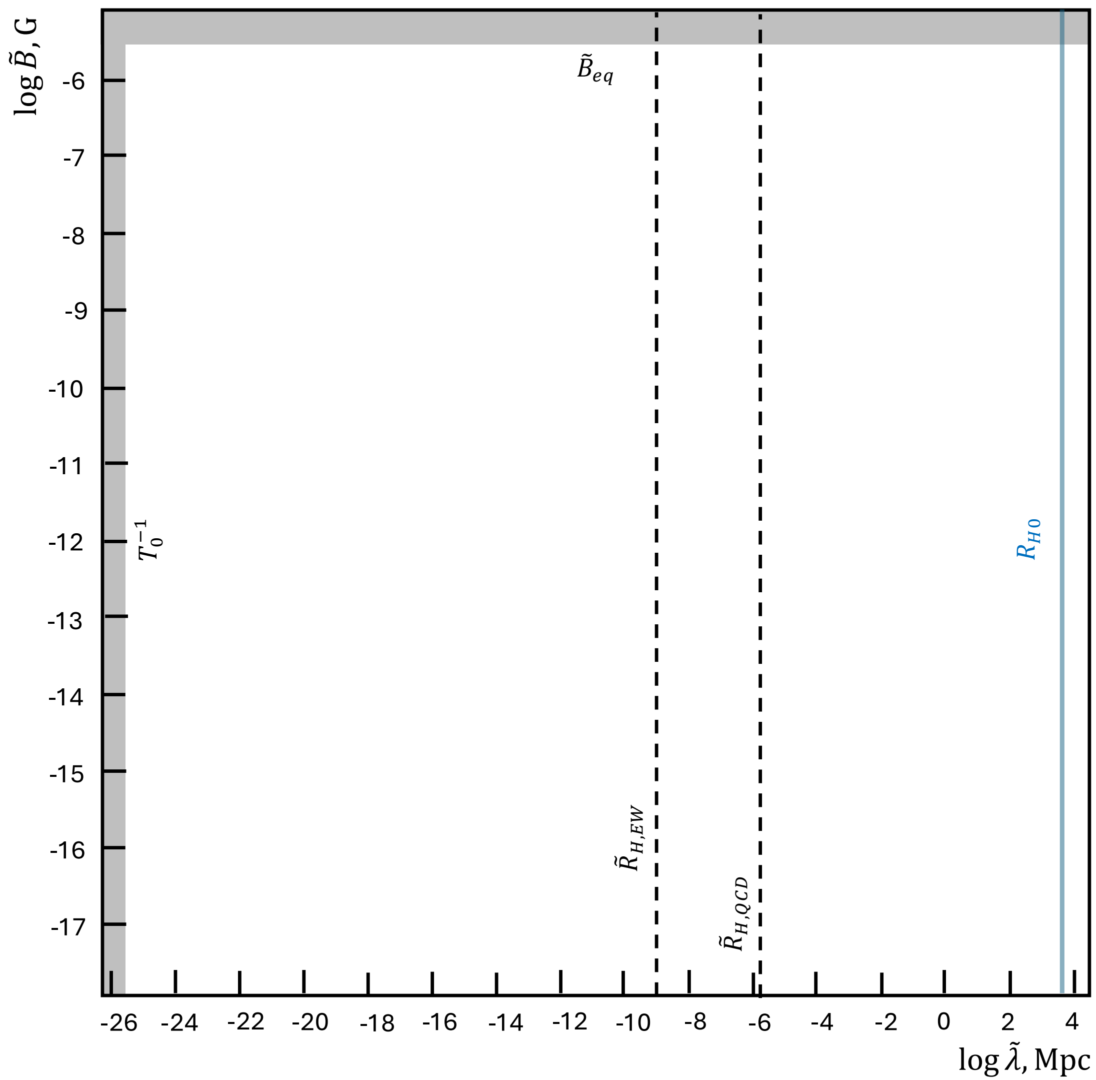
Relic cosmological magnetic field in the present-day Universe?

The magnetic fields in either present-day or early Universe do not remain constant over time (a field in a solenoid in a lab disappears as soon as one switches off the current through the coil).

The rate at which the field is transformed depends on the distance scales: it takes more time to change the field on larger scales.

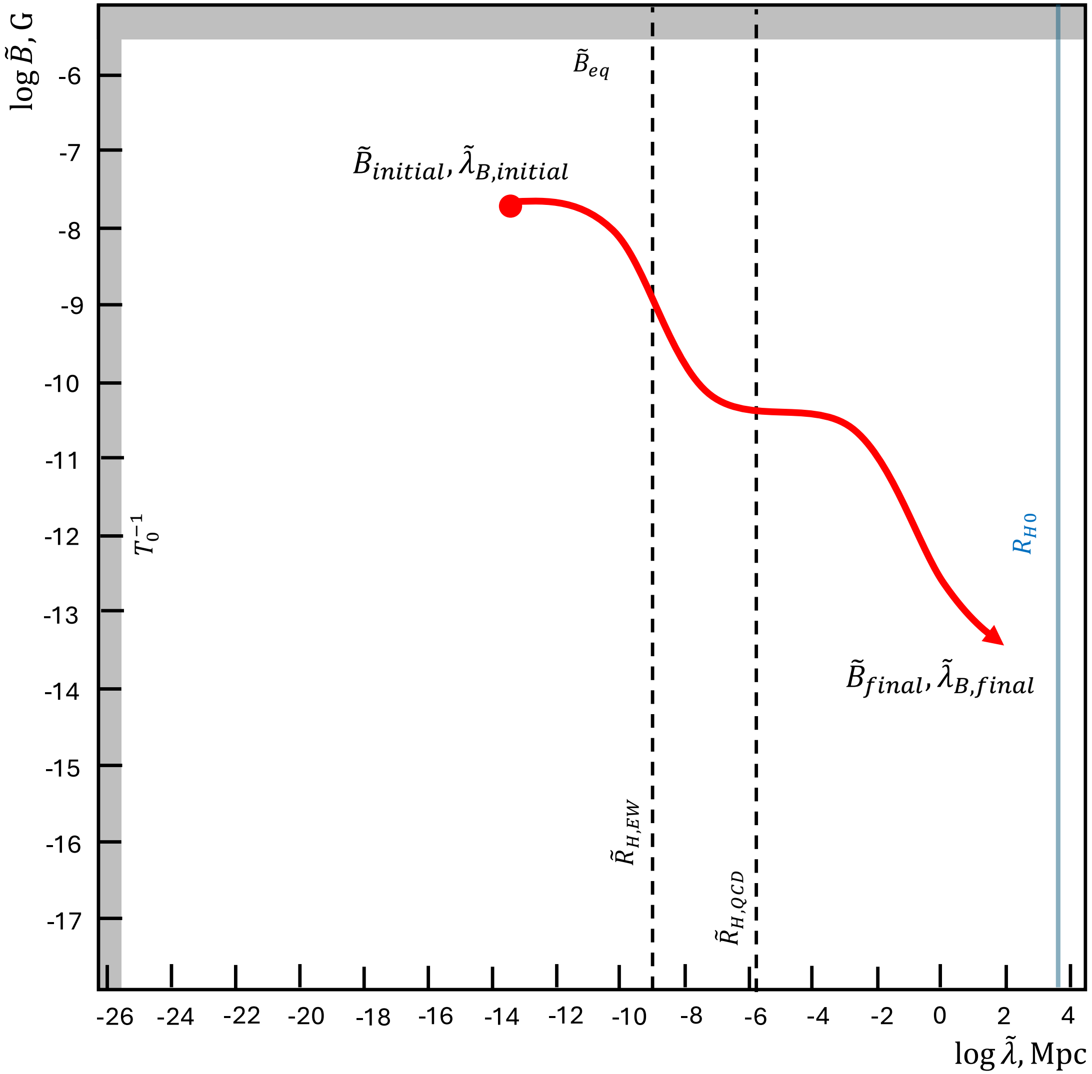
The largest scale at which the magnetic field can change in the present-day Universe is the present-day Hubble scale

$$R_{H0} = H_0^{-1} \simeq 4\ \text{Gpc}$$



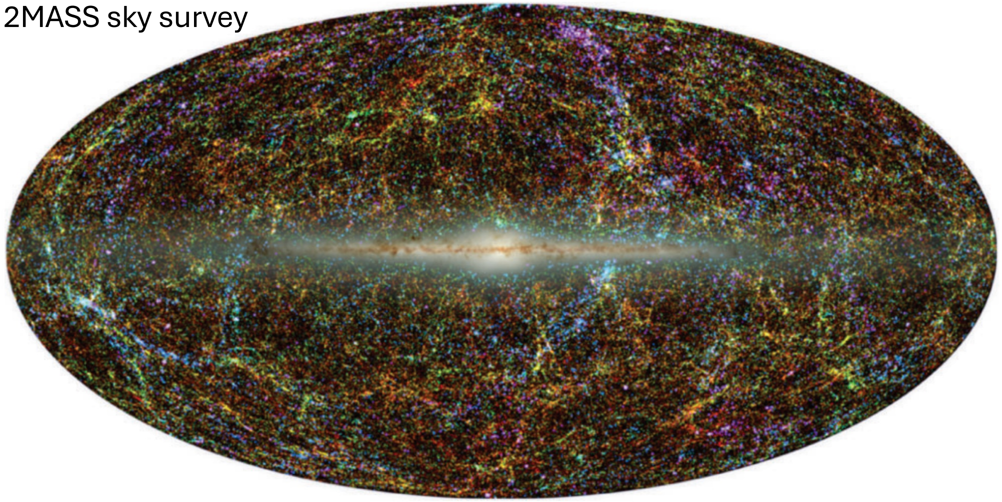
Relic cosmological magnetic field in the present-day Universe?

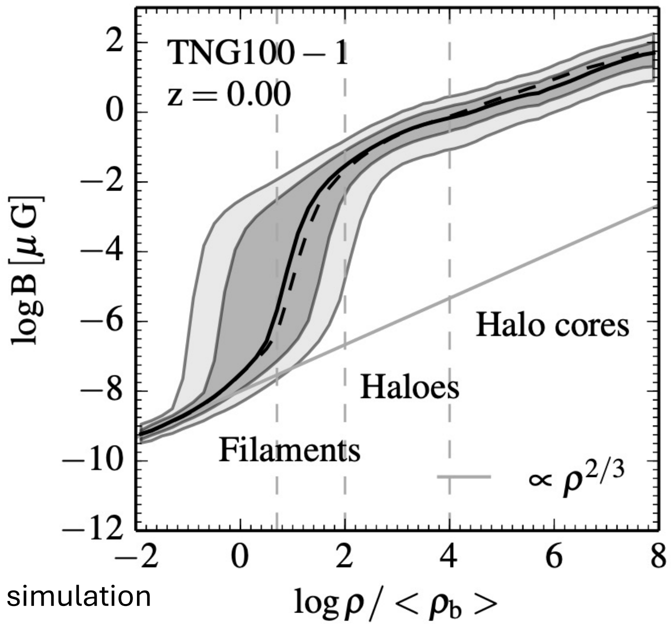
… see lectures of Brandenburg, Caprini and Vazza



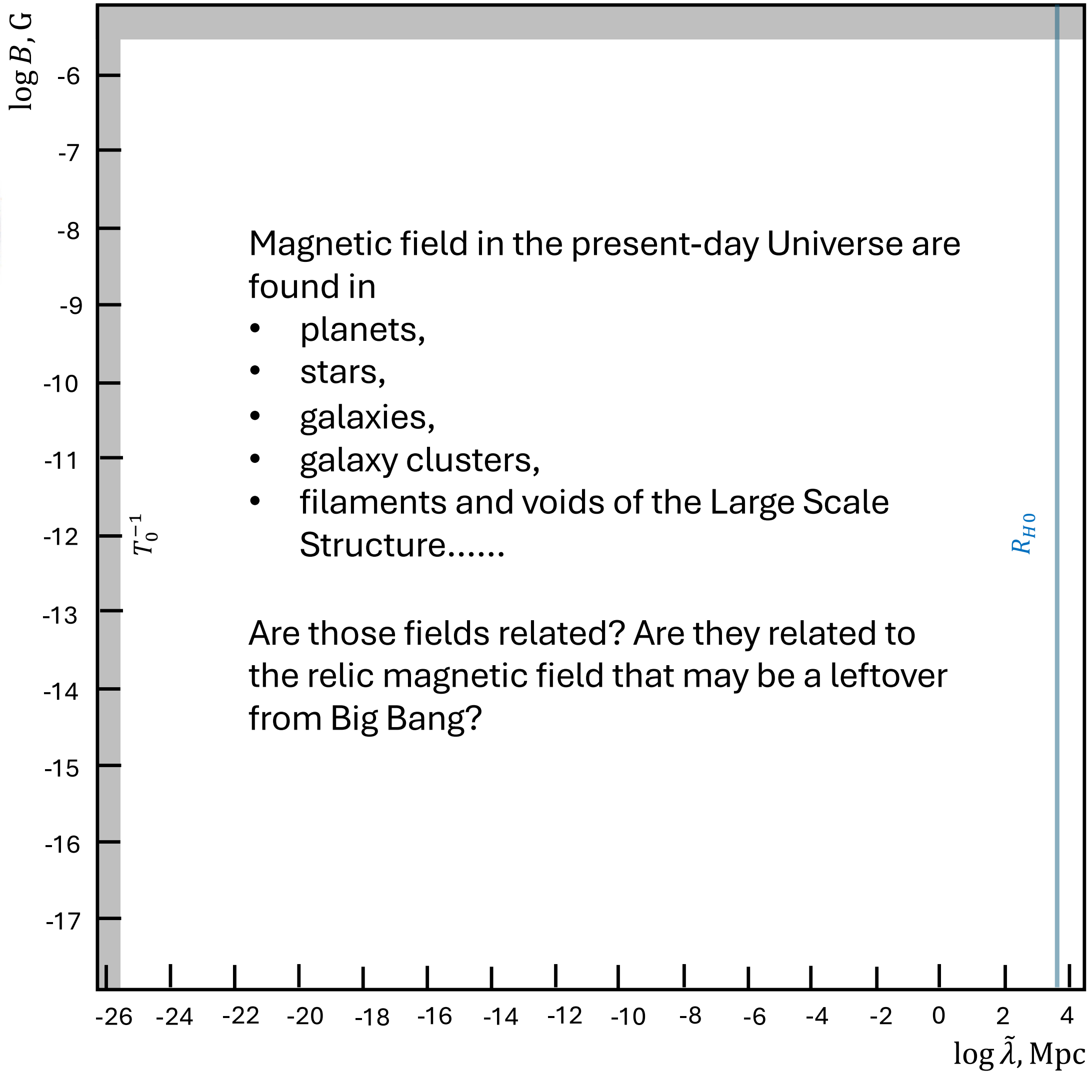
Magnetic fields in the present-day Universe

2MASS sky survey





Illustris-TNG simulation



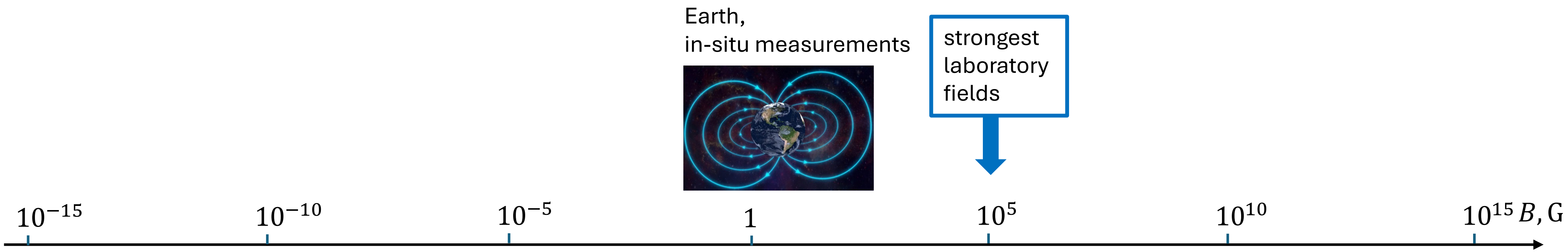
Magnetic field in the present-day Universe are found in

- planets,
- stars,
- galaxies,
- galaxy clusters,
- filaments and voids of the Large Scale Structure……

Are those fields related? Are they related to the relic magnetic field that may be a leftover from Big Bang?

Measurements of magnetic fields in present-day Universe

Measurements of magnetic fields in present-day Universe



Exercise 1. How can we measure direction and strength of the Earth magnetic field with a tabletop setup?

Exercise 2. How would Martians measure the Earth magnetic field using astronomical techniques?

Cyclotron emission

Maxwell equations

$$F^{\mu\nu}{}_{;\nu} = 4\pi J^{\mu}$$
$$F_{\mu\nu} = A_{\mu,\nu} - A_{\nu,\mu}$$
$$A_{\mu} = (\phi, \vec{A})$$
$$\partial_{\nu}\partial_{\nu}A^{\mu} = 4\pi J^{\mu}$$

Point charge moving along trajectory $\vec{r}_0(t)$:

$$J^{\mu} = e\left(\delta\big(\vec{r} - \vec{r}_0(t)\big), \vec{v}\big(\vec{r} - \vec{r}_0(t)\big)\right), \vec{v} = \dot{\vec{r}_0}$$

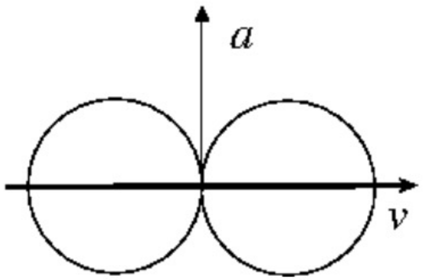
"Wave zone" solution of Maxwell equations:

$$\vec{E} = \frac{1}{r}\left(\left(\ddot{\vec{d}}\times\vec{n}\right)\times\vec{n}\right); \qquad \vec{B} = \frac{1}{r}\left(\ddot{\vec{d}}\times\vec{n}\right)$$

where $\vec{d} = e\vec{r}_0$ is the electric dipole moment, $\vec{n} = \vec{r}/r$.

Electromagnetic flux I in solid angle $d\Omega$ in direction $\vec{n}$ misaligned by angle θ w.r.t. $\ddot{\vec{d}}$

$$\vec{S} = \frac{\vec{E}\times\vec{B}}{4\pi} = \frac{B^2}{4\pi}\vec{n} \qquad \frac{dI}{d\Omega} = \vec{S}\cdot\vec{n} = \frac{\ddot{d}^2}{4\pi}\sin^2\theta \qquad I = \int\frac{dI}{d\Omega}d\Omega = \frac{2\ddot{d}^2}{3}$$



($\vec{S}$ is Poynting vector). Radiation spectrum:

$$\int\frac{dI(t)}{d\Omega}dt = \int\frac{d\hat{I}(\omega)}{d\Omega}d\omega\,; \qquad \frac{d\hat{I}(\omega)}{d\Omega} = \omega^4\left|\hat{d}(\omega)\right|^2\sin^2\theta$$

Charge moving along circular trajectory: $\vec{a}\perp\vec{v}$; $\quad a = v^2/R = \omega R$. $\ddot{d} = ea$.

$$\frac{dI}{d\Omega} = \vec{S}\cdot\vec{n} = \frac{e^2a^2}{4\pi}\,; \qquad I = \frac{2e^2a^2}{3} = \frac{2}{3}\frac{e^2v^4}{R^2}$$

Spectrum is monochromatic with the frequency $\omega_0 = v/R$.

Cyclotron emission

Electron gyrating in uniform magnetic field

$$\frac{mv^2}{R} = evB$$

$$R = \frac{mv}{eB}$$

$$\omega_0 = \frac{eB}{m_e} \simeq 1.2\times10^{-8} \left[\frac{B}{1\ \mathrm{G}}\right] \mathrm{eV} \simeq 1.8\times10^{7} \left[\frac{B}{1\ \mathrm{G}}\right] \mathrm{s}^{-1}$$

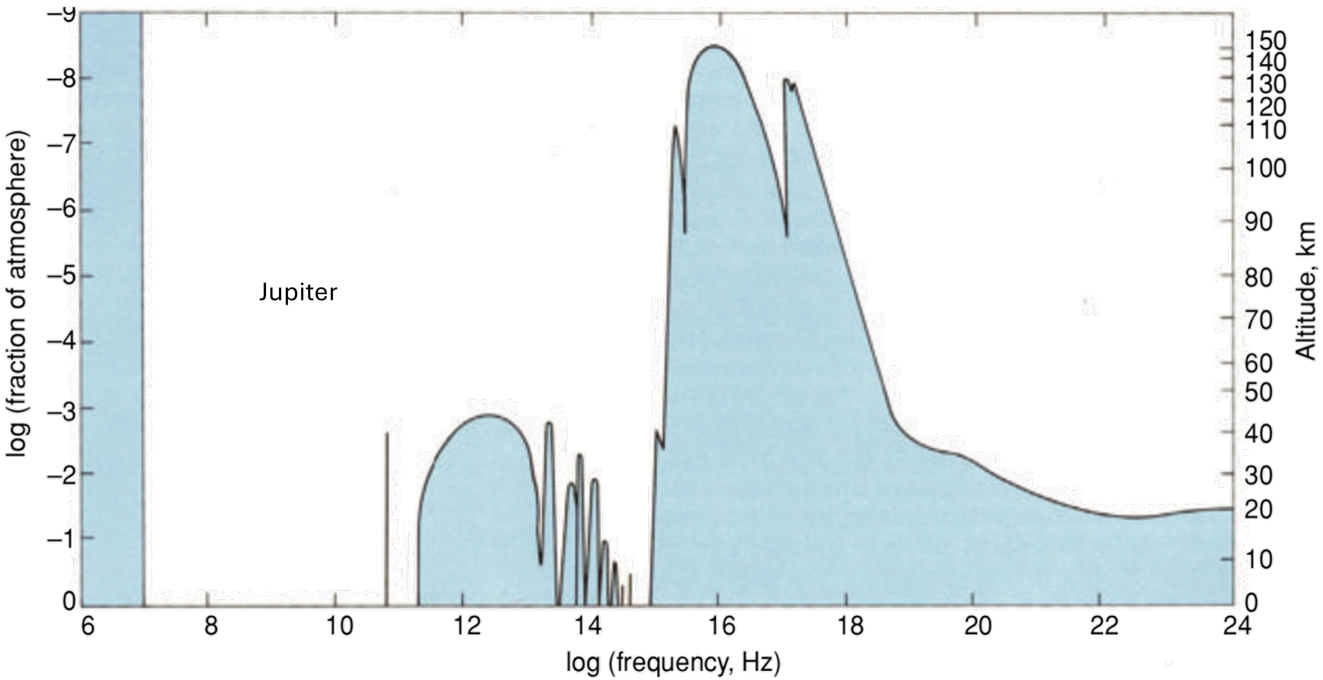
The frequency of cyclotron radiation is

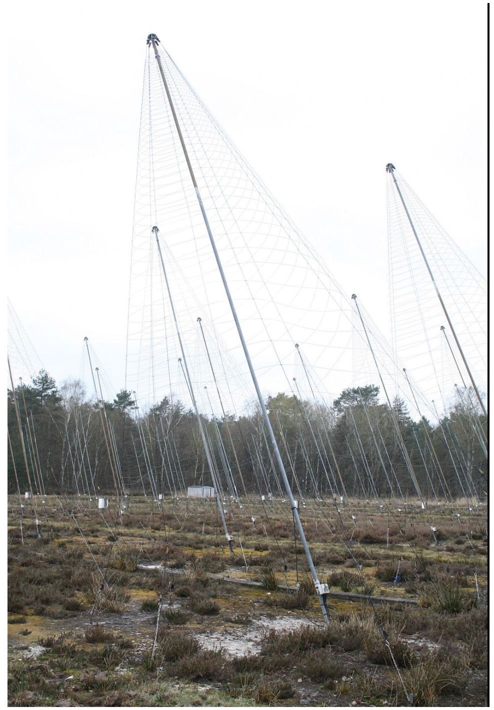
$$\nu = \frac{\omega_0}{2\pi} \simeq 3 \left[\frac{B}{1\ \mathrm{G}}\right] \mathrm{MHz}, \qquad \lambda = \frac{c}{\nu} \simeq 10^4\ \mathrm{cm} = 100\ \mathrm{m}$$

Earth may be a source of cyclotron emission if there is enough free electrons moving with high velocity ($I \propto v^4$). If this is the case, such synchrotron emission is observable in MHz range.

Exercise 3. Listen the "Voice of the Earth cyclotron" HF radio (☺). It is louder during aurorae?

Astronomical observation windows

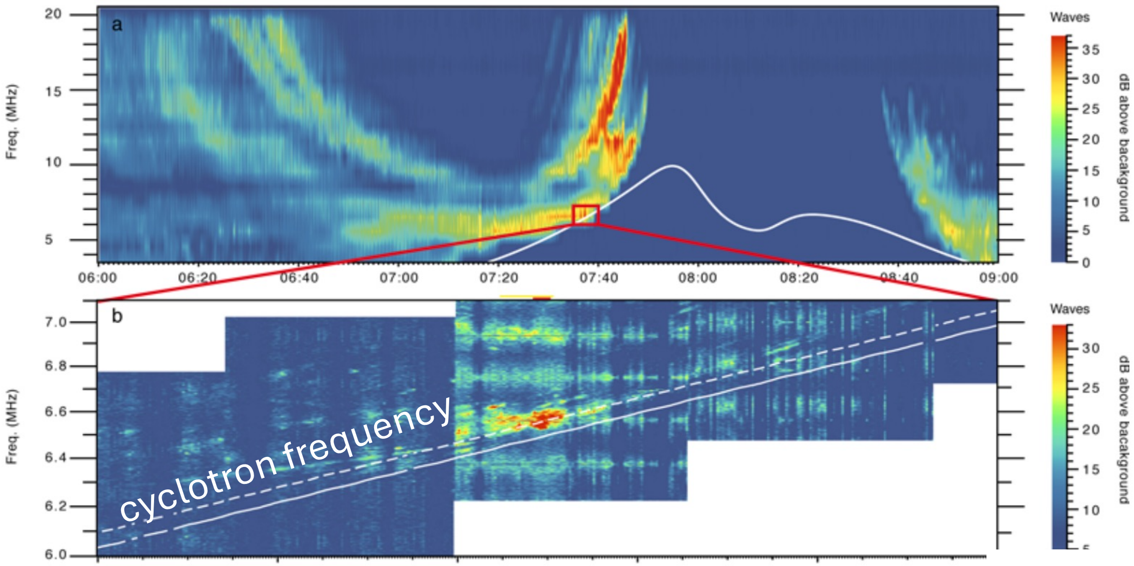




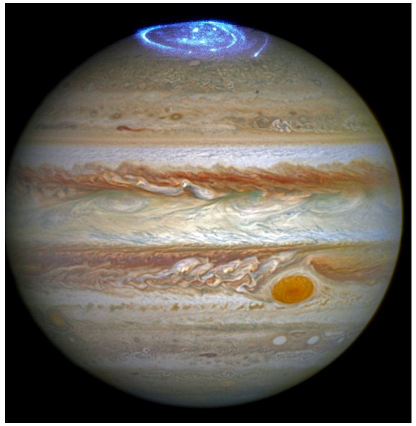
MHz waves are used for long-range communications on Earth because they are reflected by the Ionosphere (part of atmosphere ionised by the solar radiation, above 50 km) and hence are not good for astronomy.

Longest waves transimtted through the Ionosphere have wavelengths 3-30 m and detectors of such waves exist (e.g. Decametric array, Nancay, $3\text{ m} < \lambda < 30\text{ m}$, picture on the right).

Jupiter magnetic field

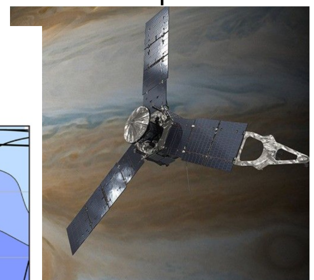


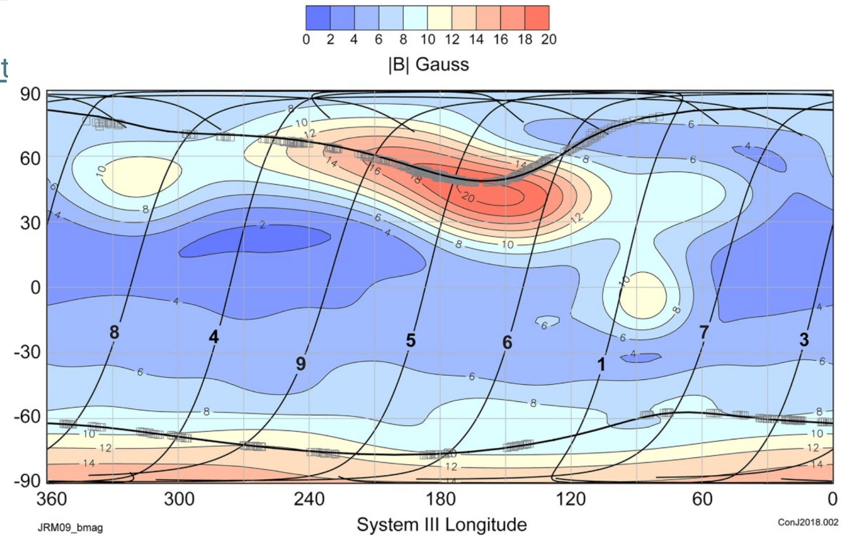
Deametric emission from Jupyter, perturbed by Ganymede
https://ui.adsabs.harvard.edu/abs/2020GeoRL..4790021L/abstract



Aurora on Jupiter (HST)

JUNO spacecraft

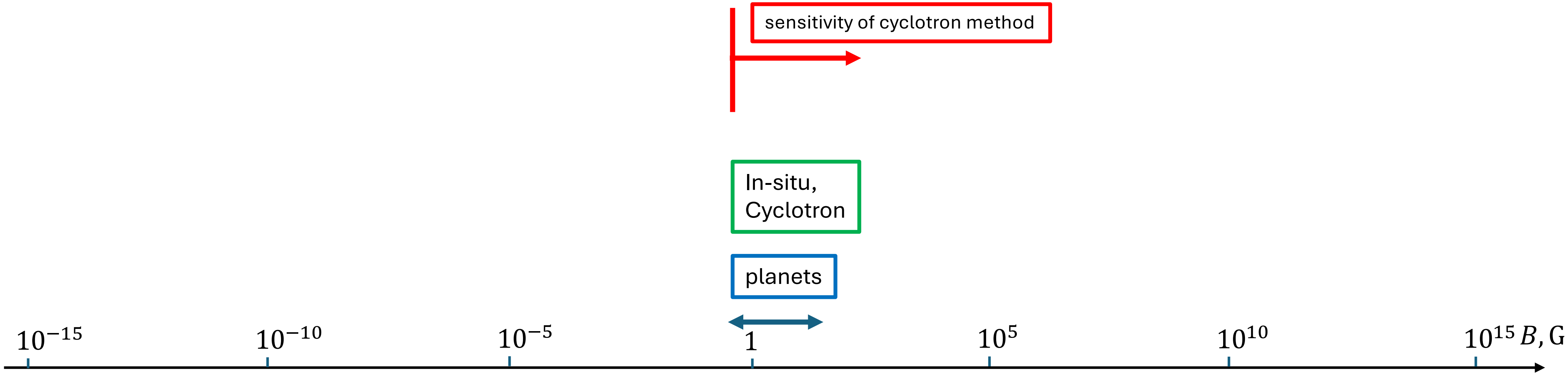




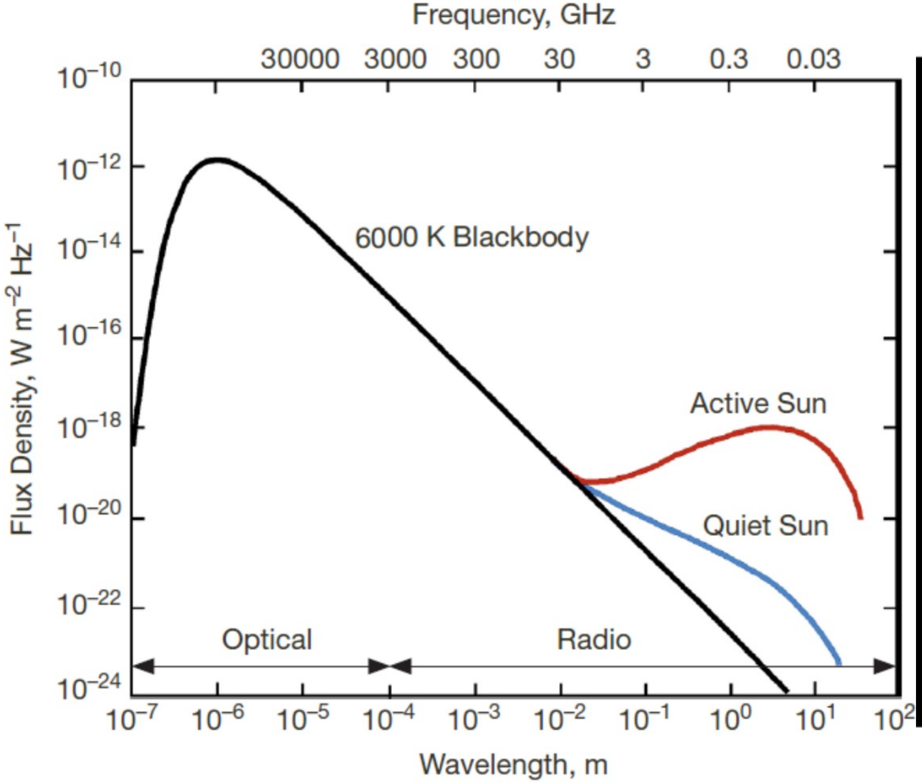
Jupiter is a cyclotron source. The decametric cyclotron emission was used to infer its magnetic field ~ 10 G.

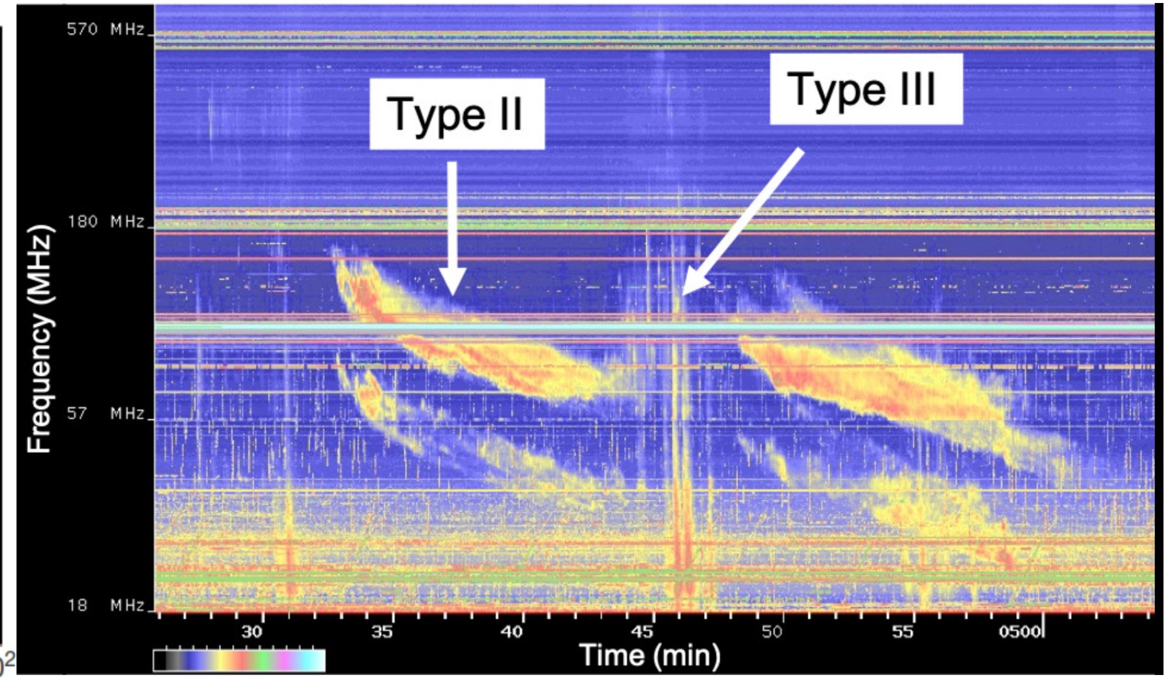
$$B \simeq 2 \left[\frac{\nu_c}{6\ \mathrm{MHz}}\right]\ \mathrm{G}$$

Measurements of magnetic fields in present-day Universe



Cyclotron emission from the Sun





The Sun has moderately strong dipole field ($\sim$ G) and stronger field in the corona, up to kG.

$$B \simeq 60 \left[\frac{\nu_c}{180\ \mathrm{MHz}}\right]\ \mathrm{G}$$

Zeeman effect

Consider electron in the Coulomb field of atomic nucleus and in external homogeneous magnetic field $\vec{B}_0$

$$i\dot{\Psi} = \left[\frac{1}{2m_e}\left(\vec{p} - e\vec{A}\right)^2 + e\phi\right]\Psi = \left[\frac{p^2}{2m_e} - \frac{e}{2m_e}\vec{B}_0\cdot(\vec{L} + g_e\vec{S}) + \frac{e^2}{8m_e}\left(r^2B_0^2 - \left(\vec{r}\cdot\vec{B}_0\right)^2\right) + e\phi\right]\Psi$$

$$\vec{L} = \vec{r}\times\vec{p}, \qquad p_i = -i\partial_i, \qquad \vec{A} = -\frac{1}{2}\vec{r}\times\vec{B}_0$$

where $\vec{L}$ is the angular momentum and $\vec{S}$ is the spin, $g_e = 2$ is the gyromagnetic ratio factor.
Consider "weak" magnetic field,

$$\frac{eB_0}{m_e} \ll \frac{1}{m_e\, r_0^2} = e^4 m_e, \qquad r_0 = \frac{1}{Me^2}\ \text{(Bohr radius)}$$

$$\boldsymbol{B_0 \ll e^4 m_e^2 \simeq 2\times 10^8\ \mathrm{G}}$$

only terms linear in B_0 can be retained (not always the case in astrophysical environments).

Energy levels of an atom are split into sub-levels with energy increments given by the expectation values of $\vec{L} + g_e\vec{S}$, because of the interaction term. Introducing the total angular momentum $\vec{J} = \vec{L} + \vec{S}$ that is conserved,

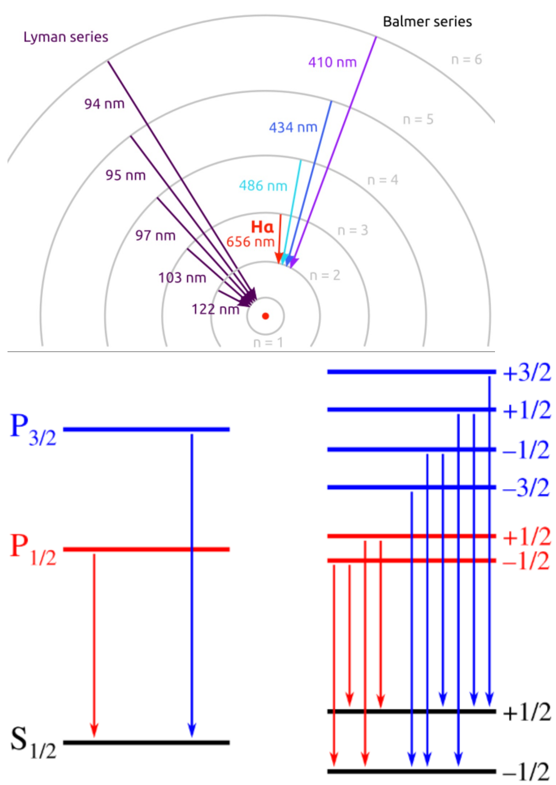
$$H_{B_0} = \frac{e}{2m_e}\vec{B}_0\left(\vec{J} + (g_e - 1)\vec{S}\,\right)$$

H, J, L, S, J_z commute so that one can consider the eigenstates of the five operators, characterised by quantum numbers: n, j, l, s, j_z:

$$\Delta E_{j,l,s,m} = \left(1 + \frac{(g_e - 1)\big(j(j+1) - l(l+1) + s(s+1)\big)}{2j(j+1)}\right)\frac{j_z}{2}\,\omega_0,$$

$$\omega_0 = \frac{eB_0}{m_e} \simeq 1.2\times 10^{-8}\left[\frac{B_0}{1\ \mathrm{G}}\right]\mathrm{eV}$$

Hydrogen Lyα line splitting



Zeeman splitting observations of the Sun

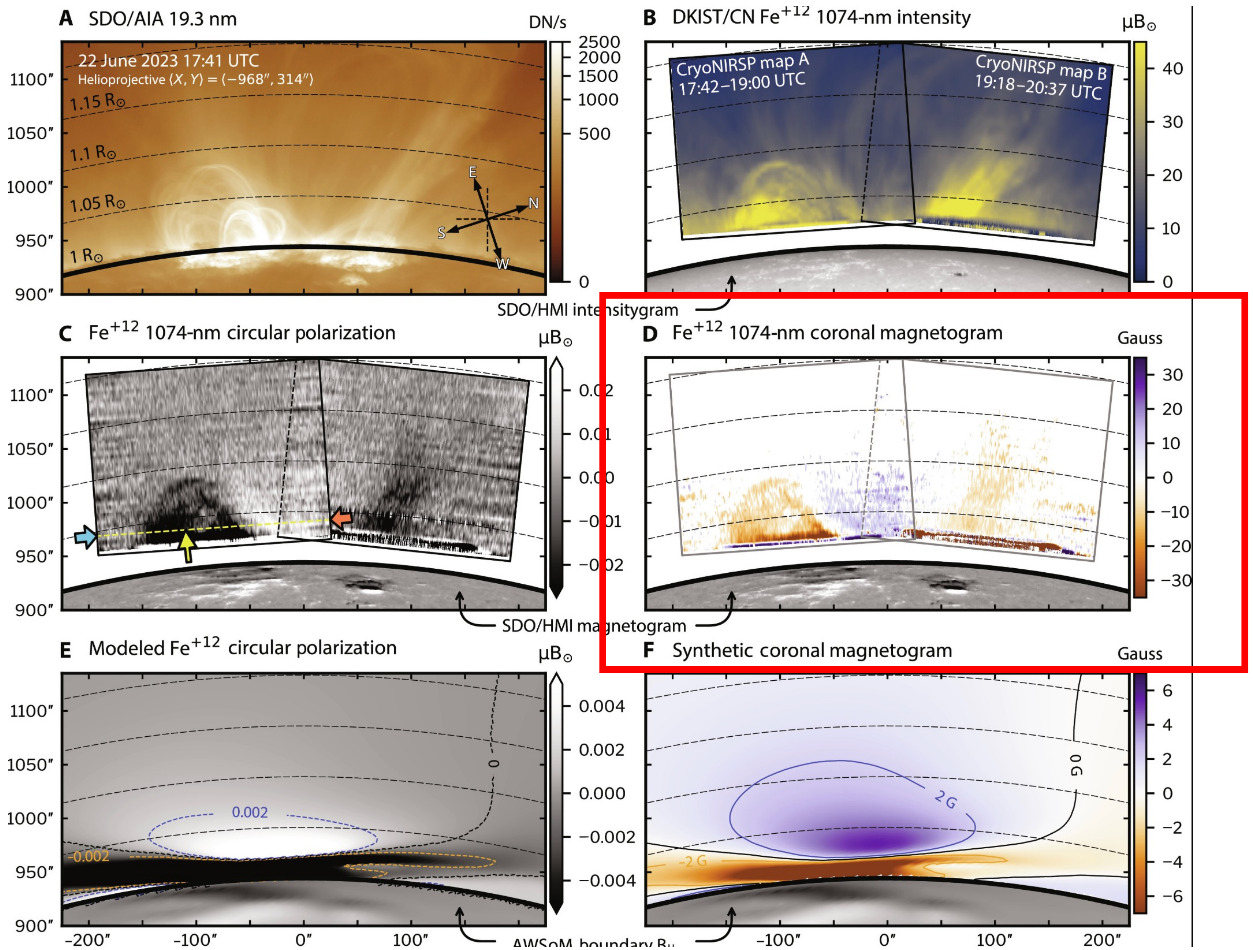


Fig. 1. The first DKIST coronal magnetogram mapping the magnetic field intensity. (**A**) SDO/AIA 19.3-nm image cropped and rotated to geometry of DKIST/CryoNIRSP observations. Vertical coordinates give arc seconds from the center of the solar disk. (**B**) The peak line amplitude of Fe^{+12} 1074 nm observed within the overlapping raster maps of CryoNIRSP in units of parts per million of the solar disk intensity, i.e., $\mu B_\odot$. (**C**) Peak red-wing amplitude of the measured antisymmetric circular polarized Fe^{+12} profile. (**D**) Inferred coronal longitudinal magnetogram in units of gauss as inferred from the weak-field approximation fitted to the circular polarized profiles. (**E**) Synthetic Fe^{+12} 1074-nm circularly polarized amplitude calculated from the Alfvén Wave Solar Atmosphere Model (AWSoM) coronal model. (**F**) Synthetic coronal magnetogram inferred from the signal in (E) in the same manner as (D).

https://arxiv.org/pdf/2410.21568

Zeeman splitting observations of stellar magnetic fields

Zeeman splitting technique is used for measurement of magnetic field of stars in general.

Zeeman splitting in magnetic white dwarfs, where the fields reach $10^6 - 10^9$ G is observed in non-linear regime.

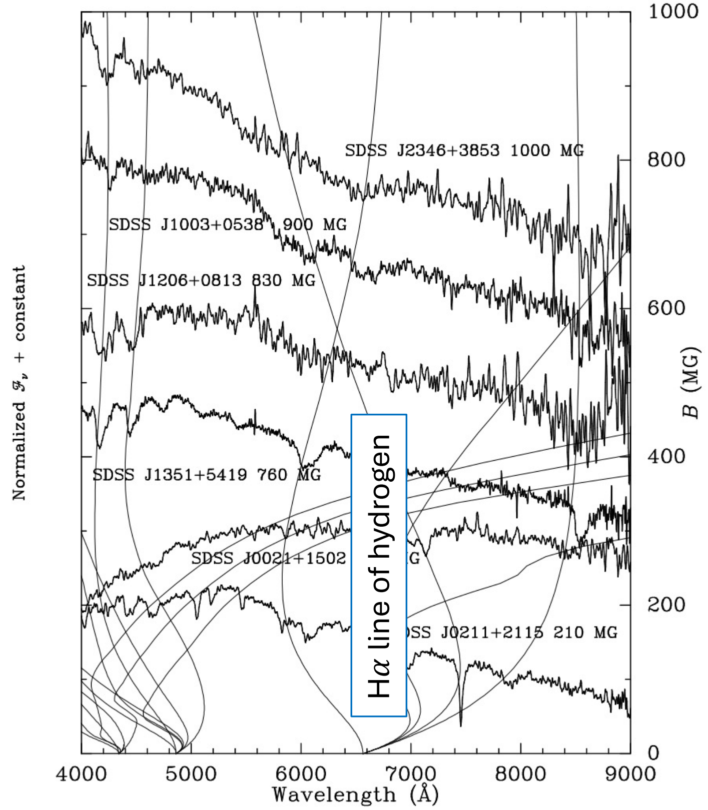
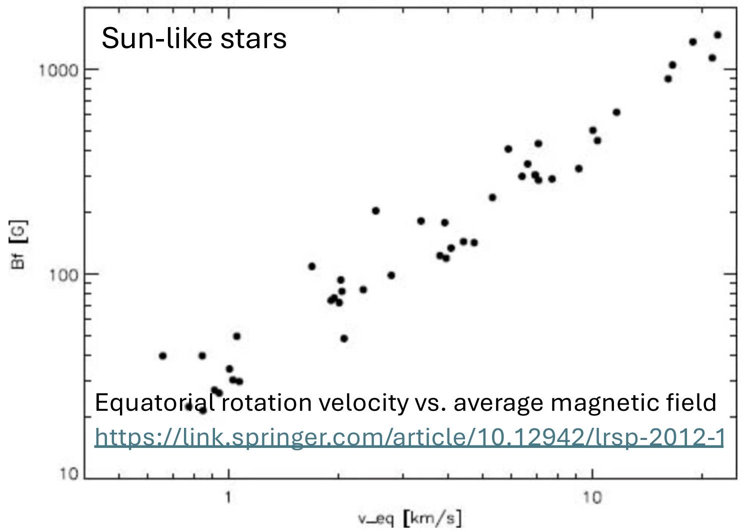
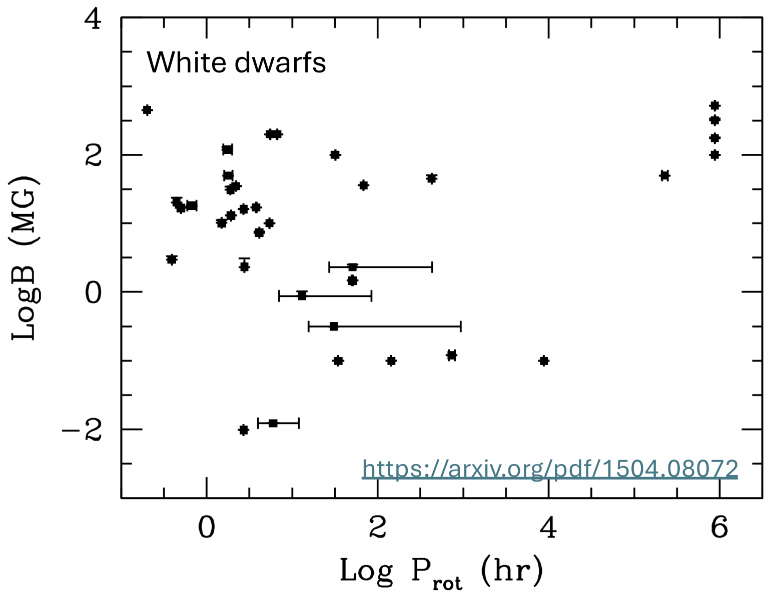
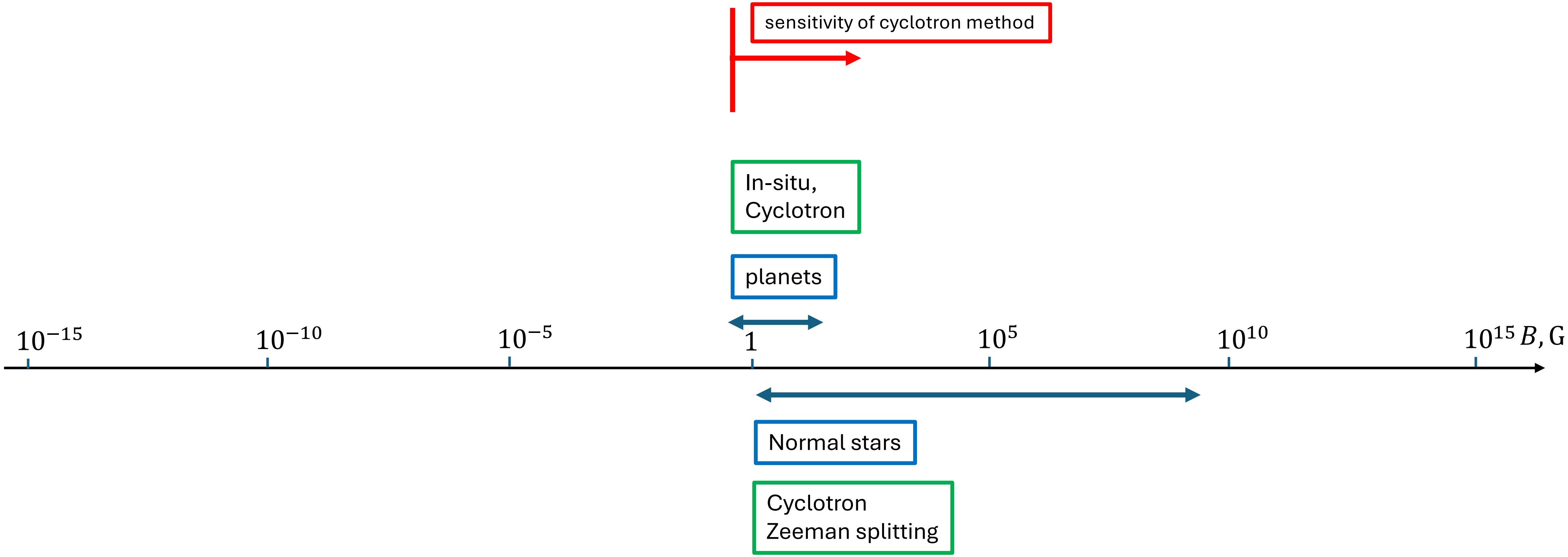


Fig. 2 Stationary Zeeman components of H_α and H_β (from Vanlandingham et al. 2005) in the spectra of strongly magnetic MWDs https://arxiv.org/pdf/1504.08072





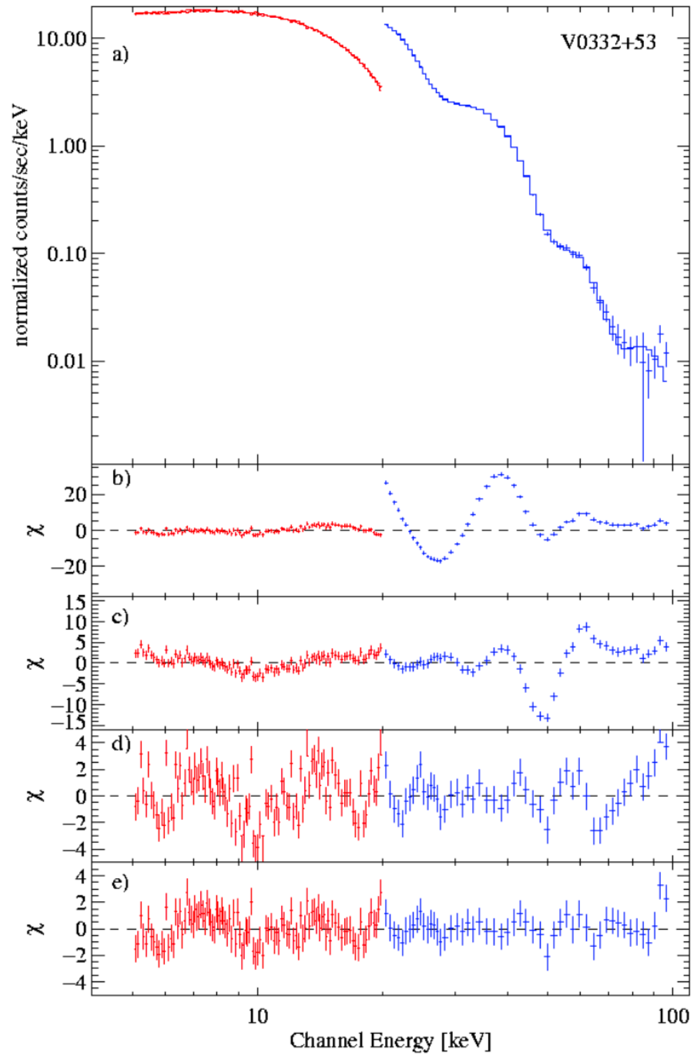
Measurements of magnetic fields in present-day Universe

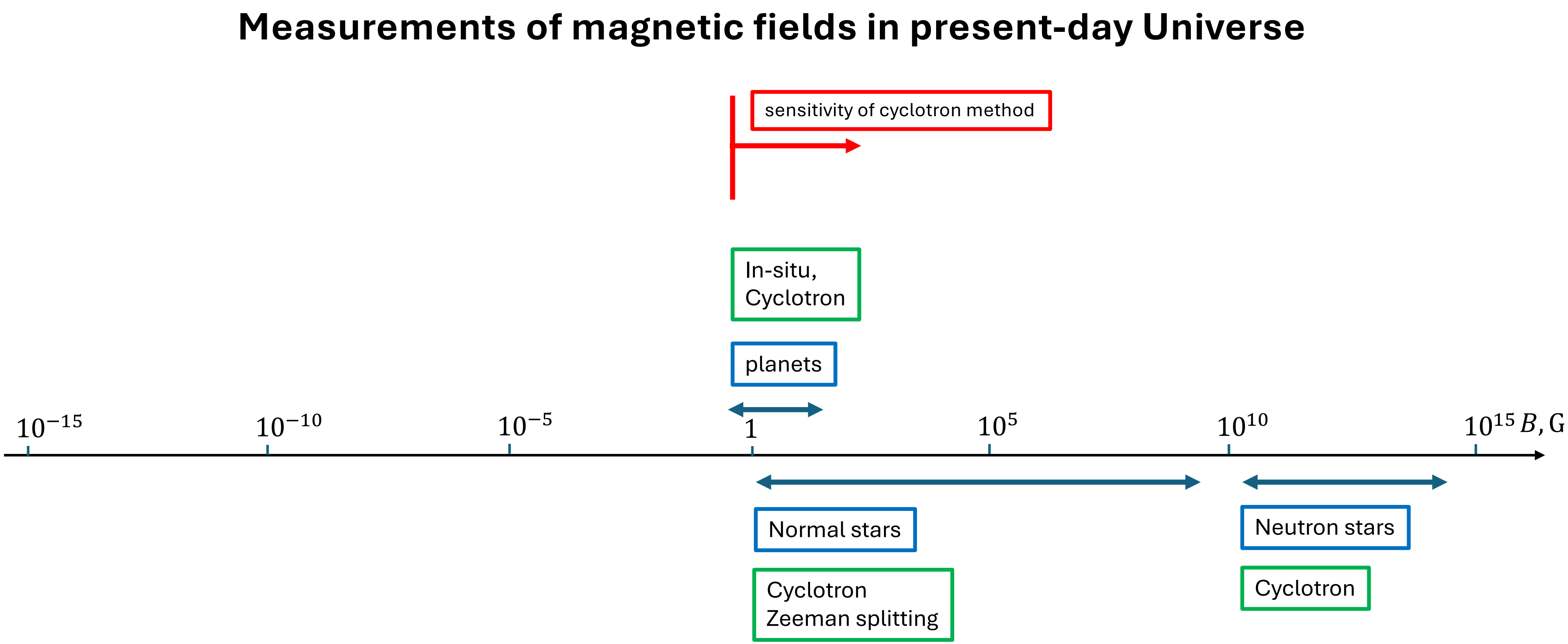


Cyclotron emission to extreme

Exercise 4. The cyclotron energy/frequency moves to the X-ray range if B grows up to 10^{12} G (check).

Write down Schroedinger equation for motion of free electron in homogeneous magnetic field and find the energy spectrum of its solutions (Landau levels). Estimate magnetic field of the neutron star in V0332+53 binary system (figure on the right), assuming that wiggles of the spectrum are harmonics of the cyclortron frequency.





Measurements of magnetic fields in present-day Universe
sensitivity of cyclotron method
In-situ,
Cyclotron
planets
10^{-15}
10^{-10}
10^{-5}
1
10^{5}
10^{10}
10^{15} B, G
Normal stars
Cyclotron
Zeeman splitting
Neutron stars
Cyclotron

Zeeman splitting to extreme

It is challenging to measure weaker magnetic fields using Zeeman splitting because the energy / frequency shifts

$$\nu_0 = \frac{\omega_0}{2\pi} \simeq 3 \left[\frac{B}{1\ \mathrm{mG}}\right] \mathrm{kHz}$$

Become increasingly small. It is not possible to observe such shifts of lines detectable in visible or infrared bands.

Lines also exist in the radio band, for example, 21 cm line of hydrogen produced by spin flips of the ground level, $\nu_{HI} = 1.42$ GHz. Other lines, like those of OH and CN molecules can also used.

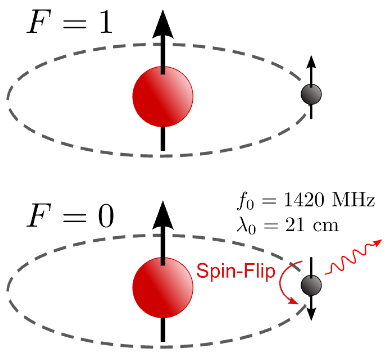
Weak magnetic fields are also difficult to measure because spectral lines are broadened by thermal velocity dispersion of atoms and molecules in the medium (e.g. due to thermal motions)

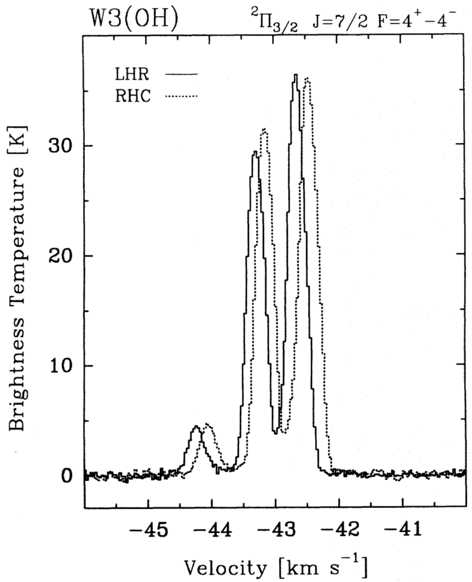
$$\frac{\delta\nu}{\nu} \sim \frac{v}{c} \simeq 10^{-5} \left[\frac{v}{3\ \mathrm{km/s}}\right]$$

If we want $\delta\nu \leq \nu_0$, we have to do measurements at the frequency

$$\nu \sim 1 \left[\frac{B}{1\ \mathrm{mG}}\right] \left[\frac{v}{1\ \mathrm{km/s}}\right]^{-1} \mathrm{GHz}$$

Such measurements are done to find mG level magnetic fields in molecular clouds and HII star forming regions.





Measurement of 3 mG magnetic field in W3 star forming region
https://ui.adsabs.harvard.edu/abs/1994A%26A...286L..51G/abstract

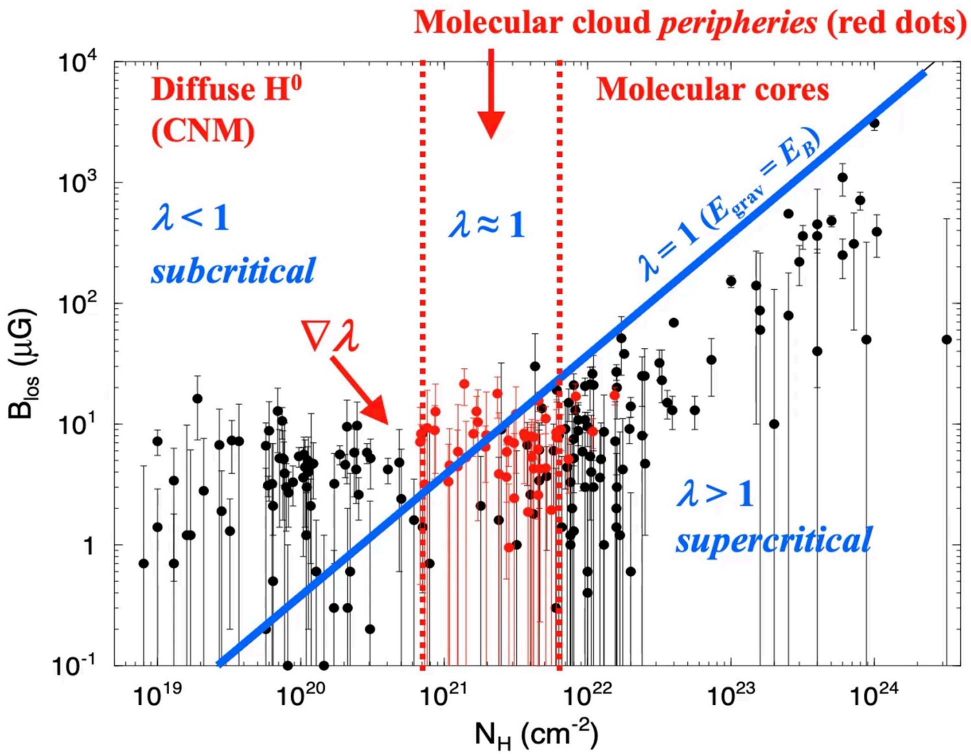
Magnetic fields in the interstellar medium from Zeeman splitting

Zeeman splitting of radio lines is used to infer magnetic field in the interstellar medium, with srength as weak as $B \sim 1 - 10\ \mu\mathrm{G}$.

Magnetic field plays crucial role in the molecular cloud physics, supporting the cloud against the gravitational collapse

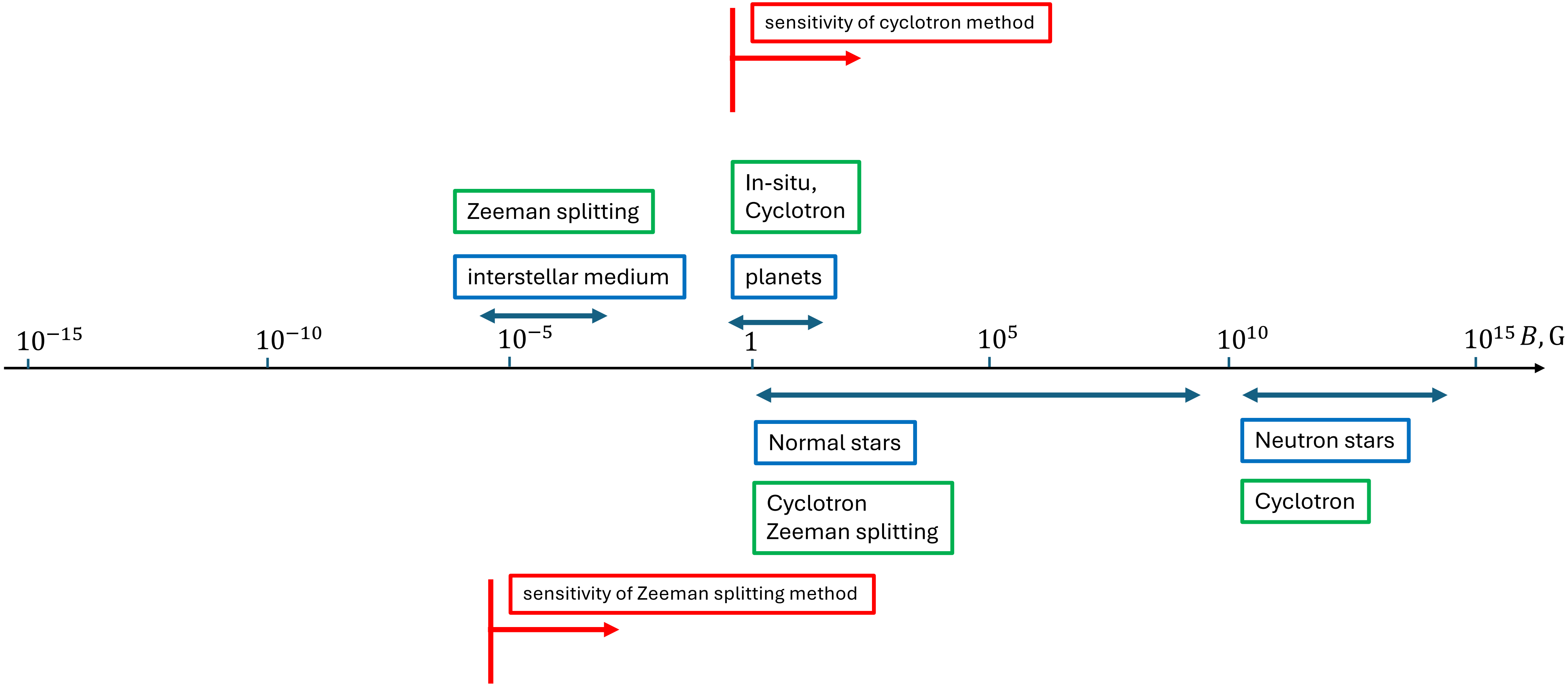
$$\lambda = \frac{E_{grav}}{E_B}$$

If $\lambda < 1$, magnetic field is strong enough to support the cloud against collapse. If $\lambda > 1$, the cloud collapses and magnetic field is amplified (like magnetic field amplification during structure formation).



https://irsa.ipac.caltech.edu/data/SOFIA/docs/sites/default/files/2023-04/MHoude-LectureNotes.pdf

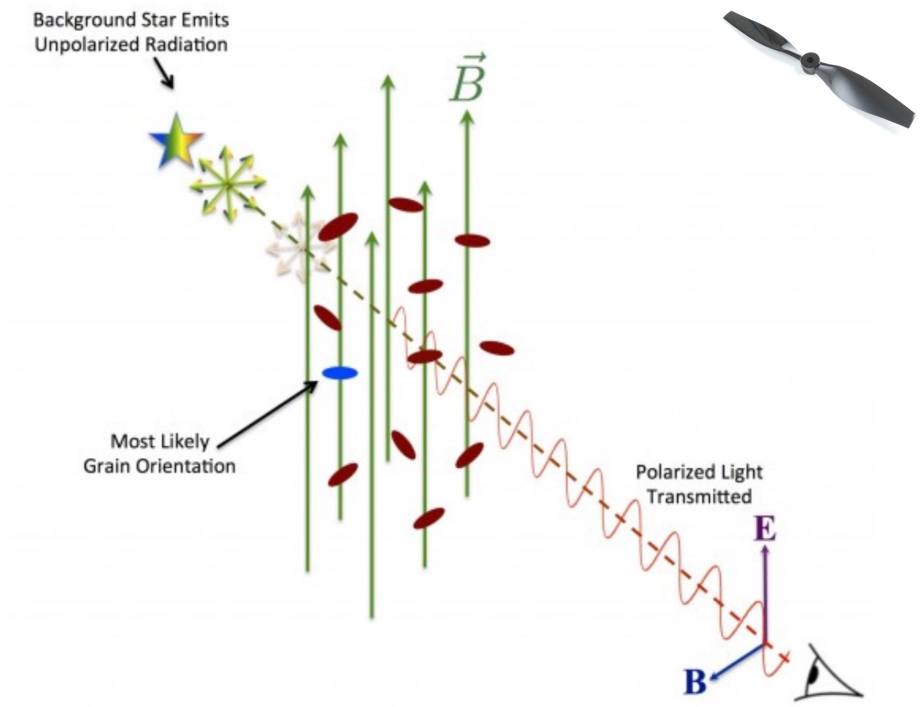
Measurements of magnetic fields in present-day Universe



Magnetic fields in the interstellar medium from starlight polarization (direction only)

Dust grains in the interstellar medium have shapes that force them into spinning due to the pressure of interstellar light fields. Spinning dust also posesses magnetic moments that tend to align with magnetic field if it is present in the interstellar medium.

Starlight passing through spinning dust grains aligned in certain direction gets polarized (in the direction perpendicular to that of the magnetic field).



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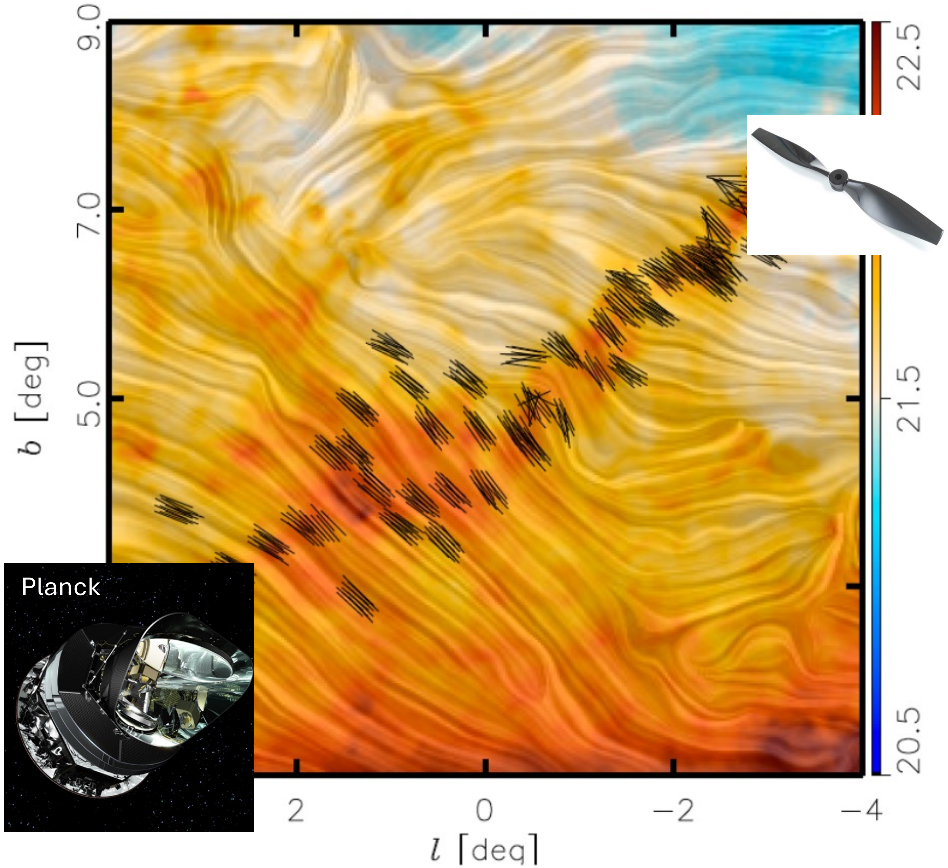
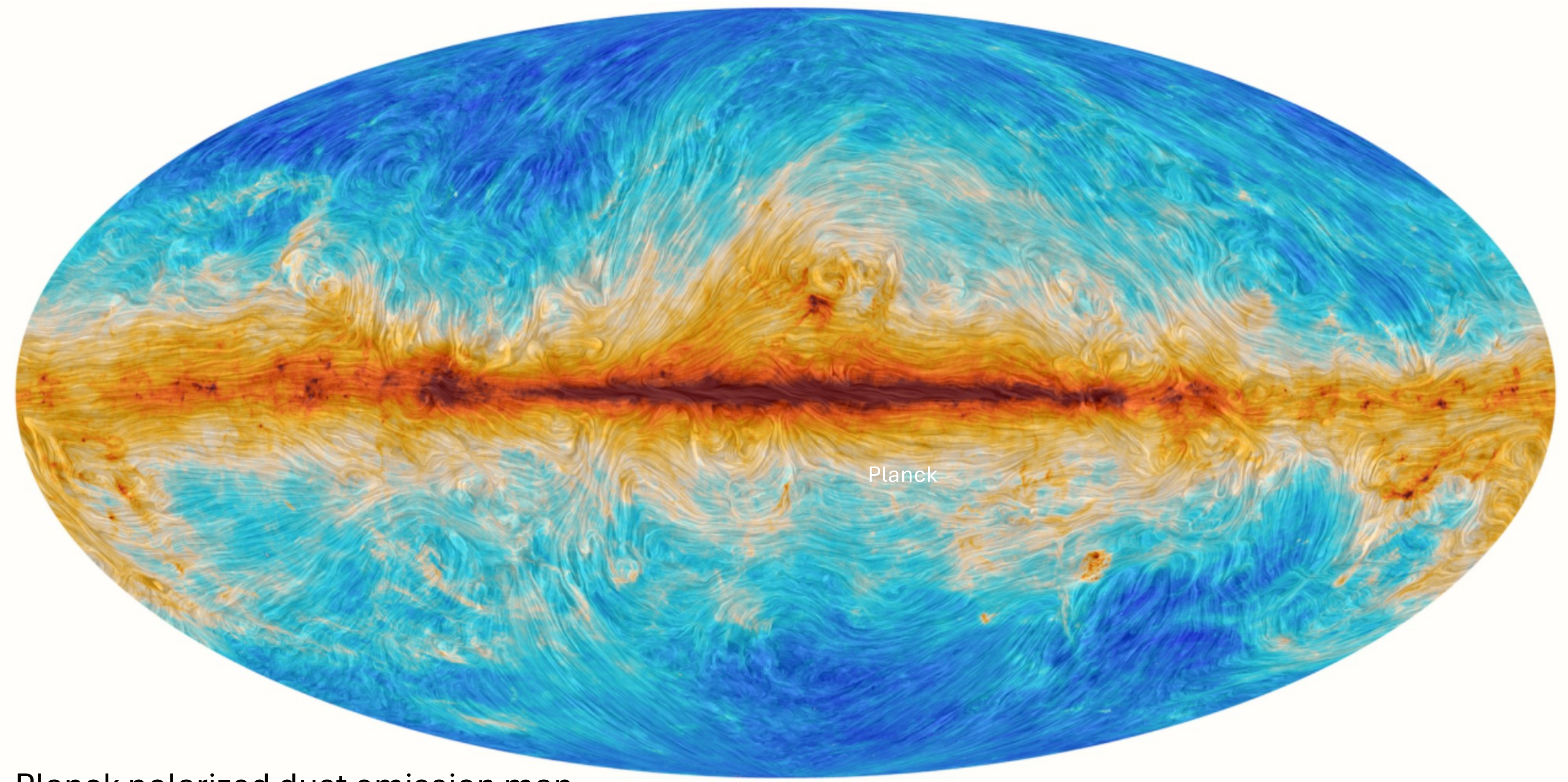
Starlight passing through spinning dust grains aligned in certain direction gets polarized (in the direction perpendicular to that of the magnetic field).

Dust absorbing interstellar radiation field heats. The heat is dissipated through infrared emission. Photons polarized along long axis of the grain are emitted more eficciently. The polarized emission is thus emitted preferentially in the direction perpendicular to that of the magnetic field.



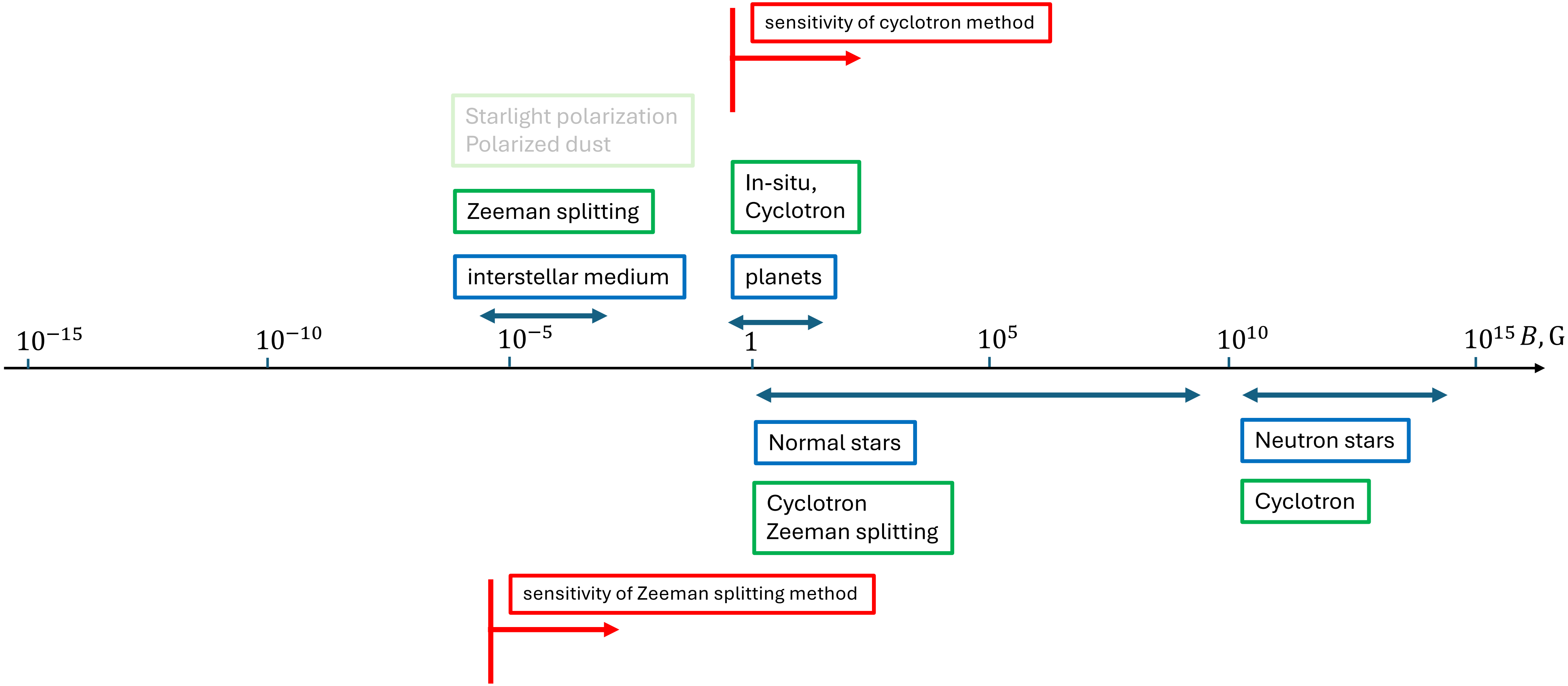
Magnetic field orientations inferred from submillimetre emission and visible or NIR extinction polarization observations towards the Pipe nebula.

Magnetic fields in the interstellar medium from dust polarization (direction only)



Planck polarized dust emission map

Measurements of magnetic fields in present-day Universe



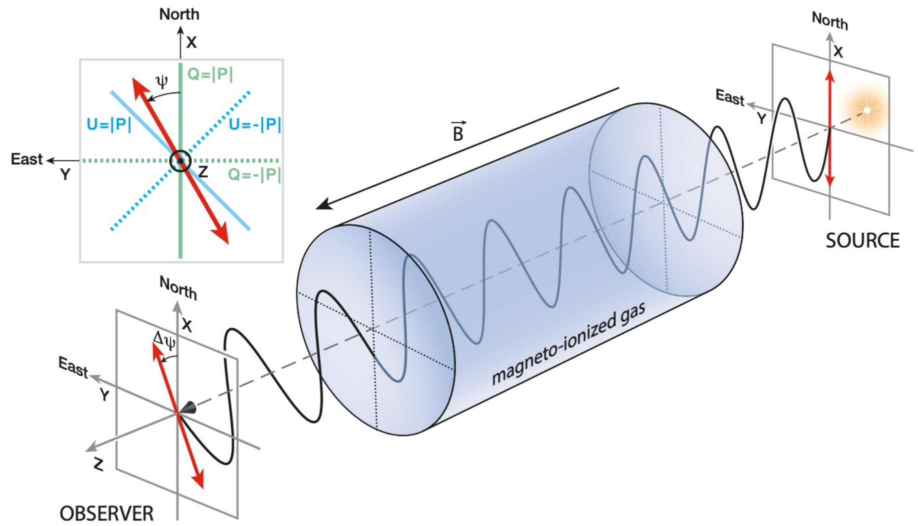
Faraday rotation

Electromagnetic wave propagates in z direction, through medium with free electron density n_e and magnetic field $\vec{B} = B_0\vec{e}_z$. Collective motions of electrons modify the electric and magnetic fields of the wave.

$$\frac{\partial \vec{E}}{\partial t} = \nabla\times\vec{B} - 4\pi\, e n_e \vec{V}_e$$

$$\frac{\partial \vec{B}}{\partial t} = -\nabla\times\vec{E}$$

$$m_e \frac{\partial \vec{V}_e}{\partial t} = e\left(\vec{E} + \vec{V}_e\times\vec{B}\right)$$



https://arxiv.org/pdf/2106.03074

Faraday rotation

Look for solutions that vary $\propto \exp\big(i(\omega t - kz)\big)$.

$$i\omega\vec{E} = -ik\vec{e}_z\times\vec{B} - 4\pi e n_e\vec{V}_e \qquad \text{(i)}$$

$$\omega\vec{B} = k\vec{e}_z\times\vec{E} \qquad \text{(ii)}$$

$$i\omega\vec{V}_e = \frac{e}{m_e}\vec{E} + \frac{eB_0}{m_e}\vec{V}_e\times\vec{e}_z \qquad \text{(iii)}$$

$\vec{e}_z\times$(last equation):

$$i\omega\vec{e}_z\times\vec{V}_e = \frac{e}{m_e}\vec{e}_z\times\vec{E} + \frac{eB_0}{m_e}\vec{V}_e$$

Reinserting back in (iii)

$$(\omega^2 - \Omega_B^2)\vec{V}_e = -i\frac{e\omega}{m_e}\vec{E} - \frac{e\Omega_B}{m_e}\vec{E}\times\vec{e}_z$$

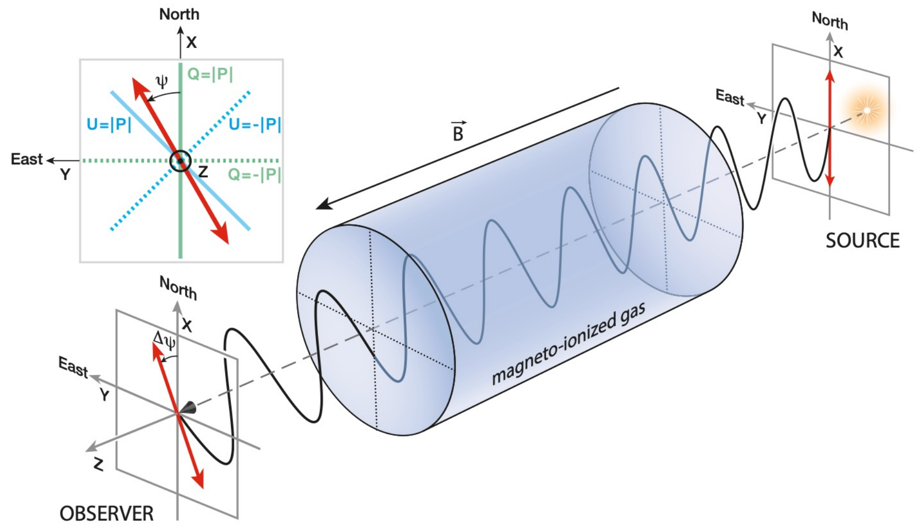
Expressing B from (ii) and $\vec{V}_e$ from the last equation, we get from (i)

$$\left(\omega^2 - k^2 - \frac{\omega_p^2\omega^2}{\omega^2 - \Omega_B^2}\right)^2 = \left(\frac{\omega_p^2\Omega_B\omega}{\omega^2 - \Omega_B^2}\right)^2$$

with $\Omega_B = eB_0/m_e$ (gyrofrequency), $\omega_p^2 = 4\pi n_e e^2/m_e$ (plasma frequency).

$$\omega^2 = k^2 + \frac{\omega_p^2\omega}{\omega \pm \Omega_B}$$

There exists two different modes (clockwise and counterclockwise polarized) propagating in z direction with different velocities.



https://arxiv.org/pdf/2106.03074

Faraday rotation

Linearly polarized wave

$$\vec{E} = E_0\, \vec{e}_x \cos\omega t$$

is a superposition of clockwise and counter-clockwise (left- and right-) polarized waves

$$\vec{E}_R = \frac{1}{2} E_0 \left(\cos\omega t\, \vec{e}_x + \sin\omega t\, \vec{e}_y\right)$$

$$\vec{E}_L = \frac{1}{2} E_0 \left(\cos\omega t\, \vec{e}_x - \sin\omega t\, \vec{e}_y\right)$$

at a fixed point (e.g. at the source). The two circularly polarized waves propagate with different phase velocities

$$v = \frac{\omega}{k} = 1 + \frac{\omega_e^2}{2\omega^2} \pm \frac{\omega_e^2 \Omega_B}{2\omega^3}$$

and a phase delay is accumulating over propagation distance L:

$$\Delta\phi = \frac{\omega_e^2 \Omega_B L}{\omega^2}$$

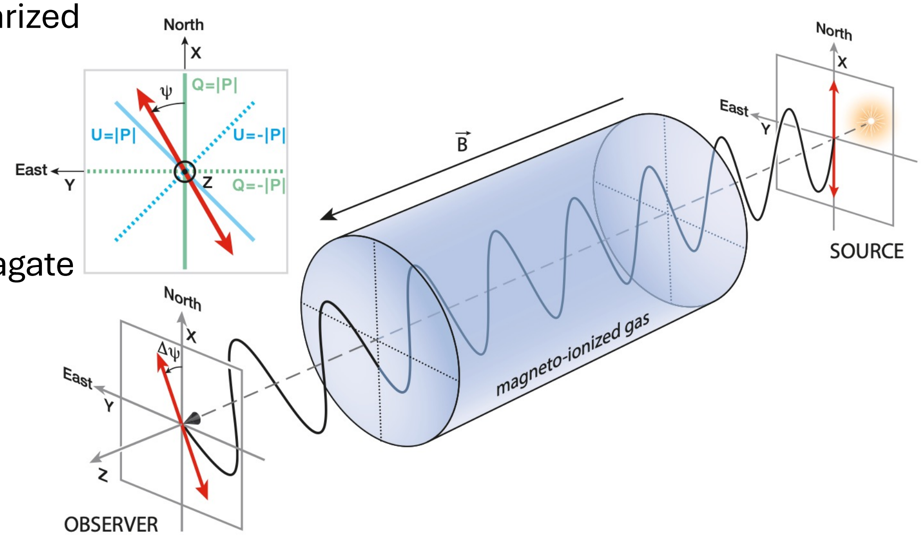
Rotation of the polarization angle is half the phase difference,

$$\Delta\Psi = \left(\frac{e^3}{2\pi\, m_e^2\, c^4} \int n_e B dl\right) \lambda^2 = RM\lambda^2$$

Where the Rotation Measure *(RM) is*

$$RM = \frac{e^3}{2\pi\, m_e^2\, c^4} \int n_e B dl \simeq 812 \int \left[\frac{n_e}{1\ \mathrm{cm}^{-3}}\right] \left[\frac{B_{||}}{1\ \mu\mathrm{G}}\right] \left[\frac{dl}{1\ \mathrm{kpc}}\right] \frac{\mathrm{rad}}{\mathrm{m}^2}$$

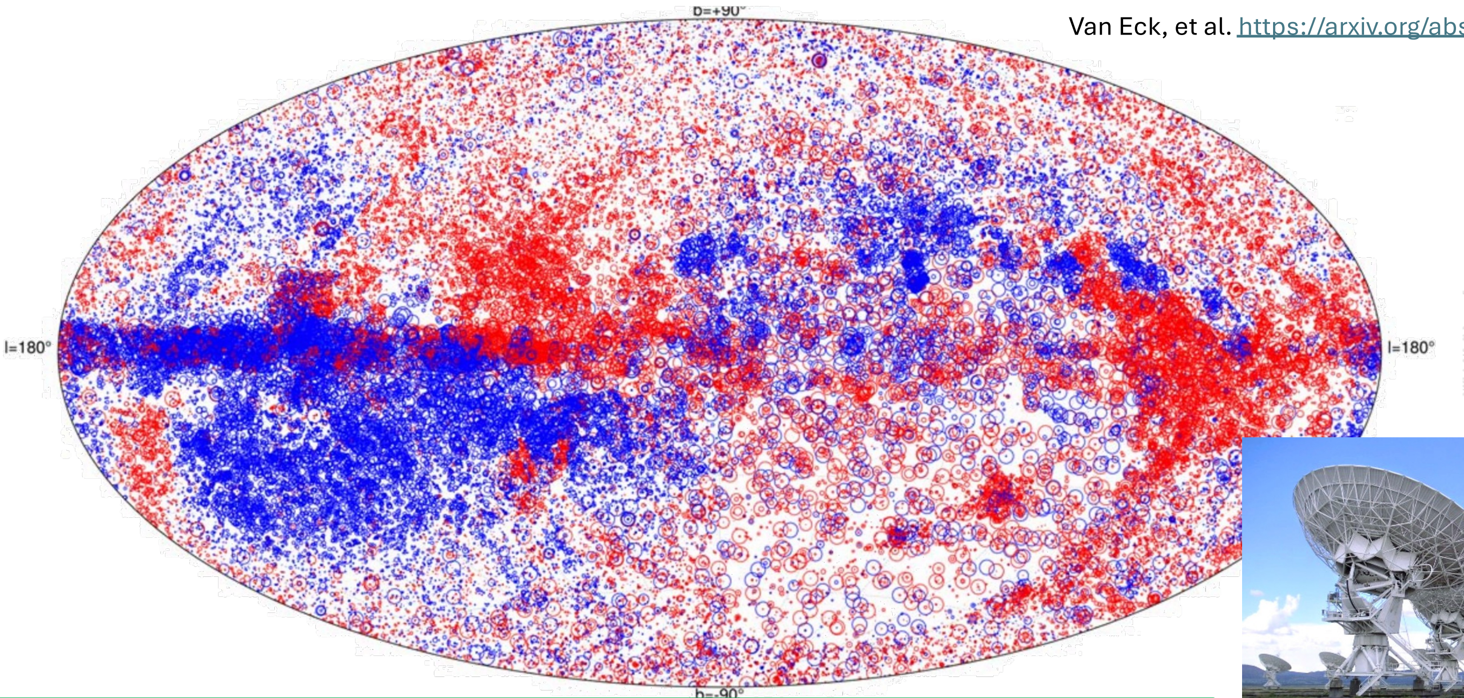
Microgauss magnetic fields in the interstellar medium lead to strong Faraday rotation of radio signals from all polarized sources.



https://arxiv.org/pdf/2106.03074

Magnetic fields in the interstellar medium from Rotation Measure

Large sample of extragalactic polarized radio sources is available. The RM of those sources are not randomly distributed, they reveal certain pattern on the sky. The map below shows RM of 55819 sources, red is positive RM, blue is negative.



Van Eck, et al. https://arxiv.org/abs/2305.16607

Exercise 4 Explore the RM dataset shown above:
https://zenodo.org/records/10963566 ; https://github.com/CIRADA-Tools/RMTable
Use astropy tools to read the FITS file of the catalog. Most of the sources in the catalog are quasars and radio galaxies. Write a script to identify them (query SIMBAD with astroquery package). Find redshifts of identified sources. How many of these sources have measured redshift?

Dispersion measure

The Rotation Measure does not directly provide a measurement of magnetic field, because we do not know the density of free electrons along the line of sight, $n(e)$. It needs to be inferred from independent measurements. Such measurements are given the dispersion measure.
Electron in the field of electromagnetic wave propagating in z direciton with electric field $E_x = E_0 e^{i(\omega t - kz)}$

$$m_e \ddot{x} = eE_x$$

The solution is $x = x_0 e^{i(\omega t-kz)}$ with $-m_e\omega^2 x_0 = eE_0$. The current density induced by electron motions is

$$J = en_e\dot{x} = ien_e\omega x_0 e^{i(\omega t-kz)} = -i\frac{n_e e^2 E_x}{m_e \omega}$$

Maxwell equation $\nabla\times\vec{B} = 4\pi\vec{J} + \partial_t\vec{E}, \nabla\times\vec{E} = -\partial_t\vec{B}$ give

$$kE_x = \omega B_y, \qquad kB_y = \omega\left(1 - \frac{4\pi\, n_e e^2}{m_e\omega^2}\right)E = \frac{\omega^2}{k_z}\left(1 - \frac{\omega_p^2}{\omega^2}\right)B_y \;\rightarrow\; k^2 = \omega^2 - \omega_p^2$$

Group velocity of waves

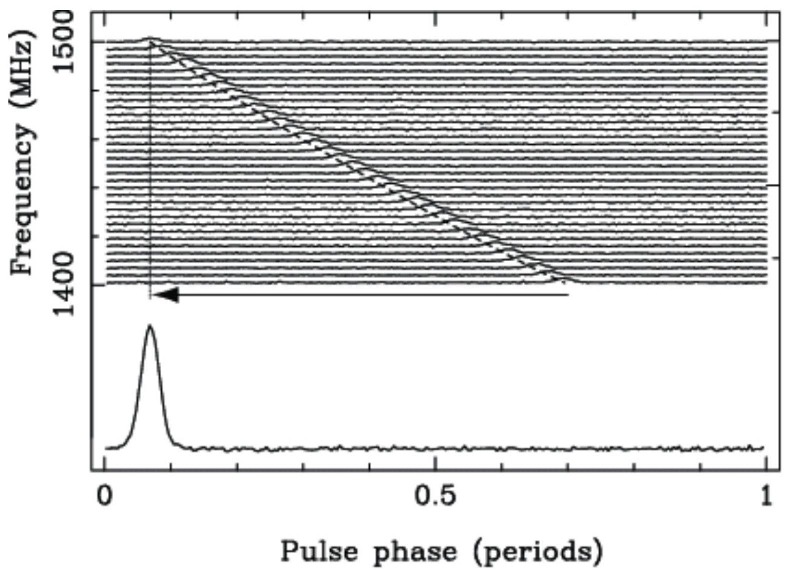
$$v_{group} = \frac{d\omega}{dk} = \frac{k}{\omega} = \sqrt{1 - \frac{\omega_p^2}{\omega^2}}, \qquad \omega_p = \sqrt{\frac{4\pi e^2 n_e}{m_e}} \simeq 5.7\times10^4\left[\frac{n_e}{1\ \mathrm{cm}^{-3}}\right]^{1/2}\ \mathrm{s}^{-1}$$

(plasma frequency). The time delay of signal due to free electrons presence is

$$t_d = \frac{D}{v_g} - \frac{D}{c} = D\left(\frac{1}{v_{group}} - 1\right) \simeq \frac{e^2}{2\pi m_e \nu^2}Dn_e = \frac{e^2}{2\pi m_e\nu^2}DM$$

Where D is distance to the source, $DM = \int n_e dl$ is the Dispersion Measure, an integral of free electron density along the line-of-sight toward the source.

DM can be measured for signals from variable (pulsed) sources, like pulsars, or Fast Radio Bursts (FRB). These sources often also yield RM measurements.



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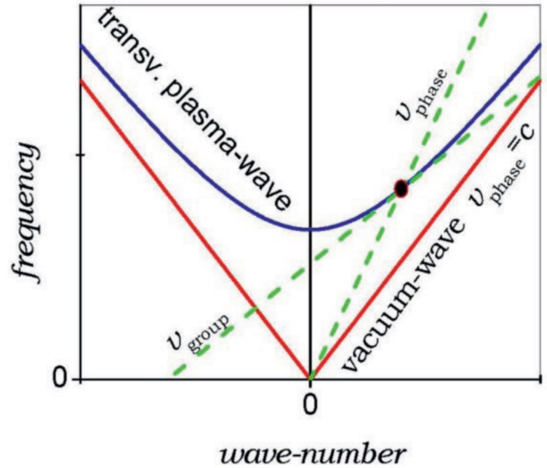

$$k^2 = \omega^2 - \frac{\omega_p^2 \omega}{\omega \pm \Omega_B} = \frac{\omega^3 \pm \omega^2 \Omega_B - \omega_p^2 \omega}{\omega \pm \Omega_B}$$

In the interstellar medium

$$\omega_p = \left(\frac{4\pi n_e e^2}{m_e}\right)^{1/2} \simeq 5.7\times10^4 \left[\frac{n_e}{1\ \mathrm{cm}^{-3}}\right]^{\frac{1}{2}} \mathrm{s}^{-1}, \qquad \Omega_B = \frac{eB}{m_e} \simeq 1.8\times10^2 \left[\frac{B}{10\ \mu\mathrm{G}}\right] \mathrm{s}^{-1}$$

Taking $\Omega_B \to 0$

$$k^2 \simeq \omega^2 - \omega_p^2$$

Group velocity

$$v_{group} = \frac{d\omega}{dk} = \frac{k}{\omega} = \sqrt{1 - \frac{\omega_p^2}{\omega^2}}$$

The time delay of signal due to free electrons presence

$$t_d = \frac{D}{v_g} - \frac{D}{c} = D\left(\frac{1}{v_{group}} - 1\right) \simeq \frac{e^2}{2\pi m_e \nu^2} D n_e = \frac{e^2}{2\pi m_e \nu^2} DM$$

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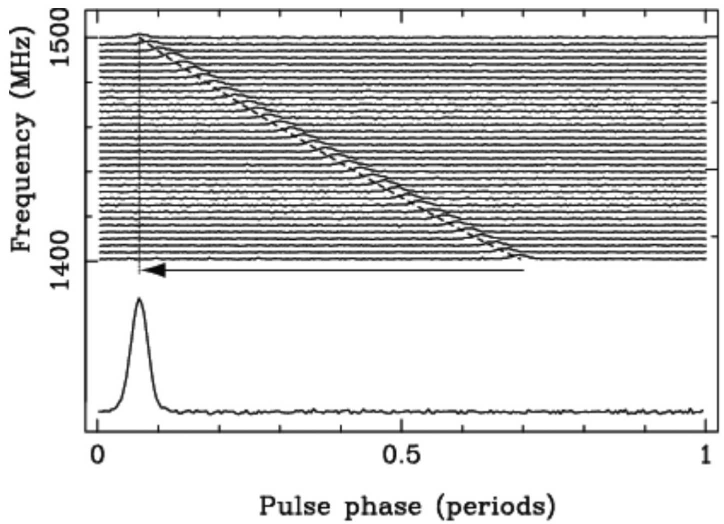


Galactic dispersion measure

DM of a set of pulsars for which distances are known has been used to derive a model of 3-d distribution of free electrons across the entire Milky Way galaxy. Publicly available models like NE2001 exist: Yao et al. YMW2016, NE2001 (Cordes, Lazio, https://arxiv.org/pdf/astro-ph/0207156, Yao et al. https://arxiv.org/abs/1610.09448

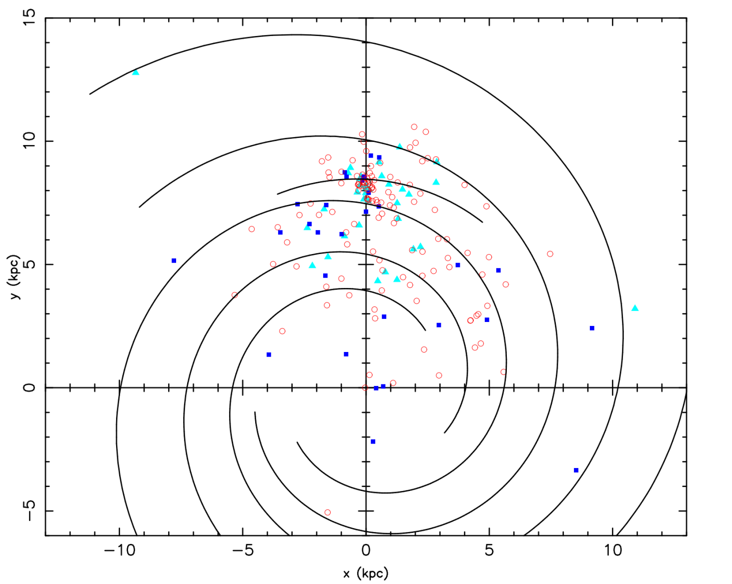
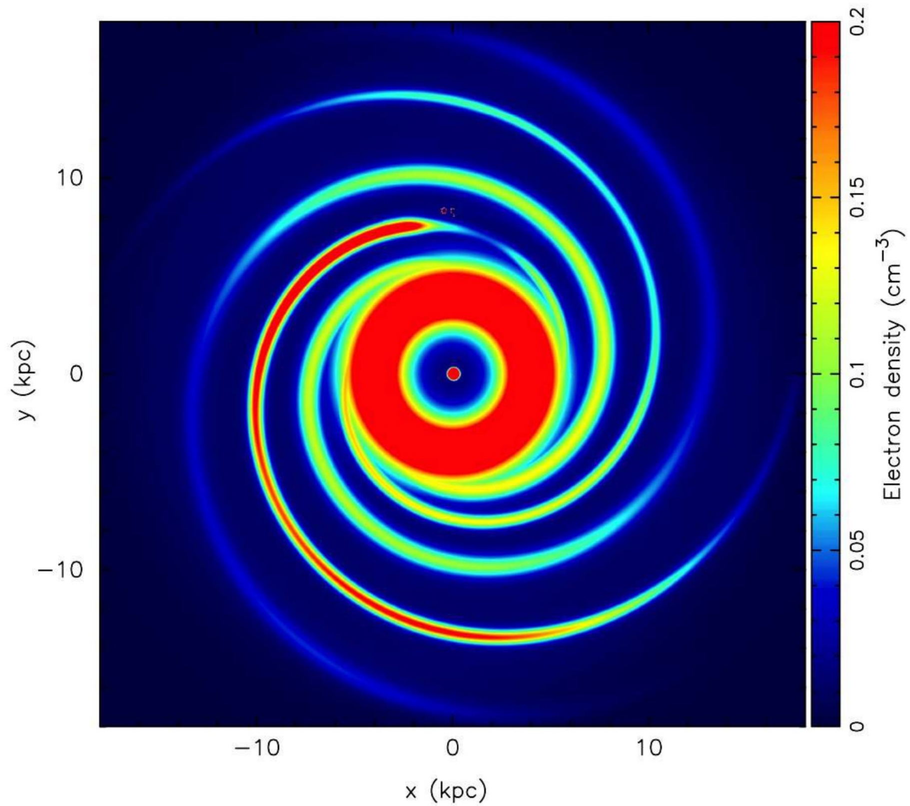
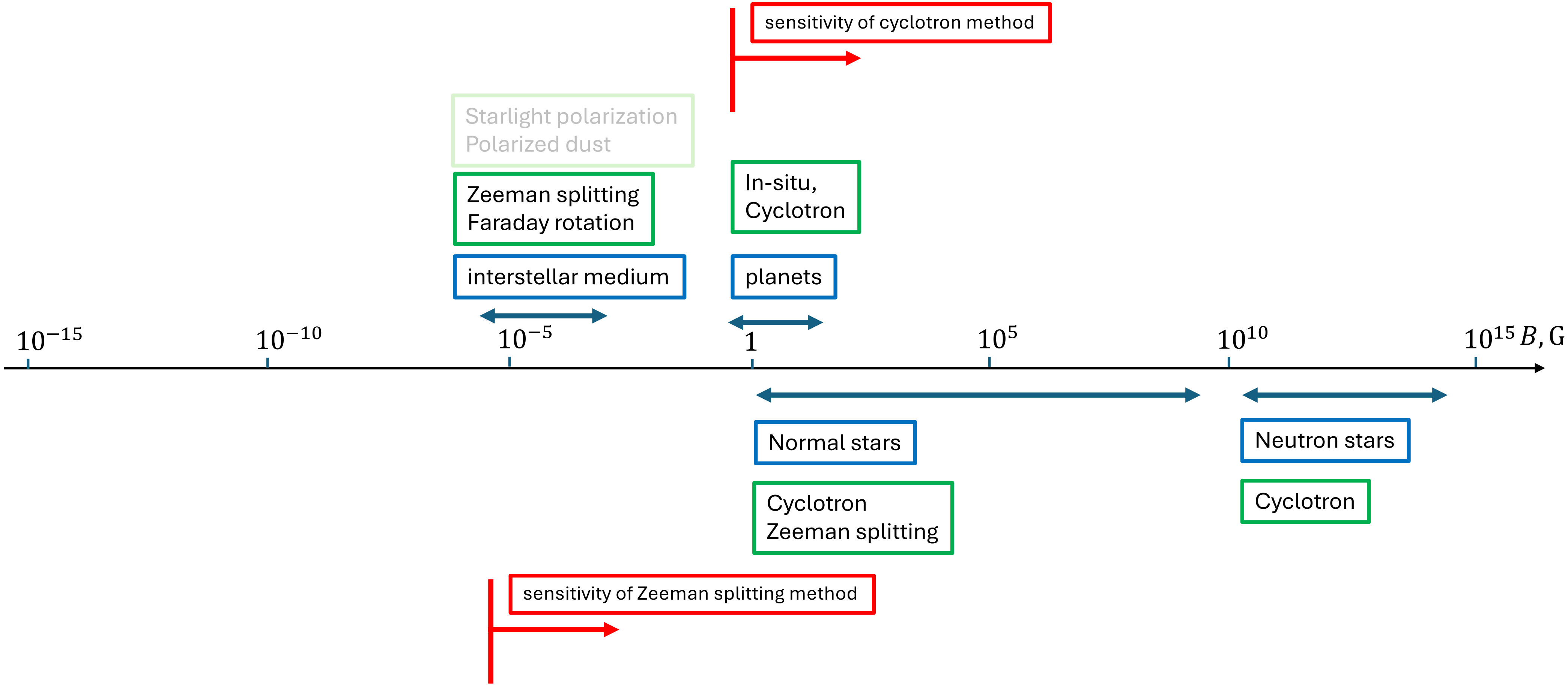


Figure 9. Positions of the 189 pulsars with model-independent distances projected onto the Galactic plane at the position of their independently estimated distance. Pulsars are plotted with the same symbols as in Figure 8.

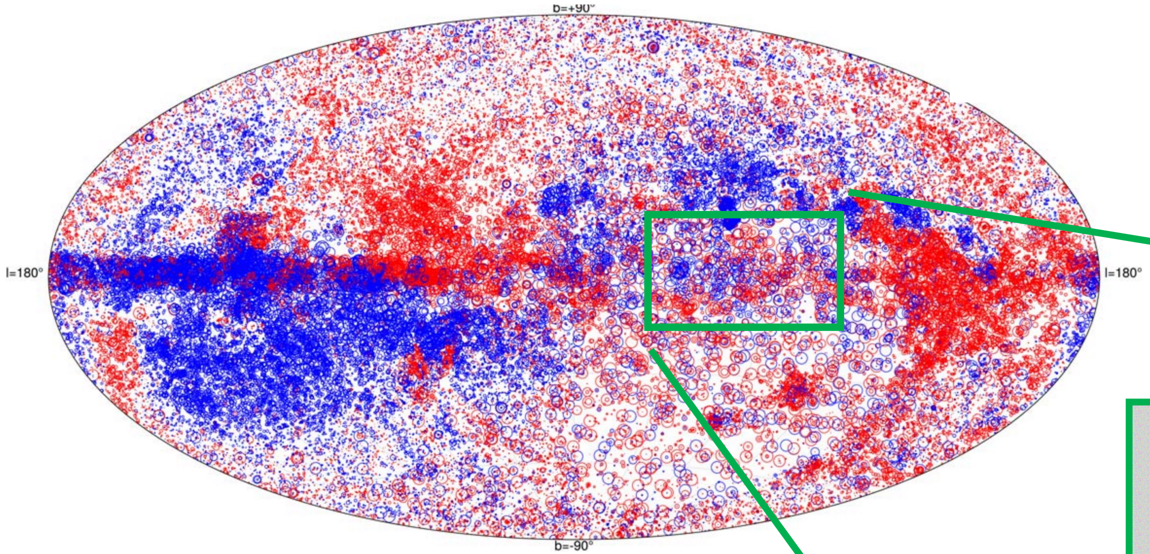


Exercise 5. Eplore python interface to NE2001 and YMW2016 models. https://github.com/FRBs/pygedm Combine the DM estimates with RM data to estimate the strength of Galactic magnetic field in the Solar neighbourhood (consider directions toward North and South Galactic poles)

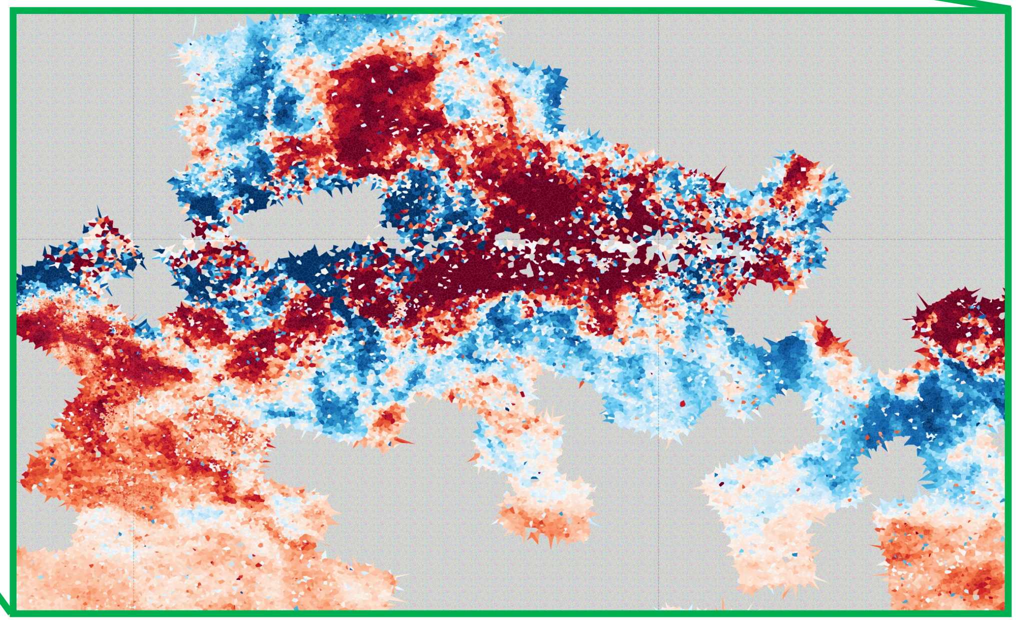
Measurements of magnetic fields in present-day Universe



New era of Faraday Rotaion data is coming!



Polarisation Sky Survey of the Universe's Magnetism (POSSUM): linear polarization & RM , 50 measurements per square degree: https://possum-survey.org 2023-2028



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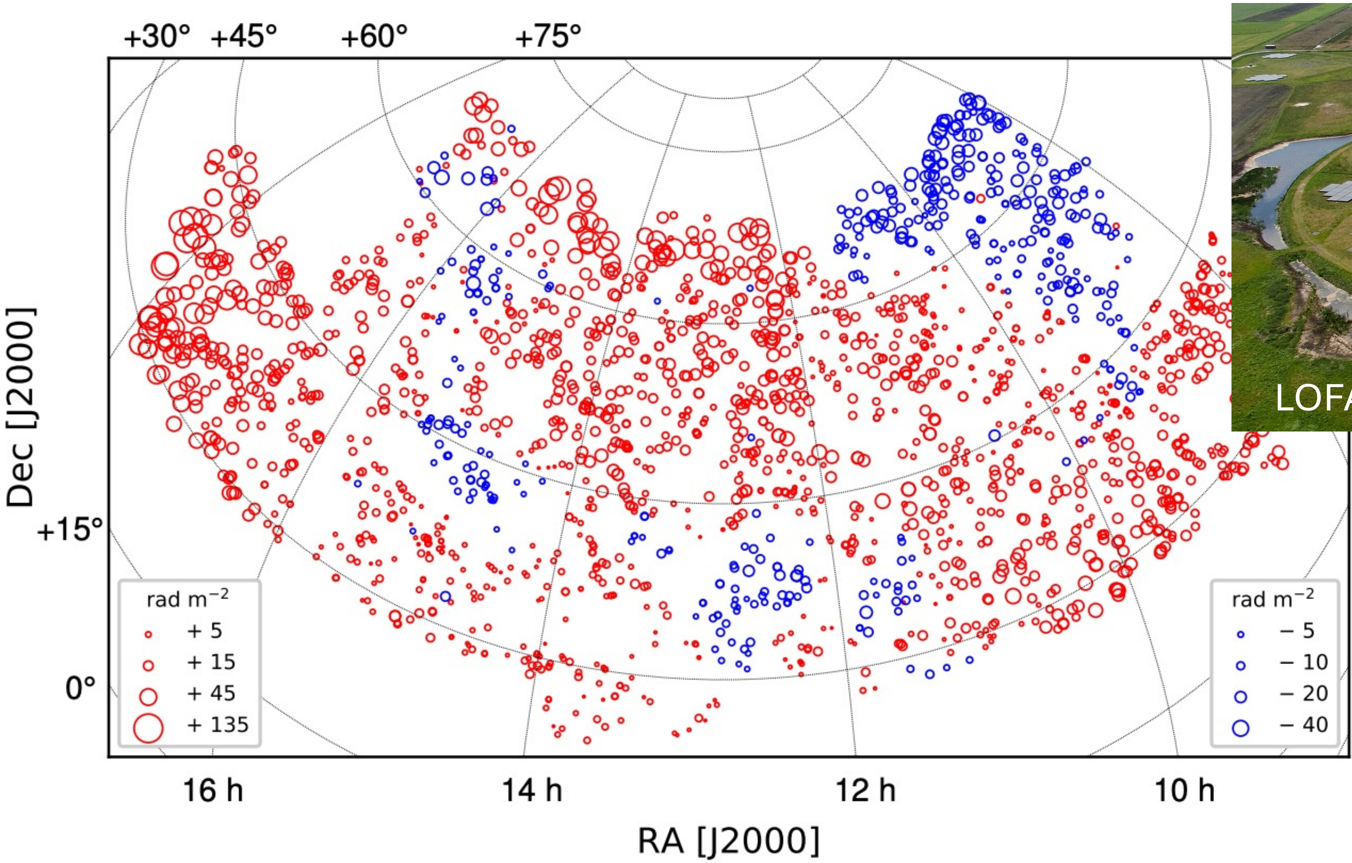

RM dataset in 120-168 MHz frequency range ($1.8\ \mathrm{m} < \lambda < 2.5\ \mathrm{m}$), sensitive to small RM (compare to $\nu \sim 1\ \mathrm{GHz}$ frequencies of POSSUM)