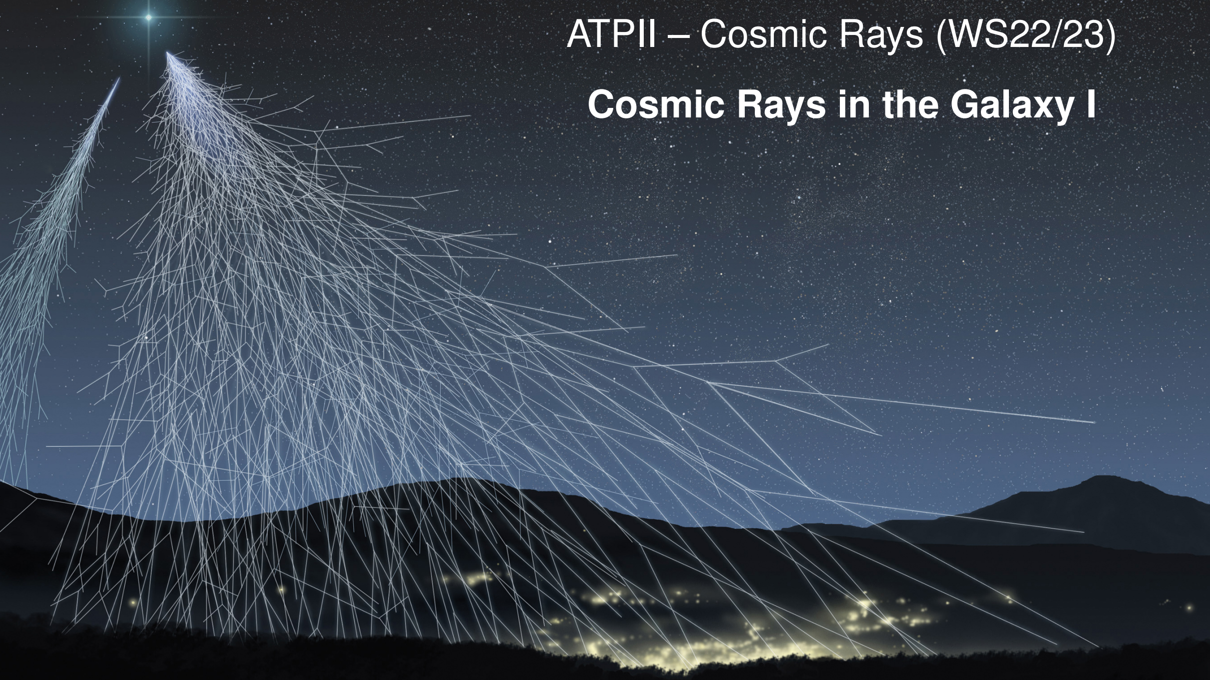
ATPII – Cosmic Rays (WS22/23)

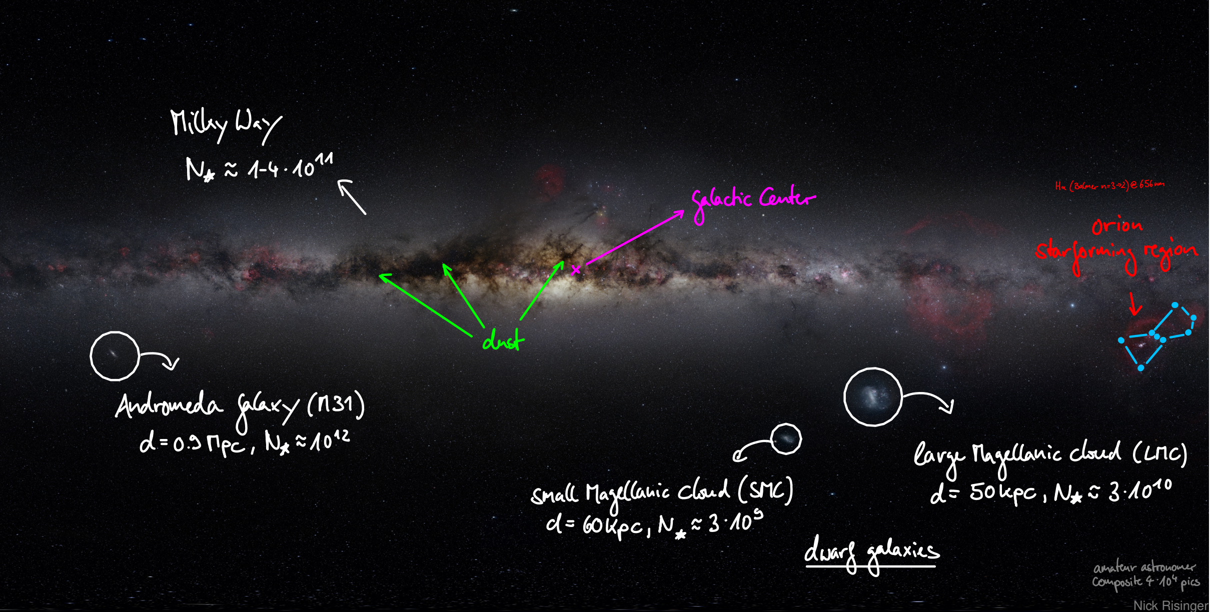
Cosmic Rays in the Galaxy I



Our Galaxy (the Milky Way)

Nick Risinger

Our Galaxy (the Milky Way)

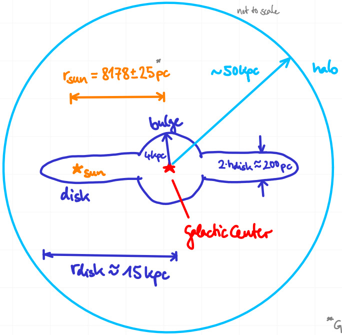


Nick Risinger

Our Galaxy (the Milky Way)

history:

- 1600s: Milky Way → collection of stars (Galileo)
- 1700s: stellar disk (Wright), one of many? (Kant)
- first crude maps by Herschel + Kapteyn (1780 → 1922)



*GRAVITY A&A 2019

thin disk: stars and interstellar medium (ISM)

gas, dust, magnetic field, cosmic rays

mass: 99% + 1% (gas + dust) → 15% of disk mass

$u_B = \frac{B^2}{2\mu_0} = 0.25\ eV/cm^3$

$u_{CR} = 0.5\ eV/cm^3$

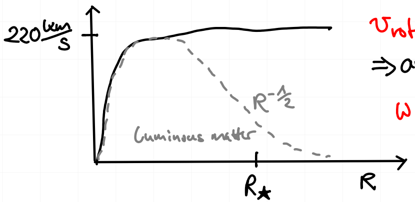
gas composition (by number): 90% H, 9% He, 1% other

neutral hydrogen: $1/cm^3$ ("HI")

ionized hydrogen: $0.1/cm^3$ ("HII")

Molecular clouds: several $10^3\ \frac{1}{cm^3}$ (in cloud) ("H_2")

"rotation curve"



$v_{rot} \approx const$

⇒ angular velocity:

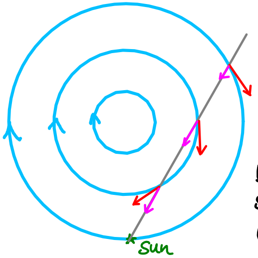
$$\omega = \frac{v(r)}{r} = \frac{const}{r}$$

Our Galaxy (the Milky Way)

"artist's impression" →

spiral structure inferred from

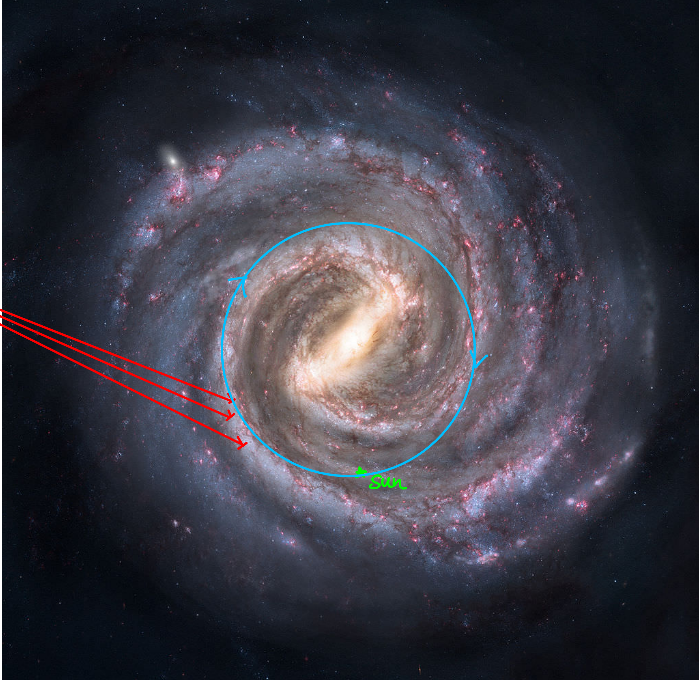
- parallax distances of starforming regions
- "kinematic distances" of gas



$\vec{v}$ and $\vec{v}_r$

($|v| \approx$ const)

blue- and red-shifting of spectral lines depending on v_r



Our Galaxy (the Milky Way)

spiral structure: “winding problem”

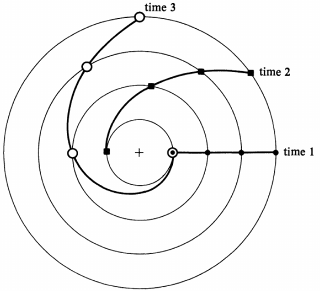


Figure 12.24. The winding dilemma associated with thinking of spiral arms as material alignments in a field of differential rotation. By the time ($\sim 10^8$ yr) the innermost gas cloud has completed one circle of rotation, an originally straight arm would have added almost a complete turn. Since spiral galaxies are likely to be 10^{10} years old, this picture cannot account for the observed spiral structures.

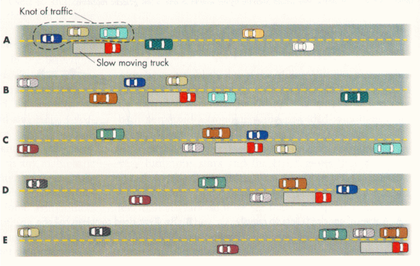
F. Shu, The Physical Universe (1982)

→ time to orbit galaxy: $T = v_{rot}/2\pi r_{sun} = 0.2$ Gyr!

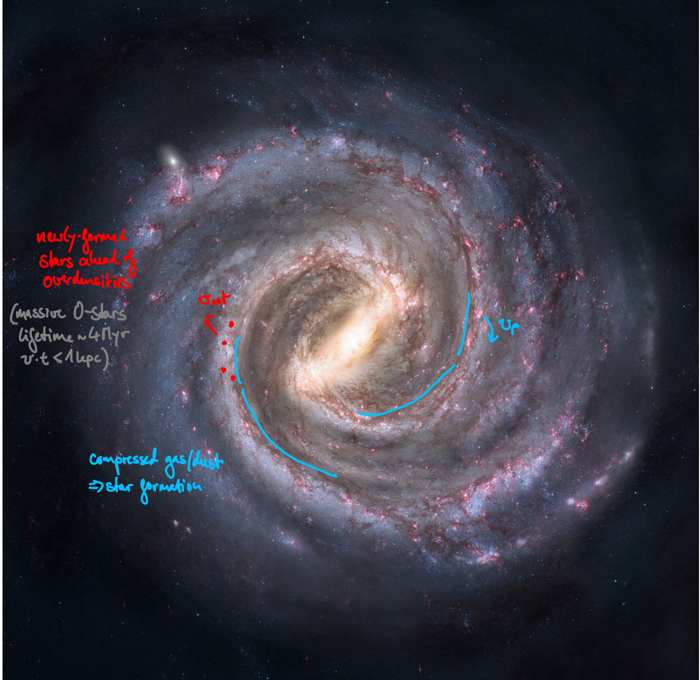
Our Galaxy (the Milky Way)

spiral structure: density wave

analogy: traffic jam



abyss.uoregon.edu/ js/ast122/

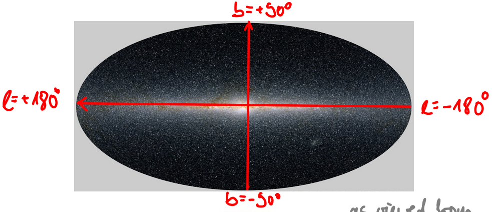


Lin + Shu 1964 : spiral density waves

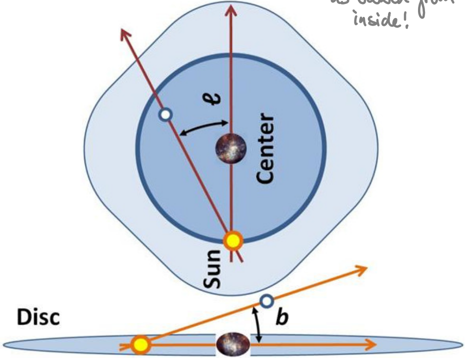
pattern speed $v_p < v_{rot}$

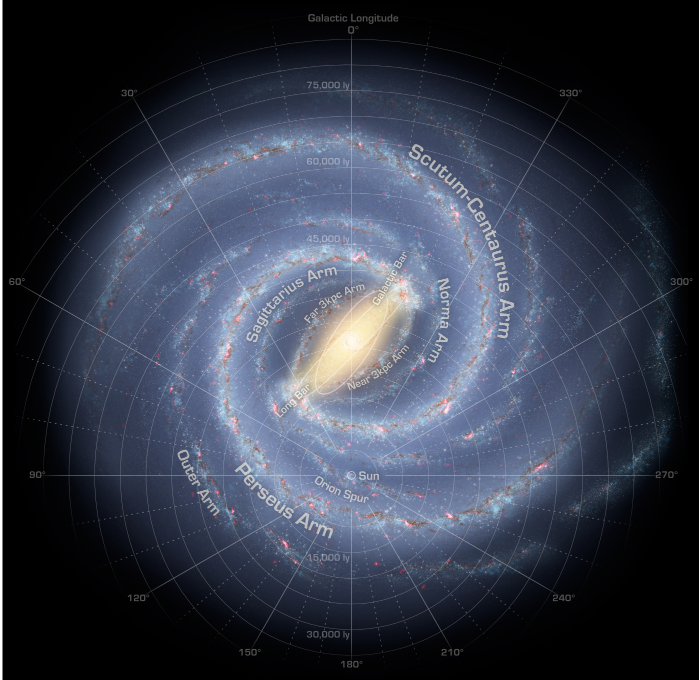
⇒ stars + gas pass through spiral arms

Galactic Coordinates



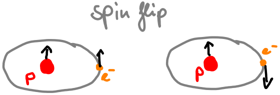
as viewed from inside!

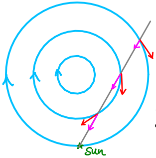




Atomic Hydrogen

"HI line", 21 cm line, 1.4 GHz

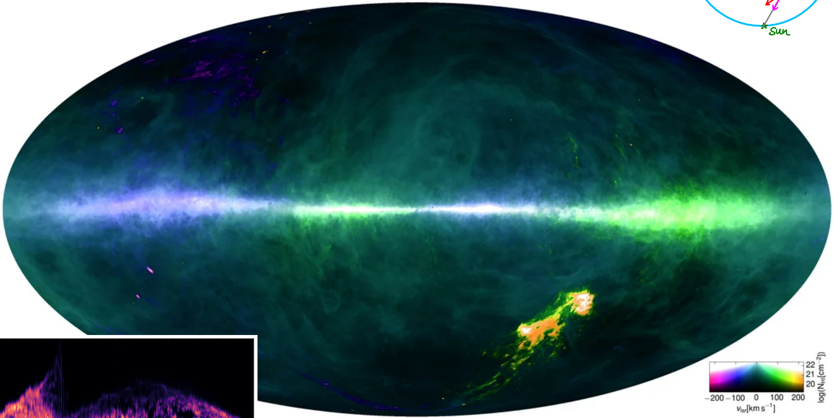




$\vec{v}$ and $\vec{v}_r$

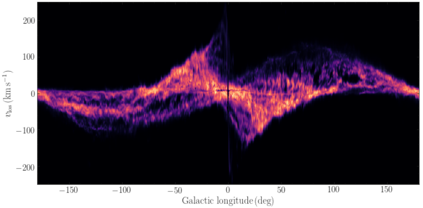
($|v| \approx$ const)

blue- and red-shifting of spectral lines depending on v_r



"lsr": local standard rest
(average motion of stars close to sun)

HI4PI Collaboration

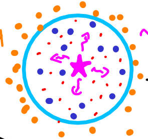


Ionized Hydrogen

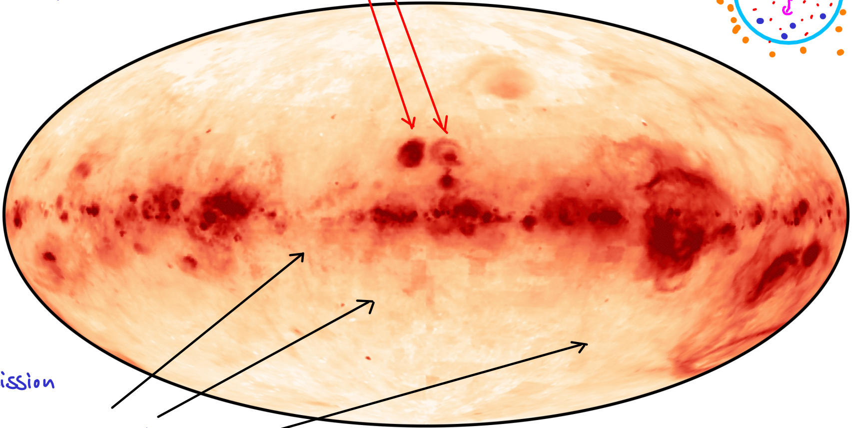
Hα (Balmer n=3→2) @ 656nm

H II regions

massive, hot stars (O/B type)



("Strömgen spheres")



Wisconsin H-Alpha Mapper (WHAM)

diffuse Hα emission

⇒ "warm ionized medium" (WIM)

T≈8000K

Gamma Rays

leptonic: inverse Compton

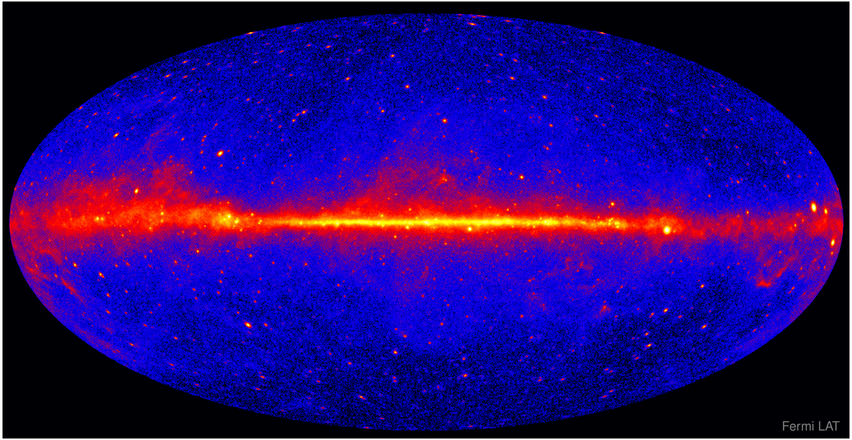
interstellar radiation field ISRF

$e^- + \gamma_{ISRF} \Rightarrow e^{-\prime} + \gamma'_{ISRF}$

angle-averaged photon energy after scattering

$$\langle h\nu' \rangle = \frac{4}{3}\gamma_e h\nu$$

$\gamma_e = \frac{E_e}{m_e}$: Lorentz-factor of e^-



hadronic: cosmic-ray interactions with ISM

$p_{CR} \rightarrow p_{ISM} \rightarrow p, \pi^{\pm}, \pi^0$

$\pi^{\pm} \rightarrow e^{\pm}$ and 3 neutrinos

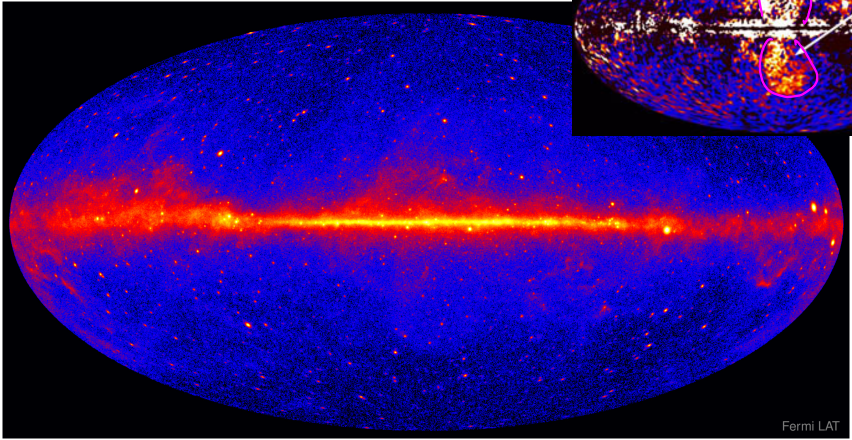
neutral pion decay

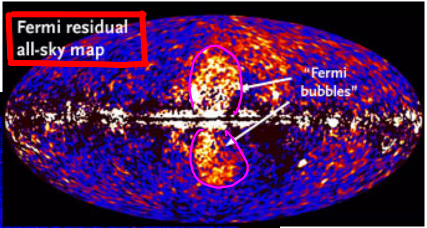
$\pi^0 \rightarrow \gamma\gamma$

$\tau \approx 8 \cdot 10^{-17}\,s$, $c \cdot \tau = 26\,nm$

Gamma Rays

past activity at Galactic Center?





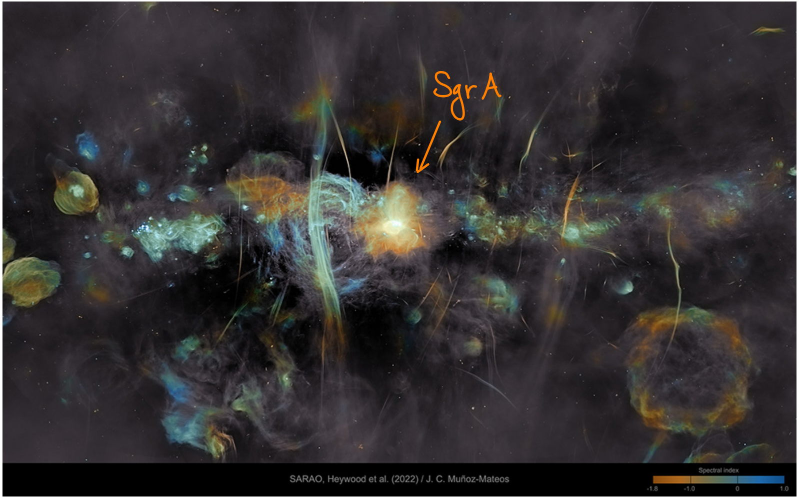
also in X-ray

The Galactic Center

3rd Kepler $T^2/a^3 = 4\pi^2/GM \Rightarrow M = 4 \cdot 10^6 M_\odot$

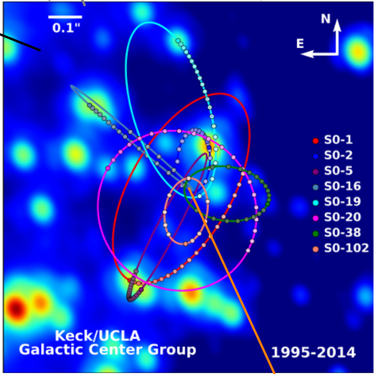
≈0.1 pc

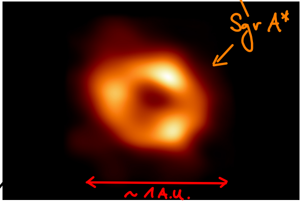
Nobel prize 2020



← ~100 pc →

radio image of galactic center (1.3 GHz)





Schwarzschild radius of black hole

Event Horizon 2022: shadow compatible with $r_s = 2GM/c^2 = 0.07$ A.U.

Galactic Magnetism

detection: → synchrotron radiation of cosmic-ray electrons ⟷ diffuse emission

⇒ probes $\vec{B}$ perpendicular to line of sight

⇒ intensity: magnetic field strength

⇒ direction of polarization: direction

polarized point sources (synchrotron)

pulsars ↓ active galactic nuclei ↓

→ Faraday effect: rotation of polarization direction in magnetized plasma ⟷ galactic or extragalactic sources

⇒ probes $\vec{B}$ parallel to line of sight

plasma density → WIM!

⇒ rotation measure $RM \sim \int B_{\parallel} n_e \, dl$ ⟷ $\theta(\lambda) = \theta_0 + \lambda^2 \cdot RM$

cf. lecture II and problem set I

⇒ coherent magnetic field in disk $B \approx 3 \mu G$

⇒ turbulent magnetic field in disk $b_{rms} \approx 5 \mu G$

cosmic-ray motion in Galaxy:

"Larmor radius / gyro radius"

$$r_L = 1.1 \, \mathrm{kpc} \, \frac{R/EV}{B/\mu G}$$

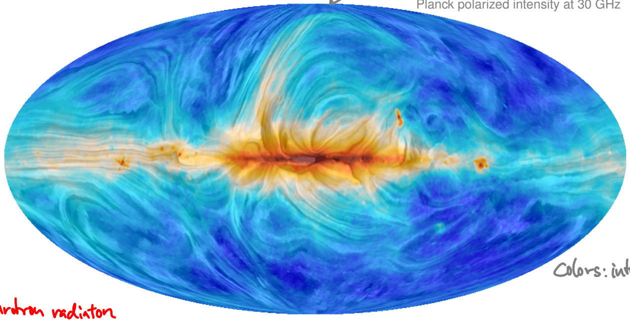
$R = \frac{p}{e \cdot Z}$ rigidity

$1 \mu G = 10^{-10} T$

Galactic Magnetism

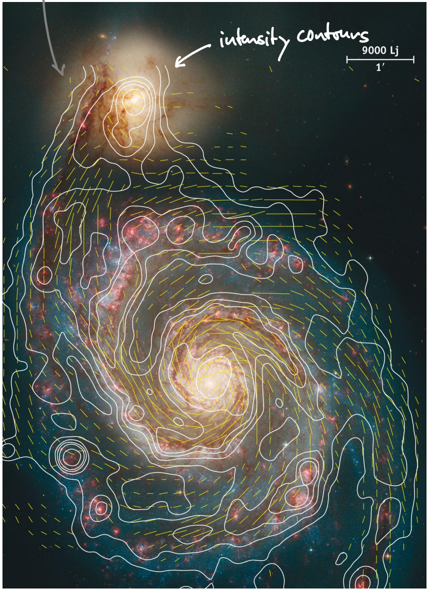
projected magnetic field orientation inferred from polarization

Planck polarized intensity at 30 GHz

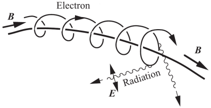


Colors: intensity

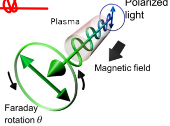
M51 (HST, MPIfR)

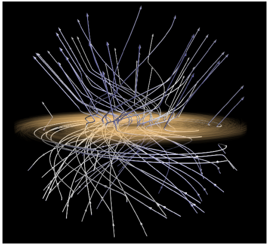


synchrotron radiaton



Faraday effect



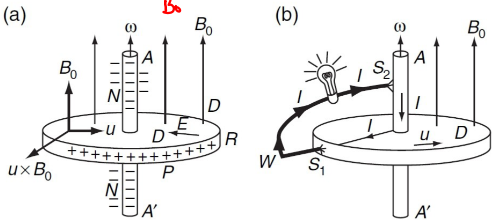


Jansson&Farrar 2012

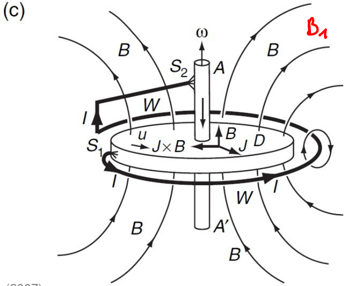
galactic magnetic field model

Galactic Magnetism – Dynamo Action?

"α-Ω dynamo"



analogy: amplification of initial seed field with "unipolar inductor"



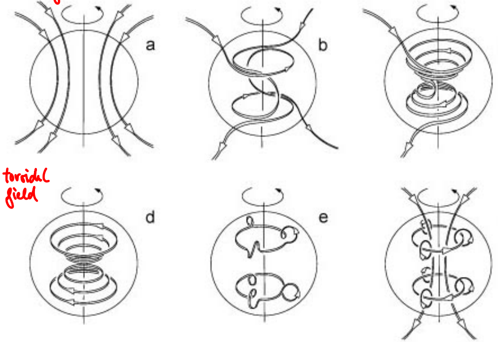
P.H. Roberts (2007)

"$B_0 + E_{kin} \to B_1 > B_0$"

Ω-effect: creation of toroidal field from differential rotation of poloidal seed field

poloidal field

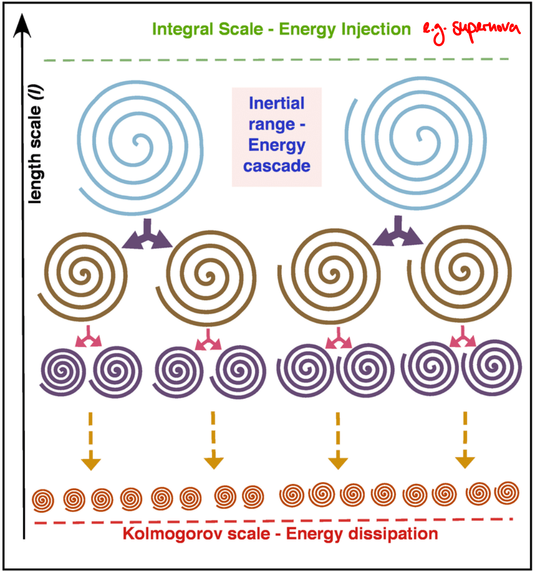
toroidal field



Love, J. J., 1999. Astronomy & Geophysics, 40, 6.14-6.19.

α-effect: creation of poloidal field from turbulence + convection

(Magnetic) Turbulence



e.g. supernova

wikipedia, flickr, S. Banerjee

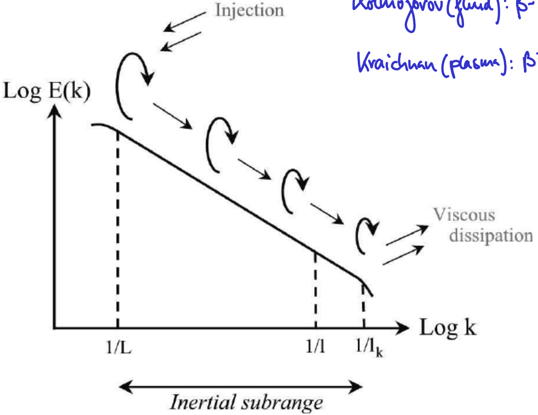
- Wave-number $K = \frac{2\pi}{\ell}$
- turbulent energy at K:

$$E(K) \sim K^{-\beta}$$

- resonant particle scattering $r_L \approx \frac{1}{K}$

Kolmogorov (fluid): $\beta = 5/3$

Kraichnan (plasma): $\beta = 3/2$



Scattering of Particles in Magnetic Fields

quasi-ballistic

helical motion

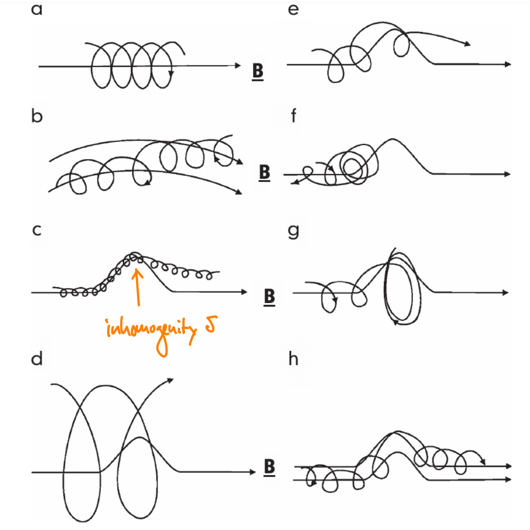
$B = \text{const}, \delta = 0$

drift

quasi-ballistic

no scattering

$r_L \gg \delta$



parallel diffusion ($\parallel \vec{B}$)

forward scattering backward

$r_L \approx \delta$

trapped (note change of r_L!)

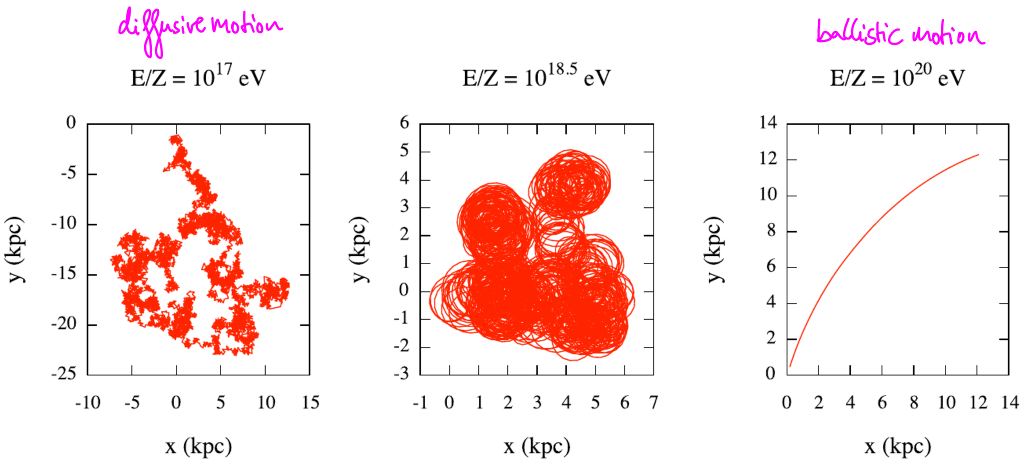
perpendicular diffusion ($\perp \vec{B}$)

scattering to next field line

$r_L \approx \delta$

H. Moraal, Space Sci. Rev. 176 (2013) 299

Scattering of Particles in Magnetic Fields



$\vec{B} = (0, 0, 3)\ \mu G$, $b_{rms} = 1\ \mu G$, arXiv:1305.4364

coherent field along z — isotropic random field