Mirror diffusion of cosmic rays

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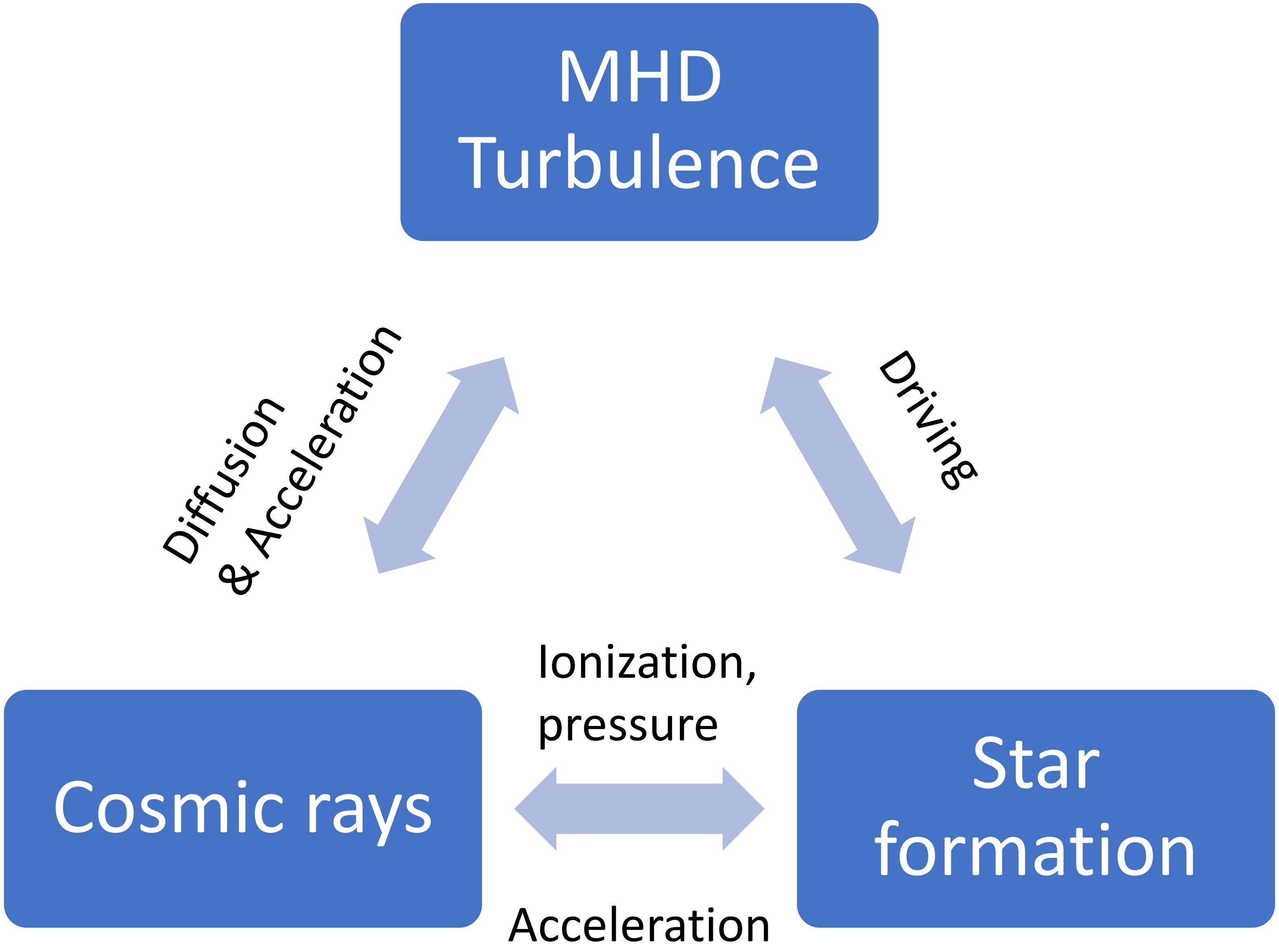
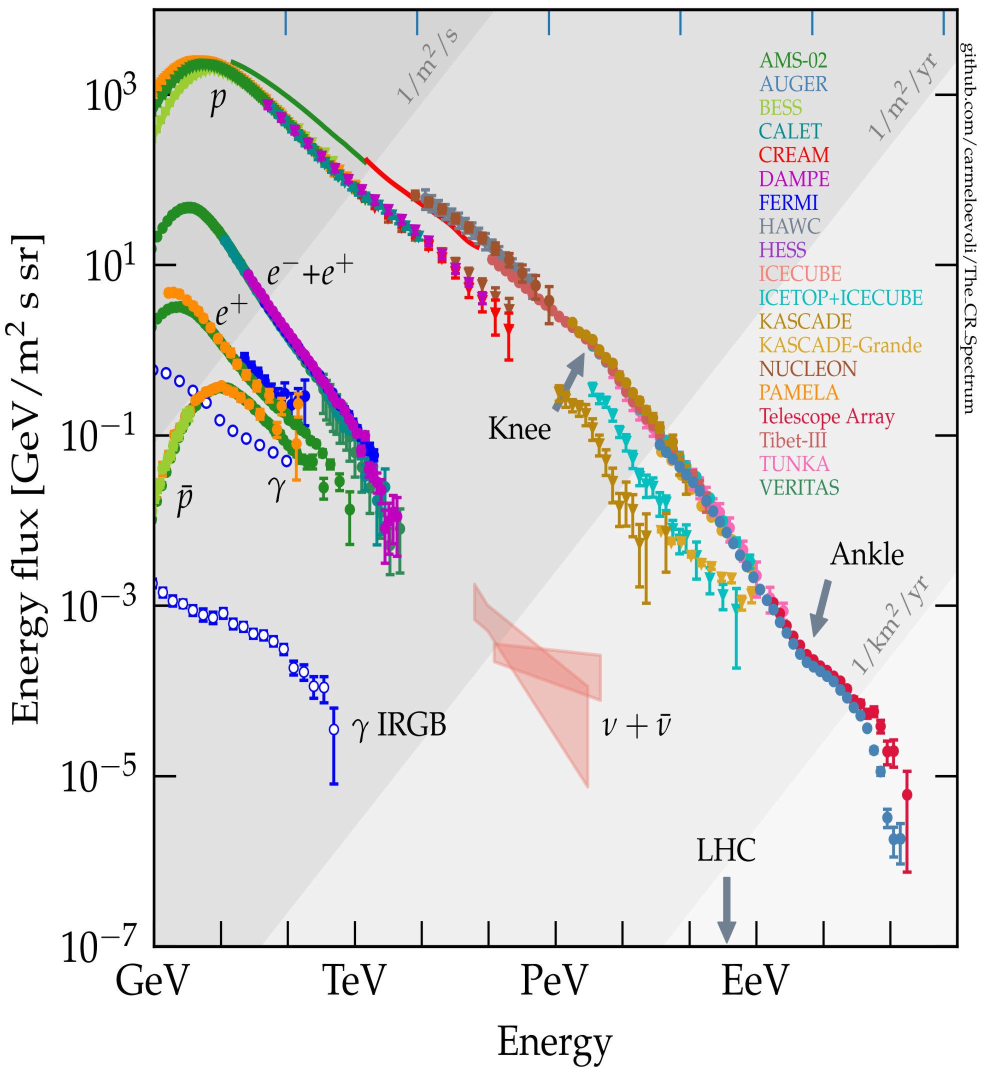

MHD
Turbulence
Diffusion
& Acceleration
Driving
Cosmic rays
Ionization,
pressure
Acceleration
Star
formation

CRs and interstellar turbulence

Cosmic ray energy spectrum

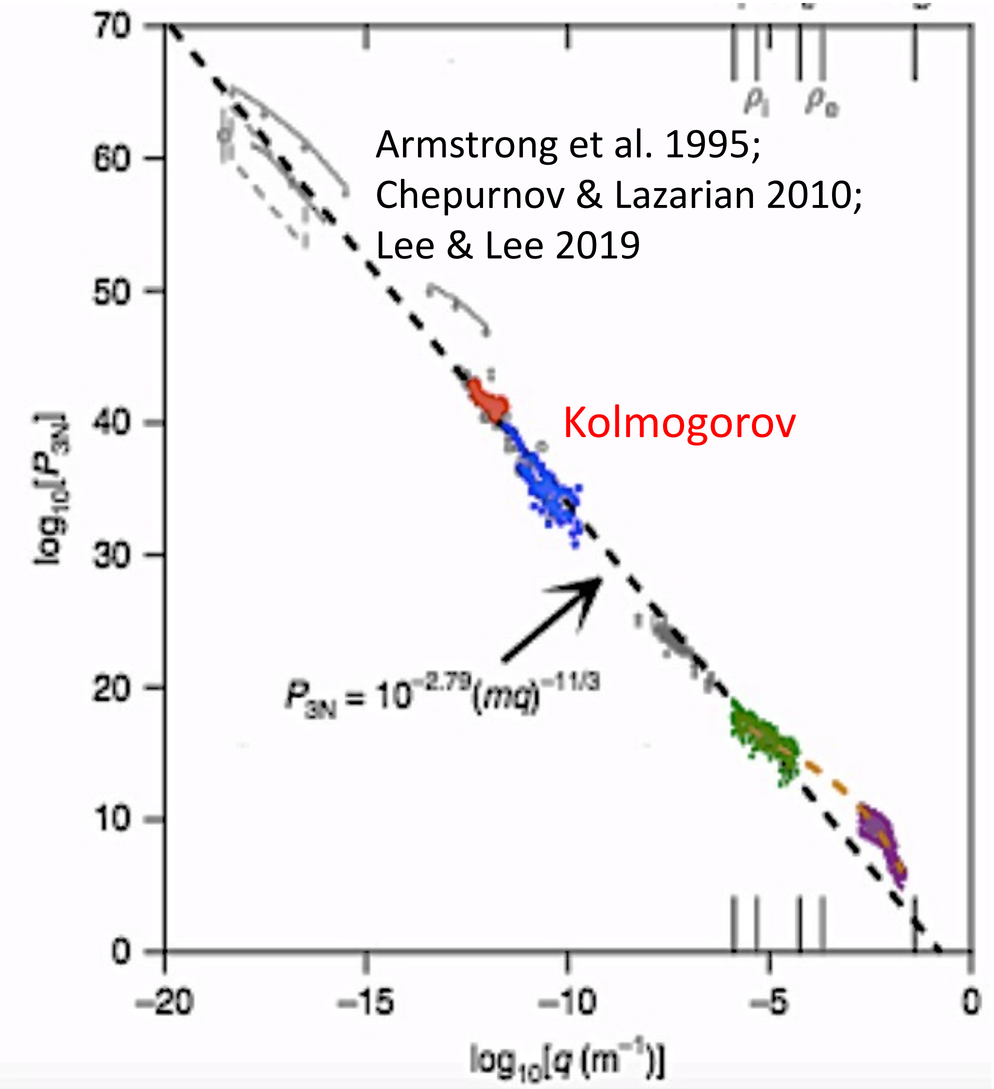
10^9 eV - 10^{20} eV

Evoli 2020



Big Power Law of interstellar turbulence

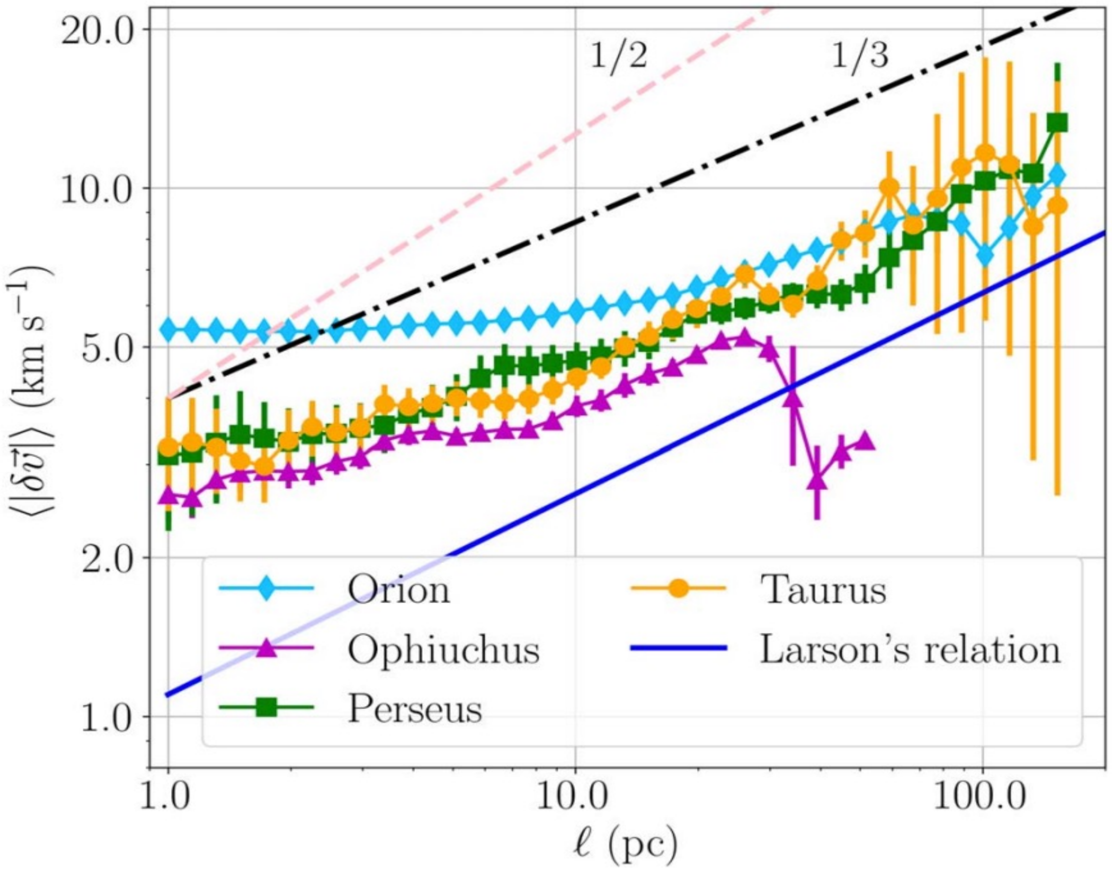
50 m – 10^{17} m



Turbulent motions of stars

Star formation in turbulent interstellar medium

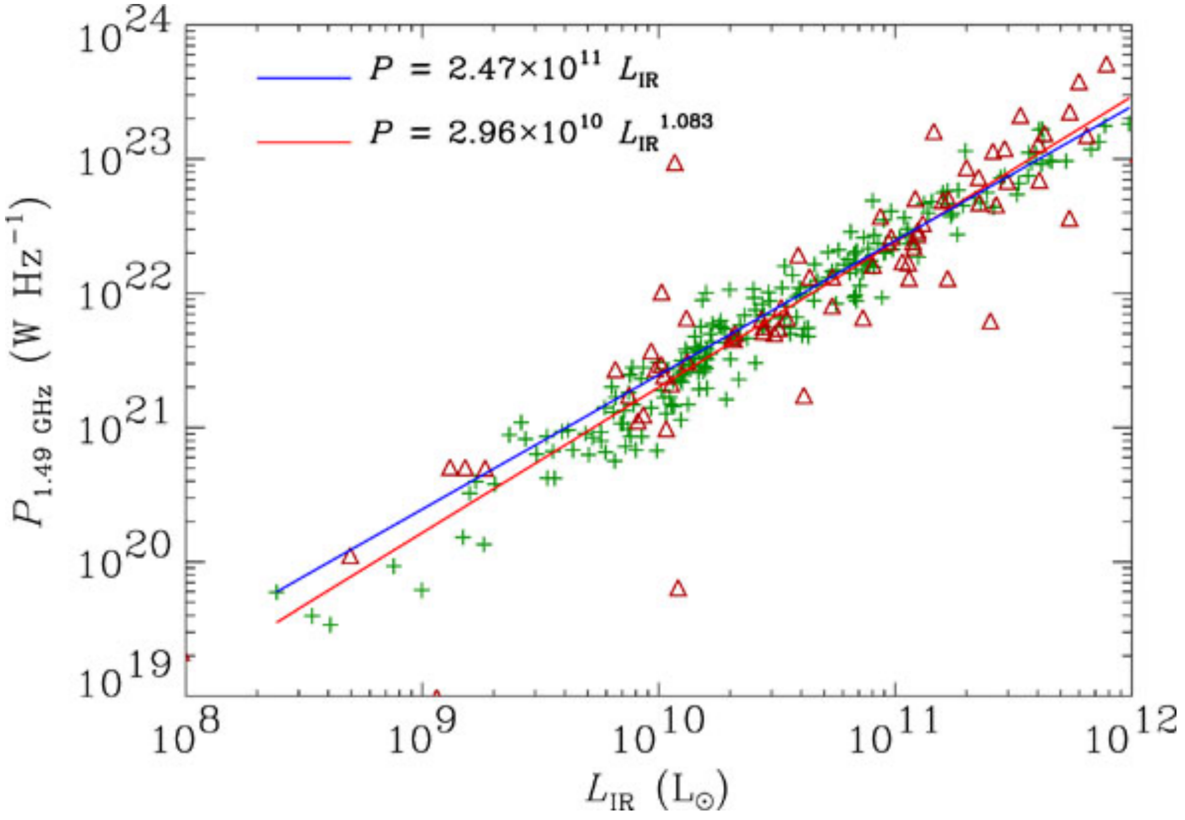
Turbulent motions of young stars



Ha, Li, Xu et al. 2021; Ha, Li, Kounkel, Xu et al. 2022

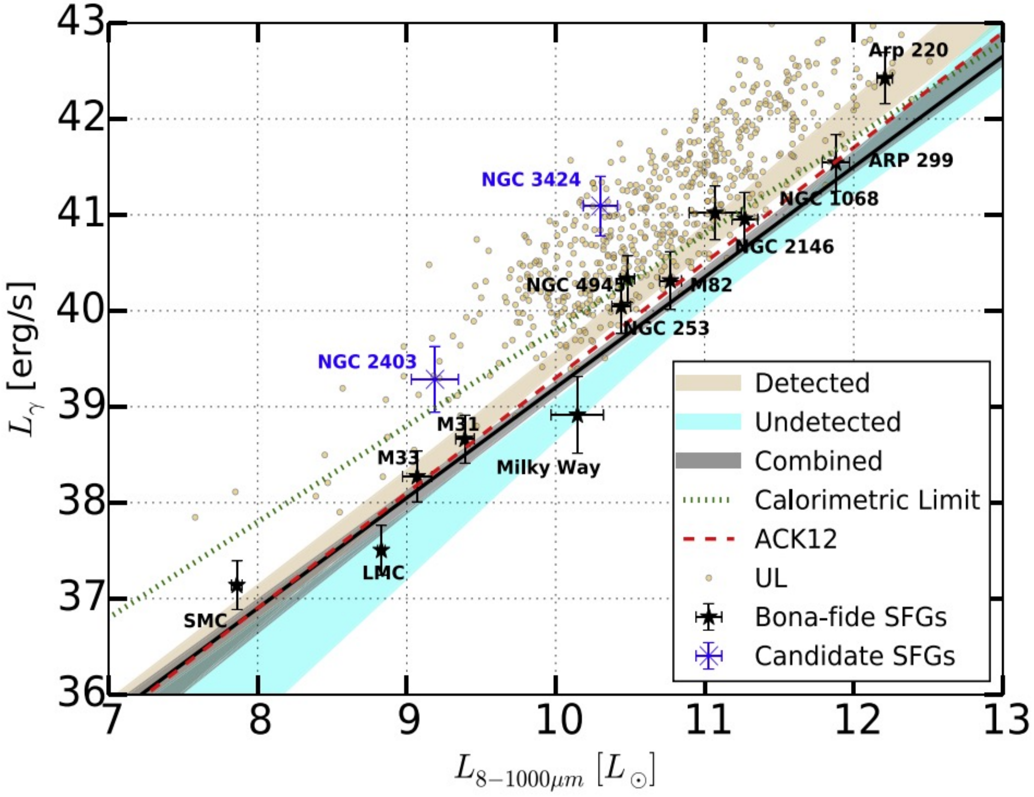
Strong correlation between CR diffusion and star formation

Radio-infrared flux correlation



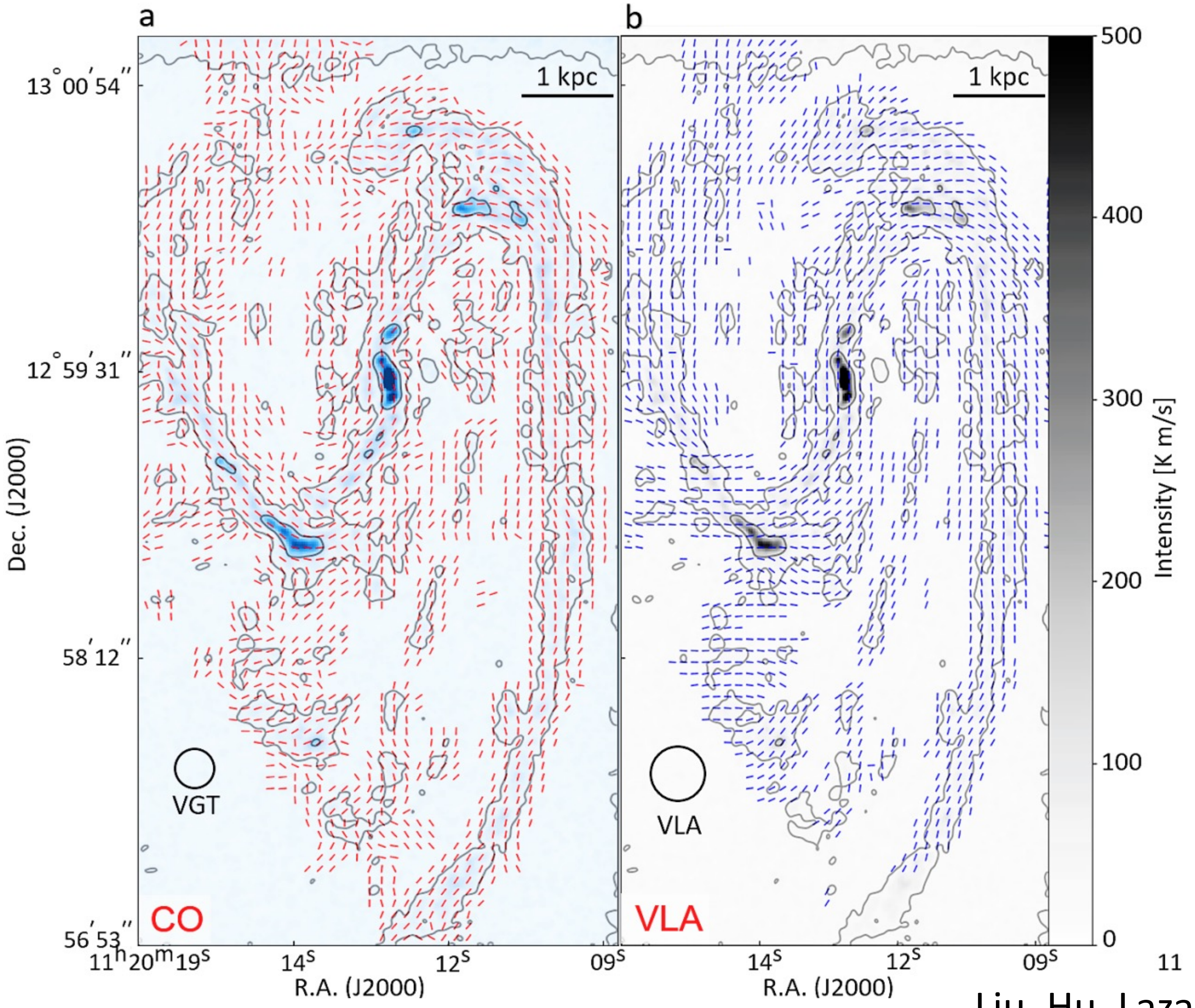
Dwek & Barker 2002

Gamma-ray vs. IR luminosities for the star forming galaxies



Ajello et al. 2020, Griffin et al. 2016

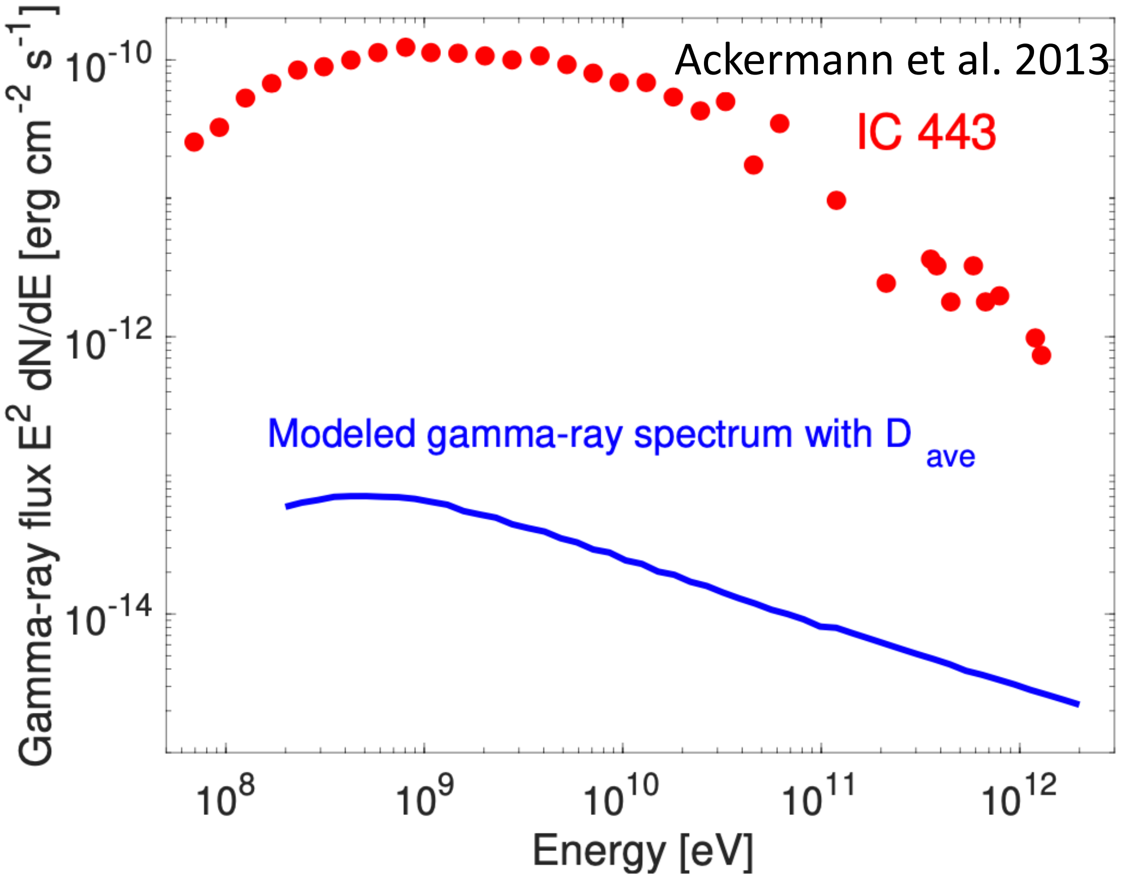
Magnetic fields traced by Gradient technique (MHD turbulence anisotropy) in CO and synchrotron emission



Liu, Hu, Lazarian, Xu, & Soida 2023

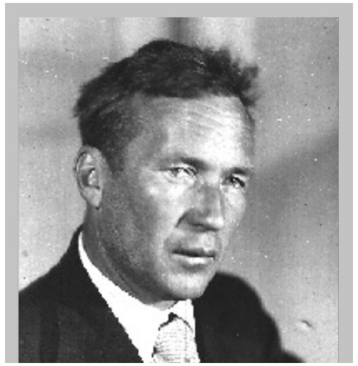
Suppressed diffusion of CRs in star-forming regions

Supernova shock – cloud interaction

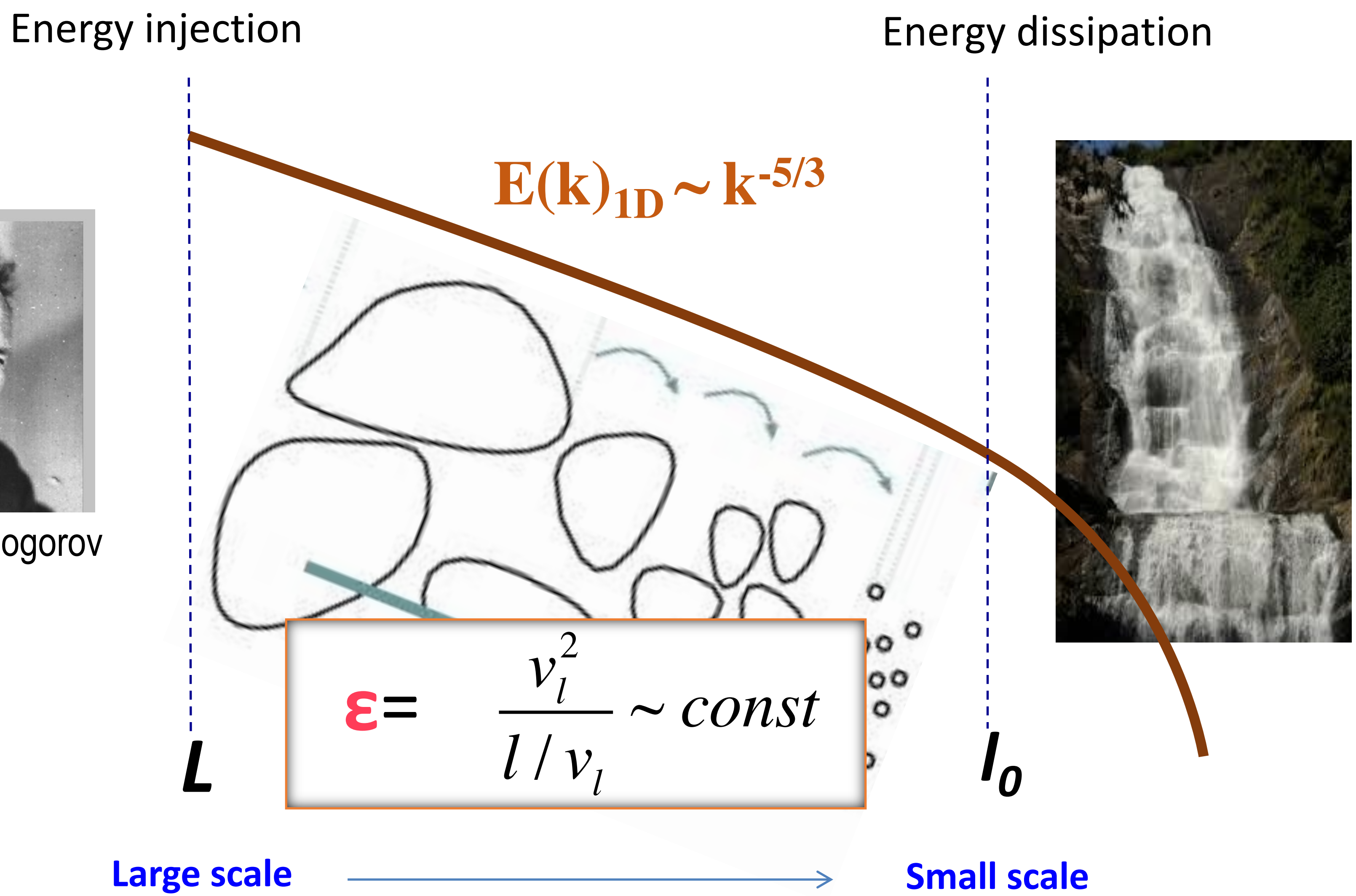


Average Galactic diffusion coefficient cannot explain gamma-ray observations

Kolmogorov turbulent energy spectrum

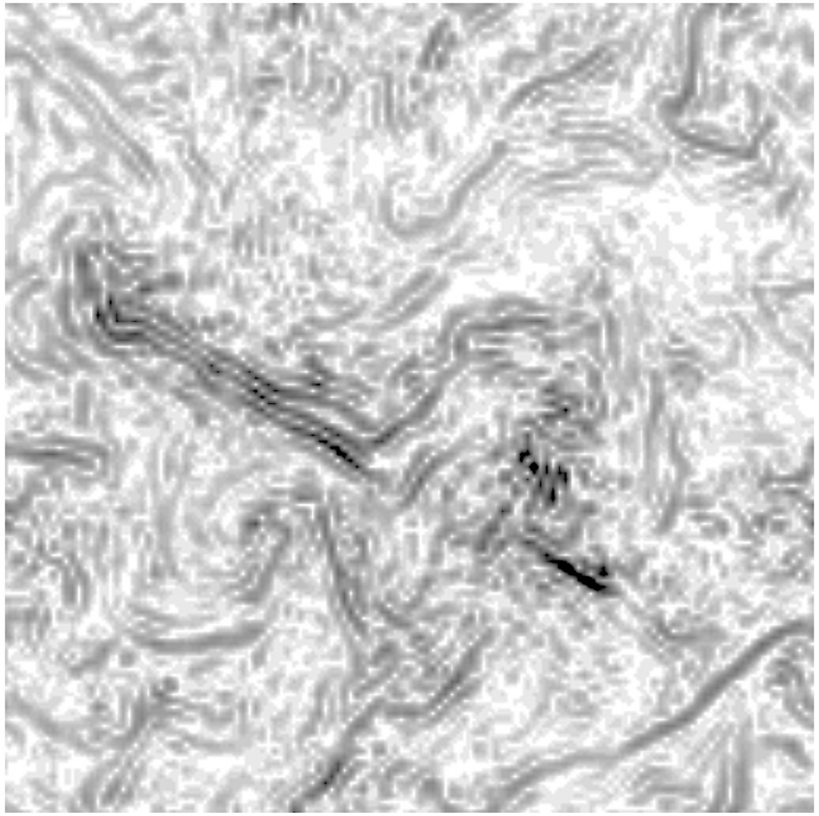


Andrey Kolmogorov
(1903-1987)

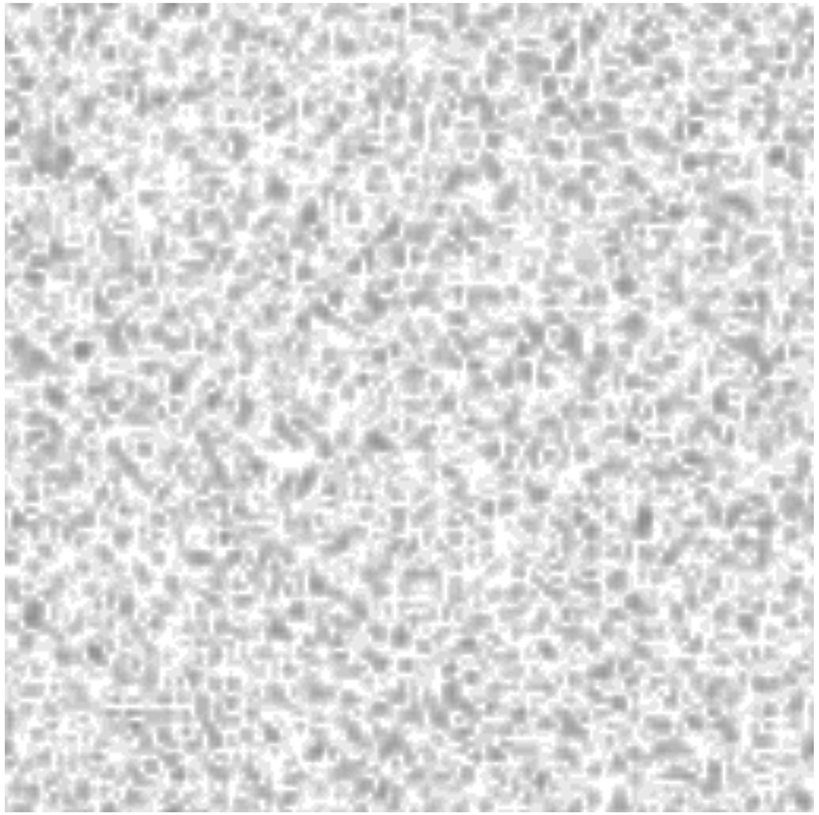


MHD turbulence is not an ensemble of waves

MHD turbulence



Waves



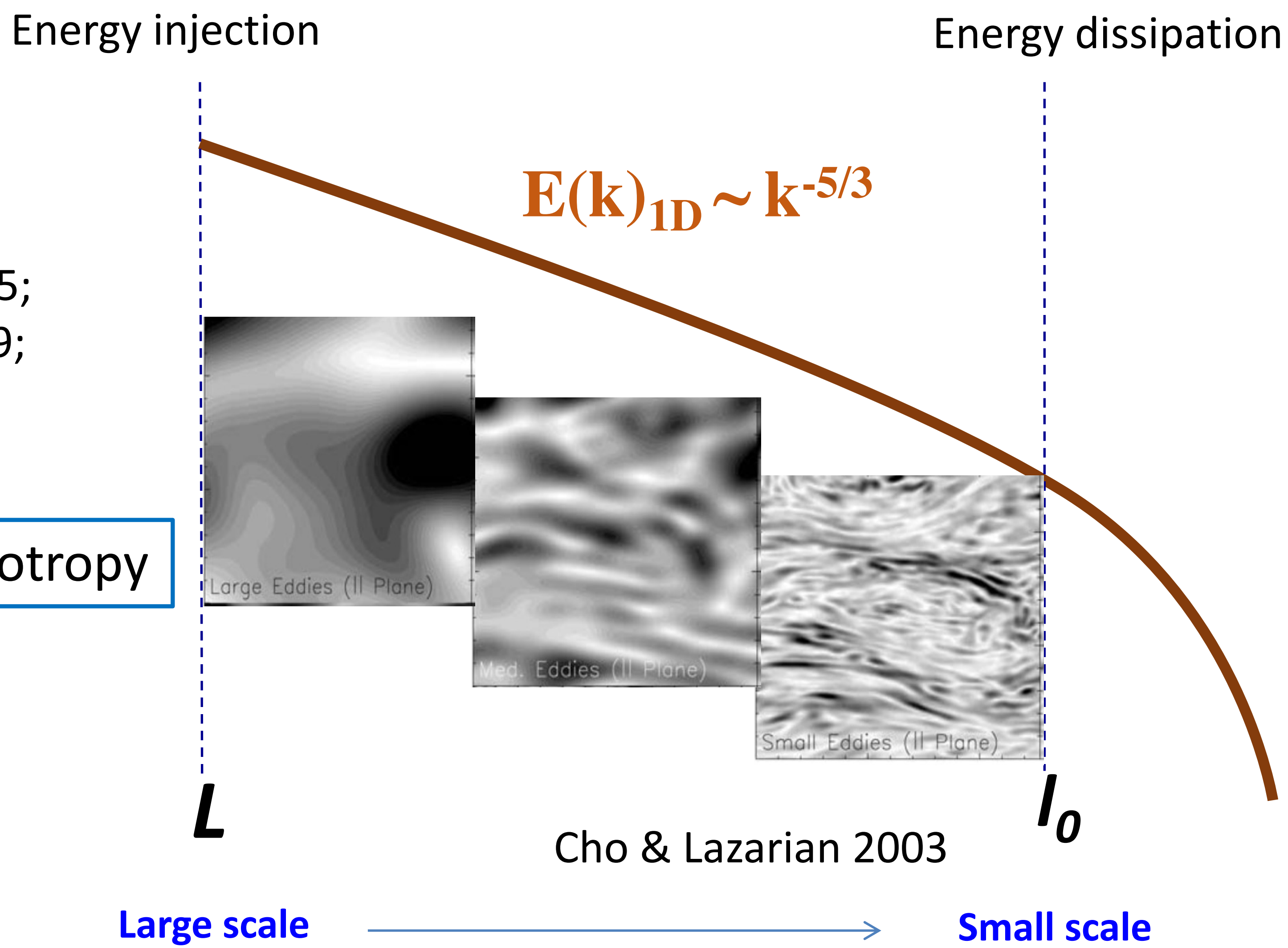
Maron & Goldreich 2001

Anisotropic MHD turbulence

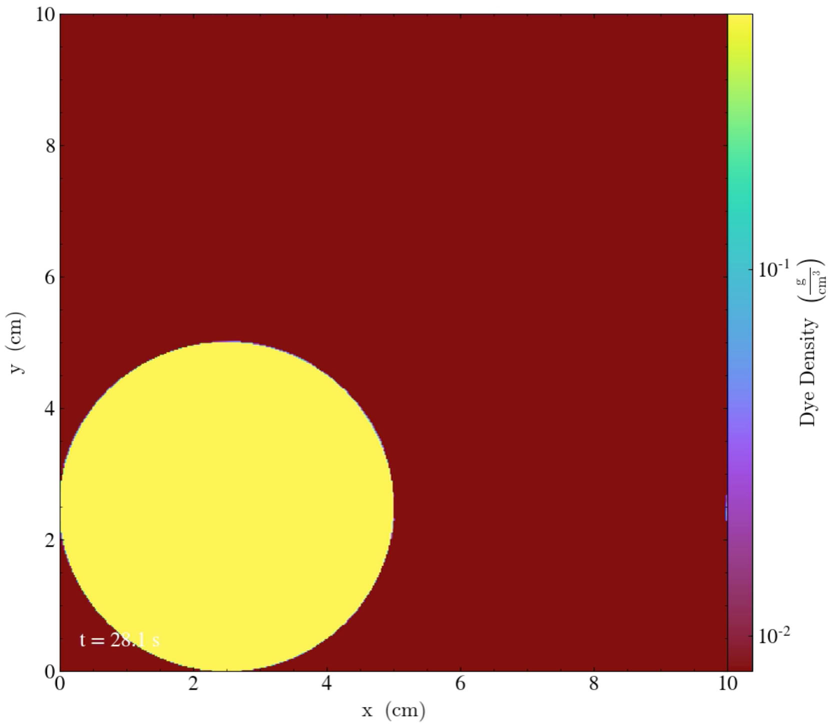
MHD turbulence

Goldreich & Sridhar 1995;
Lazarian & Vishniac 1999;
Cho & Vishniac 2000;
Cho & Lazarian 2002

Scale-dependent anisotropy



Anisotropic MHD turbulence

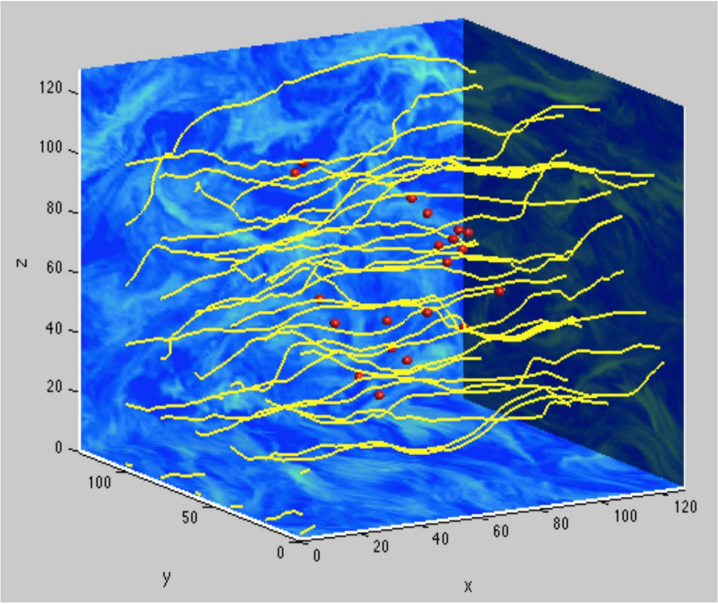


Xu, Ji & Lazarian. 2019

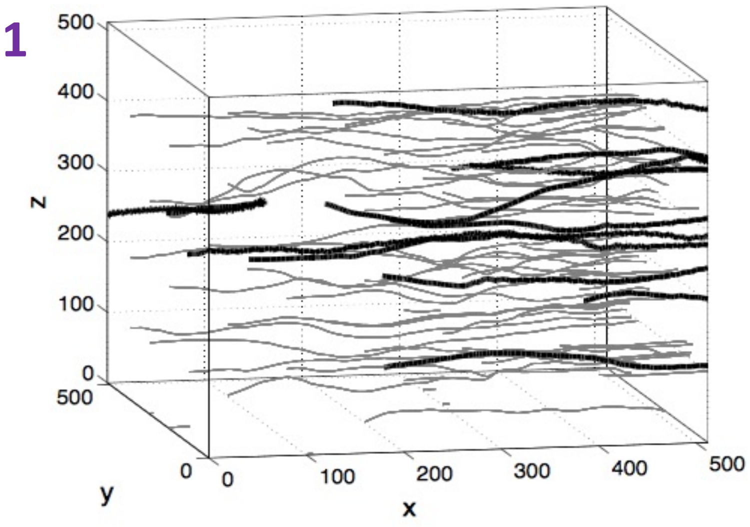
Diffusion of CRs depends on MHD turbulence

Turbulence Alfven Mach number

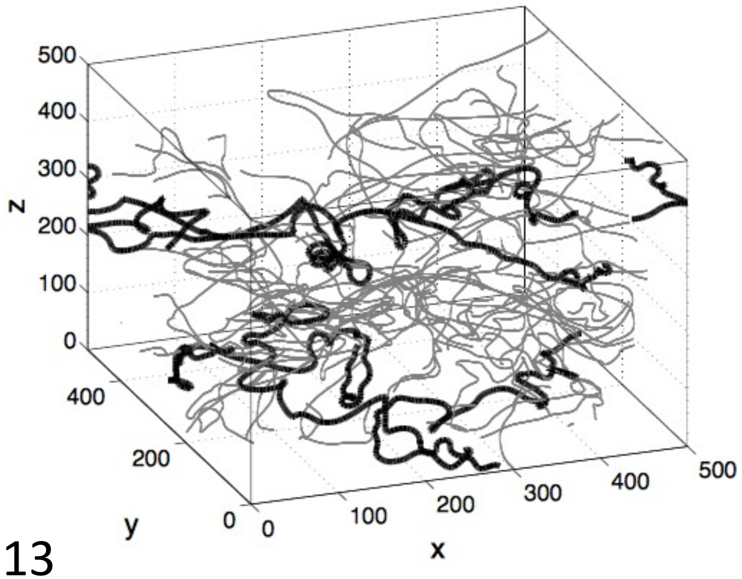
$$M_A = V_L / V_A, \quad V_A = B / \sqrt{4\pi\rho}$$



$M_A < 1$



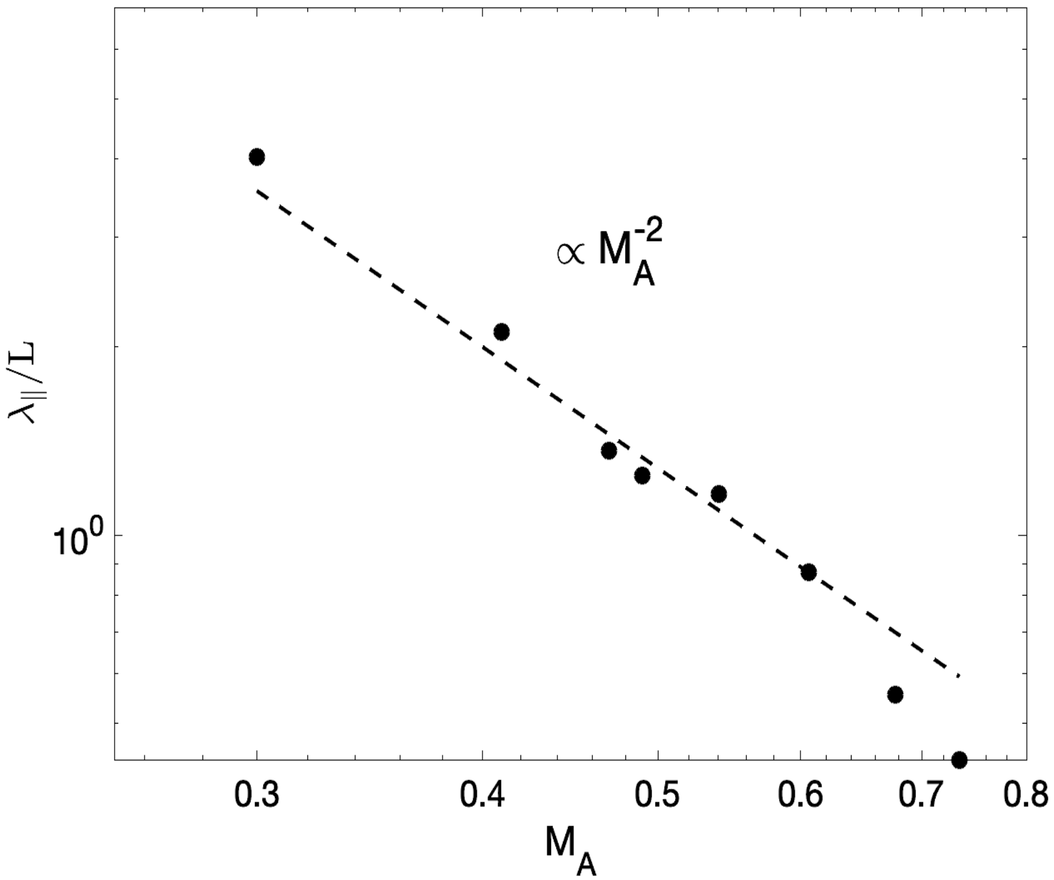
$M_A > 1$



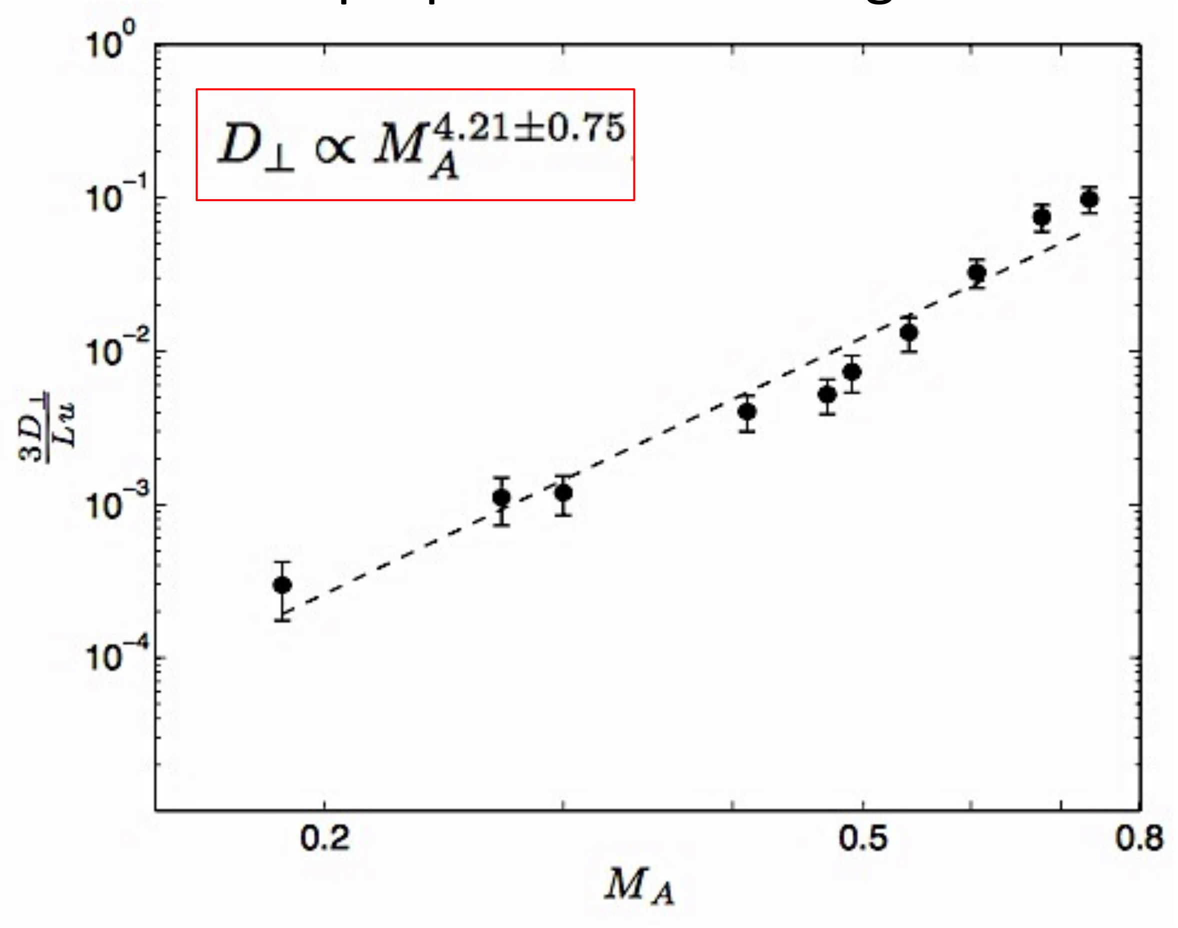
Xu & Yan 2013

Diffusion of CRs depends on M_A

Diffusion parallel to magnetic field



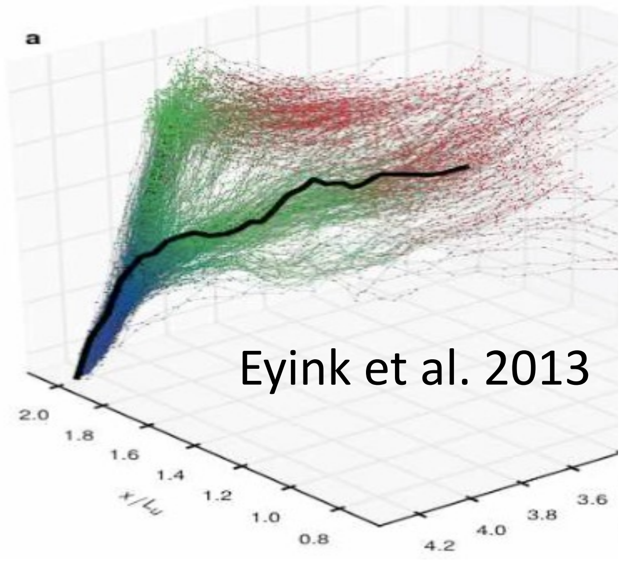
Diffusion perpendicular to magnetic field



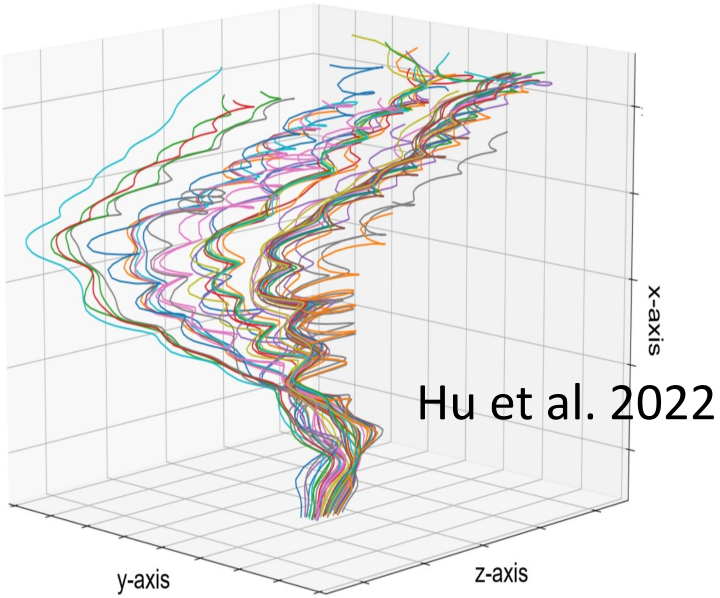
Xu & Yan 2013; Hu et al. 2022

CR perpendicular diffusion

turbulence

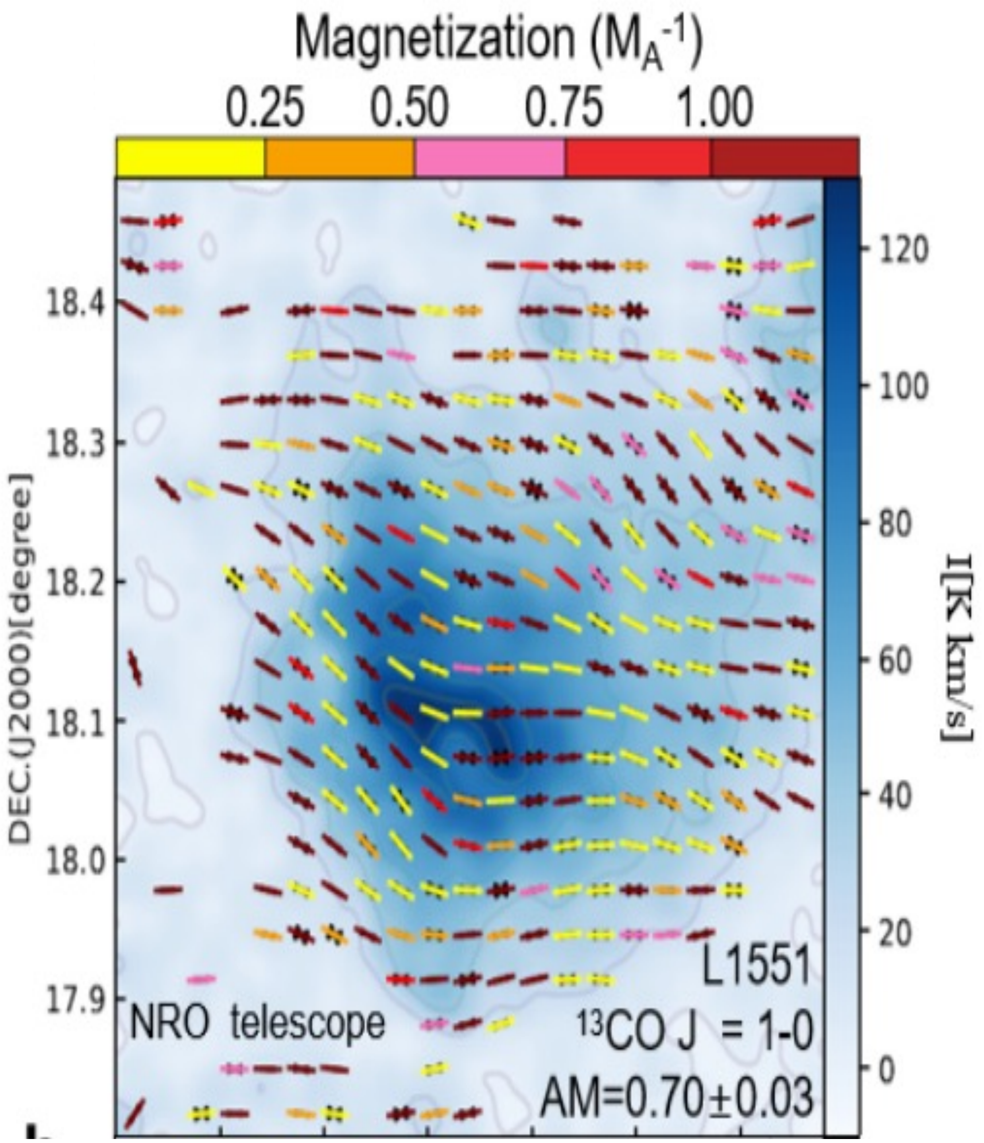


magnetic fields



CR particles

CR perpendicular diffusion comes from magnetic field perpendicular diffusion



Hu et al. 2019

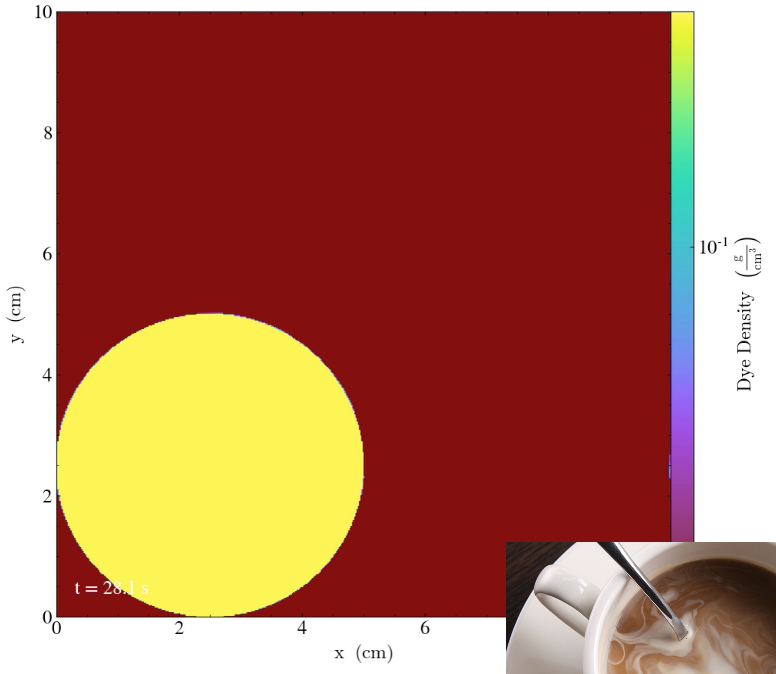
M_A dependent CR diffusion coefficients

M_A measured by Gradient Technique
(MHD turbulence anisotropy)

Self-consistently determine
CR diffusion coefficients in star-forming regions

Compressible MHD turbulence

Incompressible turbulence

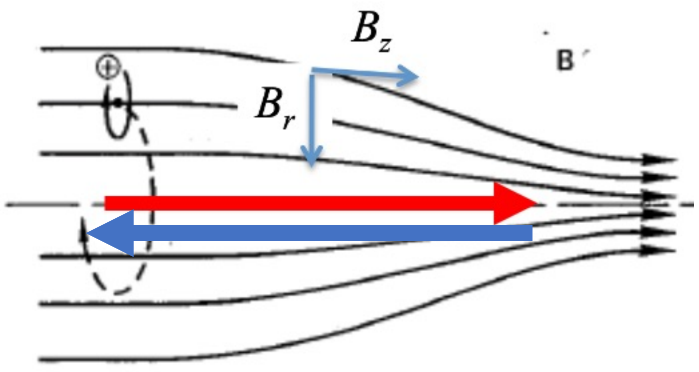


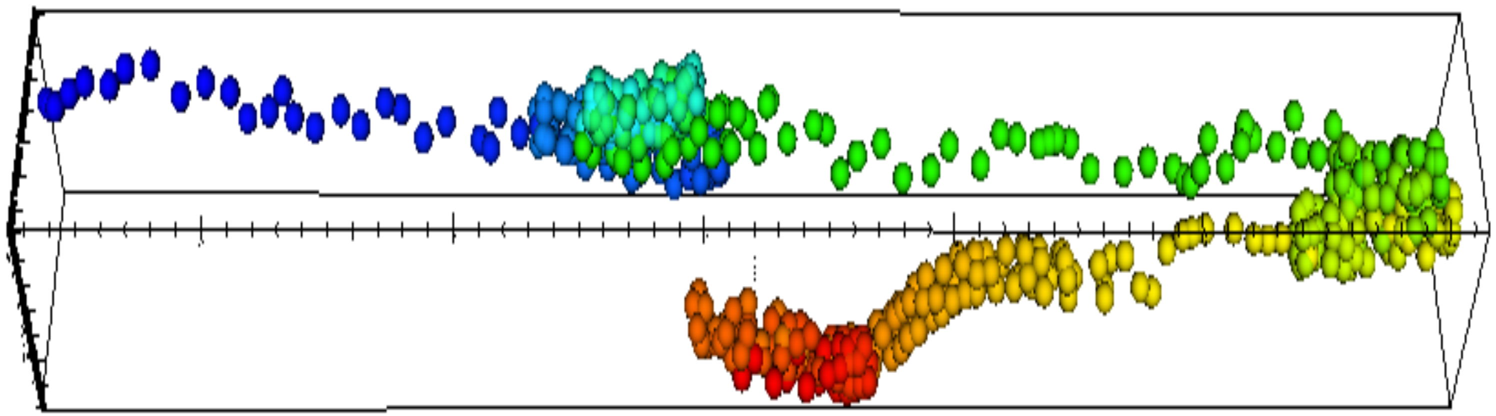
Xu et al. 2019

Compressible turbulence

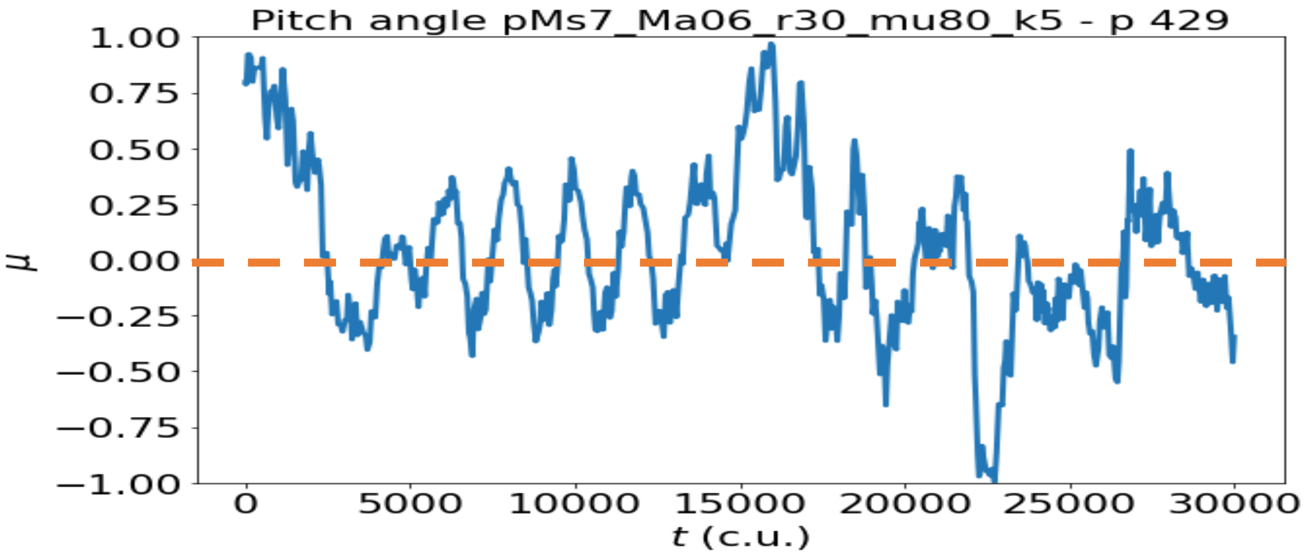
Suoqing Ji

Mirror diffusion of CRs



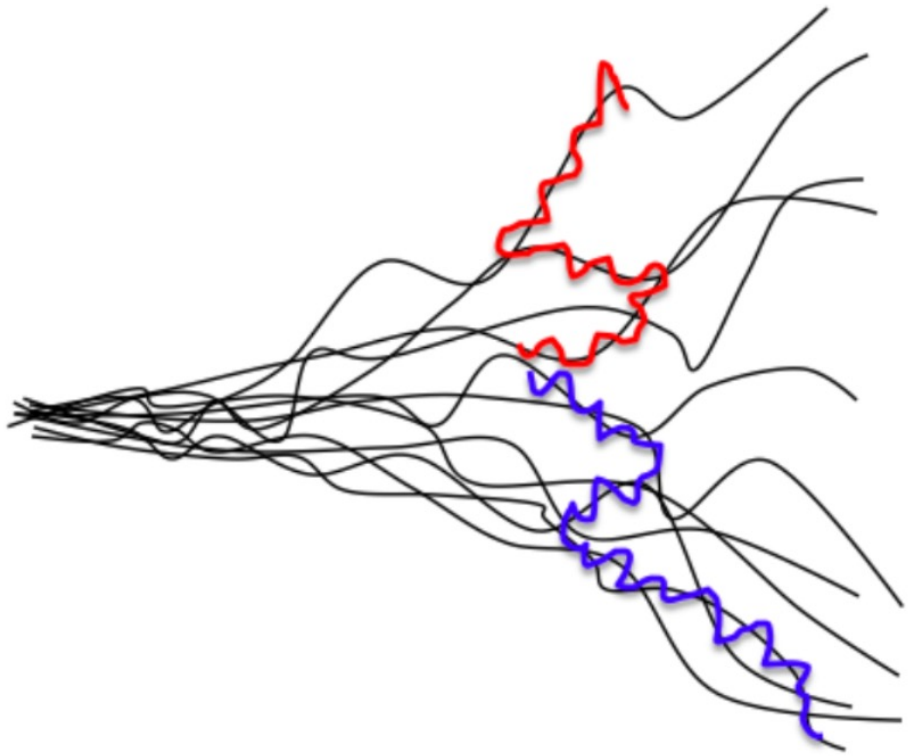


Mirror trapping



Lazarian & Xu 2021;
Barreto Mota dos Santos et al. in prep

Mirror diffusion of CRs



Mirror diffusion

Fast modes

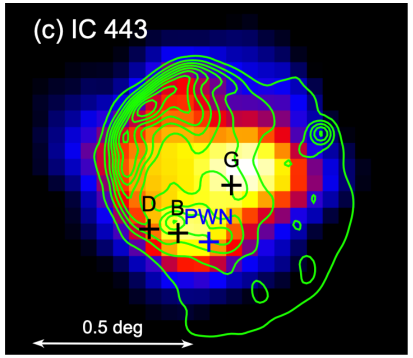
$$D_{\|}(\mu) \approx vL\left(\frac{\delta B_f}{B_0}\right)^{-4}\mu^9,$$

pitch-angle cosine

Slow modes

$$D_{\|}(\mu) \approx v_p \mu l_\mu \approx v_p L \aleph_s^{-2} \mu^5 \qquad \aleph_s = \frac{\delta B_s}{B_0}.$$

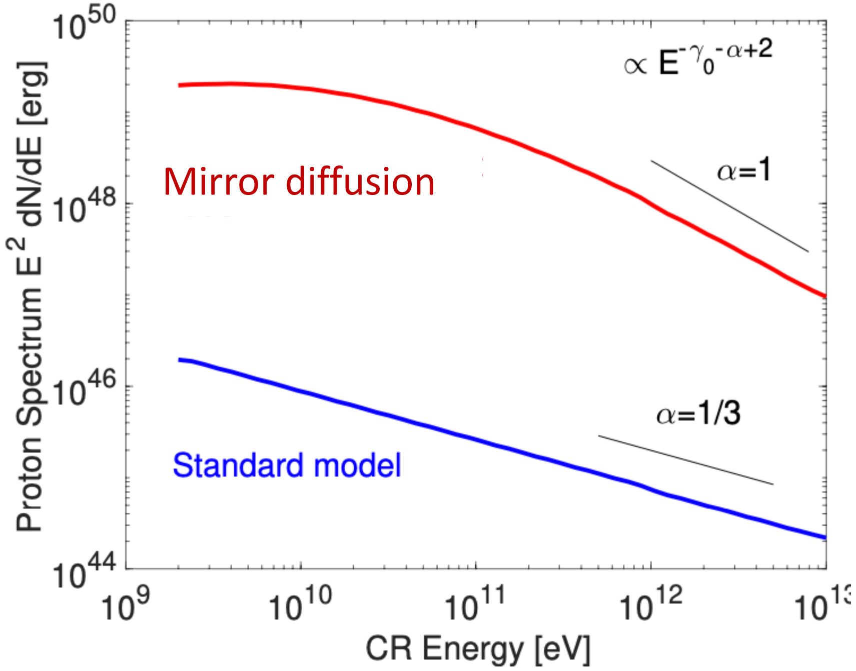
CR diffusion near mid-age supernova remnants



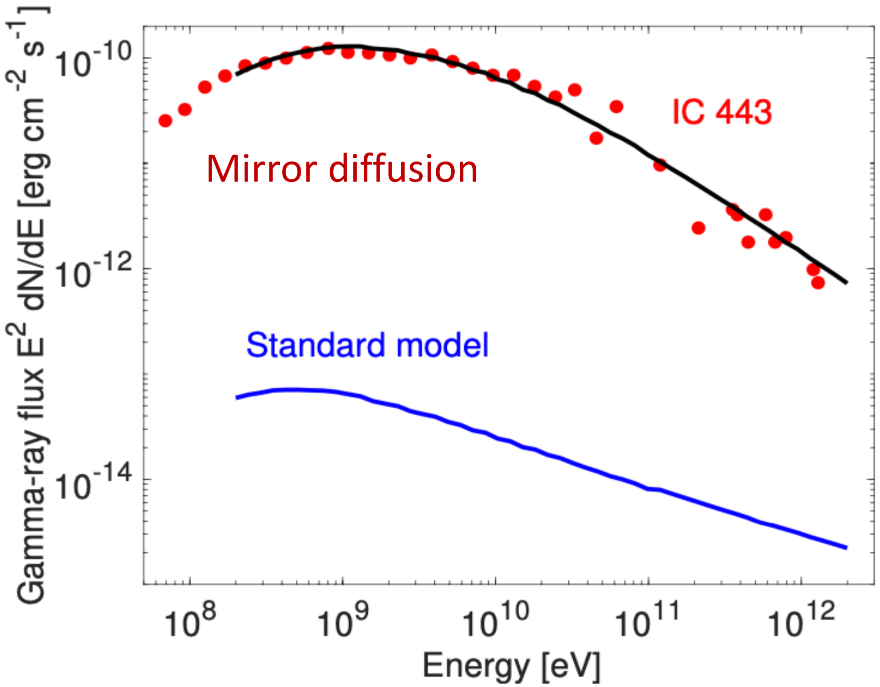
Uchiyama & Fermi LAT Collaboration 2010

Mirror diffusion near SNRs

CR proton spectrum



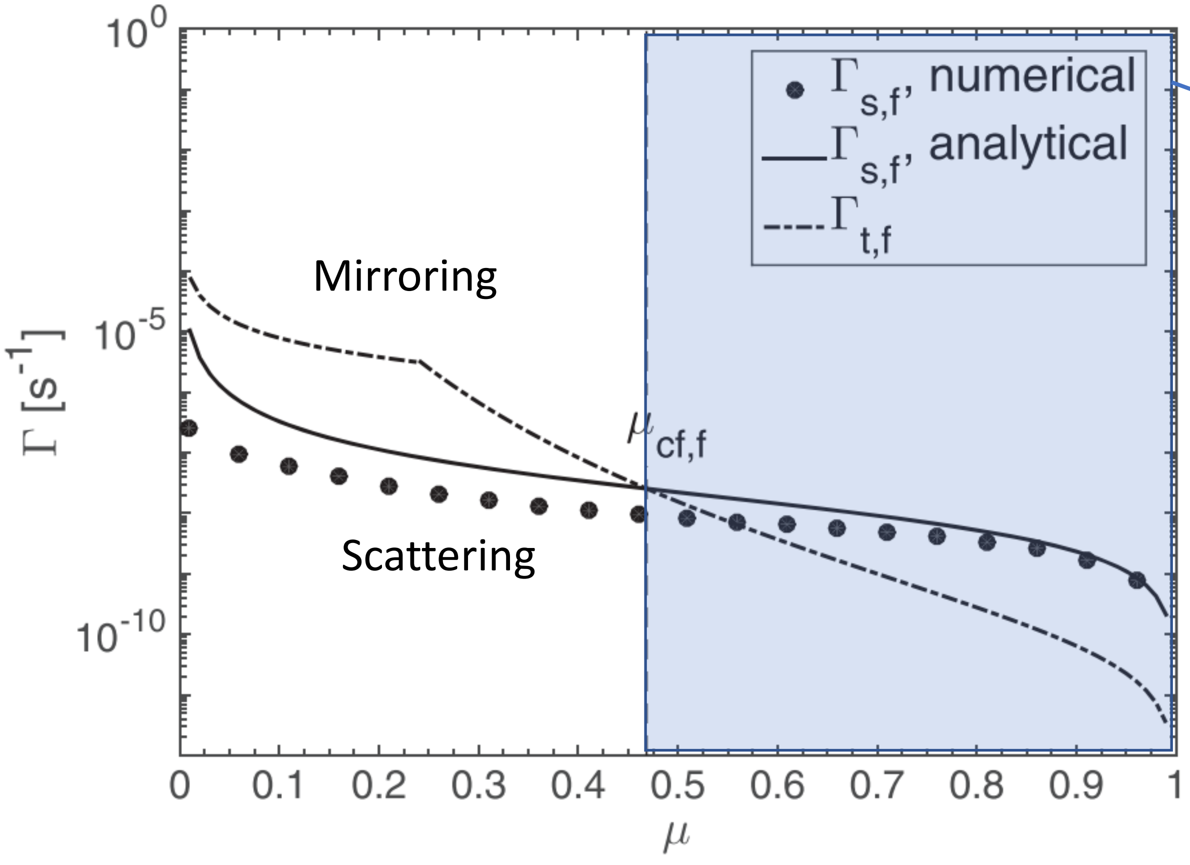
Gamma-ray spectrum



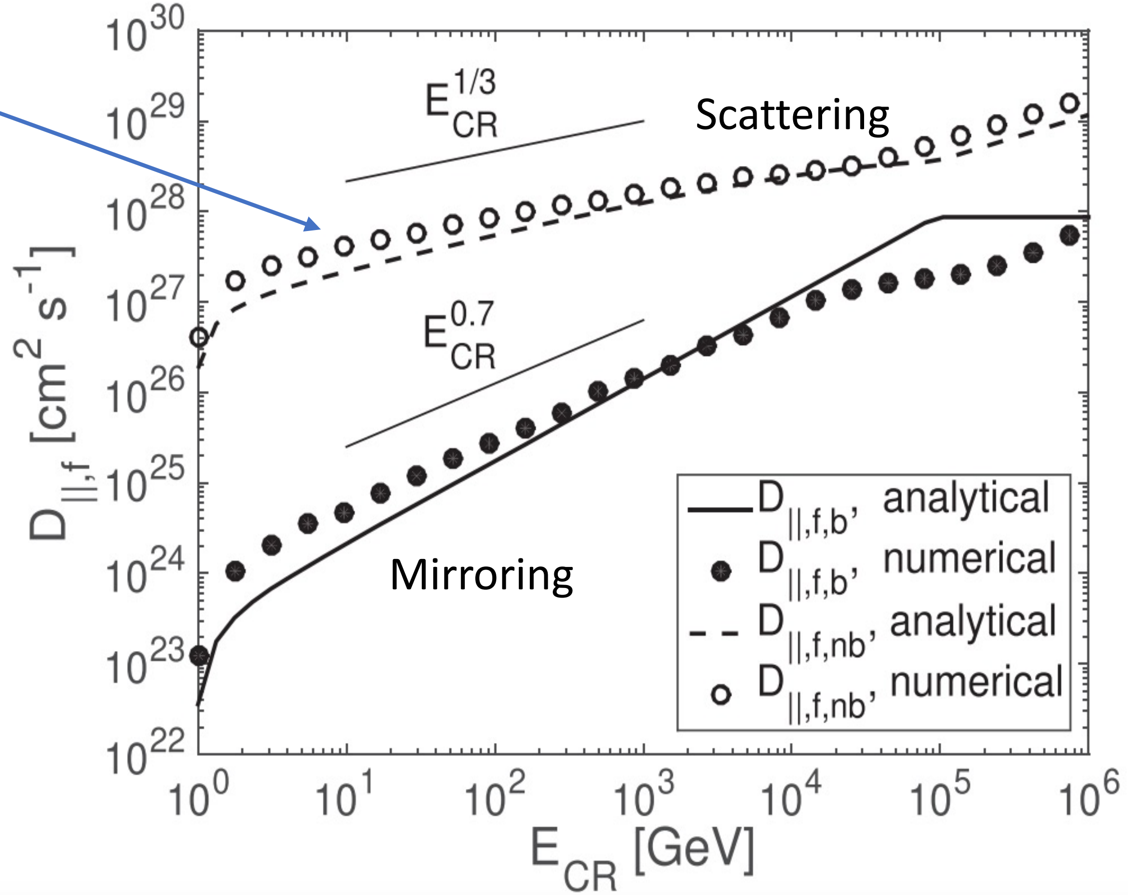
Xu 2021

Mirror diffusion and scattering diffusion

Mirroring & Scattering



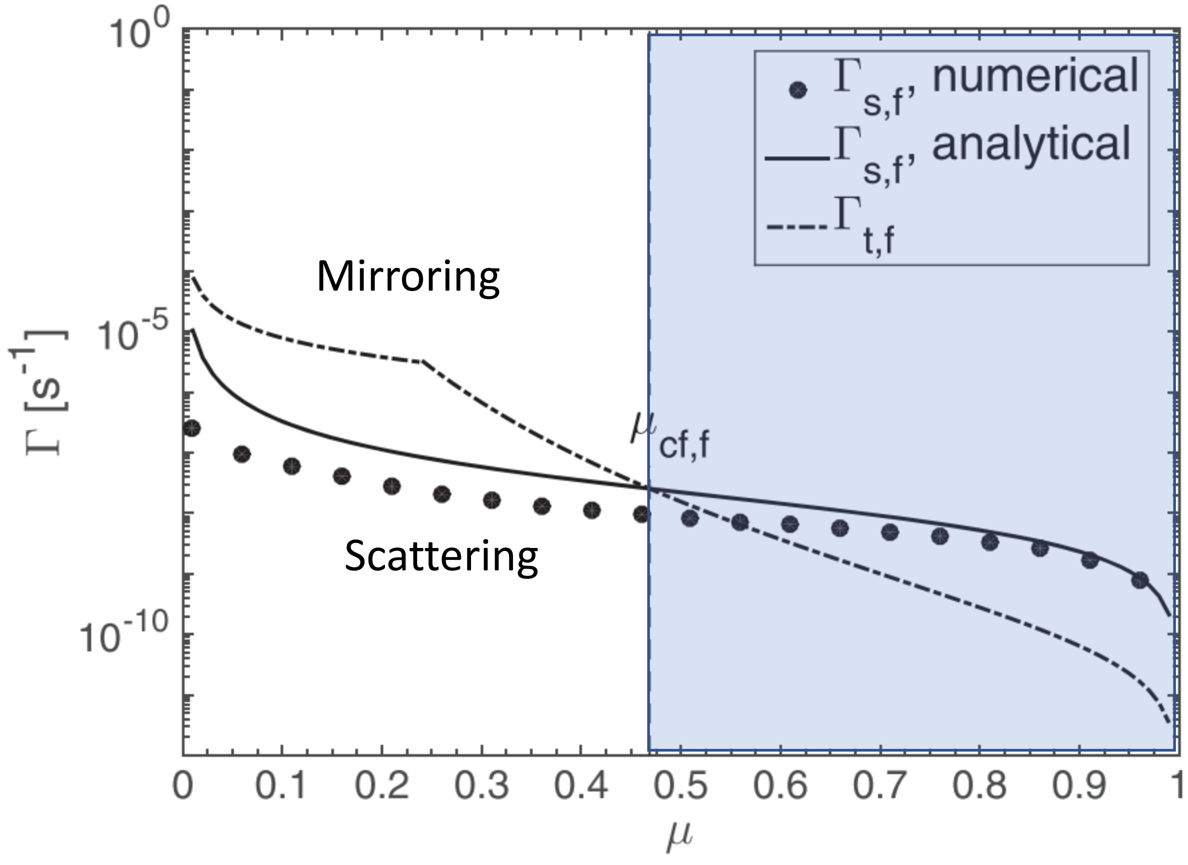
Parallel diffusion coefficients



Xu & Lazarian 2020; Lazarian & Xu 2021

Scattering diffusion of CRs

Mirroring & Scattering



Xu & Lazarian 2020; Lazarian & Xu 2021

Scattering diffusion coefficient by fast modes

$$D_{\parallel,f,nb} = \frac{v^2}{4}\int_{\mu_c}^{1} d\mu \frac{(1-\mu^2)^2}{D_{\mu\mu,\mathrm{QLT},f}(\mu)}$$

$$\approx \frac{28}{5\pi}\frac{B_0^2}{\delta B_f^2}\left(\frac{v}{L\Omega}\right)^{-\frac{1}{2}}\frac{v^2}{\Omega}[4-\sqrt{\mu_c}(5-\mu_c^2)],$$

$$\mu_{\mathrm{cf,f}} \approx \left[\frac{14}{\pi}\frac{\delta B_f^2}{B_0^2}\left(\frac{v}{L\Omega}\right)^{\frac{1}{2}}\right]^{\frac{2}{11}}.$$

- Slope
- Reduced mean free path
- ~~90 degree problem~~
- ~~Damping problem~~

Summary

- Both CR parallel diffusion and perpendicular diffusion depends on MHD turbulence
- Anisotropy of CR diffusion depends on anisotropy of MHD turbulence
- By combining with M_A measurements with Gradient Technique, we can self-consistently determine CR diffusion coefficients in star-forming regions
- Mirror diffusion ----- star-forming regions
- Scattering by fast modes in the presence of mirroring ----- diffuse ISM