Propagation of Cosmic Rays in Galactic Turbulence: Theory Confronted with Observations

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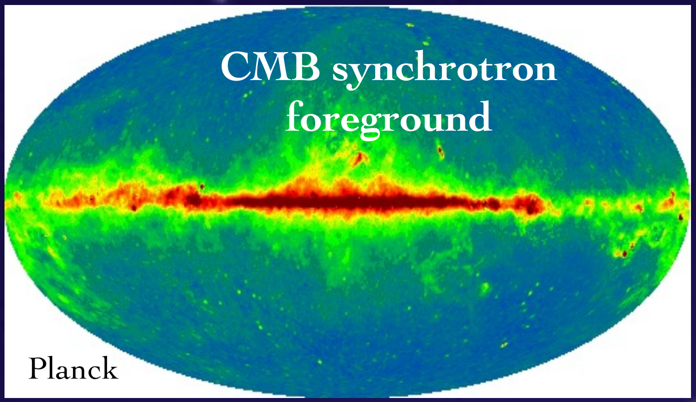
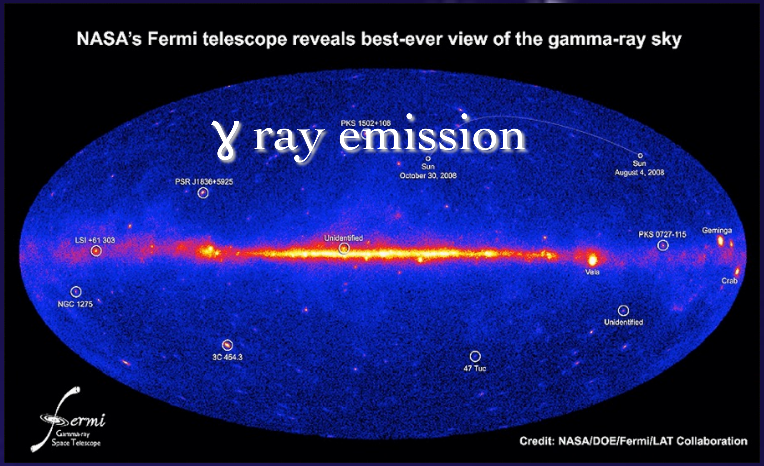
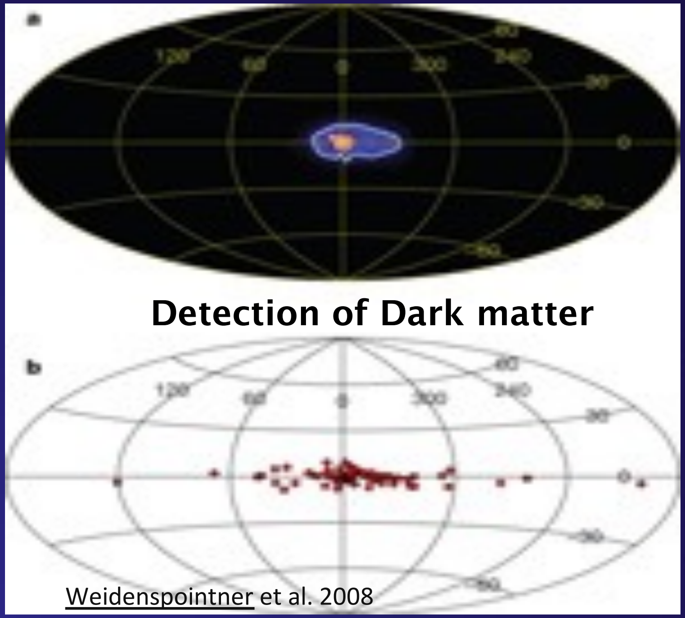
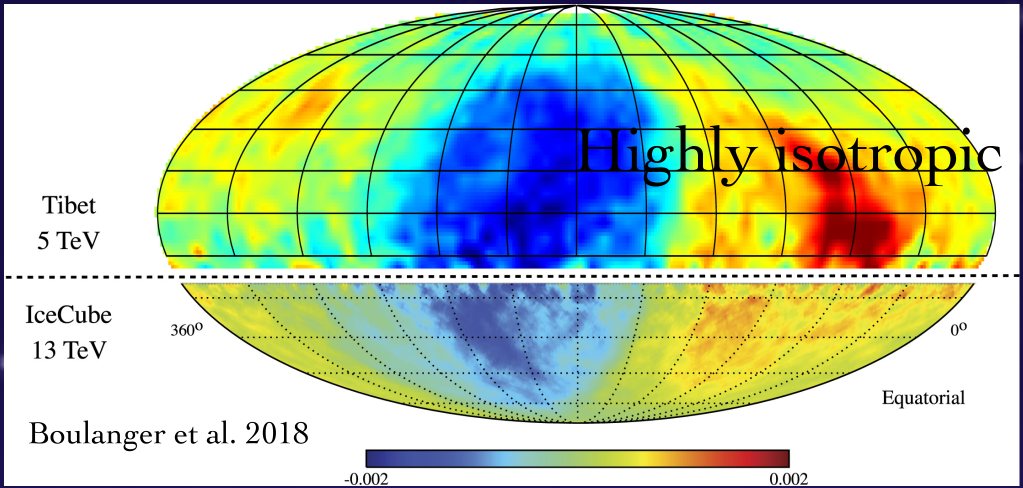
Importance of Cosmic Ray Propagation

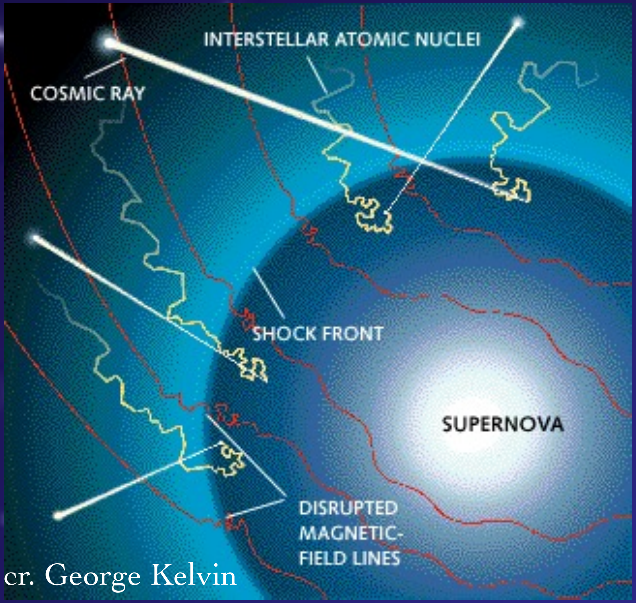






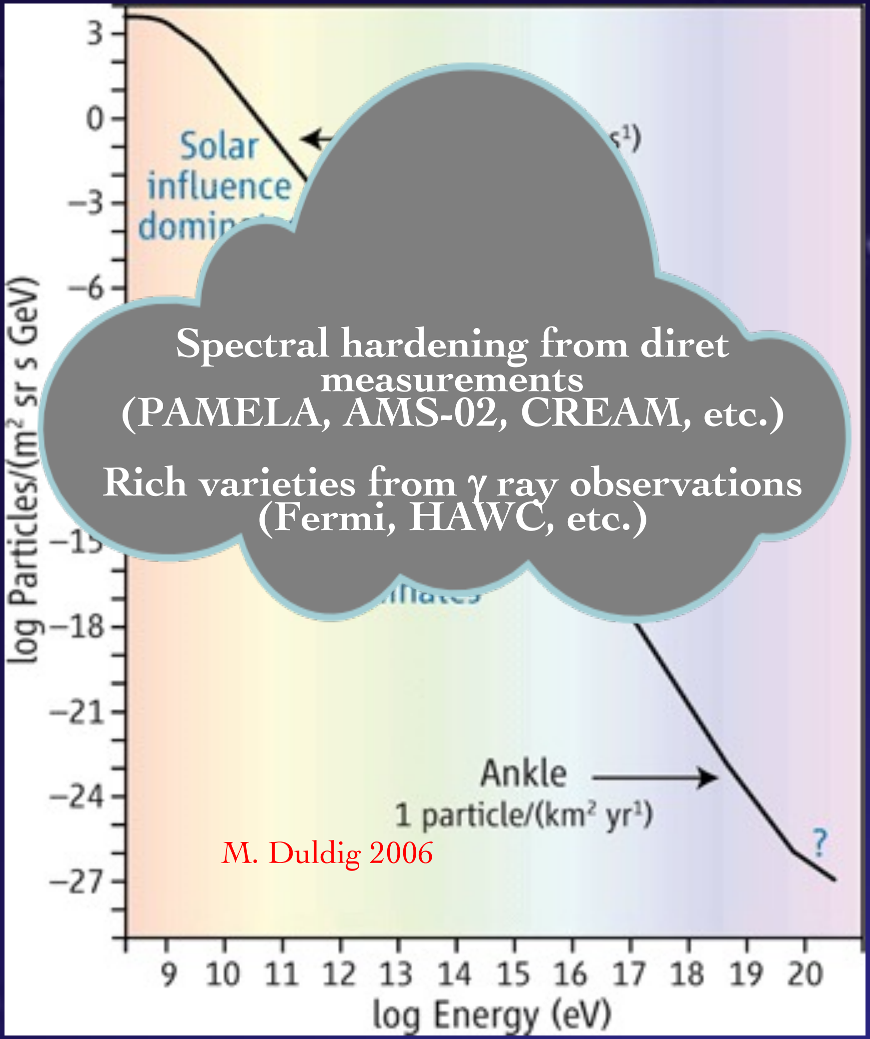
Pinpointing direct sources of CRs is impossible!





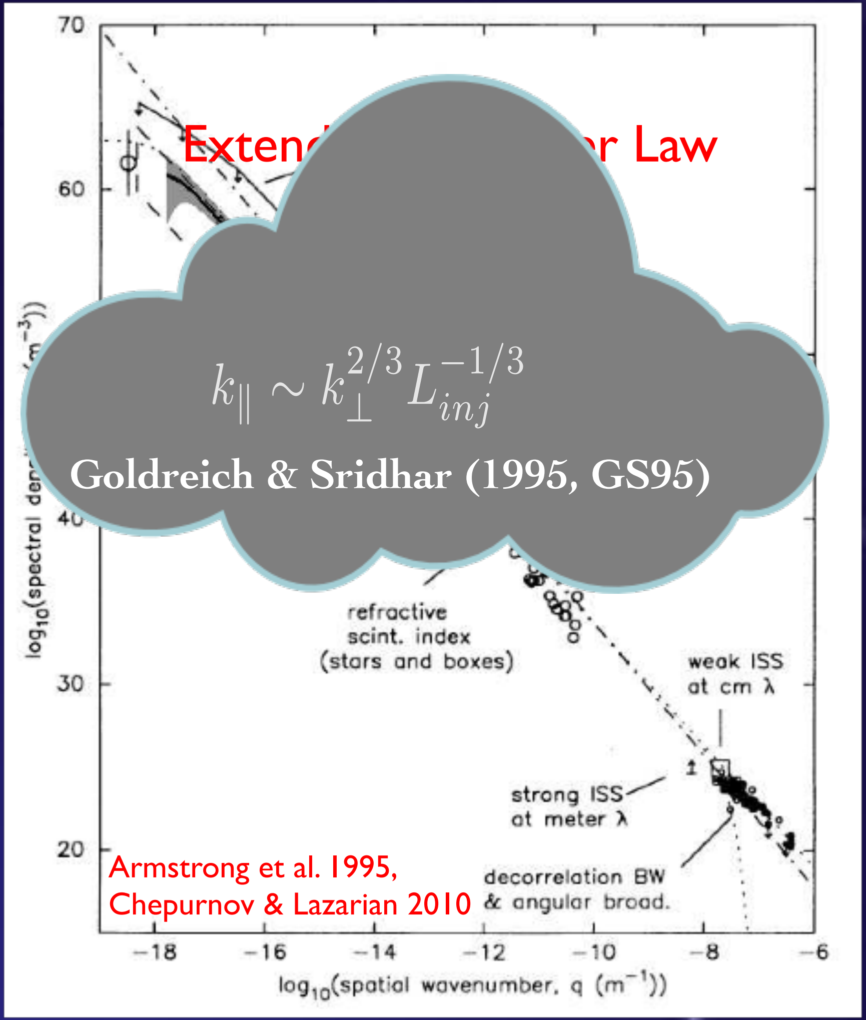
Before reaching the detector, CRs experience complicated propagation, determined by the interactions with the *magnetohydrodynamic (MHD) turbulence.*

Cosmic Rays and turbulence



Spectral hardening from diret measurements
(PAMELA, AMS-02, CREAM, etc.)

Rich varieties from γ ray observations
(Fermi, HAWC, etc.)



$$k_\parallel \sim k_\perp^{2/3} L_{inj}^{-1/3}$$

Goldreich & Sridhar (1995, GS95)

$\lambda_{CR} \propto \frac{R_L}{kW(k)} \propto R_L^{1/3}$ for classical Kolmogorov spectrum $W(k) \propto k^{-5/3}$

Outline

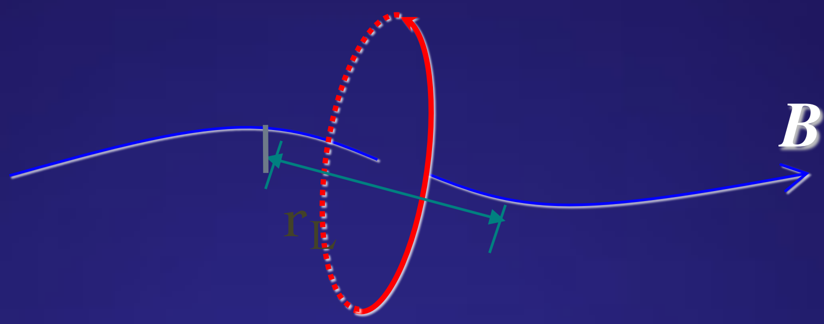
- Different regimes of GCR transport (energy dependence)
- Impact of turbulence driving and damping (energy dependence & spatial dependence)
- Cross field transport in MHD turbulence (directional dependence)

Resonance mechanism

<u>Gyroresonance</u>

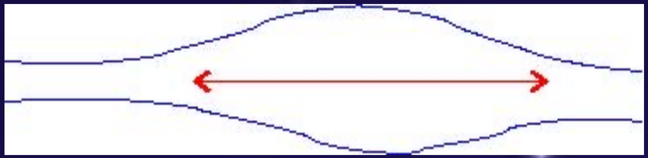
MHD wave frequency (Doppler shifted) equals to the Larmor frequency of particles. For cosmic rays, it means

$k_{\|,res} \sim \Omega / v_{\|} \sim 1/r_L$



Transit Time Damping (TTD-nonresonant mechanism)

Transit time damping (TTD)



Magnetic mirror interaction

Landau resonance condition:

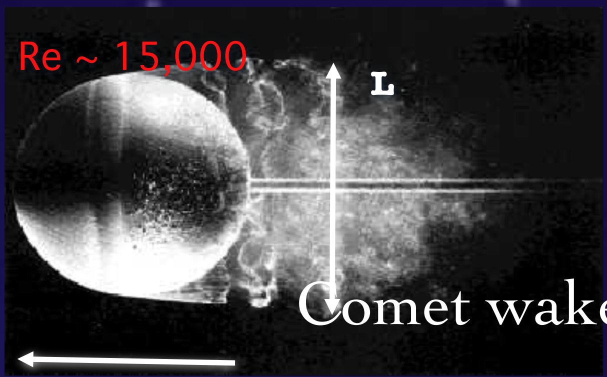
$\omega \approx k_{||} v_{||} \Rightarrow v_A = \omega/k \approx v_{||} \cos\theta$

No resonant scale.
All scales contribute.

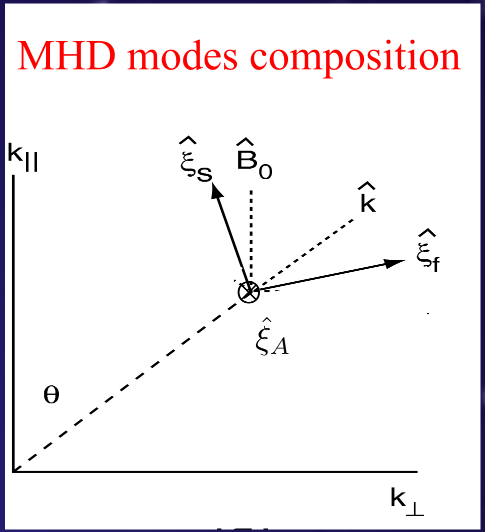
Turbulence is ubiquitous in the Universe

$$Re = LV/\nu = (L^2/\nu)/(L/V) = \tau_{diff}/\tau_{eddy}$$

Astrophysical flows have $Re>10^{10}$.



V

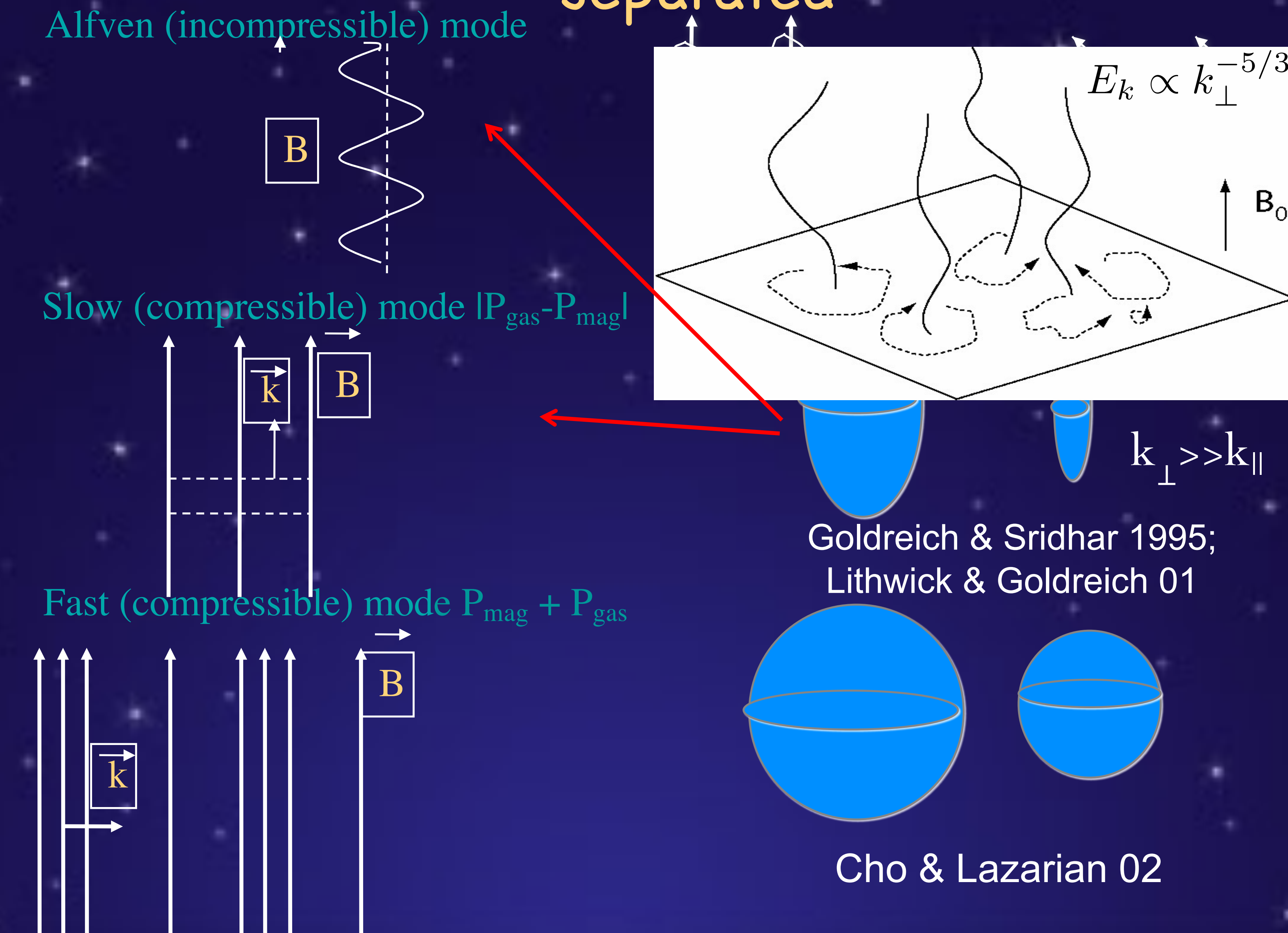


- **Interstellar medium has *finite* plasma $\beta \equiv P_{gas}/P_{mag}$** ⇒

Turbulence is compressible.

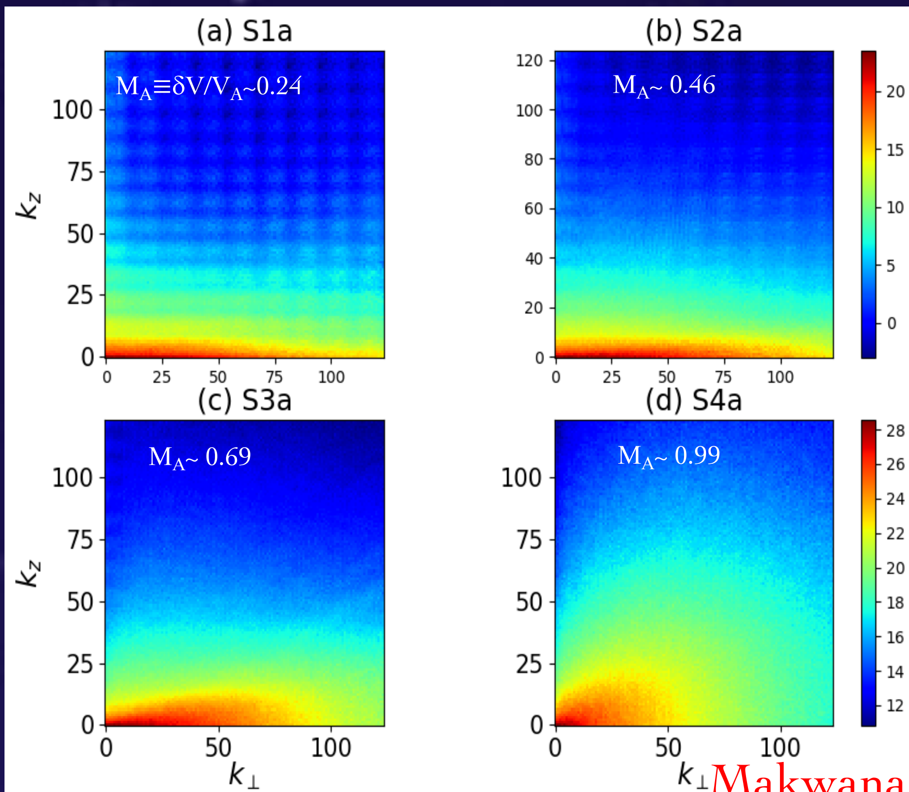
Interstellar turbulence has 3 eigen modes: Alfven, compressible fast and slow modes!

Contributions from turbulence can be separated

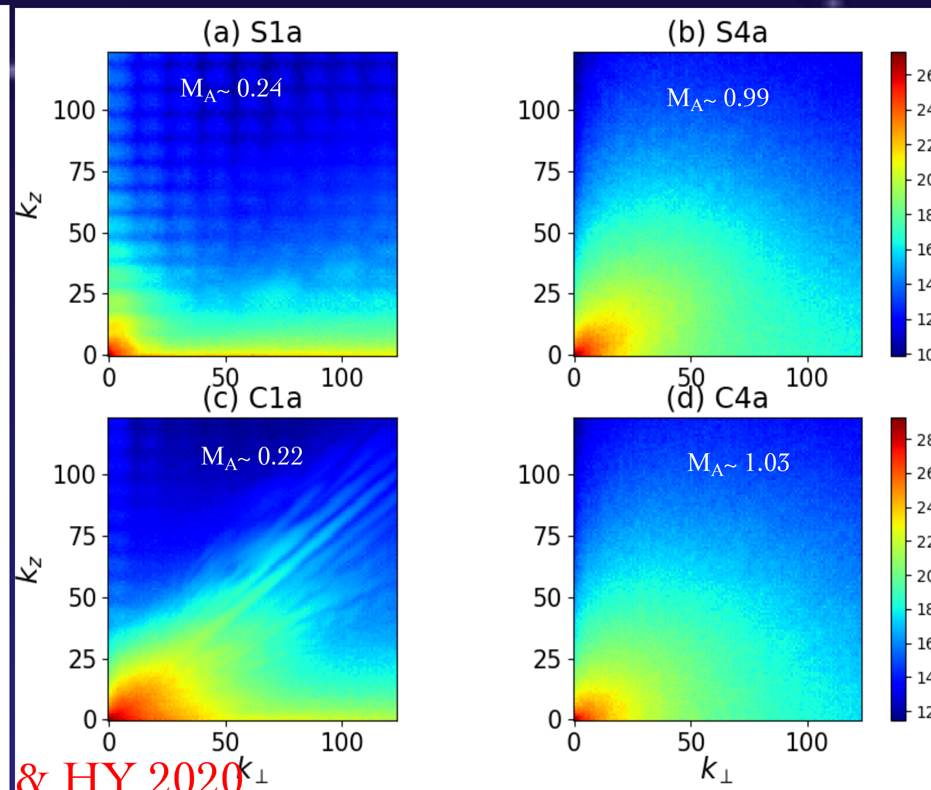


Fast compressible modes do not have 2D regime!

Alfven (incompressible) modes



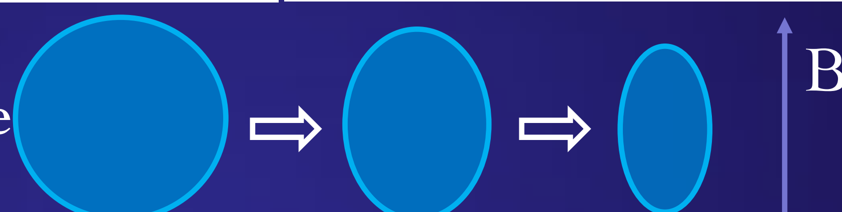
Fast (compressible) modes



Makwana & HY 2020

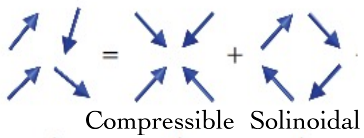
Weak turbulence regime

$M_A < 1$ or $\delta B < B_0$:



Helmholtz decomposition

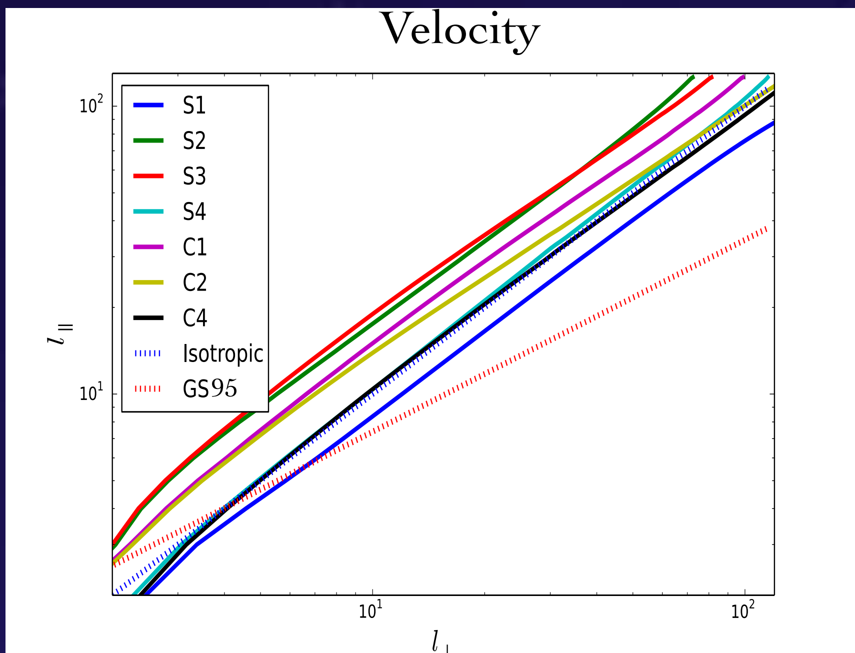
Fundamental theorem of vector fields

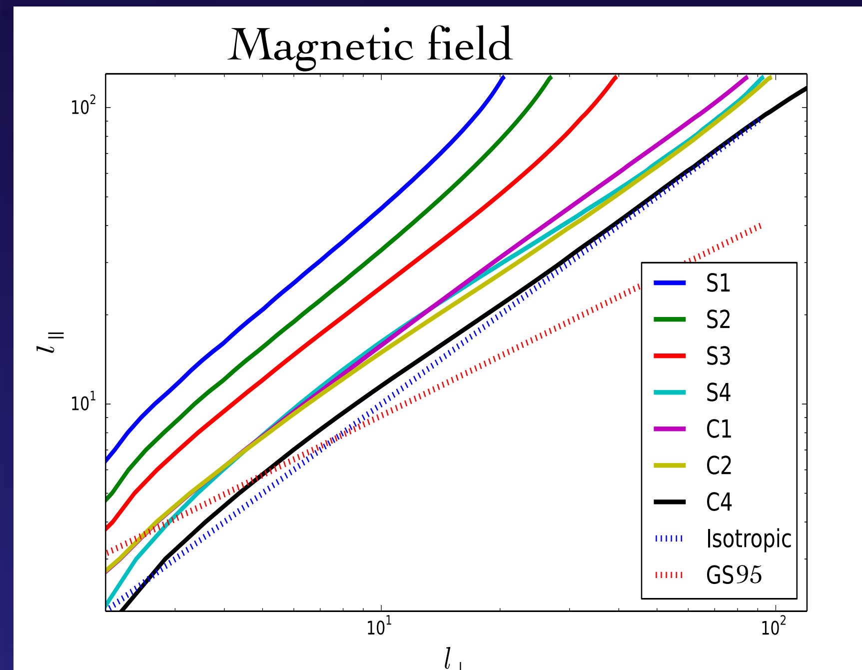


$$\vec{f} = \vec{f}_c + \vec{f}_s$$

$$\vec{\nabla} \times \vec{f}_c = \vec{0} \qquad \vec{\nabla} \cdot \vec{f}_s = 0$$

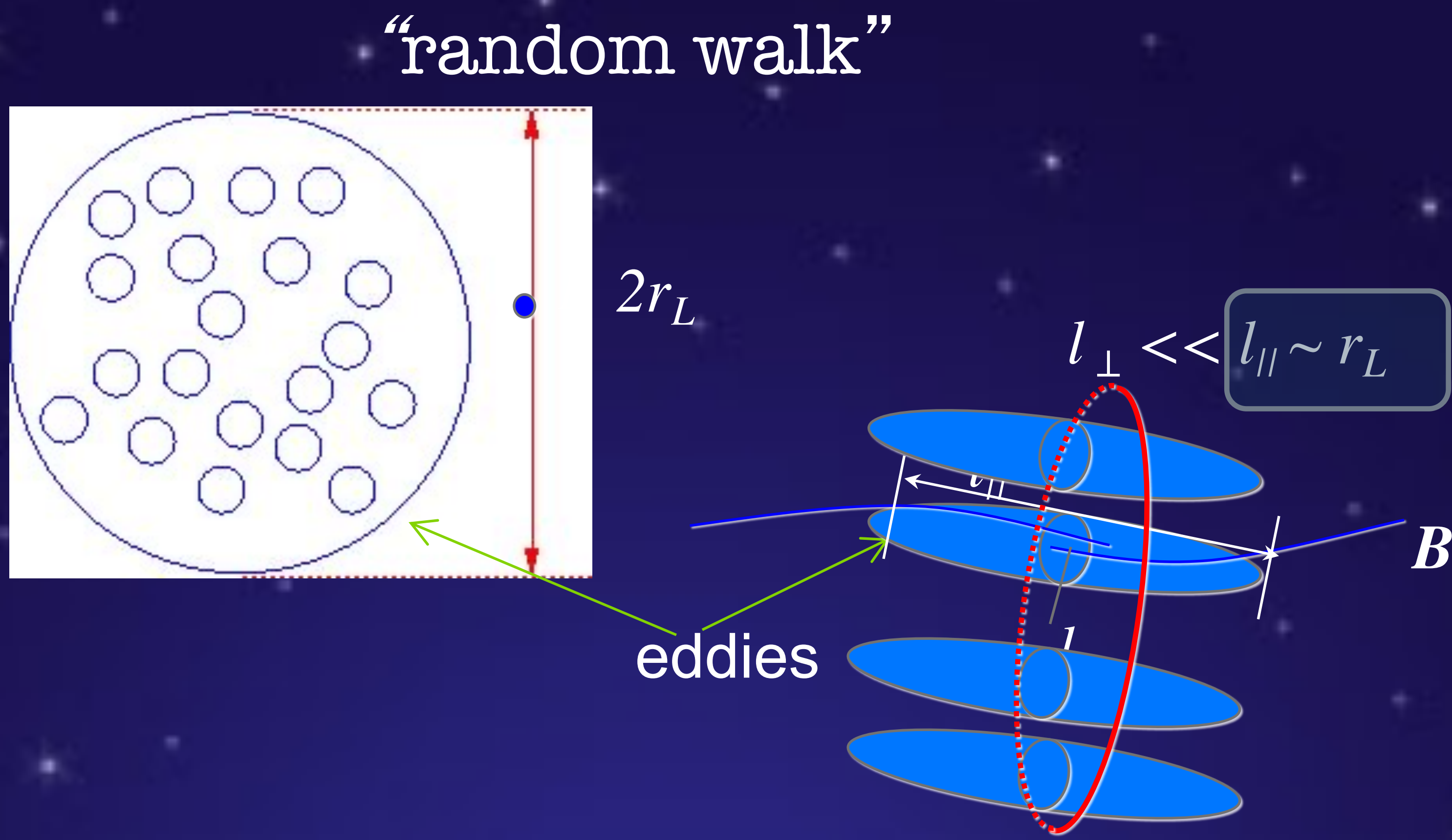
Isotropic cascade of fast (compressible) modes





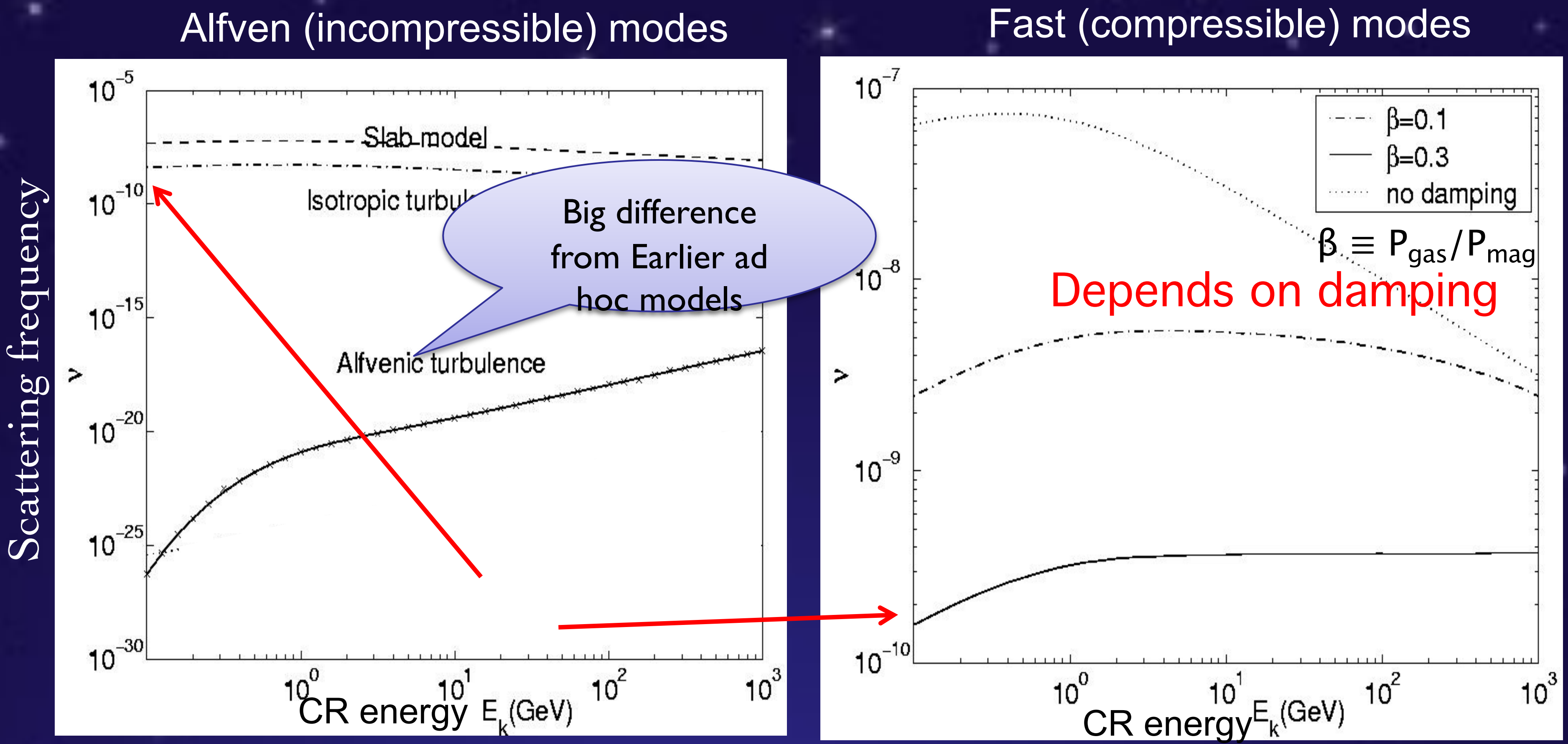
Isotropic cascade of fast modes is persistent with both incompressible and compressible driving (Makwana & HY 2020, *PRX*).

Scattering in Alfvenic (incompressible) turbulence is negligible!



Scattering efficiency is substantially suppressed!

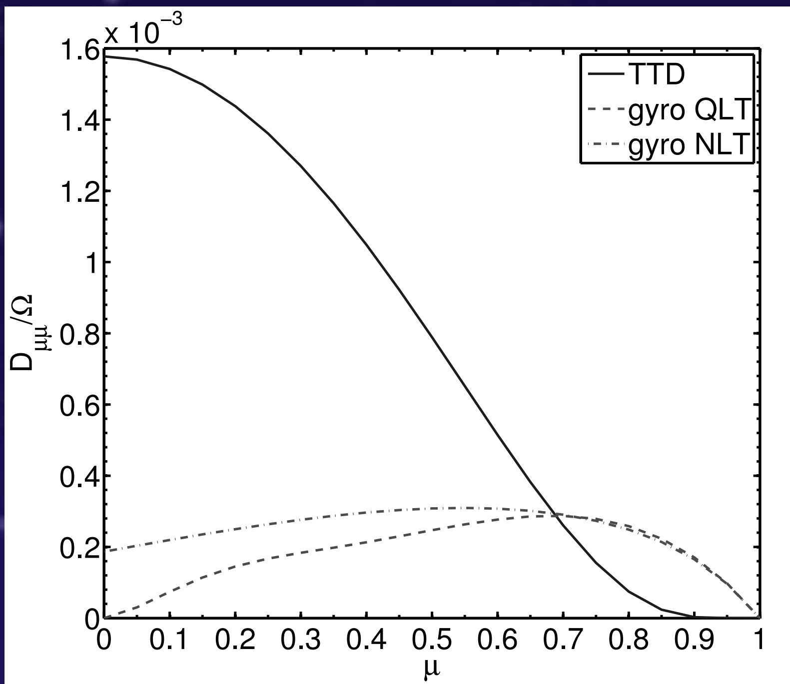
Fast (compressible) modes dominate CR scattering



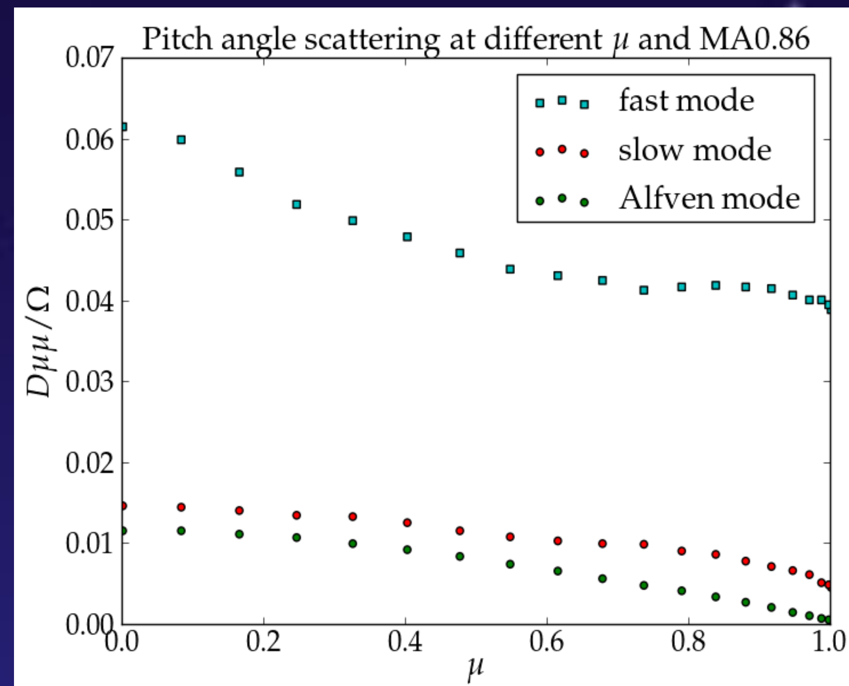
Alfven modes do not work because of anisotropy (Chandran 2000). Fast modes dominate scattering in spite of damping (HY & Lazarian 2002, 2004, 2008).

Simulations confirm the dominance of fast modes in CR scattering

Scattering frequency



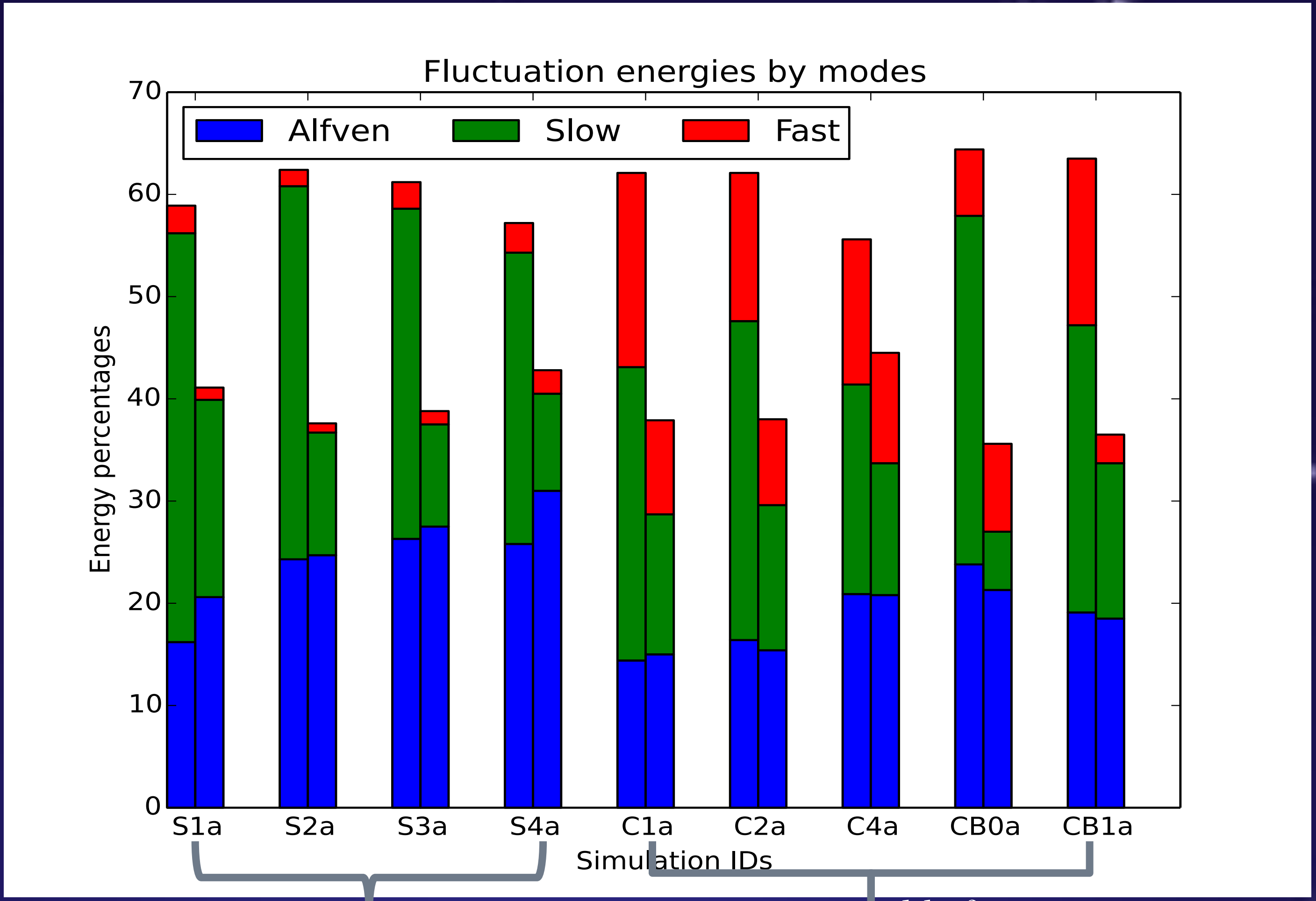
Scattering by fast modes (HY & Lazarian 2008)



Simulation by Maiti + 2021

Mirror interaction (transit time damping, TTD) dominates scattering at large pitch angles *(including 90^o^).* *F*ast modes dominate CR scattering through both TTD and gyroresonance.

Energy fraction in each plasma modes

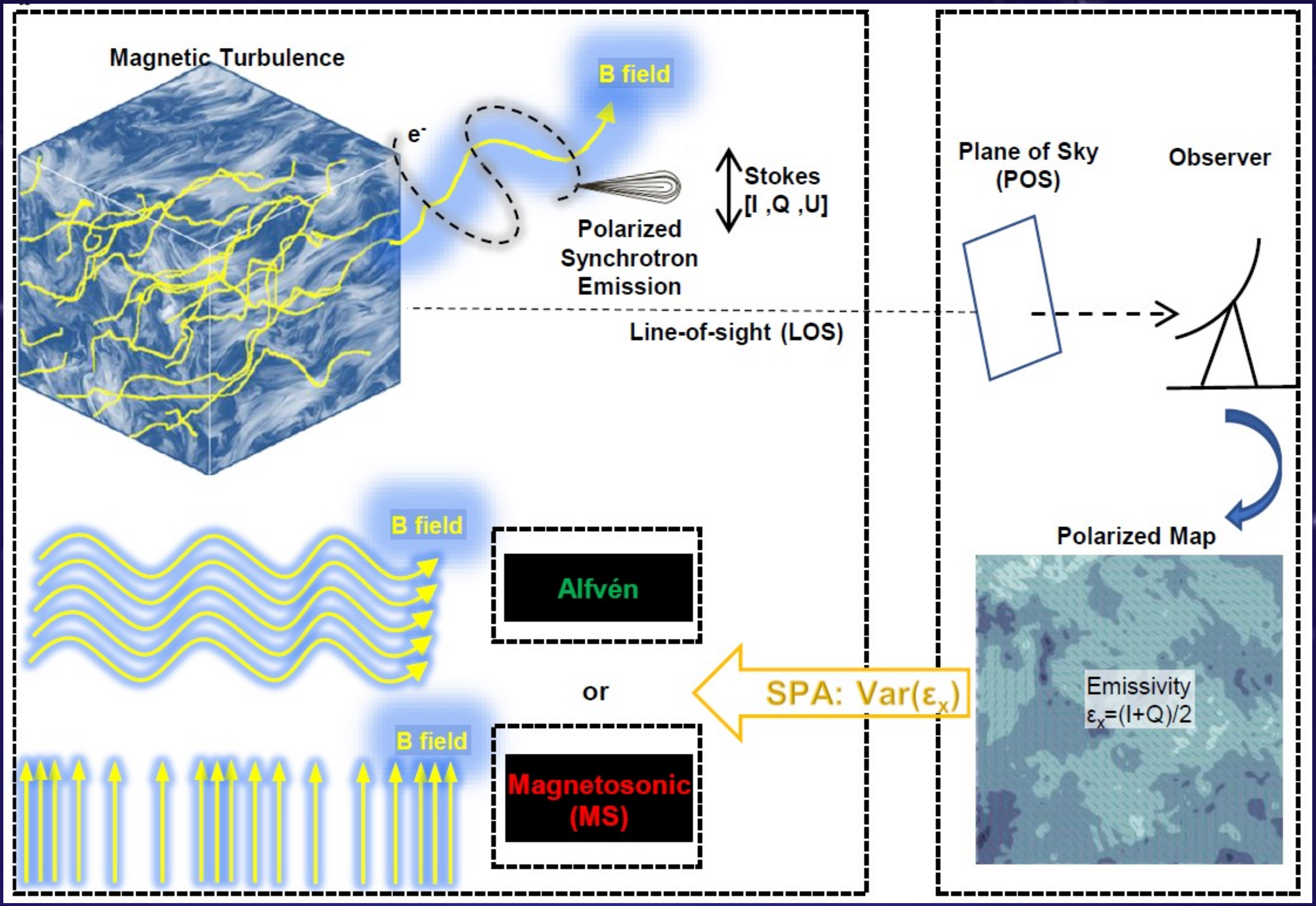


Solenoidal (incompressible) forcing

Compressible forcing

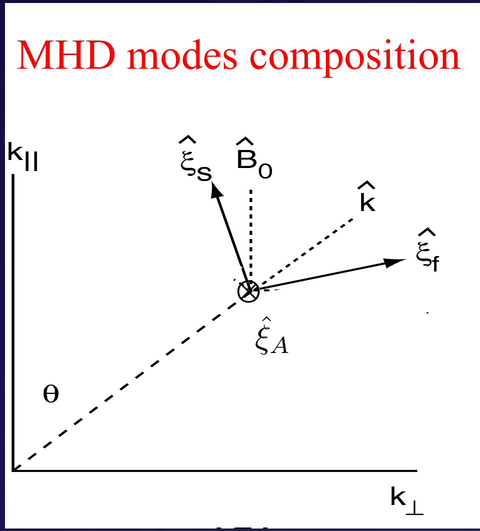
Composition of MHD turbulence depends on driving (Makwana & HY 2020).

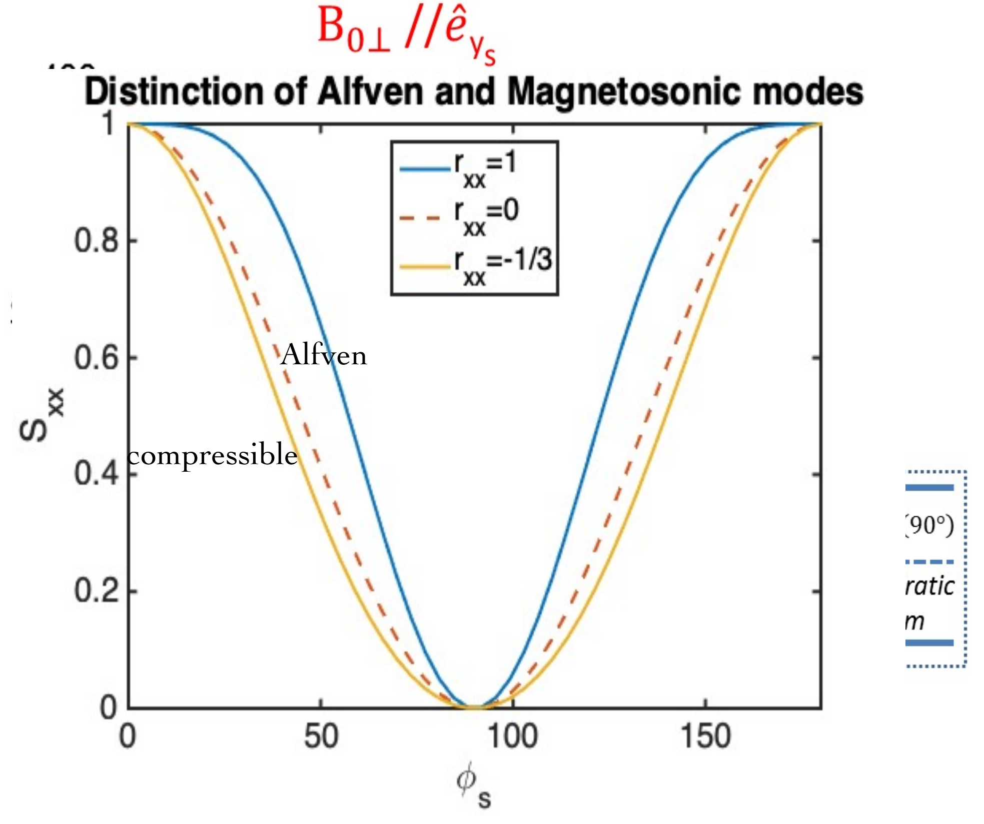
How to observate MHD turbulence?



Mode signature can be observed!

$$S_{xx}(\phi_s) = (a_{xx}\sin^2\phi_s + b_{xx})\cos^2\phi_s,\ r_{xx} \equiv a_{xx}/b_{xx}$$

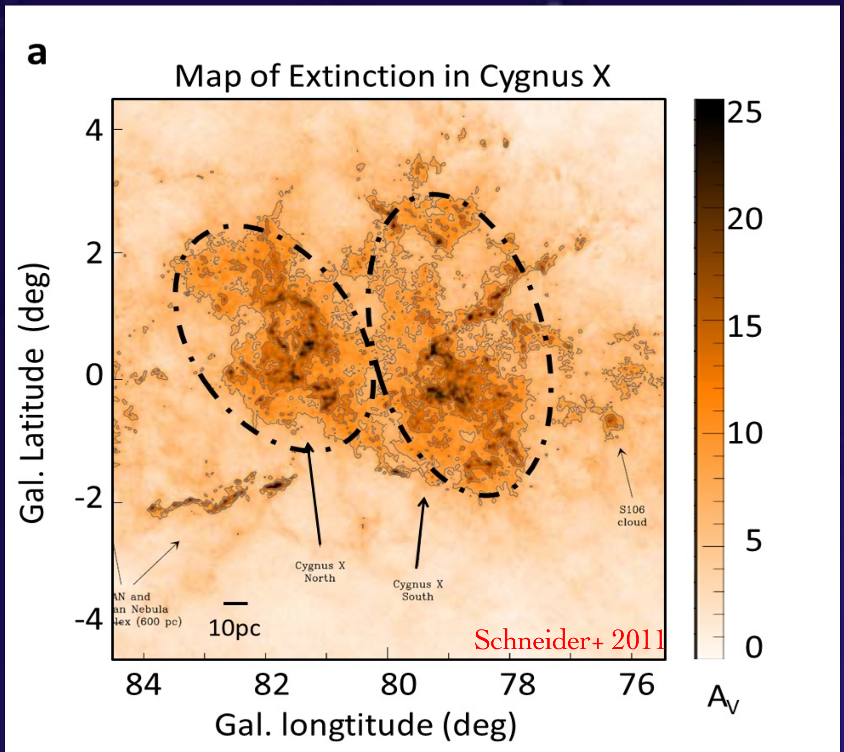


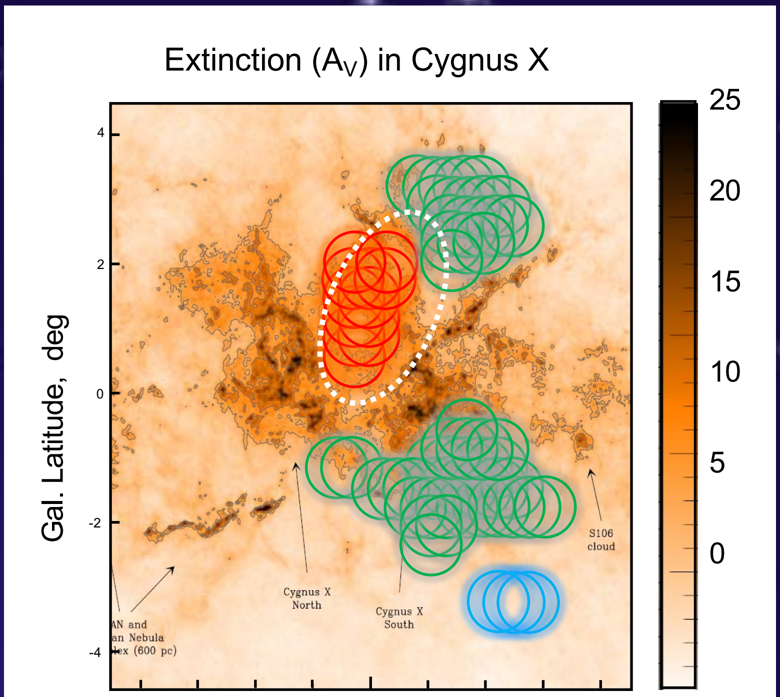


Variance S_{xx} of polarized emissivity I+Q ∝ B_{xs}^2

Synchrotron polarization analysis (SPA) we developed is a new technique to reveal plasma modes (Zhang, Chepurnov & HY+ 2020, *Nat. Astron*).

First detection of plasma modes in ISM!

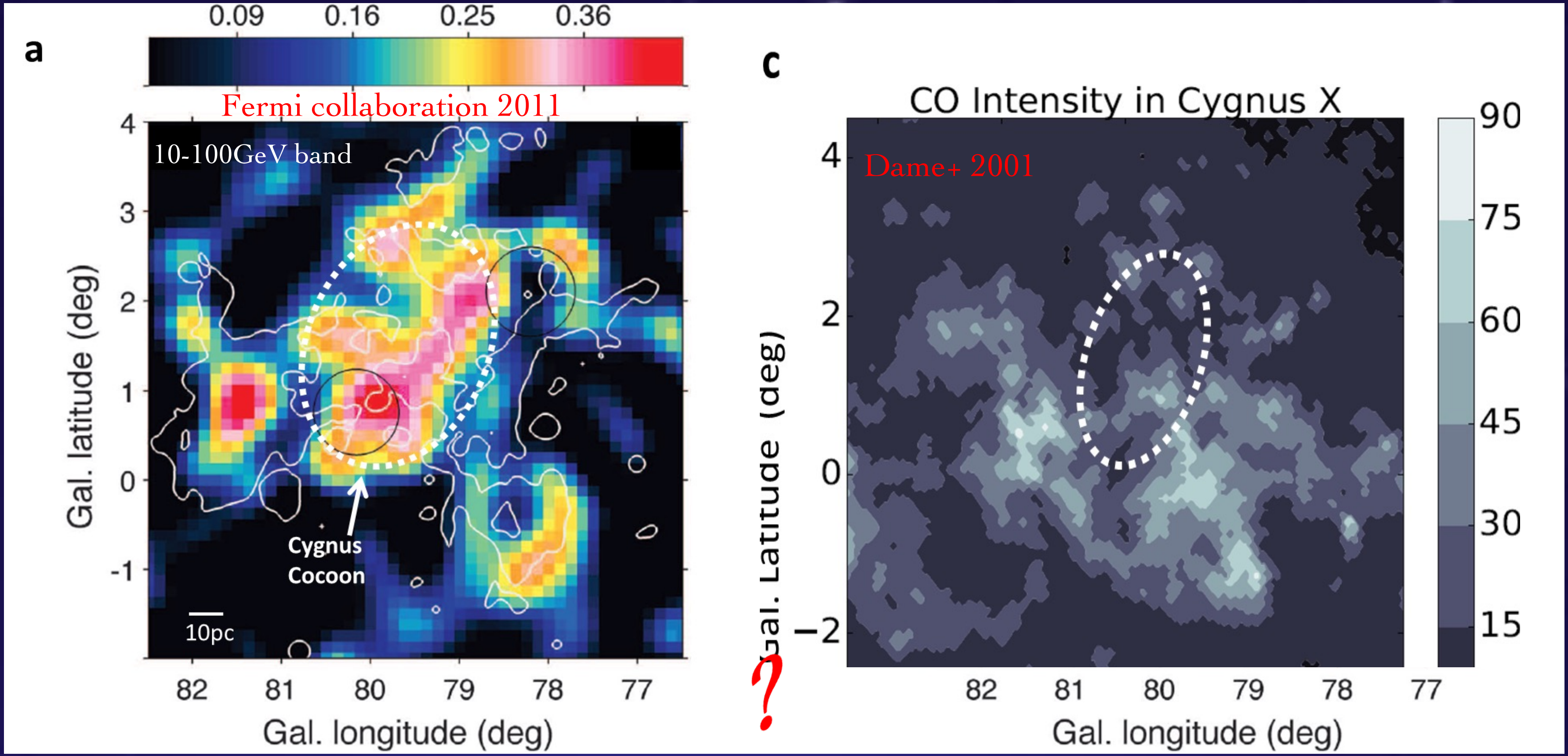




Red spots: Compressible modes dominant, green spots: Alfven modes dominant, Blue: hydrodynamic turbulence

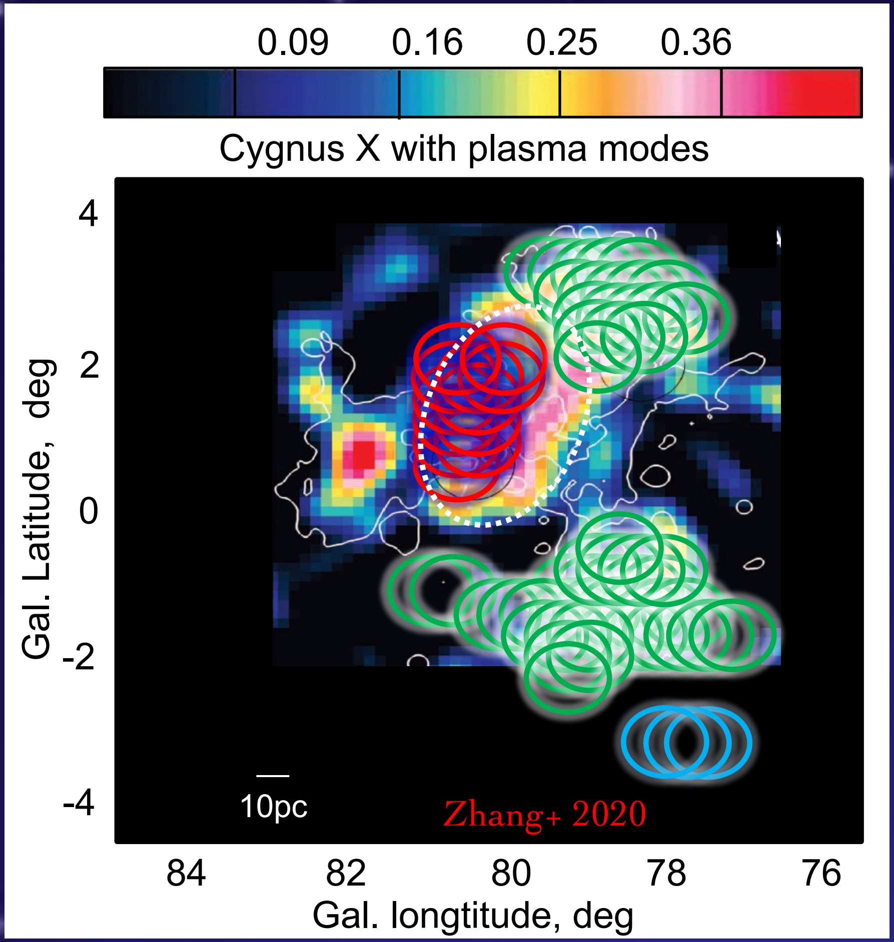
Synchrotron polarization analysis (SPA) reveals prominent plasma modes and driving mechanism. *Compressbile modes* are identified for the 1st time beyond solar system (Zhang+ 2020).

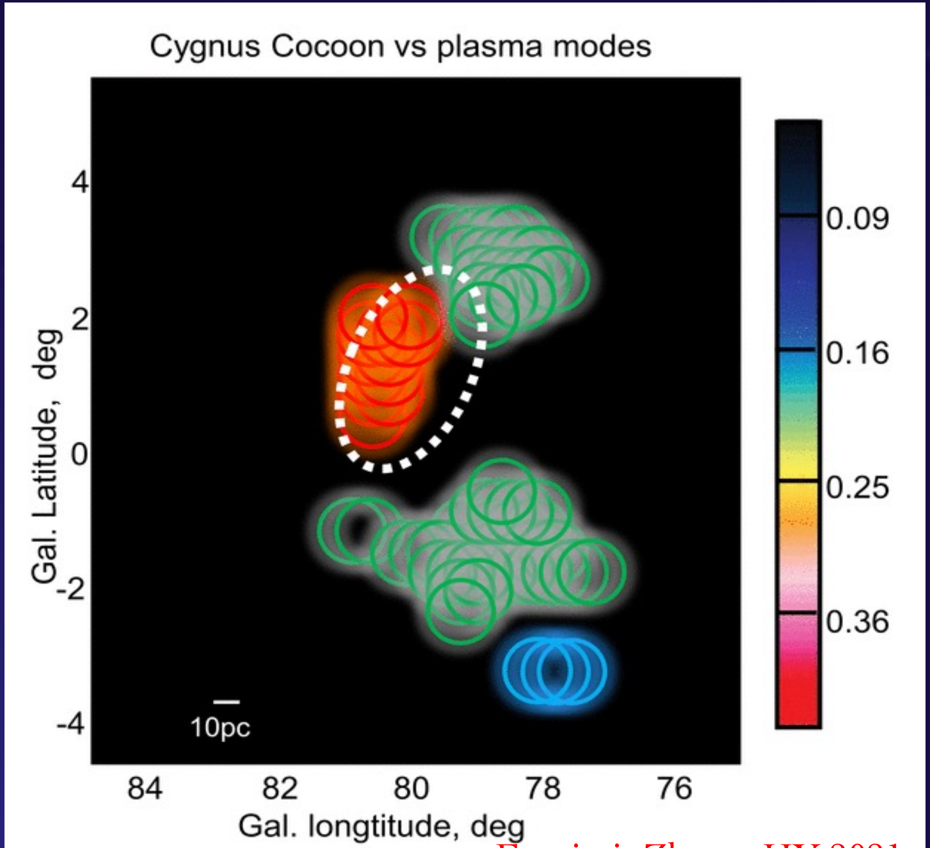
Origin of Cygnus Cocoon?



The gamma ray intensity has no apparent correlation with the density distribution.

Origin of Cygnus cocoon: role of compressible modes revealed

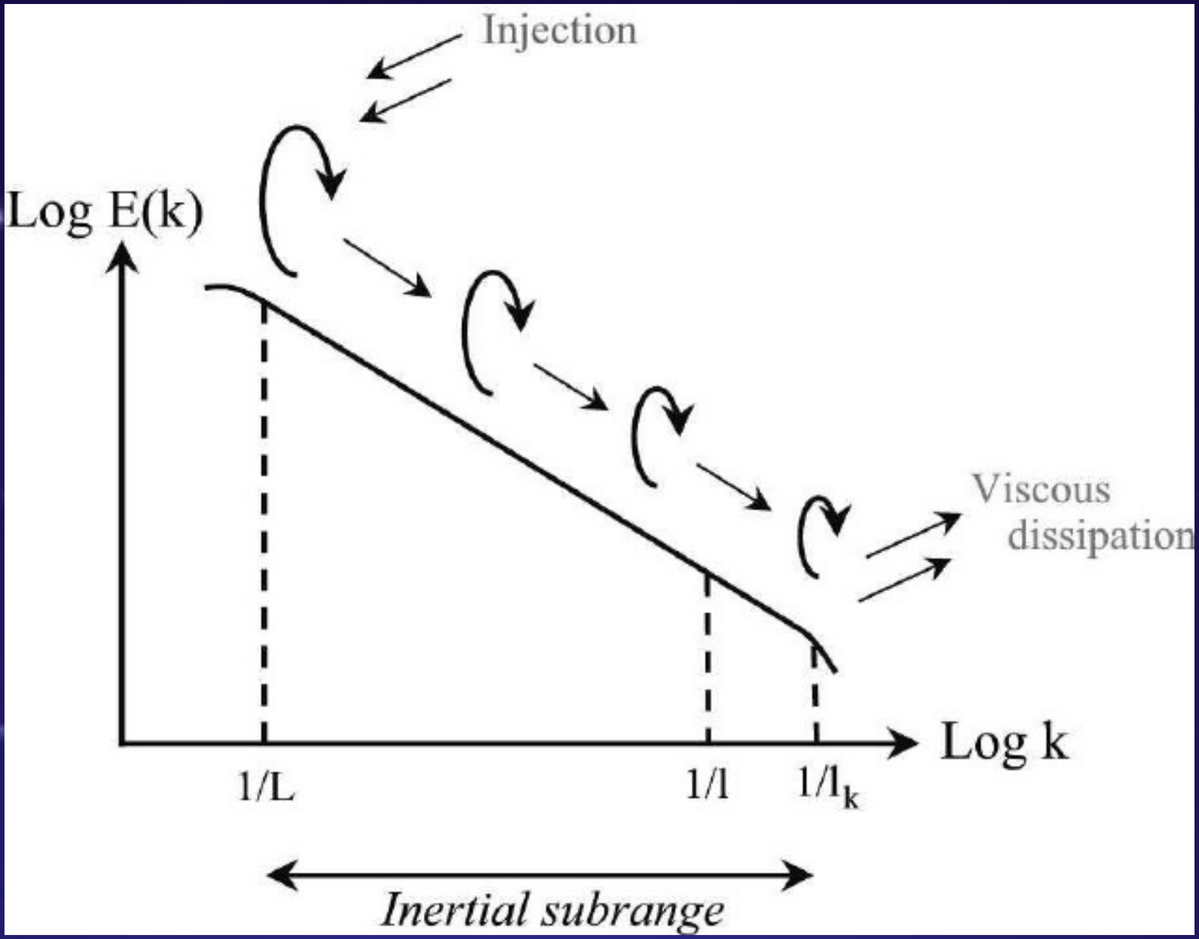




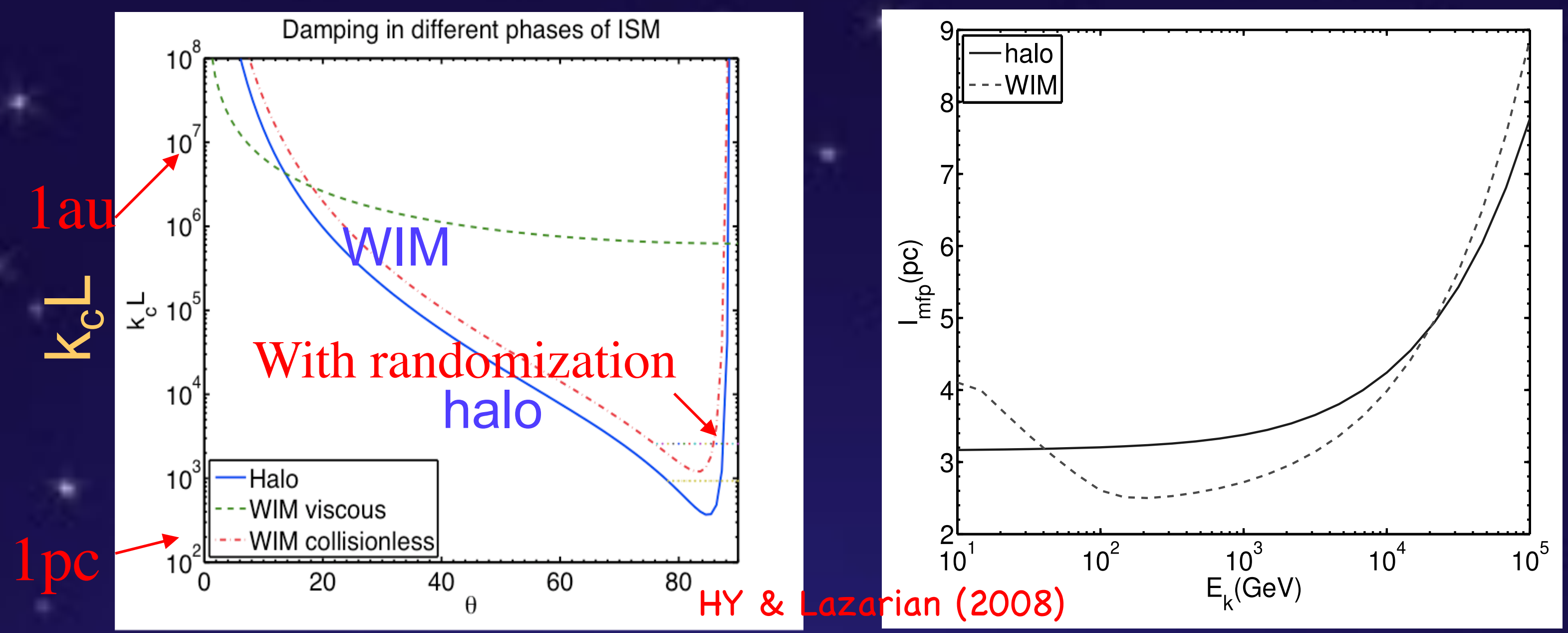
Fornieri, Zhang, HY 2021

The MS modes coincides with the Cygnus cocoon with a high degree consistency, completely in line with the theory.

Turbulence is shaped by Energy injection and damping



CR diffusion varies from place to place!



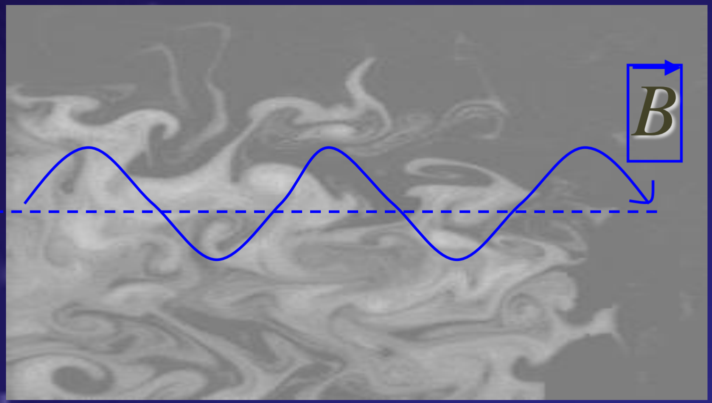
Wave pitch angle

- Damping depends on medium, transport of CRs is *inhomogeneous.*
- Mounting observational evidence for nonuniform propagation of CRs (AMS 2010; Fermi-LAT 2011,2012; PAMELA 2011, etc.): Cosmic ray spectrum; Low energy positron excess; Anisotropic distribution; Diffuse Y ray emission.

Self-confinement operates for CRs ~< a few hundred GeVs in ISM

- Cosmic Rays can be self-confined through streaming instability (reviews by Wentzel 1974, Cesarsky 1980), gyroresonance instability (e.g., HY & Lazarian 2011, Lebiga +2018).

- Growth of instability is limited by dampings even in fully ionized plasma:
  - Nonlinear Landau damping (Kulsrud 1978)
  - Damping by background turbulence (Farmer & Goldreich 2004, HY & Lazarian 2004)



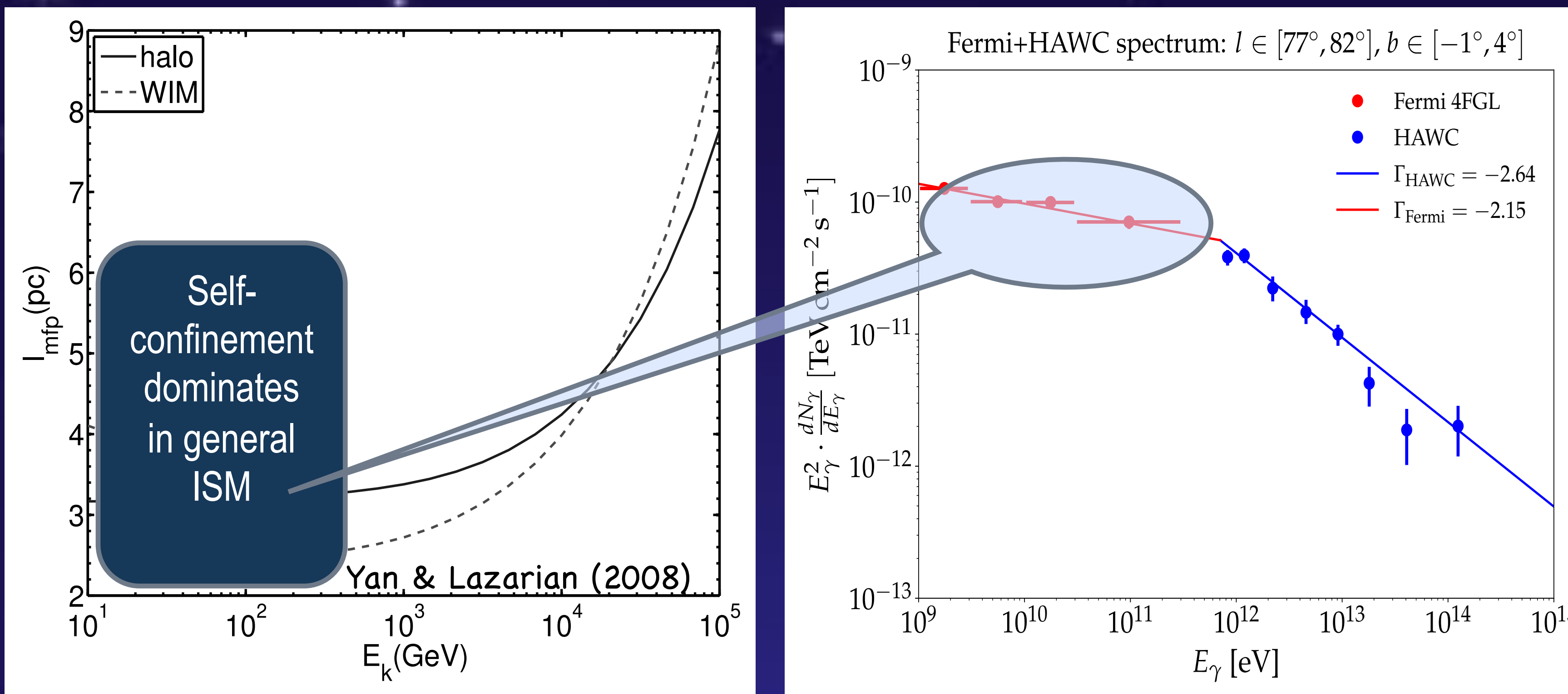
In turbulent medium, wave-turbulence interaction damps waves at a rate:

$$\Gamma = \sqrt{k/L_M} V_M$$

L_M, V_M are the injection scales of strong/GS95 MHD turbulence.

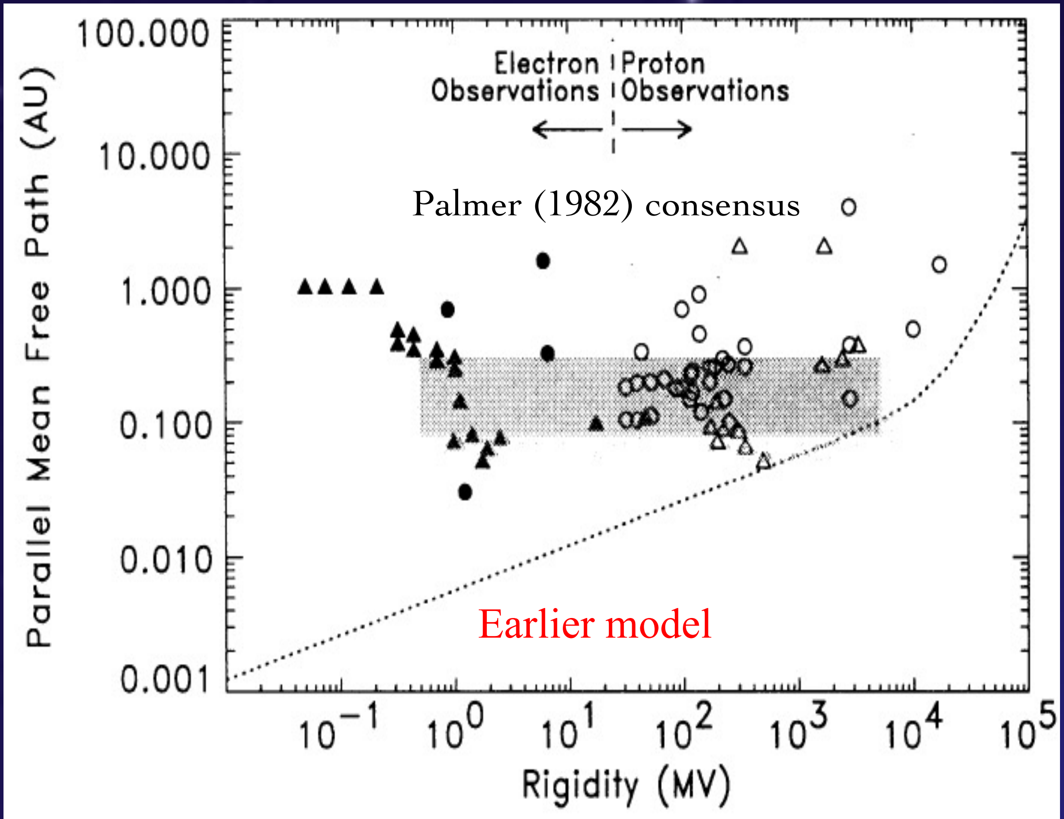
CR diffusion: self-confinement vs. pre-existing turbulence

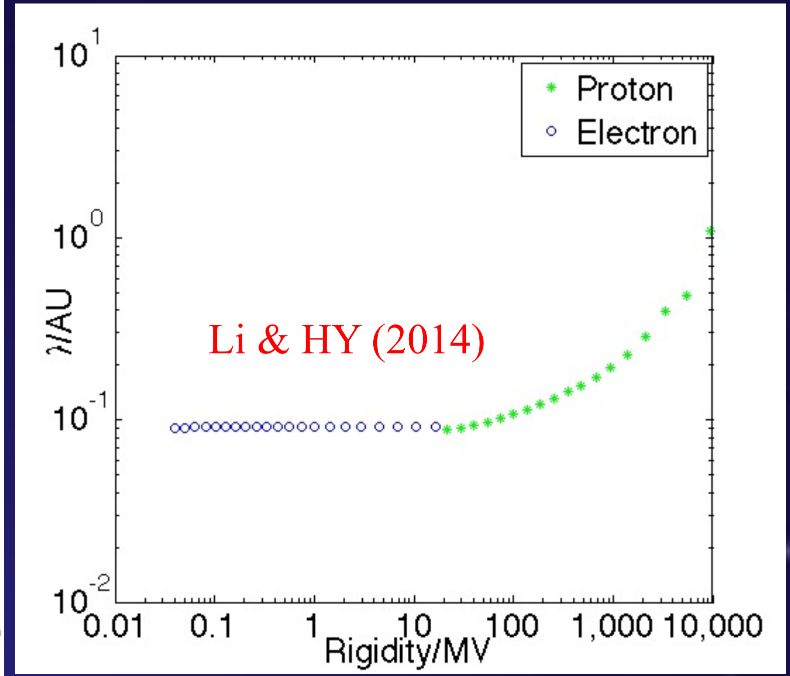
Spectrum of Cygnus X



The flat CR spectrum at Cygnus cocoon observed by Fermi is a signature of confinement by fast modes in ambient turbulence.

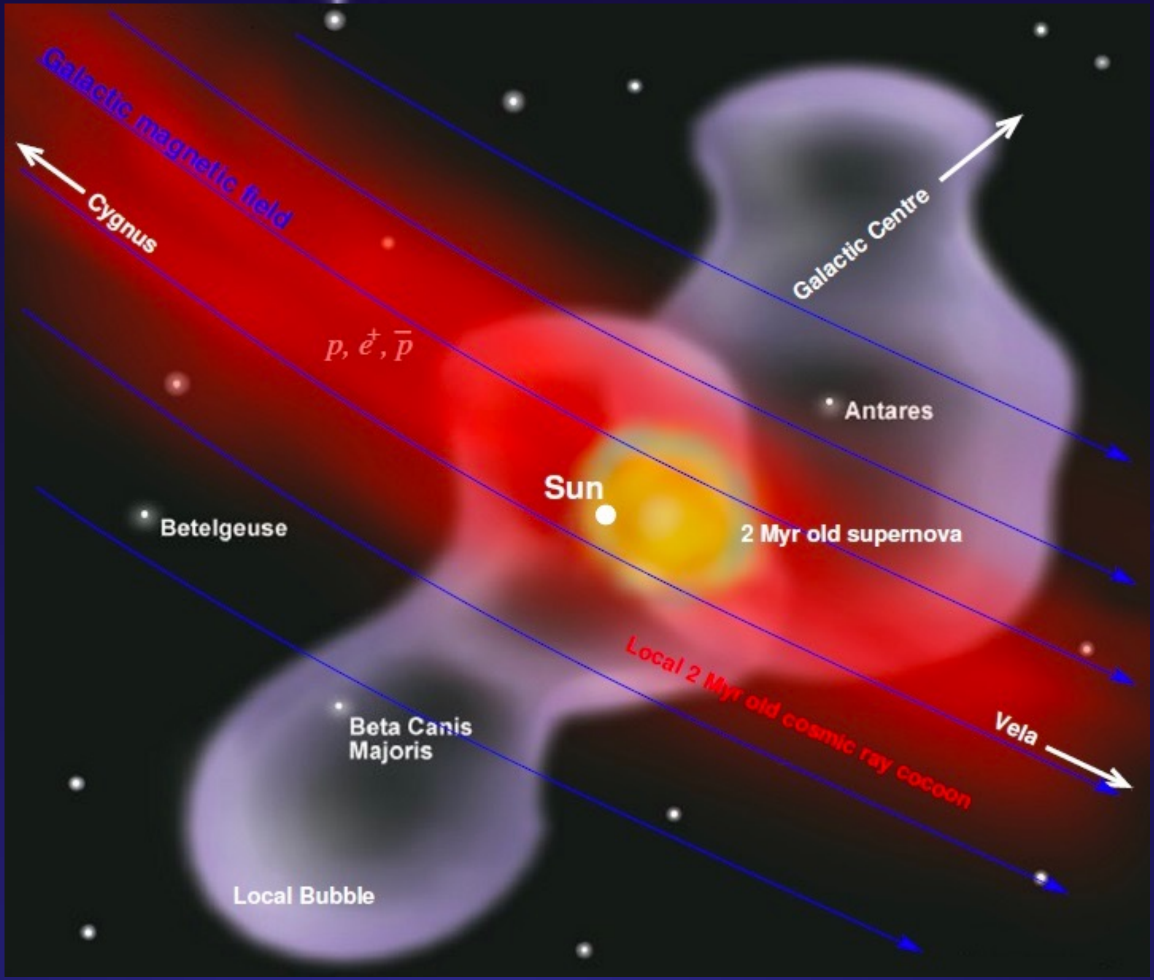
Energy independent diffusion due to collisionless damping





The flat dependence of particle mean free path observed in solar wind is also consistent with confinement by fast modes in collisionless turbulence.

Perpendicular transport is critical for Galactic CRs



Perpendicular transport is governed by turbulence

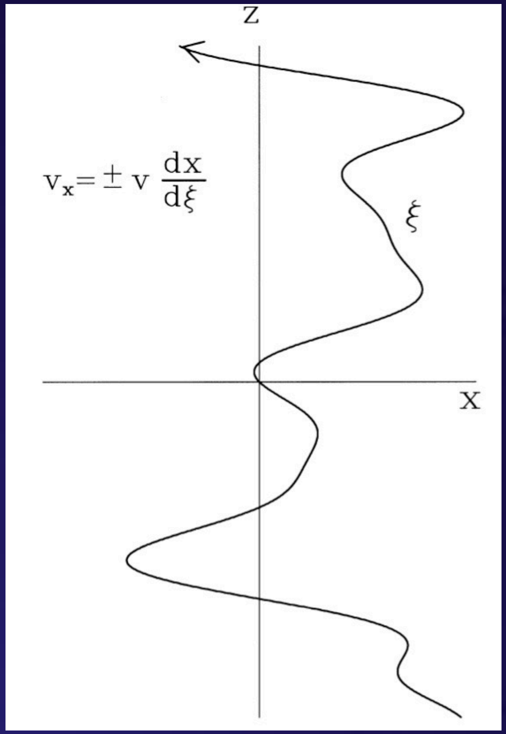
- Dominated by field line wandering.

Extensive studies:

e.g., Jokipii & Parker 1969, Forman 74, Urch 77, Bieber & Matthaeus 97, Giacolone & Jokipii 99, Matthaeus et al 03, Shalchi et al. 04

Is there subdiffusion ($\Delta x \propto t^{\alpha}$, $\alpha < 0.5$) ?

- Subdiffusion (or compound diffusion, Getmantsev 62, Lingenfelter et al 71, Fisk et al. 73, Webb et al 06) was observed in near-slab turbulence, which can occur on small scales due to instability.



$$\Delta x^2 \propto \Delta z$$

$$\Delta z^2 \propto D_{\|} \Delta t$$

$$\Delta x^2 \propto \sqrt{\Delta t}$$

What would happen then in 3D turbulence?

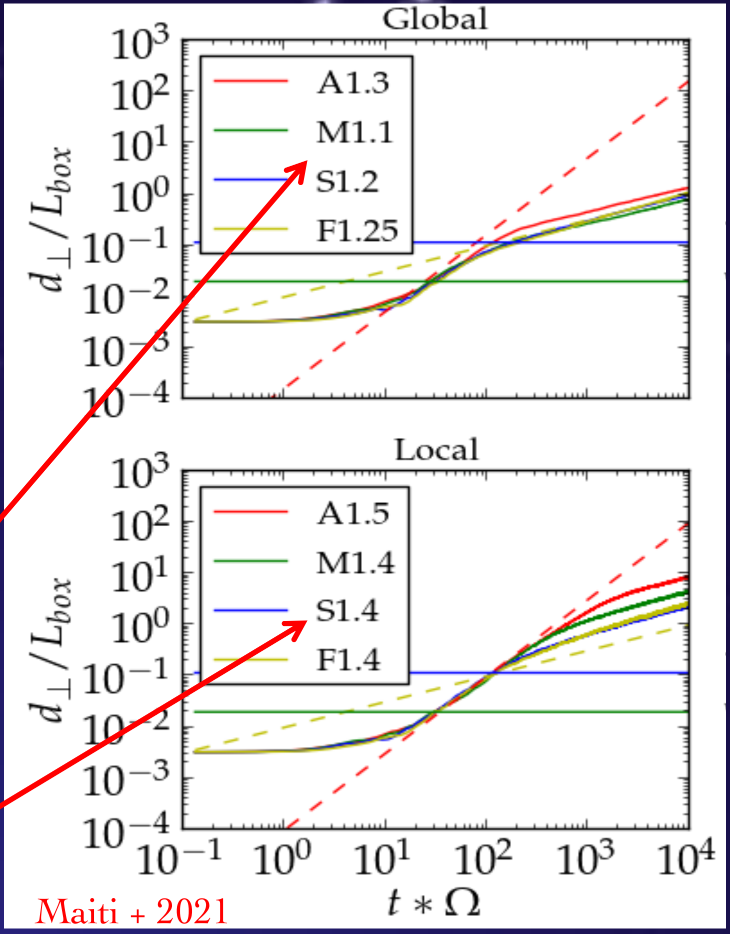
Subdiffusion is not typical!

- In turbulence, trajectories of particles become independent when field lines are separated by the smallest eddy size, $l_{\perp,min}$.

- Subdiffusion only occurs below $l_{\perp,min}$. Beyond $l_{\perp,min}$, normal diffusion applies (HY & Lazarian 2008).

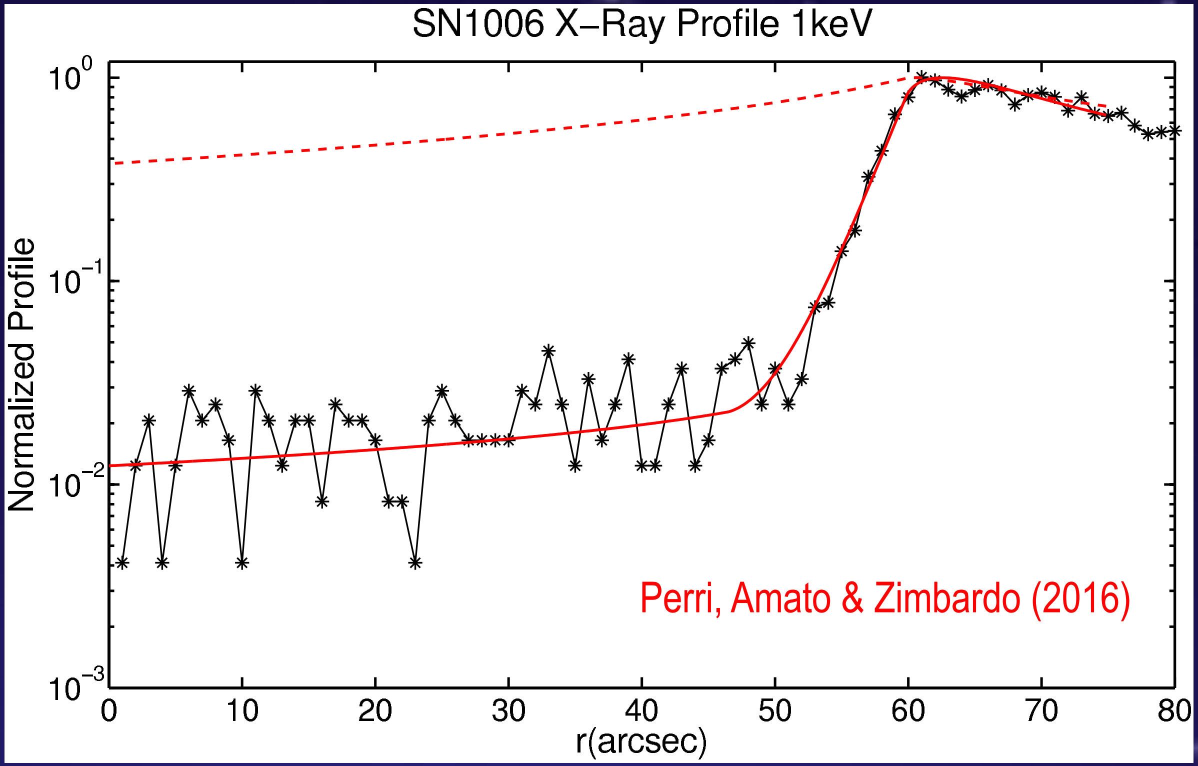
Superdiffusion in inertial range due to Richardson/Kolmogorov Law of turbulence

$$\langle |\mathbf{x}_1(t) - \mathbf{x}_2(t)|^2 \rangle \sim t^3.$$



Richardson diffusion of particles $\Delta x \propto t^{\alpha}$ (α=1.5, Lazarian & HY 2014) is well recovered in the Alfvenic data cube with local reference frame. Observed index α changes with modes composition of turbulence.

Superdiffusion has been observed



Radial profile of the emission at about 1 keV for the SN1006 remnant. The thick red line corresponds to the model integrated along the line of sight for synchrotron-loss-dominated transport downstream, diffusive transport close upstream, and superdiffusive transport far upstream (in the flatter tail of the profile).

Dependence of CRs' $D_\perp$ on $M_A \equiv \delta B/B$

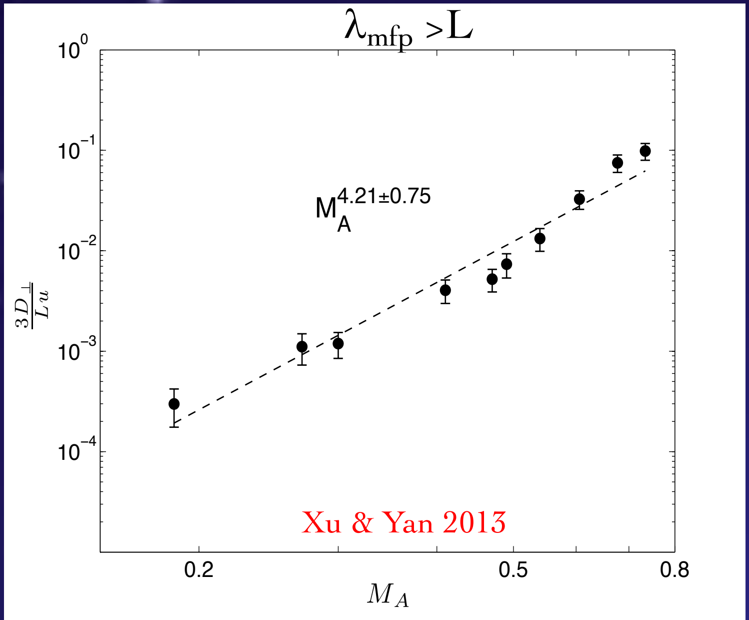
- $\lambda_{||} > L$, UHECRs or CRs in clouds free stream over distance L, and

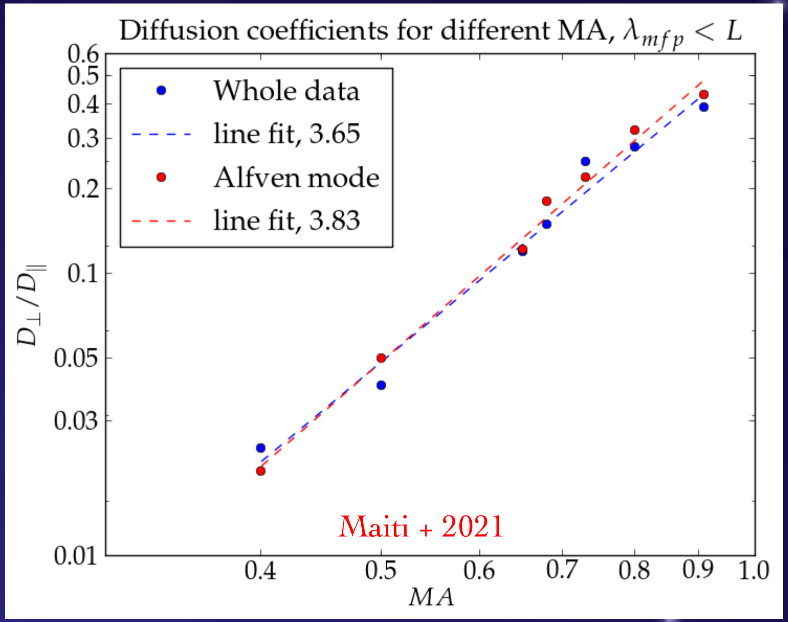
  $D_\perp = 1/3 Lv\, M_A^4$

(HY & Lazarian 2008)

- $\lambda_{||} < L$, most Galactic CRs

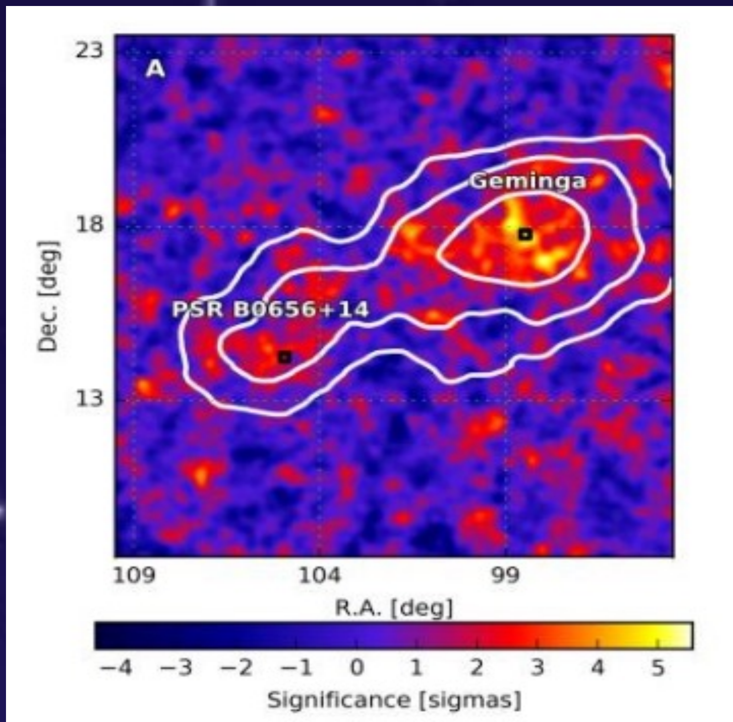
  $D_\perp / D_{||} \propto M_A^4$

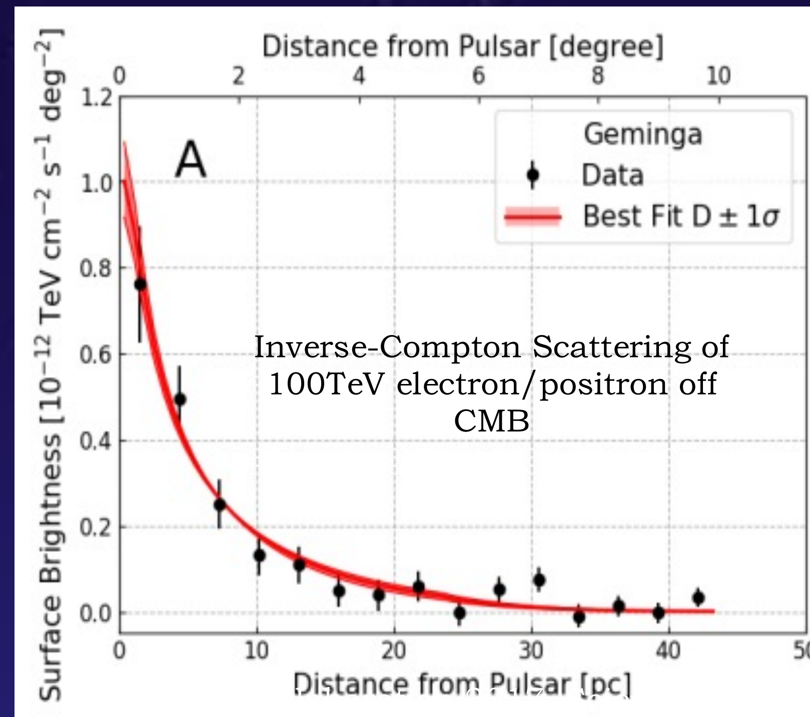




Cross field transport in 3D turbulence has M_A^4 dependence.

Puzzling observation of Geminga





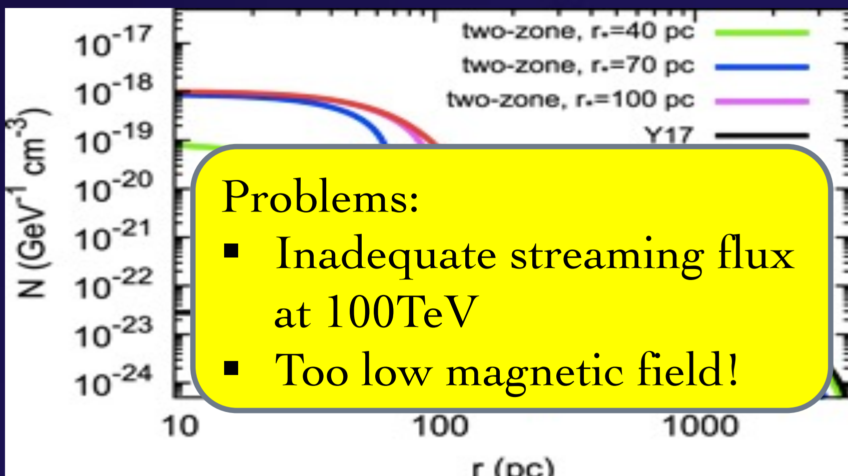
HAWC observation in 8-40TeV (Abeysekara+2017)

D_{100} (Diffusion coefficient of 100TeV electrons from joint fit of two PWNe)	[x10^{27} cm^2/sec]	4.5 ± 1.2

Observation indicates a diffusion coefficient 2 orders of magnitude smaller than the typical ISM value!

Study of CR diffusion is limited by observational info of turbulence

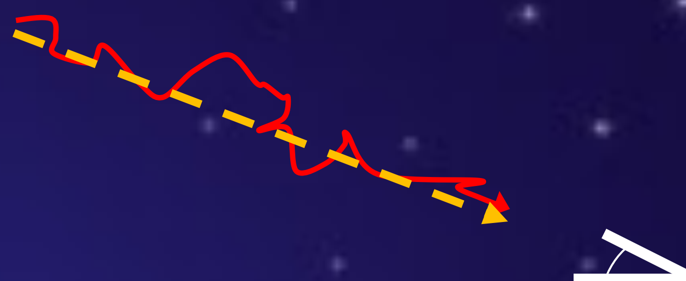
Two zone diffusion vs. Anisotropic diffusion



Problems:

- Inadequate streaming flux at 100TeV
- Too low magnetic field!

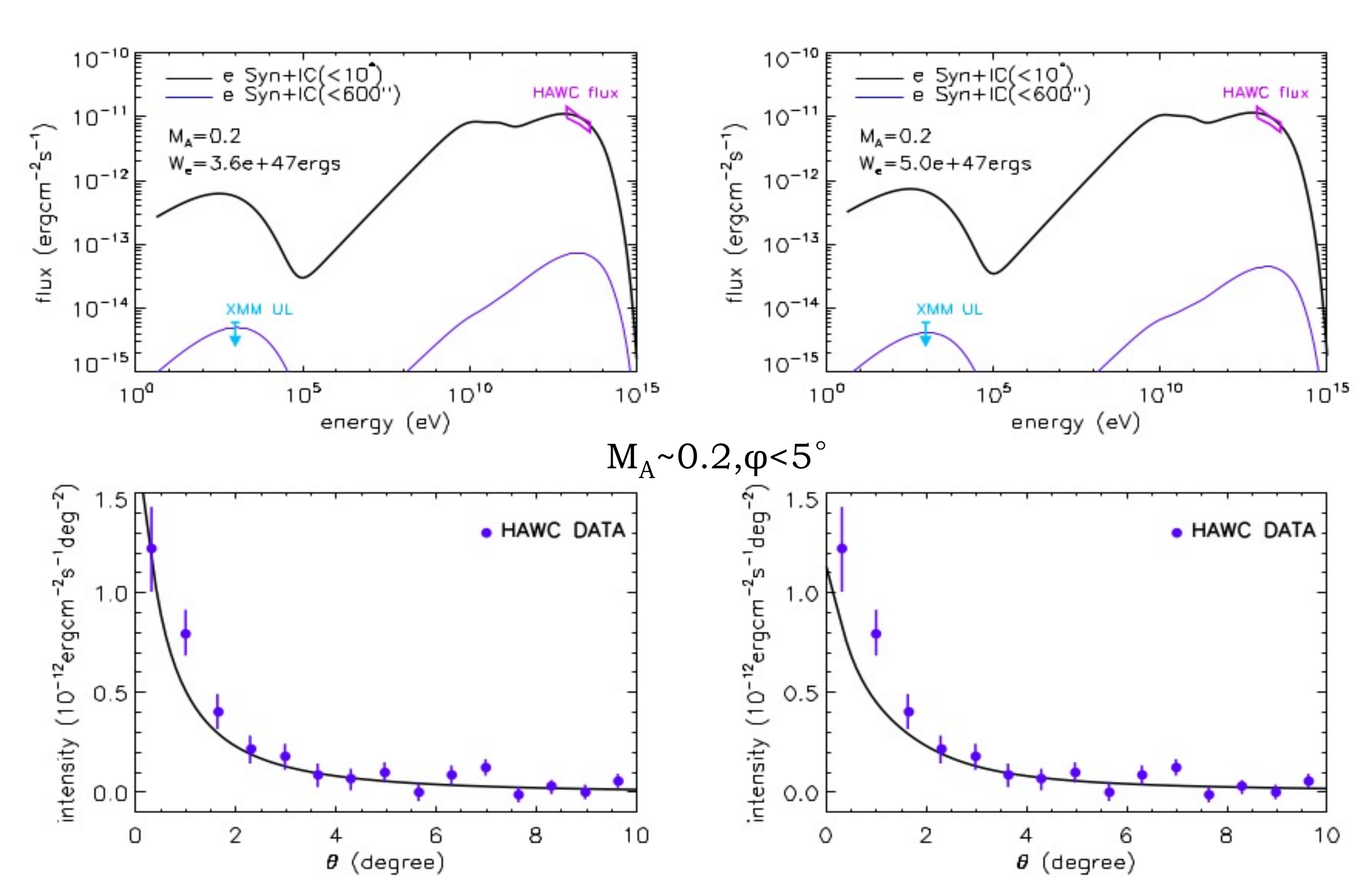
Abeysekera+2017



Observed D is actually $D_{\perp}$

Liu, HY, Zhang 2019, *PRL*

Comparison w. Geminga observations



Both the suppressed diffusion as observed by HAWC and the missing X ray emission can be well explained by sub-Alvenic turbulence with mean field close to LOS (Liu+ 2019).

Summary

- Galactic turbulence has 3D structure and profile. 1D approximation does NOT apply.

- Compressible fast modes have **isotropic cascade and dominate** CR transport through direct scattering. Near sources, and for GCRs < a few hundred GeV, plasma instabilities are more important.

- Multi-waveband study holds the key to CR research. In Cygnus X, the **γ-ray cocoon largely coincides with the Compressible modes** dominant zone, as identified with our new Synchrotron Polarization Analysis (SPA) technique.

- The efficiency and energy dependence of CR scattering depends on local turbulence properties dictated by turbulence **driving and damping**/medium parameters. CR transport is inhomogeneous, therefore.

- CR perpendicular transport is diffusive in large scale turbulence (w. $\mathbf{D_{\perp} / D_{||} \propto M_A^4}$) and superdiffusive on small scales.

CR research is synergetic with study of turbulence!