Cosmic Ray transport and acceleration in turbulent magnetic field

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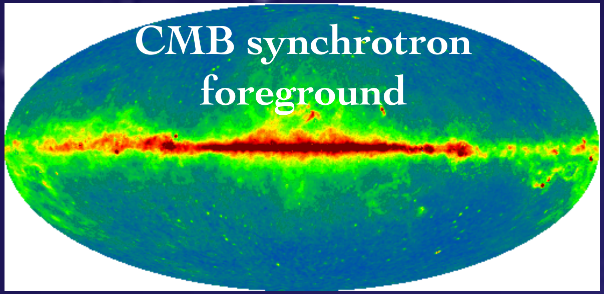
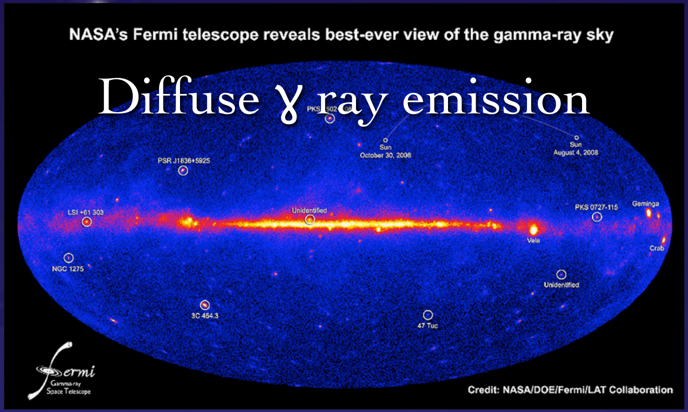
thanks to: A. Lazarian (UW-Madison)

Importance

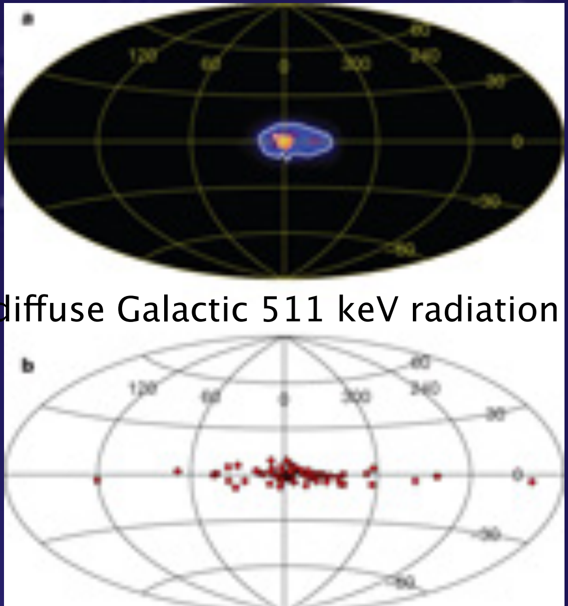
Propagation:


CMB synchrotron foreground


NASA's Fermi telescope reveals best-ever view of the gamma-ray sky

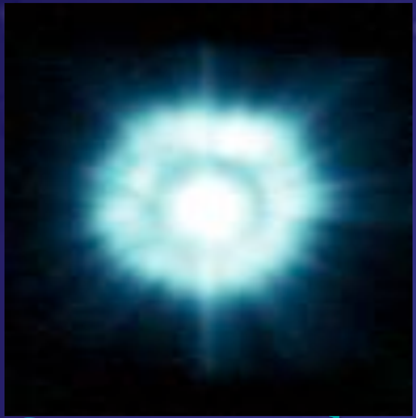
Diffuse γ ray emission

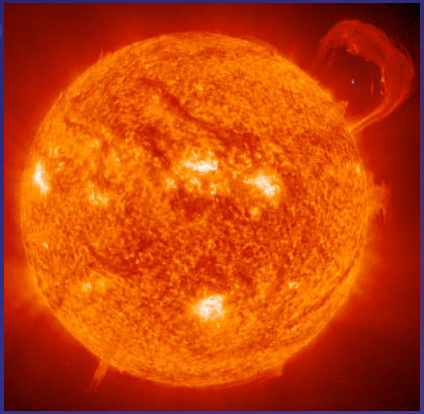
Credit: NASA/DOE/Fermi/LAT Collaboration

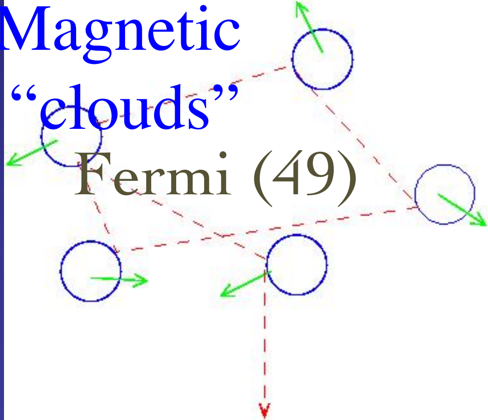


diffuse Galactic 511 keV radiation

Acceleration:


Gamma ray burst


Solar Flare


Magnetic "clouds"

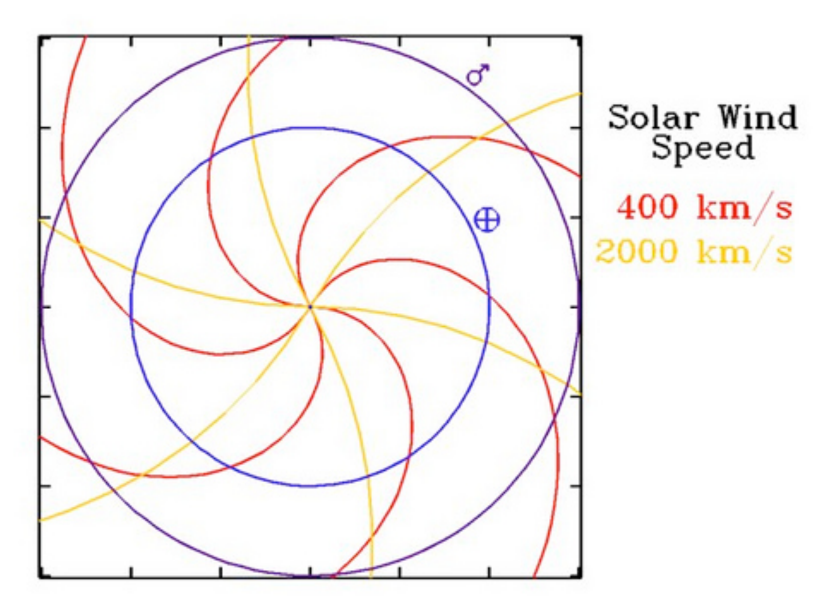
Fermi (49)

Stochastic Acceleration:

Problems of CR research

- Perpendicular CR transport
- Turbulence models
- Inadequate description of the interactions between MHD perturbations and particles.

CROSS FIELD TRANSPORT



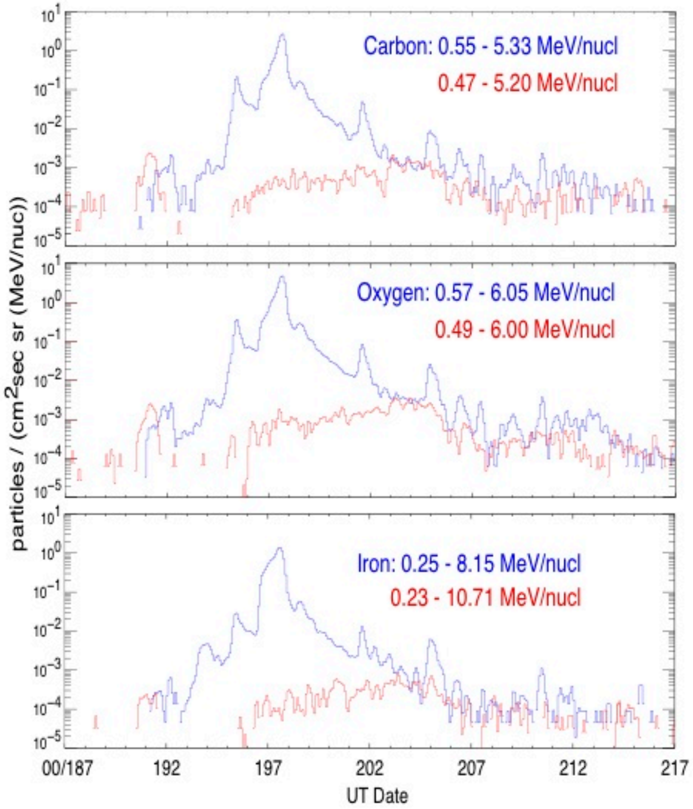
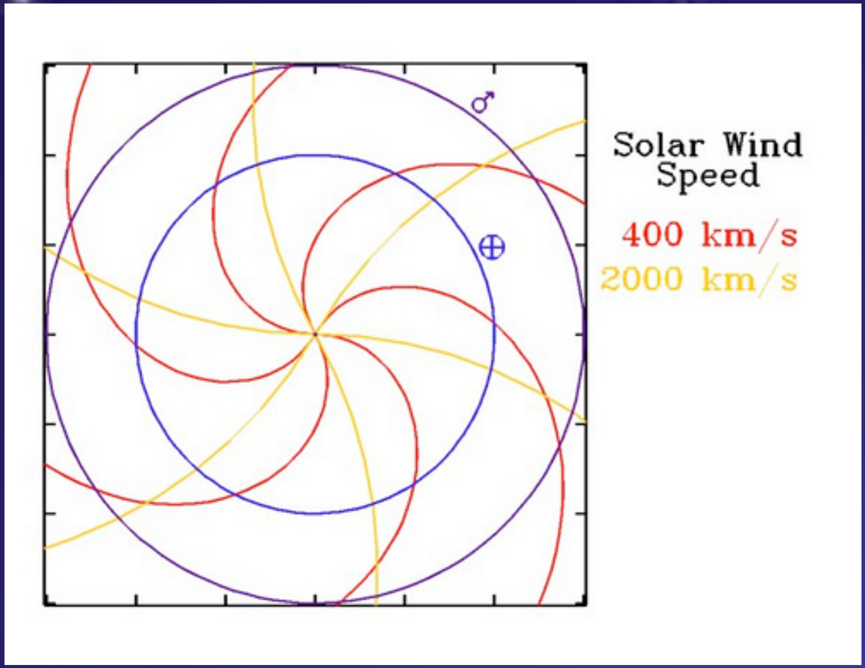
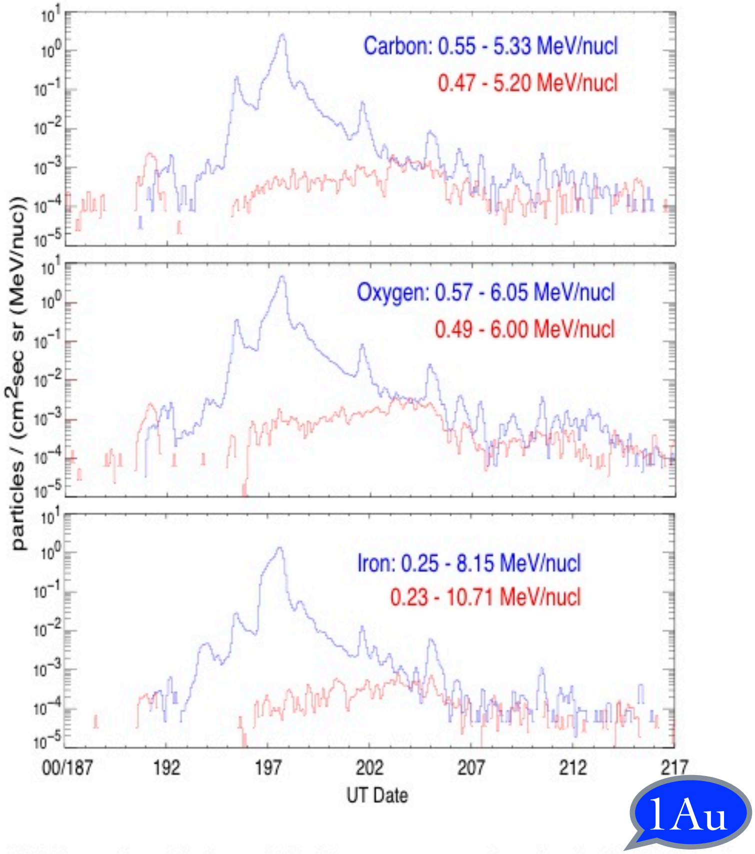


Fig. 2. Heavy ion C, O, and Fe fluxes measured on both ACE (blue) and Ulysses (red) in the July 2000 event.

from Maclennan et al. (2001)

CROSS FIELD TRANSPORT





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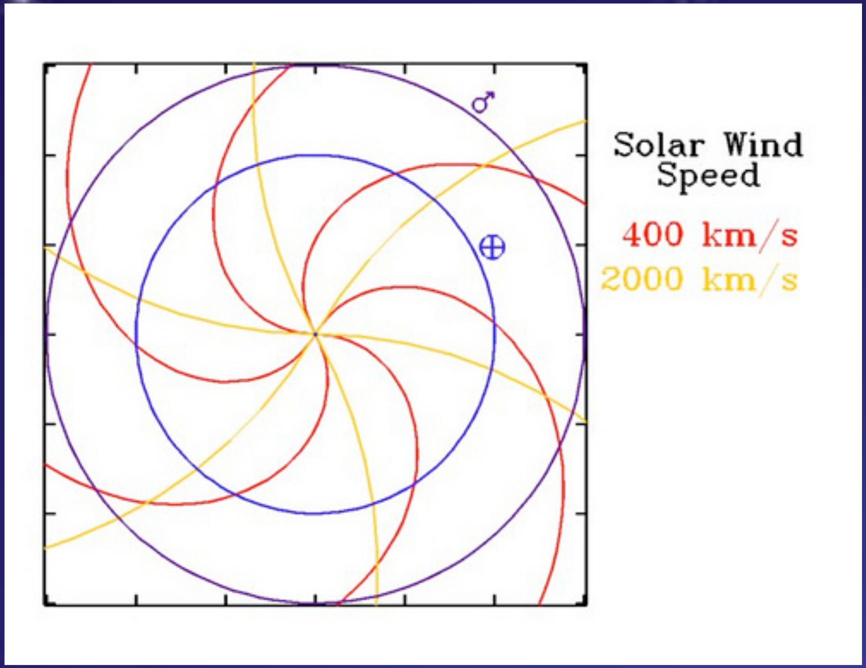
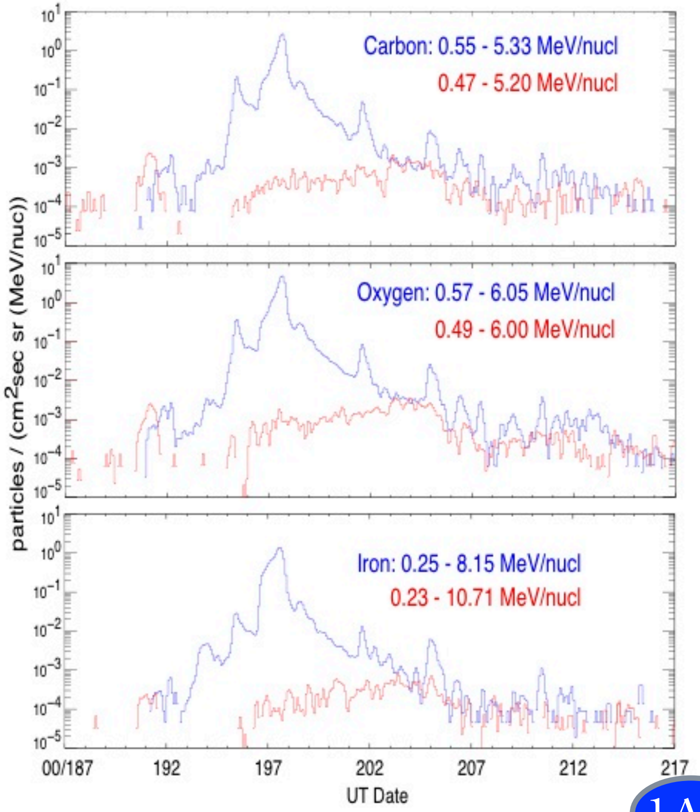




1Au

Fig. 2. Heavy ion C, O, and Fe fluxes measured on both ACE (blue) and Ulysses (red) in the July 2000 event.

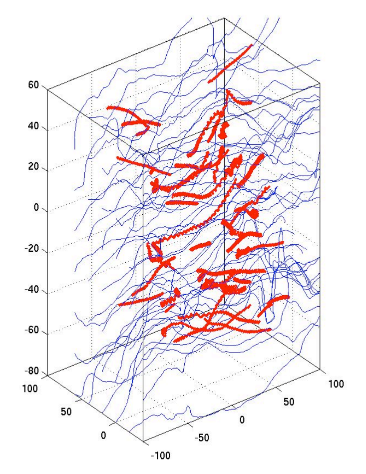
from Maclennan et al. (2001)

3.2Au

Cross field transport

- Dominated by field line wandering.

B_0



Test particle simulations with realistic turbulence

🟥 Particle trajectory

🟦 Magnetic field

Intensive studies:

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

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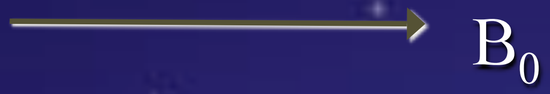

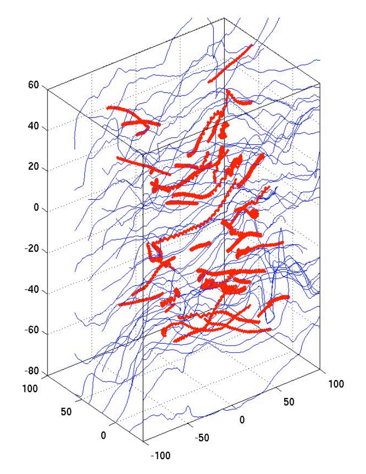

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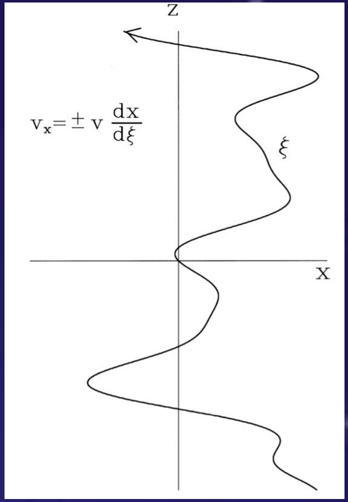
What if we use the tested model of turbulence?

Is there subdiffusion ($\Delta x^2 \propto \Delta t^a$, $a<1$) ?

- 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.



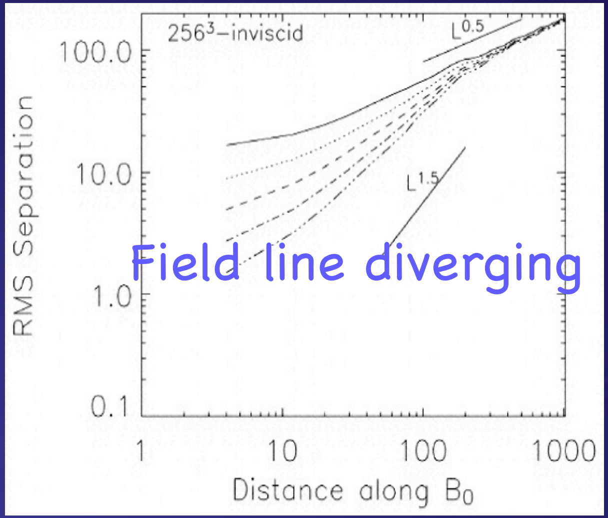
- What about large scale turbulence?

Example: diffusion of a dye on a rope

a) A rope allowing retracing, $\Delta t = l_{rope}^2 / D$

b) A rope limiting retracing within pieces l_{rope} / n, $\Delta t = l_{rope}^2 / nD$

Diffusion is slow only if particles retrace their trajectories.



Field line diverging

Subdiffusion is not typical!

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

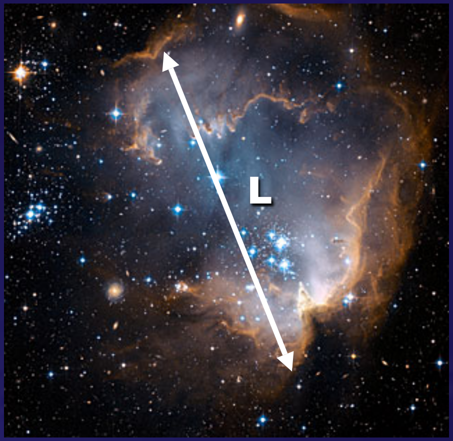
The separation between field lines for $r_0 < l_{\perp,min}$ has a Lyapunov type growth, provides Rechester-Rosembluth distance, $L_{RR} = l_{||,min} \log(l_{\perp,min} / r_L)$ (Chandran & Cowley 1998, Narayan & Medvedev 01, Lazarian 06)

- Subdiffusion only occurs below $l_{\perp,min}$.

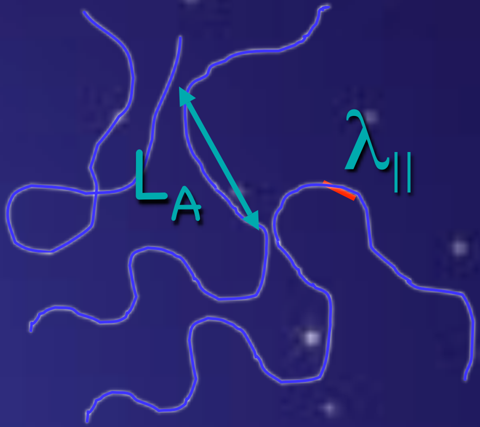
Beyond $l_{\perp,min}$, normal diffusion applies for large scale perpendicular transport (Yan & Lazarian 2008).

Perpendicular diffusion ($\lambda_{||} < L$)

- $M_A < 1$, on large scale CRs need to diffuse L in order to cover a distance LM_A^2 in ⊥ direction, thus $\Delta t = (R/LM_A^2)^2 L^2/D_{||} \Rightarrow D_\perp = R^2/\Delta t = D_{||} M_A^4$



- $M_A > 1$, $D_\perp = D_{||}$, the stiffness of B field is negligible for $\lambda_{||} << L_A$



Perpendicular diffusion depends on $M_A \equiv \delta B/B_0$.

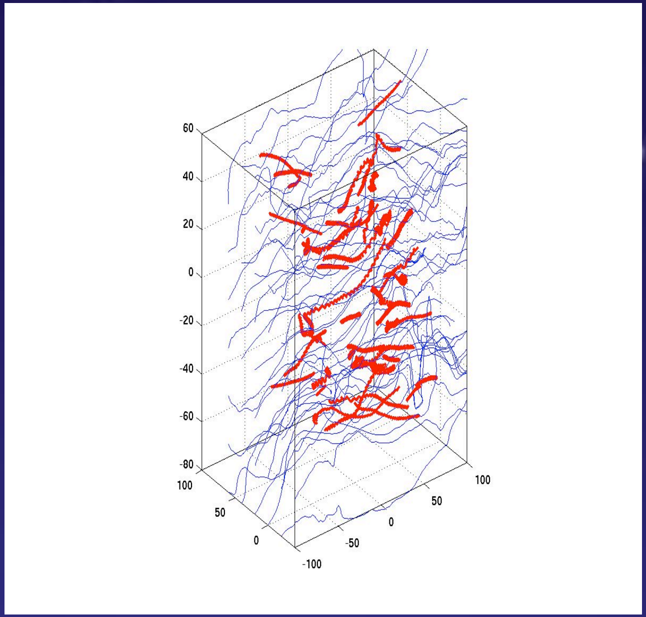
Yan & Lazarian (2008), numerically tested by Beresnyak, Yan & Lazarian (2011)

Perpendicular transport ($\lambda_{||} > L$)

- $\lambda_{||} > L$, CR diffusion is controlled by field line wandering
- $M_A < 1$, CRs free stream over distance L, thus $\Delta t = (R/L\, M_A^2)^2\, L/v_{||}$, $D_\perp = R^2/\Delta t = 1/3 L v\, M_A^4$ (differs from the FLRW result, cf. Jokipii 1966)
- $M_A > 1$, $D_\perp = D_{||} = 1/3 L_A\, v$

Whether and to what degree ⊥ diffusion is suppressed depends on M_A.

Comparison w. test particle simulation



– Particle trajectory

— Magnetic field

- a realistic fluctuatating **B** fields from numerical simulations

NORMAL DIFFUSION IS CONFIRMED IN SIMULATIONS!

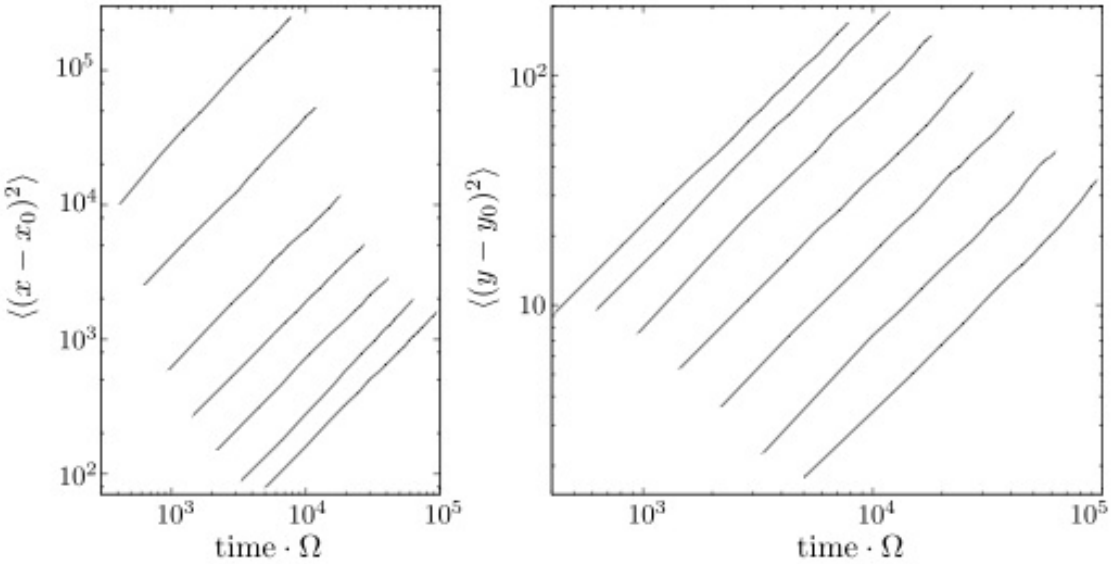
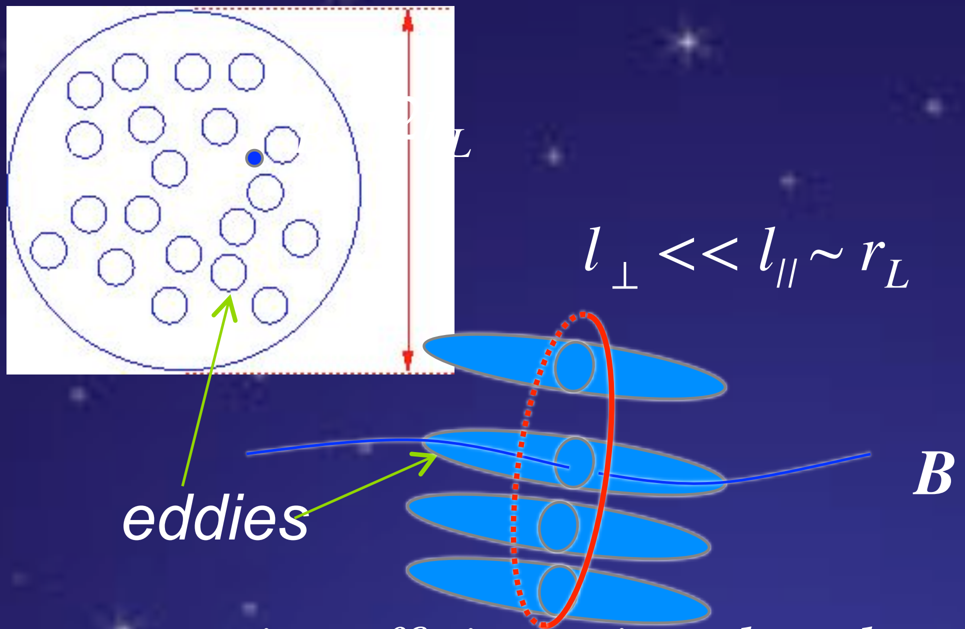


Figure 2. Diffusive behavior of the particles in the tracing simulations. For different r_L we show ensemble-averaged square deviations, which are proportional to time. x and y are measured in units of the cube size.

Beresnyak, Yan, Lazarian (2011)

Contrary to common belief: Scattering in Alfvenic turbulence is negligible!

1. "random walk"



$l_\perp << l_{||} \sim r_L$

scattering efficiency is reduced

2. "steep spectrum"

$$E(k_\perp) \sim k_\perp^{-5/3},\ k_\perp \sim L^{1/3} k_{||}^{3/2}$$

→ $$E(k_{||}) \sim k_{||}^{-2}$$

steeper than Kolmogorov!

Less energy on resonant scale

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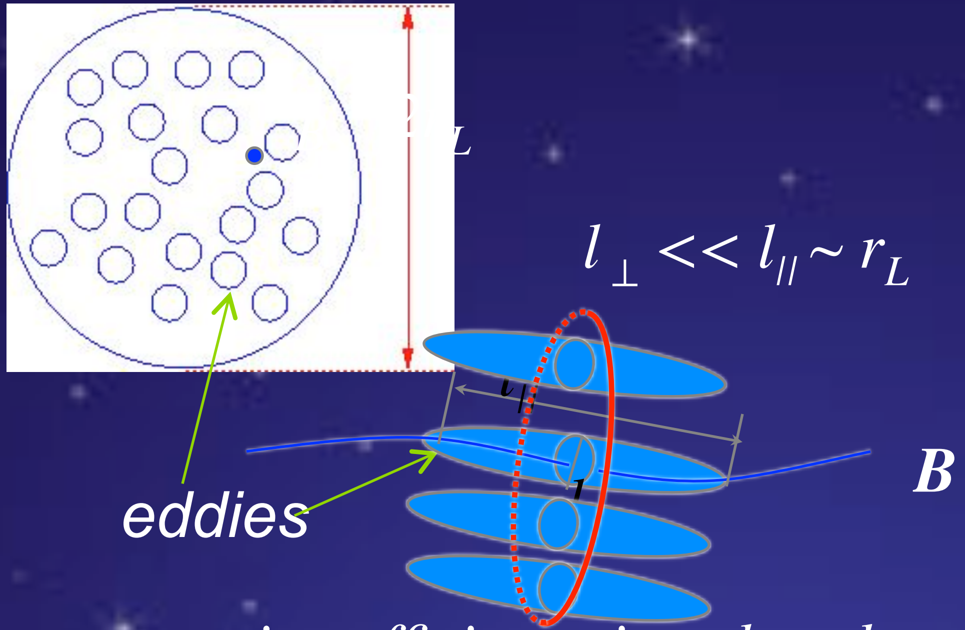

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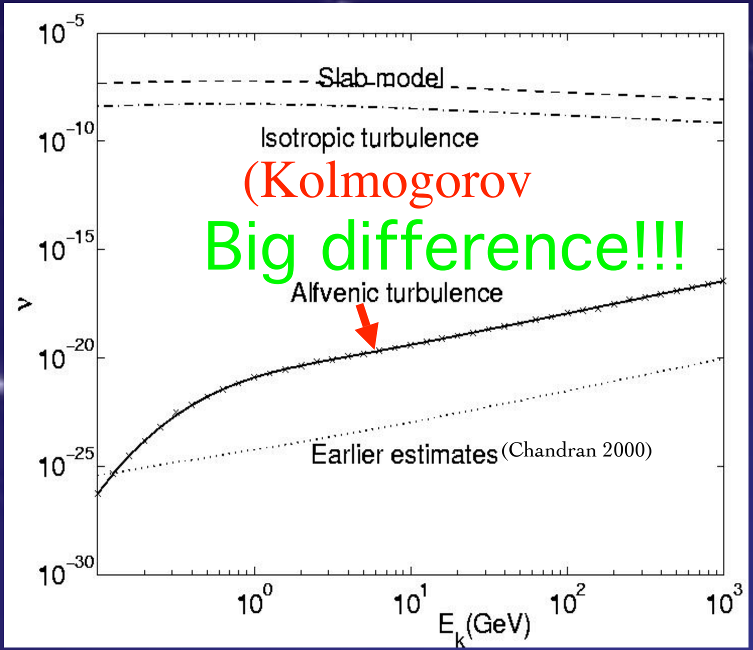
FAST MODES DOMINATE COSMIC RAY SCATTERING!

Alfven modes

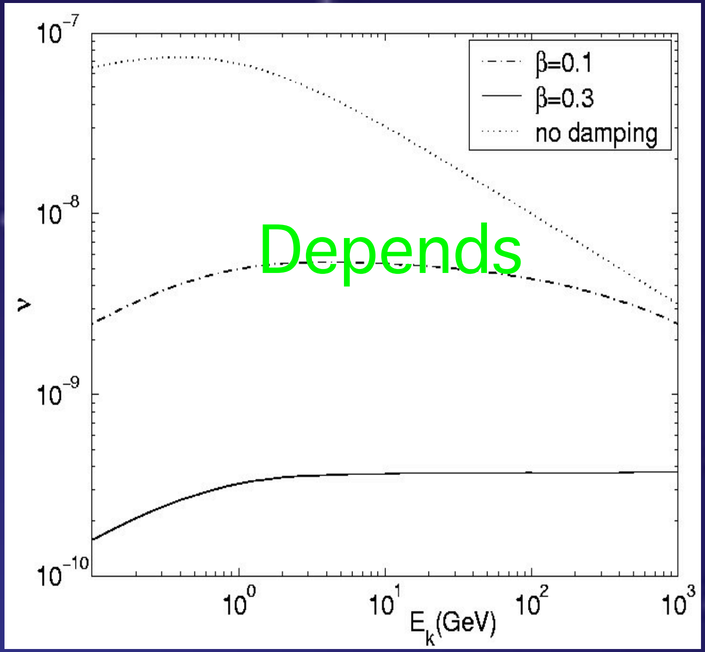


(Kolmogorov

Big difference!!!

(Chandran 2000)

fast modes



Depends

Scattering frequency

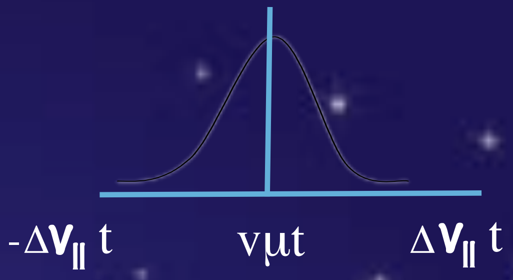
Kinetic energy

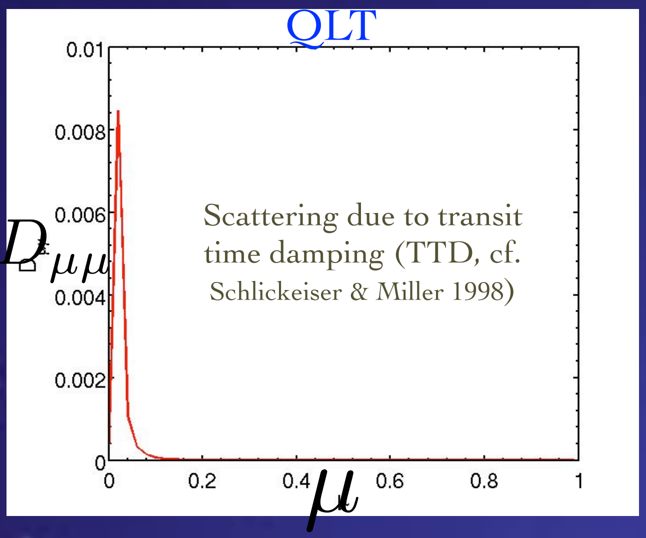
The often adopted Alfven modes are useless. Fast modes dominate CR scattering (Yan & Lazarian 02,04).

Nonlinear broadening of resonance solves the 90° problem!

- On large scale, unperturbed orbit assumption in QLT fails due to conservation of adiabatic invariant $v_\perp^2/B$ (Volk 75).

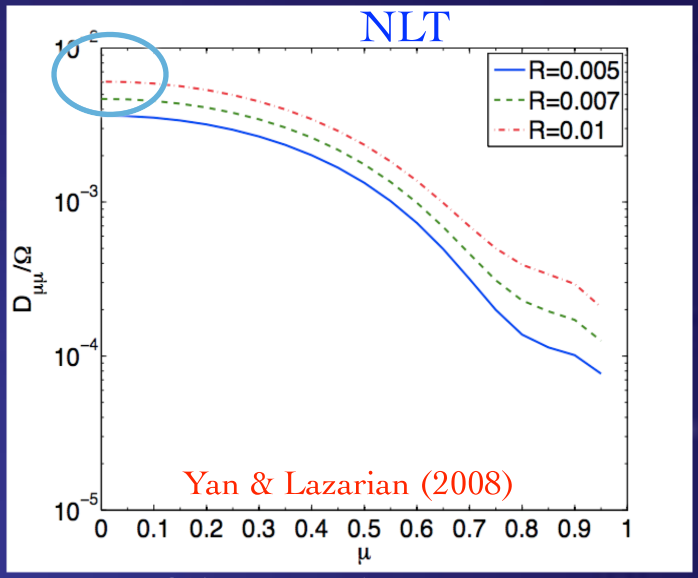
varying $v_\perp$ → varying $v_\parallel$





Scattering due to transit time damping (TTD, cf. Schlickeiser & Miller 1998)

Broadened resonance →



Yan & Lazarian (2008)

Pitch angle cosine

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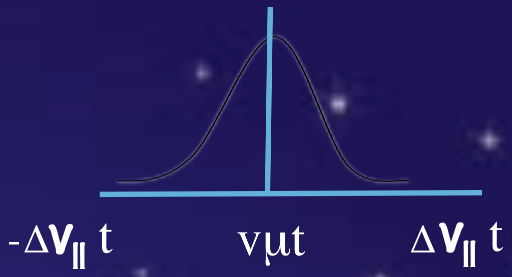
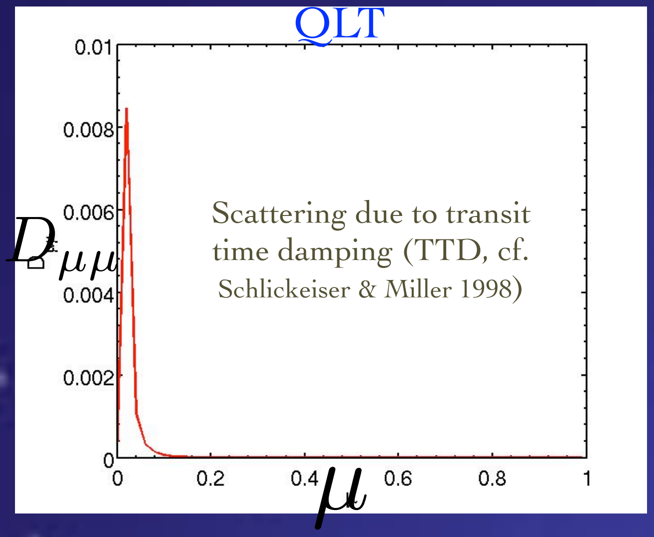
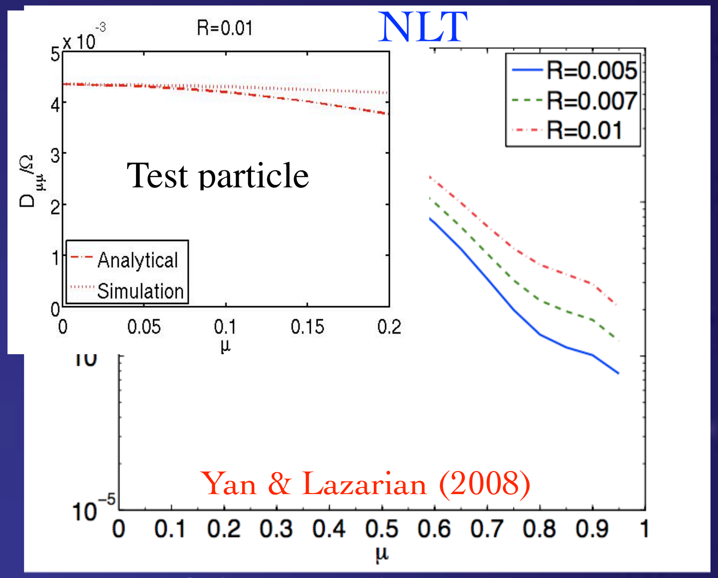



QLT

Scattering due to transit time damping (TTD, cf. Schlickeiser & Miller 1998)

Broadened resonance

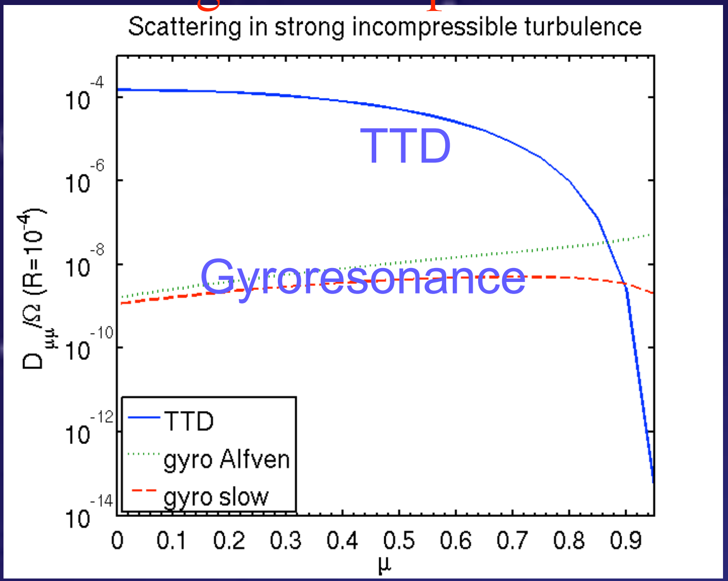

NLT

Yan & Lazarian (2008)

Pitch angle cosine

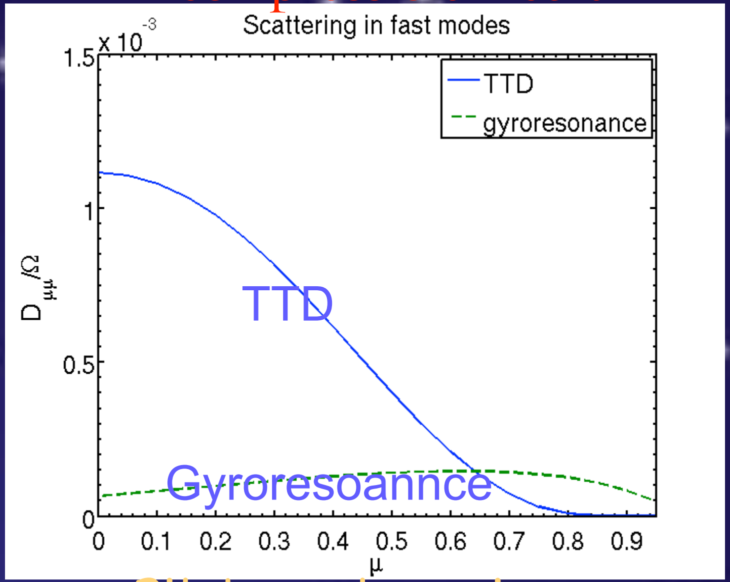
Nonlinear pitch angle diffusion

Scattering in incompressible medium



Pitch angle cosine

in compressible medium

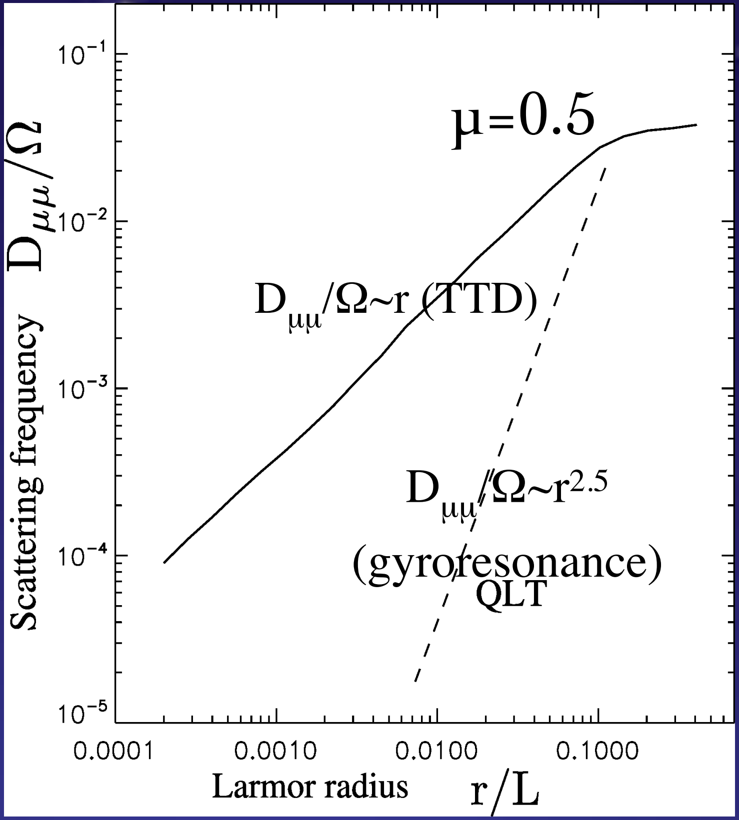


Pitch angle cosine

- NLT confirms the QLT result that gyroresonance with Alfvenic turbulence is negligible.
- At large pitch angle (including 90°), the scattering is due TTD.
- At small pitch angle, gyroresonance with fast modes dominates.

Test Particle simulation supports our theory!

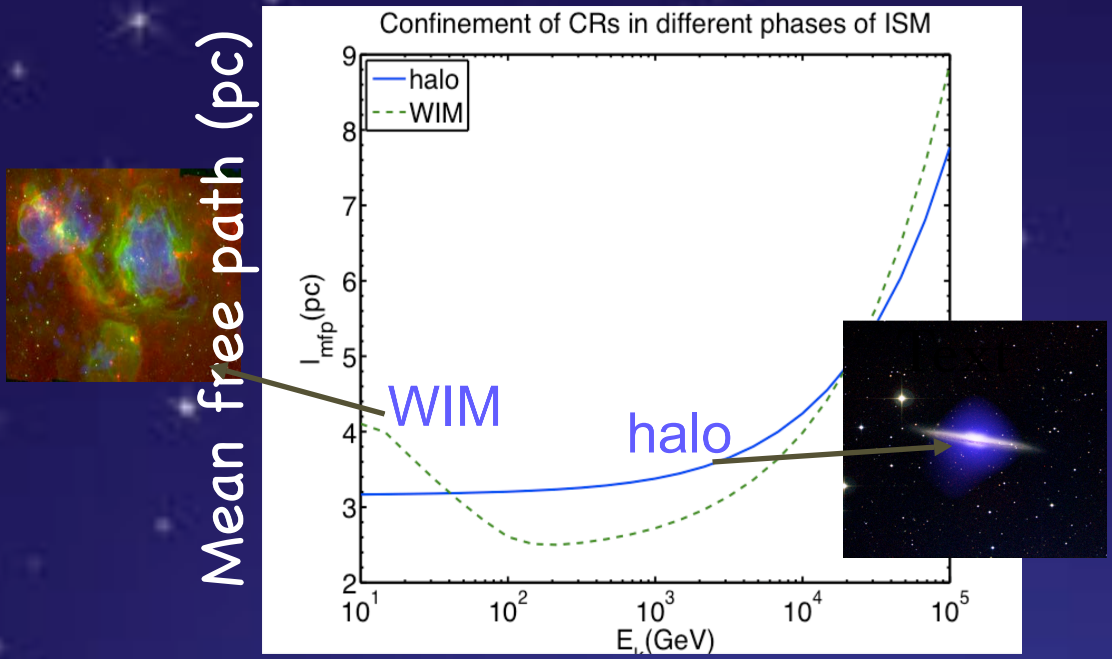
Ω — gyration frequency,
L — outer scale of turbulence.



Particle scattering in incompressible turbulence (from Beresnyak, Yan & Lazarian 2011)

CR Transport varies from place to place!

CR Transport in ISM



Kinetic energy

Flat dependence of mean free path can occur due to collisionless damping (Yan & Lazarian 2008).

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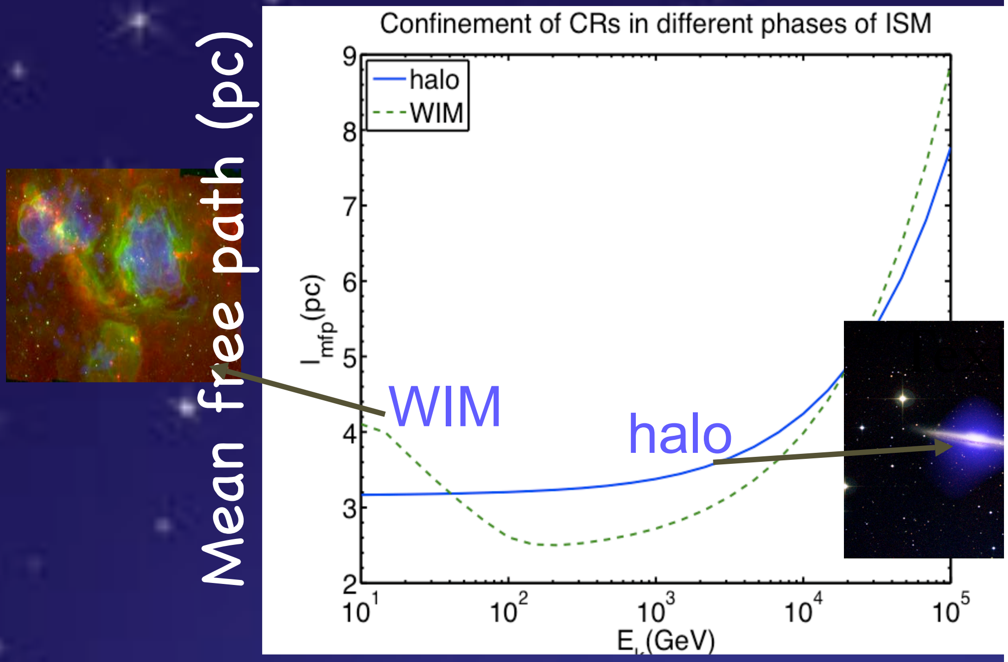
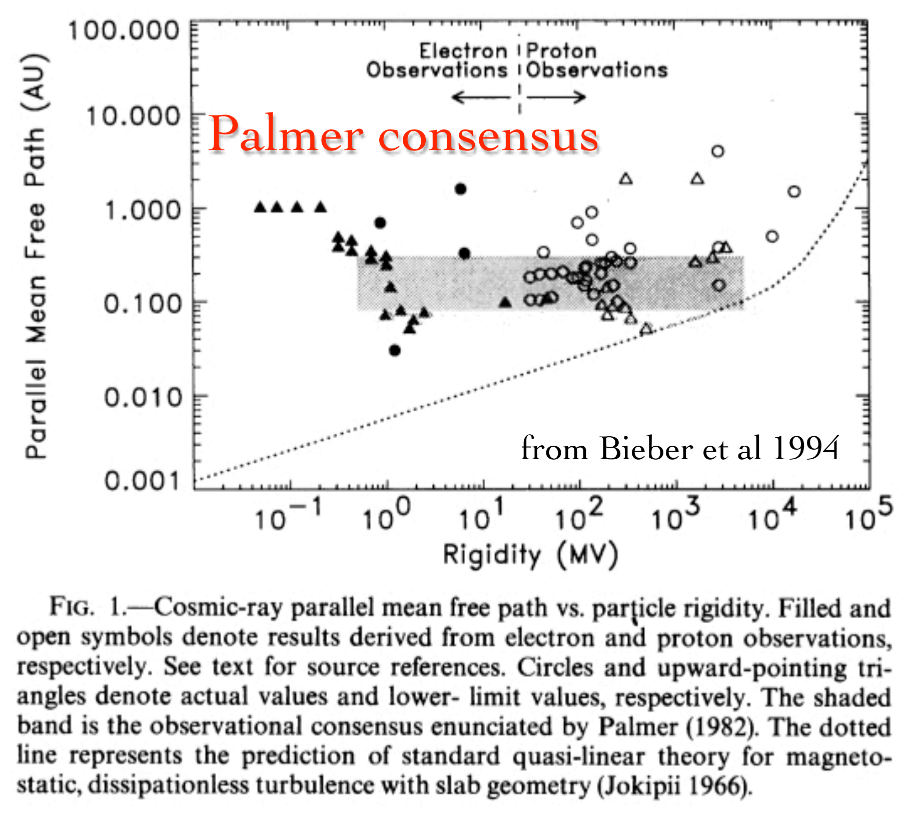


Kinetic energy



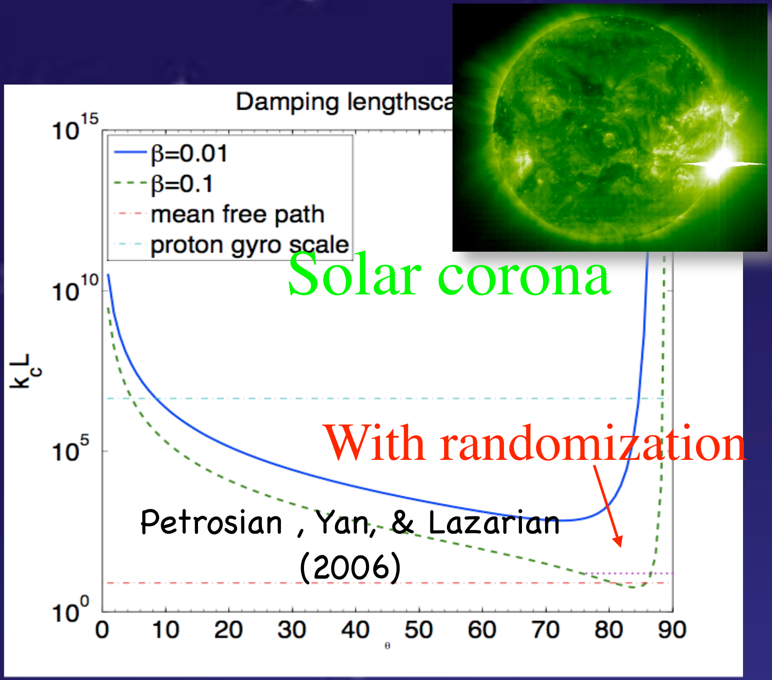
Palmer consensus

from Bieber et al 1994

FIG. 1.—Cosmic-ray parallel mean free path vs. particle rigidity. Filled and open symbols denote results derived from electron and proton observations, respectively. See text for source references. Circles and upward-pointing triangles denote actual values and lower- limit values, respectively. The shaded band is the observational consensus enunciated by Palmer (1982). The dotted line represents the prediction of standard quasi-linear theory for magnetostatic, dissipationless turbulence with slab geometry (Jokipii 1966).

Flat dependence of mean free path can occur due to collisionless damping (Yan & Lazarian 2008).

Detailed study of solar flare acceleration must include damping, nonlinear effects



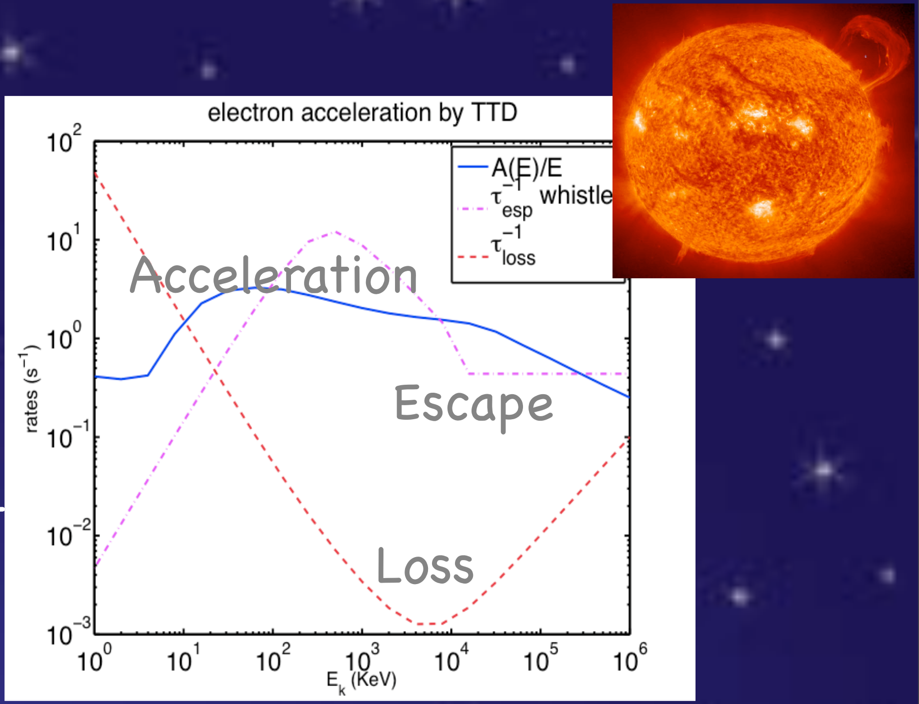
Solar corona

With randomization

Petrosian , Yan, & Lazarian (2006)

Wave pitch angle

Comparison of rates



Acceleration

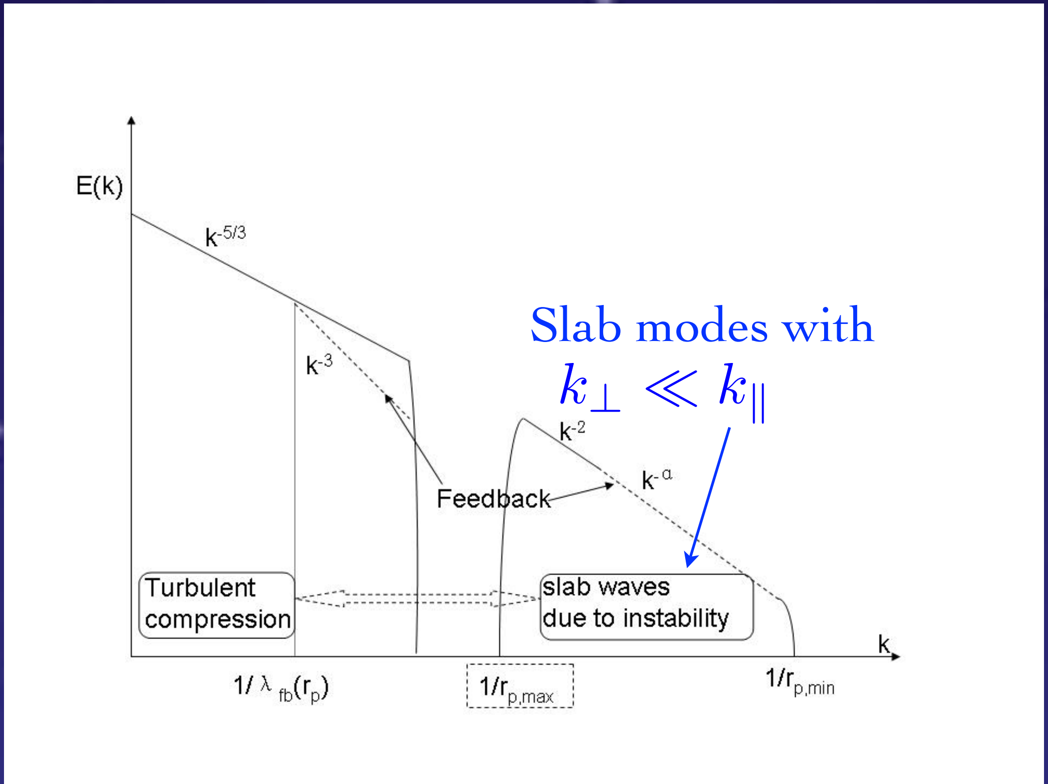
Escape

Loss

Kinetic energy

TTD Acceleration by fast modes is an important mechanism to generate energetic electrons in Solar flares (Yan, Lazarian & Petrosian 2008).

Feedback of CRs on MHD turbulence



Slab modes with $k_\perp \ll k_\parallel$

Lazarian & Beresnyak 2006 , Yan & Lazarian 2011

Wave Growth is Limited by Nonlinear Suppression!

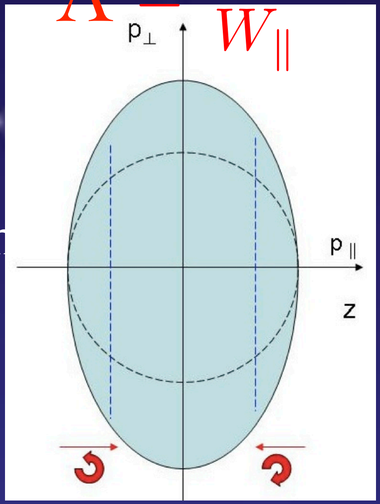
$$\frac{dA}{dt} > 0$$

Turbulence compression

$\beta \overset{\text{def}}{=}$ Pgas/P_{mag} < 1, fast modes (isotropic cascade +anisotropic damping)

β > 1 slow modes (GS95)

$$A = \frac{W_\perp}{W_\parallel} - 1$$



$$\frac{dA}{dt} < 0$$

Scattering by instability generated slab wave

Scattering by growing waves

Simple estimates:

$$\frac{dA}{dt} \sim -\nu A = -\frac{1}{W_{\parallel}}\left(\frac{dW_{\perp}}{dt} - \frac{W_{\perp}}{W_{\parallel}}\frac{dW_{\perp}}{dt}\right) \sim -\Gamma_{gr}\epsilon_N/\beta_{CR}$$

By balancing it with the rate of increase due to turbulence compression $\frac{1}{B}\frac{dB}{dt}$, we can get

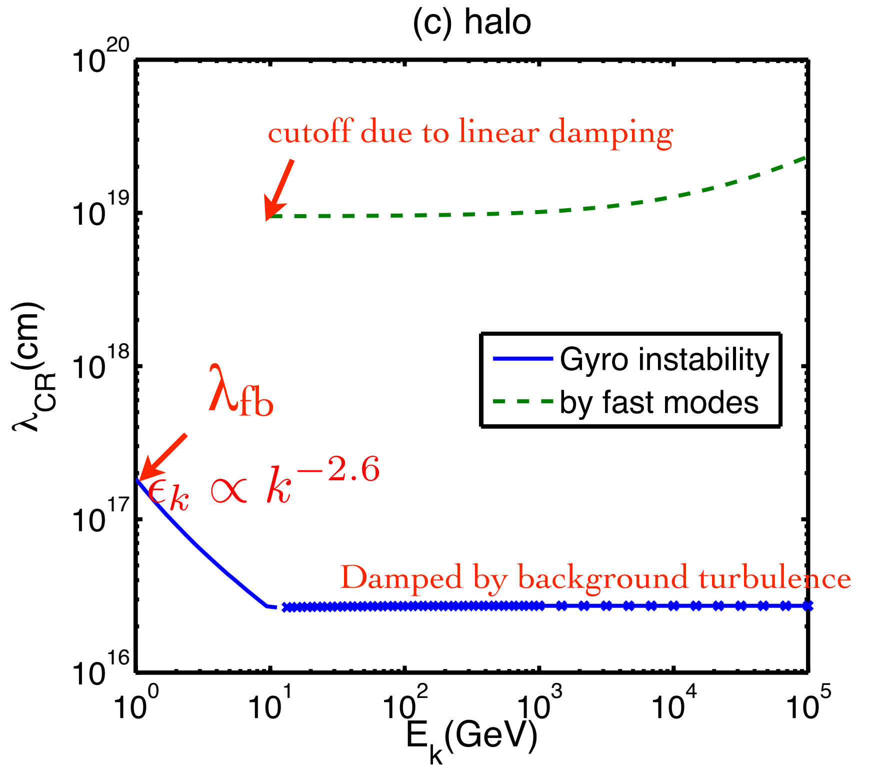
$$\boxed{\epsilon_N \sim \frac{\beta_{CR}\omega\delta v}{\Gamma_{gr} v_A}, \lambda \simeq r_p/\epsilon_N}$$

Bottle-neck of growth due to energy constraint:

$$\boxed{\epsilon_{N,max} \sim \frac{v_A}{L_{inj}\Gamma_{gr}}}$$

- Anisotropy cannot reach $\delta v/v_A$, the predicted value earlier, and the actual growth is slower and smaller amplitude due to nonlinear suppression (Yan &Lazarian 2011).

DOMAINS FOR DIFFERENT REGIMES OF CR SCATTERING



Summary

- Compressible fast modes are most important for CR scattering. CR transport therefore varies from place to place.
- Large scale mirror is essential for pitch angle scattering (including 90 degree).
- Subdiffusion does not happen in 3D turbulence .

Text

- Our results are tested using input from turbulence simulations.
- Small scale slab waves are generated in compressible turbulence by gyroresonance instability, dominating the scattering of low energy CRs (<100GeV).
- Feedback of CRs on turbulence should be included in future simulations.