# Interaction among cosmic Rays, waves and large scale turbulence

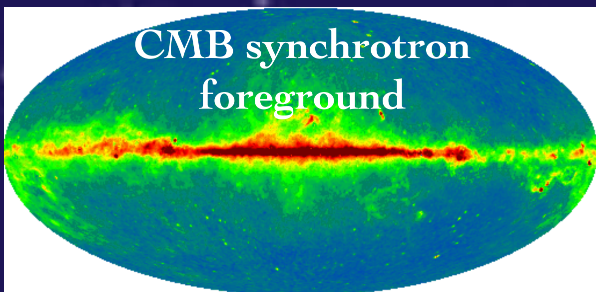

Huirong Yan

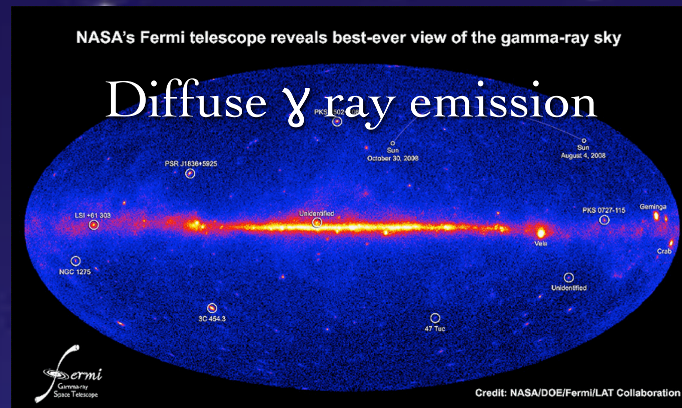
*Kavli Institute of Astronomy & Astrophysics, Peking U*

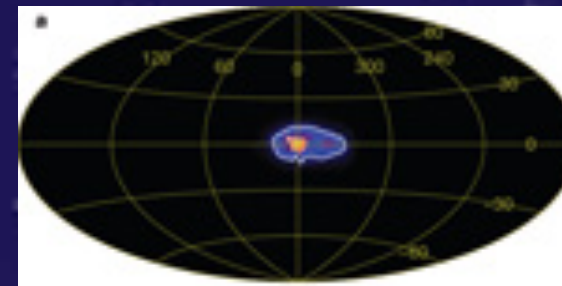
Collaboration: A. Lazarian (UW-Madison), R. Schlickeiser (U Ruhr-Bochum)

# Importance

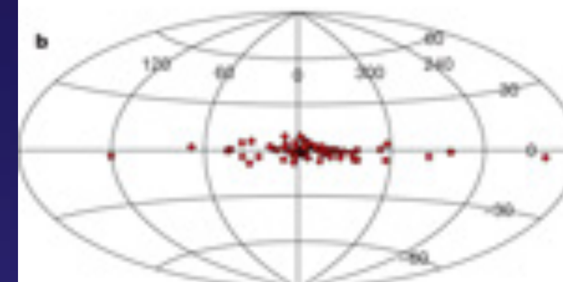
## Propagation:



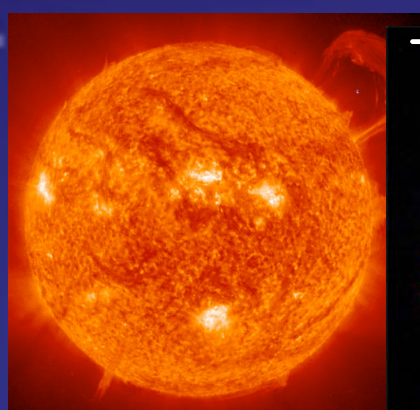




diffuse Galactic 511 keV radiation

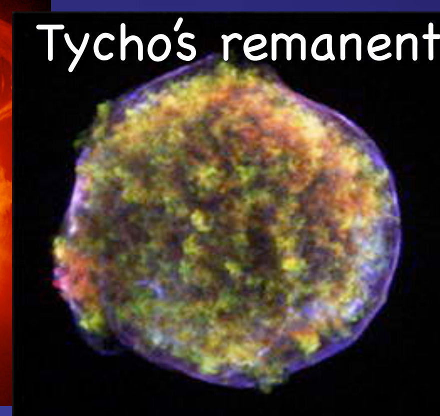



## Acceleration:

Gamma ray burst



Solar Flare




- Stochastic acceleration by turbulence
- Scattering at shock front for 1st order Fermi

# Big simulation itself is not adequate



- big numerical simulations fit results due to the existence of "knobs" of free parameters.
- Self-consistent picture can be only achieved on the basis of theory with solid theoretical foundations and numerically tested.

# Overview

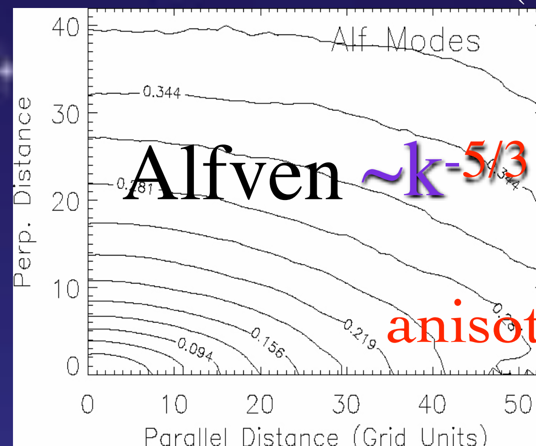
- Brief review of direct interaction w. large scale turbulence
- scattering through self-generated small scale waves
- modeling $\gamma$ ray emission near SNRs from the point of view of instability-turbulence interaction
- The other half story: perpendicular transport (no time to discuss, talk to me if interested)

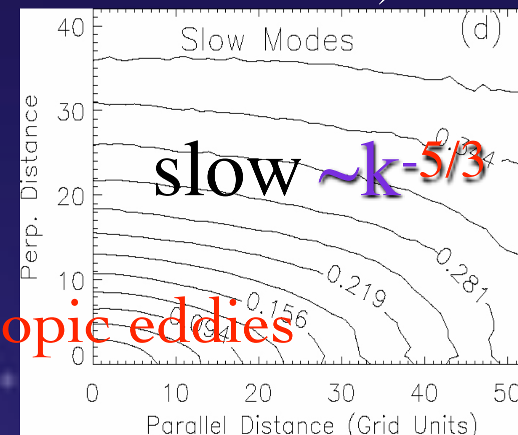
# Numerically tested models for MHD turbulence

Alfven and slow modes (GS95)

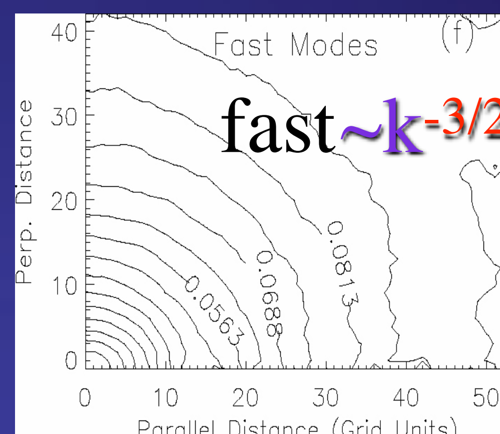

fast modes

Equal velocity correlation contour (Cho & Lazarian 02)

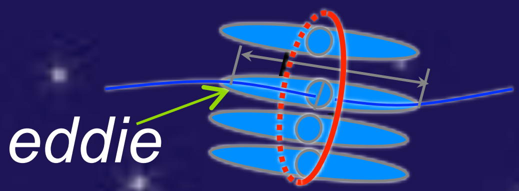


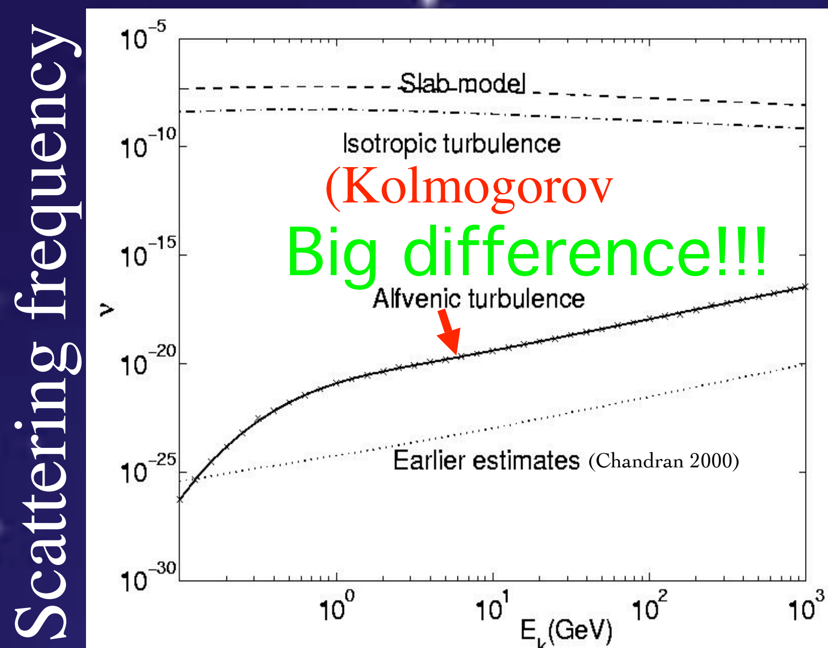

anisotropic eddies



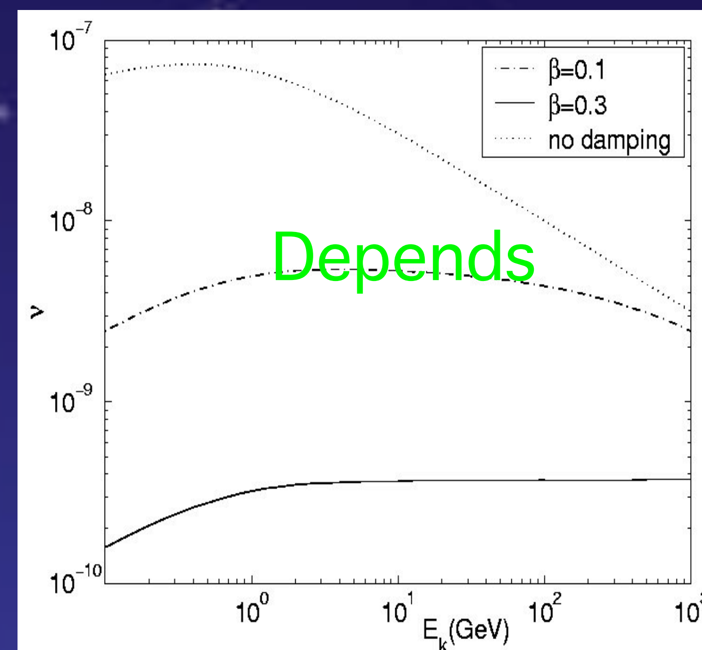
# Compressible Turbulence dominates CR scattering by gyroresonance




Alfven modes




fast modes

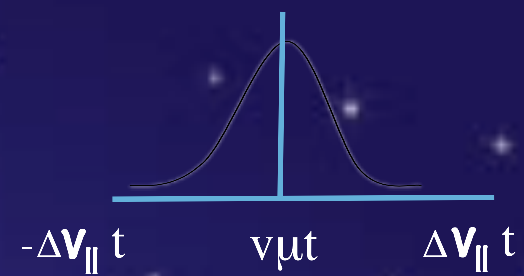


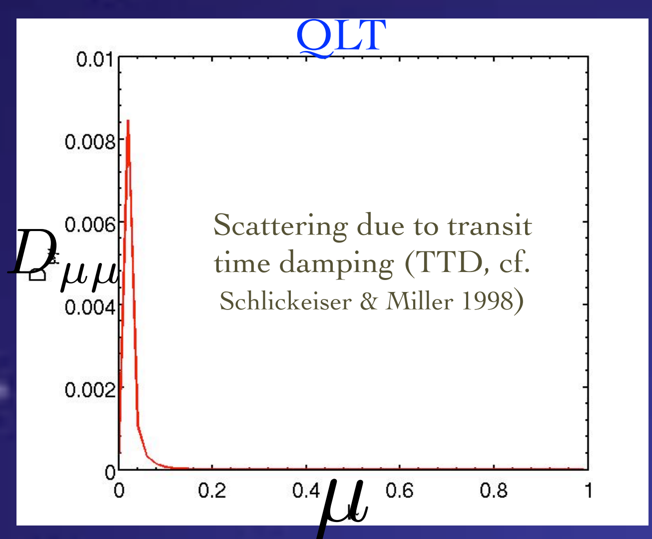

The often adopted Alfven modes are useless. Fast modes dominate CR scattering (Yan & Lazarian 02,04).

# Compressible turbulence has another substantial contribution from TTD in nonlinear theory

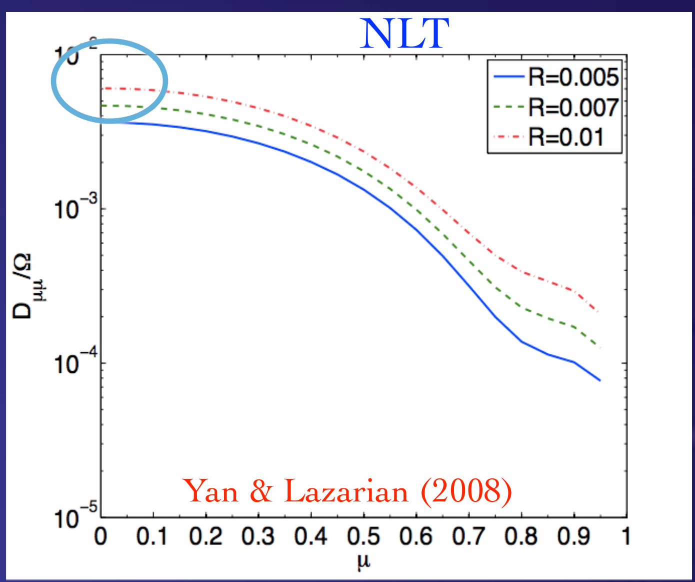
- On large scale, unperturbed orbit assumption in QLT fails due to conservation of adiabatic invariant $v_\perp^2/B$ (Volk 75).

varying $v_\perp$ → varying $v_{||}$




Broadened resonance




Pitch angle cosine

# Compressible turbulence has another substantial contribution from TTD in nonlinear theory

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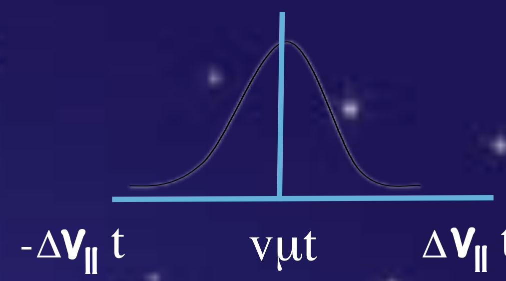


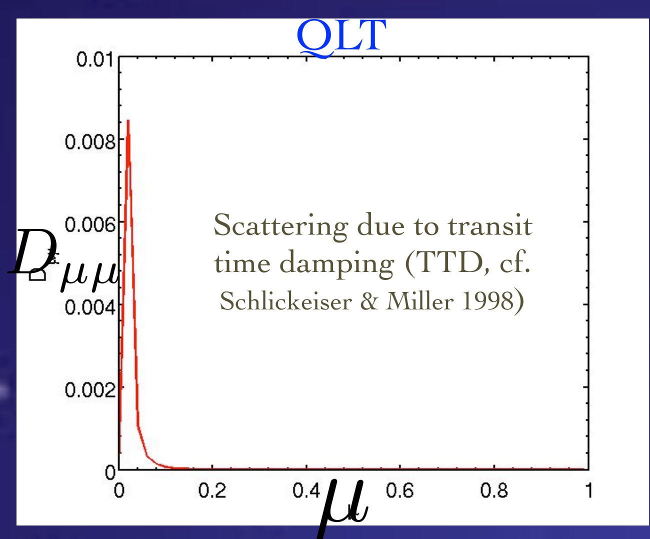


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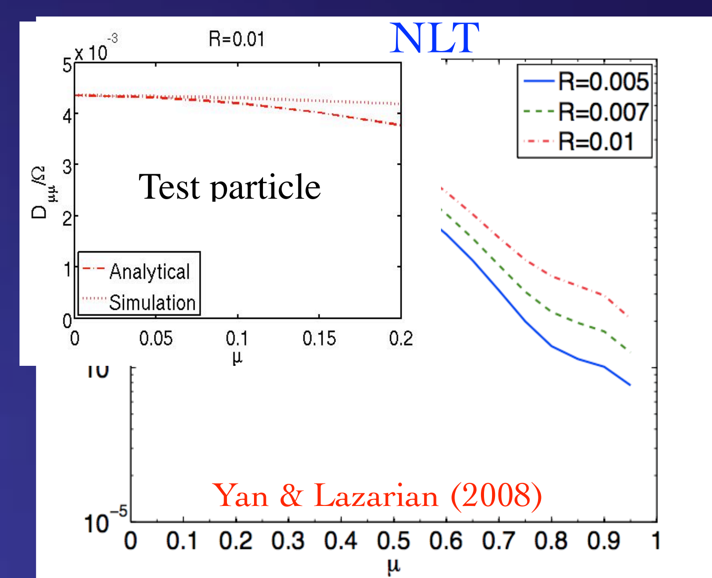
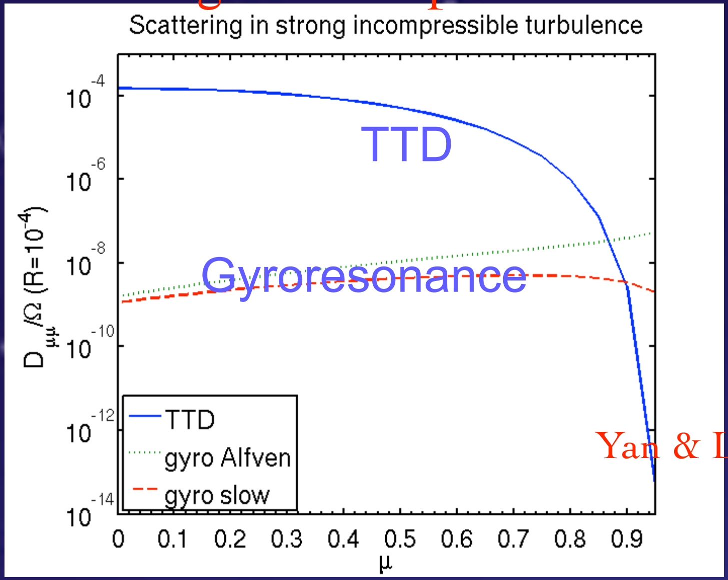



Pitch angle cosine

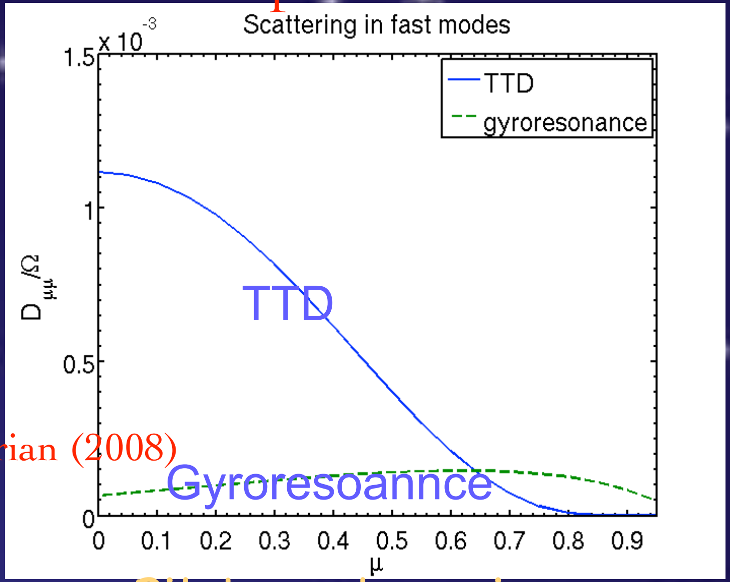
# Nonlinear pitch angle diffusion

Scattering in incompressible medium




Pitch angle cosine

in compressible medium



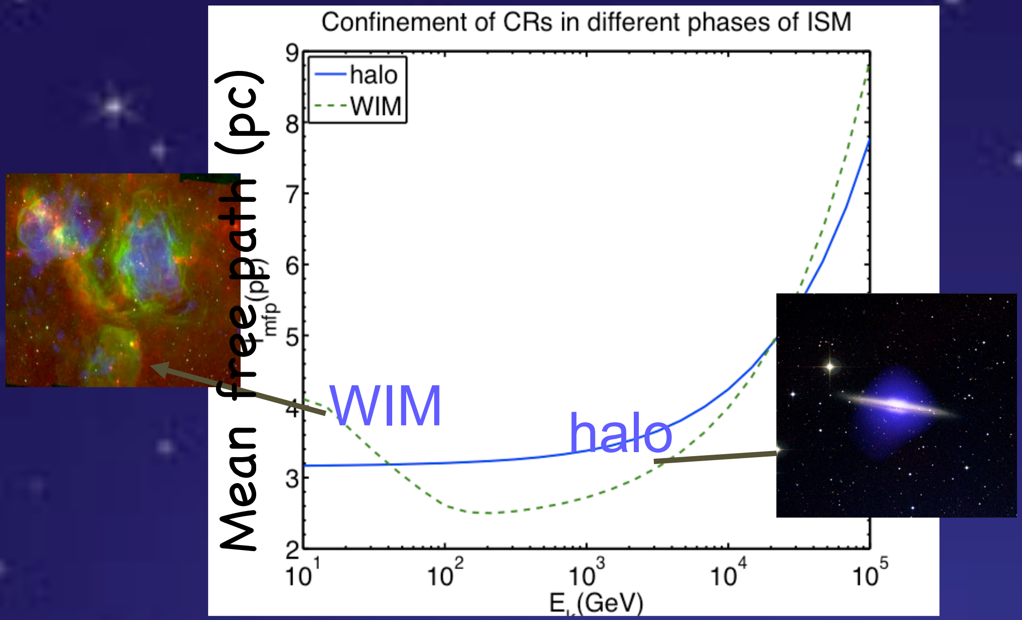

Pitch angle cosine

Yan & Lazarian (2008)

- NLT confirms the QLT result that gyroresonance with Alfvenic turbulence is negligible.
- At large pitch angle (including 90$^o$), the scattering is due to transit time damping.
- At small pitch angle, gyroresonance with fast modes dominates.

# CR Transport varies from place to place!

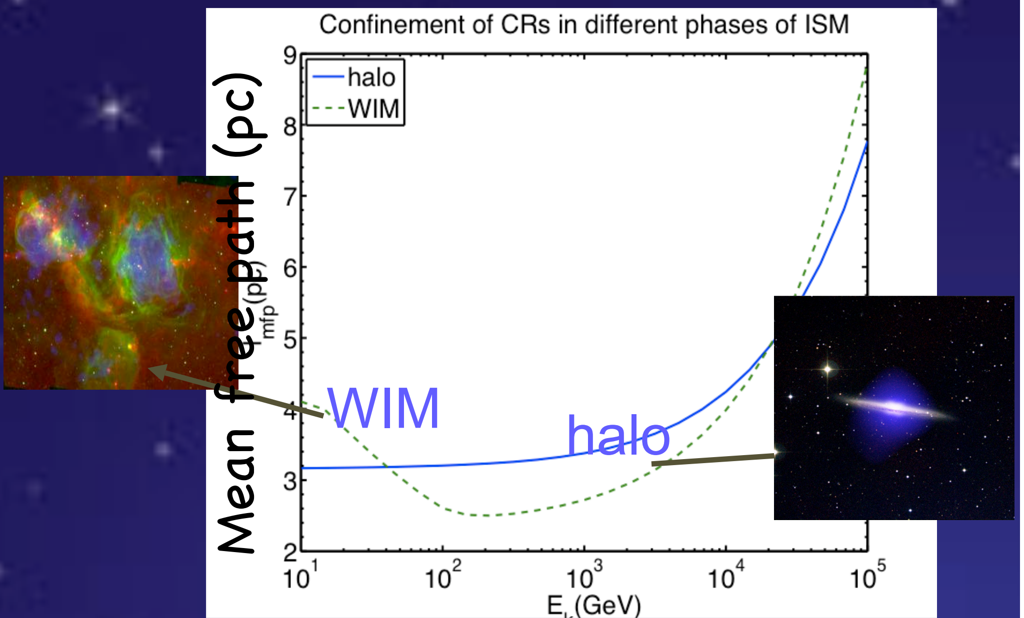
CR Transport in ISM




Kinetic energy

# CR Transport varies from place to place!

CR Transport in ISM




Kinetic energy

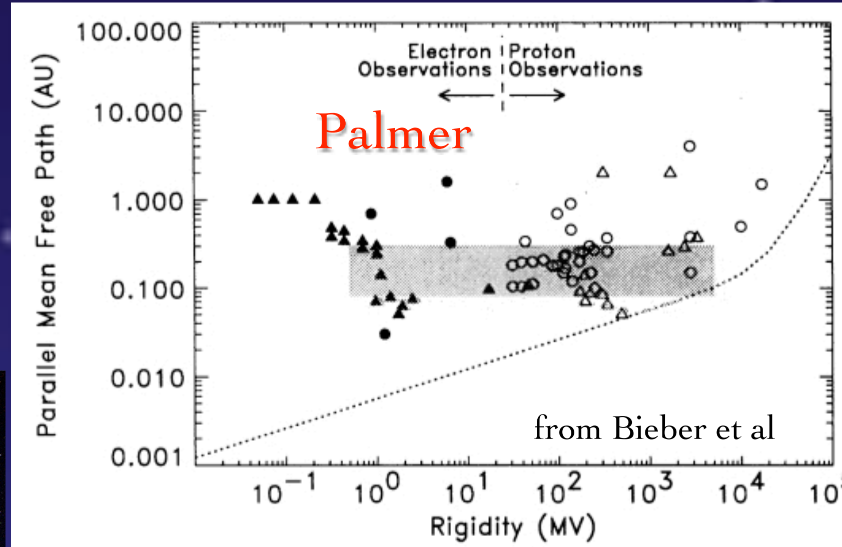
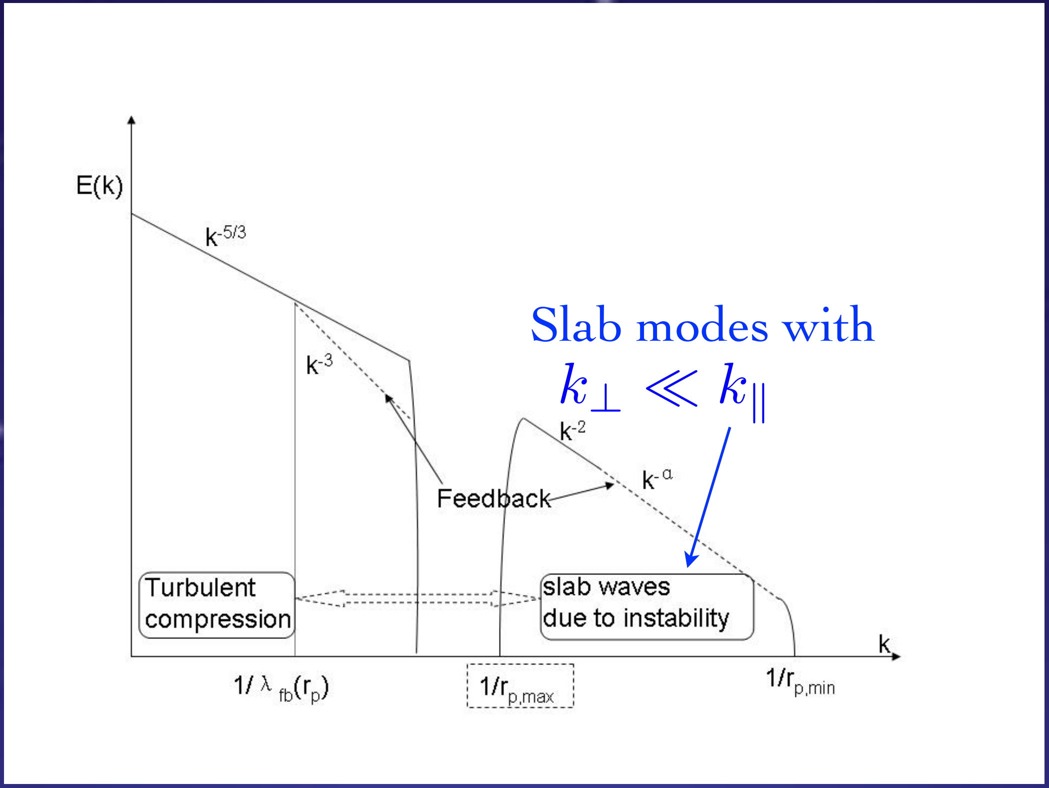



FIG. 1.—Cosmic-ray parallel mean free path vs. particle rigidity. Filled and open symbols denote results derived from electron and proton observations, respectively. See text for source references. Circles and upward-pointing triangles denote actual values and lower- limit values, respectively. The shaded 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).

# Wave generation through turbulence compression




Lazarian & Beresnyak (2006) , Yan & Lazarian (2011)

# Gyroresonance Instability

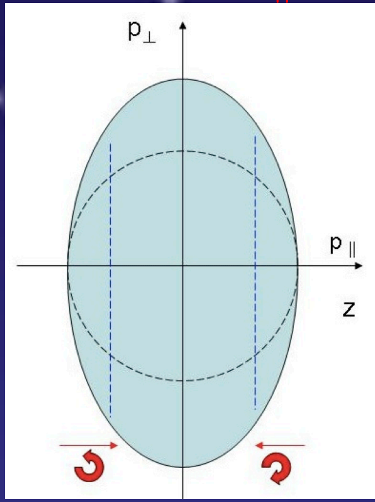
$$A \equiv \frac{W_\perp}{W_\parallel} - 1$$

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

Turbulence compression

β≝ $P_{gas}/P_{mag}$ < 1, fast modes (isotropic cascade + anisotropic damping)

β > 1 slow modes (GS95)




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

Scattering by instability generated slab wave

*Wave Growth is limited by Nonlinear Suppression!*

# Scattering by growing waves

Simple estimates:

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

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

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

Bottle-neck of growth due to energy constraint:

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

- Anisotropy cannot reach $\delta v/v_A$, the value predicted earlier (Lazarian & Beresnyak 2006), and the actual growth is slower and smaller amplitude due to nonlinear suppression (Yan &Lazarian 2011).

# Scattering by growing waves

Sin

$$\frac{\partial W_\perp}{\partial t} = 2q < \mathbf{E}_1 \cdot \int \mathbf{v} f_1 d^3p > + \frac{2q}{c} < \mathbf{B}_1 \cdot \int d^3p \mathbf{v}_\perp \times \mathbf{v} f_1 >,$$

$$\frac{\partial W_\parallel}{\partial t} = -\frac{2q}{c} < \mathbf{B}_1 \cdot \int d^3p \mathbf{v}_\perp \times \mathbf{v} f_1 >, \qquad (21)$$

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# Growth of instability is limited by background turbulence

1. MHD turbulence can suppress growth of instability (*Yan & Lazarian 2002*).

2. Calculations for weak case ($\delta B<B$):

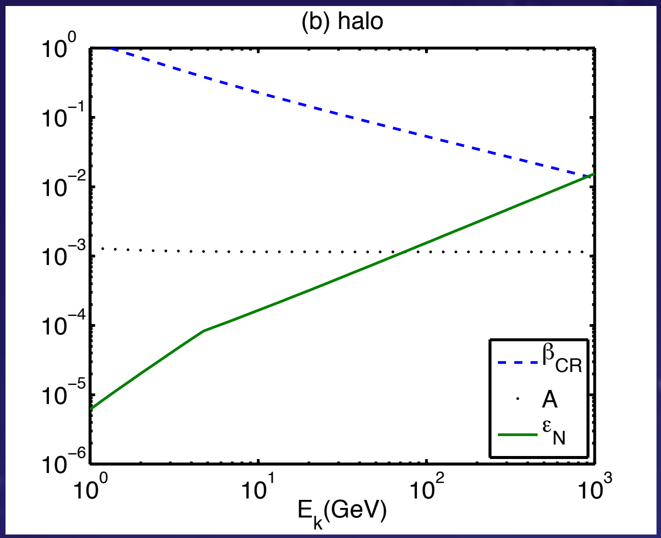
With background compressible turbulence (*Yan & Lazarian 2004*):

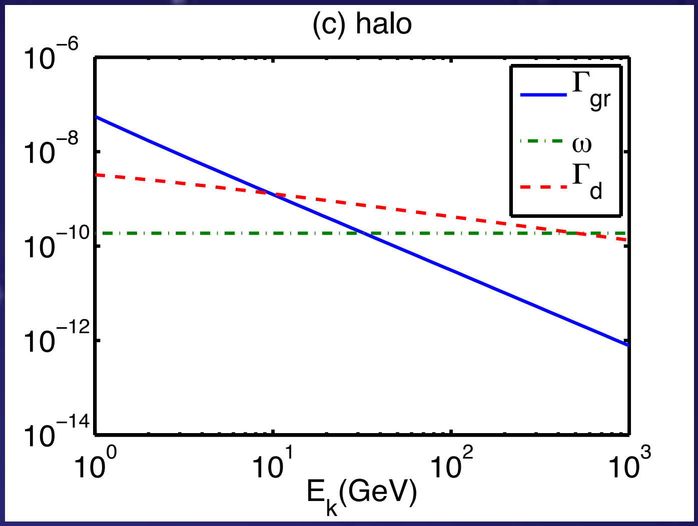
$$E_{max} \approx 1.5 \times 10^{-9} [n_p^{-1}(V_A/V)^{0.5}(Lc\Omega_0/V^2)^{0.5}]^{1/1.1}E_0$$

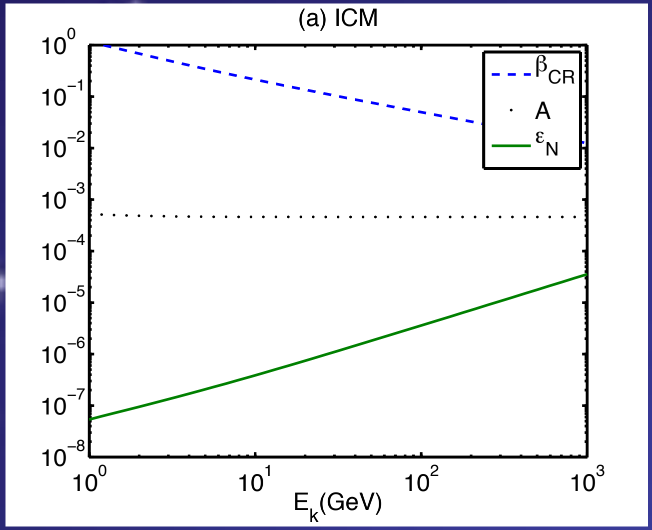
This gives $E_{max} \approx 20\text{GeV}$ for HIM.

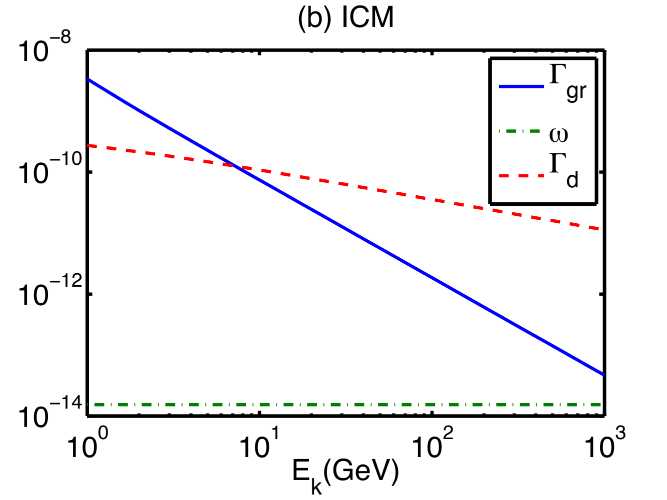
This is similar to the estimate obtained with background Alfvenic turbulence (*Farmer & Goldreich 2004*).

# Gyroresonance instabiltiy of cosmic rays

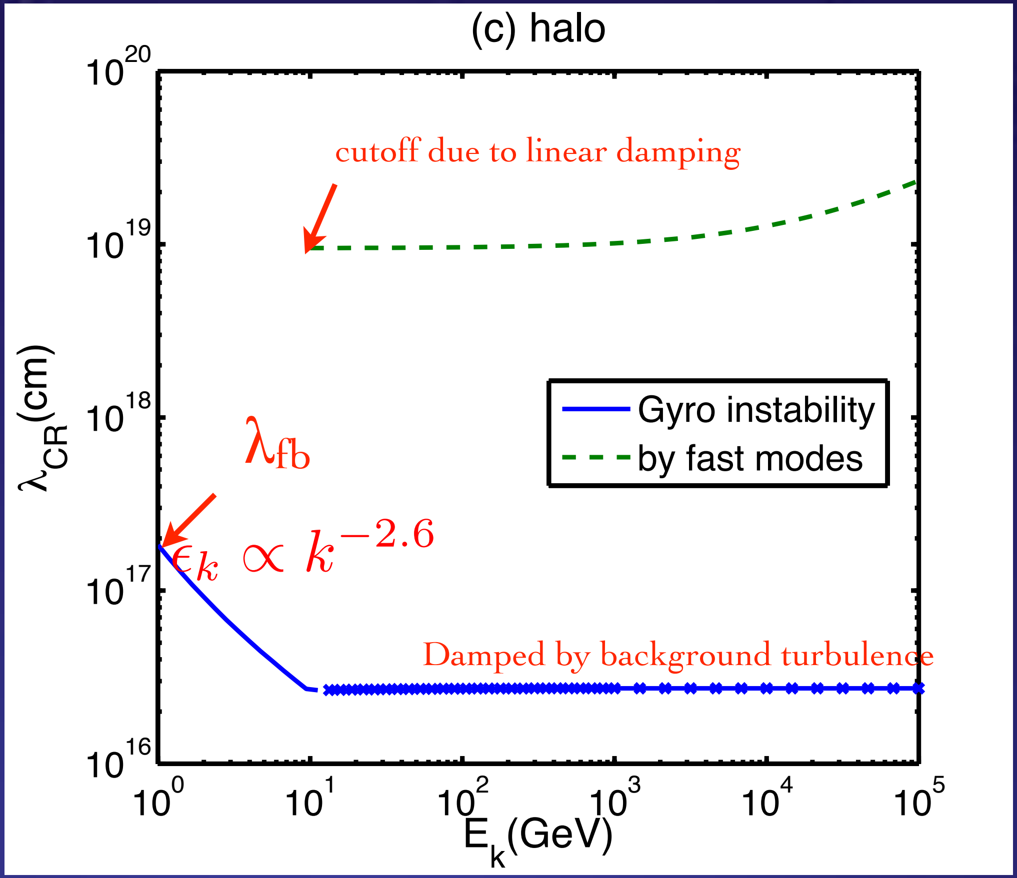


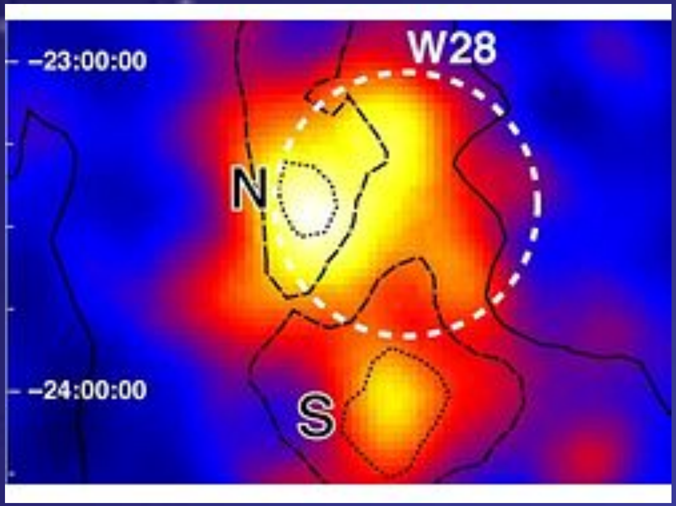



# DOMAINS FOR DIFFERENT REGIMES OF CR SCATTERING



# GAMMA RAY EMISSION NEAR SNR

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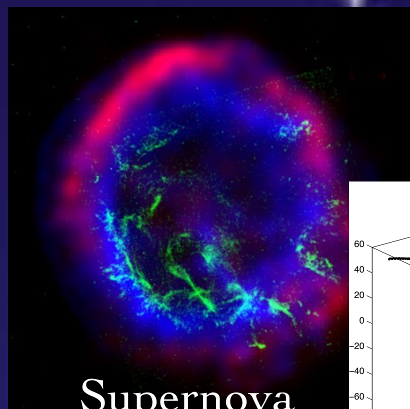
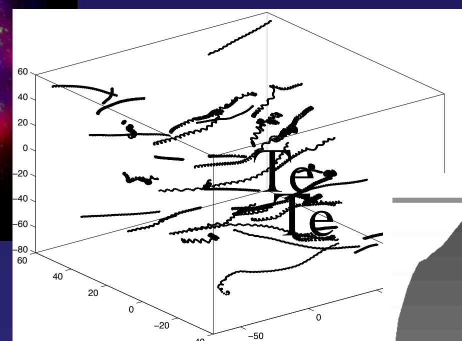
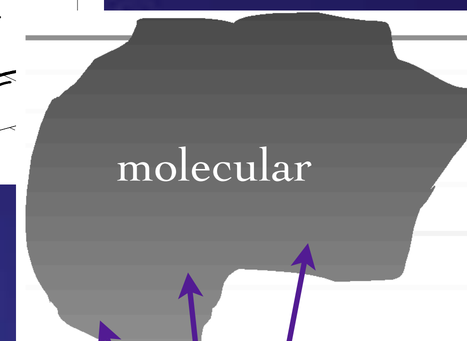
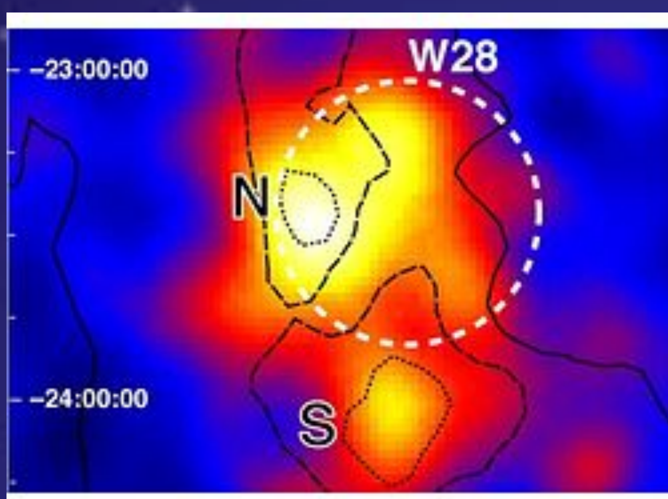



# Often adopted assumptions

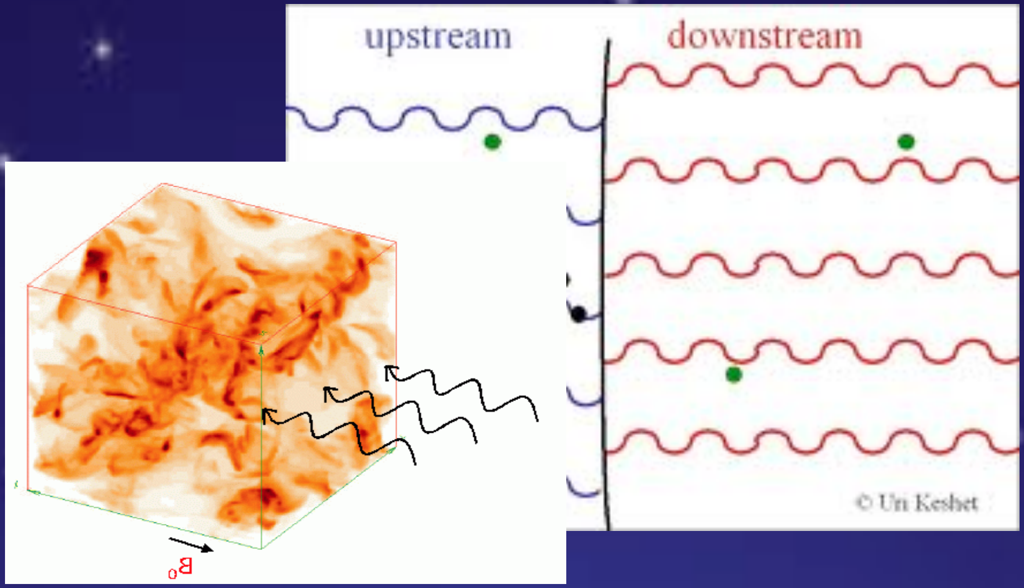
- Phenomenological power law evolution of the maximum energy accelerated at a given epoch.

$$p_{max} = p_{knee}(t/t_{sed})^{-\alpha}$$

- Bohm diffusion is assumed.
- Speculated enhanced scattering. Origin? No physical justification.

Earlier work, e.g., Fujita et al. (2009); Li & Chen (2010); Ohira (2011)

# Acceleration is limited by the wave growth at the shock front



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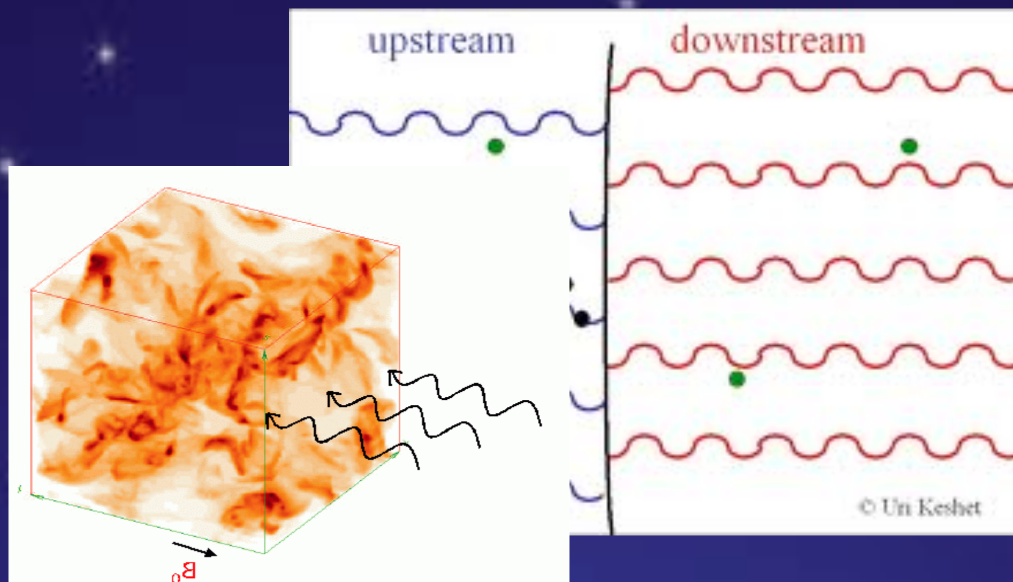
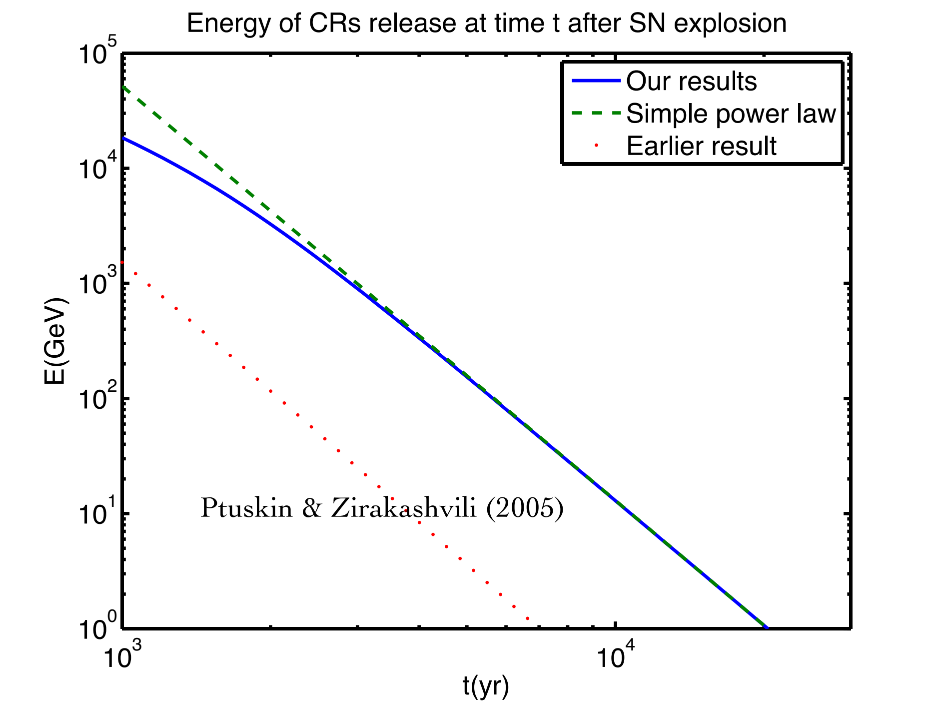



$$(U \pm v_A)\nabla W(k) = 2(\Gamma_{cr} - \Gamma_d)W(k)$$

$$\Gamma_d = V_{LM}/\sqrt{L_M r_p}$$

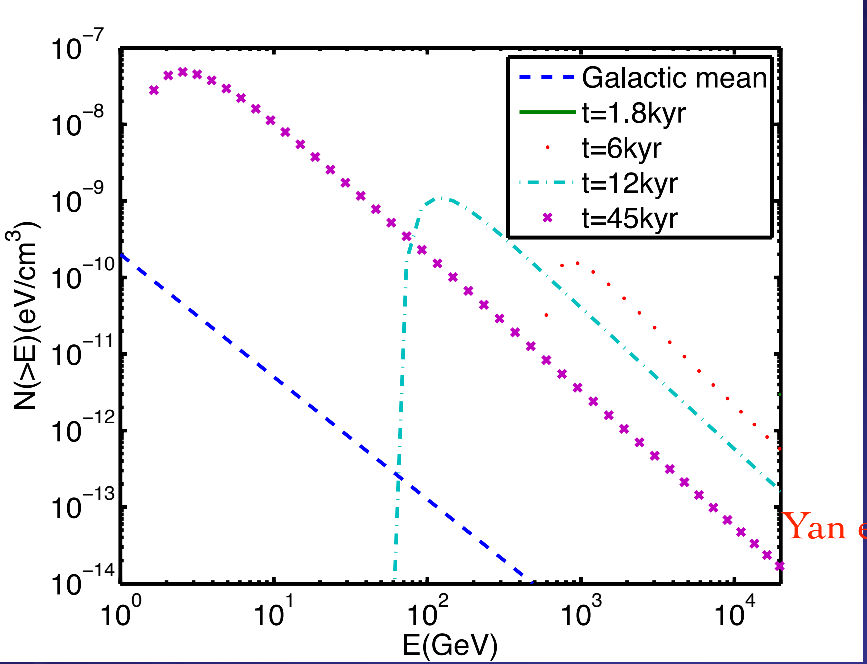
for MHD turbulence with $k_\perp >> k_\parallel$

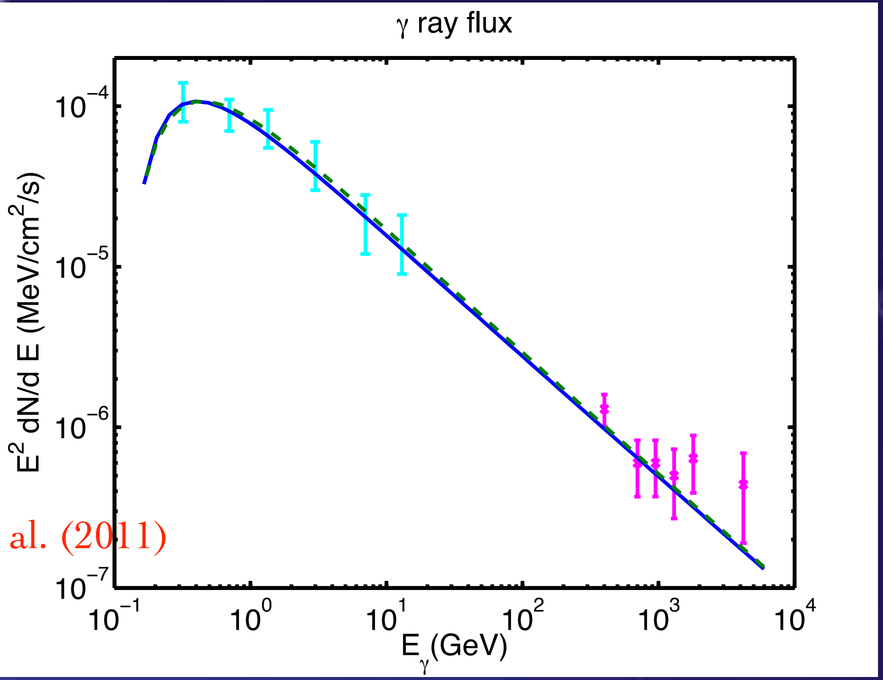
# MAXIMUM ENERGY AT A GIVE EPOCH




*Maximum energy accelerated at a given shock radius is higher than the case when the background turbulence is assumed isotropic.*

# Accelerated CR flux and γ ray emission




Yan et al. (2011)

$$F(E) \approx \frac{f(E)}{\pi^{3/2} R_d^3} \exp\left[-\left(\frac{r}{R_d}\right)^2\right]$$

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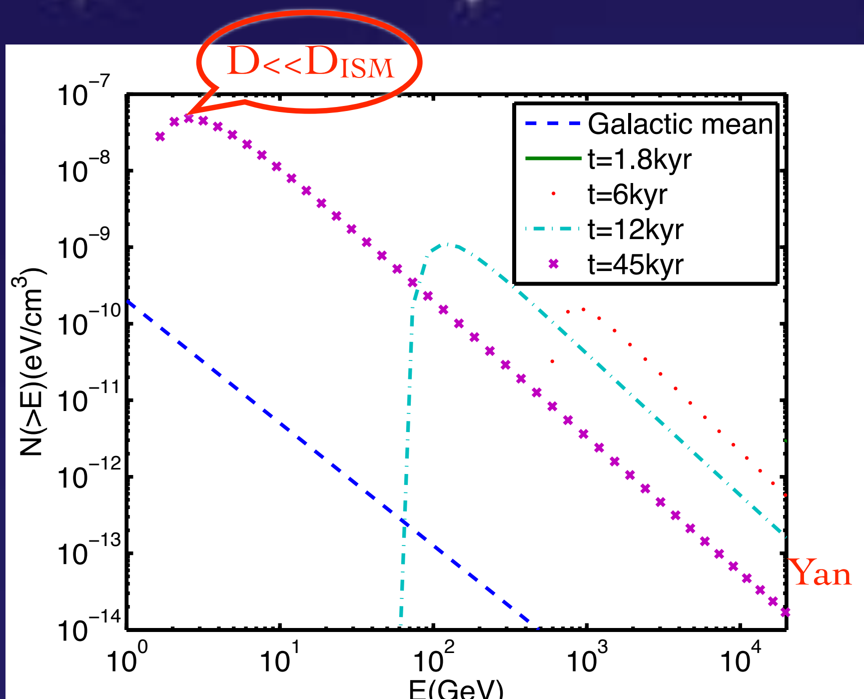
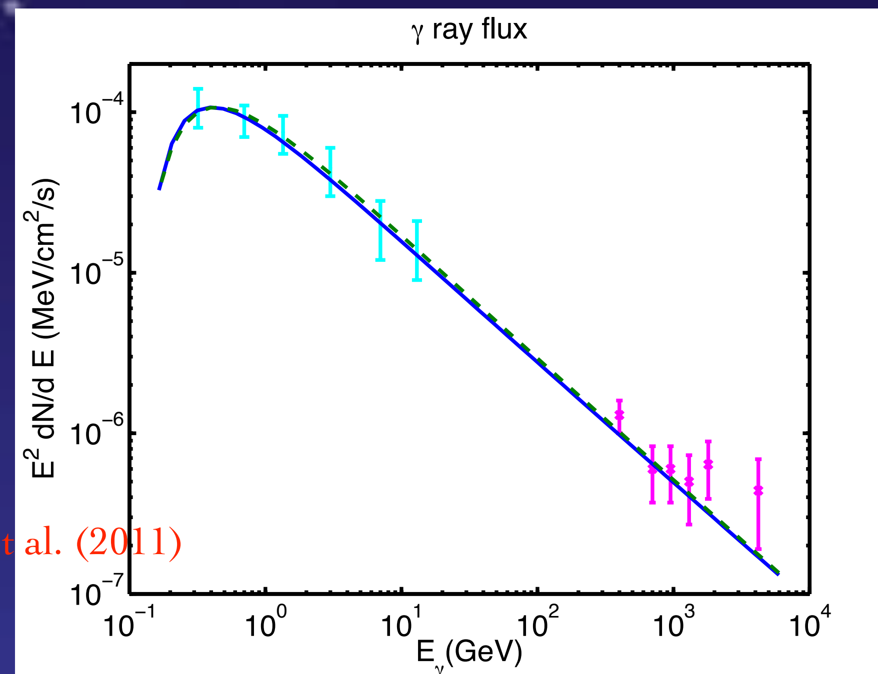
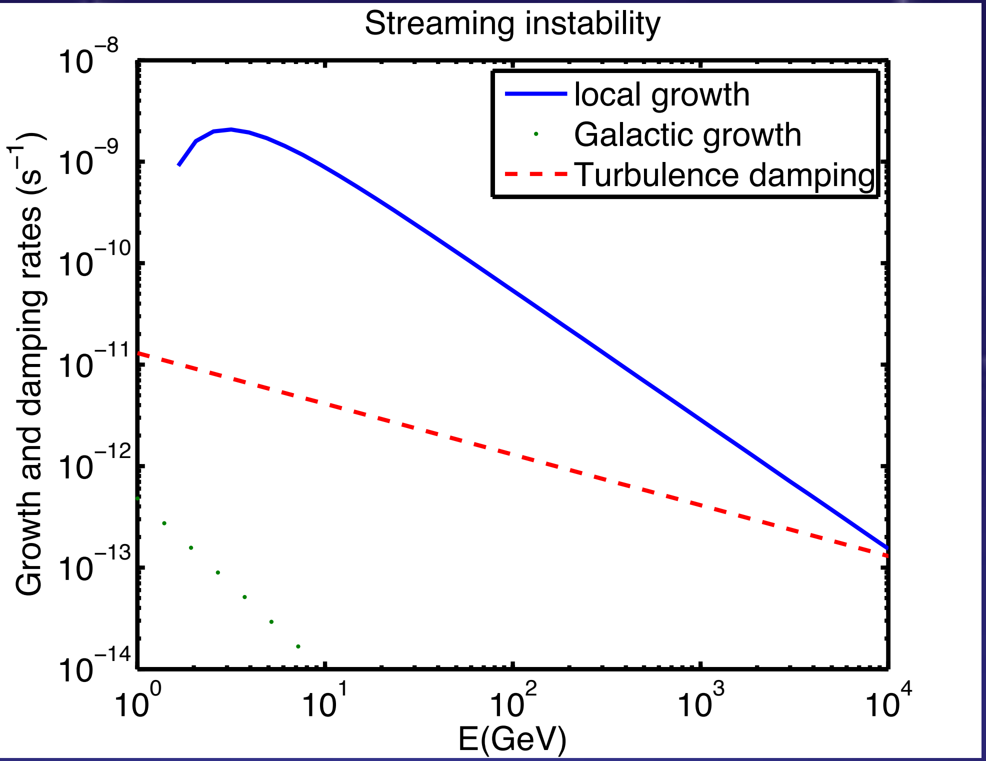



Yan et al. (2011)

$$F(E) \approx \frac{f(E)}{\pi^{3/2}R_d^3} \exp\left[-\left(\frac{r}{R_d}\right)^2\right]$$

# Result is self-consistent!




*Steaming instability due to increased CR flux is sufficient to overcome the damping by turbulence.*

# Summary

- **Compressible turbulence dominates the transport of CRs,** through both direct scattering and inducing gyroresonance instability.
- The growth of the instability is balanced by the feedback of the slab waves on the anisotropy of CRs.
- Small scale slab waves are generated in compressible turbulence by gyroresonance instability, dominating the scattering of low energy CRs (<100GeV).
- The flux of CRs near SNRs is increased enough to create strong streaming instability that can overcome the damping by background turbulence for the energy range considered.
- The enhanced scattering by the instability is enough to reproduce the observed gamma ray flux from molecular clouds. at the proximity of SNR.