Stochastic Particle Acceleration by Turbulence

Turbulence is essential ingredient not only for stochastic but most acceleration processes

Particle Acceleration in General

1. Ideally start with thermal plasma as seeds

2. In addition to turbulence it is essential to include

a. Energy Losses in the Acceleration Site

and

b. Escape From the Acceleration Site

Escape time related to Spatial Diffusion

An important distinction

between Accelerated and Escaping Spectra

Particles in the acceleration site; *N(E)*

Particles in radiating or observing sites; $\dot{Q}(E) = N(E)/T_{\rm esc}(E)$

A. Closed; no escape $T_{\rm esc} = \infty, \ \ Q(E) = 0$

more heating than acceleration

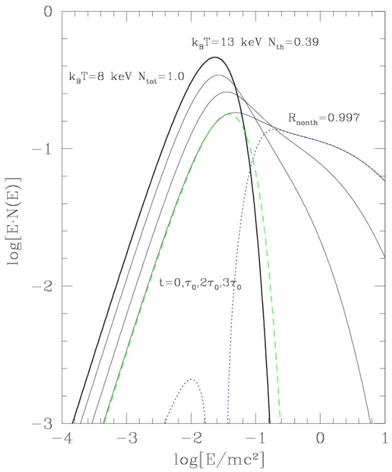
VP, East, ApJ, 2008 ; VP, Kang, ApJ, 2015

B. Open with escape

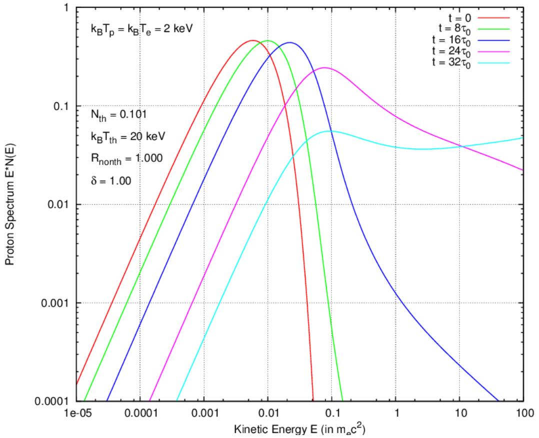
harder or softer escaping spectra

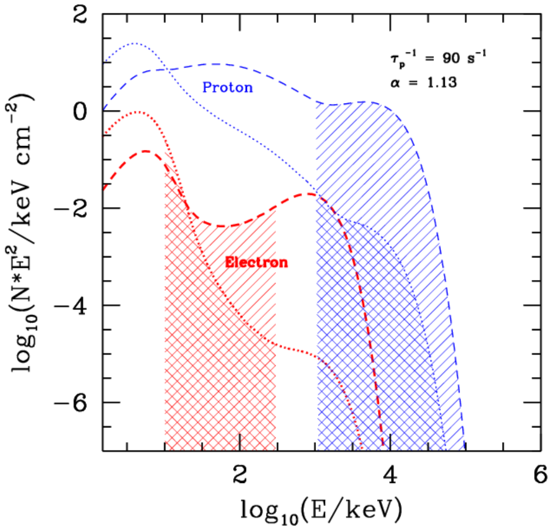
VP, Liu, ApJ, 2004

Electrons



Protons





Stochastic vs Shock Acceleration

- First order and second order Fermi acceleration?

Stochastic vs Shock Acceleration

- First order and second order Fermi acceleration?
- Shock acceleration is always faster than stochastic?

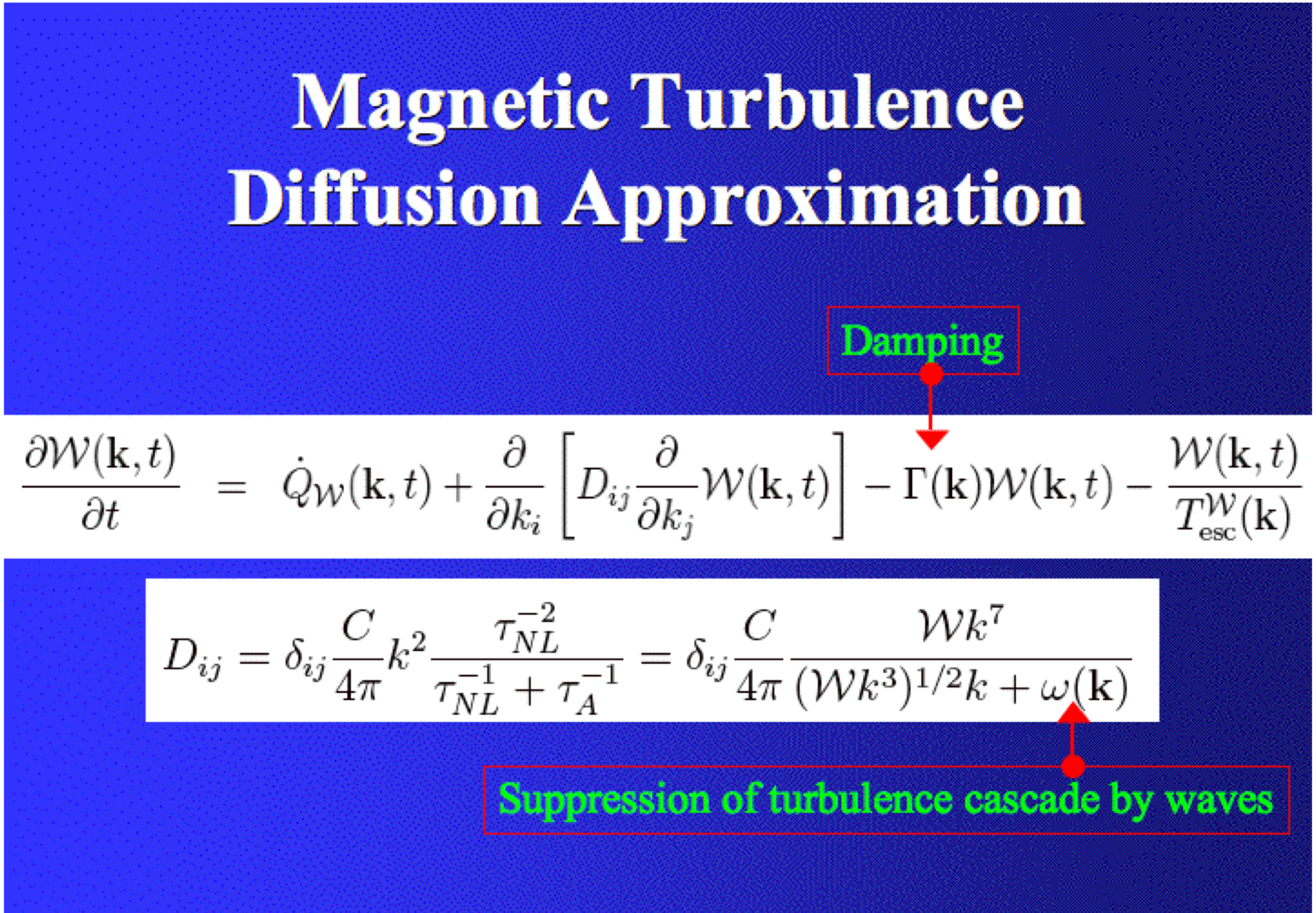
Astrophysical sources of SA

1. Solar Flares:
   - Acceleration at flare reconnection site (e/p, 3He/4He)
   - Acceleration at Coronal Mass ejection-shock
2. Clusters of Galaxies: Halo synchrotron emission
3. Sgt A* accretion disk (with Siming Liu)
4. Fermi Bubbles: IC and synchrotron (with Philipp Mertsch)
5. SA of Relativistic particles (with Lukash Stawartz)

Outstanding Questions

- Turbulence plays a role in both processes but how is it produced and what are its characteristics is an unsolved problem;
    1. Generation, cascade and damping
    2. Coupled turbulence and particle kinetic equations

The Final unknown



Magnetic Turbulence Diffusion Approximation

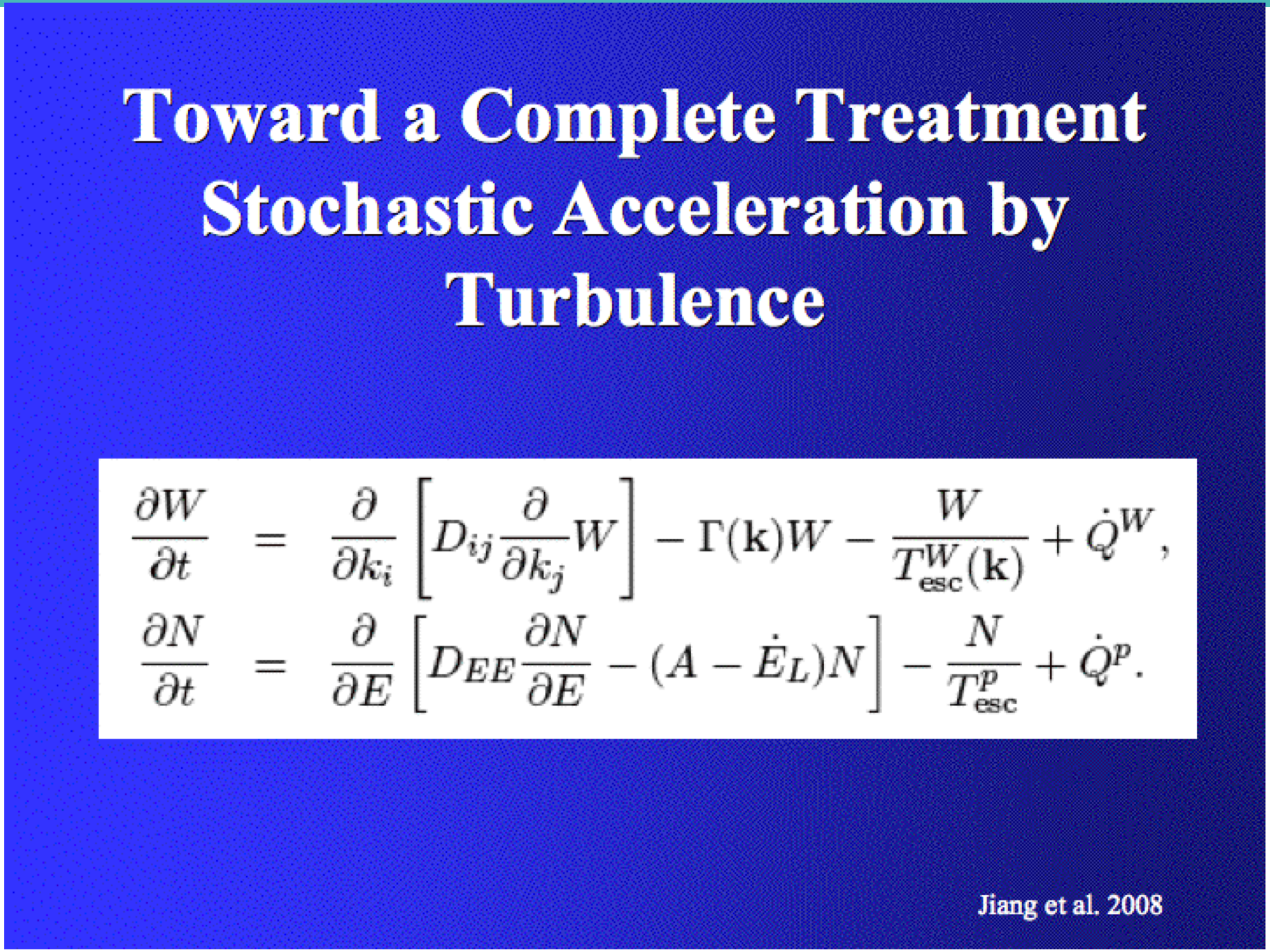
Damping

$$\frac{\partial \mathcal{W}(\mathbf{k},t)}{\partial t} = \dot{Q}_{\mathcal{W}}(\mathbf{k},t) + \frac{\partial}{\partial k_i}\left[D_{ij}\frac{\partial}{\partial k_j}\mathcal{W}(\mathbf{k},t)\right] - \Gamma(\mathbf{k})\mathcal{W}(\mathbf{k},t) - \frac{\mathcal{W}(\mathbf{k},t)}{T^{\mathcal{W}}_{\mathrm{esc}}(\mathbf{k})}$$

$$D_{ij} = \delta_{ij}\frac{C}{4\pi}k^2\frac{\tau_{NL}^{-2}}{\tau_{NL}^{-1}+\tau_A^{-1}} = \delta_{ij}\frac{C}{4\pi}\frac{\mathcal{W}k^7}{(\mathcal{W}k^3)^{1/2}k+\omega(\mathbf{k})}$$

Suppression of turbulence cascade by waves

Coupled turbulence and particle kinetic equation



Toward a Complete Treatment Stochastic Acceleration by Turbulence

$$
\begin{aligned}
\frac{\partial W}{\partial t} &= \frac{\partial}{\partial k_i}\left[D_{ij}\frac{\partial}{\partial k_j}W\right] - \Gamma(\mathbf{k})W - \frac{W}{T^W_{\mathrm{esc}}(\mathbf{k})} + \dot{Q}^W, \\
\frac{\partial N}{\partial t} &= \frac{\partial}{\partial E}\left[D_{EE}\frac{\partial N}{\partial E} - (A - \dot{E}_L)N\right] - \frac{N}{T^p_{\mathrm{esc}}} + \dot{Q}^p.
\end{aligned}
$$

Jiang et al. 2008