The Macrophysics & Microphysics of Cosmic Rays

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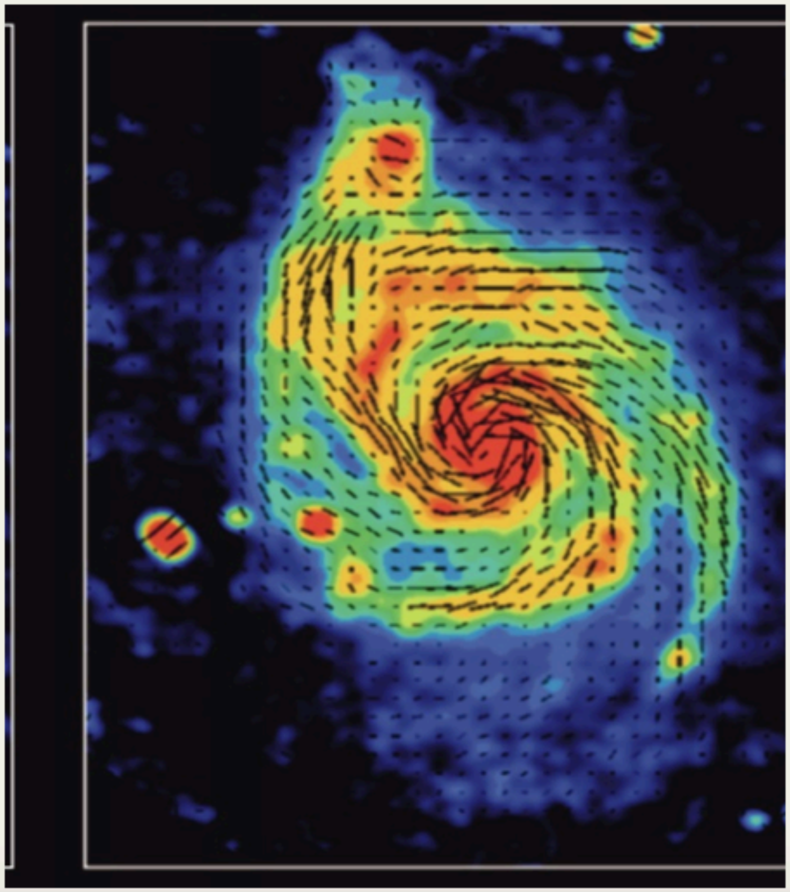
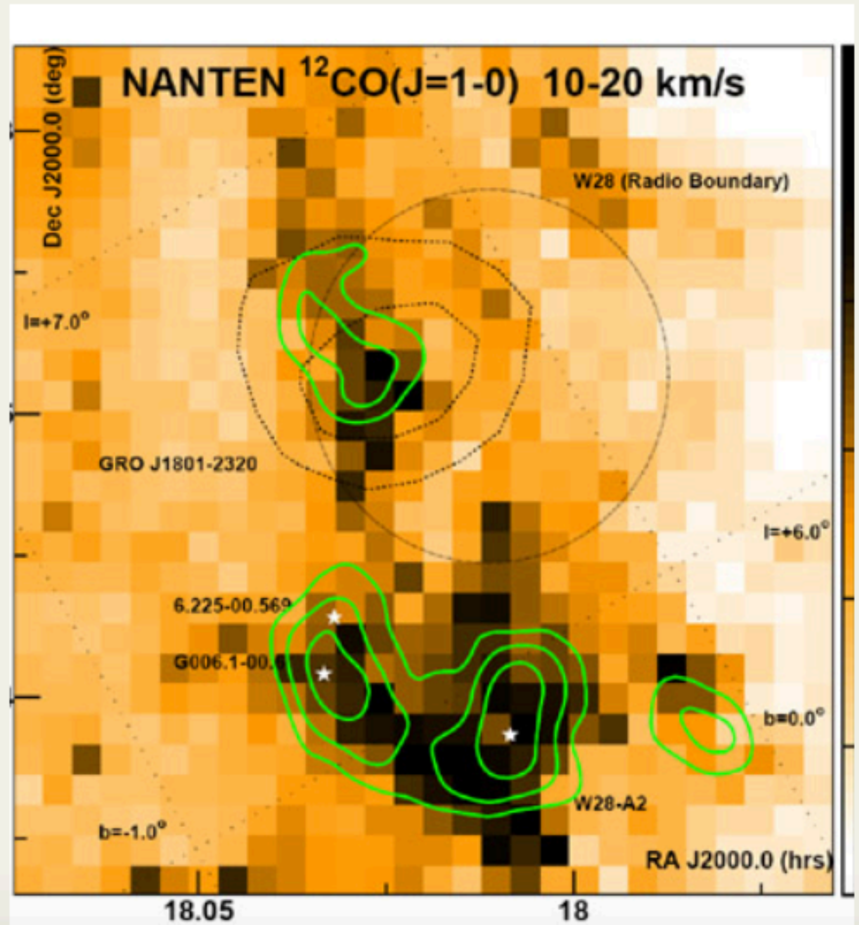
Cosmic Rays are Pervasive





Tools & Systems

- Direct probes
    - In situ particle detectors
    - Telescopes from radio to γ-ray
    - ν detectors
- Indirect probes
    - Astrochemical modeling
    - Geology
- Natural and lab plasmas
    - Space & solar
    - Diffuse and HED

Properties

Energy Spectrum

- A broken power law:

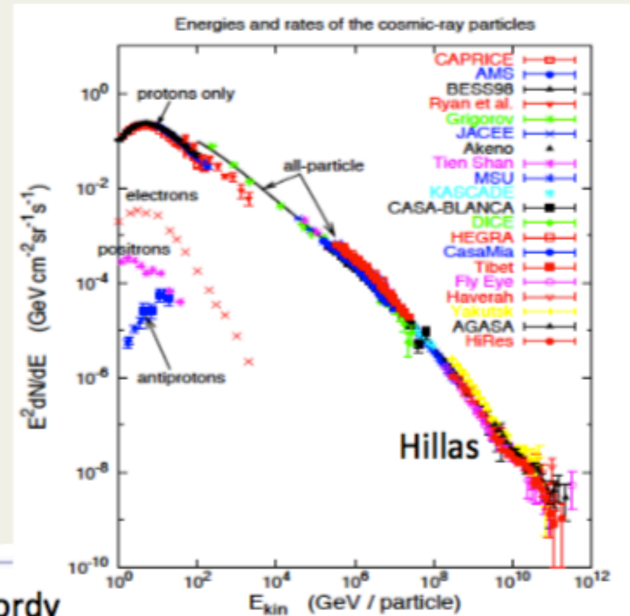
$N(E) \sim E^{-2.7}$, $E_{PeV} < 3$

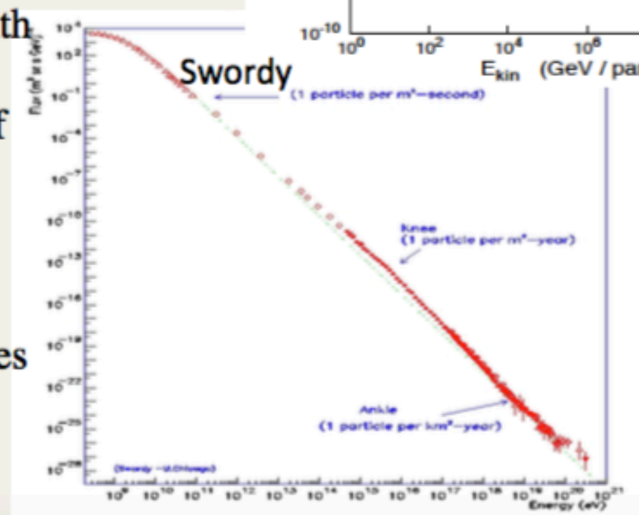
$\sim E^{-3.0}$, $3 < E_{PeV} < 100$

- Strong solar cycle modulation below ~ 10 GeV

- Energy density ~ 1 eV cm^{-3}, near equipartition with magnetic & thermal/ turbulent energy density of interstellar gas.

- Most of the pressure comes from ~ GeV particles

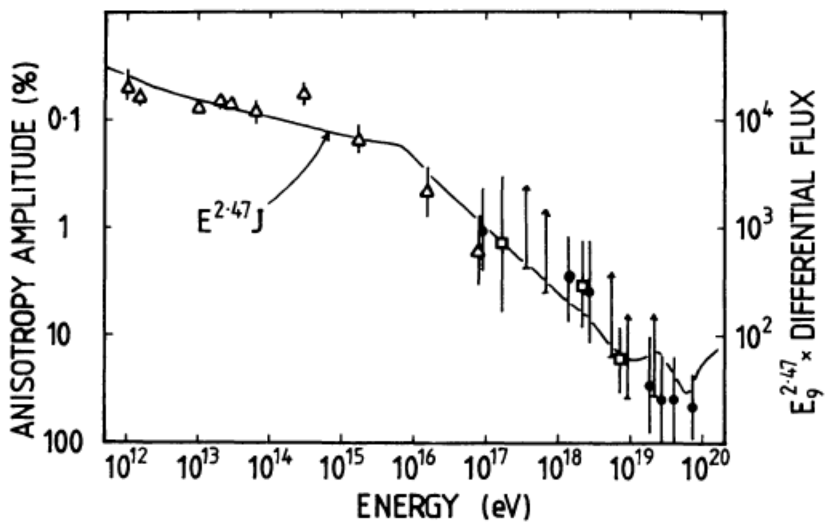




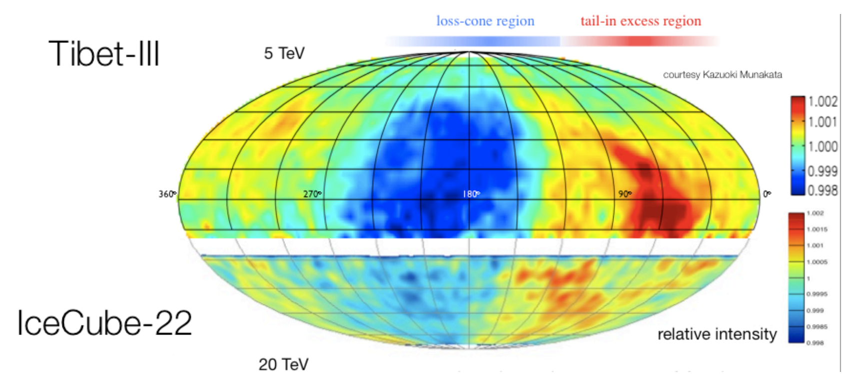
Highly isotropic & resident for ~10Myr

(An)Isotropy

<u>Left</u>: The distribution of cosmic ray arrival directions is highly isotropic, up to the knee.
<u>Right</u>: Weak fluctuations at TeV energies have been discovered recently & challenge theory.

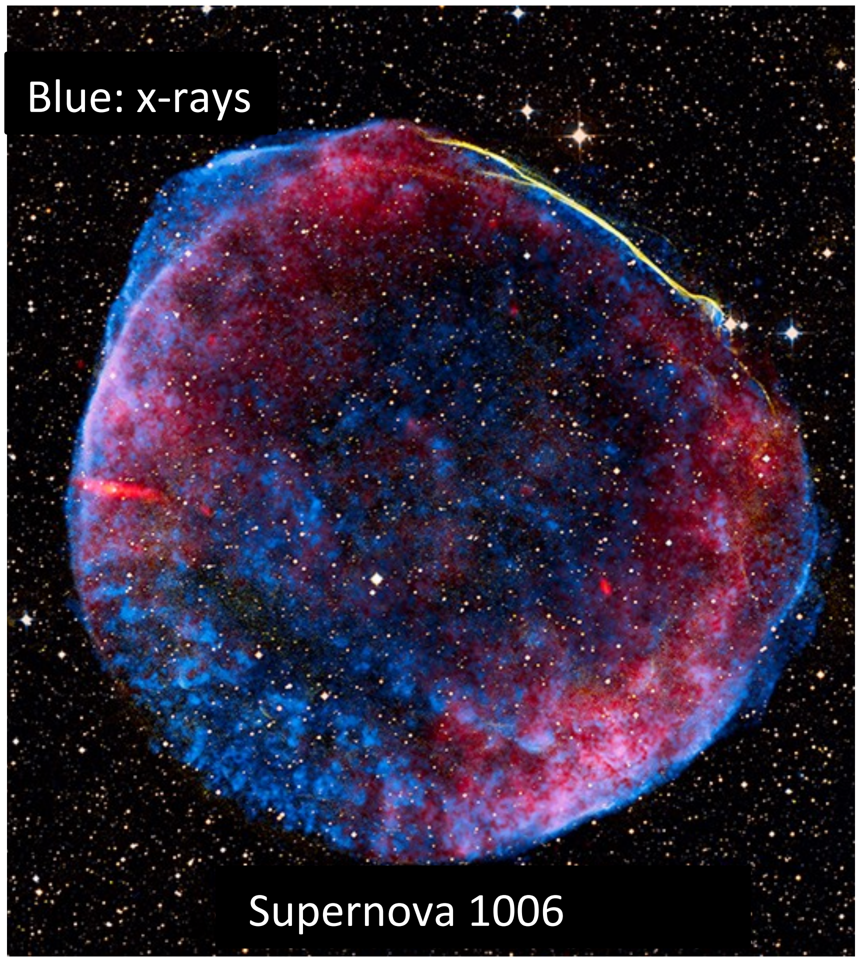


Hillas 1984

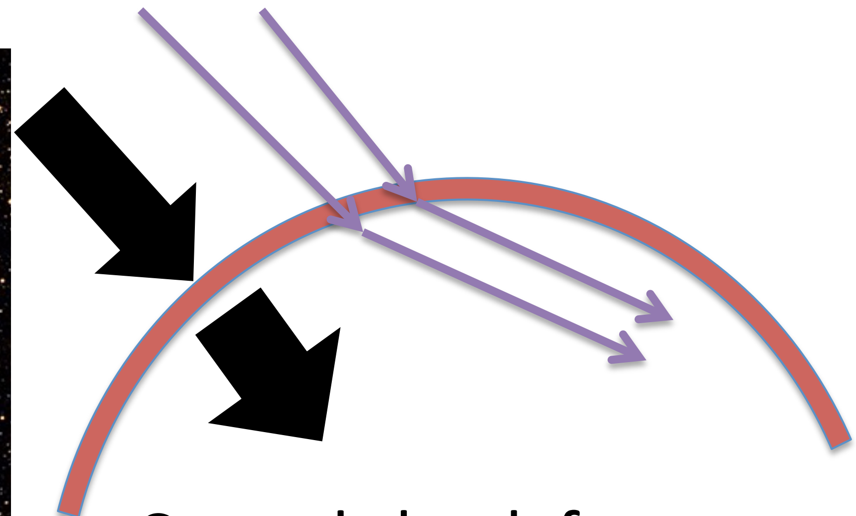


Abbasi et al. 2010

Cosmic Ray Acceleration



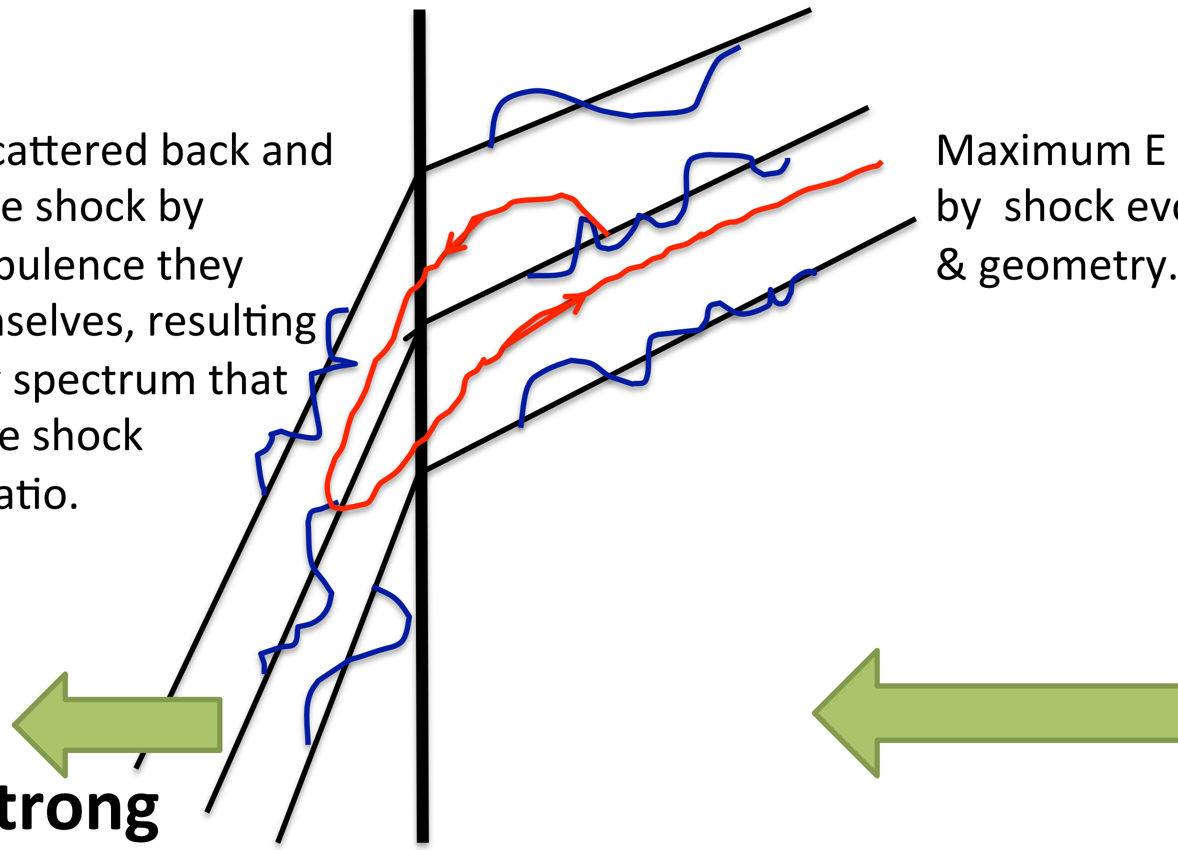
NASA image



- Curved shock front (red), fluid flow in frame of shock (black arrows), magnetic fieldlines in purple.

Diffusive Shock Acceleration

Particles are scattered back and forth across the shock by waves and turbulence they generate themselves, resulting in a power law spectrum that depends on the shock compression ratio.



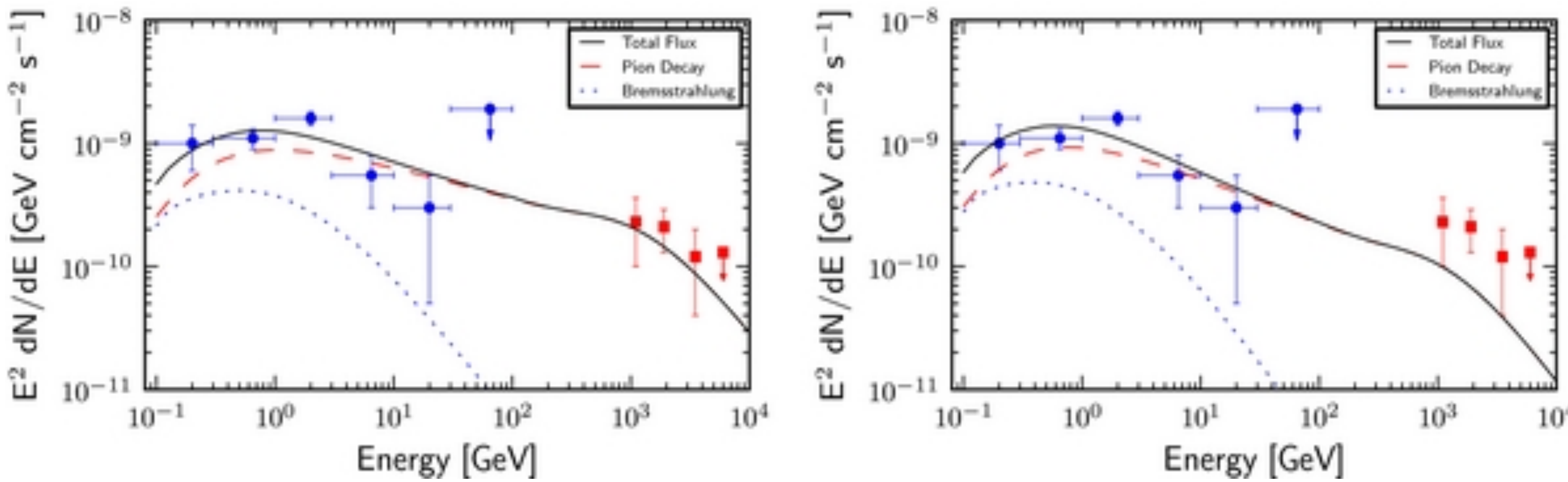
Maximum E is set by shock evolution & geometry.

E^{-2} for strong shock

Overarching Questions

- How does 10^{-9} of interstellar particles come to have as much energy as the thermal pool?
  - Observational probes
  - Acceleration & propagation processes
- How does this virtually collisionless component interact with the thermal gas & magnetic field?
  - Kinetic instabilities
  - Fluid treatments

Extend to Other Galaxies



Fits to the γ-ray spectrum of M82: Left is best fit to γ-ray spectrum, Right is best fit to radio spectrum. Milky Way-like assumptions about cosmic ray acceleration produce good fits (Yoast-Hull et al 2013)

Breakdown of Equipartition

Cosmic Rays in Arp 220

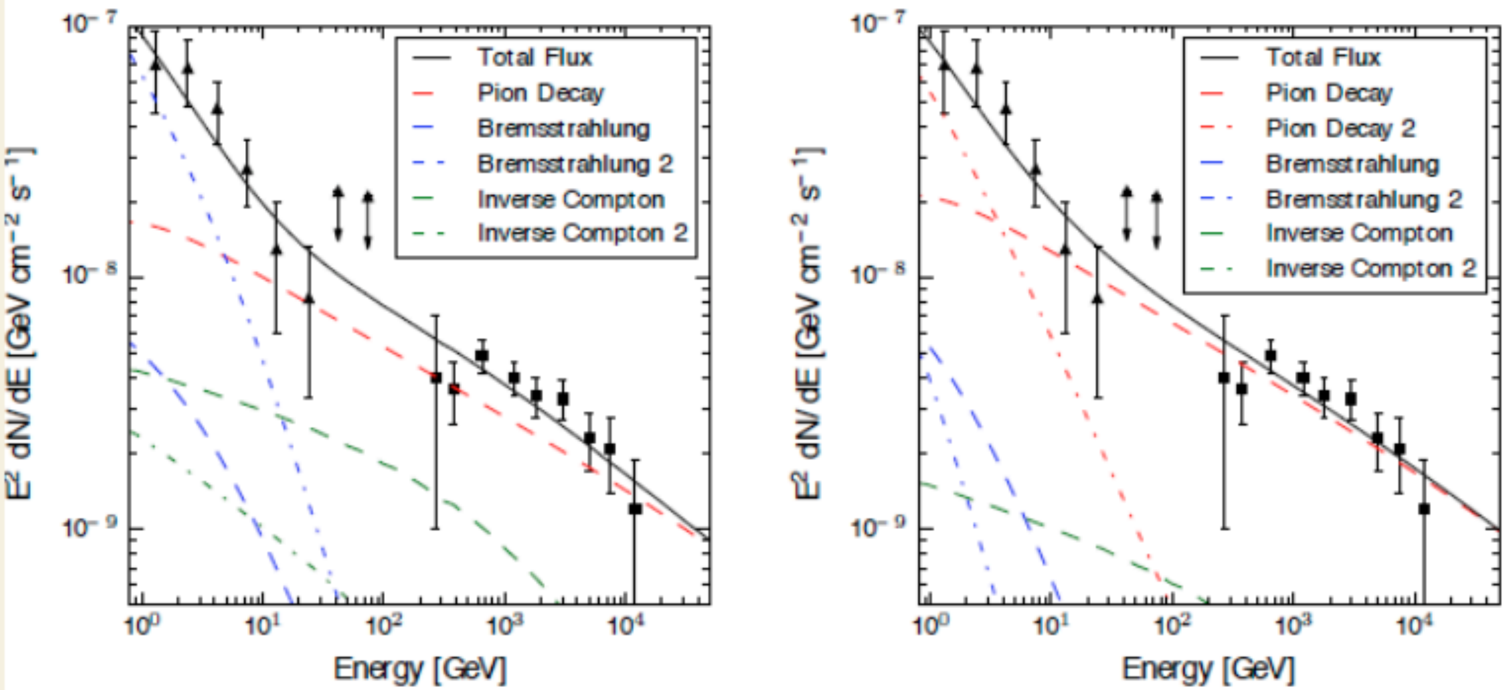
Yoast-Hull l et al. 2015

TABLE 2
ENERGY DENSITY DISTRIBUTION IN GALAXIES

	Supernova Power (erg yr^{-1})	Average Gas Density (cm^{-3})	Cosmic Ray Energy Density (eV cm^{-3})	Radiation Field Energy Density (eV cm^{-3})	Magnetic Field Energy Density (eV cm^{-3})	Magnetic Field Strength (μG)
Milky Way	2×10^{48}	1	1.4	0.3	0.9	6
M82	7×10^{48}	550	250	1000	1800	250
Arp 220 East	7×10^{49}	17,000	1300	40,000	220,000	3000
Arp 220 West CND	1.3×10^{50}	90,000	3500	440,000	890,000	6000

NOTE. — Values for the Milky Way are taken from Table 1.5 in Draine (2011). For M82 & Arp 220, the values for the cosmic ray & magnetic field energy densities taken from our best-fit models (see Section 3 above and YEGZ).

Milky Way Central Molecular Zone



(a) Model A, Soft Electron Spectrum

(b) Model A, Soft Proton Spectrum

Soft electron spectrum over produces radio; soft proton spectrum requires huge energy input. From Yoast-Hull et al. 2014.

Coupling to the Thermal Gas

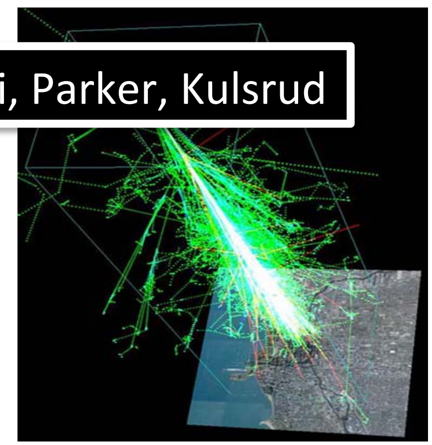
Collisional

- Ionization
  - Heating
  - Chemistry
- Radiative Processes
  - γ-rays from π^0 decay & inverse Comption
  - Bremsstrahlung
- Light element production

Collisionless

- Momentum & energy exchange mediated by the ambient magnetic field.

Fermi, Parker, Kulsrud

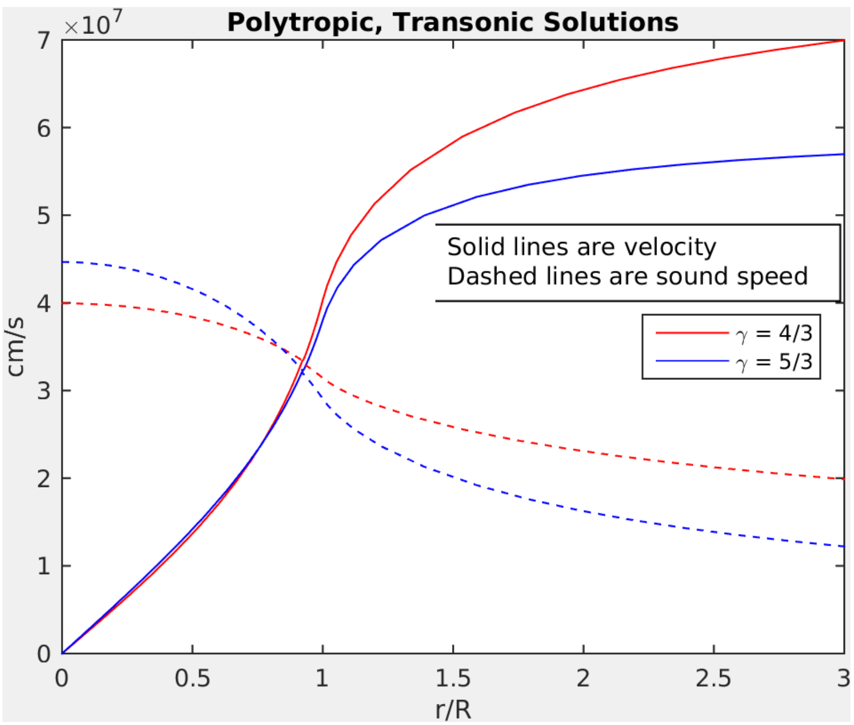


The subject of this talk

Plan of This Talk

- Motivation
- Classical Cosmic Ray Hydrodynamics
- Generalized Cosmic Ray Hydrodynamics
  - Justification for approximate treatments?
- Beyond Alfven Waves
  - Going to extremes
- Unfinished business

Galactic Winds: One Motivation



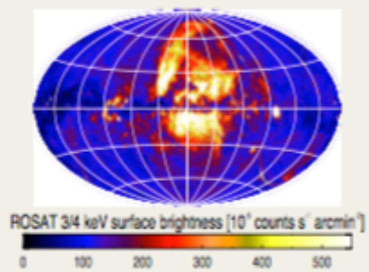
Cory Cotter & Chad Bustard

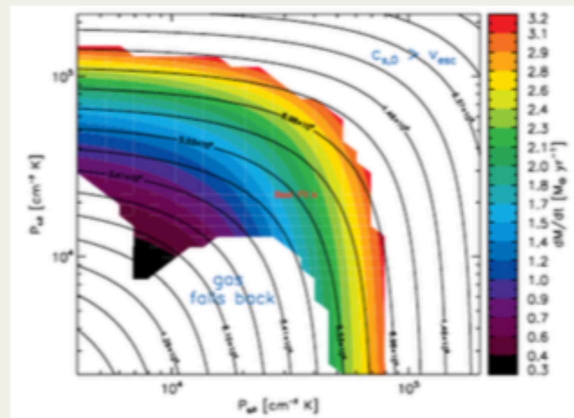
- Steady, spherically symmetric, pressure driven outflow *a la* Chevalier & Clegg 1985 but extended.

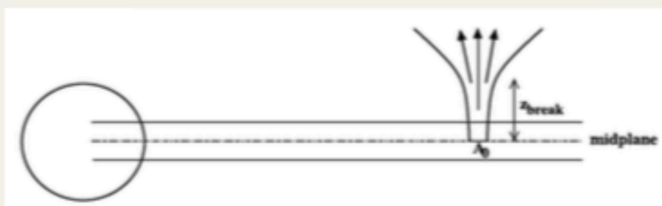
(Bustard, EZ, D'Onghia 2015)

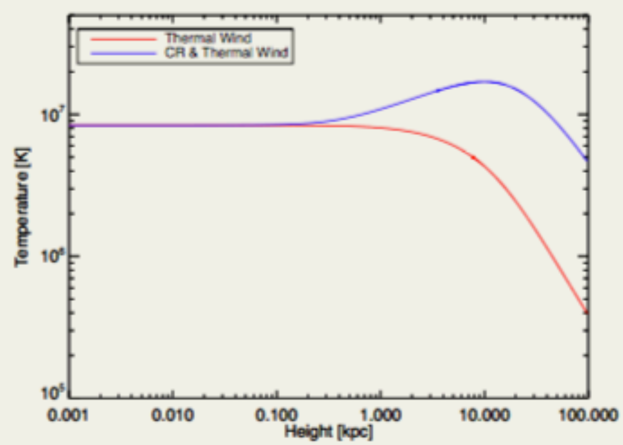
- Relativistic fluid cools more slowly & drives a faster wind.

Milky Way Wind





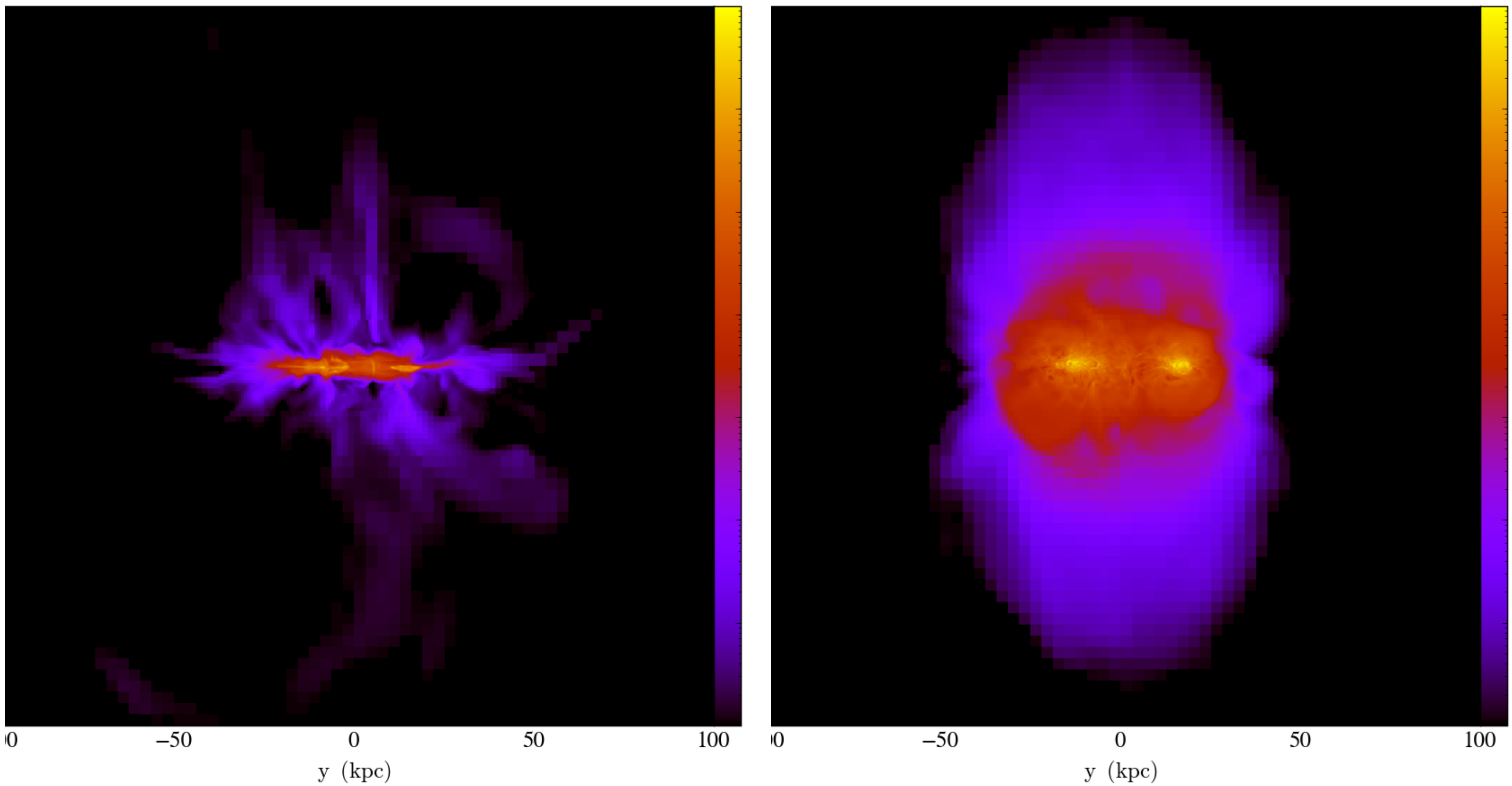




Top left: Soft x-ray sky,
Bottom left: Magnetic flux tube geometry.
Top right: Domains of flow, with mass loss rates
Bottom right: Gas temperature with & without cosmic ray heating.

Everett et al. 2008 ApJ

Recent Simulations of a Star-Forming Disk



Left: Initially toroidal magnetic field, no cosmic rays. Right: With cosmic rays. *Ruszkowski, Yang, EZ in preparation.*

Perpendicular Dynamics are Easy

Cosmic ray force balance:

$$\nabla_\perp P_c = \frac{\boldsymbol{J}_c \times \boldsymbol{B}}{c}$$

Lorentz force on thermal gas: $\boldsymbol{J}_g \times \boldsymbol{B}/c$

$$= \frac{\boldsymbol{J} \times \boldsymbol{B}}{c} - \frac{\boldsymbol{J}_c \times \boldsymbol{B}}{c}$$

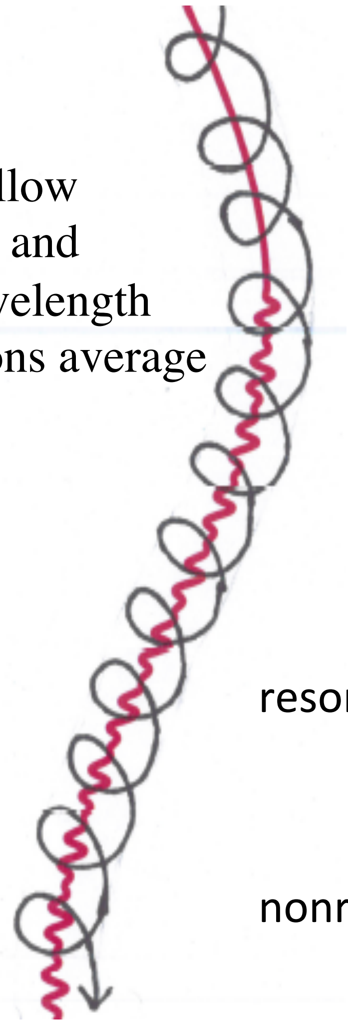
$$= \frac{\boldsymbol{J} \times \boldsymbol{B}}{c} - \nabla_\perp P_c.$$

Pressure gradient introduced through Lorentz force

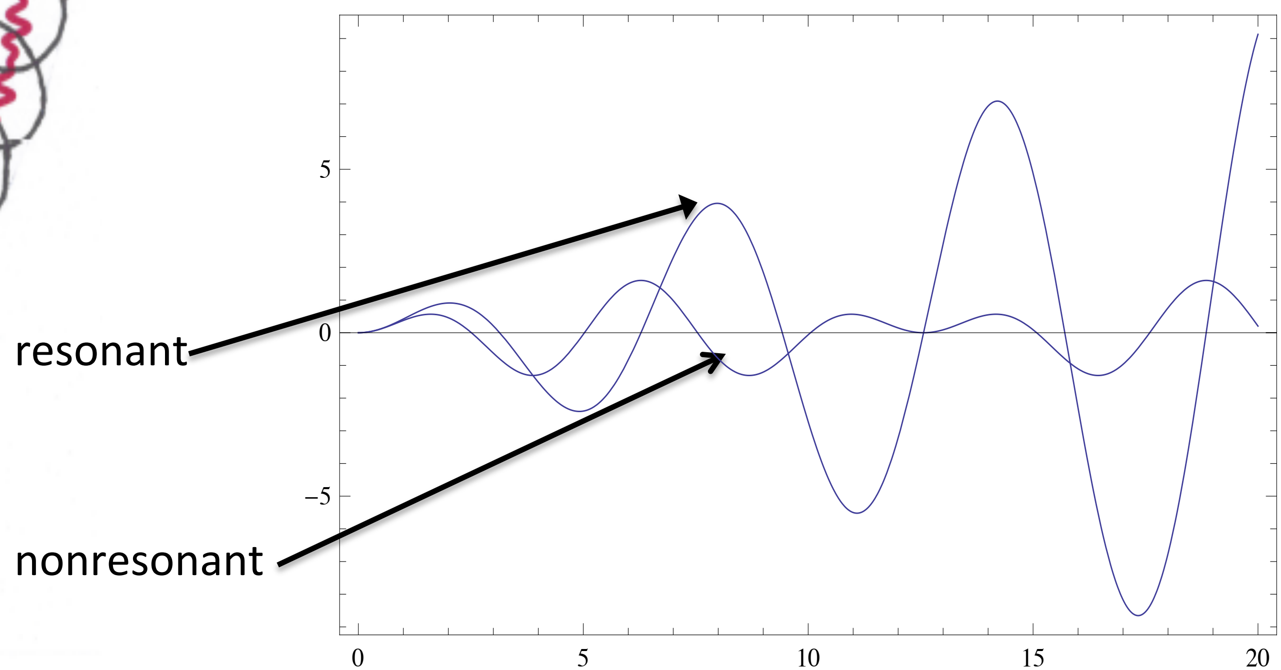
Parallel Dynamics are Subtle

Gyroresonant Scattering

Orbits follow fieldlines and short wavelength fluctuations average out.



Gyroresonant fluctuations (Doppler shifted frequency $kv_{parallel} = \omega_{cr}$) scatter in pitch angle $\cos^{-1} \mu$.



Gyroresonant Streaming Instability

$$\Gamma_{cr} = \frac{\pi^2 q^2}{2} \frac{v_A^2}{c^2} \sum_{\pm} \int \delta(\omega - kv\mu \pm \omega_c) v (1-\mu^2) \left[\frac{\partial f}{\partial p} + \left(\frac{kv}{\omega} - \mu\right) \frac{1}{p} \frac{\partial f}{\partial \mu}\right] p^2 dp d\mu,$$

resonance

damping

excitation by anisotropy

Simple approximation to the growth rate:

$$\Gamma_{cr} \sim C \omega_{ci} \frac{n_{cr}}{n_i} \left(\frac{v_D}{v_A} - 1\right)$$

Here & elsewhere I'm interested in the bulk cosmic rays w $\gamma \sim 1$

Fokker – Planck (F-P) Equation

Back reaction of waves on zero order cosmic ray distribution function f_0

$$\frac{df_0}{dt} = -\left\langle \frac{q}{m}\left(\boldsymbol{E}_1 + \frac{v \times \boldsymbol{B}_1}{c}\right) \cdot \boldsymbol{\nabla}_p f_1 \right\rangle$$
$$= \boldsymbol{\nabla}_p \cdot \boldsymbol{D} \cdot \boldsymbol{\nabla}_p f_0.$$

Small angle
Scattering by
nearly periodic
randomly
phased waves

Pitch angle scattering ($D_{\mu\mu}$) dominates:

Scattering frequency $\nu \sim \omega_c(\delta B/B)^2$

$D_{p\mu} = D_{\mu p}$ are order (v_A/c) D_{pp} is order $(v_A/c)^2$

Energy Equation

Multiply F-P eqn. by particle energy ε & integrate over momentum space:

$$\frac{\partial U_c}{\partial t} + \boldsymbol{\nabla} \cdot \tilde{\boldsymbol{W}}_c = -\int d\omega dk 2\Gamma_{cr}(\omega, k) I(\omega, k)$$

Energy density Energy flux Energy transfer to waves

Frequent Scattering Approximation

Relate anisotropy to spatial gradient:

$$D_{\mu\mu}\frac{\partial f_0}{\partial \mu} + D_{\mu p}\frac{\partial f_0}{\partial p} = -\frac{v(1-\mu^2)}{2}\frac{\partial f_0}{\partial z}$$

Energy equation simplifies to:

$$\frac{\partial U_c}{\partial t} + \boldsymbol{\nabla}\cdot\tilde{\boldsymbol{W}}_c = \boldsymbol{v}_A\cdot\boldsymbol{\nabla}P_c.$$

"frictional heating"

Equation for Waves

From Dewar's theory:

$$\frac{\partial}{\partial t}\frac{\delta B^2}{4\pi} = -\boldsymbol{\nabla}\cdot\boldsymbol{W}_w + \boldsymbol{u}\cdot\boldsymbol{\nabla}\frac{\delta B^2}{8\pi} - \boldsymbol{v}_A\cdot\boldsymbol{\nabla}P_{cr} - G.$$

$$\boldsymbol{W}_w \equiv \frac{\delta B^2}{4\pi}\left(\boldsymbol{v}_A + \frac{3}{2}\boldsymbol{u}\right)$$

Adiabatic terms

Driving & dissipation

Heating rate

$$\rho\frac{dQ}{dt} = G.$$

Fluid Treatment

- "Classical Cosmic Ray Hydrodynamics (CCRH)
  - Equations developed by Volk & collaborators based on self-confinement model
  - Stream down pressure gradient at $\mathbf{v_A}$ relative to thermal gas *(care needed in implementing this).*
  - Transfer momentum through pressure gradient
  - Heat gas at $-\mathbf{v_A}$ **grad** P_c.
  - Diffusion along B with diffusivity $\kappa \sim v^2/\nu$
- Applied to shocks, galactic winds, ISM heating, intracluster medium.

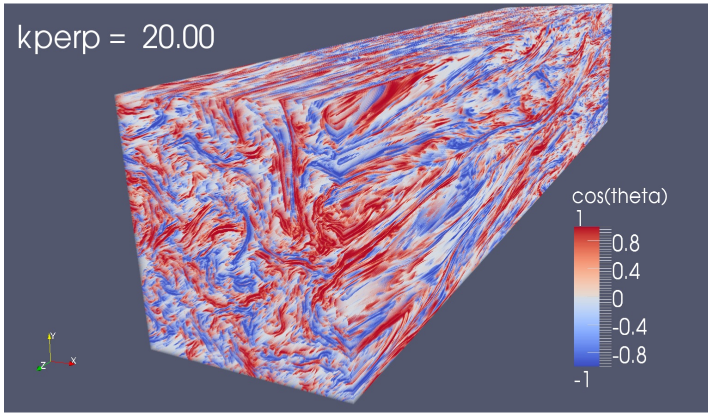
Approximations & Improvisations

- Include grad P_c, advect with fluid, ignore heating, diffusion if any is isotropic.
  - No magnetic field calculation necessary *(implicitly stochastic on gyroradius scale).*
  - No need to ensure streaming is down **grad** P_c.
- Include streaming relative to thermal gas & frictional heating, but replace v_A by thermal sound speed v_S.
  - Same advantages as previous bullet.

These are the main variants in the literature

Generalized Cosmic Ray Hydrodynamics (GCRH)

- Account for non-cosmic ray sources of waves.



MHD turbulence, Boldyrev group

- Generalize F-P equation to include waves traveling in both directions.

From Fokker-Planck Equation

- Composite streaming velocity

$$w \equiv \frac{\nu_+ - \nu_-}{\nu_+ + \nu_-} v_A$$

- Pressure gradient force is unchanged

Wave Evolution Equations

$$\frac{\partial}{\partial t}\frac{\delta B^{2,\pm}}{4\pi} = -\boldsymbol{\nabla}\cdot\boldsymbol{W}_w^{\pm} + \boldsymbol{u}\cdot\boldsymbol{\nabla}\frac{\delta B^{2,\pm}}{8\pi} \mp \frac{\nu_{\pm}}{\nu_{+}+\nu_{-}}\boldsymbol{v}_A\cdot\boldsymbol{\nabla}P_{cr} - G^{\pm} + L^{\pm},$$

$$\boldsymbol{W}_w^{\pm} \equiv \frac{\delta B^{2,\pm}}{4\pi}\left(\pm\boldsymbol{v}_A + \frac{3}{2}\boldsymbol{u}\right);$$

cosmic ray driving/damping

extrinsic driver

Balance Driving & Damping

Simple model

$$\tau_A \equiv -\frac{P_{cr}}{\boldsymbol{v}_A \cdot \nabla P_{cr}},$$

$$\frac{E_+}{E_+ + E_-}\frac{P_{cr}}{\tau_A} - 2\Gamma E_+ + \frac{\dot{E}}{2} = 0,$$

$$-\frac{E_-}{E_+ + E_-}\frac{P_{cr}}{\tau_A} - 2\Gamma E_- + \frac{\dot{E}}{2} = 0.$$

This is easily solved

Transport Velocity

$$w = \frac{v_A}{x + \sqrt{1 + x^2}}$$

$$x \equiv \frac{\dot{E}\tau_A}{2P_c}$$

w -> 0 when external driving dominates
w -> v_A when cosmic ray driving dominates

Cosmic ray heating is reduced but compensated by turbulent damping

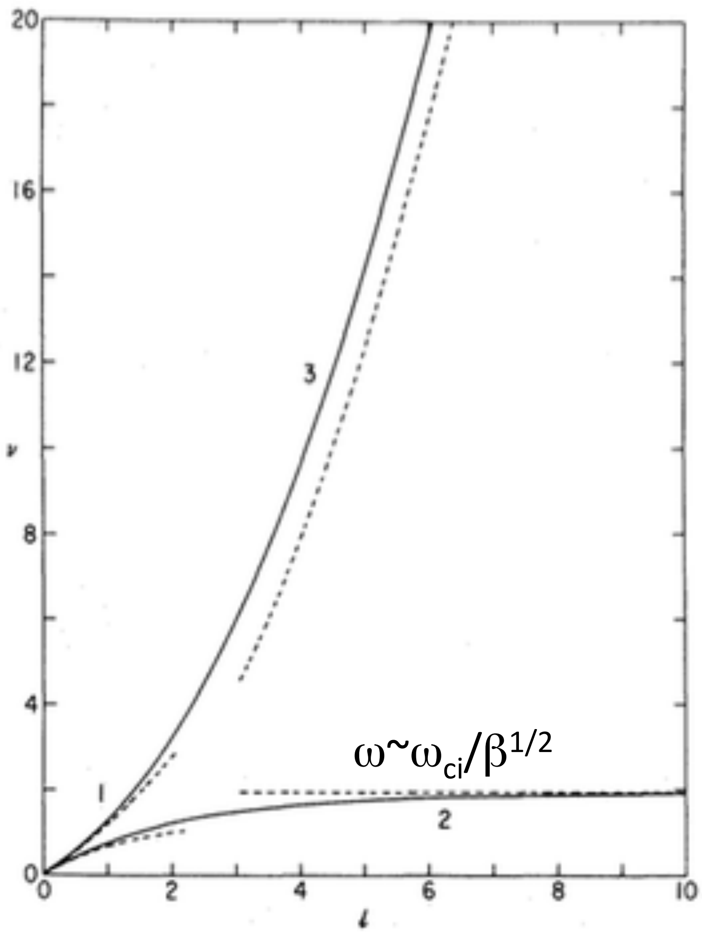
Extrinsic Turbulence Model

- Advect cosmic rays at the fluid speed v.
- Neglect cosmic ray heating.
- Retain pressure gradient force.

All hold in the limit of strongly driven, balanced turbulence.

- But, Alfven turbulence produces anisotropic, field aligned diffusion.
- Isotropic diffusion is produced by a small scale, stochastic field.

Beyond Alfven Waves – High β



- For $\beta = P_G/P_M >> 1$

- Affects waves which scatter cosmic rays with $\mu > \mu_c$

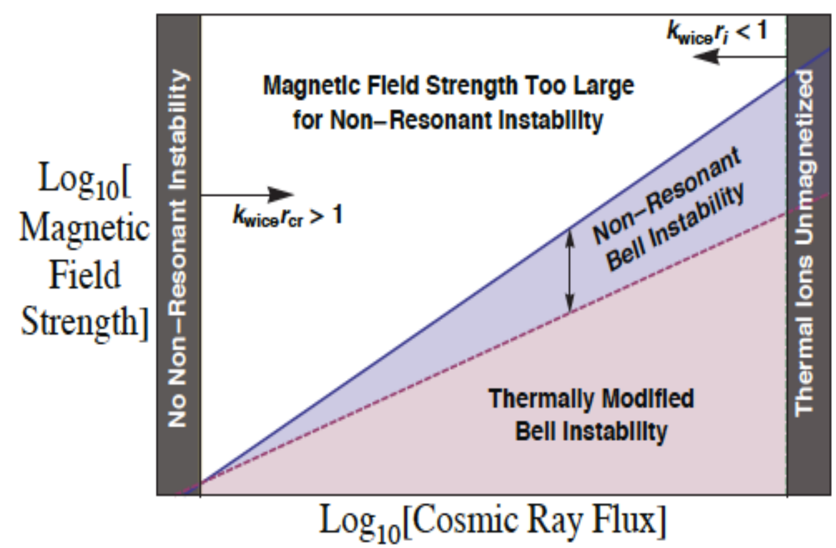
$$\mu_c \sim \frac{v_i}{c}\beta^{1/2}.$$

- Demands very weak fields, e.g B < 10^{-12}G in galaxy clusters.

Enforces sub-Alfvenic streaming

Nonresonant Instabilities

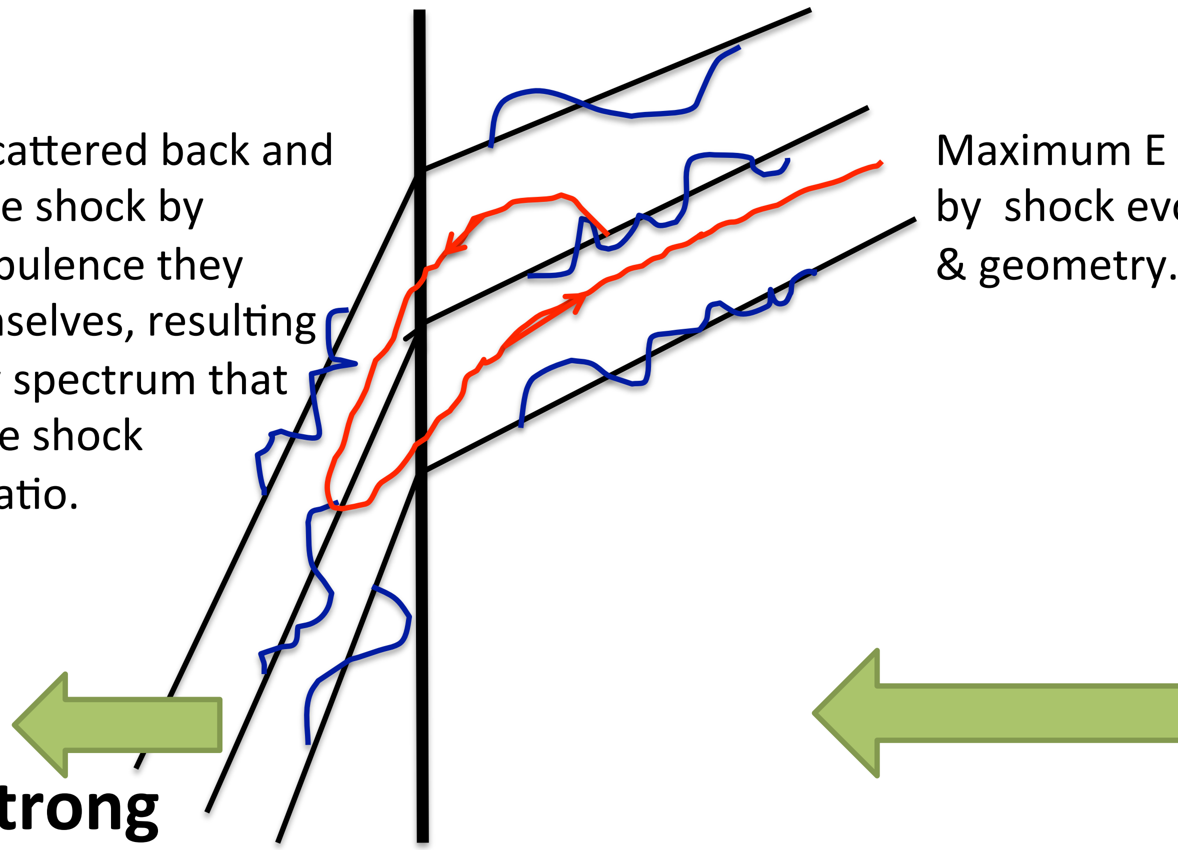
- When $U_{cr}/U_B > c/v_D$ there is a new, nonresonant instability driven by the electron current that compensates the cosmic ray current.
- Conditions are met at shocks, and possibly in young galaxies.



Evereyy & EZ 2010

Diffusive Shock Acceleration

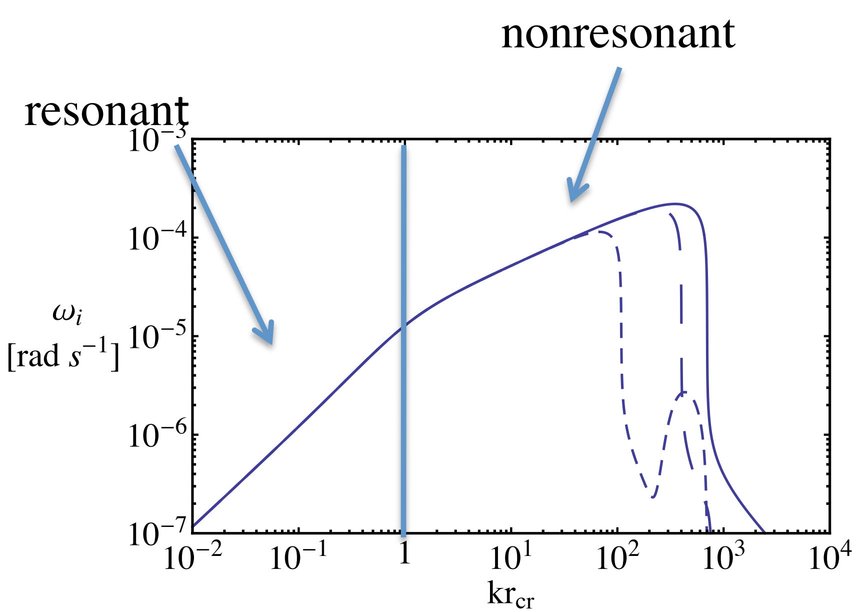
Particles are scattered back and forth across the shock by waves and turbulence they generate themselves, resulting in a power law spectrum that depends on the shock compression ratio.



Maximum E is set by shock evolution & geometry.

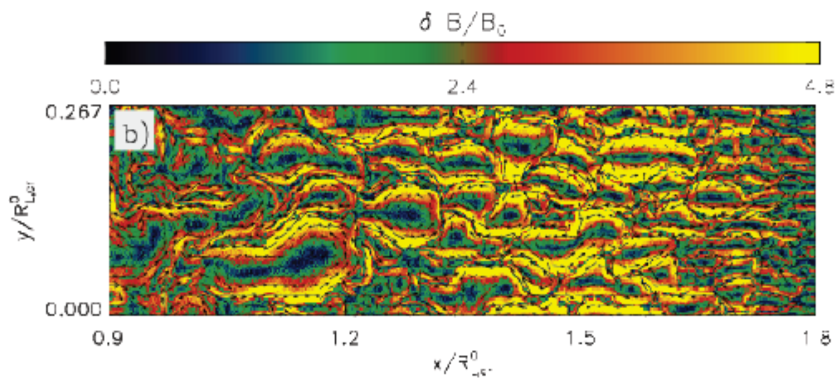
E^{-2} for strong shock

Rapid Growth to Nonlinear Amplitude



Linear growth rates (Zweibel & Everett 2010)

PIC simulation showing magnetic field growth in a shock layer.



Riquelme & Spitkovsky 2010

Beyond Alfven Speed

- Resonant instabilities enforce sub-Alfvenic streaming & require extremely weak fields.
- Nonresonant instabilities require large cosmic ray fluxes
  - Growth rates comparable to frequency require nonstandard treatments
  - Could be very interesting in weak field situations.

Summary & Prospects

- Cosmic rays appear in diffuse plasmas everywhere, in defiance of thermodynamics.
- They exchange momentum and energy with the background medium, mediated by magnetic fields.
- Advances in observation, computation, & experiment make this a wonderful time to study their acceleration, transport, and feedback.