The Physics of Cosmic Rays

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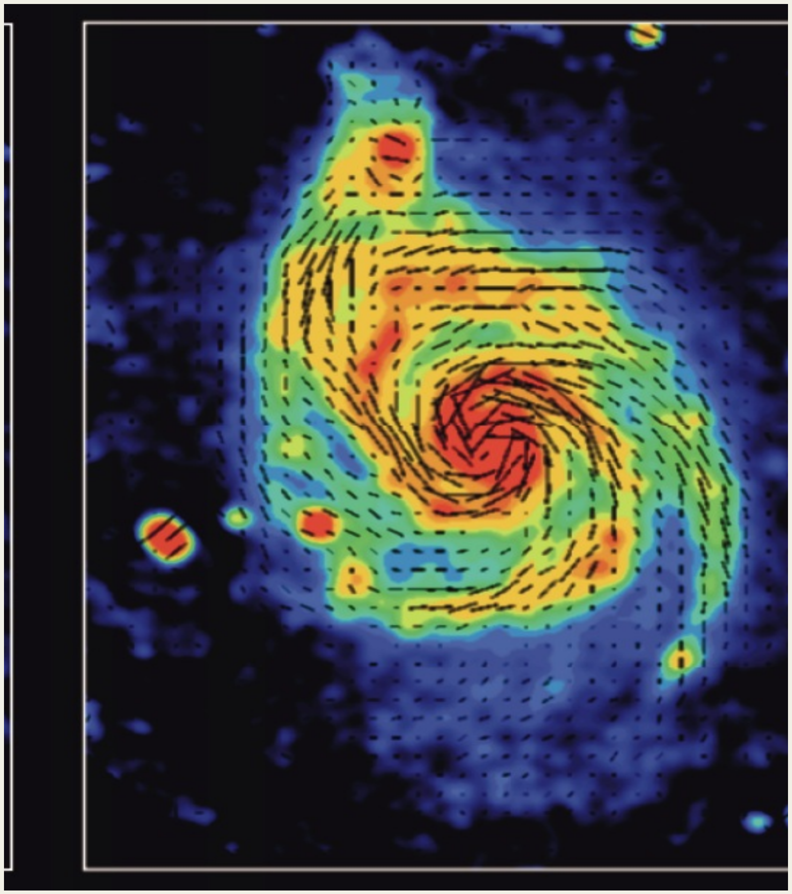
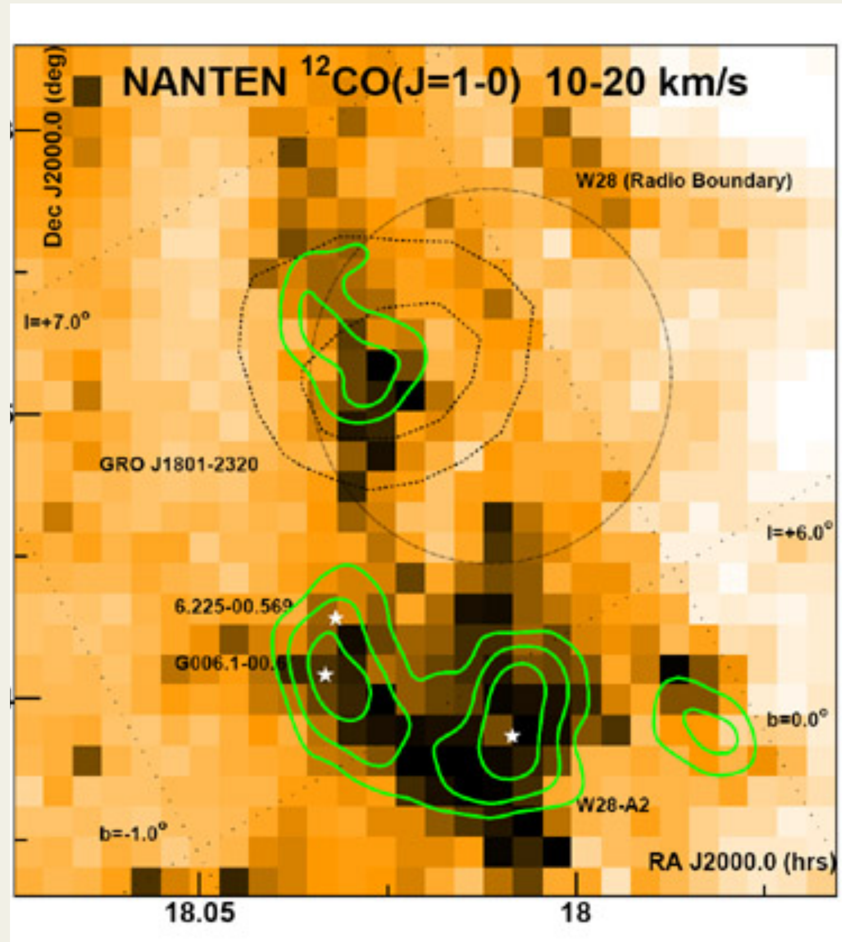
Galaxies are Pervaded by Magnetic Fields & Relativistic Particles



Synchrotron radiation from M51 (MPIfR/NRAO)



Galactic molecular clouds illuminated by γ-rays H.E.S.S. collaboration)

How is Energy Partitioned Between Gas, Magnetic Fields, and Cosmic Rays?

- How do < 10^{-9} of interstellar particles acquire as much energy as the background gas?
- What controls the cosmic ray energy spectrum and composition?
- How do cosmic rays couple thermally and dynamically to the background gas despite being virtually collisionless?
- How do cosmic rays regulate the extreme environments in which they are accelerated?

The Plan of This Talk

- Brief review of cosmic ray properties
- Cosmic ray hydrodynamics & applications
  - Galactic winds
  - Heating interstellar gas
- The lab connection
- Future opportunities

Collaborators: E. Boettcher, P. Desiati, J. Gallagher, D. Lee, P. Oh, P. Ricker, M. Ruszkowski, J. Wiener, K. Yang, T. Yoast-Hull

with support from the National Science Foundation

Some Early Milestones in Cosmic Ray Astrophysics

- *1912* Hess shows the cosmic origin of atmosphere ionization.
- *1927* Clay shows the ionizing flux is latitude dependent, suggesting that "cosmic rays" are charged particles, deflected by the geomagnetic field.
- *1934* Baade & Zwicky propose that cosmic rays originate in supernovae.
- *1949* Hall & Hiltner detect a pervasive Galactic magnetic field through its effect on starlight polarization.
- *1949* E. Fermi proposes his theory of cosmic ray acceleration

Energy Spectrum

- A broken power law:

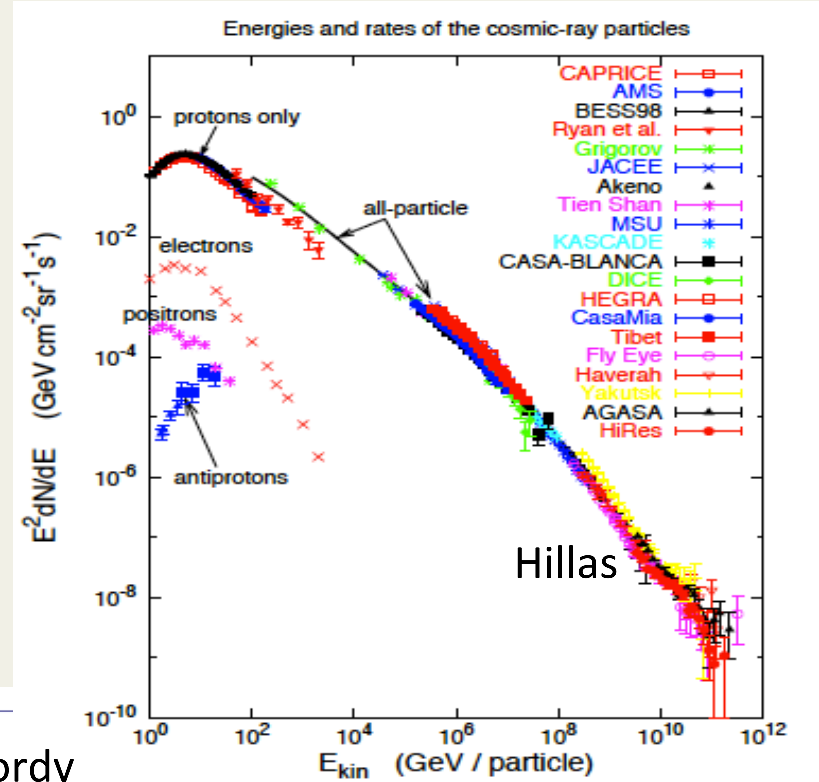
$N(E) \sim E^{-2.7}$, $E_{PeV} < 3$

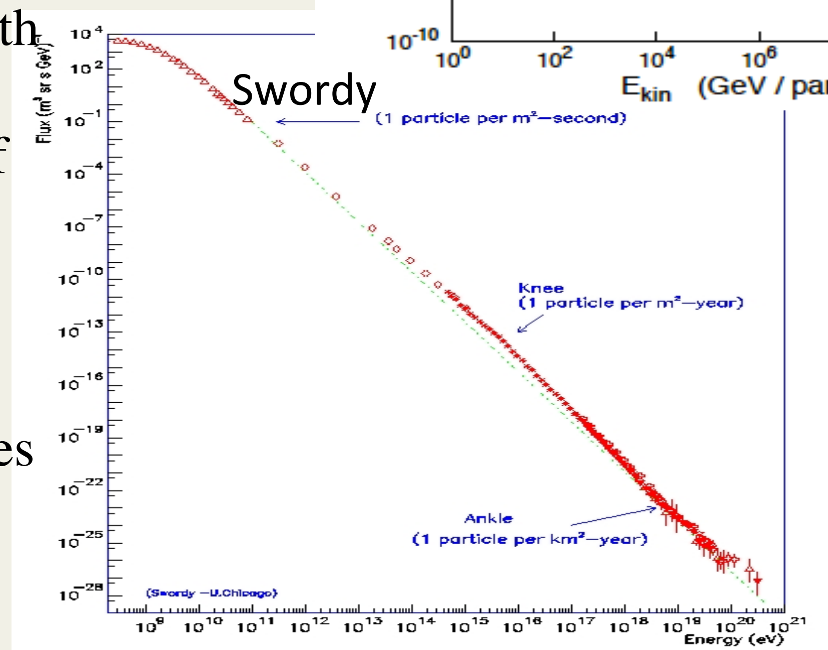
$\sim E^{-3.0}$, $3 < E_{PeV} < 100$

- Strong solar cycle modulation below ~ 10 GeV

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

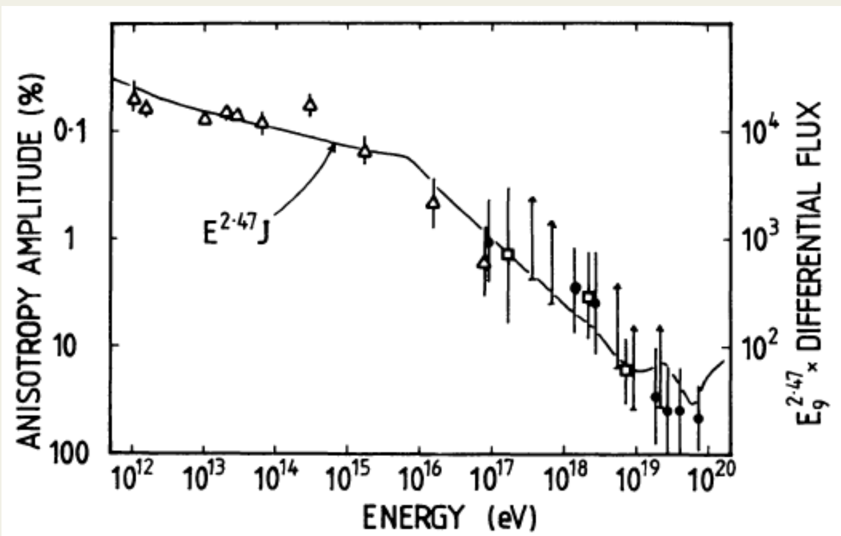
- Most of the pressure comes from ~ GeV particles



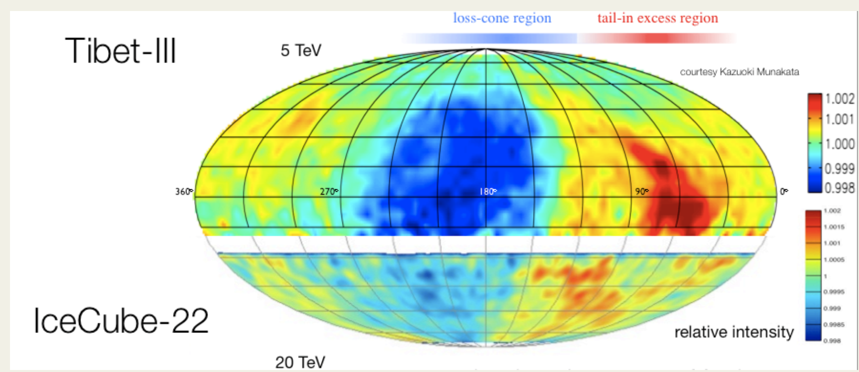


(An)Isotropy

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



Hillas 1984



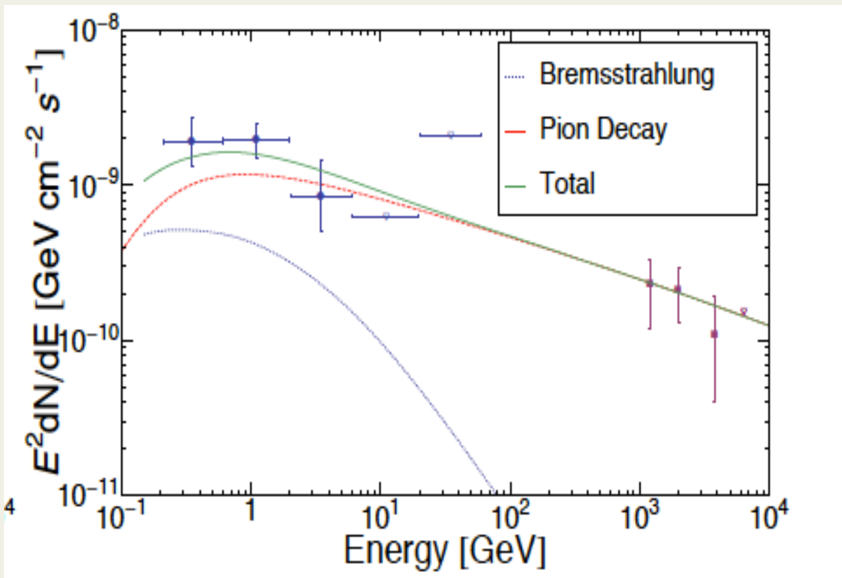
Abbasi et al. 2010

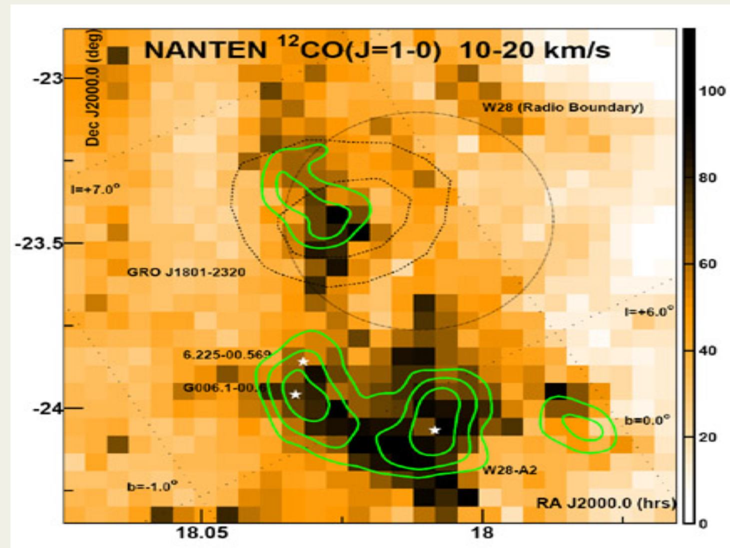
Composition and Lifetime

- Mostly protons
  - Heavier nuclei may dominate at higher energies
- Electrons ~1-2% by number
- Elemental composition similar to solar system
- Enriched in light elements (due to spallation)

- Confinement time ~ 15 Myr up to .4 GeV/ nucleon.
- Confinement times decrease with increasing E.

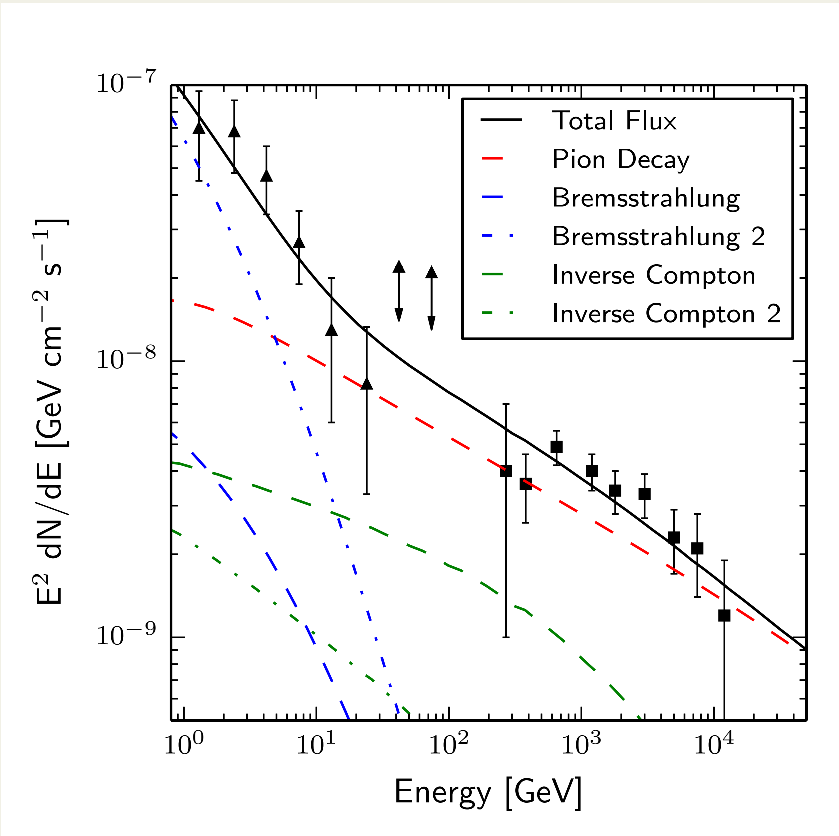
Now Remote Sensing of Cosmic Ray Nuclei

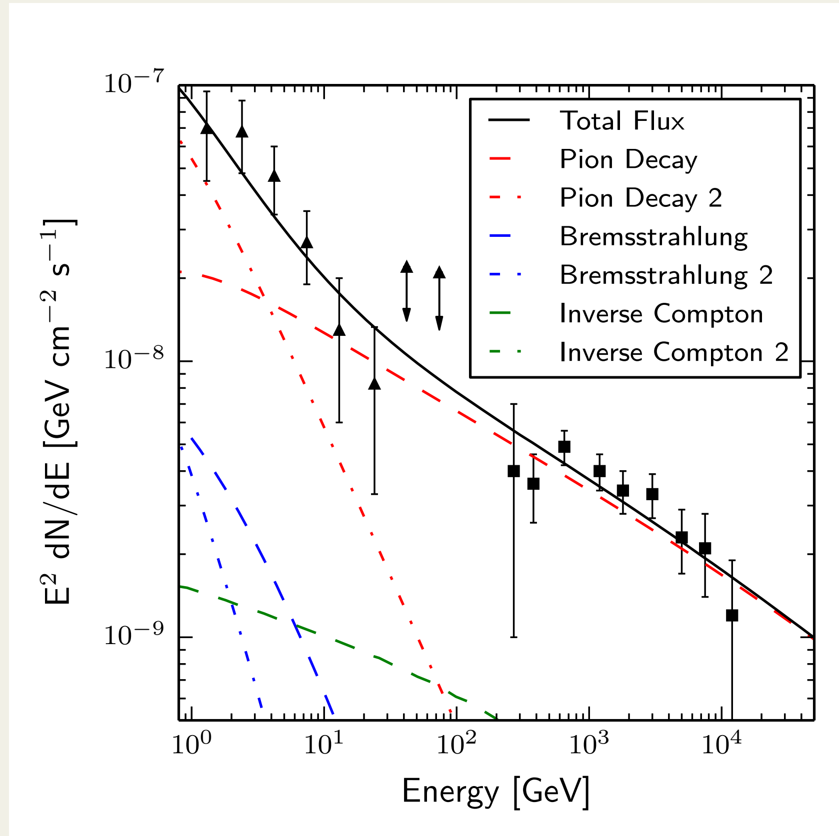




Left: Fermi & VERITAS γ-ray detections from the starburst galaxy M82, fit to a model in which a primary cosmic ray spectrum interacts with the ISM before being advected out by a wind.. *From Yoast-Hull et al. 2012.* Right: Galactic molecular clouds illuminated by γ-rays.

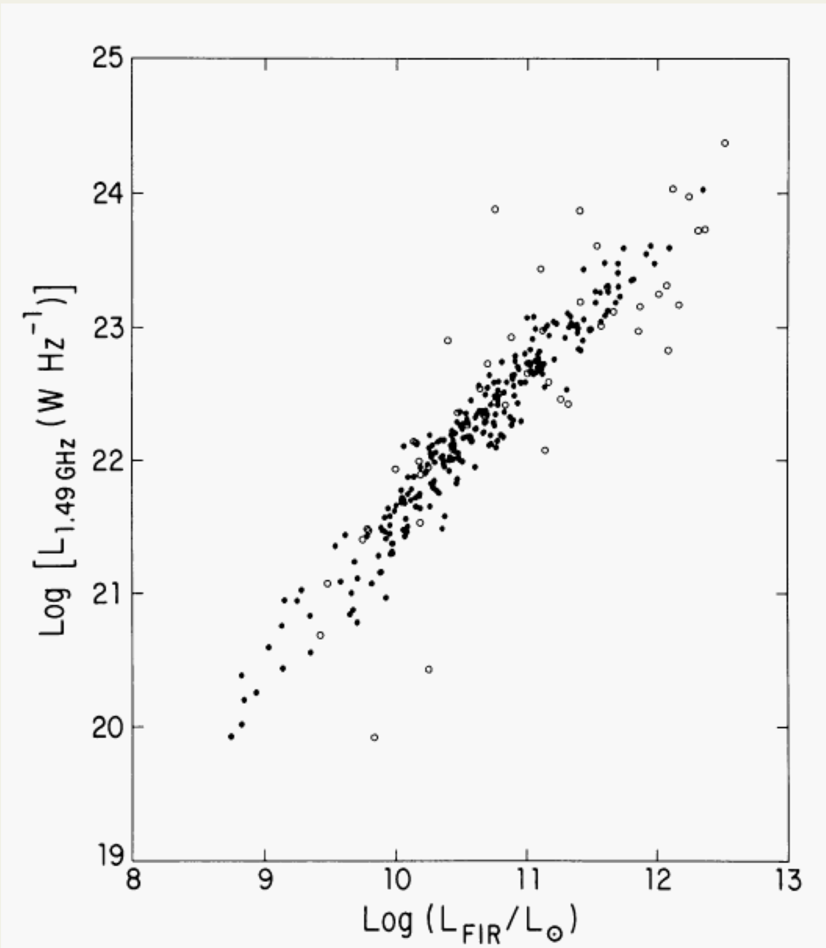
Central Molecular Zone of the Milky Way: Soft γ Excess





Spectrum can be fit with “extra” soft protons, but energy requirements are huge. “Extra” soft electrons overproduce radio. Point sources? Exotic physics*? From Yoast-Hull et al. 2014.*

Far-Infrared Radio Correlation



- Tight correlation between FIR luminosity (measure of SFR) & synchrotron luminosity ($\sim U_B x U_{crl}$)
- Appears to hold at least to $z \sim 2$.
- *Suggests a powerful self-regulation mechanism.*

Properties & Implications

Properties

- Near interstellar composition
- Broken power law spectrum
- Nearly isotropic, anisotropy increases with energy
- Long confinement times
- "Universal" $U_{B,}$ U_{crl}, SFR relationships

Implications

- Source material is interstellar, not supernova ejecta.
- Acceleration & propagation of galactic component produce a power law spectrum.
- Particles are scattered & well trapped by the Galactic magnetic field.
- Particles diffuse with an energy dependent path length that steepens the source spectrum.
- Robust particle acceleration & dynamo processes driven by star formation; possible self-regulation.

Cosmic Ray Orbits: *DNS is Infeasible*

24

100 EeV

Thickness of galactic disk

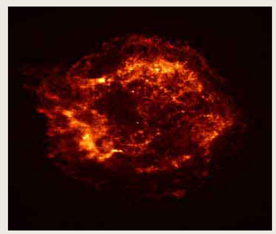
22

1 EeV

20

Young supernova remnant

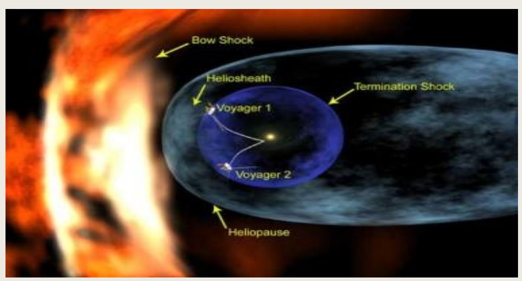
3 PeV



18

16 10 TeV

Heliosphere



14

12 1 GeV

Left scale: distance in cm

Right scale: proton energy with gyroradius at that scale in Galactic magnetic field

A few astronomical scales are also indicated

Elements of Field-Particle Interaction

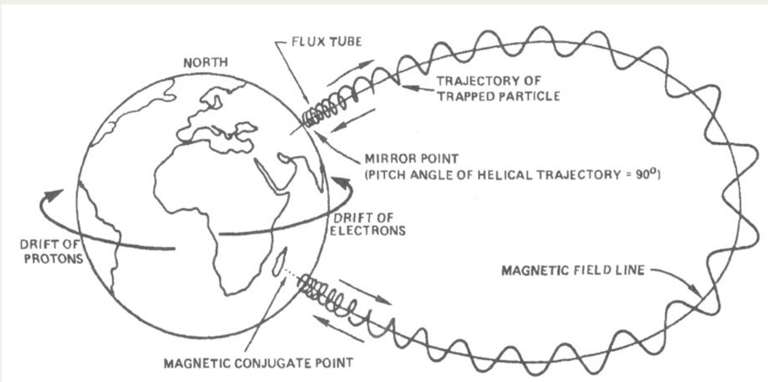
- Orbits
  - Gyromotion
  - Drifts
  - Mirroring
  - Resonant scattering
- Collective behavior
  - Resonant instabilities
  - Nonresonant instabilities *(new)*

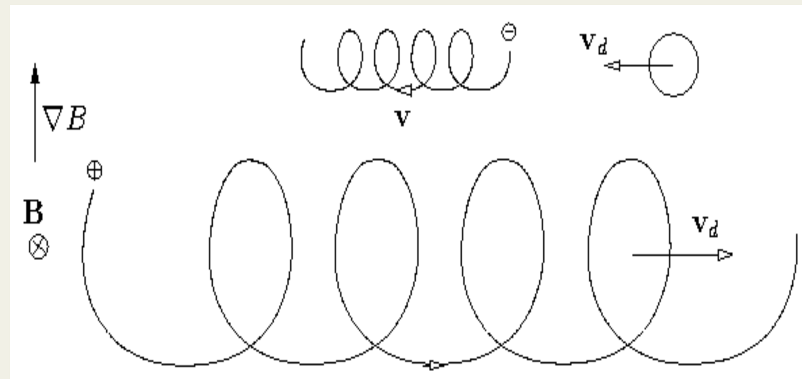
Test particle dynamics plus statistical mechanics

Plasma physics

Drifts and Mirroring

Silas.psfc.mit.edu



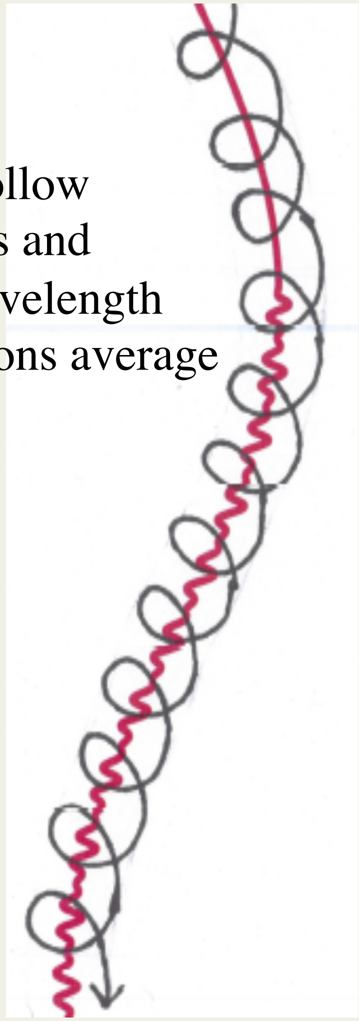


Gruntman 1997

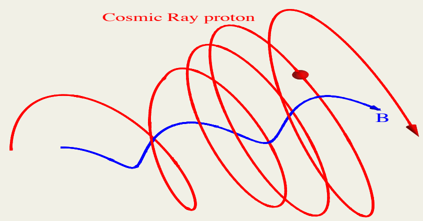
- Magnetic moment $\frac{p_\perp^2}{B}$ is invariant under slow changes in B
- A particle with gyroradius r_g in a B field which varies on scale $L \gg r_g$ drifts across fieldlines at speed $v_{drift} \sim v\frac{r_g}{L}$.

Gyroresonant Pitch Angle Scattering

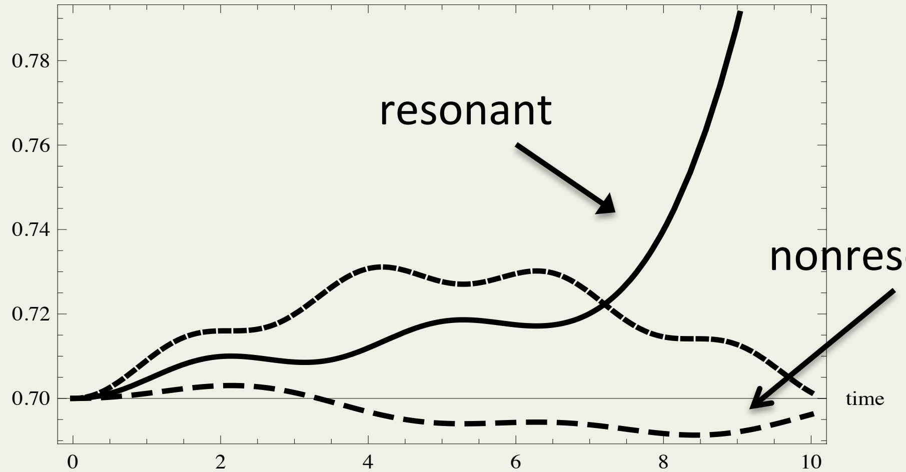
Orbits follow fieldlines and short wavelength fluctuations average out.



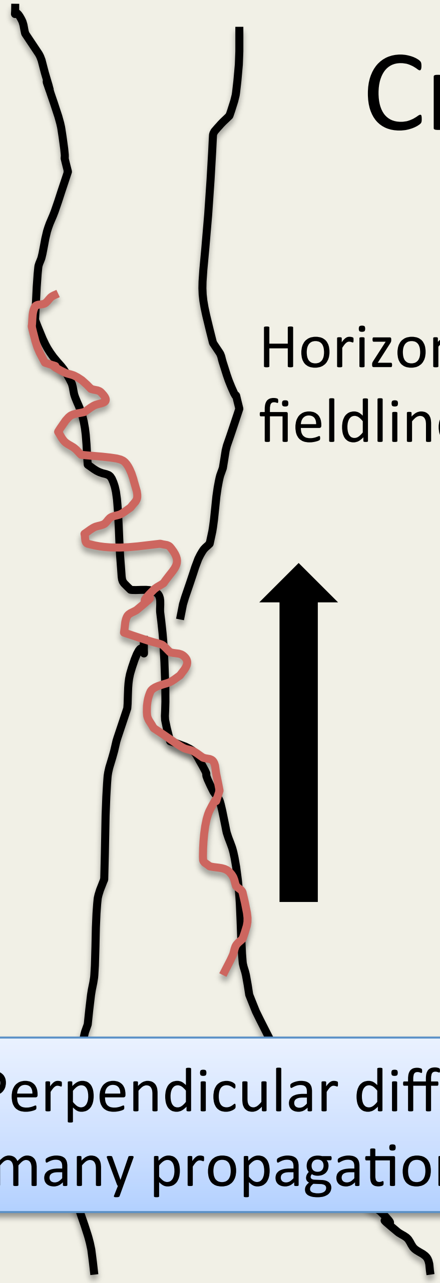
Gyroresonant fluctuations (Doppler shifted frequency $kv_{parallel} = \omega_{cr}$) scatter in pitch angle.



J. Everett

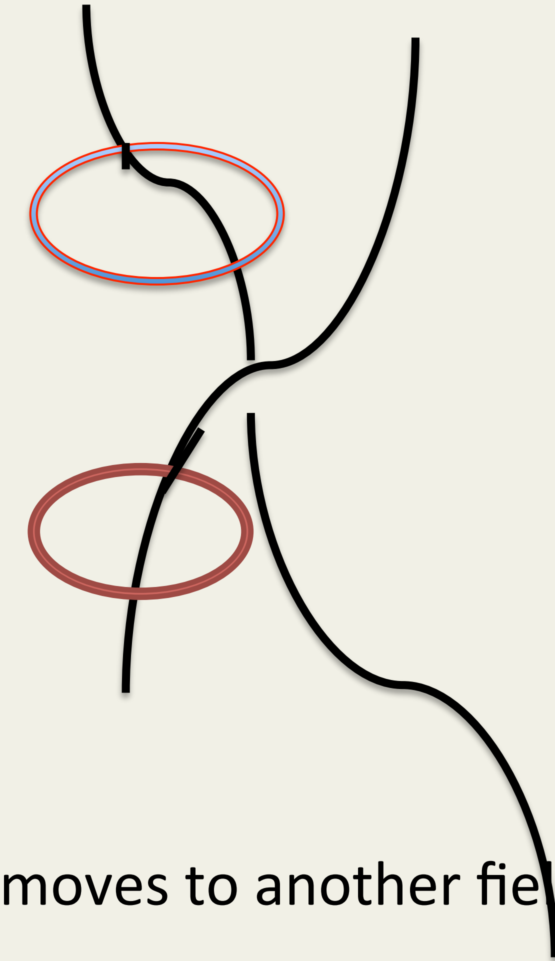


Crossfield Diffusion



Horizontal motion due to fieldline motion

Perpendicular diffusion in many propagation codes



Particle moves to another fieldline

Diffusion Coefficients

- Define the running diffusion tensor

$$D_{ij}(t) \equiv \frac{1}{2N} \sum_{n=1}^{N} \frac{[x_{i,n}(t) - x_{i,n}(0)][x_{j,n}(t) - x_{j,n}(0)]}{t}$$

- Correct for crossfield motion

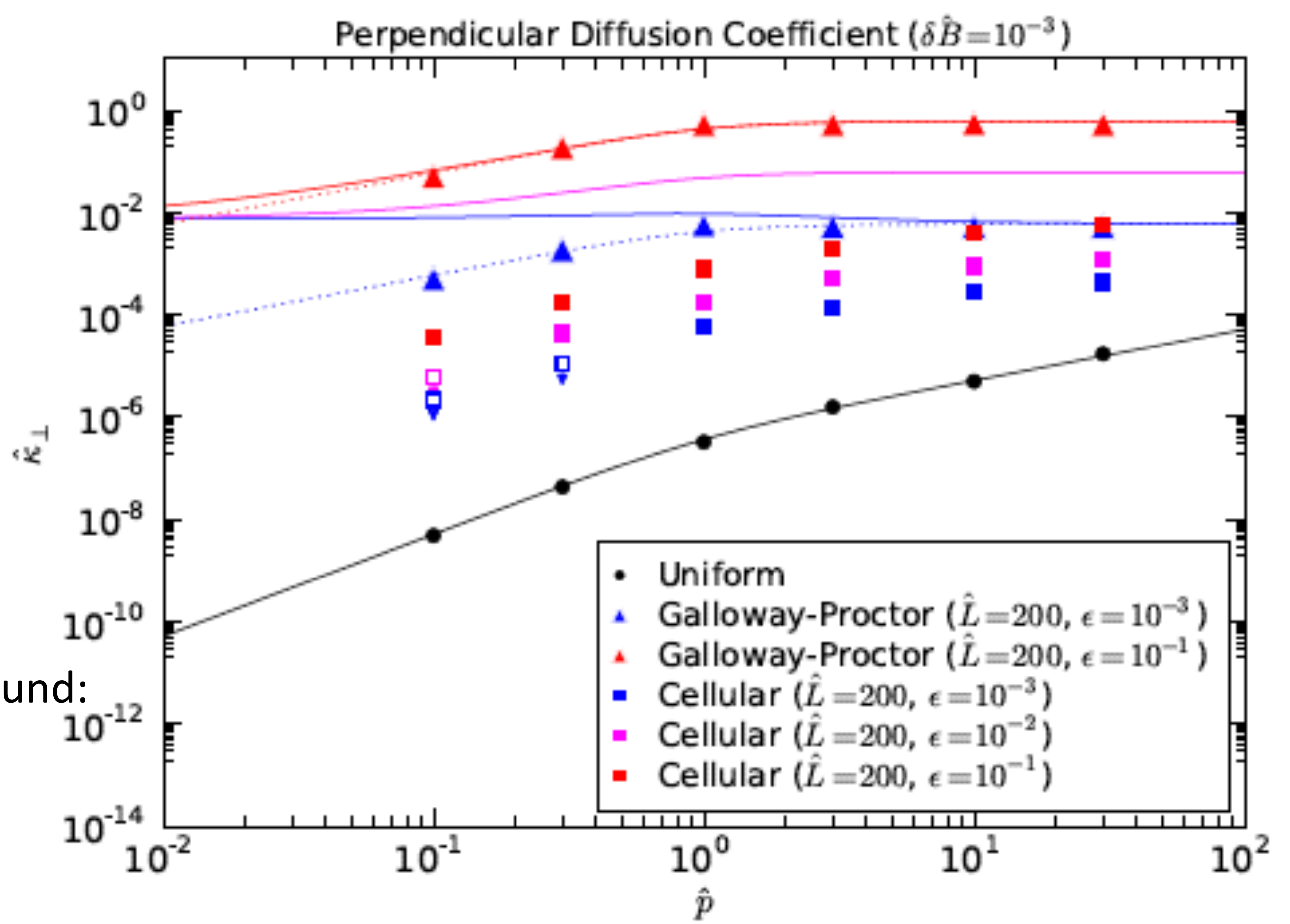
$$\boldsymbol{x}_{gc} = \boldsymbol{x} + \frac{\boldsymbol{v} \times \hat{\boldsymbol{b}}}{\omega_g}.$$

$$\Delta \boldsymbol{x} \equiv \boldsymbol{x}_{gc} - \boldsymbol{x}_f$$

- Define the corrected running diffusion tensor

$$D^c_{ij} \equiv \frac{1}{2N} \sum_{n=1}^{N} \frac{\Delta x_i(t) \Delta x_j(t)}{t}$$

Summary of Results



Upper bound:
Eddy rate
L^2/t_{orb}

Lower bound:
r_g^2/t_{sca}

Gyroresonant Scattering by Hydromagnetic Waves: *Statistical Description*

Elastic scattering *in the wave frame*

$$\frac{df}{dt}\Big|_{scattering} = \frac{\partial}{\partial \mu_w} \frac{(1-\mu_w^2)}{2} \nu \frac{\partial f}{\partial \mu_w},$$

where $\mu_w \equiv \mathbf{p} \cdot \mathrm{B}/pB$ in the wave frame and

$$\nu \equiv \frac{\pi}{4} \omega_{cr} k \frac{\delta B_k^2}{B^2}$$

is the scattering frequency due to power at the resonant $k \equiv \omega_{cr}/\mu_w v$.

Convection – Diffusion Equation

$$\frac{\partial f}{\partial t} + \mathbf{u}\cdot\boldsymbol{\nabla} f = \frac{\boldsymbol{\nabla}\cdot\mathbf{u}}{3} p \frac{\partial f}{\partial p} + \boldsymbol{\nabla}\cdot D_{\parallel}\hat{\mathbf{b}}\hat{\mathbf{b}}\boldsymbol{\nabla} f + \frac{1}{p^2}\frac{\partial}{\partial p} p^2 D_{pp}\frac{\partial f}{\partial p},$$

where

Velocity of wave frame → $\mathbf{u} \equiv \mathbf{u}_{plasma} + \frac{\nu_+ - \nu_-}{\nu_+ + \nu_-} v_A,$

Spatial diffusion → $D_{\parallel} \equiv \frac{v^2}{\nu_+ + \nu_-},$

Second order Fermi acceleration → $D_{pp} \equiv \frac{4}{3}\gamma^2 m^2 v_A^2 \frac{\nu_+ \nu_-}{\nu_+ + \nu_-},$

and "+" and "-" denote wave propagation direction.

Momentum and Energy Transfer

- Gyroresonant, streaming cosmic rays transfer momentum to co-propagating waves & absorb momentum from counter-propagating waves.
- Super-Alfvenic streaming $v_D > v_A$ destabilizes co-propagating Alfven waves ($v_A = B/(4\pi\rho)^{1/2}$).
- Growth rate Γ_{cr} for $E^{-\alpha}$ spectrum:

$$\Gamma_{cr}(E) \sim \frac{\omega_{cp}}{\gamma^{\alpha-1}} \frac{n_{cr}}{n_i} \left(\frac{v_D}{v_A} - 1 \right).$$

Typically fast under interstellar conditions

Damping Transfers Wave Energy & Momentum to the Background

- Ion – neutral friction
  - *Important in H I, H_2 gas*
- Nonlinear energy transfer to thermal ions
  - *Important in hot gas*
- Distorted by wandering of background field
  - *Important when small scale turbulence is present*

In a steady state, damping balances growth, determining the streaming rate, wave amplitude, & dissipation rate

Relate Streaming Anisotropy to Density Gradient

$$-v\hat{\mathrm{b}}\cdot\nabla f=(\nu_{+}+\nu_{-})\frac{\partial f}{\partial\mu}+v_A(\nu_{+}-\nu_{-})m\gamma\frac{\partial f}{\partial p}.$$

Cosmic ray density/pressure gradient drives anisotropy, as particles stream down their gradient

Resonant, co-propagating waves absorb cosmic ray momentum

Waves transfer momentum & energy to the background gas, accelerating & heating it.

Cosmic Ray Hydrodynamics

Cosmic ray generated waves dominate the scattering

- Cosmic rays are advected at v_A relative to fluid, but also diffuse along magnetic field.
- Cosmic ray pressure gradient along B accelerates and heats the background gas.

Externally driven turbulence dominates the scattering

- Cosmic rays advect with fluid and diffuse along magnetic field.
- Cosmic rays undergo second order Fermi acceleration by the turbulence

Which is correct? **Self-confinement prevails at least for the bulk (few GeV) particles, where streaming instability is strongest.**

Which Picture to Adopt?

- What is the spectrum of interstellar/ intergalactic turbulence down to sub-AU scales?
- How does the streaming instability work in the presence of background magnetic turbulence?
- Have all the linear & nonlinear damping mechanisms been identified?

Nature of the coupling & direction of energy flow depend on this.

Some Implications of Self-Confinement

- Cosmic rays provide hydrostatic support to the galactic disk.

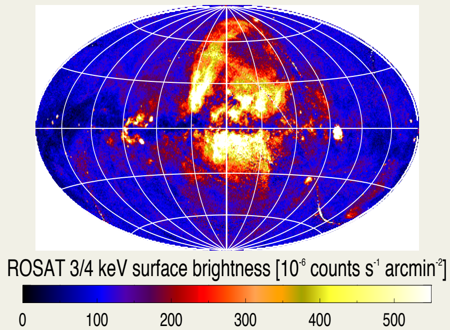
- Cosmic ray buoyancy drives escape of the galactic magnetic field.

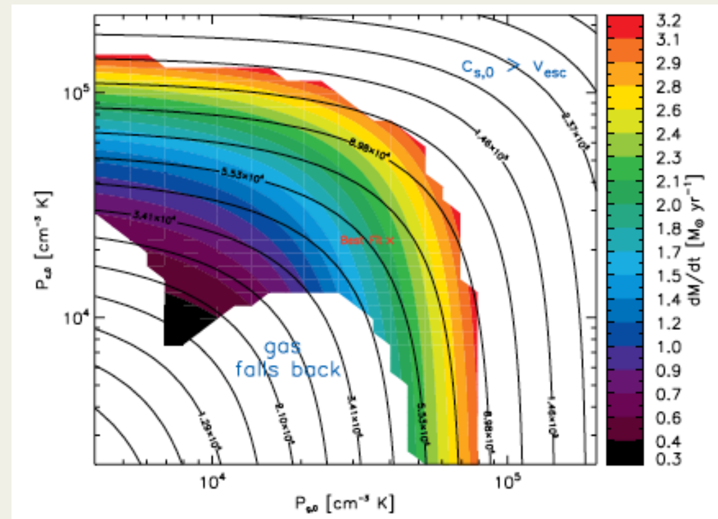
- Cosmic ray pressure gradient drives a galactic wind.

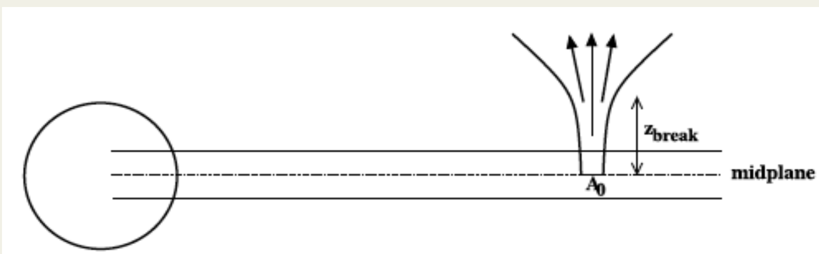
- Cosmic rays contribute to heating and convective instability in galaxies & galaxy clusters.

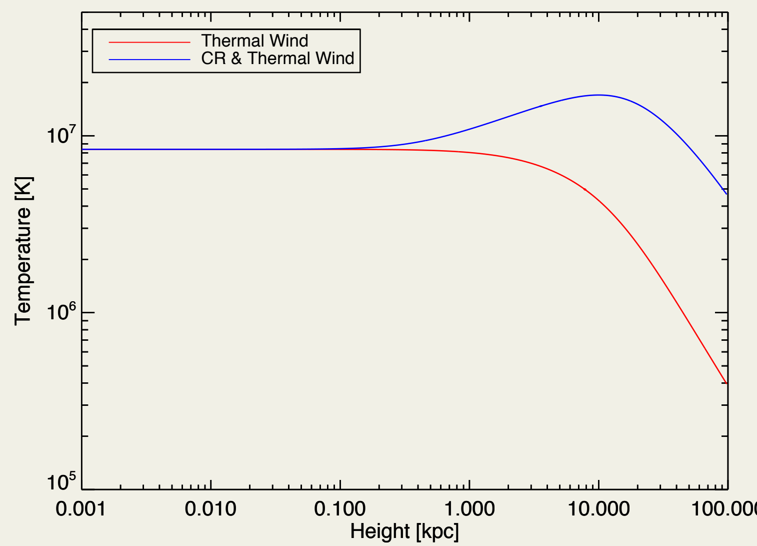
- Cosmic rays modify collisionless shocks

Galactic Wind





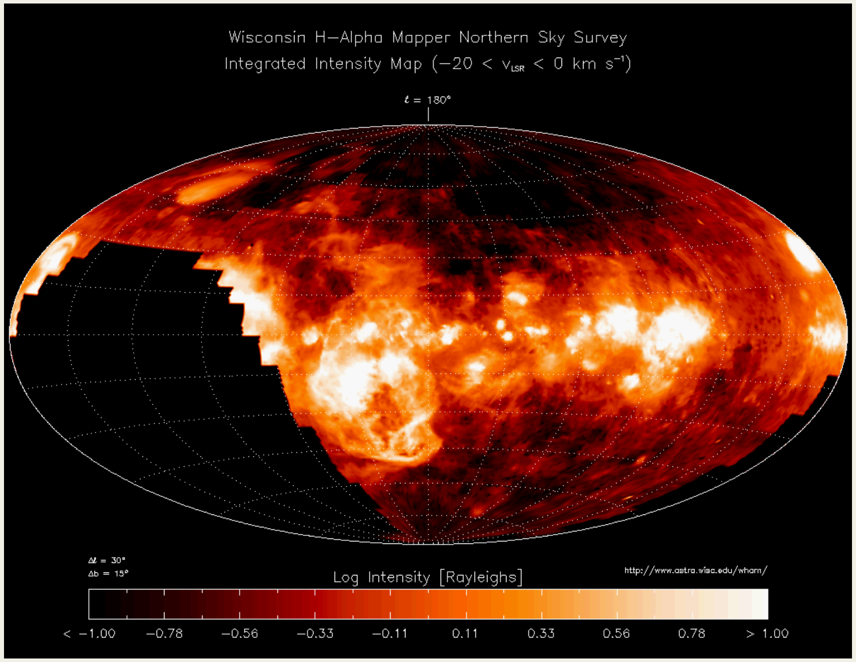


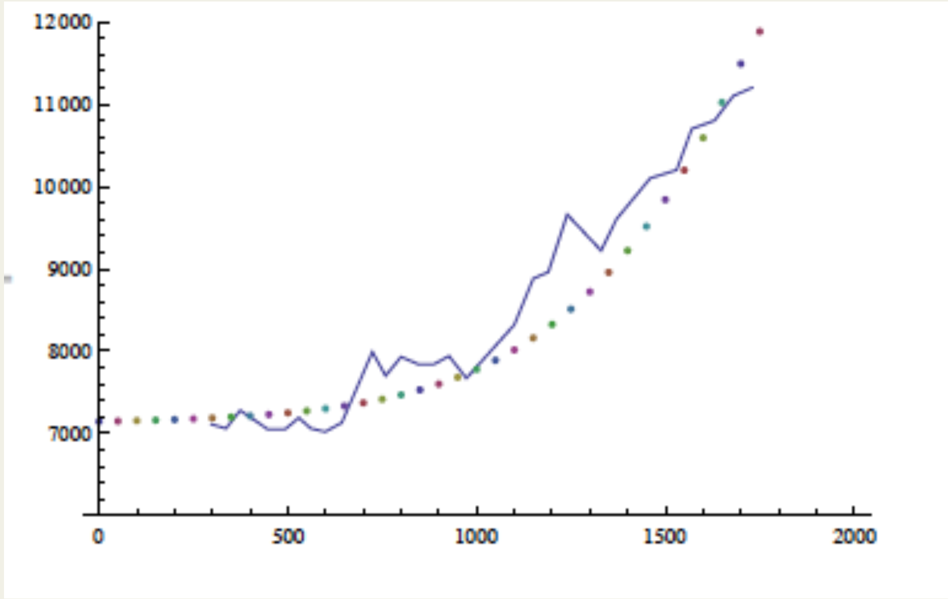


Top left: Soft x-ray sky,
Bottom left: Magnetic flux tube geometry.
Top right: Domains of flow, with mass loss rates
Bottom right: Gas temperature with & without cosmic ray heating.

Everett et al. 2008 ApJ

Cosmic Ray Heating of Diffuse Interstellar Gas

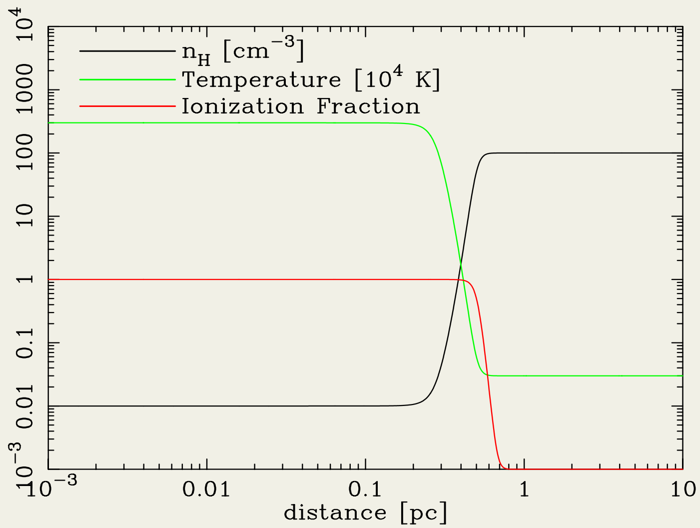


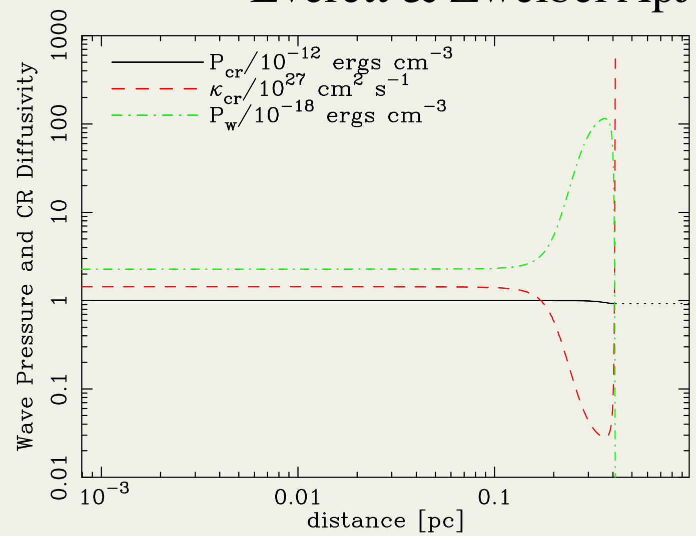


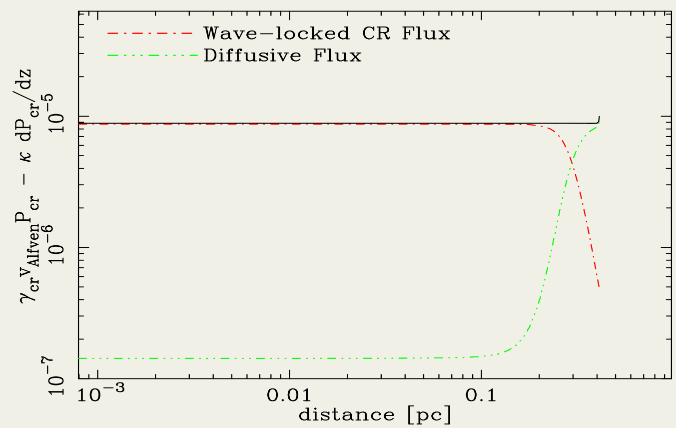
Left: Galactic Ha emission, showing a thick layer of warm ionized gas. Right: Model of thermal equilibrium , including cosmic ray heating (Wiener et al. 2013)

Cosmic Ray Coupling to Clouds

Everett & Zweibel ApJ 2011





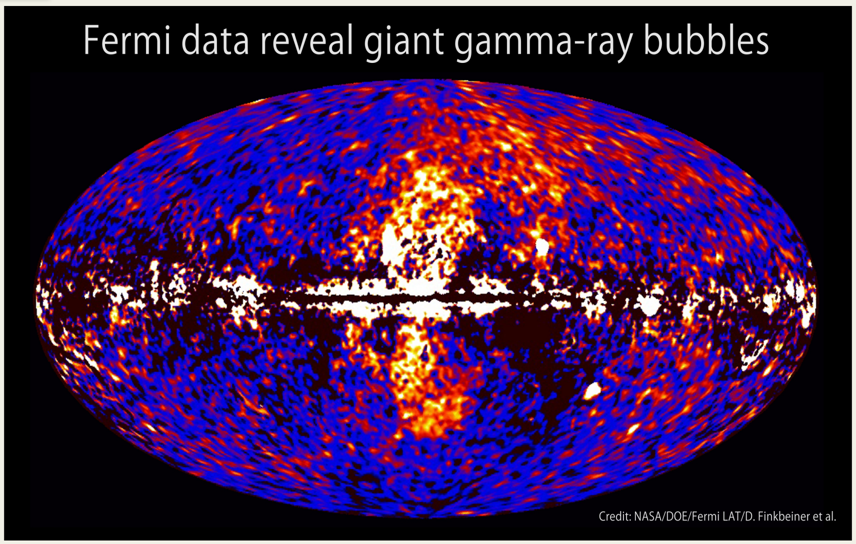


Top left: Model cloud setup. Top Right: Cosmic ray & wave pressure vs. depth. Bottom right: Transition from advection to diffusion, followed by free streaming -> **No force on the bulk of the cloud** .

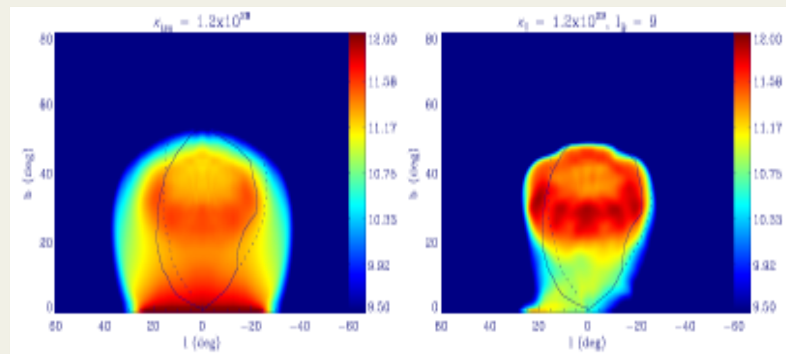
Fermi Bubbles

Gamma-ray emitting bubbles in the inner Milky Way, discovered by Fermi γ-ray observatory.

NASA



Cosmic ray energy density in a pressure inflated cavity assuming isotropic diffusion (left) and field aligned diffusion (right).



Model cavity formation by a short lived AGN jet (Guo et al. I, II)

Yang et al. ApJ in press

The Origin of Cosmic Rays

Fermi's prescription:

$$F(E) \sim E^{-(1+\tau_{acc}/\tau_{esc})}$$

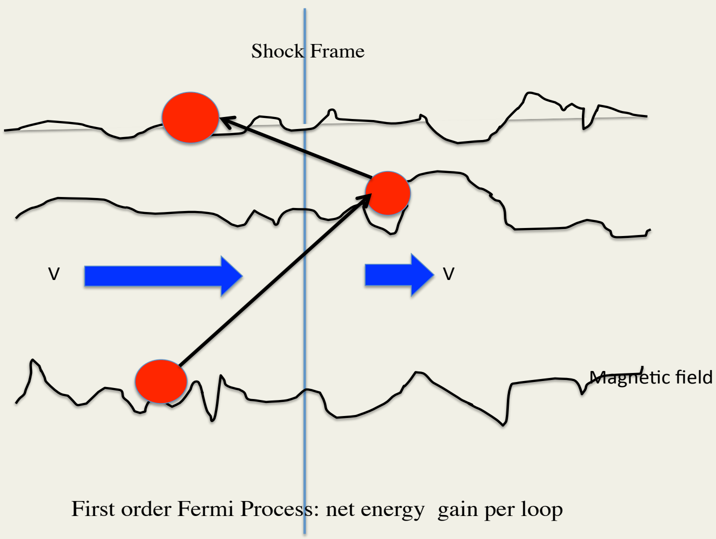
$\propto$

τ_{acc} is acceleration time, τ_{esc} is escape time.

Neither is specified in Fermi's original model.

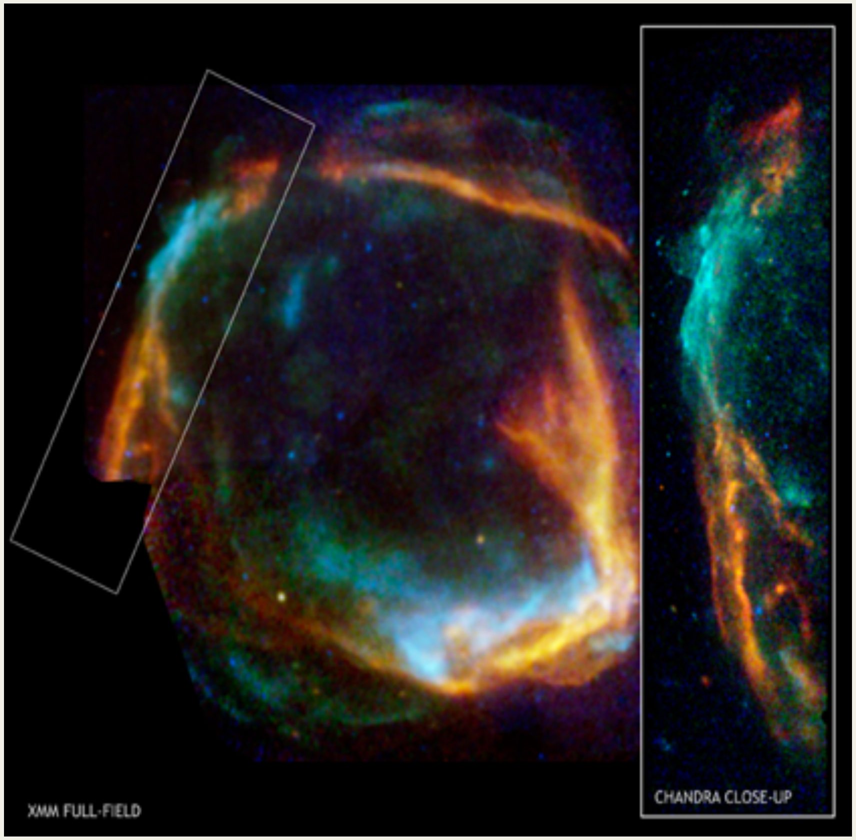
Acceleration at Shocks

Self-confinement of cosmic rays to a shock front leads to rapid acceleration.



First order Fermi Process: net energy gain per loop

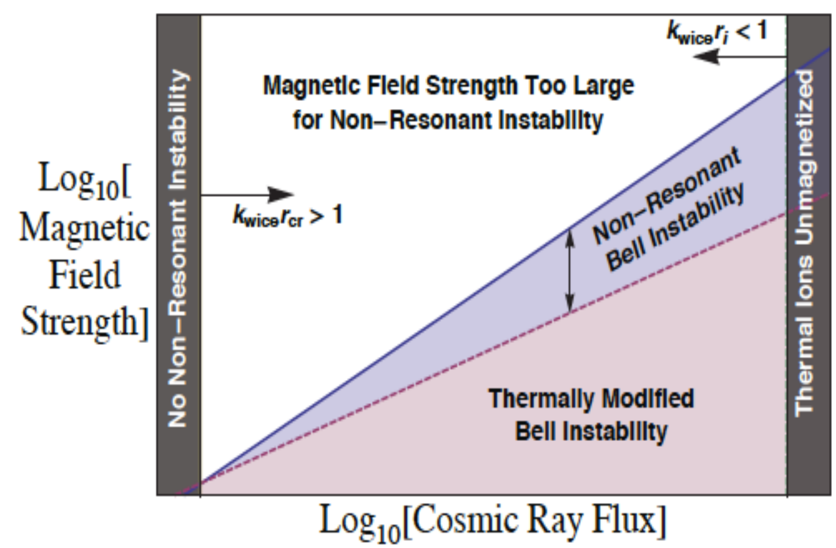
$\tau_{acc}/\tau_{esc} \sim 1$



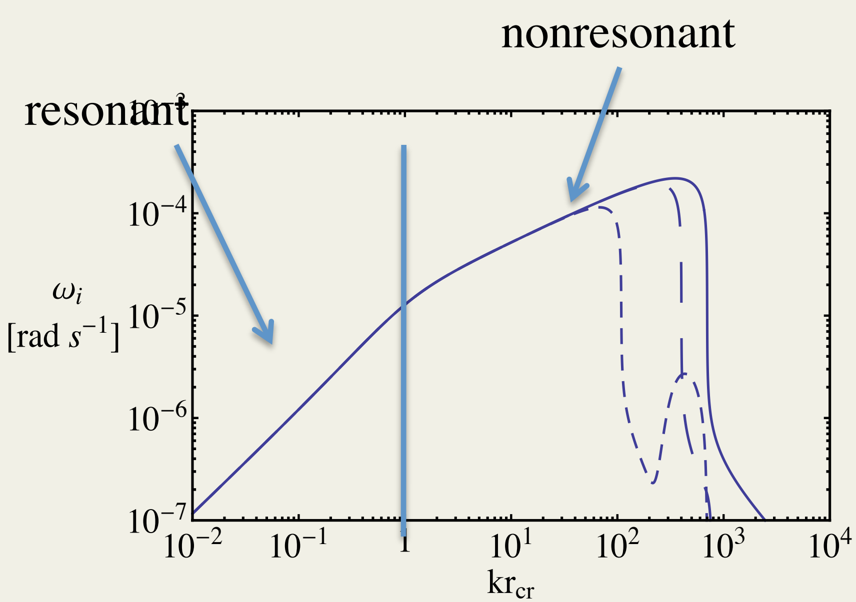
Chandra-Newton image of RCW 86

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.

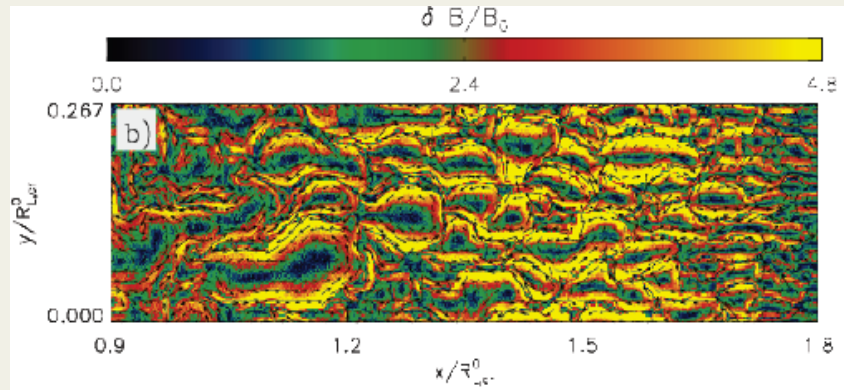


Rapid Growth to Nonlinear Amplitude



Linear growth rates (Zweibel & Everett 2010)

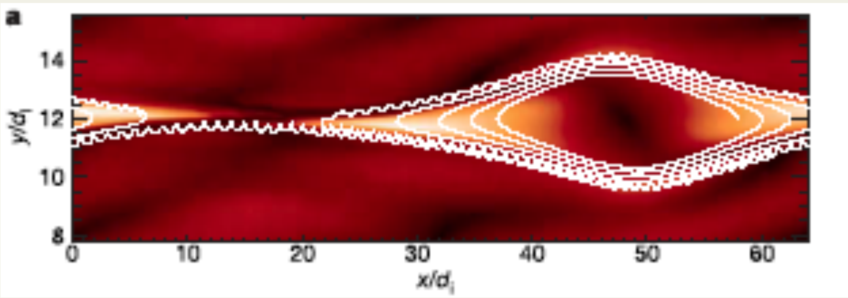
PIC simulation showing magnetic field growth in a shock layer.



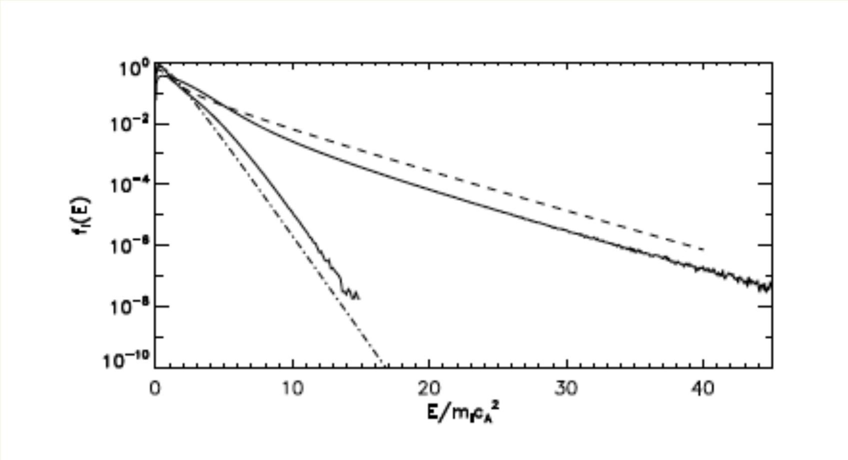
Riquelme & Spitkovsky 2010

Simulations suggest that the magnetic field can be amplified, producing the observed thin synchrotron rims, increasing the acceleration rate, producing a new saturated state.

Acceleration in Contracting Islands



Top: Particle orbits in shrinking magnetic islands formed by magnetic reconnection (Drake et al 2006).

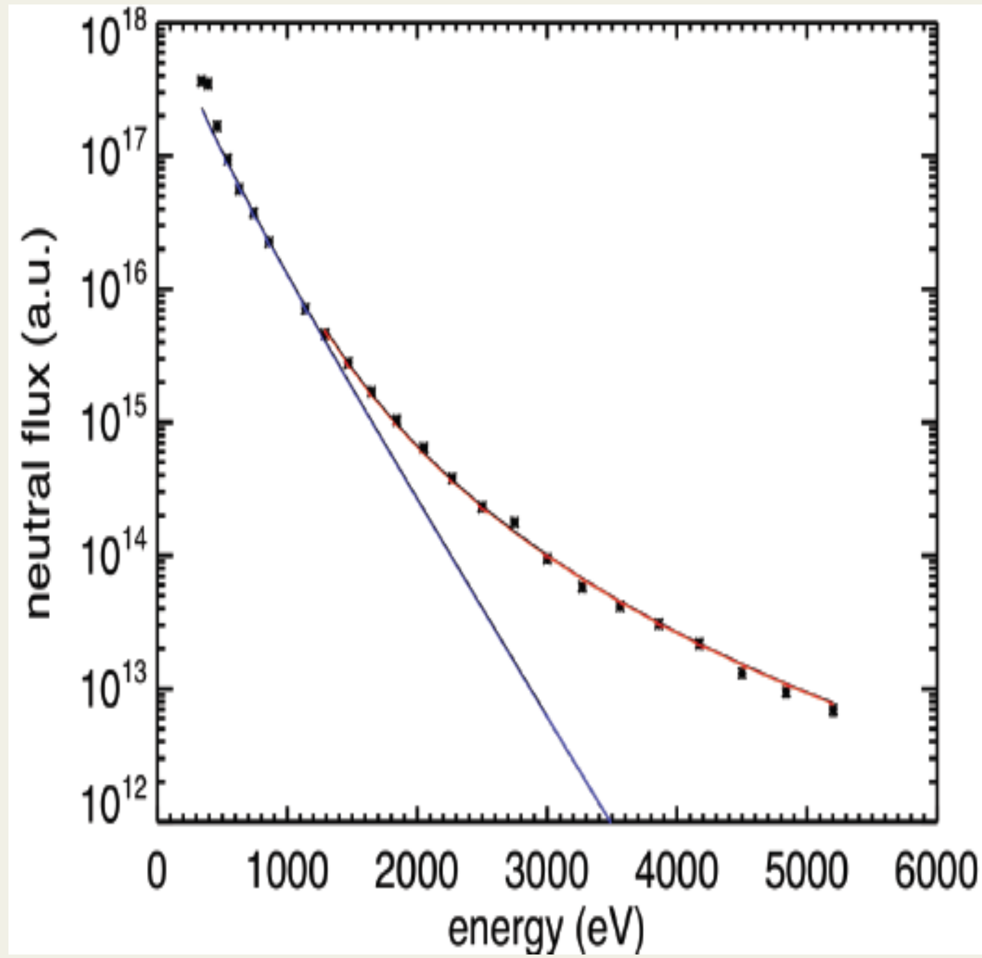


Bottom: Initial spectrum (steep) and later spectrum (flat) as particles interact with a large ensemble of islands (Drake et al 2012).

Small τ_{acc}/τ_{esc} give flat spactrum of solar system particles; fast acceleration mechanism in flares.

Lab Studies: Ion Heating in an RFP Plasma

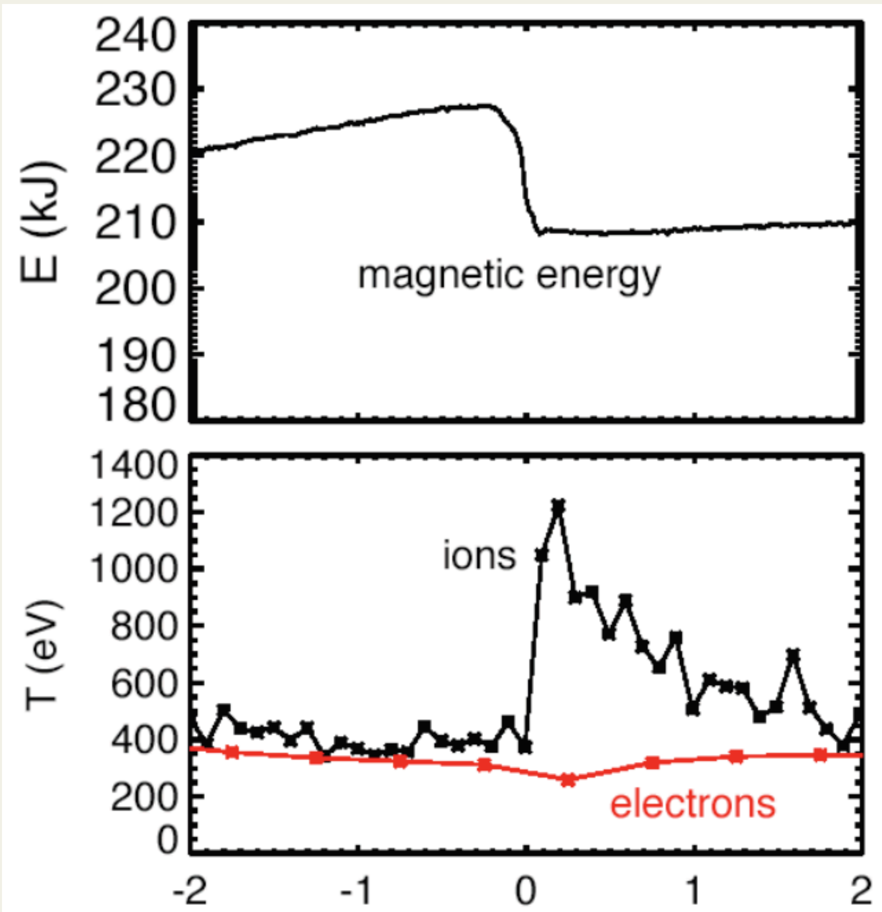
- Thermal heating of impurity ions is anisotropic ($T_\perp > T_\parallel$)
- Thermal heating has a charge/mass dependence
- Majority ions develop a high-energy tail



Ion Energy Distribution

Courtesy D. Den Hartog

Dramatic ion heating occurs during the sawtooth reconnection event.



Time (ms)
(relative to reconnection event)

Courtesy D. Den Hartog

Zooming in on dynamics at reconnection event:

–Energy stored in the equilibrium magnetic field drops suddenly

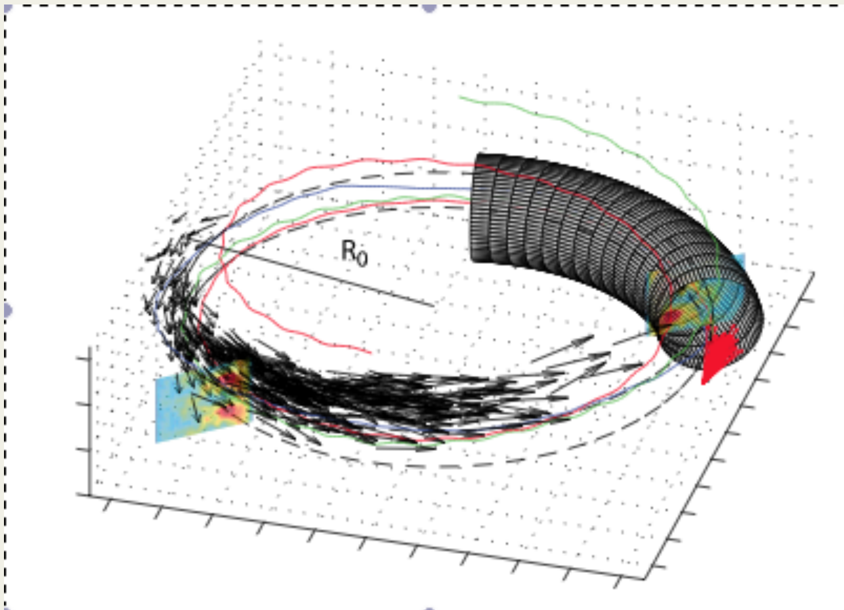
–Large fraction of released energy is transferred to ions

- Heating time (100 μs) is much faster than i-e collision time (10 ms)
- $T_i > T_e$

–Power flow from equilibrium magnetic field to ions is large

- $P_{mag} \sim$ 10 kJ/ 100 μs = 100 MW
- $P_{ohmic} \sim$ 5 MW

Experimental Study of Diffusion



- Unstable TORPEX plasma develops turbulent magnetic structure.
- Energetic particles injected by an internal source.
- Trajectories can be followed & mapped(Gustafson et al 2012 PRL).

Summary and Prospects

- Cosmic rays carry ~1/3 of the energy in the interstellar medium in galaxies.
- *If self-confined by plasma instabilities*, cosmic rays transfer energy & momentum to the background, heating the gas & driving outflows.
- New opportunities are arising from
  - a wealth of new cosmic ray & lab data.
  - advances in simulation
  - improved understanding of magnetized turbulence & how it interacts with energetic particles.

Goals

- Understand how the cosmic ray energy budget, spectrum, and composition are regulated.

- Improve the theory of cosmic ray hydrodynamics, incorporating new developments in magnetized turbulence & how it interacts with particles.

- Include cosmic rays in theories of astrophysical plasma processes such as shocks, reconnection, and dynamos.