The Plasma Physics of Cosmic Rays

Ellen Zweibel
University of Wisconsin-Madison
&
Center for Magnetic Self-Organization

CMSO

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

- How do < 10^{-9} of interstellar particles come to have as much energy as the background gas?

- 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
  - Fermi bubbles
  - Acceleration at shocks
- Recent advances
- Future opportunities

Collaborators: John Everett, Jay Gallagher, Dongwook Lee, Paul Ricker, Mateusz Ruszkowski, Karen Yang, Tova Yoast-Hull

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Some Early Milestones in Cosmic Ray Astrophysics

- 1912 V. Hess shows the sources of atmosphere ionization are cosmic.

- 1927 J. Clay shows the ionizing flux is latitude dependent, suggesting the rays are particles, deflected by the geomagnetic field.

- 1934 W. Baade & F. Zwicky propose that cosmic rays originate in supernovae.

- 1949 J. Hall & W. Hiltner observe a pervasive Galactic magnetic field through its effect on starlight polarization.

- 1949 E. Fermi proposes his theory of cosmic ray acceleration

Cosmic Rays with a Broad Brush

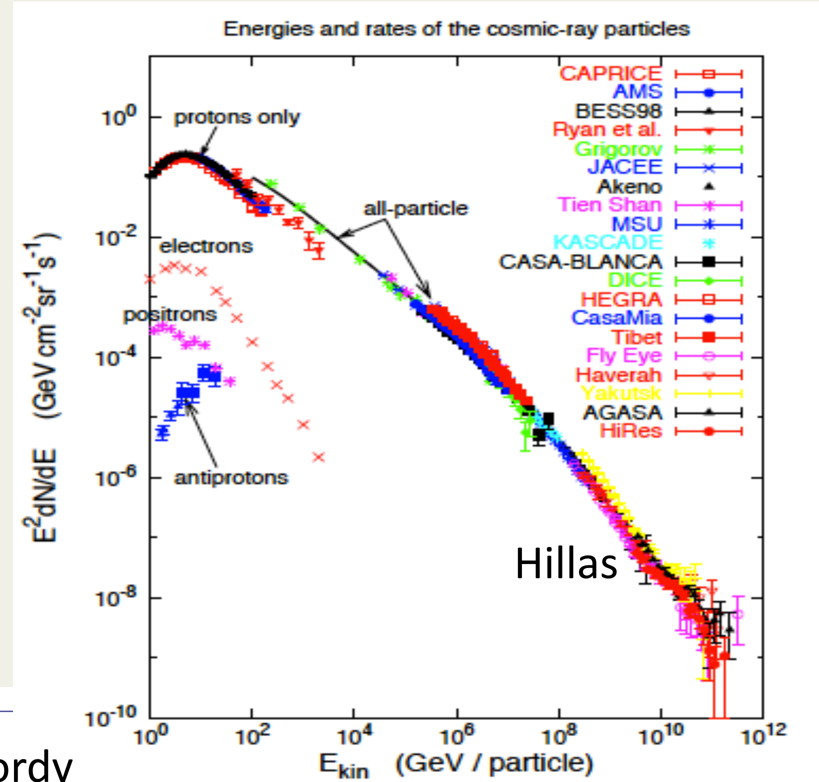
Energy Spectrum

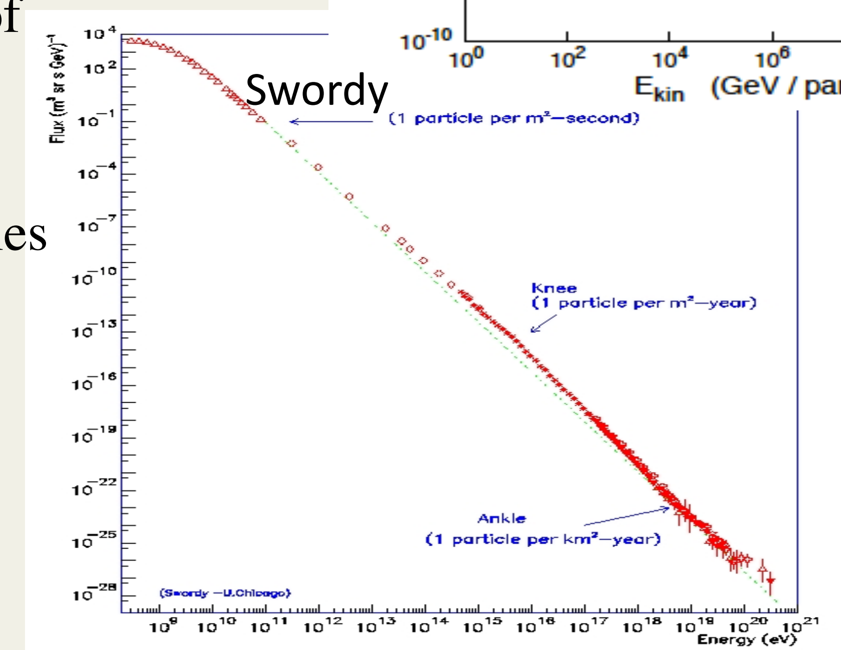
- A broken power law:

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

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

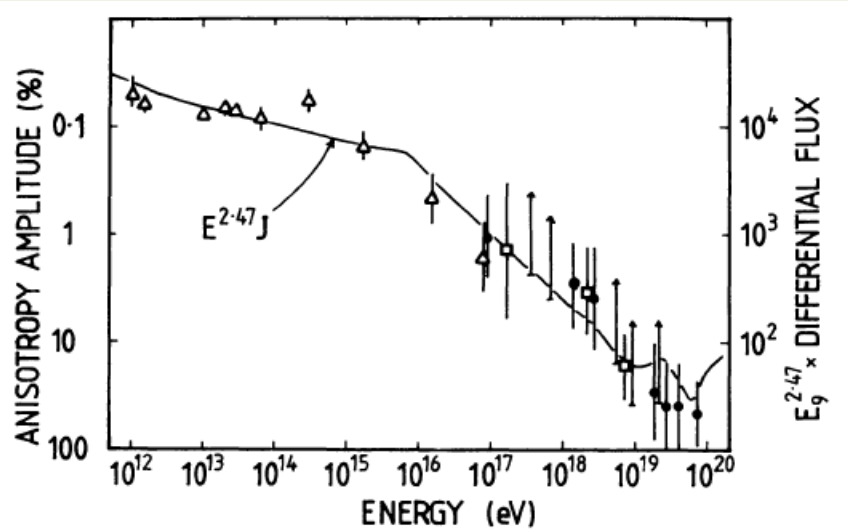
- Strong solar cycle modulation below ~ 10 GeV
- Energy density 1 eV cm^{-3}, ~magnetic & thermal/ turbulent energy density of interstellar gas.
- Most of the pressure comes from ~ GeV particles



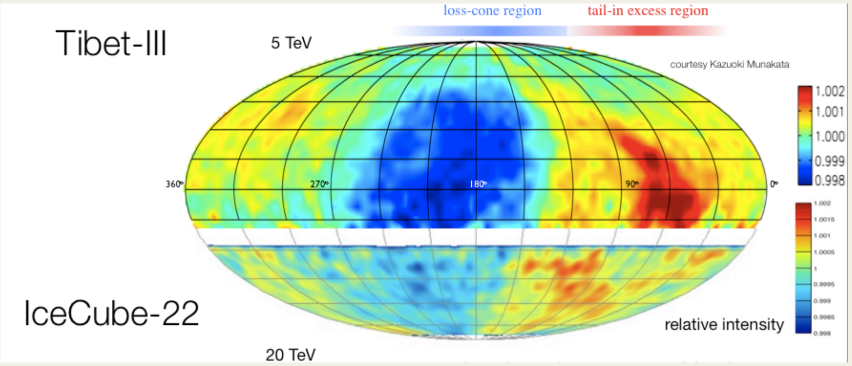


(An)Isotropy

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



Hillas 1984



Abbasi et al. 2010

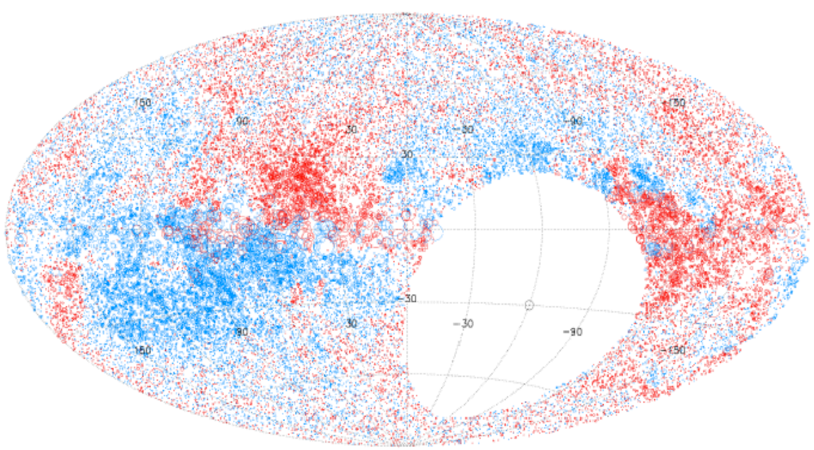
Composition and Lifetime

- Mostly protons
- Electrons ~1-2% by number
- Elemental composition similar to solar system
- Enriched in light elements

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

Galactic Magnetic Field

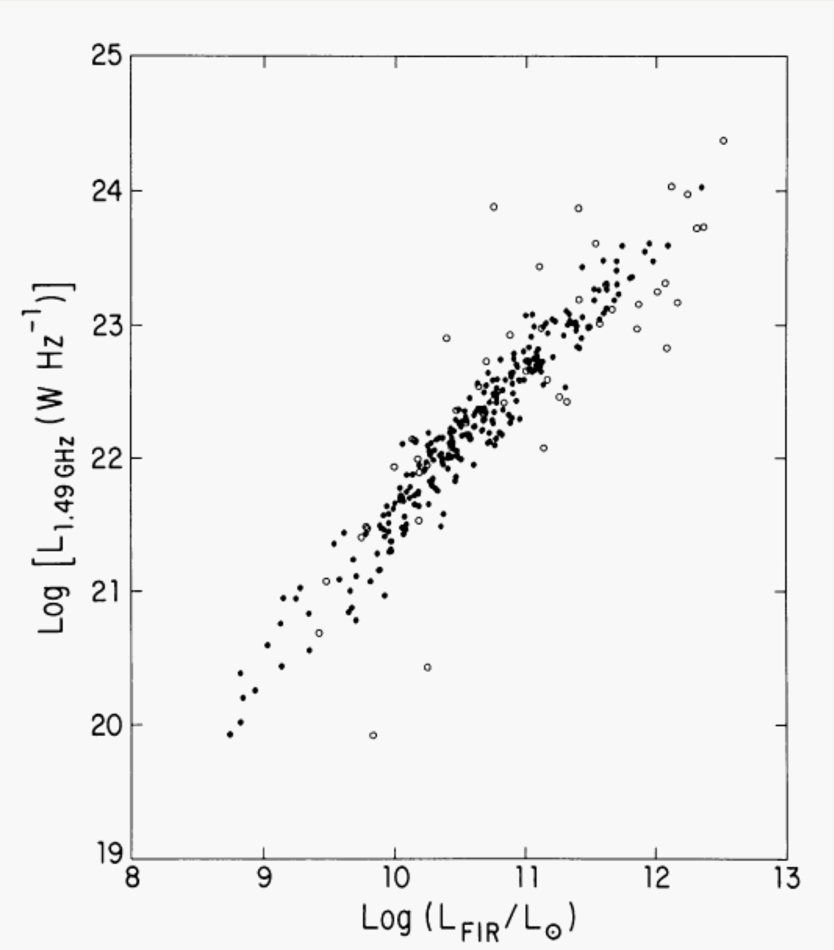
Faraday rotation measures of ~38000 extragalactic sources.



Taylor et al. 2009

- Coherent, nearly azimuthal component nearly tangent to galactic plane
- Random component, ~3 x times stronger
- Total field is ~ 5 μG
- Magnetic disk thickness is a few kiloparsecs.

Far-Infrared Radio Correlation



- Tight correlation between far-infrared luminosity (a measure of the star formation rate) and synchrotron luminosity (~ product of magnetic and cosmic ray electron energy densities) of galaxies.
- *Powerful self-regulation mechanism*

Properties & Implications

Properties

- Near interstellar composition
- Broken power law spectrum
- Nearly isotropic, anisotropy increases with energy
- Long confinement times

Implications

- Source material is interstellar.
- Acceleration of galactic component produces a power law spectrum.
- Particles are trapped by Galactic magnetic field.
- Particles diffuse with an energy dependent path length that steepens the source spectrum.

Cosmic Ray Orbits: *DNS is Infeasible*

24

100 EeV

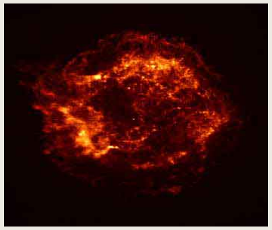
Thickness of galactic disk

22

1 EeV

20

Young supernova remnant

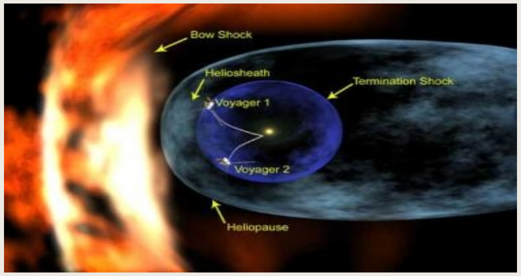


3 PeV

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

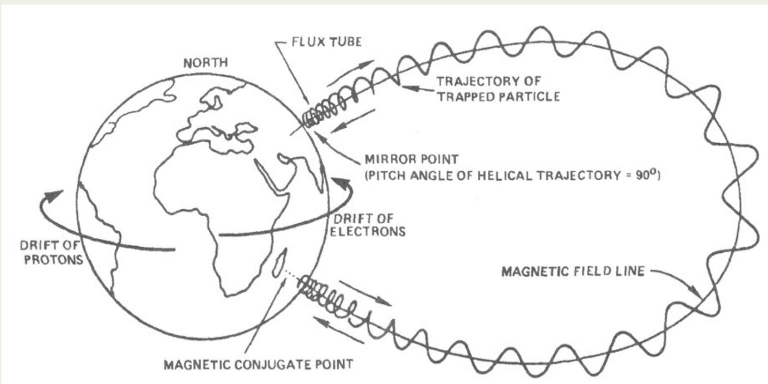
A few astronomical scales are also indicated

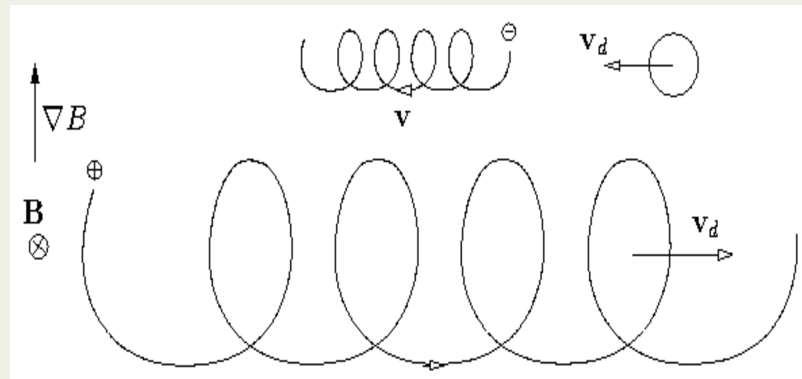
Elements of Field-Particle Interaction

- Gyromotion
- Drifts
- Mirroring
- Gyro-resonance
- Landau resonance/ transit time damping

Drifts and Mirroring

Silas.psfc.mit.edu



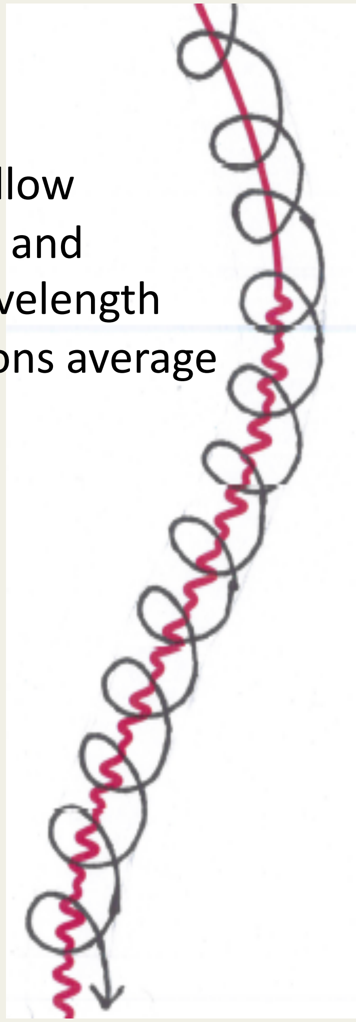


Gruntman 1997

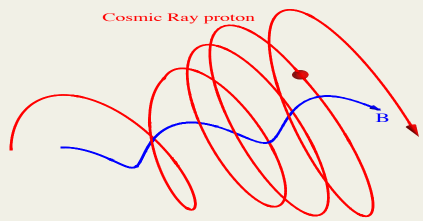
- Magnetic moment $\frac{p_\perp^2}{B}$ is invariant under slow changes in B
- A particle with gyroradius r_g in a B field which varies on scale $L \gg r_g$ drifts across fieldlines at speed $v_{drift} \sim v\frac{r_g}{L}$.

Gyroresonant Pitch Angle Scattering

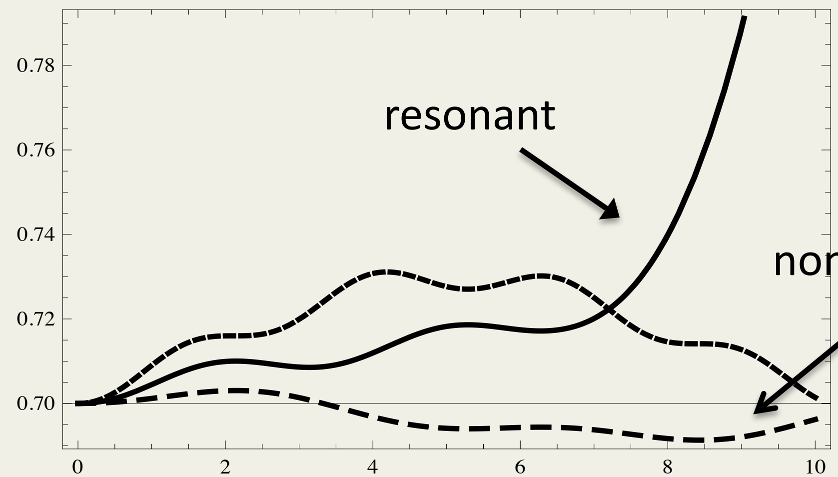
Orbits follow fieldlines and short wavelength fluctuations average out.



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



J. Everett



Gyroresonant Scattering

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

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

where

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

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

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 destabilizes co-propagating waves ($v_A = B/(4\pi\rho)^{1/2}$).

Growth rate for $E^{-\alpha}$ distribution

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

Relate Streaming Anisotropy to Density Gradient

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

Density gradient drives anisotropy: streaming

Resonant, co-propagating waves absorb cosmic ray momentum

Waves transfer momentum to the background gas

Cosmic Ray Hydrodynamics

Cosmic ray generated waves

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

Prevailing Picture

Externally driven turbulence

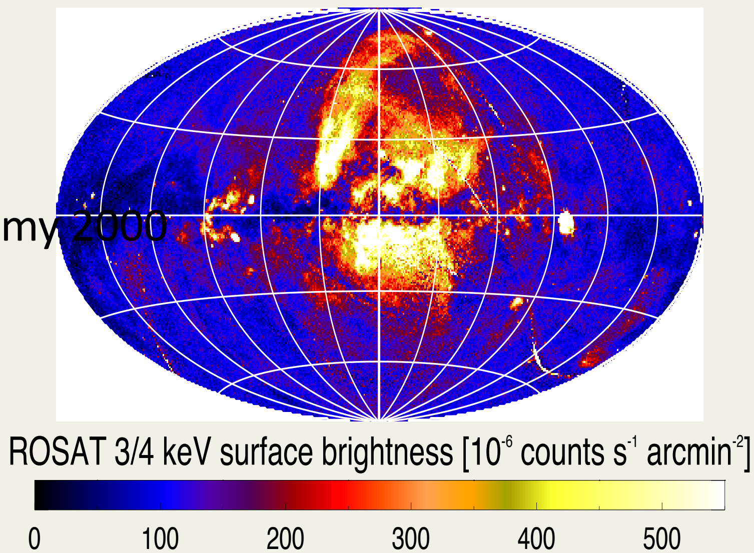
- Cosmic rays advect with fluid and diffuse along magnetic field.
- Cosmic rays undergo second order Fermi acceleration by the turbulence

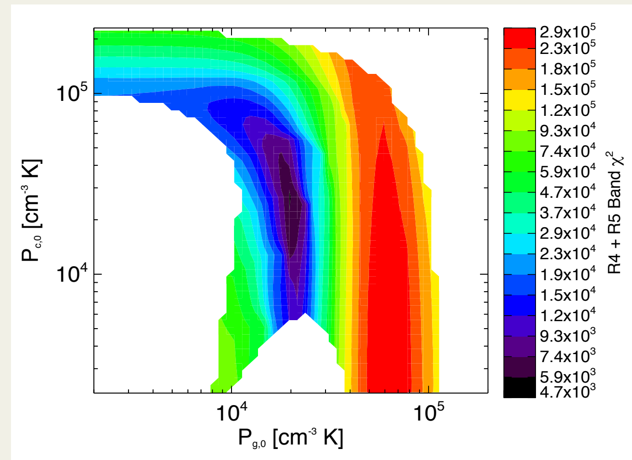
Some Implications

- 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 galaxy clusters.
- Cosmic rays modify collisionless shocks

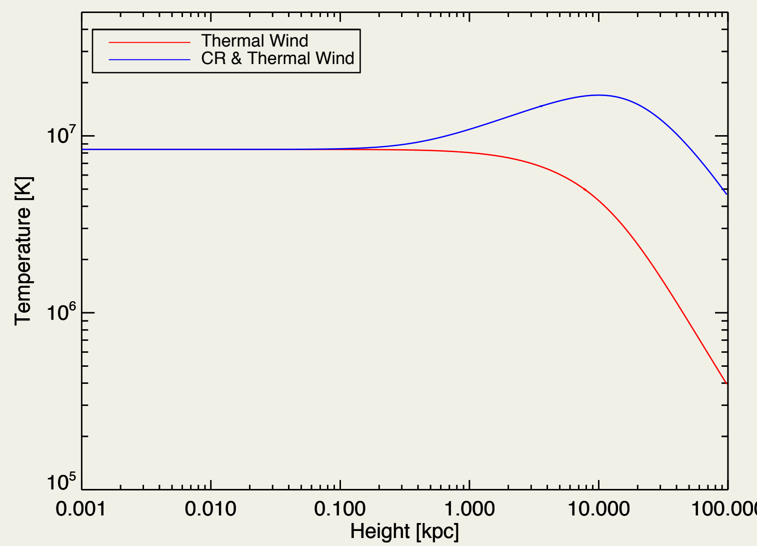
Galactic Wind

Almy 2000





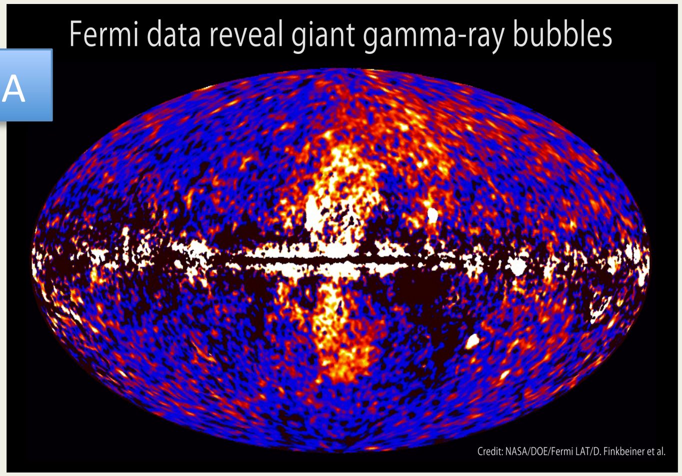
Soft x-rays from inner Galaxy are best modeled by a wind accelerated and heated by cosmic rays.



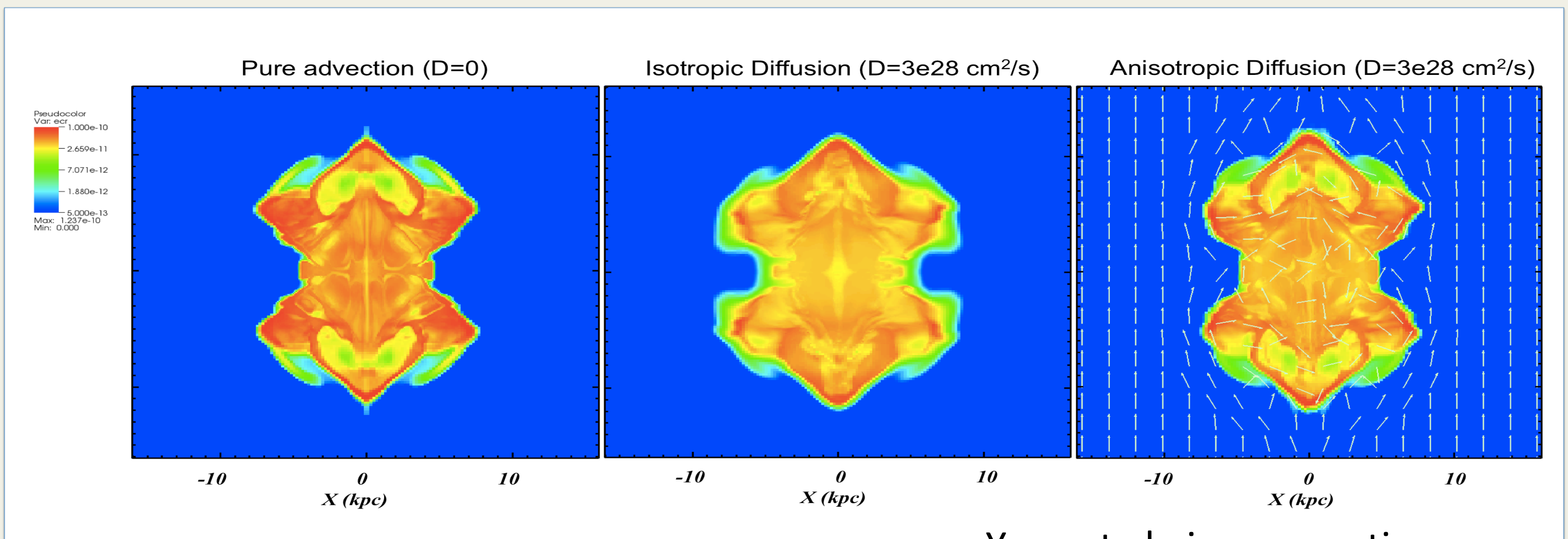
Everett et al. 2008

Fermi Bubbles

NASA



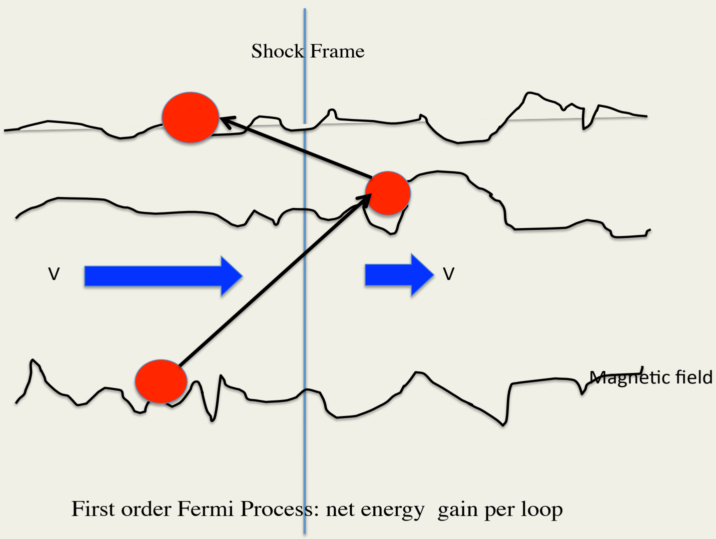
Gamma-ray emitting bubbles modeled by short-lived jet of plasma and cosmic rays which expands into the ambient medium. The 3 panels show the cosmic ray density with pure advection, isotropic diffusion, and diffusion along magnetic fieldlines only.

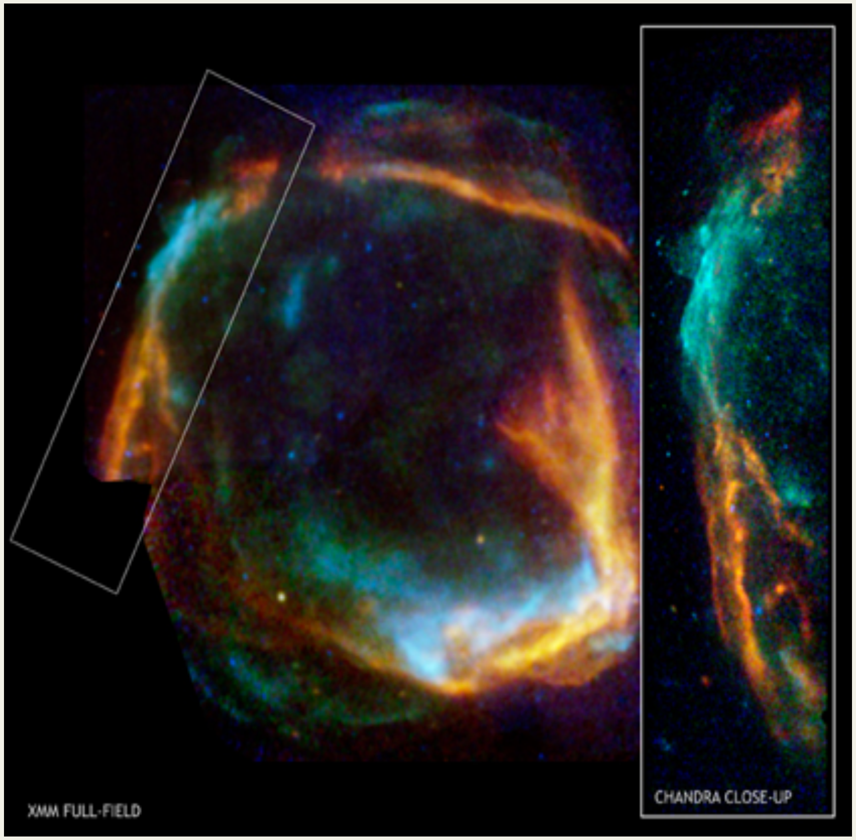


Yang et al., in preparation

Acceleration at Shocks

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



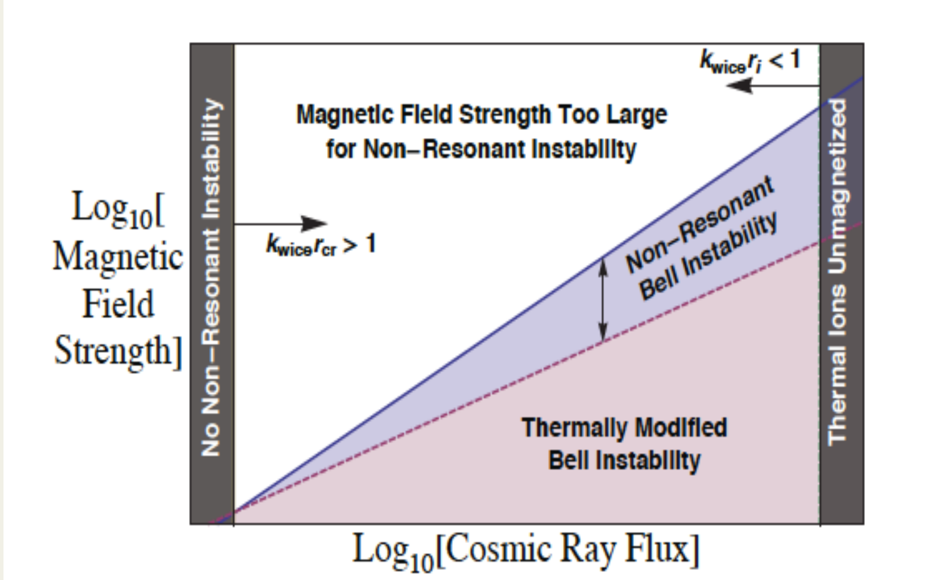


Chandra-Newton image of RCW 86

A Few New Developments

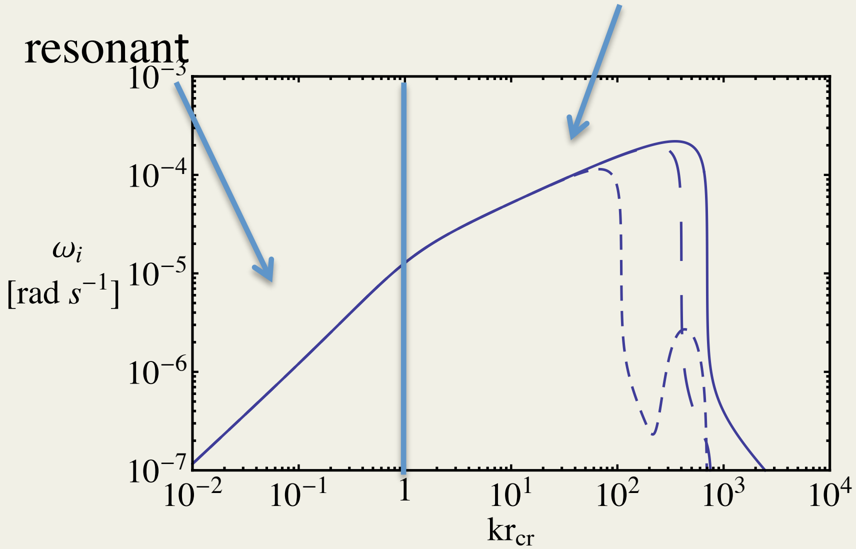
Nonresonant Instabilities

- 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.



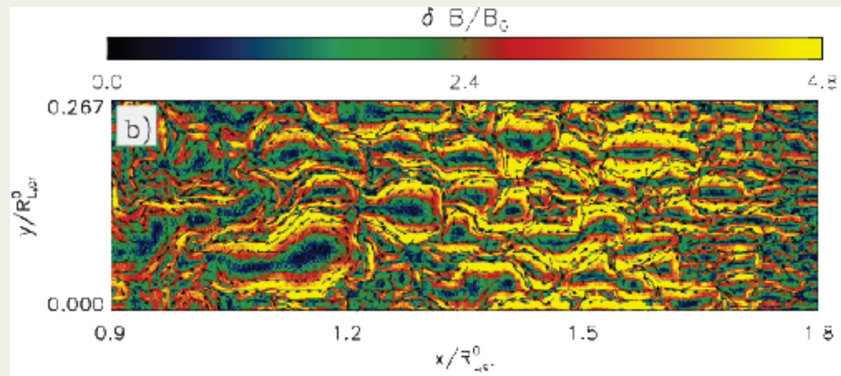
Rapid Growth to Nonlinear Amplitude

nonresonant



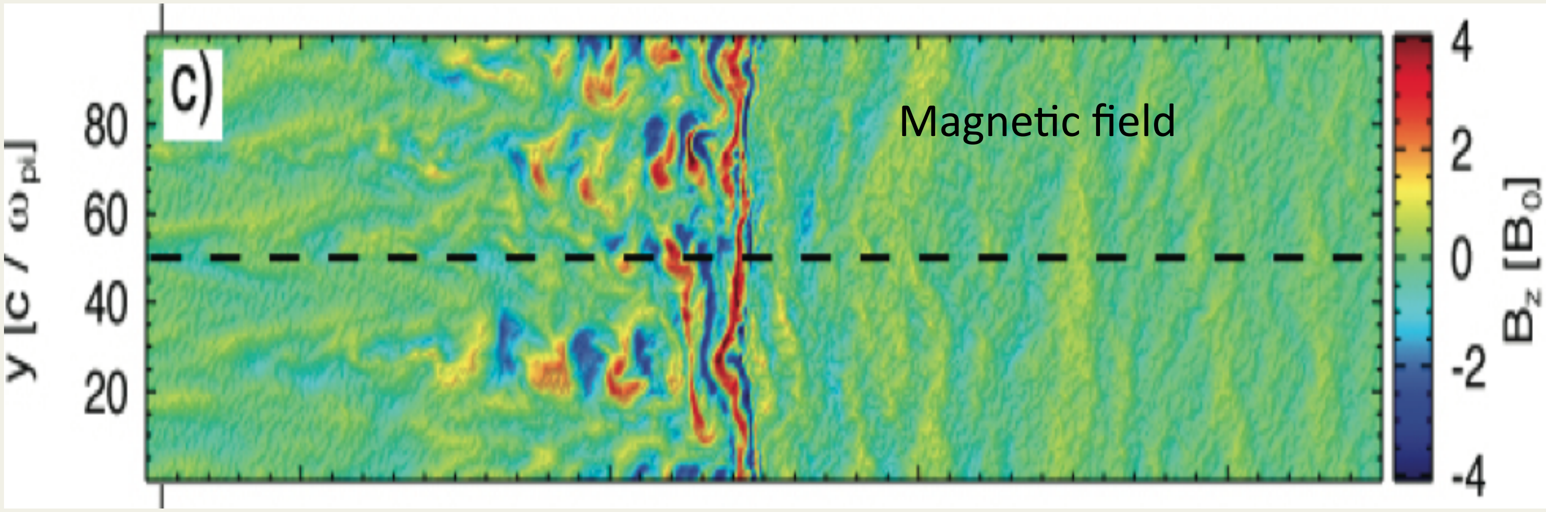
Linear growth rates (Zweibel & Everett 2010)

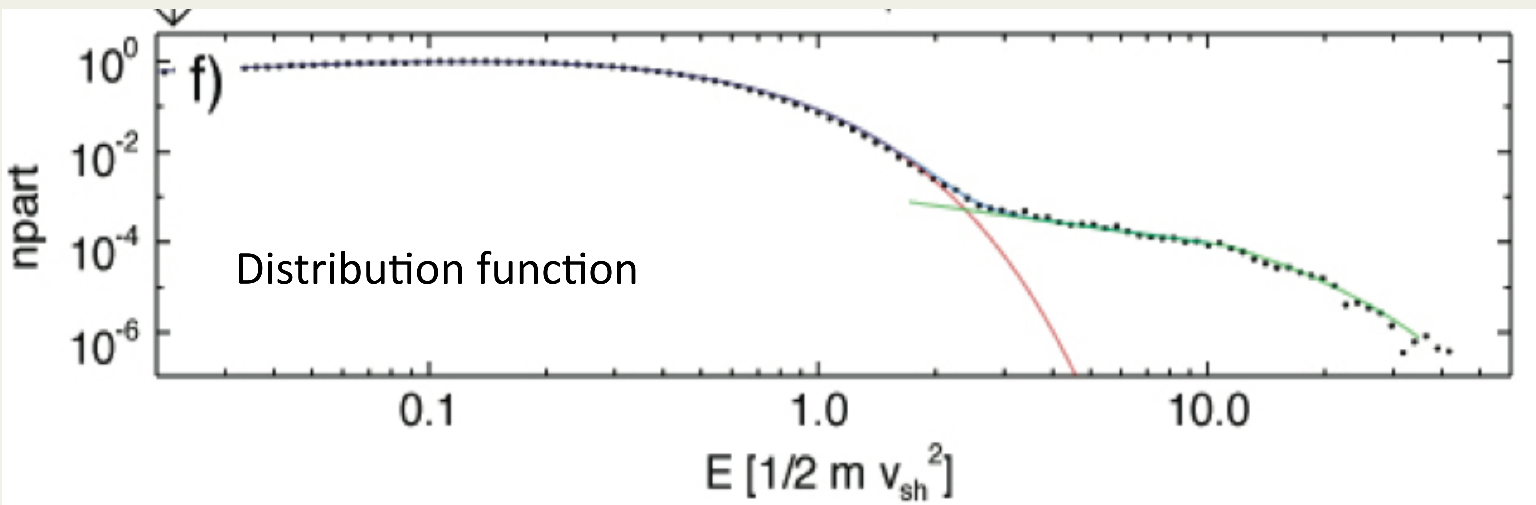
PIC simulation showing magnetic field growth in a shock layer.



Riquelme & Spitkovsky 2010

Hybrid Simulations of Shock Acceleration



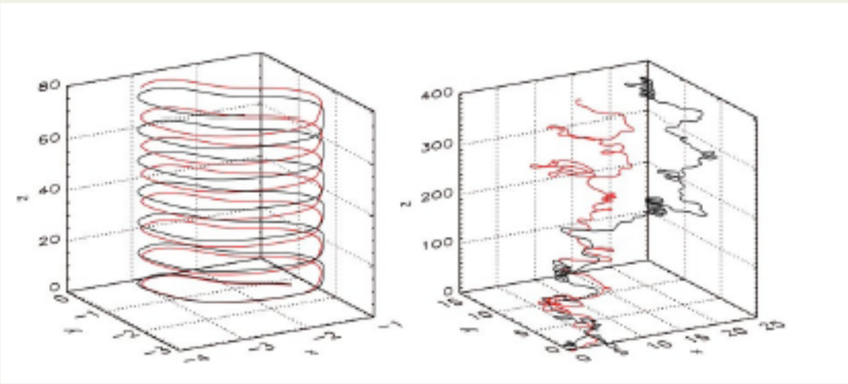


Gargate & Spitkovsky 2012

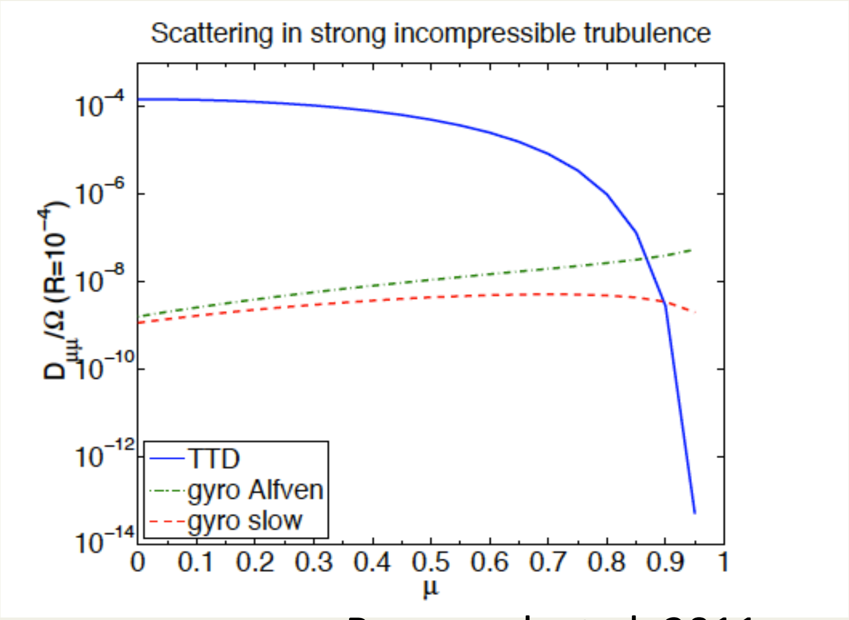
Diffusion Revisited

When fieldlines diverge within a gyro-orbit, the particles can hop across the field.

Scattering in a model of anisotropic MHD turbulence; parallel resonance dominates.



Hauff et al. 2010



Beresnyak et al. 2011

Summary and Prospects

- Observations of cosmic rays led to an elegant theory for how the cosmic ray couple to the background medium, their effects on interstellar and intergalactic gas dynamics, & their acceleration.
- New opportunities are arising from
  - new cosmic ray data (a wealth of it)
  - improved understanding of magnetized turbulence & how particles interact with it (theory, lab experiment, observations).
  - observations of magnetic fields and cosmic rays in other galaxies & over cosmic time.

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.