Cosmic Ray Propagation Through the ISM

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with thanks to Chad Bustard, Cory Cotter, Paolo Desiati, John Everett,Ryan Farber, Lukas Merten, Peng Oh,Mateusz Ruszkowski, Josh Wiener, Karen Yang

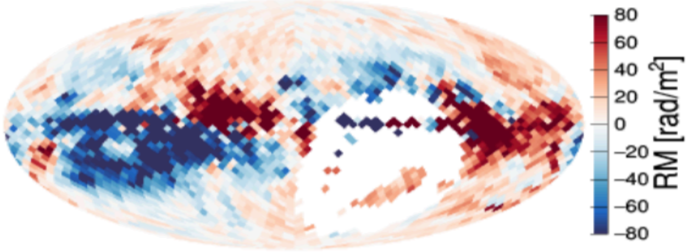
Propagation at a Glance

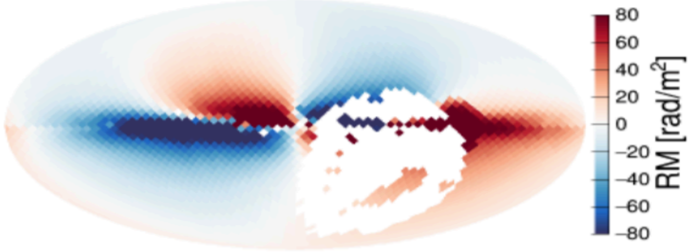
- *Historical impetus*: grammage/confinement time & near isotropy.
- *Interaction with galactic magnetic field*:
  - Follow fieldlines on scales >> gyroscale r_g, structure on scales << r_g averages out, structure at r_g scales **scatters**.
  - Field line random walk & scattering impart diffusive behavior.
  - Well scattered cosmic rays exchange energy & momentum with background plasma.
  - Below some energy (100-200 GeV) cosmic rays control their own scattering ⇔ **self confinement**.

Plan of This Talk

- Orbits
- Orbits Plus Scattering
- Scattering
- Self confinement
  - Two effects of clouds
- Application to galactic wind termination shocks.

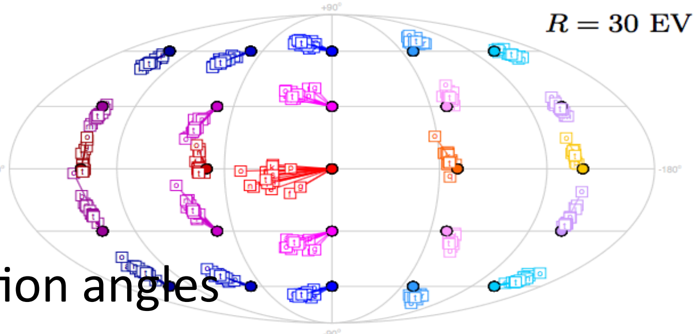
Orbits at EeV Energies

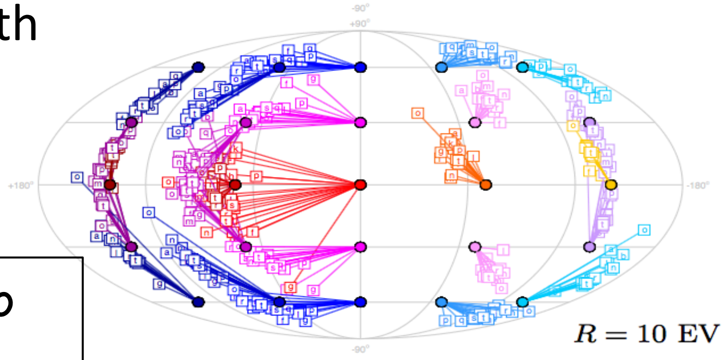




Top left: Rotation measure sky. Top right: Rotation measure sky from Galactic B & n_e model (Unger & Farrar 2017).

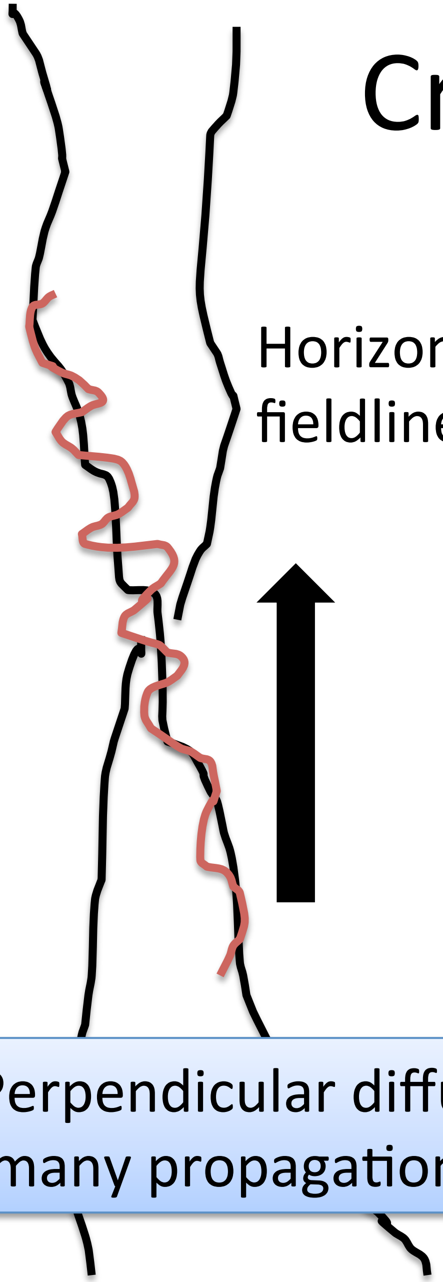
Top & bottom panels on right: source position angles calculated from different field models with fixed observer at 30 & 10 EeV (Farrar & Sutherland 2017).





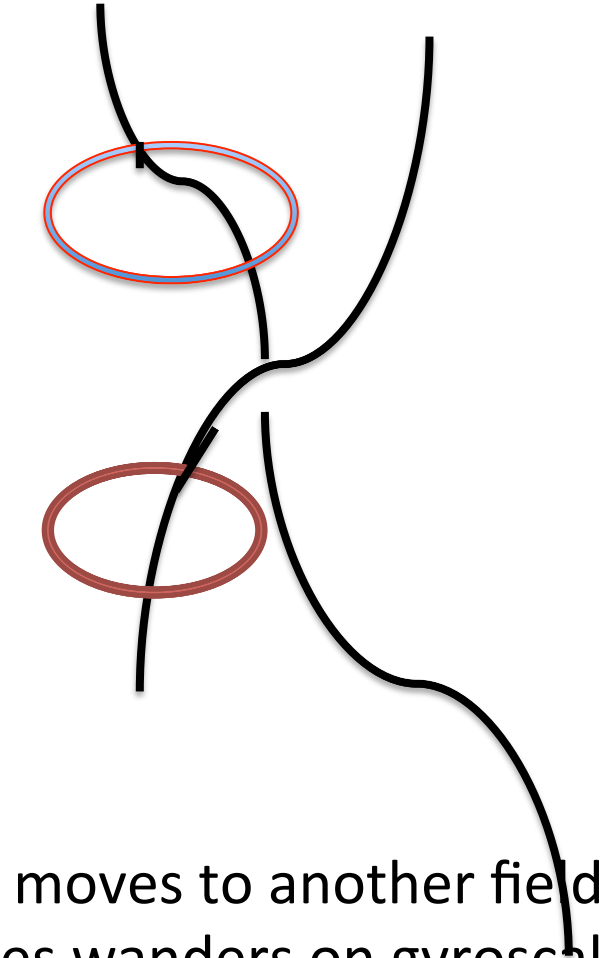
Models don't resolve finest scales. Sensitivity to small scale features decreases with energy.

Crossfield Diffusion



Horizontal motion due to fieldline motion

Perpendicular diffusion in many propagation codes



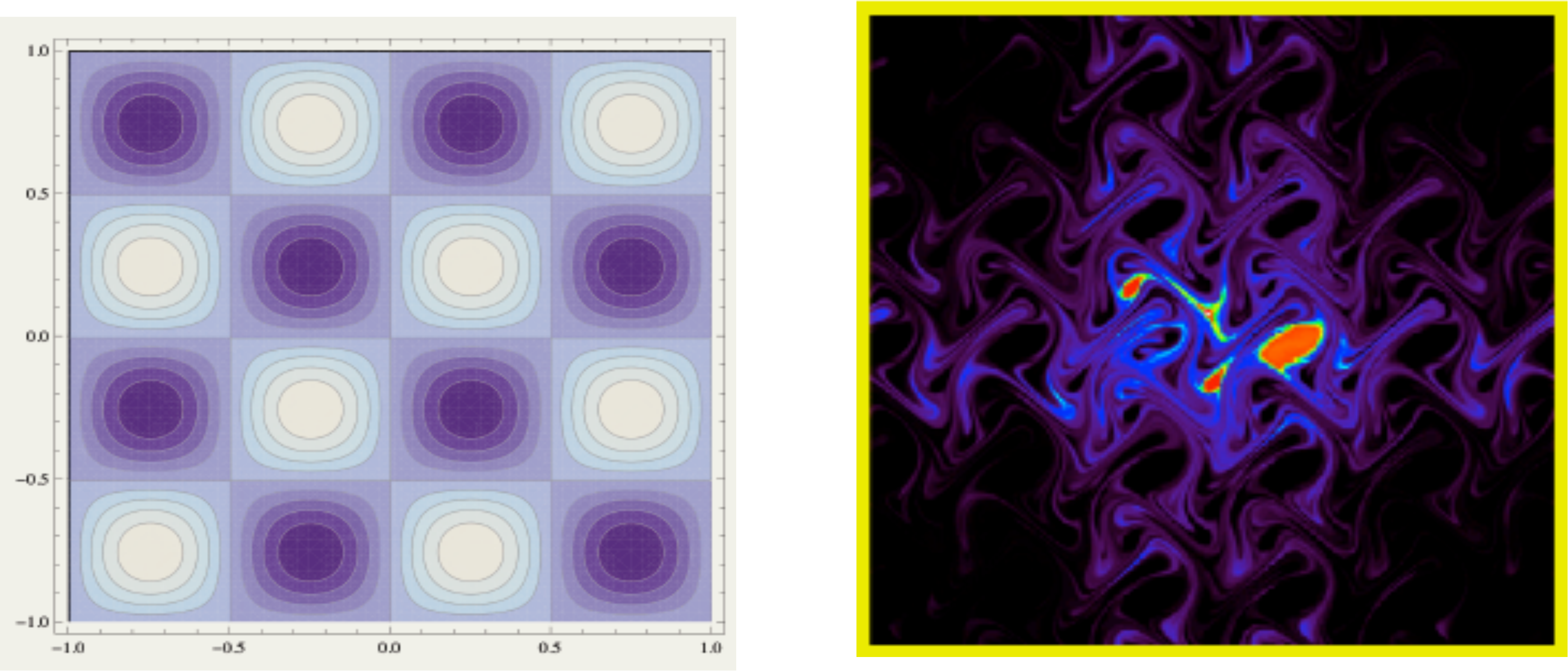
Particle moves to another fieldline (fieldlines wanders on gyroscale)

A Study of Cross-Field Transport

- ***Joint effects*** of magnetic geometry and pitch angle scattering is a powerful cross-field transporter.
- Studied in simple magnetic field models with bounded perpendicular displacement.
- Numerical integration of test particle orbits

Desiati & EZ, 2014 ApJ

Magnetic Field Models



Left: “Cellular” magnetic field projection on horizontal plane. *Right*: “Galloway-Proctor magnetic field projection revealed through mixing of a passive scalar by the analogous flow. The third field, a uniform field, is not shown.

Diffusion Coefficients

- Define the running diffusion tensor

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

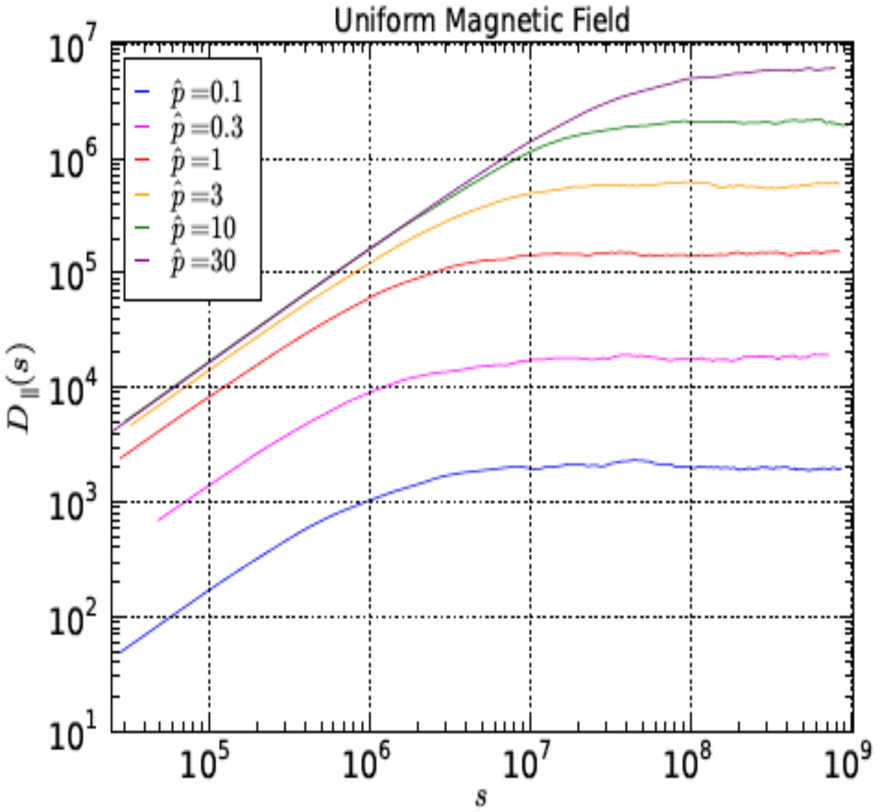
- Correct for crossfield motion

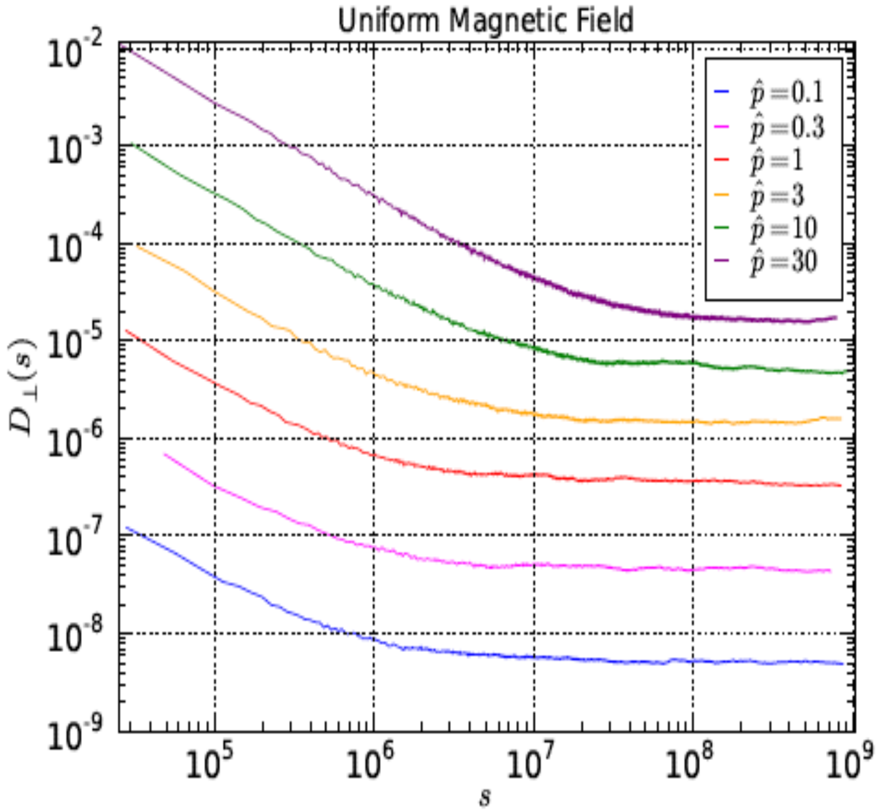
$$\boldsymbol{x}_{gc} = \boldsymbol{x} + \frac{\boldsymbol{v} \times \ddot{\boldsymbol{b}}}{\omega_g}. \qquad \Delta \boldsymbol{x} \equiv \boldsymbol{x}_{gc} - \boldsymbol{x}_f$$

- Define the corrected running diffusion tensor

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

Diffusion in a Uniform Field

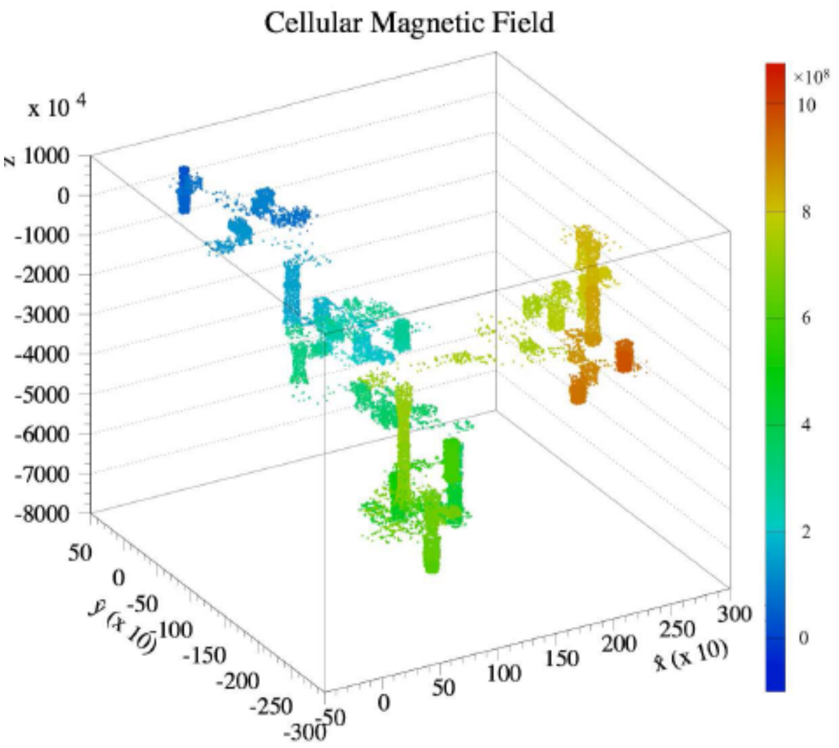


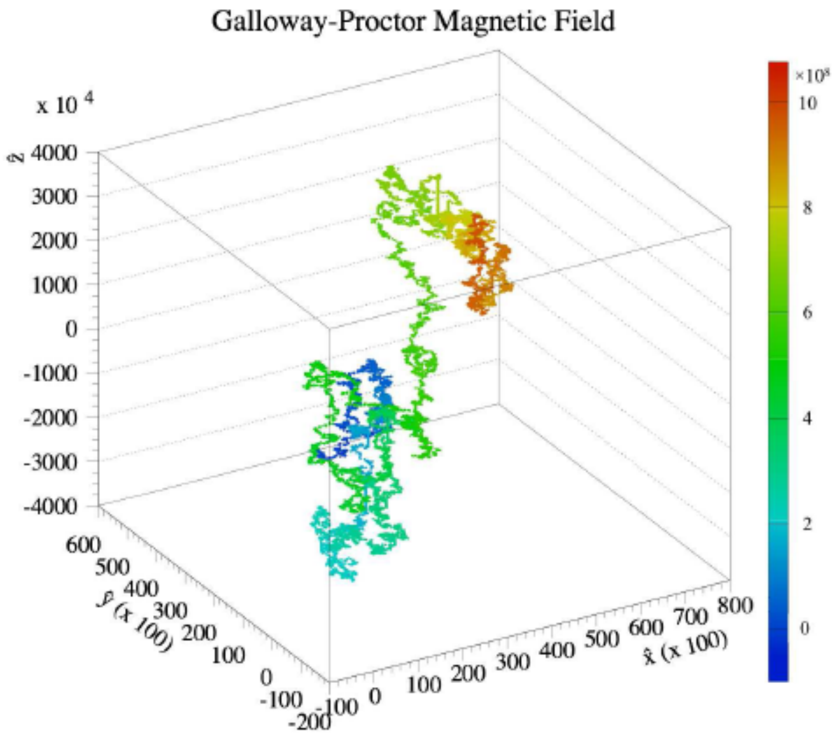


$$\kappa_\parallel = \langle \frac{v_\parallel^2}{\nu} \rangle = v^2 \frac{\int_{-1}^{1} f(\mu)\frac{\mu^2}{\nu}\, d\mu}{\int_{-1}^{1} d\mu} = \frac{v^2}{3\nu}$$

$$\kappa_\perp = \kappa_\parallel \frac{r_g^2}{\lambda_\parallel^2} = \frac{r_g^2 \nu}{3}$$

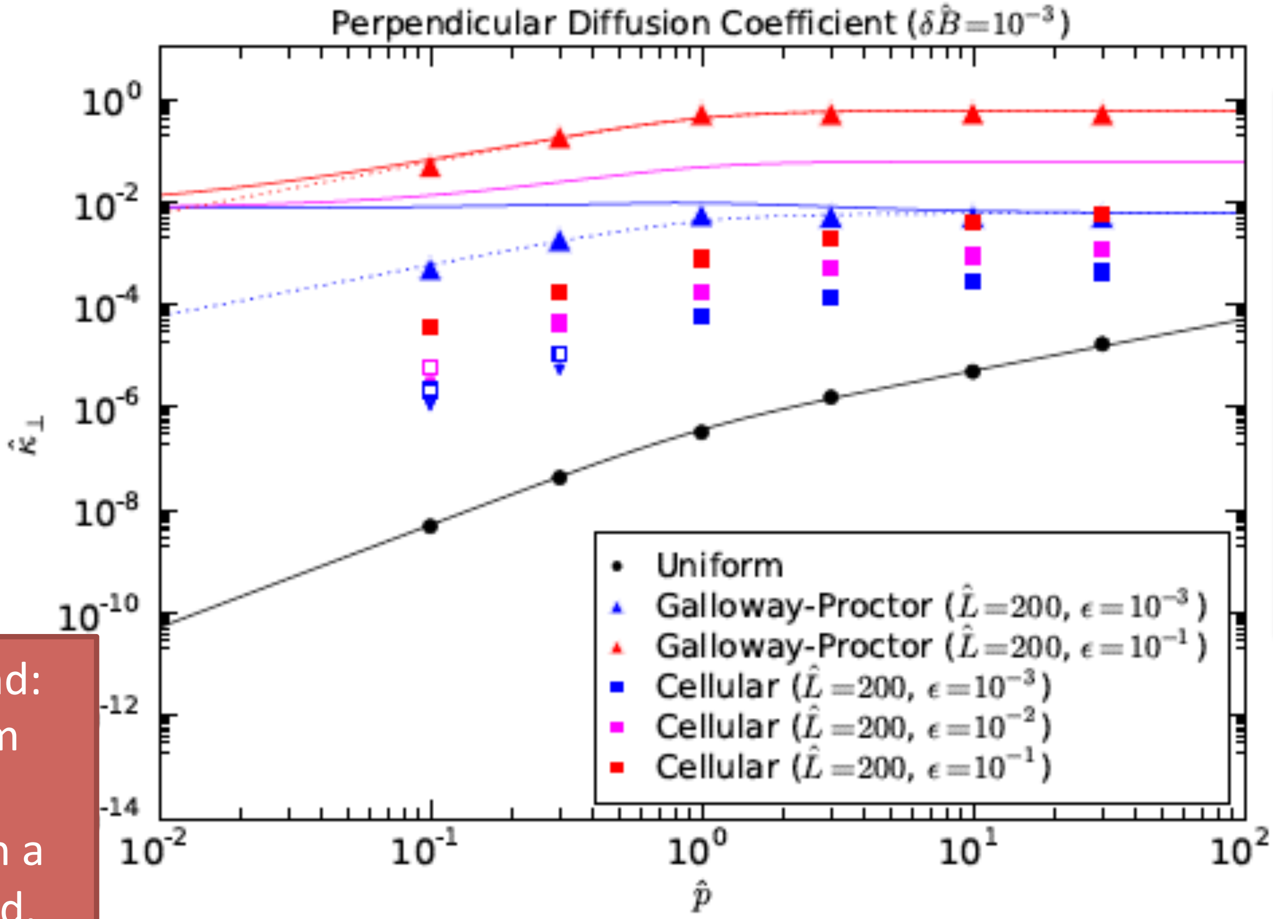
The Cellular & GP Fields


Cellular Magnetic Field


Galloway-Proctor Magnetic Field

Particles orbit in a single cell until they reach a separatrix and cross into another cell. Note the differences in scale between the cellular and GP cases.

Summary of Results

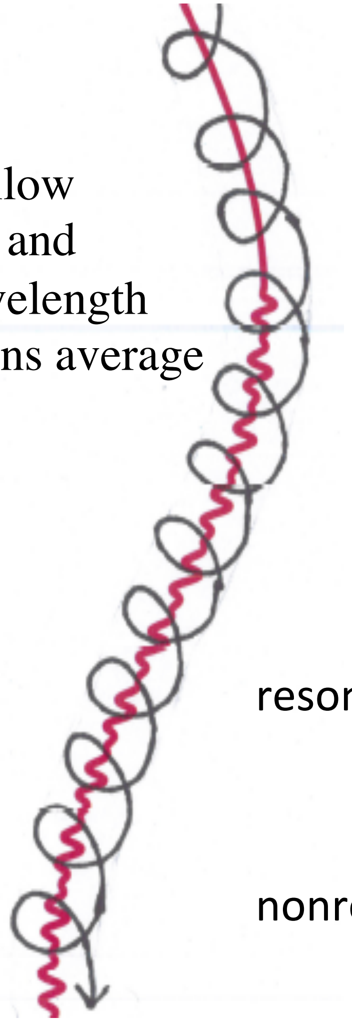


Upper bound: Eddy rate L^2/t_{orb} assumes one hop per orbit around a cell.

Lower bound: $r_g{}^2/t_{sca}$ from pitch angle scattering in a uniform field.

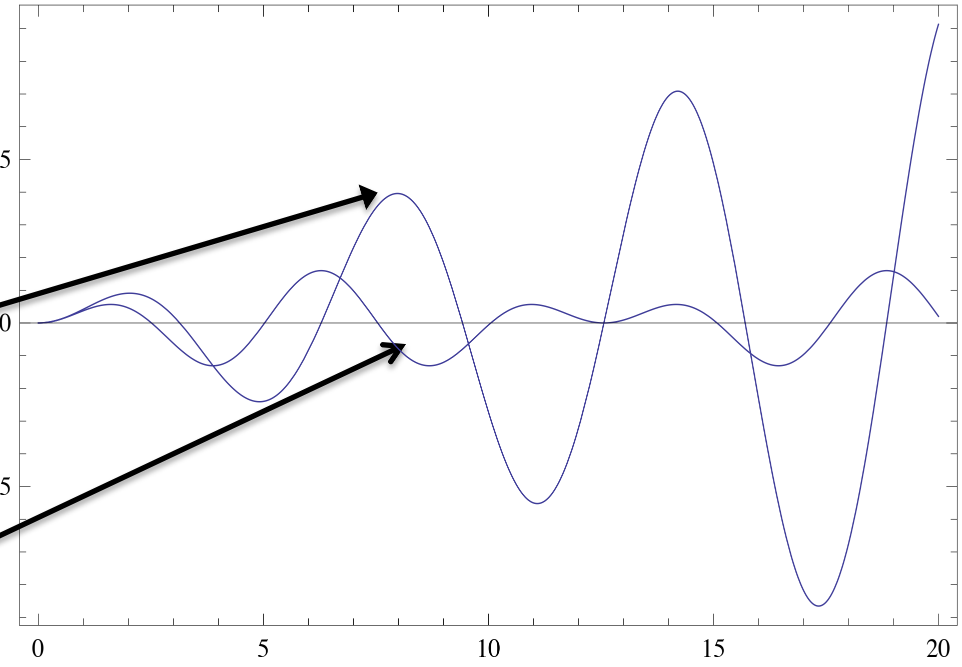
Gyroresonant Scattering

Orbits follow fieldlines and short wavelength fluctuations average out.



$$\omega - kv\mu = \pm\omega_c;$$

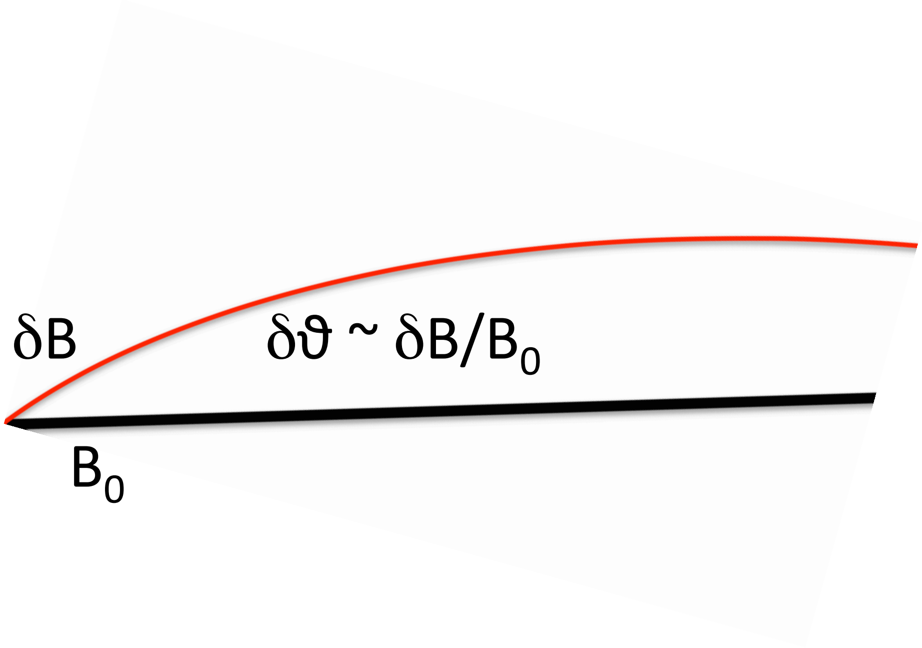
$$\mu \equiv \frac{v_{||}}{v}$$



resonant

nonresonant

Heuristic Diffusion Coefficient



Scattering frequency

$$\nu \sim \frac{\langle(\delta\theta)^2\rangle}{\delta t}$$

$$\sim \omega_c \left(\frac{\delta B}{B_0}\right)^2$$

Scattering is nearly elastic: $v_A/c \ll 1$.

Fokker – Planck (F-P) Equation

Reaction of waves on zero order cosmic ray distribution function f_0

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

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 $(v_A/c)^2$, requires waves traveling in both directions

Small angle
Scattering by
nearly
periodic
randomly
phased waves

Frequent Scattering Approximation

Relate anisotropy to spatial gradient:

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

Or, in the wave frame

$$\frac{v}{\nu}\frac{\partial f}{\partial z} = -\frac{\partial f}{\partial \mu}$$

Here the Subject Bifurcates

- Waves generated by the cosmic rays themselves
- **Self-Confinement** Picture
- **Classical** Cosmic Ray Hydrodynamics

- Waves are present as part of a turbulent cascade
- **Extrinsic Turbulence** Picture
- **Generalized** Cosmic Ray Hydrodynamics

For cosmic ray feedback on the background medium

“Streaming Instability: Gyroresonant Amplification of Alfven Waves

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

resonance

damping

excitation by anisotropy

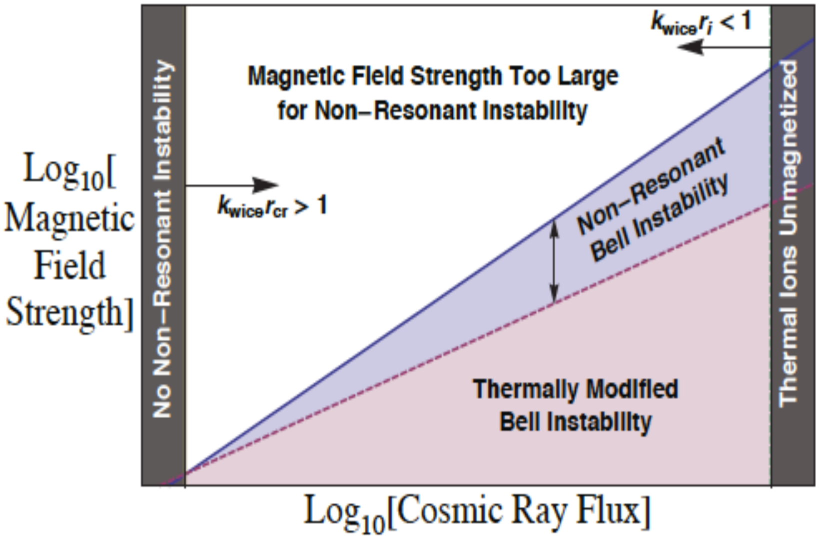
Simple approximation to the growth rate:

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

Nonresonant “Bell” Instabilities

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

EZ + Everett 2010 ApJ



Here we only discuss the “classic” gyro resonant instability.

Wave Damping Balances Growth

- 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, enhanced at high β.*

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

Self-confinement does not work above 100-200 GeV in the Milky Way.

Constrained Diffusion

From Fokker-Planck equation.

$$\frac{v}{\nu}\frac{\partial f}{\partial z} = -\frac{\partial f}{\partial \mu}$$

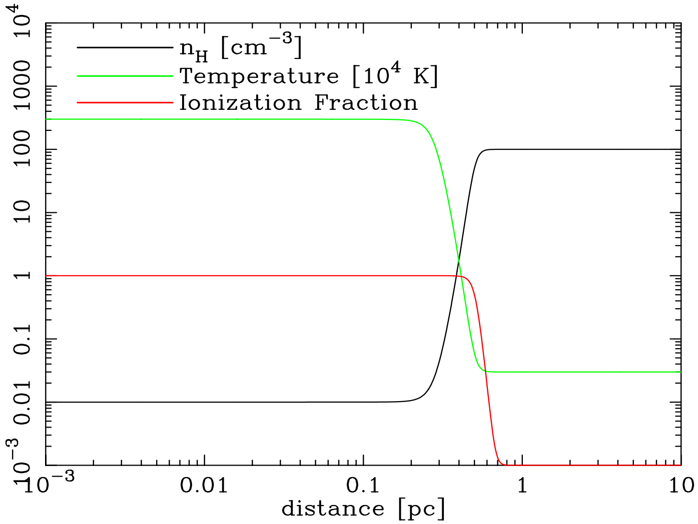
$$\frac{v^2}{\nu}\frac{\partial f}{\partial z} = \kappa_{\|}\frac{\partial f}{\partial z} = -v\frac{\partial f}{\partial \mu}$$

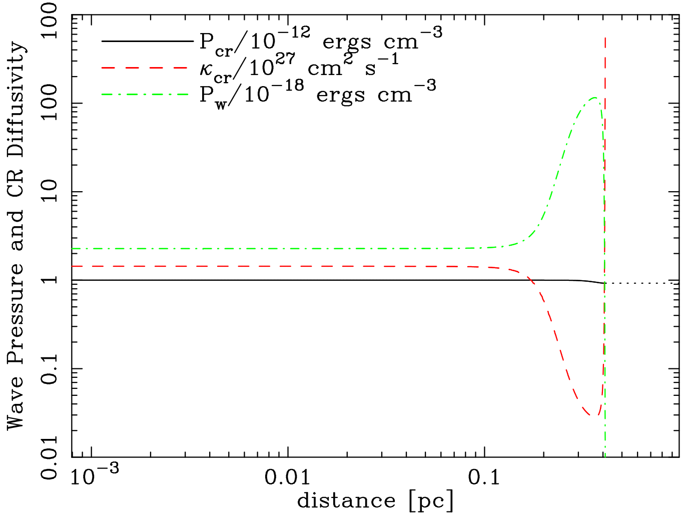
Diffusive flux

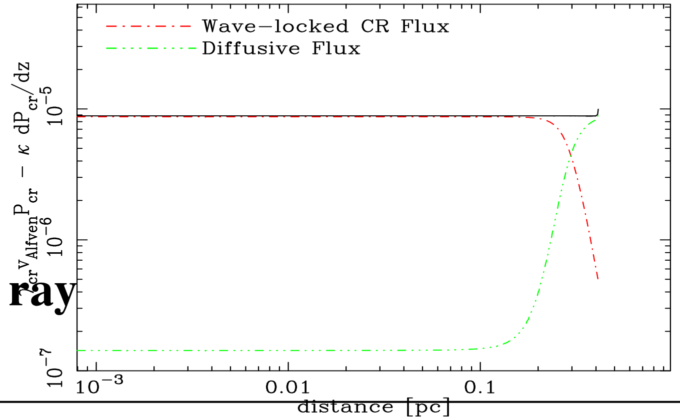
Proportional to instability growth & therefore damping rate.

Application: Cosmic Rays in Clouds

Everett & Zweibel ApJ 2011





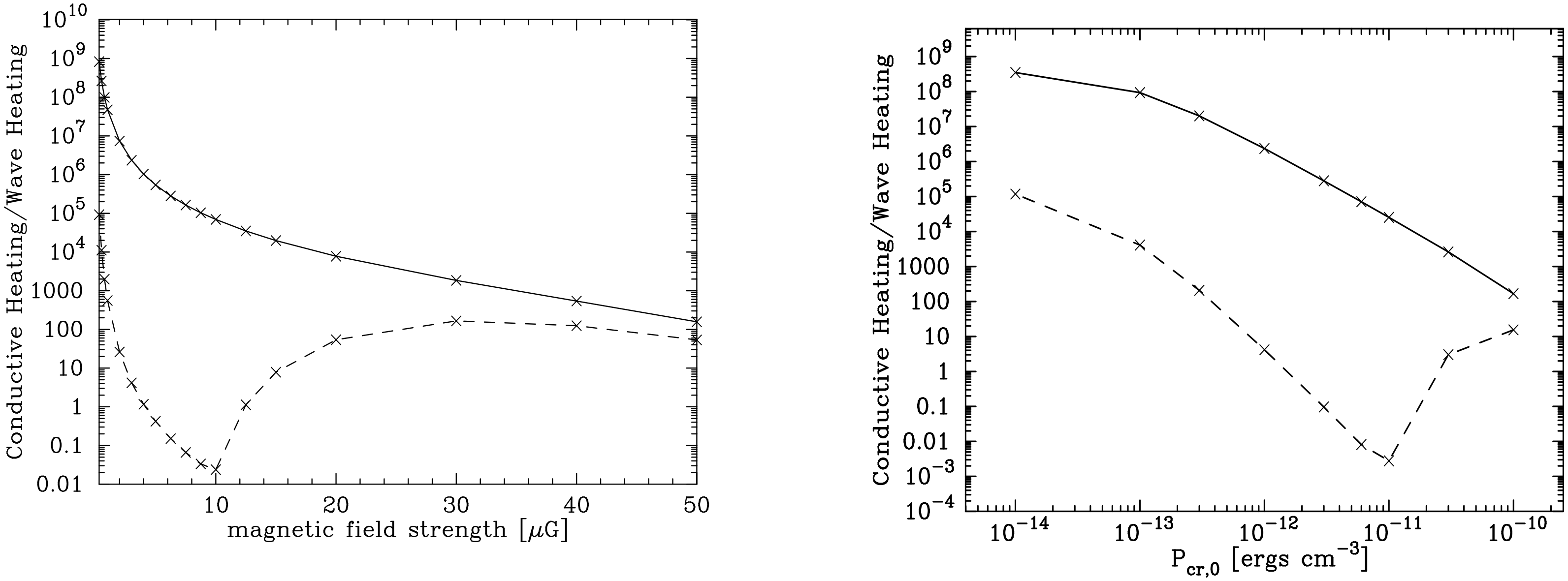


Top left: Model cloud setup. Top Right: Cosmic ray & wave pressure vs. depth. Bottom right: Transition from advection to diffusion, followed by free streaming -> **No force due to cosmic ray momentum transfer on the bulk of the cloud**.

Decoupling modeled in Farber, Ruszkowski, Yang, EZ 2017 arXiv

Cosmic Ray Heating of Clouds

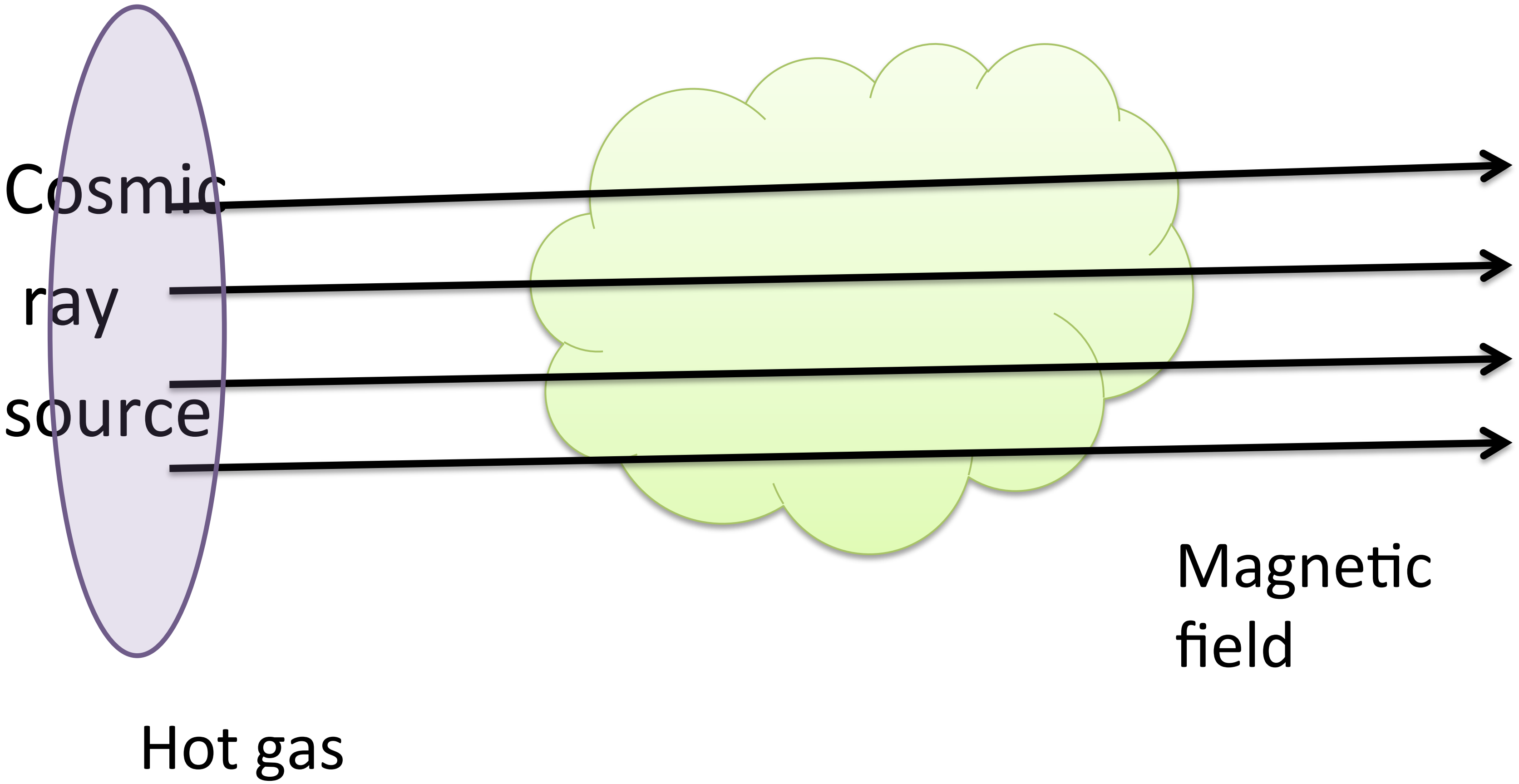
Streaming excites waves, waves damp, transferring energy & momentum to the gas. (unavoidable outcome of self confinement picture).



Ratio of conductive to wave heating in the model cloud. The upper & lower curves show maxima & minima, respectively. In the left figure B is varied, in the right figure Pcr is varied. Only a thin skin is heated, then cosmic rays decouple. From Everett & Zweibel 2011.

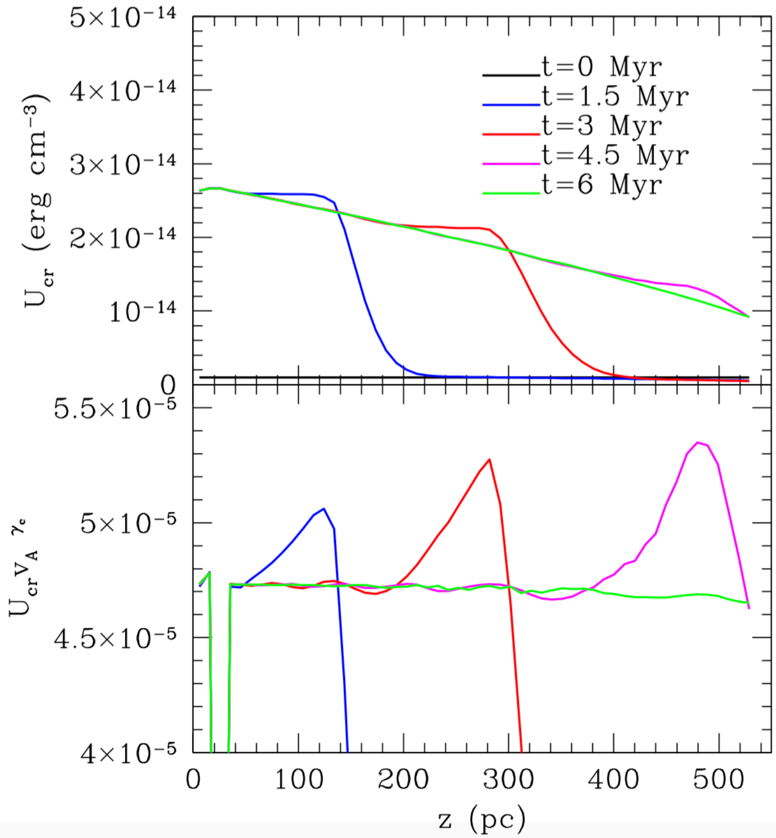
Effect on a Cool Cloud in a Hot Medium

(Wiener, Oh, EZ 2017)

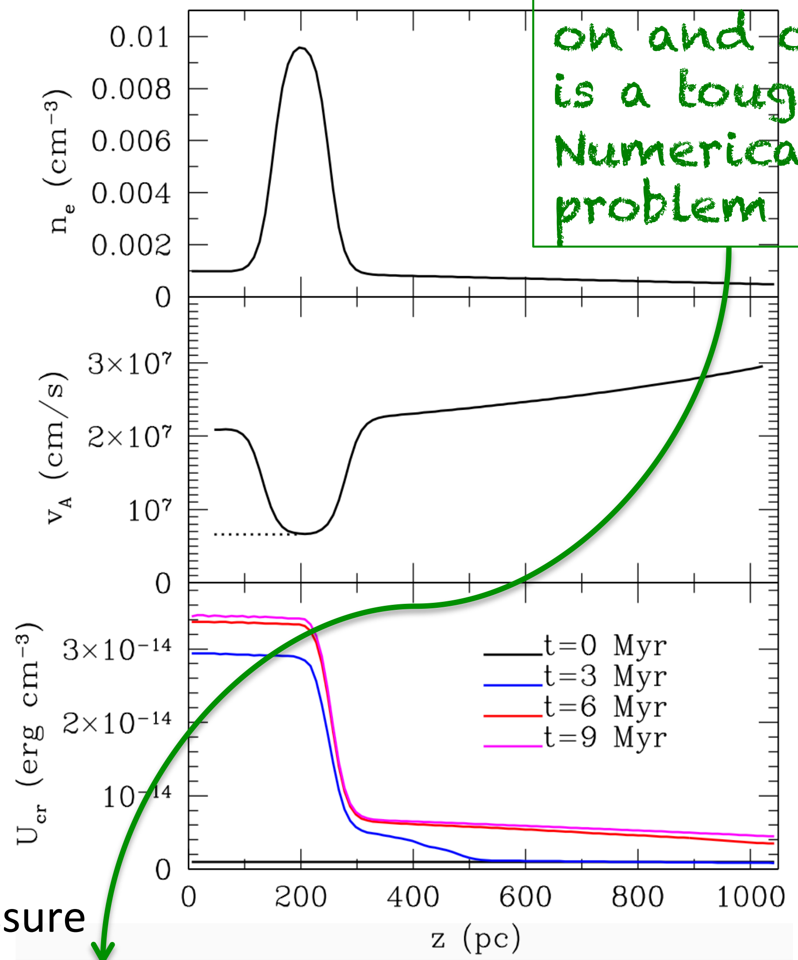


Bottleneck Effect

No Cloud



Cloud



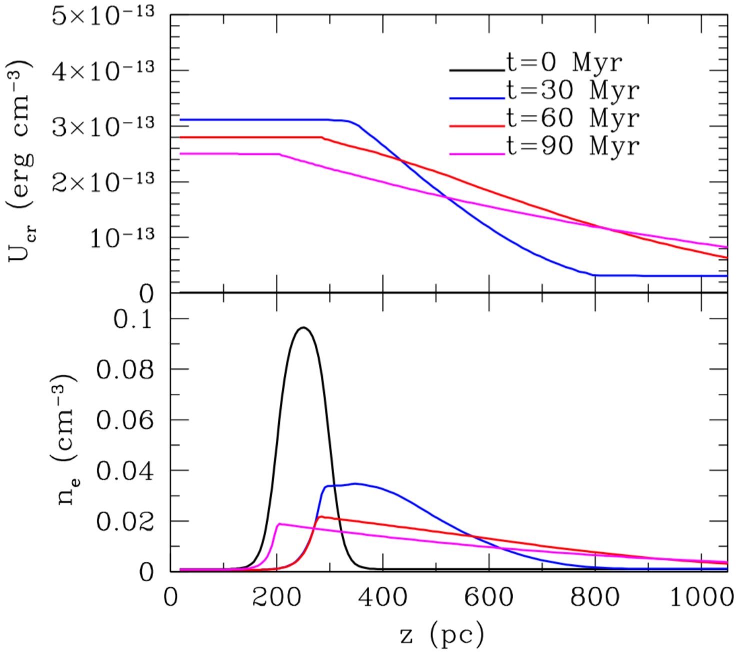
Switching the waves on and off is a tough Numerical problem

Left: Cosmic rays streaming down their pressure gradient at v_A evolve to constant $U_c v_A^{\gamma_c}/2$. If v_A has a minimum, U_c behind it must go flat (Right).

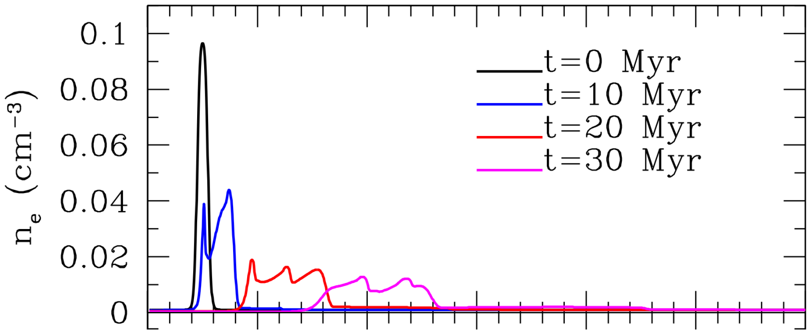
Wiener, Oh, EZ (2016)

Cloud Accelerated by Cosmic Ray Pressure

Wiener, Oh, EZ 2016



Top: Cosmic ray pressure. Bottleneck is to the left & moves back as gas is accelerated toward the right (bottom). Cloud evaporates due to heating.

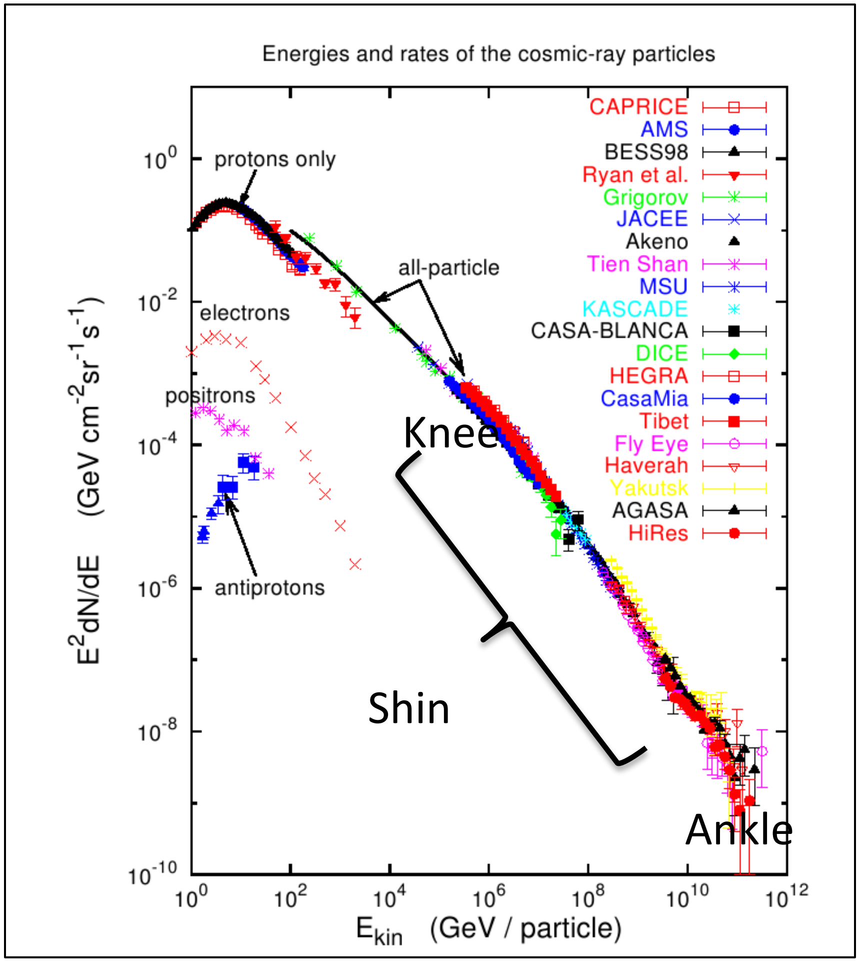


Efficient radiative cooling accelerates cloud without destroying it.

Scattering by Extrinsic Turbulence

- Alfven waves generated by MHD turbulence in the ISM have short perpendicular wavelengths & do not scatter cosmic rays efficiently.
- Compressive MHD waves generated by the Alfven waves are efficient scatterers (if not Landau damped away).
- Scattering by compressive waves provides some Fermi acceleration.
- Largely responsible for diffusion at ~ 0.2 TeV & above.

Propagation & Acceleration



- What is the origin of "shin" particles?
- Can UHECR be accelerated at galactic wind termination shocks?
- How does the termination shock affect the cosmic ray output of a galaxy?

Bustard, EZ, & Cotter 2017 ApJ
Merten, Bustard, EZ, & Becker-Tjus, in prep.

Origin of Shin Particles

- Particles with $E <$ few x 10^9 GeV are confined to the Milky Way.
- Current theories of diffusive shock acceleration by SN can accelerate up to few x 10^6 GeV (the knee).
- Seek a galactic process that fills the gap
  - A shock that is geometrically larger & longer lived than a SNR shock.

Release of Cosmic Rays into the IGM

- Milky Way cosmic ray output is few x 10^{40} erg/s.
- Static halo – this is released into the IGM
- Expanding wind with good coupling – particles lose energy adiabatically at best (E ~ 1/R).
- Can re-acceleration by a wind termination shock provide a large cosmic ray outgoing luminosity?

Wind Model

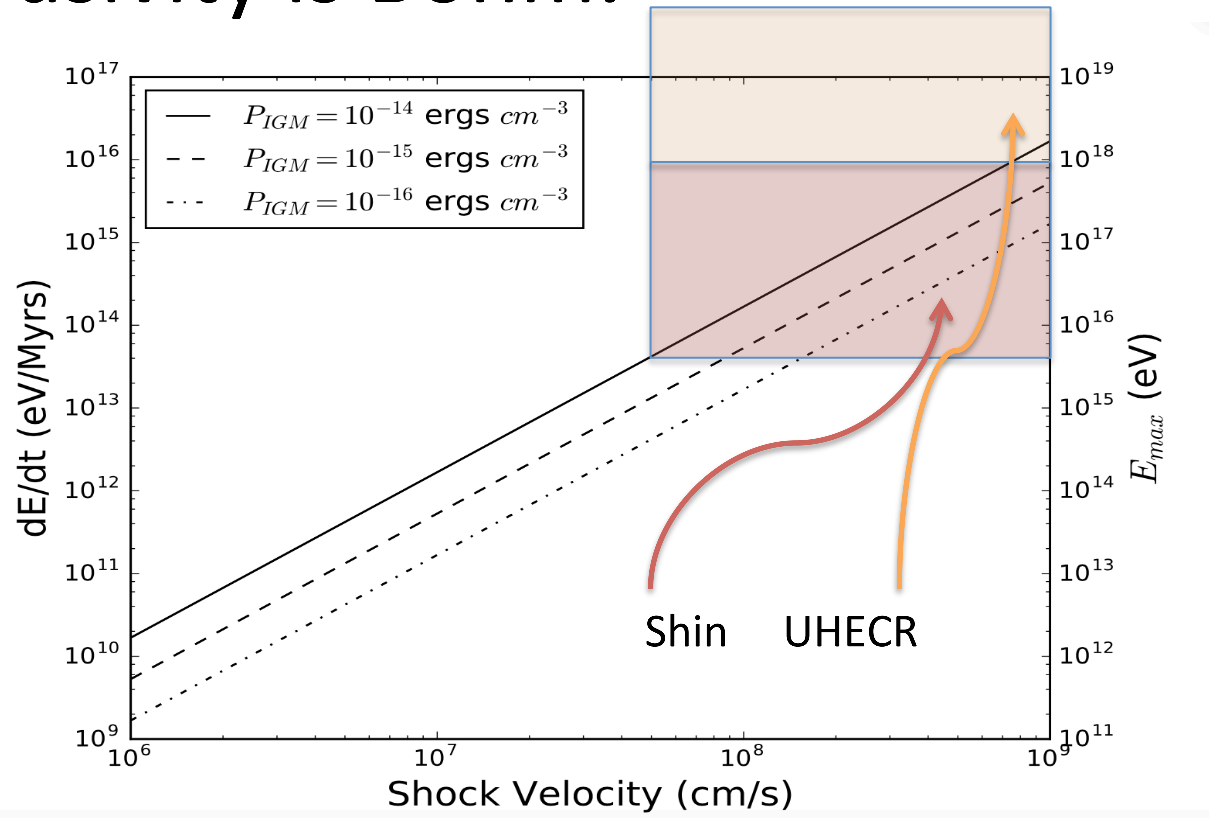
- Spherically symmetric
- Steady state
- Thermally driven,
- Radiatively cooled

Bustard, EZ, D-Onghia 2016 ApJ

Assume B is Amplified to Equipartition & Diffusivity is Bohm.

$$\frac{B^2}{4\pi} = \rho V_{\text{shock}}^2$$

Maximum rate of energy gain & E$_{\text{max}}$ after 100Myr



$$\frac{dE}{dt} = (1.5 \times 10^{-18} Z)\sqrt{4\pi P_{\text{IGM}}} V_{\text{shock}}^2 \quad \text{GeV/s}$$

Which Particles Return to the Galaxy?

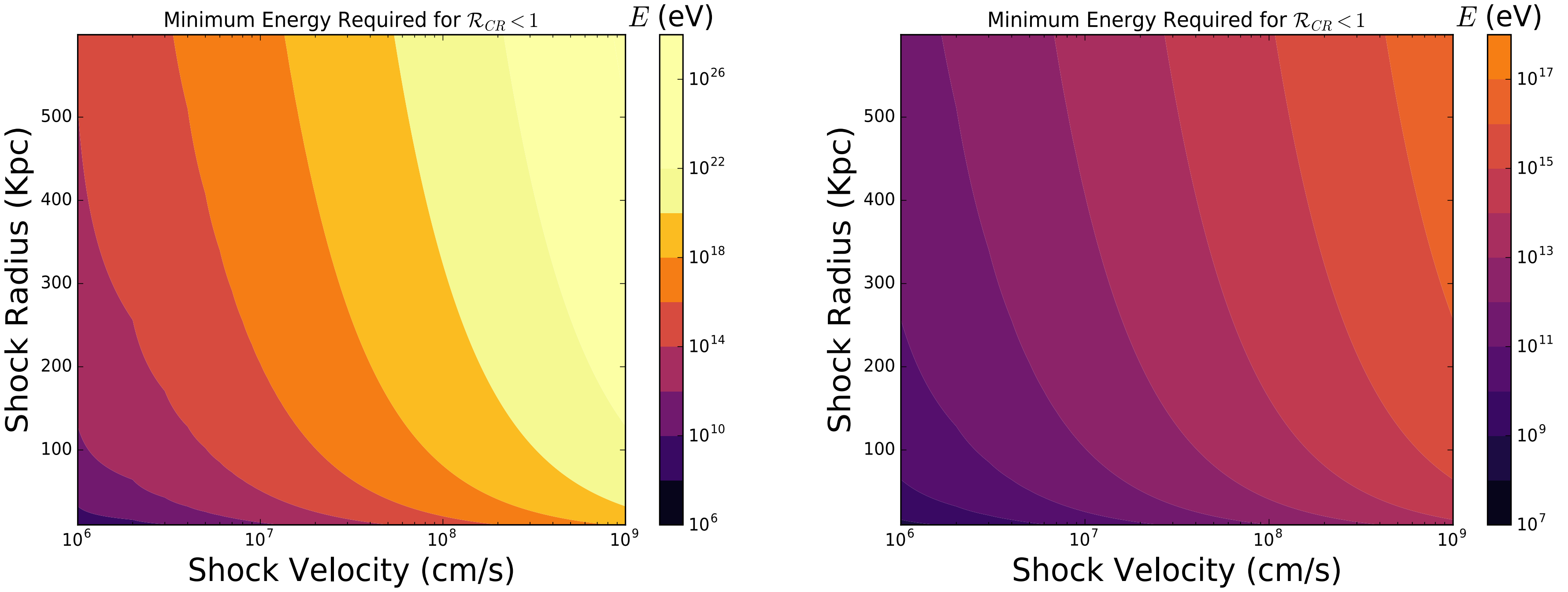
- Measure diffusion inward vs advection outward by a cosmic ray Reynolds number

$$\mathcal{R}_{\rm CR} = \frac{R_{\rm shock} V_{\rm shock}}{\kappa(E)}$$

$$\kappa(E) = D_0 \times 10^{28} {\rm cm}^2 {\rm s}^{-1} {\rm E}_{\rm GeV}^{\rm a}$$

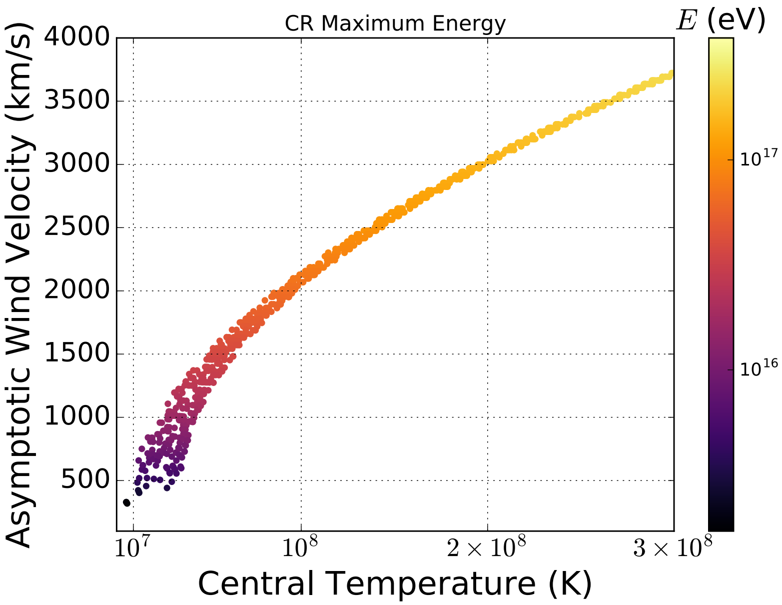
- Particles with $\mathcal{R}_{\rm CR} < 1$ are likely to diffuse back to the galaxy.

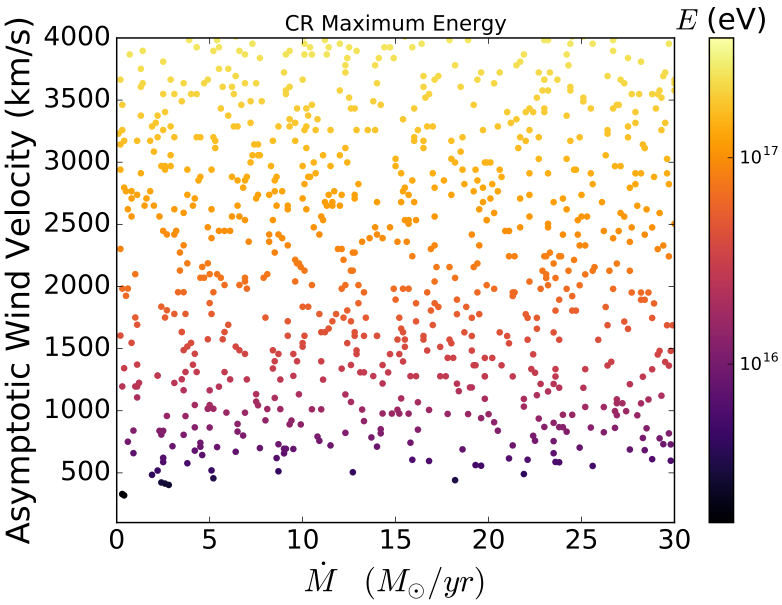
Minimum Energies Such That $\mathcal{R}_{CR} < 1$



Left panel: $\kappa \sim E^{0.3}$; right panel: κ ` $E^{0.6}$. While acceleration to high energy demands a fast wind, returning to the galaxy is more likely for a slower wind. Both conditions require high ambient pressure.

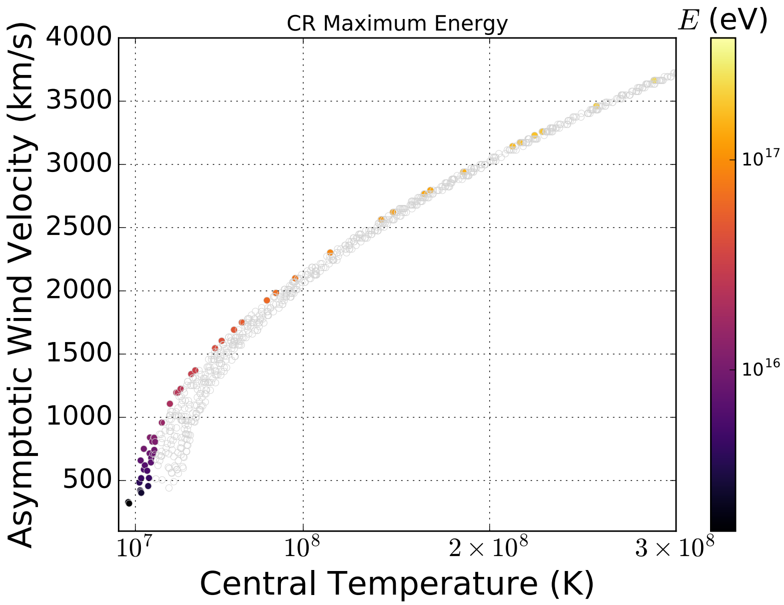
Predictions for BZD Wind Models

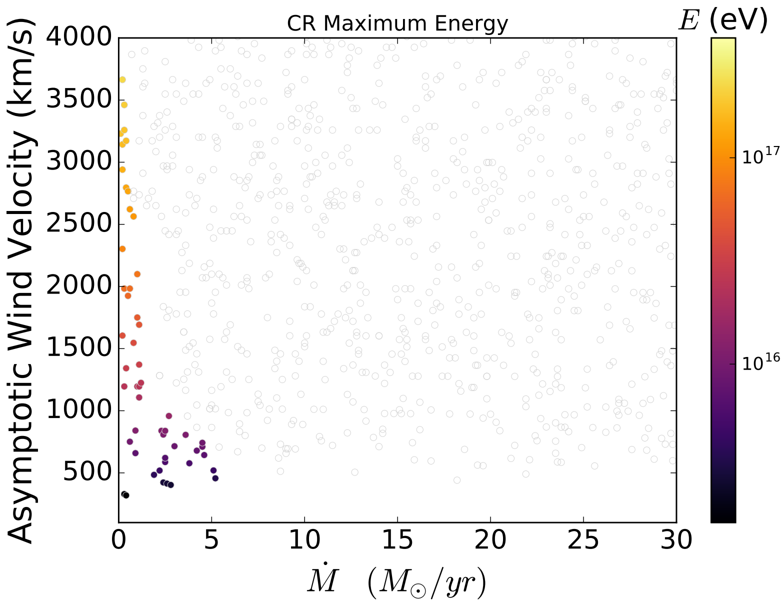




Maximum cosmic ray energy that can be accelerated at termination shocks in a Large set of wind models, by central temperature & mass loss rate.

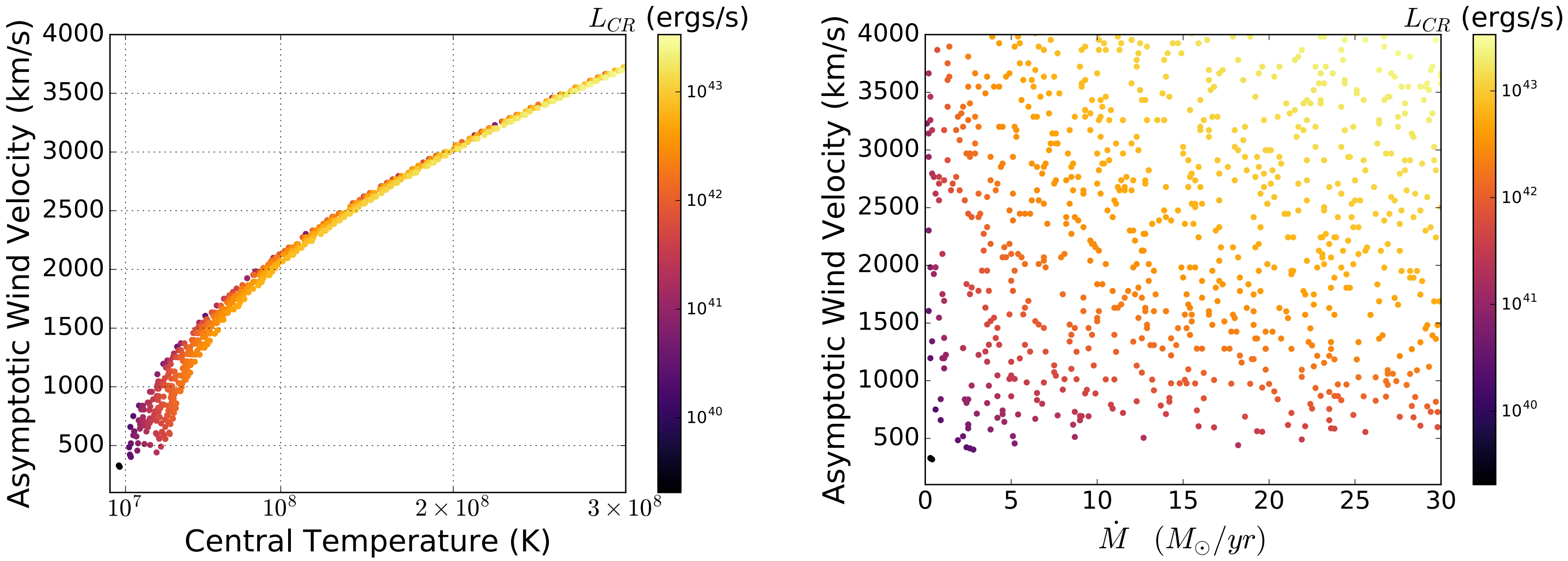
Predictions for BZD Wind Models





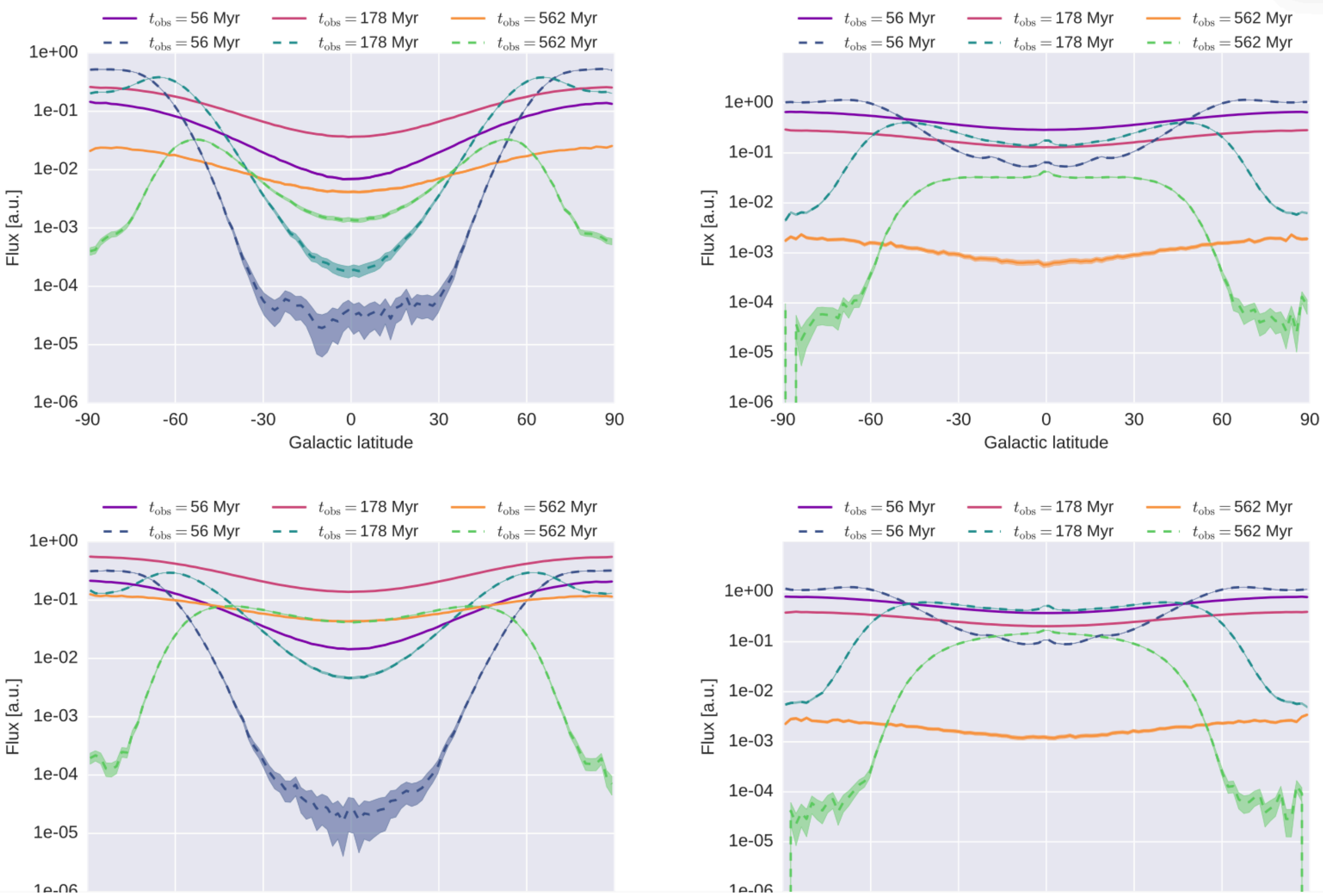
Same data set, but only cosmic rays which are likely to return to the disk are colored.

Cosmic Ray Luminosities



Cosmic ray luminosities of the same models, most of which is depositied in the IGM

Time Evolution of Arrival



Evolution in arrival direction with (top) and without (bottom) a wind, spiral field, 2 different diffusivities, allowing (solid) or not (dashed) perpendicular diffusion. From Merton, Bustard, EZ, Becker-Tjus in prep.

Summary on Termination Shocks

- With magnetic field amplification to equipartition and 100 Myr to act, galactic wind termination shocks can accelerate cosmic rays to shin energies.
- Most of these particles propagate into the IGM rather than back to the galaxy.
- Acceleration of UHECR is unlikely.

Work in progress with CR-Propa (Merton, Bustard, EZ, Becker-Tjus is consistent with these findings.

Summary and Outlook

- Much progress has been made with simply parameterized propagation models.

- Much progress has been made with plasma physics based, idealized propagation models.

Now is the time to bring them together

- Transition from diffusion to orbit description (CR-Propa)
- Geometry plus scattering
- Improved description of the ISM, winds, outflows
- Interaction with realistic forms of waves and turbulence

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