An Introduction to Cosmic Rays

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PiTP 2016

Why Study Cosmic Rays?

Collective Side

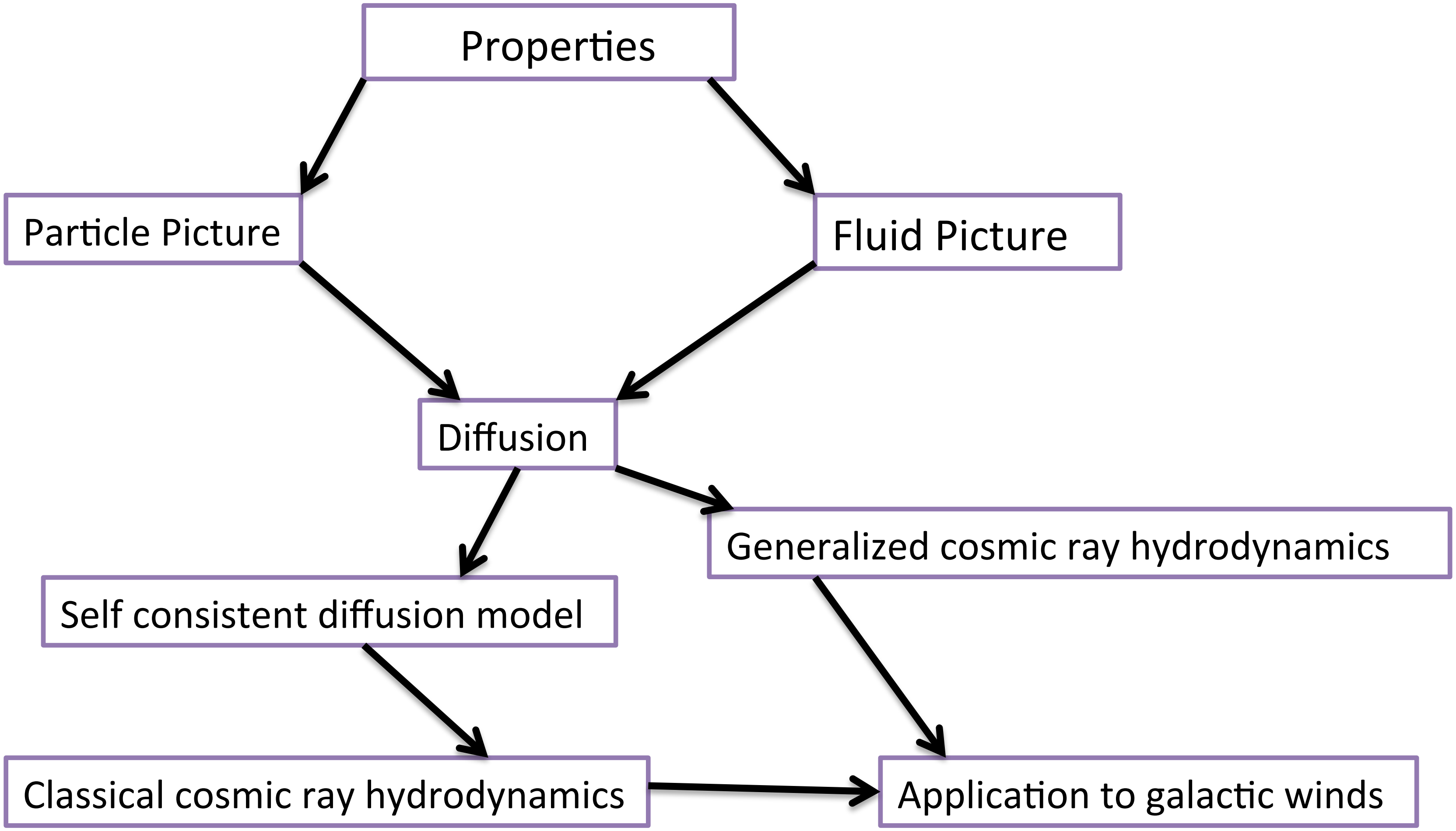
- How is the apportionment of energy between thermal gas, magnetic fields, and cosmic rays in the interstellar and intracluster medium **regulated**?
- How do cosmic rays interact with the thermal gas, despite being virtually collisionless?

✓

Particle Side

- How is the cosmic ray spectrum formed?
- How are the highest energy cosmic rays accelerated?
- What can we learn about particle physics, dark matter, and fundamental physics from cosmic rays?

Plan of Lectures



Properties

Particle Picture

Fluid Picture

Diffusion

Generalized cosmic ray hydrodynamics

Self consistent diffusion model

Classical cosmic ray hydrodynamics

Application to galactic winds

Outline of Slides

- History at a glance
- Direct detection
- Energy spectrum
- Composition
- Isotropy
- Wider view of cosmic rays in galaxies
- Behavior over time
- Interpretation
- Goals of a theory
- A bit on orbits & diffusion

Some Early Milestones in Cosmic Ray Astrophysics

- 1912 V. Hess showed the the source of atmosphere ionization, first detected by Coulomb, are cosmic.

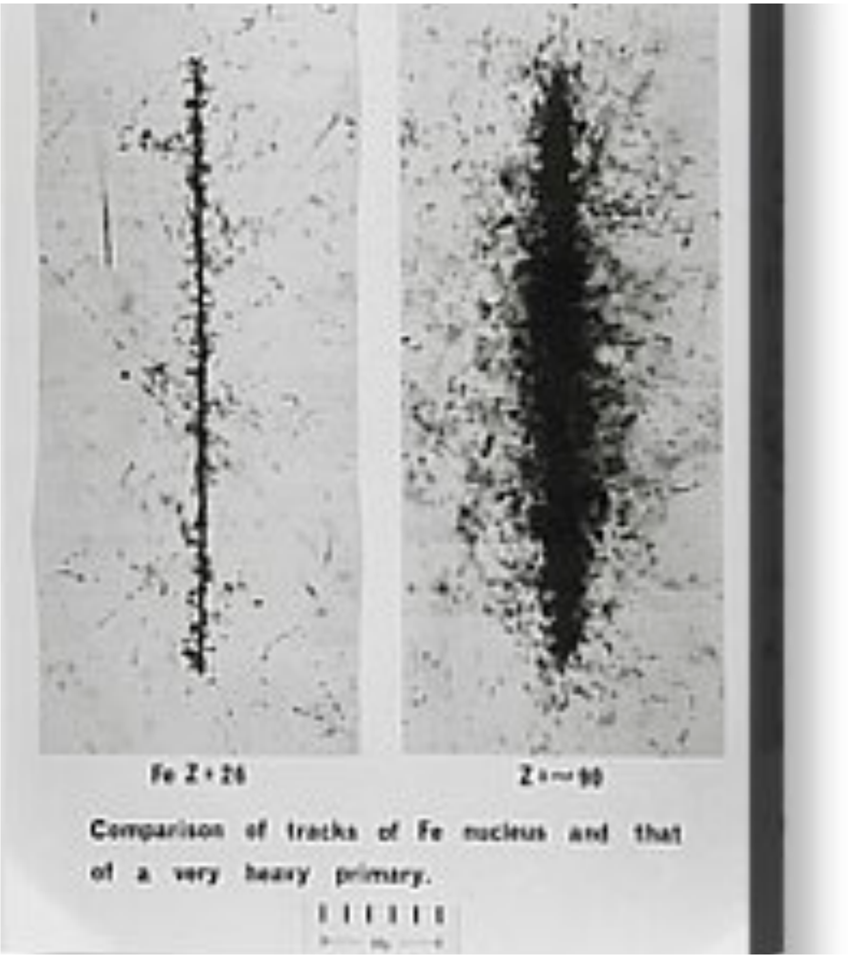
- 1927 J. Clay showed the ionizing flux is latitude dependent, suggesting the “rays” are charged particles, deflected by the geomagnetic field.

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

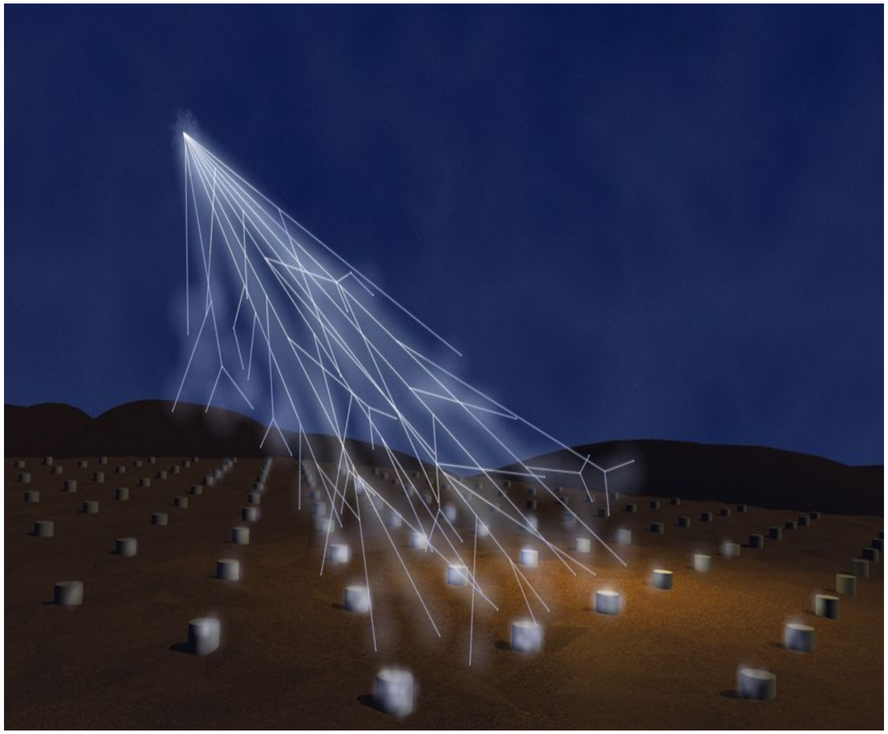
- 1949 J. Hall & W. Hiltner observed a pervasive Galactic magnetic field through starlight polarization by aligned dust grains.

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

In Situ Detection



Comparison of tracks of Fe nucleus and that of a very heavy primary.



Pierre Auger Observatory: 1600 Cerenkov detector water tanks deployed in Argentina:

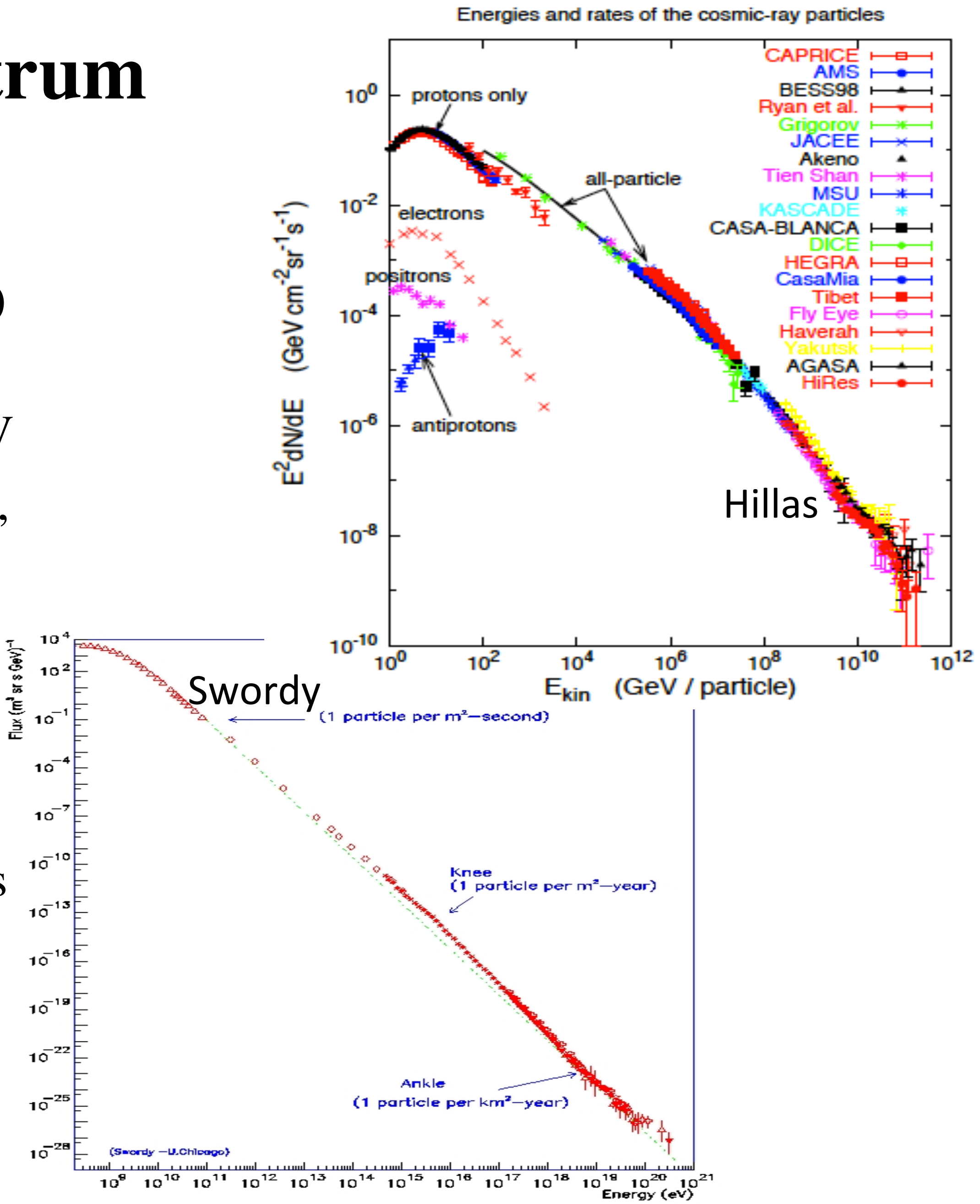
The Energy Spectrum

- A broken power law:

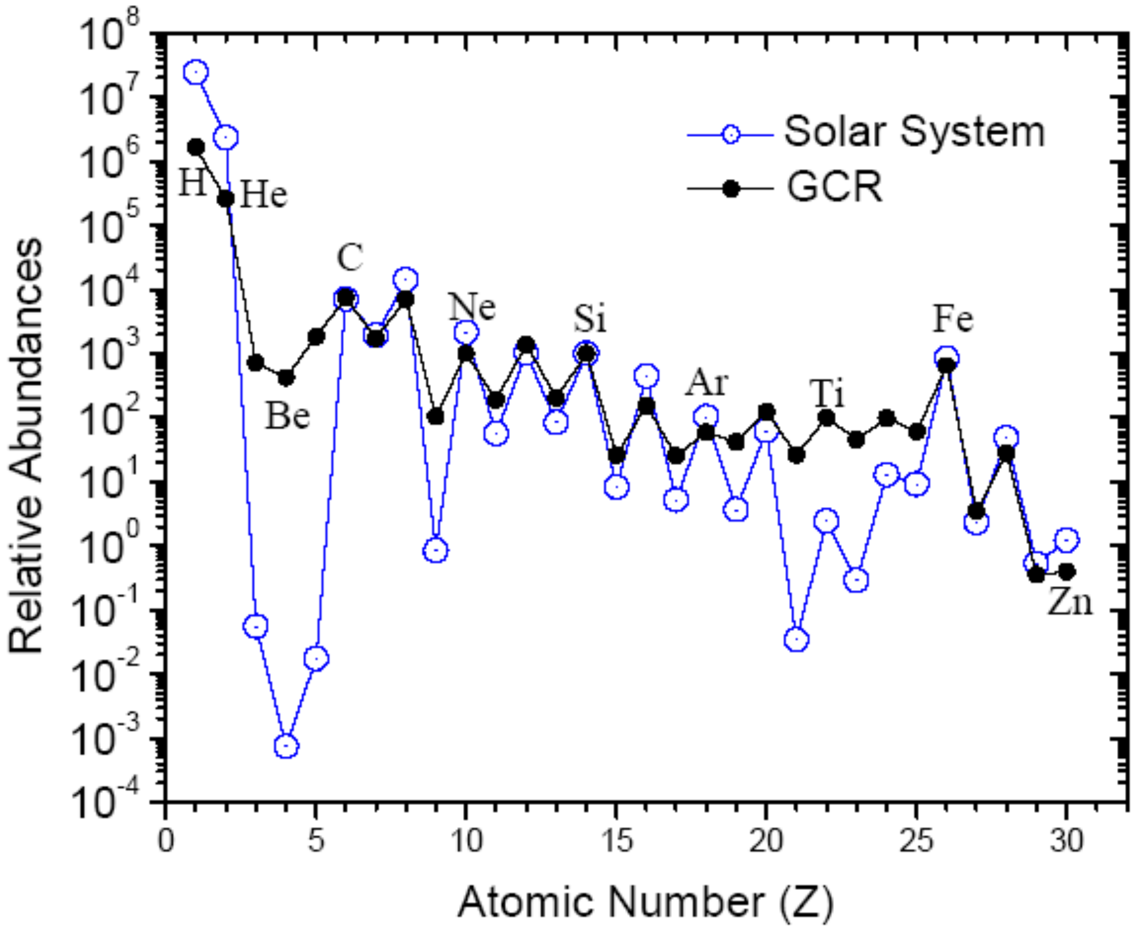
$N(E) \sim E^{-2.7}$, $E_{PeV} < 3$

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

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



Cosmic Ray Composition



Tremendous enrichment of Li, Be, B explained by collisions of C, N, O cosmic rays & interstellar gas.

Not enriched In r-process elements from supenova nucleosynthesis

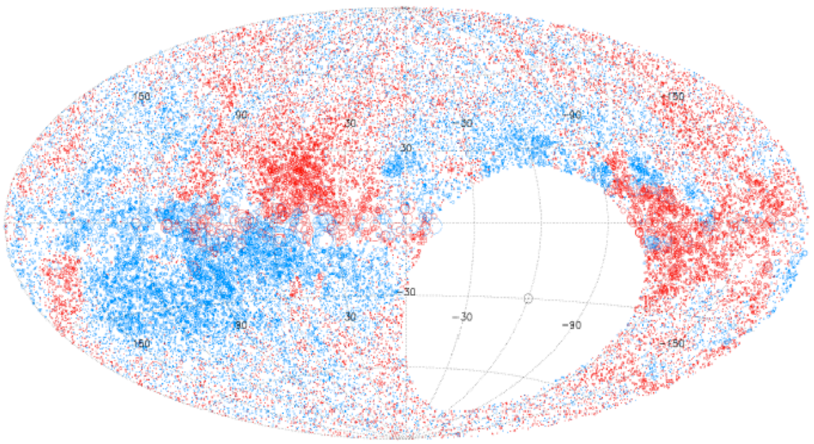
ACE Collaboration

Radioactive Dating

- ^{10}Be is an unstable isotope: $\tau_{1/2} \sim 1.6\ 10^6$ yr
- Abundance relative to other secondaries gives time of flight.
- Secondaries themselves give grammage.
- Combining these two, derive confinement time of ~ 2 – 3 10^7 yr at a mean density of -.2 cm^{-3}.
  - Lifetime decreases with E as $E^{-(0.3 - 0.6)}$

Galactic Magnetic Field

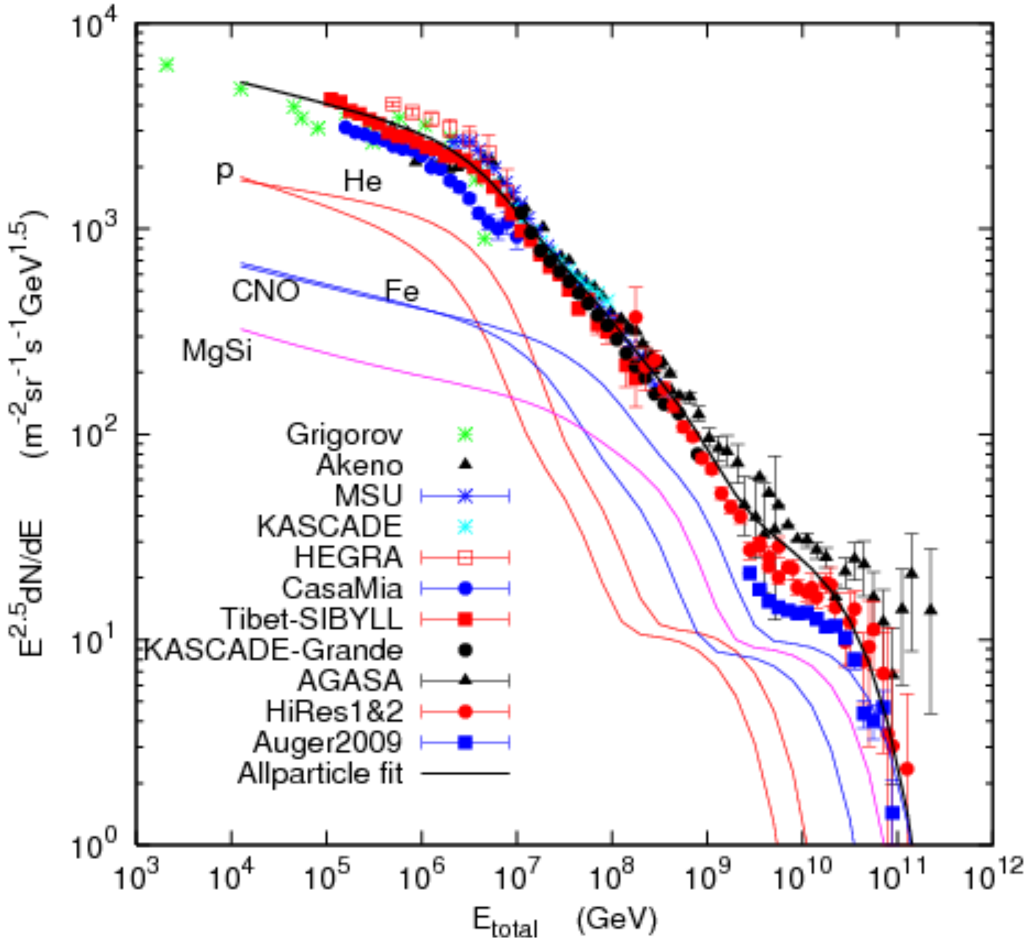
Faraday rotation measures of ~38000 extragalactic sources.



Taylor et al. 2009

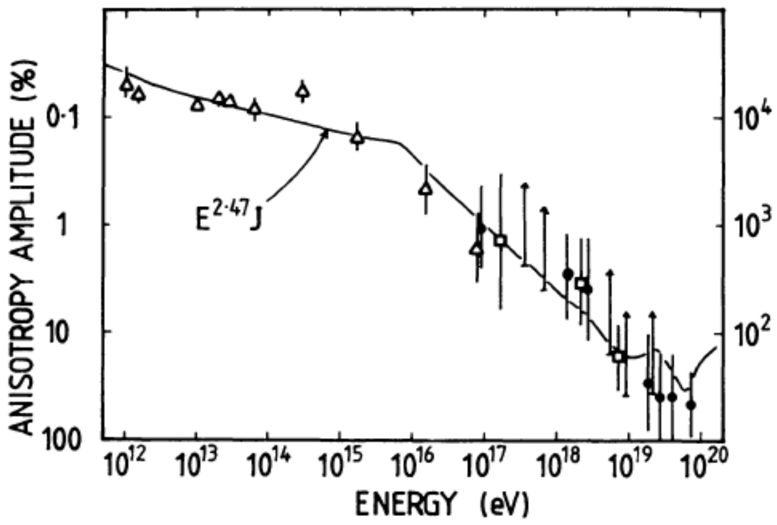
- Coherent, nearly azimuthal component nearly tangent to galactic plane
- Random component, ~3 x times stronger
- Total field is ~ 5 μG
- Magnetic disk thickness is a few kiloparsecs.

Spectrum Element by Element

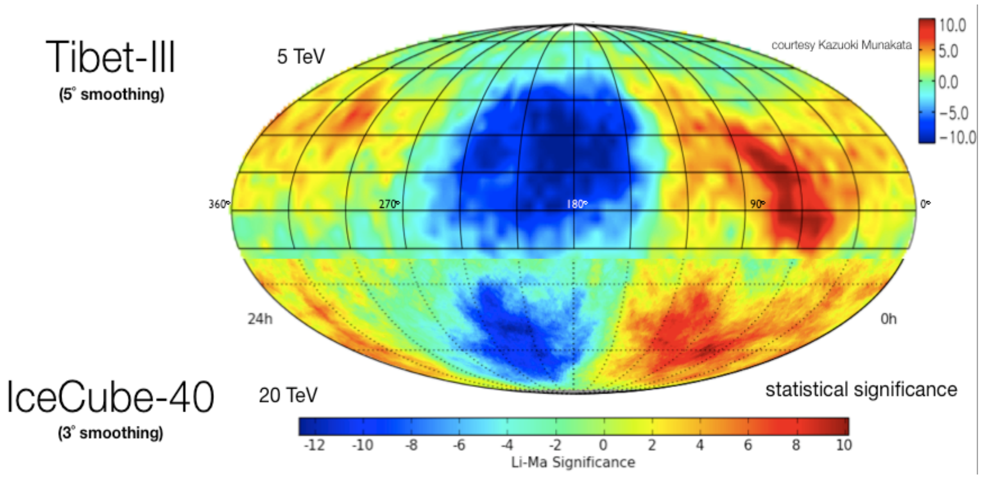


(An)isotropy

The distribution of cosmic ray arrival directions is highly isotropic, up to the knee.
Weak fluctuations at TeV energies have been discovered recently, challenge theory,
And might hold clues to origin.

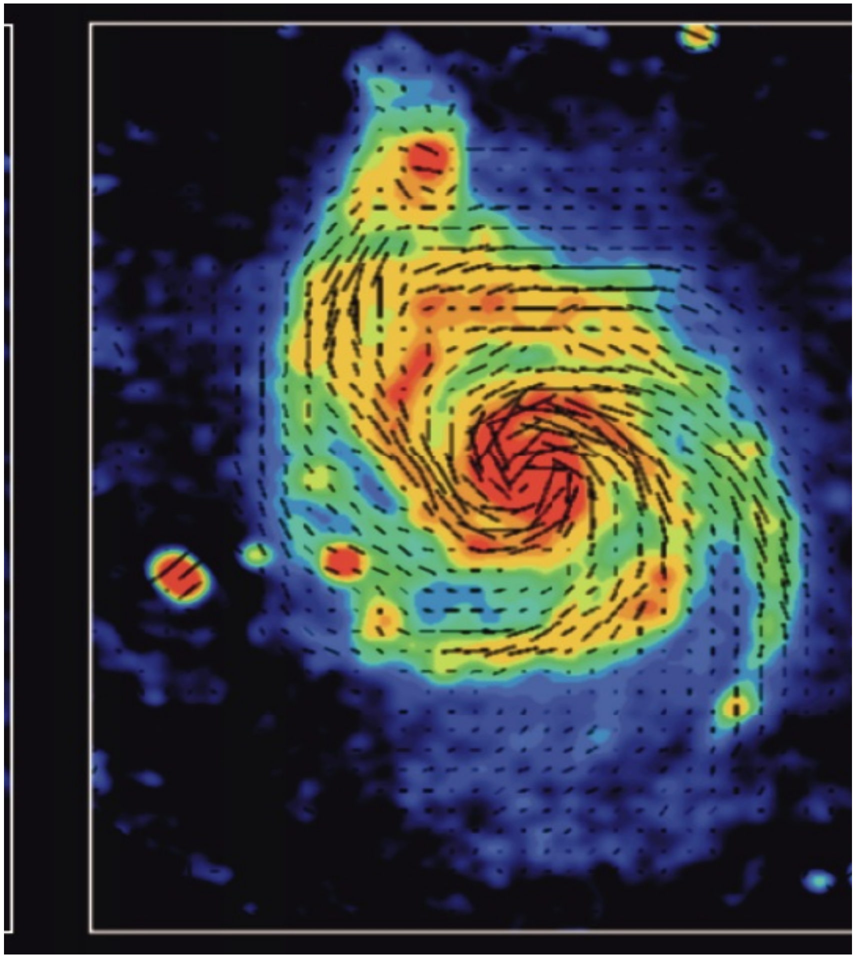


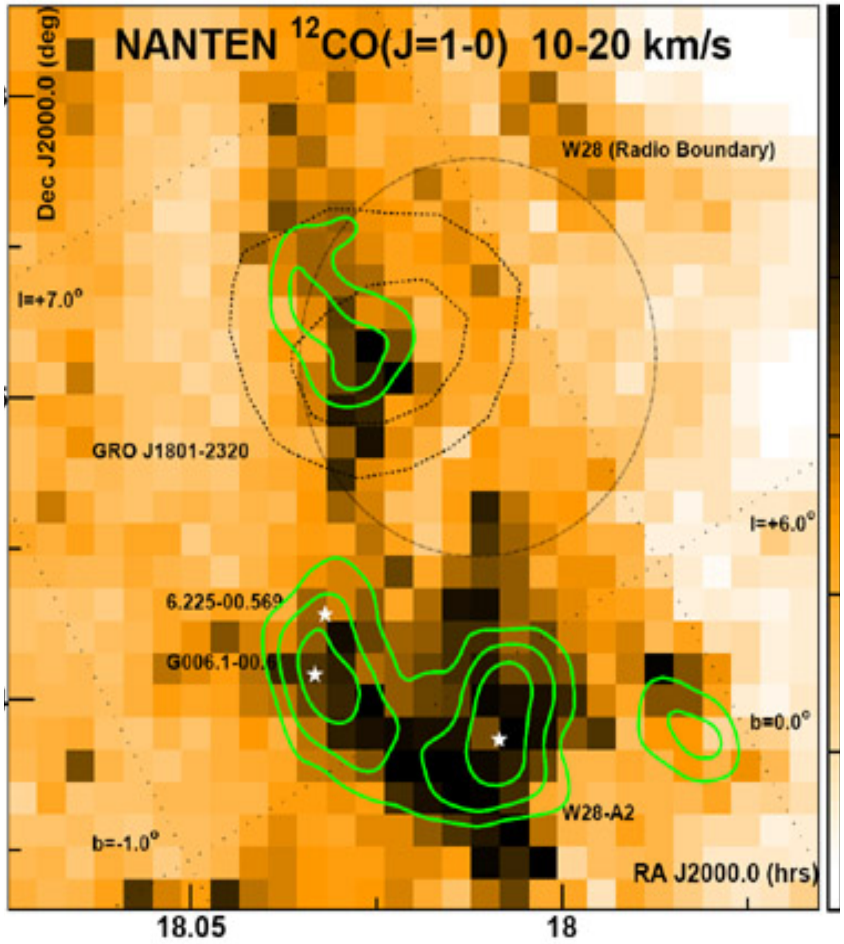
Hillas 1984



Desiati

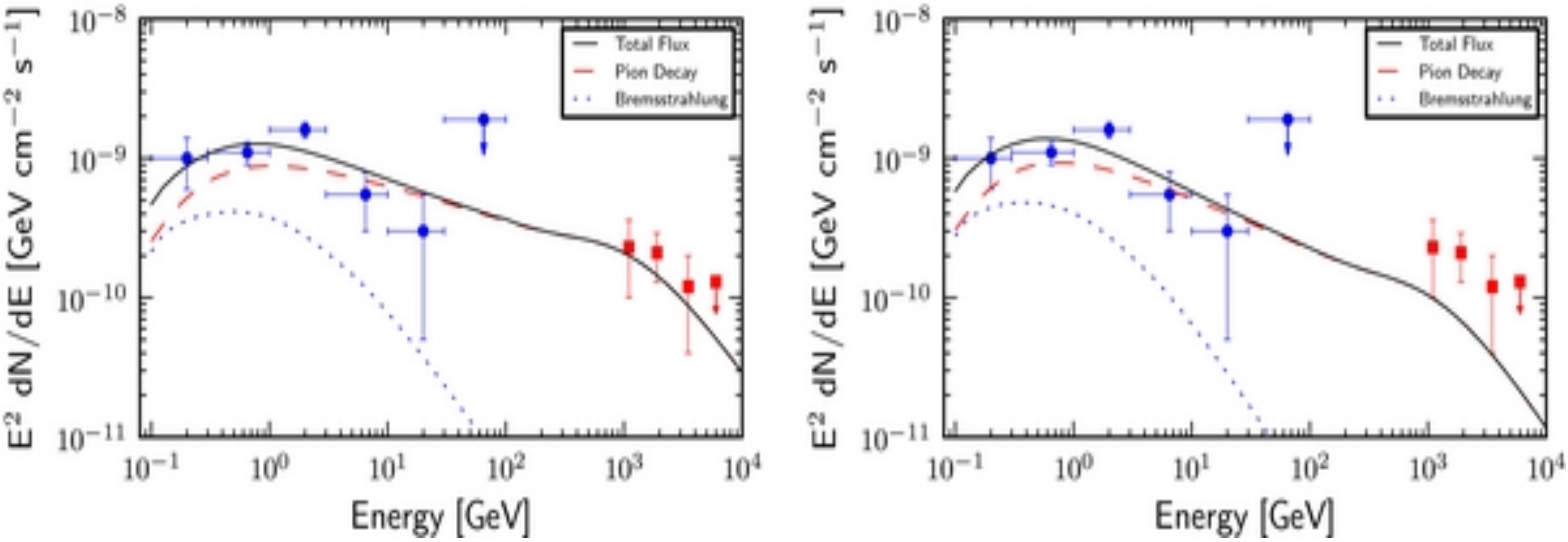
Remote Sensing: Radio Synchrotron & γ-Ray Emission





Extend to Other Galaxies

- Fits to the γ-ray spectrum of M82. Left is best fit to γ-ray spectrum; right is γ-ray spectrum for cosmic ray spectrum that best models the radio spectrum. (Yoast-Hull et al. 2013)



Equipartition is Not Universal

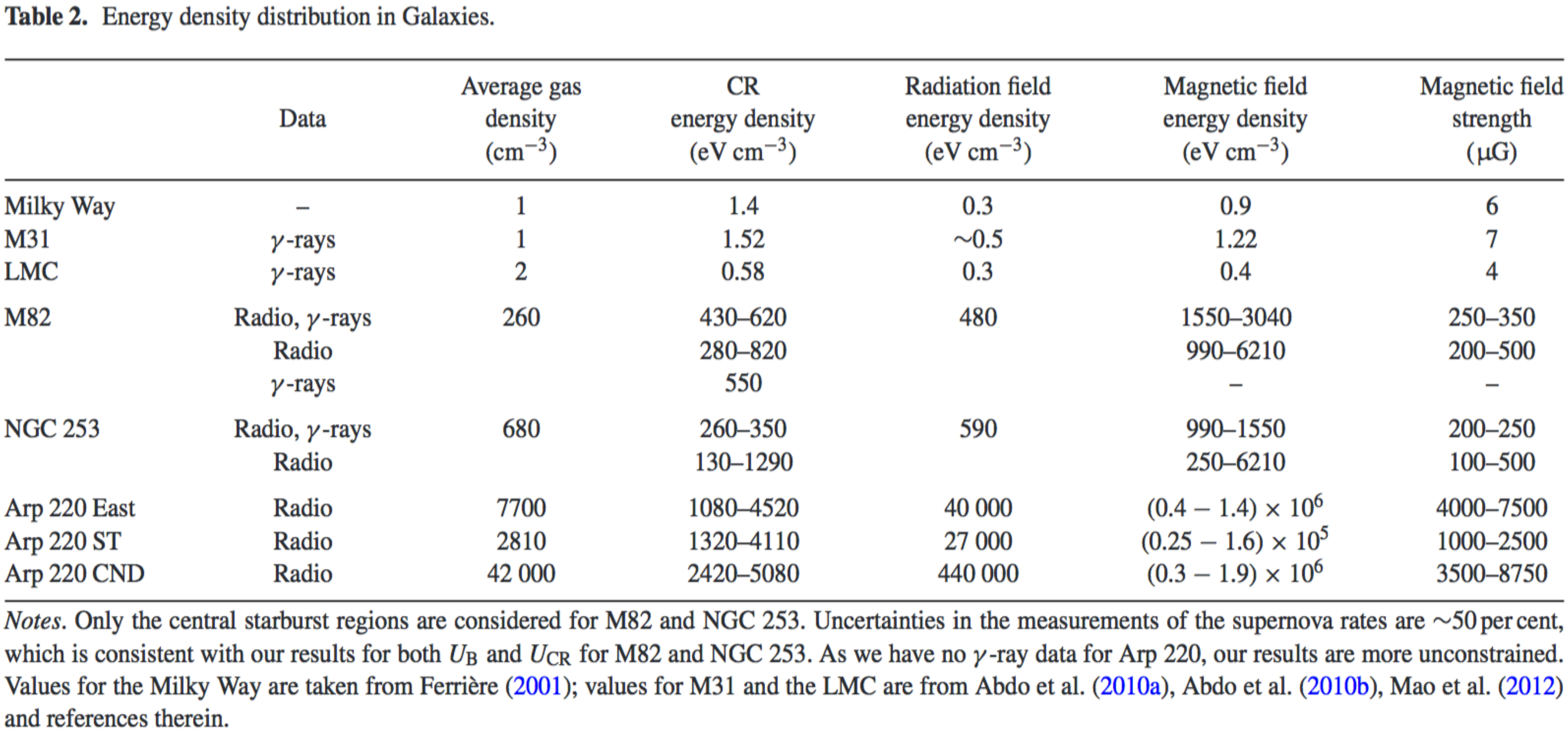


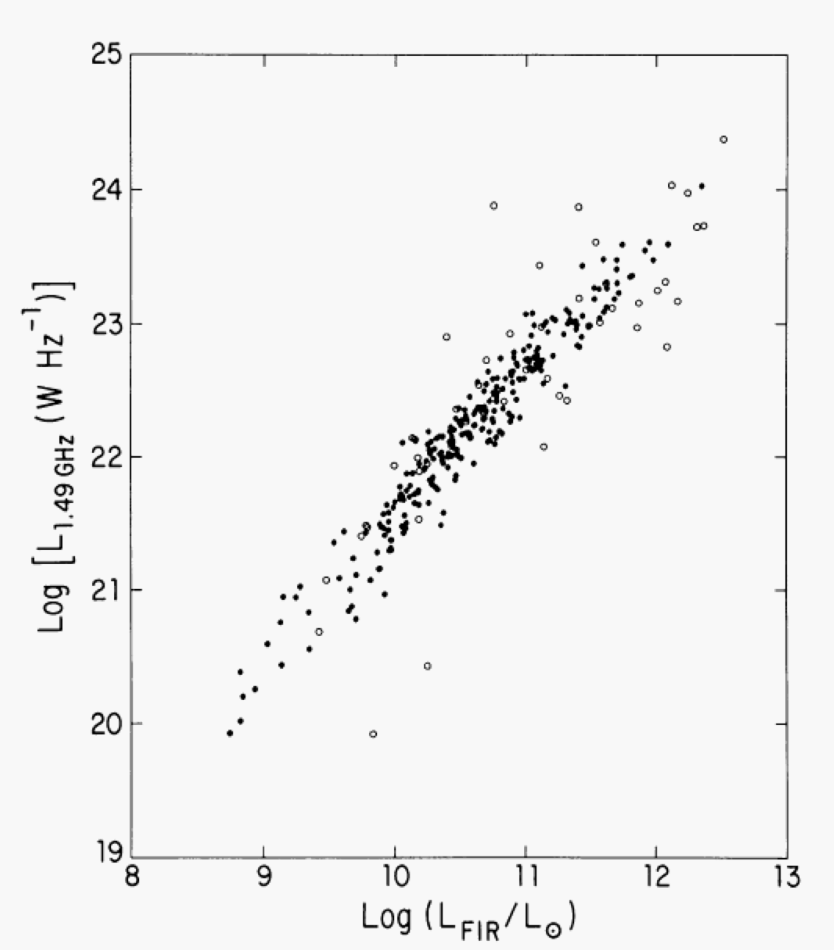
Table 2. Energy density distribution in Galaxies.

	Data	Average gas density ($\mathrm{cm^{-3}}$)	CR energy density ($\mathrm{eV\ cm^{-3}}$)	Radiation field energy density ($\mathrm{eV\ cm^{-3}}$)	Magnetic field energy density ($\mathrm{eV\ cm^{-3}}$)	Magnetic field strength (μG)
Milky Way	–	1	1.4	0.3	0.9	6
M31	γ-rays	1	1.52	~0.5	1.22	7
LMC	γ-rays	2	0.58	0.3	0.4	4
M82	Radio, γ-rays	260	430–620	480	1550–3040	250–350
	Radio		280–820		990–6210	200–500
	γ-rays		550		–	–
NGC 253	Radio, γ-rays	680	260–350	590	990–1550	200–250
	Radio		130–1290		250–6210	100–500
Arp 220 East	Radio	7700	1080–4520	40 000	$(0.4 - 1.4) \times 10^6$	4000–7500
Arp 220 ST	Radio	2810	1320–4110	27 000	$(0.25 - 1.6) \times 10^5$	1000–2500
Arp 220 CND	Radio	42 000	2420–5080	440 000	$(0.3 - 1.9) \times 10^6$	3500–8750

Notes. Only the central starburst regions are considered for M82 and NGC 253. Uncertainties in the measurements of the supernova rates are ~50 per cent, which is consistent with our results for both U_B and U_{CR} for M82 and NGC 253. As we have no γ-ray data for Arp 220, our results are more unconstrained. Values for the Milky Way are taken from Ferrière (2001); values for M31 and the LMC are from Abdo et al. (2010a), Abdo et al. (2010b), Mao et al. (2012) and references therein.

Yoast-Hull et al. 2016

Far-Infrared Radio Correlation



- Tight correlation between FIR luminosity (measure of SFR) & synchrotron luminosity (~U_BxU_{crl})
- Appears to hold at least to *z ~ 2*.
- *Suggests a powerful self-regulation mechanism*.

Cosmic Rays Through Time

- Besides the FIR-radio correlation…
- Li, Be, B in oldest Galactic halo stars -> they formed from material exposed to cosmic rays of a few hundred MeV/nucleon
- Cosmic rays in high z galaxies could contribute to the observed γ-ray background seen by Fermi.

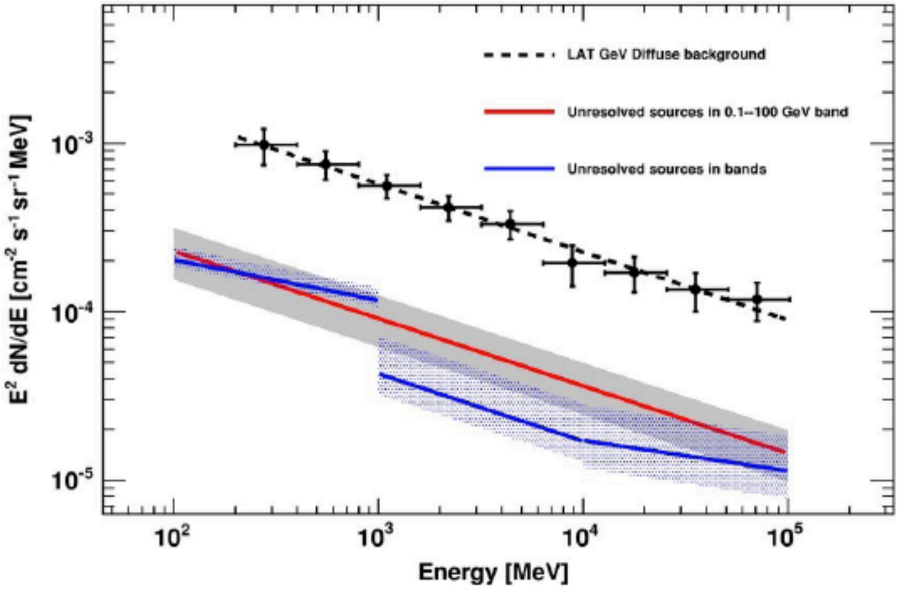
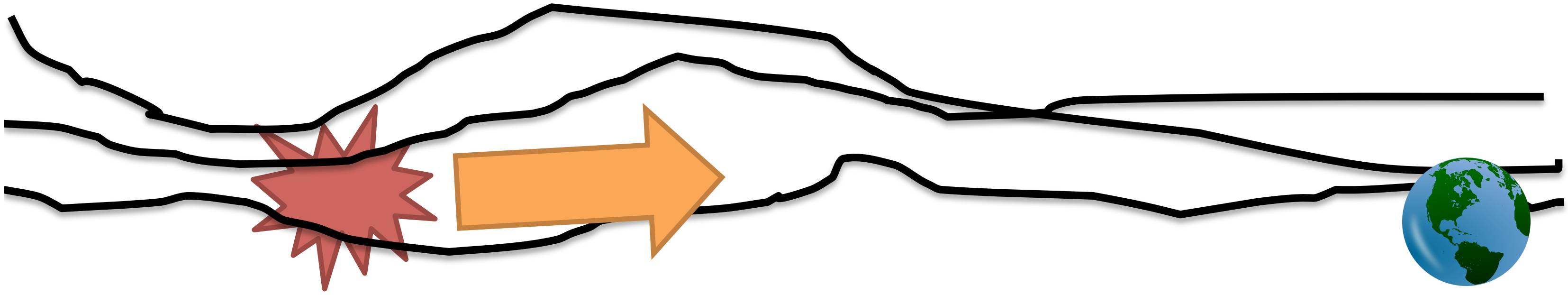


Figure 18 from The Fermi-LAT High-Latitude Survey: Source Count Distributions and the Origin of the Extragalactic Diffuse Background
A. A. Abdo et al. 2010 ApJ 720 435 doi:10.1088/0004-637X/720/1/435

Inferences From the Data

- Light element abundances (spallation + nuclear cosmochronology) -> 2.6 10^7 yr galactic confinement time at <n> ~ 0.19 ± 0.03 cm^{-3}.
- Isotropy -> diffusion, not direct propagation from sources. Diffusivity D ~ $E^{(0.3-0.6)}$



Similar Processes Occur in Other Galaxies

- Source spectrum is a power law with $N(E) \sim E^{-(2.0-2.2)}$
- Source power is equivalent to about 10% of supernova energy input.
- Primary proton/electron ratio ~ 50:1.
- Tight correlation between star formation rate & synchrotron emissivity -> feedback loop involving cosmic ray acceleration, galactic magnetic fields, and cosmic ray acceleration & propagation.
- Cosmic rays & magnetic fields were aleady present when the first low mass stars formed.

Galaxy Clusters: *Where are the Cosmic Rays?*

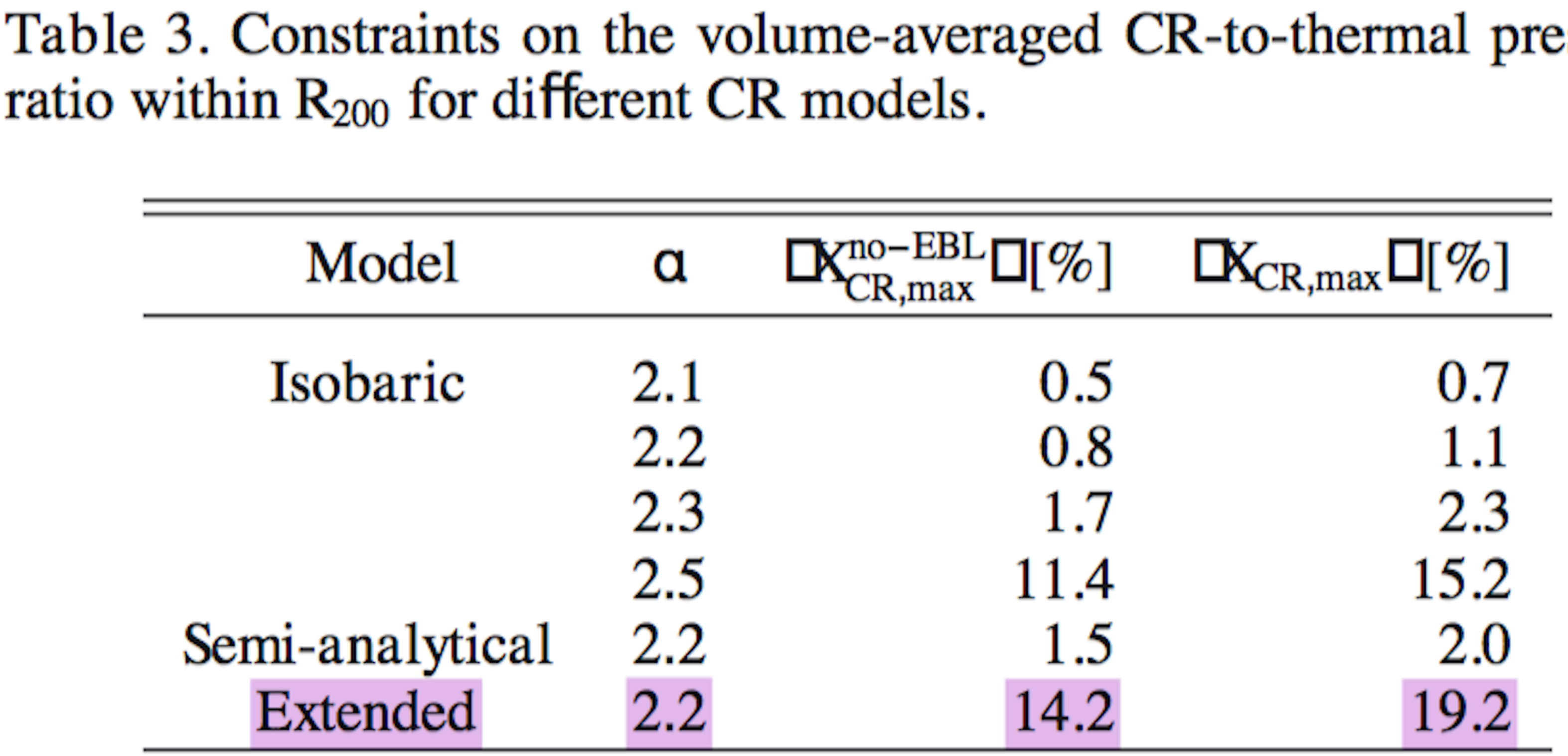


Table 3. Constraints on the volume-averaged CR-to-thermal pressure ratio within R_{200} for different CR models.

Model	α	□$X_{\mathrm{CR,max}}^{\mathrm{no-EBL}}$□[%]	□$X_{\mathrm{CR,max}}$□[%]
Isobaric	2.1	0.5	0.7
	2.2	0.8	1.1
	2.3	1.7	2.3
	2.5	11.4	15.2
Semi-analytical	2.2	1.5	2.0
Extended	2.2	14.2	19.2

Ahnen et al. 2016

Goals of Theory – Particle Realm

- Identify acceleration mechanism(s) that explain
  - Spectrum
  - Composition
  - Efficiency.
- Understand propagation
  - Energy dependence of diffusion
  - Cross-field transport
  - Loss mechanisms

Goals of Theory – Collective Realm

- How do cosmic rays modify the structure and energetics of the ambient medium?
  - Hydrostatic support in galaxies & galaxy clusters?
  - Thermal balance (collisional & collisionless heating?
  - Structure of shocks?
    - *Connects to particle realm through self consistent picture of shock acceleration*

Particle Orbits in the Galactic Magnetic Field

The **Larmor radius** is

$$r_L = \frac{mc^2\beta\gamma}{ZeB} = \frac{3.3\times 10^{12}}{ZB_\mu} T_{GeV}\left(1+\frac{1.90A}{T_{GeV}}\right)^{1/2}\ \mathrm{cm},$$

where Z and A are the charge & mass numbers, T_{GeV} is the kinetic energy in GeV, and B_μ is the magnetic field in μG.

- Direct numerical integration of cosmic rays orbits in a global simulation is infeasible.
- A multiscale problem.

Develop a *statistical* picture for transport & diffusion in (**x,p**) space.

Develop a *fluid* picture for global feedback.

Elements of Field-Particle Interaction

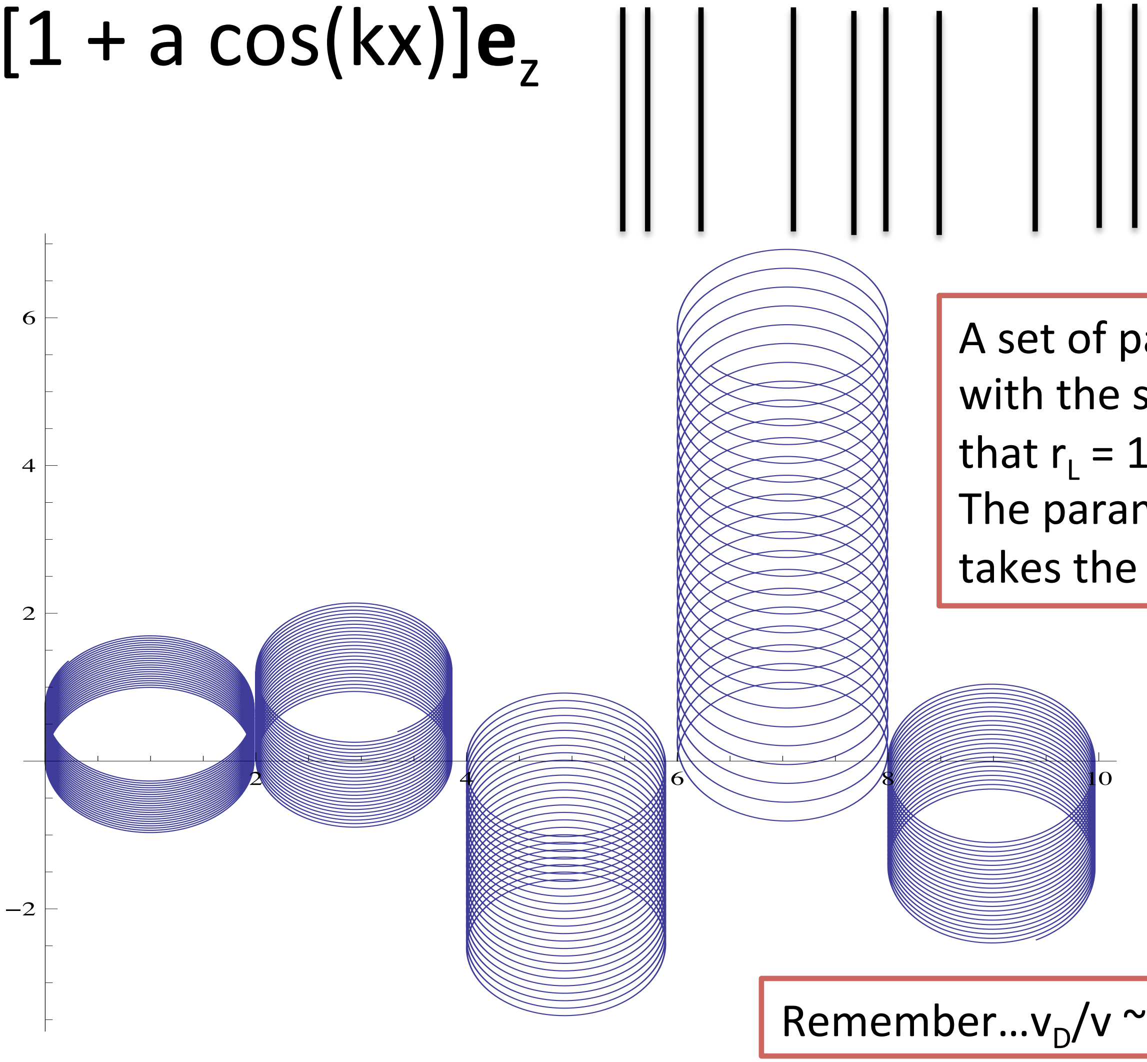
- Gyromotion
- Drifts
- Mirroring
- Gyro-resonance
- Landau resonance/ transit time damping

Breaking Down the Orbits – Grad B Drift

$\mathbf{B} = B_0[1 + a\cos(kx)]\mathbf{e}_z$

Match each k with its orbit.

0.9
0.3
2.0
0.1
0.5



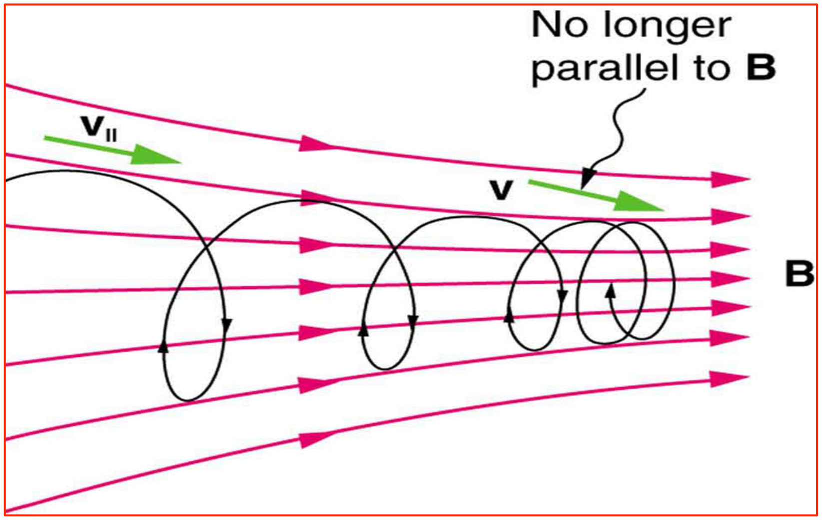
A set of particle orbits, all with the same energy, such that $r_L = 1$.
The parameter a = 0.1, and k takes the values on the left.

Remember…$v_D/v \sim r_L/L$

Magnetic Mirroring

$$\boxed{\frac{p_\perp^2}{B},}$$

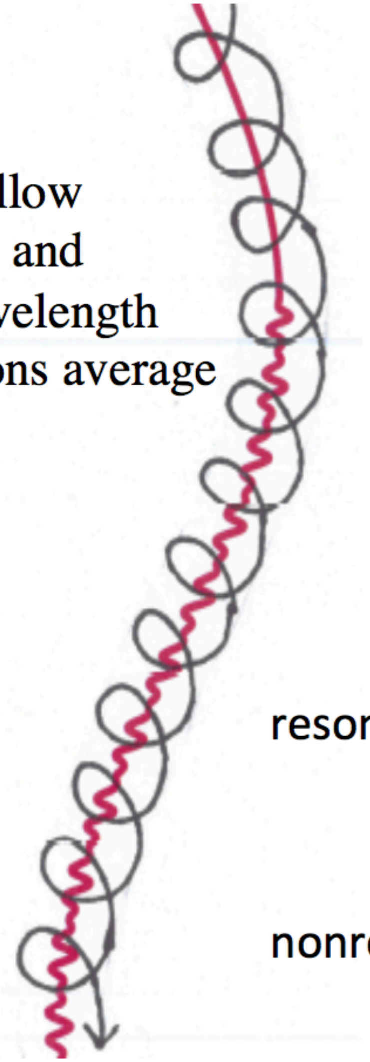
equivalent to the magnetic flux through the gyro-orbit, is a relativistic invariant.



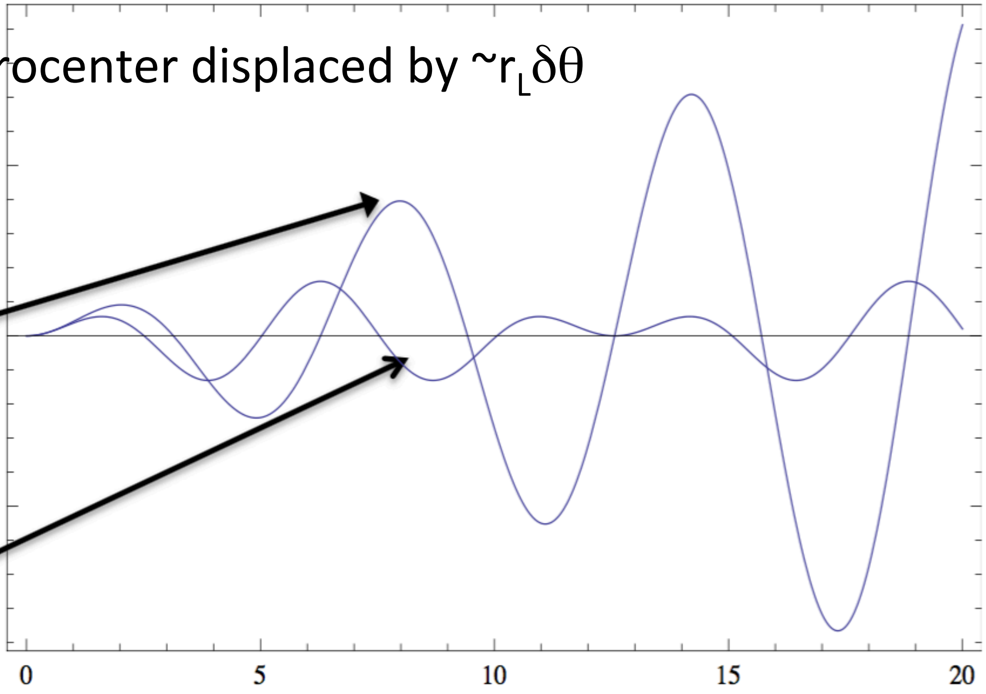
Essential part of Fermi acceleration mechanism

Gyroresonant Scattering

Orbits follow fieldlines and short wavelength fluctuations average out.



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



Gyrocenter displaced by $\sim r_L \delta\theta$

resonant

nonresonant

Landau Resonance

The **Landau resonance** is the condition

$$\omega = k_{\|} v_{\|}$$

- Resonant particles can exchange energy with a wave through $E_{\|}$.
- Most important for fast magnetosonic waves with

$$\omega = k v_A$$

and

$$k_{\perp} \gg k_{\|}$$

because $v_{\|} \sim c$.

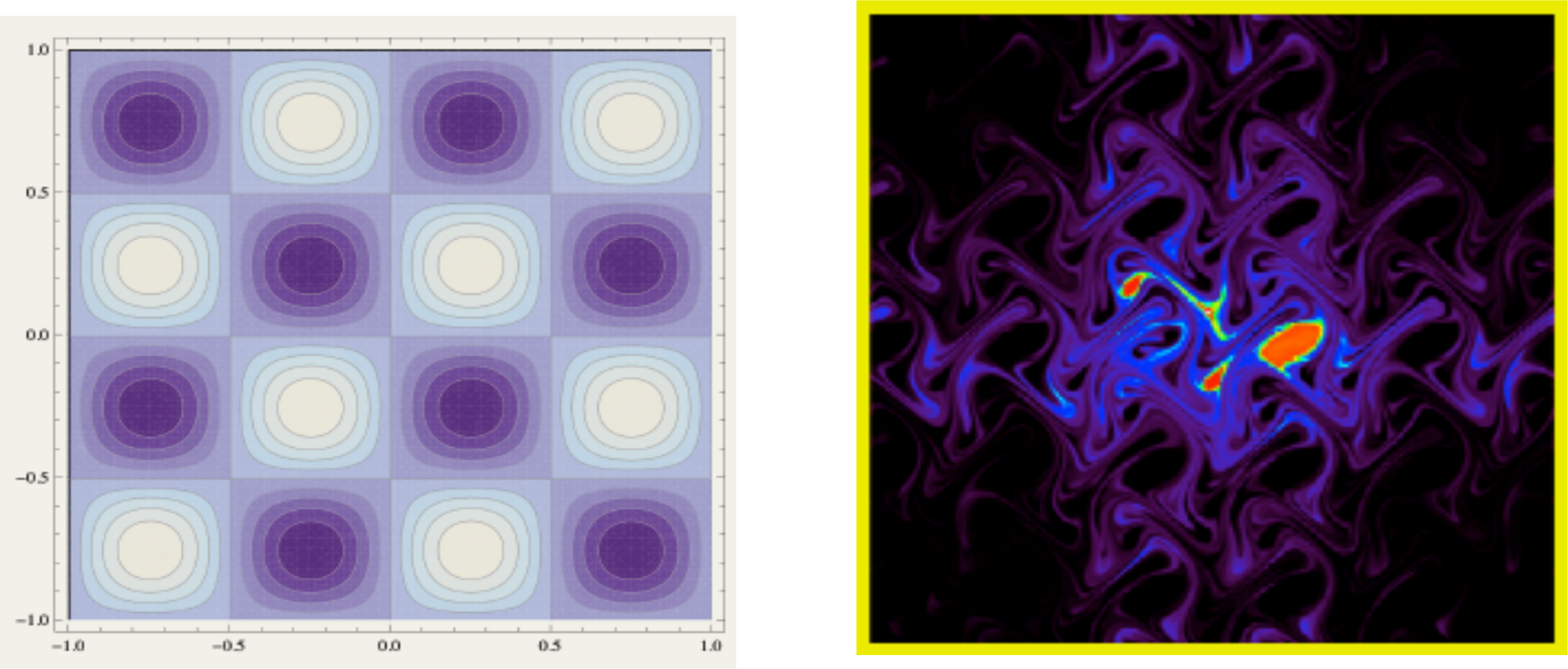
Wave dissipation by this mechanism is also called transit time damping.

A Study of Cross-Field Transport

- Numerical integration of test particle orbits
- Simple magnetic fieldlines with bounded horizontal displacement.
- Joint effects of magnetic geometry and pitch angle scattering

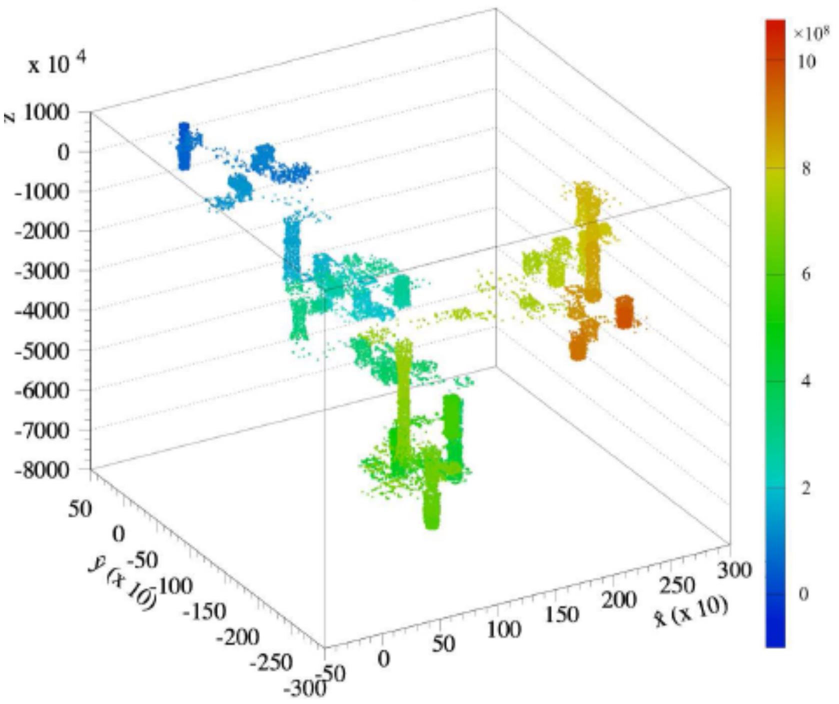
Desiati & EZ, arXiv:1402:1475

Magnetic Field Models

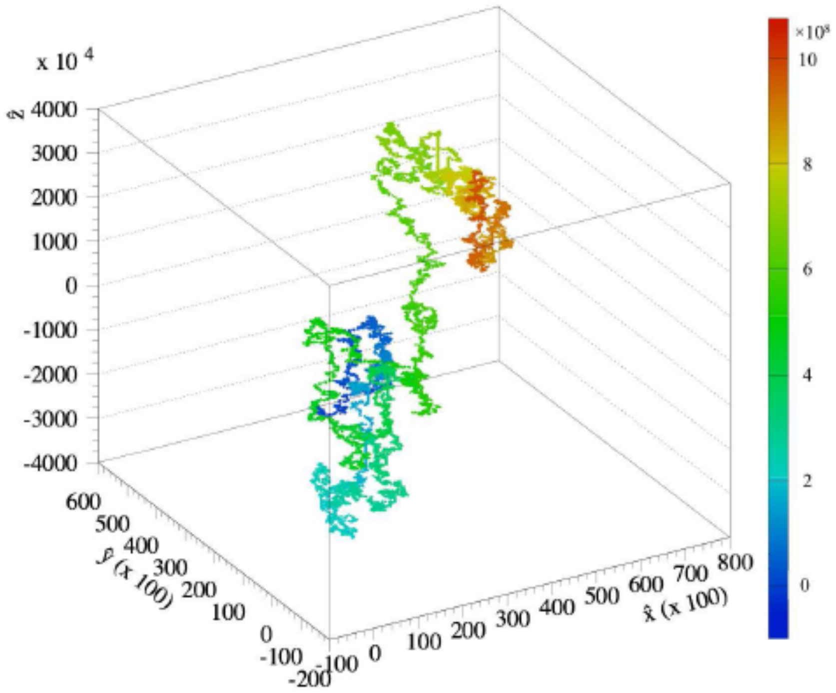


Left: “Cellular” magnetic field projection on horizontal plane. *Right*: “Galloway-Proctor magnetic field projection revealed through mixing of a passive scalar by the analogous flow. The third field, a uniform field, is not shown.

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.

Diffusion Coefficients *(see blackboard work for context)*

- Define the running diffusion tensor

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

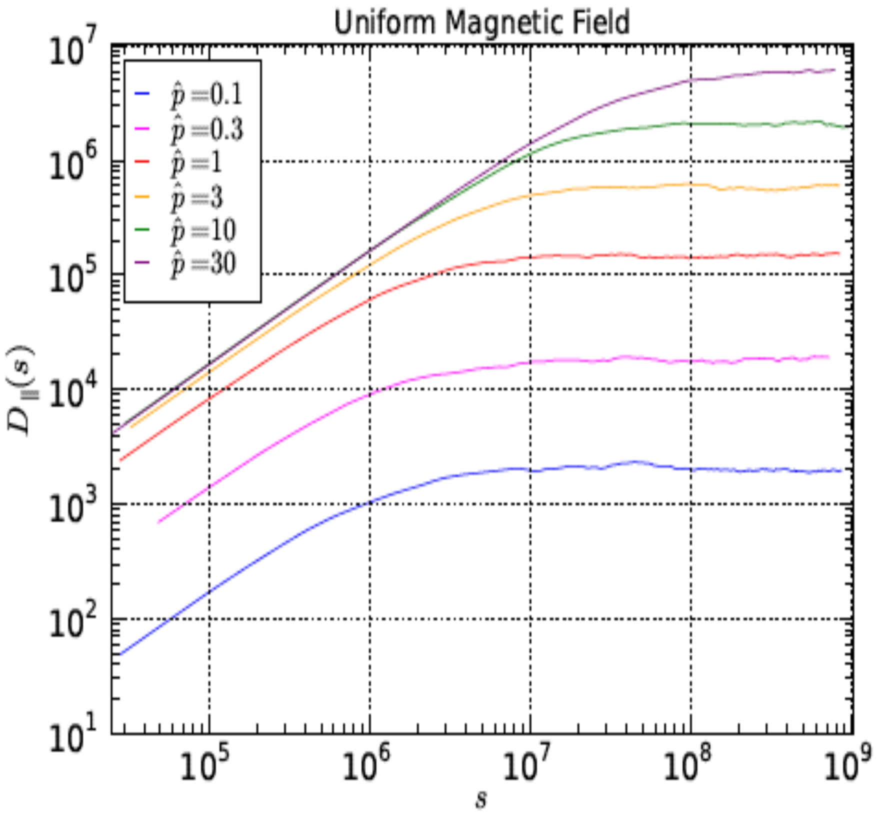
- Correct for crossfield motion

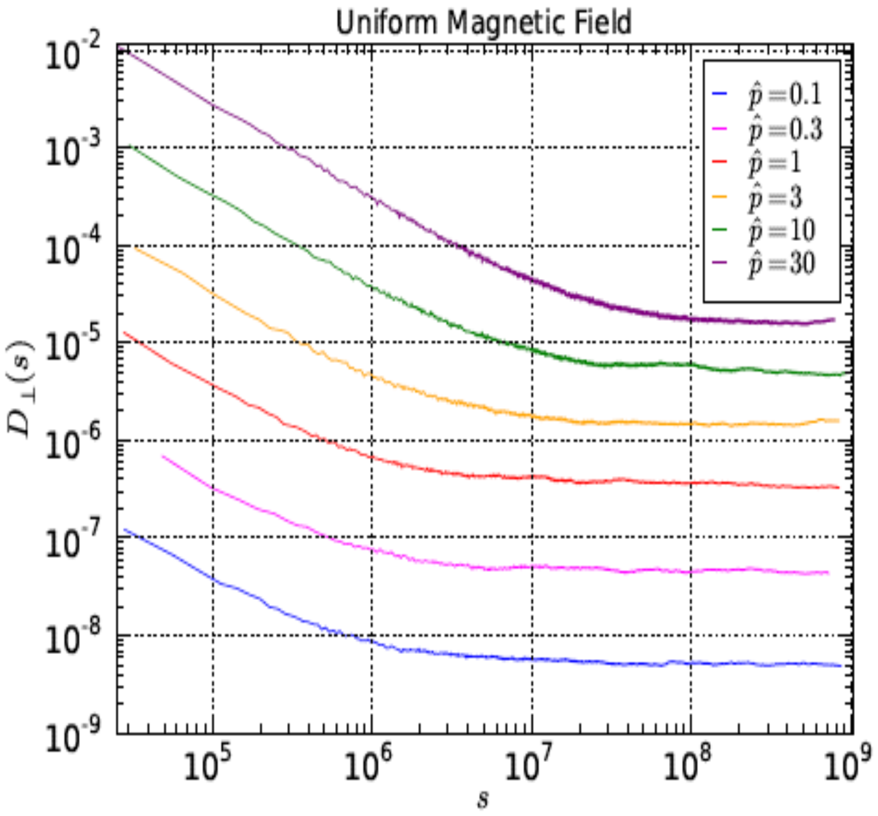
$$\boldsymbol{x}_{gc} = \boldsymbol{x} + \frac{\boldsymbol{v} \times \hat{\boldsymbol{b}}}{\omega_g}. \qquad \Delta \boldsymbol{x} \equiv \boldsymbol{x}_{gc} - \boldsymbol{x}_f$$

- Define the corrected running diffusion tensor

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

Diffusion in a Uniform Field

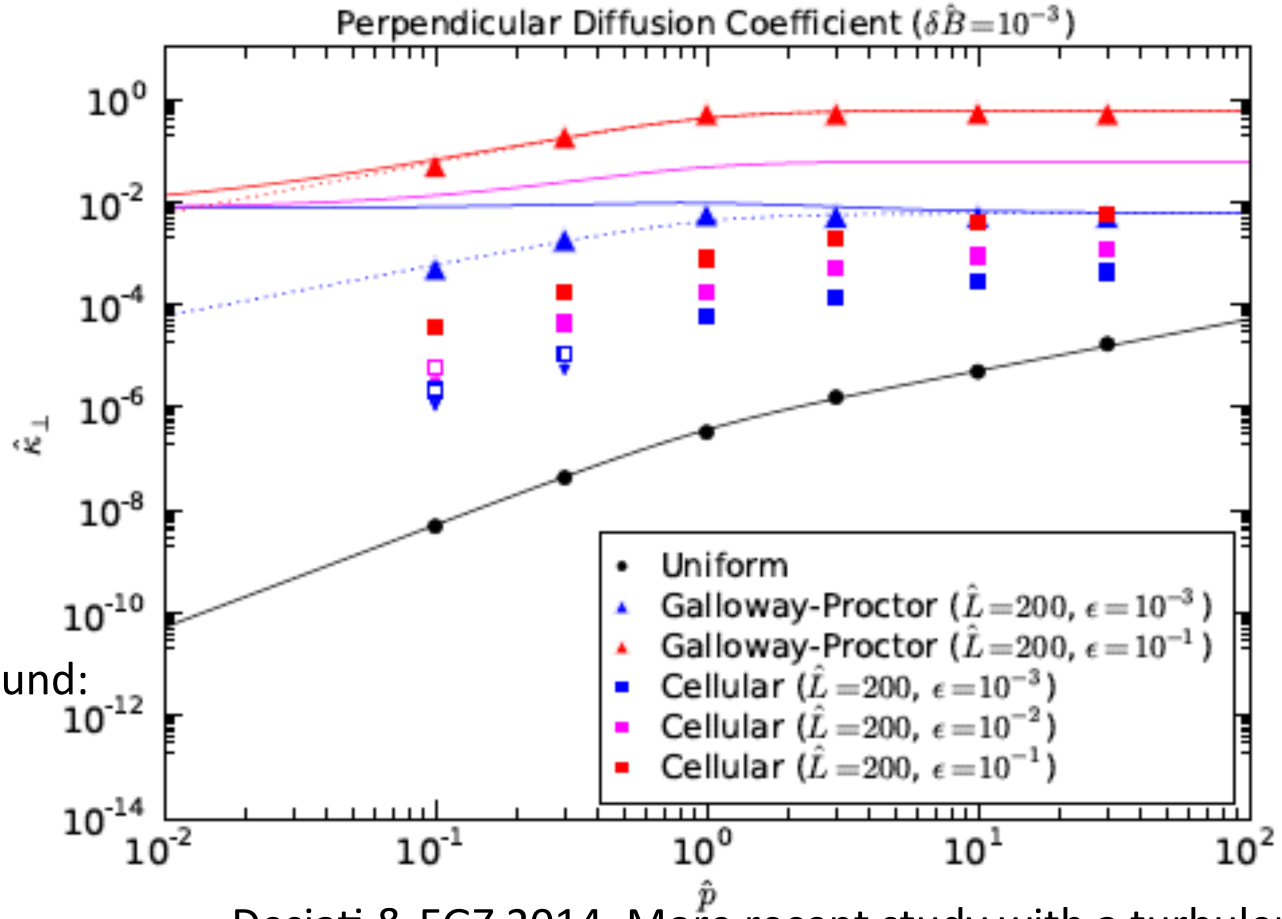




$$\kappa_\parallel = \langle \frac{v_\parallel^2}{\nu} \rangle = v^2 \frac{\int_{-1}^{1} f(\mu)\frac{\mu^2}{\nu} d\mu}{\int_{-1}^{1} d\mu} = \frac{v^2}{3\nu}$$

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

Summary of Results



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

Lower bound:
r_g^2/t_{sca}

Desiati & EGZ 2014. More recent study with a turbulent field gives similar results for similar energies at largest scale.

Next

- Cosmic ray spectrum and 2nd order Fermi acceleration
- Derivation of a Fokker-Planck equation
- Derivation of a transport equation
- Application to diffusive shock acceleration (1st order Fermi acceleration).