Galactic Sources, Magnetic Fields and the Energy-Dependent composition of UHECRs.

UCLA

Outline

Outline

- The cosmic ray spectrum

Outline

- The cosmic ray spectrum
- The Pierre Auger Observatory (PAO) and its energy-dependent chemical composition

Outline

- The cosmic ray spectrum
- The Pierre Auger Observatory (PAO) and its energy-dependent chemical composition
- The role of galactic sources

UCLA

Outline

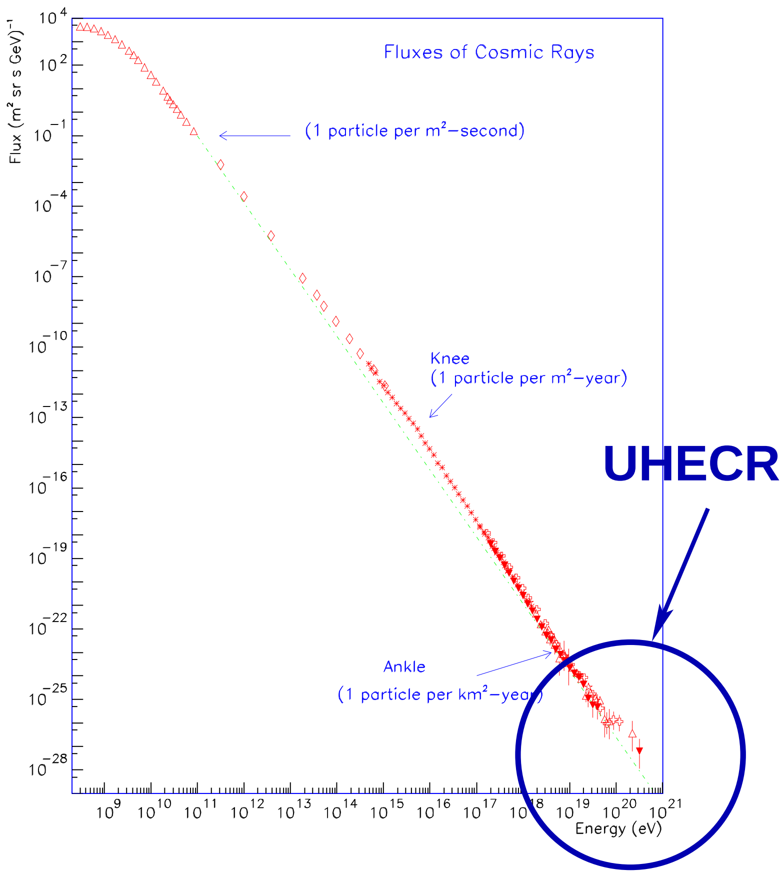
- The cosmic ray spectrum
- The Pierre Auger Observatory (PAO) and its energy-dependent chemical composition
- The role of galactic sources
- diffusion, anisotropy, spectral features

Outline

- The cosmic ray spectrum
- The Pierre Auger Observatory (PAO) and its energy-dependent chemical composition
- The role of galactic sources
- diffusion, anisotropy, spectral features

[AC, Kusenko, Nagataki]

UCLA



- $E < 1\,\mathrm{GeV}$ solar modulation make studies of the primary cosmic ray spectrum very complex
- $1\,\mathrm{GeV} < E < 10^5\,\mathrm{GeV}$ galactic origin (SNR)
- $10^5\,\mathrm{GeV} < E < 10^9\,\mathrm{GeV}$ galactic origin (supernova explosion into stellar wind)
- $E > 10^9\,\mathrm{GeV}$ Ultra High Energy Cosmic Rays (UHECRs)

Above the Ankle

UHECRs above the "ankle" $(E > 10^9\,\mathrm{GeV})$ are believed to be of extragalactic origin for two reasons:

Above the Ankle

UHECRs above the "ankle" $(E > 10^9\,\mathrm{GeV})$ are believed to be of extragalactic origin for two reasons:

- lack of plausible galactic sources

Above the Ankle

UHECRs above the "ankle" $(E > 10^9\,\mathrm{GeV})$ are believed to be of extragalactic origin for two reasons:

- lack of plausible galactic sources
- lack of galactocentric anisotropy, inconsistent with retaining protons in Galactic micro-Gauss fields.

Above the Ankle

UHECRs above the "ankle" $(E > 10^9\,\mathrm{GeV})$ are believed to be of extragalactic origin for two reasons:

- lack of plausible galactic sources
- lack of galactocentric anisotropy, inconsistent with retaining protons in Galactic micro-Gauss fields.

Both of these reasons can be challenged

Above the Ankle

UHECRs above the "ankle" $(E > 10^9\,\mathrm{GeV})$ are believed to be of extragalactic origin for two reasons:

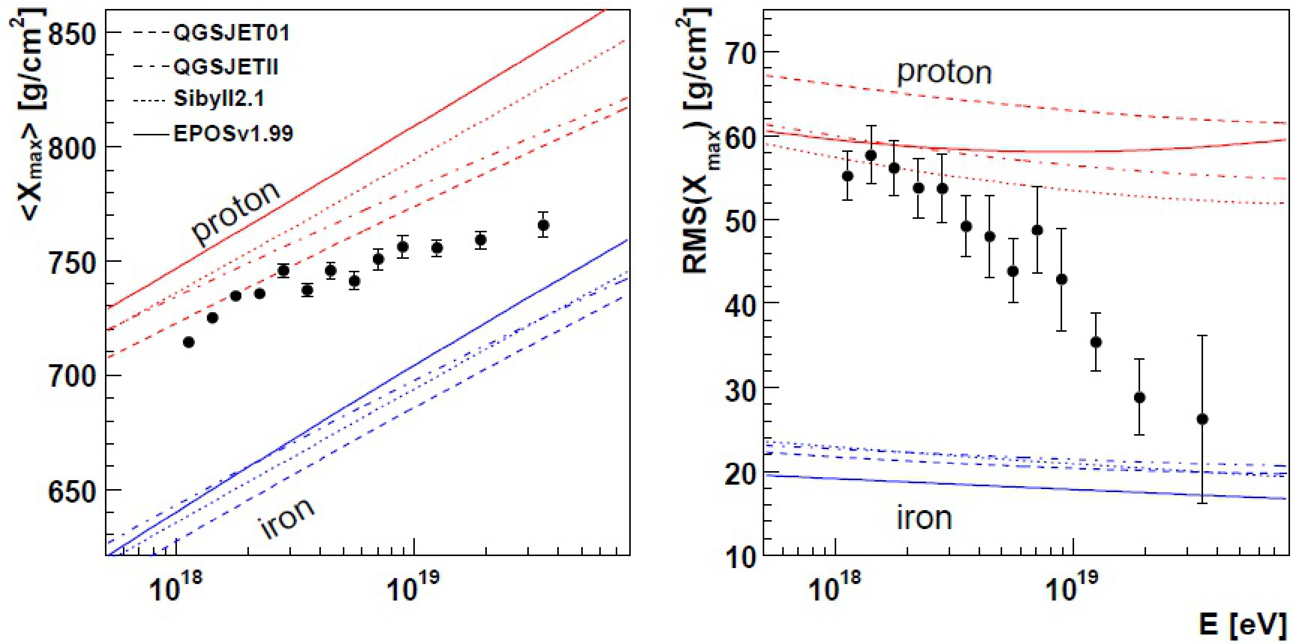
- lack of plausible galactic sources
- lack of galactocentric anisotropy, inconsistent with retaining protons in Galactic micro-Gauss fields.

Both of these reasons can be challenged

Both of these reasons should be challenged in view of a recent PAO discovery

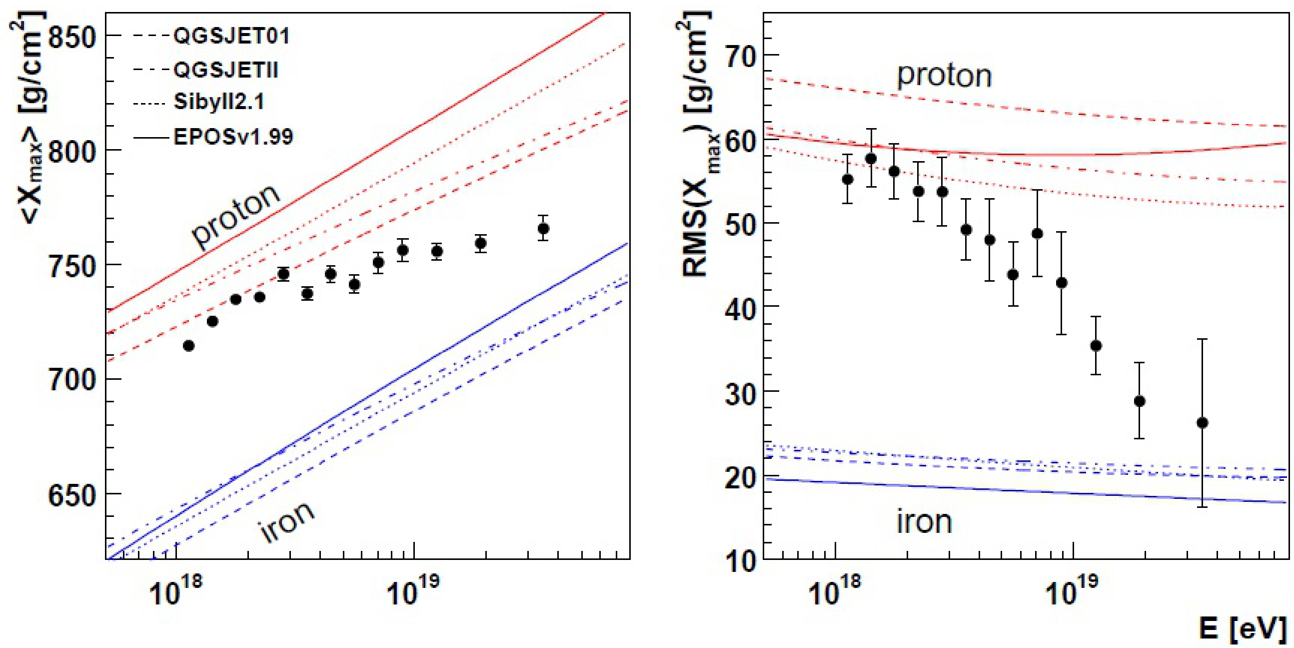
UCLA

Pierre Auger energy-dependent chemical composition



[Auger PRL 104 (2010) 091101]

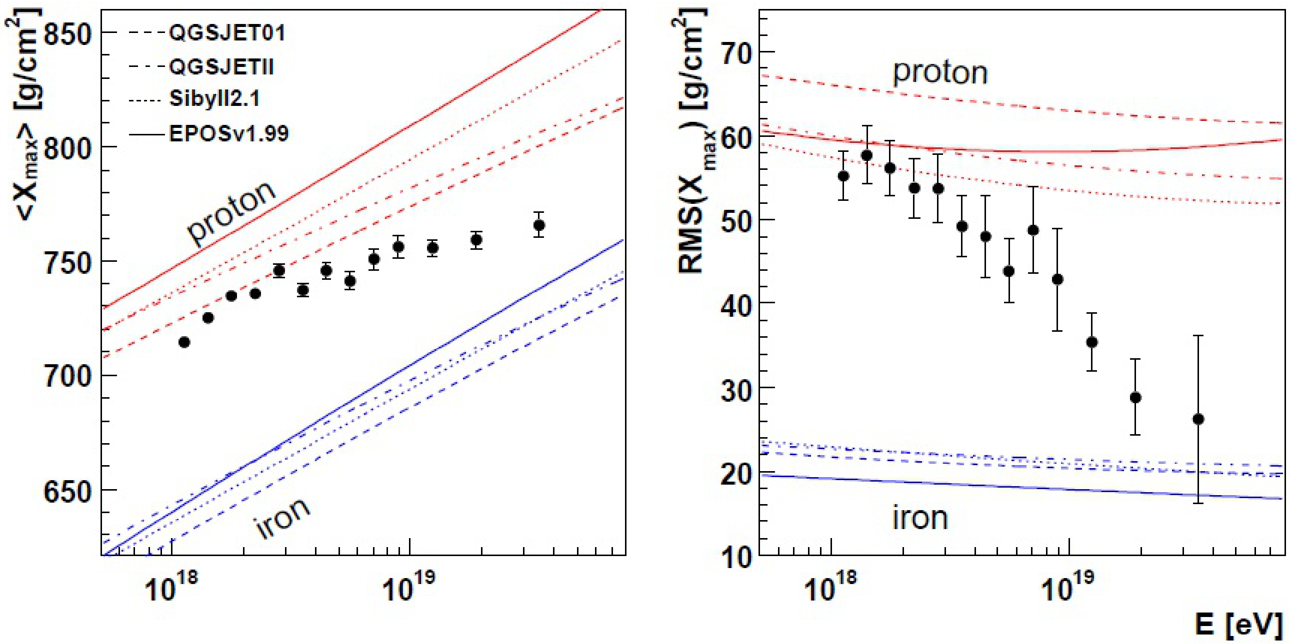
Pierre Auger energy-dependent chemical composition



[Auger PRL 104 (2010) 091101]

The composition gets heavier with energy

Pierre Auger energy-dependent chemical composition

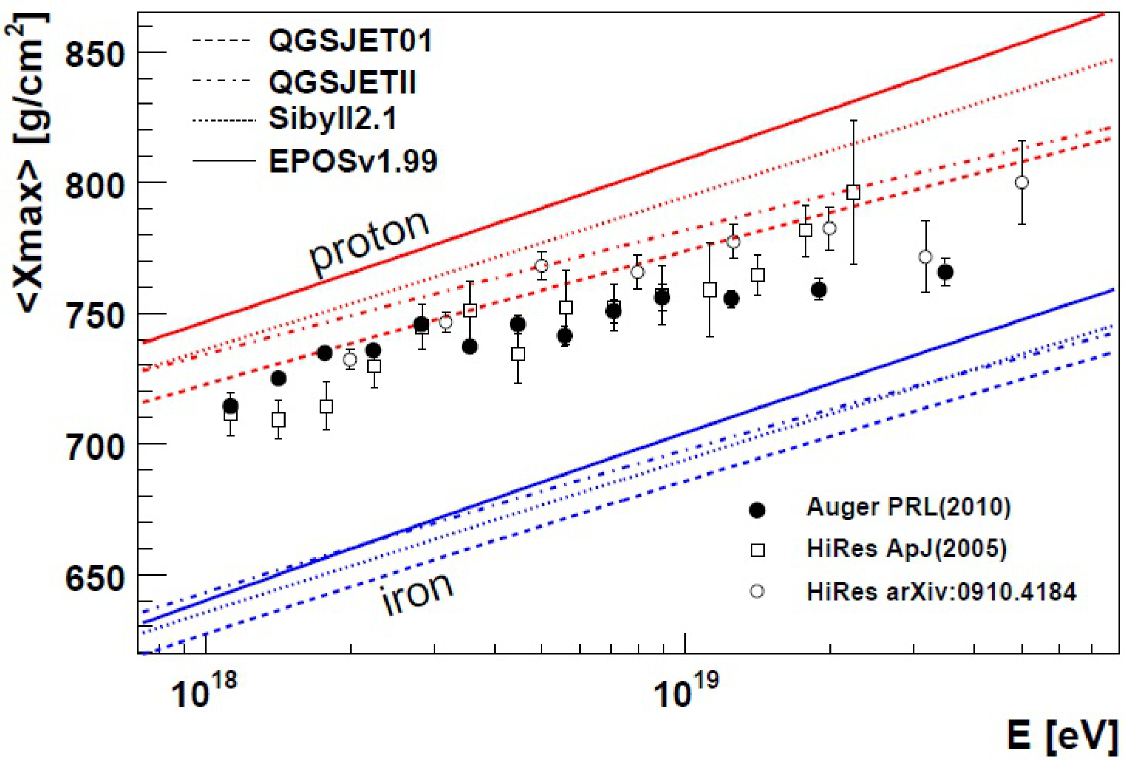


[Auger PRL 104 (2010) 091101]

The composition gets heavier with energy

What could cause this effect?

Not Observed by HiRes



[Auger PRL 104 (2010) 091101, HiRes ApJ 622 (2005) 910, HiRes arXiv:0910.4184]

Interpreting the PAO Results

There exist two possible solutions to this puzzle:

Interpreting the PAO Results

There exist two possible solutions to this puzzle:

- The segregation occurs at the source with a heavy element favored acceleration mechanism.

This is unlikely because of photodissociation

Interpreting the PAO Results

There exist two possible solutions to this puzzle:

- The segregation occurs at the source with a heavy element favored acceleration mechanism.

  This is unlikely because of photodissociation

- The acceleration mechanism affects all the particles the same way and the segregation occurs during the transport of the nuclei.

Interpreting the PAO Results

There exist two possible solutions to this puzzle:

- The segregation occurs at the source with a heavy element favored acceleration mechanism.

  This is unlikely because of photodissociation

- The acceleration mechanism affects all the particles the same way and the segregation occurs during the transport of the nuclei.

This is exactly what you would expect for Galactic sources...

UCLA

Interpreting the PAO Results

There exist two possible solutions to this puzzle:

- The segregation occurs at the source with a heavy element favored acceleration mechanism.

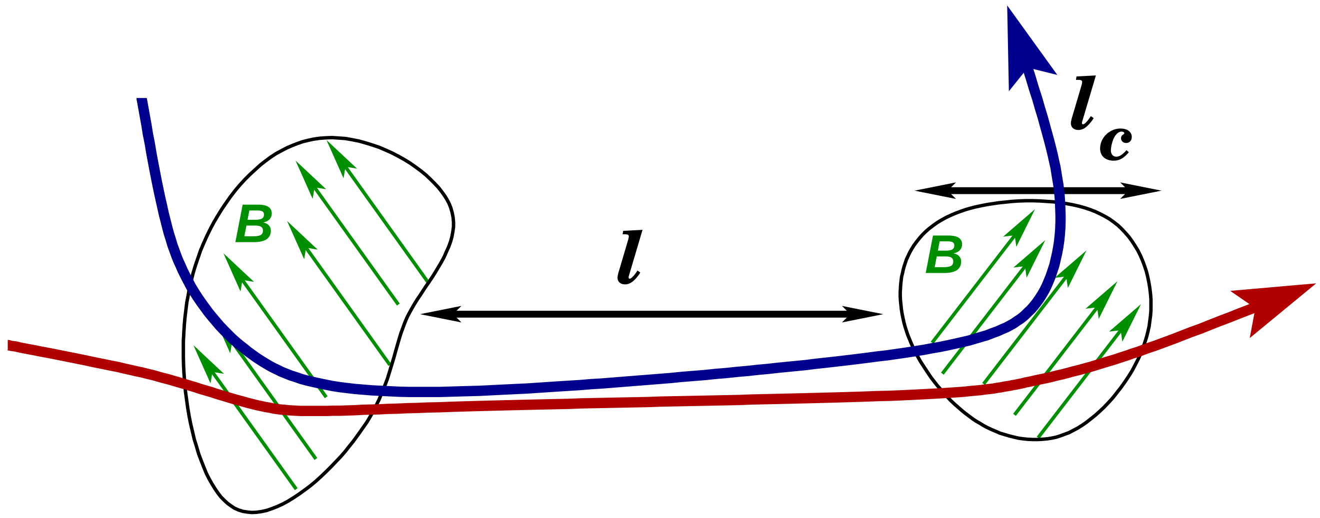
  This is unlikely because of photodissociation

- The acceleration mechanism affects all the particles the same way and the segregation occurs during the transport of the nuclei.

This is exactly what you would expect for Galactic sources...

Why?

Diffusion



Two different regimes depending on the energy of the particle

Diffusion

critical energy E_0 where $r_L = l_c$

for $E < E_0$, we get $l_c >> r_L$

- mean free path $\sim l$
- $D = \frac{l}{3} \equiv D_0$

for $E > E_0$, we get $l_c \sim r_L$

- mean free path $>> l$
- $D = D_0 \left(\frac{E}{E_0}\right)^2$

UCLA

Diffusion

critical energy E_0 where $r_L = l_c$

for $E < E_0$, we get $l_c >> r_L$

- mean free path $\sim l$
- $D = \frac{l}{3} \equiv D_0$

for $E > E_0$, we get $l_c \sim r_L$

- mean free path $>> l$
- $D = D_0 \left(\frac{E}{E_0}\right)^2$

E_0 depends on the charge of the nuclei

UCLA

Diffusion with Non-Unit Charge

For a particle with charge $q_i = eZ_i$, we get a critical energy $E_{0,i}$ with $r_{L,i} = l_c$:

- $r_{L,i} = \frac{E}{Bq_i}$
- $E_{0,i} = eBl_cZ_i$
- $\boldsymbol{E_{0,i} = Z_i \times \left(10^8\,\mathrm{eV}\right)\left(\frac{B}{3\times10^{-6}\,\mathrm{G}}\right)\left(\frac{l_c}{0.3\,\mathrm{kpc}}\right)}$

Diffusion with Non-Unit Charge

For a particle with charge $q_i = eZ_i$, we get a critical energy $E_{0,i}$ with $r_{L,i} = l_c$:

- $r_{L,i} = \frac{E}{Bq_i}$
- $E_{0,i} = eBl_cZ_i$
- $\boldsymbol{E_{0,i} = Z_i \times (10^8\,\mathrm{eV}) \left(\frac{B}{3\times10^{-6}\,\mathrm{G}}\right)\left(\frac{l_c}{0.3\,\mathrm{kpc}}\right)}$

The diffusion coefficient is therefore:

$$\boldsymbol{D_i(E) = \begin{cases} D_0\left(\frac{E}{E_{0,i}}\right)^{\delta_1} & E \leq E_{0,i}, \\ D_0\left(\frac{E}{E_{0,i}}\right)^{(2-\delta_2)} & E > E_{0,i} \end{cases}}$$

UCLA

Diffusion Equation

For a **point-like source**:

$$Q_i(E,\vec{r}) = Q_0 \xi_i \left(\frac{E}{E_{0,i}}\right)^{-\gamma} \delta(\vec{r})$$

We solve the following differential equation:

$$\frac{\partial n_i}{\partial t} - \vec{\nabla}(D_i \vec{\nabla} n_i) + \frac{\partial}{\partial E}(b_i n_i) = Q_i(E,\vec{r},t) + \sum_k \int P_{ik}(E,E') n_k(E') dE'$$

Diffusion Equation

For a **point-like source**:

$$Q_i(E,\vec{r}) = Q_0 \xi_i \left(\frac{E}{E_{0,i}}\right)^{-\gamma} \delta(\vec{r})$$

We solve the following differential equation:

$$\frac{\partial n_i}{\partial t} - \vec{\nabla}(D_i \vec{\nabla} n_i) + \frac{\partial}{\partial E}(b_i n_i) = Q_i(E,\vec{r},t) + \sum_k \int P_{ik}(E,E')n_k(E')dE'$$

Below GZK energies, energy losses are negligible thus we only consider diffusion terms.

Solution

The flux is:

$$n_i(E,r) = \frac{Q_0}{4\pi r D_i(E)} \left(\frac{E}{E_{0,i}}\right)^{-\gamma}$$

with diffusion time t_D:

$$t_D \sim \frac{R^2}{D_i} \sim 10^7 \mathrm{yr} \left(\frac{R}{10\ \mathrm{kpc}}\right)^2 \left(\frac{26}{Z_i} \times \frac{10^{19}\ \mathrm{eV}}{E}\right)^{2-\delta_2}$$

Consequences

Consequences

- Diffusion is energy denpendent

Consequences

- Diffusion is energy denpendent

The spectral slope changes at $E \sim E_{0,i}$

Consequences

- Diffusion is energy denpendent

The spectral slope changes at $E \sim E_{0,i}$

- The flux drops dramatically because the particles escape from the galaxy

Consequences

- Diffusion is energy denpendent

The spectral slope changes at $E \sim E_{0,i}$

- The flux drops dramatically because the particles escape from the galaxy

- Diffusion time depends on charge

Consequences

- Diffusion is energy denpendent

The spectral slope changes at $E \sim E_{0,i}$

- The flux drops dramatically because the particles escape from the galaxy

- Diffusion time depends on charge

Diffusion times for nuclei are longer than for protons of the same energy

UCLA

Consequences

- Diffusion is energy denpendent

The spectral slope changes at $E \sim E_{0,i}$

- The flux drops dramatically because the particles escape from the galaxy

- Diffusion time depends on charge

Diffusion times for nuclei are longer than for protons of the same energy

- **The flux drops for protons at lower energies than heavy nuclei**

UCLA

The Source Problem

Galactic sources are likely to exist, and more pertinently, **to have existed**:

The Source Problem

Galactic sources are likely to exist, and more pertinently, **to have existed**:

- Hypernovae

The Source Problem

Galactic sources are likely to exist, and more pertinently, **to have existed**:

- Hypernovae
- Collapsars

The Source Problem

Galactic sources are likely to exist, and more pertinently, **to have existed**:

- Hypernovae
- Collapsars
- Unusual Supernovae

The Source Problem

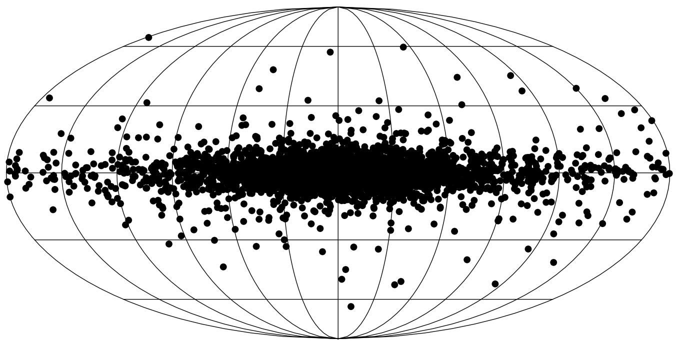
Galactic sources are likely to exist, and more pertinently, **to have existed**:

- Hypernovae
- Collapsars
- Unusual Supernovae
- **GRBs**

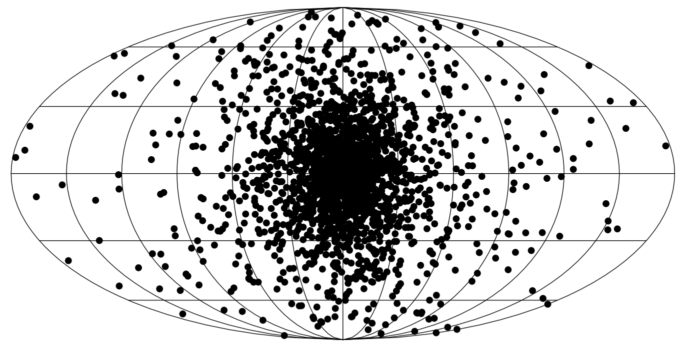
GRBs as Possible Galactic Candidates

- GRBs have been proposed as sources of *extragalactic* UHECRs [Vietri; Waxman; Dermer]
- Galactic GRBs have been considered as sources of UHECRs [Dermer *et al.*, Biermann *et al.*]
- Long GRBs: probably unusual supernova explosions or hypernovae. Short GRBs: probably mergers of compact stars.
- Both should have happened in our own Galaxy in the past, at a combined rate of one per $\mathbf{10^4 - 10^5}$ **years**.
- Past Galactic GRBs have been considered as the explanation of $511\,\mathrm{keV}$ line from the Galactic Center [Bertone, et al.; Parizot et al.; AC, Kusenko], as well as the electron excess of PAMELA/Fermi [Ioka; AC, Kusenko]

Distribution of GRBs in the Milky Way



Supernovae or long GRBs, assuming they follow star counts [Bahcall et al.]

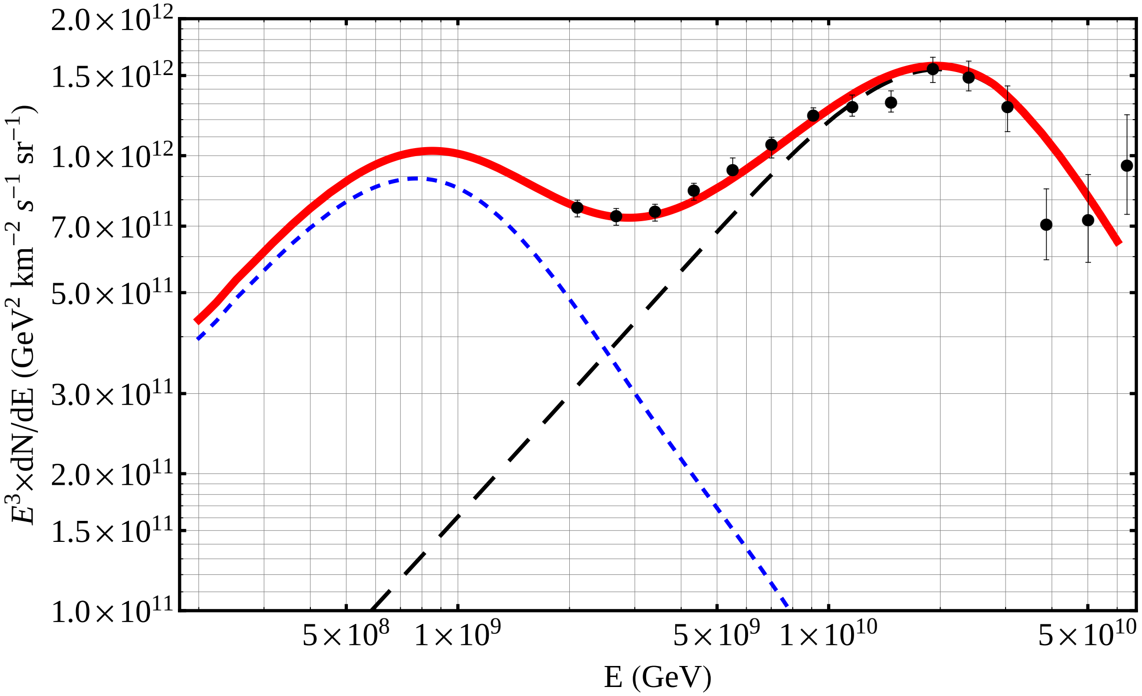


Short GRBs, based on observed distribution in other galaxies [Cui, Aoi, Nagataki]

UCLA

Comparison with Pierre Auger data

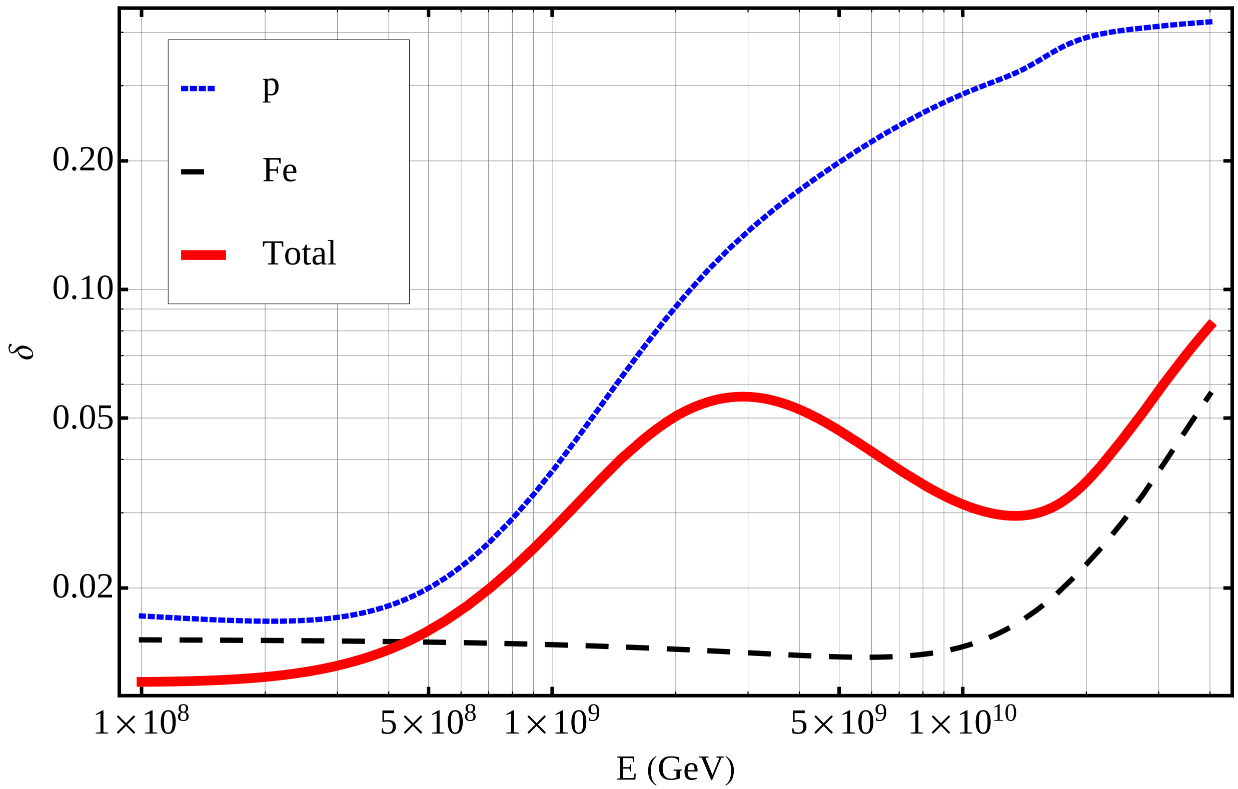
Protons, Fe, Overall Spectrum



[AC, Kusenko, Nagataki]

Energy in UHECR per source (GRB, hypernova, etc.) is 10^{44} erg above 10^{19} eV.

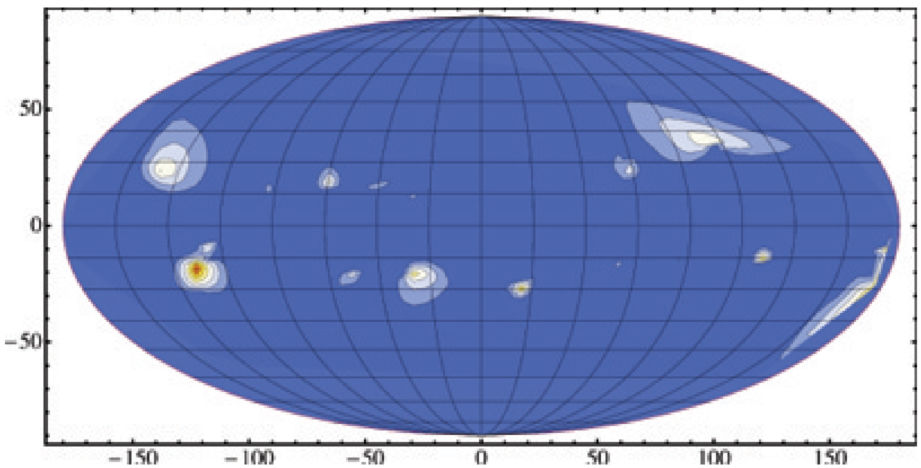
Galactocentric anisotropy (sources follow stars)



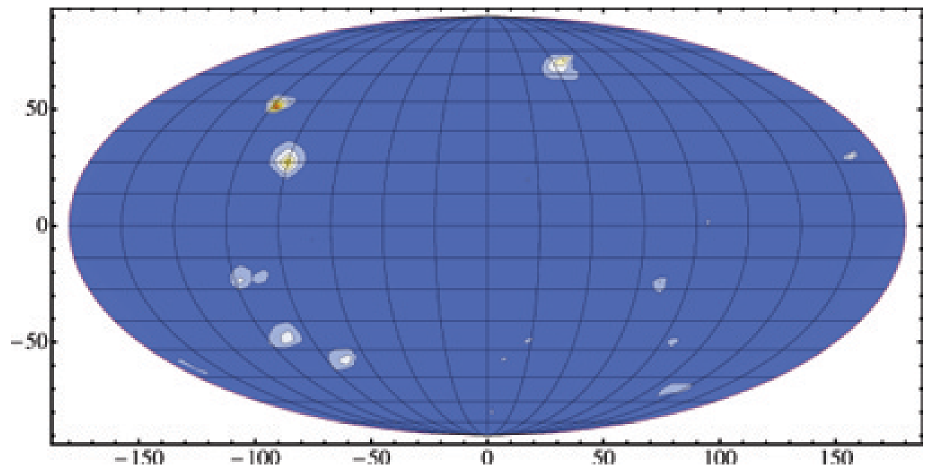
[AC, Kusenko, Nagataki]

Clusters of events from recent/closest GRBs

supernovae/long GRBs

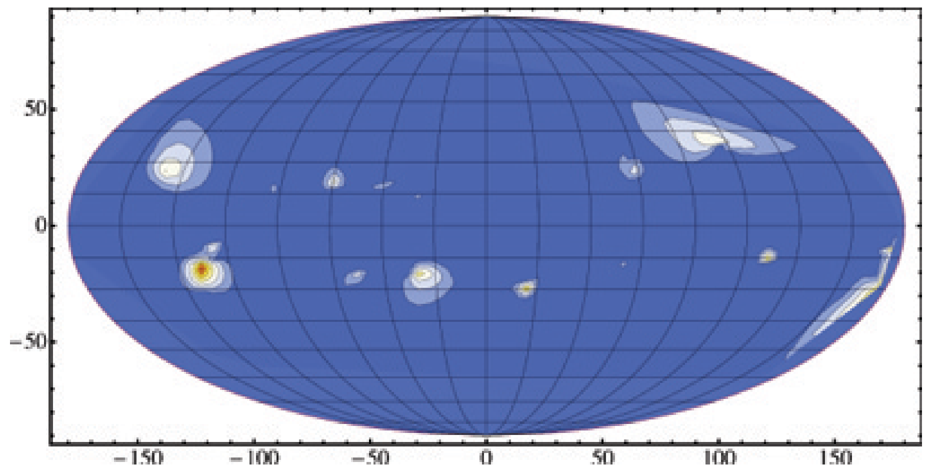


short GRBs

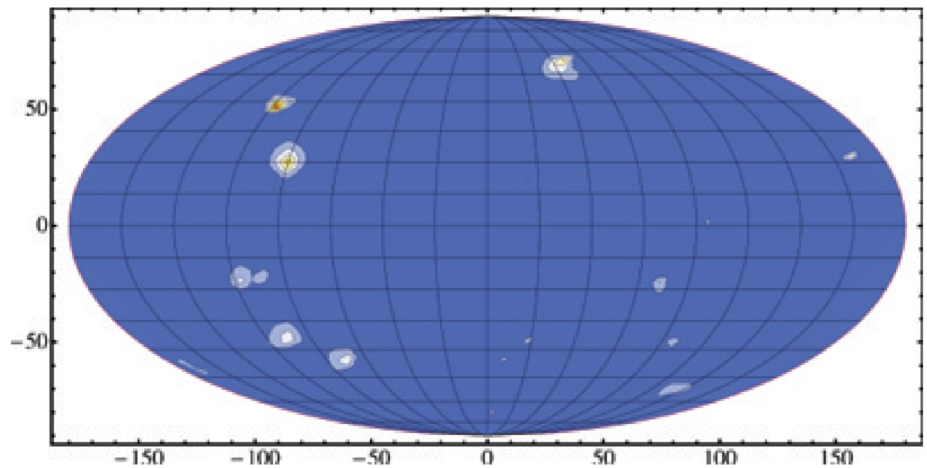


Clusters of events from recent/closest GRBs

supernovae/long GRBs



short GRBs



Extragalactic protons would also contribute to the overall spectrum above $10^{18}\,\mathrm{eV}$, and any anisotropy would be diluted by magnetic fields

UCLA

Summary

The energy-dependent composition observed by PAO motivates alternative solutions to the origin of UHECRs: **Galactic Sources**

Summary

The energy-dependent composition observed by PAO motivates alternative solutions to the origin of UHECRs: **Galactic Sources**

- Energy dependent diffusion coefficient offers a solution to the dominance of nuclei at $10^{18} - 10^{19}\,\mathrm{eV}$

- The diffusion process within galactic magnetic fields maintains the galactocentric anisotropy below a few percents

- Many possible source exist within the Milky Way

  As long as event rate exceeds $1/10^{8}\,\mathrm{year}$

- The apparent clustering could be the result of the most recent event

UCLA

Extra Slides

Magnetic Field Length Scale

Magnetic Field Length Scale

- Best fit for average random field and scale length $B \sim 5\,\mu\mathrm{G}$ and $l_c \sim 55\,\mathrm{pc}$
  [Rand & Kulkarni, ApJ 343, 760]

UCLA

Magnetic Field Length Scale

- Best fit for average random field and scale length $B \sim 5\,\mu\mathrm{G}$ and $l_c \sim 55\,\mathrm{pc}$
  [Rand & Kulkarni, ApJ 343, 760]

Based on single cell-size models of Galactic random fields

UCLA

Magnetic Field Length Scale

- Best fit for average random field and scale length $B \sim 5\,\mu\mathrm{G}$ and $l_c \sim 55\,\mathrm{pc}$ [Rand & Kulkarni, ApJ 343, 760]

  Based on single cell-size models of Galactic random fields

- Stellar wind and supernova explosions inject turbulent energy into ISM on the $10 - 100\,\mathrm{pc}$ scales

Magnetic Field Length Scale

- Best fit for average random field and scale length $B \sim 5\,\mu\mathrm{G}$ and $l_c \sim 55\,\mathrm{pc}$
  [Rand & Kulkarni, ApJ 343, 760]

  Based on single cell-size models of Galactic random fields

- Stellar wind and supernova explosions inject turbulent energy into ISM on the $10 - 100\,\mathrm{pc}$ scales

  Energy transferred to smaller scales via direct cascade

Magnetic Field Length Scale

- Best fit for average random field and scale length $B \sim 5\,\mu\mathrm{G}$ and $l_c \sim 55\,\mathrm{pc}$
  [Rand & Kulkarni, ApJ 343, 760]

Based on single cell-size models of Galactic random fields

- Stellar wind and supernova explosions inject turbulent energy into ISM on the $10 - 100\,\mathrm{pc}$ scales

Energy transferred to smaller scales via direct cascade

Energy transferred to larger scales via inverse cascade of magnetic helicity

UCLA

Magnetic Field Length Scale

- Best fit for average random field and scale length $B \sim 5\,\mu\mathrm{G}$ and $l_c \sim 55\,\mathrm{pc}$
  [Rand & Kulkarni, ApJ 343, 760]

Based on single cell-size models of Galactic random fields

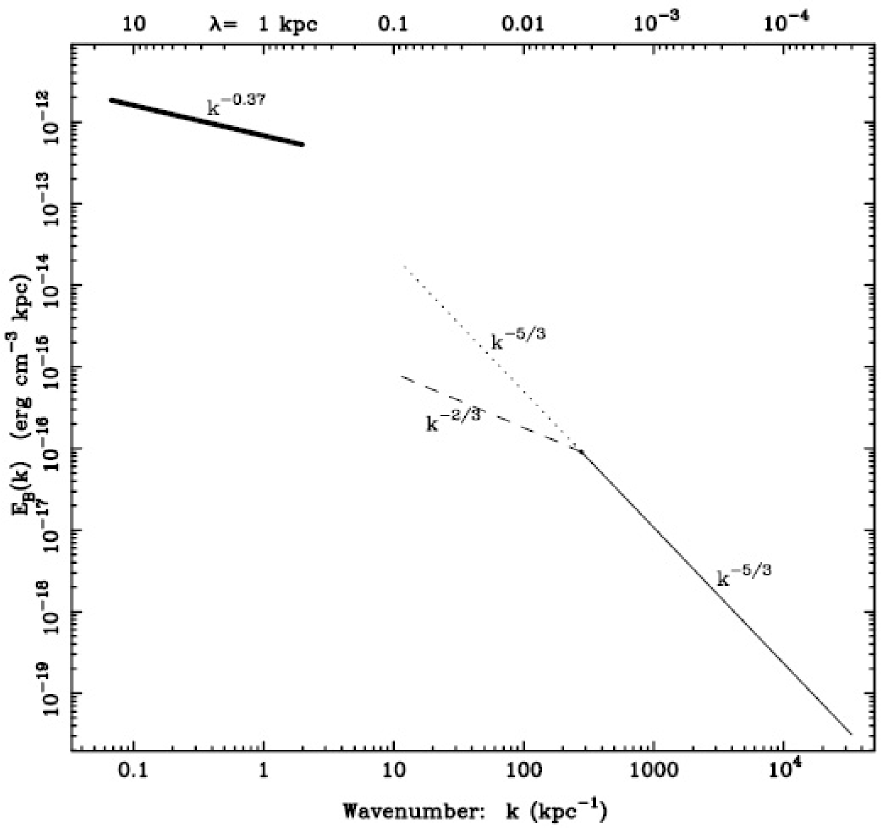
- Stellar wind and supernova explosions inject turbulent energy into ISM on the $10 - 100\,\mathrm{pc}$ scales

Energy transferred to smaller scales via direct cascade

Energy transferred to larger scales via inverse cascade of magnetic helicity

Dramatic change in the spectral slope of the magnetic energy $E_B(k)$ around $\sim 0.1\,\mathbf{kpc}$

Composite Magnetic Energy Spectrum



[Han, Ferriere and Manchester,ApJ. 610, 820 (2004)]

Composition

Composition

External Shock

Composition

External Shock

- Large dissipation radii

Composition

External Shock

- Large dissipation radii
- Nuclei can easily survive

Composition

External Shock

- Large dissipation radii
- Nuclei can easily survive

Internal Shock

The nuclei can survive if:

Composition

External Shock

- Large dissipation radii
- Nuclei can easily survive

Internal Shock

The nuclei can survive if:

- Internal shock radius is large

Composition

External Shock

- Large dissipation radii
- Nuclei can easily survive

Internal Shock

The nuclei can survive if:

- Internal shock radius is large
- Large Lorentz factor of the relativistic jets

Composition

External Shock

- Large dissipation radii
- Nuclei can easily survive

Internal Shock

The nuclei can survive if:

- Internal shock radius is large
- Large Lorentz factor of the relativistic jets
- (And/Or) In the presence of a synchrotron self-absorption break

UCLA