UHECRs & Multimessenger Astrophysics
part II

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Key points from last time

- Measurements generally agree between Auger & TA; quality of data has vastly improved in past 15 years.
- Maximum energy is mainly determined by accelerators; energy loss in propagation ("GZK") has an impact but it’s secondary.
- Composition of extragalactic component is mixed, starting as proton at lowest energy then becoming heavier with increasing energy.
  - LHC-tuned particle physics models do not correctly describe showers (relation between muons, $X_{\text{max}}$ ...)
- The mean rigidity ($E/Z$) is approximately constant, with peak about 5 EV ($E = 5$ EeV for protons).
- Larmor radius is $\sim 1$ kpc ($E_{\text{EeV}}/Z$) / $B_{\mu G}$.
Today

• Acceleration: “Hillas Criterion”, mechanisms
• Magnetic deflections
• What can be said about sources?
  • Arrival directions
  • Anisotropies
  • Indirect info from spectrum and composition data
• Using neutrinos to find sources — intro to IceCube
Acceleration

All variants on Fermi’s Classic Mechanisms:
- “2nd Order Fermi”
- “1st Order Fermi” — Shock Acceleration: spectrum $\sim E^{-2.2}$

Accelerator must be able to retain the particle

$R_{\text{Larmor}} \lesssim L$ (size of accelerating system)

$\Rightarrow$ maximum rigidity. $E_{\text{Ev}/Z} \lesssim L_{\text{kpc}} B_{\mu G} \Gamma$

Also, minimum luminosity (Poynting):

For $p$:

$$L \sim \frac{1}{6} c \Gamma^4 B^2 R^2 \gtrsim 10^{45} \Gamma^2 E_{20}^2 \text{ erg s}^{-1}$$

c.f., Blasi GSFC lecture
Magnetic deflections make source ID difficult

Larmor radius = 1.1 kpc ($R_{EV} / B_{\mu G}$)

Deflections in JF12 field model; GF+M.Sutherland, JCAP19

(de)Magnification too!
Magnetic deflections are large and uncertain at low rigidity

Source direction at E/Z = 20 EV

Deflection magnitude

Larmor radius: 1.1 kpc (R_{EV} / B_{\mu G})

Unger-Farrar 2023 Model Suite

M. Unger, CRA23 & MU+GF to appear soon
Arrival direction inhomogeneities
Clear Dipole anisotropy amplitude >6% above 8 EeV

"Hot spot" in Cen A direction at high E

Correlations seen with starburst galaxies and AGN (ignoring magnetic deflections)
TA has also reported hot spots, but so far they have failed to sustain 4\sigma
What can we deduce about UHECR sources?
Indirect constraints on sources

• Detailed fit to spectrum & composition ➔ processing in source environment  [M. Muzio+GF, ApJL23]

• Large scale anisotropy  [T. Bister+GF, in prep]

• Hotspots
Cosmic Rays are Accelerated, then fragmented

Unger, GF & Anchordoqui 2015

- Excellent fit to spectrum & composition
- Explains light population between between GCR & UHECR
Cosmic Rays are Accelerated, then fragmented

Unger, GF & Anchordoqui 2015

- Excellent fit to spectrum & composition
- Explains light population between GCR & UHECR
- Smoking gun for UFA mechanism: \( E_p \sim E_{\text{max}} / A_{\text{max}} \) not \( E_{\text{max}} / Z_{\text{max}} \)

Note large fraction of fragmented primaries

Peter’s cycle protons would peak here
Constrains the source environment (T, B,…)!

\[ \gamma_{\text{inj}} = -1.45^{+1.25}_{-1.15} \rightarrow \text{Diffusive Shock Accel. OK} \ (\text{accelerator } \neq \text{source}) \]

Muzio+GF ApJL23
Constrain the **Surroundings** of UHECR Accelerators (M. Muzio+GF, ApJL2032)

btw: $\gamma_{\text{inj}} = -1.45^{+1.25}_{-1.15}$ $\Rightarrow$ Diffusive Shock Accel. OK (accelerator $\neq$ source)

$T_{\text{surround}} = 60 - 2000$ K

$\{B_{\text{rms}}, L\}$ of source (not accelerator as in Hillas) is constrained

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**$T_{\text{surround}} = 60 - 2000$ K excludes many candidate acceleration regions**

Massive Galaxy Clusters (2 x disfavored: $T = 10^{7-8}$ K; $n_0 = 1$)

**AGN:**
- **radio lobes** ($T \approx$ few keV)
- ?internal shocks in jet? may be problematic; must also account for boost
- inner AGN disk: maybe ok ($T=60-1000$ K)
  - but nearby dangerous regions & must account boost

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**Physics of AGN**

Accretion Disks:

Heino Falcke
MPIfR Bonn

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Massive Galaxy Clusters: poor fit to UHECRs
Source Density Constraint from Anisotropy
Teresa Bister + GF, to appear soon

- **Ansatz**: UHECR sources ~ large scale structure
  → approximate illumination map
  + GMF deflections:
    Good accounting of dipole magnitude, direction & energy dependence.
    [Ding, Globus, GF ApJL 2021]

- **New**: [T. Bister+GF, in prep]
  - Self-consistent spectrum & composition
  - “Bias” of sources relative to LSS? (none seen)
  - Place constraints on source density
Modeling Anisotropy above 8 EeV

- LSS $\rightarrow$ Illumination map
- propagate thru GMF
- good fit to dipole

More accurate treatment of approach of Ding, Globus, GF ApJL 2021
Extend to
- constrain "bias" between large scale distribution of mass and UHECR sources
- strong bound on UHECR source density $> 10^{-3}$ Mpc$^{-3}$

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Source density < $10^{-3}$ Mpc$^{-3}$ strongly disfavored

Teresa Bister + GF, to appear soon

Continuum model gives good fit to dipole. Create 1000 “source catalogs”, source densities $10^{-3}$, $10^{-4}$, $10^{-5}$, $10^{-6}$ Mpc$^{-3}$

Expect intermediate multipoles if source density < $10^{-3}$ Mpc$^{-3}$.

Unlikely to see observed dipole direction and magnitude for density < $10^{-3}$ Mpc$^{-3}$.
Data take-aways

• Auger & TA in agreement on both spectrum and composition
• Spectrum now very well measured; multiple breaks. Rigidity cuts off at ~ 5 EV.
• Lowest energy extragalactic CRs are protons and He.
• Composition becomes heavier with E, possibly reaching Fe
Interpretations

• Processing in region surrounding sources (UFA, MUF, …)
  • naturally explains sub-ankle extragalactic population
  • ➔ Spectral index can be consistent with DSA: escape from source environment hardens intrinsic spectrum of accelerator

♦ Sources appear to be abundant and relatively weak

VHE Astrophysical Neutrinos
IceCube
(coming: KM3Net, Antares in Mediterranean)
IceCube current (red), Gen2 (blue) & DeepCore/PINGU* (green)

*PINGU targets much lower E neutrinos for oscillation studies
Three types of neutrino events:

- **CC Muon Neutrino**
  - track (data)
  - factor of $\approx 2$ energy resolution
  - $< 1^\circ$ angular resolution at high energies

- **Neutral Current / Electron Neutrino**
  - cascade (data)
  - $\approx \pm 15\%$ deposited energy resolution
  - $\approx 10^\circ$ angular resolution (in IceCube)
  - (at energies $\approx 100$ TeV)

- **CC Tau Neutrino**
  - "double-bang" ($\approx 10$ PeV) and other signatures (simulation)
  - (not observed yet: $\tau$ decay length is 50 m/PeV)
Neutrino Challenges

• Small interaction cross section (but grows with energy)

• Huge muon and neutrino background from CR interactions in atmosphere ($>10^6 \times$ signal)
  • use upward-going neutrinos
  • veto on accompanying muons or shower detected in IceTop
Neutrino Arrival Directions

Figure 1: Skymap of the scan for point sources in the Northern Hemisphere represents the local p-value obtained from the maximum likelihood analysis. The spectral index is fixed as a free parameter. The black circles indicate the 100 most likely source candidates. The circle of NGC 1068 also coincides with the overall Northern Sky.

statistically significant over density; nearby starburst galaxy
Neutrino correlations with transients
(multi messenger astronomy)

• Associations reported with
  • Blazar flares (Fermi TXS 0506+056, …)
  • ~3 Tidal Disruption Events

• Combination of temporal AND directional correlations reduces chance associations, but not fully accepted yet.

• IceCube places strong limits on GRB associations
Galactic Center is overhead for IceCube, so CR muon background ($10^6$ x bigger) is overwhelming. Use ML and cascade events to avoid muon contamination.
Still Early Days for neutrino spectrum and composition

Projected Gen2

Present flavor sensitivity

Glashow event: $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow \text{hadrons}$

Energy per decade of energy is roughly the same in UHECRs, IceCube Neutrinos & diffuse gamma rays.
Enjoy the UHECR-VHE neutrino future!