What are the sources of ultra-high energy cosmic rays?

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On Auger17
(Minimal) observational constraints

→ **extreme energies:** highest energy event Fly’s Eye ~300EeV
   ~10 events above 100EeV

→ **source density:** $n_s \gtrsim 10^{-6} - 10^{-4} \text{Mpc}^{-3}$

→ **energy output:** $(n \dot{E}) \sim 10^{44} - 10^{45} \text{erg/Mpc}^3/\text{yr}$

→ **anisotropies:** Auger dipole at >8EeV, hot spot at >40EeV / correlation with LSS
   Telescope Array hot spot at >57EeV

→ **composition:** ~light at EeV ... → mixed/intermediate/heavy at 100EeV?
General principles of particle acceleration

**Standard lore:**

→ Lorentz force: \( \frac{dp}{dt} = q \left( E + \frac{v}{c} \times B \right) \)

**Ideal MHD:** \( E_{\text{pl}} \approx 0 \) in plasma rest frame

→ \( E \) field is 'motional', i.e. if plasma moves at velocity \( v_p \):

\[
E \approx -\frac{v_p}{c} \times B
\]

→ need some force or scattering to push particles across \( B \)

→ lower bound to acceleration timescale:

\[
t_{\text{acc}} = \frac{p}{\beta_p e B} = \frac{t_g}{\beta_p}
\]

→ examples:

- turbulent Fermi acceleration
- Fermi acceleration at shock waves
- acceleration in sheared velocity fields

**Beyond MHD:**

→ examples:

- reconnection
- gaps
Acceleration – a luminosity bound

A generic case: acceleration in an outflow

→ acceleration timescale (comoving frame): \( t_{\text{acc}} = \mathcal{A} t_g \)

→ \( \mathcal{A} \gg 1 \) in most acceleration scenarios:
  e.g. in Fermi-type, \( \mathcal{A} \sim \text{interaction time} / \text{energy gain} \)

sub-relativistic Fermi I: \( \mathcal{A} \sim \left( t_{\text{scatt}} / t_g \right) / \beta_{\text{sh}}^2 \)
  and \( t_{\text{scatt}} > t_g \) (saturation: Bohm regime!)

sub-relativistic stochastic: \( \mathcal{A} \sim \left( t_{\text{scatt}} / t_g \right) / \beta_A^2 \)

sub-relativistic reconnection flow: \( \mathcal{A} \sim 10 / \beta_A \) (on reconnection scales)

relativistic Fermi I: \( \mathcal{A} \sim t_{\text{scatt}} / t_g \) in shock frame, much more promising?

... comparing \( t_{\text{acc}} \) and \( t_{\text{dyn}} \) bounds the luminosity of the source to reach UHE:

\[
L_{\text{tot}} \geq 0.7 \times 10^{45} \Theta^2 \Gamma^2 \beta^3 \mathcal{A}^2 Z^{-2} E_{20}^2 \text{erg/s}
\]

low lum. AGN: \( L_{\text{bol}} \ll 10^{45} \text{ ergs/s} \)
high lum. AGN: \( L_{\text{bol}} \sim 10^{46-48} \text{ ergs/s} \)
Crab pulsar: \( L_{\text{bol}} \sim 10^{39} \text{ ergs/s} \)
high lum. GRBs: \( L_{\text{bol}} \sim 10^{52} \text{ ergs/s} \)
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- $\sim 10$ events above 100EeV

→ **source density:**

- $n_s \gtrsim 10^{-6} - 10^{-4}$ Mpc$^{-3}$

→ **energy output:**

- $n_s \gtrsim 10^{-6}$ Mpc$^{-3}$: at least one source within GZK sphere (radius 100Mpc)

- $n_s \gtrsim 10^{-4}$ Mpc$^{-3}$: Auger16, from lack of multiplets...
  ... assumes small magnetic deflection

→ **anisotropies:**

- note: $n_s$ corresponds to actual density for steady sources...
  and $n_s(E) \sim \dot{n}_s \Delta t$ for transient sources, *e.g.*

$$\dot{n}_{\text{GRB}} \sim 10^{-9} / \text{Mpc}^3 \quad \Delta t \sim 10^4 - 10^5 \ E_{20}^{-2} \ D_{100 \text{Mpc}}^{2} \ \text{yr}$$
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Telescope Array hot spot at \(>57 \text{EeV}\)

→ **composition:** \(~\text{light at EeV} \ldots\) \(\rightarrow\) mixed/intermediate/heavy at \(100 \text{EeV}\)?
Extreme acceleration, but also high output

Energy output of a source:

→ to match the flux above $10^{19} \text{ eV}$, 
$$(n\dot{E})_{\text{UHECR}} \sim 10^{44} \text{ erg/Mpc}^3/\text{yr} \quad \text{(Katz+ 10)}$$

→ per source, assuming it is steady: 
$L_{\text{UHECR}} \sim 10^{43} n^{-1}_7 \text{ erg/s} \quad (n \text{ in Mpc}^{-3})$

→ per transient source: 
$E_{\text{UHECR}} \approx 10^{50} \text{ erg } \dot{n}^{-1}_6 \quad (\dot{n} \text{ in Mpc}^{-3}\text{yr}^{-1})$

e.g.:

→ high-luminosity GRBs: 
$E_{\text{UHECR/GRB}} \approx 10^{53} \text{ erg } \approx 10 E_{\gamma/GRB}$

→ protons from radio-galaxies with $L > 10^{45} \text{ erg/s}$: a few percent efficiency

→ for the whole radio-galaxy population, $nL \sim 3 \times 10^{47} \text{ erg/Mpc}^3/\text{yr}$, typically from sources with $L \sim 10^{43} \text{ erg/s}$...

... if injecting CNO to match flux at $10^{19}\text{eV}$ and if metallicity is $\sim$ solar, requires an overall efficiency in high energy CR of a few percent!

if one wants nuclei at $>E$ to circumvent luminosity bound, accounting for the protons accelerated to $>E/Z$ requires an energy input higher by $M_p/M_{\odot}$ ...

for reference, solar composition means:

$$\frac{M_H}{M_{\text{CNO}}} \bigg|_{\odot} \sim 70, \quad \frac{M_H}{M_{\text{Si-group}}} \bigg|_{\odot} \sim 1000, \quad \frac{M_H}{M_{\text{Fe-group}}} \bigg|_{\odot} \sim 500$$
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Anisotropies at UHE

Auger 17 dipole > 8 EeV...
expected for local LSS contribution with large magnetic deflection

Auger 17 ‘hotspot’ >40 EeV... correlation with LSS...
expected for weak deflection at UHE... anisotropy corresponds to 10% of particles with ~10° deflection

Telescope Array 14 hot spot >57EeV
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→ Telescope Array sees a proton (/light) – like composition...

→ Auger observes a shift from light to mixed/intermediate, from EeV to UHE...
A key question: the chemical composition, or rigidity $E/(eZ)$ at a given energy, controls all the phenomenology at ultra-high energies:

(1) sources of $E/eZ = 10^{20}$V are much more extreme than sources of $10^{18}$V particles:

... e.g., a few candidate sources for $10^{20}$eV protons vs dozens of candidate sources of $10^{20}$eV iron...

$$L_{\text{tot}} \gtrsim 10^{45} \text{ erg/s } A^2 \left(\frac{E_{20}}{Z}\right)^2$$

... for CNO composition, possible sources: powerful radio-galaxies, relativistic supernovae (low luminosity GRB)...

(2) light particles leave stronger signatures of their sources:

... e.g., anisotropies at ultra-high energies with deflections of a few deg, vs large deflections for iron-like primaries

... e.g., secondary photons and neutrino signals

⇒ do protons exist at GZK energies? ... search for ultra-rigidity particles!
Körding+ 07: energy input of radio-galaxies

(a): energy input of $10^{45}$ erg/Mpc$^3$/yr... density $0.5 \times 10^{-7}$ Mpc$^{-3}$

(b): energy input of $3 \times 10^{43}$ erg/Mpc$^3$/yr... density $10^{-11}$ Mpc$^{-3}$

... to match the flux above $10^{19}$ eV: input rate needed $10^{44}$ erg/Mpc$^3$/yr (Katz+ 09)
→ low luminosity GRBs, also associated to X-ray flashes, are interpreted as trans-relativistic supernovae with ejecta velocity $\gamma \beta \sim 1$ ... the missing link to standard supernovae?

possible sources of UHE nuclei (Wang+ 08, Chakaborty+ 11, Liu & Wang 12, Budnik+ 08)

energy budget: $\dot{n} \sim 10^{-7} - 10^{-6} \text{Mpc}^3/\text{yr}$ \quad $E_\gamma \sim 10^{50} \text{erg}$

max. energy: $E_{\text{max}} \sim Z \times 10^{18} - 10^{19} \text{eV}$ \quad $\Rightarrow$ heavy nuclei at UHE

Note:

Hillas bound assumes $A \sim 1$
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Diffuse secondary backgrounds

→ chemical composition vs multi-messengers astrophysics:

chemical composition can be tested through secondary neutrinos and photons

secondary EeV neutrinos

secondary TeV photons

Ahlers+Halzen13

⇒ pure proton composition in tension with secondary diffuse backgrounds
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$\Rightarrow$ do protons exist at GZK energies? ... search for ultra-rigidity particles!
Anisotropies vs heavy composition at UHE

→ if anisotropic signal \( >E \) is due to heavy nuclei, then one should detect a stronger anisotropy signal associated with protons of same magnetic rigidity at \( >E/Z \) eV...

**argument independent of intervening magnetic fields**... (M.L. & Waxman 09, Liu+13)

![Graph showing anisotropic flux and composition components](image)

- injection shaped by rigidity, \( s=2 \):
  \[ E_{\text{max}} \propto Z \]
- composition: \( q_p/q_{Fe} = 1/0.06 \) as in sources of GCR

\[
\frac{S/N}{p} (E/Z) \propto \frac{N_p}{N_Z} S/N|_{Z} (> E) \\
\gg S/N|_{Z} (> E)
\]

⇒ if hot spots at \( >40-60 \) EeV are not statistical accidents, there exist GZK protons, or the source metallicity is extraordinarily large...

NB: does not depend on spectral index of injection spectrum...
only assumption: particle spectra are shaped by rigidity...
→ (Robust) Constraints on the sources of ultra-high energy cosmic rays:

→ highly powerful sources (from theory): \( L \gtrsim 10^{45} \text{ erg/s } Z^{-2} A^2 E_{20}^2 \)

→ injection rate (from exp.): \( (nE) \sim 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1} \)

→ large apparent density (from exp.): \( n \gtrsim 10^{-6} - 10^{-4} \text{ Mpc}^{-3} \)

... requires large energy output per source, with \( L_{\text{UHECR}}/L_{\text{tot}} \approx \text{few } \% \text{ or more}, \text{ a strong constraint for acceleration scenarios} \)

→ Composition controls the phenomenology of this field:

→ experimentally: strong signatures from protons, weak signatures from heavies

→ theoretically: restricted landscape for proton sources, enlarged for heavies
e.g.: ... long GRBs, most powerful Radio-Gals, or fast magnetars for p?
... low-luminosity GRBs, Radio-Gals ... or else for CNO and heavier?

→ Existence of anisotropies at GZK energies (if confirmed) constrains composition:

→ either protons at GZK, or an extremely metal-rich source with \( Z > 100 \, Z_\odot \)
→ Pinpointing a source with clusters of UHECR:
  ... 10-20 events within 10deg from closest sources at >80EeV energies,
  requires about >10 times the exposure of Auger ... Rouillé d’Orfeuil+13
  ... what if the source is a transient?

→ Pinpointing a source with secondary gamma-rays:
  ... needs EeV $\gamma$-rays... or 10-100GeV $\gamma$ from synchrotron of EeV electrons
  ... for CTA sensitivity: needs $L_{p,UHE} > 10^{46} D_{Gpc}^2$ erg/s at $D_{Gpc}>1$ ...
  Aharonian02, Kotera,Allard,ML11
  ... what if the source is a transient?

→ Pinpointing a source with secondary neutrinos:
  ... EeV neutrinos from closest sources...
  ... requires an all-sky number of 100 – 1000 EeV neutrino events... Fang+16
  ... what if the source is a transient?

→ Deciphering the source with multi-messenger astrophysics + theory:
  ... e.g. constraints on acceleration from multi-messenger data of TXS0506+056

  ... a long (and likely) way ahead...