Ultra-high-energy cosmic rays

What we know and what we don't, and possible "new physics" implications

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8 February 2023
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Outline

General notes

- I'm only talking **on behalf of myself** today, **not** of any institution, collaboration, working group or similar.
- I usually picked the **most recent results** available, preferring preprints and conference contributions over even only slightly older journal papers.
- According to astronomers, anything heavier than He is "metal". CNO are "medium". Si is "heavy". Fe is "very heavy". Anything heavier hardly even exists.
- By

$$\begin{aligned} a &\approx b, & & & 0.8 &\lesssim a/b \lesssim 1.2, \\ a &\sim b, & &\text{I usually mean} & 0.5 &\lesssim a/b \lesssim 2, \\ a &= \mathcal{O}(b), & & & 0.1 &\lesssim a/b \lesssim 10. \end{aligned}$$

- Except in Section 5, all my statements should be interpreted as if prefaced by "Unless there is any new physics (e.g. Lorentz invariance violation), ...".

Outline

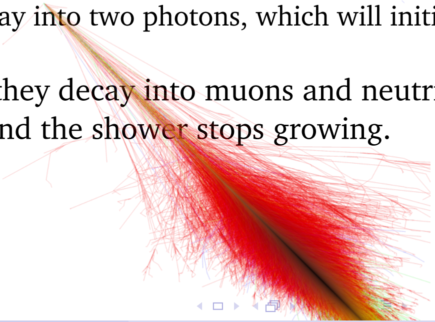
Ultra-high-energy cosmic rays

- Cosmic rays*: high-energy particles (mainly protons & other nuclei) from space
- Ultra-high-energy cosmic rays†: CRs with energies $E \geq 1$ EeV $= 10^{18}$ eV ≈ 0.16 J
  - Detected since the 1960s, up to a few hundred EeV per nucleus
  - **Very rare** ($\sim 300(E_{\text{min}}/\text{EeV})^{-2}$ nuclei with $E \geq E_{\text{min}}$ per km^2 yr sr): arrays of detectors spread over $\mathcal{O}(10^3\ \text{km}^2)$ needed
  - **Unknown sources** (mostly Galactic for $E \lesssim 10^{17}$ eV, extragalactic for $E \gtrsim 10^{18}$ eV, but unclear where exactly or how quick the transition is)
  - **Deflected by** intergalactic and Galactic **magnetic fields**:
    - Arrival directions $\neq$ source positions, by $\mathcal{O}\left(30^\circ \left(\frac{E/Z}{10\ \text{EeV}}\right)^{-1}\right)$
    - Time delays w.r.t. photons/neutrinos/GWs by $\gtrsim 1000$ yr
  - **Interactions with background photons** limit their propagation to $\mathcal{O}(100\ \text{Mpc})$ at $E \gtrsim 50$ EeV (the Greisen–Zatsepin–Kuzmin‡ limit).

*CR †UHECR ‡GZK

Production of extensive air showers*

- A UHE nucleus entering the atmosphere will collide with a N or O nucleus in air, **with $\sqrt{s} \approx 42\sqrt{\frac{E/A}{\mathrm{EeV}}}$ TeV > LHC**, producing $N = \mathcal{O}(10^2)$ secondary particles (mainly pions) with energy $E_\pi \sim E/N$ each, including:
  - $\approx\frac{2}{3}N$ charged pions, each of which will collide with another air nucleus producing N more pions with energy $\sim E/N^2$ each, and so on (hadronic shower);
  - $\approx\frac{1}{3}N$ neutral pions, each of which will decay into two photons, which will initiate electromagnetic subshowers of γ, e^+, e^-.
- Once the energy of each pion is $\lesssim 10$ GeV, they decay into muons and neutrinos before having the time to interact further, and the shower stops growing.



Simulated air shower (**hadrons**, $e^\pm$, γ, $\mu^\pm$)

*EAS

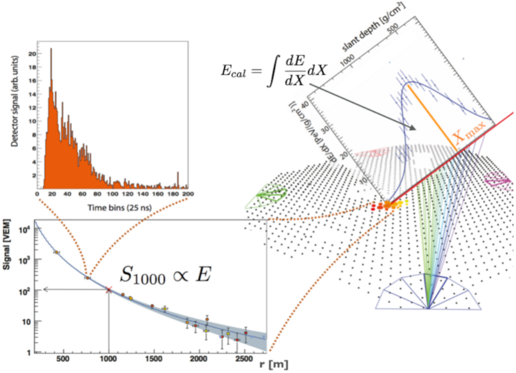
Detection of EASs

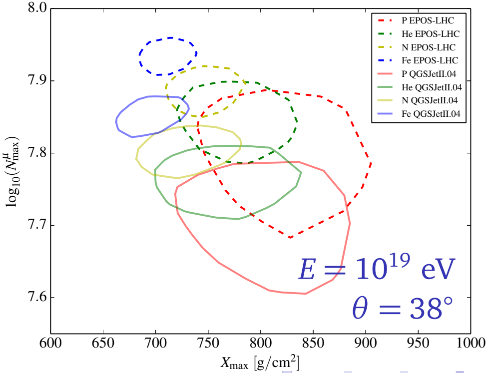
- The charged particles in a shower cause N_2 molecules to emit **fluorescence light**, which can be detected by UV telescopes called fluorescence detectors*.
- Shower particles **reaching ground level** (mainly $e^{\pm}$, γ, $\mu^{\pm}$) can be detected using arrays of surface detectors†, e.g. plastic scintillators or water Cherenkov.
- **Radio emission** by shower particles due to the geomagnetic and Askaryan effect can be detected by antennas called radio detectors‡.

*FD †SD ‡RD

- The energy and arrival direction of the primary nucleus can now be reconstructed with **reasonable precision**, but its mass number A **cannot** be directly measured.
- On average, the depth of shower maximum $X_{\max}$ and the muon number $\log N_\mu$ depend linearly on $\log(E/A)$ → knowing E, they can be used to estimate $\ln A$.

☹ **Interpretation difficult** because of **shower-to-shower fluctuations**, **unknown properties of hadronic interactions**, and **systematic uncertainties**.





Comparison of shower detection techniques

SD

- Uptime ≈ 100%
- Severe model dependency of energy estimates
- Poor energy resolution ($\sim 20\%$)
- Mass estimation hard (e/μ discr. needed)

FD

- Uptime ≈ 15% (clear moonless nights)
- Near-calorimetric E measurements
- Good energy resolution ($\sim 10\%$)
- Near-direct X_{max} measurements (syst. ~ 10 g cm^{-2}, resol. ~ 20 g cm^{-2})

Hybrid detection

- SD arrays surrounded by FDs
- Common events used for calibrating the SD energy scale to the FD one

RD

- Accuracy comparable to FDs
- Uptime comparable to SDs
- Still at the prototype stage for UHEs

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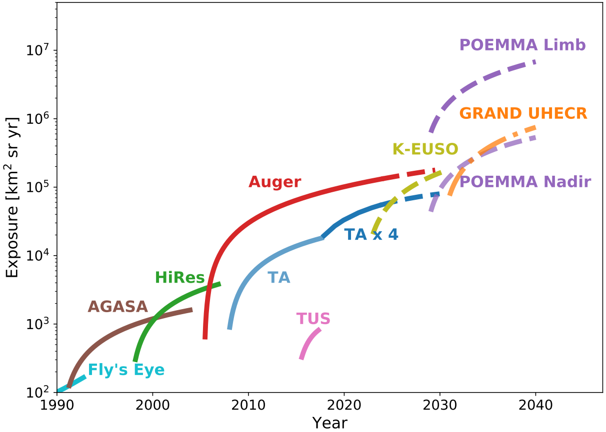
Timeline

- **1909** "Höhenstrahlung" discovered
- **1929** CRs discovered to be charged
- **1934** Air showers discovered
- **1939** 10^{15} eV CR observations
- **1962** 10^{20} eV CR observations
- **1965** CMB discovery
- **1966** GZK cutoff prediction
- **1991** Fly's Eye observes 320 EeV "Oh-My-God particle"
- **1998** AGASA claims no cutoff up to 200 EeV, people freak out
- **2006** HiRes **does see a cutoff** (and so does everybody else since)



(plot from Alves Batista et al. 2019)

The Pierre Auger Observatory (Auger) 2004–

The largest CR detector array in the world (3 in Czechia)

367 collaborators from 91 institutions in 18 countries (31 in Czechia)

Location Mendoza Province, Argentina
35.2° S, 69.2° W, 1 400 m a.s.l. (≈ 880 g/cm²)

Main array for UHE operating since 01 Jan 2004:

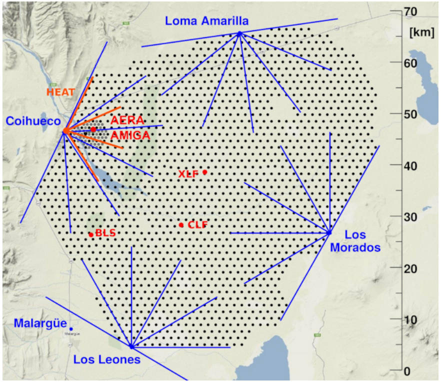
- **SD** 1 600 water Cherenkov detectors spread over a 3 000 km² triangular grid (1.5 km spacing)
- **FD** 24 telescopes on 4 sites on edge of SD array

Aperture $\theta_{\text{zenith}} < 80°$ (declination $\delta < +44.8°$)

Systematic uncertainty on energy scale ±14%

Low-energy extension (HEAT and AMIGA):

- 3 extra FD telescopes at higher elevation
- 61 extra SDs with 750 m spacing



The Telescope Array (TA) 2008–

Largest CR detector array in the Northern Hemisphere 140 collaborators, 32 institutions, 7 countries

Location Millard County, Utah, USA
39.3° N, 112.9° W, 1 400 m a.s.l. (≈ 880 g/cm^2)

Main array for UHE operating since 11 May 2008:

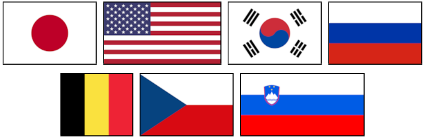
- **SD** 507 plastic scintillator detectors spread over a 700 km^2 square grid (1.2 km spacing)
- **FD** 38 telescopes on 3 sites on edge of SD array

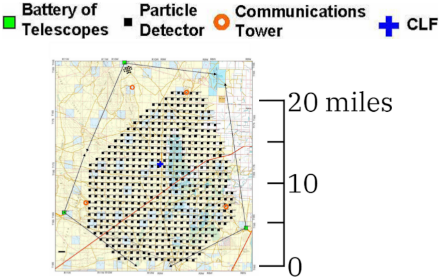
Aperture $\theta_{\text{zenith}} < 55°$ (declination $\delta > -15.7°$)

Systematic uncertainty on energy scale $\pm 21\%$

Low-energy extension (TALE):

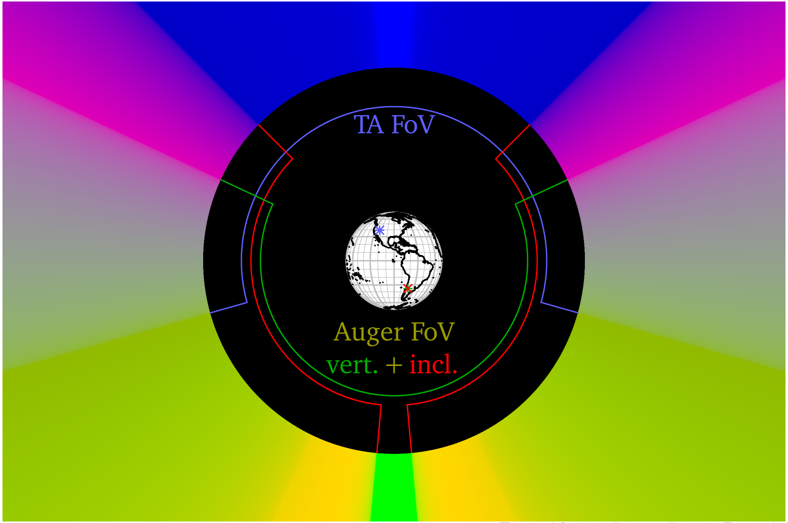
- 10 extra FD telescopes at higher elevation
- 80 extra SDs with 400 m and 600 m spacing





Field of view (FoV) of the two detector arrays

- Neither TA alone nor Auger alone covers the full sky.
- Together they do:
  - TA full northern hemisphere plus part of southern one
  - Auger vice versa
- Overlap in a band surrounding the celestial equator



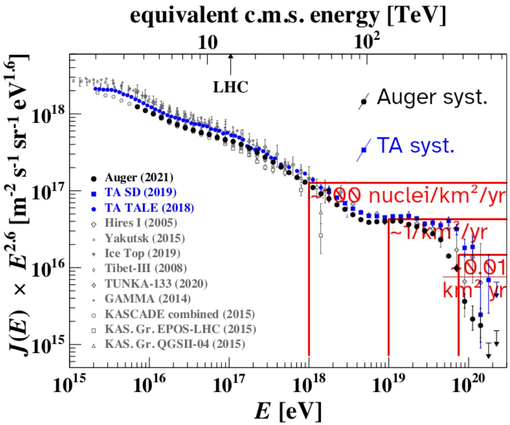
Auger–TA joint working groups (WGs)

- Several Auger–TA joint WGs have been established since the early 2010s to perform full-sky UHECR studies:
  - Energy spectrum
  - Mass composition
  - Arrival directions
  - Auger@TA
- This allows us to know whether any disagreements can be due to different FoVs or must be due to systematic errors.
- A few WGs also include other collaborations:
  - Hadronic interactions and shower physics (with EAS-MSU, IceCube, KASCADE-Grande, NEVOD-DECOR, SUGAR and Yakutsk)
  - Neutrinos (with ANTARES and IceCube)
- The WGs usually present their results (list at `http://tiny.cc/Auger-TA`) at the International Symposium on Ultra-High-Energy Cosmic Rays (UHECR) and sometimes at the International Cosmic Ray Conference (ICRC).

- I am an Auger Collaboration member, a former TA Collaboration member, and a member of the joint WG on arrival directions (but not here on behalf of either).

Outline

Energy spectrum (Auger & TA collabs. UHECR 2022)



- Approximate power-law spectrum ($J \propto E^{-\gamma}$) with spectral index $\gamma \approx 3$ over nine decades ($10^{10.5\text{–}19.5}$ eV)
- Known features (at approx. $\log_{10}(E/\text{eV})$):

		$\gamma \approx 2.7$
knee	at 15.5	
		$\gamma \approx 3.1$
low-E ankle	at 16.2	
		$\gamma \approx 2.9$
2nd knee	at 17.0	
		$\gamma \approx 3.3$
ankle	at 18.7	
		$\gamma \approx 2.5$
instep	at 19.1	
		$\gamma \approx 3.0$
cutoff	at 19.7	
		$\gamma \approx 5.1$

low-γ spectra known as hard or flat

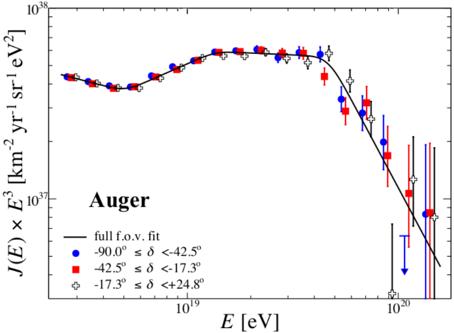
high-γ spectra known as soft or steep

:) Decent statistics thanks to huge exposures $\sim 10^4\text{–}10^5\,\text{km}^2$ sr yr

:) **Good agreement** (within systematic uncertainties), **except at highest energies**

Auger–TA difference or **declination dependence**?

"south" = [−90°, −15°], "equator" = (−15°, +25°), "north" = [+25°, +90°]



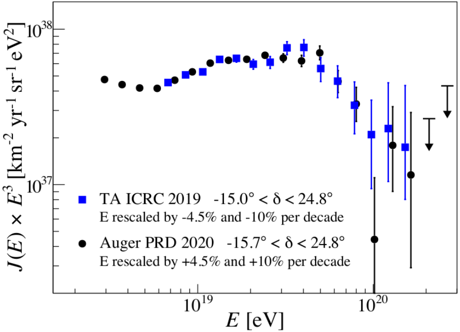
TA north	a big difference
TA equator	some difference
Auger equator	no difference
Auger south	

- Same spectrum in all declination bands to within a few percent

(Auger & TA collabs. UHECR 2022 and references therein)

Auger–TA difference or declination dependence?

"south" = $[-90°, -15°]$, "equator" = $(-15°, +25°)$, "north" = $[+25°, +90°]$



TA north	a big difference
TA equator	
	some difference
Auger equator	
	no difference
Auger south	

- Can be brought into agreement if energies are corrected via e.g.

$$E_{\text{TA}} \mapsto \left(1 - 4.5\% - 10\% \log_{10} \frac{E_{\text{TA}}}{10\ \text{EeV}}\right) E_{\text{TA}}$$

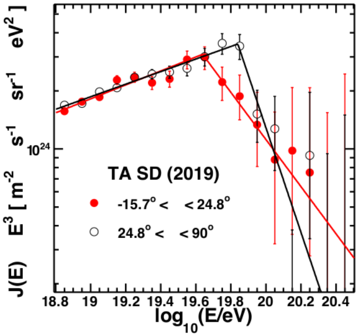
$$E_{\text{Auger}} \mapsto \left(1 + 4.5\% + 10\% \log_{10} \frac{E_{\text{Auger}}}{10\ \text{EeV}}\right) E_{\text{Auger}}$$

- Constant term **well within known systematic uncertainties** (±14% in Auger, ±21% in TA)
- **Possible causes** of energy-dependent term **under investigation** (known systematics so far: ±3%/dex in Auger, ±9%/dex in TA)

(Auger & TA collabs. UHECR 2022 and references therein)

Auger–**TA** difference or **declination dependence**?

“south” = [−90°, −15°], “equator” = (−15°, +25°), “north” = [+25°, +90°]



- Overlap with Auger $\theta < 60°$ FoV:
  - Break at $10^{19.64\pm0.04}$ eV
- Rest of the sky:
  - Break at $10^{19.84\pm0.02}$ eV
- **Post-trial significance** of difference: $\mathbf{4.3\sigma}$

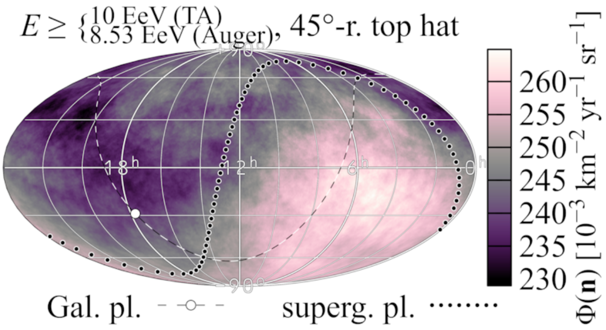
TA north / TA equator: a big difference

TA equator / Auger equator: some difference

Auger equator / Auger south: no difference

(Auger & TA collabs. UHECR 2022 and references therein)

Arrival directions above the **ankle**



(Auger & TA collabs. UHECR 2022 and refs therein)

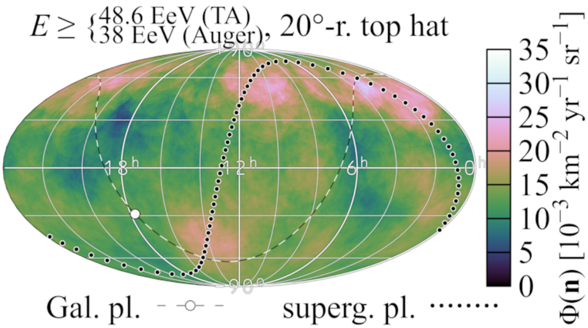
- In the latest Auger data $E \geq 8$ EeV (lower threshold than in Auger+TA): $d = 7.3\%$, significant at 6.6σ using 44k events

- Flux **nearly isotropic**, except for a dipole $\approx 5\% \times (E/10\text{ EeV})$
  - $\rightarrow$ almost all extragalactic (and/or heavy)
- At even lower energies: no detectable anisotropy

Magnetic deflections (10 EeV)

protons	$\mathcal{O}(15°–40°)$
CNO	$\mathcal{O}(100°–250°)$
heavy nuclei	diffusive

Arrival directions above the **cutoff**



(Auger & TA collabs. UHECR 2022 and refs therein)

- Correlation with **starburst galaxies** of 12% of the flux on a $\sqrt{2} \times 15°$ scale, significant at 4.7σ post trial

A few low-σ excesses in directions close to M81 Group ($\approx$ 4 Mpc), Cen A/M83 Group ($\approx$ 4 Mpc), but not e.g. Virgo ($\approx$ 16 Mpc)

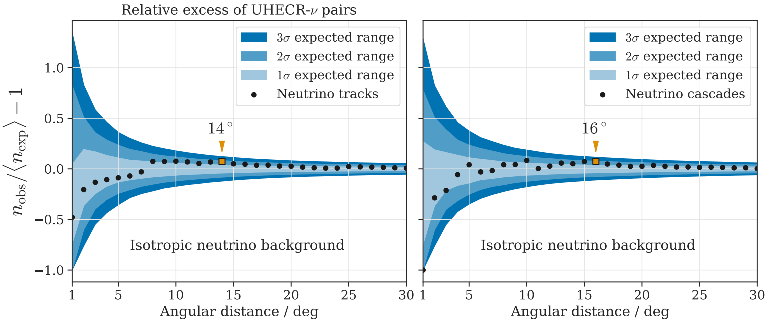
Energy loss lengths (50 EeV)

p, Fe	$\mathcal{O}$(1 Gpc)	
CNO	$\mathcal{O}$(100 Mpc)	(even less
He	$\mathcal{O}$(10 Mpc)	at higher E)

Magnetic deflections (50 EeV)

protons	$\mathcal{O}$(3°–8°)
CNO	$\mathcal{O}$(20°–50°)
heavy nuclei	$\mathcal{O}$(80°–200°)

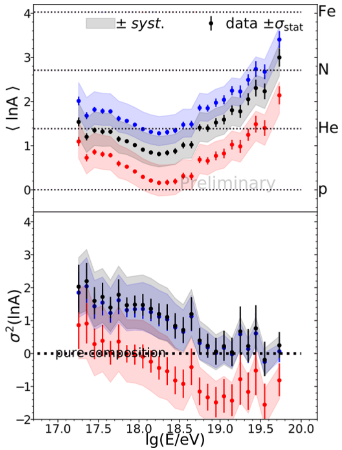
(Lack of) correlation with TeV–PeV neutrino events



Three different types of searches were performed (ANTARES, IceCube, Auger & TA collabs. 2022).

- All results compatible with the null hypothesis (**no correlation**)
- Not particularly surprising (Palladino et al. 2020):
  - Very different energies
    (PeV neutrinos from optically thick sources, EeV nuclei from optically thin ones?)
  - UHECRs can reach us only from within $\lesssim 10^3$ Mpc, neutrinos from anywhere.

Mass composition



← Auger data

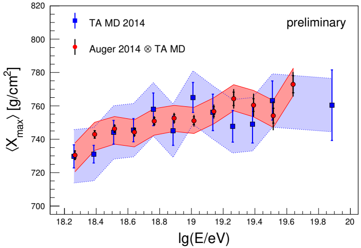
- Predominantly light composition at $E \sim 2$ EeV
- Heavier composition at lower and higher energies
- Model-dependent, large systematic uncertainties

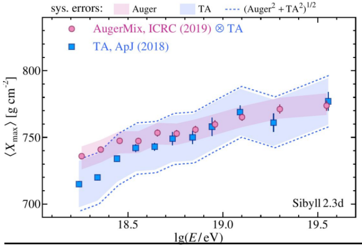
TA data (not shown)

- Agrees with Auger, but with larger uncertainties
- → Also compatible with 100% protons within error bars

Figure: Preliminary Auger X_{max} data interpreted assuming Sibyll 2.3c, Epos-LHC, QGSJet II-04 hadronic interaction models (Auger collab. ICRC 2019)

Auger vs TA mass composition





☺ X_{max} **data in agreement!** Claims of "protons in TA, heavier in Auger" due to **different hadronic models**

Non-trivial comparisons:

☹ **Detector biases** usually folded *into* simulations by TA but *out of* measurements by Auger

→ we had to fold TA biases into Auger measurements

Top Auger vs TA Middle Drum*
(Auger & TA collabs. UHECR 2014)

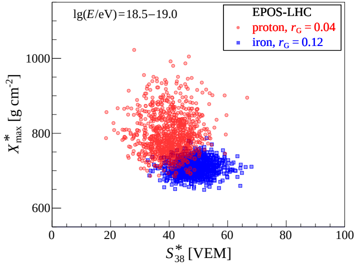
Bottom Auger vs TA Black Rock Mesa† and Long Ridge†
(Auger & TA collabs. UHECR 2022)

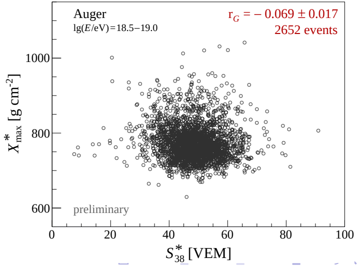
*MD, FD refurbished from HiRes-1 (1997–2006) †BRM and LR, FDs newly designed for TA

Pure or mixed?

- The observables S^*_{38} and $X^*_{\max}$ are predicted to be:
  - ***uncorrelated*** (or slightly *positively* correlated) among showers initiated by a single element
  - ***anticorrelated*** among different elements
- Rank correlation r_G (Gideon & Hollister 1987) **robust** to outliers and to nearly any possible systematics
- Among Auger events with $10^{18.5}\,\mathrm{eV} \le E < 10^{19.0}\,\mathrm{eV}$, $r_\mathrm{G} = -0.069 \pm 0.017^{+0.01}_{-0.02}$ (Auger collab. ICRC 2019)
- This **rules out any pure element** at $\gtrsim 6\sigma$ **and any p/He mixture** at $\gtrsim 5\sigma$ *using any model.*
- ***Both* p &/or He *and* heavier stuff must be present!**

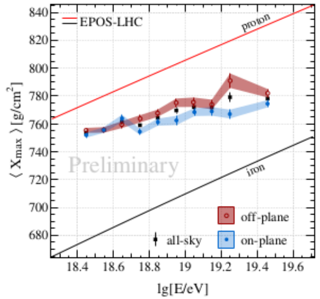
(measured $-r_\mathrm{G}$ decreasing with E, compatible with pure $\gtrsim 10^{18.8}$ eV)

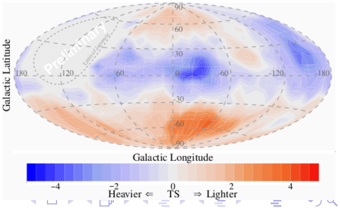




Dependence on Galactic latitude

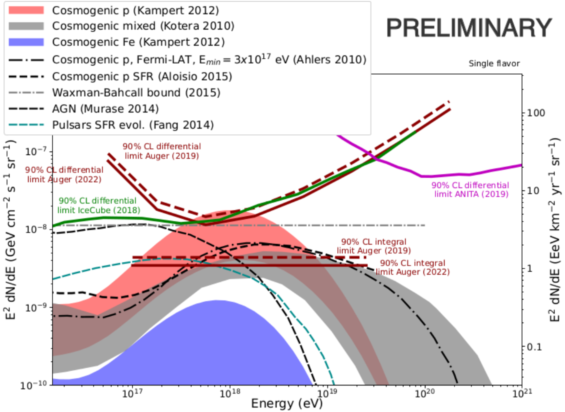
- In preliminary Auger data (Auger collab. UHECR 2022): indication of heavier composition within 30° of the Galactic plane than at higher latitudes
- Difference: $\Delta\langle X'_{\max}\rangle = (9.1 \pm 1.6^{+2.1}_{-2.2})\ \mathrm{g/cm^2}$, corresponding to an $\approx 45\%$ difference in mass
- Significant at 3.3σ (including systematics)



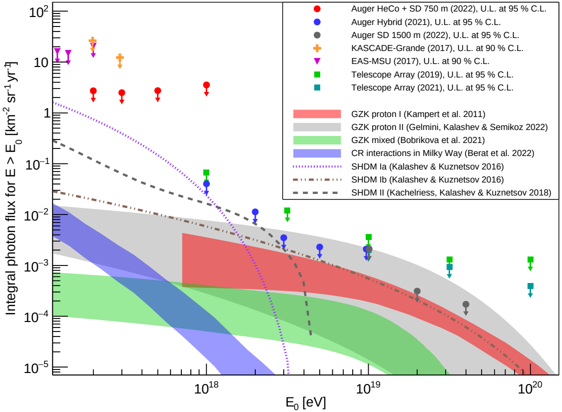


Limits on UHE neutrinos and gamma rays

(Auger collab. UHECR 2022 and refs therein)



(Auger collab. 2022 and references therein)



At $E \gtrsim 10^{18}$ eV: $J_\nu \lesssim 10^{-1} J_{\text{nuc}}$, $J_\gamma \lesssim 10^{-3} J_{\text{nuc}}$

At $E \gtrsim 10^{19}$ eV: $J_\nu \lesssim 2.5 J_{\text{nuc}}$, $J_\gamma \lesssim 10^{-2} J_{\text{nuc}}$

At $E \gtrsim 10^{20}$ eV: $J_\nu \lesssim 100 J_{\text{nuc}}$, $J_\gamma \lesssim J_{\text{nuc}}$

Summary of mass composition results

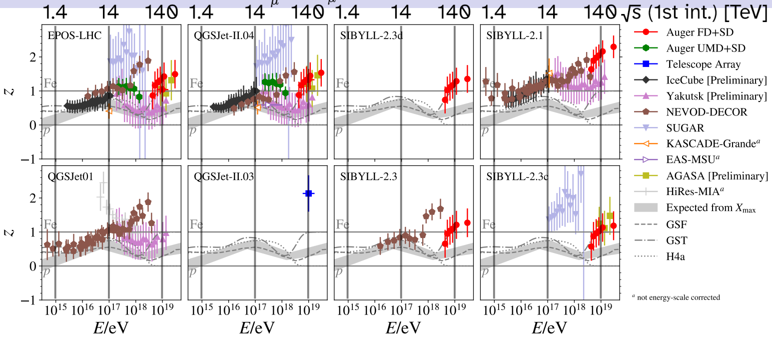
⋮		
	Apparently mostly CNO and H	(respectively Gal. and extragal.?)
$10^{18.0}$ eV		
	Dominated by H and He	
$10^{18.5}$ eV		
	Mix of both H/He and metals	(but details are model-dependent)
$10^{19.0}$ eV		
	Increasing less mixed and heavier	(but still not much iron apparently)
$10^{19.5}$ eV		
	Same as above?	(not enough statistics to be sure)
$10^{20.0}$ eV		
	Not enough data	(indirect evidence they're heavy)
⋮		

- No evidence for north–south differences
- Heavier near Galactic plane
- Few or no neutrinos or photons, except possibly at the highest energies

The air shower muon puzzle ($z \stackrel{\text{def}}{=} \frac{\ln N_\mu^{\text{obs}} - \ln N_\mu^{\text{p}}}{\ln N_\mu^{\text{Fe}} - \ln N_\mu^{\text{p}}}$)

- More μ observed (by *all* experiments) than predicted (by *all* models)
- Discrepancy growing with energy with signif. $\geq 7\sigma$

(eight collabs. UHECR 2022)

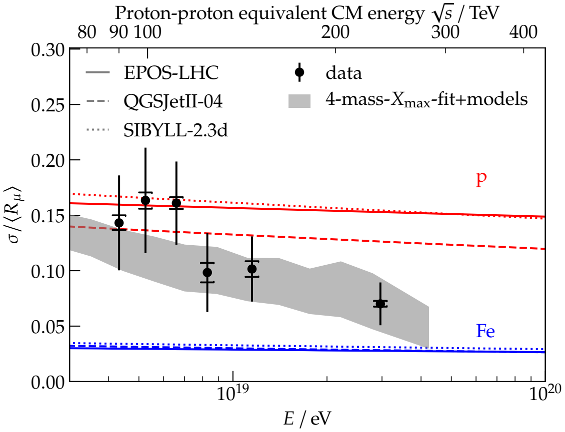


Note: kinematic regimes not easily probed in accelerator experiments

- First interactions with $\sqrt{s} \gtrsim$ LHC
- Subsequent ones initiated by pions
- Medium-mass targets (N, O)
- Extreme pseudorapidities

MODELS ARE LARGELY EXTRAPOLATIONS! (but a few dedicated measurements ongoing or planned)

Shower-to-shower fluctuations in the muon number



(Auger collab. 2021)

- **Width** of muon number distributions **in good agreement** with predictions
- **Mismatch in the average** must be due to not just major mismodelling of the first few interactions (those with extreme CoM energies), but to a **small effect accumulating** throughout the shower development (**including lower-$\sqrt{s}$ interactions** further down the shower).

Outline

Top–down and bottom–up mechanisms

Bottom–up mechanisms

Ordinary matter electromagnetically (or gravitationally) accelerated to UHEs in extreme environments:

- Gamma-ray bursts (GRBs)?
- Active galactic nuclei (AGNs)?
- Tidal disruption events (TDEs)?
- Starburst galaxies (SBGs)?
- ...

Top-down mechanisms

Super-heavy dark matter, topological defects, ..., decaying directly into UHE particles:

- Were fashionable in the late 1990s, when AGASA claimed to have observed lots of events up to 200 EeV, no cutoff
  - But all more recent experiments **do see a cutoff**
  - Energies probably systematically overestimated by AGASA, which had no FD
- Cannot be dominant, except possibly at $E \gtrsim 100$ EeV — would produce lots of γ and ν, hardly any metals

The Hillas criterion

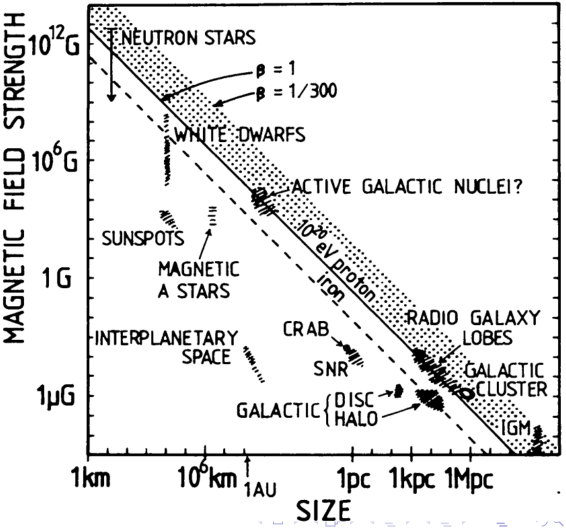
(Hillas 1984)

$$2r_{\text{Larmor}} \leq D_{\text{accelerator}}$$
$$\Rightarrow \frac{E/Z}{\text{PeV}} \leq 0.46 \frac{B}{\mu\text{G}} \frac{D}{\text{pc}}$$

Cutoff in magnetic rigidity $R = E/Z^*$

---

*For ultrarelativistic fully ionized nuclei in units with $c = e = 1$; in general, $R = p/q$



The local extragalactic environment

The Local Sheet (McCall 2014)

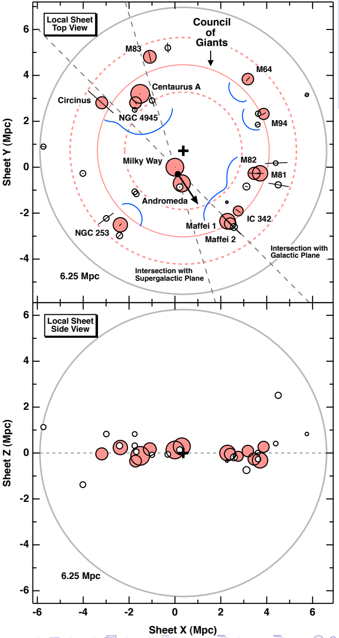
Local Group Milky Way, Andromeda (M31), and satellites

Council of Giants 12 giant galaxies in a 4 Mpc-radius ring centred on the Local Group:
NGC 253*, Circinus¶*, NGC 4945¶*, Cen A†‡, M83*, M64¶, M94, M81, M82*, IC 342*, Maffei 1‡, and Maffei 2*

- * Starburst galaxy
- ‡ Giant elliptical galaxy
- † Gamma-loud AGN
- ¶ Type-2 Seyfert galaxy

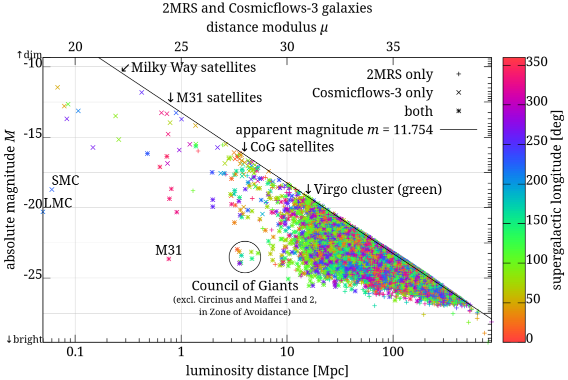
The Virgo Cluster

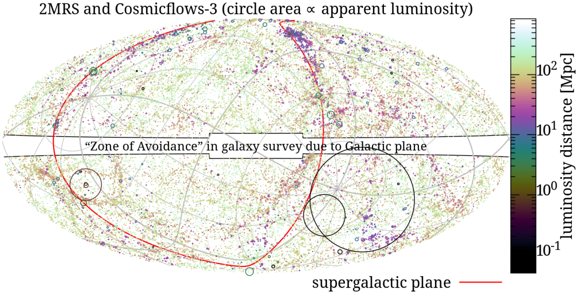
- A major cluster of galaxies ≈ 16 Mpc away



Large-scale structure of the local Universe

Clusters, walls, filaments, voids





- Clusters within $\lesssim 10^2$ Mpc tendentially aligned along the supergalactic plane
- Homogeneous and isotropic distribution at larger scales ("End of Greatness")

Propagation of extragalactic cosmic rays

Processes during extragalactic cosmic ray propagation

- Adiabatic energy losses due to the expansion of the Universe ☺☺
- Interactions with photon backgrounds:
  - Pair production ☺☺
  - Disintegration ☹
  - Pion production ☺
  - Cosmic microwave background ☺☺
  - Extragalactic background light ☹

  $\longrightarrow$ energy losses, lighter nuclei, production of secondary particles
- Deflections by intergalactic (IGMF) ☹☹ and Galactic (GMF) ☹ magnetic fields

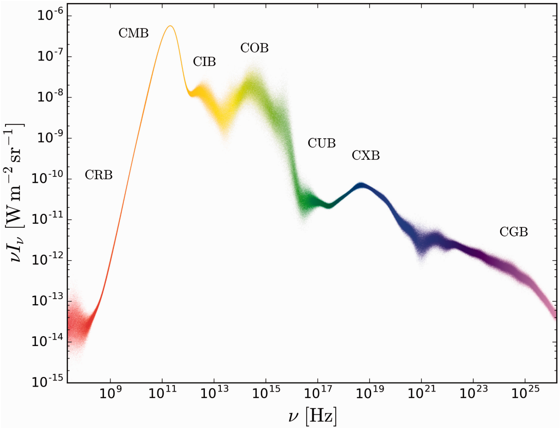
Simulation codes

- HERMES
- CRPropa 3
- TransportCR
- *SimProp* v2r4

Knowledge:

- ☺☺ Exact for all practical purposes
- ☺ Reasonably good
- ☹ Sizeable uncertainties
- ☹☹ Basically unknown

Photon backgrounds



(Hill et al. 2018)

The ones affecting UHECRs most:

Cosmic microwave background (CMB)

- Blackbody from early Universe, $T_{\text{then}} = 2\,973.2$ K, $T_{\text{now}} = 2.7255$ K :) :)
  $\langle\epsilon\rangle \approx 0.6$ meV, $\int n\,\mathrm{d}\epsilon = 411\ \mathrm{cm}^{-3}$

Extragalactic background light (EBL)

- infrared (CIB) (from dust; $\epsilon \sim 8$ meV) + optical (COB) (starlight; $\epsilon \sim 1$ eV)
- Hard to measure due to foreground (zodiacal light). :(
- Models based on various approaches:
  - :) reasonably agree on the $z = 0$ COB;
  - :(:(badly disagree on the CIB and $z \gtrsim 1$.

Interactions with background photons

photon energy: ϵ (lab frame), $\epsilon' = (1 - \cos\theta)\Gamma\epsilon$ (nucleus frame); nucleus Lorentz factor: Γ (lab frame)

Pair production ($\epsilon' \gtrsim 1$ MeV): :-) :-) very well known σ (Bethe–Heitler formula)

- $p + \gamma \to p + e^+ + e^-$ (other nuclei too) $(E_e \sim 0.05\% E_p)$

Disintegration ($\epsilon' \gtrsim 8$ MeV): :-(poorly known σ (charged ejectiles hard to detect)

- ${}^A_Z X + \gamma \to {}^{A-1}_{Z} X + n$, ${}^A_Z X + \gamma \to {}^{A-1}_{Z-1} X' + p$, etc. $(E_n, E_p = E_X/A)$
- ${}^A_Z X + \gamma \to {}^{A-4}_{Z-2} X'' + \alpha$, etc. $(E_\alpha = 4E_X/A)$

Pion production ($\epsilon' \gtrsim 150$ MeV): :-) reasonably well known σ (lots of measurements)

- $p + \gamma \to n + \pi^+$ (likewise $n + \gamma \to p + \pi^-$; bound nucleons too)

$$\pi^+ \to \mu^+ + \nu_\mu$$

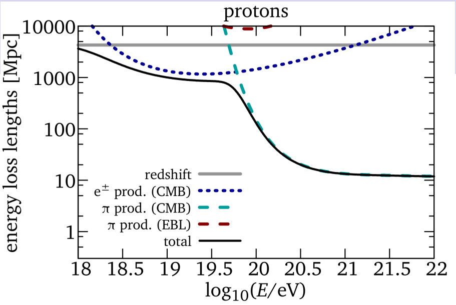
$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e \qquad (E_e, E_\nu \sim 5\% E_p)$$

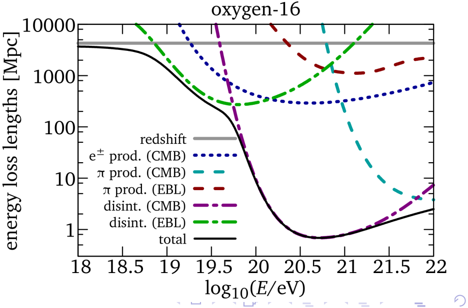
$$n \to p + e^- + \bar{\nu}_e \qquad (E_e, E_\nu \sim 0.04\% E_p)$$

- $p + \gamma \to p + \pi^0$ (likewise $n + \gamma \to n + \pi^0$; bound nucleons too)

$$\pi^0 \to \gamma + \gamma \qquad (E_\gamma \sim 10\% E_p)$$

Energy loss lengths





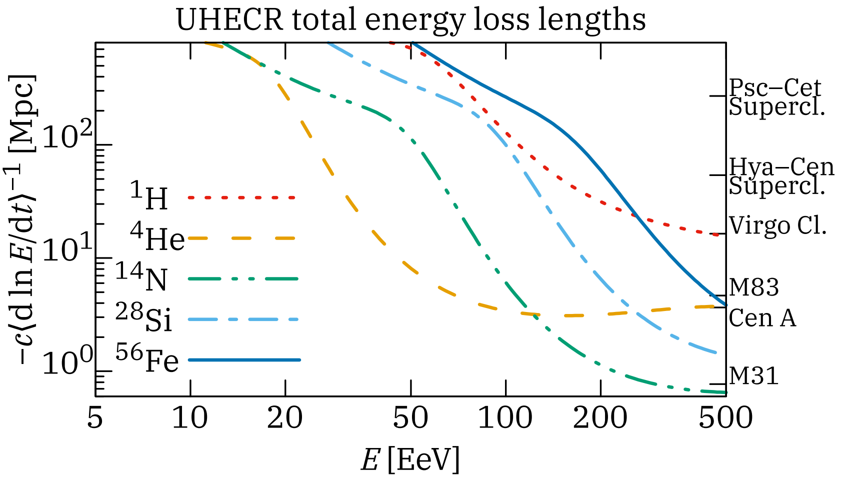
Pair production mean free path $\lesssim 1$ Mpc,
but inelasticity $\lesssim 0.1\%$
(can be approximated as continuous)

Disintegration mean free path $\lesssim 10$ Mpc,
inelasticity $\sim 1/A$

Pion production mean free path ~ 6 Mpc,
but inelasticity $\sim 20\%$

(pion production interactions with EBL photons have negligible effects on the energy spectrum, but may be a non-negligible source of PeV neutrinos)

Propagation lengths at the highest energies



No He $\gtrsim$ 50 EeV, CNO $\gtrsim$ 100 EeV should arrive from outside the Local Sheet!

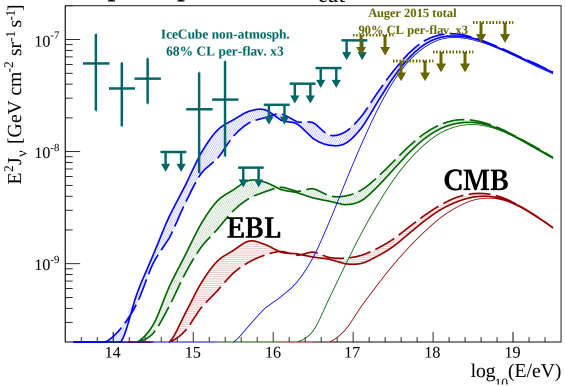
Extreme-E CRs can only be:

- local, &/or
- protons, &/or
- heavy nuclei

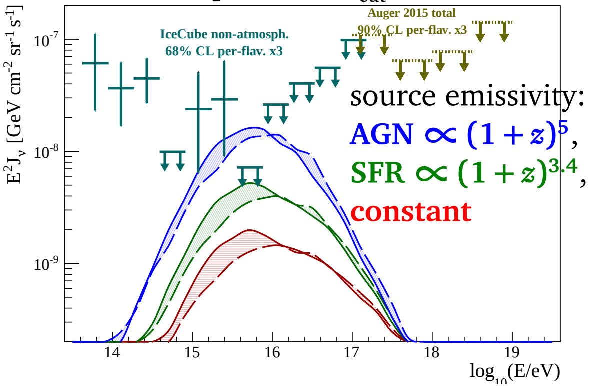
Secondary neutrinos

(Aloisio et al. 2015) — but more recent works find similar results too

pure protons ($R_{cut} \approx +\infty$)



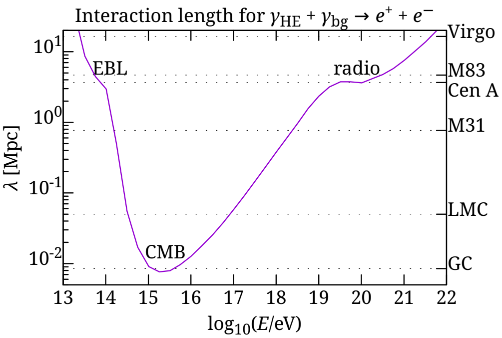
mixed composition ($R_{cut} = 6$ EV)



- Once produced, they can propagate basically forever.
  - → Their flux depends on source behaviour at high z, even if the UHECR flux doesn't.

Secondary gamma rays

- UHE photons from π^0 decay undergo $\gamma_{\text{HE}} + \gamma_{\text{bg}} \to e^+ + e^-$ straight away
- The $e^\pm$ in turn undergo inverse Compton $e^\pm + \gamma_{\text{bg}} \to e^\pm + \gamma_{\text{HE}}$, and so on
- Resulting cascade of $\lesssim 100$ GeV photons, with spectrum independent of initial $E_{e^\pm}$ and only weakly dependent on initial z $\rightarrow$ only their total energy matters
- Can contribute to the diffuse extragalactic gamma-ray background



- In principle, we could use this to constrain the source evolution or composition;

but we don't know foregrounds well, or even the angular spread of cascades (anything from point-like to isotropic depending on IGMFs); various authors get different results :-(

Galactic magnetic fields **rather hard to estimate** :-(

- No 3D measurements available, only line-of-sight integrals:

Faraday rotation $\mathrm{RM} \propto \int n_e B_r \, \mathrm{d}r$ (probes radial component)

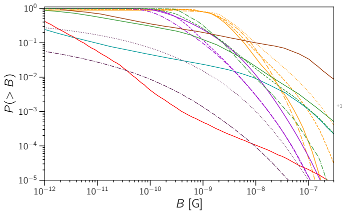
Synchrotron emission $\mathrm{I} \propto \int n_{\mathrm{CRE}}(B_l^2 + B_b^2)\,\mathrm{d}r$, $\mathrm{Q} \propto \int n_{\mathrm{CRE}}(B_l^2 - B_b^2)\,\mathrm{d}r$, $\mathrm{U} \propto \int 2n_{\mathrm{CRE}} B_l B_b \,\mathrm{d}r$
(probe transverse components, those relevant to UHECR deflections)

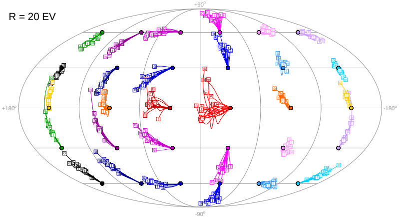
→ need to assume a model for the overall 3D structure

- Uncertain n_e, n_{CRE} model estimates
- Very noisy RM, I, Q, U measurements

:-(IGMFs **even harder** — people usually rely on cosmological simulations.

- Even if we did know them, we still **don't know the electric charges** of UHECRs.



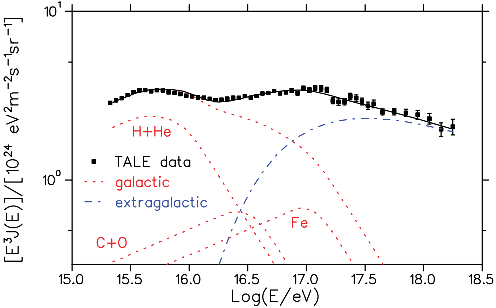


← Various models of:
Left: IGMF filling factors (Alves Batista et al. 2019)
Right: GMF deflections (Unger & Farrar 2019)

Outline

Possible explanation of the data below the ankle

(Abu-Zayyad et al. 2018)

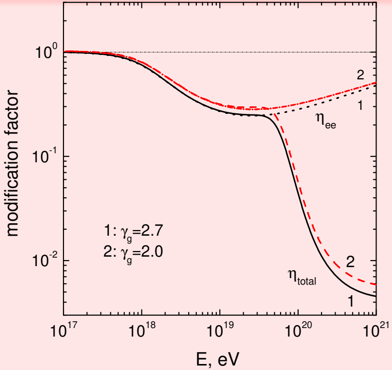


(Galactic CR mass composition extrapolated from satellite-based direct measurements at lower energies)

- Knee: cutoff in Galactic H+He spectrum (maximum acceleration energy &/or reduced magnetic confinement)
- Other elements: similar features at the same $R \to$ cutoff at $E = ZE_p$
- Low-energy ankle: due to Li/Be/B scarcity
- Second knee: due to Fe cutoff
- Gradual transition between heavy Galactic and light extragal. population $\mathcal{O}(10^{17}\ \mathrm{eV})$
  - $\to$ Lighter composition at higher energies, as in Auger $X_{\max}$ data up to 2 EeV
  - But Auger shows sizeable CNO fraction; Wolf–Rayet stars (Thoudam et al. 2016)?

Possible explanations of the data around the ankle — I

Signature of e^+e^- pair production on CMB photons ("dip model")



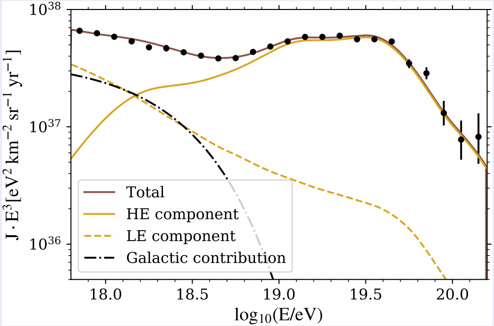
(Aloisio et al. 2007)

☹ **Only works with pure H** — even just 20% He would spoil it (and Auger data robustly excludes any pure composition around the ankle)

$$\frac{dN_{\text{Earth}}}{dE} \propto \eta \frac{dN_{\text{inj}}}{dE} \qquad \eta = \mathcal{O}\left(\frac{\text{energy loss time}}{\text{age of the Universe}}\right)$$

Possible explanations of the data around the ankle — II

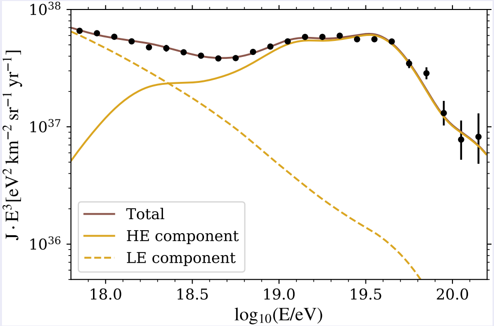
Transition between two populations



- Possible examples:
  - **Galactic and extragalactic sources?**
  - Two types of extragalactic sources?
  - Secondary neutrons and surviving nuclei from photodisintegration by radiation in the accelerator environment?
- See Auger collab. (2022) and refs therein

Possible explanations of the data around the ankle — II

Transition between two populations



- Possible examples:
  - Galactic and extragalactic sources?
  - **Two types of extragalactic sources?**
  - Secondary neutrons and surviving nuclei from photodisintegration by radiation in the accelerator environment?
- See Auger collab. (2022) and refs therein

Possible explanations of the data above the ankle

1. Source rigidity cutoff $R_{\text{cut}} \gtrsim 60$ EV (may be pure protons):
   - Highest-E nuclei (if any) quickly fully photodisintegrated
   - Observed cutoff due to pion photoproduction (GZK cutoff*)
2. $60\text{ EV} \gtrsim R_{\text{cut}} \gtrsim$ a few EV (medium-mass nuclei required):
   - Cutoff in all-particle spectrum due to photodisintegration
   - Cutoff in secondary protons at $ZR_{\text{cut}}/A \approx R_{\text{cut}}/2$
3. $R_{\text{cut}} \lesssim$ a few EV (mixed mass composition required):
   - Propagation effects relatively unimportant
   - All-particle energy spectrum ≈ convolution of rigidity cutoff and mass composition (Peters cycle)

↑ more neutrinos
more gamma rays
more anisotropy
easier to test LIV

fewer neutrinos
fewer gamma rays
↓ less anisotropy
("disappointing model")

*The original papers (Greisen 1966, Zatsepin & Kuz'min 1966) discussed both pion production and disintegration, but certain authors only use the name "GZK cutoff" for the former.

Possible explanations of the data above the ankle

1 $R_{\text{cut}} \gtrsim 60$ EV (pion prod. cutoff)

2 $60\ \text{EV} \gtrsim R_{\text{cut}} \gtrsim$ a few EV (disintegration cutoff)

3 $R_{\text{cut}} \lesssim$ a few EV (source cutoff)

- **1 is incompatible with Auger $X_{\max}$ data** and in tension with the failure to observe any EeV neutrinos or any strong anisotropies.
- **2 and especially 3 require extremely hard injection spectrum** ($\gamma \approx 1$ and $\gamma \approx -1.5$ respectively, whereas most hypothesized source mechanisms result in $\gamma \sim 2$).
- But the latter finding has loopholes (source evolution, IGMFs, . . .).
- **Very hard to tell 2 and 3 apart** (very similar predictions of observables at Earth)

Outline

UHECRs and new physics

- Modelizations of *nearly anything* about UHECRs must assume that standard physics continues to apply in regimes where it has not otherwise been tested.

- For example, interactions in extragalactic propagation and in EAS development occur in centre-of-mass frame with very large Lorentz factors ($\gtrsim 10^9$, $\gtrsim 10^6$) with respect to the laboratory frame.
- Hence, even a modest violation of Lorentz invariance might have non-negligible effects on UHECRs and EASs.

- Other possible new physics we can probe using UHECR data includes exotic particles, for example super-heavy dark matter.

Modified dispersion relations

- Special relativity assumes that any process looks the same in all reference frames, and that frames can be converted to each other via Lorentz transformations.
- Certain candidate theories of quantum gravity predict this is not exactly true:

  Lorentz invariance violation* Lorentz transformations stay the same, but background tensor fields pick a privileged frame.

  Deformed special relativity† Still no privileged frame, but transformations between frames more complicated

- Effects can usually be described by modified dispersion relations‡,

$$E_i^2 = m_i^2 + (1 + \delta_i^{(0)})p_i^2 + \delta_i^{(1)}p_i^3 + \delta_i^{(2)}p_i^4 + \delta_i^{(3)}p_i^5 + \cdots,$$

  where i is the particle type (standard dispersion relations: $\delta_i^{(n)} = 0$ for all n).
  - Alternatively, dimensionless $\eta_i^{(n)} = \delta_i^{(n)} M_{\mathrm{Pl}}^n$ or energies $E_{\mathrm{QG},i}^{(n)} = 1/\sqrt[n]{\delta_i^{(n)}}$ can be used

*LIV †DSR ‡MDR

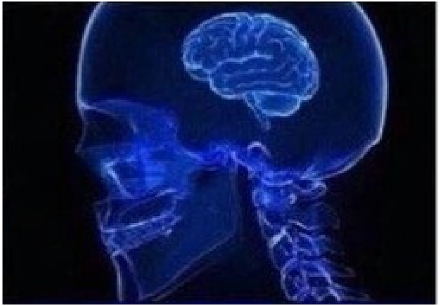
Effects on UHECR propagation

- MDRs can allow processes which would otherwise be kinematically forbidden, or vice versa, or alter the rates of processes which would be allowed either way.
- See Addazi et al. (2022) for a recent extensive review (119 pages!) of possible quantum gravity effects in astroparticle physics.
- `https://qg-mm.unizar.es/wiki/tiki-index.php?page=Reference-Table` is a publicly available database of experimental bounds on quantum gravity effects.

- The first example I'm going to discuss: superluminal LIV of hadrons ($\delta_{\text{had}}^{(n)} > 0$) could avert GZK interactions (Auger collab. 2022).

“We observe cosmic rays with $E > E_{\mathrm{GZK}}$, hence their propagation must be violating Lorentz invariance.”

(People said this in the AGASA days.)



“We observe many fewer cosmic rays with $E > E_{\mathrm{GZK}}$ than the extrapolation from lower energies, hence their propagation cannot be violating Lorentz invariance too much.”

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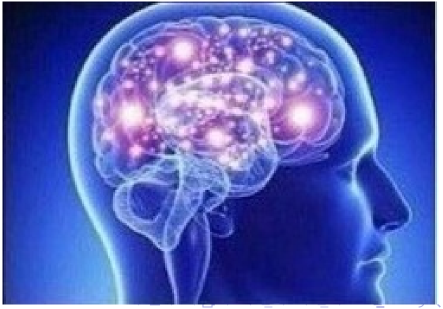

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"Even taking into account that the sources may or may not have finite R_{cut}, we get a worse fit to the data assuming Lorentz invariance, hence Lorentz invariance is probably violated."

"Even taking into account that the sources may or may not have finite R_{cut}, we get a worse fit to the data assuming Lorentz invariance, hence Lorentz invariance is probably violated."

"But even allowing Lorentz invariance violation, the goodness of fit is still rather poor, hence our models (of sources, propagation, and measurement systematics) are too simple, and we'd need better models to tell whether Lorentz invariance is violated."

(Auger collab. 2022)

Other possible effects — I

- Subluminal LIV of photons ($\delta_\gamma^{(n)} < 0$) could avert $\gamma_{\text{UHE}} + \gamma_{\text{bg}} \to e^+ + e^-$.
  - If we saw EeV photons, that would be evidence of LIV.
  - But we don't.
  - If there was a sizeable fraction of protons among the highest-energy cosmic rays, we could use this to set limits on LIV (Auger collab. 2022).
  - But for all we know, they might all be heavy nuclei, in which case no EeV photons get produced in the first place.
- Subluminal LIV of pions ($\delta_\pi^{(n)} < 0$) would delay or forbid their decay, so some pions will interact hadronically (continuing the hadronic shower) which would have otherwise decayed (initiating electromagnetic subshowers).
  - This would increase the number of muons in the showers.
  - But it would also decrease the fluctuations in their number, but those do agree with the models → we can set limits on subluminal pion LIV (Auger collab. UHECR 2022).

Other possible effects — II

- Superluminal photon LIV would allow photon decay, resulting in lower $\langle X_{\max} \rangle$ but the same $\sigma(X_{\max})$ (Duenkel et al. 2021).
- Subluminal photon LIV would allow vacuum Cherenkov radiation, $p \to p + \gamma$, with human-scale energy loss lengths. The mere existence of UHECRs can be used to set limits on this (Klinkhamer & Risse 2008).

New physics other than LIV

- Breaking news! The non-observation of extreme-energy photons by Auger can set limits on the couplings of SHDM (Auger collab. 2023) (Auger collab. 2023).
- Even crazier stuff has been searched for in UHECR data (Berezhiani UHECR 2022 and references therein).

Thanks for your attention!