Ultrahigh-energy cosmic rays: what we know, what we don't, and possible "new physics" implications

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Barcelona, Spain

Outline

1. Introduction
   - UHECRs and air showers
   - Past, present and future experiments
   - Brief overview of main experimental results (details tomorrow)
2. UHECR theory
   - Possible sources
   - Propagation effects
3. UHECR phenomenology
   - Possible explanations of data below, around and above the ankle
4. UHECRs and possible new physics
   - Effects in UHECR propagation
   - Effects in air shower development
   - Past mistakes and ideas for the future

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Ultrahigh-energy cosmic rays

- Cosmic rays (CRs): high-energy particles (mainly protons and other nuclei) from space
- Ultrahigh-energy cosmic rays (UHECRs): CRs with energies over 1 EeV $= 10^{18}$ eV ≈ 0.16 J

- Cosmic rays with energies over 100 EeV have been observed since the 1960s.
- Very rare ($\sim 0.3 \left(\frac{E_{\min}}{10\ \mathrm{EeV}}\right)^{-2}\ \mathrm{km}^{-2}\ \mathrm{yr}^{-1}\ \mathrm{sr}^{-1}$) $\rightarrow$ large detector arrays needed to study them
- Their origin is still unknown, but widely believed to be extragalactic.
- Magnetic deflections $\sim 30^\circ \left(\frac{E/Z}{10\ \mathrm{EeV}}\right)^{-1}$ $\rightarrow$ arrival directions $\neq$ source positions; time delays
  - But any large- or medium-scale anisotropy should be mostly preserved.
- Interactions with background photons $\rightarrow$ propagation limited to a few–a few hundred Mpc

Key quantities

- $E =$ energy per nucle**us**
- Lorentz factor $\Gamma = E/M \propto$ energy per nucle**on** E/A
- Magnetic rigidity $R = E/Z =$ energy per proton (for ultrarel. fully ion. nuclei, in $c = e = 1$ units)

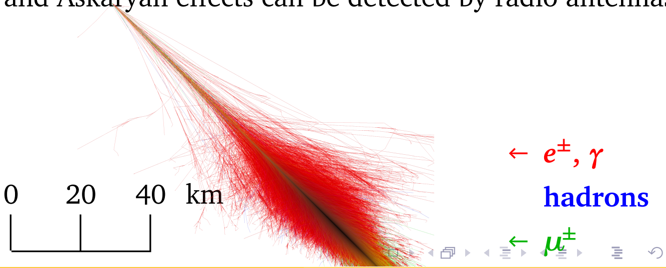
Extensive air showers

- Nuclei with $\Gamma \gtrsim 10^9$ ($E \gtrsim A$ EeV) impacting the atmosphere $\rightarrow \sqrt{s} \gtrsim 40$ TeV $\approx 3 \times$ LHC
- Resulting high-energy hadrons can interact in turn, and so on $\rightarrow$ extensive air showers
  - $\pi^0 \rightarrow 2\gamma \rightarrow$ electromagnetic subshowers (containing $e^\pm$ and γ)
  - High-energy π^+ (in "young" showers): interact further, continuing the hadronic shower
  - Low-energy π^+ (in "old" showers): $\rightarrow \mu^+ + \nu_\mu$, which dump their energy in the ground
- Charged particles cause the N_2 to emit fluorescence, which can be seen by UV telescopes.
- $e^\pm$, γ, $\mu^\pm$ reaching the surface can be detected by scintillator or Cherenkov detectors.
- Radio emission from geomagnetic and Askaryan effects can be detected by radio antennas.

10^{15} eV proton simulation $\rightarrow$

(Schmidt & Knapp 2005)

Real events tomorrow at Auger and TA highlight talks

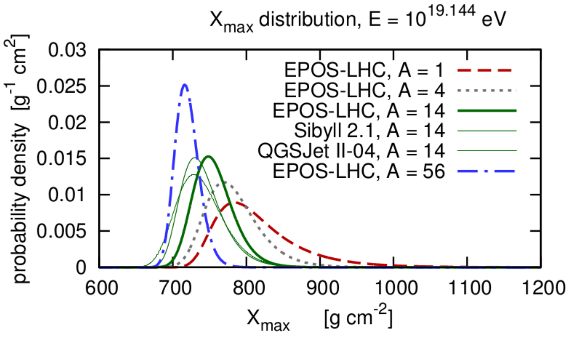


Shower properties

Calorimetric energy, E_{cal}: energy deposited in the atmosphere ($\sim 85\%$ of E of primary nucleus)

Invisible energy, E_{inv}: dumped into the ground by neutrinos and muons ($= E - E_{\mathrm{cal}} \sim 15\% E$)

Depth of shower maximum, X_{max}: on average, linear in $\log(E/A) \to$ mass estimator ($\approx \frac{17\ \mathrm{g/cm^2}}{\text{factor of 2}}$) but with major shower-to-shower fluctuations and model dependence



$X \lesssim X_{\mathrm{max}}$: shower dominated by $e^{\pm}$ and γ

$X \gg X_{\mathrm{max}}$: shower dominated by $\mu^{\pm}$

$\leftarrow$ predicted by hadronic interaction models extrapolated from LHC measurements

☹ CR mass composition nontrivial to even estimate statistically; impossible to precisely measure event by event

Shower detection techniques

Surface detector (SD) arrays

(scintillators or Cherenkov detectors)

- ☺ $\approx$ 100% uptime
- ☹ Badly model-dependent energy estimates
- ☹ Poor energy resolution ($\sim$ 20%)
- ☹ Mass estimation hard (e/μ discr. needed)
- ☺ Angular resolution $\sim 1.5°$

Fluorescence detectors (FDs)

(UV telescopes)

- ☹ $\approx$ 15% uptime (clear moonless nights)
- ☺ Near-direct E_{cal} measurement
- ☺ Good energy resolution ($\sim$ 10%)
- ☺ $X_{\max}$ measured (10 g/cm² syst., 20 g/cm² res.)
- ☺ Angular resolution $\sim 0.6°$ (hybrid or stereo)

Hybrid detectors

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

Radio detectors

- ☺ Reconstruction quality comparable to FDs
- ☺ Uptime comparable to SDs
- ☹ Not widely deployed for UHE until 2021

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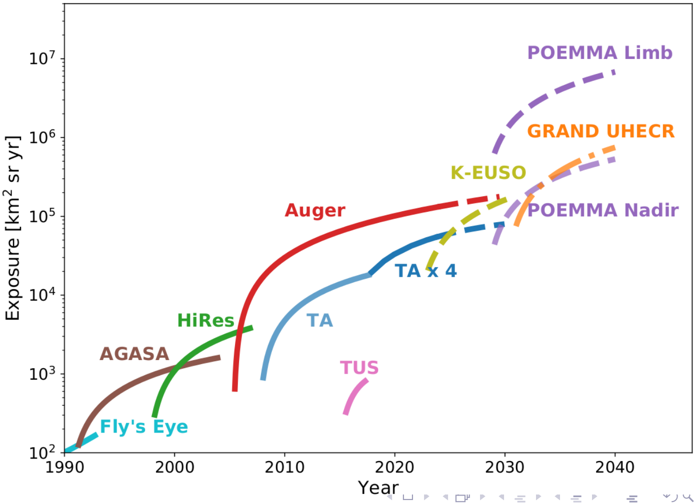
Timeline

R. Alves Batista et al., *Front. Astron. Space Sci.* **6** (2019) 23 [1903.06714]

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 and people freak out
2006 HiRes does see a cutoff (and so does everybody else since)



The Pierre Auger Observatory (Auger) 2004–

The largest CR detector array in the world

385 collaborators from 89 institutions in 17 countries

Location: Mendoza Province, Argentina
$35.2°$ S, $69.2°$ W, 1 400 m a.s.l. (≈ 880 g/cm^2)

Main array for UHE taking data since 01 Jan 2004:

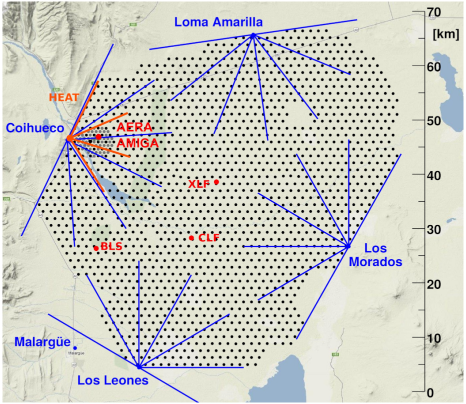
- **SD:** 1 600 water Cherenkov detectors on a 1.5 km-spacing triangular grid (3 000 km^2 total)
- **FD:** 4 sites on edge of SD array (24 telescopes total)

Low-energy extension (HEAT, Infill):

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

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

Systematic uncertainty on energy scale: $\pm 14\%$



Highlight talk by Francesco Salamida tomorrow

The Telescope Array (TA) 2008–

The largest CR detector array in the Northern Hemisphere

147 collaborators from 36 institutions in 6 countries

Location: Millard County, Utah, USA
39.3° N, 112.9° W, 1 400 m a.s.l. ($\approx 880\ \mathrm{g/cm^2}$)

Main array for UHE taking data since 11 May 2008:

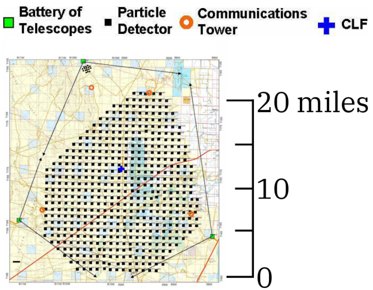
- **SD:** 507 plastic scintillator detectors on a 1.2 km-spacing square grid (700 $\mathrm{km^2}$ total)
- **FD:** 3 sites on edge of SD array (38 telescopes total)

Low-energy extension (TALE):

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

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

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

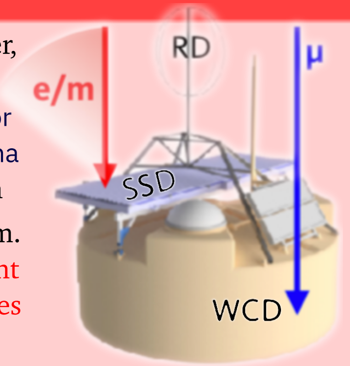


Highlight talk by AdM tomorrow

Extensions of Auger and TA currently being deployed

AugerPrime

Extension of Auger, adding a plastic scintillator detector and a radio antenna to each SD station

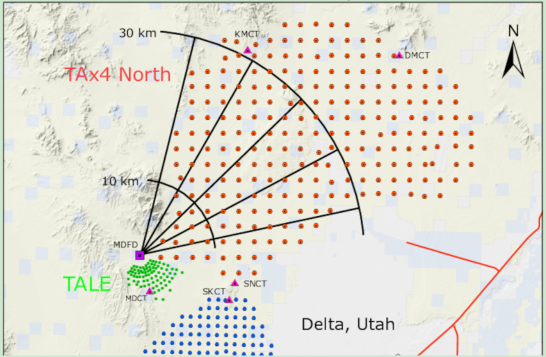


- $e^{\pm}/\mu^{\pm}$ discrim.
  - → event-by-event mass estimates even during the daytime
  - → mass-dependent anisotropy studies
- Tests of hadronic interaction models

TA×4

Extension of TA, adding more SDs and FDs to get more statistics in the Northern Hemisphere

TA/TALE/TAx4 Array



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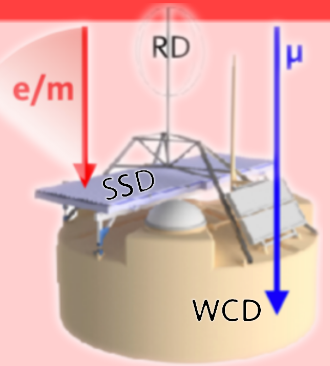

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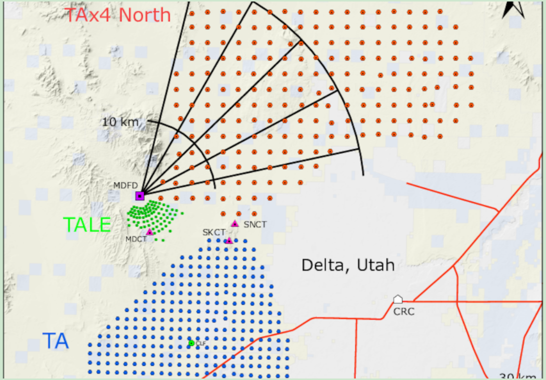

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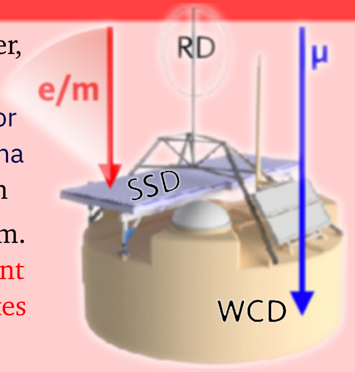

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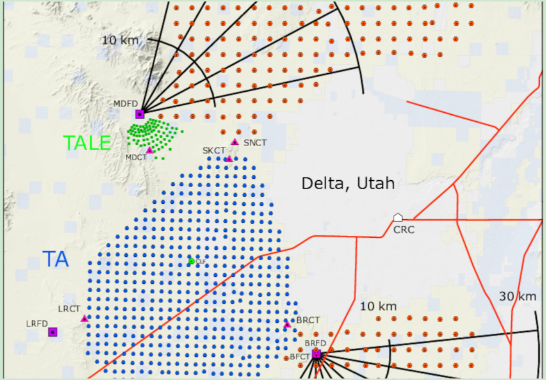

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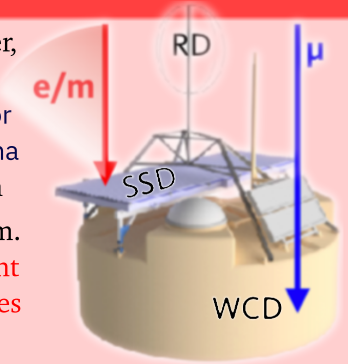

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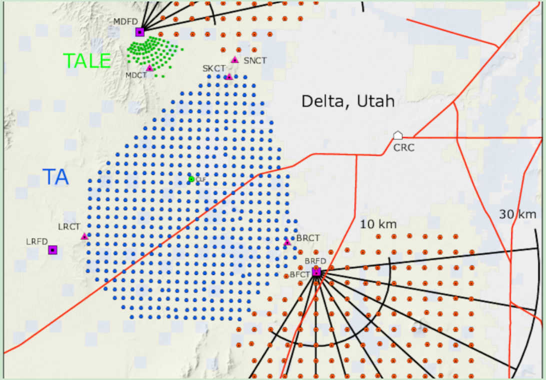

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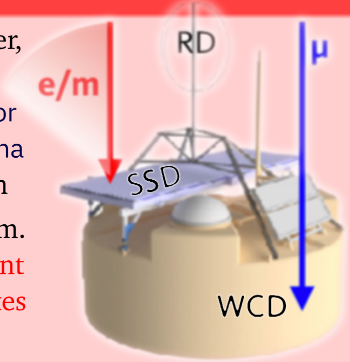

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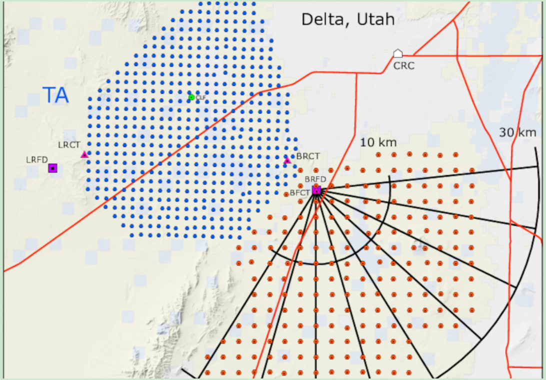

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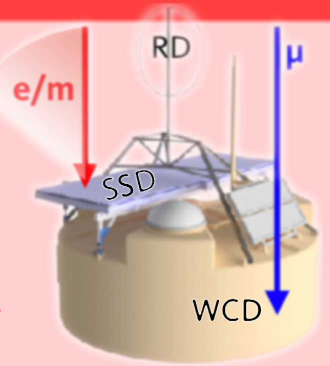

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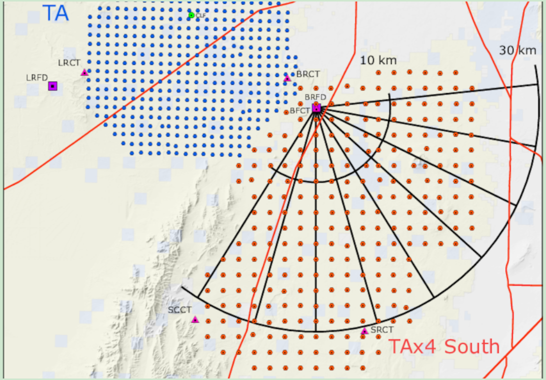

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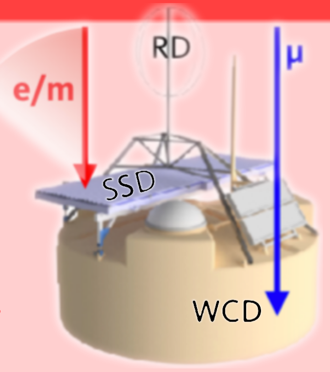

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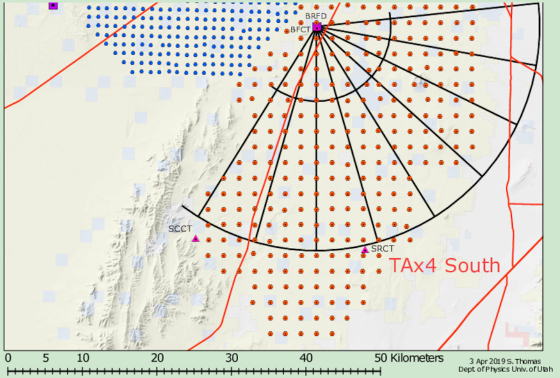

Future experiments

FAST (Fujii+ '15) and CRAFFT (Tameda+ '19)

- Huge arrays of very cheap FDs, each with very poor spatial but excellent temporal resolution
- Good geometry reconstruction possible in stereo mode or in combination with SDs
  - Prototypes at TA and Auger (2014–19)

GRAND (Alvarez-Muniz+ '20)

- 20 arrays of 10k radio antennas each
  - 300-antenna prototype in 2020–
  - First 10k-antenna array in 2025–
  - 19 more arrays in 2030–
- 200 000 km^2 total effective area
- Good sensitivity to UHE ν, γ and CRs

EUSO (Ricci+ '16) and POEMMA (Olinto+ '19)

- Fluorescence detection of extensive air showers from space
  - EUSO-TA (2013–)
  - EUSO-Balloon (2014)
  - TUS (2016–17)
  - EUSO-SPB1 (2017)
  - Mini-EUSO (2019)
  - EUSO-SPB2 (2022)
  - K-EUSO (2023–)
  - POEMMA (2029–)
- Huge effective areas at the highest energies (K-EUSO $\sim$ 100 000 km^2, POEMMA $\sim$ 300 000 km^2)

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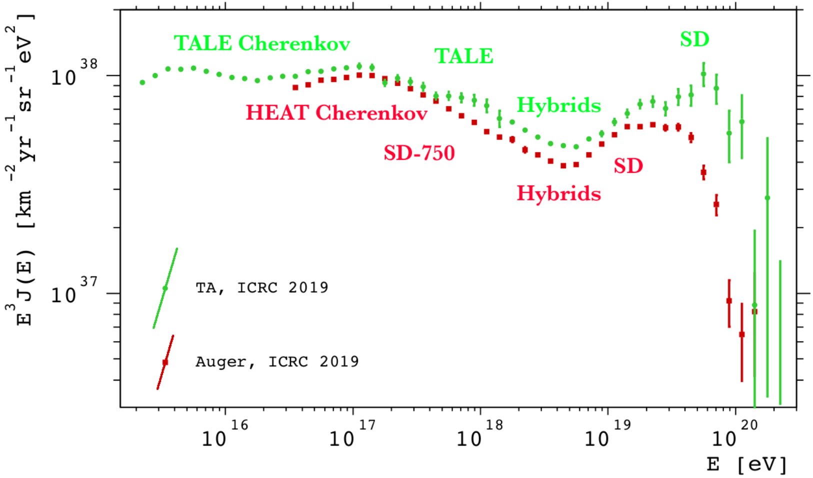
Energy spectrum

Auger + TA, PoS (ICRC2019) 234 and references therein



Power law $dN/dE \propto E^{-\gamma}$

(hard or flat spectrum: low γ)
(soft or steep spectrum: high γ)

Breaks (approx.):

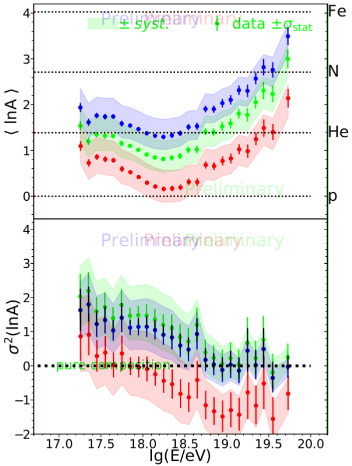
	$\log_{10}(E/\mathrm{eV})$
knee	15.5
low-E ankle	16.2
2nd knee	17.0
ankle	18.7
cutoff	19.8

γ
2.7
3.1
2.9
3.3
2.7
5.4

← Agree within systematics except at highest energies

Mass composition

Auger, PoS (ICRC2019) 482; Auger + TA, *EPJ Web Conf.* **210** (2019) 01009 [1905.06245] and references therein



← Auger data

- Predominantly light composition at $E \sim 2$ EeV
- Heavier composition at lower and higher energies
- Major model dependence and systematic uncertainties

TA data (not shown)

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

← Preliminary Auger X_{max} data interpreted assuming Sibyll 2.3c, EPOS LHC, QGSJet II-04 hadronic interactions

The air shower muon puzzle

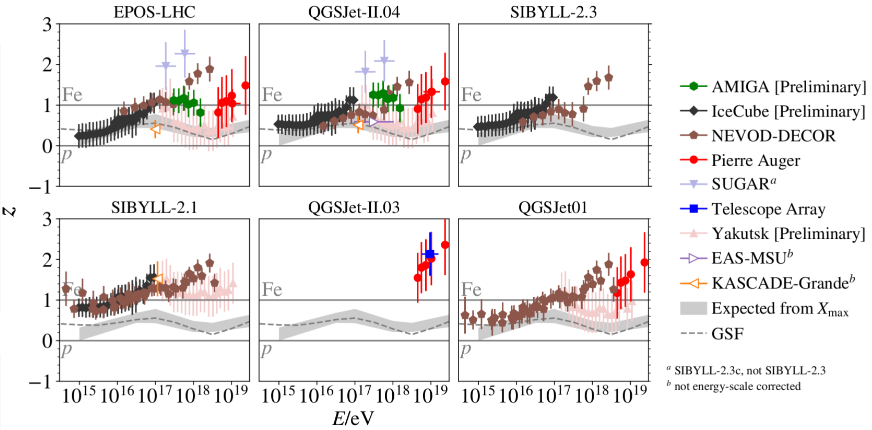
Eight collaborations, PoS (ICRC2019) 214 and references therein

$$z \stackrel{\text{def}}{=} \frac{\ln N_\mu^{\text{observed}} - \ln N_\mu^{\text{p model}}}{\ln N_\mu^{\text{Fe model}} - \ln N_\mu^{\text{p model}}}$$

$z = \ln A / \ln 56$ if model accurate

$N_\mu^{\text{observed}} > N_\mu^{\text{predicted}}$

- Consistently — all experiments, all models
- Discrepancy growing with E (8σ significance)



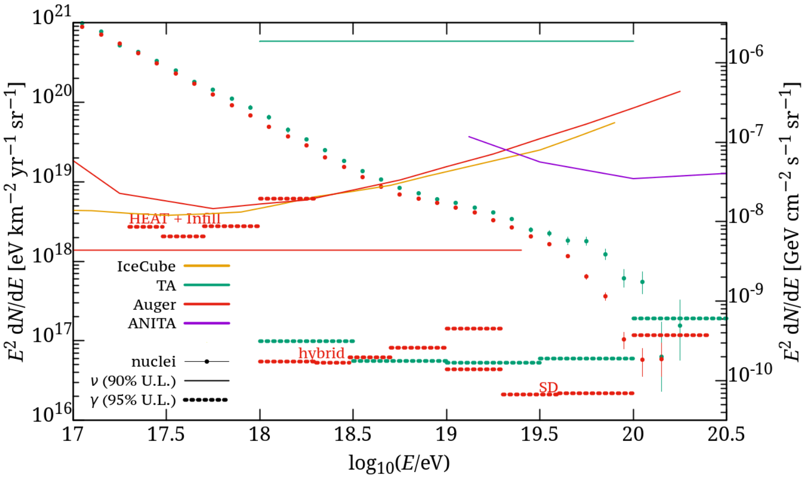
Why?

- Early interact. $\sqrt{s} \sim 100$ TeV
- Later interact. π-initiated
- Medium-mass targets (N, O)
- Very high pseudorapidity

← Impossible to probe at LHC ● Dedicated measurements ongoing

Limits on UHE neutrinos and gamma rays

Auger, PoS (ICRC2019) 979 (neutrinos) and PoS (ICRC2019) 398 (photons);
TA, arXiv:1905.03738 (neutrinos) and TA, *Astropart. Phys.* **110** (2019) 8 [1811.03920] (photons)



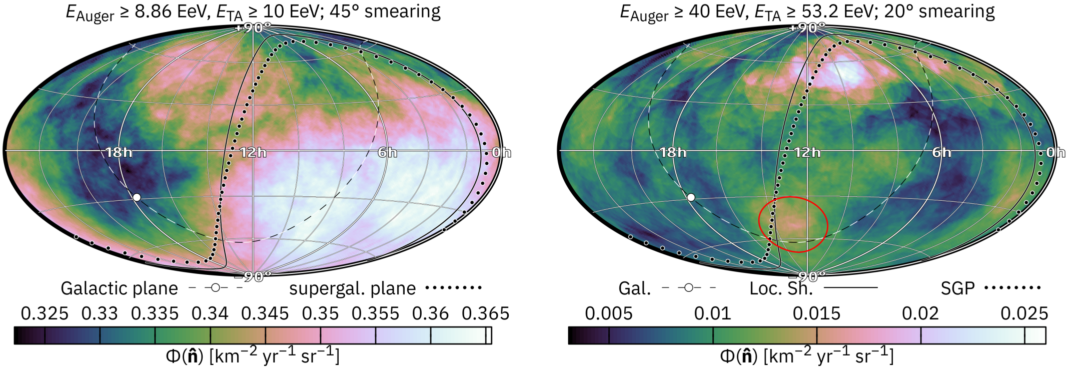
At $E \gtrsim 1$ EeV:

- $J_\nu \lesssim 0.1 J_{\mathrm{nuclei}}$ (Disfavours certain exotic scenarios)
- $J_\gamma \lesssim 10^{-3} J_{\mathrm{nuclei}}$ (Reassuring — shouldn't reach us exc. from nearby)

(Integral limits converted to differential ones assuming E^{-2} spectrum)

Arrival directions

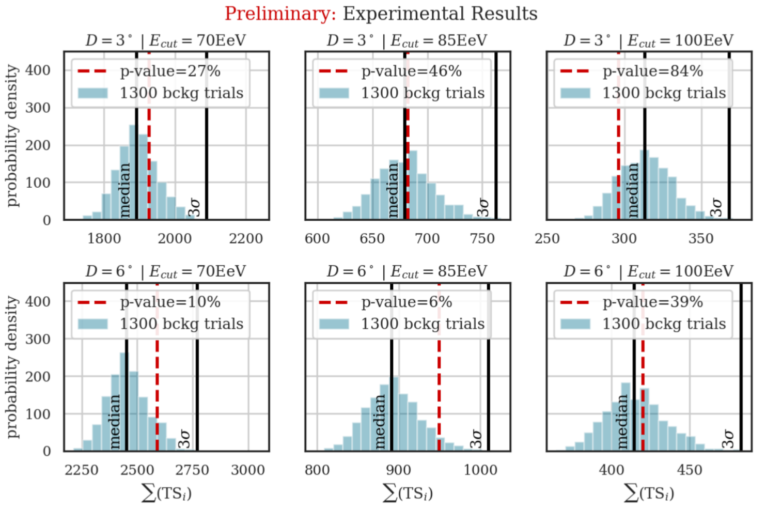
Auger + TA, PoS (ICRC2019) 439 and references therein



- At lower energies: Nearly isotropic distribution, except for $\approx 5.5 \left(\frac{E}{10\ \mathrm{EeV}}\right)^{0.8}$ % dipole
  - → Almost all of the flux must be of extragalactic and/or heavy.
- At the highest energies: A few excesses seemingly aligned with galaxies a few Mpc away

(Lack of) correlation with TeV–PeV neutrino events

IceCube + Auger + TA + ANTARES, PoS (ICRC2019) 842 and references therein



- All analyses compatible with null hypothesis (no correlation)
- Not extremely surprising:
  - Very different energies ("low"-E $\nu \leftarrow$ optically thick sources? UHECRs $\leftarrow$ optically thin ones?)
  - UHECRs only reach us from within $\lesssim 10^2$ Mpc, neutrinos from anywhere.

Outline

Top–down and bottom–up mechanisms

Top–down mechanisms: Superheavy dark matter, topological defects, or similar decaying directly into UHE particles

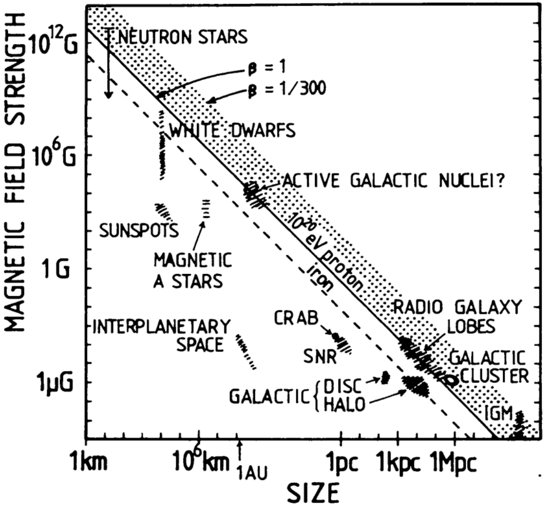
- Used to be fashionable in the late 1990s, when AGASA claimed to have observed lots of events up to 200 EeV with no cutoff
  - But all more recent experiments do see a cutoff; energies probably systematically overestimated by AGASA, which had no FD
- Cannot be dominant, except possibly at $E \gtrsim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

Bottom–up mechanisms: Ordinary matter in extreme astrophysical environments electromagnetically (or gravitationally) accelerated to UHEs

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

The Hillas criterion

A.M. Hillas, *Ann. Rev. Astron. Astrophys.* **22** (1984) 425 []



$$D_{\text{accelerator}} \geq 2r_{\text{Larmor}}$$

$$\frac{B}{\mu\text{G}}\frac{D}{\text{pc}} \geq 2.2\frac{E/Z}{\text{PeV}}$$

(Cutoff in magnetic rigidity $R = E/Z$)

The local extragalactic environment

M.L. McCall, *MNRAS* **440** (2014) 405 [1403.3667]

The Local Sheet

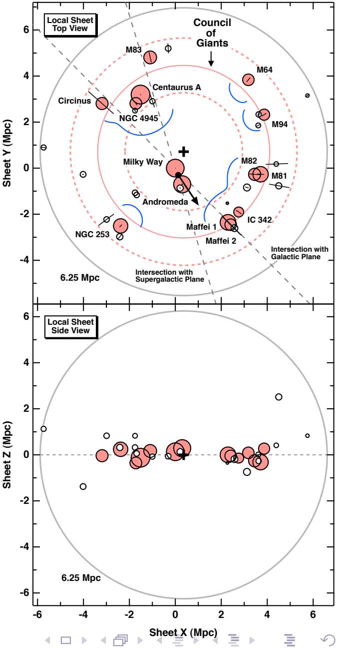
Local Group The Milky Way, Andromeda (M31), and satellites

Council of Giants 12 giant galaxies in a 4 Mpc-radius ring centered 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 † Gamma-loud AGN
‡ Giant elliptical galaxy ¶ Type-2 Seyfert galaxy

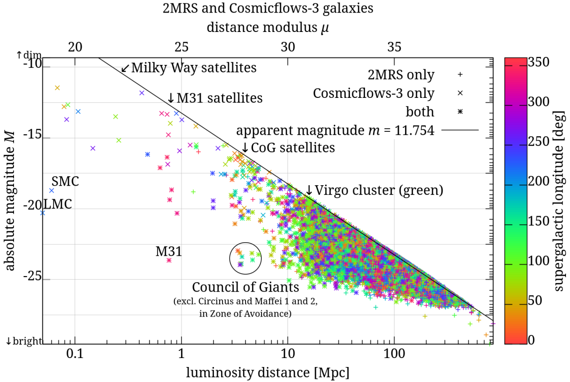
The Virgo Cluster

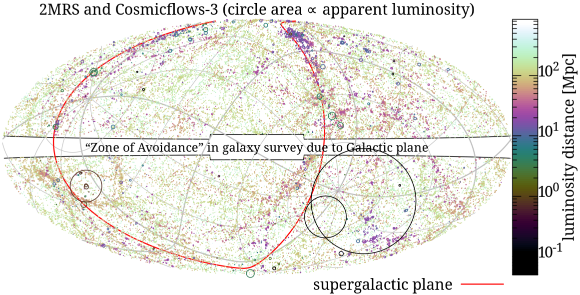
Major galaxy cluster ≈ 16 Mpc away



Large-scale structure of the local Universe

Clusters, walls, filaments, voids





- Clusters within a few tens of Mpc preferentially aligned along the supergalactic plane
- Homogeneous and isotropic distribution at larger scales ("End of Greatness")

Outline

1. Introduction
   - UHECRs and air showers
   - Past, present and future experiments
   - Brief overview of main experimental results (details tomorrow)
2. UHECR theory
   - Possible sources
   - Propagation effects
3. UHECR phenomenology
   - Possible explanations of data below, around and above the ankle
4. UHECRs and possible new physics
   - Effects in UHECR propagation
   - Effects in air shower development
   - Past mistakes and ideas for the future

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 ☹

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

Simulation codes

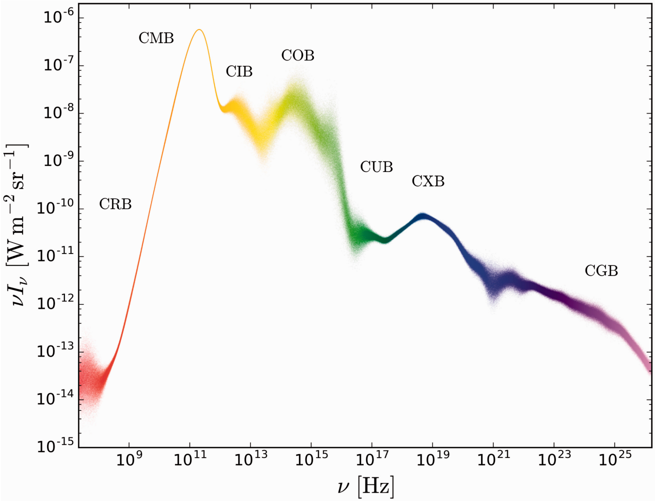
- HERMES
- TransportCR
- CRPropa 3
- *SimProp* v2r4

Knowledge:

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

Photon backgrounds

R. Hill, K.W. Masui, & D. Scott, *Appl. Spectrosc.* **72** (2018) 663 [1802.03694]



The ones affecting UHECRs most:

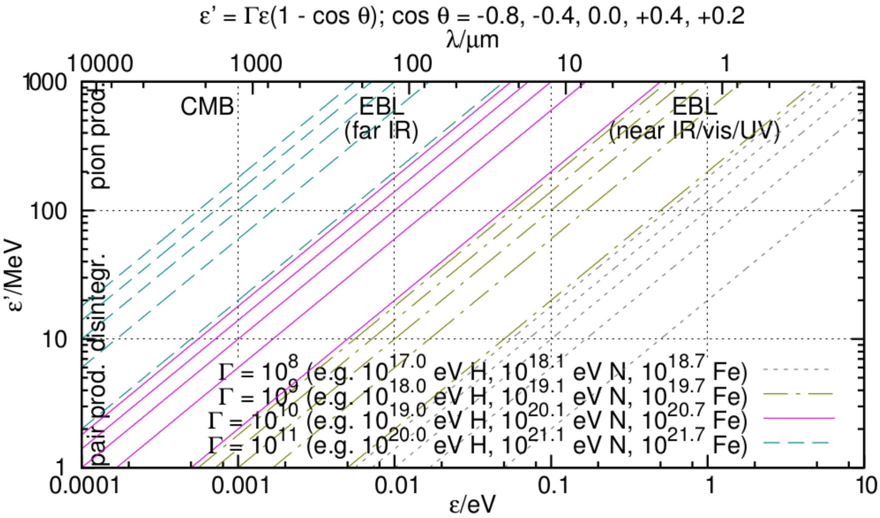
CMB (cosmic microwave background):

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

EBL (extragalactic background light):

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

Lorentz boost of background photons in UHECR frame



Assuming standard Lorentz invariance, background photons look like gamma rays to UHE nuclei.

Interactions with background photons

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

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

- $p + \gamma \to p + e^+ + e^-$ (also with other nuclei)
- Each $e \sim 0.05\%$ of initial p energy

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

- ${}^A_Z X + \gamma \to {}^{A-1}_{Z-1}X' + p$, ${}^A_Z X + \gamma \to {}^{A-1}_{Z}X + n$, etc.
- Each $p, n = 1/A$ of initial X energy
- ${}^A_Z X + \gamma \to {}^{A-4}_{Z-2}X'' + \alpha$, etc.
- Each $\alpha = 4/A$ of initial X energy

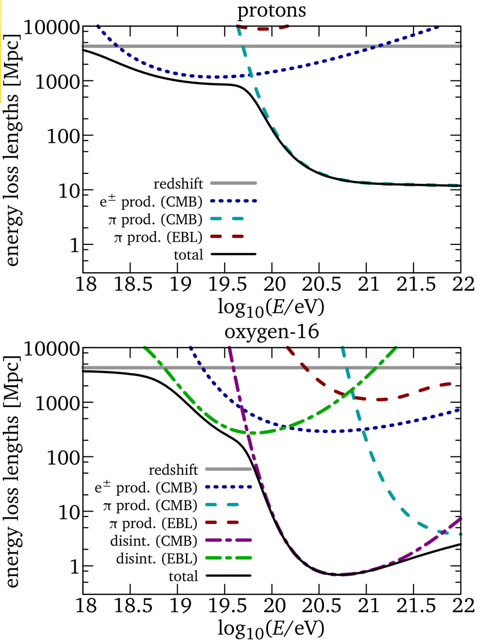
Pion production ($\epsilon' \gtrsim 150$ MeV): Cross sections reasonably well known (lots of measurements)

- $p + \gamma \to n + \pi^+$ (likewise for $n + \gamma \to p + \pi^-$, also with bound nucleons)
  - $\pi^+ \to \mu^+ + \nu_\mu$
  - $\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$
    - Each $e, \nu \sim 5\%$ of initial p energy
  - $n \to p + e^- + \bar{\nu}_e$
    - Each $e, \nu \sim 0.04\%$ of initial p energy
- $p + \gamma \to p + \pi^0$ (likewise for $n + \gamma \to n + \pi^0$, also with bound nucleons)
  - $\pi^0 \to \gamma + \gamma$
    - Each $\gamma \sim 10\%$ of initial p energy

Energy loss lengths

Pair prod. Very short mean free path ($\lesssim 1$ Mpc)
but very small inelasticity ($\lesssim 0.1\%$)
(often approximated as continuous energy loss)

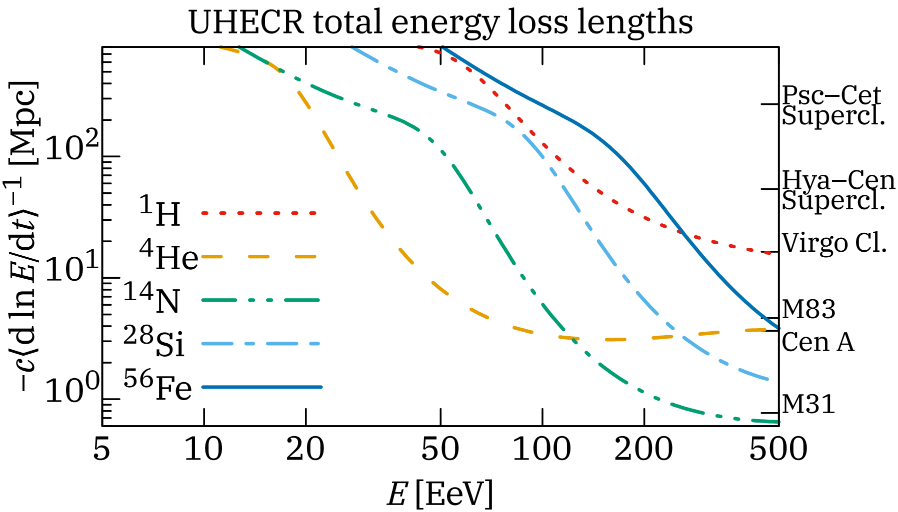
Pion prod. Longer mean free path ($\sim$ a few Mpc)
but sizeable inelasticity ($\sim 20\%$)



Note:

- Pion prod. on EBL: tiny effects on the spectrum (only affects a few percent of the protons) but major source of ~ 10 PeV neutrinos

Energy loss lengths

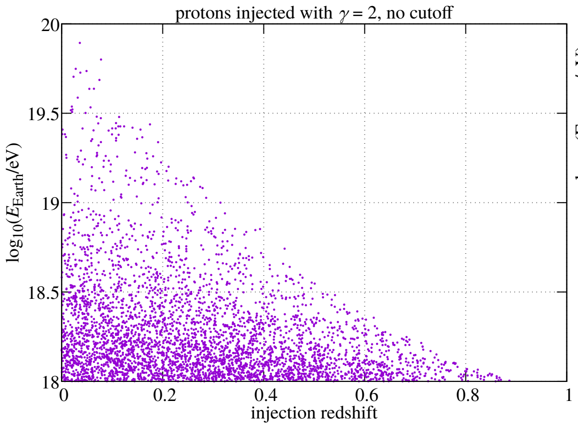


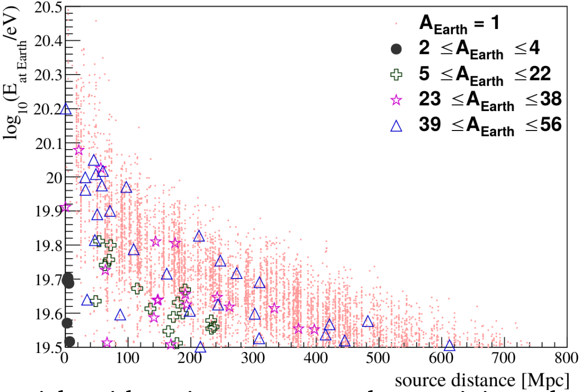
No He $\gtrsim$ 50 EeV, CNO $\gtrsim$ 100 EeV expected (except possibly from Local Sheet)

Extreme-E CRs can only be:

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

Effects of interactions

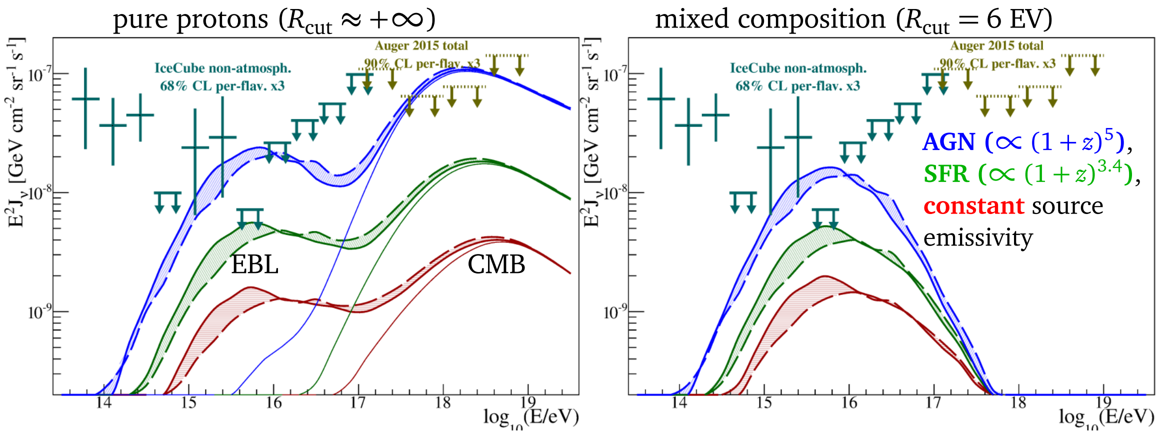




- Upper limit to the distance from which a particle with a given E_{Earth} can have originated (GZK limit, predicted by Greisen 1966, Zatsepin & Kuz'min 1966 shortly after discovery of CMB)
- Photodisintegration → there would be protons at Earth even if only heavy nuclei injected

Secondary neutrinos

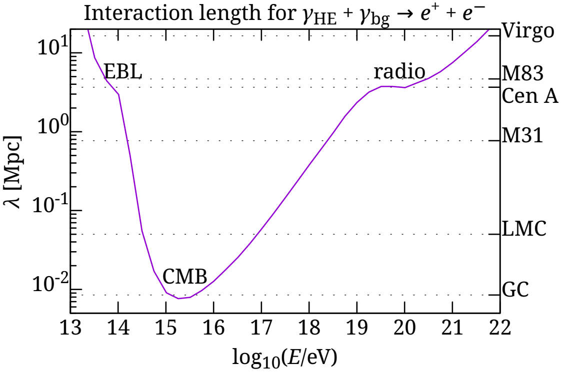
e.g. R. Aloisio et al., *JCAP* **10** (2015) 006 [1505.04020]



- 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 $\gamma_{\mathrm{HE}} + \gamma_{\mathrm{bg}} \to e^+ + e^-$ straight away
- The $e^\pm$ in turn undergo inverse Compton $e^\pm + \gamma_{\mathrm{bg}} \to e^\pm + \gamma_{\mathrm{HE}}$, 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
  → only their total energy matters
- Can contribute to extragalactic gamma-ray background

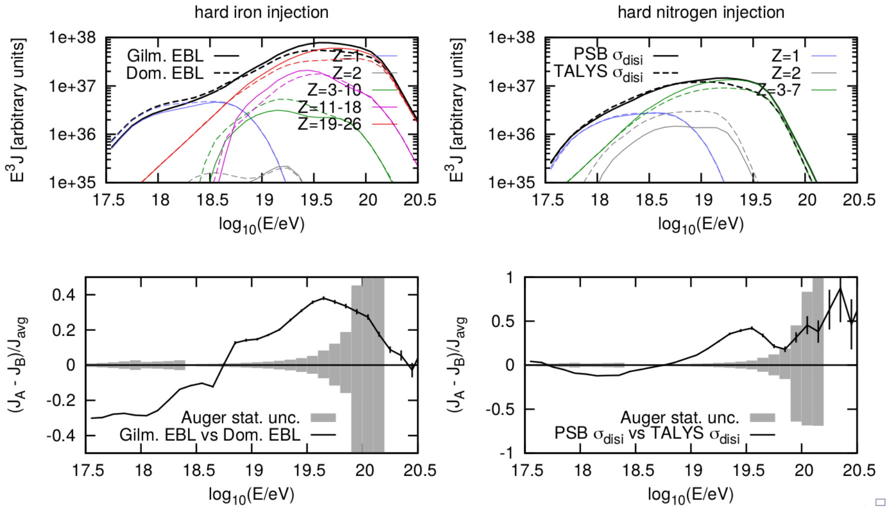


- In principle, we could use this to constrain UHECR source evolution or composition,

but we don't know the foregrounds well, or even the expected angular spread of cascades (from point-like to isotropic, depending on IGMF strength) → various authors got very different results.

Effects of uncertainties

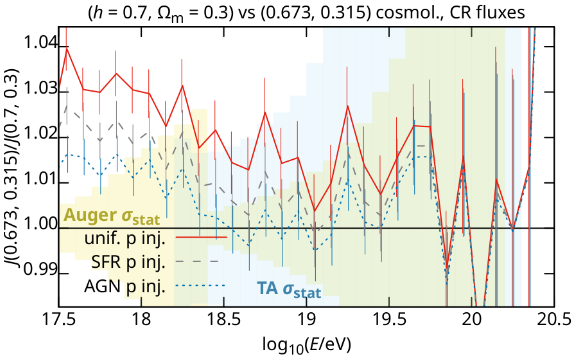
R. Alves Batista et al., *JCAP* **10** (2015) 063 [1508.01824]

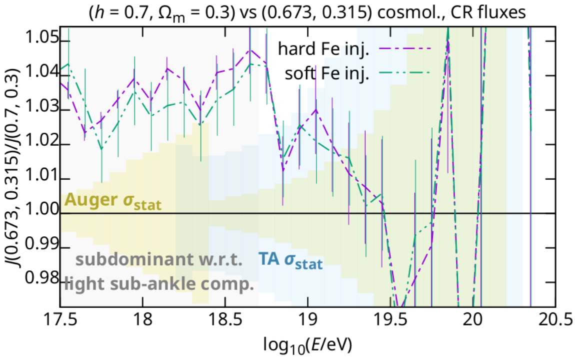


- Major impact of EBL uncertainty
- Sizeable impact of cross-section uncertainty (only for medium-mass nuclei)

Effects of uncertainties

R. Alves Batista et al., *JCAP* **05** (2019) 006 [1901.01244]





- Negligible impact of uncertainty on cosmology

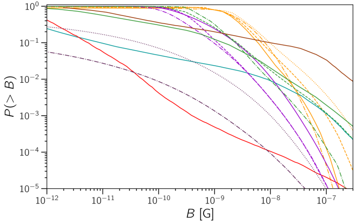
Magnetic deflections

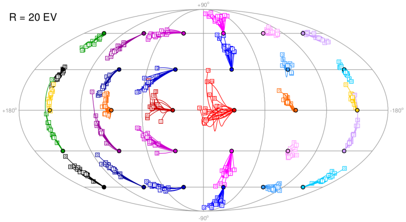
- Galactic magnetic fields very hard to estimate:
    - No 3D measurements available, only line-of-sight integrals:

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

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

      → need to assume a model for the overall 3D structure
    - n_e, n_{CRE} uncertain, and RM, I, Q, U data themselves very noisy
- Intergalactic magnetic fields even harder – people usually rely on cosmological simulations.
- And even if we knew them, we still don't know UHECRs' electric charges.





← Various models of:

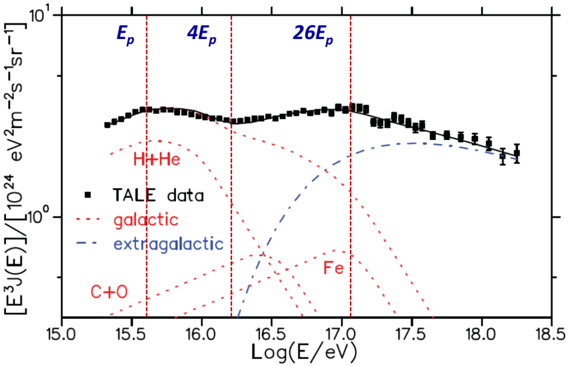
Left: IGMF filling factors (Alves Batista et al. 2019)

Right: GMF deflections (Unger & Farrar 2019)

Outline

Possible explanation of data below the ankle

e.g. T. Abu-Zayyad et al., arXiv:1803.07052

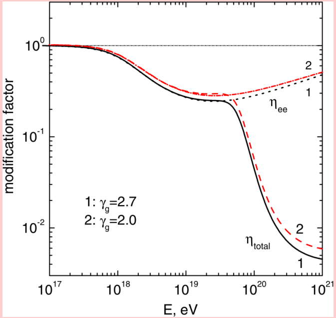


(Galactic CR mass composition extrapolated from satellite-based direct measurements at lower energies)

- Knee due to cutoff in Galactic H spectrum (due to maximum acceleration energy and/or reduced magnetic confinement)
- Spectra of other elements have similar features at the same rigidity (i.e. at Z times as much energy)
- Low-energy ankle due to Li/Be/B scarcity
- Second knee due to Fe cutoff
- Gradual transition between heavy Gal. and light extragal. population somewhere around 10^{17} eV
  - → lighter composition at higher energies, as in lowest-E Auger X_{max} data

Possible explanations of data around the ankle — I

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



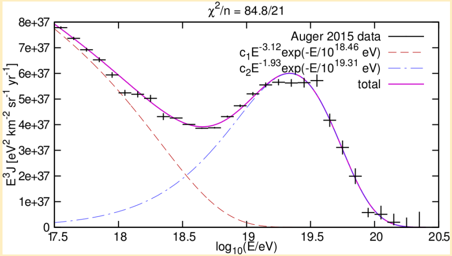
e.g. R. Aloisio et al., *Astropart. Phys.* **27** (2007) 76 [astro-ph/0608219]

☹ Only works with pure H — even just 20% He would spoil it (and the Auger $X_{\max}$–S_{1000} correlation around the ankle robustly excludes any pure compositions)

$$\frac{\mathrm{d}N_{\mathrm{Earth}}}{\mathrm{d}E} \propto \eta \frac{\mathrm{d}N_{\mathrm{inj}}}{\mathrm{d}E} \qquad \left(\eta \sim \frac{\text{energy loss time}}{\text{age of the Universe}}\right)$$

Possible explanations of data around the ankle — II

Transition between two populations



(Note: linear y-axis)

- The ankle is very sharp.
  - → The low-E population must have a steep cutoff **and** the high-E one a rather flat spectrum at Earth.
- Possible examples:
  - Galactic and extragalactic sources
    - Sizeable Galactic contribution at these energies now considered very unlikely for lots of reasons
  - Two types of extragal. sources (e.g. Aloisio+ ’14)
  - Secondary neutrons and surviving nuclei from photodisintegration by radiation fields surrounding accelerators (e.g. Globus+ ’15, Unger+ ’15)

Possible explanations of data above the ankle

Source rigidity cutoff $R_{\text{cut}} \gtrsim 60$ EV (also with pure protons):

- Highest-E nuclei (if any) quickly fully photodisintegrated
- Observed cutoff due to pion photoproduction (GZK cutoff[1])

a few EV $\lesssim R_{\text{cut}} \lesssim 60$ EV (medium-mass nuclei required):

- Cutoff in all-particle spectrum due to photodisintegration
- Cutoff in secondary protons at $ZR_{\text{cut}}/A \approx R_{\text{cut}}/2$

$R_{\text{cut}} \lesssim$ 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

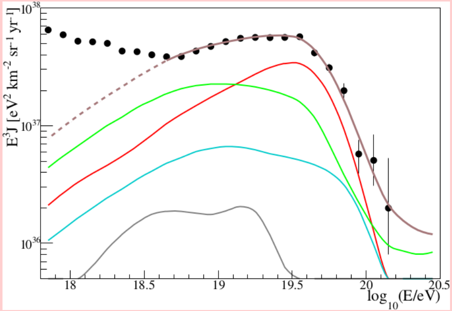
fewer neutrinos
fewer gamma rays
less anisotropy
↓ (“disappointing model”)

[1] The original papers (Greisen 1966, Zatsepin & Kuz’min 1966) mentioned both pion production and disintegration, but some authors only use “GZK cutoff” for the former and call the latter GR cutoff (Gerasimova & Rozental’ 1961, which actually only mentioned the EBL and not the then-unknown CMB)

Possible explanations of data above the ankle

- 1. $R_{\mathrm{cut}} \gtrsim 60$ EV (pion prod. cutoff)
- 2. a few EV $\lesssim R_{\mathrm{cut}} \lesssim 60$ EV (disintegration cutoff)
- 3. $R_{\mathrm{cut}} \lesssim$ a few EV (source cutoff)

Auger, *JCAP* **04** (2017) 038 [1612.07155]

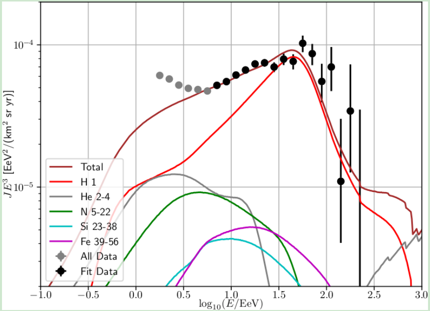


$10^{19.88}$ V, $\gamma = 2.04$

$10^{18.68}$ V, $\gamma = 0.96$

$\approx 10^{18.2}$ V, $\gamma < -1$

TA, PoS (ICRC2019) 190



1514 EV, $\gamma = 2.00$

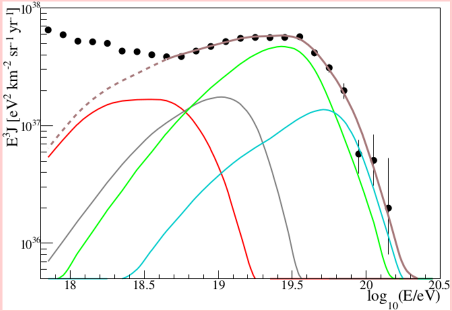
5.495 EV, $\gamma = 0.79$

2.239 EV, $\gamma = -1.50$

Possible explanations of data above the ankle

- 1. $R_{cut} \gtrsim 60$ EV (pion prod. cutoff)
- 2. a few EV $\lesssim R_{cut} \lesssim 60$ EV (disintegration cutoff)
- 3. $R_{cut} \lesssim$ a few EV (source cutoff)

Auger, *JCAP* **04** (2017) 038 [1612.07155]



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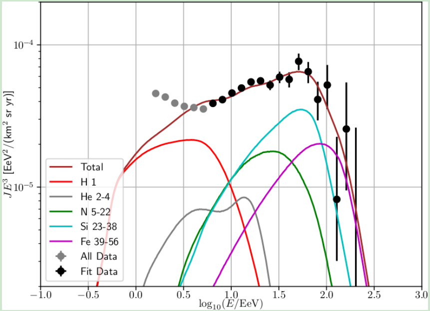
TA, PoS (ICRC2019) 190



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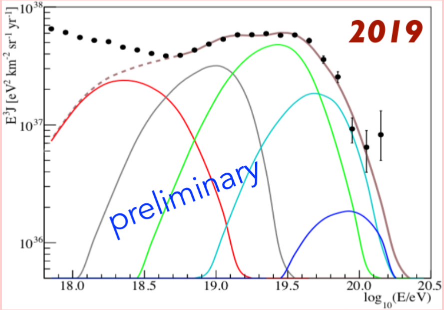
Auger, PoS (ICRC2019) 004



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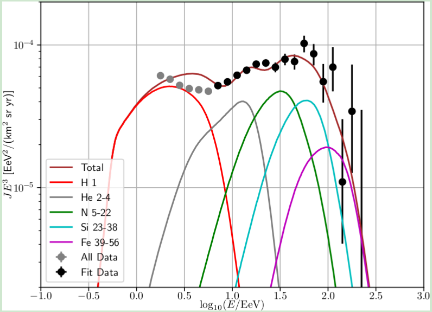
TA, PoS (ICRC2019) 190



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Possible explanations of data above the ankle

- 1. $R_{\mathrm{cut}} \gtrsim 60$ EV (pion prod. cutoff)
- 2. a few EV $\lesssim R_{\mathrm{cut}} \lesssim 60$ EV (disintegration cutoff)
- 3. $R_{\mathrm{cut}} \lesssim$ a few EV (source cutoff)

- 1. is disfavoured by the data (it predicts broader X_{max} distributions than observed), unless hadronic interactions in air shower development are modelled by QGSJet (in which case *all* source scenarios predict broader X_{max} distributions than observed), as well as by limits on neutrino fluxes, anisotropies, etc.
- On the other hand, 2. and especially 3. require much harder injection spectrum ($\gamma \approx 1$ and $\gamma \approx -1.5$ respectively) than most hypothesized acceleration mechanisms result in ($\gamma \approx 2$) (unless the source emissivity is $\propto (1+z)^m$ with $m \ll 0$, i.e. more and/or brighter recent than ancient sources, or there are very strong intergalactic magnetic fields) and extreme source metallicities.
- Very hard to tell 2. and 3. apart (generally, 3. is favoured when using bright EBL models, 2. when assuming dim ones, but it depends on even minor details of the propagation).

Outline

Lorentz invariance violations and UHECRs

- Both intergalactic UHECR propagation and extensive air shower development can be modified in certain Lorentz invariance-violating scenarios.
- For example, if dispersion relations are modified ($E_i^2 = m_i^2 + p_i^2 + \delta_i^{(1)} E_i^3 + \delta_i^{(2)} E_i^4 + \cdots$):
  - $\delta_{\text{hadrons}} > 0$ could suppress pion production in propagation.
  - $\delta_\gamma < 0$ could suppress UHE photon absorption by CMB photons.
  - $\delta_\pi < 0$ could suppress pion decay in air showers.
- UHECRs already set stringent limits on certain LIV scenarios, such as
  - Non-birefringent modified Maxwell theory (vacuum Cherenkov $\rightarrow$ very fast energy losses)

(See talk by Nick Mavromatos tomorrow)

Hadron LIV in extragalactic cosmic ray propagation

Auger, PoS (ICRC2019) 327 and references therein

- If $\delta_p = \delta_\pi = \delta_{\rm had} > 0$, mean free paths of photonuclear interactions increase.
- (If $\delta_{\rm had} \to +\infty$, they become outright impossible.)
- But reasonable fits to Auger data still possible → no limit on $\delta_{\rm had}$ from this

Scenario	γ	$\lg(R_{\rm cut}/V)$	$f_{\rm H}$	$f_{\rm He}$	$f_{\rm N}$	$f_{\rm Si}$	$D(J)$	$D(X_{\max})$	$D_{\rm total}$
LI, $\delta_{\rm had} = 0$	-1.13	18.25	70.1	29.5	0.4	0.02	19.9	236.6	256.5
LIV, $\delta_{\rm had}{}^{(0)} = 5\times10^{-24}$	-1.26	18.24	68.9	30.8	0.3	0.02	19.5	235.6	255.1
LIV, $\delta_{\rm had}{}^{(0)} = 1\times10^{-23}$	-1.20	18.25	67.4	32.2	0.4	0.02	19.9	236.1	256.0
LIV, $\delta_{\rm had}{}^{(0)} = 1\times10^{-22}$	-1.42	18.22	68.4	31.4	0.2	0.01	17.7	231.8	249.5
max LIV, $\delta_{\rm had} \to \infty$	0.91	18.47	52.3	42.3	5.4	0.	34.4	189.7	224.1

Table 1: Best fit parameters for the LI reference model and LIV cases (using *SimProp* simulations).

- (Better fits than LI, actually — but systematic uncertainties neglected here)

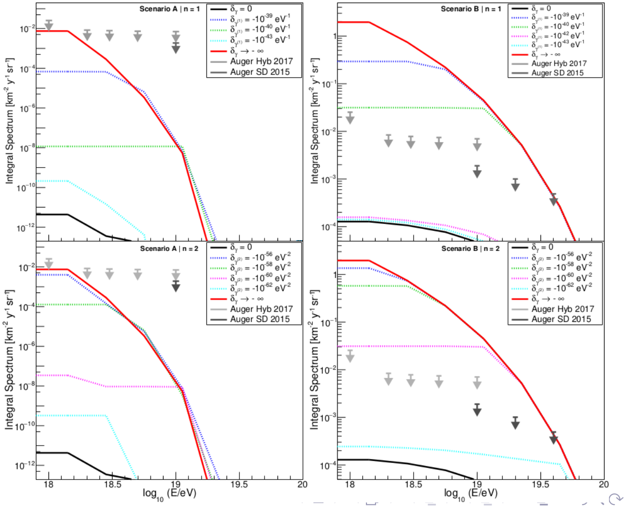
Photon LIV and propagation of secondary gamma rays

Auger, PoS (ICRC2019) 327 and references therein

- If $\delta_\gamma^{(1)}$ or $\delta_\gamma^{(2)} < 0$, the mean free path of $\gamma_{\mathrm{HE}} + \gamma_{\mathrm{bg}} \to e^+ + e^-$ increases

$\rightarrow$ we can see UHE photons even from far.

- But we don't $\rightarrow$ limits on $-\delta_\gamma$ …
- …but only in high-R_{cut} scenarios (right); in low-R_{cut} scenarios (left) not many γ_{HE} produced in the first place.



Outline

Pion LIV in air shower development

Auger, PoS (ICRC2019) 327 and references therein

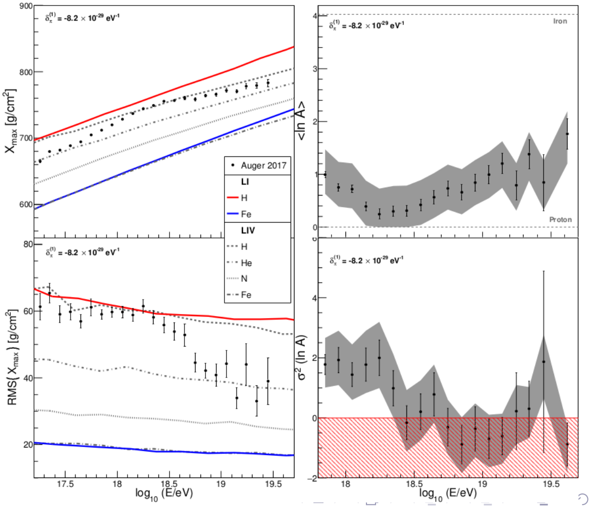
- If $\delta_\pi^{(1)} < 0$, then π^0 above a certain energy cannot decay

→ more hadronic, less electromagnetic showers

→ primaries look heavier than they actually are.

- This can be useful to constrain $\delta_\pi^{(1)}$ in the future.

Example: EPOS-LHC with $\delta_\pi^{(1)} = 0$ (solid) and $-1/M_{\mathrm{Planck}}$ (dotted)



Outline

Past mistakes

- In the AGASA days, when the UHECR spectrum seemed to smoothly extend to ~ 200 EeV, it was pointed out that LIV could enable UHECRs to evade the GZK cutoff.
- Afterwards HiRes, Auger, and TA did see a cutoff more or less where expected.
- Some people claimed that this sets a limit on LIV.
- But they assumed no maximum rigidity at sources and a cutoff due to pion production.
- We don't actually know there's no source cutoff; we expect one due to the Hillas criterion, and limits on $\sigma(X_{\text{max}})$, neutrinos, anisotropies, etc. suggest there indeed is one.
- If there is a source cutoff rigidity, there needn't be pion production for us to see a cutoff; we can find reasonable fits even with "infinite" LIV.

but. . .

Ideas for the future

Arrival directions

- Fits compatible with LIV do not use arrival directions.
- They don't assume much about sources, except that they are homogeneously distributed.
- But the local Universe isn't homogeneous.
- Statistically, the distribution of sources should match that of galaxies (at least for $z \ll 1$).

e.g.: The Local Sheet contains 14 major galaxies and over 100 minor ones;
the Virgo Cluster contains several times as many;
→ any kind of object common in the Local Sheet is **very** unlikely to be absent in the Virgo Cluster, and if we find any significant differences, we can assume them to be due to propagation effects.

But beware of magnetic deflections! (High-E large-scale anisotropies should be fine.)

New shower observables

Thanks to Cherenkov + scintillator + radio detectors on each SD station, AugerPrime will have both $X_{\max}$ and N_μ estimates for all events → more statistical power to simultaneously constrain both hadronic interaction models (whether LI or LIV) and the mass composition.

Thanks for your attention!