UHE cosmic rays: knowns, unknowns, and possible “new physics”

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10th International Workshop on Air Shower Detection at High Altitudes
7–10 January 2020, Nanjing, China

Outline

Ultra-high-energy cosmic rays

Particles (mainly protons and other nuclei) from space with energies over $1\ \mathrm{EeV} = 10^{18}\ \mathrm{eV} \approx 0.16\ \mathrm{J}$

- Cosmic rays with energies over 100 EeV have been observed since the 1960s.
- When they reach Earth's atmosphere, interaction cascades → air showers over many km^2

- 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.
  - FD: fluorescence detectors
  - SD: surface detectors
- Radio emission from geomagnetic and Askaryan effects can be detected by radio antennas.

- Hadronic interactions in showers very uncertain (kinematic regimes hard to study at LHC):
  - Early interactions with $\sqrt{s} = \mathcal{O}(10^2\ \mathrm{TeV})$
  - Later interactions mainly initiated by pions
  - Medium-mass targets (N, O)
  - Very high pseudorapidity
- Shower-to-shower fluctuations further complicate analyses.

The Pierre Auger Observatory (Auger) 2004–

The largest CR detector array in the world

375 collaborators from 88 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:

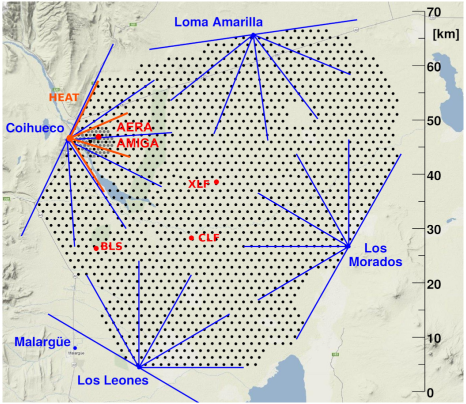
- **SD:** 1 600 water Cherenkov detectors on a 1.5 km-spacing triangular grid (3 000 km^2 total)
- **FD:** 4 sites on edge of SD array (24 telescopes total)

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: ±14%

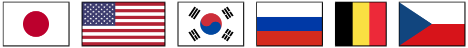


The Telescope Array (TA)

2008–

The largest CR detector array in the Northern Hemisphere

149 collaborators from 36 institutions in 6 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 taking data since 11 May 2008:

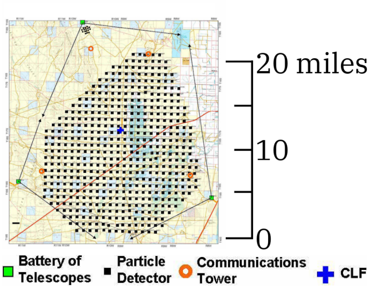
- **SD:** 507 plastic scintillator detectors on a 1.2 km-spacing square grid (700 km^2 total)
- **FD:** 3 sites on edge of SD array (38 telescopes total)

Low-energy extension (TALE):

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

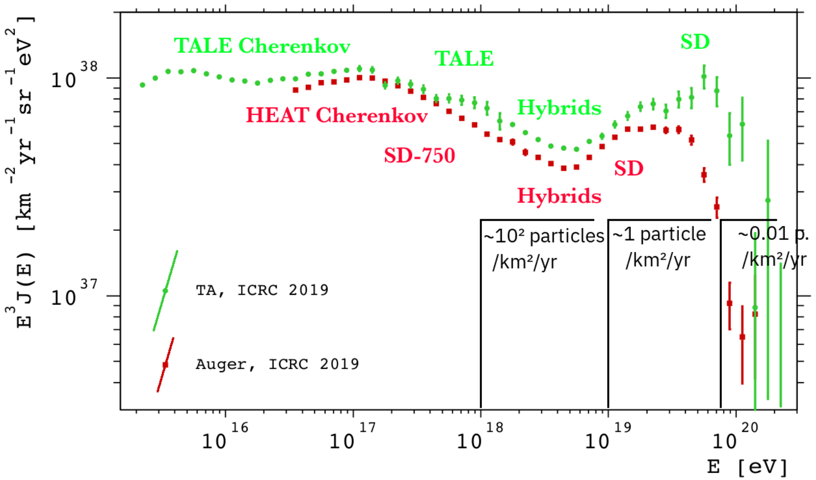
Aperture: $\theta_{\text{zenith}} < 55^\circ$ (declination $\delta > -15.7^\circ$)

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



Energy spectrum

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



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

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

Breaks (approx.):

	$\log_{10}(E/\mathrm{eV})$	γ
		2.7
knee	15.5	
		3.1
low-E ankle	16.2	
		2.9
2nd knee	17.0	
		3.3
ankle	18.7	
		2.7
cutoff	19.8	
		5.4

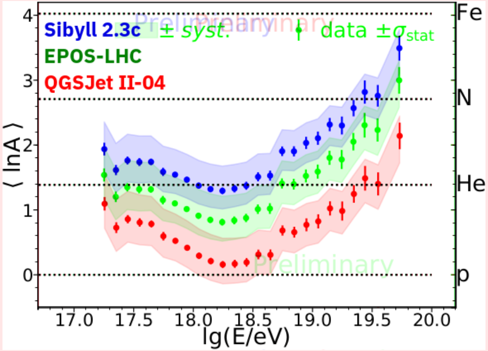
↖ Agree within systematics except at highest energies

Decent statistics thanks to huge exposures ($\sim 10^4$–10^5 km^2 sr yr)

Mass composition

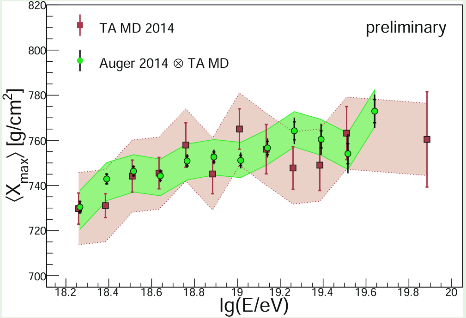
Auger, PoS (ICRC2019) 482 and refs therein

Auger data (interpreted according to hadronic models)



- Predominantly light at $E \sim 2$ EeV
- Heavier at lower and higher energies
- Huge model dependence and systematics

TA data (raw X_{max} measurements)

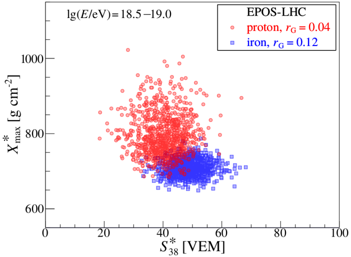


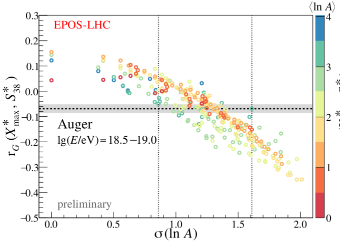
- $\langle X_{max} \rangle$ data agree with Auger, but larger statistical and systematic uncertainties → also compatible with 100% protons at all energies (if using QGSJet)

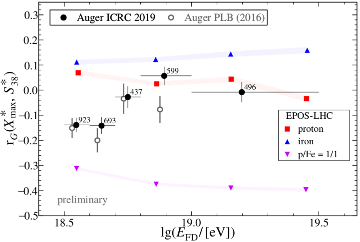
Pure or mixed?

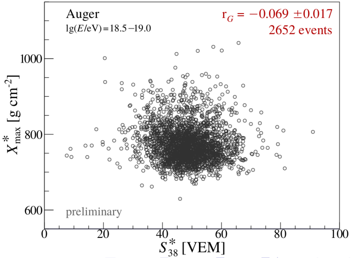
Auger, PoS (ICRC2019) 482 and refs therein

- Among showers initiated by a single element, S_{38}^* and $X_{\max}^*$ are uncorrelated or slightly positively correlated.
- For different elements, they are anticorrelated.
- Shifts or stretches in S_{38}^* or $X_{\max}^*$ distributions can't change this
  - → Analysis **insensitive to systematic errors** on data or models
- In Auger data, they are anticorrelated (6.4σ significance).
  - → **Mixed composition**, with both H/He and heavier stuff



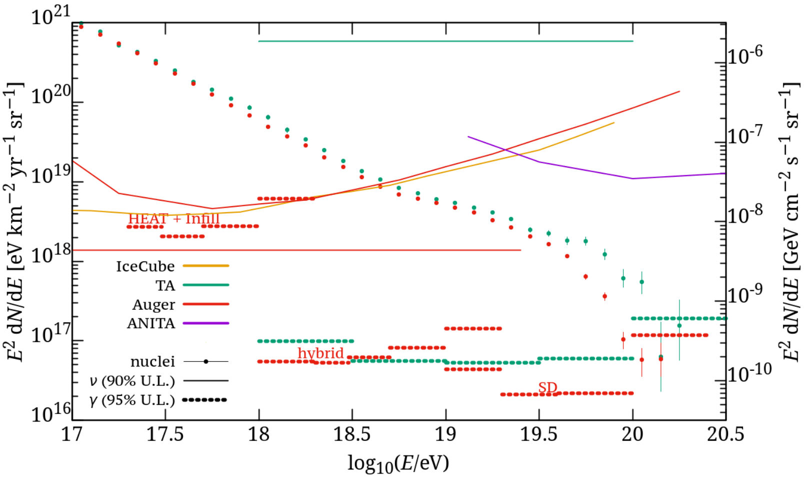






Limits on UHE neutrinos and gamma rays

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:

- $J_\nu \lesssim 0.1 J_{\text{nuclei}}$
- $J_\gamma \lesssim 10^{-3} J_{\text{nuclei}}$

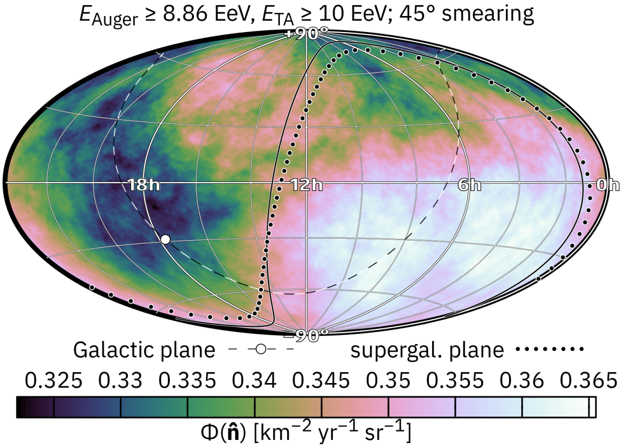
- This disfavours certain exotic scenarios.

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

Arrival directions at medium energies

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

Auger and TA energy thresholds cross-calibrated to each other using intersection of FoVs



Flux nearly isotropic, except for a dipole $\approx 5.5\left(\frac{E}{10\ \text{EeV}}\right)^{0.8}\%$

→ almost all extragalactic (and/or heavy)

At even lower energies: no detectable anisotropy

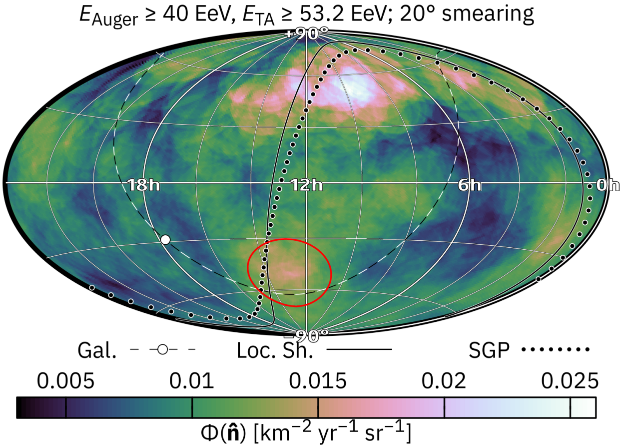
Magnetic deflections ∼ 10 EeV

protons	$\mathcal{O}(15\text{–}40°)$
CNO	$\mathcal{O}(100\text{–}300°)$
heavy nuclei	diffusive

Arrival directions at the highest energies

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

Auger and TA energy thresholds cross-calibrated to each other using intersection of FoVs



A few excesses in directions close to M81 Group (≈ 4 Mpc), Cen A/M83 Group (≈ 4 Mpc), but not e.g. Virgo (≈ 16 Mpc)

Energy loss lengths ∼ 50 EeV

p, Fe	$\mathcal{O}$(1000 Mpc)	(even less
CNO	$\mathcal{O}$(100 Mpc)	at higher E)
He	$\mathcal{O}$(10 Mpc)	

Magnetic deflections ∼ 50 EeV

protons	$\mathcal{O}$(3–10°)
CNO	$\mathcal{O}$(20–60°)
heavy nuclei	$\mathcal{O}$(80–200°)

Outline

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 → secondary neutrinos and gamma rays
- Deflections by intergalactic (IGMF) ☹☹ and Galactic (GMF) ☹ magnetic fields

Simulation codes

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

Our knowledge level:

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

UHECR source models

- Top-down mechanisms (exotic objects decaying directly into UHE particles) disfavoured, at least below 100 EeV (would produce lots of photons and neutrinos, few heavier nuclei)
- Bottom-up mechanisms: ordinary matter accelerated to UHEs in extreme environments (gamma-ray bursts? active galactic nuclei? tidal disruption events? starburst galaxies? ...?)
  Must have a maximum rigidity $R_{\text{cut}} \propto$ size × magnetic field strength (Hillas criterion)
  - If $R_{\text{cut}} \gtrsim 60$ EV (also with pure protons):
    - Highest-E nuclei (if any) quickly fully photodisintegrated
    - Observed cutoff due to pion photoproduction (GZK cutoff)
    - ☹ Disfavoured by the data assuming recent hadronic models
  - If 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 $ZR_{\text{cut}}/A \approx R_{\text{cut}}/2$
  - If $R_{\text{cut}} \lesssim$ 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")

Outline

1. Current UHECR experiments and their main results
2. UHECR theory
   - Source and propagation scenarios
   - Possible “new physics” effects
3. Future directions
   - Future UHECR experiments
   - COST Action CA18108 (QG-MM)
   - What else to look forward to

Modified dispersion relations and UHECRs

- Standard UHECR simulations assume Lorentz invariance as predicted by special relativity.
- Certain candidate theories of quantum gravity predict that this isn't exactly correct.
  - Lorentz invariance violation (LIV): Lorentz transformations stay the same, but background tensor fields pick a privileged frame.
  - Deformed special relativity (DSR): Still no privileged frame, but transformations between frames more complicated
- Effects can usually be described by modified dispersion relations (MDRs) ($i =$ particle type):

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

(standard dispersion relations: $\delta_i^{(n)} = 0$ for all n) (odd $n \to$ CPT violation)

- This can allow processes which in the laboratory frame would be kinematically forbidden, or vice versa. (Note: Earth velocity in CMB isotropy frame $\approx 0.013c$, i.e. mostly negligible)
- UHECR propagation and air shower development would be modified.

Examples

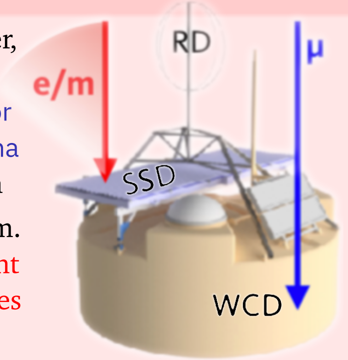
- Photon MDRs can allow vacuum Cherenkov radiation $N \to N + \gamma$ → quick energy losses
  - → Stringent limits from the fact that UHE nuclei still make it to Earth
- Hadron MDRs can prevent photodisintegration and pion photoproduction → no GZK
  - People used this to explain the lack of observed cutoff in AGASA measured spectrum (1998).
  - When more recent experiments did observe a cutoff (2006–), people used it to set limits on LIV, but they were assuming there was no R_{cut} at sources.
  - If there is a low R_{cut} at sources, spectrum data can be fitted with or without GZK.
  - What about the distribution of arrival directions? (We don’t know much about sources, but surely they should follow the large-scale distribution of galaxies?)
- Other photon MDRs can enable secondary EeV photons from pion production to reach us (otherwise they would undergo $\gamma_{\mathrm{UHE}} + \gamma_{\mathrm{bg}} \to e^+ + e^-$ into cascades with $\lesssim$ 1 TeV/photon)
  - → Limits from lack of observed EeV photons, but only with high or no R_{cut} at sources; with low source R_{cut}, not many EeV photons are produced in the first place.
- Pion MDRs can prevent π^0 decays → more hadronic, less electromagnetic showers
  - Experiments observe more muons than predicted — could this be (part of) the reason?

Outline

Extensions of Auger and TA currently being deployed

AugerPrime

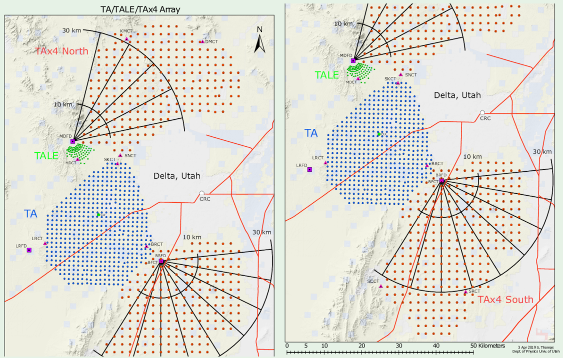
Extension of Auger, adding a plastic scintillator detector and a radio antenna to each SD station



- $e^\pm/\mu^\pm$ 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



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 ~ 100 000 km^2, POEMMA ~ 300 000 km^2)

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What is a COST Action

More info: https://www.cost.eu/cost-actions/what-are-cost-actions/

COST: a European organization funding COST Actions

- 38 Full Member countries, including ↘
  22 Inclusiveness Target Countries (ITCs) ↘
- 1 Cooperating Member country (Israel) ↘
- 1 Partner Member country (South Africa) (not shown)
- 16 Near Neighbour Countries* in North Africa and West Asia

COST Action: a four-year project to enable researchers from different communities to learn about each other's work and cooperate on a goal, by funding:

- Workshops, conferences and working group meetings
- Training Schools
- Short Term Scientific Missions
- Conference Grants for young† researchers from ITCs
- Public lectures and other outreach activities

*technically not members of the COST Association

†≤ PhD + 8 yr

COST Action CA18108

Quantum gravity phenomenology in the multi-messenger approach <https://qg-mm.unizar.es/>

*Main aim: to investigate **possible signatures** predicted by **quantum gravity models** in the **observation of different cosmic messengers**, by creating the conditions for a **close collaboration** between **theorists** and the **various experimental communities** involved in the detection of such cosmic messengers.*

Start date: 14 Mar 2019 End date: 13 Mar 2023

Keywords

- Lorentz invariance violation and deformation
- gamma-ray astronomy
- cosmic neutrinos
- UHE cosmic rays
- gravitational waves

241 members *Near Neighbour Country

- 225 in COST countries
  - 54 in Spain
  - 24 in Italy
- 16 in non-COST countries
  - 3 in Armenia*
  - 3 in the US
  - 2 in Canada
  - 2 in Chile
  - 2 in Russia*
  - 1 in China

Action chair

- José Manuel Carmona (U. of Zaragoza, Spain)

Action vice-chair

- Giovanni Amelino-Camelia (U. of Naples, It.)

Working groups leaders and vice-leaders

WG1 ⟷ WG2 ⟷ [WG3 ⟷ WG4 ⟷ WG5 ⟷ WG6]

The same person can be in several WGs at once.

Theory

Working Group 1: **Theoretical frameworks for QG effects below Planck energy** (110 m.)

- L Christian Pfeiffer (University of Tartu, Estonia)
- V Giulia Gubitosi (University of Burgos, Spain)

Working Group 2: **Phenomenology of quantum gravity** (106 members)

- L Flavio Mercati (University of Naples, Italy)
- V Stefano Liberati (SISSA, Trieste, Italy)

Outreach Committee (22 members)

- L Mariam Tórtola (IFIC, Valencia, Spain)

Experiments

Working Group 3: **Gamma rays** (45 members)

- L Dijana Dominis Prester (U. of Rijeka, Croatia)
- V Julian Sitarek (University of Łódź, Poland)

Working Group 4: **Neutrinos** (54 members)

- L Rodrigo Gracia Ruiz (IPHC, Strasbourg, Fr.)
- V Carlos Pérez de los Heros (Upps. U., Swed.)

Working Group 5: **Cosmic rays** (36 members)

- L Armando di Matteo (INFN Torino, Turin, Italy)
- V Günter Sigl (University of Hamburg, Germany)

Working Group 6: **Gravitational waves** (84 m.)

- L Tanja Hinderer (U. of Amsterdam, Netherl.)
- V Germano Nardini (Univ. of Stavanger, Norway)

Who can join

People affiliated to institutions in:

- * COST Full Member countries not yet in the Action (Albania, Austria, Cyprus, Iceland, Latvia, Lithuania, Luxembourg, Moldova, Montenegro, North Macedonia, Slovakia, Turkey)
- † COST Full Member countries already in the Action (≈ rest of Europe)
- ‡ COST Cooperating Member country (Israel)
- § COST Partner Member country (South Africa)
- ¶ COST Near Neighbour Countries (≈ former USSR + North Africa + Middle East)
- ‖ International Partner Countries (everywhere else)

†,‡ can immediately join the Action (after approval by Action chair, vice-chair, or one WG leader).

*,§,¶,‖ need to be approved by the Action Management Committee first.

*,†,‡,¶ can be reimbursed for meetings and for Short-Term Scientific Missions (which anyone in the Action can host).

§,‖ must pay their own travel expenses (unless invited as a trainer to a Training School).

New members welcome, especially experts on:

- Theoretically modelling high-energy astrophysical sources (e.g. AGNs or GRBs), in order to disentangle intrinsic source properties from possible propagation effects
- Characterizing atmospheric properties (e.g. aerosols using LIDAR), in order to correct telescope measurements and reduce systematics

No previous experience in QG phenomenology needed — **skeptics welcome!**

Are you interested? (Or do you know someone who might be?)

Please fill the form at: `https://qg-mm.unizar.es/?page_id=140`

- Participation from under-represented groups particularly appreciated:
  - Women
  - Early Career Investigators (PhD students and researchers $<$ PhD $+$ 8 yr)
  - People working in Inclusiveness Target Countries ($\approx$ eastern Europe, Portugal, Malta)

Next meeting: Annual conference, 10–13 March 2020, Granada, Spain

Current milestone goal: To complete the first draft of a review of existing searches for QG effects in high-energy astrophysical observations (due by 30 April 2020)

Outline

Continued cooperation between Auger and TA will hopefully help us better understand the data and their systematics

New cross-section measurements with medium-mass targets, in the forward region . . .

Galactic magnetic fields The **In**terstellar **Mag**netic Field **In**ference **E**ngine (IMAGINE) will allow Bayesian combined studies of GMF and UHECR data.

- Parallax and polarization measurements of lots of stars in the Galaxy → first tomographic map of the GMF
- Knowledge of the GMF ⟶ source positions from arrival directions

New gamma-ray detectors e.g. CTA, LHAASO, . . . will provide high-resolution images of SBGs, AGNs, GRBs, . . . and help us understand them, constrain EBL models, and much more.

New neutrino detectors IceCube-Gen2, ARA, ARIANNA, KM3NeT, GRAND, POEMMA, . . . will either finally detect UHE neutrinos or further lower the limits, helping constrain the UHECR source evolution.

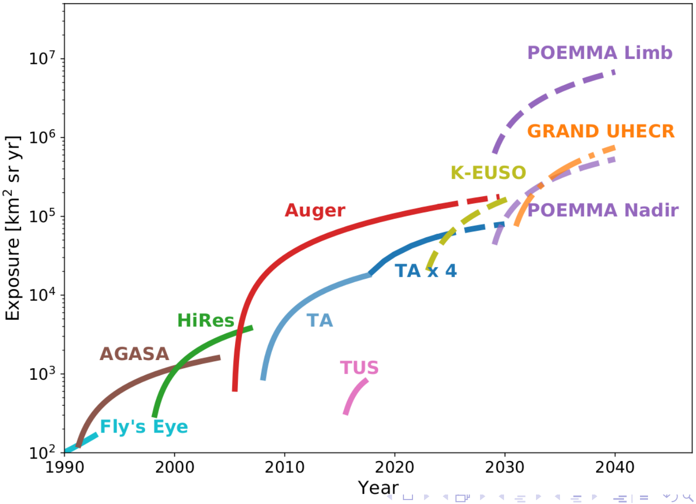
Stay tuned!

Back-up slides

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

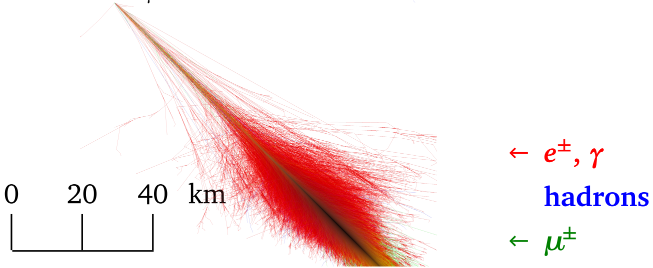


Extensive air showers

- Nuclei with $\Gamma \gtrsim 10^9$ ($E \gtrsim A$ EeV) impacting the atmosphere $\to \sqrt{s} \gtrsim 40$ TeV $\approx 3 \times$ LHC
- Resulting high-energy hadrons can interact in turn, and so on $\to$ extensive air showers
  - $\pi^0 \to 2\gamma \to$ 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): $\to \mu^+ + \nu_\mu$, which dump their energy in the ground

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

(Schmidt & Knapp 2005)

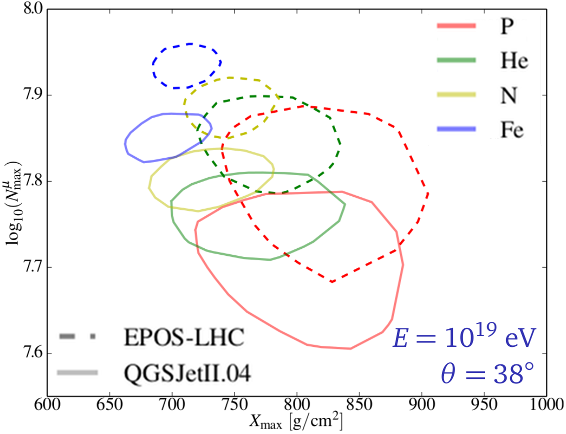


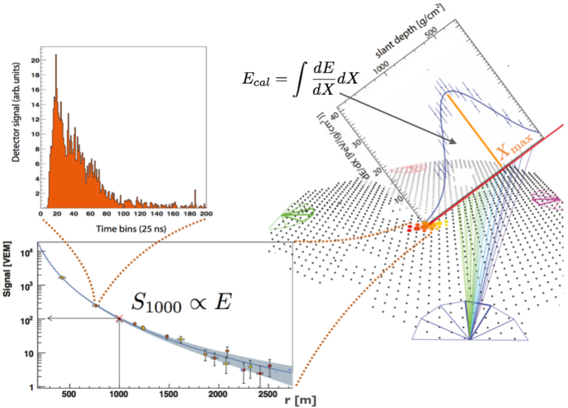
Shower properties

Zenith angle	θ, 0° for vertical showers, 90° for horizontal showers
Atmospheric depth	$X = \int_{+\infty}^{h} \rho_{\text{air}}(z)\,\mathrm{d}l$ where $\mathrm{d}l = -\mathrm{d}z/\cos\theta$ (vertically: 1033 g/cm^2 at sea level, 875 g/cm^2 at 1 400 m a.s.l.)
Depth at first interaction	X_0
Shower profile	$\mathrm{d}E/\mathrm{d}X$, energy deposited per unit atmospheric depth
Depth at shower maximum	$X_{\max}$, the X at which $\mathrm{d}E/\mathrm{d}X$ is largest
Calorimetric energy	$E_{\text{cal}} = \int_0^{+\infty} \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X \approx 0.85E$, total energy deposited in atmosphere
Invisible energy	$E_{\text{inv}} = E - E_{\text{cal}} \sim 0.15E$, carried underground by ν and μ
Lateral distribution function	$S(r)$, particles reaching the ground per m^2 at distance r from axis
Muon number	N_μ, total number of muons produced in the shower

Air shower universality At $X \gg X_0$, all showers with the same E, θ, $X_{\max}$ and N_μ look alike.

- On avg., $X_{\max}$, $\log N_\mu$ linear in $\log(E/A)$
  → mass estimators (but major shower-to-shower fluct. and model depend.)





$X \lesssim X_{\max}$: mostly $e^\pm, \gamma$ $X \gg X_{\max}$: mostly $\mu^\pm$

☹ Mass composition difficult to estimate

← Predictions by hadronic interact. models extrapolated from LHC measurements

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/cm^2 syst., 20 g/cm^2 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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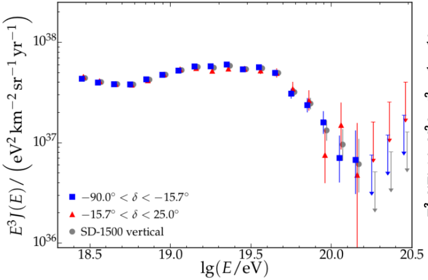
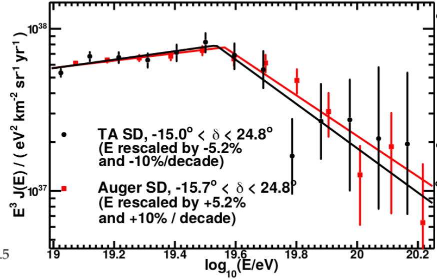
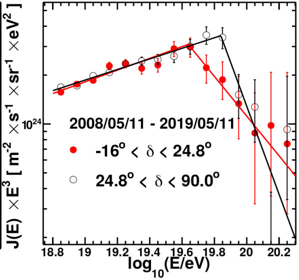
Auger–TA differences and declination dependence of spectrum

“south” = [–90°, –15°], “equat.” = (–15°, +25°), “north” = [+25°, +90°]







TA north

large diff. PoS (ICRC2019) 298

TA equat.

small diff. PoS (ICRC2019) 234

Auger equat.

no diff. PoS (ICRC2017) 486

Auger south

- Same spectra, to within a few percent

Auger–TA differences and declination dependence of spectrum

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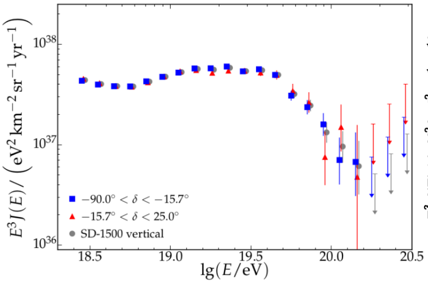

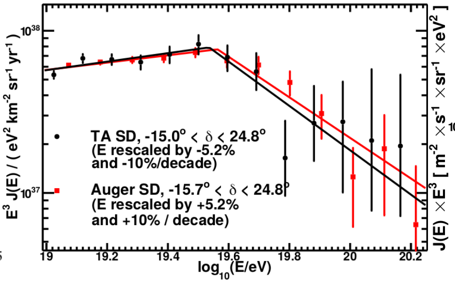

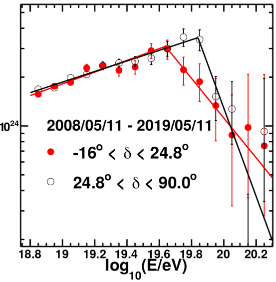

TA north
TA equat.
Auger equat.
Auger south

large diff. PoS (ICRC2019) 298
small diff. PoS (ICRC2019) 234
no diff. PoS (ICRC2017) 486

- Can be brought into agreement by e.g.

$$E = \left(1 \mp 5.2\% \mp 10\% \log_{10} \frac{E^{\mathrm{TA}}_{\mathrm{Auger}}}{10\ \mathrm{EeV}}\right) E^{\mathrm{TA}}_{\mathrm{Auger}}$$

- $0.4\sigma + 2.1\sigma$ discrepancy
  (syst. uncert.: $\pm 14\%, \pm 3\%/\mathrm{decade}$ (Auger), $\pm 21\%, \pm 9\%/\mathrm{decade}$ (TA))

Auger–TA differences and declination dependence of spectrum

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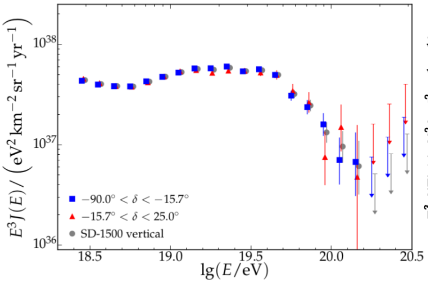
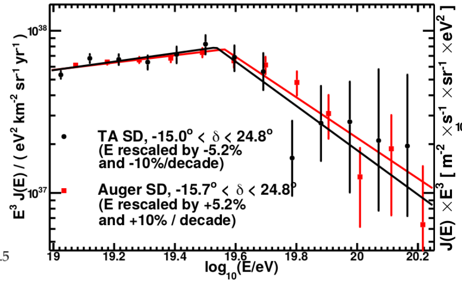
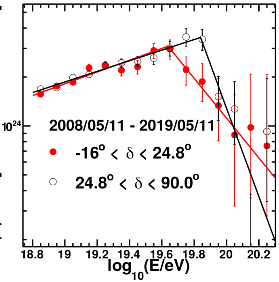






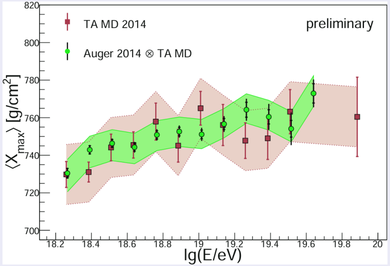
TA north	
TA equat.	large diff. PoS (ICRC2019) 298
Auger equat.	small diff. PoS (ICRC2019) 234
Auger south	no diff. PoS (ICRC2017) 486

- 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: 4.3σ

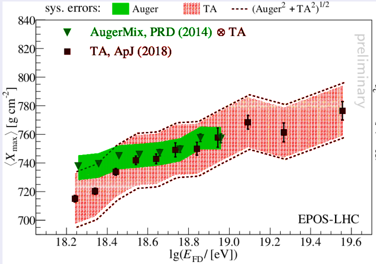
Auger vs TA mass composition

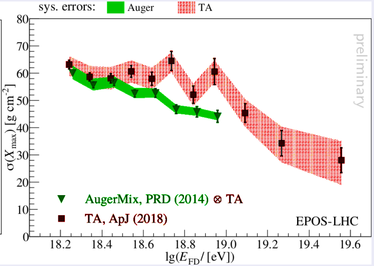
Auger and TA collabs., *EPJ Web Conf.* **210** (2019) 01009 [1905.06245] and references therein

Middle Drum*



Black Rock Mesa and Long Ridge†



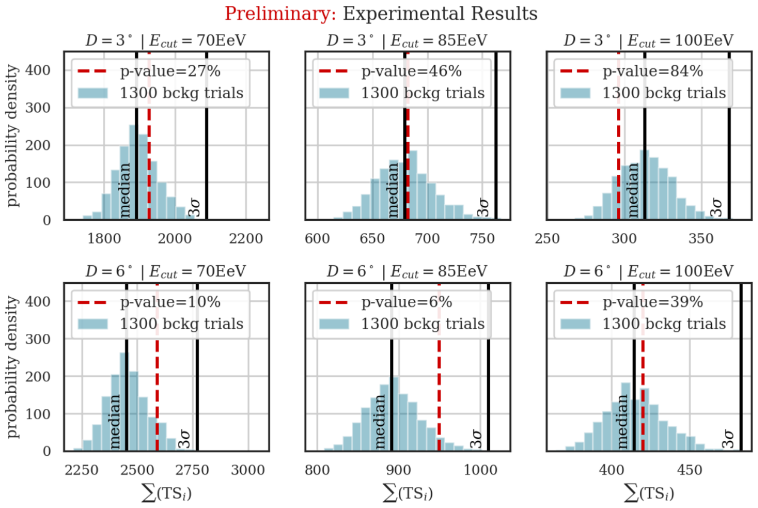


- Detector biases usually folded into simulations by TA, out of measurements by Auger
  - → Non-trivial comparisons (we had to fold TA biases into Auger measurements)
- **Data in agreement!** Claims of "protons in TA, heavier in Auger" due to different models

*FDs refurbished from HiRes-1 experiment (1997–2006) †FDs newly designed for TA

(Lack of) correlation with TeV–PeV neutrino events

IceCube + Auger + TA + ANTARES, PoS (ICRC2019) 842 and refs 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.

The air shower muon puzzle

Eight collaborations, PoS (ICRC2019) 214 and refs therein

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

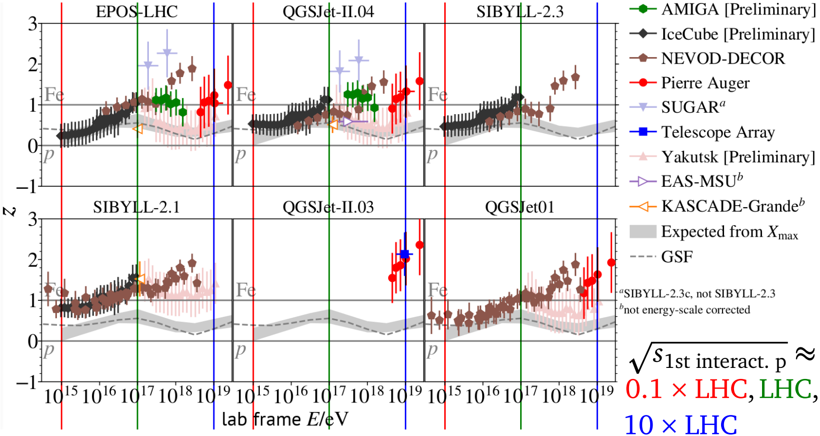
$z = \ln A / \ln 56$ if model accurate

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

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

Why?

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



$\sqrt{s_{\text{1st interact. p}}} \approx$ $0.1 \times$ LHC, LHC, $10 \times$ LHC

← Impossible to probe at LHC • Dedicated measurements ongoing

The local extragalactic environment

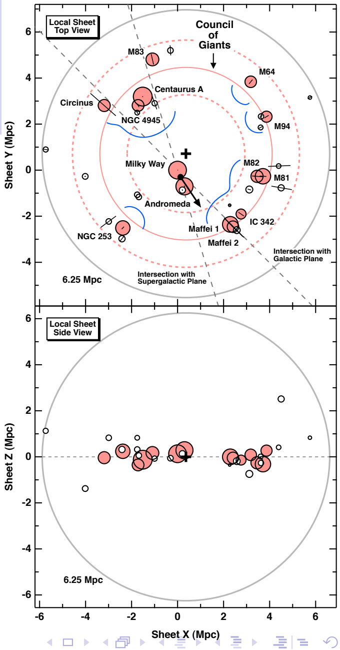
M.L. McCall, *MNRAS* **440** (2014) 405 [1403.3667]

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

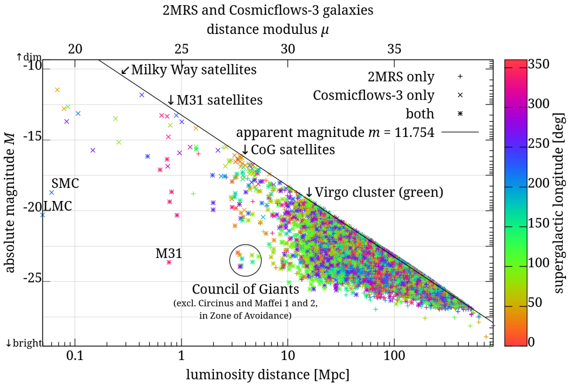


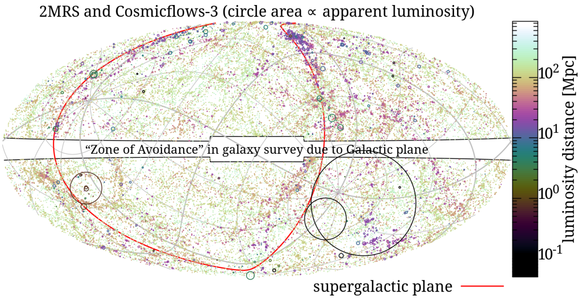
The Virgo Cluster

Major galaxy cluster ≈ 16 Mpc away

Large-scale structure of the Universe

Clusters, walls, filaments, voids

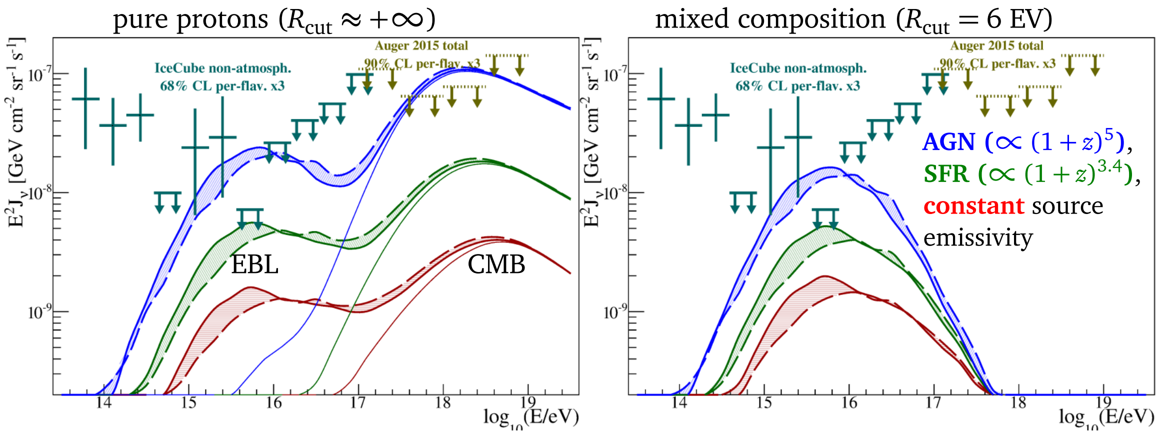




- Clusters within a few tens of Mpc preferentially aligned along the supergalactic plane
- Homogeneous and isotropic distribution at larger scales ("End of Greatness")

Secondary neutrinos

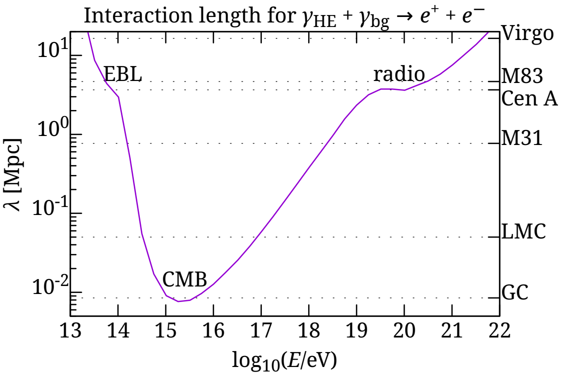
e.g. R. Aloisio et al., *JCAP* **10** (2015) 006 [1505.04020]



- 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 $\gamma_{\text{HE}} + \gamma_{\text{bg}} \to e^+ + e^-$ 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
  → only their total energy matters
- Can contribute to extragalactic gamma-ray background

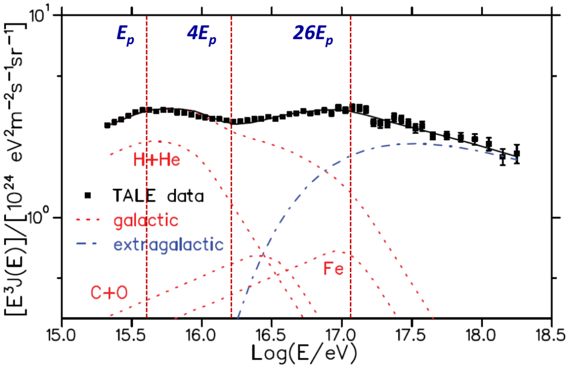


- In principle, we could use this to constrain UHECR source evolution or composition,

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.

Possible explanation of the data below the ankle

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

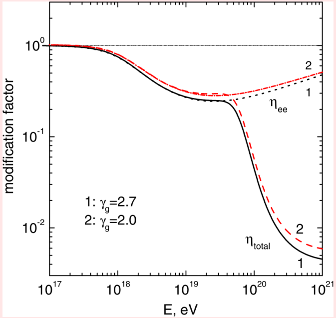


(Galactic CR mass composition extrapolated from satellite-based direct measurements at lower energies)

- 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 the data around the ankle — I

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



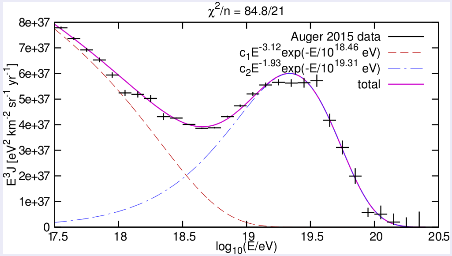
e.g. R. Aloisio et al., *Astropart. Phys.* **27** (2007) 76 [astro-ph/0608219]

☹ 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)

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

Possible explanations of the data around the ankle — II

Transition between two populations



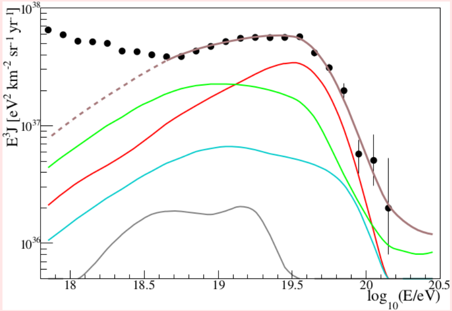
(Note: linear y-axis)

- 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 the 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]

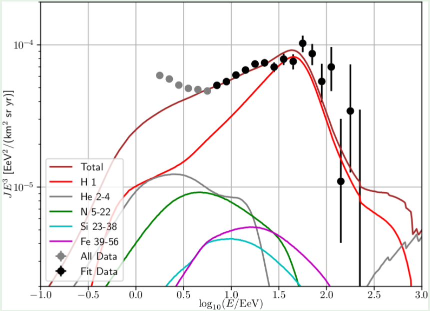


$10^{19.88}$ V, $\gamma = 2.04$

$10^{18.68}$ 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, $\gamma = -1.50$

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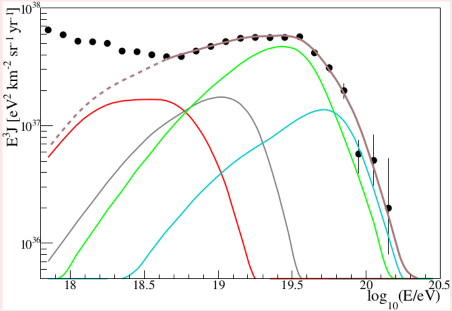

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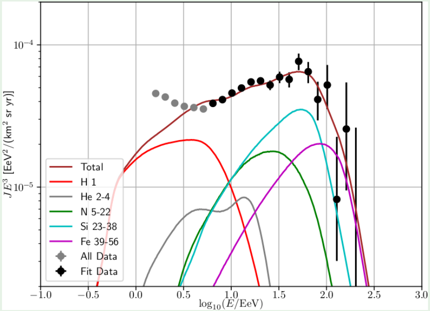

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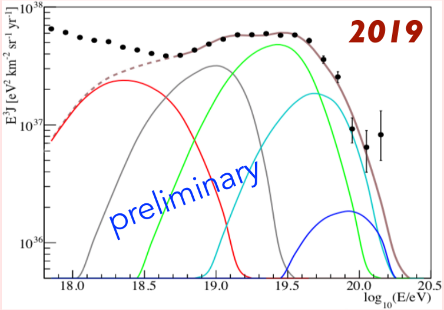
Auger, PoS (ICRC2019) 004



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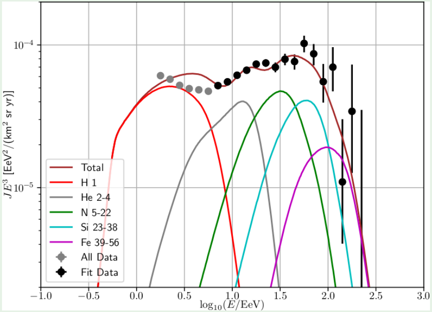
$\approx 10^{18.2}$ V, $\gamma < -1$

TA, PoS (ICRC2019) 190



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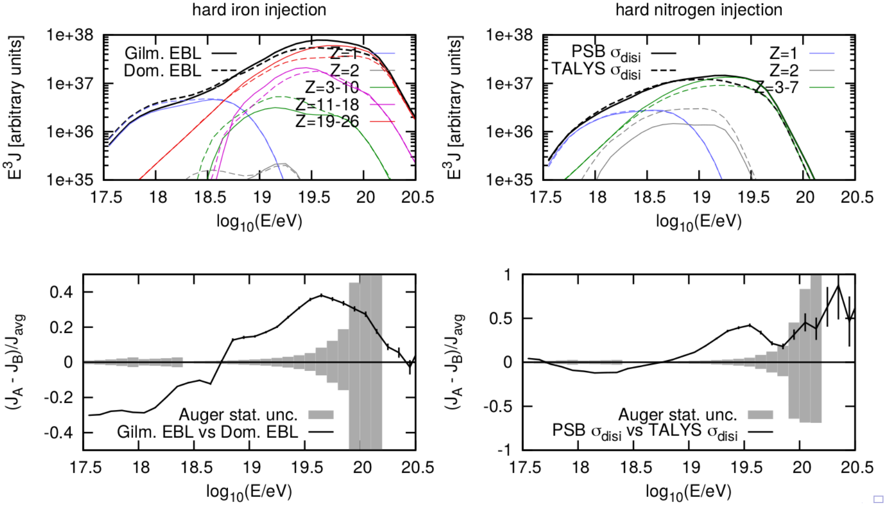
- 1. is disfavoured by the data (it predicts broader X_{max} distributions than observed), unless hadronic interactions in air shower development are modelled by QGSJet (in which case *all* source scenarios predict broader X_{max} distributions than observed), as well as by limits on neutrino fluxes, 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).

Effects of uncertainties

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



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

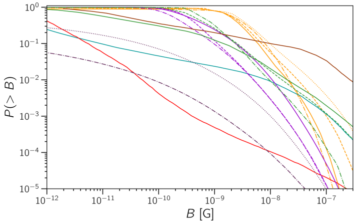
Magnetic deflections

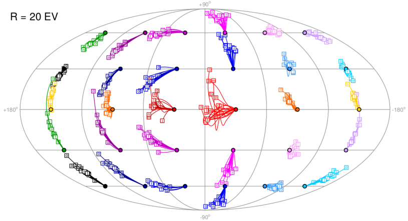
- Galactic magnetic fields very hard to estimate:
  - No 3D measurements available, only line-of-sight integrals:

    Faraday rotation 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 the electric charges of UHECRs.





← Various models of:

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

Right: GMF deflections (Unger & Farrar 2019)

Hadron LIV in extragalactic cosmic ray propagation

Auger, PoS (ICRC2019) 327 and references therein

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

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

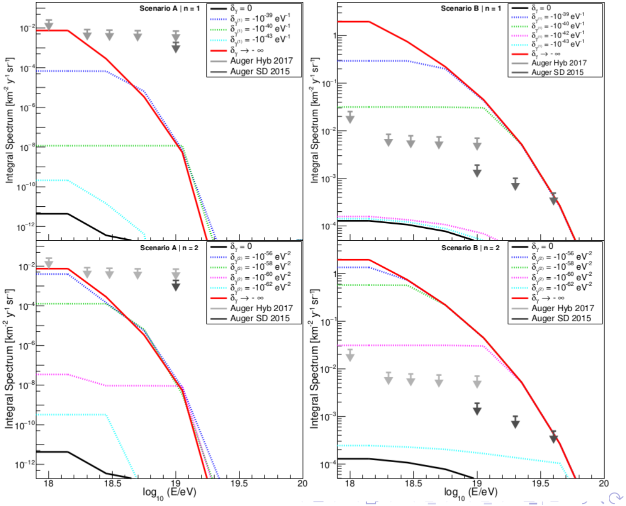
Photon LIV and propagation of secondary gamma rays

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

→ we can see UHE photons even from far.

- But we don't → 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.



Pion LIV in air shower development

Auger, PoS (ICRC2019) 327 and references therein

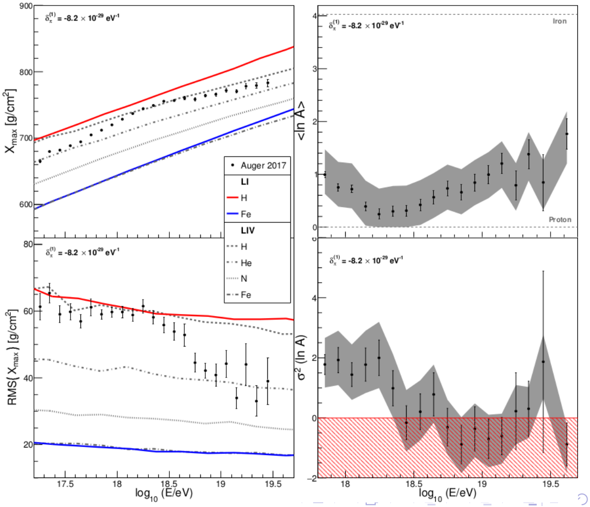
- If $\delta_\pi^{(1)} < 0$, then π^0 above a certain energy cannot decay

→ 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 $-1/M_{\text{Planck}}$ (dotted)



Committee for outreach and gender balance activities

- 19 members
- Science Communication Manager: Mariam Tórtola (IFIC, Valencia, Spain)
- Coming soon:
  - Outreach newsletter
  - YouTube channel

1st Action meeting (BCN, Oct 2019)

Public lectures

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