Fundamental physics with the Pierre Auger Observatory

Dedicated to the memory of Aurelio Grillo (1945–2017), from the L'Aquila Auger group

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Outline

1. Lorentz invariance violations
   - Constraints from intergalactic UHECR propagation
   - Constraints from air shower development
2. Searches for exotic particles
   - Superheavy dark matter
   - ANITA-like anomalous upward neutrinos
   - Magnetic monopoles

UHECRs and new physics

- Models of *nearly anything* about UHECRs must assume that standard physics applies in **regimes where it has not otherwise been tested**.

  e.g. interactions in centre-of-mass frames with **very large Lorentz factors** w.r.t. the lab frame ($\gtrsim 10^9$ in intergalactic propagation, $\gtrsim 10^6$ in air shower development)

  → even modest violations of Lorentz invariance might have **sizeable effects on UHECRs and EASs**.

- Other possible new physics we can probe using UHECR data includes exotic particles, for example super-heavy dark matter.
  - "Top-down" mechanisms **would produce lots of photons and/or neutrinos** in addition to nuclei.
  - Their air showers would be distinguishable from those of nuclei.

Modified dispersion relations

- Special relativity assumes **any process looks the same in any reference frame**, 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 (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**
- It can be shown (Carmona et al. *PRD* **86** (2012) 084032) the effects are those of modified dispersion relations (MDR),

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

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

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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.
  - Extensive review of possible quantum gravity effects in astroparticle physics (Addazi et al. *PrPNP* **125** (2022) 103948) and follow-up white paper (Alves Batista et al. *CQGra* **42** (2025) 032001)
    - Major contributions from members of the Torino and L'Aquila Auger groups
  - Publicly available database of experimental bounds on quantum gravity effects
    - One of the main contributors: Caterina Trimarelli, then a PhD student in the L'Aquila Auger group

- The first example I'm going to discuss: superluminal LIV of hadrons ($\delta^{(n)}_{\text{had}} > 0$) could avert GZK interactions (Auger collab. *JCAP* **01** (2022) 023).
  - The situation is not as simple as you might have heard ...

"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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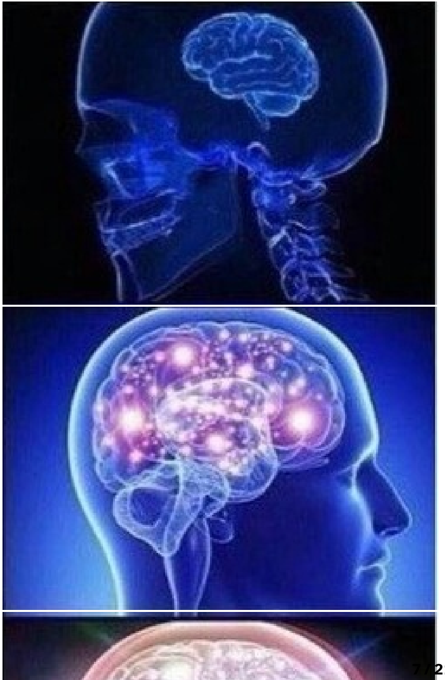

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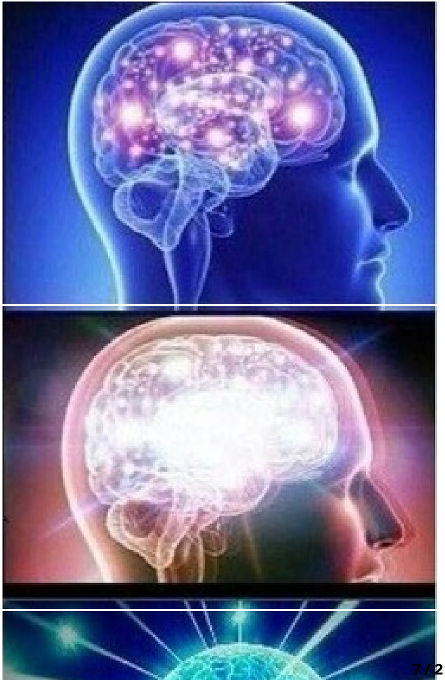

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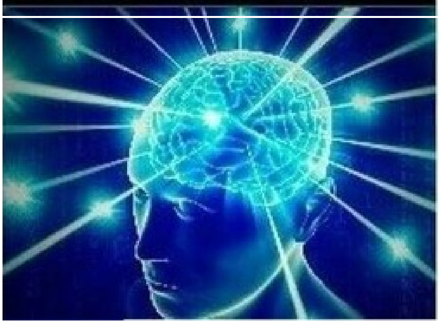

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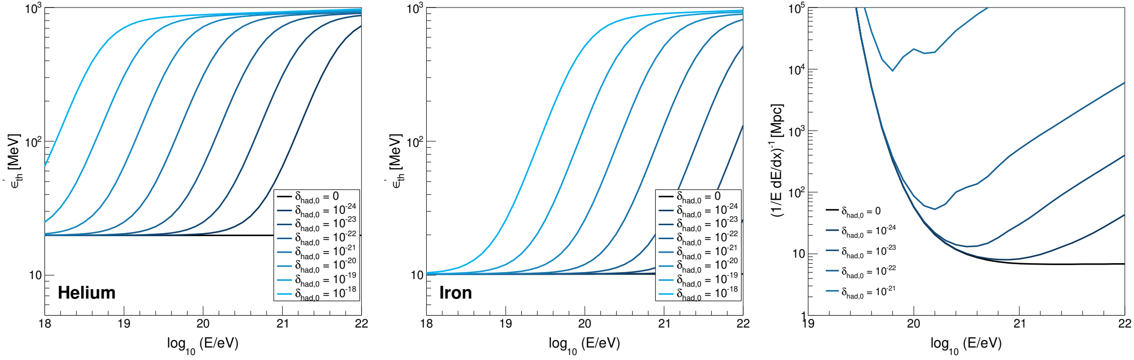
LIV in the hadronic sector

Apologies for the font sizes in the plots

- Superluminal LIV in the hadronic sector would increase the threshold for pion production, allowing nuclei to propagate much farther.
  - We're assuming the same LIV for all hadrons ($\delta_{\text{had}}^{(n)} = \delta_p^{(n)} = \frac{1}{2}\delta_\pi^{(n)} = A^n\delta_A^{(n)}$).



- We can still get an acceptable fit with $\delta_{\text{had}}^{(0)} = 10^{-20}$.
- On the other hand, we can exclude $\delta_{\text{had}}^{(0)} \geq 10^{-19}$, $\delta_{\text{had}}^{(1)} \geq 10^{-38}\ \text{eV}^{-1}$, $\delta_{\text{had}}^{(2)} \geq 10^{-57}\ \text{eV}^{-2}$ at the 5σ level.

Analysis by the São Paulo and L'Aquila Auger groups (Auger collab. *JCAP* **01** (2022) 023).

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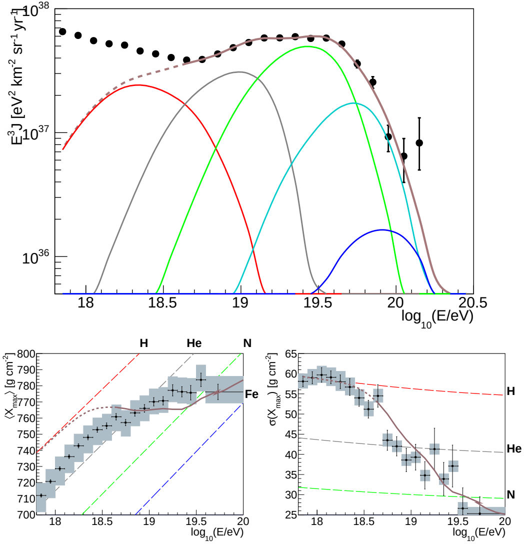

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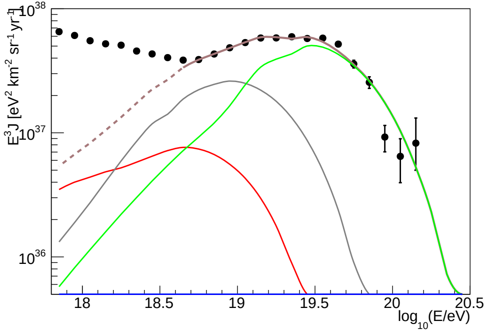
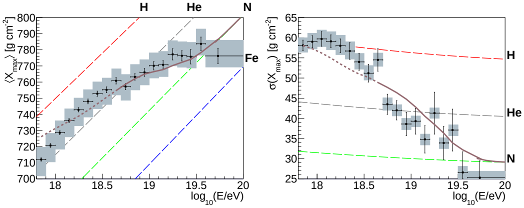
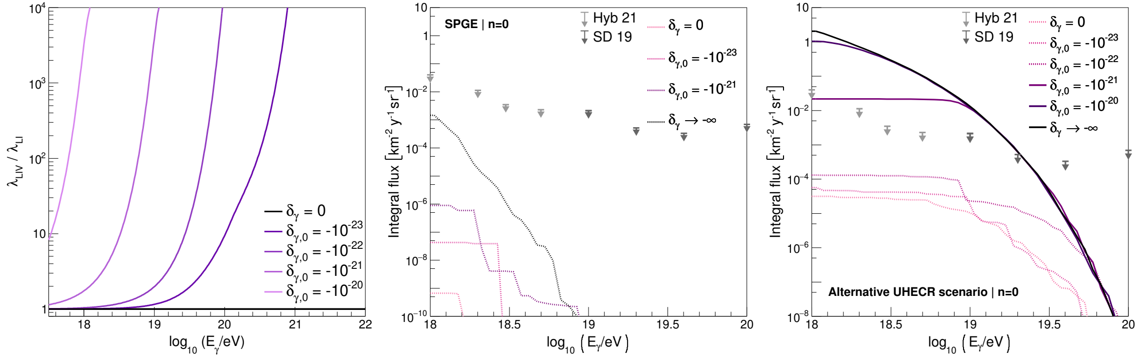




Analysis by the São Paulo and L'Aquila Auger groups (Auger collab. *JCAP* **01** (2022) 023).

LIV in the photon sector (ibid.)

- Subluminal LIV of photons ($\delta_\gamma^{(n)} < 0$) could prevent $\gamma_{\rm UHE} + \gamma_{\rm bg} \to e^+ + e^-$.
- In the best fit to the current Auger data, not many photons are produced in the first place (due to heavy UHECR composition).
- If there were a proton admixture, we'd be able to set limits on photon LIV.



Examples of other studies

Using Auger data, but not authored by the Auger collaboration

- L.A. Anchordoqui et al., "New test of Lorentz symmetry using ultrahigh-energy cosmic rays", *Phys. Rev. D* **97** (2018) 043010
- M.D.C.Torri et al., "Predictions of Ultra-High Energy Cosmic Ray Propagation in the Context of Homogeneously Modified Special Relativity", *Symm.* **12** (2020) 1961
- Z. Berezhiani, "Extreme energy cosmic rays: a quest for new physics?", talk at UHECR 2022
- L.A. Anchordoqui, "Dark dimension, the swampland, and the origin of cosmic rays beyond the Greisen-Zatsepin-Kuzmin barrier", *Phys. Rev. D* **106** (2022) 116022
- N.T. Noble et al., "Probing the dark dimension with Auger data", *Phys. Dark Univ.* **42** (2023) 101278

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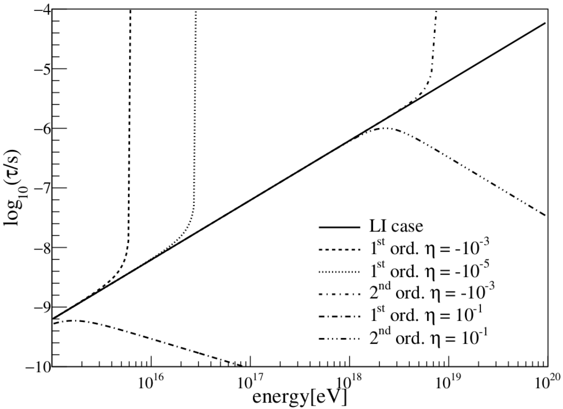
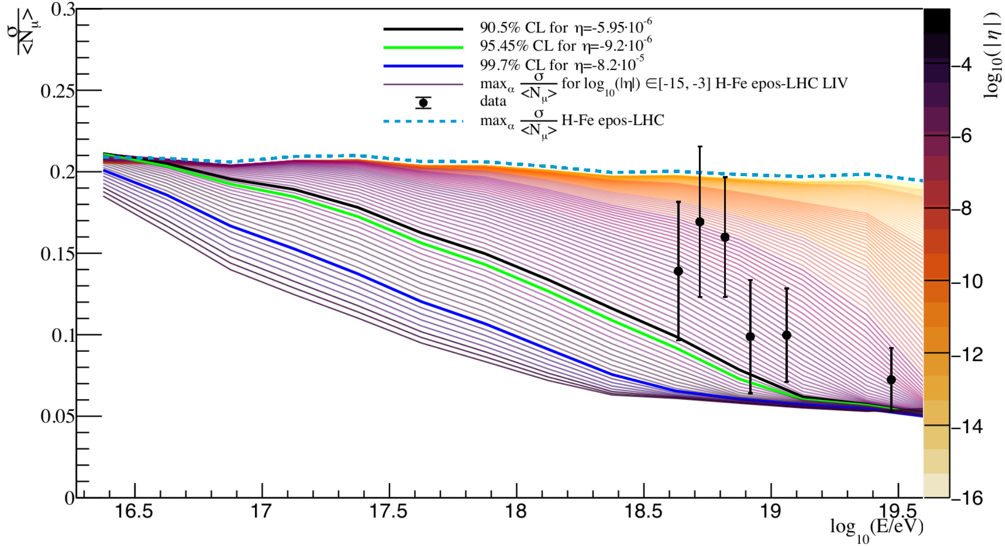
Neutral pion LIV in air showers

- Subluminal LIV of neutral pions would **delay or stop their decay**, allowing them to continue the hadronic cascade rather than starting electromagnetic subshowers.
- This would **decrease shower-to-shower fluctuations** in the number of muons.
  (It would also increase the average, but that's too model-dependent to be useful.)



Analysis by the L'Aquila Auger group (C. Trimarelli for the Auger collab. *PoS* **395** (ICRC2021) 340).

(Superluminal LIV would speed up their decay, but it's already much faster than all other relevant timescales in the LI case anyway.)

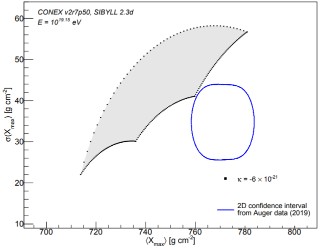


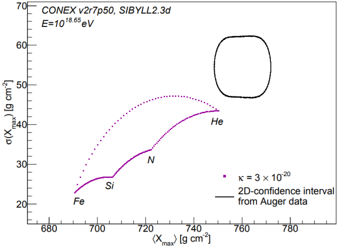
- We can use this to exclude $\eta_\pi^{(1)} < -6 \times 10^{-6}$ at the 90.5% CL (ibid.).
- Full-author-list collaboration paper in preparation by the L'Aquila Auger group

Limits on isotropic nonbirifrengent LIV in the photon sector

Using Auger data, but not authored by the full Auger collaboration

- Superluminal photon LIV would allow **photon decay** into electron–positron pairs → **shallower air showers** (Duenkel et al. *PRD* **104** (2021) 015010)
  - Using Auger X_{max} data, we can exclude $\kappa \leq -6 \times 10^{-21}$ at the 98% CL.
- Subluminal photon LIV would allow charged particles to emit **vacuum Cherenkov radiation** → **no nuclei above a certain energy** (near-instantaneous losses); **shallower air showers** (Duenkel et al. *PRD* **107** (2023) 083004)
  - Combining Auger energy and X_{max} data, we exclude $\kappa \geq 3 \times 10^{-20}$ at the 98% CL.





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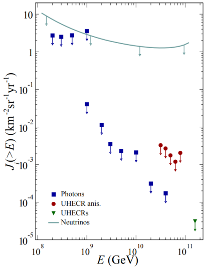
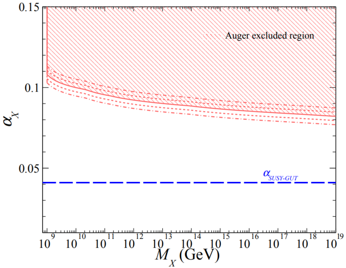
- Superheavy dark matter particles would be subject to instanton-induced decays.
- The decay products of SHDM particles in the Galactic halos — photons, (anti-)neutrons, (anti-)protons — could be detected in Auger data.
- Assuming the observed dark matter density is entirely due to SHDM, for each possible mass we can set limits on the reduced coupling constant.

(Auger collab. *PRL* **130** (2023) 061001) (Auger collab. *PRD* **107** (2023) 042002)





- In the case of SHDM coupled to sterile neutrinos, we can also set limits on their mixing angle with active neutrinos (Auger collab. *PRD* **109** (2024) L081101)

Major contribution from Roberto Aloisio from the L'Aquila Auger group

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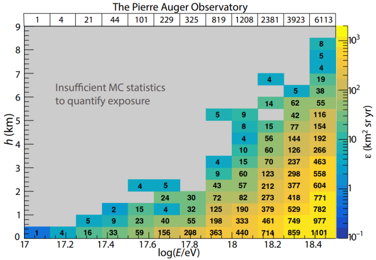
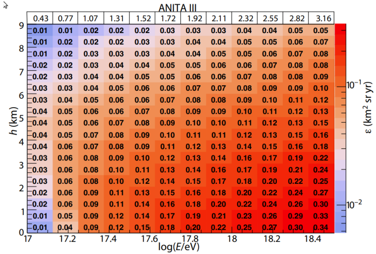
Search for upgoing events in Auger (Auger collab. [PRL **134** (2025) 121003])

- ANITA detected events looking like upward-going ν_τ-initiated air showers, at angles that should not be possible according to the Standard Model.
- Auger FD data were searched for similar showers.
- After filtering misreconstructed downgoing showers and calibration laser shots out, one event survived (**compatible with the expected background**).
- This fact and the exposure (computed via MC) were used to set limits to upgoing τ leptons.

Major contributions from the Lecce and L'Aquila Auger groups





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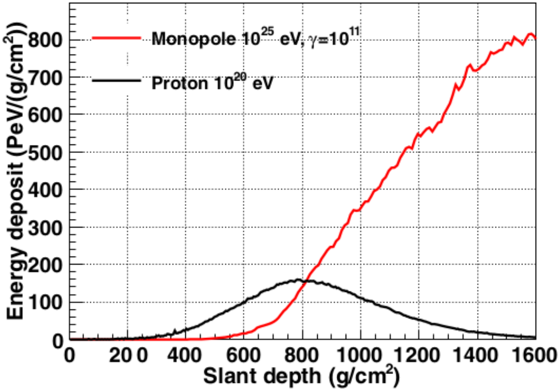
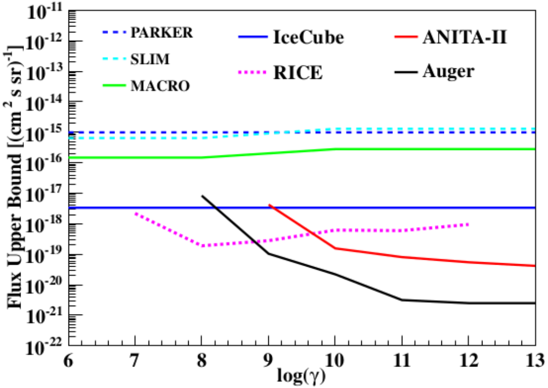
Search for ultrarelativistic magnetic monopoles

(Auger collab. *PRD* **94** (2016) 082002)

- Ultrarelativistic monopoles would produce very bright, very deep air showers.
- No such showers were found in Auger data.
- This was used to set limits on the flux of magnetic monopoles.






That's all Folks!