2.5 Ultra-High-Energy (UHE) Cosmic rays

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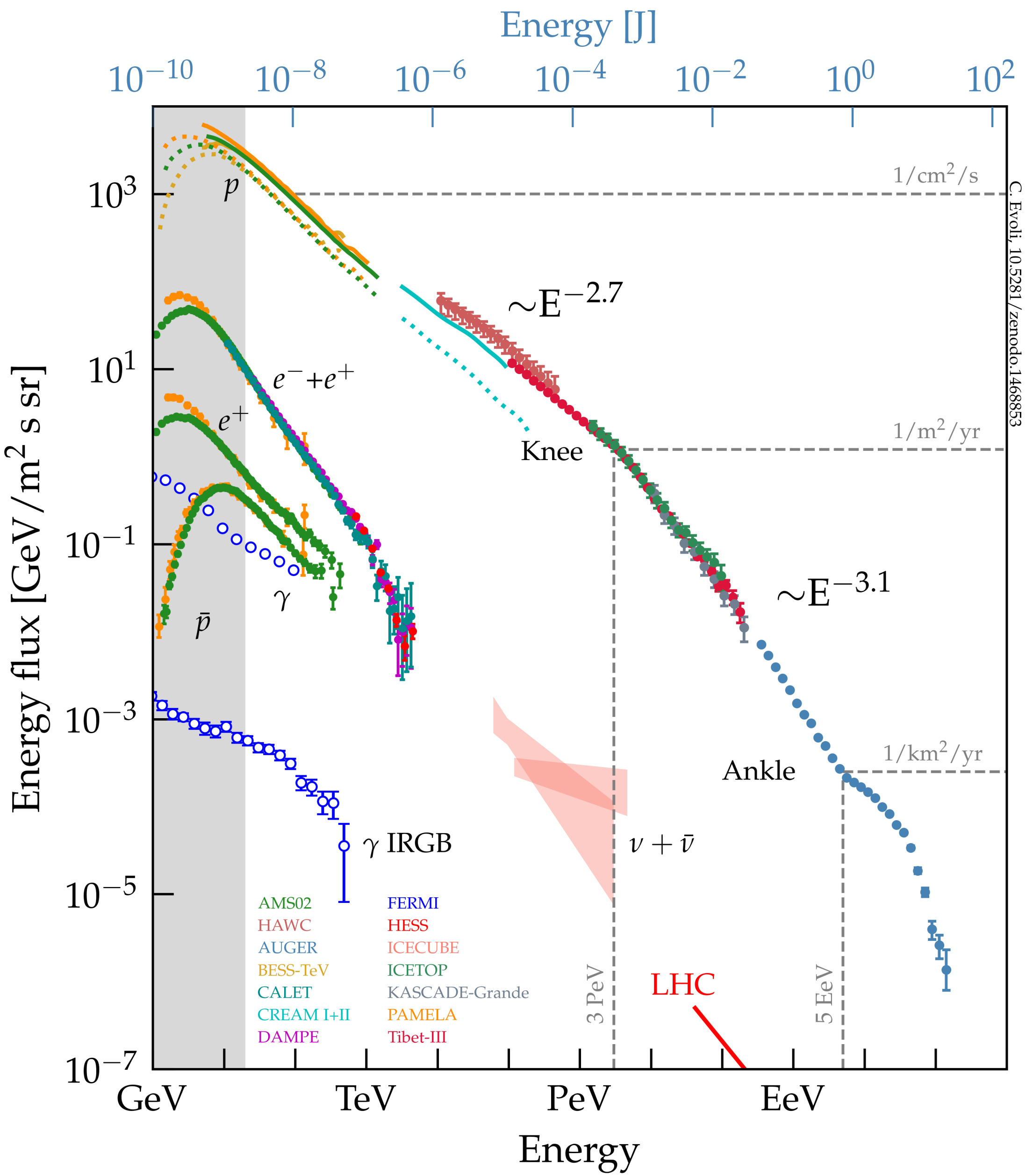
UHECR

- Source
- Direction
- Composition
- Energy features

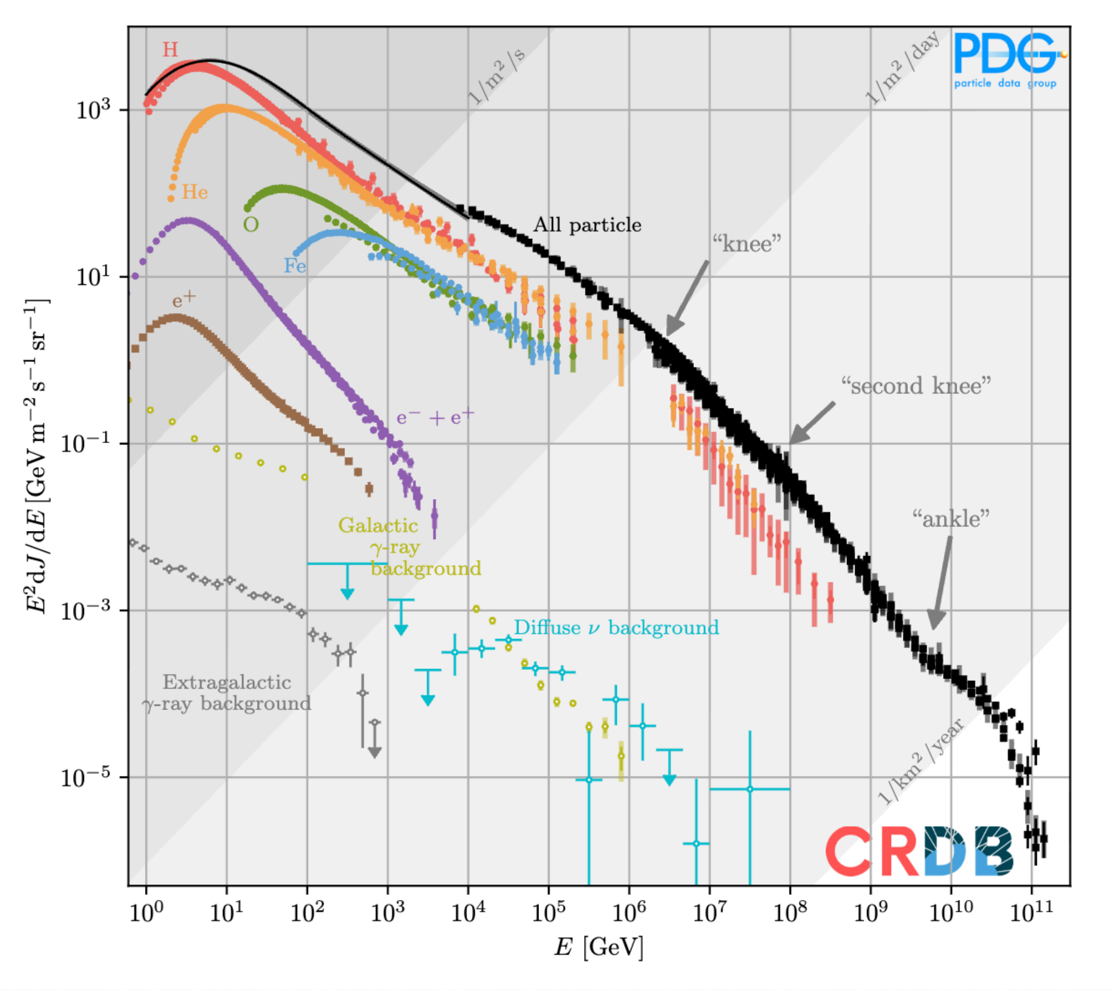
Cosmic rays so far

- We have discussed lots of cosmic ray physics below roughly 1 PeV.
- Now let's discuss cosmic rays above the "Knee" energy



Galaxy Confinement

- Lamor radius
- $r_g \simeq 3.3\text{m}\left(\frac{E}{\text{GeV}}\right)\left(\frac{e}{|q|}\right)\left(\frac{1\,\text{T}}{B}\right)$
- For R ~ 10kpc and B ~ 3 μG
- $E \sim \; 3 \times 10^{10} GeV$ for **Protons**
- We have observed cosmic rays beyond 10^{11} GeV
- This implies that if the source of 10^{11} GeV CRs are galactic, we should see them.
    - The actual "confinement" energy is even lower, as the fields are more turbulent than coherent.



Direction Information

Arrival Directions of Cosmic Rays above 32 EeV from Phase One of the Pierre Auger Observatory

The Pierre Auger Collaboration

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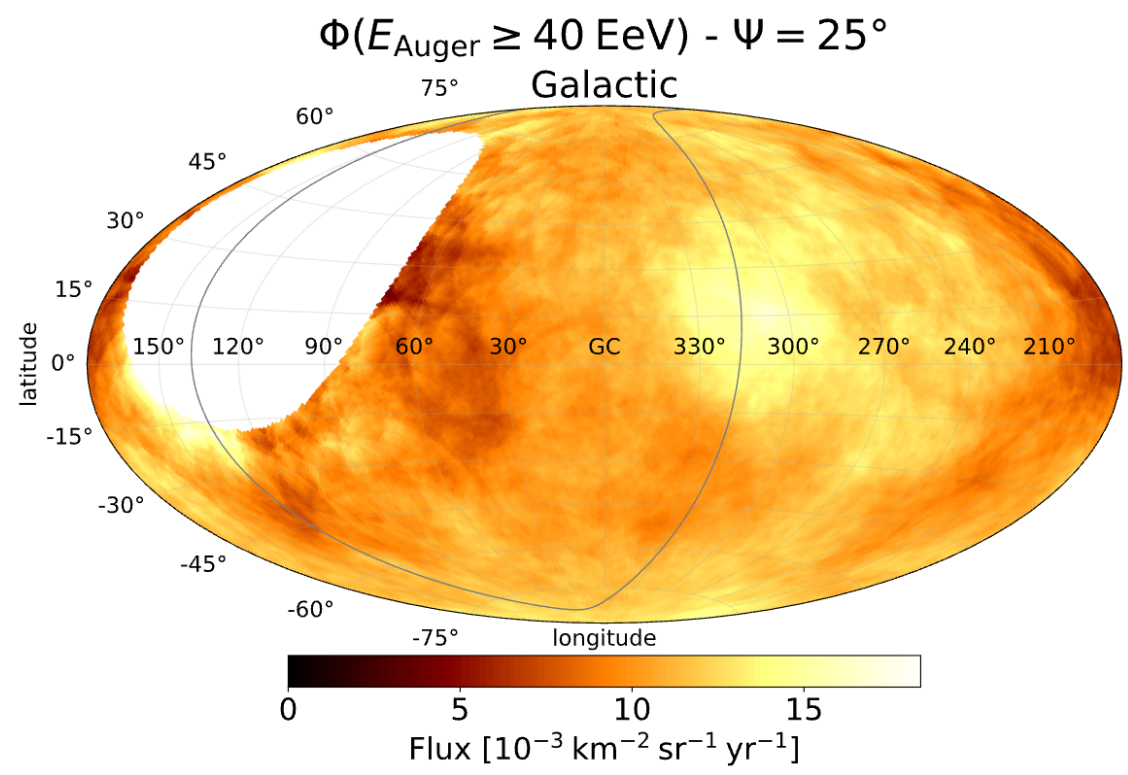
Submitted to ApJ

ABSTRACT

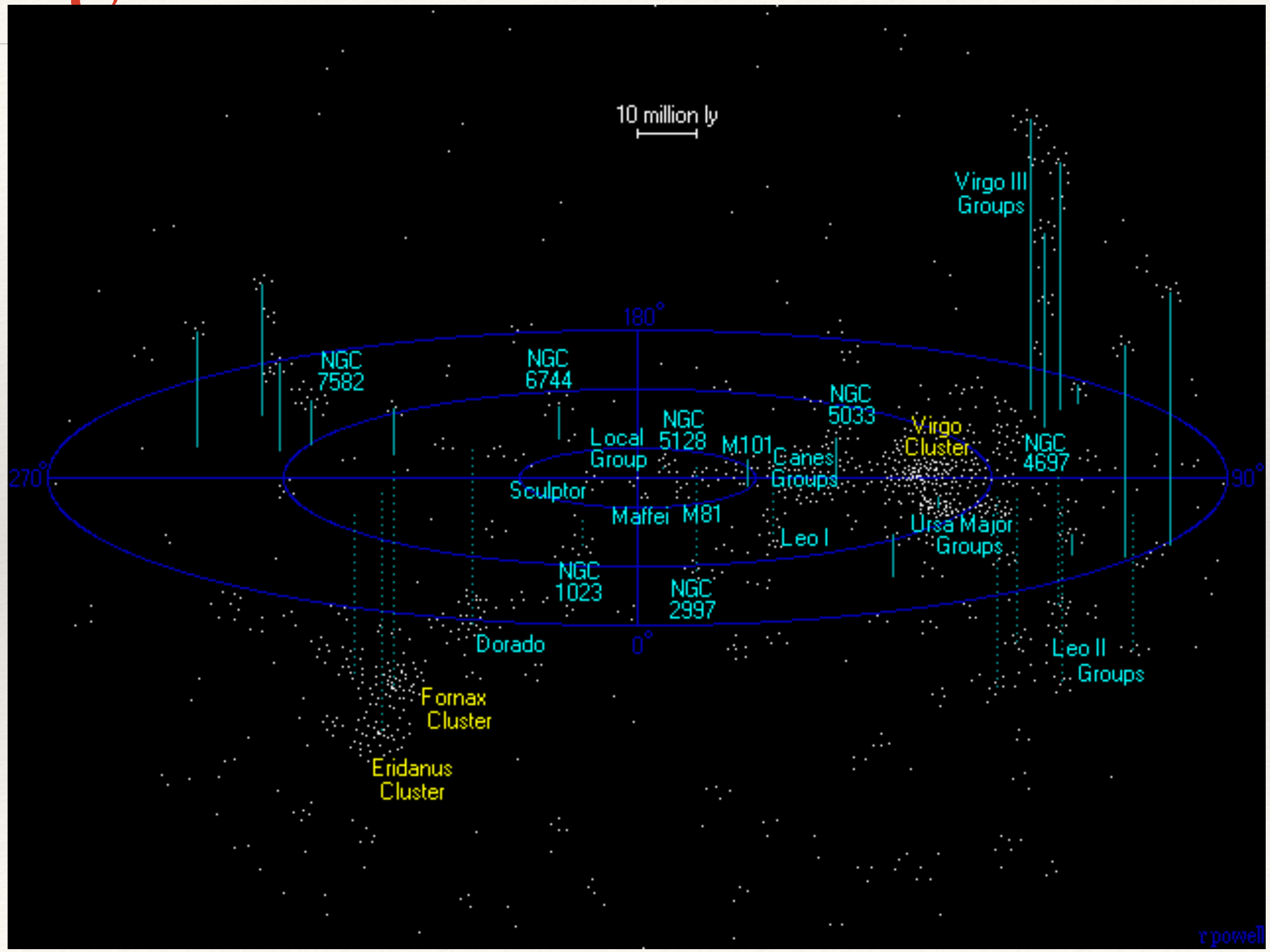
A promising energy range to look for angular correlation between cosmic rays of extragalactic origin and their sources is at the highest energies, above few tens of EeV ($1\,\mathrm{EeV} \equiv 10^{18}\,\mathrm{eV}$). Despite the flux of these particles being extremely low, the area of $\sim$3,000 km^2 covered at the Pierre Auger Observatory, and the 17-year data-taking period of the Phase 1 of its operations, have enabled us to measure the arrival directions of more than 2,600 ultra-high energy cosmic rays above 32 EeV. We publish this data set, the largest available at such energies from an integrated exposure of 122,000 km^2 sr yr, and search it for anisotropies over the 3.4π steradians covered with the Observatory. Evidence for a deviation in excess of isotropy at intermediate angular scale, with $\sim 15°$ Gaussian spread or $\sim 25°$ top-hat radius, is obtained at the $4\,\sigma$ significance level for cosmic-ray energies above ~ 40 EeV.



Super-galactic Plane?

- Only a small hint
- Still a mystery where the cosmic ray comes from

- **But one thing for sure, no galactic UHECR source**

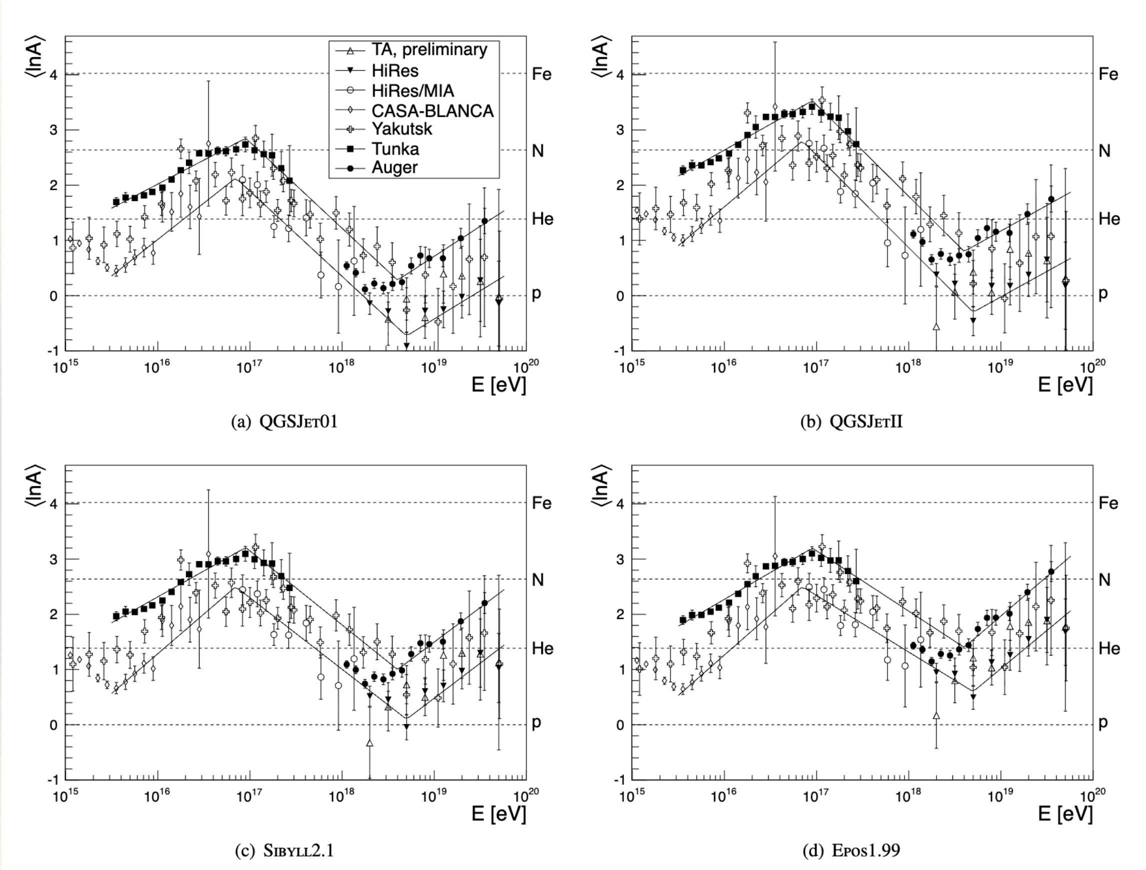


Impact of composition

- One challenge to infer direction, is that Larmor radius is inversely proportional to charge of the particles.

- So for the same energy, a proton and a Iron cosmic ray can travel very differently

- So, let's try to measure composition!
  - UHECR detector detection air showers, so it relies on interaction model to infer the composition
  - Unfortunately, the uncertainties can be large
  - (Though the trend seems consistent.)



(a) QGSJet01 (b) QGSJetII (c) Sibyll2.1 (d) Epos1.99

Muon puzzle

The Muon Puzzle in cosmic-ray induced air showers and its connection to the Large Hadron Collider

Johannes Albrecht[1] · Lorenzo Cazon[2] · Hans Dembinski[1] · Anatoli Fedynitch[3] · Karl-Heinz Kampert[4] · Tanguy Pierog[5] · Wolfgang Rhode[1] · Dennis Soldin[6] · Bernhard Spaan[1] · Ralf Ulrich[5] · Michael Unger[5]

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- In fact, one way to infer the composition is to use the number of muons in the shower
- But interactions model predicted too few muons!
- Resulted in composition that are kind of absurd.

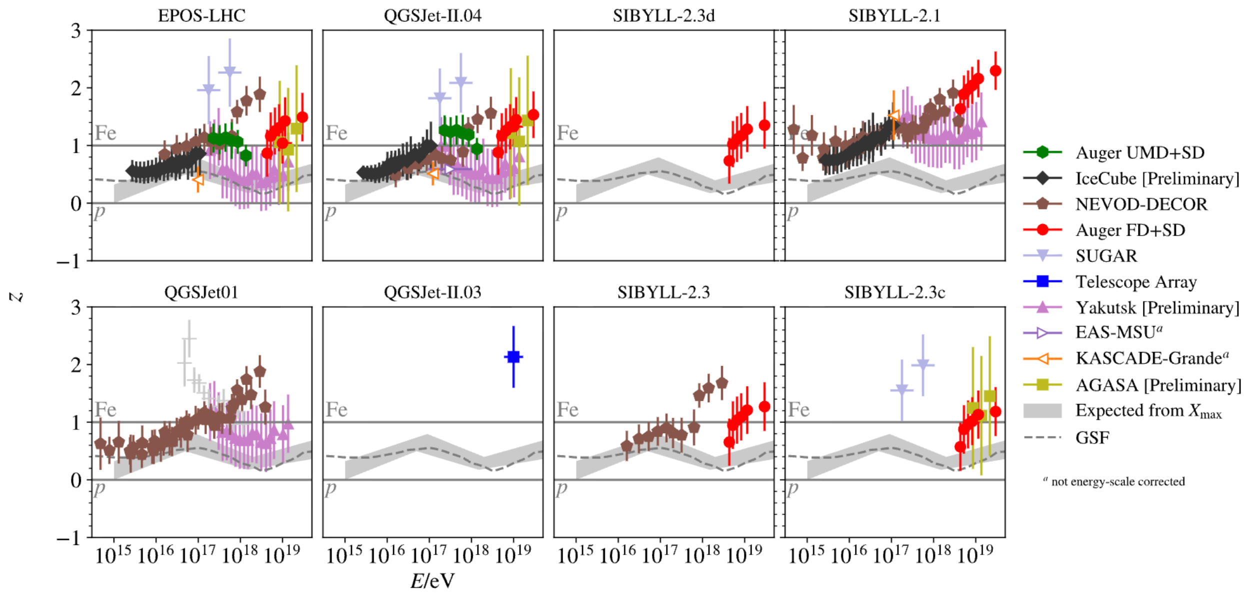
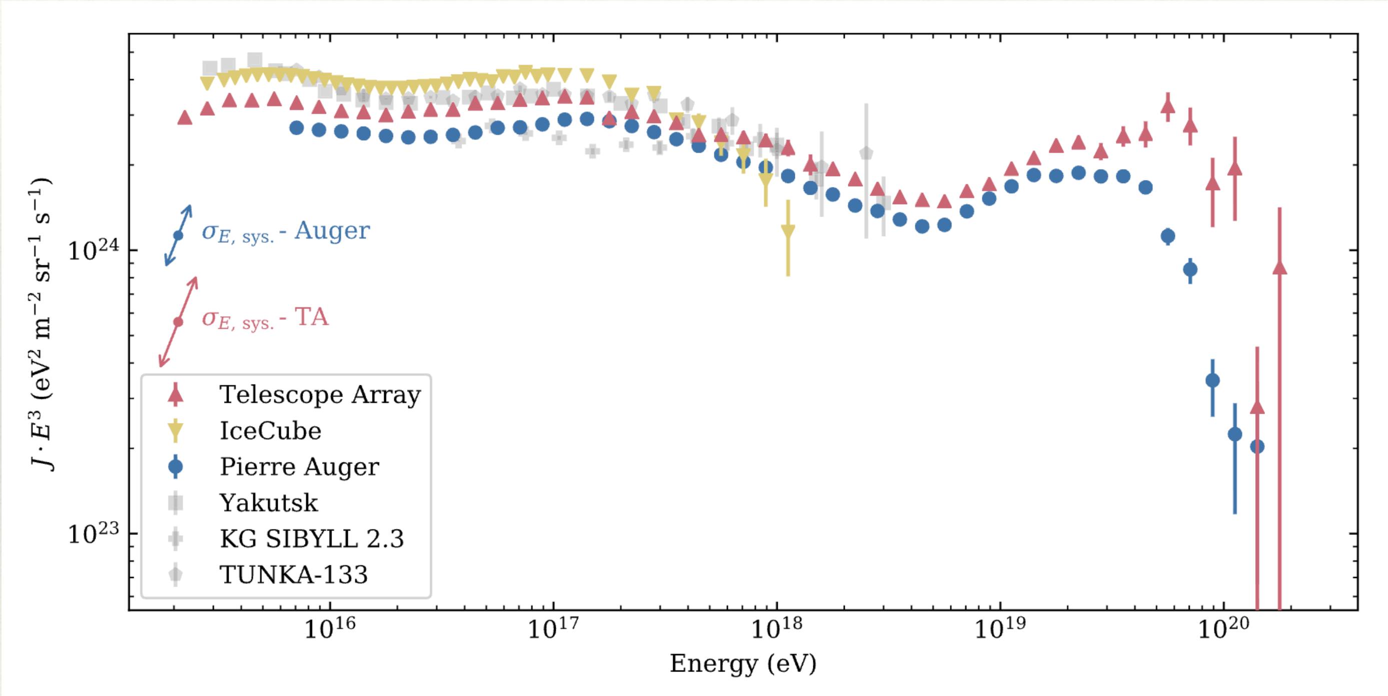


Fig. 3 Compilation of muon measurements converted to the abstract z-scale and after cross-calibrating the energy scales of the experiments as described in the text (image from Soldin 2021). Shown for comparison are predicted z_{mass}-values based on air shower simulations and X_{max}-measurements (grey band). The prediction from the GSF model (Dembinski et al. 2018) for z_{mass} is also shown (dashed line)

Energy information

- Spectrum cutoff sharply above about $10^{11} GeV$



Greisen–Zatsepin–Kuzmin limit

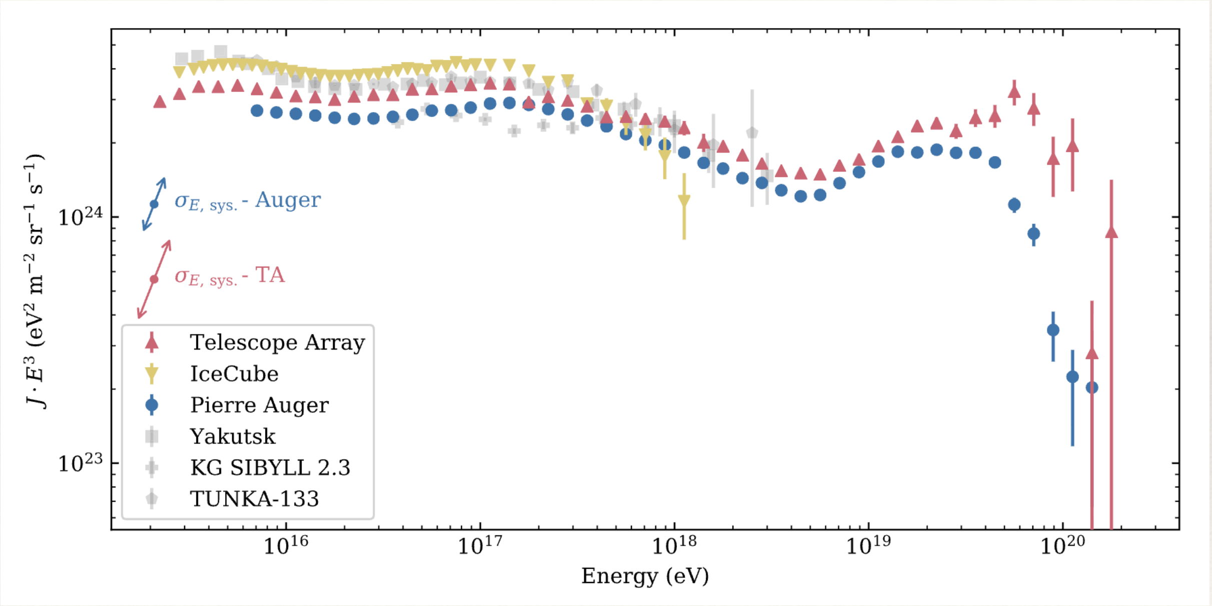
- After the detection of the cosmic microwave background

$$p + \gamma_{\text{CMB}} \rightarrow \Delta^{+} \rightarrow p + \pi^{0} \ ,$$

or

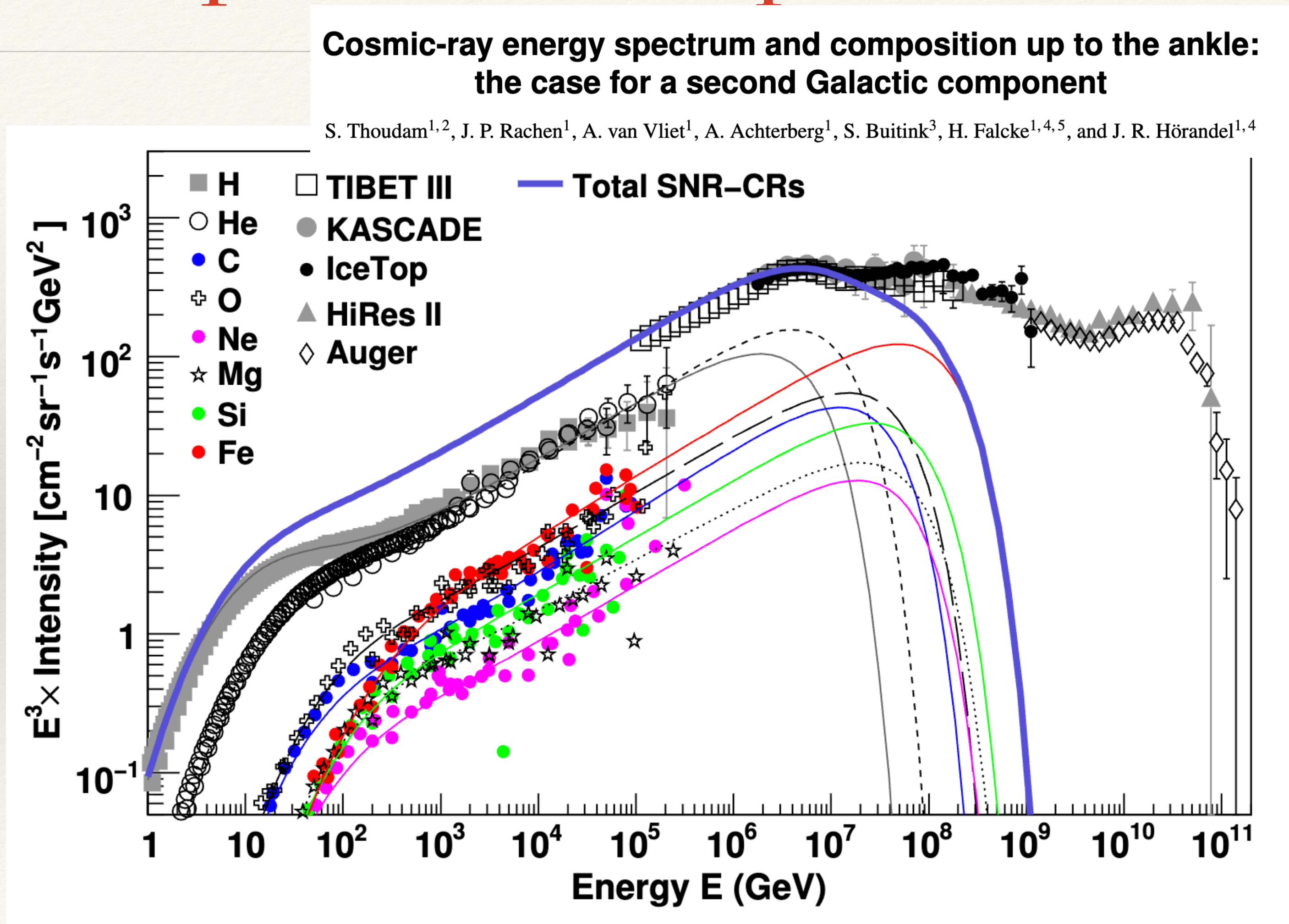
$$p + \gamma_{\text{CMB}} \rightarrow \Delta^{+} \rightarrow n + \pi^{+} \ .$$

- It is noted that protons can loss energy by interacting with CMB at energy around $10^{19.5} eV$
- This seems to agree with observation!
- However, this energy only works for protons, if they are nuclei, then the cutoff energy would be different.
- The observed cutoff could be a coincidence matching the maximum acceleration energy of the source?



Modeling CR spectrum examples

- The galactic Component
- The maximum accelerated energy is higher for high-Z particles



Modeling CR spectrum examples

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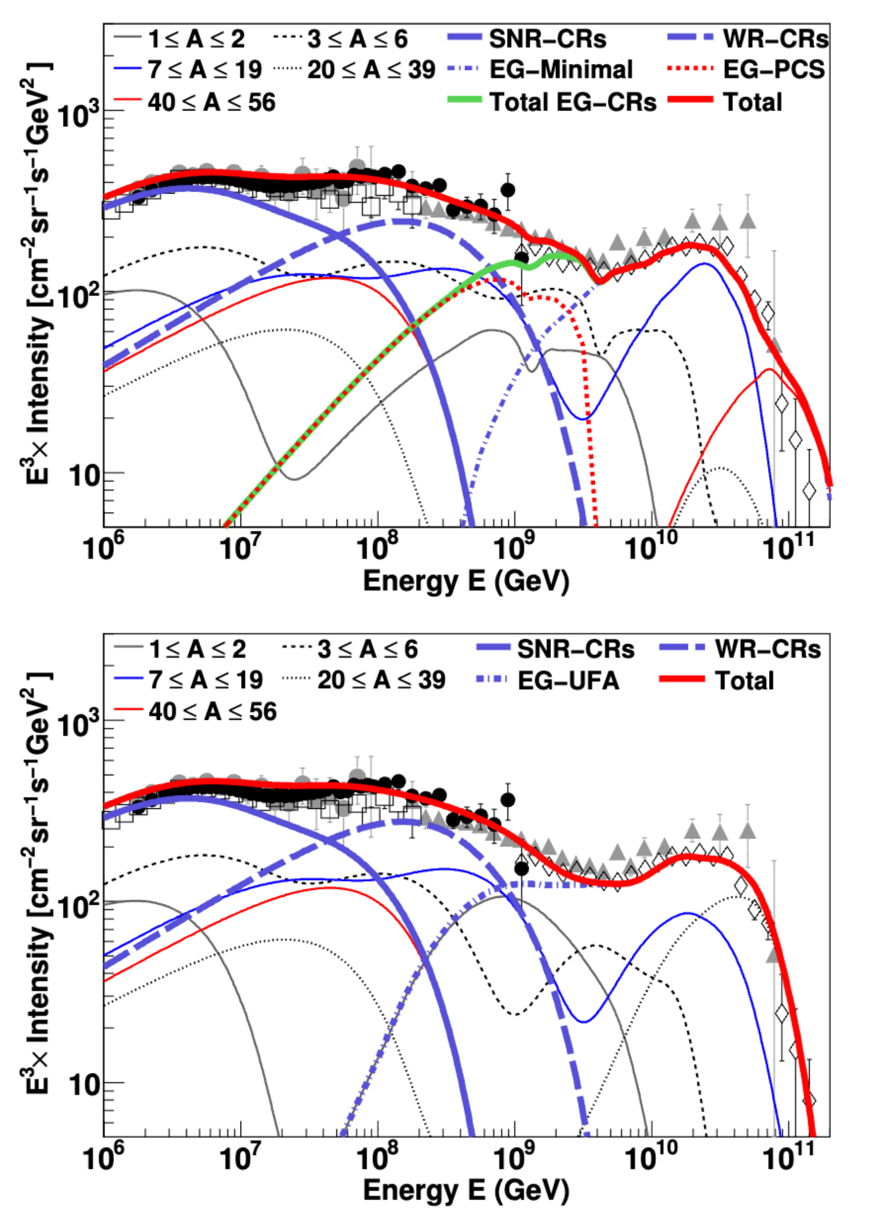


UHECR

- Source
  - We dont know yet
- Direction
  - Only hints, may not even have direction if composition is heavy
- Composition
  - Very difficult without fixing the interaction models.
- Energy features
  - Depends on composition model

How to identify UHECR sources?

- CR direction:
  - We cannot see beyond about 1 Mpc
  - Due to GZK absorption
- Photon direction
  - For high-energy photons, they are also absorbed by photon background via
  - $\gamma + \gamma \rightarrow e^{+} + e^{-}$

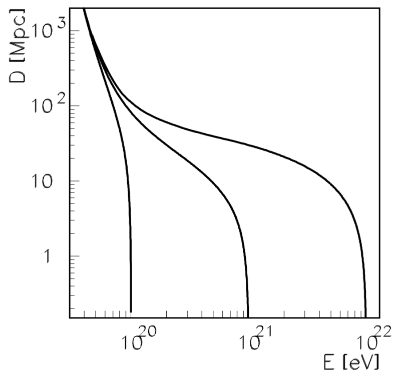
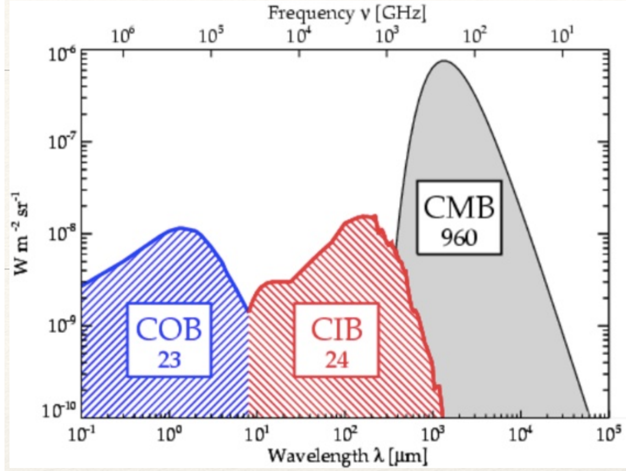
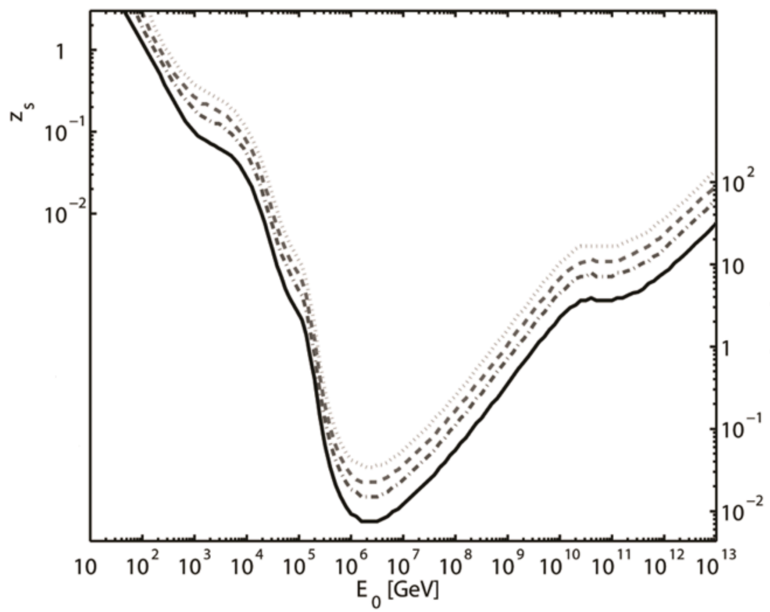


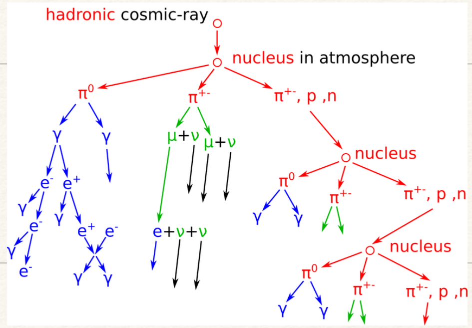
Fig. 3: Energy attenuation length of protons in the intergalactic medium. For proton sources beyond ≈ 100 Mpc, the observed proton energy is $< 10^{20}$eV regardless its initial value. From Ref. [37].



4 *De Angelis, Galanti, Roncadelli*



The logic of neutrino astronomy



- Want to know cosmic-ray sources
- Cosmic rays themself
  - Charged, doesnt point
- Gamma rays
  - Could be Absorbed
  - Hadronic vs Leptonic
- **Neutrinos**
- **GW (though not directly related to CR)**