Ultrahigh-Energy Cosmic Rays

State of the Art and Implications for Current and Future Multi-Messenger Experiments

Michael Unger, IAP, KIT

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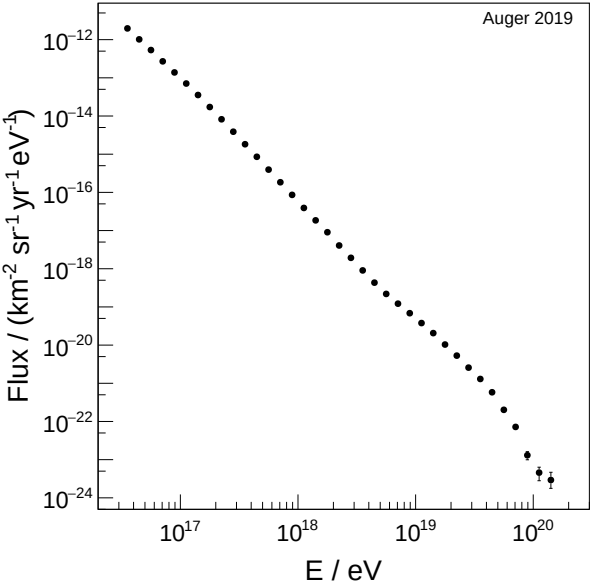
Energy Spectrum of Ultrahigh-Energy Cosmic Rays (UHECRs)



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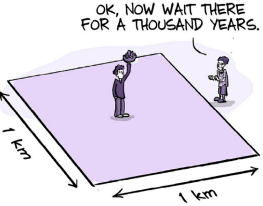
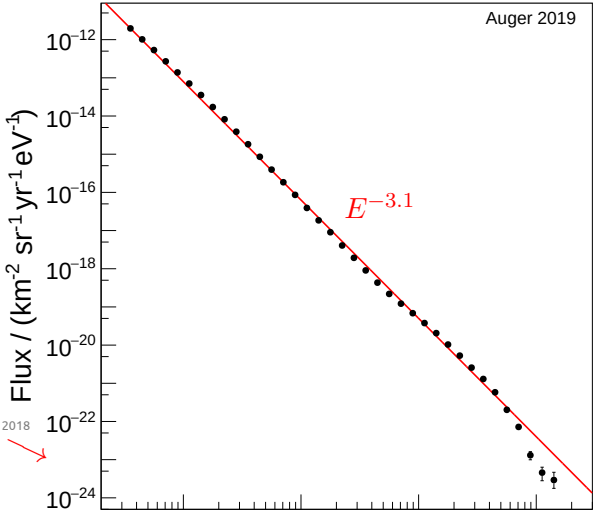


Cham&Whiteson "We have no idea", Penguin, 2018



$\sim$20 J!

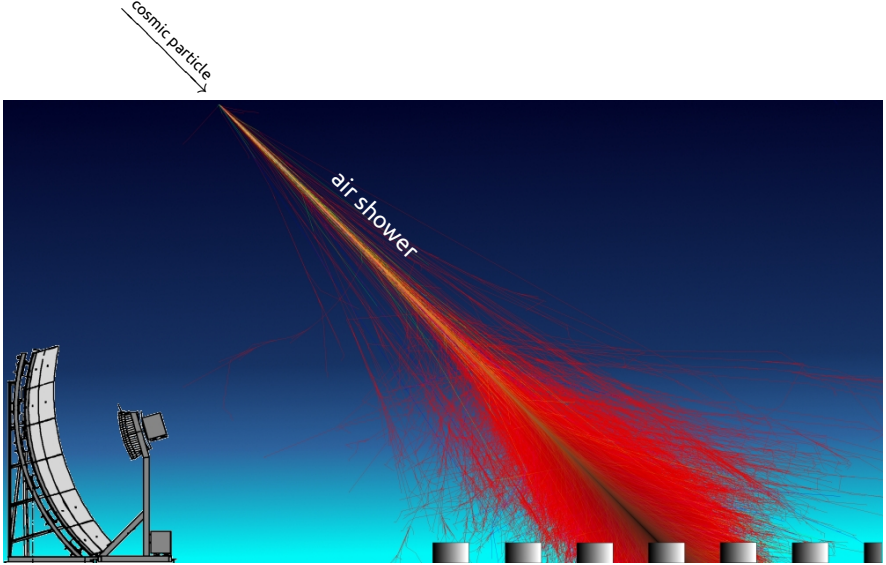
Serena Williams' 2nd serve

$E_{\text{beam}}^{\text{LHC}} = 7 \times 10^{12}$ eV

$\sqrt{s_{\text{pp}}^{\text{LHC}}}$

$\sqrt{s_{\text{pp}}} = 450$ TeV

Detection of UHECRs: Air Showers

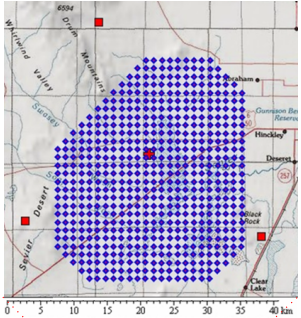


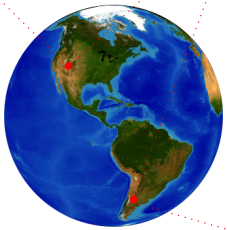
fluorescence telescope

particle detector

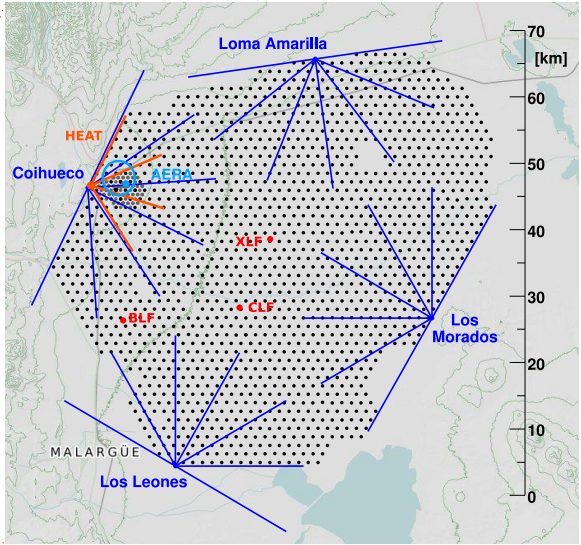
UHECR Observatories

Telescope Array





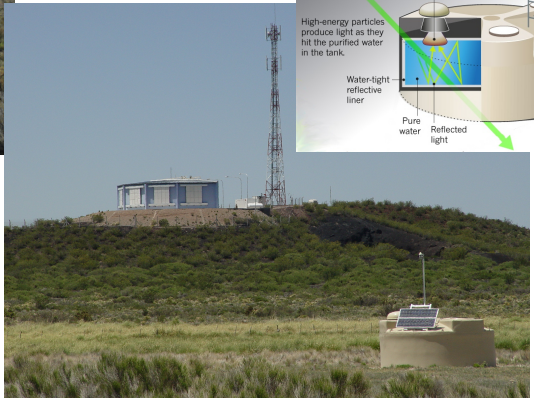
Pierre Auger Observatory

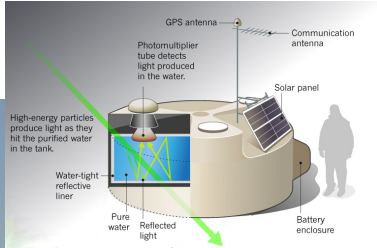


UHECR Observatories

Telescope Array

Pierre Auger Observatory

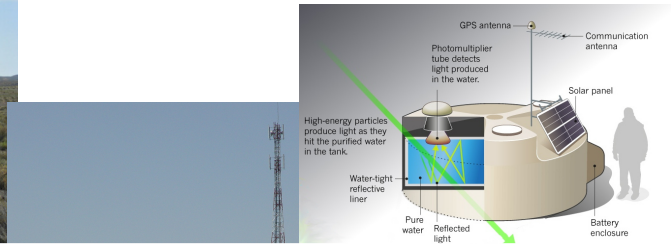




UHECR Observatories

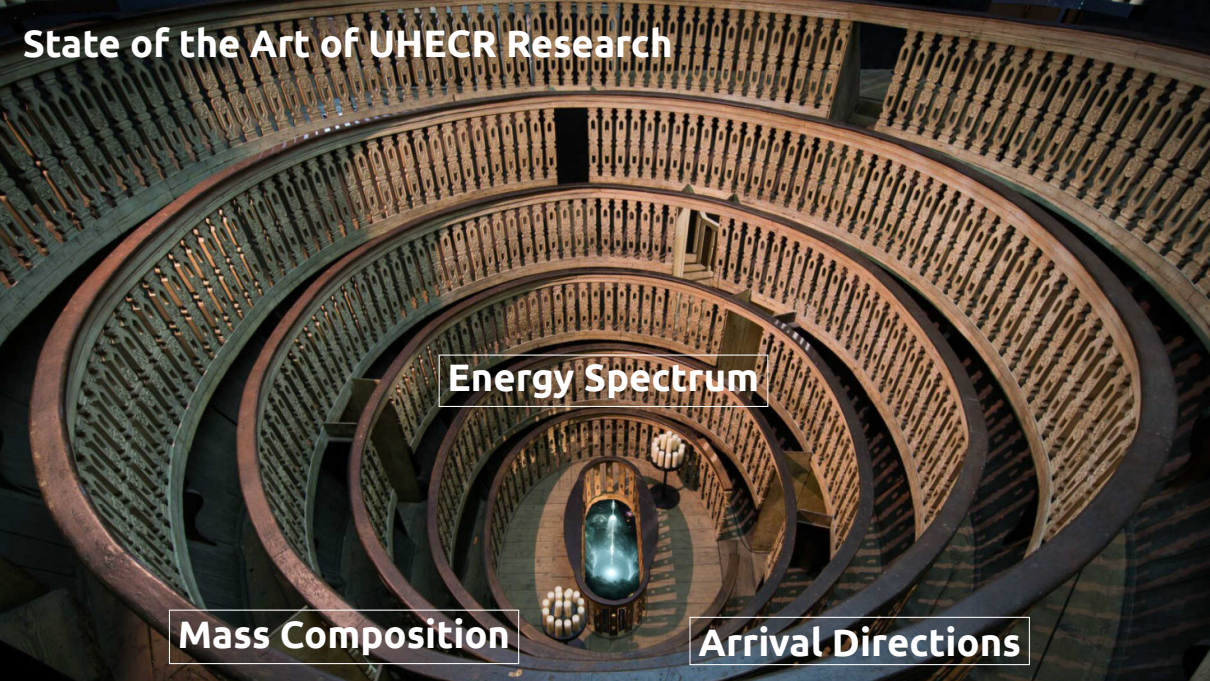
Telescope Array

Pierre Auger Observatory



NB: Excellent UHE ν and γ Detector!
(see talks by Viviana Scherini and Michael Schimp, Tuesday Parallel2)

State of the Art of UHECR Research



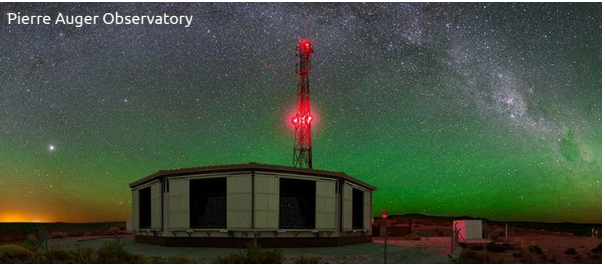
State of the Art of UHECR Research

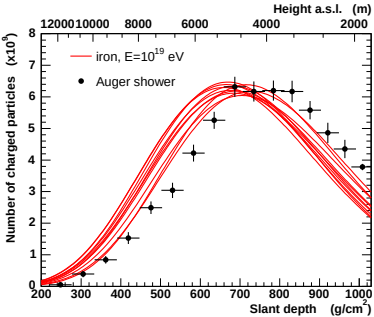
Energy Spectrum

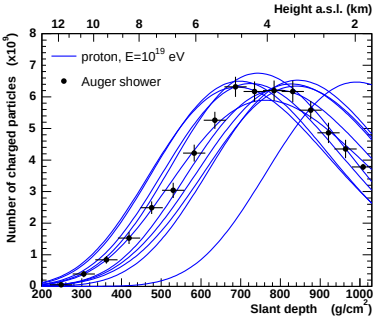
Mass Composition

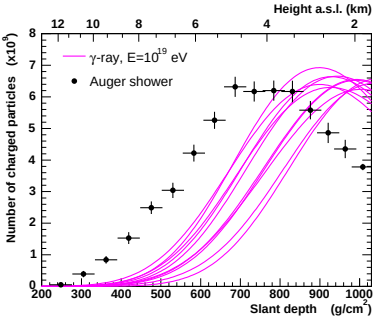
Arrival Directions

Longitudinal Shower Development (Fluorescence Telescopes)

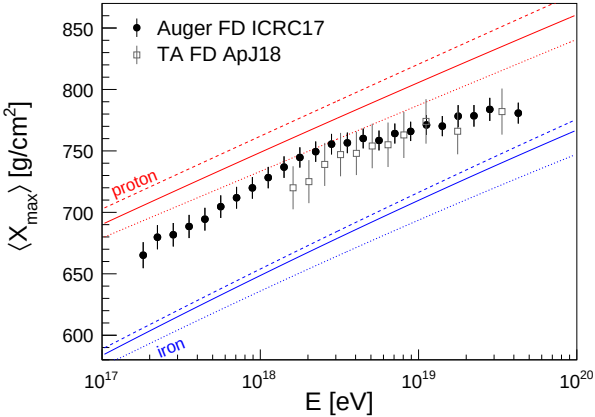


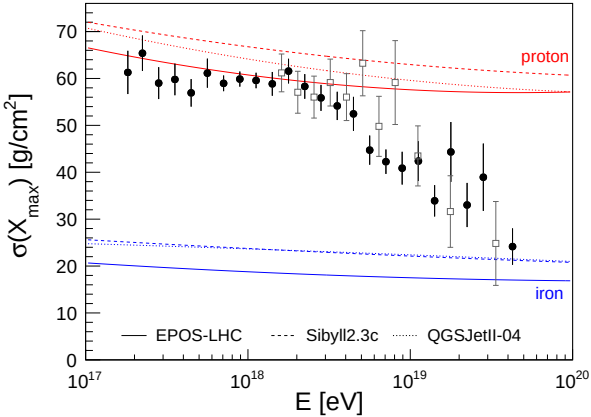






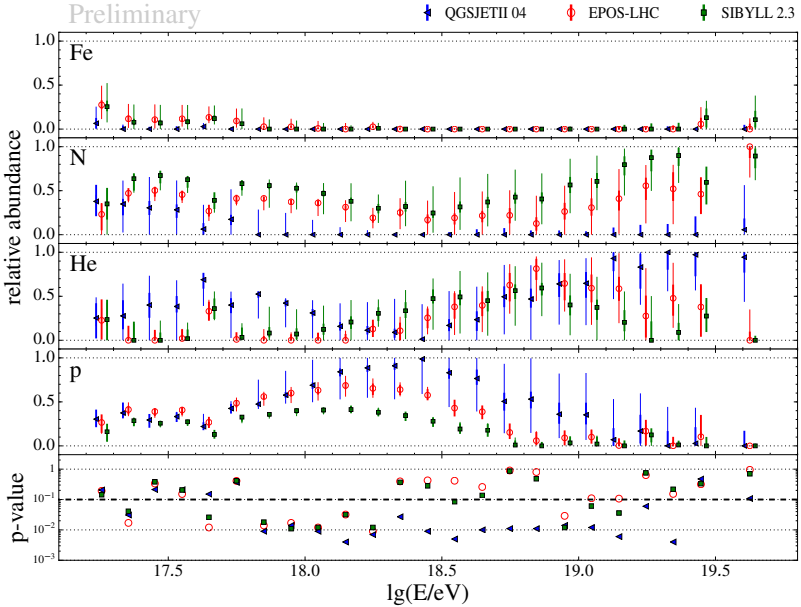
Mean and Standard Deviation of X_{max} Distributions



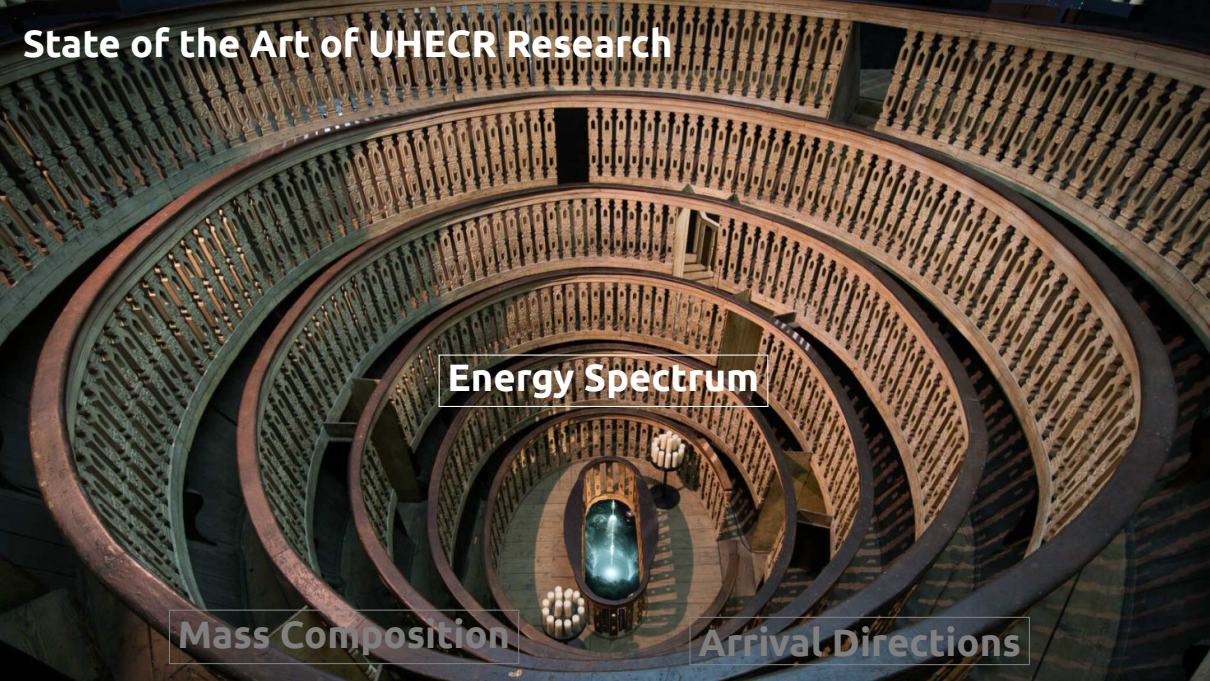


Pierre Auger Coll., ICRC17, see also update at ICRC19; TA Coll. ApJ18; TA&Auger Composition WG UHECR18; MIAPP review, FASS19

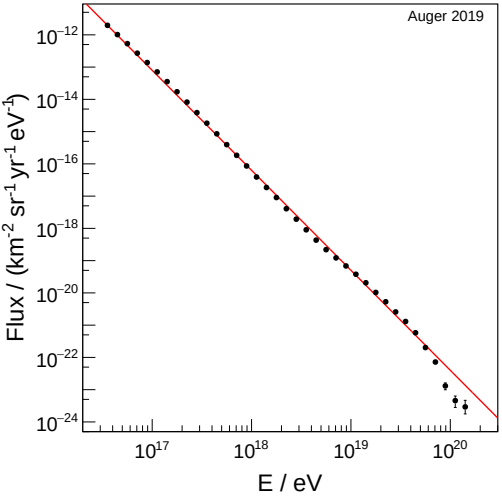
Inferred Mass Composition

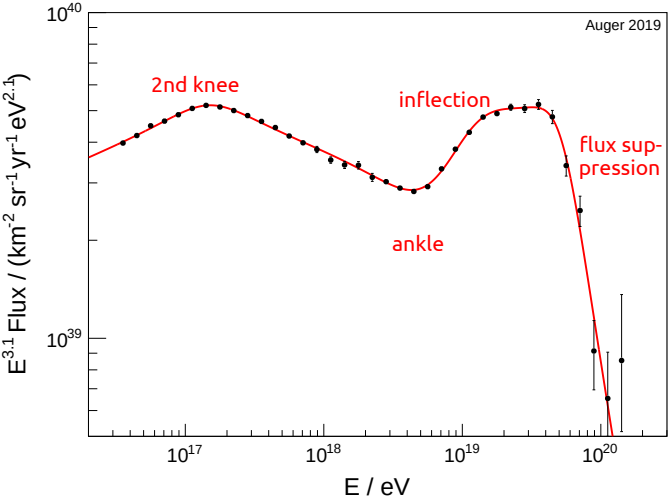


State of the Art of UHECR Research



Energy Spectrum

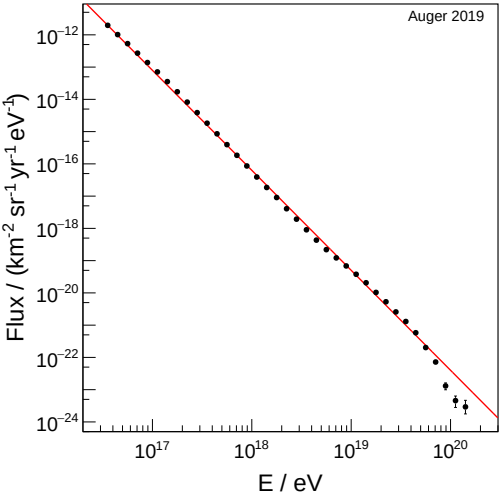




Pierre Auger Coll., PRD 2020, PRL 2020 (twice editor's choice)

Physics See Viewpoint: The Anatomy of Ultrahigh-Energy Cosmic Rays

Energy Spectrum



Measurement of Local CR Energy Density

$$\rho = 4\pi/c \int_{E_{\rm ankle}}^{\infty} E\ \mathrm{Flux}(E)\ \mathrm{d}E$$
$$= (5.66 \pm 0.03 \pm 1.40) \times 10^{53}\ \mathrm{erg\ Mpc}^{-3}$$

$\rightarrow$ source luminosity density

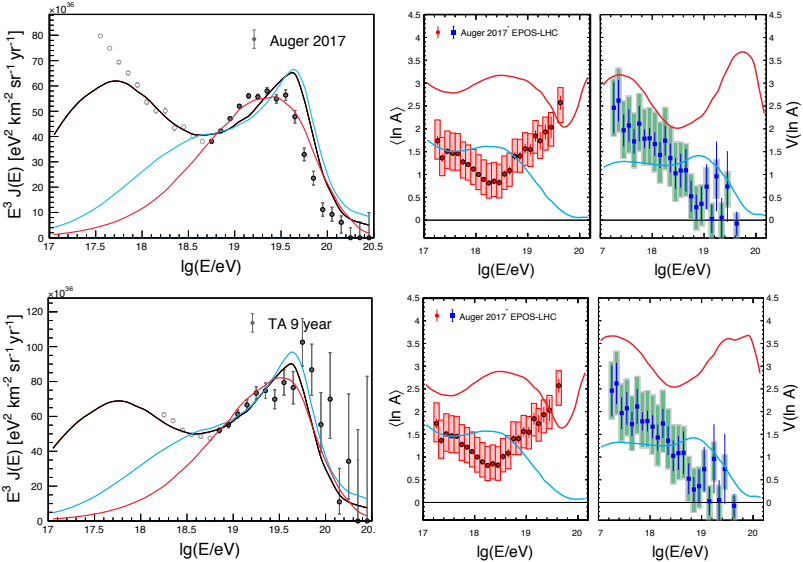
$$\mathcal{L} \sim \rho / t_{\rm loss} = 2 \times 10^{44}\ \mathrm{erg\ Mpc}^{-3}\ \mathrm{yr}^{-1}$$

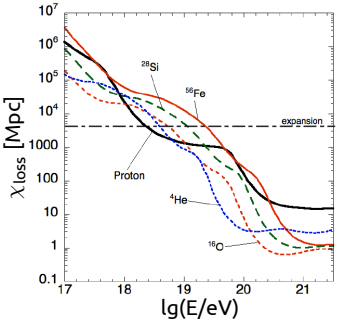
Typical energy loss time $t_{\rm loss} \sim 1\ \mathrm{Gpc/c}$ at $E_{\rm ankle} = 5 \times 10^{18}$ eV

Full calculation with SimProp gives $\mathcal{L} = 6 \times 10^{44}$ erg Mpc^{-3} yr^{-1})

Pierre Auger Coll., PRD 2020, PRL 2020 (twice editor's choice) Physics See Viewpoint: The Anatomy of Ultrahigh-Energy Cosmic Rays

GZK Flux Suppression? $(p + \gamma_{\mathrm{CMB}} \to n/p + \pi^{+/0} \text{ or } A + \gamma_{\mathrm{CMB}} \to (A-1) + p/n)$





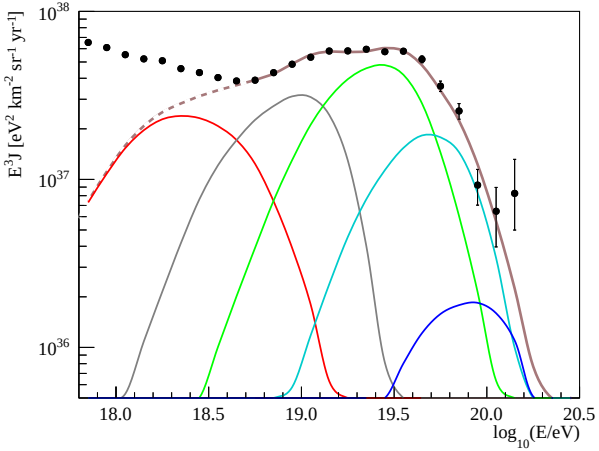
D.Allard Astropart.Phys. **39** (2012) 33

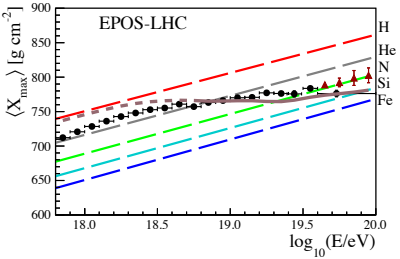
MIAPP review, Front.Astron.Space Sci. 6 (2019) 23

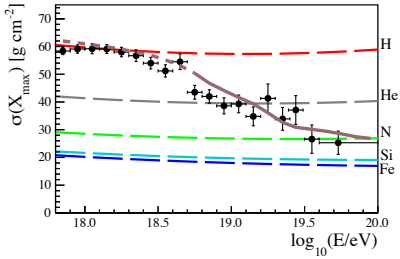
Maximum Rigidity Model, Peters Cycle?

B. Peters, Nuovo Ciemento **22** (1961) 800

energy spectrum at source $\propto (E/Z)^{-\gamma}$







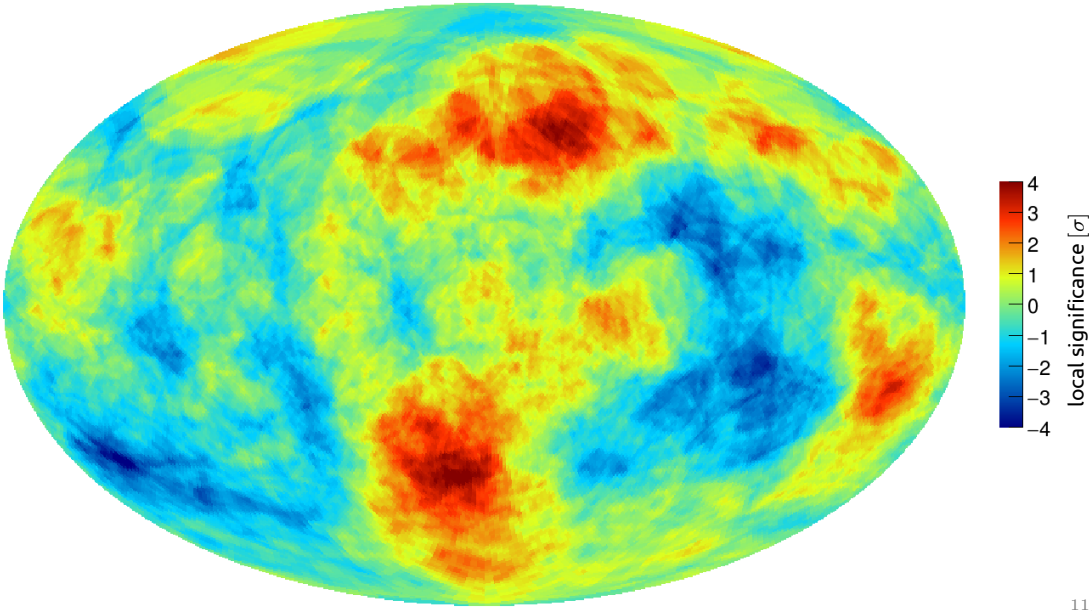
A. Castellina for the Auger Coll. ICRC19 and JCAP **1704** (2017) 038

State of the Art of UHECR Research

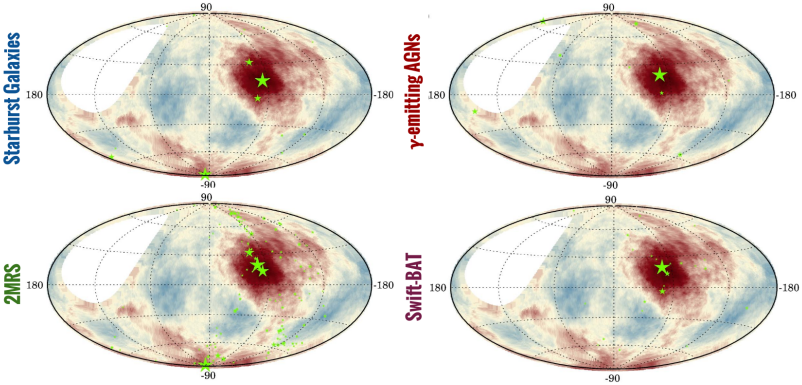
Arrival Directions – Blind Search

Auger/TA Anisotropy Working Group UHECR18

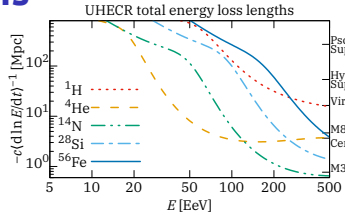
$E > 40/52.3$ EeV, 20° top-hat 0.21%/2.5% post-trial



Arrival Directions – Catalogue-based Analysis



Pierre Auger Coll, ApJ Lett. 853 (2018) L29



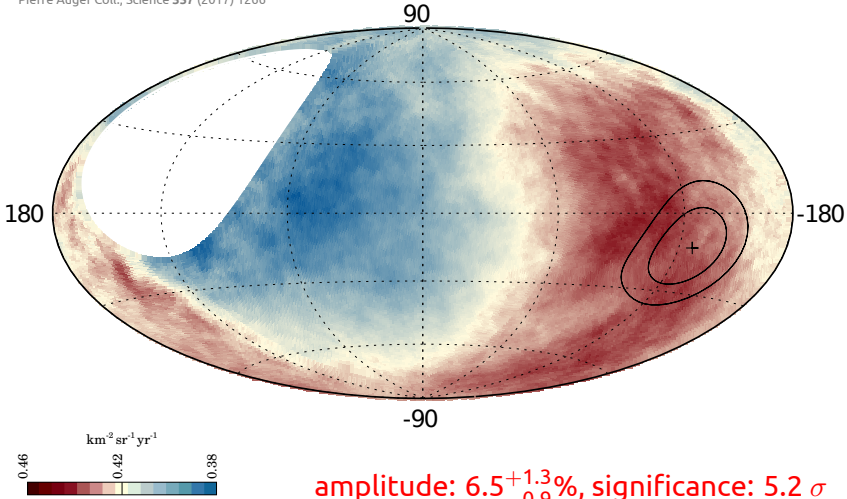
Catalog	E_{th}	θ	f_{aniso}	TS	Post-trial
Starburst	38 EeV	15^{+5}_{-4}°	11^{+5}_{-4}%	29.5	4.5 σ
γ-AGNs	39 EeV	14^{+6}_{-4}°	6^{+4}_{-3}%	17.8	3.1 σ
Swift-Bat	38 EeV	15^{+6}_{-4}°	8^{+4}_{-3}%	22.2	3.7 σ
2MRS	40 EeV	15^{+7}_{-4}°	19^{+10}_{-7}%	22.0	3.7 σ

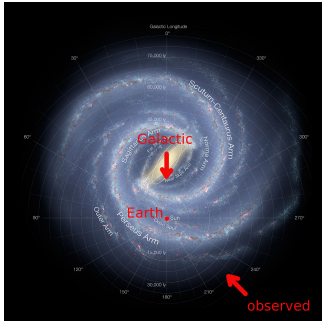
TA compatible with both, starburst model and isotropy TA Coll, ApJ Lett. 867 (2018) L27

L. Caccianiga for the Pierre Auger Coll. ICRC19, ApJ853 (2018) 2

Observation of a Dipolar Anisotropy of UHECRs (E> 8 EeV)

Pierre Auger Coll., Science **357** (2017) 1266





amplitude: $6.5^{+1.3}_{-0.9}$%, significance: 5.2 σ

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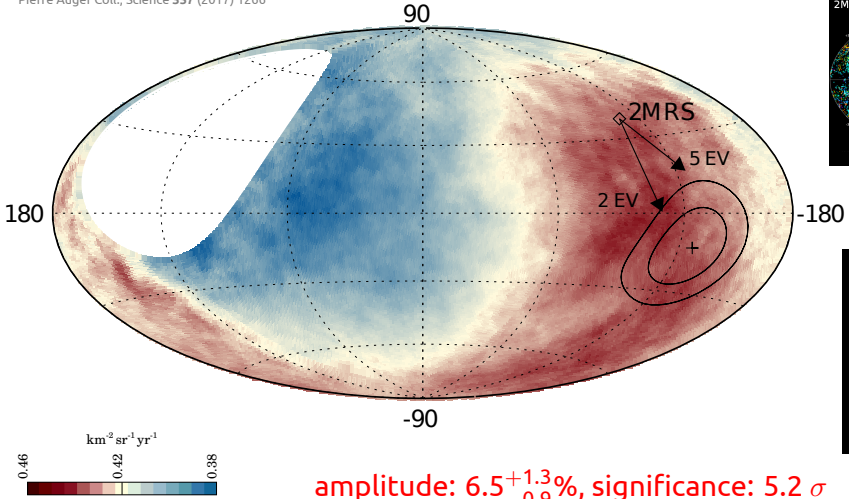
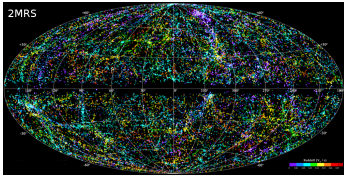
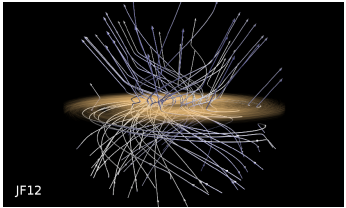
Pierre Auger Coll., Science **357** (2017) 1266



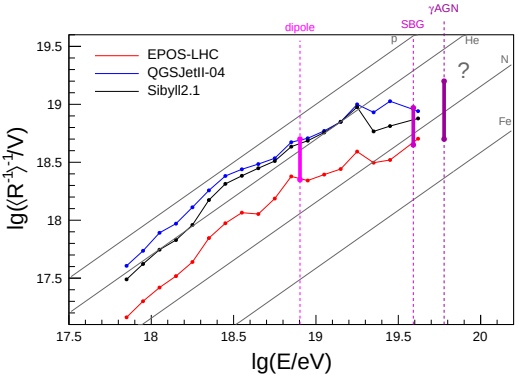




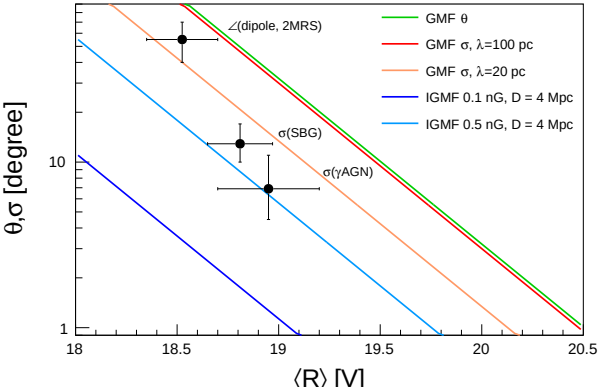
amplitude: $6.5^{+1.3}_{-0.9}$%, significance: 5.2 σ

Charged Particle Astronomy?

average rigidity $R = E/Z$



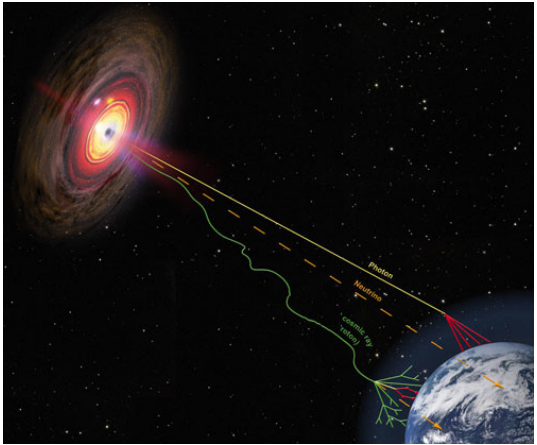
deflection in magnetic field



Galactic: $\theta_{\rm coh} \sim 3^\circ \left(\frac{R}{10^{20}\ {\rm V}}\right)^{-1}$, $\sigma_{\rm rand} \sim 3^\circ \left(\frac{\lambda_{\rm coh}}{100\ {\rm pc}}\right)^{\frac{1}{2}} \left(\frac{R}{10^{20}\ {\rm V}}\right)^{-1}$ Farrar&Sutherland, arXiv:1711.02730

Extragalactic: $\sigma_{\rm rand} \sim 0.4^\circ \left(\frac{\lambda_{\rm coh}}{1\ {\rm Mpc}}\right)^{\frac{1}{2}} \left(\frac{D}{50\ {\rm Mpc}}\right)^{\frac{1}{2}} \left(\frac{B}{10^{-10}\ {\rm G}}\right) \left(\frac{R}{10^{20} V}\right)^{-1}$ Durrer&Neronov, AAR **21** (2013) 6

Implications for Current and Future Multi-Messenger Experiments



Need Charge Sensitivity and Full-Sky Coverage for UHECR Observations

Under Construction: **AugerPrime**

arXiv:1604.03637

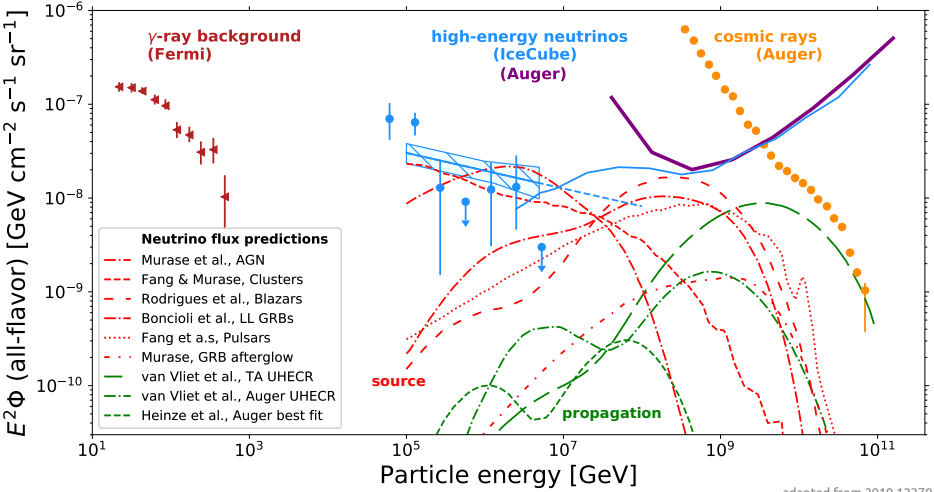
Under Construction: **TAx4**

EPJ **210** (2019) 06001

Launch 2029: **POEMMA**?

Parallel03 at 17:30, PRD **101** (2020) 023012

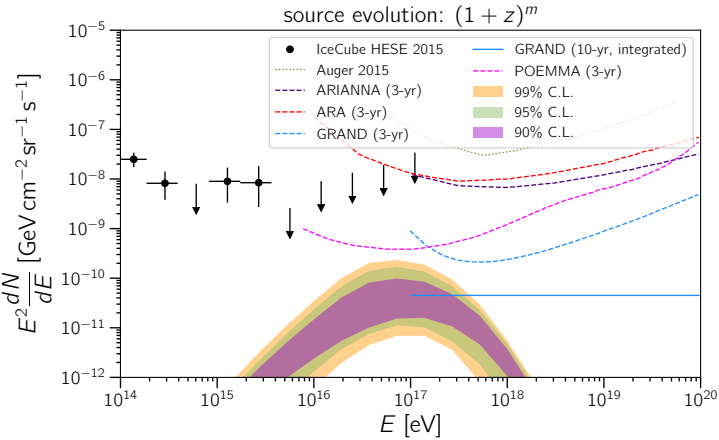
Implications for Neutrino Studies



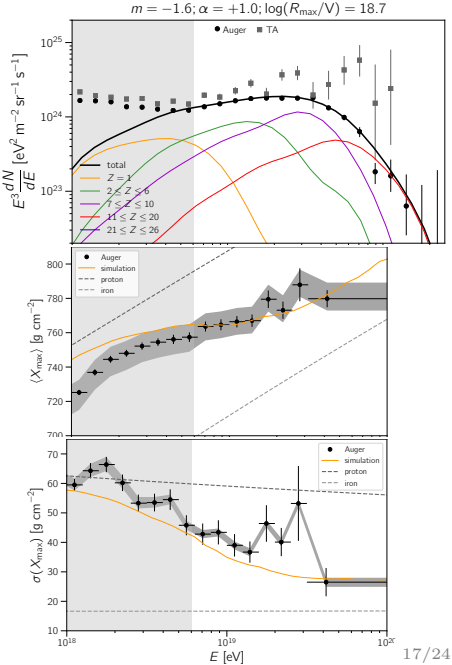
adapted from 2010.12279

see talks by Rodrigues, Rudolph, Batista, Murase

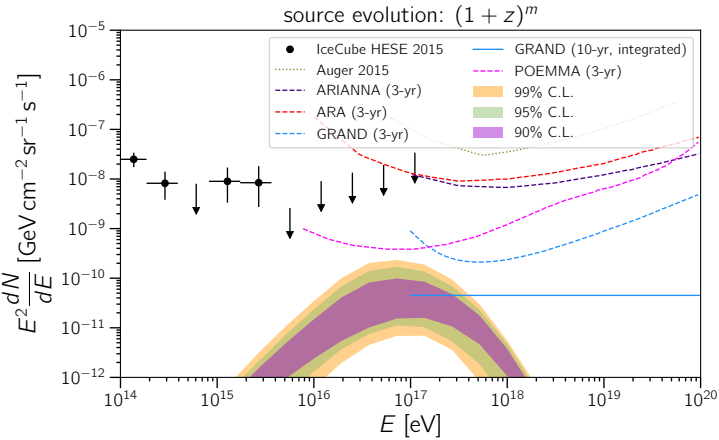
Peters Cycle and Cosmogenic Neutrinos



negative source evolution ($m = -1.6$) and $z_{\text{max}} = 1$ Batista et al, JCAP 01 (2019) 002



Peters Cycle and Cosmogenic Neutrinos



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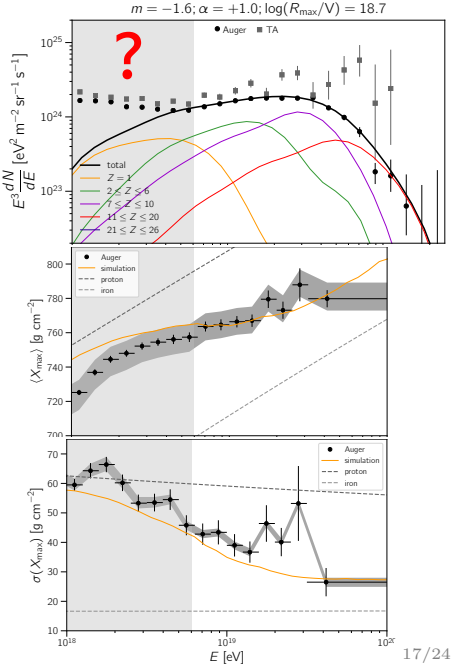
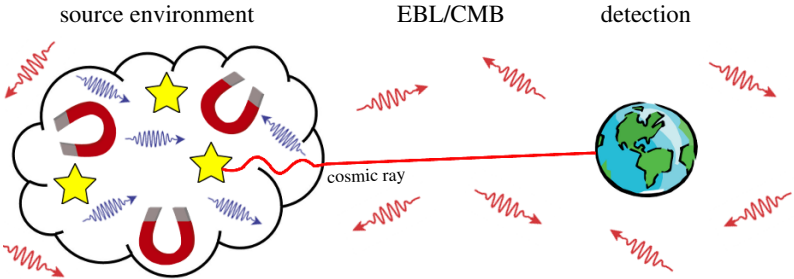
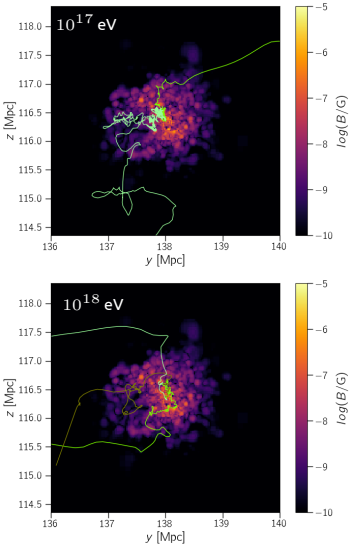


Photonuclear Interactions in Source Environment?

$$A + \gamma \rightarrow (A-1) + p/n$$
$$p + \gamma \rightarrow n/p + \pi^{+/0} \rightarrow 2\gamma/(3\nu + \mathrm{e})$$

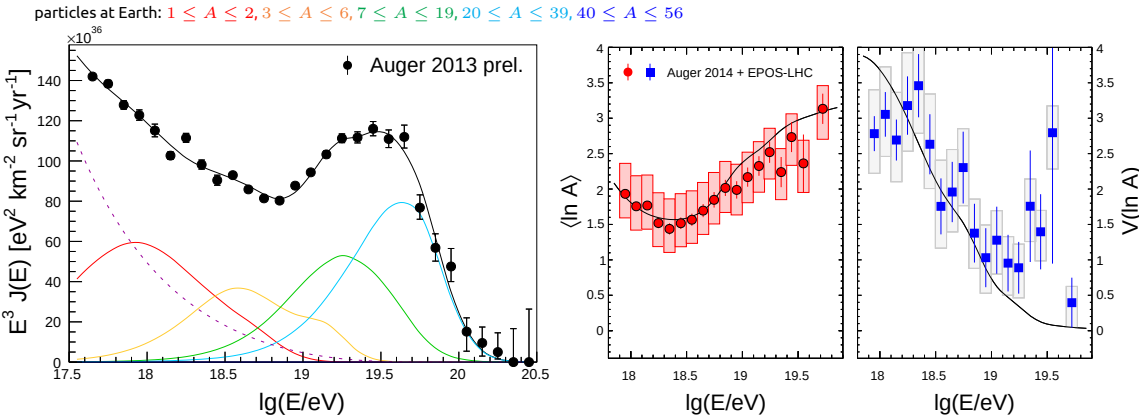




MU+15, Globus+15, Biel+17, Kachelriess+17, Supanitsky+18, Boncioli+19, Muzio+19

Virgo Cluster sim., R.A. Batista et al, arXiv:1811.03062

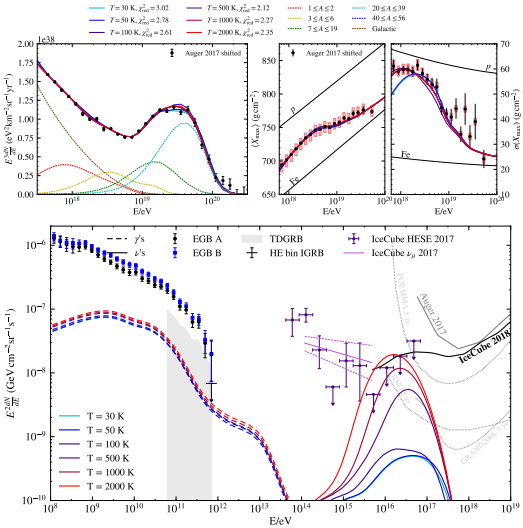
Photonuclear Interactions in Source Environment?



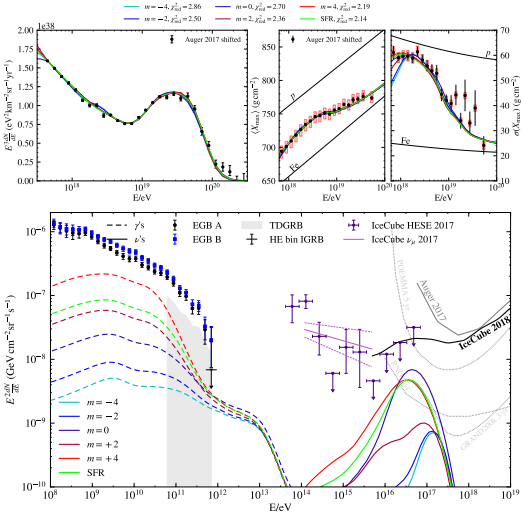
MU, G. Farrar, L. Anchordoqui, PRD **92** (2015) 123001

Multimessenger Studies of Source Properties

photon field temperature



source evolution



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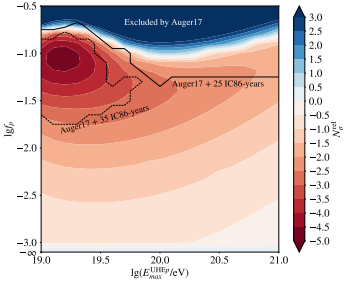
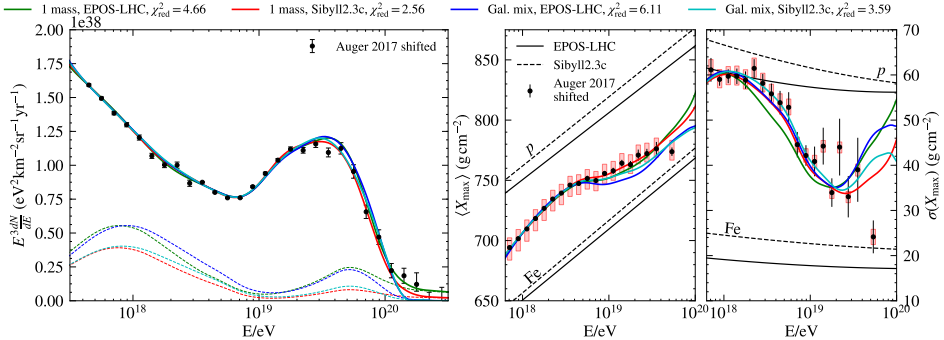
Proton Fraction at UHE?

energy fraction escaping source:

$$f_p = \frac{\int_{E_{\rm ref}}^{\infty} E\, Q_p \mathrm{d}E}{\int_{E_{\rm ref}}^{\infty} E\,(Q_p + Q_{\rm mix})\mathrm{d}E}$$

($Q_p \sim E^{\gamma_p}\, e^{-E/E_{\rm max}^{{\rm UHE}p}}$, $\gamma_p = -1$ and $E_{\rm ref} = 10^{19}$ eV)





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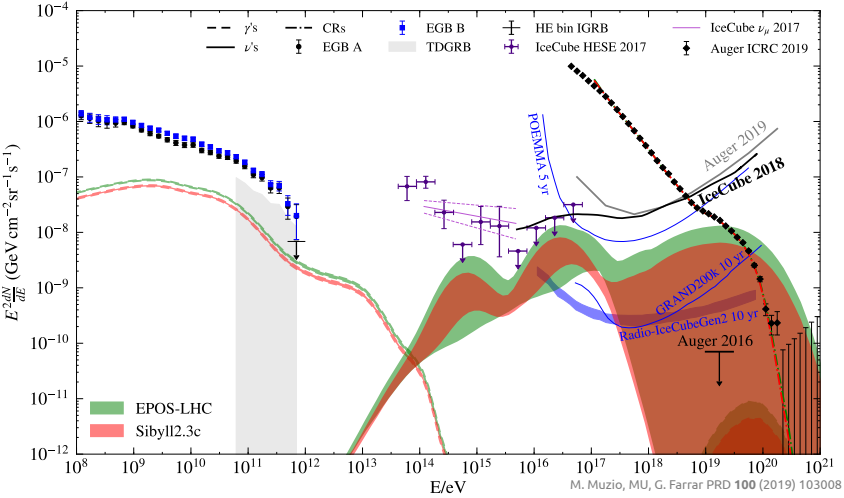
Source Neutrinos from UHECR Constraints



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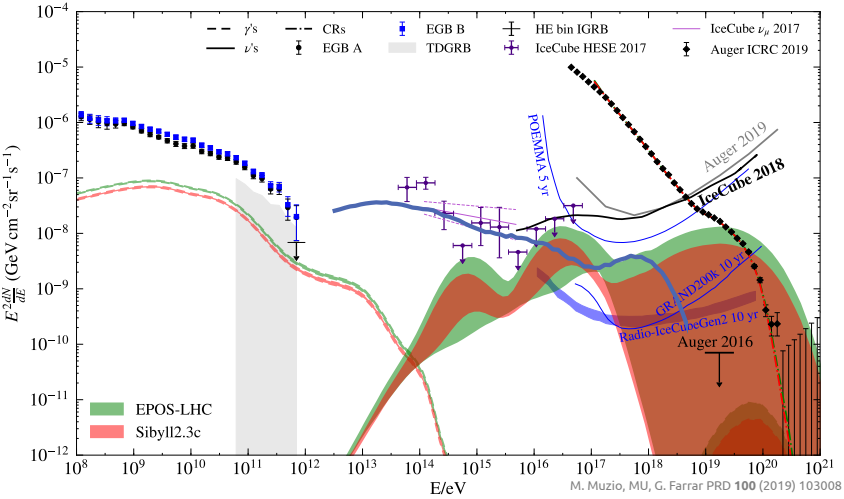
Source Neutrinos from UHECR Constraints



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additional degree of freedom: hadronic interactions with ambient gas
→ unified models e.g. Kachelriess+17, Fang+2017, Muzio+21 (in prep.)

Summary

- **Golden Age of UHECR Research**
  - high-precision flux measurement
  - unexpected mass composition
  - large scale anisotropy
  - hints for clustering at intermediate angular scales
  - soon equal-exposure sky coverage (TAx4) and charge sensitivity (AugerPrime)
  - next-generation large-exposure facilities? (POEMMA, GCOS...)
- **Multi-Messenger Implications**
  - dawn of charged particle astronomy?
  - low flux of cosmogenic neutral secondaries
  - UHECR proton measurements and $> 10^{18}$ eV ν flux for source evolution
  - detection (or limits on) source-neutrinos is key to understand UHECR sources
  - $10^{16} - 10^{17}$ eV ν flux to constrain source properties

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Pierre Auger Observatory Open Data

February 2021 release

The Pierre Auger 2021 Open Data is the public release of 10% of the Pierre Auger Observatory data presented at the 36th International Cosmic Ray Conference held in 2019 in Madison, USA, following the Auger collaboration open data policy.

This website hosts the datasets for download. An online event display is available to explore the released events, and example analysis codes are provided. See below for a brief overview of the Pierre Auger Observatory and of the Auger Open Data.

Datasets

the complete released datasets and their complementary data

Visualize

an online look at the released pseudo raw data

Analyze

example analysis codes in online python notebooks to run on the datasets