

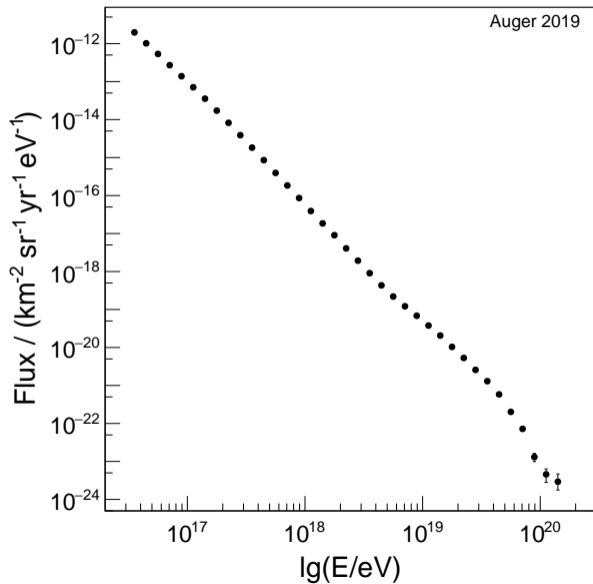
Cosmic Particles at Extreme Energies

Michael Unger

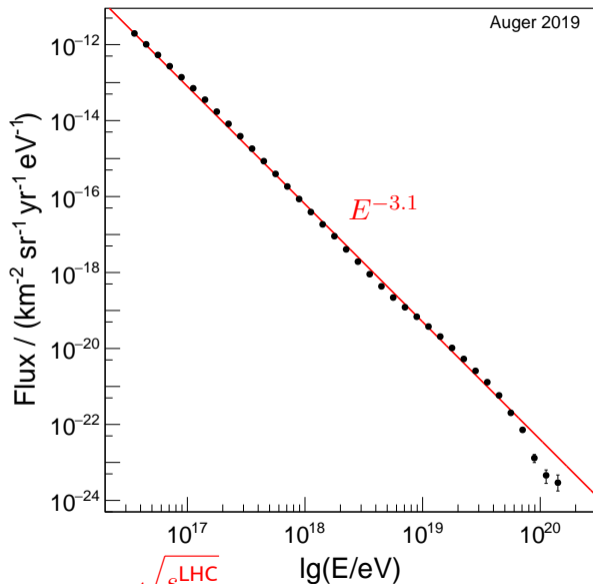
Karlsruhe Institute for Technology



Energy Spectrum of Ultrahigh-Energy Cosmic Rays (UHECRs)



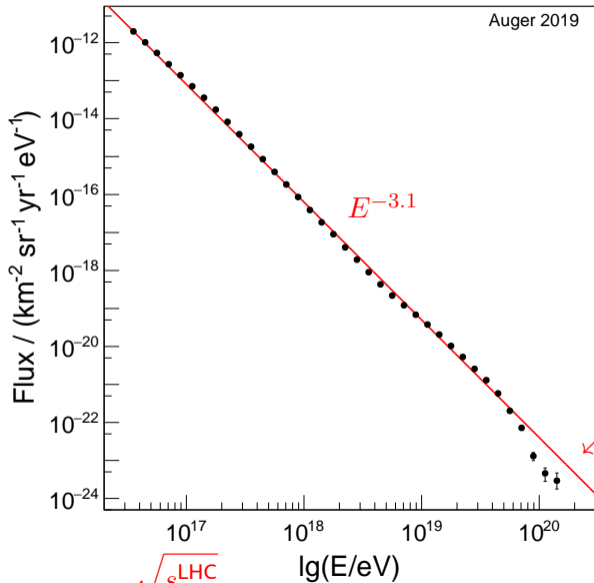
Energy Spectrum of Ultrahigh-Energy Cosmic Rays (UHECRs)



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

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

Energy Spectrum of Ultrahigh-Energy Cosmic Rays (UHECRs)



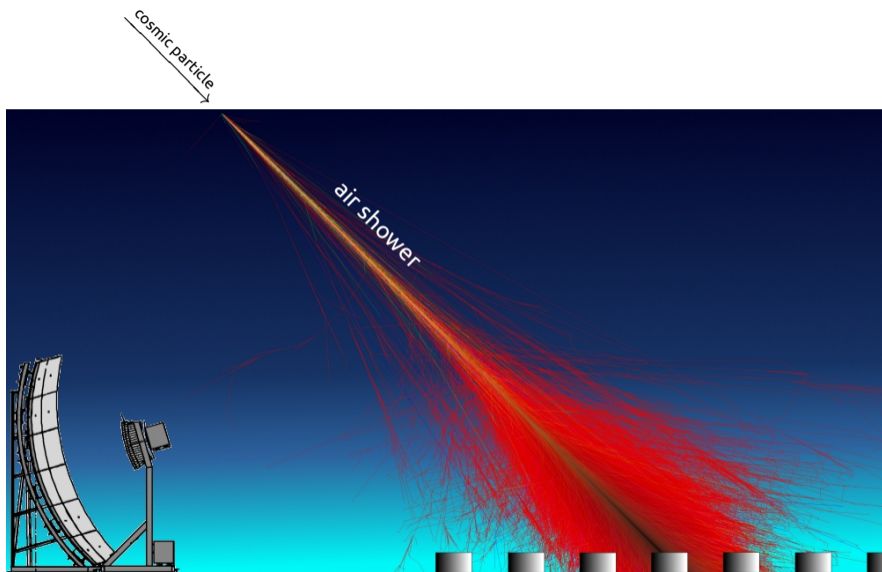
Serena Williams' 2nd serve

$\sim 20 \text{ J!}$

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

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

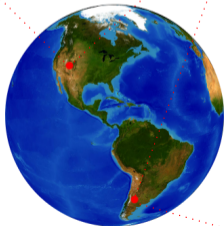
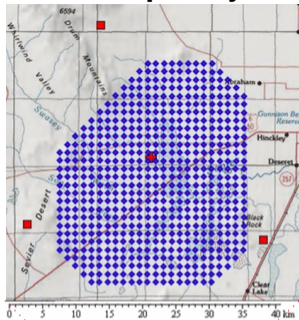
Detection of UHECRs: Air Showers



fluorescence telescope

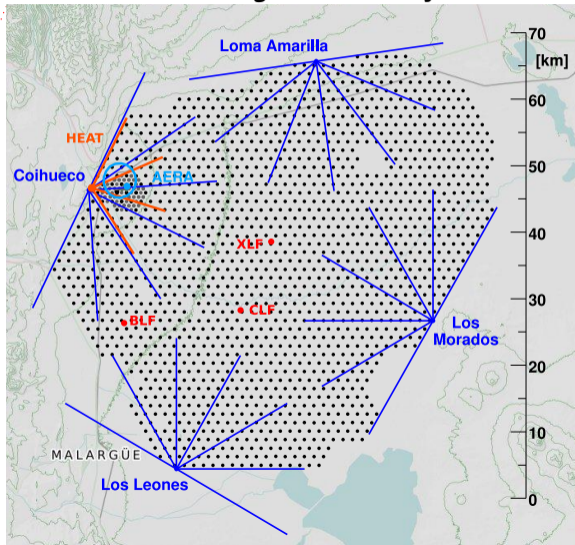
particle detector

Telescope Array

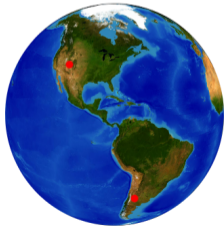


UHECR Observatories

Pierre Auger Observatory



Telescope Array



UHECR Observatories

Pierre Auger Observatory



- **Astrophysics at Extreme Energies**
- **Particle Physics at Extreme Energies**

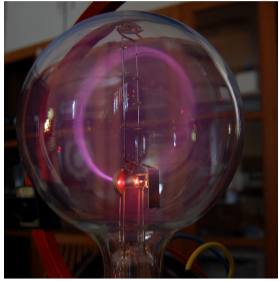


- **Astrophysics at Extreme Energies**
- Particle Physics at Extreme Energies

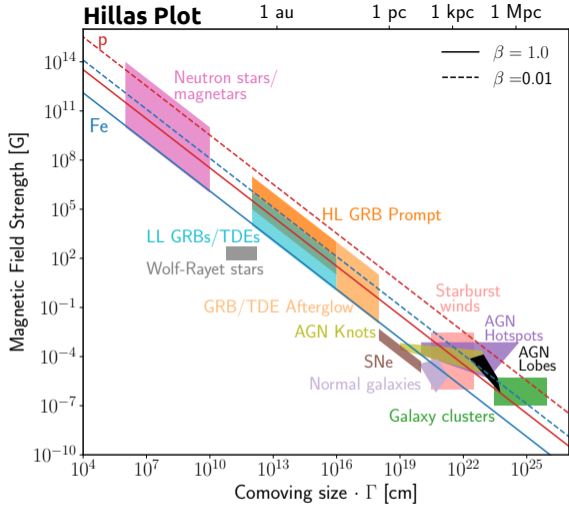


Source Candidates

magnetic confinement during acceleration



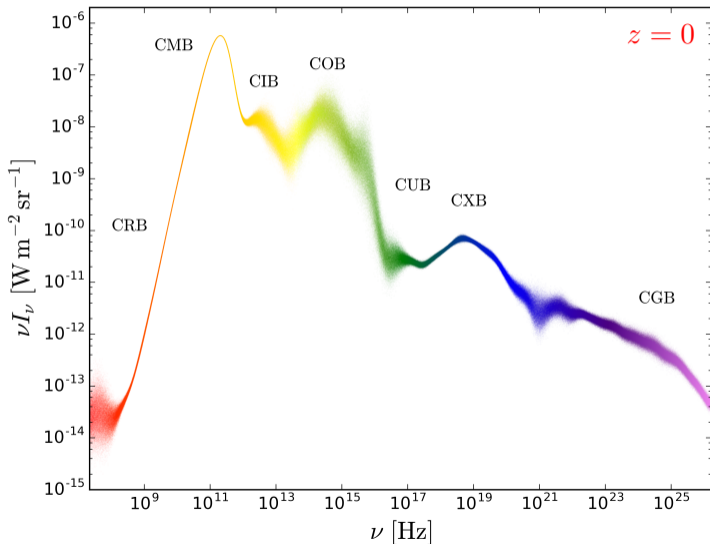
using LHC magnets at 10^{20} eV:



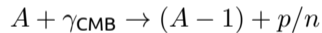
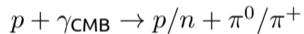
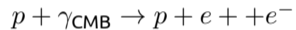
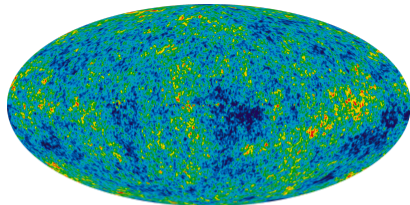
MAPP review, FrontAstron.Space Sci. 6 (2019) 23



Propagation of UHECRs in Photon Fields



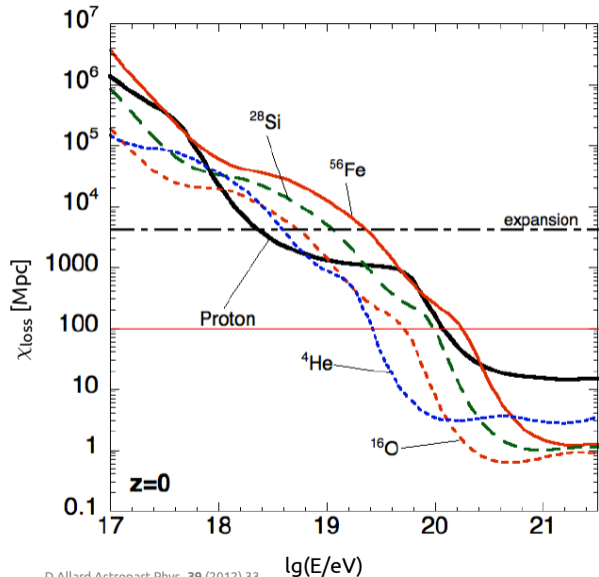
CMB (WMAP)



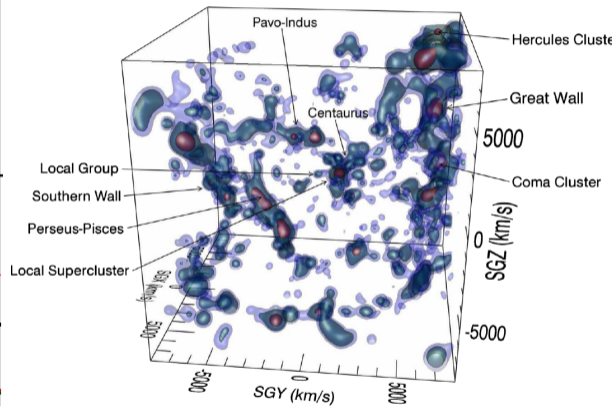
Greisen, Zatsepin & Kuzmin (GZK) 1966



Propagation of UHECRs in Photon Fields



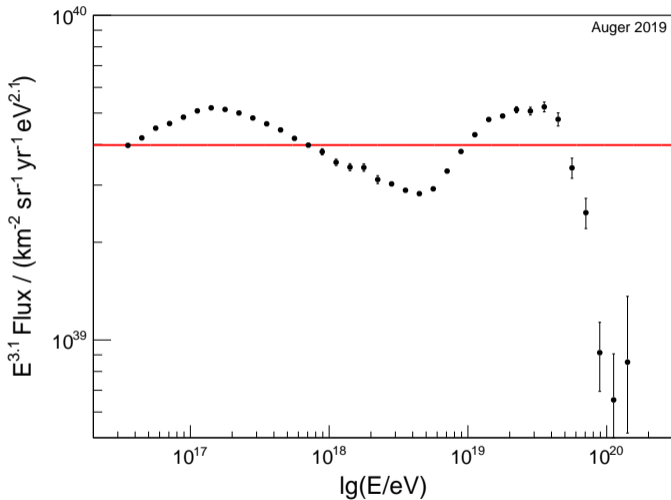
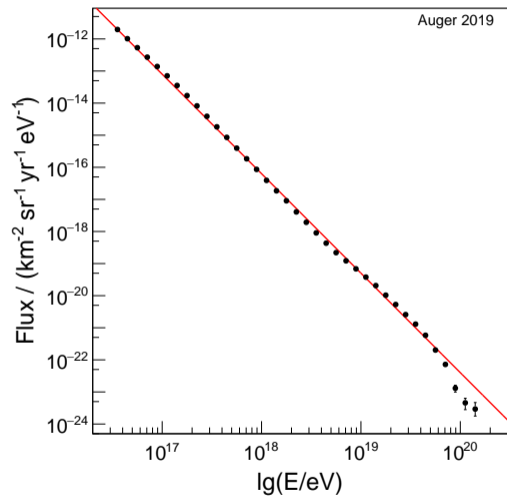
D.Allard *Astropart.Phys.* 39 (2012) 33



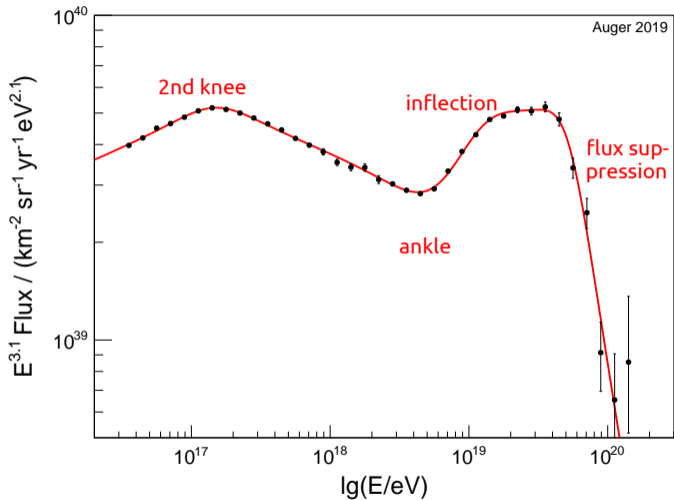
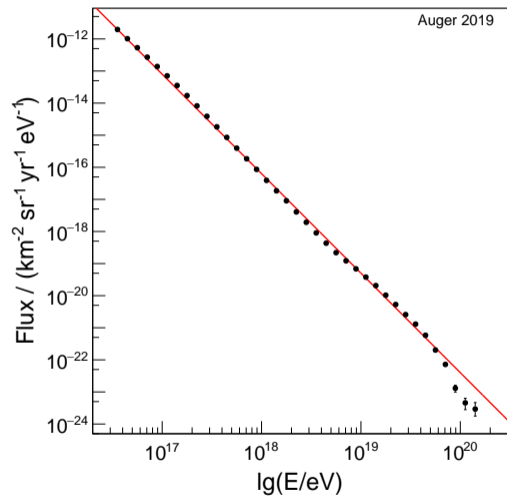
Y.Hoffman et al, *Nat.Astron.* 2 (2018) 680

local universe: inhomogeneous and anisotropic!

Energy Spectrum



Energy Spectrum

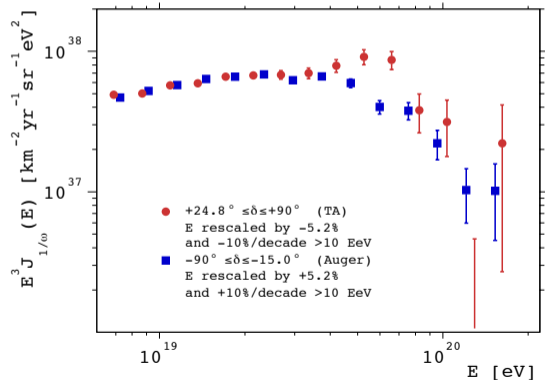
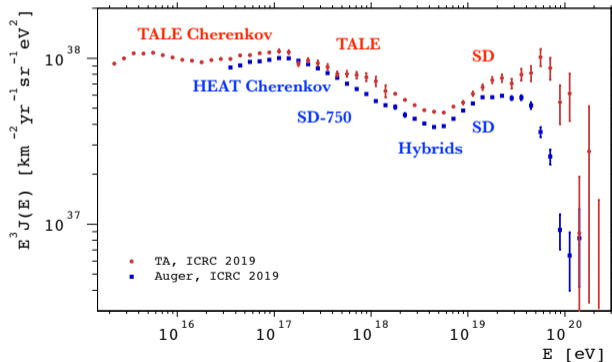


Energy Spectrum

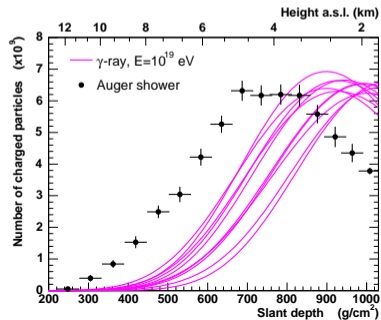
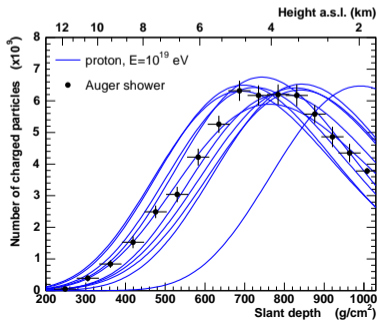
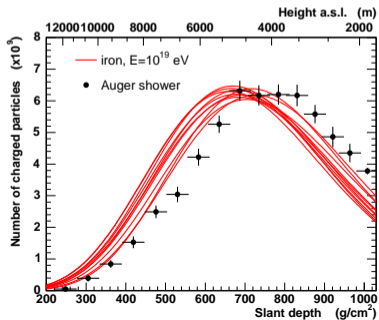


UHECR2018 Paris

Difference in Northern and Southern hemisphere? → UHECR Spectrum Working Group (TA+Auger)



UHECR Composition



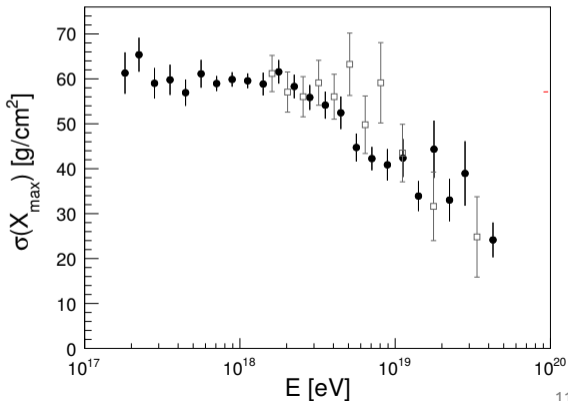
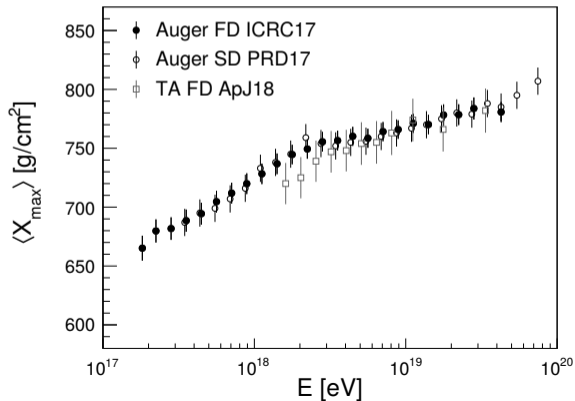
UHECR Composition

Telescope Array Coll. ApJ 858 (2018) 2

Pierre Auger Coll. PRD90 (2014) 12 and 1708.06592

A. Yushkov for the Auger and TA Coll. EPJ210 (2019) 01009

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



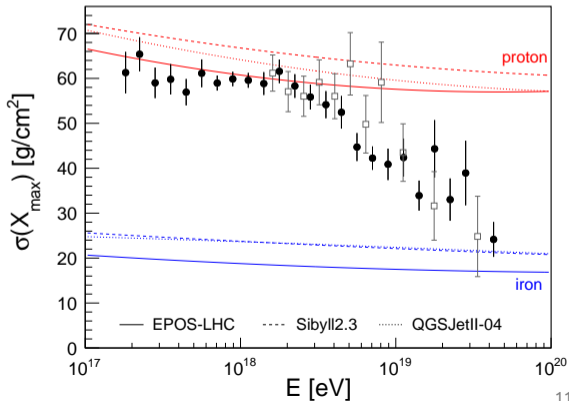
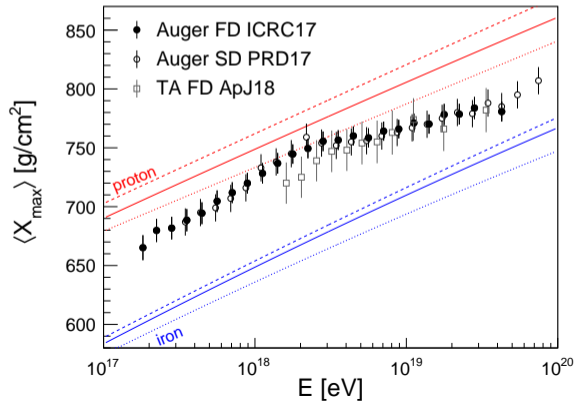
UHECR Composition

Telescope Array Coll. ApJ 858 (2018) 2

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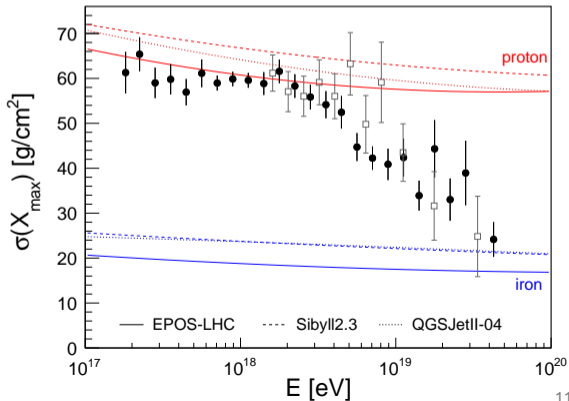
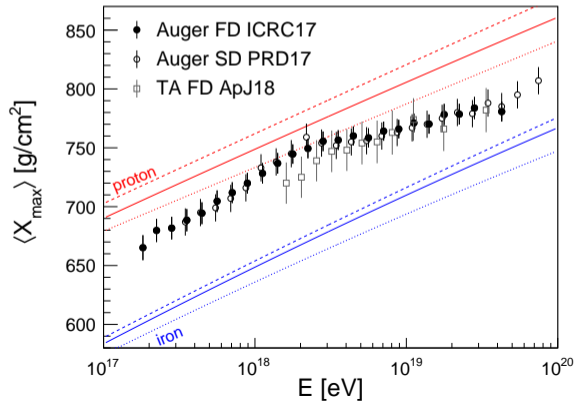
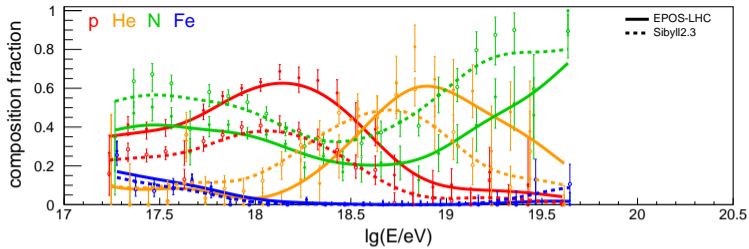
UHECR Composition

Telescope Array Coll. ApJ 858 (2018) 2

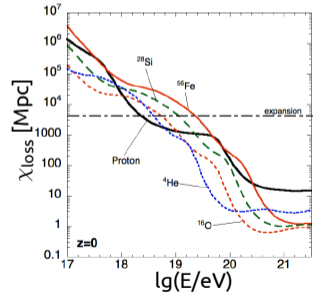
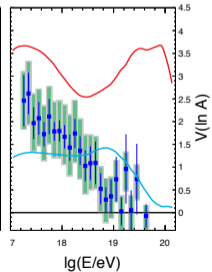
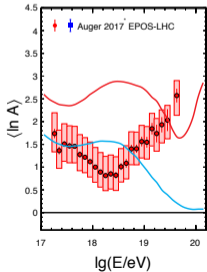
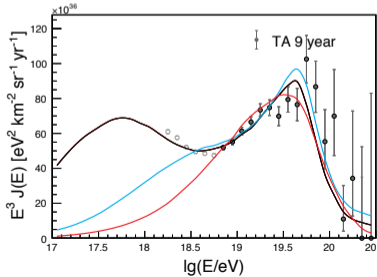
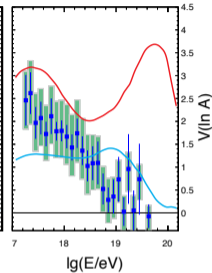
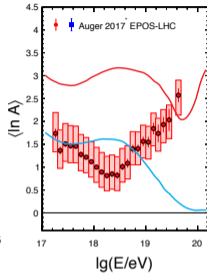
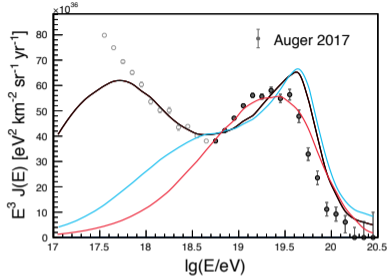
Pierre Auger Coll. PRD90 (2014) 12 and 1708.06592

A. Yushkov for the Auger and TA Coll. EPJ210 (2019) 01009

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



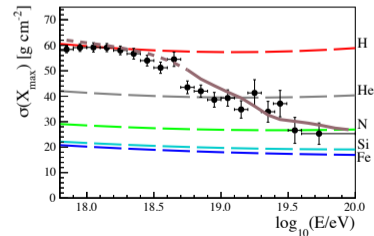
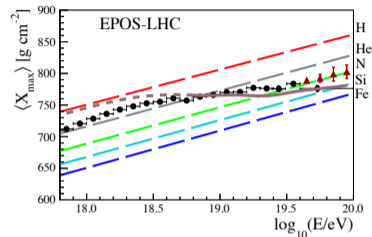
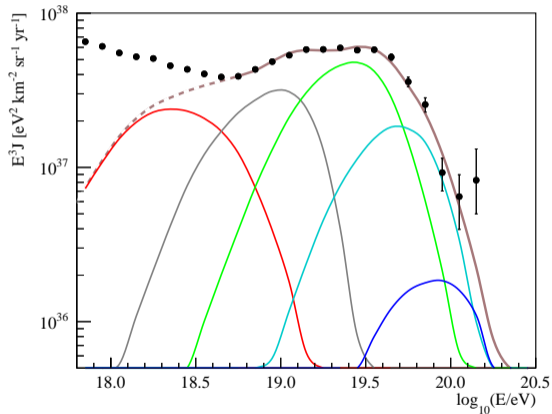
GZK Flux Suppression?



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

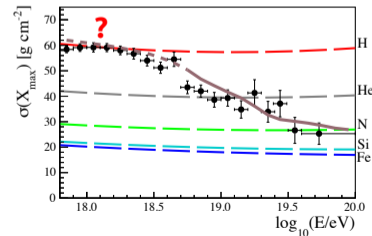
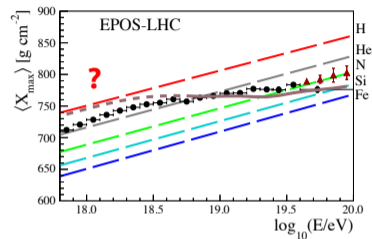
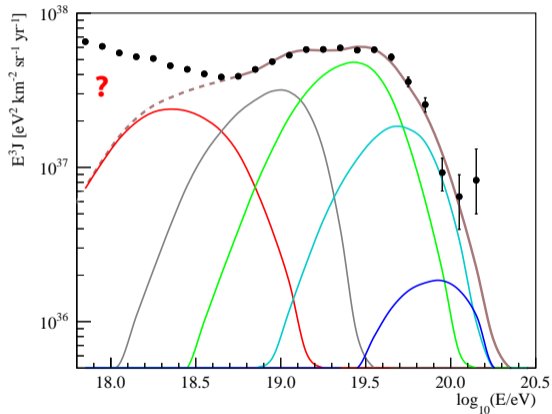
Maximum Rigidity Model, Peters Cycle?

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

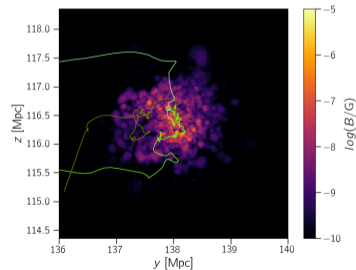
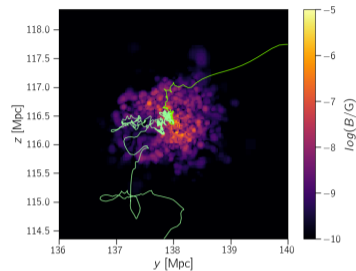
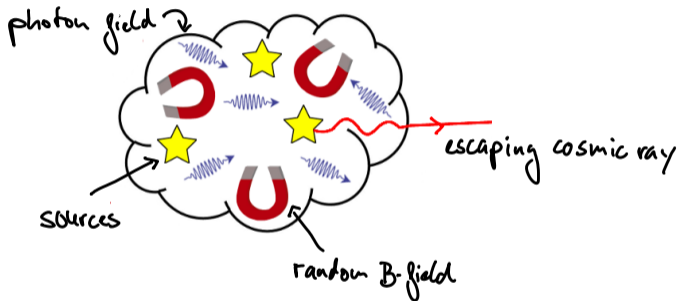


Maximum Rigidity Model, Peters Cycle?

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



Photonuclear Interactions in Source Environment?

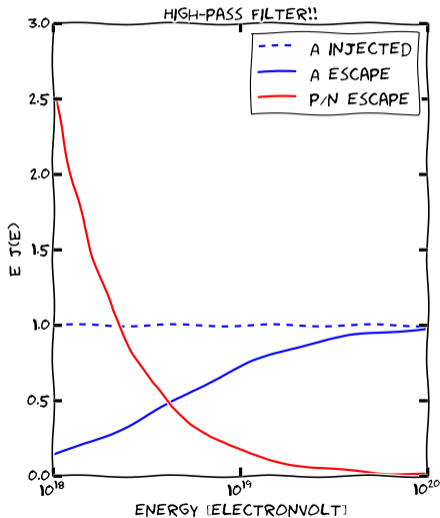
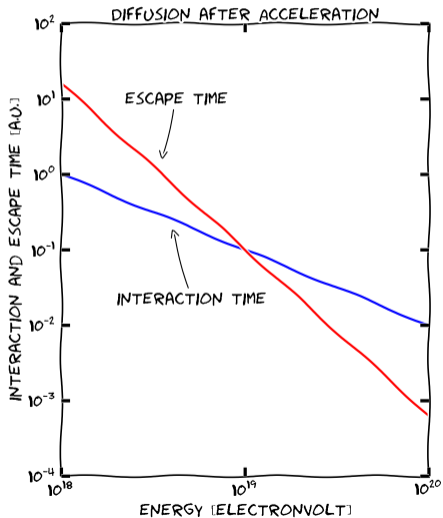


MU, G. Farrar, L. Anchordoqui, PRD **92** (2015) 123001 and M. Muzio, MU, G. Farrar arXiv:1906.06233
see also Globus+15, Biel+17, Kachelriess+17, Supanitsky+18

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

Photonuclear Interactions in Source Environment?

analytic example: full spallation of nucleus A , diffusion $\tau_{\text{esc}} \propto E^\alpha$, $\tau_{\text{int}} \propto E^\beta$

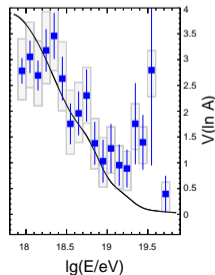
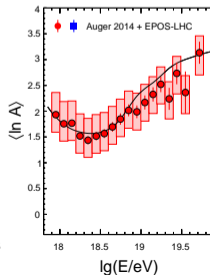
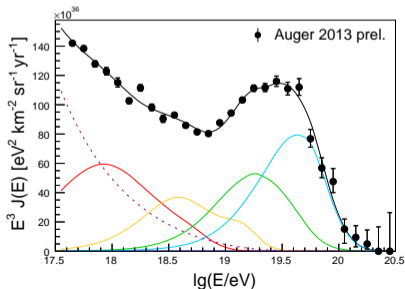
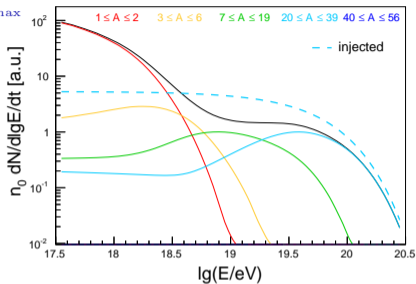


Single Mass + Photonuclear Interactions in Source Environment

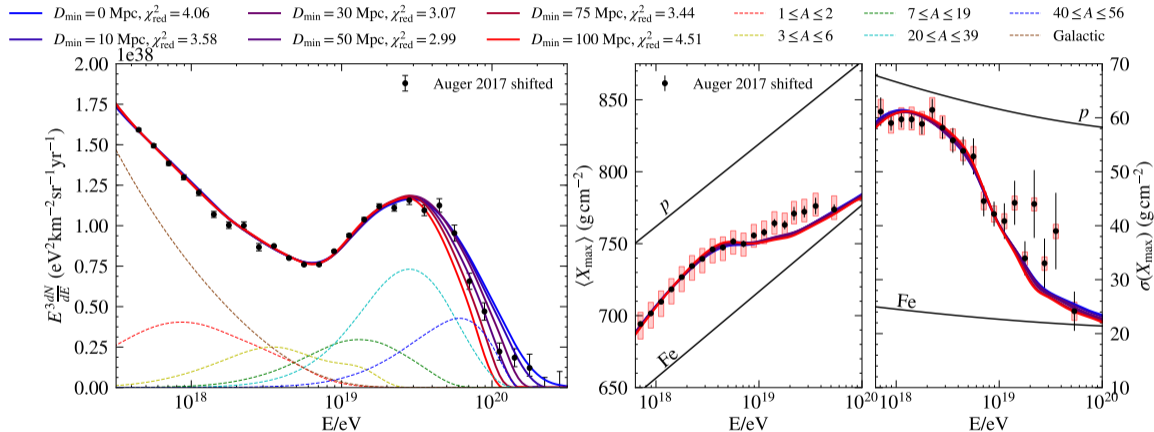
Fiducial Scenario $+1\sigma_E -1\sigma_{X_{\max}}$

^{29}Si injected, escaping
flux at source

flux and composition
at Earth

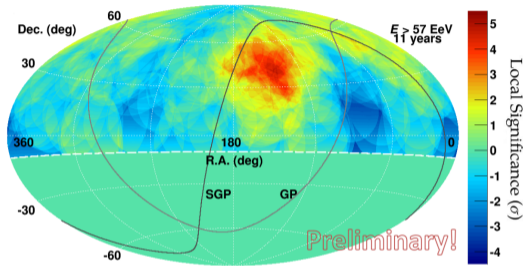


Peters Cycle (Galactic Composition) + Photonuc. Int. in Source



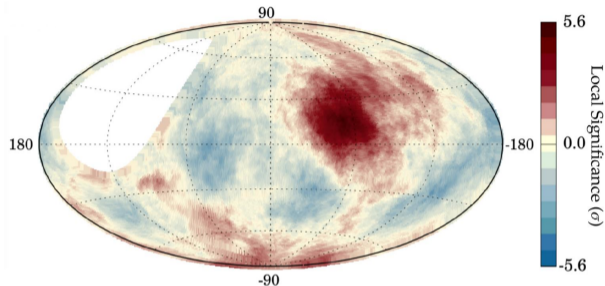
Arrival Directions – Blind Search

Telescope Array (equatorial coordinates)



- energy threshold $5.7 \times 10^{19} \text{ eV}$
- search radius 25°
- $n_{\text{obs}} = 38, n_{\text{exp}} = 14.2$
- 5.1σ local significance
- 0.21% post-trial chance probability

Pierre Auger Observatory (Galactic coordinates)

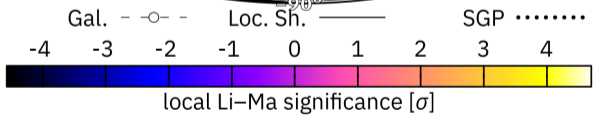
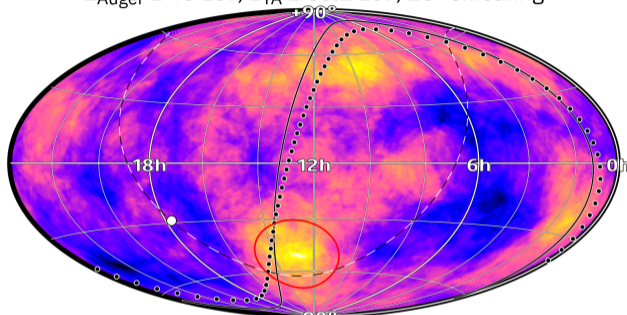


- energy threshold $3.8 \times 10^{19} \text{ eV}$
- search radius 27°
- $n_{\text{obs}} = 188, n_{\text{exp}} = 125$
- 5.6σ local significance
- 2.5% post-trial chance probability

Arrival Directions – Blind Search

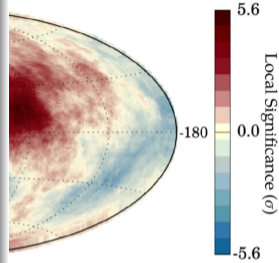
Full-sky analysis (equatorial coordinates)

$E_{\text{Auger}} \geq 40 \text{ EeV}$, $E_{\text{TA}} \geq 53.2 \text{ EeV}$; 20° smearing



- Most statistically significant excesses:
- 20° radius around $(12^{\text{h}} 50^{\text{m}}, -50^\circ)$ 4.7σ pre-trial (2.2σ post-trial)
 - 15° radius around $(9^{\text{h}} 30^{\text{m}}, +54^\circ)$ 4.2σ pre-trial (1.5σ post-trial)

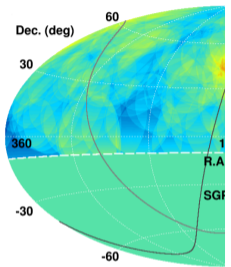
(Galactic coordinates)



10^{19} eV

probability

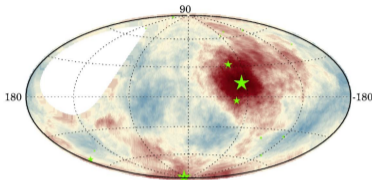
Telescope Array (equatorial coordinates)



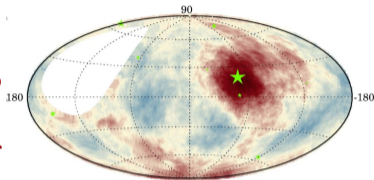
- energy threshold
- search radius 25°
- $n_{\text{obs}} = 38$, $n_{\text{exp}} =$
- 5.1σ local significance
- 0.21% post-trial probability

Arrival Directions – Catalogue-based Analysis

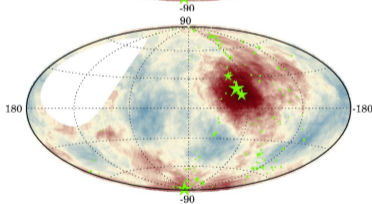
Starburst Galaxies



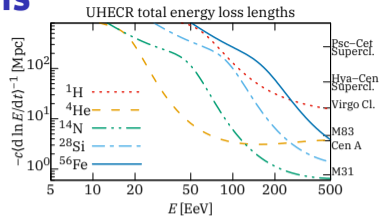
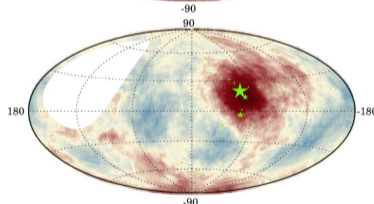
γ -emitting AGNs



2MRS



Swift-BAT

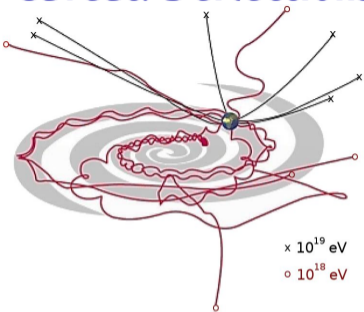


Catalog	E_{th}	θ	f_{aniso}	TS	Post-trial
Starburst	38 EeV	$15^{+5}_{-4}^\circ$	$11^{+5}_{-4}\%$	29.5	4.5σ
γ -AGNs	39 EeV	$14^{+6}_{-4}^\circ$	$6^{+4}_{-3}\%$	17.8	3.1σ
Swift-Bat	38 EeV	$15^{+6}_{-4}^\circ$	$8^{+4}_{-3}\%$	222	3.7σ
2MRS	40 EeV	$15^{+7}_{-4}^\circ$	$19^{+10}_{-7}\%$	220	3.7σ

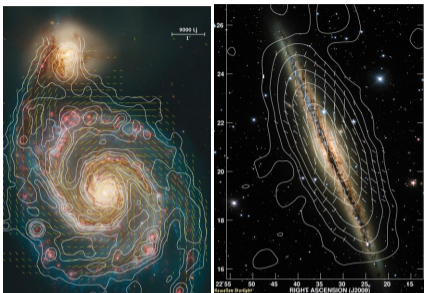
L. Caccianiga for the Pierre Auger Coll. ICRC19, ApJ853 (2018) 2

(using flux-weights attenuated for cosmic-ray energy loss during propagation)

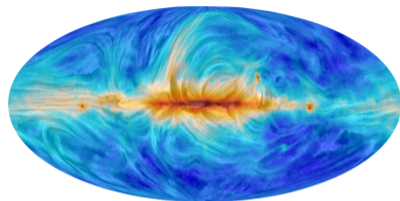
Caveat: Deflections in Galactic Magnetic Field



D. Harari

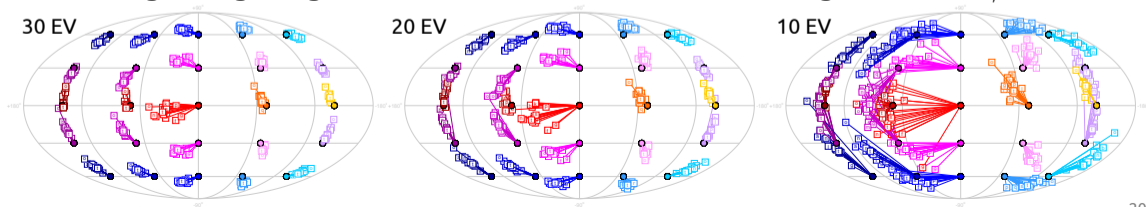


MPIfR (left: M51, right: NGC891)



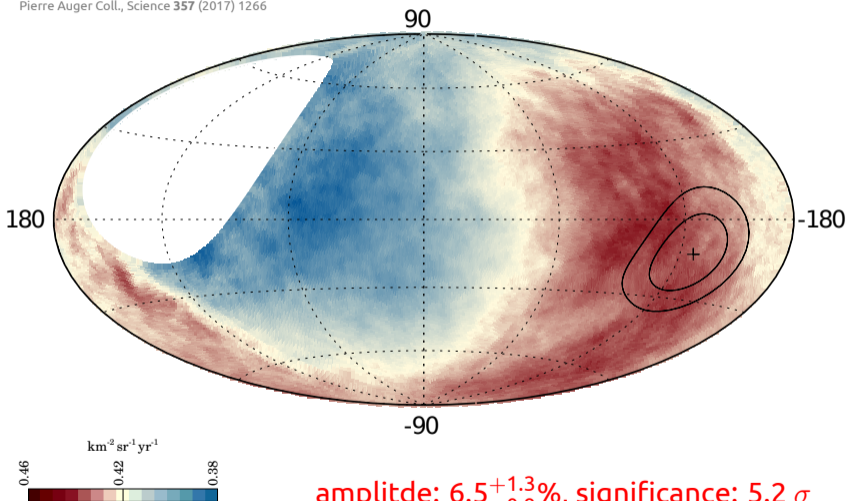
Planck PI@30 GHz

backtracking through magnetic field model variations at different rigidities $R = E/Z$



Observation of a Dipolar Anisotropy of UHECRs ($E > 8 \text{ EeV}$)

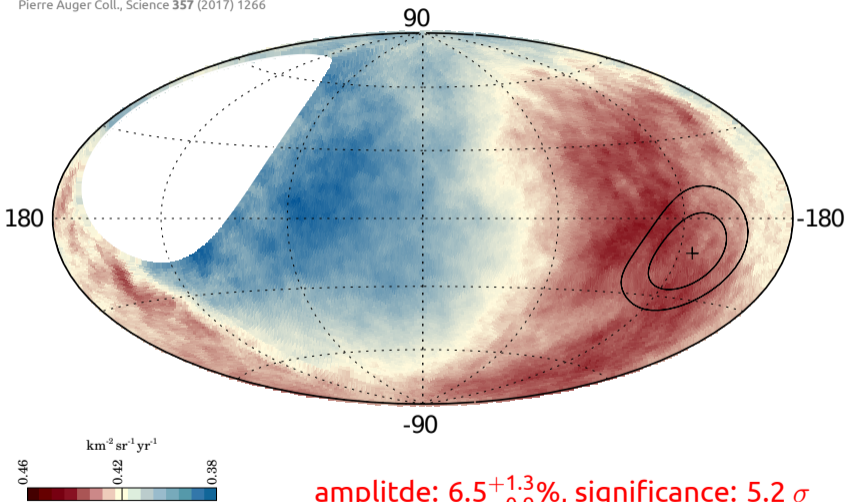
Pierre Auger Coll., Science 357 (2017) 1266



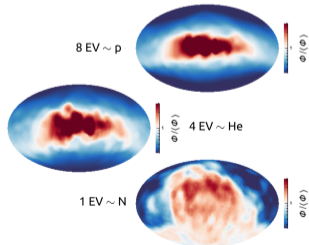
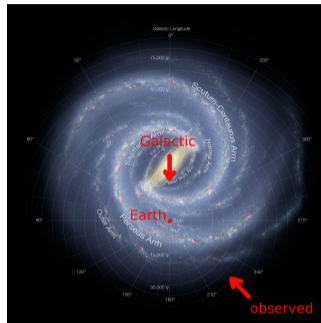
amplitude: $6.5^{+1.3}_{-0.9}\%$, significance: 5.2σ

Observation of a Dipolar Anisotropy of UHECRs ($E > 8 \text{ EeV}$)

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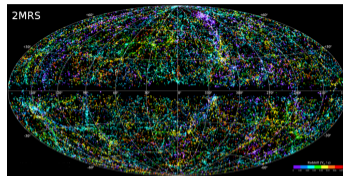
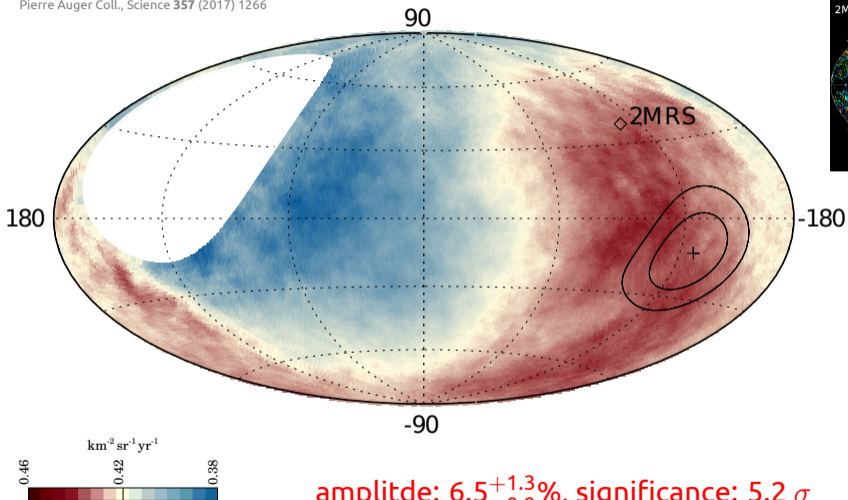


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Observation of a Dipolar Anisotropy of UHECRs ($E > 8 \text{ EeV}$)

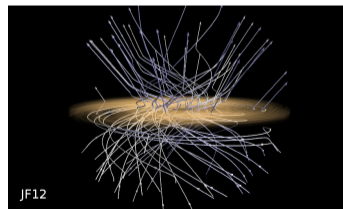
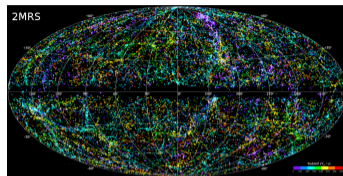
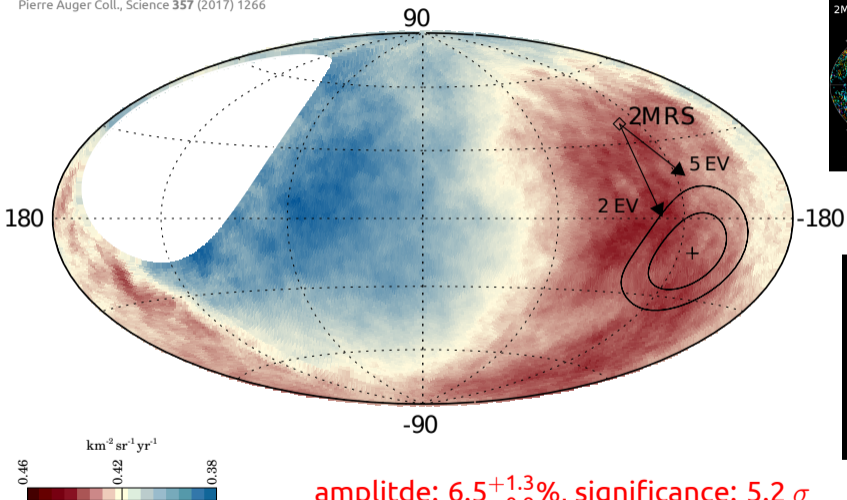
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Observation of a Dipolar Anisotropy of UHECRs ($E > 8 \text{ EeV}$)

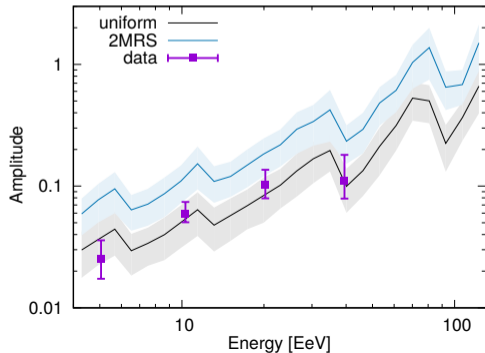
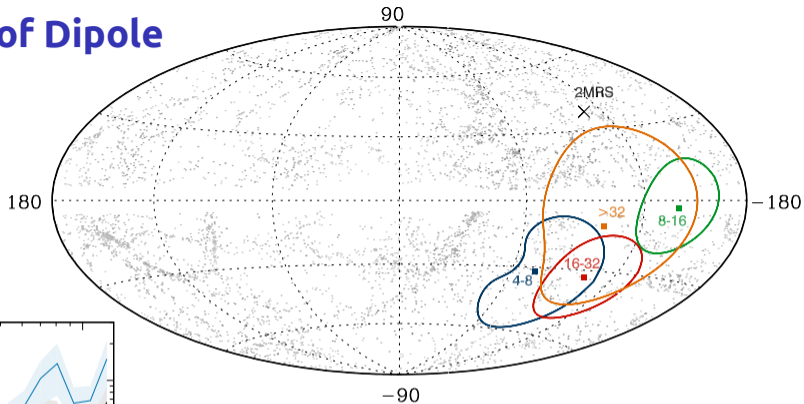
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amplitude: $6.5^{+1.3}_{-0.9}\%$, significance: 5.2σ

Energy Dependence of Dipole

dipole position →

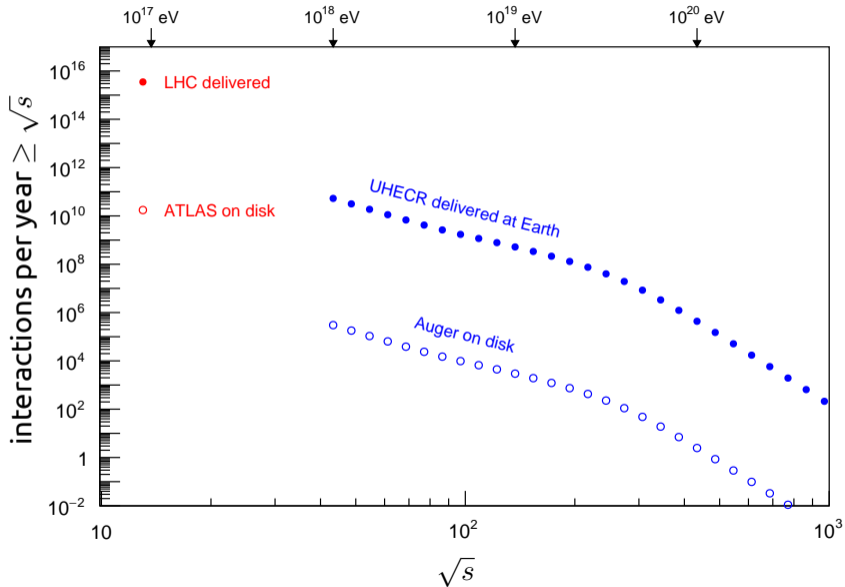


← model: mixed composition
 $R_{\max} = 6 \text{ EeV}, \rho = 10^{-4} \text{ Mpc}^{-3}$

- Astrophysics at Extreme Energies
- Particle Physics at Extreme Energies

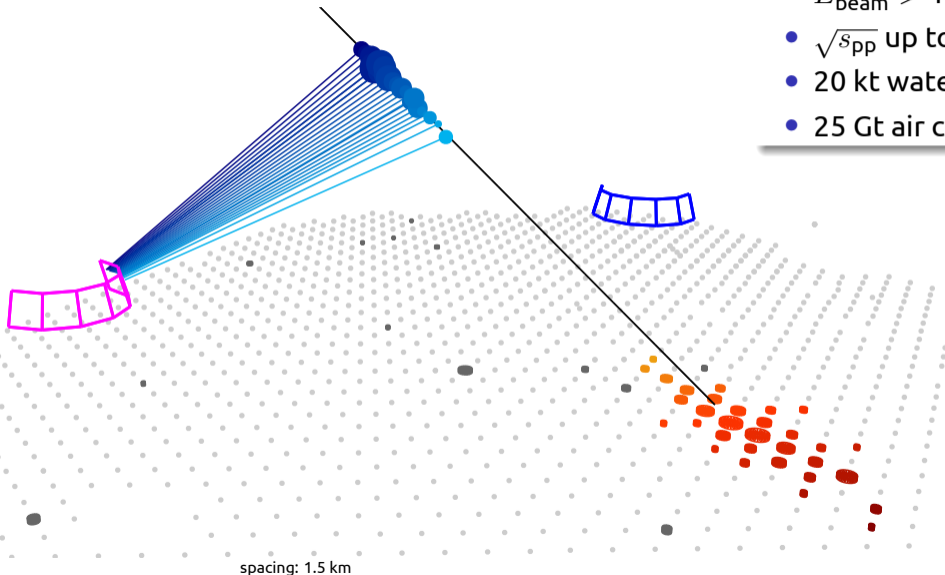


Beam Luminosity



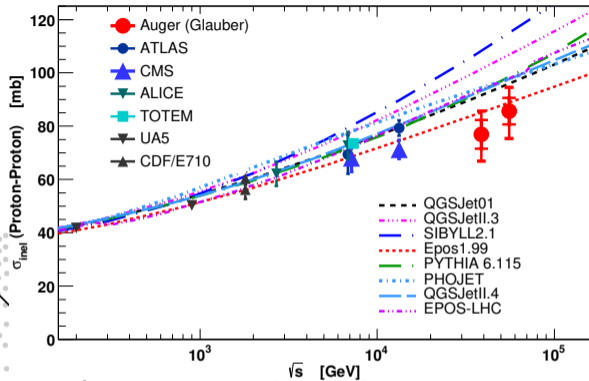
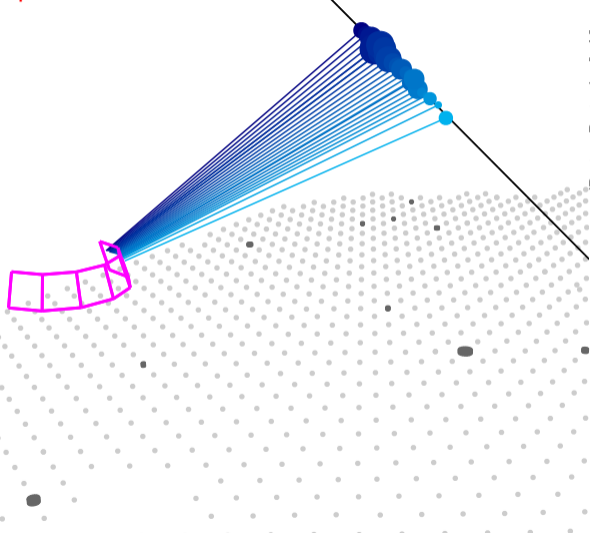
Particle Detector

- $E_{\text{beam}} > 1 \times 10^8 \text{ TeV}$
- $\sqrt{s_{pp}}$ up to 400 TeV
- 20 kt water-Cherenkov
- 25 Gt air calorimeter

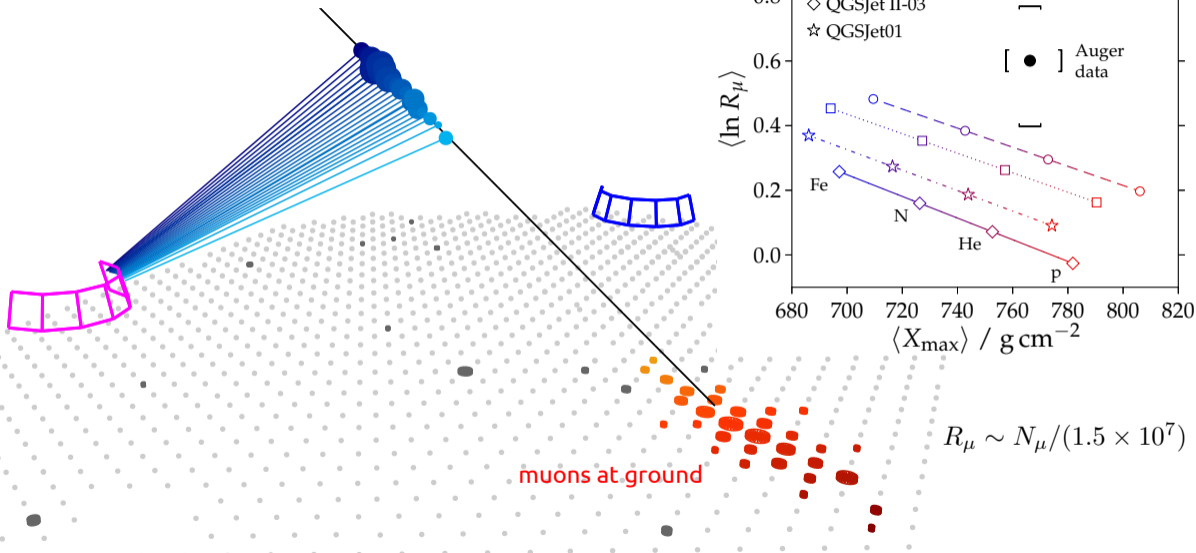


UHE Proton+Proton Cross Section

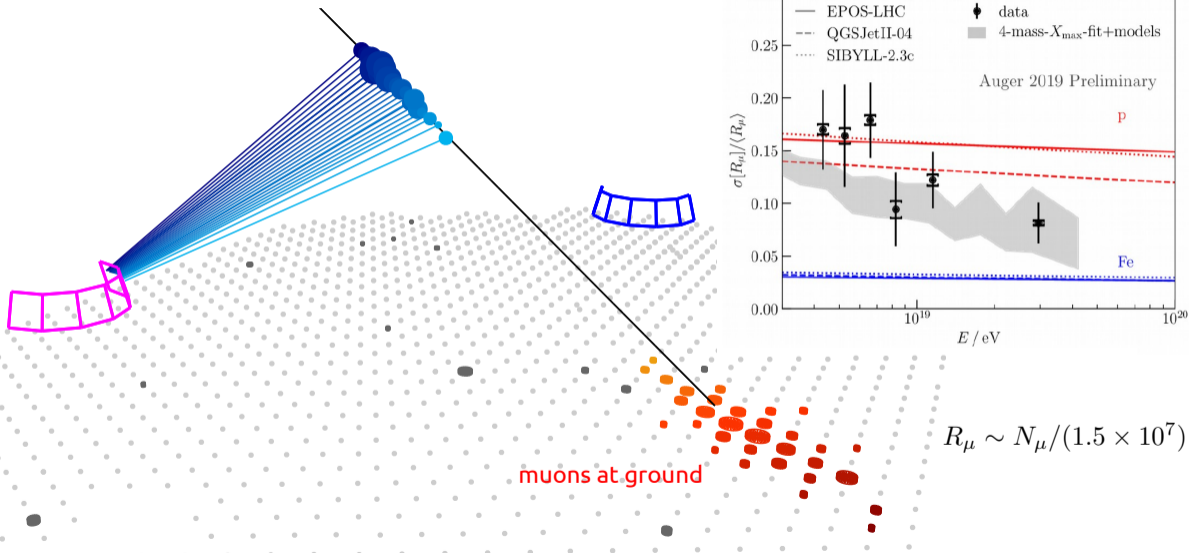
point of first interaction → ●



Muon Production in Air Showers



Muon Production in Air Showers



Summary: Cosmic Particles at Extreme Energies

previously

today



Las Meninas by Diego Velazquez 1656



Las Meninas by Pablo Picasso 1957

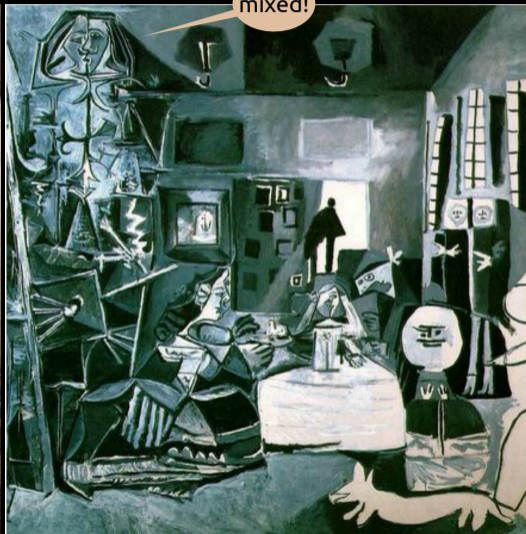
Summary: Cosmic Particles at Extreme Energies

previously

today

mixed!

proton!



Las Meninas by Diego Velazquez 1656

Las Meninas by Pablo Picasso 1957

Summary: Cosmic Particles at Extreme Energies

previously

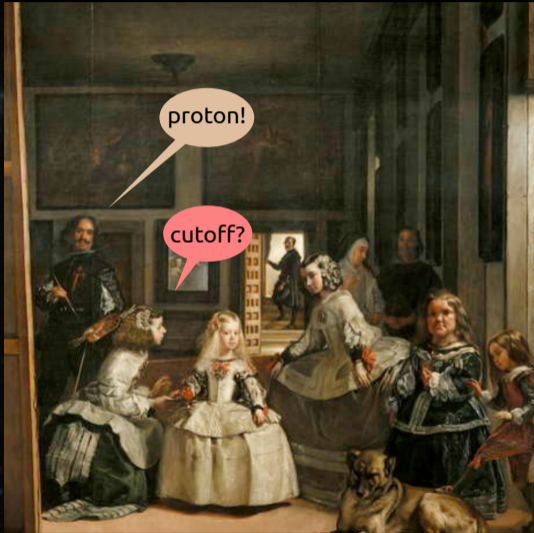
today

mixed!

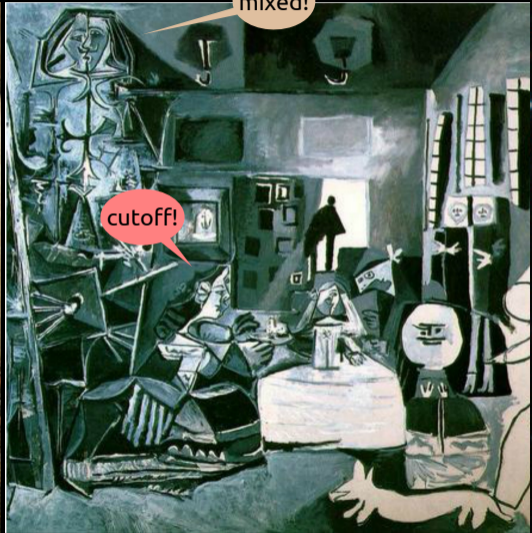
proton!

cutoff?

cutoff!



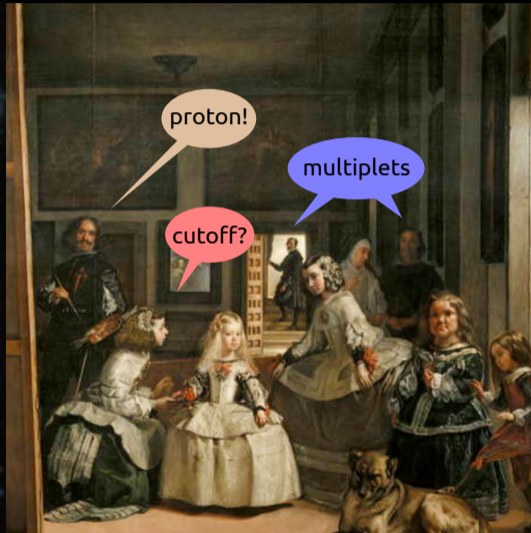
Las Meninas by Diego Velazquez 1656



Las Meninas by Pablo Picasso 1957

Summary: Cosmic Particles at Extreme Energies

previously



Las Meninas by Diego Velazquez 1656

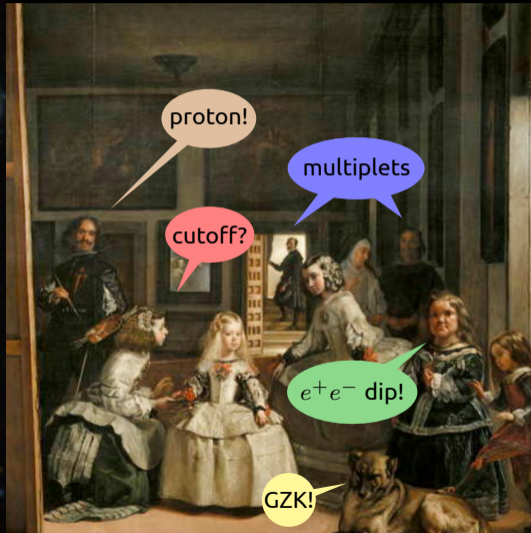
today



Las Meninas by Pablo Picasso 1957

Summary: Cosmic Particles at Extreme Energies

previously



Las Meninas by Diego Velazquez 1656

today



Las Meninas by Pablo Picasso 1957

Stay Tuned!

Under Construction: **AugerPrime**



arXiv:1604.03637

Under Construction: **TAX4**



EPJ210 (2019) 06001

Launch 2029: **POEMMA?**



PRD101 (2020) 023012