



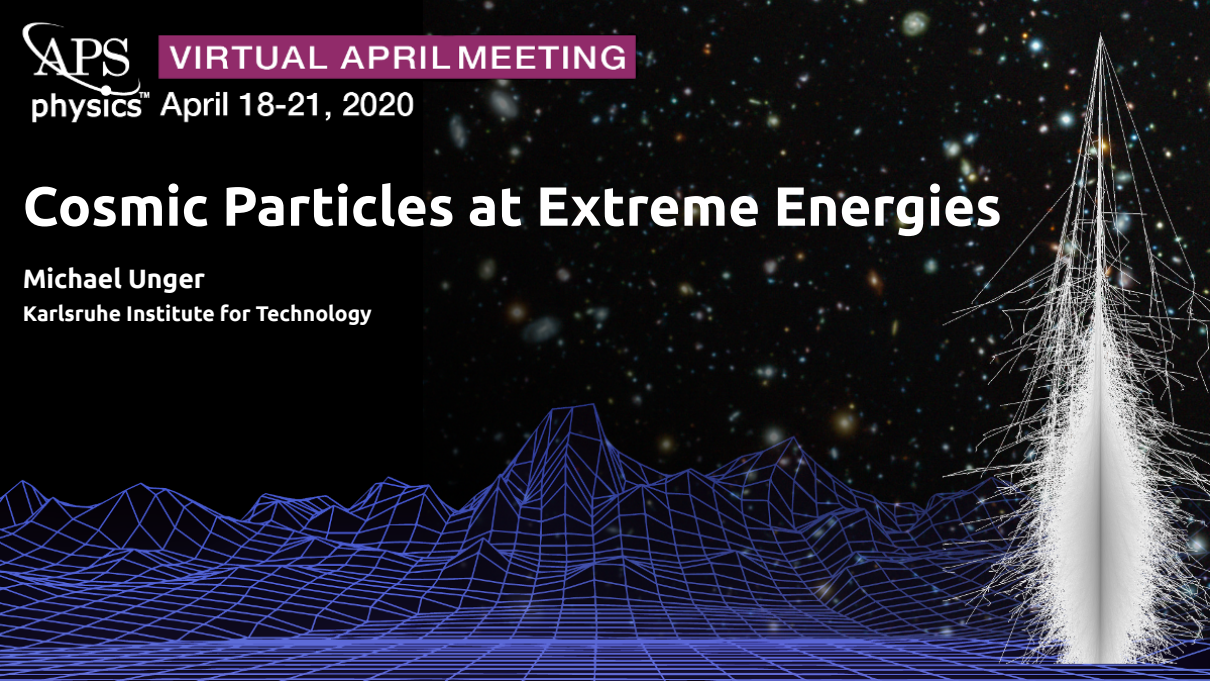
VIRTUAL APRIL MEETING

April 18-21, 2020

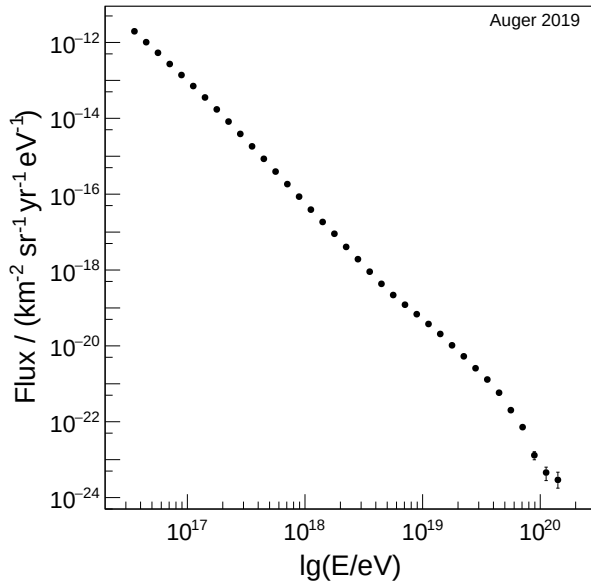
Cosmic Particles at Extreme Energies

Michael Unger

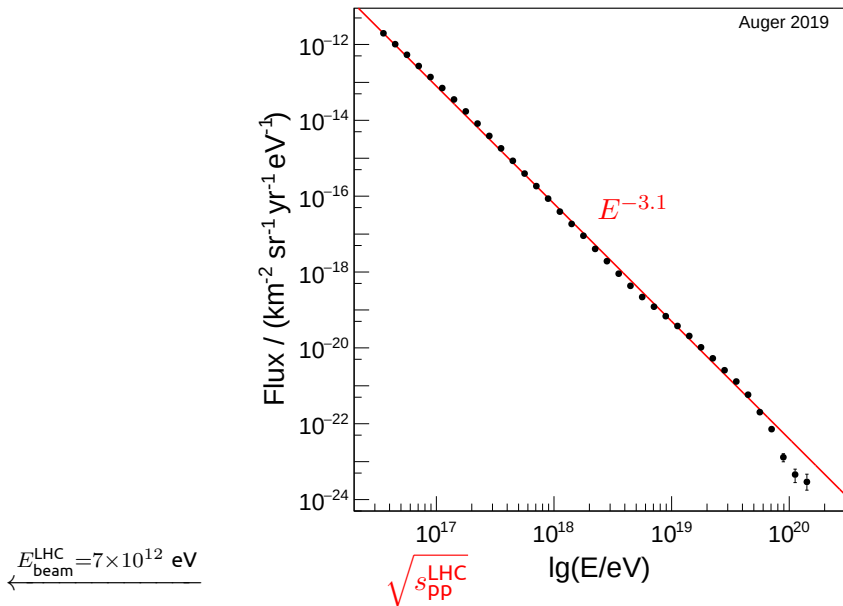
Karlsruhe Institute for Technology



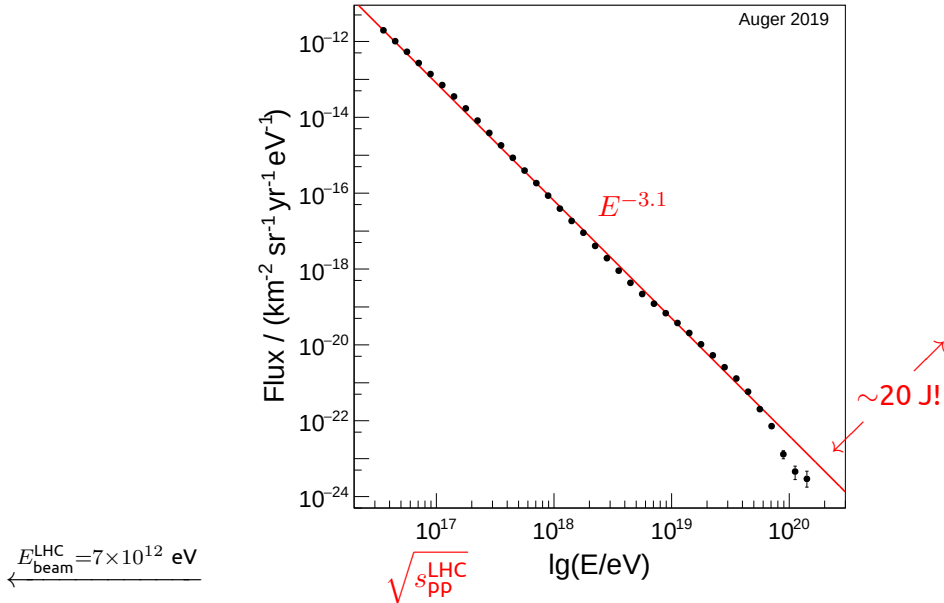
Energy Spectrum of Ultrahigh-Energy Cosmic Rays (UHECRs)



Energy Spectrum of Ultrahigh-Energy Cosmic Rays (UHECRs)

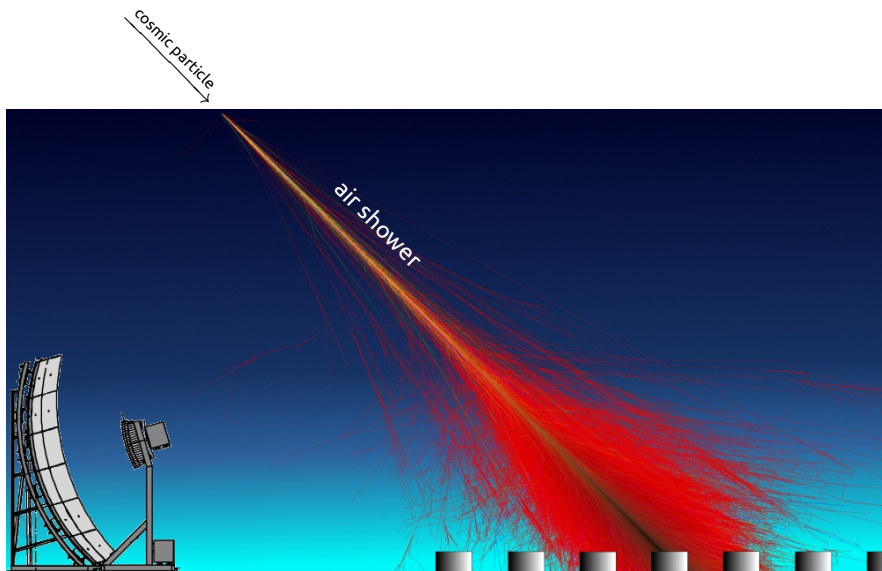


Energy Spectrum of Ultrahigh-Energy Cosmic Rays (UHECRs)



Serena Williams' 2nd serve

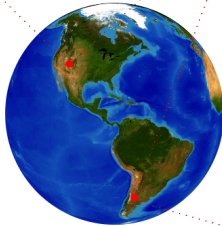
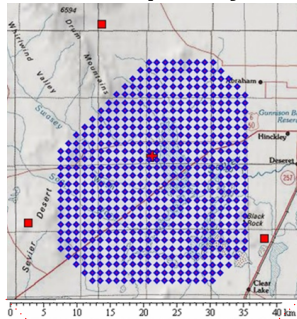
Detection of UHECRs: Air Showers



fluorescence telescope

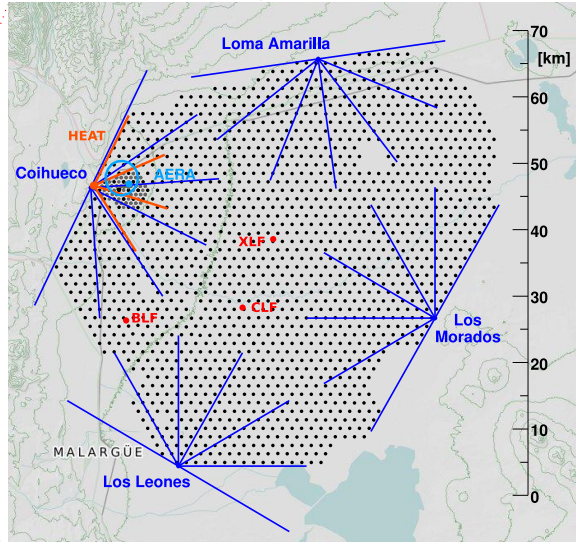
particle detector

Telescope Array



UHECR Observatories

Pierre Auger Observatory



Telescope Array



UHECR Observatories

Pierre Auger Observatory

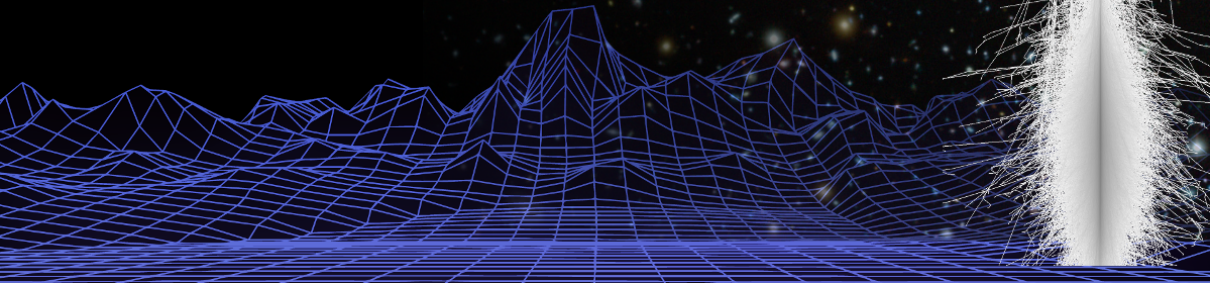




VIRTUAL APRIL MEETING

April 18-21, 2020

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

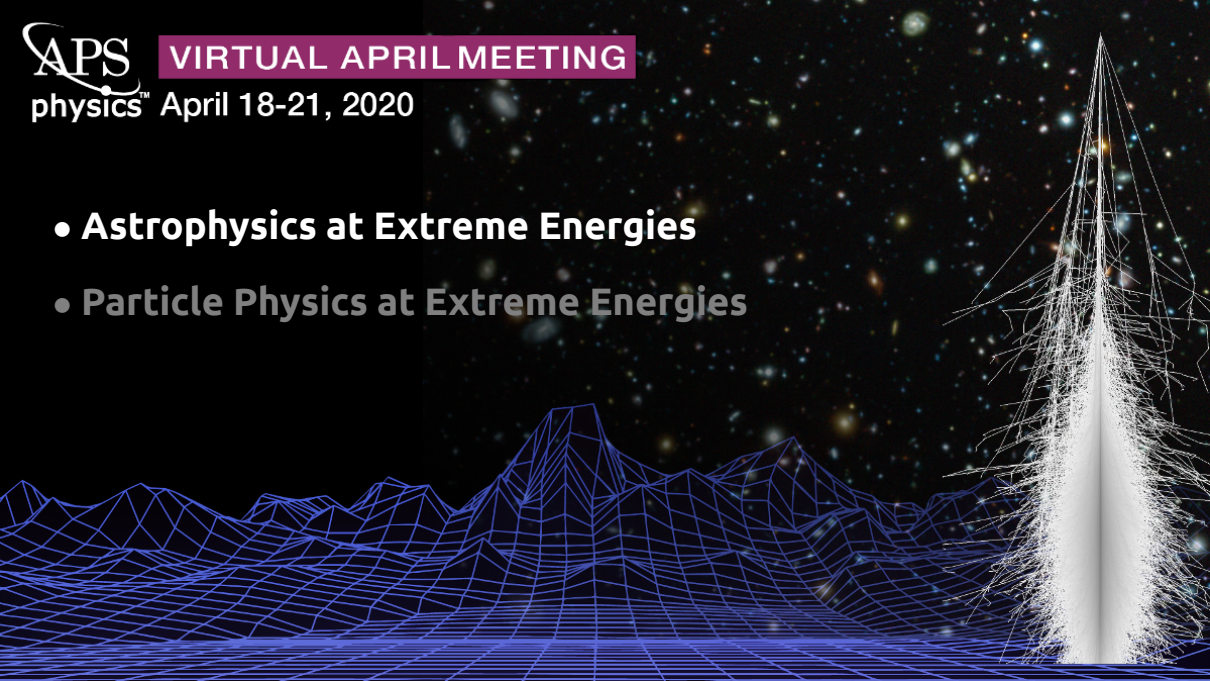




VIRTUAL APRIL MEETING

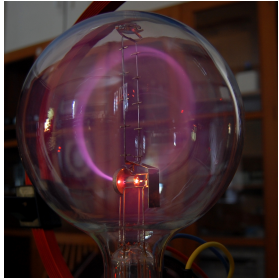
April 18-21, 2020

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

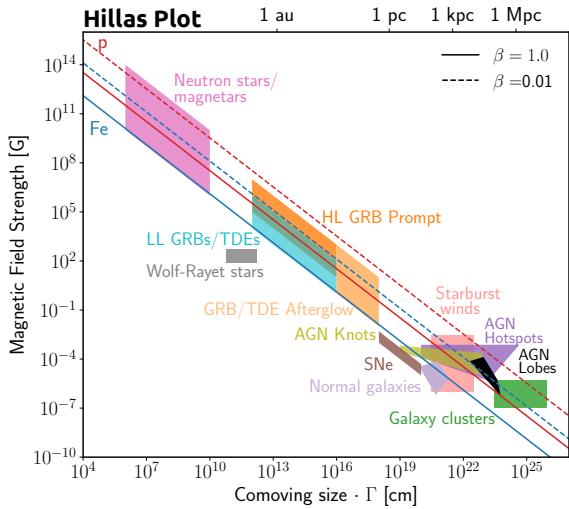


Source Candidates

magnetic confinement during acceleration



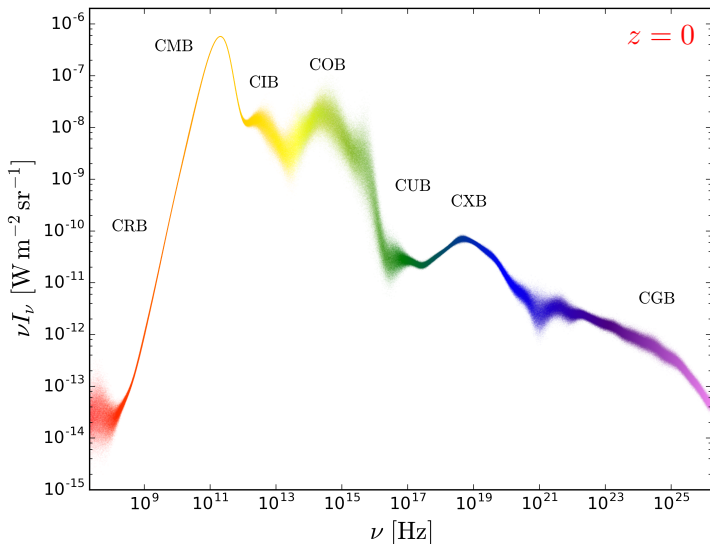
using LHC magnets at 10^{20} eV:



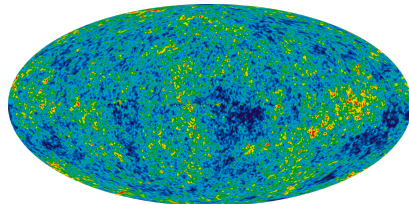
MAAPP review, Front.Astron.Space Sci. 6 (2019) 23



Propagation of UHECRs in Photon Fields



CMB (WMAP)



$$p + \gamma_{\text{CMB}} \rightarrow p + e + e^-$$

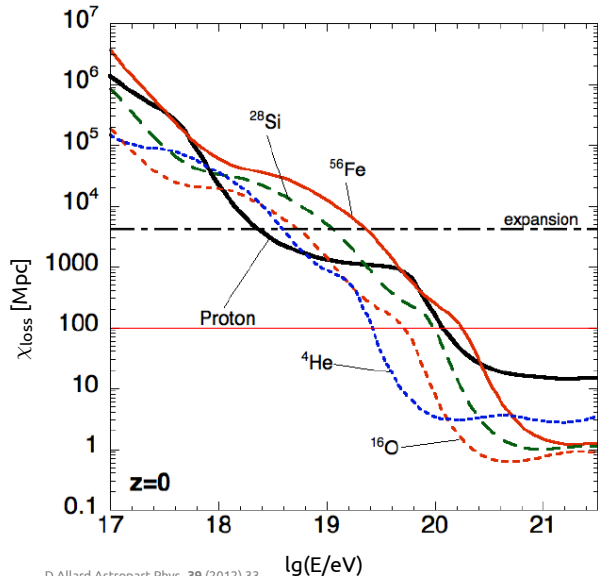
$$p + \gamma_{\text{CMB}} \rightarrow p/n + \pi^0/\pi^\pm$$

$$A + \gamma_{\text{CMB}} \rightarrow (A - 1) + p/n$$

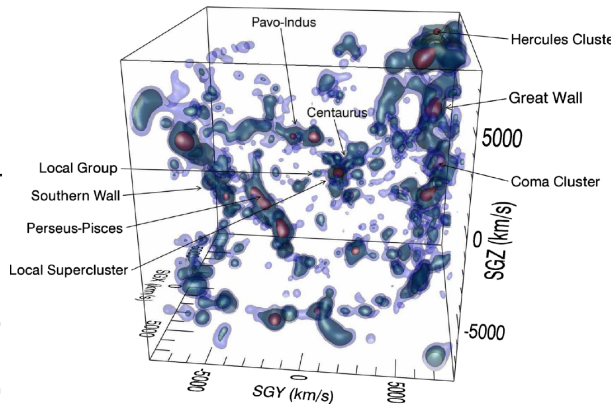
Greisen, Zatsepin & Kuzmin (GZK) 1966



Propagation of UHECRs in Photon Fields



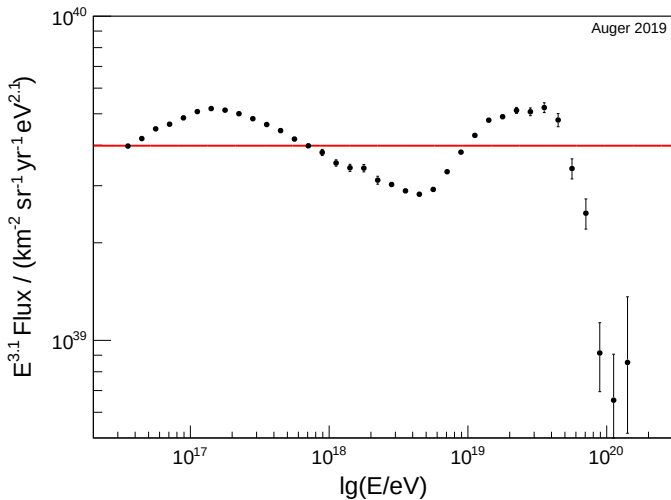
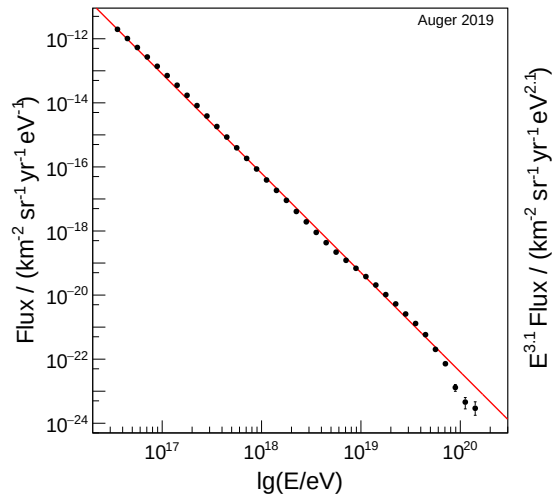
D.Allard Astropart.Phys. 39 (2012) 33



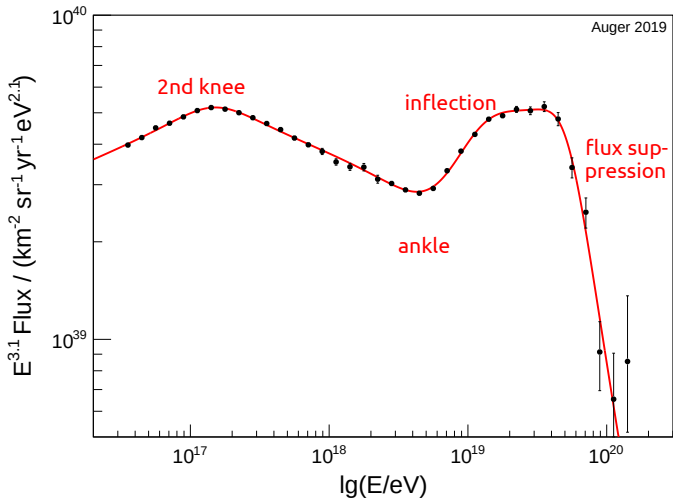
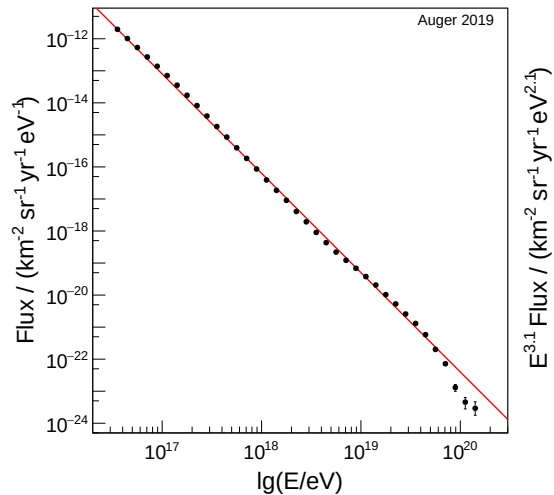
Y.Hoffman et al, Nat.Astron. 2 (2018) 680

local universe: inhomogeneous and anisotropic!

Energy Spectrum



Energy Spectrum

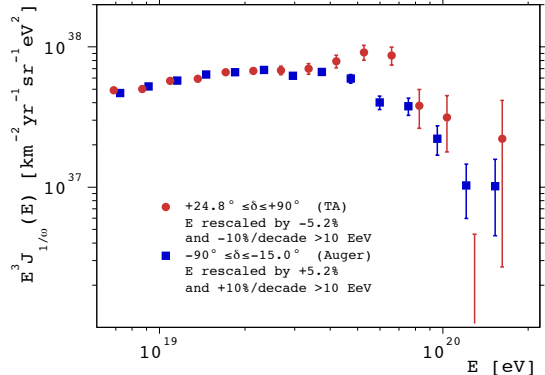
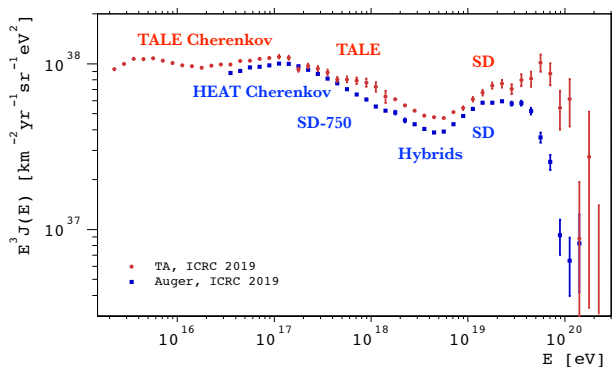


Energy Spectrum



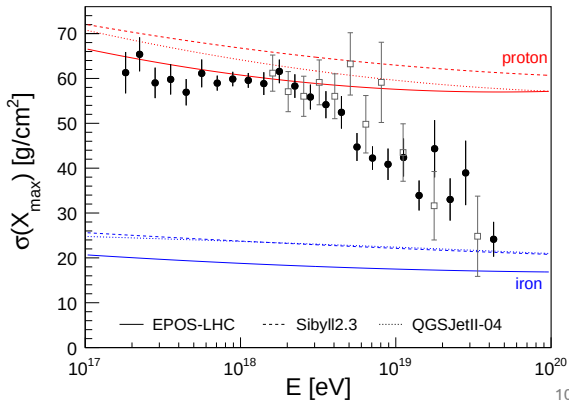
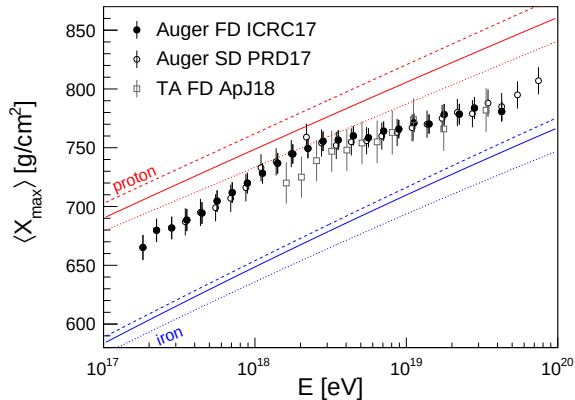
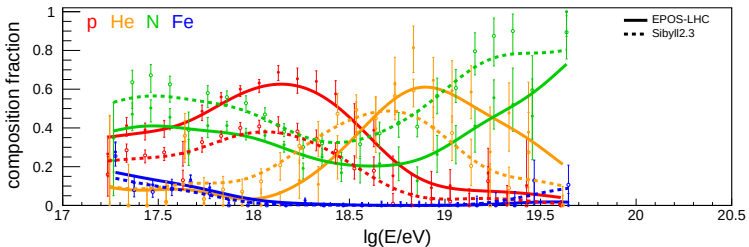
UHECR2018 Paris

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

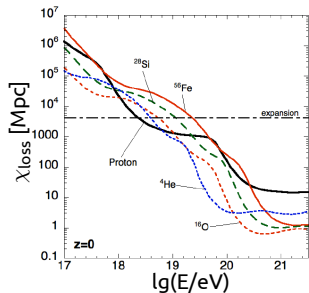
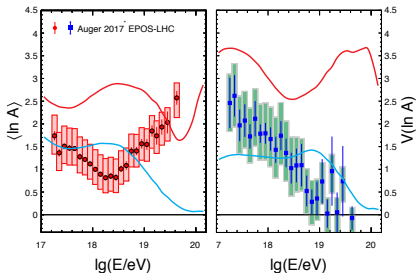
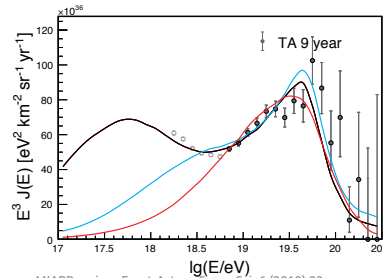
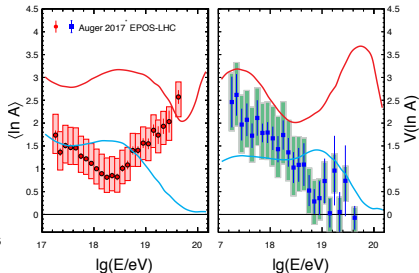
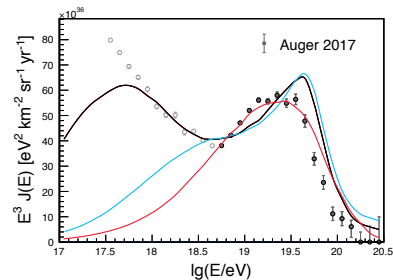


UHECR Composition

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



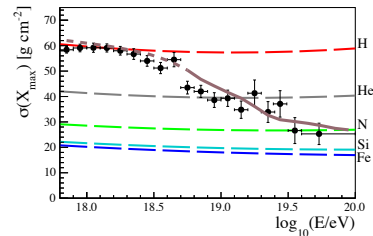
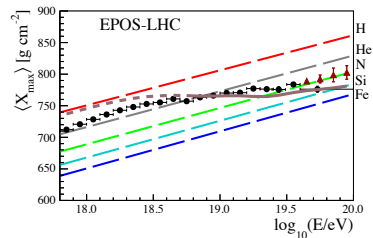
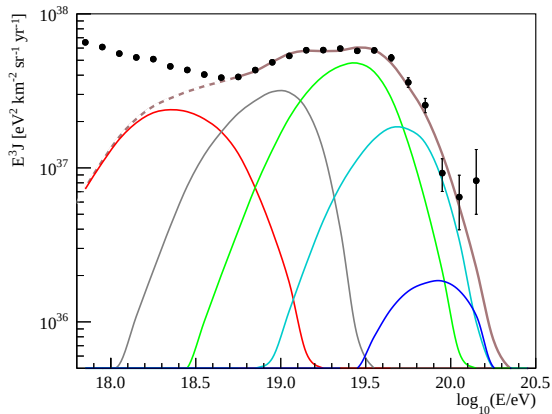
GZK Flux Suppression?



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

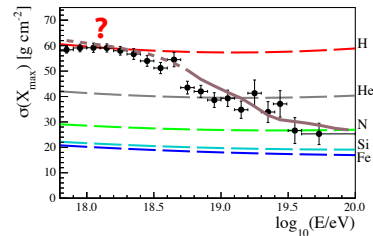
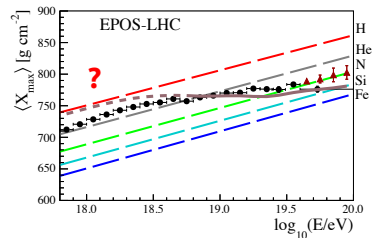
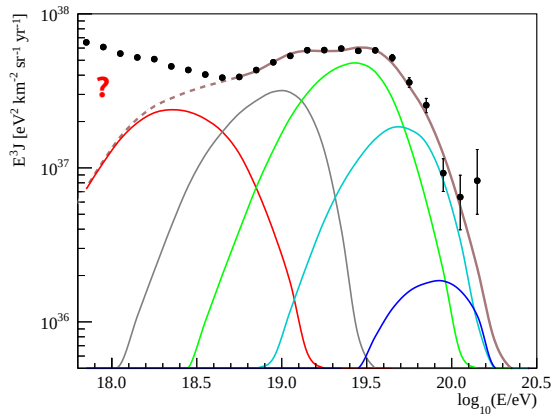
Maximum Rigidity Model, Peters Cycle?

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

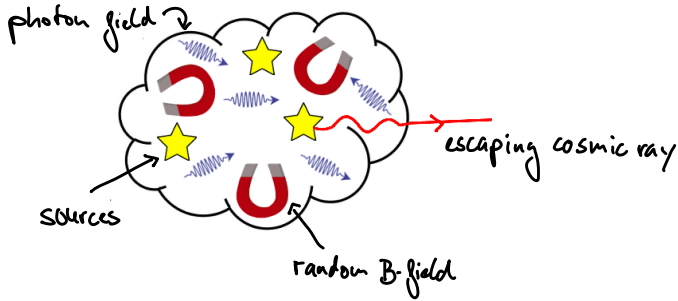


Maximum Rigidity Model, Peters Cycle?

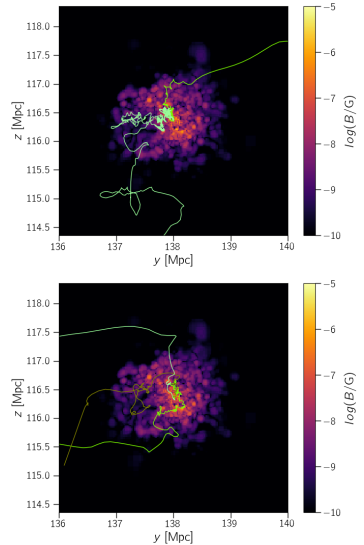
energy spectrum at source $\propto (E/Z)^{-\gamma}$



Photonuclear Interactions in Source Environment?



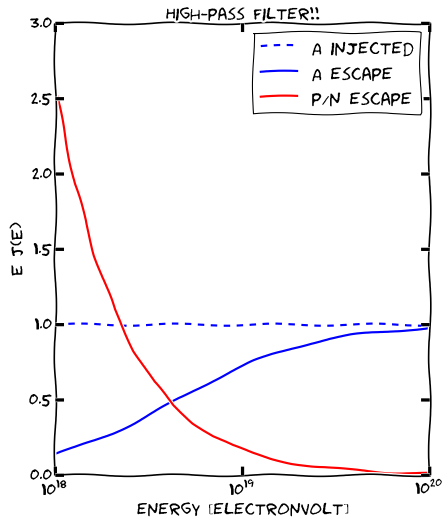
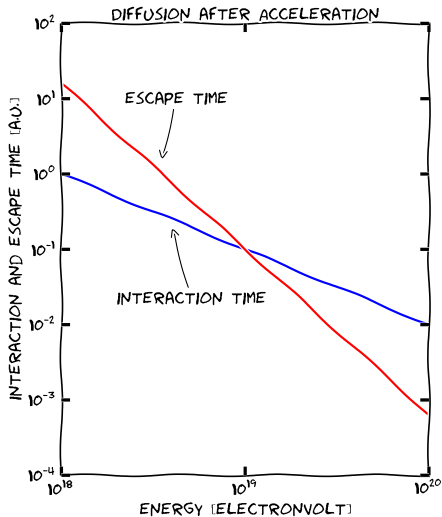
MU, G. Farrar, L. Anchordoqui, PRD **92** (2015) 123001 and M. Muzio, MU, G. Farrar arXiv:1906.06233
see also Globus+15, Biel+17, Kachelriess+17, Supanitsky+18



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

Photonuclear Interactions in Source Environment?

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

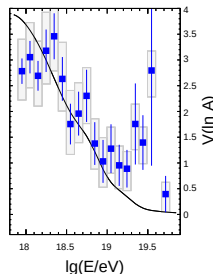
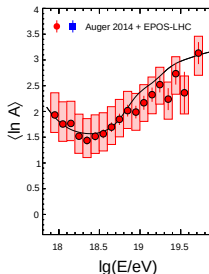
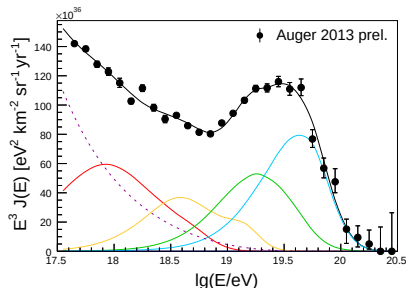
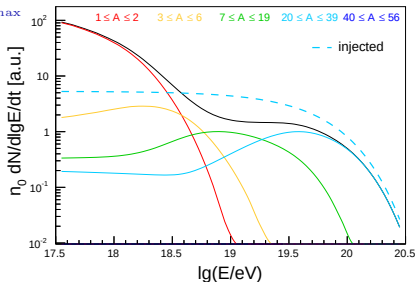


Single Mass + Photonuclear Interactions in Source Environment

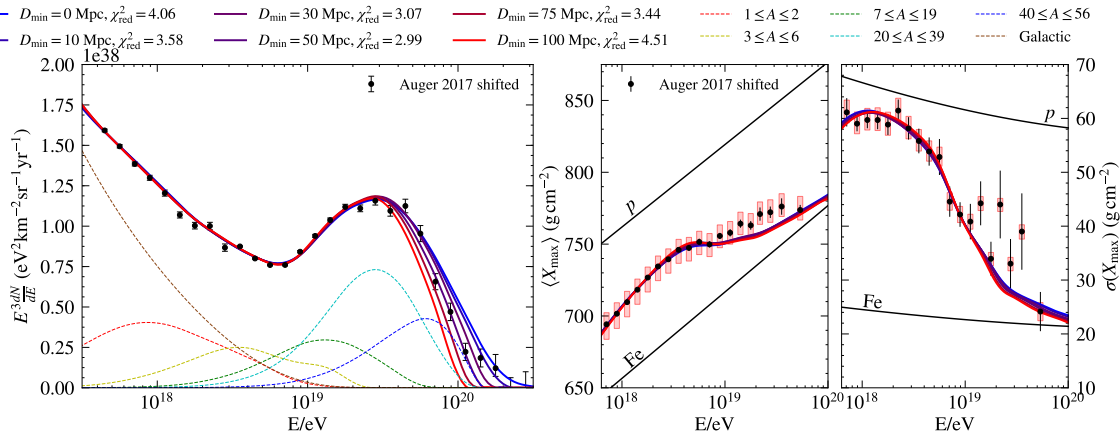
Fiducial Scenario $+1\sigma_E -1\sigma_{X_{\max}}$

^{29}Si injected, escaping
flux at source

flux and composition
at Earth

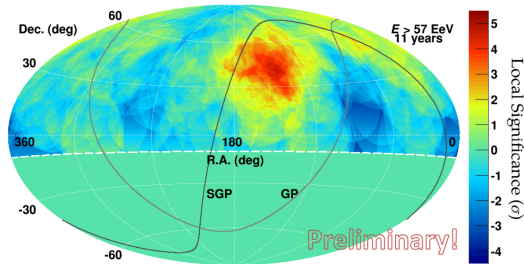


Peters Cycle (Galactic Composition) + Photonuc. Int. in Source



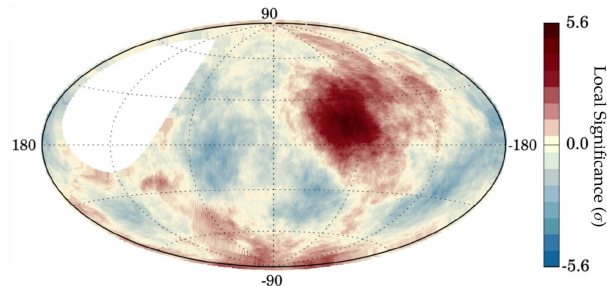
Arrival Directions – Blind Search

Telescope Array (equatorial coordinates)



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

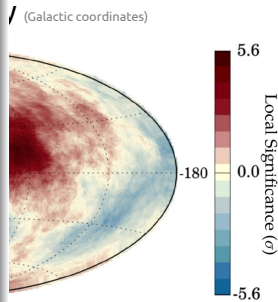
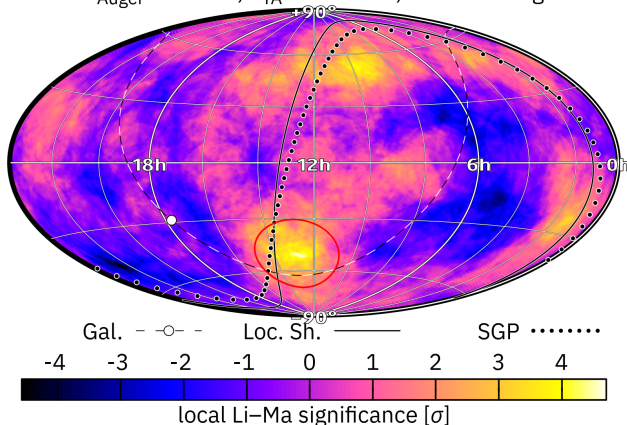
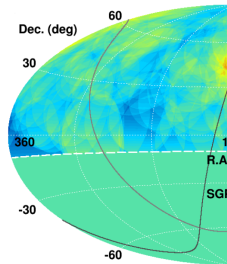
Pierre Auger Observatory (Galactic coordinates)



- energy threshold 3.8×10^{19} 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

Telescope Array (eq)

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

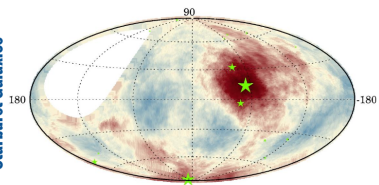
- energy threshold
- search radius 25°
- $n_{\text{obs}} = 38, n_{\text{exp}} =$
- 5.1σ local significance
- 0.21% post-trial p -value

 10^{19} eV

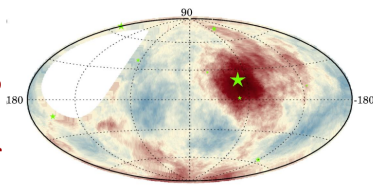
probability

Arrival Directions – Catalogue-based Analysis

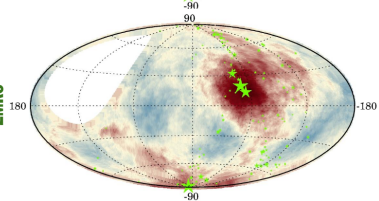
Starburst Galaxies



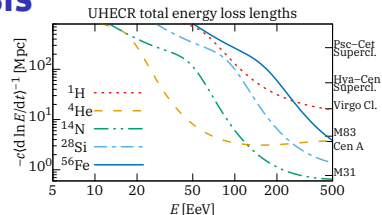
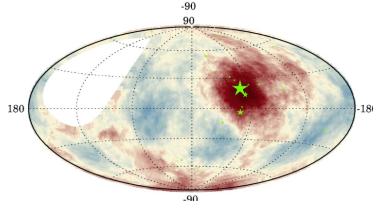
γ -emitting AGNs



2MRS



Swift-BAT

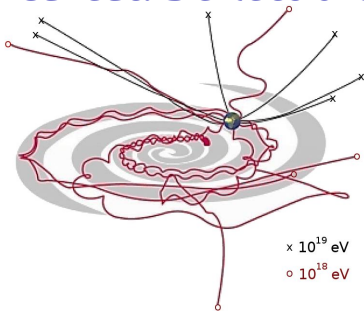


Catalog	E_{th}	θ	f_{aniso}	TS	Post-trial
Starburst	38 EeV	$15^{+5}_{-4}^\circ$	$11^{+5}_{-4}\%$	29.5	4.5σ
γ -AGNs	39 EeV	$14^{+6}_{-4}^\circ$	$6^{+4}_{-3}\%$	17.8	3.1σ
Swift-Bat	38 EeV	$15^{+6}_{-4}^\circ$	$8^{+4}_{-3}\%$	222	3.7σ
2MRS	40 EeV	$15^{+7}_{-4}^\circ$	$19^{+10}_{-7}\%$	220	3.7σ

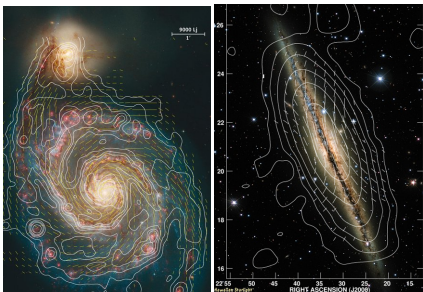
J. Farmer D09, L. Caccianiga for the Pierre Auger Coll. ICRC19, ApJ853 (2018) 2

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

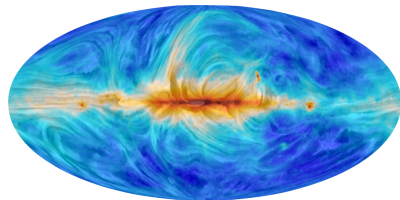
Caveat: Deflections in Galactic Magnetic Field



D. Harari

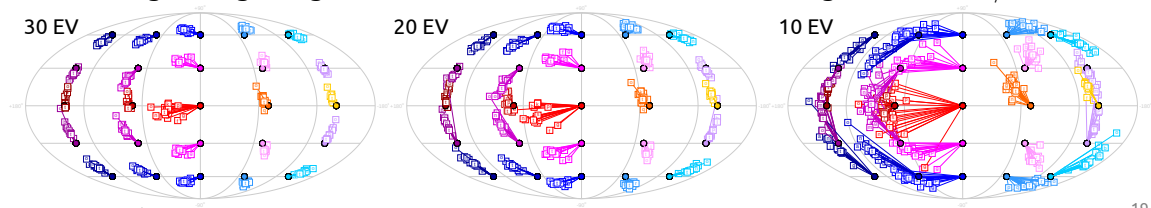


MPIFR (left: M51, right: NGC891)

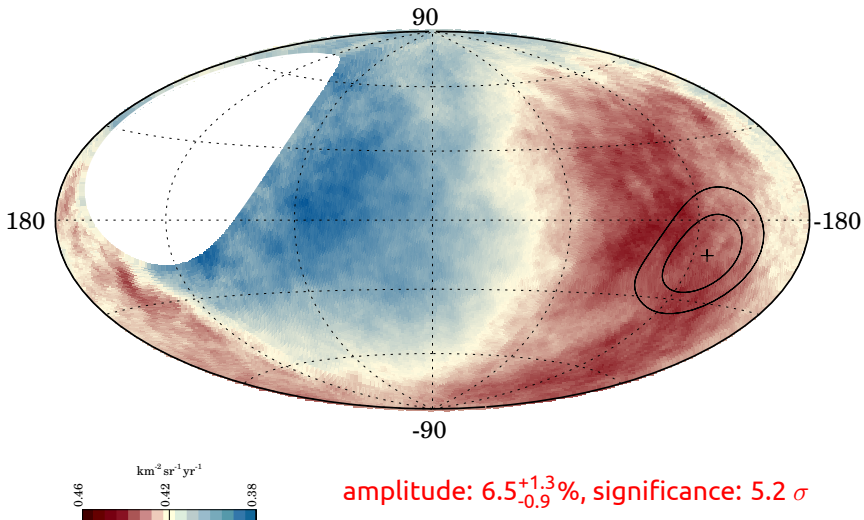


Planck PI@30 GHz

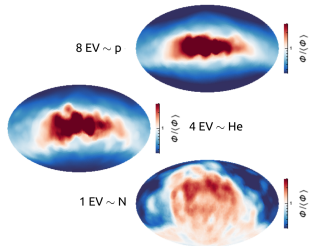
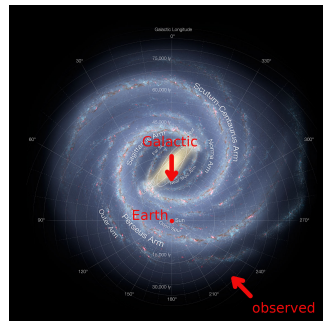
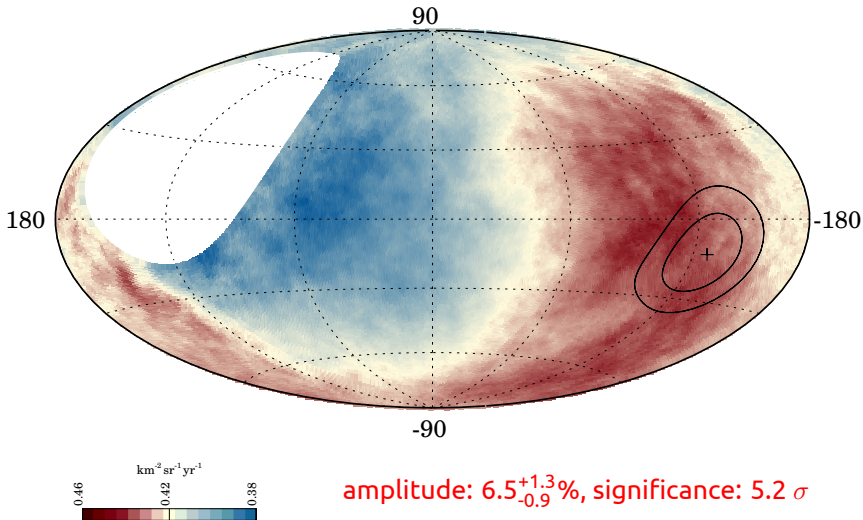
backtracking through magnetic field model variations at different rigidities $R = E/Z$



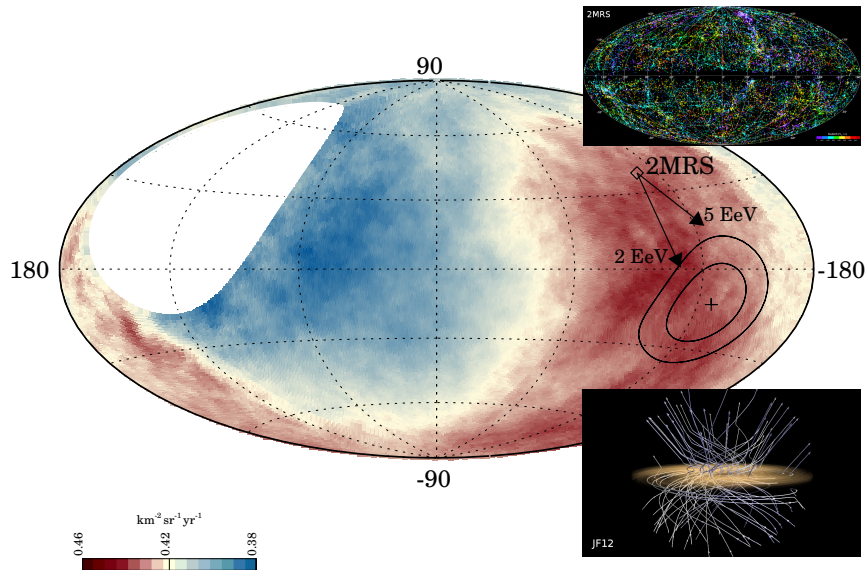
Observation of a Dipolar Anisotropy of UHECRs ($E > 8$ EeV)



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

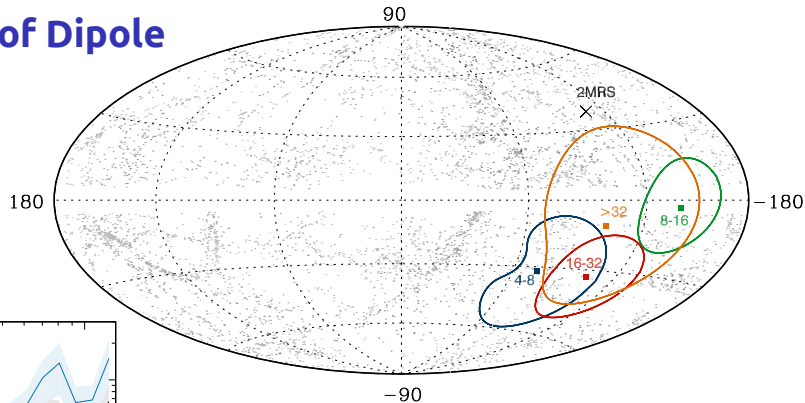
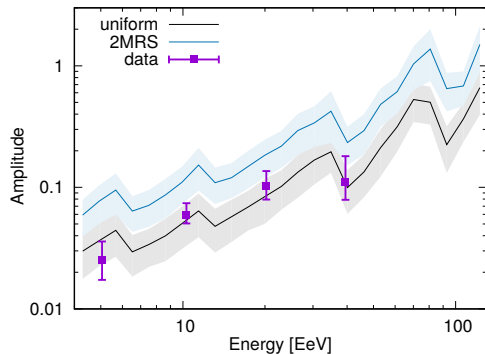


Observation of a Dipolar Anisotropy of UHECRs ($E > 8$ EeV)



Energy Dependence of Dipole

dipole position →



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

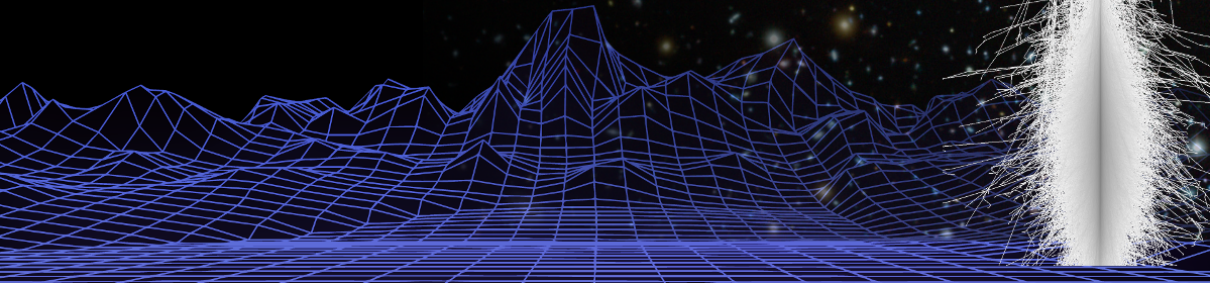
Pierre Auger Coll., ApJ868 (2018) 4
(see also Chen Ding et al C09 session)



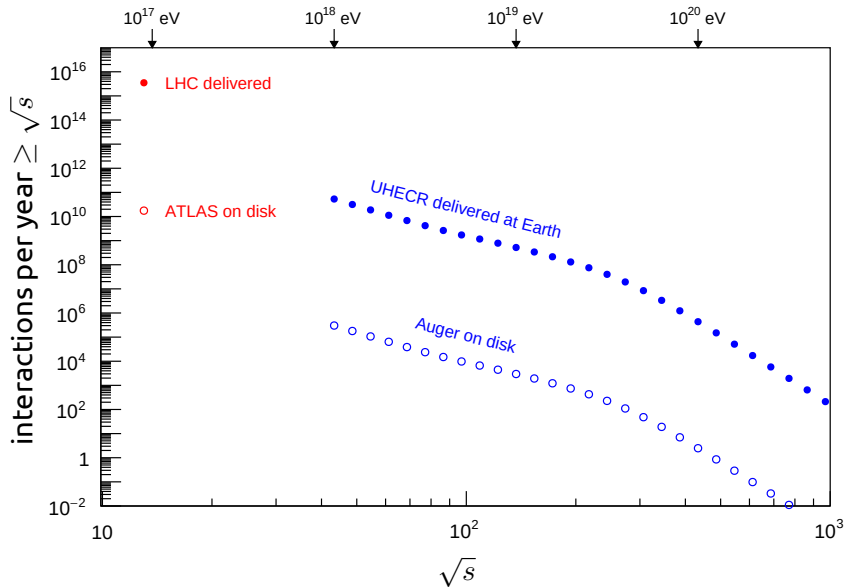
VIRTUAL APRIL MEETING

April 18-21, 2020

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

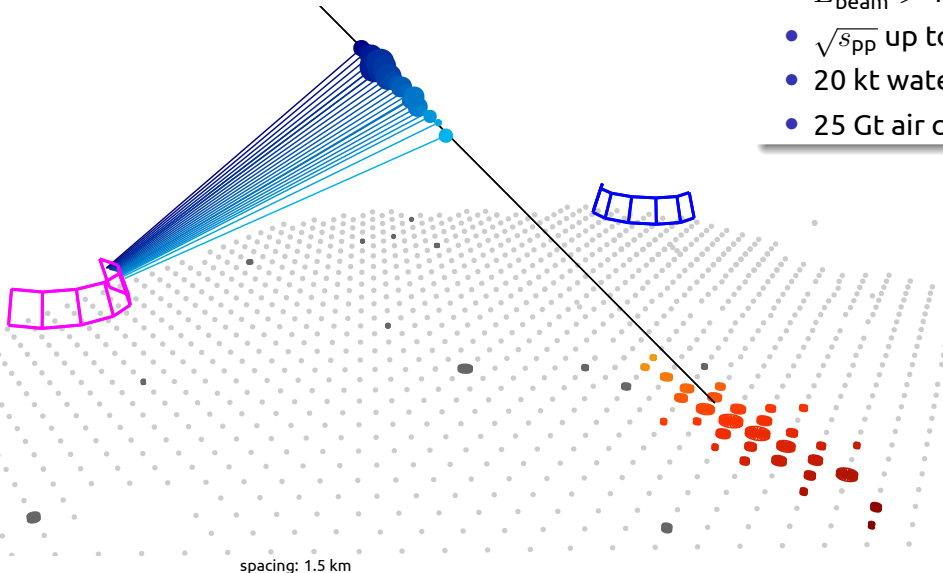


Beam Luminosity



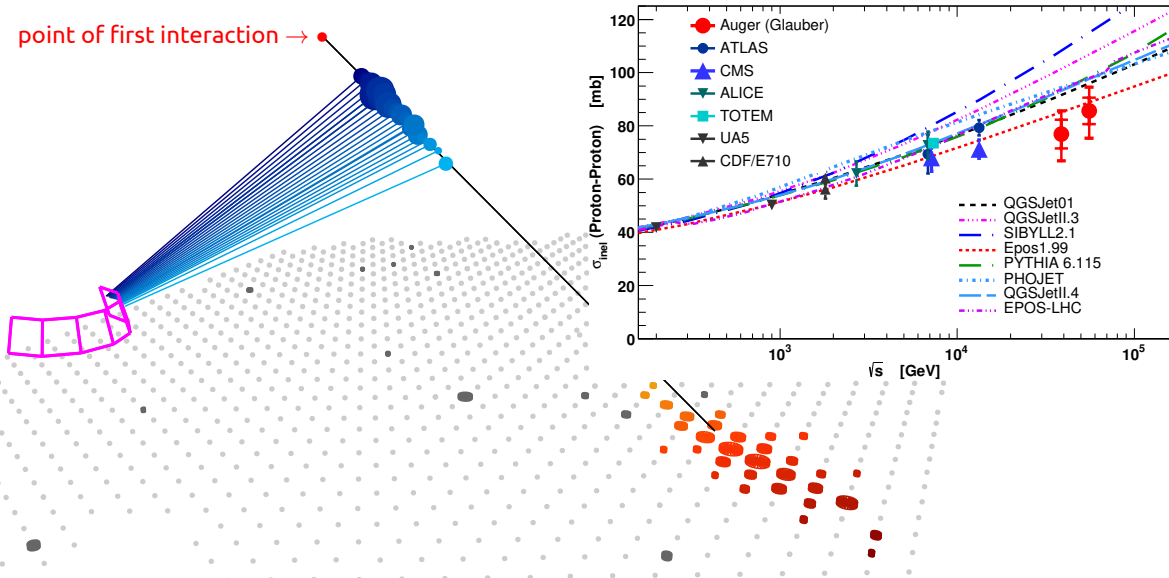
Particle Detector

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

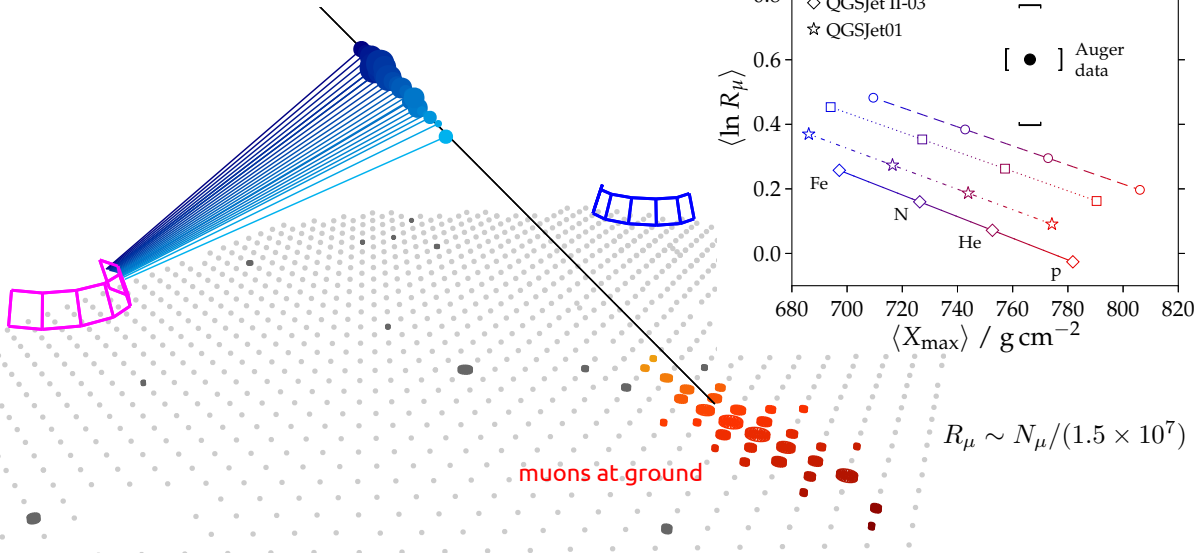


UHE Proton+Proton Cross Section

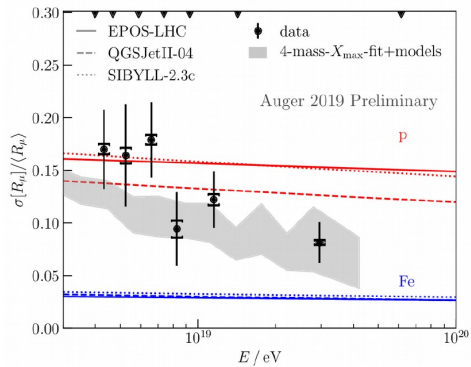
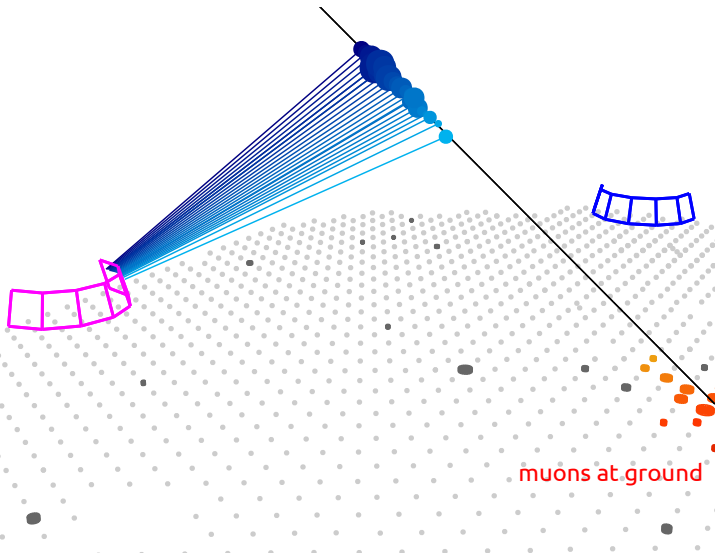
point of first interaction $\rightarrow$



Muon Production in Air Showers



Muon Production in Air Showers



$$R_\mu \sim N_\mu / (1.5 \times 10^7)$$

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

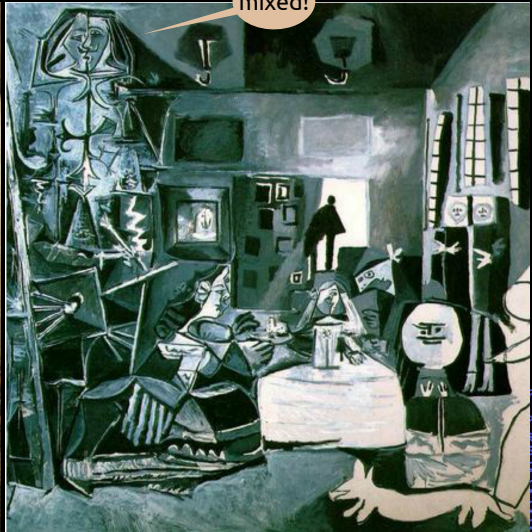
today

mixed!

proton!



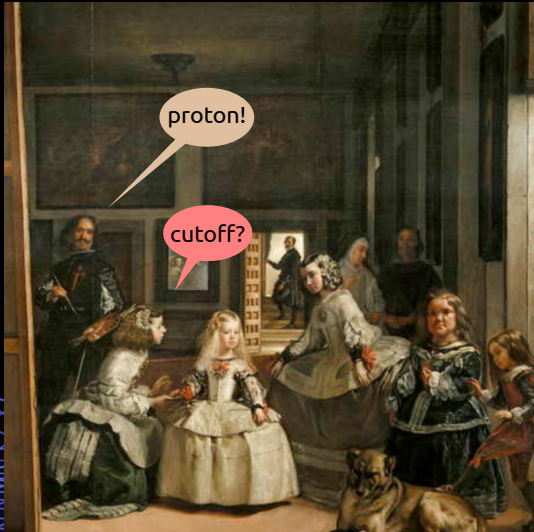
Las Meninas by Diego Velazquez 1656



Las Meninas by Pablo Picasso 1957

Summary: Cosmic Particles at Extreme Energies

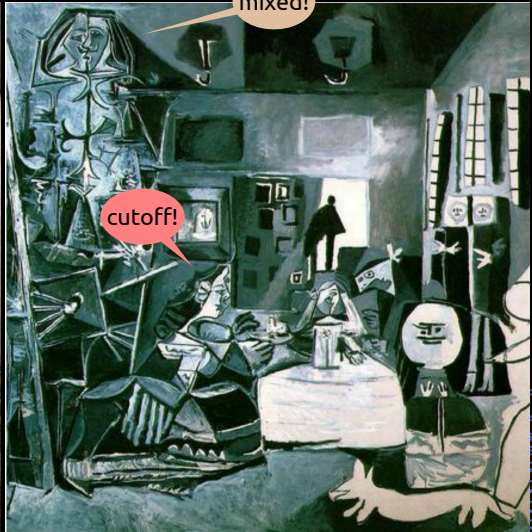
previously



Las Meninas by Diego Velazquez 1656

today

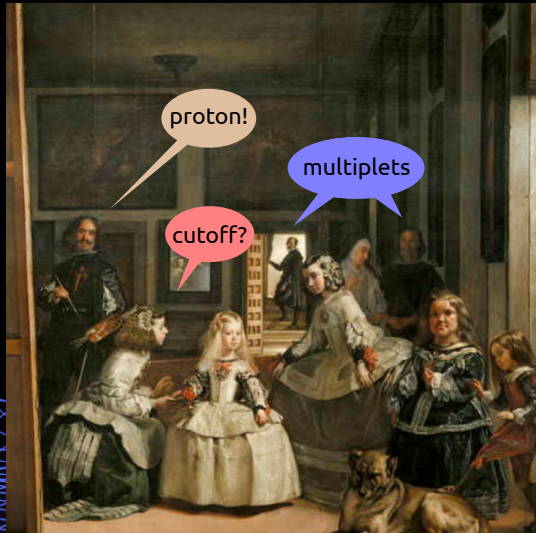
mixed!



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previously



Las Meninas by Diego Velazquez 1656

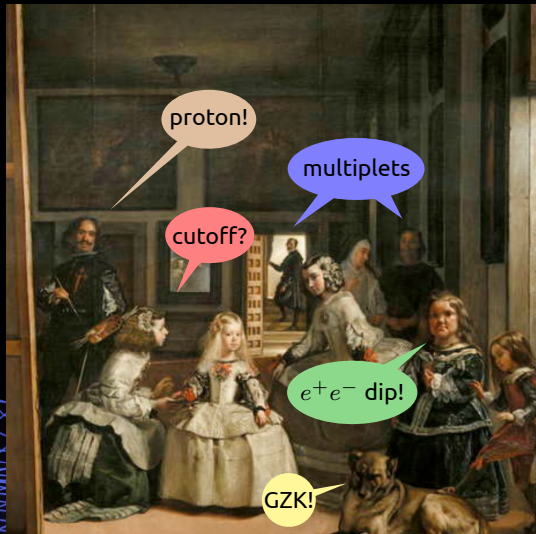
today



Las Meninas by Pablo Picasso 1957

Summary: Cosmic Particles at Extreme Energies

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Las Meninas by Diego Velazquez 1656

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Las Meninas by Pablo Picasso 1957

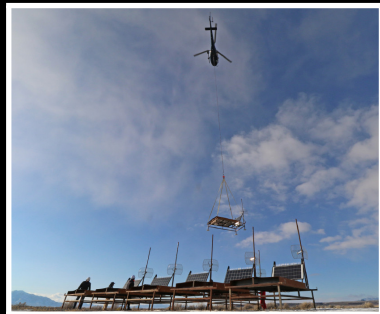
Stay Tuned!

Under Construction: **AugerPrime**



arXiv:1604.03637

Under Construction: **TAx4**



EPJ210 (2019) 06001

Launch 2029: **POEMMA?**



see PRD101 (2020) 023012 and
T09 session Monday 3:30 p.m.