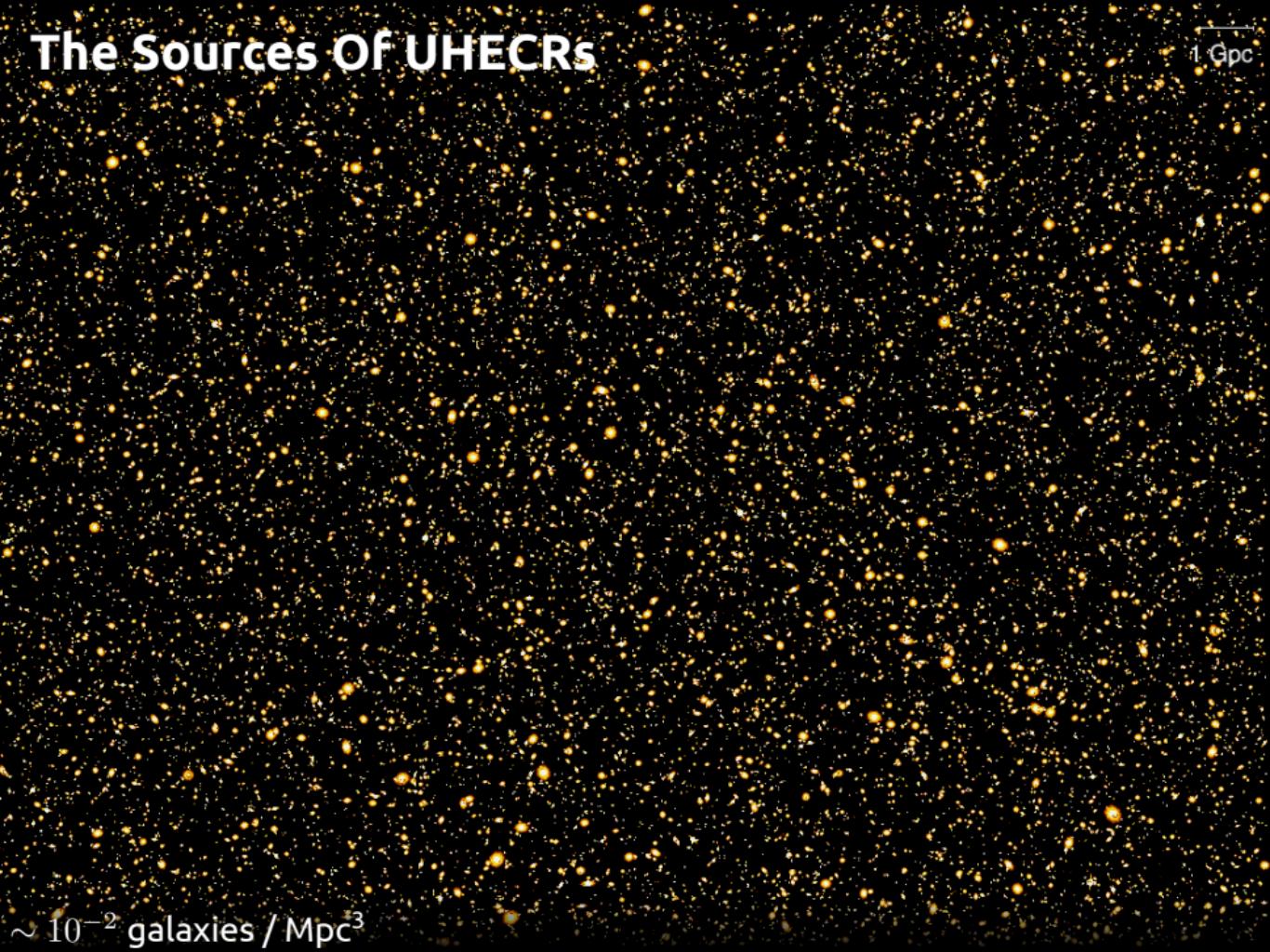


Astro- and Particle Physics with UHECRs

Michael Unger (KIT)

The Sources Of UHECRs

1 Gpc



$\sim 10^{-2}$ galaxies / Mpc³

Redshift Horizon

1 Gpc

$$I(z)/I(0) \propto \int_{E_0}^{\infty} (1+z) (E(1+z))^{-2} dE / \int_{E_0}^{\infty} E^{-2} dE = (1+z)^{-1}, \chi_{\text{loss}} \sim 5 \text{ Gpc}$$

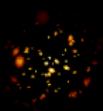
Source Evolution

1 Gpc

star formation rate from B.E. Robertson et al. *Astrophys.J.* 802 (2015) no.2, L19

UHECR Energy Loss (20 EeV p)

1 Gpc



intensity attenuation $p + \gamma_{\text{CMB}} \rightarrow p + e^+ + e^-$, $\chi_{\text{loss}} \sim 1 \text{ Gpc}$

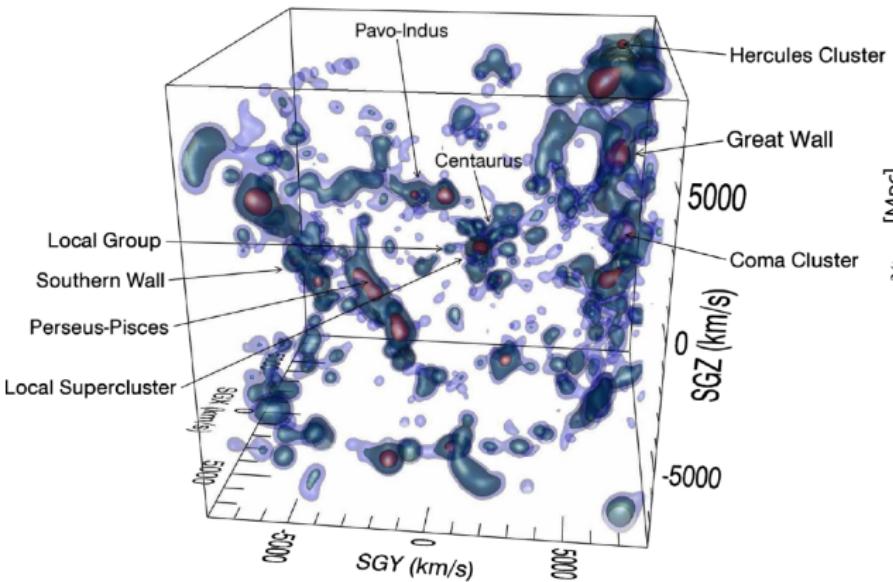
UHECR Energy Loss (50 EeV p)

1 Gpc

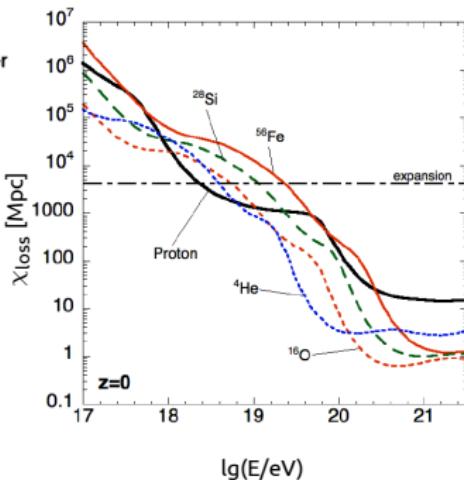


intensity attenuation $p + \gamma_{\text{CMB}} \rightarrow p/n + \pi^{0/+}$, $\chi_{\text{loss}} \sim 100 \text{ Mpc}$

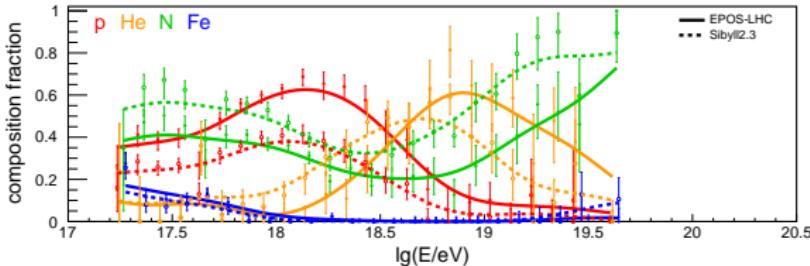
The Local Large Scale Structure



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



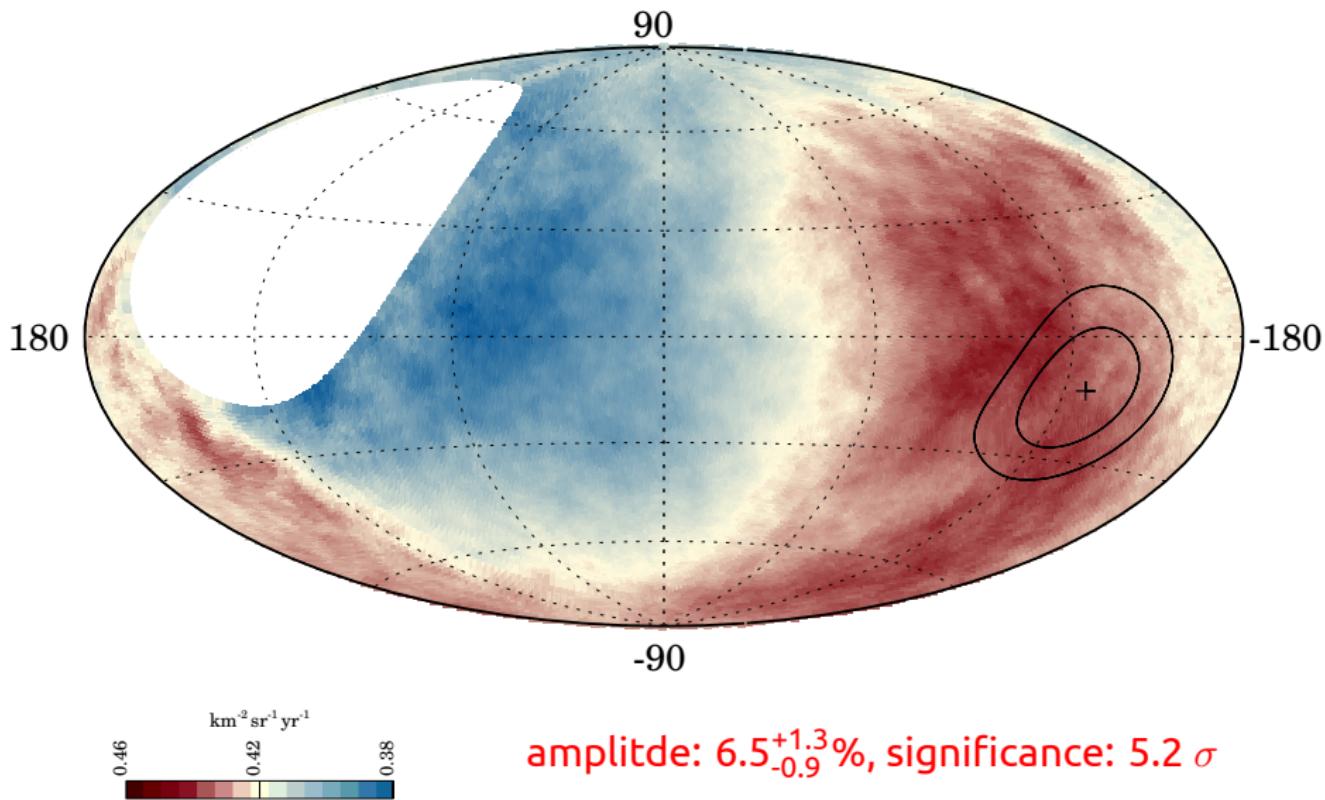
D.Allard Astropart.Phys. 39 (2012) 33



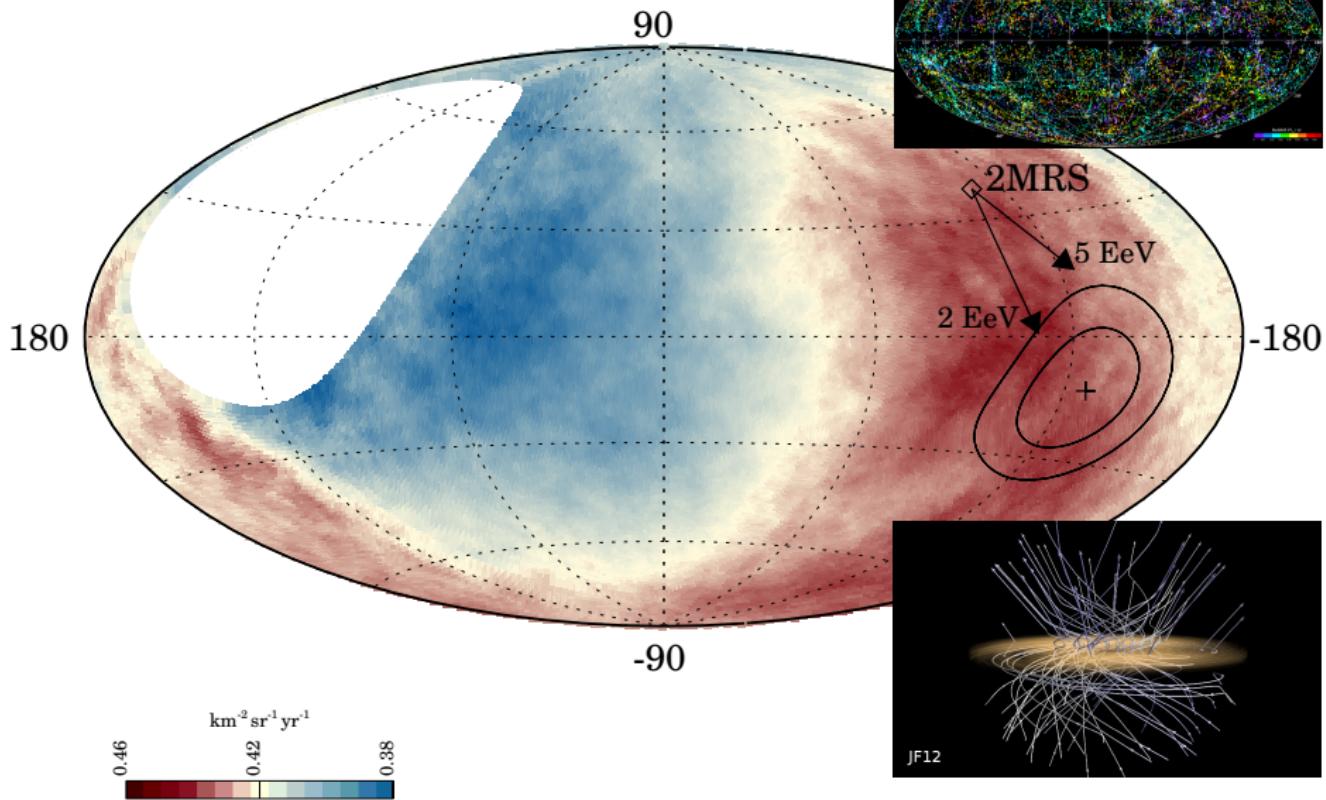
Pierre Auger Coll., PRD 2014 and ICRC17 (only stat. uncert. shown)

[7 of 23]

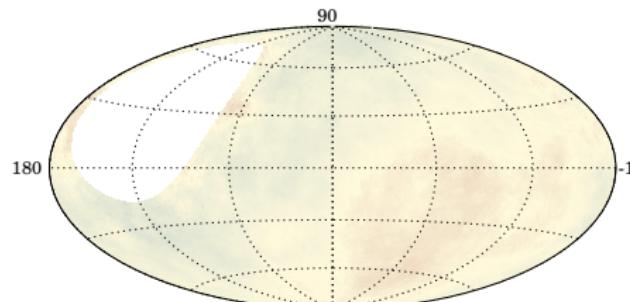
Observation of a Dipolar Anisotropy of UHECR ($E > 8$ EeV)



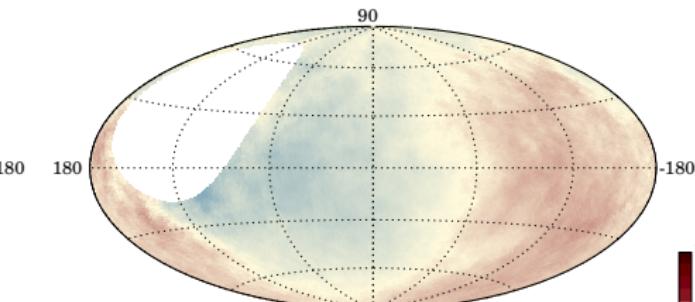
Observation of a Dipolar Anisotropy of UHECR ($E > 8$ EeV)



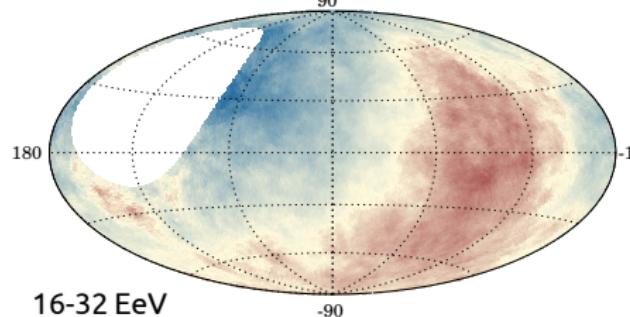
Energy Dependence of UHECR Dipole



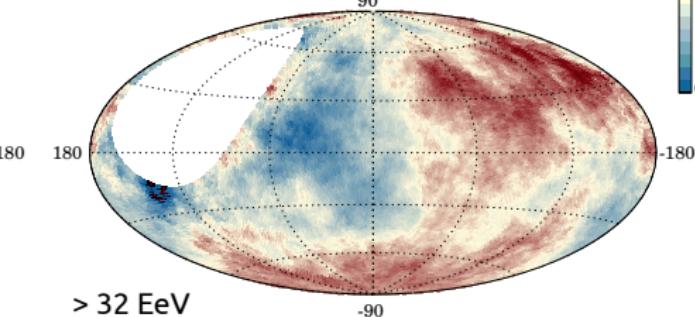
4-8 EeV



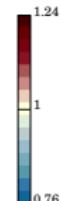
8-16 EeV



16-32 EeV

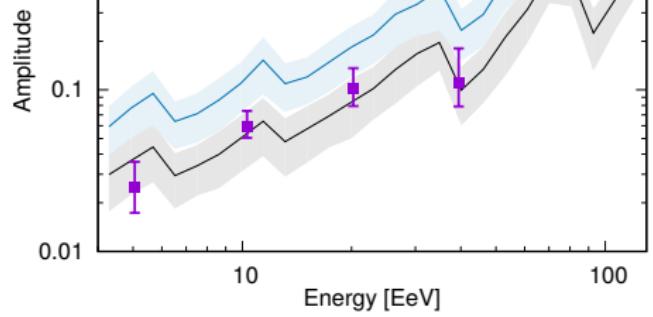
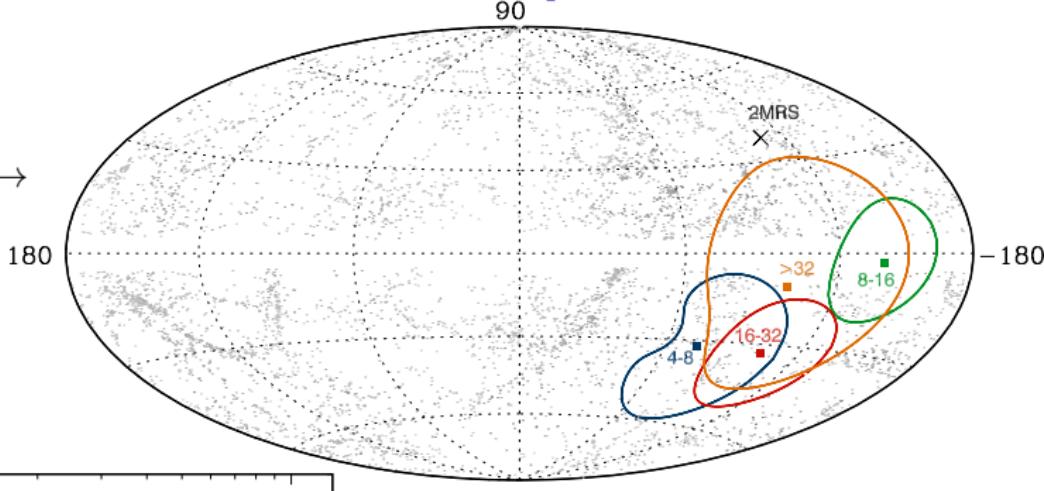


> 32 EeV



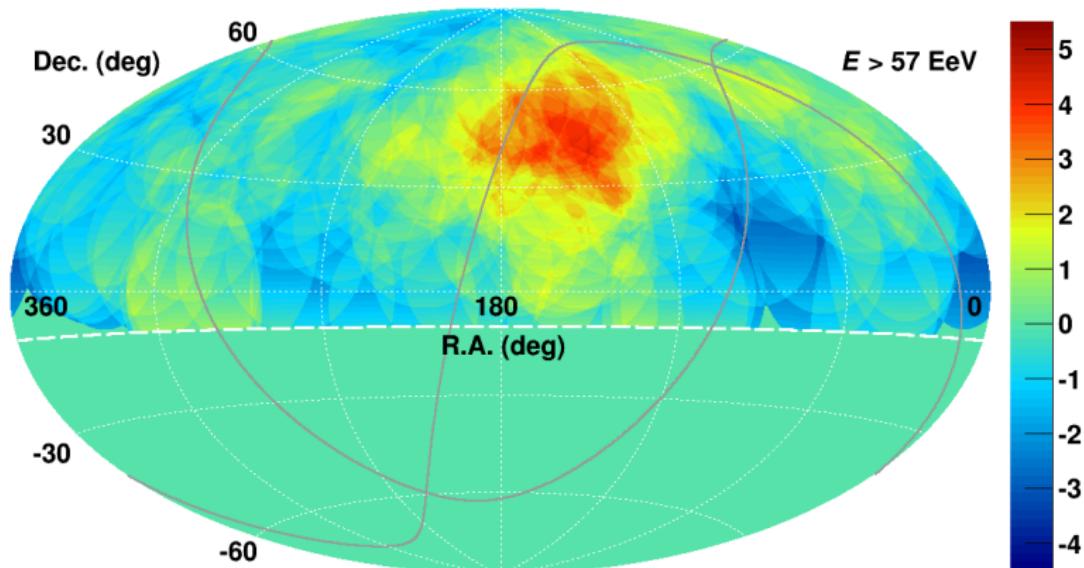
Energy Dependence of UHECR Dipole

dipole position →



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

“Hot Spot” (Telescope Array, $E > 57 \text{ EeV}$, $\sim 3 \sigma$)



Total events: 143

Observed: 34

Expected : 13.5

Best circle center: RA=144.3°, Dec=+40.3°

Best circle radius: 25°

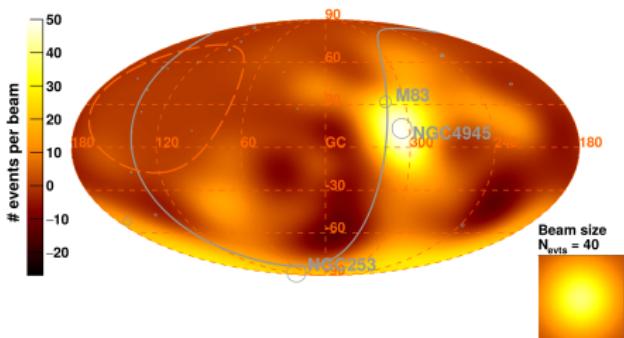
Local significance : 5 σ

Global significance : 3 σ

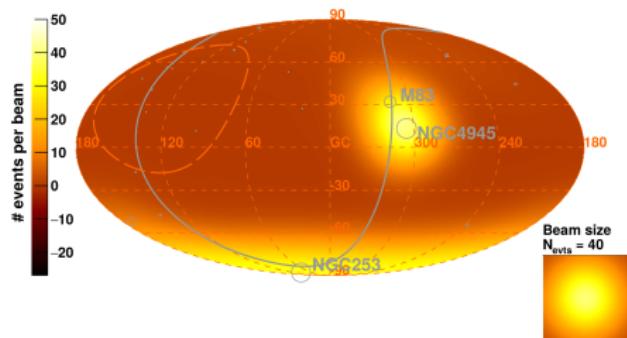
Intermediate-scale Anisotropy (Pierre Auger Observatory)

starburst galaxies ($E > 39$ EeV, 9.7%, 12.9° , 4.0σ)

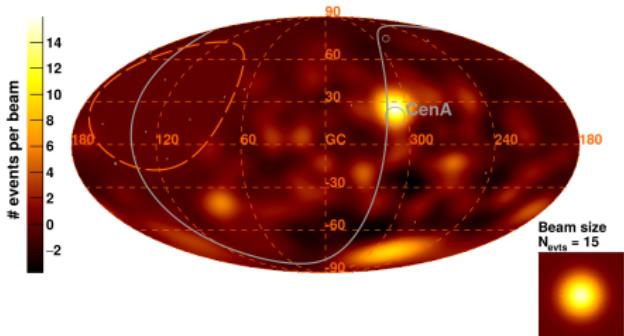
Observed Excess Map - $E > 39$ EeV



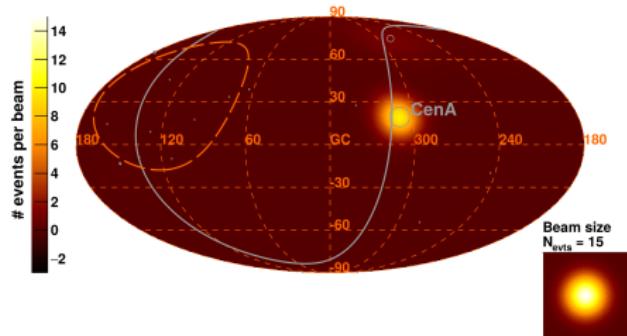
Model Excess Map - Starburst galaxies - $E > 39$ EeV



Observed Excess Map - $E > 60$ EeV

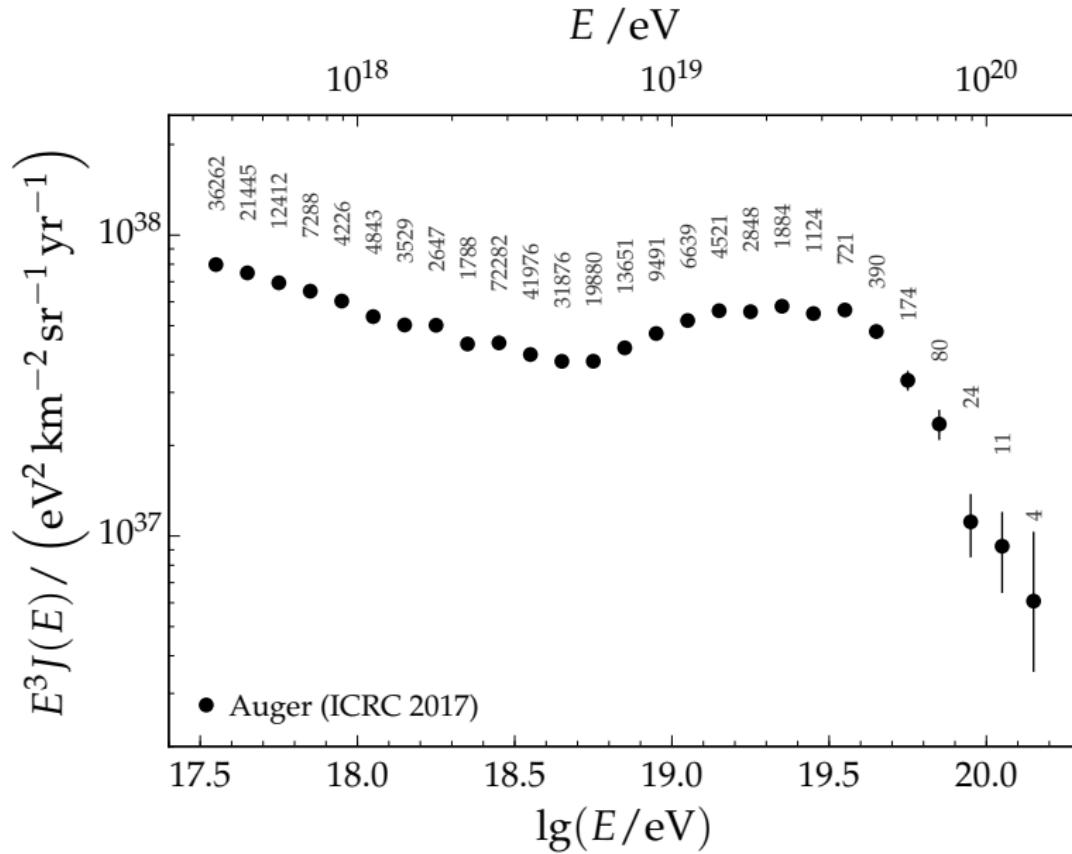


Model Excess Map - Active galactic nuclei - $E > 60$ EeV

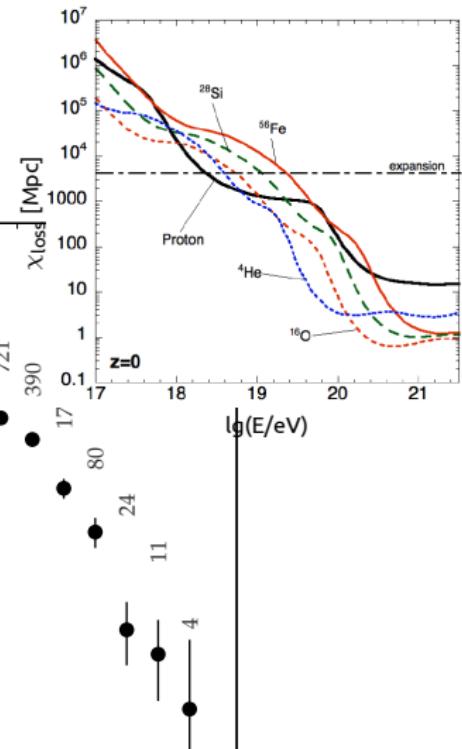
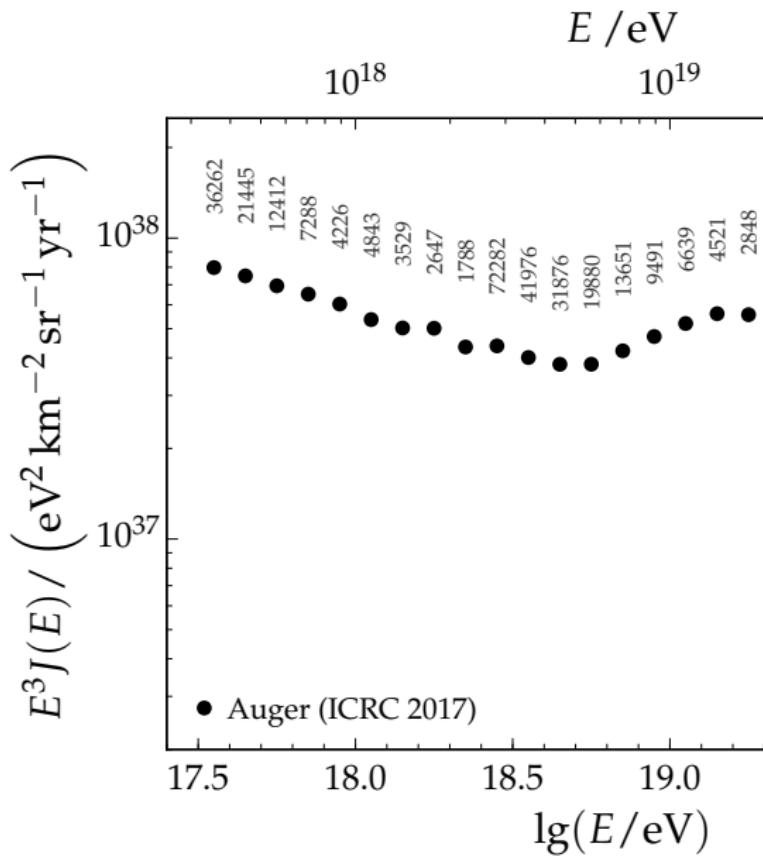


γ AGN ($E > 60$ EeV, 6.7%, 6.9° , 2.7σ)

UHECR Energy Spectrum



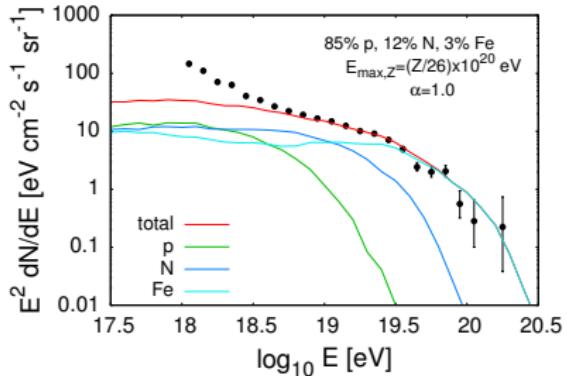
UHECR Energy Spectrum



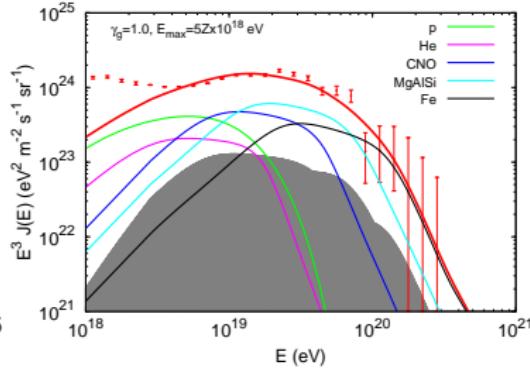
Energy Spectrum and Composition $E_{\max} = R_0 Z$

e.g.

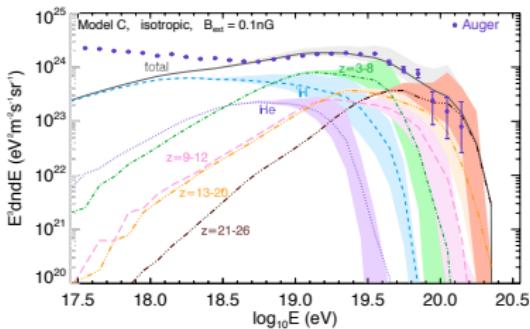
Taylor et al. 2014



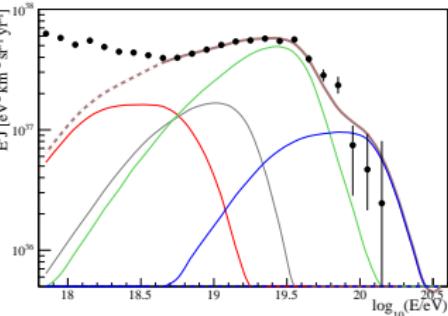
Aloisio et al 2014



Globus et al 2014

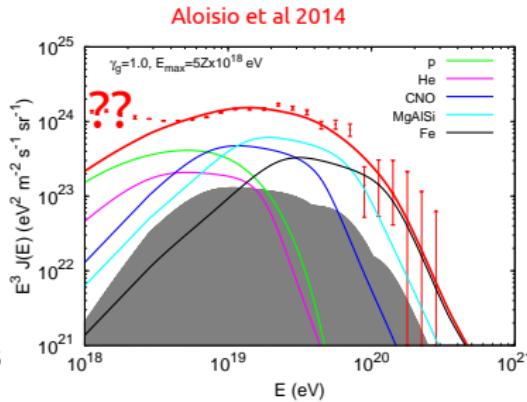
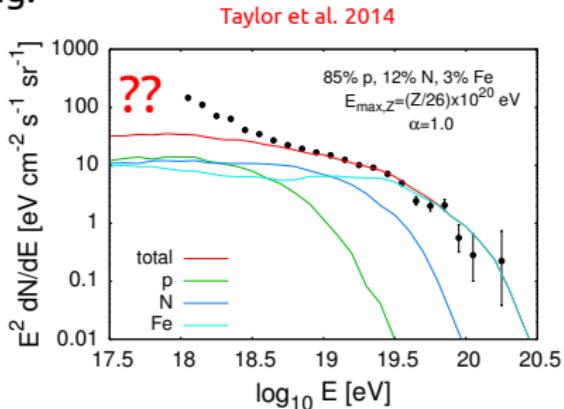


Pierre Auger Coll. 2017

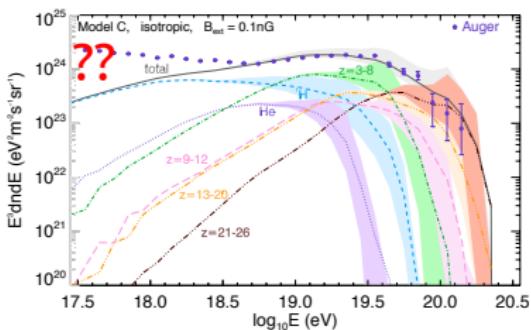


Energy Spectrum and Composition $E_{\max} = R_0 Z$

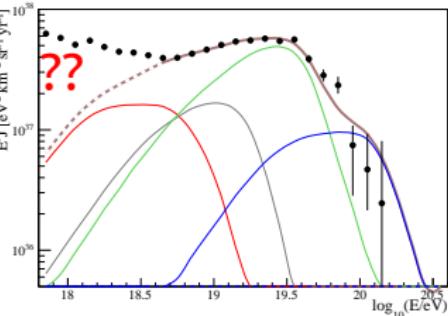
e.g.



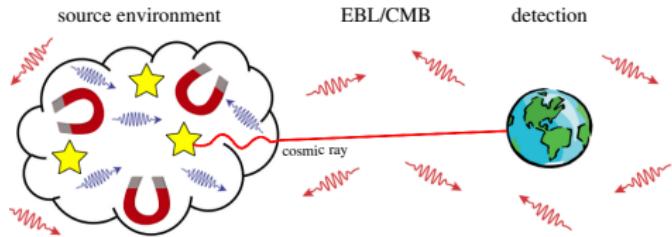
Globus et al 2014



Pierre Auger Coll. 2017

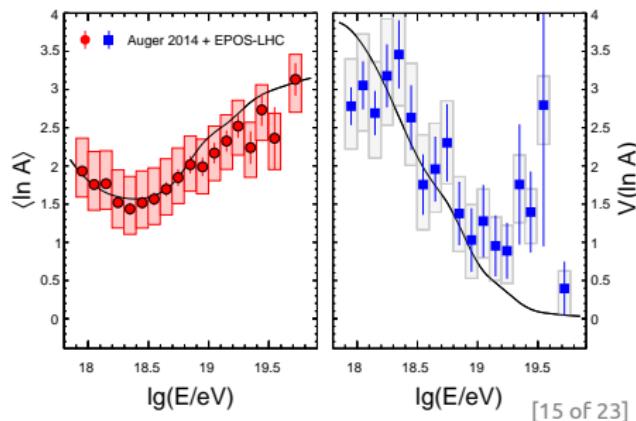
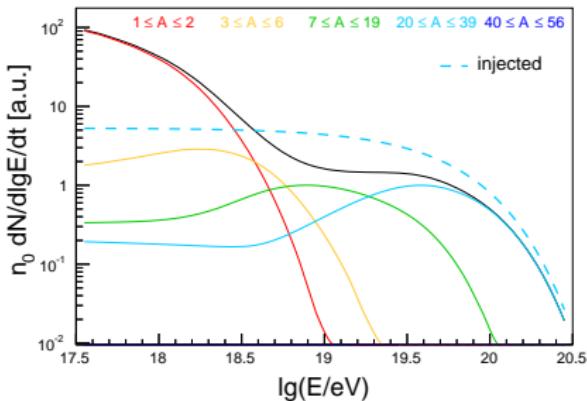
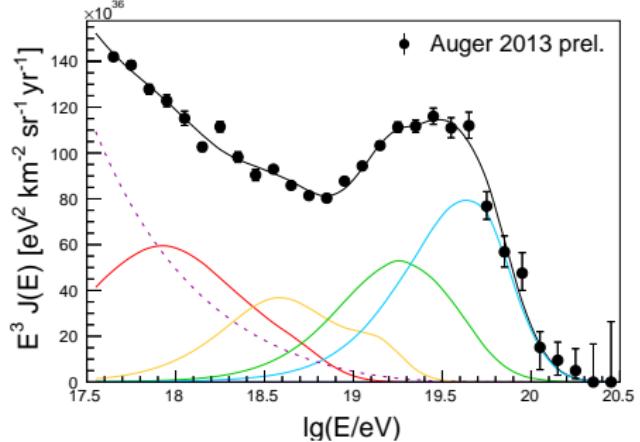


$A + \gamma$ Interactions at Source → Origin of "Ankle"?

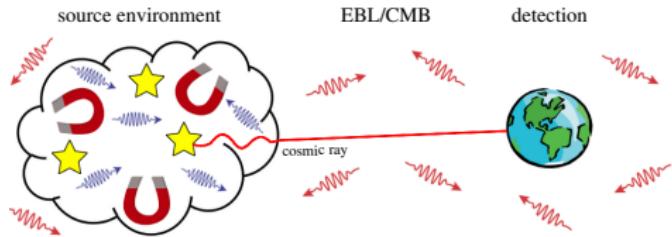


MU, G.Farrar, L.Anchordoqui PRD 92 (2015) 123001

$1 \leq A \leq 2$ $3 \leq A \leq 6$ $7 \leq A \leq 19$ $20 \leq A \leq 39$ $40 \leq A \leq 56$ galactic ($A=56$)

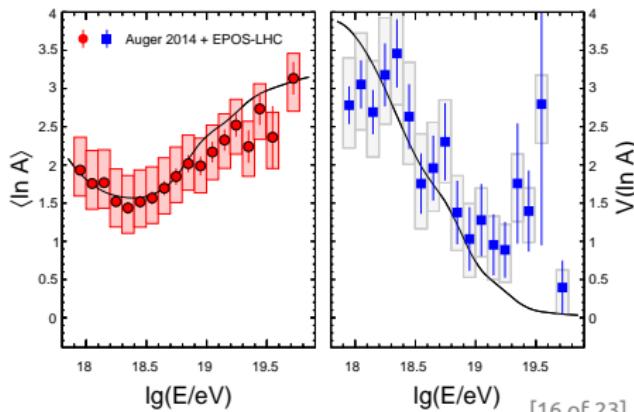
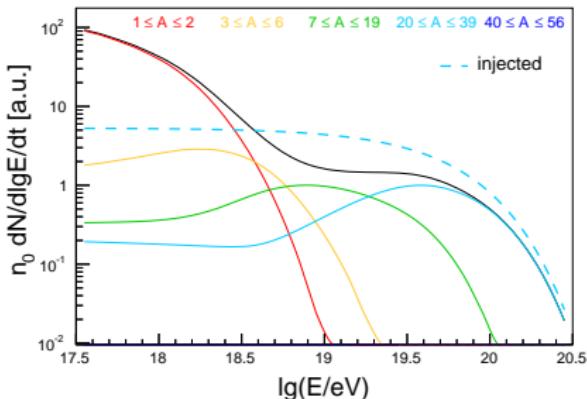
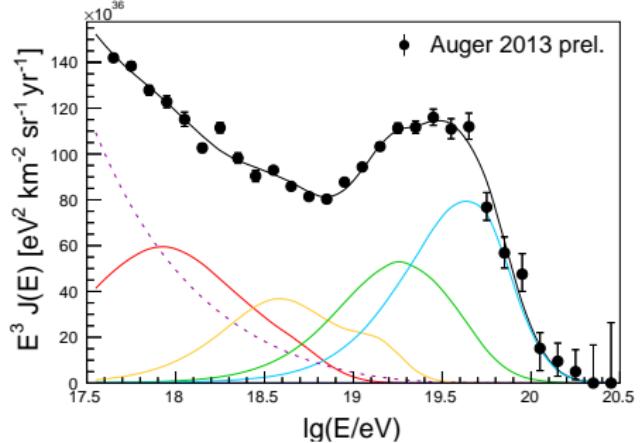


$A + \gamma$ Interactions at Source single $A_{\text{inj}} \rightarrow E_{\text{max}} = E_0 A$

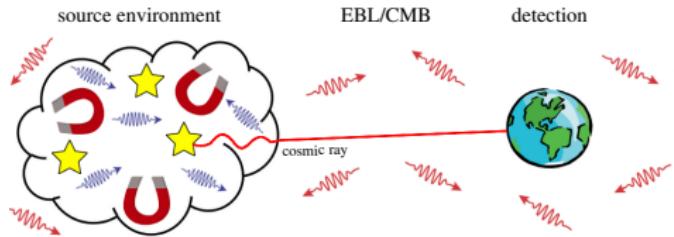


MU, G.Farrar, L.Anchordoqui PRD 92 (2015) 123001

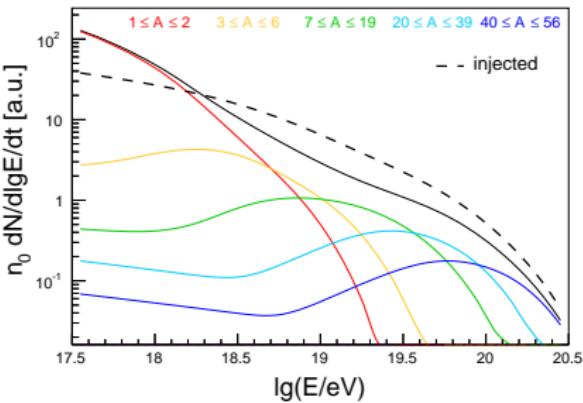
$1 \leq A \leq 2$ $3 \leq A \leq 6$ $7 \leq A \leq 19$ $20 \leq A \leq 39$ $40 \leq A \leq 56$ galactic ($A=56$)



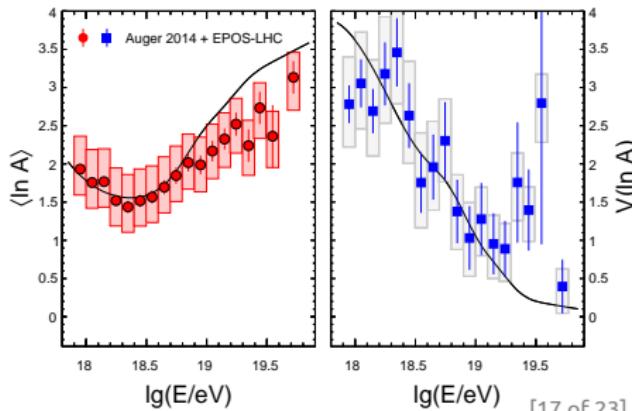
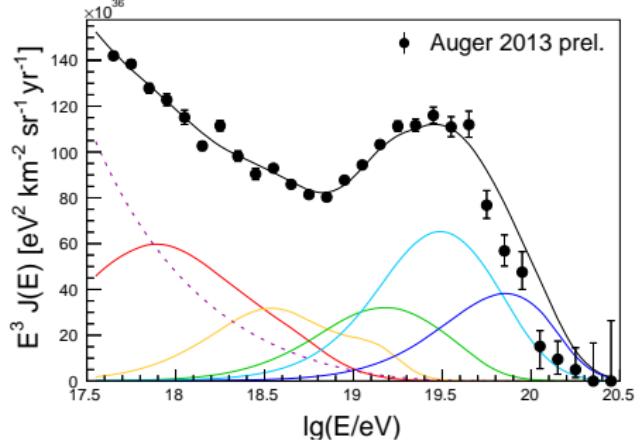
$A + \gamma$ Interactions at Source galactic mix $\rightarrow E_{\max}$ = complicated



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

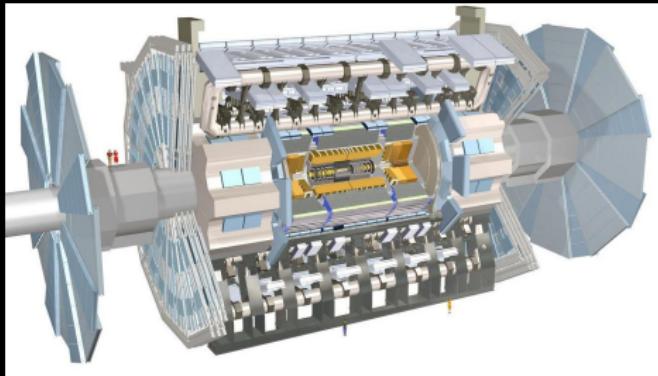


$1 \leq A \leq 2$ $3 \leq A \leq 6$ $7 \leq A \leq 19$ $20 \leq A \leq 39$ $40 \leq A \leq 56$ galactic ($A=56$)

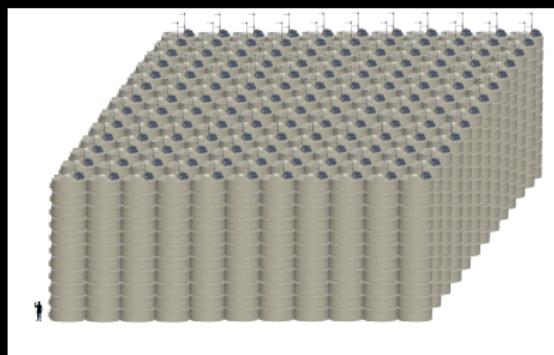


Particle Physics at UHE

ATLAS@LHC



Pierre Auger Observatory*

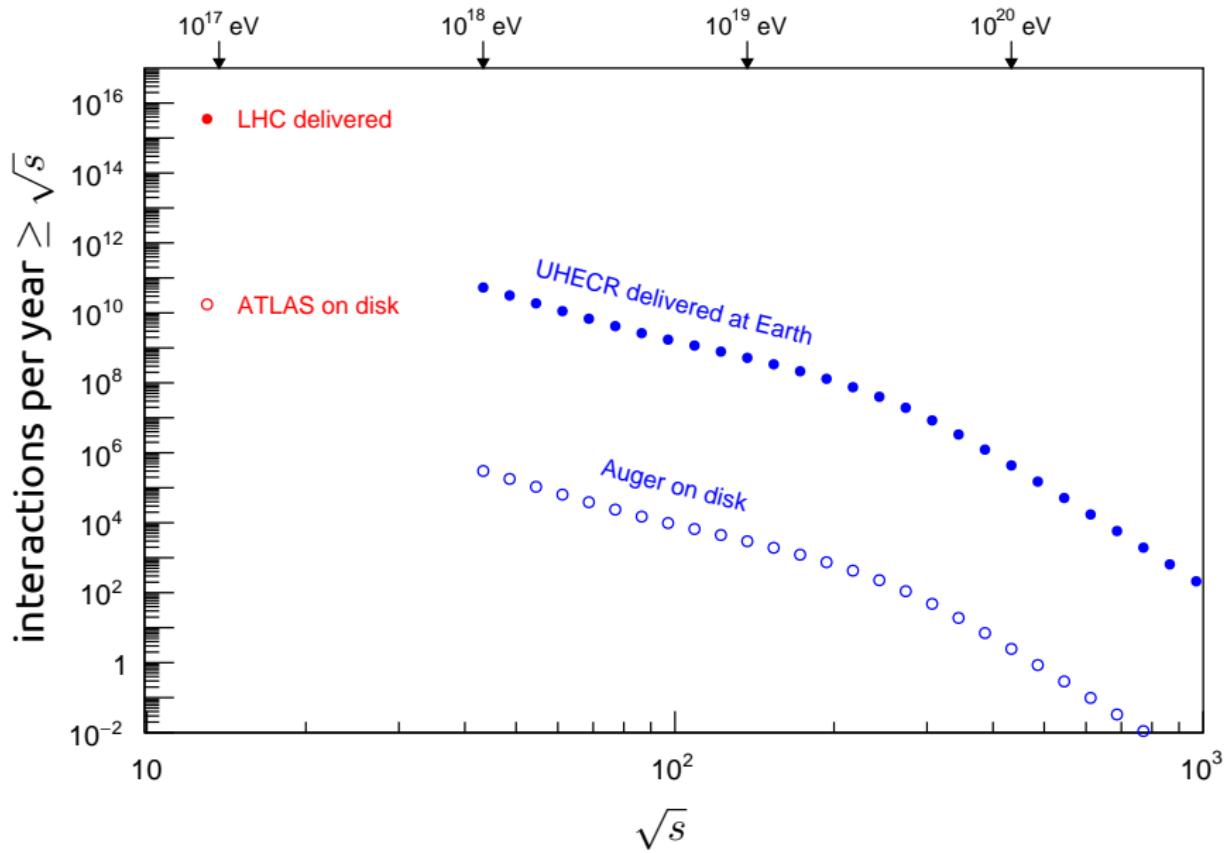


- $E_{\text{beam}} = 6.5 \text{ TeV}$
- $\sqrt{s} = 13 \text{ TeV}$
- 7 kt detector
- $E_{\text{beam}} > 1 \times 10^8 \text{ TeV}$
- $\sqrt{s} > 400 \text{ TeV}^{**}$
- 20 kt water-Cherenkov
- 25 Gt air calorimeter

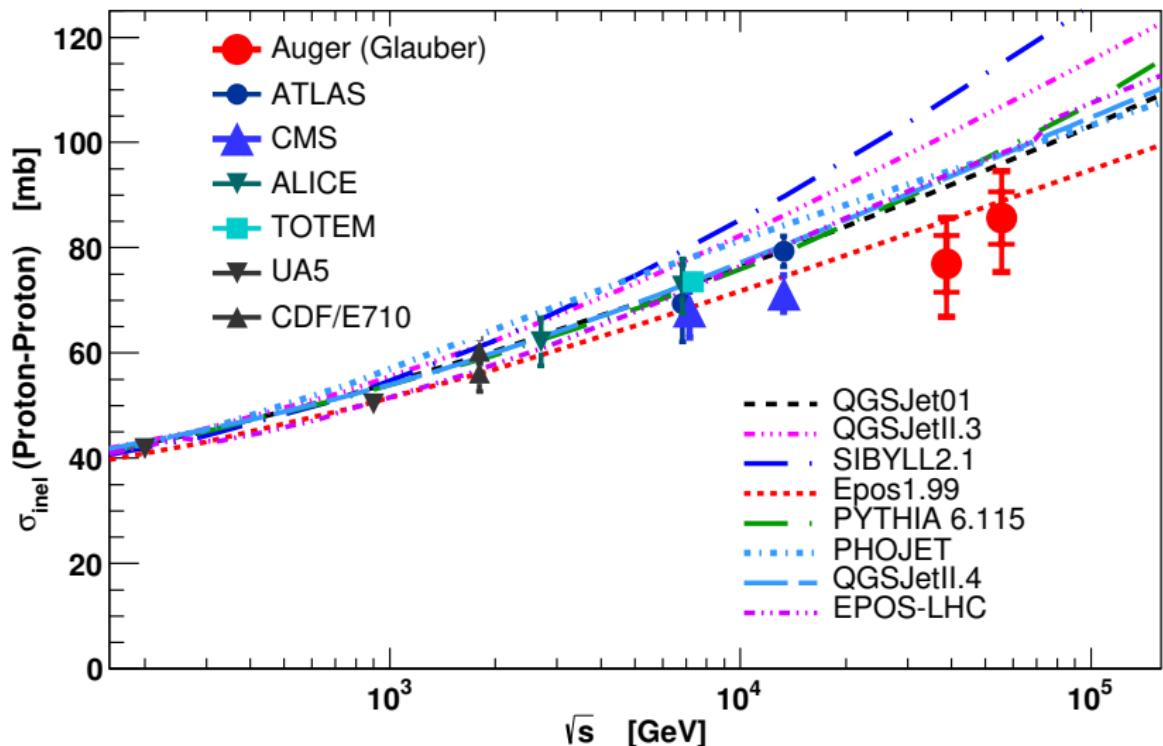
* to scale but stacked, actual area: 3000 km^2

** for $p+\text{air}$ ($> 60 \text{ TeV}$ for $\text{Fe}+\text{air}$)

LHC and UHECR Luminosity

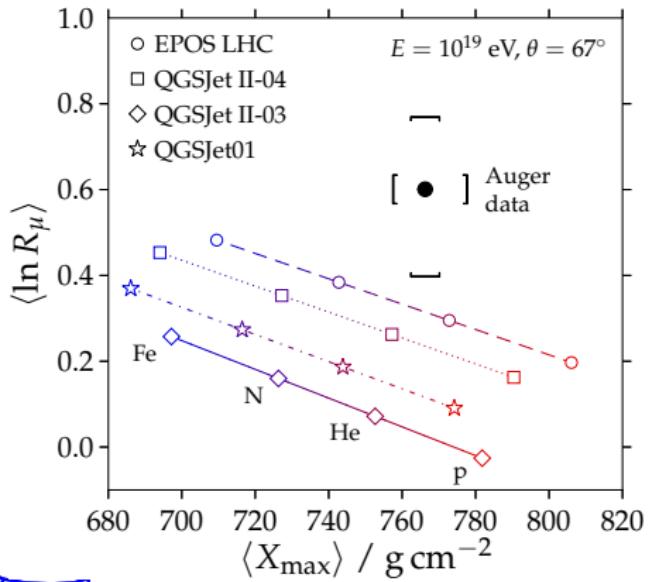
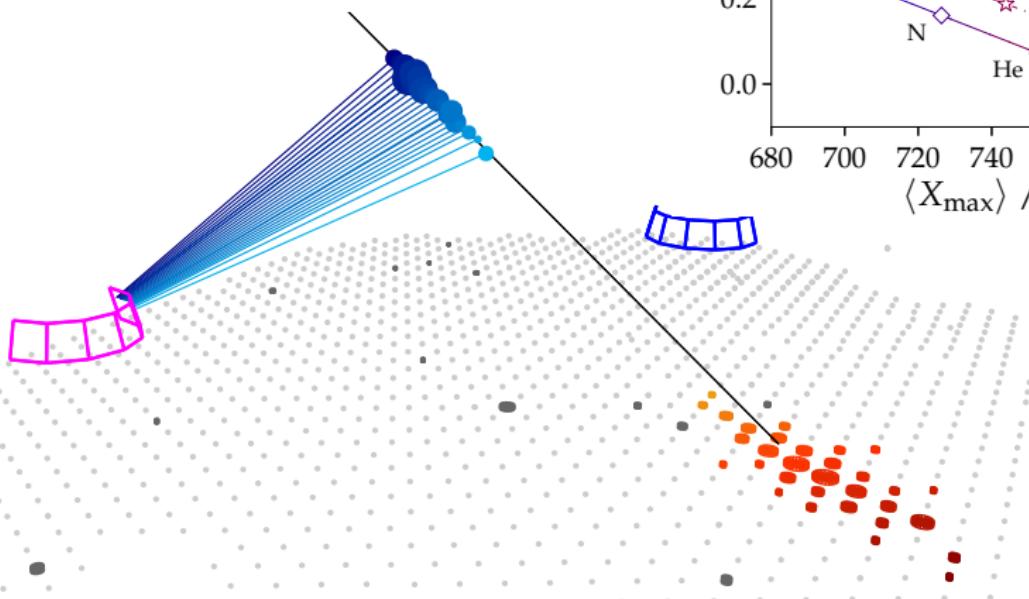


Proton+Proton Cross Section at $\sqrt{s} = 39$ and 66 TeV



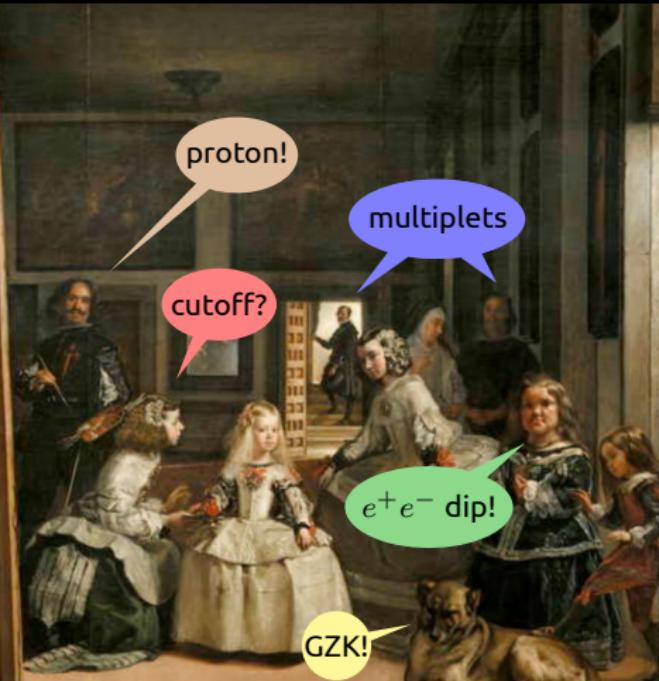
Muon Production in Air Showers

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



Conclusions

UHECR in 2004



Las Meninas by Diego Velazquez 1656

UHECR in 2018



Las Meninas by Pablo Picasso 1957

Stay tuned for AugerPrime and TAx4 Results!

1 Gpc



Las Meninas by Pablo Picasso 1957