# The Pierre Auger Observatory

## Spectrum, Composition, Anisotropies, Hadronic Interactions

**M. Unger (KIT)**

# The Pierre Auger Observatory

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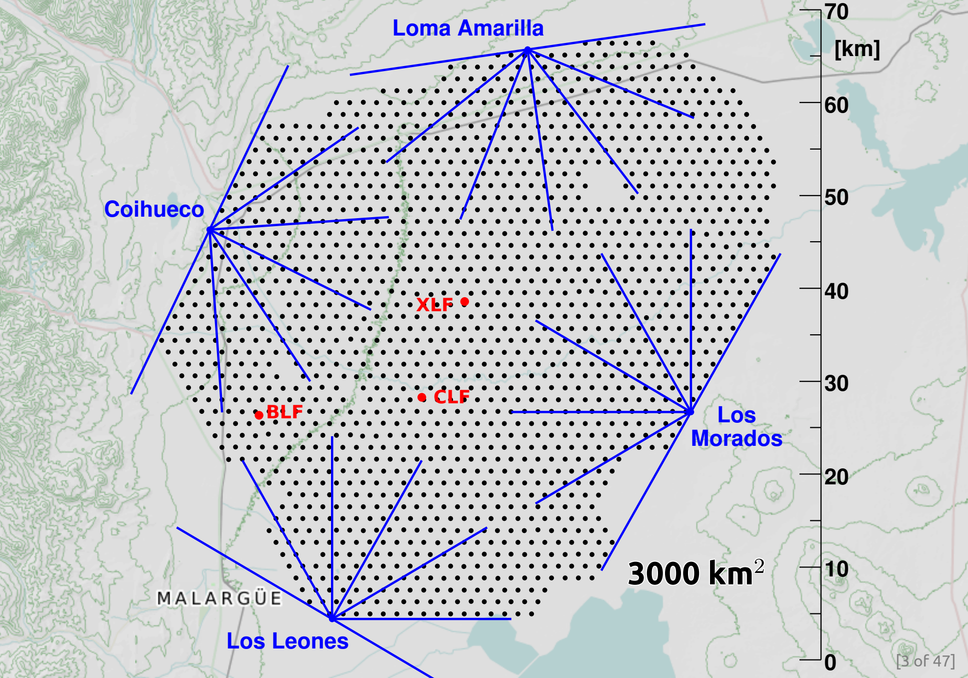
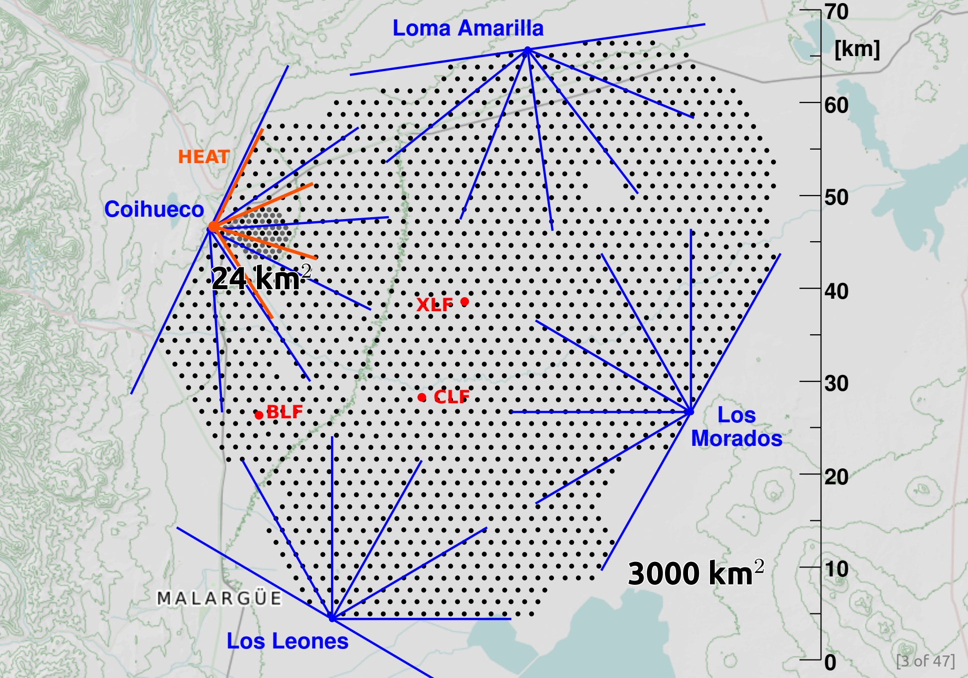
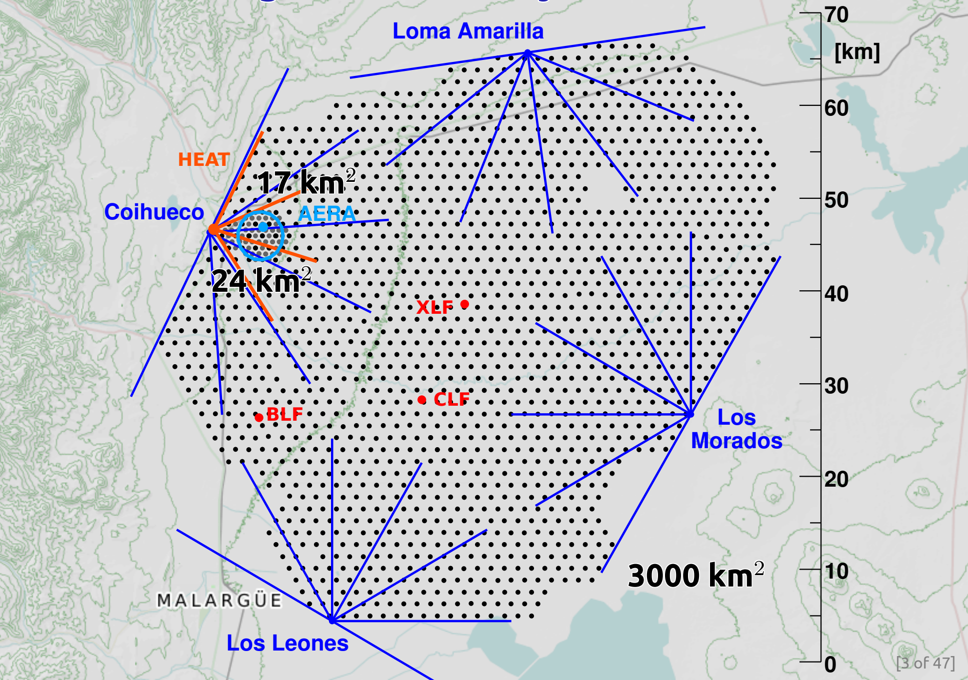


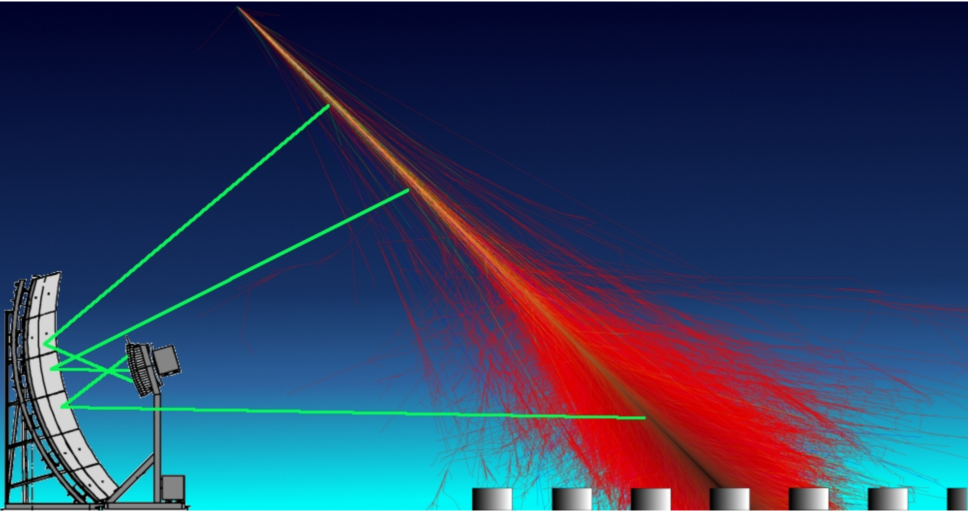
# The Pierre Auger Observatory



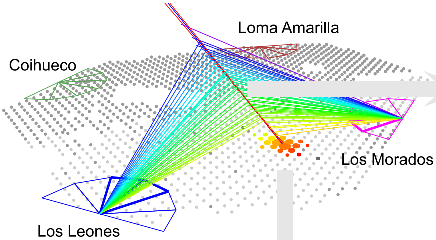
# The Pierre Auger Observatory

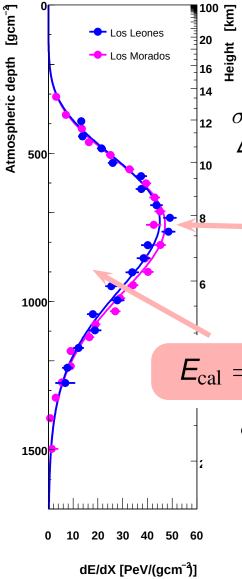


# Hybrid Detection of Air Showers



# Hybrid Detection of Air Showers



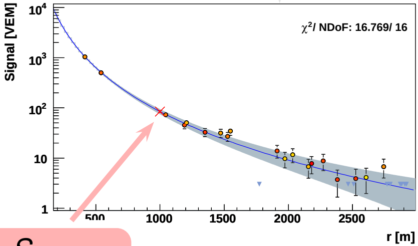




$\sigma_{X_{\max}} \lesssim 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \lesssim 10\,\mathrm{g/cm^2}$

$X_{\max}$

$E_{\mathrm{cal}} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X$

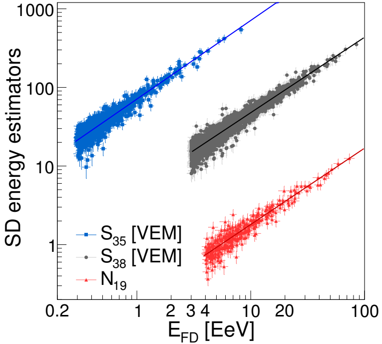
$\sigma_E/E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 15\,\%$

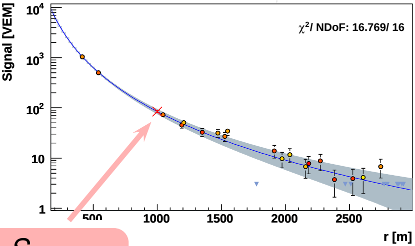



$S_{1000}$

$E_{\mathrm{surface}} = f(S_{1000},\, \theta)$

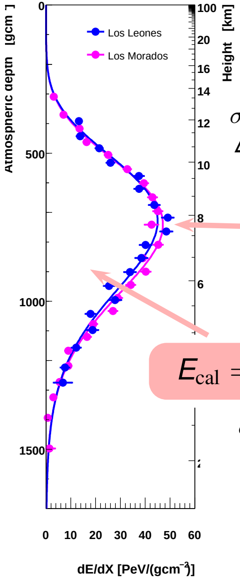
# Energy Calibration




$S_{1000}$

$$E_{\text{surface}} = f(S_{1000},\ \theta)$$




$$\sigma_{X_{\max}} \lesssim 20\ \text{g/cm}^2$$
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$$\sigma_E/E \sim 8\,\%$$
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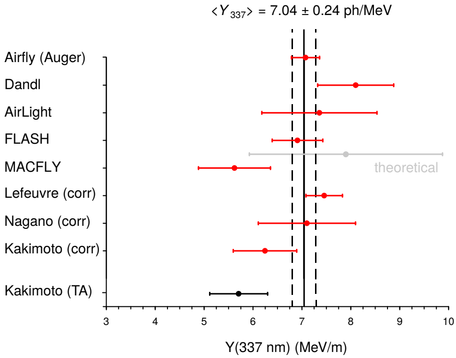
# Energy Scale

## fluorescence yield in air:




Rosado, Bianco, Arqueros, APP 55 (2014) 51

## energy scale uncertainty:

| | |
|---|---|
| Absolute fluorescence yield | 3.4% |
| Fluor. spectrum and quenching param. | 1.1% |
| Sub total (Fluorescence yield - sec. 2) | **3.6%** |
| Aerosol optical depth | 3%÷6% |
| Aerosol phase function | 1% |
| Wavelength depend. of aerosol scatt. | 0.5% |
| Atmospheric density profile | 1% |
| Sub total (Atmosphere - sec. 3) | **3.4%÷6.2%** |
| Absolute FD calibration | 9% |
| Nightly relative calibration | 2% |
| Optical efficiency | 3.5% |
| Sub total (FD calibration - sec. 4) | **9.9%** |
| Folding with point spread function | 5% |
| Multiple scattering model | 1% |
| Simulation bias | 2% |
| Constraints in the Gaisser-Hillas fit | 3.5% ÷ 1% |
| Sub total (FD profile rec. - sec. 5) | **6.5% ÷5.6%** |
| Invisible energy (sec. 6) | **3%÷1.5%** |
| Stat. error of the SD calib. fit (sec. 7) | **0.7%÷1.8%** |
| Stability of the energy scale (sec. 7) | **5%** |
| **Total** | **14%** |

V.Verzi for the Pierre Auger Collaboration, ICRC2013

# Energy Spectrum

# Energy Spectrum

$$\Phi(E) = \frac{N(E, E+\Delta E)}{t\,\Omega\,A\,\Delta E} \equiv \frac{N(E, E+\Delta E)}{\mathcal{E}\Delta E}$$

- number of particles $N$
- measurement time $t$
- area $A$
- solid angle $\Omega$
- “exposure” $\mathcal{E}$ (e.g. $\mathrm{km}^2$ sr yr)

more precisely (for a flat detector):

$$\mathcal{E} = t \int_0^{2\pi} \int_{\cos\theta_{\text{min}}}^{1} \cos\theta\, A\, \mathrm{d}\cos\theta$$
$$= A\,t\,\pi\,(1 - \cos^2\theta_{\text{min}})$$

SD: geometric area, $A = \text{const}$
FD: $A = f(E)$ (and $t_{\text{FD}} \sim 0.15\, t_{\text{SD}}$)

# UHECR Energy Spectrum 14 Years Ago

Physics Letters B 556 (2003) 1–6

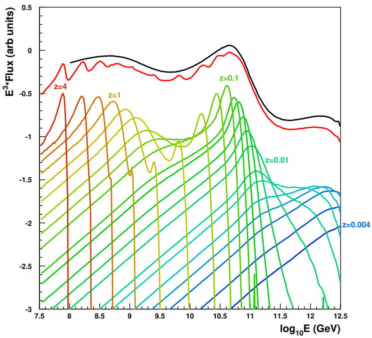
Has the GZK suppression been discovered?

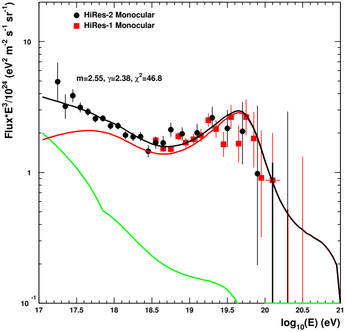
John N. Bahcall [a], Eli Waxman [b]

PHYSICAL REVIEW D **74,** 043005 (2006)

**On astrophysical solution to ultrahigh energy cosmic rays**

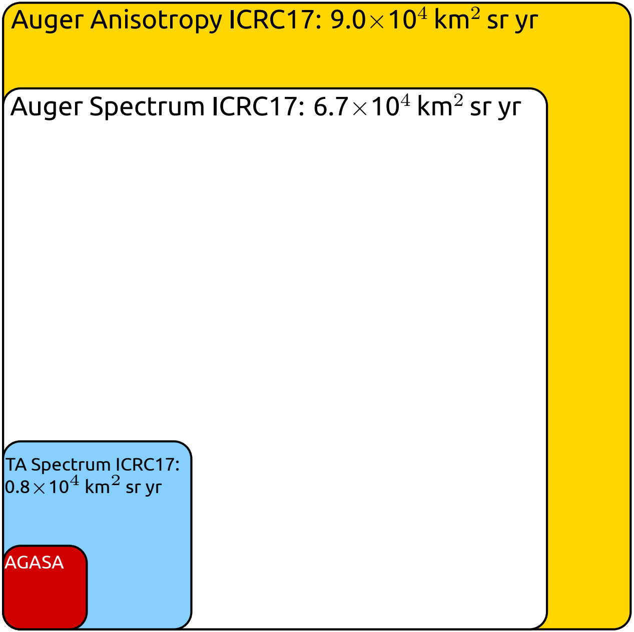
Veniamin Berezinsky



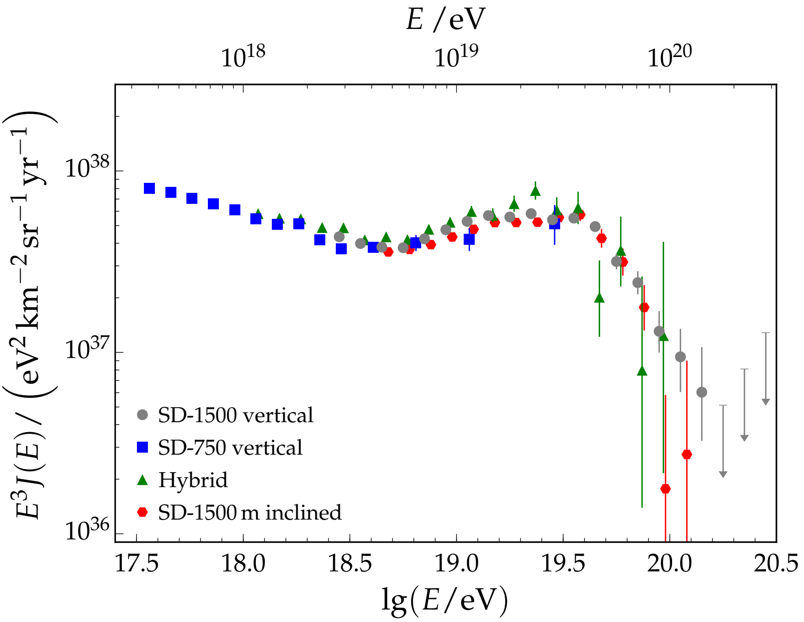




HiRes Collaboration, Proc. 29th ICRC (2005)

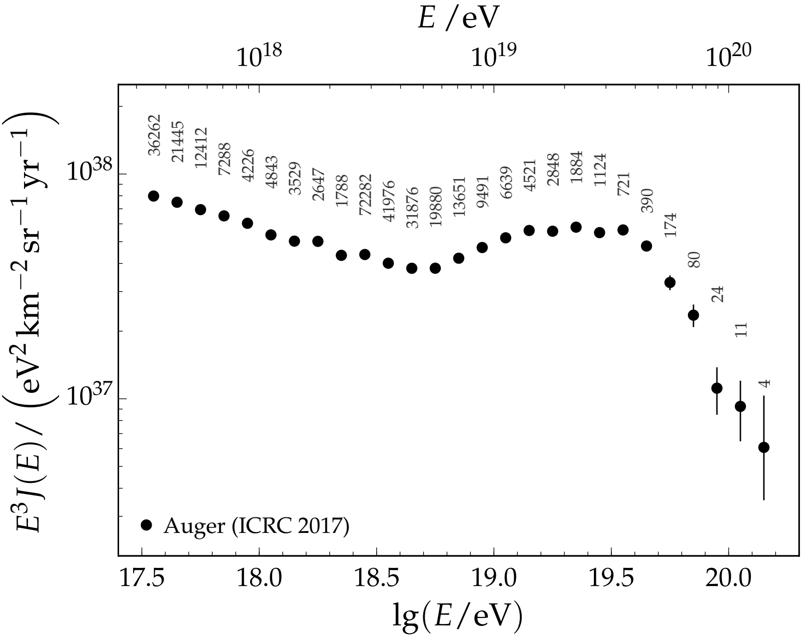
# UHE Exposure



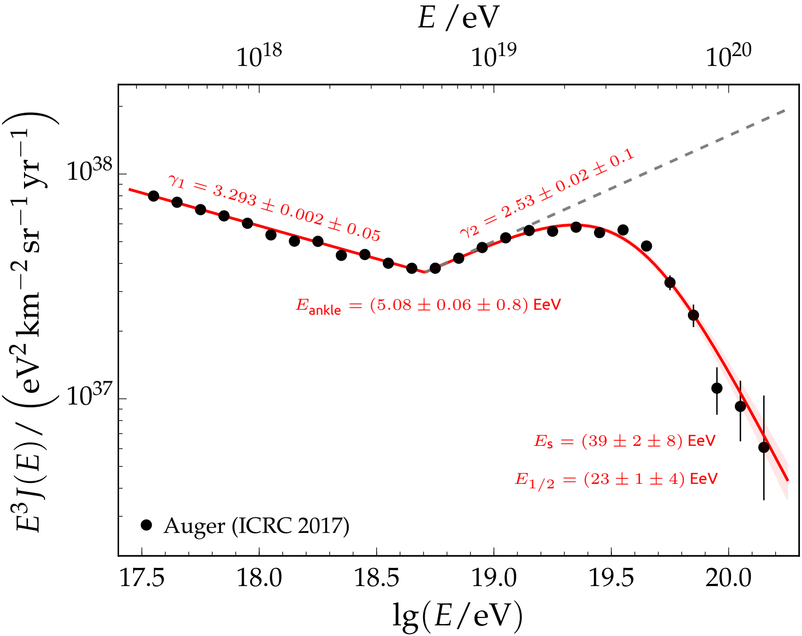
# Auger Energy Spectra



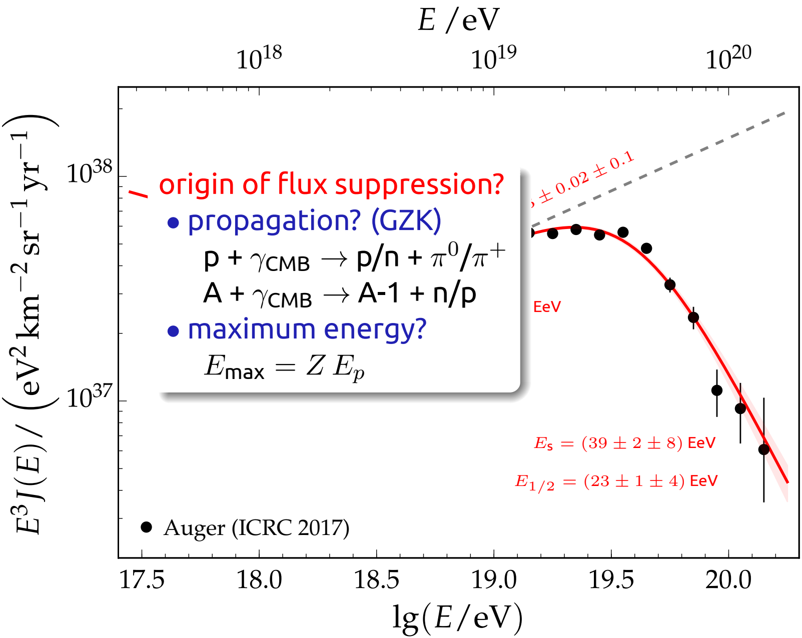
# Combined Energy Spectrum



# Combined Energy Spectrum



# Combined Energy Spectrum




origin of flux suppression?

- propagation? (GZK)

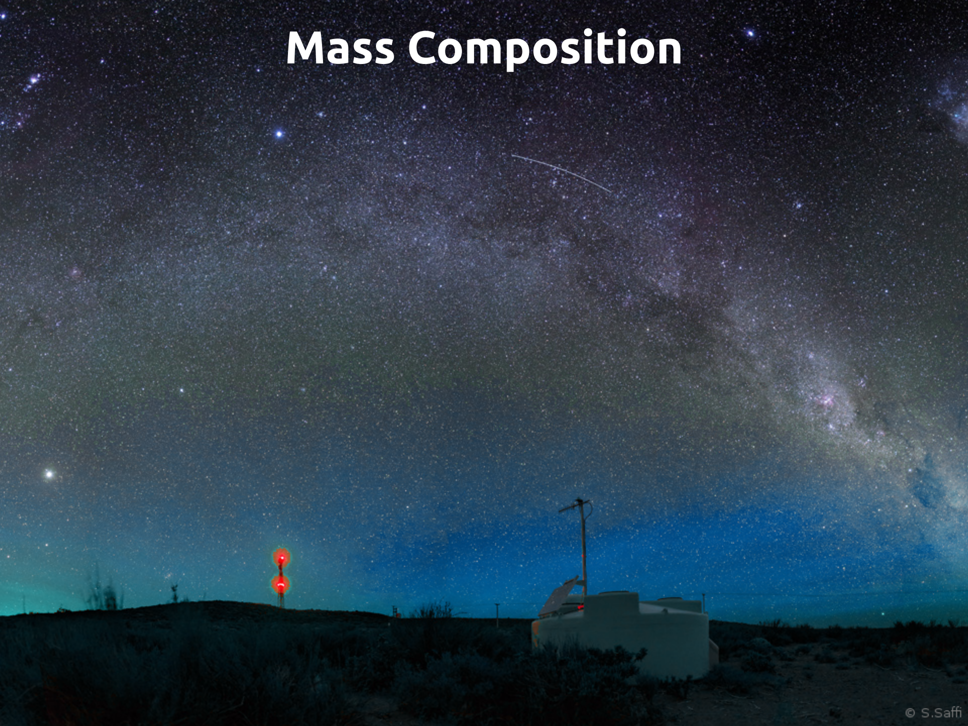
  $p + \gamma_{CMB} \rightarrow p/n + \pi^0/\pi^+$

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

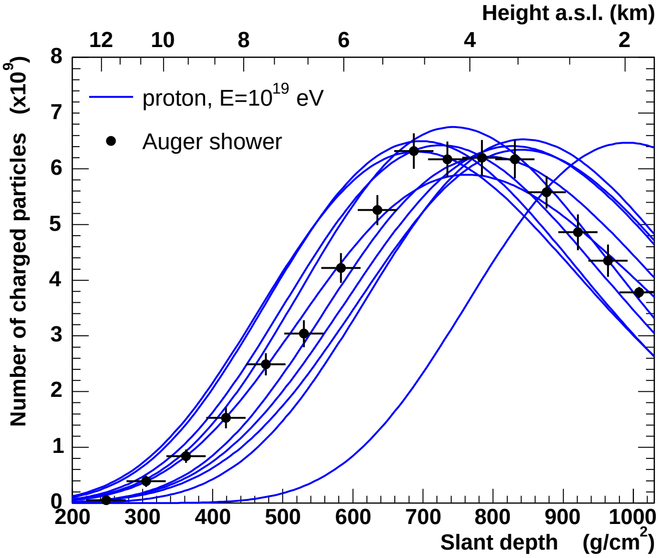
- maximum energy?

  $E_{max} = Z\, E_p$

# Mass Composition

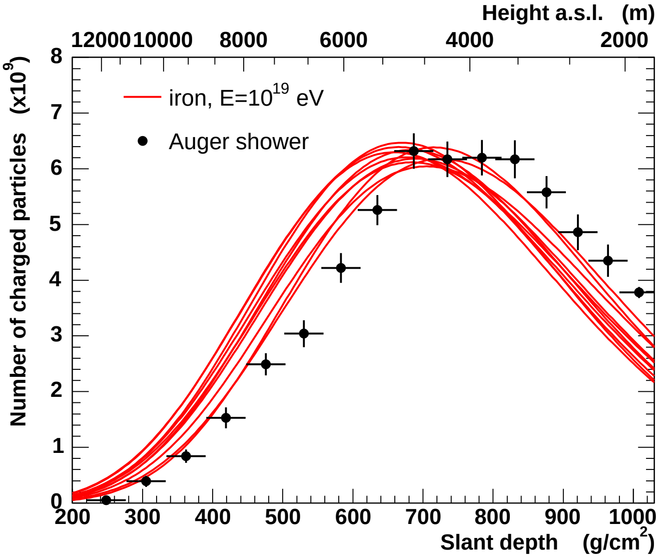


# Primary Mass and Longitudinal Shower Profiles



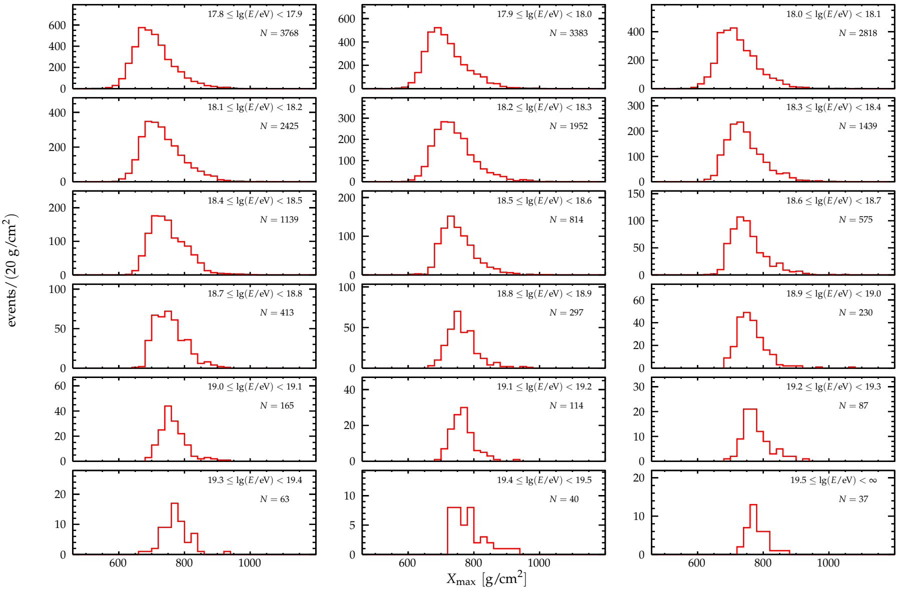

R. Engel 2004

# Primary Mass and Longitudinal Shower Profiles



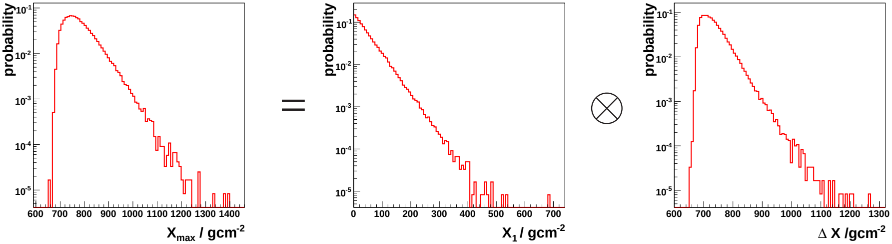

R. Engel 2004

# $X_{max}$ Distributions




Pierre Auger Coll., PRD **90** (2014) 12, 122005

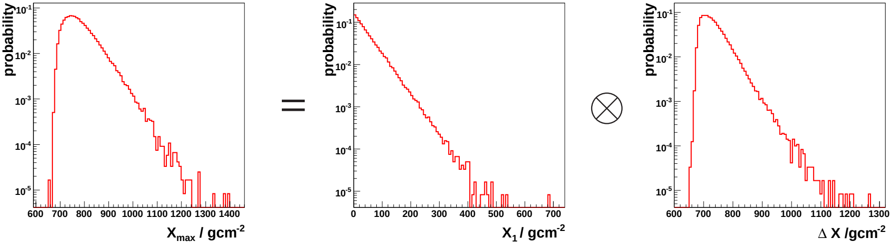
# $X_{max}$ Distribution – Mean




- first interaction $\langle X_1 \rangle$: $\lambda_p$
- shower development: $\langle \Delta X \rangle$: $\propto \ln E$
- $\langle X_{max} \rangle_p = \lambda_p + D \ln E$

$E$ : primary energy, $\lambda_p$ : proton interaction length, $D$ : elongation rate, $A$ : mass number

# $X_{max}$ Distribution – Mean




- first interaction $\langle X_1 \rangle$: $\lambda_p$
- shower development: $\langle \Delta X \rangle$: $\propto \ln E$
- $\langle X_{\text{max}} \rangle_p = \lambda_p + D \ln E$

- superposition model: nucleus $(E,\ A) \equiv A$ nucleons $(E/A, 1)$
- $\langle X_{\text{max}} \rangle_A = \lambda_p + D \ln(E/A)$

$E$ : primary energy, $\lambda_p$ : proton interaction length, $D$ : elongation rate, $A$ : mass number


why

$$\langle X_{\mathsf{max}} \rangle_A = \lambda_p + D \ln(E/A)$$

and not

$$\langle X_{\mathsf{max}} \rangle_A = \underline{\lambda_A} + D \ln(E/A)$$

?


why

$$\langle X_{\text{max}} \rangle_A = \lambda_p + D \ln(E/A)$$

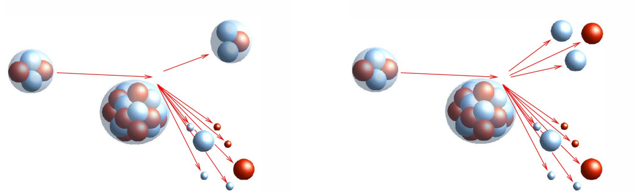
and not

$$\langle X_{\text{max}} \rangle_A = \underline{\lambda_A} + D \ln(E/A)$$

?

$\rightarrow$ Semi-superposition theorem

J. Engel et al., PRD (1992)



If the number of participating nucleons scales as

$$\langle n_{\text{part}} \rangle = A \frac{\lambda_A}{\lambda_p}$$

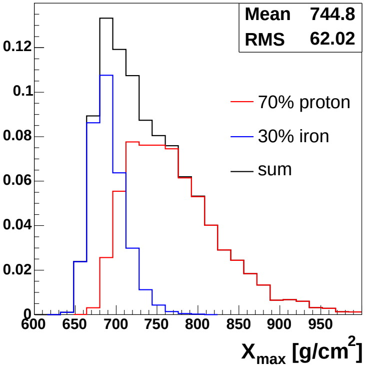
then the inclusive distribution of depths of nucleon interactions is

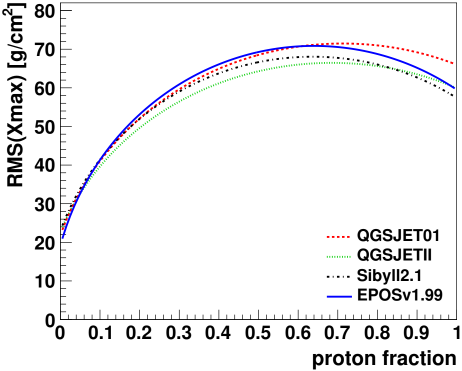
$$f(X) = 1/\lambda_p \exp(-X_{\text{int}}/\lambda_p)$$

(independently of how the spectators fragment!)

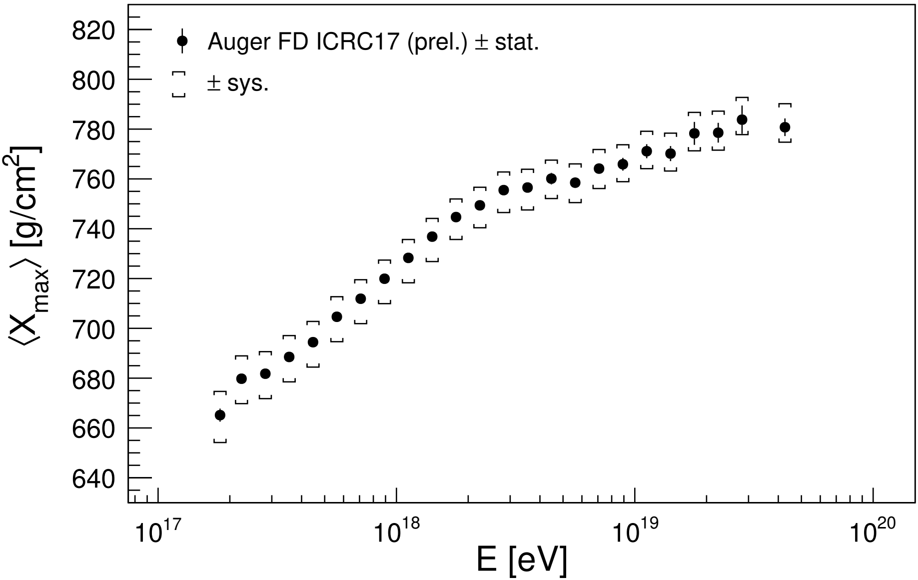
# Standard Deviation of $X_{max}$ Distribution

- $\sigma(X_{\text{max}})^2_A = \lambda^2_A + \sigma(X_{\text{max}} - X_{\text{first}})^2_A$
- $\sigma(X_{\text{max}})_p > \sigma(X_{\text{max}})_A > \sigma(X_{\text{max}})_p / \sqrt{A}$
- mixed composition:
  $\sigma(X_{\text{max}})^2 = \langle \sigma_i^2 \rangle + \left( \left\langle \langle X_{\text{max}} \rangle_i^2 \right\rangle - \langle X_{\text{max}} \rangle^2 \right)$



# Average $X_{max}$ Fluorescence Detector



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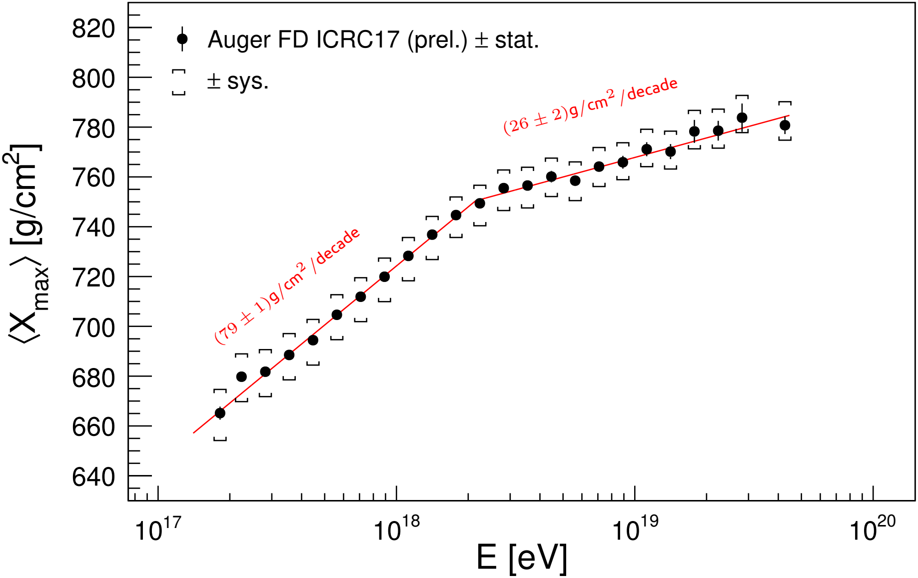
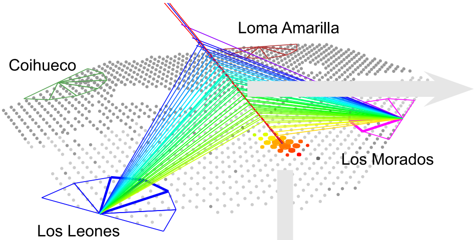
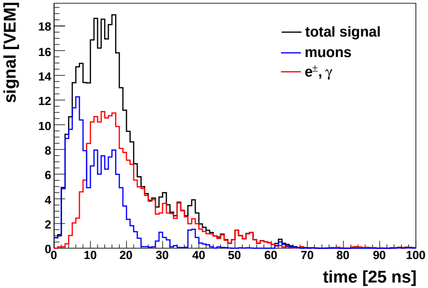
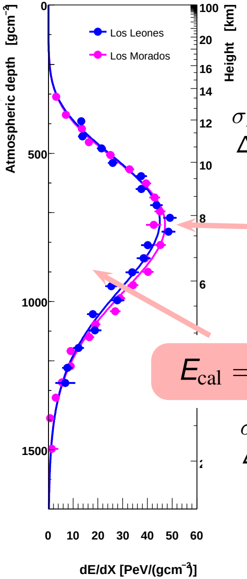


# $X_{max}$ with SD




$\sigma_{X_{\rm max}} \lesssim 20\,{\rm g/cm^2}$
$\Delta_{\rm sys} \lesssim 10\,{\rm g/cm^2}$

$X_{\rm max}$

$E_{\rm cal} = \int \frac{{\rm d}E}{{\rm d}X}\,{\rm d}X$

$\sigma_E/E \sim 8\,\%$
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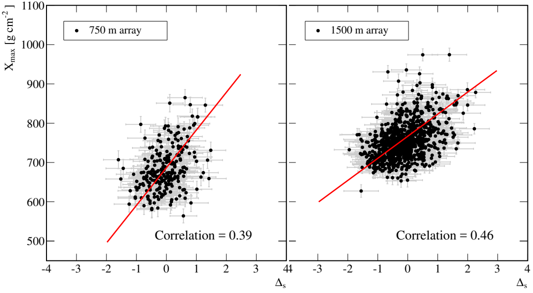
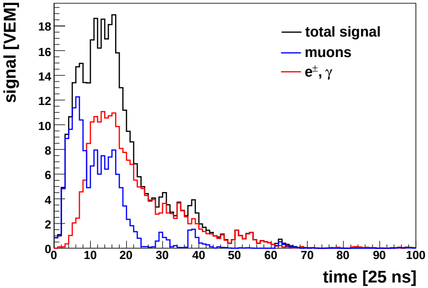
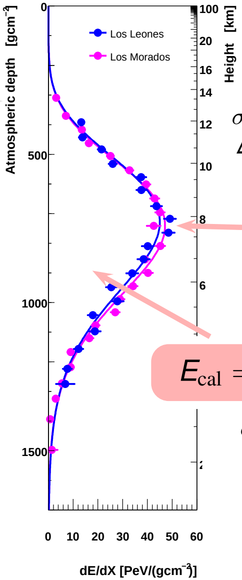
# $X_{max}$ with SD




$\sigma_{X_{max}} \lesssim 20\,\mathrm{g/cm^2}$

$\Delta_{sys} \lesssim 10\,\mathrm{g/cm^2}$

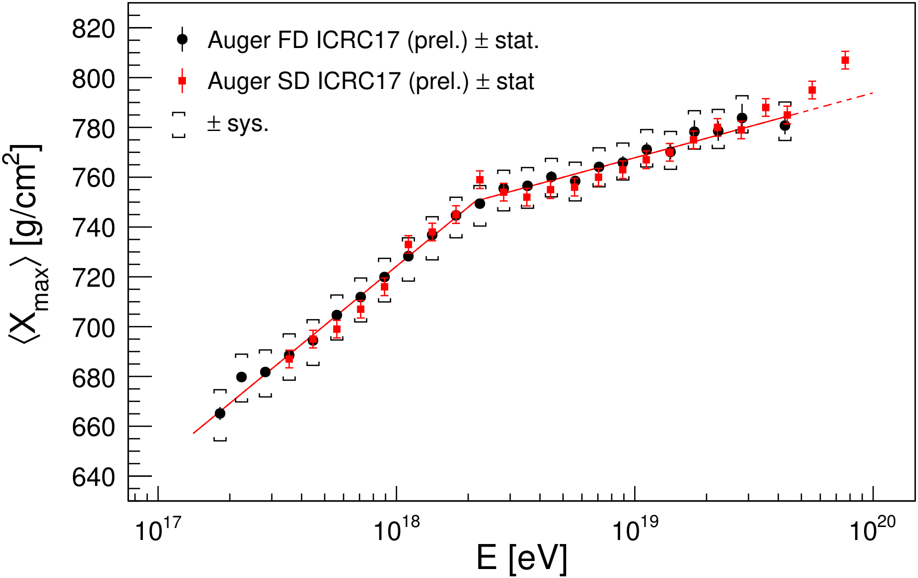
$X_{max}$

$E_{cal} = \int \frac{dE}{dX}\, dX$

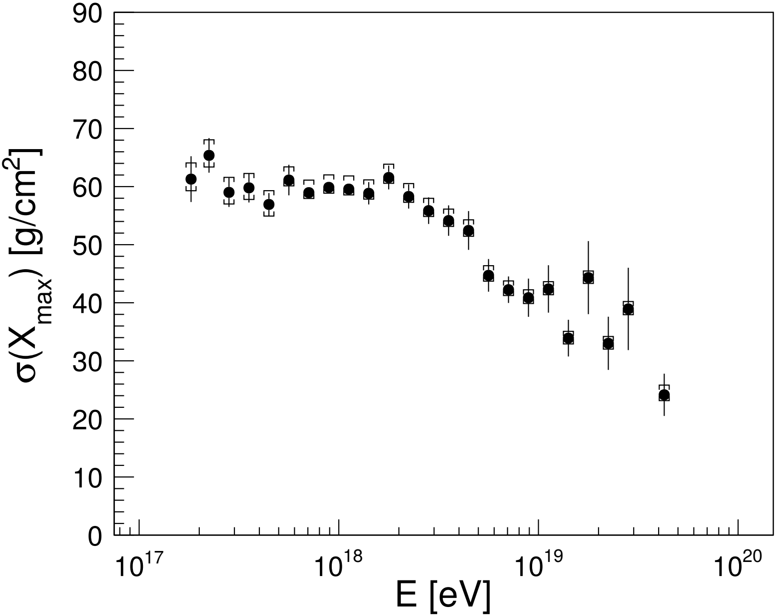
$\sigma_E/E \sim 8\,\%$

$\Delta_{sys} \approx 15\,\%$

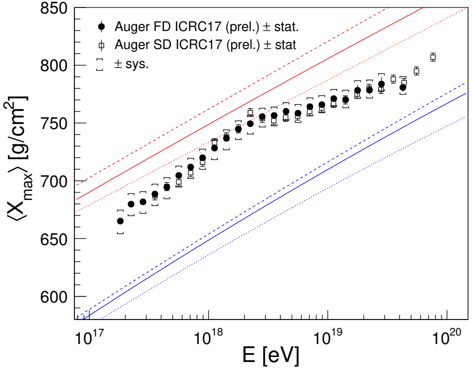
# Average $X_{max}$ Fluorescence and Surface Detector

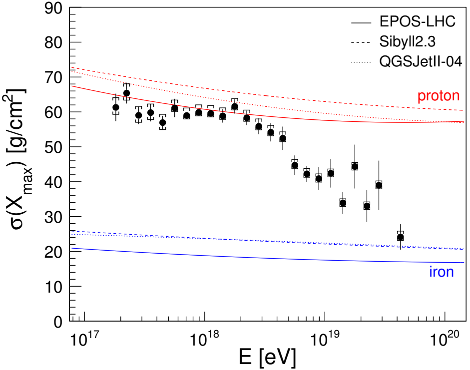


# Standard Deviation of $X_{max}$ Distribution (FD)



# $X_{max}$ Moments vs. Air Shower Simulations



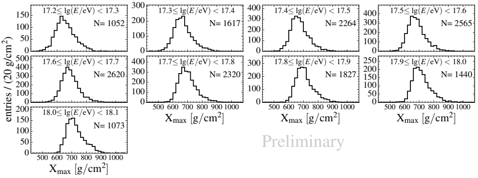




lines: air shower simulations using post-LHC hadronic interaction models

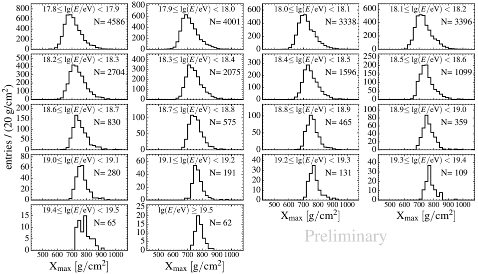
# (p-He-N-Fe)-fit of $X_{max}$ Distributions

FD data:

$\lg(E/\mathrm{eV}) = 17.2 \ldots 18.1$

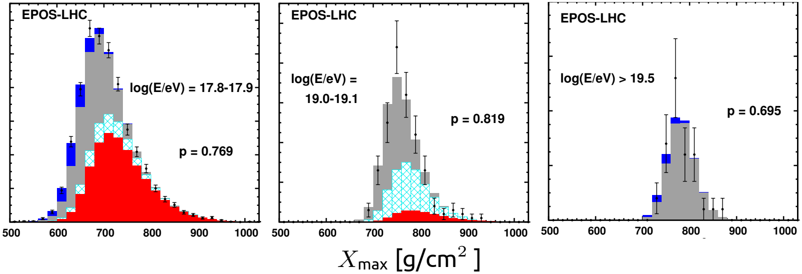



$\lg(E/\mathrm{eV}) = 17.8 \ldots > 19.5$

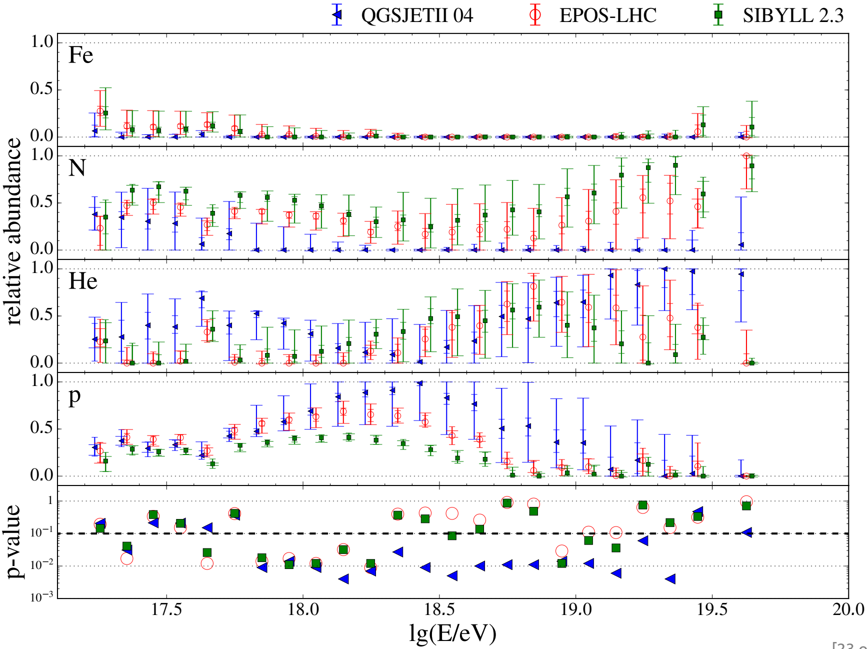



Examples of 4-component fit:

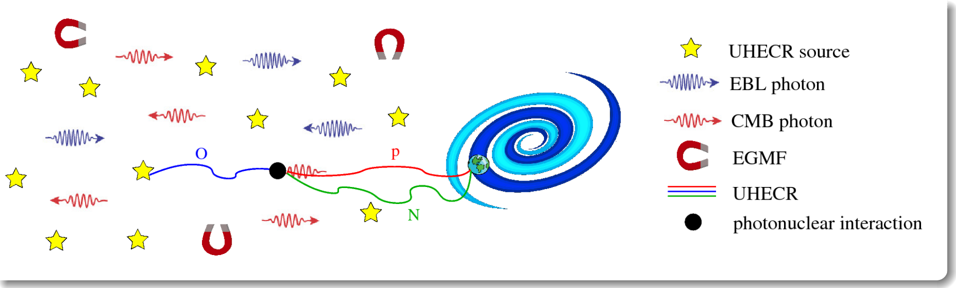
p He N Fe



# Composition Fractions



# Combined Fit of Spectrum and $X_{max}$ Distributions




## minimal astrophysical model

Pierre Auger Coll., JCAP 1704 (2017) no.04, 038

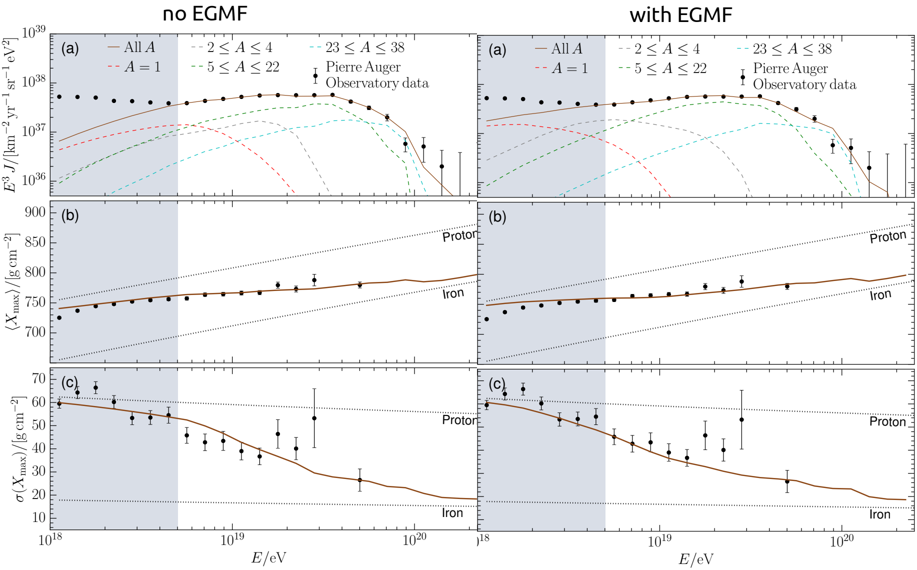
- $E_{\text{max}} = R_{\text{cut}}\, Z$
- power law injection $E^{-\gamma}$
- five mass groups: p, He, N, Si
- source evolution $(1+z)^m$
- 1D propagation with CRPropa3
- Gilmore+12 EBL photon field

## extended model

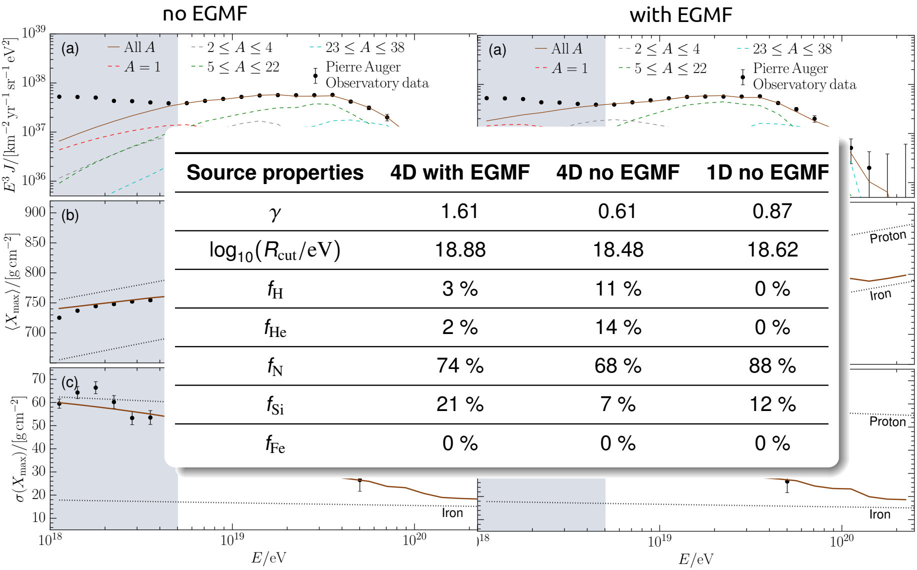
D. Wittkowski for the Pierre Auger Coll., ICRC15

- local large scale structure (Dolag+12)
- extragalactic magnetic field (Sigl+03)
- 4D propagation with CRPropa3

# Combined Fit of Spectrum and $X_{max}$ Distributions



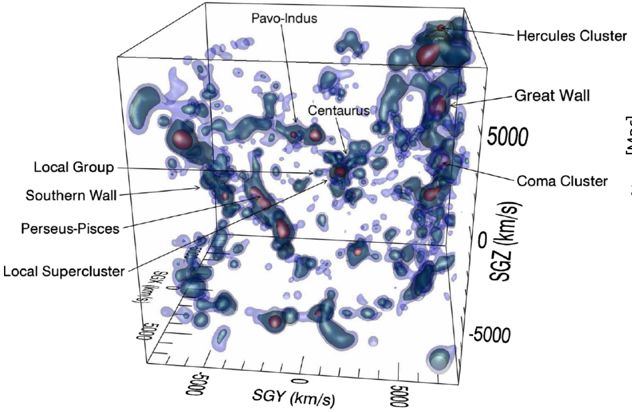
# Combined Fit of Spectrum and $X_{max}$ Distributions



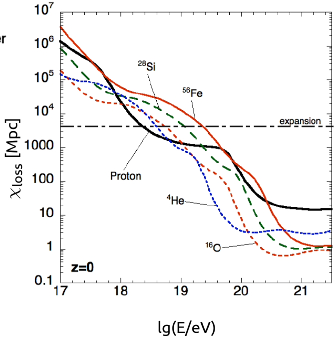

| Source properties | 4D with EGMF | 4D no EGMF | 1D no EGMF |
|---|---|---|---|
| $\gamma$ | 1.61 | 0.61 | 0.87 |
| $\log_{10}(R_{cut}/eV)$ | 18.88 | 18.48 | 18.62 |
| $f_H$ | 3 % | 11 % | 0 % |
| $f_{He}$ | 2 % | 14 % | 0 % |
| $f_N$ | 74 % | 68 % | 88 % |
| $f_{Si}$ | 21 % | 7 % | 12 % |
| $f_{Fe}$ | 0 % | 0 % | 0 % |

# Searching for the Sources of UHECRs
# (a) Large-scale Anisotropy

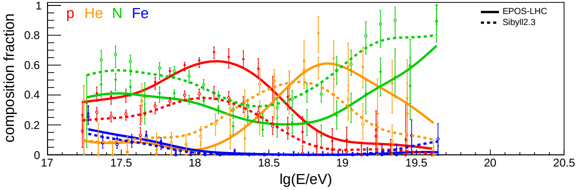
# The Local Large Scale Structure




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

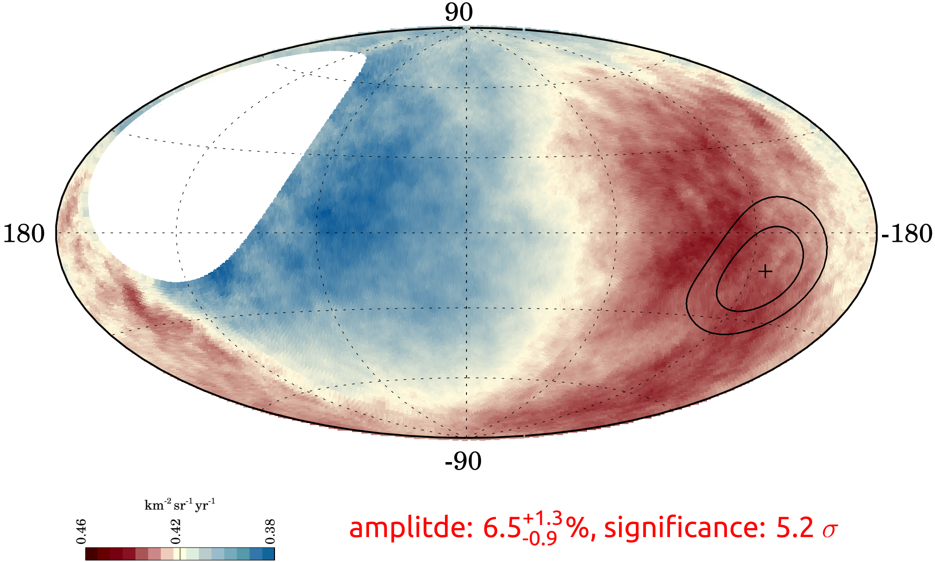



D.Allard Astropart.Phys. **39** (2012) 33




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

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



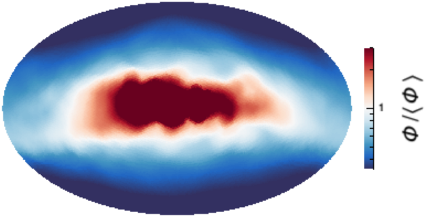

amplitde: $6.5^{+1.3}_{-0.9}$%, significance: 5.2 $\sigma$

Pierre Auger Coll., Science **357** (2017) 1266 (smoothed at 45°)

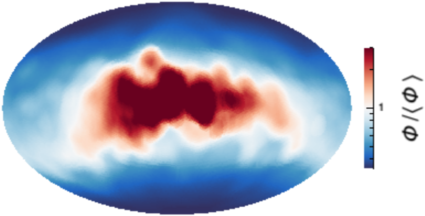
# UHECRs from Galaxy?

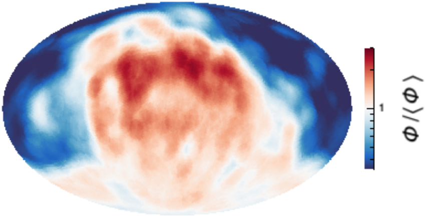
stellar distribution from Weber&deBoer10, coherent and random JF12 field

8 EV $\sim$ p $\rightarrow$



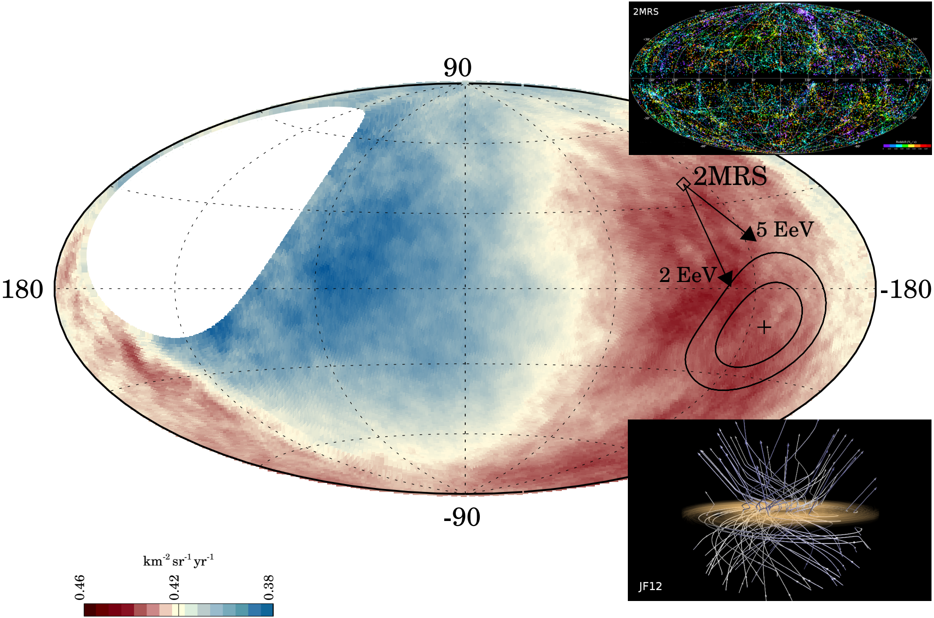

4 EV $\sim$ He $\rightarrow$



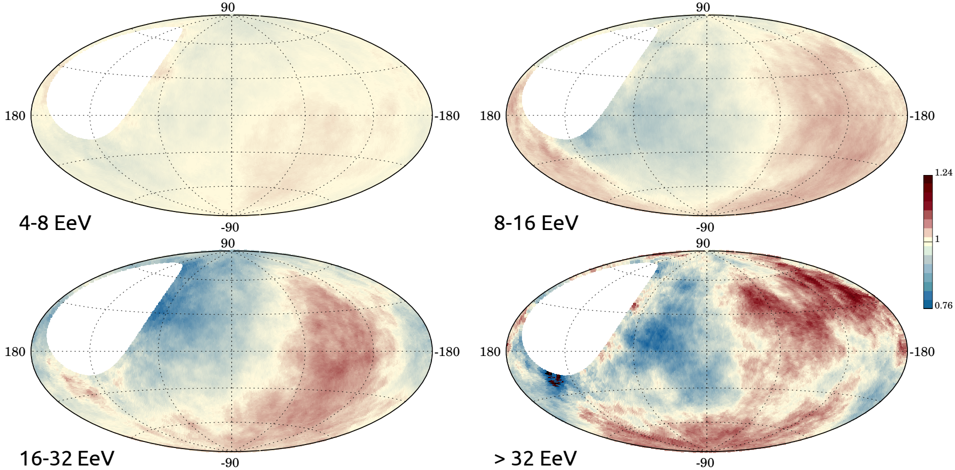

$\leftarrow$ 1 EV $\sim$ N

# Dipolar Anisotropy and Large Scale Structure




Pierre Auger Coll., Science **357** (2017) 1266 (smoothed at 45°)

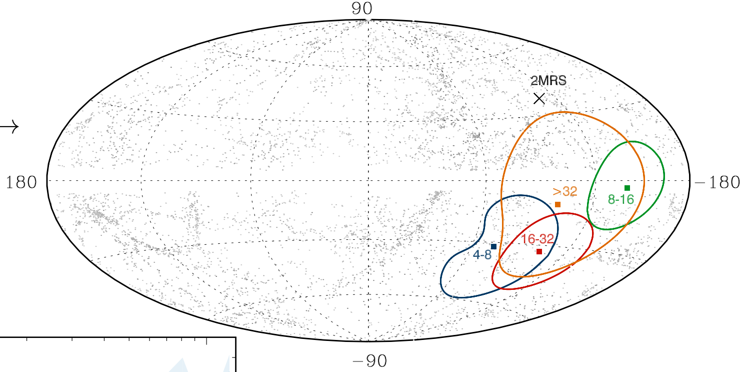
# Energy Dependence of UHECR Dipole

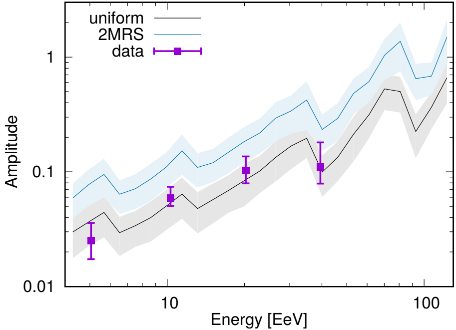



Pierre Auger Coll., subm. to Astrophys.J., arXiv:1808.03579

# Energy Dependence of UHECR Dipole

dipole position →



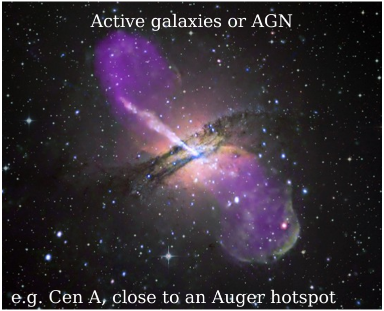




← model: mixed composition
$R_{\text{max}} = 6$ EeV, $\rho = 10^{-4}$ Mpc$^{-3}$

# Searching for the Sources of UHECRs
# (b) Intermediate-scale Anisotropy

# Intermediate-scale Anisotropy

## test for isotropy using catalogues of extragalactic $\gamma$-ray sources




AGNs from the 2FHL Catalog
(*Fermi*-LAT, > 50 GeV)
within 250 Mpc

Ackermann+ 16


'Starbursts' from *Fermi*-LAT search lis
(HCN survey) within 250 Mpc
with radio flux > 0.3 Jy

Gao & Salomon 05

**Assumption: UHECR flux ∝ non-thermal photon flux**

**Analysis: unbinned maximum-likelihood analysis vs isotropy**
Sky model: [**α**×sources + (1-**α**)×isotropic] ⊗ Fisher(**θ**)

Pierre Auger Coll., ApJ. Lett. 853 (2018) L29, slide from J.Biteau (Auger Coll.) MIAPP 2018

# Intermediate-scale Anisotropy

**Active galaxies**

> 60 EeV: N~180 events, TS=15

α=7%, θ=7°

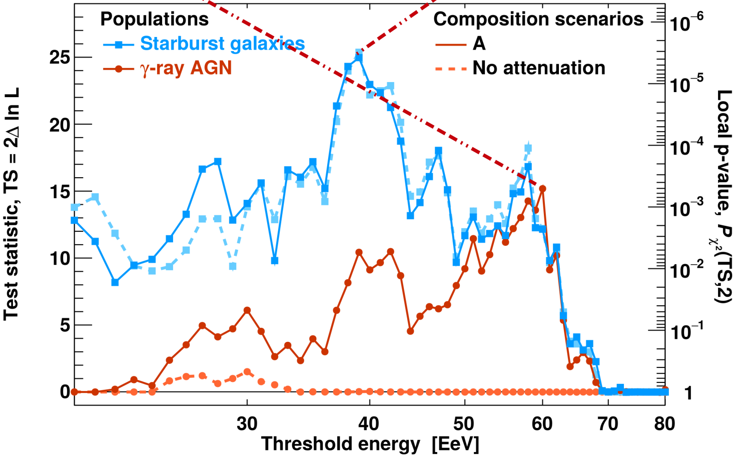
2 free par. + E-scan → 2.7σ

**Starforming galaxies**

> 39 EeV: N~900 events, TS~25

α=10%, θ=13°

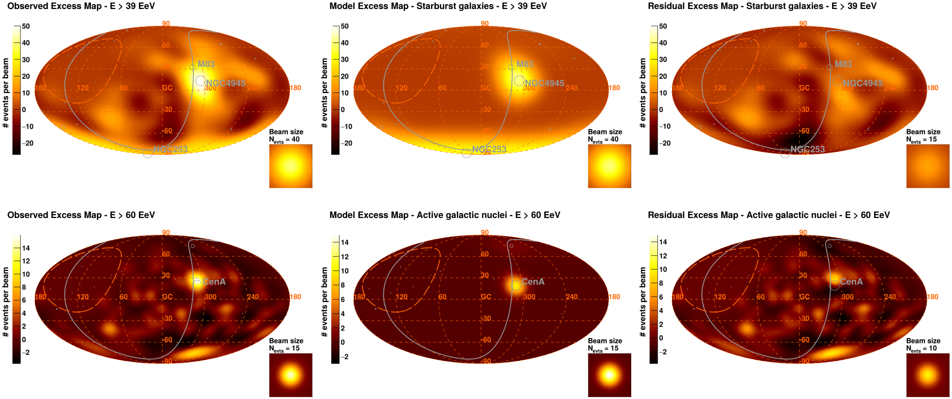
2 free par. + E-scan → 4.0σ




Pierre Auger Coll., ApJ. Lett. 853 (2018) L29, slide from J.Biteau (Auger Coll.) MIAPP 2018

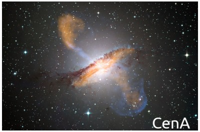
# Intermediate-scale Anisotropy


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



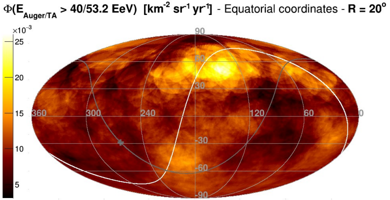

$\gamma$AGN ($E > 60$ EeV, 6.7%, 6.9°, $2.7\,\sigma$)

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



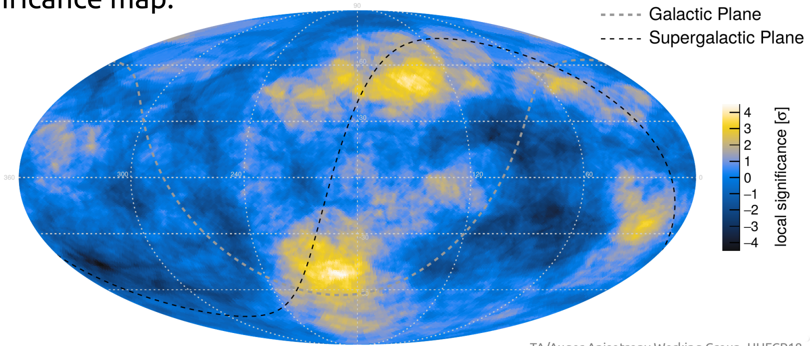
# The Full (-sky) Picture: TA and Auger

flux map:



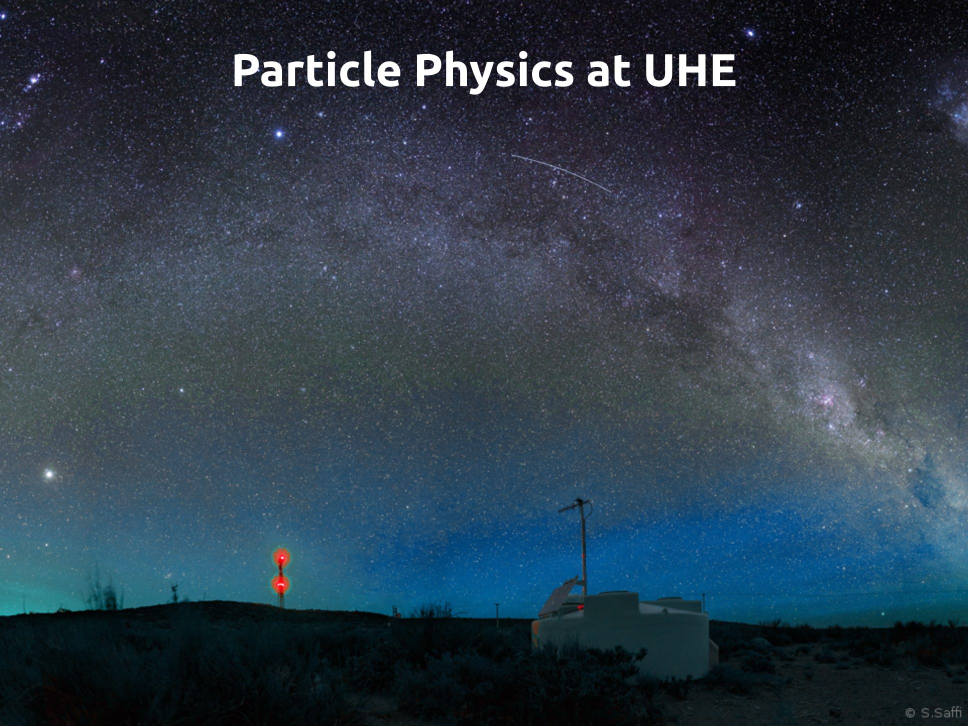

- two "warm spots" with 4.7/4.2 $\sigma$ local significance
- post-trial 2.2/1.3 $\sigma$
- aligned along super-galactic plane?

significance map:



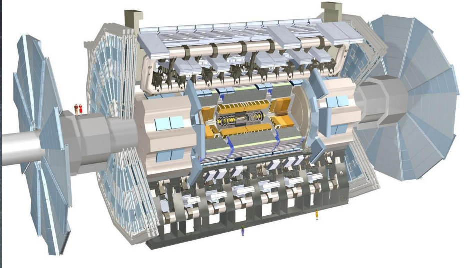

TA/Auger Anisotropy Working Group, UHECR18

# Particle Physics at UHE



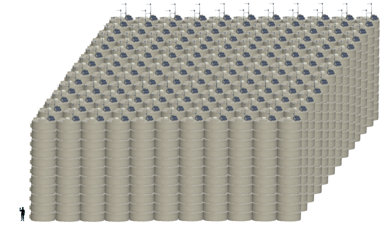
# Particle Physics at UHE

## ATLAS@LHC



- $E_{\text{beam}} = 6.5$ TeV
- $\sqrt{s} = 13$ TeV
- 7 kt detector

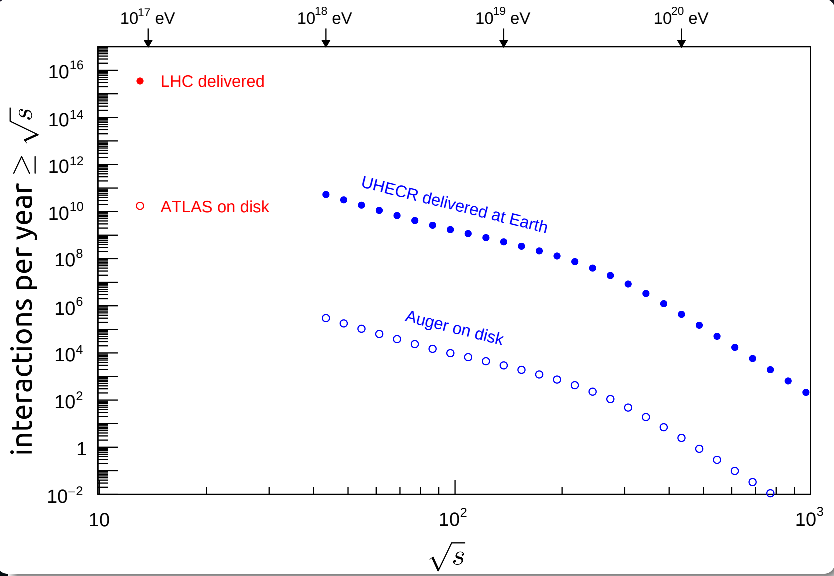
## Pierre Auger Observatory*



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

* to scale but stacked, actual area: 3000 km$^2$
** for $p$+air ($>$ 60 TeV for Fe+air)

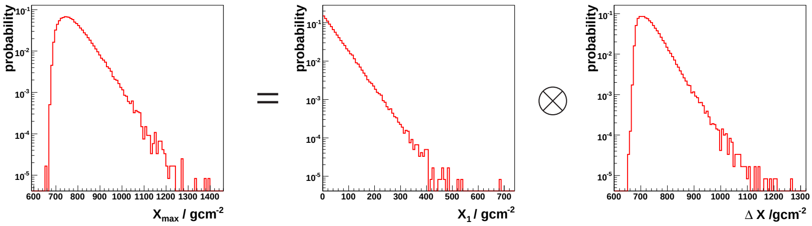
# LHC and UHECR Luminosity

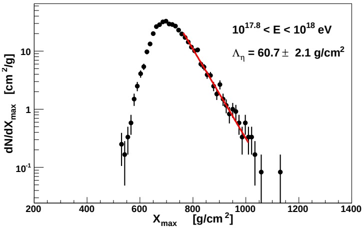


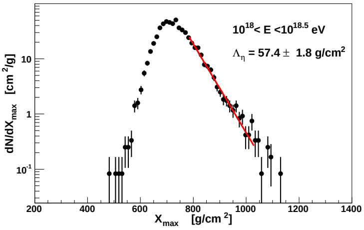
# Hadronic Interactions at UHE
# (a) Cross Section

# Measurement of the UHE Proton+Air Cross Section

## tail of $X_{max}$ distribution:



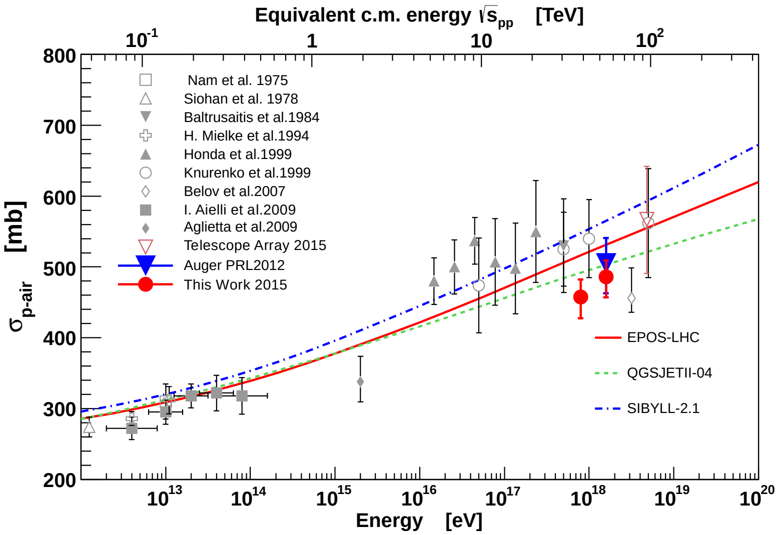

$\langle E \rangle = 10^{17.90}$ eV

$\Lambda_\eta = 60.7 \pm 2.1(\text{stat}) \pm 1.6(\text{syst})\,\text{g/cm}^2$

$\langle E \rangle = 10^{18.22}$ eV

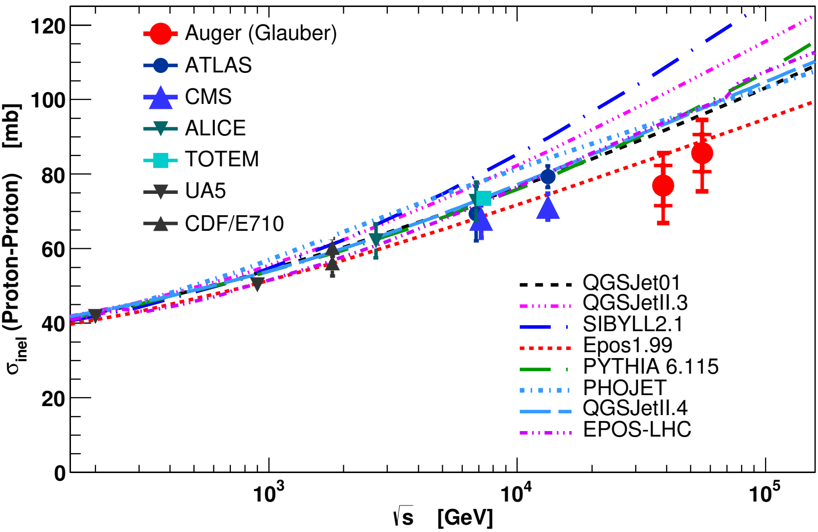
$\Lambda_\eta = 57.4 \pm 1.8(\text{stat}) \pm 1.6(\text{syst})\,\text{g/cm}^2$

# Measurement of the UHE Proton+Air Cross Section




R. Ulrich for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

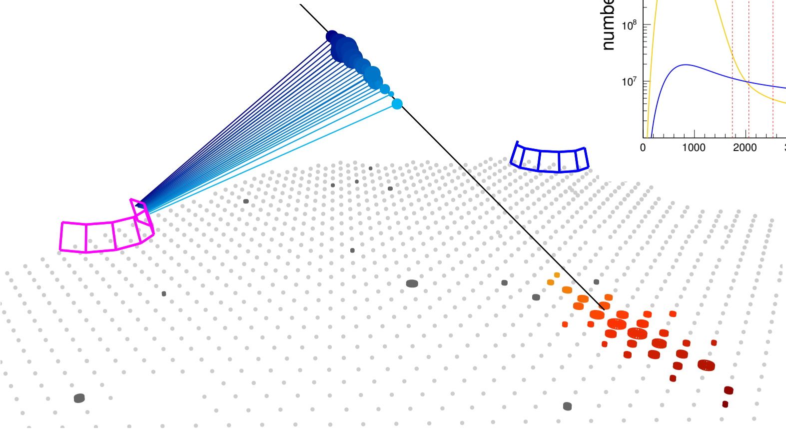
# Proton+Proton Cross Section at $\sqrt{s} = 39$ and 66 TeV

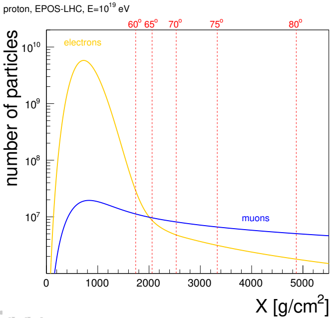



R. Ulrich for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

# Hadronic Interactions at UHE
# (b) Muons in Air Showers

# Muon Studies with Inclined Hybrid Events (62°-80°)

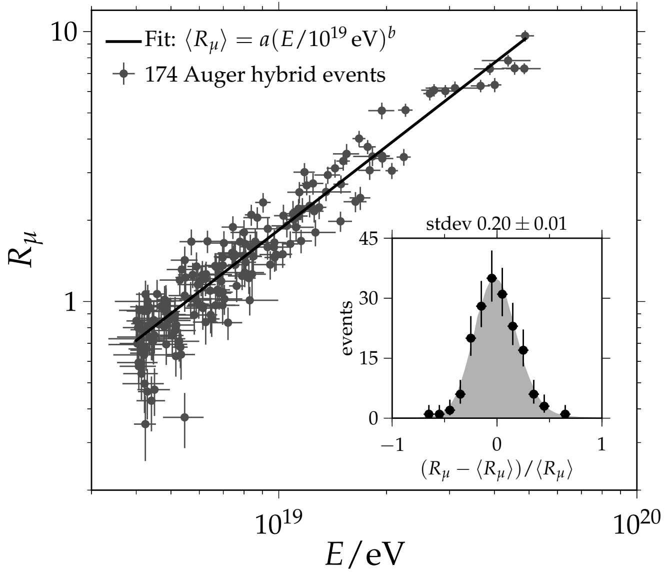





event 201114505353, $\theta = 75.6^{\circ}$, $E = 15.5$ EeV

# $R_\mu$ vs. $E_{FD}$

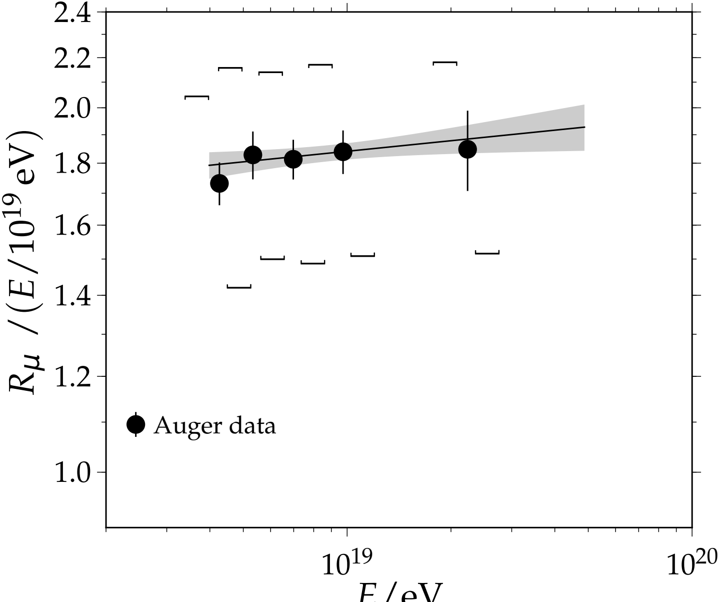
Pierre Auger Coll., PRD **D91** (2015) 3, 032003




QGSJetII-03, $p$, $E = 10^{19}$ eV $\rightarrow R_\mu = 1$

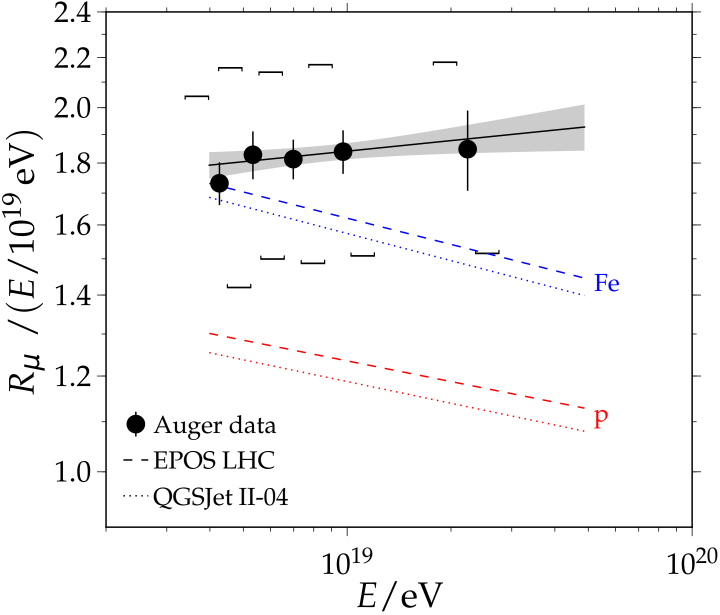
# $\langle R_\mu \rangle / E_{FD}$ vs. $E_{FD}$

Pierre Auger Coll., PRD **D91** (2015) 3, 032003

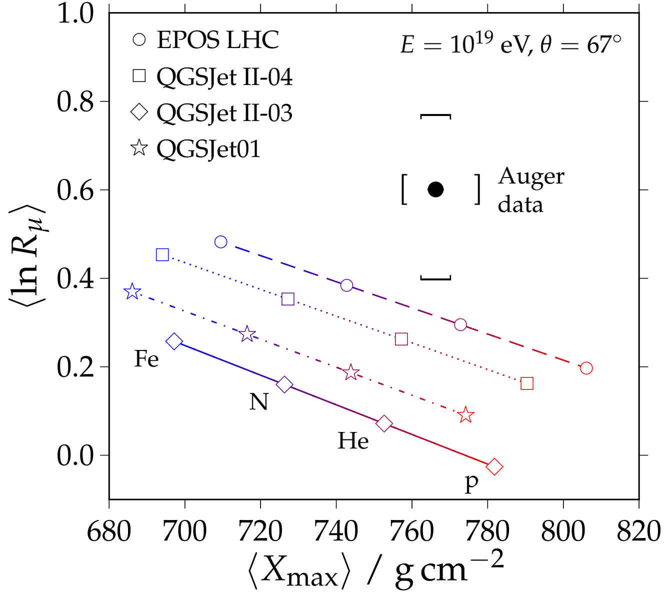


# $\langle R_\mu \rangle / E_{FD}$ vs. $E_{FD}$

Pierre Auger Coll., PRD **D91** (2015) 3, 032003



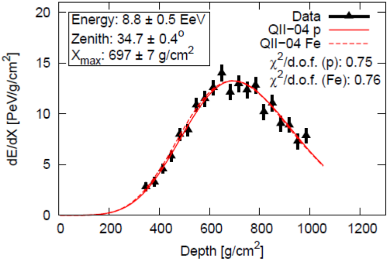
# Muon Scale vs. $X_{max}$ (FD)

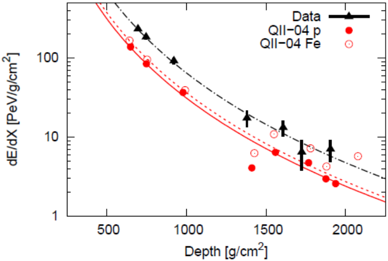



Pierre Auger Coll., PRD **D91** (2015) 3, 032003

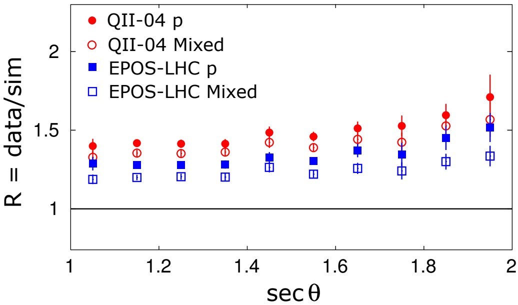
# Hybrid Events, Data vs. Simulation

**example:**



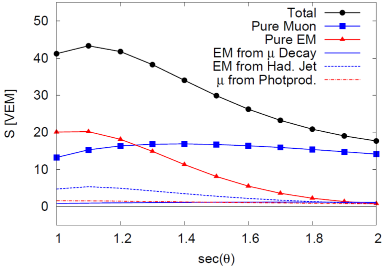

**ratio of S(1000) data/MC:**

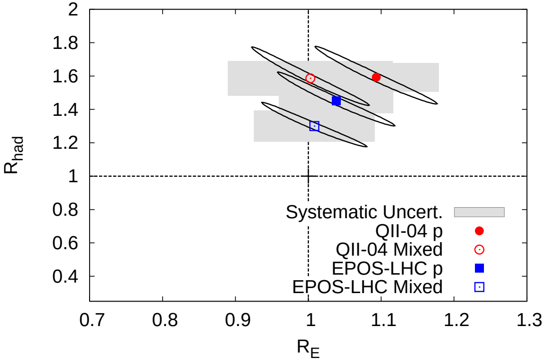



Pierre Auger Coll. PRL **117** (2016) 192001

# Hybrid Events, Data vs. Simulation

Combined fit of energy scale $R_E$ and had. component rescaling $R_{\text{had}}$




| model | $R_E$ | $R_{\text{had}}$ |
|---|---|---|
| QGSJetII-04, $p$ | $1.09 \pm 0.08 \pm 0.09$ | $1.59 \pm 0.17 \pm 0.09$ |
| QGSJetII-04, mixed | $1.00 \pm 0.08 \pm 0.11$ | $1.61 \pm 0.18 \pm 0.11$ |
| Epos-LHC, $p$ | $1.04 \pm 0.08 \pm 0.08$ | $1.45 \pm 0.16 \pm 0.08$ |
| Epos-LHC, mixed | $1.00 \pm 0.07 \pm 0.08$ | $1.33 \pm 0.13 \pm 0.09$ |

Pierre Auger Coll. PRL **117** (2016) 192001

# Conclusions

UHECR before Auger

UHECR in 2019

Las Meninas by Diego Velazquez 1656

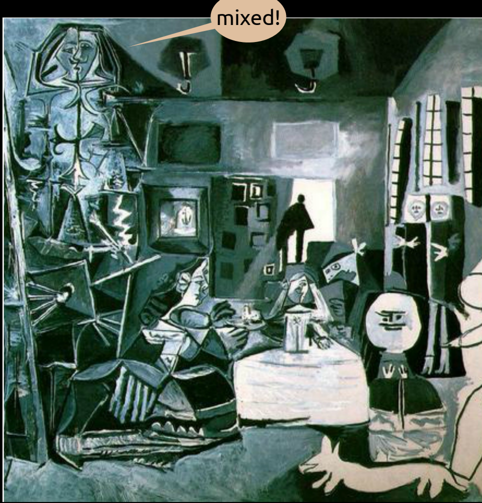
Las Meninas by Pablo Picasso 1957

# Conclusions

UHECR before Auger


Las Meninas by Diego Velazquez 1656

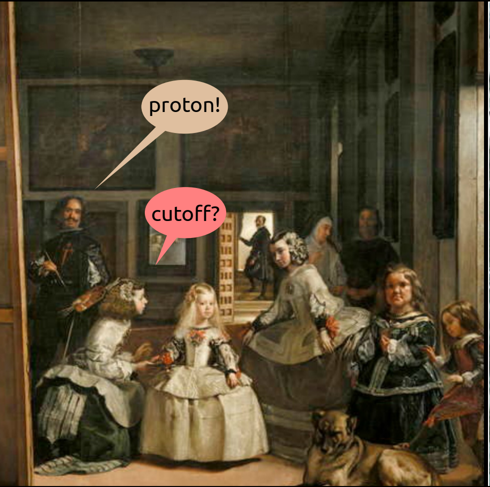
UHECR in 2019




Las Meninas by Pablo Picasso 1957

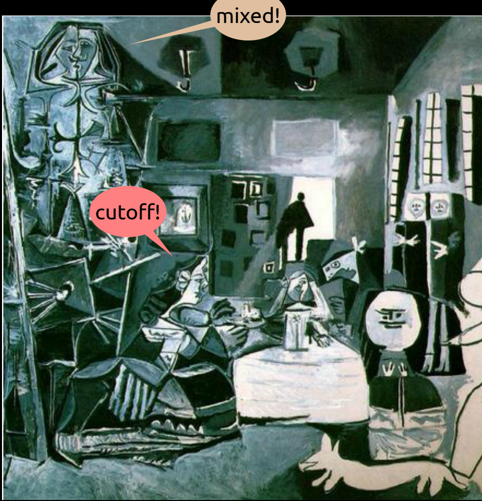
# Conclusions

UHECR before Auger




Las Meninas by Diego Velazquez 1656

UHECR in 2019

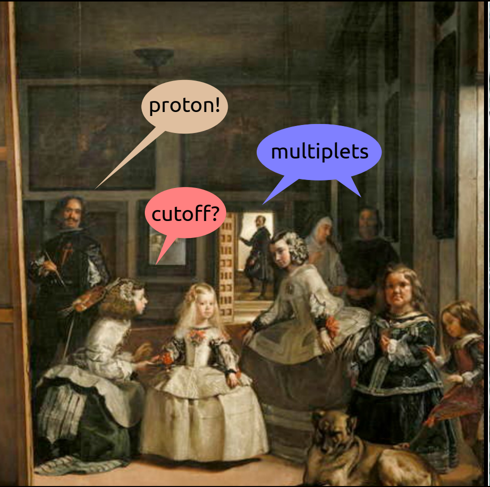



Las Meninas by Pablo Picasso 1957

# Conclusions

UHECR before Auger

UHECR in 2019

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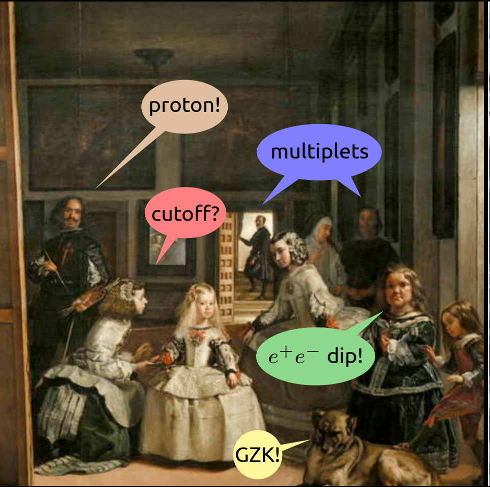
# Conclusions

UHECR before Auger

UHECR in 2019

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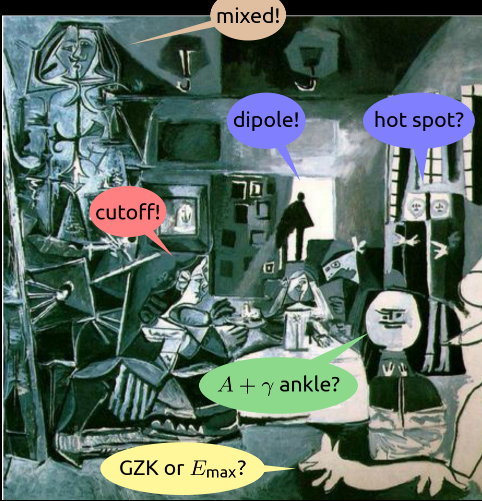


Las Meninas by Pablo Picasso 1957

# Thanks!