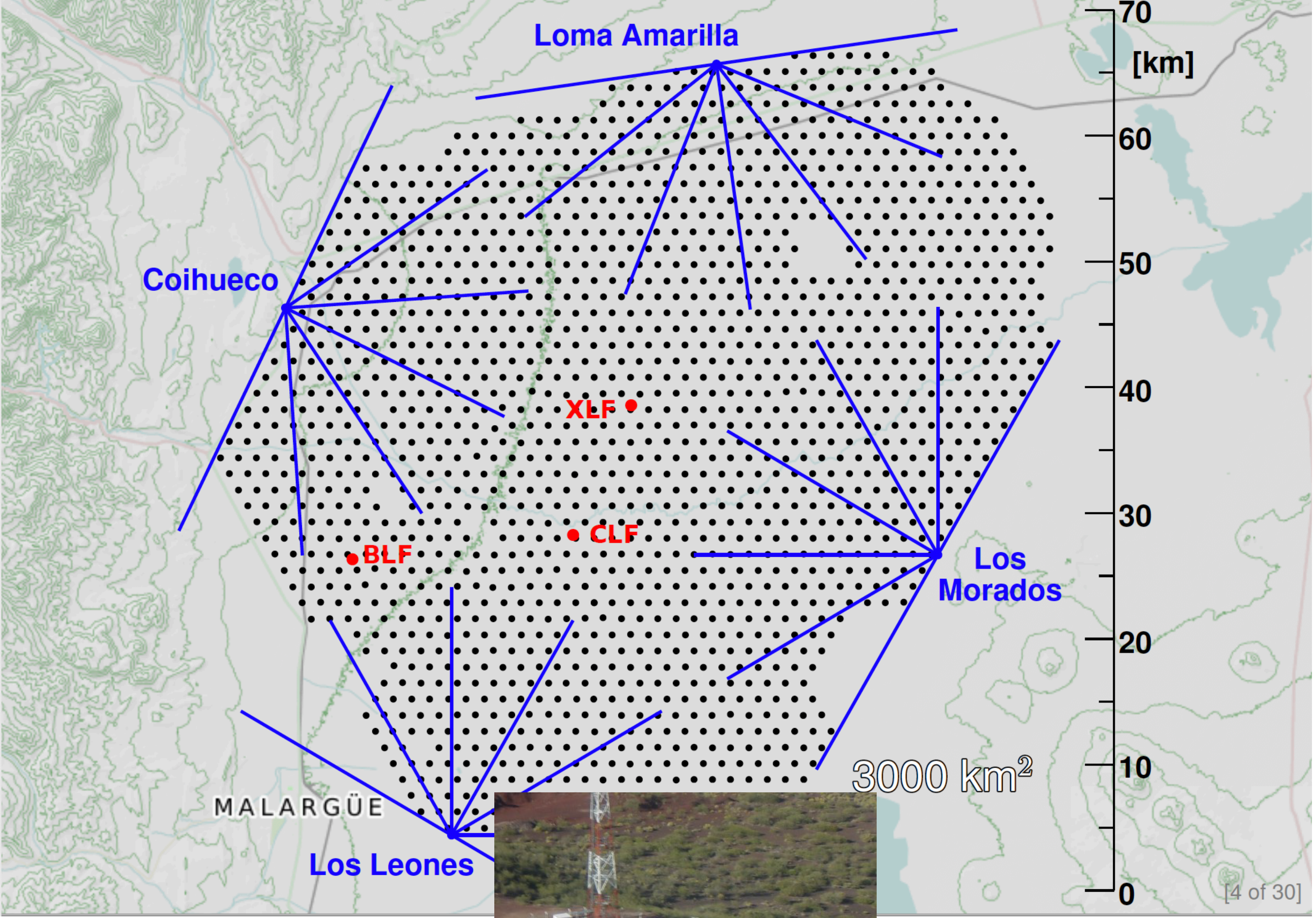
Recent results from the Pierre Auger Observatory

Sergio Petrera, *GSSI and INFN, L'Aquila, Italy*

PHOTON 2019 - International Conference on the Structure and the Interactions of the Photon
3-7 June 2019
INFN - LNF, Frascati

Satellite Workshop:
Photon Physics and Simulation at Hadron Colliders
6-7 June 2019

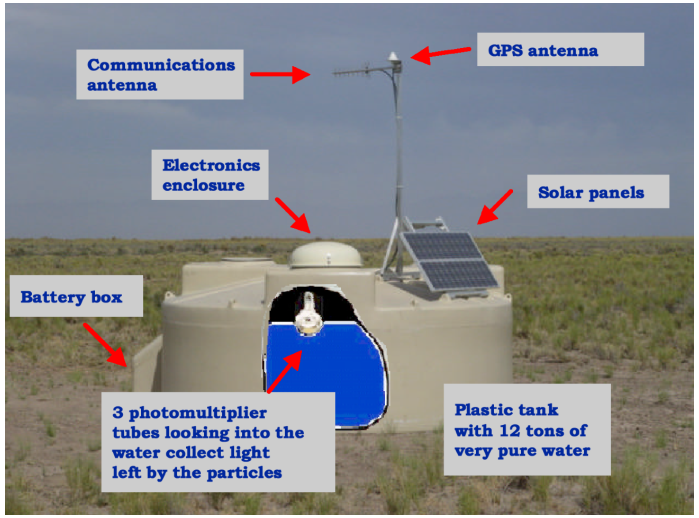


The Pierre Auger Observatory

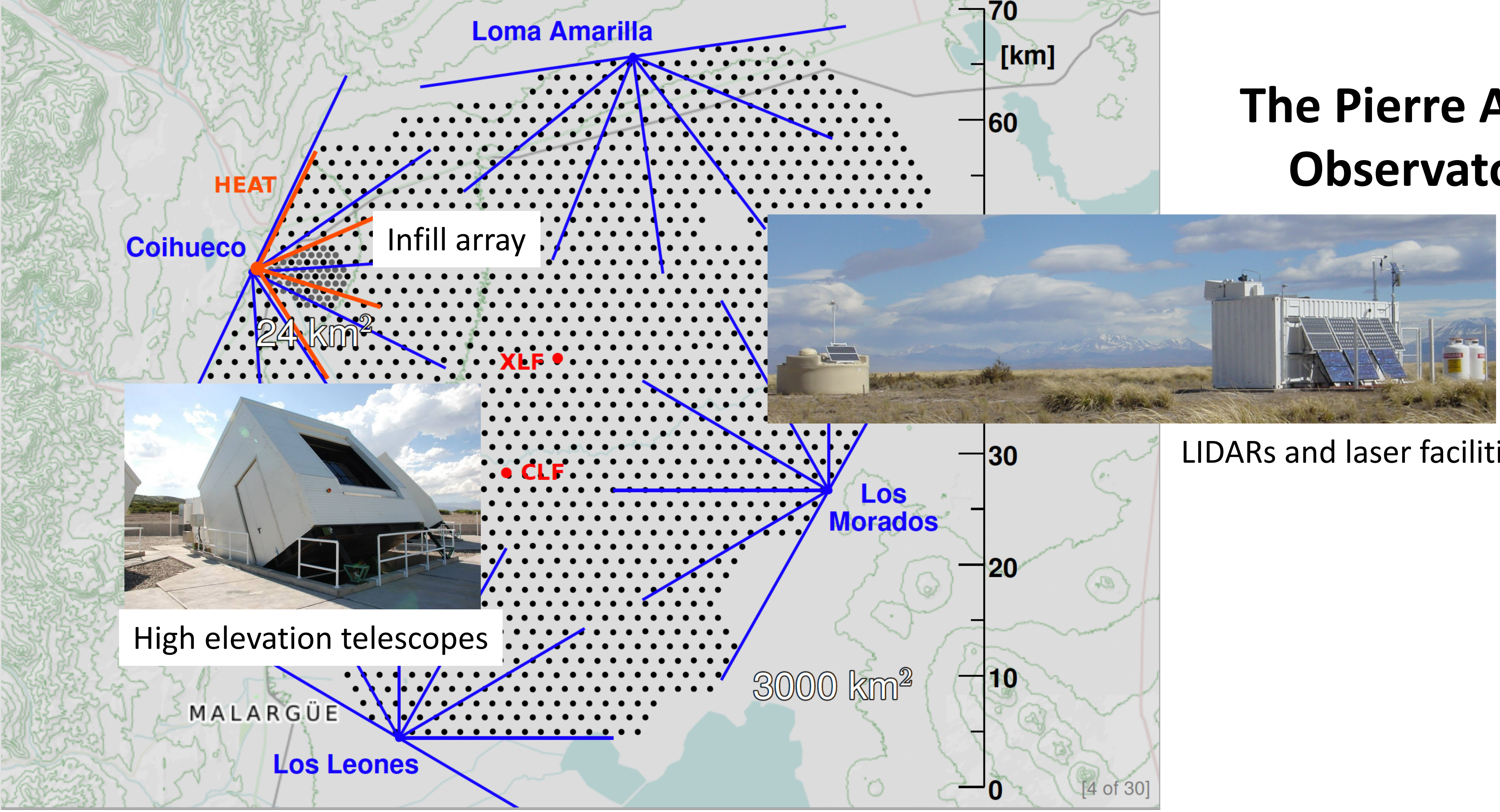
Province Mendoza
Argentina

1665 surface detectors:
water-Cherenkov tanks
(grid of 1.5 km, 3000 km^2)

4 fluorescence sites
(24 telescopes in total)

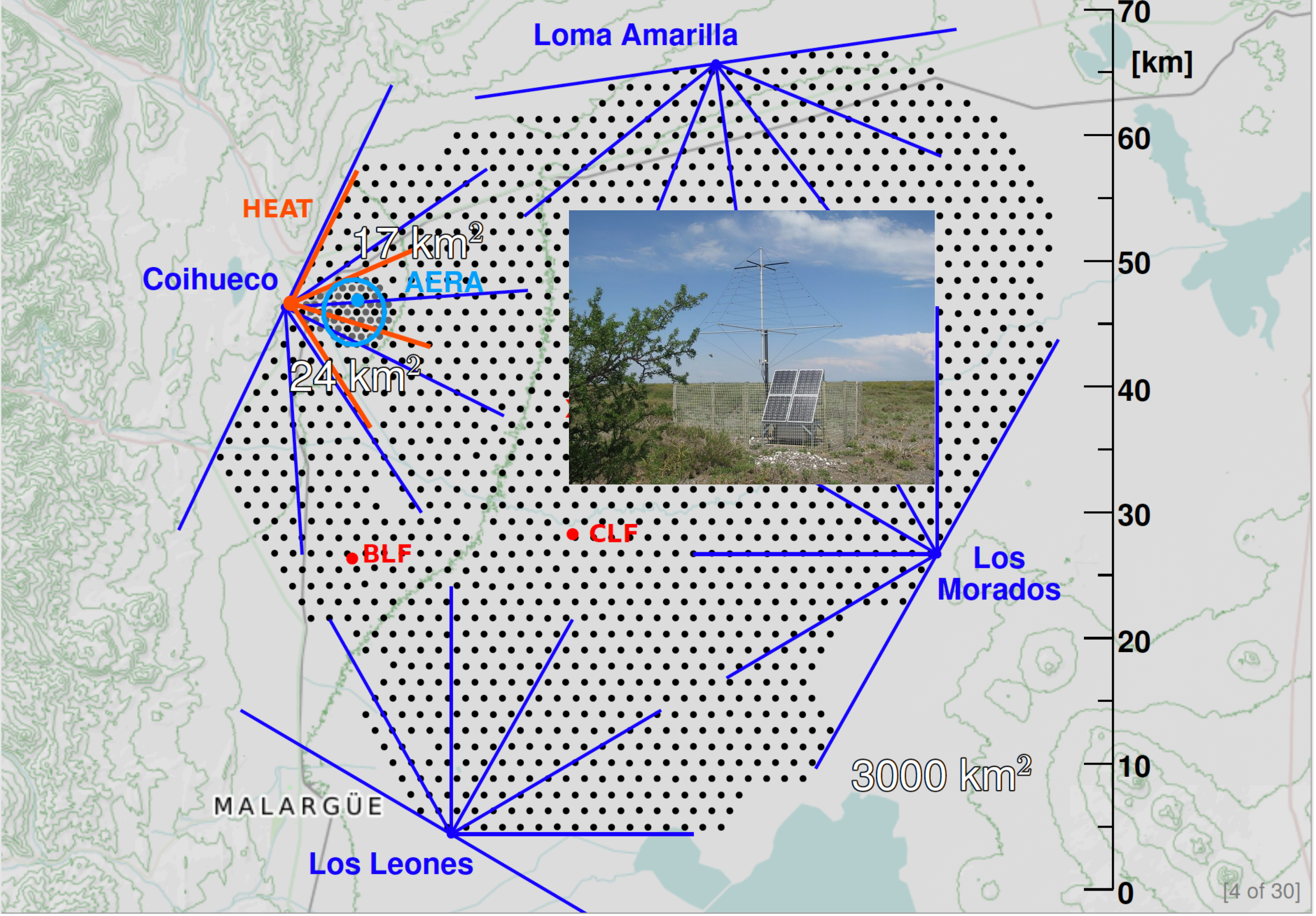


The Pierre Auger Observatory



High elevation telescopes

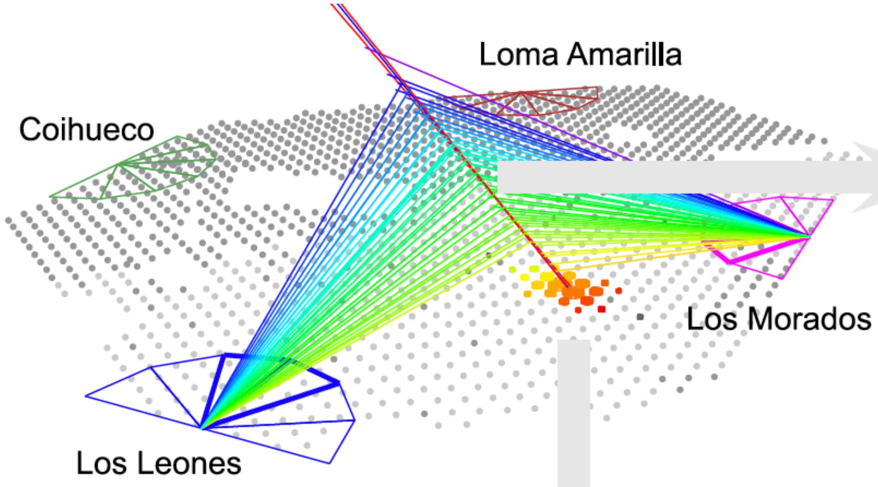
LIDARs and laser facilities

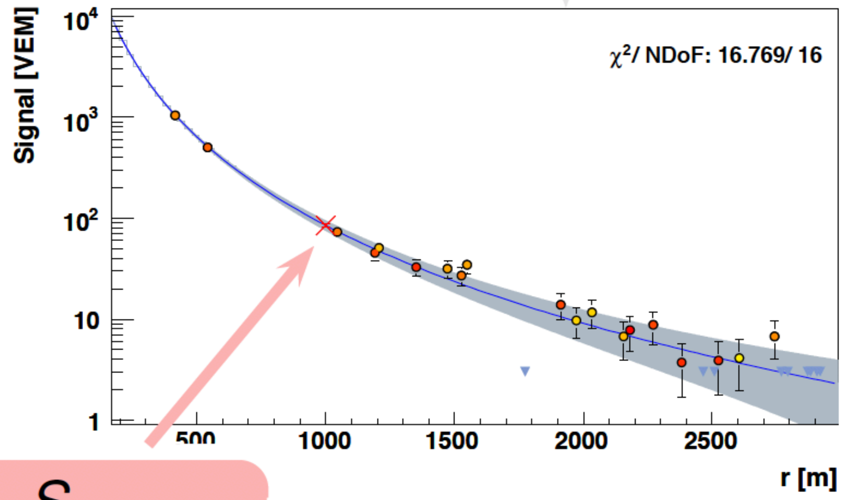


The Pierre Auger Observatory

AERA: radio antenna array

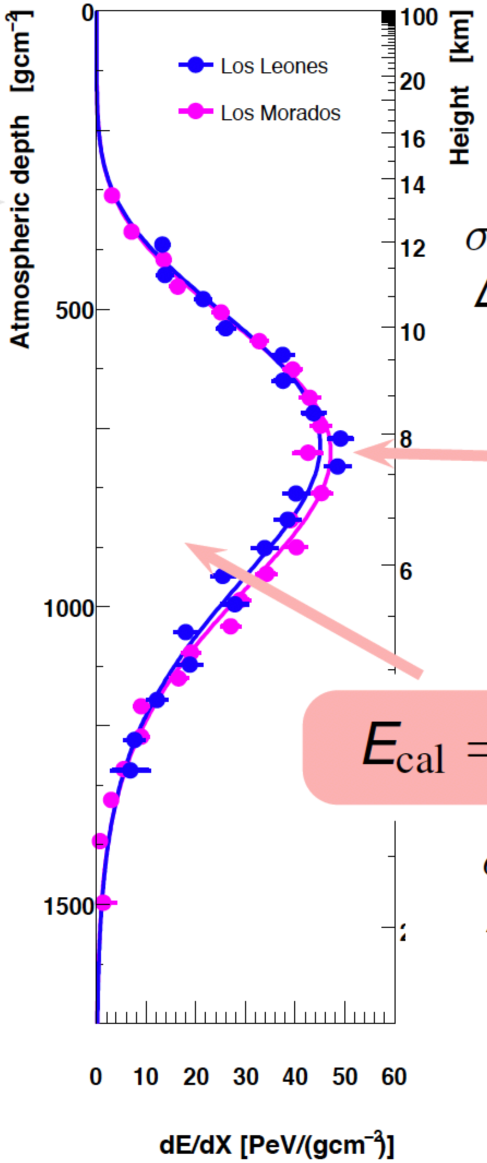
Hybrid detection of air showers





S_{1000}

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



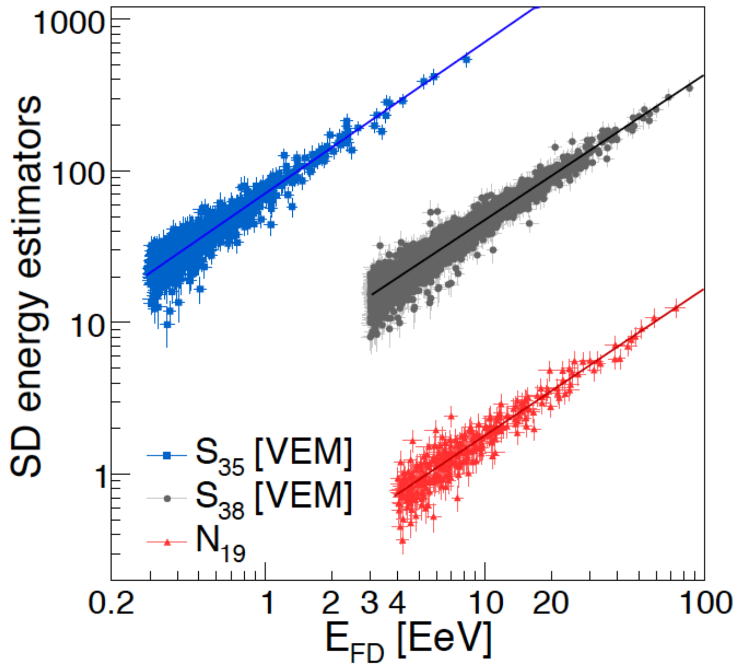
$\sigma X_{\max} \leq 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \leq 10\,\mathrm{g/cm^2}$

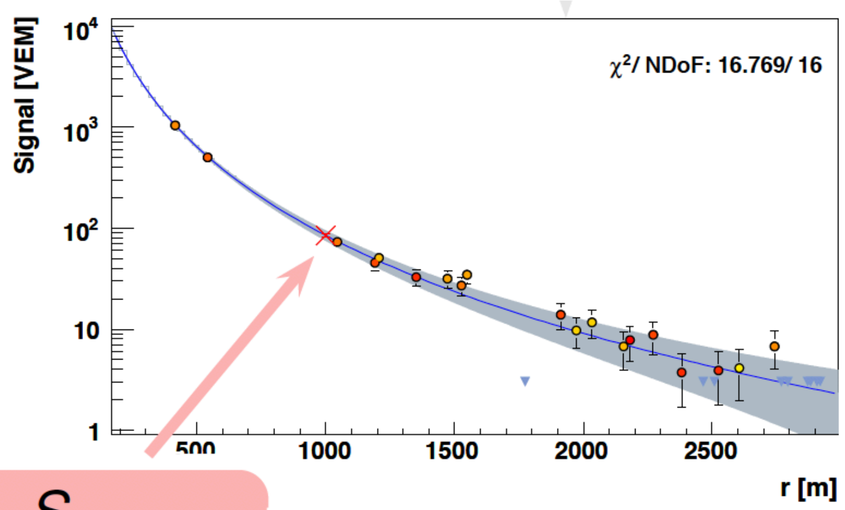
$X_{\max}$

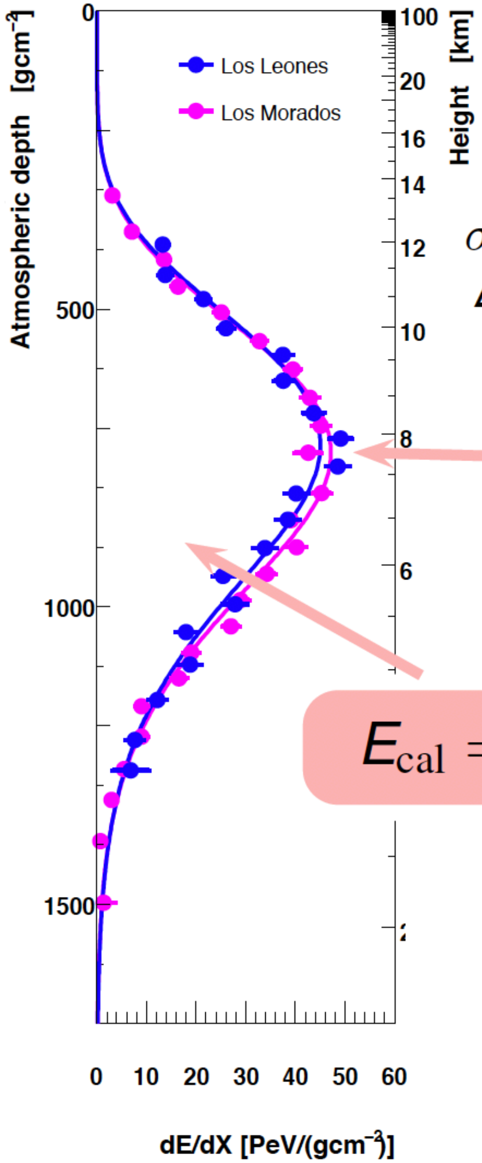
$E_{\mathrm{cal}} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X$

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

Energy calibration







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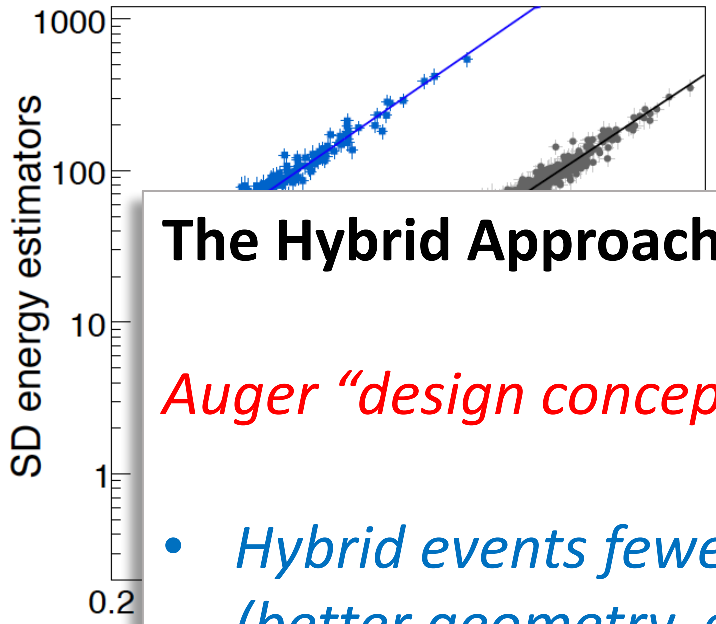

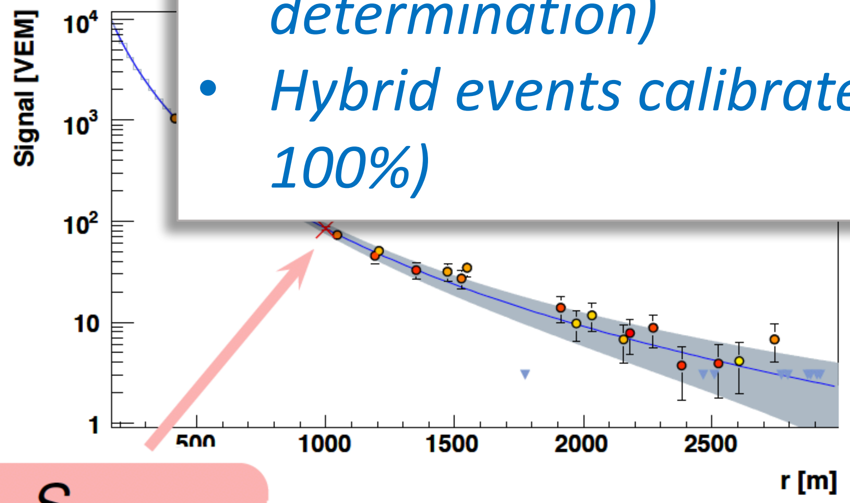

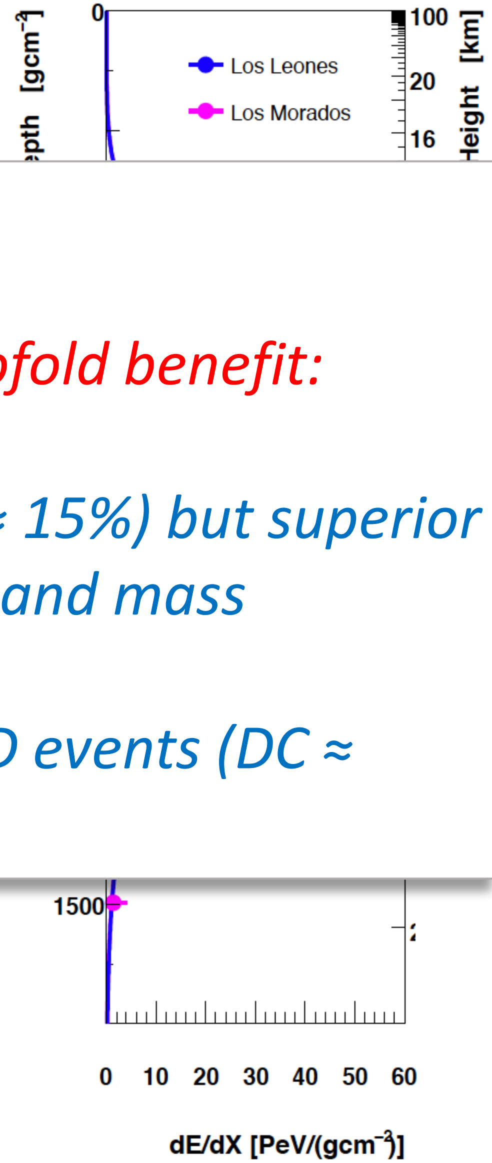

The Hybrid Approach

Auger "design concept". Twofold benefit:

- *Hybrid events fewer (DC ≈ 15%) but superior (better geometry, energy and mass determination)*
- *Hybrid events calibrate SD events (DC ≈ 100%)*

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

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

X_{max}

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

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

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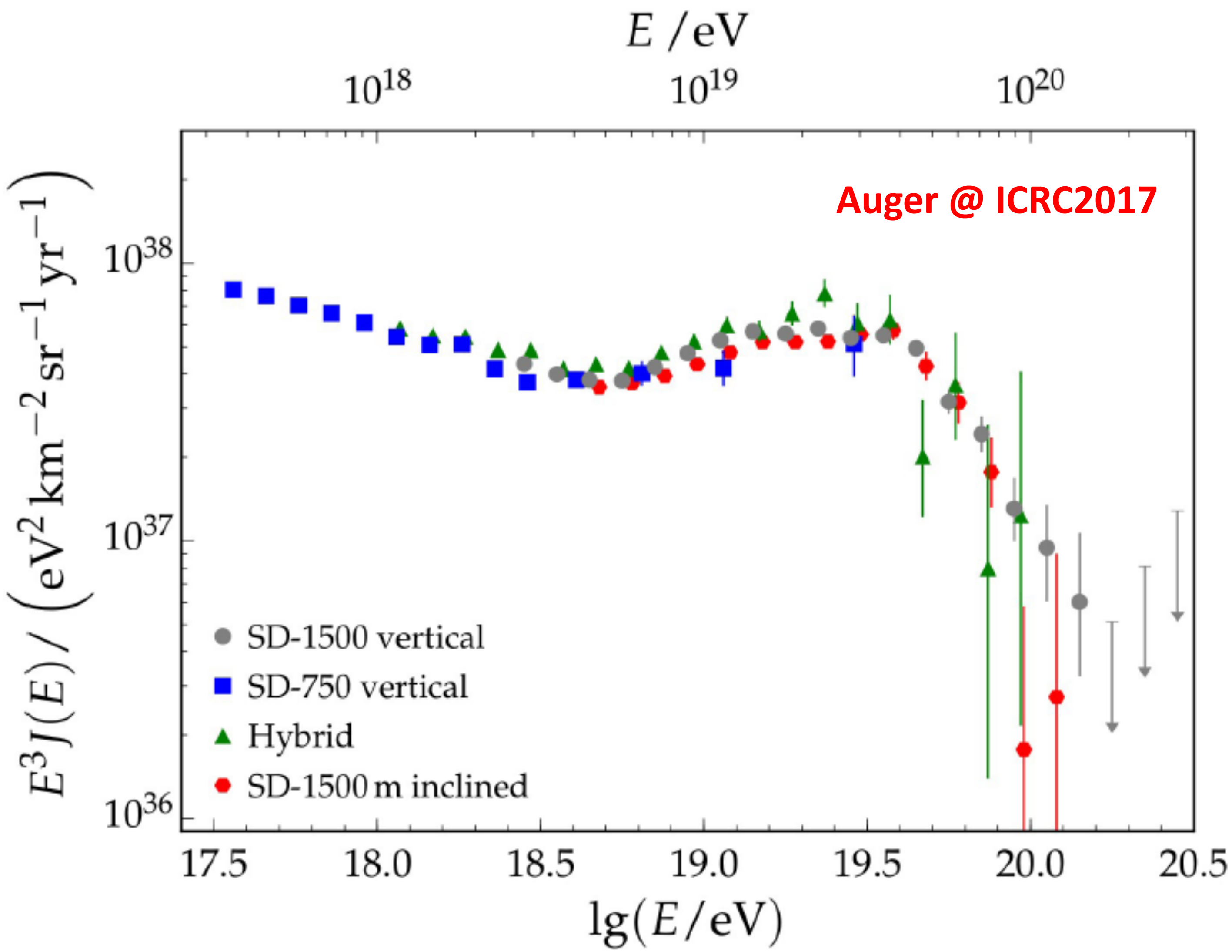
S_{1000}

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

Energy spectrum (all-particle flux)



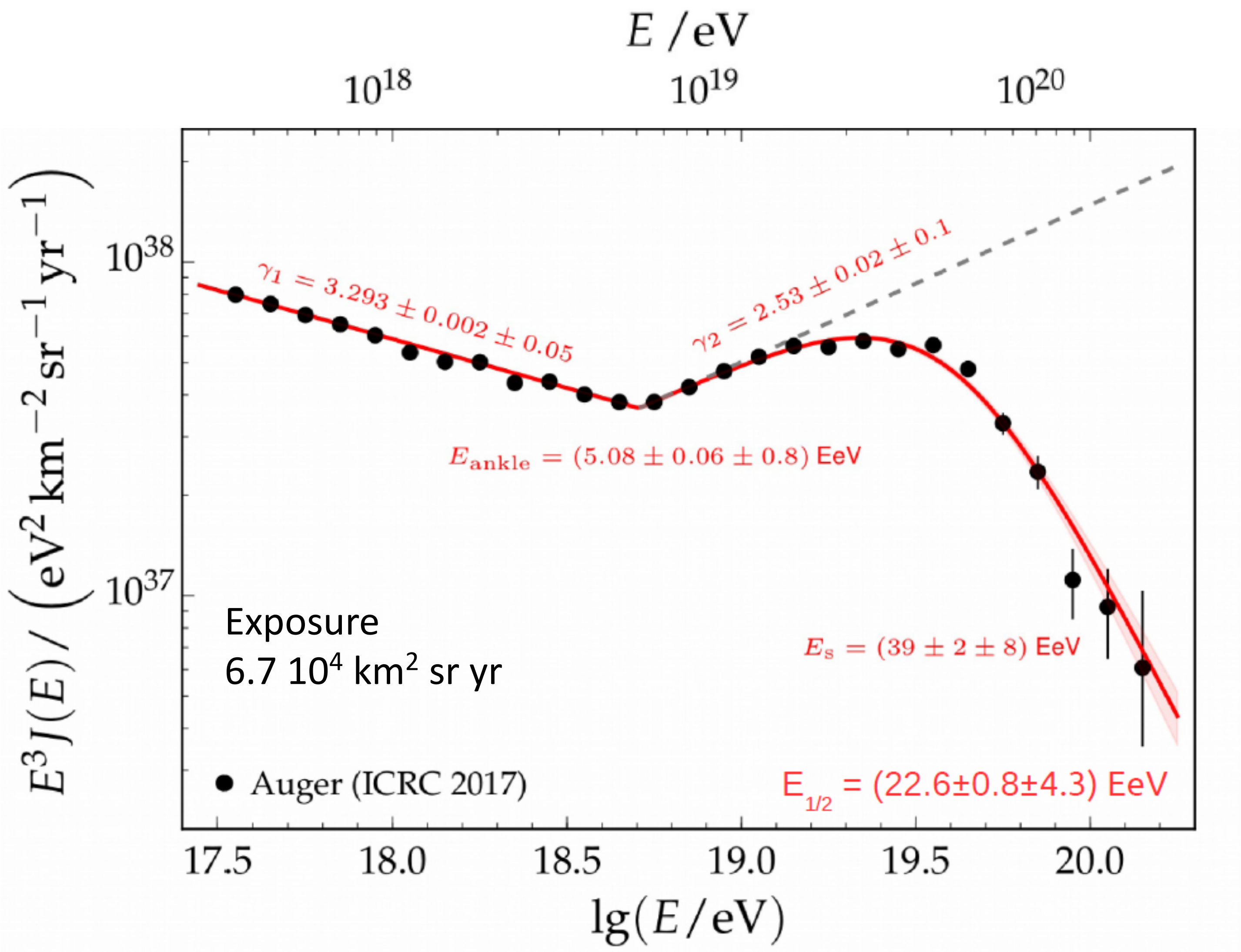
Four independent measurements

Flux uncertainties:
7-14% SD dense array
6% SD vertical (< 60°)
5% SD inclined (60°-80°)
10% Hybrid vertical (< 60°)

Energy resolution
13% SD dense array
15% SD vertical (< 60°)
19% SD inclined (60°-80°)
10% Hybrid vertical (< 60°)

14% Energy scale uncertainty

Energy spectrum (all-particle flux)



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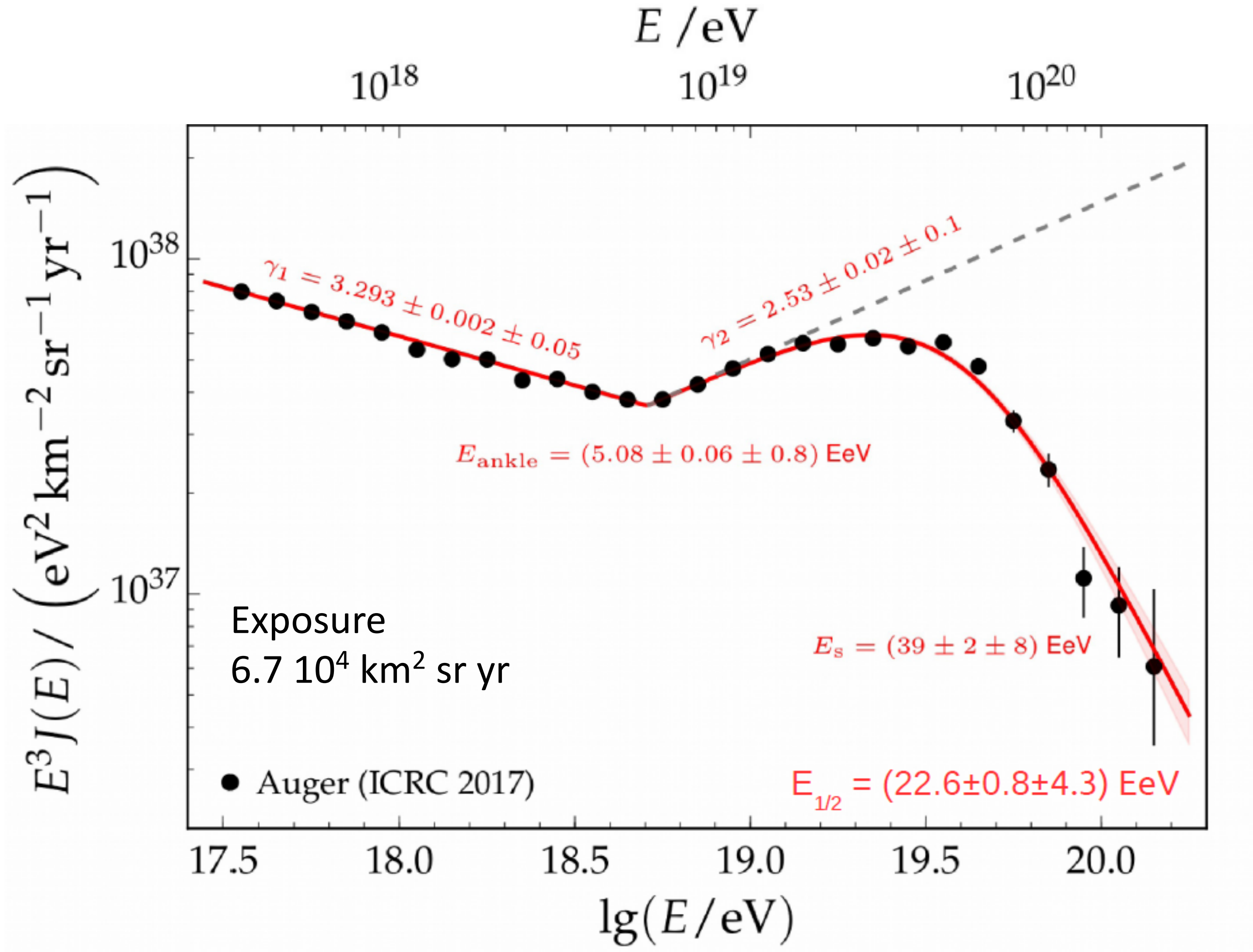


What is the origin of the flux suppression?

- *Propagation effect?*
  "Greisen-Zatsepin-Kuzmin"

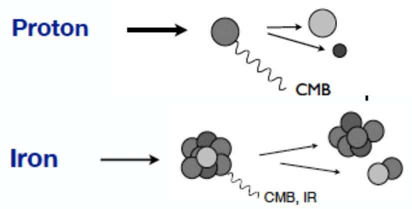


Photo-pion production

Photo-disintegration

- *Maximum injection energy?*

What is the origin of the ankle?

- *Propagation effect?*

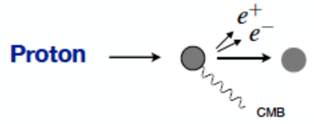
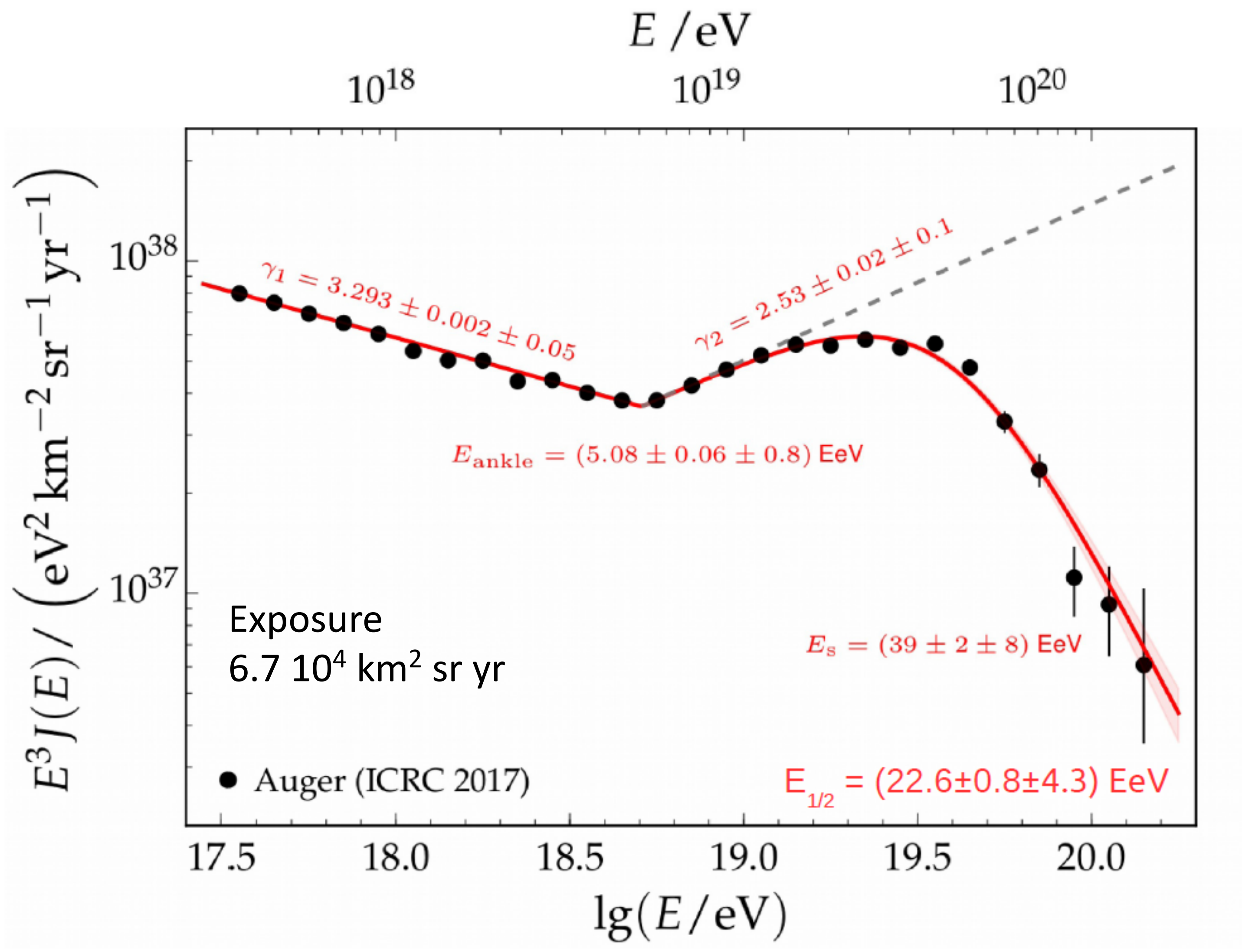


Photo-pair production

- *Transition effect?*
- *Interactions in the source environment?*

Energy spectrum (all-particle flux)



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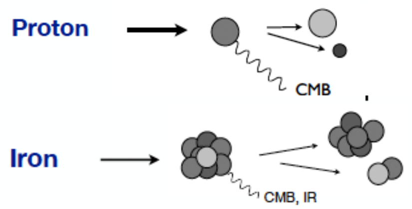


Photo-pion production

Photo-di...

- *Ma... energy?*

Energy spectrum alone remains ambiguous concerning interpretations

...the origin of the ankle?

- *Propagation effect?*

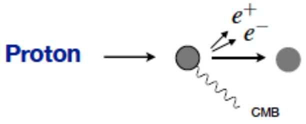
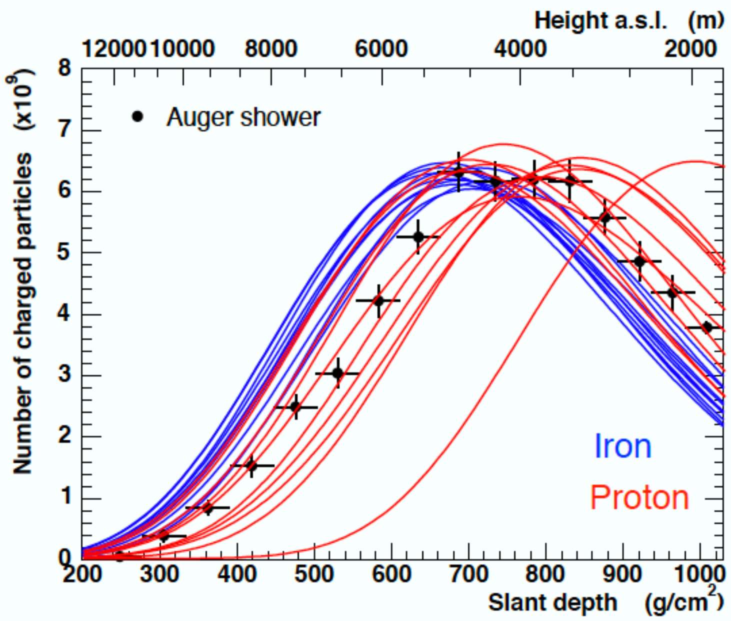
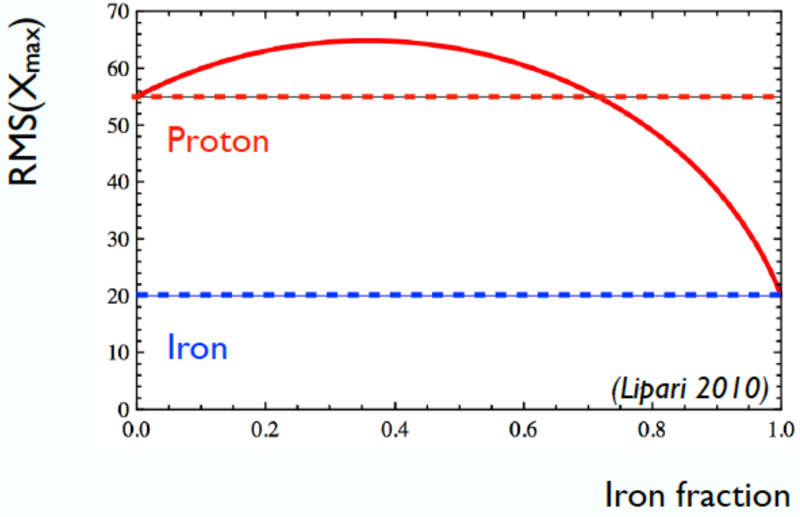


Photo-pair production

- *Transition effect?*
- *Interactions in the source environment?*

Depth of shower maximum





p-induced showers

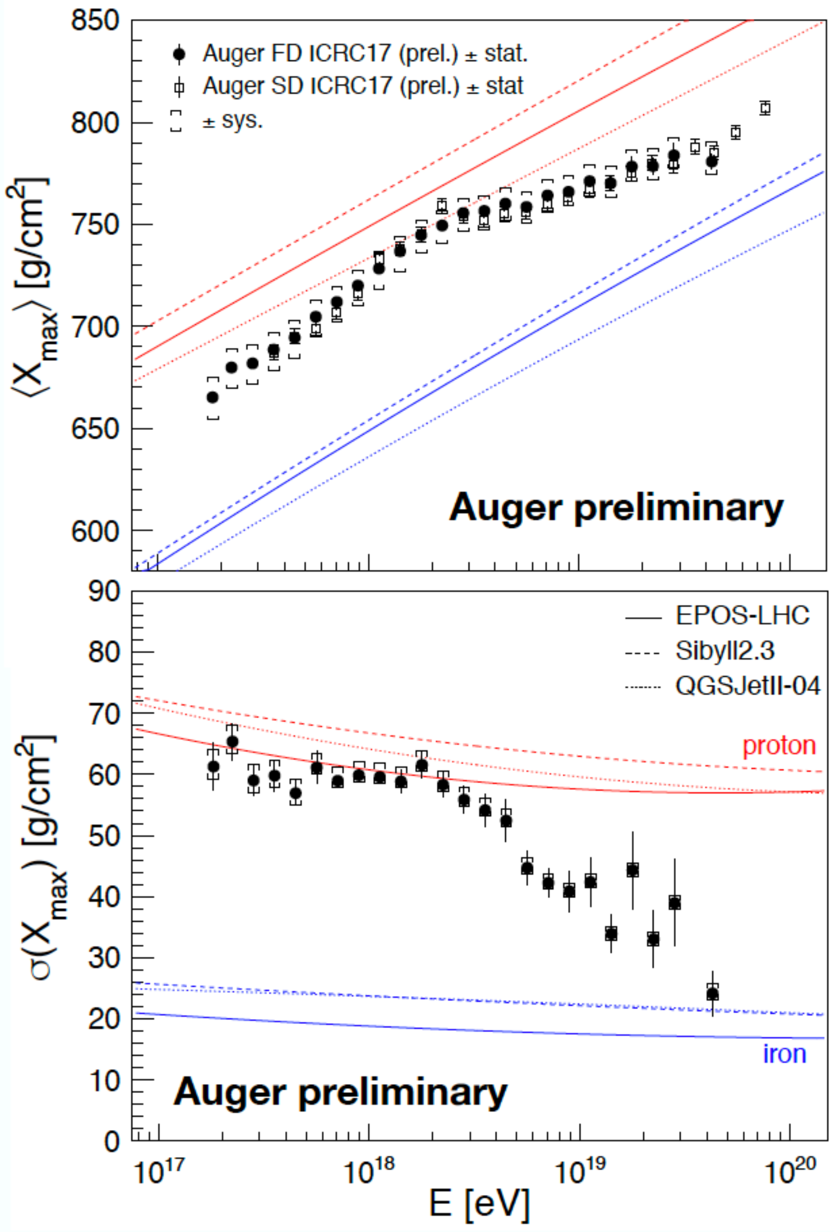
develop deeper than

Fe-induced ones

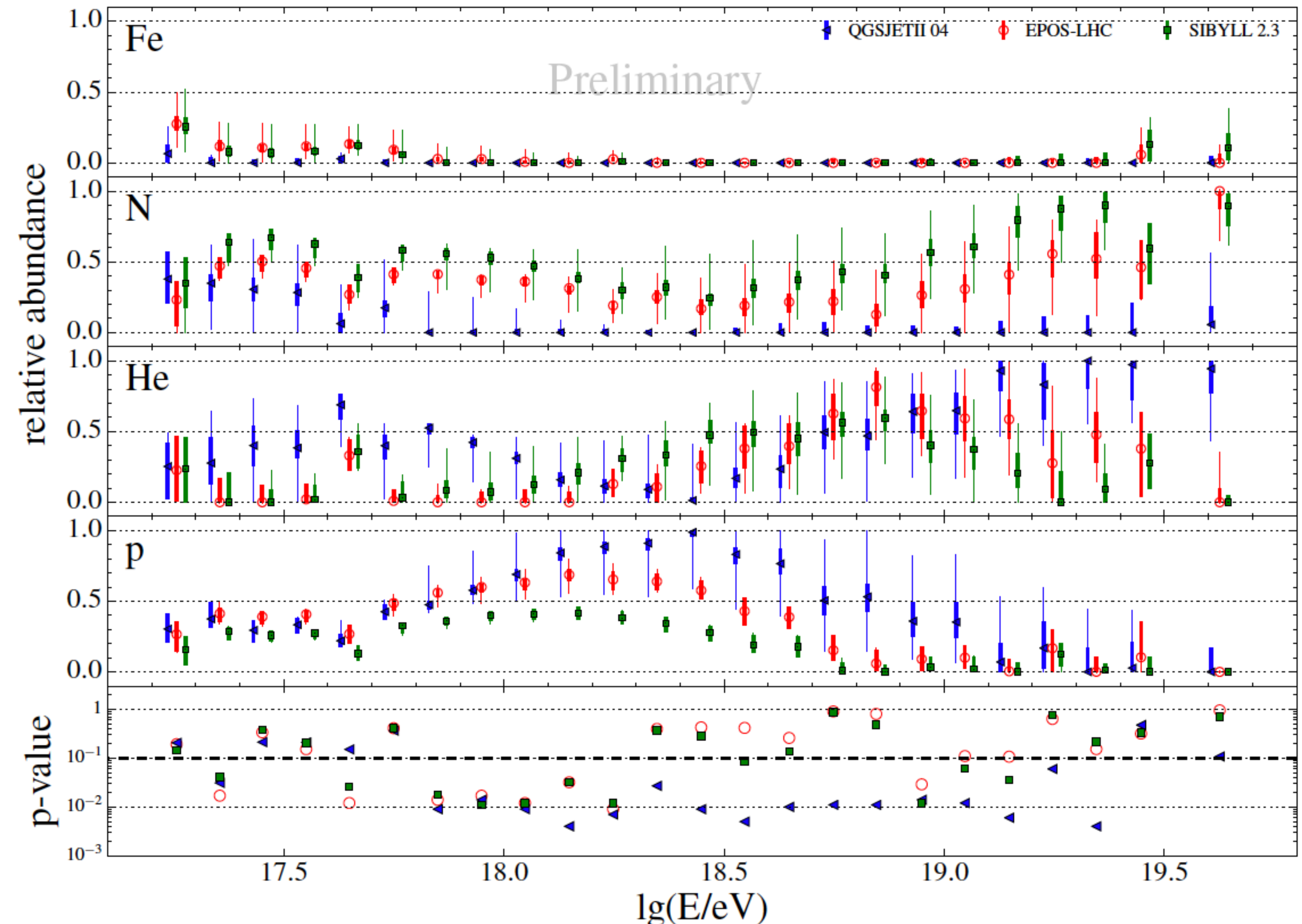
and have larger fluctuations

Break in the elongation rate just below the ankle

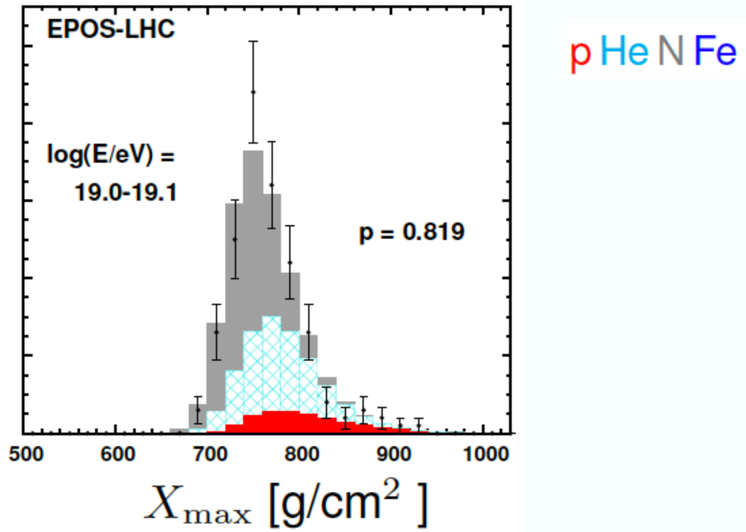
Xmax fluctuations very small



Mass composition @ Earth (top of the atmosphere)

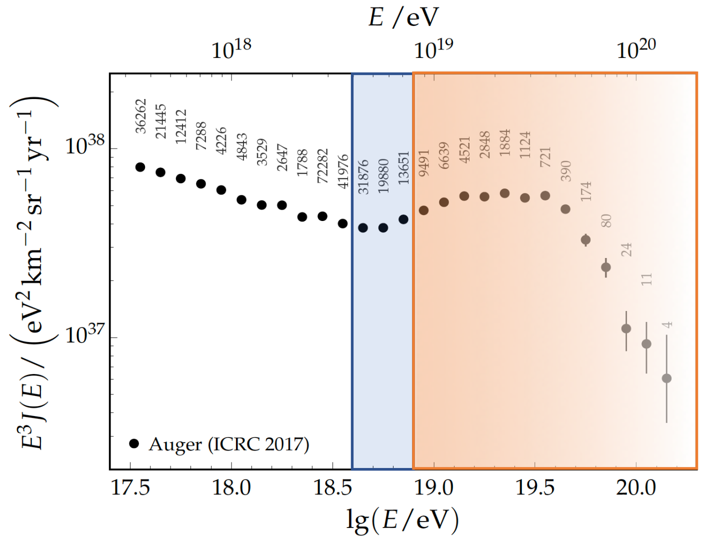


(Bellido ICRC 2017)



- **Xmax distributions fitted with four-mass CONEX showers from LHC-tuned interaction models.**
- **Fit quality not always good (QGSJet worse).**
- **Large proton fractions below the ankle.**
- **Iron almost absent.**

Anisotropy: Large scale



Combination of vertical and inclined showers

Harmonic analysis in right ascension α

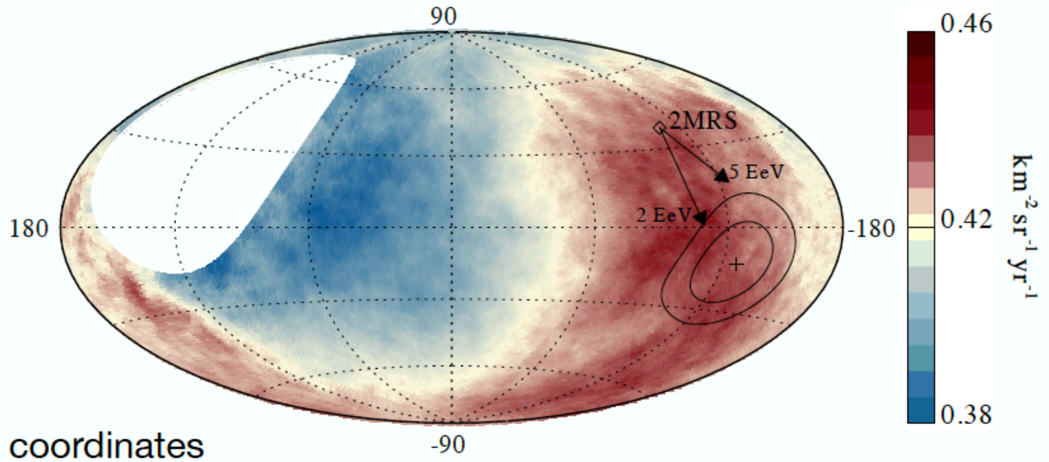
E [EeV]	events	amplitude r	phase [deg.]	$P(\geq r)$
4-8	81701	$0.005^{+0.006}_{-0.002}$	80 ± 60	0.60
> 8	32187	$0.047^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

significant modulation at 5.2σ (5.6σ before penalization for energy bins explored)

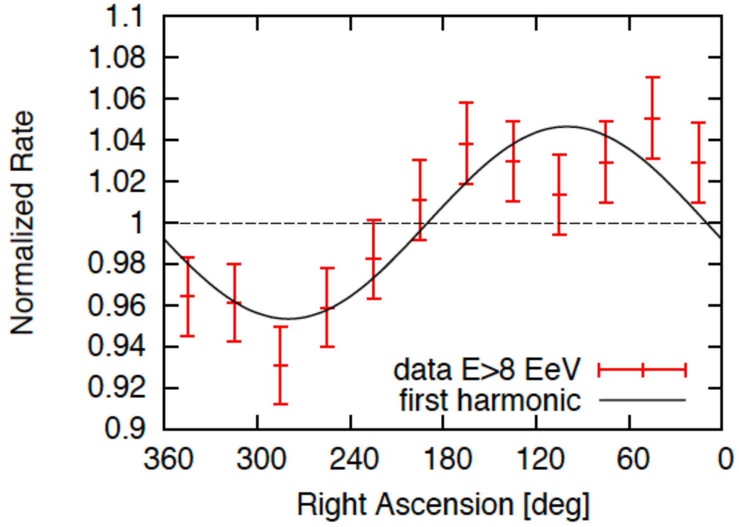
Auger Coll., Science (2017), APJ (2018)

3-d dipole above 8 EeV:

$(6.5^{+1.3}_{-0.9})\%$ at $(\alpha, \delta) = (100°, -24°)$ $(l,b) = (233°, -13°)$



gal. coordinates



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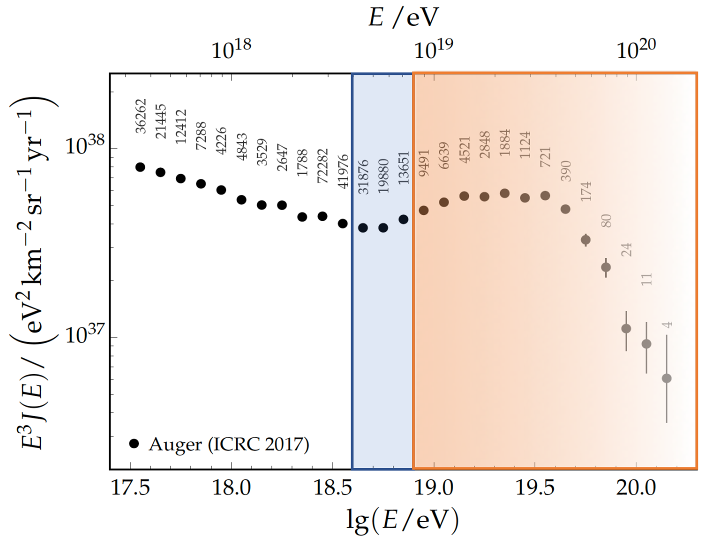

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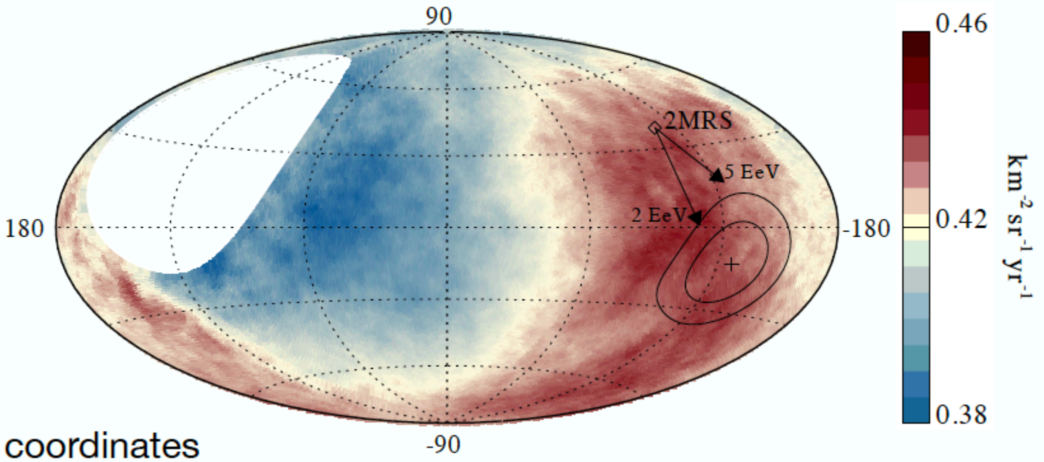


gal. coordinates

- Expected if cosmic rays diffuse to Galaxy from sources distributed similar to near-by galaxies *(Harari, Mollerach PRD 2015, 2016)*
- Deflection of dipolar pattern due to Galactic magnetic field
- **Strong indication for extragalactic origin** dipole direction ~ 125° from GC

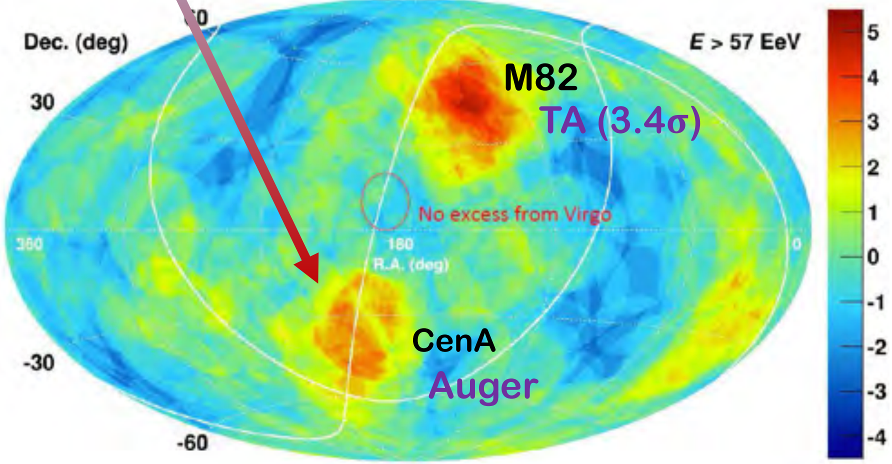
Anisotropy: Intermediate scale

Search for flux excesses wrt iso. flux

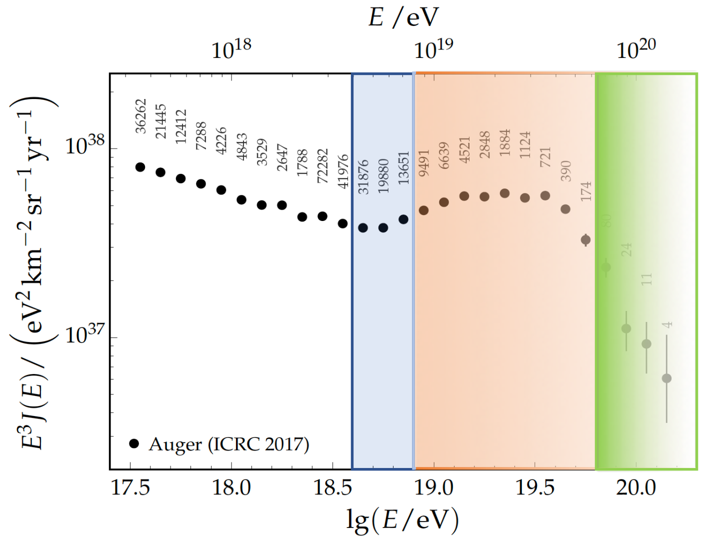
Largest excess for

E> 58 EeV, ψ = 15°: obs = 19, exp = 6

Post-trial prob ≈ 10^{-3}



Giaccari, ICRC 2017



Correlation with catalogs

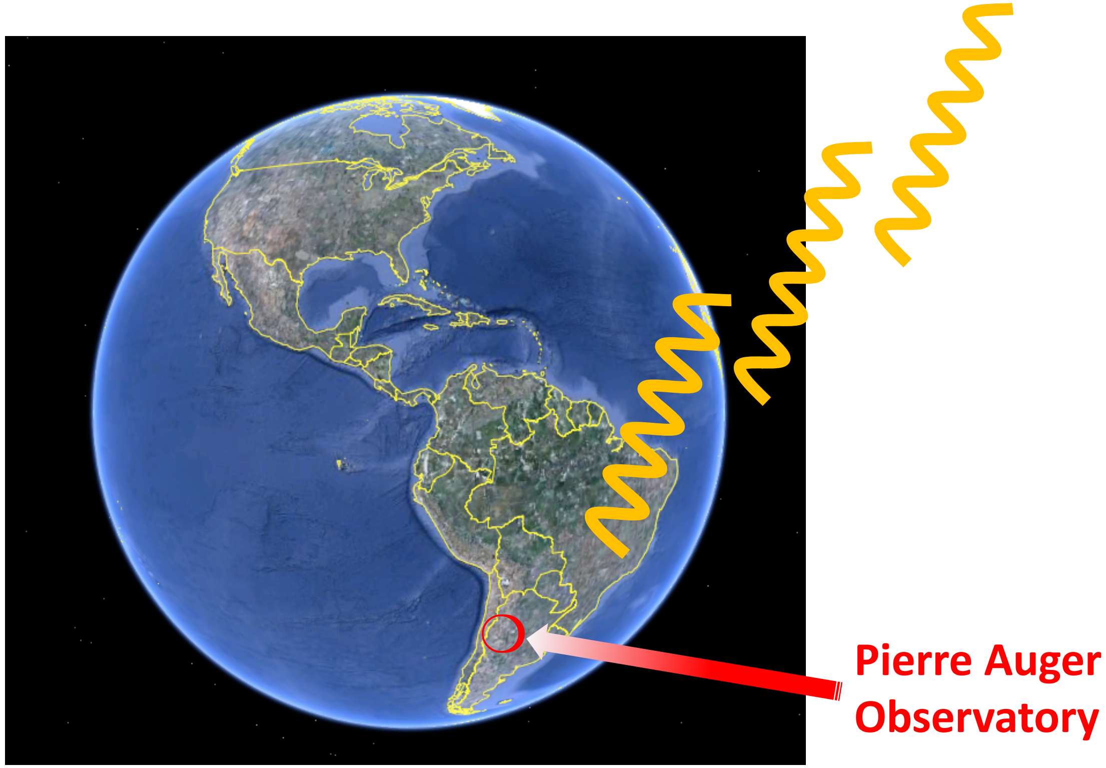
- **Active Galactic Nuclei (γ-AGN)**
- **Starburst Galaxies**

Assuming CR flux ∝ non thermal photon flux

Best result for SBG

E > 39 EeV: f_{ani} = 10%, Ψ = 13°
TS = 24.9 ⇒ After penalization ~4.0 σ

The photon-Auger connection



How photons influence Auger science?

1. The search for UHE photons
2. The role of photon background in CR propagation
3. The role of photon fields around the sources

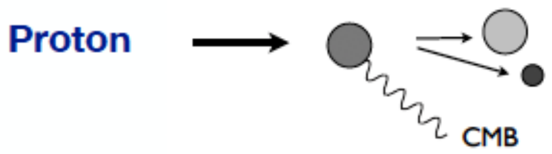
… …

1. The search for UHE photons

Why? Where do they come from?

Two traditional scenarios:

- **Bottom-up:** *photons produced from protons propagating through photon bkgr: photo-pion production against CMB, EBL*



process occurring at sources and in the propagation from sources *(cosmogenic photons)*

- **Top-down:** *photons from the decay of relic super-massive particles*

several models mostly hypothesized for trans-GZK events (Z-bursts, Topological defects, SH Dark Matter, ...)

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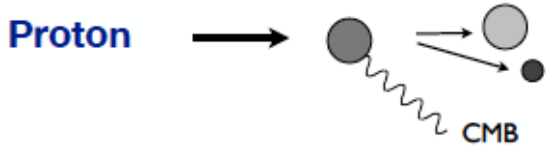

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- **Top-down:** *photons from the decay of relic super-massive particles*

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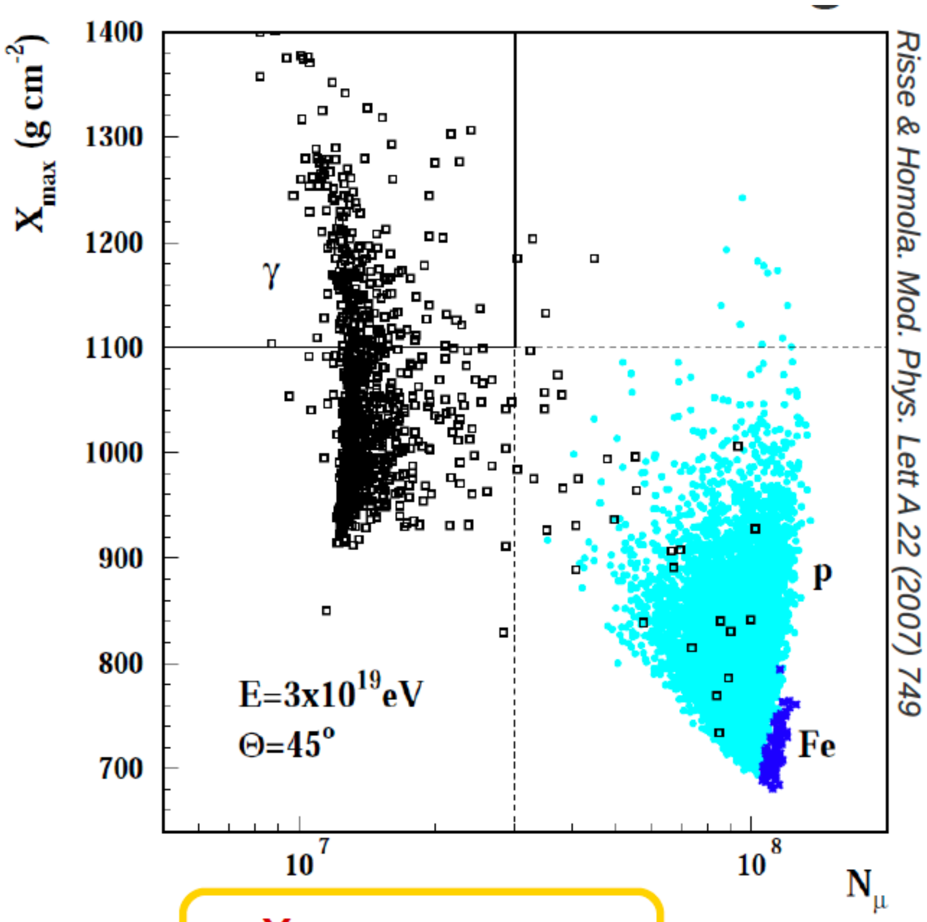
expected photons/CR

< 1 %

≈ few 10%

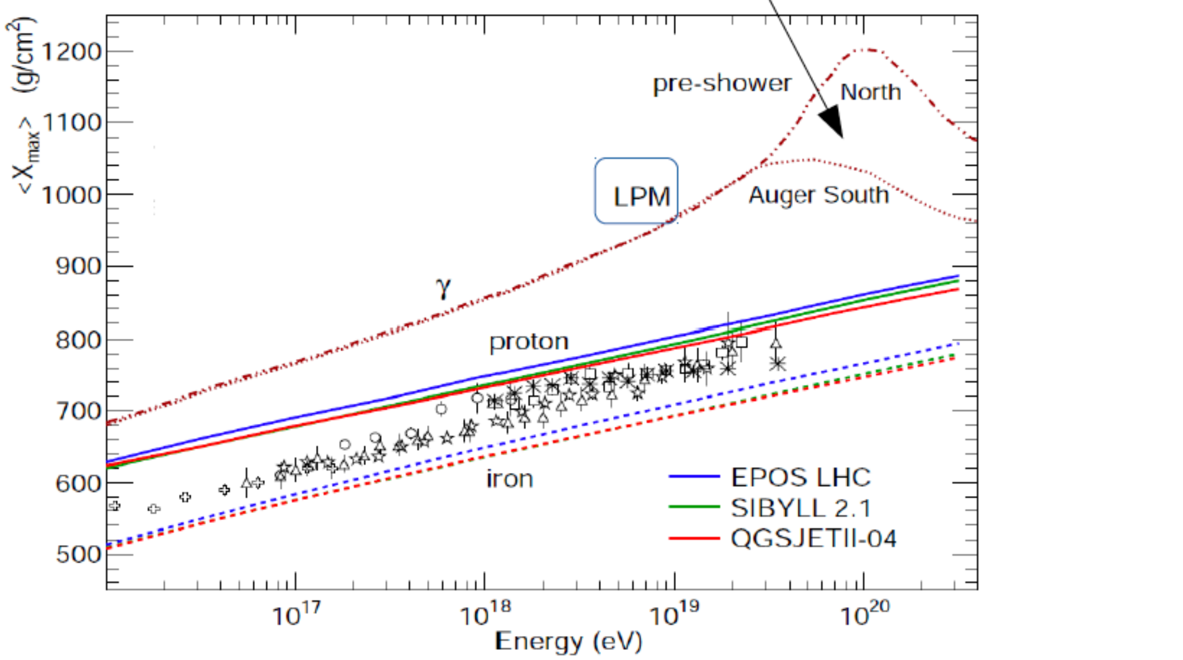
How to recognize a photon shower



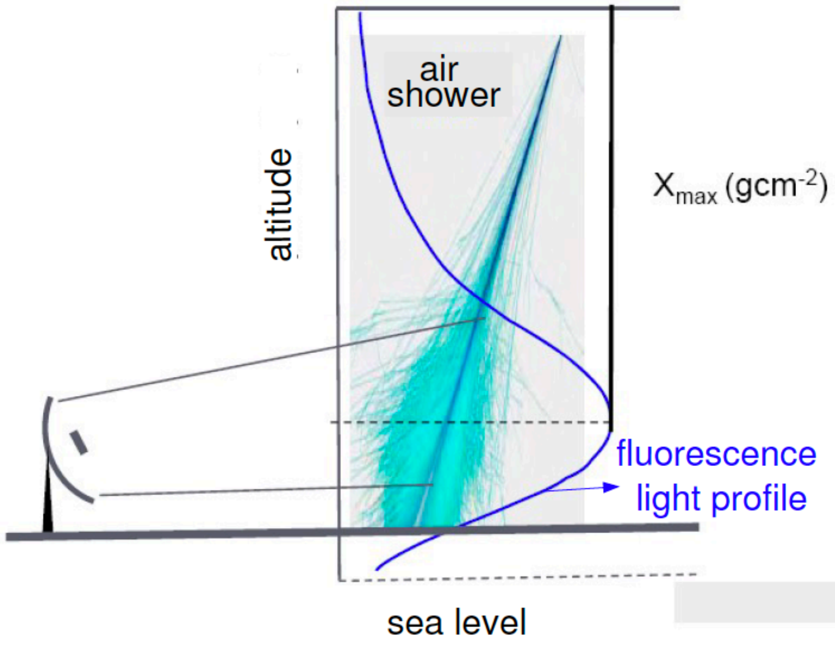
→ **Xmax**
→ **Muon content**

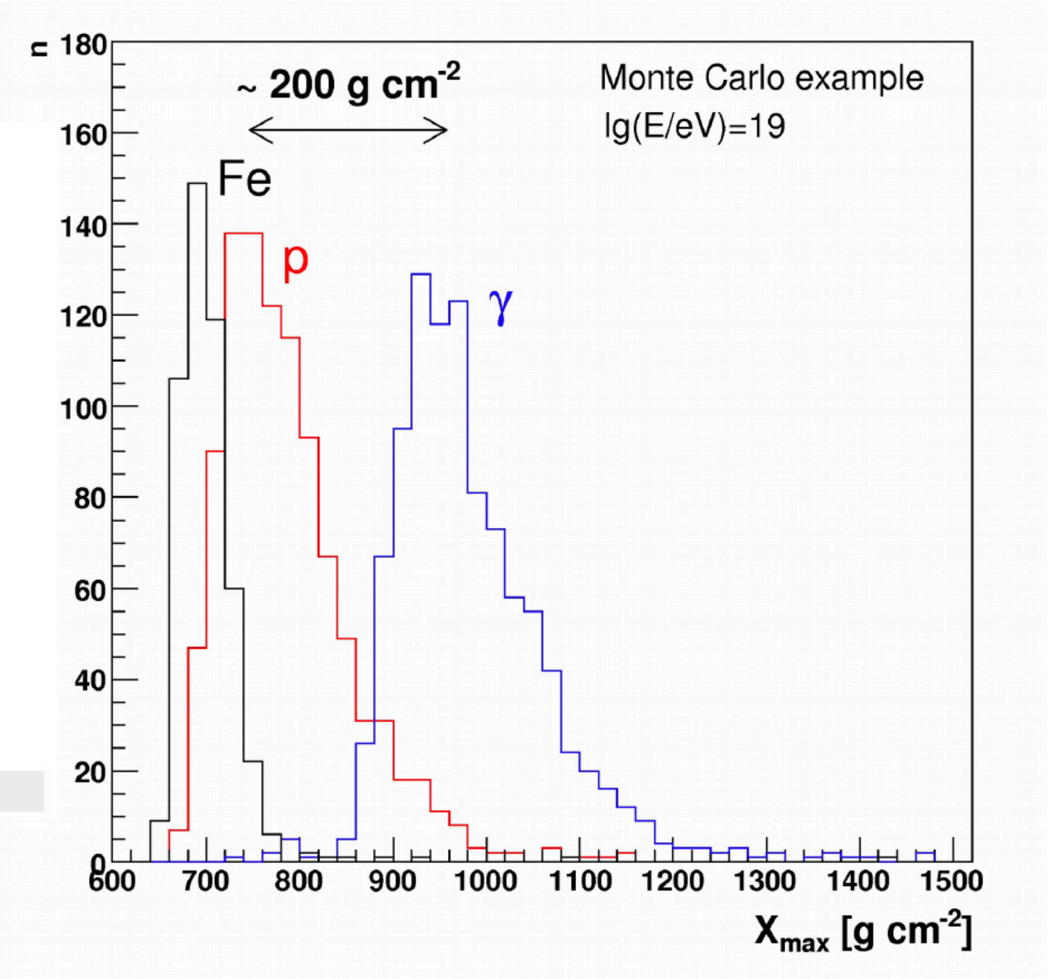
- Mostly EM showers
- Minor photo-nuclear or muon pair production
- Contribution from LPM (Landau-Pomeranchuk-Migdal) effect and pre-showering in Earth magn. field

Pre-shower in the geomagnetic field



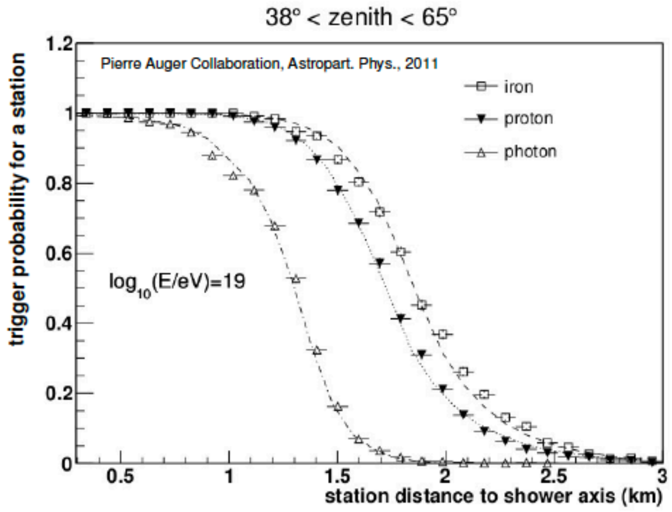
Xmax *from longitudinal profiles in* ***hybrid events*** *($E \lesssim 10^{19}$ eV)*





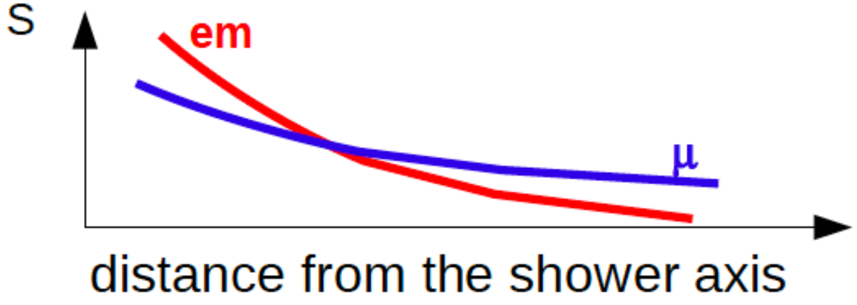
$X_{max}(Fe) < X_{max}(p) < X_{max}(\gamma)$

Muon content**: photons produce at ground **smaller footprint** & **faster rise-time

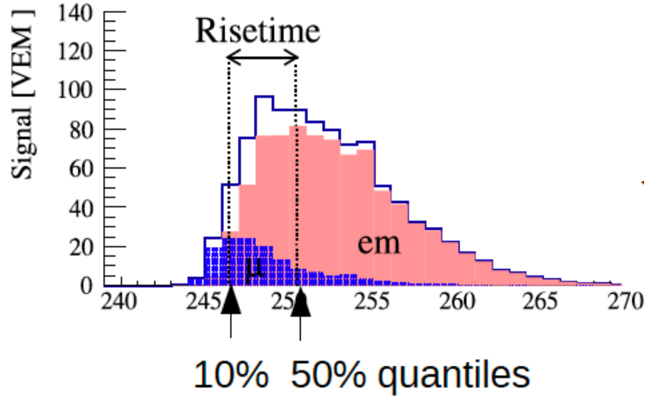


$$S_b = \sum_i^N S_i \left(\frac{R_i}{R_0}\right)^b$$

Lateral distribution



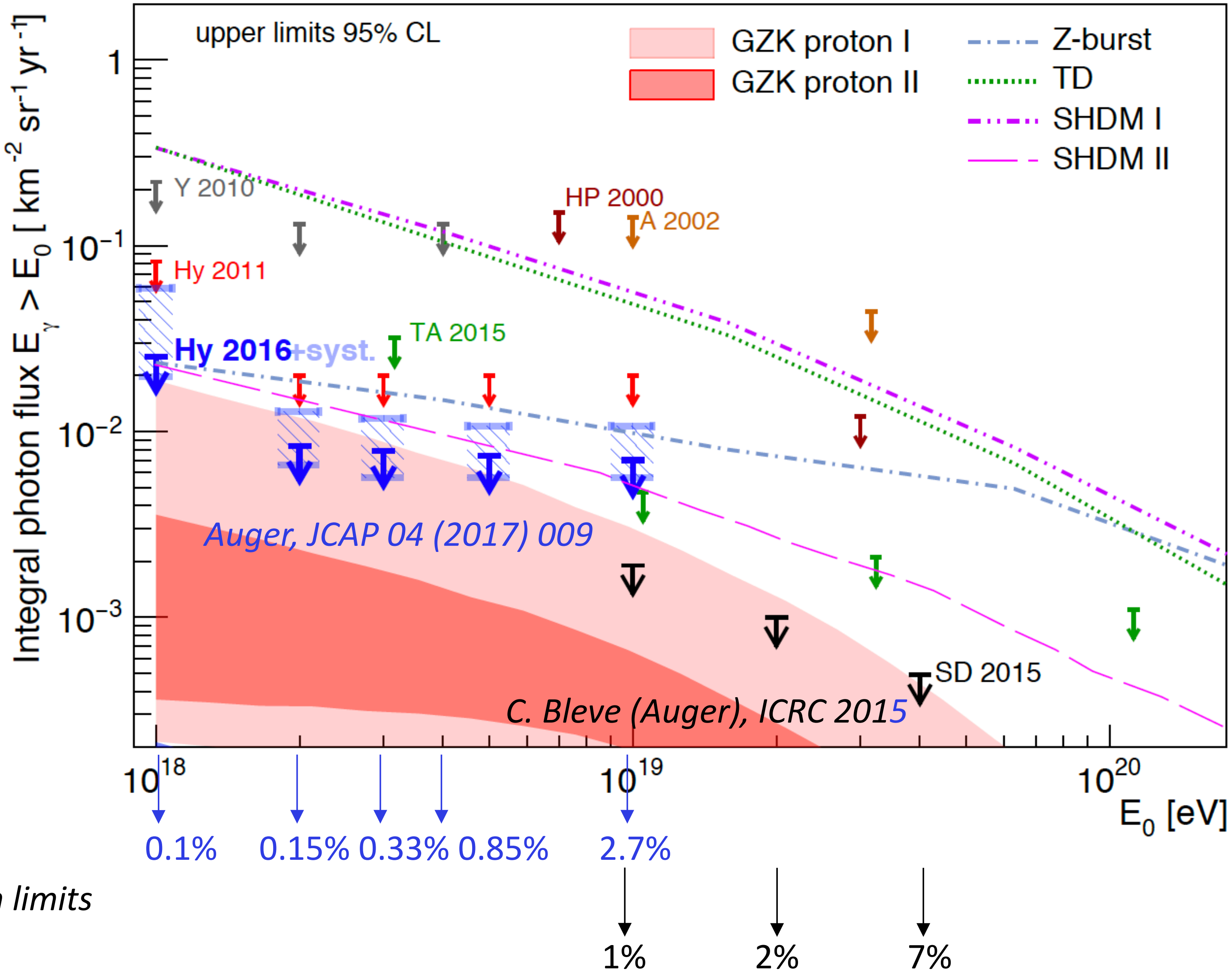
FADC trace



Search for diffuse photons:

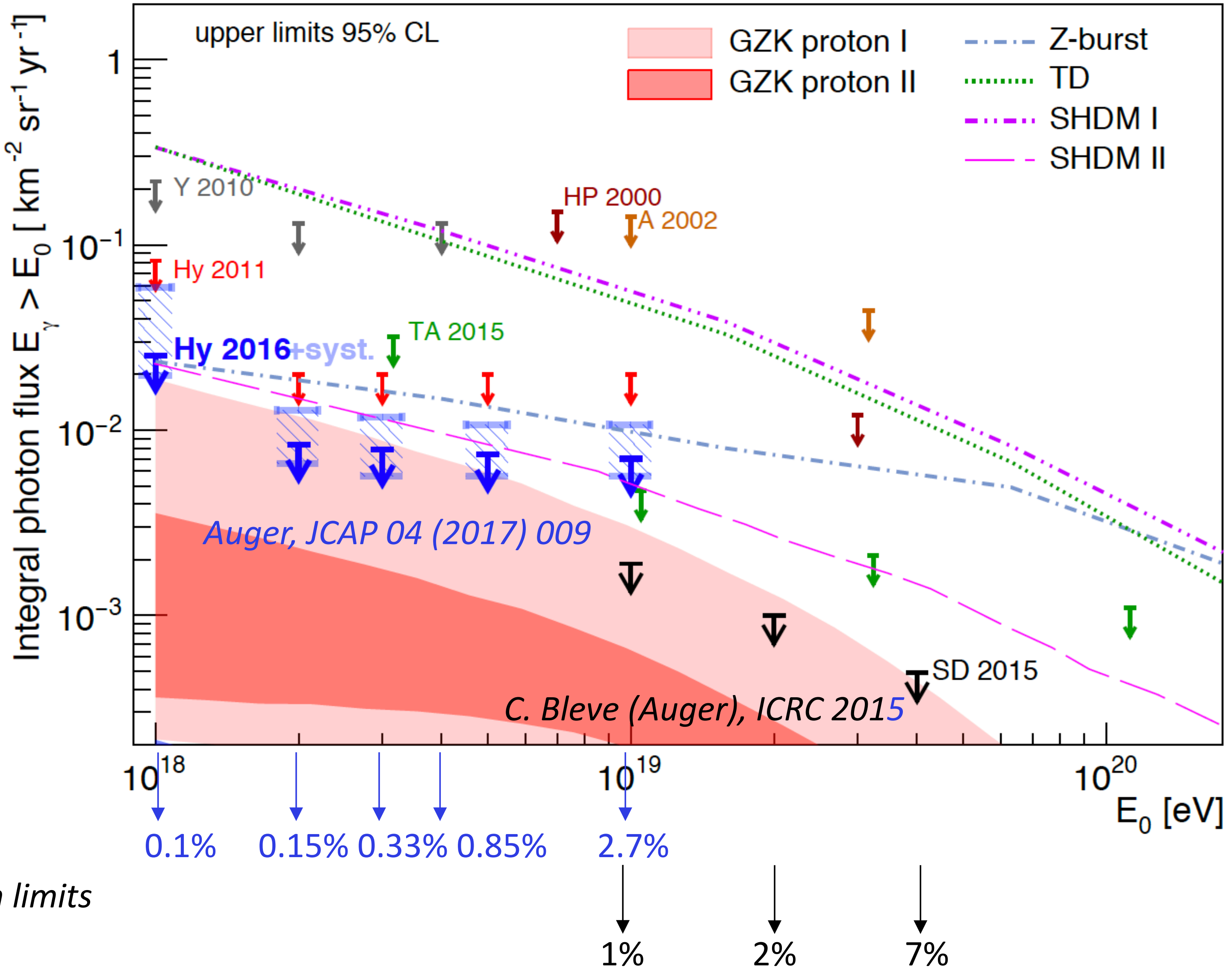
- $\lesssim 10^{19}$ eV *hybrid data set: MVA analysis using Xmax, Nstat, Sb*
- $\gtrsim 10^{19}$ *eV SD data set: LDF and rise-time*

Diffuse photon limits



photon fraction limits

Diffuse photon limits



photon fraction limits

No UHE photon found

Current limits:

- rule out most of the top-down models.
- Start to explore the region of predictions for cosmogenic photons.

Other photon searches

Blind search of point sources of EeV photons

Auger, APJ 2014

- *Directional grouping of "photon-like" events*
- *Declination -85° < δ < +20°*
- *Lower energy range (17.3 < lgE < 18.5) (negl. diffuse flux)*

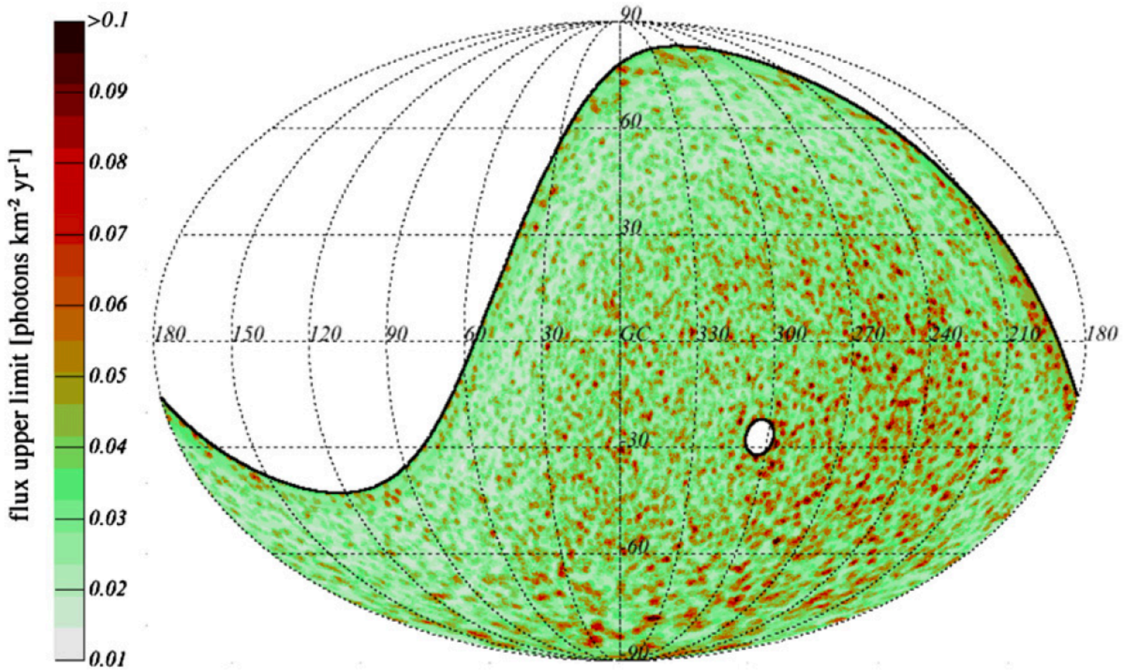
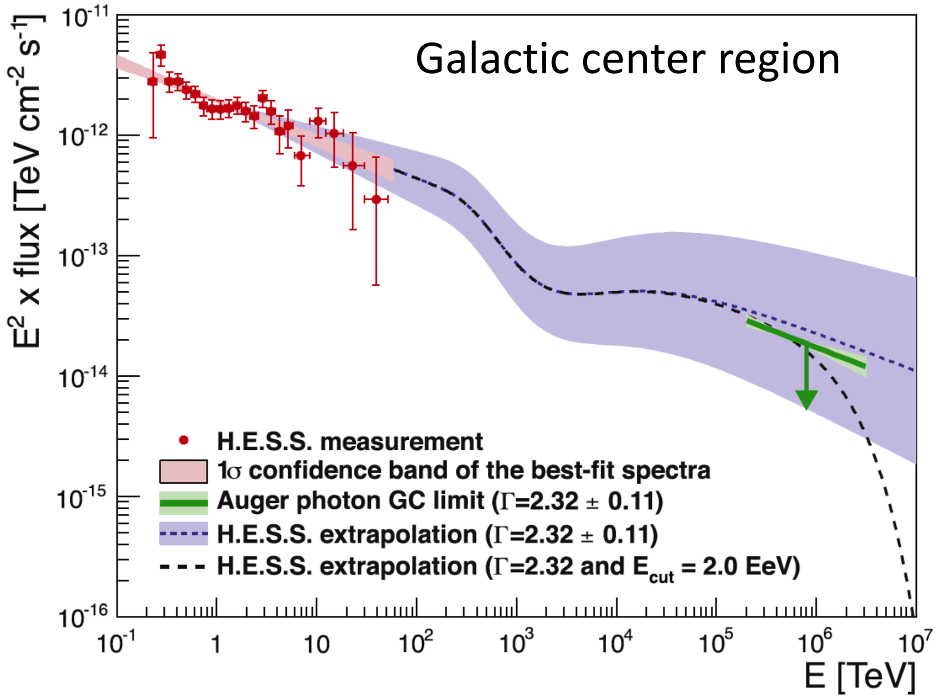


Figure 10. Celestial map of photon flux upper limits in photons km^{-2} yr^{-1} illustrated in Galactic coordinates. (A color version of this figure is available in the online journal.)

Targeted search of point sources of EeV photons

Auger, APJL 2017

- *Grouping sources to reduce stat. penalization*
- *Search for excesses of EeV "photon-like" events*



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Auger, APJ 2014

- *Directional group*
- *Declination -85°*
- *Lower energy ra*
  diffuse flux)

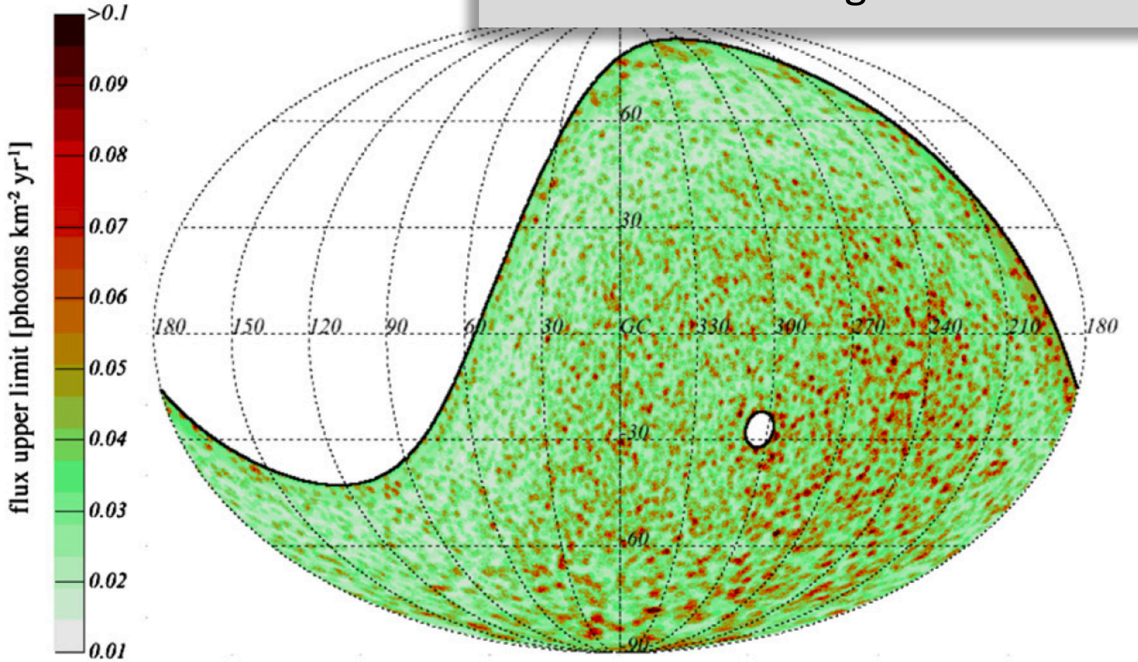
Targeted search of point sources of EeV photons

Auger, APJL 2017

- *stat. penalization*
- *"photon-like" events*

No EeV photon flux detected: upper limits 0.06 (0.25) mean (max) eV cm^{-2} s^{-1} (blind), 0.04-0.08 eV cm^{-2} s^{-1} (targeted)

- EeV photons from extra-galactic sources?
- Transient galactic sources?



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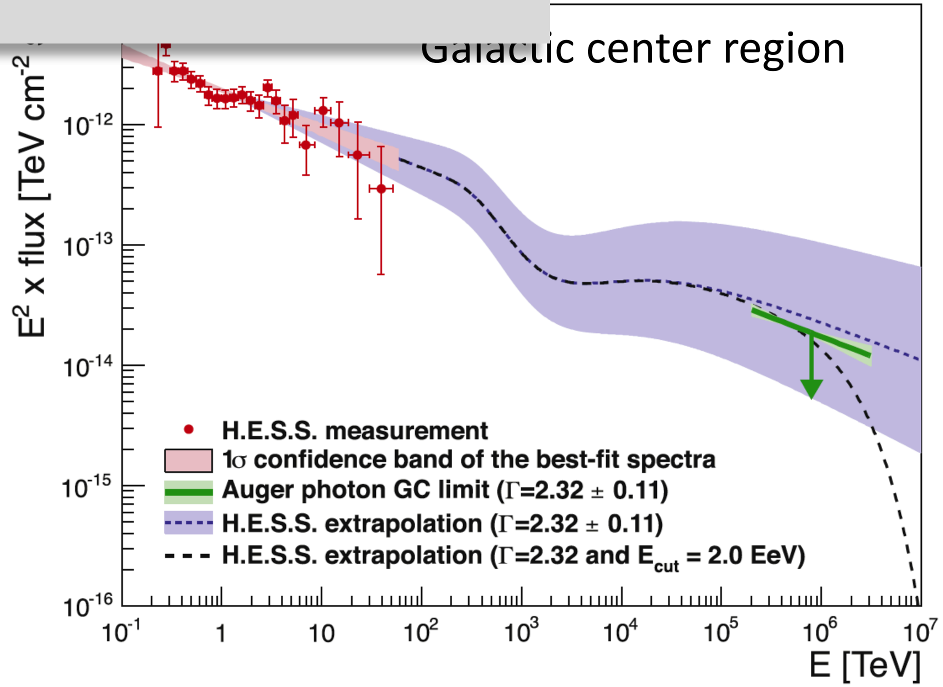
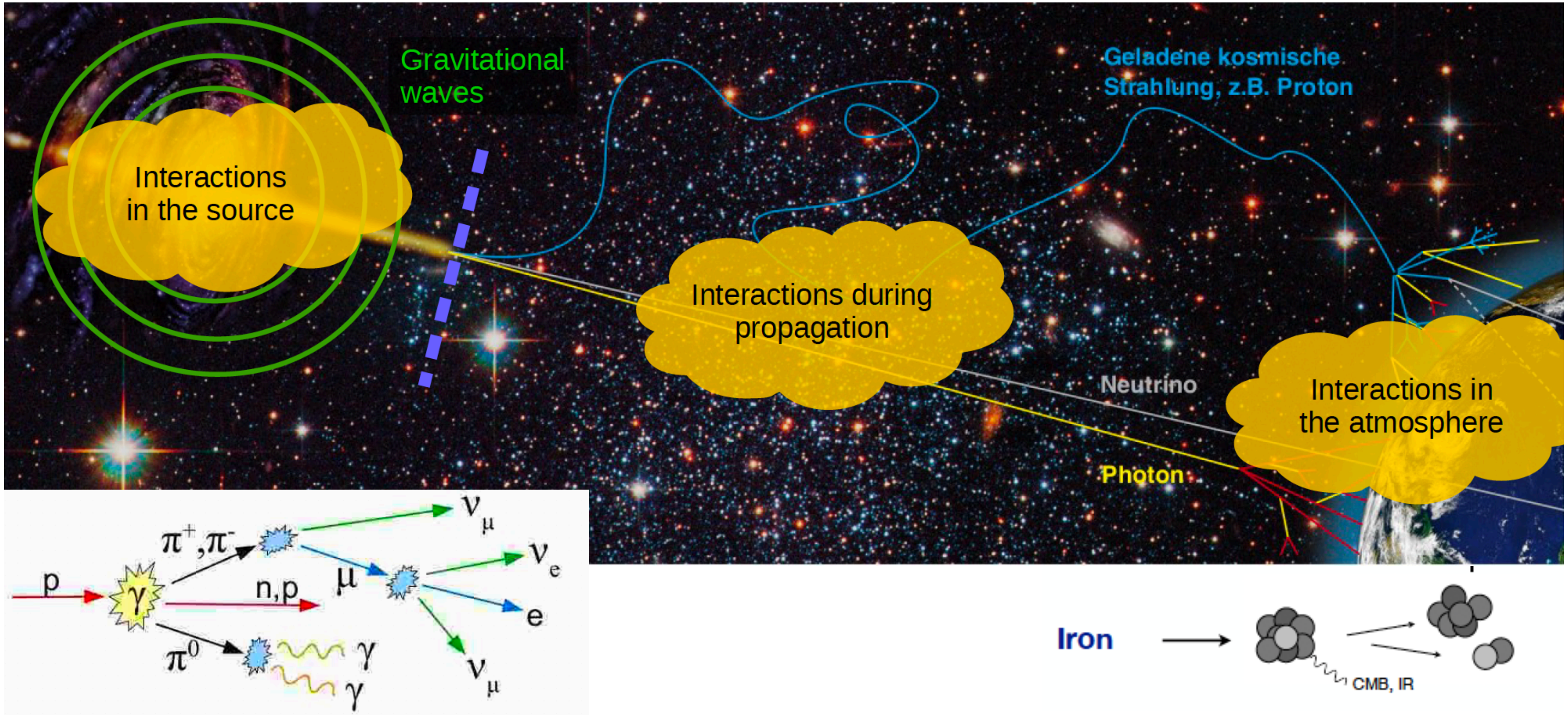


2. The role of photon background in CR propagation



- The energy spectrum we measure is that of propagated particles/nuclei: $E_{det} < E_{inj}$
- The particles/nuclei are the ones surviving propagation: $M_{det} < M_{inj}$
- Photons and neutrinos are generated along the path ⇒ **MM**

Modeling photon fields and interaction cross sections in propagation codes

Fitting astrophysical properties of sources (distribution, injection spectrum and composition)

Astrophysical interpretation possible for simple scenarios:

- 1D propagation;
- Homogeneous distribution of identical sources of p, He, N (, Si) and Fe nuclei;
- CR injection = power-law + rigidity cutoff.

Same basic scenario used in many interpretation papers, e.g.
Aharonian, Ahlers, Allard, Aloisio, Berezinsky, Blasi, Hooper, Olinto, Parizot, Taylor, …:

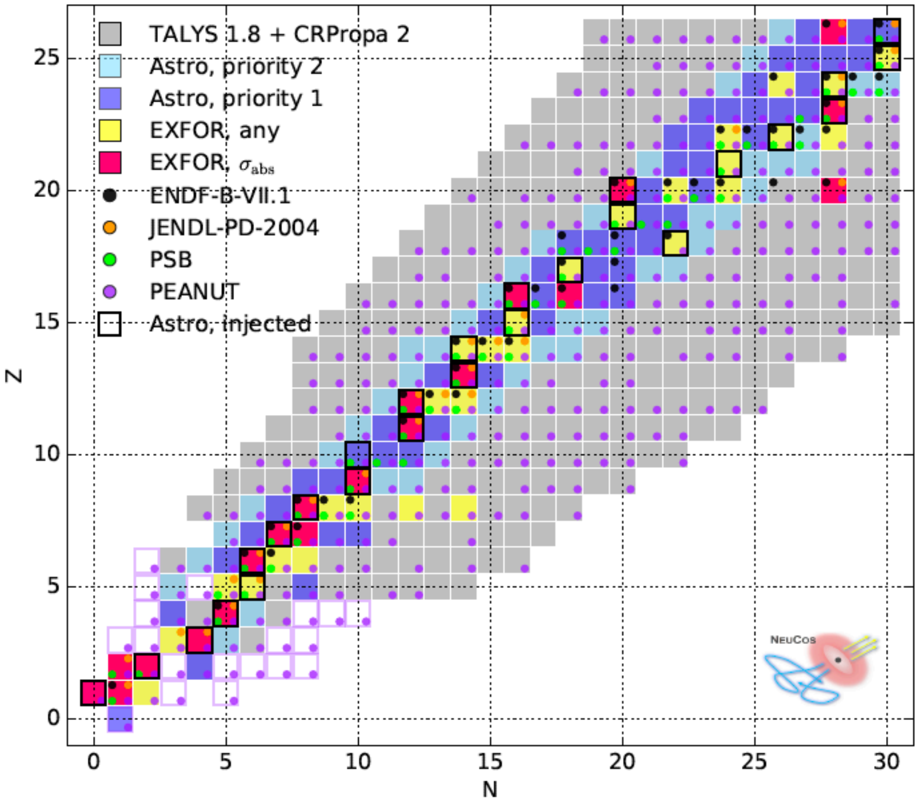
Hard/very-hard injection unless nearby sources assumed

Auger combined fit of spectrum and composition data *JCAP 04 (2017) 038*
A comprensive study of model and data uncertainties

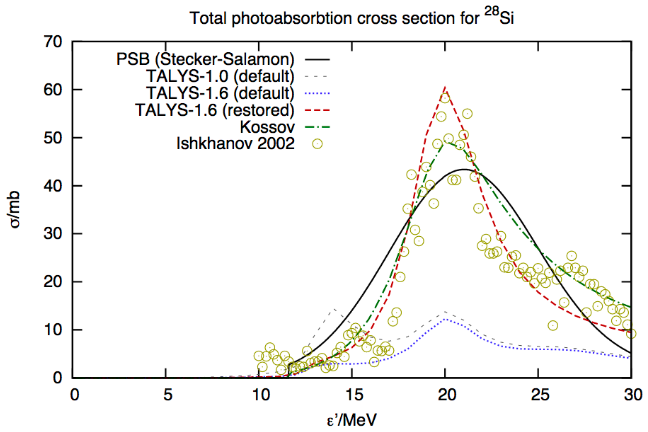
Model dependence:

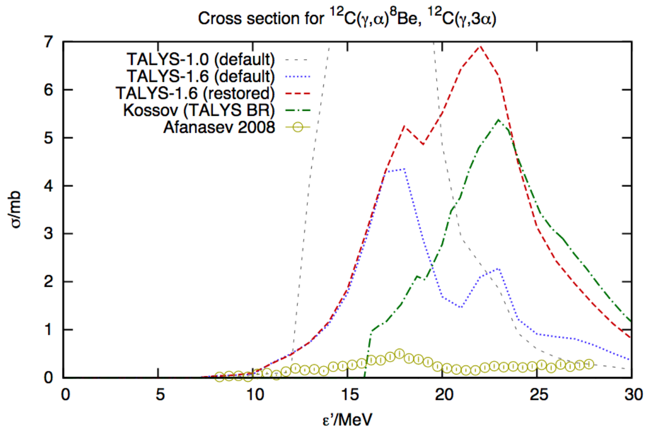
- Propagation codes
- Cross-sections
- EBL models

Involved nuclei

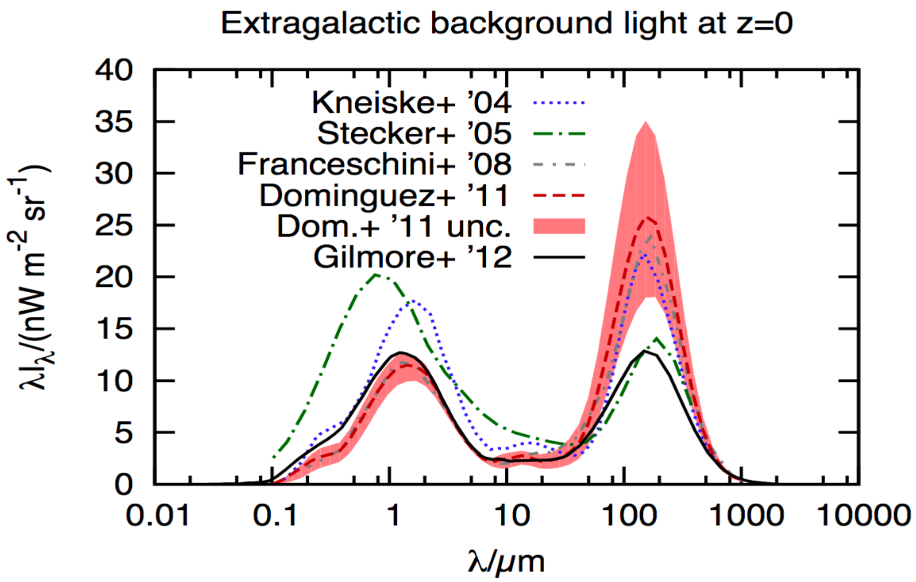


Boncioli, Fedynitch, Winter, et al., Sci. Rep., 7, 4882 (2017)





Alves Batista et al., JCAP 10 (2015) 063



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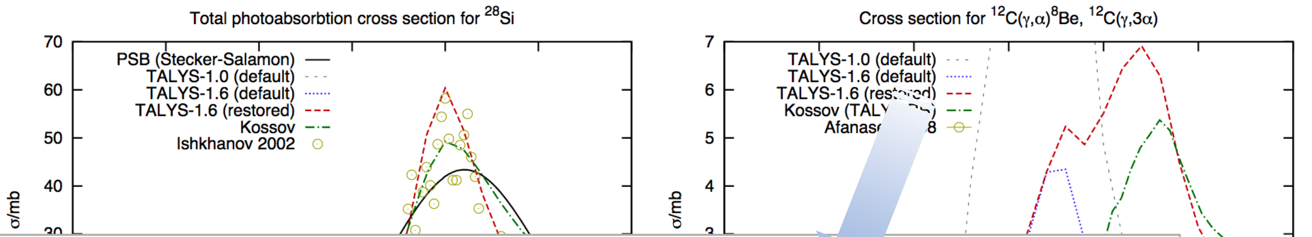
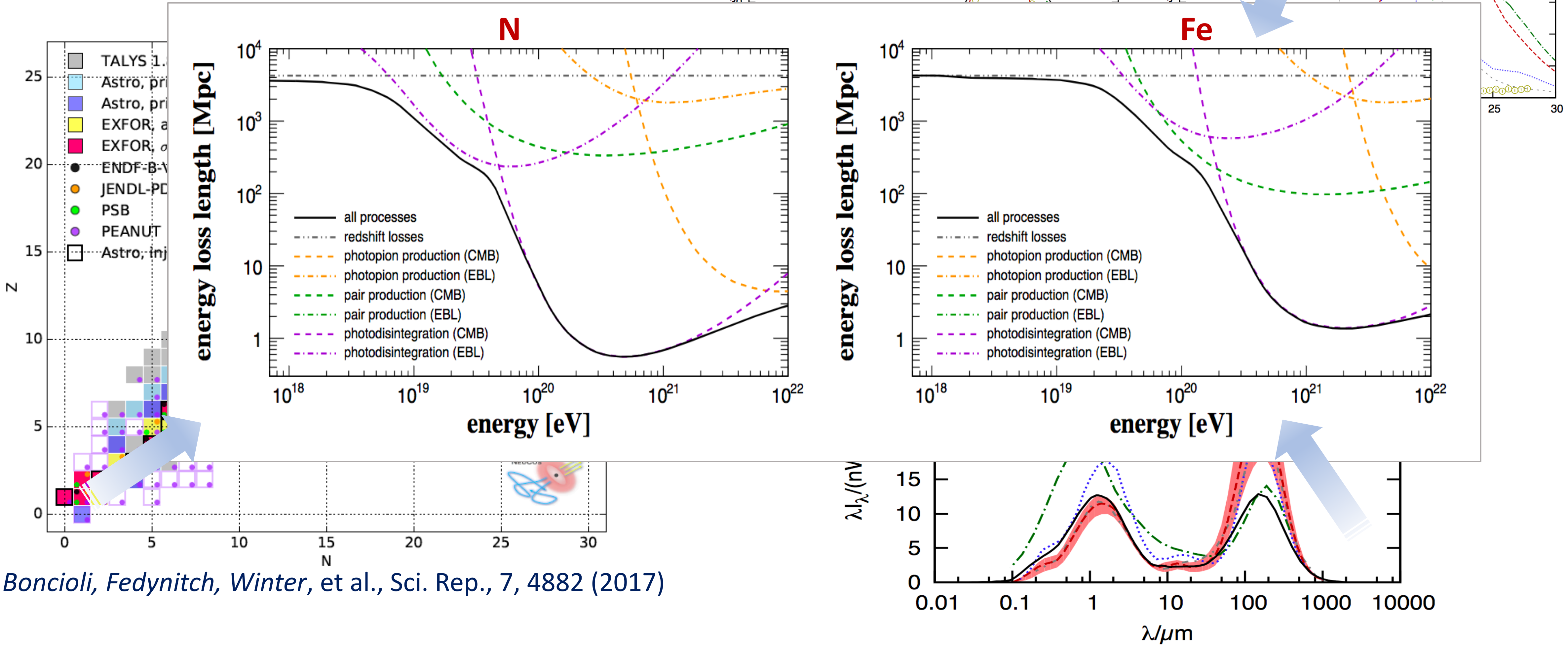




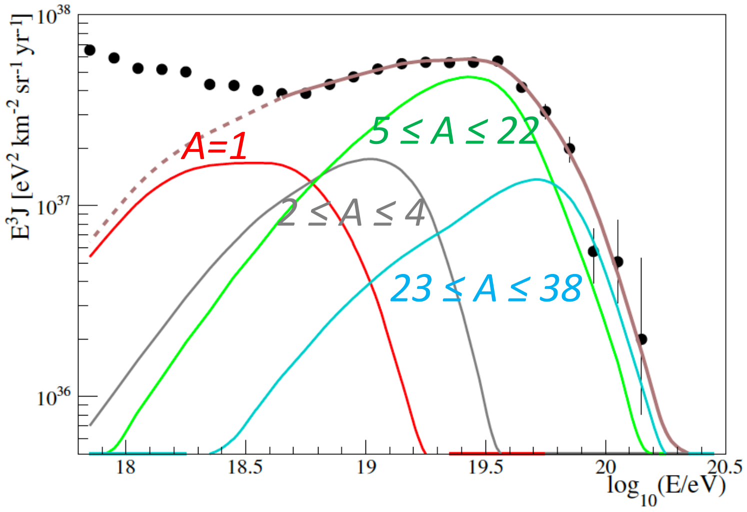
Boncioli, Fedynitch, Winter, et al., Sci. Rep., 7, 4882 (2017)

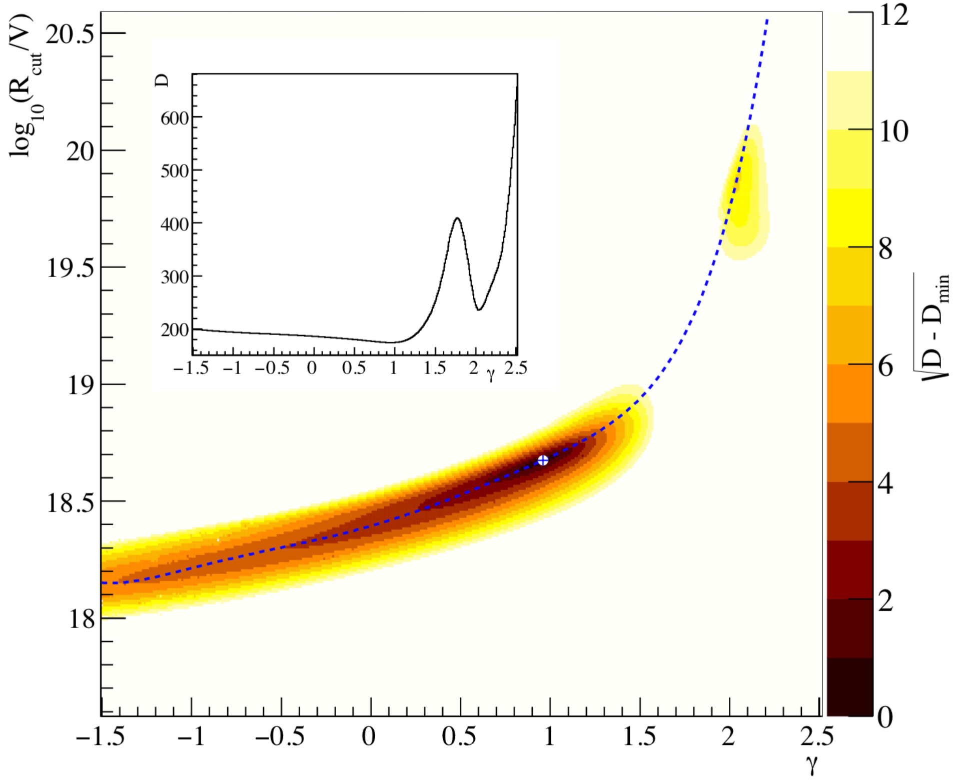
Best fit results for reference model

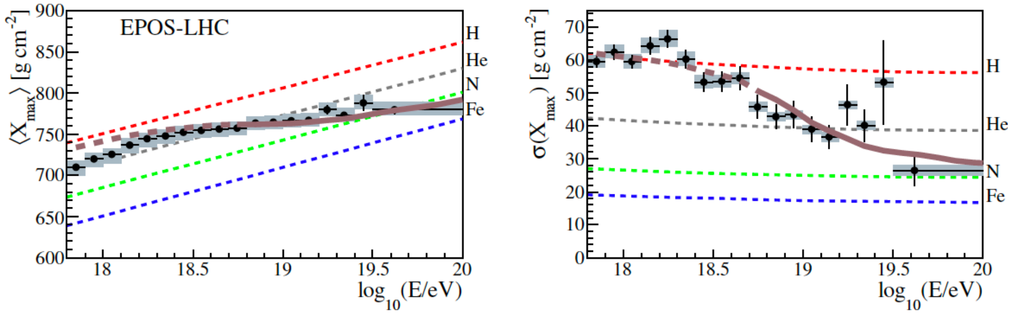
SPG (SimProp, PSB x-sect, Gilmore '12 EBL) + EPOS-LHC

$$\frac{dN}{dE} = J_0 \sum_\alpha f_\alpha E_0^{-\gamma} \begin{cases} 1 & \text{for} \quad E_0/Z_\alpha < R_{\rm cut}\,, \\ \exp(1 - \frac{E_0}{Z_\alpha R_{\rm cut}}) & \text{for} \quad E_0/Z_\alpha \geq R_{\rm cut} \end{cases}$$

reference model	best fit	average	shortest 68% int.
γ	1.22	1.27	$1.20 \div 1.38$
$\log_{10}(R_{\rm cut}/{\rm V})$	18.72	18.73	$18.69 \div 18.77$
$f_{\rm H}(\%)$	6.4	15.1	$0.0 \div 18.9$
$f_{\rm He}(\%)$	46.7	31.6	$18.9 \div 47.8$
$f_{\rm N}(\%)$	37.5	42.1	$30.7 \div 51.7$
$f_{\rm Si}(\%)$	9.4	11.2	$5.4 \div 14.6$
$\Delta X_{\rm max}/\sigma_{\rm syst}$	-0.63	-0.69	$-0.90 \div -0.48$
$\Delta E/\sigma_{\rm syst}$	$+0.00$	$+0.12$	$-0.57 \div +0.54$
D/n	166.5/117		
$D\ (J),\ D\ (X_{\rm max})$	12.9, 153.5		



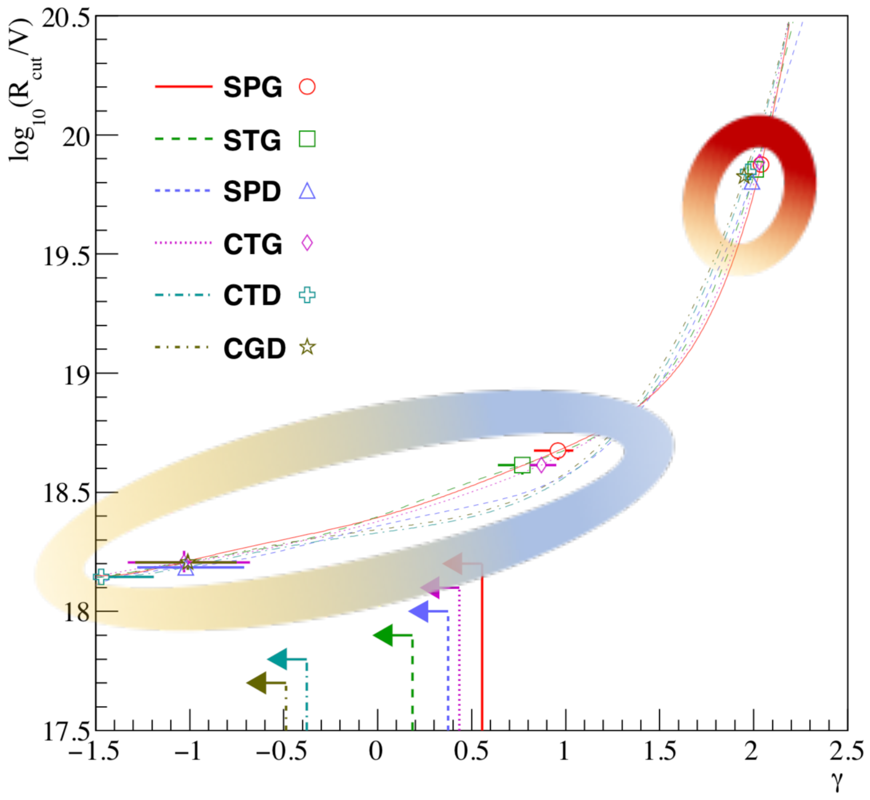




JCAP 04 (2017) 038

Changing model parameters

	MC code	$\sigma_{photodisint.}$	EBL model
SPG	SimProp	PSB	Gilmore 2012
STG	SimProp	TALYS	Gilmore 2012
SPD	SimProp	PSB	Domínguez 2011
CTG	CRPropa	TALYS	Gilmore 2012
CTD	CRPropa	TALYS	Domínguez 2011
CGD	CRPropa	Geant4	Domínguez 2011



Best minimum for γ < 1: ***here the position depends strongly on model (EBL, ph-dis x-sections);***

Local minimum at $\gamma \approx 2$: ***almost independent of model parameters (CMB dominated)***

Changing model parameters

	MC code	$\sigma_{\text{photodisint.}}$	EBL model
SPG	SimProp	PSB	Gilmore 2012
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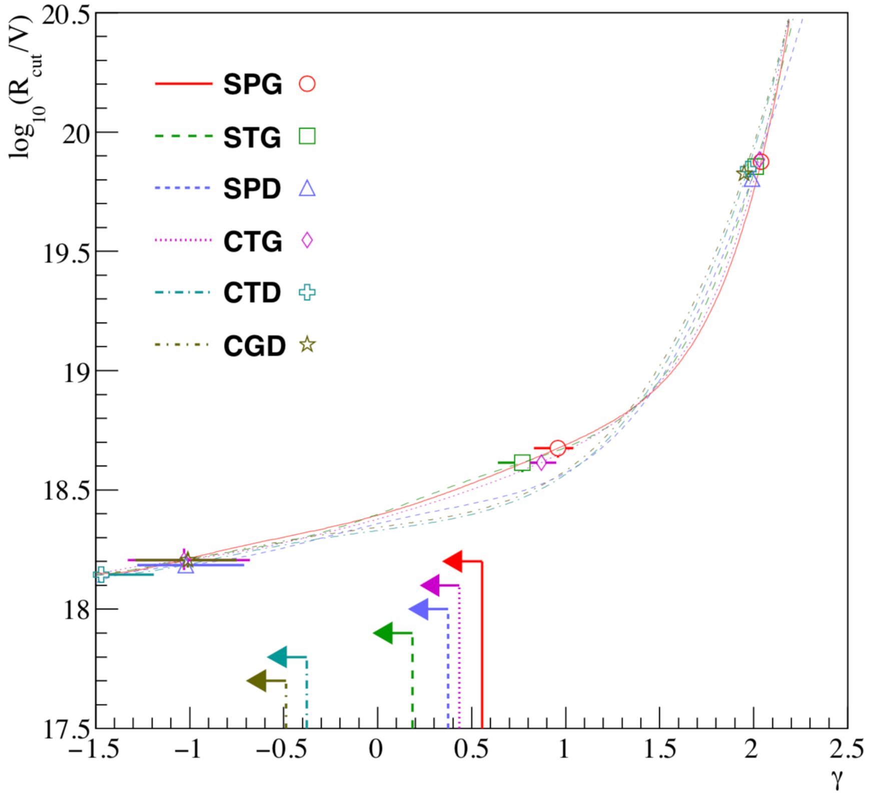
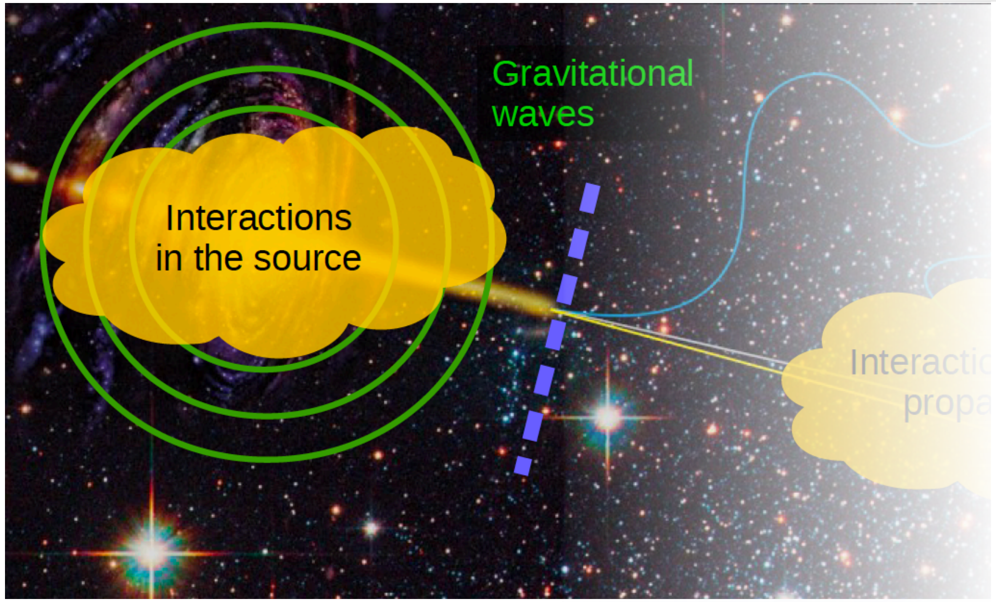


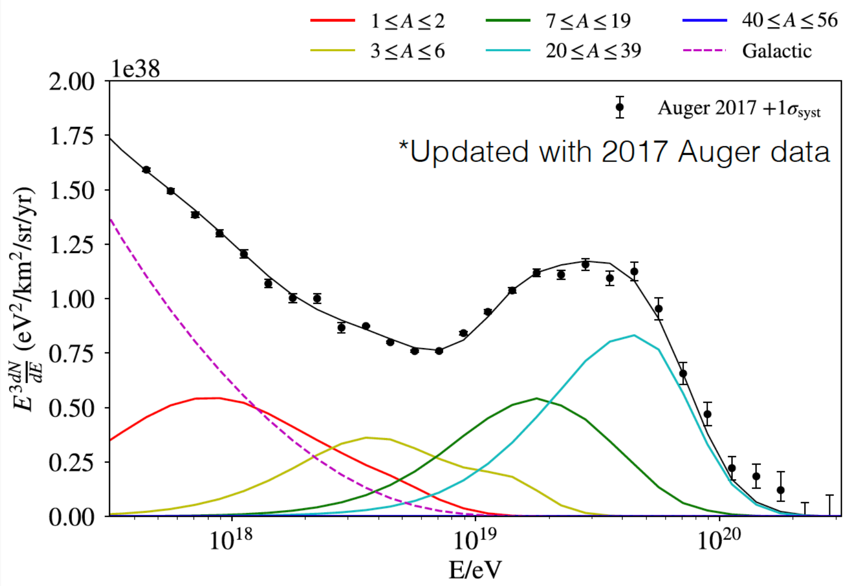
Changing interaction model

EPOS-LHC gives the best agreement
(initial tests with Sibyll 2.3 c …)

model	γ	$\log_{10}(R_{\text{cut}}/\text{V})$	D	$D(J)$	$D(X_{\max})$
EPOS-LHC	$+0.96^{+0.08}_{-0.13}$	$18.68^{+0.02}_{-0.04}$	174.3	13.2	161.1
Sibyll 2.1	$-1.50^{+0.05}$	$18.28^{+0.00}_{-0.01}$	243.4	19.7	223.7
QGSJet II-04	$+2.08^{+0.02}_{-0.01}$	$19.89^{+0.01}_{-0.02}$	316.5	10.5	306.0
	$-1.50^{+0.02}_{*}$	$18.28^{+0.01}_{-0.00}$	334.9	19.6	315.3

3. The role of photon fields around the sources





Interaction of nuclei in the source photon environment

Unger, Farrar, Ancordoqui, PRD (2015) + …

- Natural mechanism to produce the `ankle' in UHECR spectrum
- Interplay between interaction and escape mechanisms
- Photodisintegration within source environment

➠ *mixed-composition escaping the source*

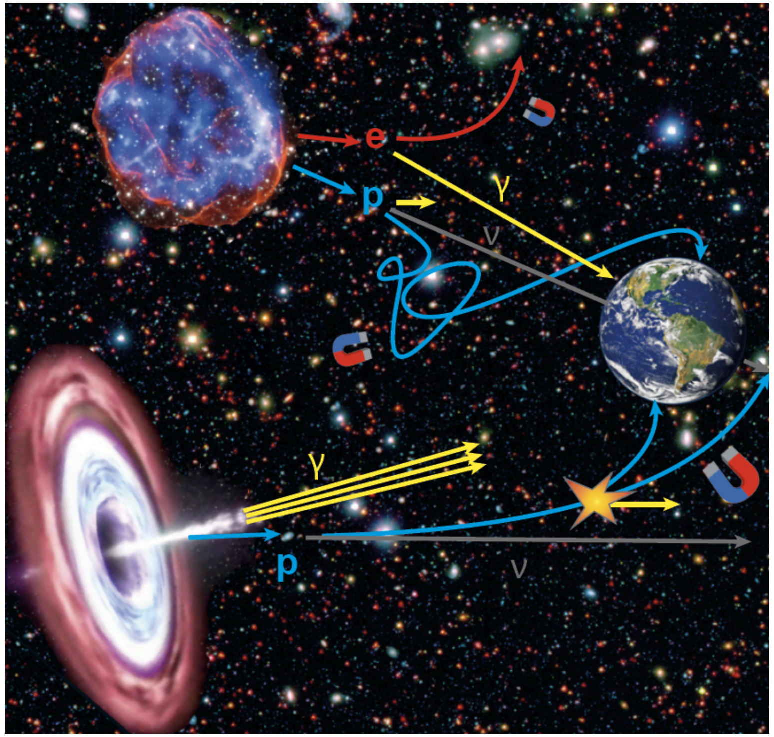
➠ *ankle & sub-ankle protons*

Summary

- Pierre Auger Observatory taking data since 20 years
- Several results on spectrum, composition, anisotropy, …
- Absence of photons (and neutrinos) support propagation scenarios
- Interpretation of data in term of source scenarios made difficult by large model uncertainties
- Current upgrade – **AugerPrime** – will provide better mass sensitivity in the suppression region

Backup material

Making the astrophysical model more realistic



4D propagation using CRPropa3

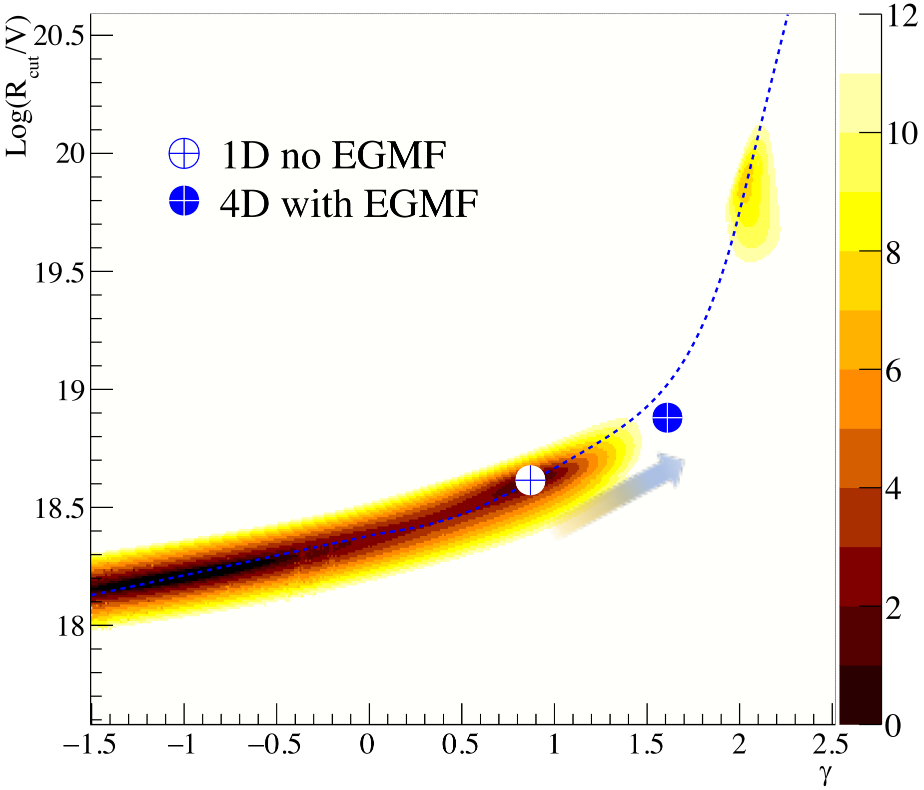
Large scale structure for CR sources *(Dolag '12)*

Results for a single model (CTG + EPOS-LHC):
Wittkowski ICRC 2017

Source properties	4D with EGMF	4D no EGMF	1D no EGMF[1]
γ	1.61	0.61	0.87
$\log_{10}(R_{cut}/\mathrm{eV})$	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 %

[1] Homogeneous source distribution, see [A. Aab et al., JCAP 2017, 038 (2017)]

Making the astrophysical model more realistic



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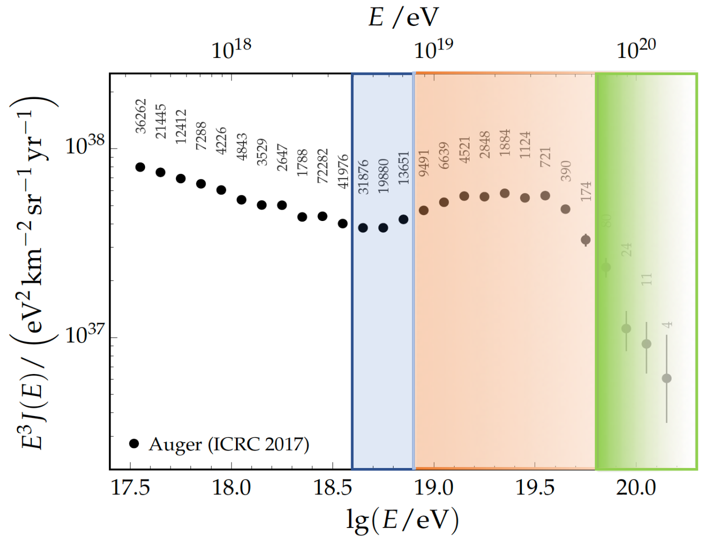
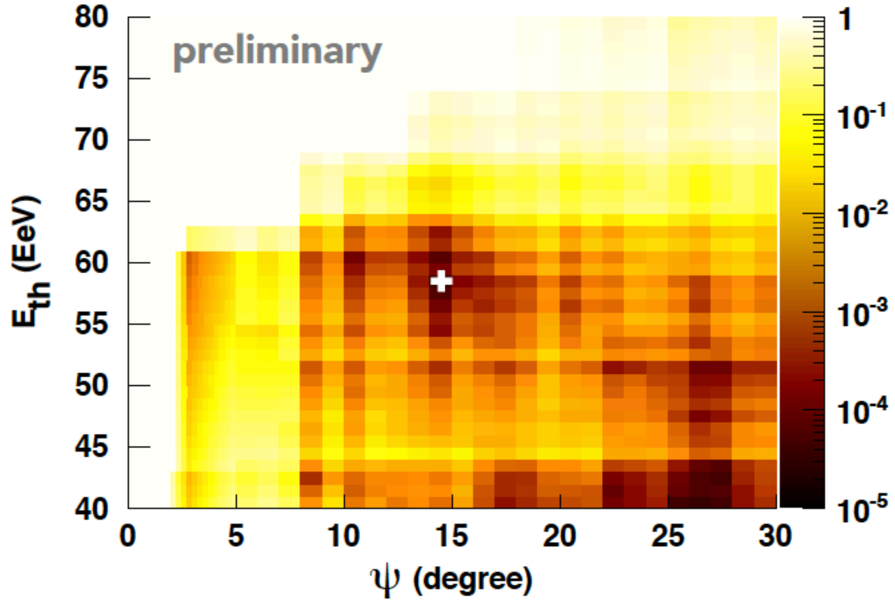
Anisotropy: Intermediate scale

- Compare the cumulative number of observed (n_{obs}) events with the expected on average from isotropic simulations (n_{exp})
- Compute the cumulative binomial probability (P) to measure n_{obs} given $<n_{exp}>$
- Scan in parameters: *E_{th} in [40; 80] EeV in steps of 1 EeV*
  Ψ in [1°; 30°] in steps of 0.25° up to 5°, 1° for larger angles





(Giaccari ICRC 2017)

Largest excess

E_{th} = 58 EeV, Ψ = 15°

n_{obs} = 19, n_{exp} = 6.0

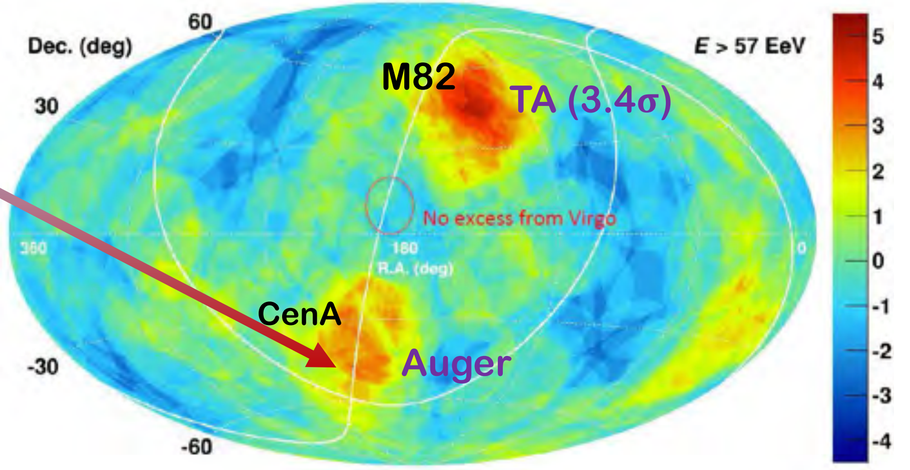
$P \sim 1.1 \times 10^{-5}$

Post-trial probability

$\sim 1.1 \times 10^{-3}$

(fraction of isotropic simulations that have a smaller probability under the same scan)

Region of secondary minima above ~40 EeV



Anisotropy: Correlation with catalogs

[Auger Coll., Ap.J. 853 (2018) L29]

Active Galactic Nuclei (γ-AGN)

- *Selected from 2FHL Catalog (Fermi-LAT, 360 sources):*
  Φ(> 50 GeV) ---> proxy for UHECR flux.
- *Selection of the 17 objects within 250 Mpc.*
- *Majority blazars of BL-Lac type and radio-galaxies of FR-I type.*

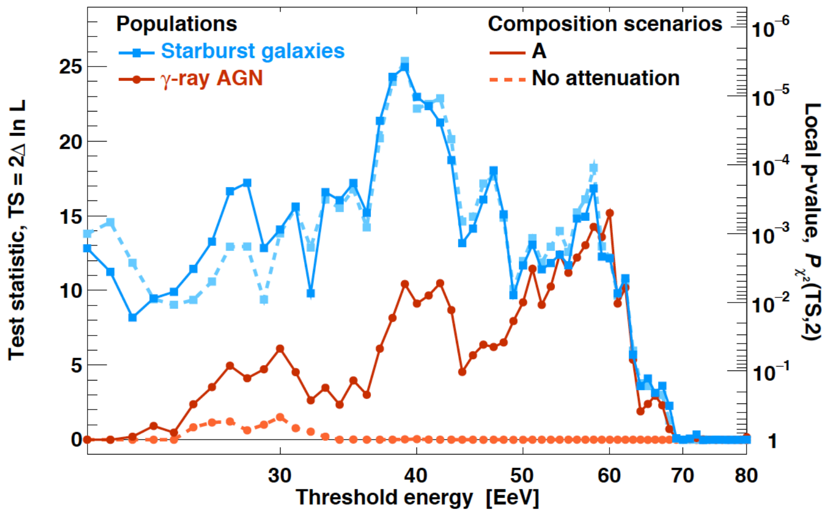
Starburst Galaxies

Use of Fermi-LAT search list for star-formation objects (Ackermann+ 2012)

- *63 objects within 250 Mpc, only 4 detected in gamma rays:*
  correlated Φ(> 1.4 GHz) ---> proxy for UHECR flux
- *Selection of brightest objects (flux completeness) with Φ(> 1.4 GHz) > 0.3 Jy*
- *23 objects, size similar to the gamma-ray AGN sample*

Assumption UHECRs flux proportional to non thermal photon flux

E > 60 EeV: f_{ani} = 7%, Ψ = 7°
TS = 15.2 ⇒ After penalization ~2.7 σ



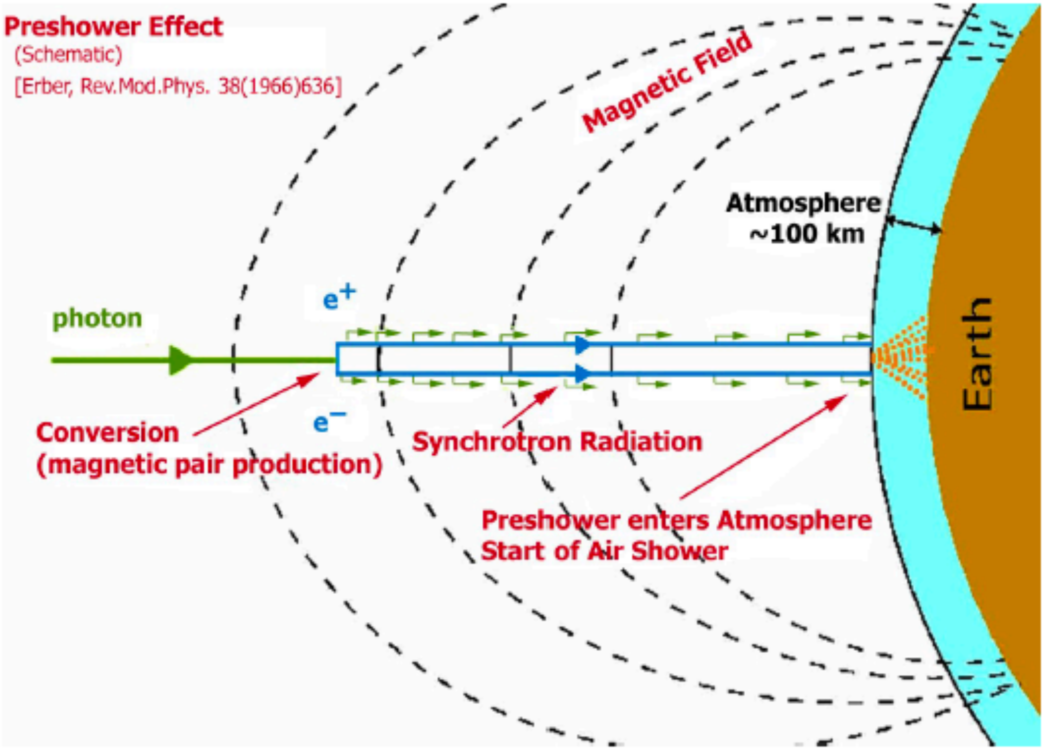
E > 39 EeV: f_{ani} = 10%, Ψ = 13°
TS = 24.9 ⇒ After penalization ~4.0 σ

Preshowers: a must to study UHE photons

Preshower (important for $E_\gamma > 10^{19}$ eV):

→ contains typically 100 particles

(created at around 1000 km a.s.l.)



→ dependence on E and $B_\perp$ (to be seen in data?)

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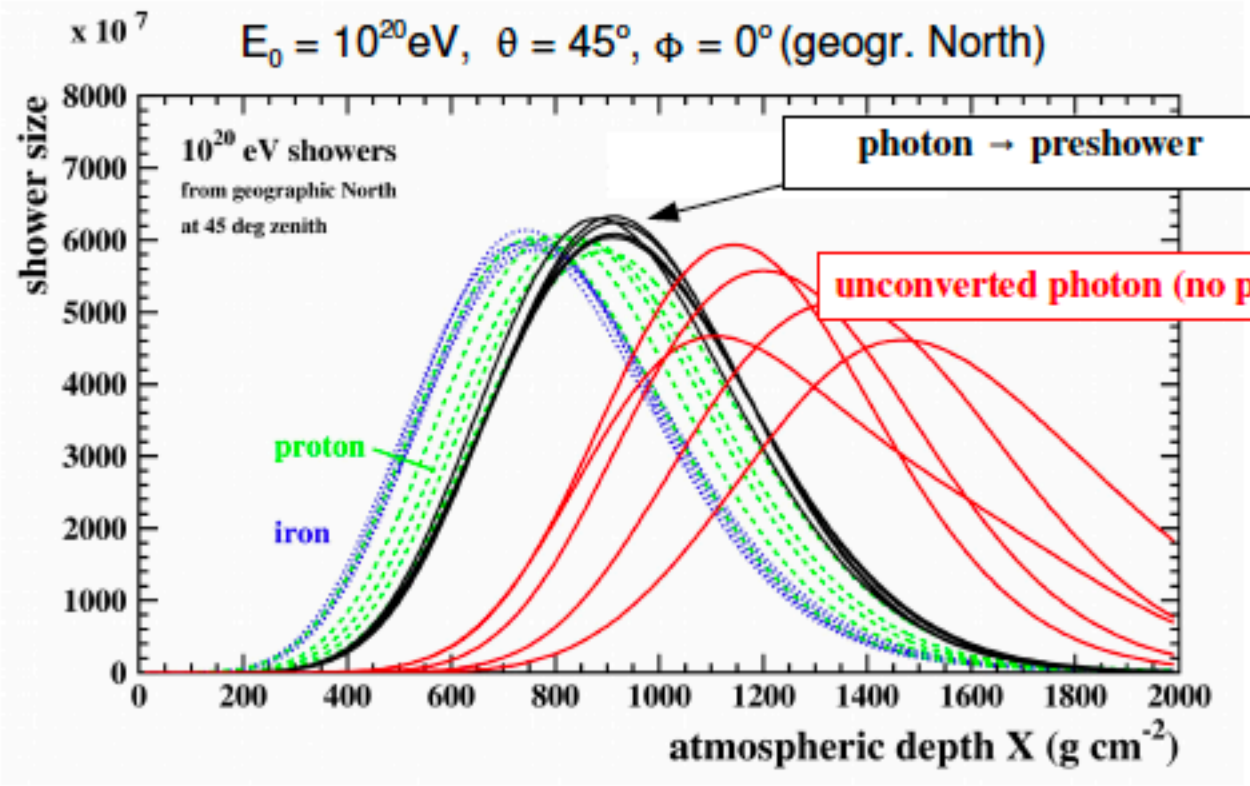
Preshowers and EAS development



LPM (in top layers of atmosphere is important for $E_\gamma > 10^{19}$ eV):
→ **deep** X_{max}, **large** fluctuations of X_{max}

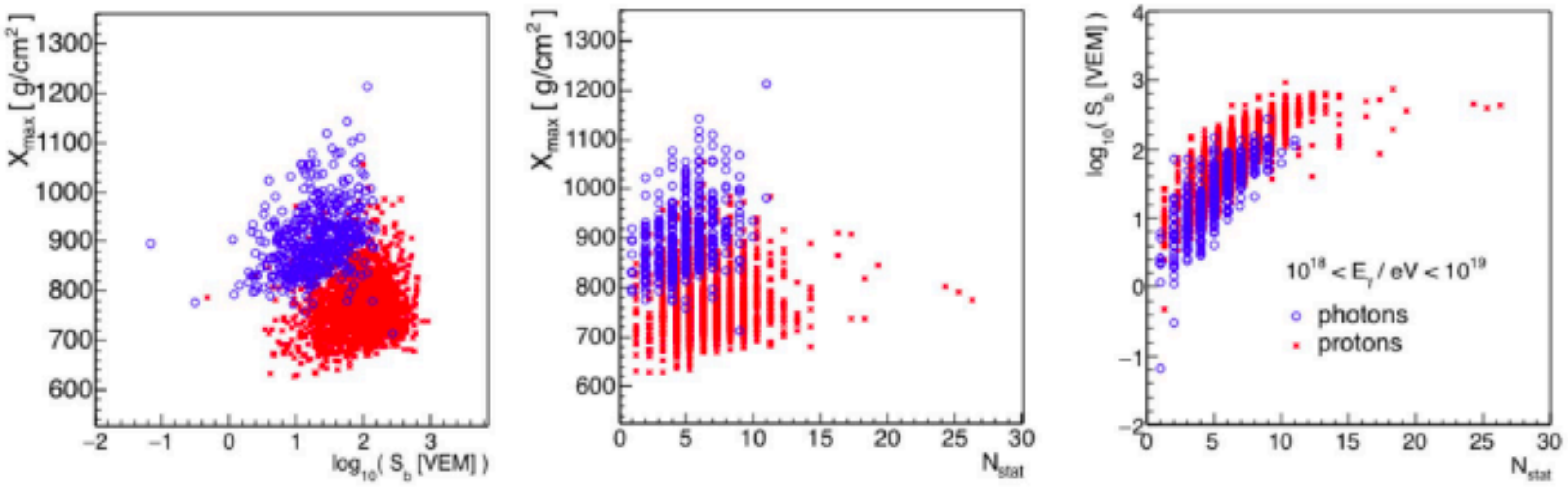
PRESHOWER (primary E_γ split into preshower particles):
→ **shallow** X_{max}, **small** fluctuations of X_{max}

13

Diffuse UHE photon search: mulitvariate

Pierre Auger Collaboration, JCAP 2017

X_{max} S_b N_{stat}



VEM: vertical equivalent muon

Targeted UHE photon search: source classes

Pierre Auger Collaboration, ApJL 2017

Groupping sources in classes

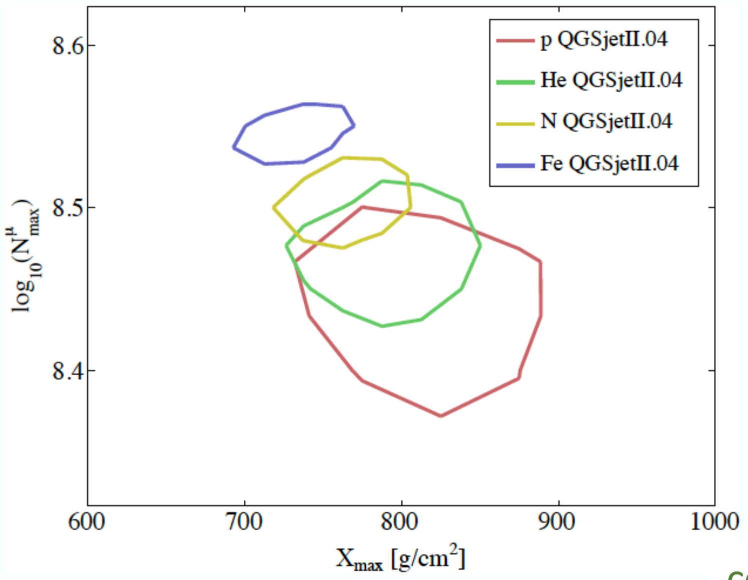
Class	No.	$\mathcal{P}_w$	$\mathcal{P}$
msec PSRs	67	0.57	0.14
γ-ray PSRs	75	0.97	0.98
LMXB	87	0.13	0.74
HMXB	48	0.33	0.84
H.E.S.S. PWN	17	0.92	0.90
H.E.S.S. other	16	0.12	0.52
H.E.S.S. UNID	20	0.79	0.45
Microquasars	13	0.29	0.48
Magnetars	16	0.30	0.89
Gal. Center	1	0.59	0.59
LMC	3	0.52	0.62
Cen A	1	0.31	0.31

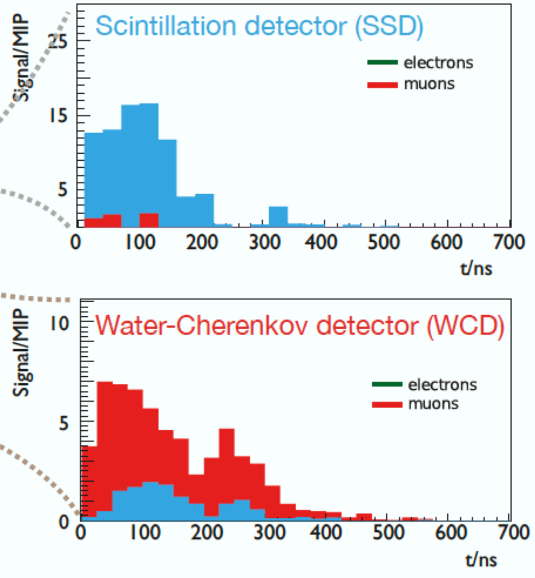
Minimum p-values statistically insignificant

Upgrade of the Pierre Auger Observatory: *AugerPrime*

To increase exposure with composition sensitive data Surface array needed!

Duty cycle: 100% (SD) vs 15% (FD)





complementarity of light responses used
to discriminate e.m. and muonic components

$$S_{\mu,\mathrm{WCD}} = a\,S_{\mathrm{WCD}} + b\,S_{\mathrm{SSD}}$$
$$S_{\mathrm{em,WCD}} = c\,S_{\mathrm{WCD}} + d\,S_{\mathrm{SSD}}$$

(AugerPrime design report 1604.03637)

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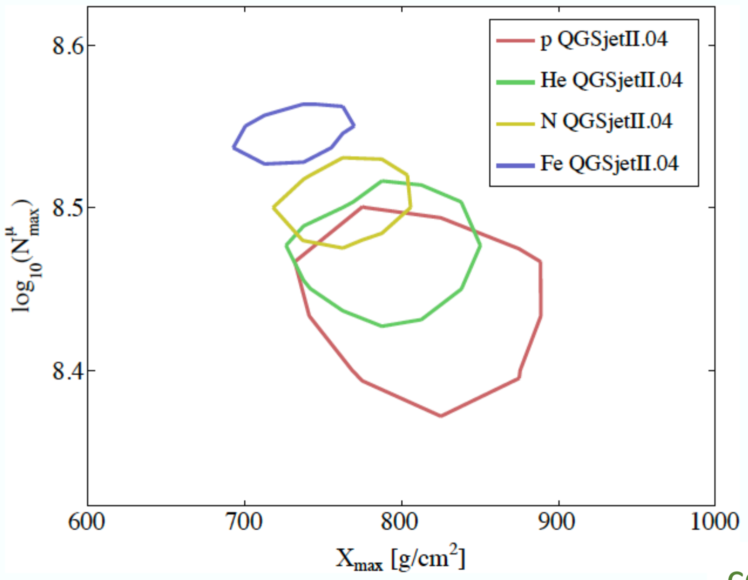
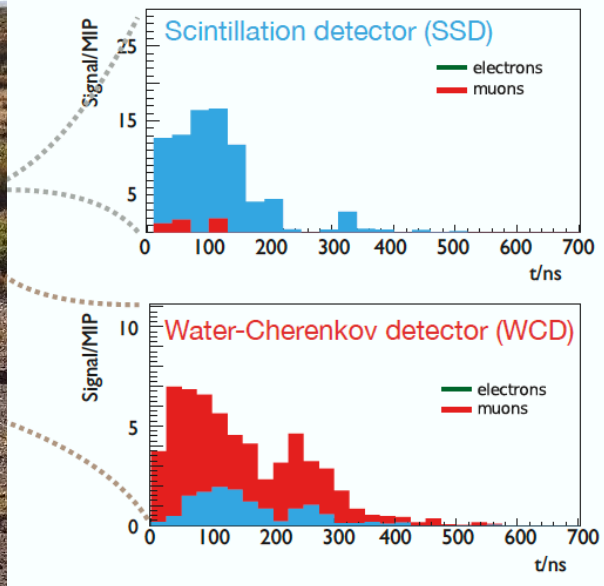


(AugerPrime design report 1604.03637)



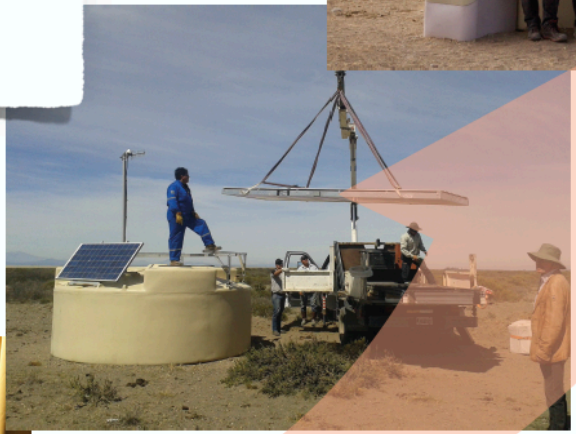
complementarity of light responses used to discriminate e.m. and muonic components

Moreover

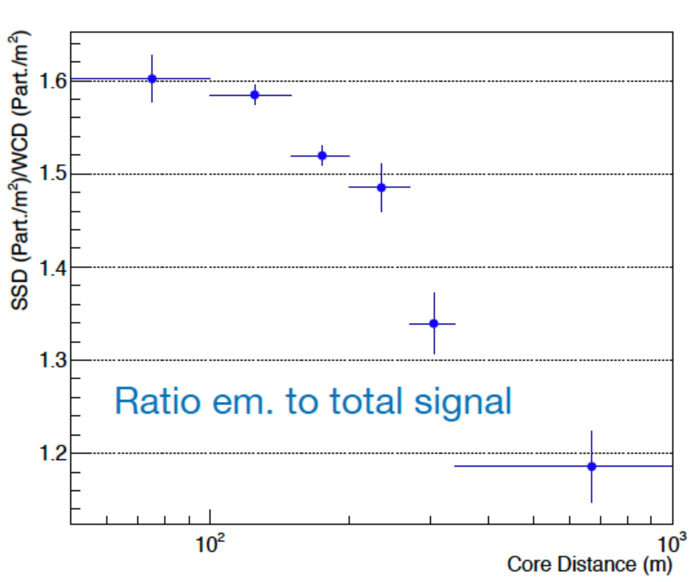
- Upgraded and faster electronics
- Extension of the dynamic range
- Cross check with underground buried AMIGA detectors
- Extension of the FD duty cycle

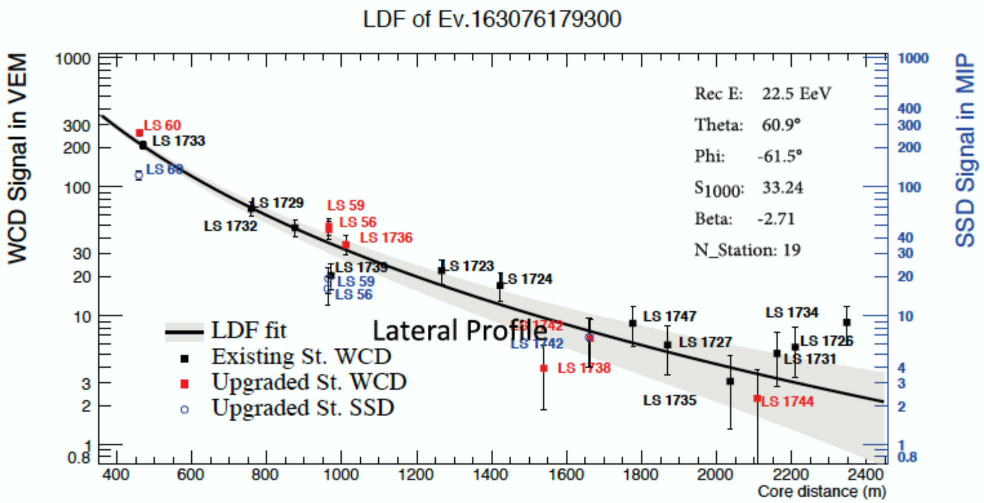
Status and plans for *AugerPrime*

- **Composition measurement at 10^{20} eV**
- **Composition selected anisotropy studies**
- **Particle physics with air showers**



2016: engineering array; 12 stations
2018-19: deployment
2019-25: data taking (40,000 km2 sr yr)





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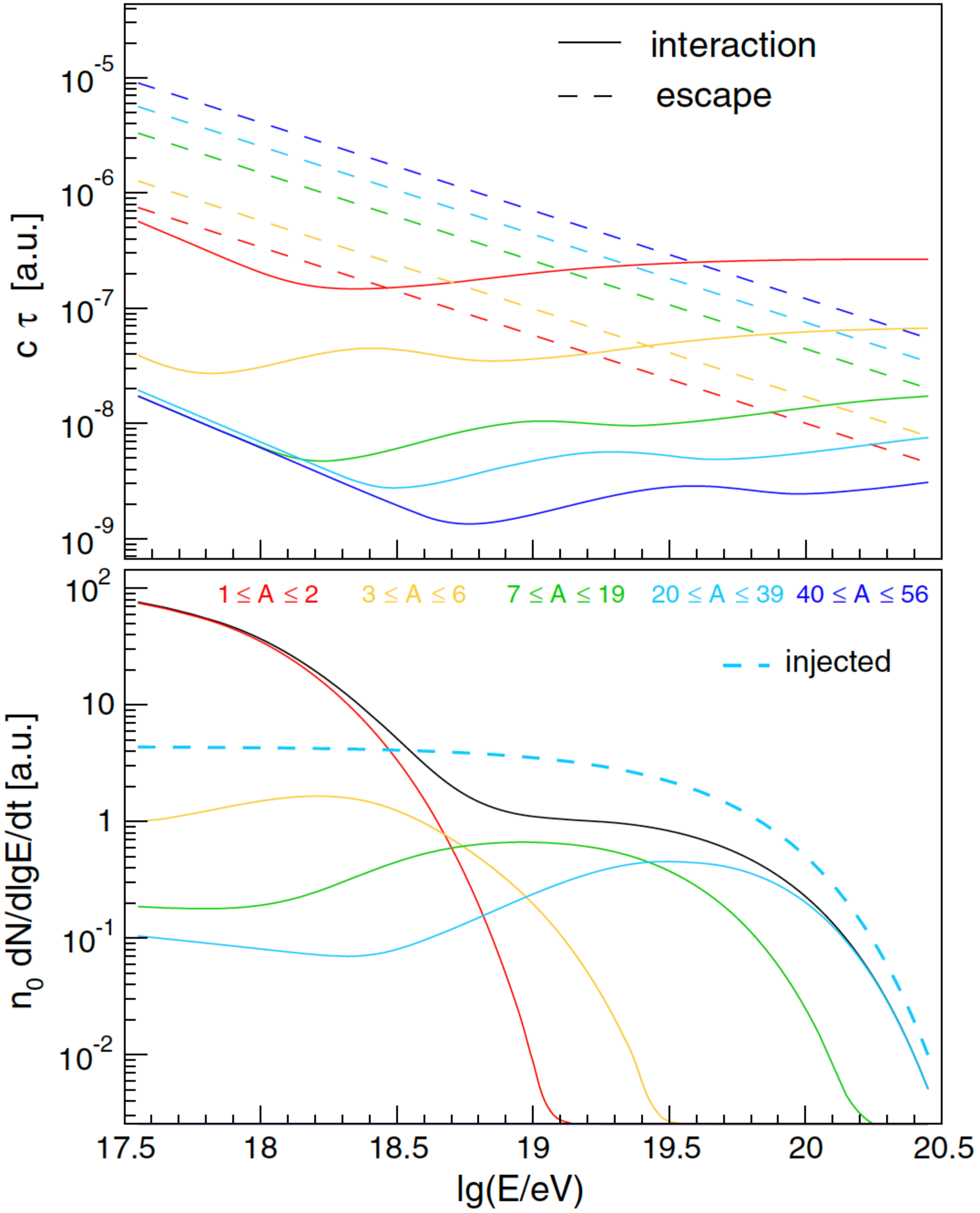

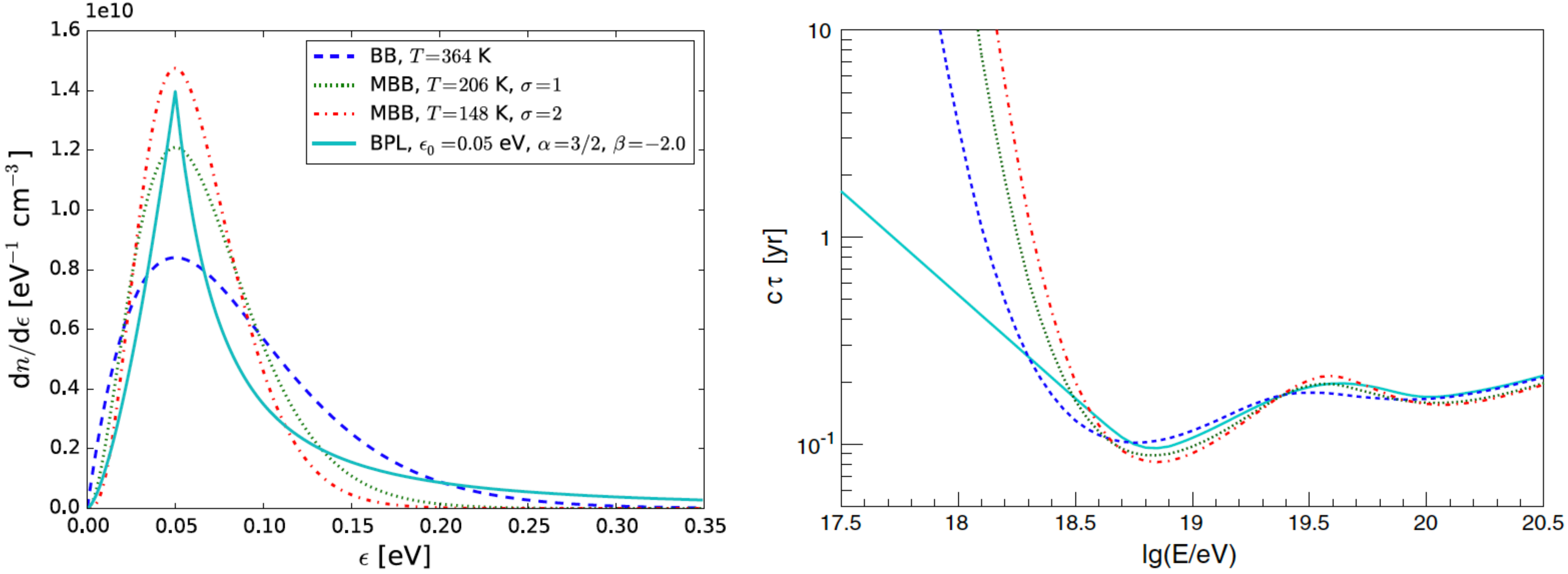

FIG. 13 (color online). Left: Comparison of photon spectra. BPL: Broken power law (solid), BB: black body spectrum (dashed), MBB: modified black body spectrum (dotted and dash-dotted). The curves are normalized to match the integral of the black body spectrum and the temperatures are chosen to match the peak energy of the broken power law. Right: Interaction times corresponding to the four photon spectra.