The quest for the sources of ultra-high energy cosmic rays: results and perspectives

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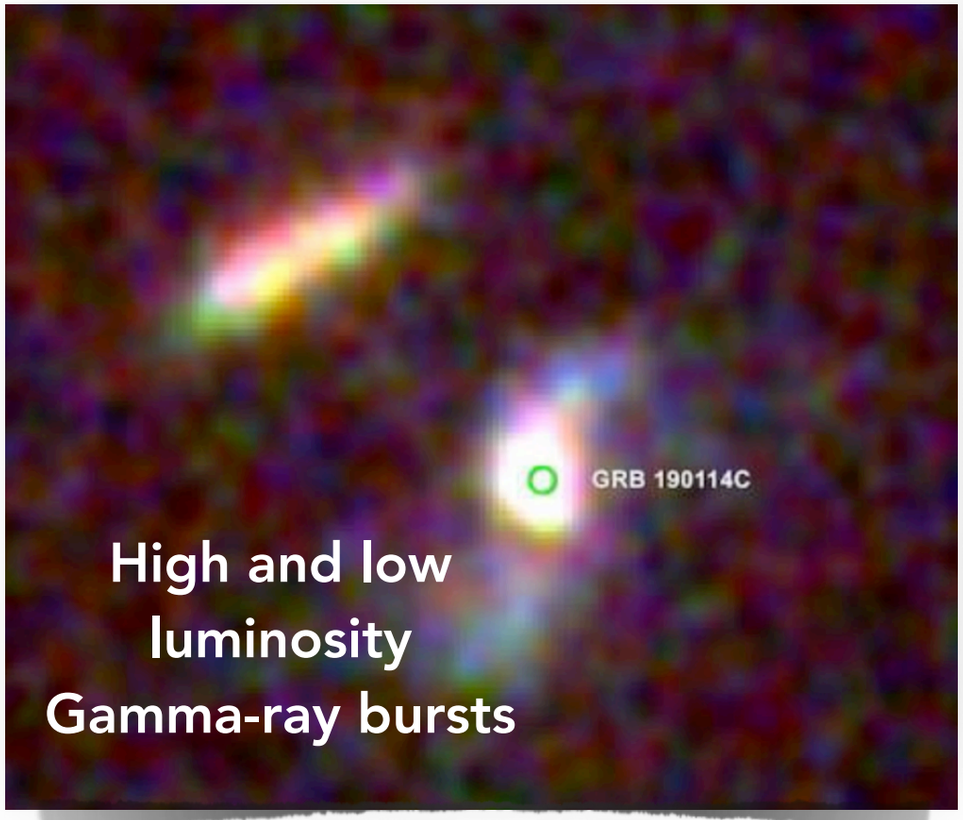
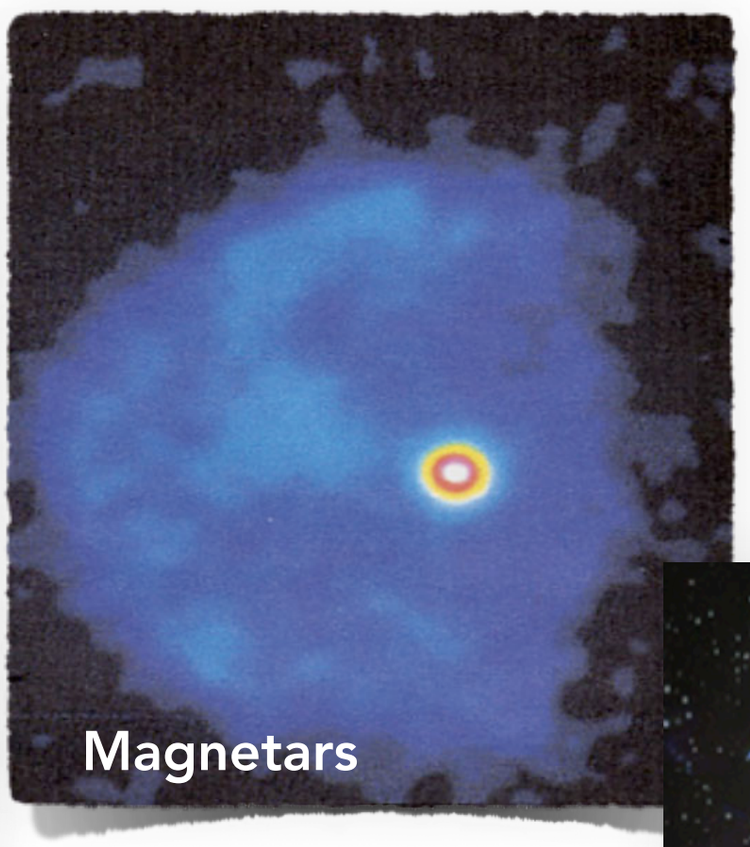
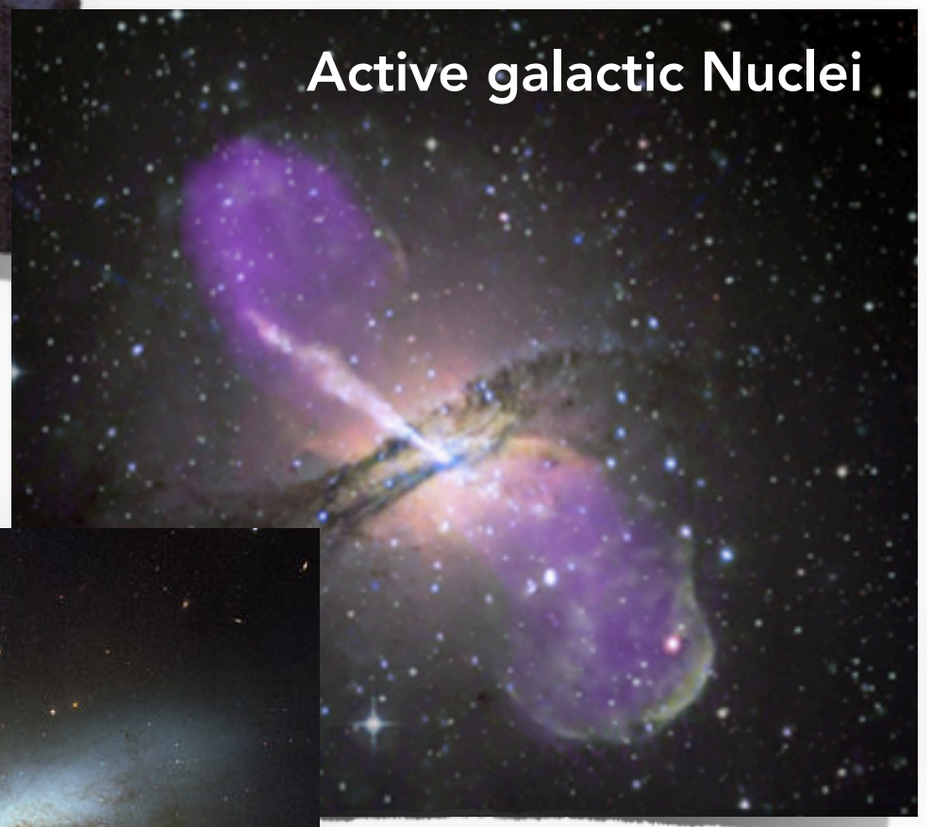
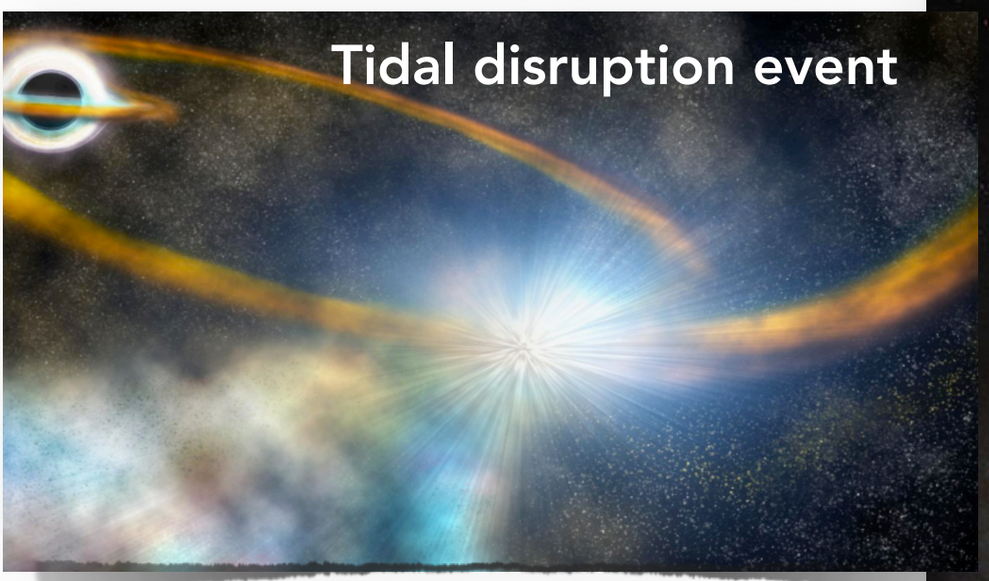
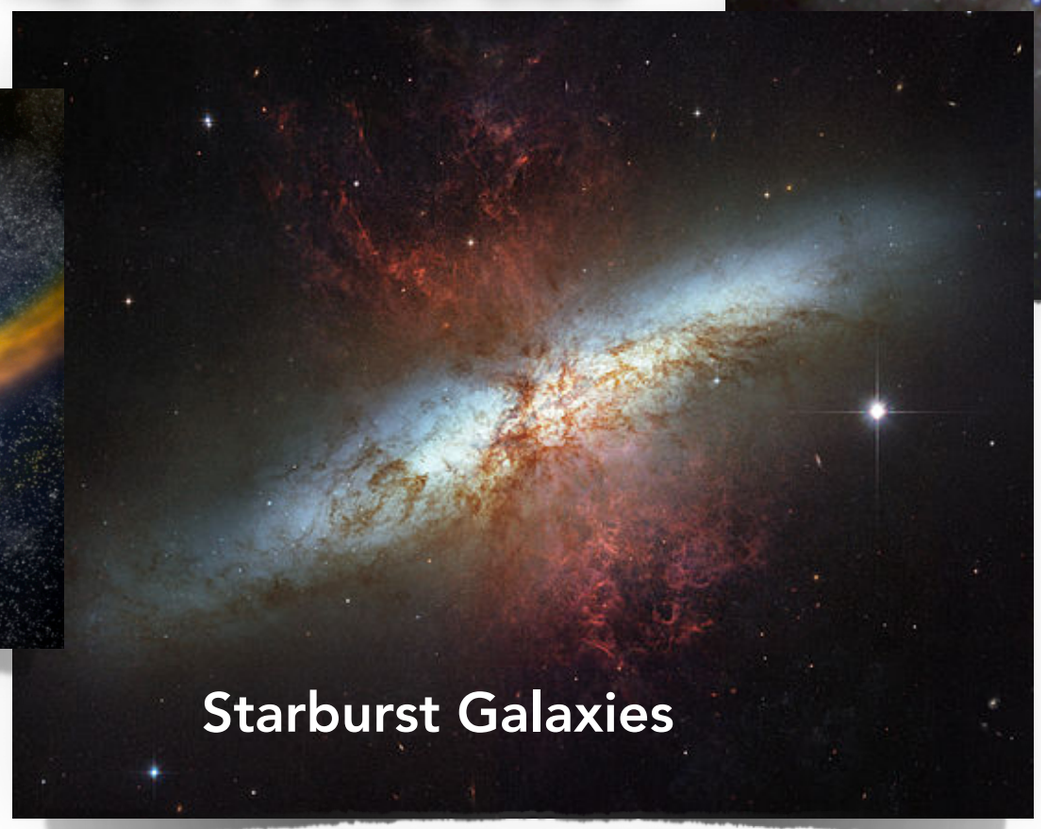






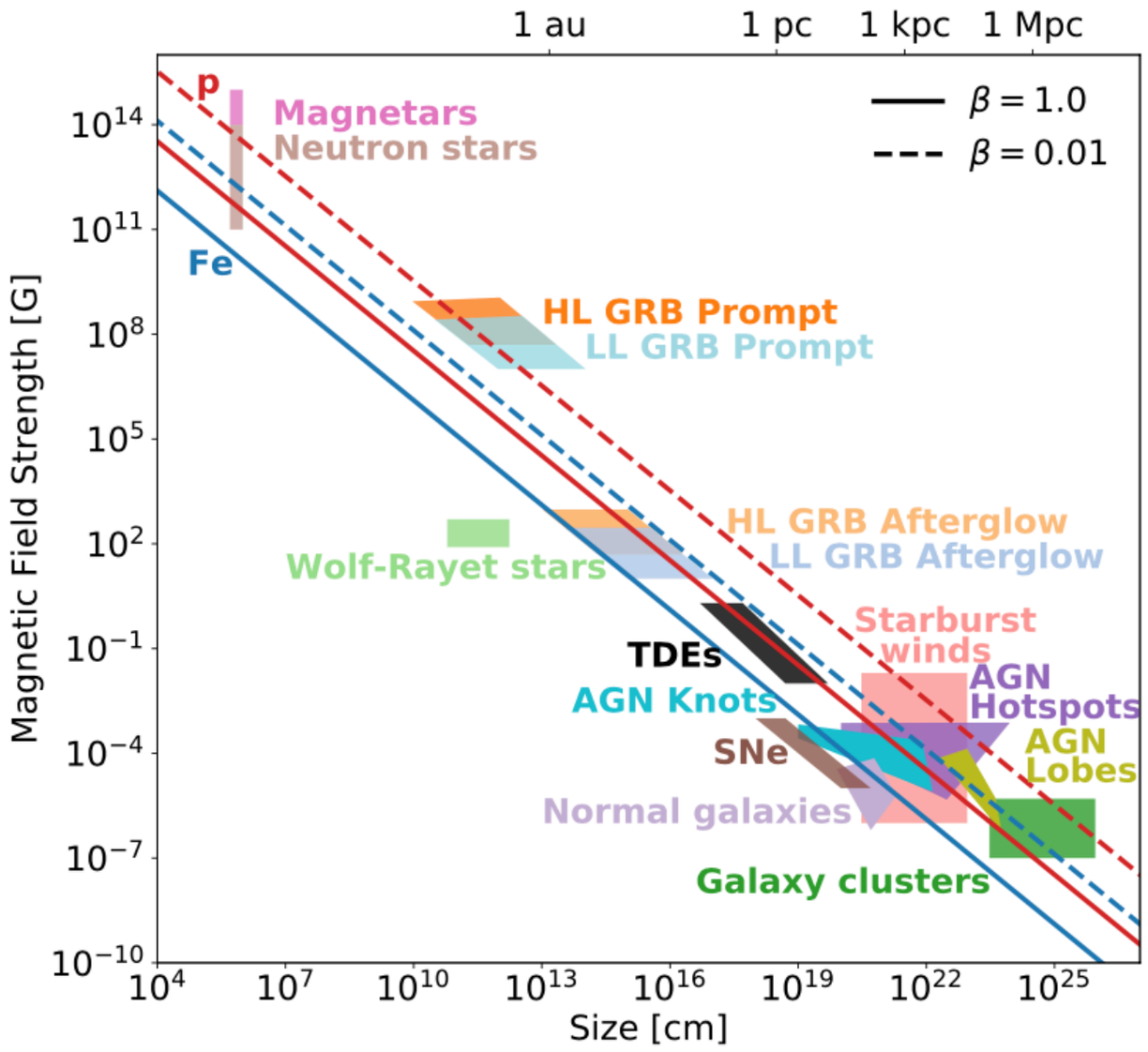
Candidates of UHECR sources

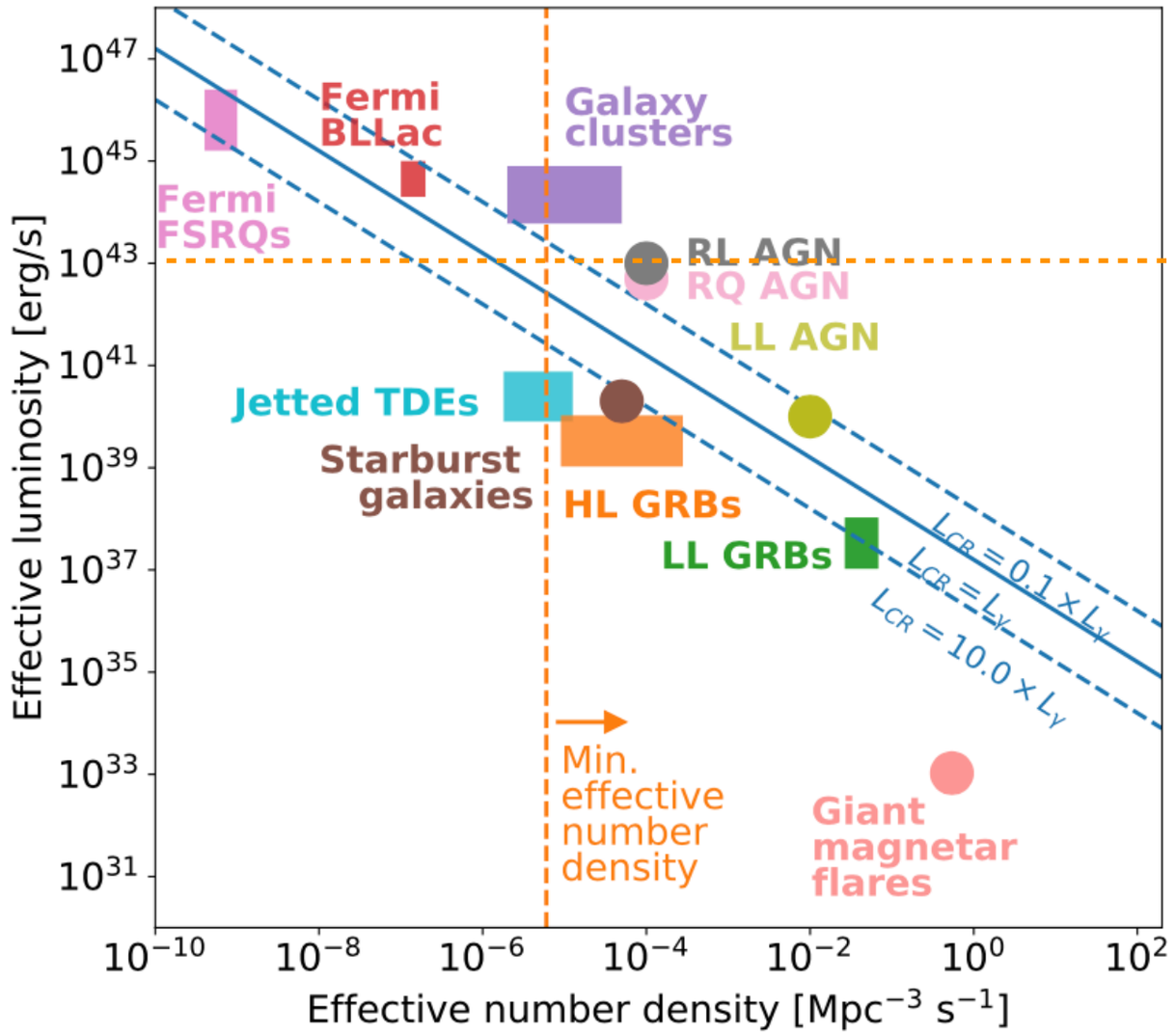




...and many others

Constraints on UHECR sources





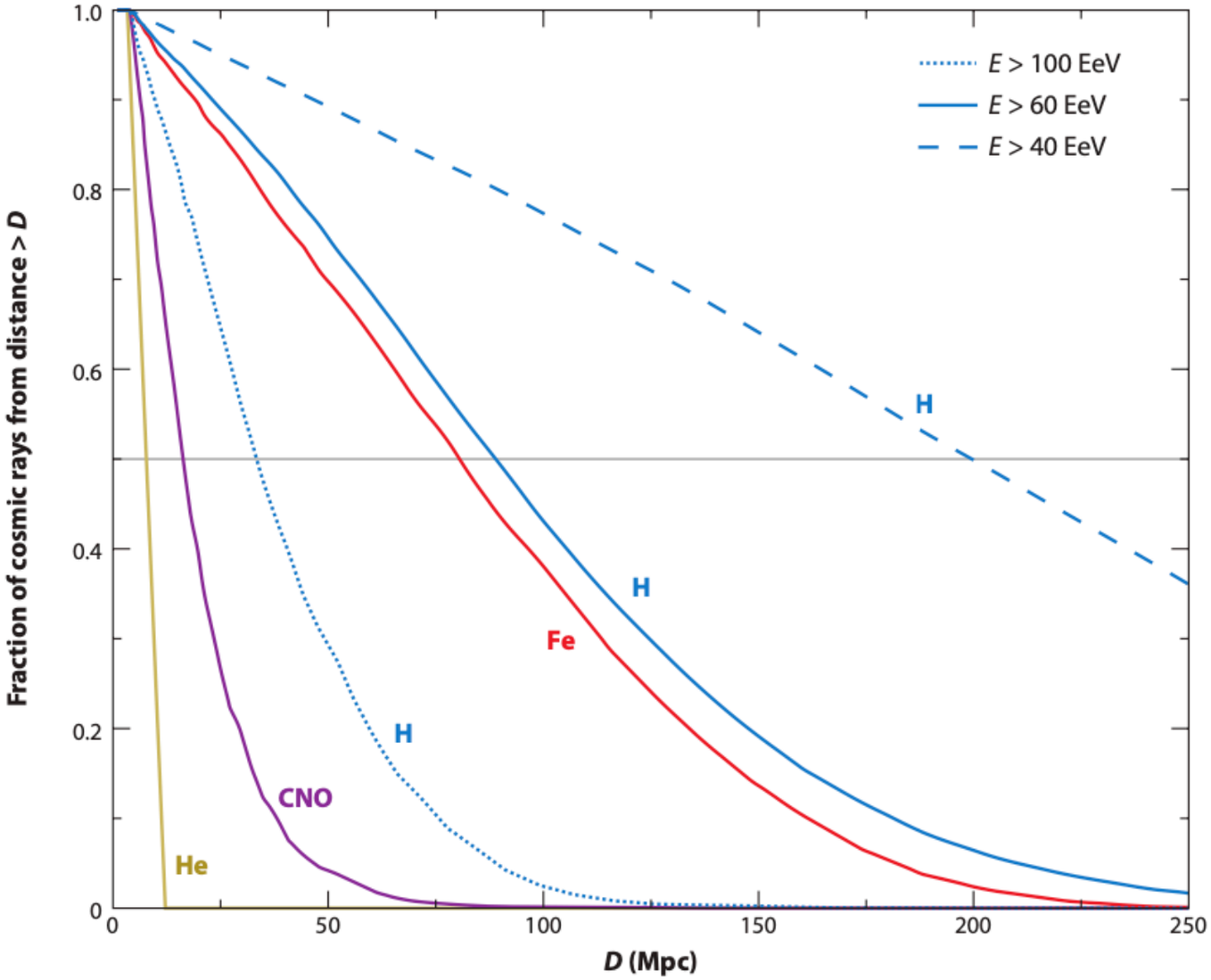
$$E_{\rm max} = \beta_{\rm sh} e B R \Gamma$$

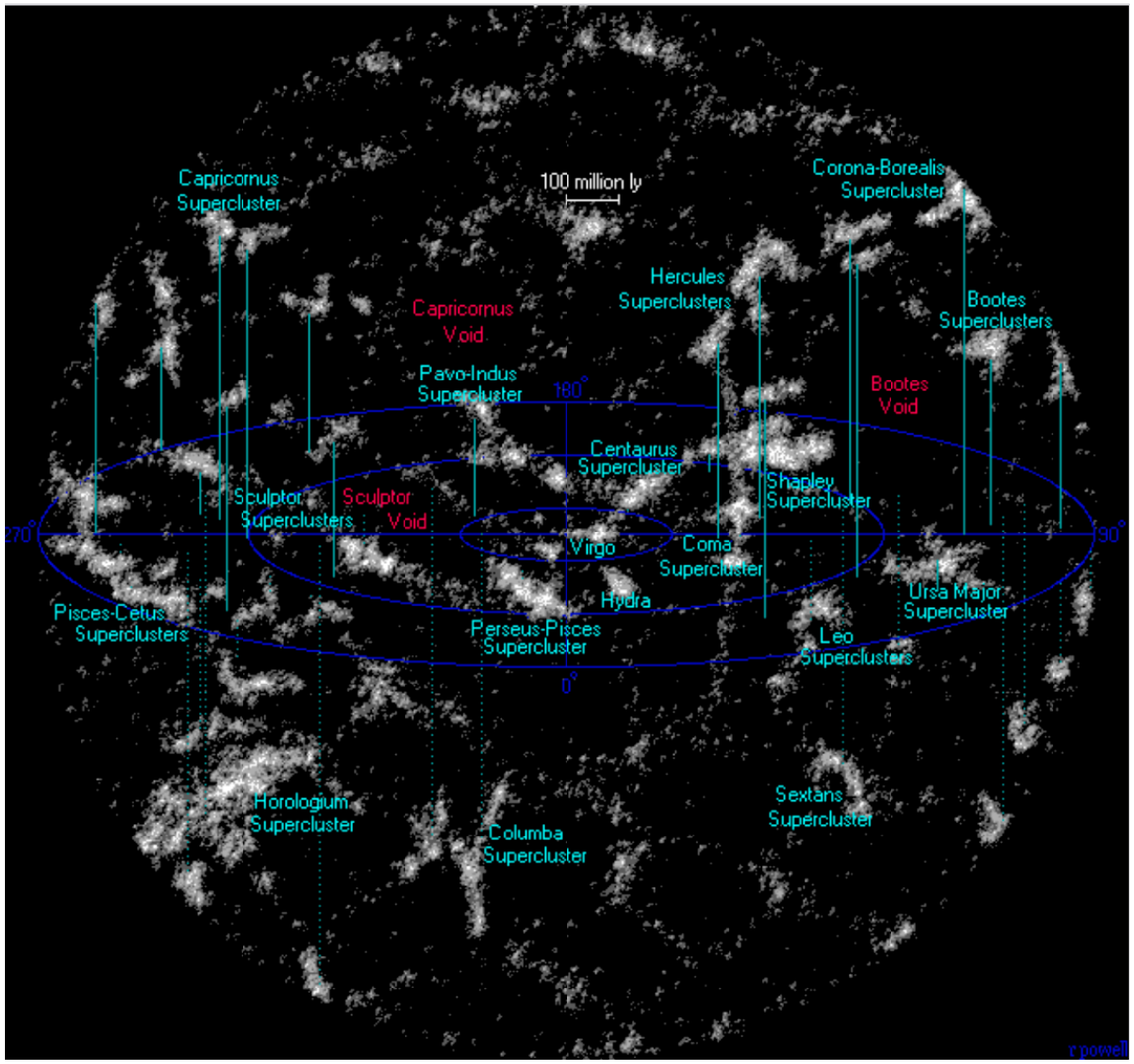
$$L_\gamma > 3 \times 10^{44}\ {\rm erg\ s^{-1}} \times \left(\frac{E/Z}{10^{18.5}\ {\rm eV}}\right)^2 \times \left(\frac{\Gamma^2/\beta}{100}\right)$$

$$Q \sim 10^{45}/erg/Mpc^3/yr$$

measured UHECR emissivity

The GZK cutoff



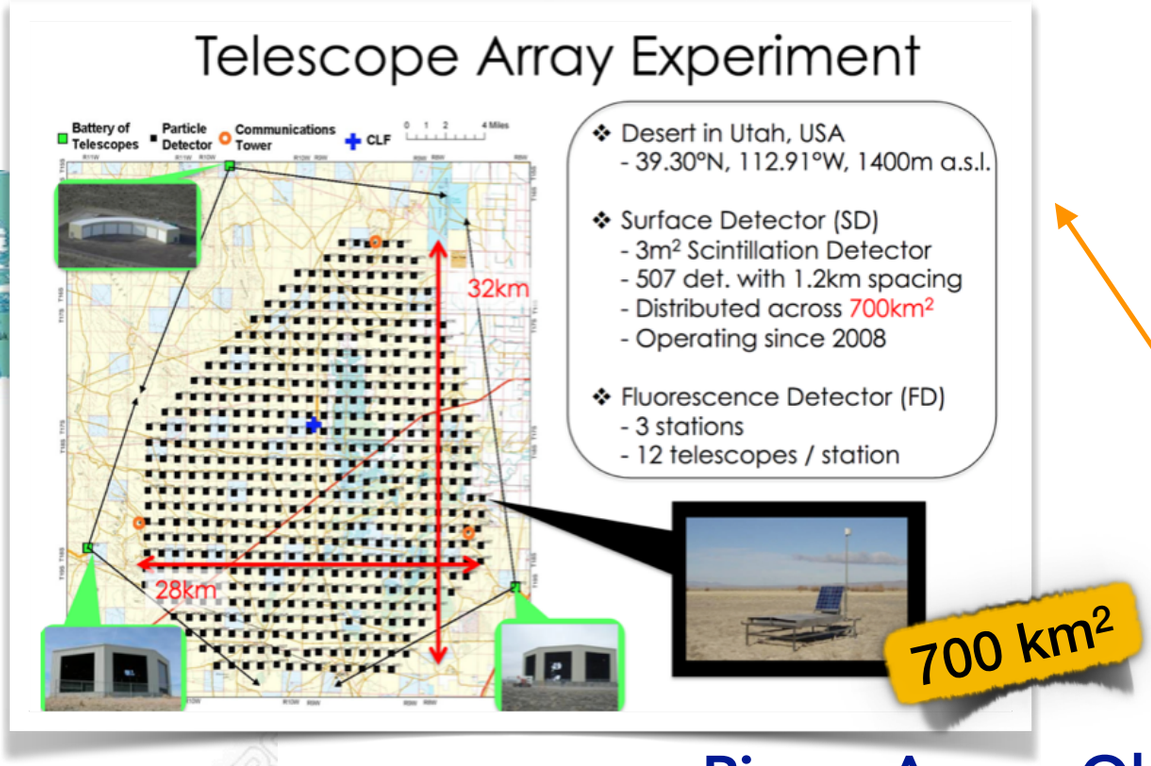


- the vast majority of events above ~60 EeV come from distances D< 200 Mpc (~652 Mly)

the contribution of distant sources is thus eliminated:
the higher the energy, the smaller the size of the collection region

UHECR detectors

Telescope Array Experiment

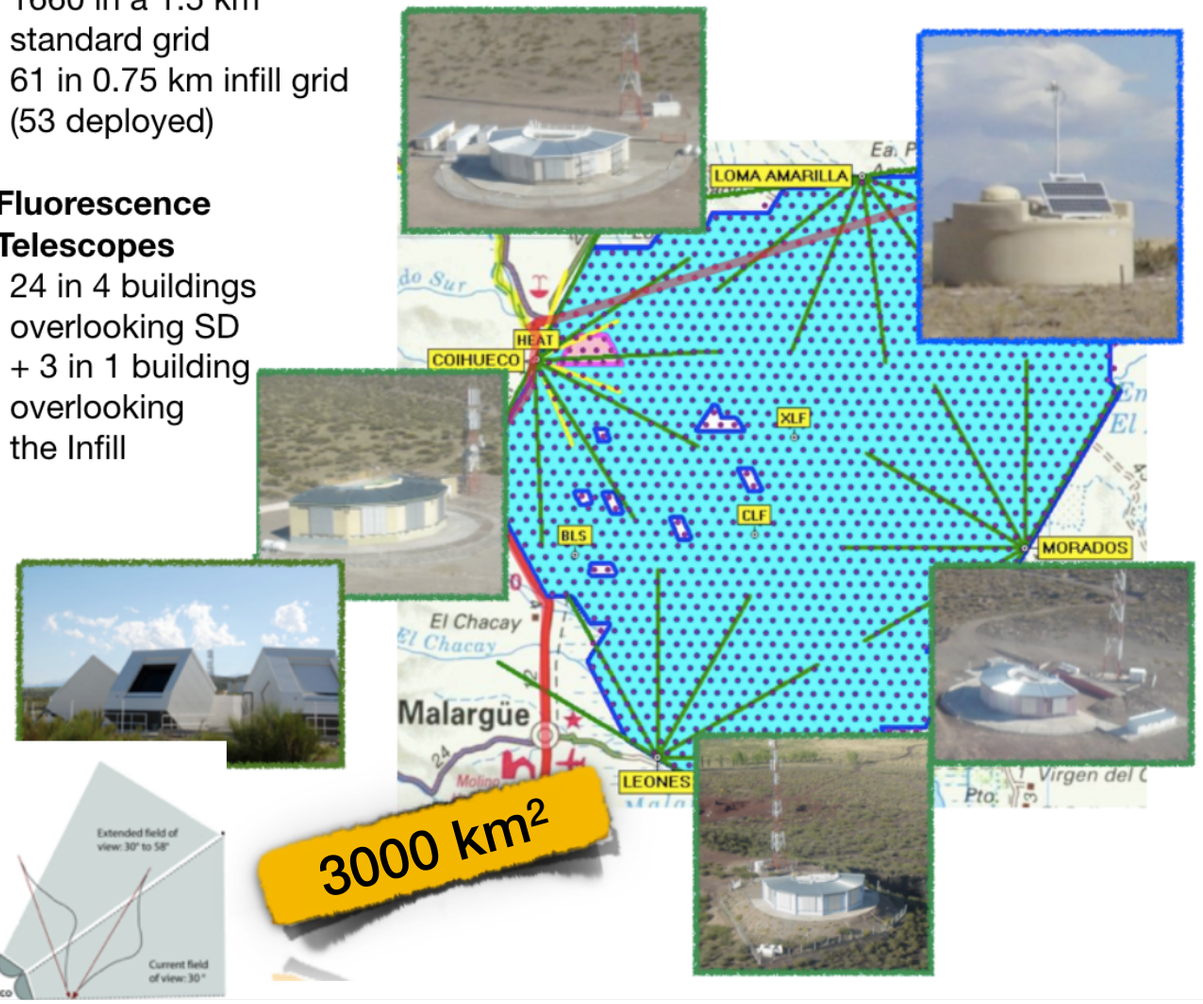


not in scale !

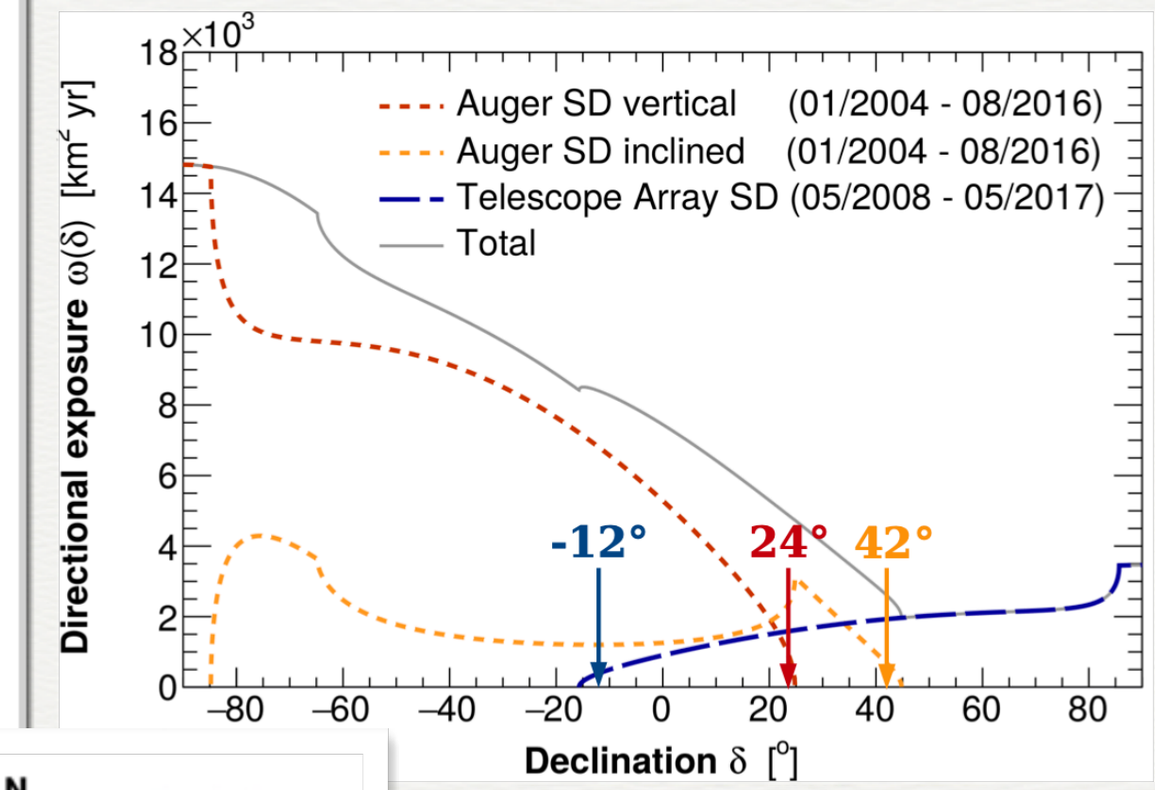
Pierre Auger Observatory

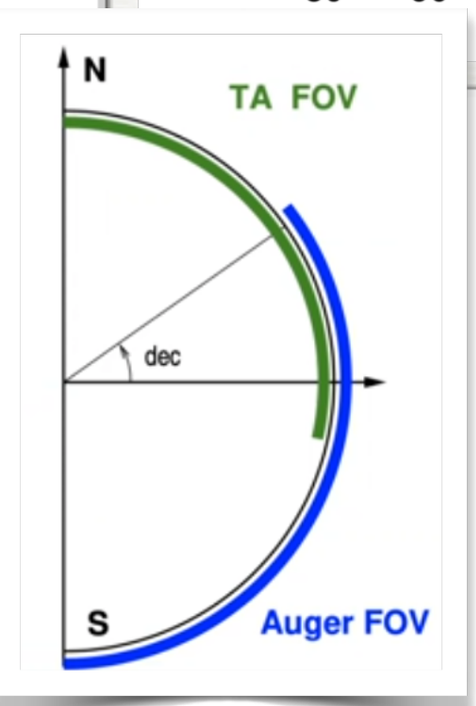
✓ **Water-Cherenkov tanks**
1660 in a 1.5 km standard grid
61 in 0.75 km infill grid
(53 deployed)

✓ **Fluorescence Telescopes**
24 in 4 buildings overlooking SD
+ 3 in 1 building overlooking the Infill

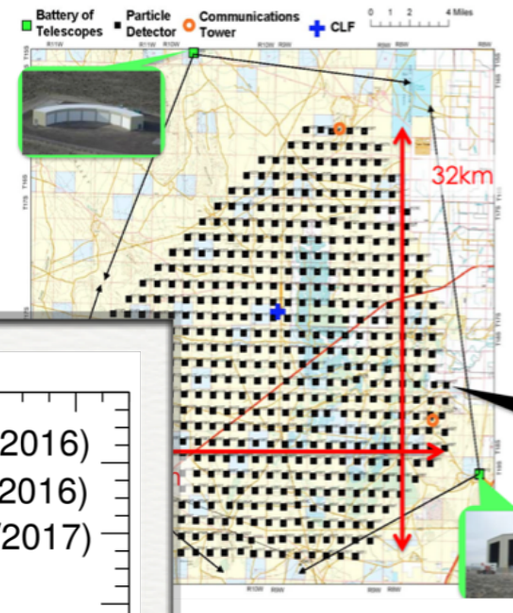


UHECR detectors





...and their exposure



- Desert in Utah, USA
  - 39.30°N, 112.91°W, 1400m a.s.l.
- Surface Detector (SD)
  - 3m² Scintillation Detector
  - 507 det. with 1.2km spacing
  - Distributed across 700km²
  - Operating since 2008
- Fluorescence Detector (FD)
  - 3 stations
  - 12 telescopes / station

700 km²

not in scale !

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Water-Cherenkov tanks
1660 in a 1.5 km standard grid
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Fluorescence Telescopes
24 in 4 buildings overlooking SD
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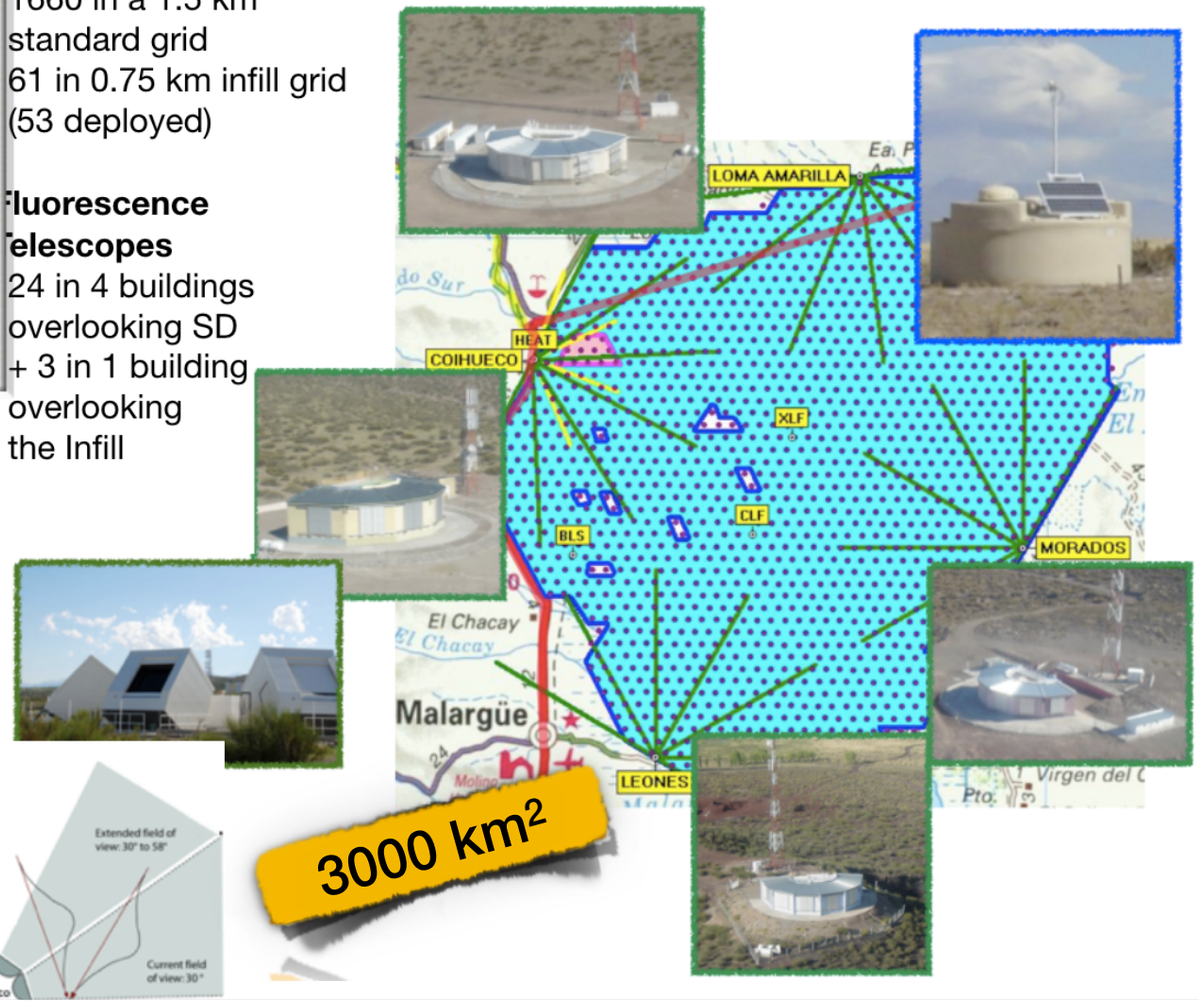
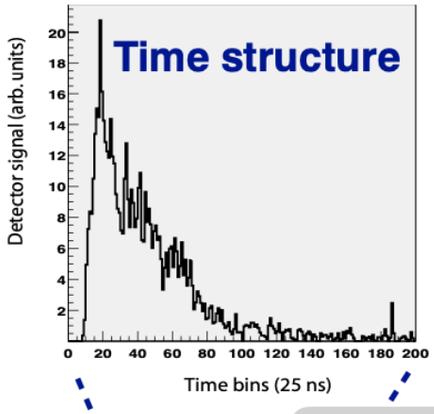
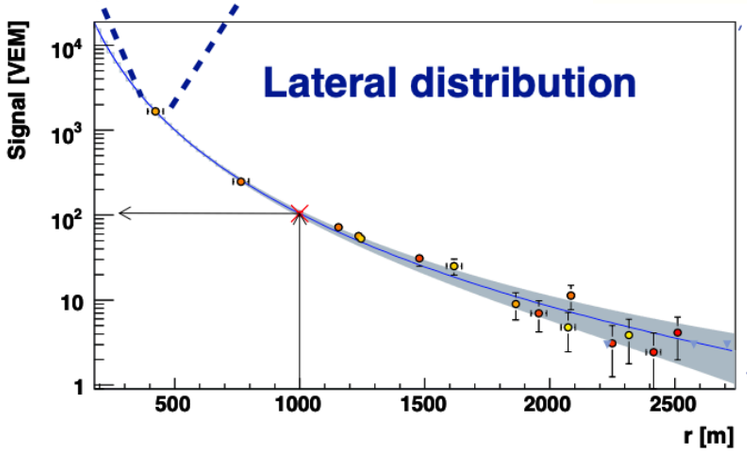


3000 km²

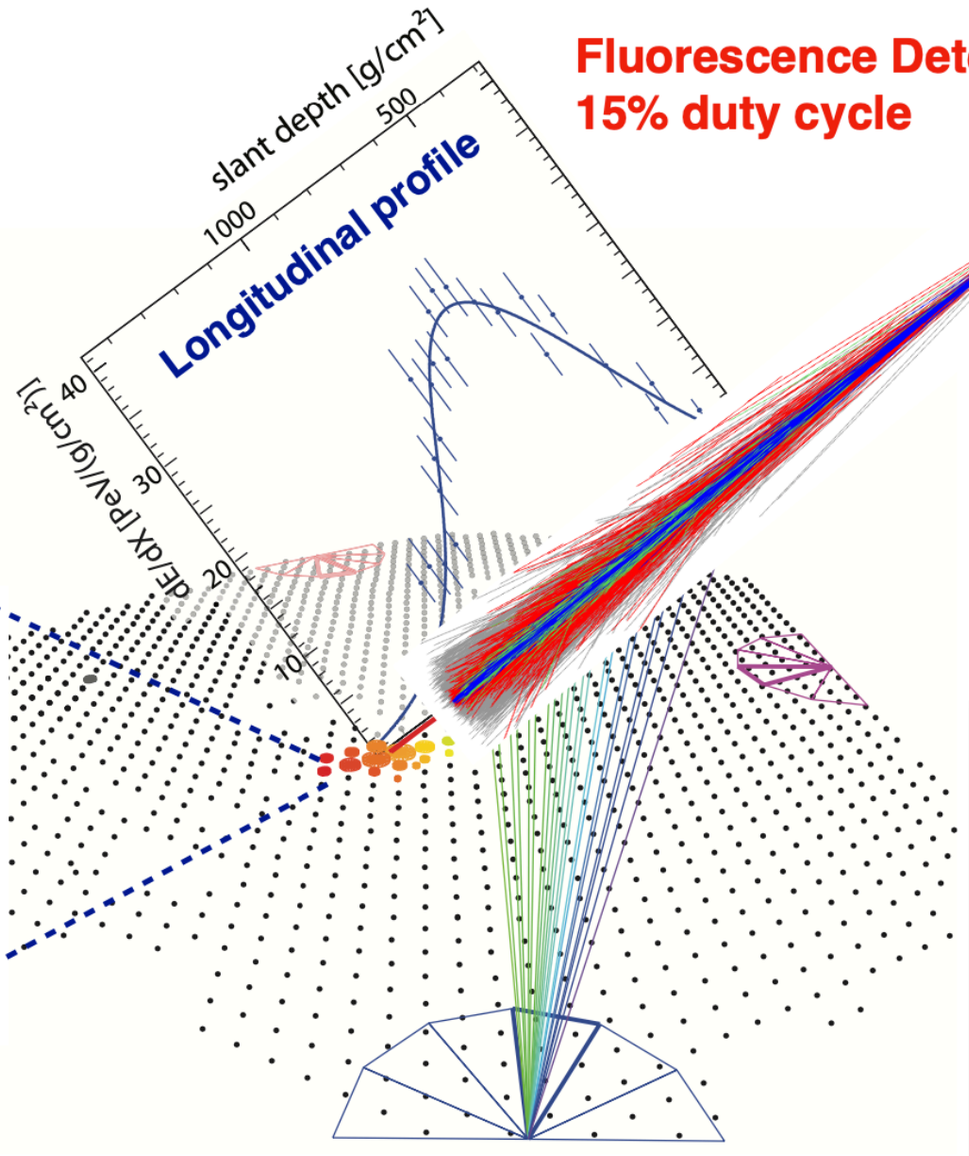
Detecting extensive air showers



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



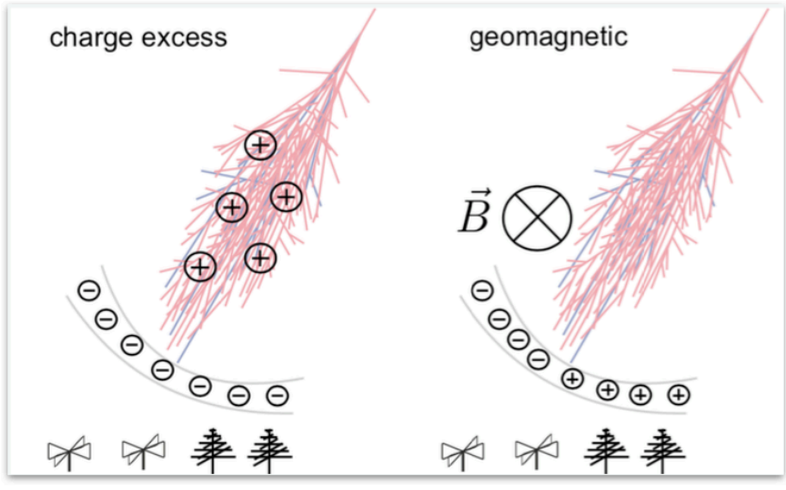
Surface Detector (SD)
100% duty cycle



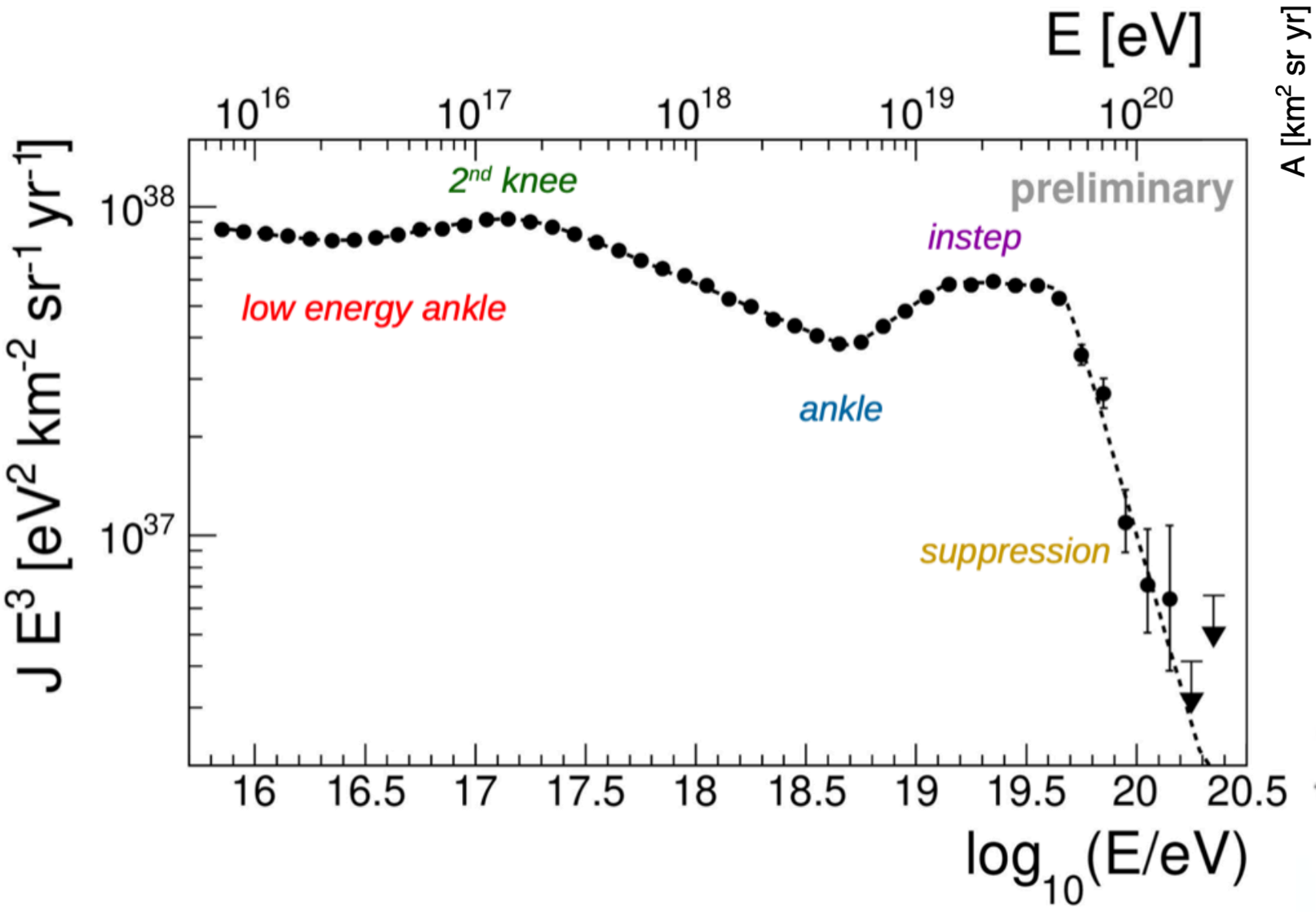
Fluorescence Detector (FD):
15% duty cycle

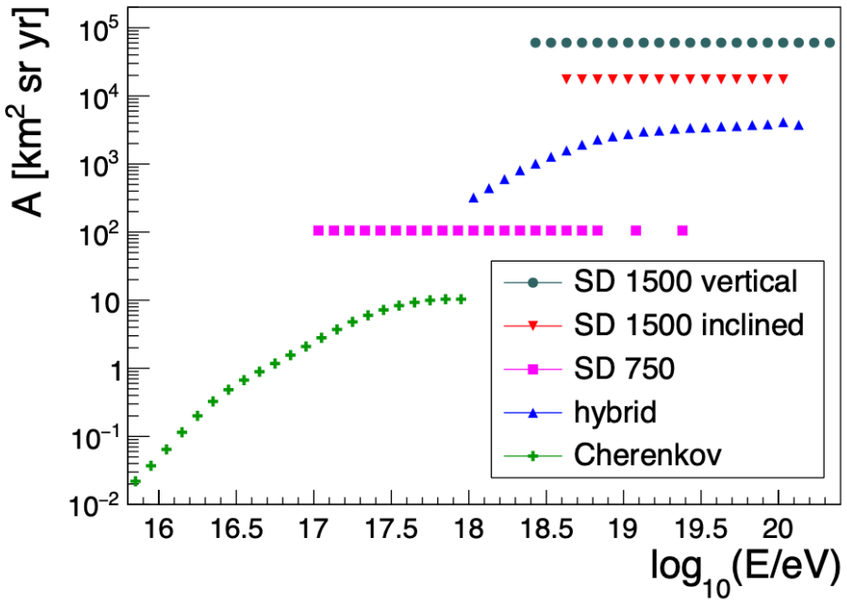
$$E_{\rm cal} = \int_0^\infty \left(\frac{{\rm d}E}{{\rm d}X}\right)_{\rm obs} {\rm d}X$$

Radio Detector (RD):
100% duty cycle

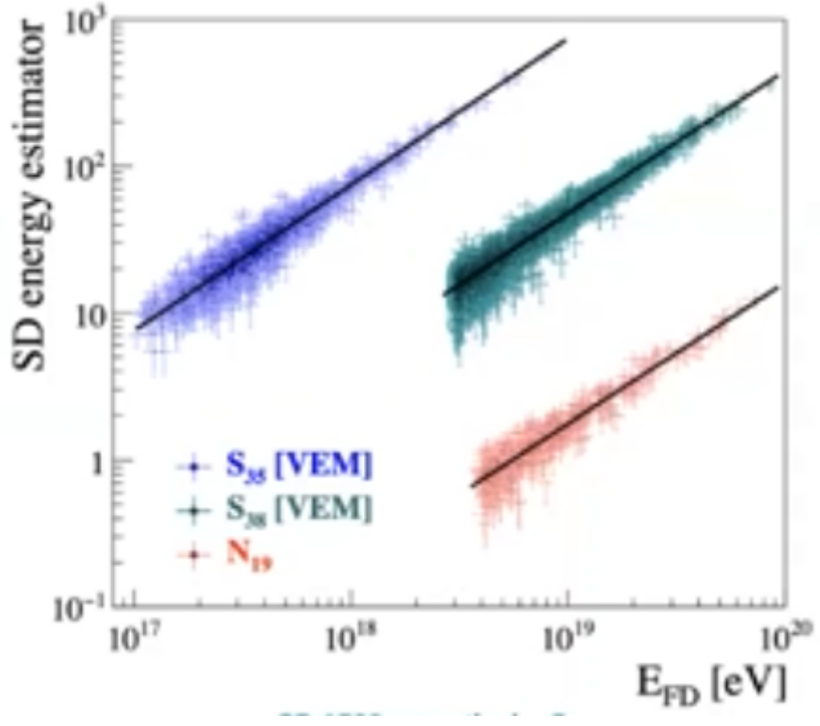


Energy spectrum

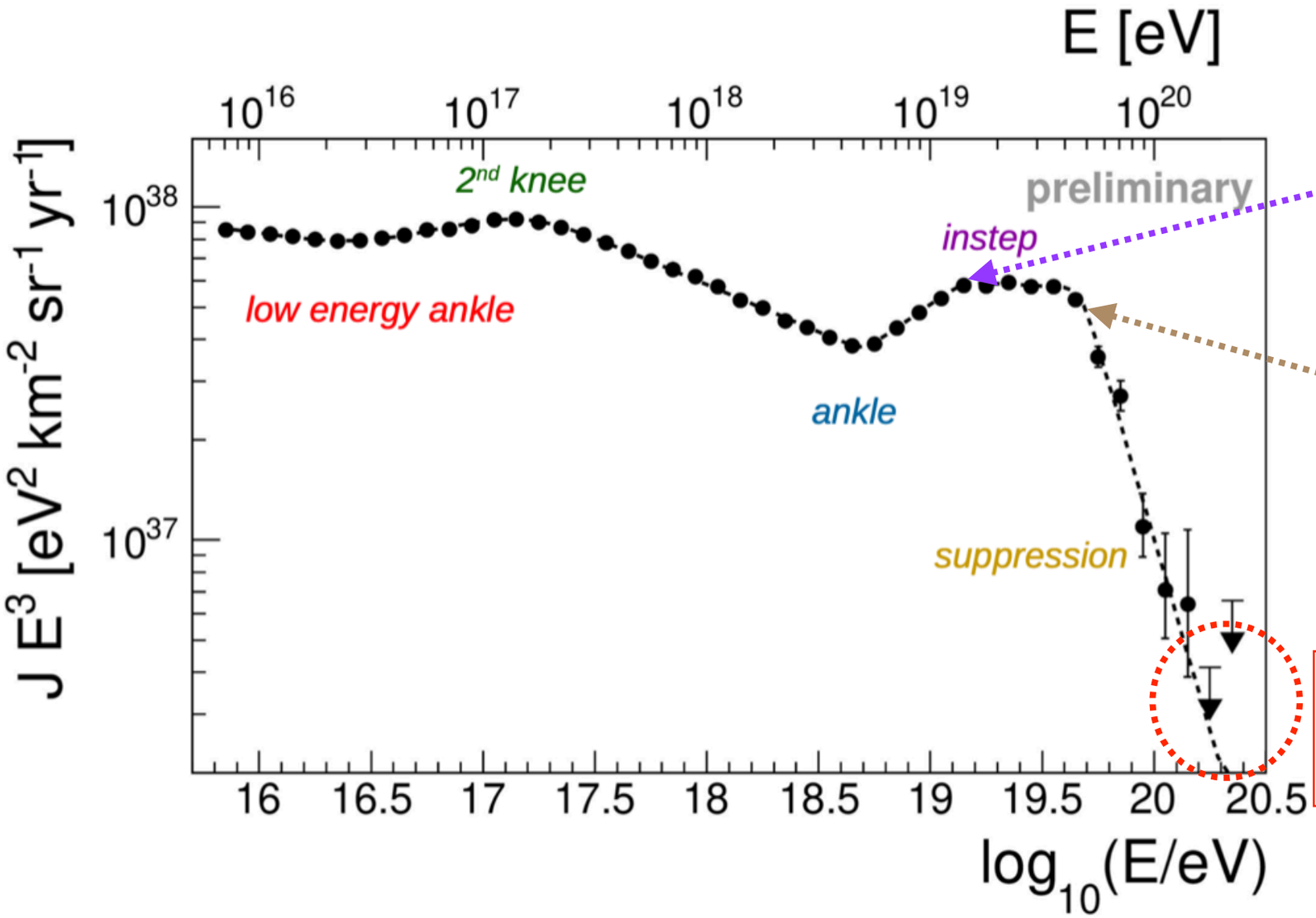




Phys.Rev.Lett. 125 (2020) 121106
Phys.Rev. D102 (2020) 062005
Subm. to Eur.Phys.J. C (2021)



Energy spectrum



New feature around
1.4 10^{19} eV

Suppression
4.7 10^{19} eV

Flux recovery?
…foreground source of protons

$$J(E) = J_0 \left(\frac{E}{10^{16}\ \mathrm{eV}}\right)^{-\gamma_0} \prod_{i=0}^{4} \left[1 + \left(\frac{E}{E_{ij}}\right)^{\frac{1}{\omega_{ij}}}\right]^{(\gamma_i - \gamma_j)\omega_{ij}}, j = i + 1$$

Phys.Rev.Lett. 125 (2020) 121106
Phys.Rev. D102 (2020) 062005
sub. to Eur.Phys.J. C (2021)

fit parameters (± stat. ± syst.)

$\gamma_0 = 3.09 \pm 0.01 \pm 0.10$

$E_{01} = (2.8 \pm 0.3 \pm 0.4) \times 10^{16}$ eV

$\gamma_1 = 2.85 \pm 0.01 \pm 0.05$

$E_{12} = (1.58 \pm 0.05 \pm 0.2) \times 10^{17}$ eV

$\gamma_2 = 3.283 \pm 0.002 \pm 0.10$

$E_{23} = (5.0 \pm 0.1 \pm 0.8) \times 10^{18}$ eV

$\gamma_3 = 2.54 \pm 0.03 \pm 0.05$

$E_{34} = (1.4 \pm 0.1 \pm 0.2) \times 10^{19}$ eV

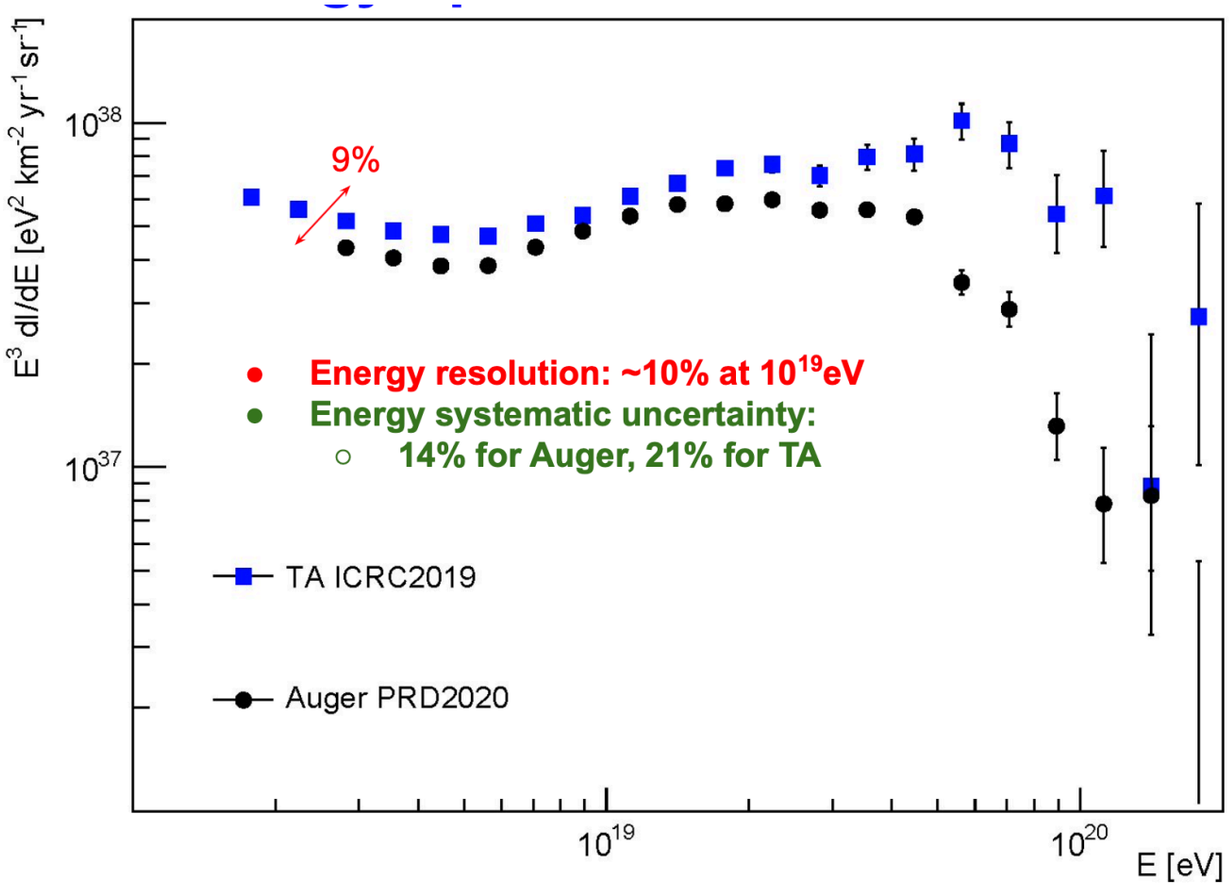
$\gamma_4 = 3.03 \pm 0.05 \pm 0.10$

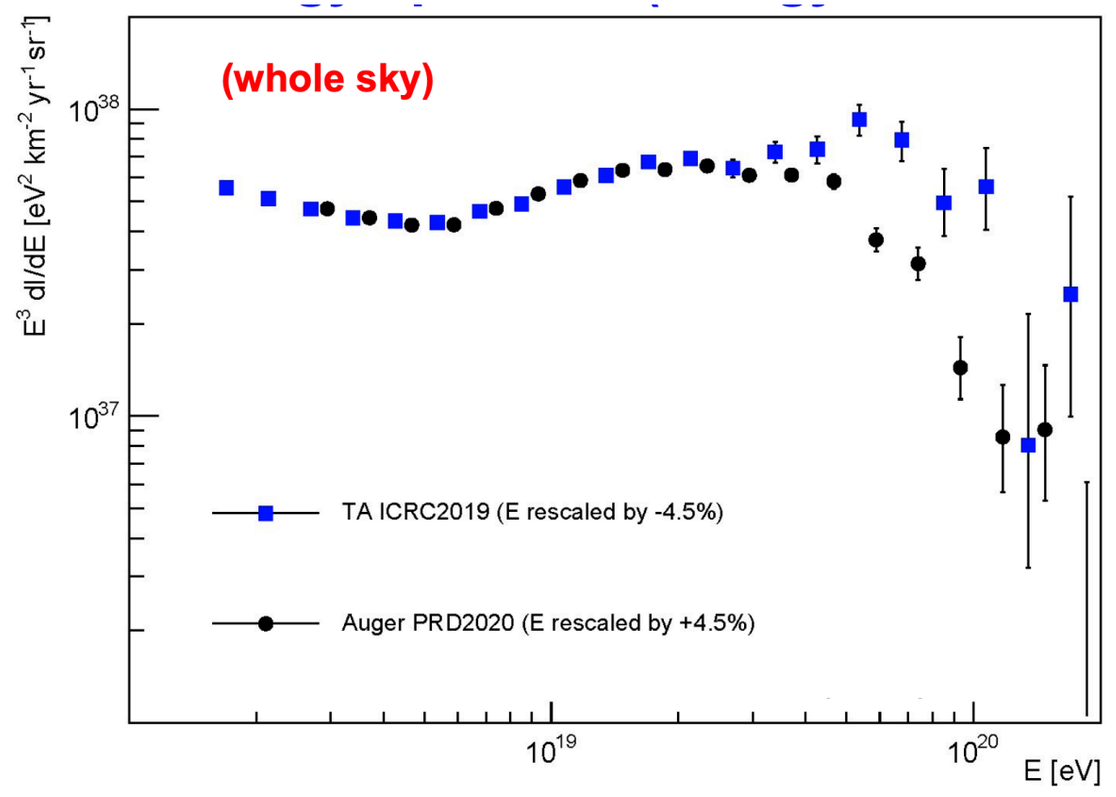
$E_{45} = (4.7 \pm 0.3 \pm 0.6) \times 10^{19}$ eV

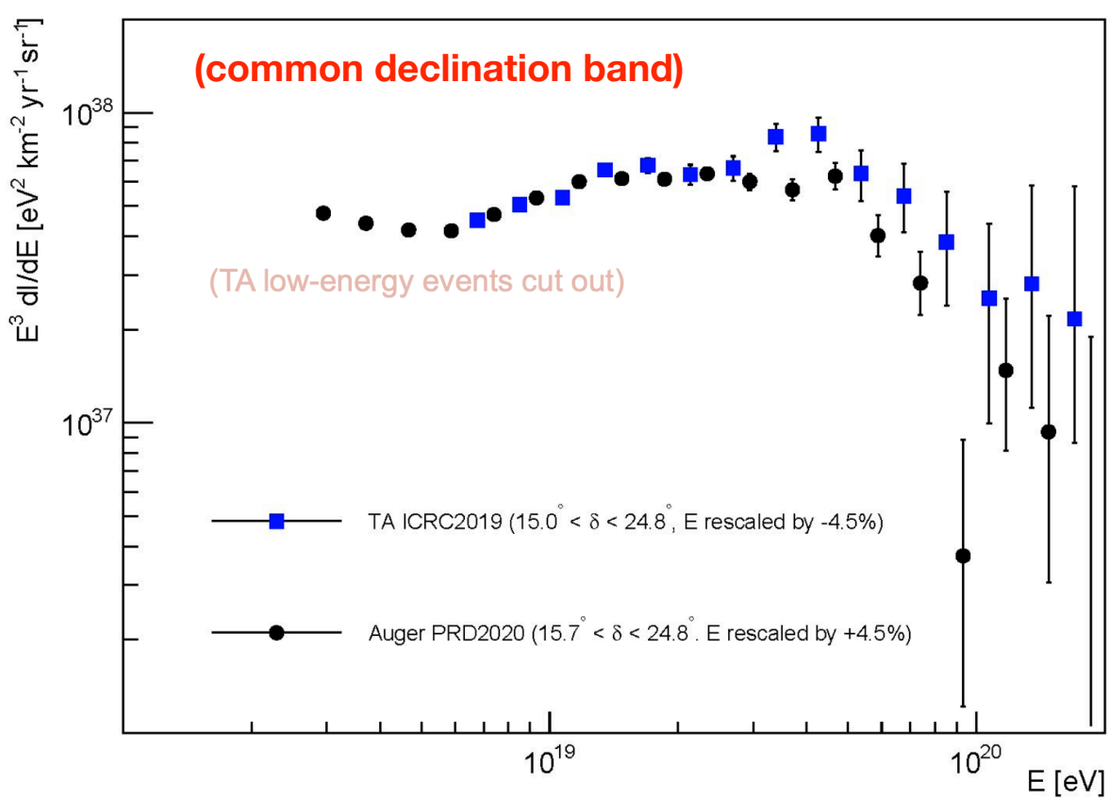
$\gamma_5 = 5.3 \pm 0.3 \pm 0.1$

$J_0 = (8.34 \pm 0.04 \pm 3.40) \times 10^{-11}$ km^{-2} sr^{-1} yr^{-1} eV^{-1}

Auger vs TA: overall agreement?



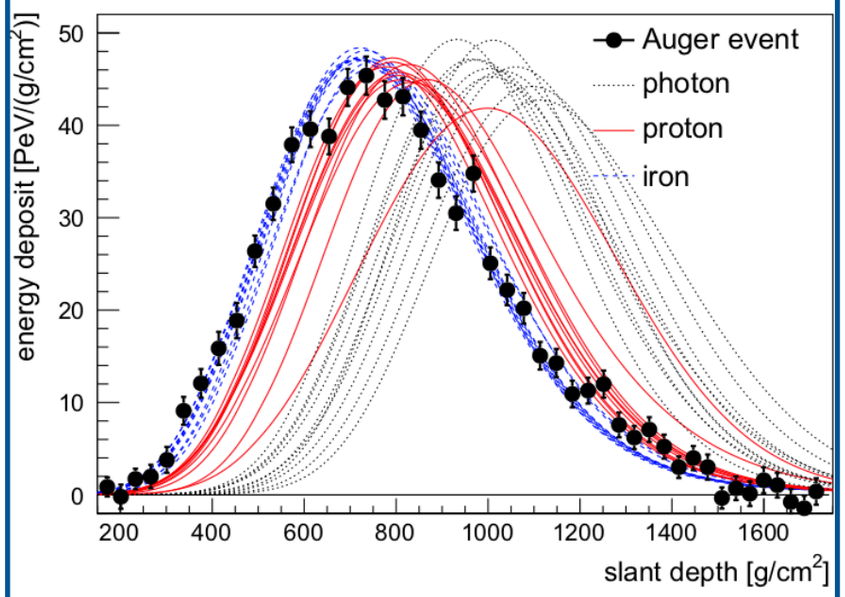




- good agreement in the common declination band ($-15^0<\delta<24.8^0$) within systematics
- declination dependence of the spectrum in the highest energy region:
  - not seen in Auger (except for dipole)
  - seen in TA at ~4.3σ level, not explained by any systematic effects. Astrophysical effect?

*Y.Tsunesada (**PAO+TA working group**), ICRC 2021*

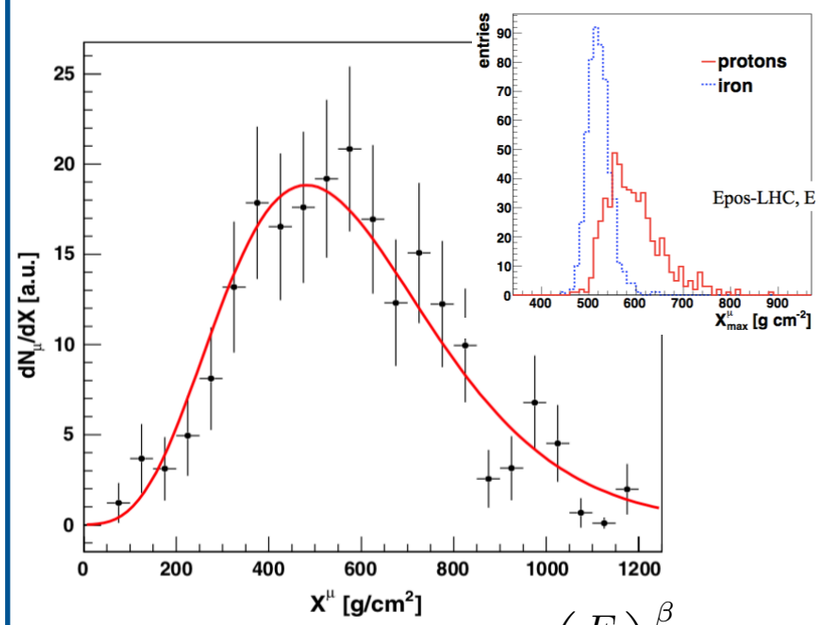
Mass composition



$$\langle X_{max} \rangle = \langle X^p_{max} \rangle + f_E \langle lnA \rangle$$

$$\sigma^2(X_{max}) = \langle \sigma^2_{sh} \rangle + f_E \sigma^2_{lnA}$$

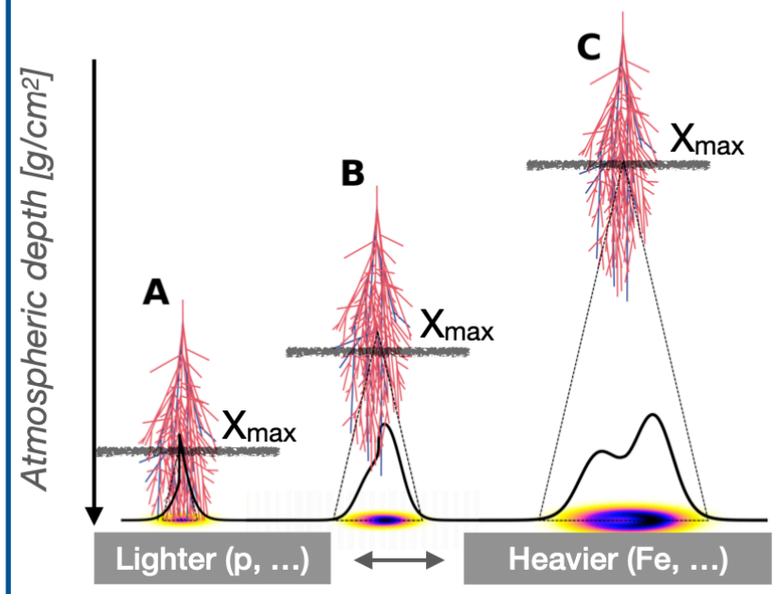
FD



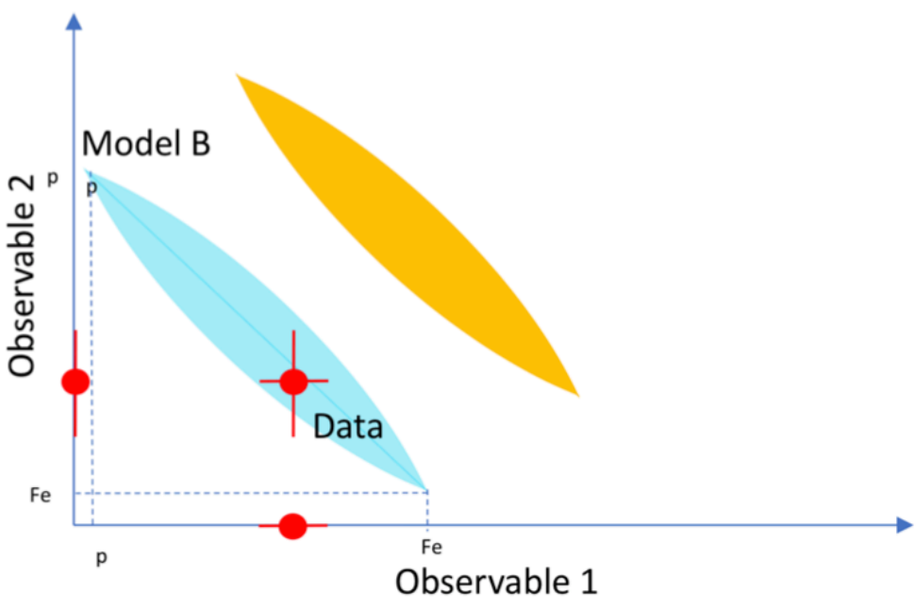
$$N^p_\mu \sim \left(\frac{E}{\epsilon^\pi_d} \right)^\beta$$

$$N^A_\mu \sim A \left(\frac{E/A}{\epsilon^\pi_d} \right)^\beta = N^p_\mu \, A^{1-\beta}$$

SD



RD

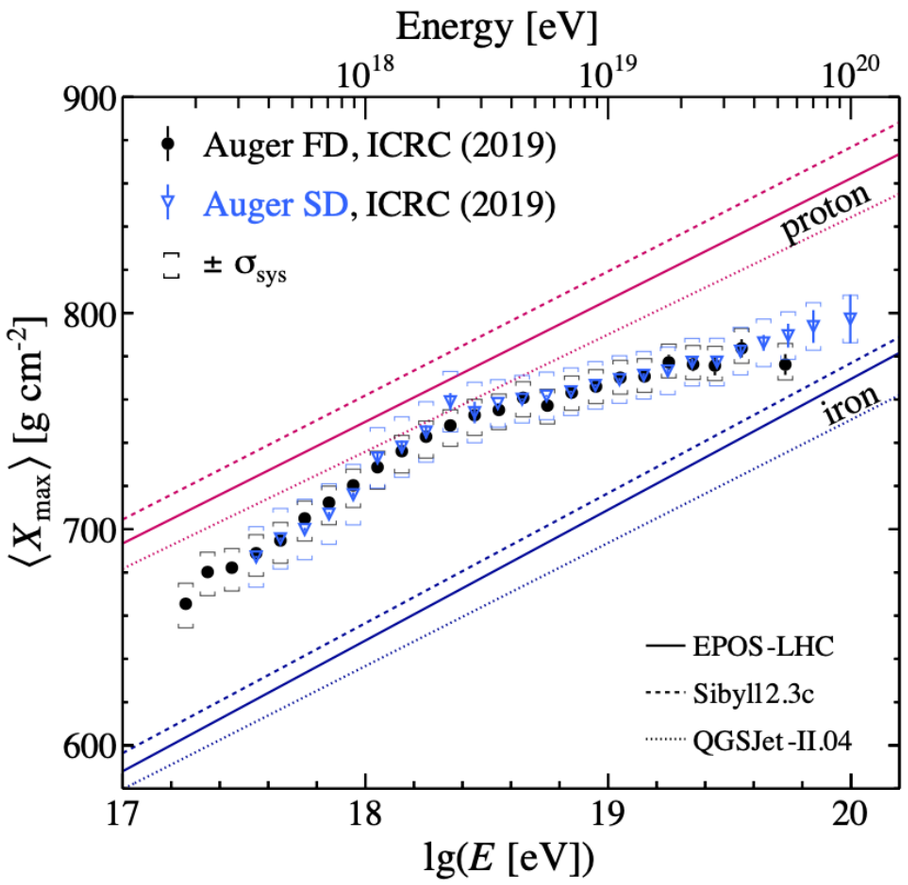


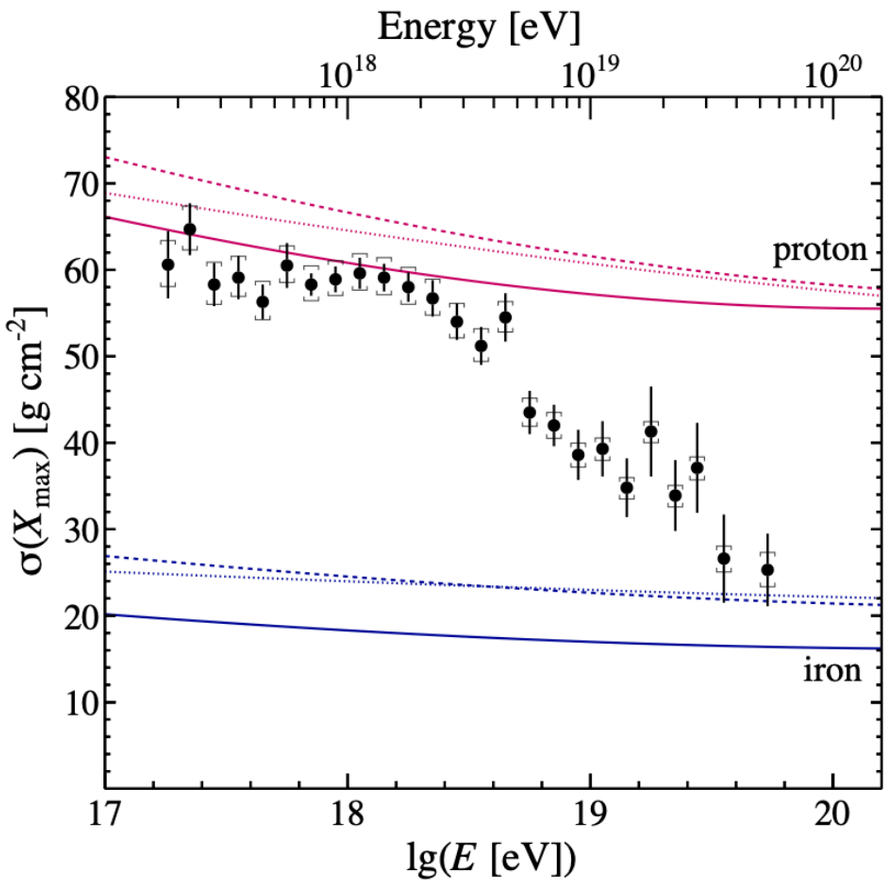
Air shower+hadronic interaction models are required to convert N_μ and X_{max} to A

model uncertainty = maximum contribution to systematics

- lack of data on multiparticle production in very forward phase space in hadron-nucleus interactions at UHE
- increasing with energy (far from the tested region)

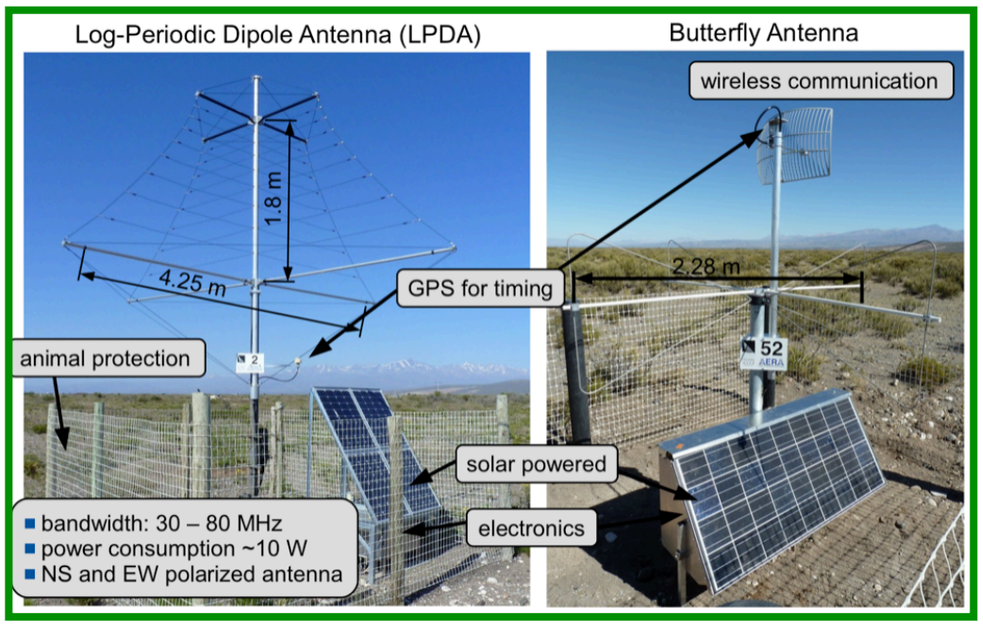
Mass composition

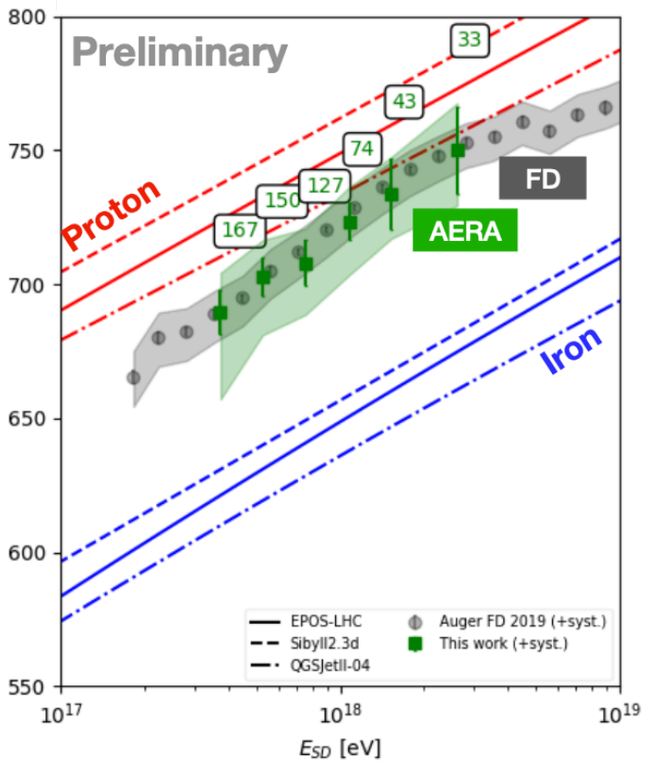


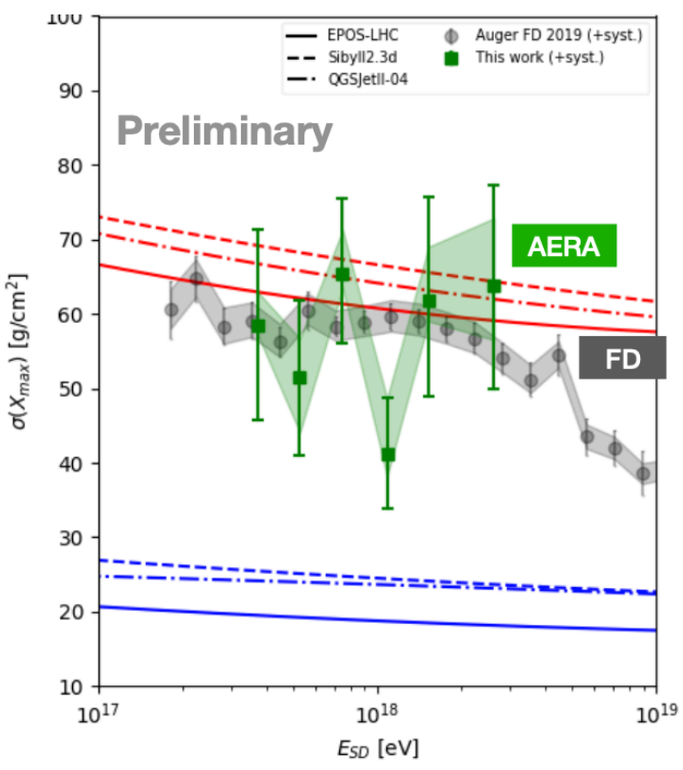


Phys.Rev. D90 (2014) 122005
Phys.Rev. D96 (2017) 122003

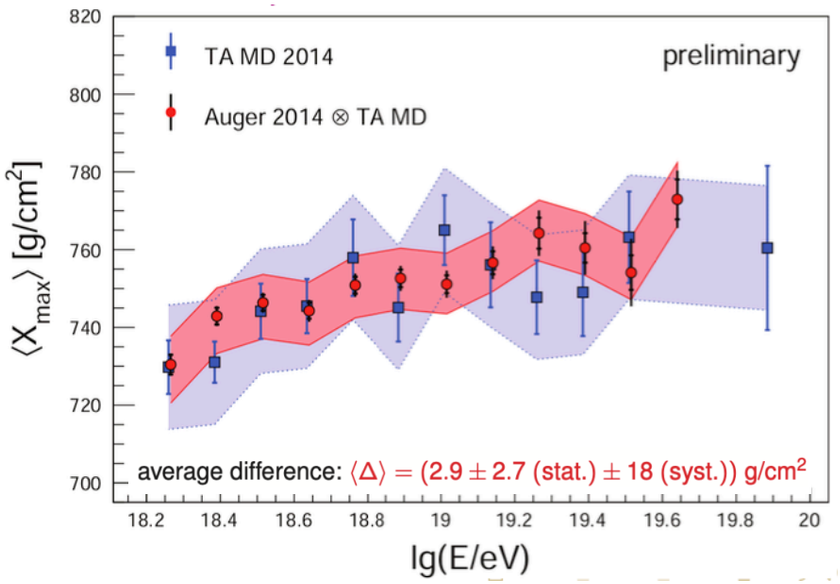
+ ICRC2021

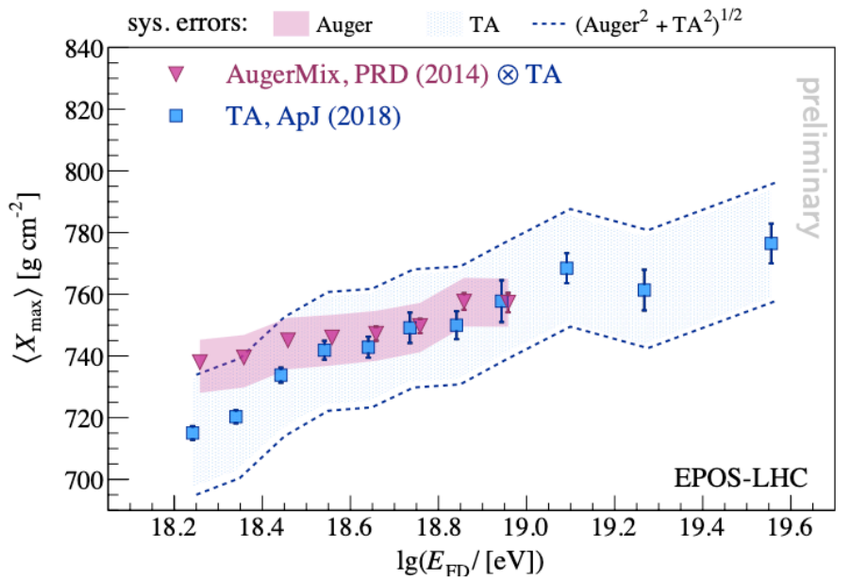


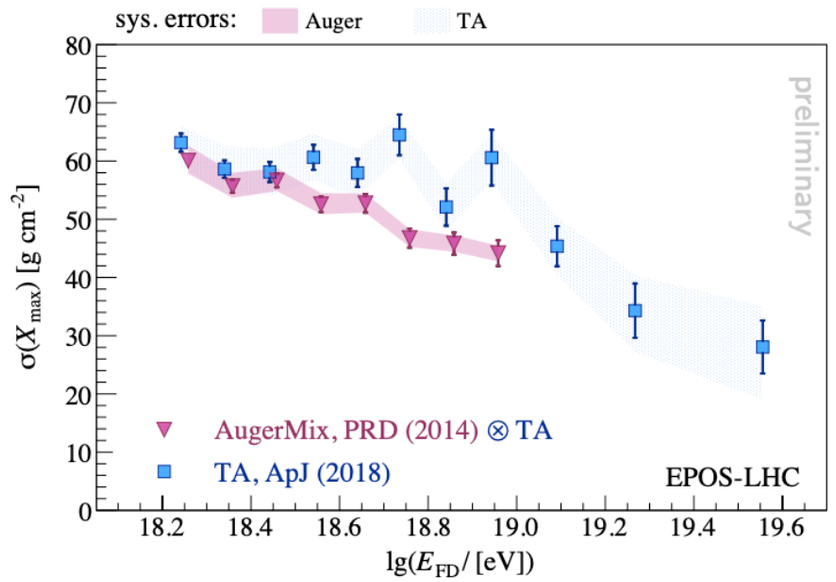




Auger vs TA: overall agreement?



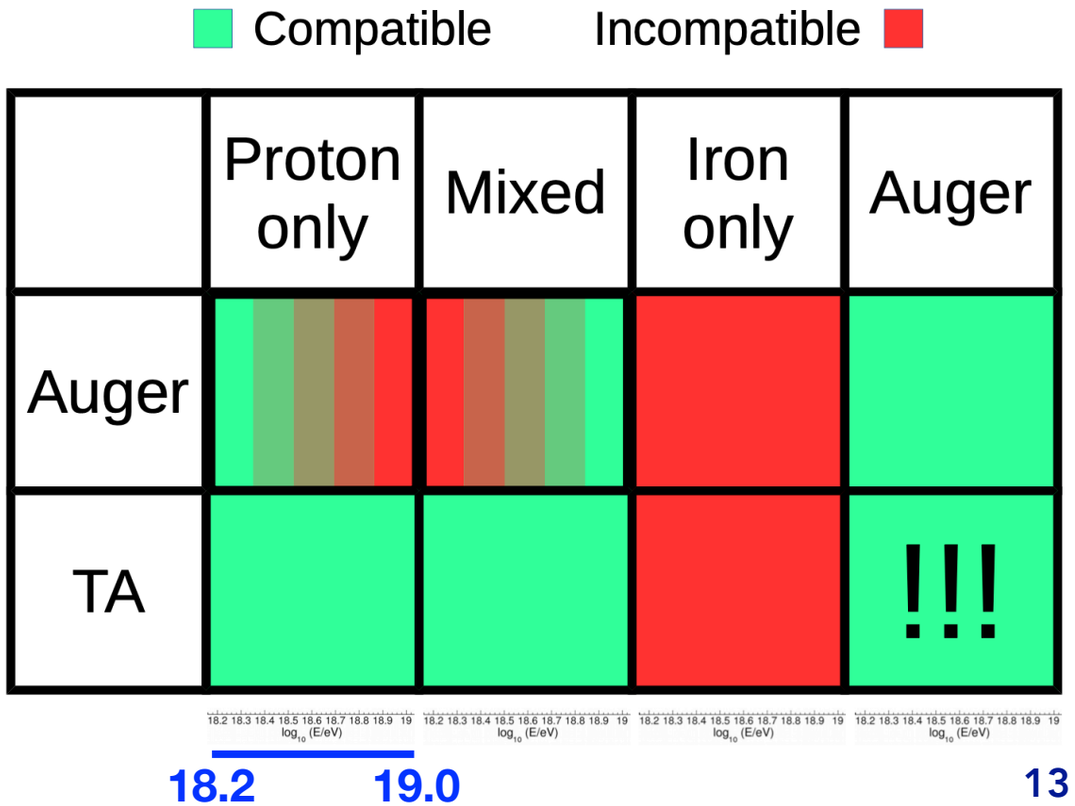




*R.Abbasi et al. (**PAO+TA working group**), JPS Cons.Proc. 9 (2016) 010016*
*A.Yushkov et al. (**PAO+TA working group**), EPJ Web of Cons. 210 (2019) 010009*

Non trivial comparison !   

- TA and Auger measurements of X_{max} **agree within systematics up to 10^{19} eV: the TA distributions in this range are as compatible to pure protons as they are to AugerMix**
- no comparison has been performed above 10 EeV up to now by TA choice
- WG active again: stay tuned !



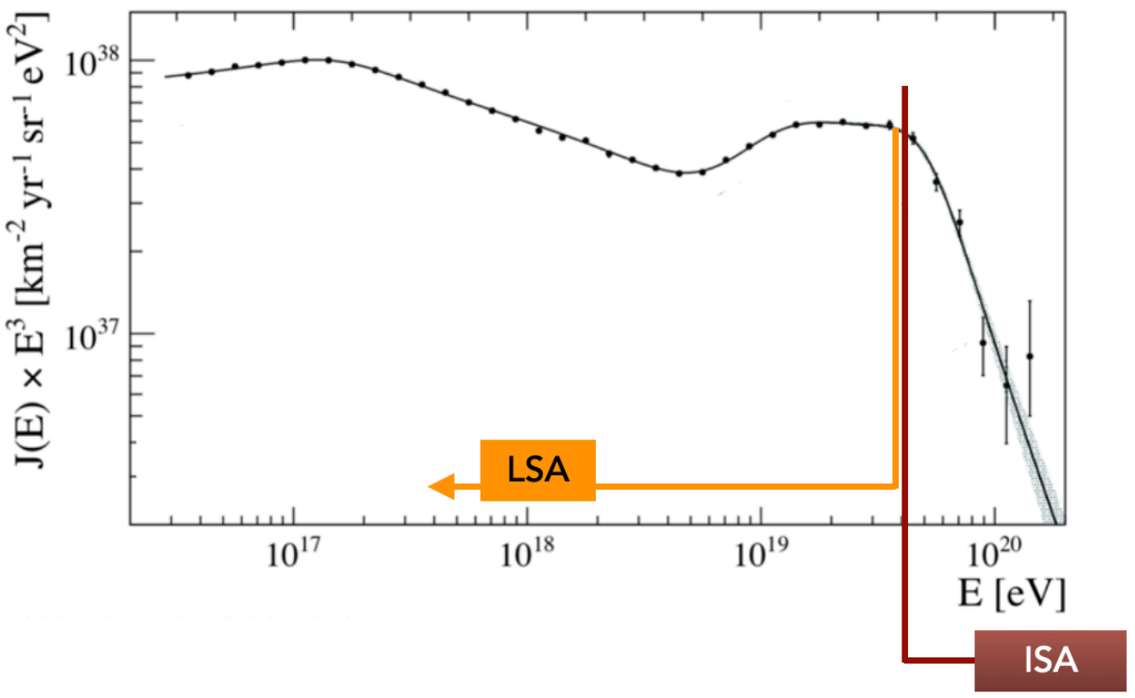
The UHECR Sky

γ, ν messengers for which directional astronomy is possible

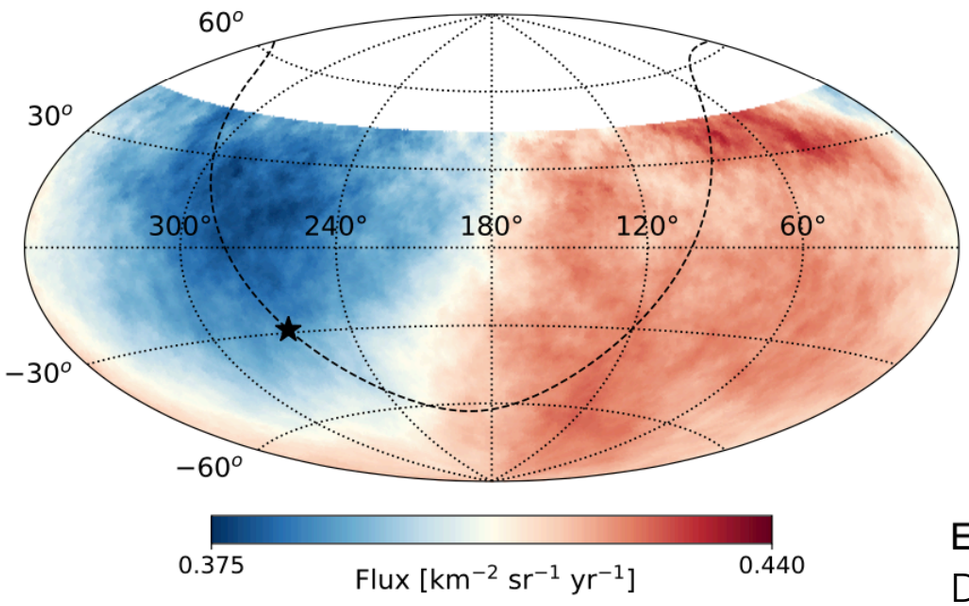
charged CRs arrival directions and energy are measurable
further complications : magnetic fields deflections, mass composition

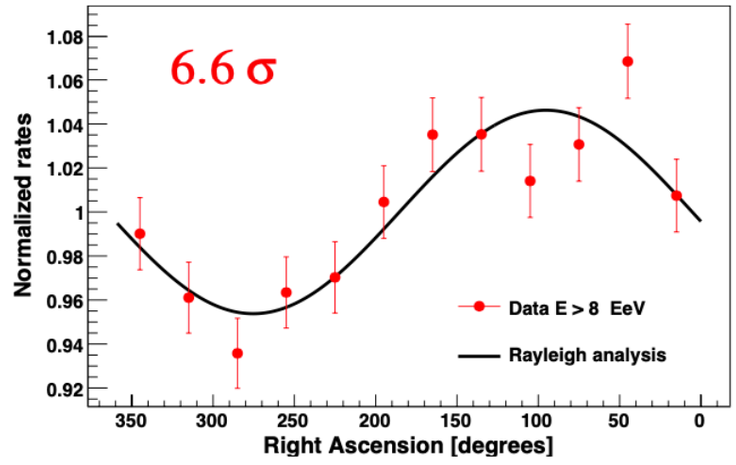
Large Scale Anisotropies
- Galactic : diffusion and escape of GCRs
- Transition from Galactic to Extra-Galactic
- extra-Galactic: small dipole due to our motion

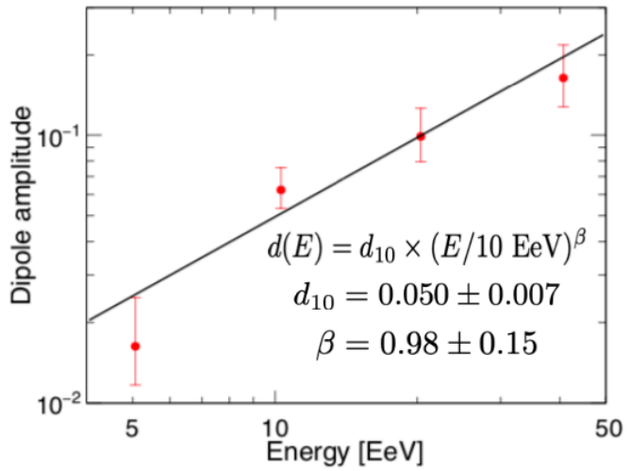
Intermediate/Small scale anisotropies
- high rigidity, nearby sources
- clustering of events from the same source
- correlation with a population of sources



Large Scale Anisotropy







Exposure until end of 2020 (θ < 80°): 110.000 km² sr yr

Dipolar distribution consistent with nearby galaxy stellar mass distribution (2MRS)

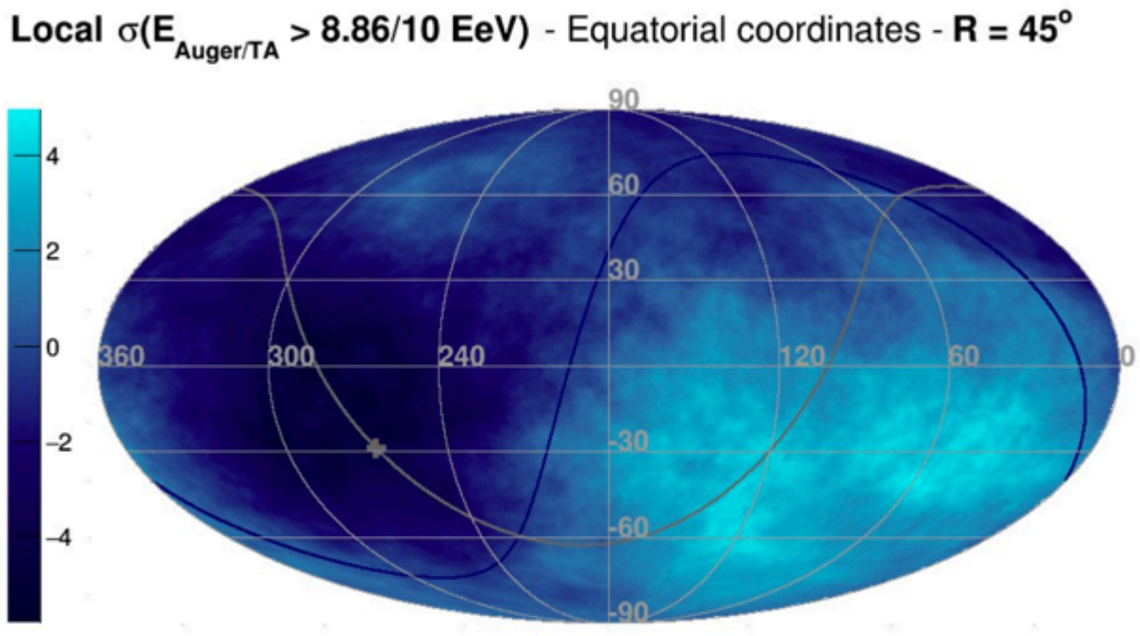
D.Harari et al., PRD92 (2015) 06314;
Ding et al., arXiv2101.04564

AUGER
Science 357 (2017) 1266; Astrophys. J. 891 (2020) 142;
R. De Almeida, PoS(ICRC2021) 335

AUGER&TA : FULL SKY SEARCH

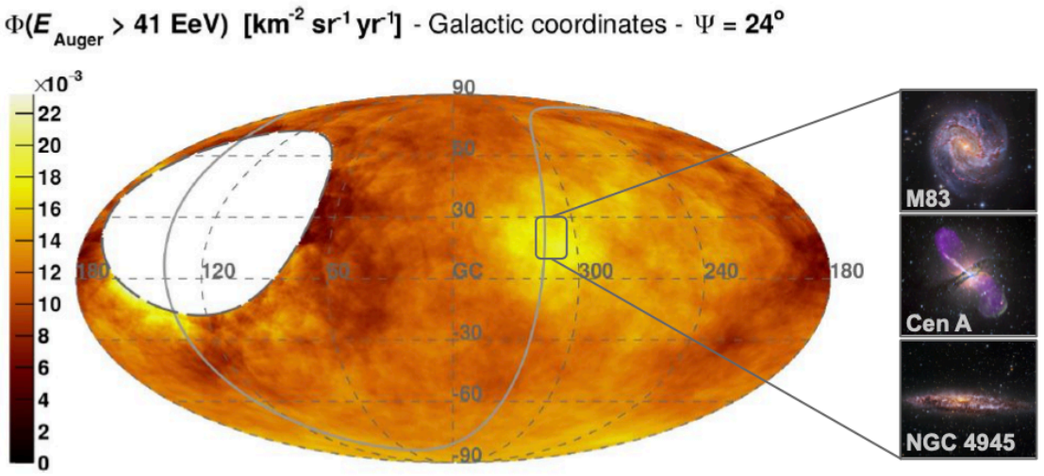
- no need to make assumptions on higher moments
- results compatible with Auger-only, but smaller uncertainties (can be reduced with more exposure in Northern hemisphere in the future)
- only significant moment is the dipole

*P.Tinyakov et al. (**PAO+TA working group**), PoS(ICRC2021) 375*



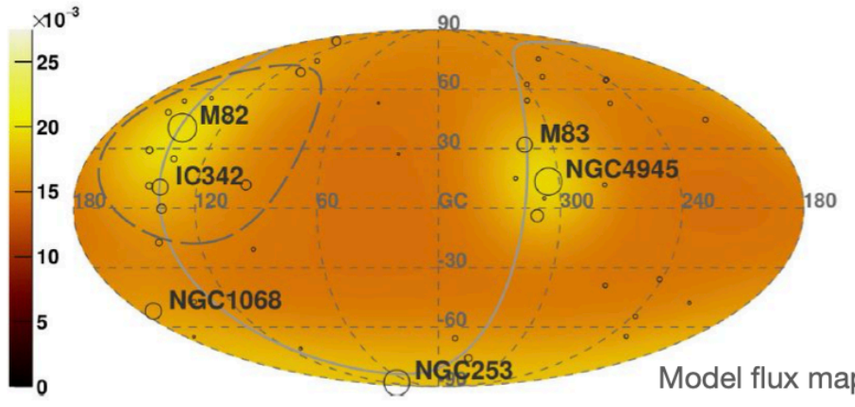
Significance: $\sigma \propto \sqrt{\varphi\omega}$

The UHECR Sky



Direction fixed to that of Cen A, free E_{th} and Ψ

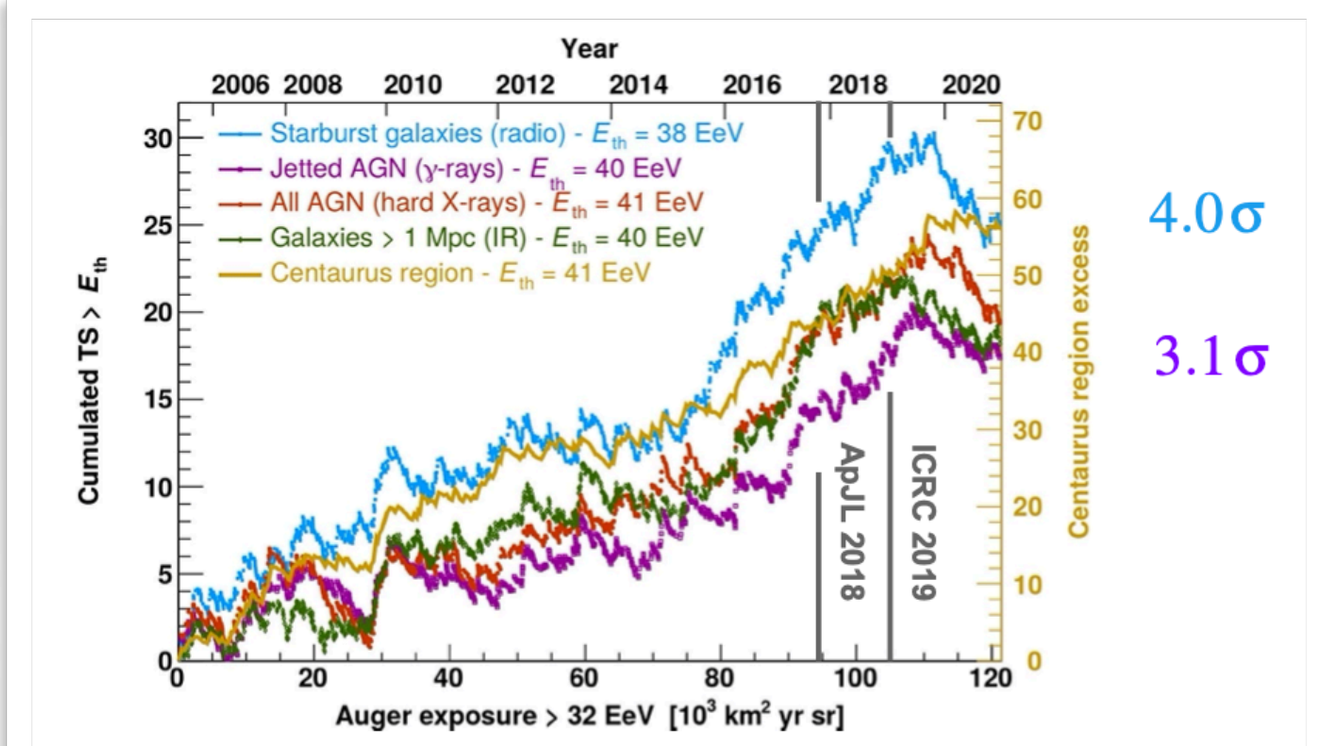
E_{th} > 41 EeV, Ψ = 27°: **3.9σ post-trial** deviation from isotropy (5% excess)



(Jonathan F

Model flux map

Catalog	E_{th} [EeV]	Ψ [deg]	α [%]	TS	Post-trial p-value
All galaxies (IR)	40	24^{+16}_{-8}	15^{+10}_{-6}	18.2	6.7×10^{-4}
Starbursts (radio)	38	25^{+11}_{-7}	9^{+6}_{-4}	24.8	3.1×10^{-5}
All AGNs (X-rays)	41	27^{+14}_{-9}	8^{+5}_{-4}	19.3	4.0×10^{-4}
Jetted AGNs (γ-rays)	40	23^{+9}_{-8}	6^{+4}_{-3}	17.3	1.0×10^{-3}



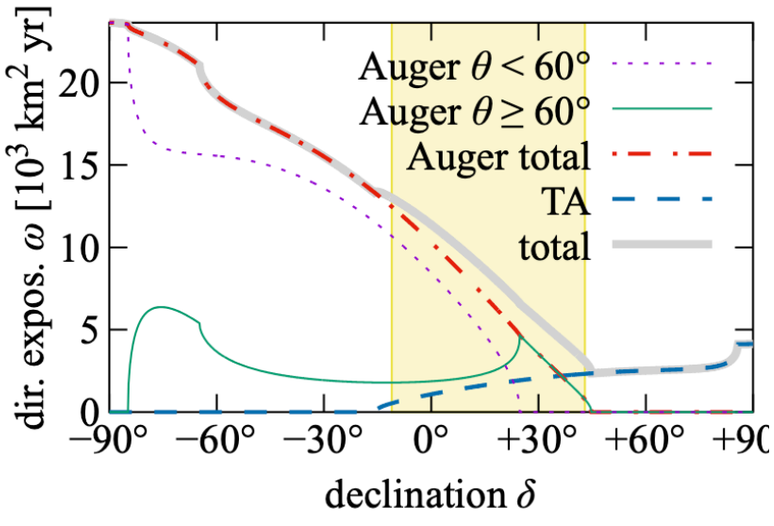
All catalogs: most significant signal at E>38-41 EeV on top-hat scale 23-27⁰ with signal fraction 6-15%

Significance compatible with linear growth within expected variance

Observation (discovery) level (≳5**σ**) expected within few years

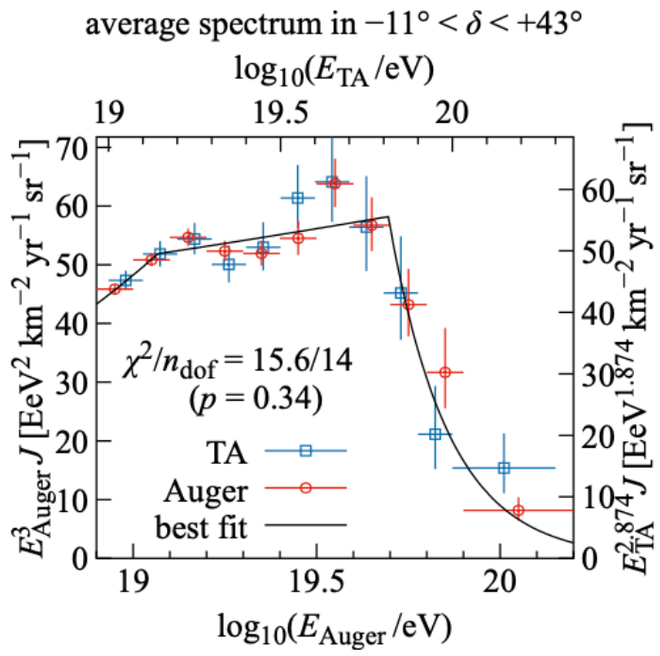
*J.Biteau et al. (**Auger Coll.**,) PoS(ICRC2021) 307*

Auger&TA: full sky search



Auger (θ < 80°): 120,000 km² sr yr

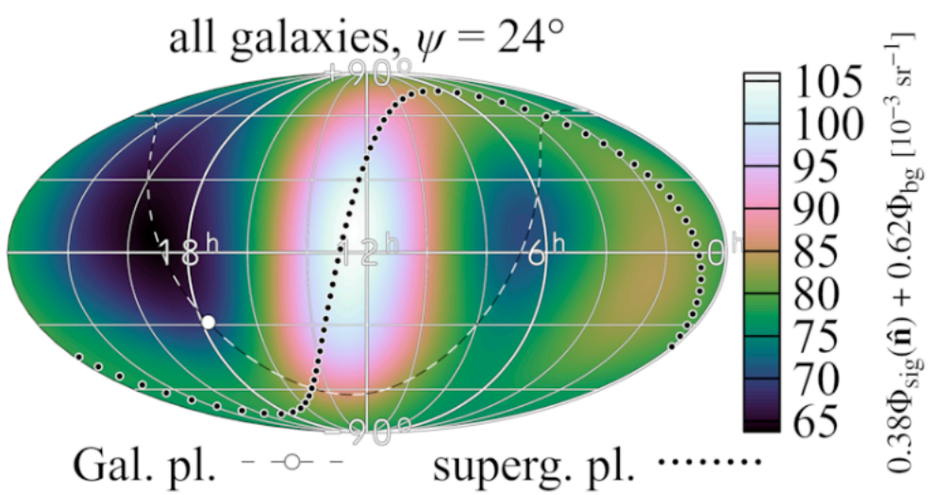
TA (θ < 55°): 14,000 km² sr yr

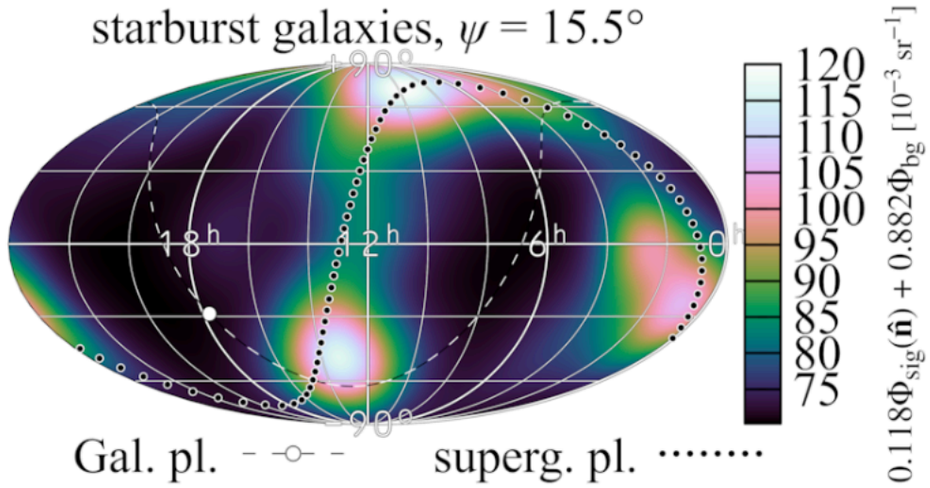


Energy scale conversion

$$\frac{E_{Auger}}{10\ EeV} = 0.857 \left(\frac{E_{TA}}{10\ EeV}\right)^{0.937}$$

$$\frac{E_{TA}}{10\ EeV} = 1.179 \left(\frac{E_{Auger}}{10\ EeV}\right)^{1.067}$$

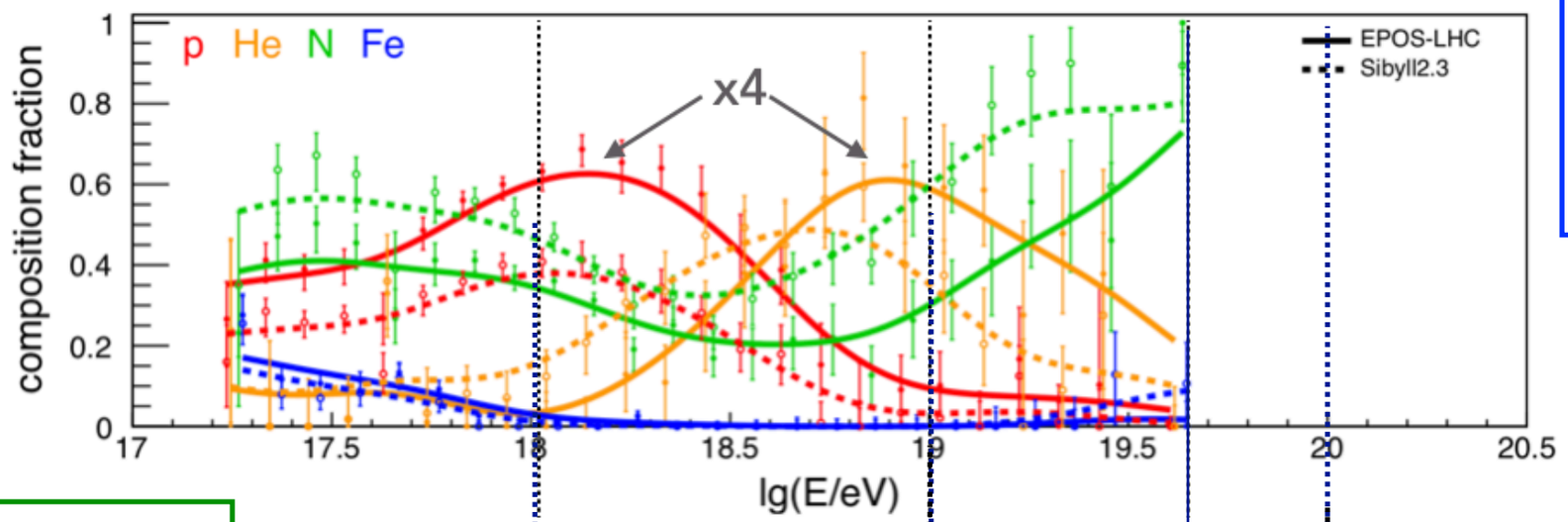




catalog	E_{min} (Auger)	E_{min} (TA)	ψ	equiv. top-hat radius	f	TS	Post-trial significance
all galaxies	41 EeV	53 EeV	$24°^{+13°}_{-8°}$	$38°^{+21°}_{-13°}$	$38\%^{+28\%}_{-14\%}$	16.2	2.9σ
starburst galaxies	38 EeV	49 EeV	$15.5°^{+5.3°}_{-3.2°}$	$24.6°^{+8.4°}_{-5.1°}$	$11.8\%^{+5.0\%}_{-3.1\%}$	27.2	4.2σ

*A.di Matteo et al. (**Auger-TA working group**) PoS(ICRC2021) 308*

What can we learn from data

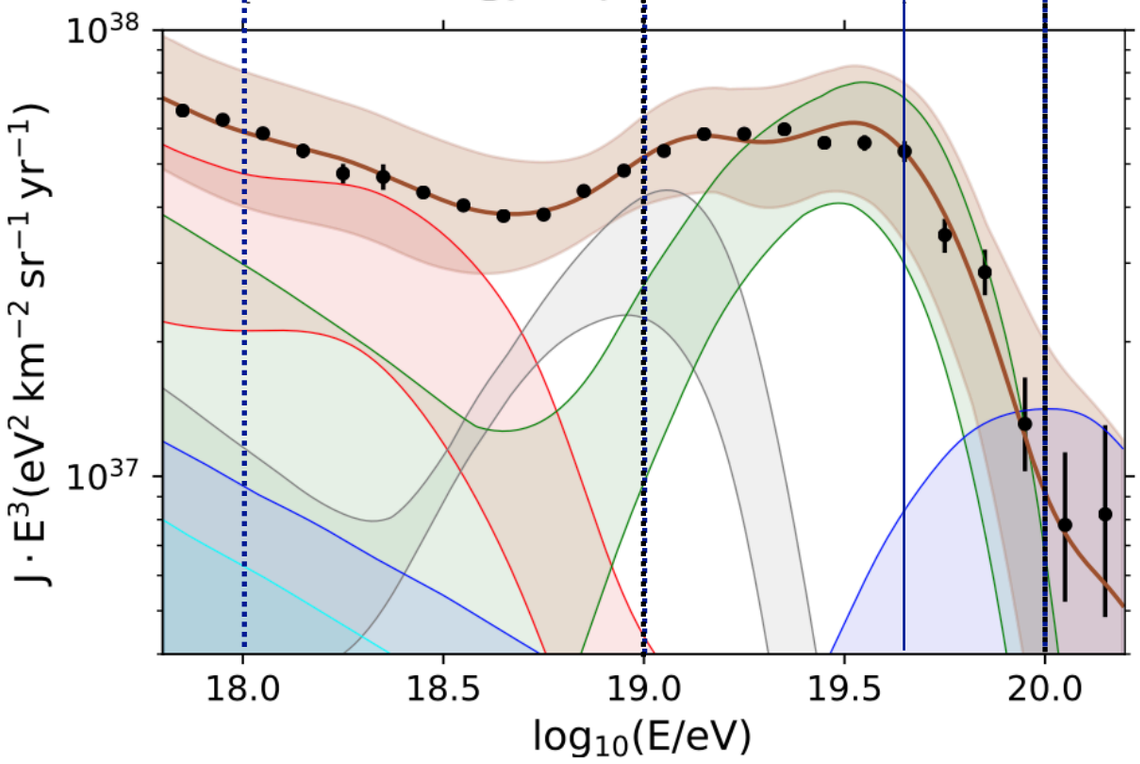


The composition of the primary beam is **mixed and getting heavier** above ~ 2 10^{18} eV

Peter's cycle ∝ ***E/Z***
or
spallation ∝ ***E/A ?***

Pure/light composition excluded in ankle region

Transition from Gal. to EGCR below the ankle



Well established suppression of the flux: **sources must be nearby (<200 Mpc).** Propagation (GZK horizon) and/or source (maximum acceleration energy) effects ?

Combined fit of energy spectrum and X_{max} distribution

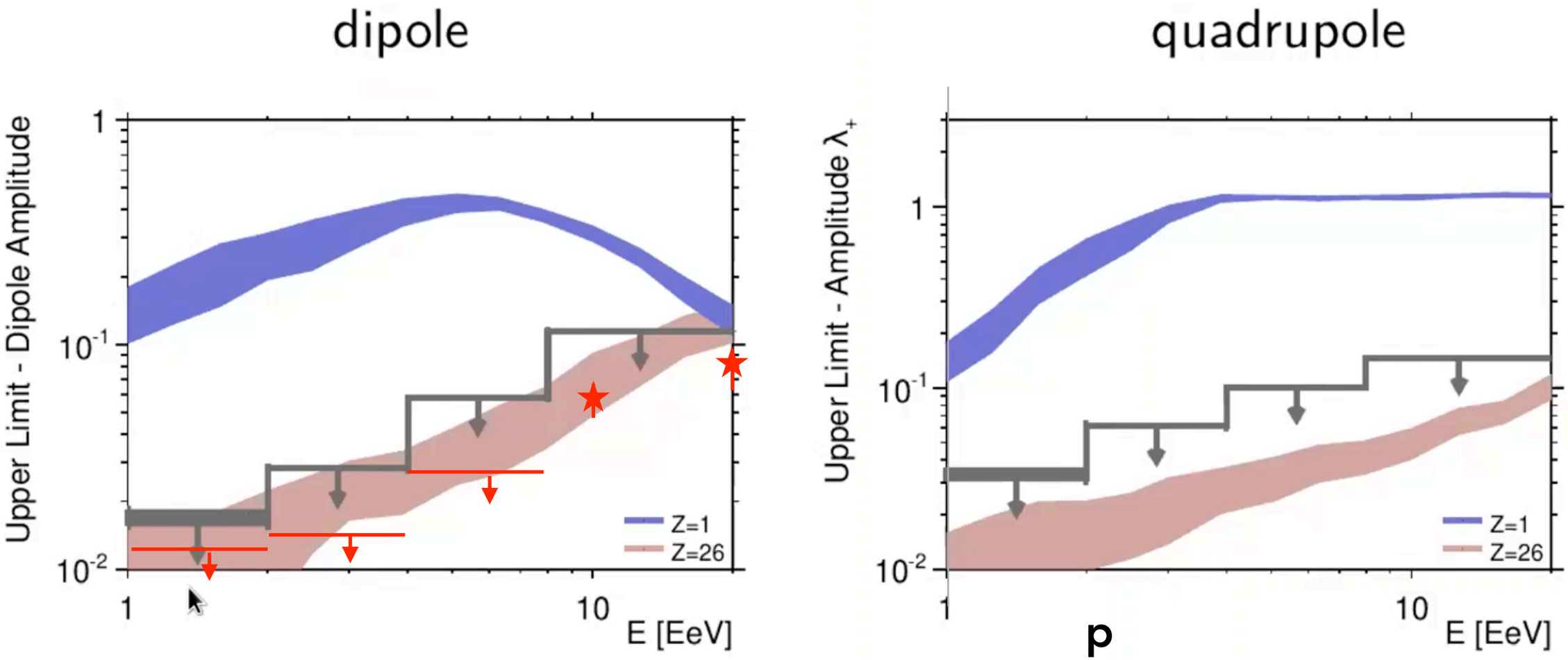
Example from a simplified astrophysical model

Limits on the local density of sources
L_{tot} ~ 6 10^{44} erg Mpc $^{-3}$ yr $^{-1}$
n_s ~ 10^{-6} — 10^{-4} Mpc $^{-3}$

\+

- Observation of a dipolar anisotropy at large scale at >8 EeV : **UHECR above this energy are extragalactic**
- **Hints of correlation with SBGs**
- Strong limits on the flux of neutrinos and gammas: can't have new physics, rather **ordinary matter**

The Transition region



- Bounds on the dipolar component imply that
  - the observed light component must be extragalactic
  - the ankle is a feature of the EG spectrum, the transition must be below its energy
- Upper limits can be respected if mix of Galactic heavier nuclei+EG protons (around EeV)

Auger Coll., Astrop.J.Lett.762 (2013) L13

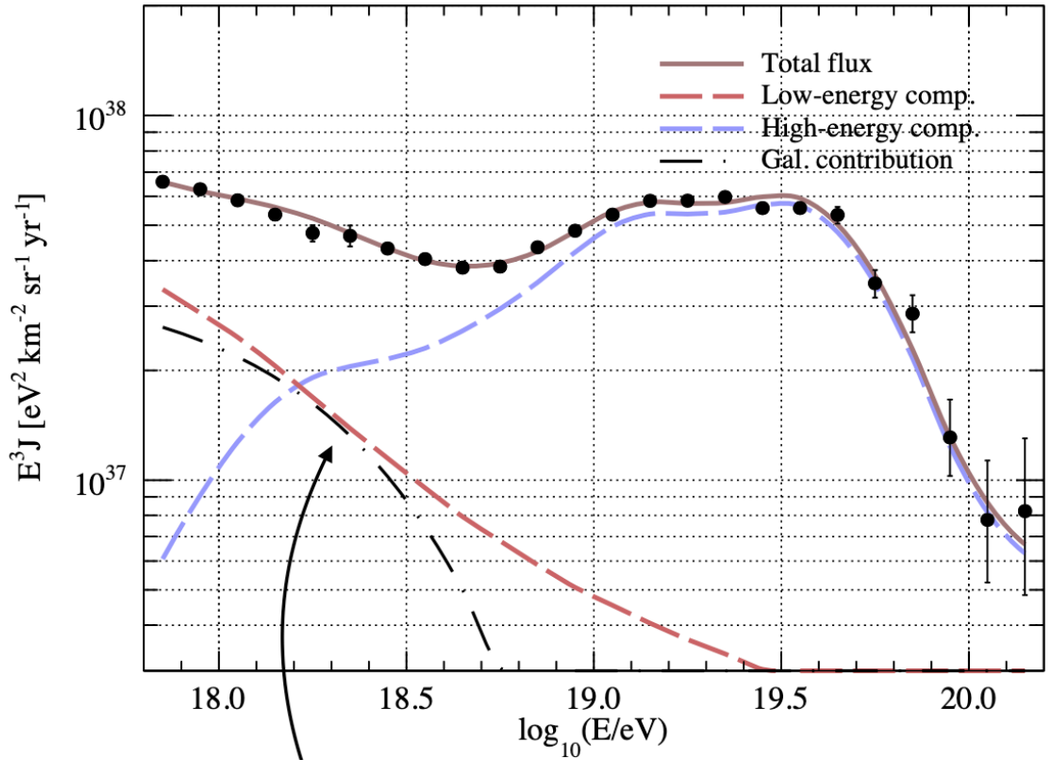
The measured spectrum and composition of UHECR can be described by

- the interplay of two EG populations of sources: a HE one, with hard spectrum, and a LE one with a softer spectrum (plus possibly a secondary Galactic component)
  - ➡Homogenous sources
  - ➡Different sources

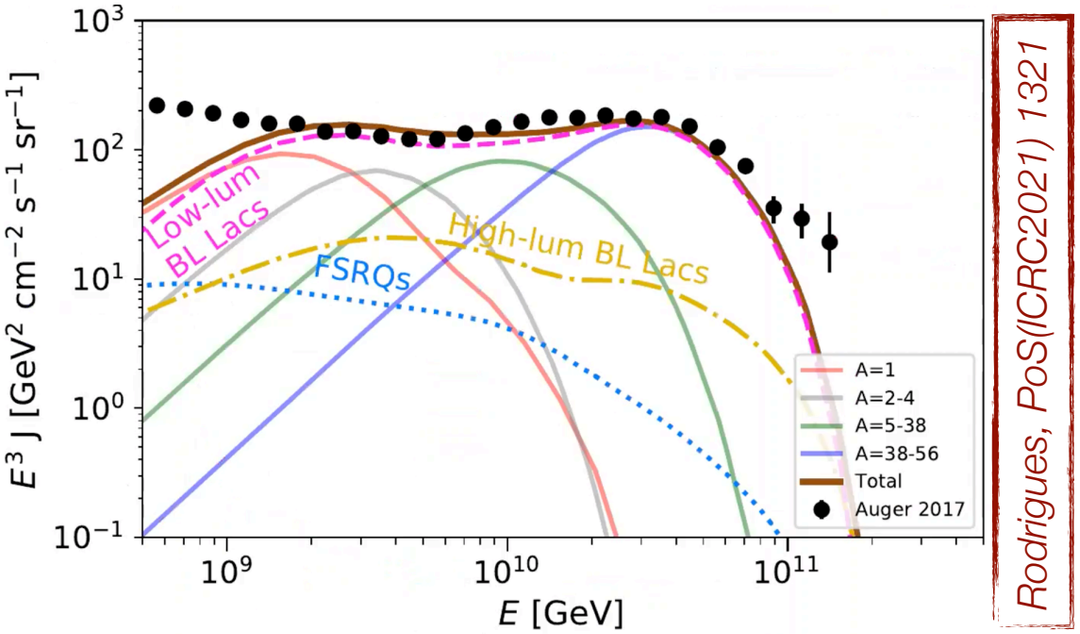
$$dN_s/dE_{max} \sim E_{max}^{-\beta}$$

$$dN_{inj}/dE \sim E^{-\alpha}$$

$$\rightarrow dN_{CR}/dE \sim E^{-\alpha-\beta+1}$$

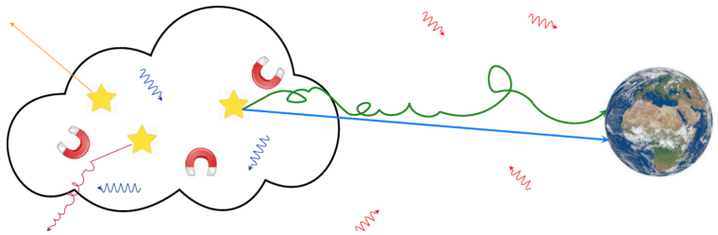


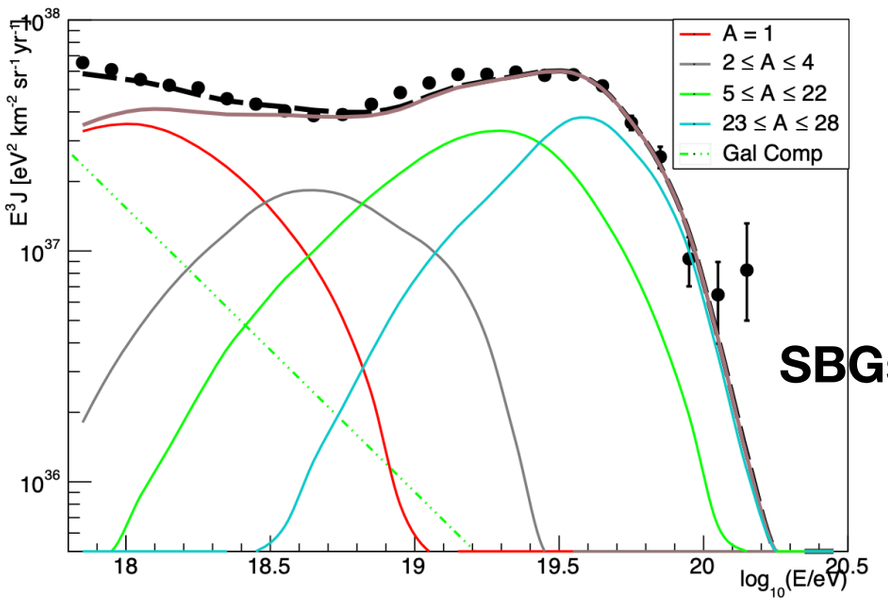
E.Guido, PoS(ICRC2021) 311



Rodrigues, PoS(ICRC2021) 1321

- Considering both the escaping and injected spectra (interactions at the source)





SBGs

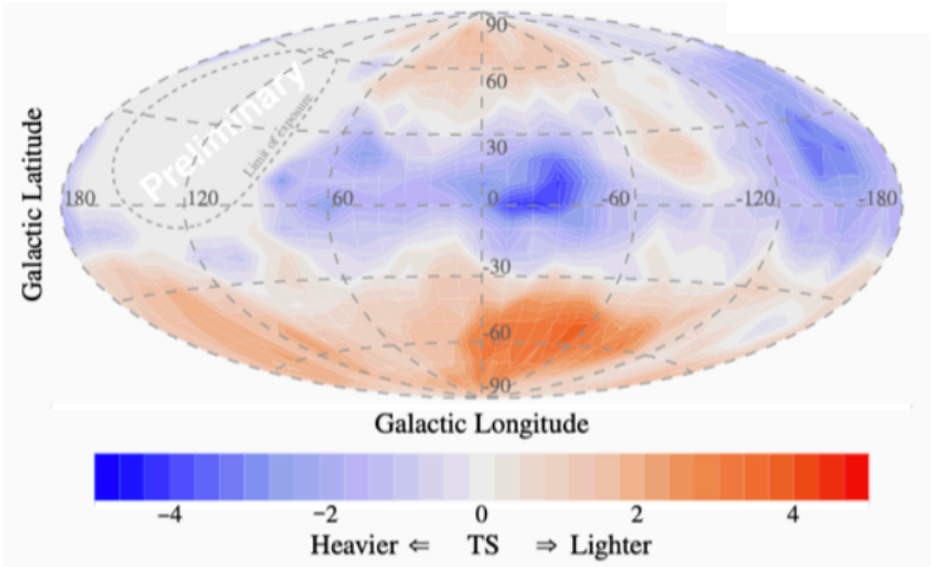
A. Condorelli, PoS(ICRC2021) 959

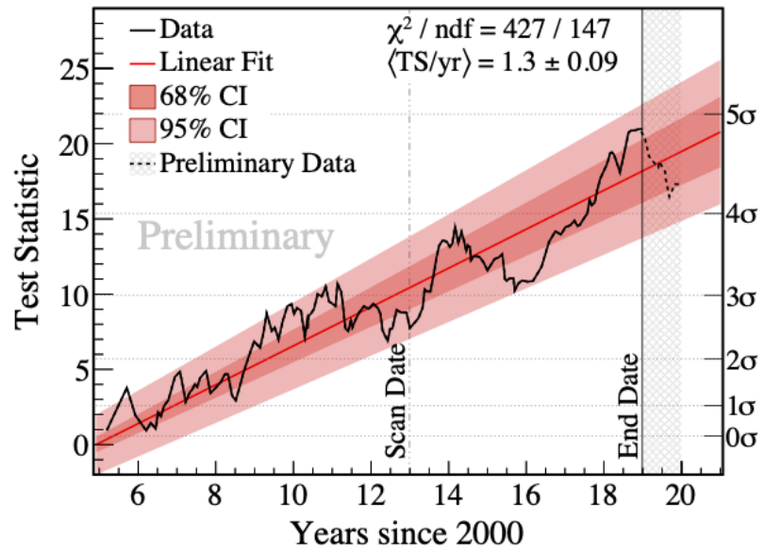
Outlook

Composition-sensitive anisotropy

On-plane: $|\, b_i \,| \leq b_{\text{split}}$ Off-plane: $|\, b_i \,| > b_{\text{split}}$

- Verification of the mixed composition above the ankle
- May not be related to the GMF
- Local source distribution or mass dependent horizons?
- Still no independent confirmation





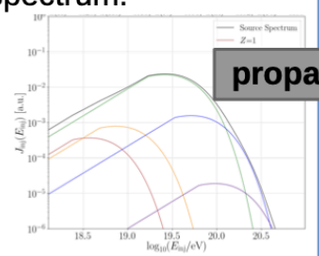
E.Mayotte et al. PoS(ICRC2021) 321

Spectrum +Composition +Anisotropy Combined fit

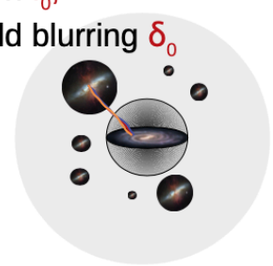
T.Bister et al. PoS(ICRC2021) 368

Universe model setup:

injected spectrum:
γ, R_{cut}, a_i

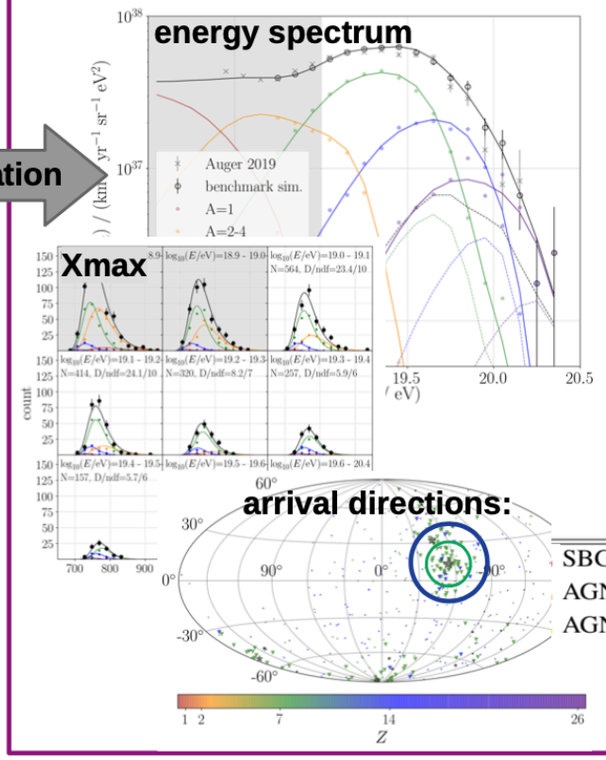


3d setup:
signal fraction f_0,
magnetic field blurring δ_0



propagation

Simulated observables:



Fit of model parameters to

- energy spectrum,
- Xmax distribution
- arrival direction distribution

Flux and Xmax data:
fluxes of different mass groups at Earth

Arrival direction distribution:
distance sensitivity (deflection, production of secondaries)

	Deviance			Likelihood	
	D_E	$D_{X_{\max}}$	D_{total}	$2 \log \frac{\mathcal{L}_{\text{AD}}}{\mathcal{L}_{\text{AD}}^{\text{ref},m=3.4}}$	$2 \log \frac{\mathcal{L}_{\text{sum}}}{\mathcal{L}_{\text{sum}}^{\text{ref},m=3.4}}$
SBG model ($m = 3.4$) → *sim. truth*	5.5	80.2	85.7	30.6	32.4
AGN model ($m = 3.4$)	6.0	81.8	87.8	11.2	10.8
AGN model ($m = 5.0$)	5.6	84.1	89.9	1.4	−1.0

Outlook (2025-2030)

AugerPrime

a large exposure detector with composition sensitivity above ~4 10^{19} eV

On each Water-Cherenkov station (WCD):

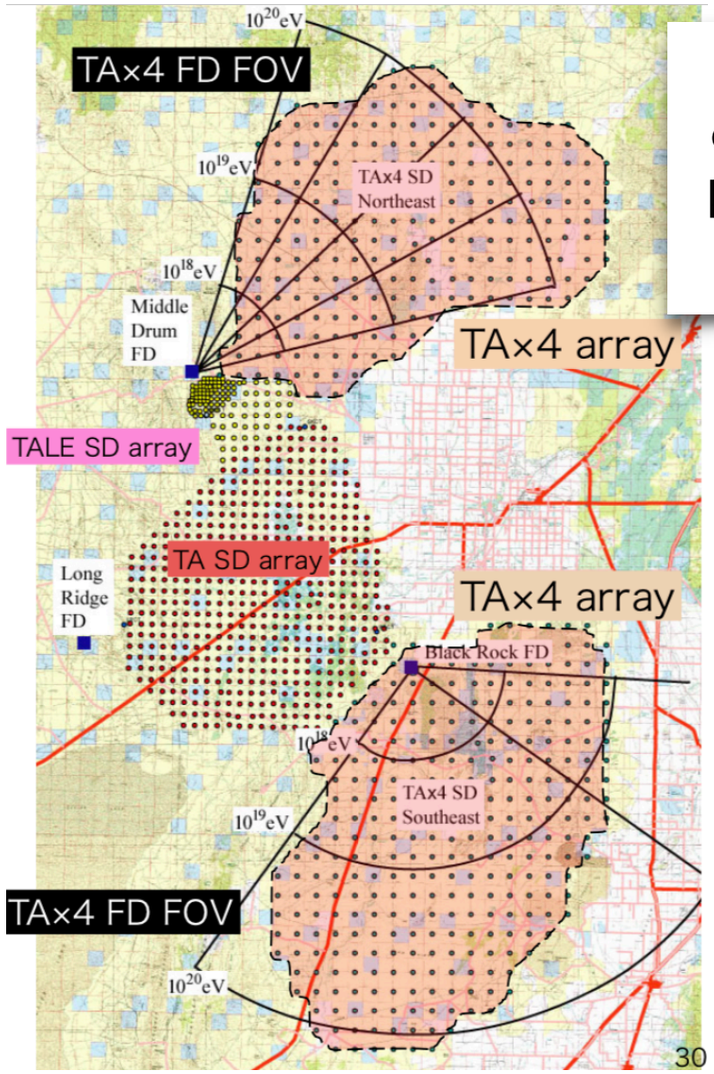
- ➡ the SSD (Surface Scintillator Detector)
- ➡ The RD (Radio Detector)
- ➡ New electronics, wider dynamic range

In the Infill region (61 WCD)

- ➡ The UMD (Underground Muon Detector)

A.Castellina, EPJ Web Conf., 210 (2019) 06002

TAx4



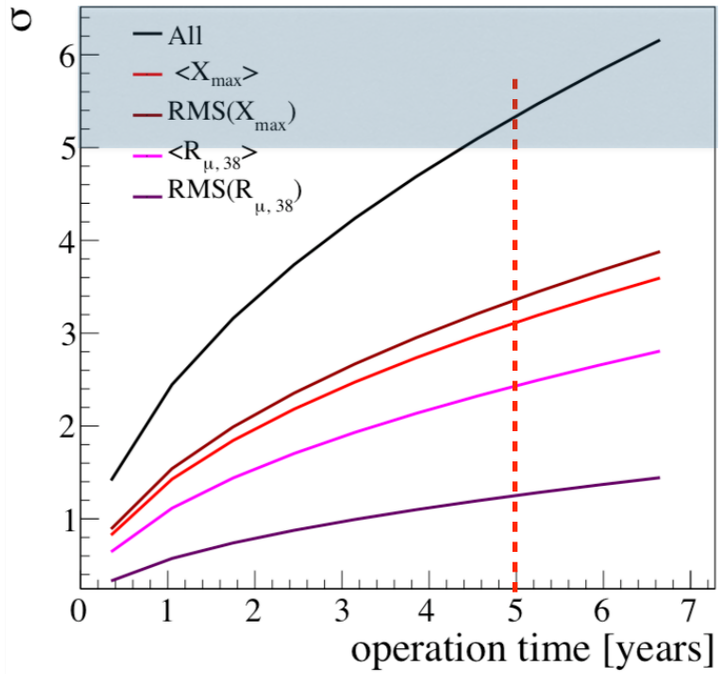
increase the coverage to ~3000 km² to increase the statistics at UHE

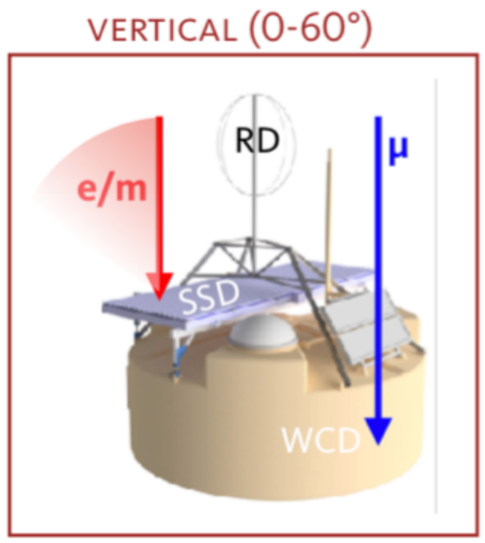
- ➡ the SD array: +500 stations with 2 km spacing
- ➡ the FD telescopes:+4 FD in the Northern site, 8 in the Southern site
- ➡ TALE hybrid: low energy extension of TA hybrid sensitivity down to 10^{16} eV

S.Ogio, PoS(ICRC2019) 013

Outlook: AugerPrime = FD+SD+RD+UMD

Vertical showers



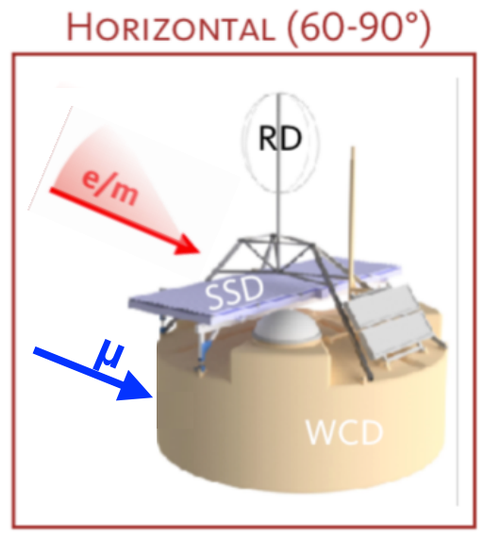


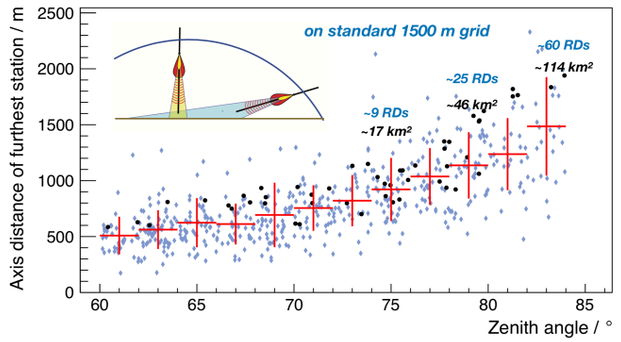
Significance of distinguishing two different realisations of Scenario 1 (maximum rigidity model) :

- as it predicts, i.e. no protons at UHE
- adding 10% protons

>5σ in 5 years of operations

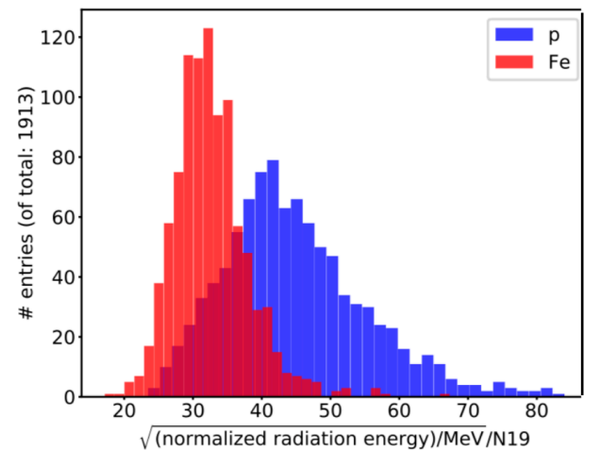
Horizontal showers

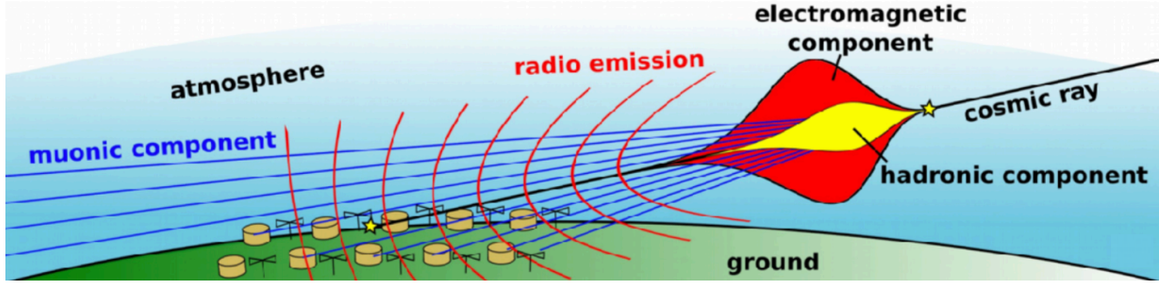


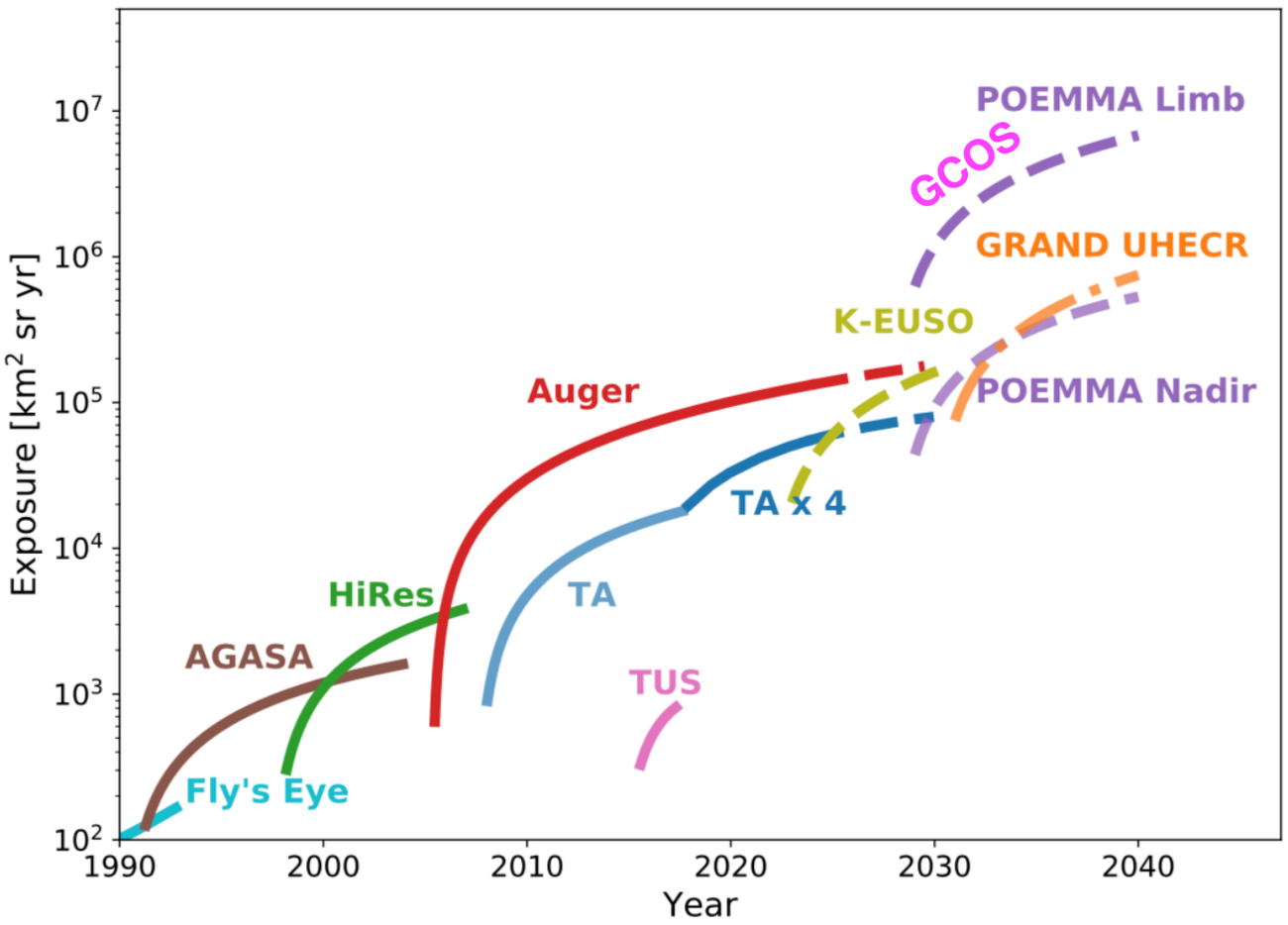


$E_{30\text{-}80}$ MHz = 15.8 MeV @ 10^{18} eV

Hybrid:
E_{rad} from radio
muons from WCD





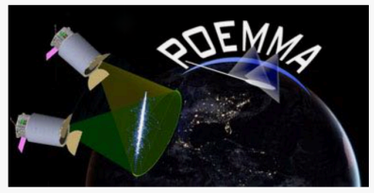


Thank you !

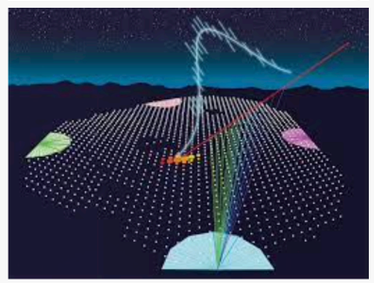
Complementarity of approaches

Space - ground

POEMMA:
intrinsic full-sky coverage



GCOS:
particles, radio, fluorescence
better resolution (E, X_{max})
study (hadr.) interactions



Complementarity of techniques

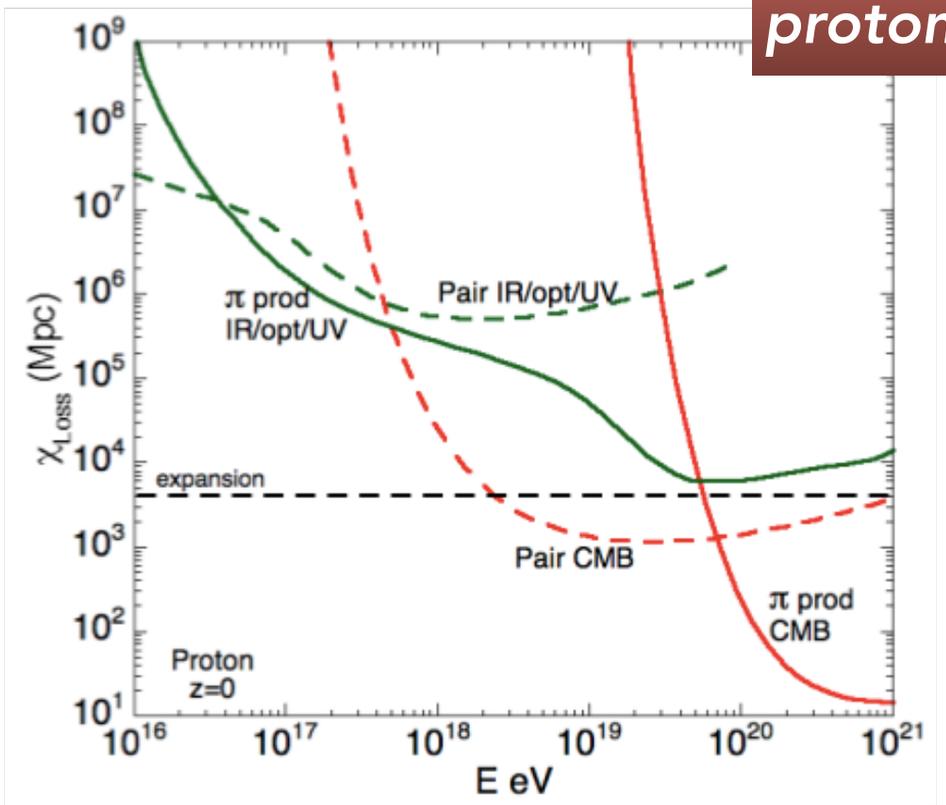
The Giant Radio Array for Neutrino Detection

200'000 radio antennas over 200'000 km^2
~20 sub-arrays of 10'000 antennas
over favorable sites in China and worldwide

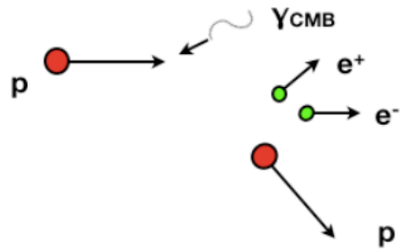
GRAND

BACKUP SLIDES

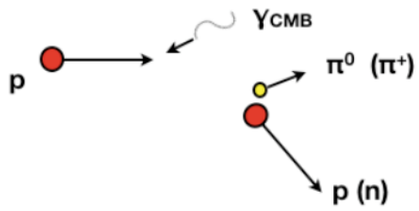
protons



- adiabatic energy losses
- pair production

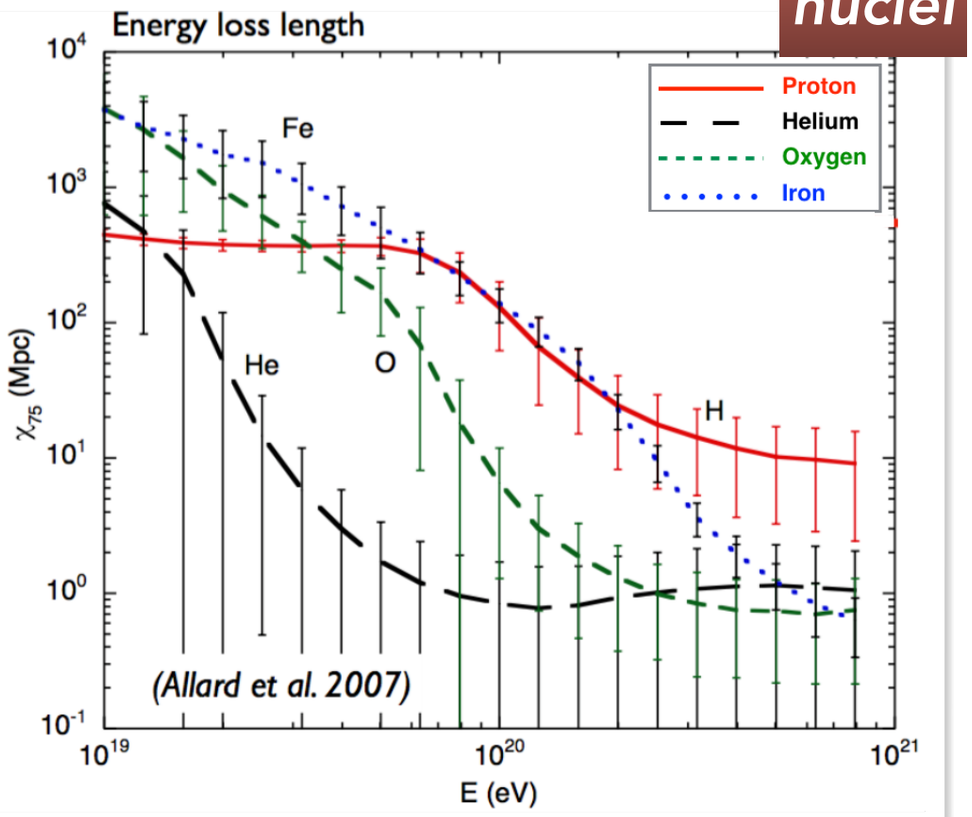


- photopion production



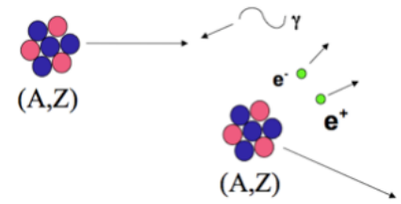
- contribution of IR/UV/Opt photons irrelevant

nuclei

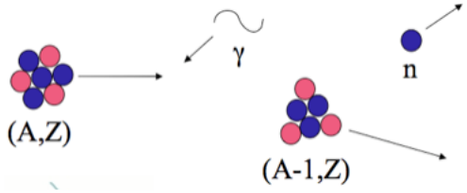


- decrease in Lorentz factor
  - ✓adiabatic losses
  - ✓pair production losses

$$\Gamma = \frac{E}{m_p A}$$

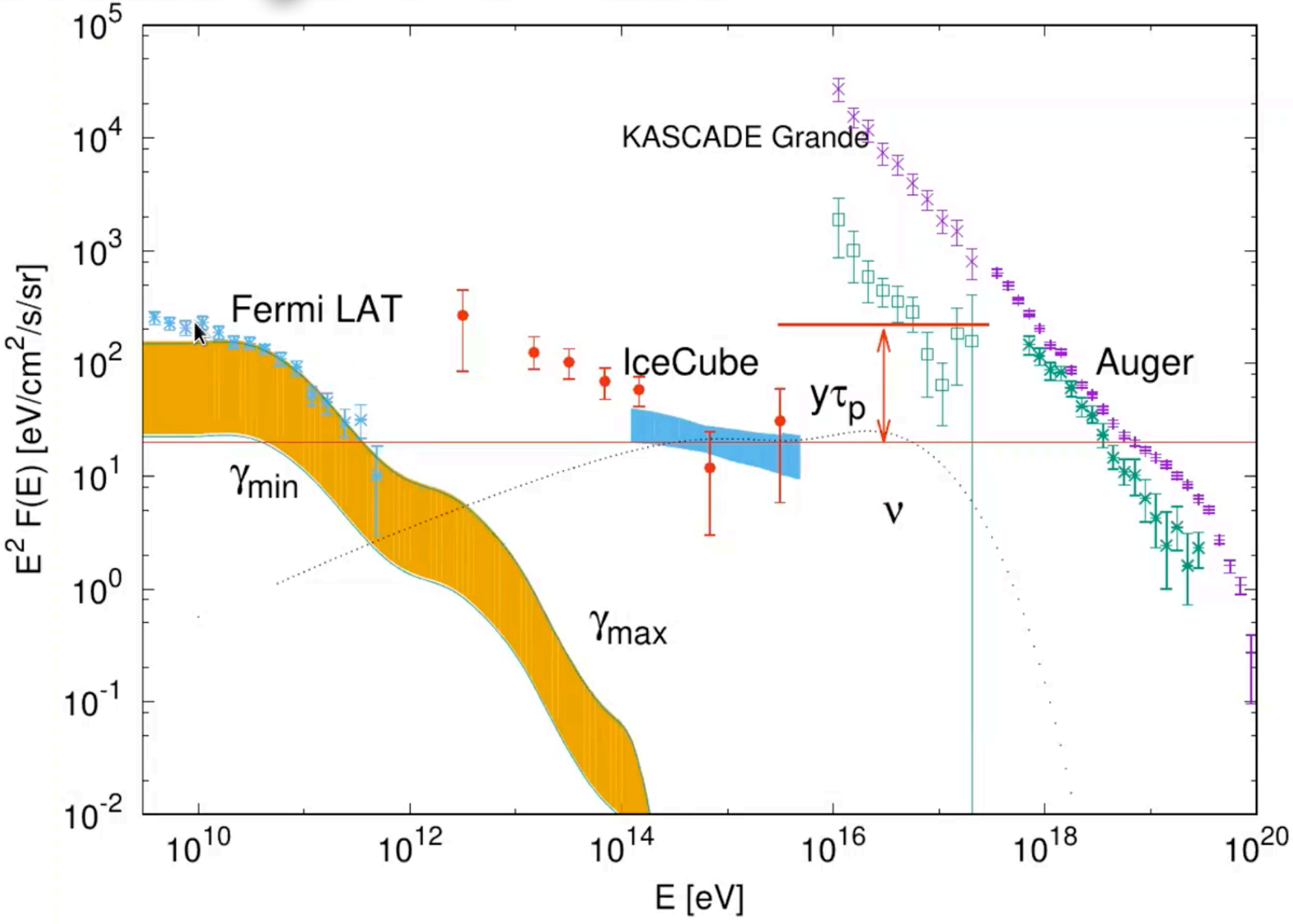


- photodisintegration processes
  - ✓Giant dipole resonance (GDR)
  - ✓quasi-deuteron processes (QD)



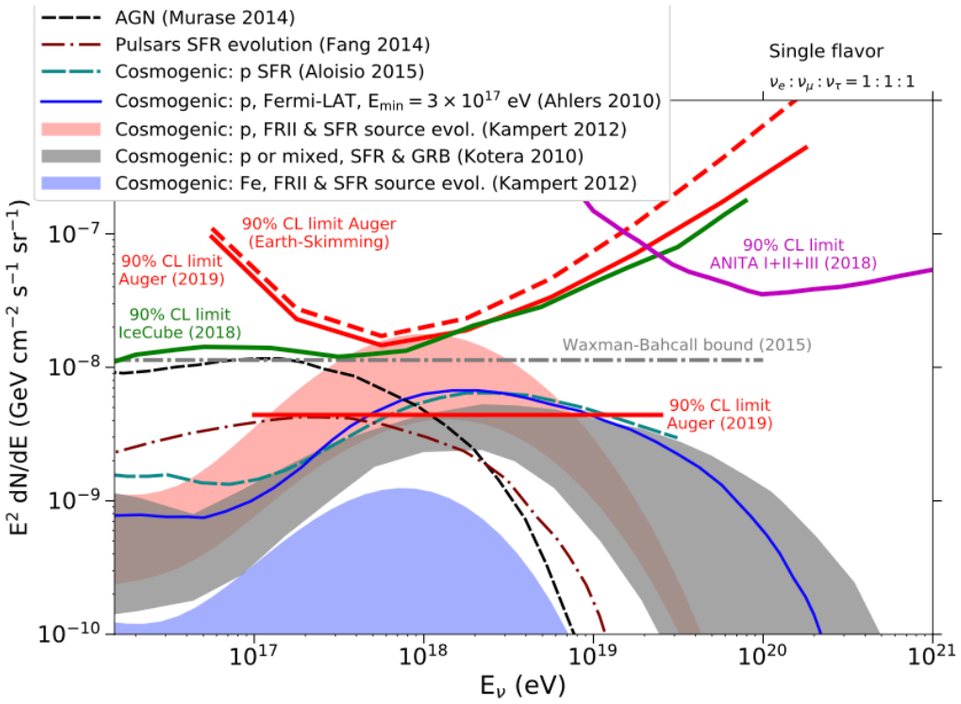
- pion production
  - ✓pion production [A x $E_{thr}(p)$]

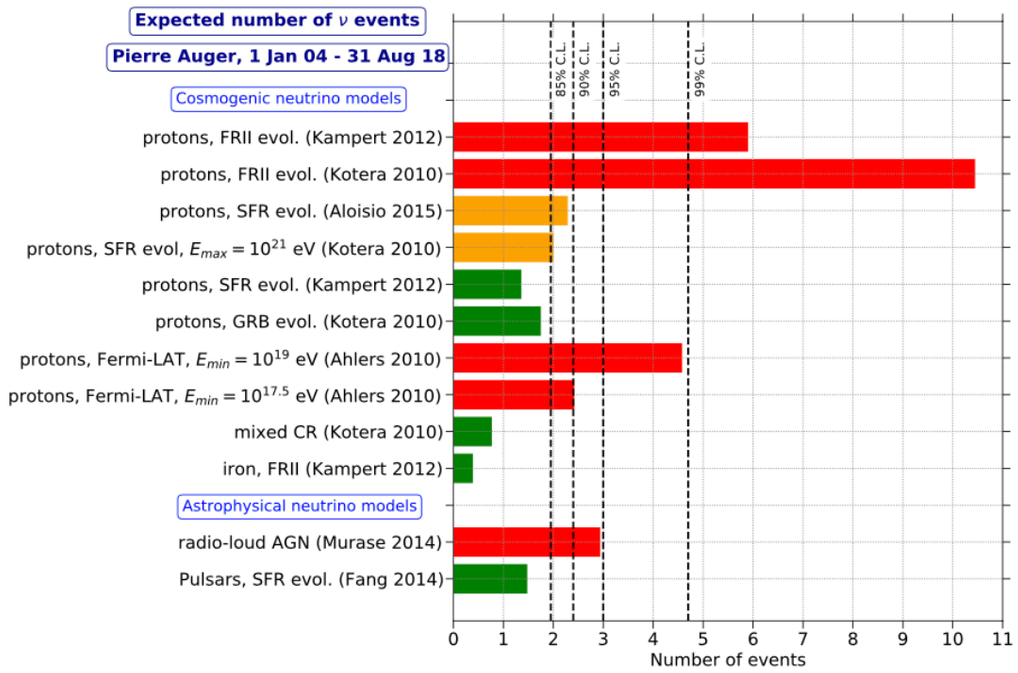
Multimessenger information



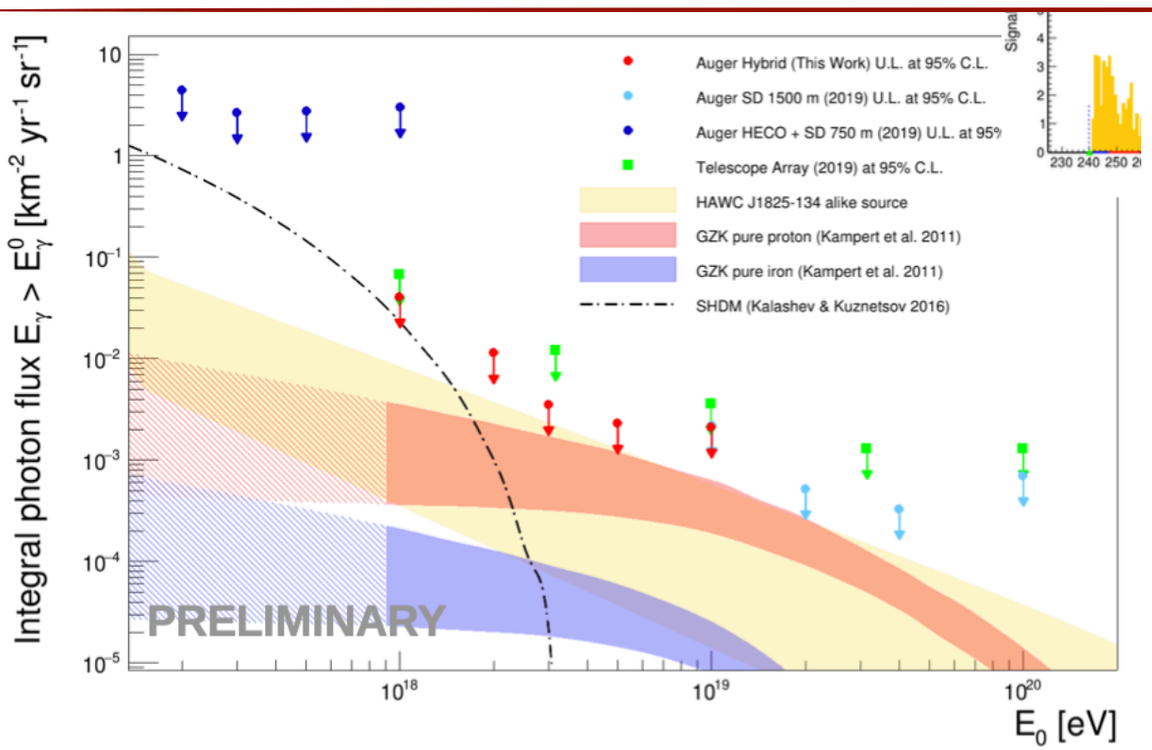
- From blazars: (86+15)% of EGγbck, but only <17% IceCube neutrinos
- UHEp can reproduce only the HE tail of the neutrino flux
- Additional component needed

Neutral messengers





JCAP 10 (2019) 022; JCAP 11 (2019) 004



Cut at 50% photon efficiency (median)

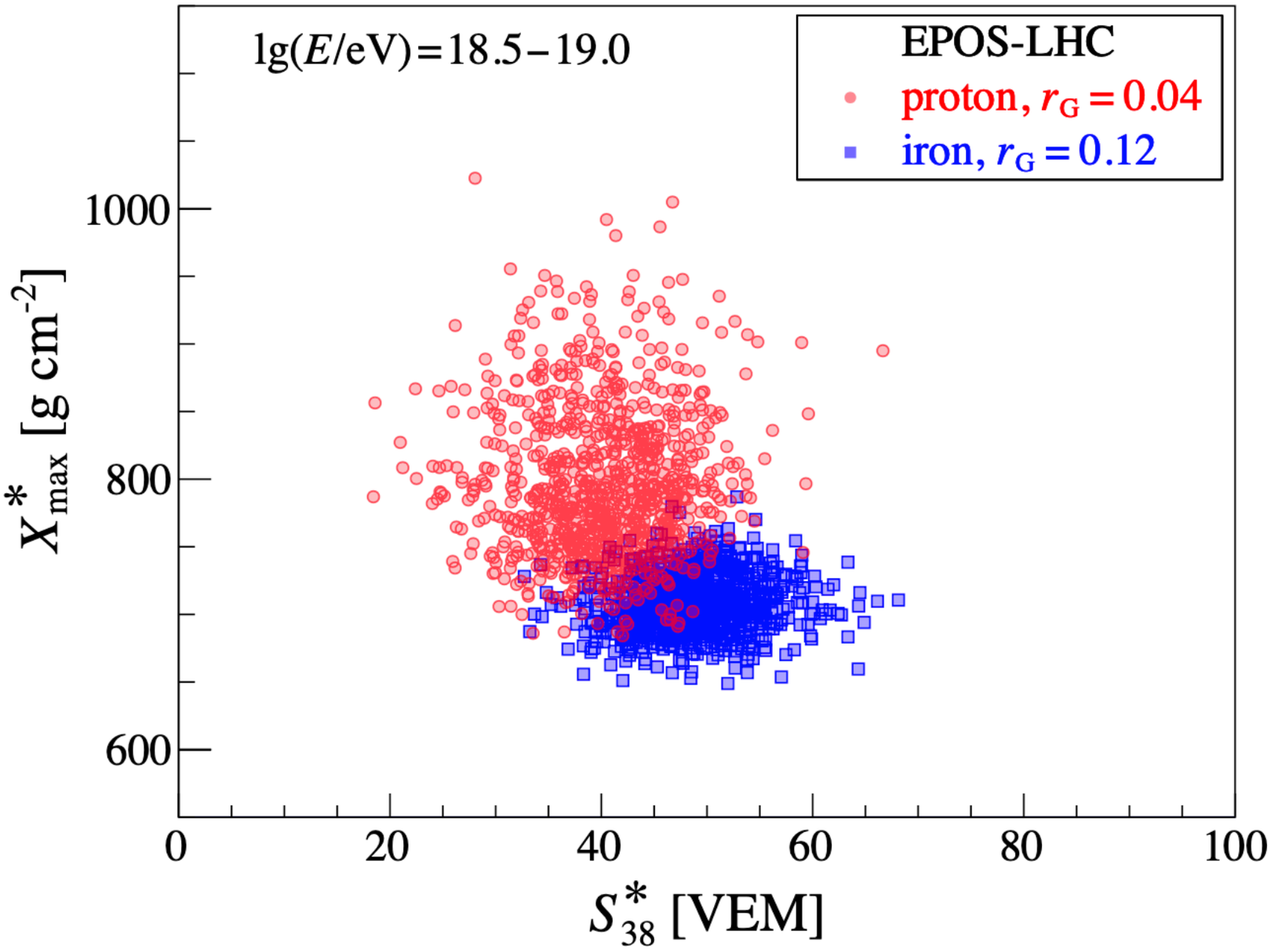
Background compatible with stat. expectation (burn sample of data)

Multi-messenger: searches for photons in coincidence with GW events

Phase II: additional data for photon/hadron separation or photon discovery

PoS (ICRC2021) 373; PoS (ICRC2021) 449

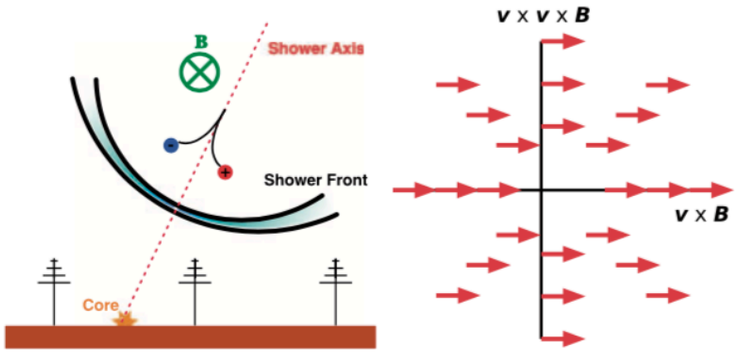
Mass composition



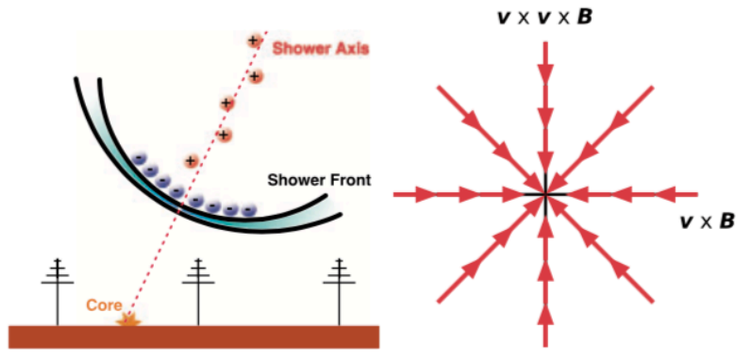
- pure compositions excluded in the range [$10^{18.5}$-10^{19} eV] at > 6**σ**
- mix of p+He excluded in the range [$10^{18.5}$-10^{19} eV] at > 5**σ**

Auger Coll., *Phys.Lett. B762 (2016) 288*
A.Yushkov, PoS(ICRC2019) 482

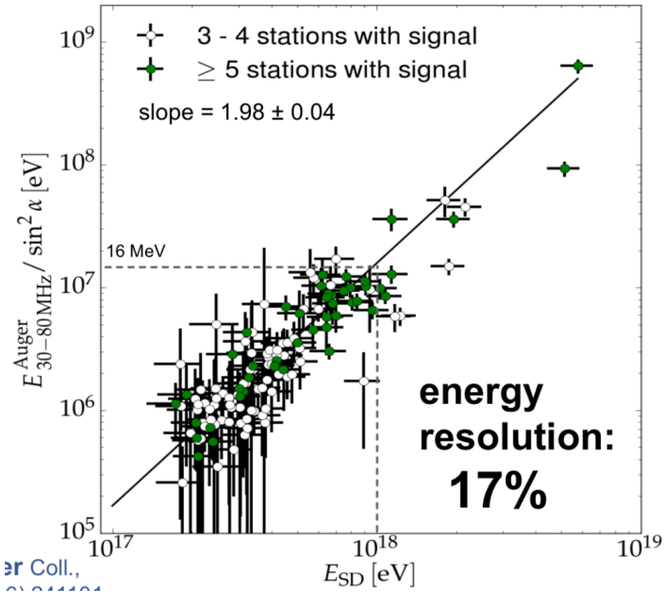
The Radio Detector of AugerPrime



Geomagnetic emission (~90%)



Charge-exchange (Askaryan effect, ~10%)



As it is not absorbed in atmosphere, the radio emission depends on the source distance and not on the amount of traversed matter

$E_{RD} \propto E_{CR}^2$

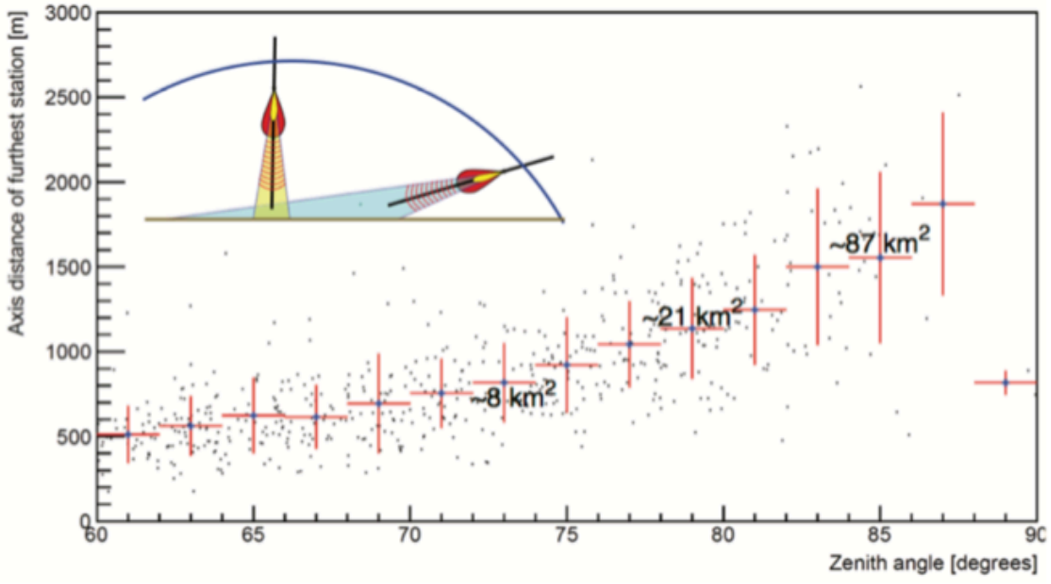
$\sigma_{syst}(E_{RD})$ ~ 28% —>

$\sigma_{syst}(E^{Radio}_{CR})$ ~ 14% at 1 EeV

inclined air showers can be detected by a sparse antenna grid (> 1 km mutual distance)

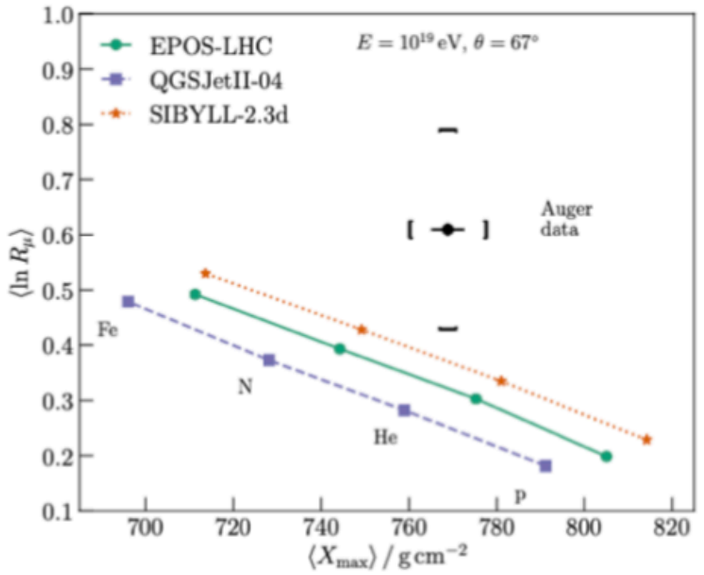
- lower E amplitude
- larger footprint
- less steep LDF

≥5 stations with signals above bkg



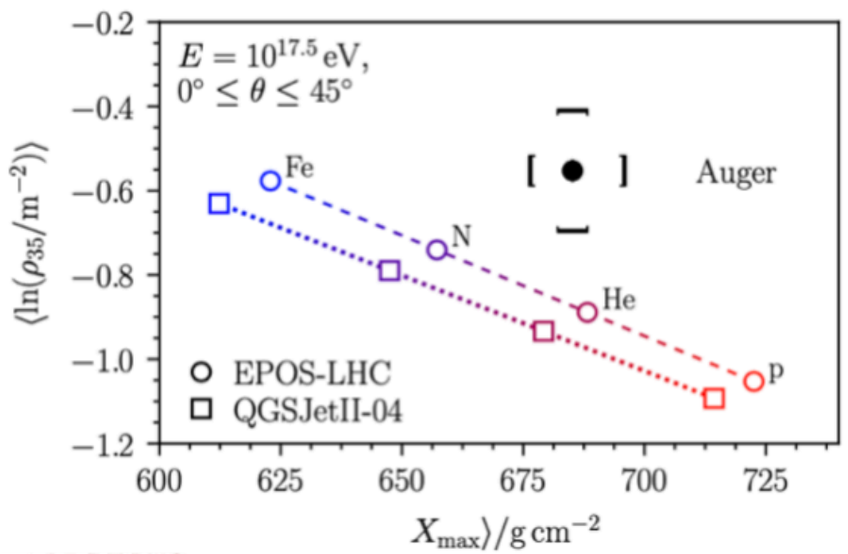
Muon deficit in hadronic interaction models

Hybrid events and inclined showers



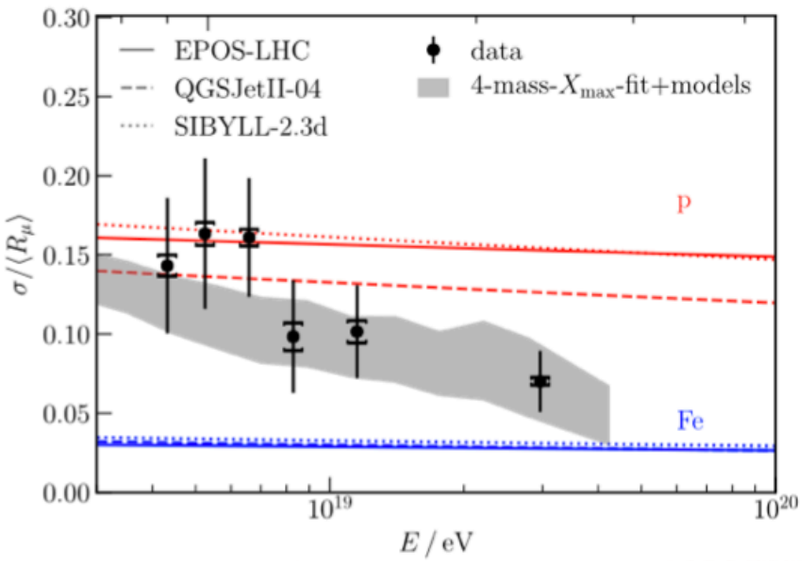
Auger Coll., Phys.Rev..Lett.117 (2016) 192001
Auger Coll., Phys.Rev.D91 (2015) 032003

Muon counters and vertical showers

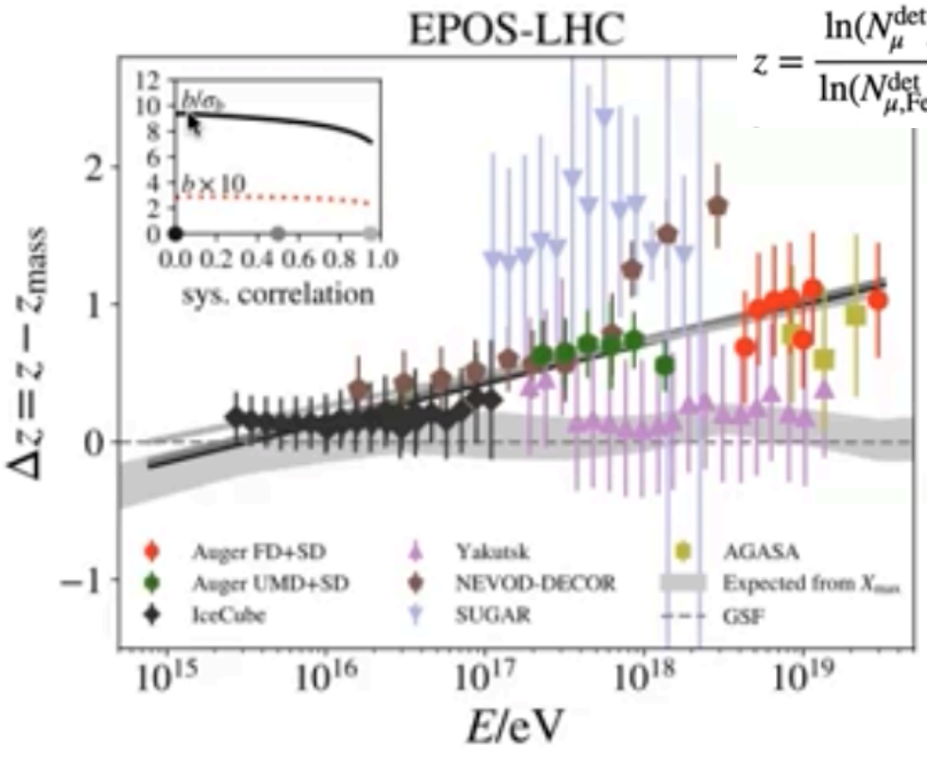


Auger Coll., Eur.Phys.J. C80 (2021) 751

Muon fluctuations driven by first interactions



Auger Coll., Phys.Rev.Lett.126 (2021) 152002



- Clear deficit of muons in the hadronic interaction models
- First measurement of the muon intrinsic fluctuations: well described by models

- Working group ongoing work with data from 9 experiments: significant slope of muon excess vs energy (wrt models) at ~8**σ** level

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