Recent results from the Pierre Auger Observatory

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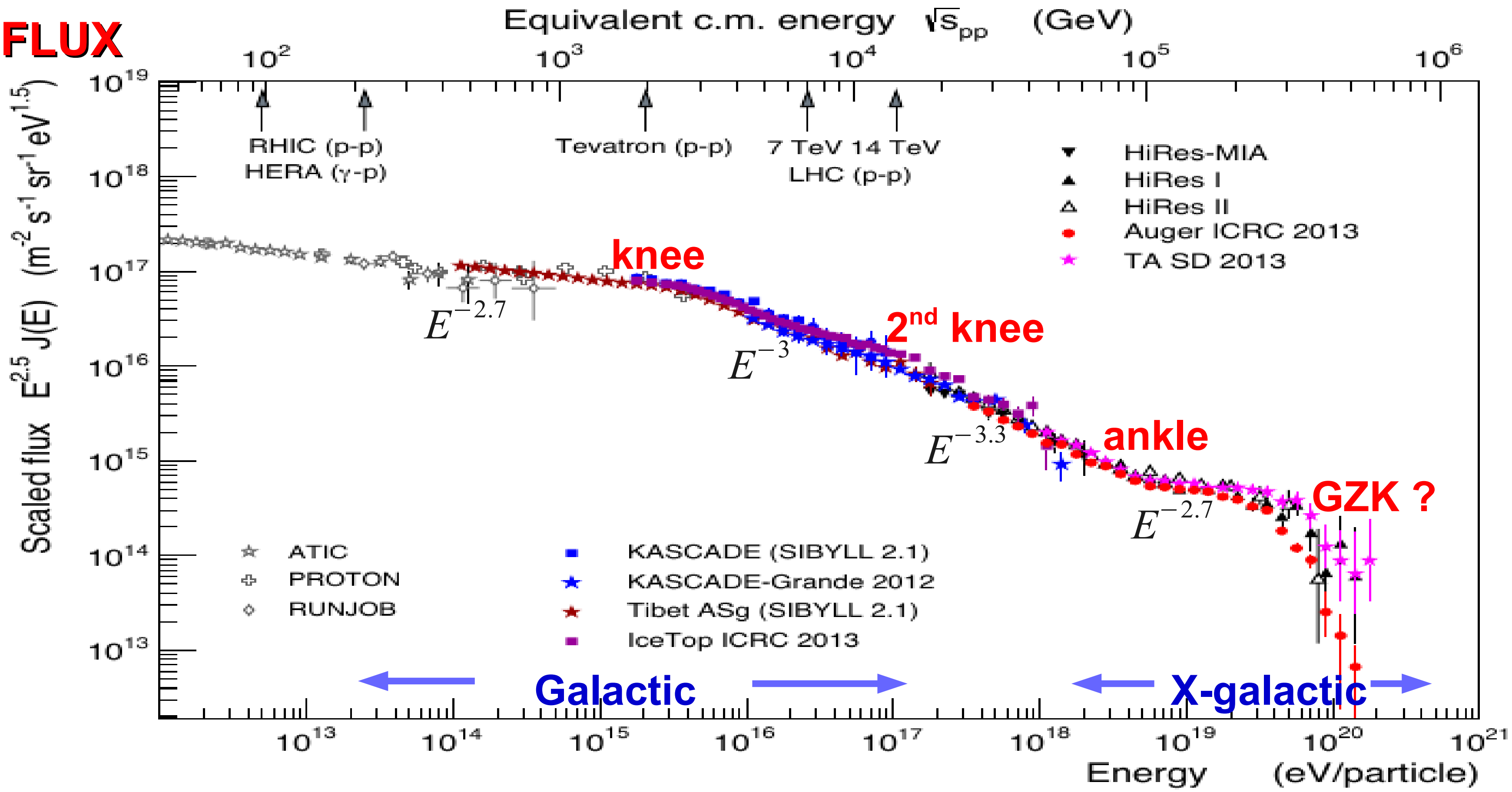
Main questions regarding Ultra-High Energy Cosmic Rays:

What are they
Which are the sources
How they get accelerated
What produces the changes in the spectrum & composition
How do they propagate, effects of Galactic and X-gal B fields
What are the effects of interactions with the CMB or EBL
Are neutrinos & photons produced
How are the hadronic interactions at the highest E
….

Main CR observables:

Spectrum, composition and anisotropies

$E^{2.5}$ x FLUX

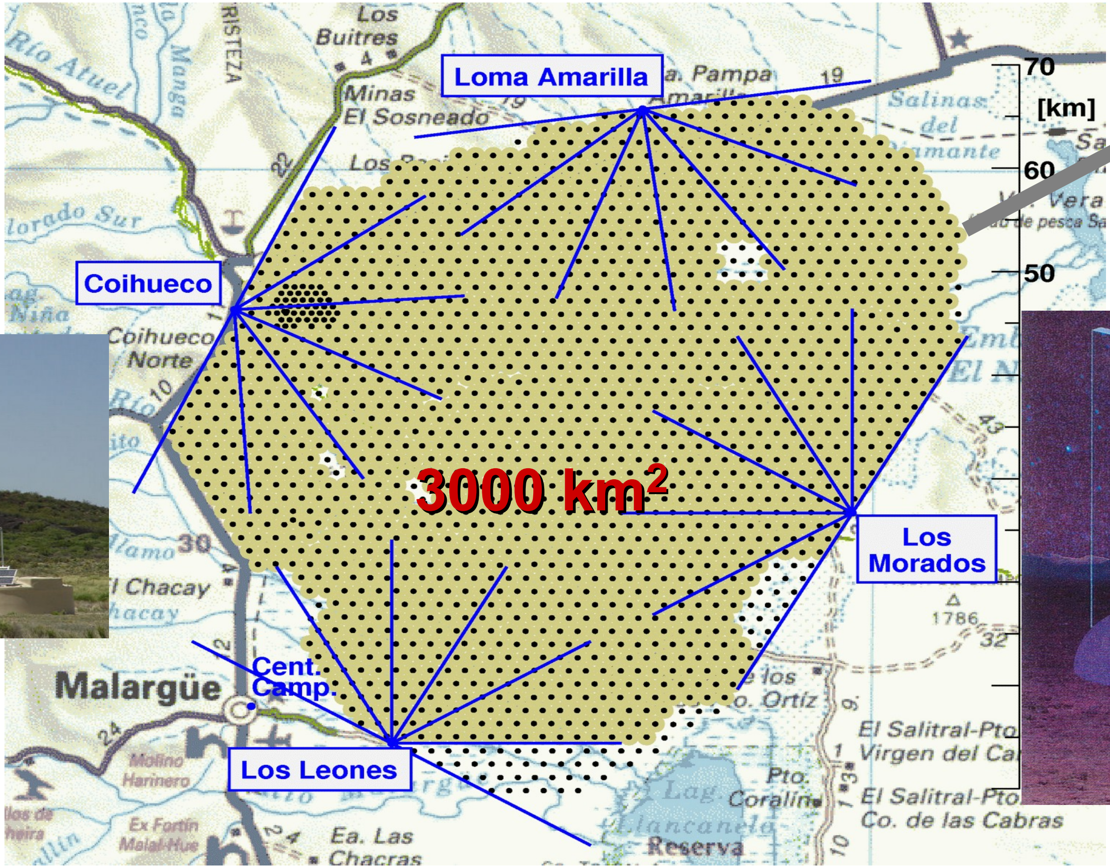


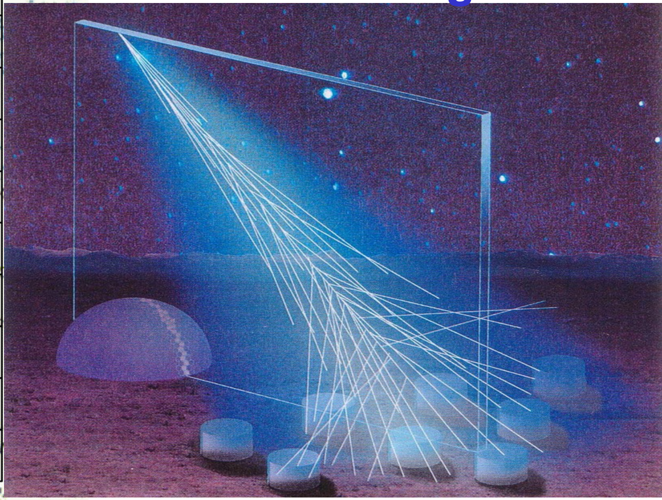
at the highest energies, only few cosmic rays arrive per km^2 per century !

to see some, huge detectors are required

THE PIERRE AUGER OBSERVATORY

Malargüe,
Argentina





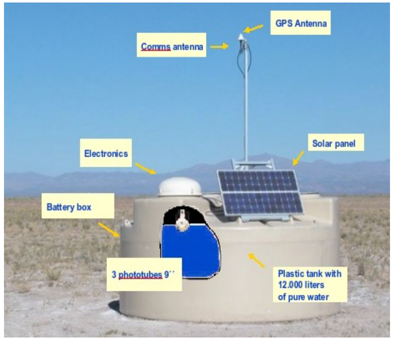
the Auger Collaboration: ~ 400 scientists, 17 countries, taking data since 2004

Argentina Australia Belgium Brazil Czech-Republic France Germany Italy Mexico Netherlands Poland Portugal Slovenia Spain USA Colombia Romania

HYBRID CONCEPT

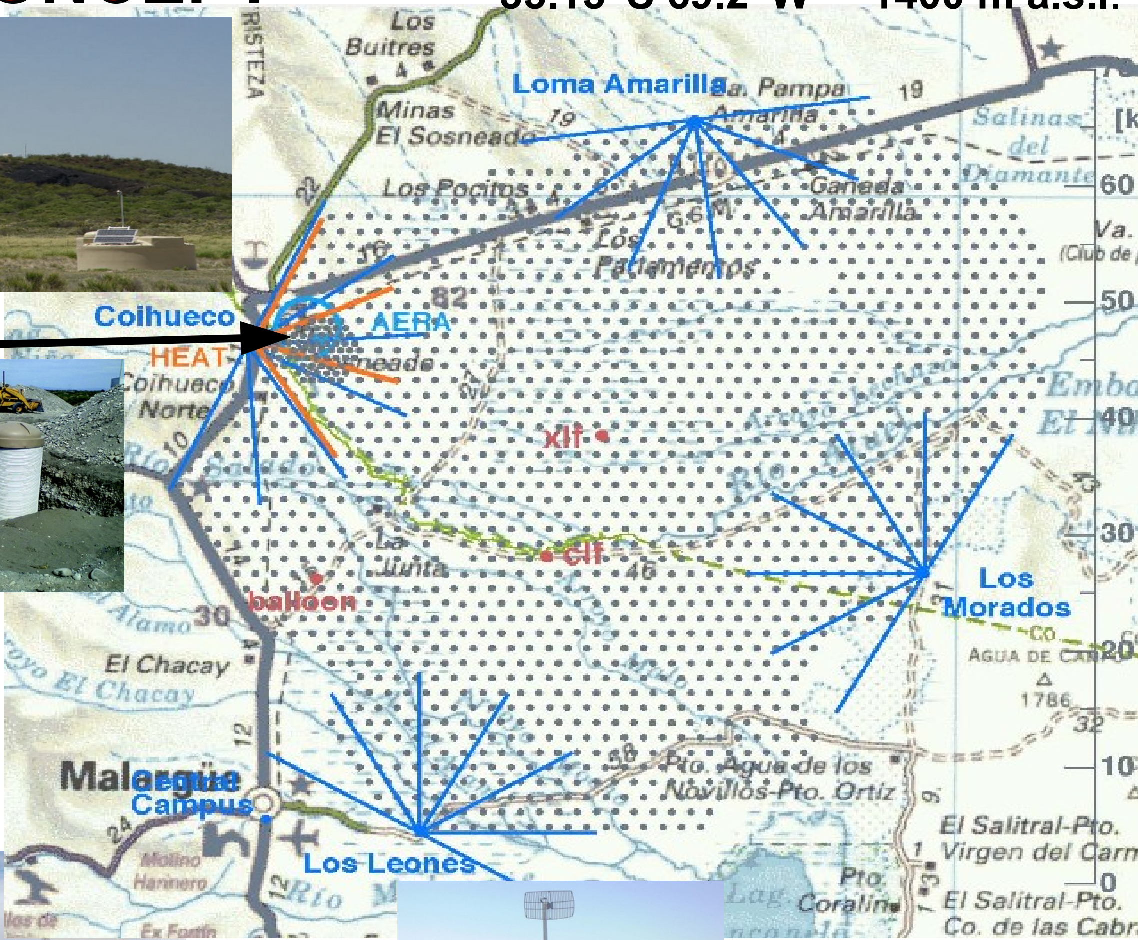
35.15° S 69.2° W ~ 1400 m a.s.l.

Surface Detector
1660 water-Cherenkov stations



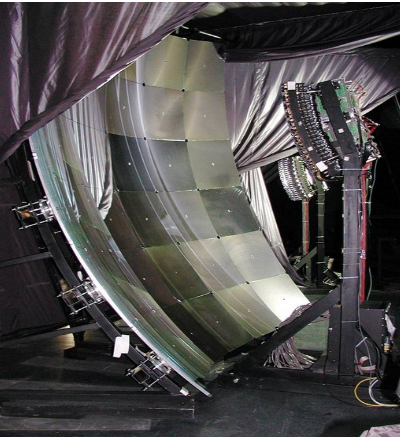
SD1500:
1,5 km grid
3,000 km^2

SD750:
750 m grid
24 km^2



MD: AMIGA
muon detectors

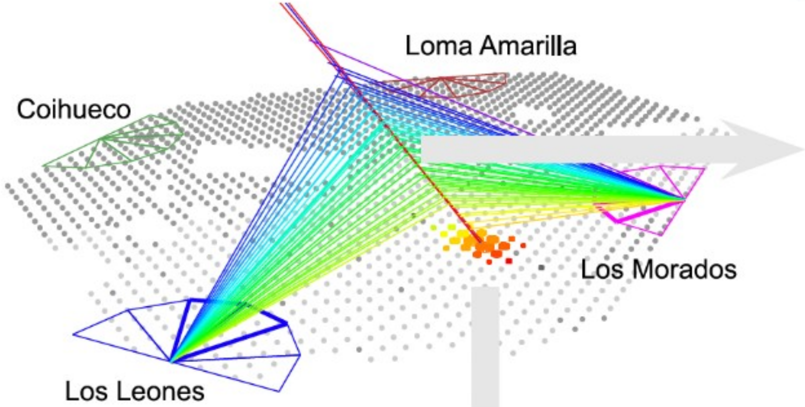
FD: Fluorescence Detector
24 telescopes in 4 locations

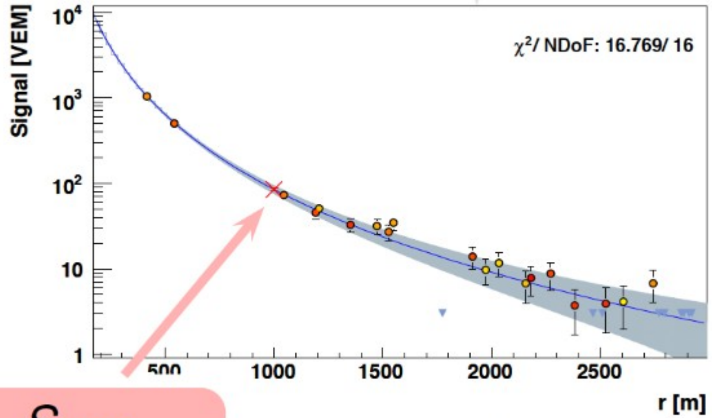


HEAT:
3 higher elevation telescopes

AERA:
radio detection
17 km^2

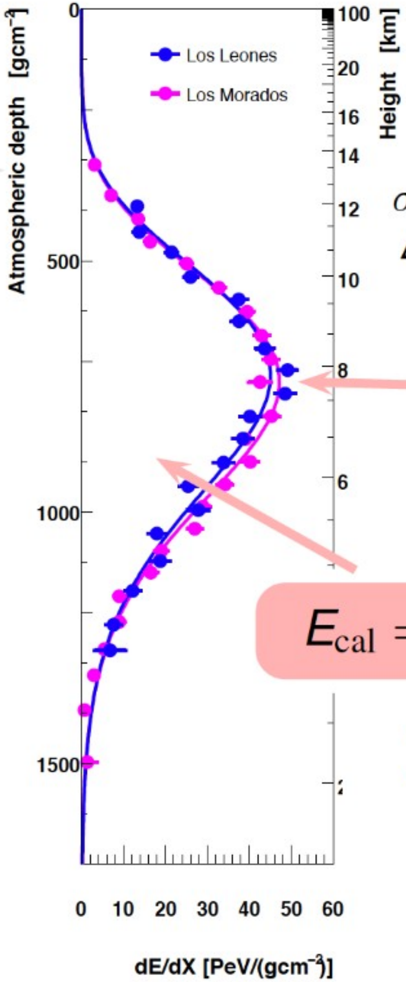
HYBRID CR AIR SHOWER DETECTION





S_{1000}

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



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

X_{max}

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

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

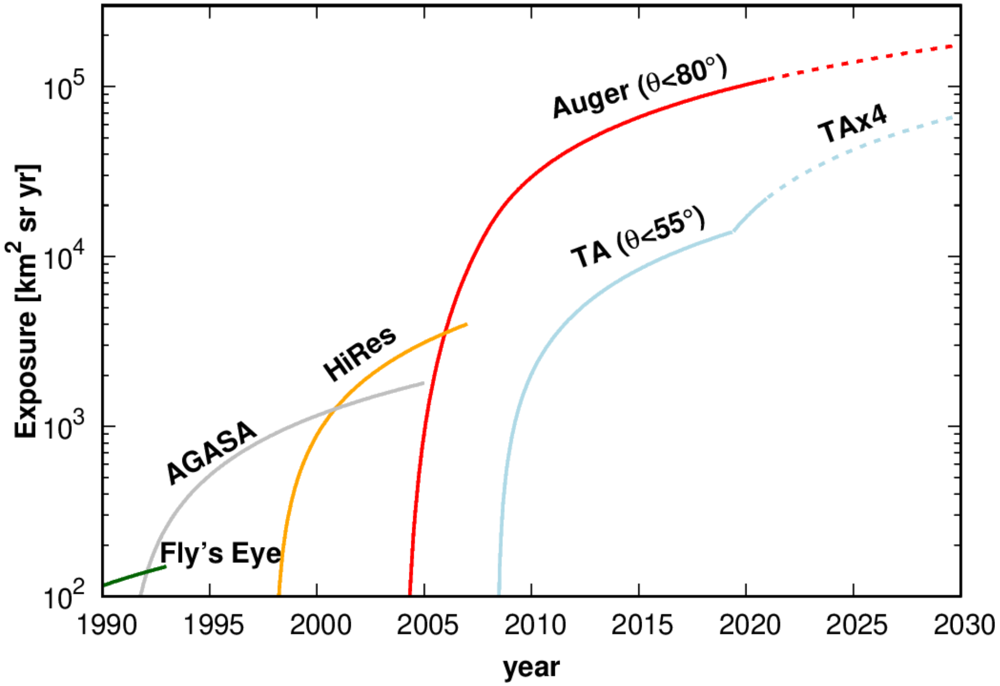
WATER-CHERENKOV SURFACE DETECTORS
(~100% duty cycle)

SD1500:
fully efficient for E > 2.5 EeV (θ < 60º), > 4 EeV (θ < 80º)

* Vertical spectrum: θ < 60º and strict trigger requirement
(all 6 stations around hottest one be active)
→ Exposure [1/04 - 9/18]: 6×10^4 km² yr sr

* anisotropies E>4 EeV: θ < 80º and relaxed trigger
(hottest station surrounded by 5 or 6 active stations)
→ Exposure [1/04 - 1/21]: 1.1×10^5 km² yr sr

* also study muon content, signal rise time, ...



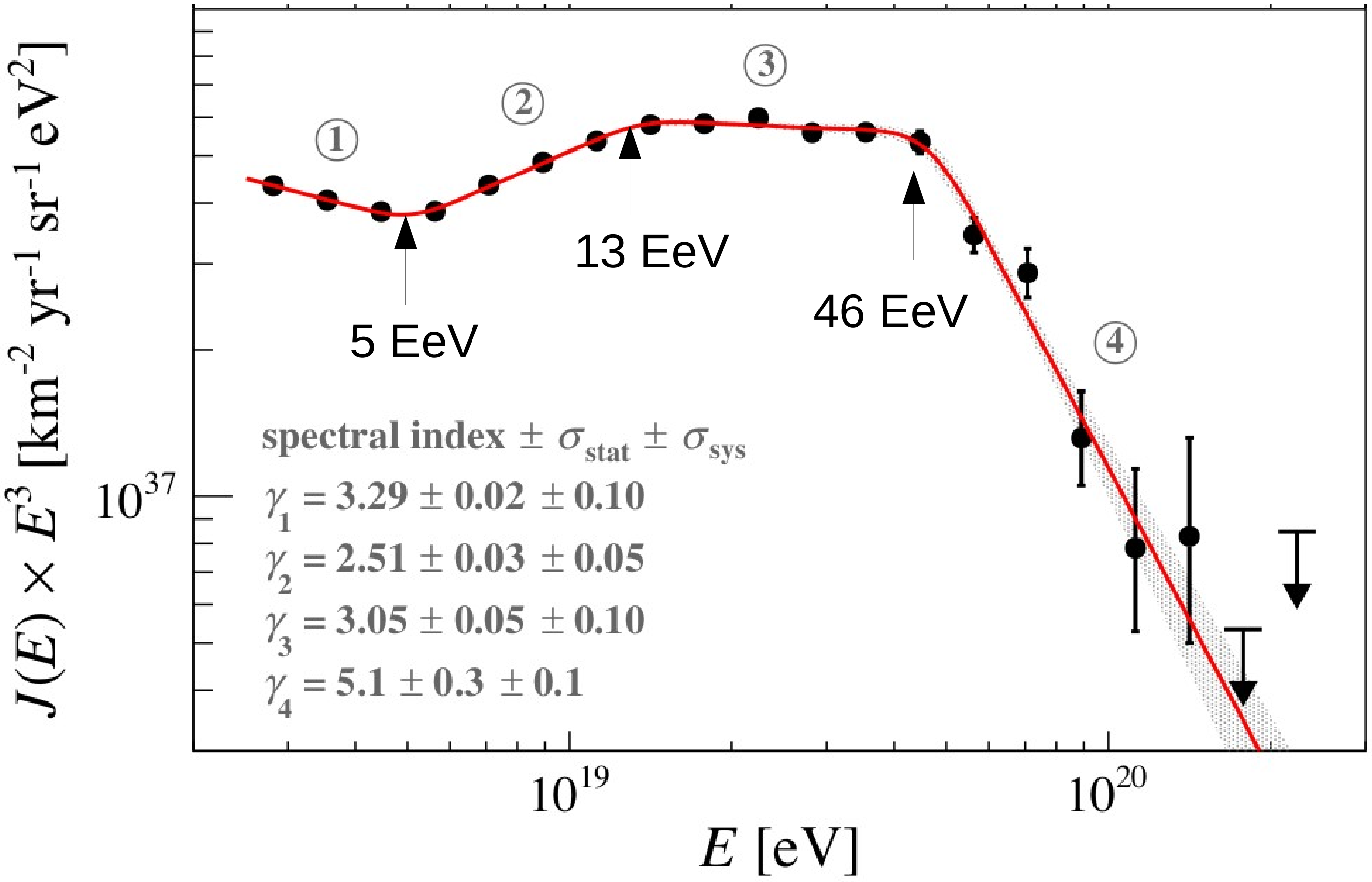
SD750:
fully efficient for E > 0.3 EeV for θ < 55º), E>0.1 EeV for θ < 40º & new trigger
* Measure spectrum and large scale anisotropies down to ~0.1 EeV

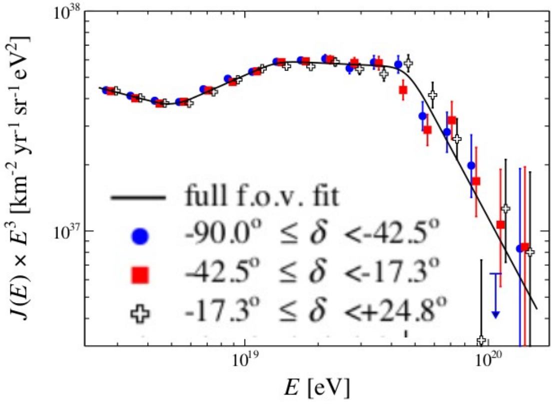
FLUORESCENCE DETECTORS
(~13% duty cycle)

Measure X_{max} → composition, used for E calibration, p-air cross section, spectrum down to $\sim 10^{16}$ eV, observation of Elves, ...

THE VERTICAL SPECTRUM

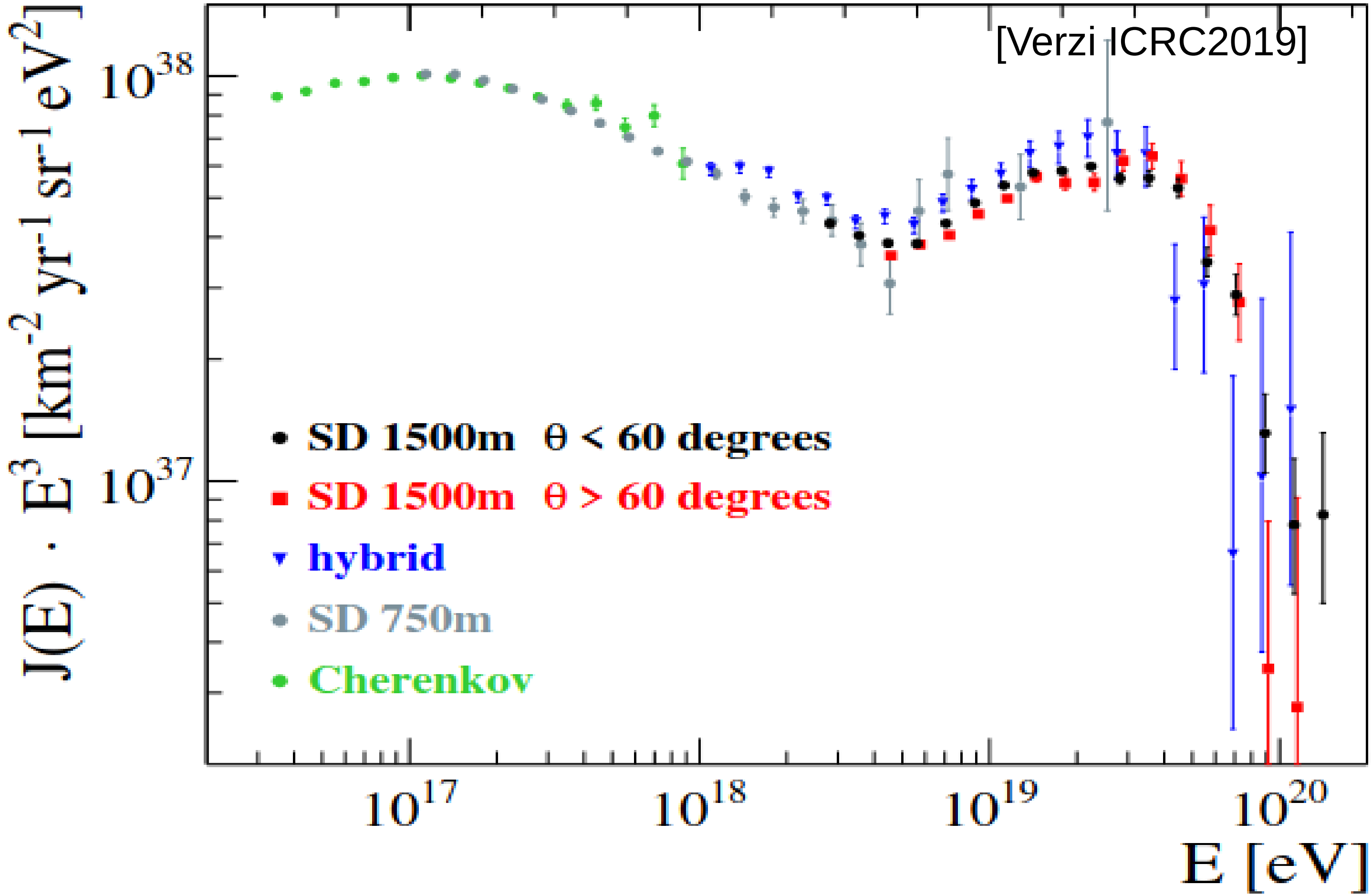
[Auger PRL&PRD 2020]





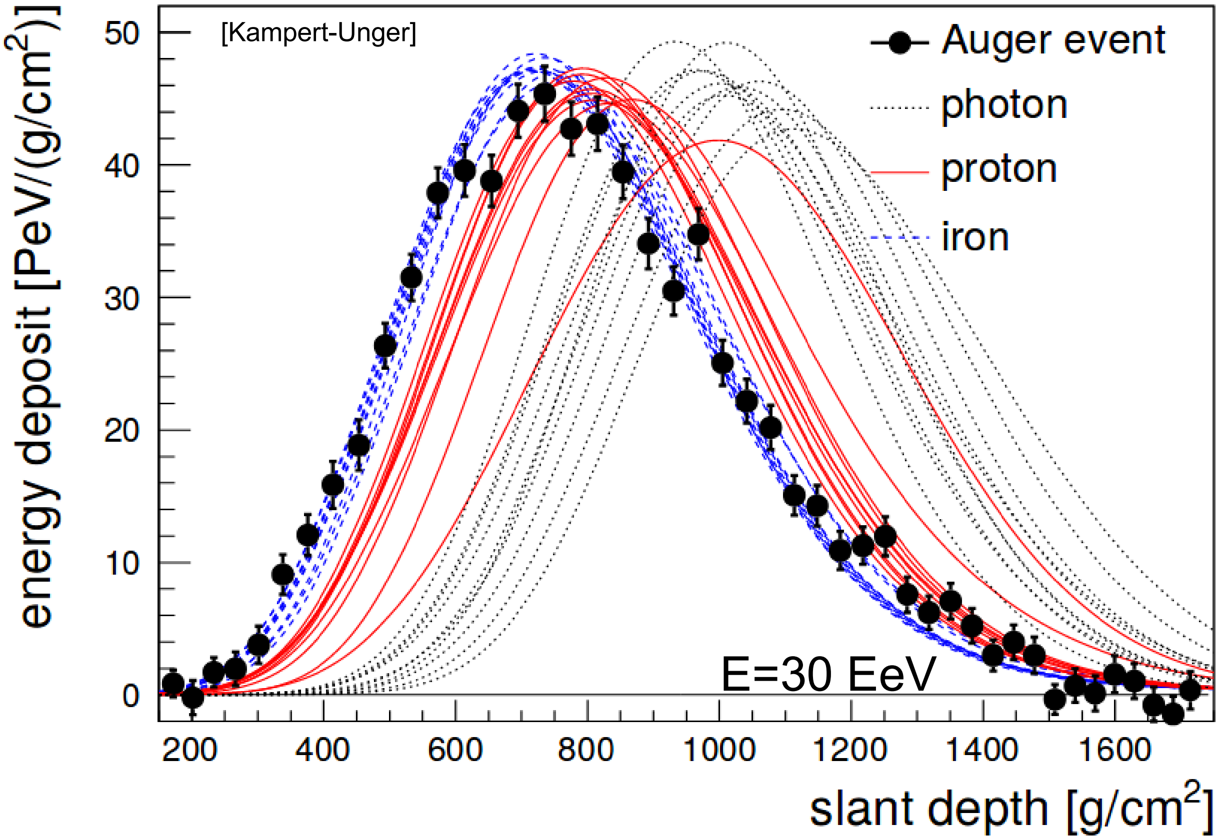
inflection identified at ~13 EeV (steepening), no declination dependence observed

THE COMBINED SPECTRUM



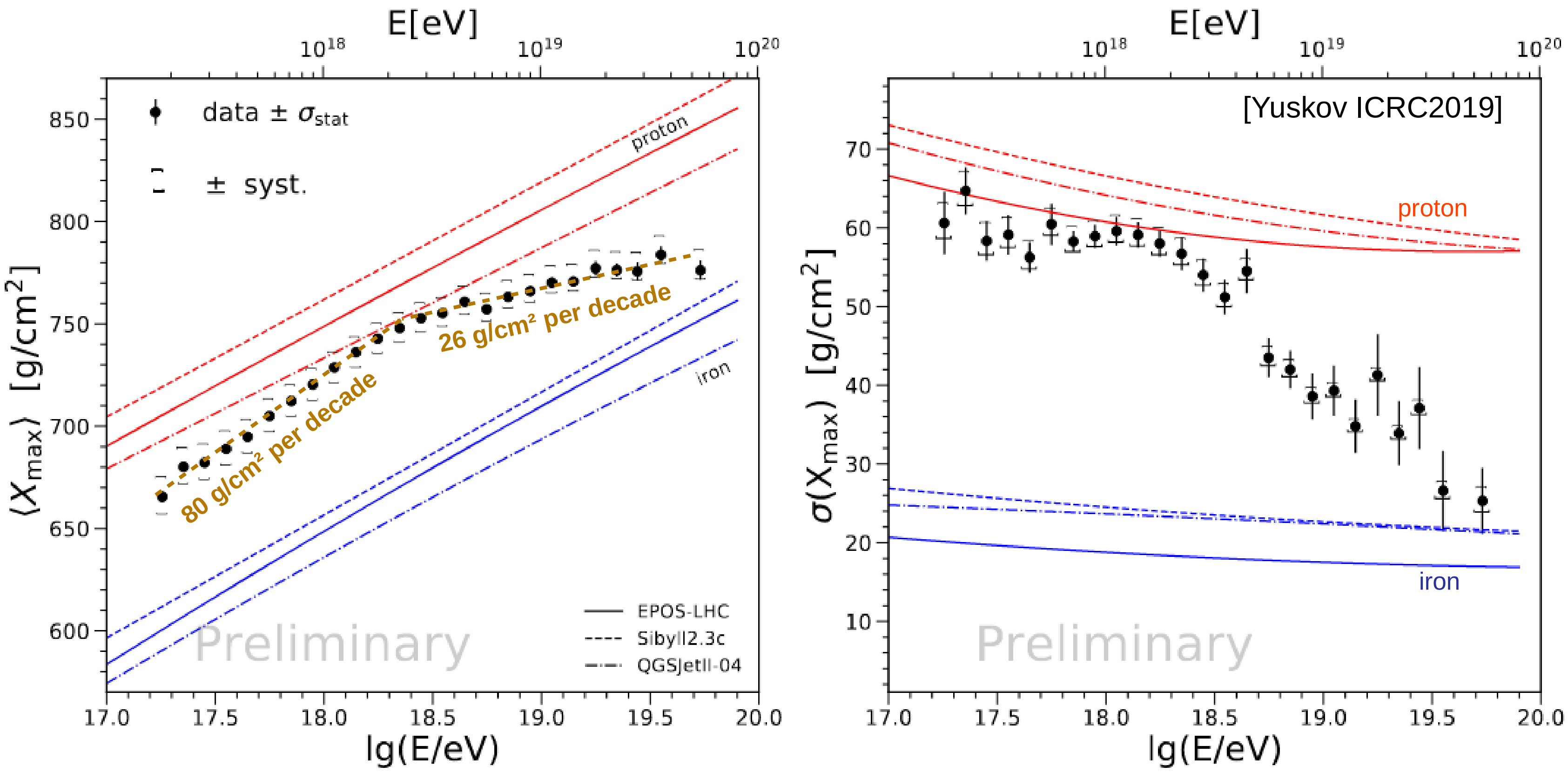
slight offsets between different spectra related to E calibrations

Xmax vs. COMPOSITION



Nuclei behave as A nucleons with E_n = E/A → less penetrating, smaller fluctuations

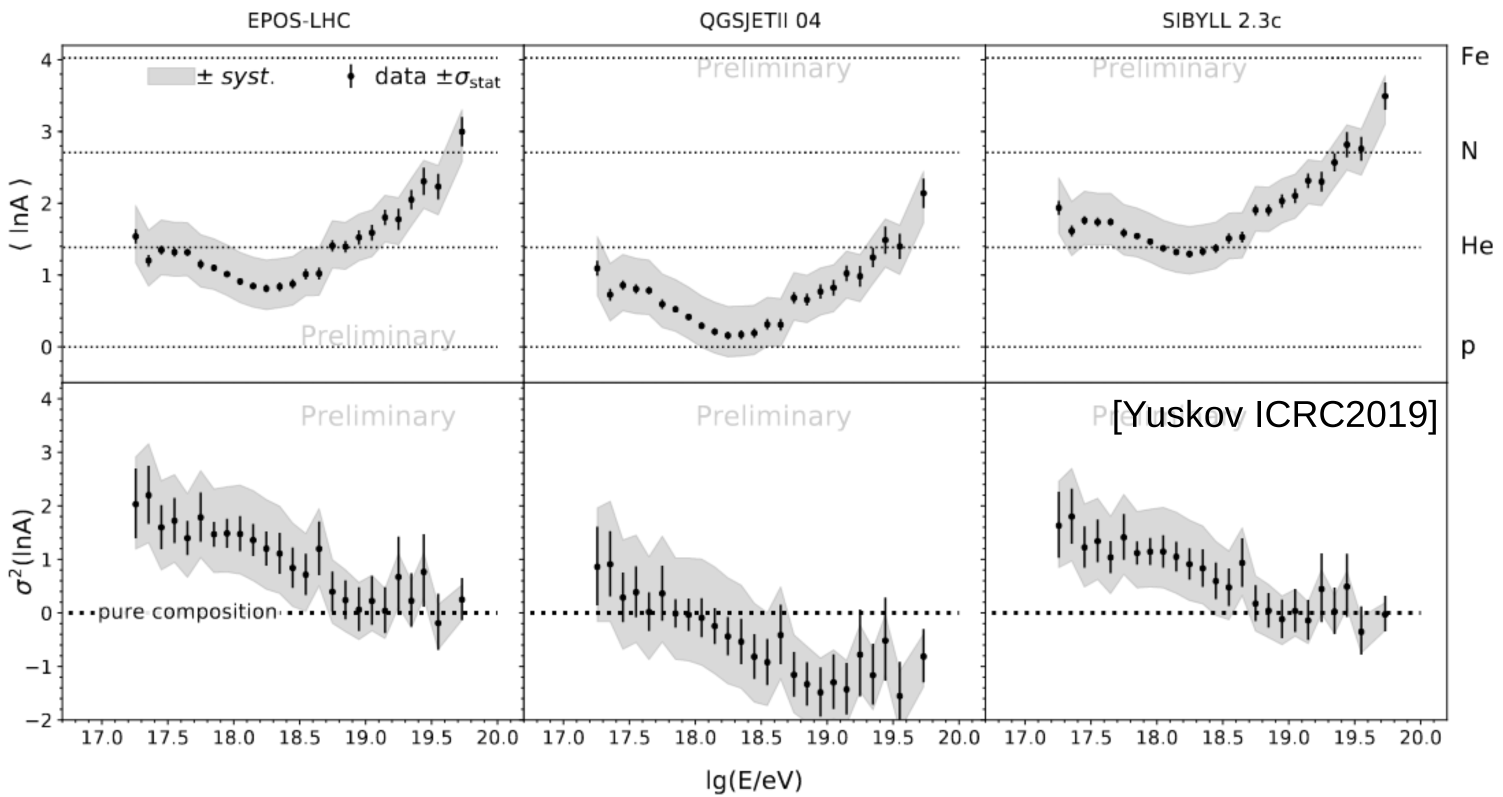
COMPOSITION FROM X_{max} at Auger



change in X_{max} slope around 2 EeV

A large spread σ can be due to light composition or to admixture of different masses

Inferred < ln A> and σ^2 ln A vs. E

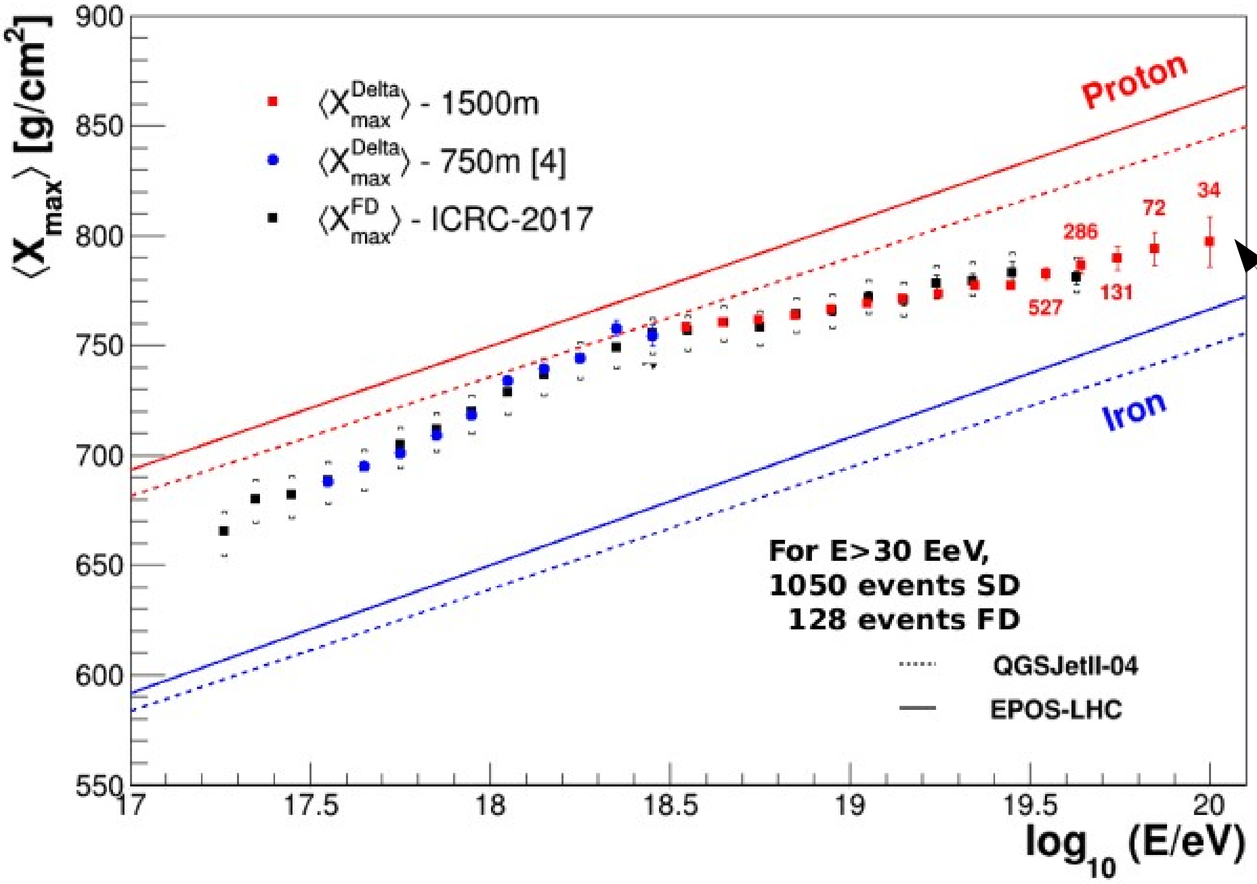


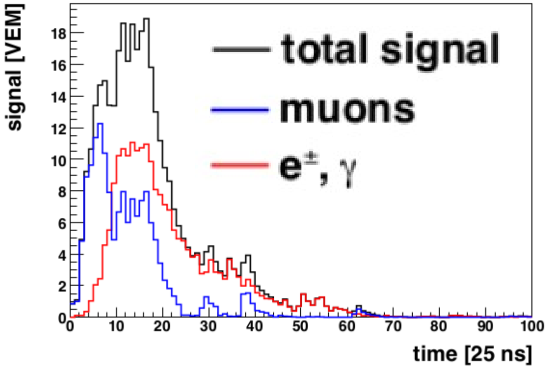
Inferred composition depends on hadronic model assumption

Composition becomes light approaching 2 EeV and heavier for increasing energies

Very little mass admixture above 10 EeV

X_{max} from SD signal rise-times





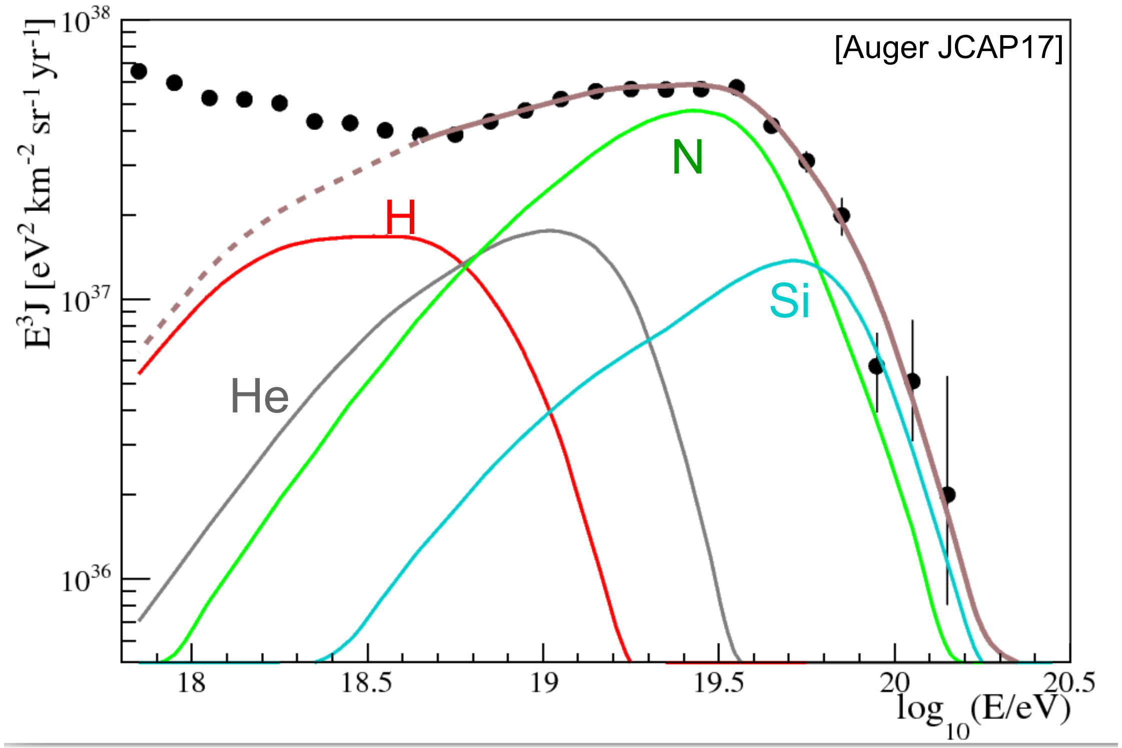
Deeper showers have larger em fraction → longer rise times

Trend towards heavier masses persists at highest energies

[Todero-Peixoto ICRC2019
Phys Rev D 2017 122003-20]

Trying to explain both spectrum and composition in mixed composition scenarios with power-law sources and rigidity cutoff:

favor scenarios with hard spectra ($dN/dE \sim E^{-1}$) and low rigidity cutoff (few EV)



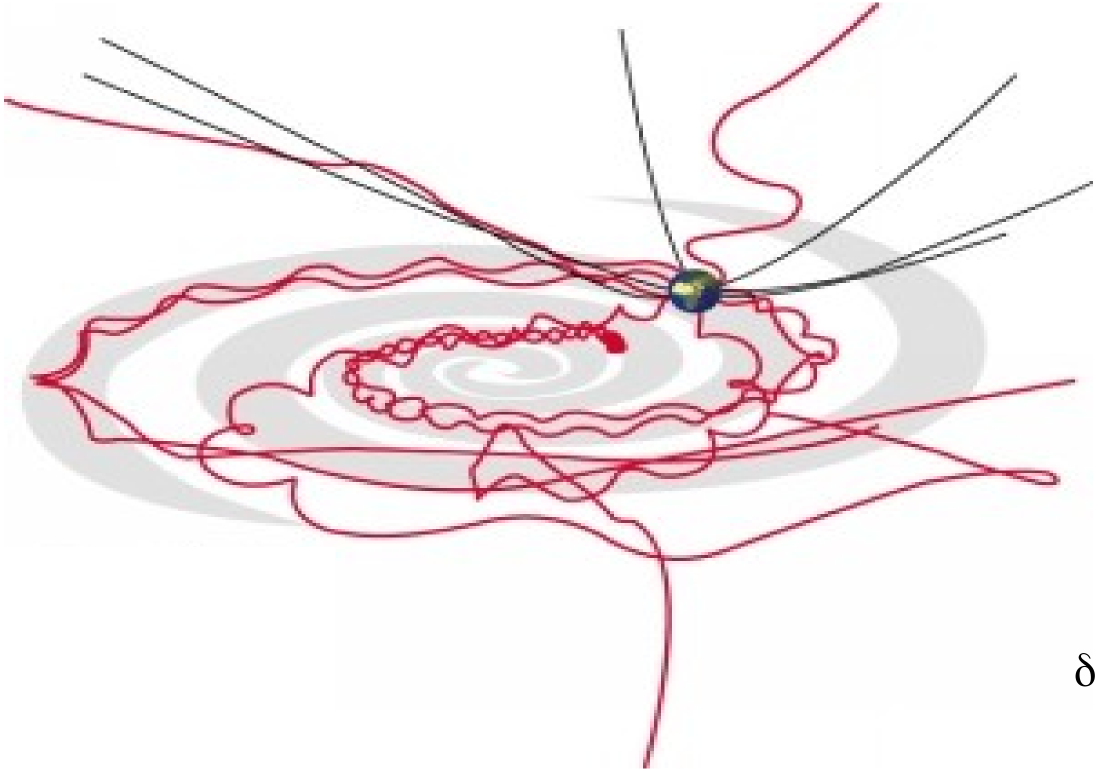
Low rigidity cutoff required to avoid admixture of light elements at highest energies

Suggests that suppression is, to a large extent, due to maximum acceleration at the sources

hard spectra required to avoid too many heavy elements near the ankle

alternatively, source spectrum could be softer ($\sim E^{-2}$) but low rigidity CRs don't have enough time to reach us due to slow diffusion in B fields (magnetic horizon)? [Mollerach&ER, JCAP 2013]

being charged nuclei, CRs get deflected by Galactic (and extra-galactic) magnetic fields



E/Z = 10 EeV

E/Z = 1 EeV

$$\delta \simeq 3^o Z \frac{B}{3\mu G} \frac{L}{kpc} \frac{6\times 10^{19} eV}{E}$$

astronomy with CRs may become possible at the highest energies

ANISOTROPIES CAN HELP TO UNDERSTAND THE UHECR ORIGIN

Large angular scale anisotropies could originate from:

- **anisotropies in the distribution of extragalactic CR sources**
- **diffusive propagation from individual sources**
- **diffusive escape from the Galaxy**

They can be present at all energies

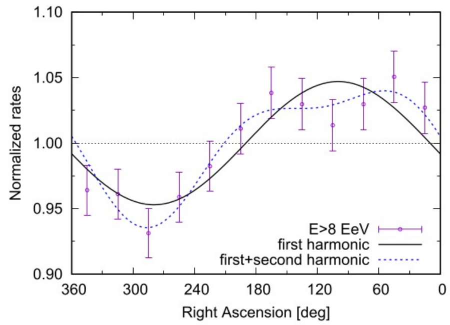
localized anisotropies at small (few degrees) or intermediate (few tens degrees) angular scales may appear at the highest energies as CR trajectories straighten up

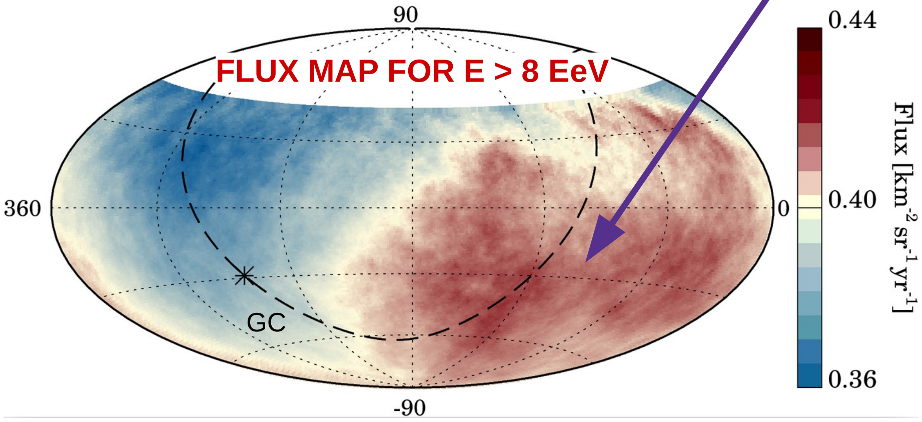
above 4 EeV, SD1500 fully efficient up to 80° → cover 85% of the sky (dec < 45°)

equatorial dipole ($d_\perp$) , NS component (d_z) , total amplitude (d) and direction

Energy [EeV] interval	median	N	$d_\perp$	d_z	d	α_d [°]	δ_d [°]
4 - 8	5.0	88,325	$0.010^{+0.007}_{-0.004}$	-0.016 ± 0.009	$0.019^{+0.009}_{-0.006}$	69 ± 46	-57^{+24}_{-20}
≥ 8	11.5	36,928	$0.060^{+0.010}_{-0.009}$	-0.028 ± 0.014	$0.066^{+0.012}_{-0.008}$	98 ± 9	-25 ± 11
8 - 16	10.3	27,271	$0.056^{+0.012}_{-0.010}$	-0.011 ± 0.016	$0.057^{+0.014}_{-0.008}$	97 ± 12	-11 ± 16
16 - 32	20.2	7,664	$0.075^{+0.023}_{-0.018}$	-0.07 ± 0.03	$0.10^{+0.03}_{-0.02}$	80 ± 17	-44 ± 14
≥ 32	39.5	1,993	$0.13^{+0.05}_{-0.03}$	-0.09 ± 0.06	$0.16^{+0.06}_{-0.03}$	152 ± 19	-34^{+19}_{-20}

has $P = 1.4 \times 10^{-9}\ (6\sigma)$

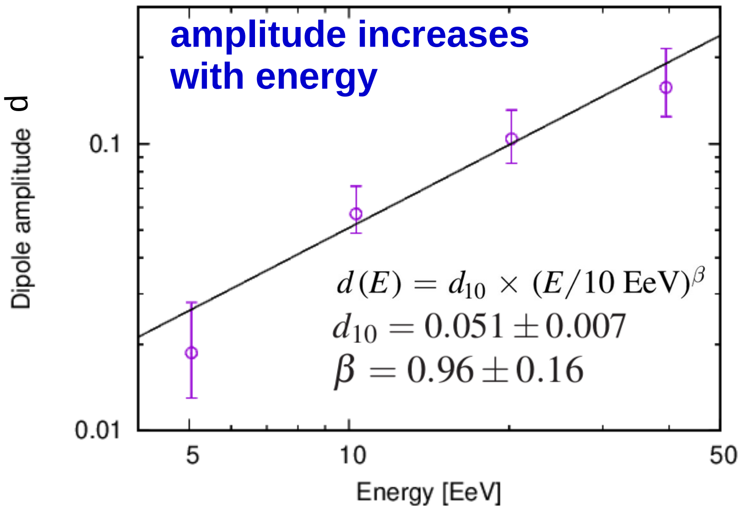


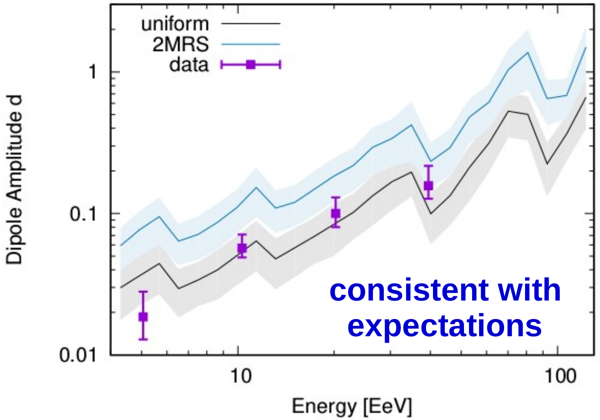


equatorial coordinates, smoothed on 45° radius windows

[Science 357 (2017) 1266
ApJ 868 (2018) 4]

Energy dependence of dipolar modulation



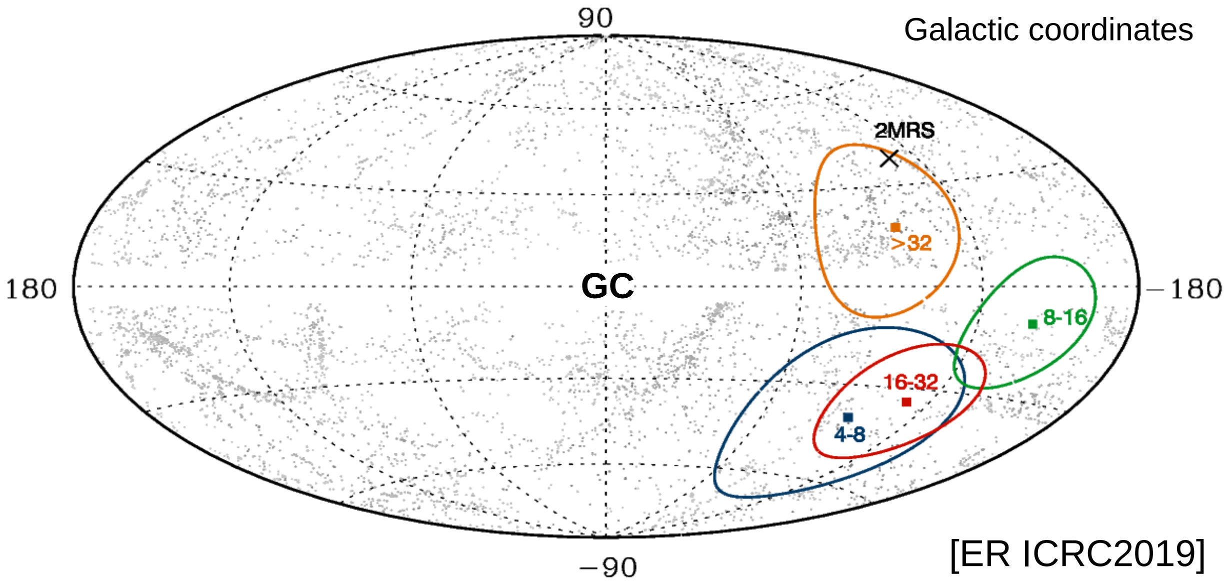


[models with source density 10^{-4} Mpc^{-3} from PRD92 (2015) 063014]

dipole direction away from Galactic Center

close to outer spiral arm in all E bins above 4 EeV

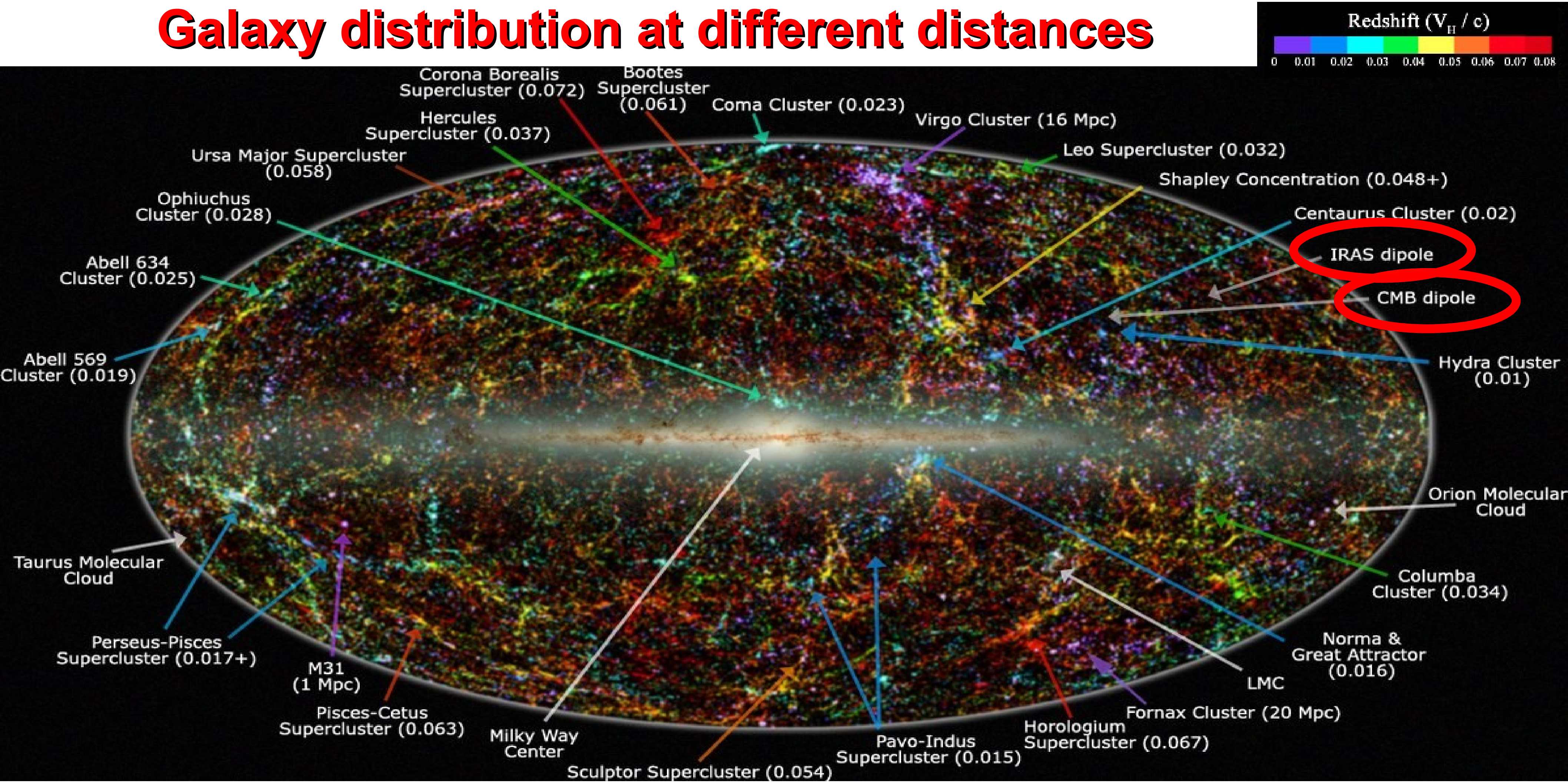
Galactic coordinates



[ER ICRC2019]

suggests that at these energies CRs are predominantly extragalactic

Galaxy distribution at different distances

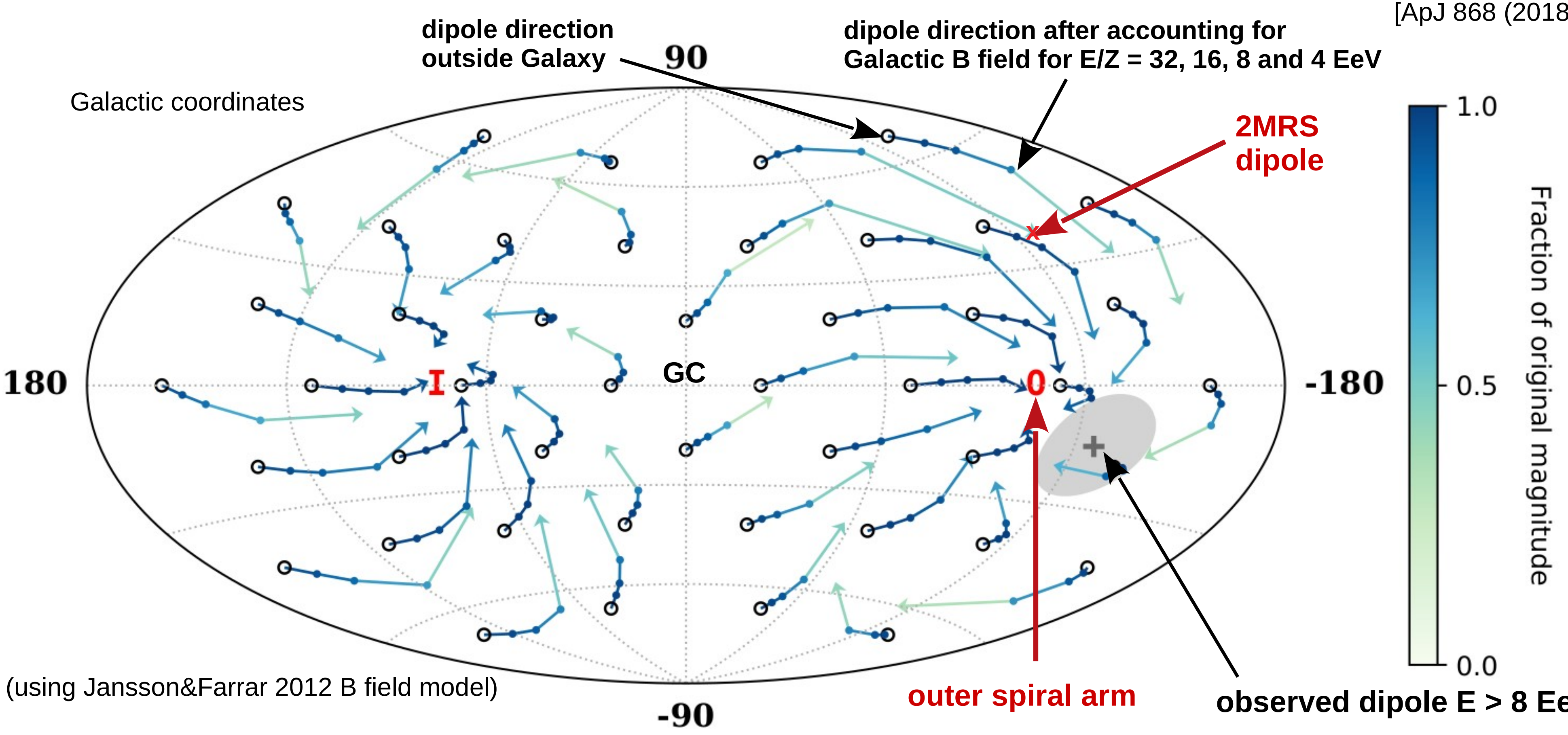


We are falling towards a region with more galaxies → dipole of the CMB

In this direction there are more galaxies, there should also be more CR sources

Effect of Galactic B field on extragalactic dipole direction (and amplitude)

[ApJ 868 (2018) 4]

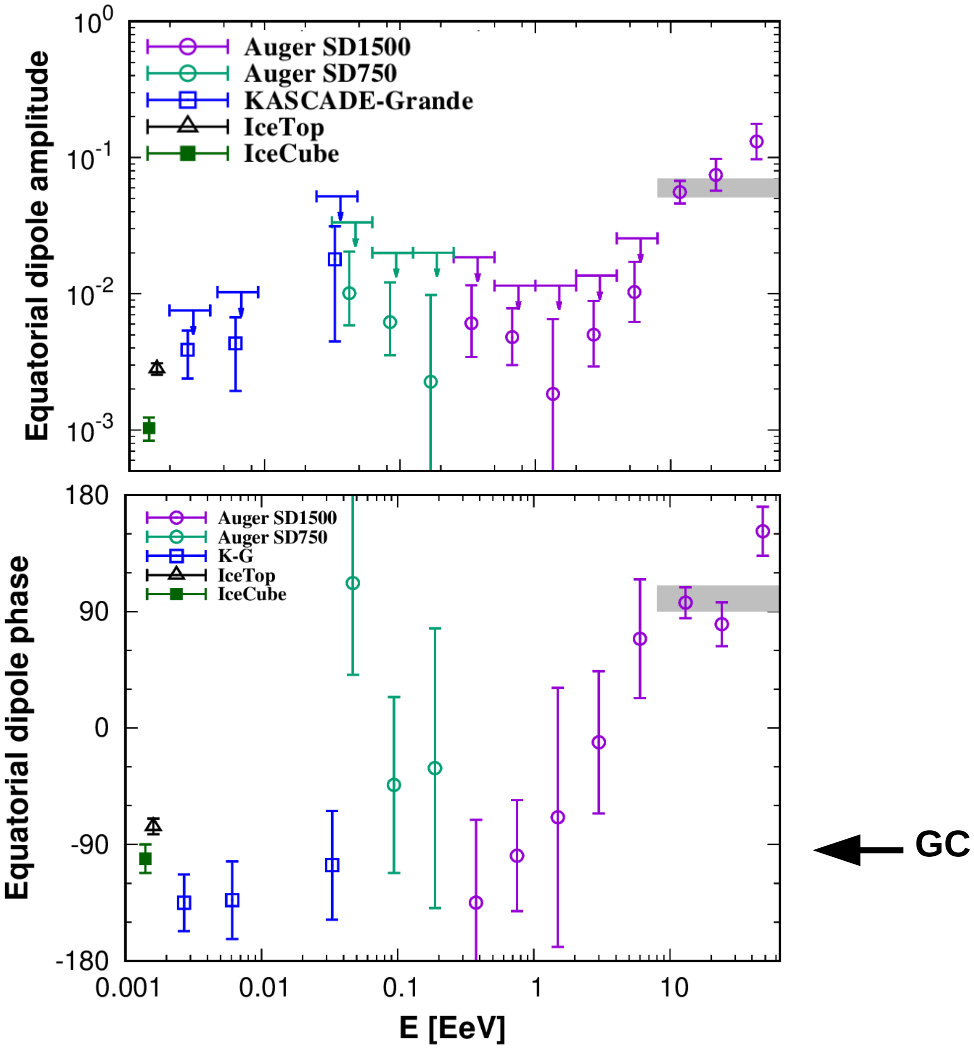


(using Jansson&Farrar 2012 B field model)

extragalactic dipole direction gets shifted towards spiral arms by Galactic B field

EQUATORIAL DIPOLE RESULTS ABOVE 0.03 EeV

[ApJ 891 (2020) 142]



(using East-West method below 2 EeV)

amplitudes grow, from below 1% to above 10%

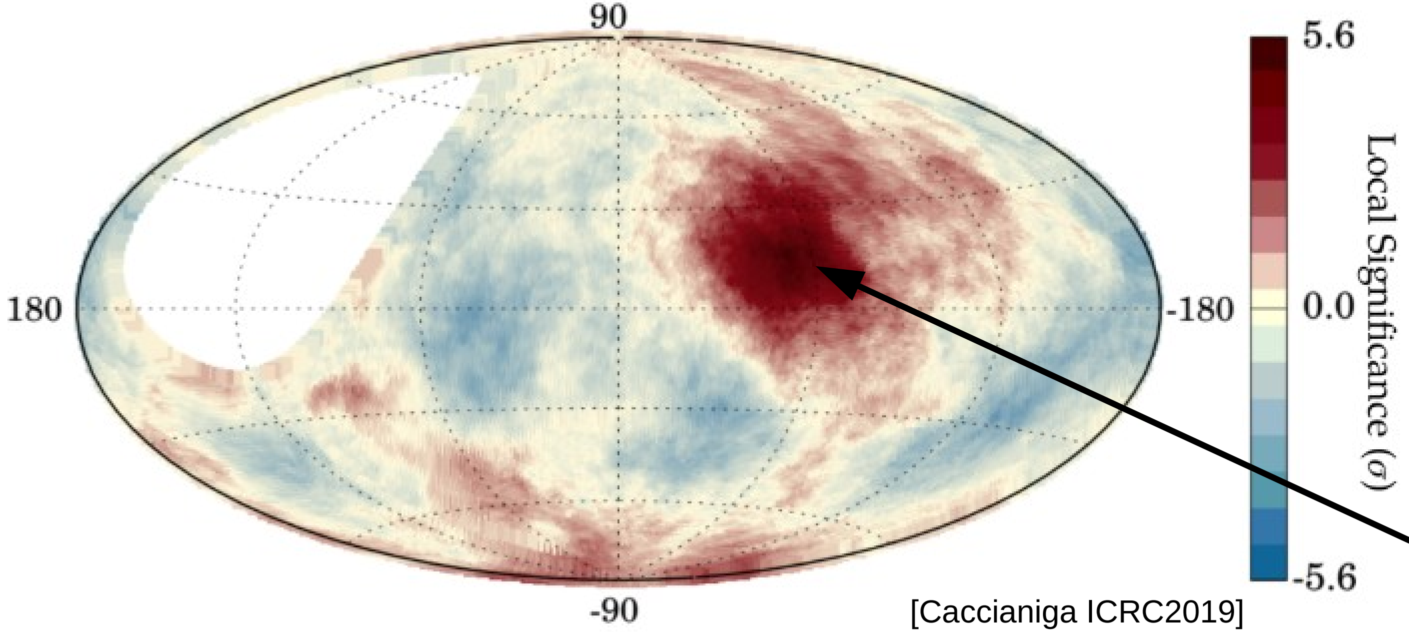
phases shift, from around the GC to almost opposite direction

Suggests transition from anisotropies of Galactic origin below ~1 EeV to extragalactic origin above few EeV

Extragalactic component could be sizeable below 1 EeV, as long as it is sufficiently isotropic

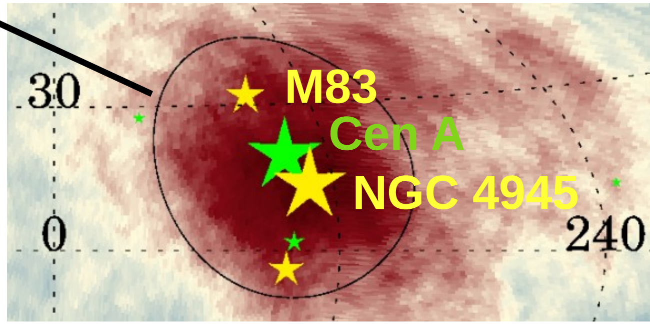
OVERDENSITIES, most significant excess for E > 38 EeV and 27° radius

(RA=202,dec=-45)
obs/exp = 188/125



[Caccianiga ICRC2019]

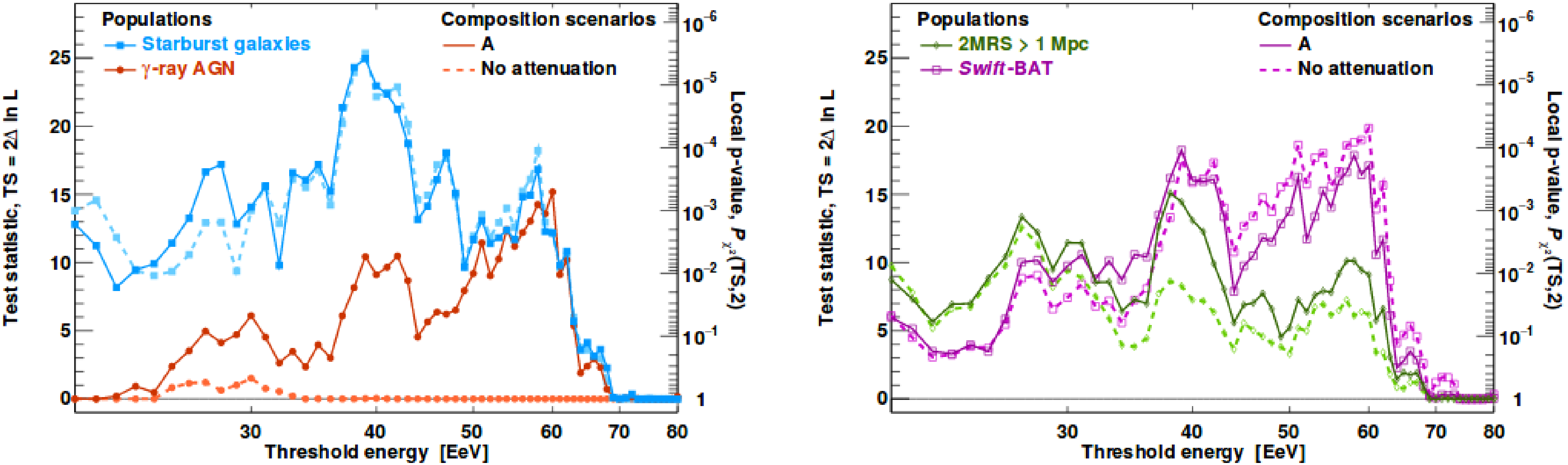
Figure 1: Map in Galactic coordinates of the local significance found when searching for excesses in circular windows with 27° radius above 38 EeV. The post-trial p-value for the most significant excess is 2.5%. See



[ApJ 804 (2015) 15; ApJ Lett. 853 (2018) L29]

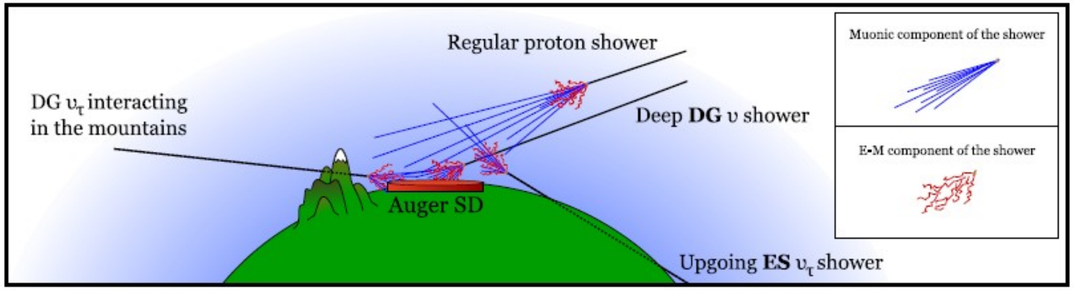
Search for correlations using Likelihood method

(using EM flux as proxy for CR flux, accounting for CR attenuation, ...) [ApJL 2018]



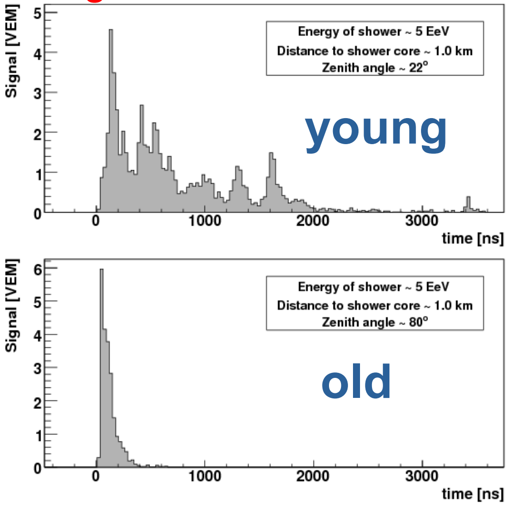
Starburst Galaxy catalog compiled by Fermi team (weighted by radio-flux)
AGNs observed by Fermi: mostly Cen A + M87 + Blazars (weighted by gamma flux)
2MRS Galaxies (weighted by IR flux)
Swift-BAT AGNs (weighted by X-ray flux)

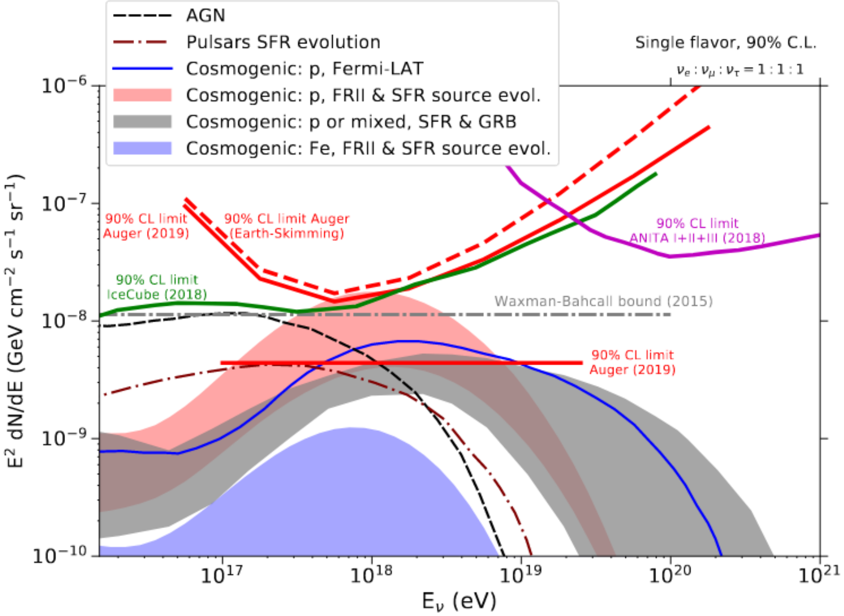
NEUTRINO DETECTION IN AUGER



Only neutrinos can produce young horizontal showers

Signal vs. time at WCD





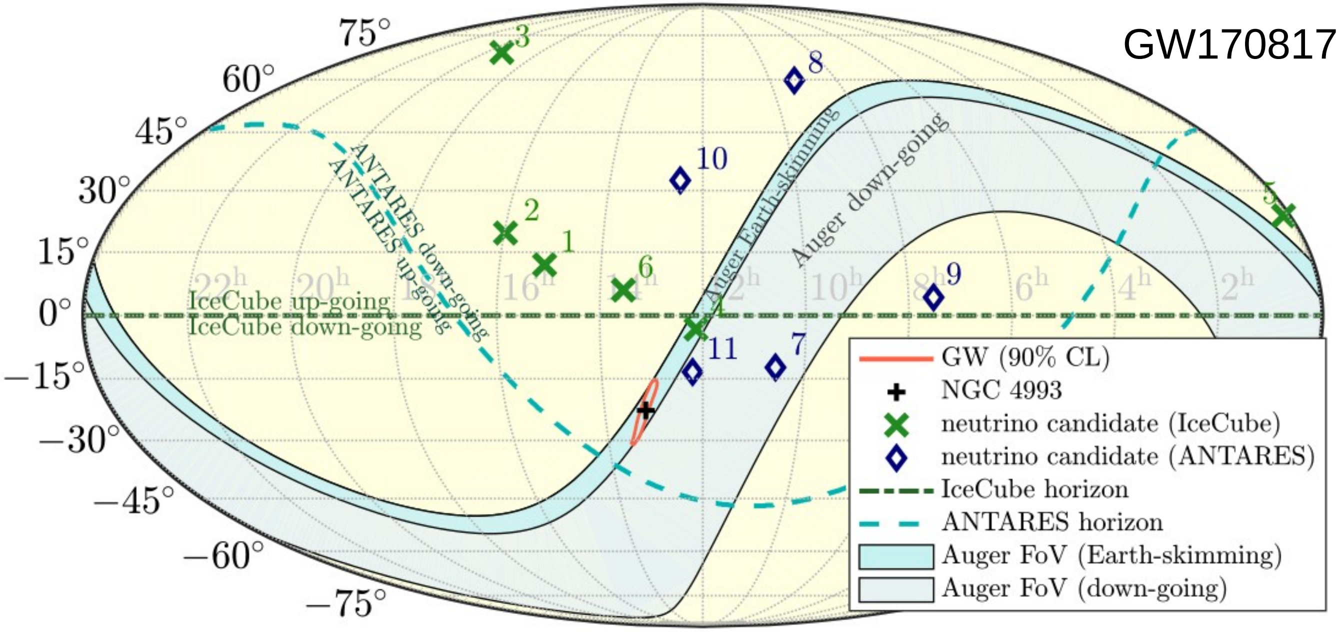
[ICRC 2019]

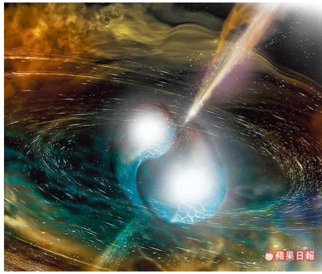
0 events observed → bounds scale linearly with exposure

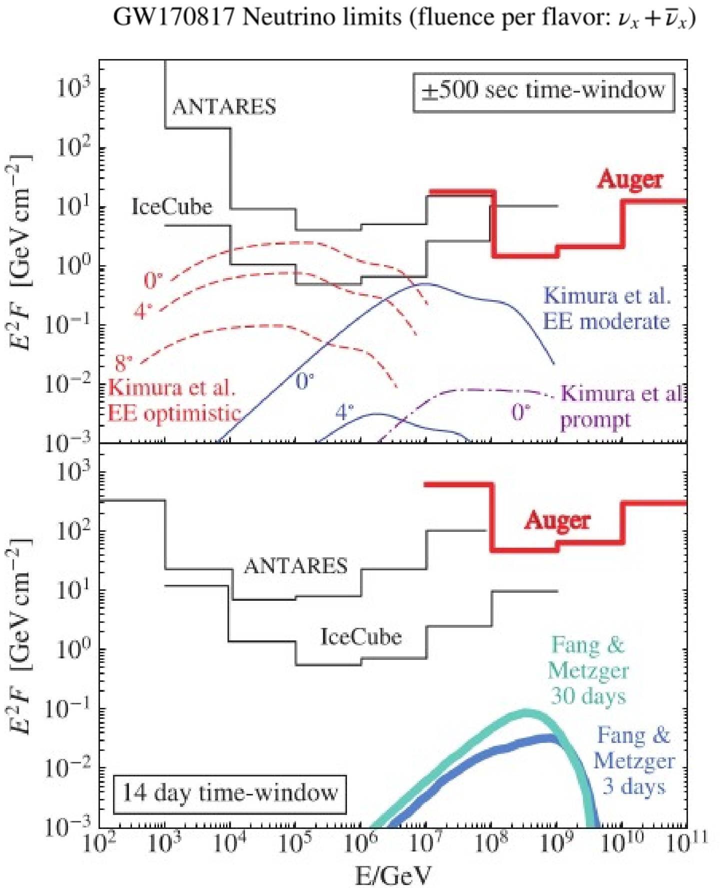
IYSICAL JOURNAL LETTERS, 850:L35 (18pp), 2017 December 1

NEUTRINOS FROM BINARY MERGERS

GW170817







Neutrinos searched in Auger, IceCube and Antares
nothing observed → flux upperbounds

Still waiting for simultaneous GW, γ and ν observation

(CRs, being charged, arrive much later)

Also didn't see UHEν from TXS 0506+056 at Auger [ApJ 2020]

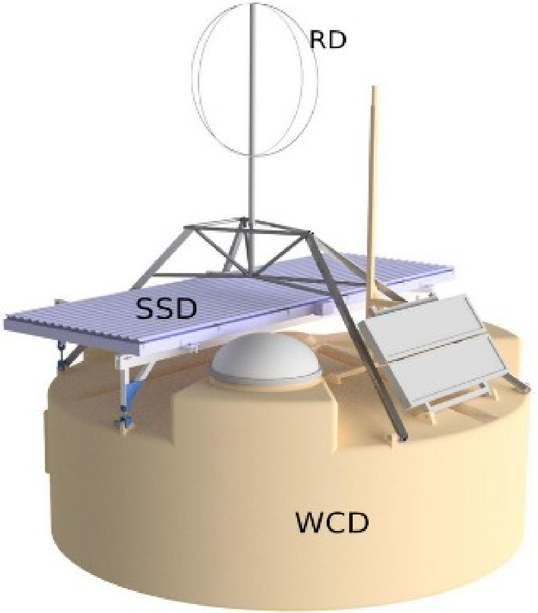
THE FUTURE: ONGOING UPGRADE

SSD: Scintillators on top of the Surface Detectors (2019-2021)

additional scintillator detectors on top of each station
refurbished electronics
small PMT to increase dynamic range

This will make it possible to separate muonic and electromagnetic signals
→ allow for composition measurements event by event
- do astronomy with light nuclear component

and help to understand:
- origin of the flux suppression at highest energies
- proton contribution at the highest energies
- EAS physics and hadronic multiparticle production



AMIGA:
Scintillators underground in Infill

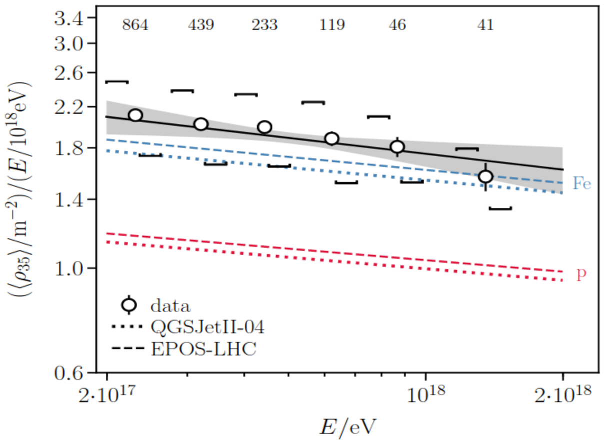
RADIO UPGRADE:

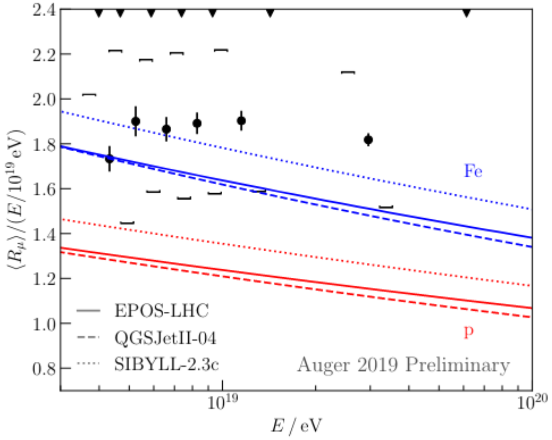
AERA: 17 km^2
→ 3000 km^2

BACKUP

MUON SIGNAL EXCESS

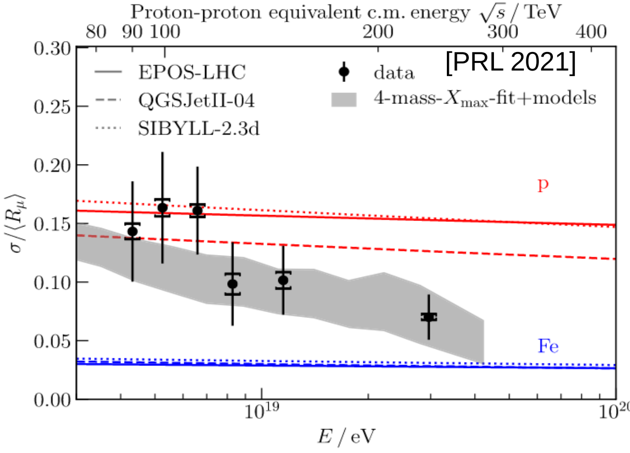
Muons vs. E





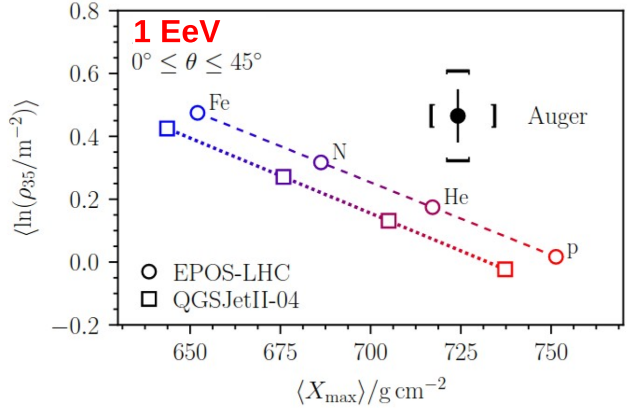
[EPJ 2020]

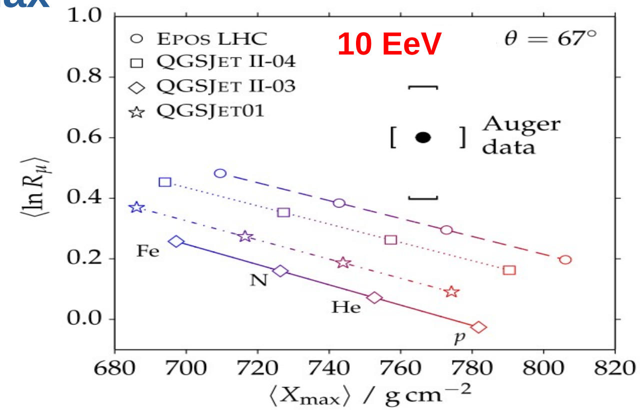
Muon fluctuations vs. E



[PRL 2021]

Muons vs. Xmax



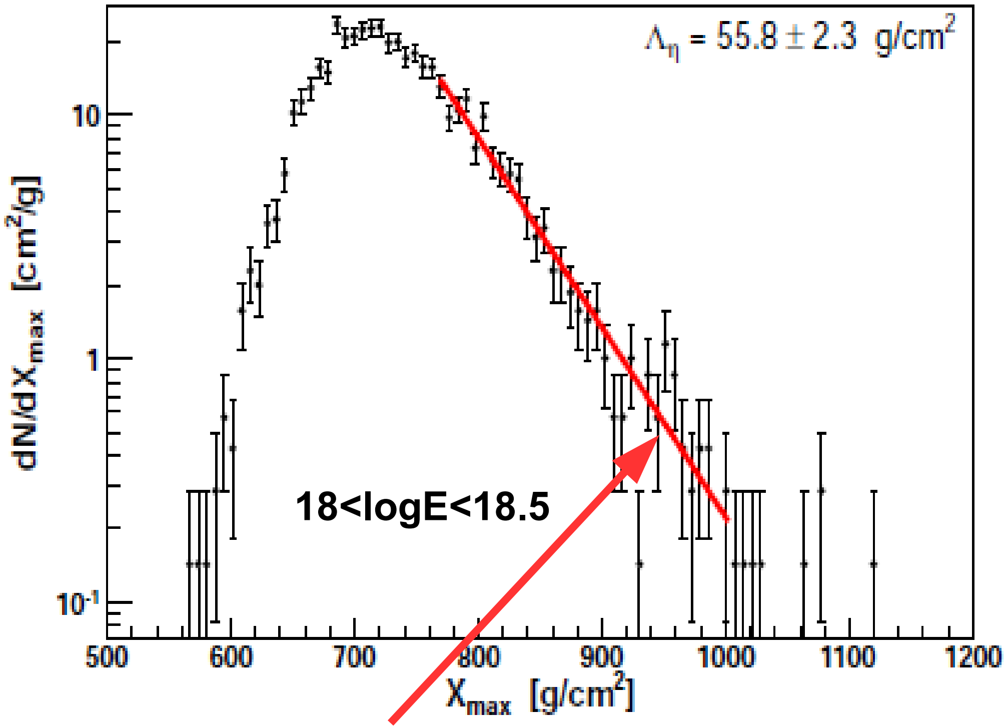


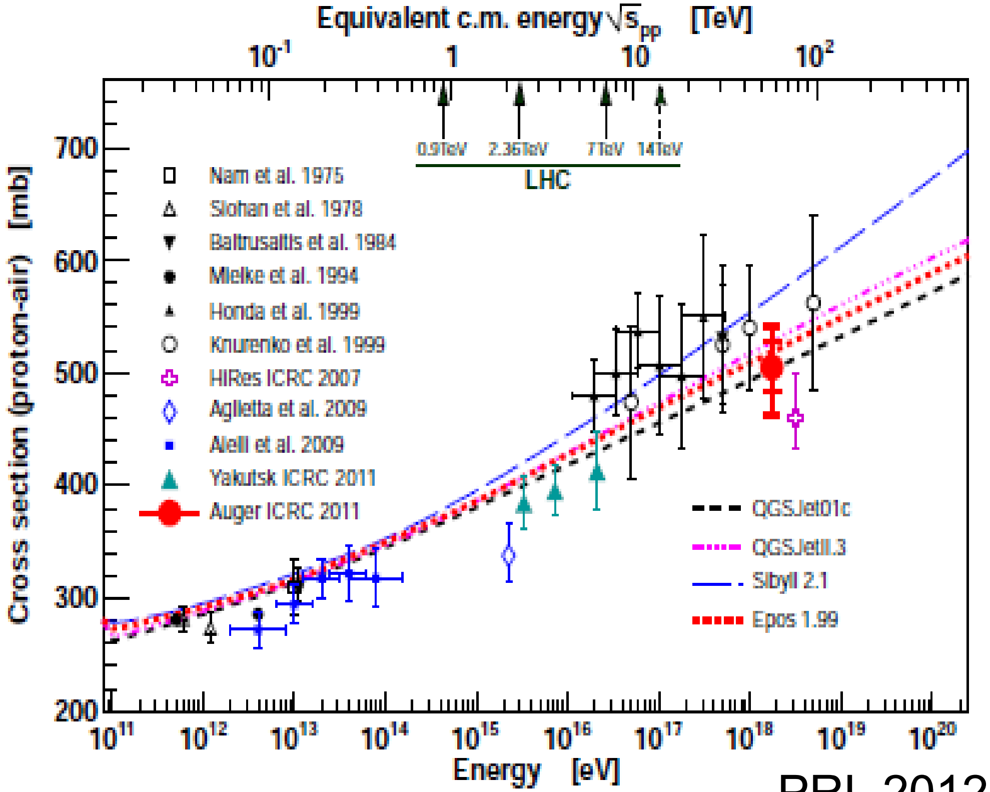
[PRD 2015]

more muons are produced than expected → hadronic models need revision
fluctuations OK → not just the first interaction, but cummulative effect in shower

p-air CROSS SECTION FROM AIR SHOWERS

Xmax distribution sensitive to depth of first interaction → to p-air cross-section





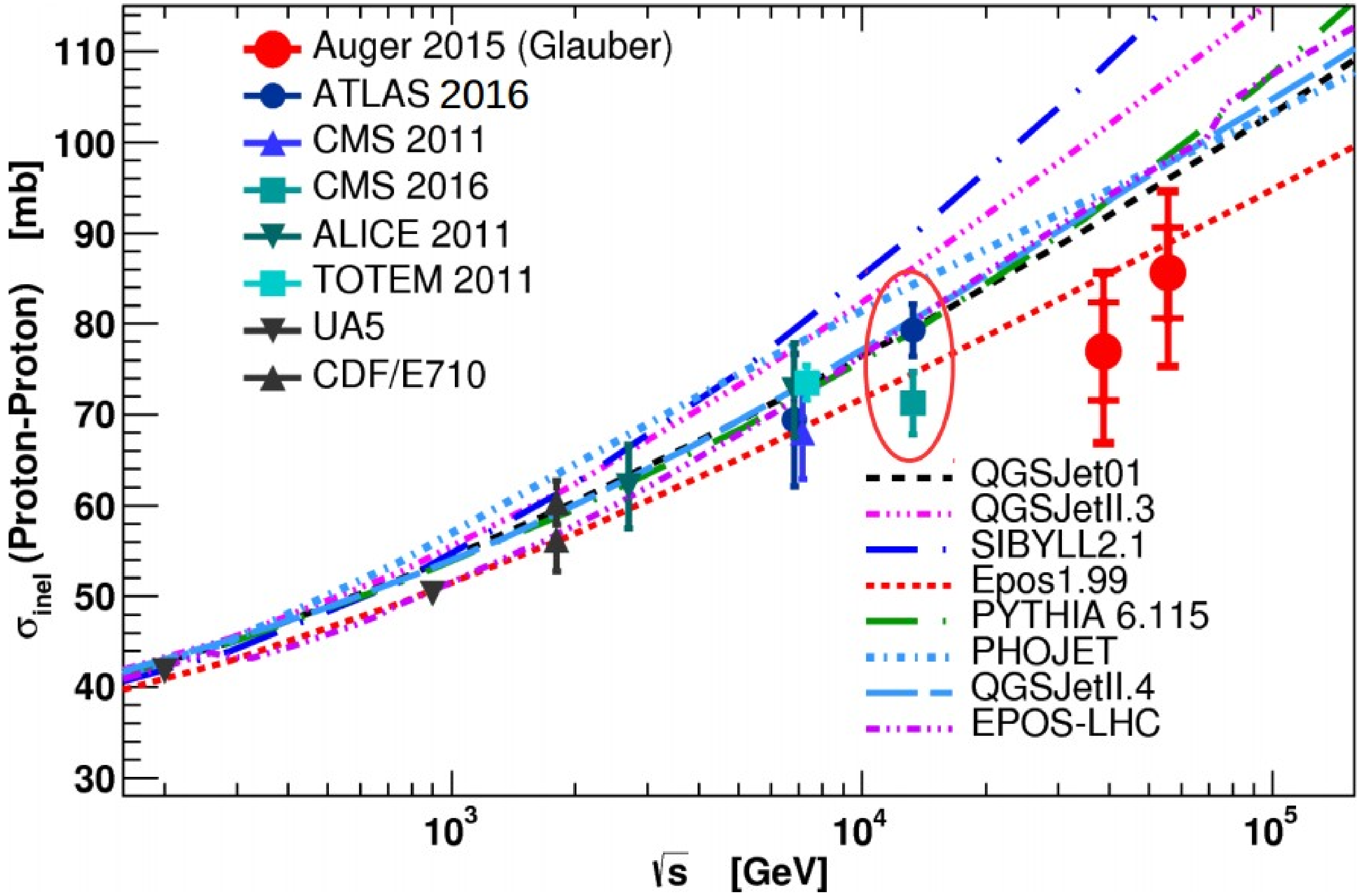
would be steeper for larger cross section

PRL 2012

p-air cross section looks 'normal'

also pp cross section can be inferred

p-p CROSS SECTION CAN BE INFERRED



Dipole allowing also for the presence of quadrupolar components

Dipole and quadrupole components in the two energy bins. The x axis is in the direction $\alpha = 0^\circ$

Energy [EeV]	d_i	Q_{ij}
4 - 8	$d_x = -0.001 \pm 0.008$	$Q_{zz} = -0.003 \pm 0.039$
	$d_y = 0.008 \pm 0.008$	$Q_{xx} - Q_{yy} = -0.004 \pm 0.028$
	$d_z = -0.014 \pm 0.022$	$Q_{xy} = 0.006 \pm 0.014$
		$Q_{xz} = -0.008 \pm 0.018$
		$Q_{yz} = -0.005 \pm 0.018$
≥ 8	$d_x = -0.004 \pm 0.012$	$Q_{zz} = 0.032 \pm 0.061$
	$d_y = 0.054 \pm 0.012$	$Q_{xx} - Q_{yy} = 0.077 \pm 0.048$
	$d_z = -0.011 \pm 0.035$	$Q_{xy} = 0.038 \pm 0.024$
		$Q_{xz} = 0.015 \pm 0.029$
		$Q_{yz} = -0.016 \pm 0.029$

no significant quadrupolar components

→ dipolar amplitudes consistent with dipole only results

EQUATORIAL DIPOLE RESULTS ABOVE 0.3 EeV

	E [EeV]	N	$d_\perp$	α_d [°]	$P(\geq d_\perp)$	$d_\perp^{99}$	$d_\perp^{UL}$
East-West (SD750)	0.03125 - 0.0625	432,155	$0.010^{+0.010}_{-0.004}$	112 ± 71	0.54	0.028	0.033
	0.0625 - 0.125	924,856	$0.006^{+0.006}_{-0.003}$	-44 ± 68	0.50	0.016	0.020
	0.125 - 0.25	488,752	$0.002^{+0.008}_{-0.002}$	-31 ± 108	0.94	0.019	0.020
East-West (SD1500)	0.25 - 0.5	770,316	$0.006^{+0.005}_{-0.003}$	-135 ± 64	0.45	0.015	0.018
	0.5 - 1.0	2,388,467	$0.005^{+0.003}_{-0.002}$	-99 ± 43	0.20	0.008	0.011
	1 - 2	1,243,103	$0.0018^{+0.0047}_{-0.0002}$	-69 ± 100	0.87	0.011	0.011
Fourier (SD1500)	2 - 4	283,074	$0.005^{+0.004}_{-0.002}$	-11 ± 55	0.34	0.010	0.014
	4 - 8	88,325	$0.010^{+0.007}_{-0.004}$	69 ± 46	0.23	0.018	0.026
	8 - 16	27,271	$0.056^{+0.012}_{-0.010}$	97 ± 12	2.3×10^{-6}	0.033	–
	16 - 32	7,664	$0.075^{+0.023}_{-0.018}$	80 ± 17	1.5×10^{-3}	0.063	–
	≥ 32	1,993	$0.13^{+0.05}_{-0.03}$	152 ± 19	5.3×10^{-3}	0.12	–
	≥ 8	36,928	$0.060^{+0.010}_{-0.009}$	98 ± 9	1.4×10^{-9}	0.028	–

99 %CL upper-bounds

6 σ