HIGH ENERGY COSMIC PARTICLES

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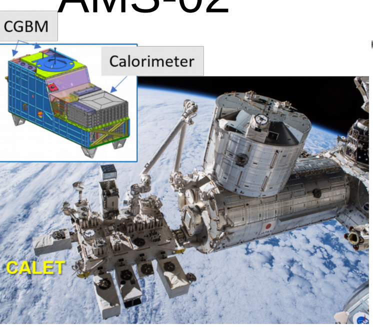
Centro Atomico Bariloche
CONICET

SPECTRUM OF COSMIC PARTICLES

Direct detection
from space

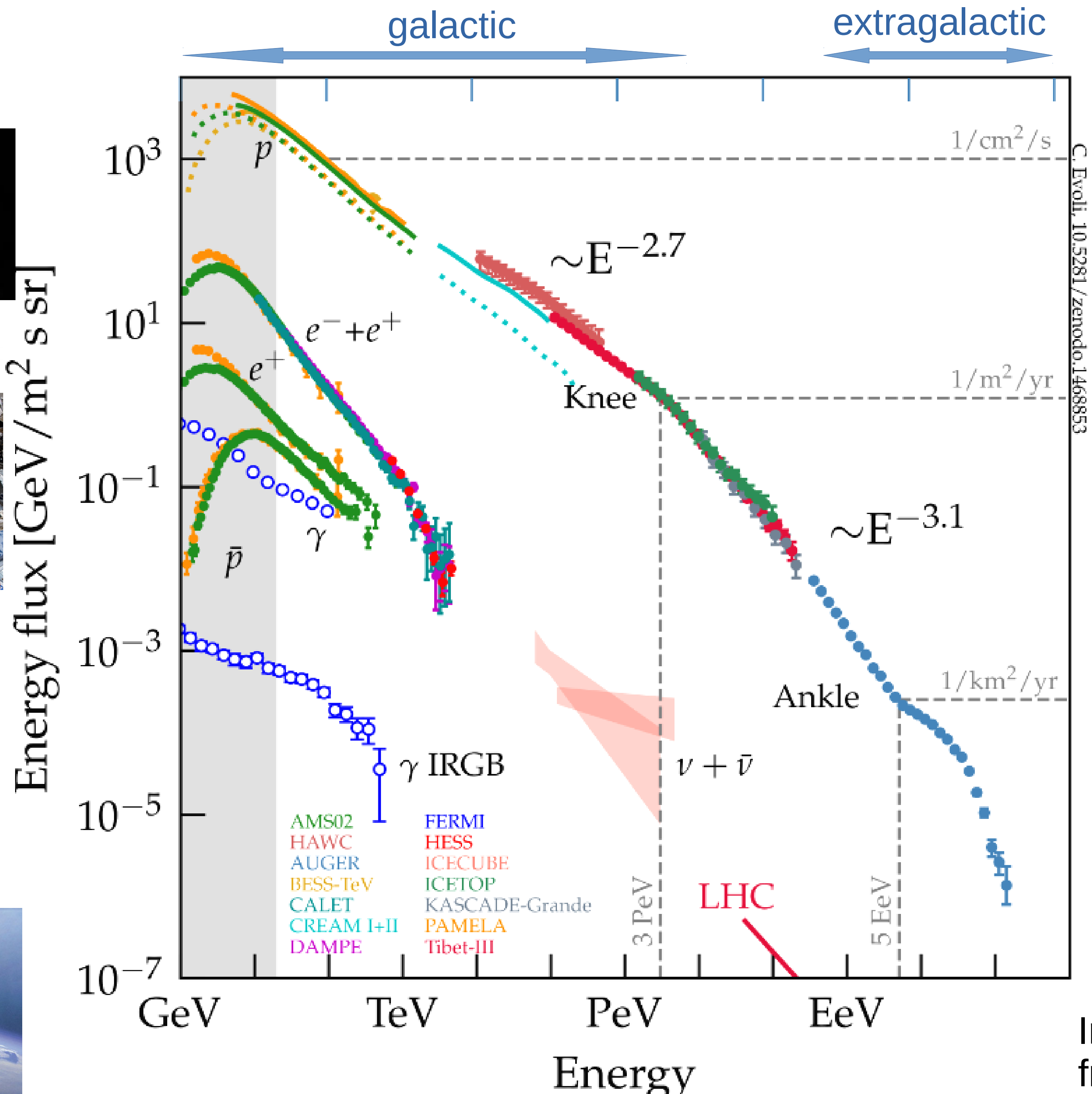
AMS-02

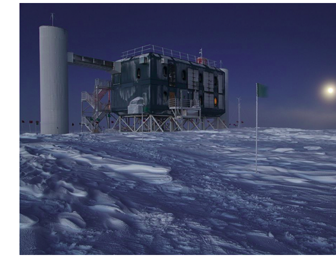


CALET

PAMELA

Fermi LAT





ICECUBE

HAWC

TA

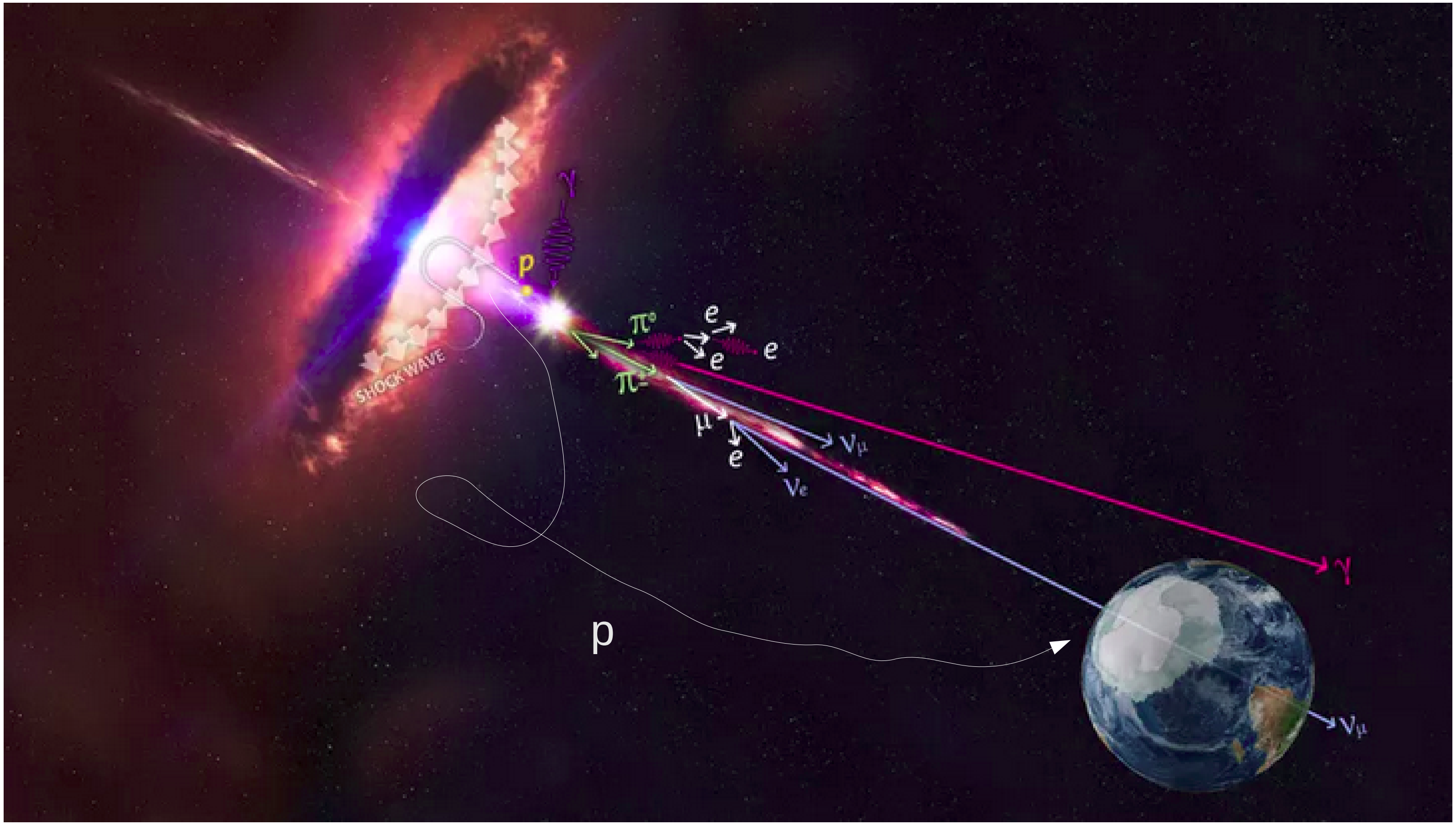
AUGER

Indirect detection
from Earth:
air-showers

Main questions:

Where and how are cosmic particles accelerated?
How is their propagation to the Earth?

e, p, nuclei: interact with gas & radiation and are deflected by magnetic fields
Photons: interact with gas & radiation, easy to be detected but attenuated
Neutrinos: weak interactions, difficult to detect but not attenuated

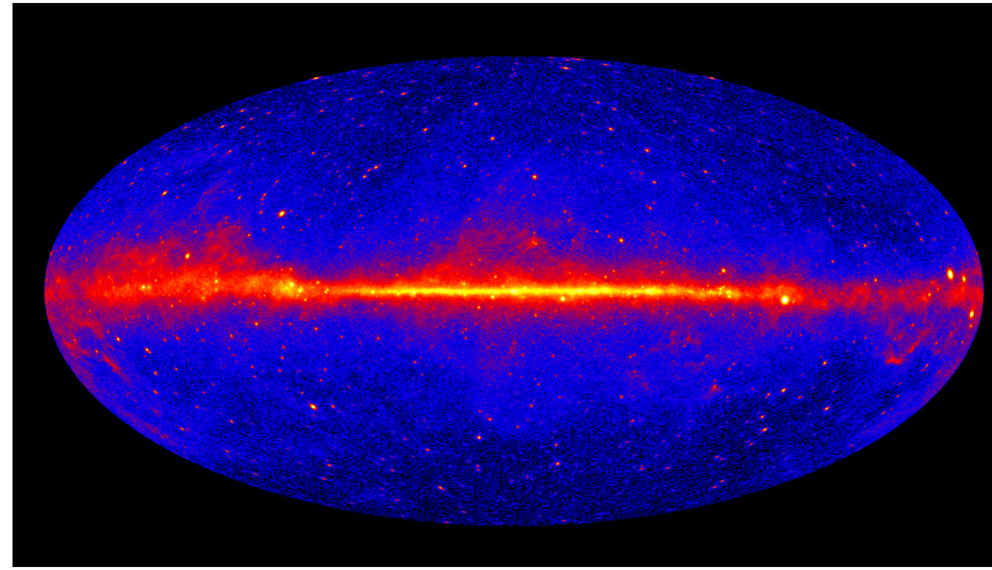


IceCube/NASA

GALACTIC COSMIC RAYS

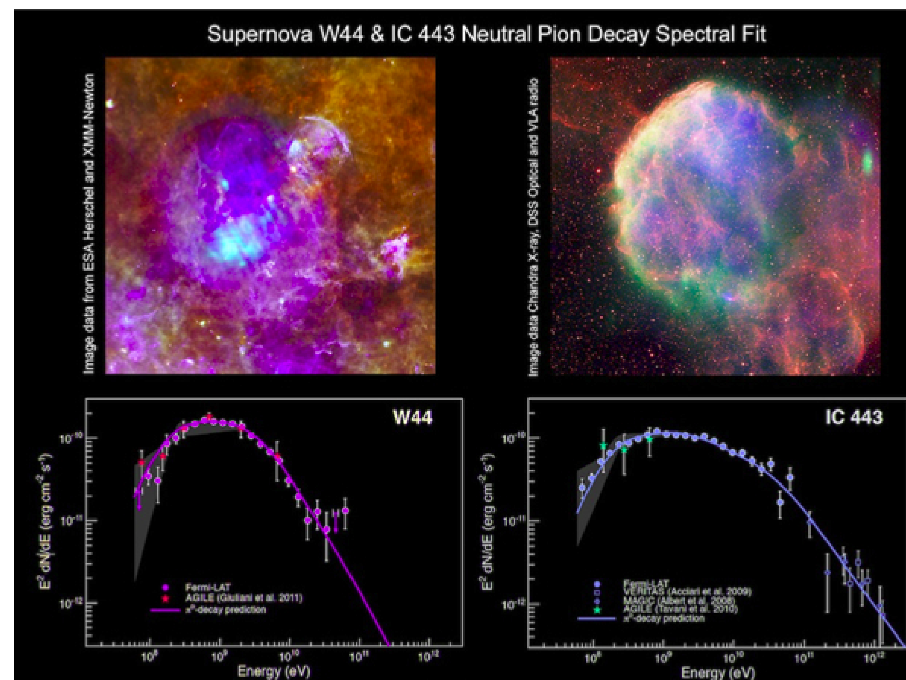
Standard scenario:
CRs accelerated in shock waves in SN explosions and propagate diffusively in the interstellar medium (ISM)

- Bright diffuse GeV gamma-ray emission from the Galactic disk explained as the result of the decay of neutral pions produced in CR interactions with the gas
$p + gas \rightarrow \pi^0 \rightarrow \gamma\gamma$



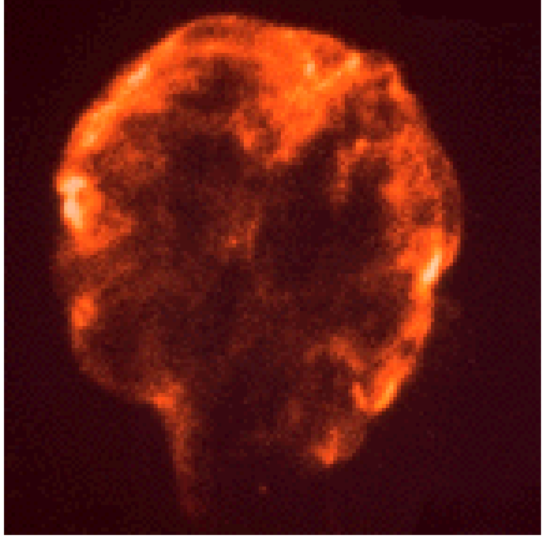
Fermi LAT diffuse gamma ray map

- Several SNRs as IC443 and W44 have gamma emission characteristic of π^0 decay
$\rightarrow$ evidence that hadrons are accelerated to CR energies in SNR shocks

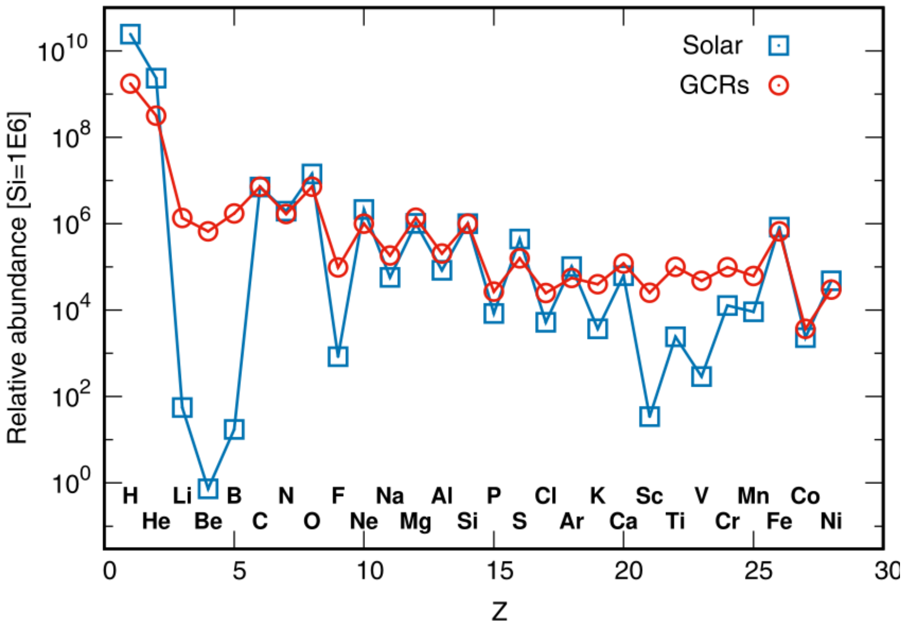


SUPERNOVA REMNANTS

Energetics: Galactic SNR can provide enough energy in CRs (~ 10% efficiency)
Diffusive shock acceleration (DSA) predicts $Q \propto E^{-2}$



Cygnus Loop in X-rays



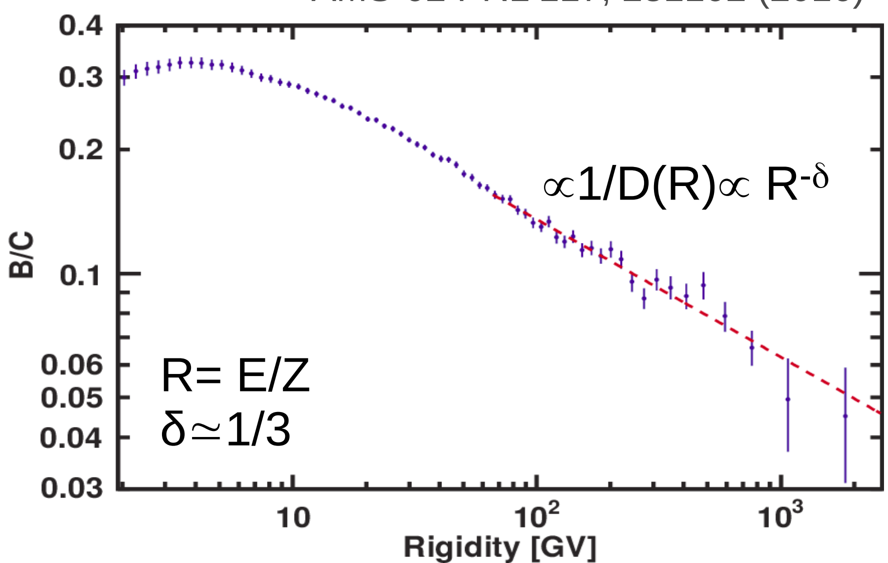
Accelerated particles are expected to have similar composition as ISM
Li, Be, B, F, Sc-Mn produced by spallation of heavier primaries

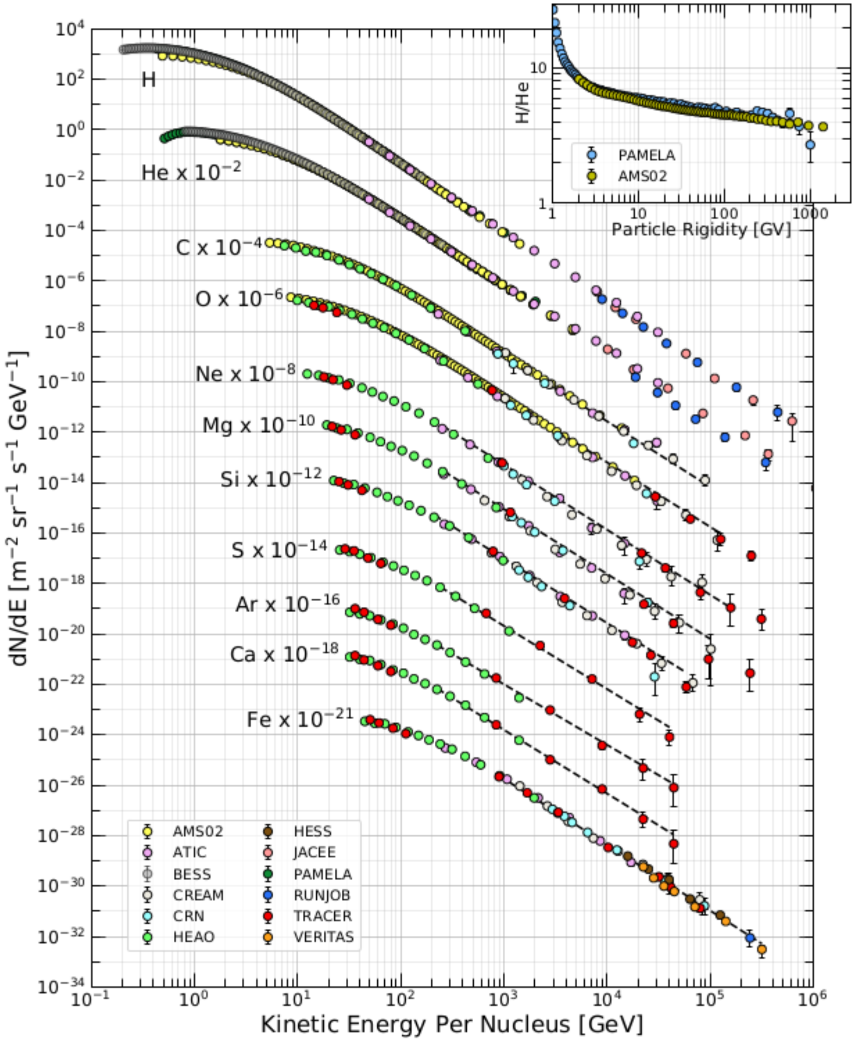
SECONDARY/PRIMARY ABUNDANCE

B/C(10GV) ~ 0.3 → traversed matter ~ 5 g/cm²
→ residence time τ(10GV) ~ 5 Myr
($\gg$ distance from the Galactic center ~0.03 Myr)

→ propagation is diffusive: charged CRs wander around for long times in Galactic B field

AMS-02 PRL 117, 231102 (2016)

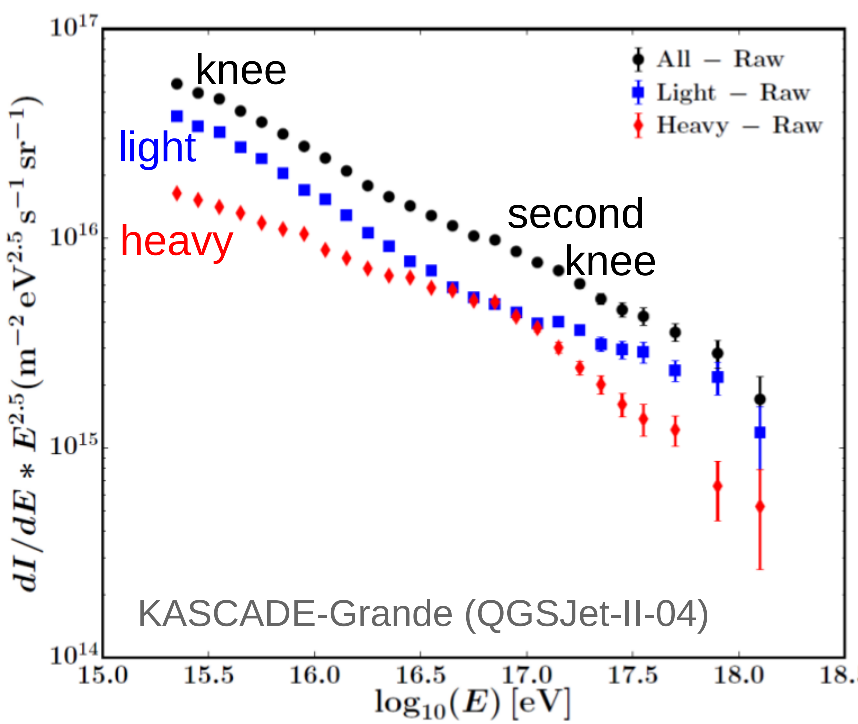




PDG 2019

GALACTIC COSMIC RAYS:

Very detailed measurements of spectrum of individual nuclei (and isotopes), e^- and e^+
Explaining spectral features lead to lively interplay between experiments & theories: details of transport D(R), new astrophysical sources, DM signals?
several talks by the AMS collaboration
reviewed by Zhili Weng 3/7

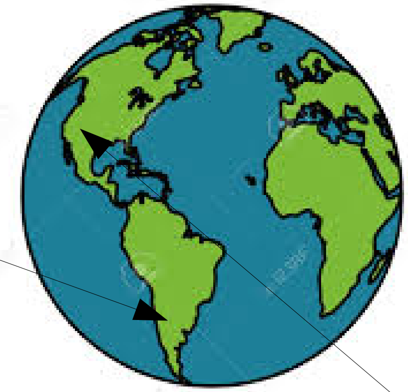


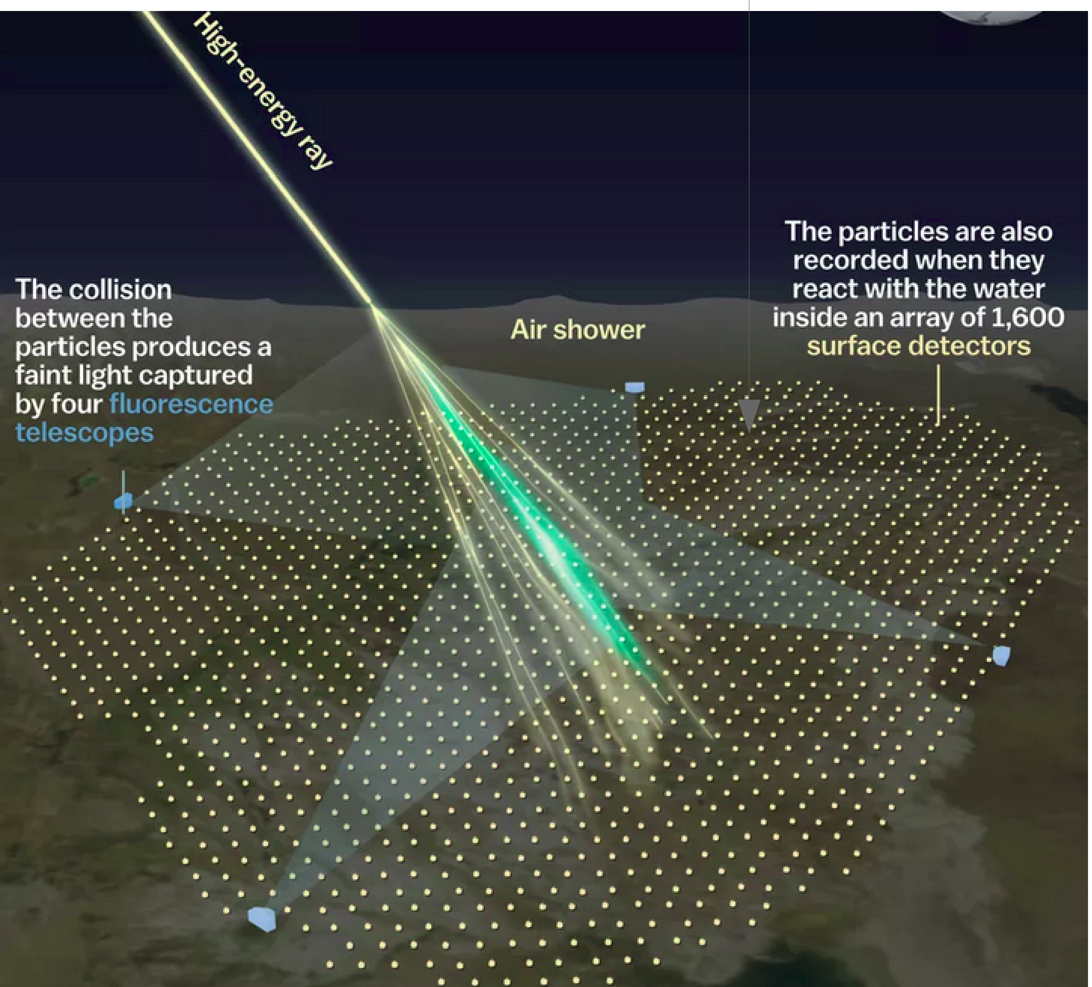
END OF GALACTIC COSMIC RAYS?

Knee @ 4 PeV: end of proton spectrum?
2nd knee @ 100 PeV: end of Fe?

EXTRAGALACTIC COSMIC RAYS: AIR SHOWERS DETECTION

Pierre Auger Observatory, Mendoza, Argentina
1660 water Cherenkov detectors, 1.5 km grid, 3000 km^2
27 fluorescence telescopes (13% duty cycle)
7 underground muon detectors
153 radio antenas

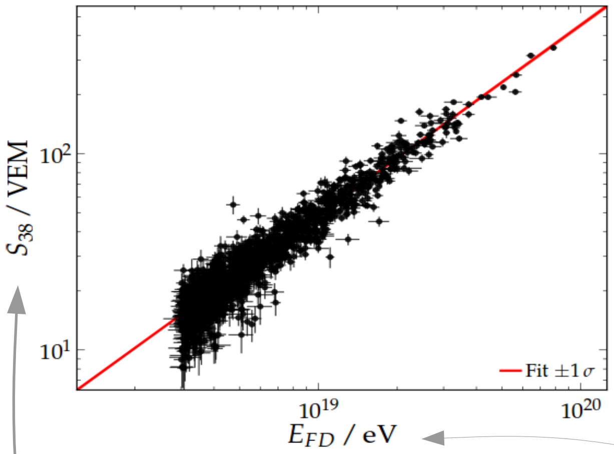


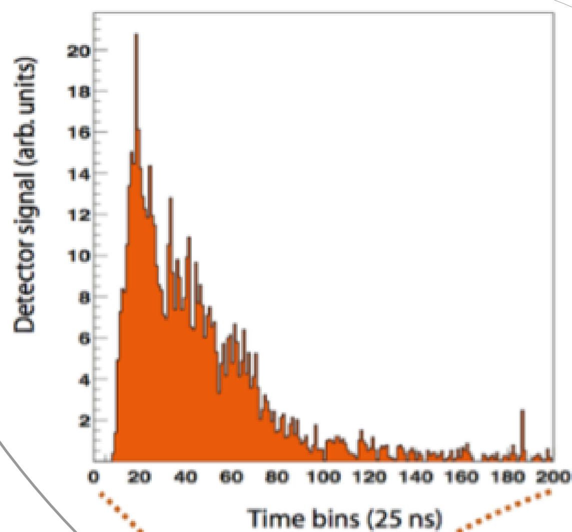


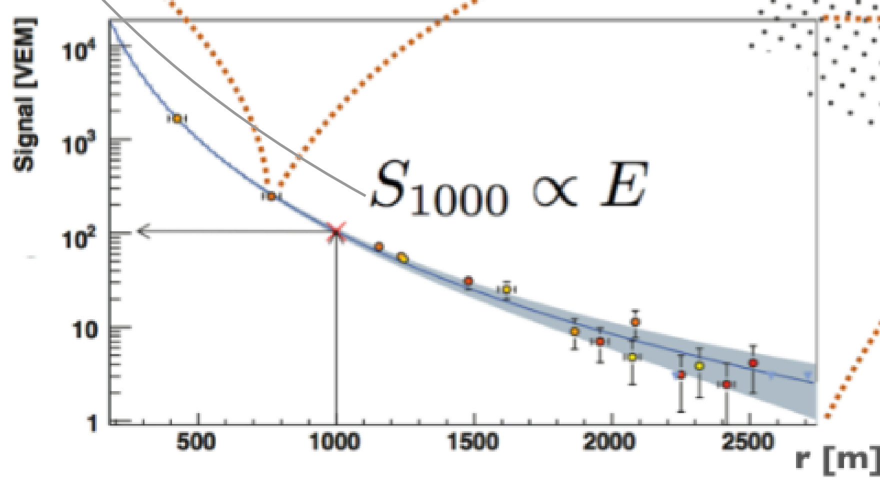
Telescope Array (TA)
Delta, UT, USA
507 scintillator detectors,
1.2 km grid, 700 km^2
36 fluorescence telescopes

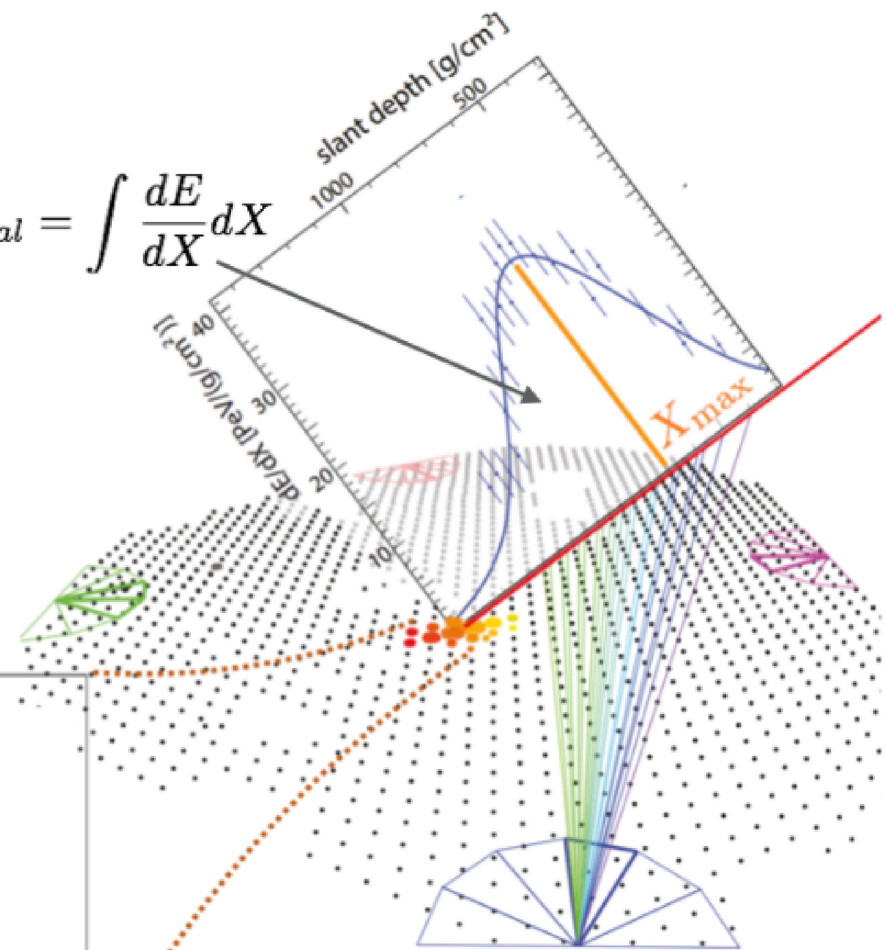
AUGER HYBRID OBSERVATORY: ENERGY RECONSTRUCTION

$E_{FD} = E_{cal} + E_{inv}$
$\sigma(E_{FD})/E_{FD} \sim 7\%$
Systematic uncertainty 14%

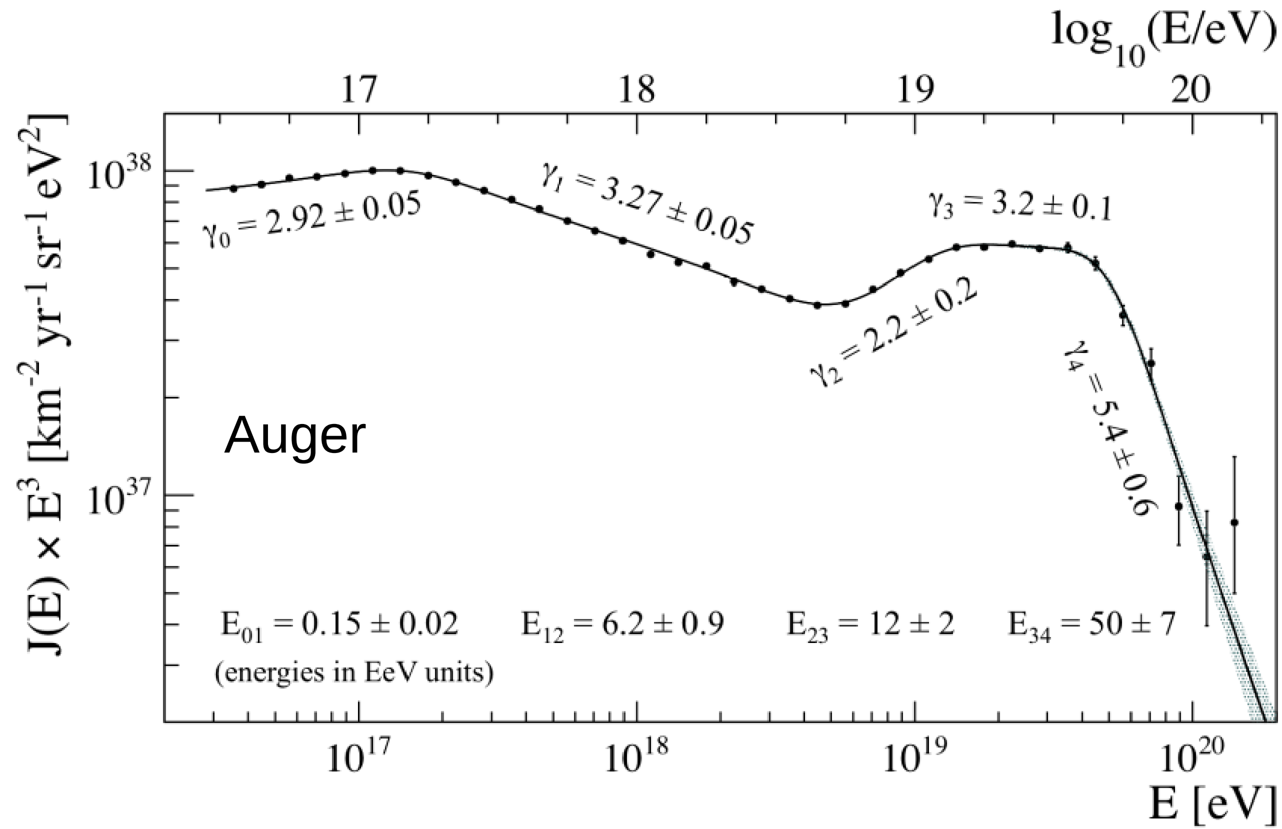




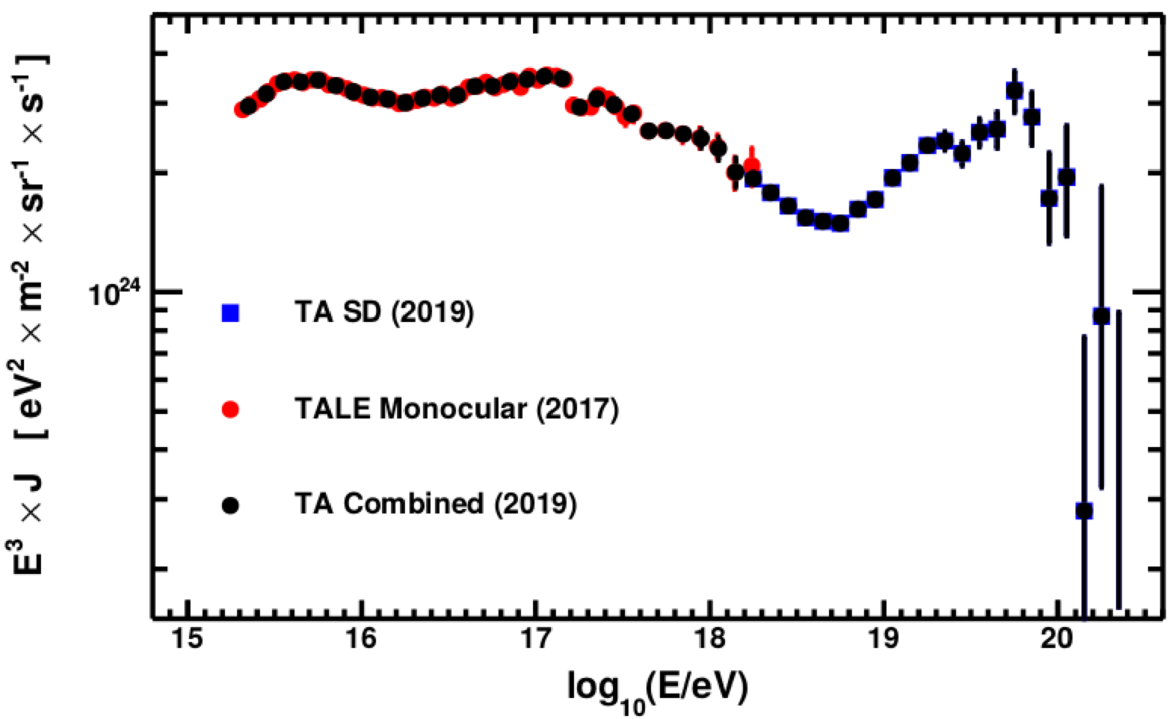




ENERGY SPECTRUM



Auger PRD (2020)

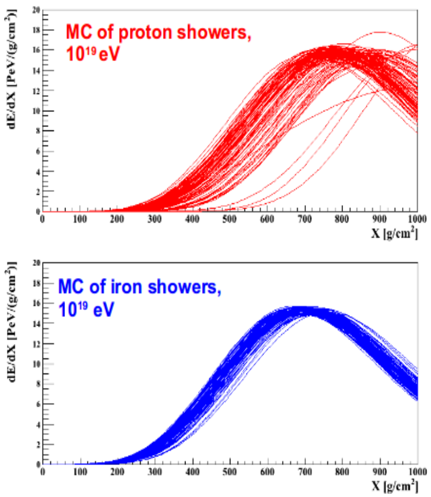


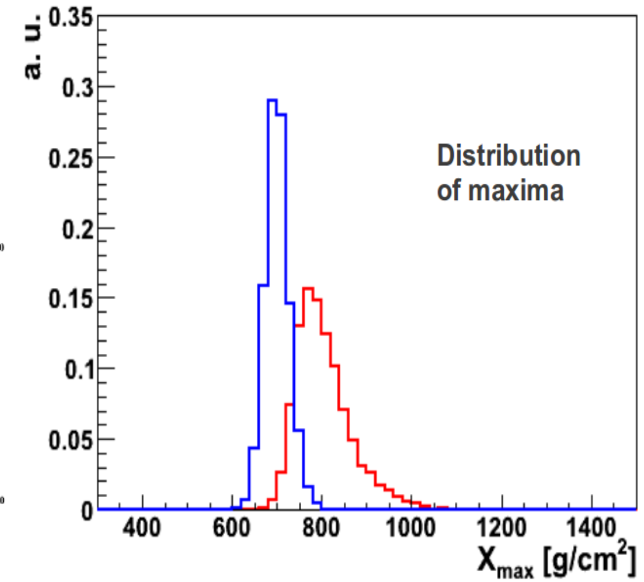
Telescope Array

D Ivanov (for TA coll) ICRC 2019

MASS COMPOSITION

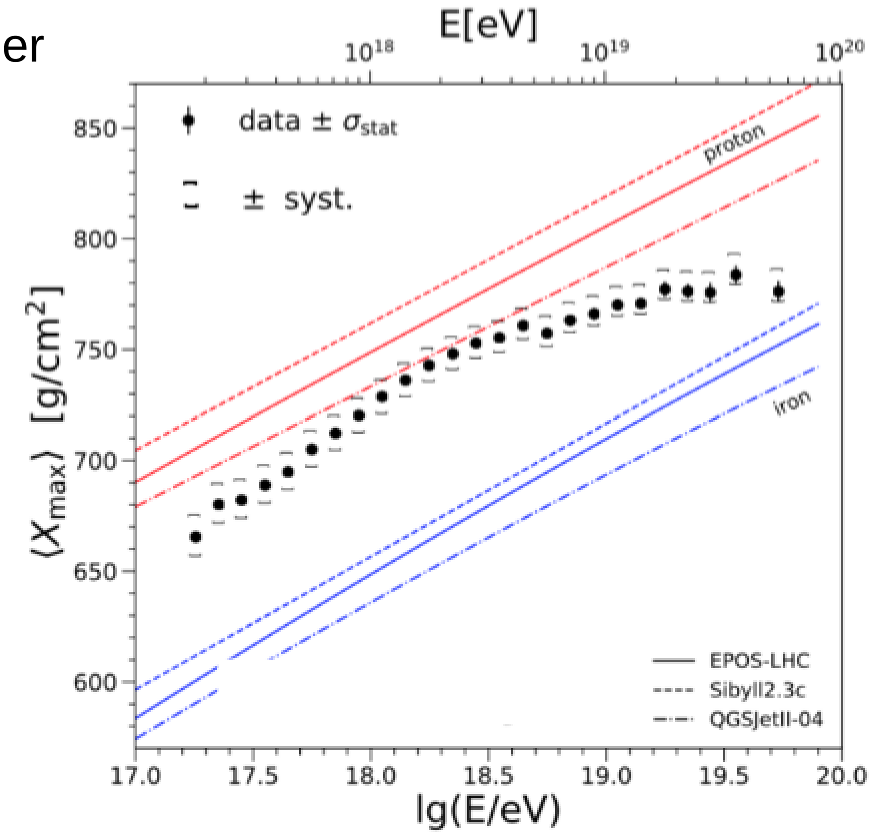
Indirect indicator of composition:
air column density traversed up to the shower maximum
Heavy nuclei showers develop higher in the atmosphere and have smaller fluctuations (superposition of nucleons)

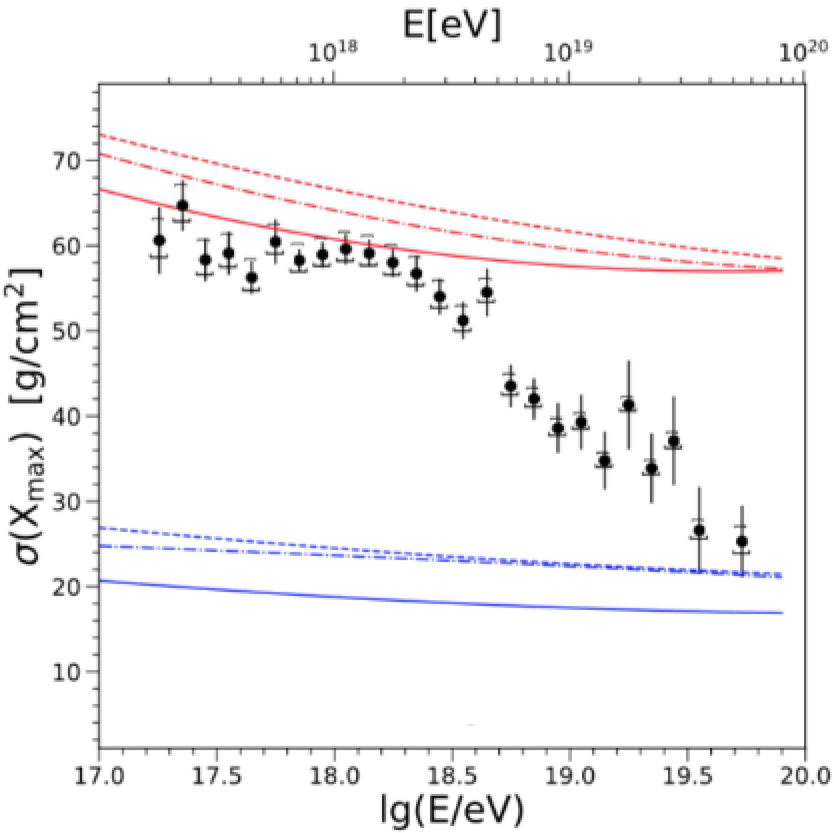




A Yushkov (for Auger coll) ICRC 2019

Auger





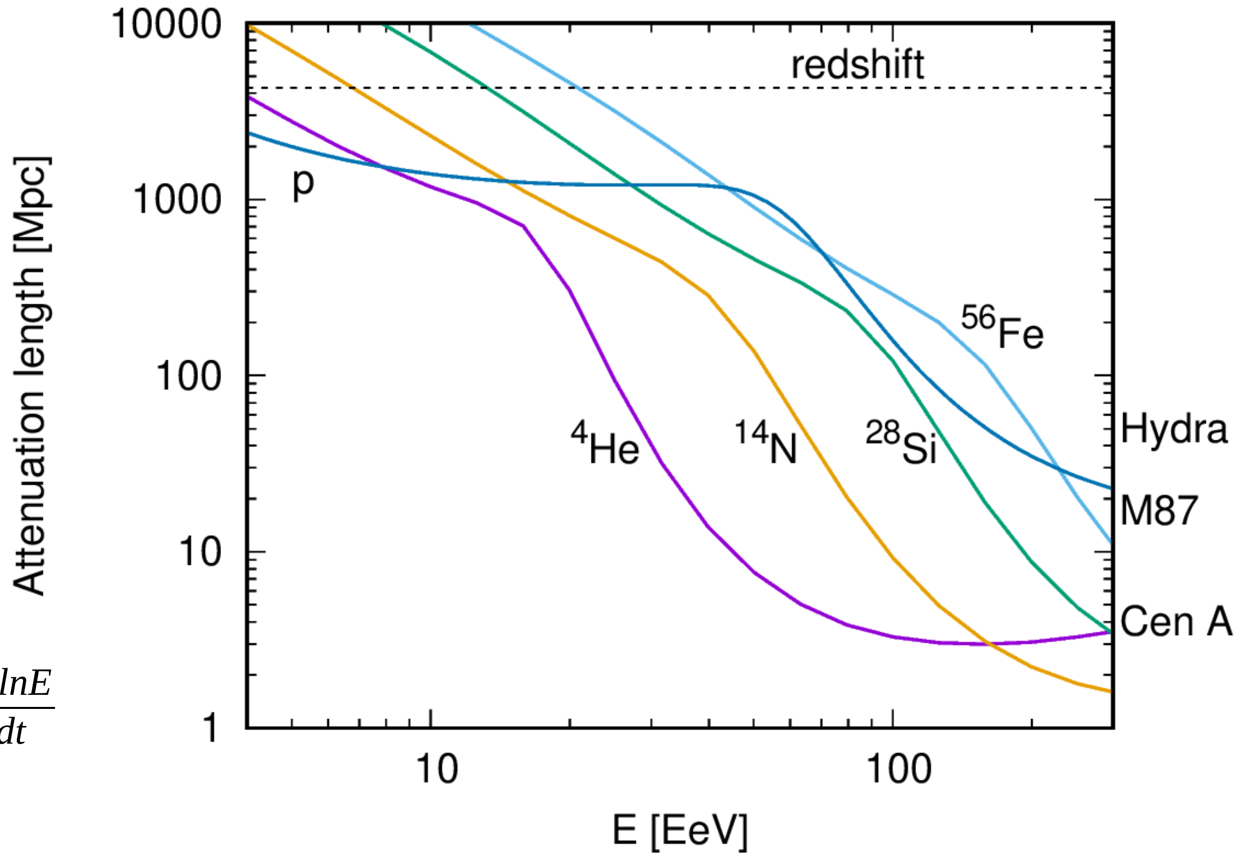
Composition becoming lighter up to 2 EeV and heavier above

PROPAGATION FROM SOURCES TO EARTH

CRs are subject to interactions with radiation backgrounds (CMB and IR/visible/UV extragalactic background light) → energy losses, composition changes

Greisen, Zatsepin & Kuz'min (1966)

- e^--e^+ pair production: $A+\gamma \rightarrow A+e^-+e^+$
- disintegration of nuclei: $A+\gamma \rightarrow (A-i) + i\,N$
- photopion production: $p+\gamma \rightarrow p+\pi^0, n+\pi^+$ or $n+\gamma \rightarrow n+\pi^0, p+\pi^-$

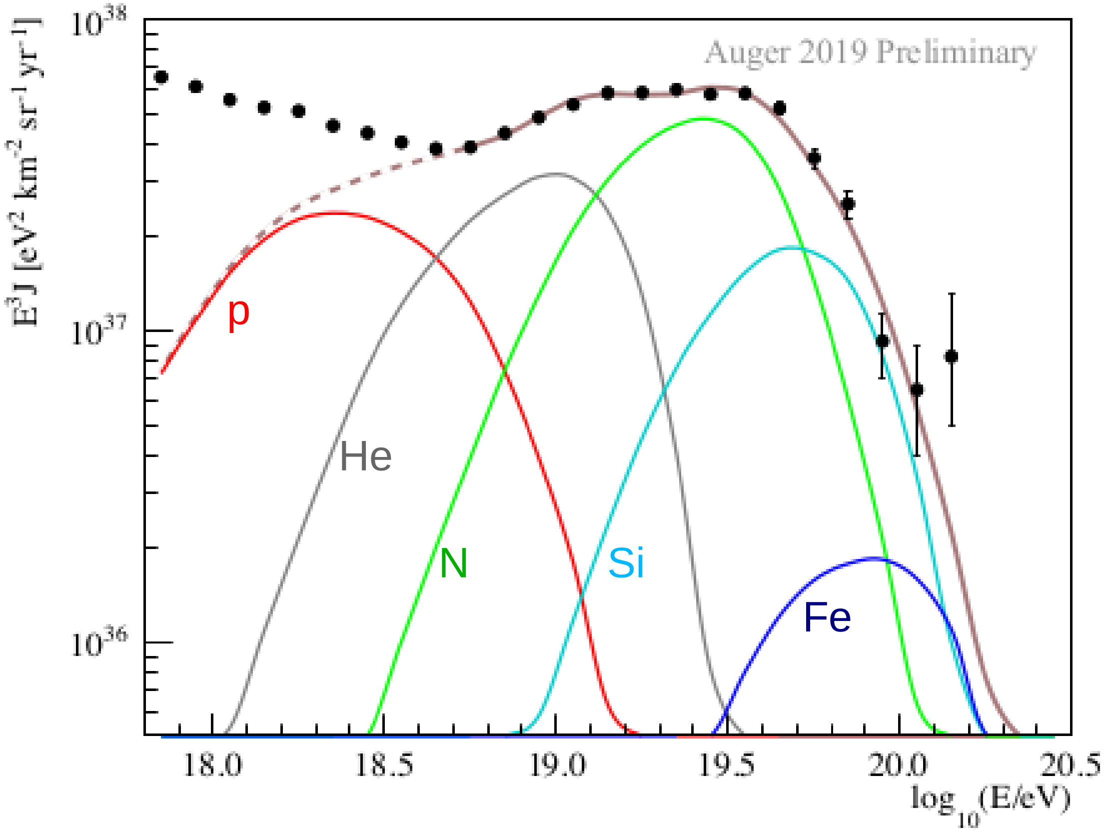


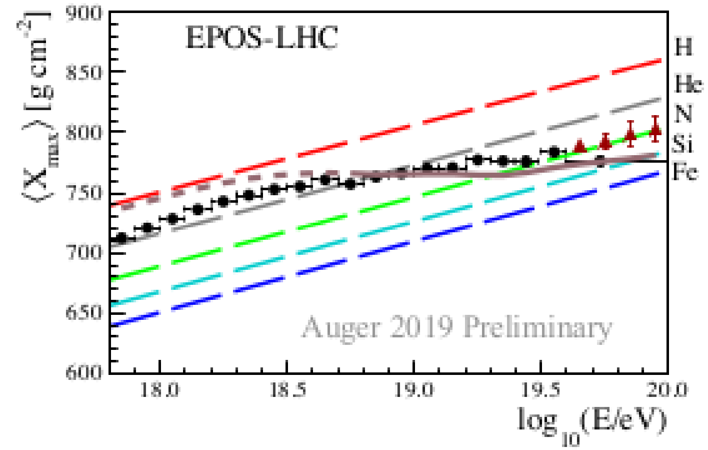
$$\lambda^{-1} = -\frac{1}{c}\frac{d\,lnE}{dt}$$

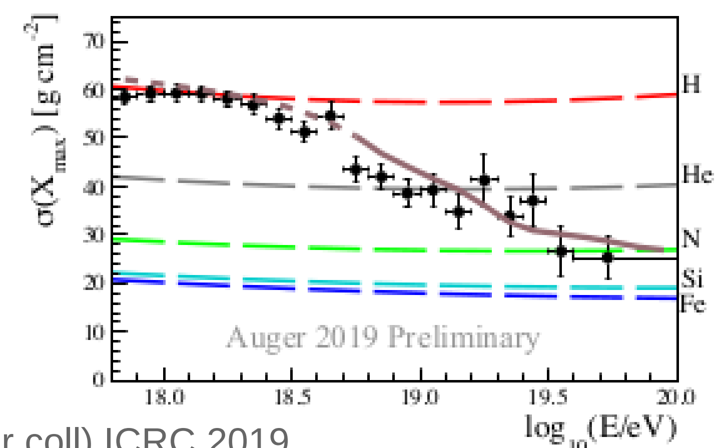
These processes also lead to the production of secondary particles: nucleons, e^--e^+ pairs, neutrinos, gamma rays

BEST FIT OF SPECTRUM AND COMPOSITION OF UHECRs (above the ankle)

Simple model of sources continuously distributed and accelerating particles with rigidity dependent spectrum (power law with exponential cutoff)







A Castellina (Auger coll) ICRC 2019

Auger favors mixed composition with hard rigidity dependent spectrum and low rigidity cutoff $R_{cut} = E_{cut}/Z \sim 5$ EV

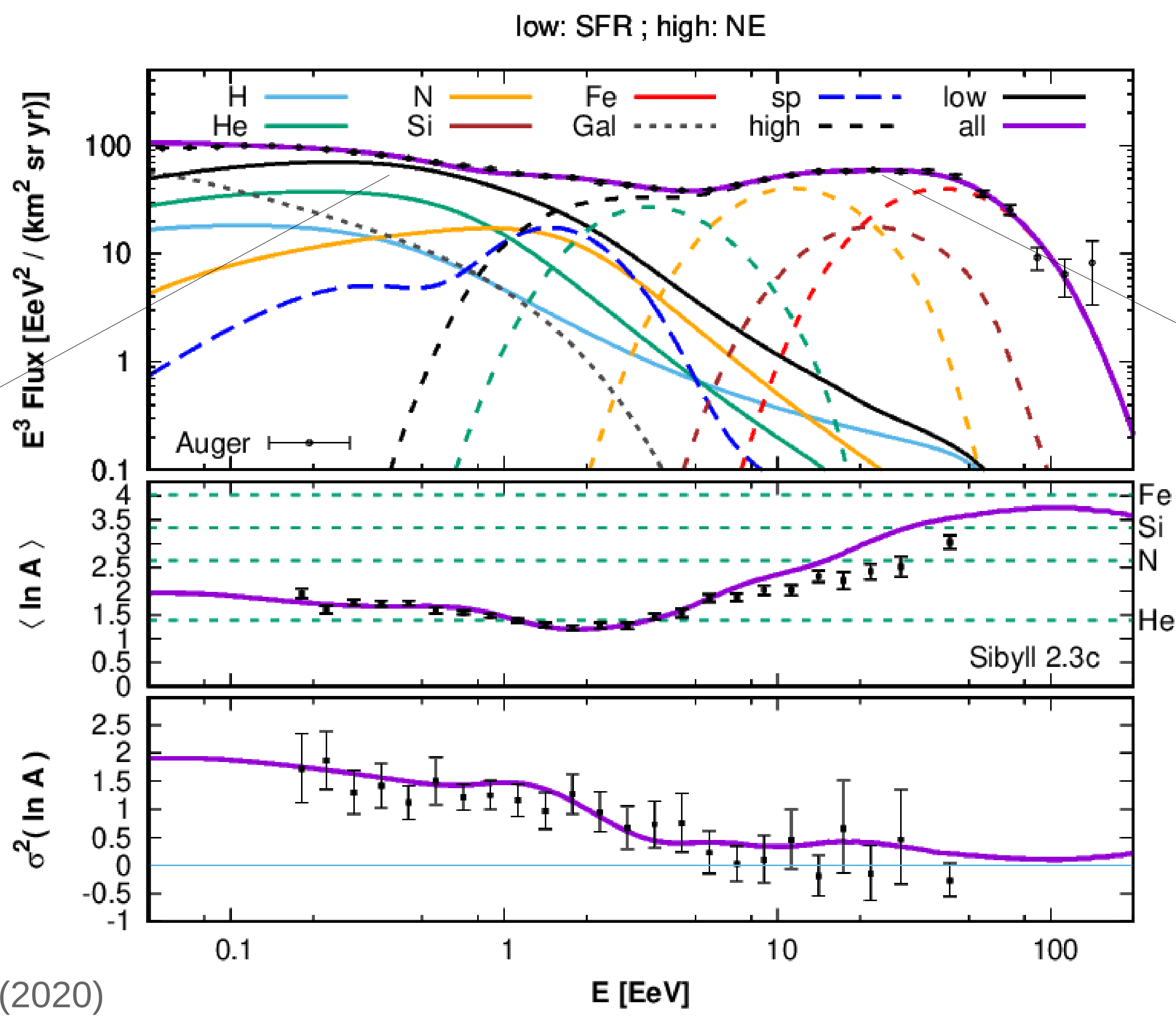
Final steepening of the spectrum is combination of propagation and maximum rigidity at the source

GALACTIC TO EXTRAGALACTIC TRANSITION

- Galactic Cosmic Rays are supressed above the second knee (100 PeV)
- UHECRs sources are dominant above the ankle (5 EeV)

- Still need another extragalactic component in between

Possible scenario: two extragalactic populations diffusing in a large extragalactic magnetic field

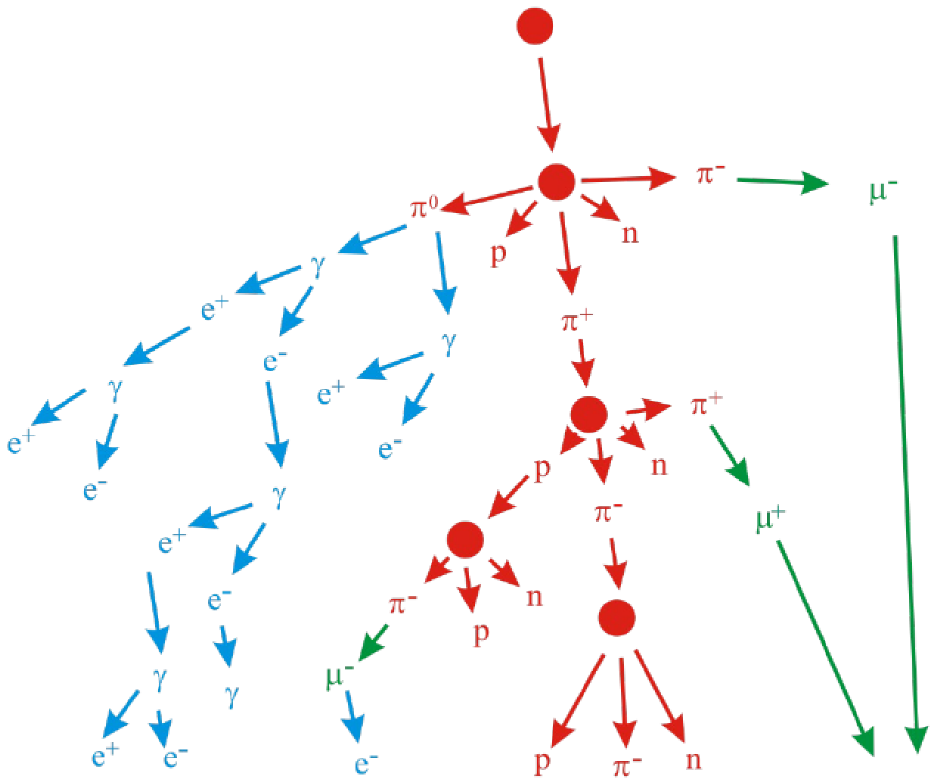


Low energy:
High density population
(~ 10^{-3} Mpc^{-3})
with steep spectrum ($E^{-3.5}$)

High energy:
low density population
(< 10^{-4} Mpc^{-3})
→ magnetic horizon suppression of spectrum at low energies and rigidity dependent cutoff at few EV

SM, E Roulet PRD101(2020)

HADRONIC INTERACTIONS IN AIR SHOWERS



Shower components

Electromagnetic (EM) from decay of neutral pions
+ from muon decay
+ from low energy pion decay

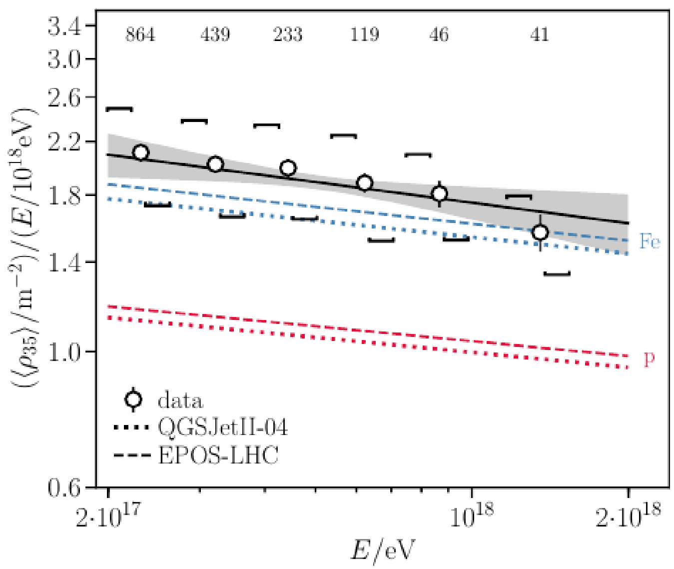
Muonic from decay of charged pions
+ from photo-production

Higher mass primaries produce more muons

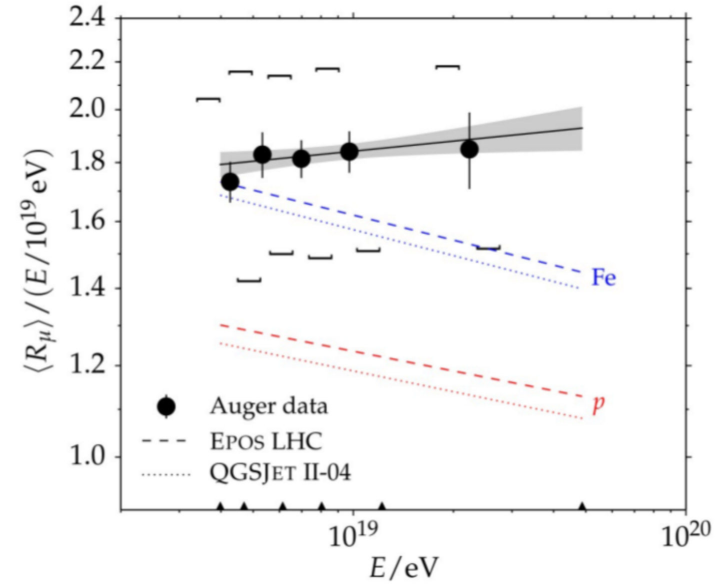
D Schmidt (Auger coll) talk 31/7

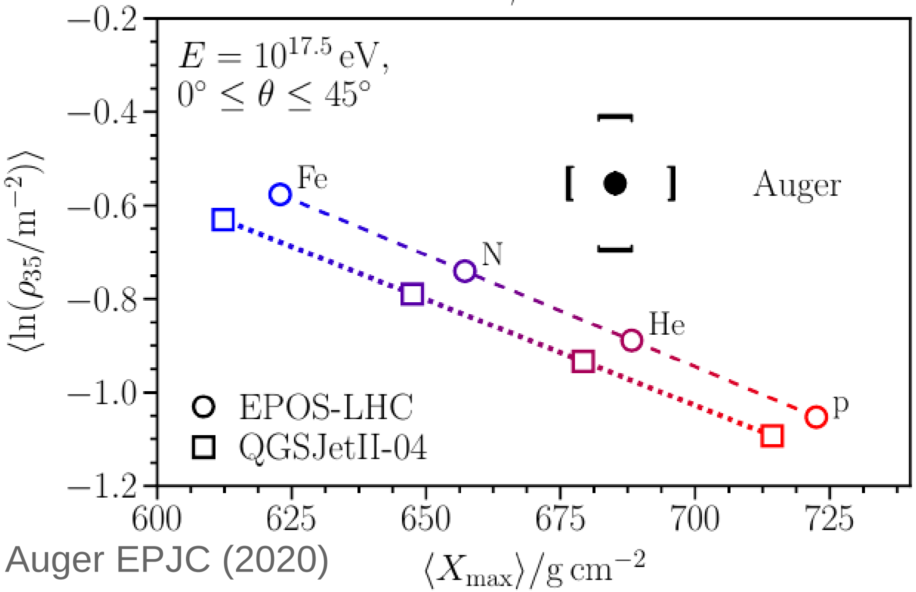
MUON CONTENT MEASUREMENTS AT AUGER

UNDERGROUND MUON DETECTORS

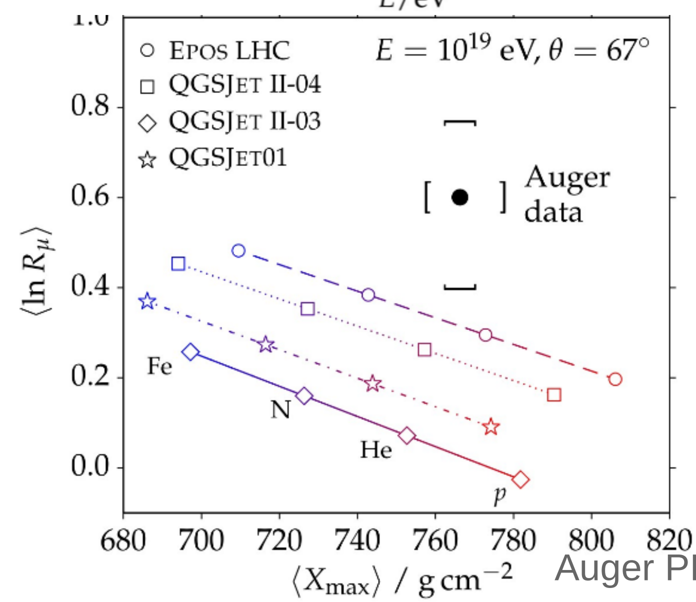


HIGHLY INCLINED SHOWERS





Auger EPJC (2020)



D Schmidt (Auger coll) talk 31/7

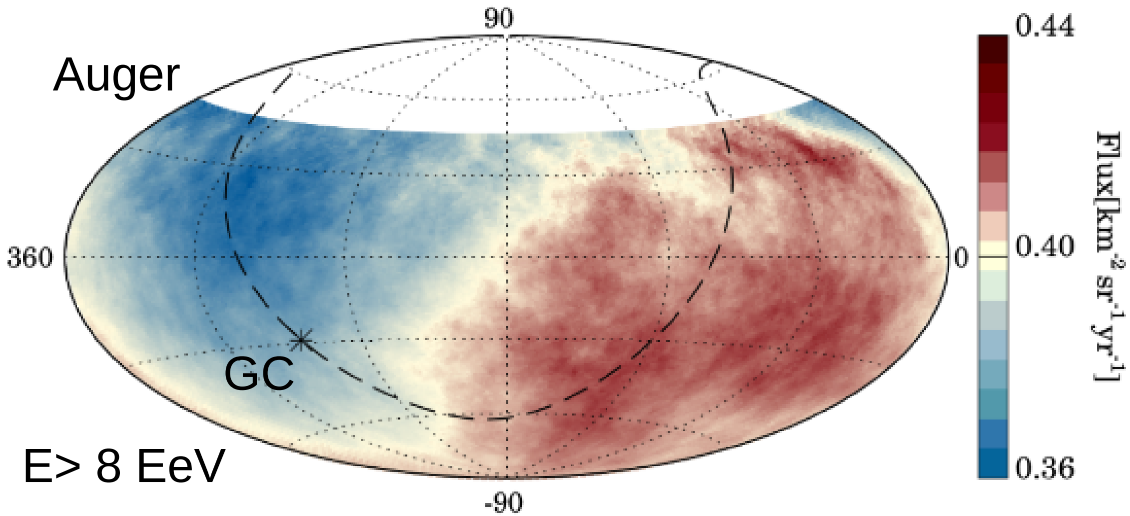
Auger PRD 91 (2015)

MonteCarlo simulations of EAS predict a muon density at ground smaller than observed considering the mass composition inferred from X_{max} measurements

30-50% increase in $\langle N_\mu\rangle$ is required: need some modification of hadronic interactions ...

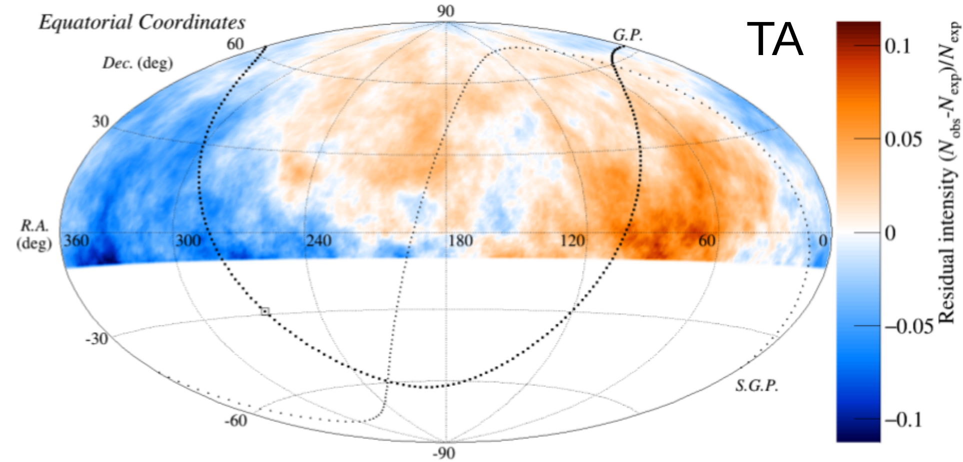
(or invoke new processes at the highest energies: e.g. higgsplosion → see talk by M Reininghaus 29/7)

LARGE SCALE ANISOTROPY



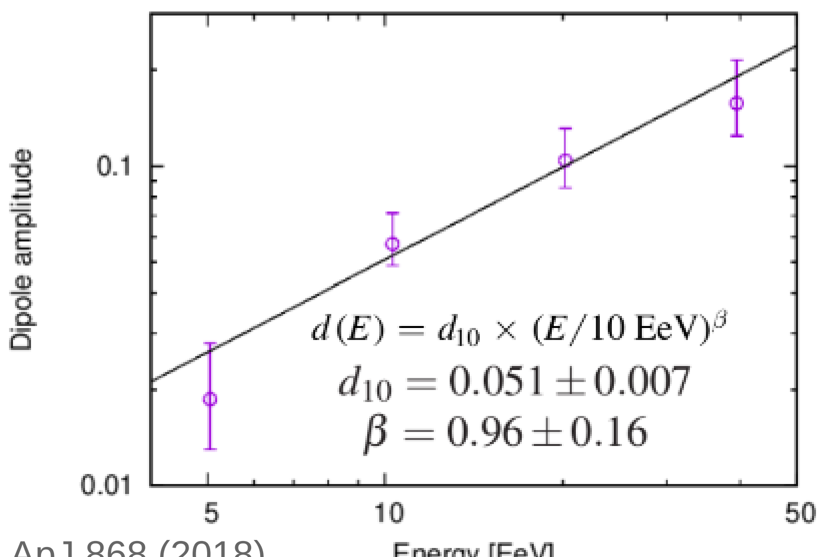
Dipole amplitude d=0.066$^{+0.012}_{-0.009}$ (6σ) pointing to (α,δ)=(98°,-25°) → at 135° from the GC
→ evidence of extragalactic origin (d$_\perp$=0.060±0.010)

E Roulet (Auger coll) ICRC 2019



r=0.033±0.019 ϕ=131°±33°
compatible with Auger dipole
and with isotropy TA coll, arXiv:2007.00023

d$_\perp$=r/⟨cosδ⟩ ~ 1.3 r ~ 0.043± 0.025

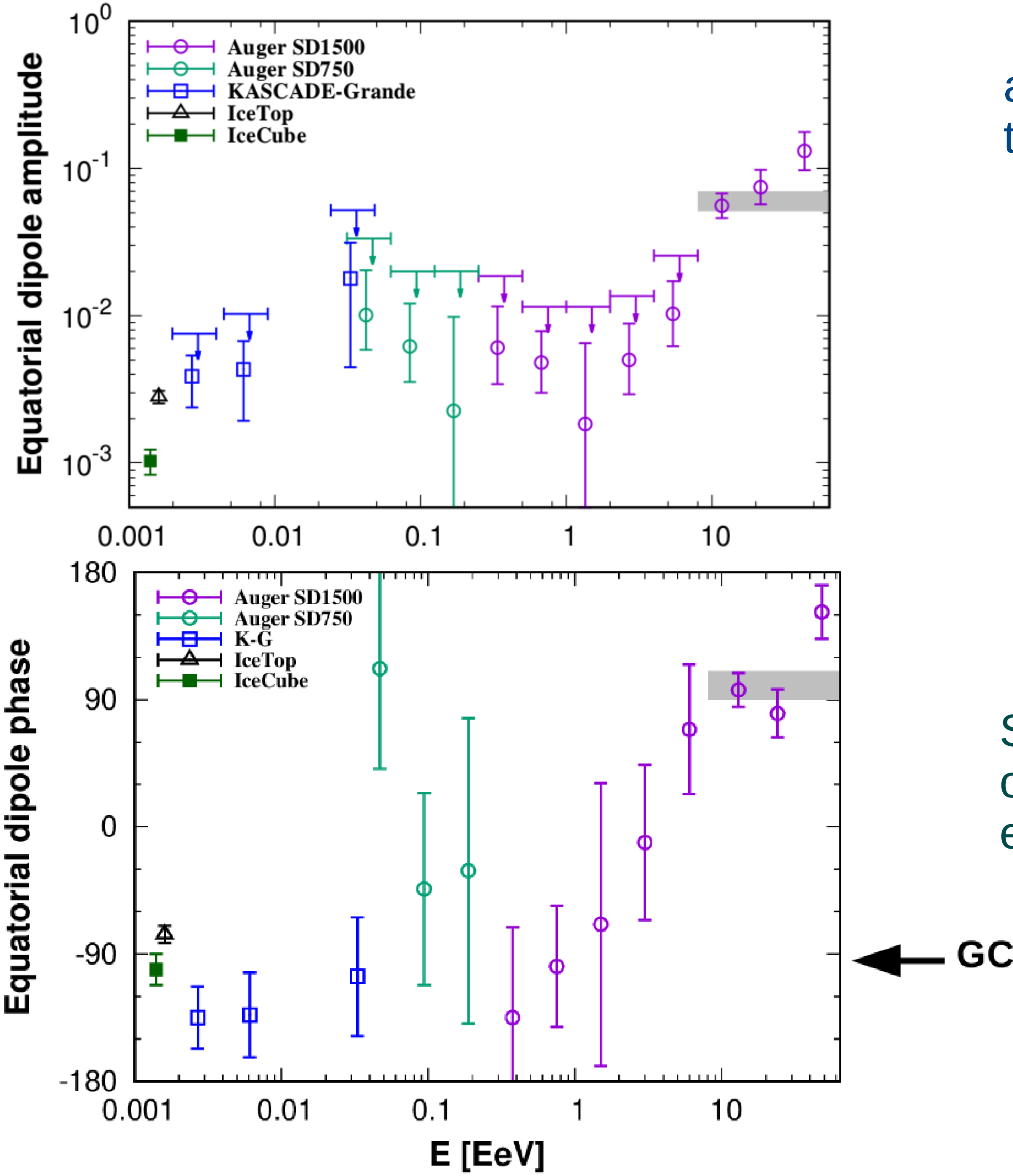


Auger coll, ApJ 868 (2018)

Amplitude increases with energy

Accounting for the effect of Galactic magnetic field on extragalactic particle trajectories: extragalactic dipole directions within 30° from the dipole direction observed by Auger
Bakalová, Trávnícek & Vícha
Poster session (29/7)

EQUATORIAL DIPOLE FROM 1 PeV TO 100 EeV



amplitudes grow, from below 1% to above 10%

phases shift, from ~ GC to ~ opposite direction

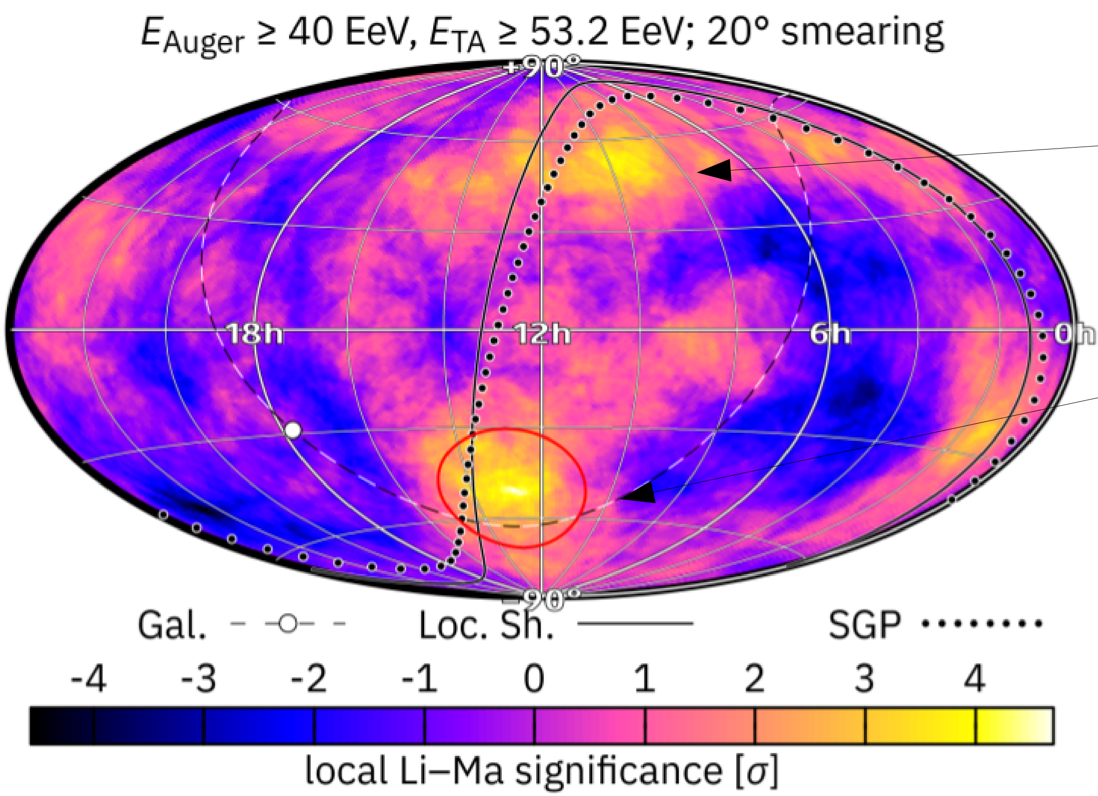
Suggests transition from anisotropies of Galactic origin below ~1 EeV to extragalactic origin above few EeV

Auger coll, ApJ 891(2020)

MEDIUM-SCALE ANISOTROPIES AT THE HIGHEST ENERGIES

full sky analysis combining Auger & TA data

A. di Matteo et al. (Auger and TA colls.), ICRC 2019



15° radius around $(\alpha,\delta)=(142^{o}, +54^{o})$
4.2σ pre-trial (1.5σ post-trial)

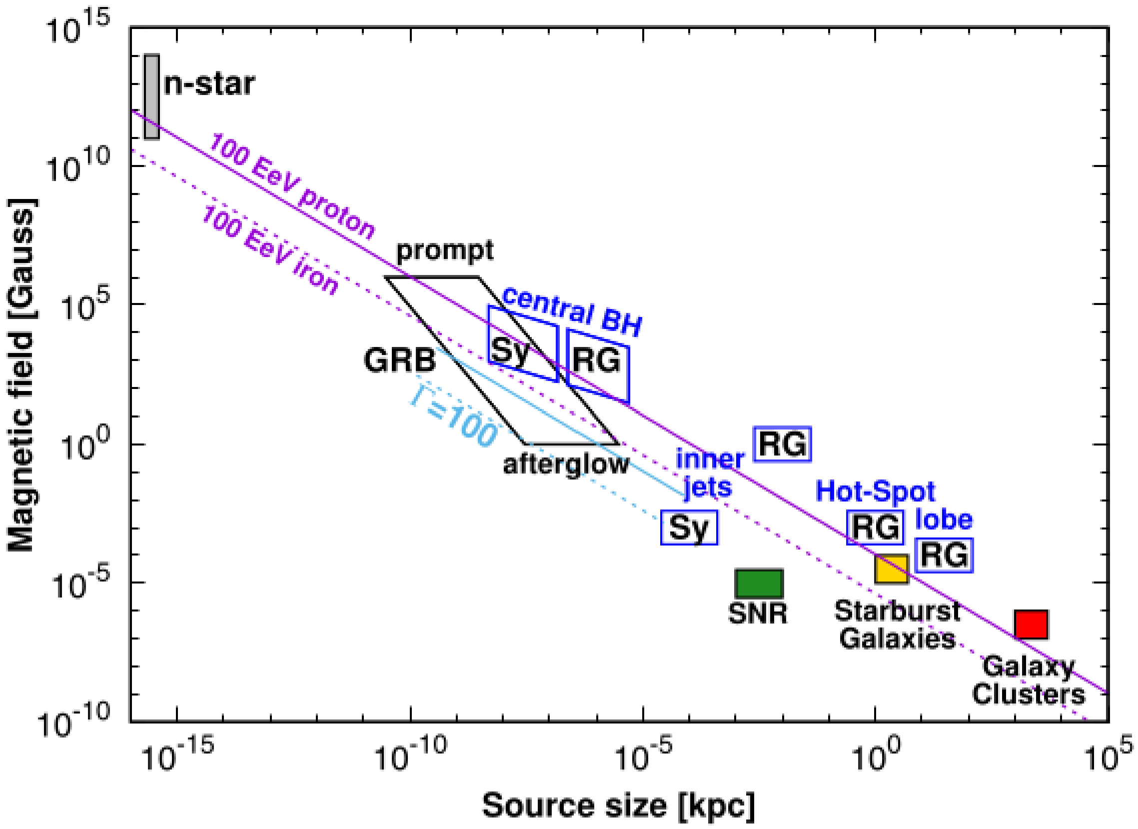
20° radius around $(\alpha,\delta)=(192^{o}, -50^{o})$
4.7σ pre-trial (2.2σ post-trial)

ANISOTROPIES:
- Significant dipole above 8 EeV -
- Hints of medium scale anisotropies above 40 EeV
- No significant small scale anisotropy

→ PROBABLY INDICATING LARGE DEFLECTIONS IN INTERGALACTIC B FIELD
(consistent with heavy composition at highest energies)

WHERE ARE UHECRs ACCELERATED?

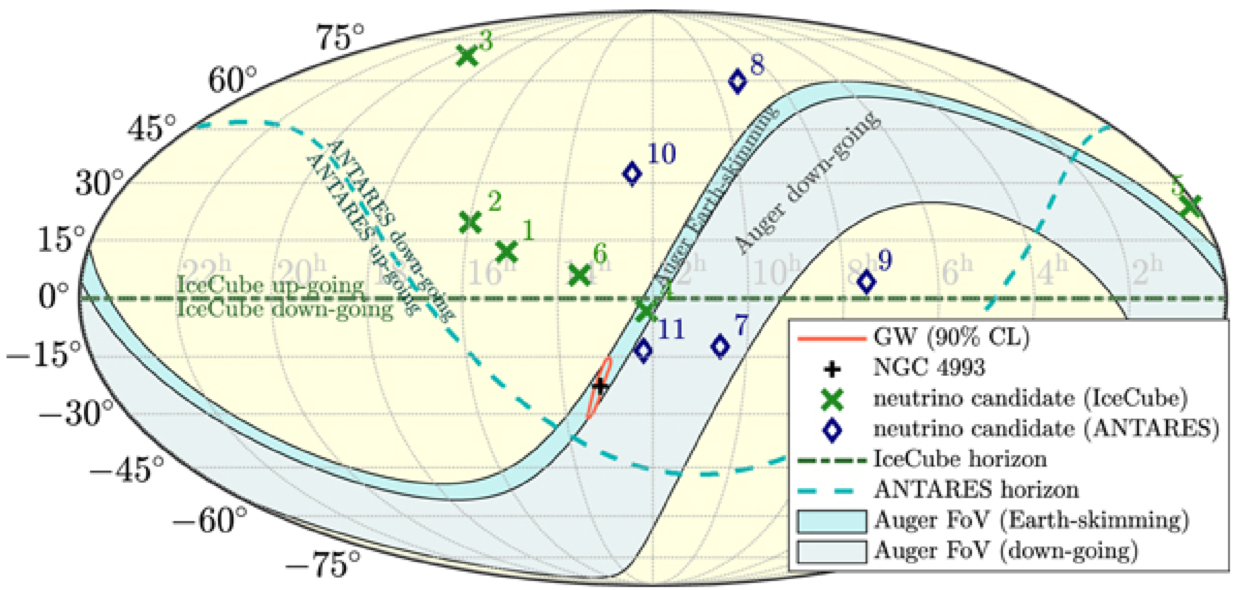
Few proposed candidates meet minimal conditions for accelerator sites: AGNs, Starburst galaxies, GRBs, magnetars

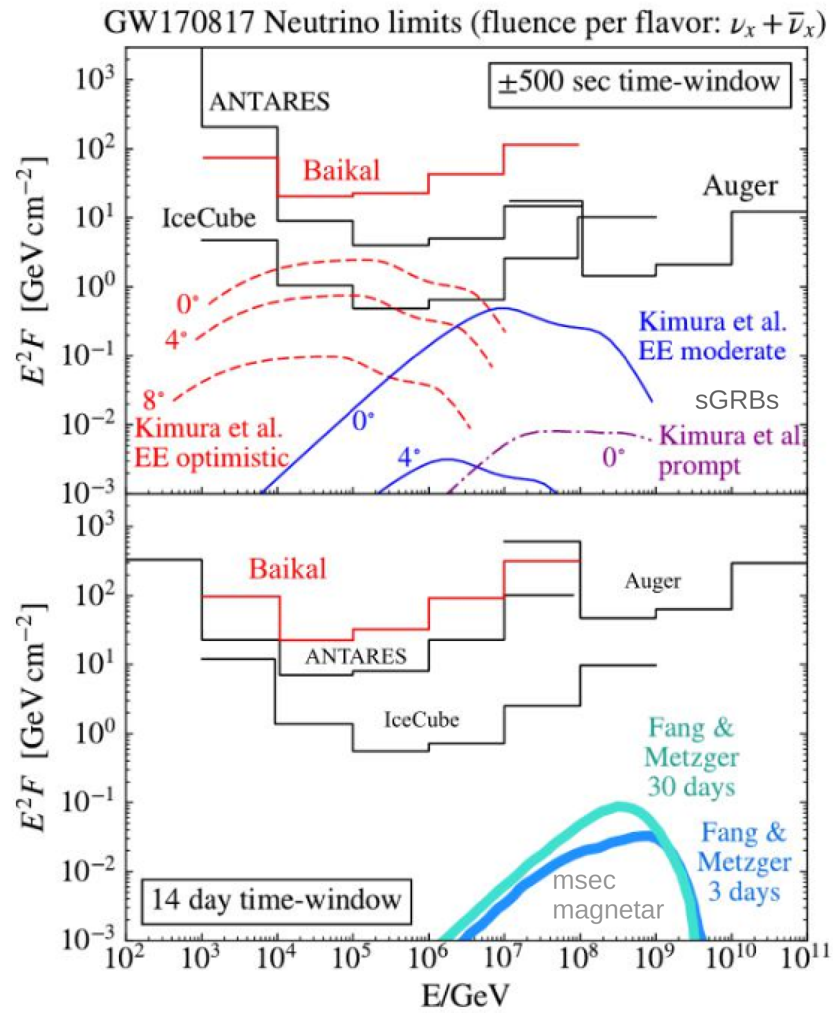


But identification is difficult since arrival direction of CRs do not point to their sources due to magnetic deflections

MULTIMESSENGER ASTRONOMY
could other messengers help to identify UHECRs sources?

Search for HE neutrinos in coincidence with a GW event: BNS merger GW170817 (LIGO+Virgo) + short GRB (Fermi-GBM, INTEGRAL)



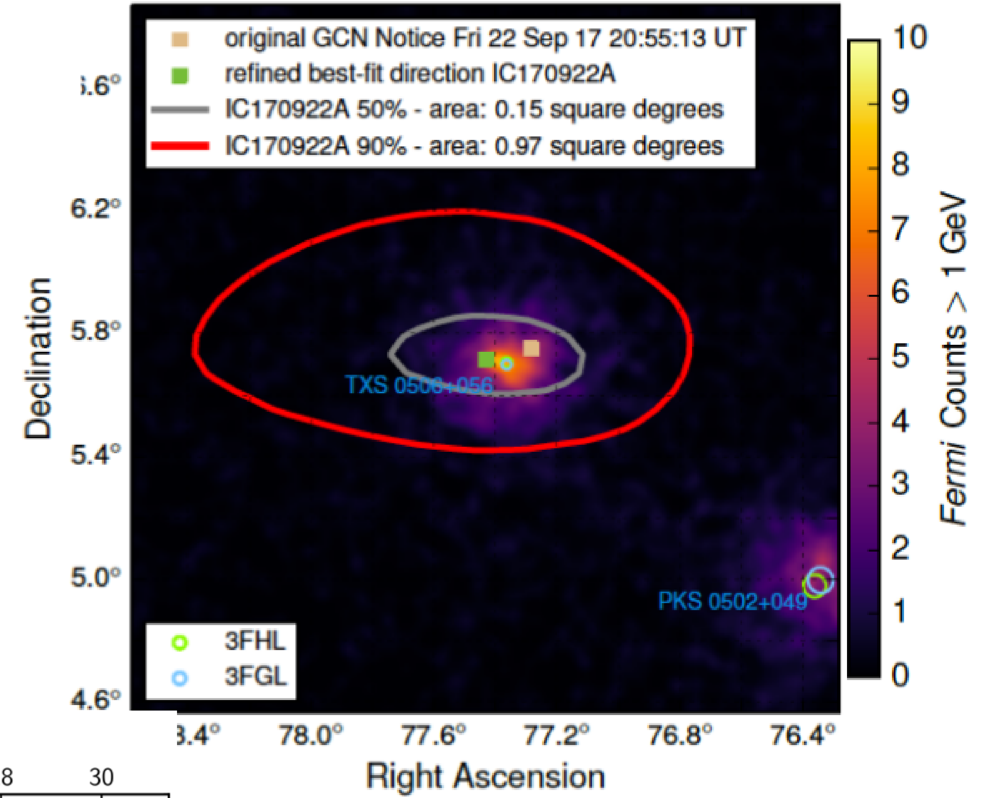


L Zehrer (Auger coll) talk 31/7
Baikal bound: G Safranov talk 31/7

no significant neutrino counterpart within a ±500 s window, nor in the subsequent 14 days.

Antares, IceCube & Auger ApJ, 850, L35 (2017)

FIRST EXTRAGALACTIC COSMIC RAY ACCELERATOR

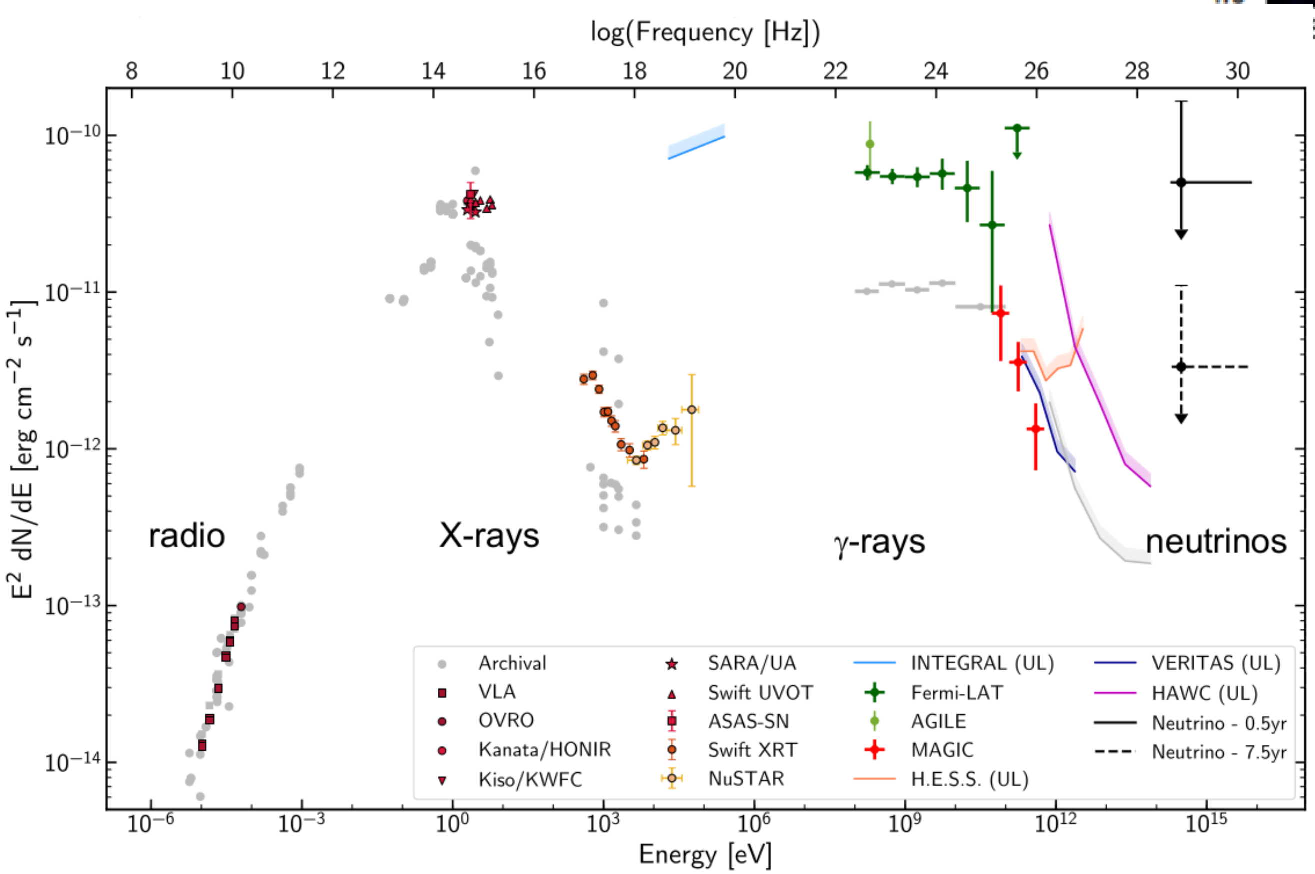


A rotating supermassive black hole: Blazar TXS 0506+056 at a redshift of 0.33

IceCube 170922: 290 TeV

Fermi-LAT: flaring blazar within 0.06° (7x steady flux)

MAGIC: emission of > 100 GeV gammas

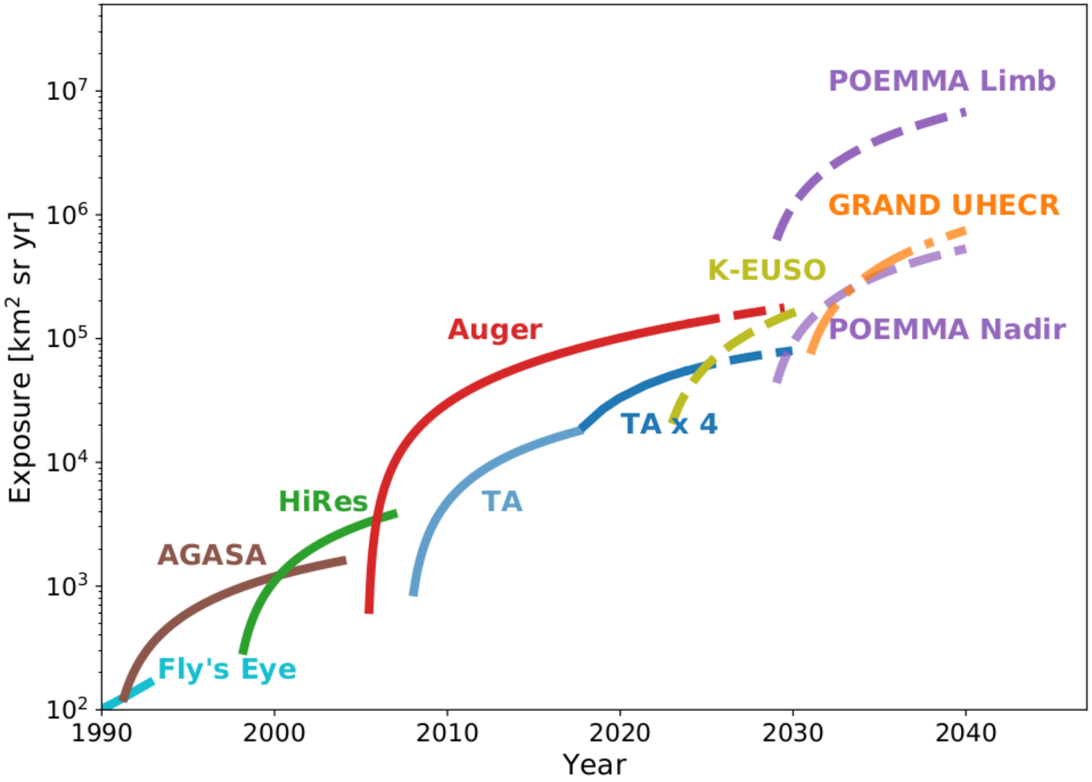


IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, HESS, INTEGRAL, Science 361(2018)

THE FUTURE

Auger: upgrade aimed to improve the sensitivity to mass composition of SD

Telescope Array: TAx4 → cover 3000 km^2



V Scotti talk 31/7

S De Jong talk 31/7

Many recent advances in understanding high energy cosmic particles
Still many open questions
New projects being developed and planned

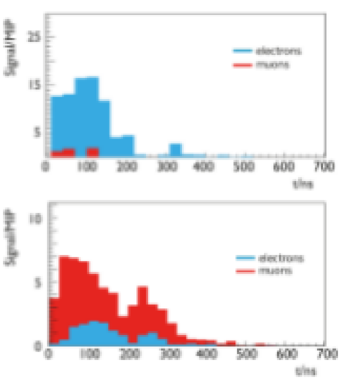
BACK UP

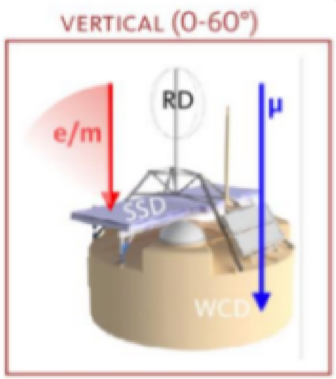
AugerPrime: The concept

Use complementary of response of detectors to discriminate muonic and em components on 3000km^2

Vertical showers

SSD





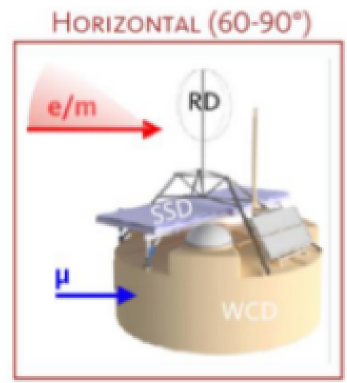
$S_{\mu,WCD} = a\, S_{WCD} + b\, S_{SSD}$

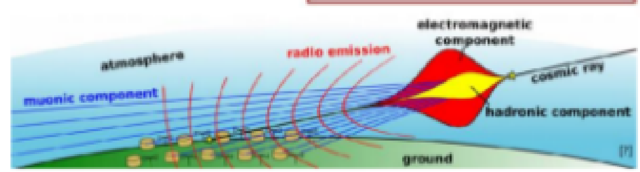
+

Horizontal showers

RADIO

Hybrid:
E_{rad} from radio
muons from WCD





S De Jong talk 31/7

+

G Cattaldi talk 28/7

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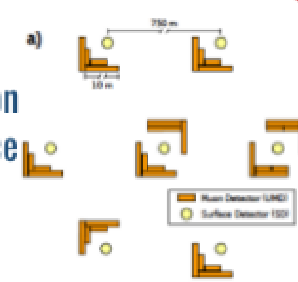
- ✓ New electronics (faster)
- ✓ Addition of a small PMT in the WCD (extension of dynamic range)

+

AMIGA

61 Underground Muon Detectors in coincidence with 750 m array

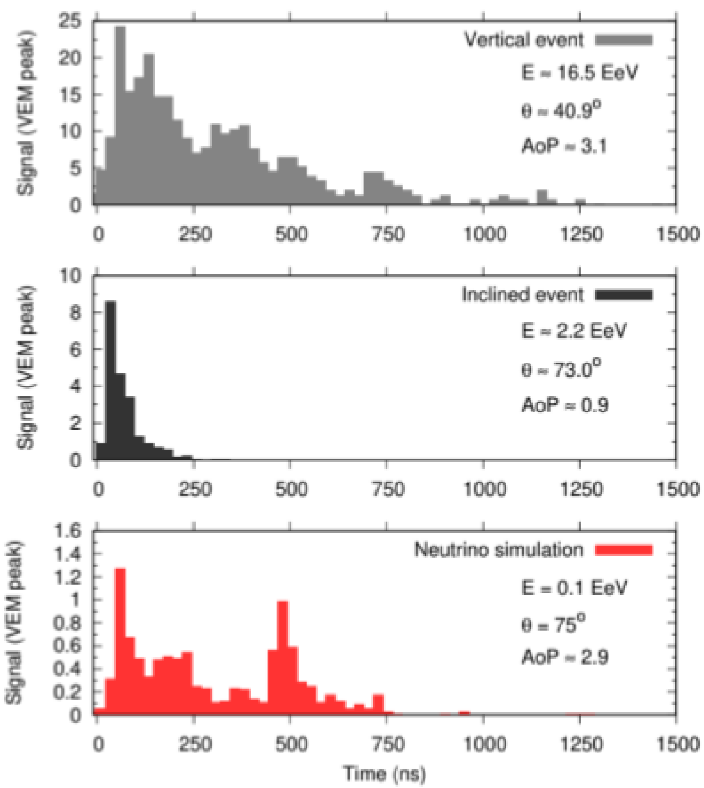


Extend operations to >2025, increasing the statistics

NEUTRINO DETECTION AT AUGER

→ Hadrons initiate inclined showers high in the atmosphere.
Shower front at ground: • EM component absorbed in atmosphere • mainly muons remaining

→ Neutrinos can initiate deep showers close to ground.
Shower front at ground: EM + muonic components



Searching for neutrinos

⇒ searching for inclined showers with EM component

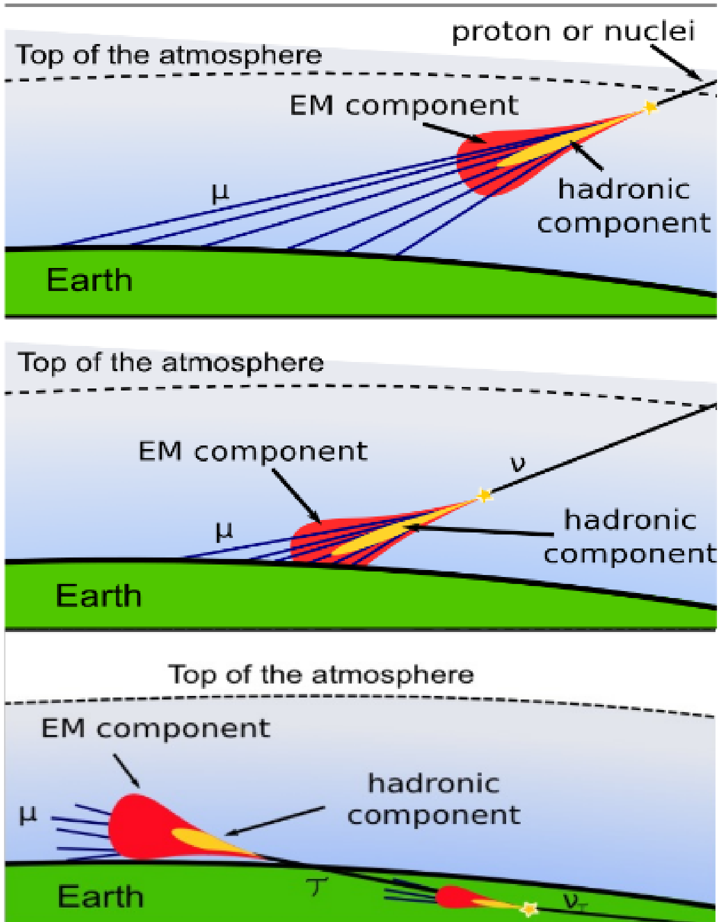
Down going: all flavours

Down-going low angle DGL 60°-75°

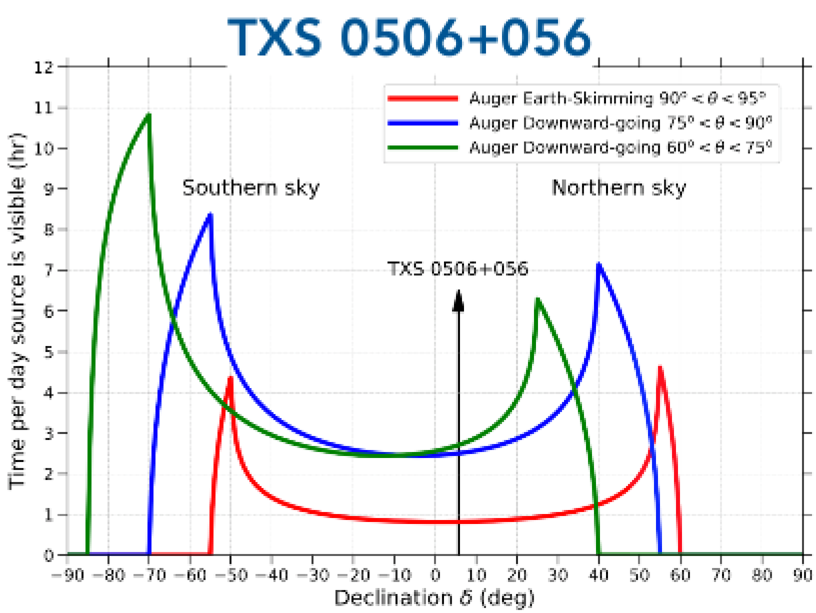
Down-going high angle DGH 75°-90°

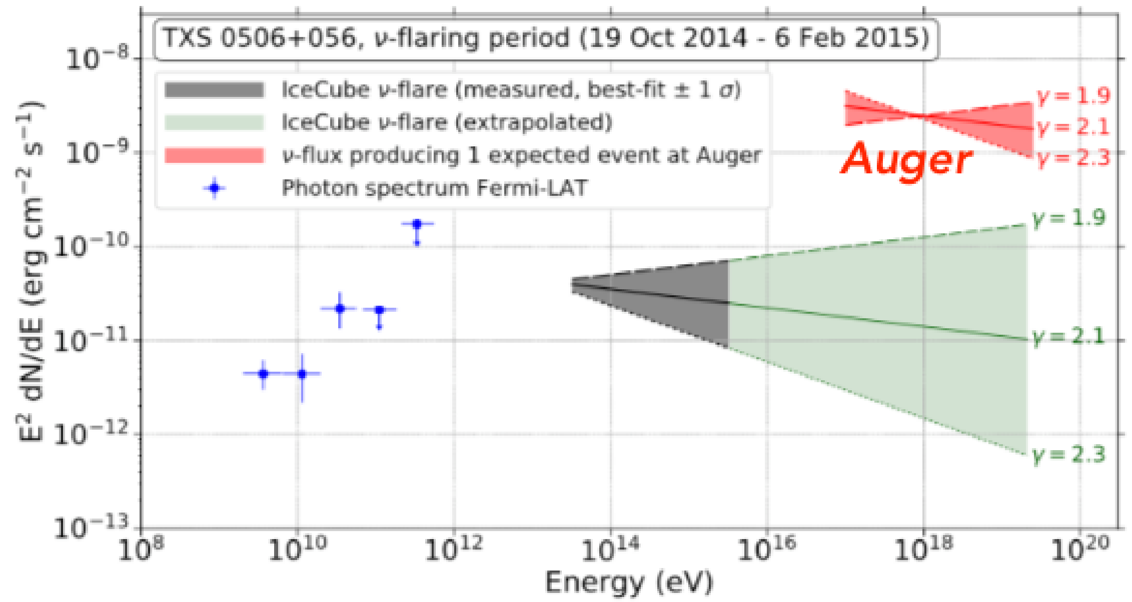
Up-going: ν_τ

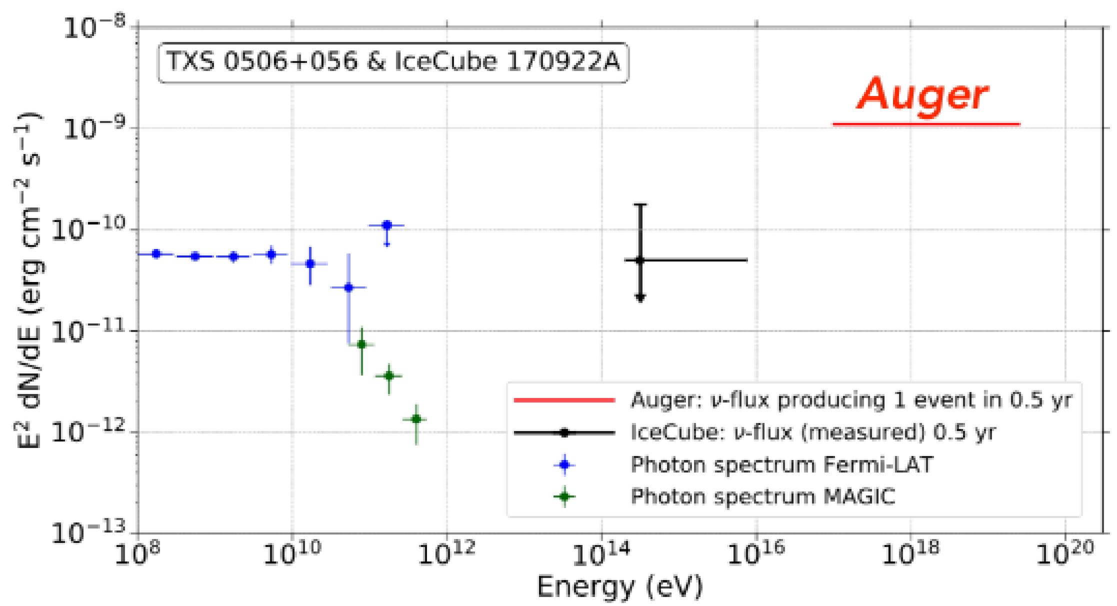
Earth-skimming ES 90°-95°



Neutrinos from TXS 0506+056 follow-up at Auger



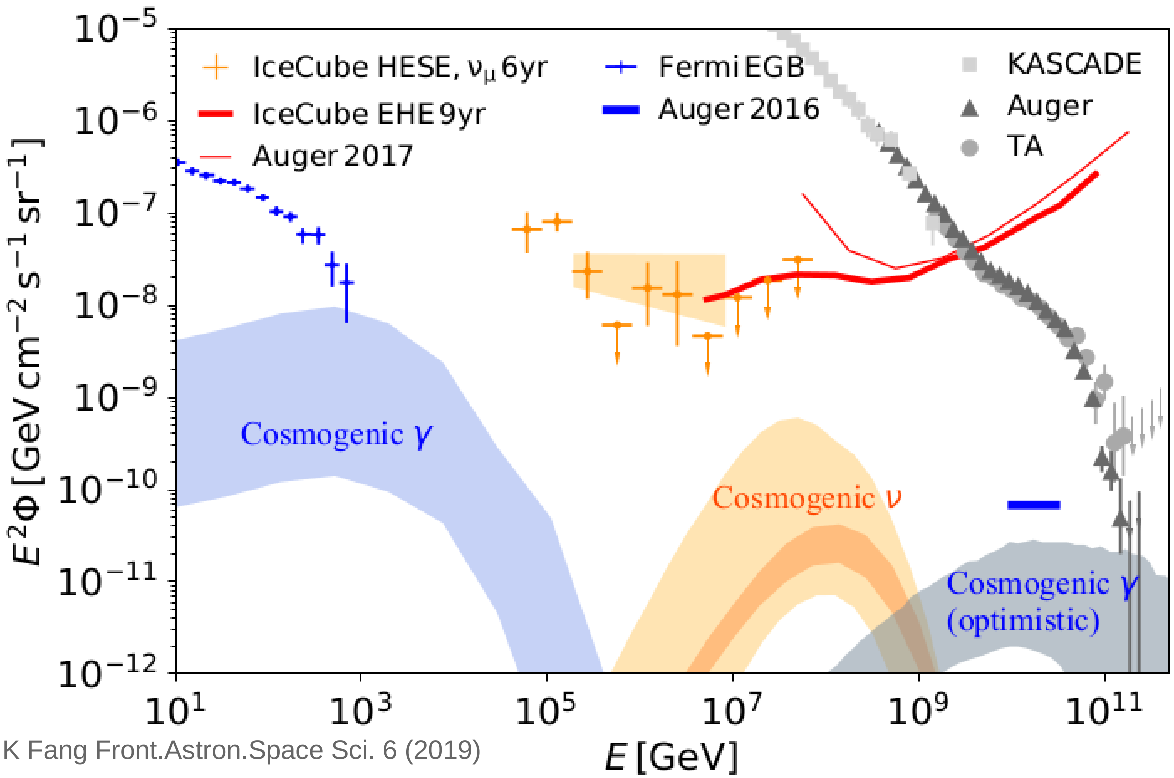




no neutrinos found

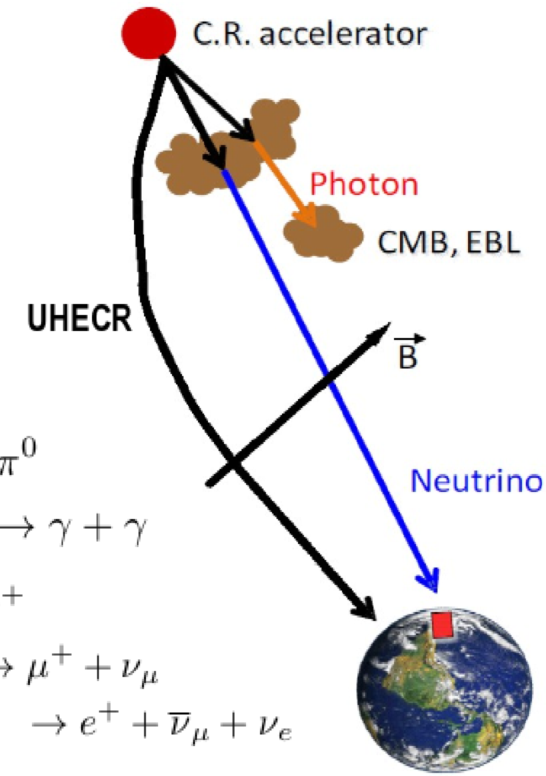
M Schimp (Auger coll) ICRC 2019

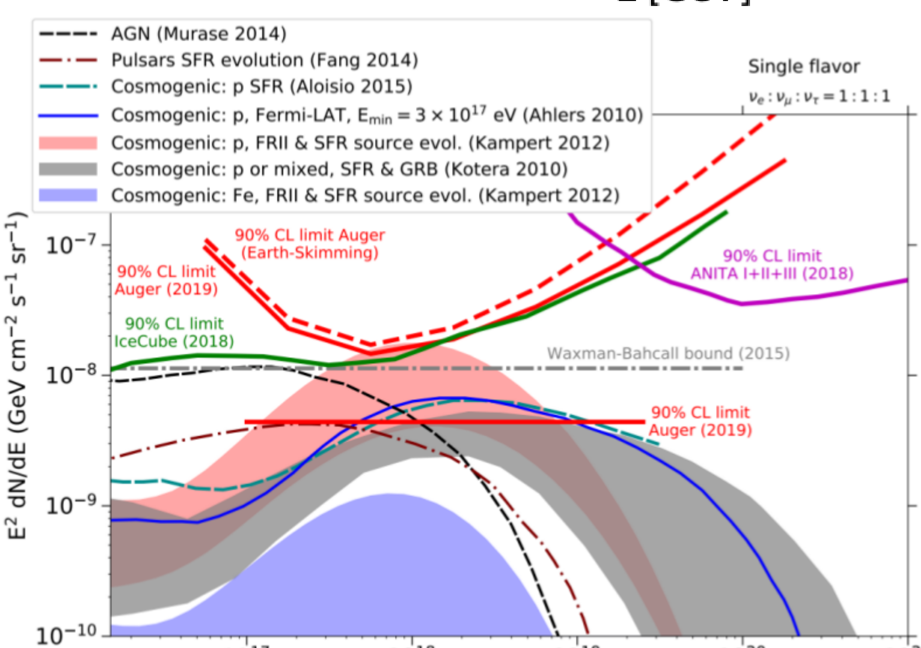
COSMOGENIC NEUTRINO AND PHOTON DIFFUSE FLUXES



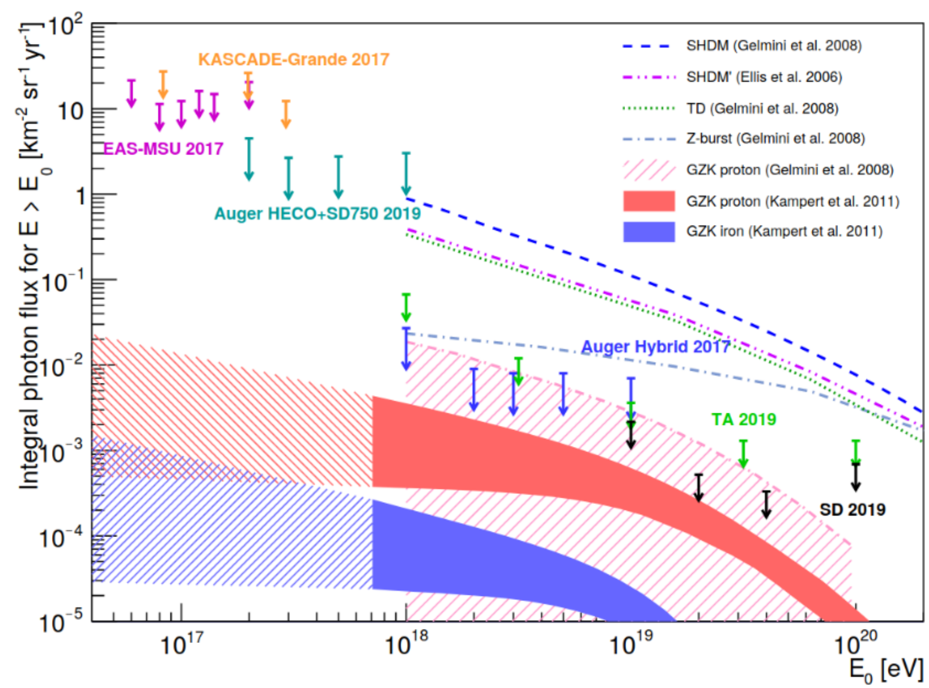
K Fang Front.Astron.Space Sci. 6 (2019)

$$p + \gamma \to p + \pi^0$$
$$\to \gamma + \gamma$$
$$p + \gamma \to n + \pi^+$$
$$\to \mu^+ + \nu_\mu$$
$$\to e^+ + \overline{\nu}_\mu + \nu_e$$





L Zehrer (Auger) talk 31/8



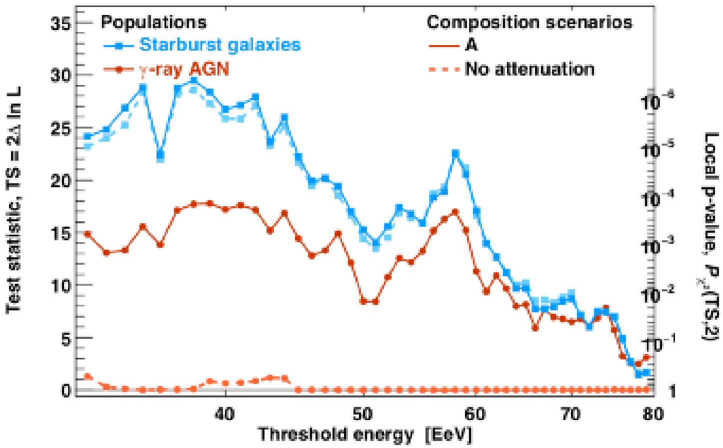
CORRELATION WITH ASTROPHYSICAL CATALOGS

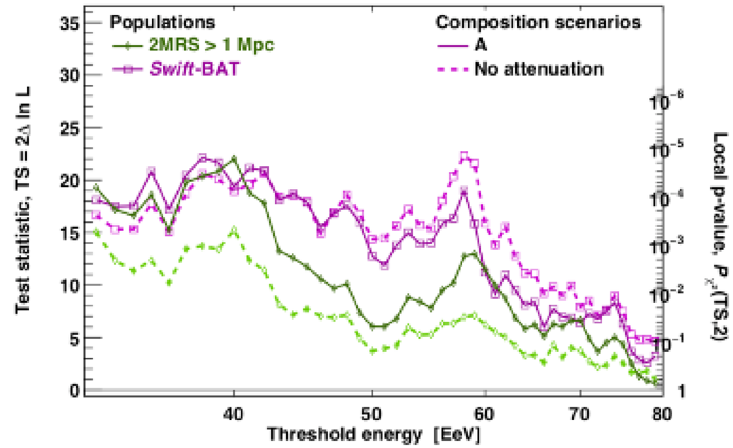
γ AGNs
3FHL catalog < 250 Mpc
33 sources (CenA, Fornax A, M87…)
Flux proxy ϕ(>10 GeV)

Starburst Galaxies
32 sources (Circinus, M82, M83,…)
<250 Mpc
Flux proxy ϕ(>1.4 GHz), > 0.3 Jy

Swift-BAT
>300 radio loud and quiet sources
<250 Mpc
$\phi > 13.4\ 10^{-12}$ erg cm^{-2} s^{-1}

2MRS
~10^4 sources with D>1 Mpc
<250 Mpc
Flux proxy ϕ(14-195 keV)



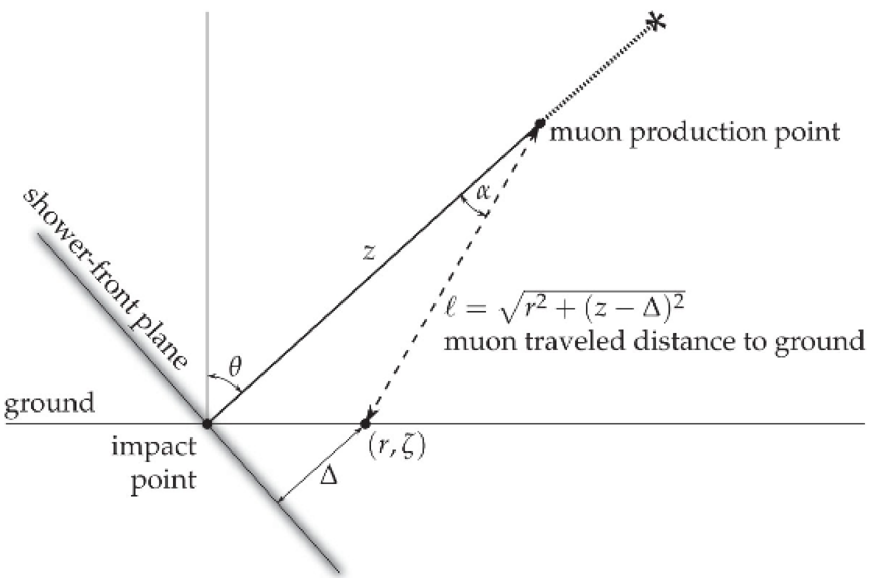


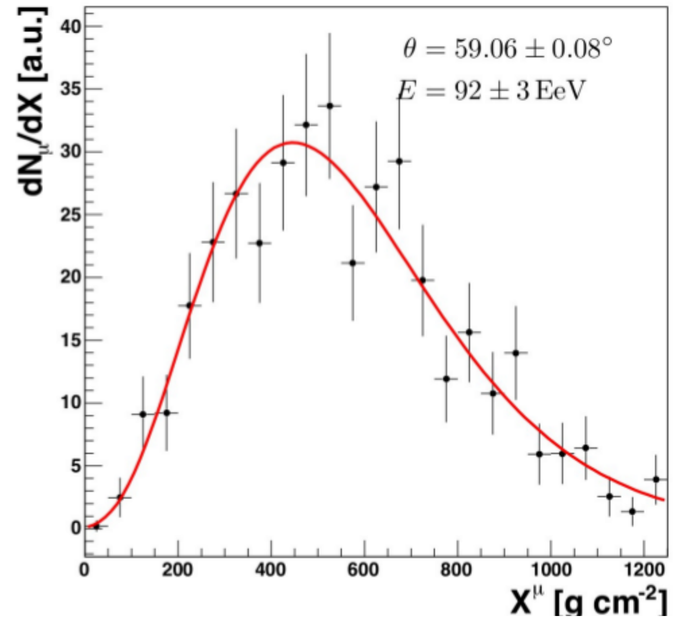
Likelihood analysis

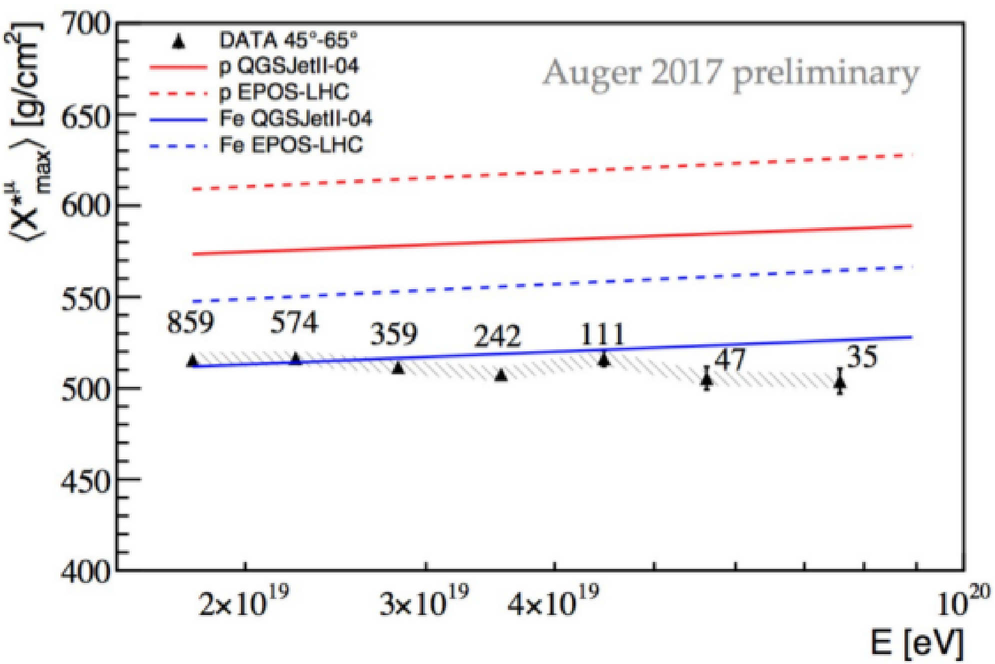
$$TS = 2Log\left[L(\psi, f_{anis})/L(f_{anis}=0)\right]$$

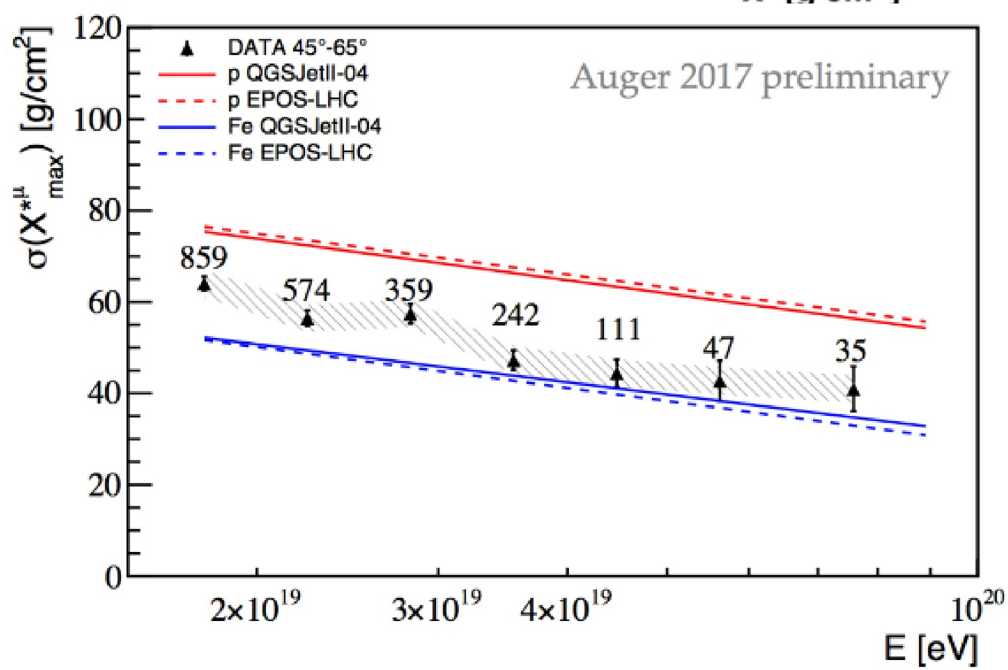
Catalog	E_{th}	TS	Local p-value	post-trial	f_{aniso}	θ
Starburst	38 EeV	29.5	4×10^{-7}	4.5 σ	$11^{+5}_{-4}\%$	15^{+5}_{-4} °
γ−AGN	39 EeV	17.8	1×10^{-4}	3.1 σ	$6^{+4}_{-3}\%$	14^{+6}_{-4} °
Swift-BAT	38 EeV	22.2	2×10^{-5}	3.6 σ	$8^{+4}_{-3}\%$	15^{+6}_{-4} °
2MRS	40 EeV	22.0	2×10^{-5}	3.6 σ	$19^{+10}_{-7}\%$	15^{+7}_{-4} °

MUON PRODUCTION DEPTH







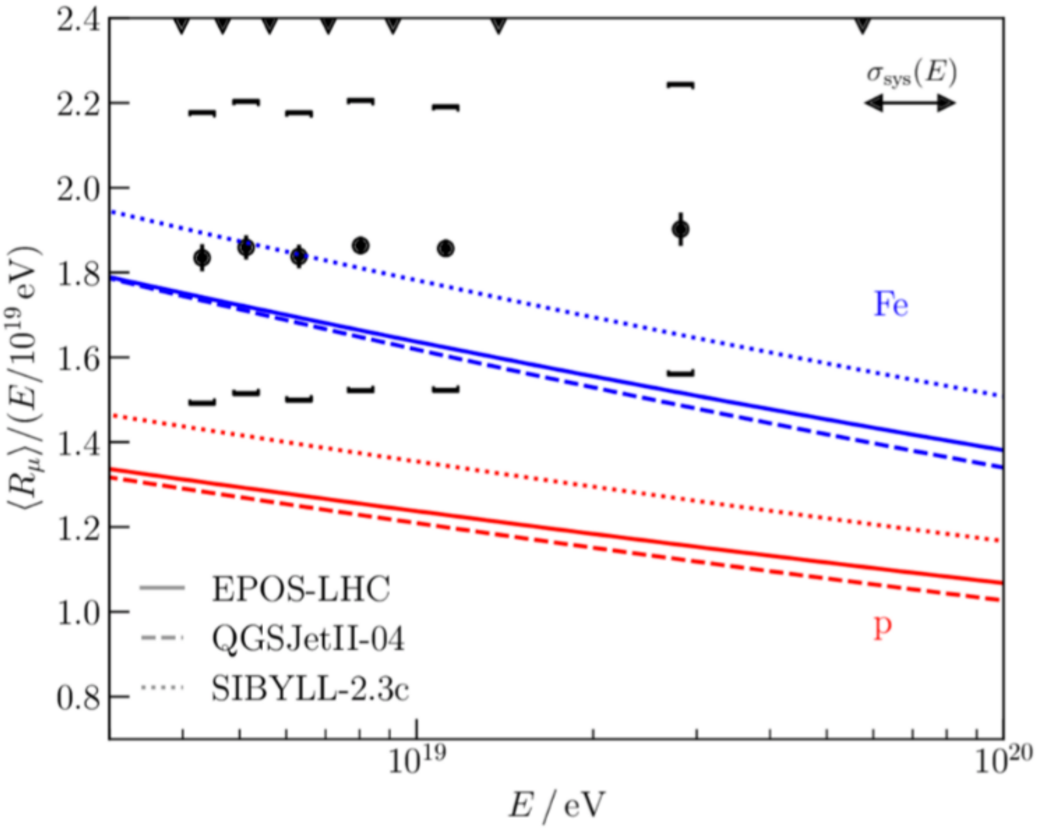


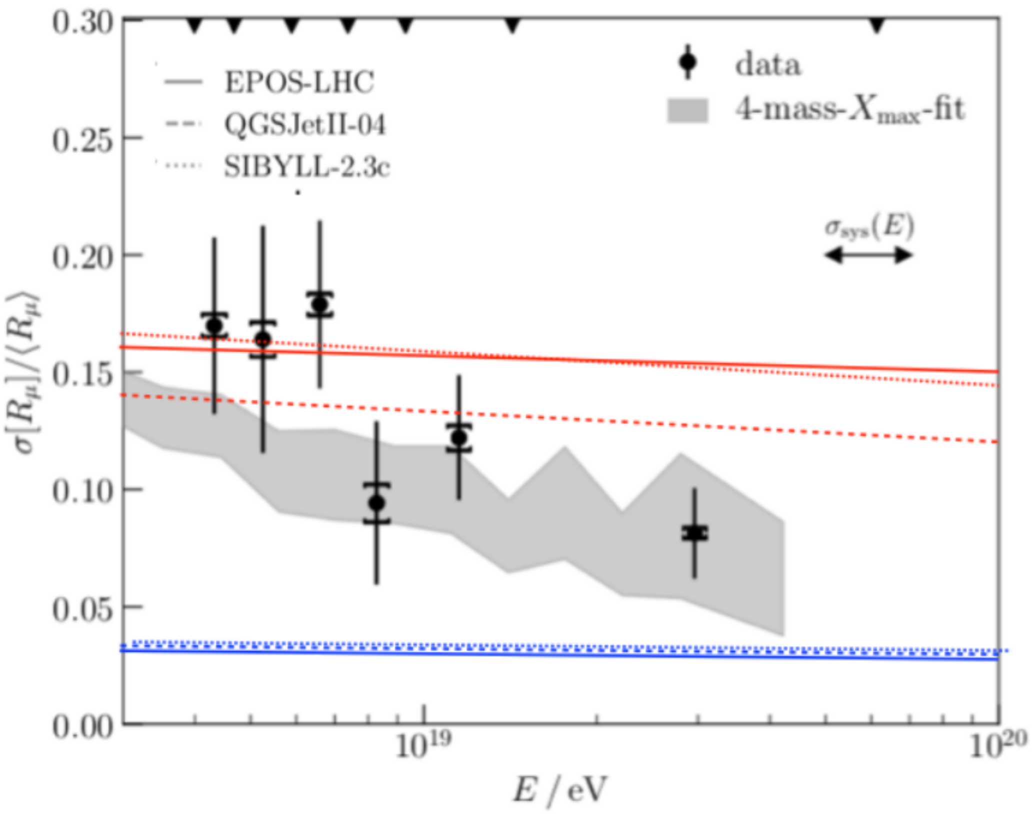
Hadronic interaction models not only produce fewer muon than observed but they are produced at a larger atmospheric depth

Auger PRD 90, 012012 (2014)

FLUCTUATIONS OF THE MUON NUMBER

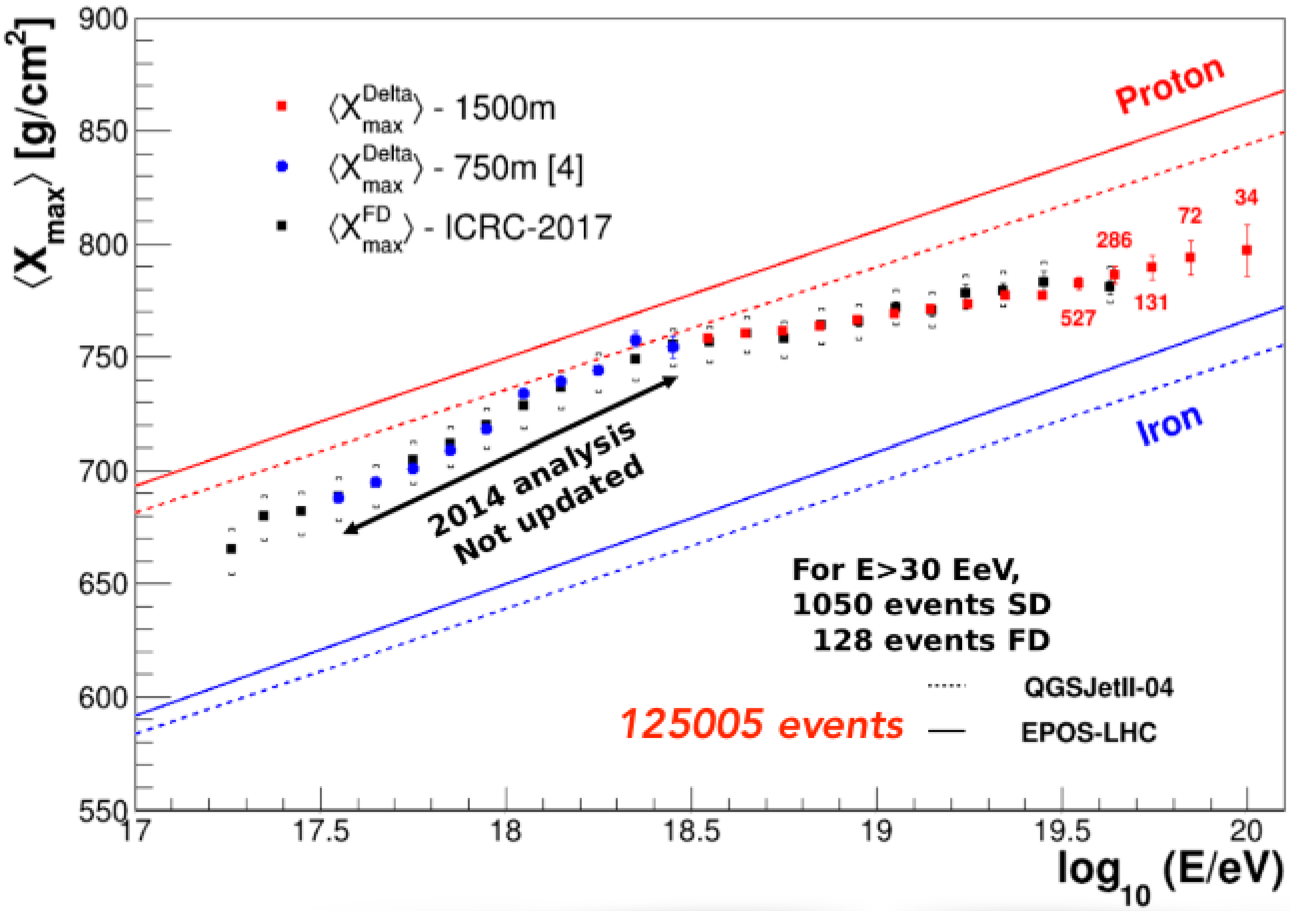
using inclined hybrid events





Fluctuations in the muon number → probe of the first interaction at UHE
Post-LHC models give a good description of particle production in the first interaction
Muon deficit more probably due to small deviations in the particle production accumulated over several generation of interactions

$<X_{max}>$ from SD



$\langle X_{max} \rangle$ [g/cm^2]
900
850
800
750
700
650
600
550
17
17.5
18
18.5
19
19.5
20
$\log_{10}$ (E/eV)
$\langle X_{max}^{Delta} \rangle$ - 1500m
$\langle X_{max}^{Delta} \rangle$ - 750m [4]
$\langle X_{max}^{FD} \rangle$ - ICRC-2017
Proton
Iron
286
72
34
527
131
2014 analysis
Not updated
For E>30 EeV,
1050 events SD
128 events FD
QGSJetII-04
125005 events
EPOS-LHC