STATUS OF ULTRA-HIGH ENERGY COSMIC RAYS

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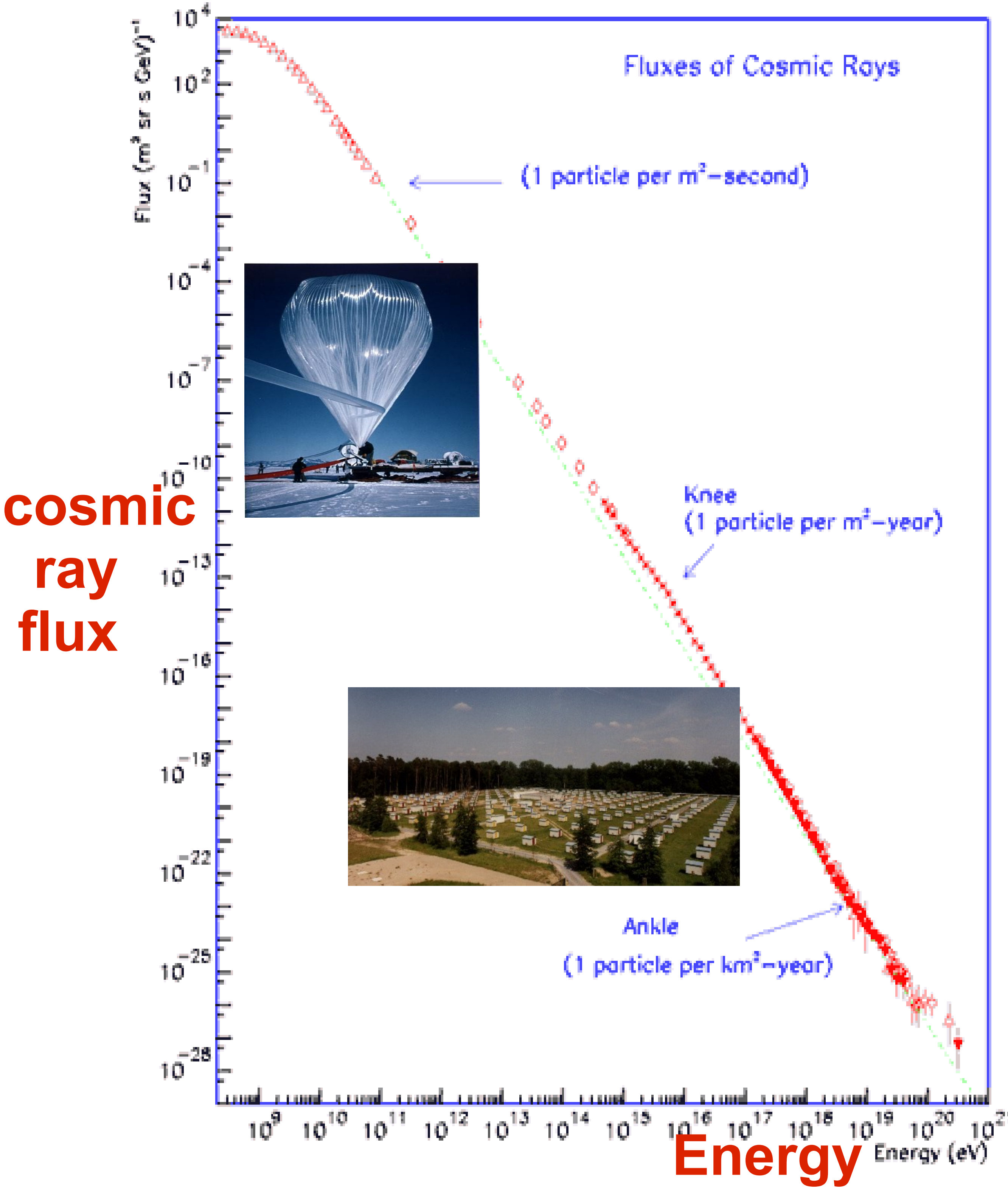
TeVPA/IDM 2014

Main questions regarding Cosmic Rays:

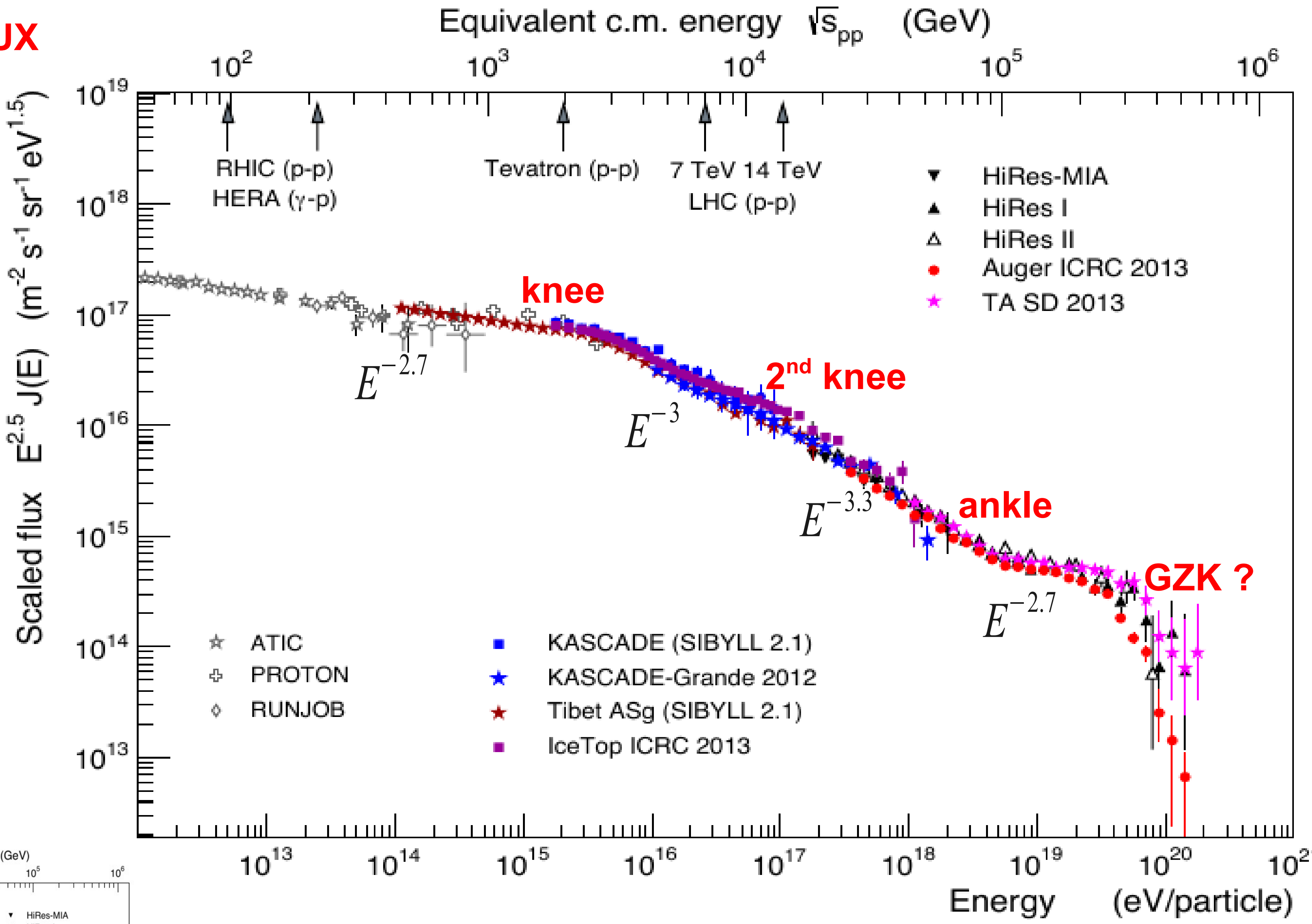
What are they
Where and how are they accelerated
What produces the changes in spectrum & composition
How are the hadronic interactions at the highest E
How do they propagate, effects of galactic and X-gal B fields
What are the effects of interactions with CMB
Are neutrinos & photons produced
….

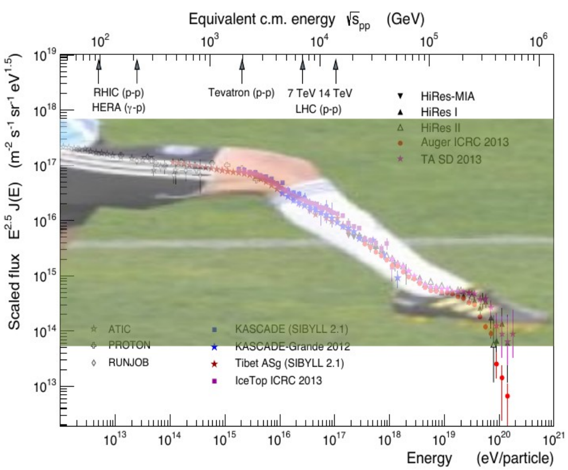
Main CR observables:

Spectrum, composition and anisotropies


Fluxes of Cosmic Rays
(1 particle per m²–second)
Knee
(1 particle per m²–year)
Ankle
(1 particle per km²–year)
Flux (m² sr s GeV)⁻¹
Energy (eV)
cosmic ray flux
Energy

$E^{2.5}$ x FLUX

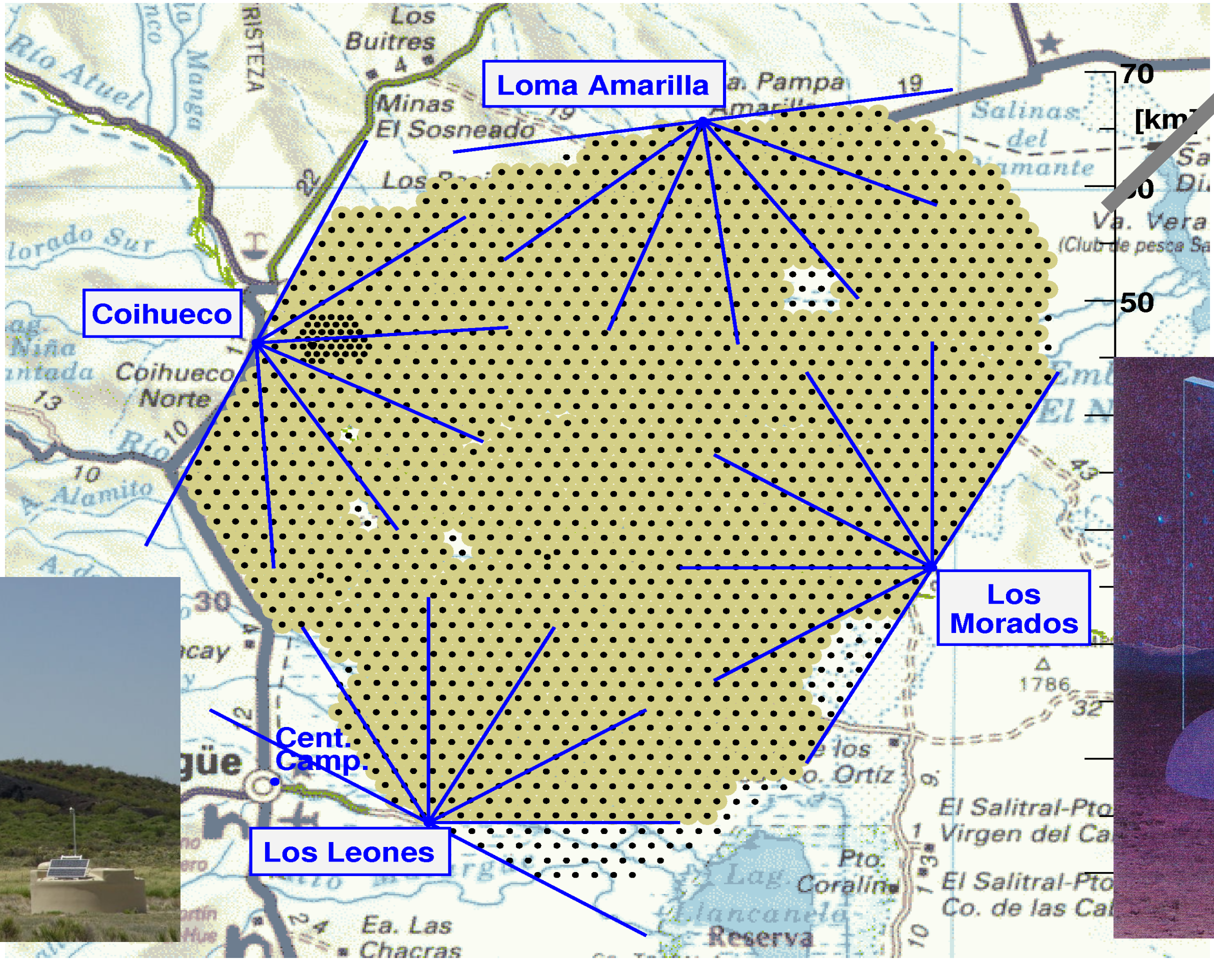


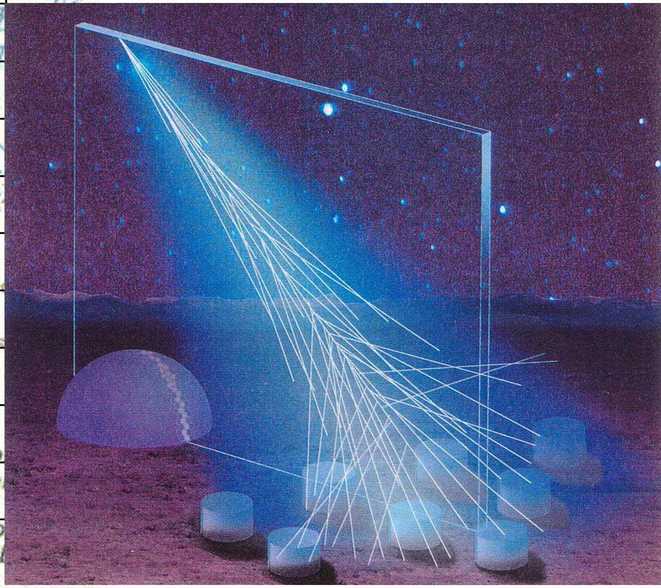


this talk

DETECTING UHECRs: 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

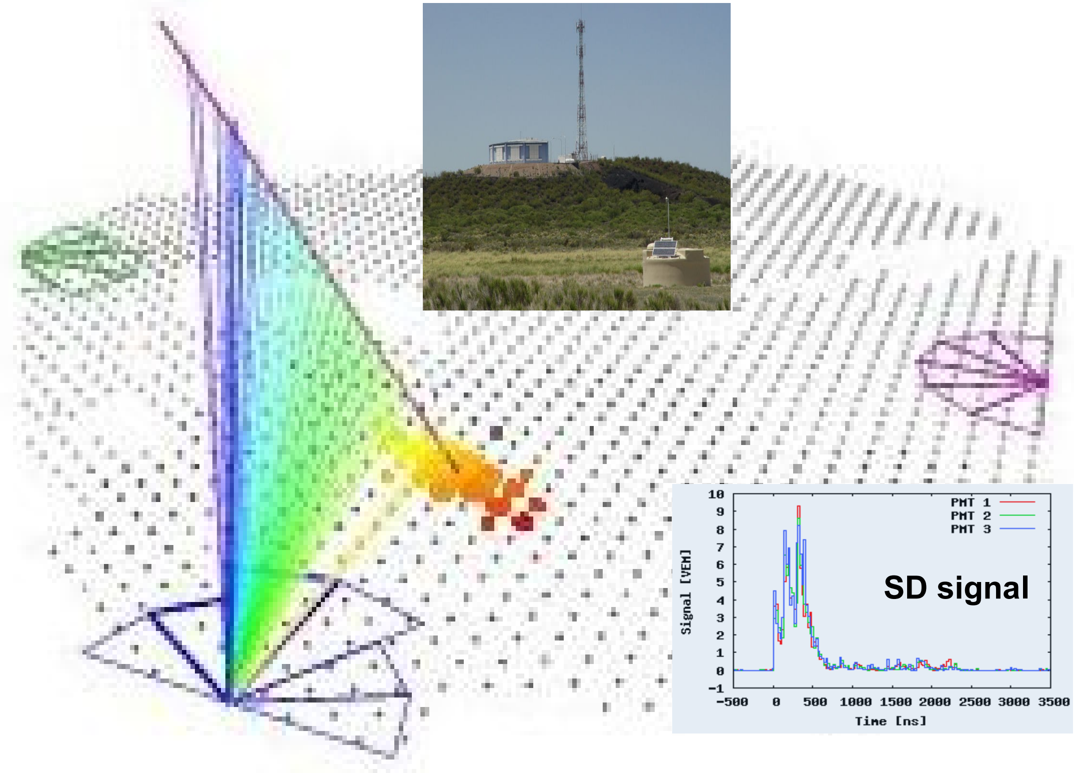




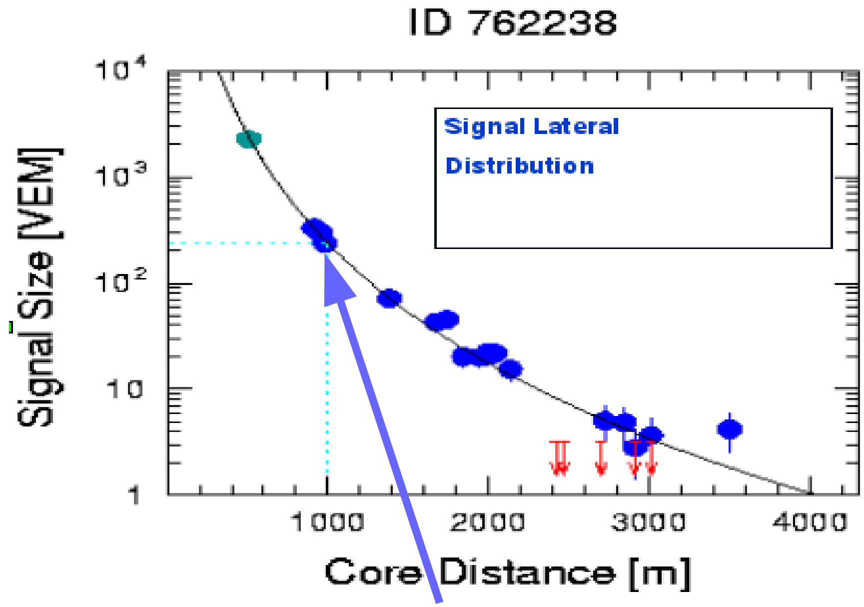
1660 detectors instrumenting 3000 km^2 and 27 telescopes

the Auger Collaboration: 18 countries, ~ 400 scientists, since 2004

CR AIR SHOWER DETECTION

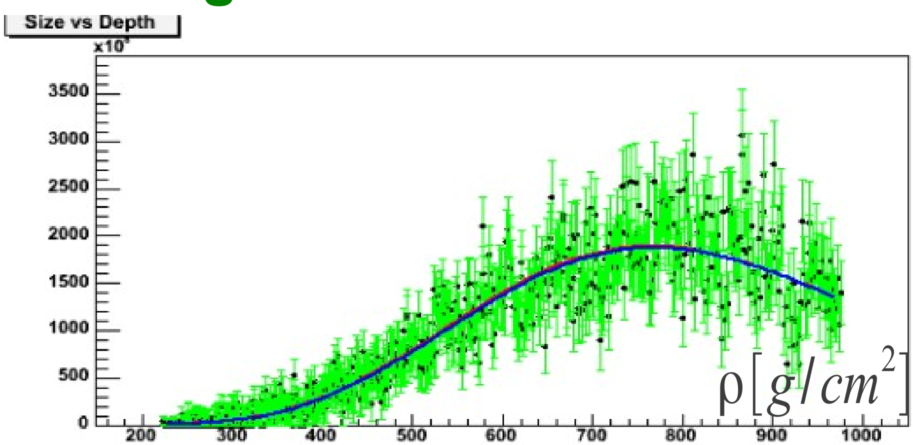


Lateral distribution at ground

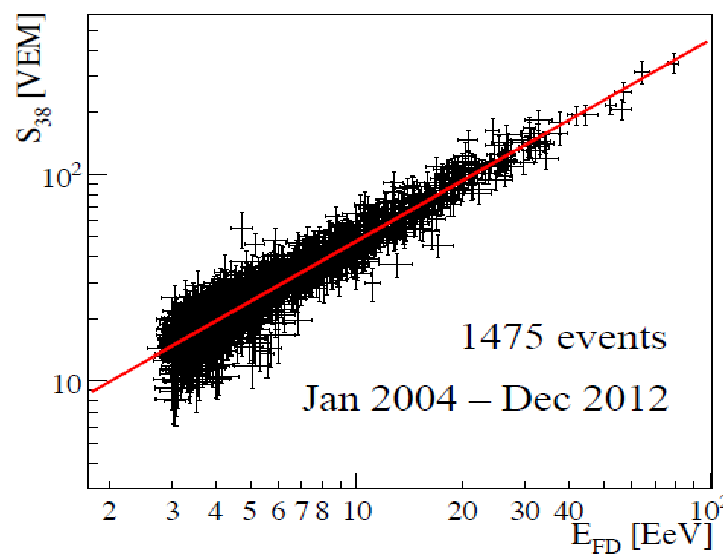


E_{SD} estimated from S(1000 m)

Longitudinal distribution in air



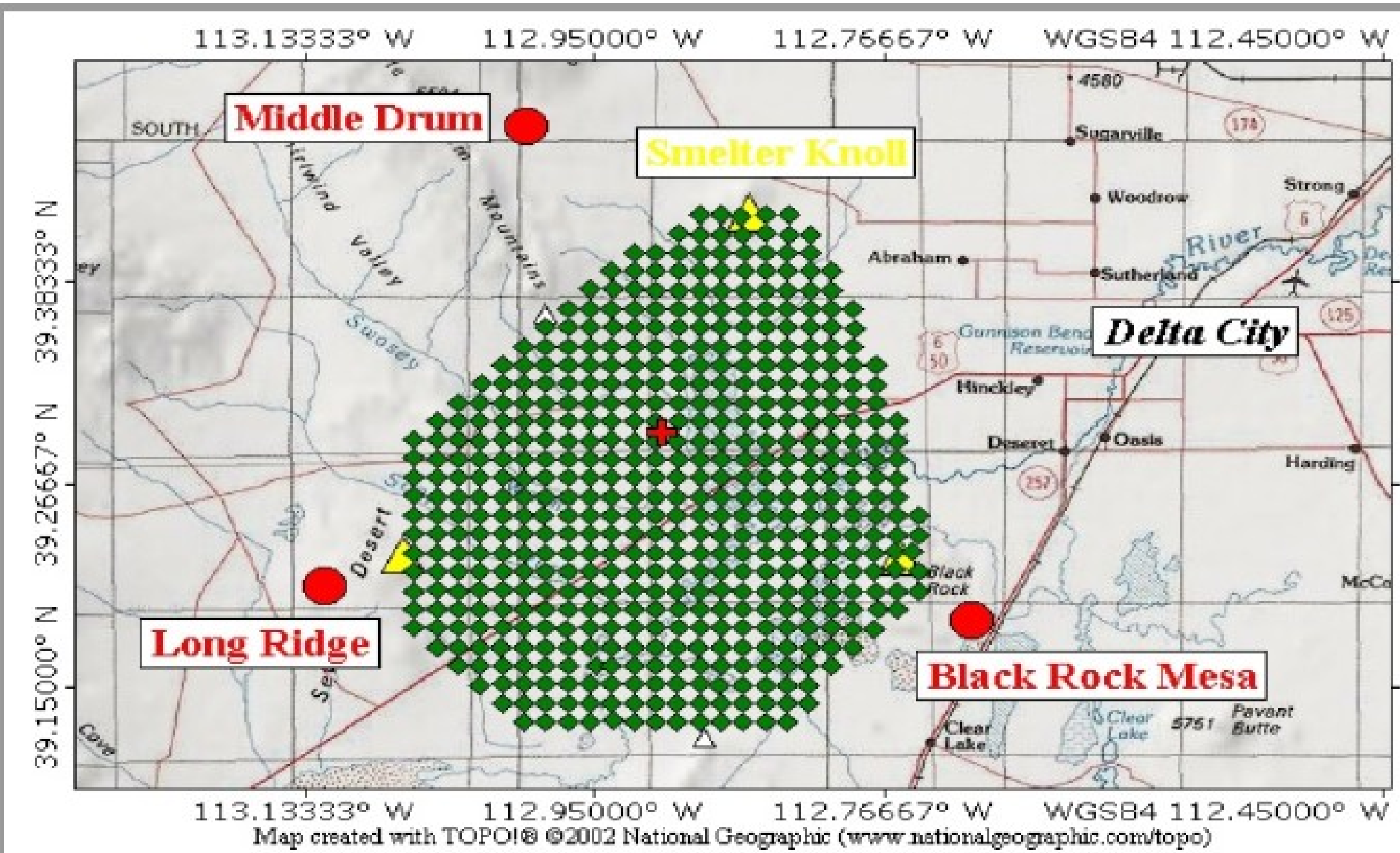
(FD duty cycle ~15%)



Energy calibration

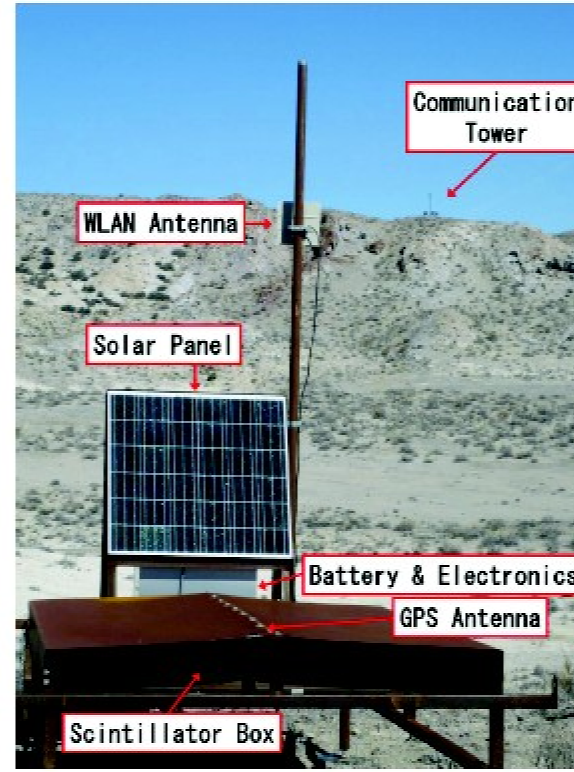
TELESCOPE ARRAY in Utah

Since 2008



- 507 scintillator detectors covering 680 km^2
- 3 fluorescence sites, 38 telescopes

1.2 km spacing



Mostly sensitive to the em component

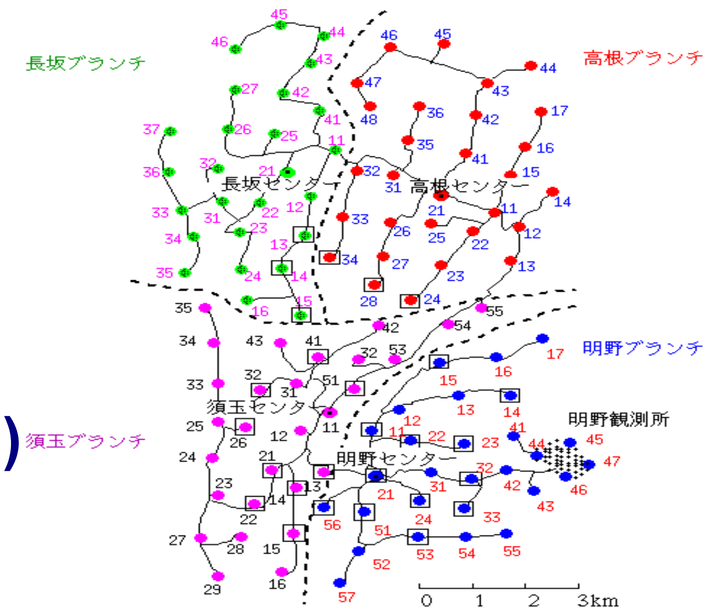
E from $S(800\ m)$

TA Exposure (θ < 45) ~ 1/6 Auger Exposure (θ < 60)

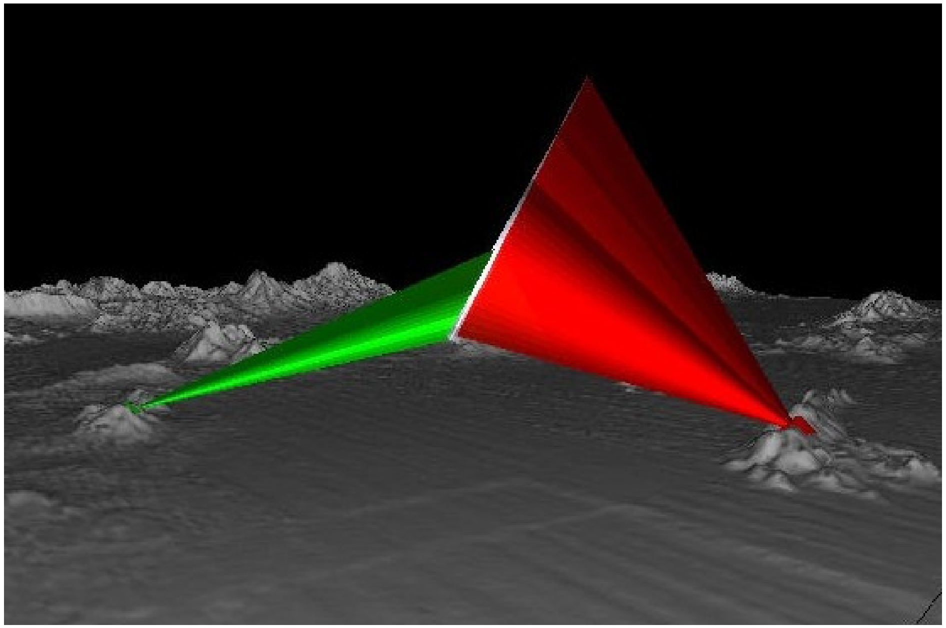
Calibration → E_{MC}=1.27 E_{FD}
(explains AGASA E scale)

Also Yakutsk (Cherenkov telescopes and scintillators ~10 km^2, since '70s)

Previous experiments:



AGASA: **(Akeno, Japan 1990-2004)**
Area: 100 km^2
111 Scintillators (e^+e^-) and
27 shielded proportional counters (muons)



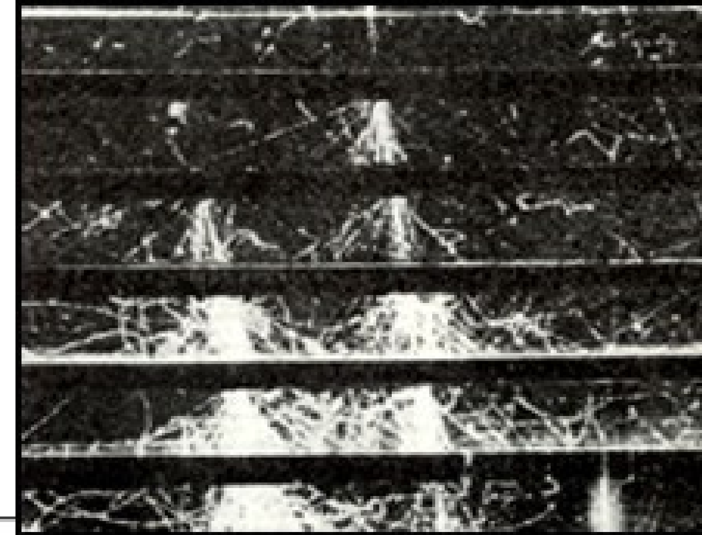
Fly's Eye **(1981-1993) Utah, USA**
HiRes **(1997-2006)**

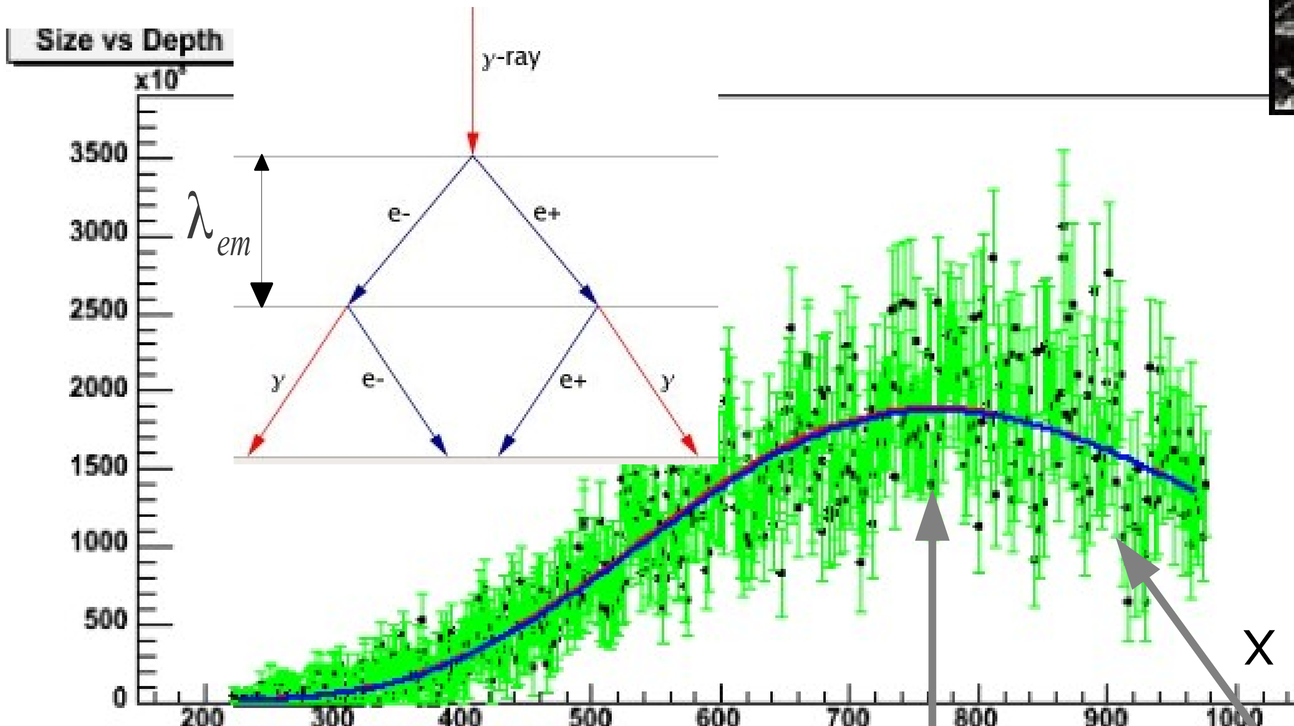
Fluorescence telescopes

Also Kascade-Grande, Volcano Ranch, Haverah Park, Sugar, ...

Some basics on air showers:

ELECTROMAGNETIC SHOWERS (e^+ , e^- , γ)





N grows exponentially

$$N = 2^n , \; with \; n = X / \lambda_{em}$$

$$X_{max} = n \, \lambda_{em} = X_R \ln(E_0 / E_c)$$

$$E_e < E_c \simeq 86 \; MeV$$

Ionisation losses dominate

$$N_{max} \simeq \frac{E_0}{E_c} \simeq 10^{11} \frac{E_0}{10^{19} eV}$$

HADRONIC SHOWERS

Hadronic interactions produce large number of pions (multiplicity n_{tot})
Neutral pions feed EM component, charged pions reinteract multiplying again the number of hadrons.
After 5-6 generations pions can decay → muons and neutrinos

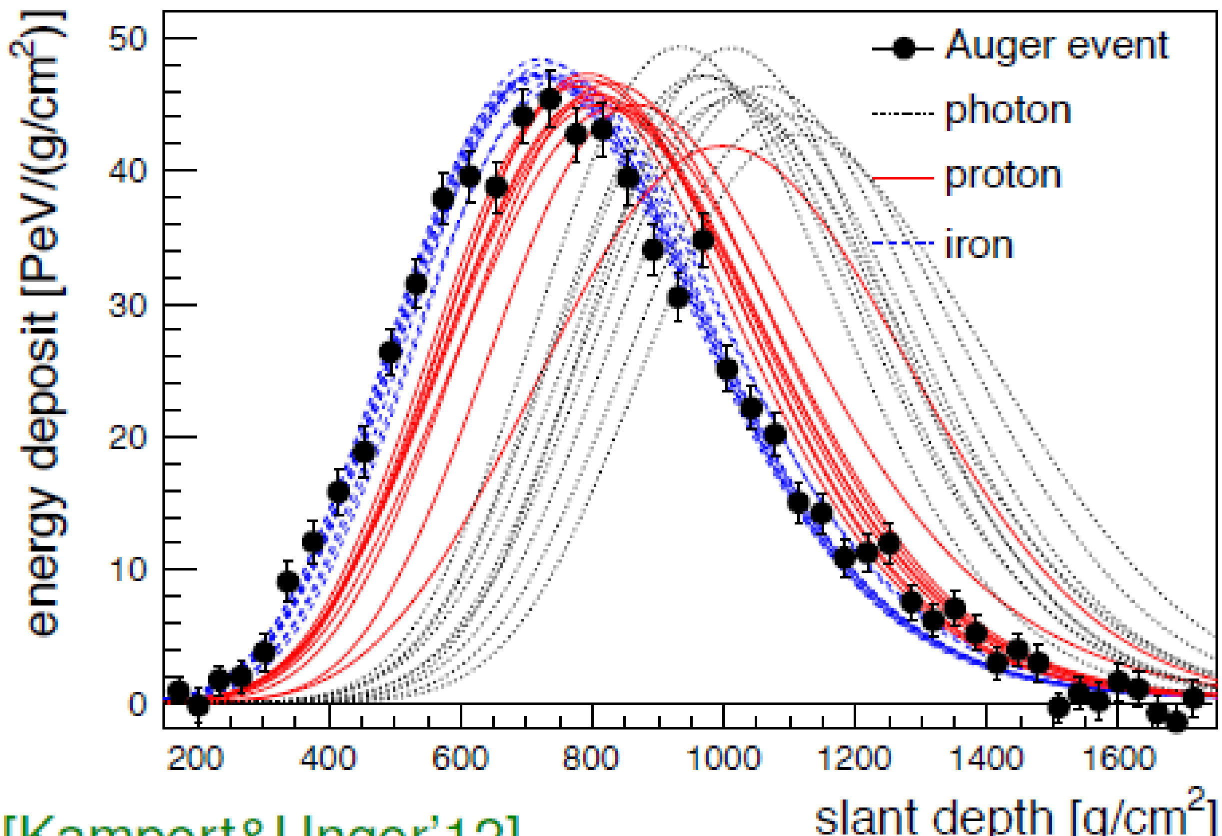
$$\left(typically\ \ E_{EM} \simeq 0.9\, E_{tot}\ \ while\ \ E_{\nu} + E_{\mu} \simeq 0.1\, E_{tot}\right)$$

$$X_{max} \simeq \lambda_I + X_R \ln\left(\frac{E_0 / n_{tot}}{E_c}\right)$$

$$\lambda_I \sim \sigma_{p-air}^{-1}$$

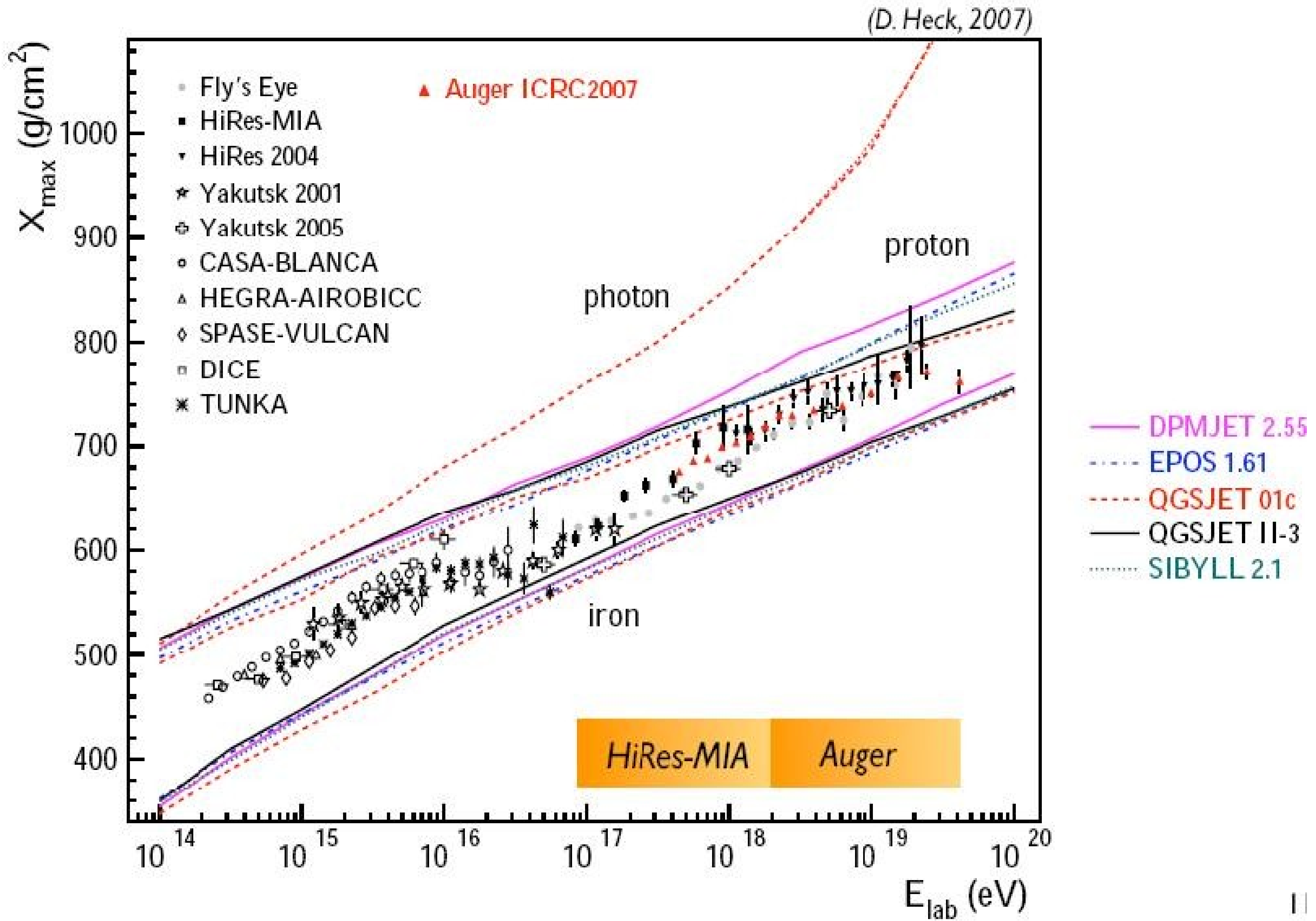
Nuclei behave as A **nucleons with** $E_n = E_0 / A$

→ less penetrating,
smaller fluctuations



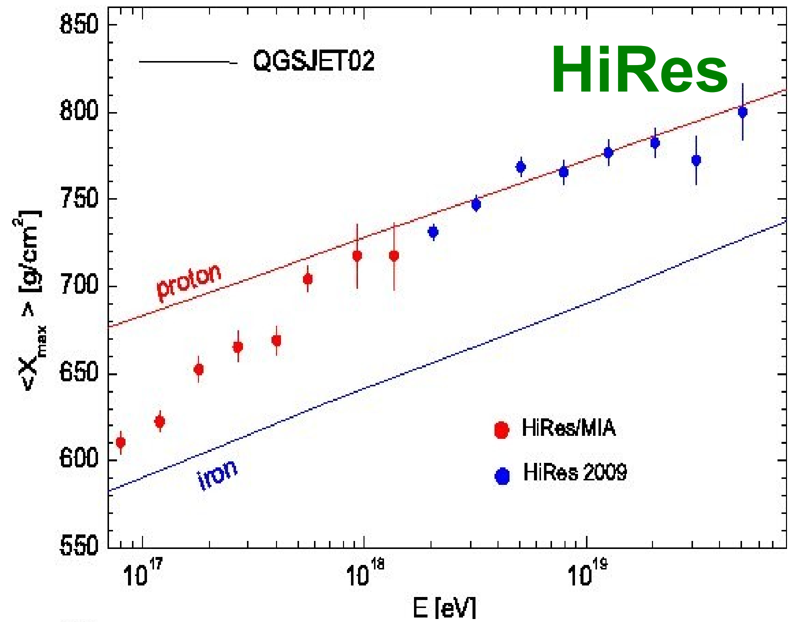
[Kampert&Unger'12]

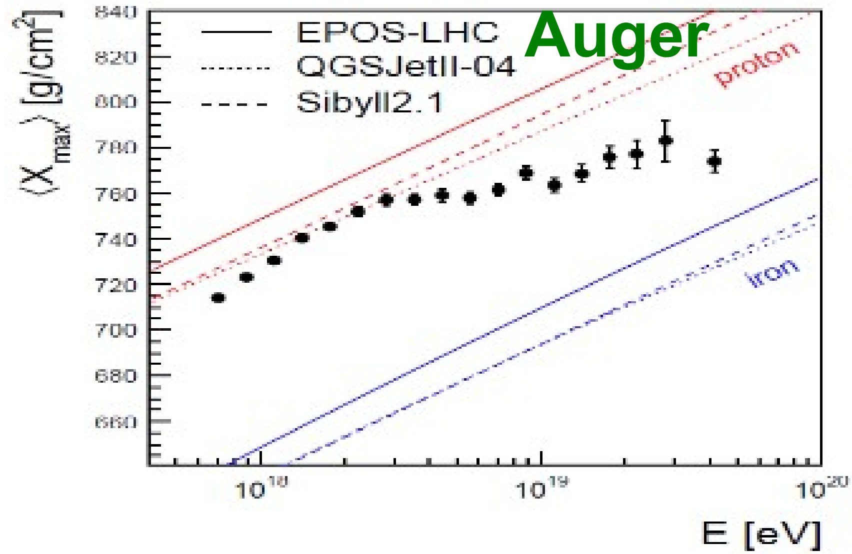
COMPOSITION FROM X_{max}



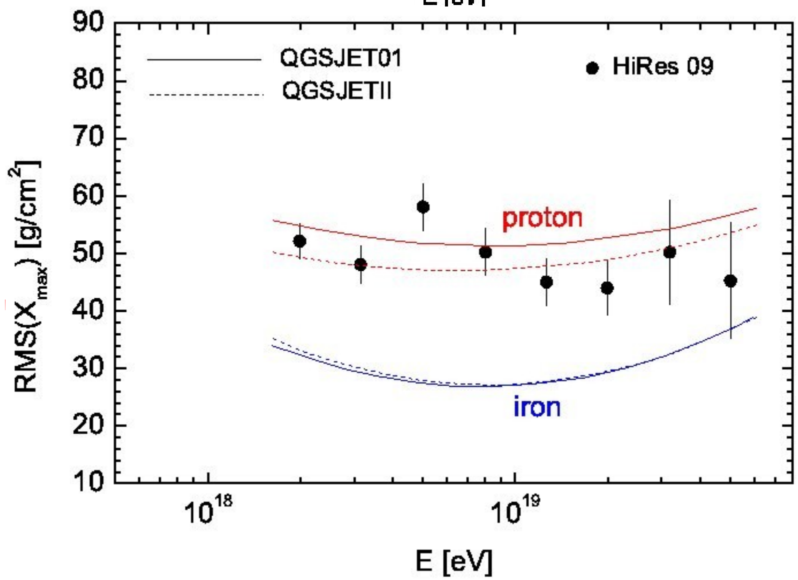
CONFLICTING RESULTS AT UHE ?

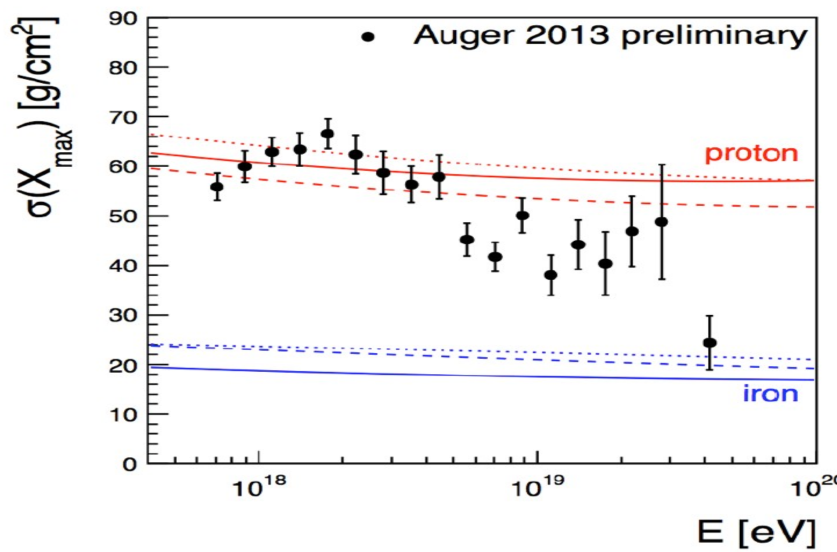
X_{max}





RMS

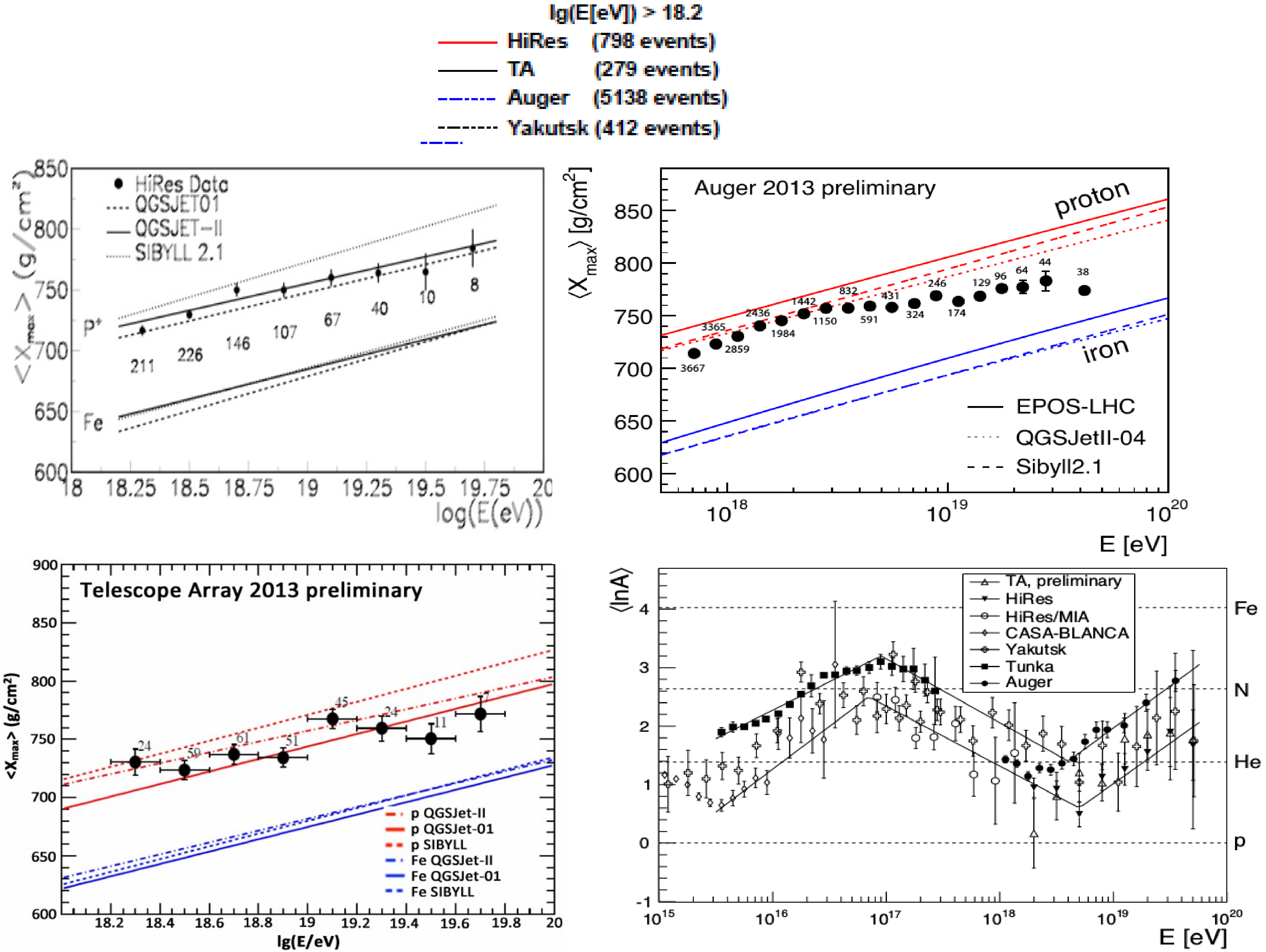




HiRes: consistent with protons (similarly TA)

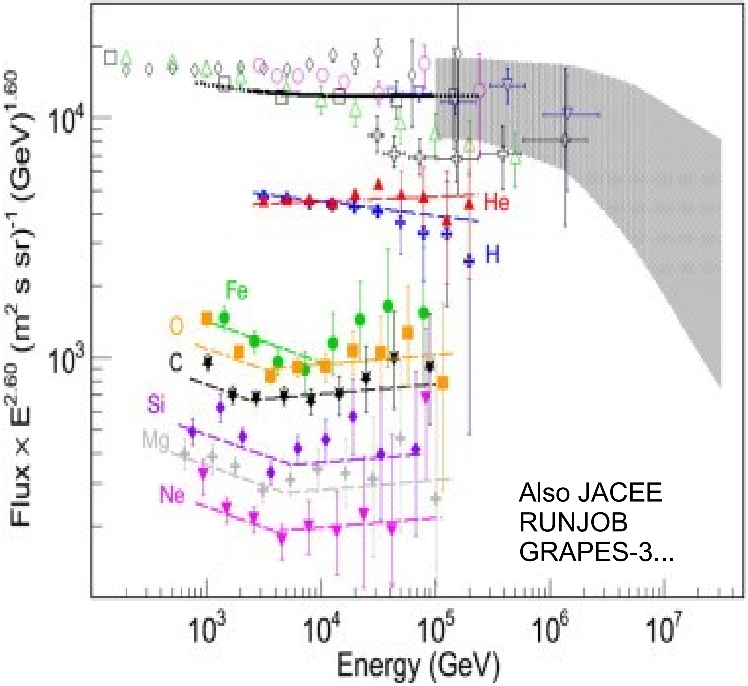
Auger: transition to heavier above ankle or change in hadronic interactions?

HiRes & TA: Xmax with detector bias, Auger: cuts to have unbiased Xmax → they should not be plotted together

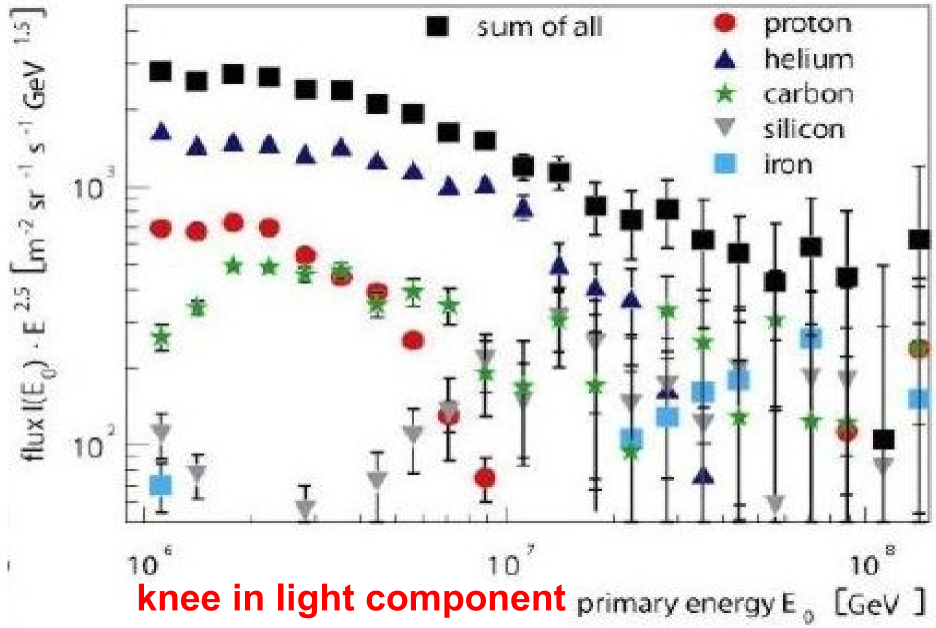


(needs much more statistics from TA to see if there is real conflict)

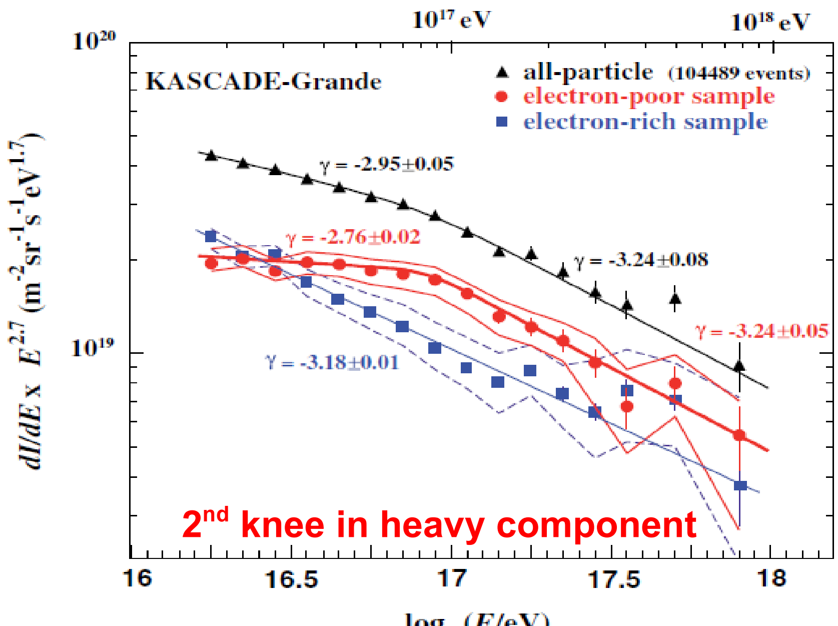
1-100 TeV CREAM



1-100 PeV Kascade

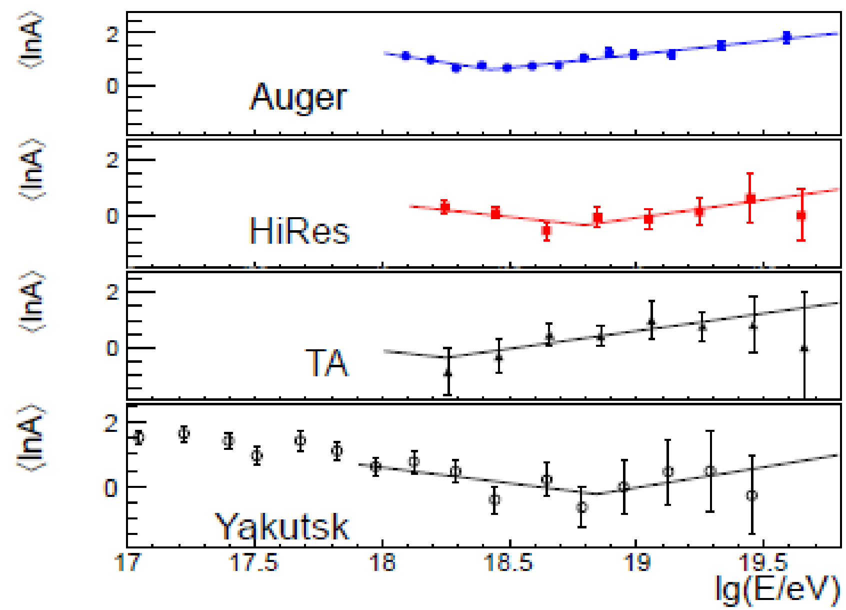


10 PeV – 1 EeV Kascade-Grande



Ankle in light component ?

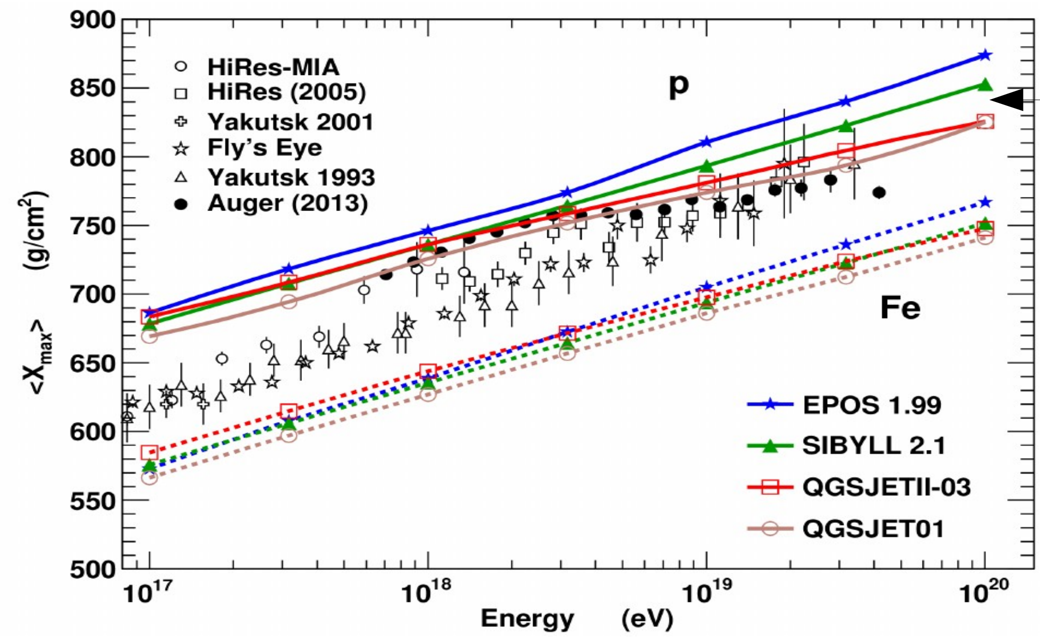
1 – 30 EeV



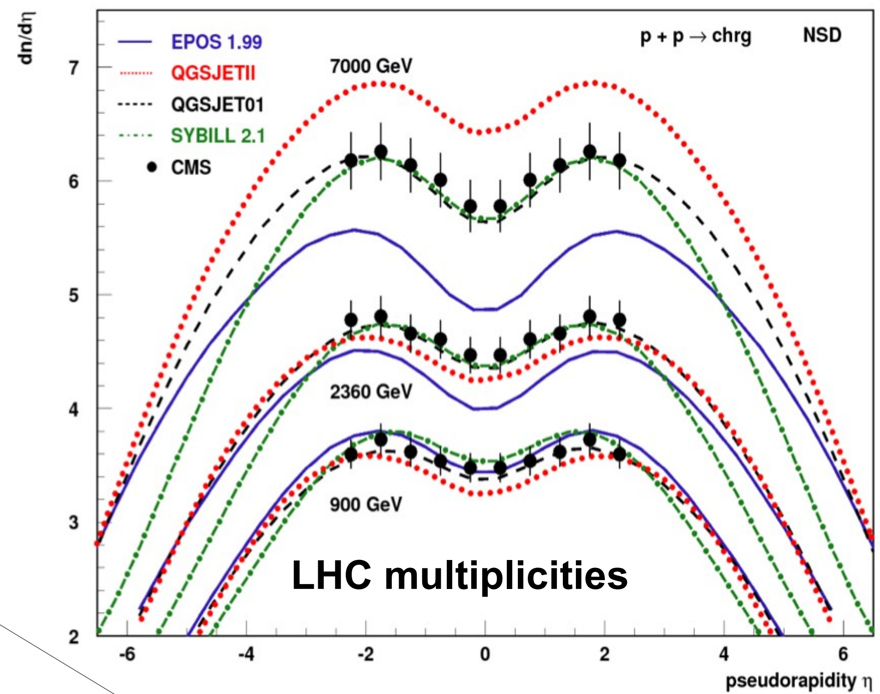
UHECR 2012

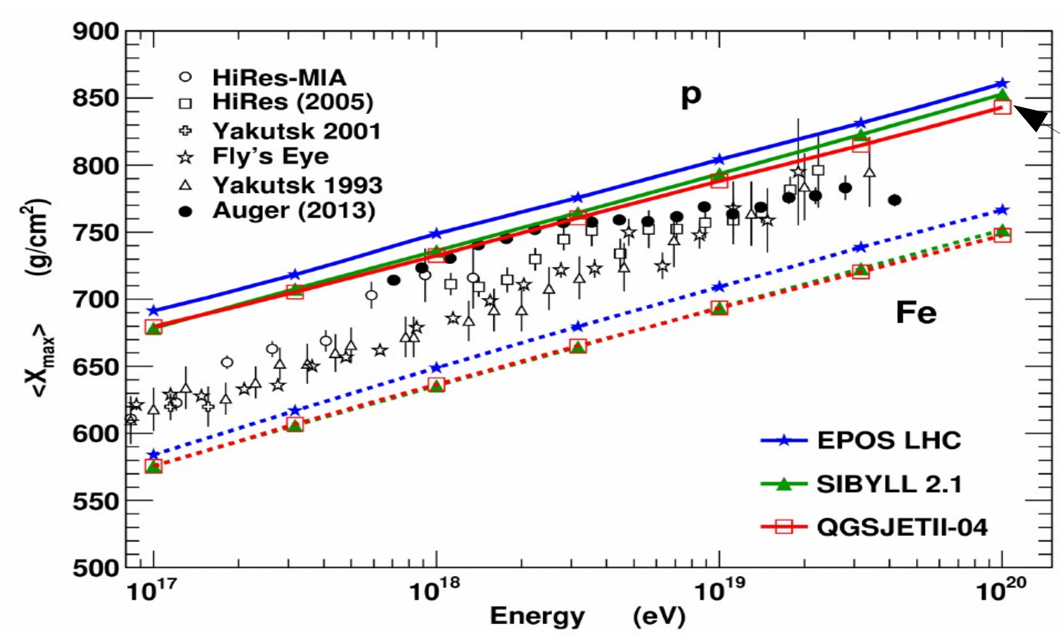
Need few more years to see compatibility TA-Auger

Average Xmax vs E and model predictions for p/Fe



Hadronic models before LHC





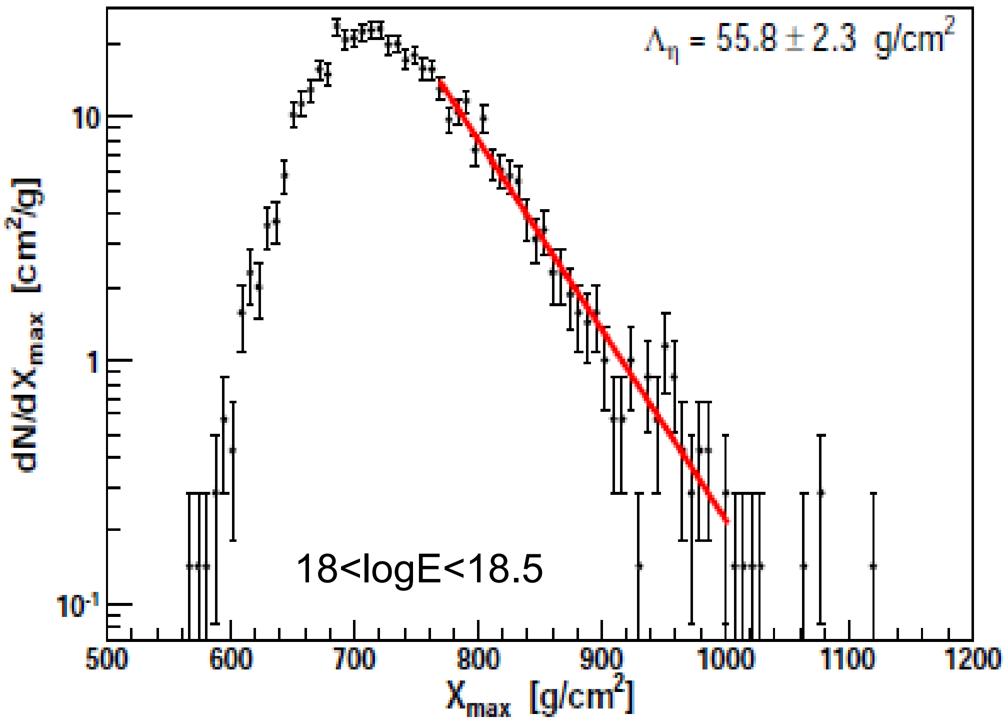
Hadronic models after LHC

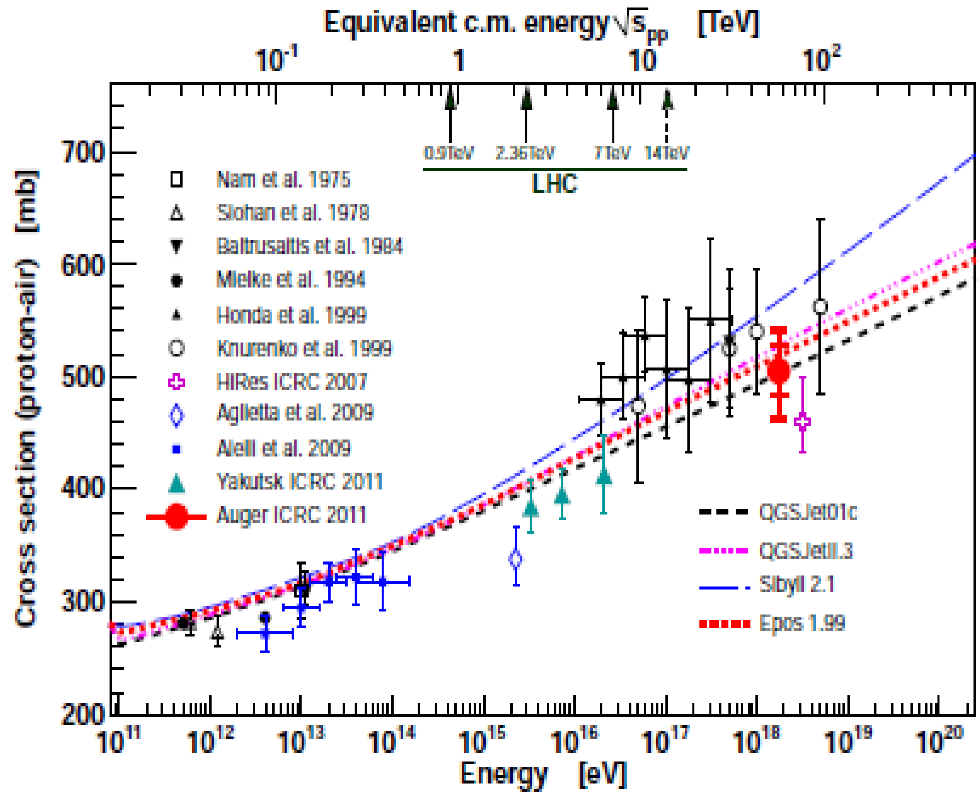
Pierog 2014

(Compared to QGSJET CRs are now 'heavier')

p-air CROSS SECTION FROM AIR SHOWERS

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

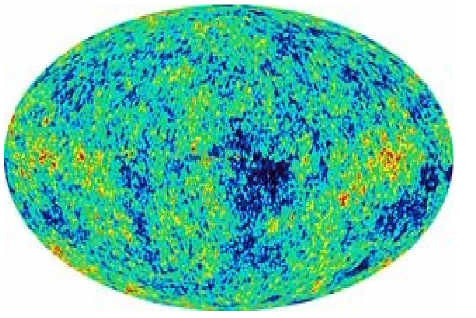


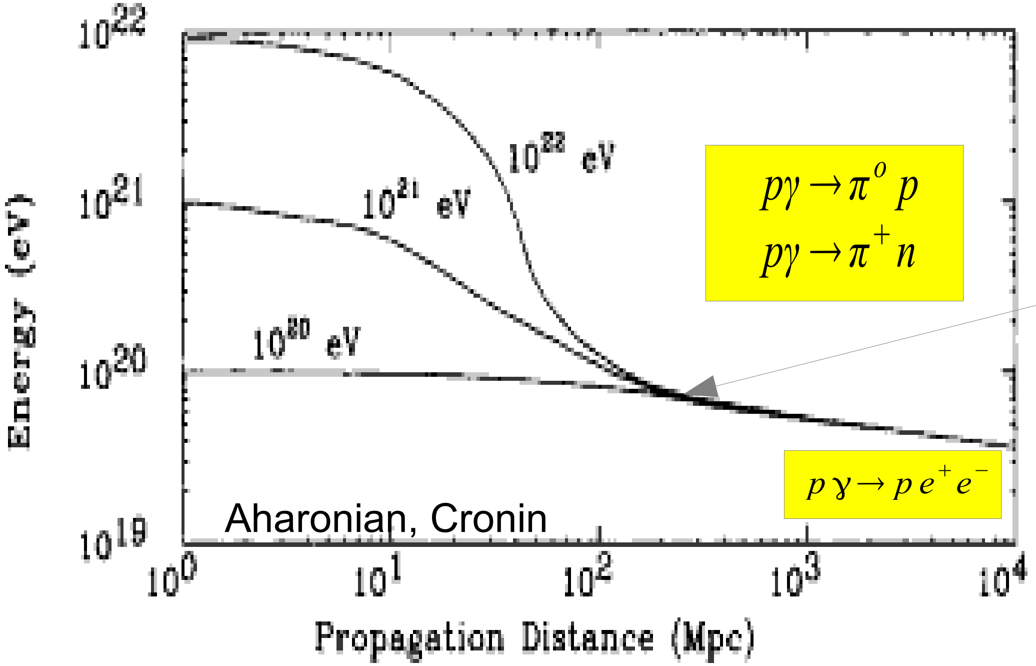


Inferred p-air cross section looks 'normal'

the Greisen-Zatsepin-Kuzmin effect (1966)

AT THE HIGHEST ENERGIES, CRs LOOSE ENERGY BY INTERACTIONS WITH THE CMB BACKGROUND

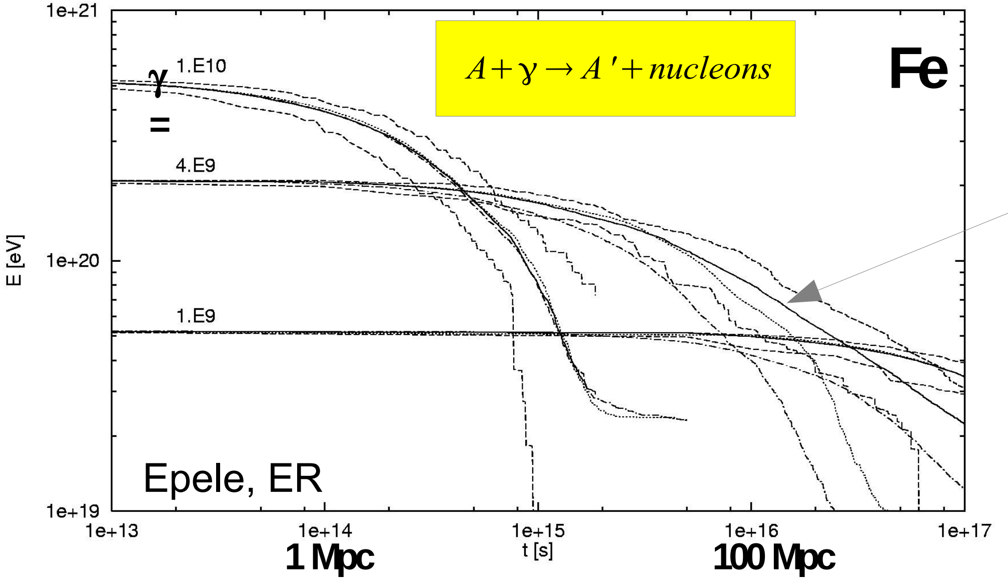




PROTONS CAN NOT ARRIVE WITH E > 6×10^{19} eV FROM D > 200 Mpc

($\pi^{\pm}$ produce cosmogenic neutrinos)

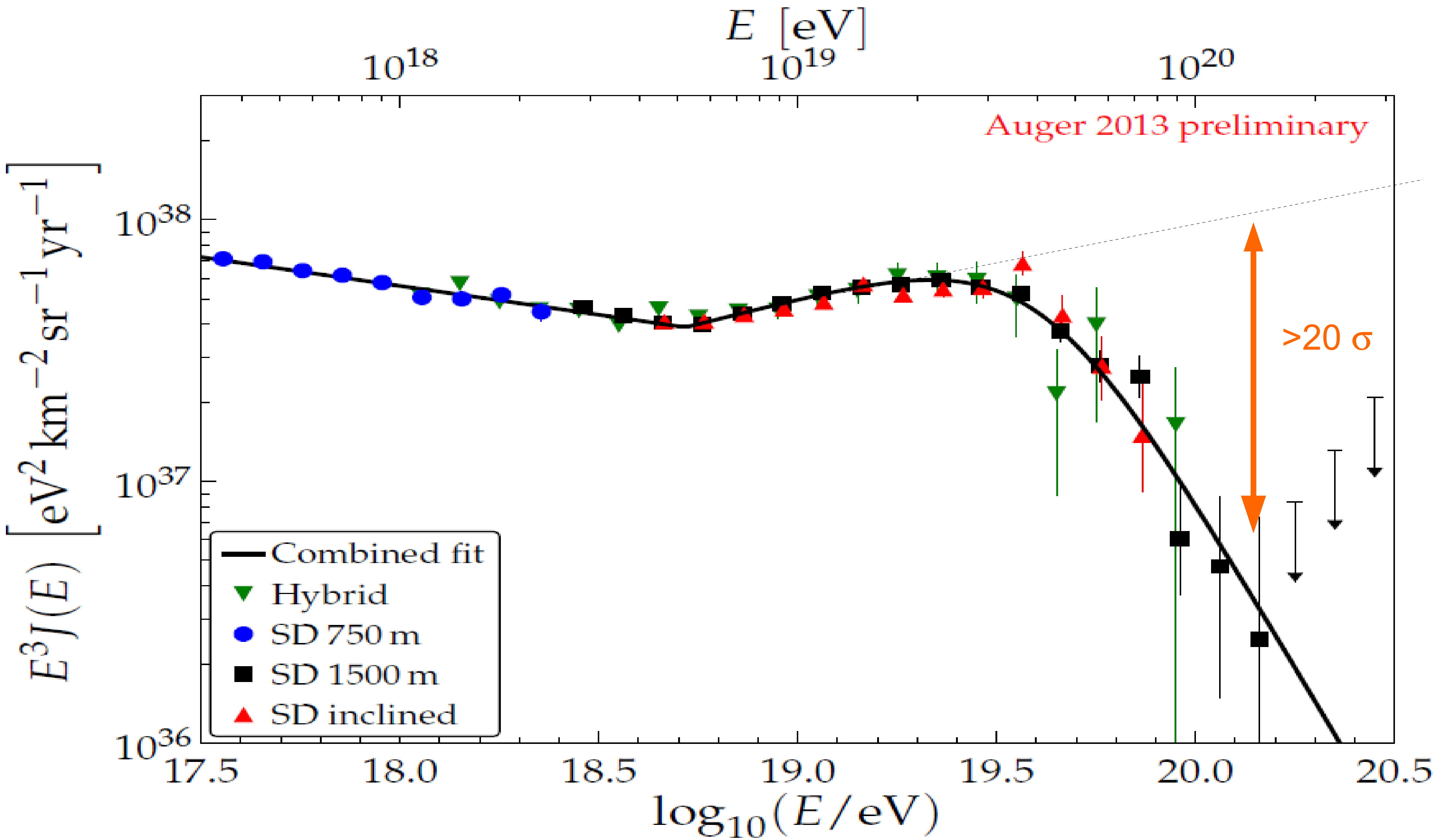
(π^0 produce GZK photons)



For Fe nuclei:
after ~ 200 Mpc the leading fragment has E < 6×10^{19} eV

ligther nuclei get disintegrated also down to lower E

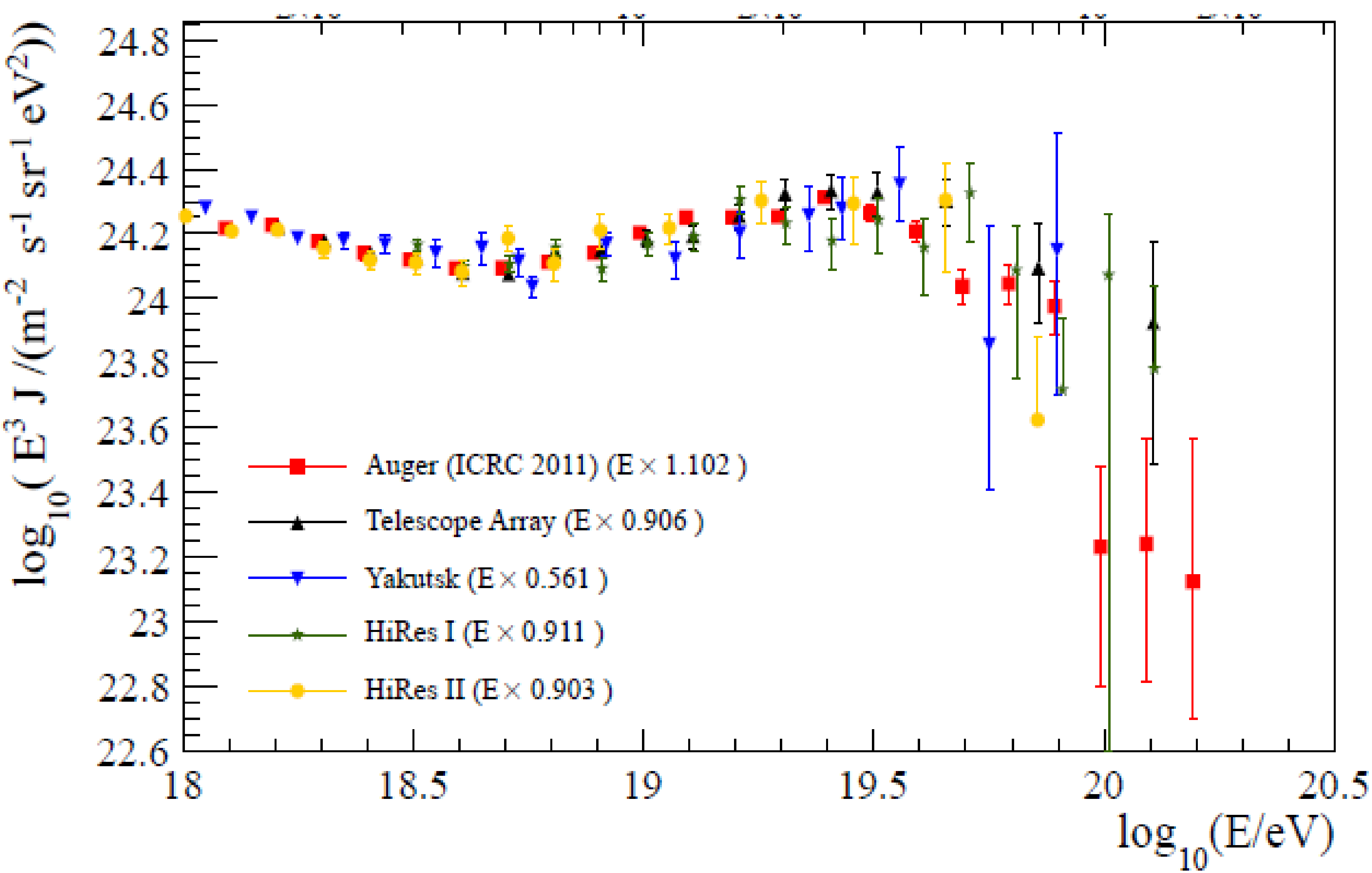
AUGER 2013 SPECTRA



Normalizations: Hybrid: 0.94, 750 m array: 1.02, Inclined: 1.05

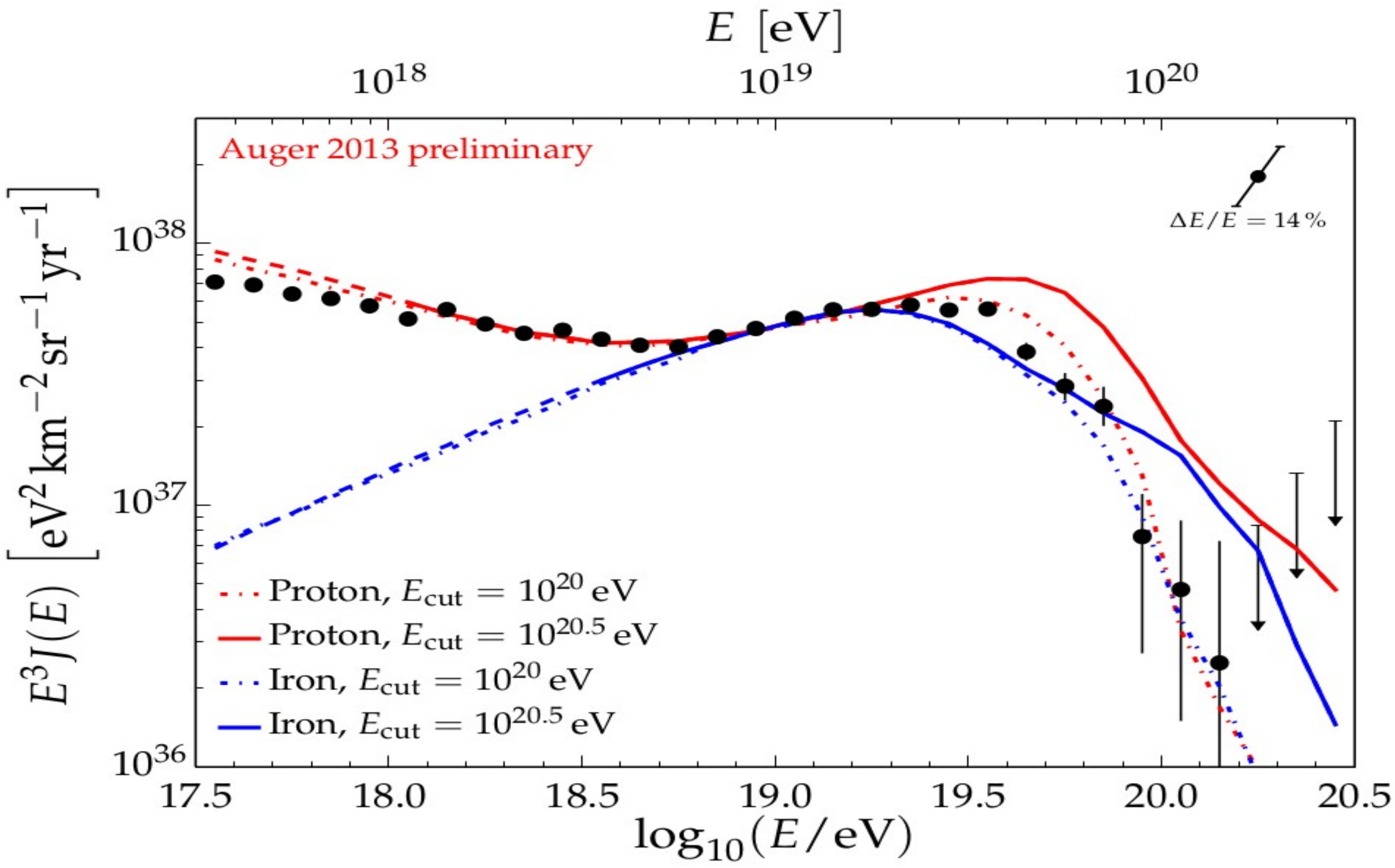
HiRes and TA see GZK at more than 5

Rescaled spectra UHECR 2012 WG



spectra from different experiments consistent within systematics

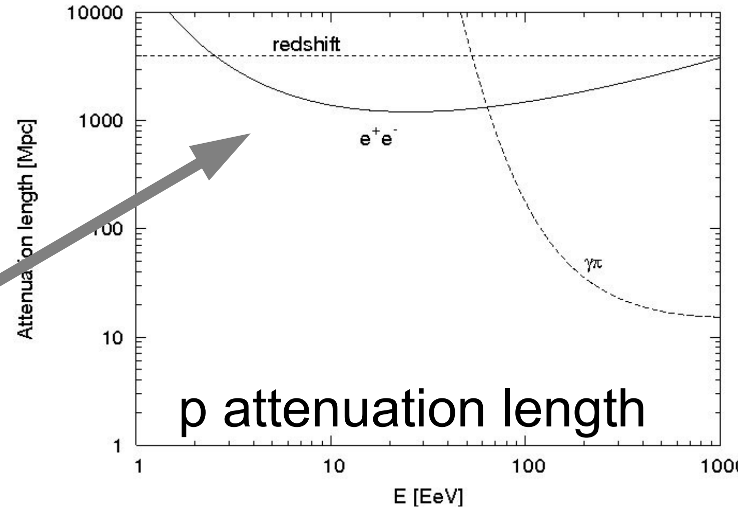
Fit to Auger with p or Fe models



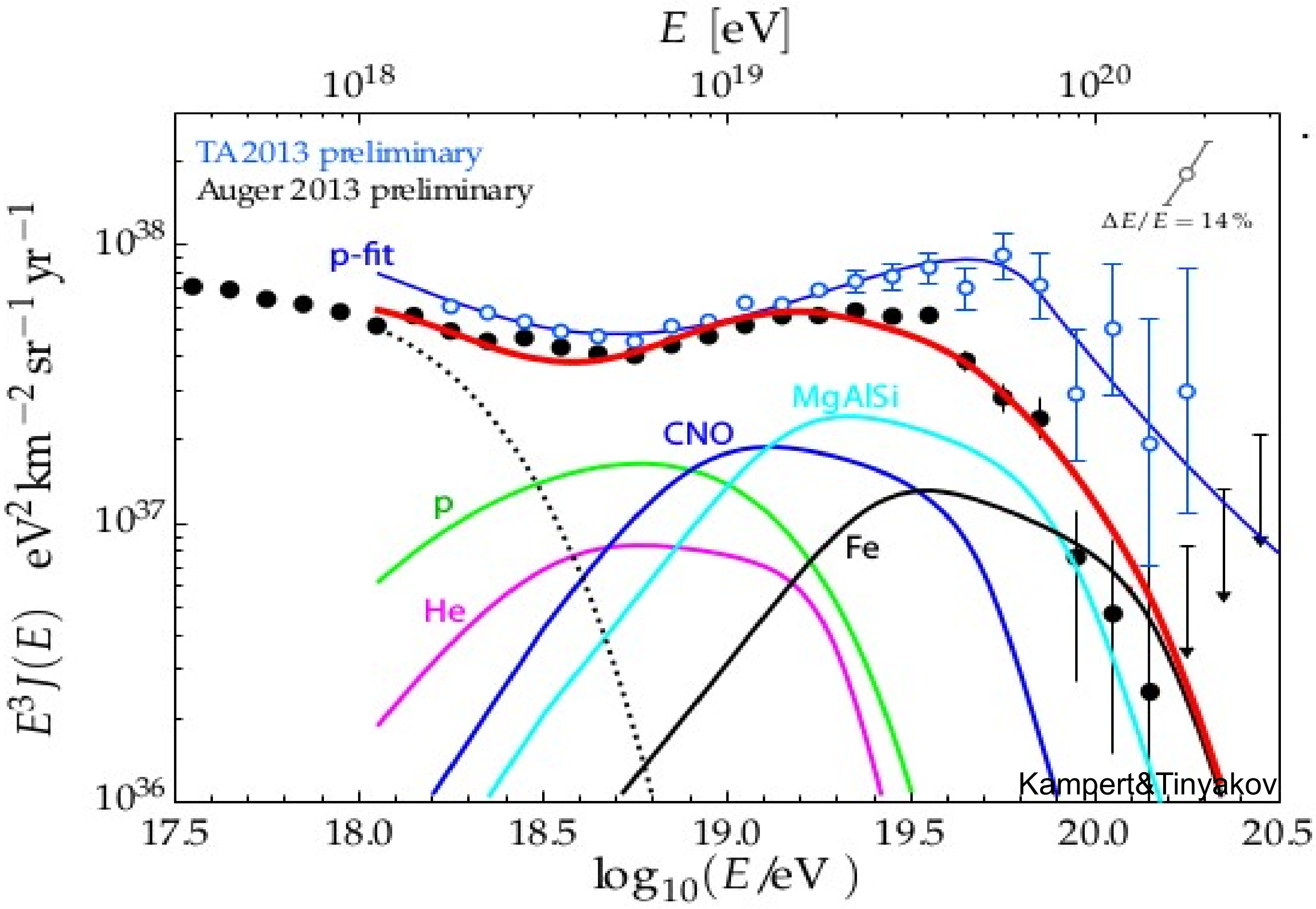
GZK: **proton or Fe suppression ?**
(and/or exhaustion of sources?)

Ankle: **Galactic – extragalactic transition**
or e^+e^- dip in Xgal protons ?

or Xgalactic mixed composition?



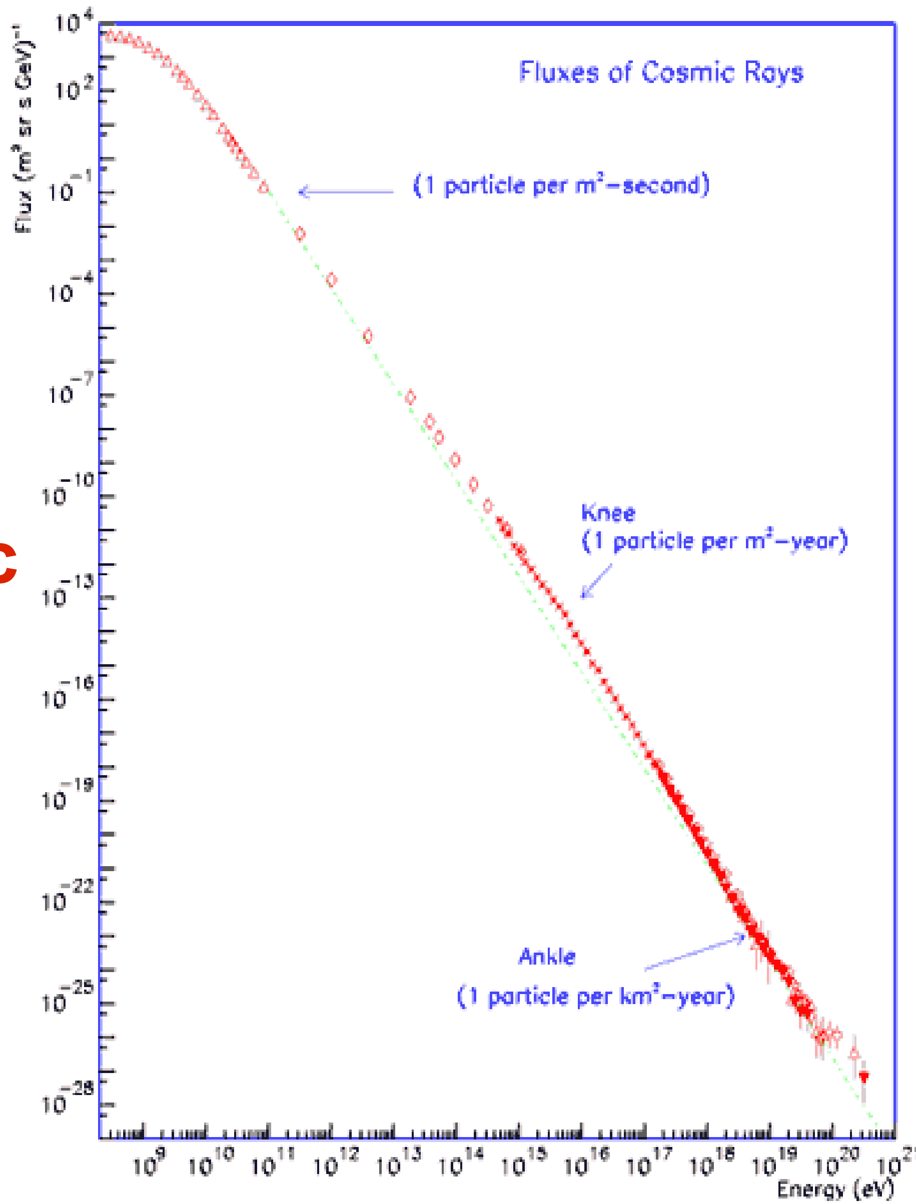
Trying to explain both spectrum and composition:
proton dip models for TA
Xgalactic mixed composition for Auger

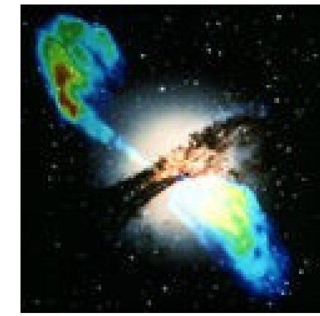


note that hard spectra, E^{-1}, seem to be required in mixed models to avoid too much mixture at given E, i.e. to reduce RMS(Xmax)

Power law flux → stochastic (Fermi) acceleration in shocks

cosmic ray flux



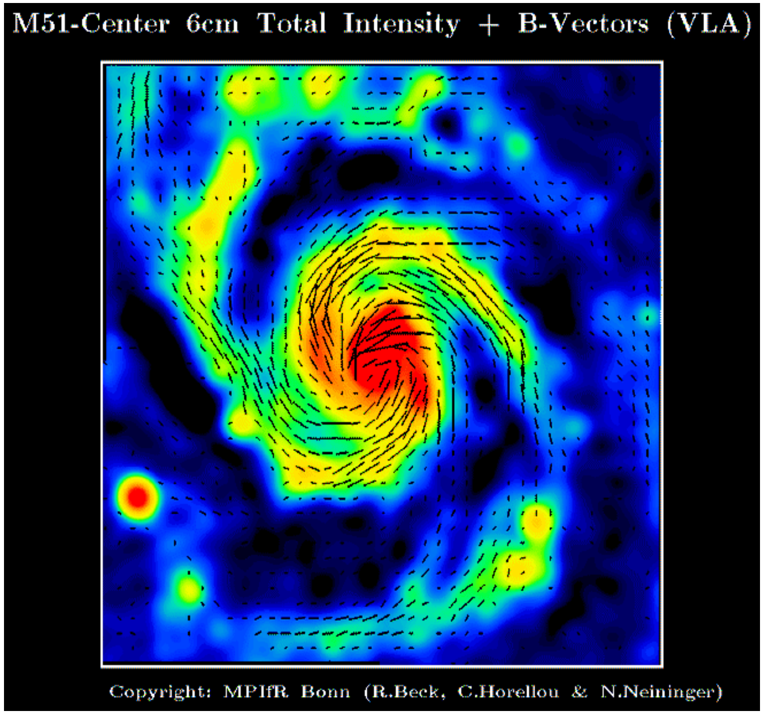


Small fractional energy gain after each shock crossing

$$\rightarrow \quad \frac{dN}{dE} \sim E^{-\alpha} \quad with\ \alpha \simeq 2-2.4$$

← galactic ? X-galactic →

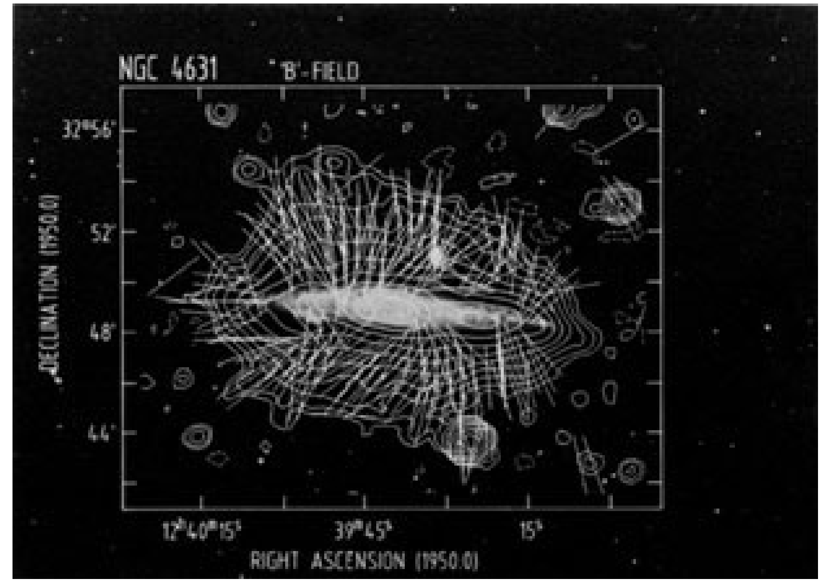
Galactic magnetic fields



M51

Regular B field follows spiral arms

NGC 4631

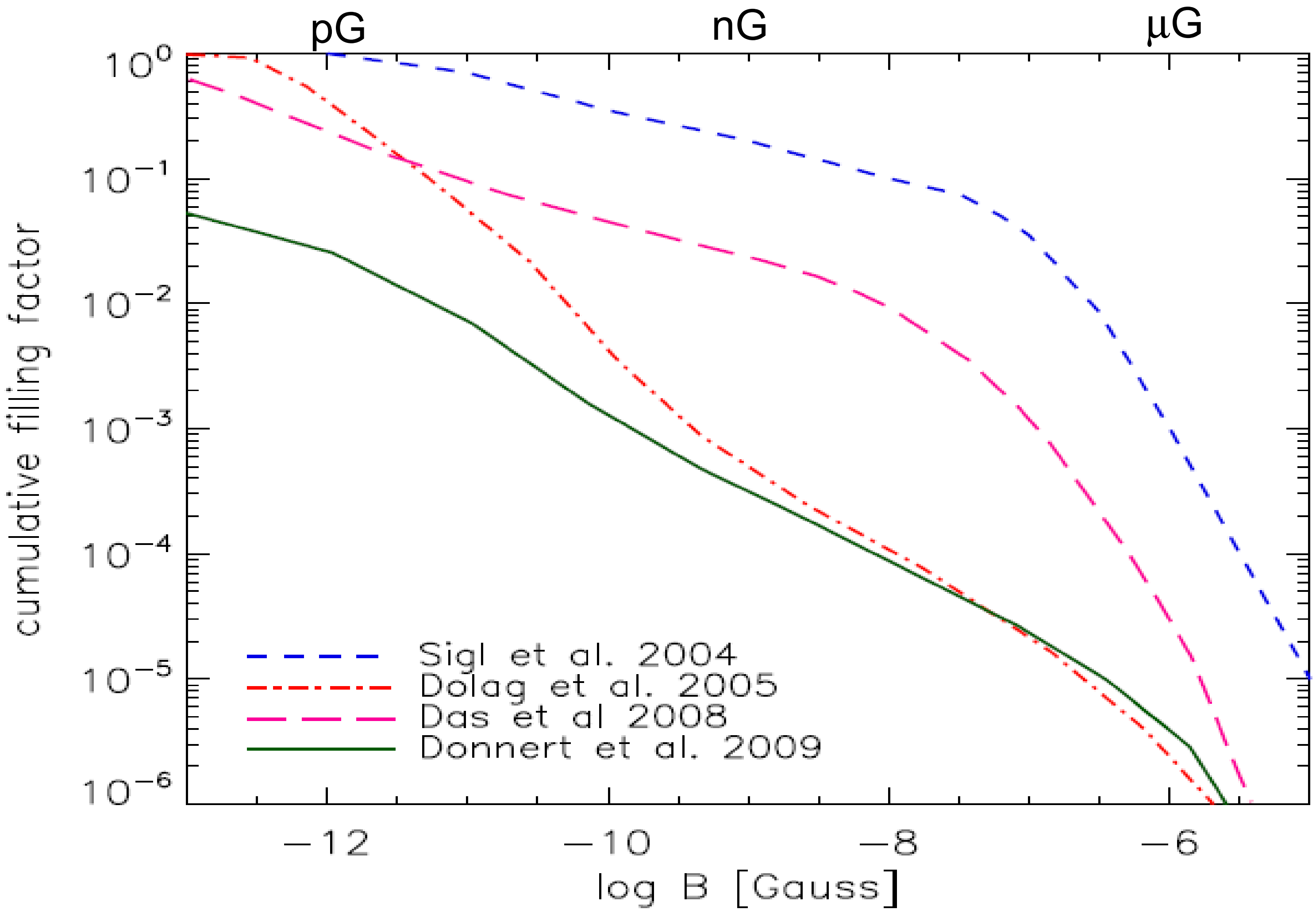


Radio signal from magnetic halo (z_h~few kpc)

Local regular field of our Galaxy ~ 3 μG

Also turbulent field with assumed Kolmogorov spectrum ($dE_B/dk \sim k^{-5/3}$)
with maximum scale L_{max} ~ 100 pc , and Brms ~ few μG

Extra-Galactic magnetic fields filling factors (simulations)



B > nG turbulent fields may be present in a significant fraction of the Universe

Lc ~ Mpc

At low energies CRs diffuse

for steady state diffusion, neglecting convection, E losses, drifts, this is just

$$\nabla \cdot J^D = Q \qquad \textbf{with} \qquad J^D = -D \nabla N$$

where $D(E) \propto E^{\alpha}$

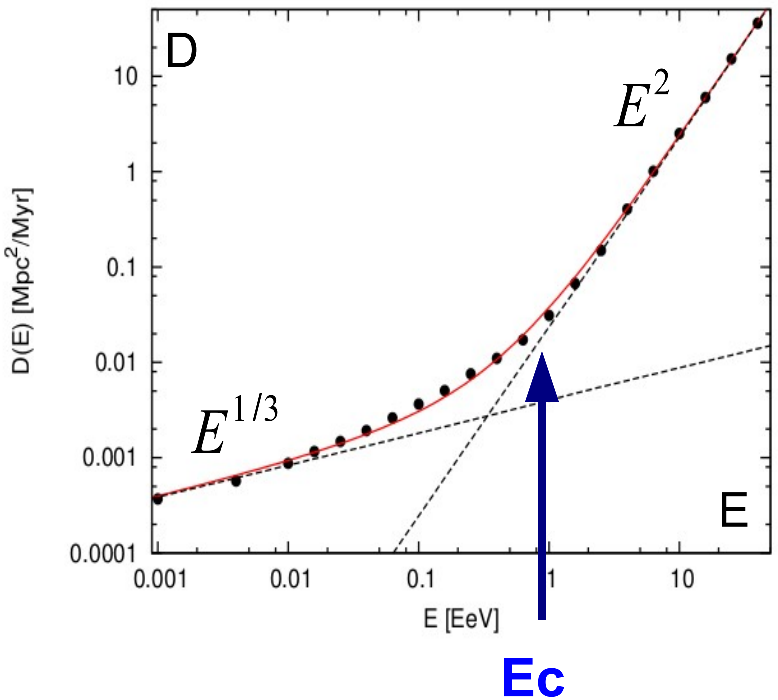
E < Ec : resonant diffusion

$\alpha \approx 1/3$ (for Kolmogorov)

E > Ec : small deflection in lc

$\alpha \approx 2$

Harari, Mollerach, ER '14



critical energy Ec: Larmor radius(Ec) = coherence length

$$\frac{E_c}{Z} \simeq \frac{B}{nG} \frac{l_c}{Mpc} EeV \sim \begin{cases} 10^{16} eV & \textbf{gal p} \\ EeV & \textbf{X-gal p} \end{cases}$$

Turbulent diffusion in Galactic B fields do shape the galactic CR spectrum:

$$\left(\frac{dJ}{dE}\right)_{source} \sim E^{-\gamma} \quad (\gamma \simeq 2 - 2.4)$$

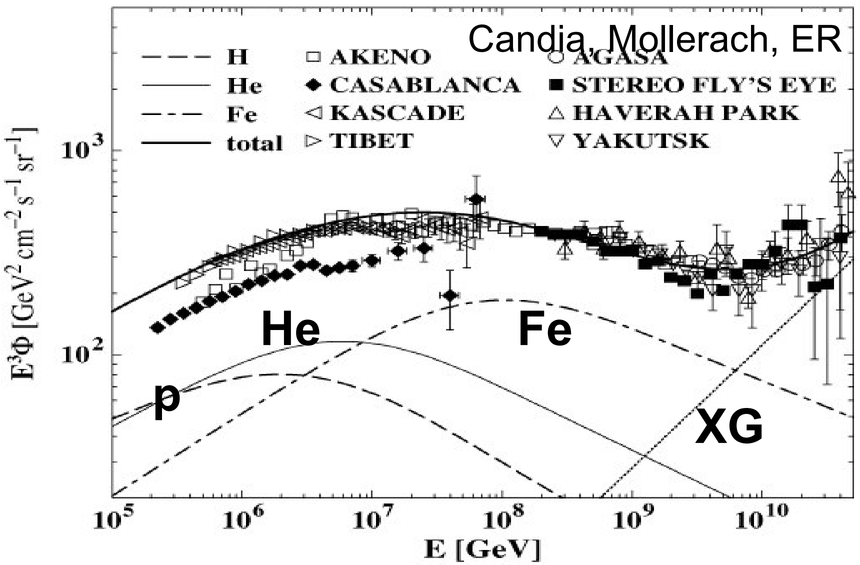
but

$$\tau_{diff} \sim \frac{1}{D} \sim E^{-\alpha}$$

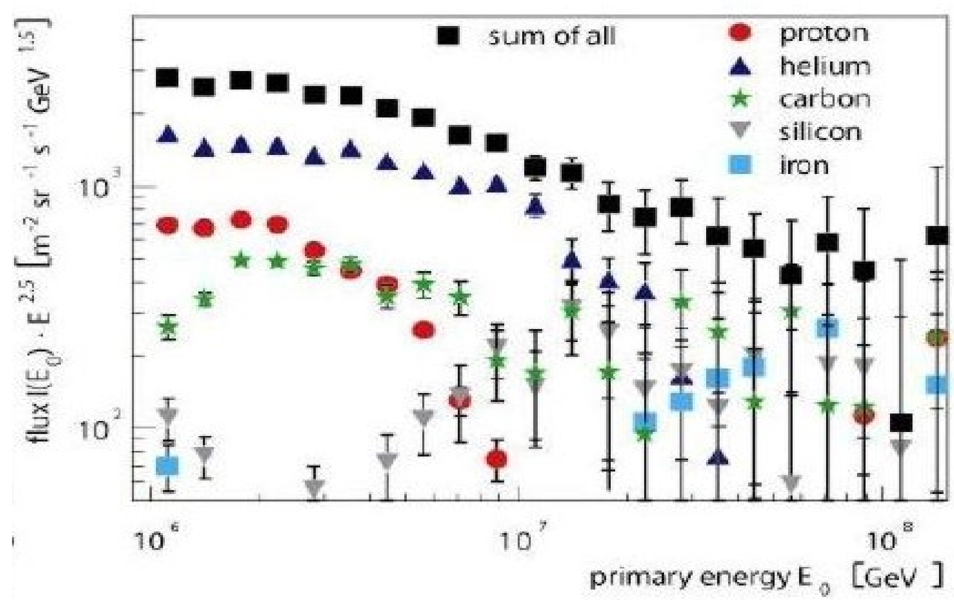
$$\left(\frac{dJ}{dE}\right)_{Earth} \sim E^{-\gamma-\alpha} \quad (\gamma + \alpha \simeq 2.7)$$

low E CRs stay longer confined in the Galaxy

In addition, enhanced diffusion at high energies (helped by drifts) can explain the knee by more efficient escape from Galaxy



Diffusion and drift scenario



KASCADE

Diffusion in X-galactic B fields:

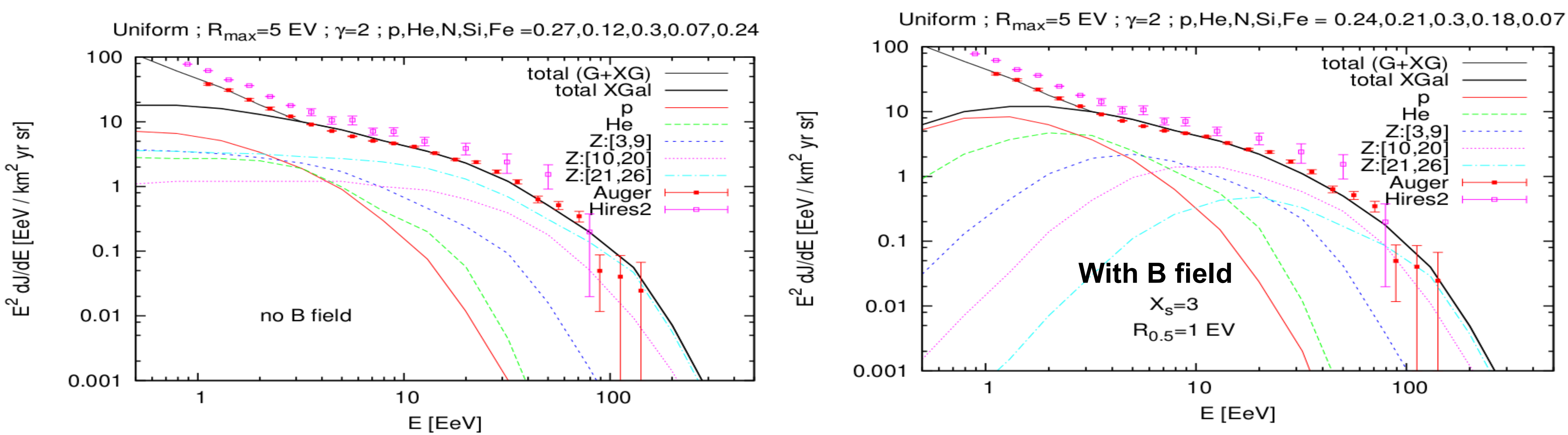
At high E → rectilinear propagation → spectrum only shaped by E-losses

But what about low energies?

$$\tau_{diff} \sim \frac{d_s^2}{6\,D} \sim 1.5\ 10^{10}\ yr \left(\frac{d_s}{100\mathrm{Mpc}}\right)^2 \left(\frac{E_c}{E}\right)^2 \left(\frac{Mpc}{l_c}\right)$$

It may take more than the age of the Universe to arrive from a source → at low E far away sources do not contribute and nearby ones suppressed

Diffusion in X-gal turbulent B fields can modify spectra and composition at UHE

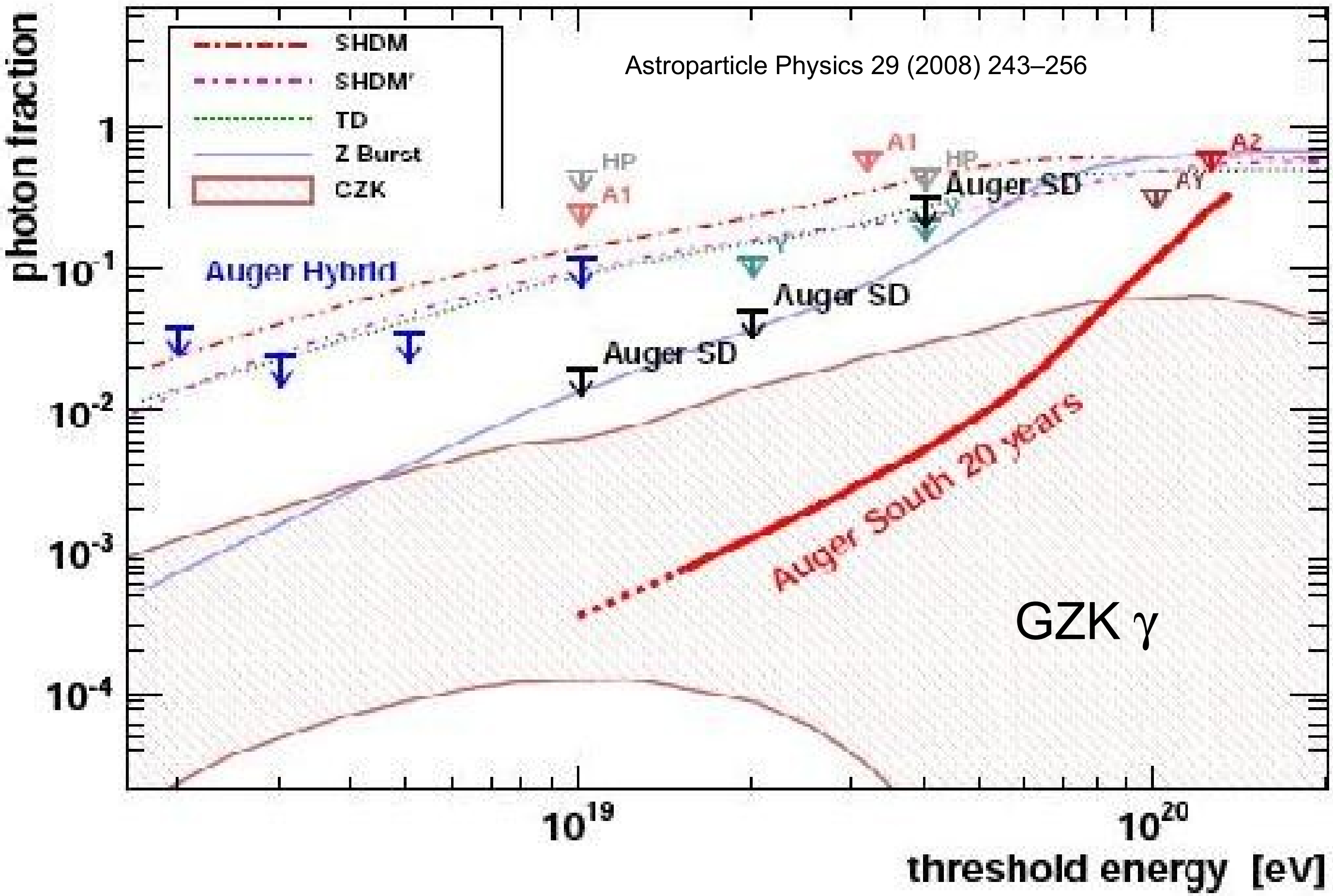


No need to invoke too hard source spectra to suppress heavy nuclei at E < Z EeV → helps to account for observed spectrum and composition

Mollerach & Roulet (JCAP '13)

AUGER SD photon bound

photon showers are more penetrating (small curvature radius) and lack muons (electromagnetic signal in detectors have long rise times)
→ essentially no UHE photon candidates observed

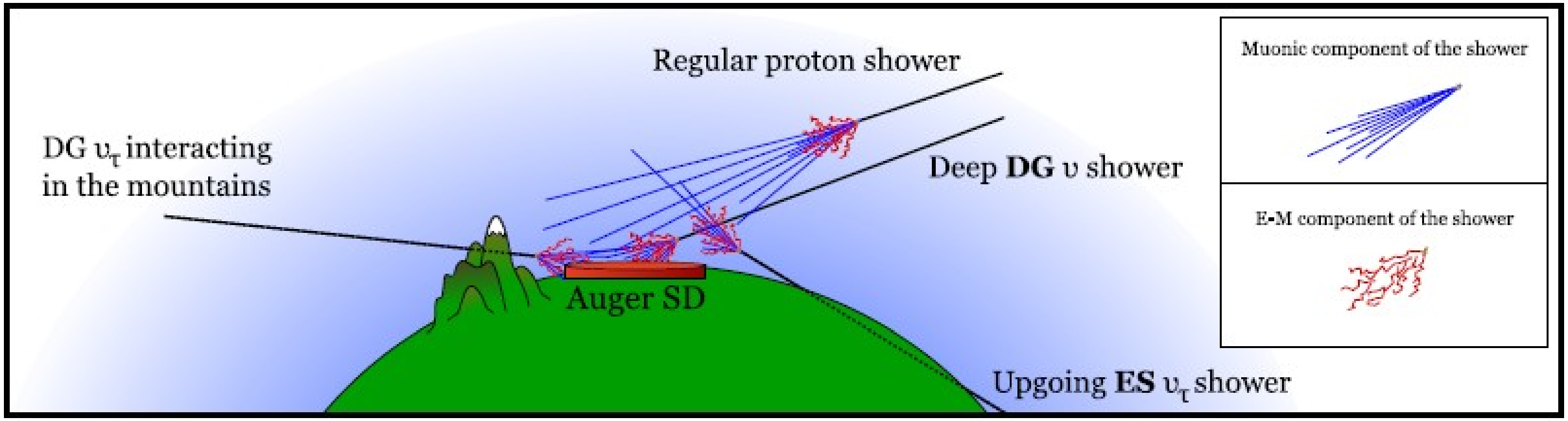


photon fraction:
< 2% at E > 10 EeV

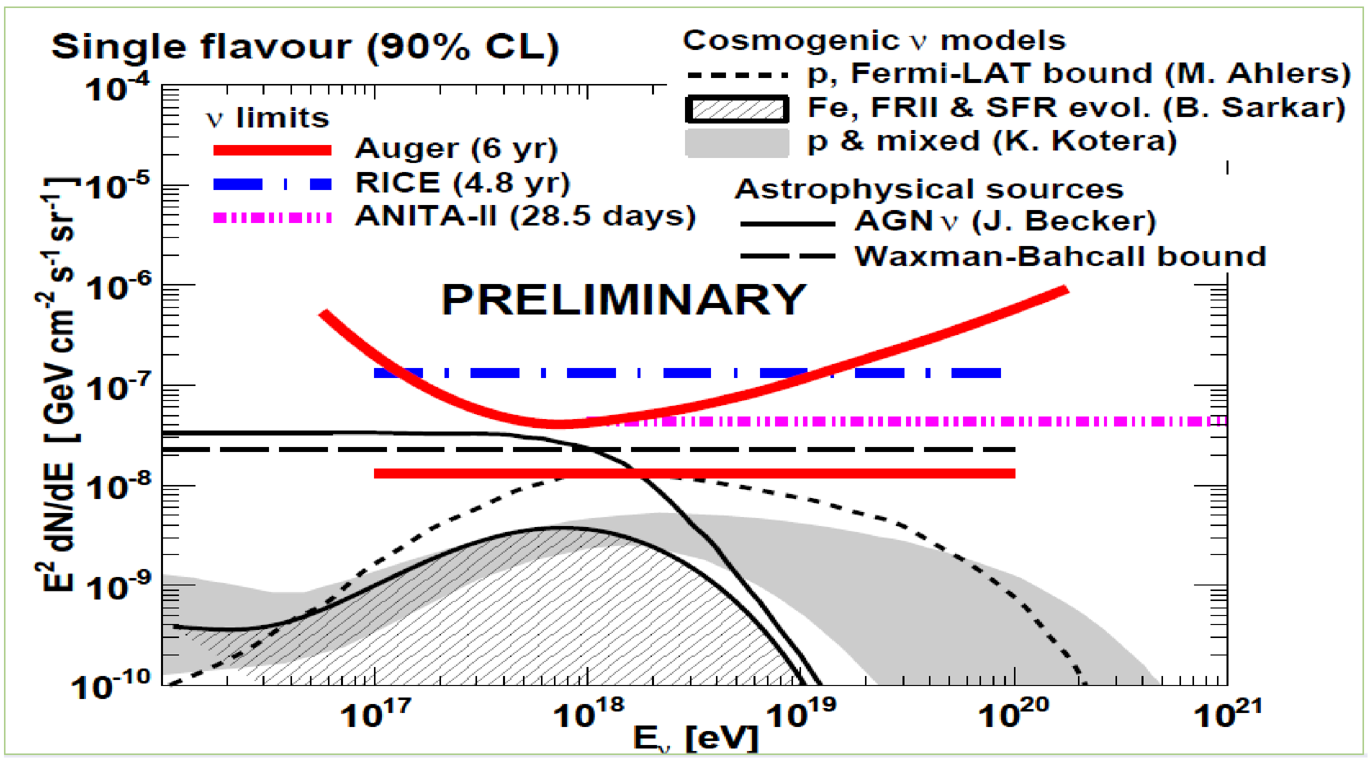
< 31% at E > 40 EeV

excludes most top-down models, but still above optimistic GZK photons

Neutrino detection in AUGER



Only neutrinos can produce young horizontal showers

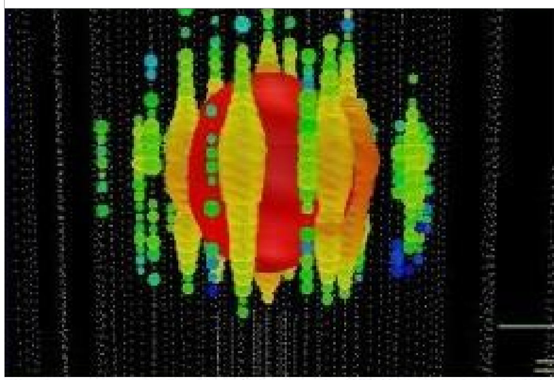


0 events observed
→ bounds scale linearly with exposure

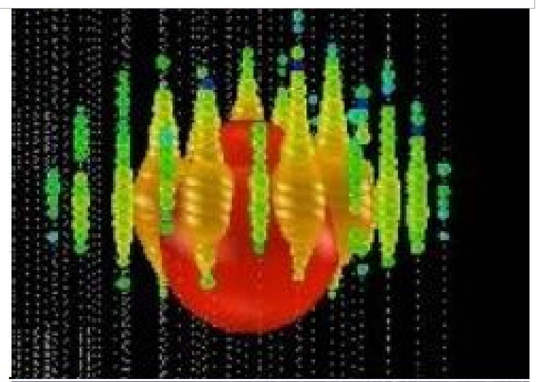
Icecube will be more sensitive
ARA even better

PeV neutrino events observed by ICECUBE

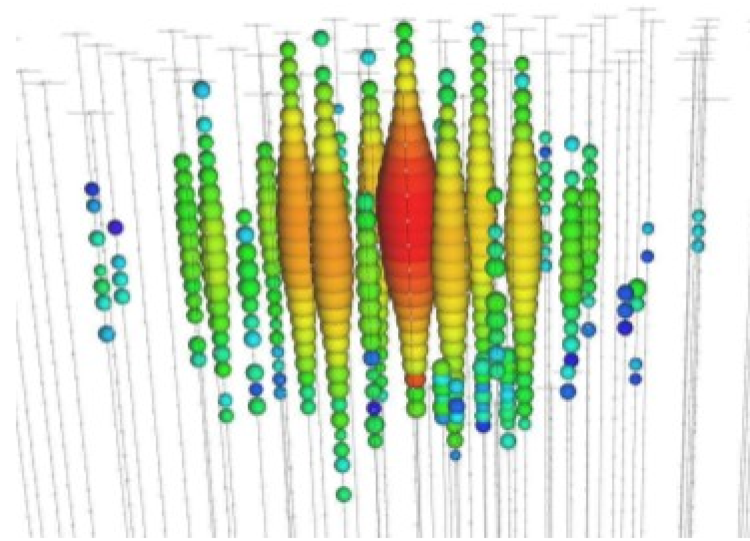
E= 1.04 PeV

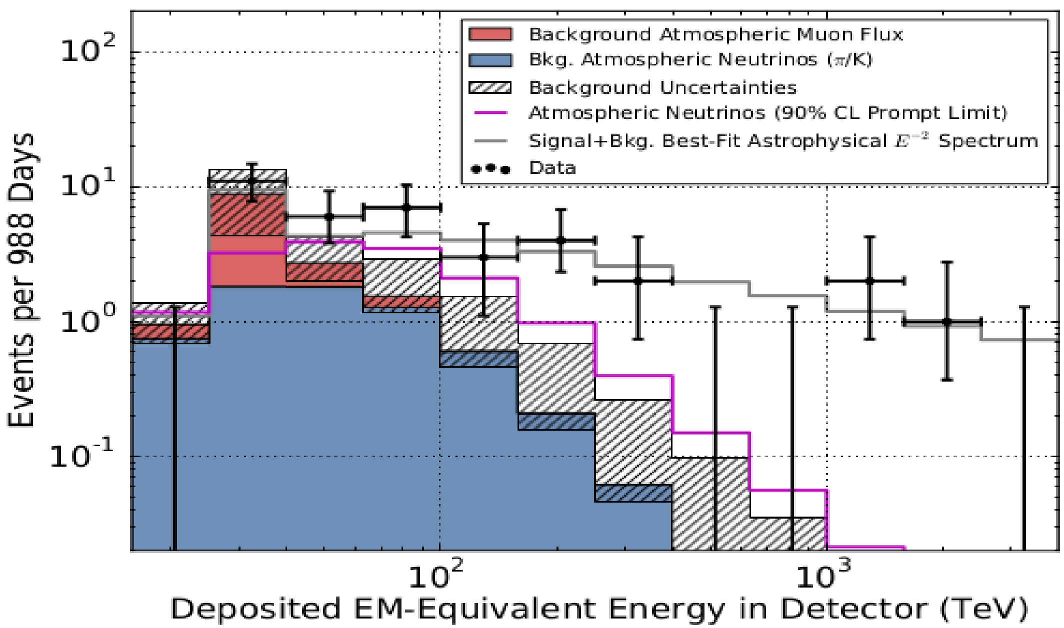


E=1.14 PeV

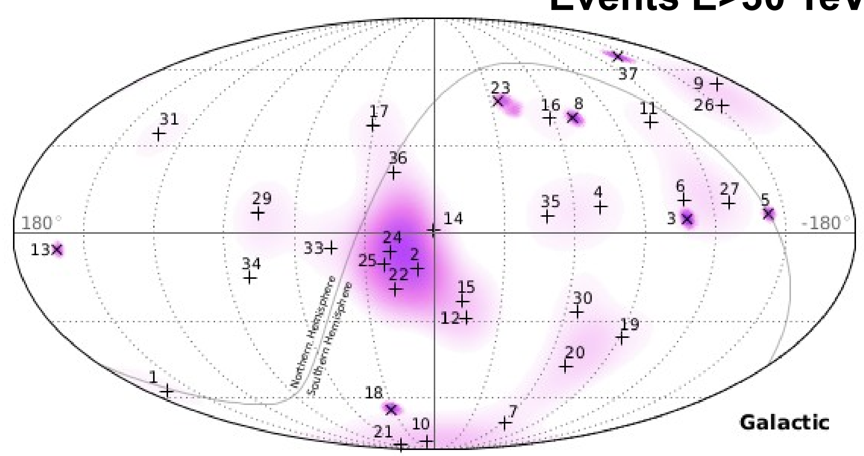


E= 2 PeV





Events E>30 TeV



excess above atmospheric bckd (~isotropic)

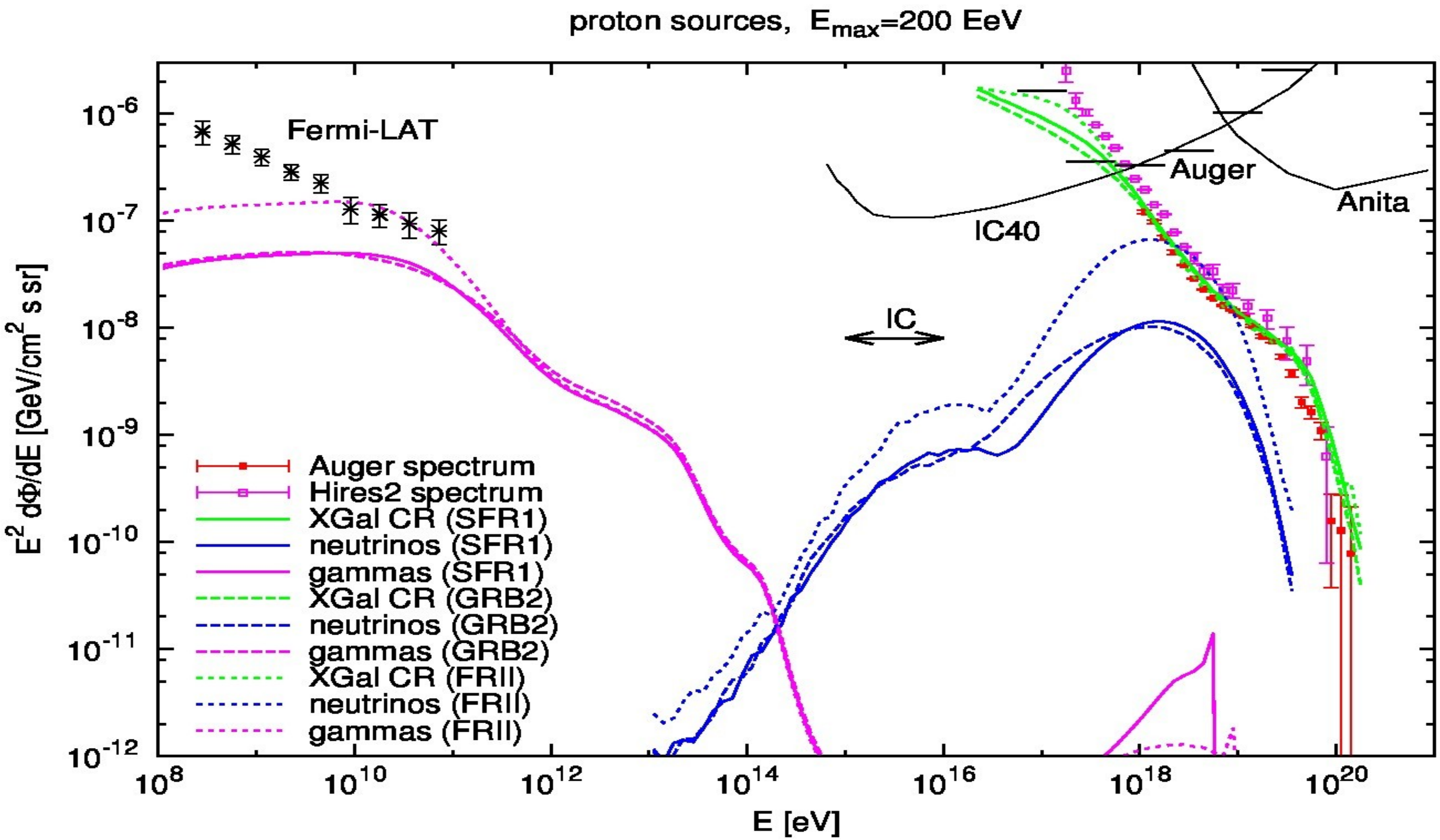
Can they be related to EeV cosmogenic neutrinos being searched by Auger (and Icecube)?

ν and γ for different proton scenarios & cascade bound

ν $\quad p\,\gamma_b \rightarrow \pi^+ n \qquad \pi^+ \rightarrow \mu\,\nu_\mu \rightarrow e\,\nu_\mu\,\bar{\nu}_\mu\,\nu_e \qquad n \rightarrow p\,e\,\bar{\nu}_e$

γ $\quad p\,\gamma_b \rightarrow \pi^0 p \qquad \pi^0 \rightarrow \gamma\,\gamma \qquad p\,\gamma_b \rightarrow p\,e^+ e^-$

$\gamma\,\gamma_b \rightarrow e^+ e^- \qquad e\,\gamma_b \rightarrow e\,\gamma$ Cascades down to GeV-TeV

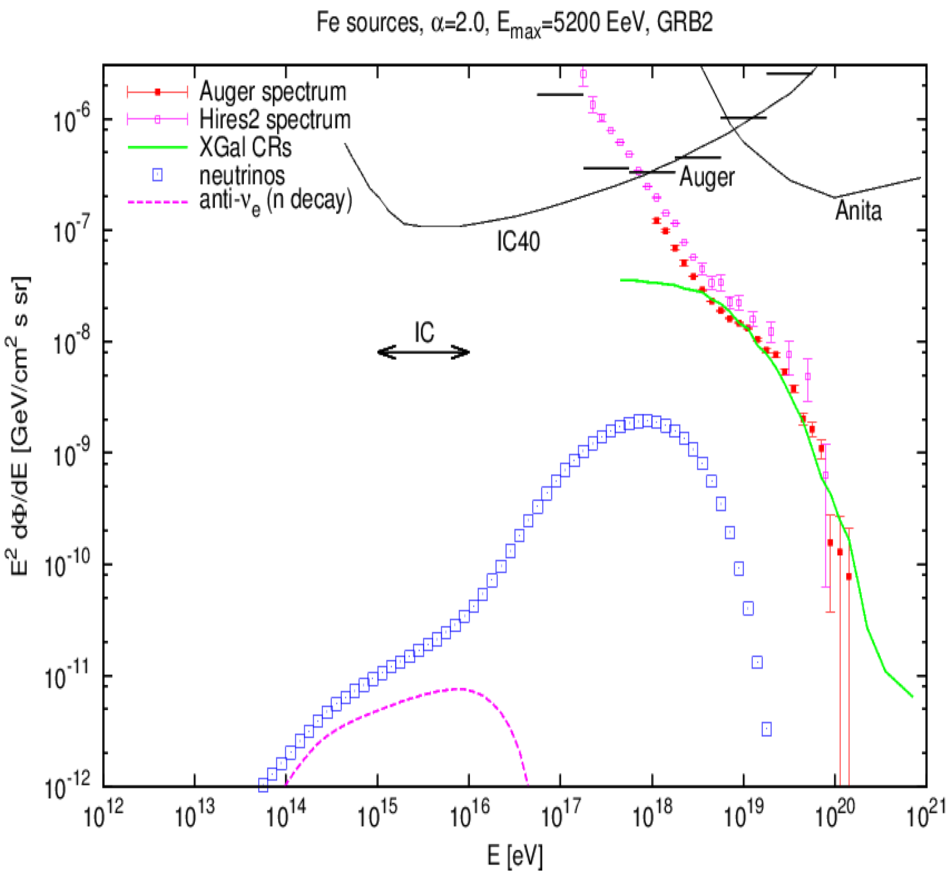


Different Source evolution

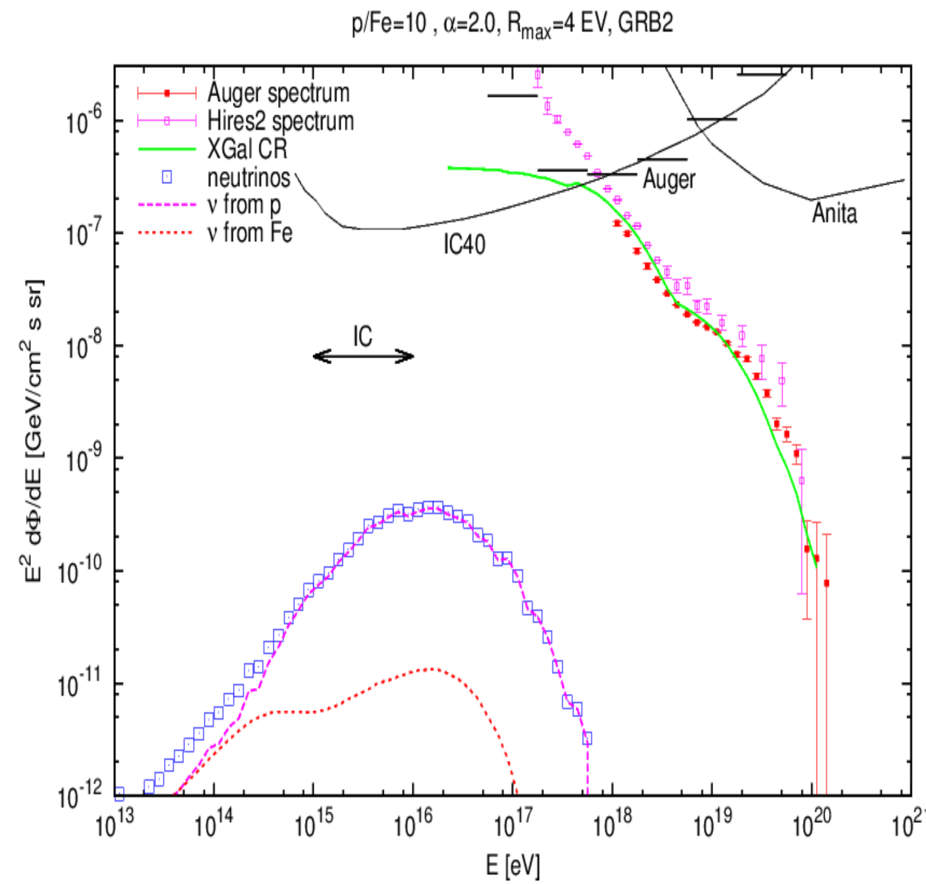
(enhancing PeV neutrinos can conflict GeV photon bounds)

ER, Sigl, vVliet, Mollerach 2012

Fe composition with large cutoff



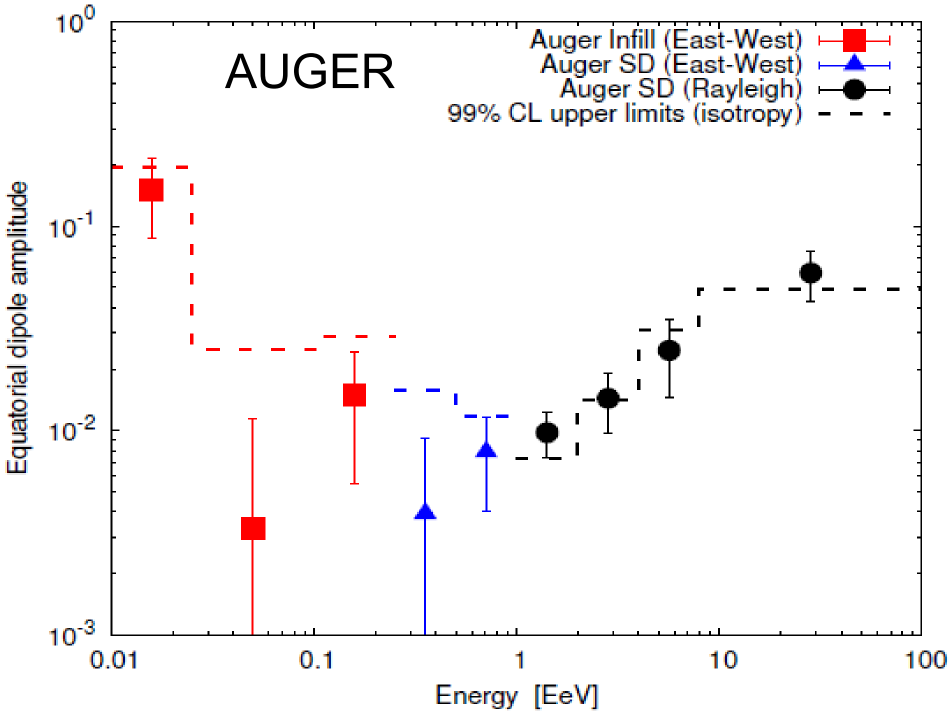
Mixed p / Fe composition with low cutoff

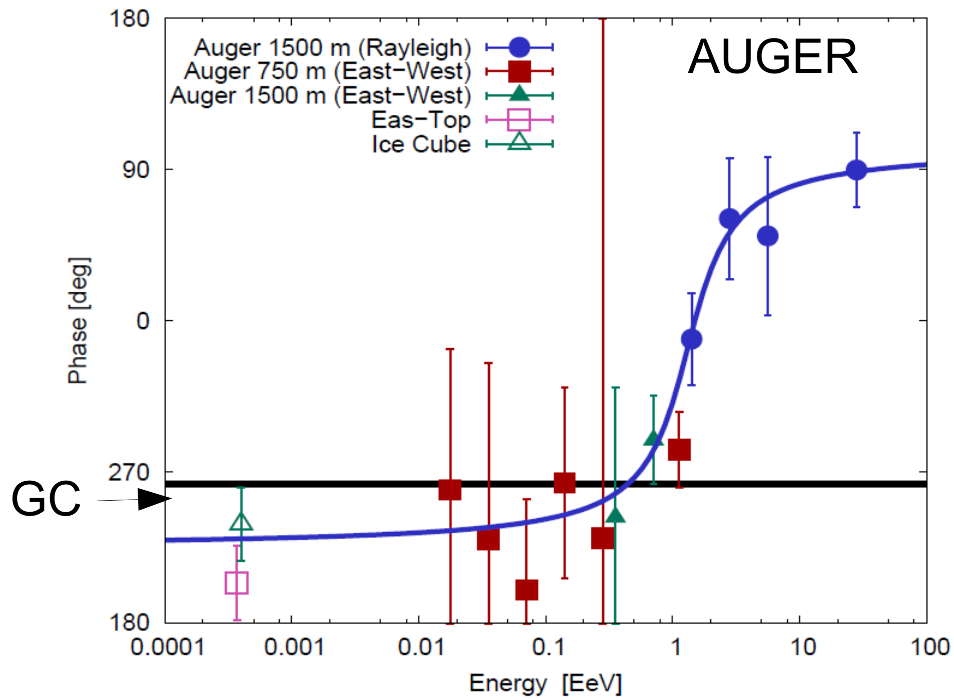


PeV neutrinos produced by 20 PeV nucleons
→ no direct implications for EeV neutrinos accessible to Auger
cosmogenic PeV neutrino fluxes low
→ PeV neutrinos likely produced at sources, not during CR propagation

LARGE SCALE ANISOTROPIES

Amplitude and Phase of equatorial dipole component

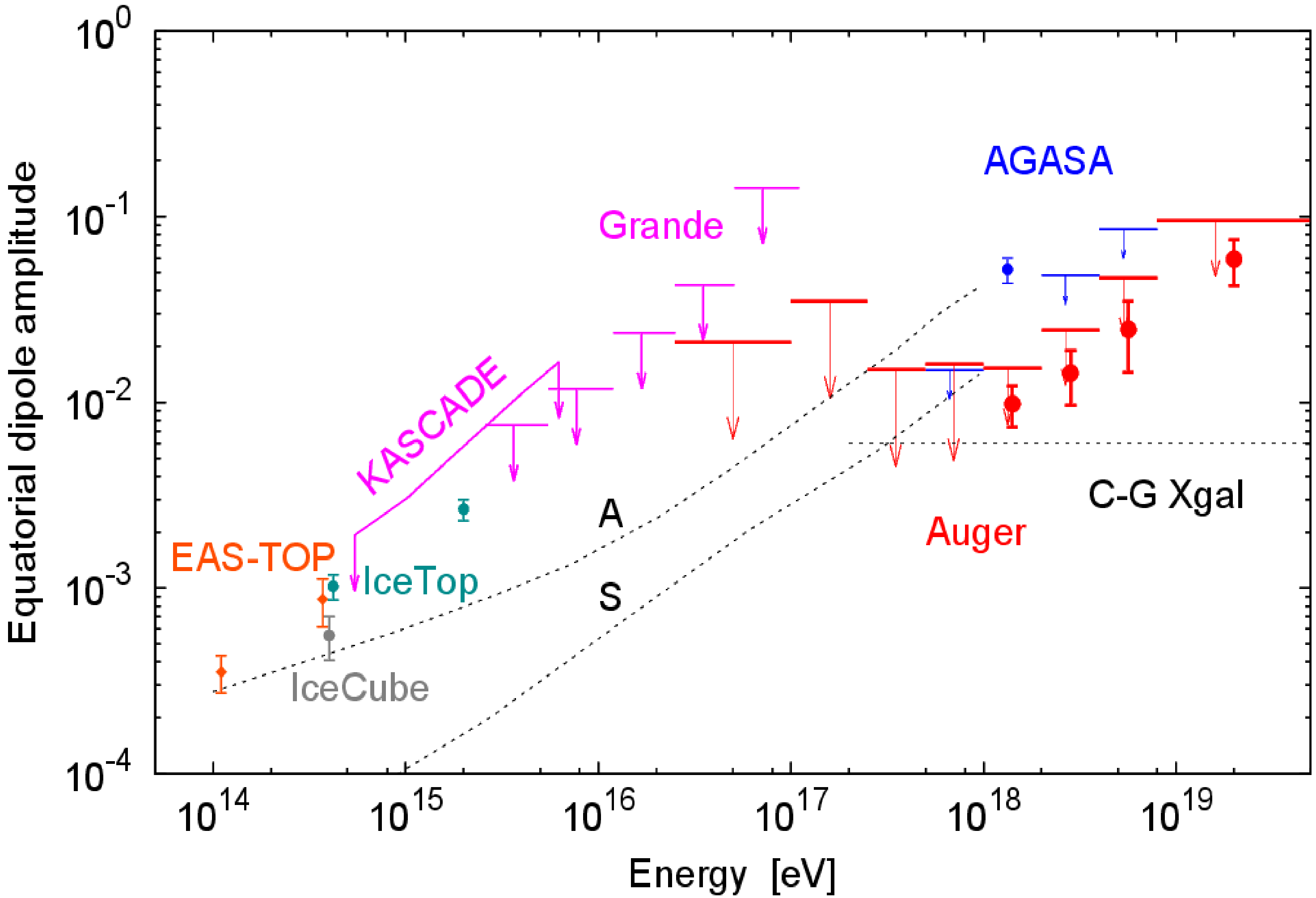




3 bins above EeV have amplitude with <1% chance from isotropy (significance still marginal)

Transition in phase between 'GC' below EeV and extragalactic flux above ankle?

Amplitude of equatorial dipole component



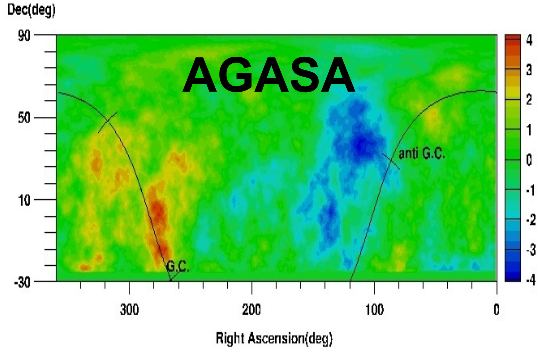


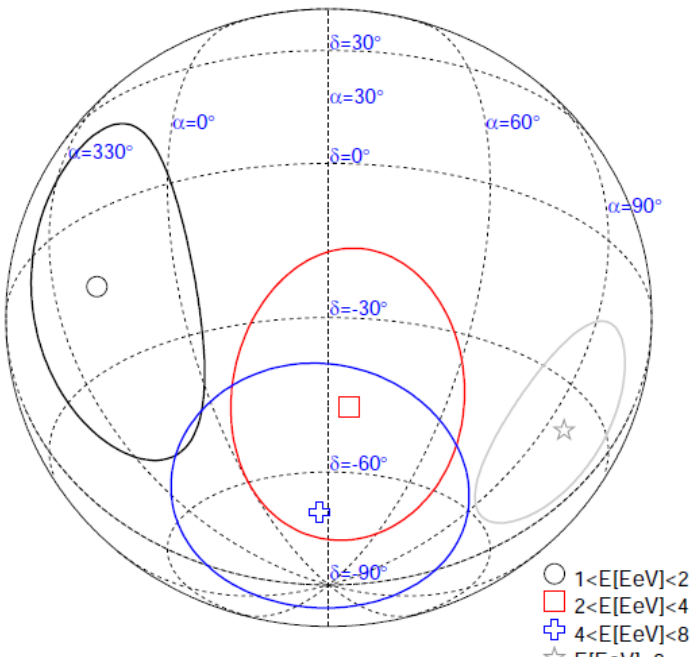
Fig. 2. The significance of event density in equatorial coordinates. The statistical significance of deviation is evaluated for each 1° grid with the aperture of 20 degrees radius. The excess and deficit can be seen with 4 σ statistical significance near the Galactic center and anti-galactic center, respectively.

AGASA excess excluded

Amplitude below ~2% at EeV energies challenges some galactic models

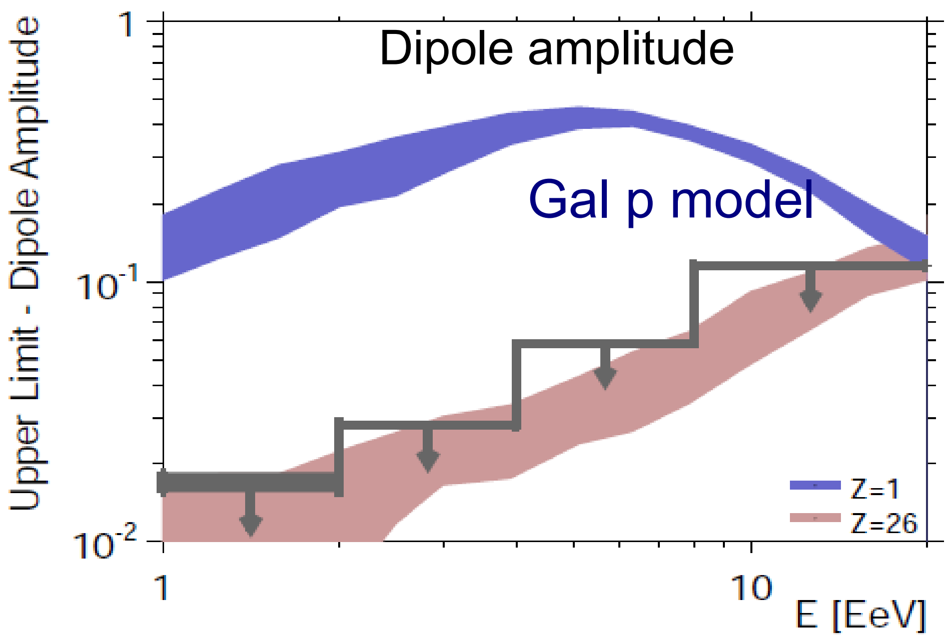
3D dipole reconstruction

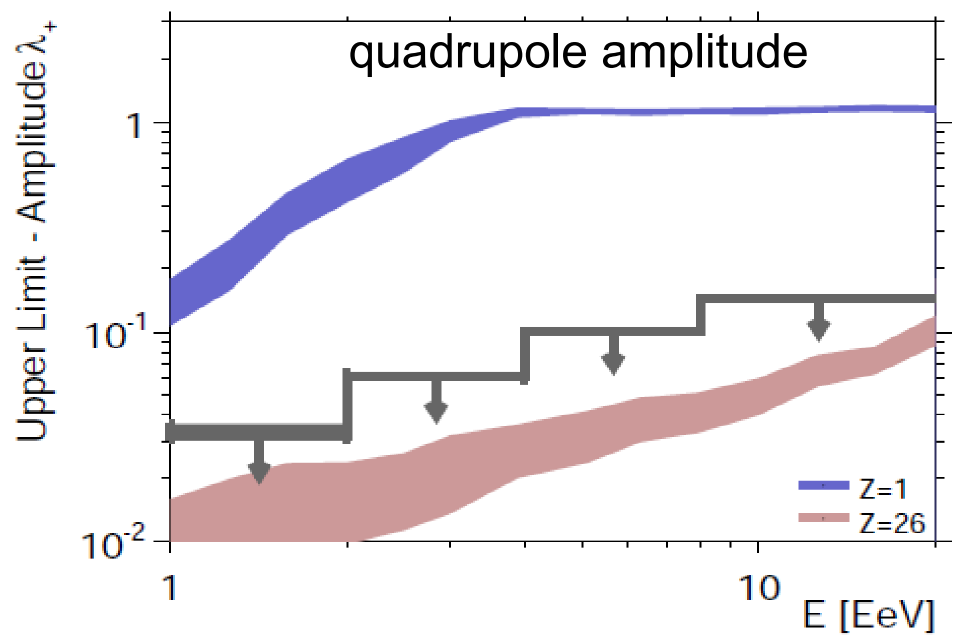
Auger APJ L 2012



Dipole towards southern directions
But amplitudes not significant

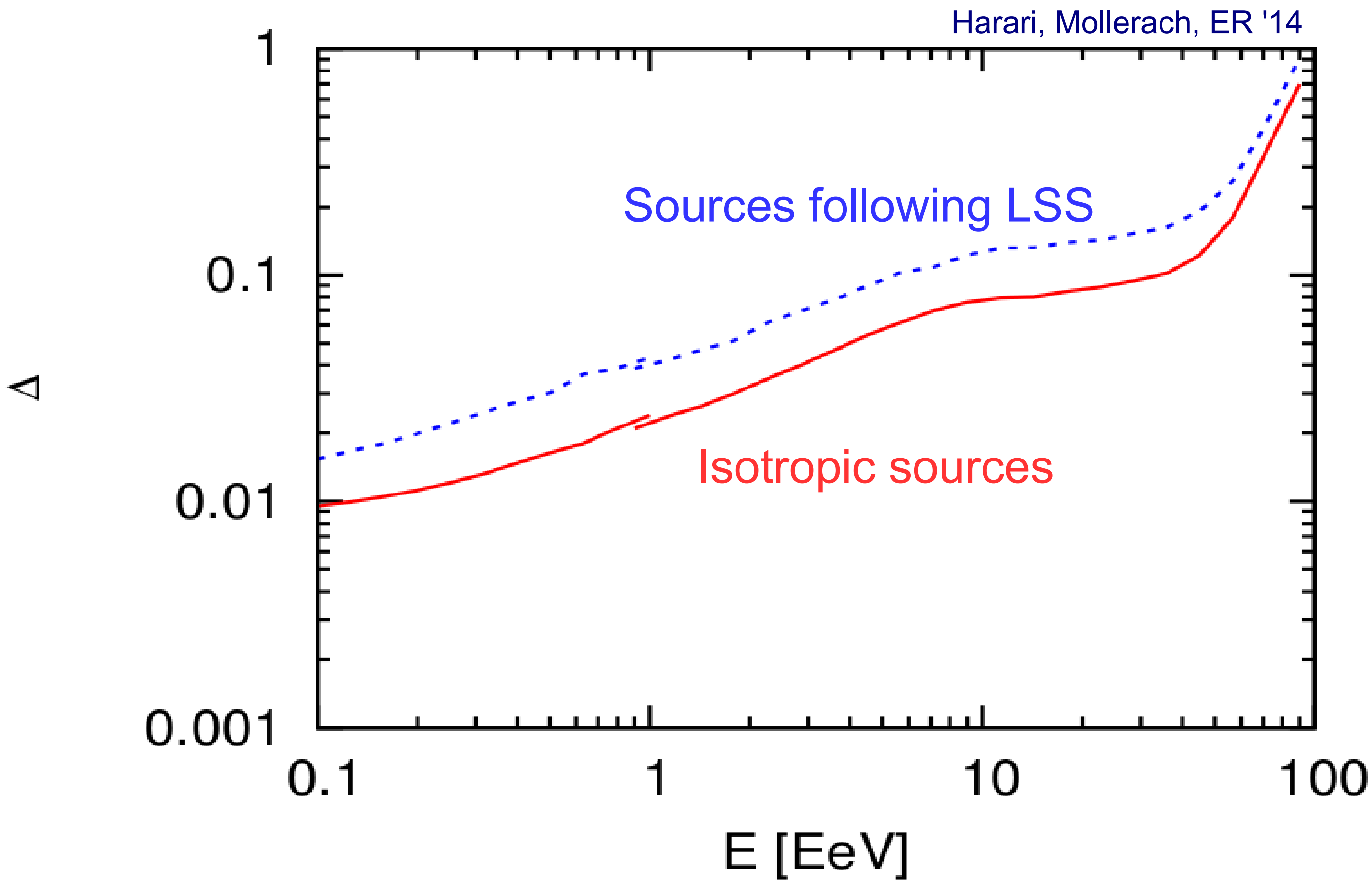
Models with light galactic components excluded for E > EeV





Light composition at EeV is already extragalactic ?

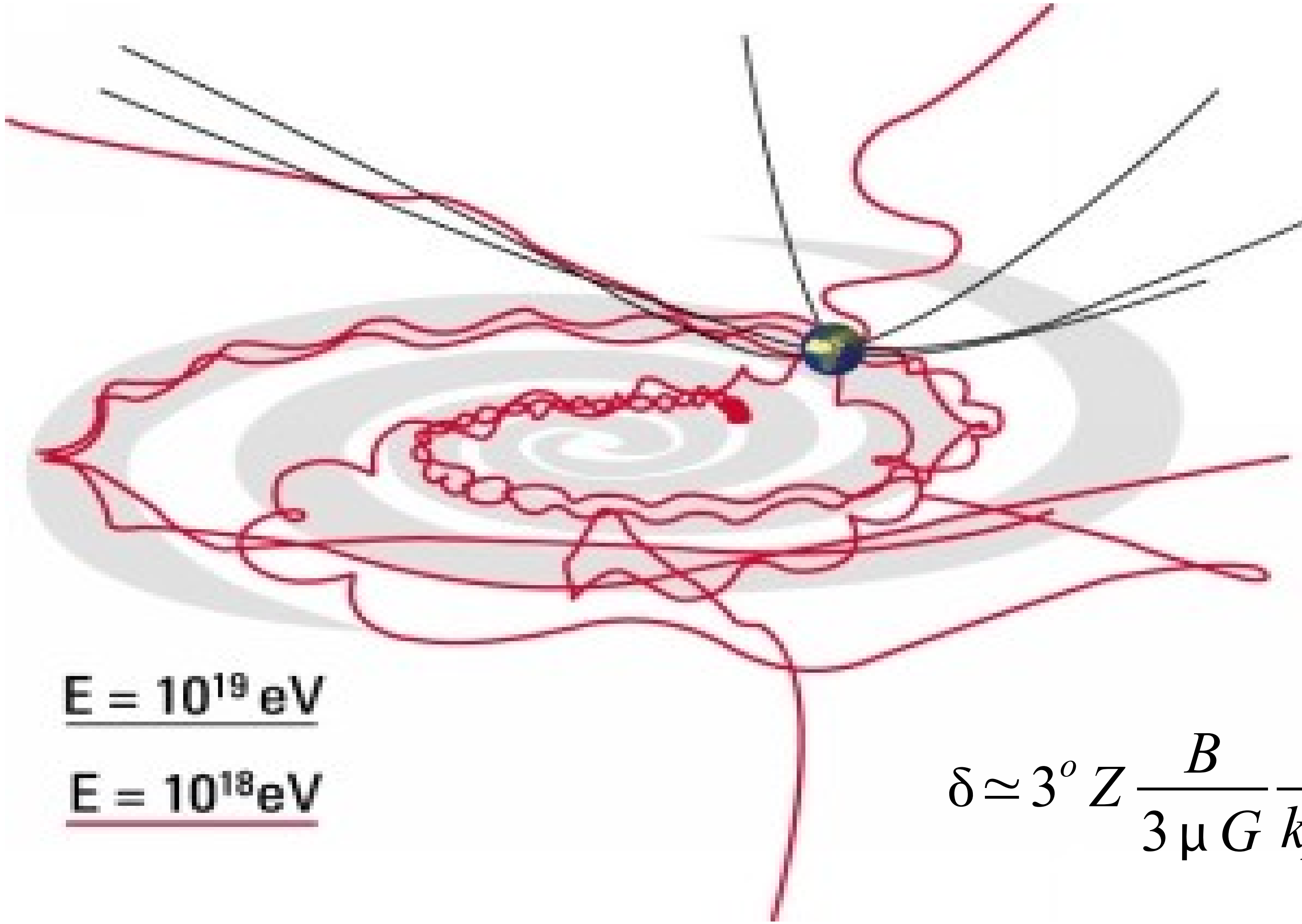
Anisotropy from CR diffusing from extragalactic sources



Sources distributed (anisotropically) according to nearby galaxy distribution can give rise to enhanced anisotropies consistent with present hints

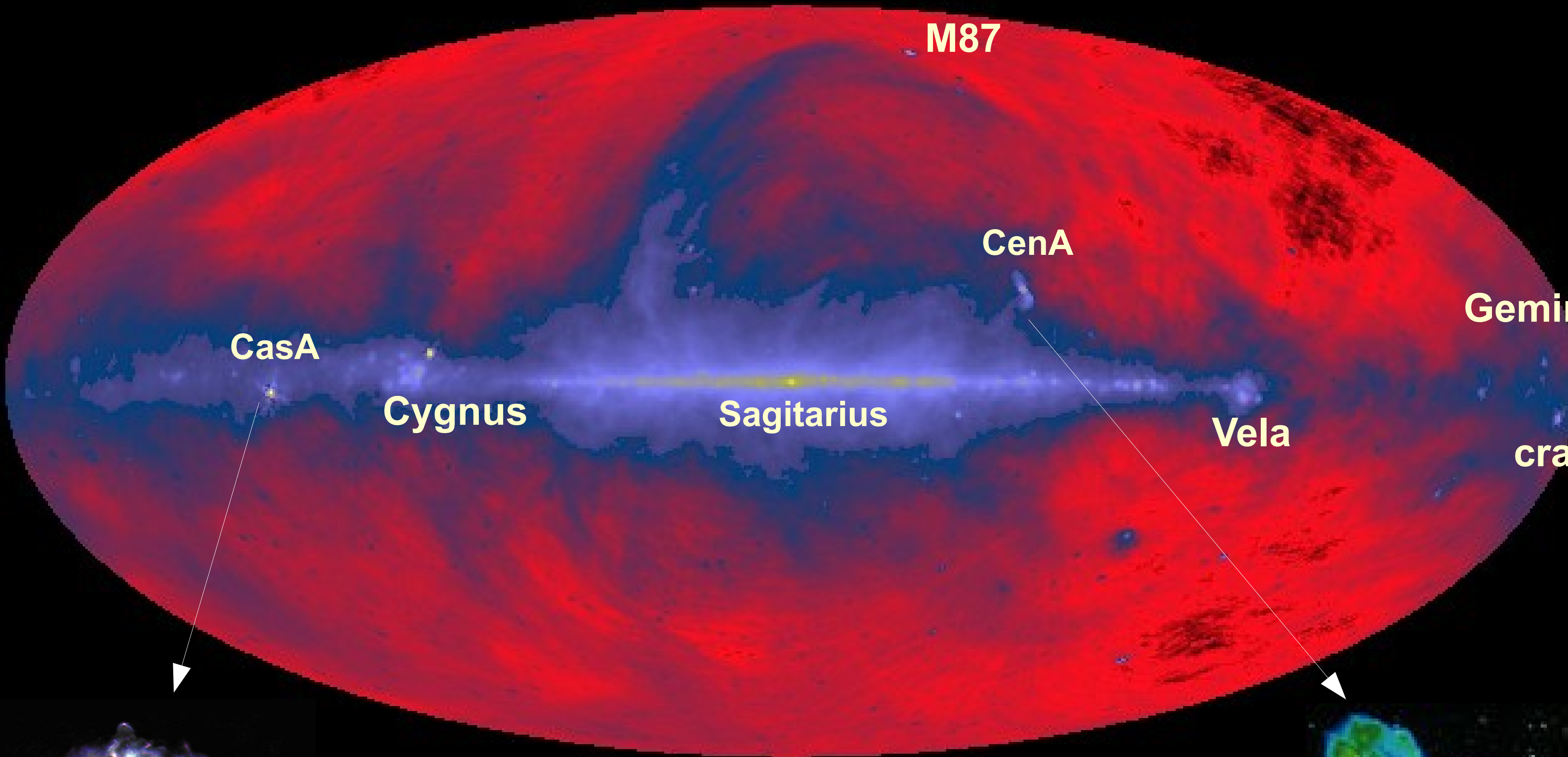
Anisotropy in LSS explains CMB dipole (is responsible for our peculiar velocity) and also leads to anisotropic Xgalactic CR flux

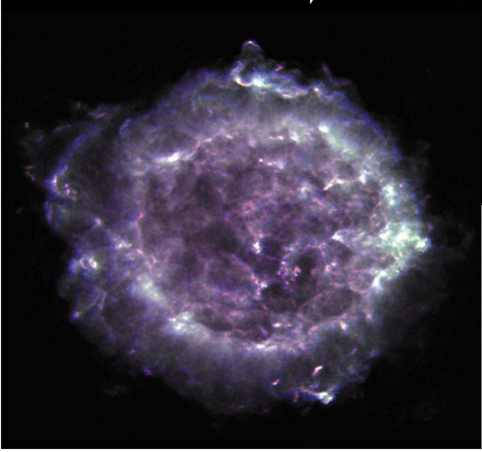
AT HIGHEST ENERGIES COSMIC RAY TRAJECTORIES STRAIGHTER
IS ASTRONOMY POSSIBLE ?



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

the radio sky

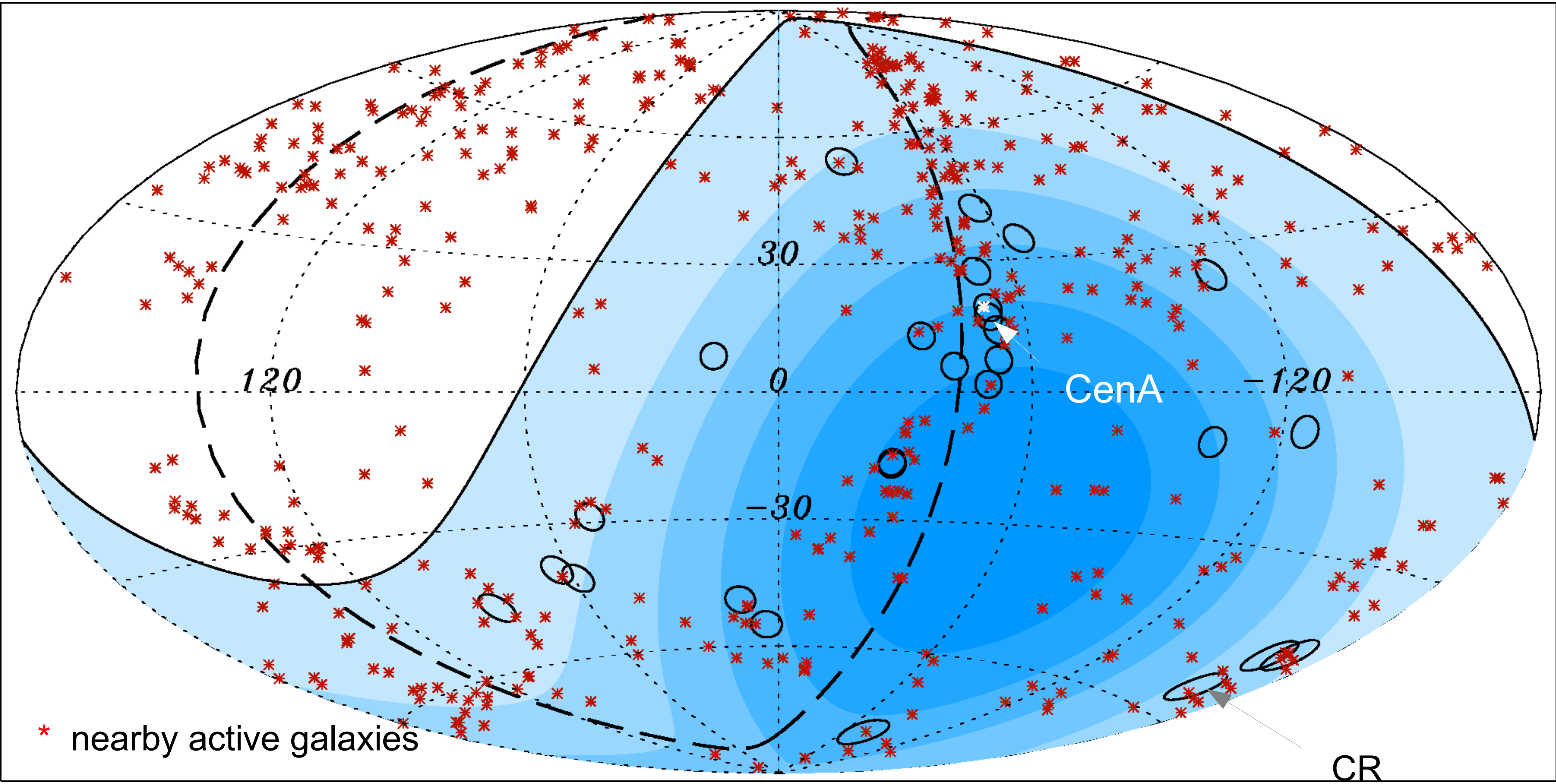




supernovae: preferred candidate sources for E < 10^{18} eV

active galaxies: plausible candidates for E > 10^{18} eV

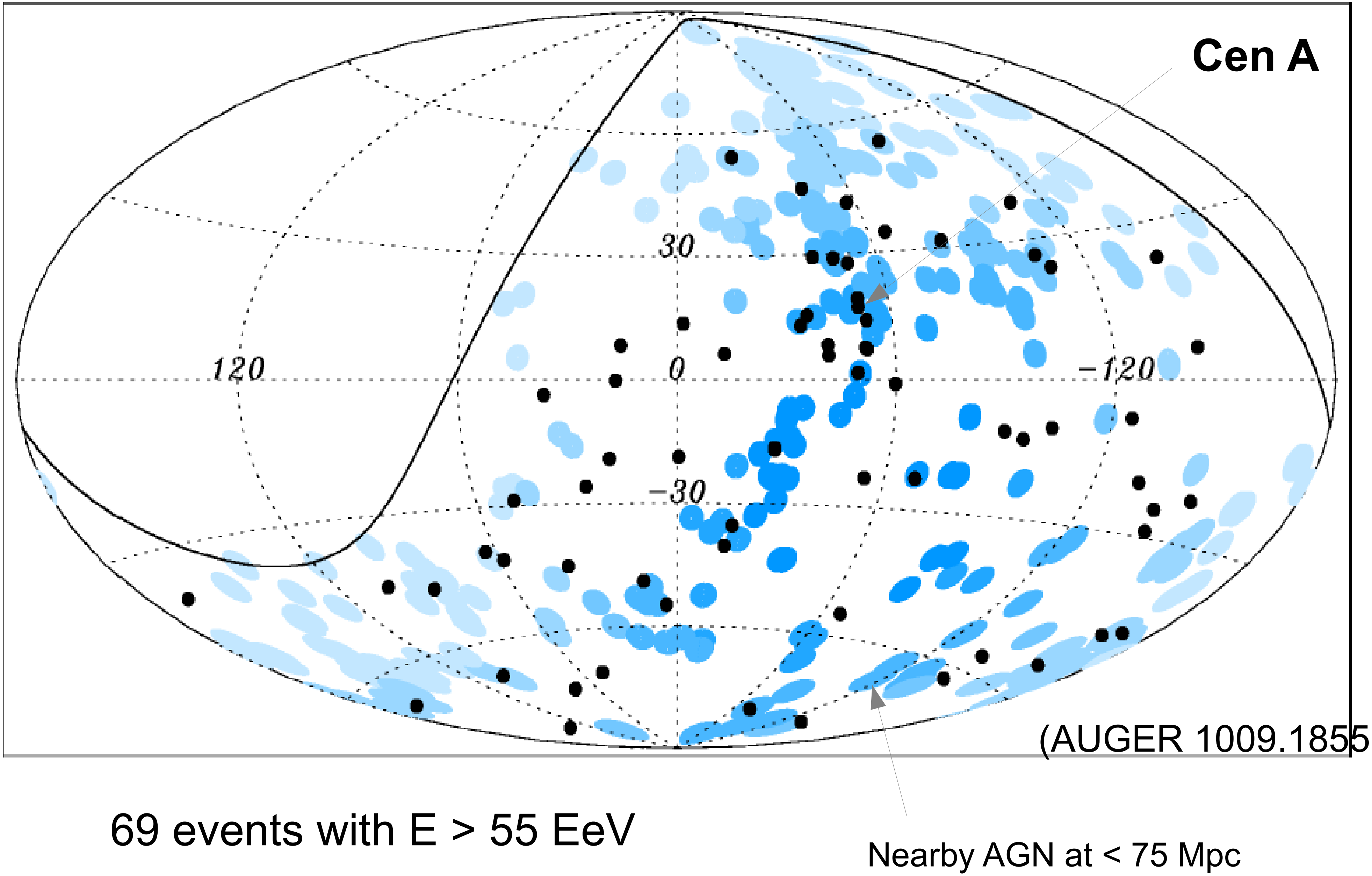
SEARCH FOR CORRELATIONS WITH AGN



with the data up to 31 august 2007, from the 27 CRs with highest energies, 20 were at less than ~ 3 degrees from an active galaxy at less than ~ 75 Mpc , while 6 were expected

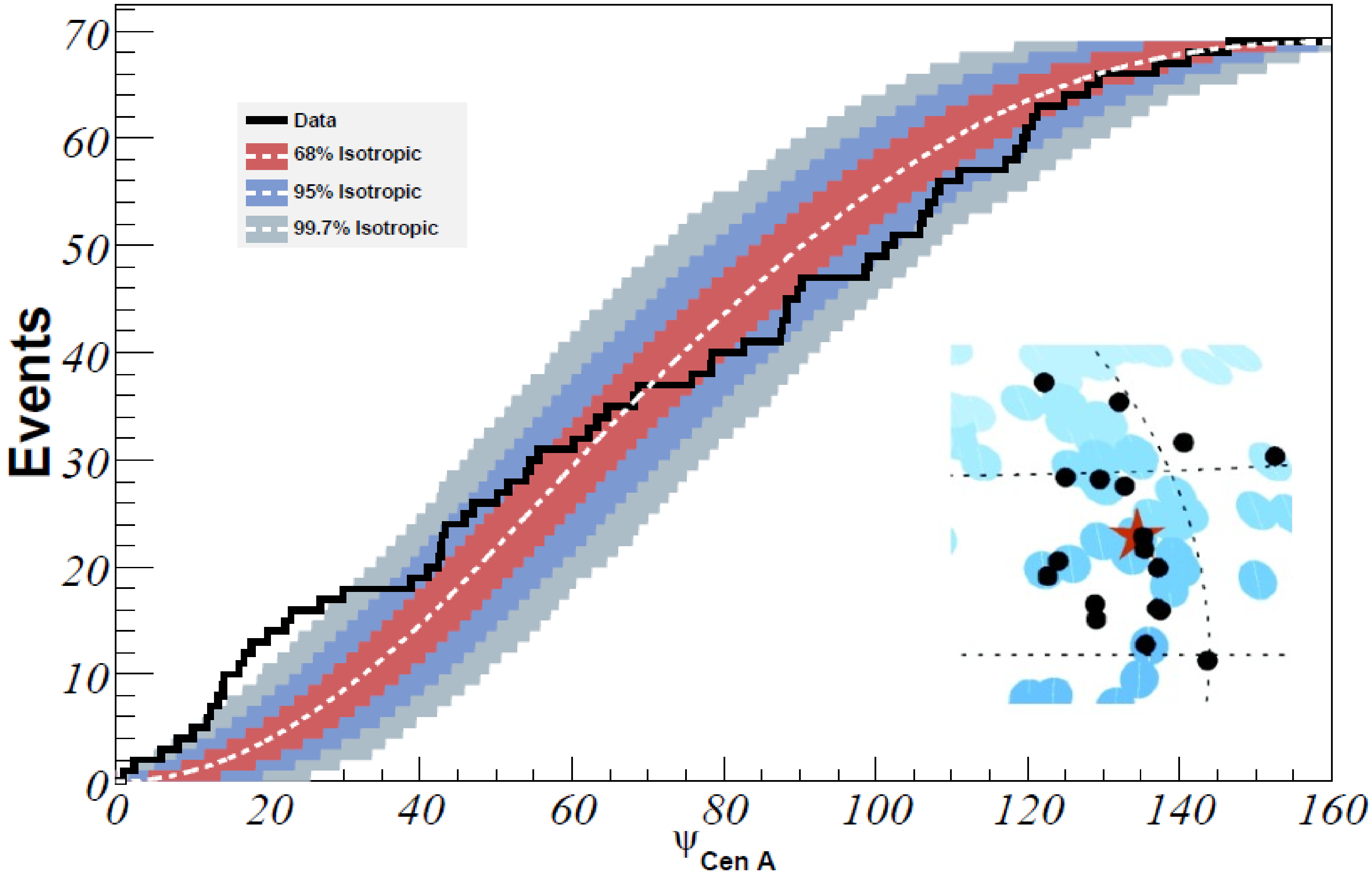
But with data up to june 2011, 28/84 correlate (excluding those before may 2006) → 33+-5 % correlation (while isotropy → 21%)

AUGER sky map above 55 EeV



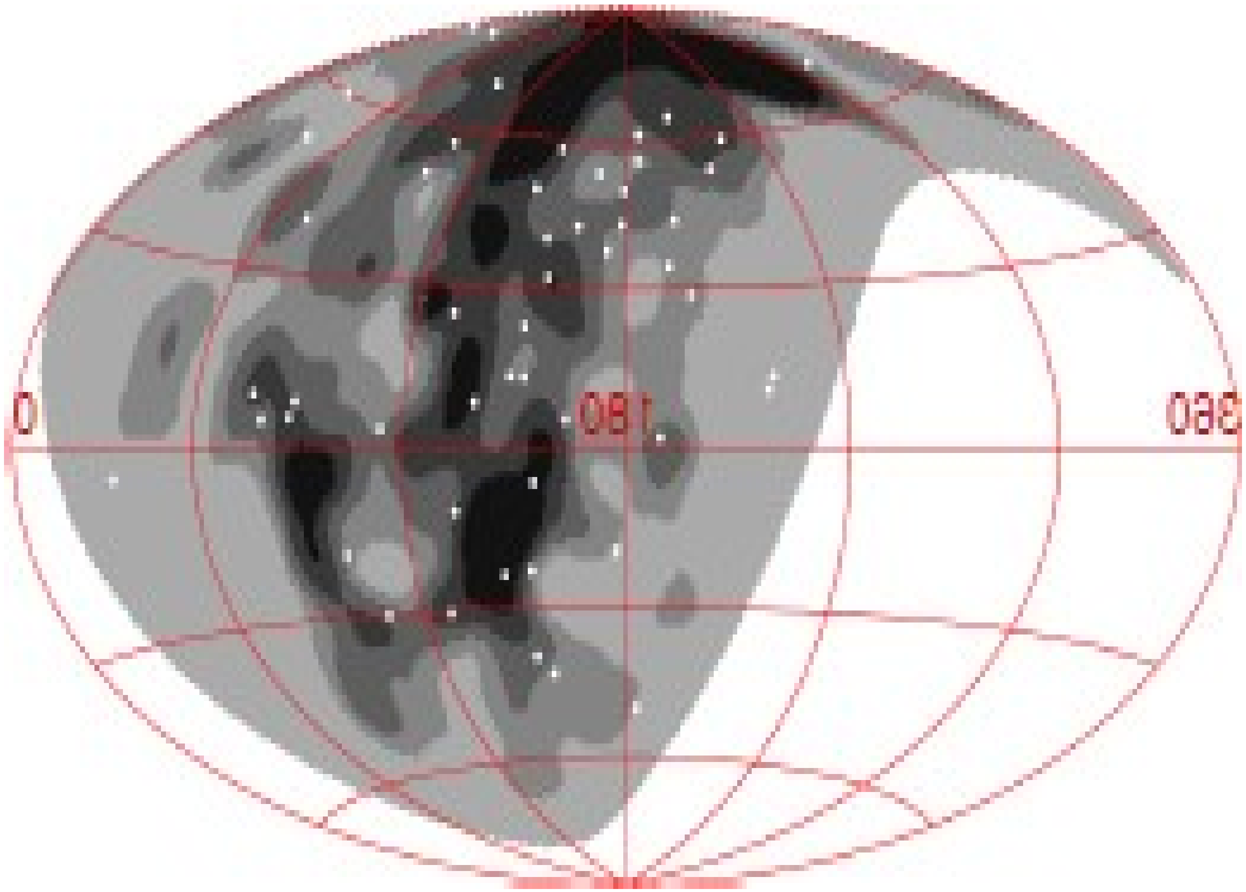
69 events with E > 55 EeV

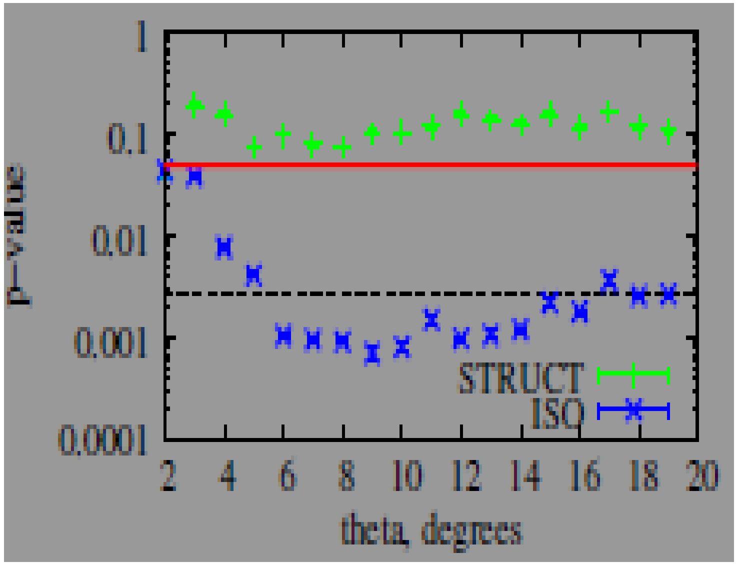
Auger excess around Centaurus A: closest AGN



13/69 events within 18 deg of CenA, while 3.2 expected for isotropy

TA distribution above 57 EeV

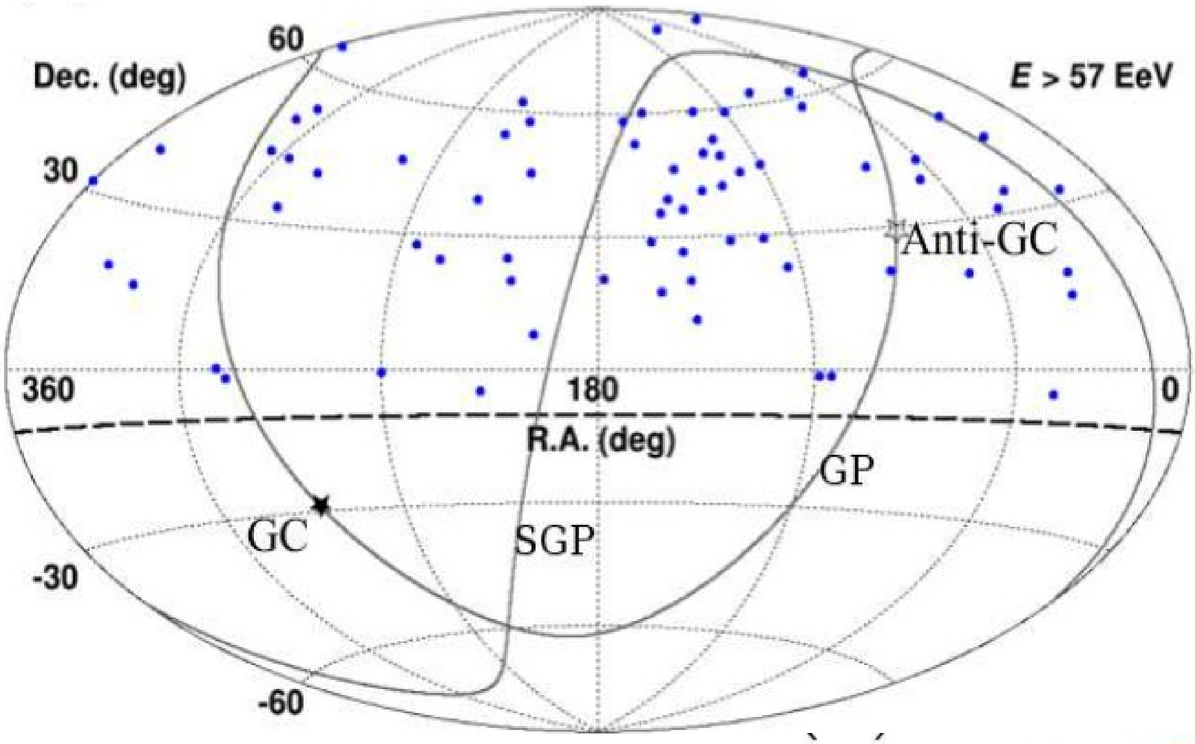




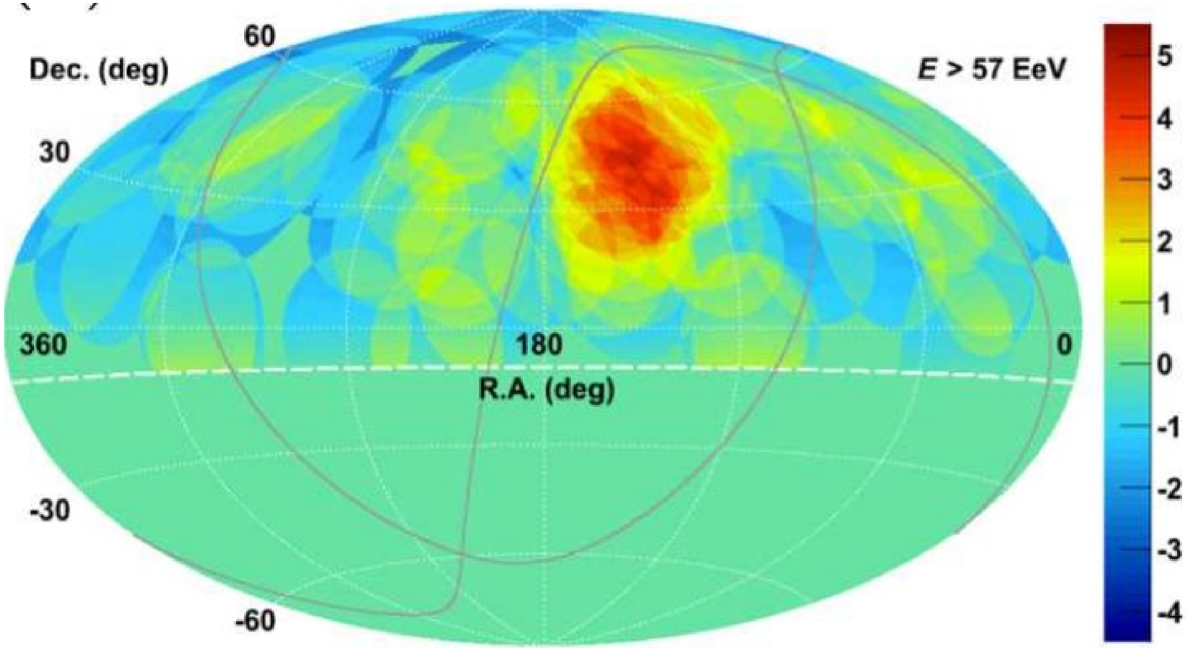
better fit to LSS than to isotropy

ArXiv:1404.5890

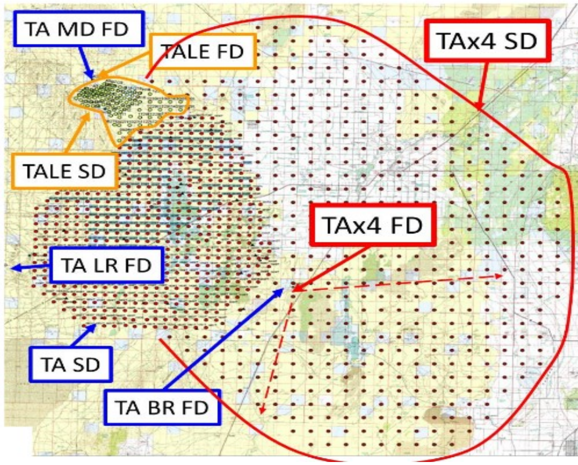
TA: Including 5 yrs and relaxed trigger



Hot spot with 3.6 sigma (fixing angle at 20 deg & Eth at 57 EeV)



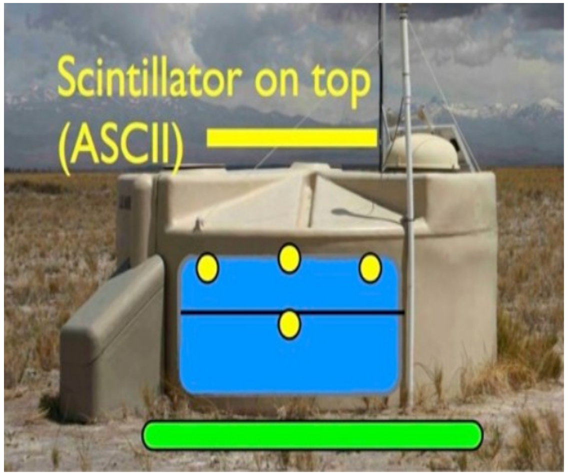
THE FUTURE



TA extensions:

TA x 4 : match size of Auger in the northern hemisphere
TALE: low energy extensions → down to $10^{16.5}$ eV

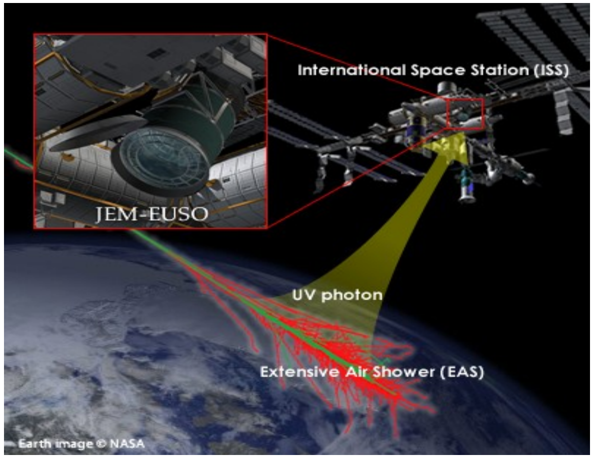
Also radio echo, electron beam calibration,....



Auger upgrade:

allow for composition measurements event by event adding additional detectors (scintillator, segmented tank, ….)
→ Origin of the flux suppression at highest energy;
Proton contribution at the highest energy;
EAS physics and hadronic multiparticle production

Also radio array (AERA) and a lot of R&D



JEM/EUSO:

Look at EHECRs (E> 10^{20} eV) from space (ISS)
Increased exposure by order of magnitude beyond 2020

CONCLUSIONS

Suppression for E > 40 EeV reliably established,
but is it p GZK ? Fe GZK ? Maximum source E ?

Hardening at the ankle at ~ 4 EeV
but is it due to galactic/X-gal, pair prod dip, or mixed X-gal ?

Light composition at ~ EeV
challenges galactic models extending up to the ankle

Hints of large scale anisotropies at 1-10 EeV
Nearby extragalactic sources?

Composition becoming heavier above ankle (Auger)
is this due to maximum source rigidity?   But Hires/TA ?

Or could there be changes in hadronic interactions?
nice connection with LHC results

Is there a fraction of protons at the highest energies?
crucial for anisotropies, for EeV neutrinos and photons,
and to further test hadronic interactions