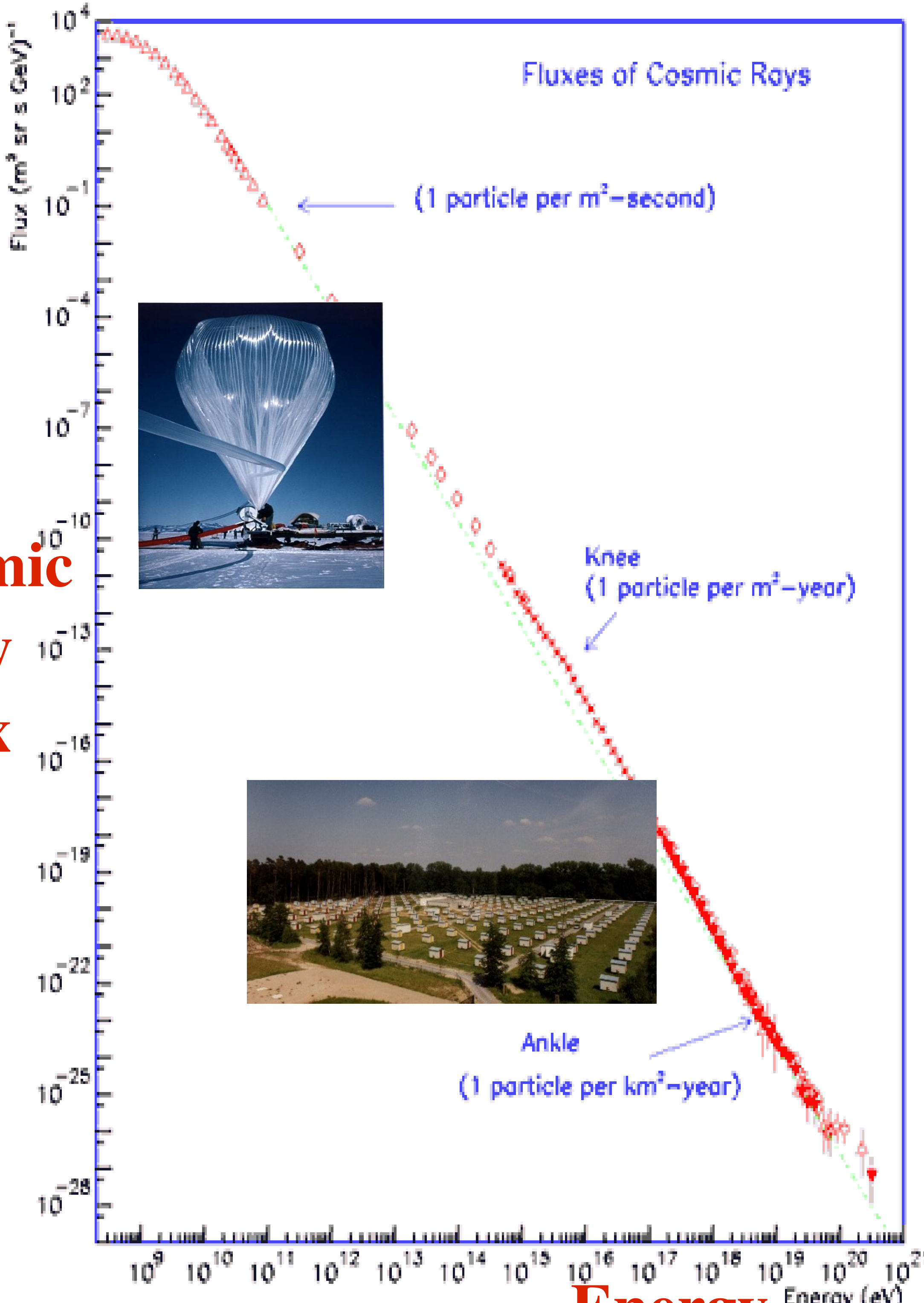
STATUS OF ULTRA-HIGH ENERGY COSMIC RAYS

Esteban Roulet (Bariloche)

COSMO / CosPA 2010, Tokyo

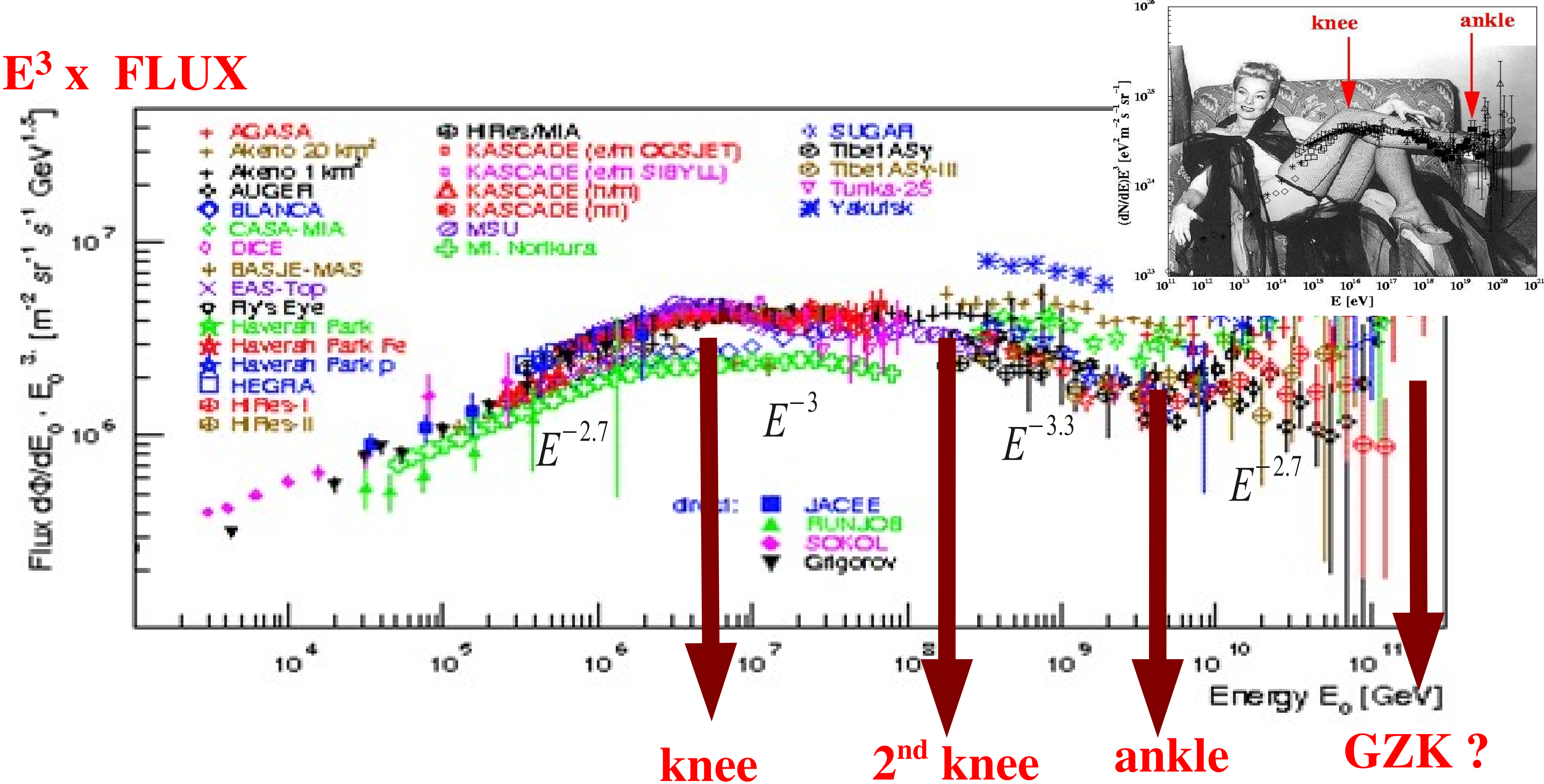


Power law flux → stochastic (Fermi) acceleration in shocks

Small fractional energy gain after each shock crossing →

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

E^3 x FLUX



For E < Z 10^{17} eV, r_L < 100 pc → diffusive propagation in Galaxy

escape time is E dependent $\tau_{esc}(E) \sim E^{-\beta}$ *with* $\beta \simeq 0.3-1$

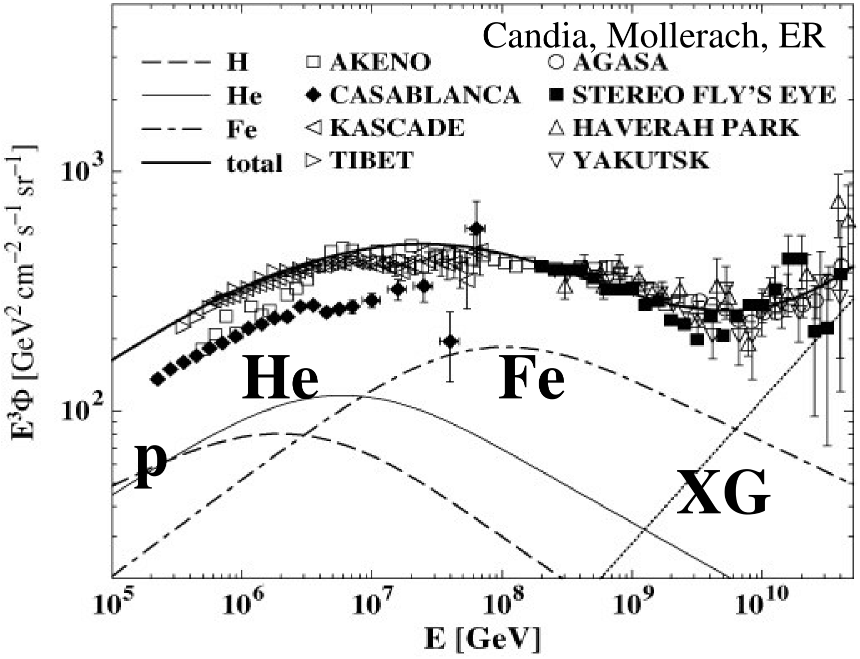
Spectrum: convolution of source spectrum + escape time $\frac{dN}{dE} \sim E^{-(\alpha+\beta)}$

For E > 10^{18} eV, CRs are likely extragalactic, source spectrum is shaped by attenuation during propagation through CMB

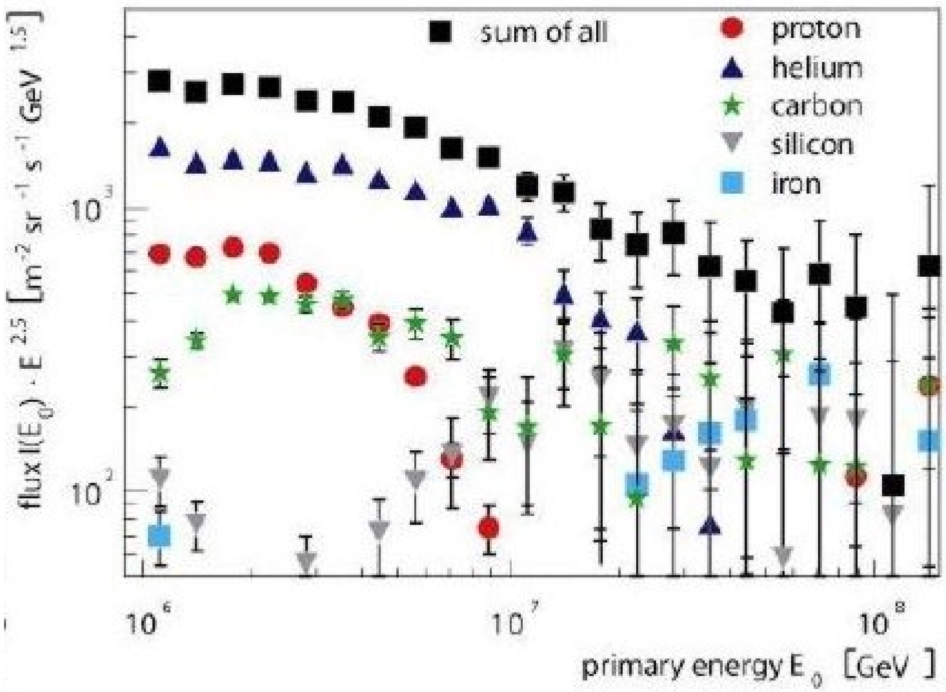
Knee due to:

- **limit in acceleration by galactic sources ?**
- **more efficient escape from galaxy (drift effects) ?**

rigidity (E/Z) dependent effects



Diffusion and drift scenario

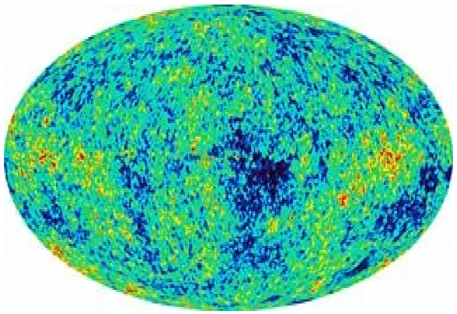


KASCADE

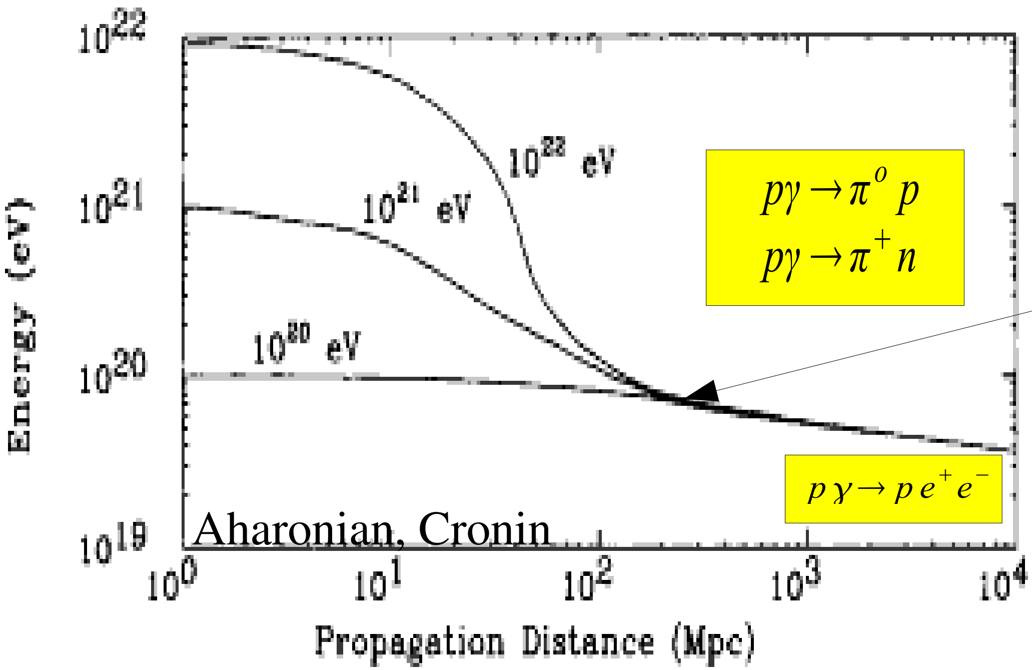
Ankle due to:

- **galactic extragalactic transition ? (ankle scenario)**
- **pair production dip ? (dip scenario)**

the Greisen-Zatsepin-Kuzmin effect (1966)



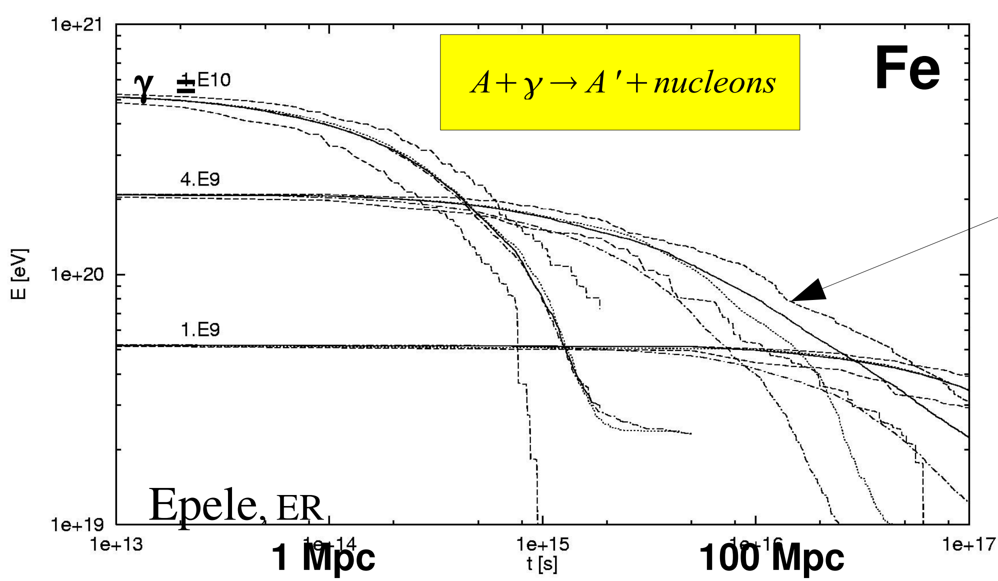
AT THE HIGHEST ENERGIES, PROTONS LOOSE ENERGY BY INTERACTIONS WITH THE CMB BACKGROUND



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

(π^{0} produce GZK photons)

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

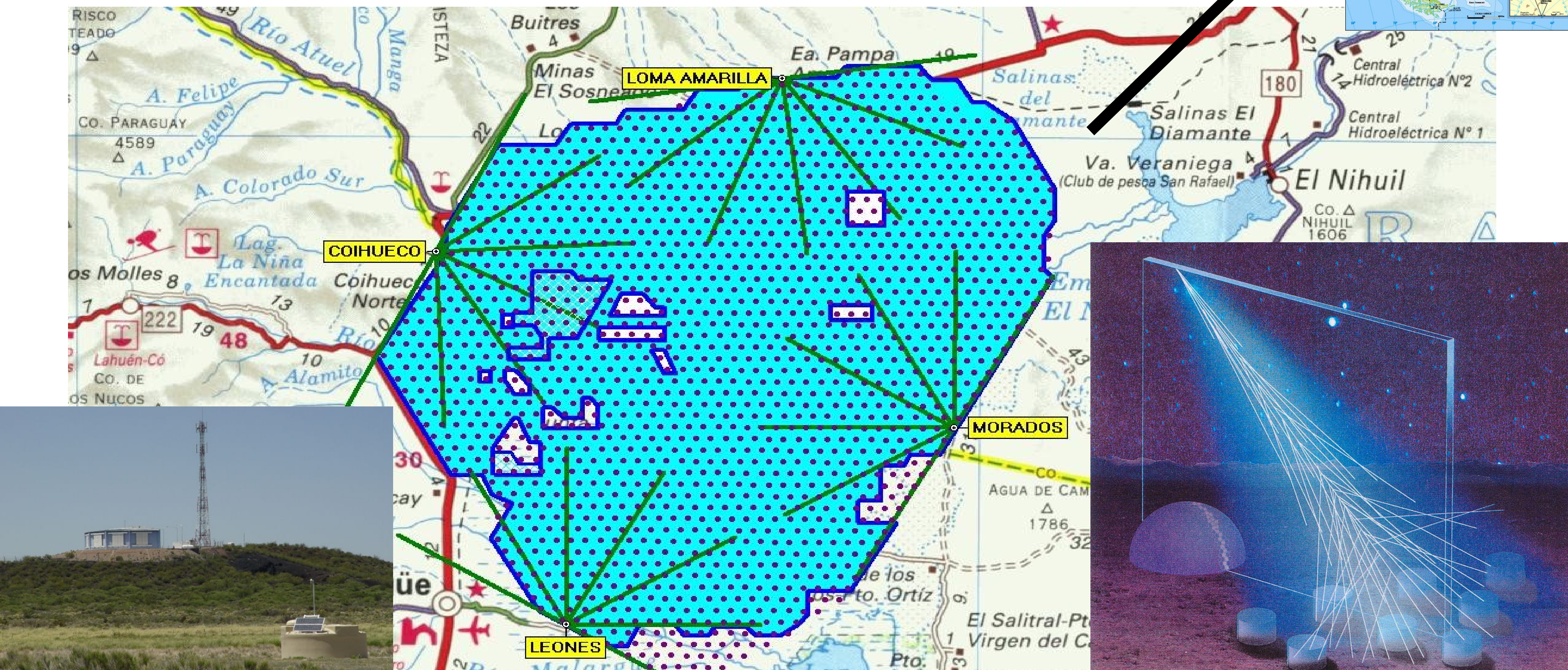


For Fe nuclei:
after ~ 200 Mpc the leading fragment has E < 6×10^{19} eV

ligther nuclei get disintegrated on shorter distances

DETECTING UHECRs: **at the highest energies,**
only few cosmic rays arrive per km^2 per century !
to see some, huge detectors are required:

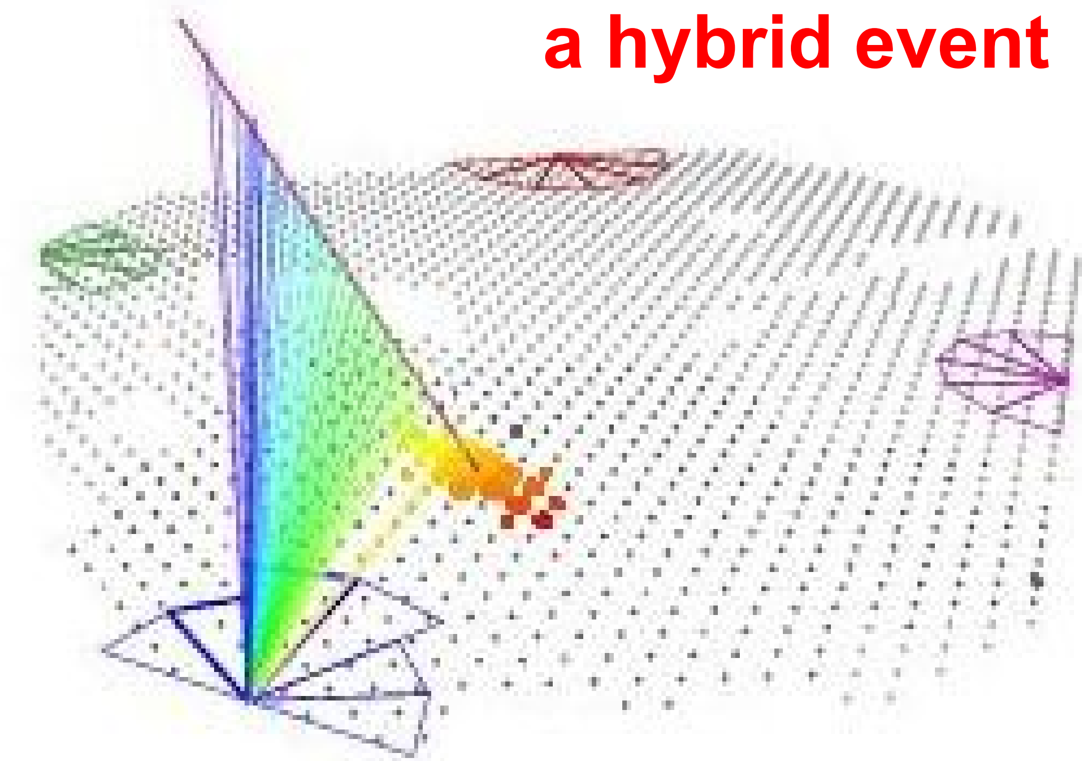
THE PIERRE AUGER OBSERVATORY



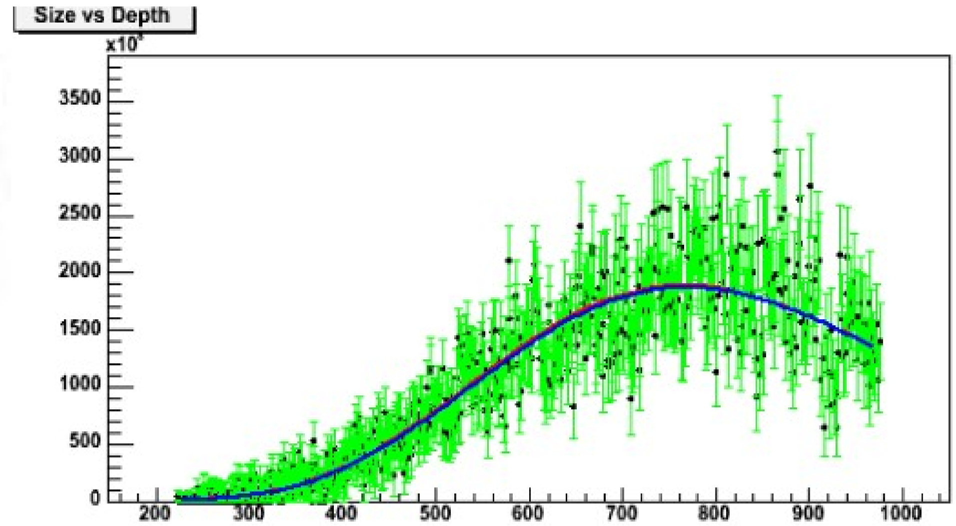
1600 detectors instrumenting 3000 km^2 and 24 telescopes

the Auger Collaboration: 18 countries, ~ 400 scientists

a hybrid event



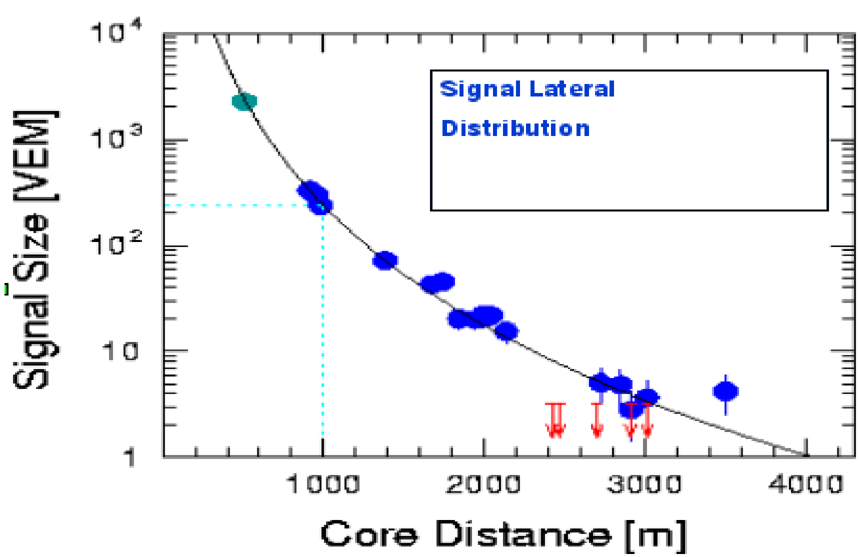
Longitudinal distribution in air



(duty cycle ~15%)

Lateral distribution at ground

ID 762238



Measure Xmax

Energy calibration

angular resolution < 1^{o}

(duty cycle ~100%)

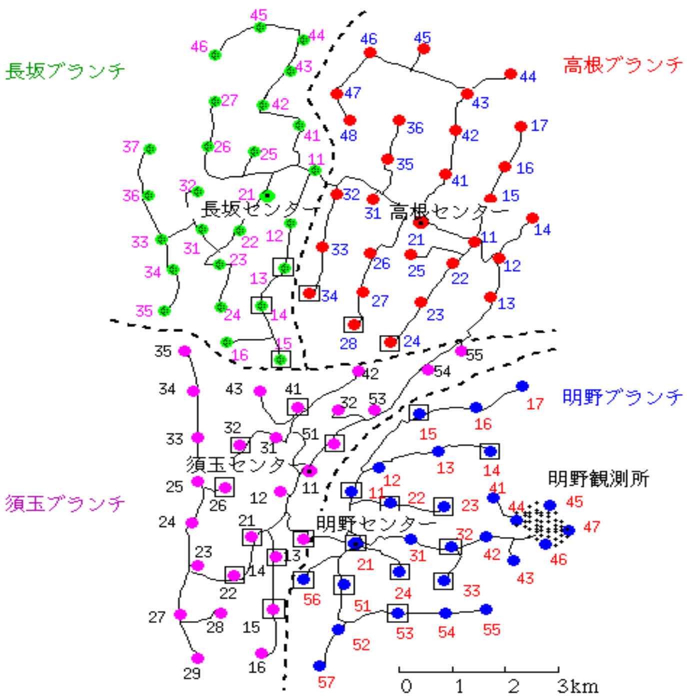
Previous experiments:

AGASA: (Akeno, Japan 1990-2004)

Area: 100 km^2

111 Scintillators (e^+e^-) and

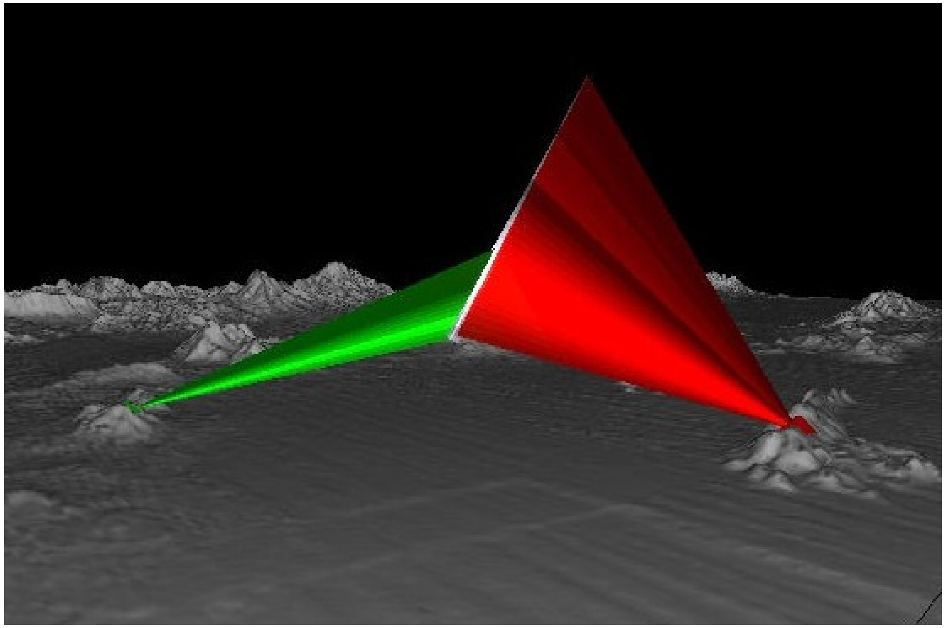
27 shielded proportional counters (muons)



Fly's Eye (1981-1993) Utah, USA

HiRes (1997-2006)

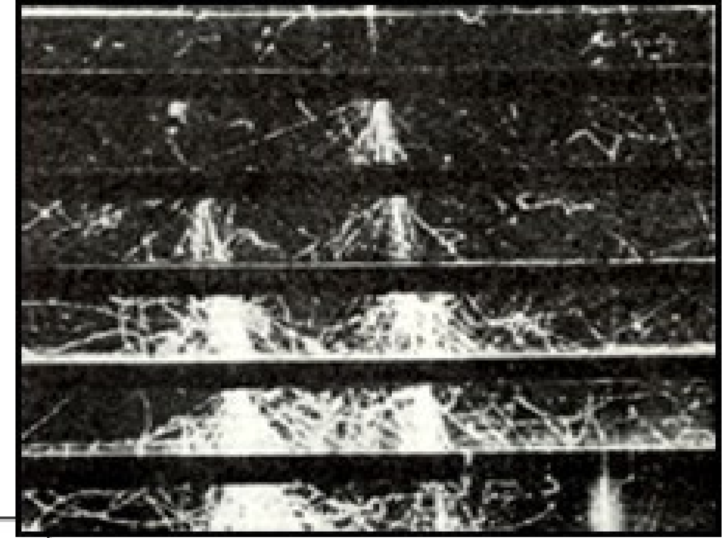
Fluorescence telescopes

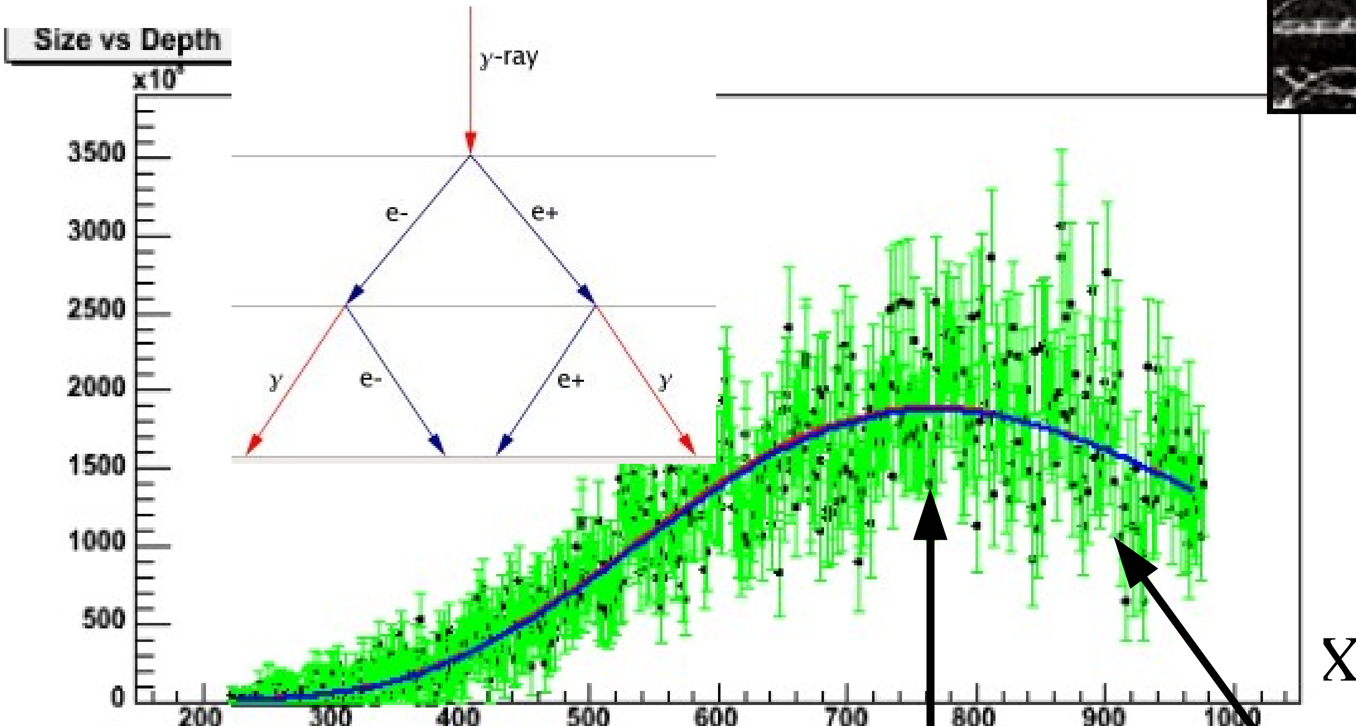


Also Volcano Ranch, Haverah Park, Yakutsk, Sugar, ...

Some basics on air showers:

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





$E_e < E_c \simeq 86\ MeV$

N grows exponentially

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

Ionisation losses dominate

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

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

HADRONIC SHOWERS

each interaction produces n_{tot} pions (multiplicity)

$n_{neut} = n_{tot}/3 \quad (\pi^0 \rightarrow 2\gamma)$ **em component**

$n_{ch} = 2\, n_{tot}/3 \quad (\pi^{\pm})$ **reinteract until** $E < E_{dec} \simeq 20\mathrm{GeV} \quad (\pi \rightarrow \mu \nu \nu)$

Number of $\pi^{\pm}$ generations from: $E_0 / n_{tot}^n = E_{dec} \quad (typically\ n \sim 5-6)$

Energy of em component: $E_{em} = E_0 - (2/3)^n E_0 \qquad (\sim 0.9\, E_0 \ for\ 10^{19}\, eV)$

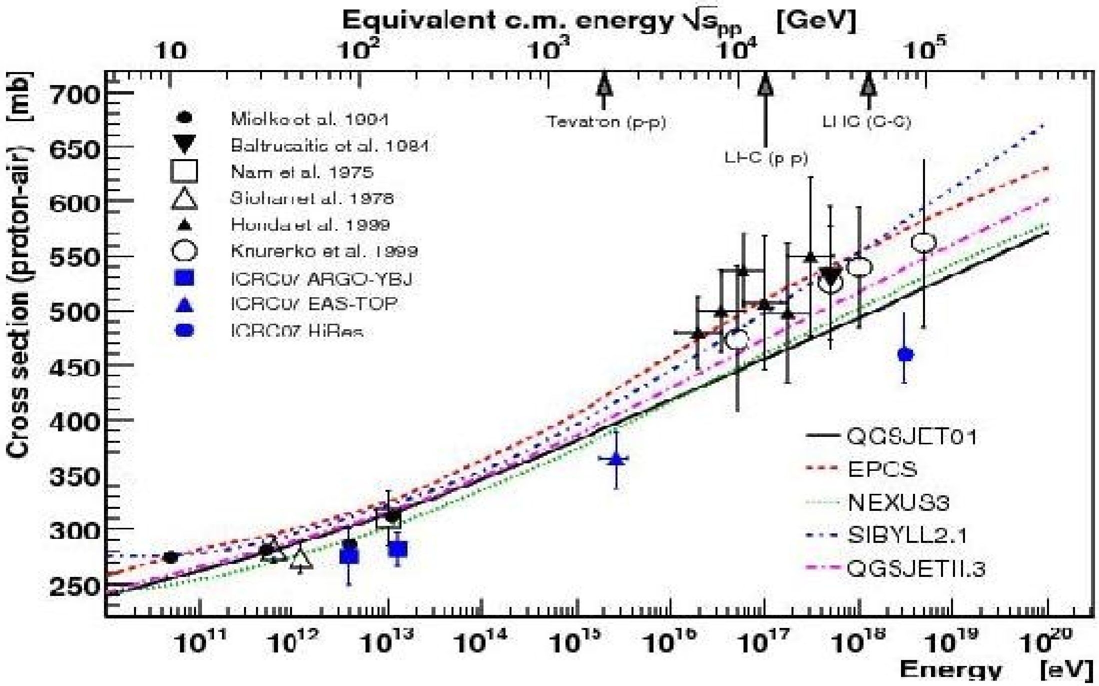
Estimating X_{max} as the maximum of the first generation π^0 s:

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

depends on $\lambda_I \sim \sigma_{p-air}^{-1}$
and on multiplicity

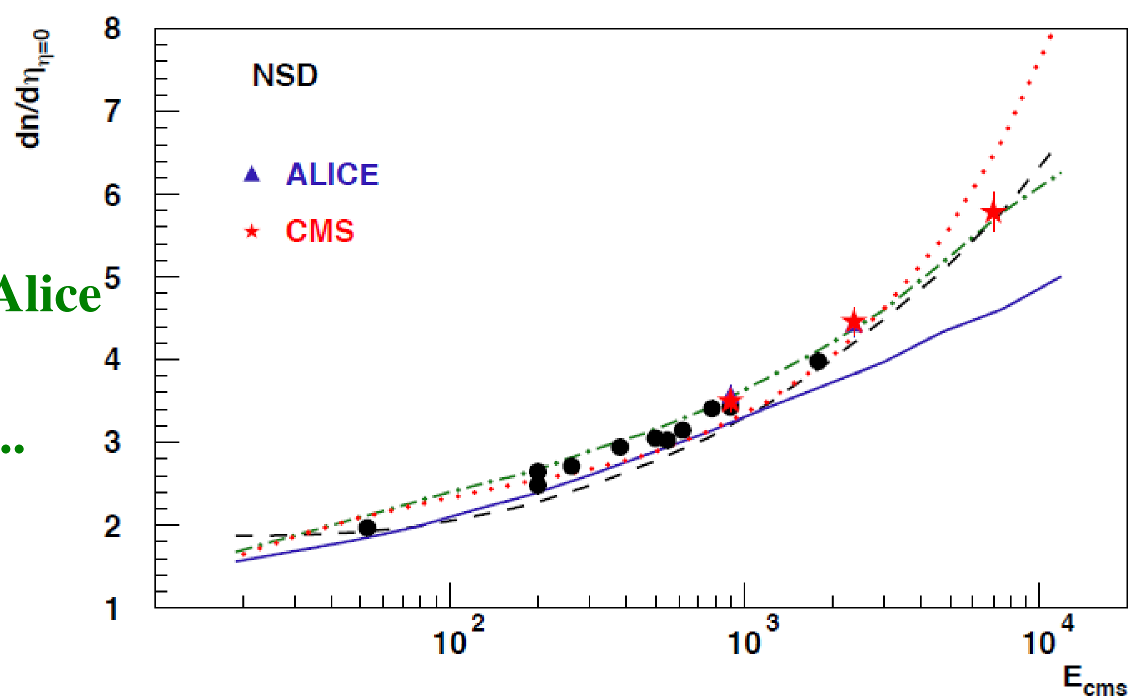
For nuclei: A nucleons with $E_n = E_0 / A$ **(smaller X_{max})**

CROSS SECTIONS

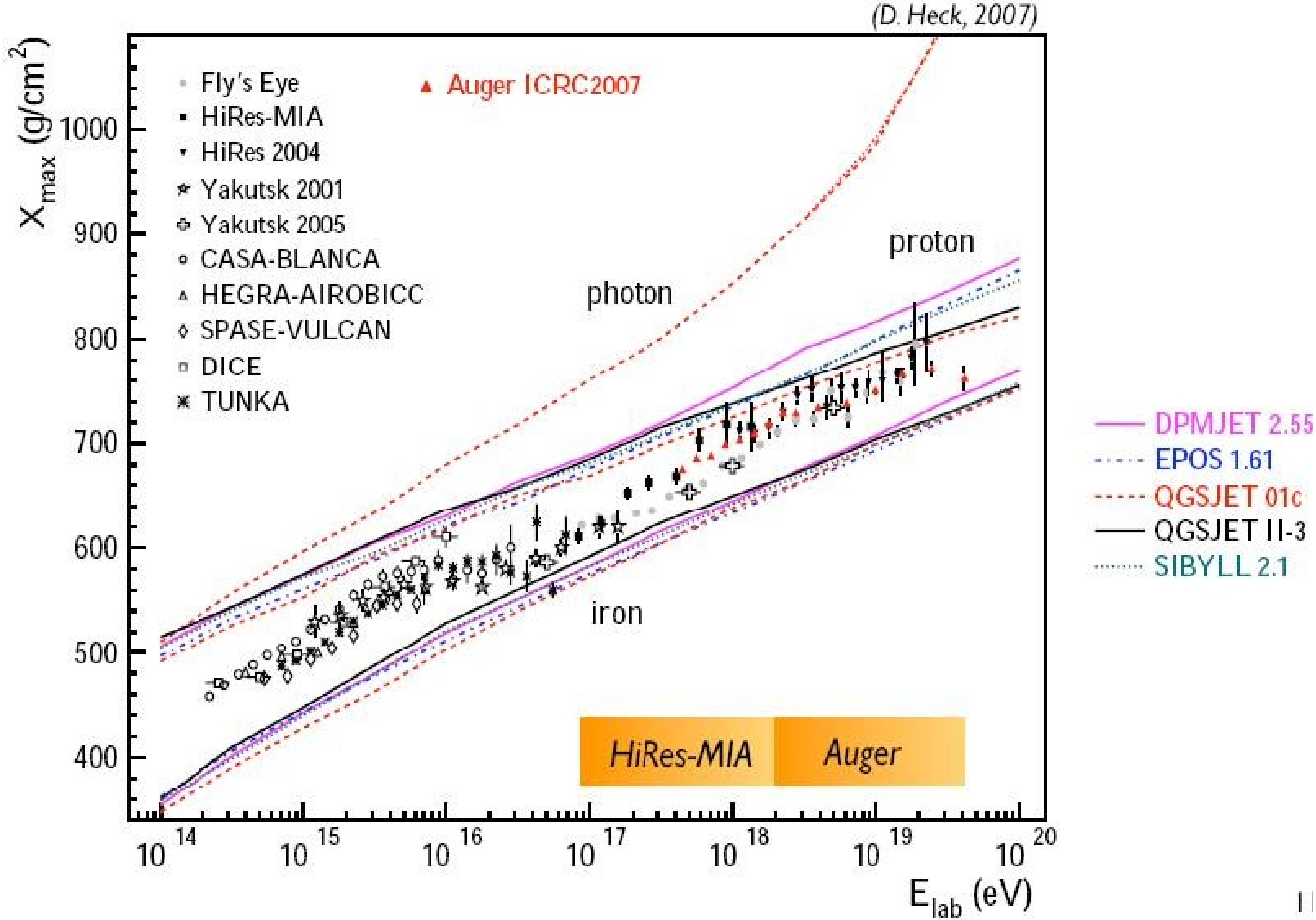


MULTIPLICITIES

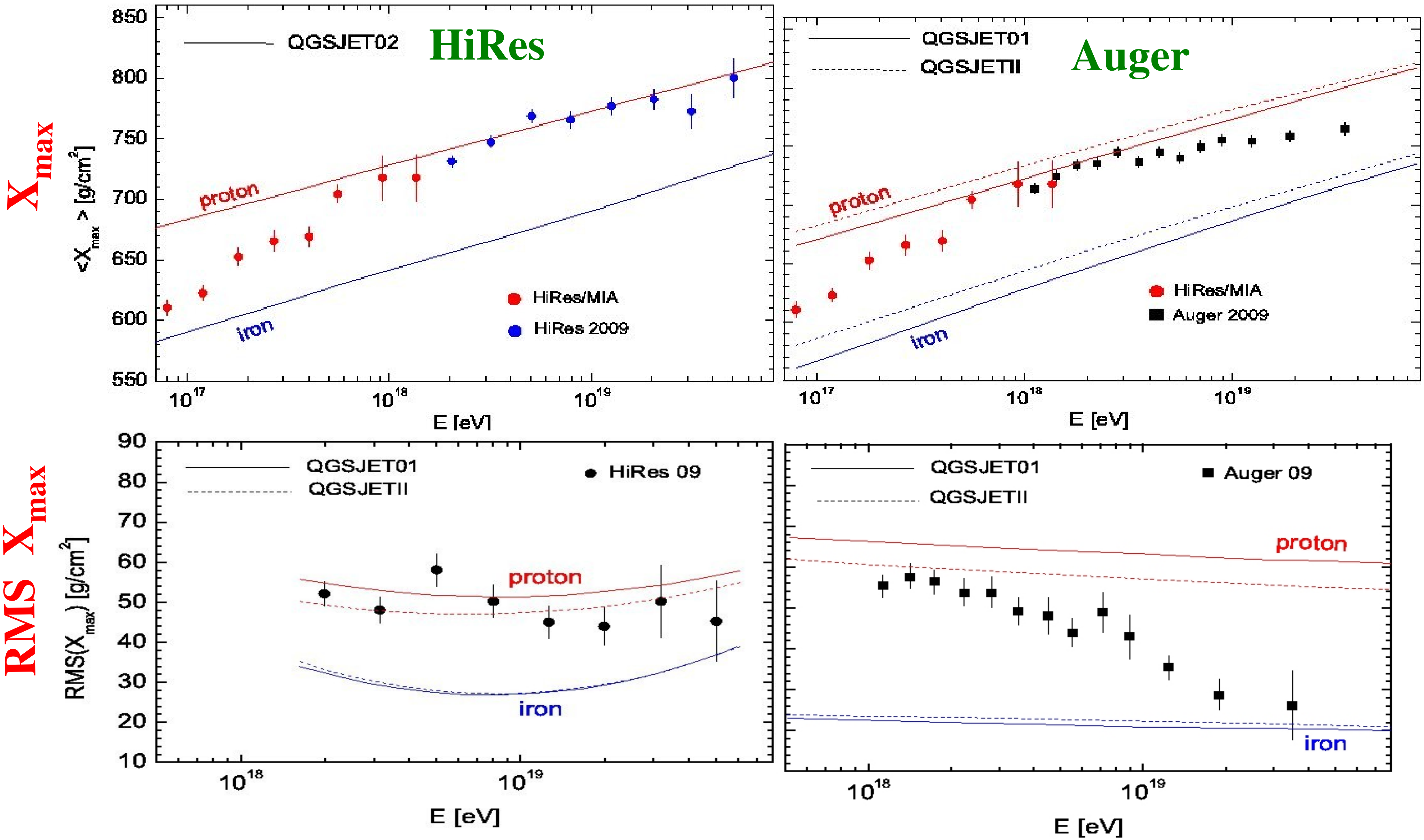
Some results in central region (η~0) already published by CMS, Atlas and Alice results from forward region (large η) expected from Totem, Castor, LHCf, ... will allow to improve hadronic models



COMPOSITION FROM X_{max}



CONFLICTING RESULTS AT UHE ?

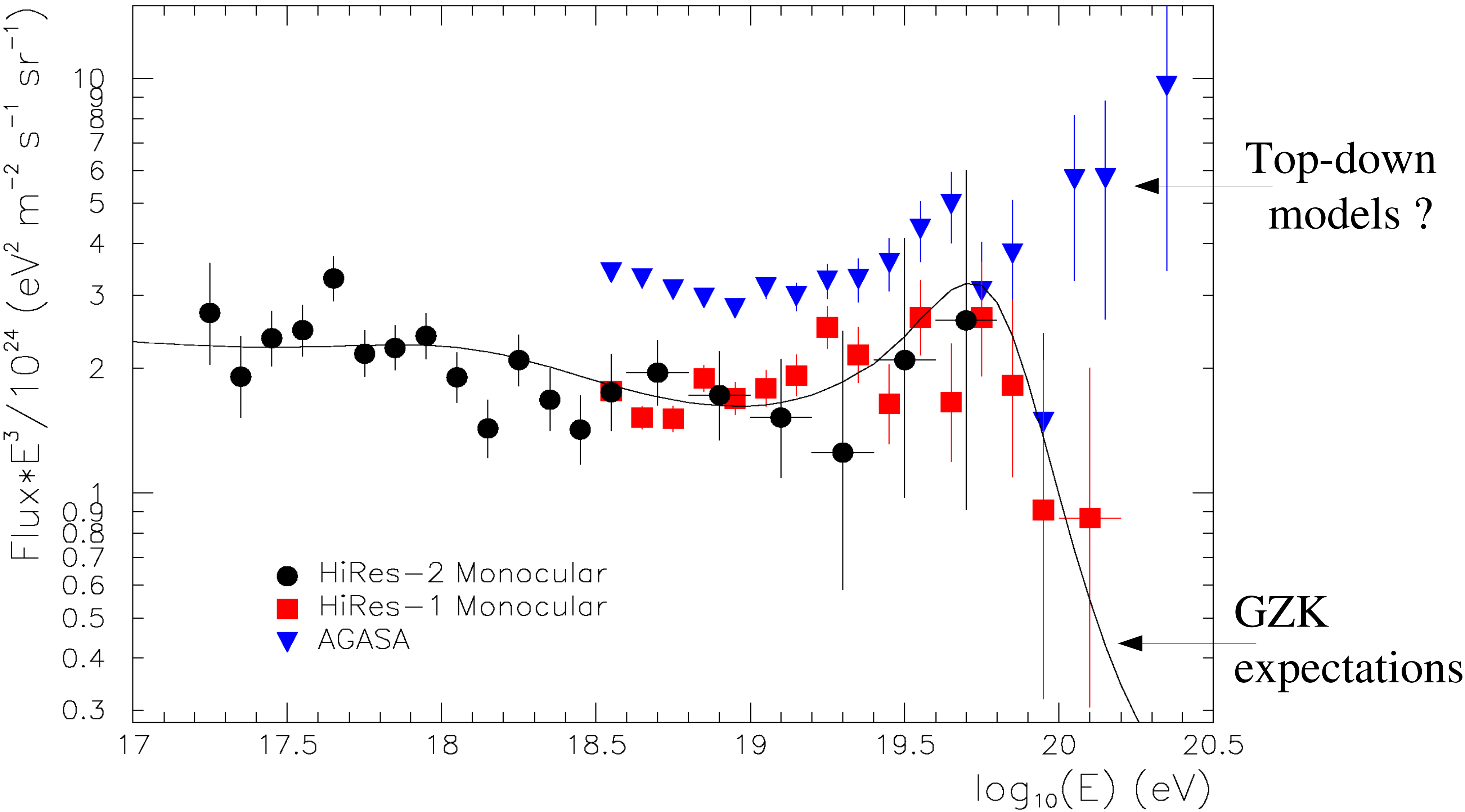


HiRes: consistent with protons

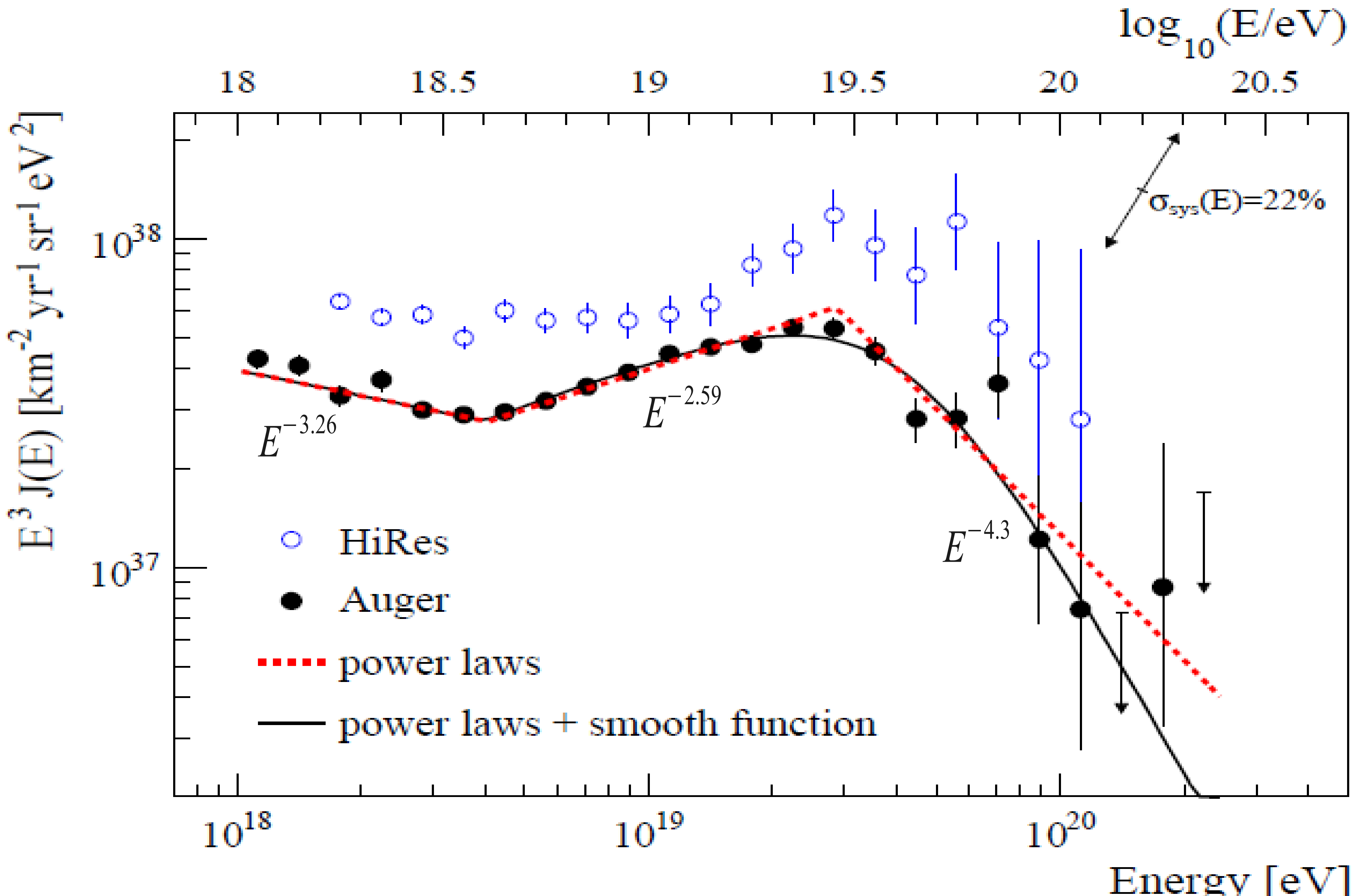
Auger: transition towards heavy component or change in hadronic interactions?

THE END OF THE SPECTRUM: GZK?
previous results

AGASA: NO **HiRes: YES**



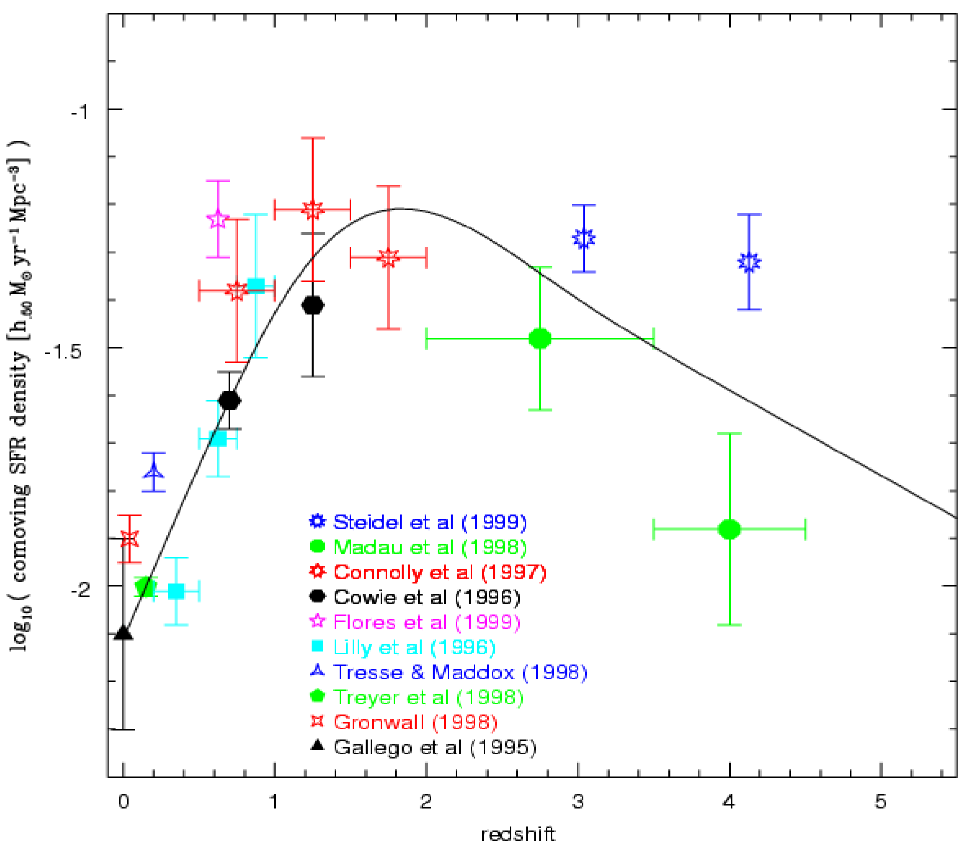
AUGER and HiRes SPECTRA



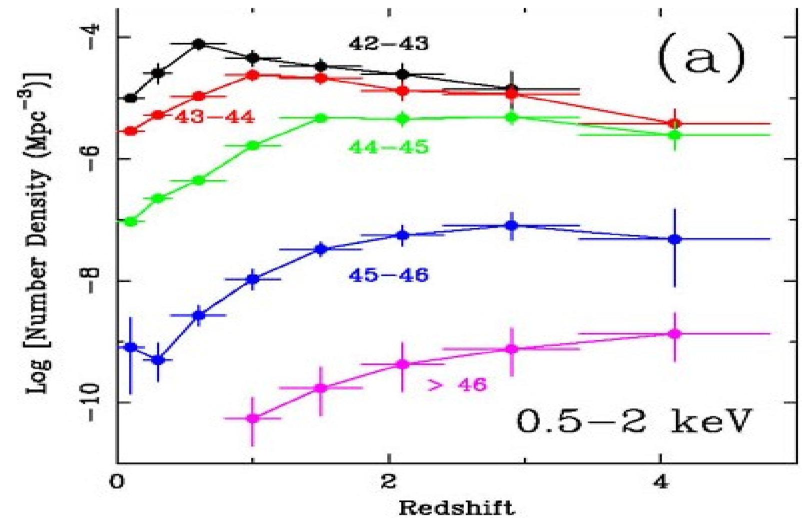
Auger, arXiv:1002.1975

to compare spectrum with theoretical expectations, source redshift evolution is relevant

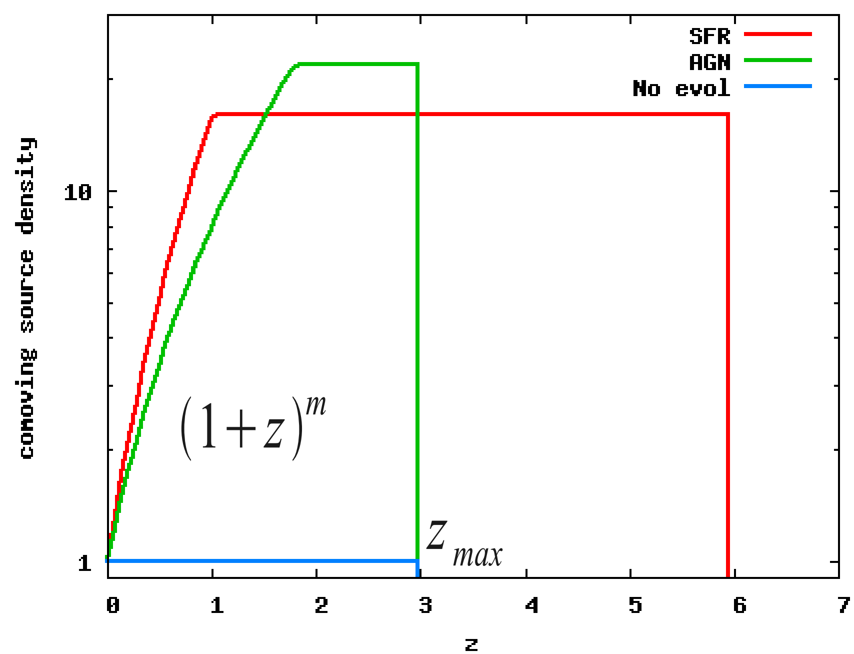
Star Formation Rate

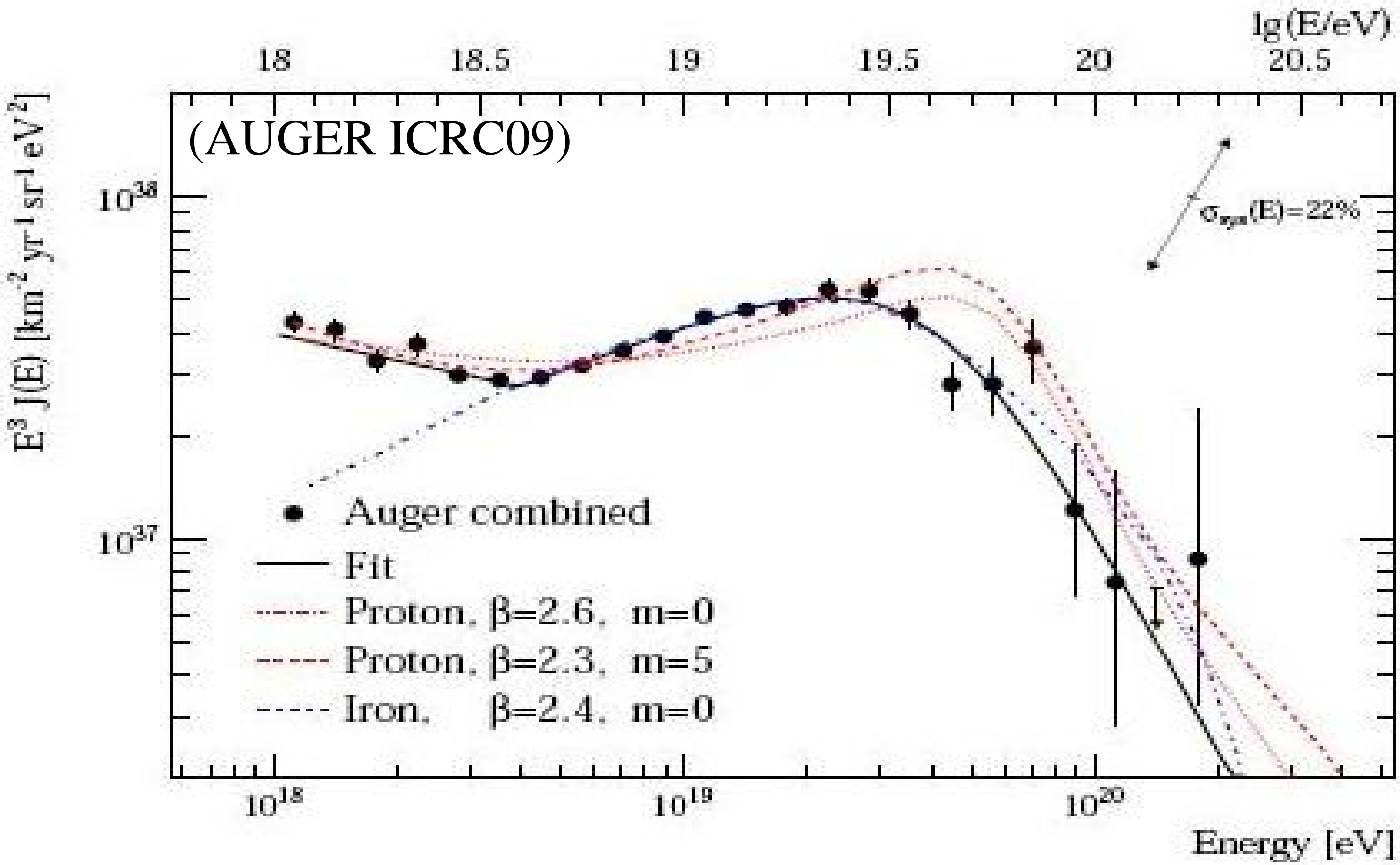


AGN density



Simple models for UHECR sources

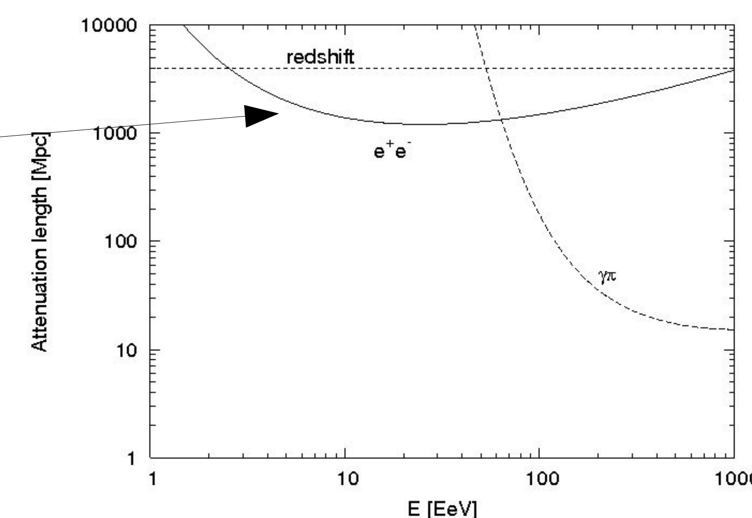




dip scenario requires steep spectrum and/or strong evolution $dn/dz \sim (1+z)^m$

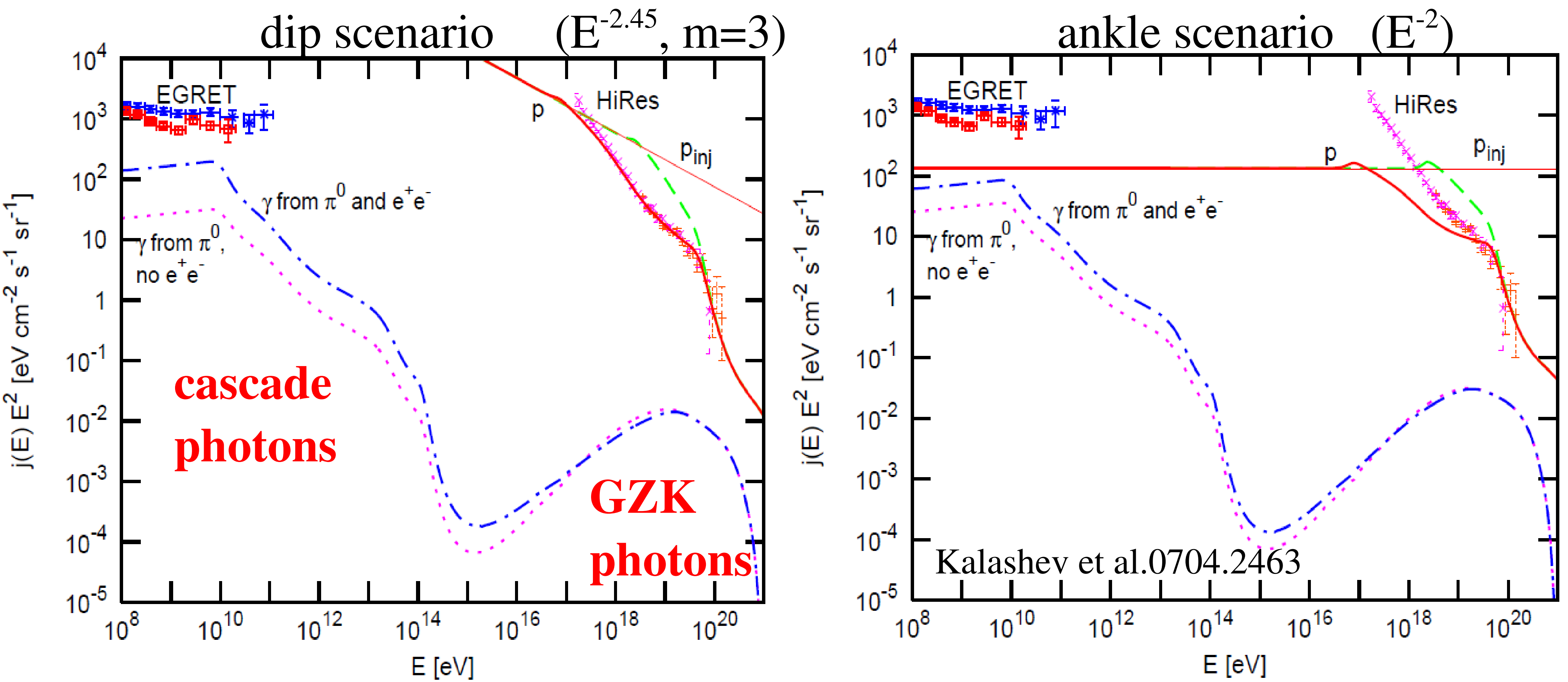
featureless galactic extragalactic transition below 10^{18} eV ?

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



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

ASSOCIATED PHOTON FLUXES

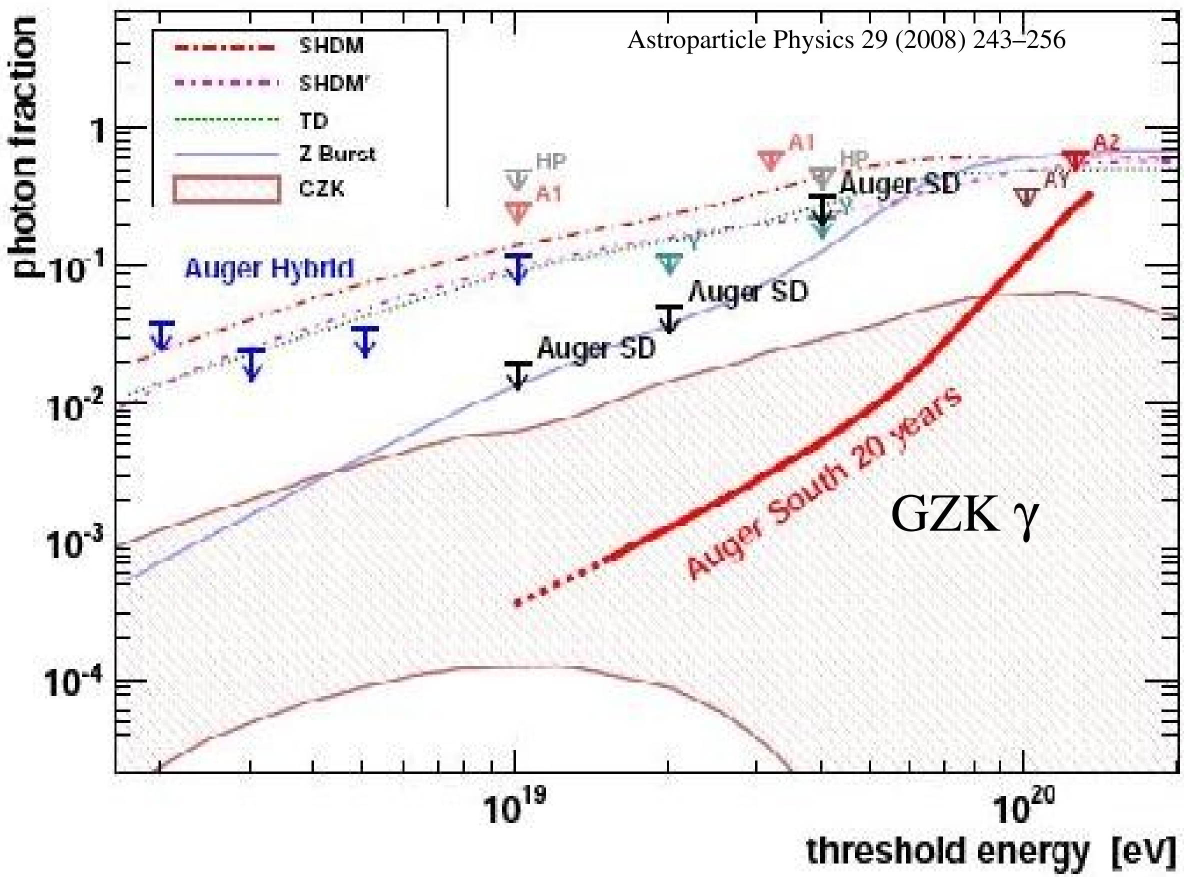


- **dip models lead to significant cascade fluxes from pair production → restricts large m**

- **ankle models (harder fluxes) lead to larger GZK photon fluxes**

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



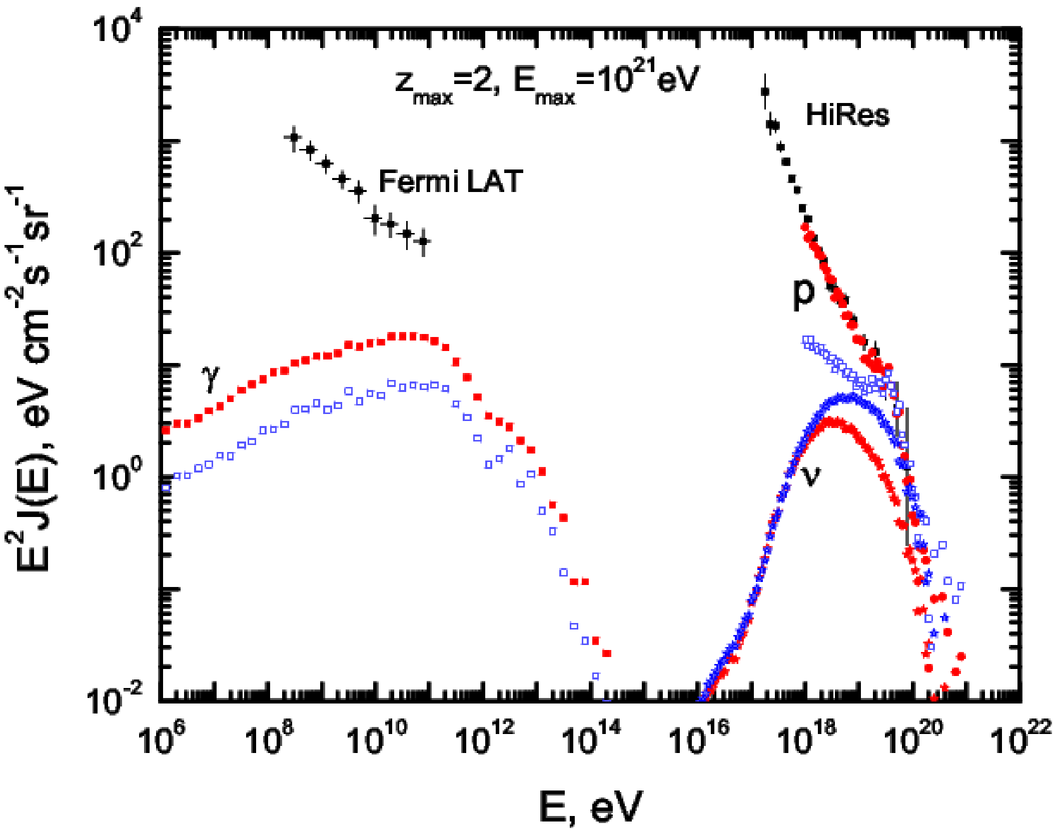
photon fraction:
< 2% at E > 10 EeV

< 31% at E > 40 EeV

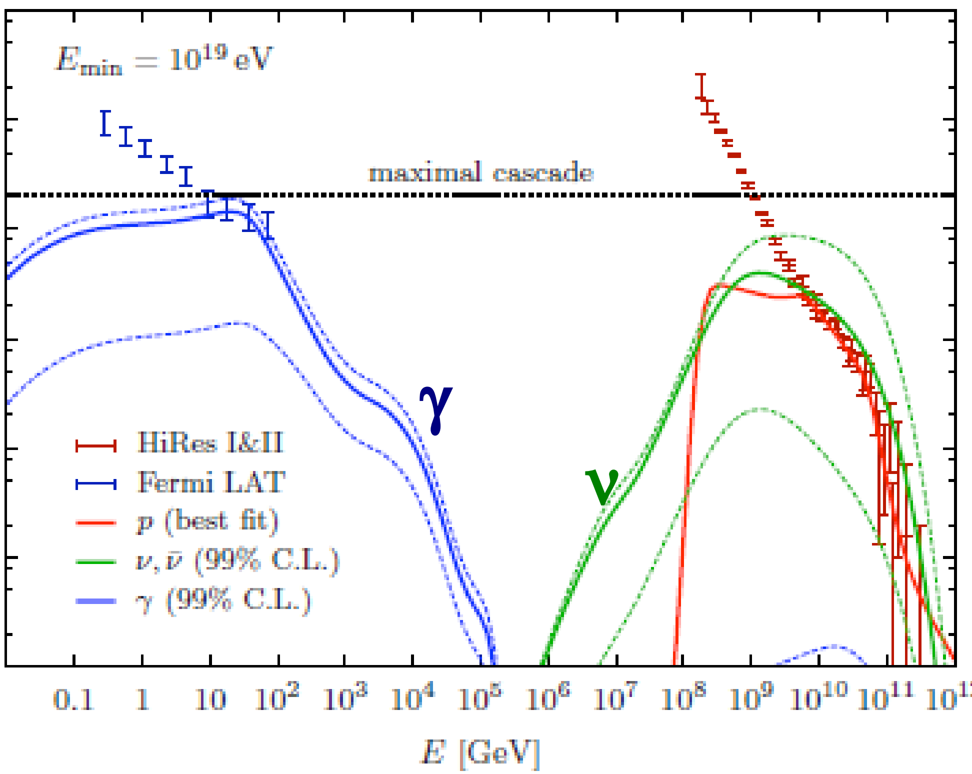
excludes most top-down models, but still above GZK photons

ASSOCIATED COSMOGENIC NEUTRINO FLUXES:

Berezinsky et al., arXiv:1003.1496



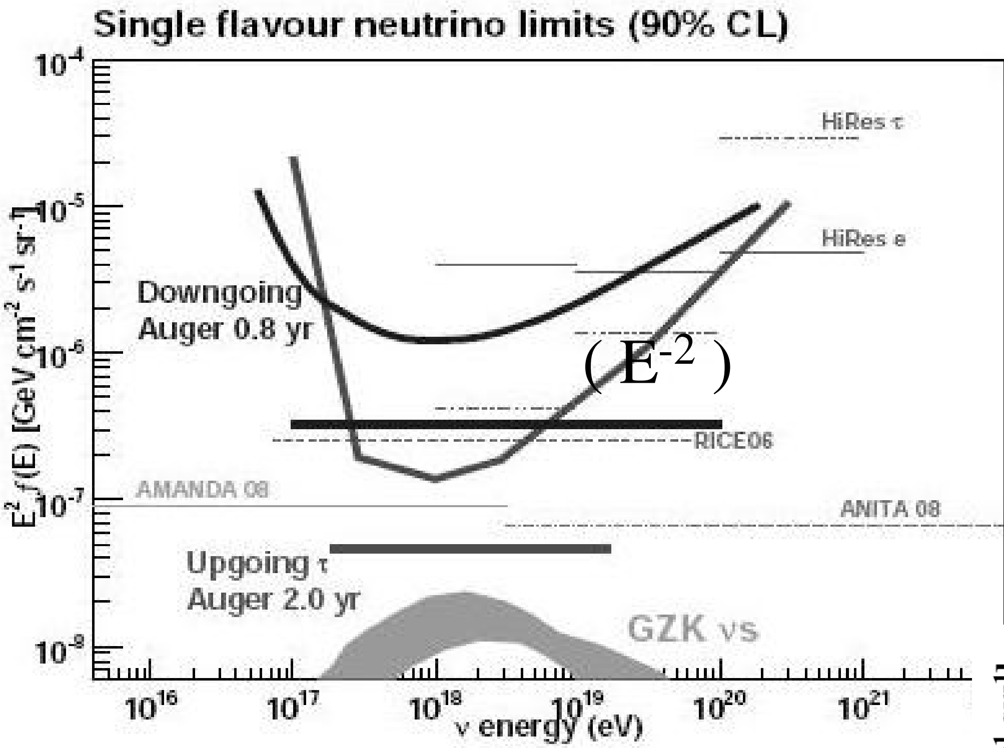
Ahlers et al., arXiv:1005.2620



- New Fermi bounds on GeV-TeV gamma fluxes (stronger than EGRET)
- ankle models (harder fluxes) lead to larger cosmogenic neutrino fluxes

BOUNDS ON DIFFUSE NEUTRINO FLUXES

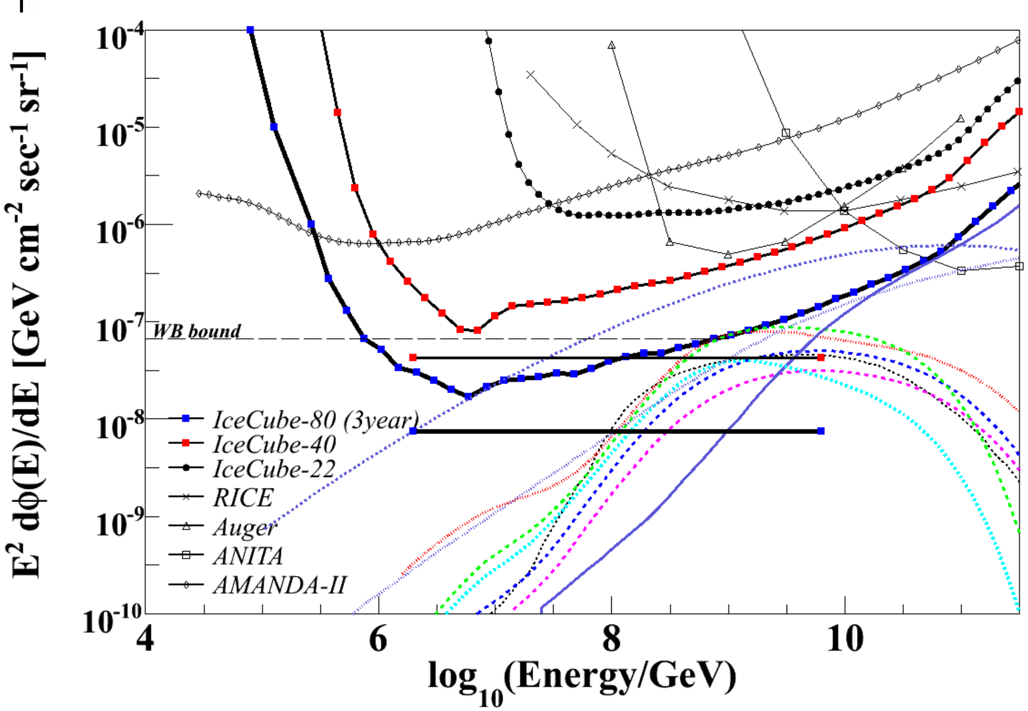
Auger., ICRC09



Looking at:
young horizontal air showers,
upcoming tau leptons
radio Cherenkov in ice, ...

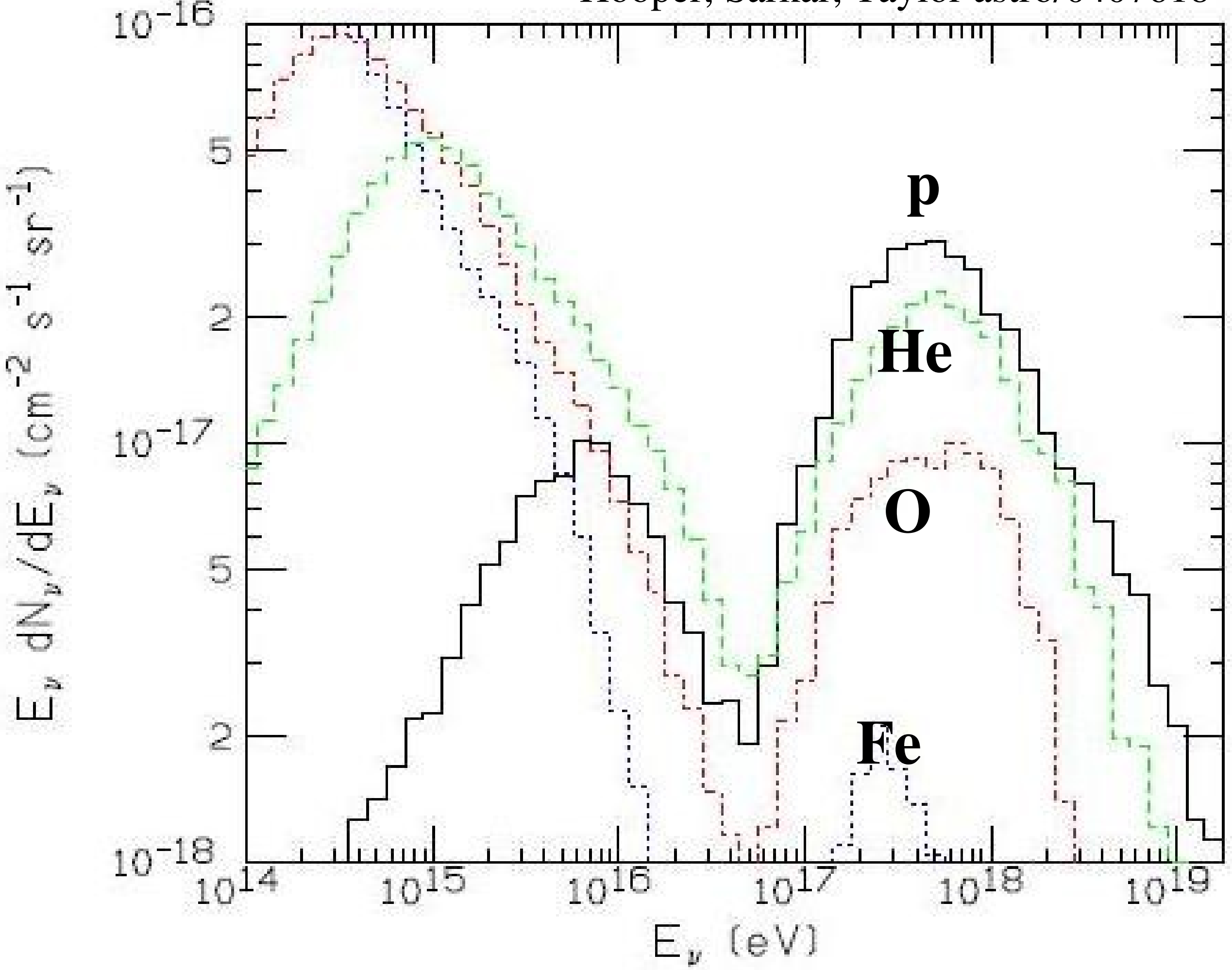
present bounds still an order of magnitude above optimistic expectations

Icecube, talk by Aya Ishihara

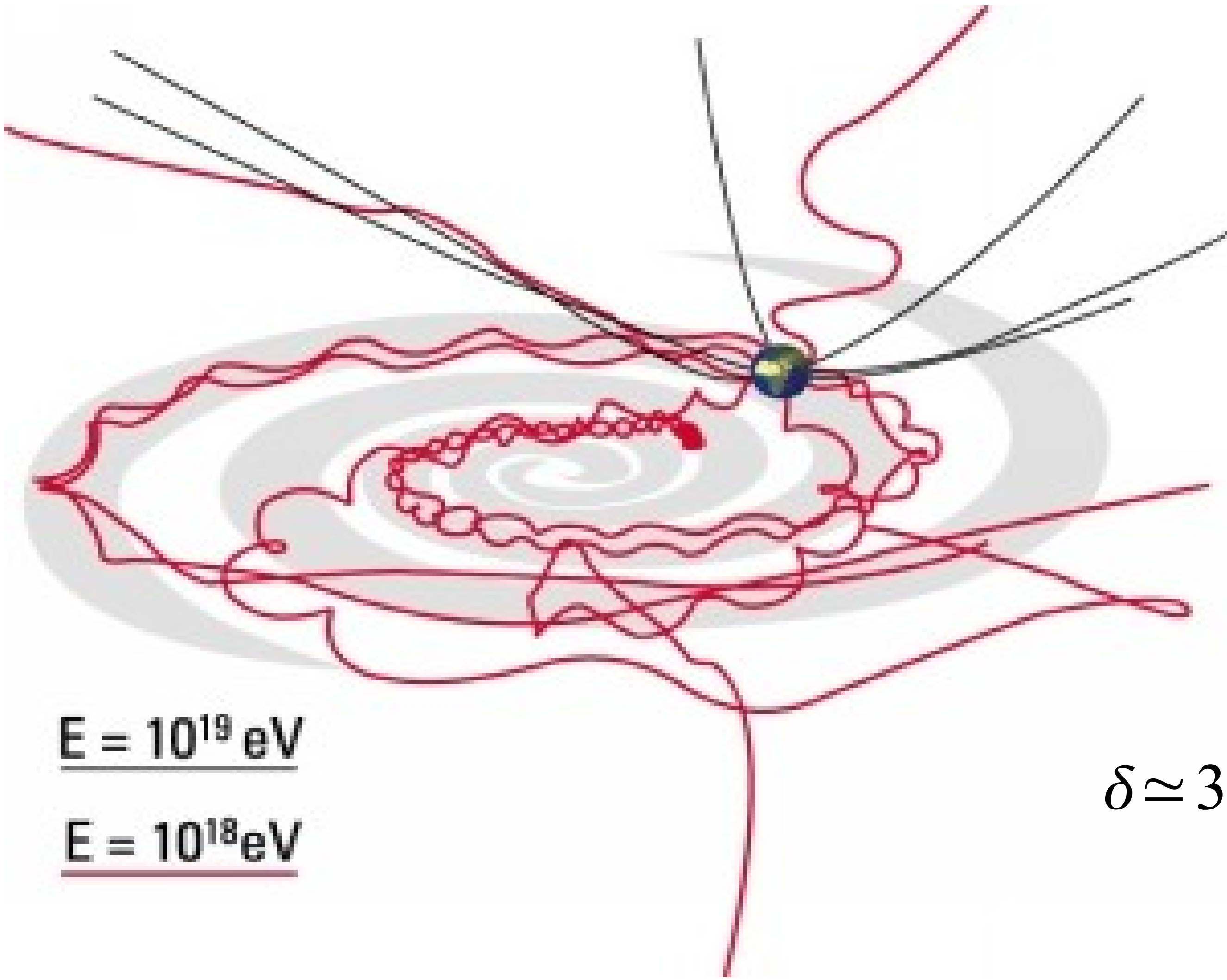


If cosmogenic neutrinos were observed, it would be a strong hint favoring a light composition

Hooper, Sarkar, Taylor astro/0407618



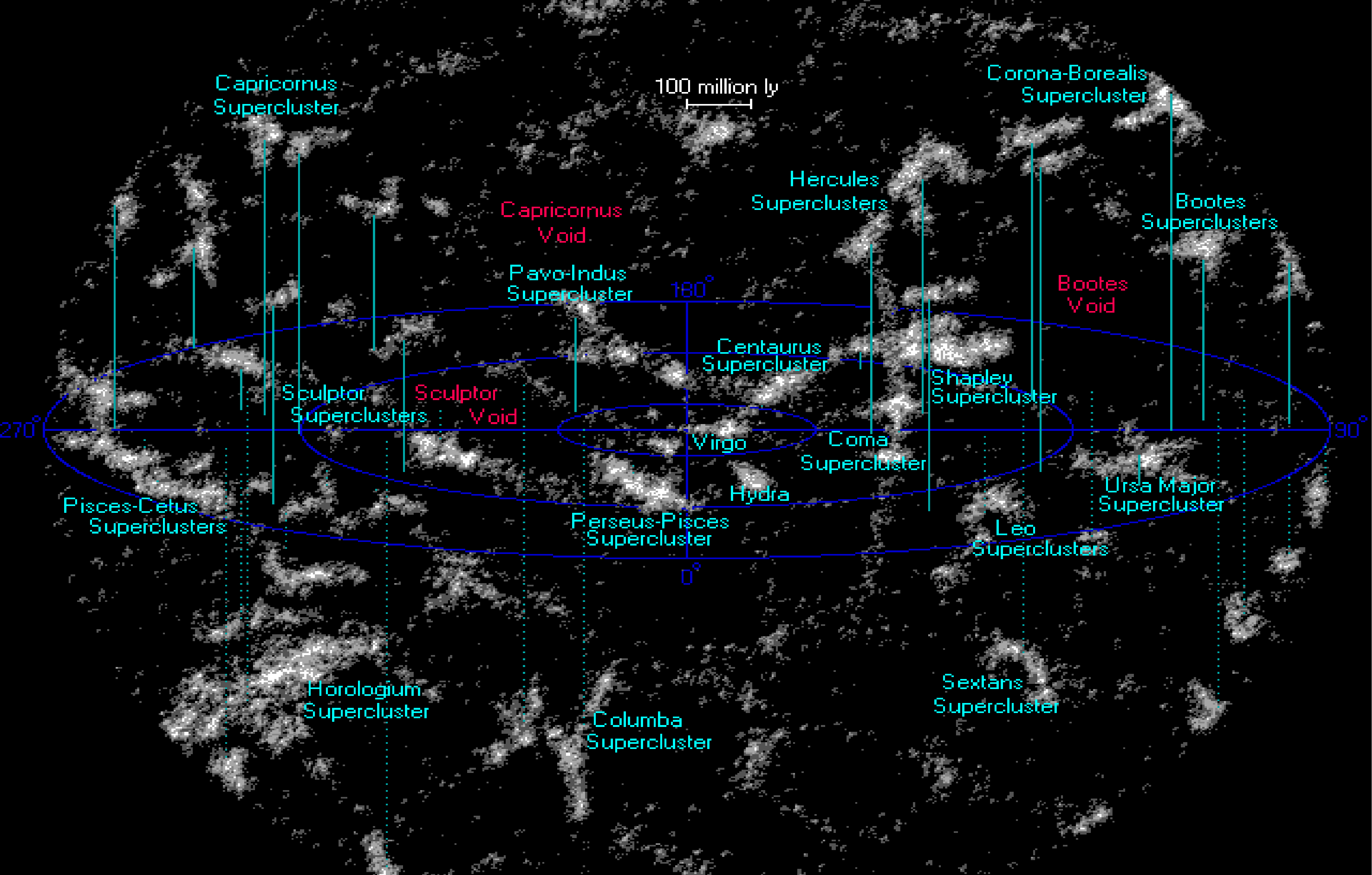
COSMIC RAY ASTRONOMY ?



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

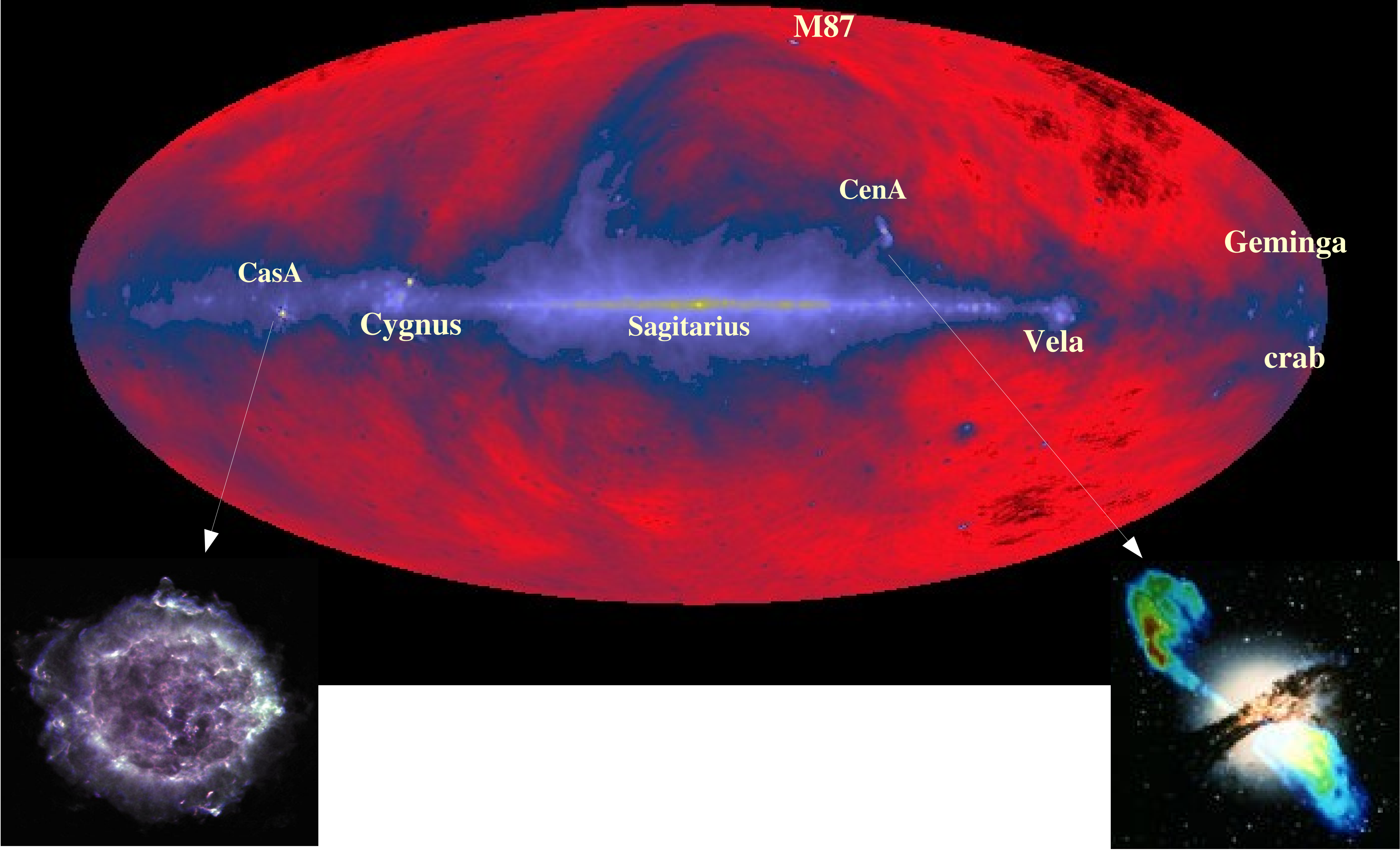
only for E/Z $\gg$ 10^{19} eV deflections in galactic magnetic fields become less than a few degrees and CR astronomy could become feasible

galaxies up to 100 Mpc



the nearby Universe is quite inhomogeneous

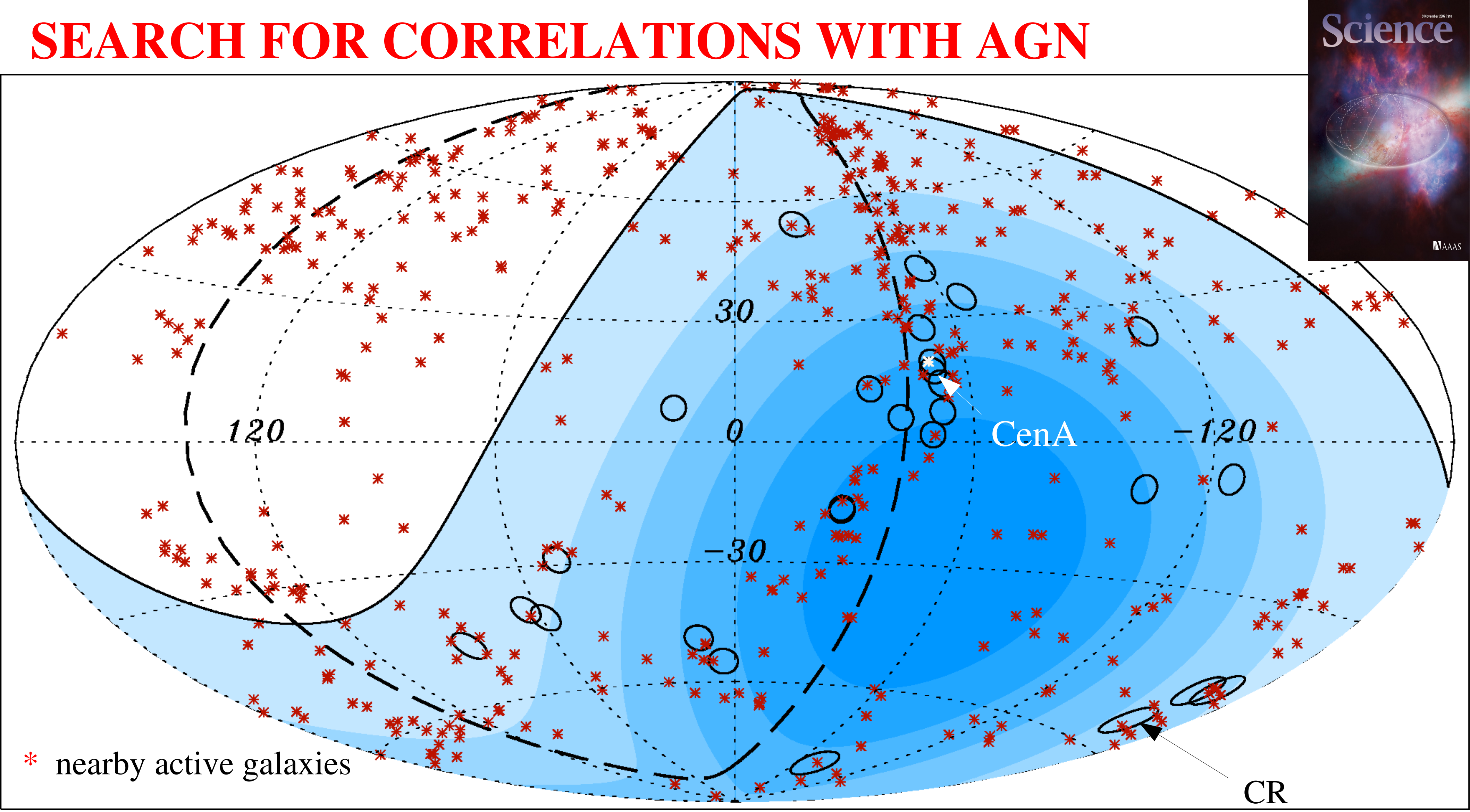
the radio sky



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

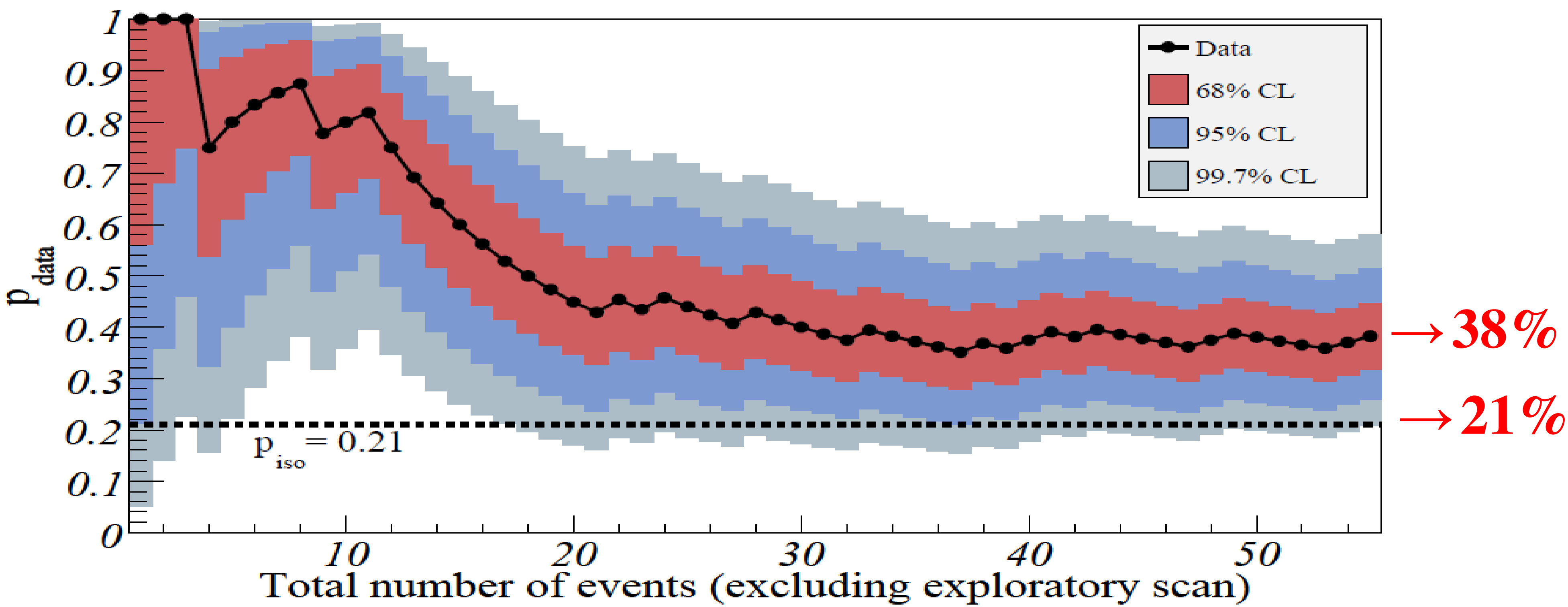
(from the 7 which are not, 5 have $|b_G| < 12$ deg, where catalog is largely incomplete)

(AUGER arXiv1009.1855)

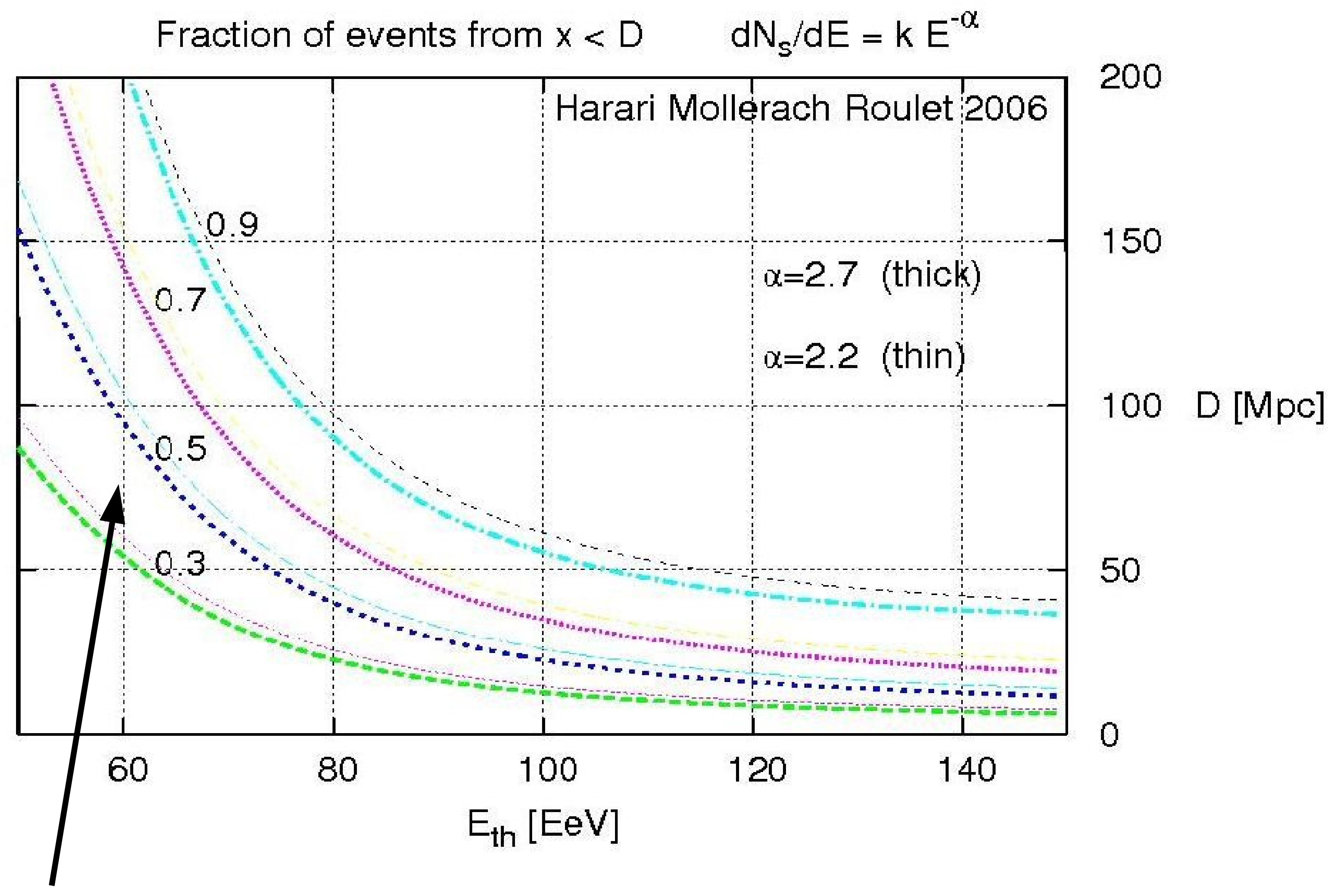
What happened thereafter ?

From 31 August 2007 until 31 December 2009:
Auger has 42 events with E > 55 EeV (new calibration)
and 12 are within 3.1 deg of an AGN closer than 75 Mpc

Fraction correlating (after 5/2006)



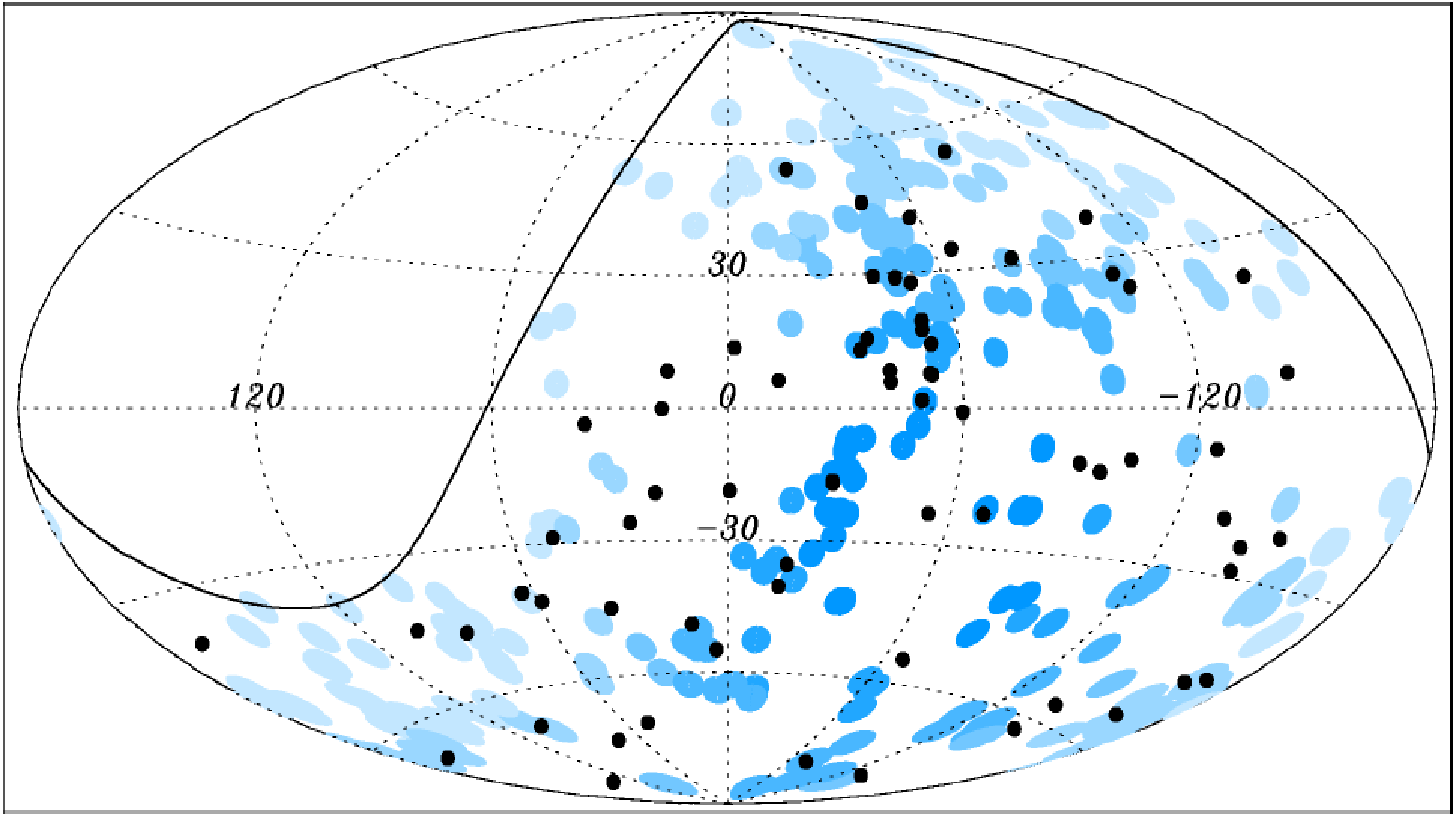
(from the 9 new events which have $|b_G| < 10$ deg, none correlate)



about 40% are expected to come from within 75 Mpc for E > 60 EeV

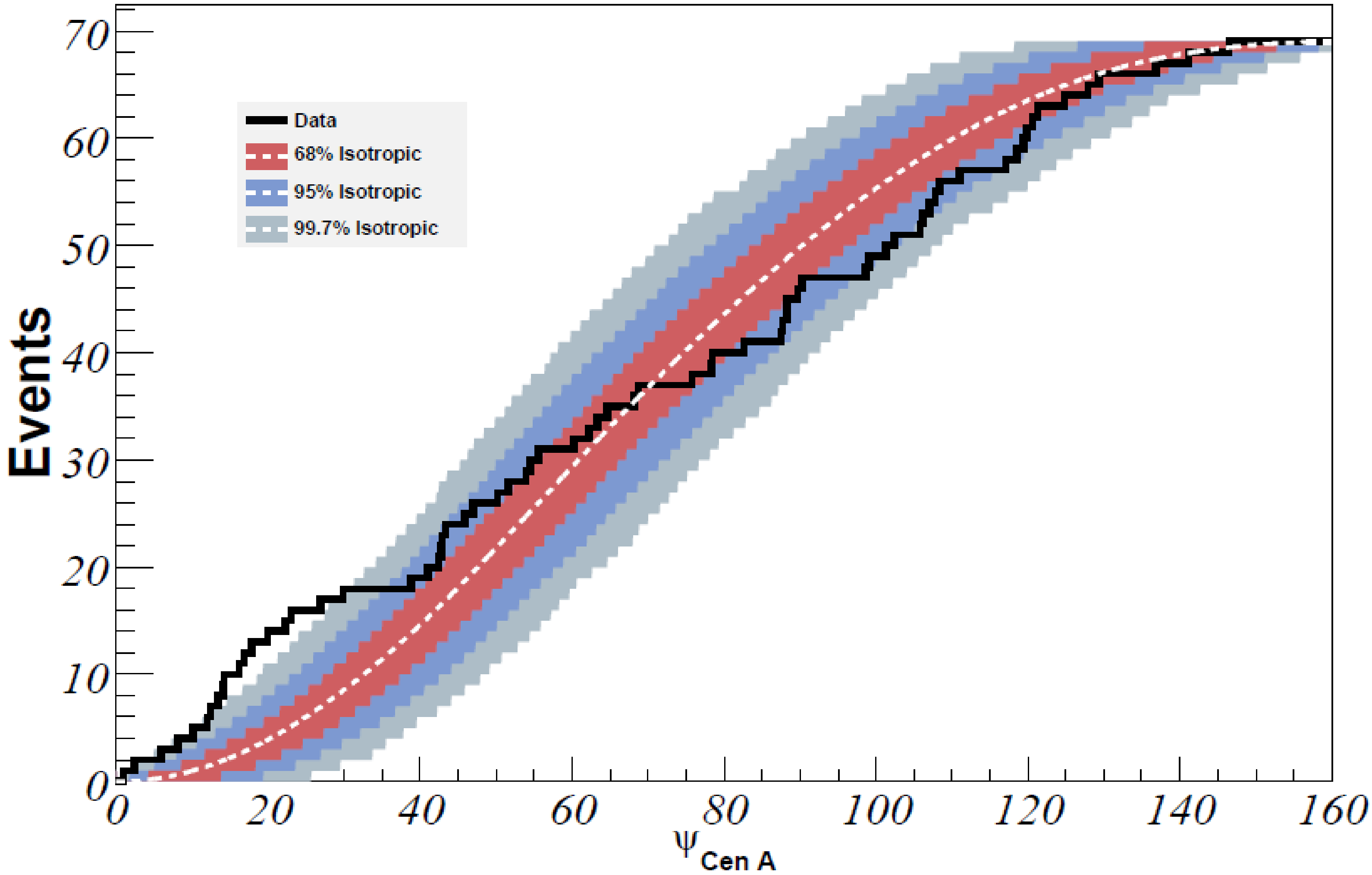
(AUGER arXiv1009.1855)

(in total, 29 out of 69 are in correlation within 3 deg of AGNs within 75 Mpc, while ~14.5 expected if isotropic)



69 events with E > 55 EeV

Excess around Centaurus A: closest AGN

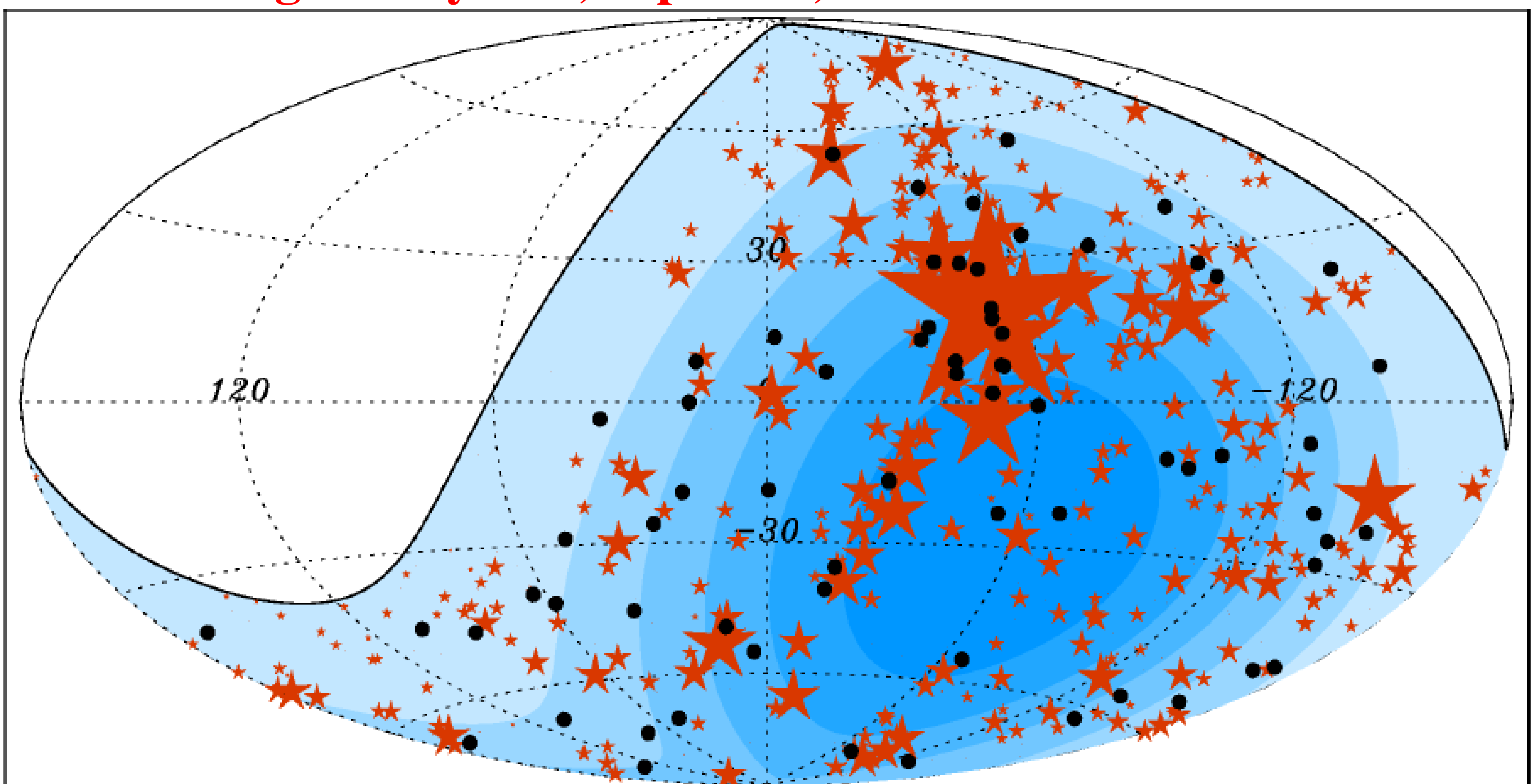


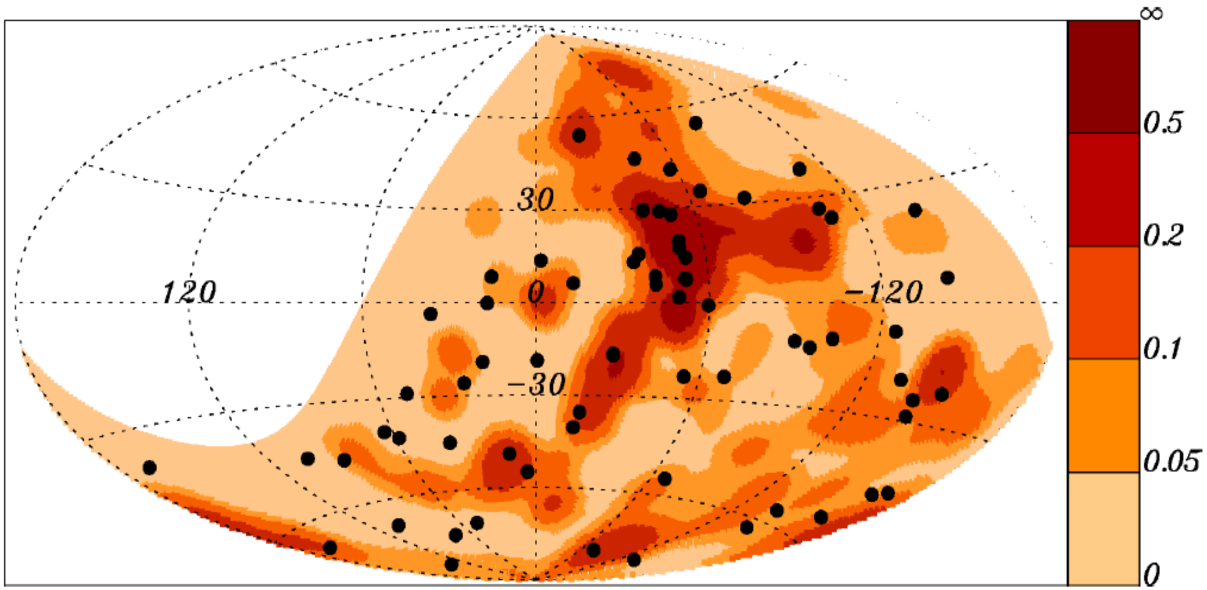
13 events within 18 deg of CenA, while 3.2 expected for isotropy

AGNs may be just tracers of nearby large scale structure which may host other CR sources (GRBs, colliding Galaxies, ...).

Or UHECR sources may be a particular AGN subclass

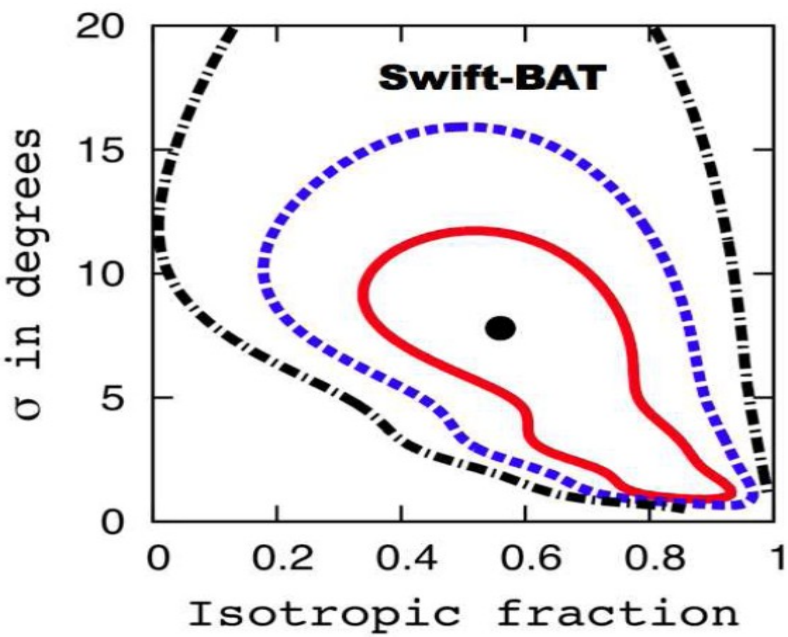
Example: AGNs from SWIFT X-ray catalog, weighted by flux, exposure, GZK attenuation

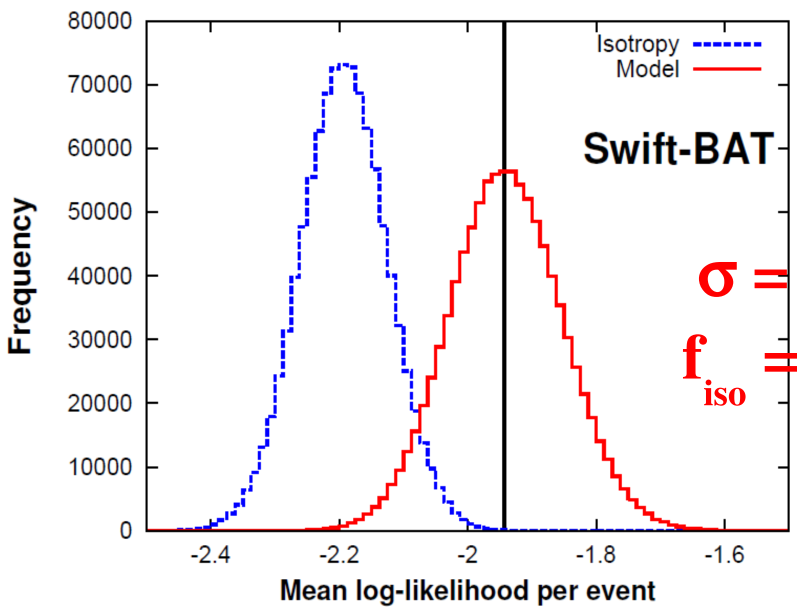




Smoothed SWIFT map in σ = 5 deg

Scan of likelihood vs. smoothing angle and added isotropic fraction





$\sigma = 7.8^o$

$f_{iso} = 0.56$

Best fit to data requires adding ~ 60% isotropic fraction:

Due to sources beyond 100 Mpc? Or to heavy composition contribution?

CONCLUSIONS

Evidence that CRs are attenuated by GZK effect

CRs arriving to Earth with $E > 6x10^{19}$ eV are correlated with the distribution of nearby extragalactic matter

Sources preferentially in regions at less than ~ 100 Mpc in which Active Galactic Nuclei are present
(if other than AGN, sources must have a similar spatial distribution)

Interesting excess in Centaurus A region

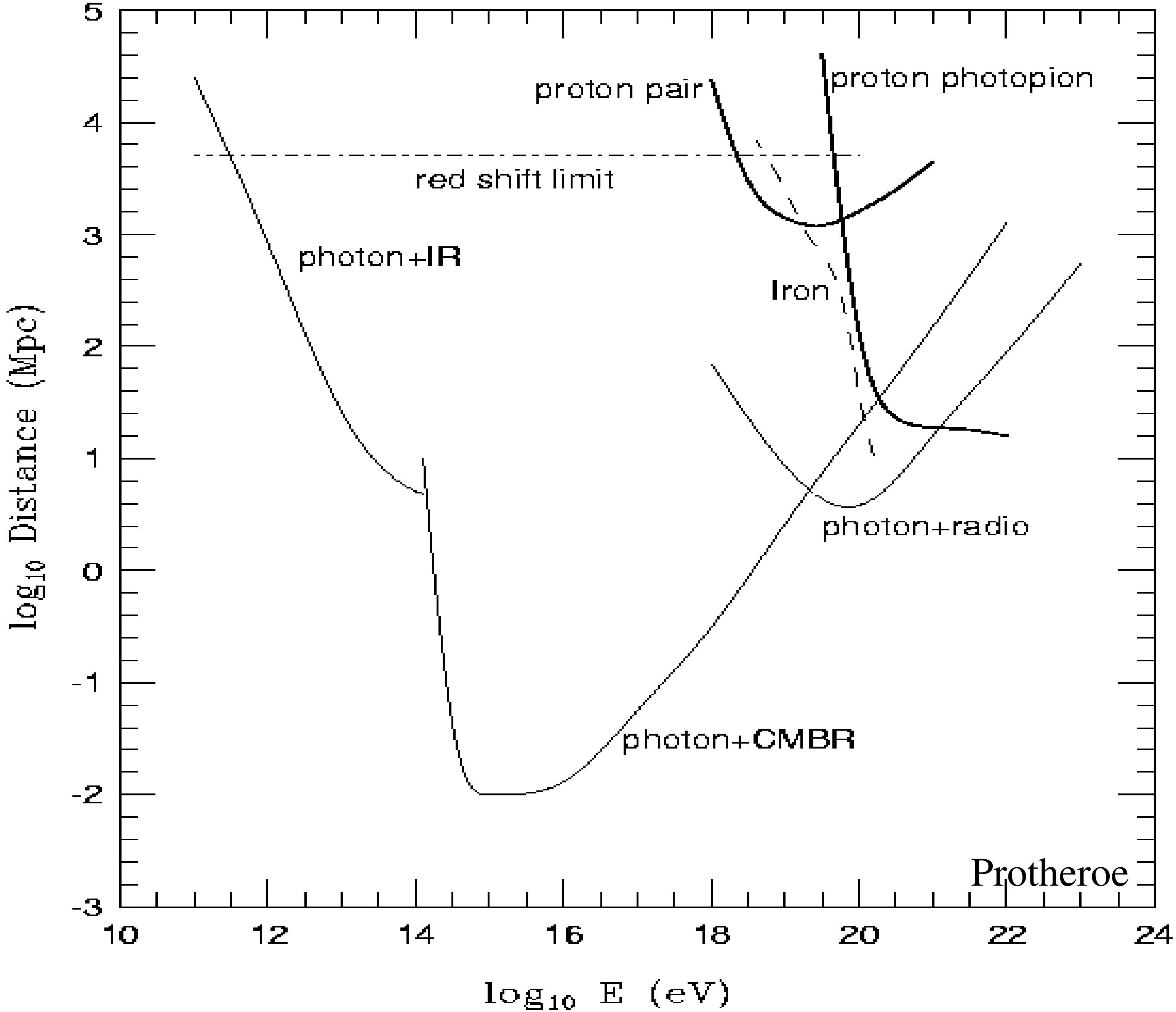
Puzzling results on X_{max} (composition or cross sections?)

Photon fraction small (< 2% above 10 EeV) → ~~top-down~~

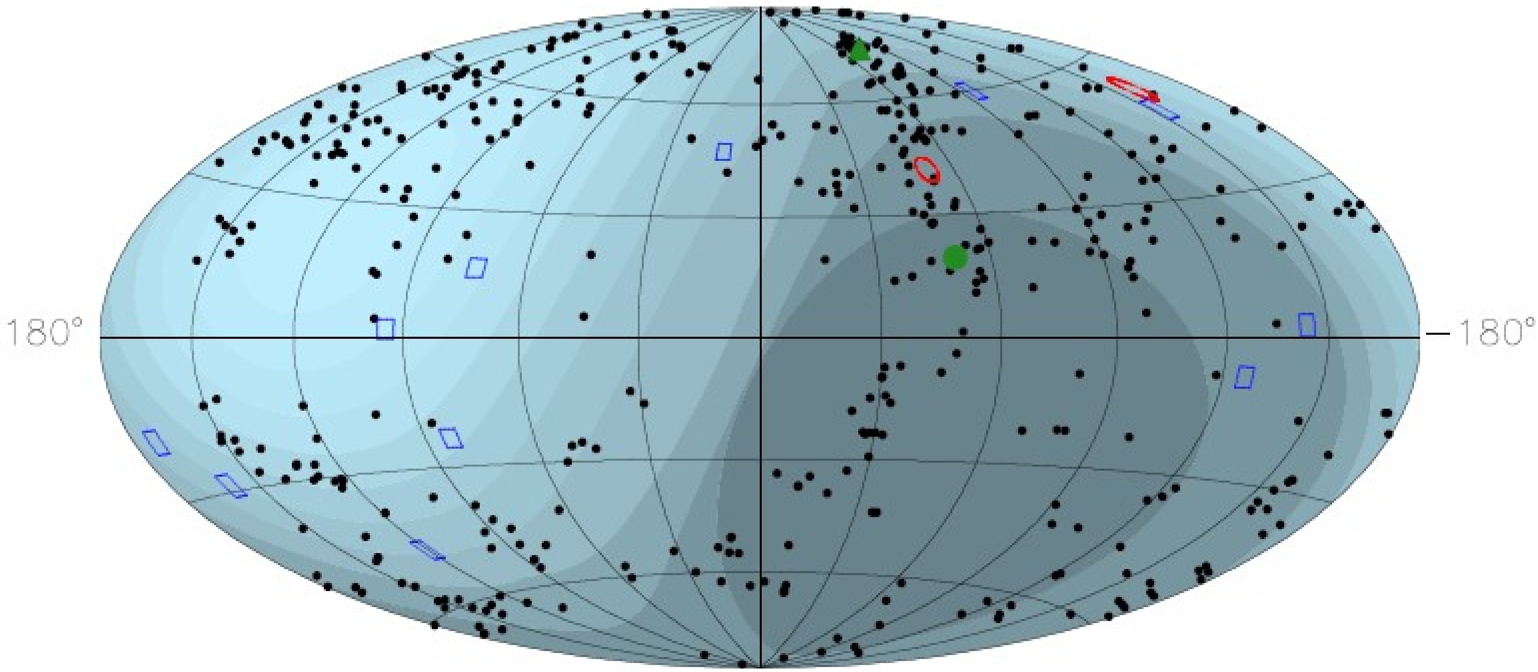
No neutrinos yet

Unambiguous identification of sources would be next breakthrough

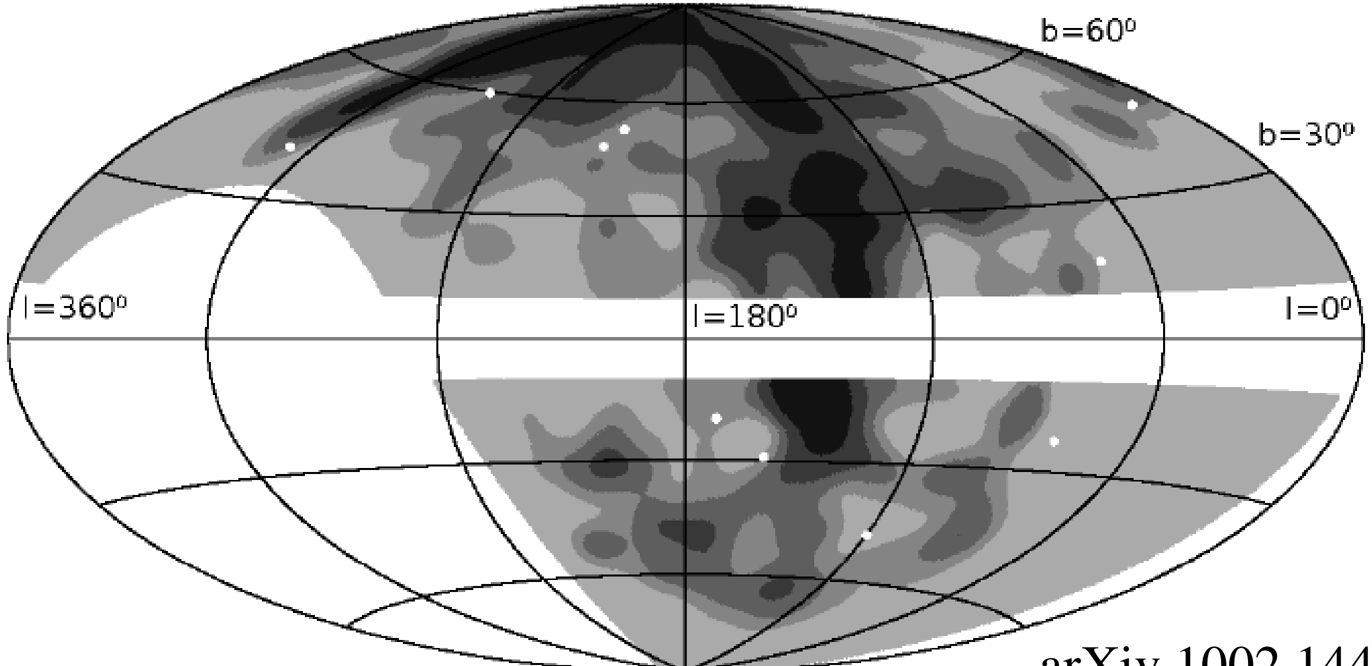
Attenuation lengths vs E



HiRes (E > 55 ?)



HiRes vs 2MASS



arXiv 1002.1444