# WHERE DO ULTRA-HIGH ENERGY COSMIC RAY RESULTS LEAD US ?

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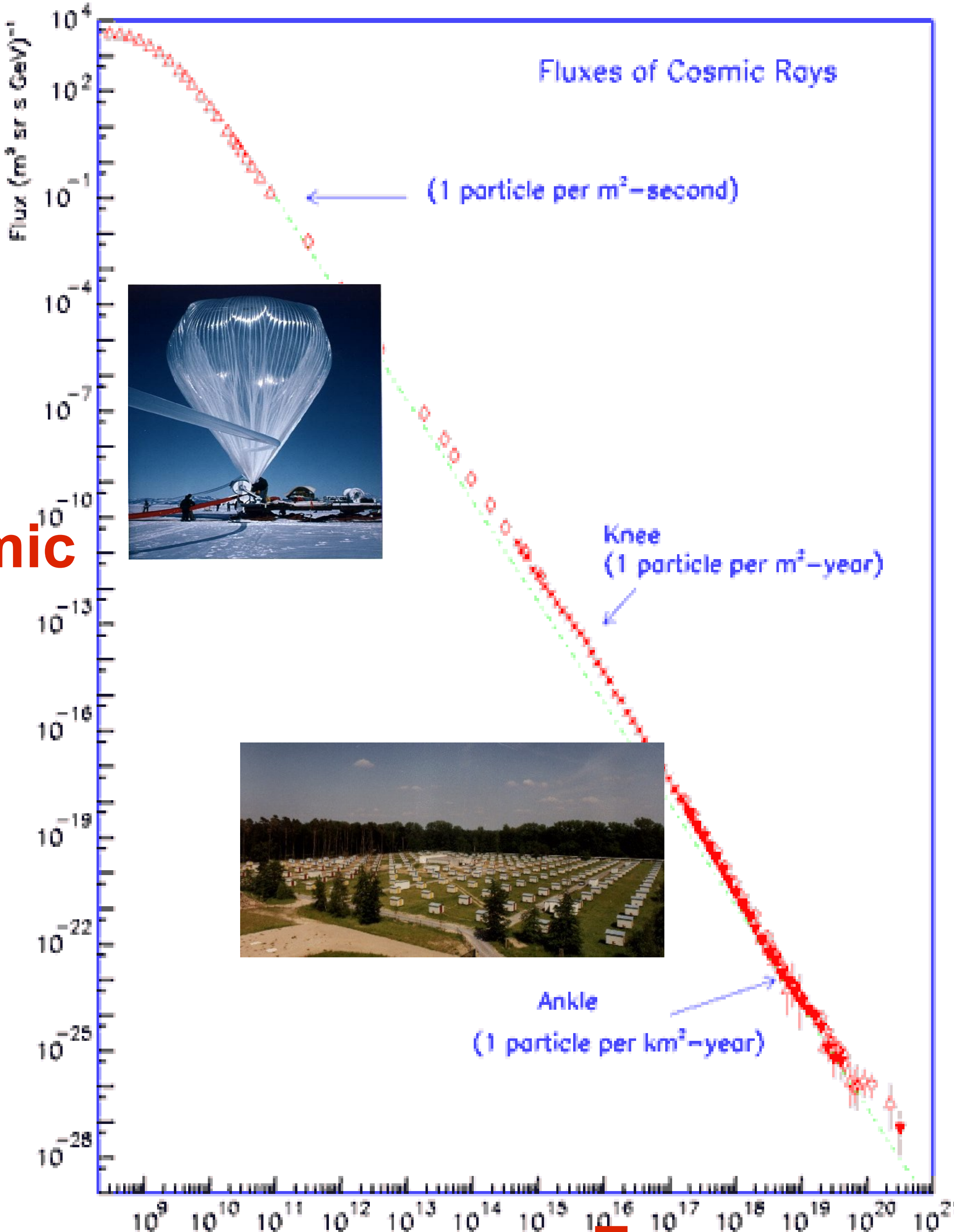
Win 2013, Natal

## Main cosmic ray observables:

Spectrum, composition and anisotropies

## Main questions:

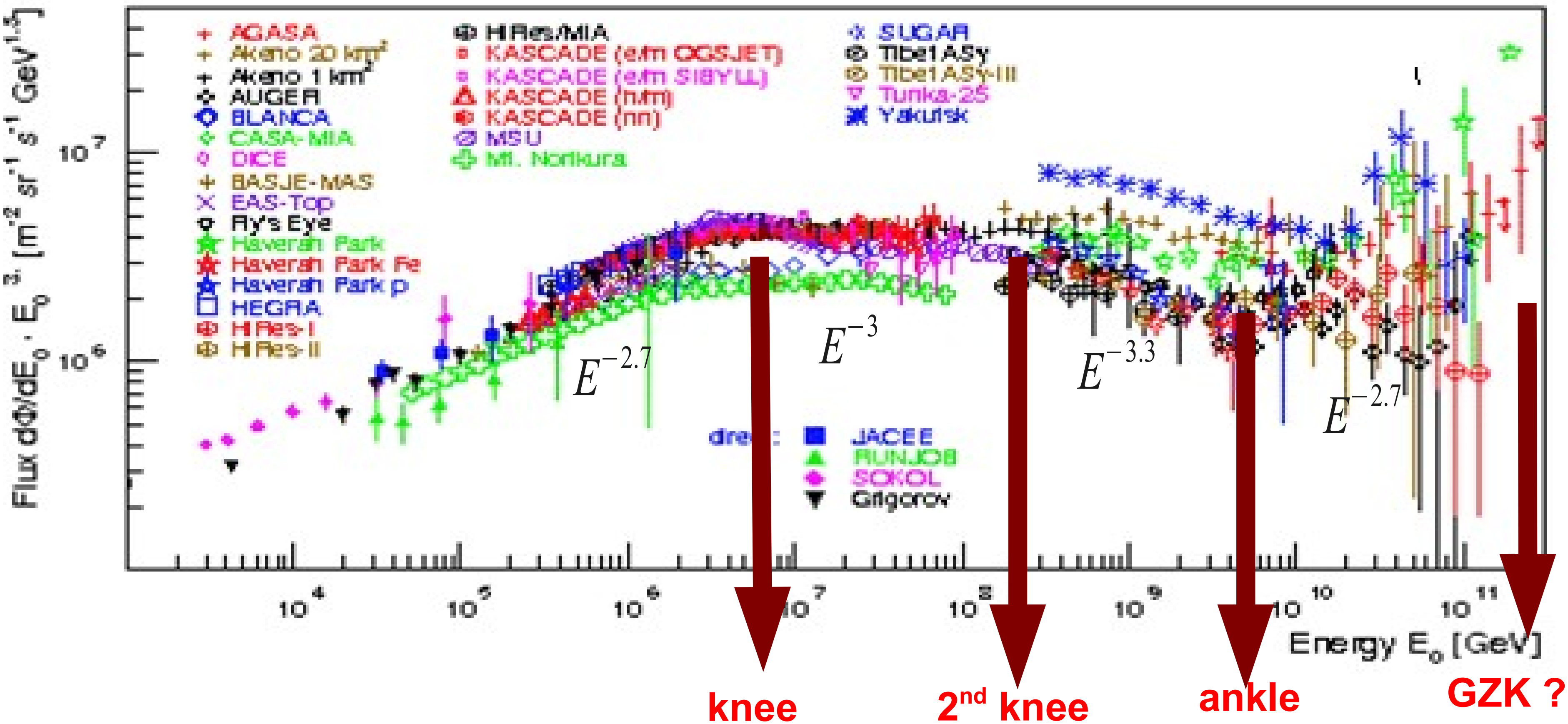
What are they
Where and how are they accelerated
What produces the changes in spectrum/composition
How do they propagate
What are the effects of galactic and X-galactic B fields
How are the hadronic interactions at the highest E
Are neutrinos/photons produced
….



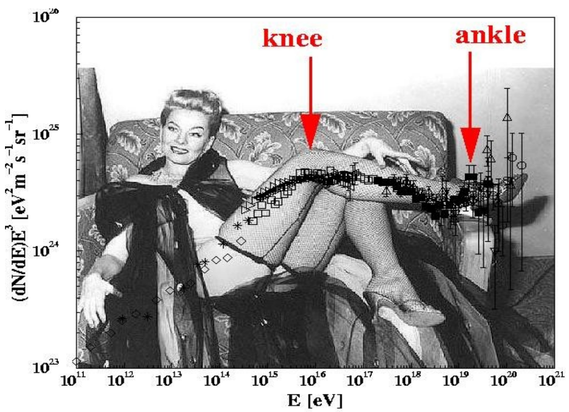

cosmic ray flux

Energy

## $E^3$ x FLUX

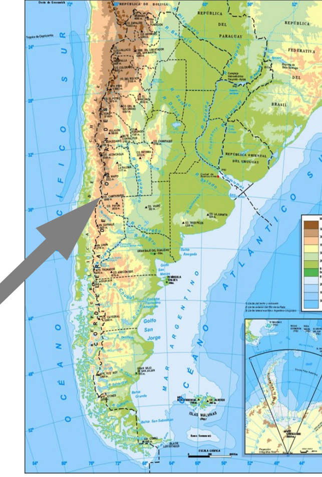


Flux dΦ/dE$_0$ · E$_0$$^3$ [m$^{-2}$ sr$^{-1}$ s$^{-1}$ GeV$^{1.5}$]
AGASA
Akeno 20 km²
Akeno 1 km²
AUGER
BLANCA
CASA-MIA
DICE
BASJE-MAS
EAS-Top
Fly's Eye
Haverah Park
Haverah Park Fe
Haverah Park p
HEGRA
HiRes-I
HiRes-II
HiRes/MIA
KASCADE (e/m QGSJET)
KASCADE (e/m SIBYLL)
KASCADE (h/m)
KASCADE (nn)
MSU
Mt. Norikura
SUGAR
Tibet ASγ
Tibet ASγ-III
Tunka-25
Yakutsk
JACEE
RUNJOB
SOKOL
Grigorov
$E^{-2.7}$
$E^{-3}$
$E^{-3.3}$
$E^{-2.7}$
Energy E$_0$ [GeV]
knee
2nd knee
ankle
GZK ?

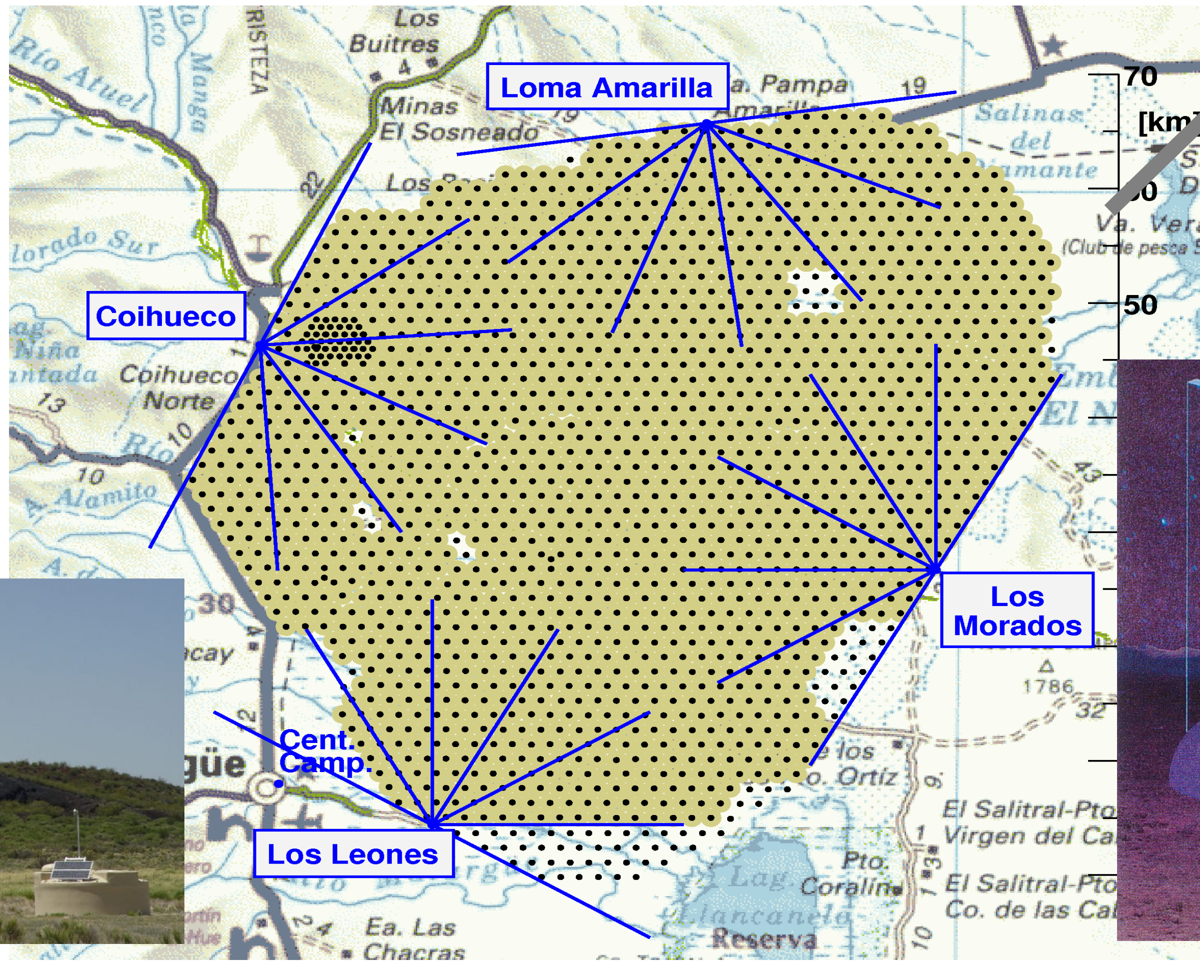



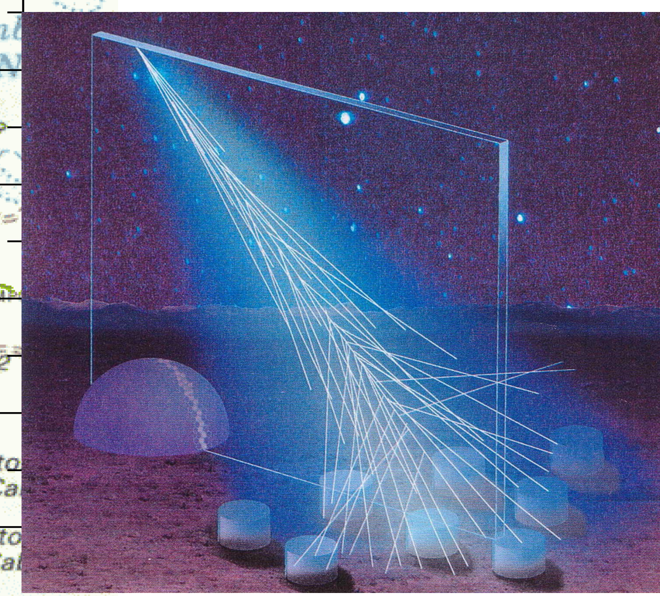
knee
ankle
(dN/dE)E$^3$ [eV$^2$ m$^{-2}$ s$^{-1}$ sr$^{-1}$]
E [eV]

# 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



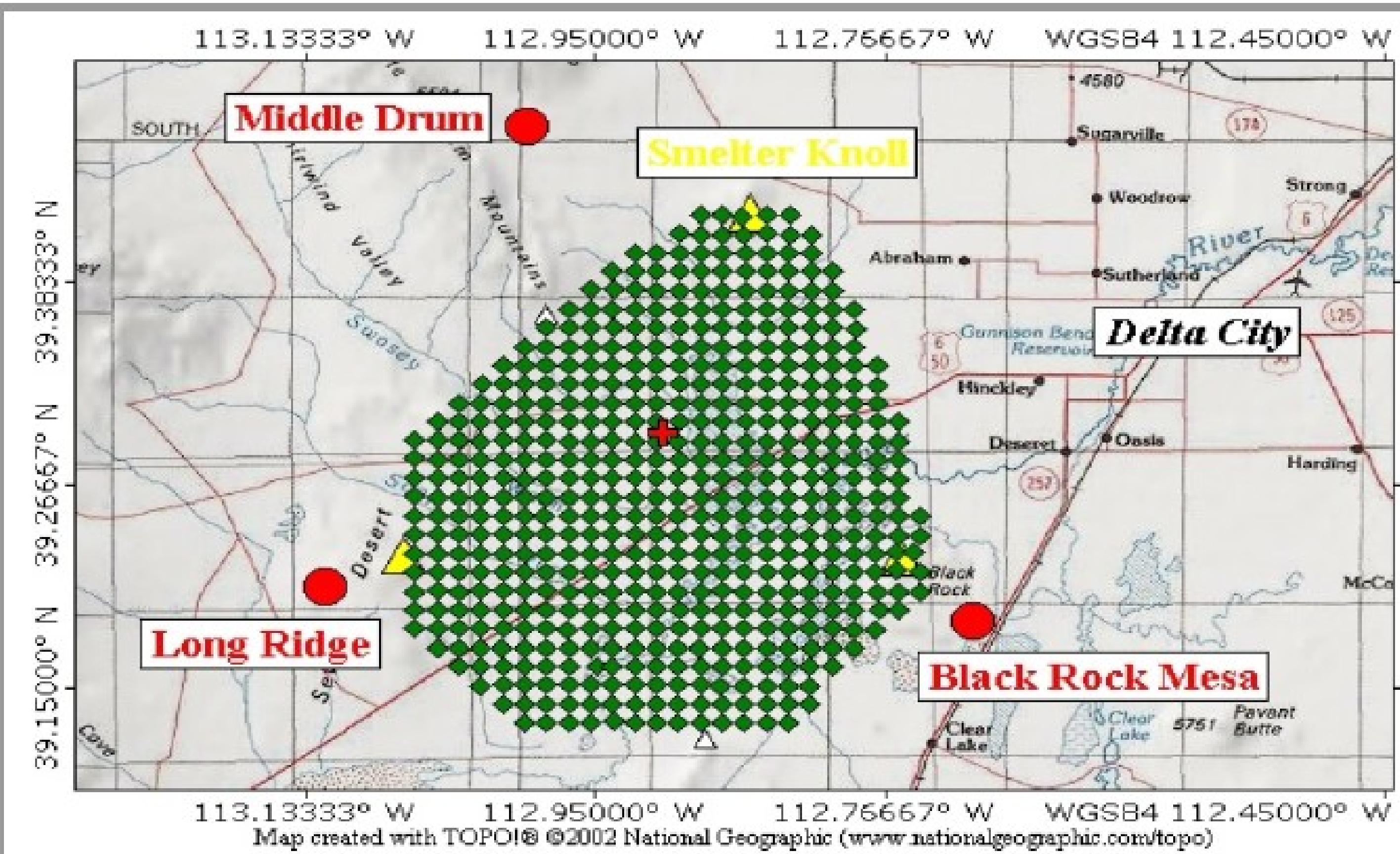



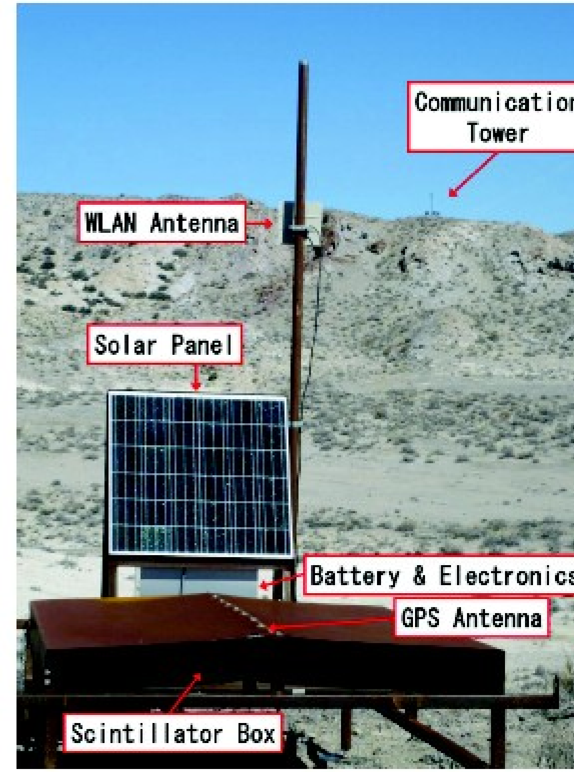
**1660 detectors instrumenting 3000 km$^2$ and 27 telescopes**

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

**TELESCOPE ARRAY in Utah**

Since 2008




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

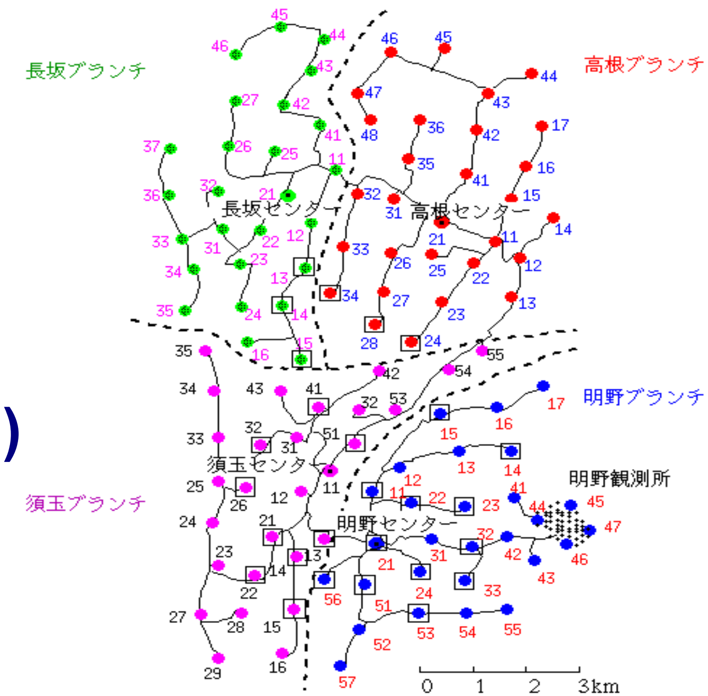
1.2 km spacing

Mostly sensitive to the em component

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

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

# Previous experiments:




**AGASA:** (Akeno, Japan 1990-2004)

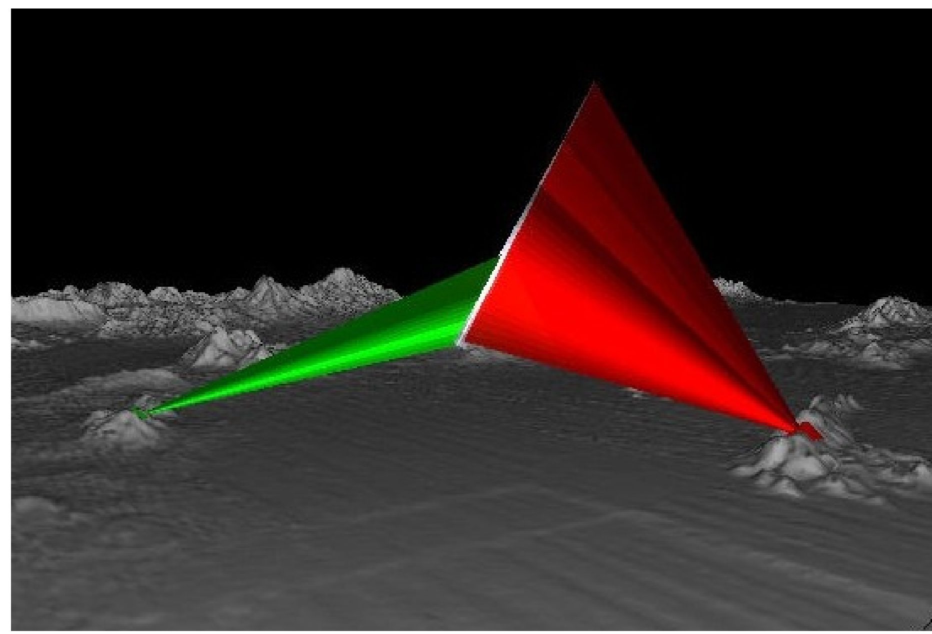
Area: 100 km$^2$

111 Scintillators ( $e^+e^-$ ) and

27 shielded proportional counters (muons)

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

**HiRes** (1997-2006)

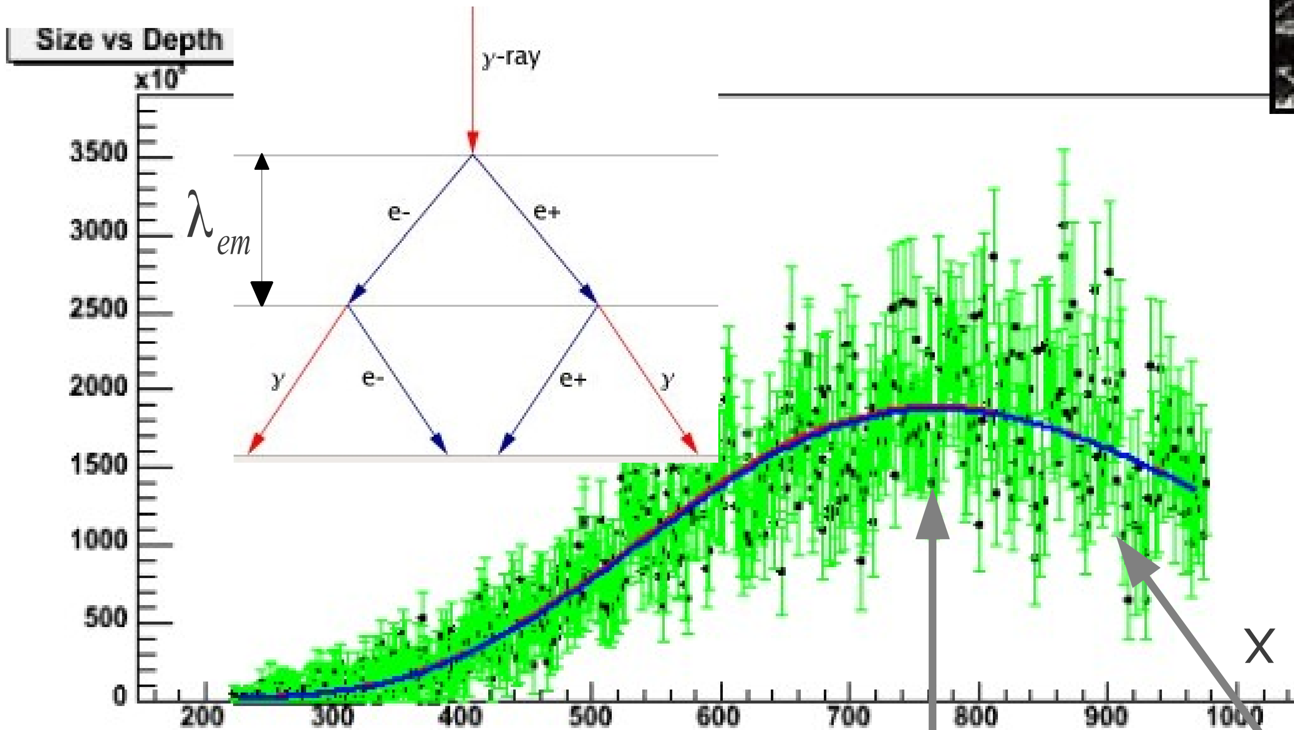


Fluorescence telescopes

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

**Some basics on air showers:**

**ELECTROMAGNETIC SHOWERS ( $e^+$ , $e^-$ , $\gamma$ )**




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

**Ionisation losses dominate**

**N grows exponentially**

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

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

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

# 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**

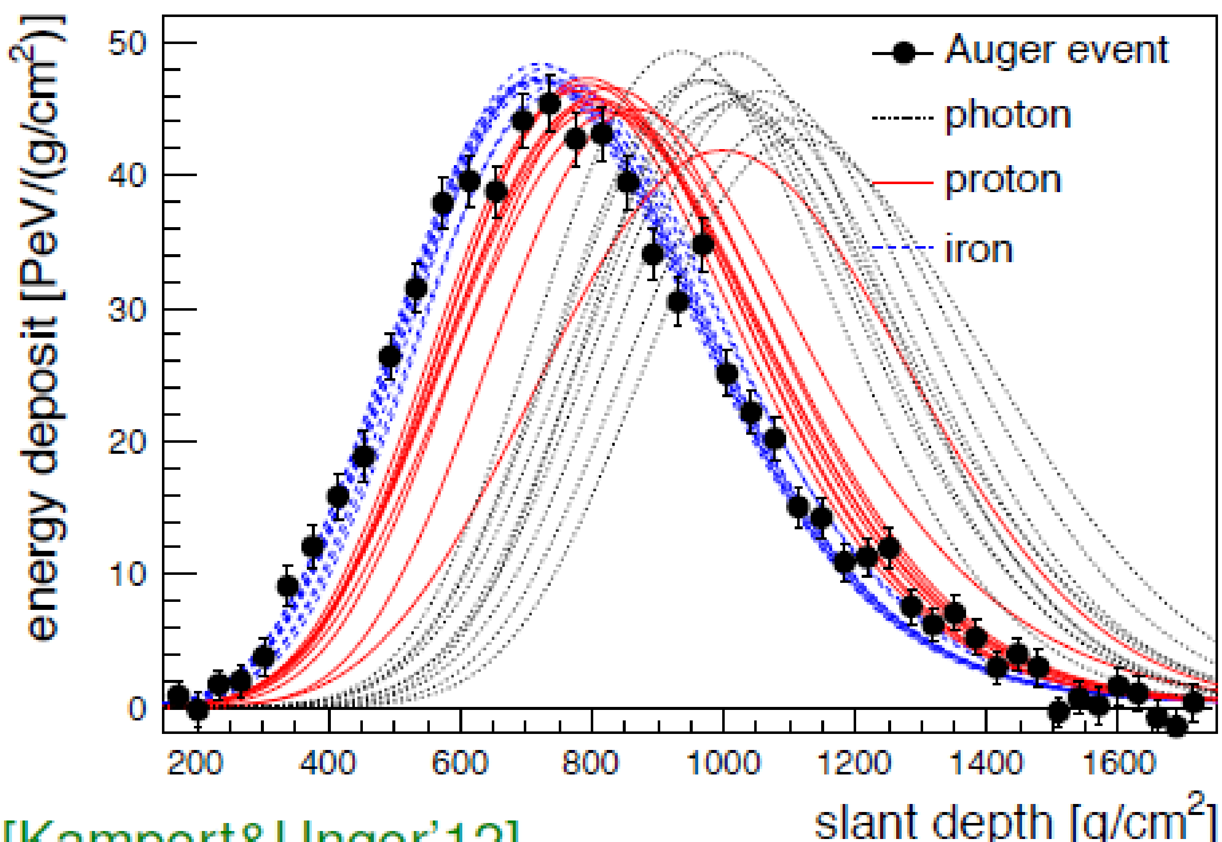
$$\left( typically \;\; E_{EM} \simeq 0.9\, E_{tot} \;\; while \;\; E_{\nu} + E_{\mu} \simeq 0.1\, E_{tot} \right)$$

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

$$\lambda_I \sim \sigma^{-1}_{p-air}$$

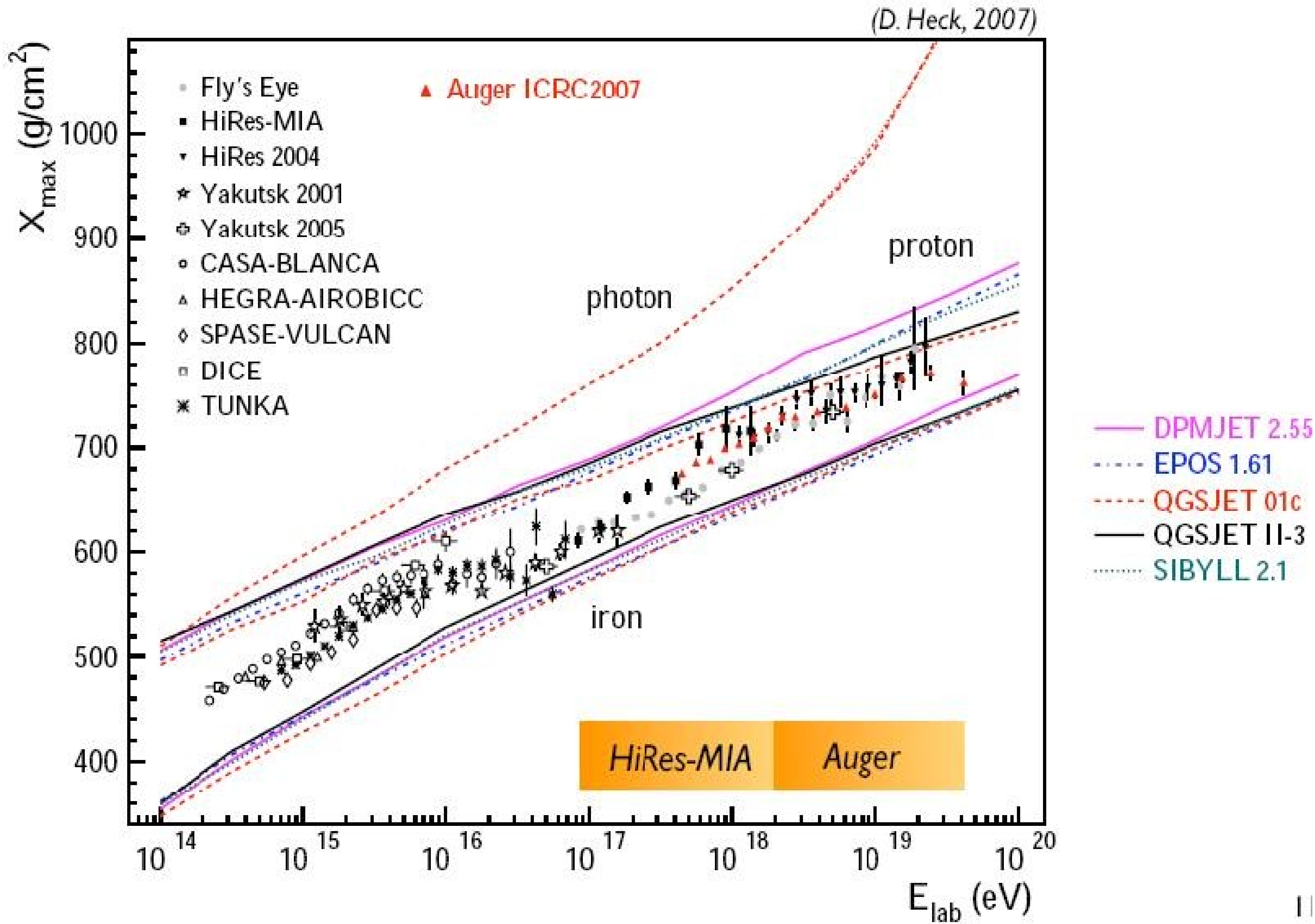
**Nuclei behave as** $A$ **nucleons with** $E_n = E_0 / A$

→ less penetrating, smaller fluctuations



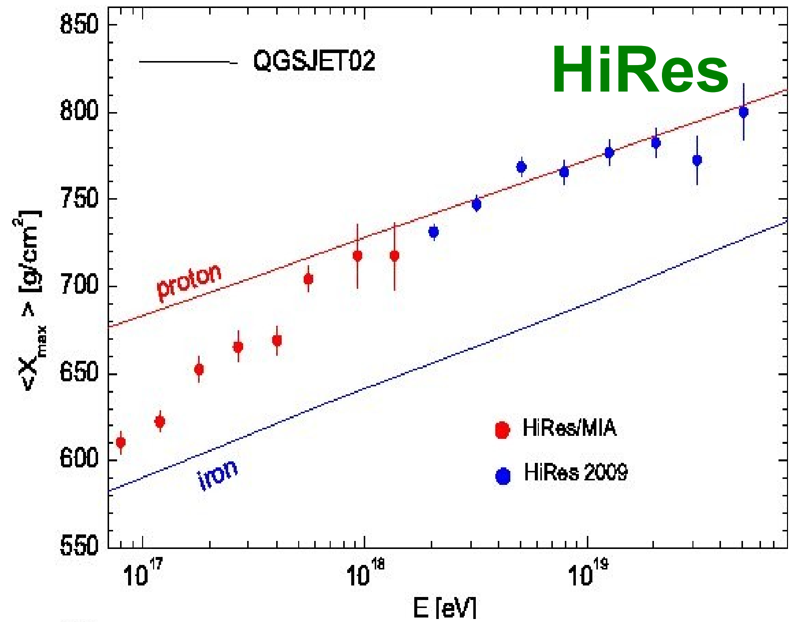

[Kampert&Unger'12]

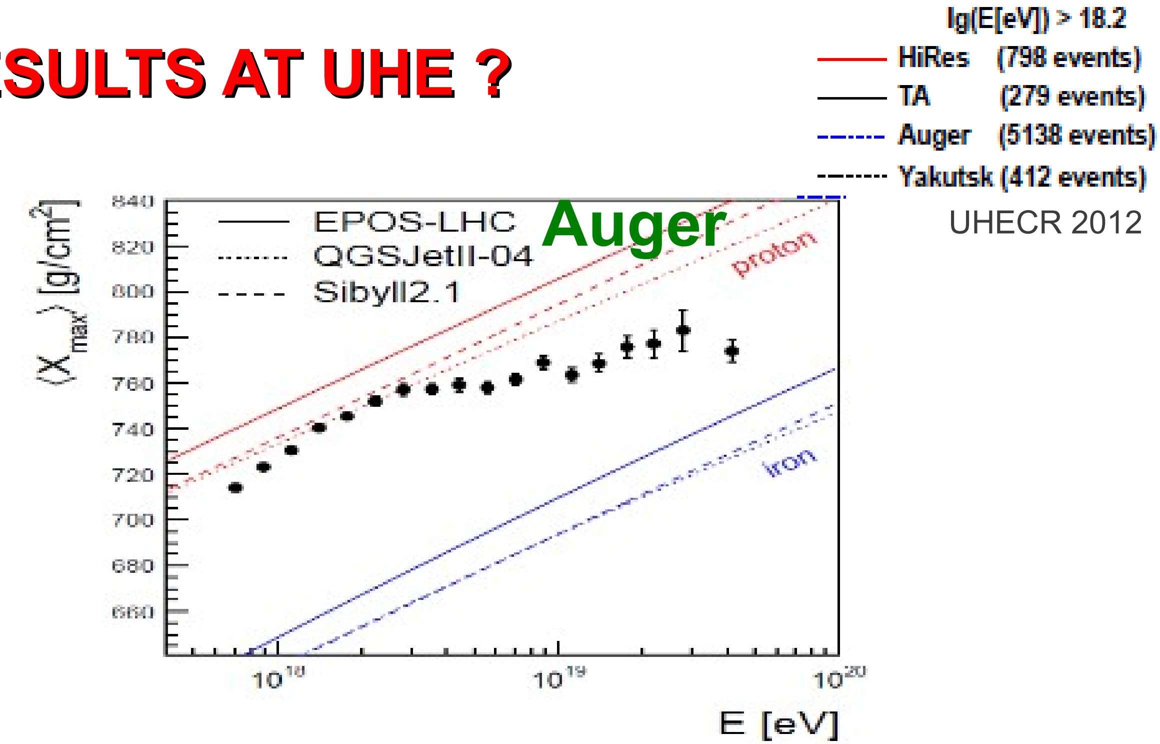
# COMPOSITION FROM $X_{max}$



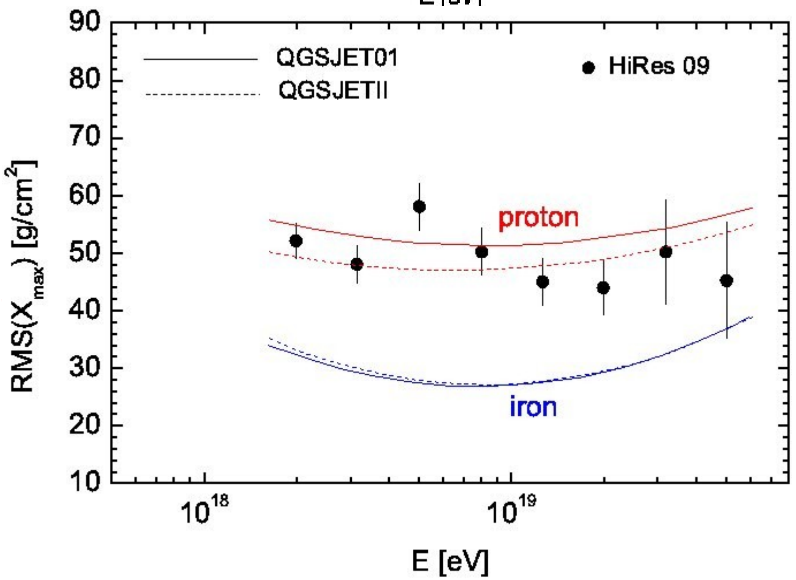
# CONFLICTING RESULTS AT UHE ?

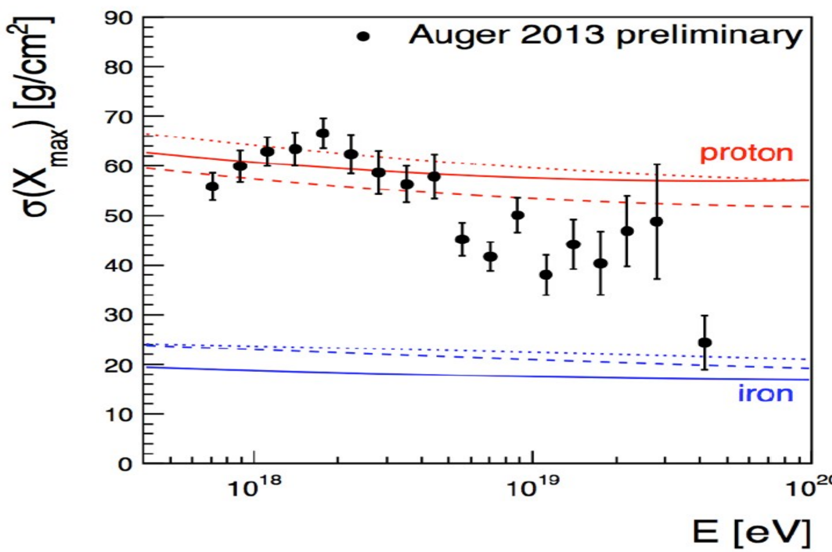
$X_{max}$




RMS



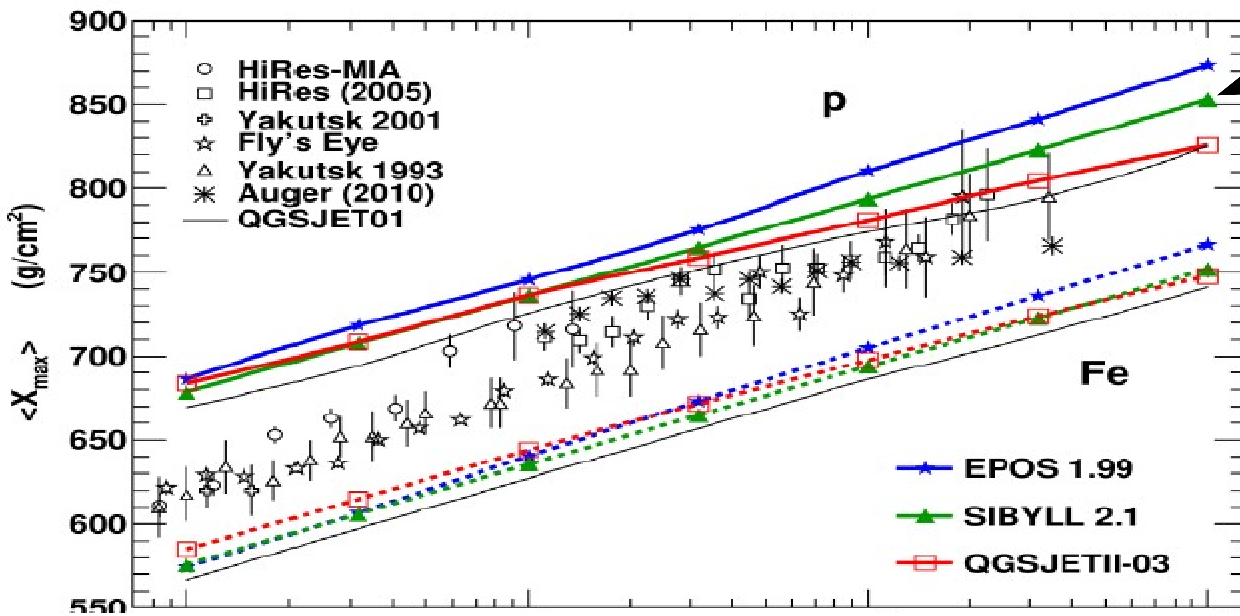




**HiRes: consistent with protons (similarly TA)**

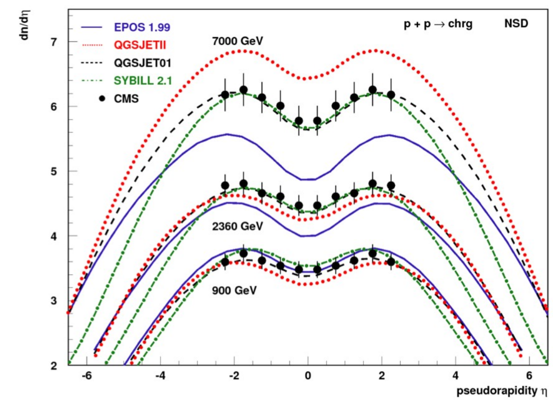
**Auger: transition to heavier above ankle or change in hadronic interactions?**

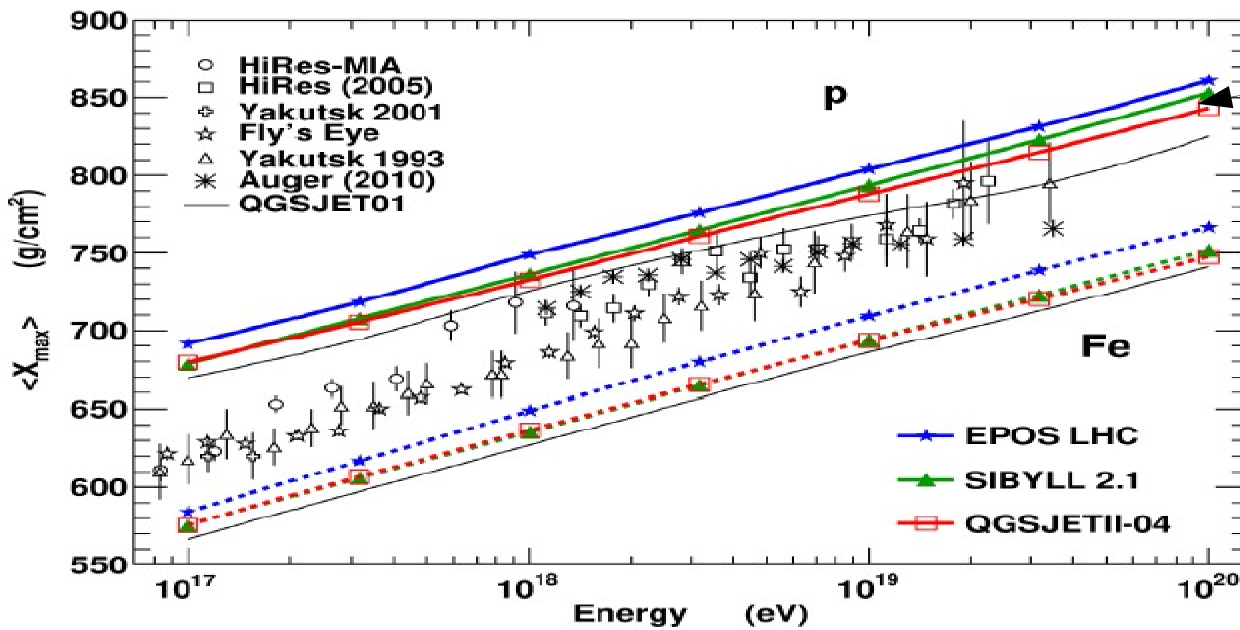
**HiRes & TA: Xmax with detector bias, Auger: cuts to have unbiased Xmax → they should not be plotted together**

# Average Xmax vs E and model predictions for p/Fe




Hadronic models before LHC



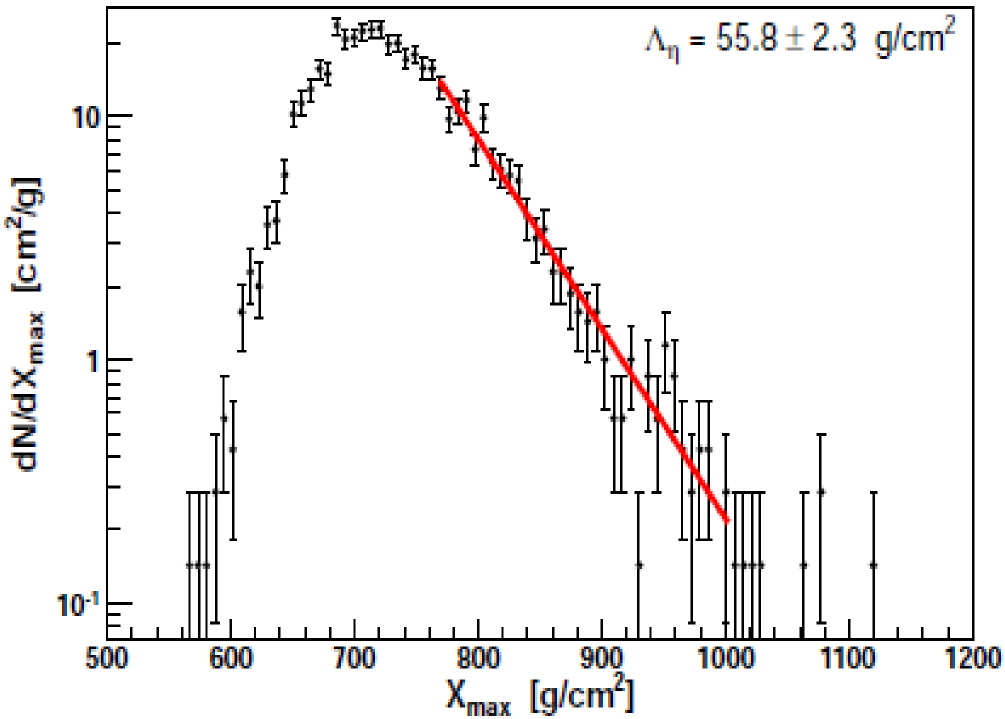

Hadronic models after LHC

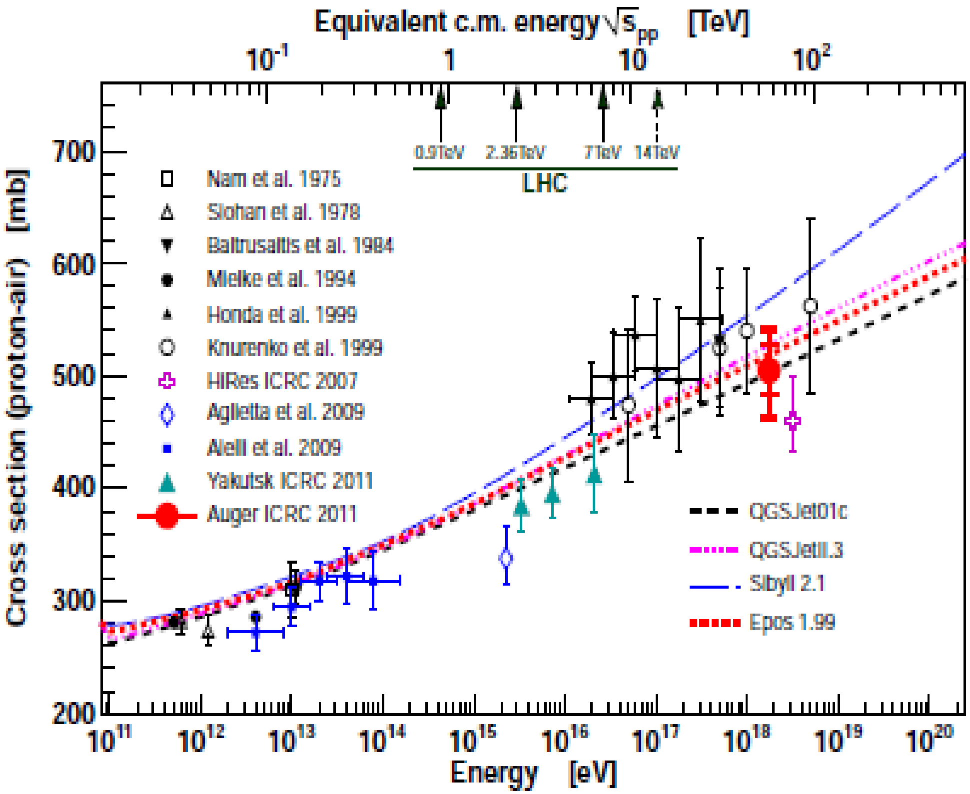
Pierog 2013

(warning: Hires Xmax should actually be in a different plot)

# p-air CROSS SECTION FROM AIR SHOWERS

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



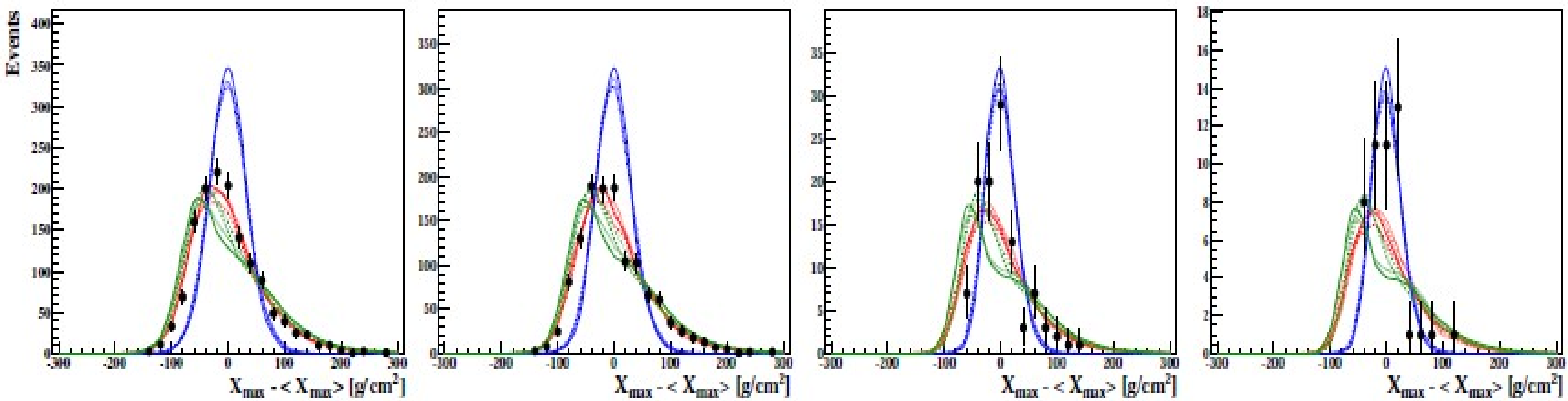




**Inferred p-air cross section looks 'normal'**

# Auger

**Assuming hadronic models valid → can infer composition from Xmax distributions**

**Fe p 50-50**

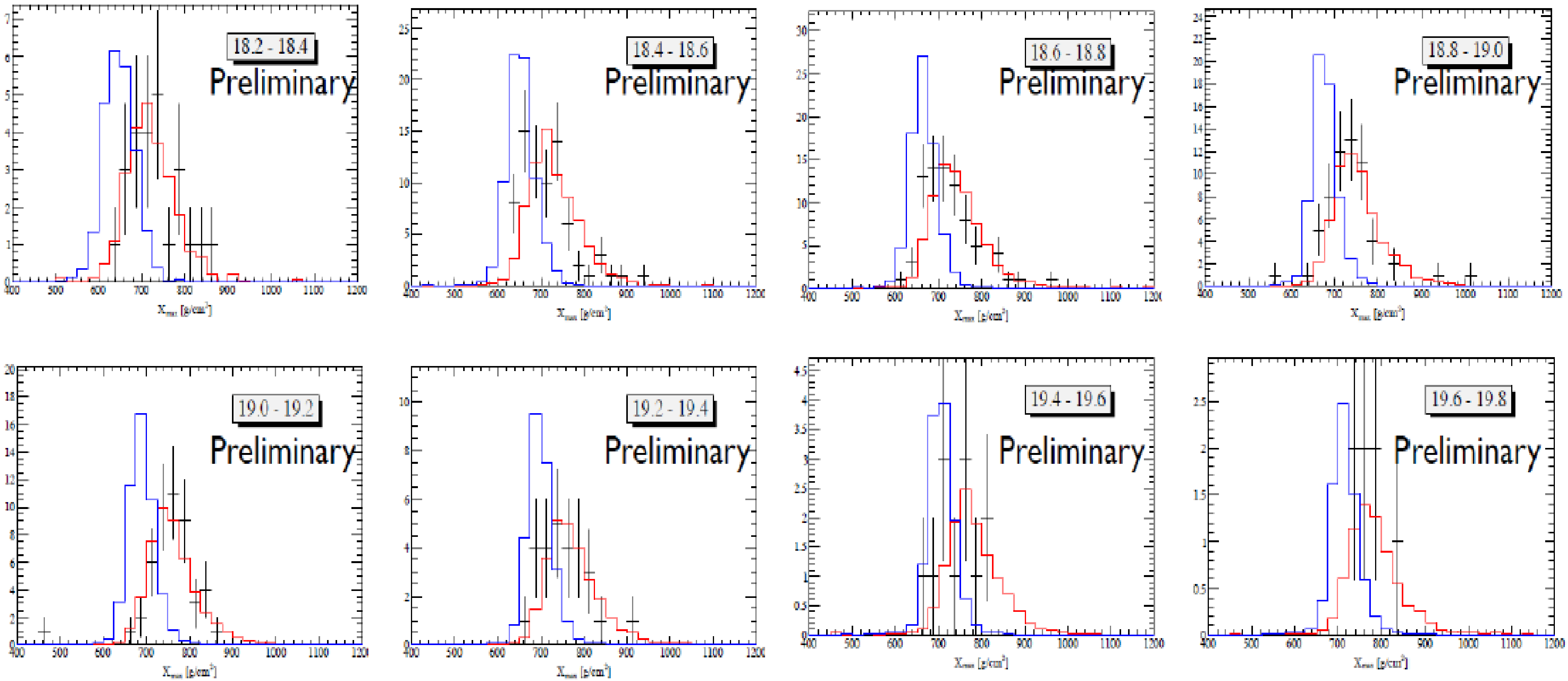



(a) $18.0 < \lg E/\mathrm{eV} < 18.1$ (b) $18.1 < \lg E/\mathrm{eV} < 18.2$ (c) $19.2 < \lg E/\mathrm{eV} < 19.4$ (d) $\lg E/\mathrm{eV} > 19.4$

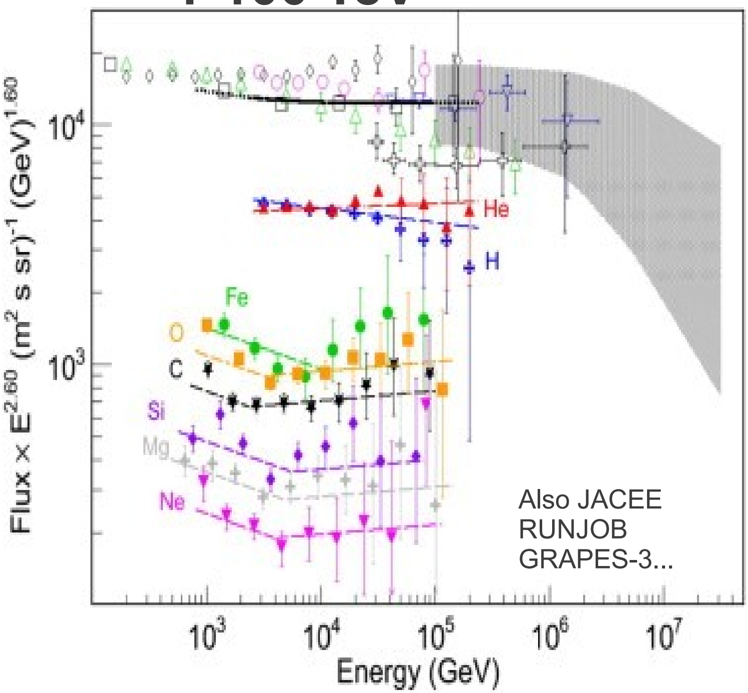
**Suggest transition from light (at EeV) to heavy (at 30 EeV)**

# Telescope Array

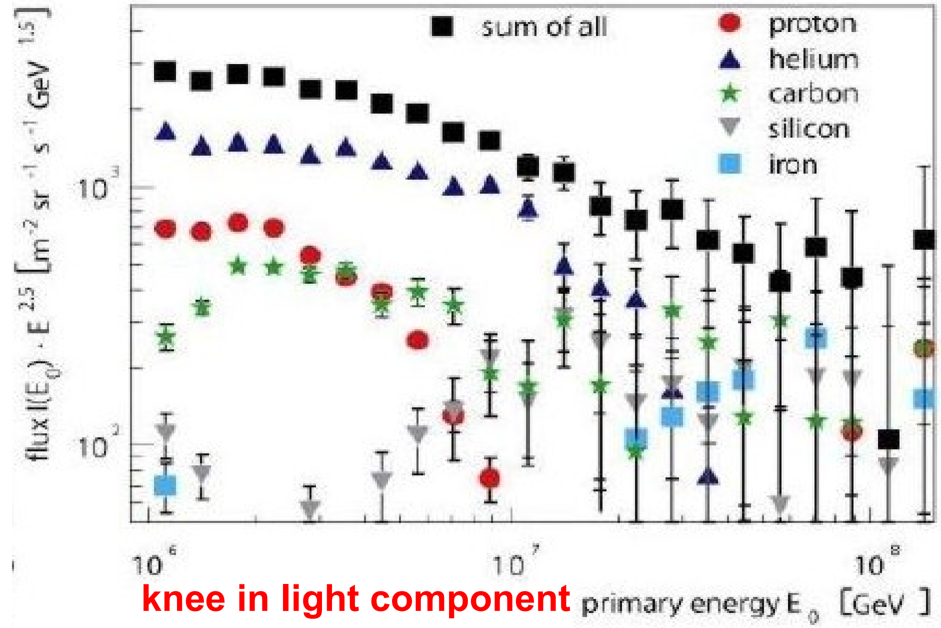
- 5-year data (Nov., 2007 – Nov. 2011)
  - Data: TA
  - Red histogram: QGSJET-II proton model
  - Blue histogram: QGSJET-II iron model



## 1-100 TeV CREAM

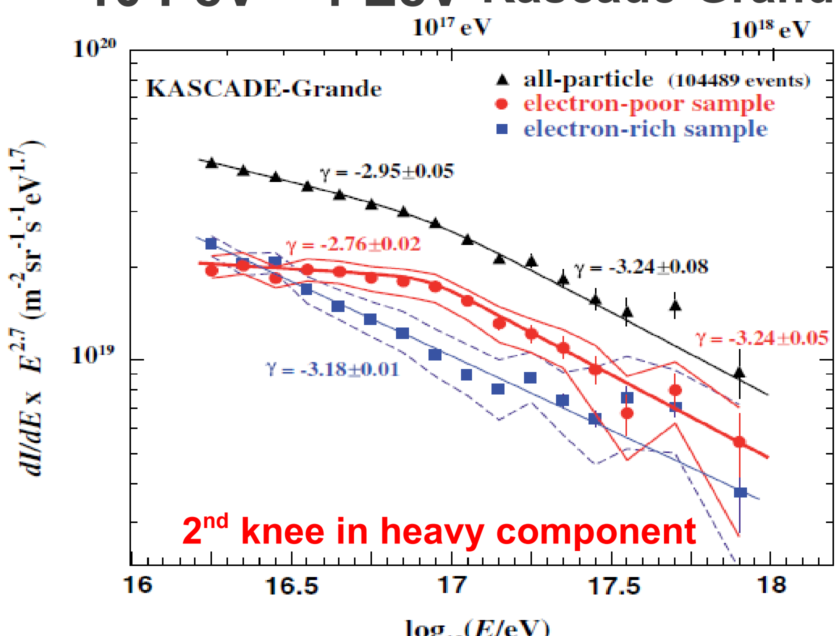



## 1-100 PeV Kascade



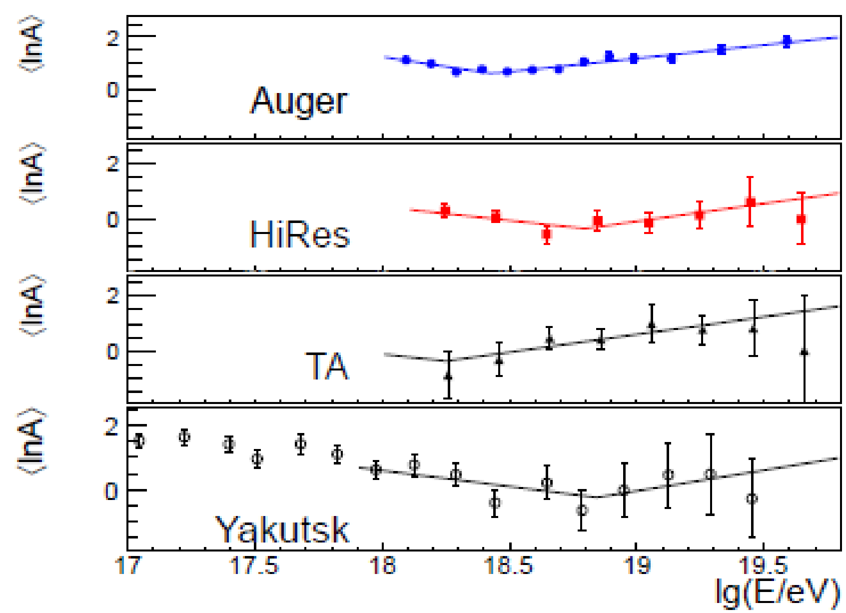

knee in light component

## 10 PeV – 1 EeV Kascade-Grande




Ankle in light component ?

## 1 – 30 EeV

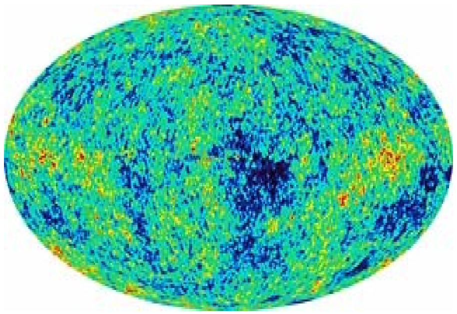


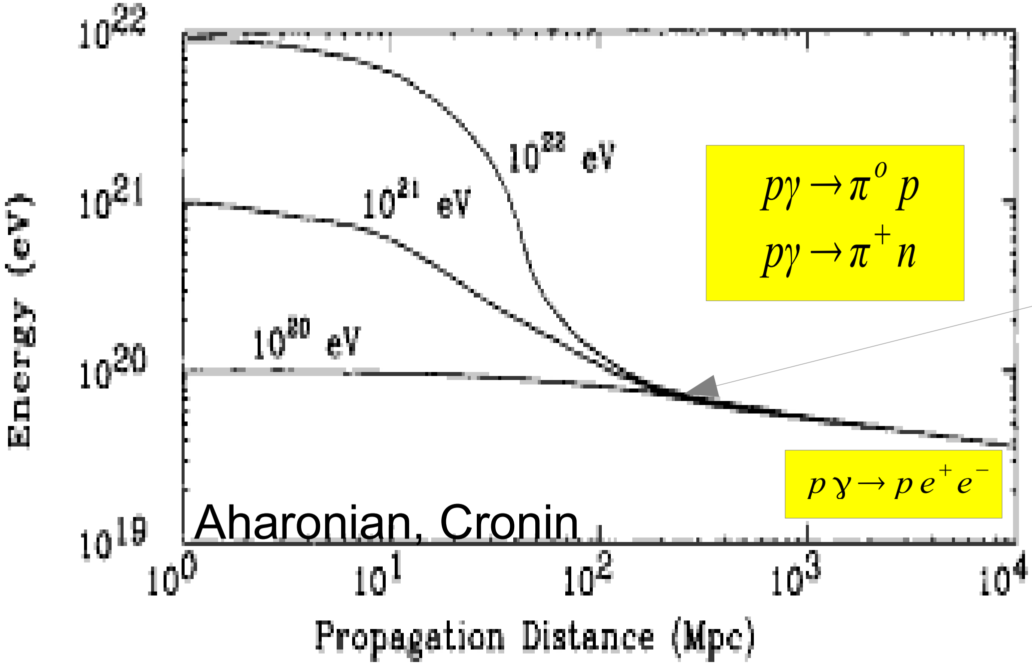

UHECR 2012

Need few more years to see compatibility TA-Auger

# the Greisen-Zatsepin-Kuzmin effect (1966)

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

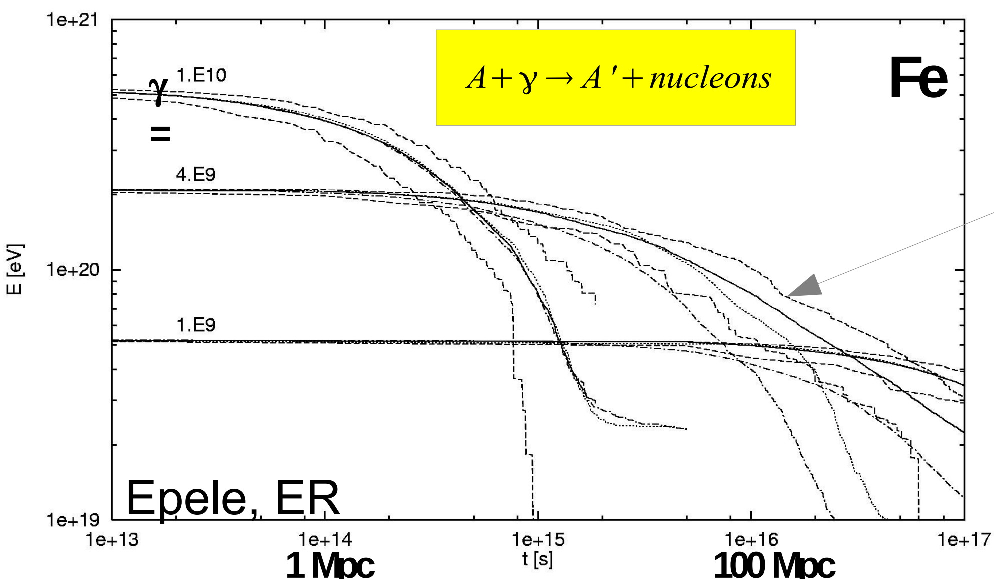





**PROTONS CAN NOT ARRIVE WITH E > $6\times10^{19}$ eV FROM D > 200 Mpc**

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

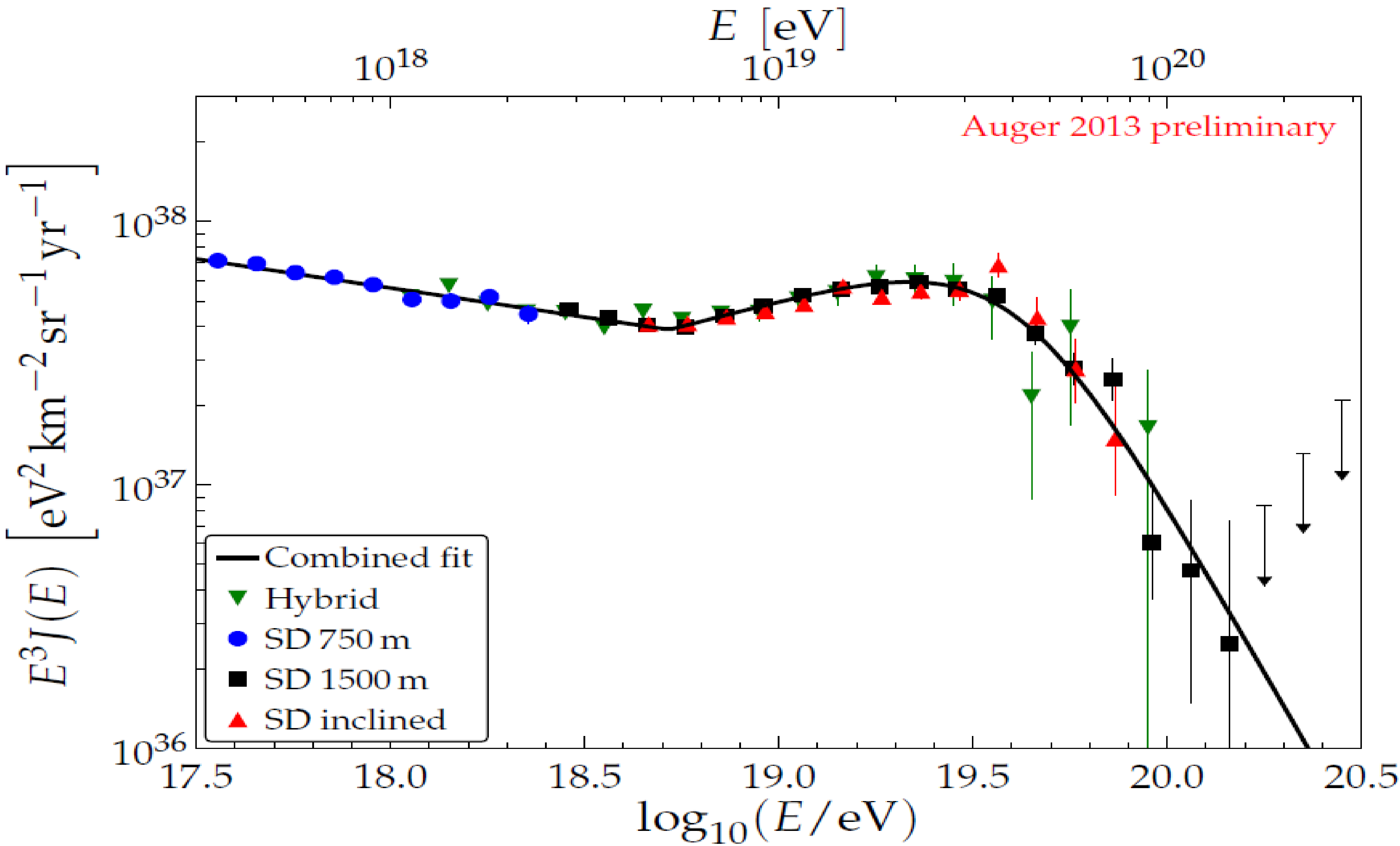
( $\pi^0$ produce GZK photons)




**For Fe nuclei: after ~ 200 Mpc the leading fragment has E < $6\times10^{19}$ eV**

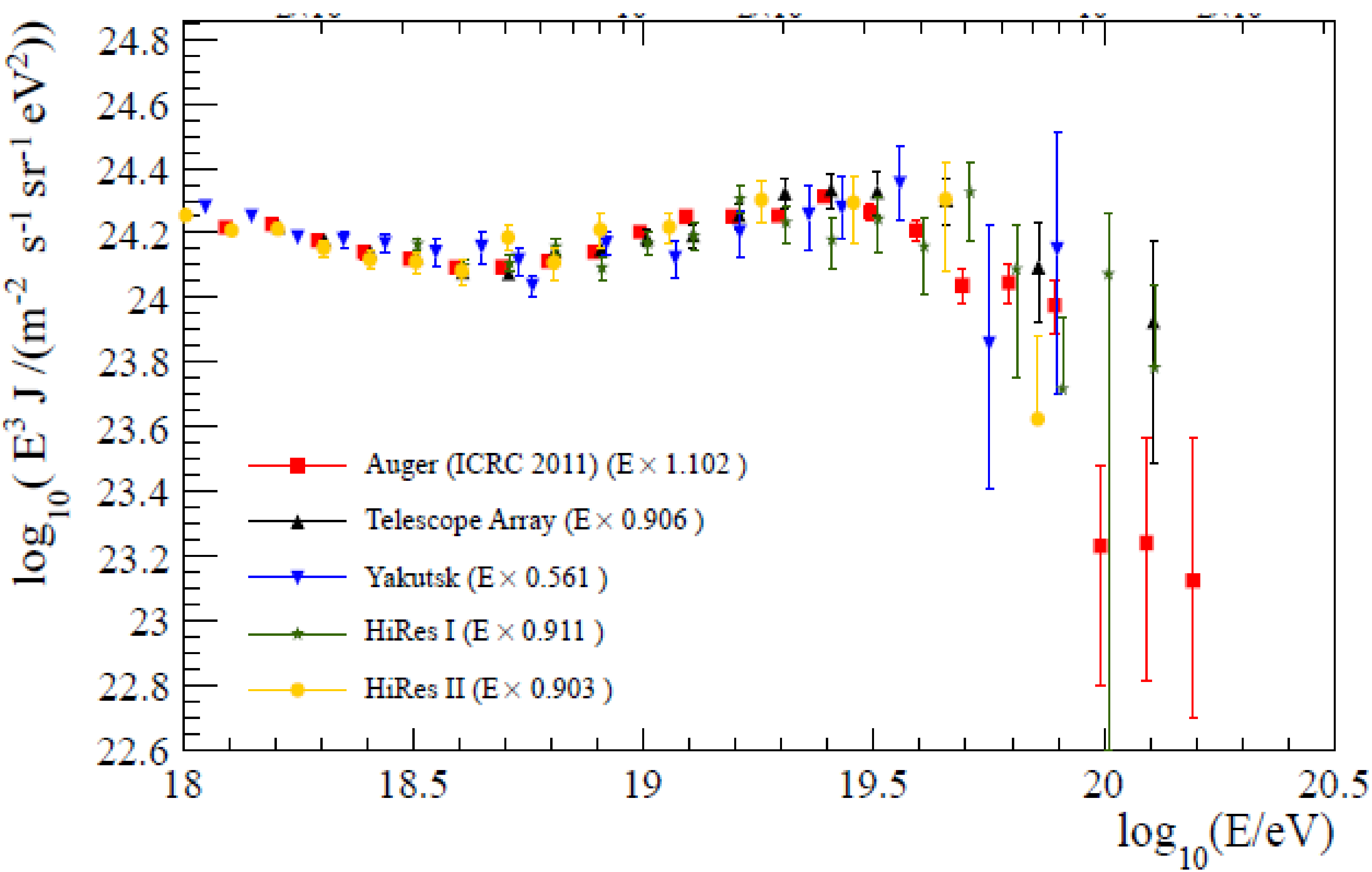
**ligther nuclei get disintegrated also down to lower E**

# AUGER 2013 SPECTRA

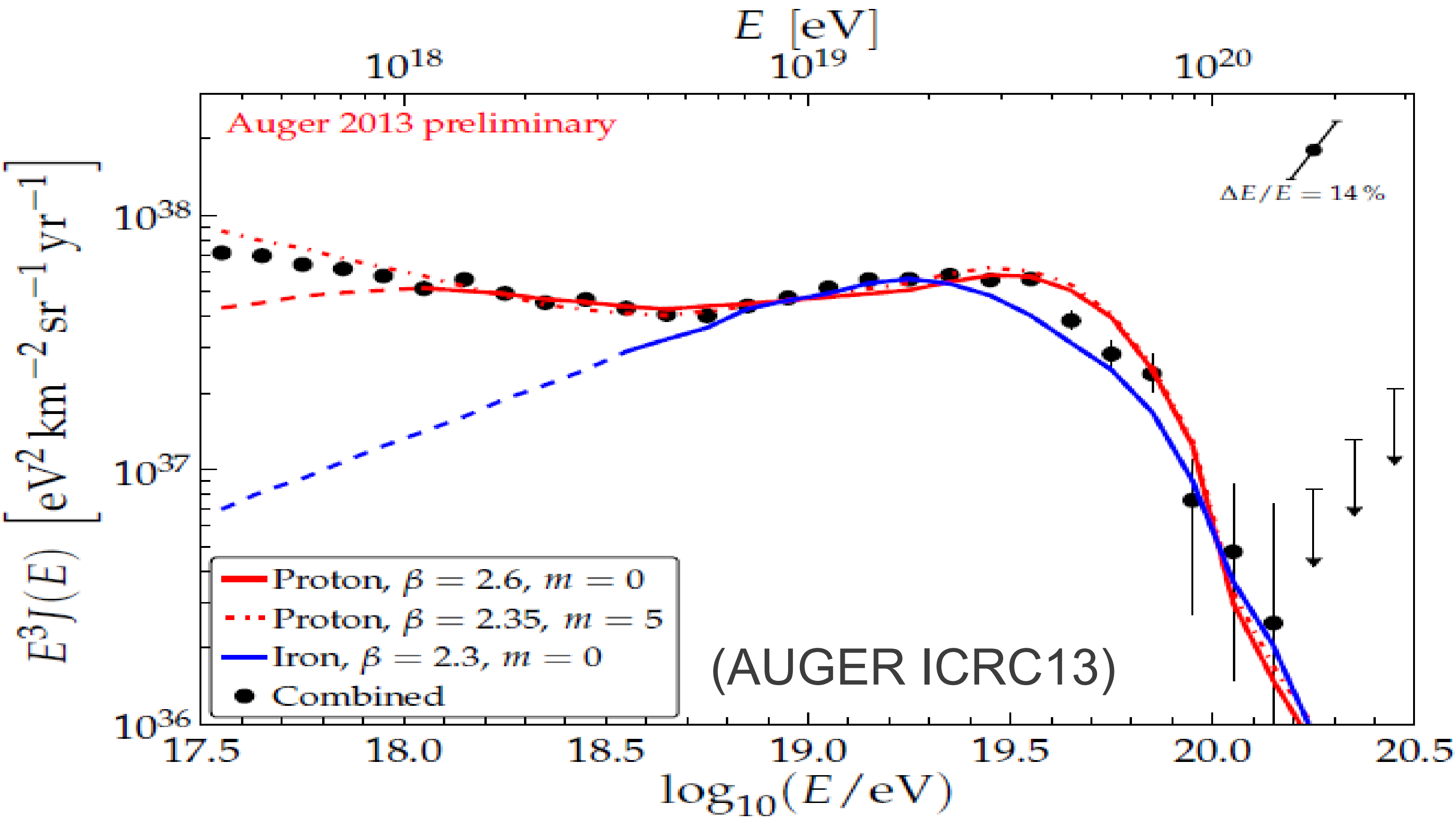



Normalizations: Hybrid: 0.94, 750 m array: 1.02, Inclined: 1.05

# Rescaled spectra UHECR 2012 WG

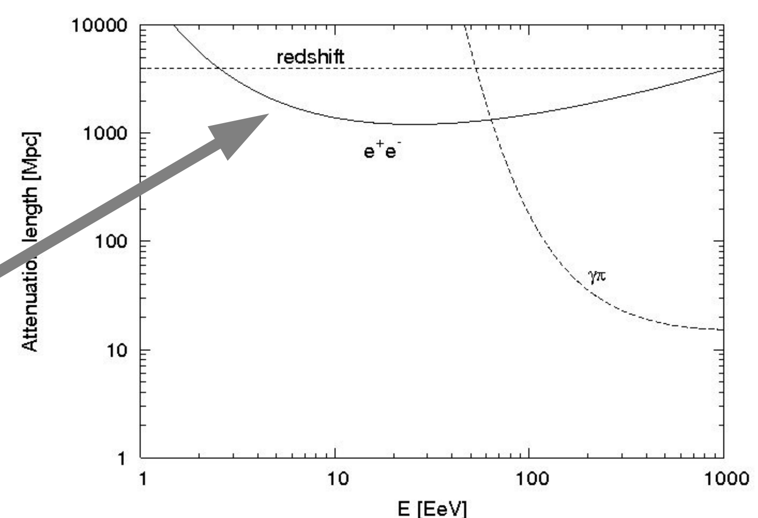



**spectra from different experiments consistent within systematics**



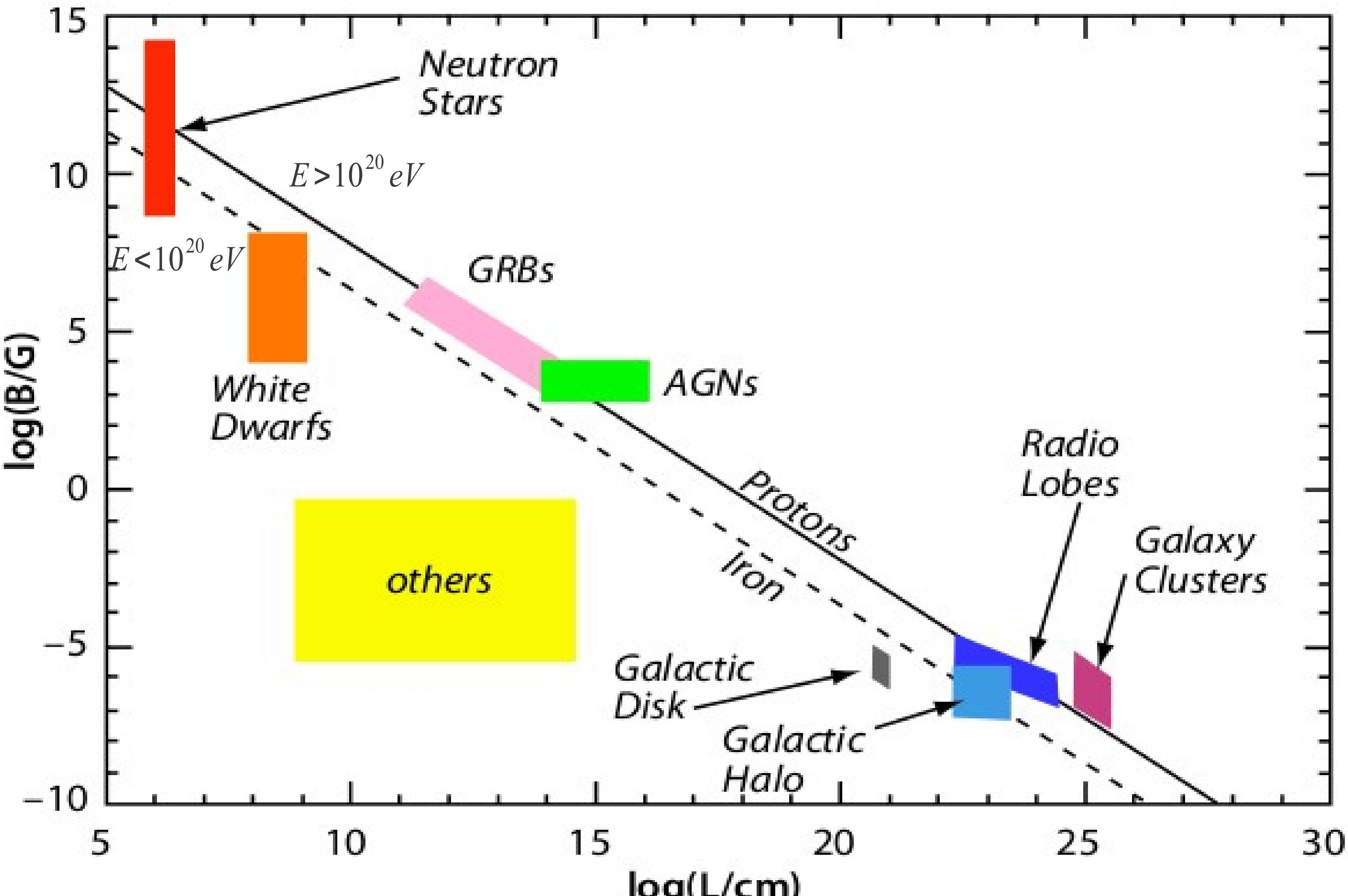

**GZK:** **proton or Fe suppression ?**
**(and/or exhaustion of sources?)**

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

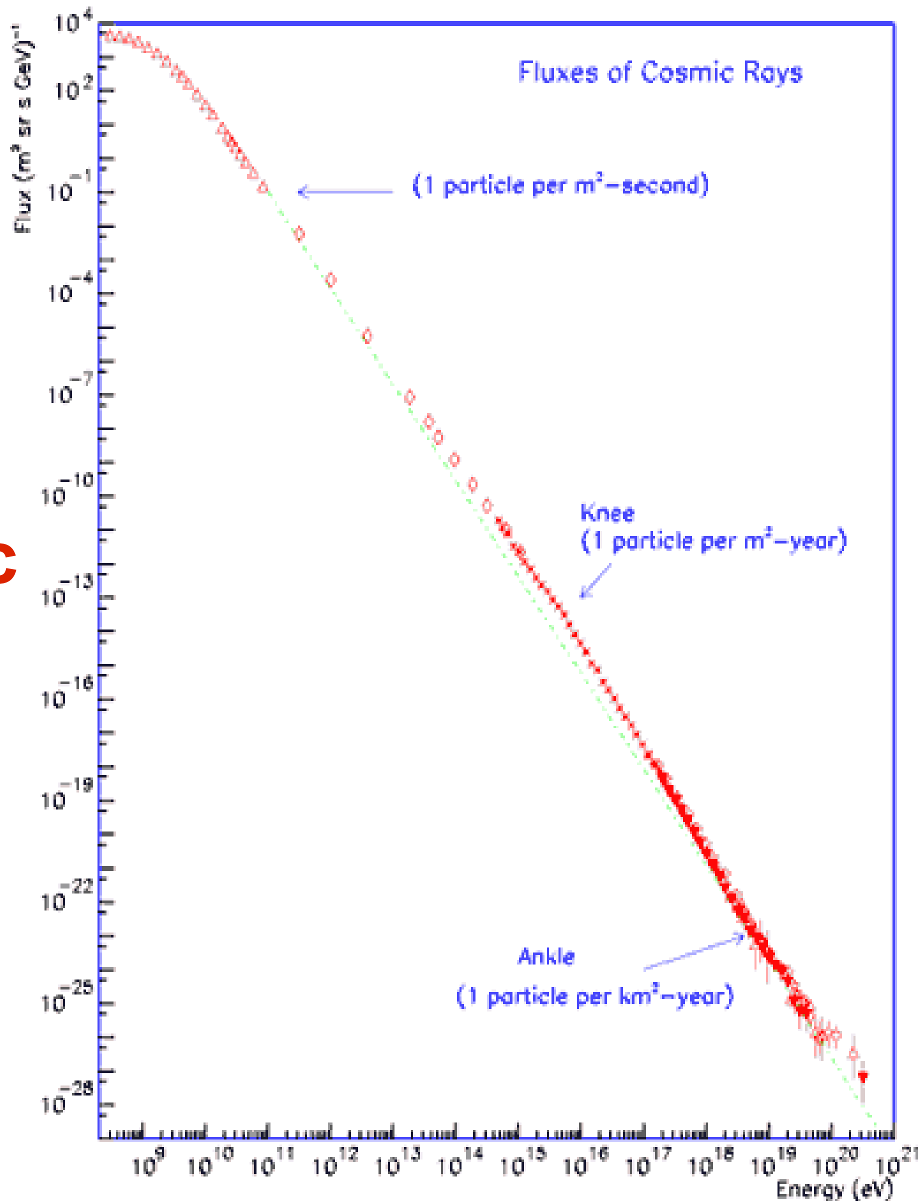


# The HILLAS PLOT

## (acceleration to $10^{20}$ eV requires large size and/or B field in source region)



**cosmic ray flux**




**?**

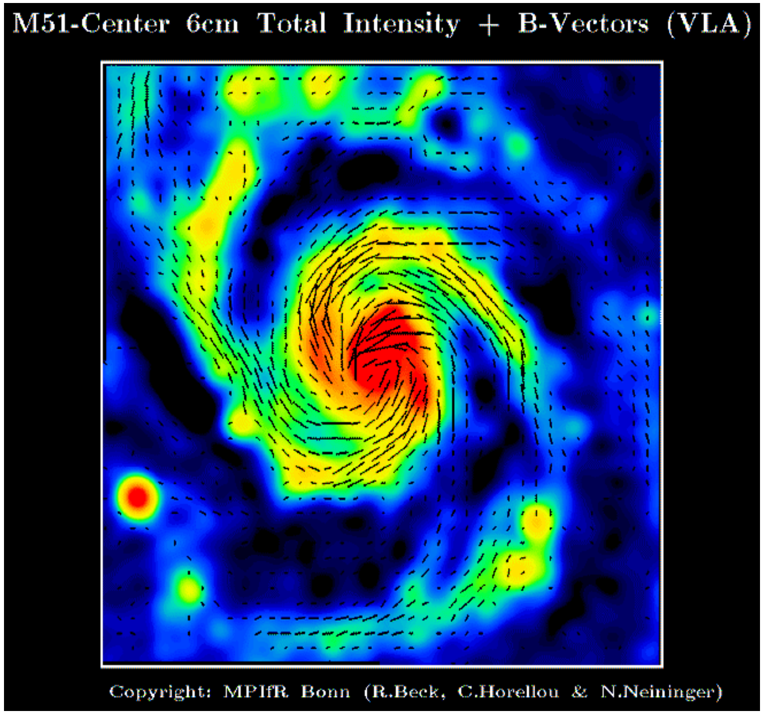
**galactic** ← → **X-galactic**

**Power law flux → stochastic (Fermi) acceleration in shocks**

**Small fractional energy gain after each shock crossing**

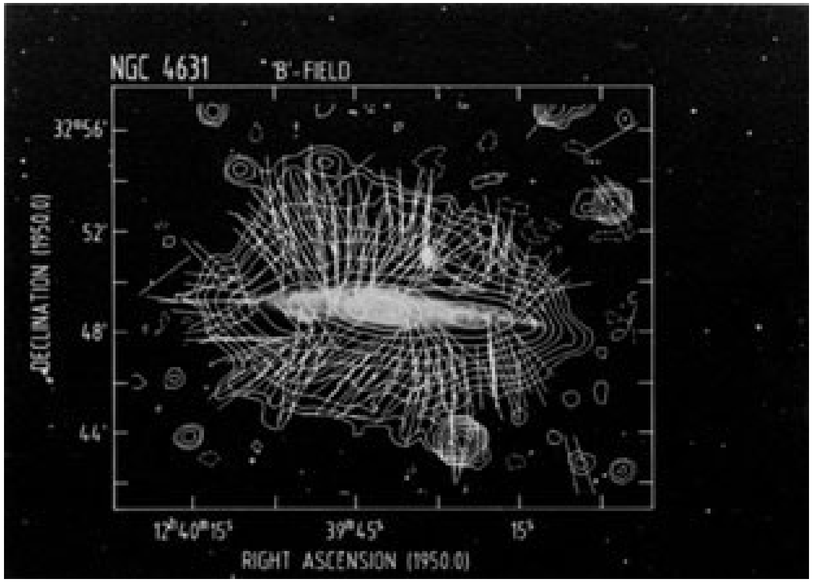
$$\rightarrow \quad \frac{dN}{dE} \sim E^{-\alpha} \quad with\ \alpha \simeq 2 - 2.4$$

# Galactic magnetic fields




M51

NGC 4631



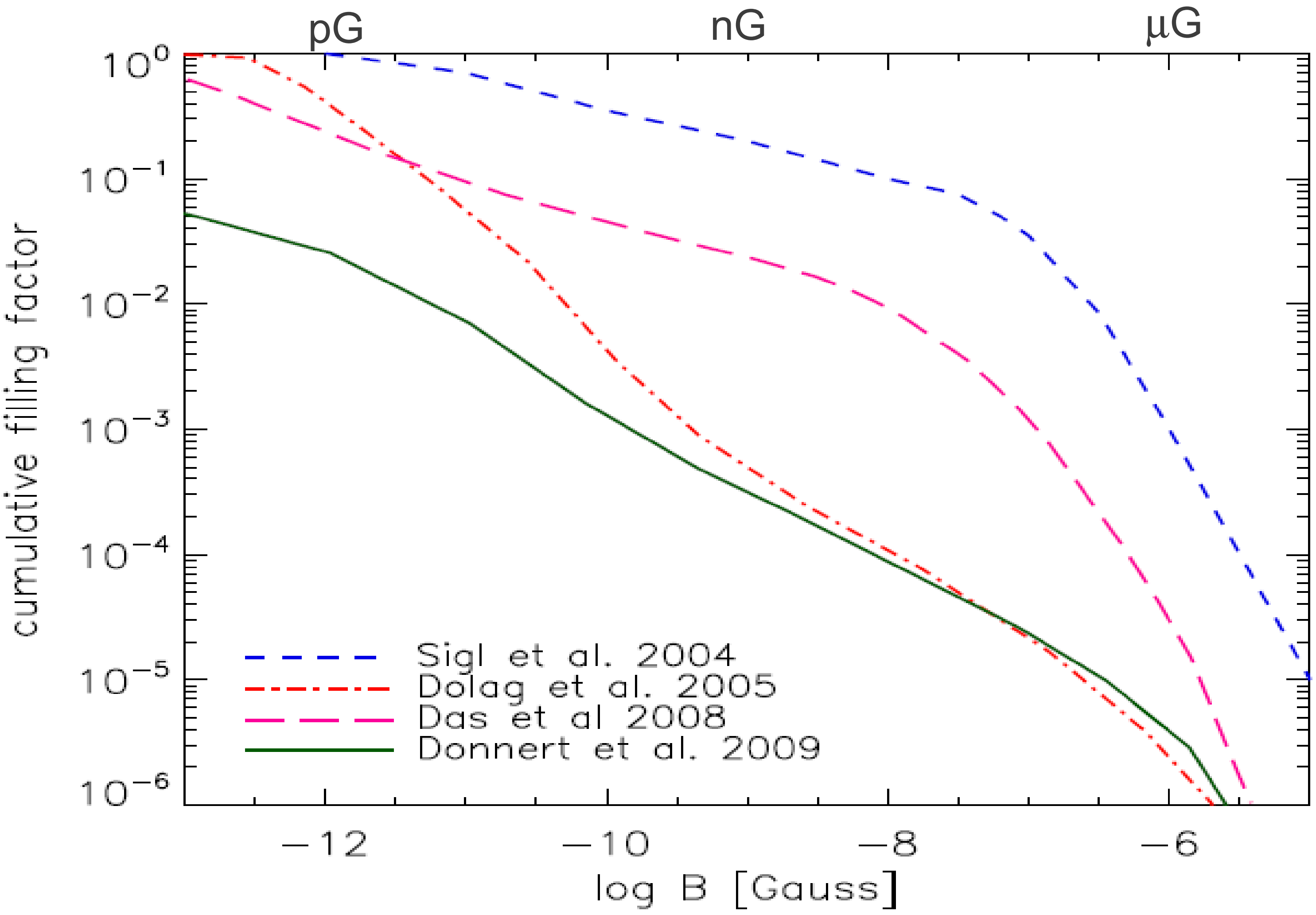

Regular B field follows spiral arms

Radio signal from magnetic halo ($z_h$~few kpc)

Local regular field of our Galaxy ~ 3 $\mu$G

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

# Extra-Galactic magnetic fields filling factors (simulations)




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

# At low energies CRs diffuse

$$\frac{\partial N_i}{\partial t} = Q_i - \nabla\cdot\left(VN_i + J_i^D\right) + \frac{\partial}{\partial E}\left(b(E)N_i\right) - \frac{N_i}{\tau_i} + \sum_{j>i}\frac{P_{ji}}{\tau_j}N_j$$

Source convection/difffusion energy loss/gain decay / spallation

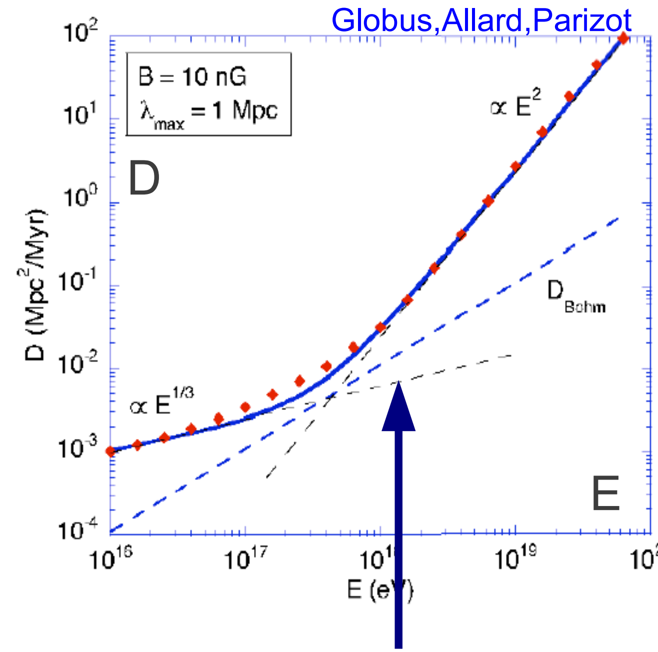
→ **the steady state diffusion eq neglecting convection, E losses, drifts, is just**

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

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

**with α ≈ 1/3 for E < Ec** (for Kolmogorov)

**and α ≈ 2 for E > Ec**




**critical energy Ec:**

Larmor radius(Ec) = coherence length

$$r_L(E_c) = l_c \Rightarrow E_c \simeq Z\frac{B}{nG}\frac{l_c}{Mpc}EeV \sim \begin{cases}\dfrac{B}{\mu G}\dfrac{l_c}{10\ pc}10^{16}eV & \textbf{gal p}\\[2ex] \dfrac{B}{nG}\dfrac{l_c}{Mpc}EeV & \textbf{X-gal p}\end{cases}$$

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

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

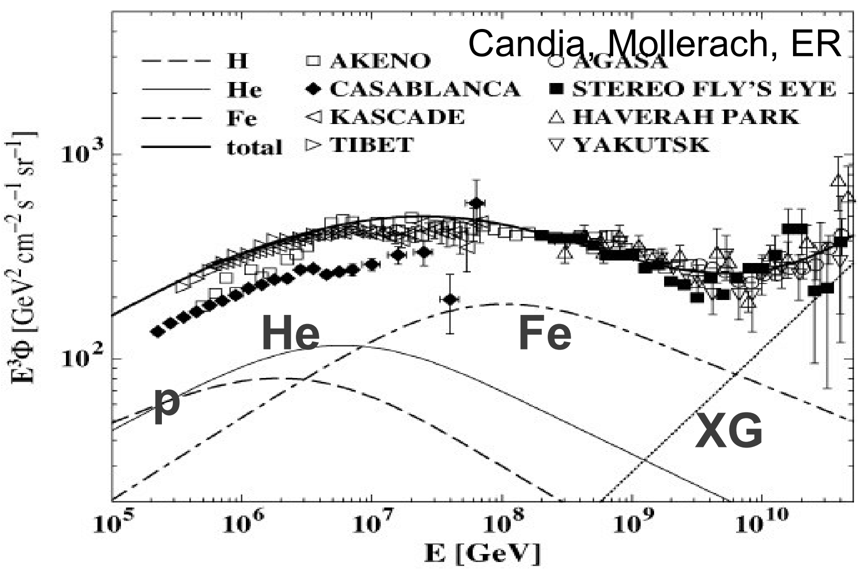
**but**

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

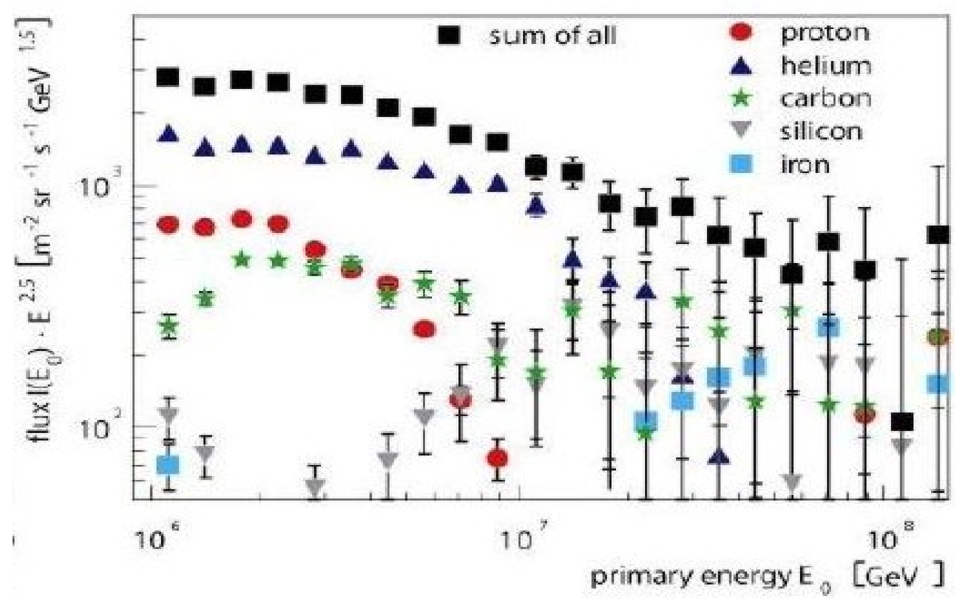
$$\left(\frac{dJ}{dE}\right)_{Earth} \sim E^{-\gamma-\alpha} \quad (\gamma+\alpha \simeq 2.7)$$

low E CRs stay longer confined in the Galaxy

## In addition, enhanced diffusion at high energies can explain the knee by more efficient escape from Galaxy




Diffusion and drift scenario




**KASCADE**

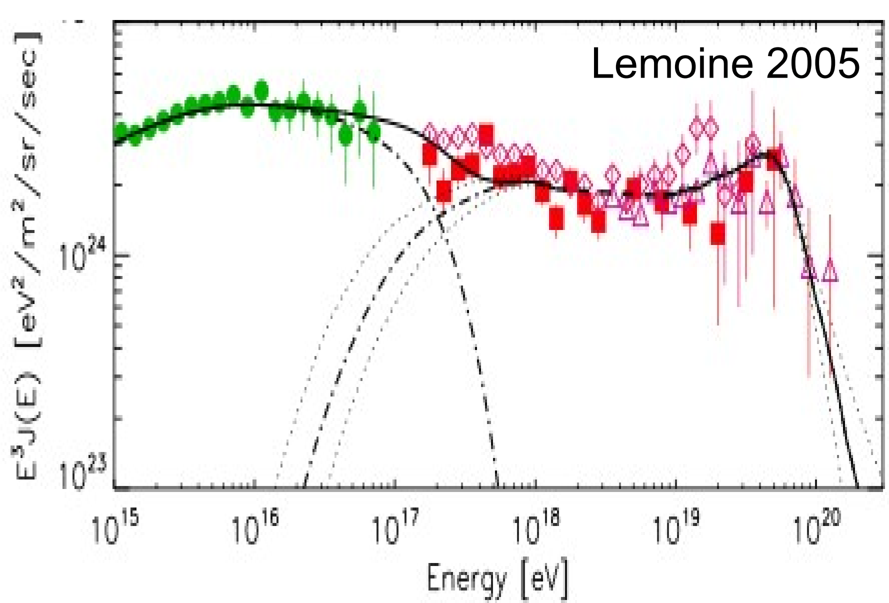
**Diffusion in X-galactic B fields:**

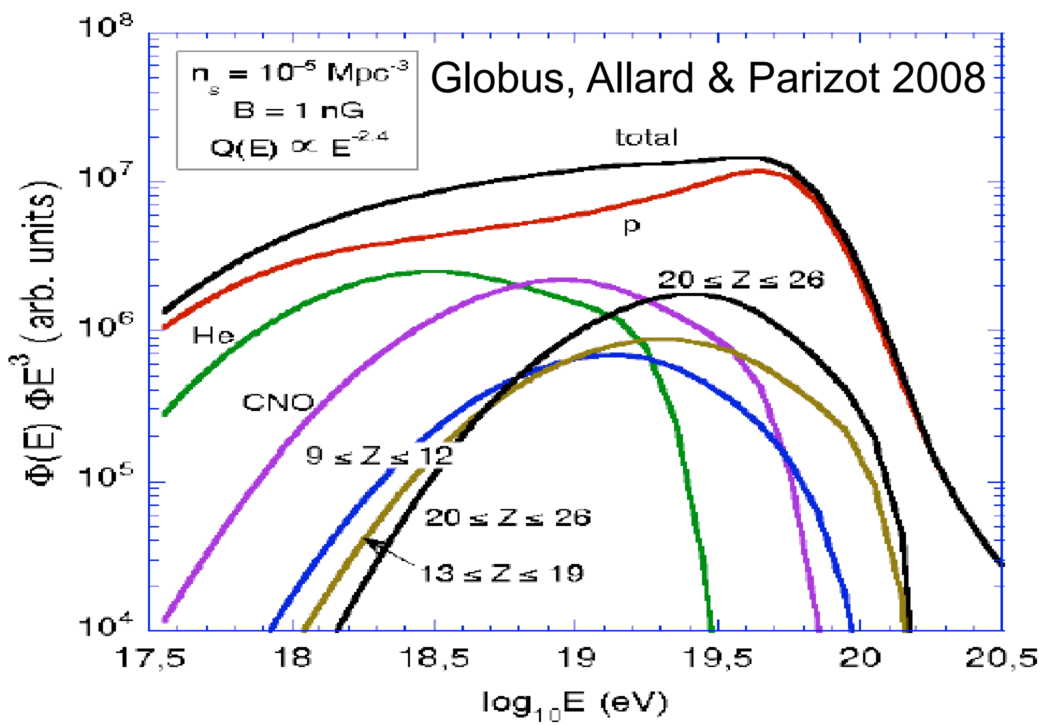
**At high E → rectilinear propagation → spectrum only shaped by E-losses**

**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 source**
**→ far away sources do not contribute at low E and nearby ones suppressed**



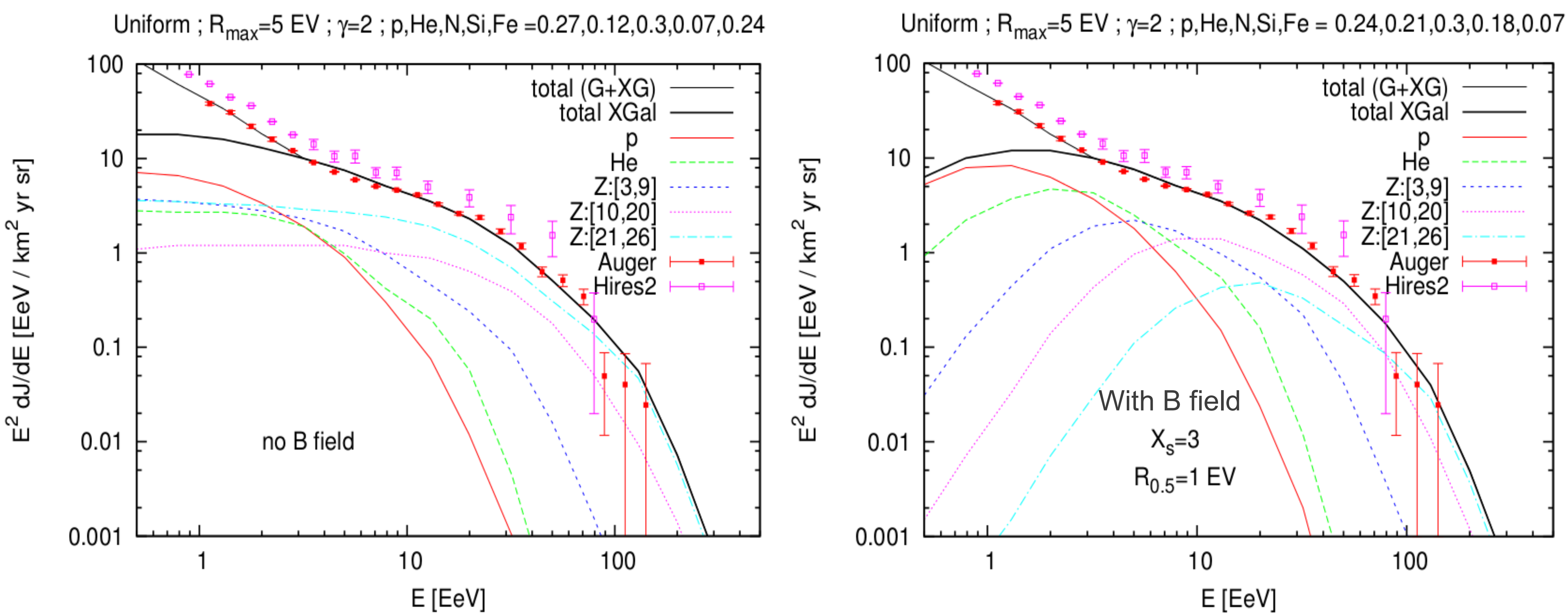




**protons**

**Mixed composition**

Considered large Emax → light composition

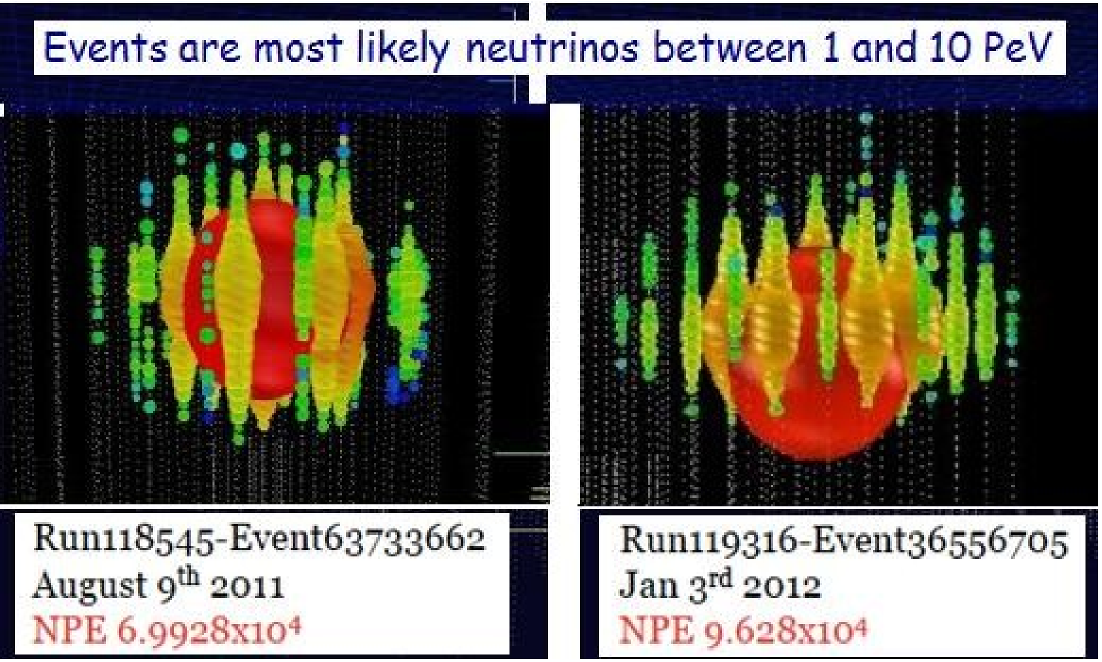
# Diffusion in X-gal turbulent B fields can modify spectra and composition at UHE




**Allows to suppress heavy nuclei at E < Z EeV** [reducing RMS(Xmax) ]
**No need to invoke too hard source spectra**
**→ helps to account for observed spectrum and composition**

Mollerach & Roulet (arXiv 1305.6519)

# The two highest energy neutrino events observed by ICECUBE

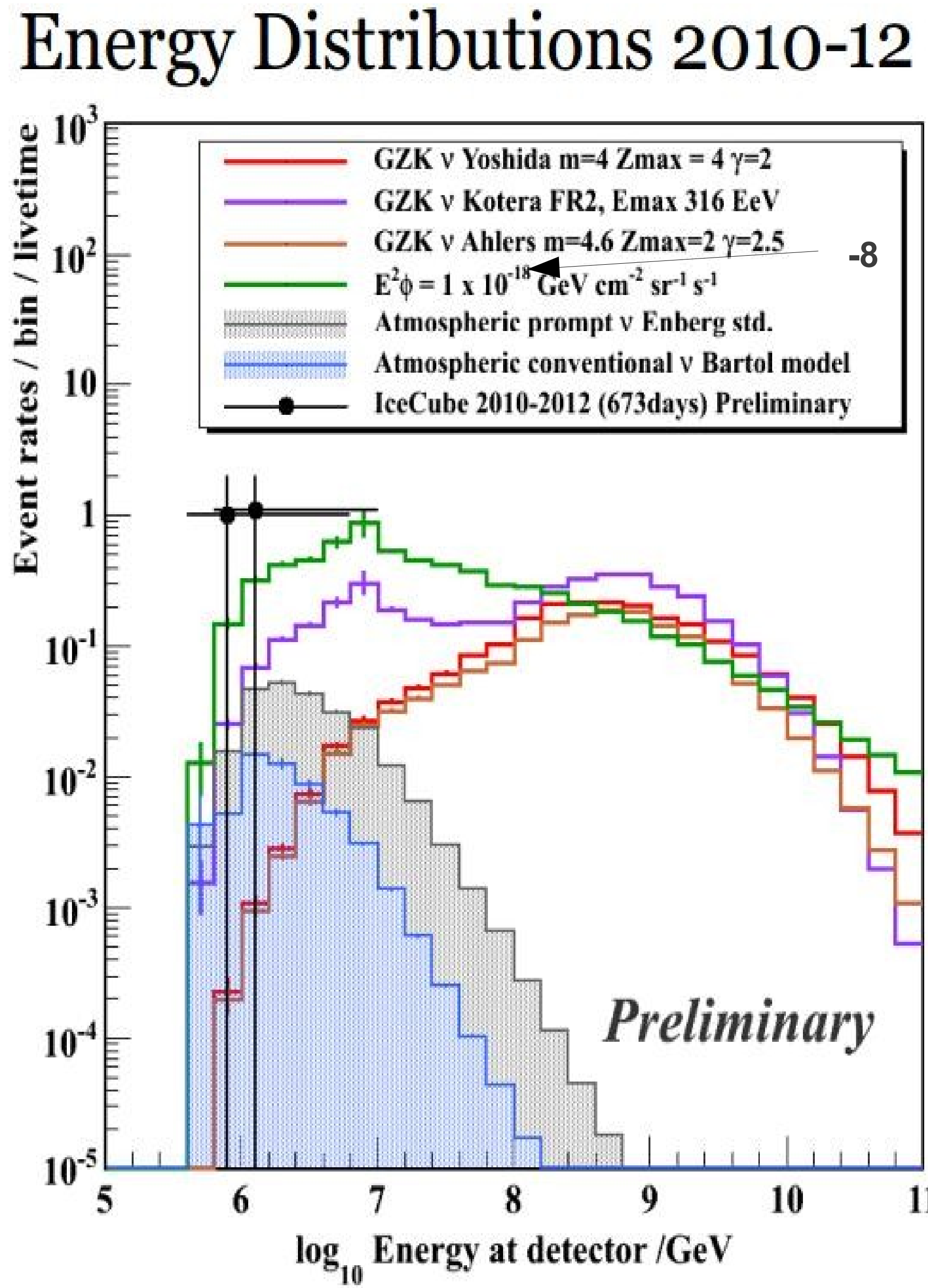



Possibility of the origin includes

- cosmogenic ν
- on-site ν production from the cosmic-ray accelerators
- atmospheric prompt ν
- atmospheric conventional ν

but no coincident signals in ICE-Top

They are cascade events

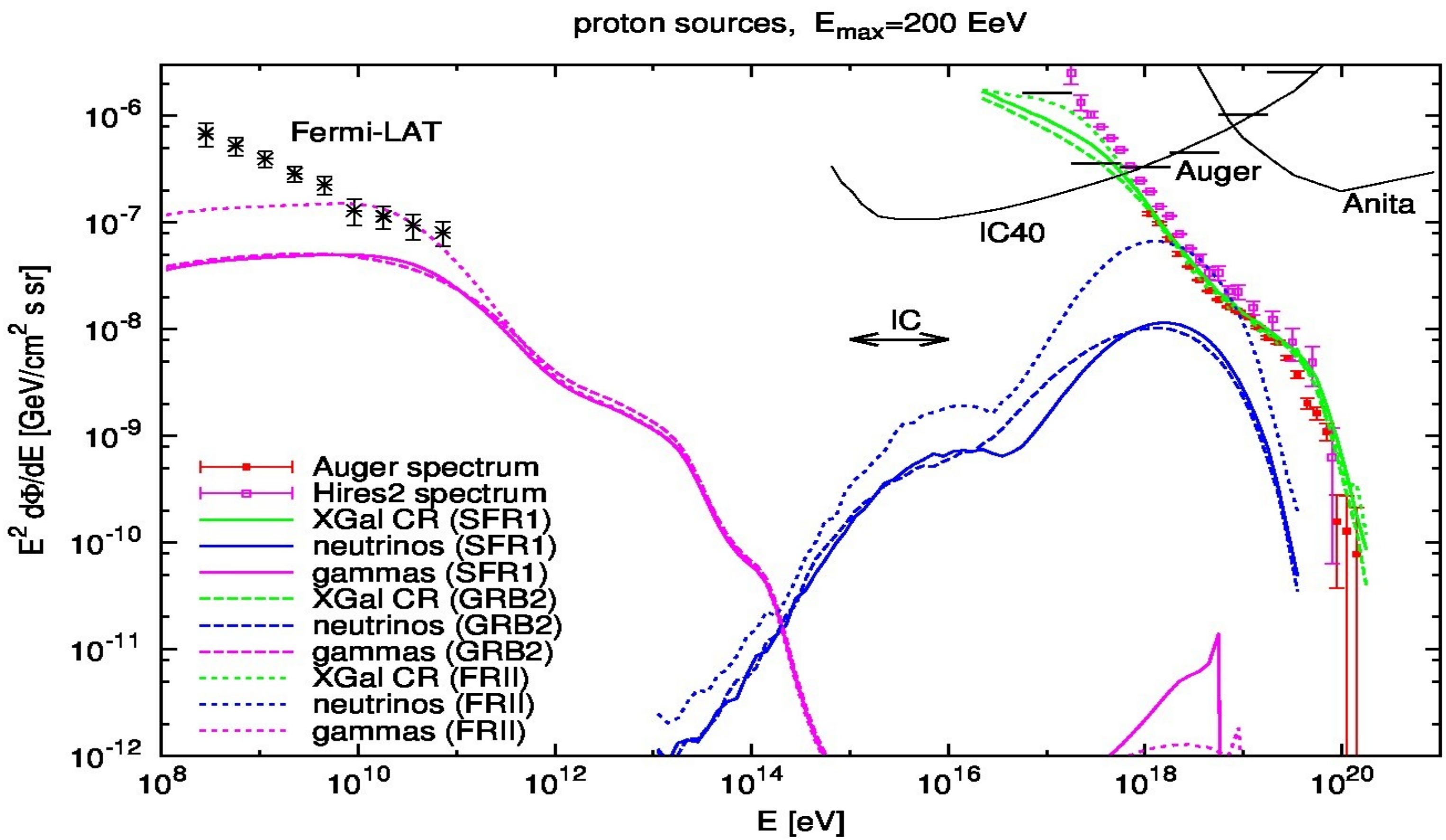


# ν and γ for different source evolutions & cascade bound

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

**γ** $p\,\gamma \rightarrow \pi^0 p$ $\pi^0 \rightarrow \gamma\,\gamma$ $p\,\gamma \rightarrow p\,e^+ e^-$

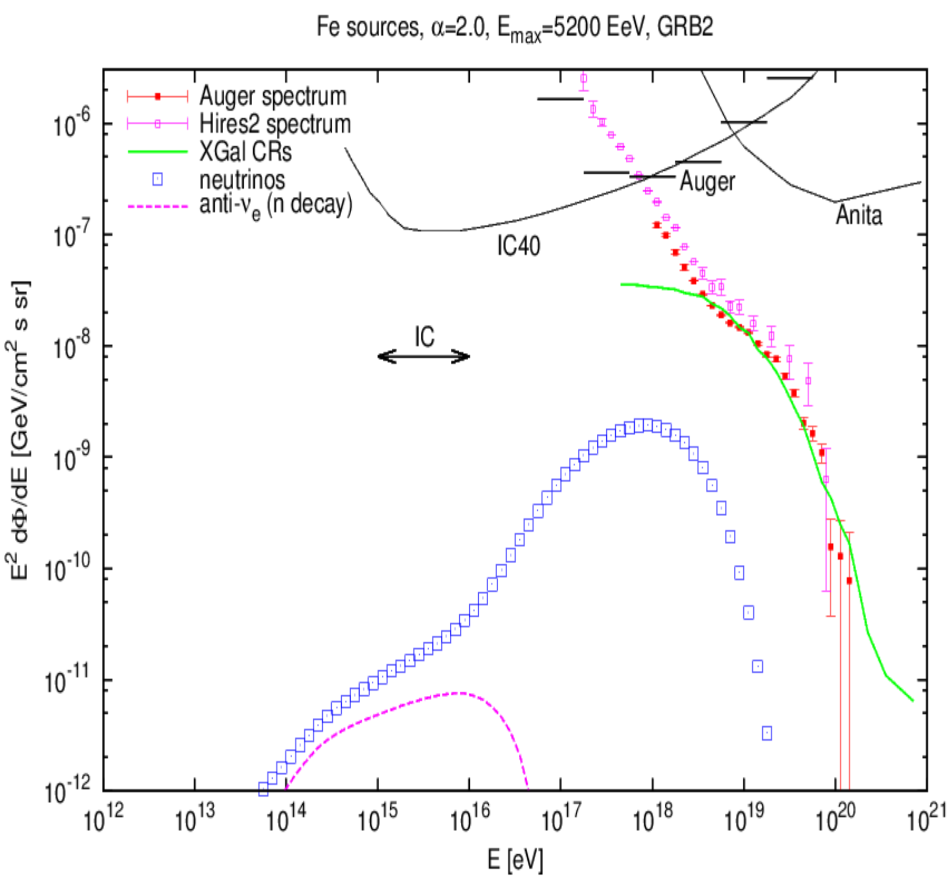
$\gamma\,\gamma_{bckg} \rightarrow e^+ e^-$ $e\,\gamma_{bckg} \rightarrow e\,\gamma$ Cascades down to GeV-TeV



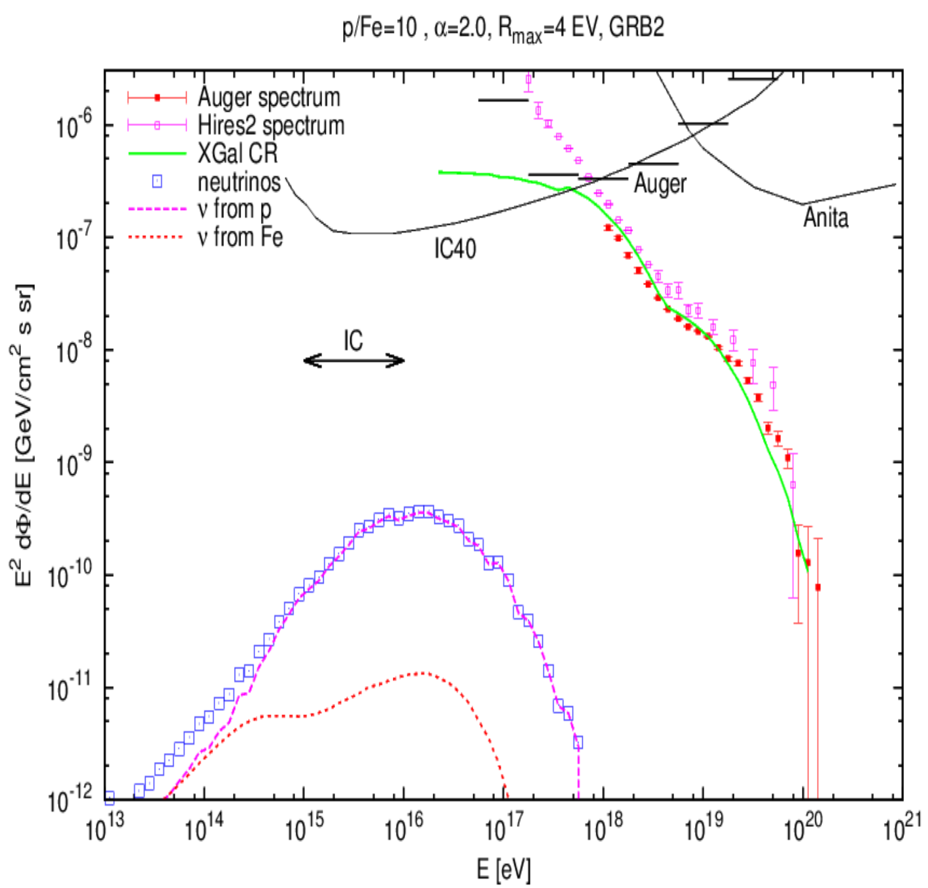

(PeV neutrinos mainly from 0.1 EeV protons colliding 1 eV photons)

Roulet et al. 2012

## Fe composition with large cutoff




## Mixed p / Fe composition with low cutoff

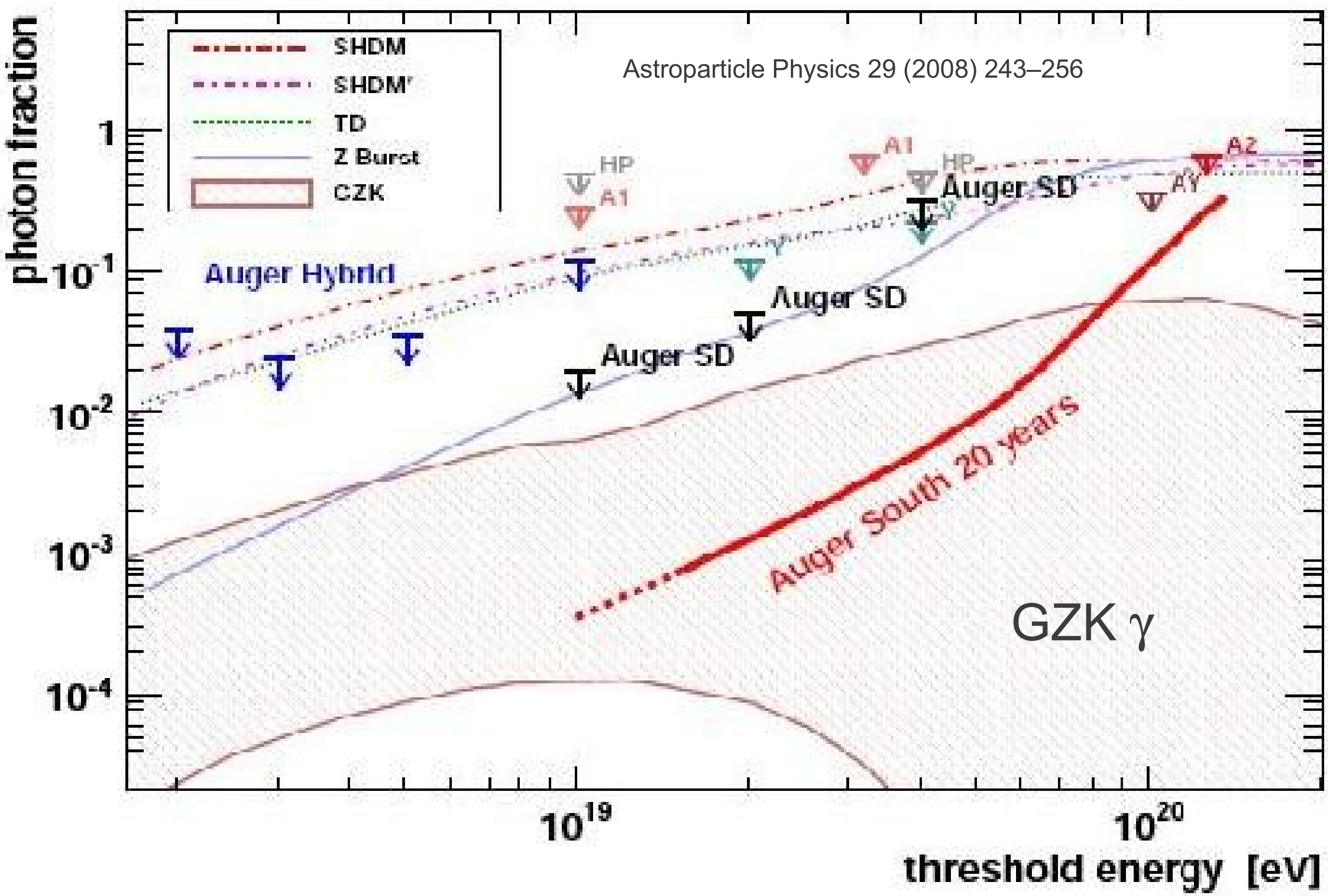



**PeV neutrinos produced by 100 PeV nucleons, no direct implications for EeV neutrinos accessible to Auger.**

**Predicted cosmogenic PeV neutrino fluxes low, likely produced at sources**

# 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**

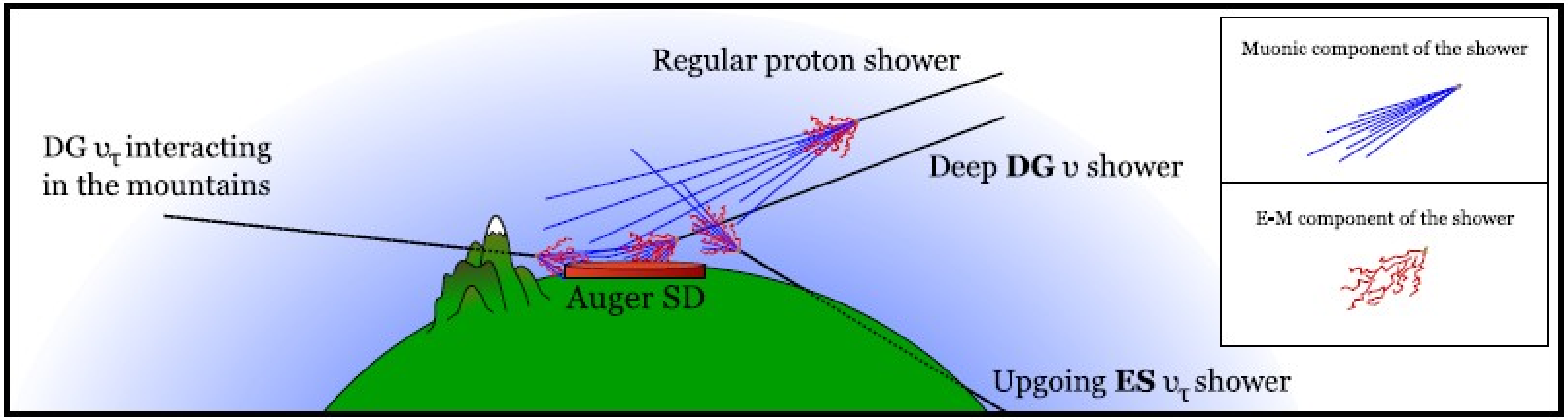



**photon fraction:**
**< 2% at E > 10 EeV**

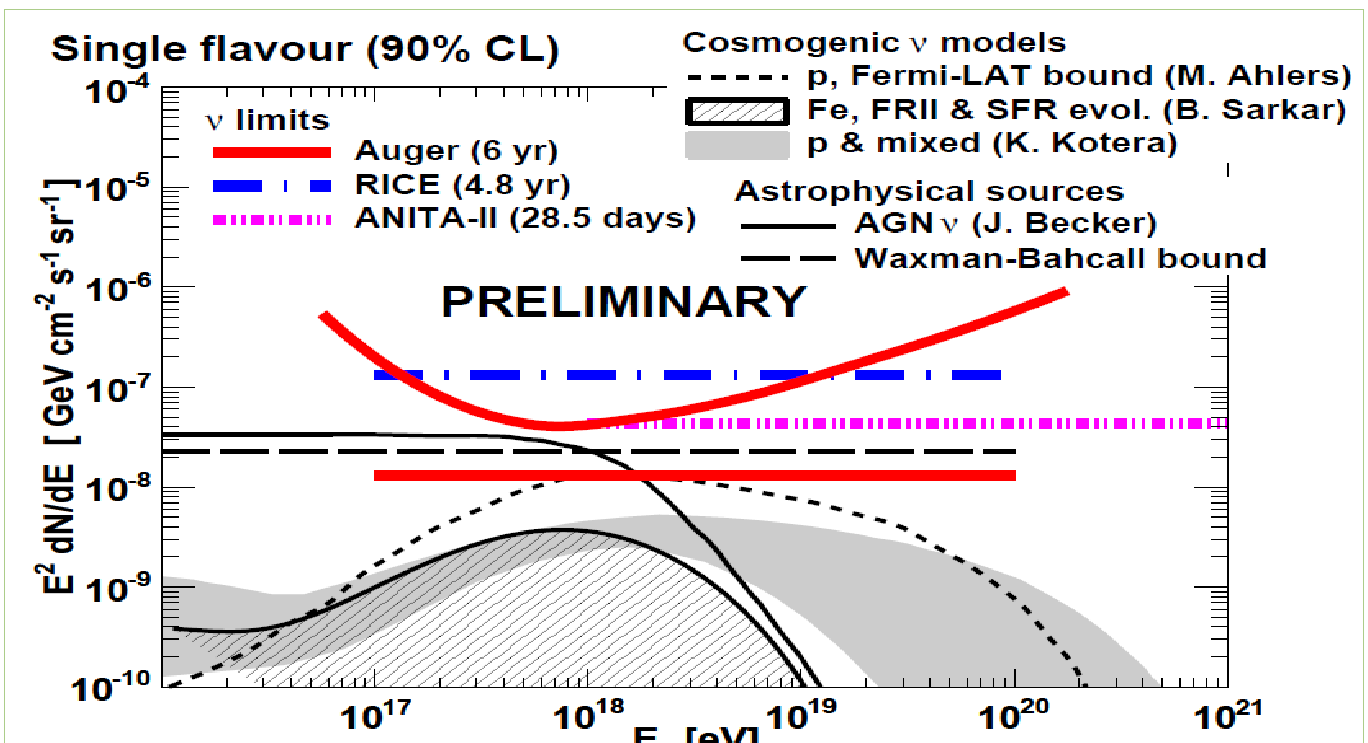
**< 31% at E > 40 EeV**

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

# Neutrino detection in AUGER




## Only neutrinos can produce young horizontal showers

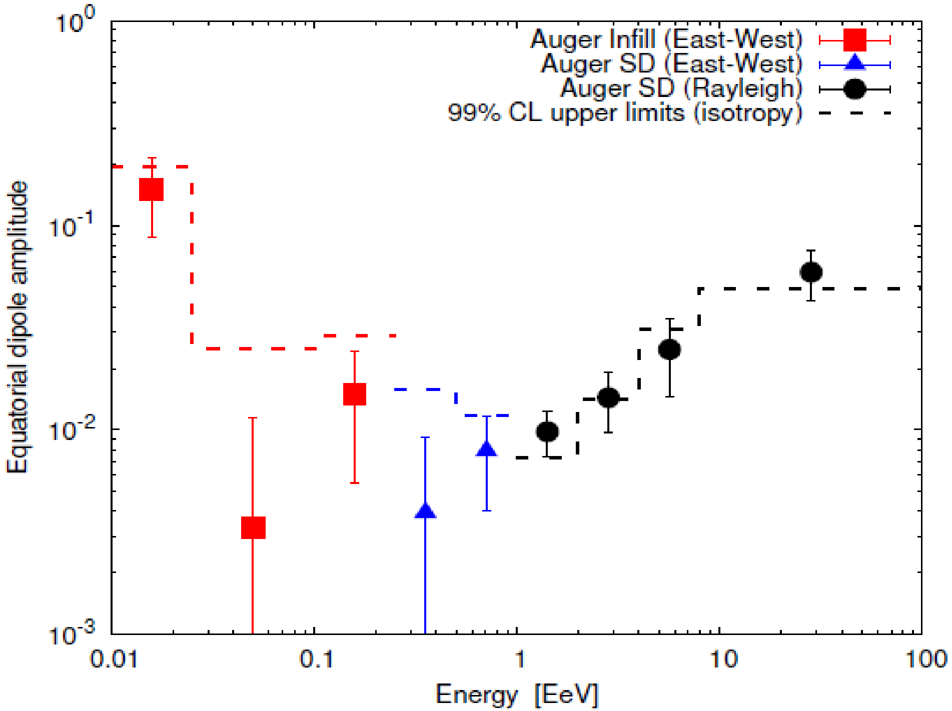


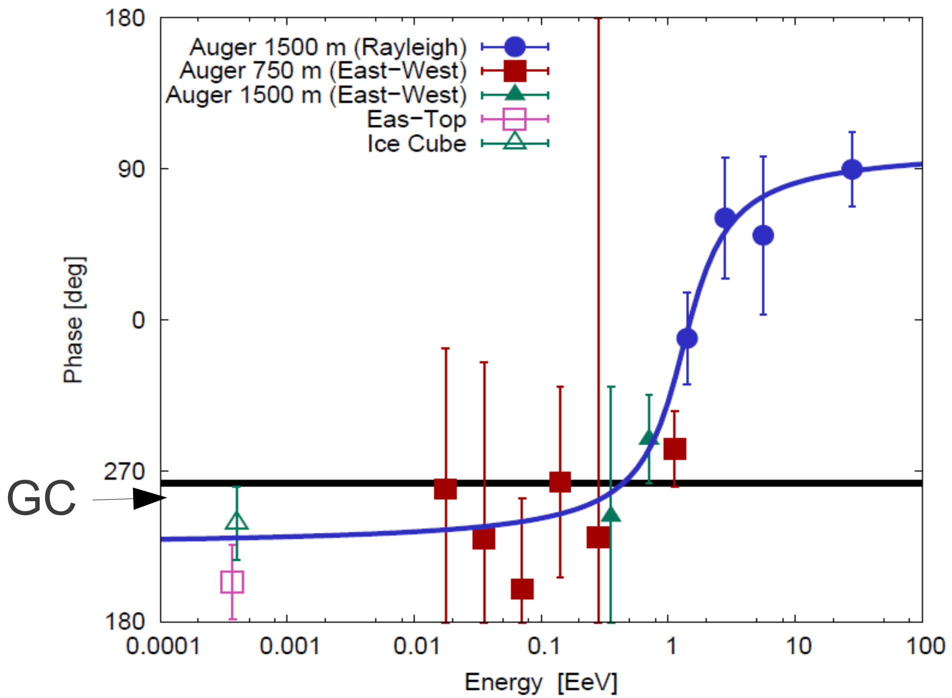

0 events observed → bounds scale linearly with Exposure

Icecube will be more sensitive
ARA even better

# LARGE SCALE ANISOTROPIES

## Amplitude and Phase of equatorial dipole component



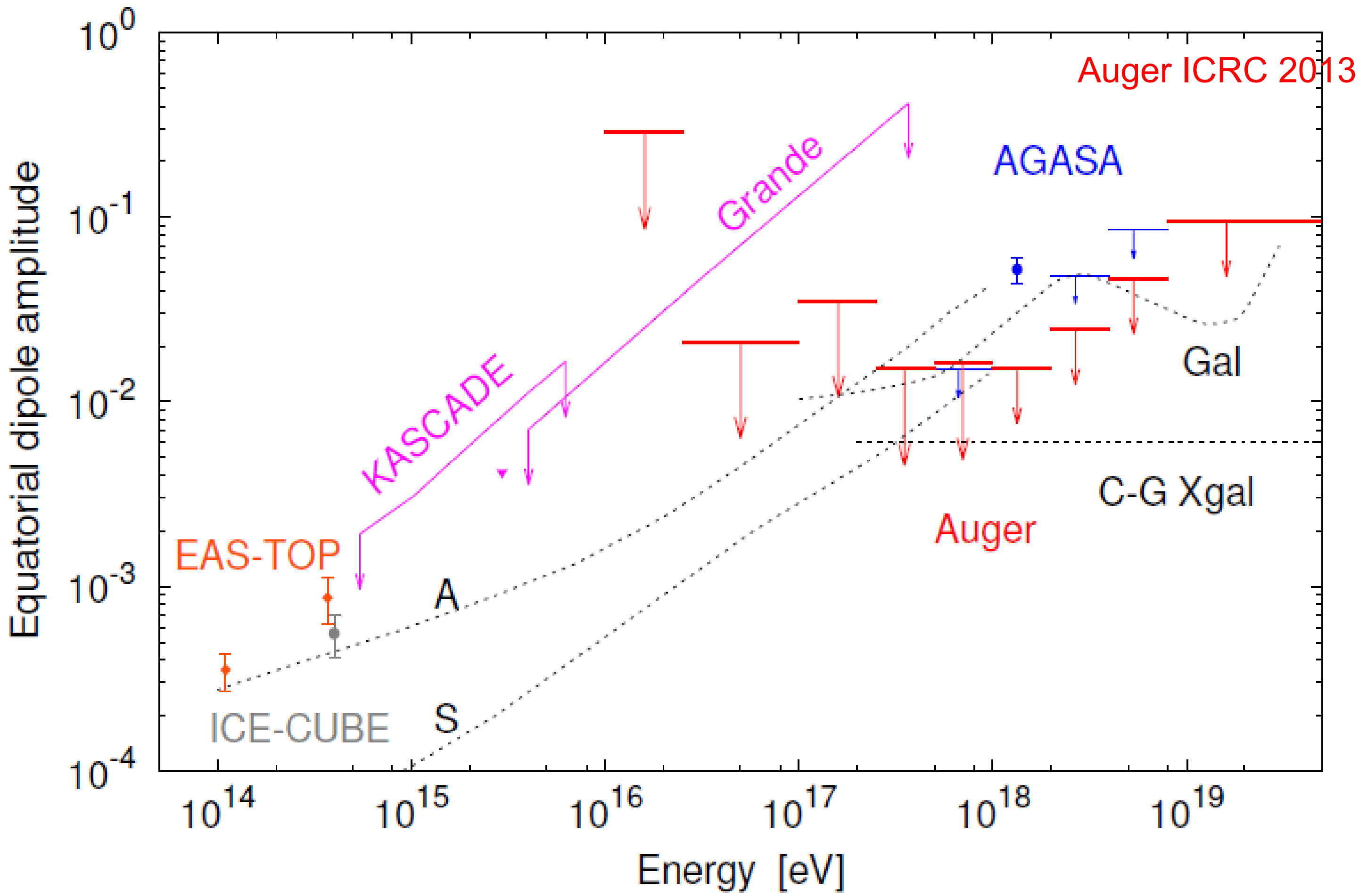




**3 bins above EeV have amplitude with <1% chance from isotropy** (significance still marginal)

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

# Amplitude of equatorial dipole component

Auger, ICRC 2013



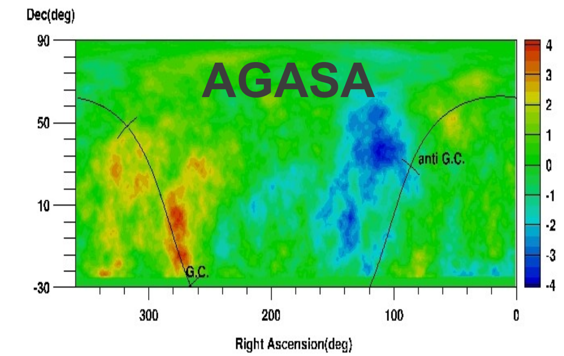



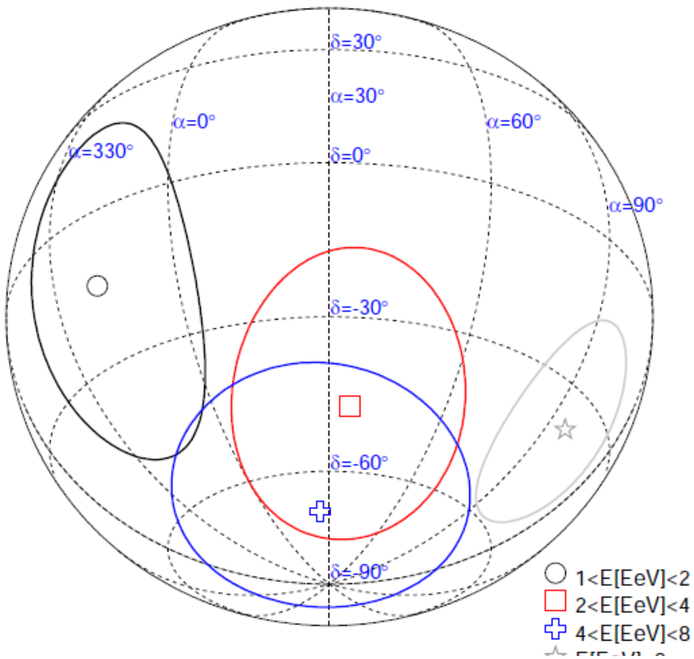

**Fig. 2.** The significance of event density in equatorial coordinates. The statistical significance of deviation is evaluated for each 1° grid with the aperture of 20 degrees radius. The excess and deficit can be seen with 4 $\sigma$ statistical significance near the Galactic center and anti-galactic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

AGASA excess excluded

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

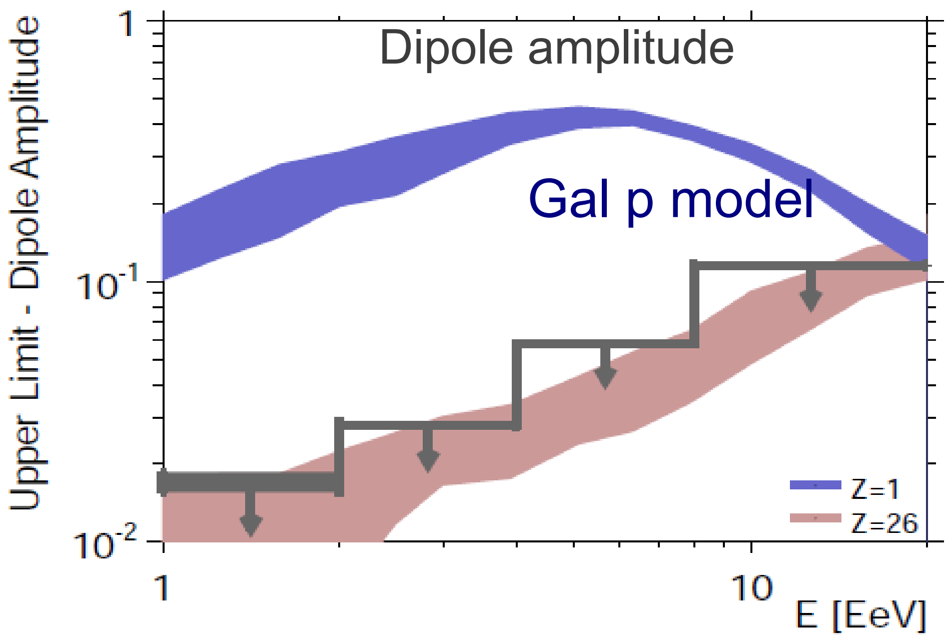
# 3D dipole reconstruction

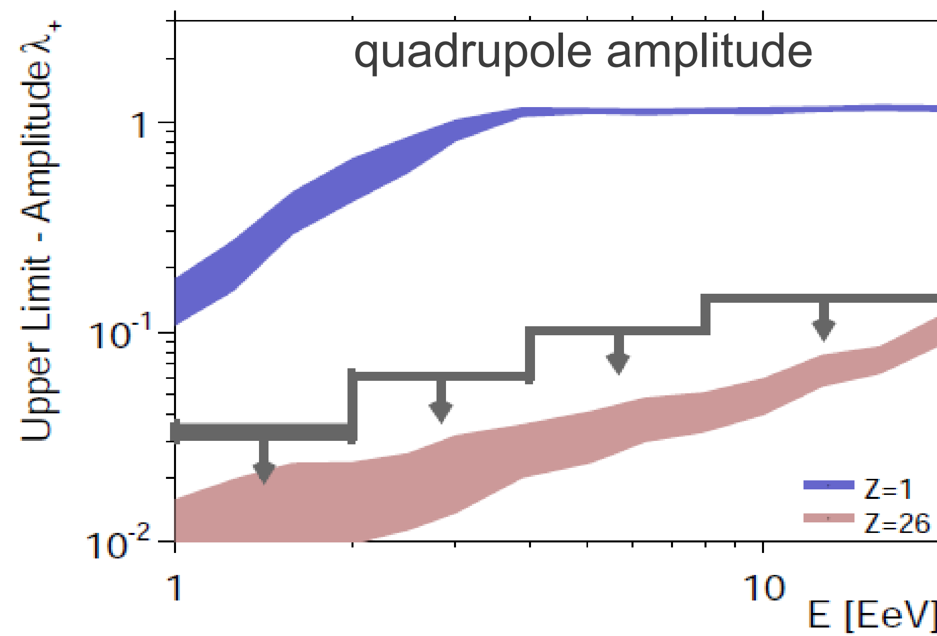
Auger APJ L 2012




**Dipole towards southern directions**
**But amplitudes not significant**

**Models with light galactic components excluded for E > EeV**

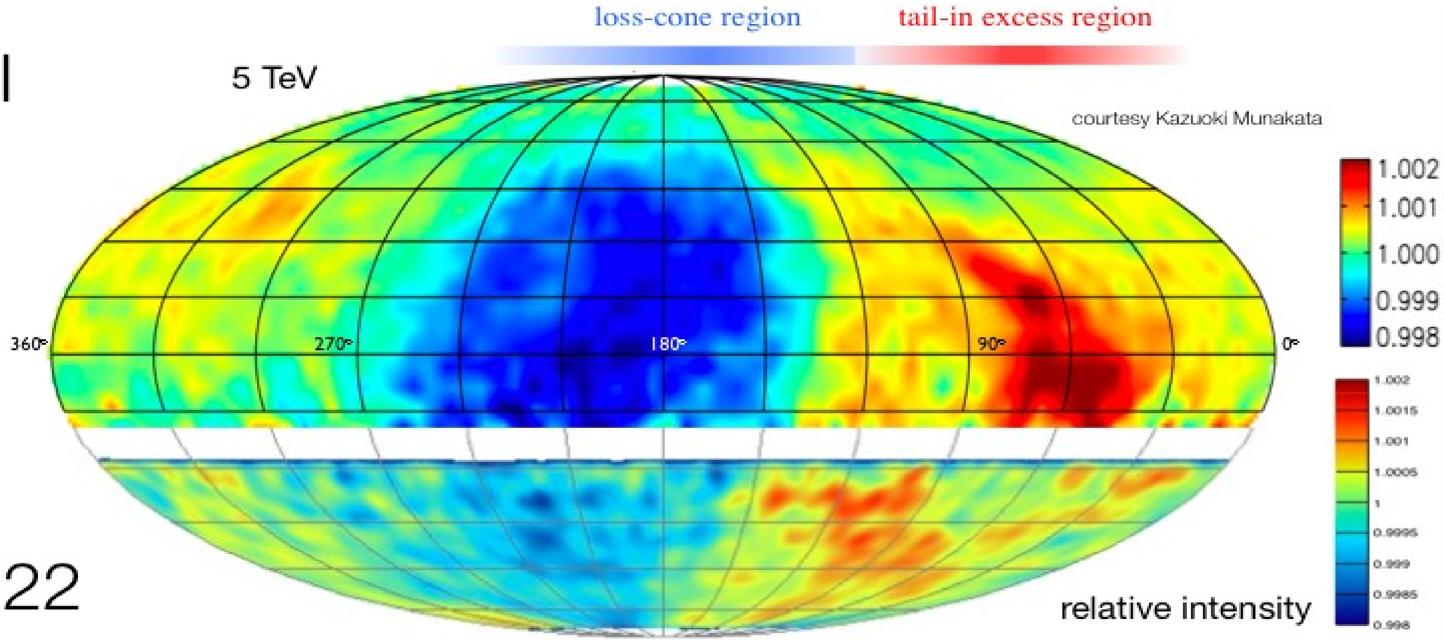



**Light composition at EeV is already extragalactic ?**

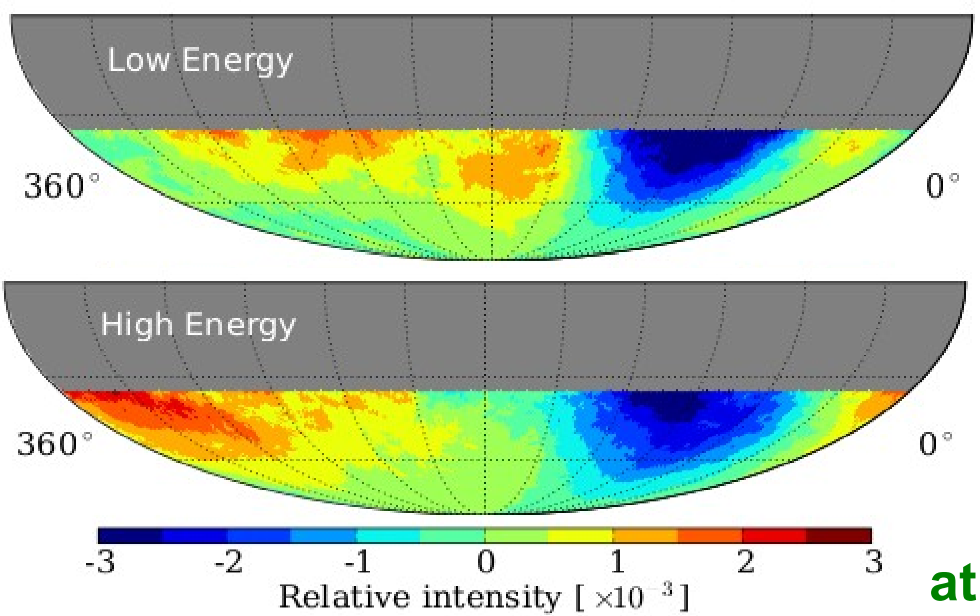
# Sidereal frequency anisotropies at lower E

Tibet-III




IceCube-22

They match pretty well



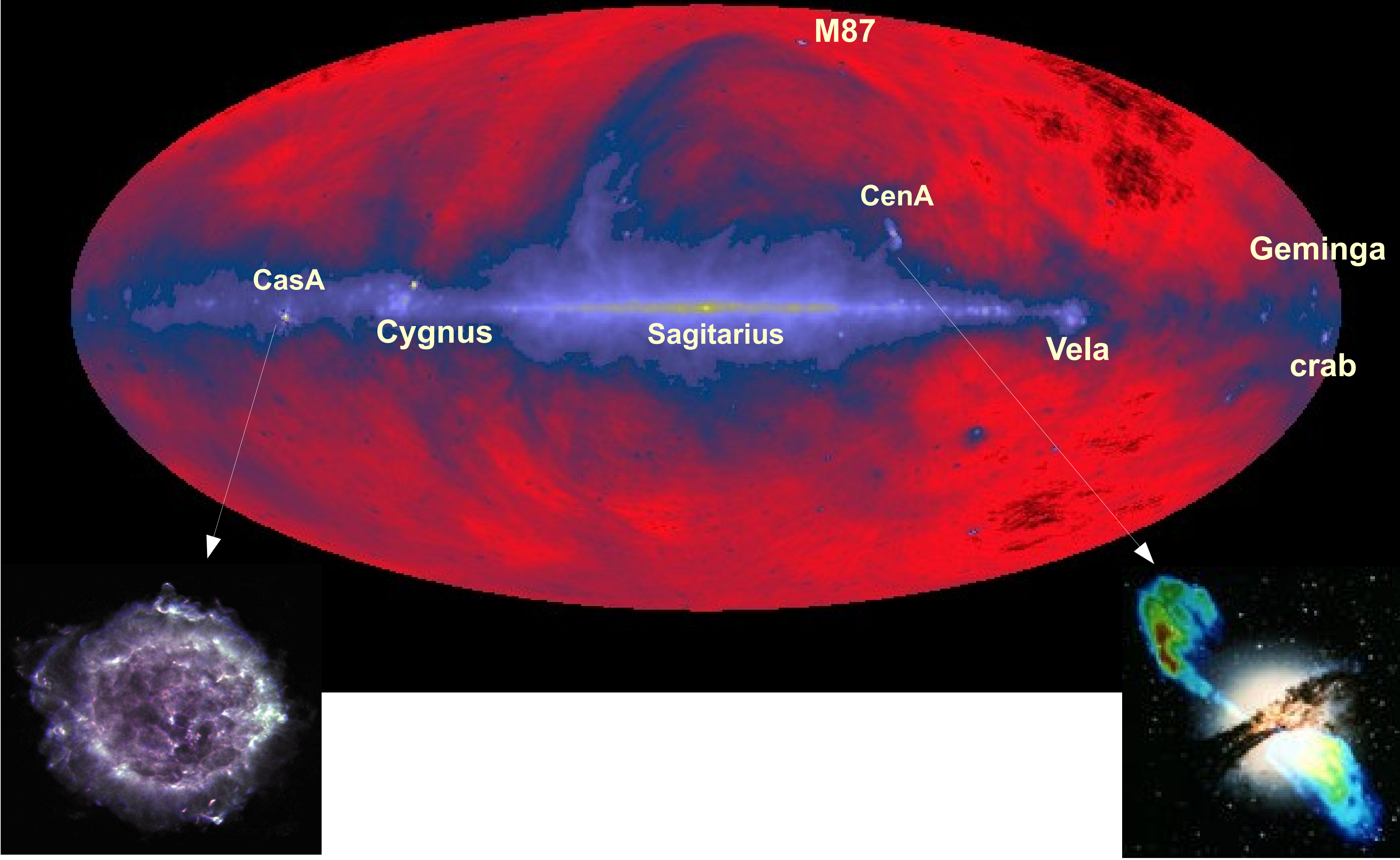

**IceTop** '12

E = 400 TeV

E = 2 PeV

**at PeVs, maximum ~ 300, like Auger?**

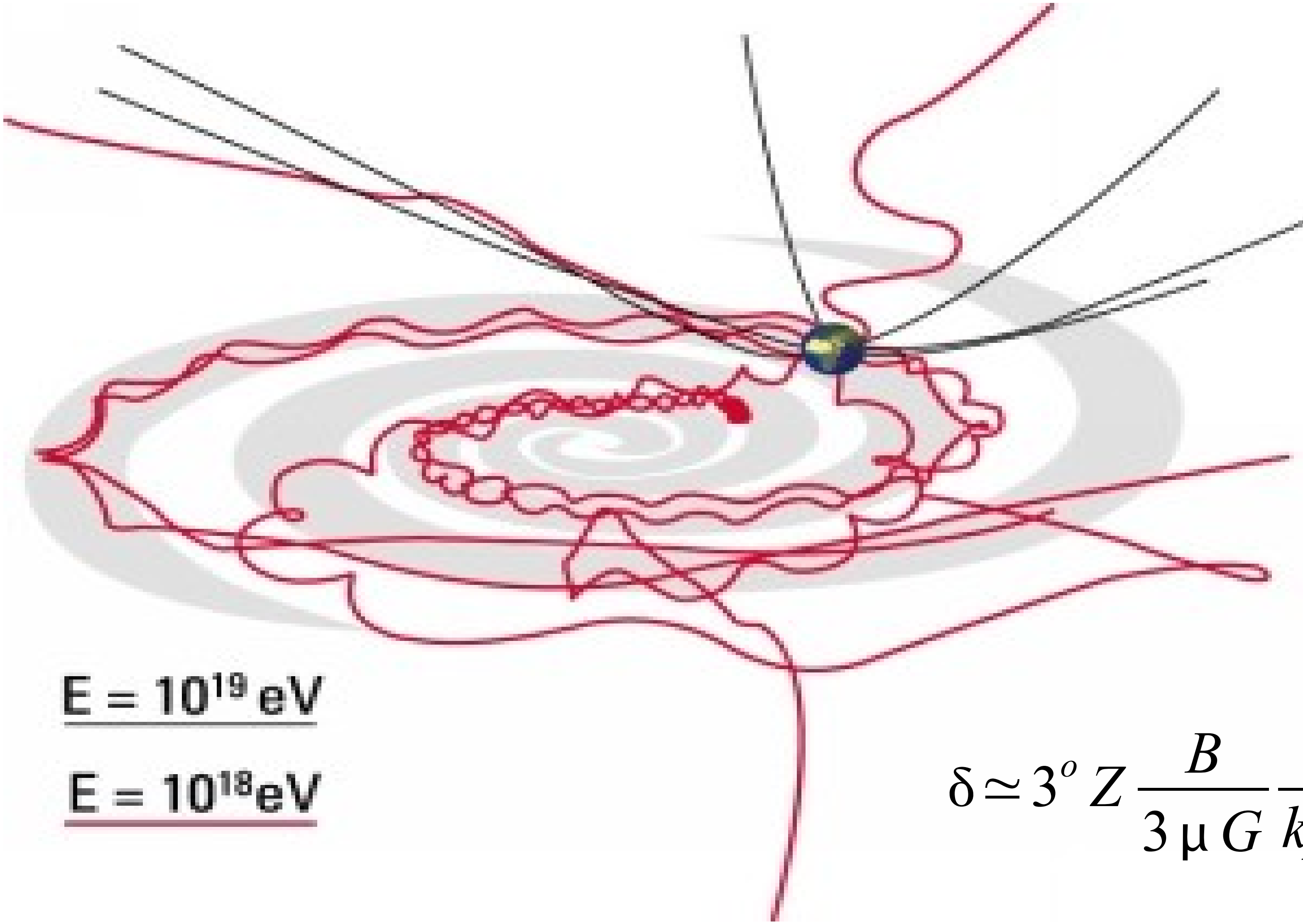
# the radio sky




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

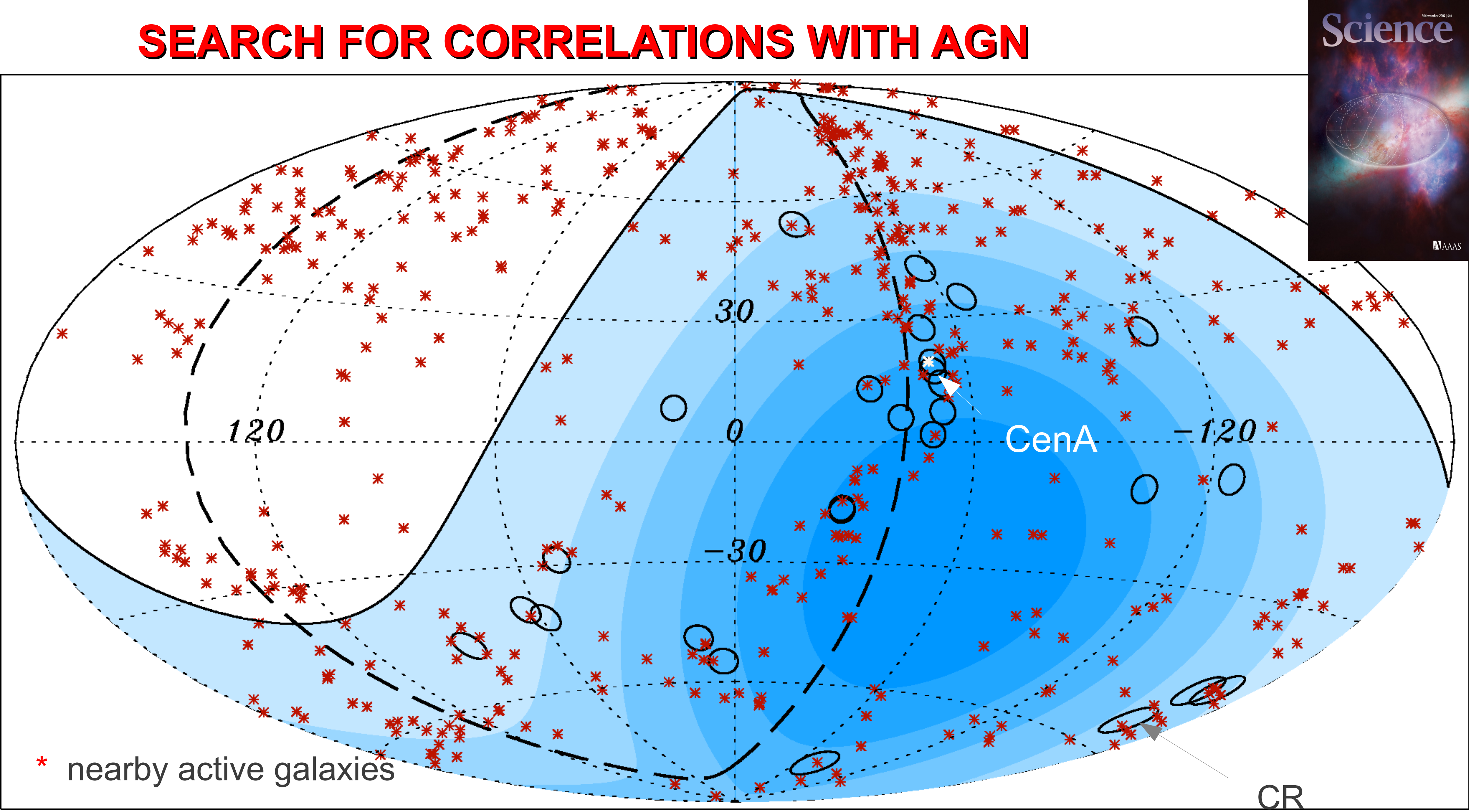
active galaxies: plausible candidates for E > $10^{18}$ eV

# AT HIGH ENERGY COSMIC RAY TRAJECTORIES STRAIGHTER
# IS ASTRONOMY POSSIBLE ?




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

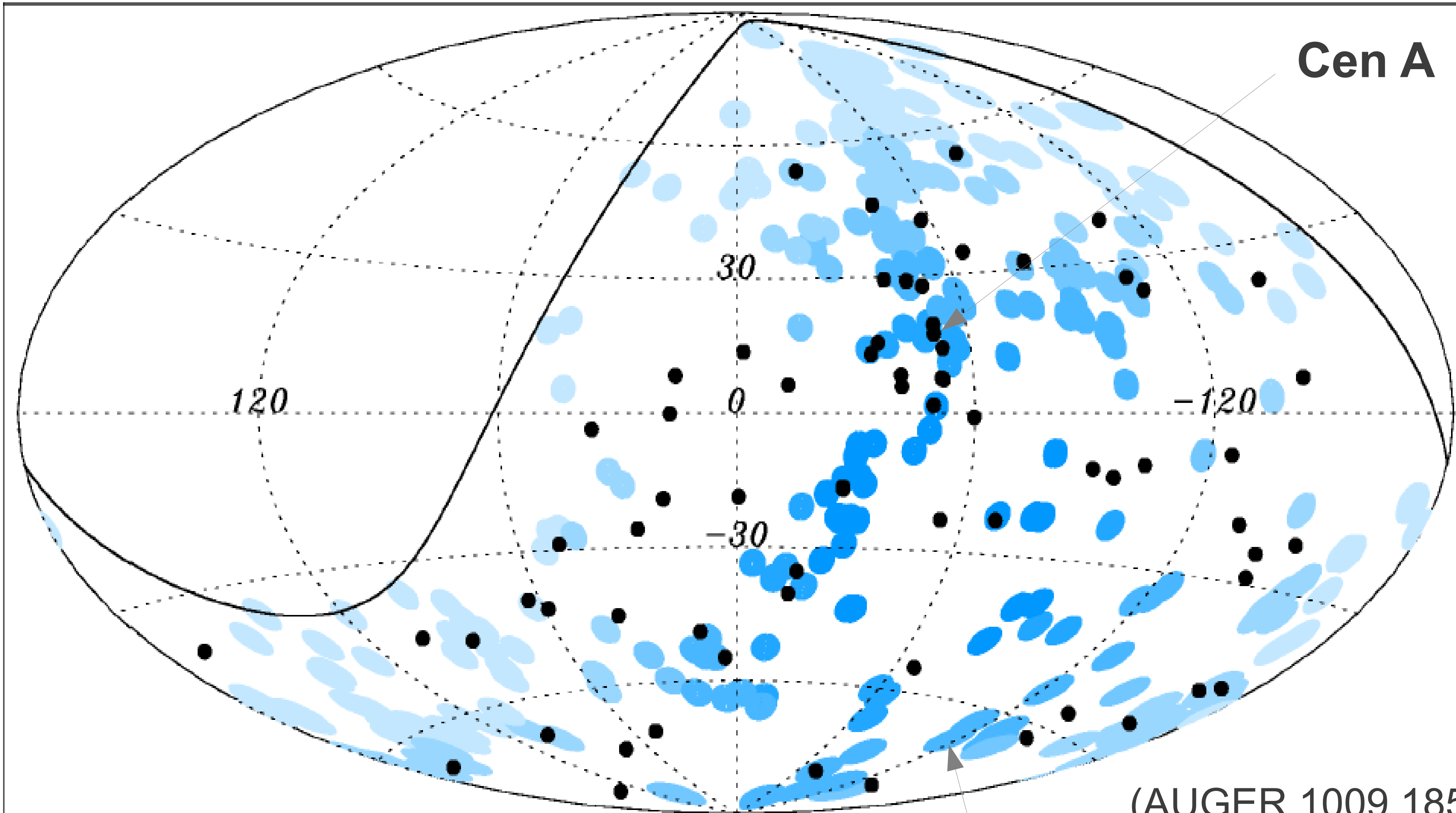
# SEARCH FOR CORRELATIONS WITH AGN




**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% correlation (while isotropy → 21%)**

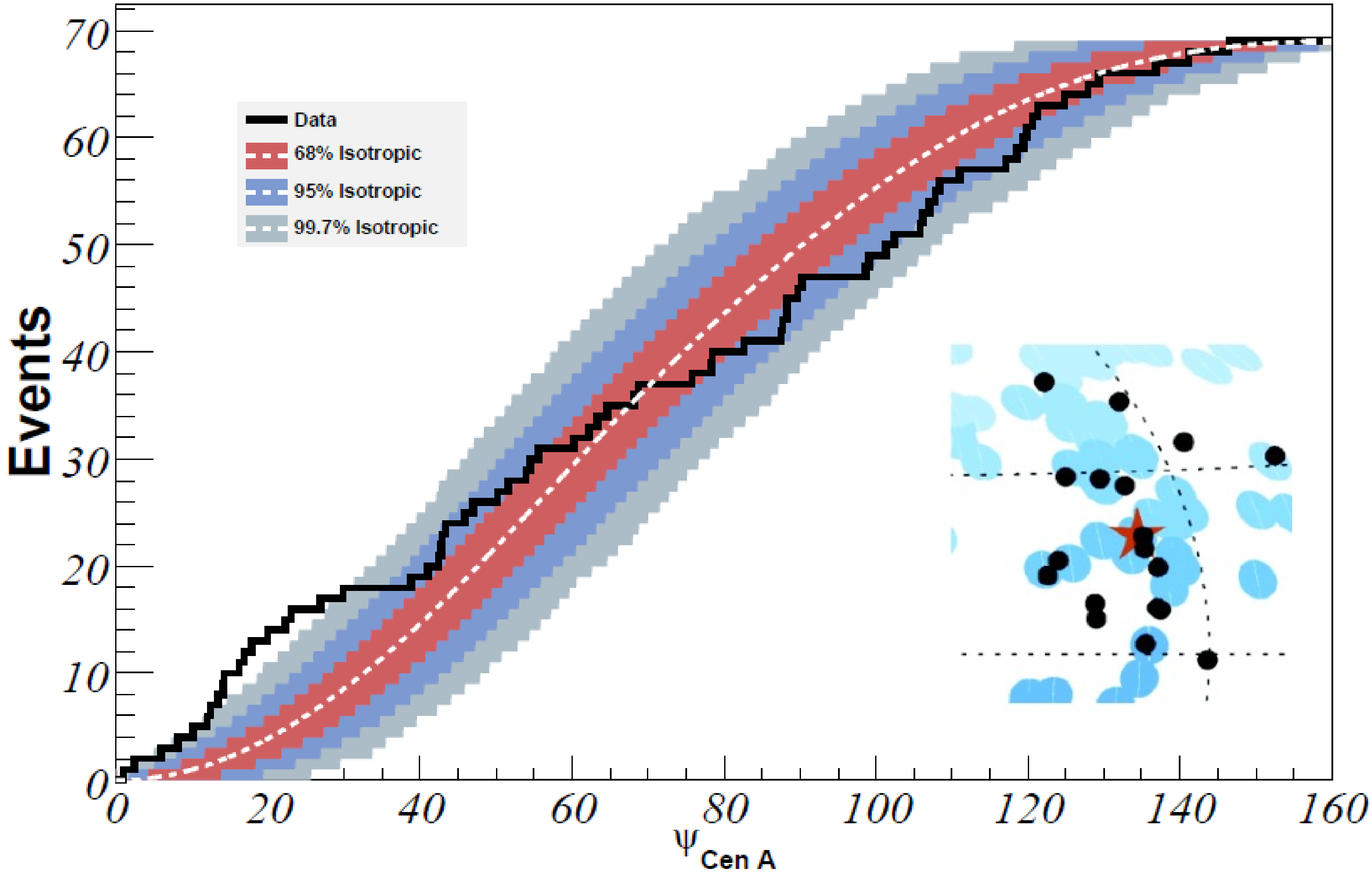
# AUGER sky map above 55 EeV




69 events with E > 55 EeV

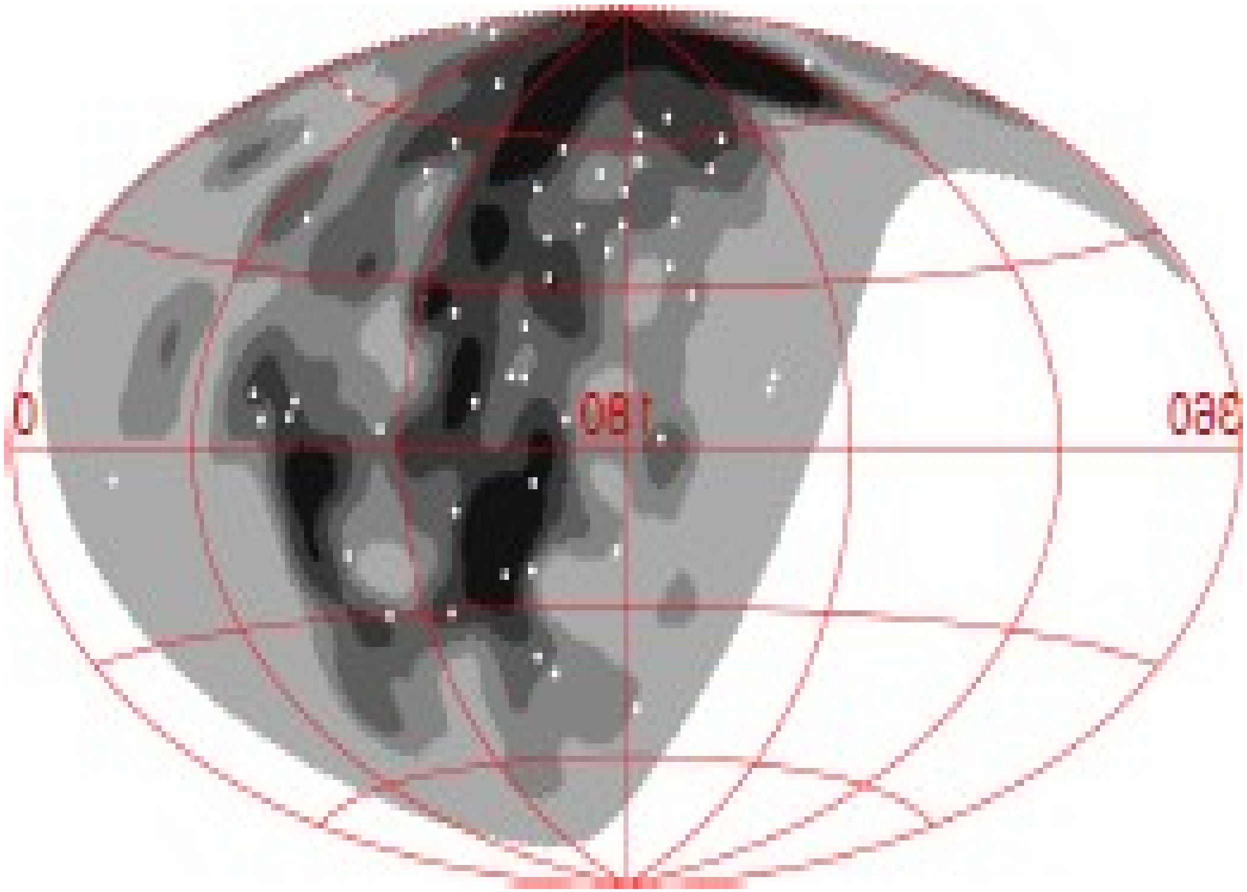
Nearby AGN at < 75 Mpc

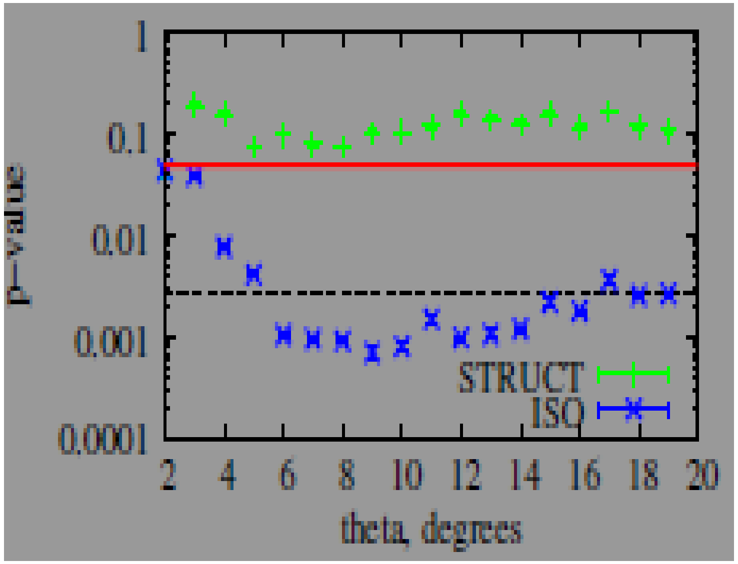
# Auger excess around Centaurus A: closest AGN




**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
but need more data

# 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