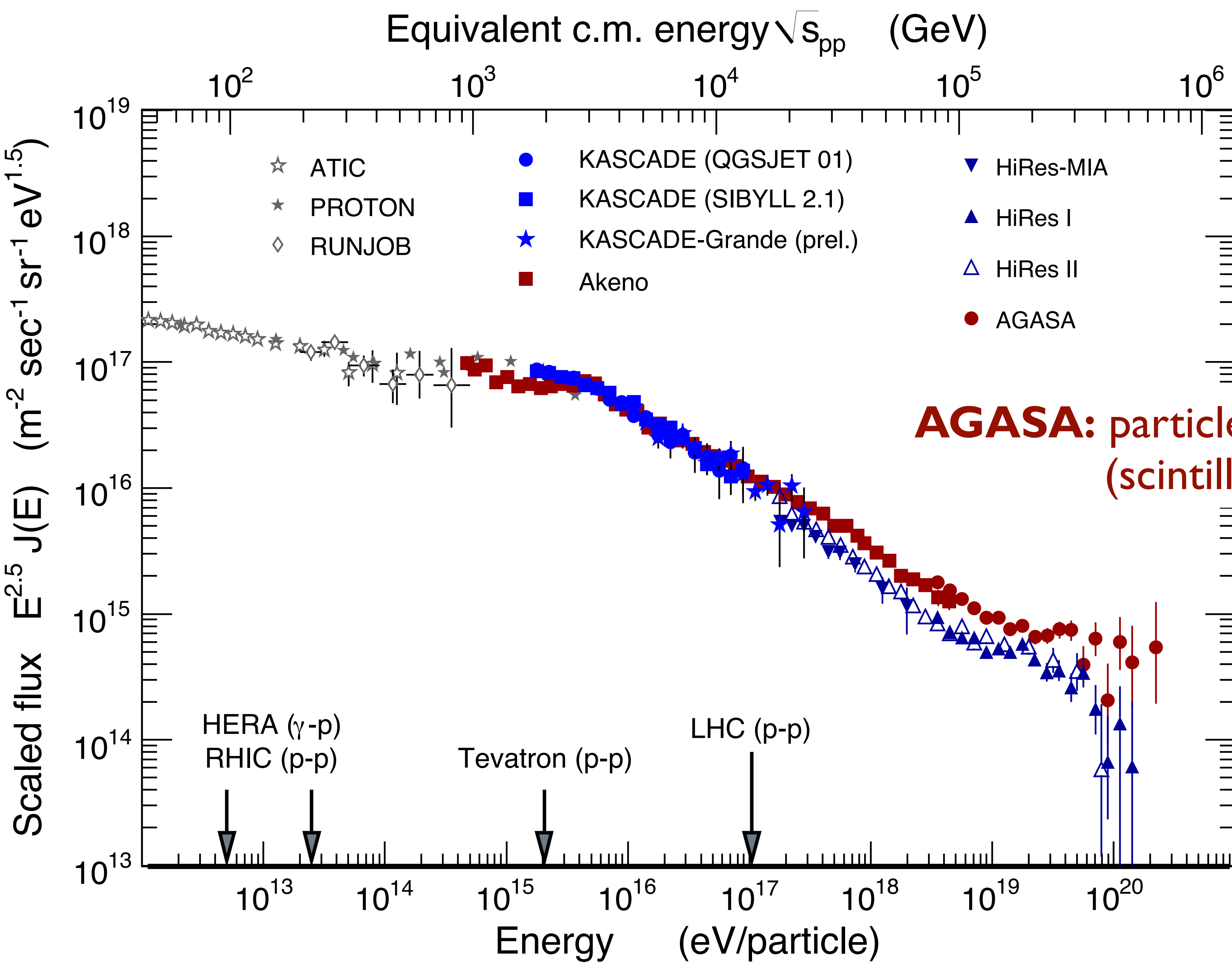
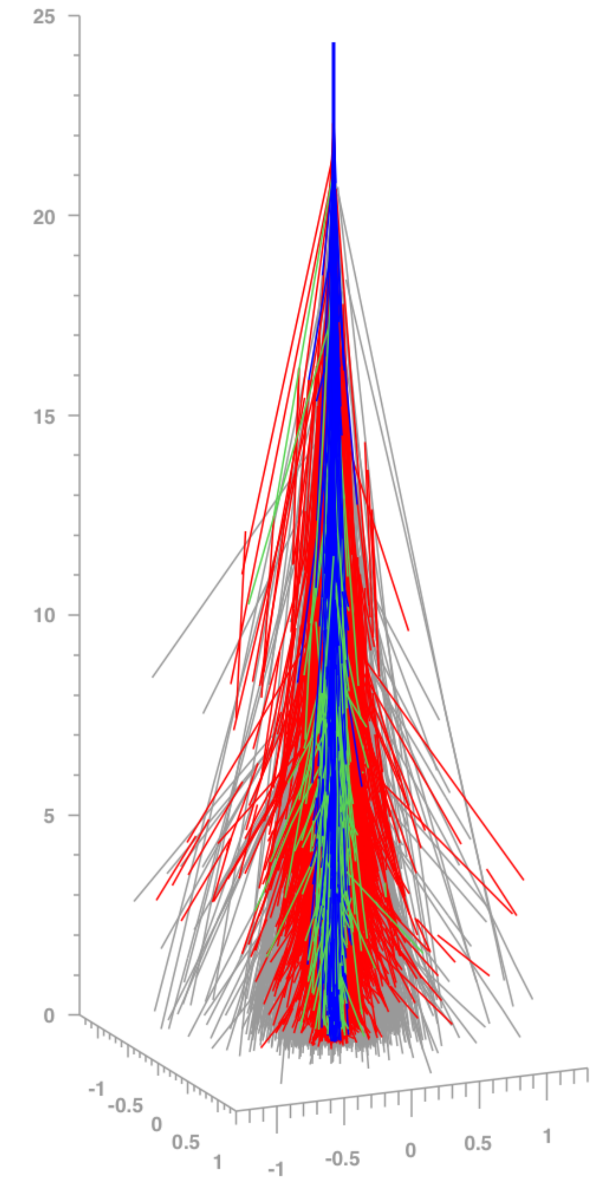
On the Importance of Determining the Energy Scale of UHECR Detectors

Ralph Engel (Karlsruhe Institute of Technology)

Status of data some years ago



AGASA: particles at ground (scintillator array)



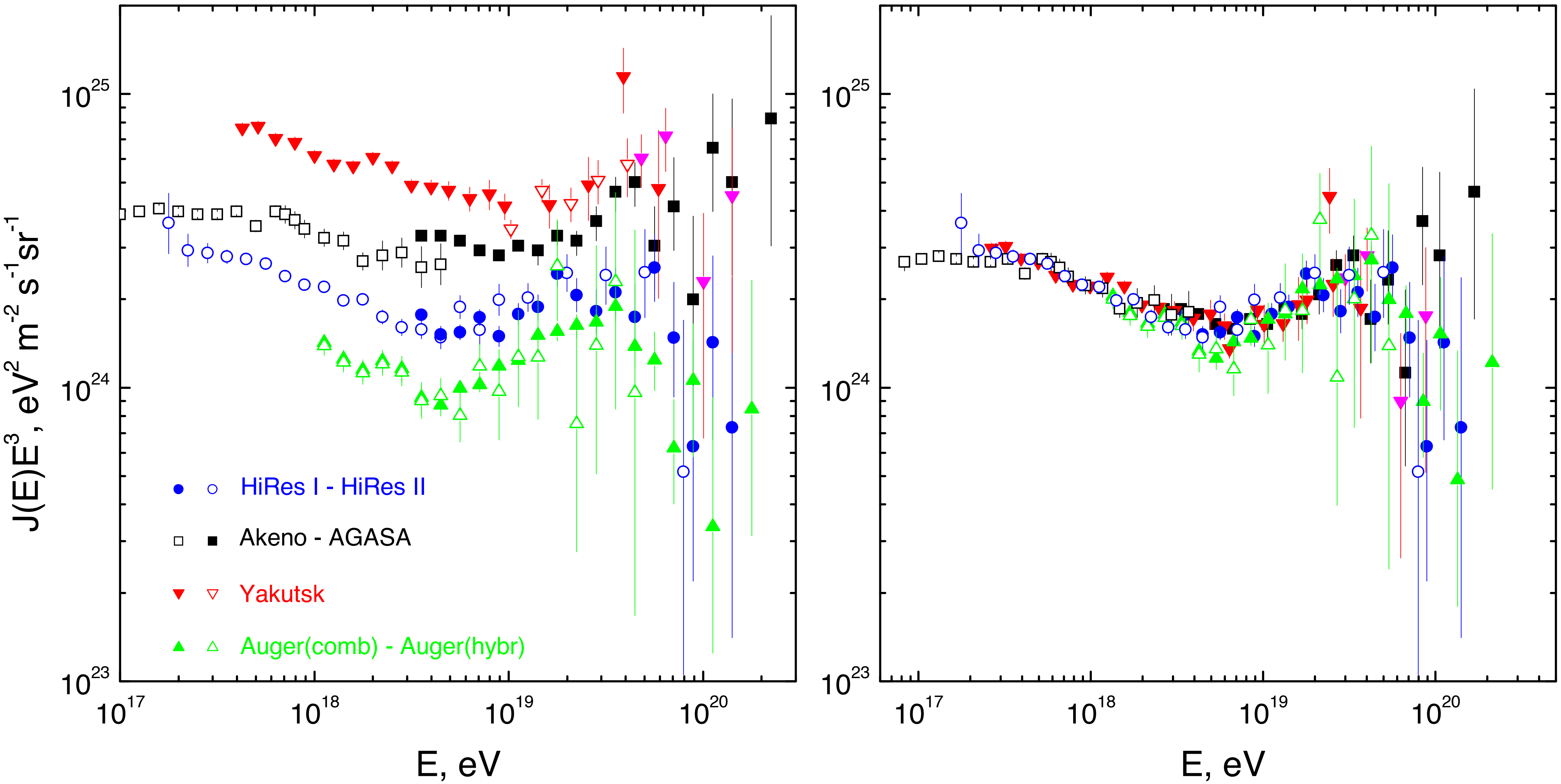
HiRes Fly´s Eye: longitudinal shower profile (fluorescence telescopes)

Flux data contradictory
Composition light ?
Apparent isotropy ?

Discrepancy related to shortcomings in shower simulation?

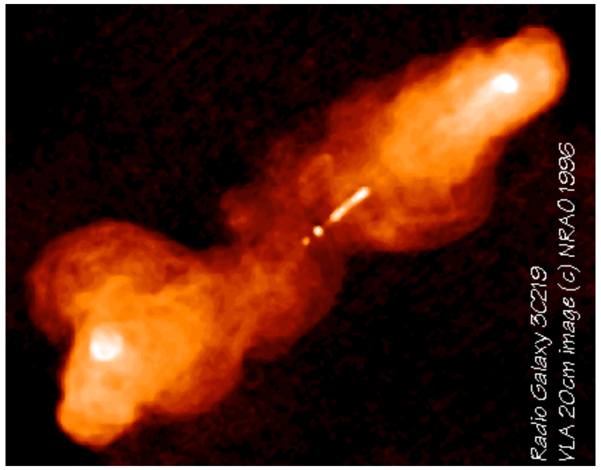
Energy scale uncertainty vs. all-particle flux

Good agreement between different experiments if energy is shifted



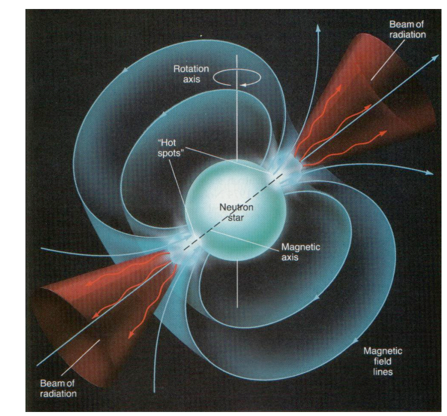
(Berezinsky, J. Phys. Conf. Ser., 2008)

Exotic source and propagation scenarios ?



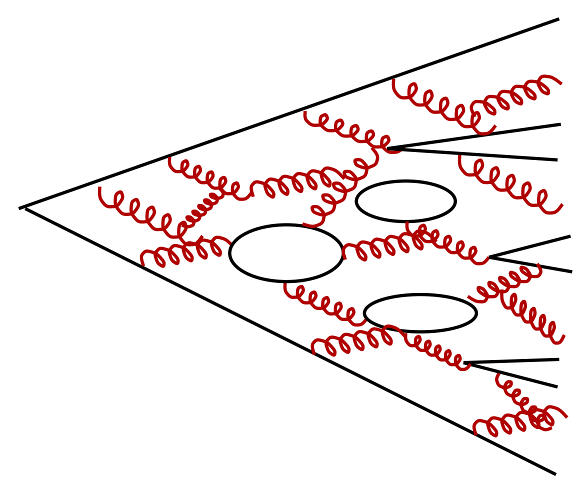
Active Galactic Nuclei (AGN):
Black Hole of ~10^9 solar masses

Magnetars:
magnetic field up to ~10^{15} G



	Process	Distribution	Injection flux
AGNs, GRBs, ... (☆)	Diffuse shock acceleration	Cosmological	p ... Fe
Young pulsars (☆☆)	EM acceleration	Galaxy & halo	mainly Fe
X particles (☆☆☆)	Decay & particle cascade	(a) Halo (SHDM) (b) Cosmological	ν, γ-rays and p
Z-bursts (☆☆☆☆)	Z^0 decay & particle cascade	Cosmological & clusters	ν, γ-rays and p

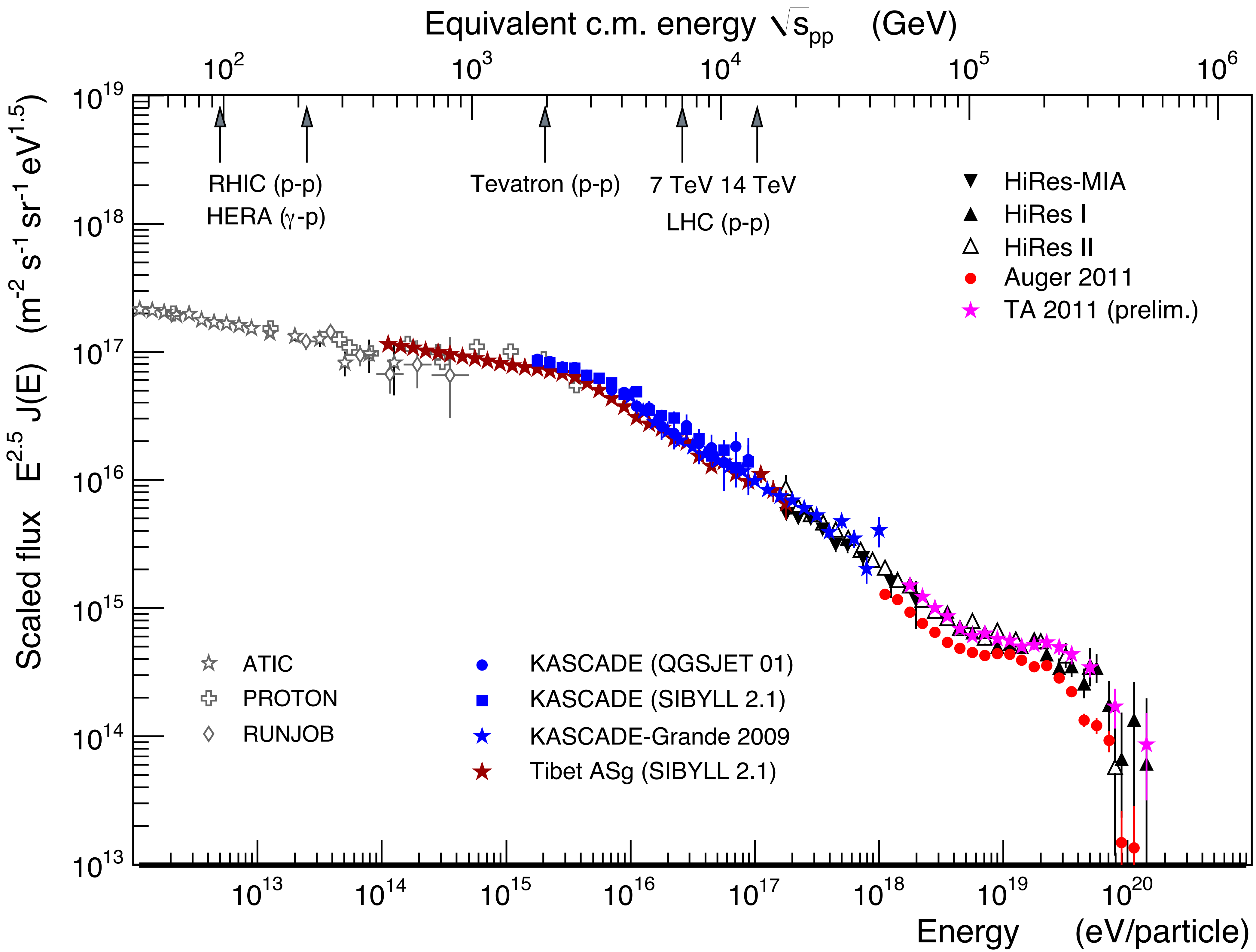
Super-heavy particles, topological defects:
$M_X \sim 10^{23}$ - 10^{24} eV



large fluxes of photons and neutrinos

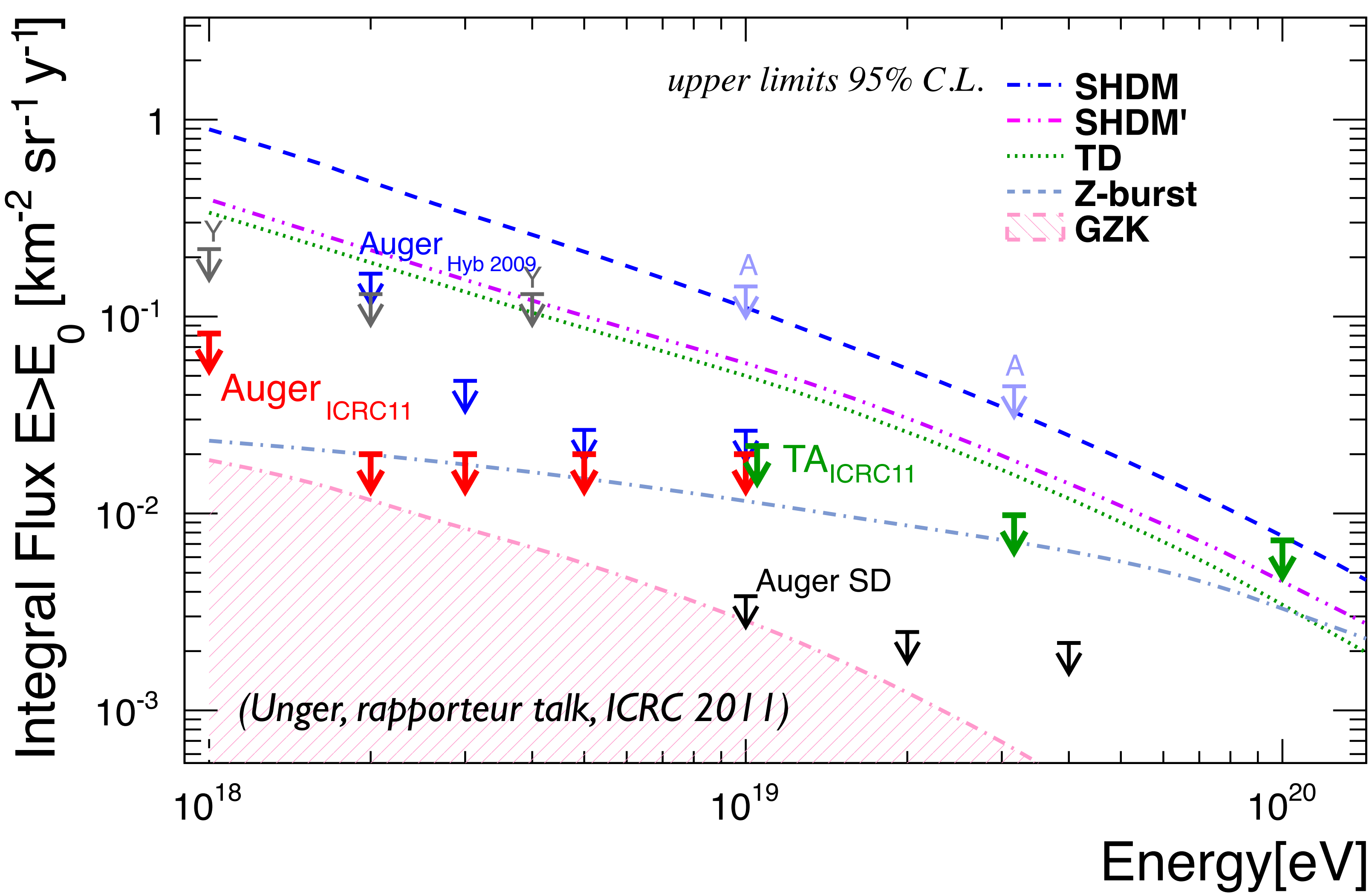
(RE, Nijmegen Summer School, 2006)

Current status of all-particle flux



Limits on exotic source scenarios

Searches for photon- and neutrino-induced showers: integral limits

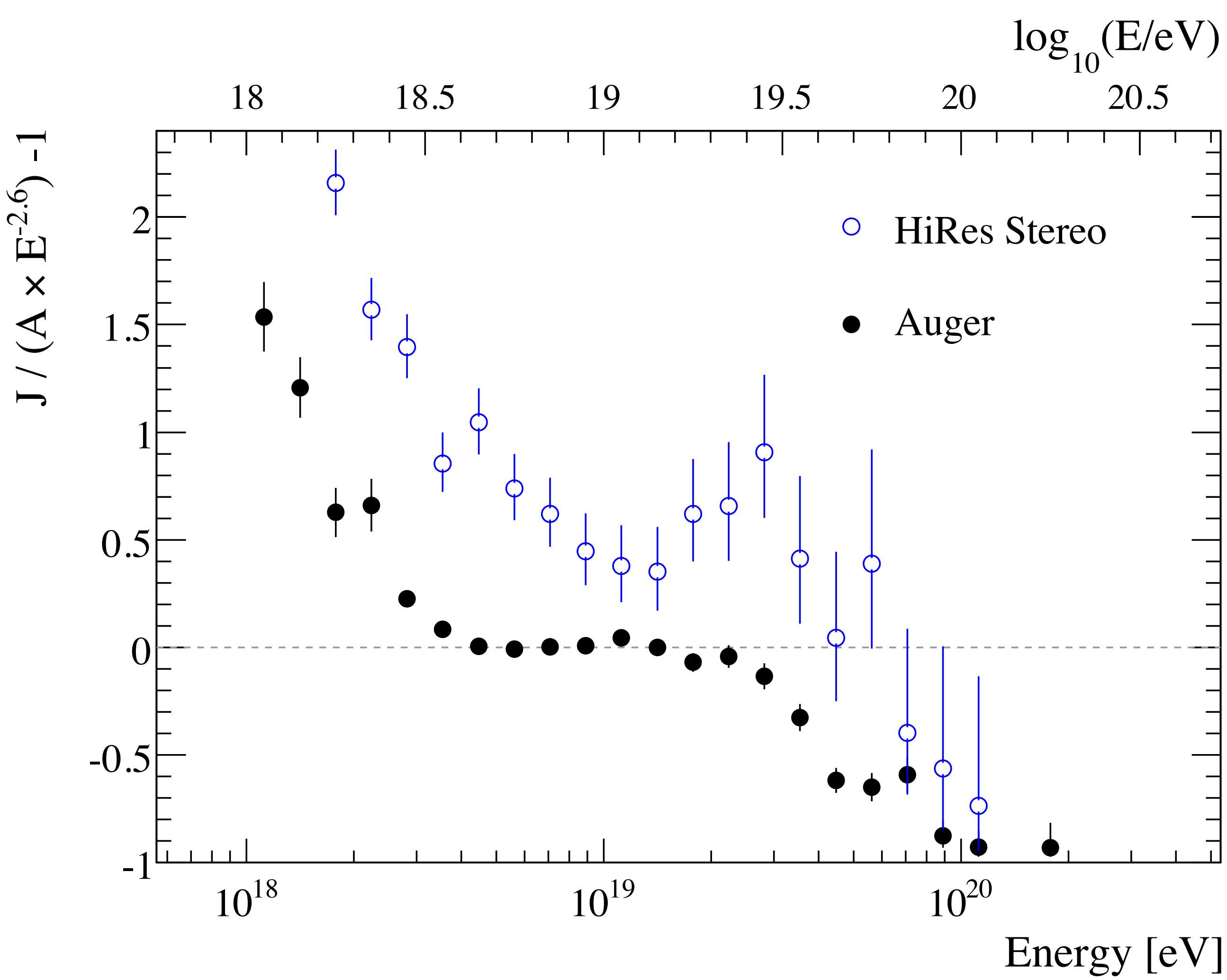


G.I. Rubtsov [TA Coll.], icrc1266

M. Settimo [Auger Coll.], icrc393

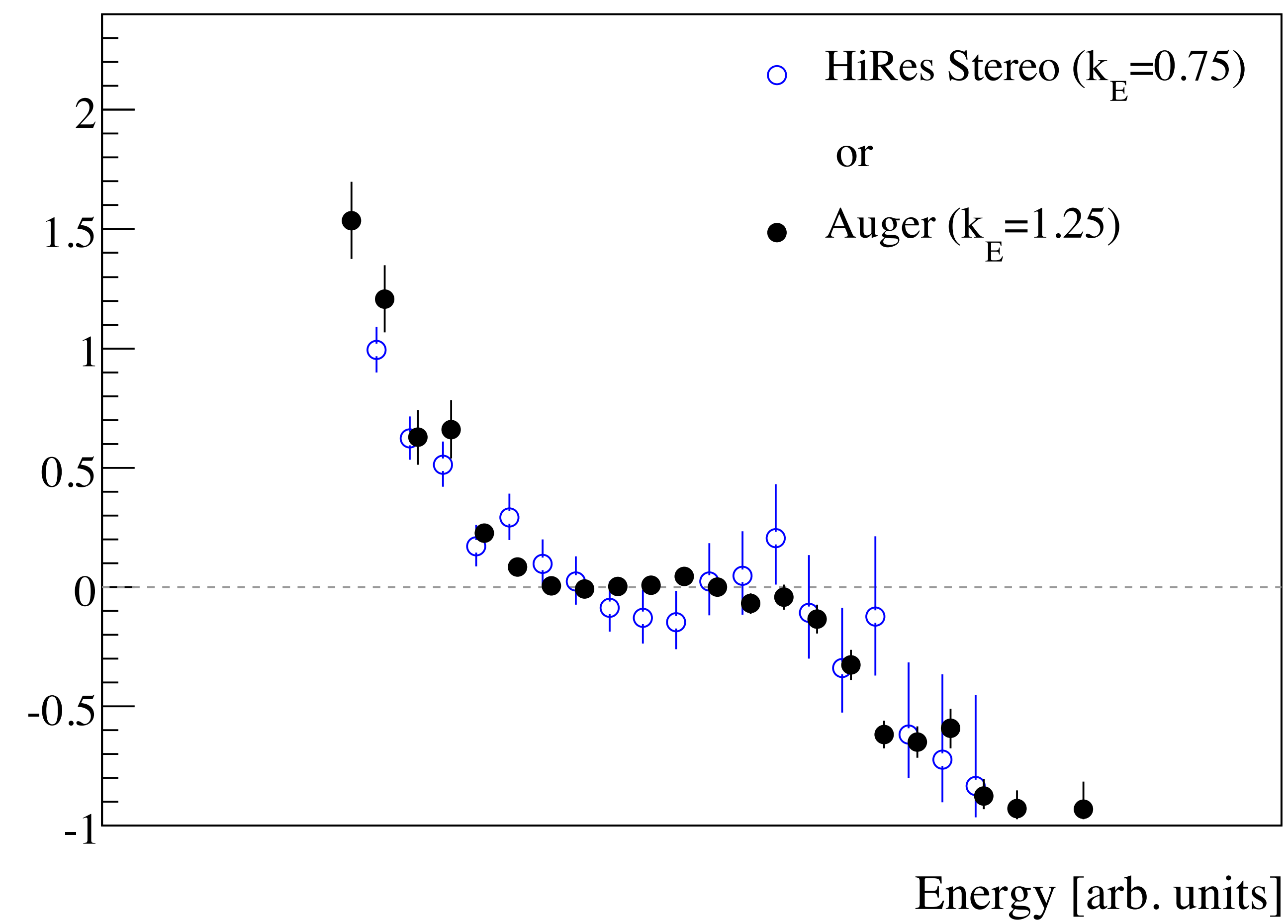
Most exotic source scenarios excluded or strongly disfavoured, similar results for ultra-high energy neutrino searches

Energy scale uncertainty vs. all-particle flux (i)



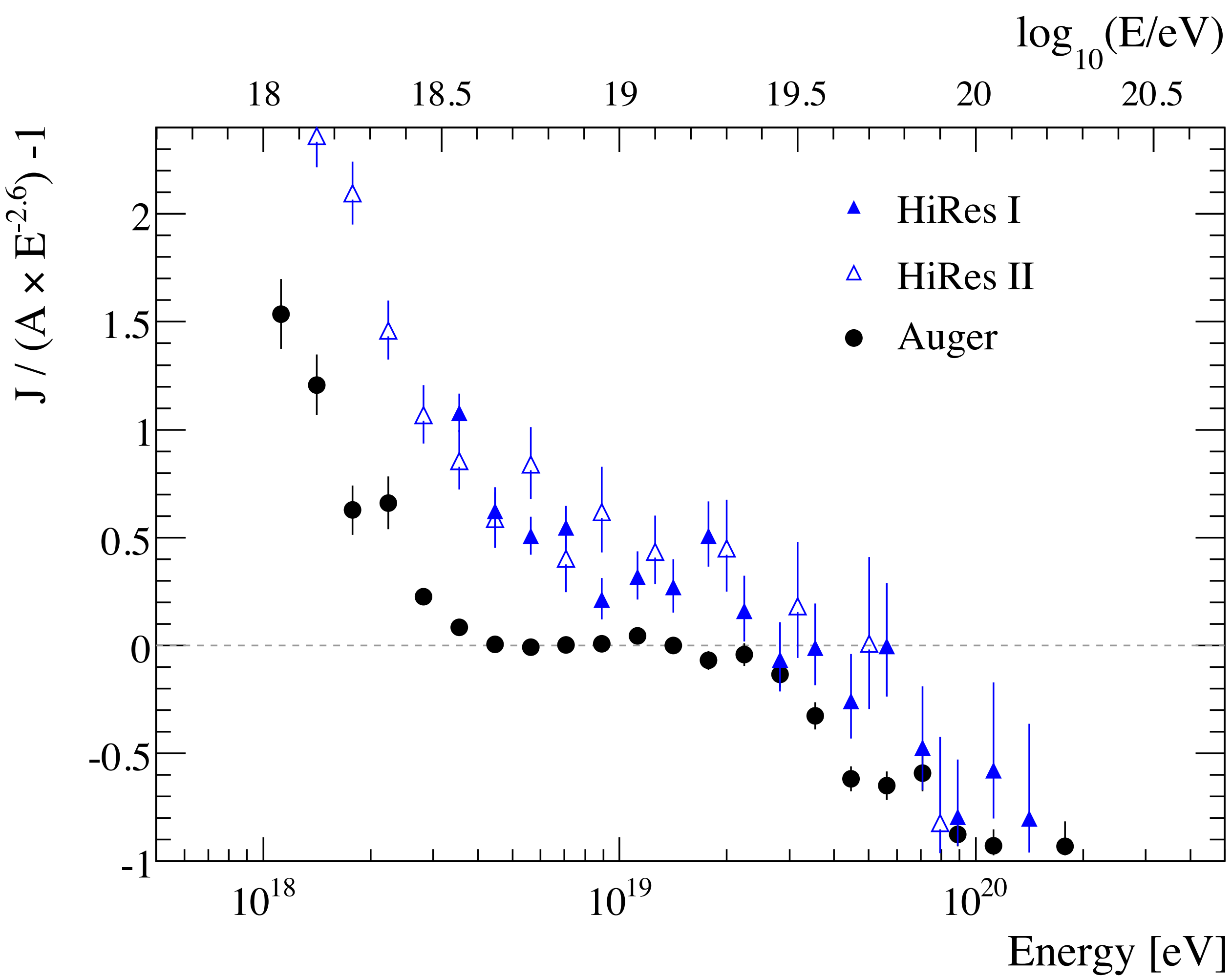
HiRes stereo spectrum:
17% sys. uncertainty

Auger combined spectrum:
22% sys. uncertainty

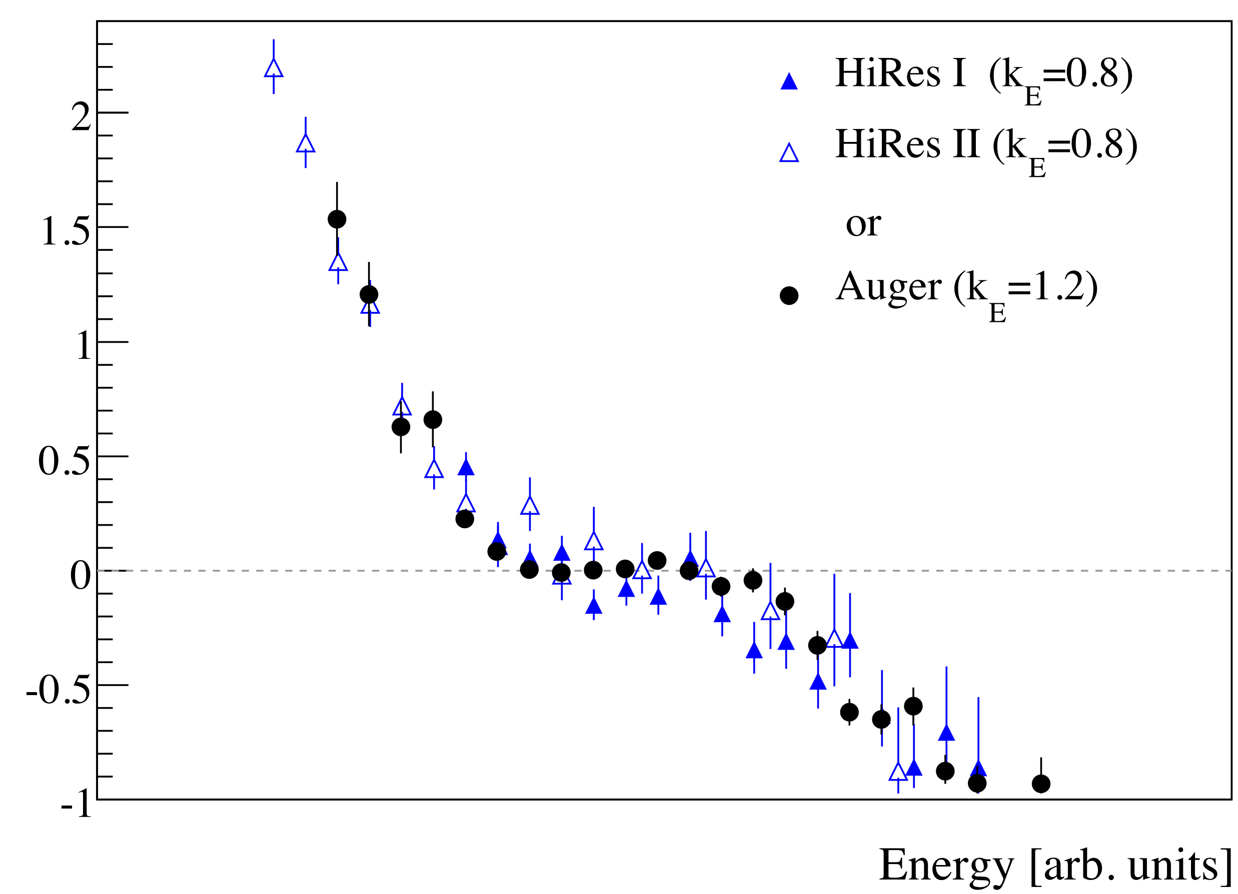


Total energy shift ~25%

Energy scale uncertainty vs. all-particle flux (ii)



Auger combined spectrum:
22% sys. uncertainty

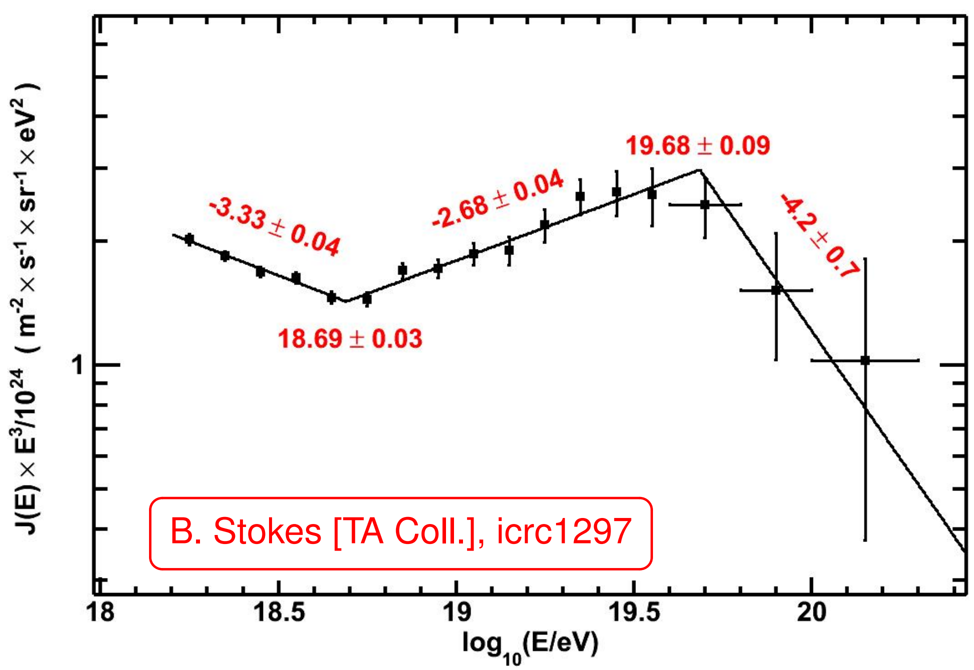


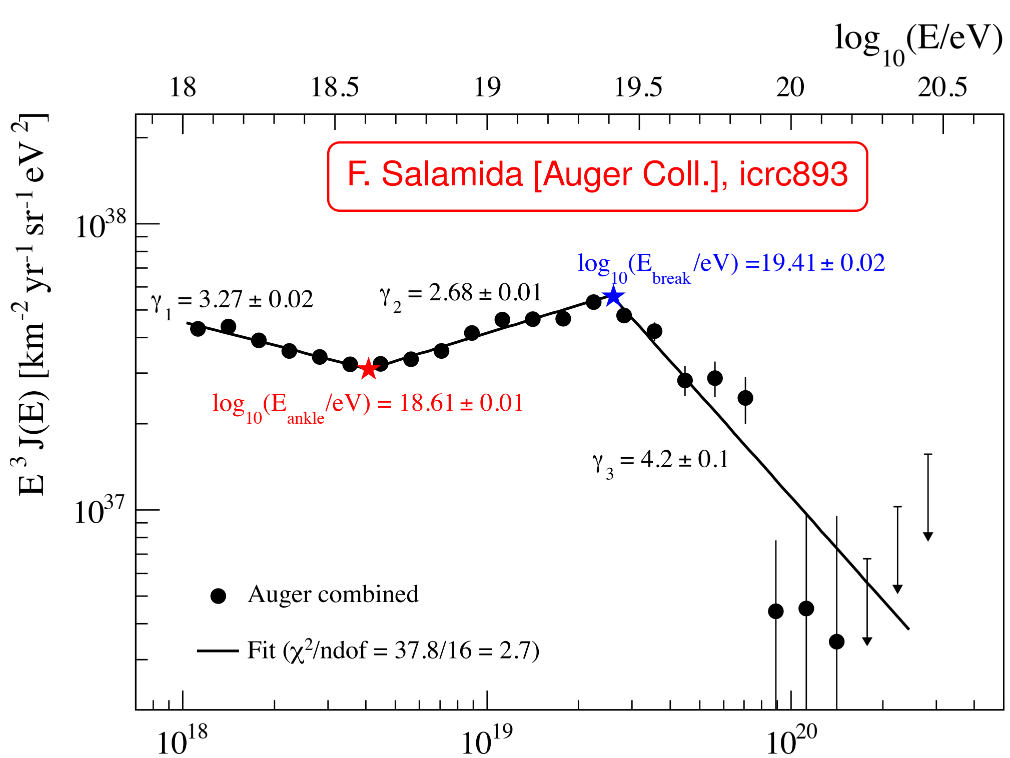
HiRes I & II mono spectra:
17% sys. uncertainty

Total energy shift ~20%

Energy scale uncertainty vs. all-particle flux (iii)

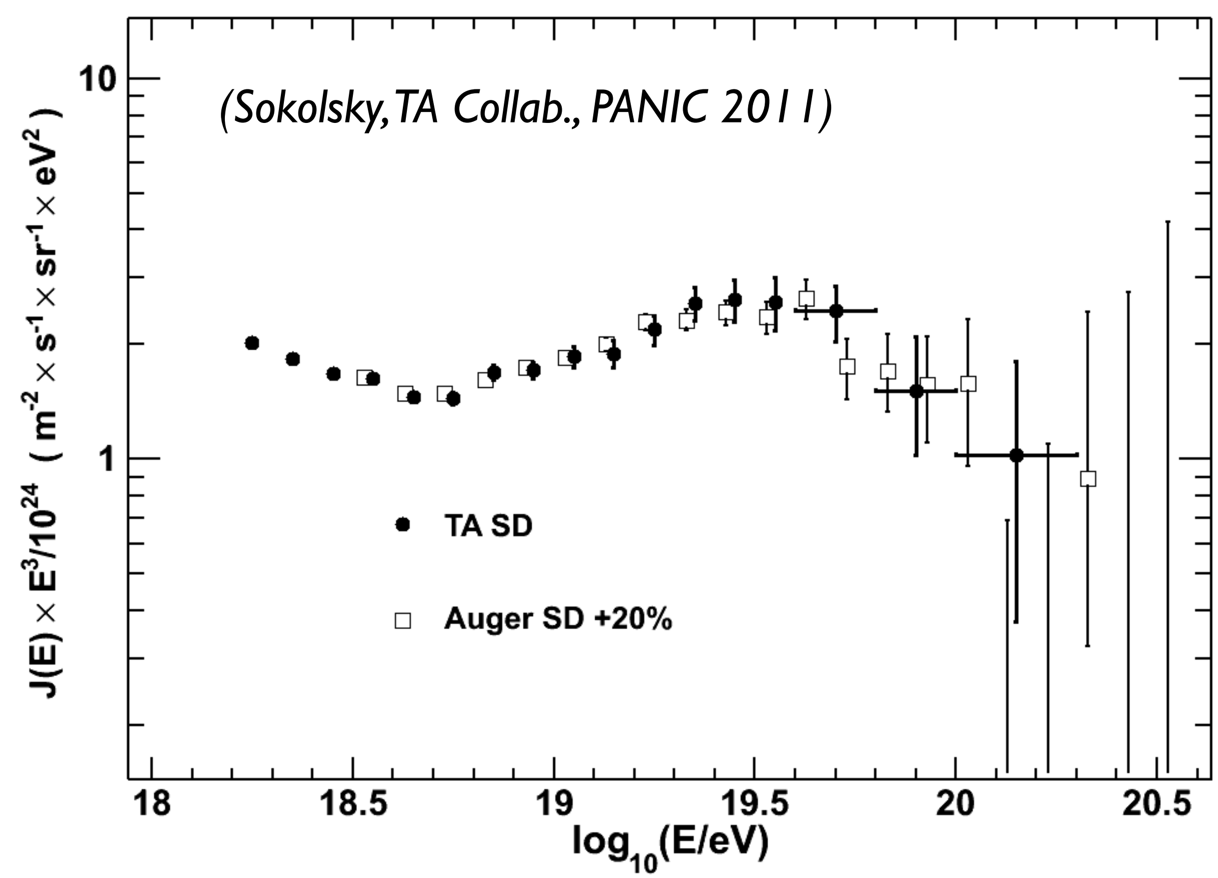
Power-law fits made only to characterize spectra





	TA	Auger
γ_1	3.33 ± 0.04	3.27 ± 0.02
γ_2	2.68 ± 0.04	2.68 ± 0.01
γ_3	4.2 ± 0.7	4.2 ± 0.1
$\lg(E_1/\mathrm{eV})$	18.69 ± 0.03	18.61 ± 0.01
$\lg(E_2/\mathrm{eV})$	19.68 ± 0.09	19.41 ± 0.02

(Unger, rapporteur talk, ICRC 2011)

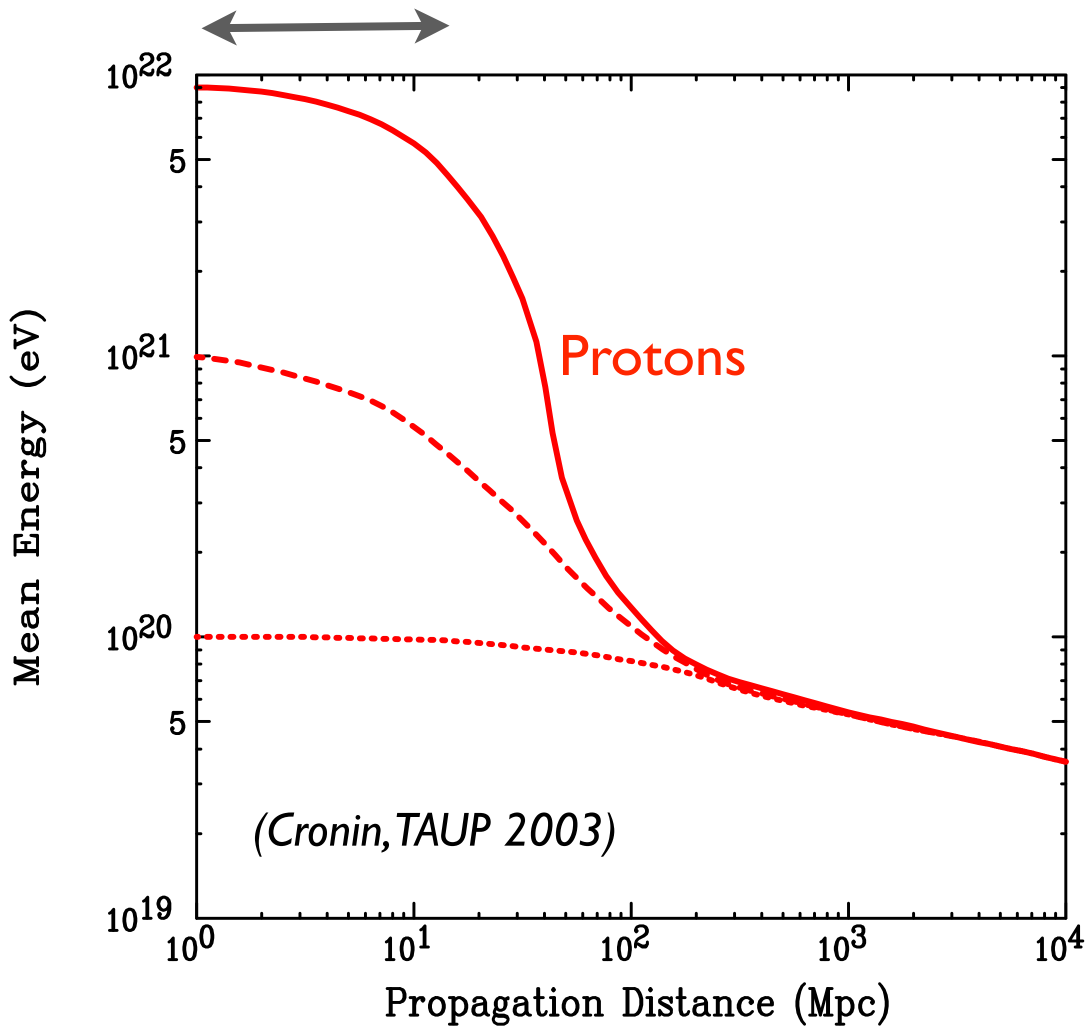


Differences well within ~20% sys. uncertainty

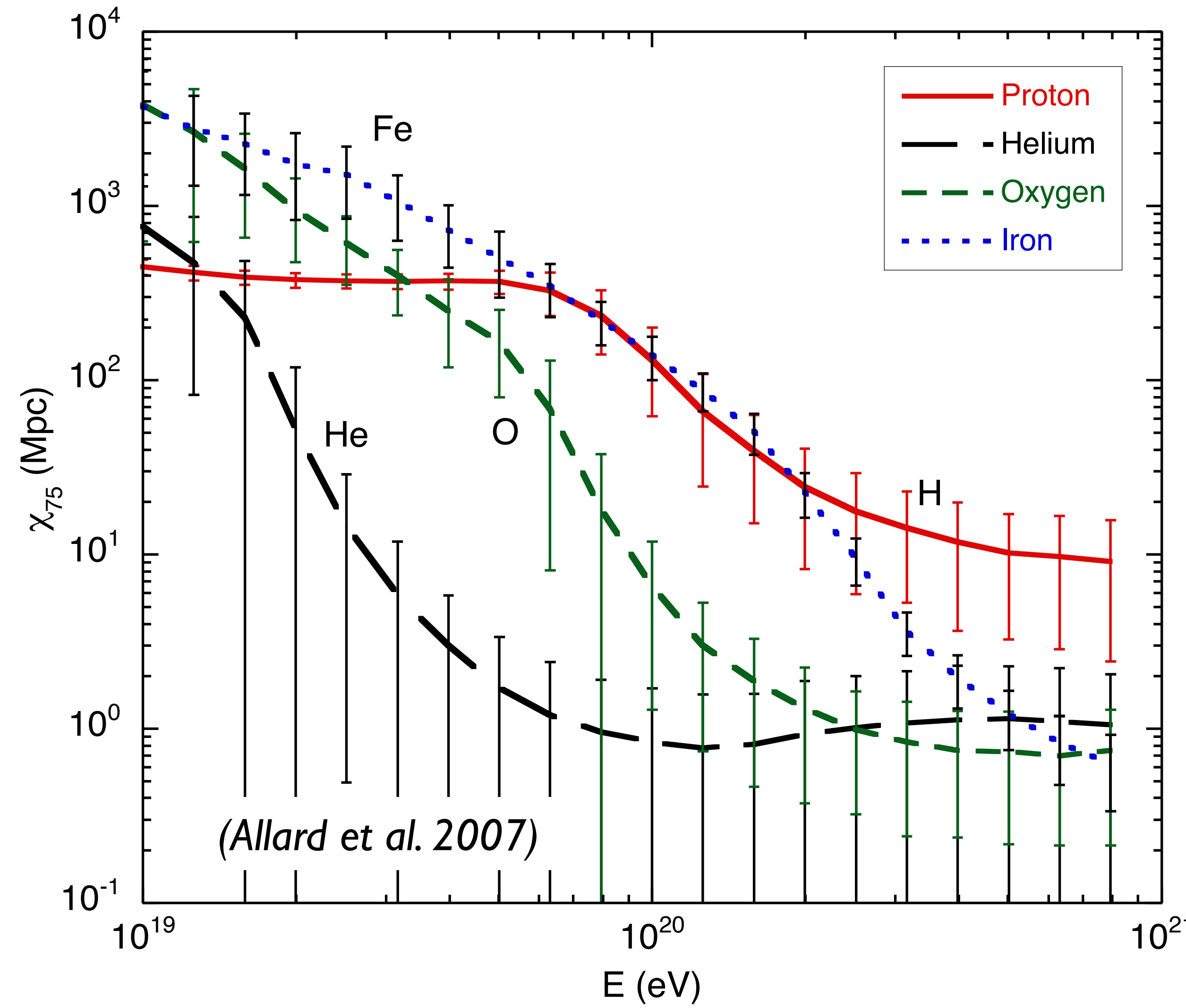
Interpretation as GZK suppression

Recap: features of the GZK effect

Energy loss length



Energy loss length



Greisen-Zatsepin-Kuzmin effect (1966)

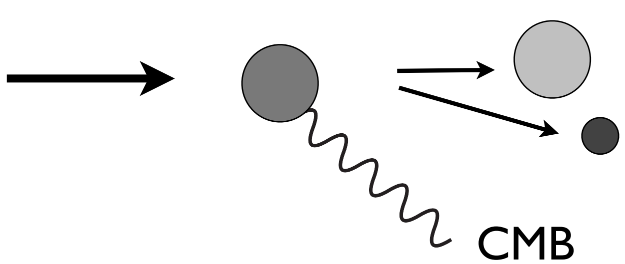
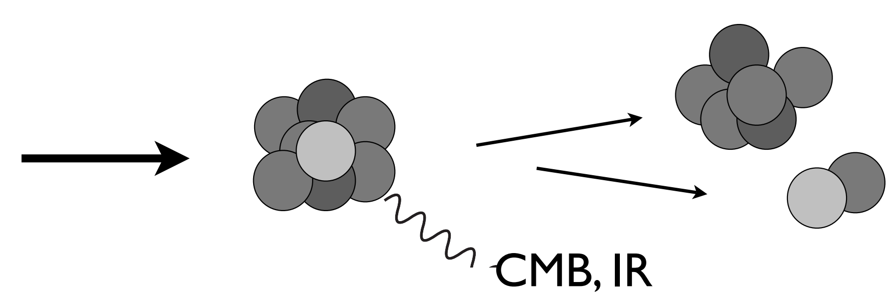


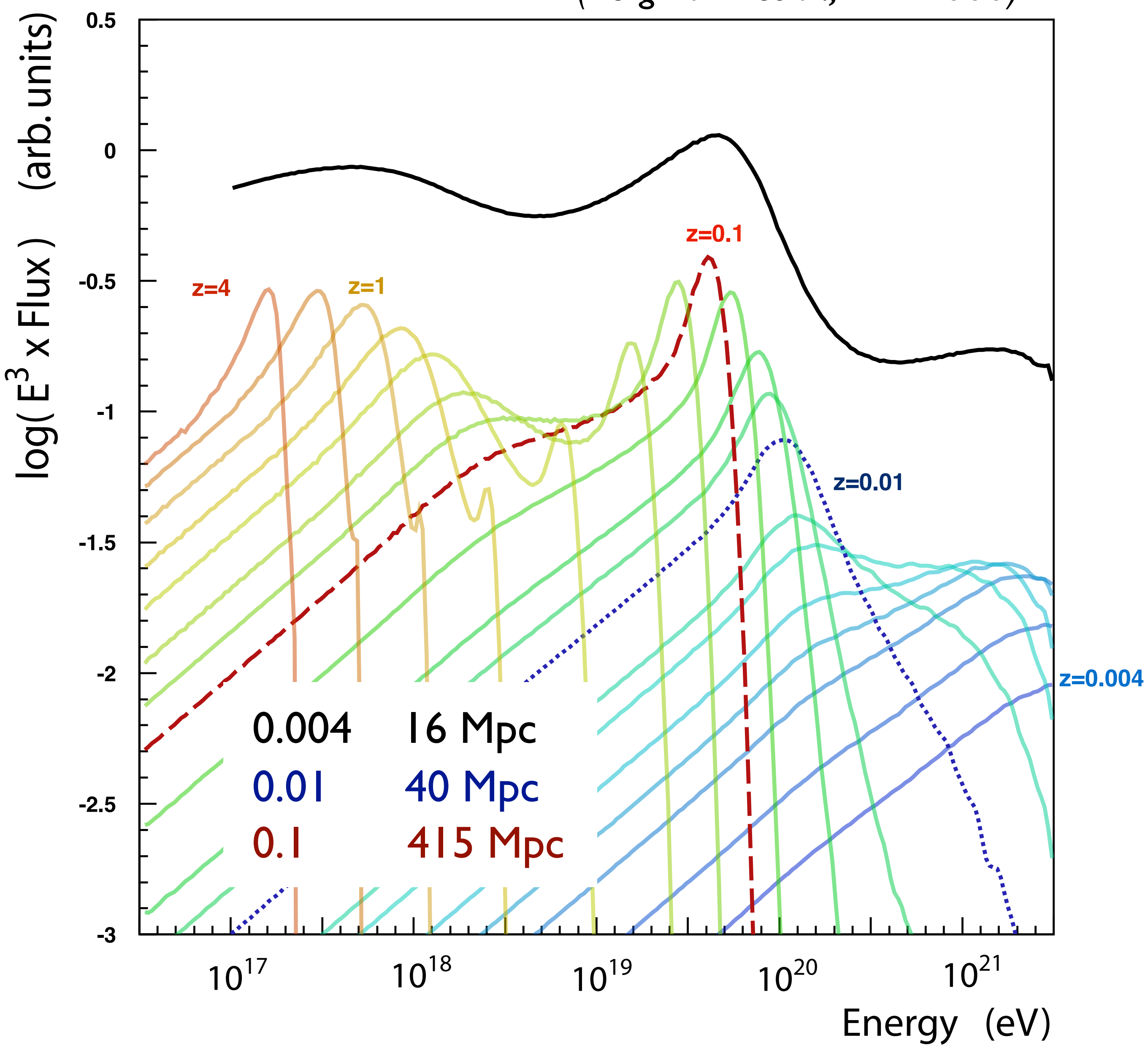
Photo-pion production

Photo-dissociation (giant dipole resonance)



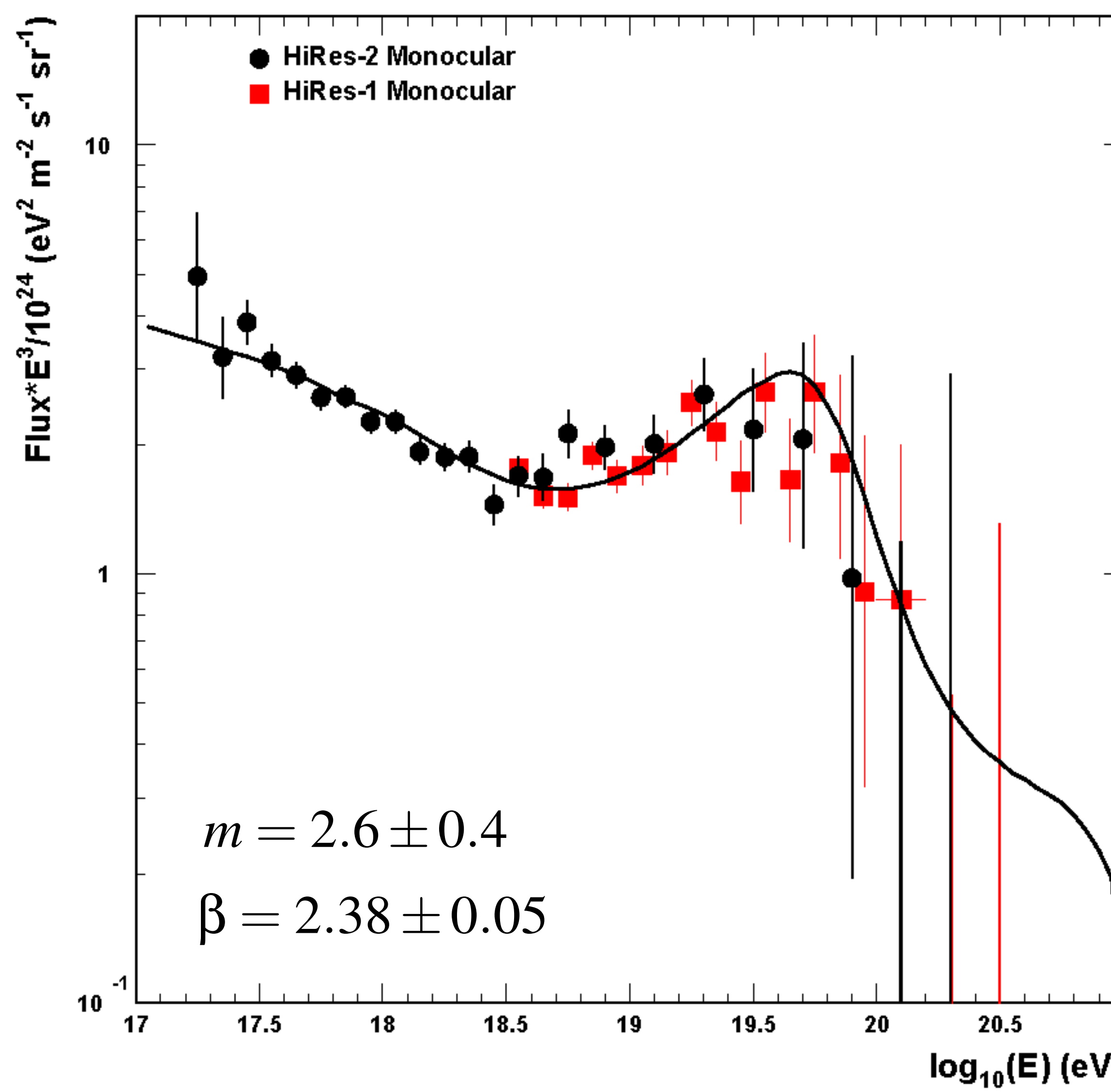
Fit with protons and homogeneous source distribution

(Bergmann et al., PLB 2006)



$$\frac{\mathrm{d}N_{\mathrm{inj}}}{\mathrm{d}E} \sim (1+z)^m\, E^{-\beta}$$

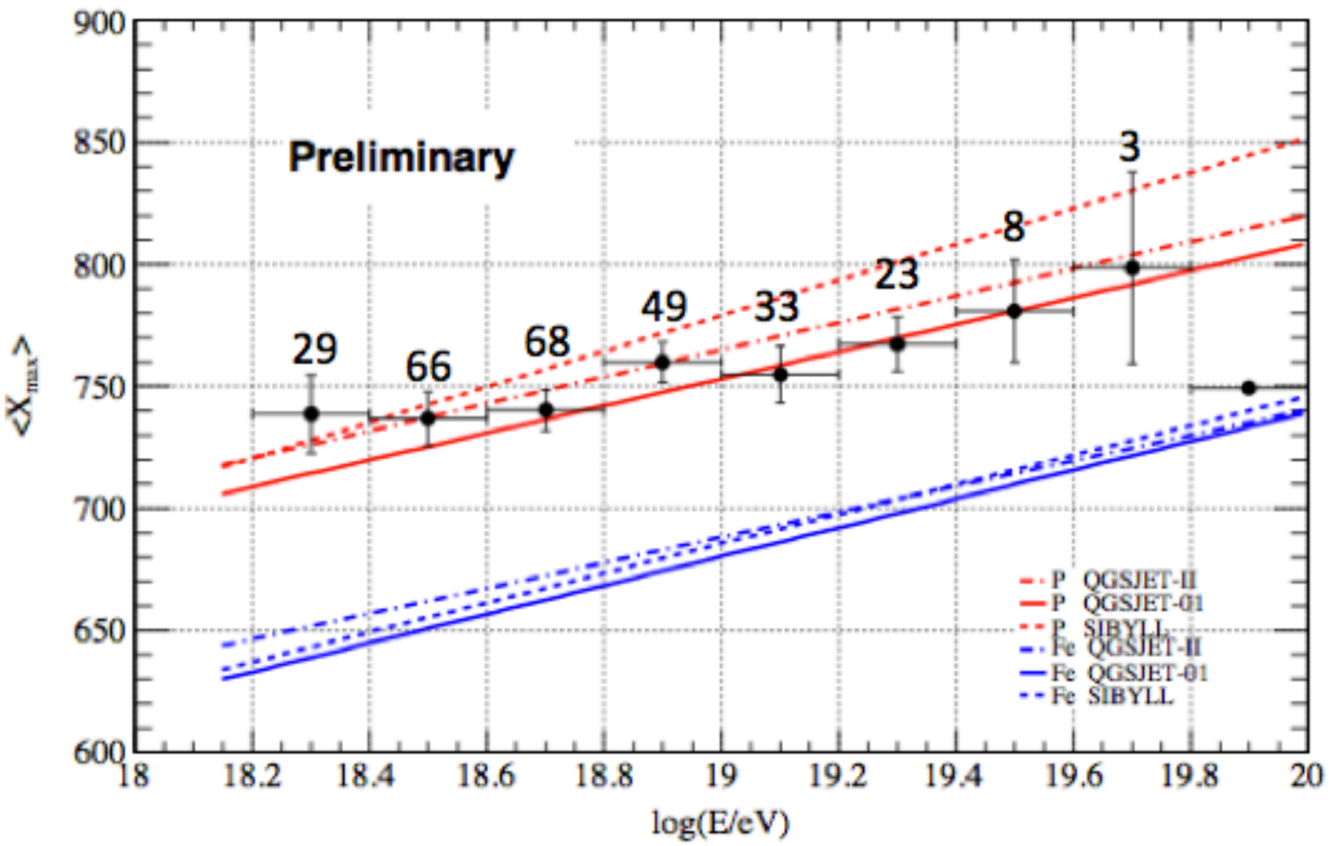
(HiRes, Phys. Lett. B, 2005)



Berezinsky et al. (dip model)

- use energy of dip for absolute calibration
- proton dominated composition only

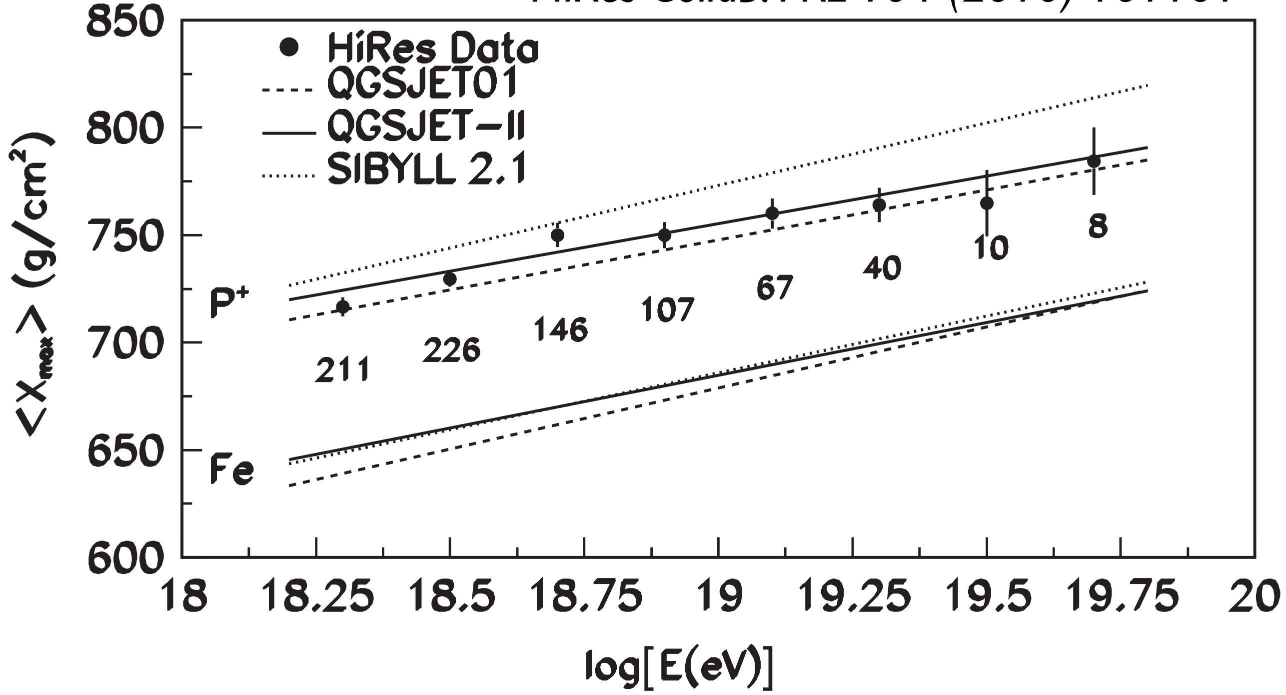
HiRes and Telescope Array: light composition



TA & HiRes data compatible with light composition (independent analyses)

(Tameda, TA Collab., ICRC 2011)

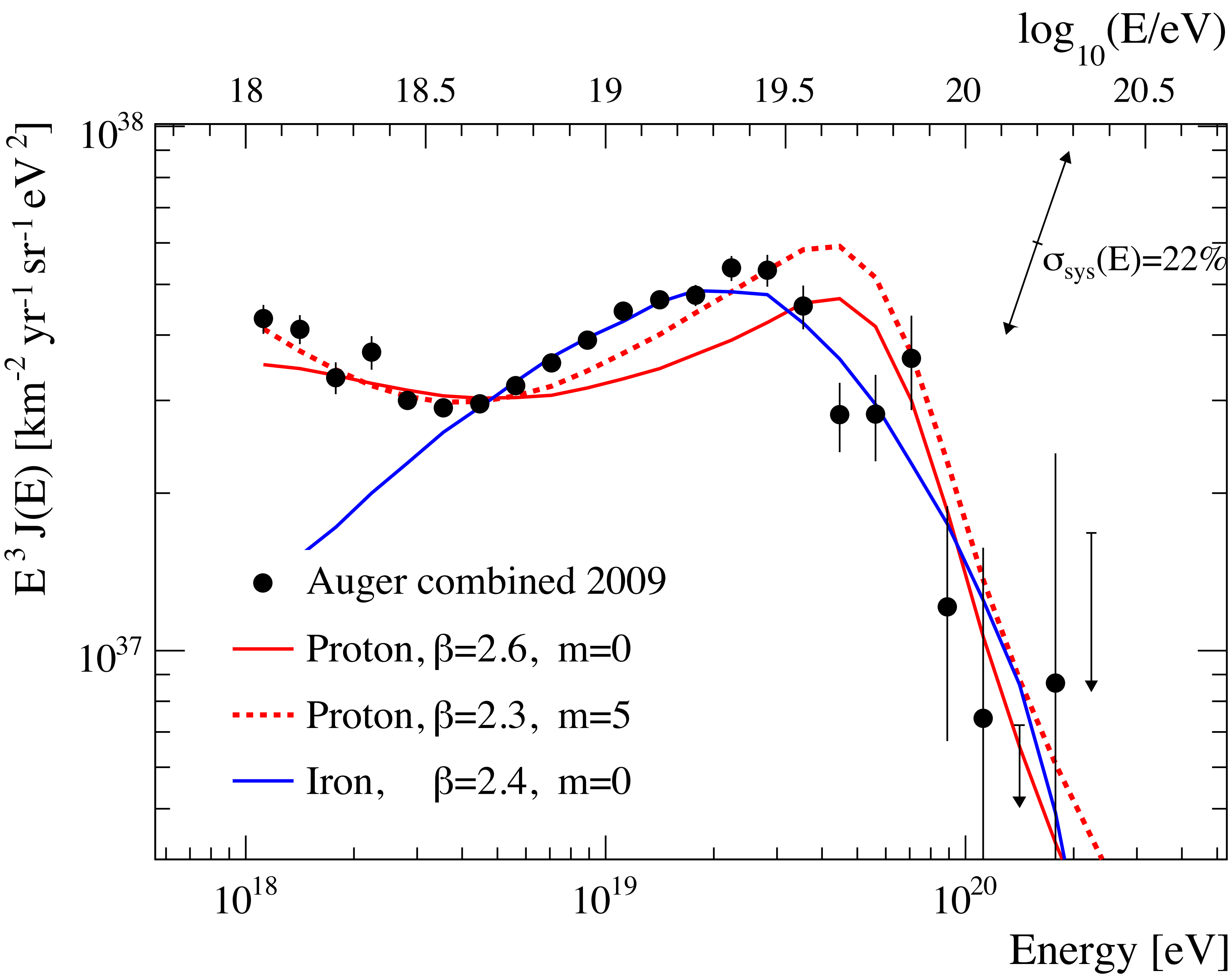
HiRes Collab. PRL 104 (2010) 161101



Note: no direct comparison of data with Auger results possible:

- Auger: fiducial volume cuts to avoid shower selection bias
- TA: selection bias included in MC simulations, not explicitly corrected for to increase statistics
- Data still compatible within sys. uncertainties

Similar fits using Auger energy spectrum



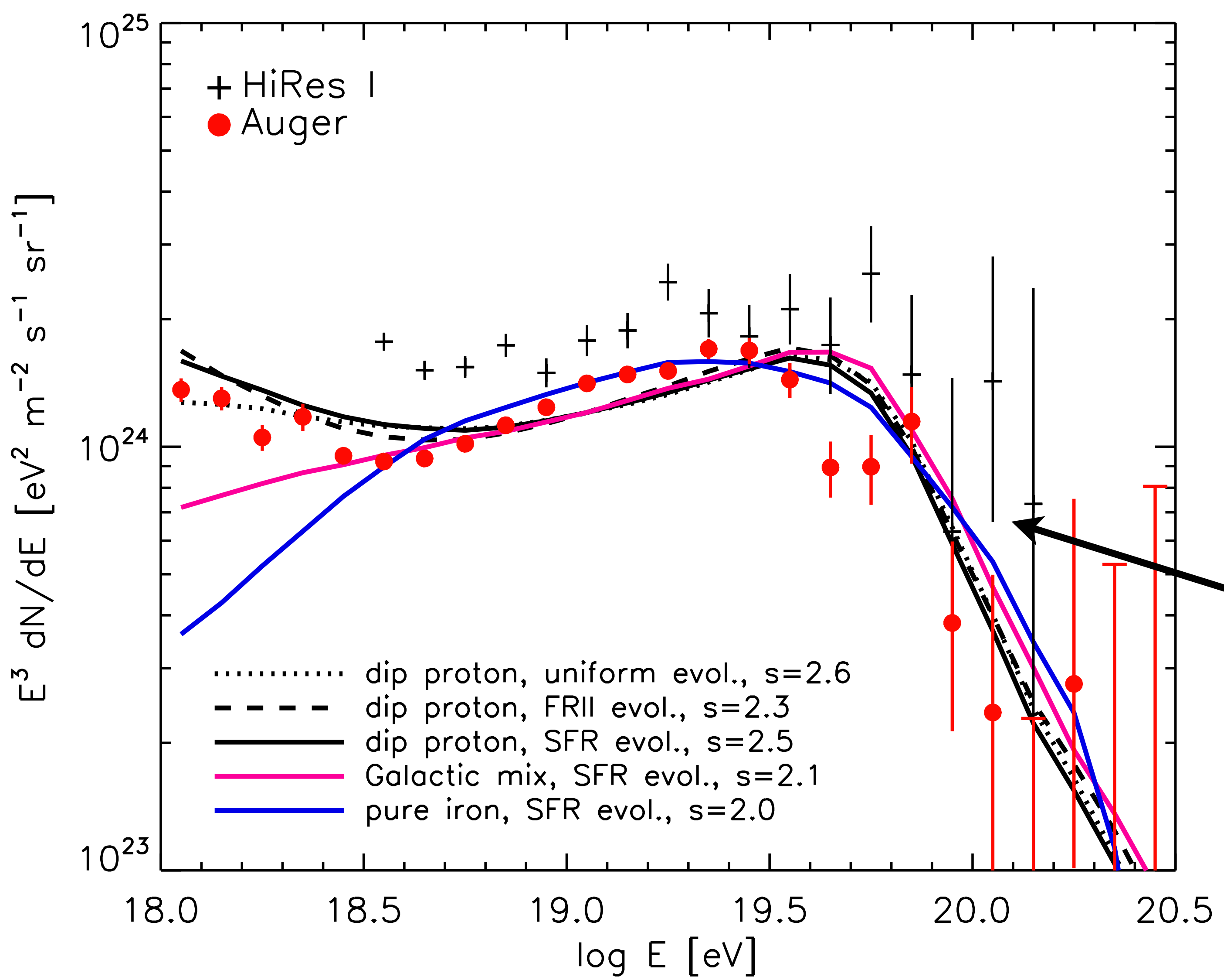
$$\frac{dN_{inj}}{dE} \sim (1+z)^m \, E^{-\beta}$$

No good fit found for proton dominated composition and nominal energy scale

(Auger, ICRC 2009)

Parameters and uncertainties of model fits

(Kotera & Olinto, 1101.4256)



Many free parameters

- cosmological evolution of sources
- nearby source distribution
- magnetic fields (galactic, extra-galactic)
- injection spectrum, max. energy
- mass composition at injection
- contribution from galactic sources

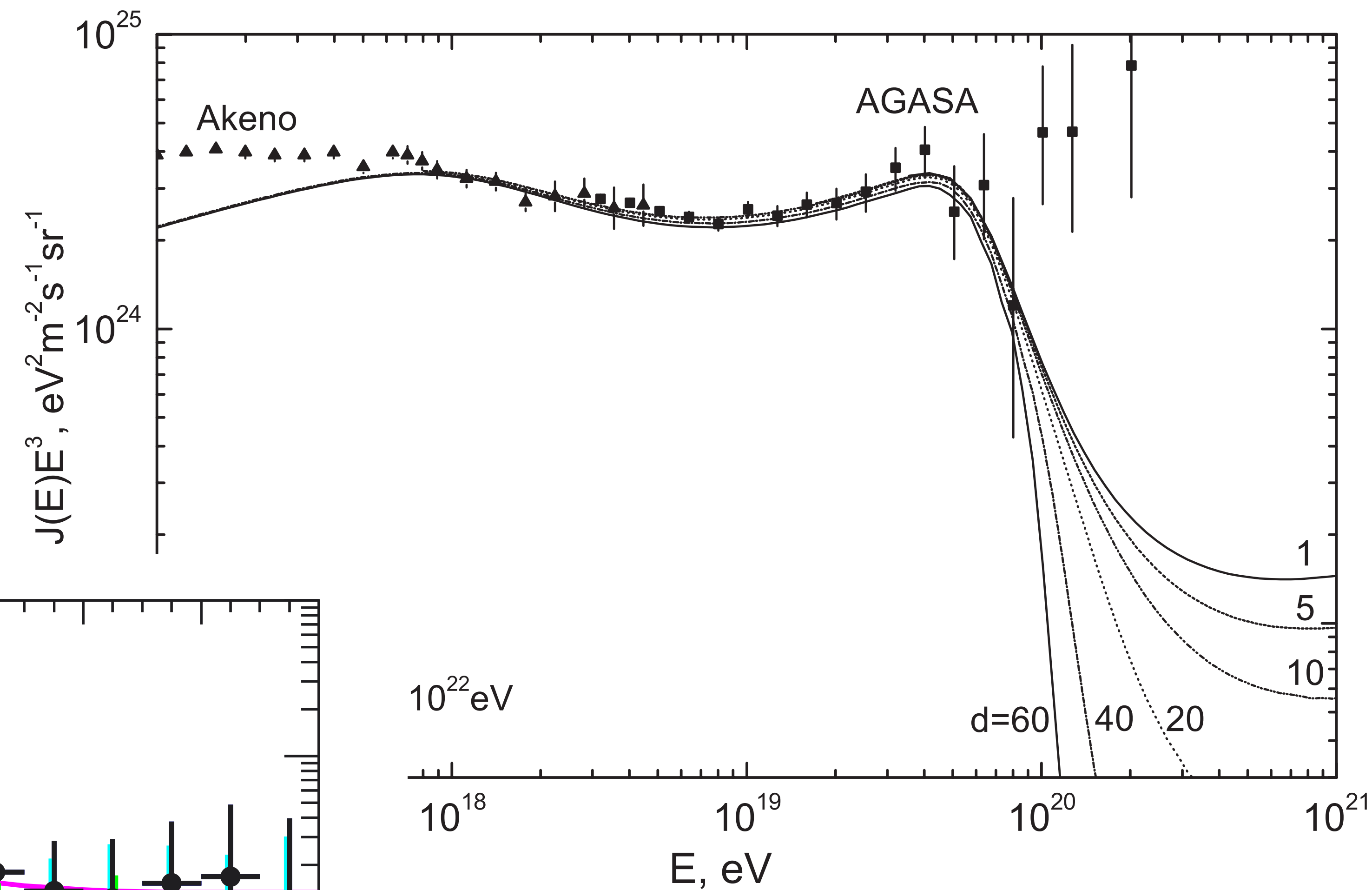
Results very insensitive to model assumptions

$$\frac{\mathrm{d}N_{\mathrm{inj}}}{\mathrm{d}E} \sim E^{-s}$$

But: deviation well within systematic uncertainty of energy scale of ~20%

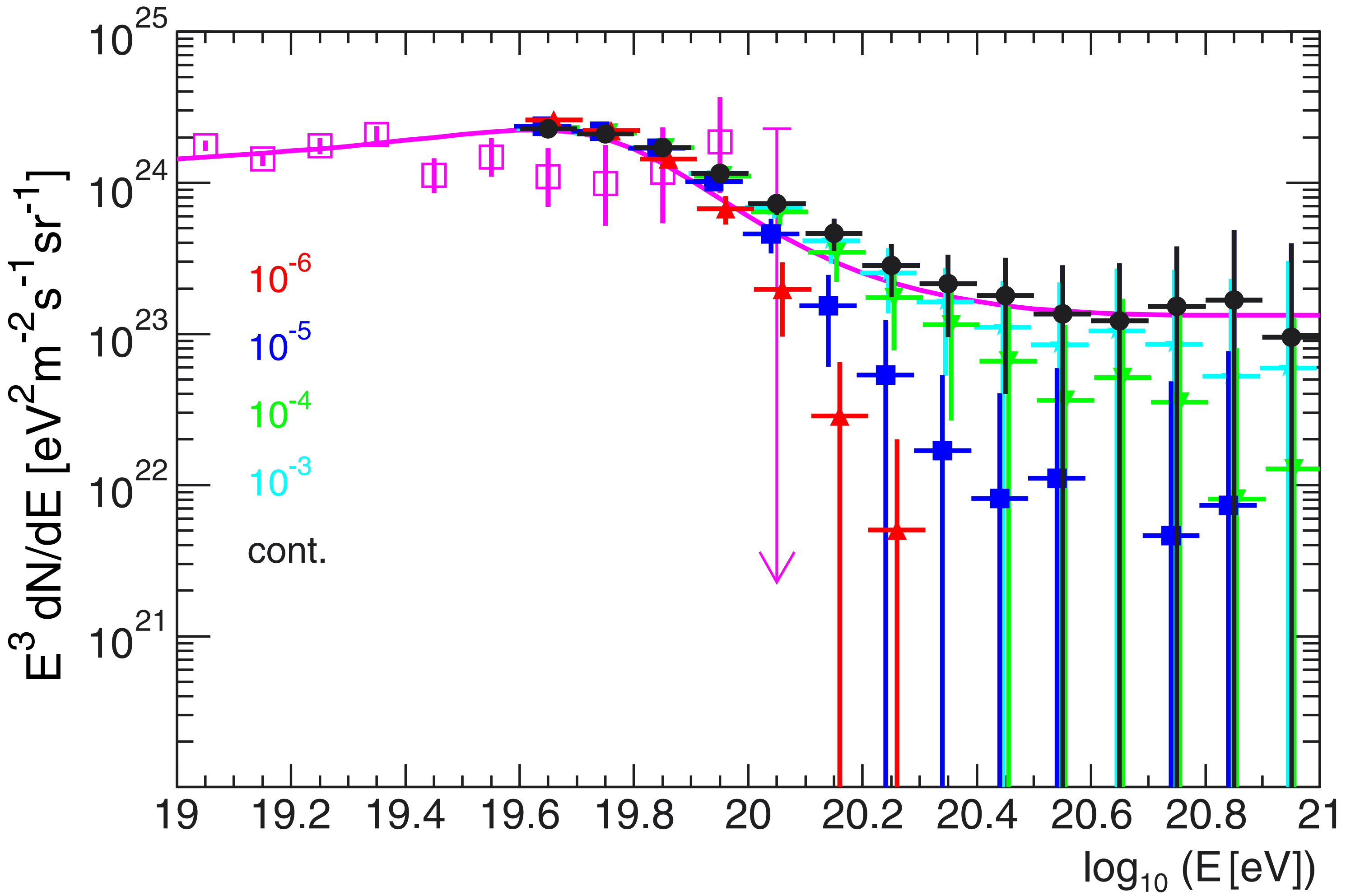
Influence of distribution of sources

Distance to local sources important
(simulations for protons, identical sources)



(Berezinsky, Gazizov, Grigorieva, PRD74, 2006)

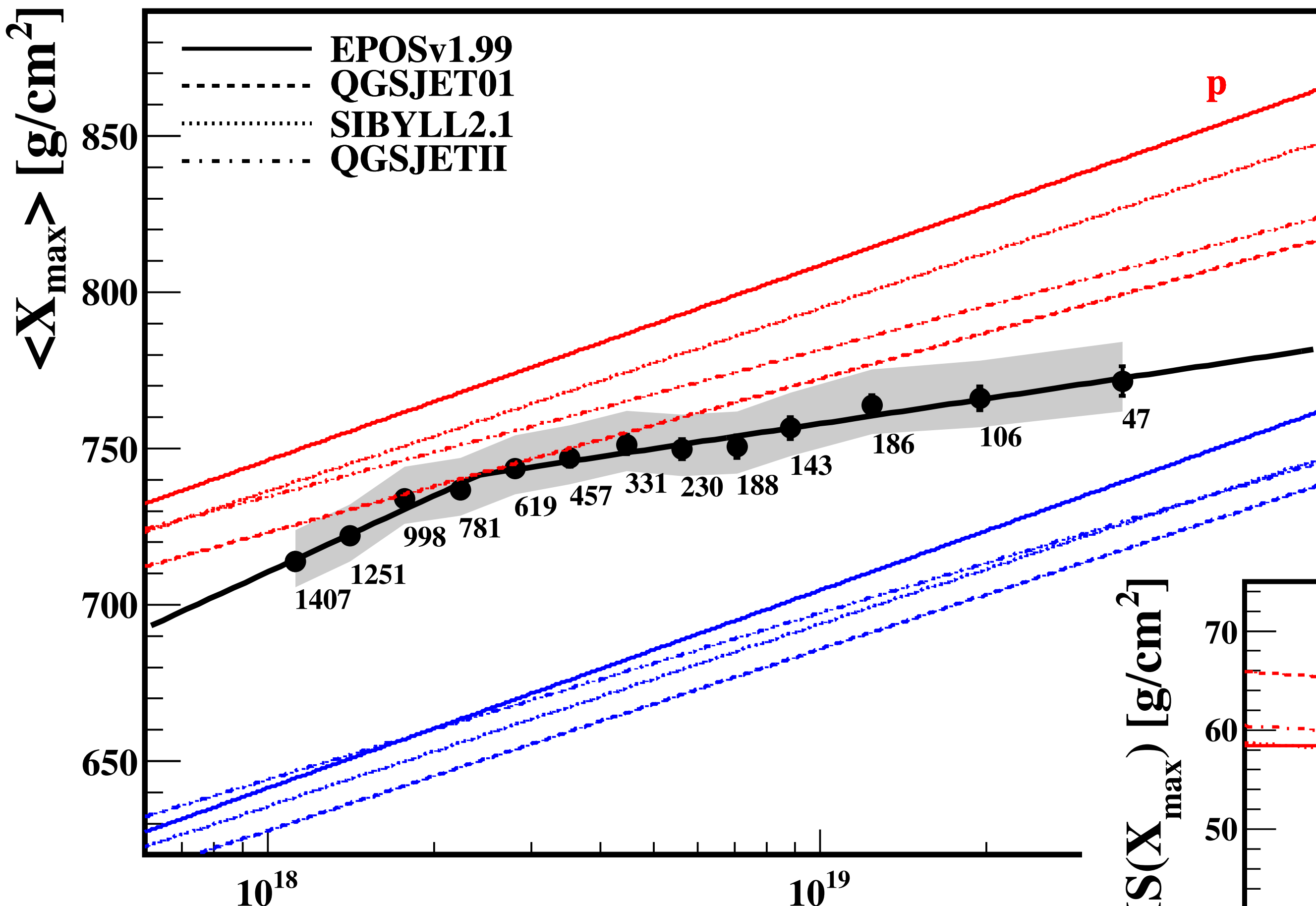
(De Marco, Blasi, Olinto JCAP07, 2006)



Energy of suppression almost model-independent

Auger Observatory: composition data

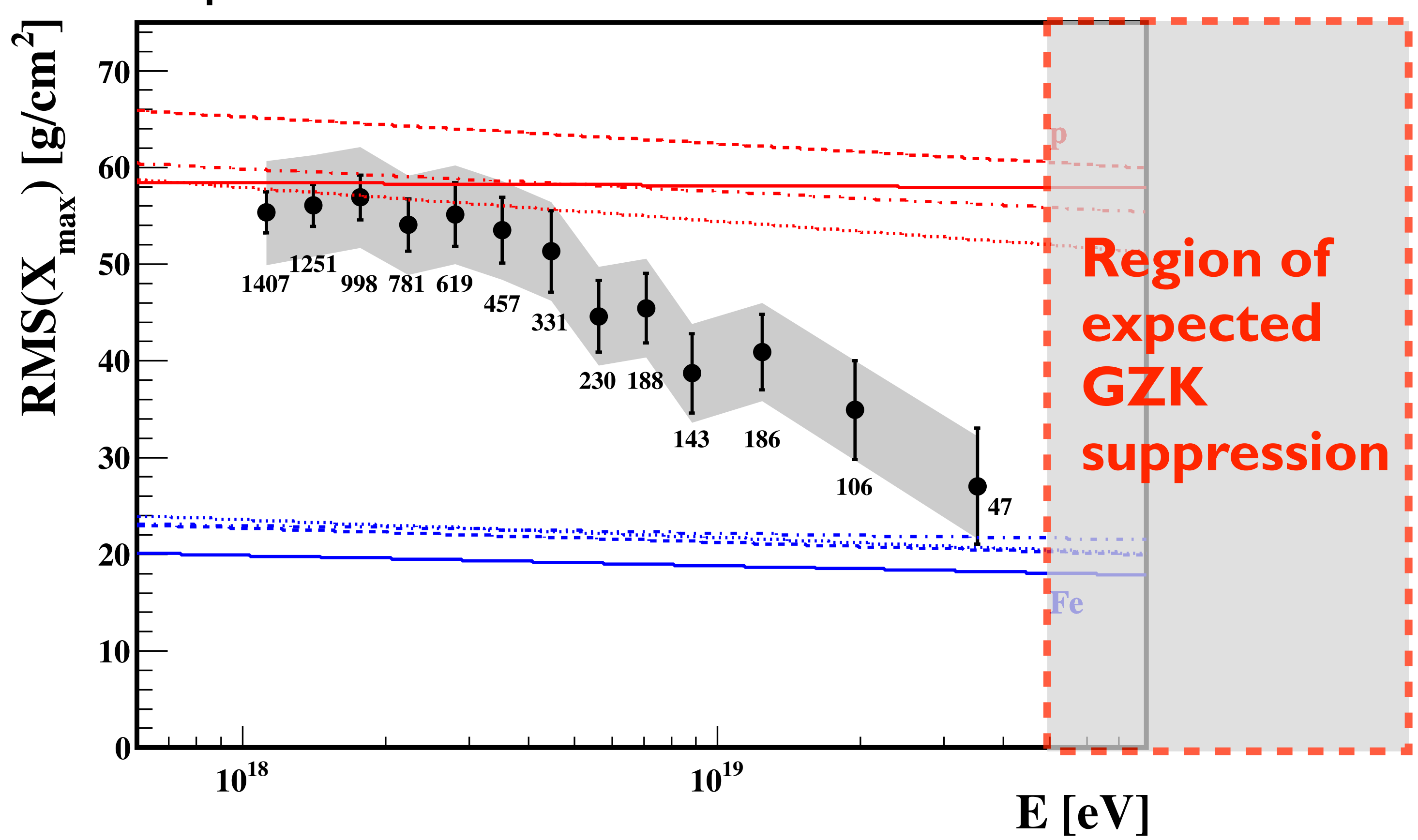
(Auger Collab. PRL 104, 2010, updated: Facal, ICRC 2011)



Change of cosmic ray composition from mixed or light to heavy ?

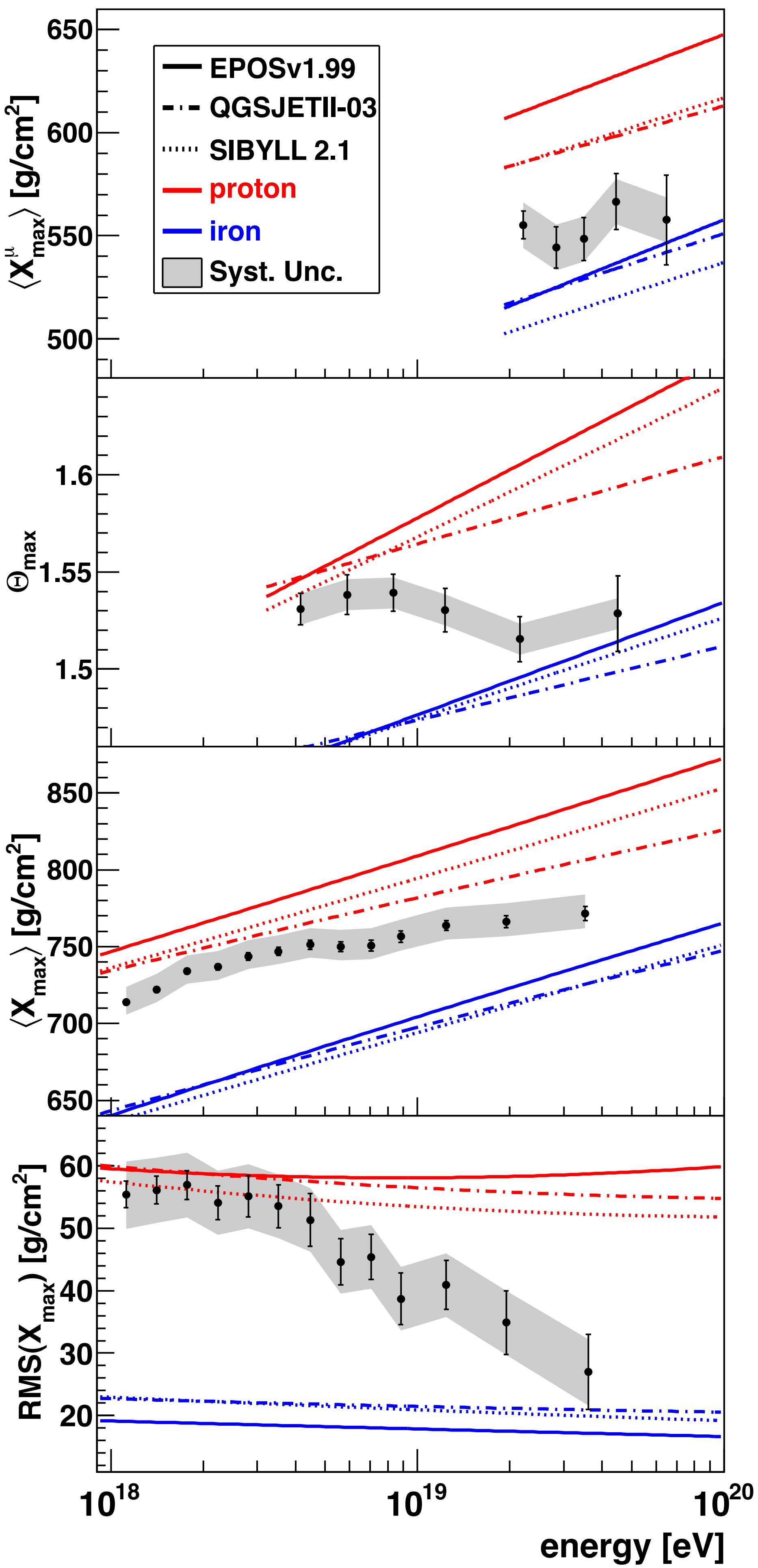
Indications of some tension: LHC cross section data

Sys. uncertainty: 13 g/cm^2 (mean)
6 g/cm^2 (RMS)



Independent confirmation from other composition indicators

Interpretation of fluctuations less model dependent



Measures of characteristics of longitudinal profile

Muon arrival times at large distance from shower core

Asymmetry in rise time of signal in surface detectors about shower core

Average depth of shower maximum of charged particles

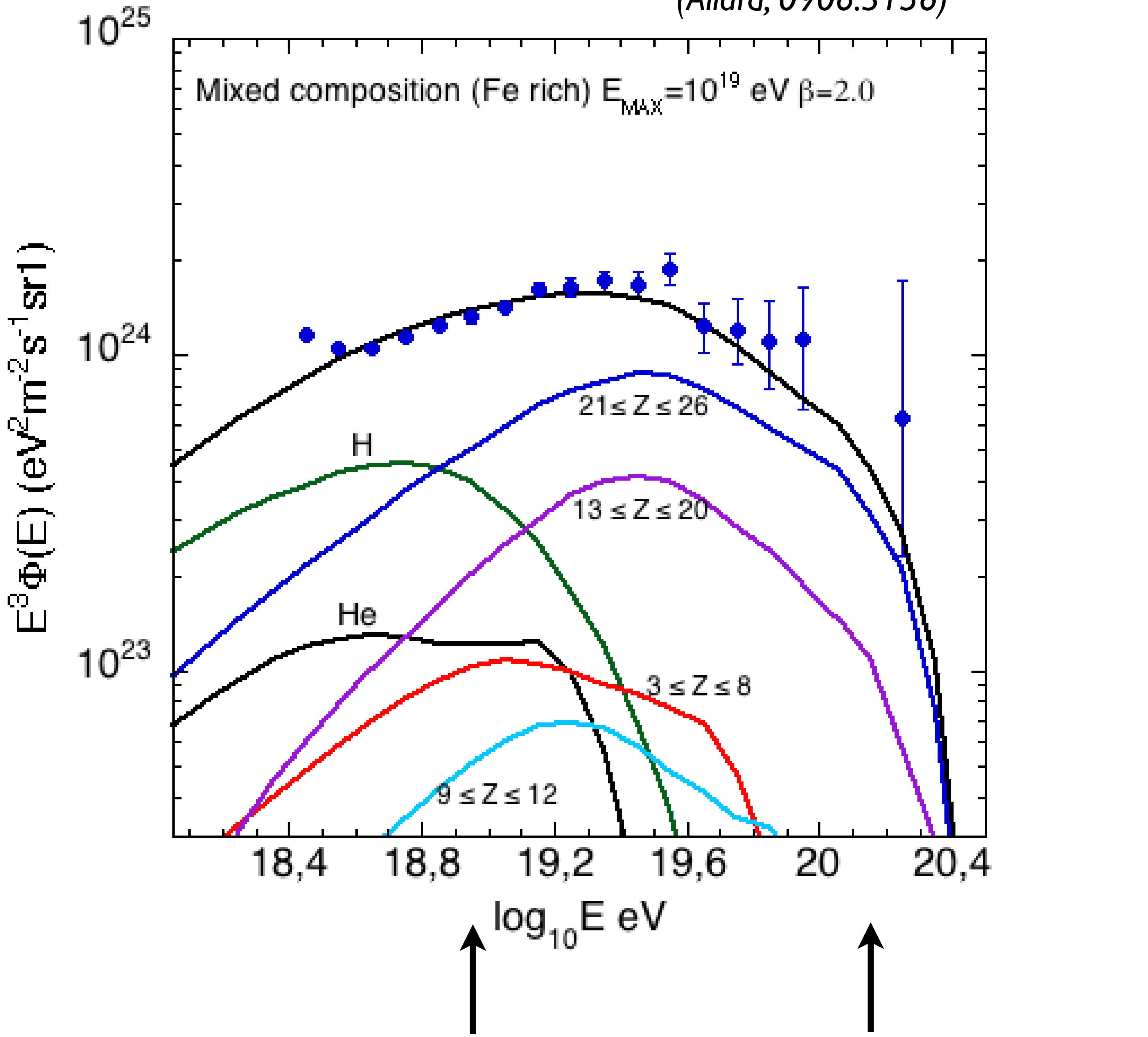
Shower-to-shower fluctuations of depth of shower maximum of charged particles

(Garcia-Pinto, Auger Collab., ICRC 2011 & 1107.4804)

Interpretation as GZK suppression

Superposition of max. injection energy and GZK effect

(Allard, 0906.3156)



Maximum injection energy for protons $E_{max,p}$

Maximum injection energy for iron $E_{max, Fe} = 26\ E_{max,p}$

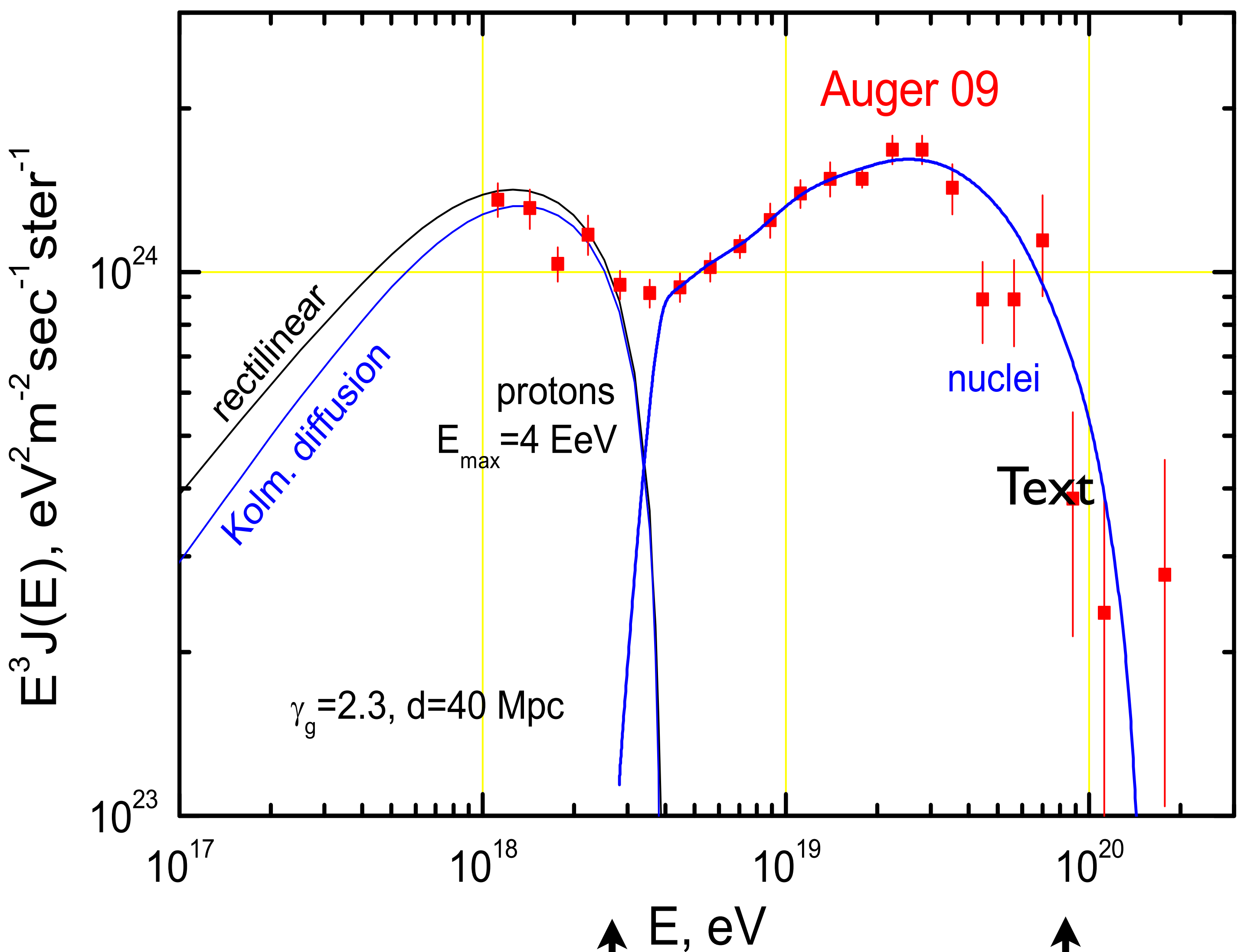
Rigidity-dependent maximum injection energy

Natural transition to heavier composition at high energy !

Net effect: flux suppression stronger than expected from GZK effect only

Suppression due to maximum injection energy

(Aloisio et al., Astropart. Phys. 34, 2011)



Flux suppression due mainly to upper end of injection spectrum

(Galactic sources: Calvez et al. Phys. Rev. Lett. 105, 2010)

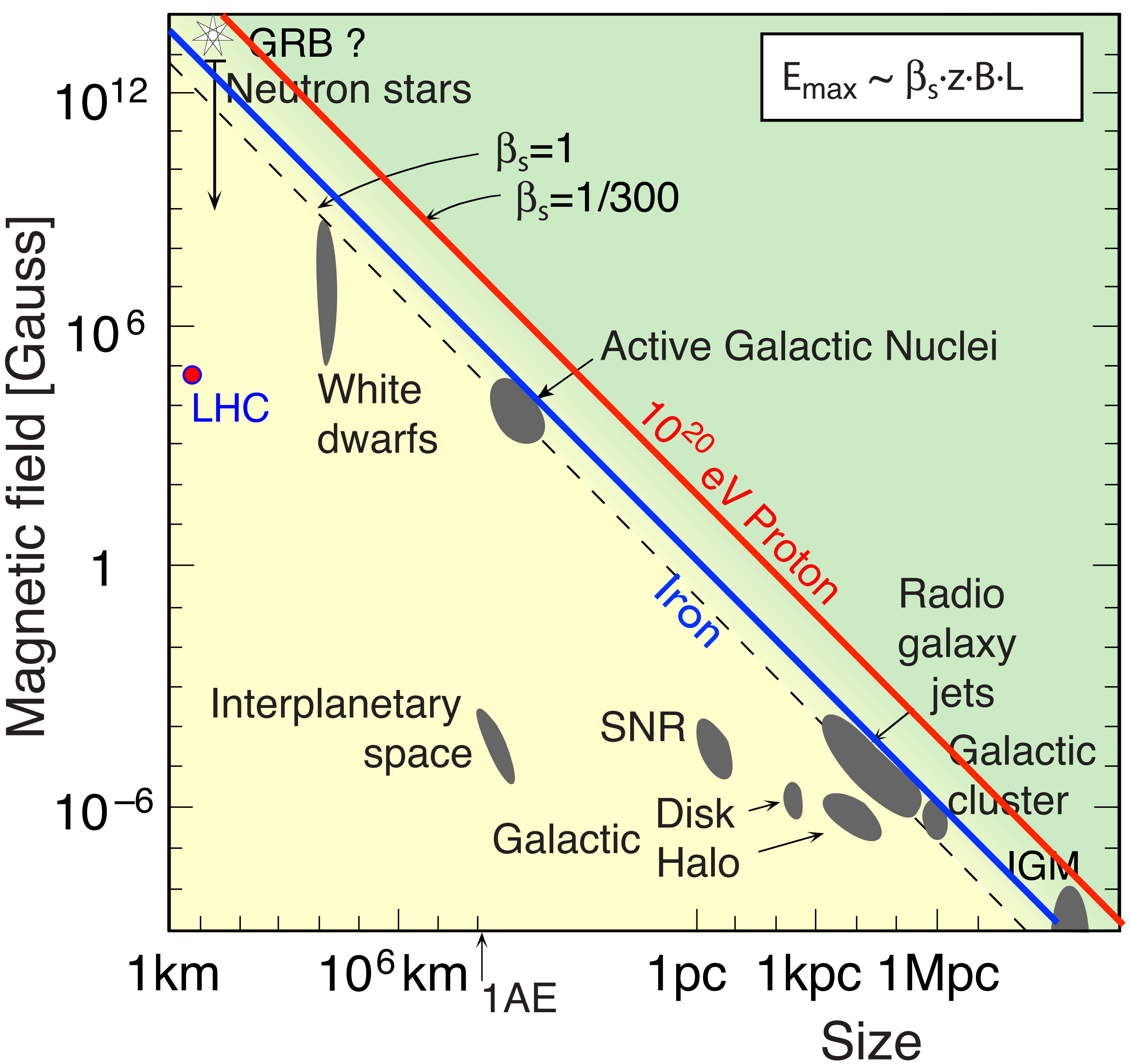
Suppression energy: free parameter of the model

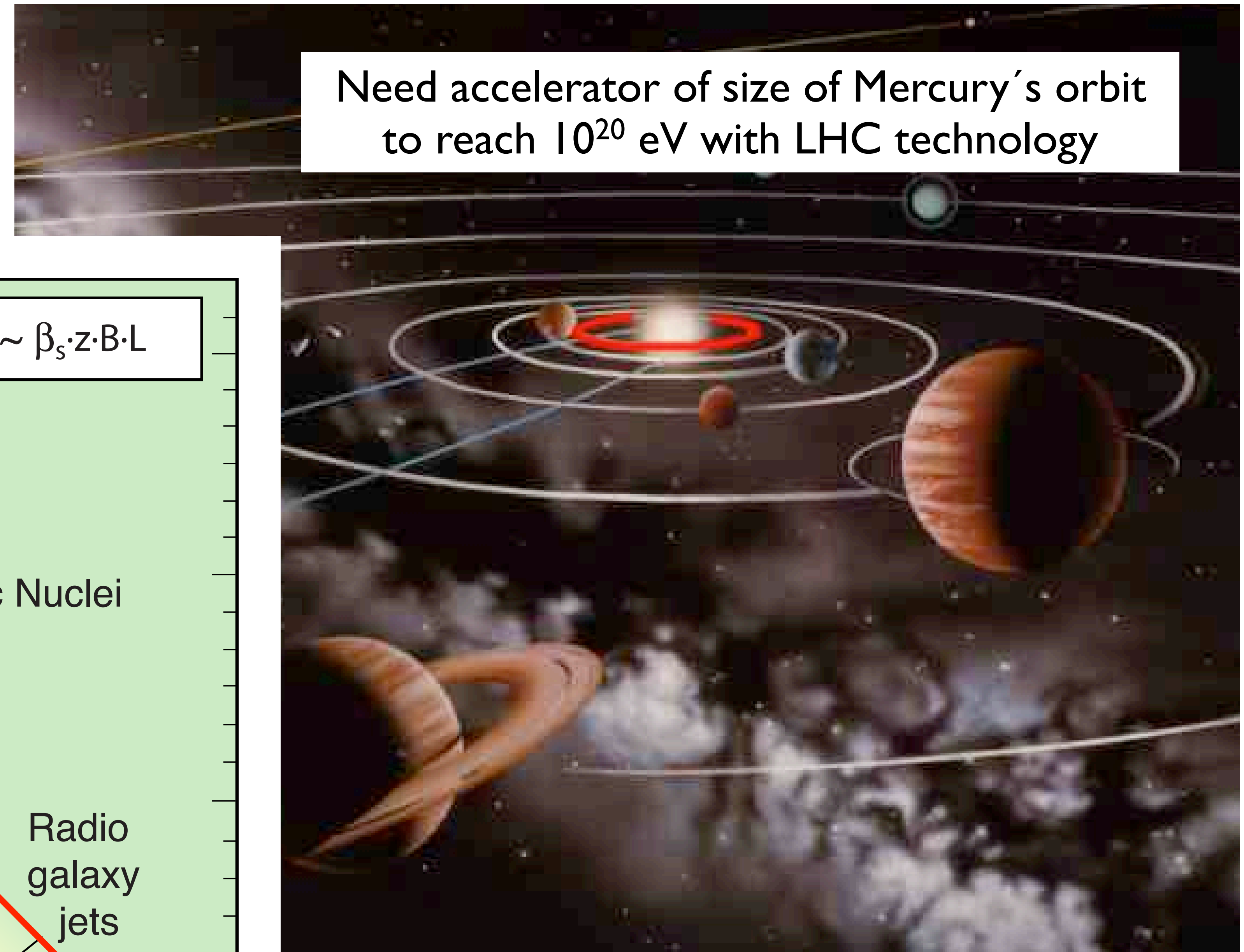
Maximum injection energy for protons $E_{max,p}$

Maximum injection energy for iron $E_{max, Fe} = 26\ E_{max,p}$

Recap: maximum injection energy

Hillas plot (1984)



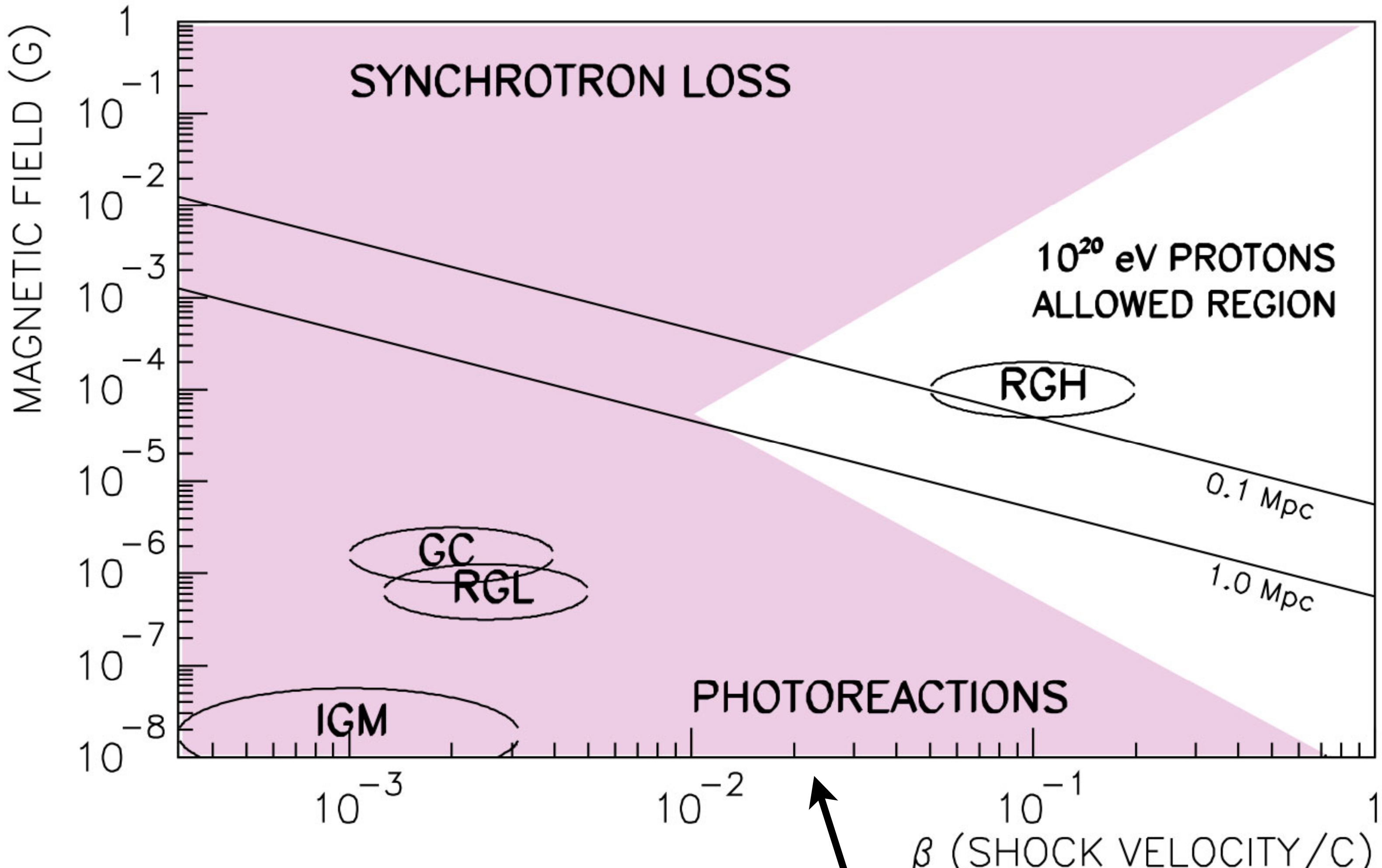


Realistic constraints more severe

- small acceleration efficiency
- synchrotron & adiabatic losses
- interactions in source region

Limits on acceleration efficiency

M. Hillas, 1984:



Acceleration time scale

$$t_A \sim \eta r_g / \beta^2$$

Synchrotron energy loss

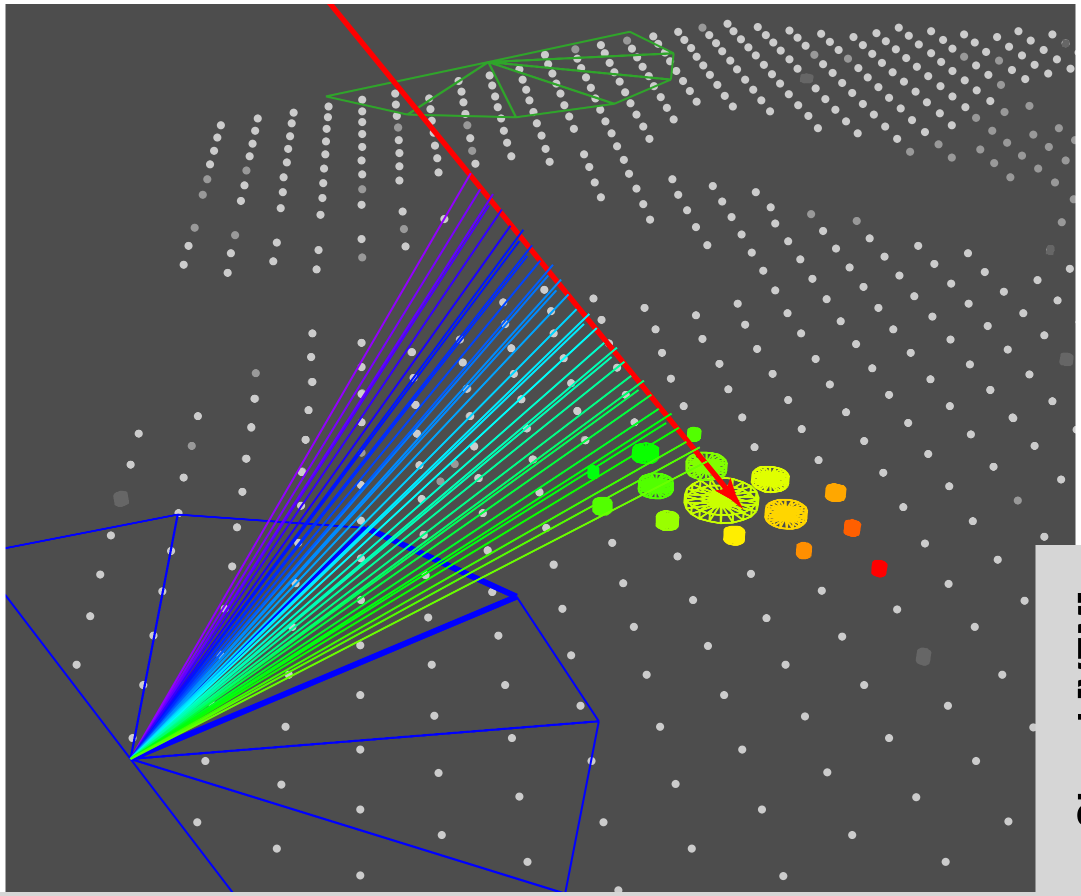
$$t_s \sim 1.4\,\mathrm{yr} \times \left(\frac{10^{20}\mathrm{eV}}{E}\right)\left(\frac{\mu\mathrm{G}}{B}\right)^2\left(\frac{A}{Z}\right)^4$$

Interaction with
local radiation fields

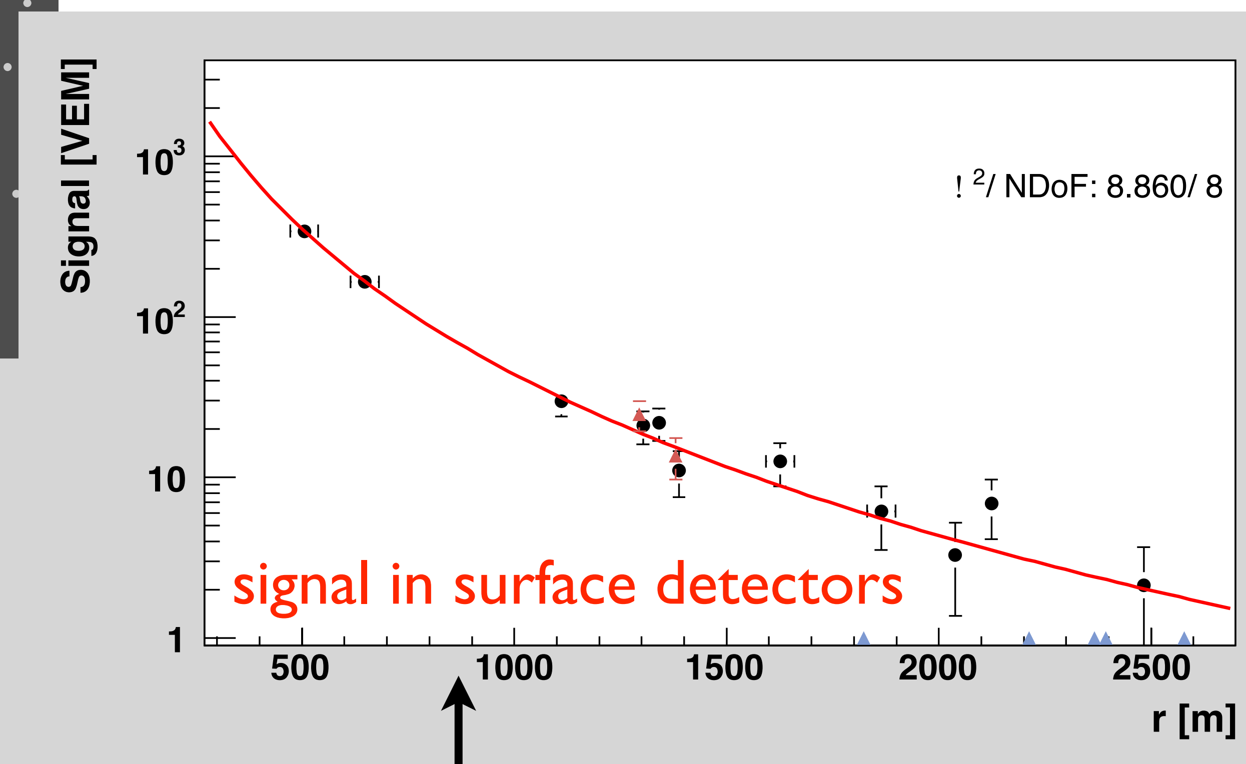
Heavy nuclei can be accelerated more easily

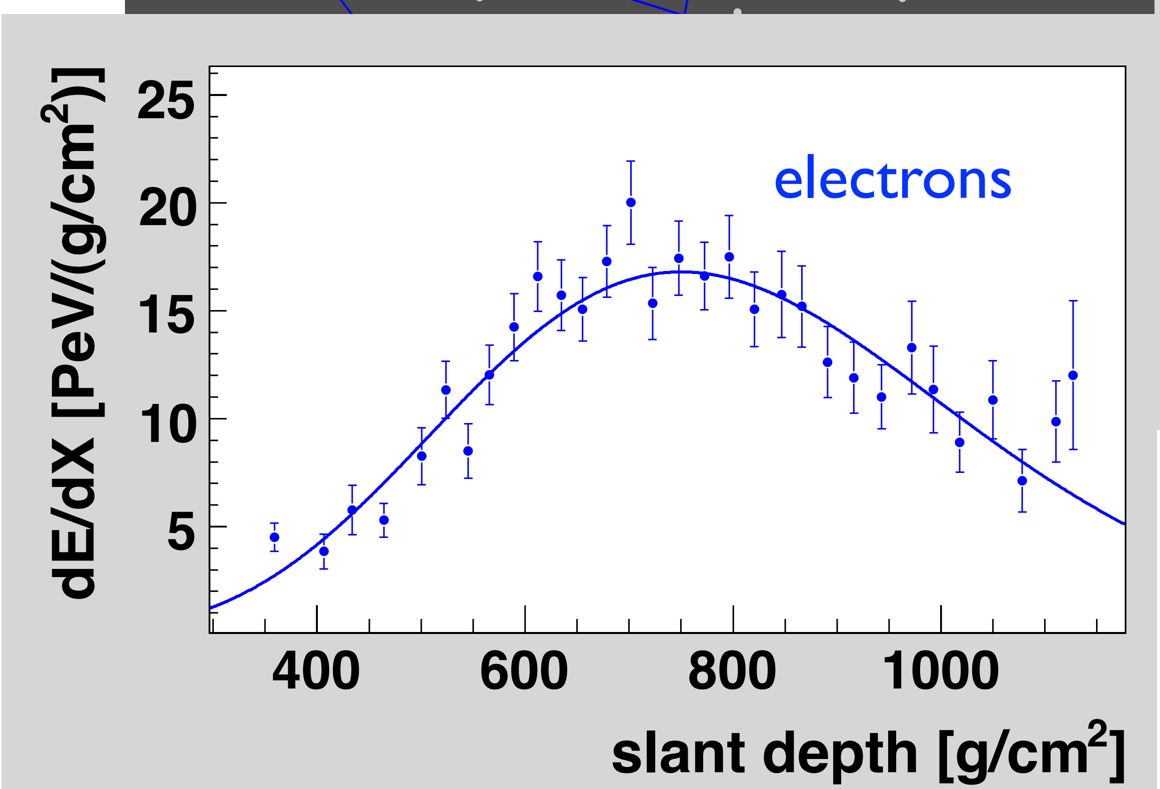
Studying hadronic interaction models

Hybrid events used for calibration of surface detector



Lateral distribution



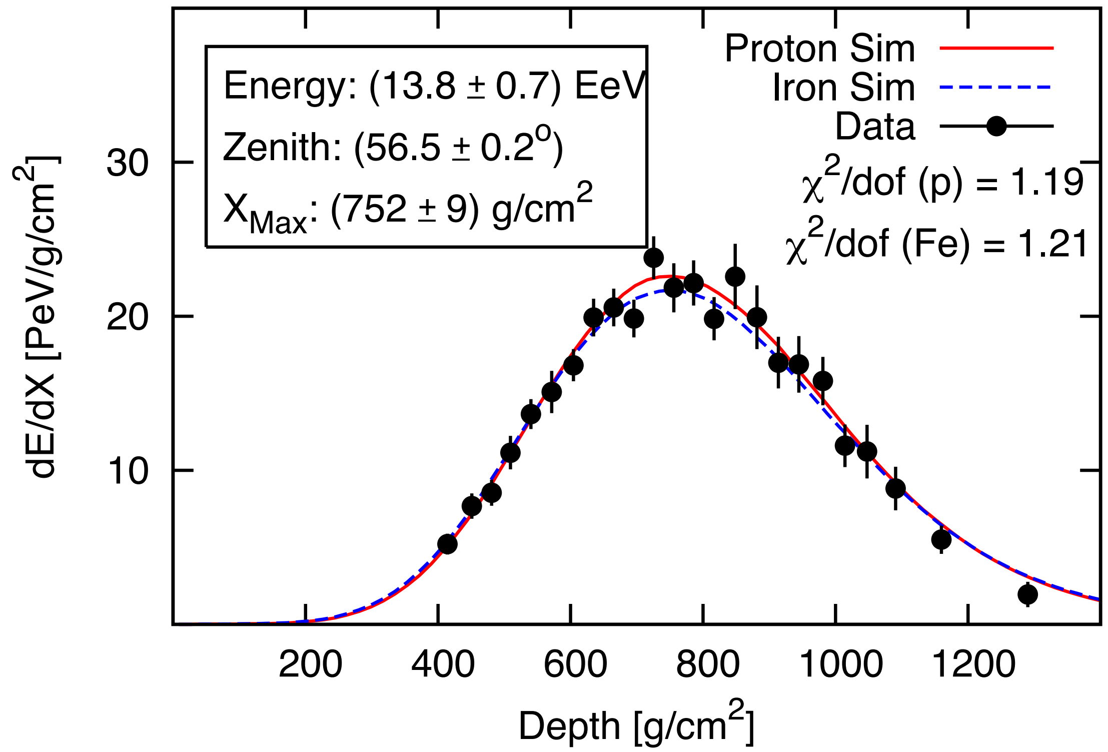


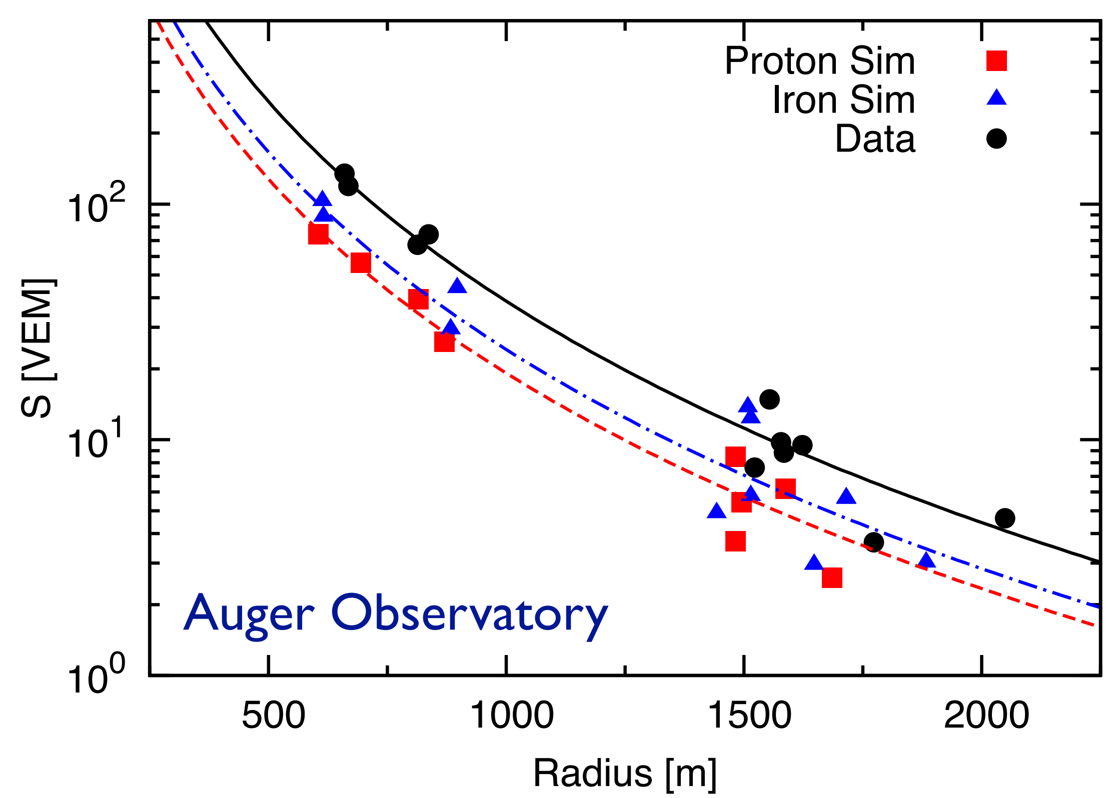
calibration of S800 / S1000

Integral over ionization energy deposit (longitudinal profile): calorimetric energy

Shower longitudinal profile

Discrepancy between data and simulated showers





Procedure

- High-quality showers E ~10^{19} eV
- Proton or iron primaries
- surface detector simulation for best longitudinal profiles

Results

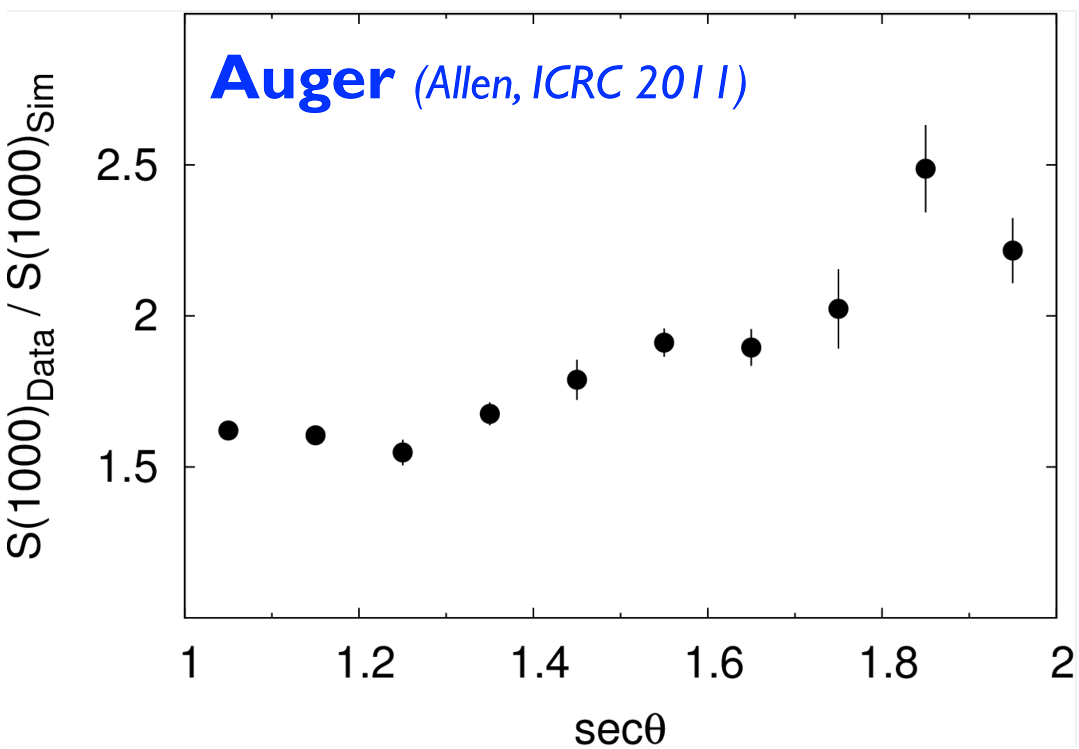
- Signal deficit found for **both** proton and iron like showers
- Showers with same X_{max} show only 10-15% variation
- Discrepancy much larger than 22% energy calibration uncertainty

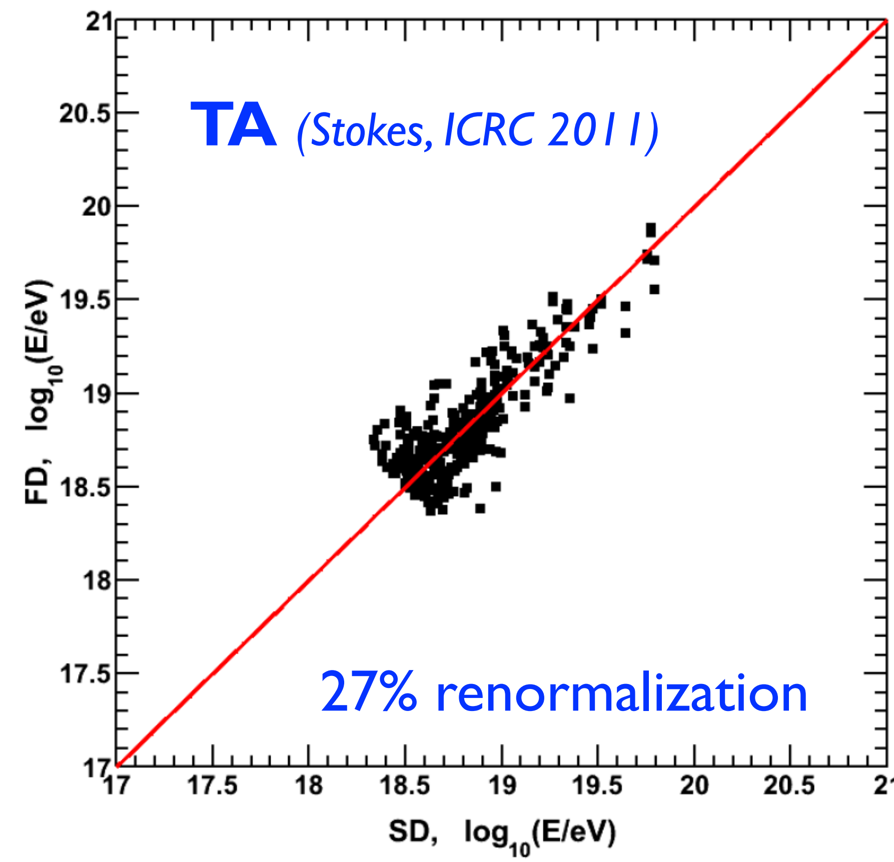
Monte Carlo simulations cannot be used for energy calibration (reason for AGASA excess?)

(Pierre Auger Collab. 1107.4804)

Comparison to proton showers

QGSJET II.03 as reference model, proton-induced showers





Angular dependence: predicted number of muons smaller than measured one

No angular dependence (Θ < 40°), as would be expected for thin scintillators

Discrepancy between simulation and data not understood, possibly related to antibaryon production (need LHC data)

(Pierog & Werner, PRL 101 (2008) 17110)

Systematic uncertainty of fluorescence energy scale

Auger R. Pesce, icrc1160

calibration	9.5%
reconstruction	10%
atmospheric	8%
fluorescence yield*	14%
invisible energy†	4%
tot. quad. sum	**22%**

Telescope Array D. Ikeda, icrc1264

calibration	10%
reconstruction	10%
atmospheric	11%
fluorescence yield** invisible energy††	11%
tot. quad. sum	**21%**

(Unger, ICRC 2011)

* yield: Nagano, spectrum: AIRFLY ** yield: Kakimoto, spectrum: Bunner † QGSJet mixed †† QGSJet proton

HiRes mono spectra 2008

Photon calibration	10 %
Fluorescence yield	6 %
Missing energy correction	5 %
Aerosol concentration	5 %
Mean energy loss estimate	10 %
Total quad. sum	**17 %**

Systematic uncertainty of fluorescence energy scale

Uncertainty (%)	Source
14	Absolute fluorescence yield
10	Reconstruction of the longitudinal shower profile
9	Absolute calibration of the fluorescence telescopes
7	Aerosol optical depth
5	Water vapour quenching
4	Invisible energy
3	Wavelength dependent response
1	Molecular optical depth
1	Multiple scattering models
22	Total

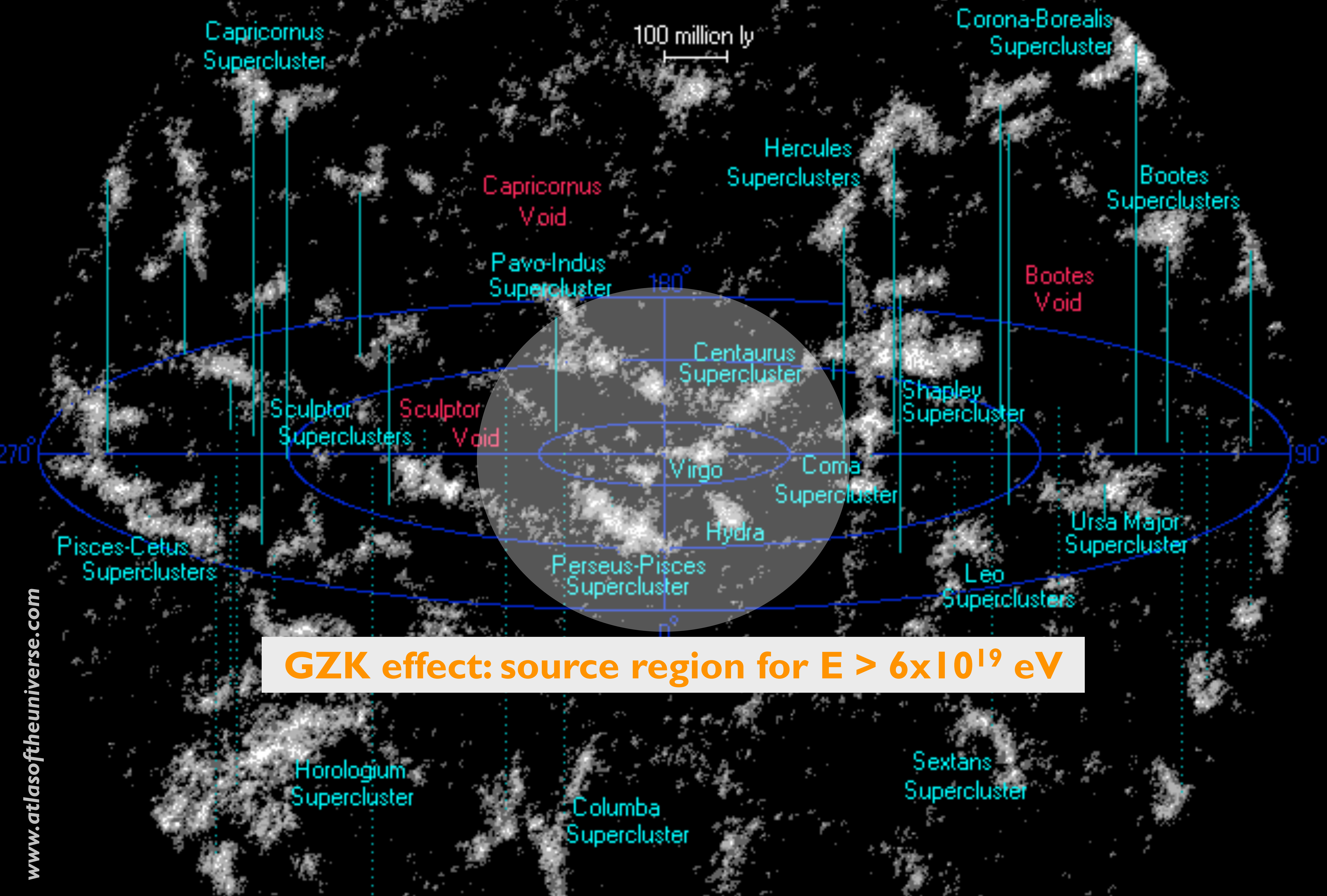
Auger Observatory 2009/2010

Photon calibration	10 %
Fluorescence yield	6 %
Missing energy correction	5 %
Aerosol concentration	5 %
Mean energy loss estimate	10 %
Total	**17 %**

HiRes mono spectra 2008

Other sources of information

GZK effect: anisotropy expected for light elements



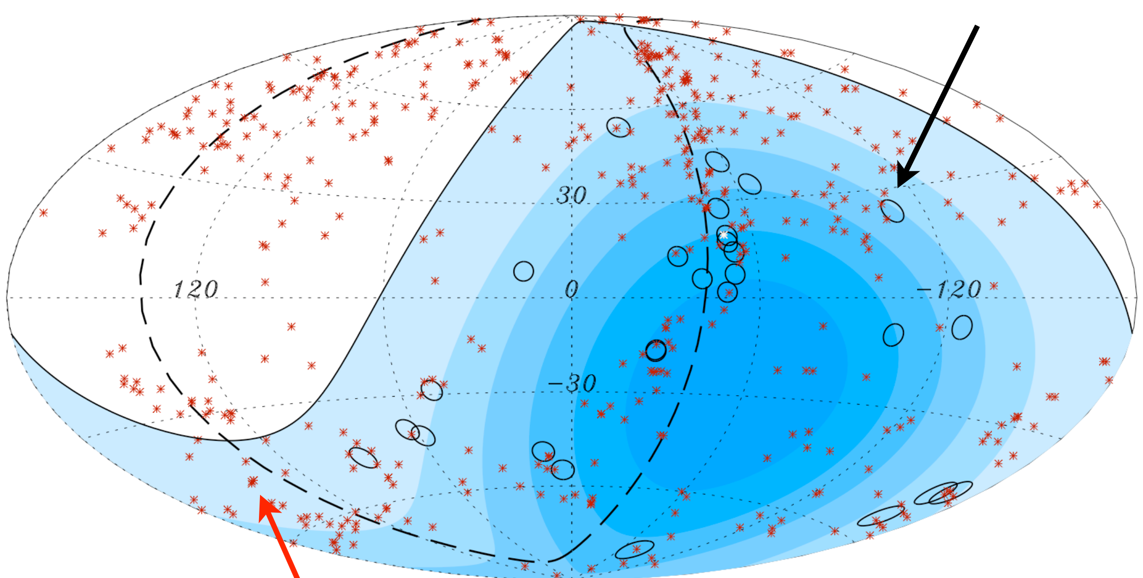
Correlation of arrival directions with AGNs

Auger Observatory (2007)

(Science 318, 2007)

Scan: 12 out of 15, prescription

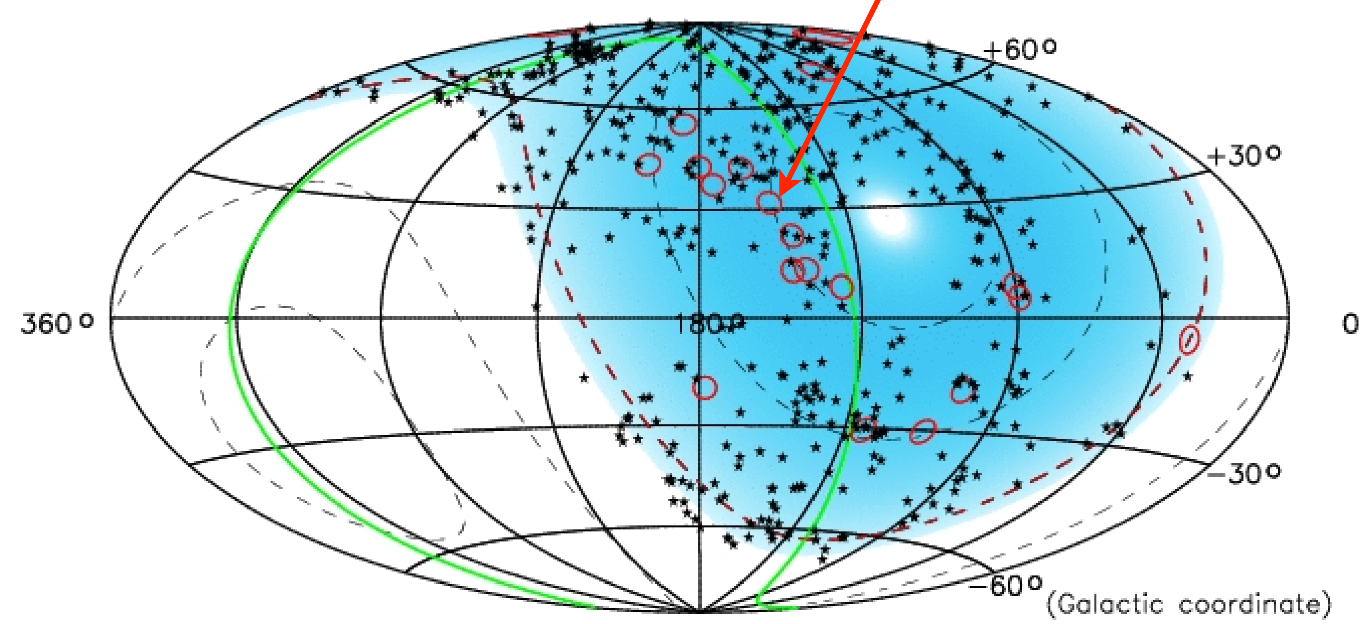
Arrival direction of cosmic ray



Active Galactic Nucleus (AGN) (Veron-Cetty & Veron catalog)

Telescope Array (2011)

Arrival direction of cosmic ray



E > 5.5 x 10^{19} eV
D < 75 Mpc

8 out of 20 events correlated,
no stat. significant correlation found

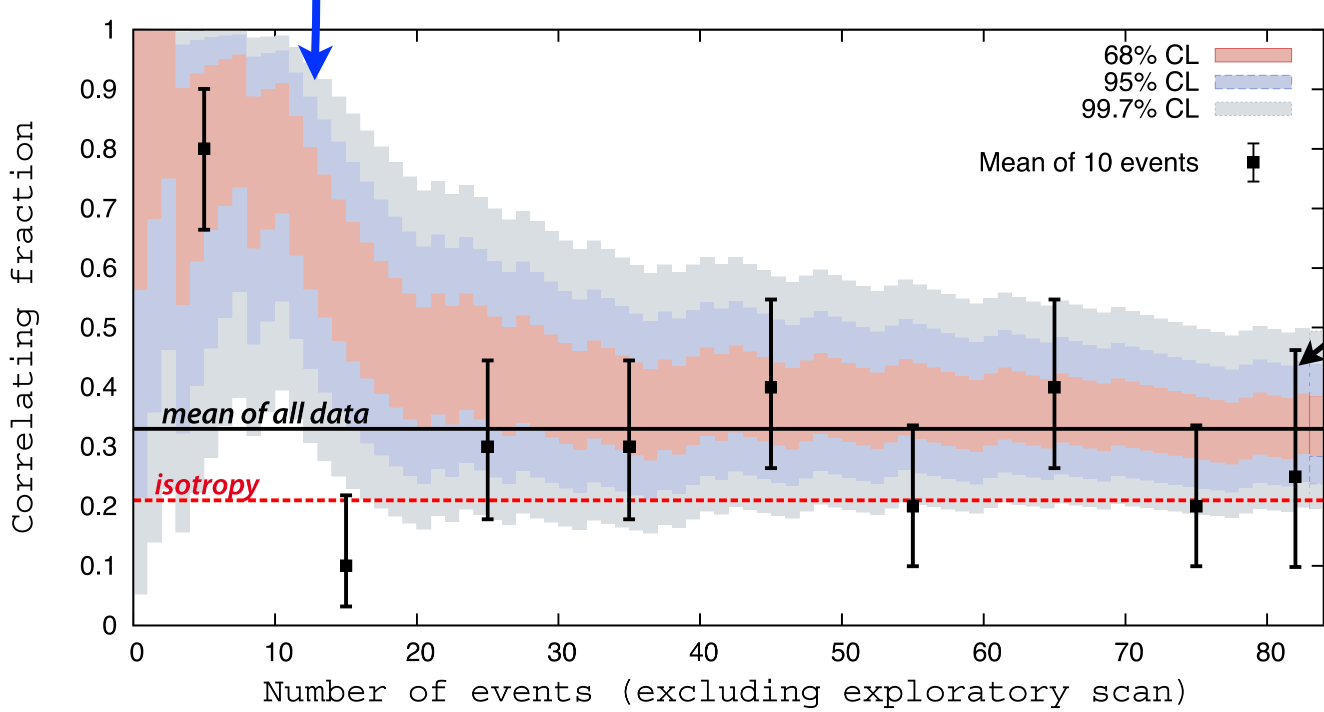
20 out of 27, ~70% correlation, 21% expected

Anisotropy only for source distances up to GZK sphere (as one would expect)
Small deflection angle indicates presence of **light elements** (protons?)

Current status of correlation with AGNs

Auger Observatory (2011)

Science publication: 9/13 events ~69% correlated, expectation for isotropy 21%

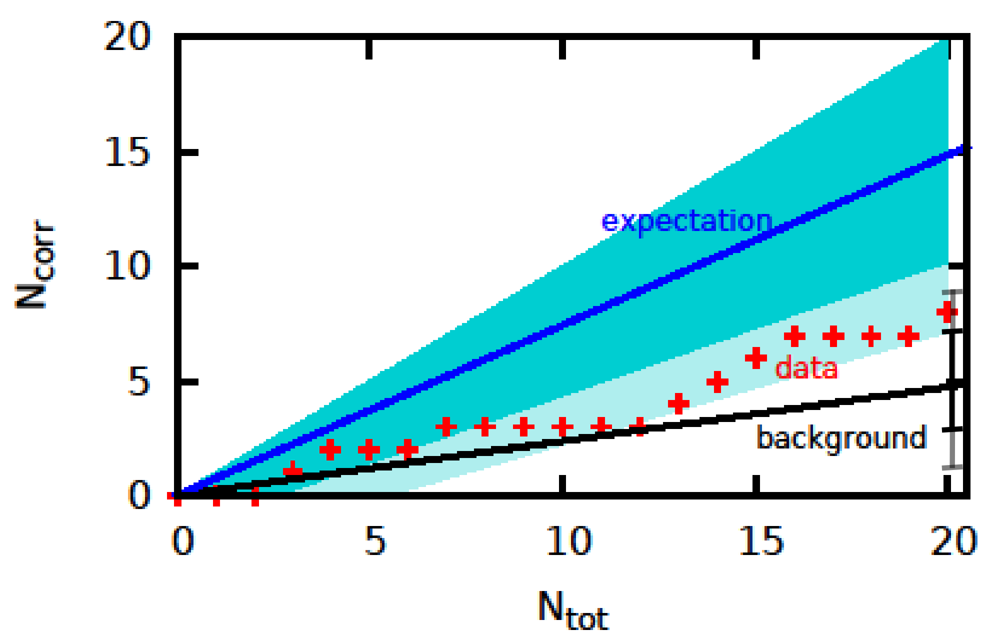


Differential estimate every 10 events

June 2011: 28 out of 84 correlated estimate now 33 ± 5% (P = 0.006)

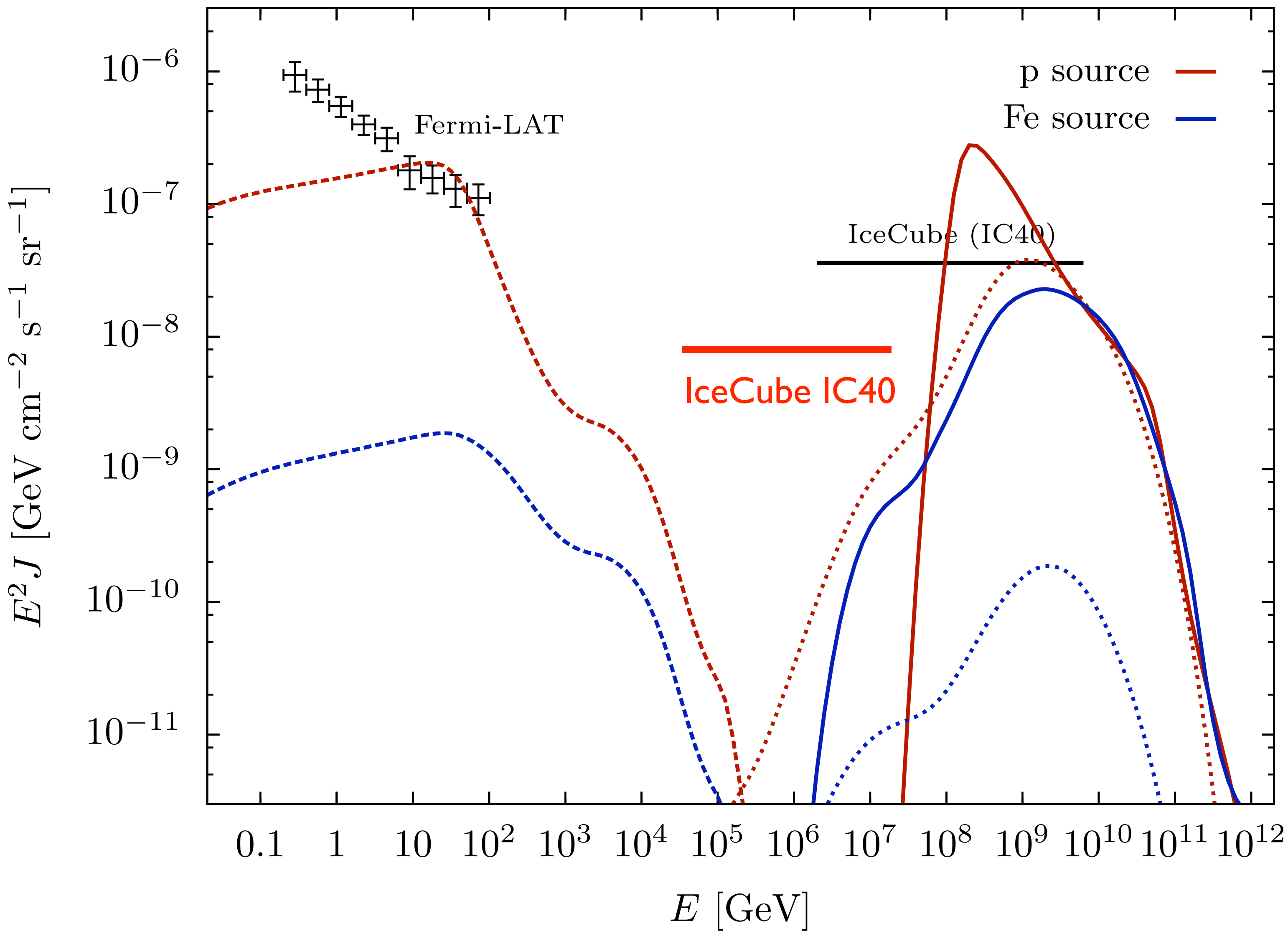
Telescope Array (2011)

Expectation comes from Auger 69% (=9/13) which is converted to northern sky 73%. The background chance probability is 25%



Neutrino and gamma-ray limits

(Ahlers, Salvado: 1105.5113)



Gamma-rays **Neutrinos**

Secondary neutrinos and gamma-rays due only to propagation

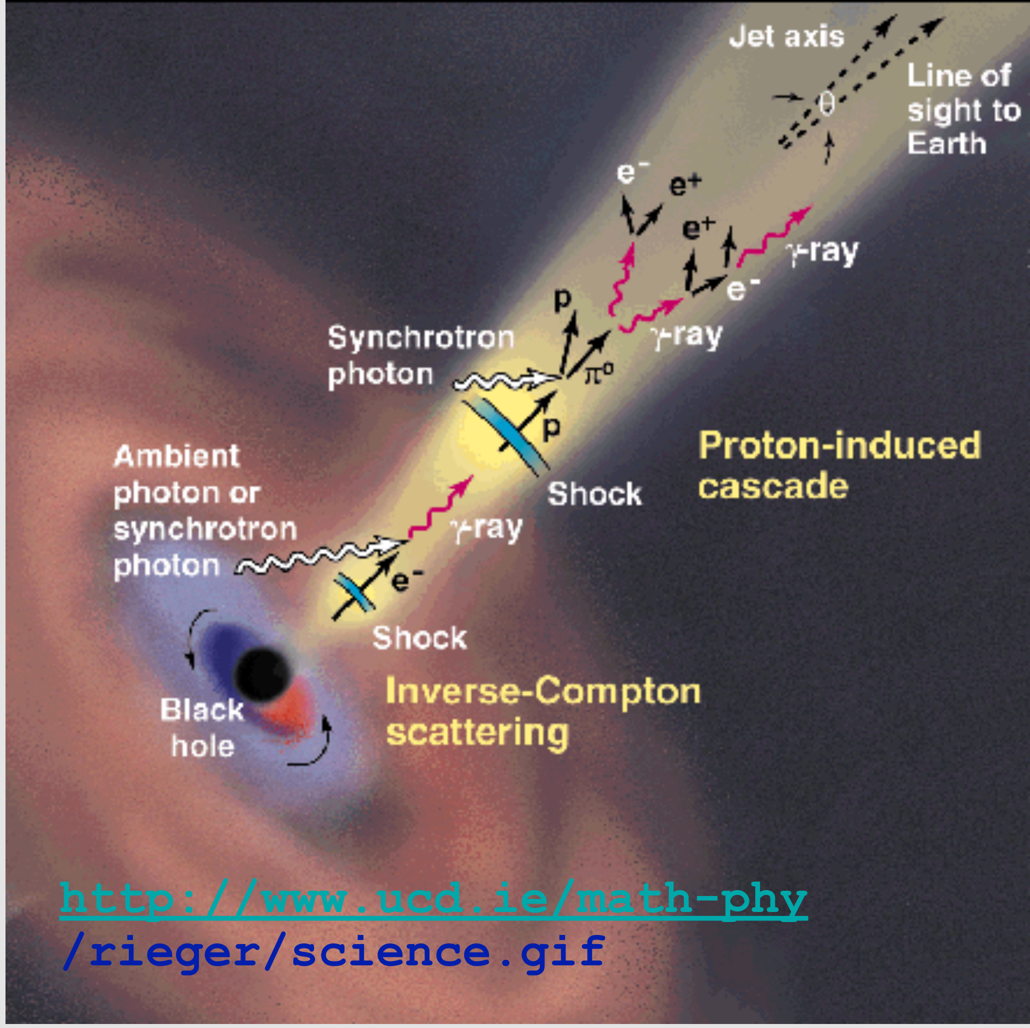
Generic argument:
Waxman-Bahcall limit

IceCube: no neutrinos found for

- diffuse flux, factor 2 below Waxmann-Bahcall limit *(1104.5187)*
- GRB correlated flux *(TeVPA)*

Backup slides

Generic model I



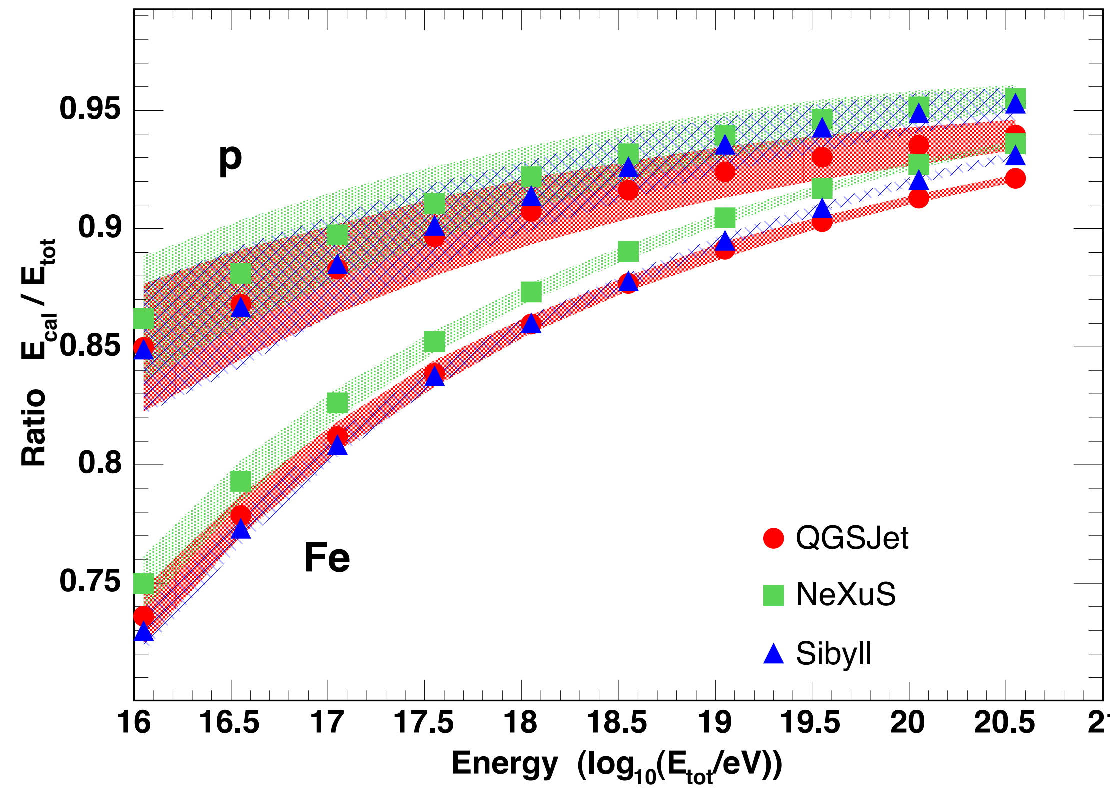
- CR acceleration occurs in jets
  - AGN or GRB
- Abundant target material
  - Most models assume photo-production:
    - $p + \gamma \rightarrow \Delta^+ \rightarrow p + \pi^0 \rightarrow p + \gamma\,\gamma$
    - $p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+ \rightarrow n + \mu + \nu$
- Ideal case (~ "Waxman-Bahcall limit")
  - Strong magnetic fields retain protons in jets
  - Neutrons escape, decay to protons & become UHECR
  - Extra-galactic cosmic rays observed as protons
  - Energy content in neutrinos ≈ energy in UHECR
- This picture disfavored as limits go below W-B

Waxman, Bahcall, PRD 59, 023002 (1998). Also TKG astro-ph/9707283v1

Calorimetric vs. total shower energy

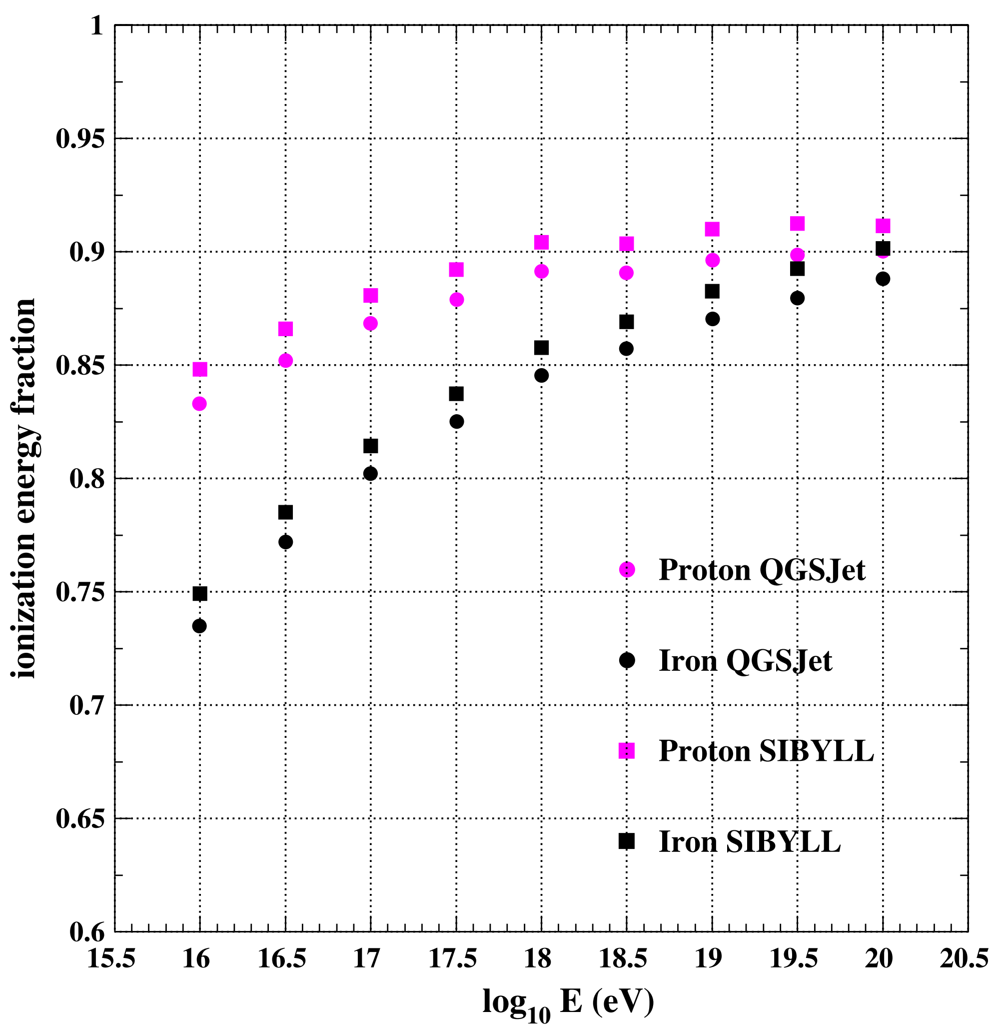
Auger reconstruction:

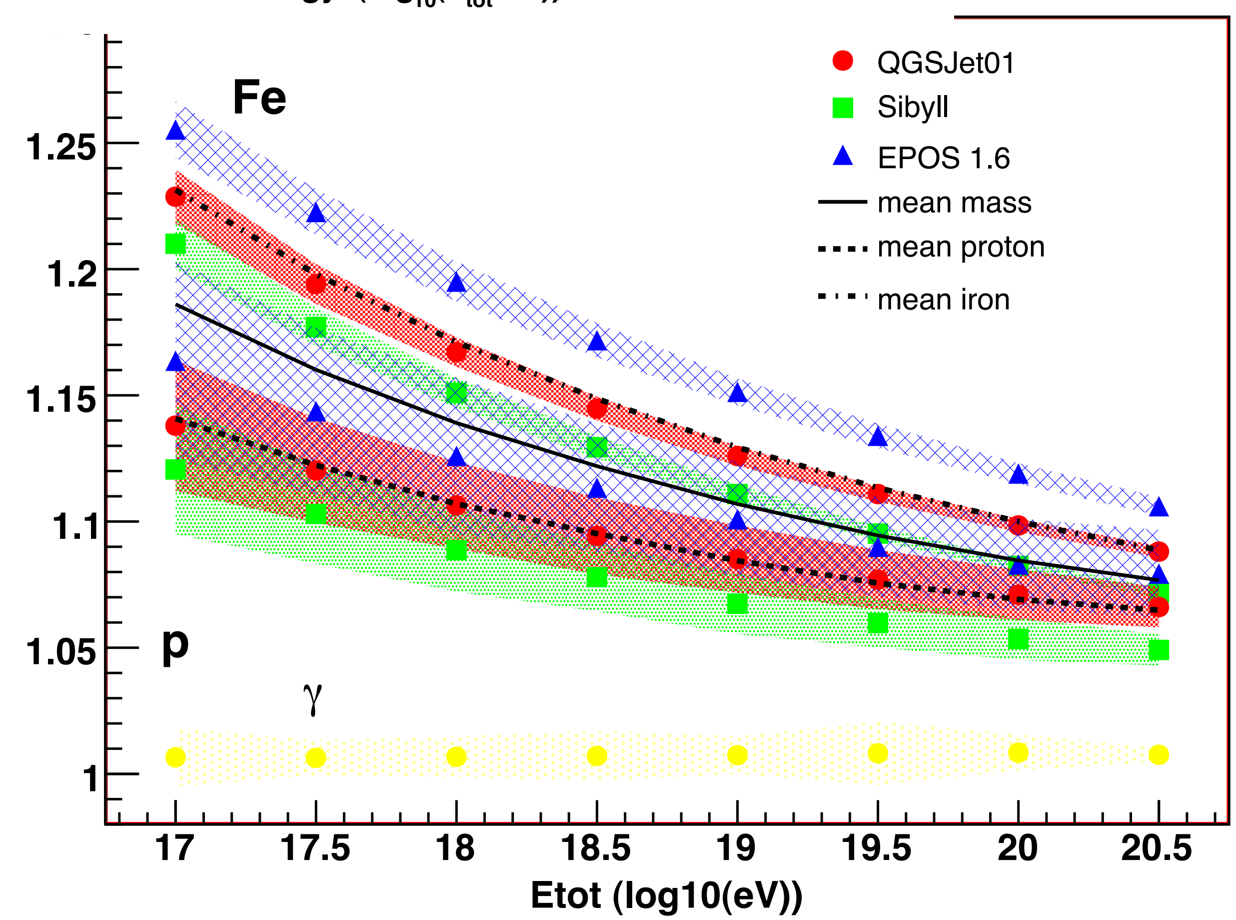
- energy correction for QGSJET 01
- mean of p and Fe
- *Barbosa et al. APP 22 (2004) 159*



T. Pierog et al., ICRC 2007)

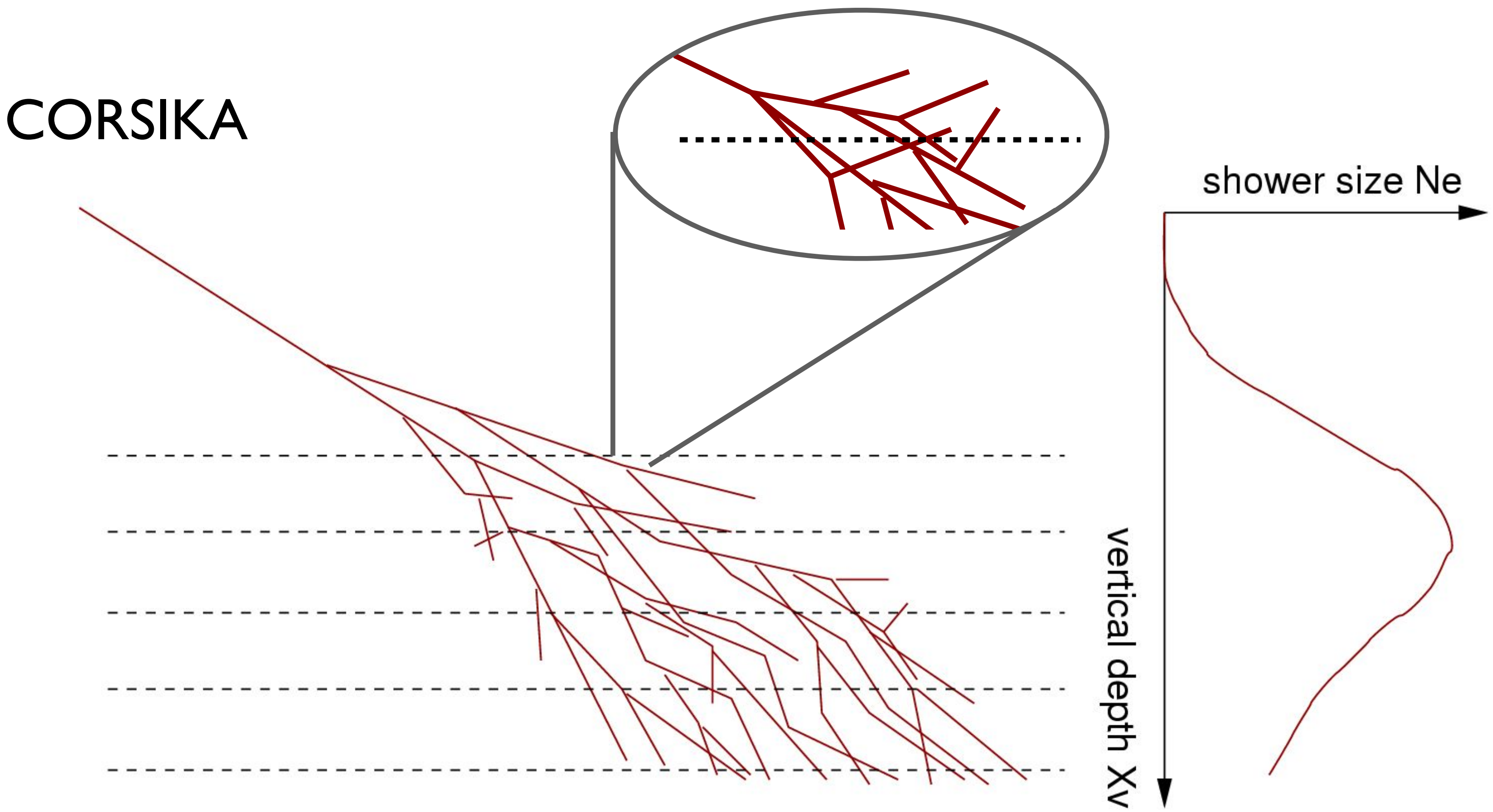
(HiRes, APP 27 (2007) 370)





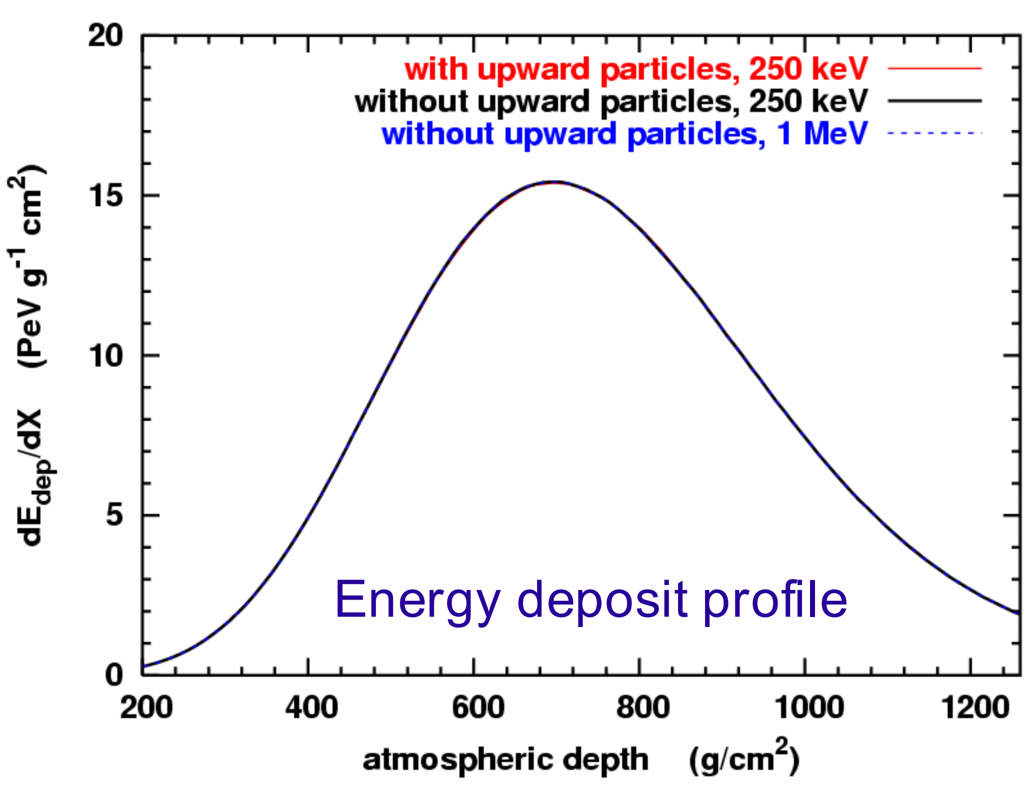
Energy deposit vs. shower size (i)

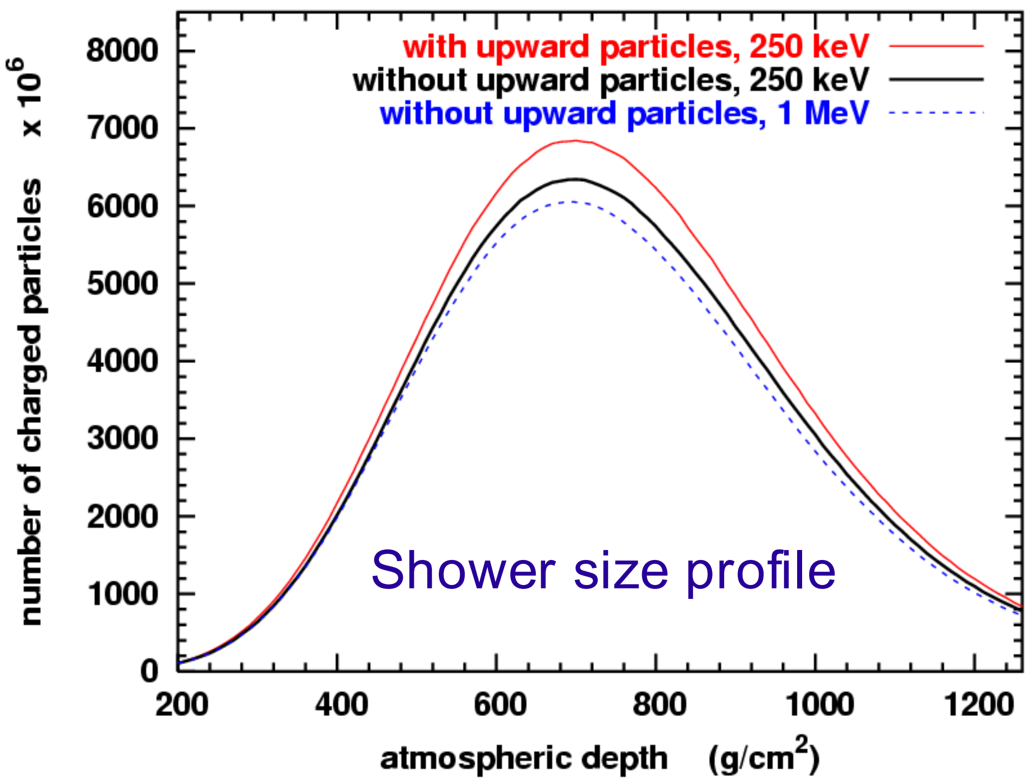
Shower size is not well defined quantity



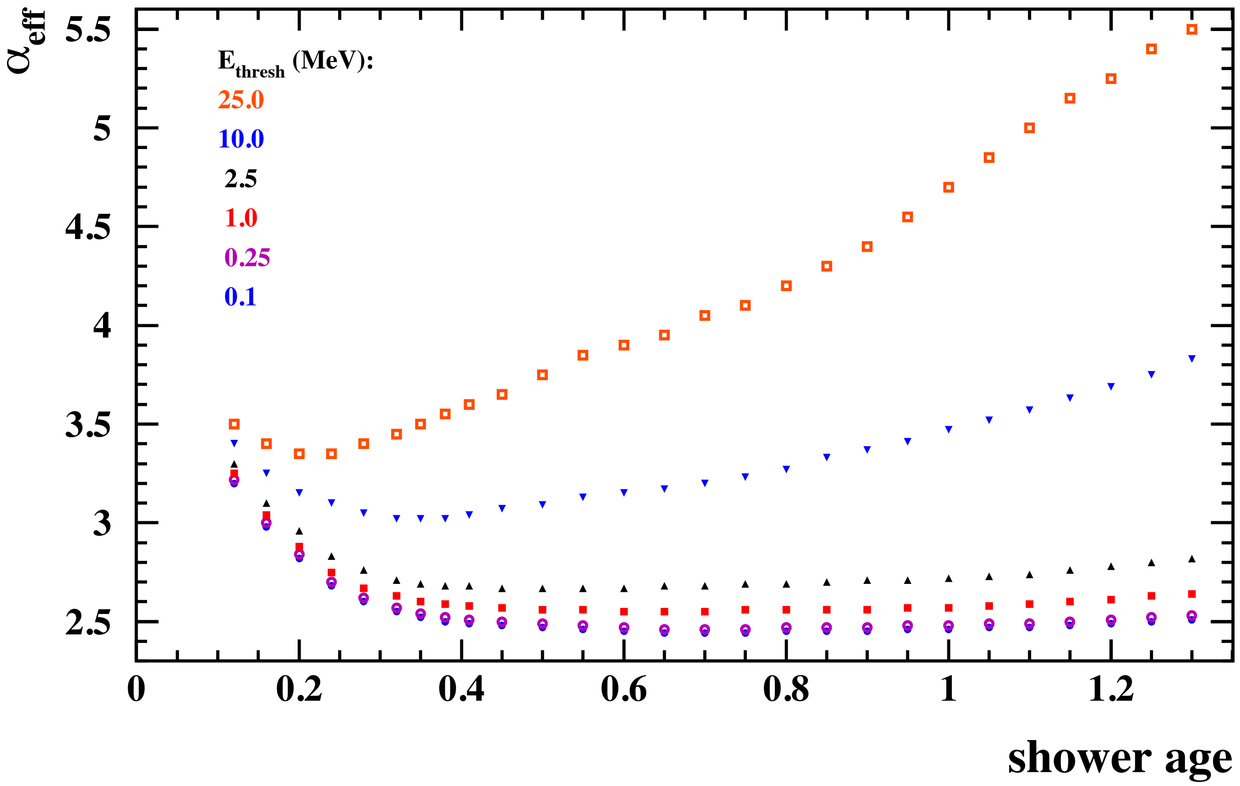
$$E_{\rm cal} = \alpha_{\rm eff} \int N_{\rm ch}(X)\, {\rm d}X$$

(Risse & Heck, APP 20 (2004) 661)



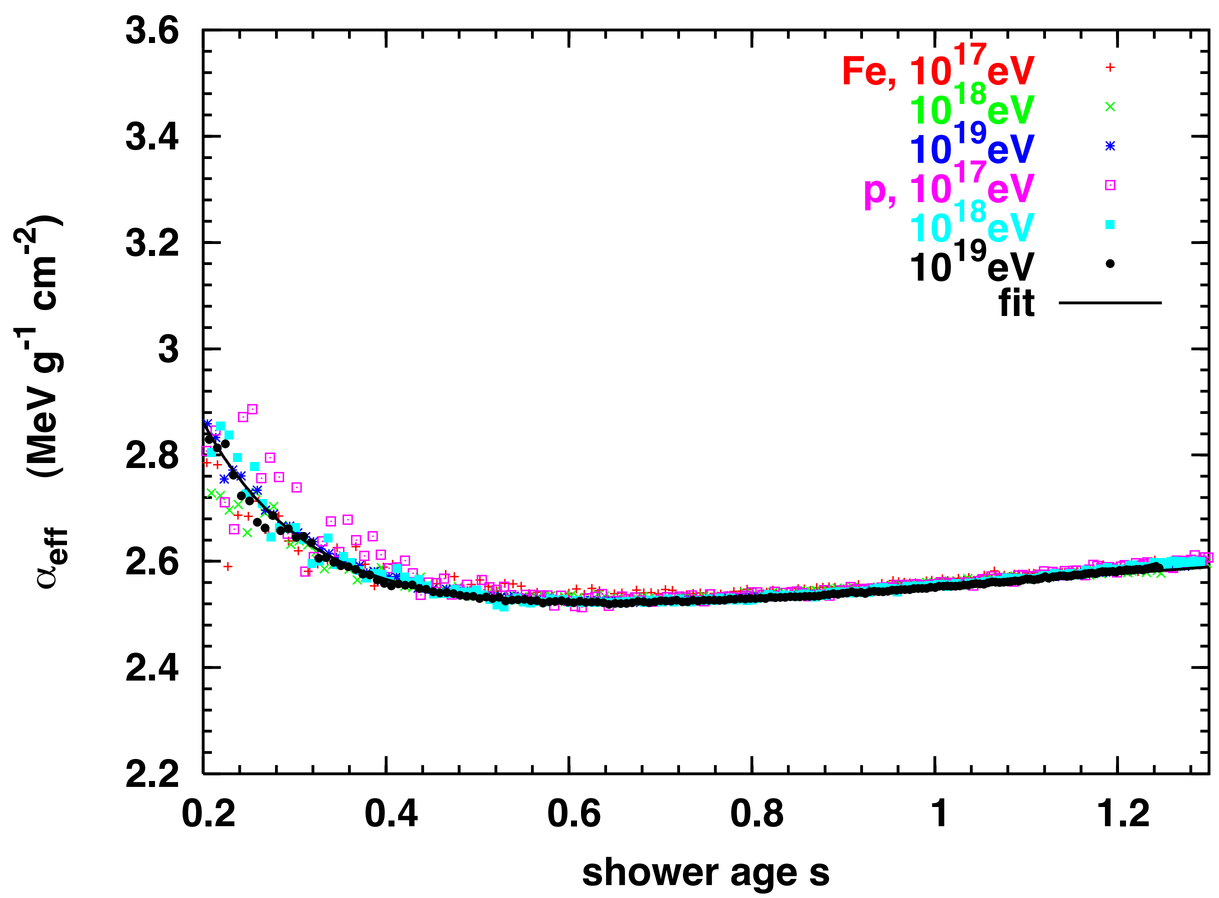


Energy deposit vs. shower size (ii)



Conversion from energy deposit to particle number for fixed low-energy threshold

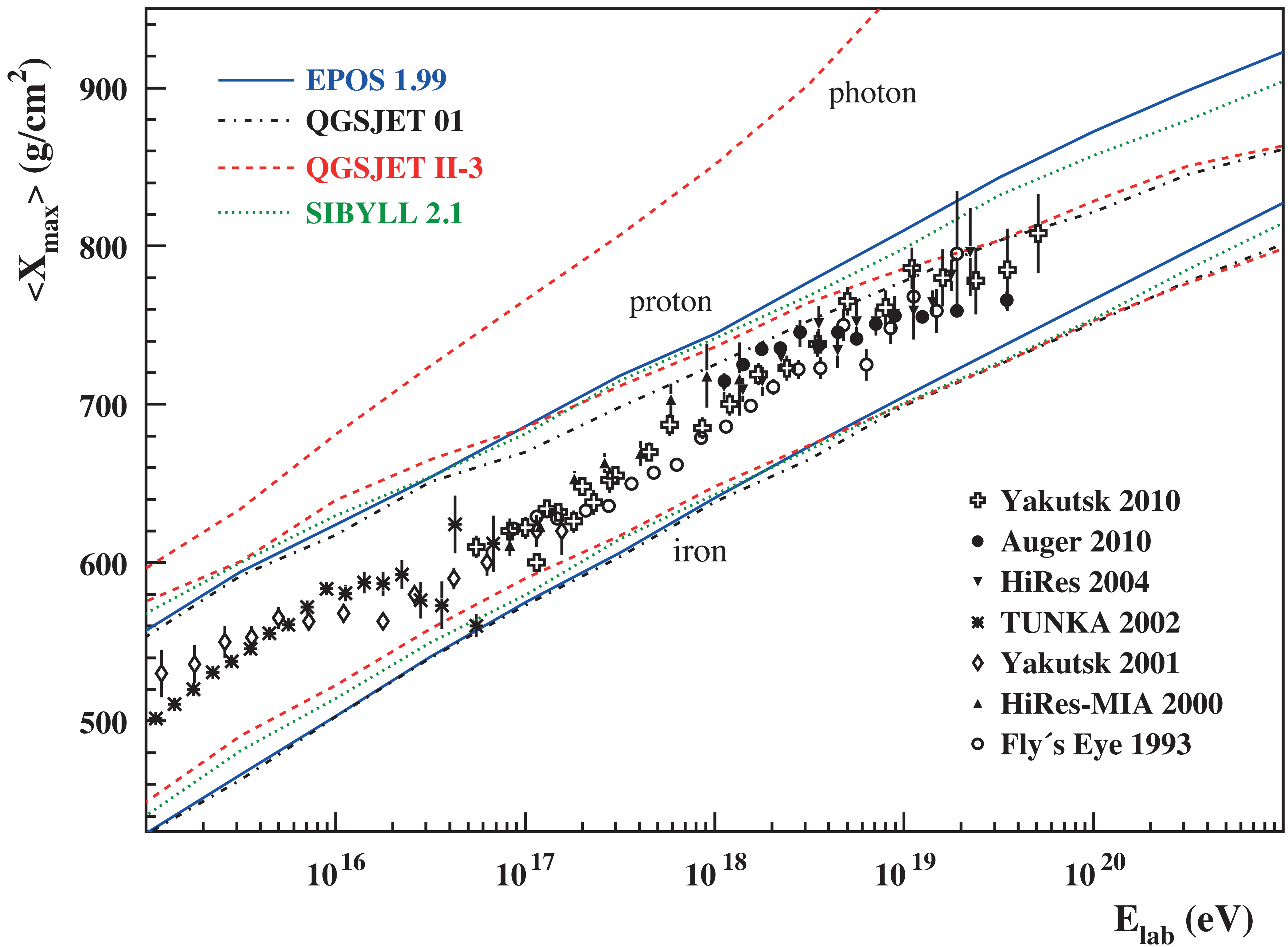
(Nerling et al. APP 24 (2006) 421)



$$N_{\rm ch}(X) = \frac{1}{\alpha_{\rm eff}(s, E_{\rm cut})} \frac{{\rm d}E_{\rm ion}}{{\rm d}X}$$

Shower universality:
energy and particle independent function

Mean depth of shower maximum (composition?)



(RE, Pierog, Heck, ARNPS 2011)

Proposal: cross-calibration of Auger and TA

(Diploma theses Maria Radosz, Julia Parrisius, Felix Werner)

Electronically stabilised

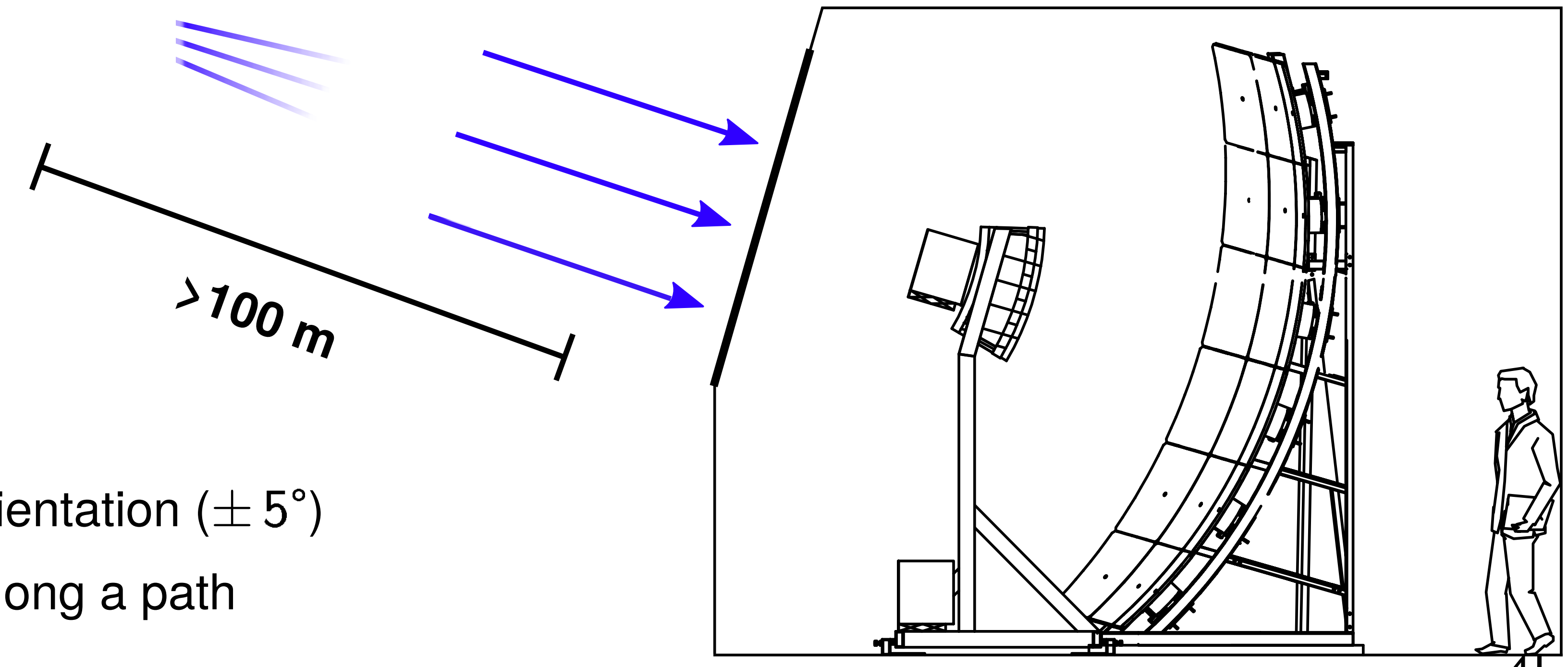
2.5 kg without payload

Payloads up to ~1 kg

Powered by LiPo battery (4S)

20 min flight time

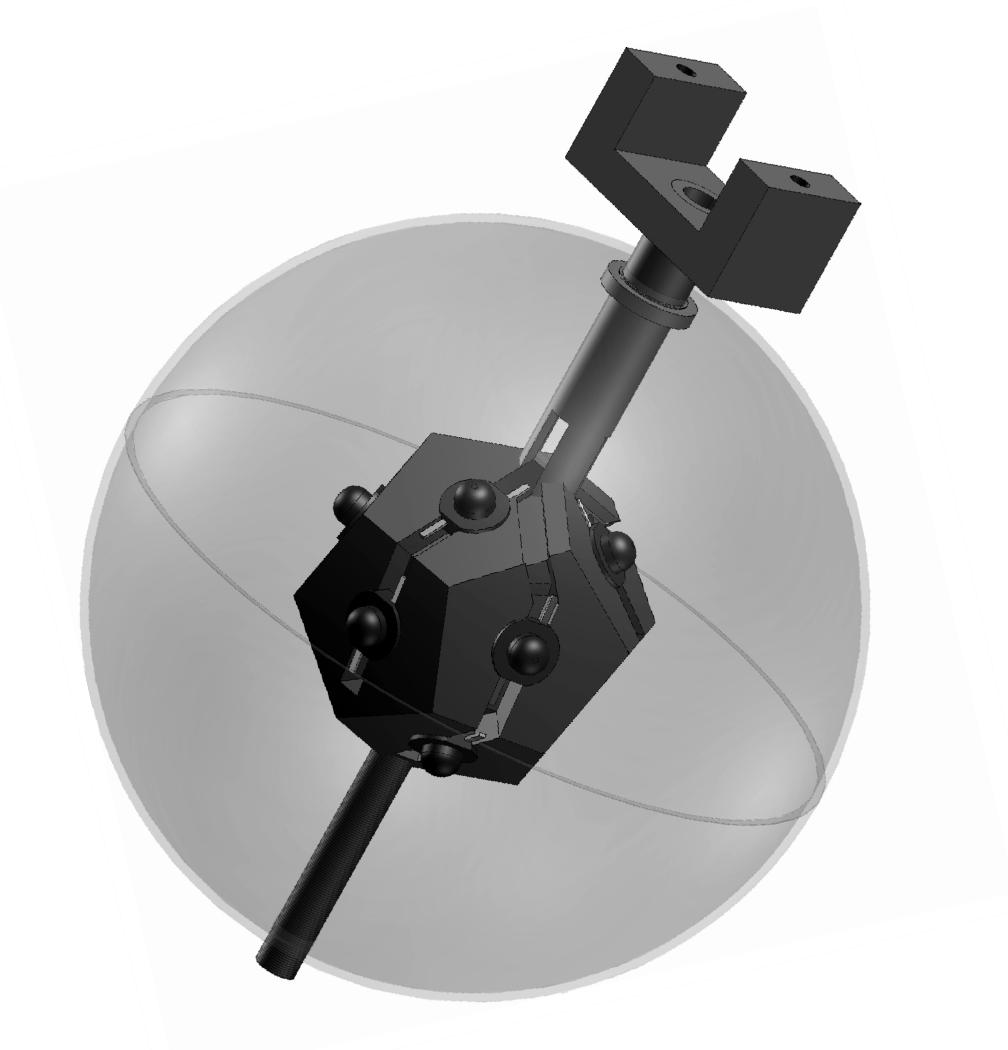
40 km/h rising speed



GPS receiver and 3d compass:

- Stabilisation of position ($\pm$ 2 m) and orientation ($\pm$ 5°)
- **2d waypoint flight** → program to fly along a path

Calibrated and stabilized light source



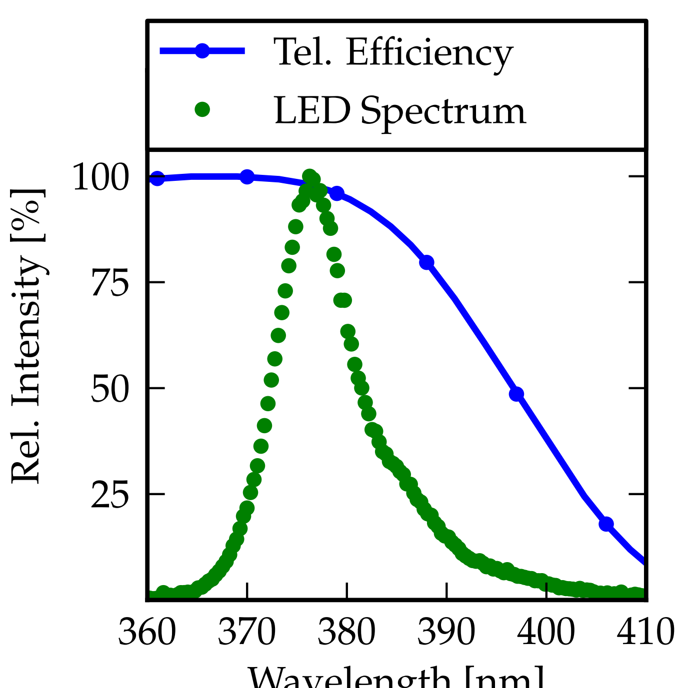
12 UV-LEDs with silicone lenses

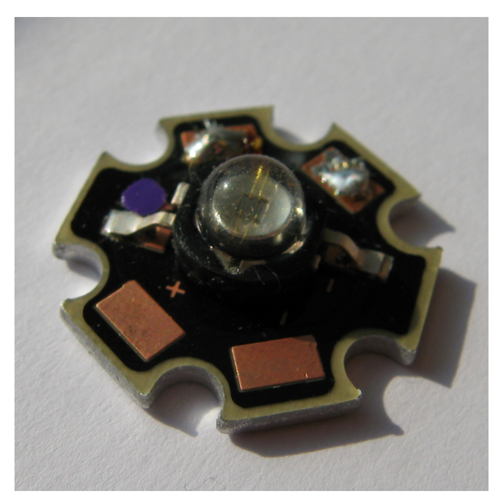
Dodecahedron (ABS) as body

Tyvek coating of body

∅ 10 cm diffuser (polystyrene)

Uncertainty (%)	Source
2.0	Reflections and geometry
2.0	Inaccuracy of electrometer
1.5	Responsivity and active area of photodiode (from NIST)
1.0	Intensity stability of the light source
3.4	Total





Roithner-Laser H2A1-H375