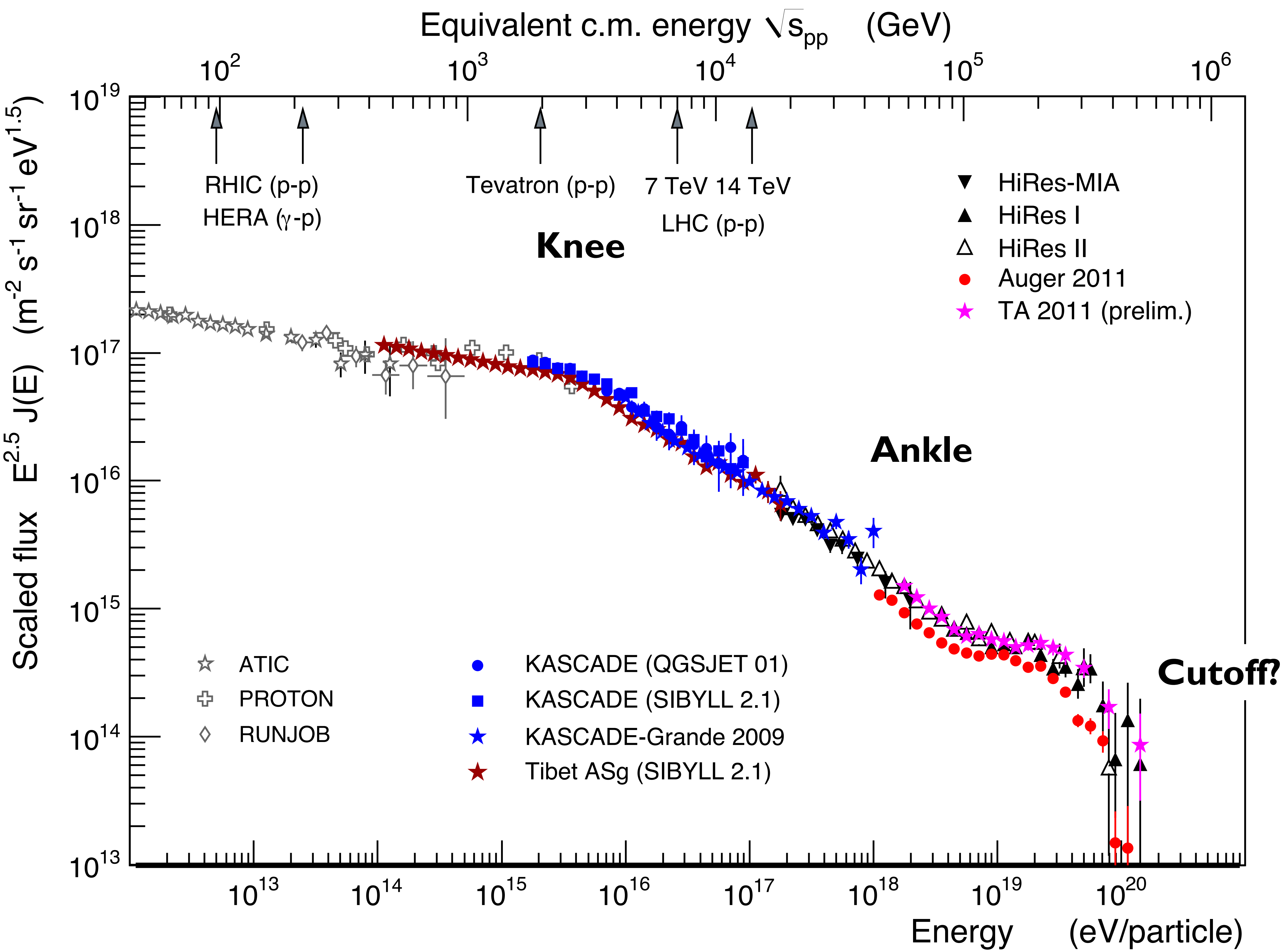
The Physics of Cosmic Rays – New Results

Ralph Engel

Karlsruhe Institut für Technologie (KIT)

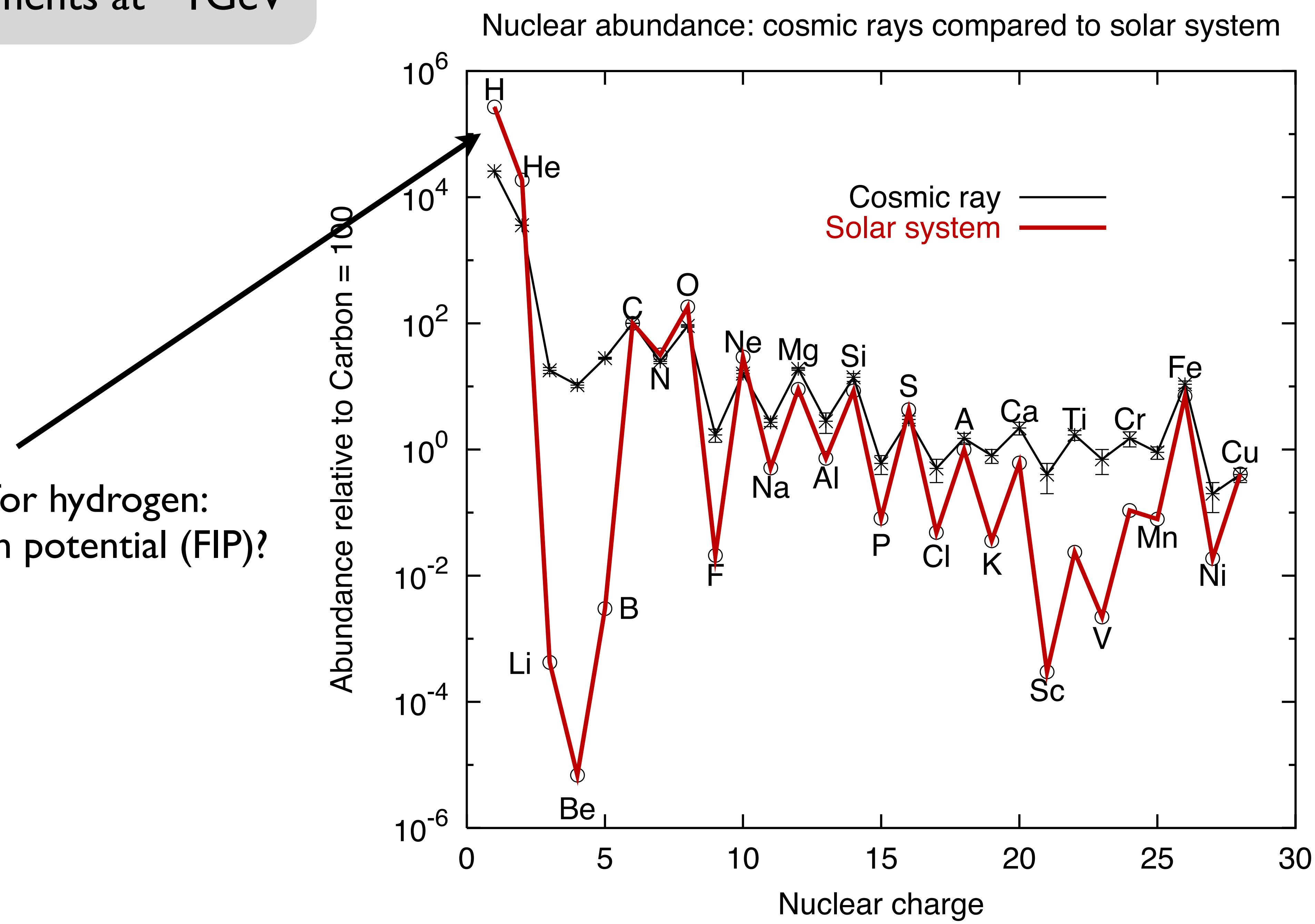
Re-scaled flux: several breaks in power law



Comparison of element abundances

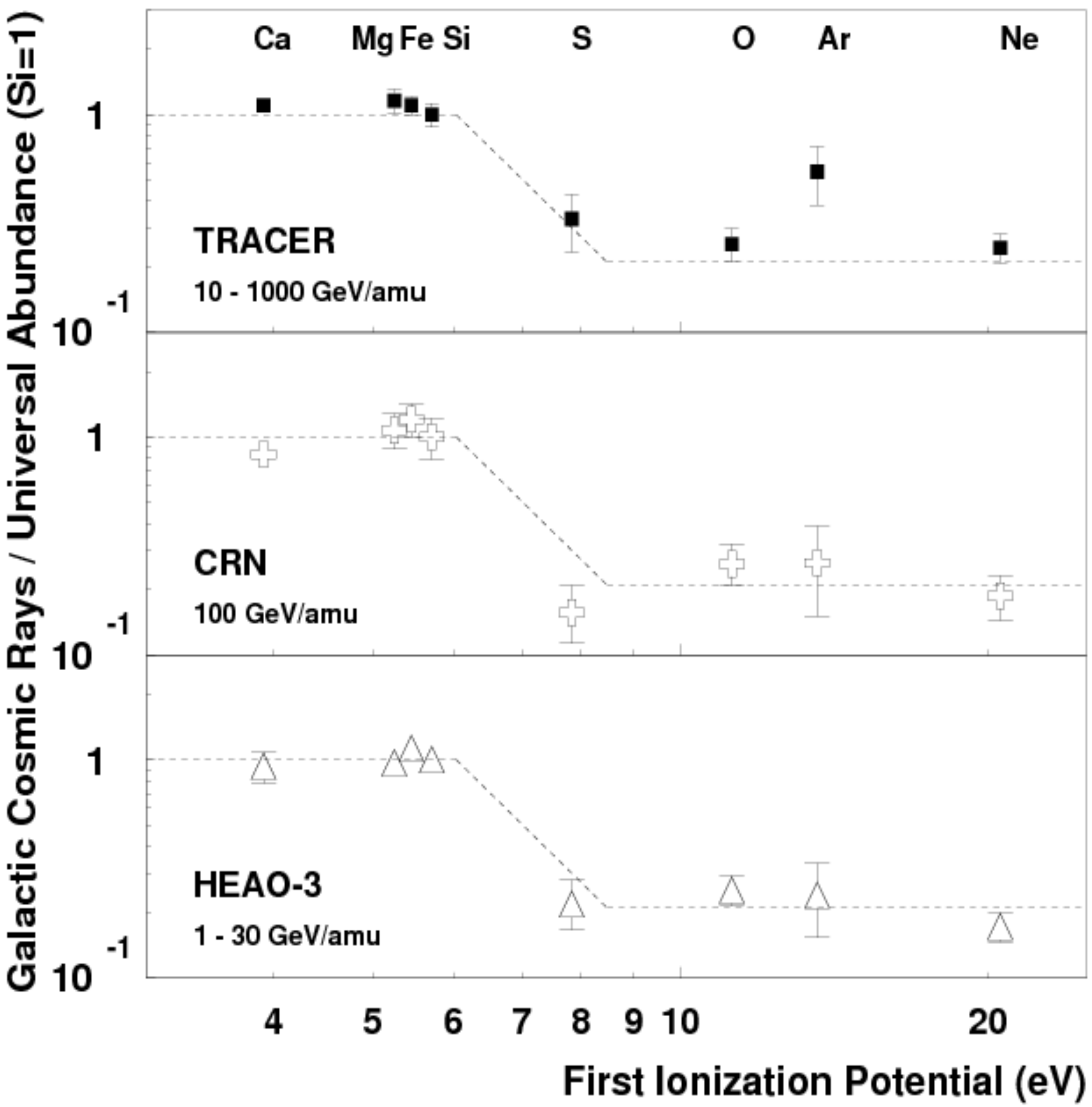
Flux of elements at ~1GeV

Discrepancy for hydrogen:
first ionization potential (FIP)?



(Gaisser & Stanev, NPA 2006)

Correlation with first ionization potential



Detailed analysis shows correlation with first ionization potential:

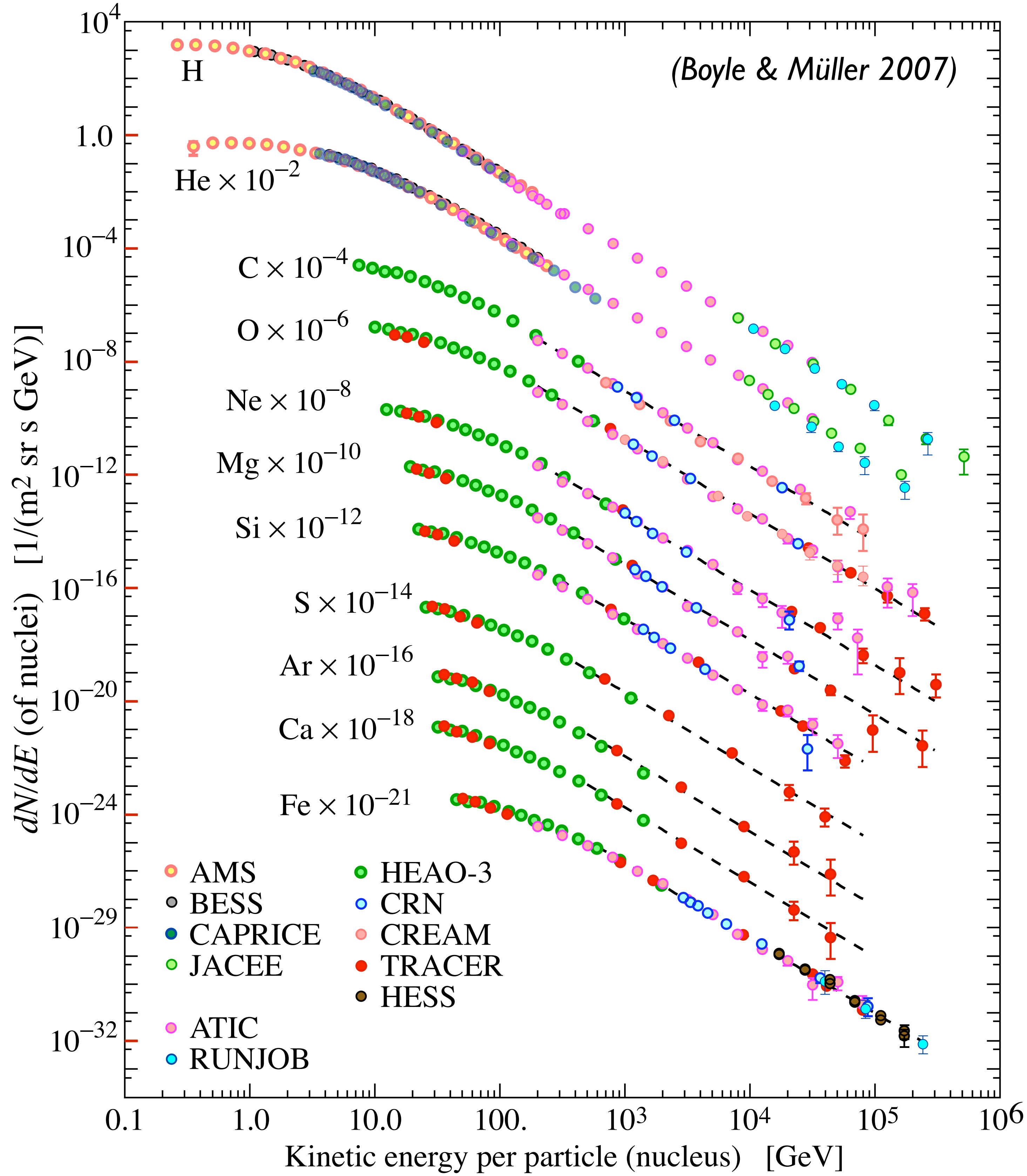
Acceleration of particles from dust grains ?

Injection problem:
shock acceleration only efficient for particles of ~GeV or higher energy

Fluxes of individual elements

Power law also found for individual elements

Index of power law almost identical (heavier elements harder spectra?)



Relative abundance of nuclei

H	He	Z= 6-9	10-20	21-30
1	0.38	0.22	0.15	0.4

Standard model of galactic cosmic rays

Source spectra	$Q(E) \sim \left(\frac{E}{Z}\right)^{-p}$	$p = 2 \ldots 2.3$
Local energy spectrum	$\frac{\mathrm{d}N}{\mathrm{d}E} \sim \left(\frac{E}{Z}\right)^{-(p+\delta)}$	$\delta = 0.4 \ldots 0.7$
Traversed column depth	$\lambda_{\mathrm{esc}} \sim \lambda_0 \left(\frac{E}{Z}\right)^{-\delta}$	$\lambda_0 \approx 10\,\mathrm{g/cm^2}$
Typical lifetime	$\tau_{\mathrm{esc}} \sim 2 \times 10^7\,\mathrm{yr}$	$\tau_{\mathrm{disk}} \approx 10^6\,\mathrm{yr}$

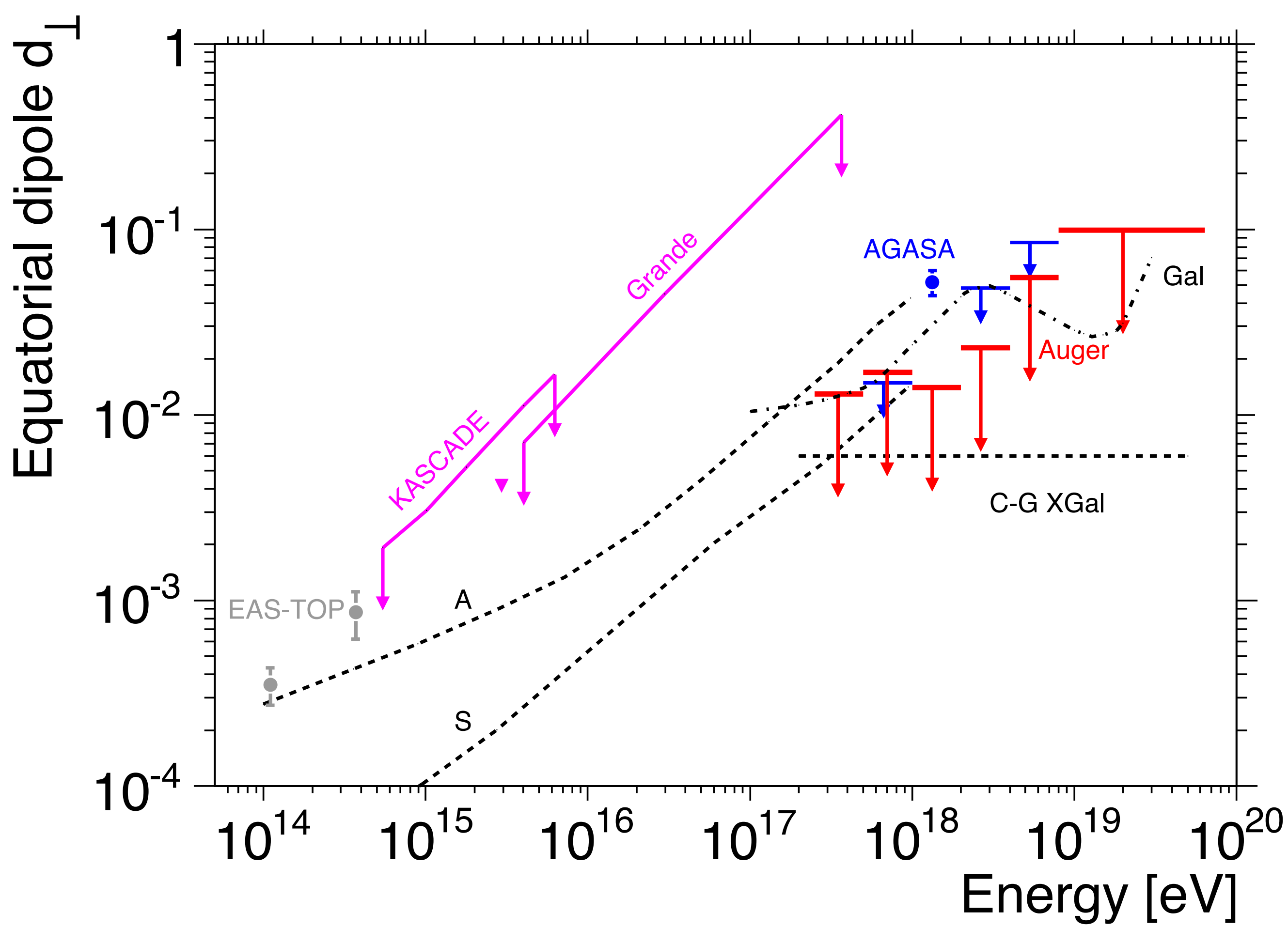
Problems discussed up to now:

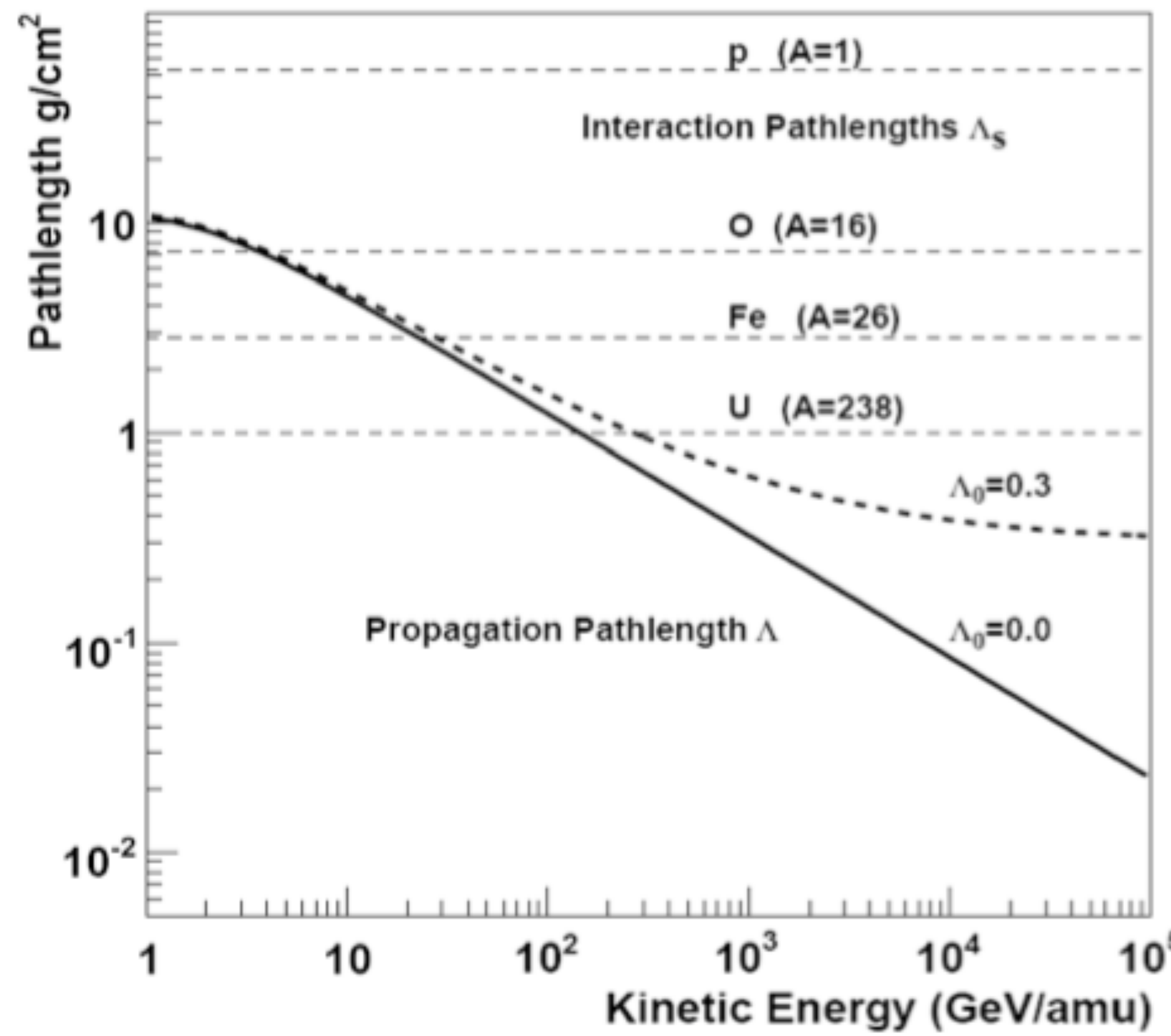
Energy range beyond the knee (anisotropy, column depth, transition from galactic to extragalactic sources)

Breakdown of Leaky Box model

Elementary geometry:

$$\lambda_{esc} \geq l_{min} \cdot \rho_{ISM}$$



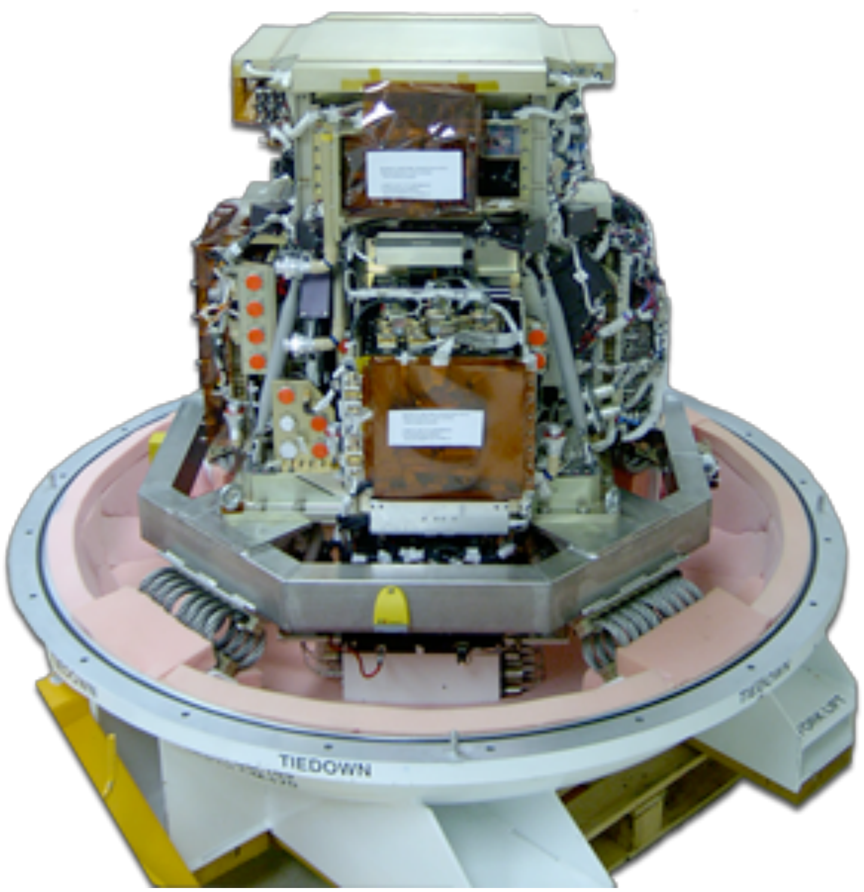


Leaky box model not valid above knee energy

Features of the energy spectra of elements

PAMELA-Detektor

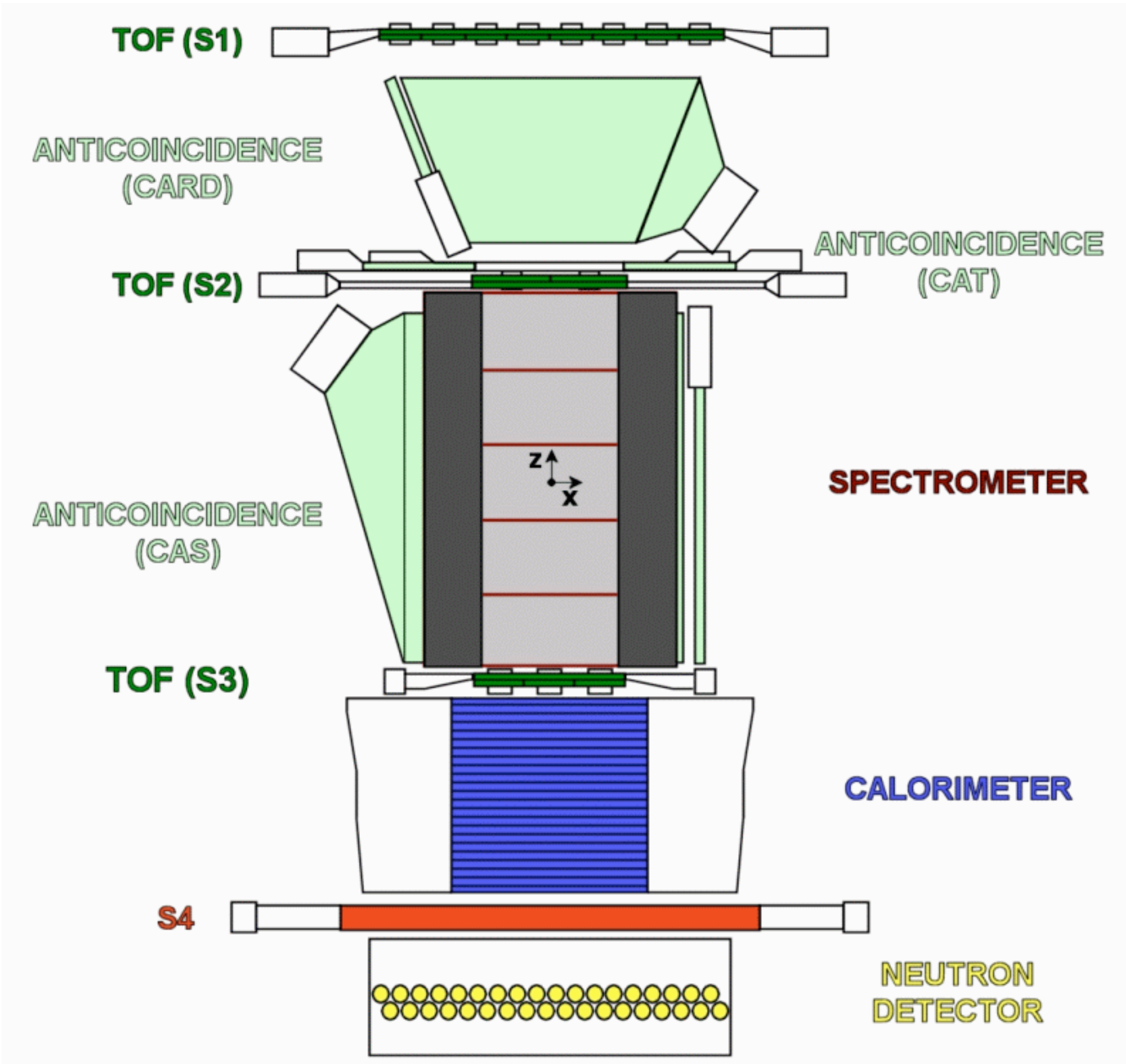
Payload for Antimatter Matter Exploration
and Light nuclei Astrophysics



Launch June 15, 2006, 350- 600 km

Aim: Light elements in energy range 80 MeV to about 7×10^{11} eV (700 GeV)

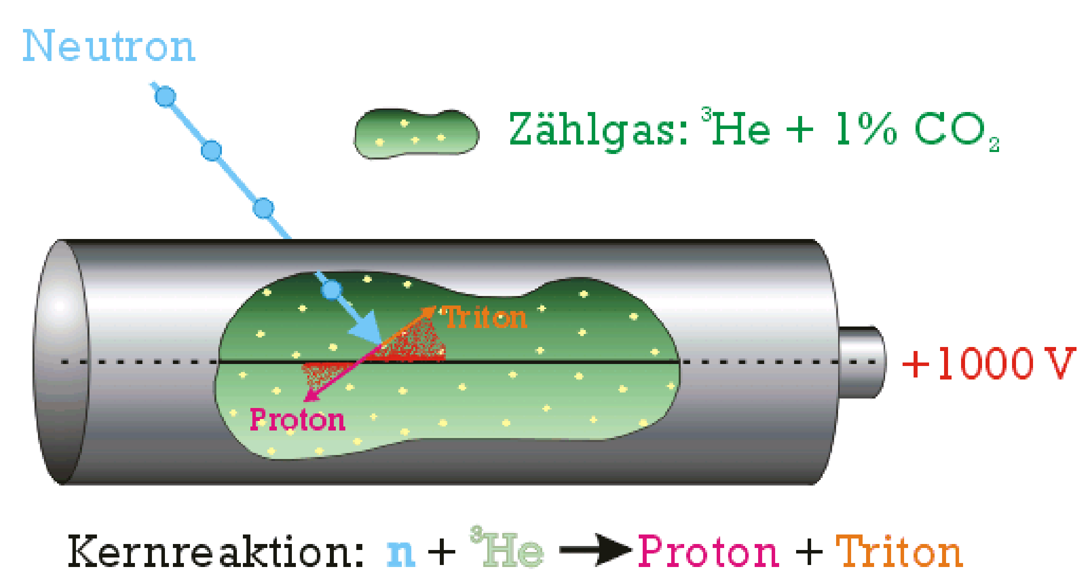
Cross section of PAMELA detector



Time of flight: 120 ps resolution

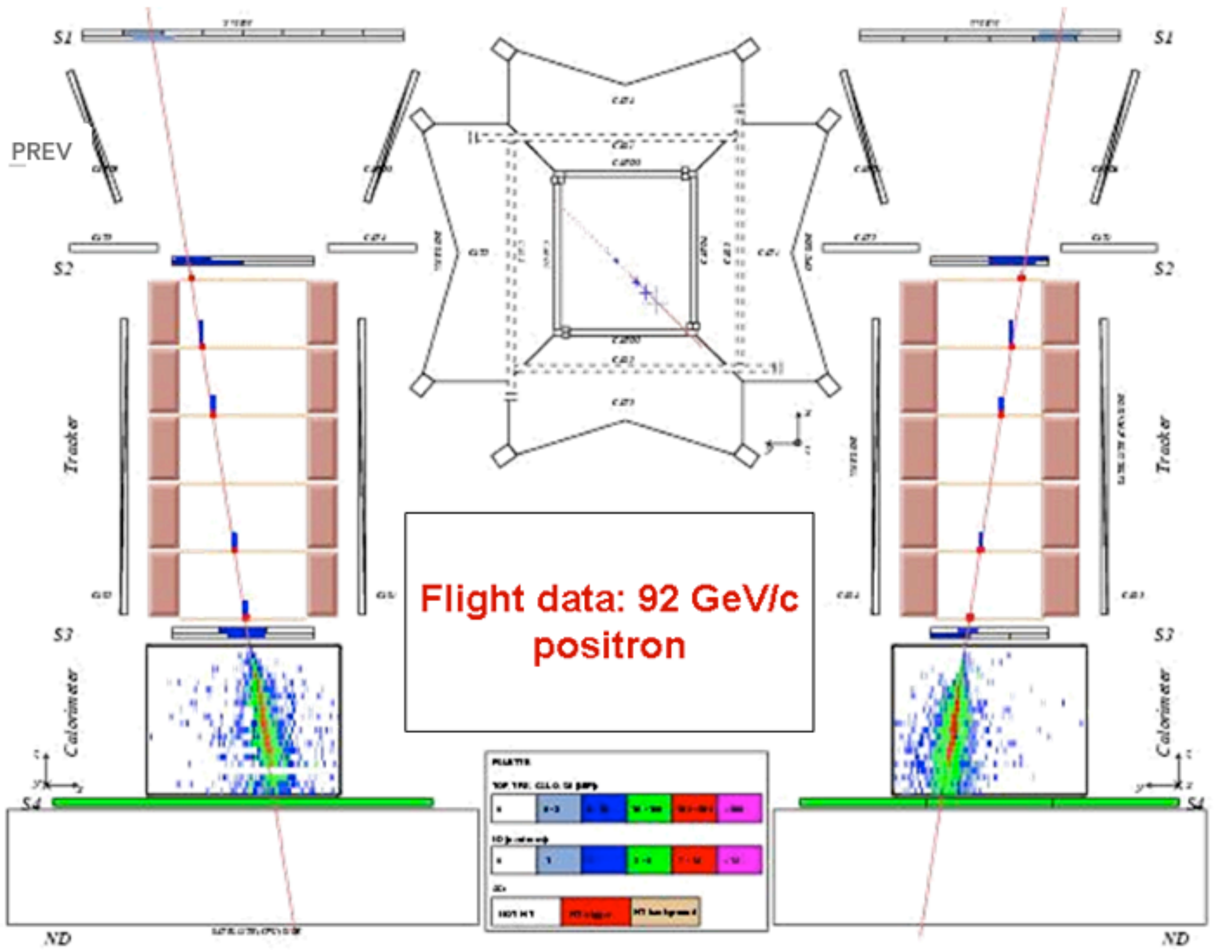
Permanent magnet B = 0.4 T

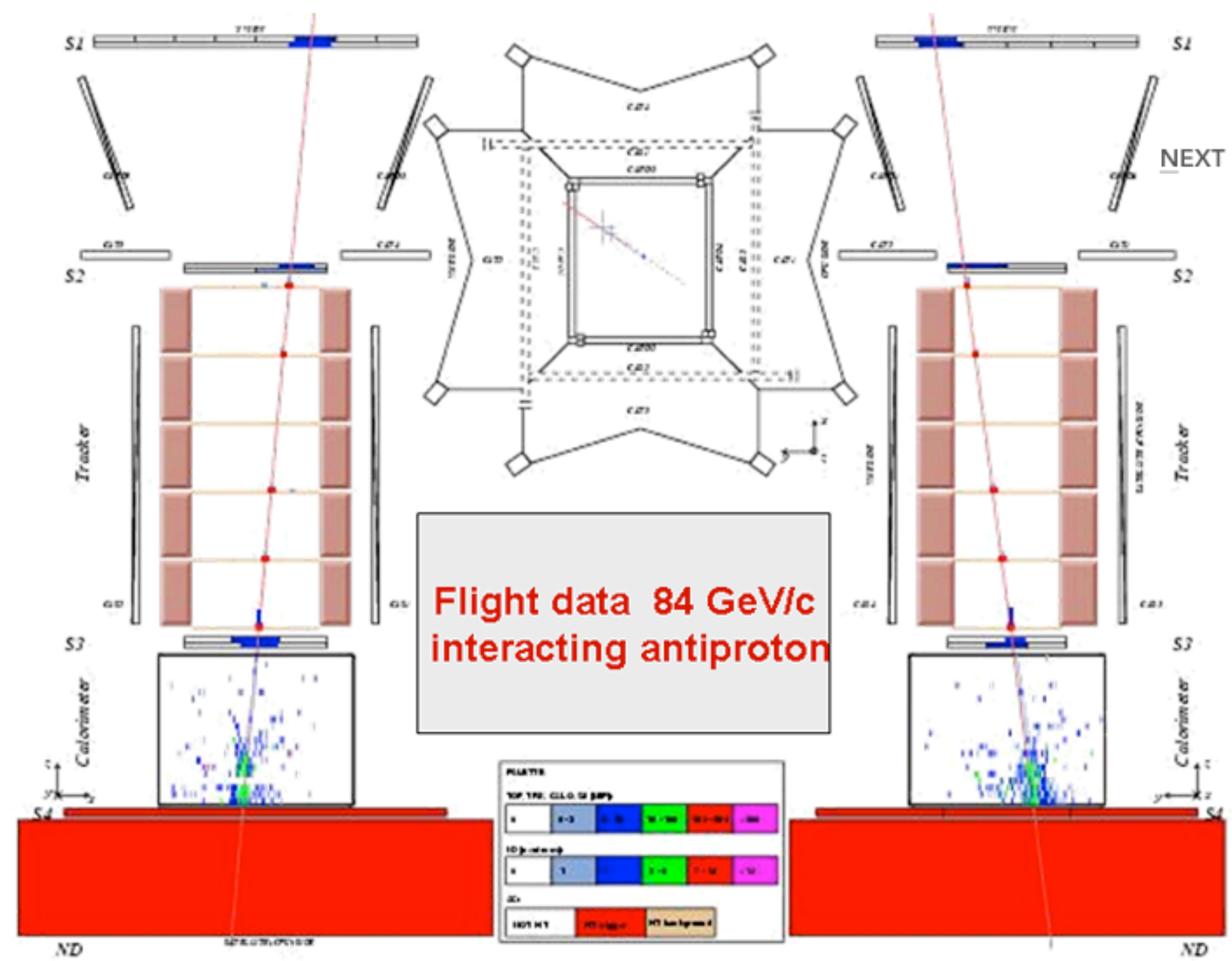
Silicon strip detector ~4µm



Silicon-tungsten calorimeter:
- ~ 0.6 had. interaction lengths
- ~ 16.3 radiation lenghts

Event displays of measured events

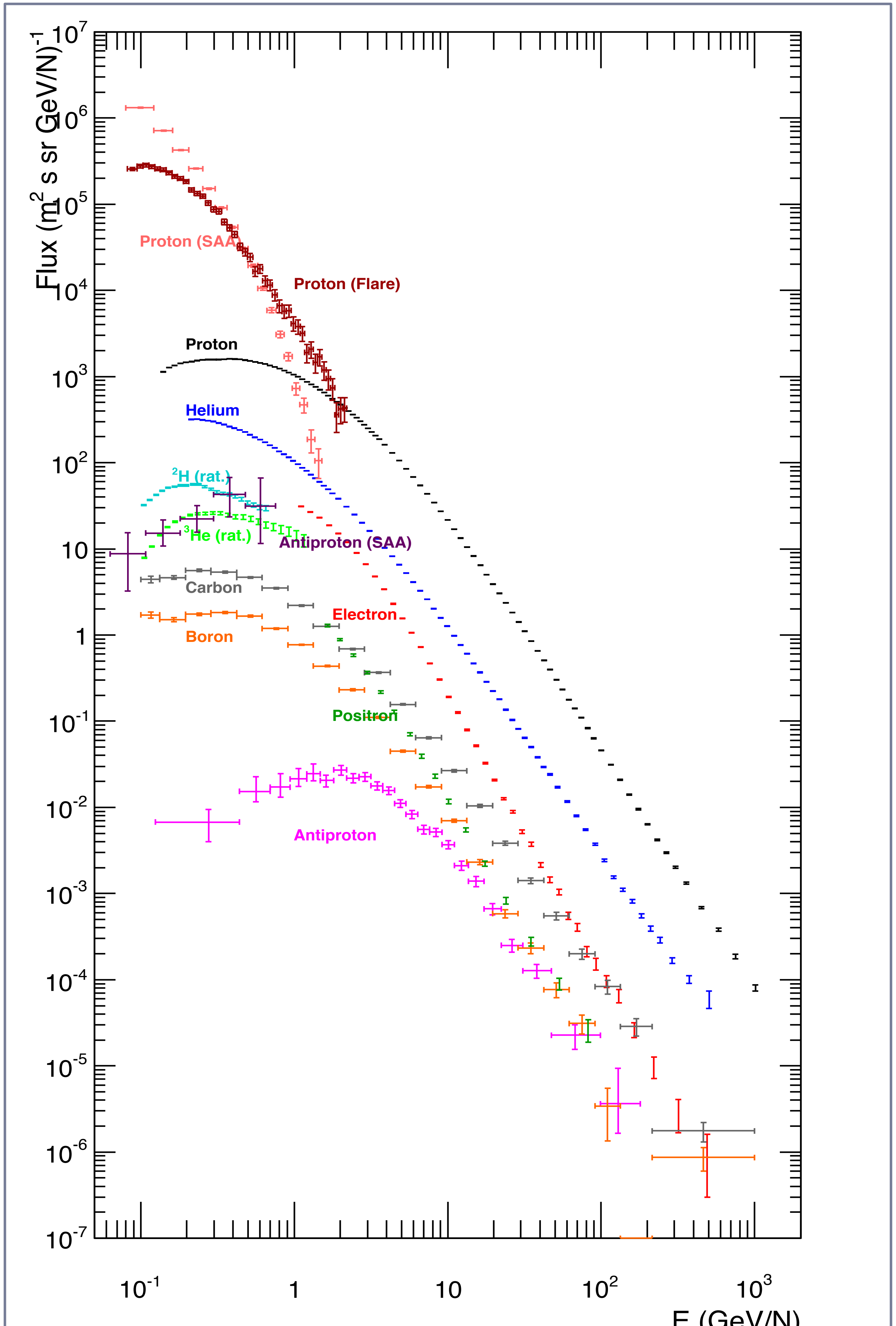




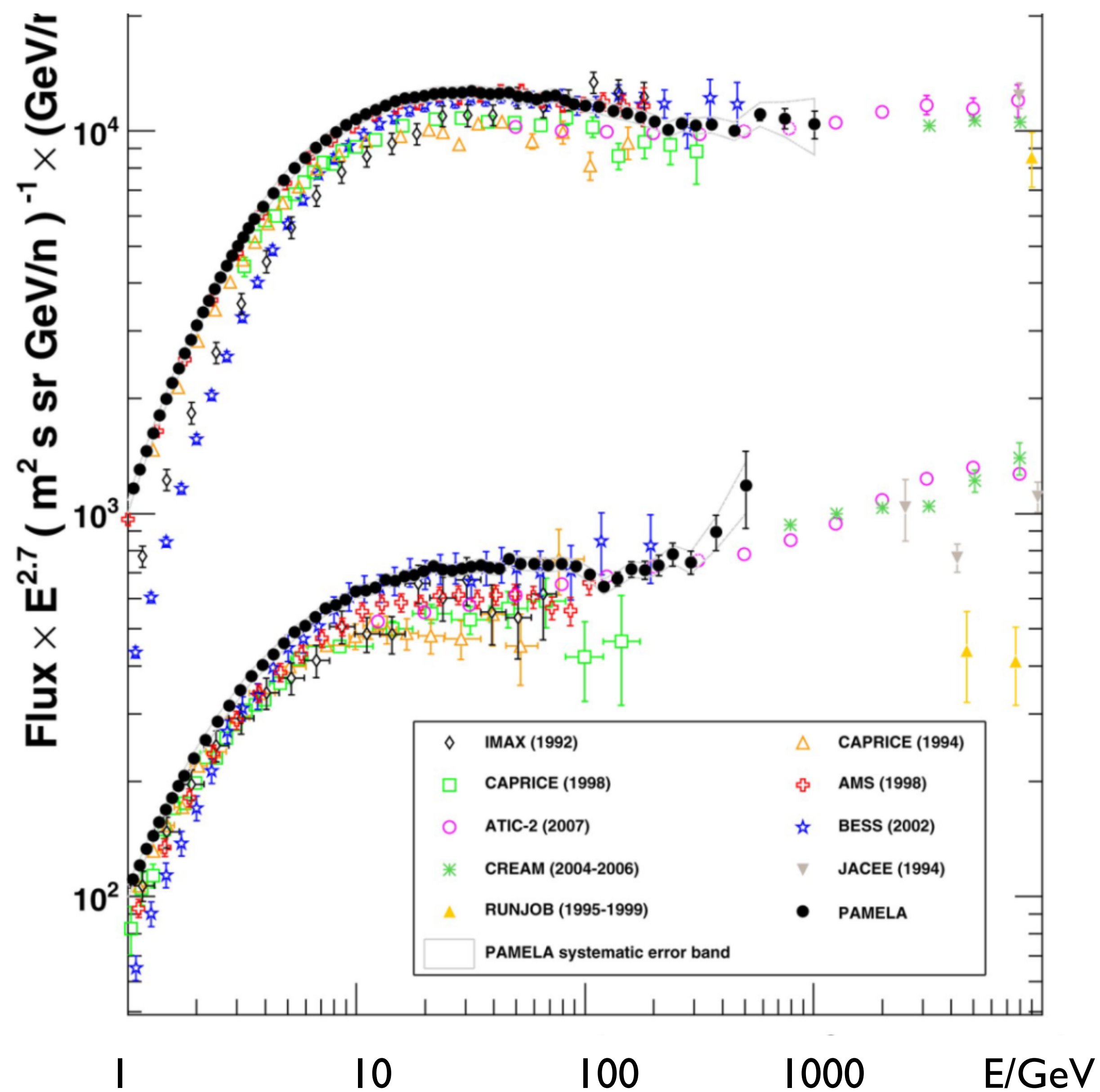
Clear signal in em. calorimeter

Additional signal in neutron detector

PAMELA results

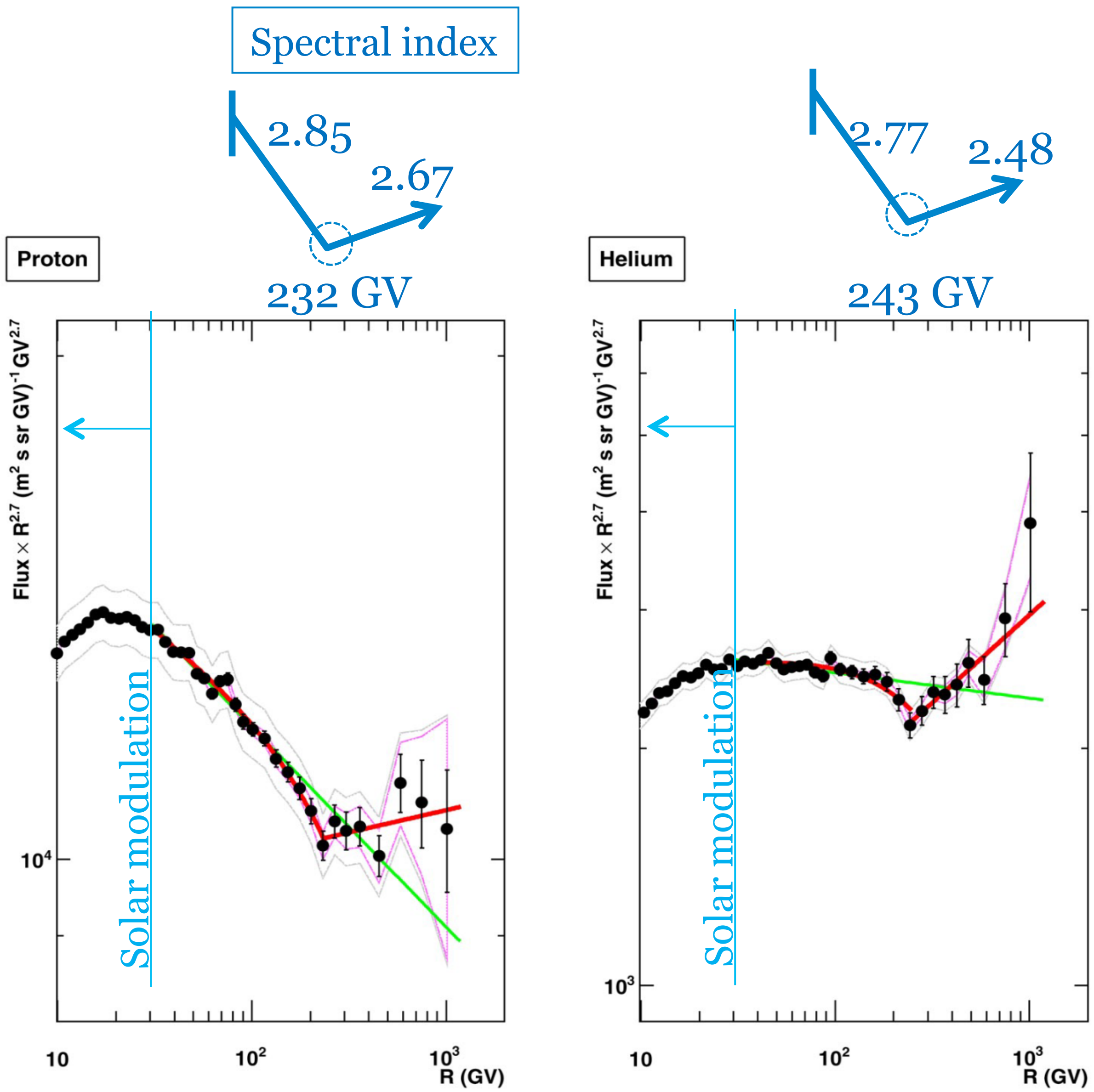


P and He together with other data

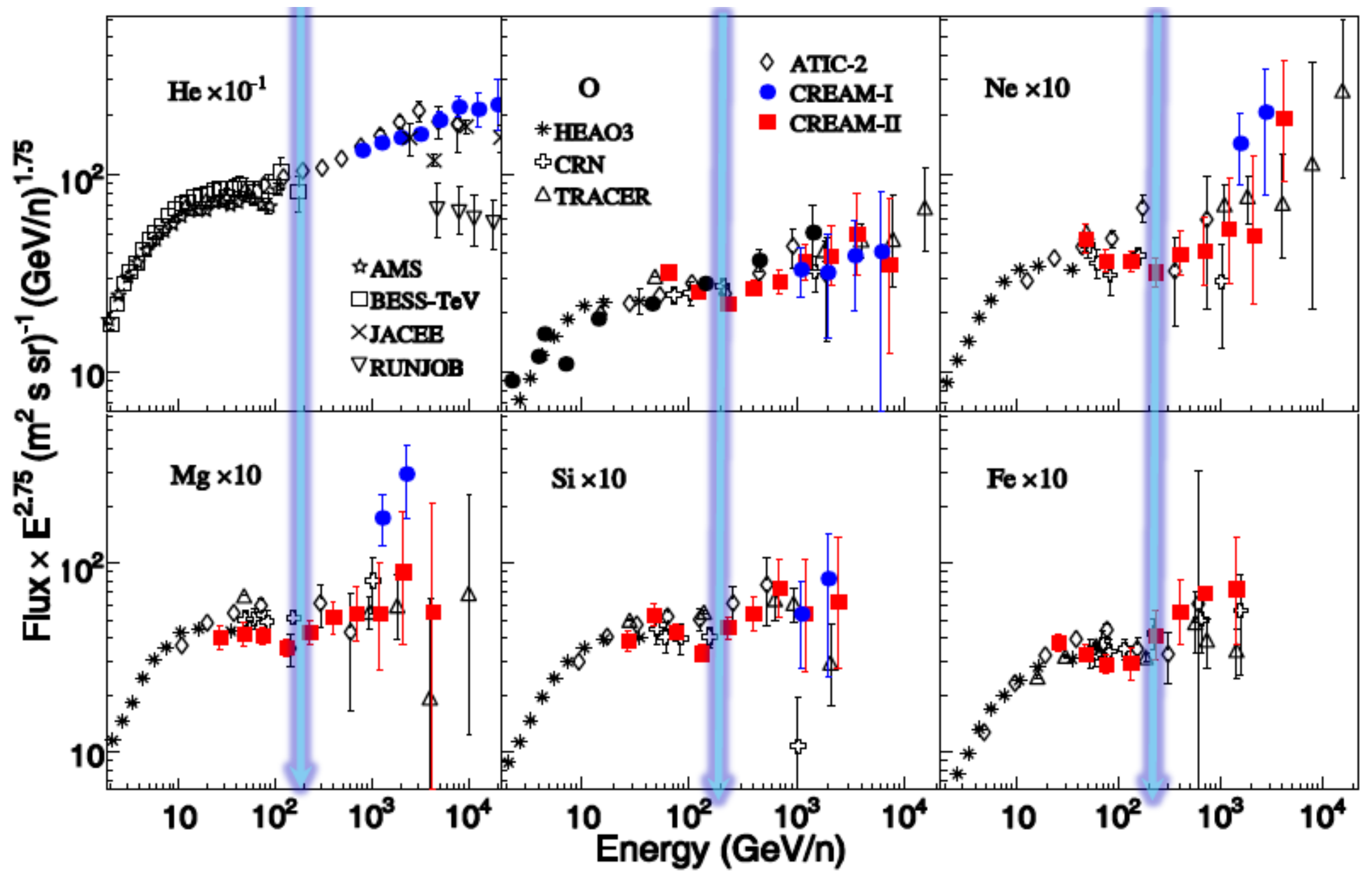


(Sparvioli, ISVHECRI 2012)

Energy spectra are not simple power laws

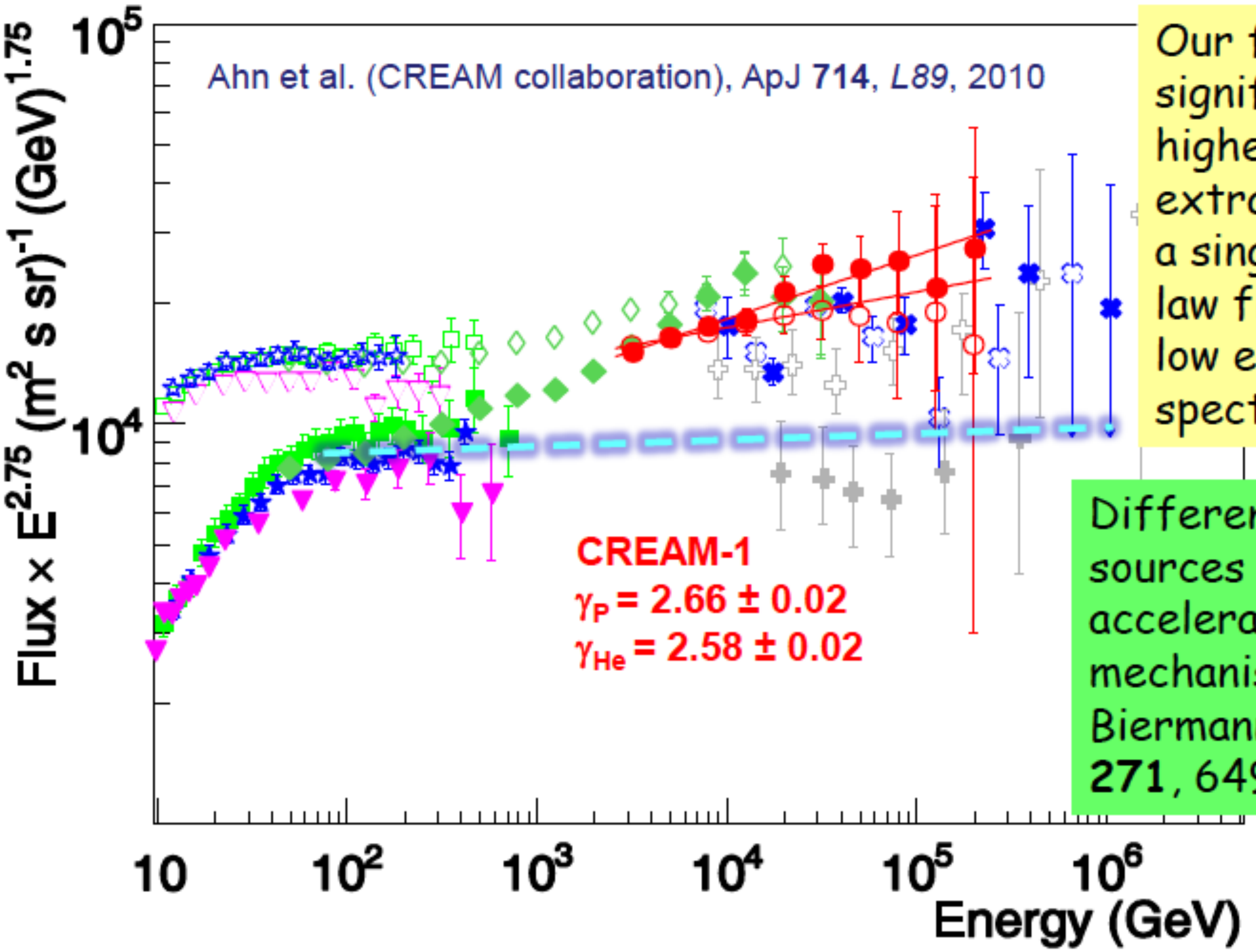


Indications for similar features in fluxes of heavier elements



Break observed at same rigidity (230 - 240 GV)

Evidence for harder helium spectrum



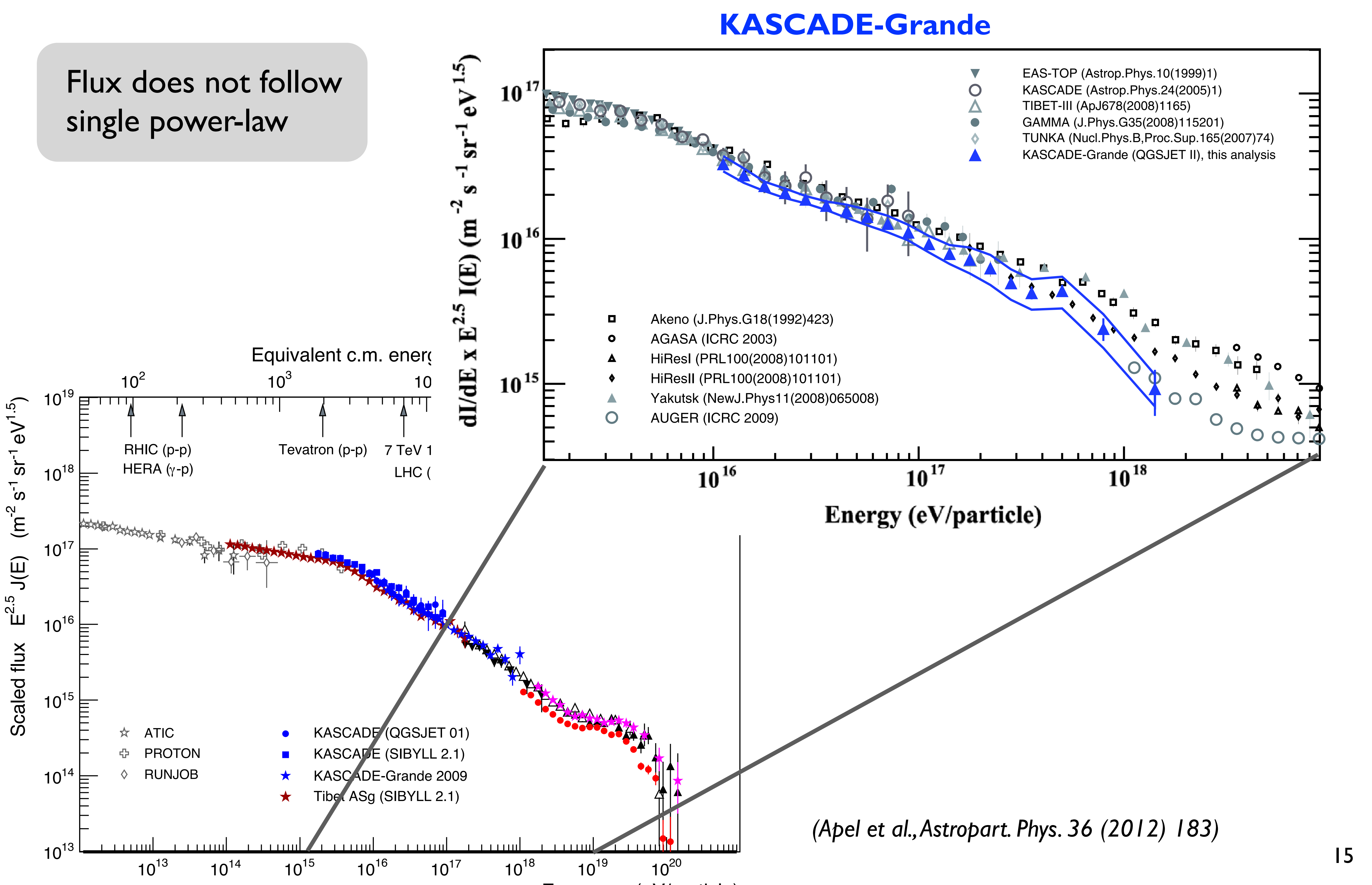
Our fluxes are significantly higher than the extrapolation of a single-power law fit to the low energy spectra

Different types of sources or acceleration mechanisms? (e.g., Biermann, P. L. *A&A* **271**, 649,1993)

Crossing of p and He fluxes cannot be explained with shock acceleration

Structures above the knee (i)

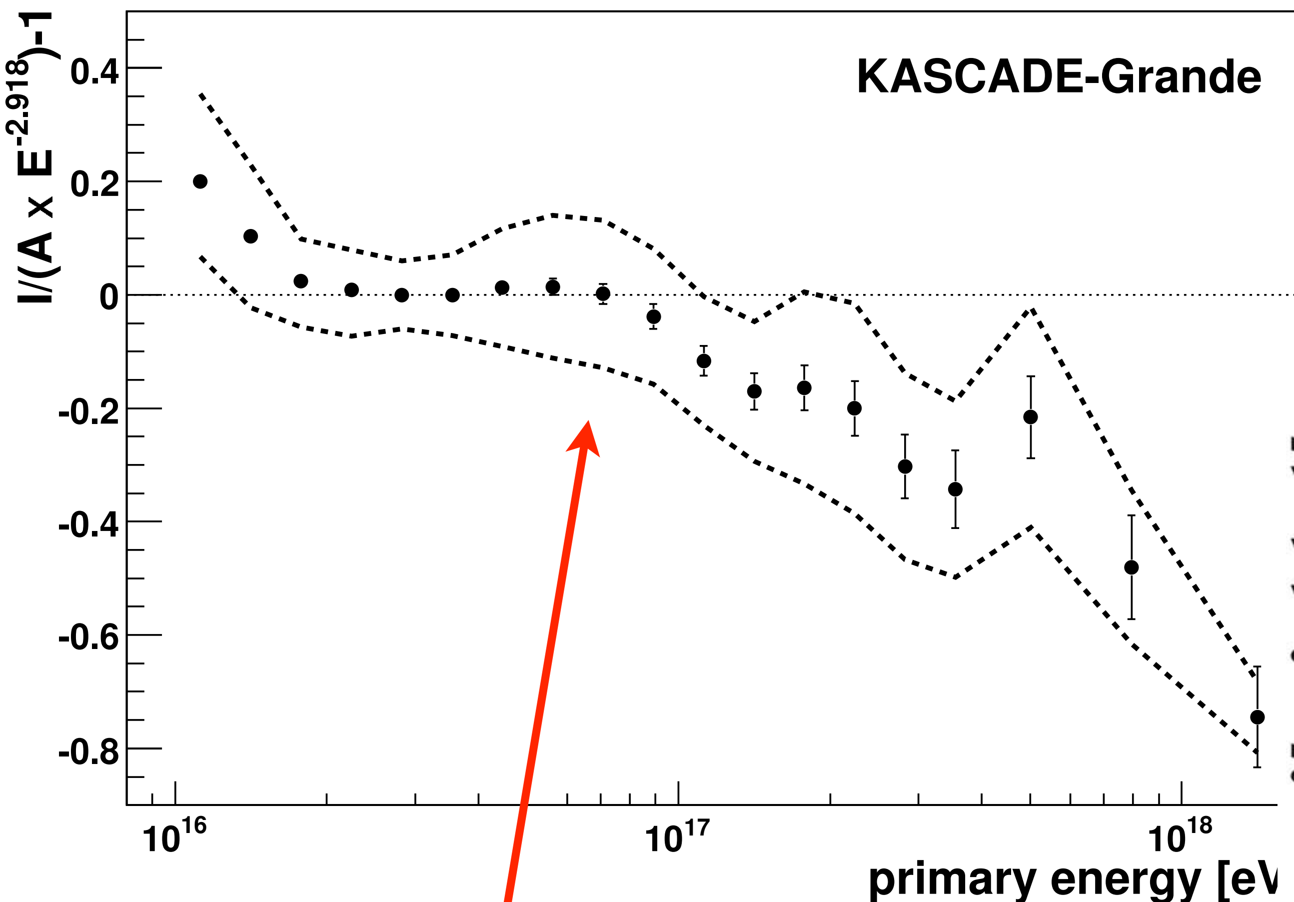
Flux does not follow single power-law



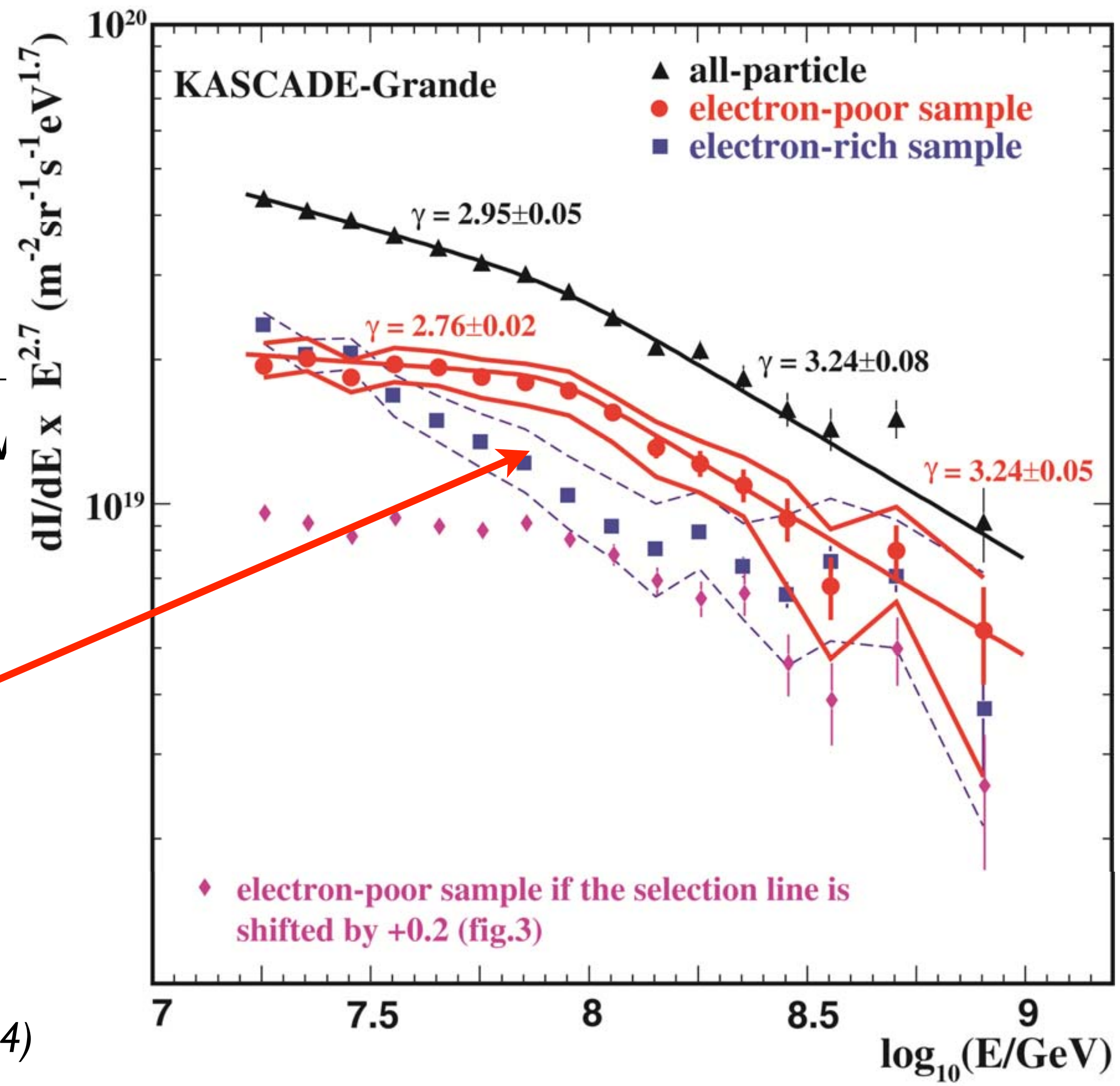
(Apel et al., Astropart. Phys. 36 (2012) 183)

Structures above the knee (ii)

Relative difference to power law.



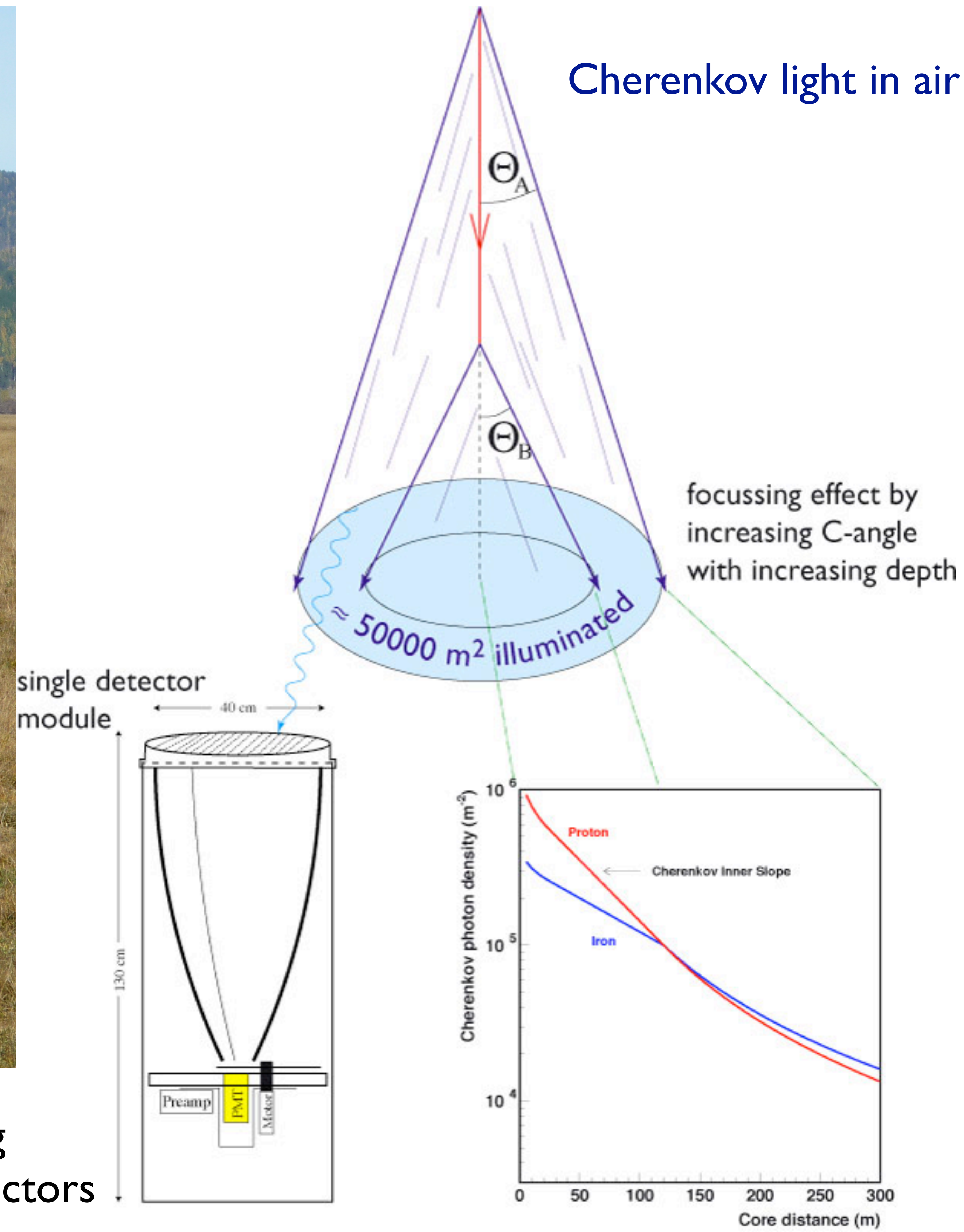
Composition estimate



knee of heavy elements

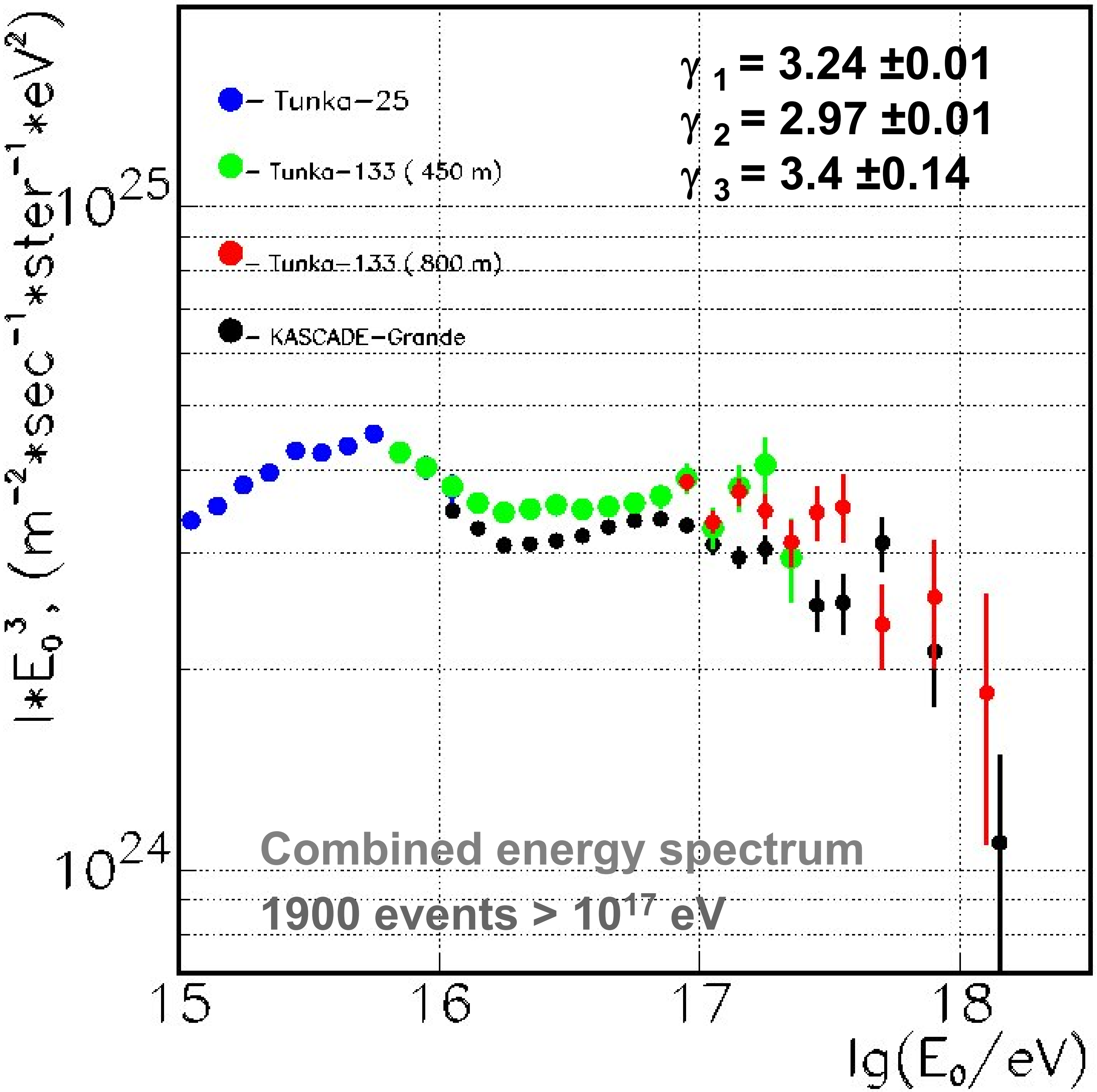
(Apel et al., Phys.Rev.Lett. 107 (2011) 171104)

Independent measurement: Tunka Cherenkov array



133 non-imaging
Cherenkov detectors

Structures above the knee (iii)



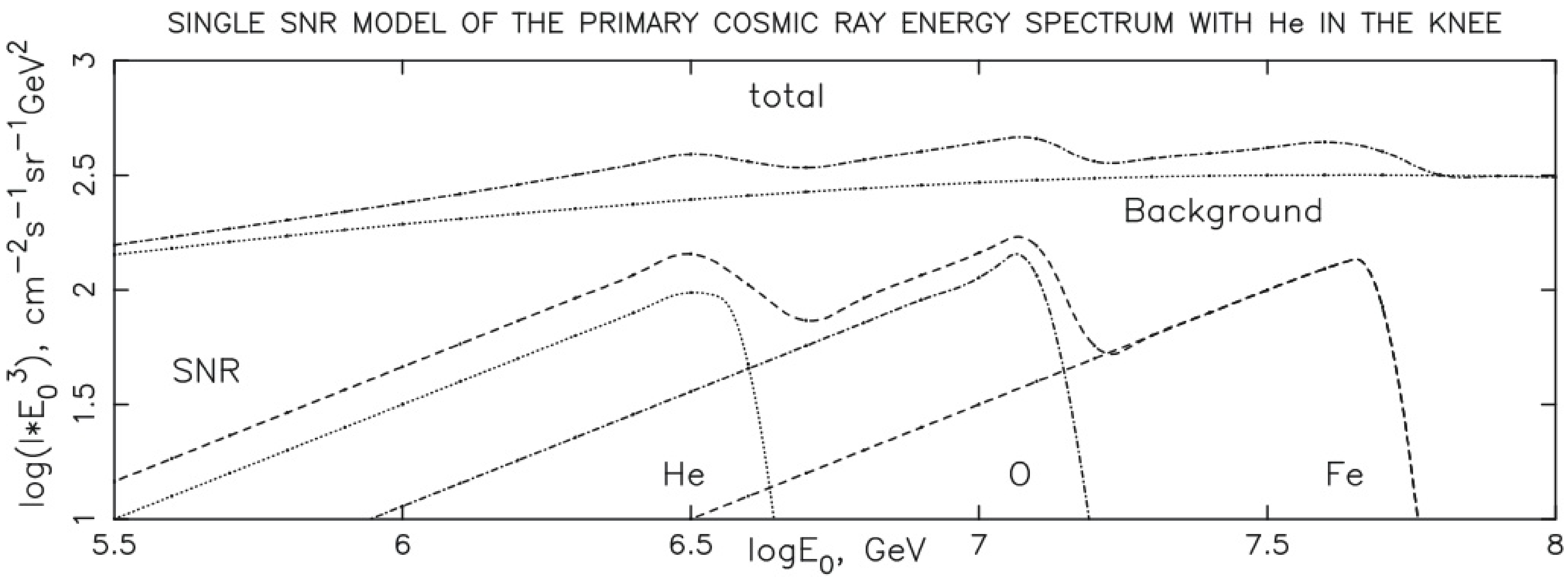
Structure of dip and additional knee found by several experiments (including Yakutsk and IceTop)

Interpretation unclear

(Kuzmichev, ECRS 2012, Moscow)

Models that predict such features of the spectrum

Anisotropy likely at some level

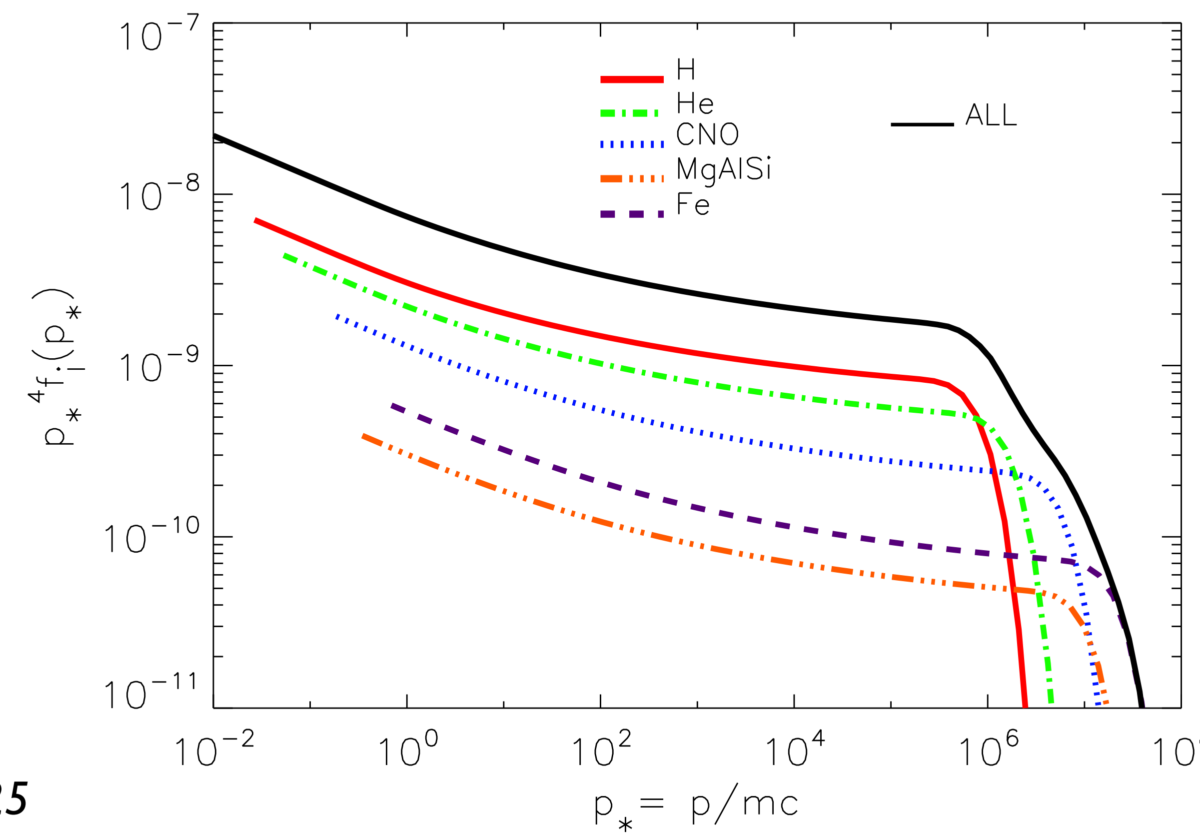


Erlykin & Wolfendale, J.Phys.G32:1-8,2006

Non-linear shock acceleration

Bell & Lucek, 2001 (several papers)
Berezhko, Völk, ...

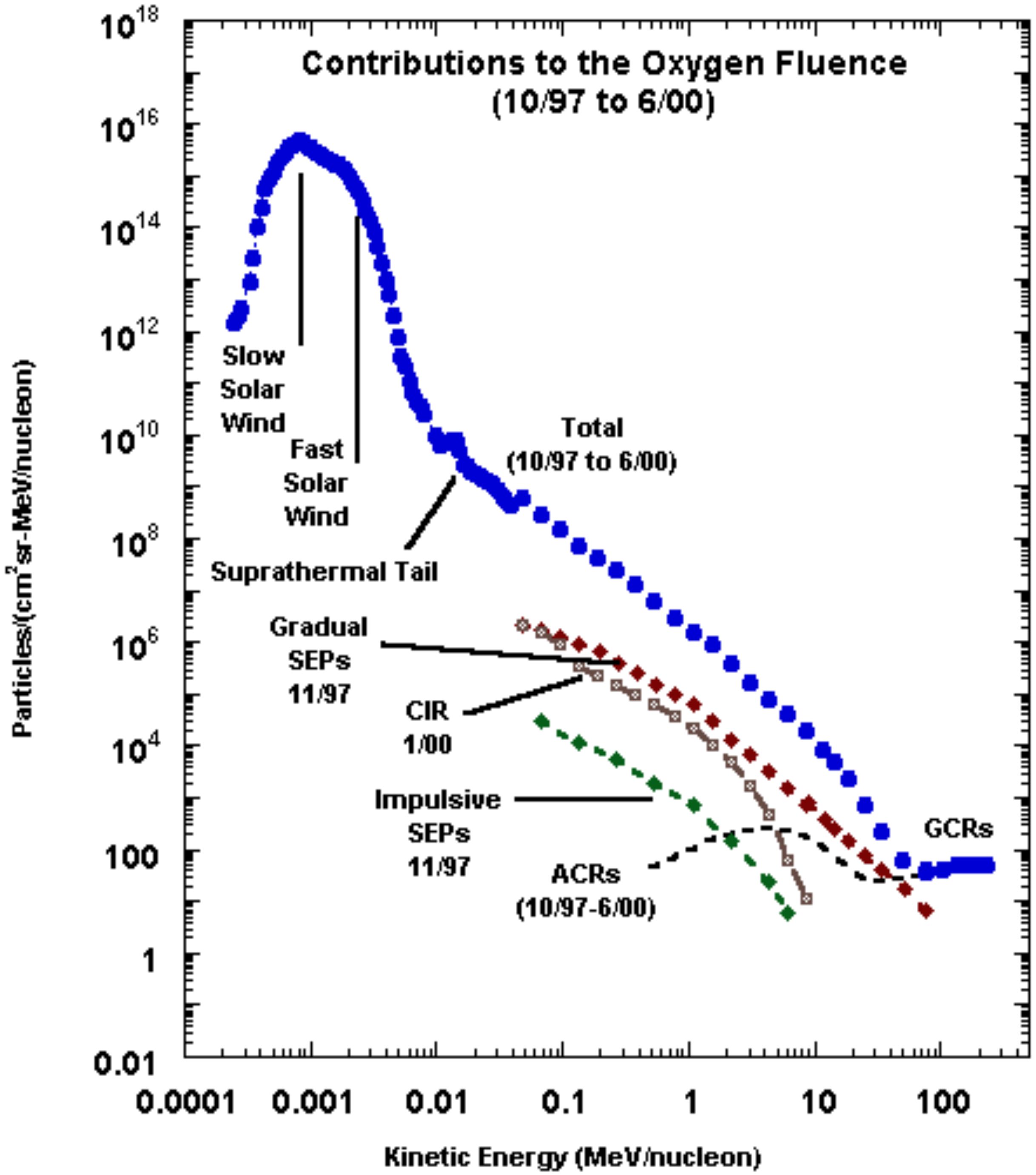
Magnetic field amplification, similar end values for different environments

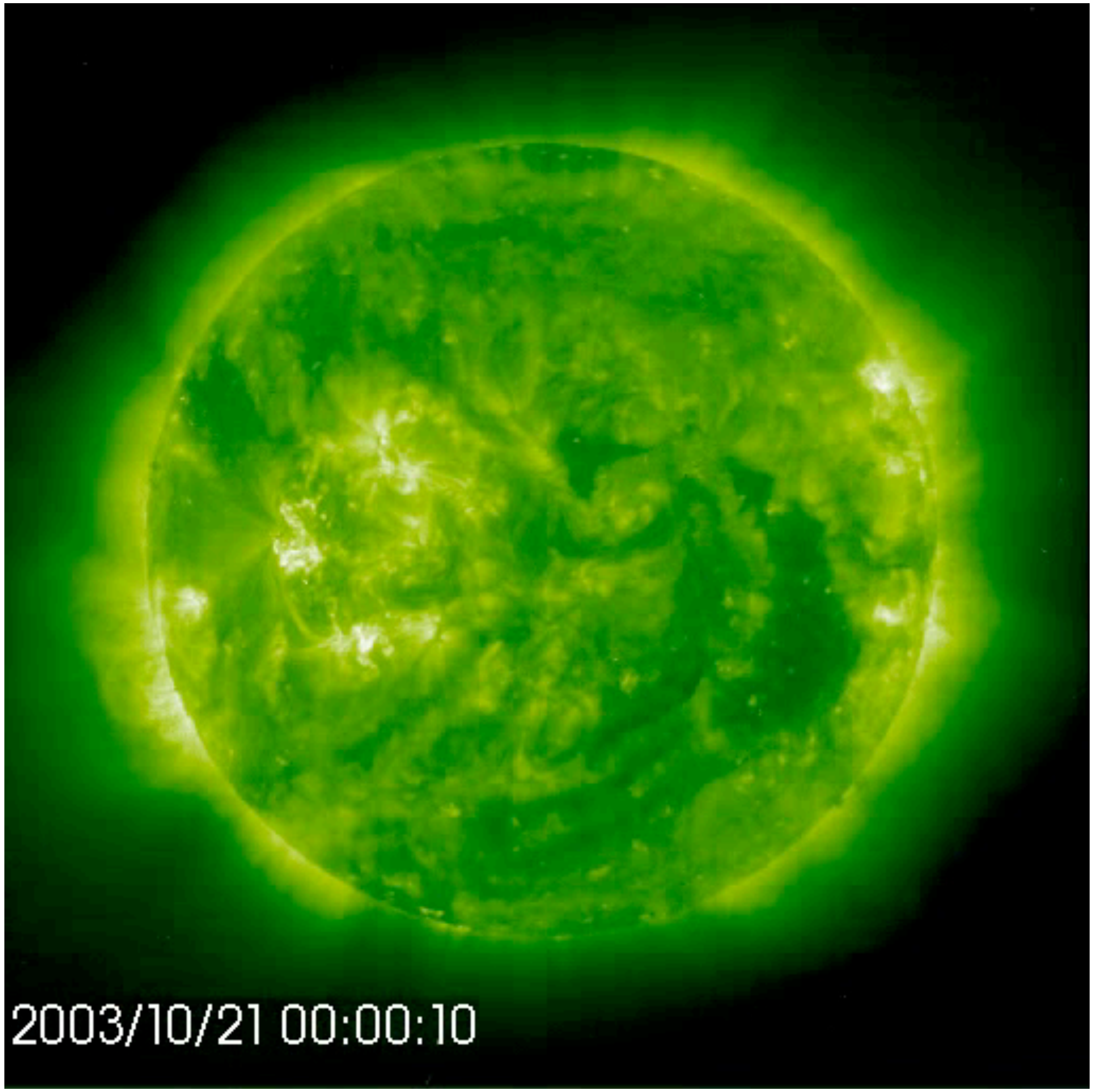


Caprioli, Blasi, Amato, astro-ph/1007.1925

Acceleration of particles at the sun

Direct detection of particles
from shock acceleration





Aufnahme mit LASCO (SOHO)

(Mewaldt et al., A.I.P. Conf. Proc. 598 (2001) 165)

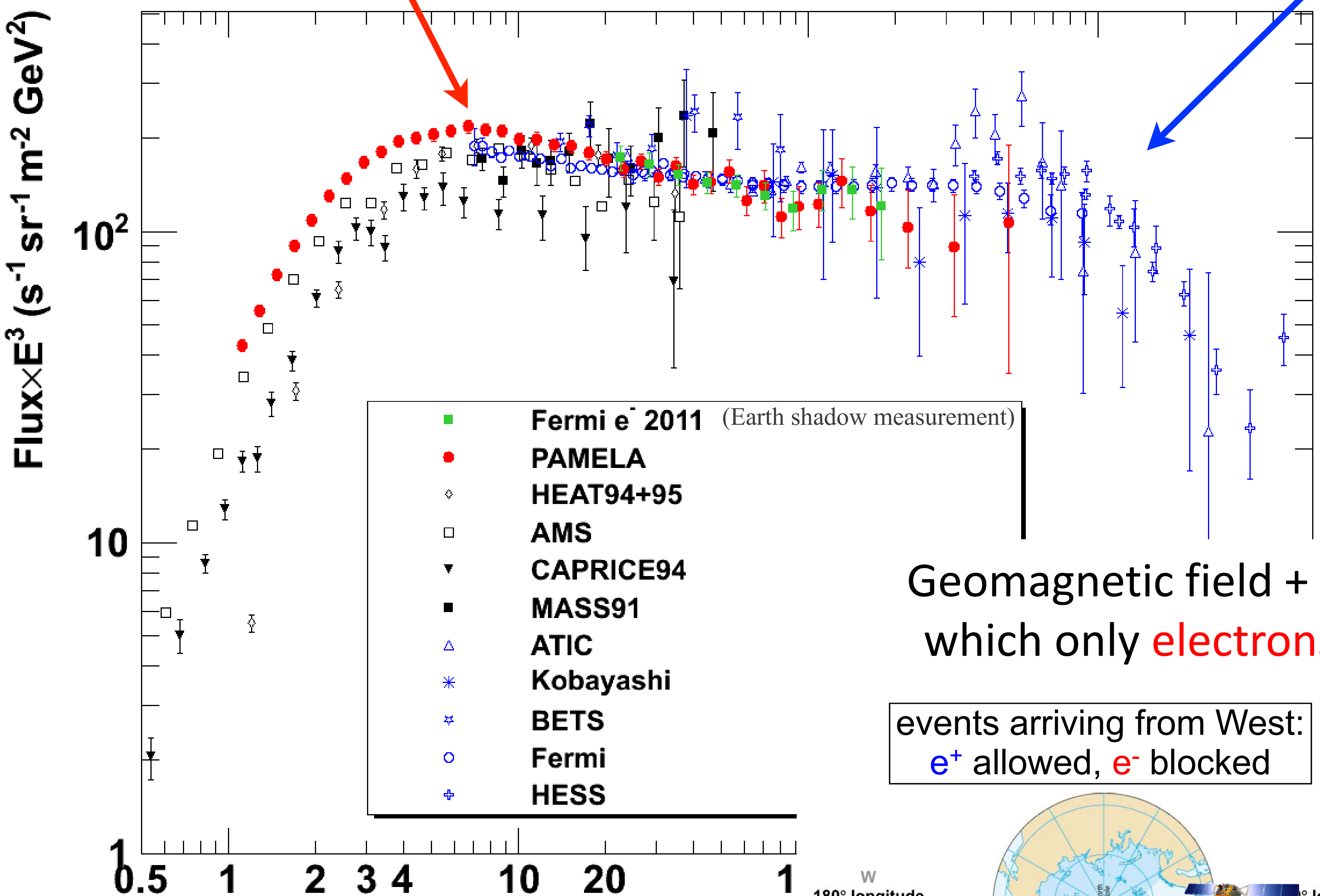
Electron and positron excess

Electron flux measurements

Spectrometers: e⁻

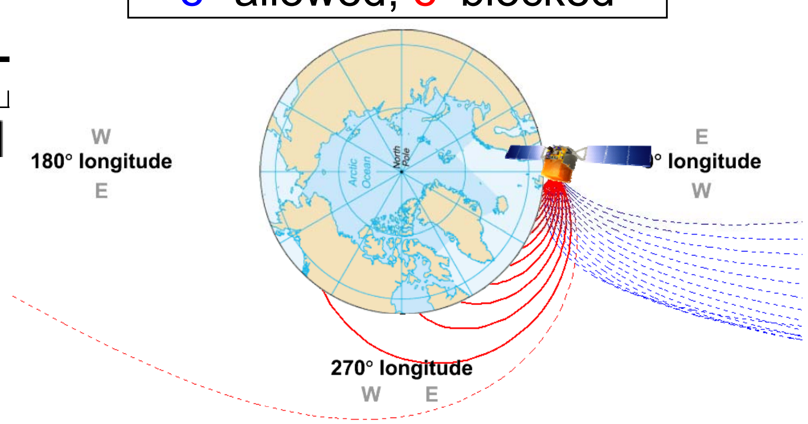
Calorimetric measurements:
Sum of e⁺ and e⁻

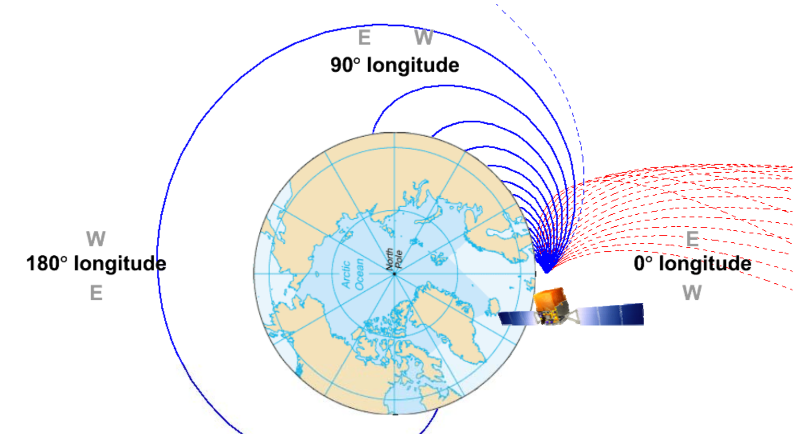
(Adriani et al., PRL 106 (2011) 201101)



Geomagnetic field + Earth shadow = directions from which only electrons or only positrons are allowed

events arriving from West:
e⁺ allowed, e⁻ blocked

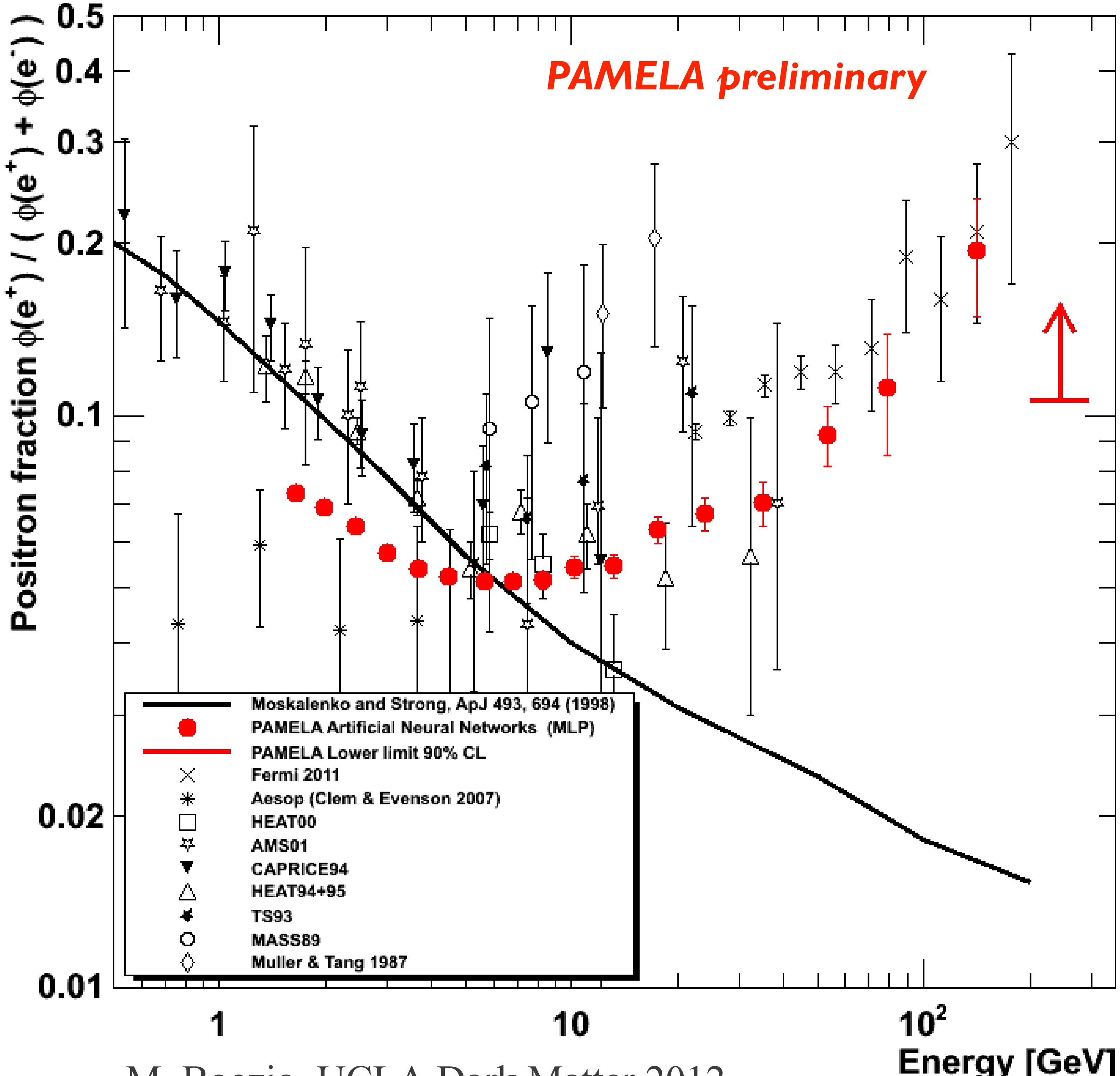




events arriving from East:
e⁻ allowed, e⁺ blocked

M. Boezio, UCLA Dark Matter 2012

Positron to electron ratio



M. Boezio, UCLA Dark Matter 2012

Acceleration: Electrons much more abundant than positrons

Symmetric production

$$p + p_{\rm ISM} \longrightarrow \pi^0 + X$$

$$\pi^0 \longrightarrow e^+ e^-$$

Expectation from diffusion model

Expectation in standard diffusion model

Leaky box model from lecture 1:

$$\frac{\partial N(E)}{\partial t} = -\frac{1}{\tau_{\rm esc}} N(E) + Q(E)$$

Include energy losses (bremsstrahlung important for e^+ and e^-)

$$\frac{\partial N_{e^\pm}}{\partial t} = -\frac{N_{e^\pm}}{\tau_{\rm esc}} - \frac{N_{e^\pm}}{\tau_{\rm loss}} + Q_{e^\pm}$$

$$\begin{aligned} N_{e^\pm} &= \tau_{\rm loss}\, Q_{e^\pm} \\ &= \frac{\tau_0}{E}\, Q_{e^\pm} \end{aligned}$$

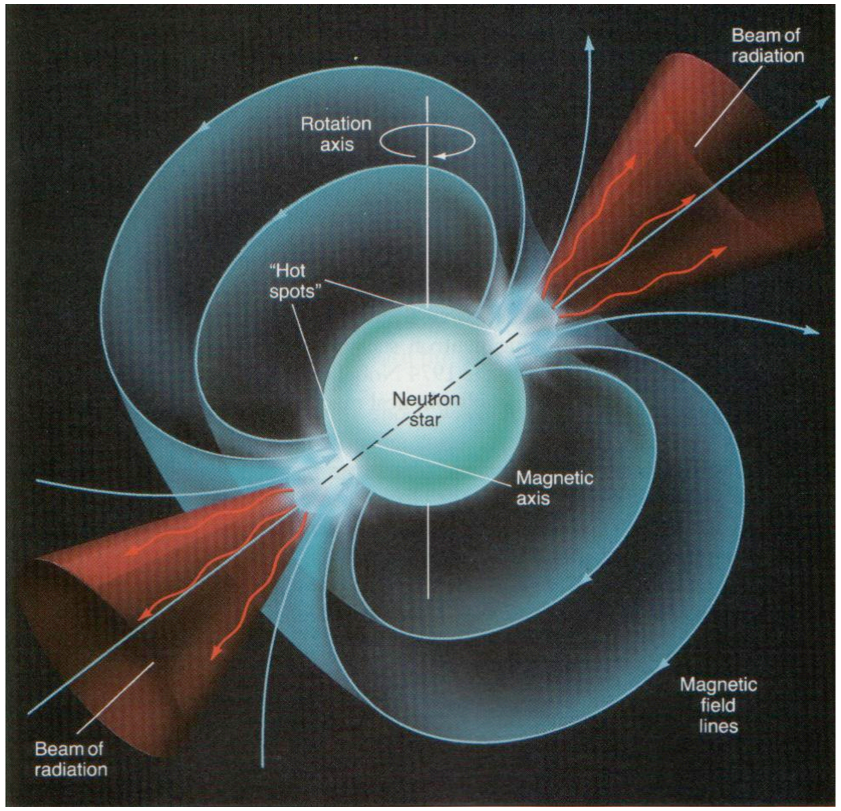
$$Q_{e^-} \sim E^{-p}$$

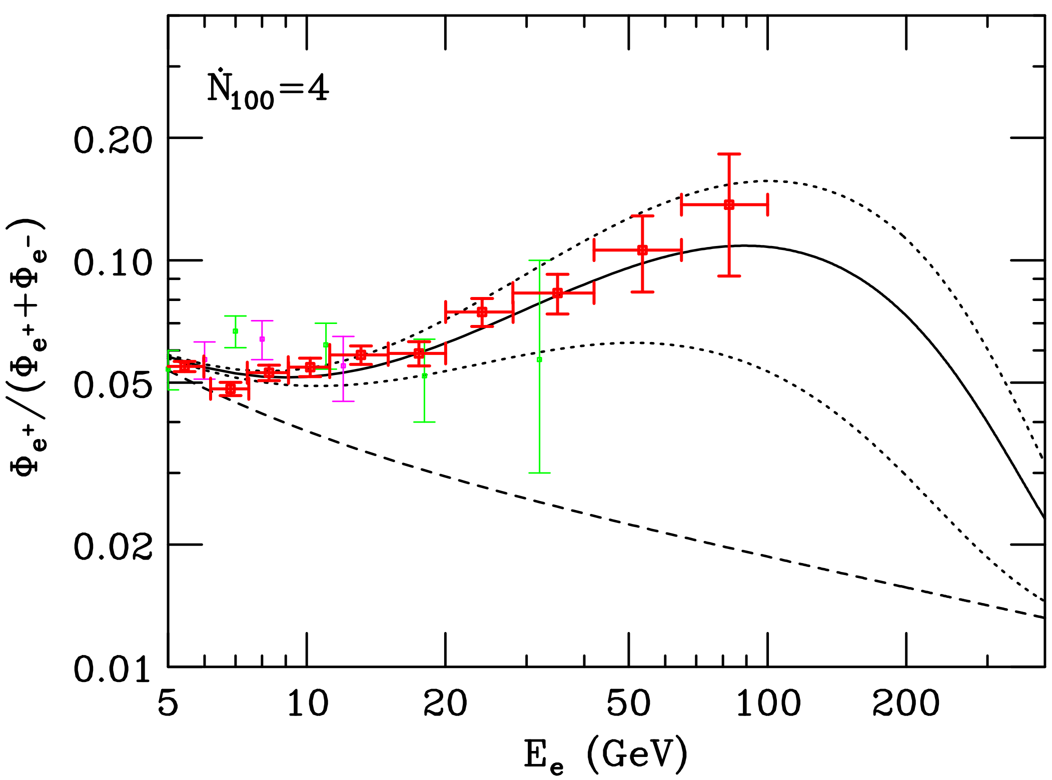
$$Q_{e^+} \sim \rho_{\rm ISM}\, N_p(E) \sim E^{-p-\delta}$$

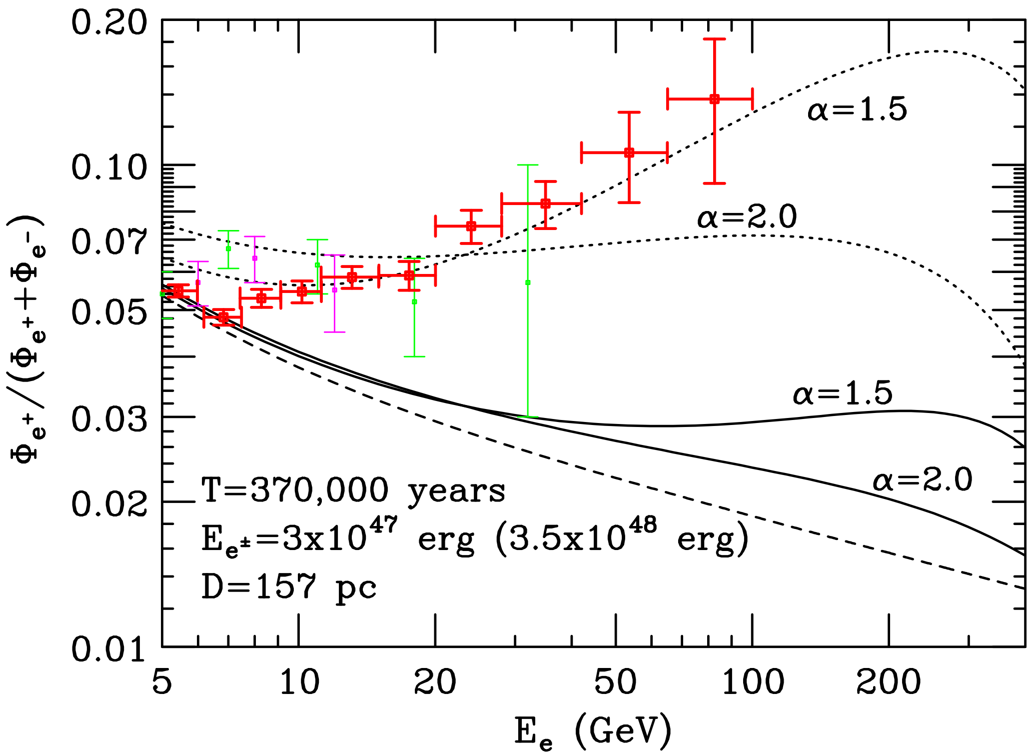
$$N_{e^-}(E) \sim E^{-p-1}$$

$$N_{e^+}(E) \sim E^{-p-\delta-1}$$

Production in pulsars not too far from us







MHD condition: $\vec{E} = \vec{V} \times \vec{B}$

$$E_{\max} \sim Ze|\vec{E}|d \sim Ze\omega r^2 B$$

$$R \simeq 10\,\text{km}$$
$$T \simeq 10\ldots100\,\text{ms}$$
$$B \simeq 10^9\,\text{T} \ (= 10^{13}\,\text{G})$$

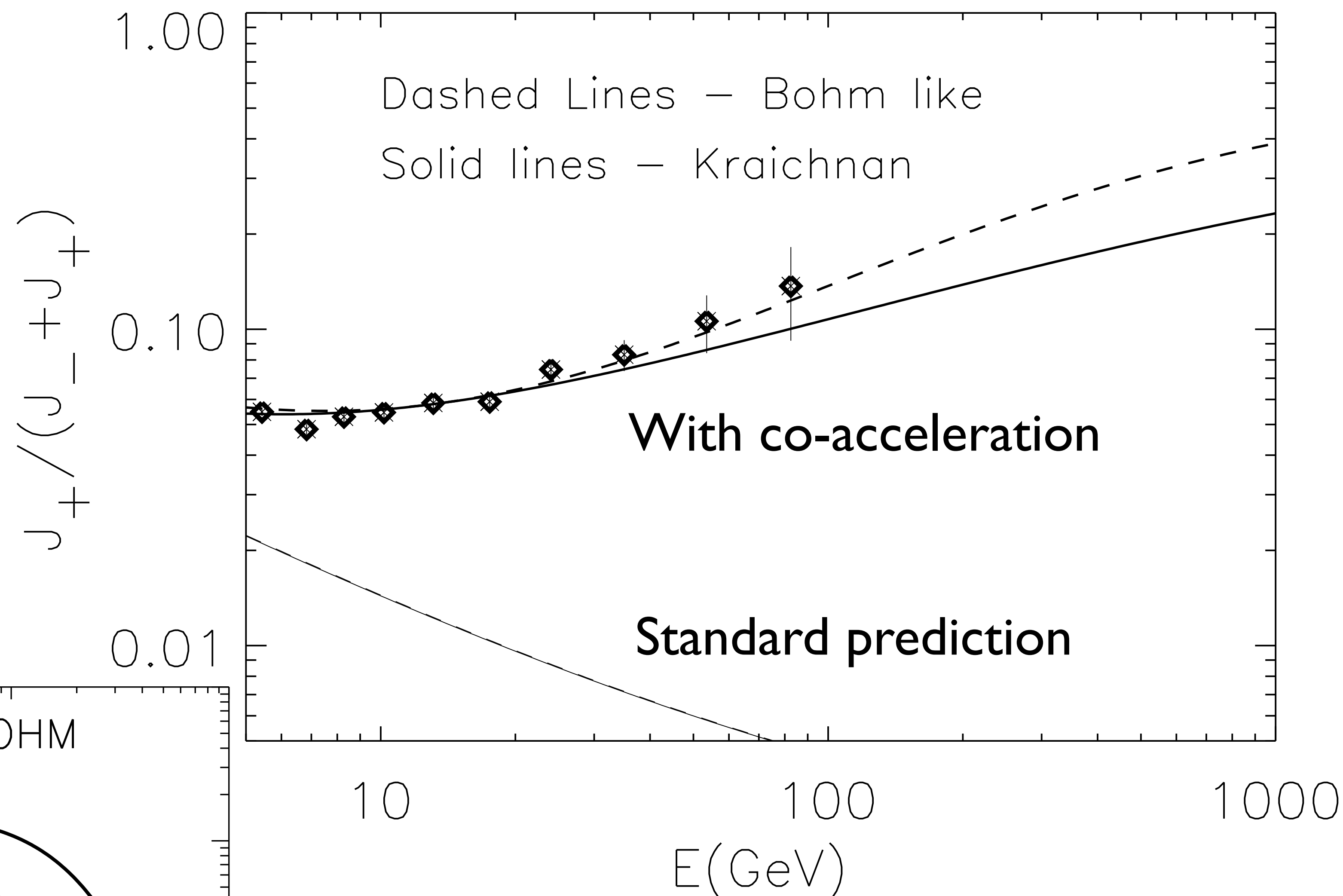
Anisotropy expected if pulsar(s) are at close distance

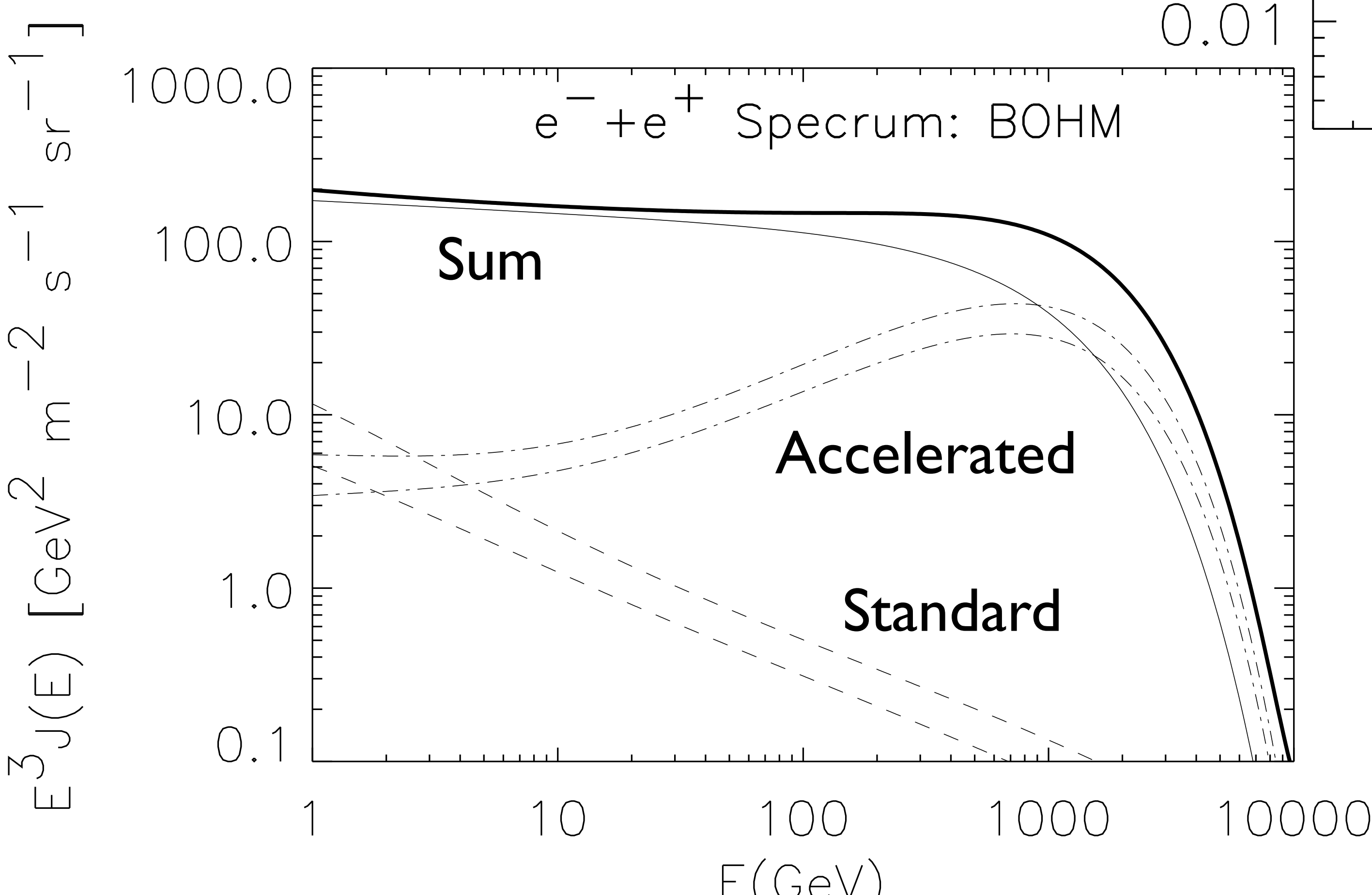
(Hooper et al. JCAP (2009) 025)

Production in acceleration regions

$$Q_{e^+} \sim \rho_{\rm ISM}\, N_p(E) \sim E^{-p-\delta}$$

$$Q_{e^+} \sim E^{-p}$$



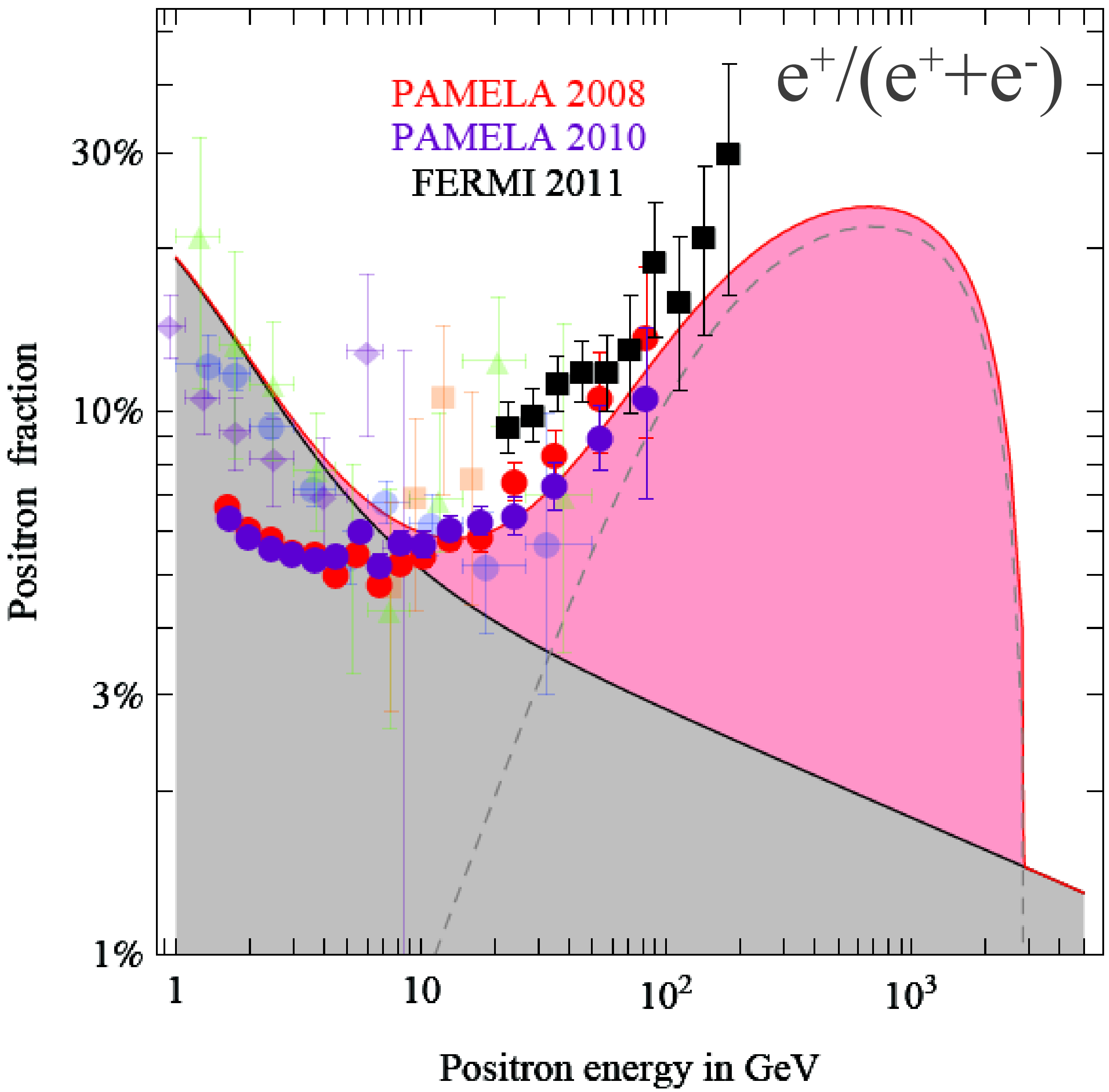


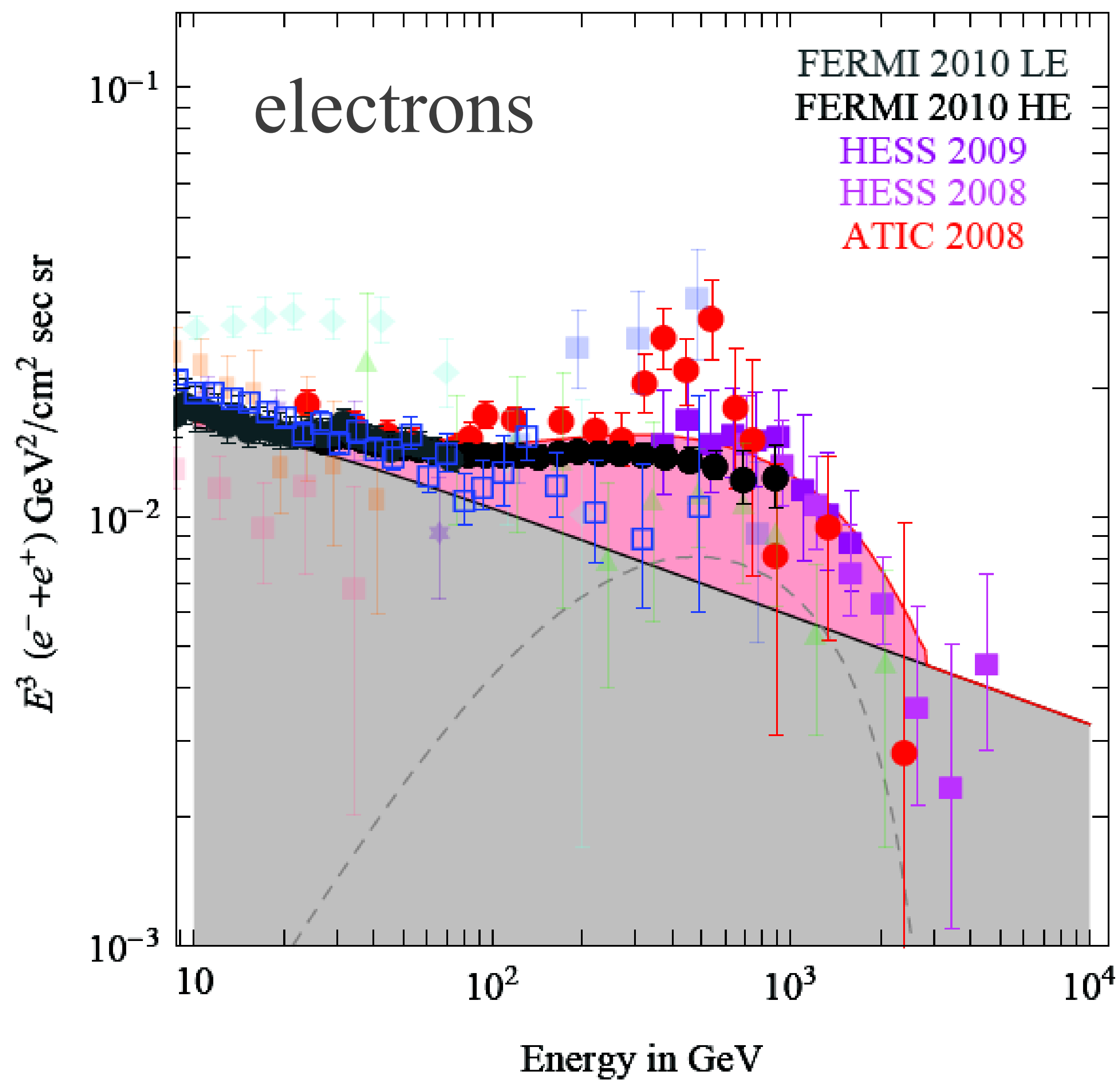
Model parameter: cutoff at ~1TeV for accleration

(Blasi, Phys. Rev. Lett. 2009)

Example: Interpretation as Dark Matter signal

M. Cirelli, arXiv: 1202.1454 (2012)

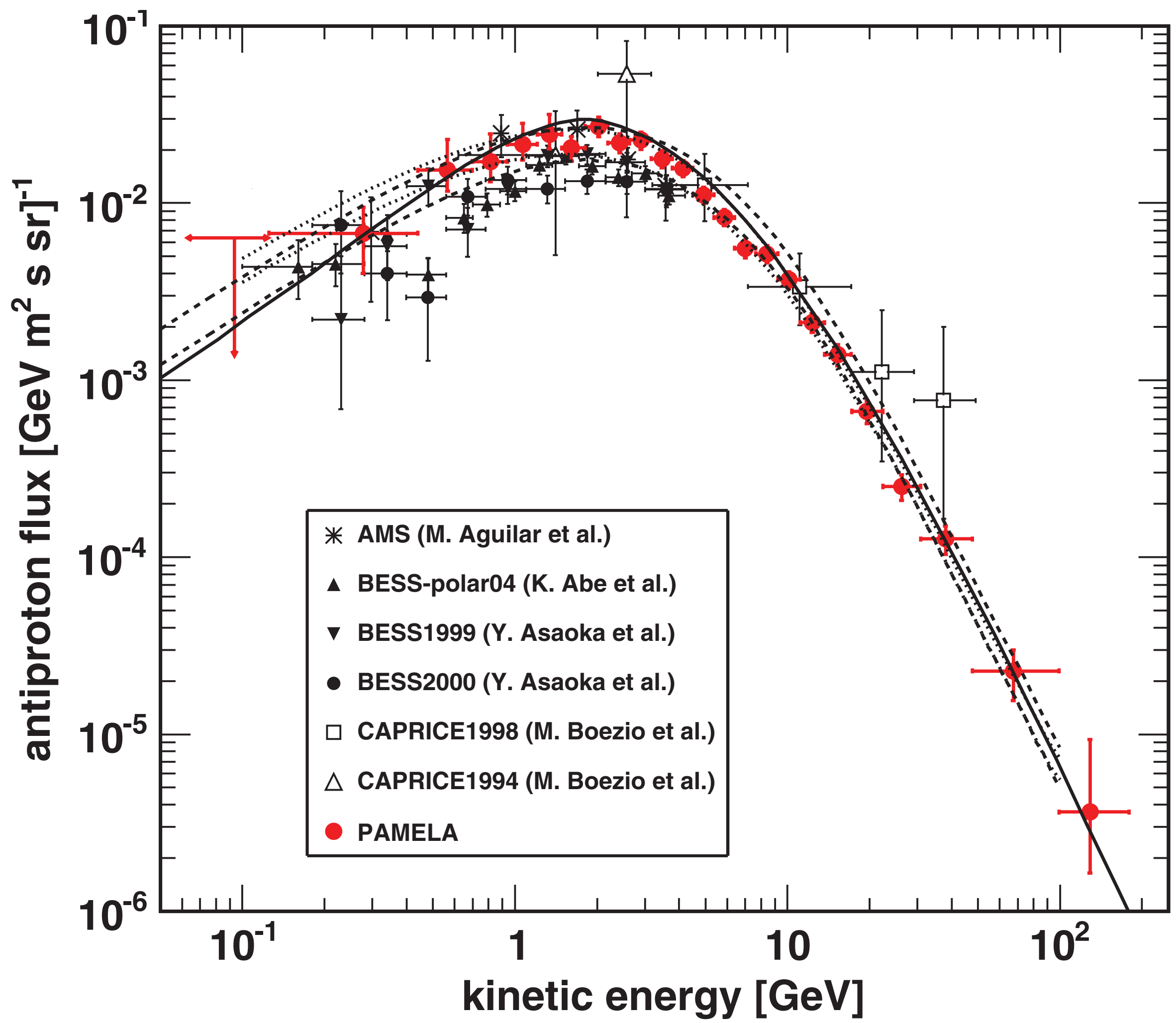


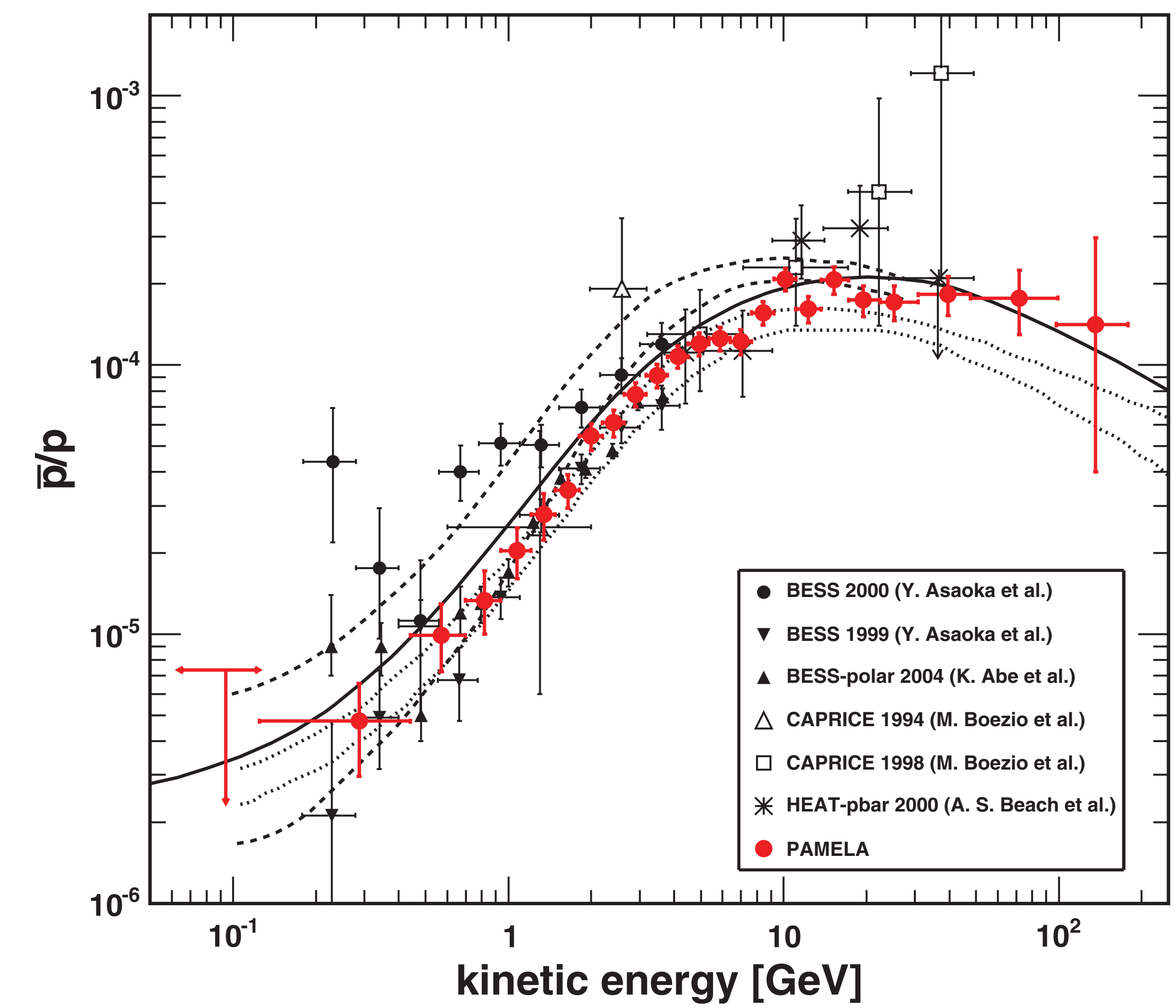


Preferred annihilation channel $\chi^0\chi^0 \longrightarrow \tau^+\tau^-$ (Particle of 3 TeV mass)

Cross-check: Antiproton flux

(Adriani et al., PRL 105 (2010) 121101)

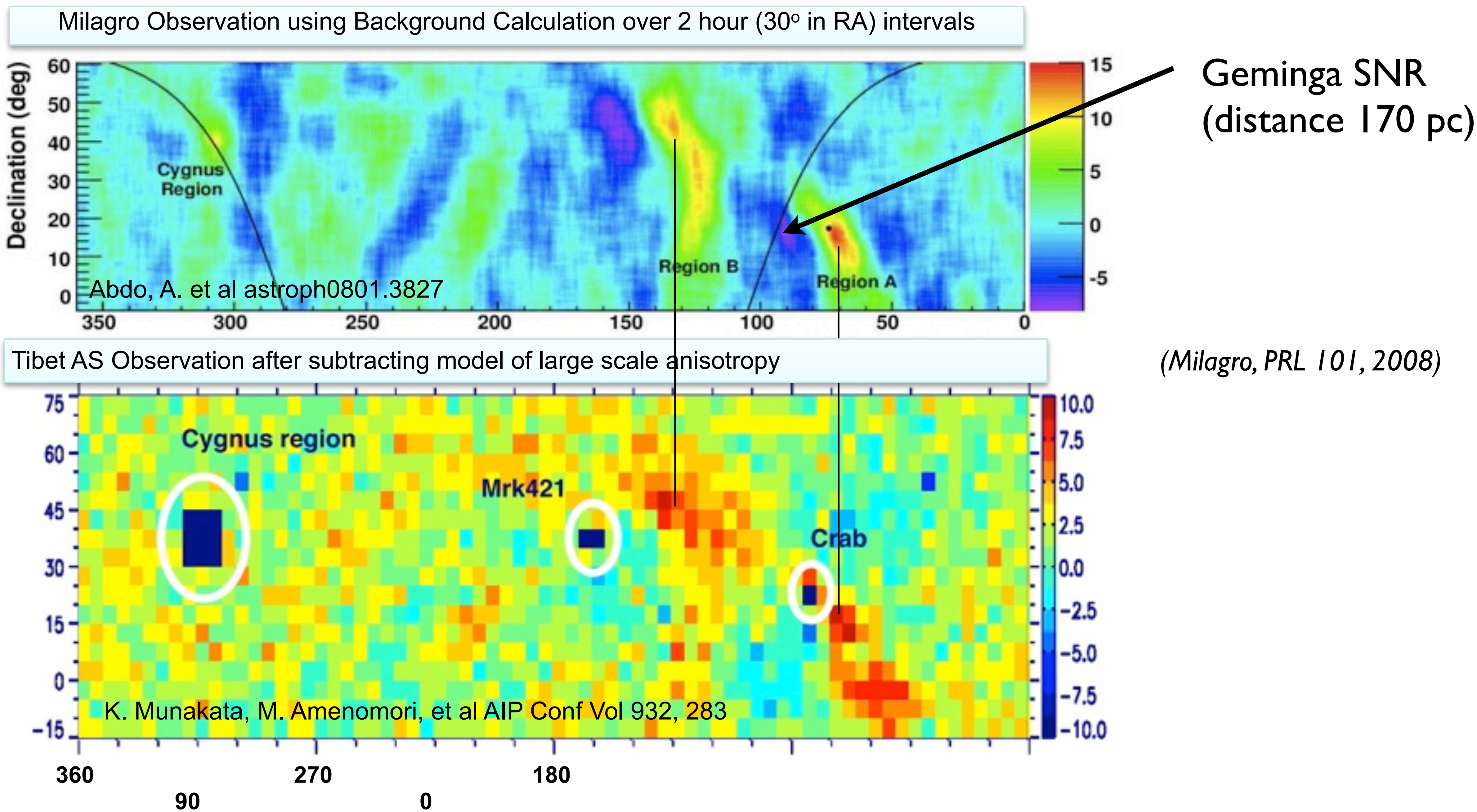




No excess found in channel $\chi^0\chi^0 \longrightarrow \bar{p}p$ (Particle has to be leptophile)

Anisotropy measurements

Anisotropy detection (i)

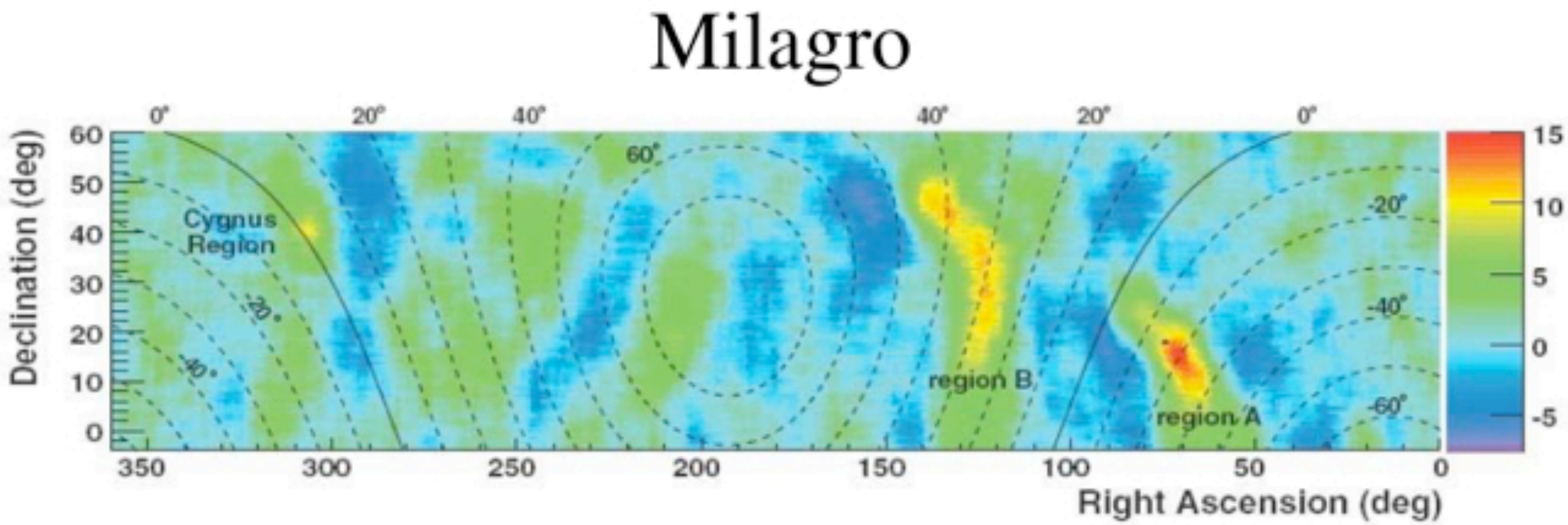


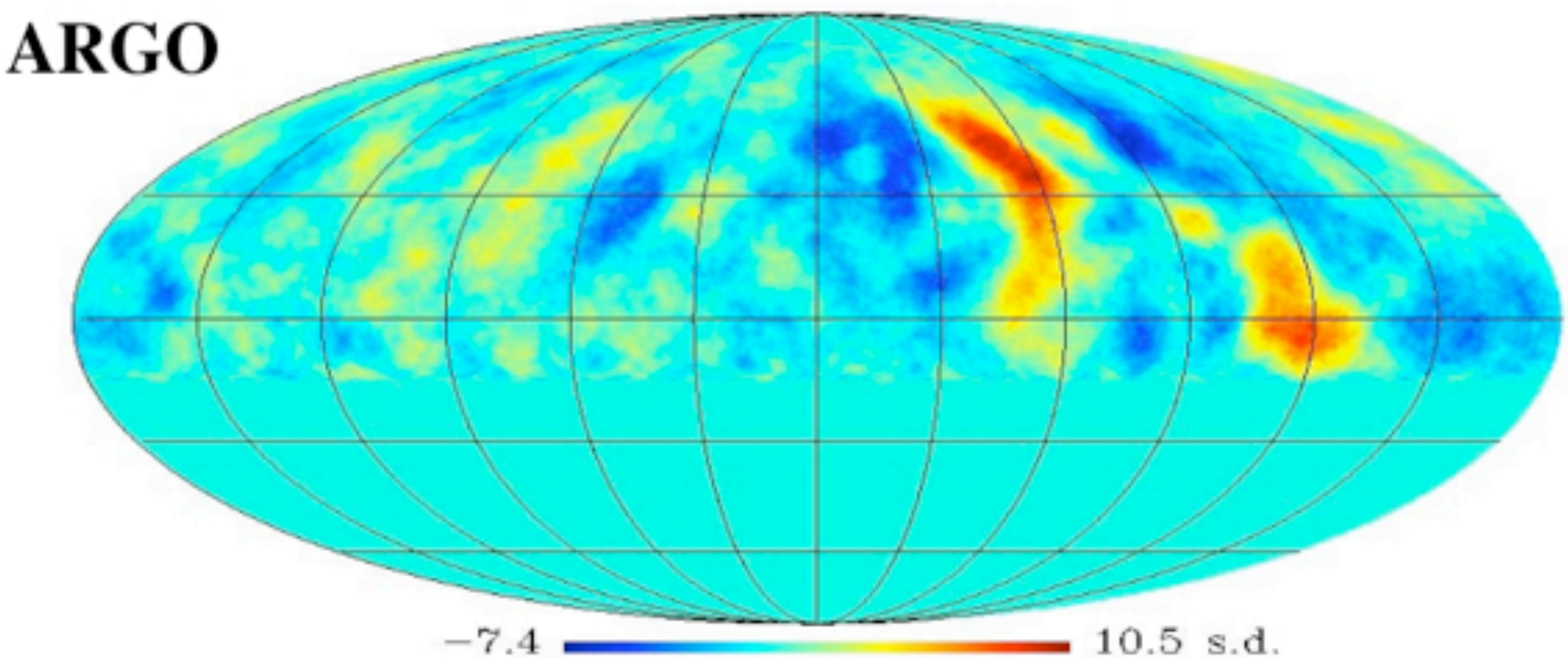
(Milagro, PRL 101, 2008)

Milagro: Relative excess of 4-6 10^{-4}, more than 10 sigma significance
Energy of cosmic rays ~10^{13} eV = 10 TeV (Lamor radius < 10^{-2} pc)

(Goodman, ICRC 2009)

Anisotropy detections (ii)





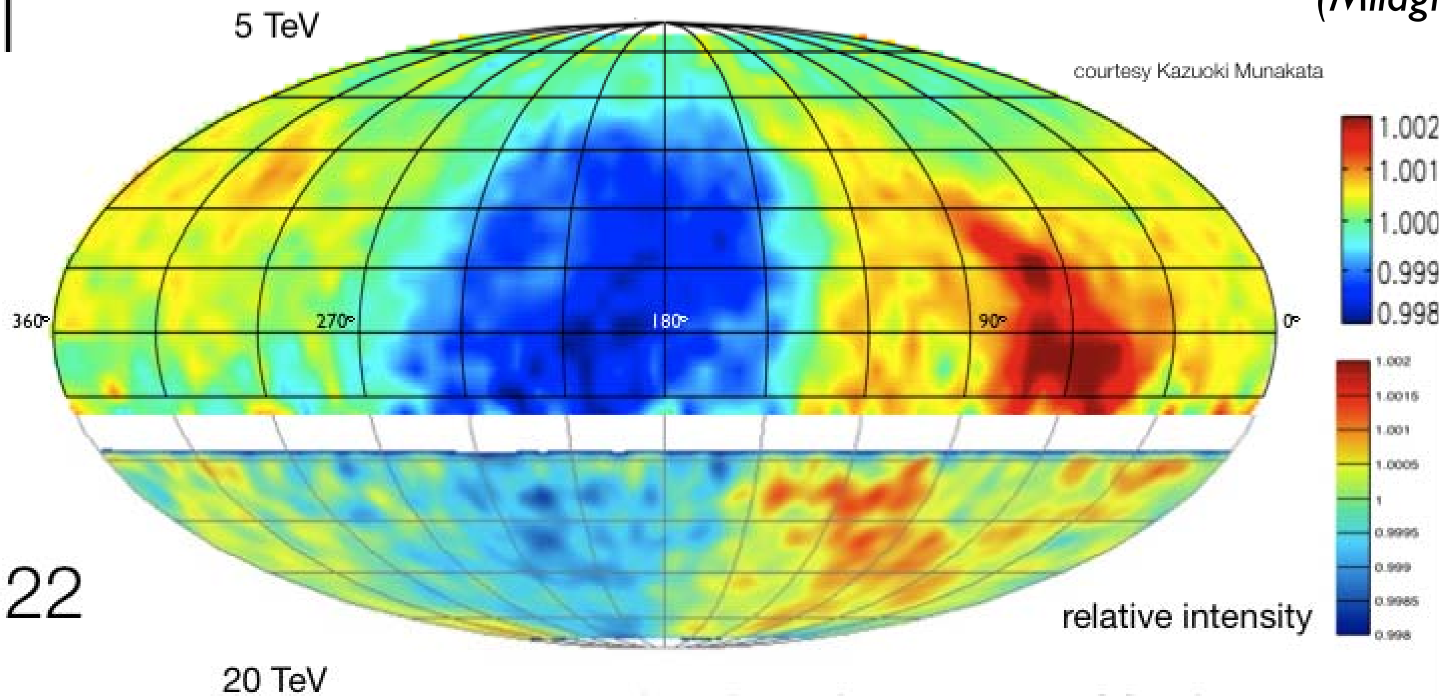
http://people.roma2.infn.it/~aldo/RICAP09_trasp_Web/Vernetto_ARGO_RICAP09ar.pdf

(Goodman, ICRC 2009)

Anisotropy detections (iii)

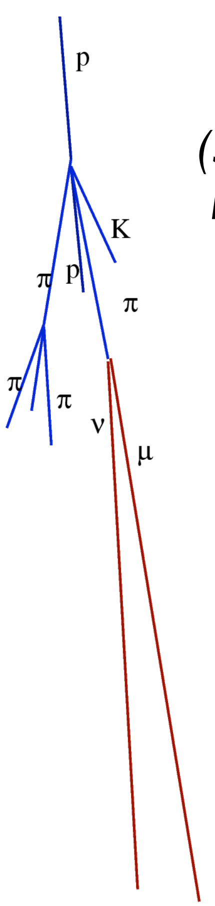
(Milagro, Tibet, ARGO air shower arrays 2010)

Tibet-III

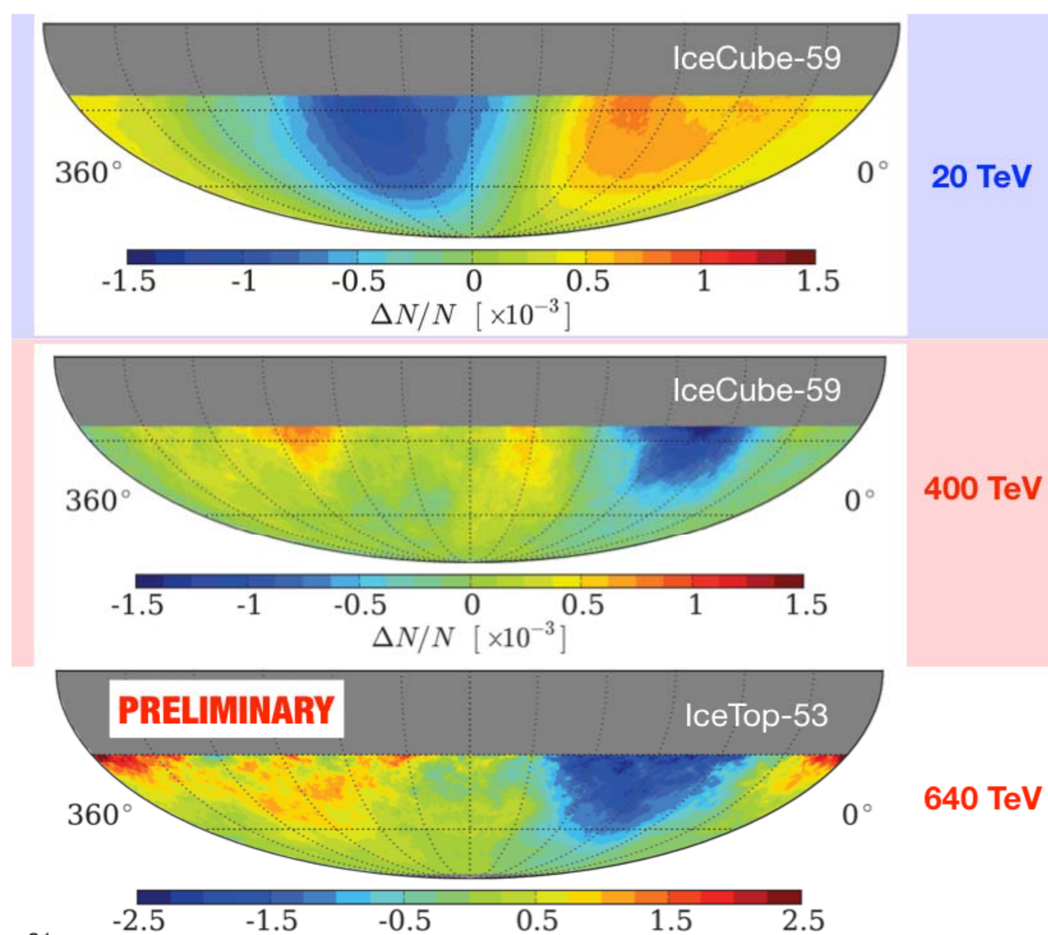


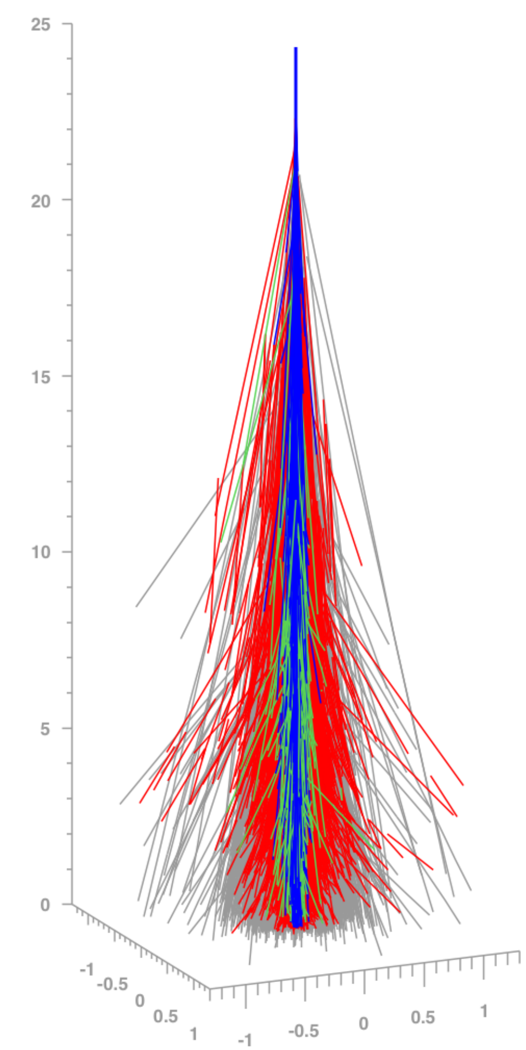
IceCube-22

(IceTop air shower array 2012)

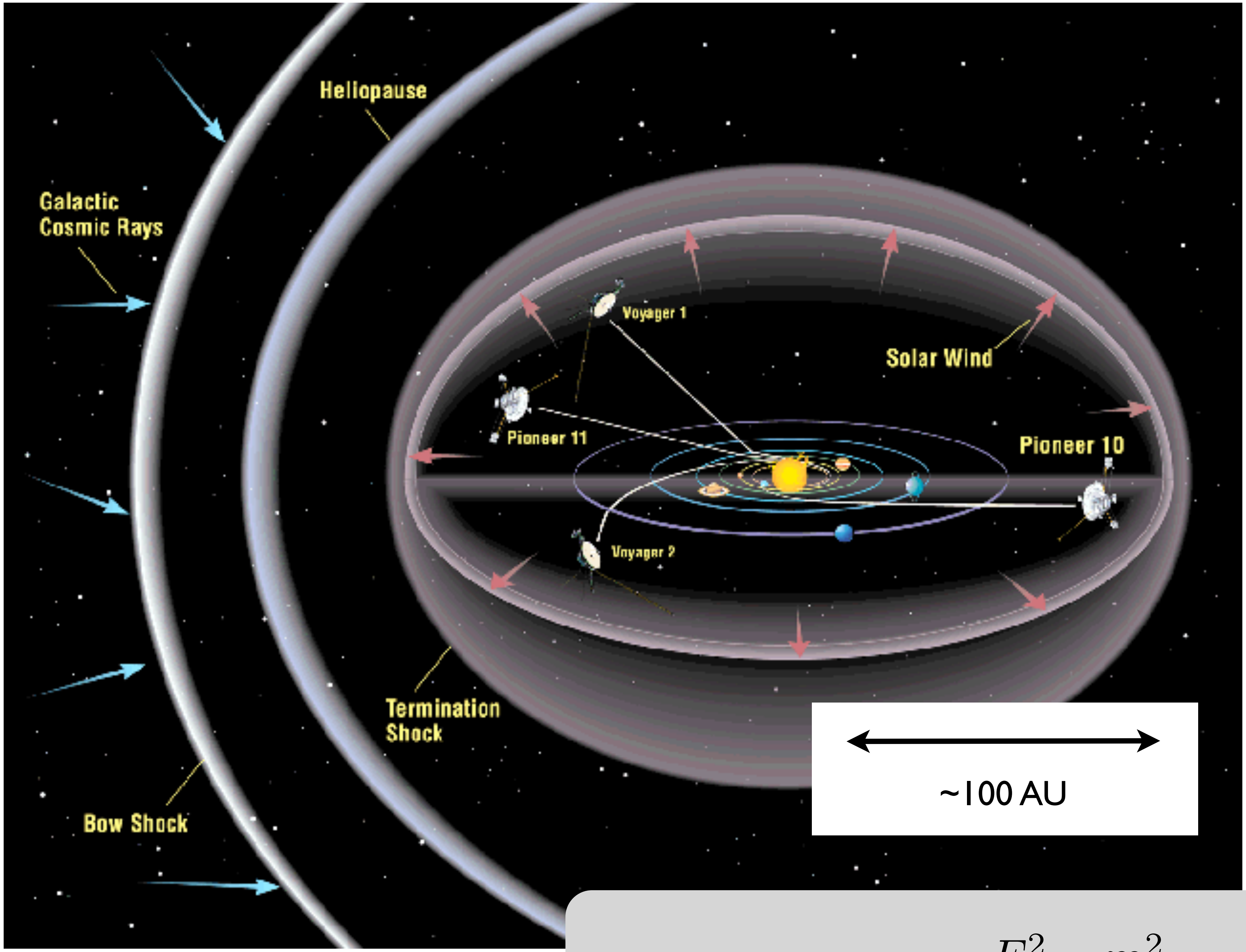


(SuperKamiokande 2009,
IceCube downgoing muons 2011)





Anisotropy due to asymmetry of heliosphere ?



Solar system moves with

220 km/s about gal. center
20 km/s relative to ISM

$$\Phi_{\mathrm{Earth}}(E) = \frac{E^2 - m^2}{(E + Z \cdot V_{\mathrm{pot}})^2 - m^2} \Phi_{\mathrm{ISM}}(E + Z \cdot V_{\mathrm{pot}})$$

$V_{\mathrm{pot}} \approx 400 \ldots 750\,\mathrm{GV}$

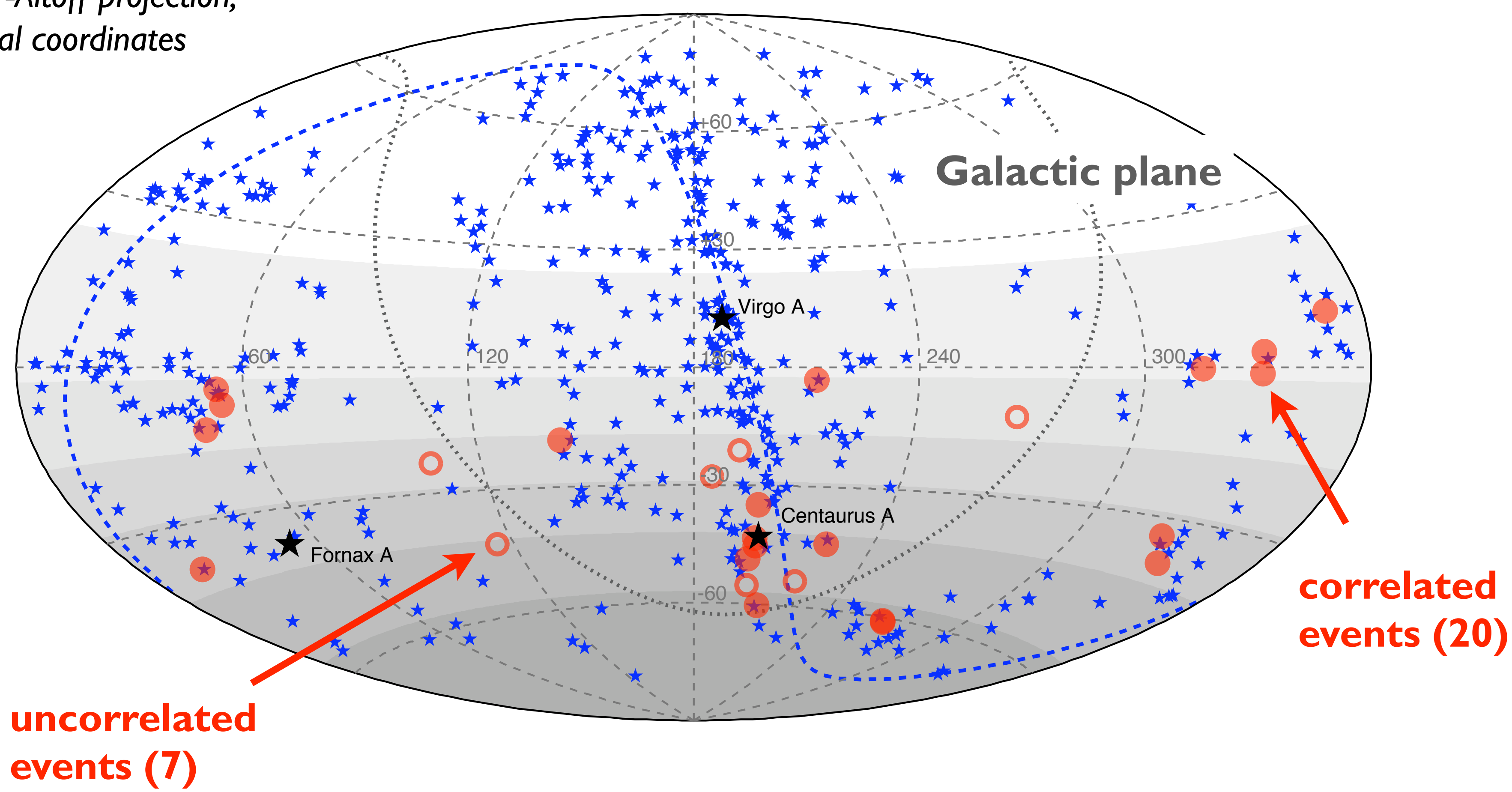
Interpretation of the data at the highest energies

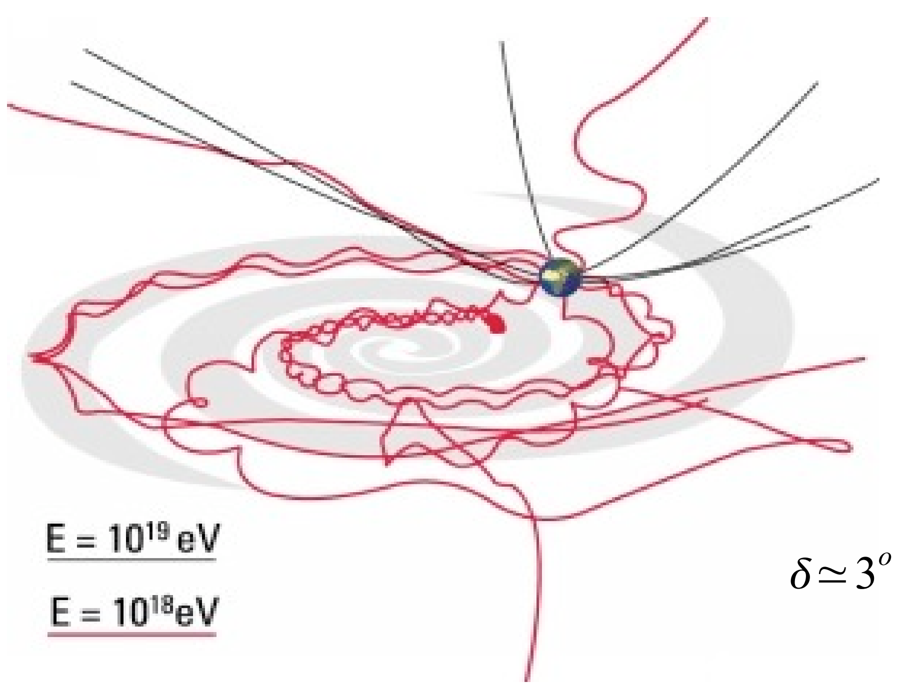
Anisotropy of arrival direction distribution

less than 1% chance probability

Hammer-Aitoff projection,
Equatorial coordinates

Auger Collab. 2007



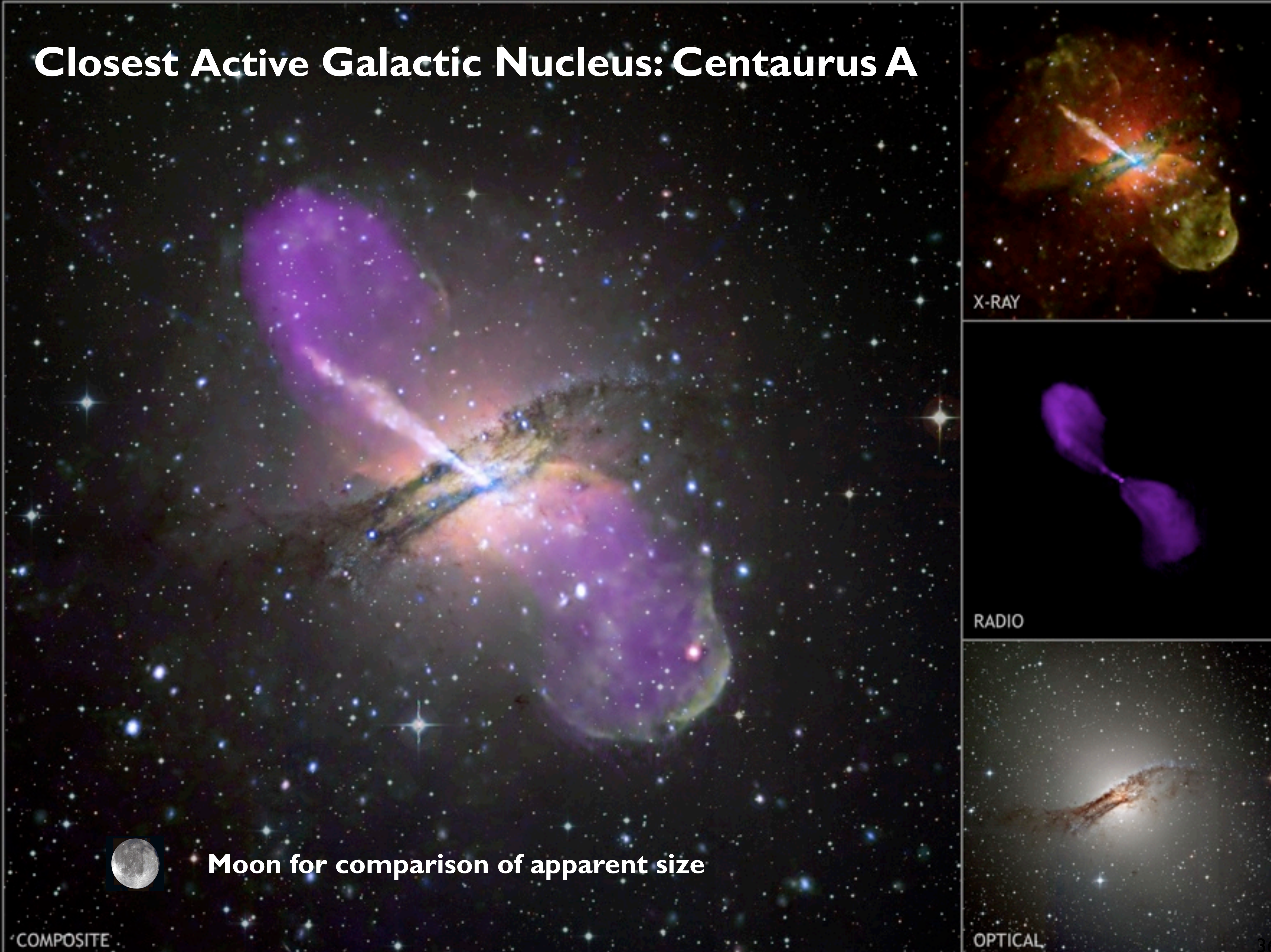


$$\delta \simeq 3^o \frac{B}{3\,\mu G} \frac{L}{kpc} \frac{6\times10^{19} eV}{E/Z}$$

Active Galactic Nuclei: sources or tracer of sources
Small magnetic deflection: protons or light nuclei

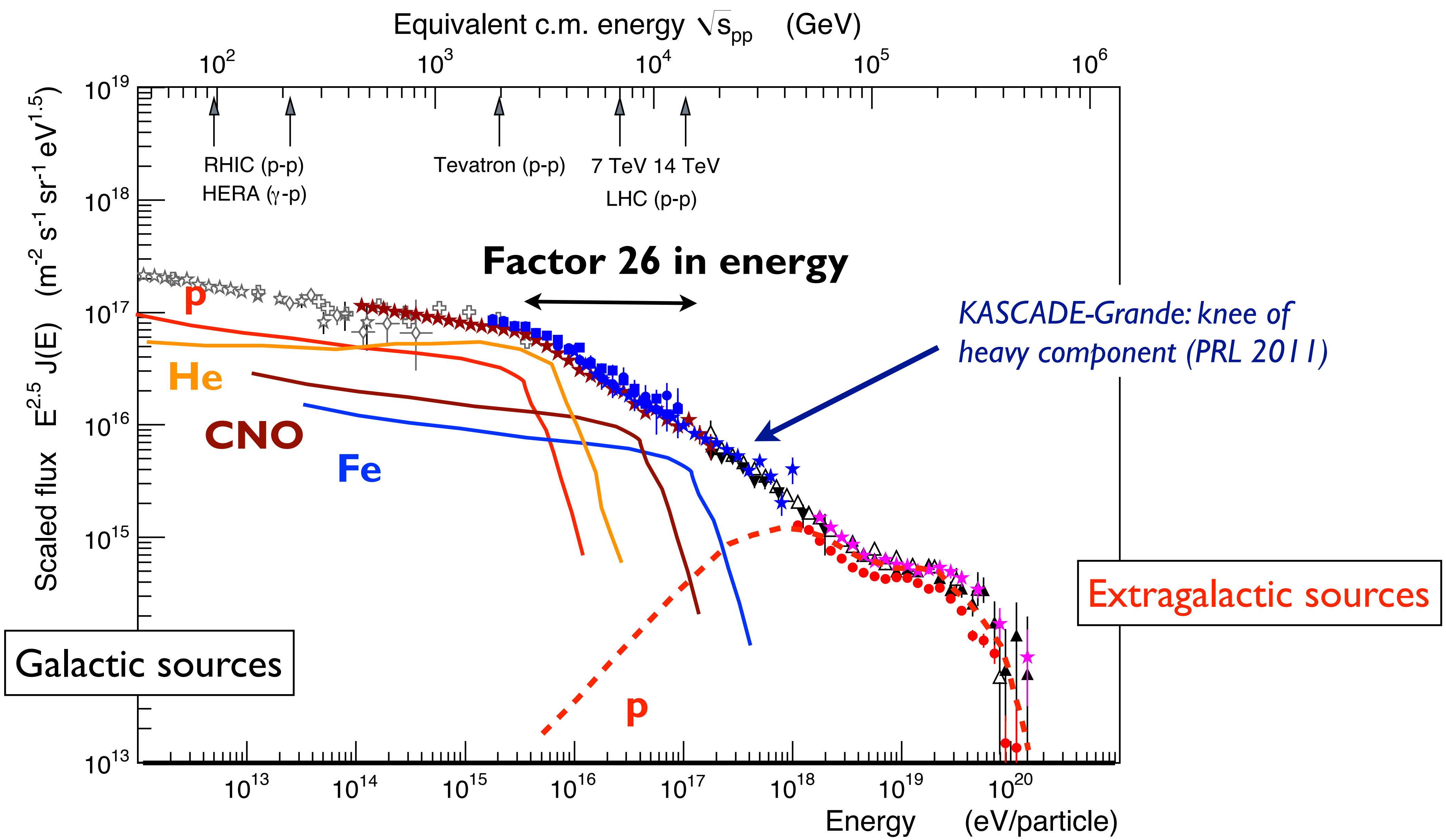
70% of particles with E > 5.5 10^{19} eV correlated with AGNs (D < 75 Mpc) within 3.1°, 21% expected

Closest Active Galactic Nucleus: Centaurus A

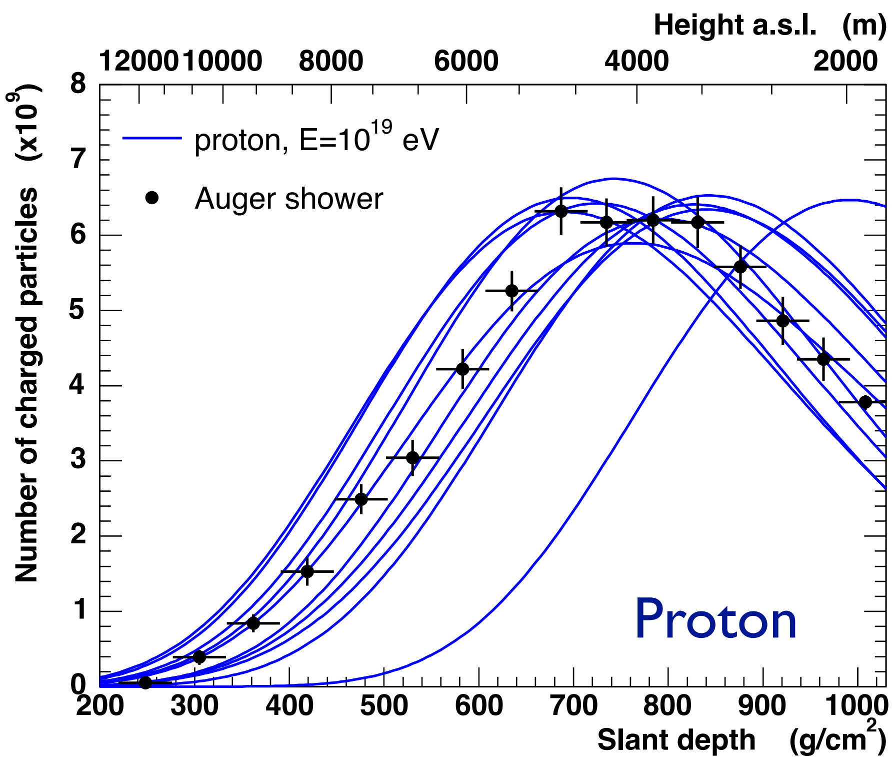


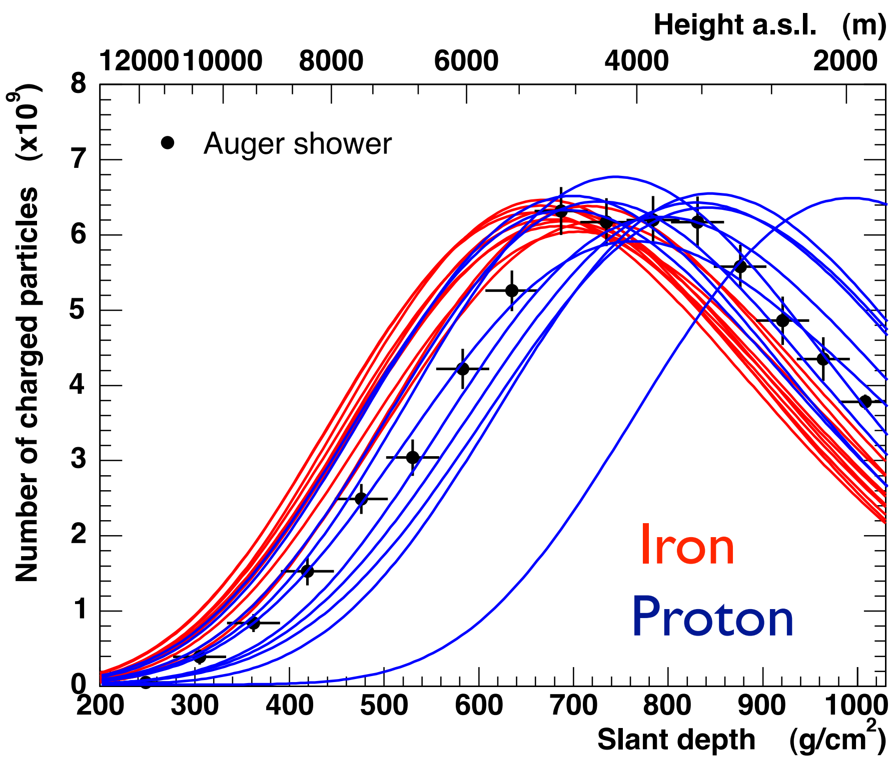
Standard model of extragalactic cosmic rays ?

- **GZK suppression of flux confirmed**
- Particles accelerated in astrophysical environments (exotic sources not dominating)
- Sources related to AGNs or distributed similar to AGNs
- More than 80% of particles should be protons (dip model)

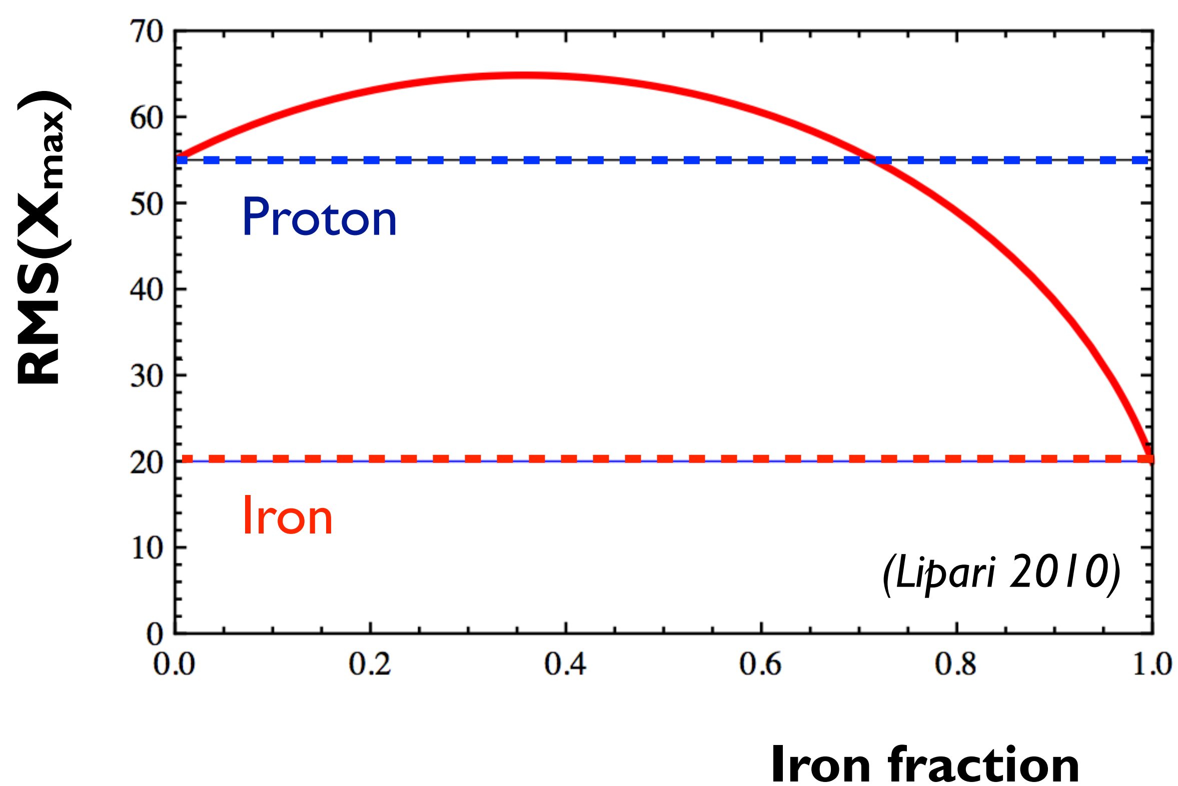


Auger data on shower profiles





Fluctuations of depth of shower maximum



Mean depth of shower profiles and shower-to-shower fluctuations as measure of composition

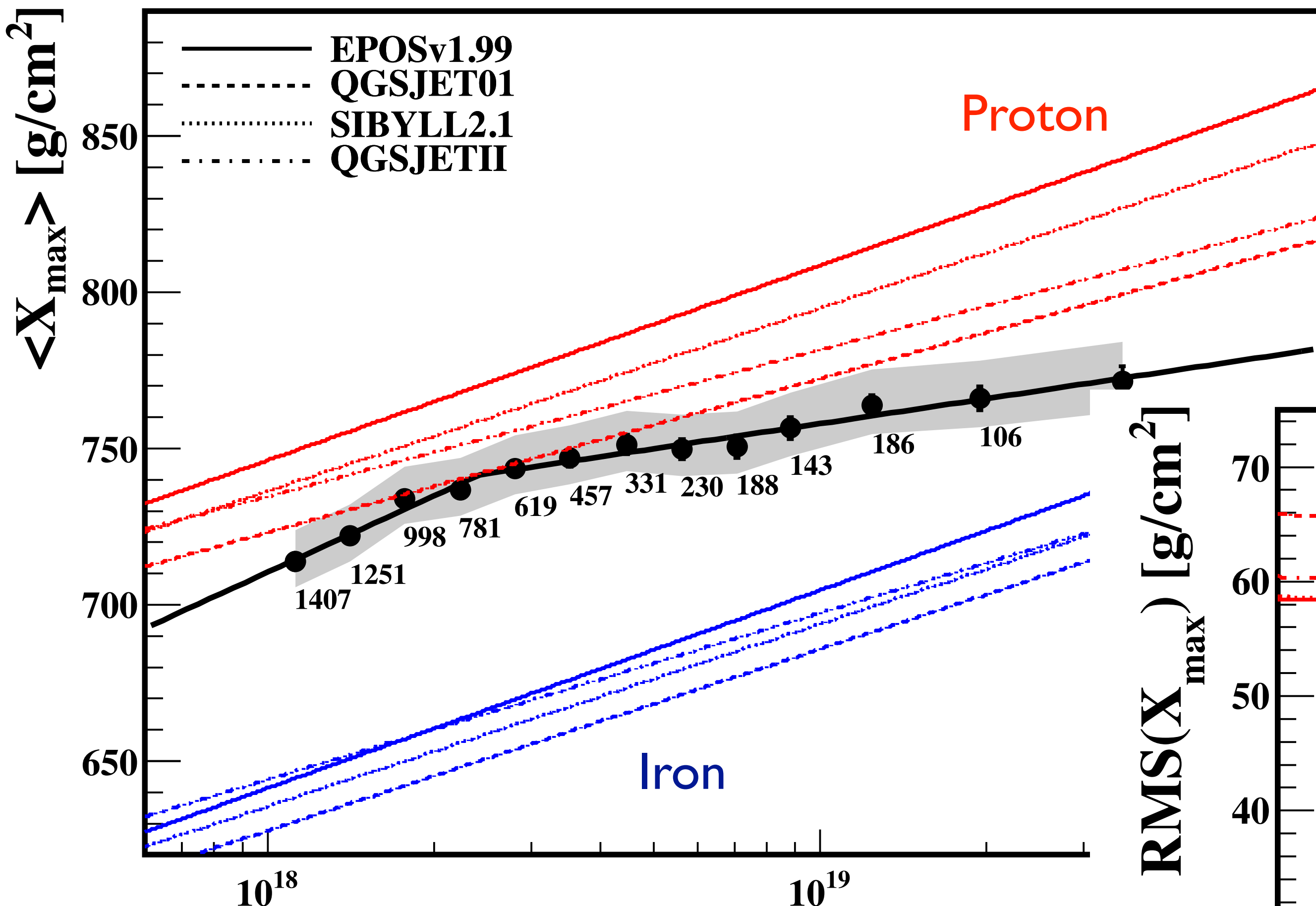
Example: event measured by Auger Collab.

Auger Observatory: Composition data

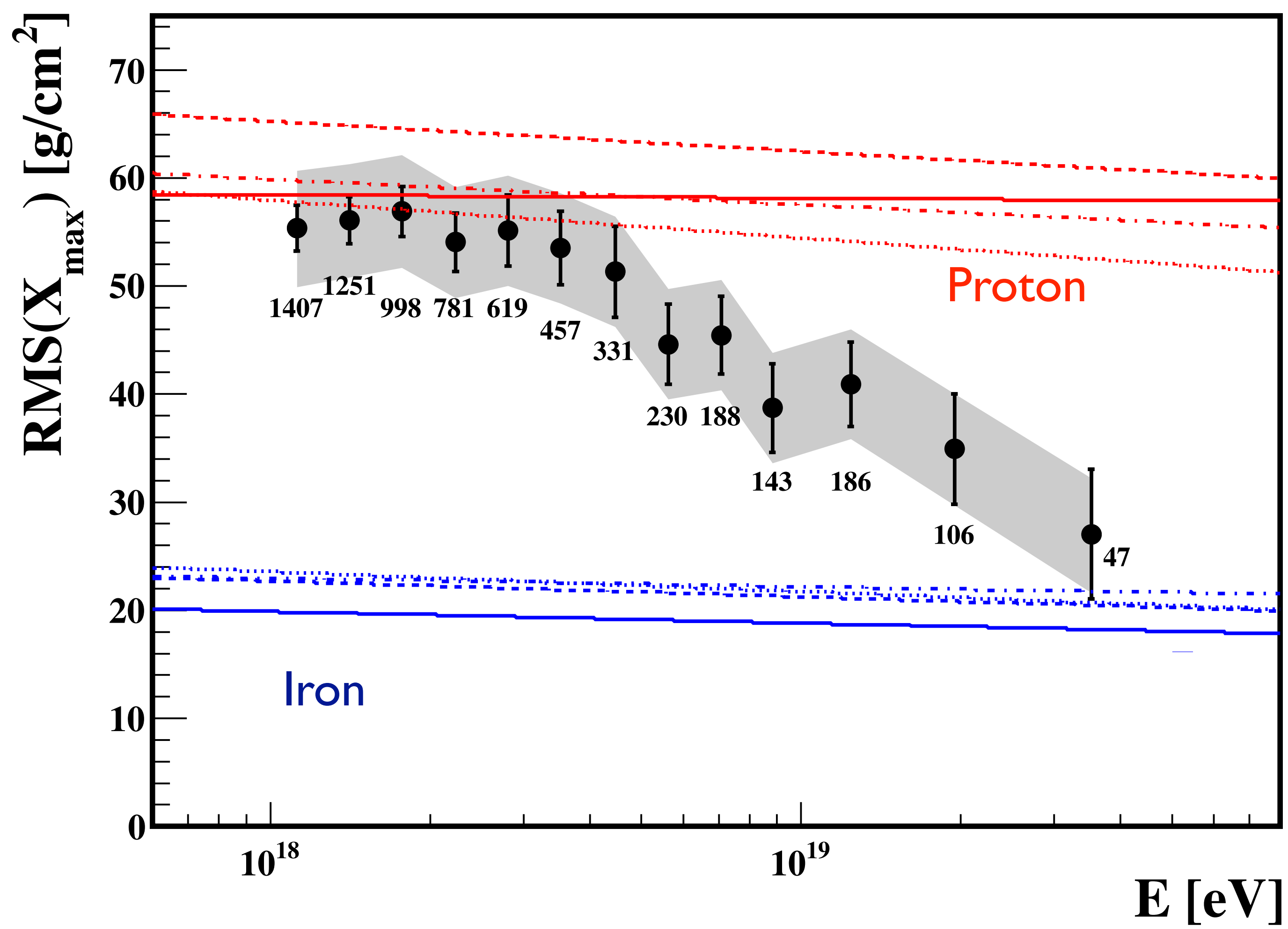
Change of cosmic ray composition from mixed or light to heavy ?

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

Mean depth of shower maximum



Fluctuations of depth of shower maximum

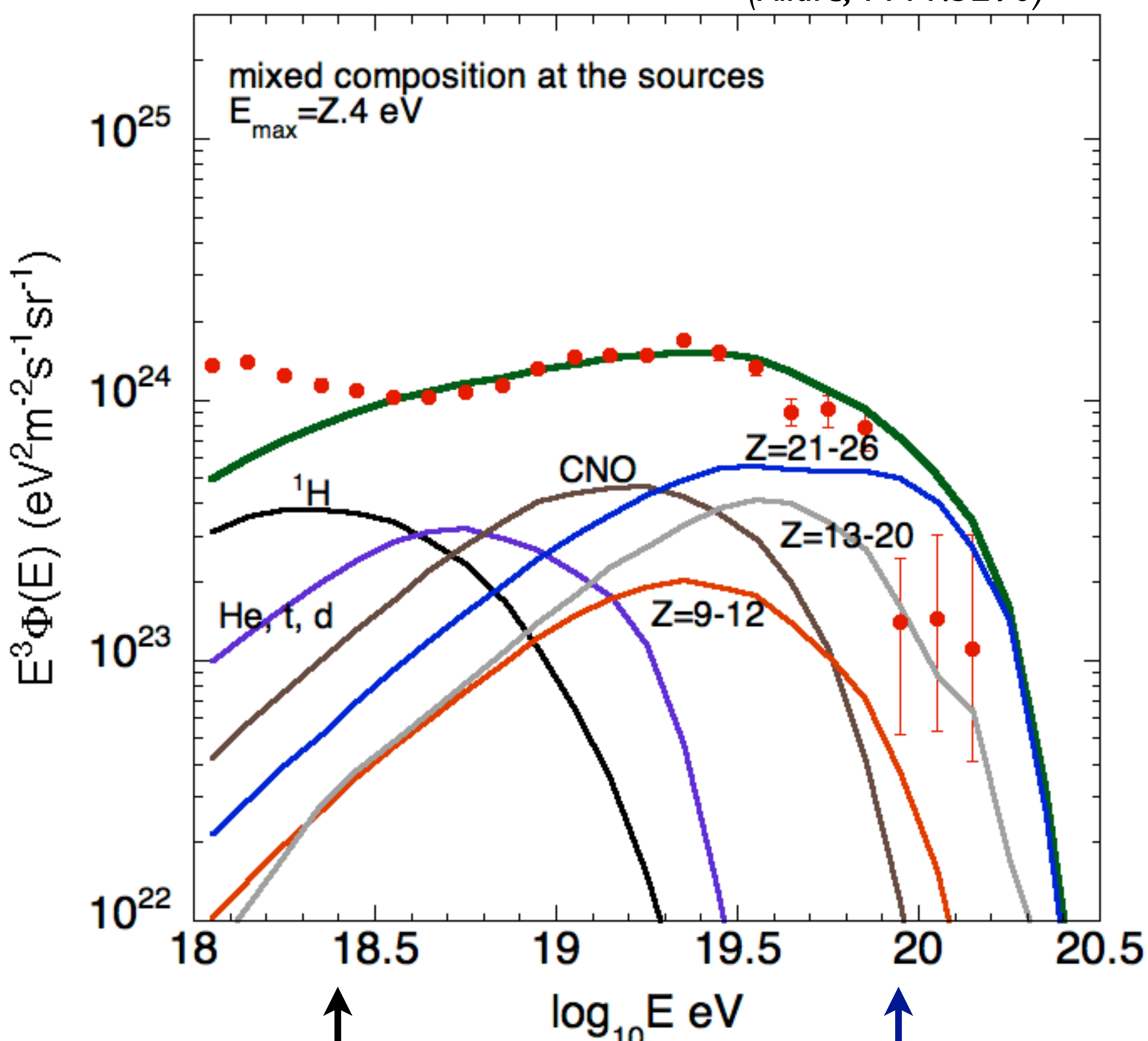


Sys. uncertainty: 13 g/cm^2 (mean)
6 g/cm^2 (RMS)

$$\sigma_X^2 = f_p\, \sigma_p^2 + (1-f_p)\, \sigma_{\rm Fe}^2 + f_p(1-f_p)\, \left(\langle X_p\rangle - \langle X_{\rm Fe}\rangle\right)^2$$

Upper end of source energy spectrum seen ?

Particle flux *(Allard, 1111.3290)*

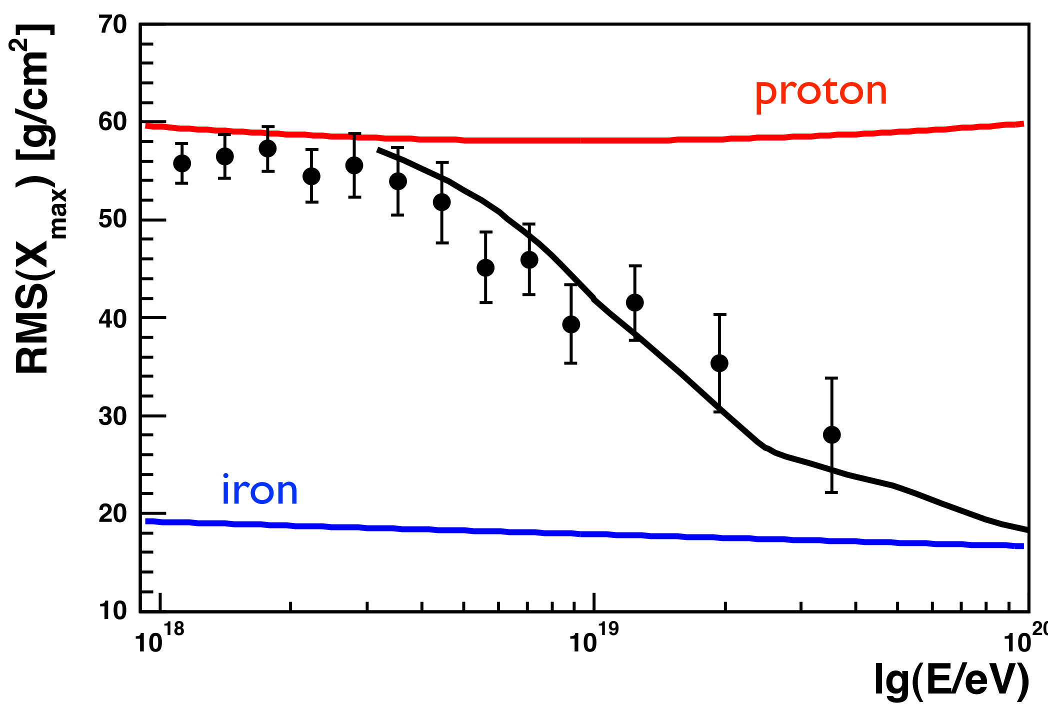


Protons $E_{max,p} = 10^{18.4}$ eV

Iron $E_{max,Fe} = 26\ E_{max,p}$
$= 10^{20}$ eV

Natural transition to heavier composition at high energy !

Fluctuations of X_{max} *(Unger 2012)*



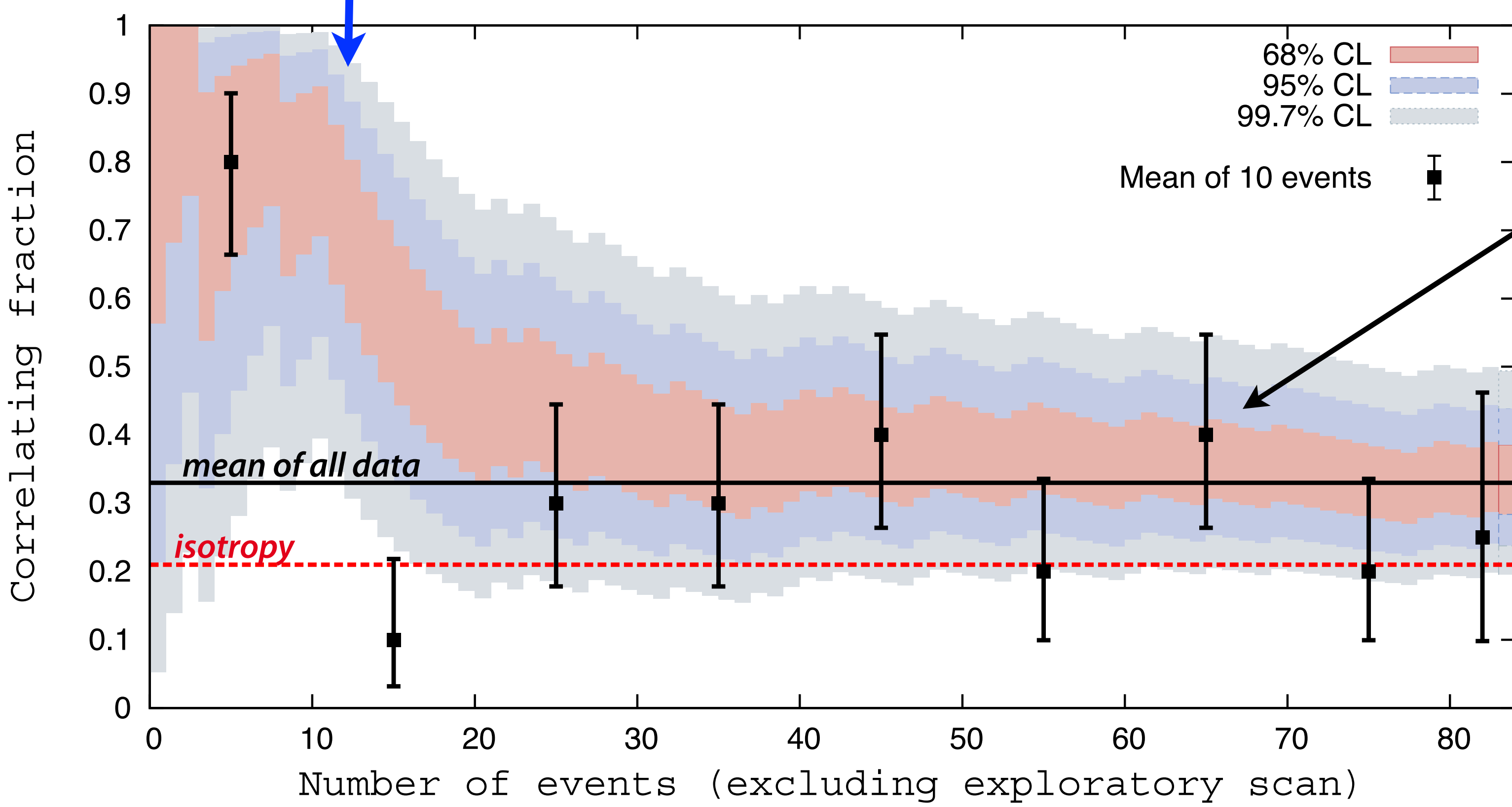
Flux not suppressed due to GZK effect

(Calvez et al. 2010, Aloisio et al. 2011)

Current status of correlation with AGNs

Auger Observatory (2011)

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

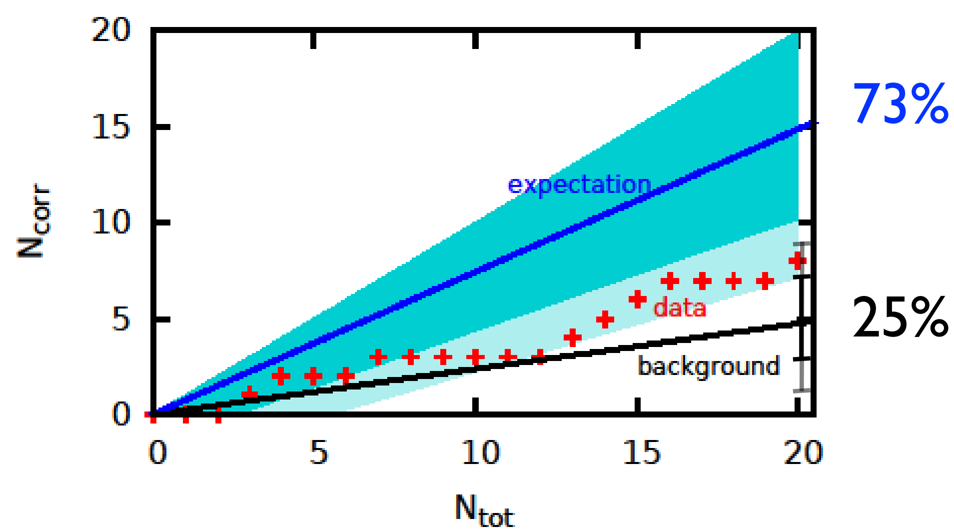


Differential estimate every 10 events

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

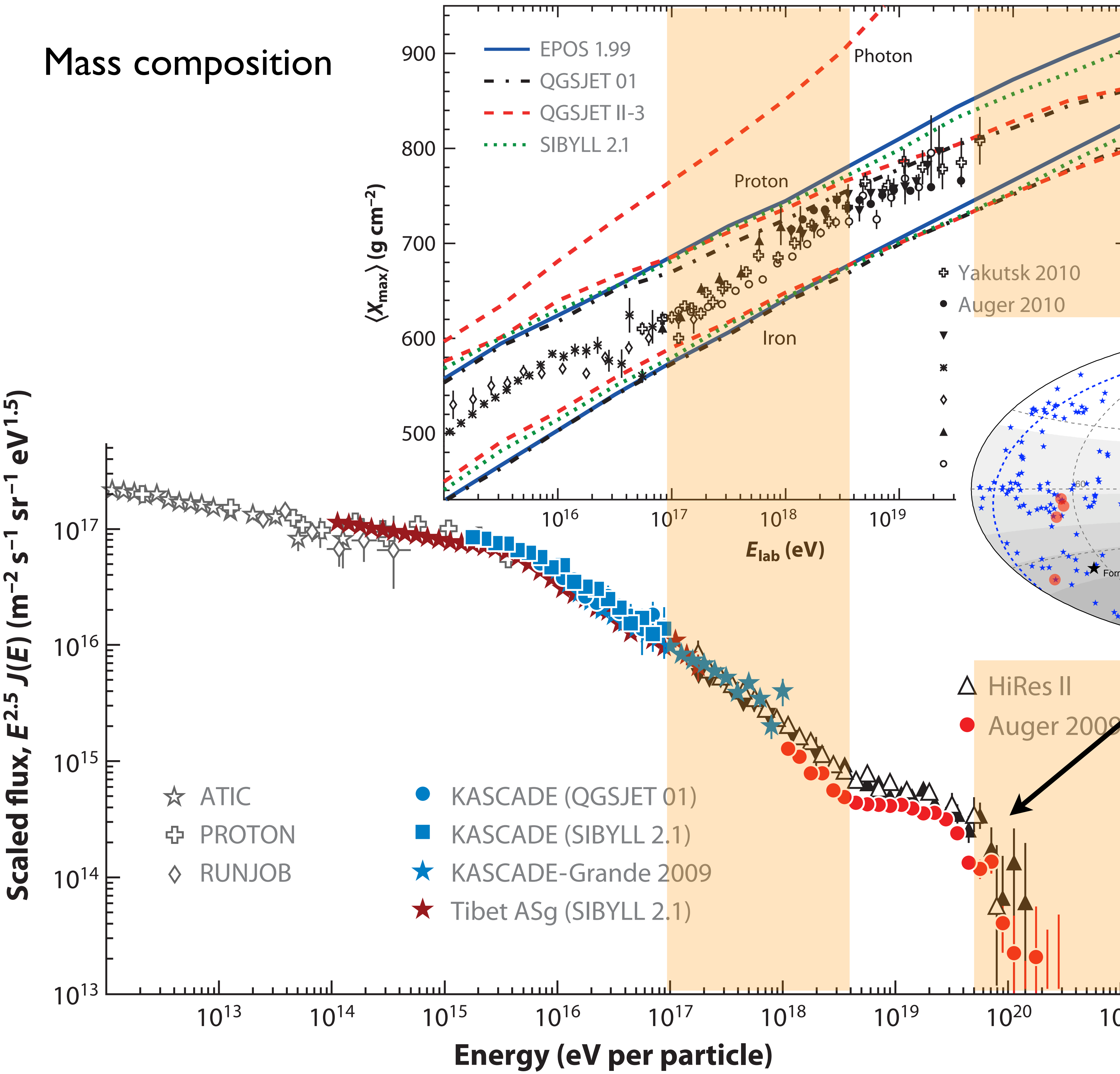
Telescope Array (2011)

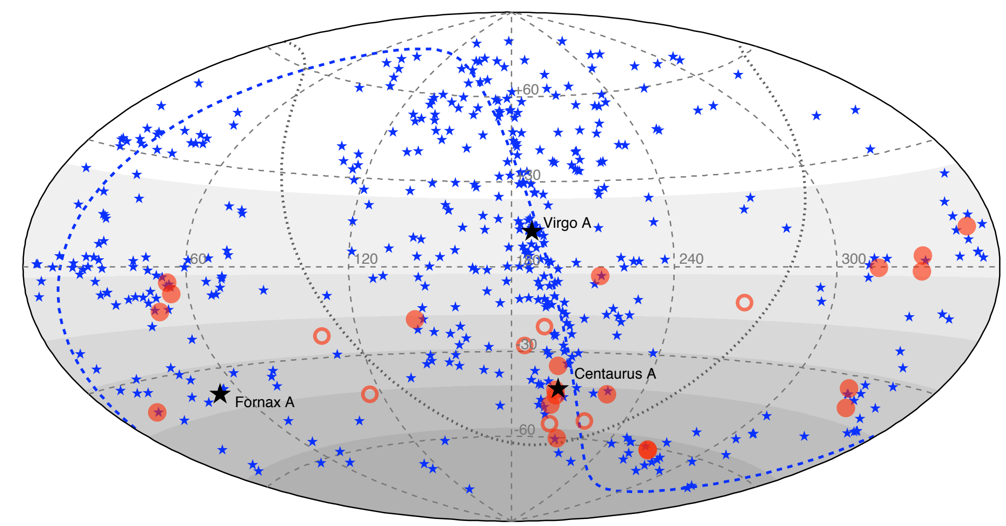
Expectation comes from Auger 69% (=9/13) which is converted to northern sky 73%. The background chance probability is 25%



Overall picture of cosmic ray data

Mass composition



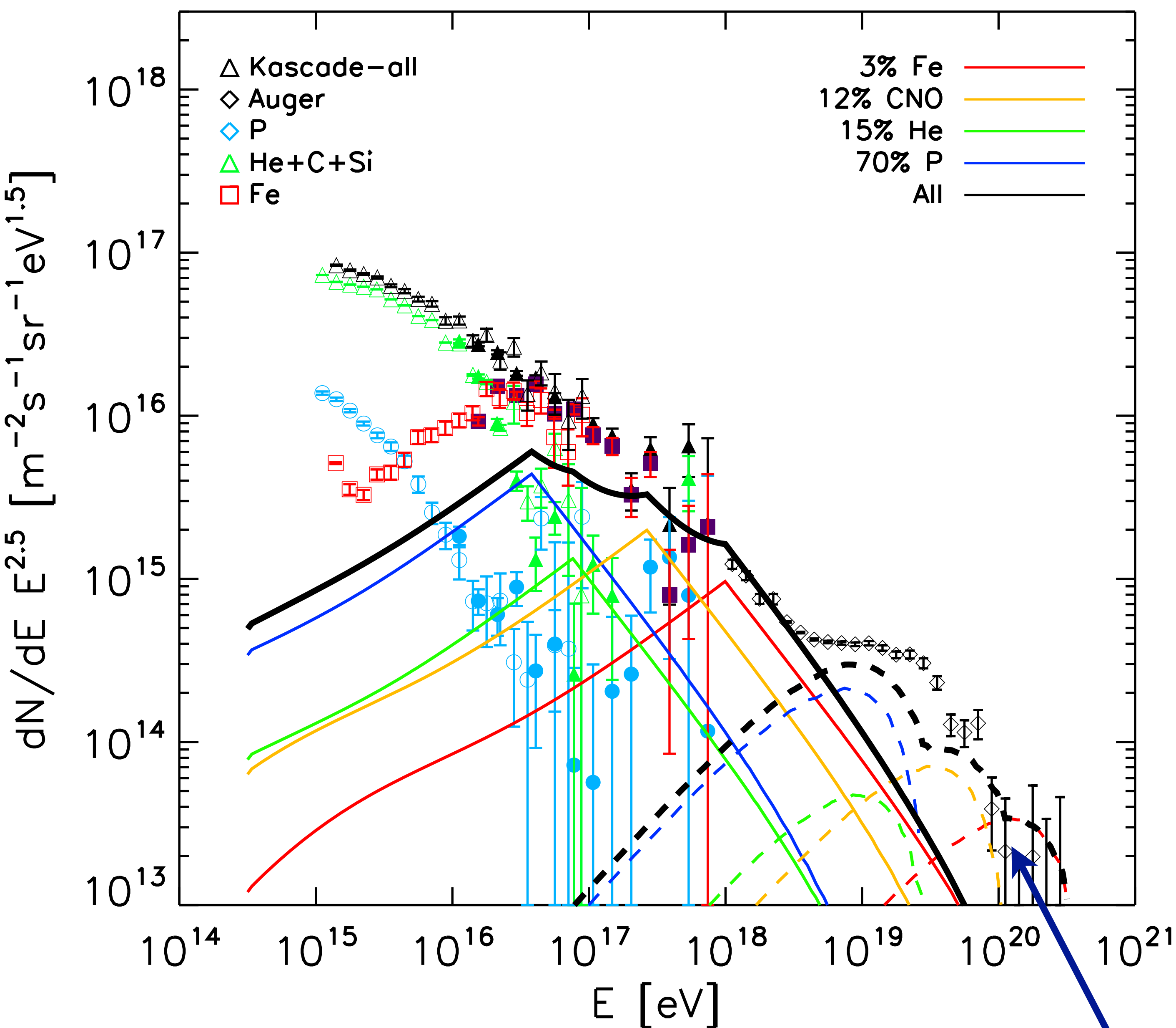


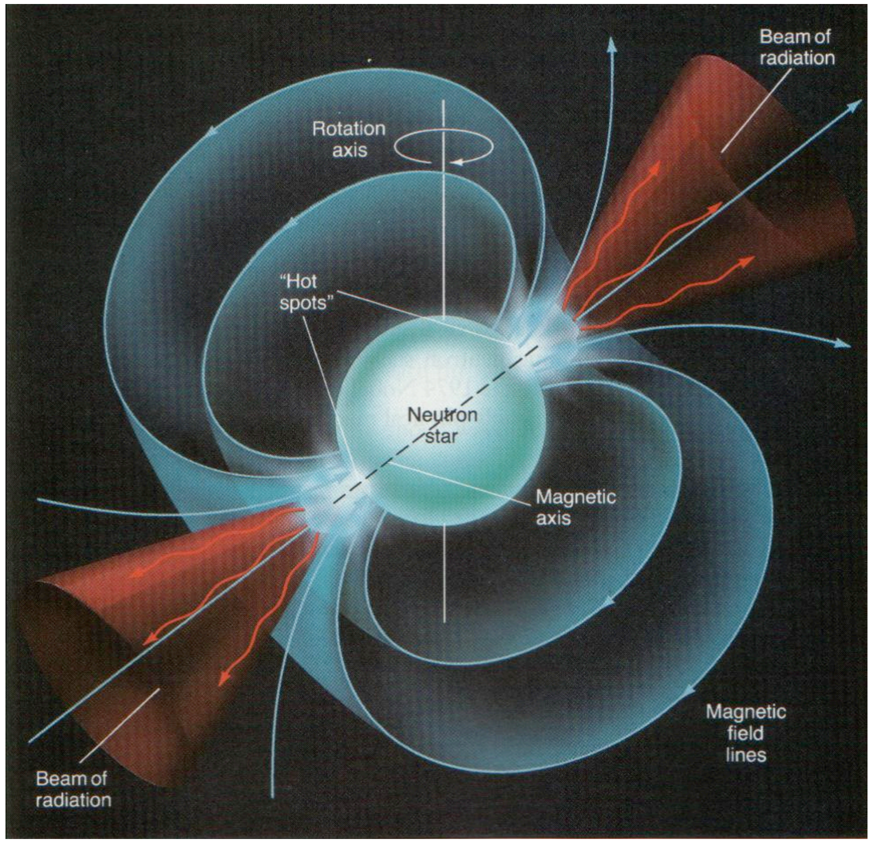
Auger: Correlation with sources / source regions?

(RE, Heck & Pierog, Ann. Rev. Nucl. Part. Sci. 61, 2011)

The magnetar model

(Olinto, Kotera et al., 2012)



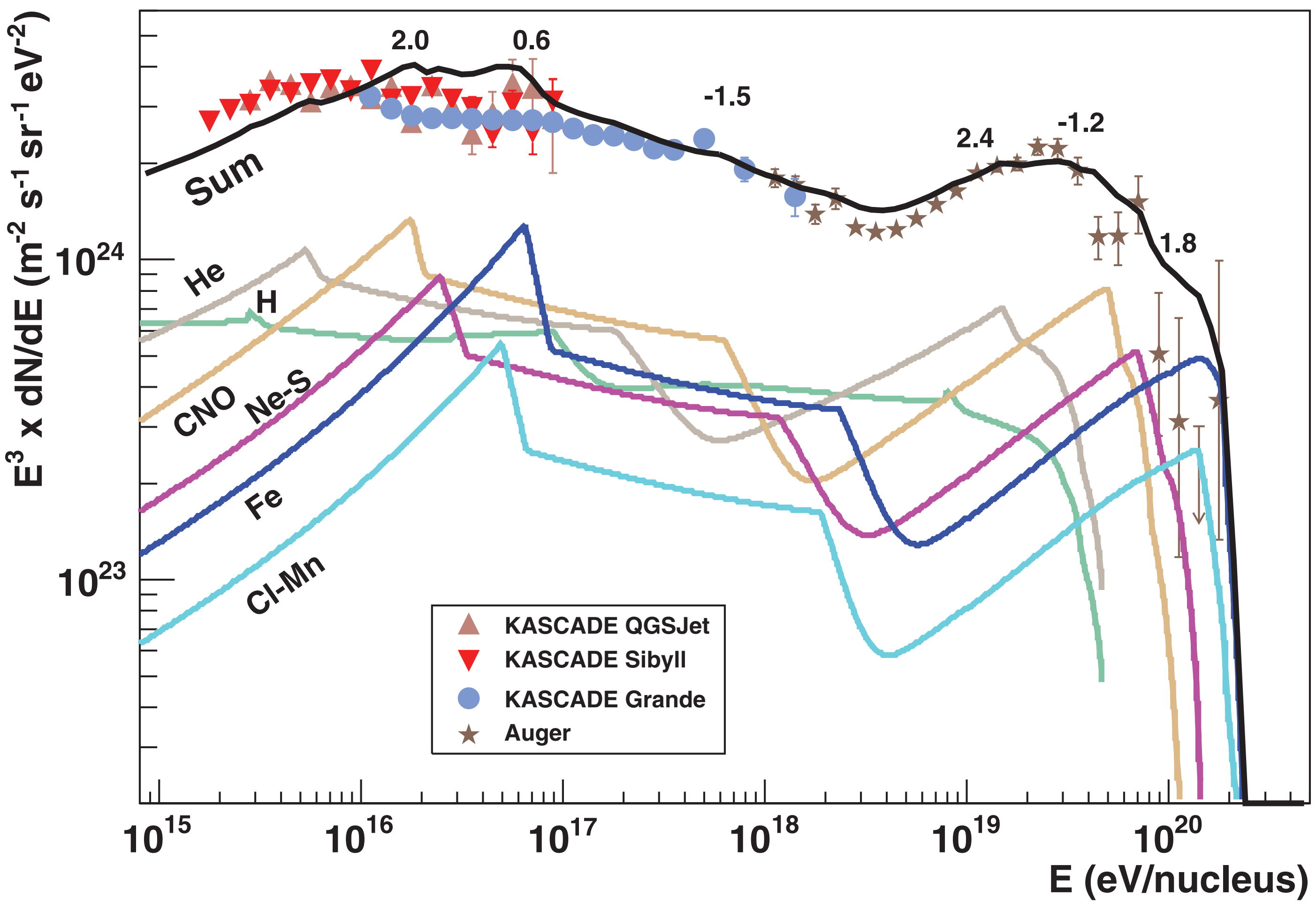


$$R \simeq 10\,\mathrm{km}$$
$$T \simeq 10\ldots100\,\mathrm{ms}$$
$$B \simeq 10^9\,\mathrm{T}\ \ (= 10^{13}\,\mathrm{G})$$

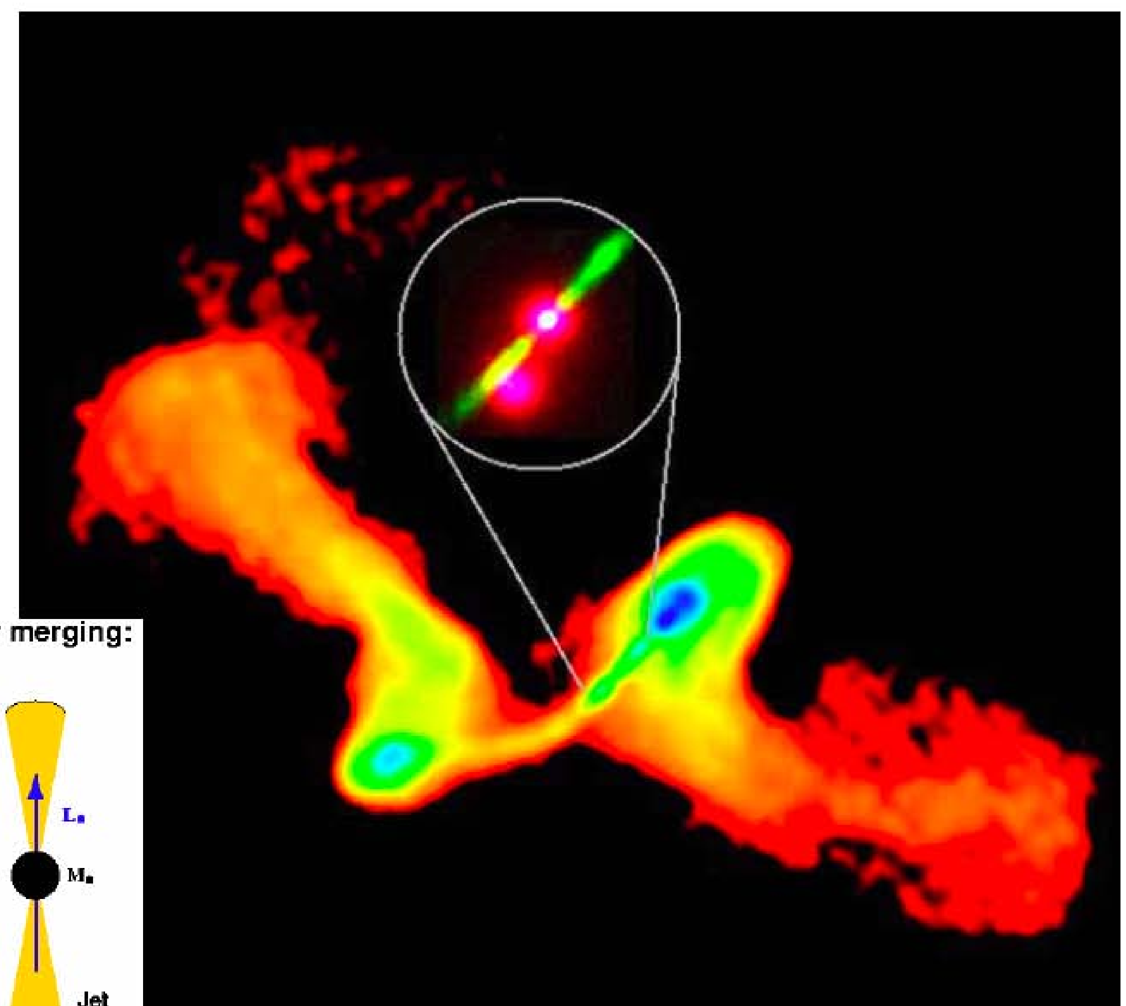
Low-energy part:
many galactic magnetars

High-energy part:
extragalactic (extreme) magnetar

Centaurus A as dominating local source

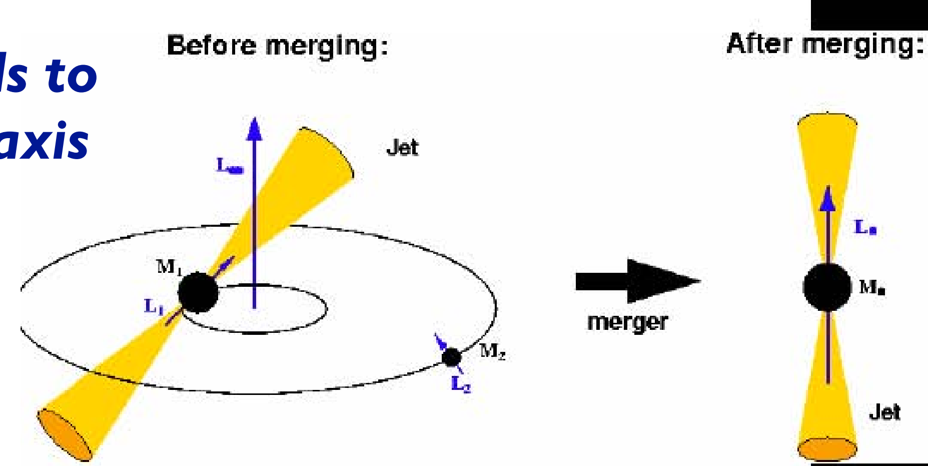


Single reflection of galactic population of cosmic rays on ultra-relativistic shock front of AGN jet



National Radio Astronomy Observatory / AUI, Murgia et al.; STScI (for the inset).

Spin flip of black hole leads to re-orientation of rotation axis



(Biermann et al. 2012)

Inclusive flux of secondary particles

Example: Waxman-Bahcall limit

Example: Waxman-Bahcall neutrino limit (i)

Maximum ``reasonable´´neutrino flux due to interaction of cosmic rays in sources

Assumptions:

- sources accelerate only protons (other particles yield fewer neutrinos)
- injection spectrum at sources known (power law index -2)
- each proton interacts once on its way to Earth (optically thin sources)

Proton flux at sources

$$\Phi_p(E_p) = \frac{dN_p}{dE_p dA dt d\Omega} = A\, E_p^{-\alpha}$$

Master equation

$$\Phi_\nu(E_\nu) = \int \frac{dN_\nu}{dE_\nu}(E_p)\, \Phi_p(E_p)\, dE_p$$

Number of neutrinos produced in interval $E_\nu \ldots E_\nu + dE_\nu$, per proton interaction

Spectrum weighted moments (i)

$$\Phi_\nu(E_\nu) = \int \frac{dN_\nu}{dE_\nu}(E_p)\, \Phi_p(E_p)\, dE_p$$

Aim: re-writing of equation for scaling of yield function

Scaling of neutrino yield

$$x = \frac{E_\nu}{E_p}$$

fraction of proton energy given to neutrino

$$\frac{dN_\nu}{dE_\nu}(E_p) = \frac{1}{E_p}\frac{dN_\nu}{dx} \qquad (1)$$

energy-independent yield function

Elementary math

$$dE_p = \frac{E_\nu}{x^2}\, dx \qquad (2)$$

$$\Phi_p(E_p) = A\, E_p^{-\alpha} = A\left(\frac{E_\nu}{x}\right)^{-\alpha} = x^\alpha\, A\, E_\nu^{-\alpha} \qquad (3)$$

Spectrum weighted moments (ii)

$$\Phi_\nu(E_\nu) = \int \frac{dN_\nu}{dE_\nu}(E_p)\, \Phi_p(E_p)\, dE_p$$

substitutions (1) - (3)

$$\Phi_\nu(E_\nu) \;=\; \int_0^1 x^{\alpha-1}\, \frac{dN_\nu}{dx}\, A\, E_\nu^{-\alpha}\, dx$$

$$\Phi_\nu(E_\nu) \;=\; \left[\int_0^1 x^{\alpha-1}\, \frac{dN_\nu}{dx}\, dx\right] A\, E_\nu^{-\alpha}$$

Spectrum weighted moment
(just a number that depends
only on particle physics)

Proton flux
(but with neutrino energy
instead of proton energy)

Example: Waxman-Bahcall neutrino limit (ii)

Proton spectrum
with $\alpha = 2$

$$\Phi_\nu(E_\nu) = \left[\int_0^1 x \frac{dN_\nu}{dx}\, dx\right] A\, E_\nu^{-2}$$

Spectrum weighted moment for α=2:
mean energy fraction of proton given to neutrino
times number of neutrinos per interaction

Relevant interaction & decay chain (33% of all interactions with small E_{cm})

$$p + \gamma \longrightarrow n\, \pi^+ \longrightarrow n\, \mu^+\, \nu_\mu \longrightarrow n\, e^+\, \nu_e\, \bar{\nu}_\mu\, \nu_\mu$$

20% of p
energy

each particle has 25% of the
energy of the π^+

$$\Phi_{\nu_\mu}(E_{\nu_\mu}) = 0.33 \times 0.2 \times 0.25\ \ A E_{\nu_\mu}^{-2}$$