- models according to scenarios 1) & 2) are compatible with the measurements

- scenario 3) yeilds a light composition at energies 10 - 100 PeV which is not observed

- tests of hadronic interaction models with air shower data yield no evidence for scenario 4)

anisotropy of arrival directions

the observed anisotropy is compatible with scenario 2) (leakage from Galaxy)

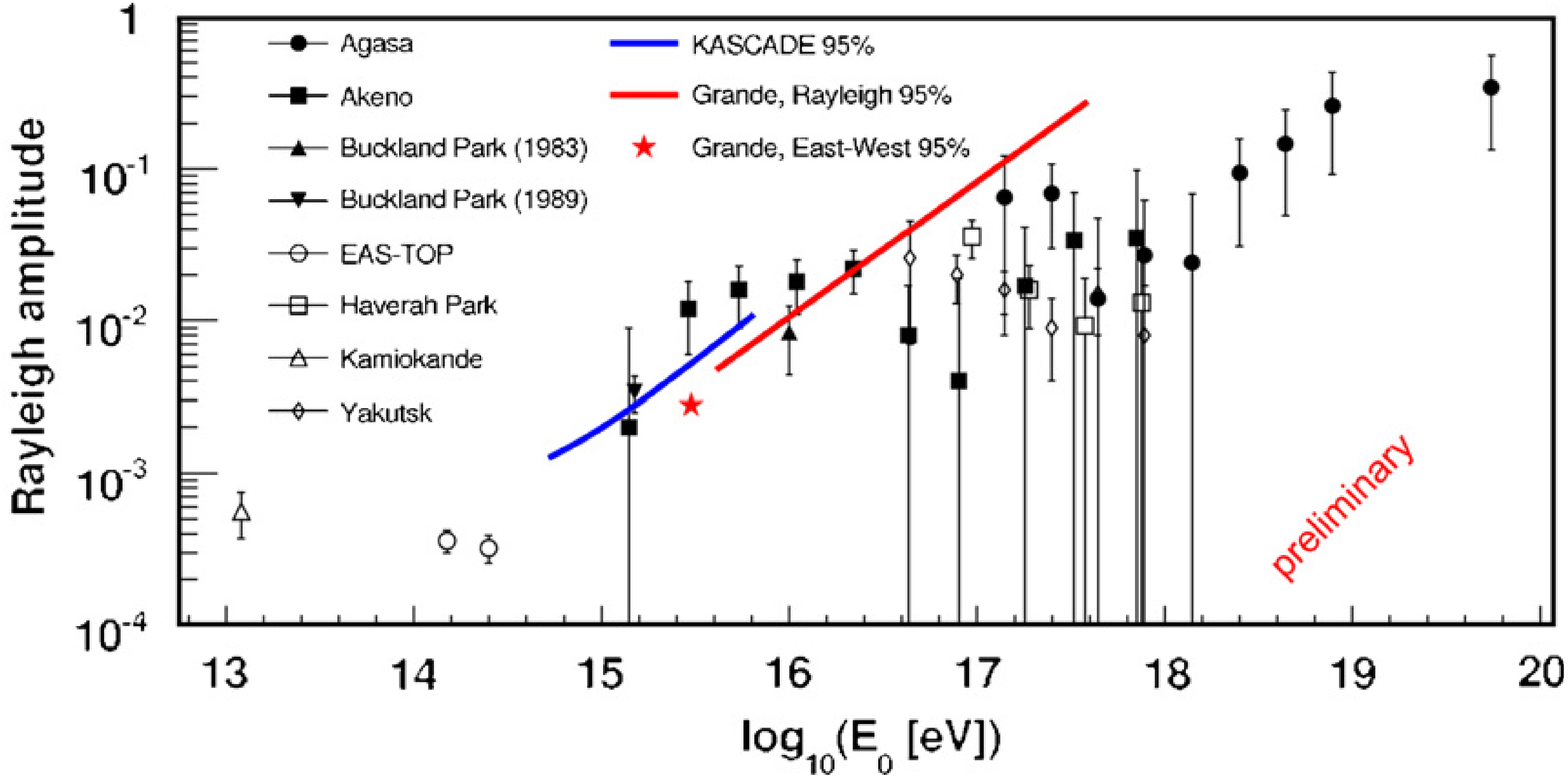


Fig. 6. Rayleigh amplitudes as function of energy as observed by different experiments [39].

(an)isotropy of the arrival direction of cosmic rays

but open question: models typically predict some small anisotropy which is not observed.

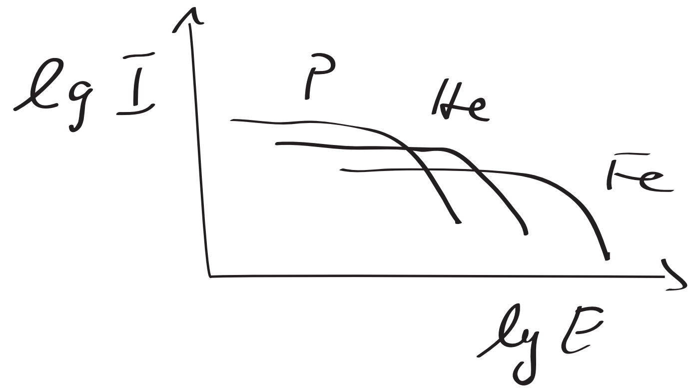
Summary

- no (big) inconsistencies in the description of hadronic interactions
  -> knee is an astrophysical effect (no particle physics in the atmosphere)

- increase of mean (logarithmic) mass as function of energy

- strong indications for a rigidity ($\propto Z$) dependent cut-off of the spectra for groups of elements

$E_k \propto Z$



=> most likely the knee is caused by a combination of two (astrophysical) effects:

- maximum energy of accelerators (supernovae)
- leakage from galaxy

Transition from galactic to extragalactic cosmic rays

at energies between 10^{17} and 10^{18} eV all elements of the Galactic cosmic-ray component should reach their cut-off energies

→ observed all-particle flux at high energies is mostly composed of particles from other galaxies (extragalactic cosmic rays)

Different scenarios are discussed in the literature, most expect a transition from galactic to extragalactic origin of the cosmic-ray particles at energies between 10^{17} and 10^{18} eV.

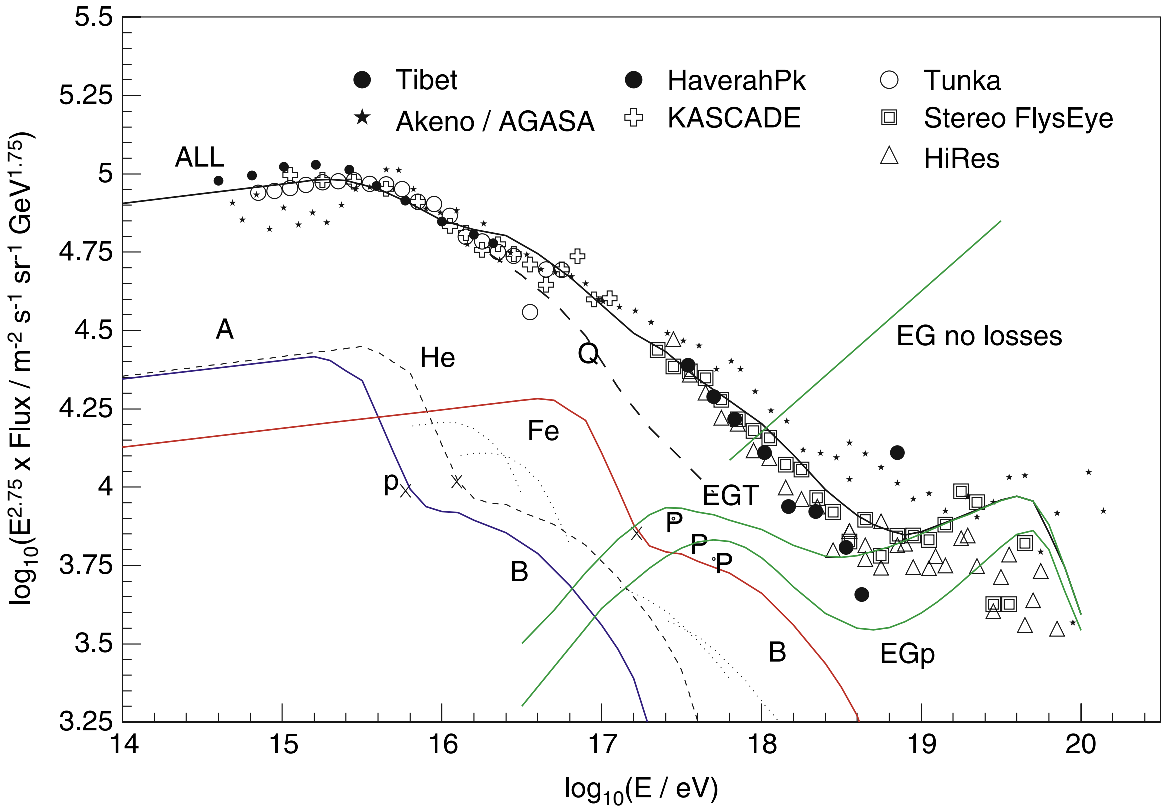


Fig. 25. The breakdown of the cosmic-ray spectrum according to a model of Hillas [449] as the sum of galactic H, He, CNO, Ne–S, and Fe components with the same rigidity dependence, and extragalactic H + He having a spectrum $\propto E^{-2.3}$ before suffering losses by cosmic microwave background and starlight interactions. The galactic components were given a turn-down shape based on a KASCADE knee shape as far as the point marked *x*. The dashed line *Q* is the total galactic SNR flux if the extended tail (component *B*) of the galactic flux is omitted [449].

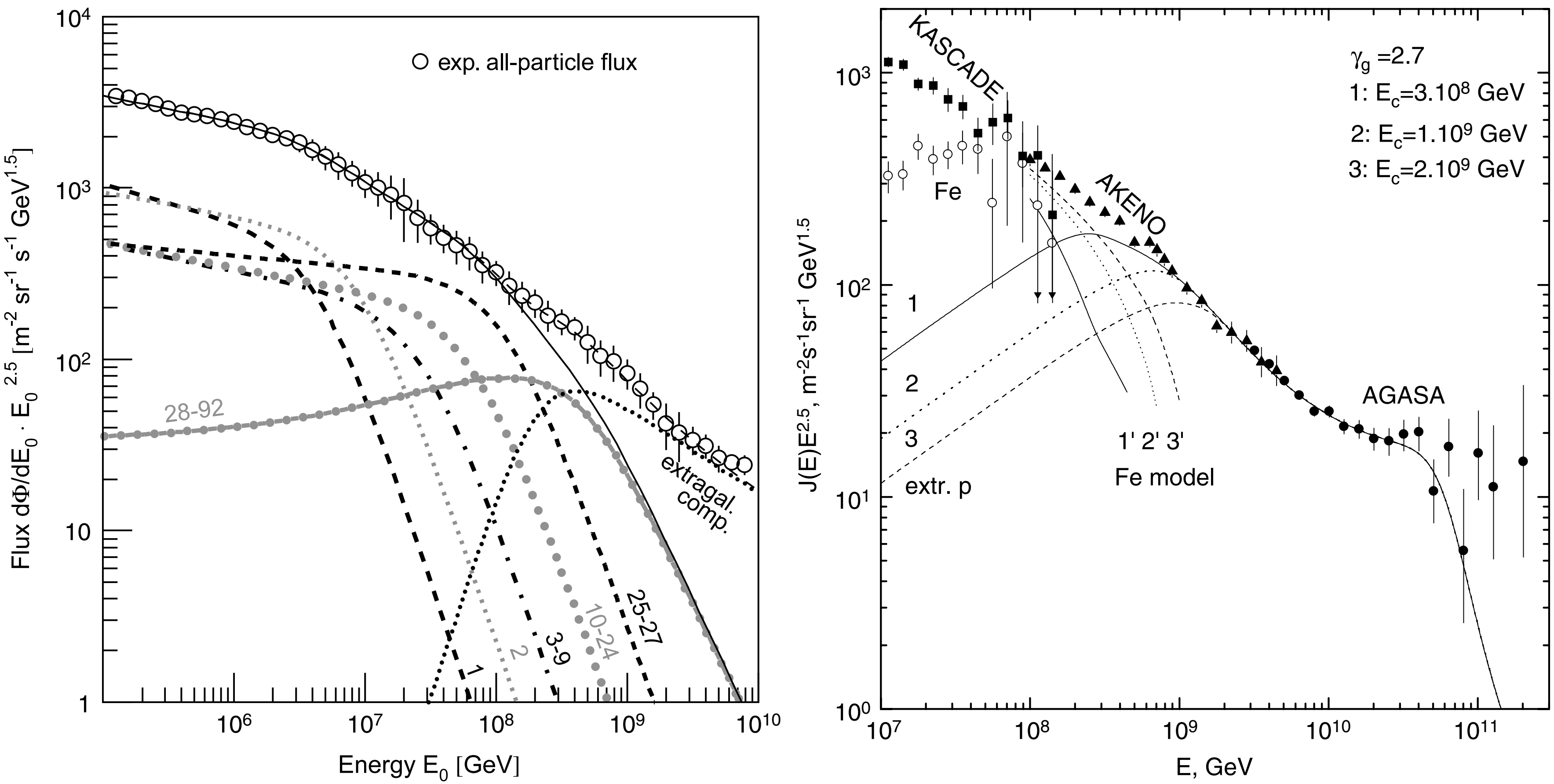


Fig. 26. *Left panel*: Cosmic-ray energy spectra according to the poly-gonato model [2]. The spectra for groups of elements are labeled by their respective nuclear charge numbers. The sum of all elements yields the galactic all-particle spectrum (—) which is compared to the average measured flux. In addition, a hypothetical extragalactic component is shown to account for the observed all-particle flux (- - -). *Right panel*: Transition from galactic to extragalactic cosmic rays according to Berezinsky et al. [451]. Calculated spectra of extragalactic protons (curves 1, 2, 3) and of galactic iron nuclei (curves 1′, 2′, 3′) are compared with the all-particle spectrum from the Akeno and AGASA experiments. KASCADE data are shown as filled squares for the all-particle flux and as open circles for the flux of iron nuclei.

The highest energy particles in the Universe

1962: first observation of a cosmic ray with $E > 10^{20}$ eV

10^{20} eV is a macroscopic energy: 50 J

Can such particles originate from our Galaxy?

simple argument:

radius of trajectory of particles in B-field

$$r = \frac{P}{Ze\,B} \qquad r(\mathrm{pc}) = 1{,}08\ \frac{E\,(\mathrm{PeV})}{Z \cdot B\,(\mu G)}$$

→ particles above $\sim 10^{18}$ eV cannot be magnetically bound to Galaxy

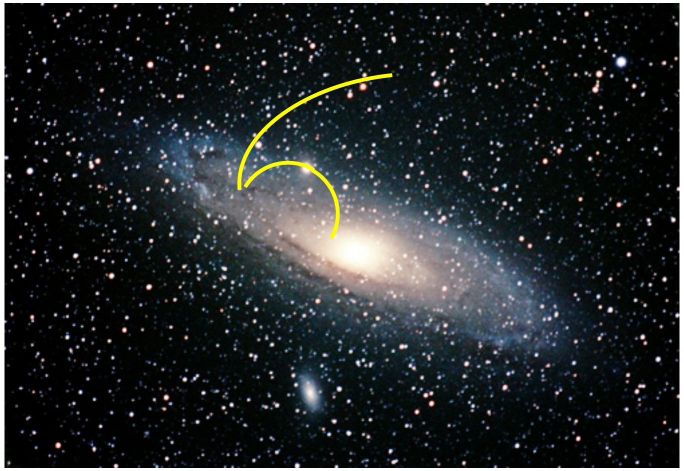
→ extragalactic origin

Vulcano Ranch, New Mexico, John Linsley

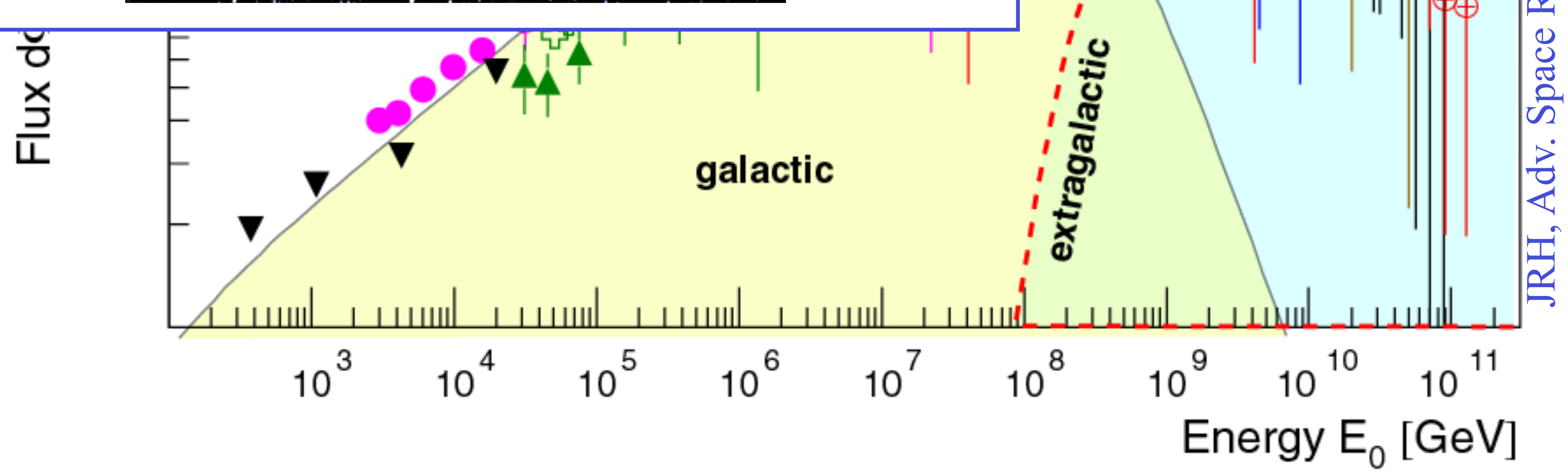
first EAS with 10^{20} eV measured 1962

Radius of particle in magnetic field

$$r = \frac{p}{ZeB} \qquad r[pc]=1.08^* \frac{E\ [PeV]}{B\ [\mu G]}$$



extragalactic cosmic rays



r= 0.04 pc 3.6 pc 360 pc 36 kpc

Energy content of extragalactic cosmic rays

$$\rho_E = \frac{4\pi}{c}\int \frac{E}{\beta}\frac{dN}{dE}dE$$ ρ_E=3.7 10^{-7} eV/cm^3

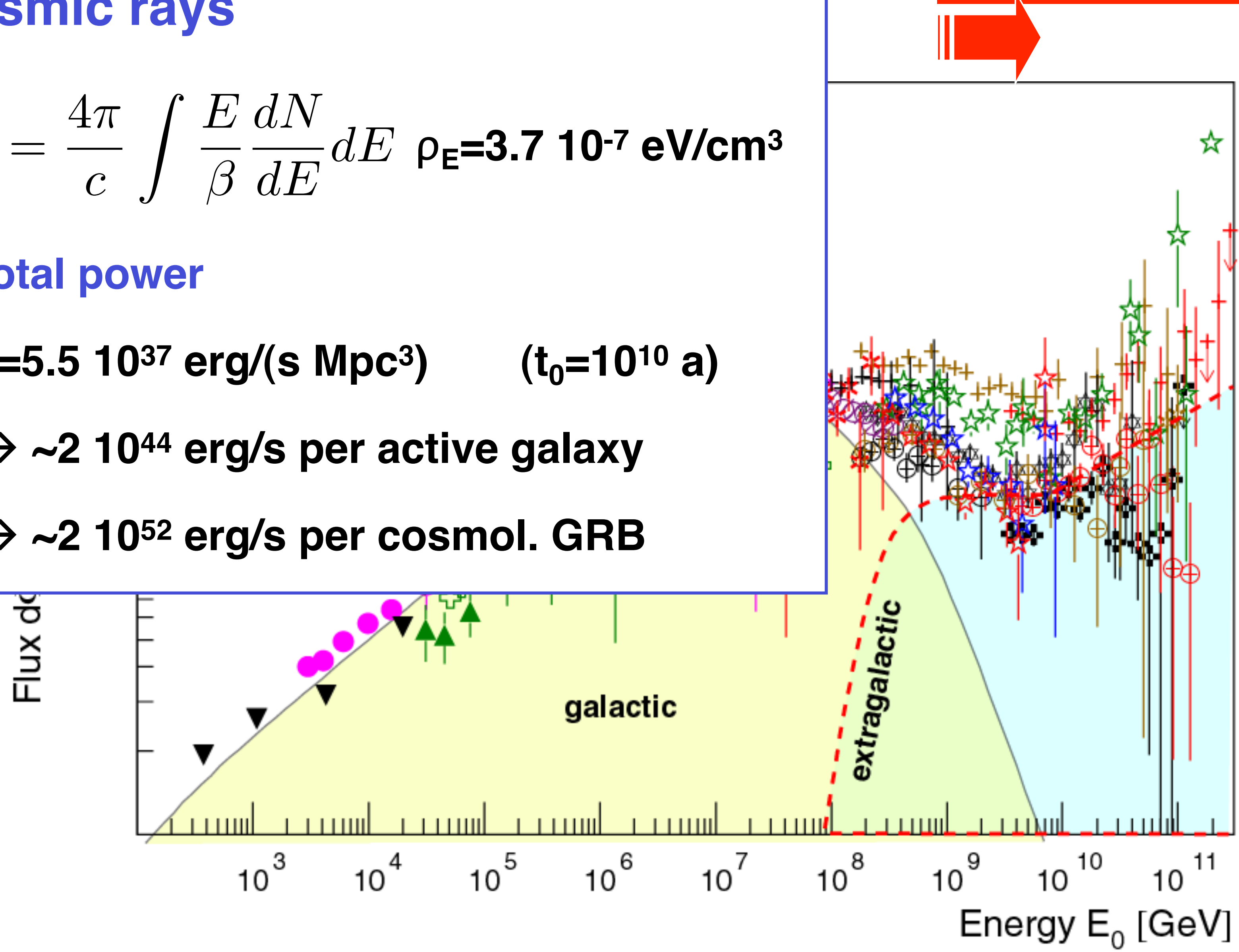
total power

P=5.5 10^{37} erg/(s Mpc^3)   (t_0=10^{10} a)

→ ~2 10^{44} erg/s per active galaxy

→ ~2 10^{52} erg/s per cosmol. GRB

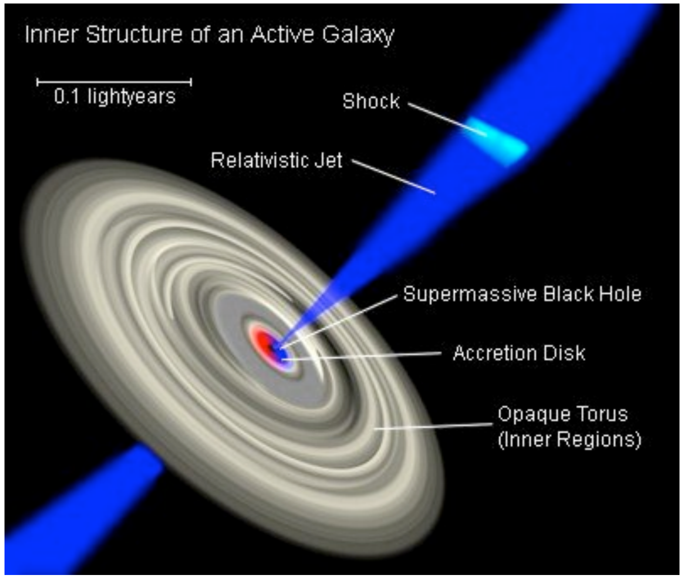
extragalactic cosmic rays

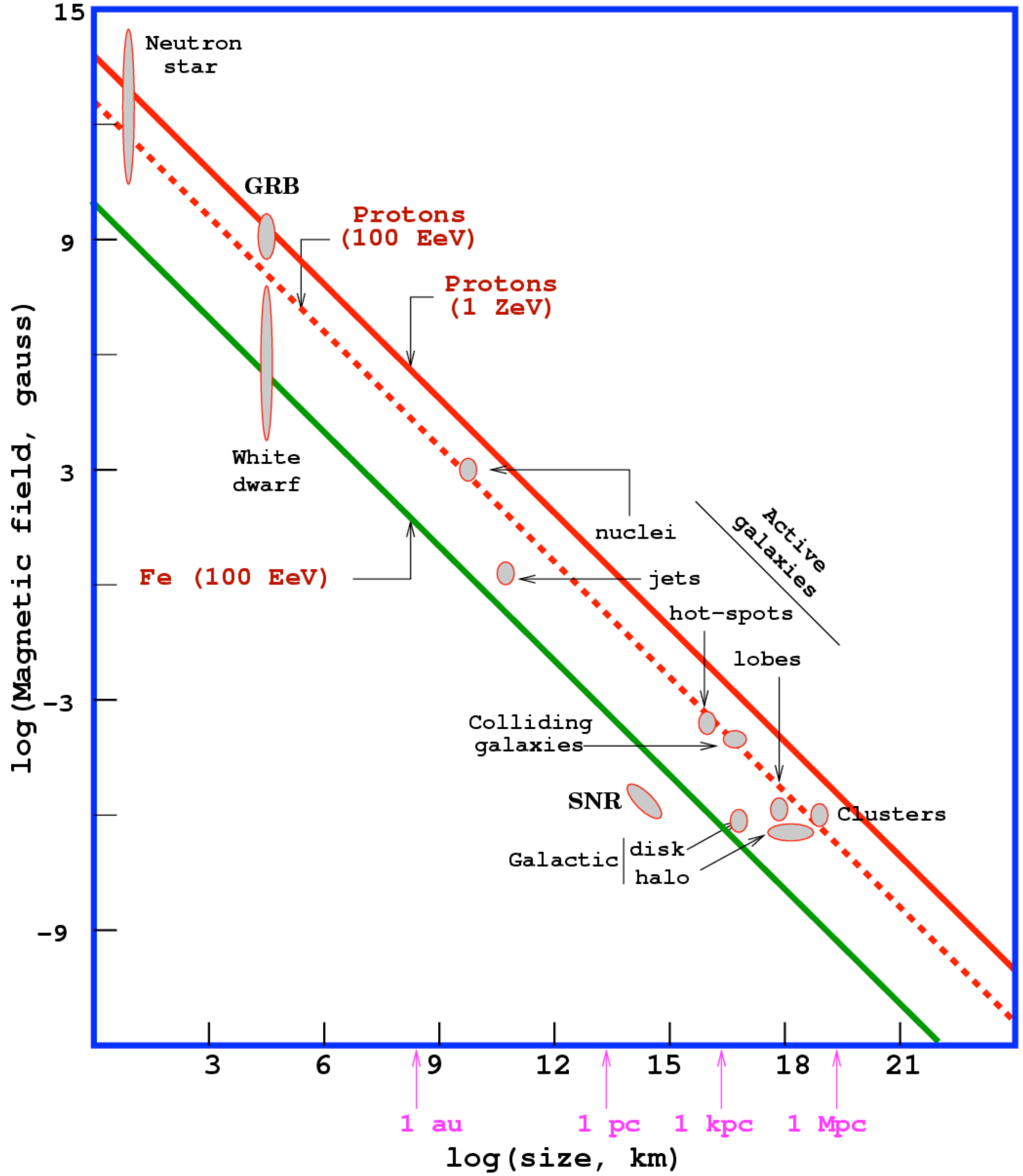


JRH, Rev. Mod. Astron. 20 (2008) 203 (arXiv:0803.3040)

Accelerator dimensions and magnetic field

B[μG] L[pc] > 2 E[PeV]/(Zβ)





$E_{max} \sim$ ZBL (Fermi)

$E_{max} \sim$ ZBLΓ (Ultra-relativistic shocks-GRB)

Potential sources of extragalactic cosmic rays are

- GRB
- AGN

motivated by energy budget
by Hillas diagram

typical distance $\sim 10 - 100\,\mathrm{Mpc}$

can particles with $E = 10^{20}\,\mathrm{eV}$ reach Earth from such a distance?

1964: discovery of 3K microwave background

photons were generated 380 000 a after the Big Bang.

during recombination $p + e \rightarrow H$ atoms

$$T_{today} = \frac{T_{rec}}{1+z} \qquad z \text{ red shift}$$

$$= \frac{3000\,K}{1100} = 2{,}73\,K$$

black body spectrum

$$I(\nu)\,d\nu = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1} d\nu$$

integration of energy spectrum

energy density $\varepsilon_\gamma = \sigma T^4$ Stefan Boltzmann law

particle number density

$$n_\gamma = \frac{\varepsilon_\gamma}{\langle \varepsilon_\gamma \rangle} \approx 20{,}3\, T^3 \frac{1}{cm^3} = 411 \frac{\text{photons}}{cm^3}$$

in whole Universe

already 1965 Greisen, Zatsepin, and Kuz'min realized

$E_p \; \bullet \longrightarrow \qquad \longleftarrow\!\sim\!\sim\!\sim \; \varepsilon_\gamma$

$10^{20}\,\mathrm{eV}$ $\qquad$ $3\,\mathrm{K}\ \gamma$

p $\qquad$ $\sim 0.5\,\mathrm{meV}$

Lorentz transformation

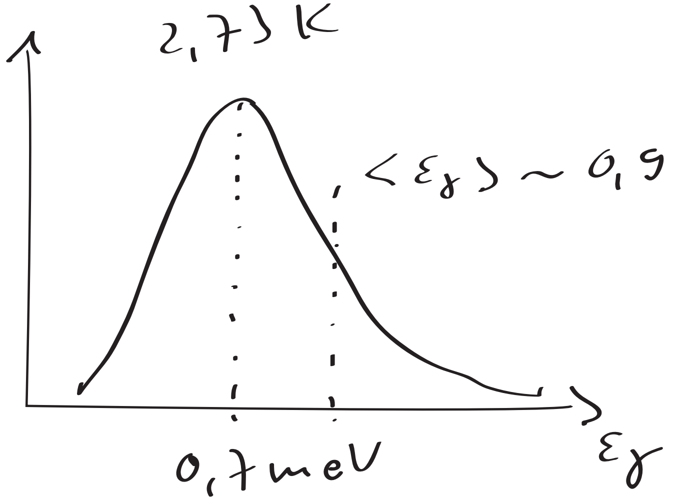
$$E_{CM}^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$

$\overset{\bullet}{p}$ resting $\quad \longleftarrow\!\sim\!\sim$ $300\,\mathrm{MeV}\ \gamma$

$$\Rightarrow E_{CM}^2 = 4 E_p E_\gamma + m_p^2 c^4$$

resonance if $E_{CM} = m_\Delta c^2$

Δ resonance $m_\Delta c^2 = 1232\,\mathrm{MeV}$



$$4 E_p E_\gamma \geq (m_\Delta^2 - m_p^2)\, c^4$$

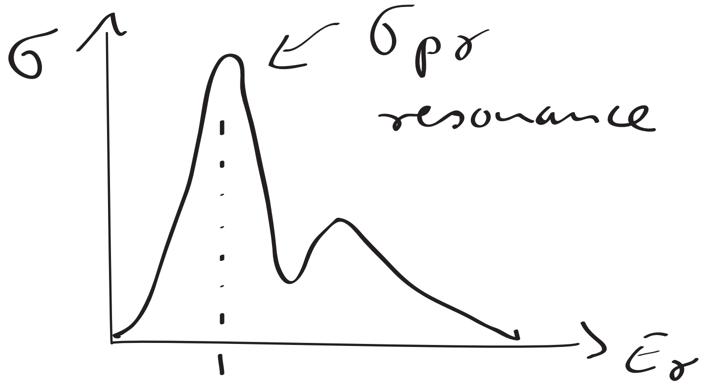
$$\Rightarrow E_p \approx 6 \cdot 10^{19}\ \text{eV}$$

threshold energy of GZK effect

above this energy the proton generates a Δ resonance

this is well known from accelerators

$\sigma_{res} \sim 500\ \mu b$ $\qquad 1\, b = 10^{-24}\ cm^2$



how far can a proton travel?

$$\lambda_{p\lambda} = \frac{1}{n_\gamma \sigma_{p\gamma}} = \frac{1}{411\ \mathrm{cm}^{-3} \cdot 300 \cdot 10^{-30}\ \mathrm{cm}^2}$$

$$= 8.1 \cdot 10^{24}\ \mathrm{cm} = 2.6\ \mathrm{Mpc}$$

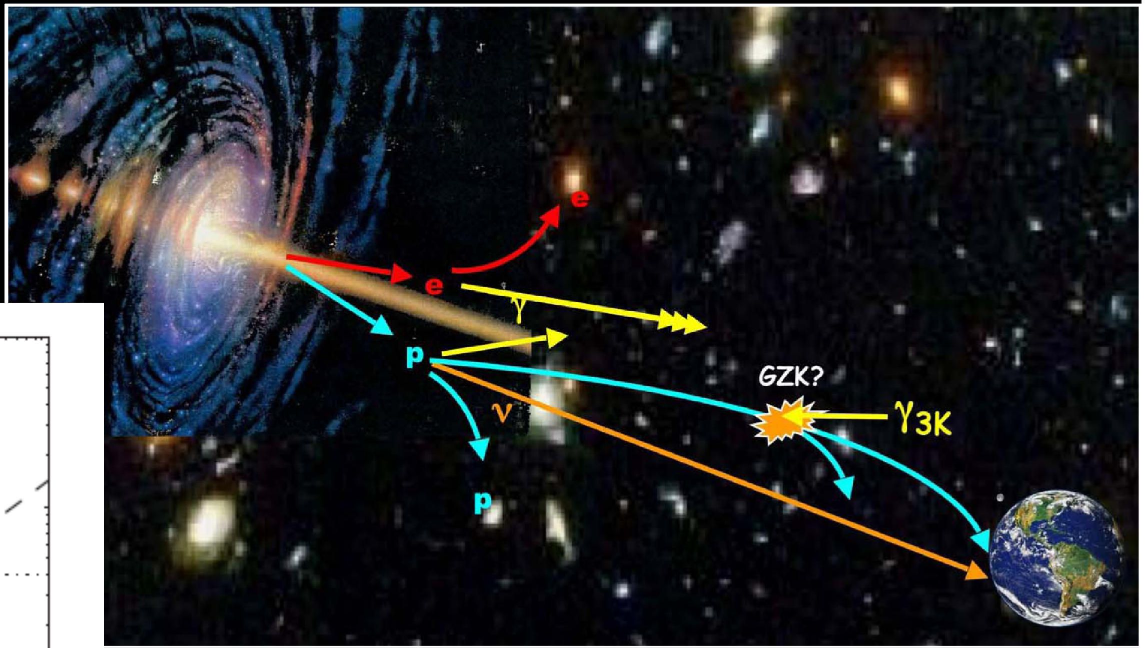
interaction

$$p + \gamma_{3K} \longrightarrow \Delta^+ \xrightarrow{10^{-22}\ s} \begin{array}{l} p + \pi^0 \\ n + \pi^+ \end{array}$$

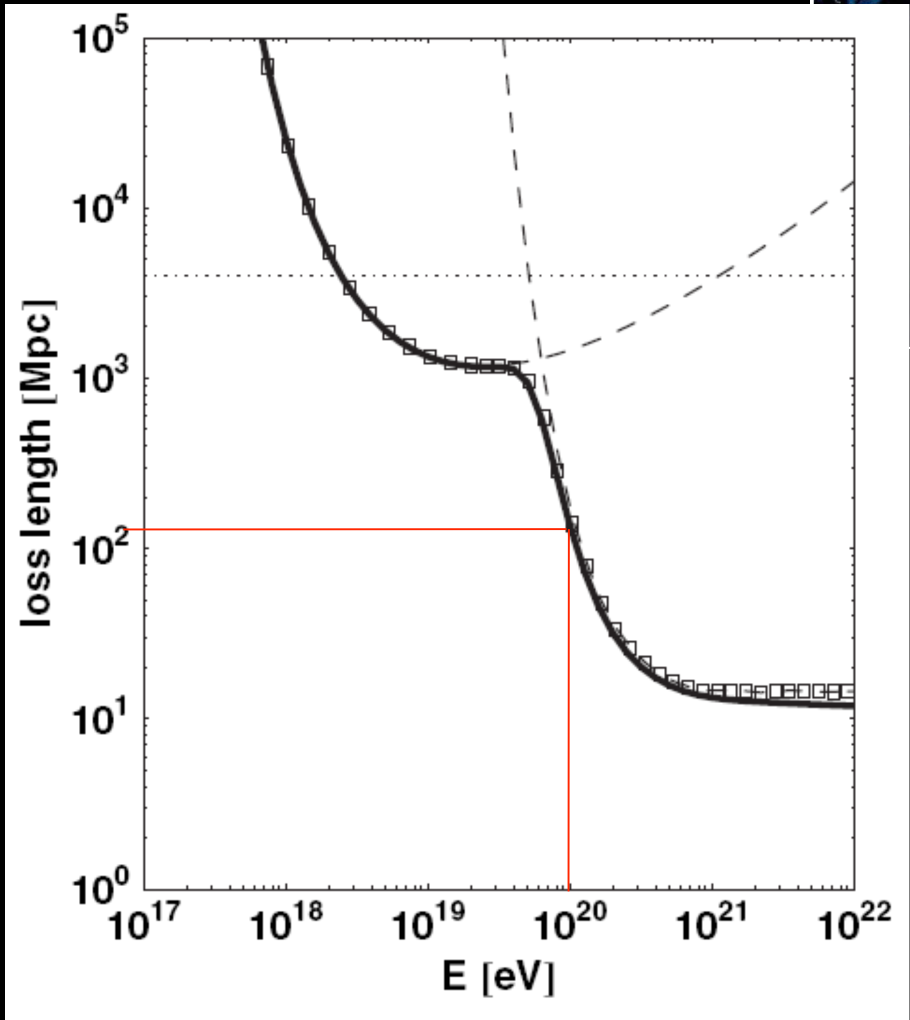
on average looses the proton about 20-30% of its energy during the interaction

-> after ≥ 10 Mpc the energy has been reduced to $1/e$

„Optical depth" of the Universe – The GZK Effect



Energy loss length



$p + \gamma_{3K} \rightarrow \Delta^+ \rightarrow p + \pi^0$; $n + \pi^+$

threshold: $E_{GZK} \approx 6 \cdot 10^{19}$ eV

⇒ **at highest energies field of view is reduced to < 100 Mpc**

Stanev & de Marco, PRD 72 (2005) 081301

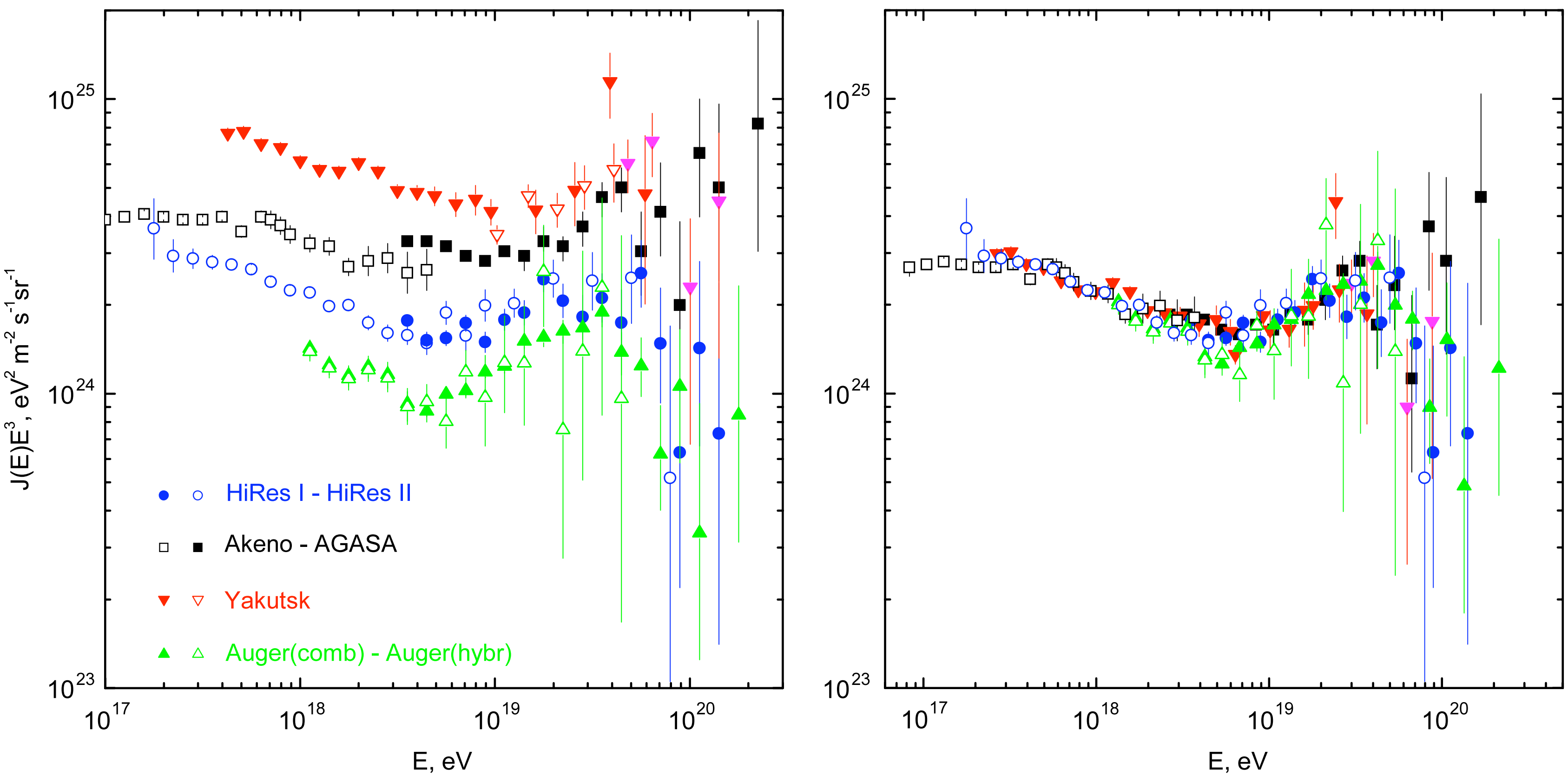


Fig. 12. Flux of UHECRs as measured with the four detectors that have the largest exposures, namely Yakutsk [285] AGASA [165,283], Auger [169], and HiRes [229]. *Left panel*: Cosmic-ray spectra as derived by the Collaborations using the calibration of the detectors. *Right panel*: Cosmic-ray spectra after re-scaling of the energy scale of the experiments to obtain a common position of the dip, from [286,287]. The nominal energy scales of the experiments have been multiplied by 1.2, 1.0, 0.75, 0.625 for Auger, HiRes, AGASA, and Yakutsk, respectively.

$\rightarrow$ attenuation length ~ 10 Mpc

particles exist at energies $E > E_{GZK}$

$\Rightarrow$ 1) sources are close by

2) ideas about GZK effect are not realistic

Lorentz transformation not valid at

high energies

$\rightarrow$ new theory

speculative solutions:

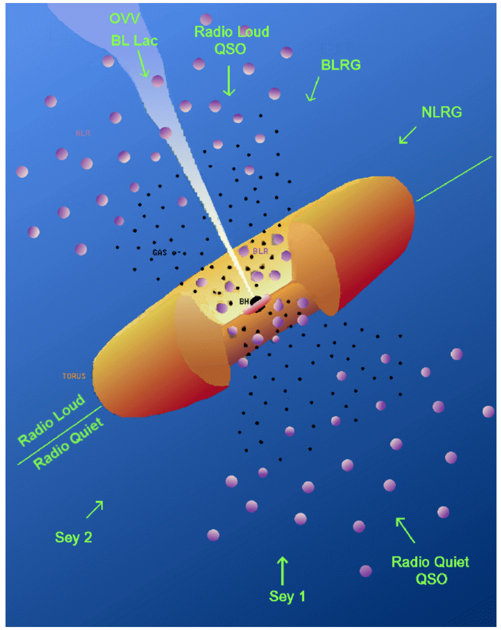
top down models

topological defects TD $(m \sim 10^{24}\,eV)$

$\hookrightarrow$ X, Y bosons

Possible sources of extragalactic cosmic rays

Bottom up models



- Active galactic nuclei (AGN)
- Coalescence of neutron stars, black holes
- Gamma ray bursts

$p+p$ or $p+\gamma \rightarrow \pi^{+/-} \rightarrow \nu_\mu + \nu_e + \ldots$

$\rightarrow \pi^0 \rightarrow \gamma + \gamma$

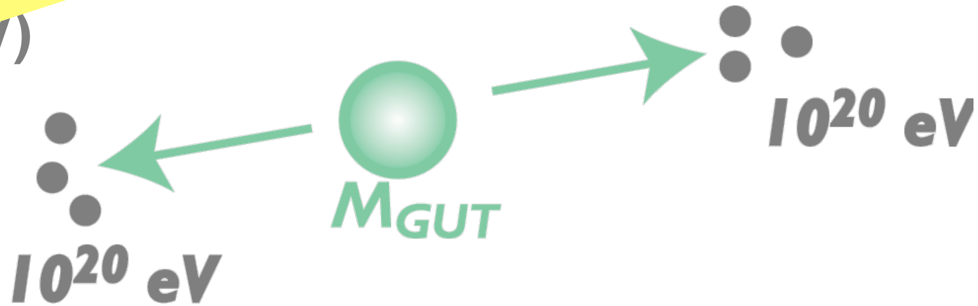
Top down models

Super heavy relicts of Big-Ba… …ol. defects)

X-particle (m … eV)

…ons

$\gamma, \nu, p\ldots$

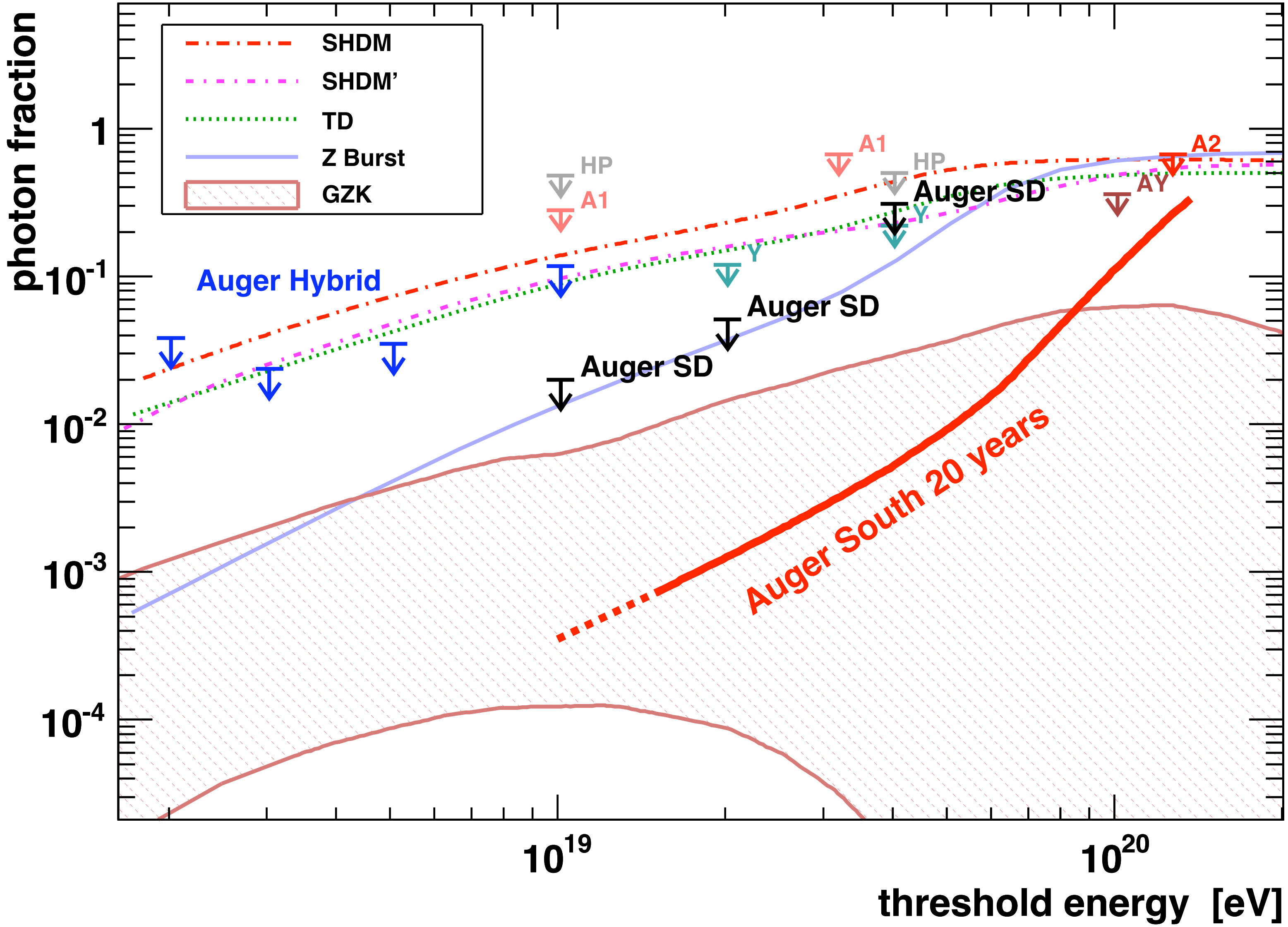


Already severe constraints by Auger

→ Multi Messenger Approach

Neutrino astronomy	Proton astronomy	TeV γ-ray astronomy
km³ net Ice Cube	Pierre Auger (full sky)	HESS, MAGIC, CTA

Limit on γ flux

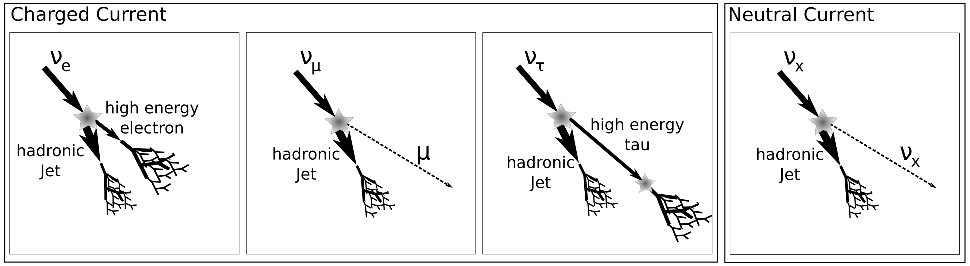


constraints on exotic CR models

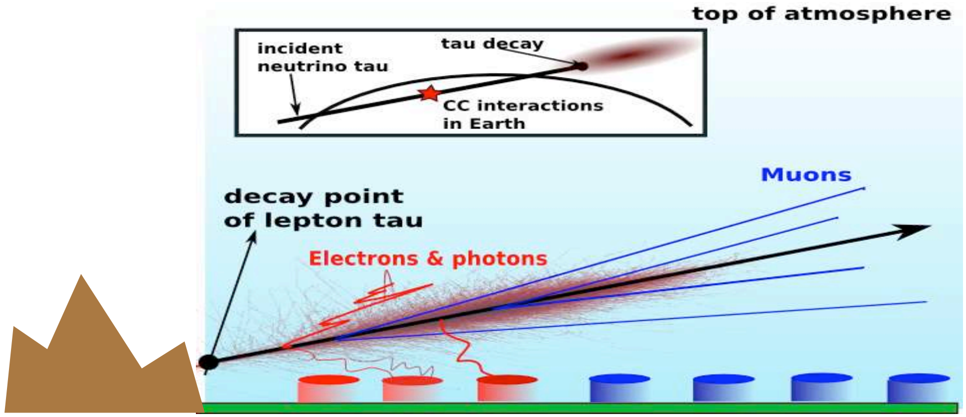
J. Abraham et al., Astroparticle Physics 29 (2008) 243

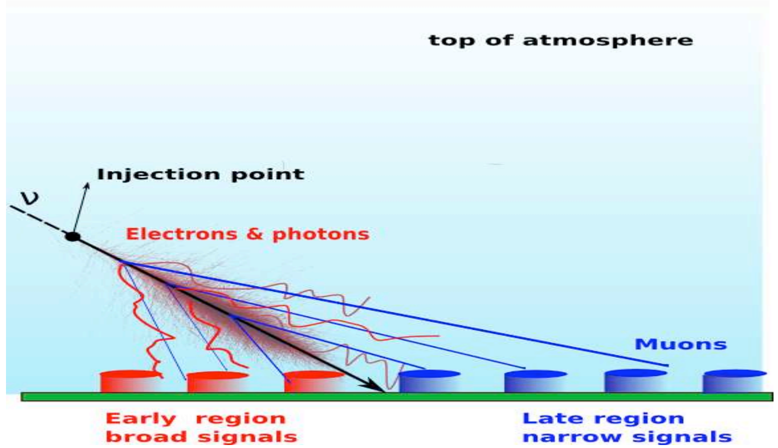
P. Homola et al., ICRC 2009

Neutrino Detection in Auger

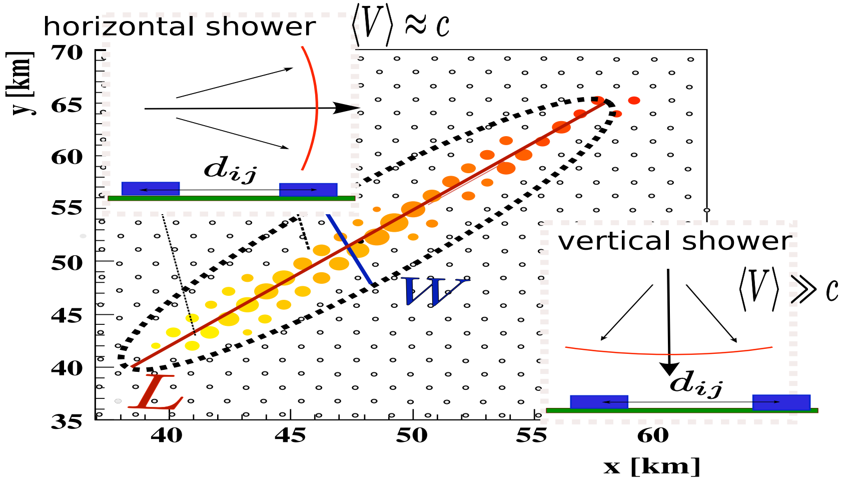


neutrinos initiate showers in atmosphere

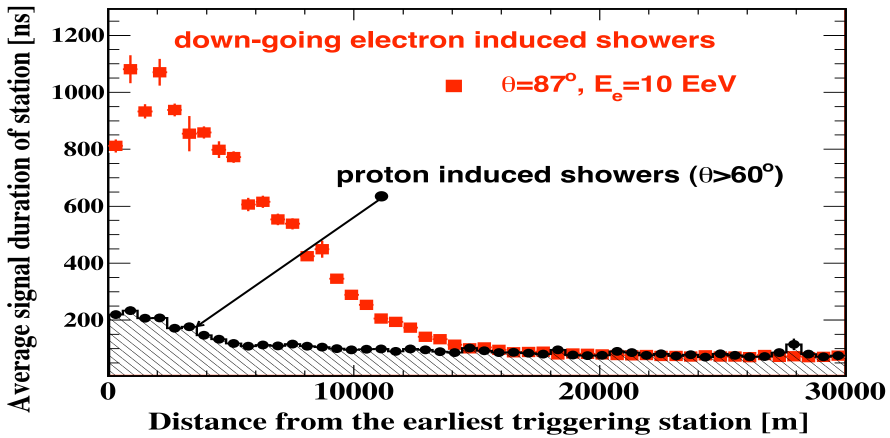




horizontal shower

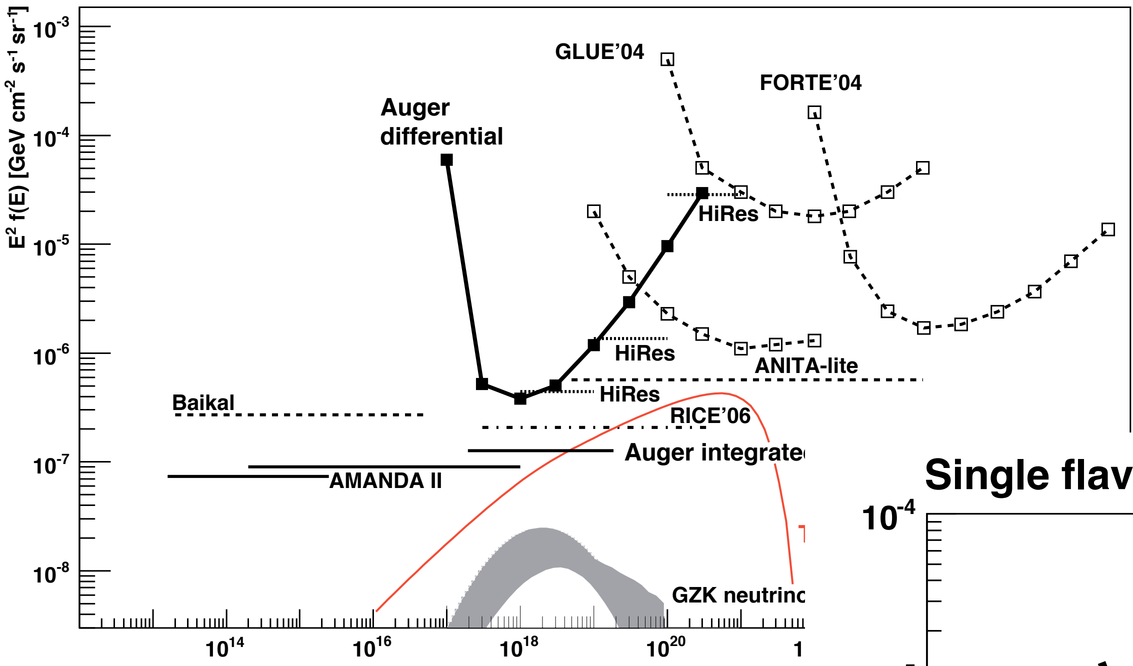


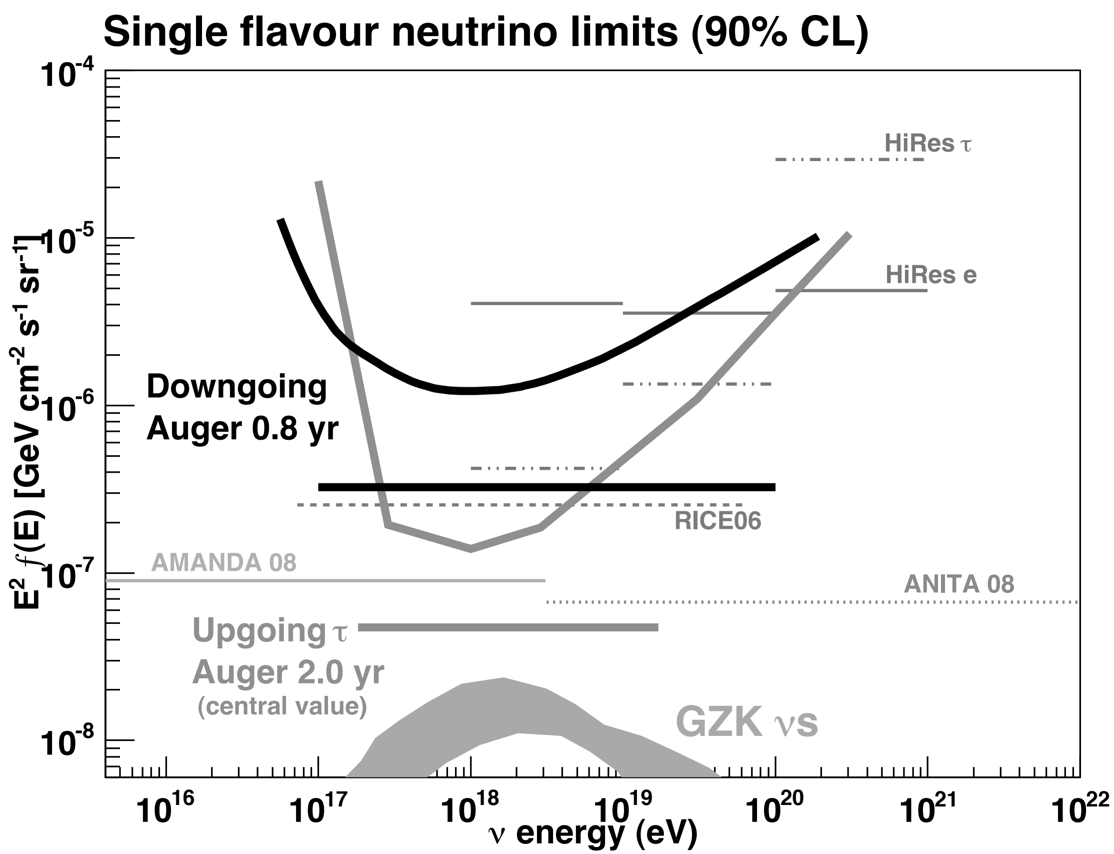
time structure



D. Gora et al., ICRC 2009 J. Tiffenberg et al., ICRC 2009 J. Abraham et al., PRL 100 (2008) 211101

Limit on τ neutrino flux





constraints on exotic CR models

D. Gora et al., ICRC 2009

J. Tiffenberg et al., ICRC 2009

J. Abraham et al., PRL 100 (2008) 211101

$\hookrightarrow$ W, Z bosons

$\hookrightarrow$ p, γ, ν

however, these models are heavily constrained by Auger data (γ flux, ν flux)

origin of the highest energy particles in the Universe

three main observables

- energy spectrum
- mass composition
- arrival direction