Transport of ultra-high energy cosmic rays in expanding Universe

V.S. Ptuskin, S.I. Rogovaya, V.N. Zirakashvili

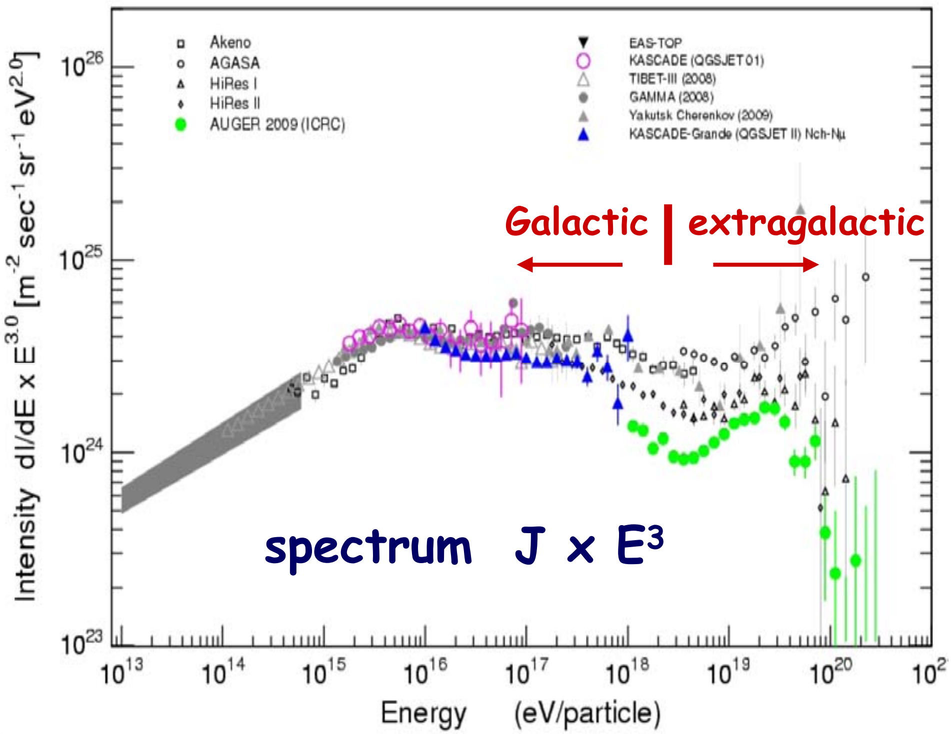
IZMIRAN, Russia

22nd ECRS, Turku 2010

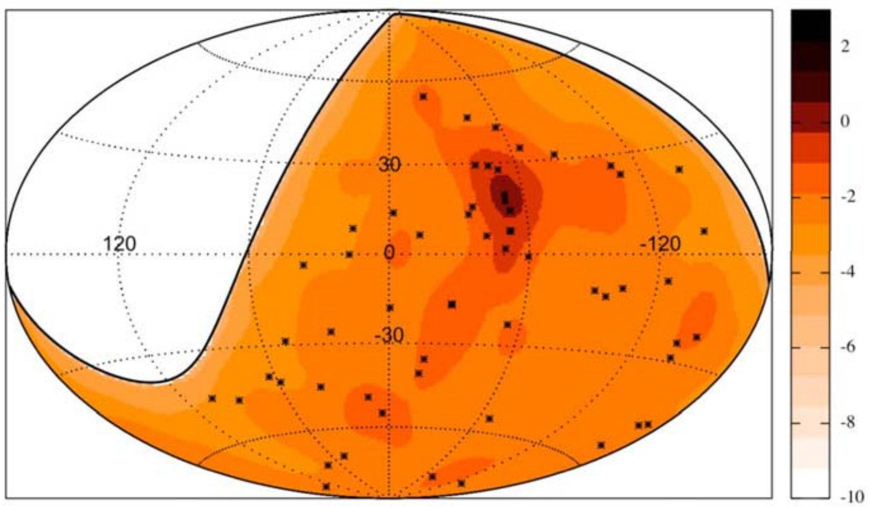
cosmic ray sources

Galactic component:
SNRs
+ bubbles, pulsars, gal. wind

extragalactic component:
AGN & radiogalaxies
+ GRB, cluster accretion shocks

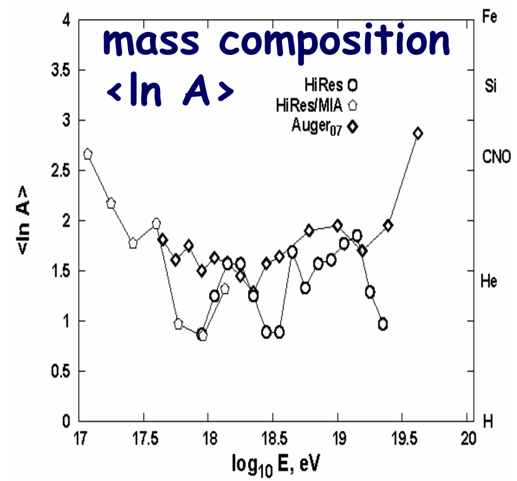


Anisotropy of ultra-high energy cosmic rays



58 events now (with Swift-BAT AGN density map)

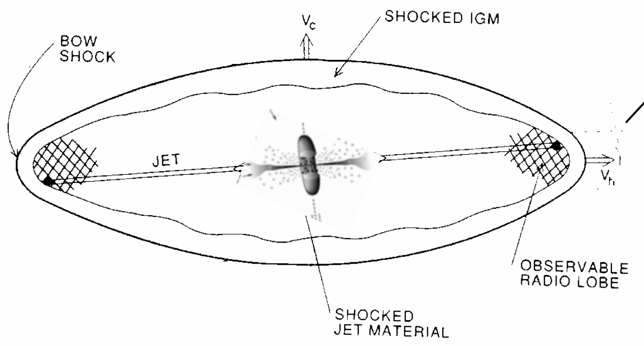
J.Aublin – Auger Coll., ICRC09



energy balance for extragalactic sources

- energetics
  10^{40} erg/(s Mpc^3)
  at present epoch, z = 0

SN	AGN jets	GRB	cluster accretion	in cosmic rays at $E > 10^{19.5}$ eV
3×10^{-1}	3	3×10^{-4}	10	3×10^{-4} (Auger)
mechanical	mechanical; 6×10^{-2} for jets with $L > 10^{44}$ erg/s	X/γ	mechanical	



Schematic diagram of overpressured cocoons around jets (Begelman & Cioffi 1989).

maximum energy of accelerated particles

Lovelace 1976, Biermann & Strittmatter 1987, Blandford 1993, Norman et al 1995, Waxman 1995, Farrar & Gruzinov 2009, Lemoine & Waxman 2009

$$\mathbf{E_{max} = Ze \times \beta \times B \times l}$$ - Hillas criterion

general electrodynamics estimate

$$L_{\rm jet} = \beta c \frac{B^2}{6\pi} \pi R^2$$ - power of magnetized flow

$$E_{\max} = Ze\left(\frac{6\beta}{c} L_{\rm jet}\right)^{1/2}$$

$$\approx \mathbf{2.7 \times 10^{20} Z\beta^{1/2} L_{jet,45}^{1/2}\ eV}$$

shock acceleration with Bohm diffusion

$$L_{jet} = 0.5\pi\rho u^3 R^2$$ proton-electron jet

$$w_{cr} = \eta_{cr}\rho u^2$$

$$B = (4\pi\beta w_{cr})^{1/2}$$ Bell 2004

$$E_{\max} = Ze\beta\left(\frac{8\eta_{cr}}{c} L_{jet}\right)^{1/2}$$

$$\approx \mathbf{1 \times 10^{20} Z\beta \left(\eta_{cr}/0.1\right) L_{jet,45}^{1/2}\ eV}$$

- very optimistic estimates of E_{max} for not ultrarelativistic jets

calculation of average CR production

in (cm³ s eV)$^{-1}$

efficiency

(A) $$q_p(E) = \xi_{cr} n_{jet} L_{jet} E^{-2} H(E_{max} - E)$$

number density

- **power law spectrum E^{-2} of individual jet,**
$E_{max} = E_* L_{jet,45}^{1/2}$

$$< q_p(E) >= \xi_{cr} E^{-2} \int_{(E/E_*)^2} P_{kin}(L_{jet,45}) \frac{dL_{jet,45}}{L_{jet,45}}$$

- **average spectrum**

in erg/s/Mpc³/log(L_{jet})

(B) $$q_d(E) = \xi_{cr} n_{jet} L_{jet} E_{max}^{-1} \delta(E - E_{max})$$

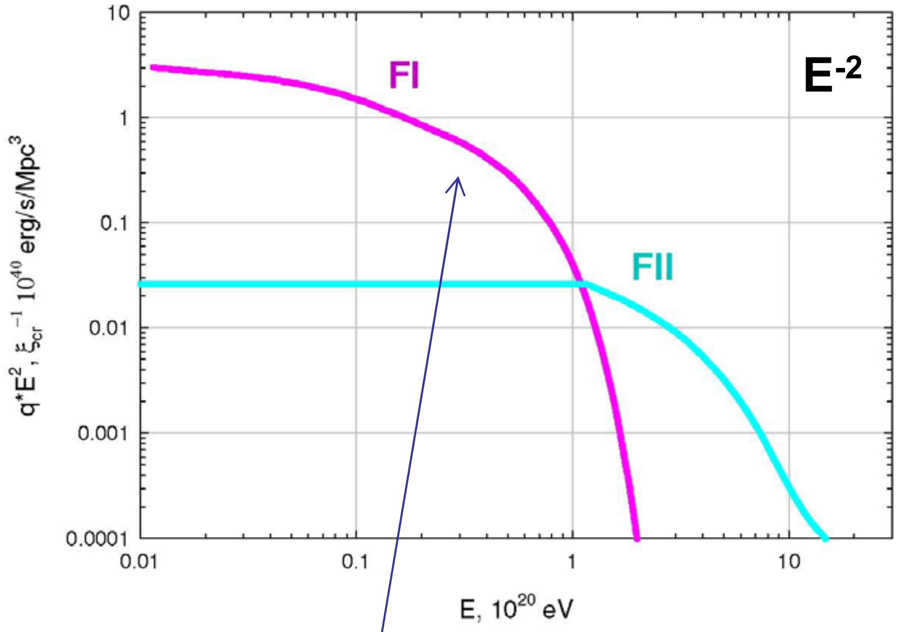
- **delta function spectrum of individual jet**

$$< q_d(E) >= 2\xi_{cr} E^{-2} P_{kin}\left(L_{jet,45} = \left(\frac{E}{E_*}\right)^2 \right)$$

- **average spectrum**

(A)

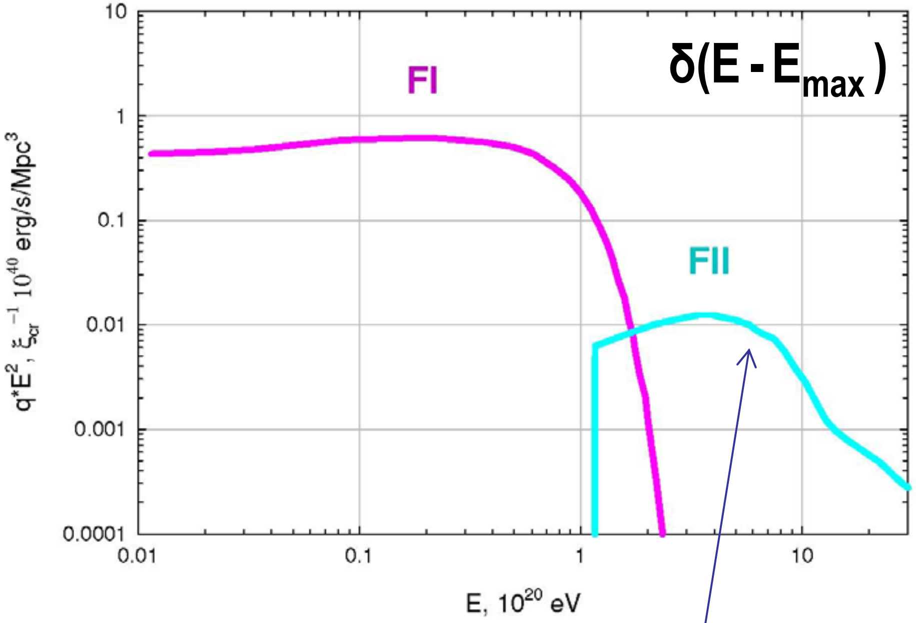
average proton source function <q> x E^2 for AGN jets with individual spectra $1/E^2$ and E_{max} = 2.7×10^{20} Z $L_{45}^{1/2}$ eV in units $\xi_{cr}^{-1} \times 10^{40}$ erg/s/Mpc^3



very steep

(B)

average proton source function <q> x E^2 for AGN jets with individual spectra $\delta(E - E_{max})$ and E_{max} = 2.7×10^{20} Z $L_{45}^{1/2}$ eV in units $\xi_{cr}^{-1} \times 10^{40}$ erg/s/Mpc^3



very limited ?

energy loss of ultra-high energy cosmic rays

microwave & EBL photons

- pair production $p\gamma \rightarrow pe^+e^-$
- pion production $p\gamma \rightarrow N\pi$

GZK cutoff at $E_{GZK} \sim 6{\times}10^{19}$ eV

Greisen 1966; Zatsepin & Kuzmin 1966

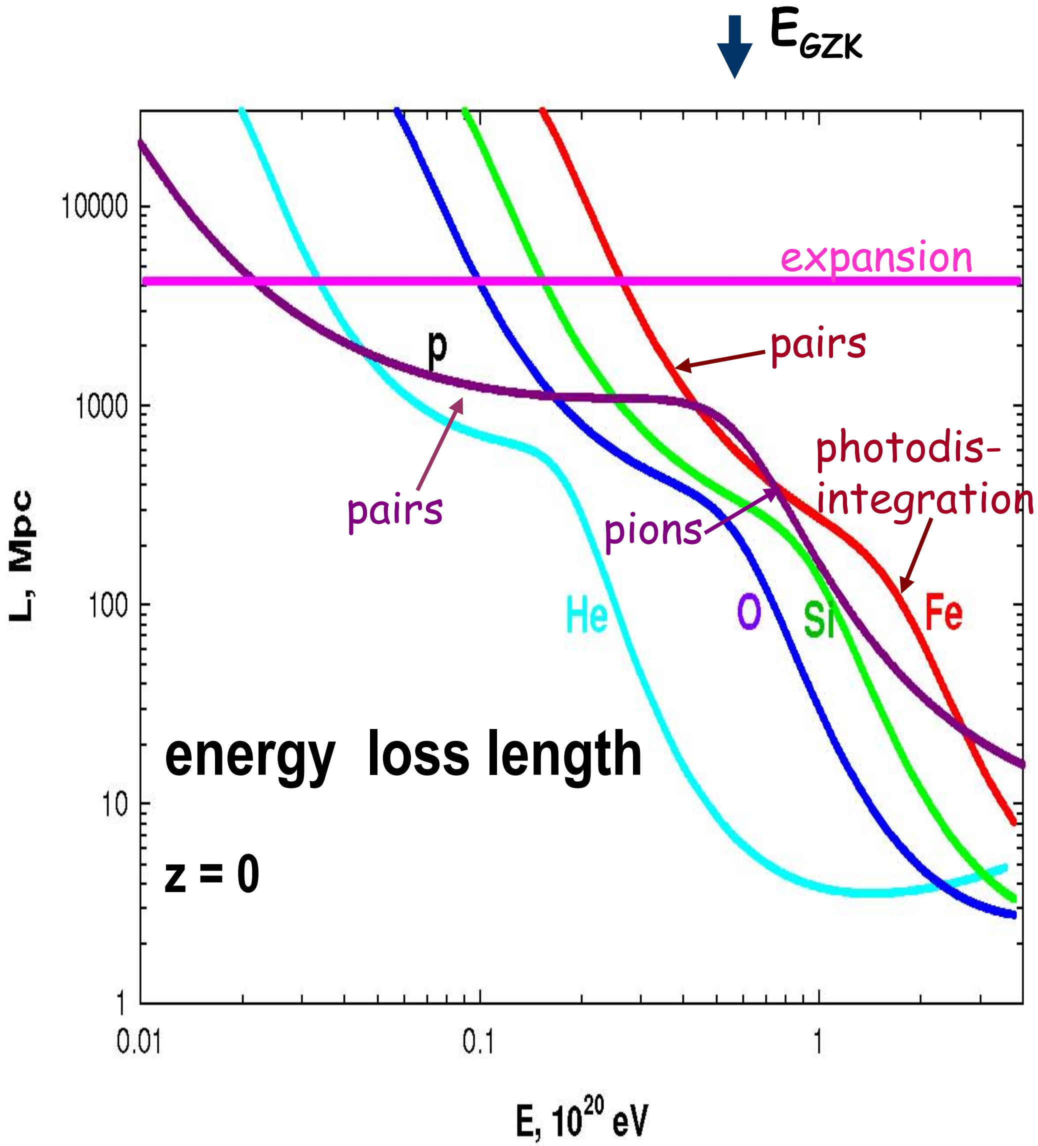
- photodisintegration of nuclei

Stecker 1969

- Universe expansion

$-\,(1/E)\,(dE/dt)_{adiabatic} = H$

H_0=100h km/(s Mpc), h=0.71



cosmic ray nuclei in expanding Universe

for homogeneous source distribution and arbitrary character of cosmic-ray propagation:

$$-H(z)(1+z)\frac{\partial}{\partial z}\left(\frac{F(A,\varepsilon,z)}{(1+z)^3}\right)-\frac{\partial}{\partial \varepsilon}\left(\varepsilon\left(\frac{H(z)}{(1+z)^3}+\frac{1}{\tau(A,\varepsilon,z)}\right)F(A,\varepsilon,z)\right)$$

$$+\nu(A,\varepsilon,z)F(A,\varepsilon,z)=\sum_{i=1,2...}\nu(A+i\rightarrow A,\varepsilon,z)F(A+i,\varepsilon,z)+<q(A,\varepsilon)>(1+z)^m$$

Ptuskin et al 1999

$F(A,\varepsilon,z)$ - cosmic ray distribution function, Z = 1 ... 26,

$\varepsilon = E/A$ - energy per nucleon,

z - redshift,

$q(A,\varepsilon)$ - source term at $z=0$, m describes source evolution,

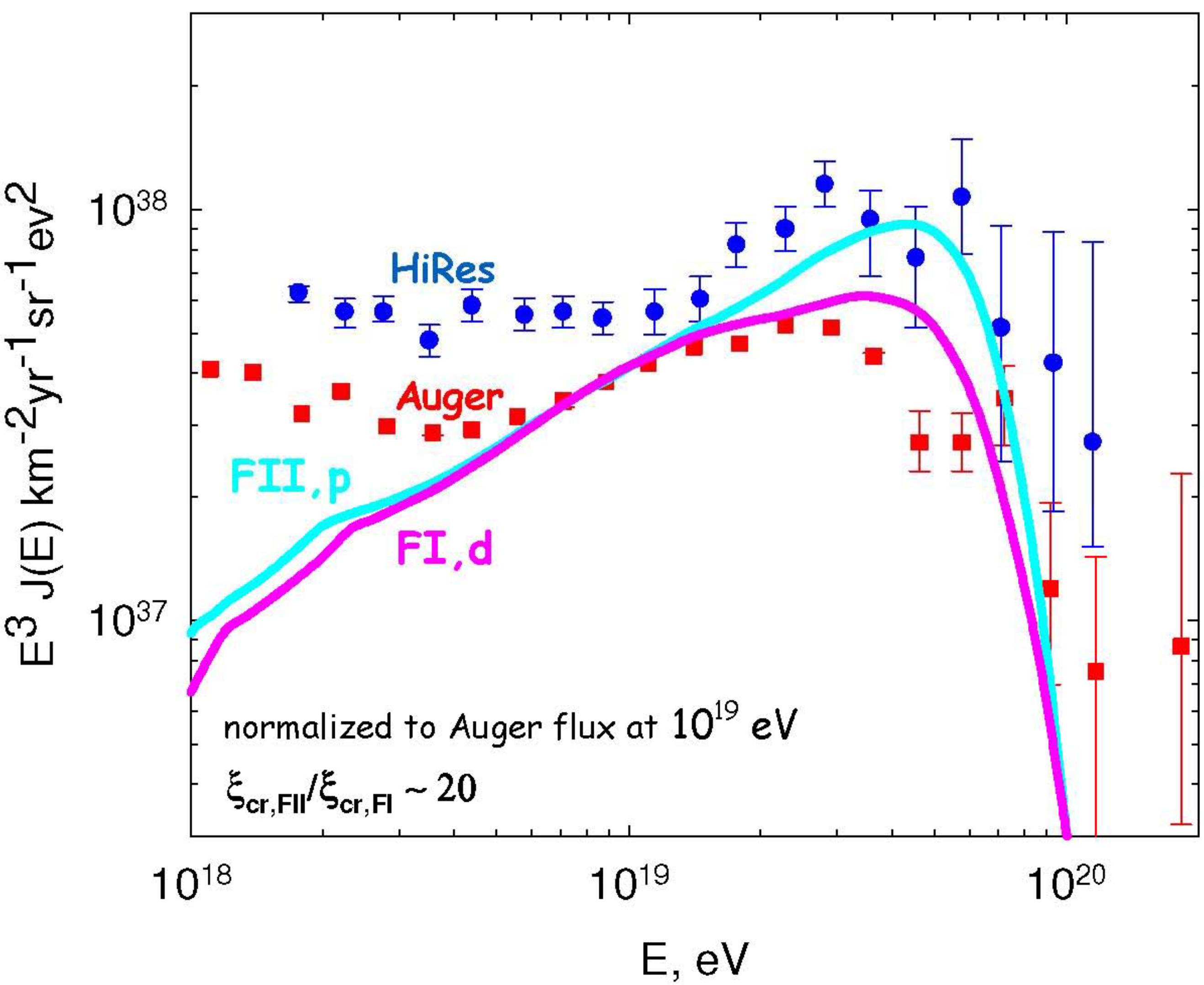
$\tau(A,\varepsilon,z)$ - energy loss time on e^+e^- and π^0 photoproduction,

$\nu(A,\varepsilon,z)$ - photodisintegration rate,

$H(z)=H_0\sqrt{(1+z)^3\Omega_m+\Omega_\Lambda}$ - Hubble constant (at $\Omega_m+\Omega_\Lambda=1$).

numerical solution by finite difference method **Godunov & Ryabenky 1977**

cross sections: **Puget et al 1976, Karakula & Tkaczyk 1993, Rachen 1996, Khan et al 2005**



CR spectra at the Earth produced by two populations of AGN jets at $E_* = 2.7\times10^{20}$ Z eV, $z_{max}= 2$, m = 0:
FI with source function (B) - pink line; FII with source function (A) – cyan line.
Source composition coincides with galactic CR source composition. HiRes & Auger data are shown.

Conclusion

Observed spectra of ultra-high energy cosmic rays can be produced or by the population of numerous low-luminosity AGN jets (L_{jet} < 10^{44} erg/s) with delta-function source spectra or by the population of rare high-luminosity AGN jets (FR II radiogalaxies & radioloud quasars, L_{jet} > 10^{44} erg/s) with power-law source spectra ~ E^{-2}.

Required efficiency of transformation of jet kinetic luminosity to cosmic rays is very different for these two AGN populations: $\frac{\xi_{cr,FI}}{\xi_{cr,FII}} \sim \frac{1}{30}$.