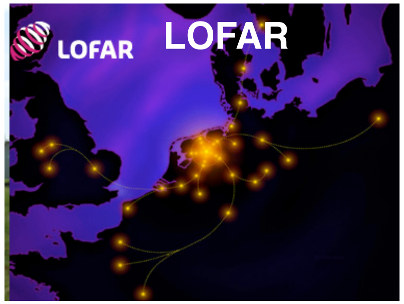
Schule für Astroteilchenphysik 2011

Universität Erlangen-Nürnberg

Aktuelle Ergebnisse zur kosmischen Strahlung



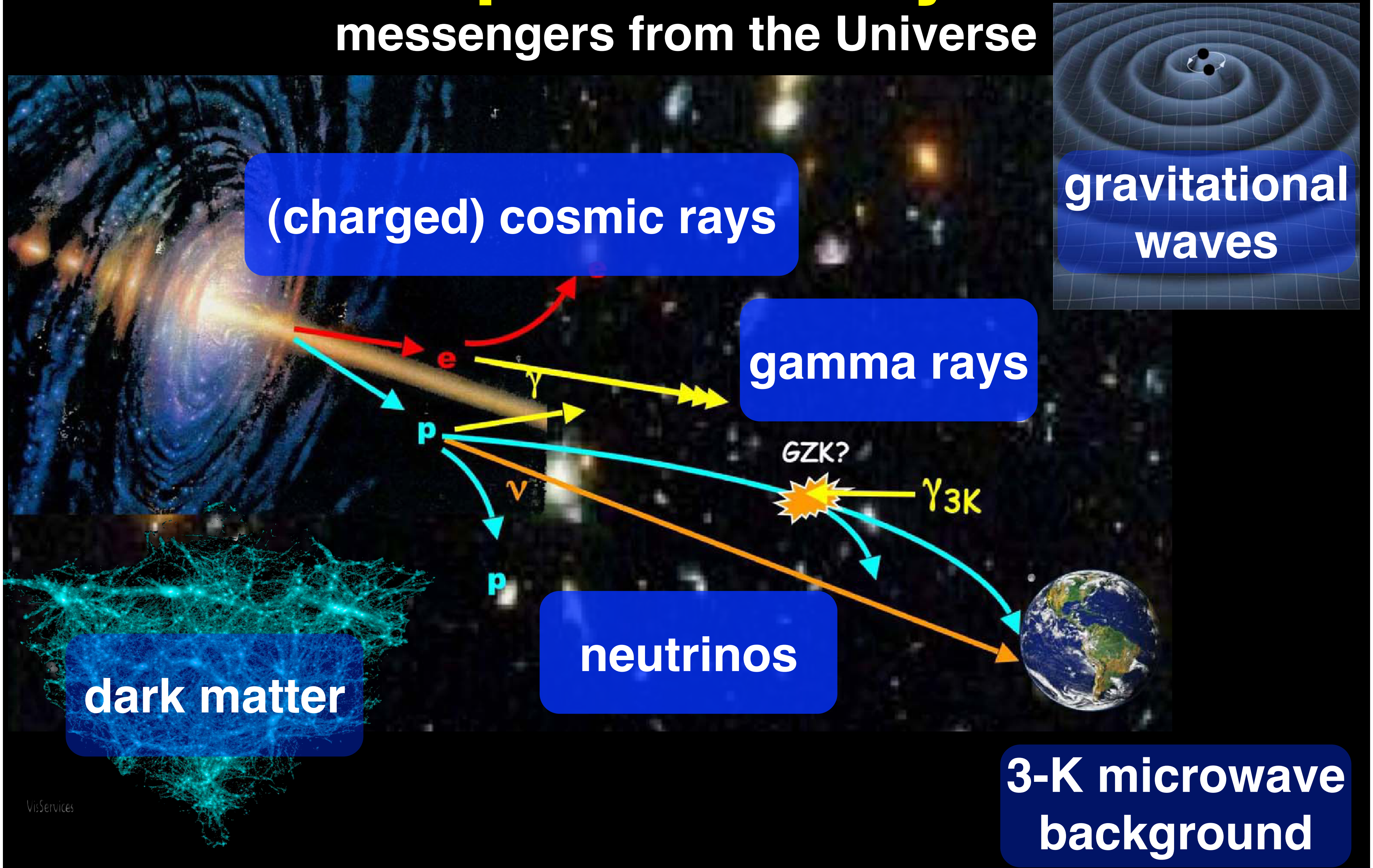
Jörg R. Hörandel

Radboud University Nijmegen

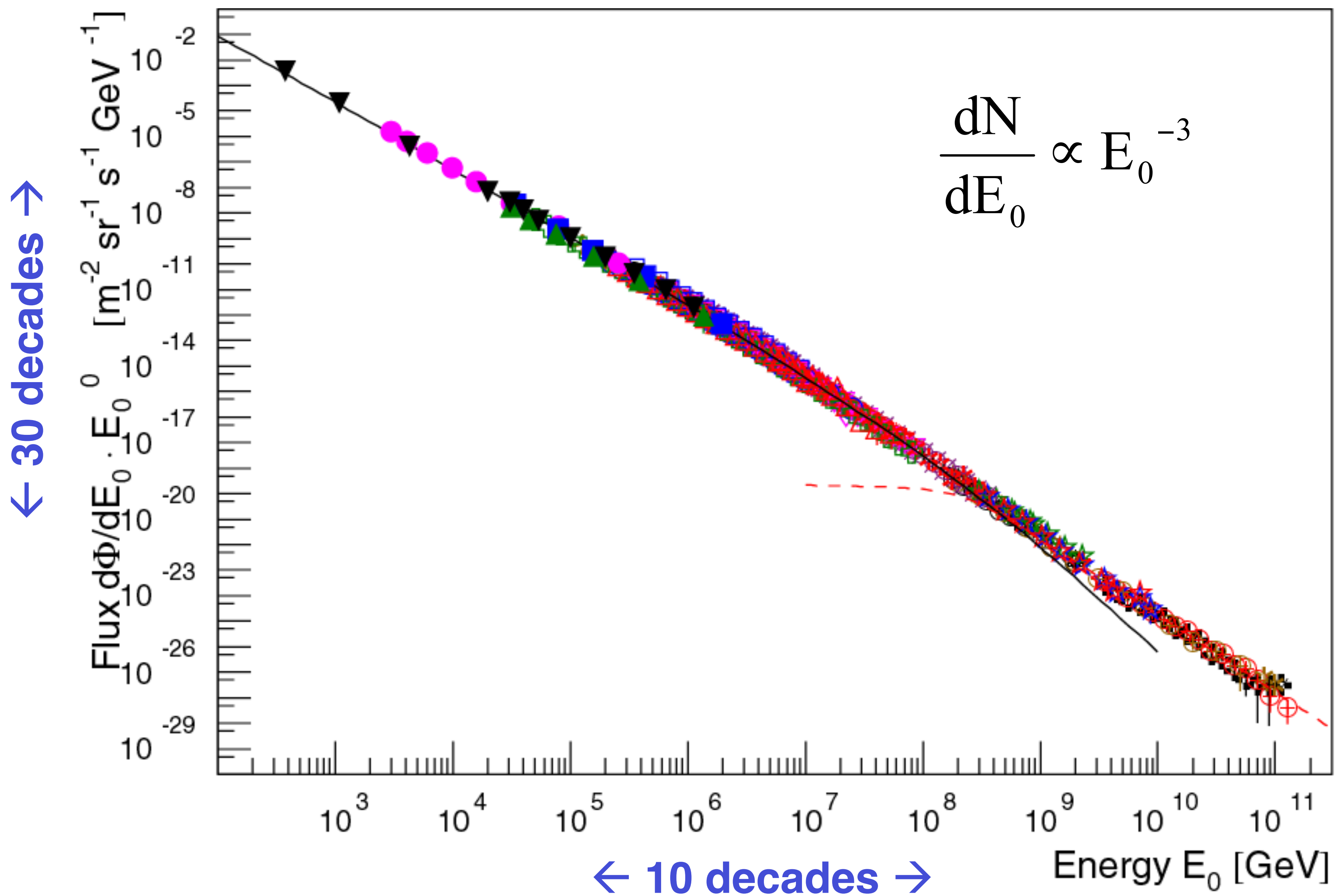
http://particle.astro.ru.nl

Astroparticle Physics

messengers from the Universe



Cosmic-Ray Energy Spectrum



Energy content of cosmic rays

energy density

$$\rho_E = \frac{4\pi}{c} \int \frac{E}{\beta} \frac{dN}{dE} dE \approx 1 \ \frac{\mathrm{eV}}{\mathrm{cm}^3}$$

for comparison:

$$\rho_B = \frac{B^2}{2\mu_0} \approx 0.25 \ \mathrm{eV/cm}^3$$

$$\rho_{SL} \approx 0.3 \ \mathrm{eV/cm}^3$$

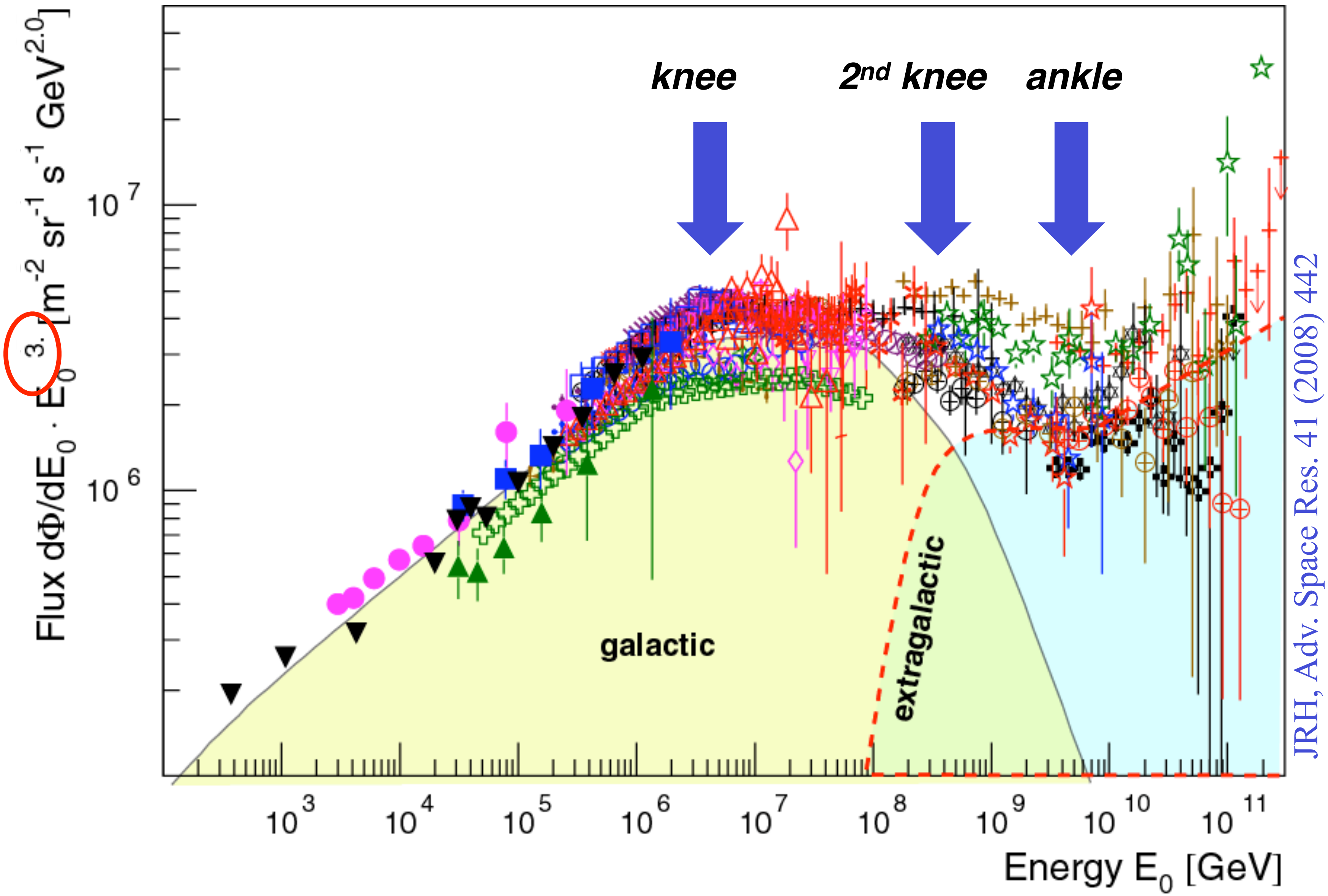
$$\rho_{IR} \approx 0.4 \ \mathrm{eV/cm}^3$$

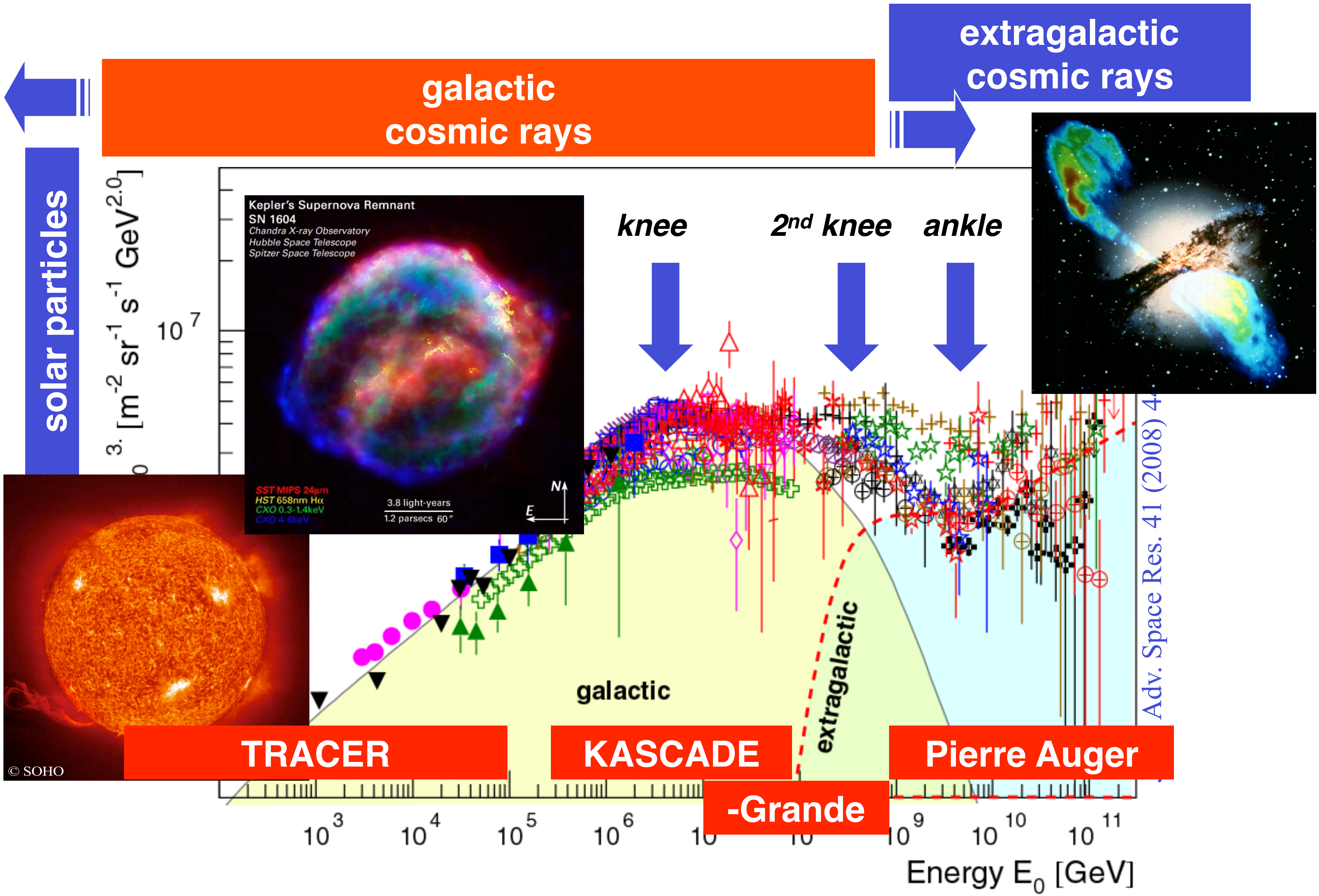
$$\rho_{3K} \approx 0.25 \ \mathrm{eV/cm}^3$$

power in (galactic) cosmic rays

$$L_{CR} = \frac{\rho_{CR} \cdot V_G}{\tau_{esc}} \approx 10^{41} \ \frac{\mathrm{erg}}{\mathrm{s}}$$

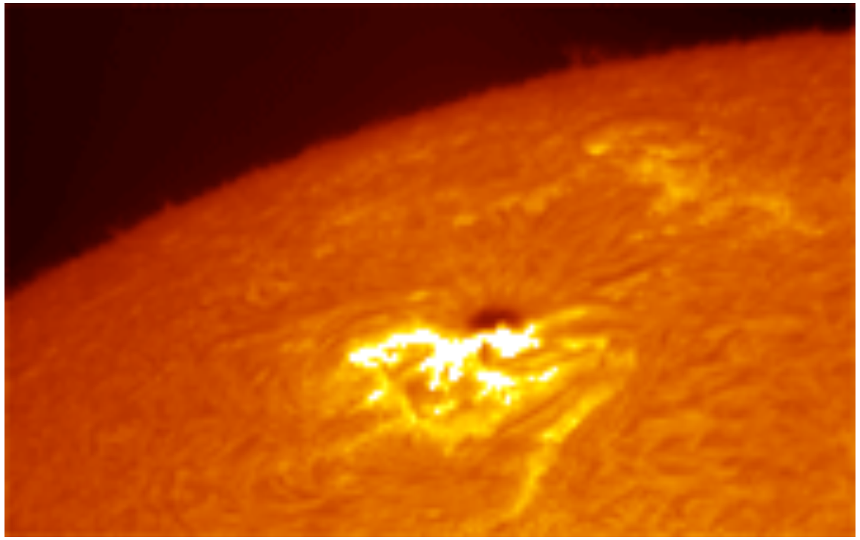
Cosmic-Ray Energy Spectrum

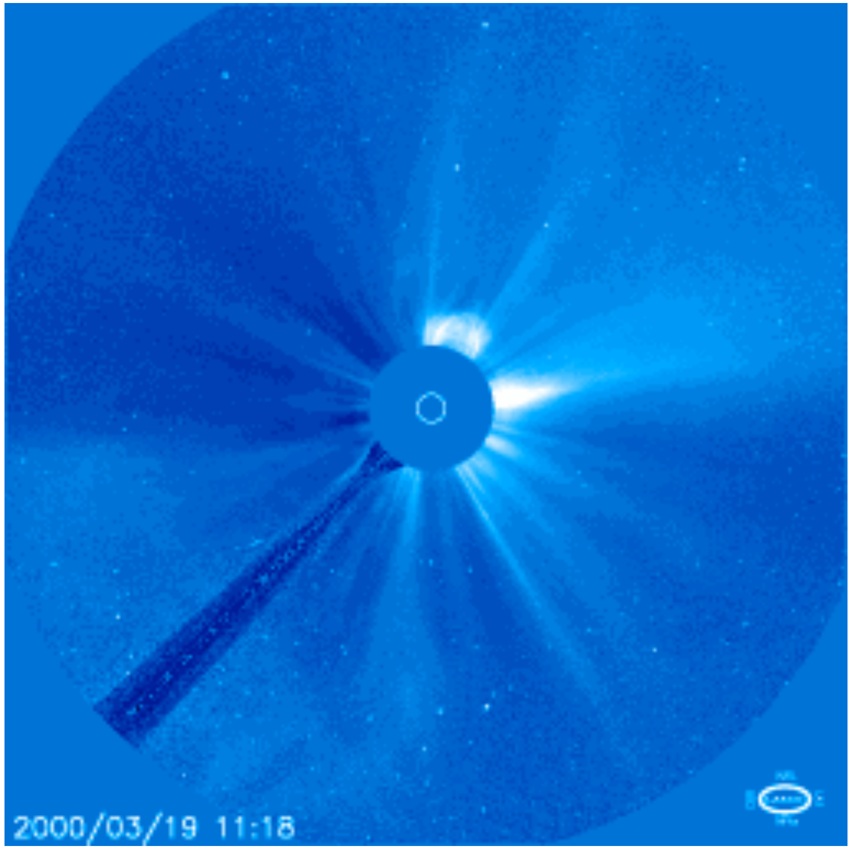


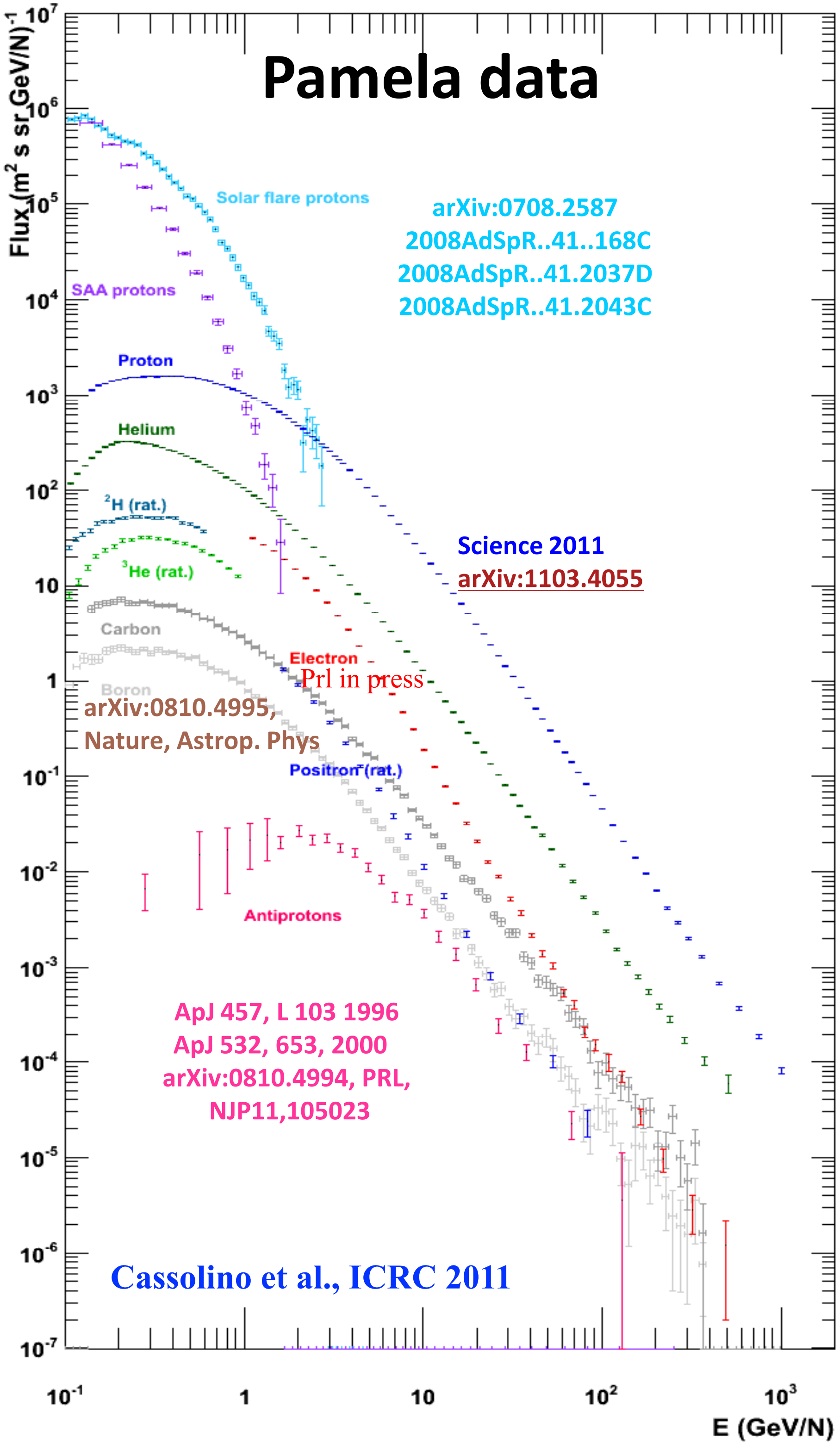


extragalactic
cosmic rays
galactic
cosmic rays
solar particles
Kepler's Supernova Remnant
SN 1604
Chandra X-ray Observatory
Hubble Space Telescope
Spitzer Space Telescope
3.8 light-years
1.2 parsecs 60″
knee
2nd knee
ankle
galactic
extragalactic
© SOHO
TRACER
KASCADE
-Grande
Pierre Auger
Energy E0 [GeV]
Adv. Space Res. 41 (2008)

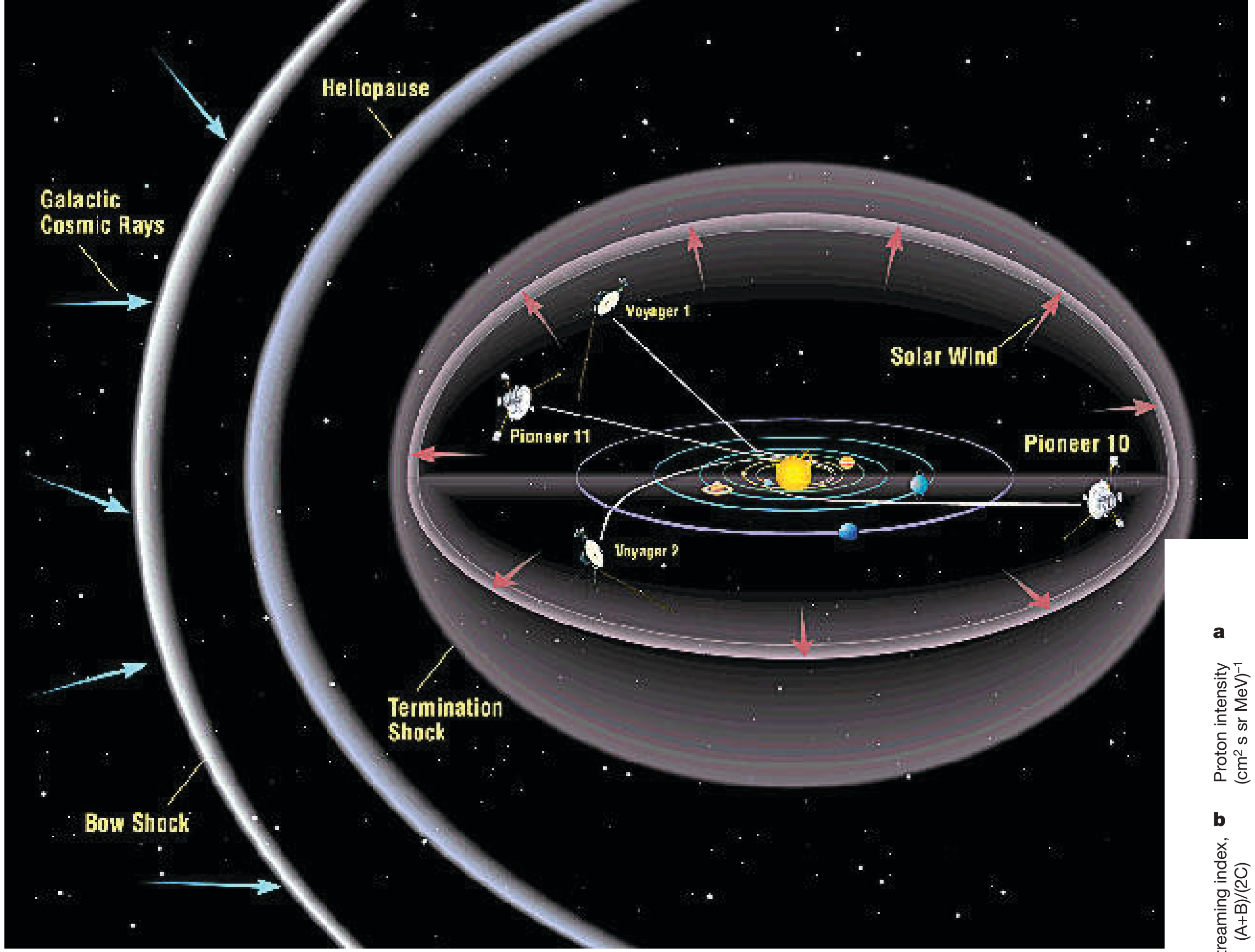
Solar flares







Galactic Cosmic Rays and the Heliosphere



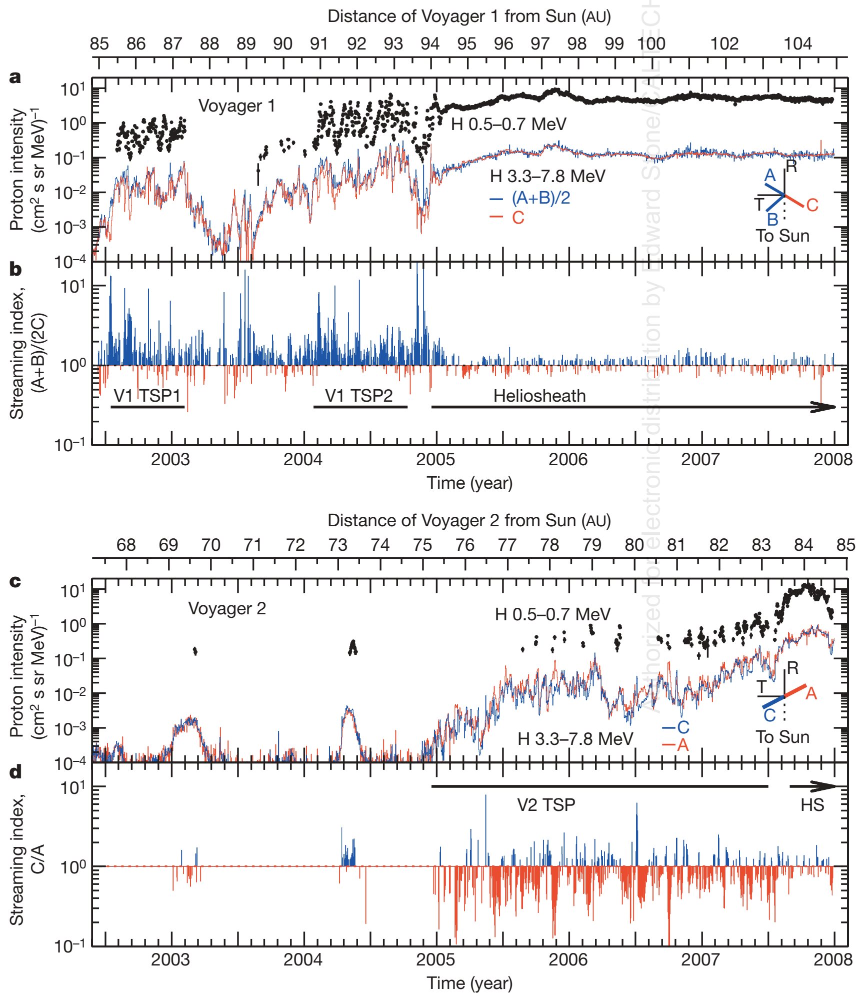
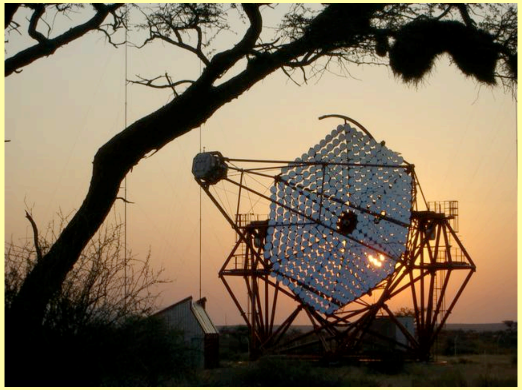
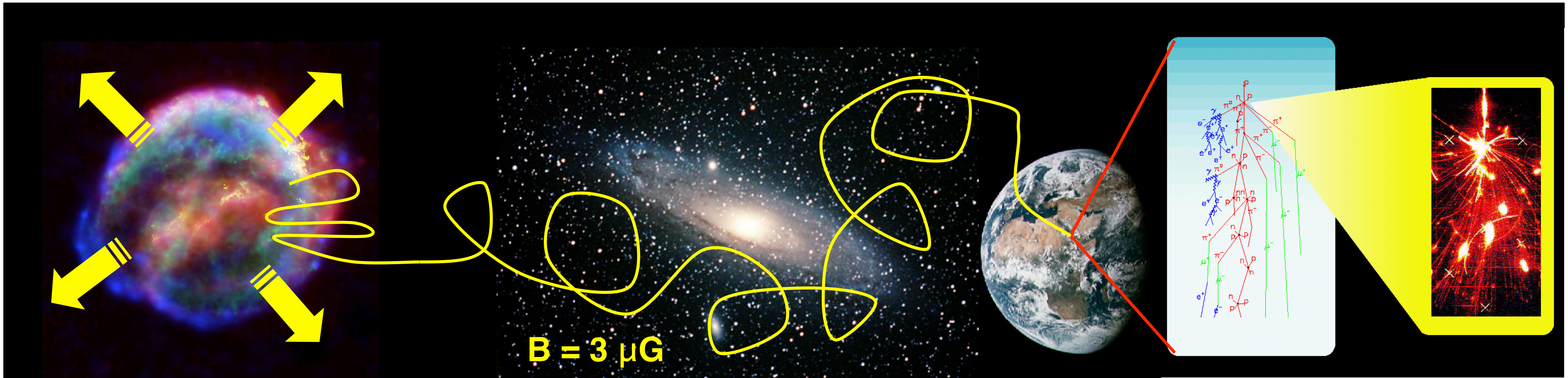


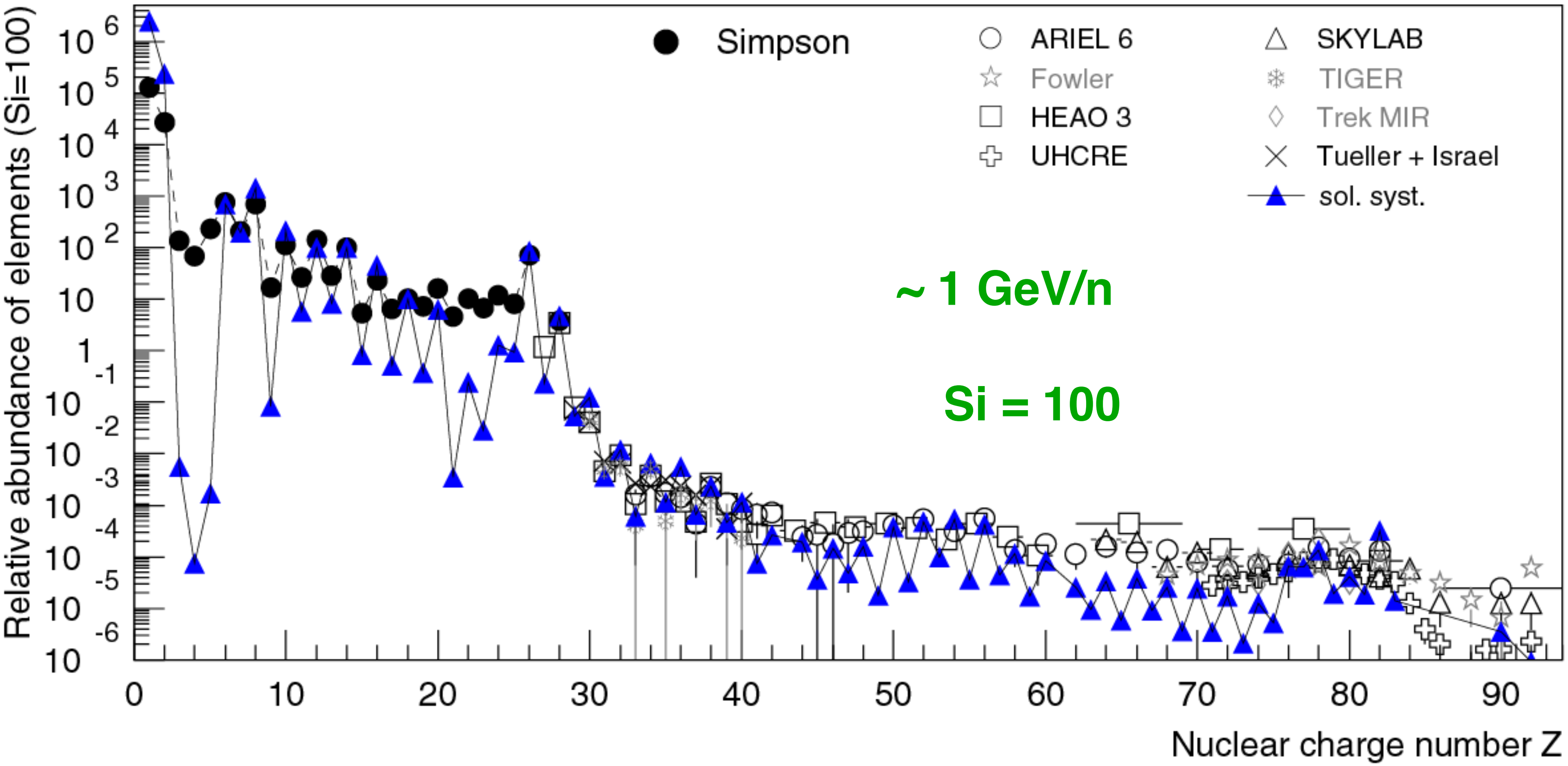
Figure 1 | Daily-averaged intensities and streaming of energetic termination shock particles that are accelerated at nearby regions of the shock. Voyager 1 and Voyager 2 crossed the shock and entered the heliosheath on 2004.96 (16 December 2004) at heliographic coordinates of (34.3°, 173°) and on 2007.66 (30 August 2007) at (−27.5°, 216°), respectively. Insets, telescope (A, B and C) viewing directions projected into the R–T plane, where −R is towards the Sun and T is azimuthal. Error bars on black filled circles, ±1s.d.

Origin of galactic cosmic rays
explored with complementary approaches

γ-ray astronomy	direct measurements above the atmosphere	air shower measurements
		
sources acceleration	elemental/isotopic composition propagation in Galaxy	structures in E-spec. end of gal. comp. anisotropy acceleration., propag.



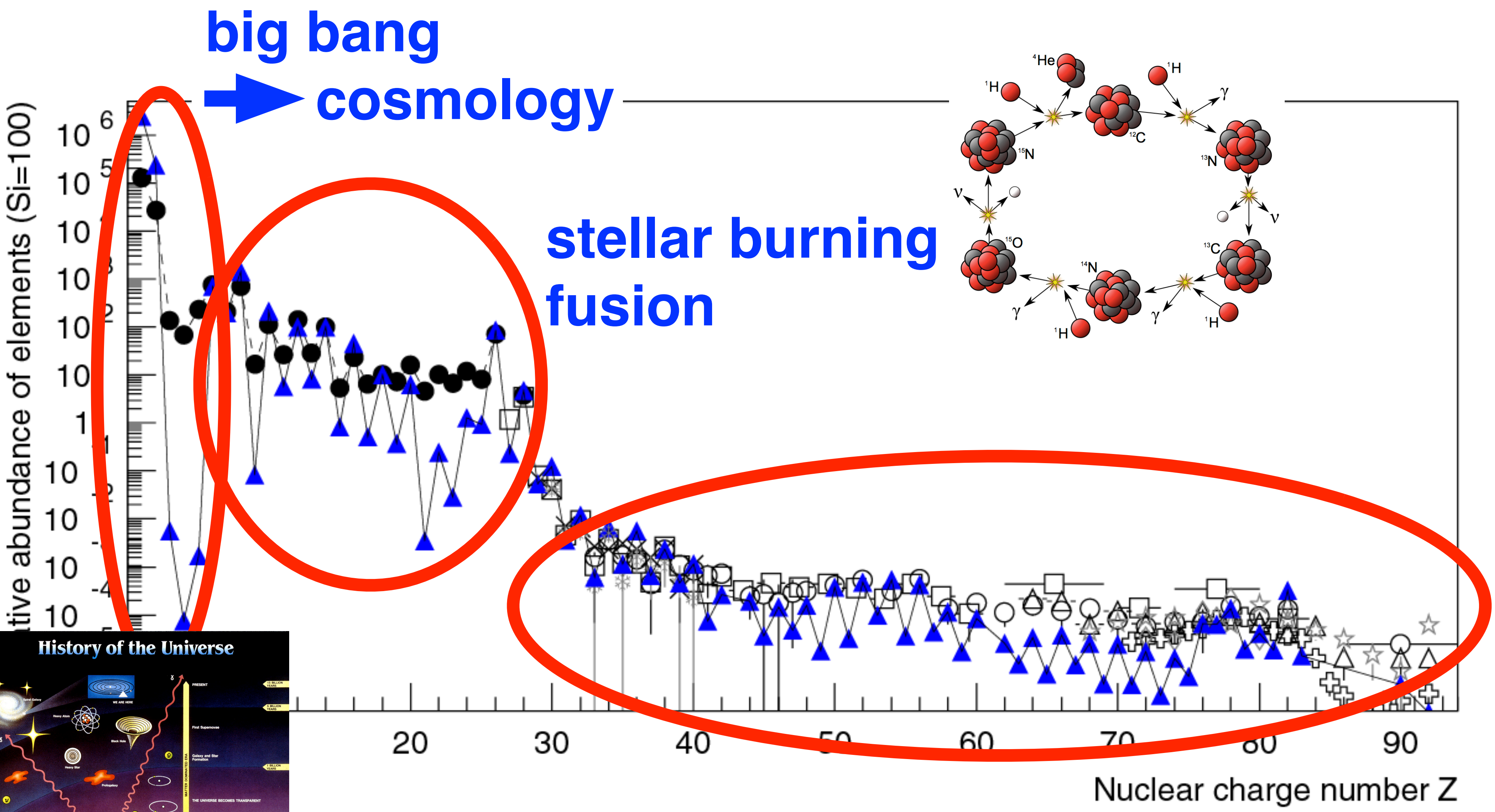
Relative abundance of elements at Earth

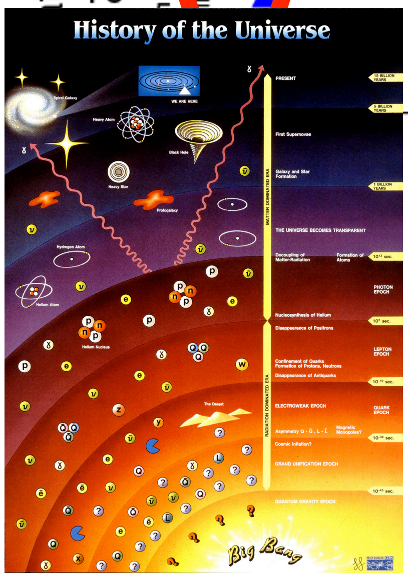


→Cosmic rays are „regular matter",
accelerated to extremely high energies

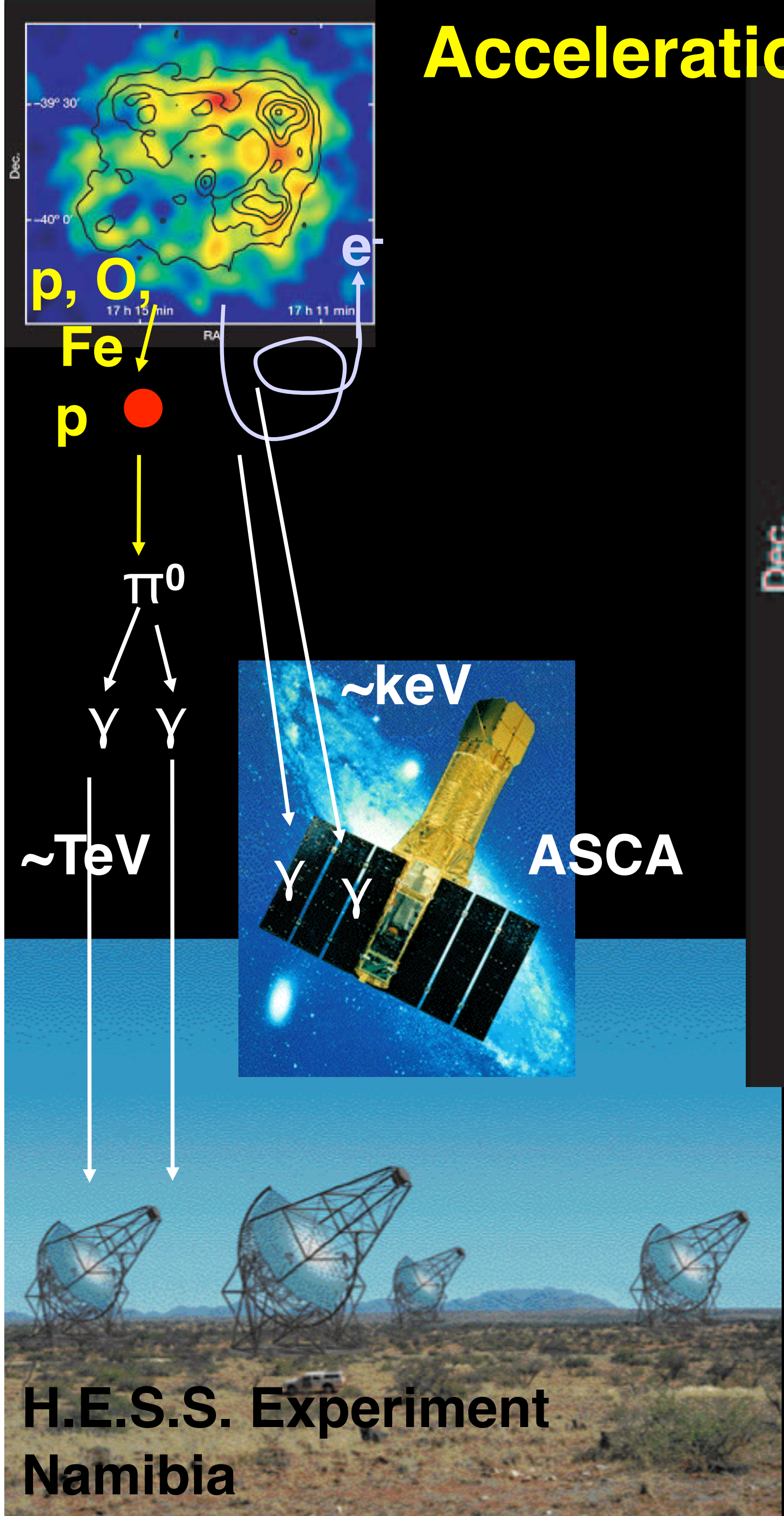
JRH, Adv. Space Res. 41 (2008) 442

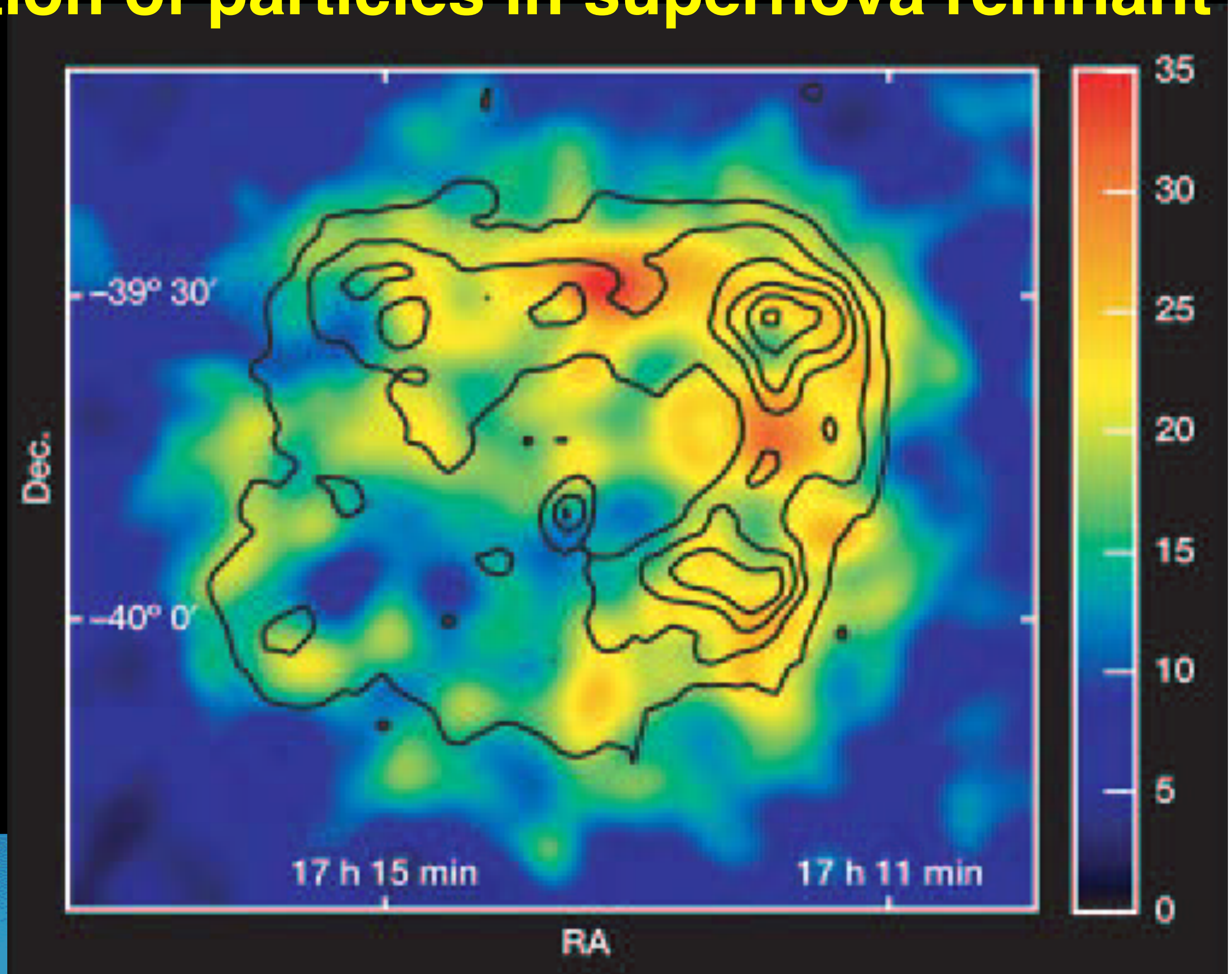
Origin of the Elements





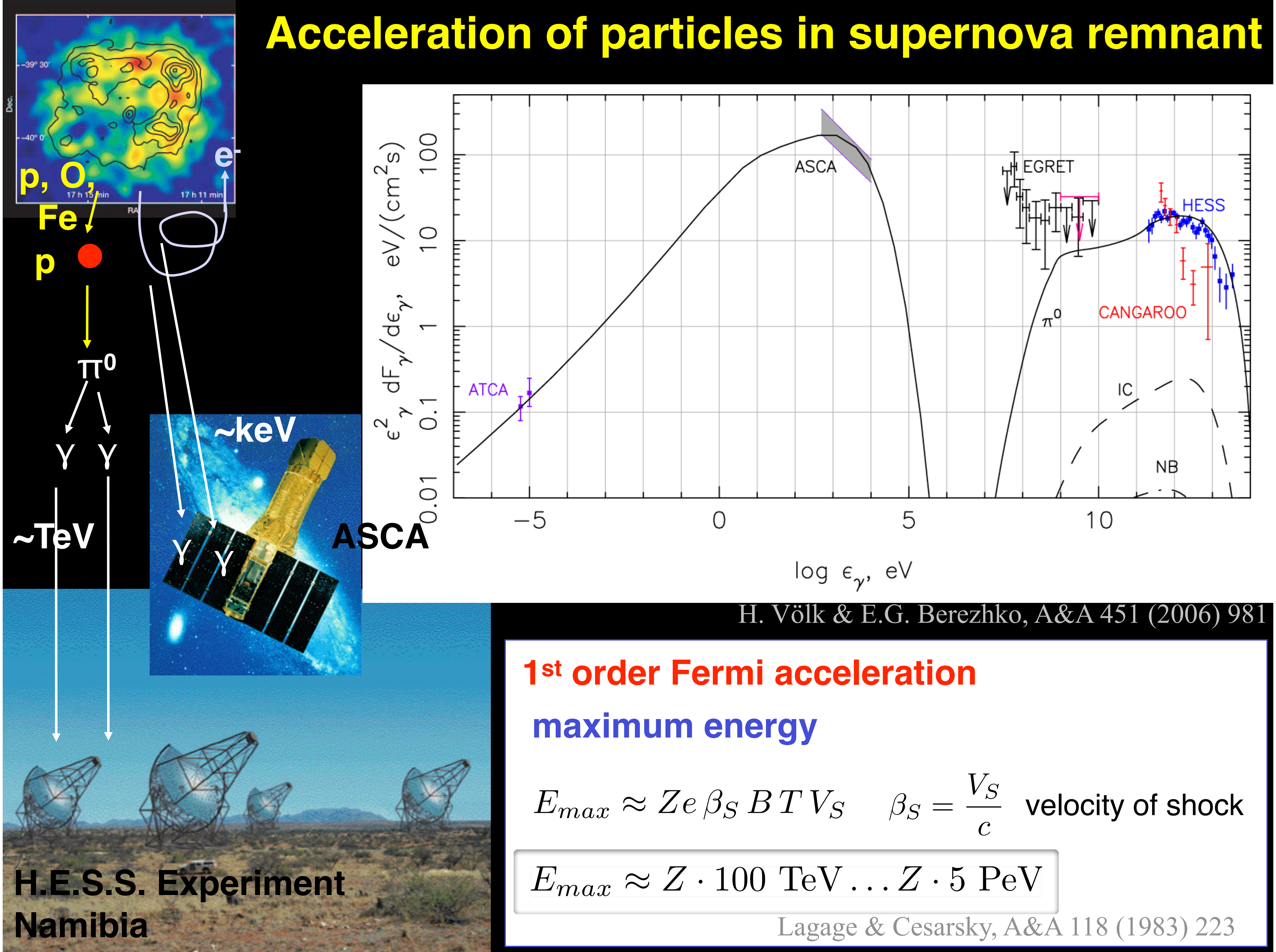
Acceleration of particles in supernova remnant





SN R RX J1713.7-3946
H.E.S.S.: TeV-Gamma rays
ASCA: X-rays (keV)

F.A. Aharonian, Nature 432 (2004) 75



$$E_{max} \approx Ze\,\beta_S\,B\,T\,V_S \qquad \beta_S = \frac{V_S}{c}$$

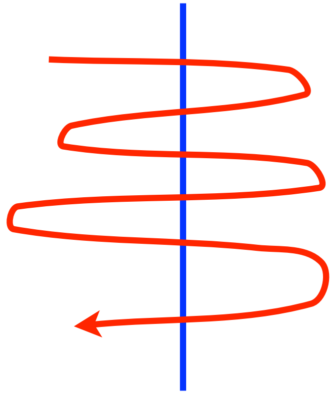
$$\boxed{E_{max} \approx Z \cdot 100\ \mathrm{TeV} \ldots Z \cdot 5\ \mathrm{PeV}}$$

Fermi acceleration

particle gains small amount of energy $E_1 = E_0 \cdot \xi$

after k interactions $E_k = E_0(1+\xi)^k$

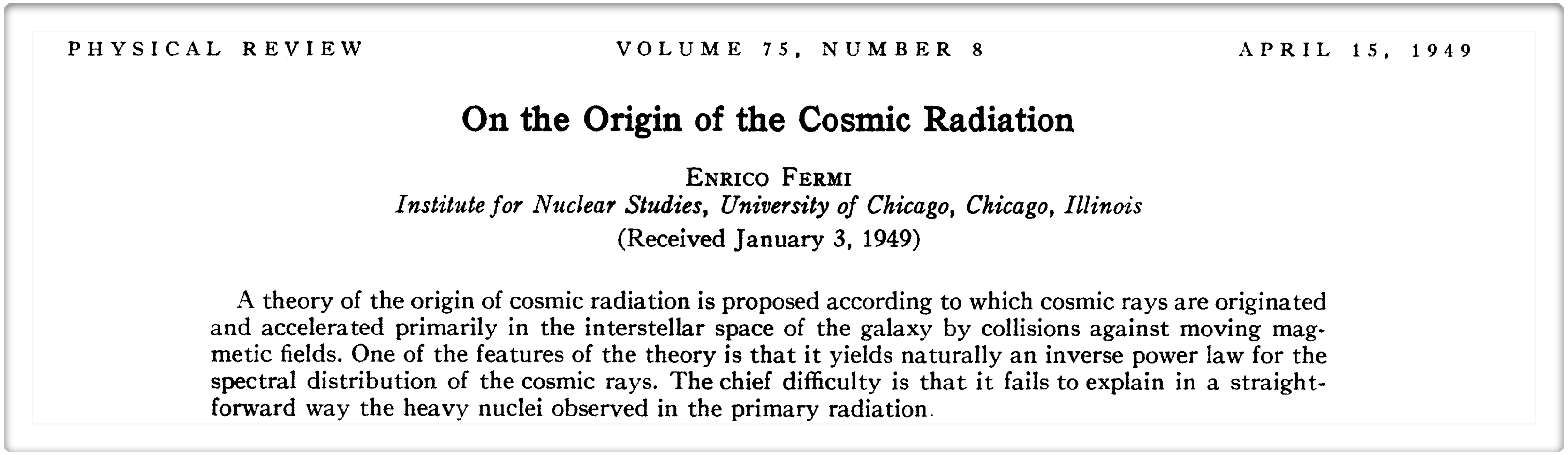
escape probability P$_{esc}$ $N_k = N_0 \cdot P_{esc}^k$



$$k = \frac{\ln(E_k/E_0)}{\ln(\xi+1)} = \frac{\ln(N_k/N_o)}{\ln P_{esc}}$$

$$\boxed{\frac{N_k}{N_0} = \left(\frac{E_k}{E_0}\right)^{\frac{\ln P_{esc}}{\ln(\xi+1)}}}$$

power law

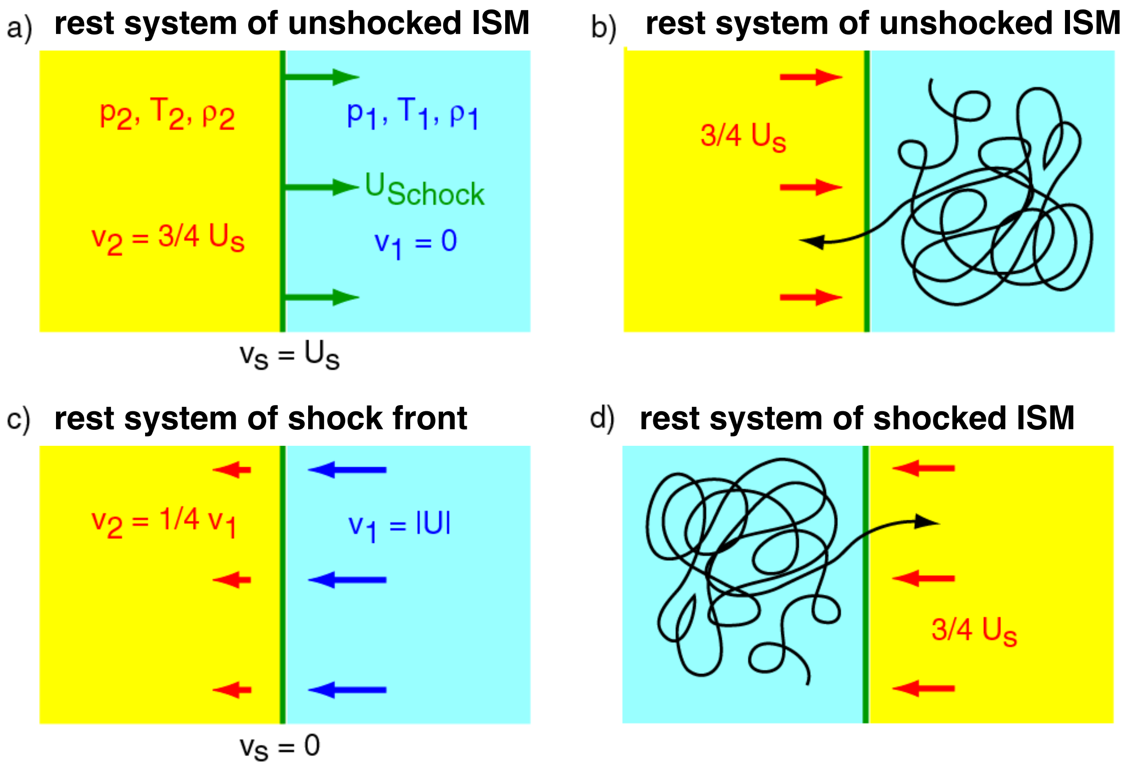

PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 1949

On the Origin of the Cosmic Radiation

Enrico Fermi
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 3, 1949)

A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magnetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

1st order Fermi acceleration at strong shock

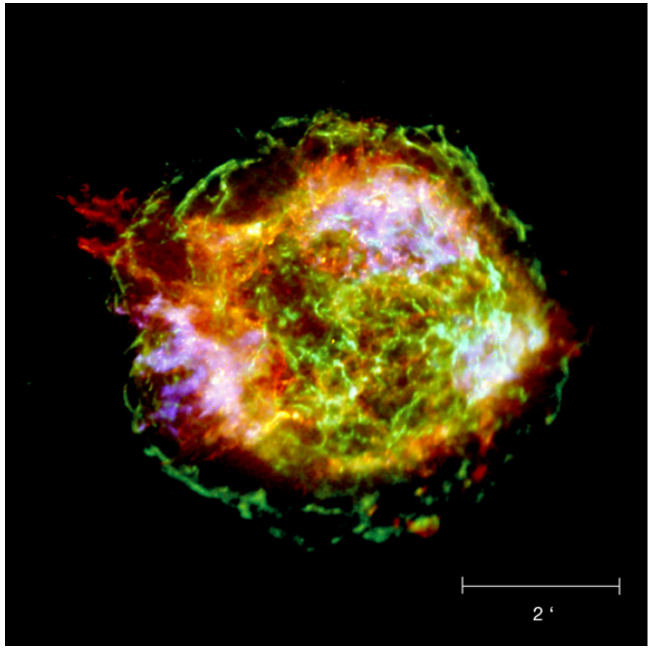


Bell, Blanford,Ostriker (1978)

energy gain $\dfrac{\Delta E}{E} \propto \dfrac{U_s}{c}$

$$\Rightarrow \quad N(E)\,dE \propto E^{-2}\,dE$$

power law with spectral index -2.0 ... -2.1



Supernova remnant (SNR) Cassiopeia A

Transport equation for cosmic rays in the Galaxy

diffusion

energy loss (Bethe Bloch)

loss through interactions with ISM (spallation)

loss through radioactive decay

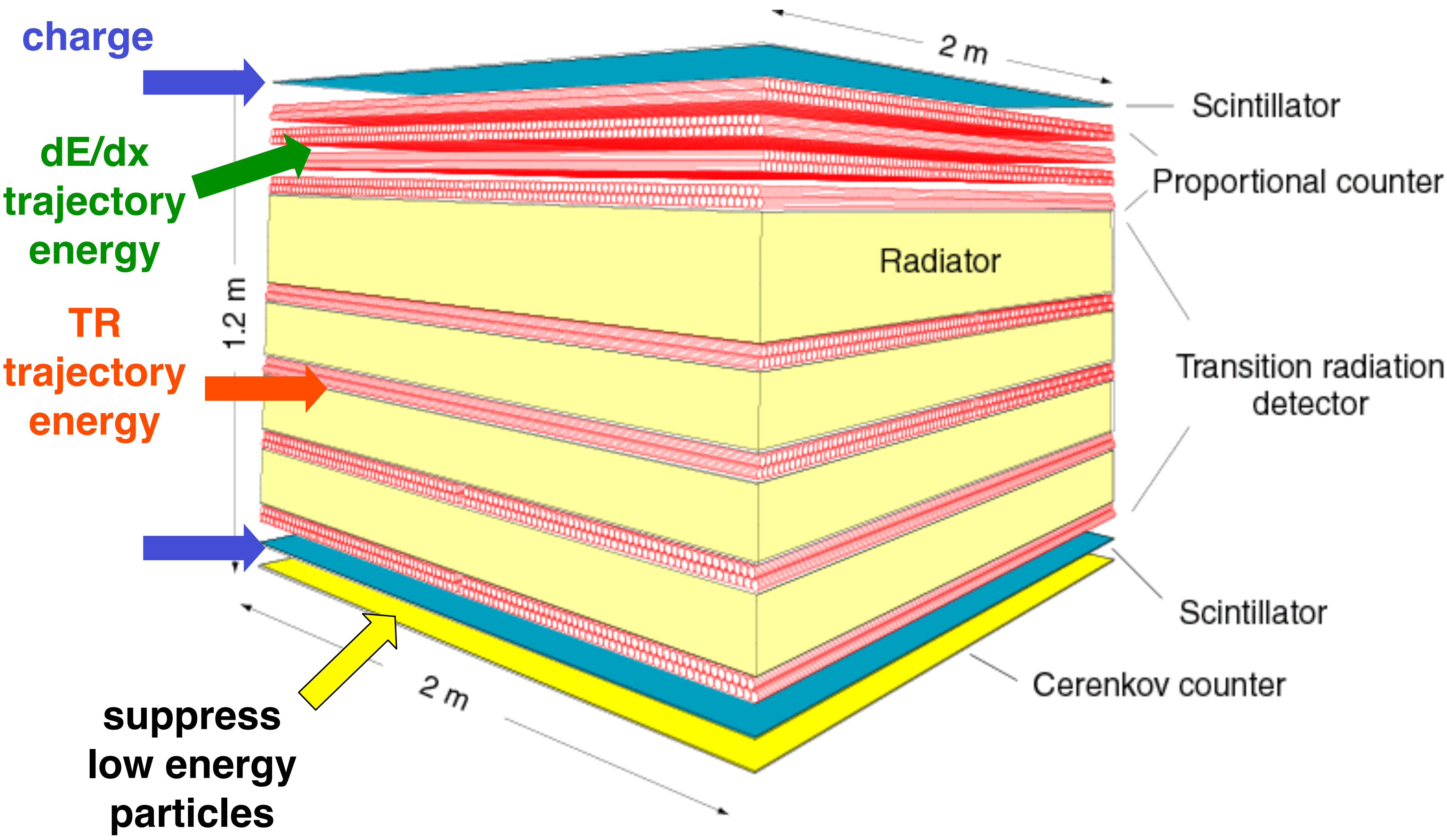
$$\frac{\partial N_i}{\partial t} = \nabla(D_i \nabla N_i) - \frac{\partial}{\partial E}(b_i N_i) - n\nu\sigma_i N_i - \frac{N_i}{\gamma\tau_i} + Q_i + \sum_{j>i} n\nu\sigma_{ij} N_j + \sum_{j>i} \frac{N_j}{\gamma_j \tau_{ij}}$$

source term

production through spallation of heavy neulcei

production through decay of heavy nuclei

Transition Radiation Array for Cosmic Energetic Rays

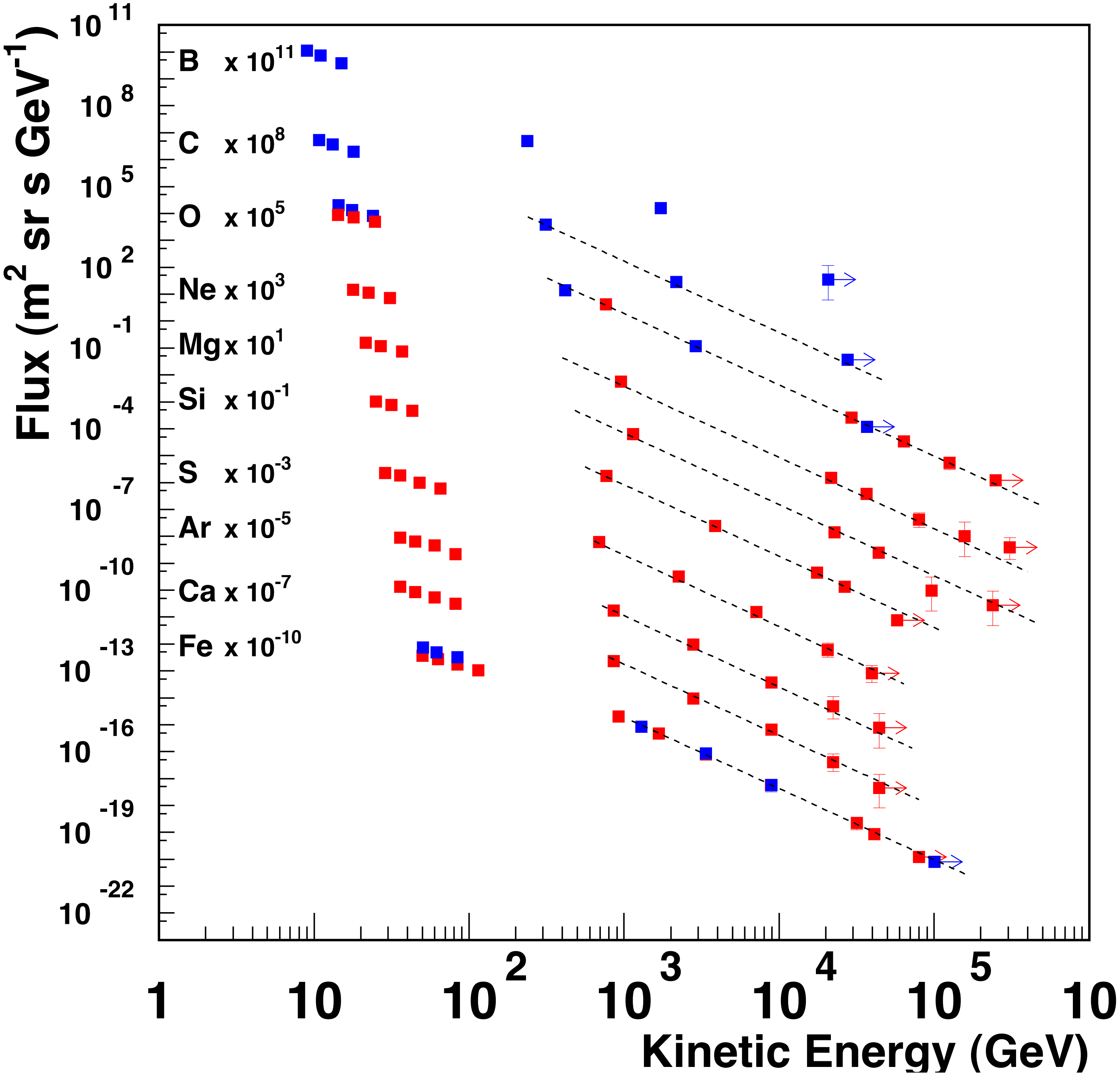


Geometric factor: 5 m² sr

1600 proportional tubes total


SOUTHERN OCEAN
FALKLAND ISLANDS (UK)
South Orkney Is.
Scotia Sea
ARGENTINA
Weddell Sea
South Shetland Is.
Larsen Ice Shelf
Ronne Ice Shelf
CHILE
Antarctic Penin.
Alexander I.
ANTARCTICA
KERGUELEN (Fr.)
HEARD & MCDONALD ISLANDS (Austr.)
Amery Ice Shelf
Vinson Massif 4897 m
South Pole
Thurston I.
INDIAN OCEAN
Mt. Kirkpatrick 4528 m
Ross Ice Shelf
Roosevelt I.
Ross Sea
SOUTHERN OCEAN
Balleny Is.
PACIFIC OCEAN
MACQUARIE I. (Austr.)
CAMPBELL IS. (N.Z.)
AUCKLAND IS. (N.Z.)
ANTIPODES IS. (N.Z.)
AUSTRALIA
NEW ZEALAND
60°
70°
80°
100°
120°
140°
160°

TRACER: Energy spectra for individual elements



P. Boyle et al., ICRC 2011

TRACER: propagation of cosmic rays

Leaky-Box Propagation Parameters

- Continuity equation:

$$N_i(E) = \frac{1}{\Lambda_{esc}(E)^{-1} + \Lambda_i^{-1}} \times \left(\frac{Q_i(E)}{\beta c \rho} + \sum_{k>i} \frac{N_k}{\lambda_{k \to i}} \right)$$

- Source Spectrum:

$$Q_i(E) = n_i \cdot E^{-\alpha}$$

- Escape Path Length:

$$\Lambda_{esc}(E) = CE^{-\delta} + \Lambda_0$$

- Spallation Path Length:

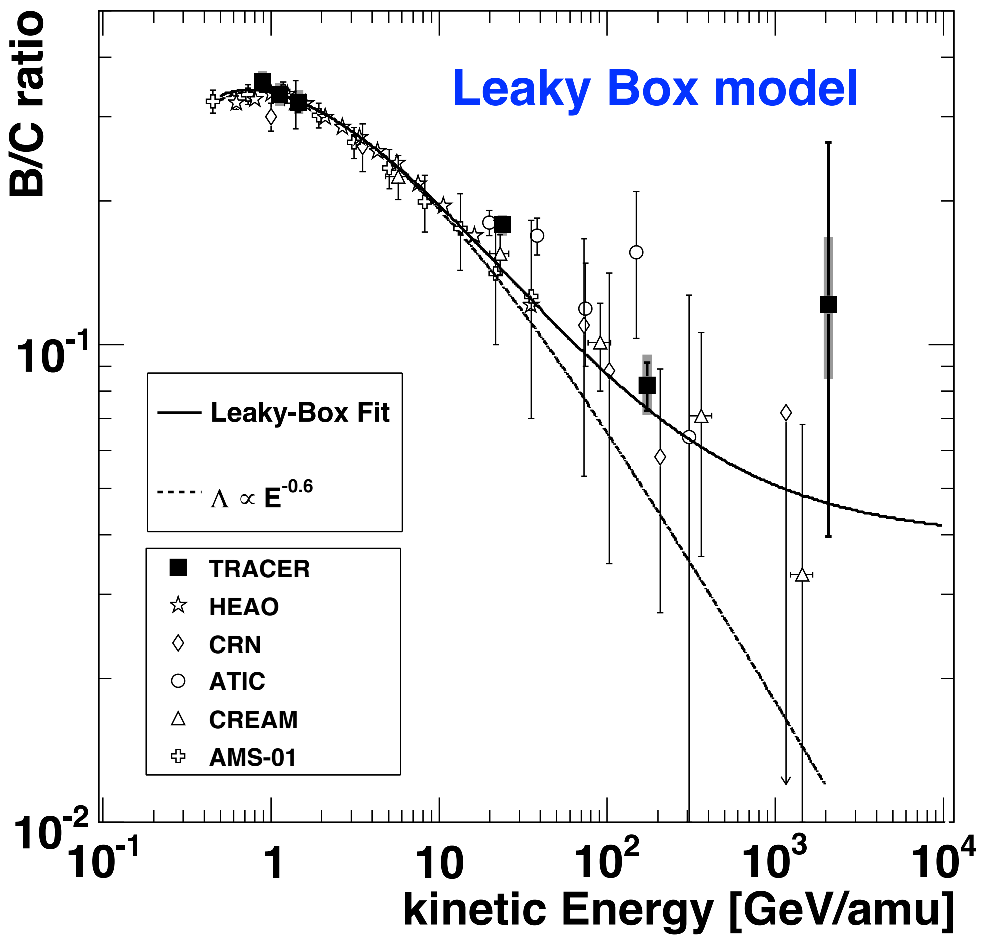
$$\Lambda_i = \frac{m}{\sigma(A)}$$

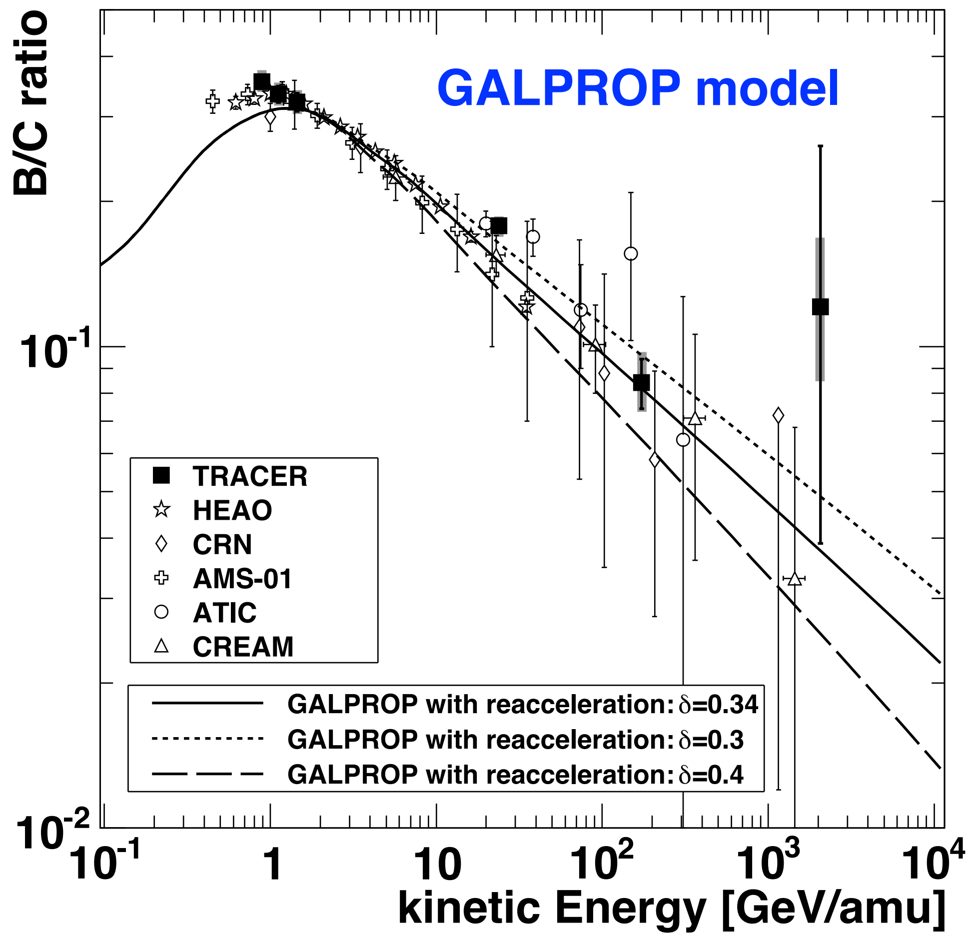
Boron to Carbon ratio

$$\frac{N_B}{N_C} = \frac{\lambda_{\to B}^{-1}}{\Lambda_{esc}(E)^{-1} + \Lambda_B^{-1}}$$

A. Obermeier et al., ICRC 2011

TRACER: propagation of cosmic rays





Escape Path Length:

$$\Lambda_{esc}(E) = CE^{-\delta} + \Lambda_0$$

- Propagation index: $\delta = 0.64 \pm 0.02$.
- Residual path length: $\Lambda_0 = 0.7 \pm 0.2$ g/cm^2.

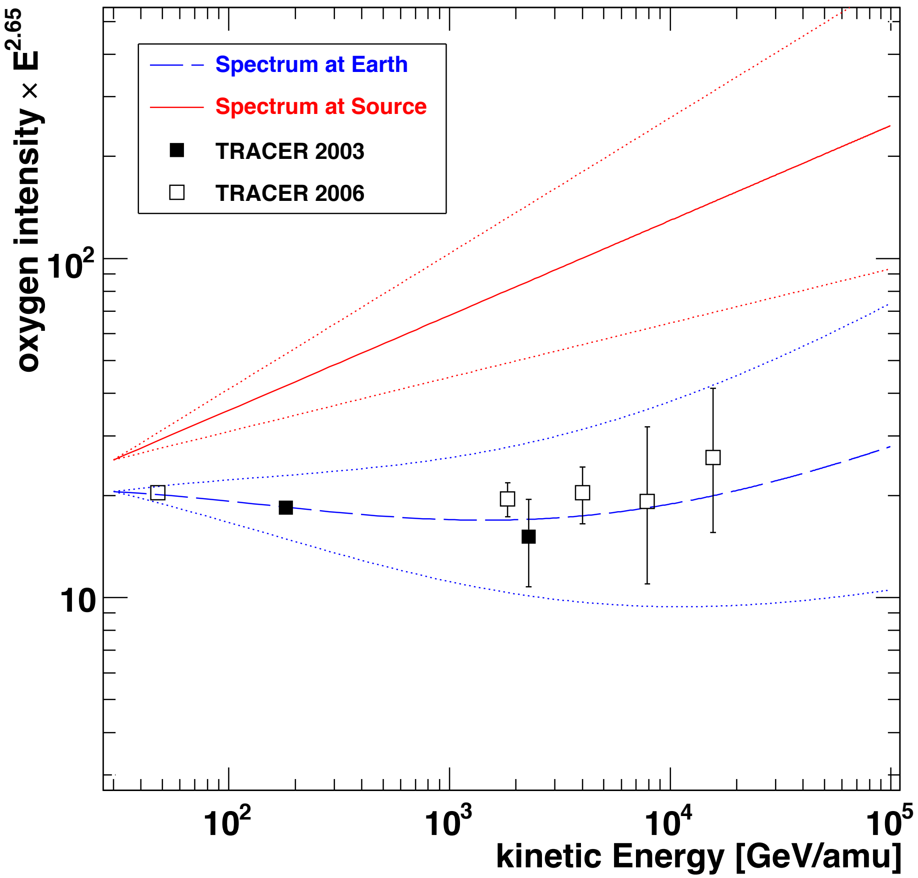
- Diffusion Index: $\delta = 0.34$.
- **Source index:** $\alpha = 2.34$.

A. Obermeier et al., ICRC 2011

TRACER: propagation of cosmic rays

The Source Spectrum

- Fit to TRACER oxygen data.
- $\delta = 0.64$, $\Lambda_0 = 0.7$ g/cm^2



- Free parameter: α.
- Source spectrum: power law.

Result

- Source index: $\alpha = 2.37 \pm 0.12$.

- Agrees with previous results.
- Model predicts spectrum at Earth may not be a power law (Λ_0).

A. Obermeier et al., ICRC 2011

Pathlength vs. interaction length

pathlength in Galaxy $\lambda_{esc} = 5 - 10 \ \mathrm{g/cm^2}$

interaction length

nuclear radius $r = r_0 A^{1/3} \qquad r_0 = 1.3 \cdot 10^{-13} \ \mathrm{cm}$

cross section $\sigma_{p-A} = \pi (r_p + r_0 A^{1/3})^2$

ISM: protons $n = 1/\mathrm{cm^3} \quad \rho = 1.67 \cdot 10^{-24} \ \mathrm{g/cm^3}$

interaction length

$$\lambda_{p-A} = \frac{\rho}{\sigma_{p-A} \cdot n}$$

$$\lambda_{p-p} = 21 \ \mathrm{g/cm^2}$$

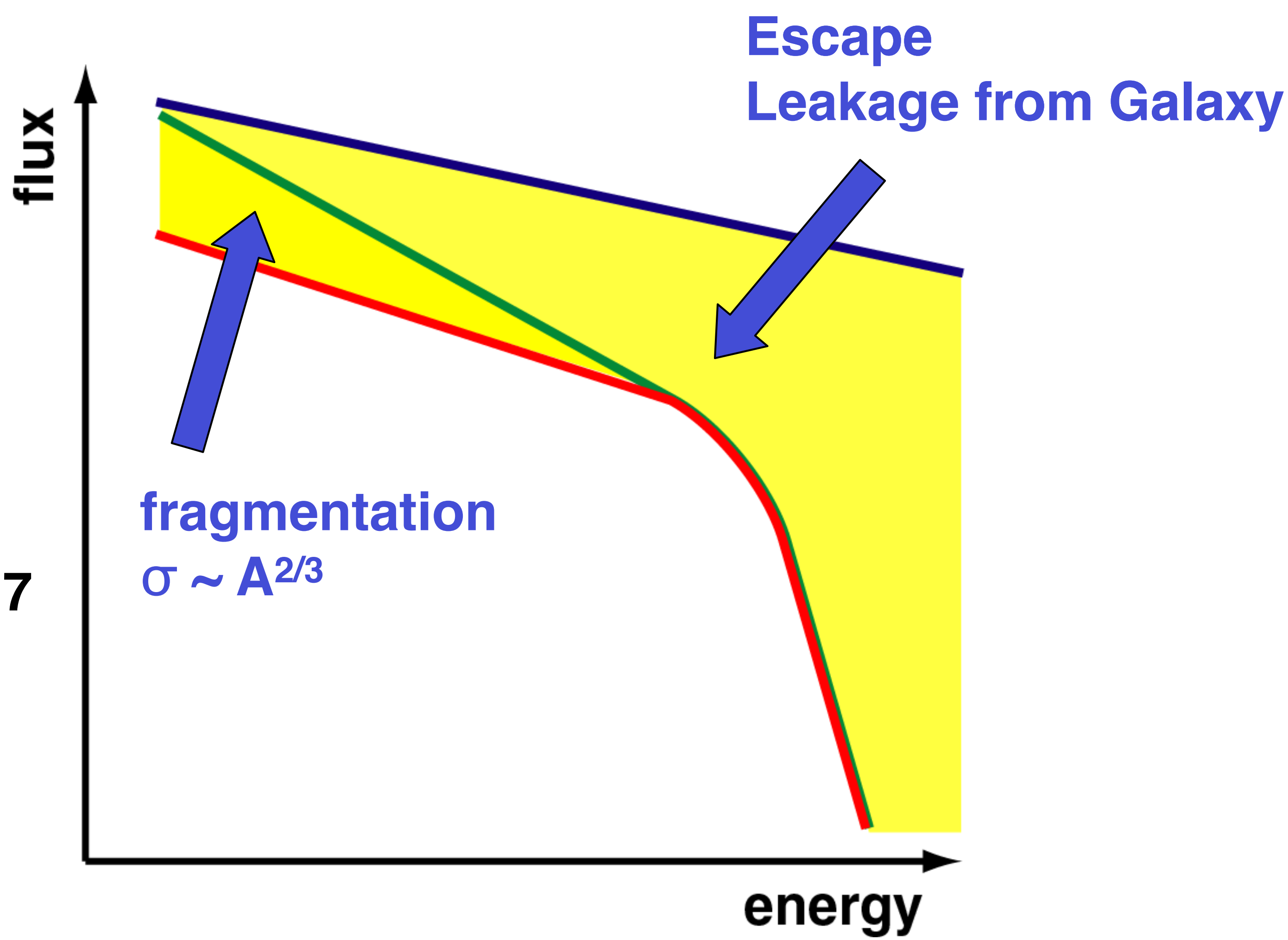
$$\lambda_{p-Fe} = 1.6 \ \mathrm{g/cm^2}$$

Shape of energy spectrum

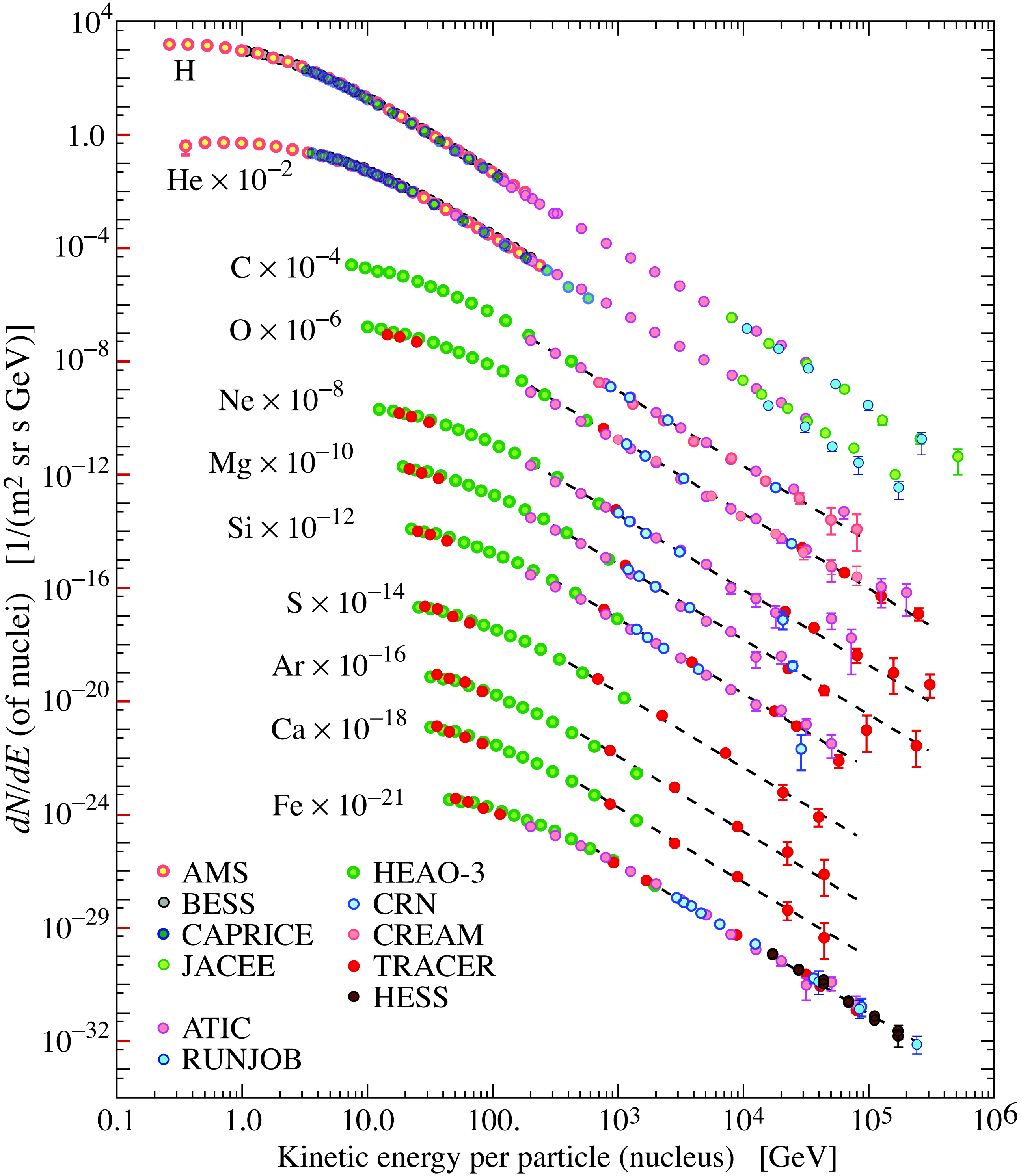
$$\frac{dN}{dE} \propto E_0^{\gamma}$$

at source $\gamma \sim -2.1$

at Earth $\gamma \sim -2.6$ to -2.7

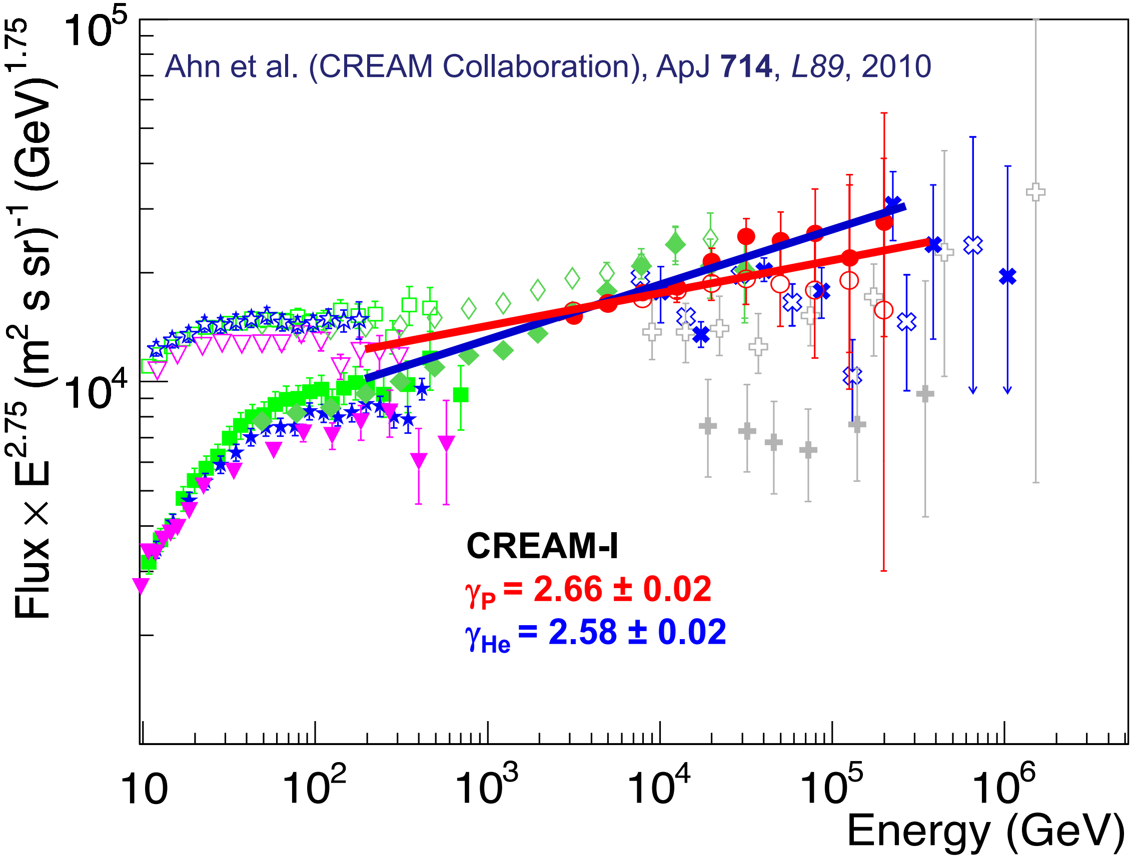


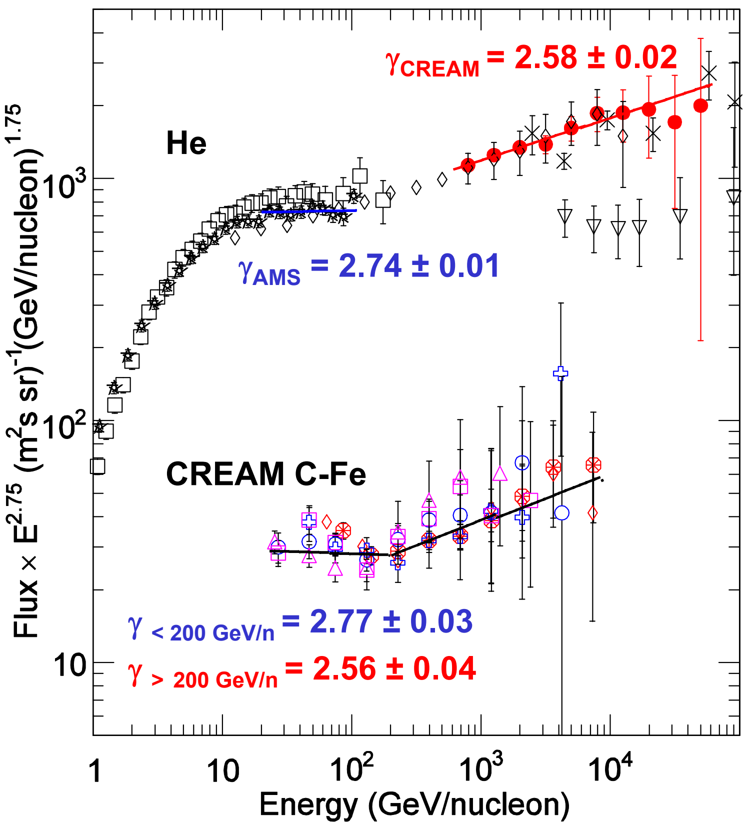
Energy spectra of main elements in cosmic rays



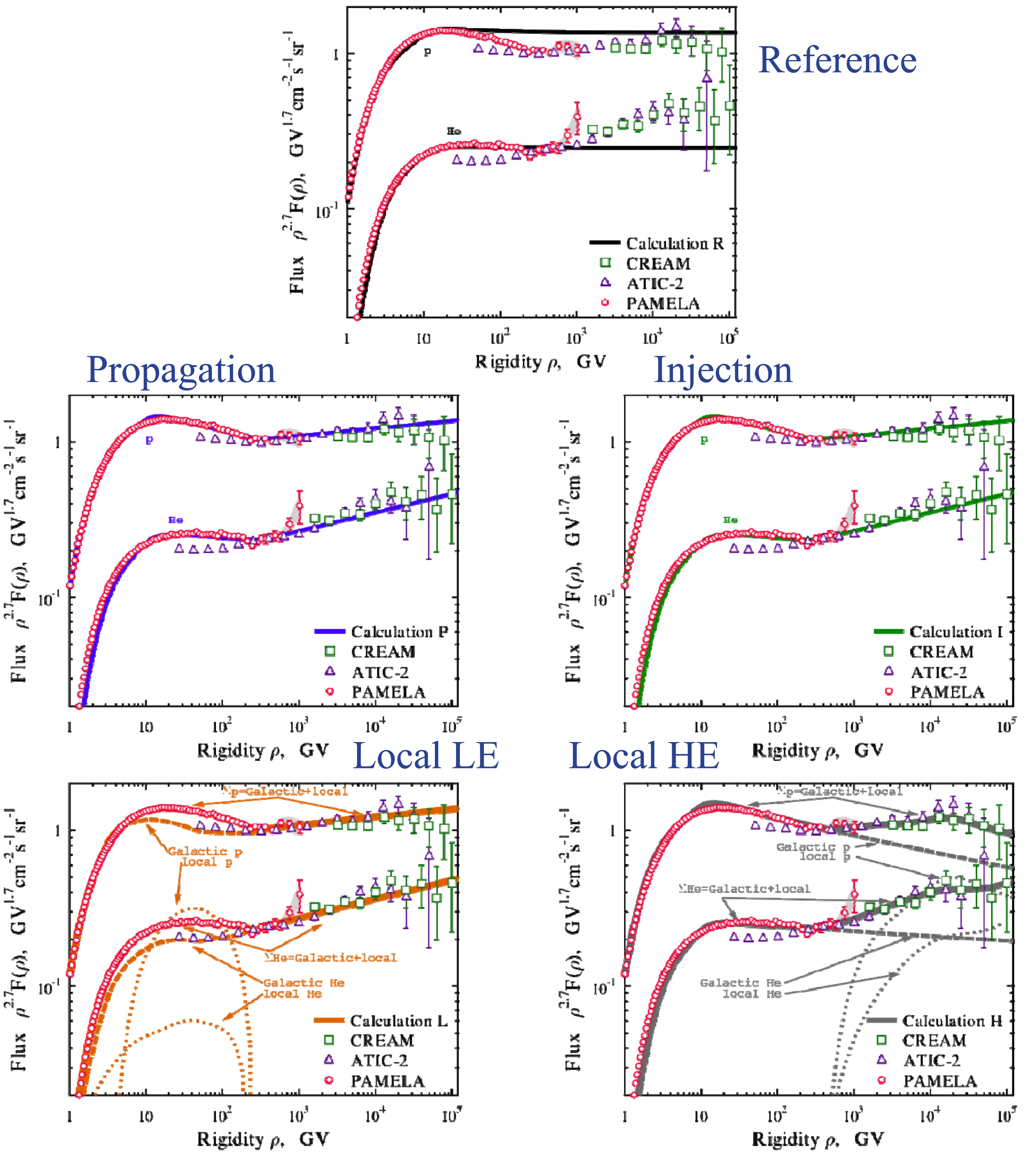
Particle Data Group

CREAM: are CR spectra not single power laws?





E. Seo, ICRC 2011

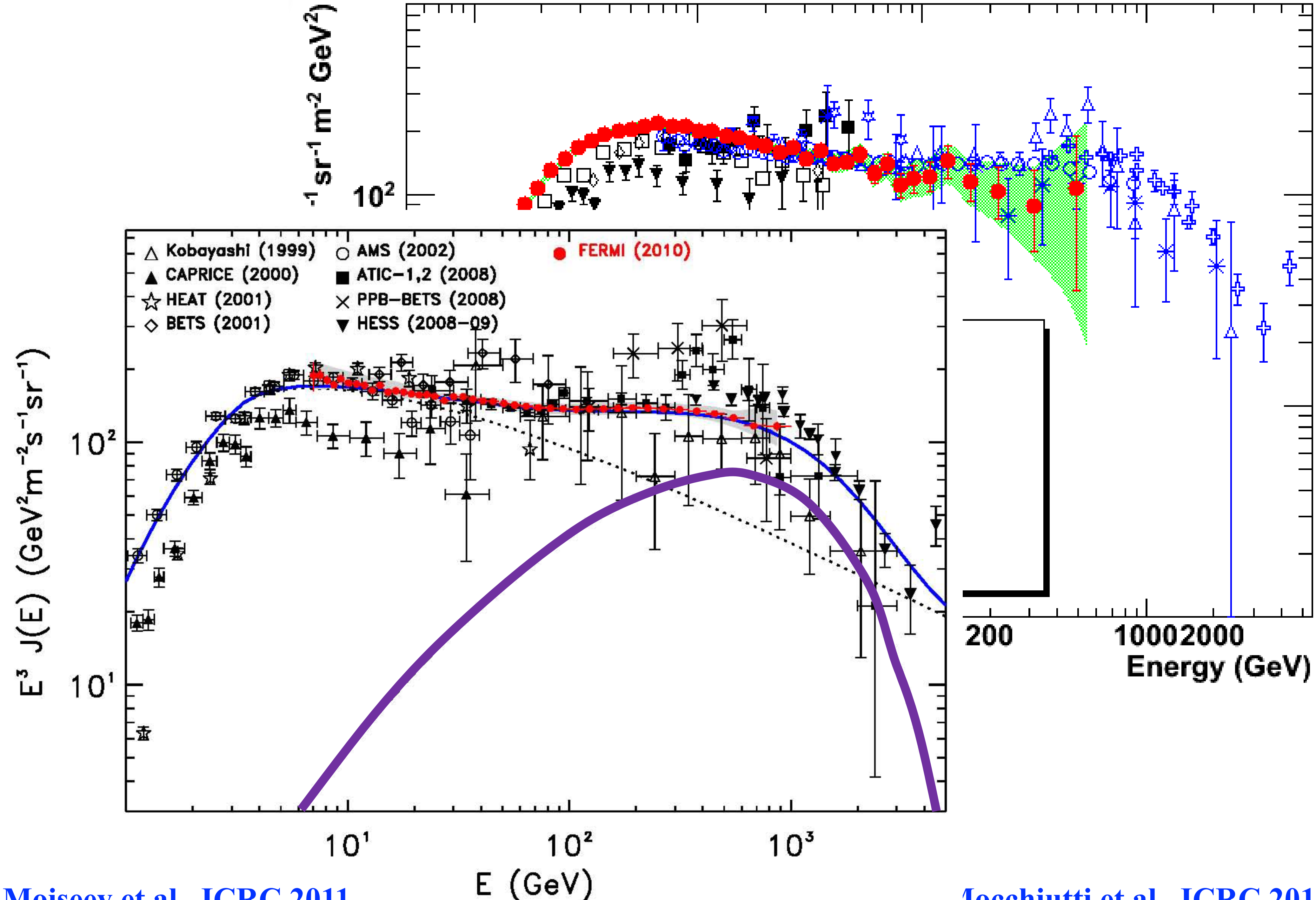


P and He spectra in different scenarios

- All scenarios are tuned to the data, except the Reference scenario
- Scenarios L and H: the local source component is calculated by the subtraction of the propagated Galactic spectrum from the data
- The local source is assumed to be close to us, so no propagation; only primary CR species

Moskalenko et al., ICRC 2011

Electron energy spectrum

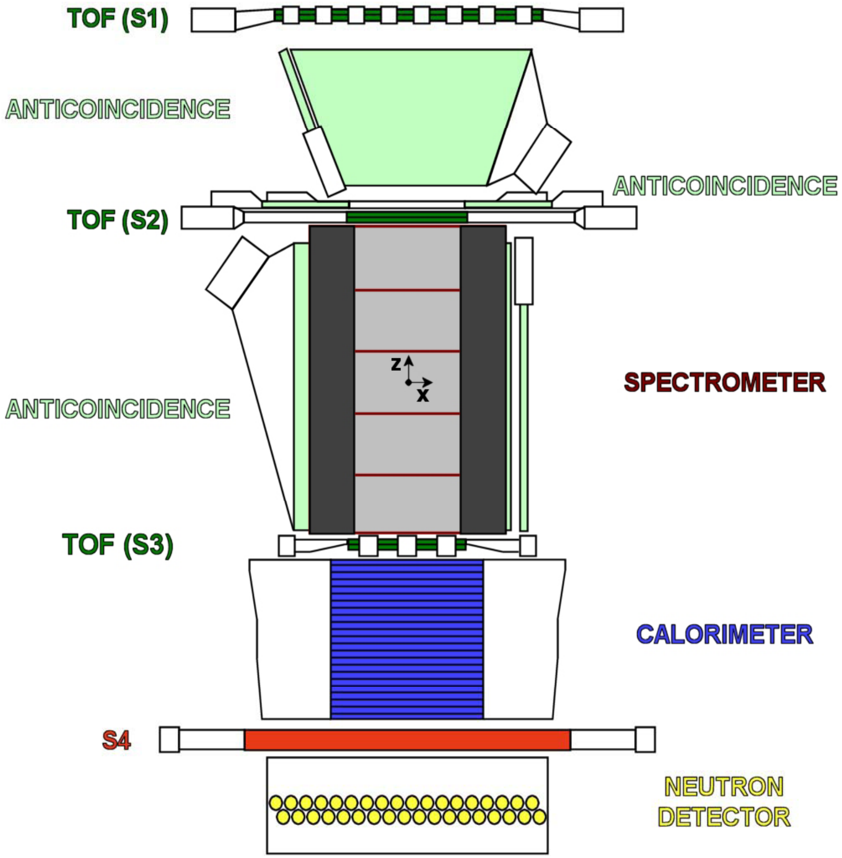


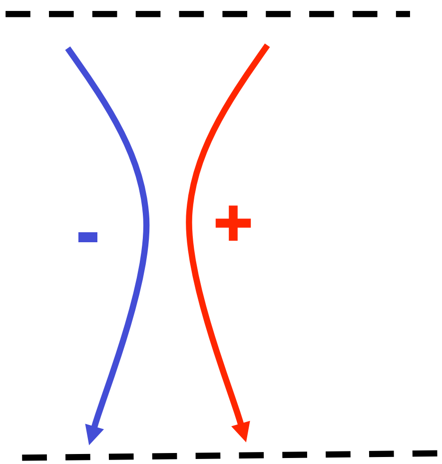
Moiseev et al., ICRC 2011

Iocchiutti et al., ICRC 2011

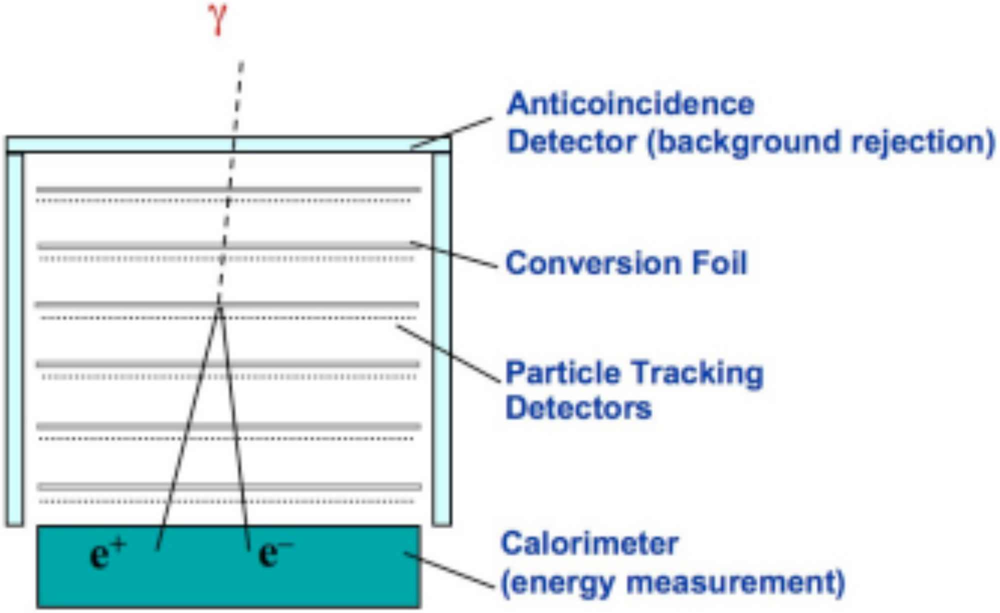
How to determine the charge of e+/e-

PAMELA

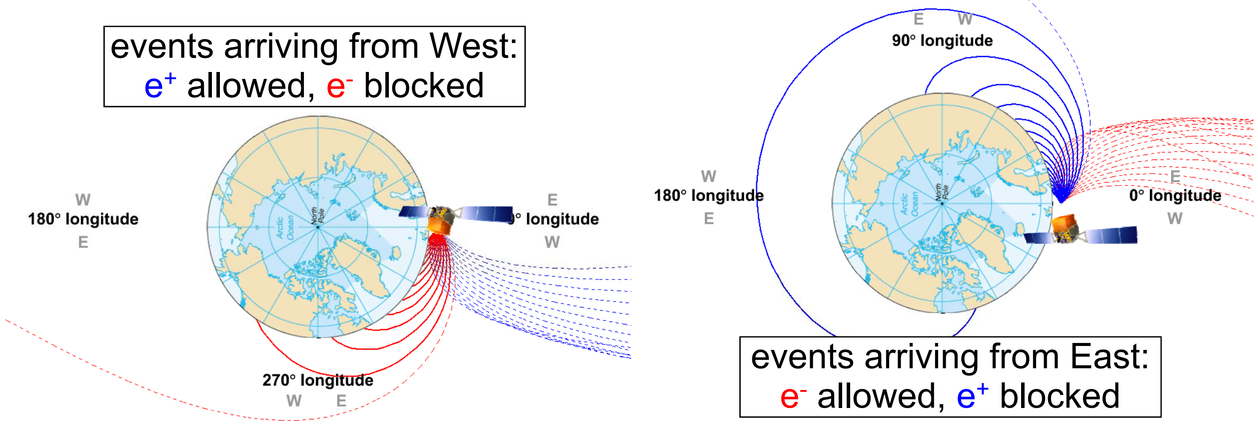




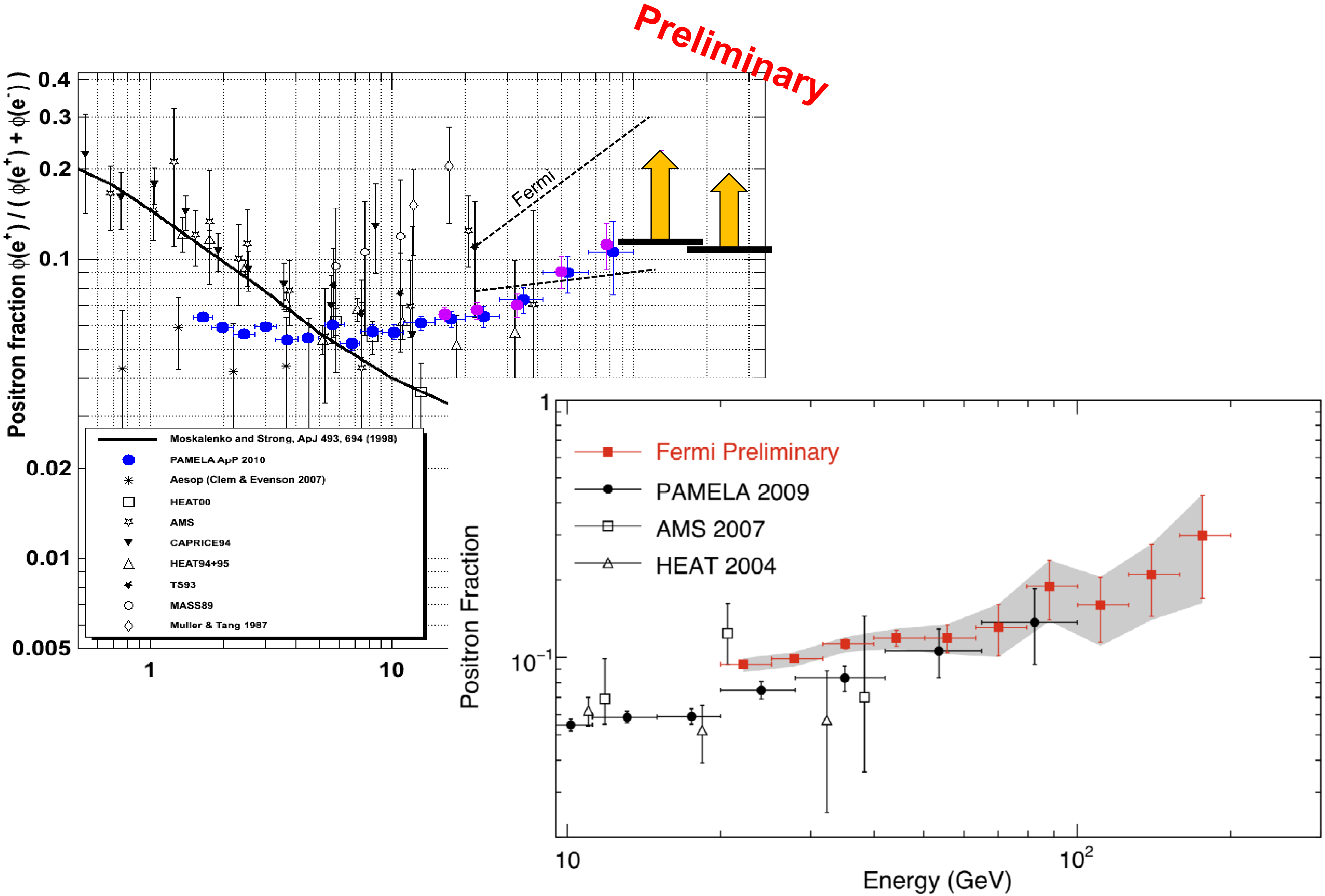
Fermi



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



Positron-to-Electron fraction



Mocchiutti et al., ICRC 2011

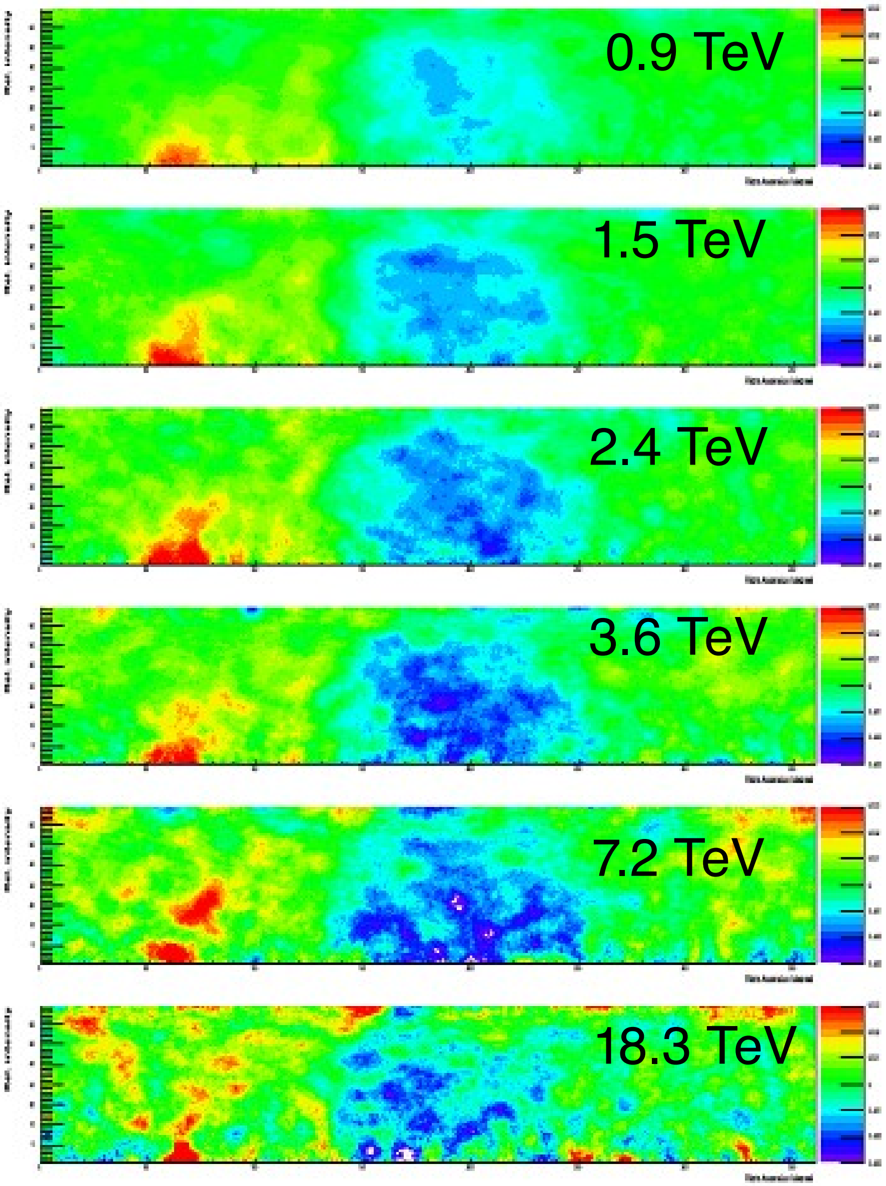
Vandenbroucke et al., ICRC 2011

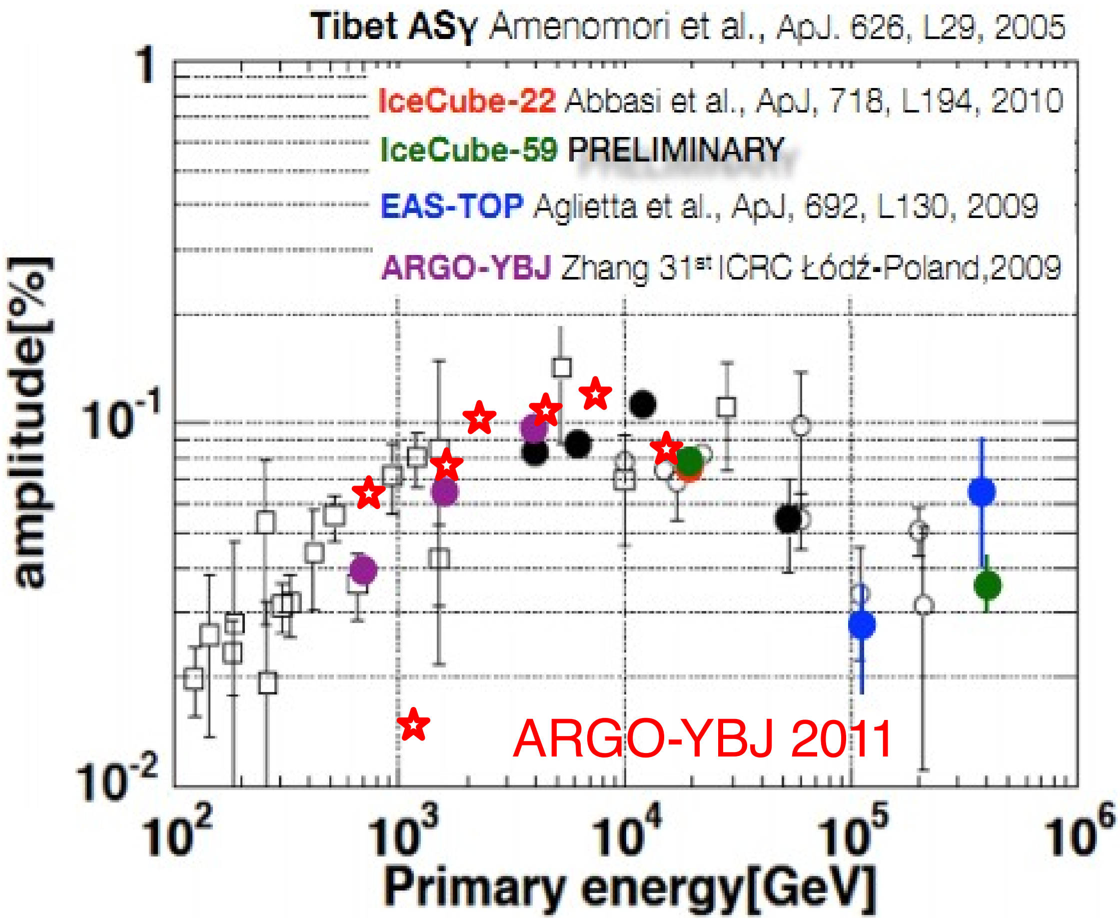
many (new) ideas:
several hundreds of articles on arXiv

- **modifications of diffuse background due to local sources**
- **local astrophysical sources (e.g. pulsars)**
- **reacceleration at supernova remnants**
- **dark matter annihilation**

Cosmic-ray anisotropy at TeV energies

ARGO

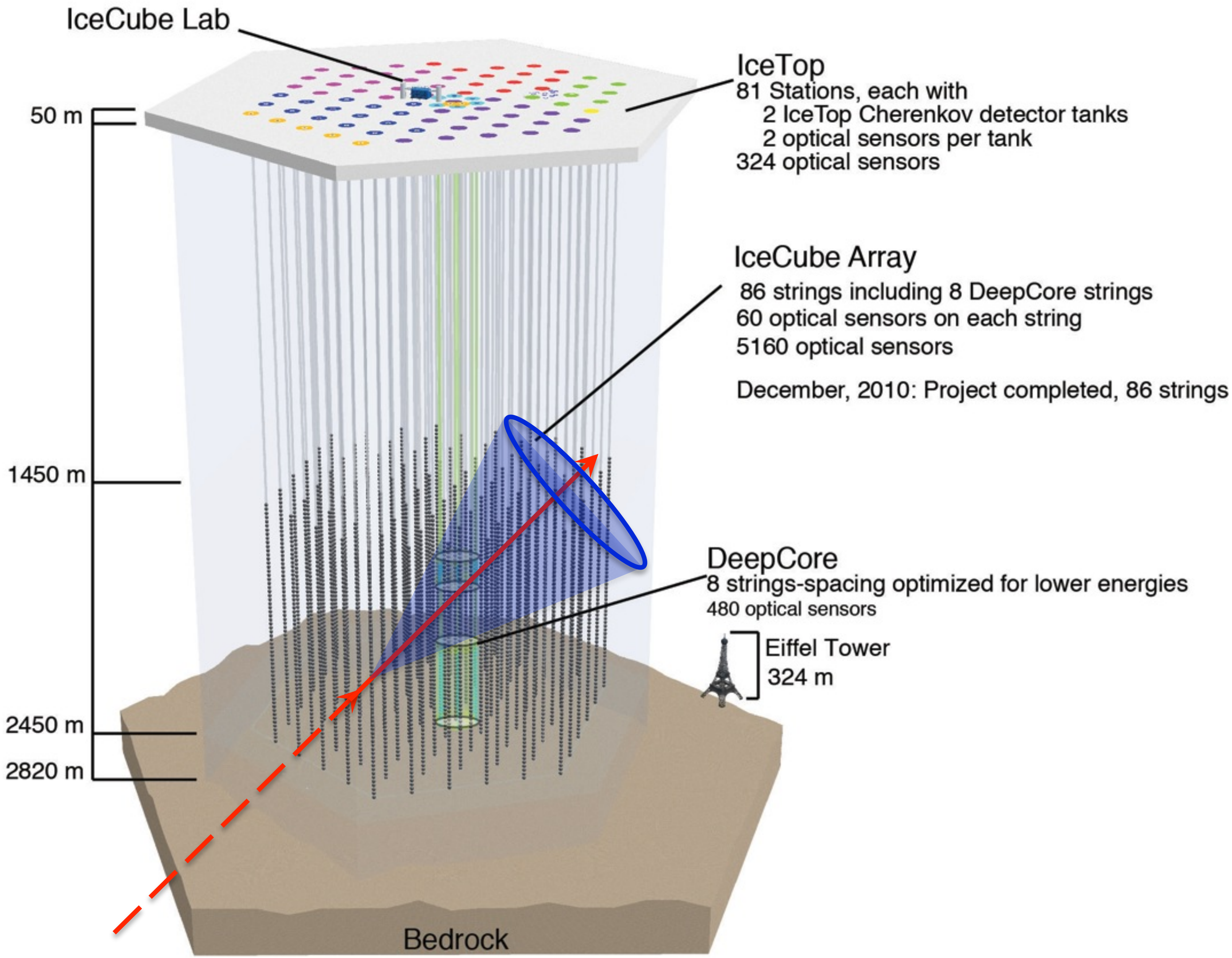




The tail-in broad structure appears to dissolve to smaller angular scale spots.

B. D'Ettore Piazzoli et al., ICRC 2011

IceCube Detector

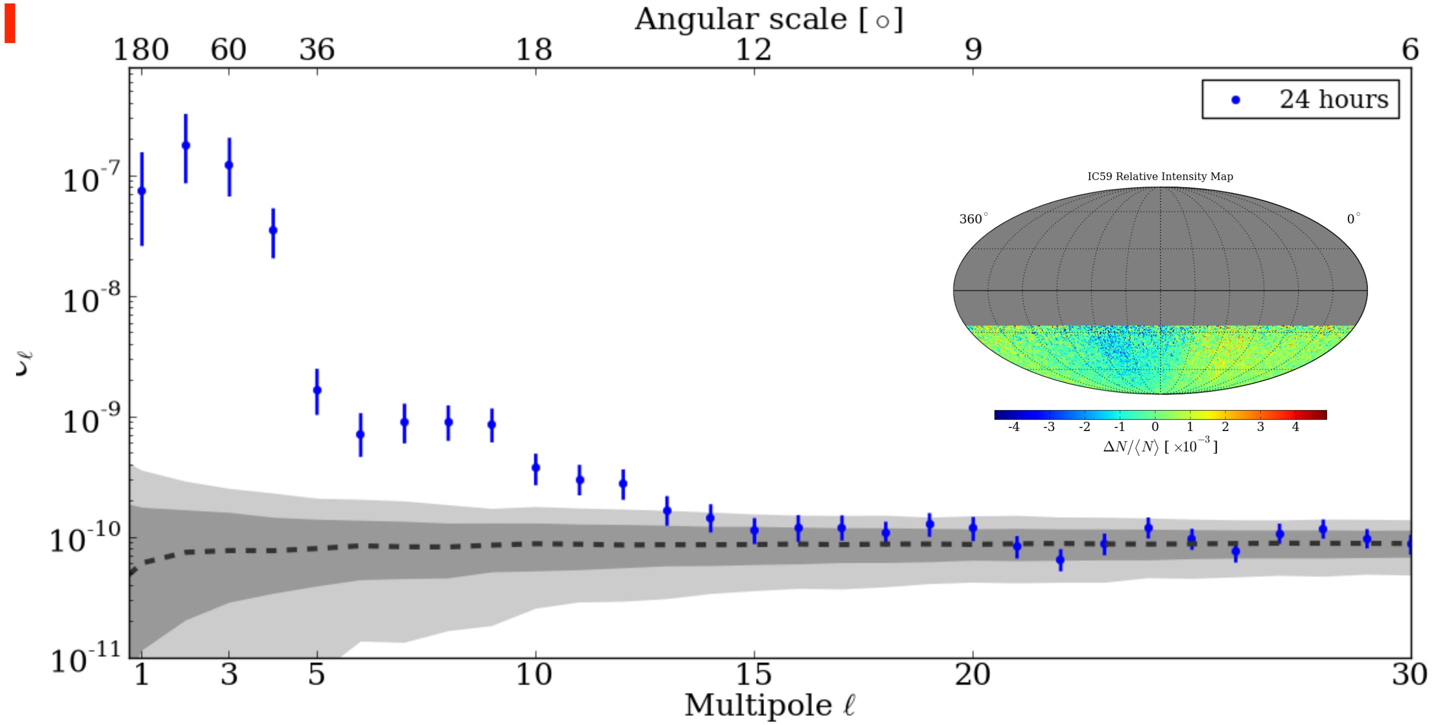


Neutrinos and cosmic rays are detected using Cherenkov emission in ice sheet

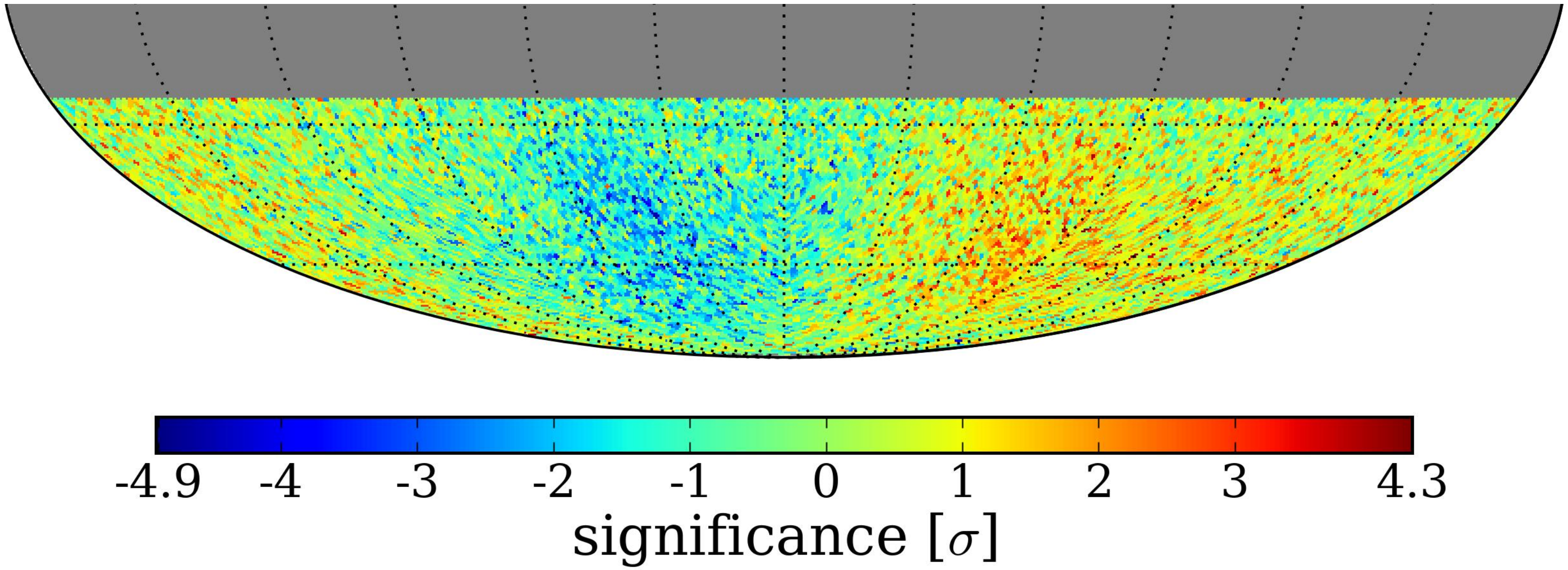
IceCube-59 Power Spectrum

Observat distributi IceCube

#306 BenZvi

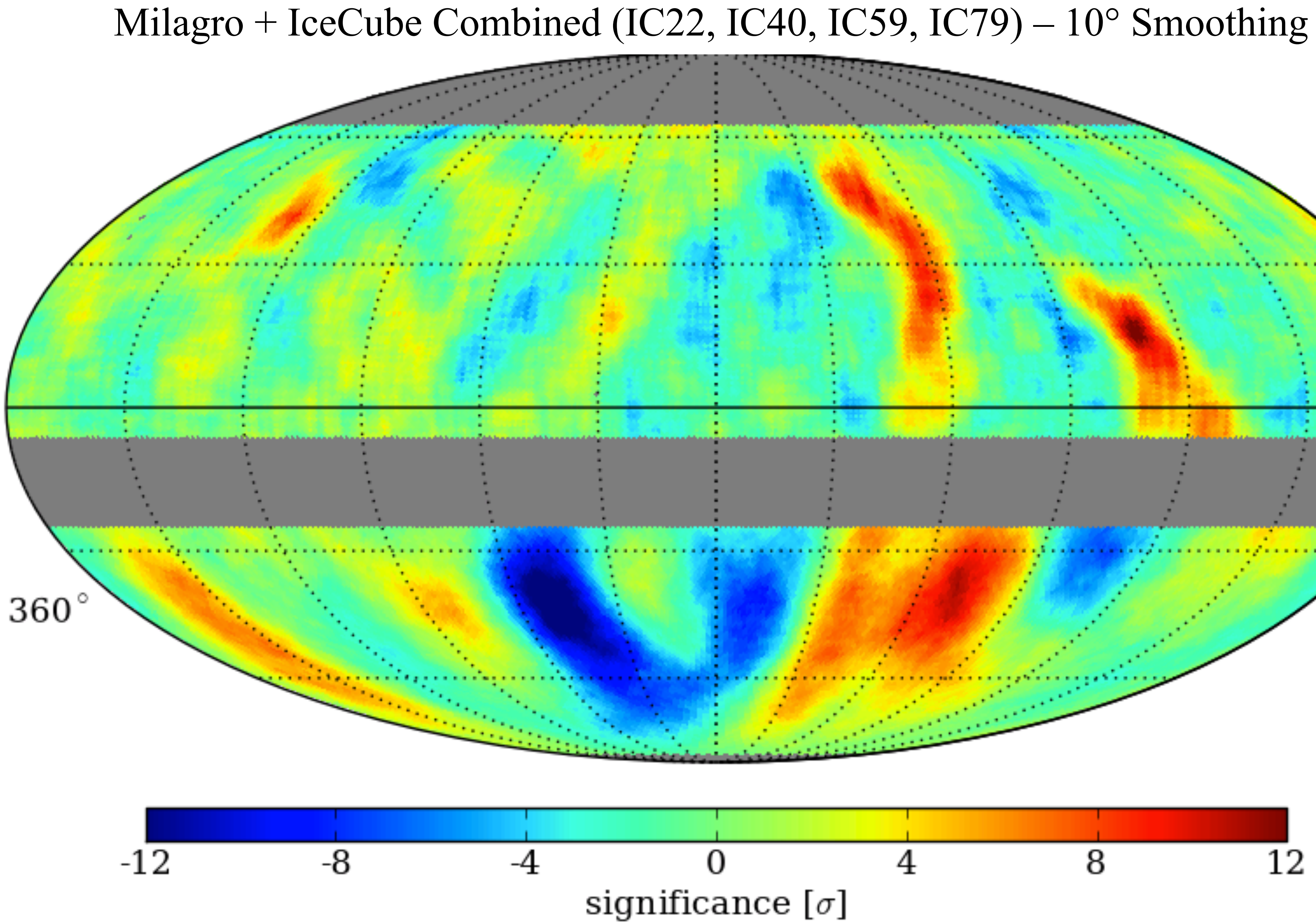


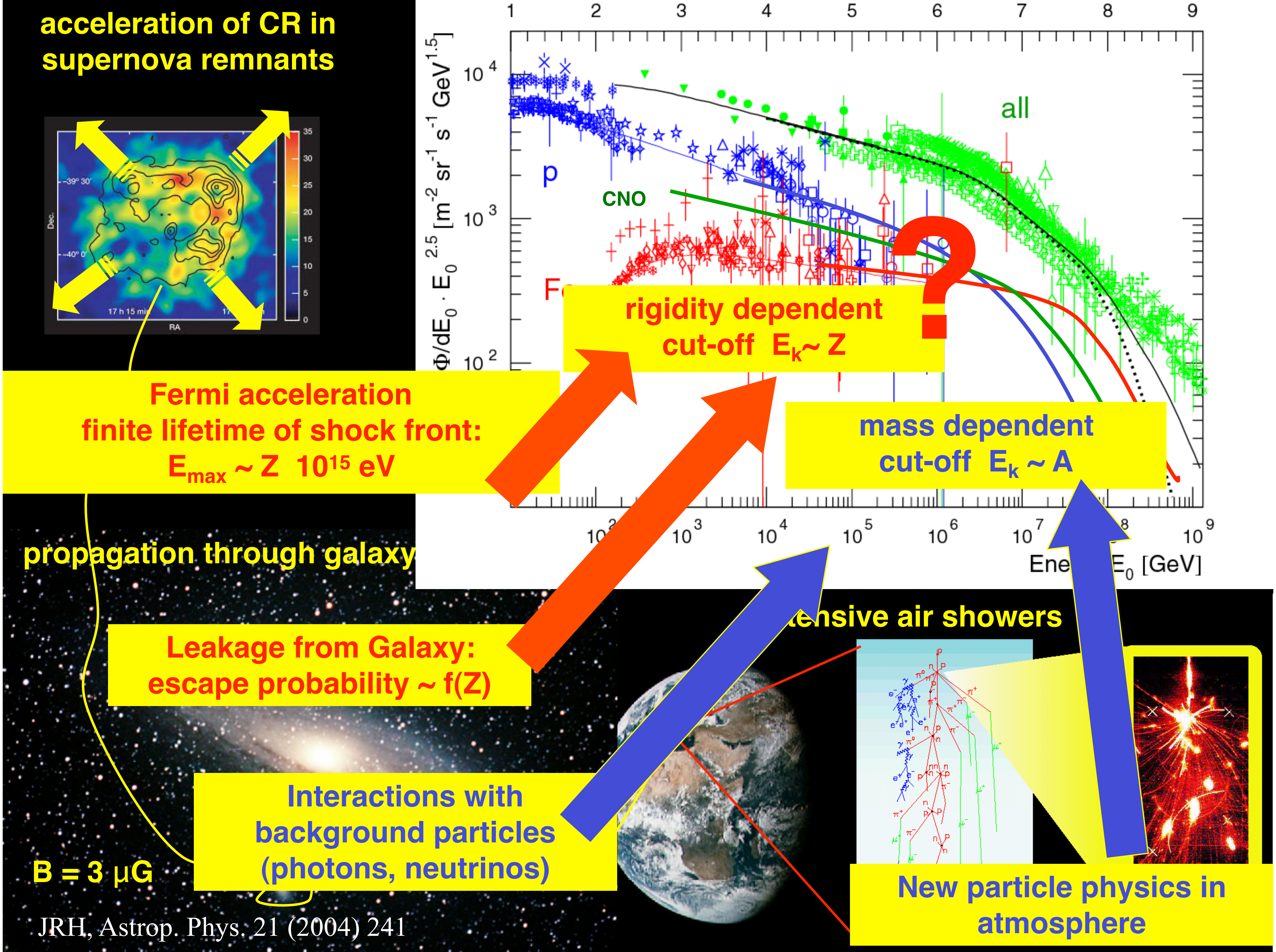
- Sky map contains correlations at several angular scales
- Gray bands: 68% and 95% bands of simulated isotropic maps



Observation of anisotropies in the arrival direction distribution of cosmic rays above TeV energies in IceCube

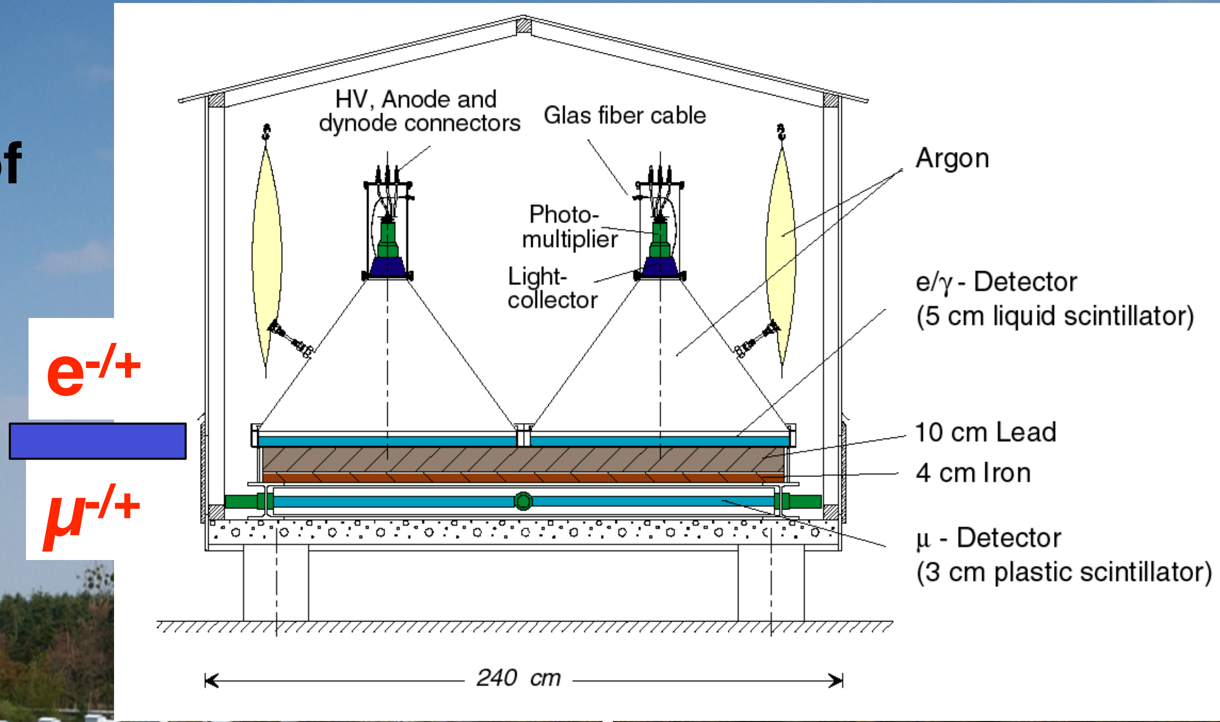
#306
BenZvi




acceleration of CR in supernova remnants
Dec.
RA
all
p
CNO
Fe
?
$\Phi/dE_0 \cdot E_0^{2.5}$ [m^{-2} sr^{-1} s^{-1} $GeV^{1.5}$]
Energy E_0 [GeV]
rigidity dependent cut-off $E_k \sim Z$
Fermi acceleration
finite lifetime of shock front:
$E_{max} \sim Z$ 10^{15} eV
mass dependent cut-off $E_k \sim A$
propagation through galaxy
Leakage from Galaxy:
escape probability ~ f(Z)
extensive air showers
Interactions with background particles (photons, neutrinos)
B = 3 μG
New particle physics in atmosphere
JRH, Astrop. Phys. 21 (2004) 241

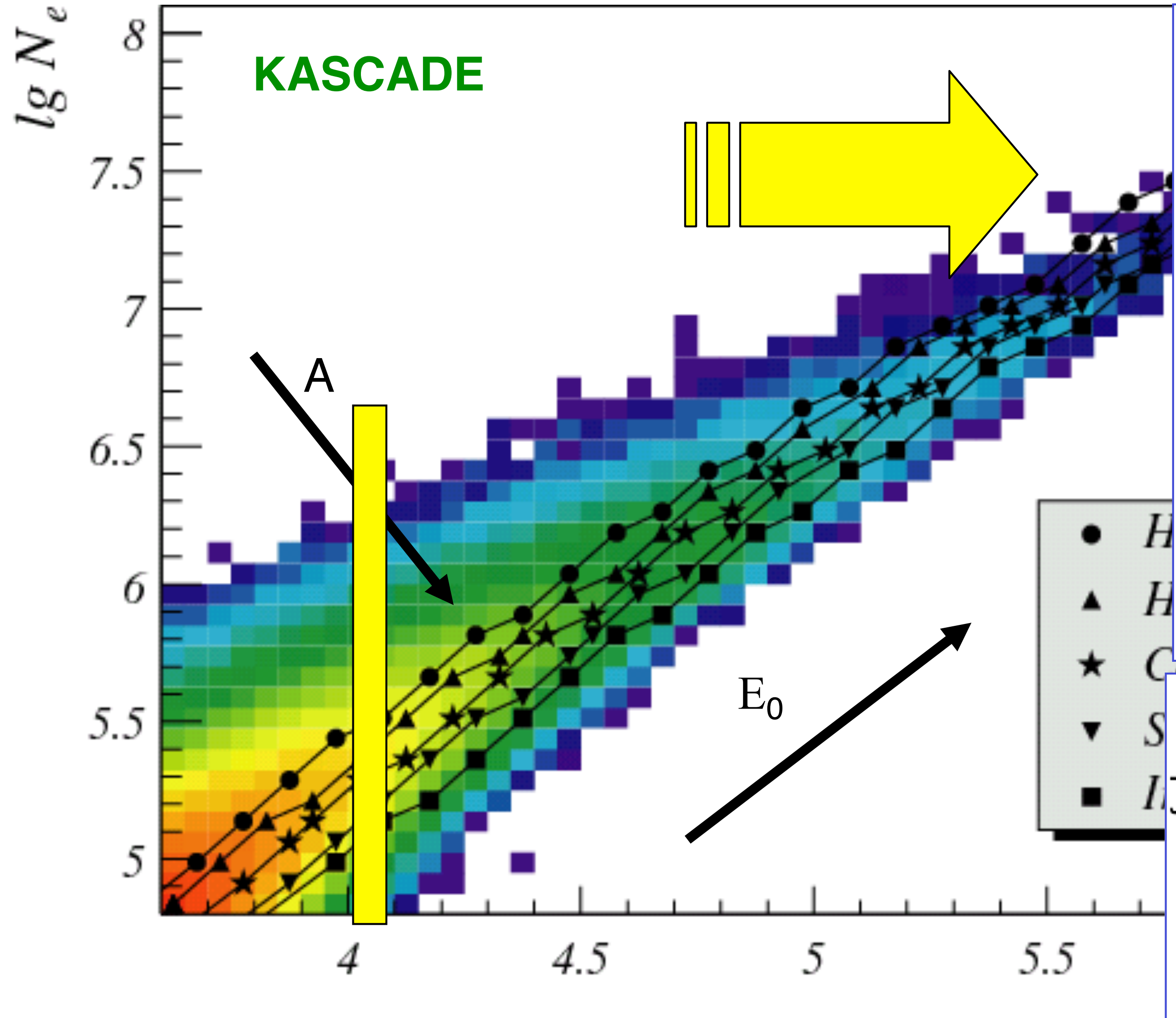
KArlsruhe Shower Core and Array DEtector

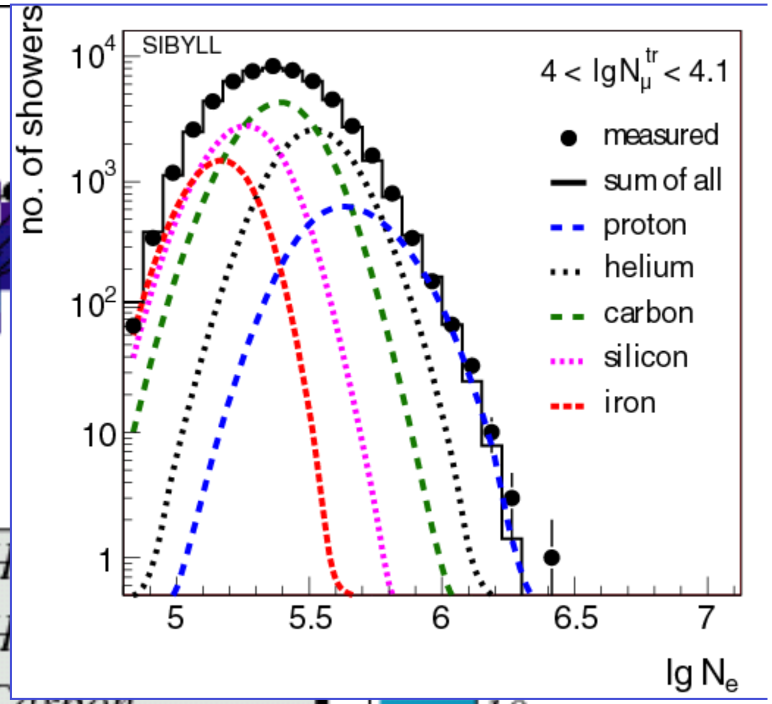
Simultaneous measurement of
electromagnetic,
muonic,
hadronic
shower components

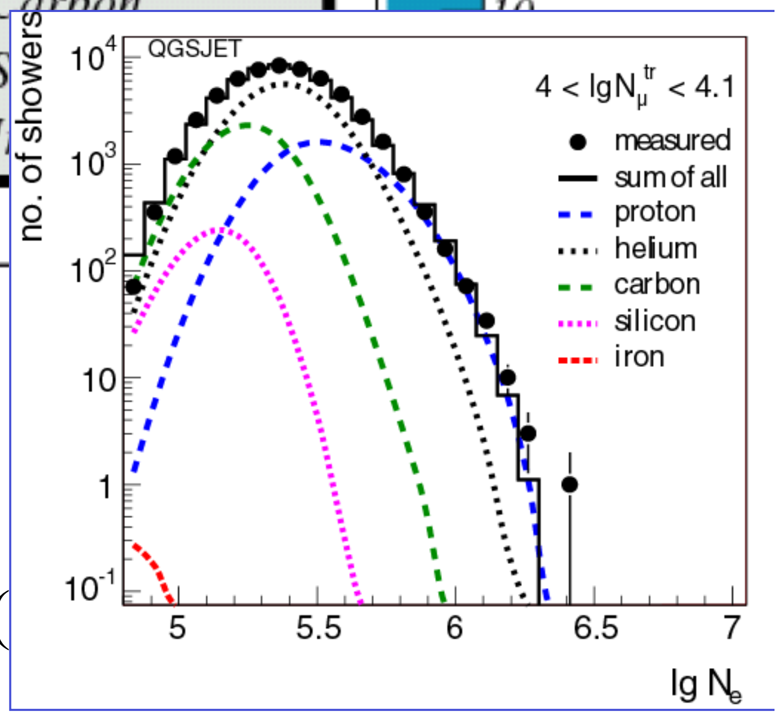


T. Antoni et al, Nucl. Instr. & Meth. A 513 (2004) 490

Two dimensional shower size spectrum lg N_e vs. lg N_μ





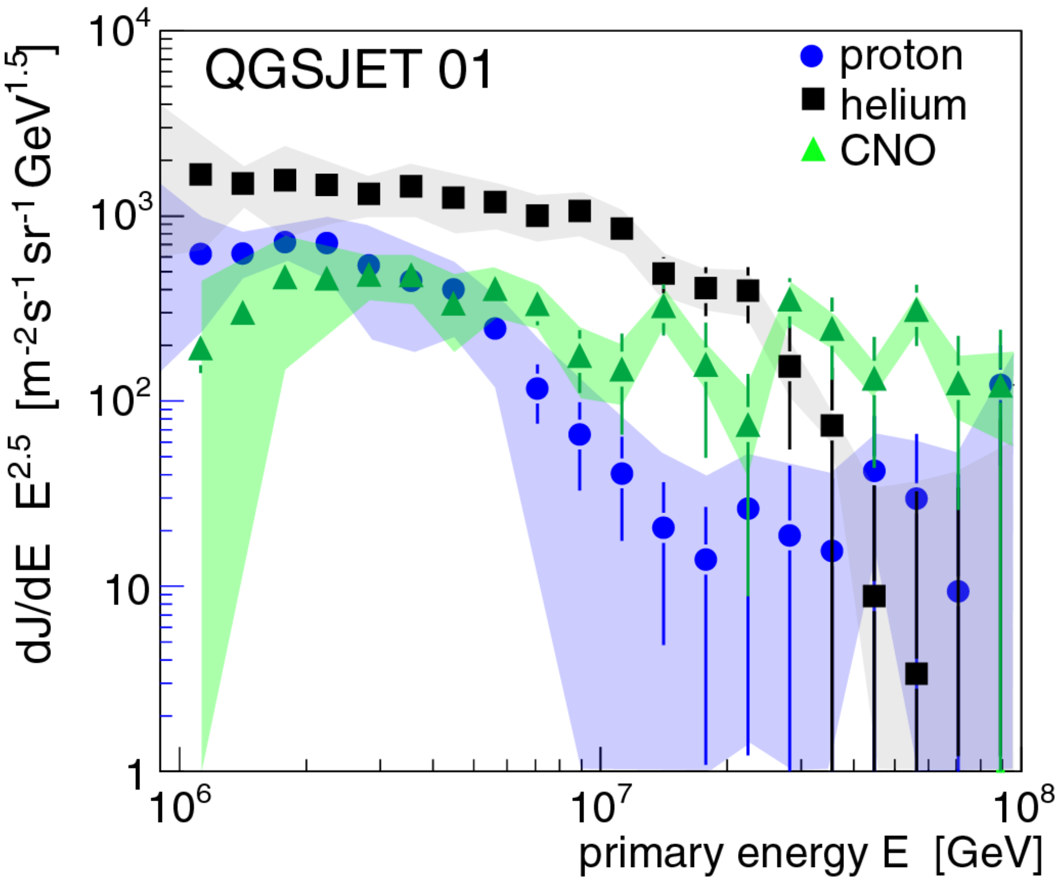


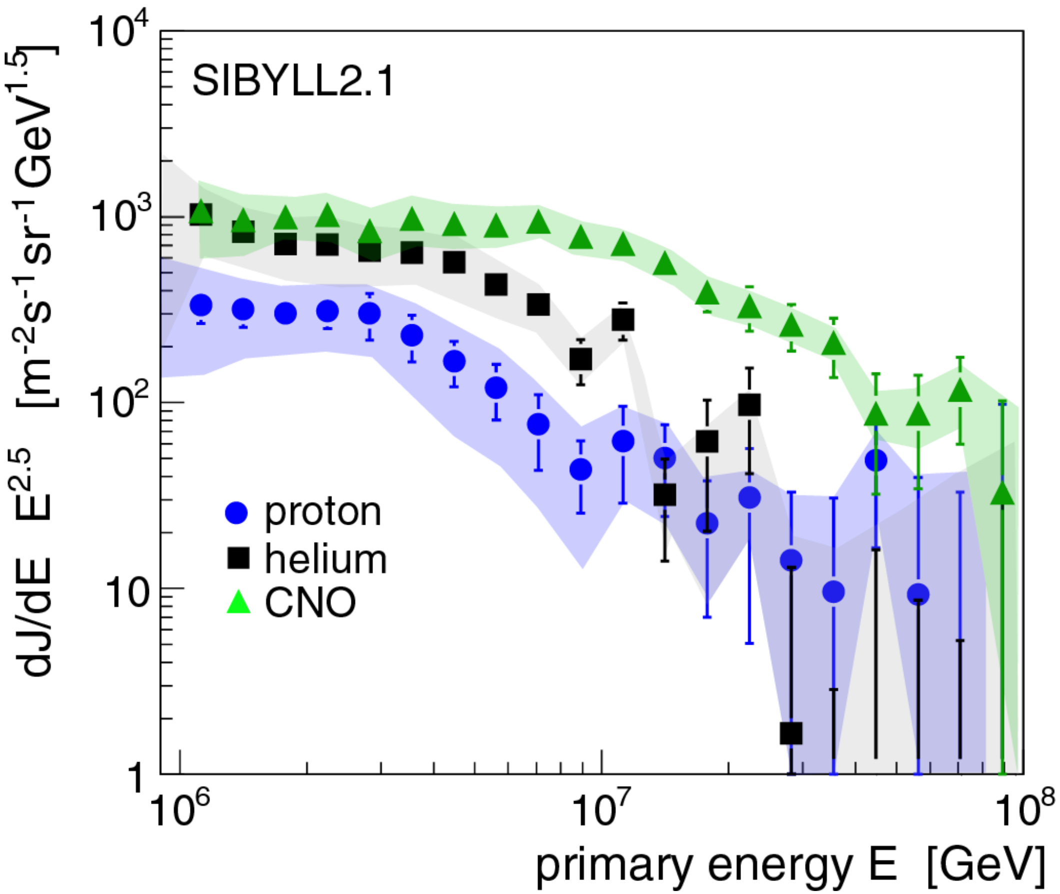
- derive E_0 and A from N_e and N_μ data
- Fredholm integral equations of 1st kind:

$$g_i(\lg N_e, \lg N_\mu) = \int_0^\infty t_i(\lg N_e, \lg N_\mu \mid E)\, p_i($$

T. Antoni et al., Astropart. Phys. 24 (2005) 1

KASCADE: Energy spectra for elemental groups



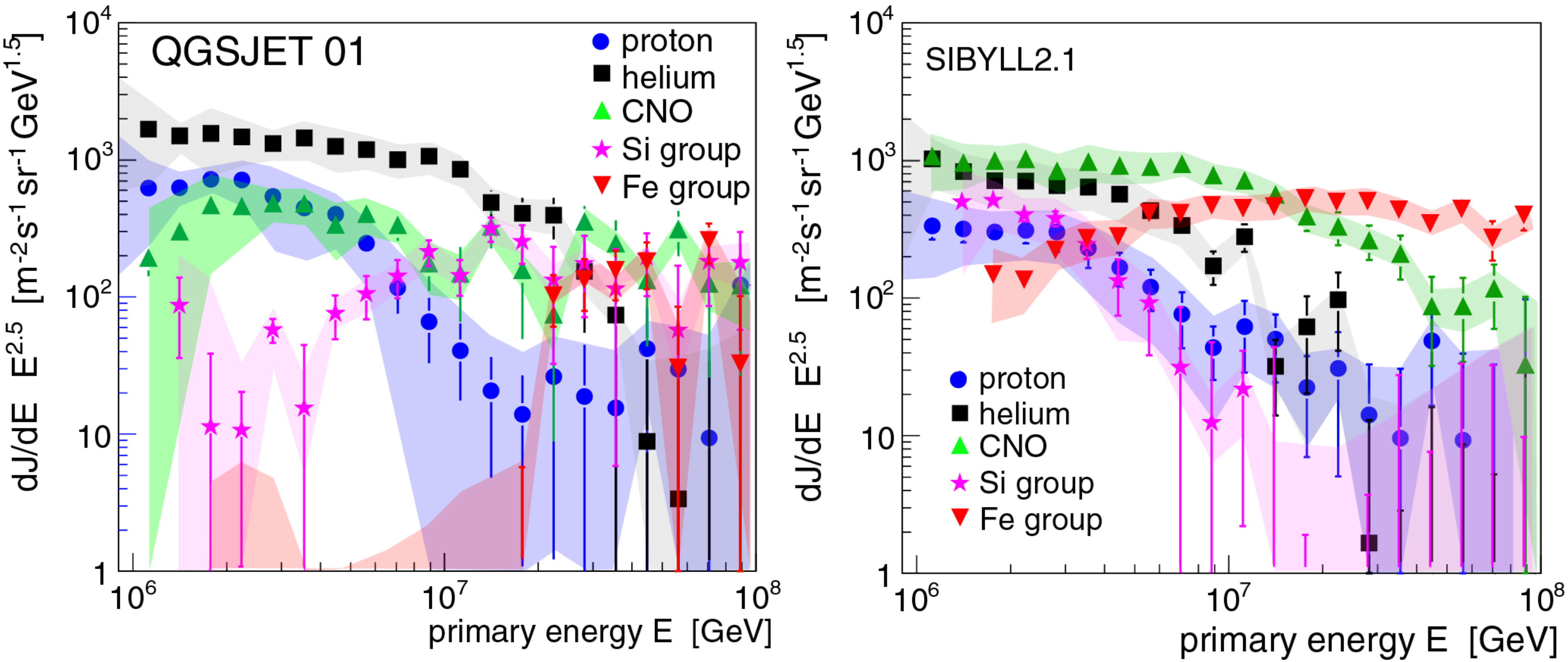


➡ **Knee caused by cut-off for light elements**

Astrophysical interpretation limited by description of interactions in the atmosphere

T. Antoni et al., Astropart. Phys. 24 (2005) 1

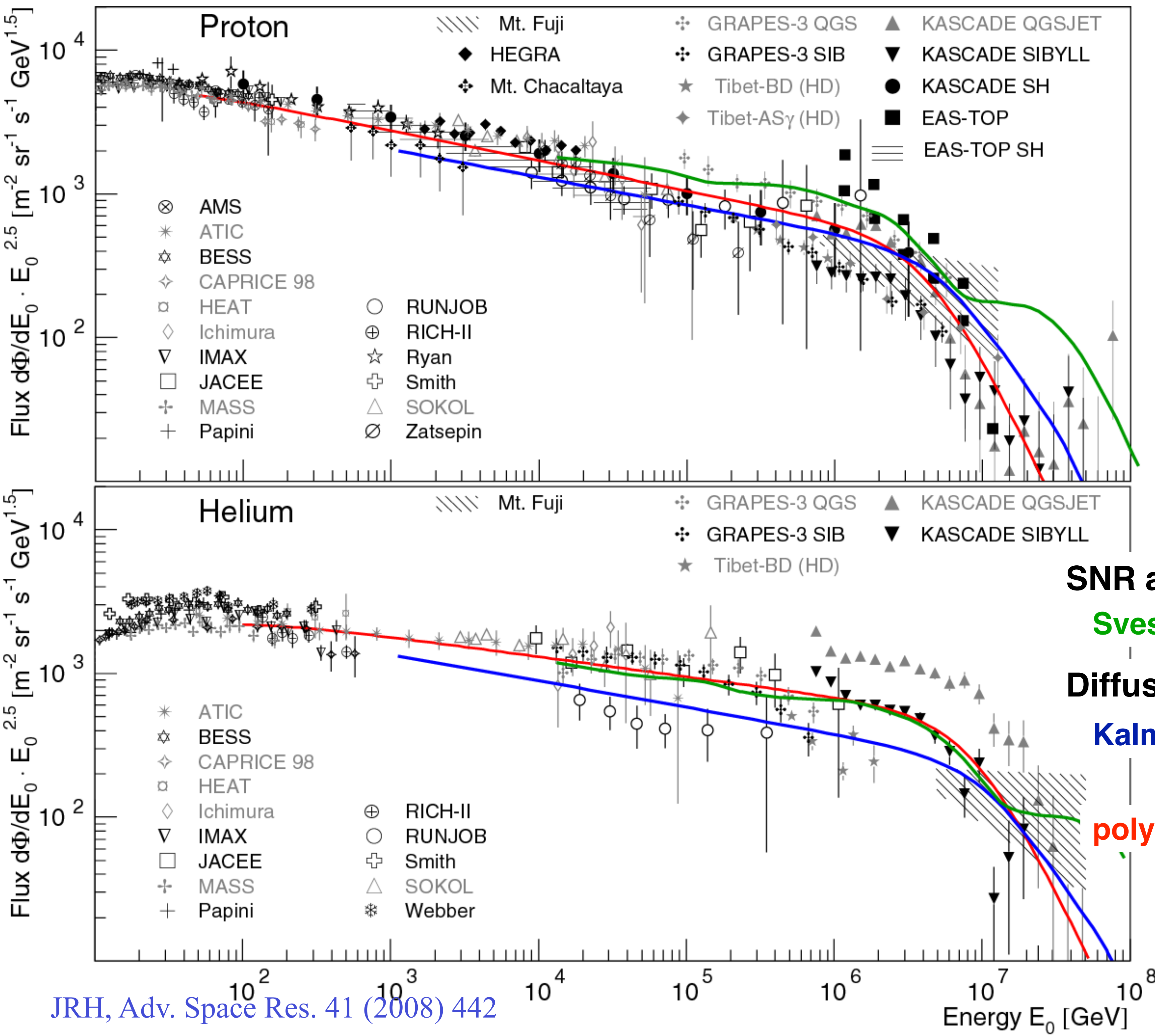
KASCADE: Energy spectra for elemental groups



Knee caused by cut-off for light elements

Astrophysical interpretation limited by description of interactions in the atmosphere

T. Antoni et al., Astropart. Phys. 24 (2005) 1



SNR acceleration:

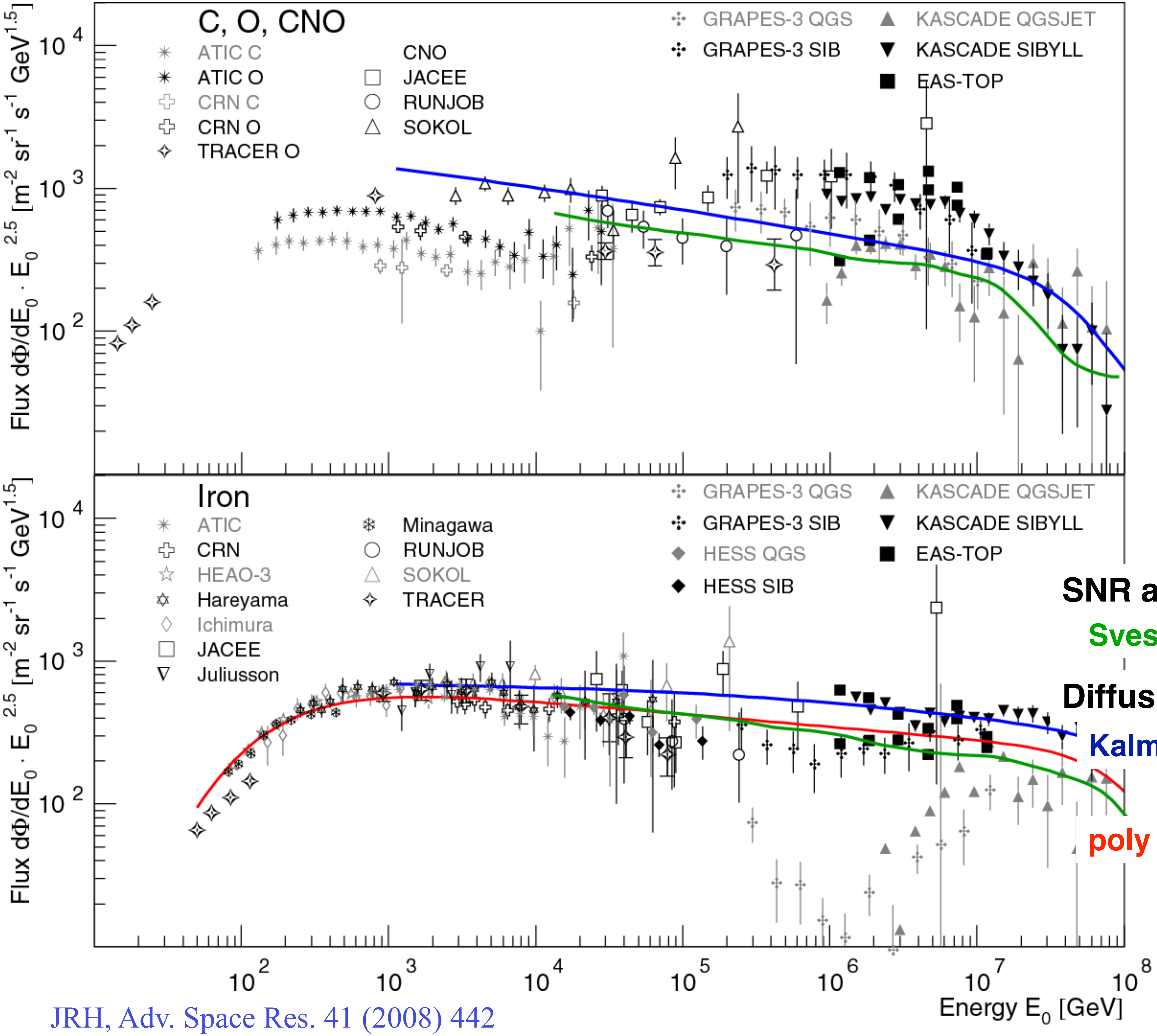
Sveshnikova++ 2003

Diffusion:

Kalmykov+JRH 2007

poly gonato ~Z

JRH, Adv. Space Res. 41 (2008) 442



SNR acceleration:

Sveshnikova++ 2003

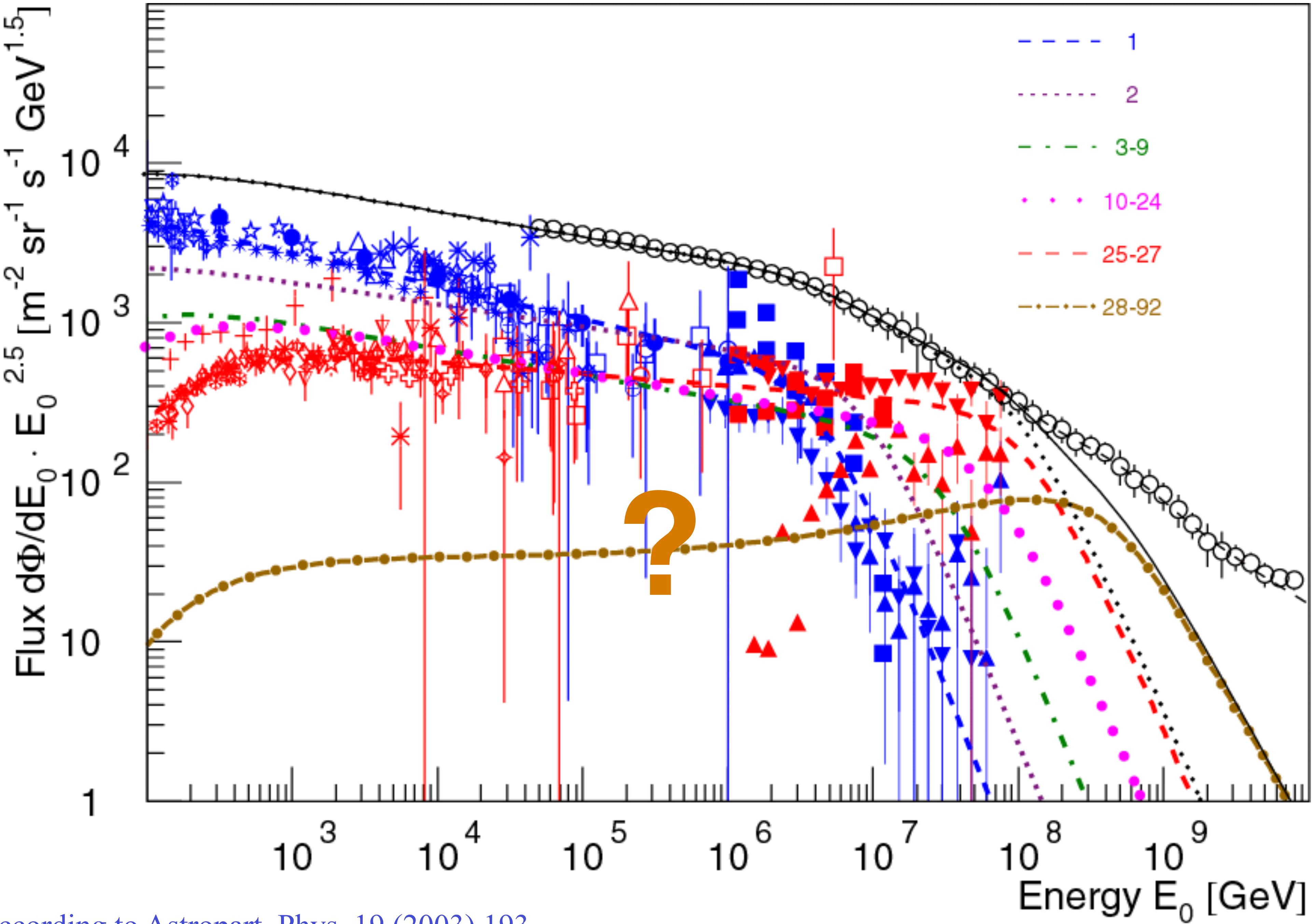
Diffusion:

Kalmykov+JRH 2007

poly gonato ~Z

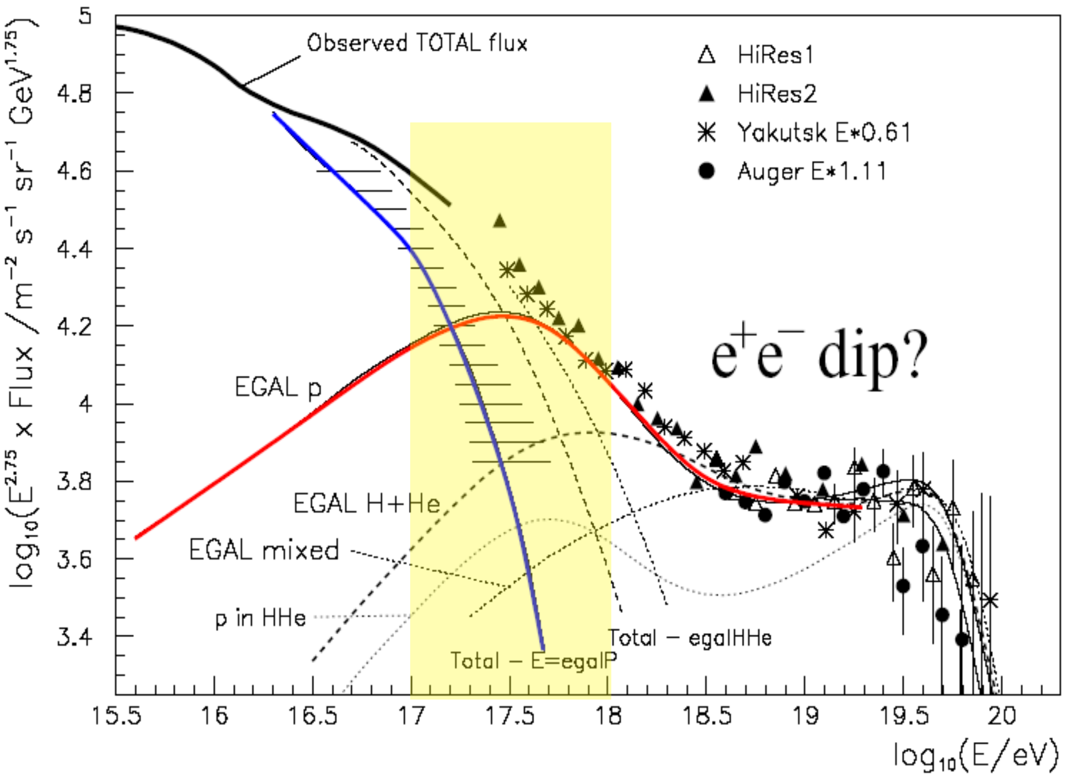
JRH, Adv. Space Res. 41 (2008) 442

Cosmic-ray energy spectrum



according to Astropart. Phys. 19 (2003) 193

Transition to extragalactic CR component

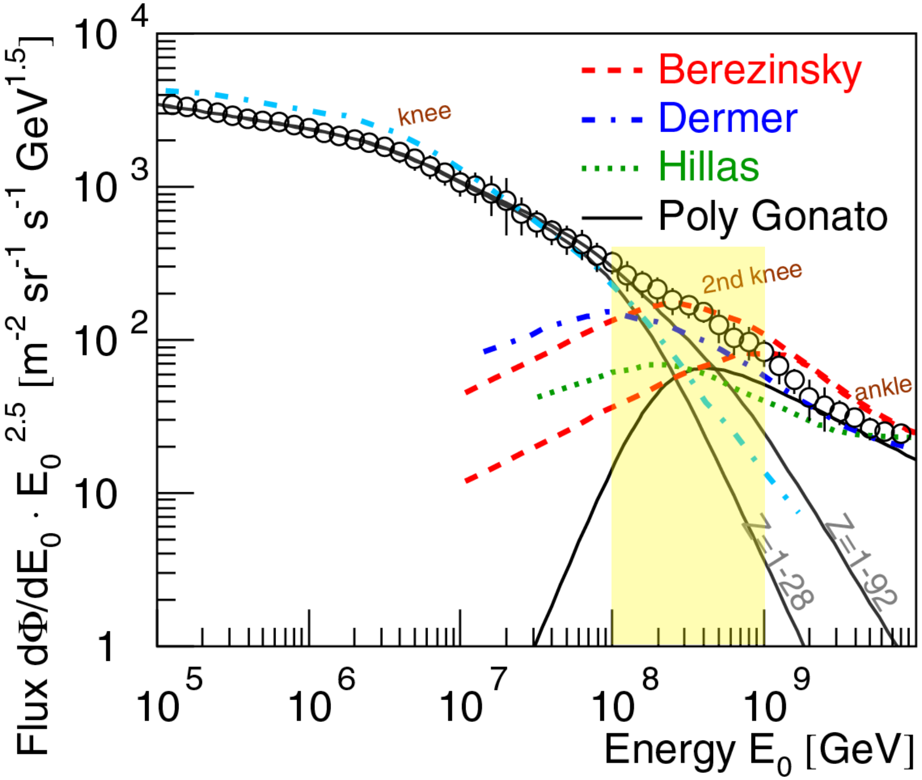


Origin of dip?

- pair production?

$p+\gamma_{3K} \rightarrow p+e^{+}+e^{-}$

Berezinsky astro-ph/0702488



JRH, Adv. Space Res. 41 (2008) 442

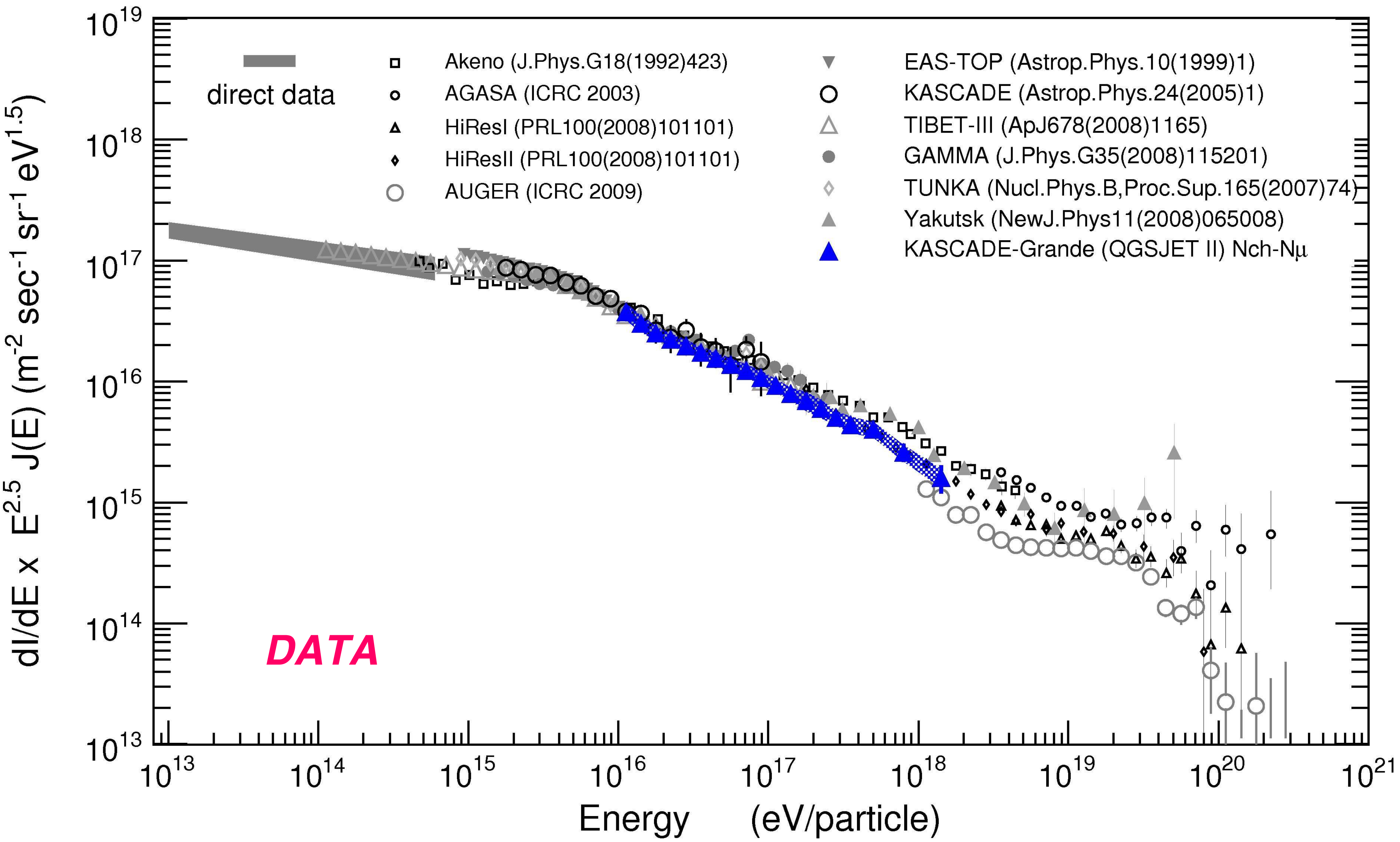
KASCADE GRANDE Array

37 detector stations

370 m² e/γ: scintillation counter

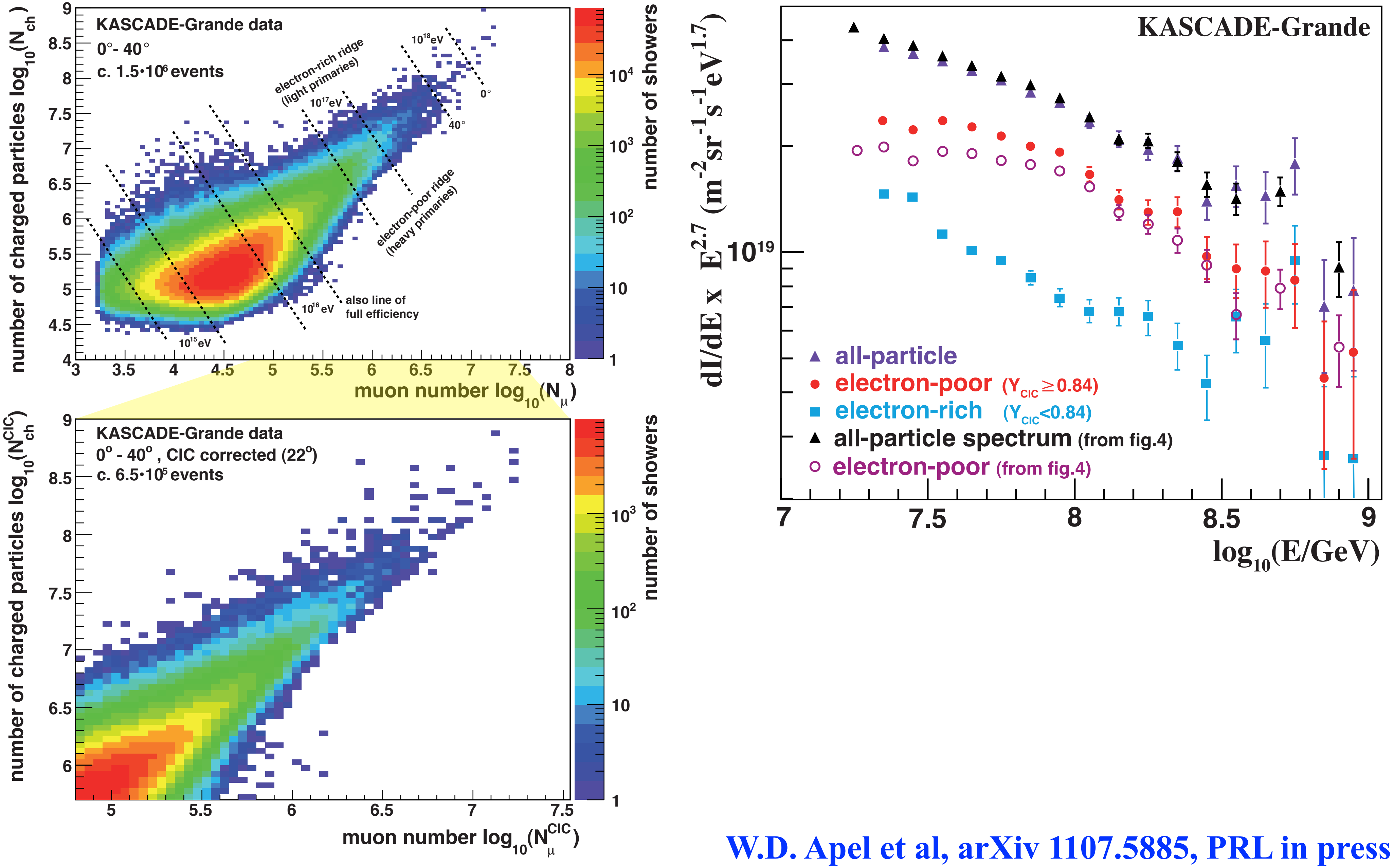
G. Navarra et al., Nucl Instr & Meth A 518 (2004) 207

The all-particle energy spectrum

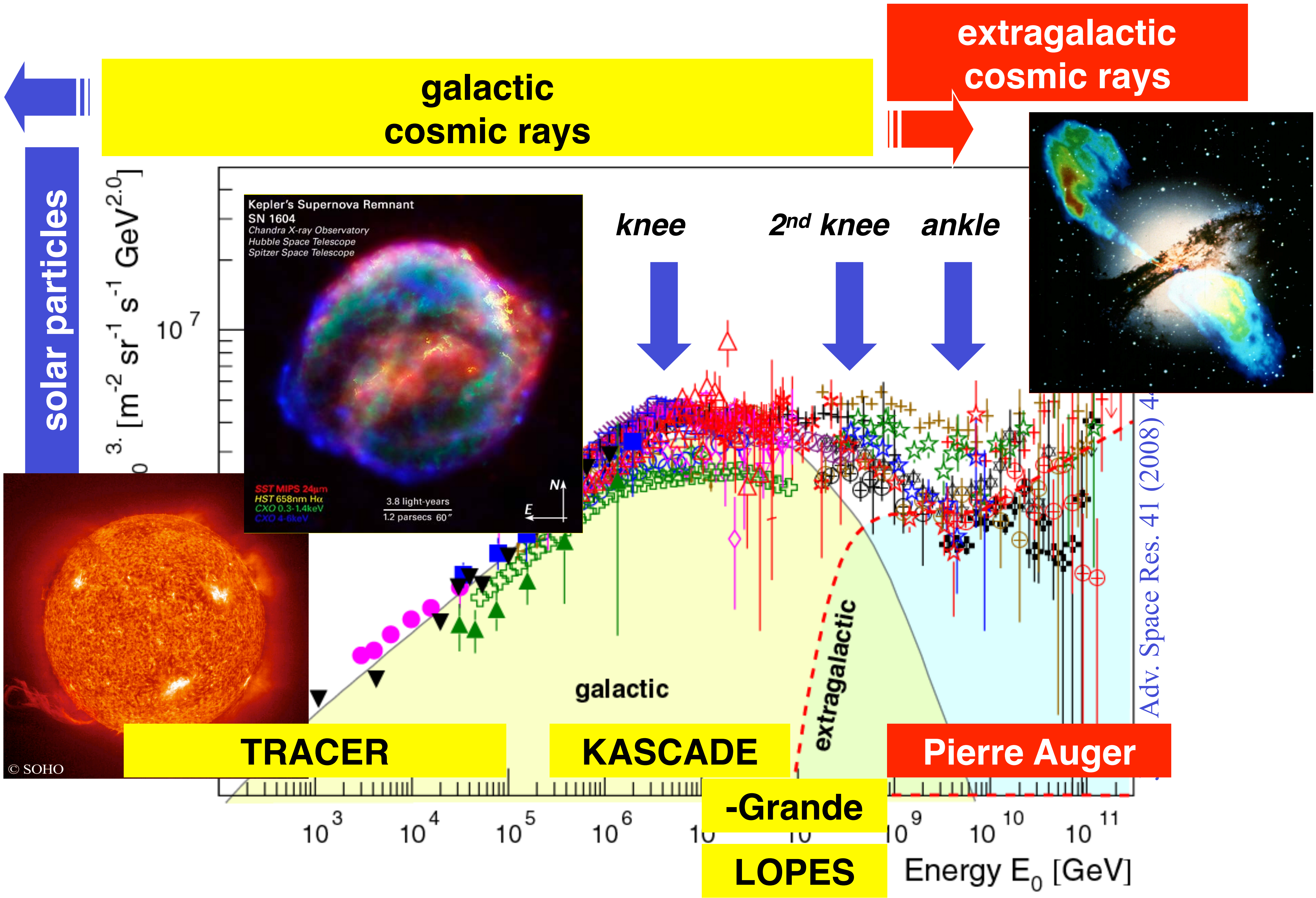


M. Bertaina, ECRS (2010)

A knee-like structure in the spectrum of the heavy component of cosmic rays



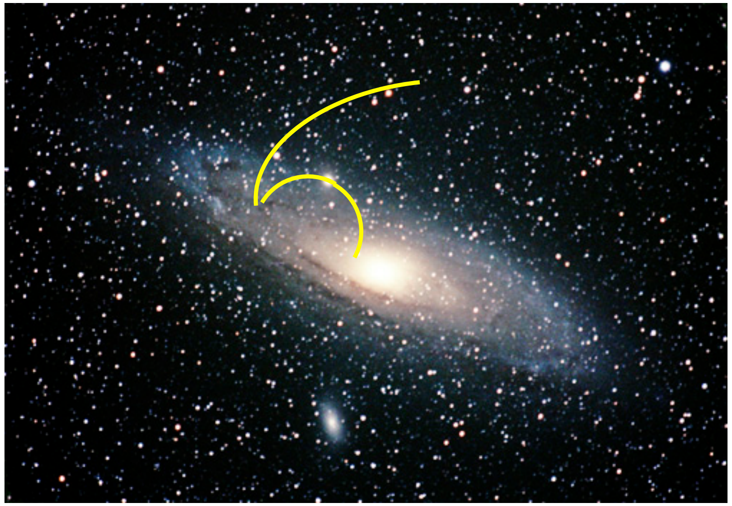
W.D. Apel et al, arXiv 1107.5885, PRL in press



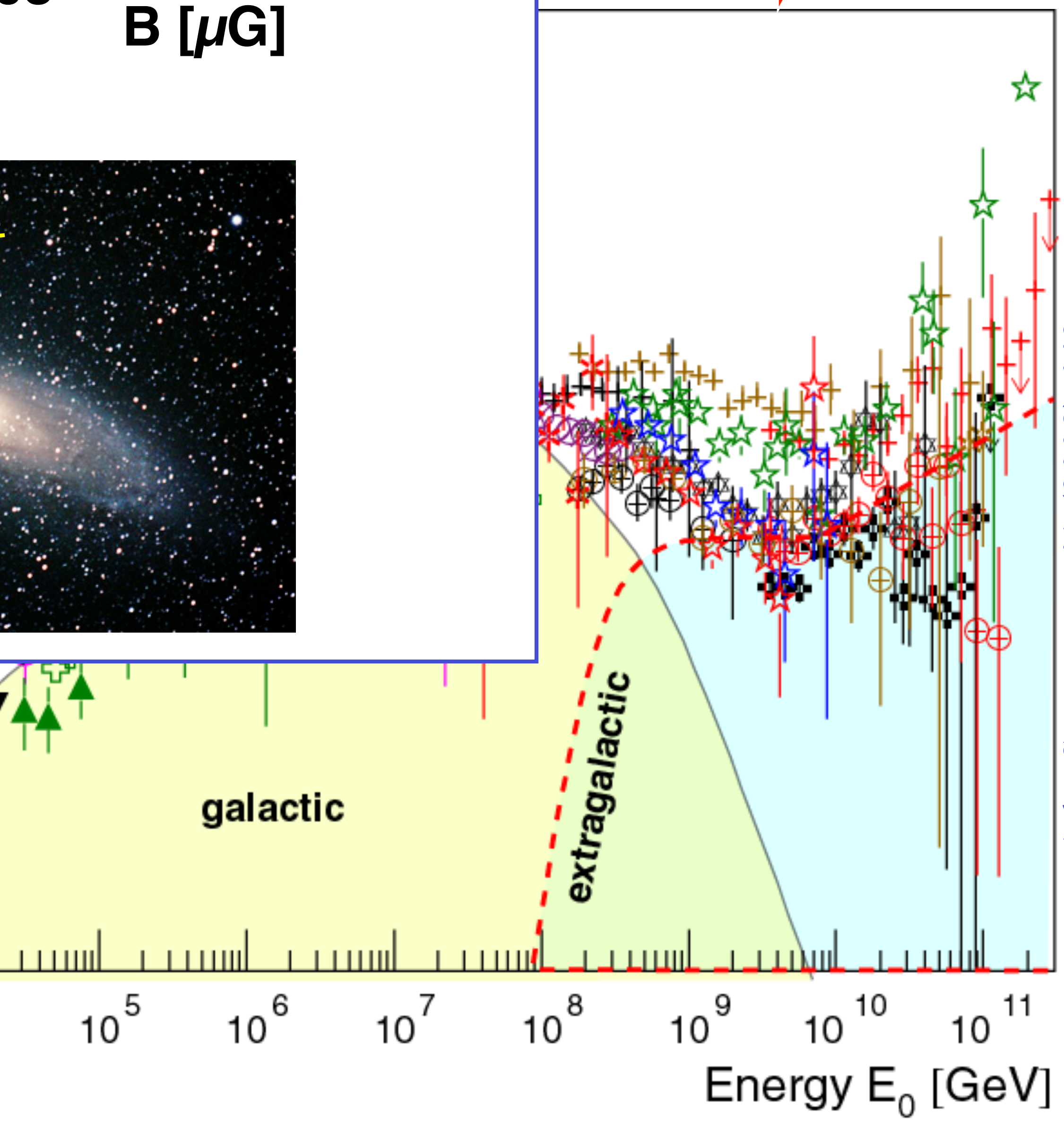
J. Blümer, R. Engel, JRH, Progr. Part. Nucl. Phys. 63 (2009) 293

Radius of particle in magnetic field

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



extragalactic cosmic rays



r= 0.04 pc 3.6 pc 360 pc 36 kpc

JRH, Adv. Space Res. 41 (2008) 442

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

Energy content of extragalactic cosmic rays

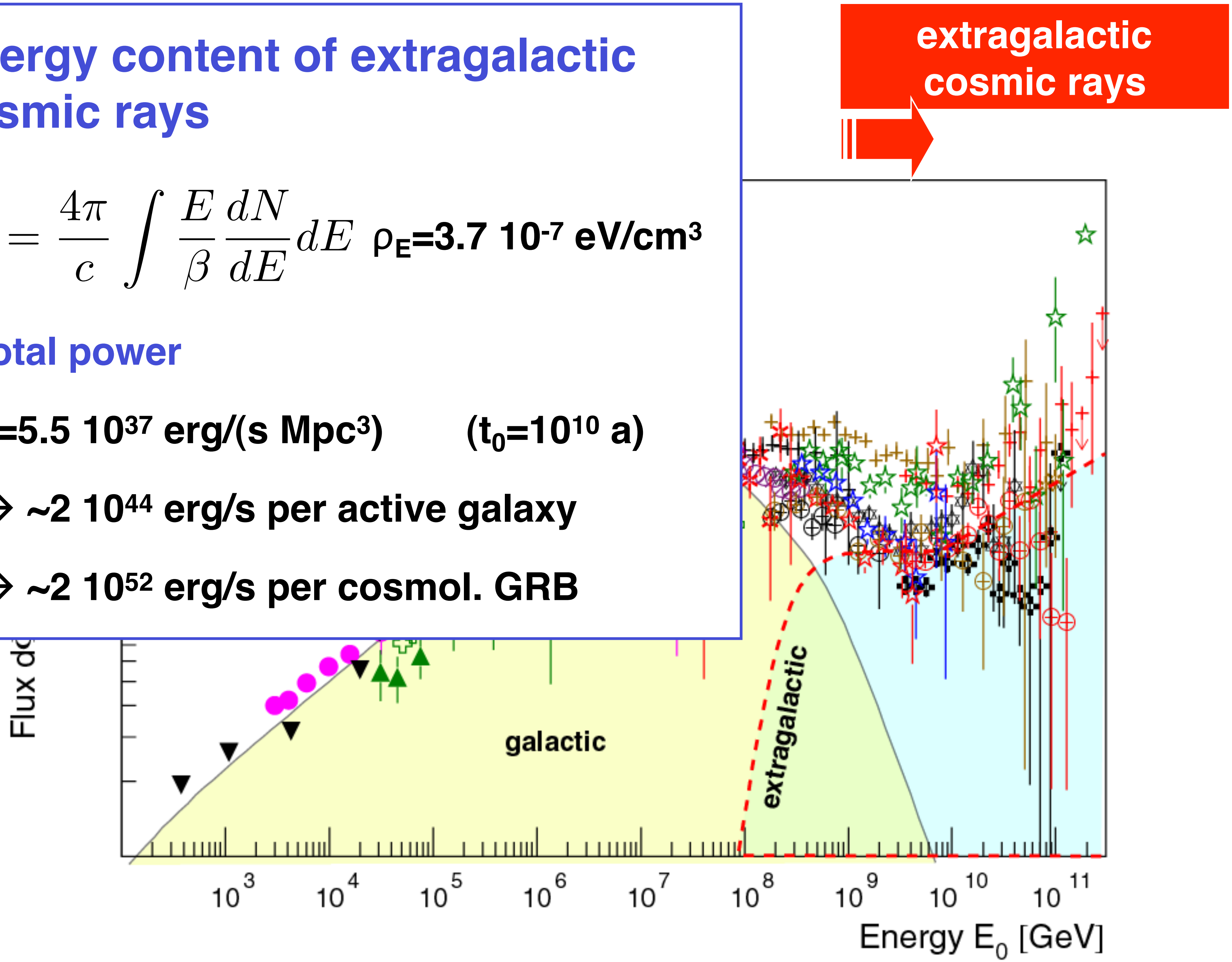
$$\rho_E = \frac{4\pi}{c} \int \frac{E}{\beta} \frac{dN}{dE} dE$$ ρ_E=3.7 10^{-7} eV/cm^3

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



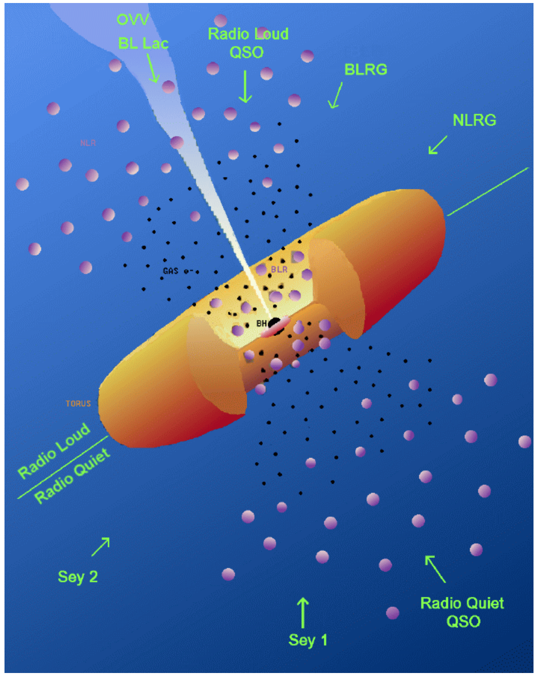
JRH, Rev. Mod. Astron. 20 (2008) 203 (arXiv:0803.3040)

Possible sources of extragalactic cosmic rays

Bottom up models

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

$$p + p \text{ or } p + \gamma \rightarrow \pi^{+/-} \rightarrow \nu_\mu + \nu_e + \ldots$$
$$\rightarrow \pi^0 \rightarrow \gamma + \gamma$$



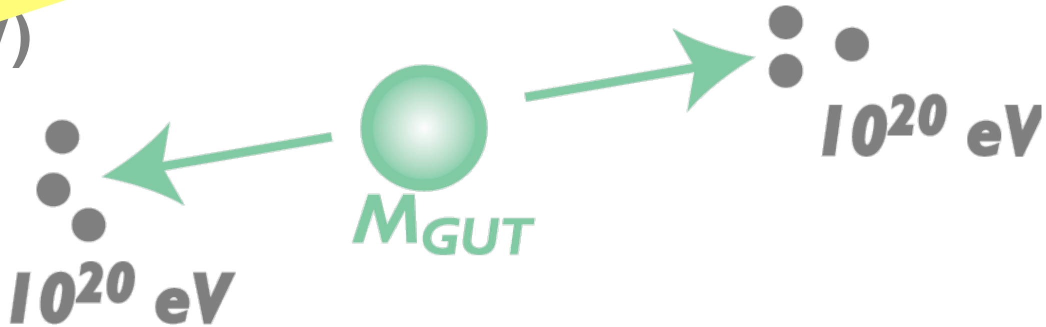
Top down models

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

X-particle (m ... eV)

...ons

γ, ν, p...

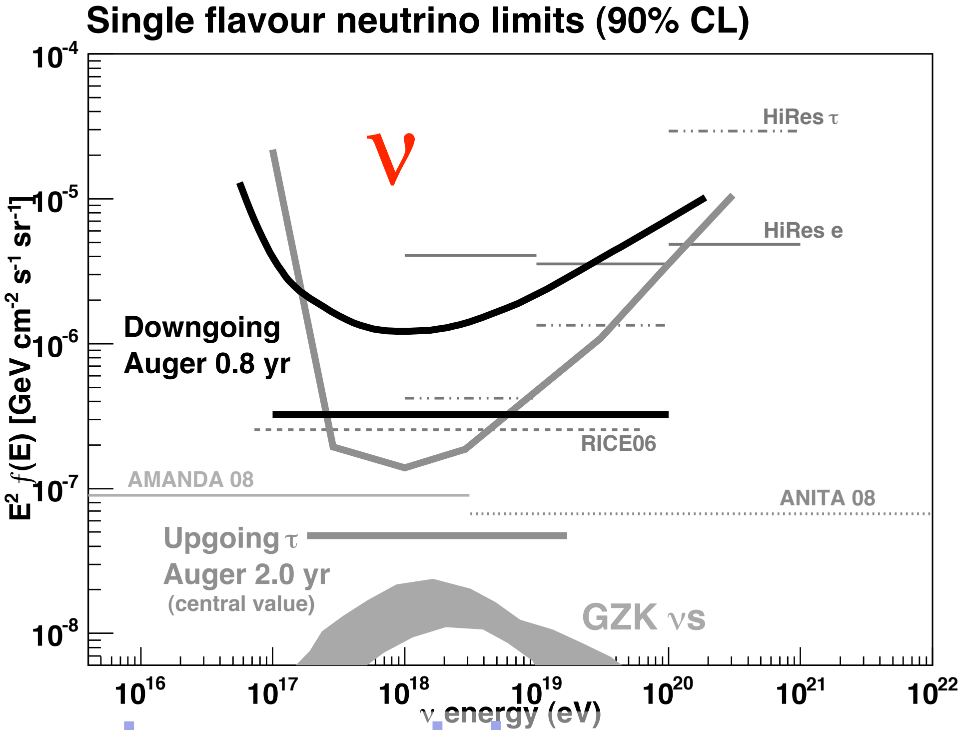


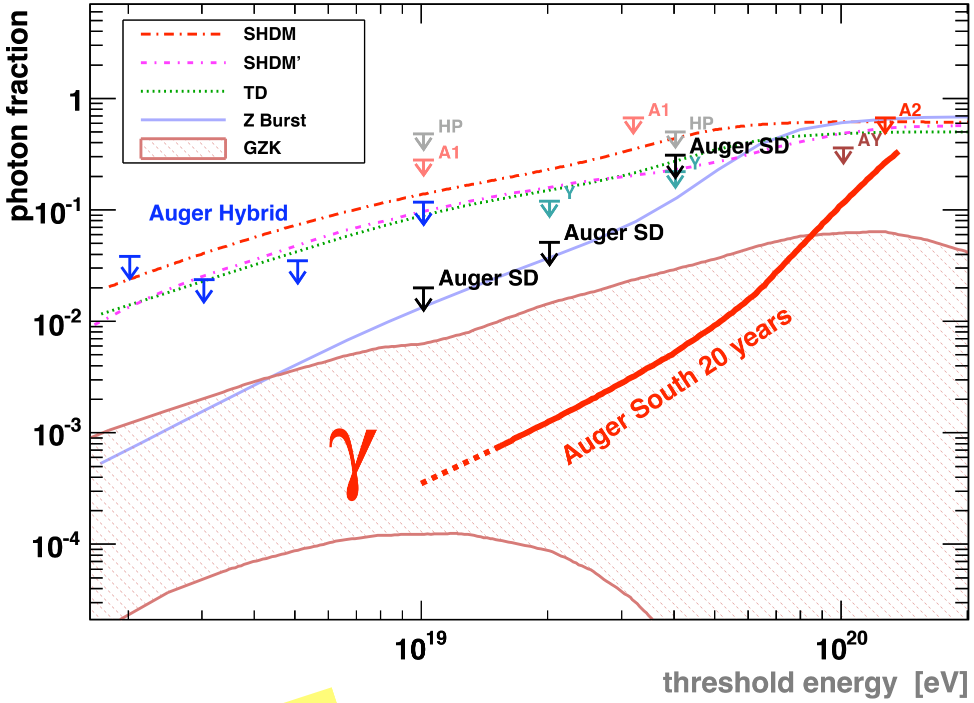
Already severe constraints by Auger

→ Multi Messenger Approach

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

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





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

Top down models

Super heavy relicts of Big-Ba... ...pol. defects)

X-particle (m ... eV)

...ons

γ, ν, p...

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

Which objects accelerate particles to 10^{20} eV?

Larmor radius in B field

$$r_L = 1.08 \frac{E_{15}}{Z B_{\mu G}} \text{ pc}$$

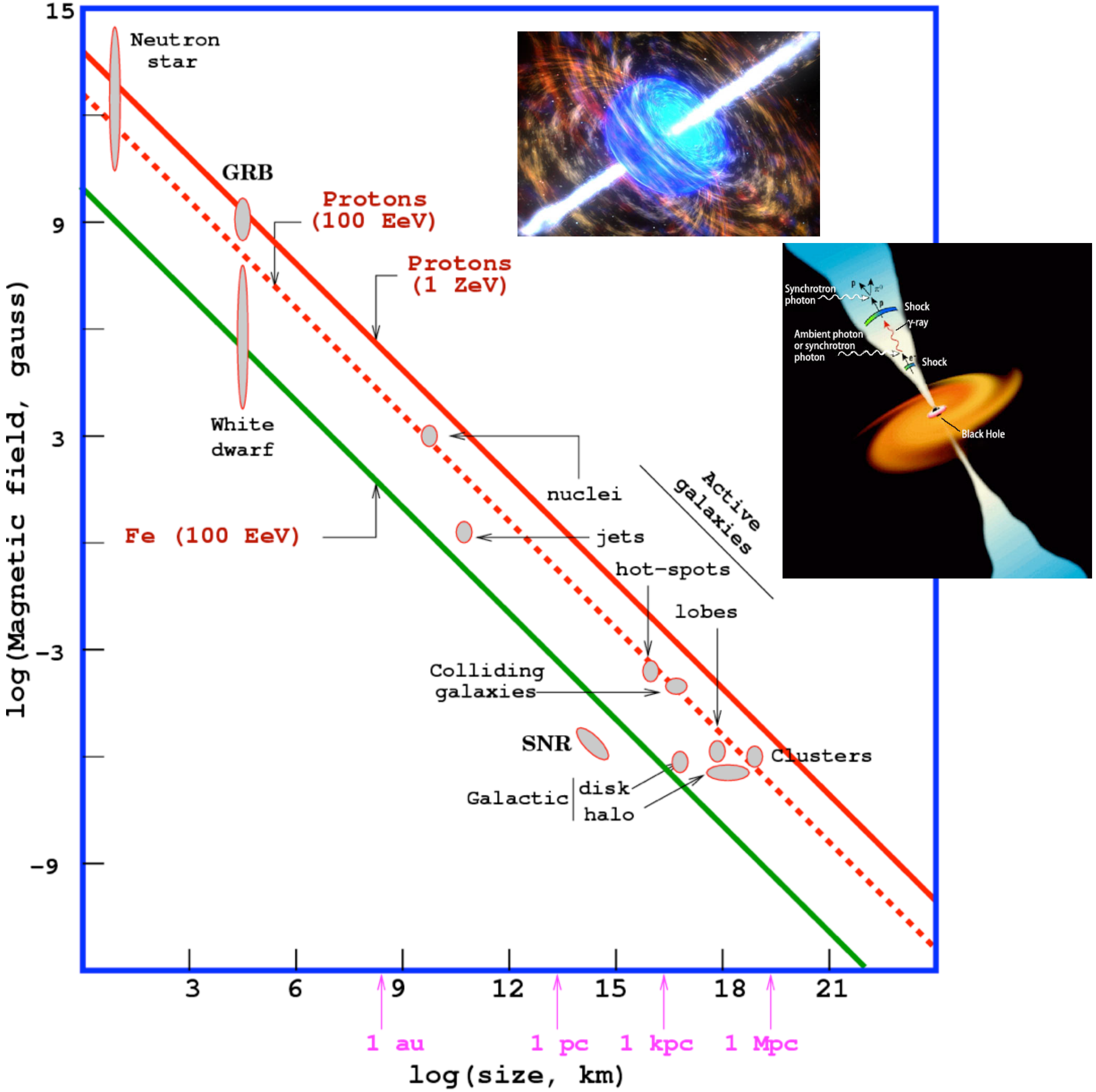
size of acceleration region

$$L > 2 r_L$$

Hillas relation

$$B_{\mu G} L_{pc} > \frac{2 E_{15}}{(Z\beta)}$$

Hillas-plot
(candidate sites for E=100 EeV and E=1 ZeV)



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

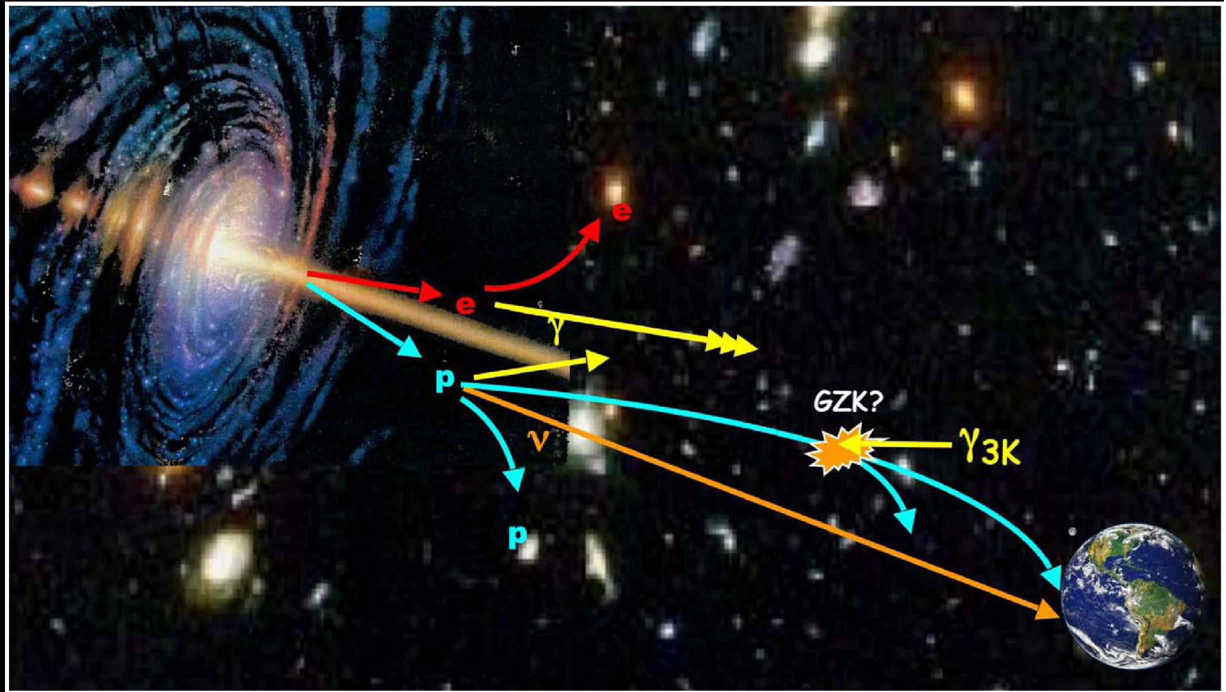
$E_{max} \sim ZBL\Gamma$ (Ultra-relativistic shocks-GRB)

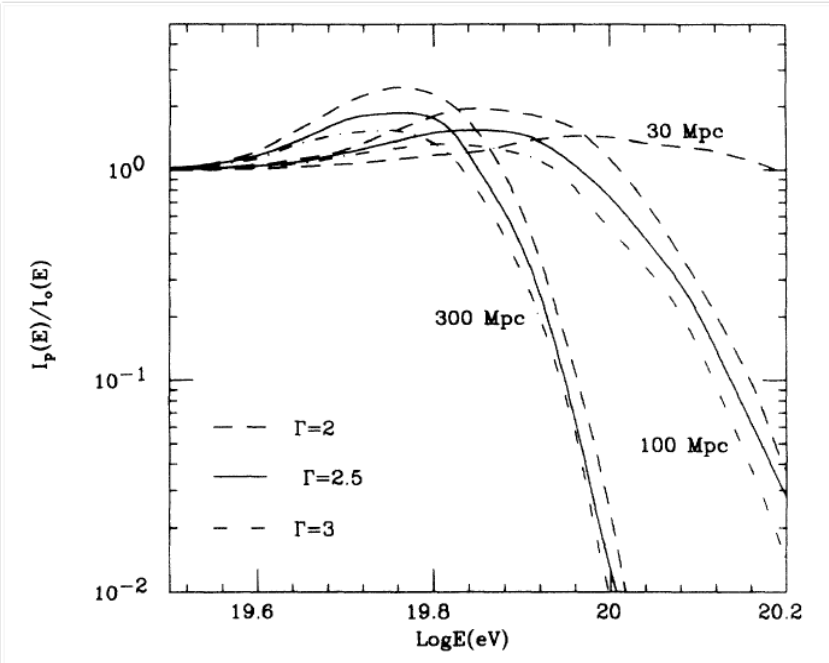
M. Ostrowski, Astropart. Phys. 18 (2002) 229

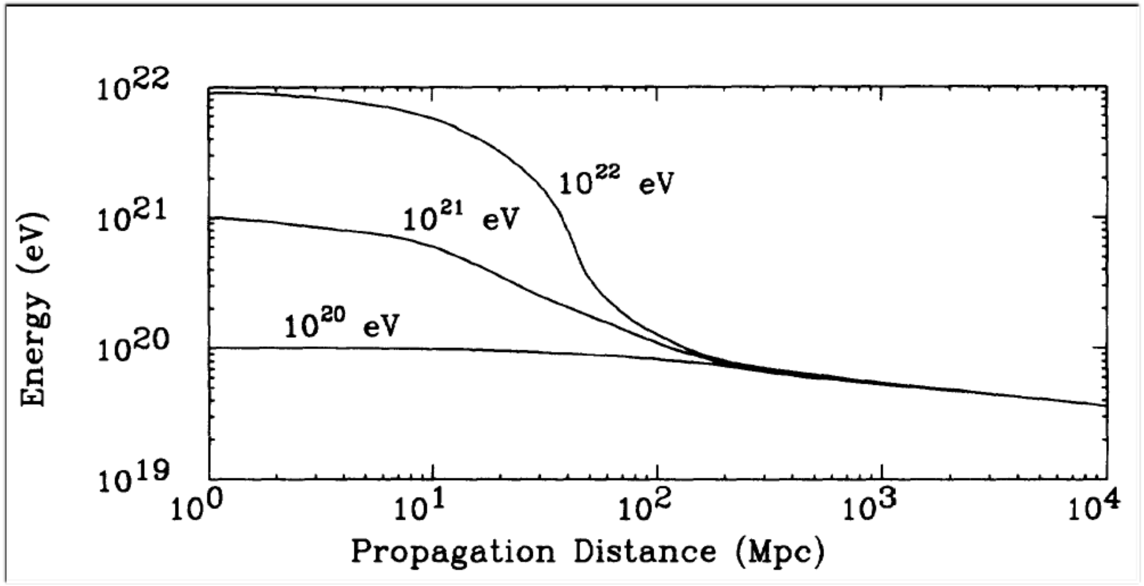
„Optical depth“ of the Universe – The GZK Effect

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

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



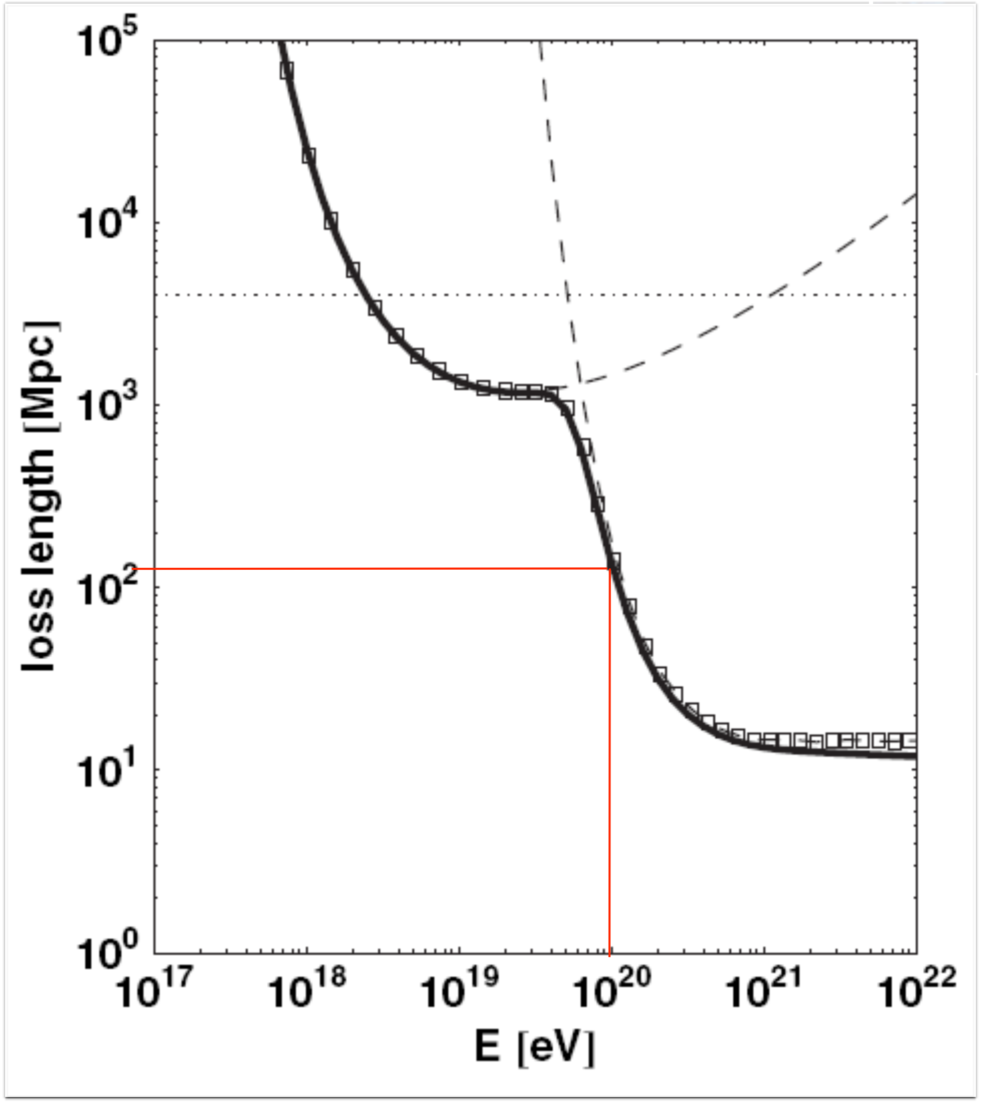


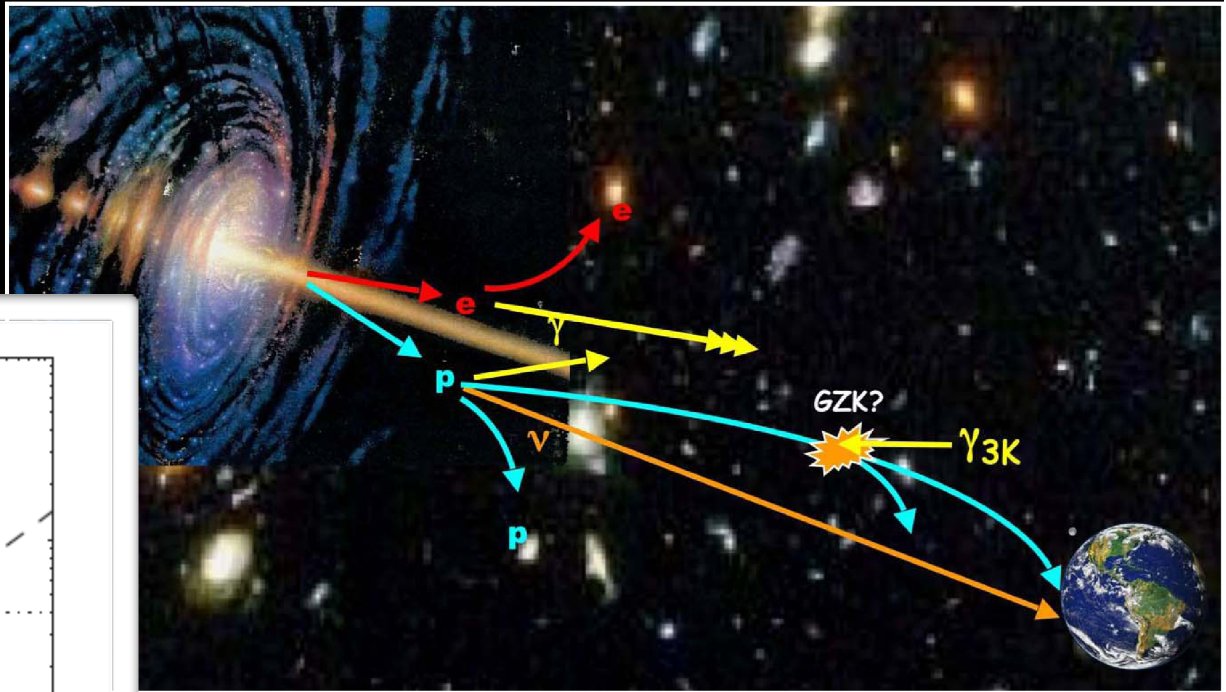


F.A. Aharonian, J.W. Cronin, Phys. Rev. D 50 (1994) 1892

„Optical depth“ of the Universe – The GZK Effect

Energy loss length

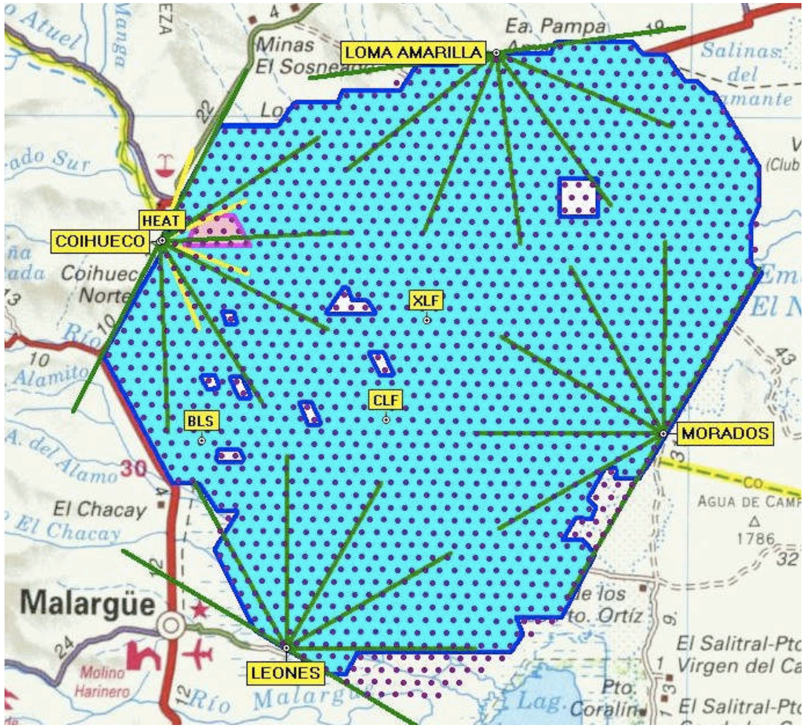




⇒ **at highest energies field of view is reduced to < 100 Mpc**

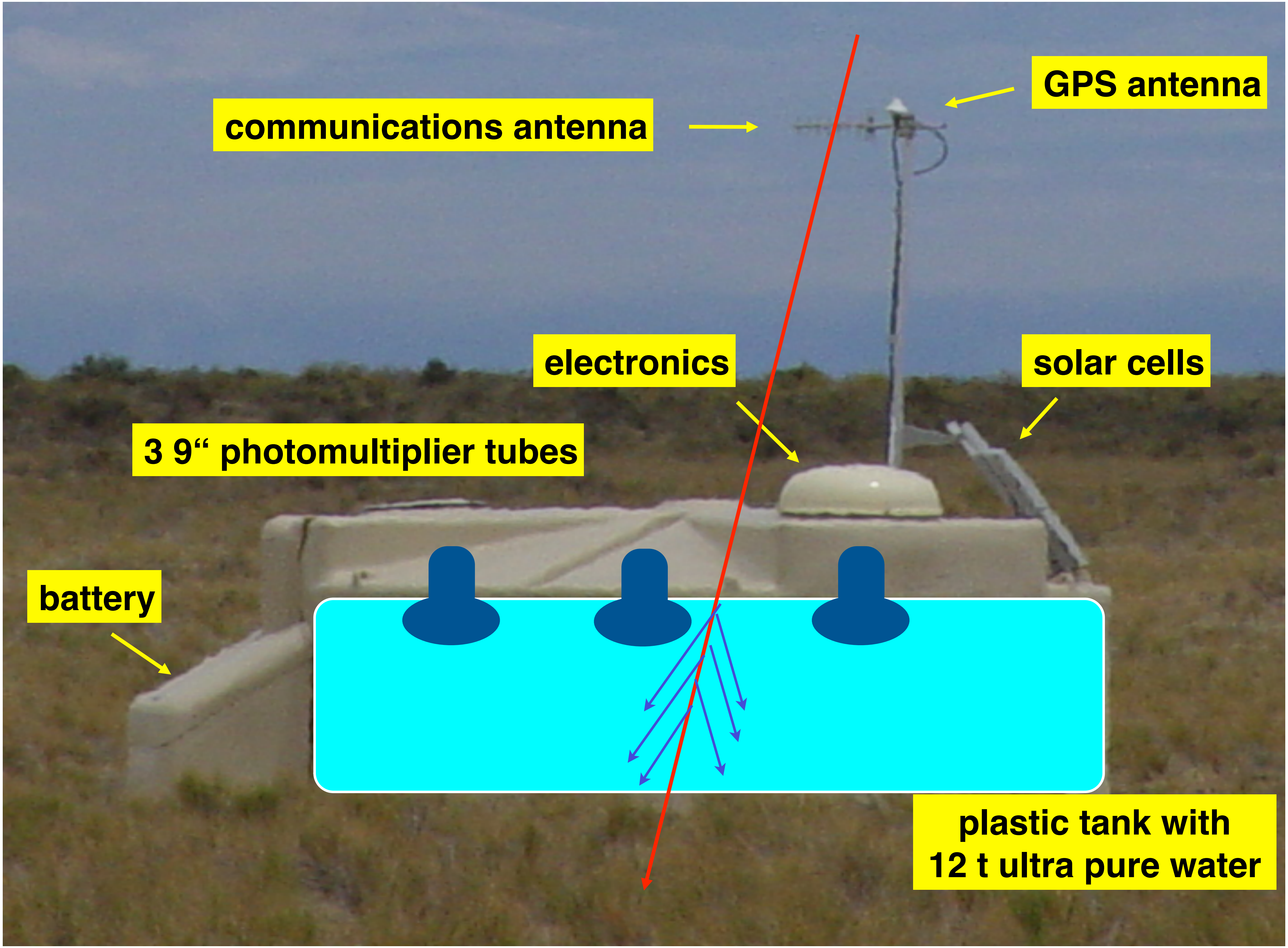
Stanev & de Marco, PRD 72 (2005) 081301

The Pierre Auger Observatory

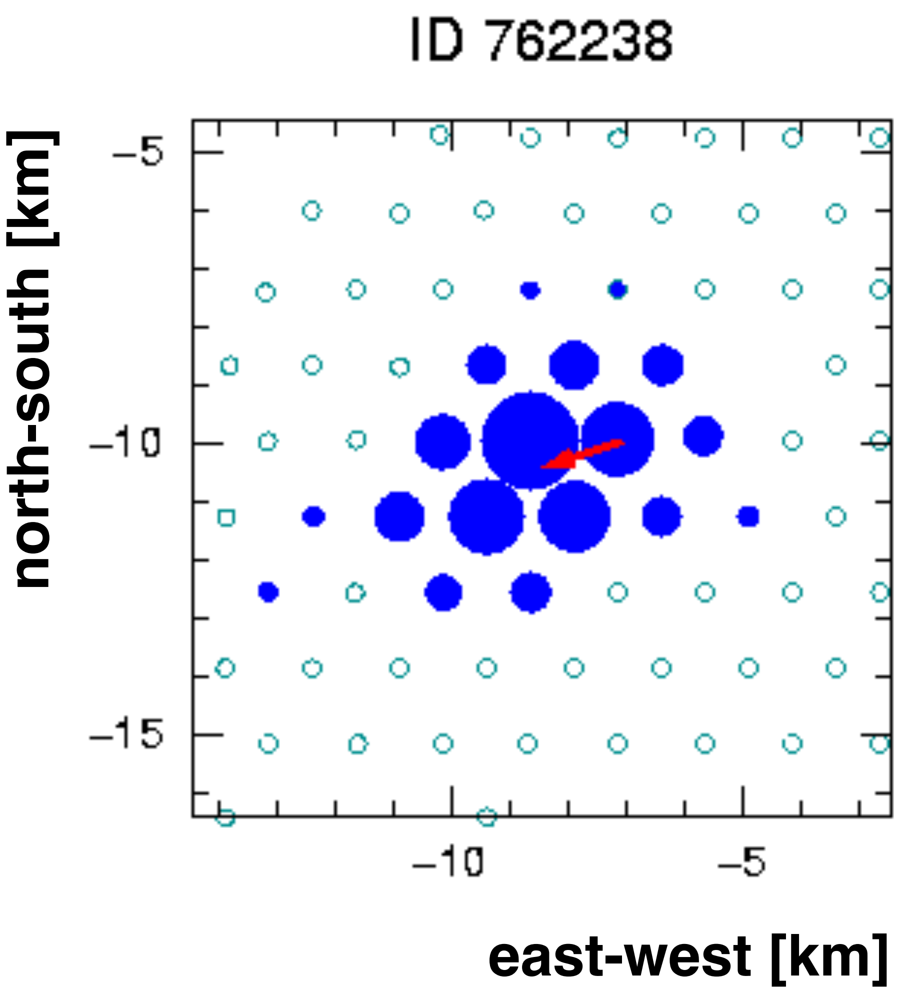


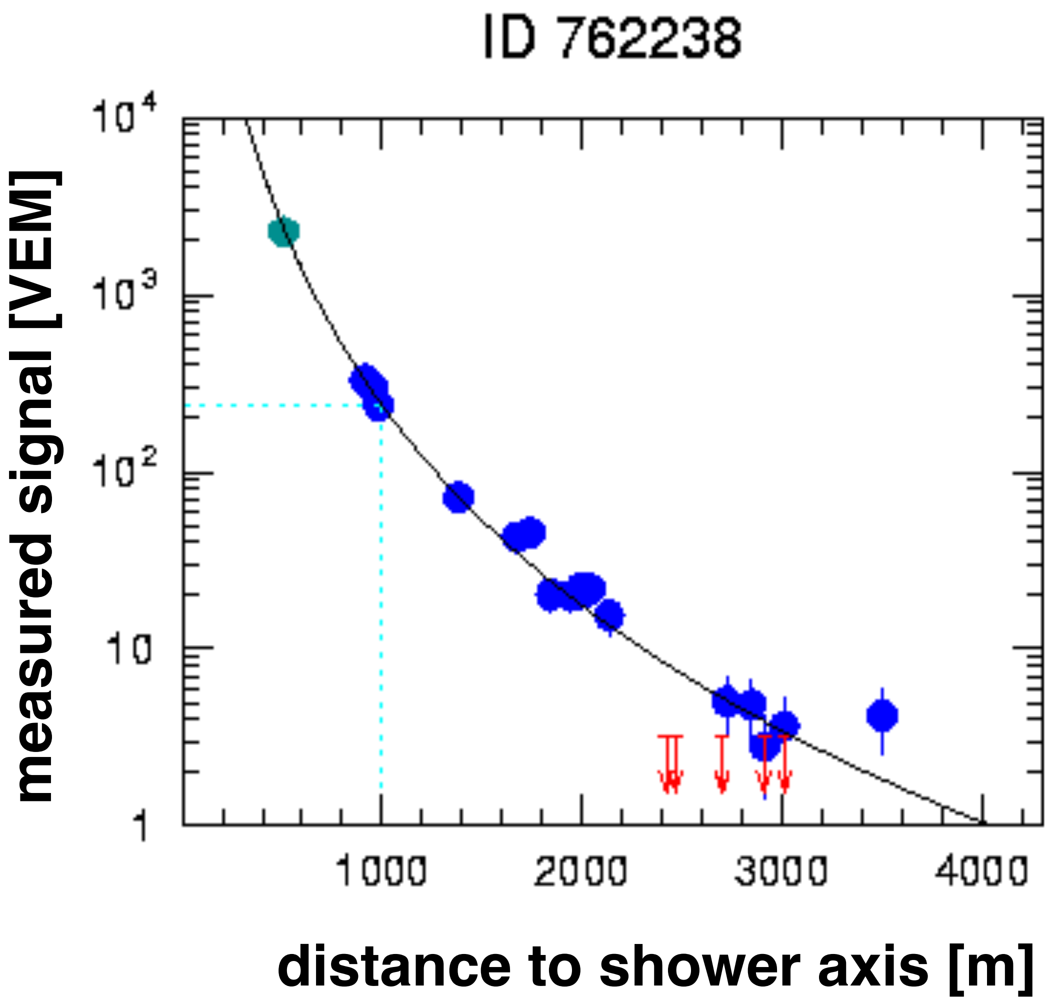
3000 km²
1600 water Cherenkov detectors

4 telescope buildings
6 fluorescence telescopes each

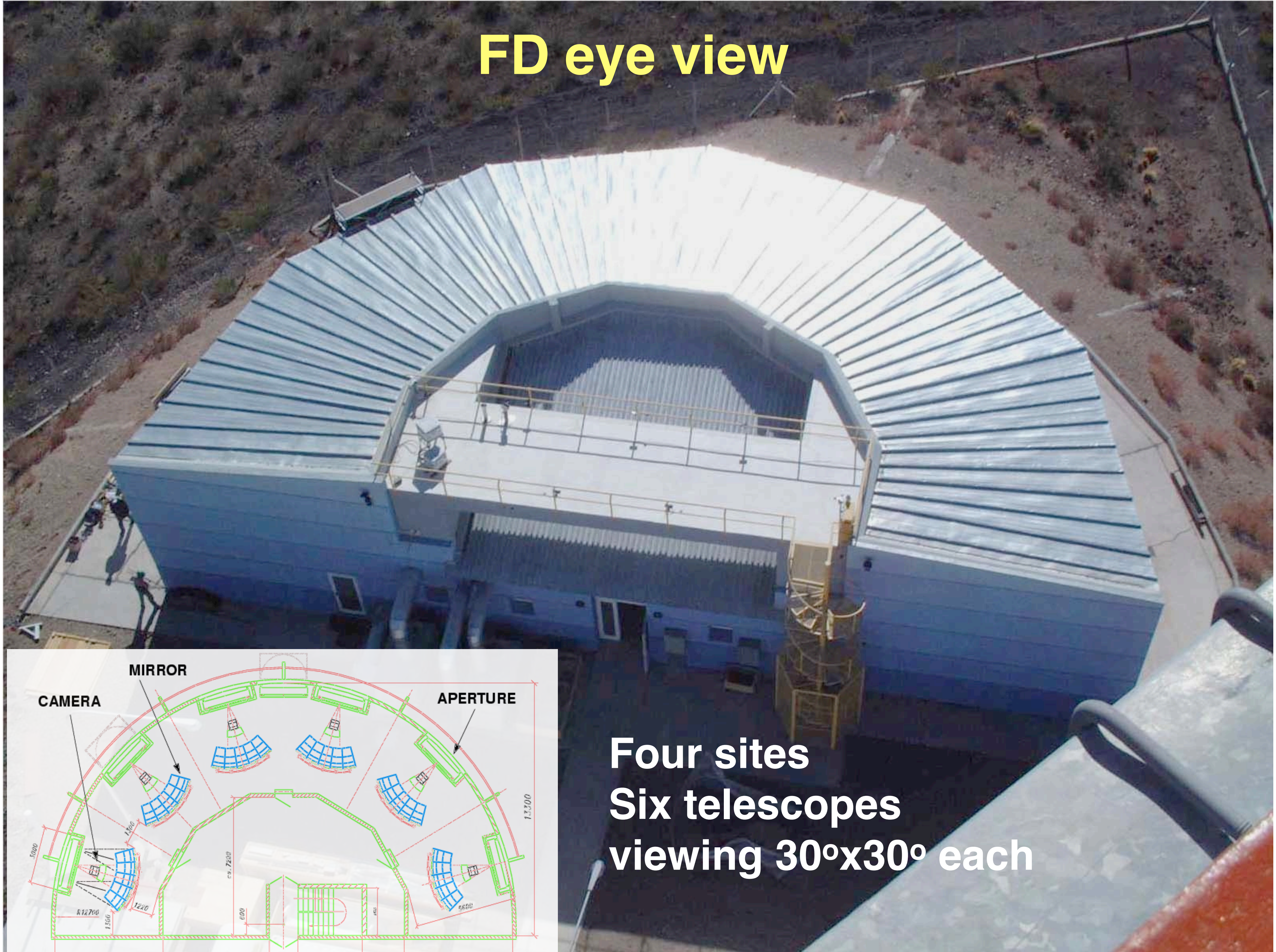

GPS antenna
communications antenna
electronics
solar cells
3 9“ photomultiplier tubes
battery
plastic tank with
12 t ultra pure water

Air shower registered with water Cherenkov detectors

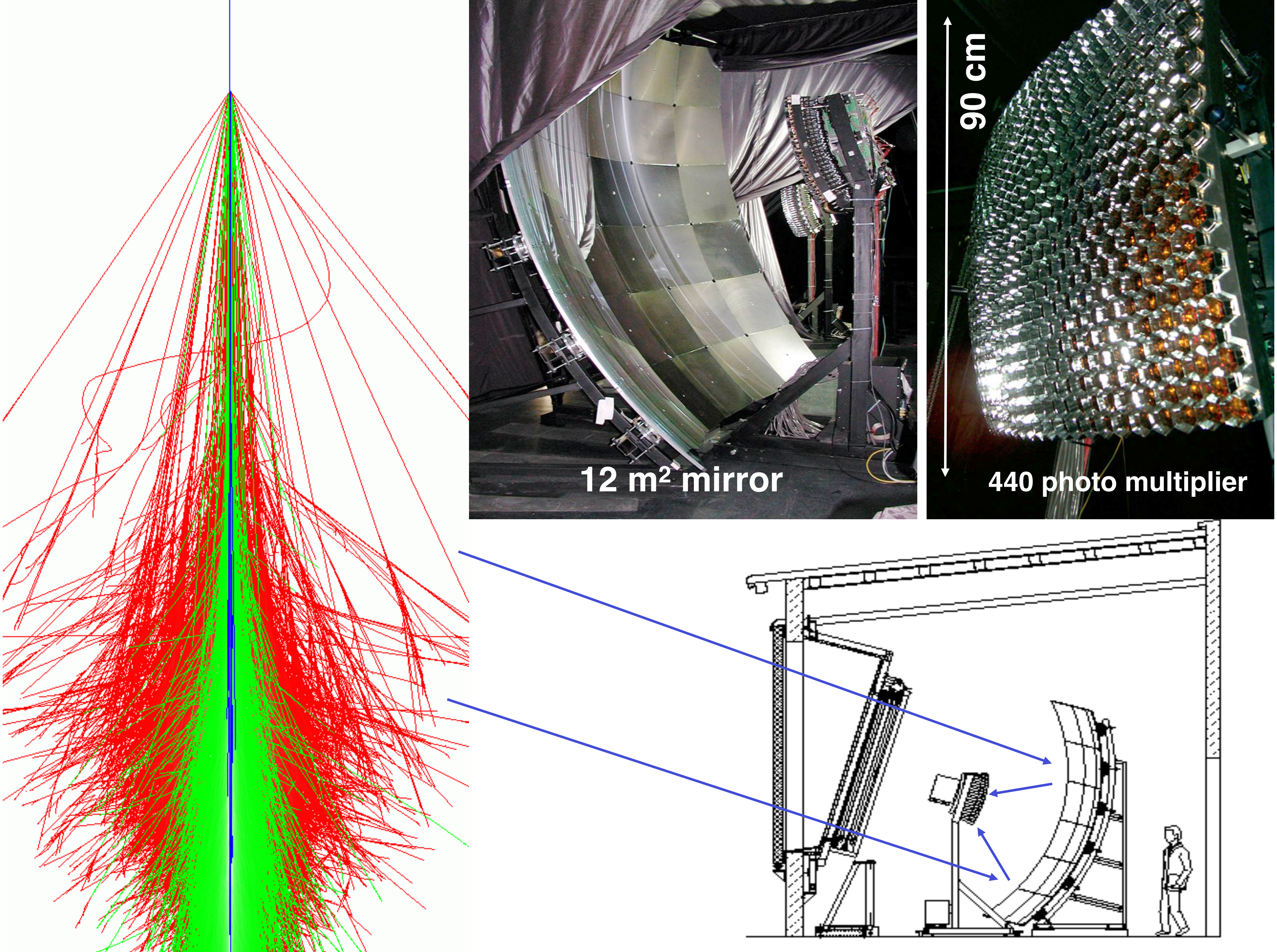


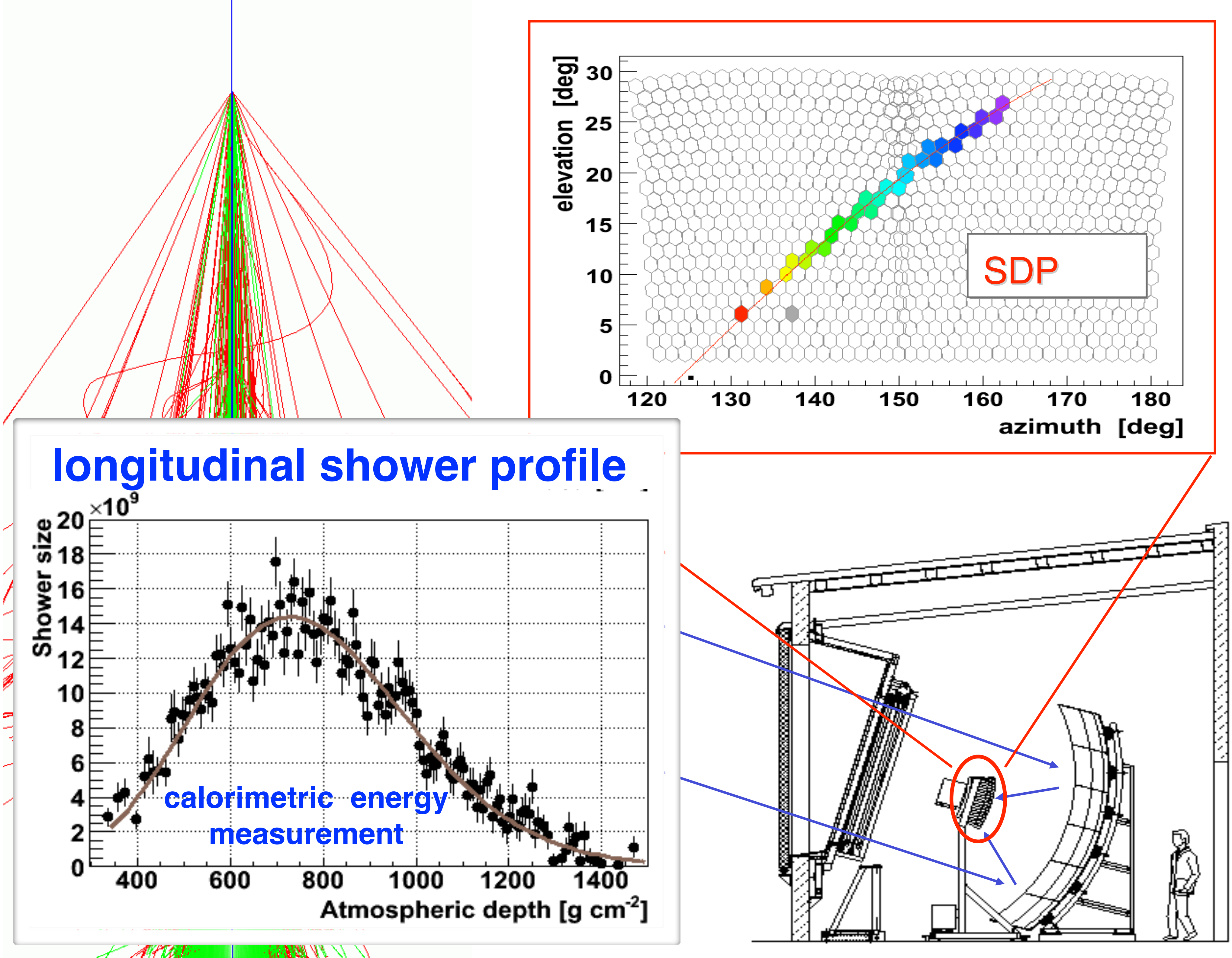


FD eye view



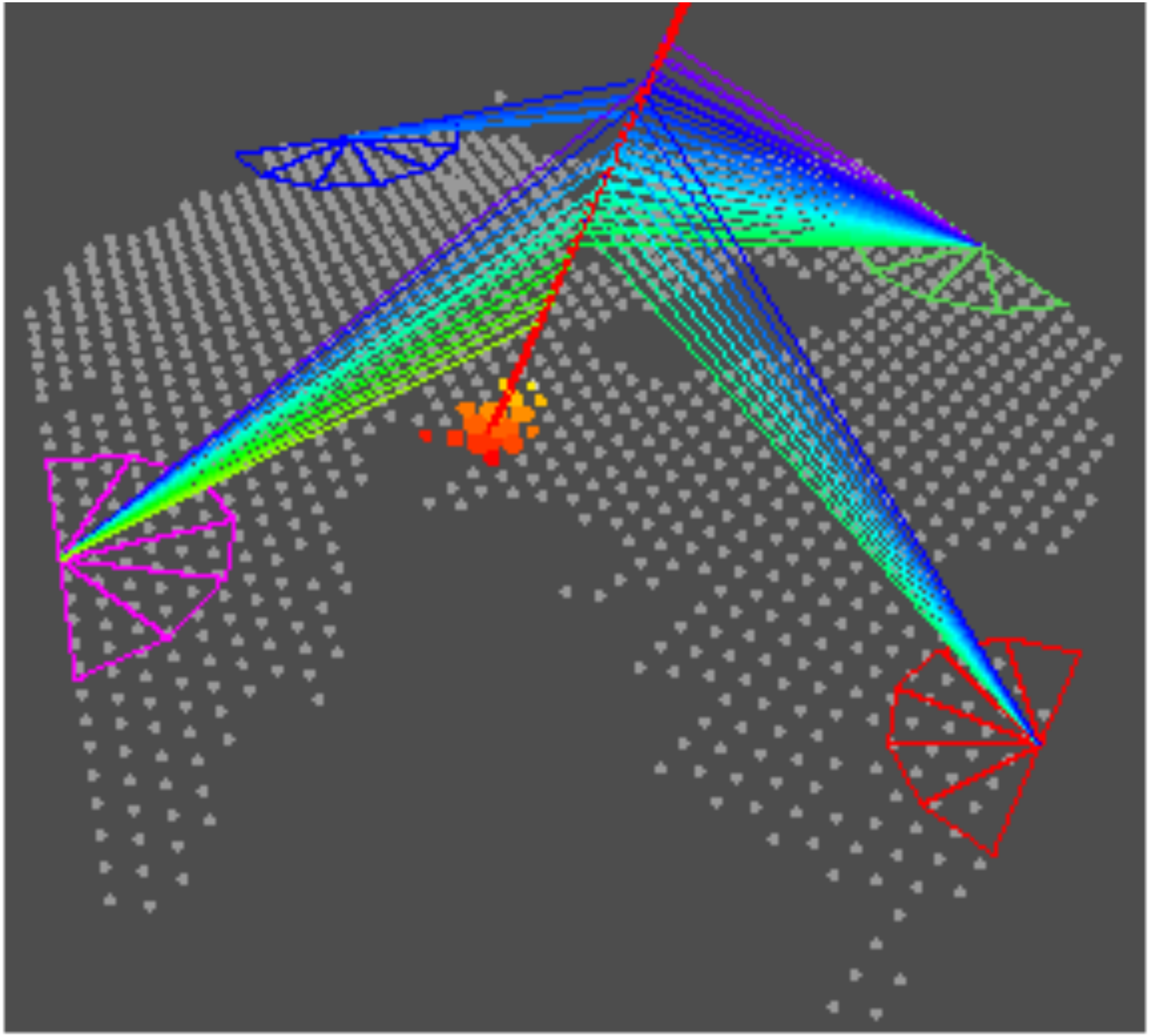
Four sites
Six telescopes
viewing 30°x30° each


12 m² mirror
90 cm
440 photo multiplier



elevation [deg]
30
25
20
15
10
5
0
120
130
140
150
160
170
180
azimuth [deg]
SDP
longitudinal shower profile
×10^9
Shower size
20
18
16
14
12
10
8
6
4
2
0
400
600
800
1000
1200
1400
Atmospheric depth [g cm^-2]
calorimetric energy
measurement

A Hybrid Event



20 May 2007   E ~ 10^{19} eV

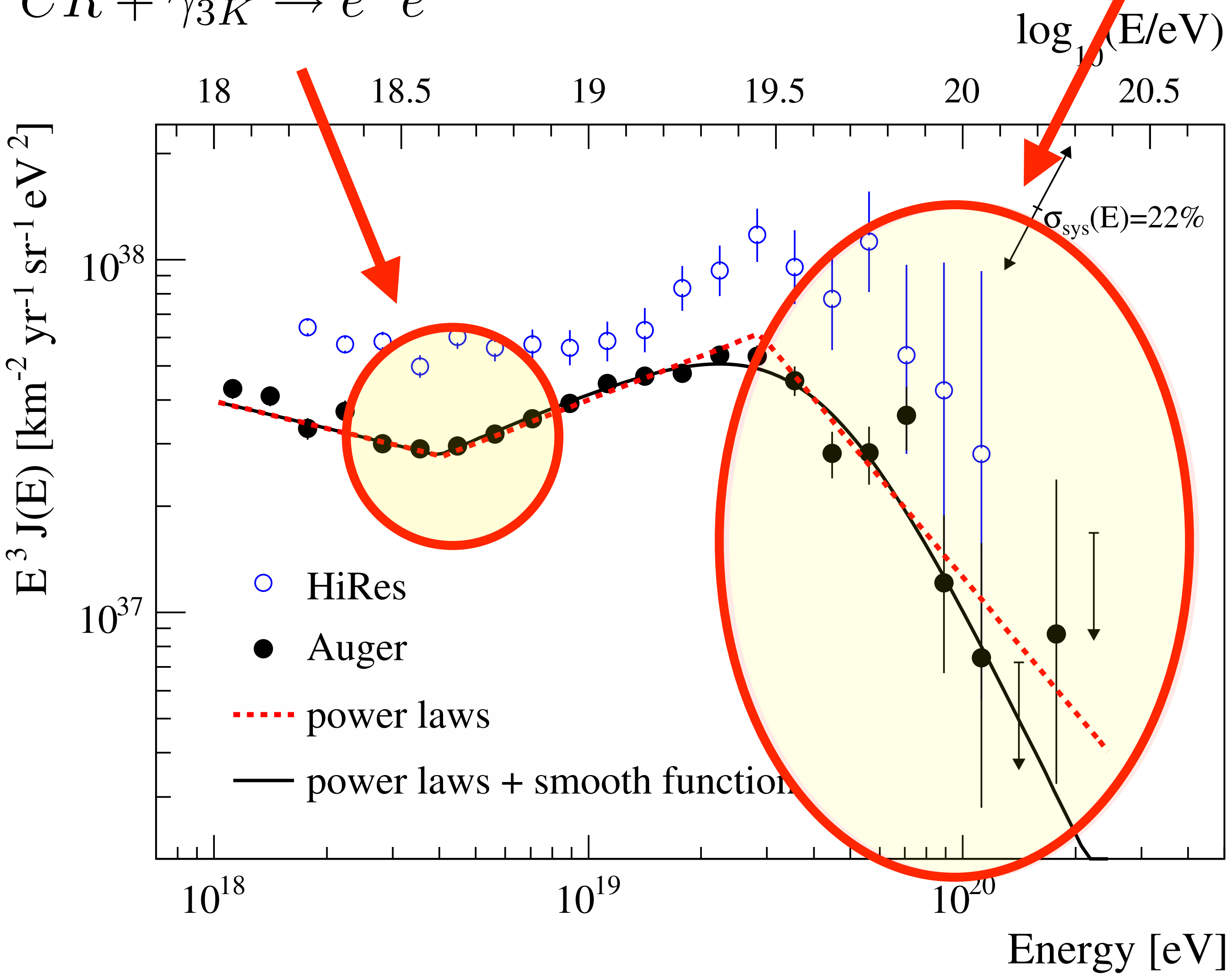
Energy spectrum

ankle E=4 10^{18} eV

pair production at 3-K photons

$$CR + \gamma_{3K} \rightarrow e^+ e^-$$

depression E>4 10^{19} eV



- **photo pion production at 3-K photons GZK effect**

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

➡ **light composition**

- **maximum energy of accelerators**

$$E_{max} \propto Z \cdot B \cdot L$$

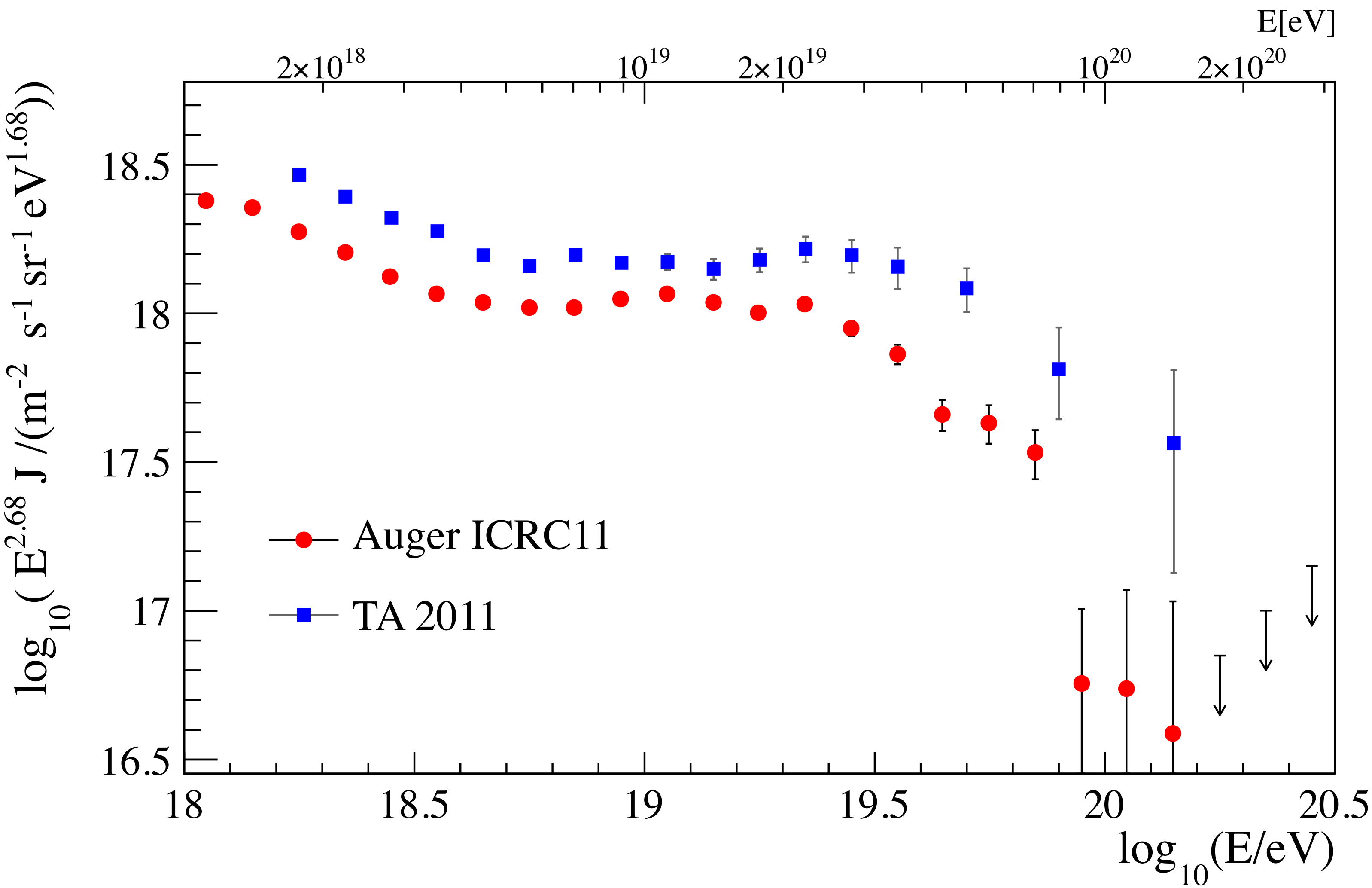
(Hillas condition)

➡ **heavy composition**

J. Abraham et al., Physics Letters B 685 (2010) 239

Cosmic-ray spectrum at highest energies

Comparison of Spectra

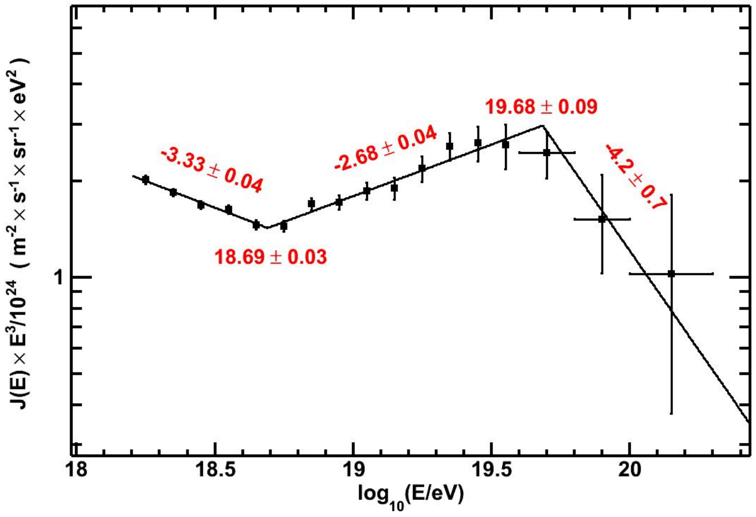


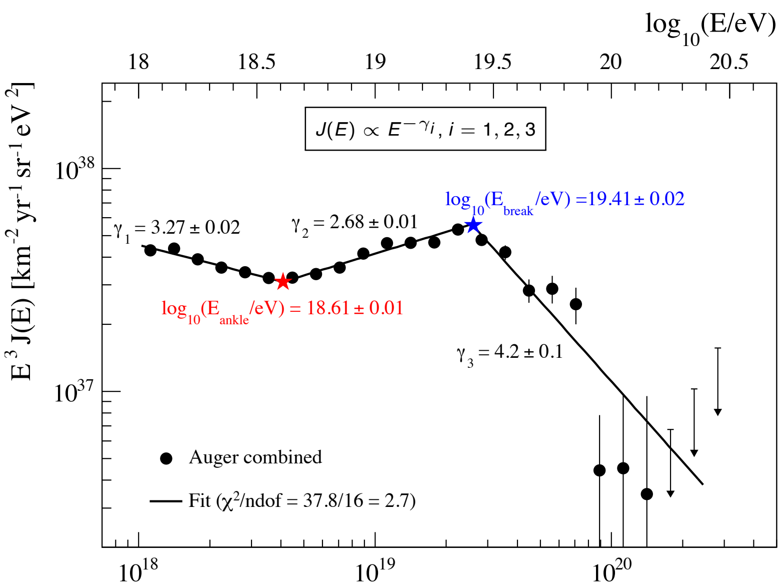
energy scale difference of ∼ 20%?

M. Unger, ICRC 2011

Cosmic-ray spectrum at highest energies

Comparison of spectral features





	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

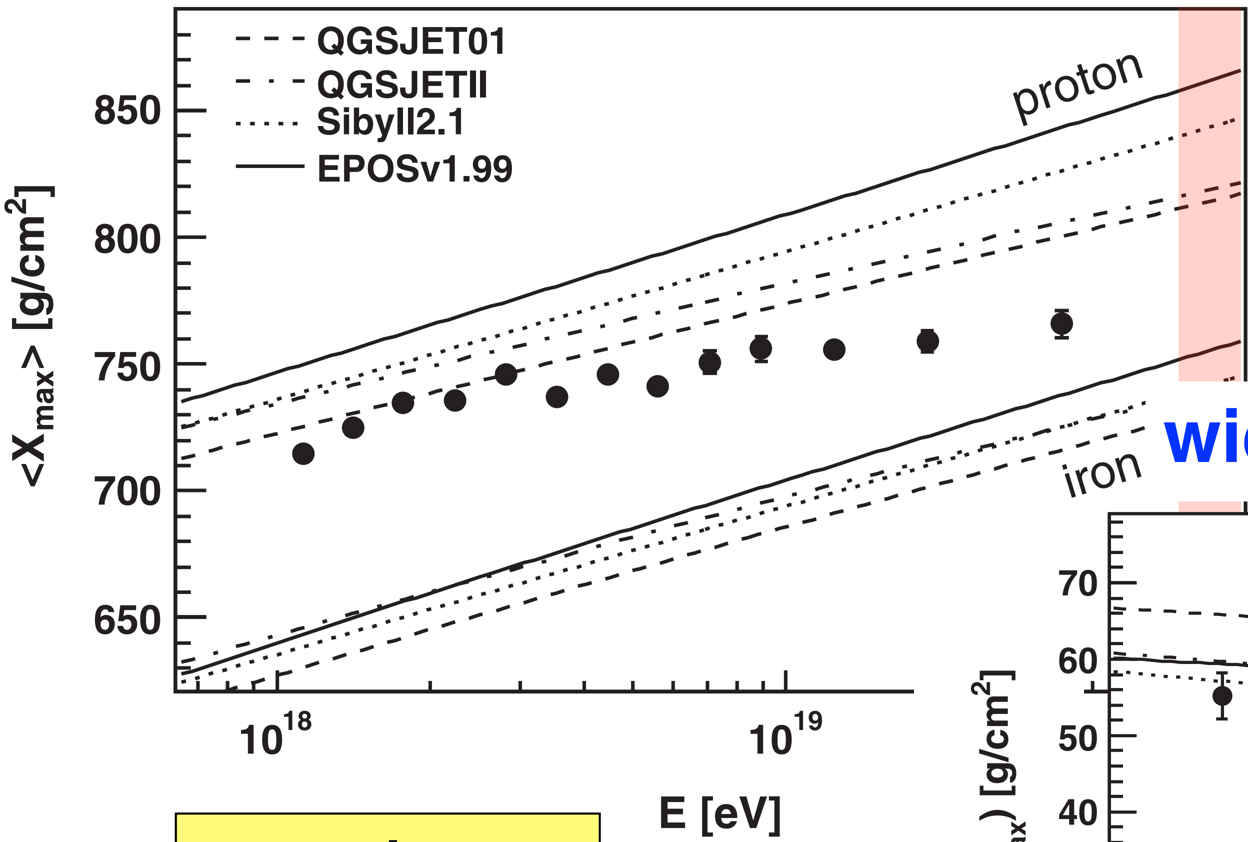
B. Stokes [TA Coll.], icrc1297

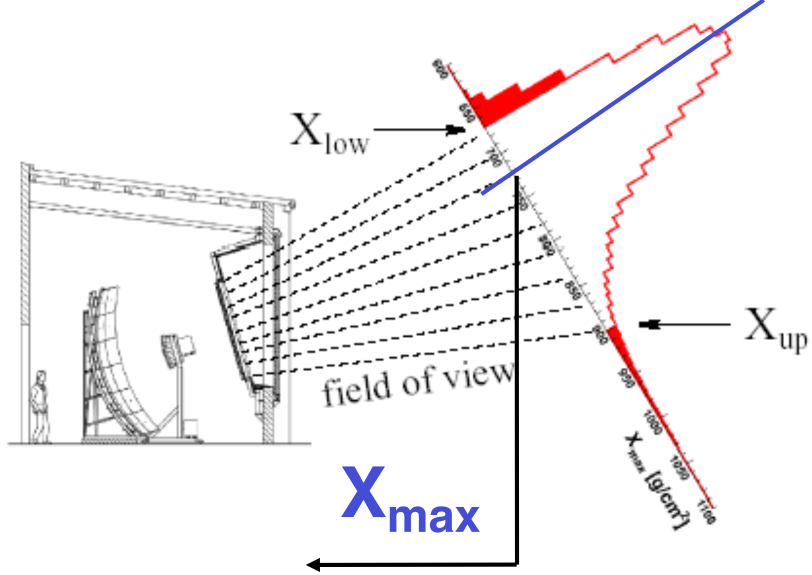
F. Salamida [Auger Coll.], icrc893

M. Unger, ICRC 2011

Mass Composition

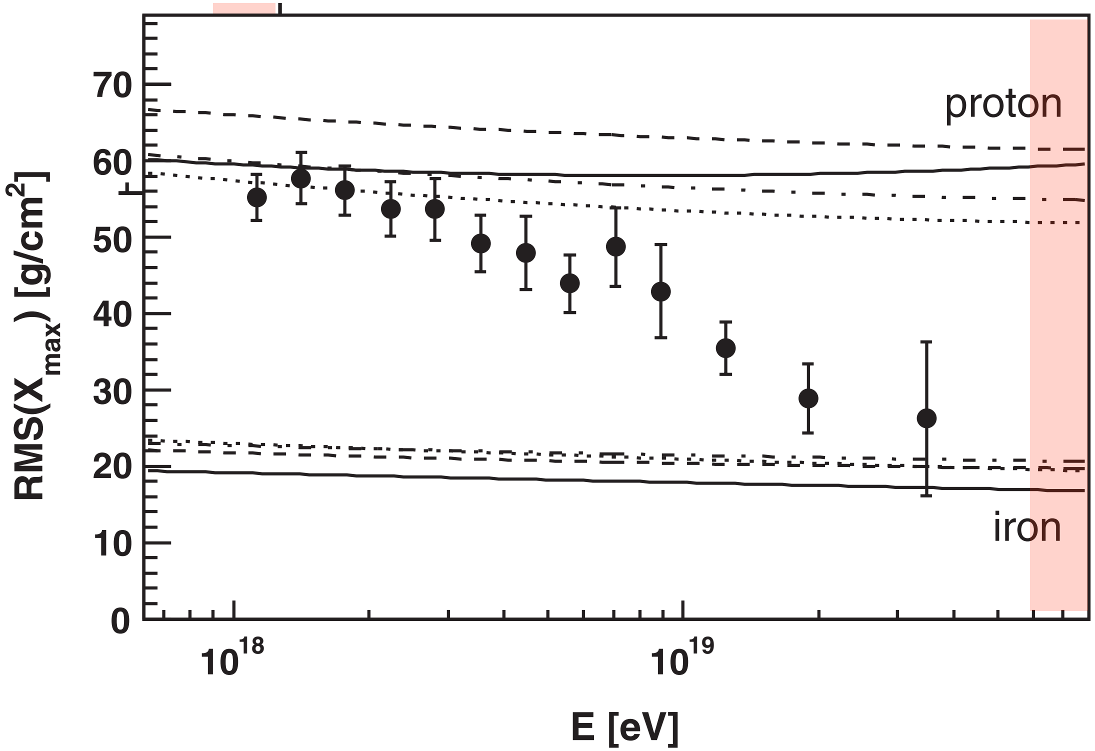
Depth of the shower maximum X_{max}





remember:
GZK effect requires light particles!

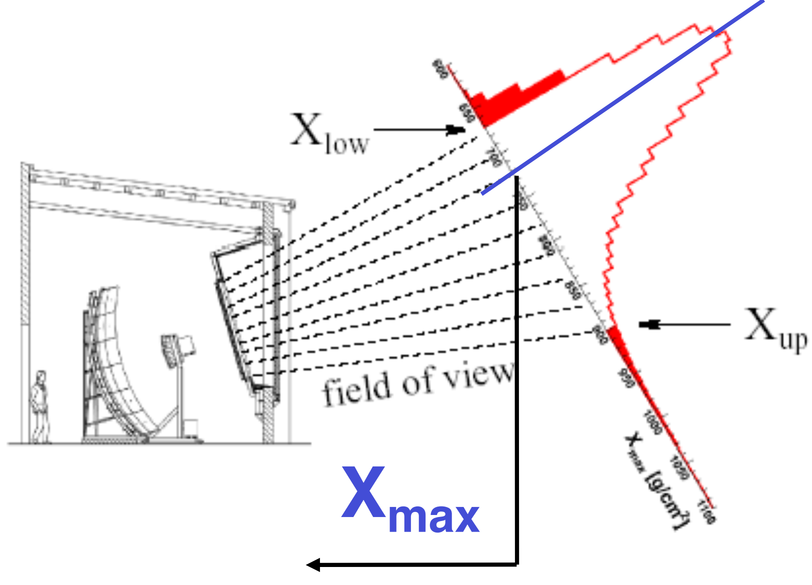
width of X_{max} distribution

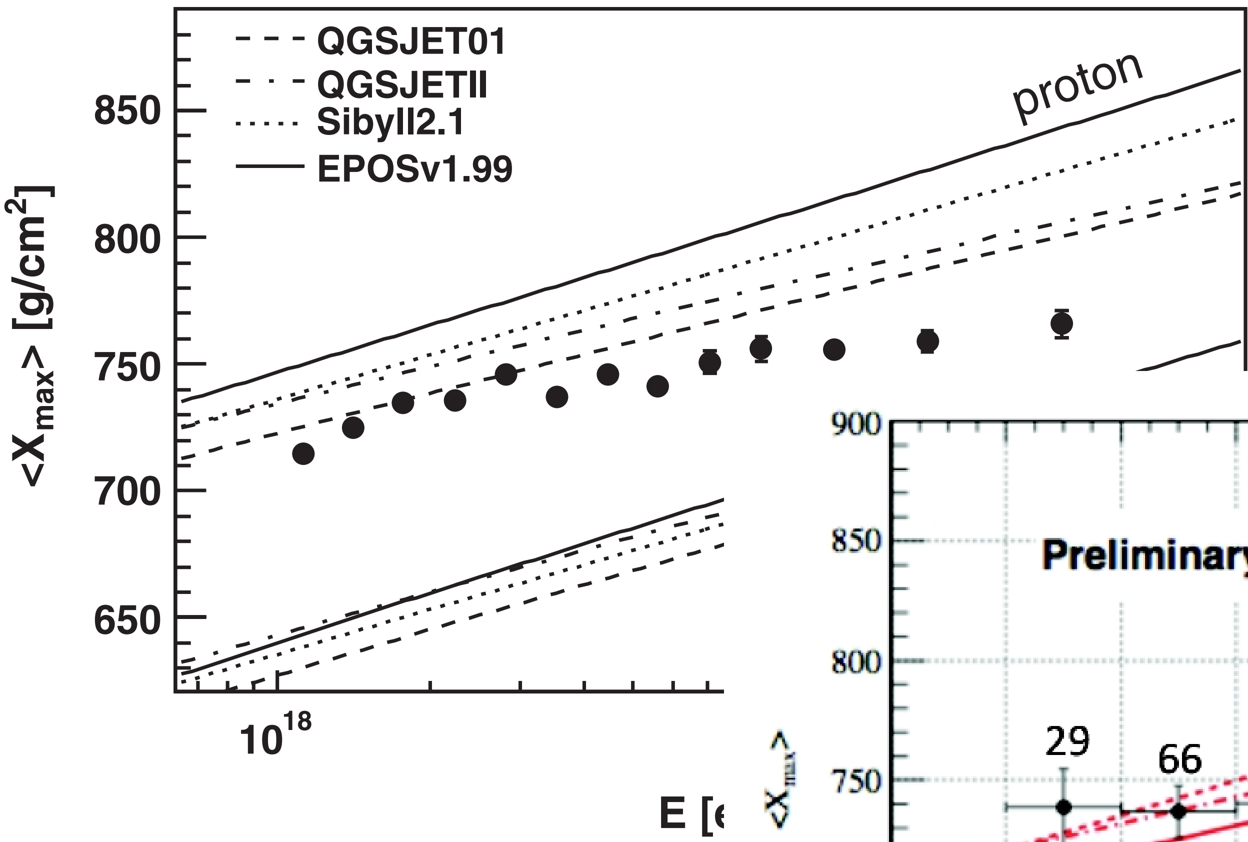


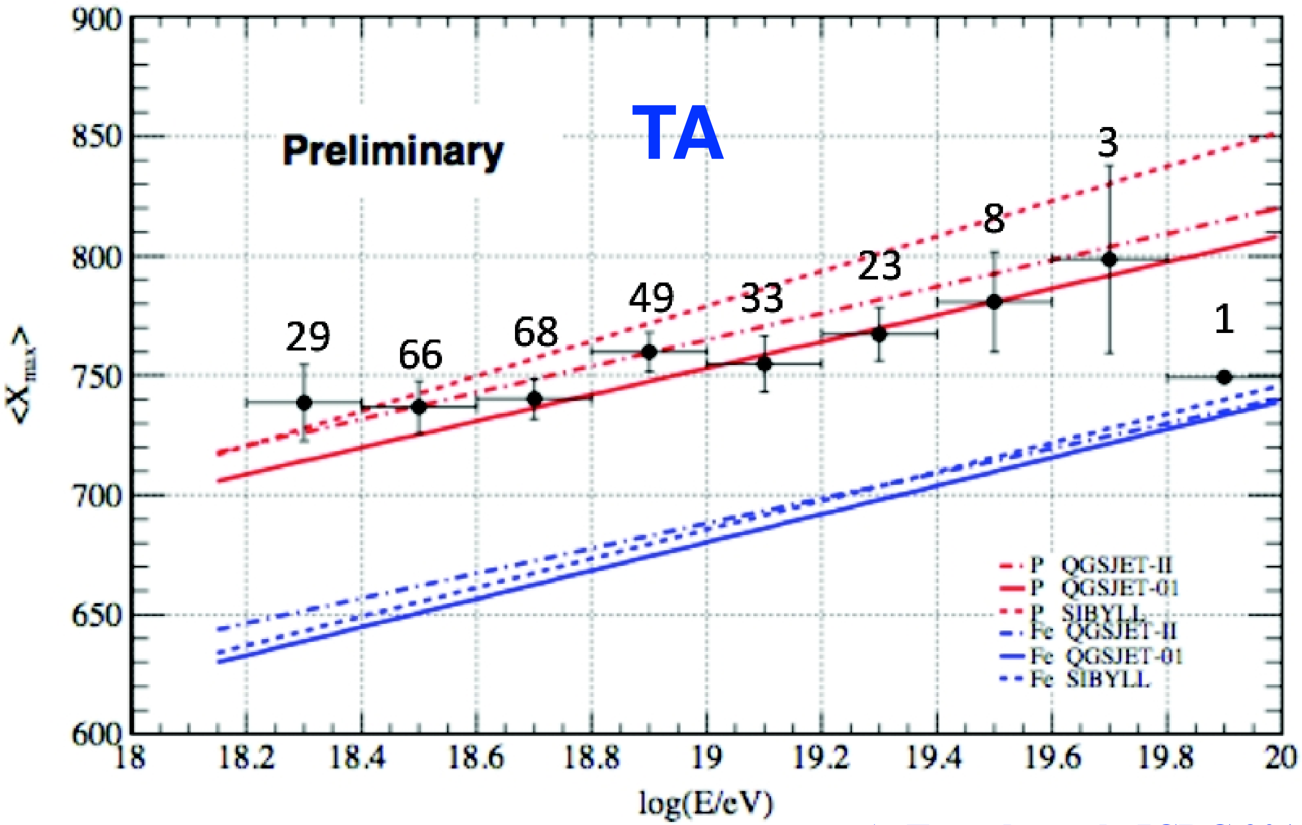
J. Abraham et al., Physical Review Letters 104 (2010) 091101

Mass Composition

Depth of the shower maximum X_{max}







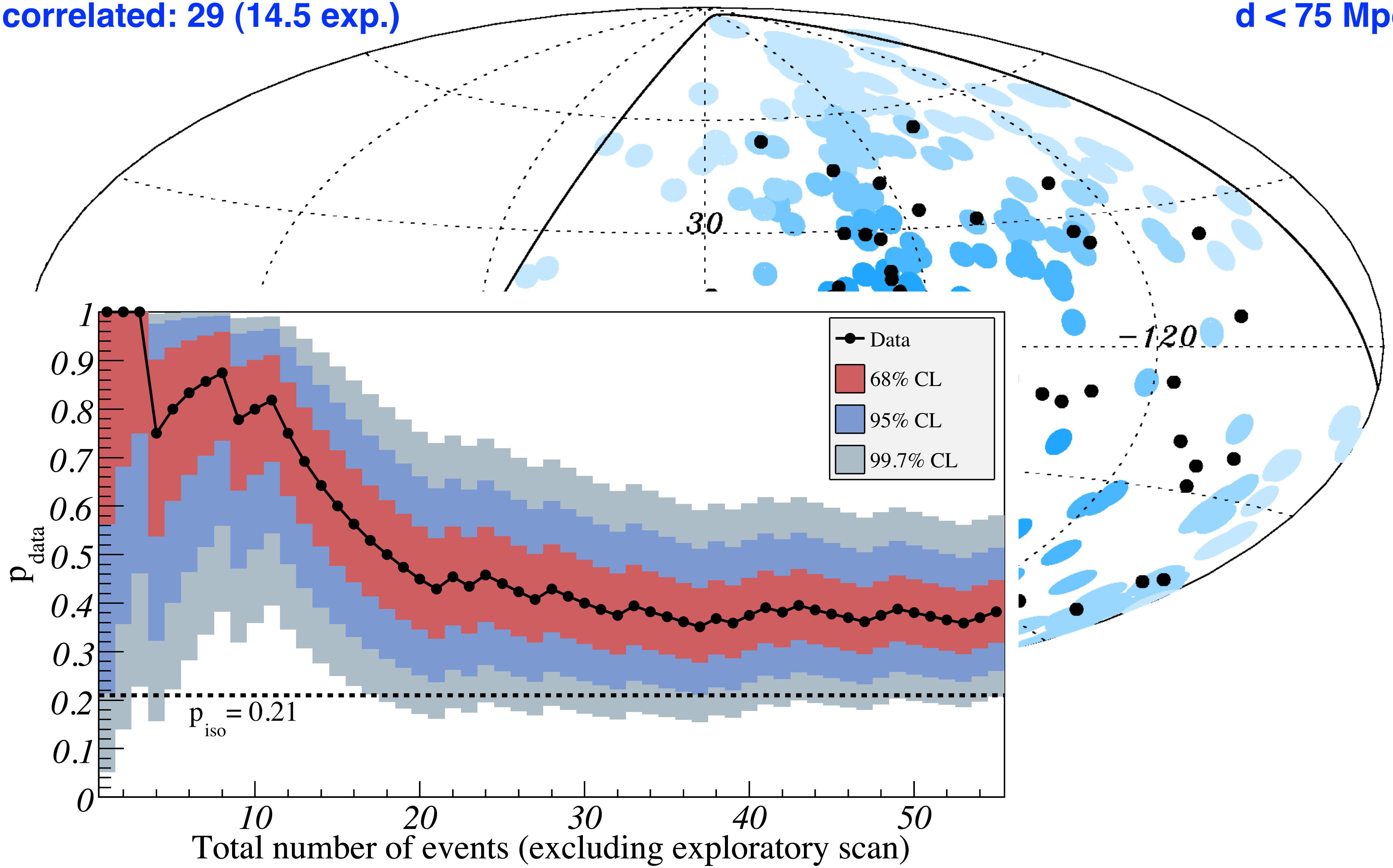
J. Abraham et al., Physical Review Letters 104

A. Tameda et al., ICRC 2011

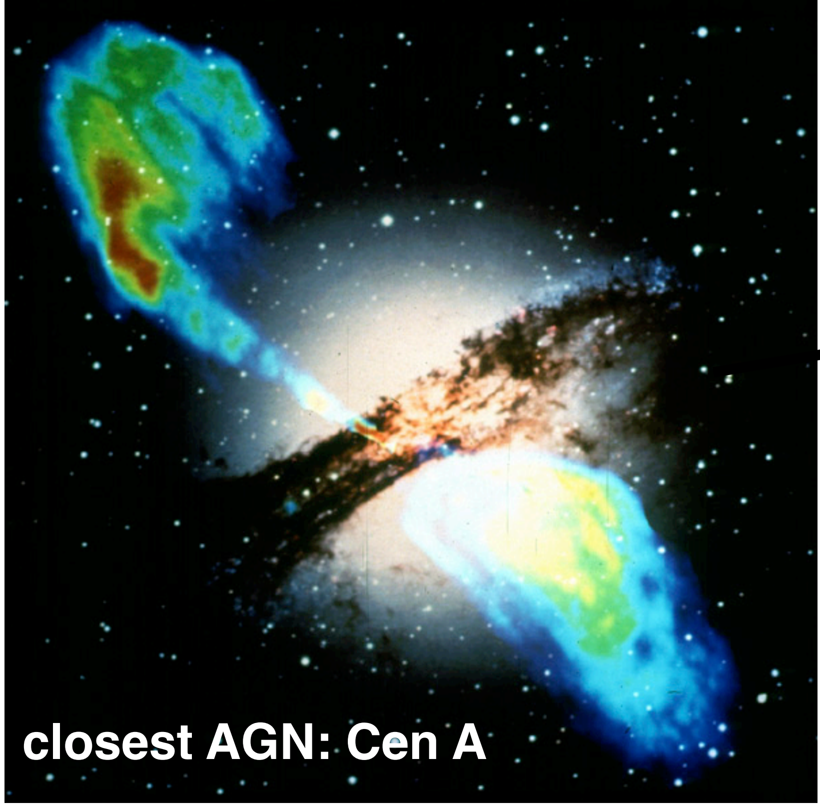
Arrival directions of highest-energy cosmic rays

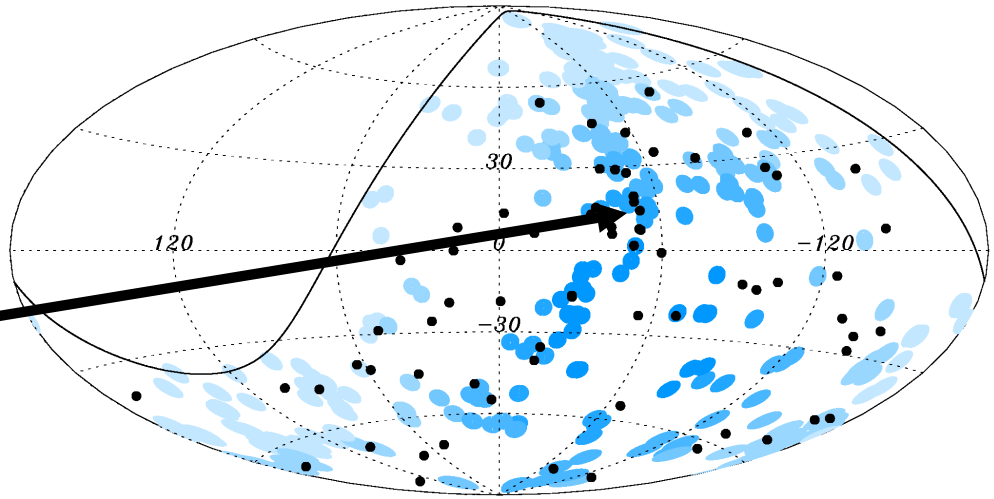
data up to 31.12.2009
69 events E > 55 EeV
correlated: 29 (14.5 exp.)

position of AGNs from
VCV catalog (3.1°)
d < 75 Mpc

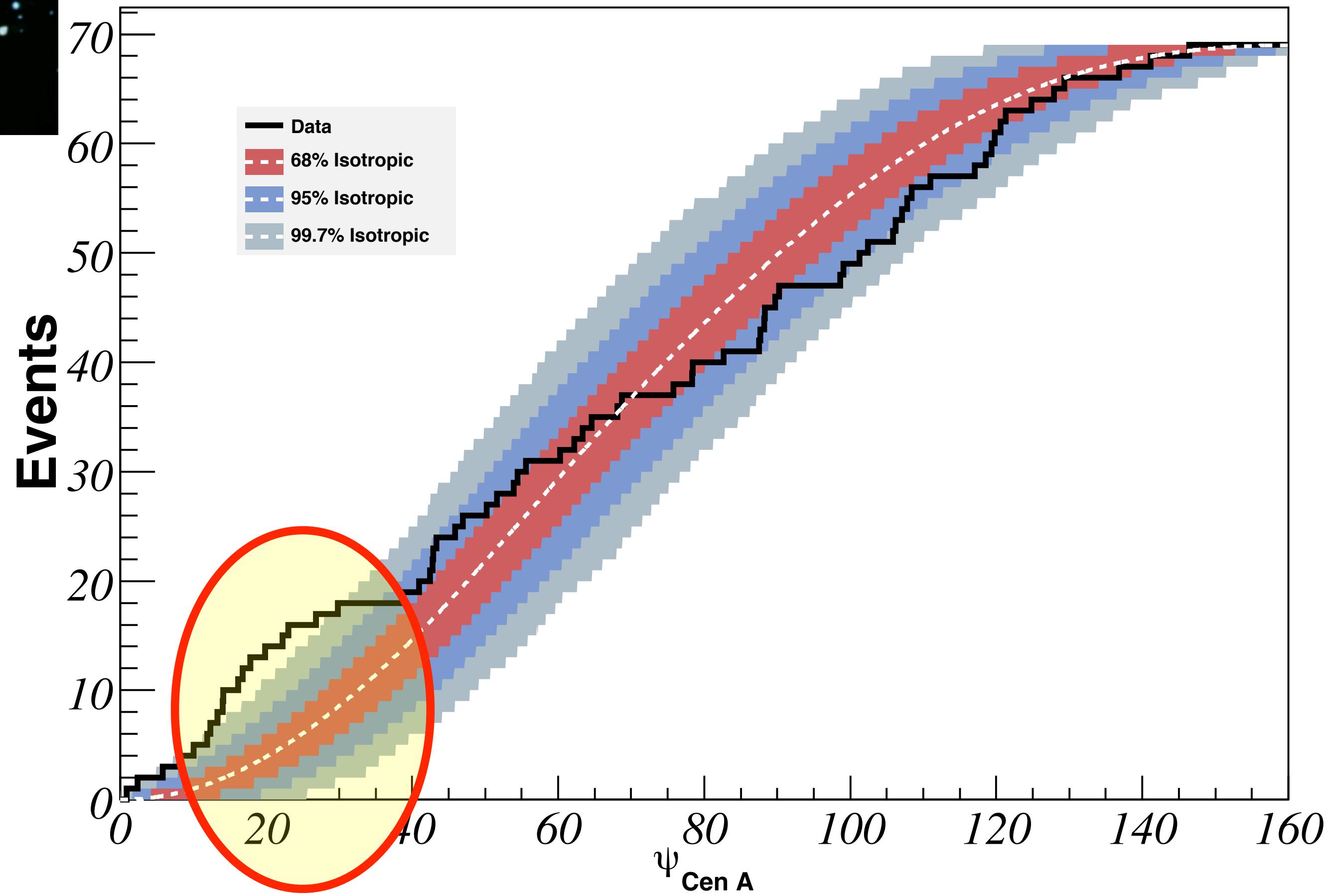


P. Abreu et al., Astropart. Phys. (2010)



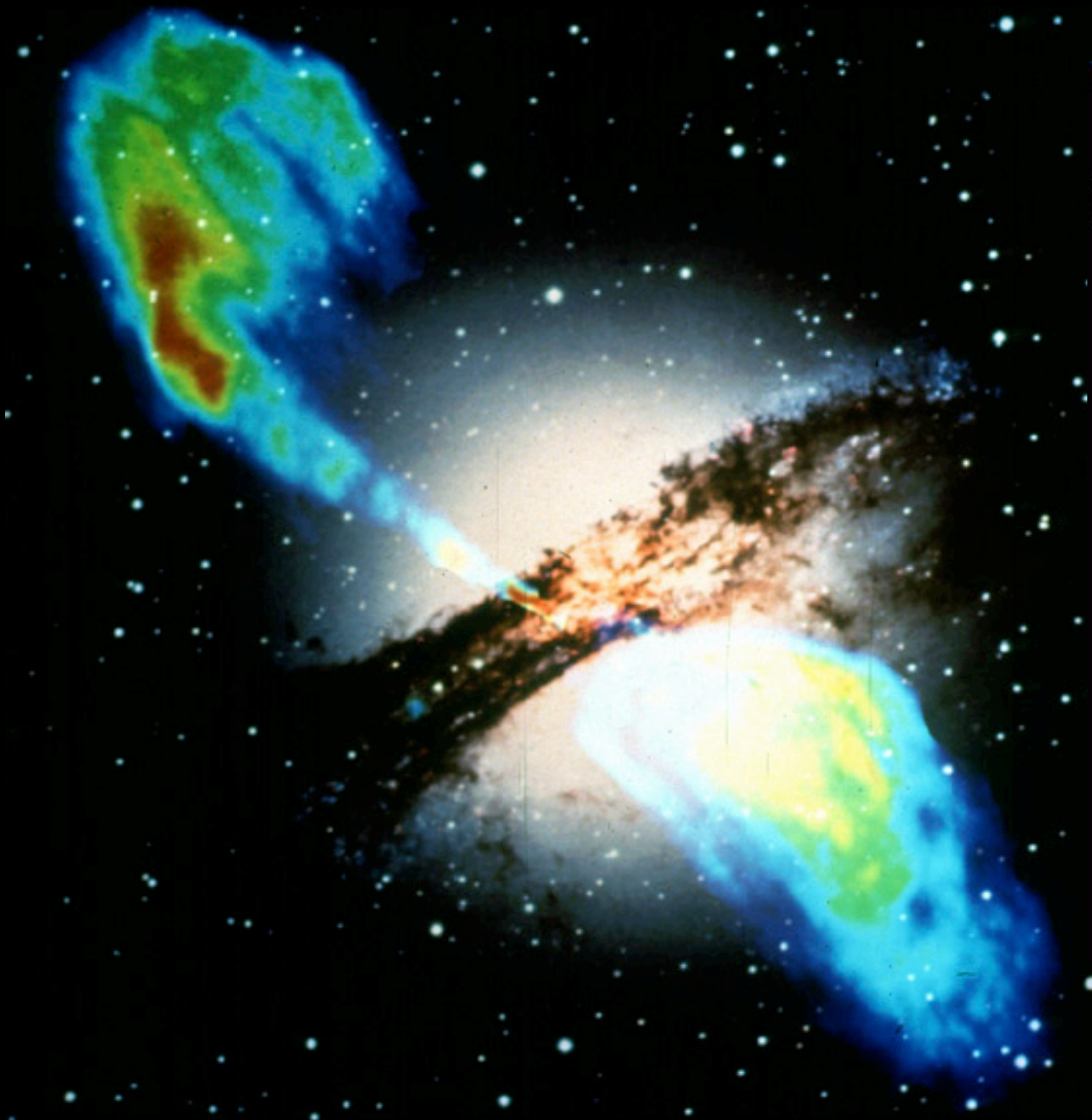


Distance to Cen A

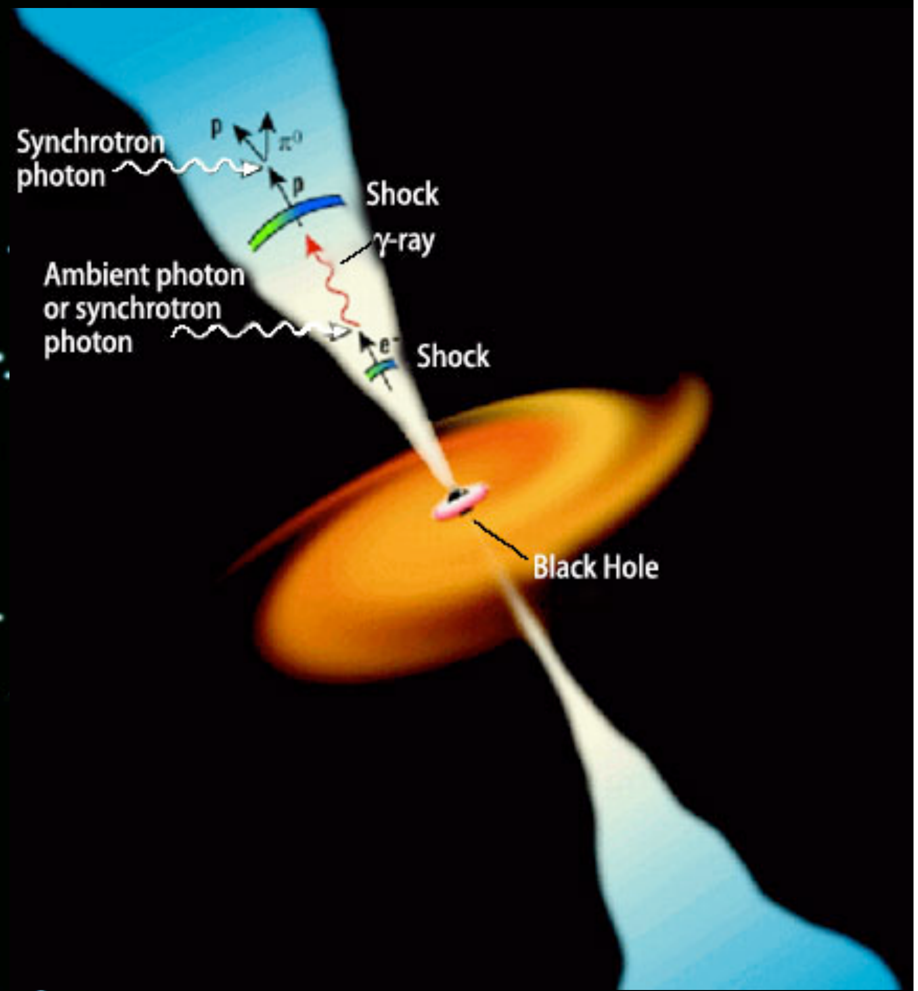


P. Abreu et al., Astropart. Phys. (2010)

Active Galactic Nuclei (AGN)



closest AGN: Cen A, d~4 Mpc

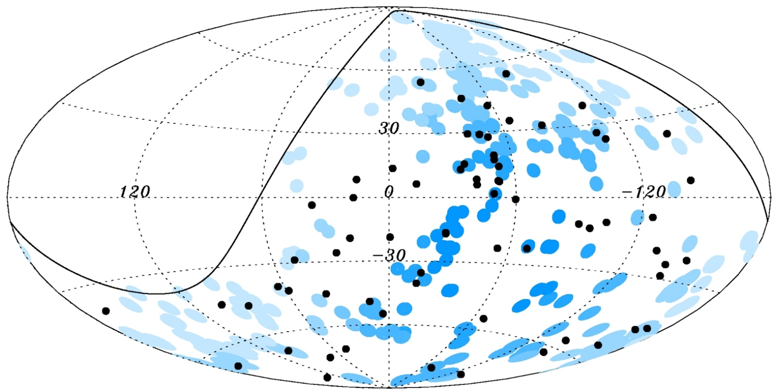


Acceleration of highest-energy cosmic rays at AGN

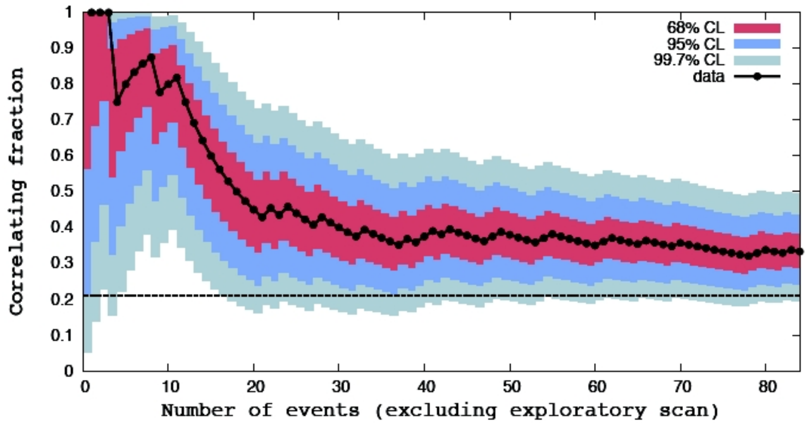
Cosmic-ray correlation with AGNs

VCV catalogue, E$>$ 57 EeV, z$<$0.018, distance $<$ 3.1 deg.

Auger

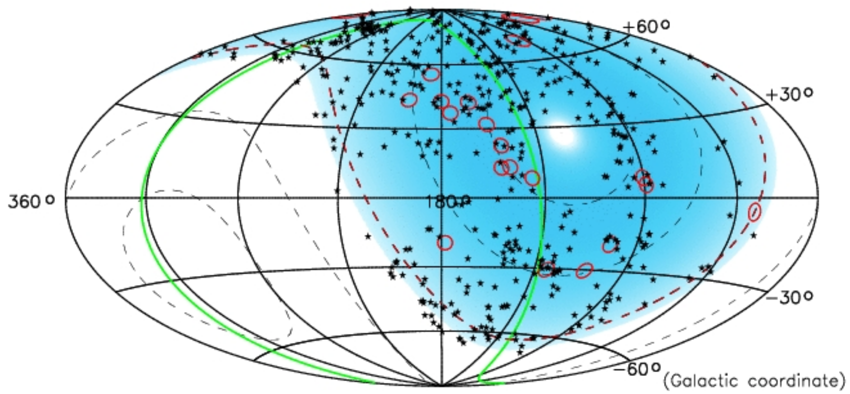


28 out of 84 correlate

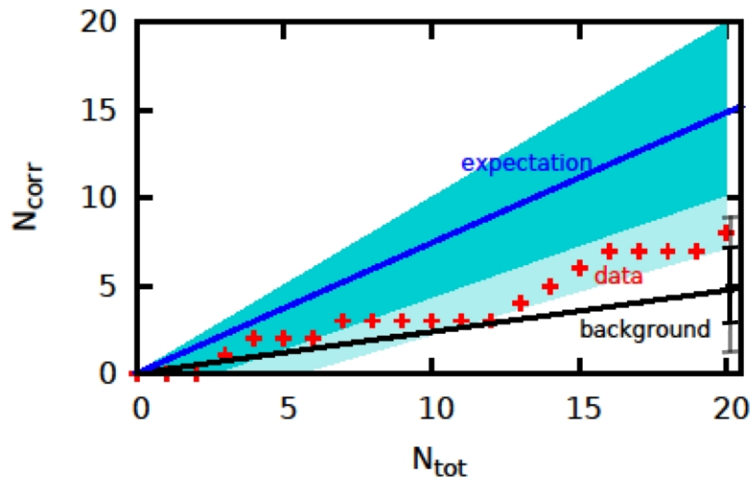


$P = 0.006$, $f = 33 \pm 5\%$

TA



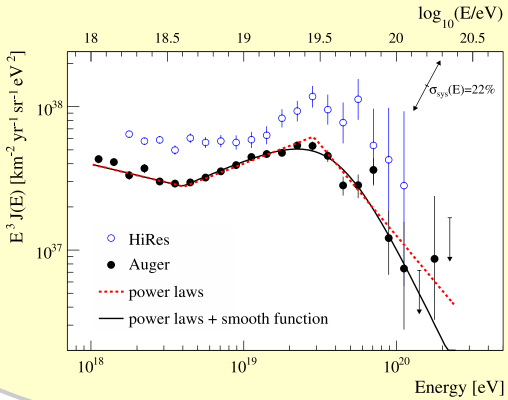
8 out of 20 correlate

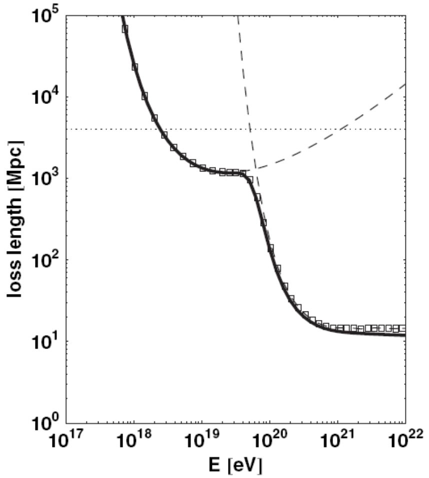


compatible with isotropy and updated (!) Auger

M. Unger, ICRC 2011

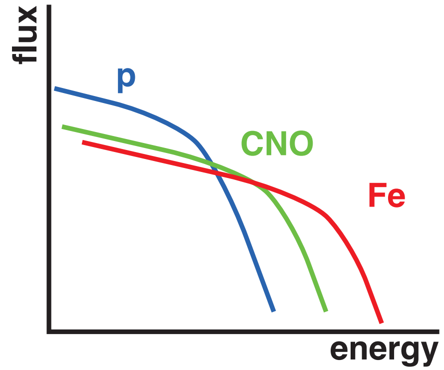
energy spectrum





GZK effect

light composition

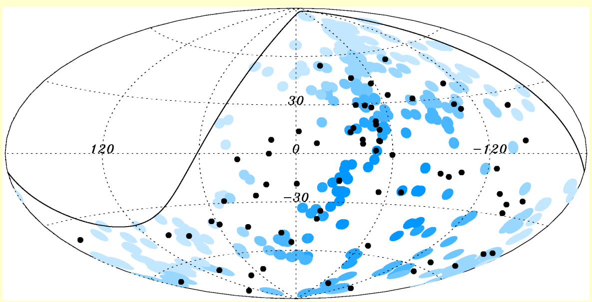


max energy of accelerators

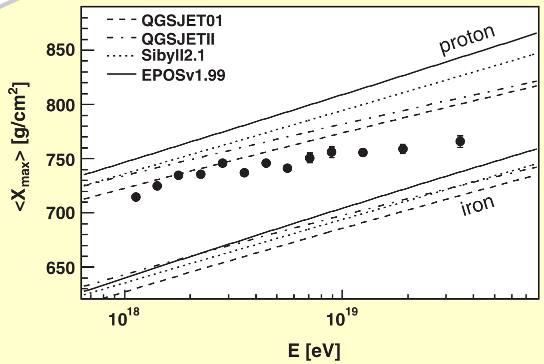
heavy composition

PIERRE AUGER
OBSERVATORY

?



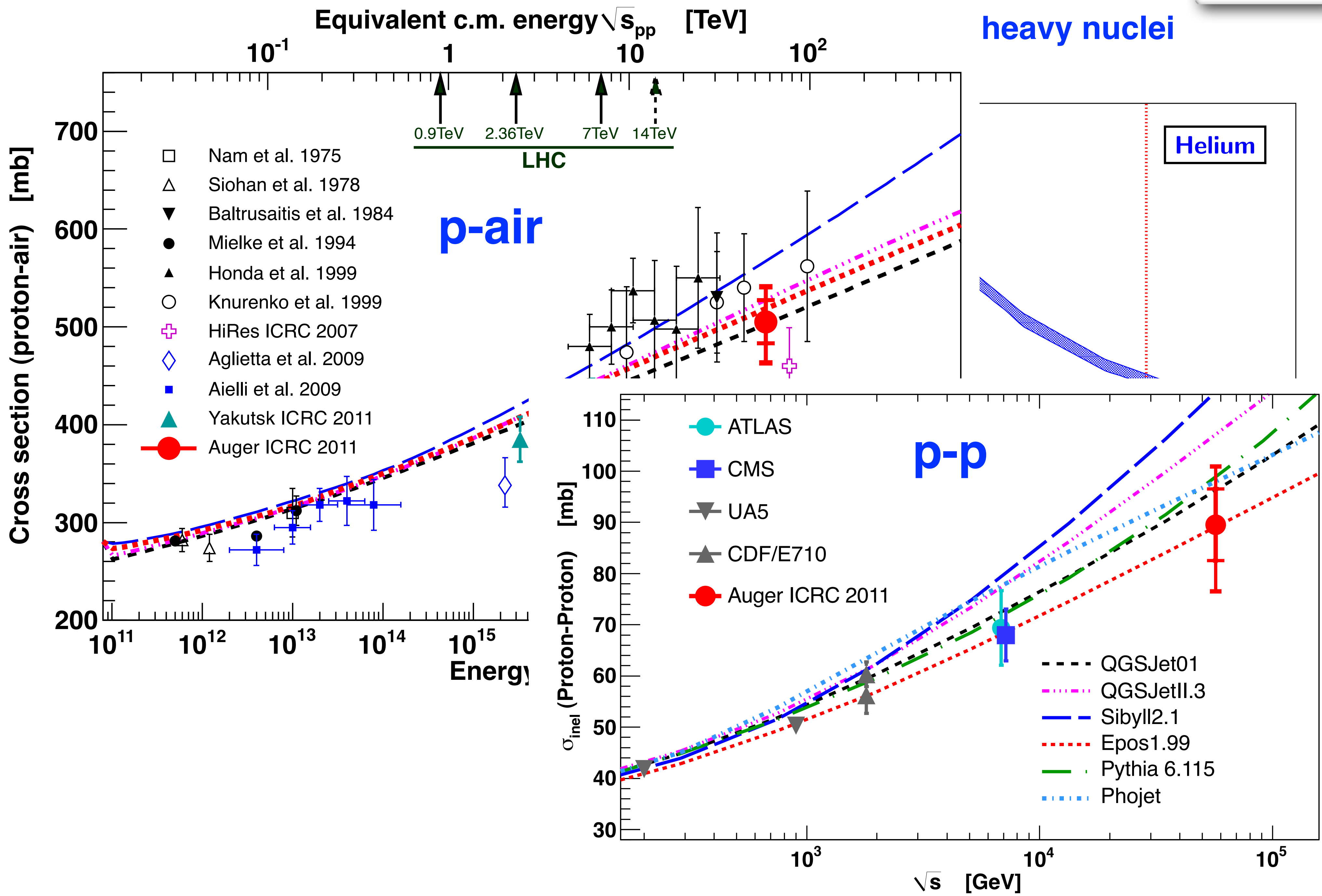
arrival direction



mass composition

Estimation of the proton-air cross section with the Pierre Auger Observatory

#946 Ulrich



Aktuelle Ergebnisse zur kosmischen Strahlung

Thanks to all my colleagues from TRACER, KASCADE (-Grande), and the Pierre Auger Observatory!

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