ARGO-YBJ Rome International Conference on Astro-Particle Physics
University "Sapienza" June 20th - 22nd 2007 Roma - Italy

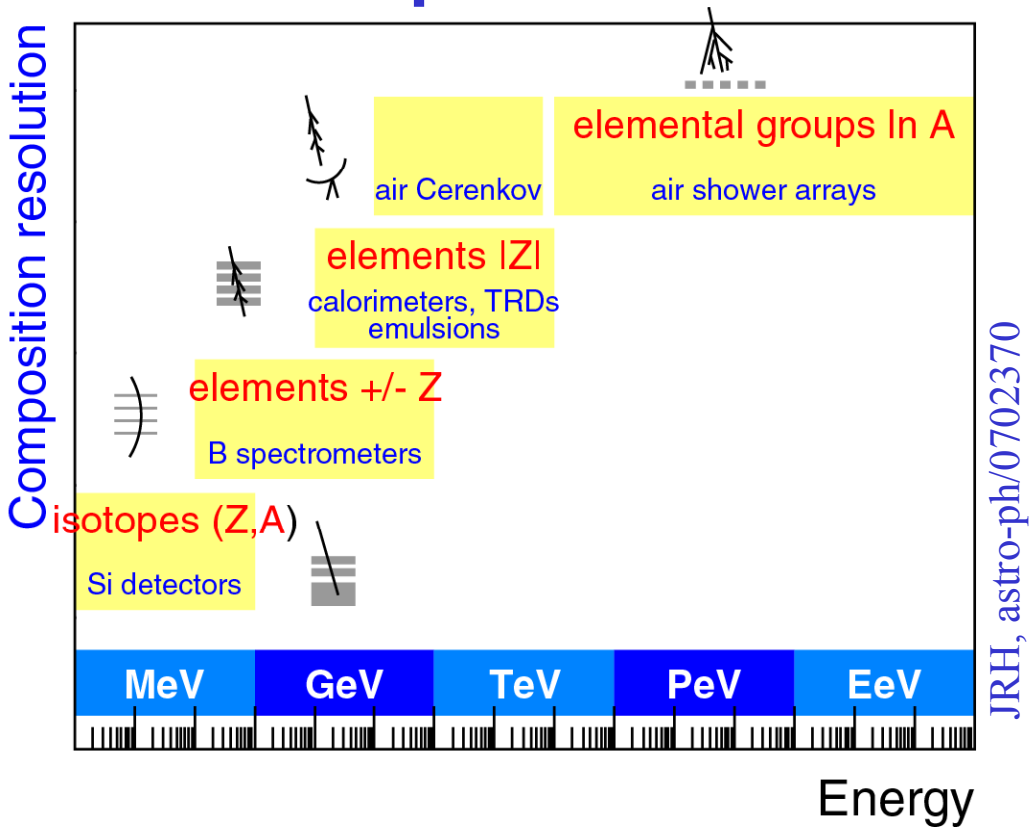
The origin of galactic cosmic rays

Jörg R. Hörandel
Radboud University Nijmegen, The Netherlands
www-ik.fzk.de/~joerg

ARGO-YBJ Rome International Conference on Astro-Particle Physics
University "Sapienza" June 20th - 22nd 2007 Roma - Italy

The origin of galactic cosmic rays

Resolution for composition measurements



Jörg R. Hörandel
Radboud University Nijmegen, The Netherlands
www-ik.fzk.de/~joerg

Extensive air showers – Energy and Mass

Simple Heitler model of (hadronic) showers

Primary mass:

- **Average depth of shower maximum X_{max}**

$$X_{max}^{A} \sim \ln \frac{E_0}{A}$$

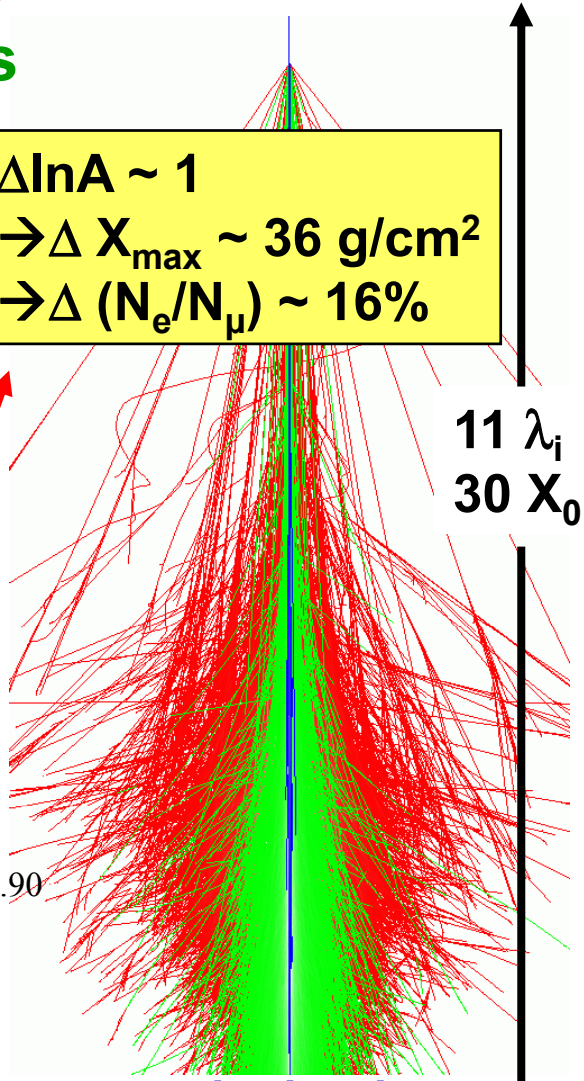
$$X_{max}^{A} = X_{max}^{p} - X_0 \ln A$$

$$X_{max}^{Fe} = X_{max}^{p} - 150\,\mathrm{g/cm^2}$$

ΔlnA ~ 1
→Δ X_{max} ~ 36 g/cm²
→Δ (N_e/N_μ) ~ 16%

- **N_e-N_μ ratio**

$$\frac{N_e}{N_\mu} \approx 35.1 \cdot \left(\frac{E_0}{A \cdot \mathrm{PeV}} \right)^{0.15} \quad \textbf{or} \quad \lg\left(\frac{N_e}{N_\mu}\right) = C - 0.065 \ln A$$



Energy:

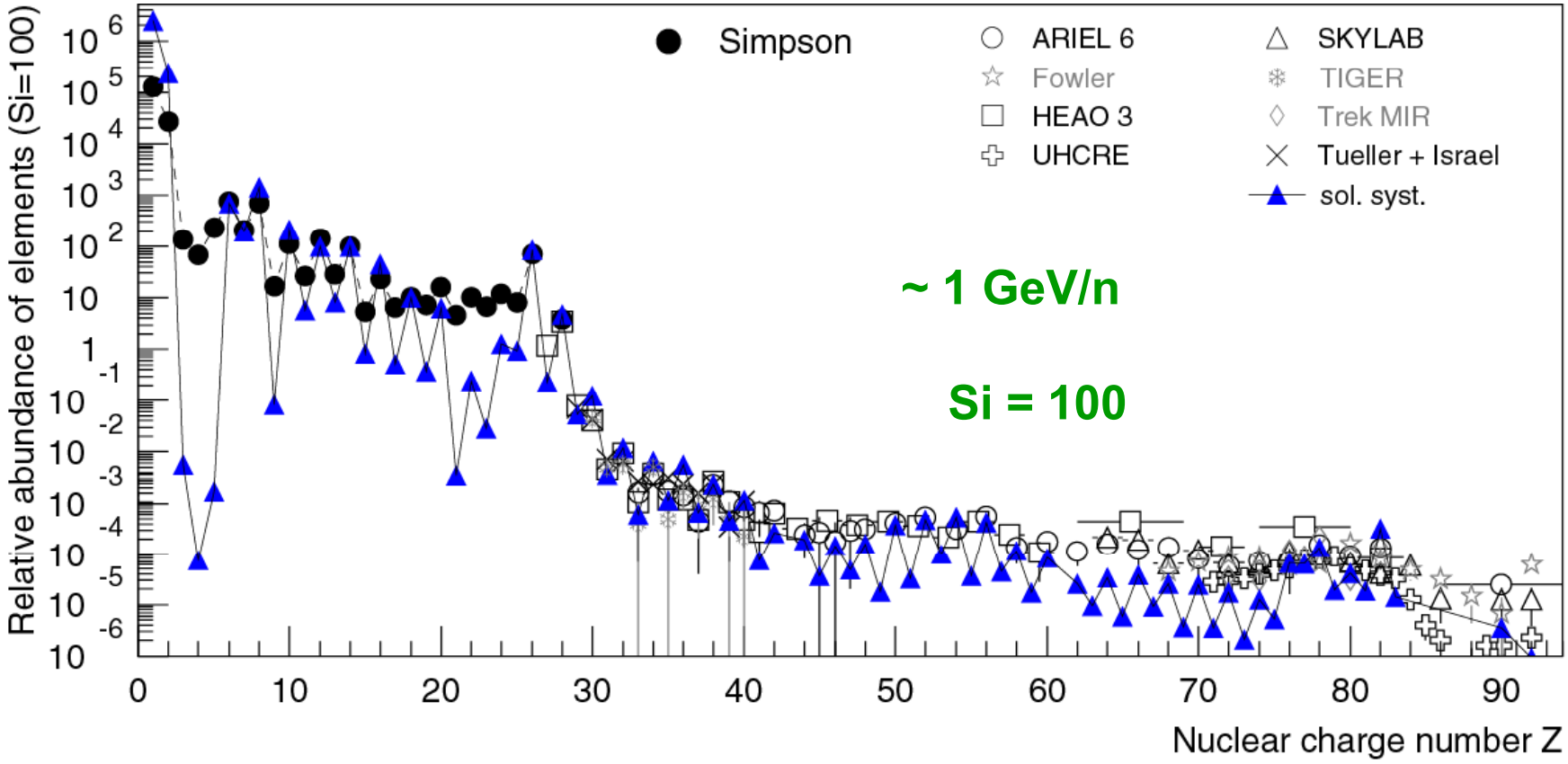
$$N_\mu = A\left(\frac{E_0}{AE_c^\pi}\right)^{\beta} = \left(\frac{E_0}{E_c^\pi}\right)^{\beta} A^{1-\beta} \approx 1.7 \cdot 10^4\, A^{0.10} \left(\frac{E_0}{\mathrm{PeV}}\right)^{0.90}$$

$$N_e = \frac{E_{em}}{gE_c^e} \approx 5.95 \cdot 10^5\, A^{-0.046} \left(\frac{E_0}{\mathrm{PeV}}\right)^{1.046}$$

$$\frac{E_{em}}{E_0} = \frac{E_0 - N_\mu E_c^\pi}{E_0} = 1 - \left(\frac{E_0}{AE_c^\pi}\right)^{\beta-1}$$

JRH, astro-ph/0611387

Relative abundance of elements at Earth

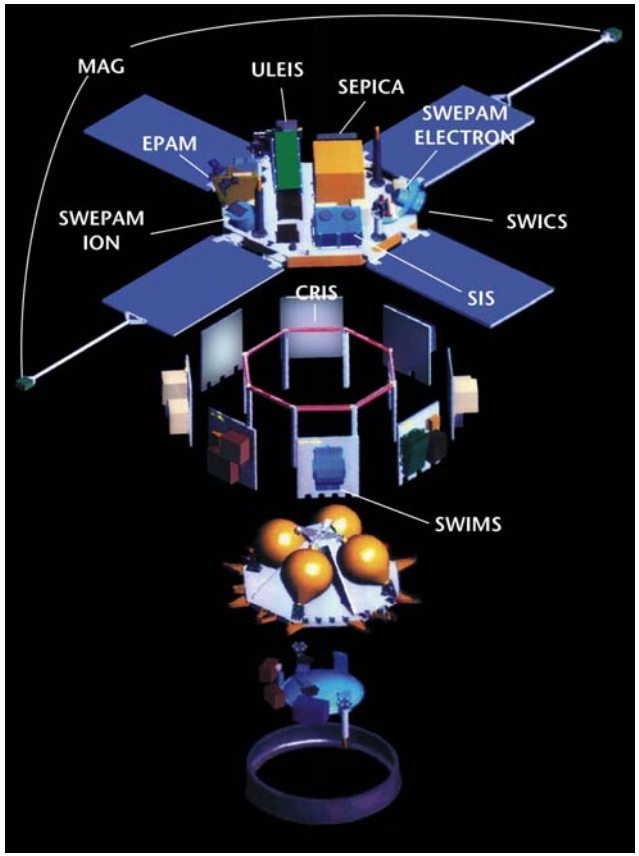


→Cosmic rays are „regular matter“,
accelerated to extremely high energies

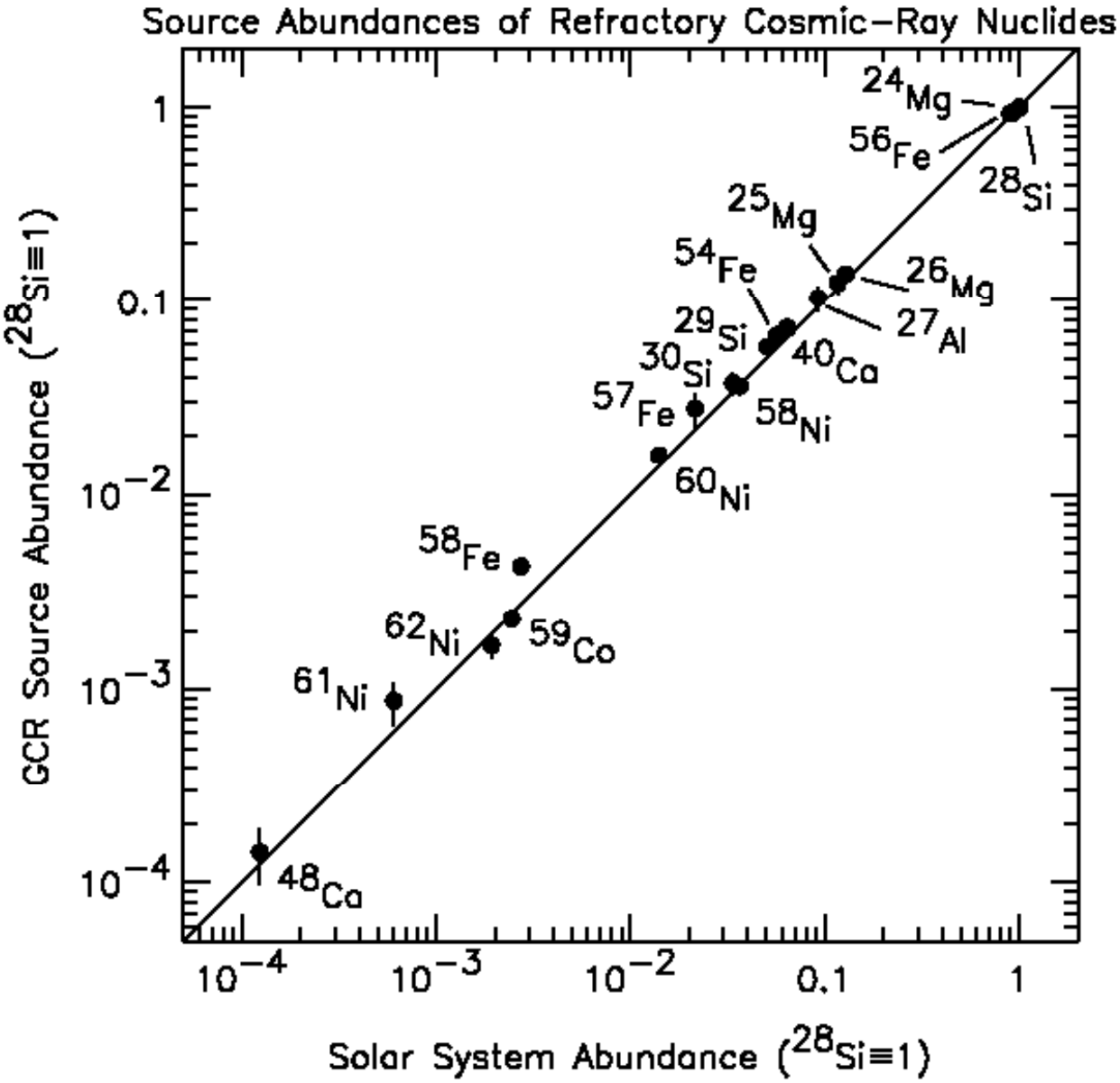
JRH, astro-ph/0702370

Cosmic ray source composition

ACE/CRIS Experiment

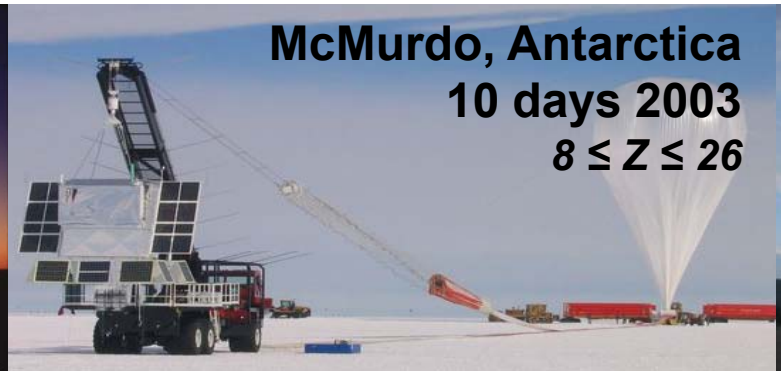


Proc. 28th ICRC 4 (2003) 1899



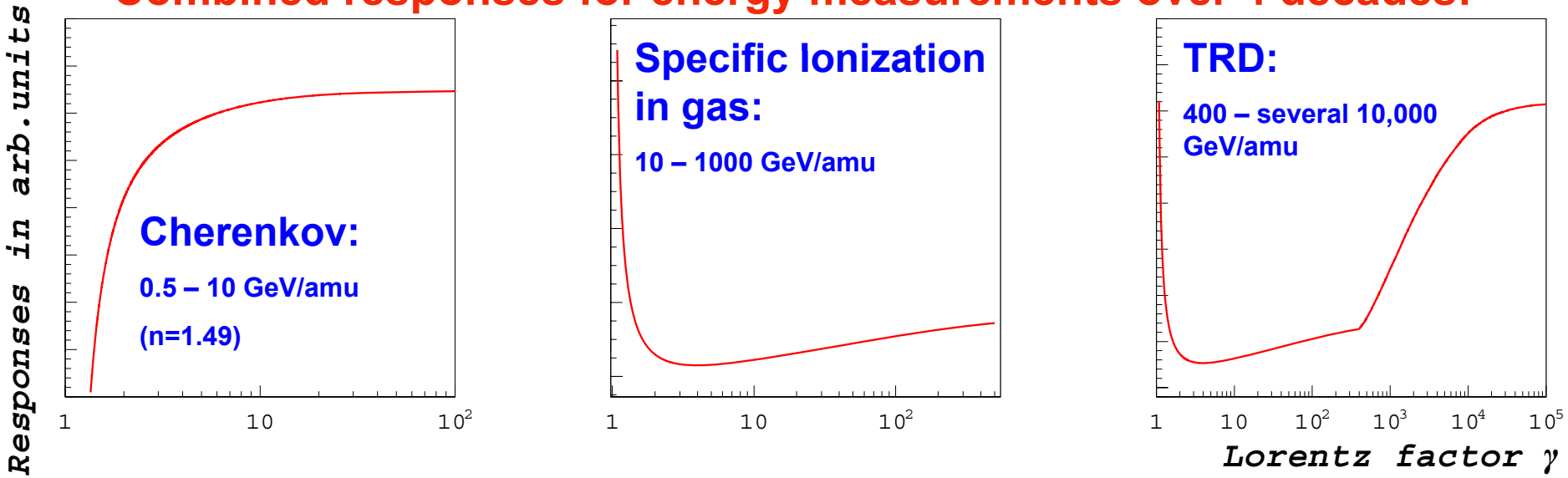
Acceleration of cosmic rays out of a sample of well-mixed interstellar matter

Transition Radiation Array for Cosmic Energetic Radiation



Direct measurement of the composition of cosmic rays from 0.5 to 10,000 GeV/amu with single elemental resolution

Combined responses for energy measurements over 4 decades:

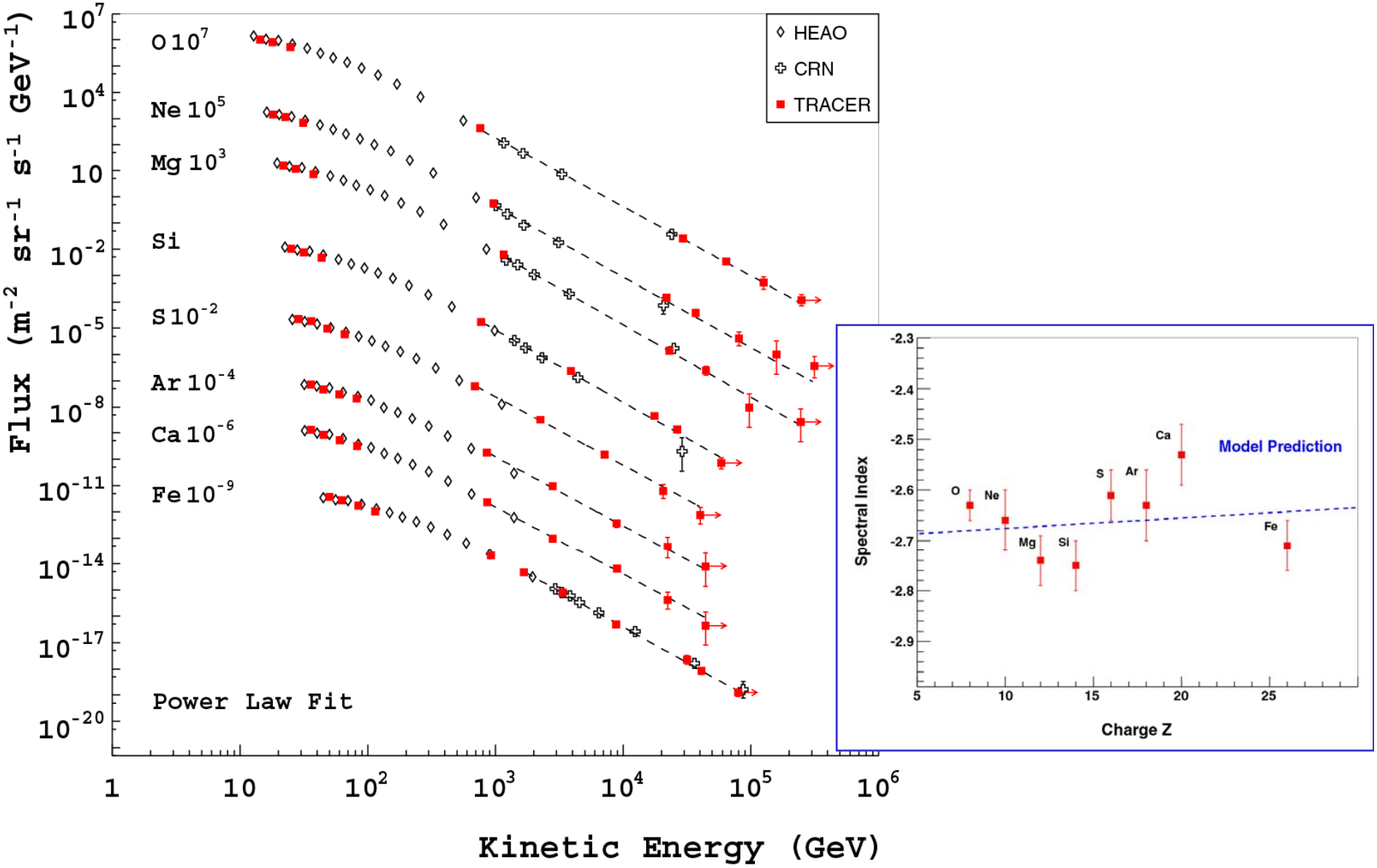


$L \sim (1 - 1/n^2\beta^2)$ $\quad dE/dx \sim 1/\beta^2 \ln(E)$ $\quad TR = dE/dx + \text{x-rays}$

all signals scale with Z^2

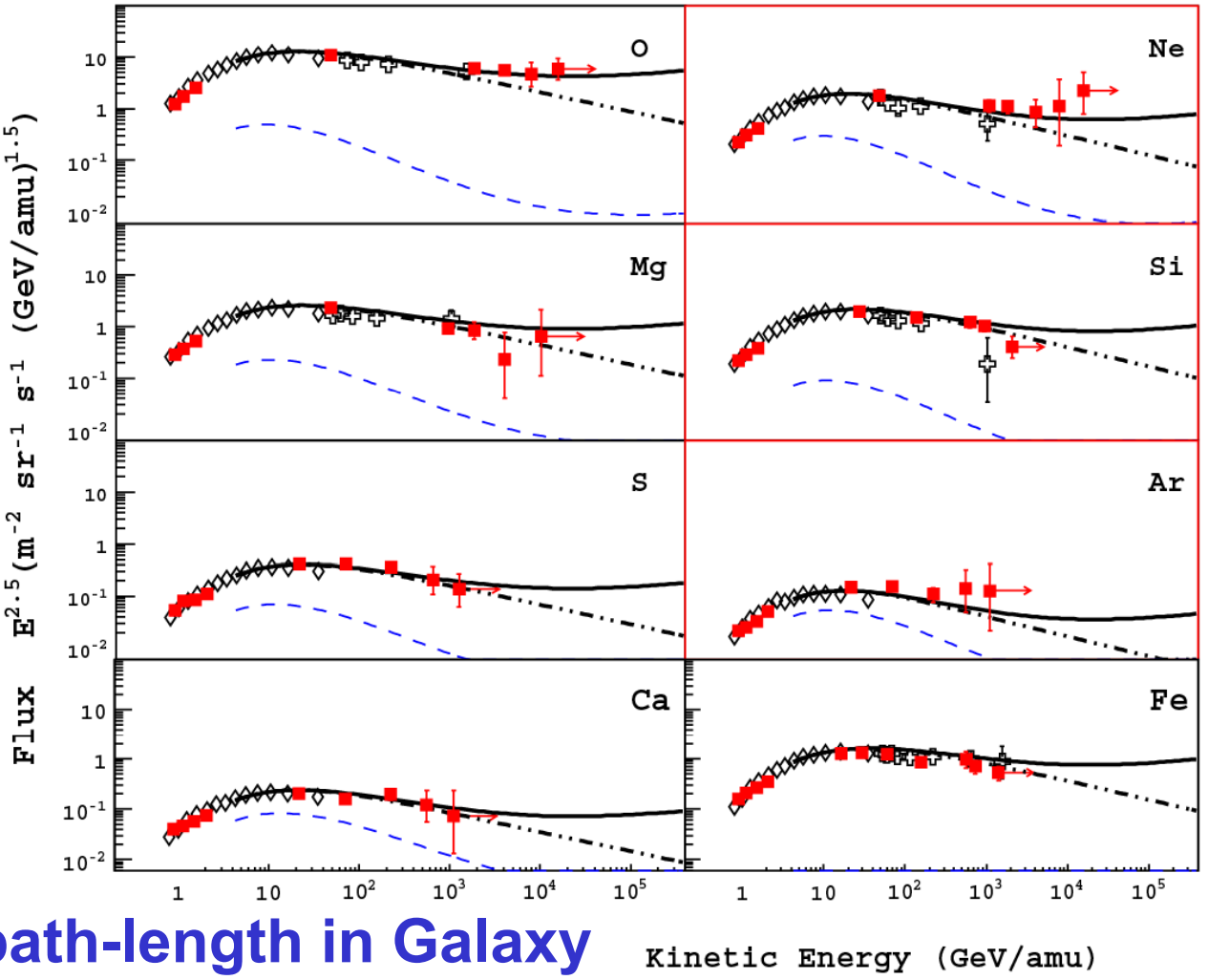
$5m^2$ sr - currently the largest cosmic-ray detector on balloons

TRACER Energy Spectra for individual elements



D. Müller et al., ICRC 2007

TRACER Energy Spectra for individual elements



2003 data Mc Murdo

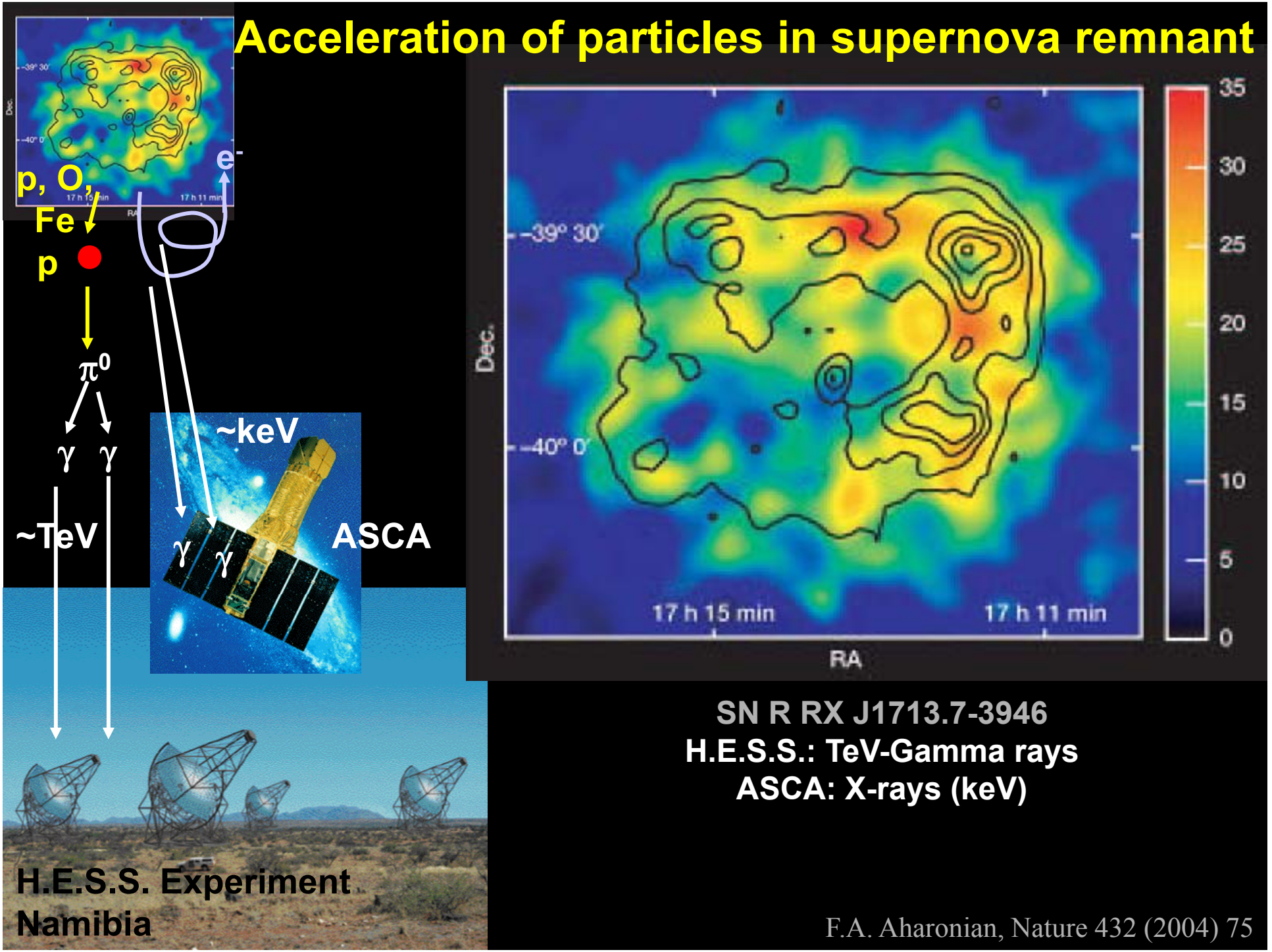
CR path-length in Galaxy

$$\Lambda = \frac{26.7\beta}{(\beta R)^{0.58} + \left(\frac{\beta R}{1.4}\right)^{-1.4}} + \Lambda_0$$

Λ_0=0.1 g/cm^2 residual path-length

D. Müller et al., ICRC 2007

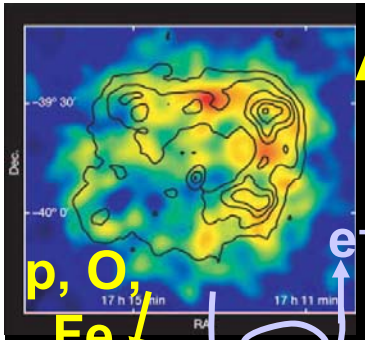
Acceleration of particles in supernova remnant



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

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

Acceleration of particles in supernova remnant



p, O, Fe

p

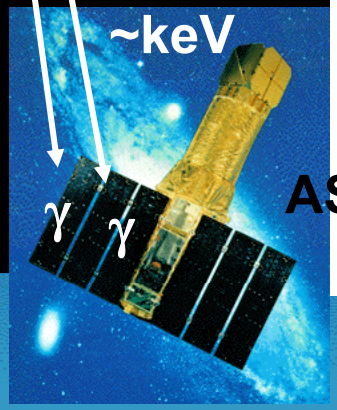
e^-

π^0

γ γ

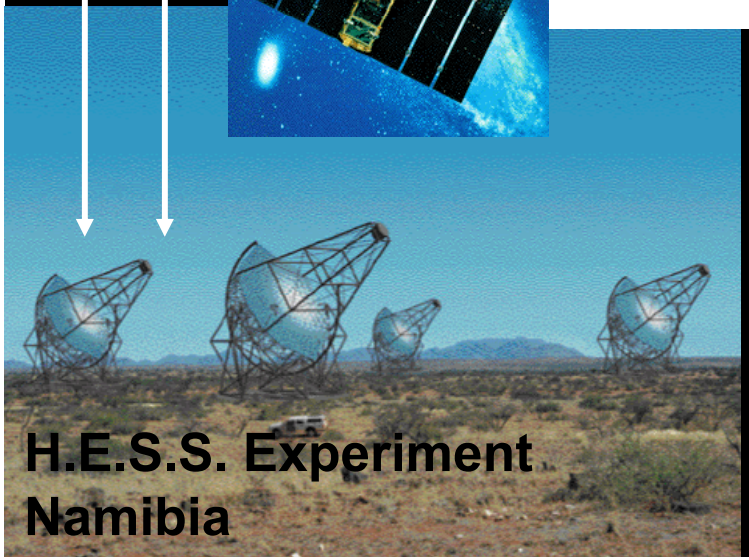
~TeV

~keV

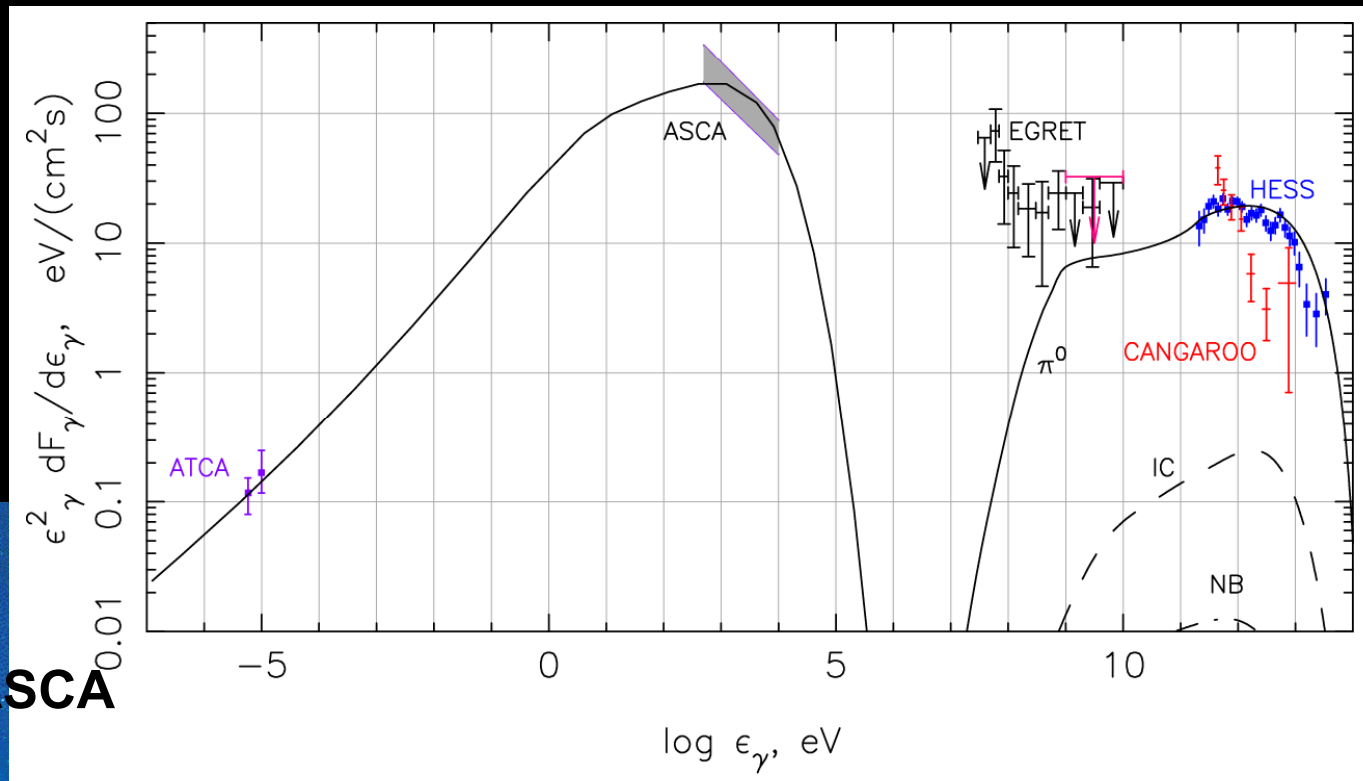


γ γ

ASCA



H.E.S.S. Experiment
Namibia



H. Völk & E.G. Berezhko, A&A 451 (2006) 981

1st order Fermi acceleration

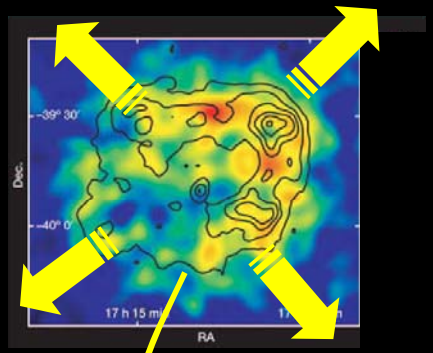
maximum energy

$$E_{max} \sim Ze\beta_s \cdot B \cdot TV_s \qquad \beta_s = \frac{V_s}{c}$$ velocity of shock

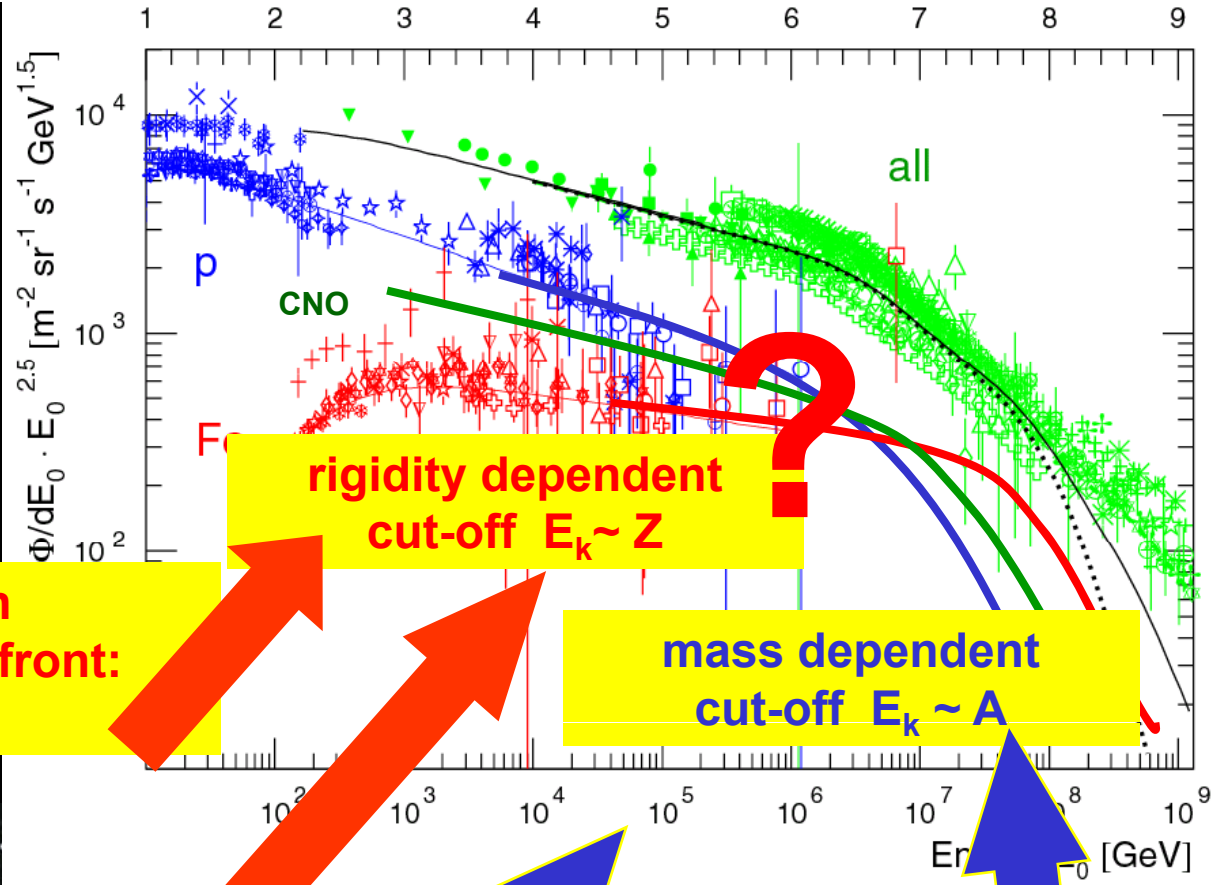
E_{max} ~ Z*100 TeV .. Z*5 PeV

Lagage & Cesarsky, A&A 118 (1983) 223

acceleration of CR in supernova remnants



Fermi acceleration
finite lifetime of shock front:
$E_{max} \sim Z \; 10^{15}$ eV

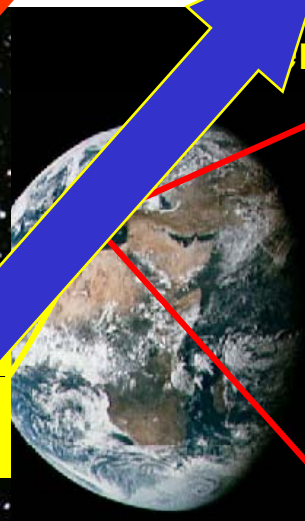


propagation through galaxy

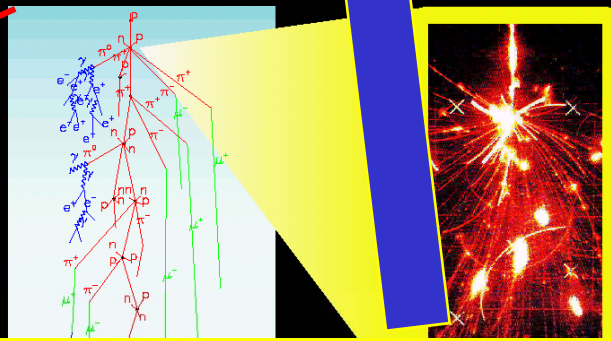
Leakage from Galaxy:
escape probability ~ f(Z)

Interactions with background particles (photons, neutrinos)

B = 3 μG

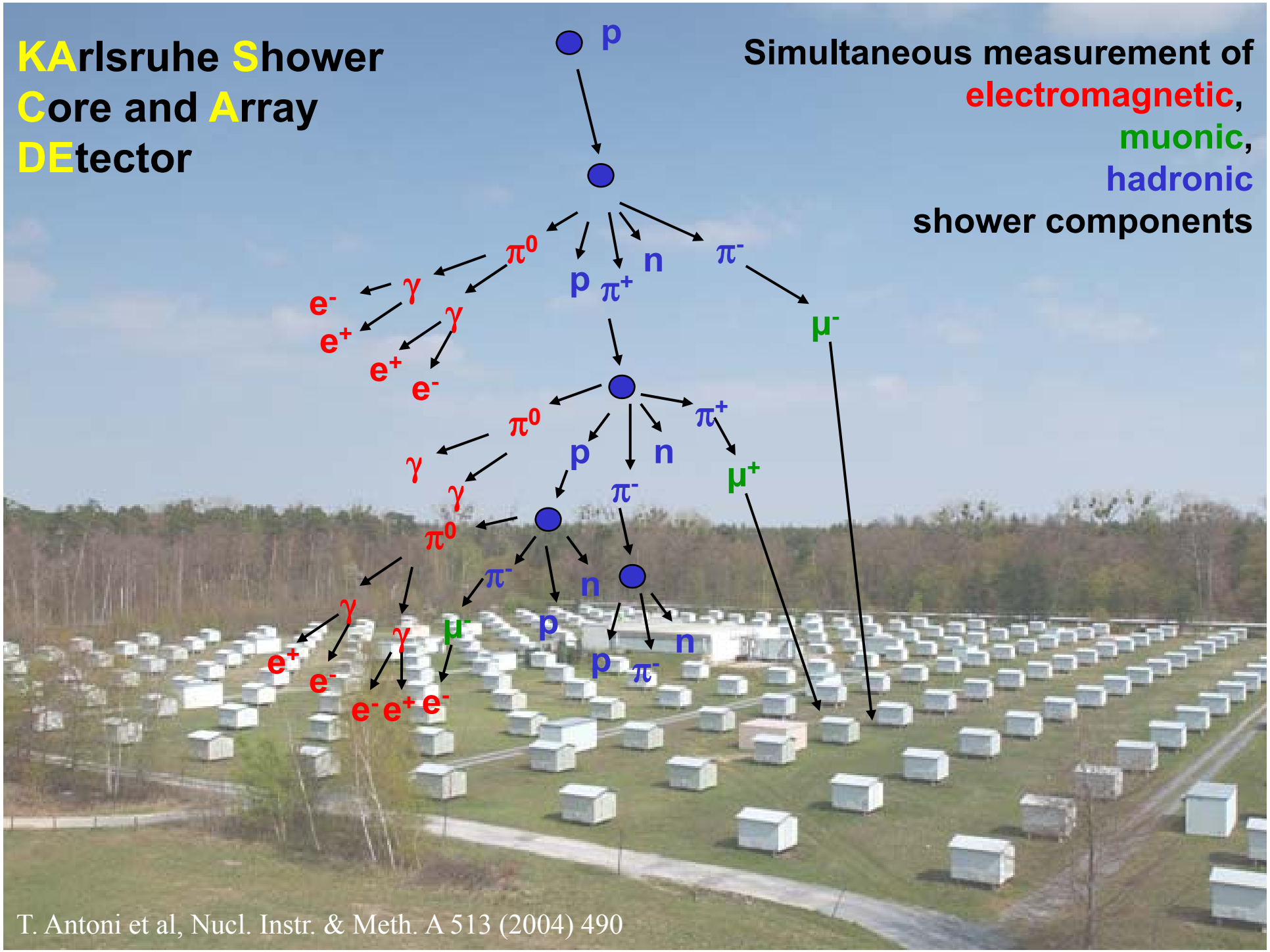


nsive air showers



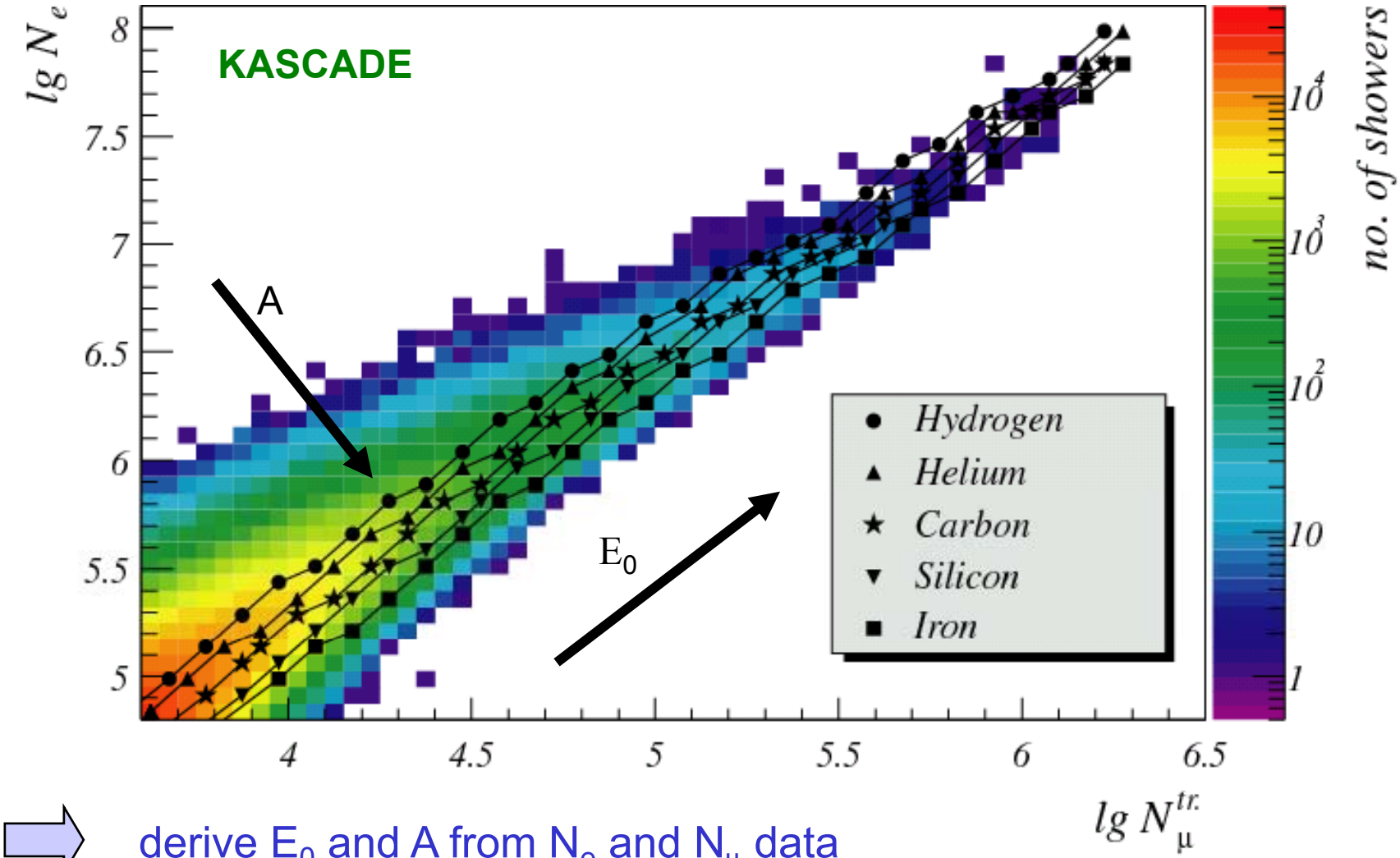
New particle physics in atmosphere

JRH, Astrop. Phys. 21 (2004) 241



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

Two dimensional shower size spectrum lg N_e vs. lg N_μ



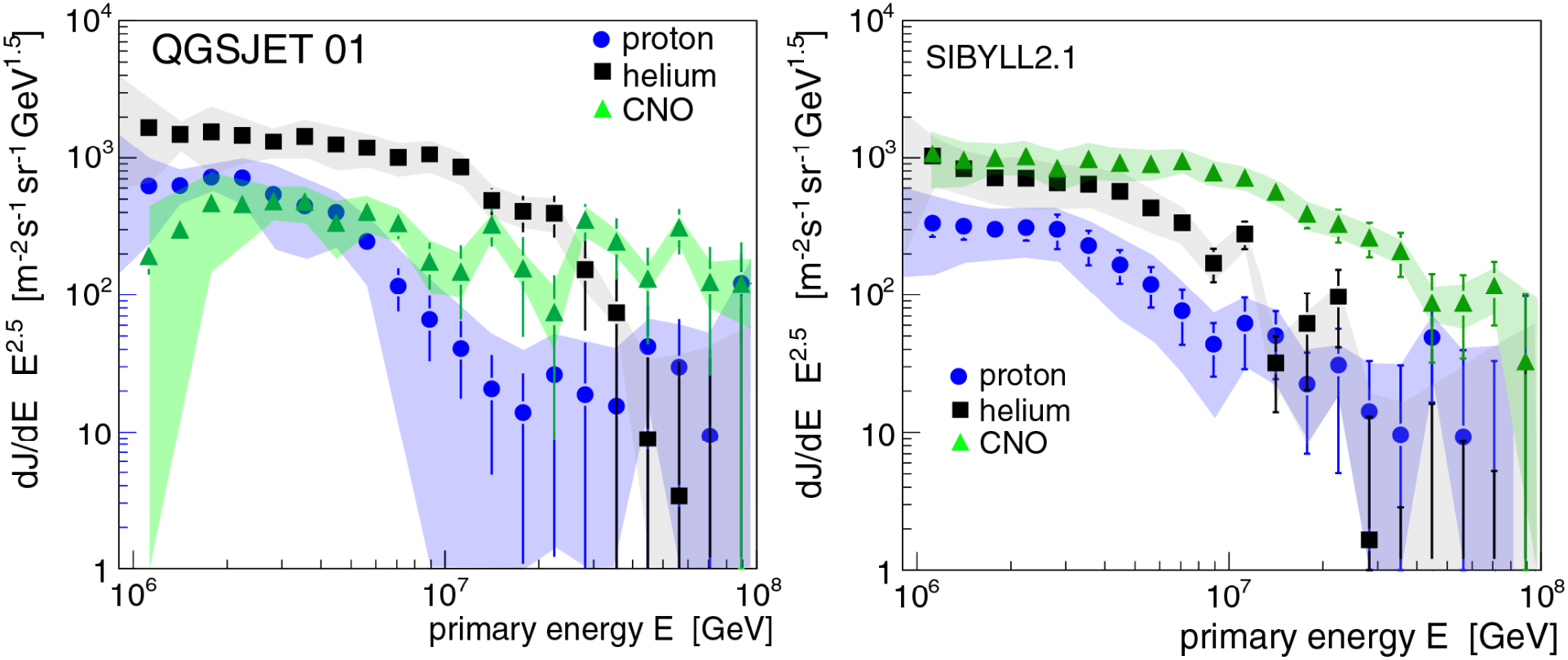
derive E_0 and A from N_e and N_μ data

Fredholm integral equations of 1st kind:

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

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

KASCADE: Energy spectra for elemental groups



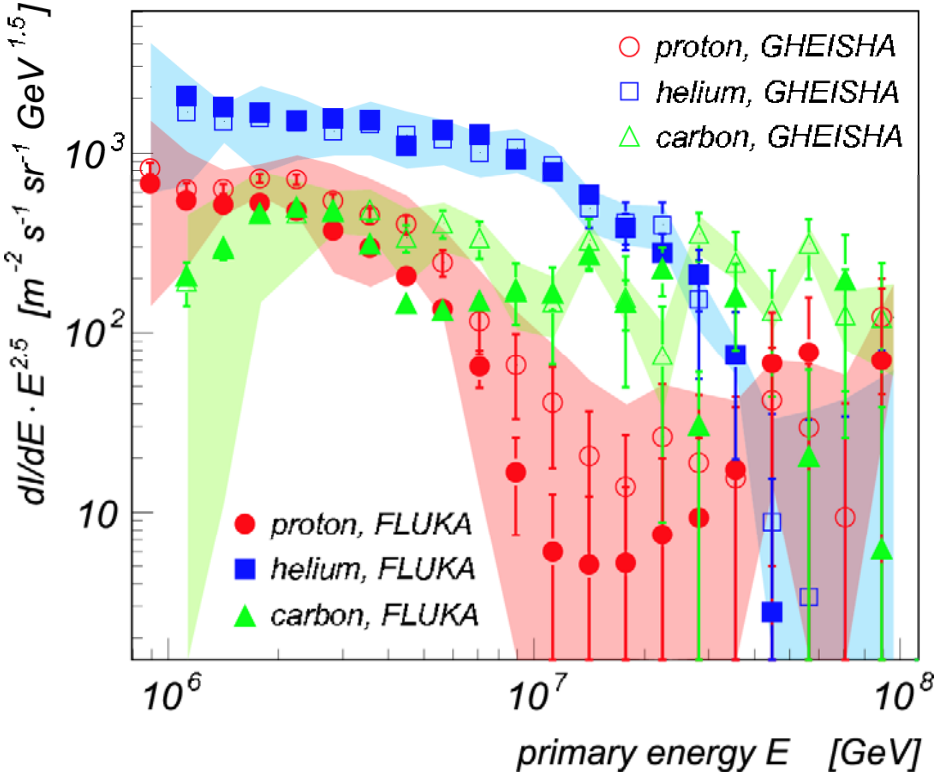
Knee caused by cut-off for light elements

Astrophysical interpretation limited by description of interactions in the atmosphere

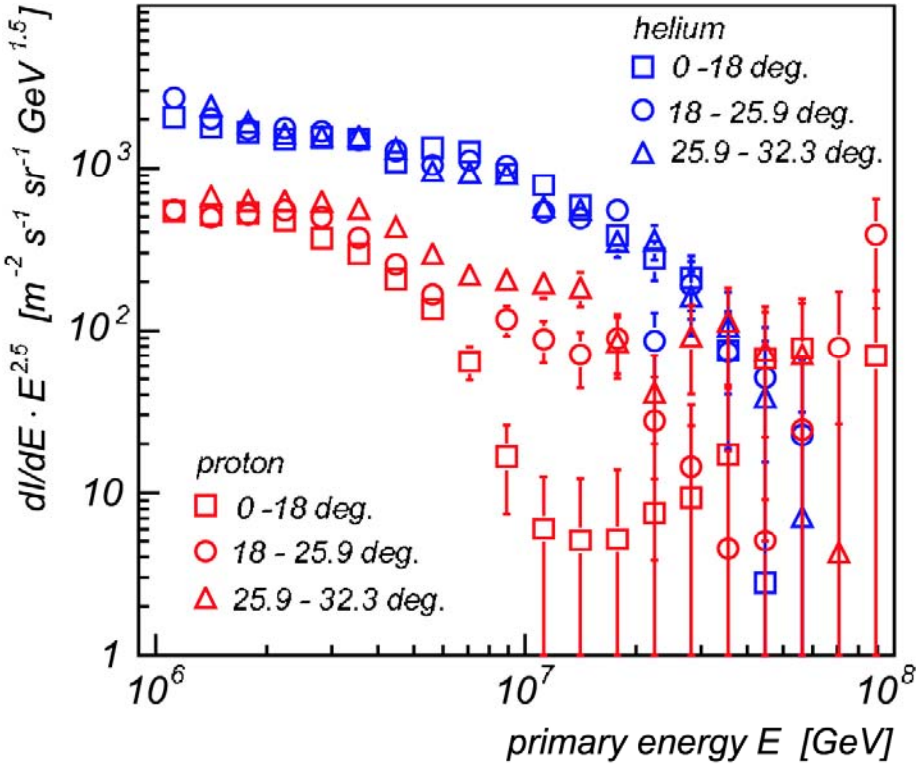
T. Antoni et al., Astropart. Phys. 24 (2005) 1

KASCADE: Energy spectra for elemental groups II

Low energy interactions FLUKA ←→ GHEISHA

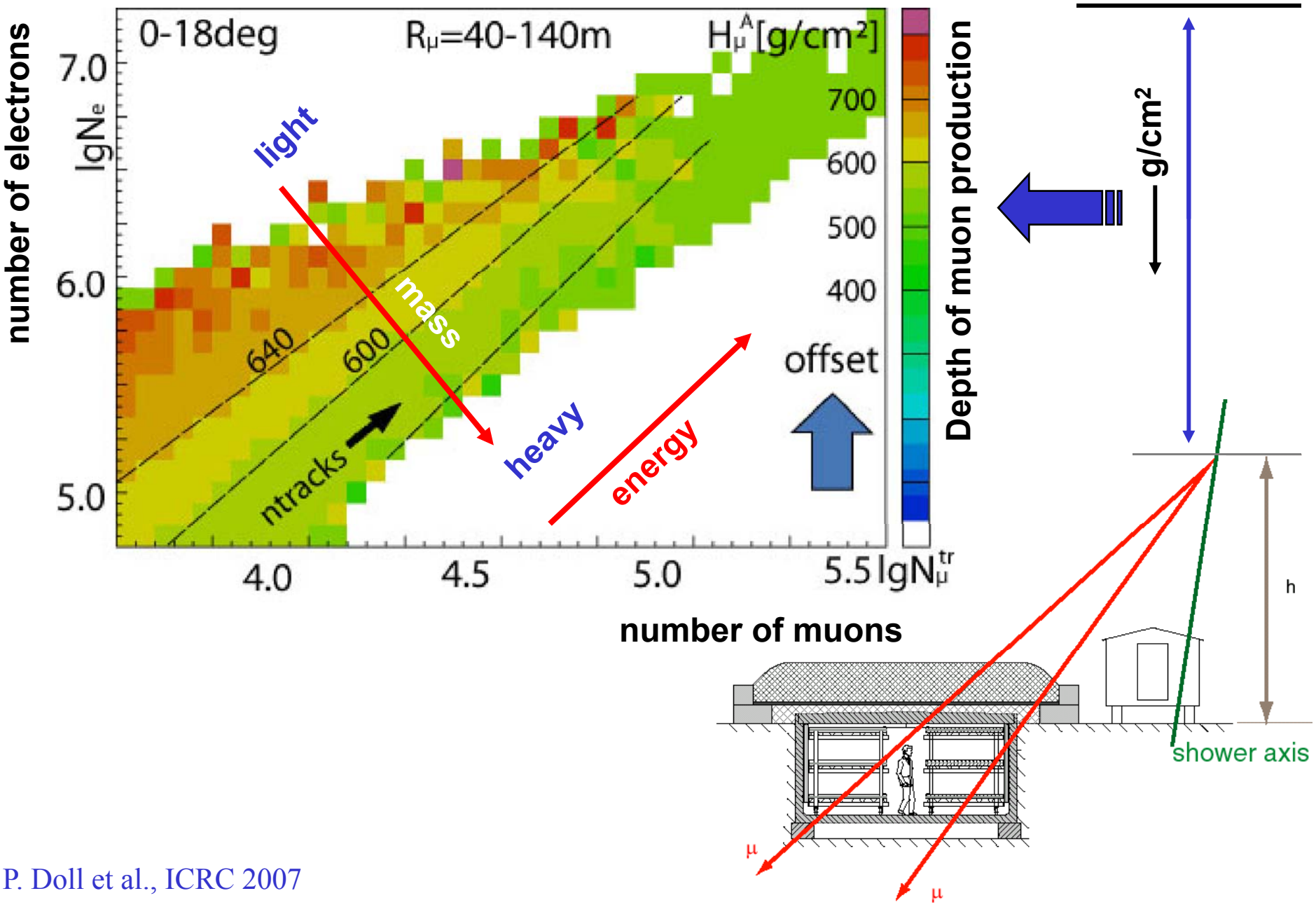


Different zenith angle bins

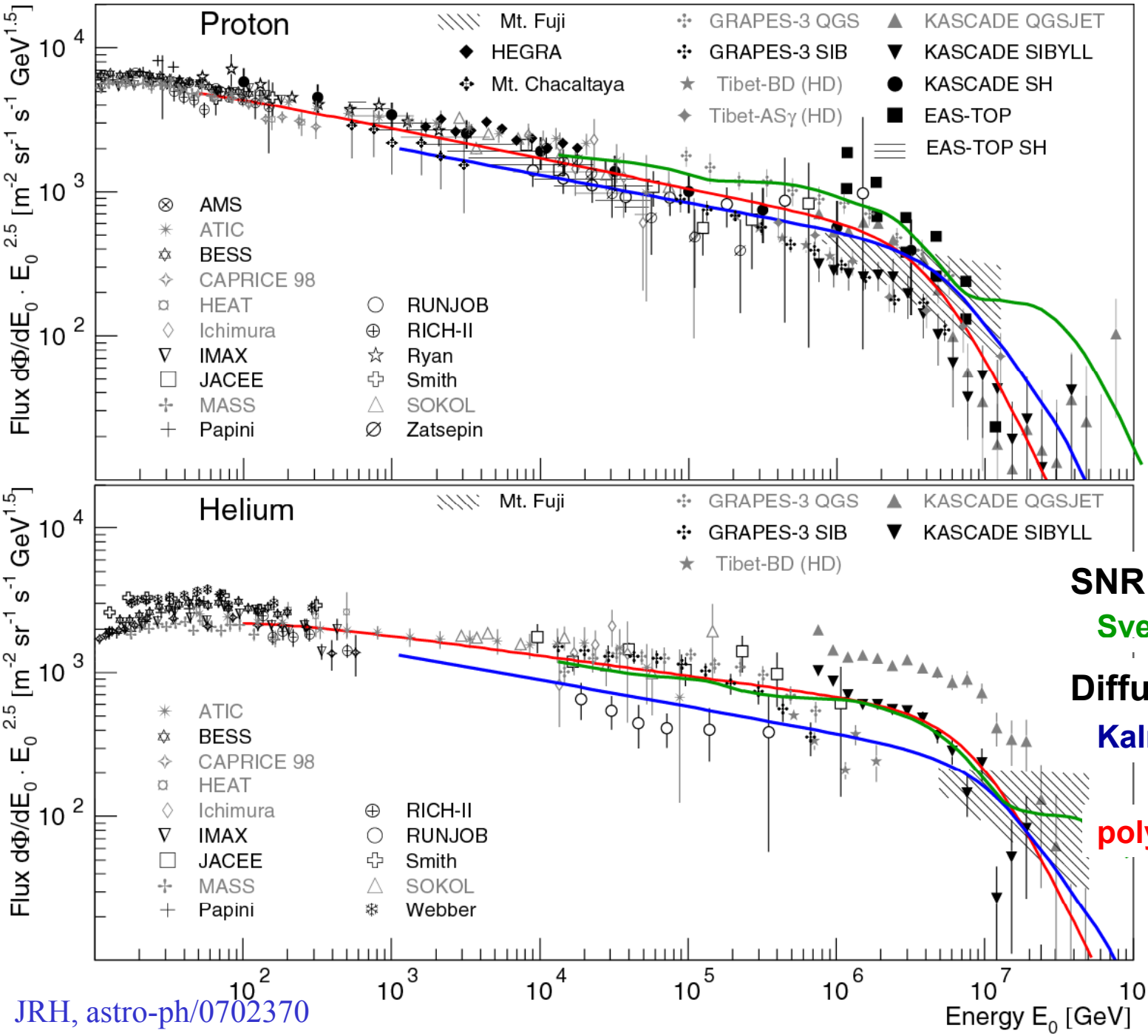


M. Finger, Diploma thesis 2006
H. Ulrich et al., Nucl. Pys. B (Proc. Suppl.) in press

Muon production height – KASCADE muon tracking detector



P. Doll et al., ICRC 2007



SNR acceleration:

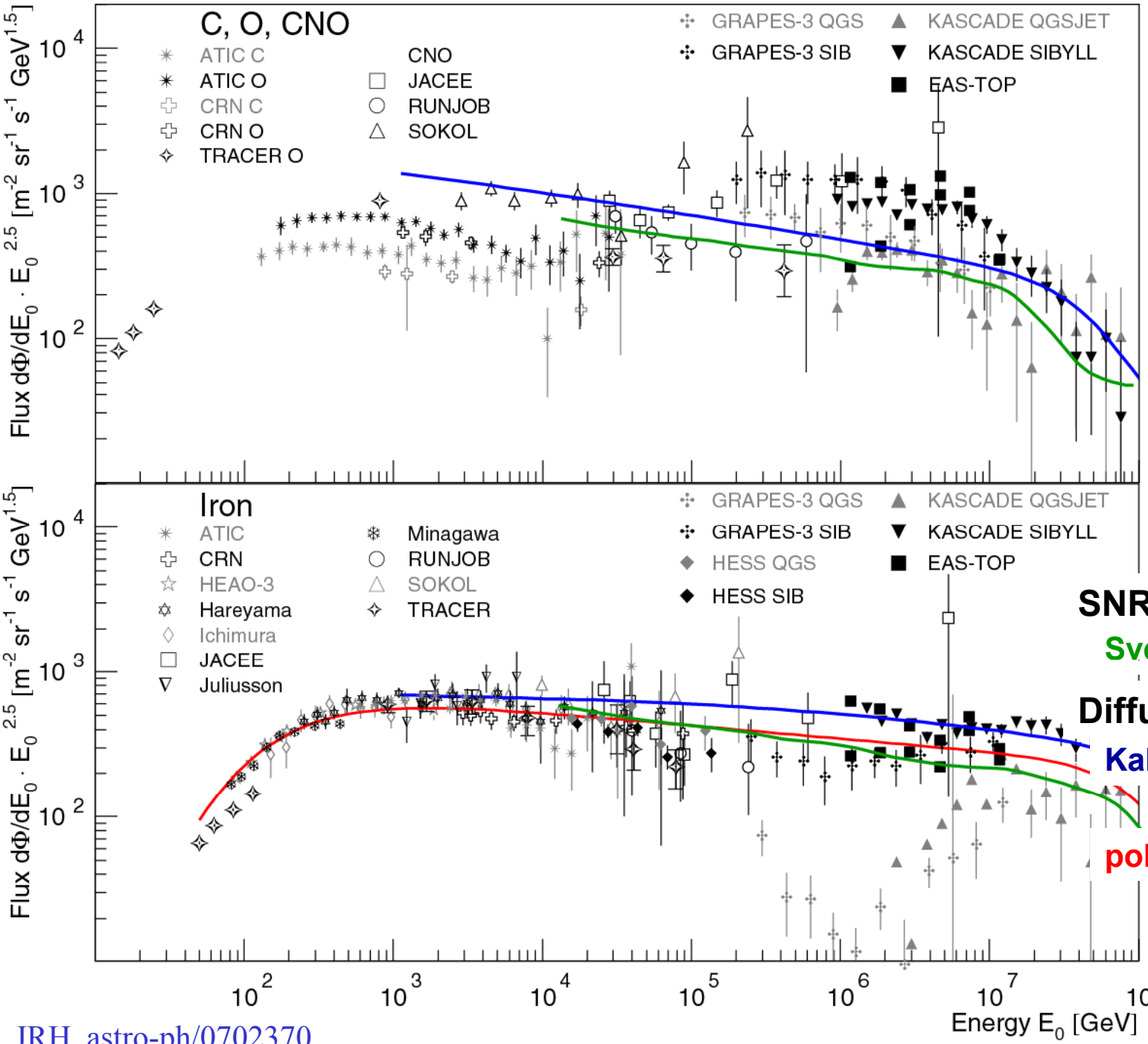
Sveshnikova++ 2003

Diffusion:

Kalmykov+JRH 2007

poly gonato ~Z

JRH, astro-ph/0702370



SNR acceleration:

Sveshnikova++ 2003

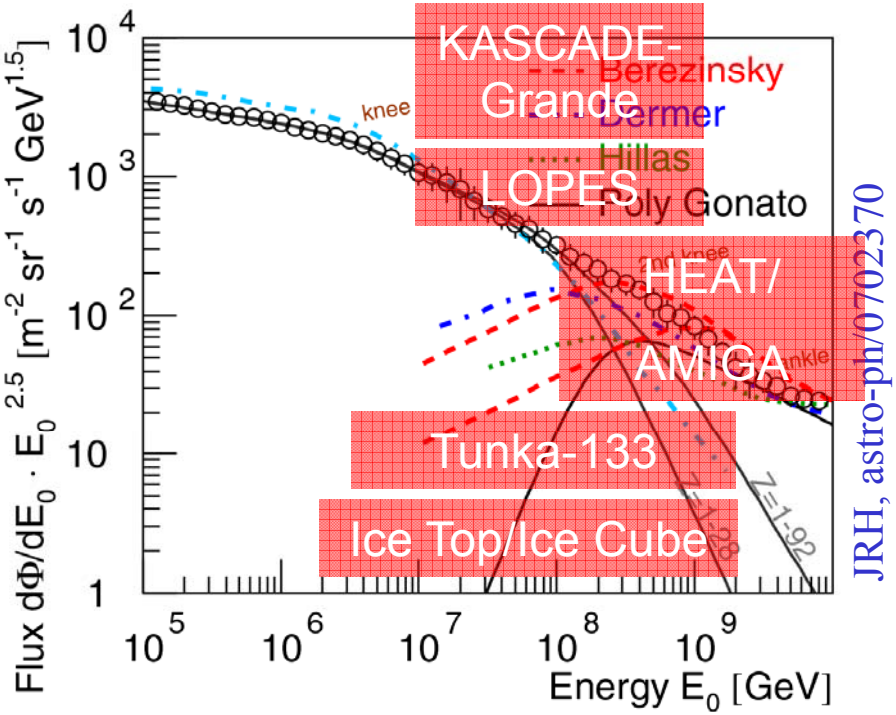
Diffusion:

Kalmykov+JRH 2007

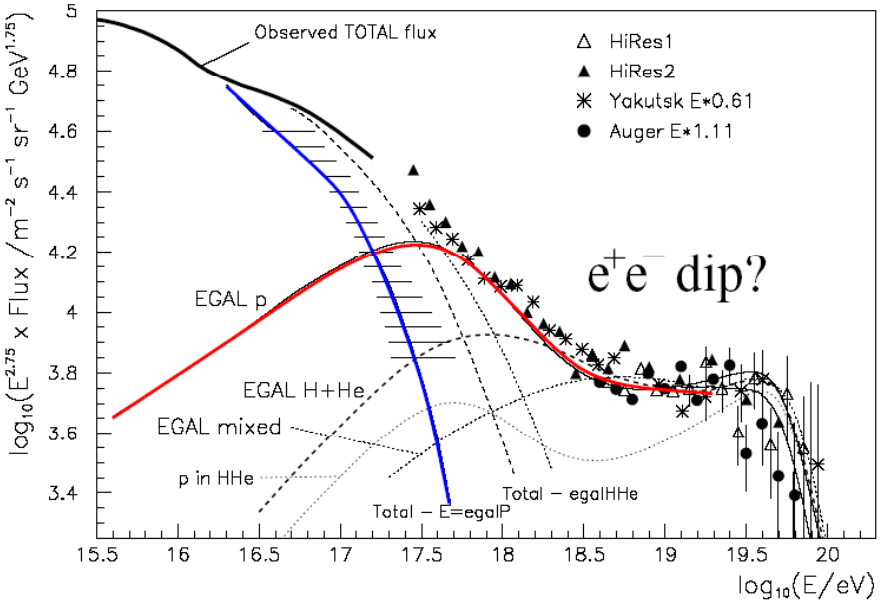
poly gonato ~Z

JRH, astro-ph/0702370

Transition to extragalactic CR component

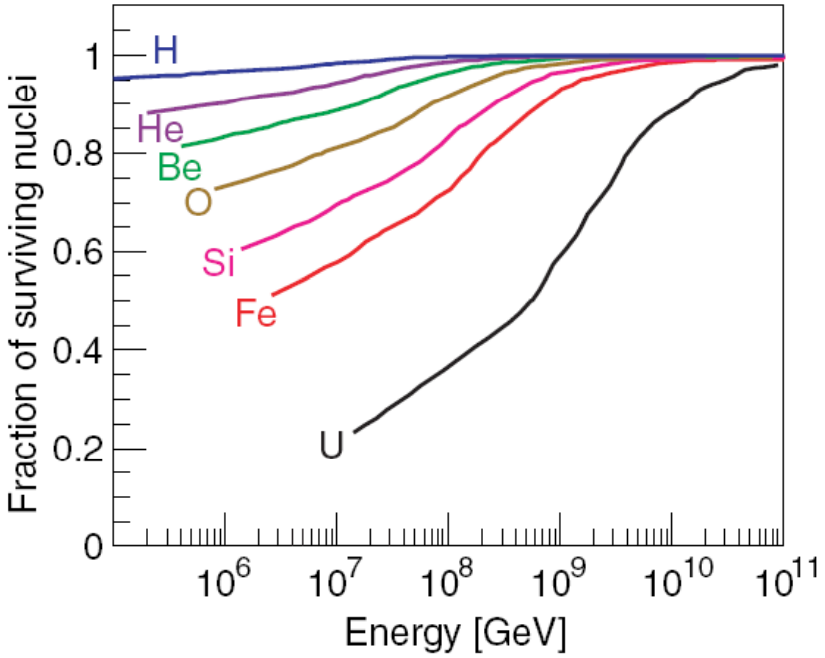


JRH, astro-ph/0702370



Origin of second knee?

- end of galactic component?
- significant contribution of ultra-heavy elements



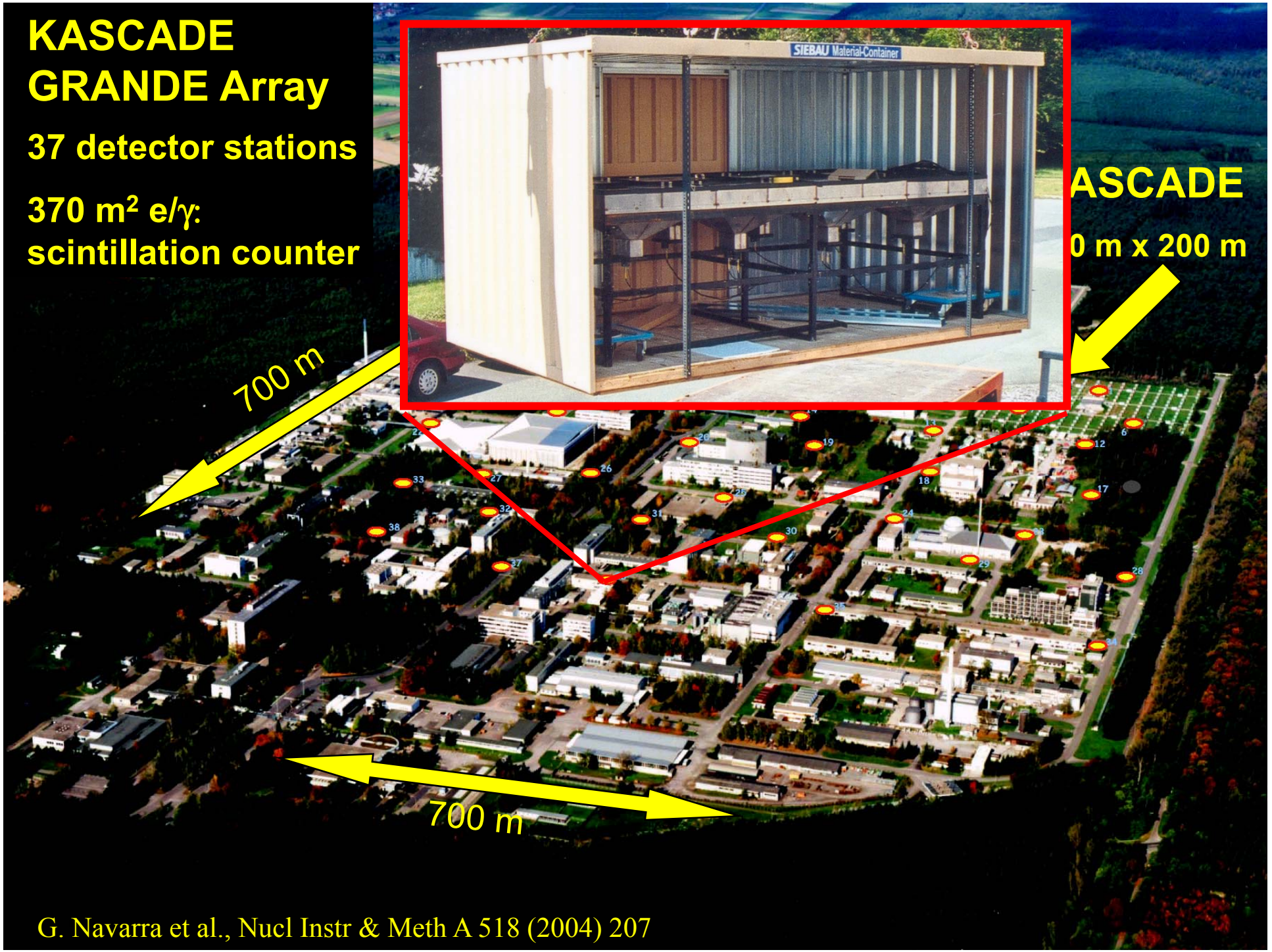
JRH et al, Astrop. Phys. 27 (2007) 119

Origin of dip?

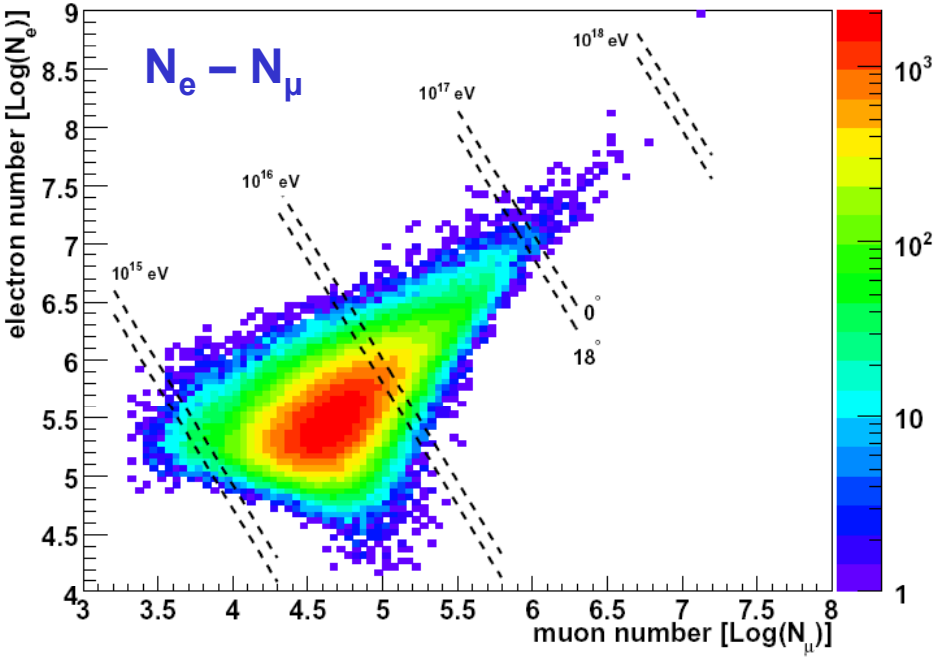
- pair production?

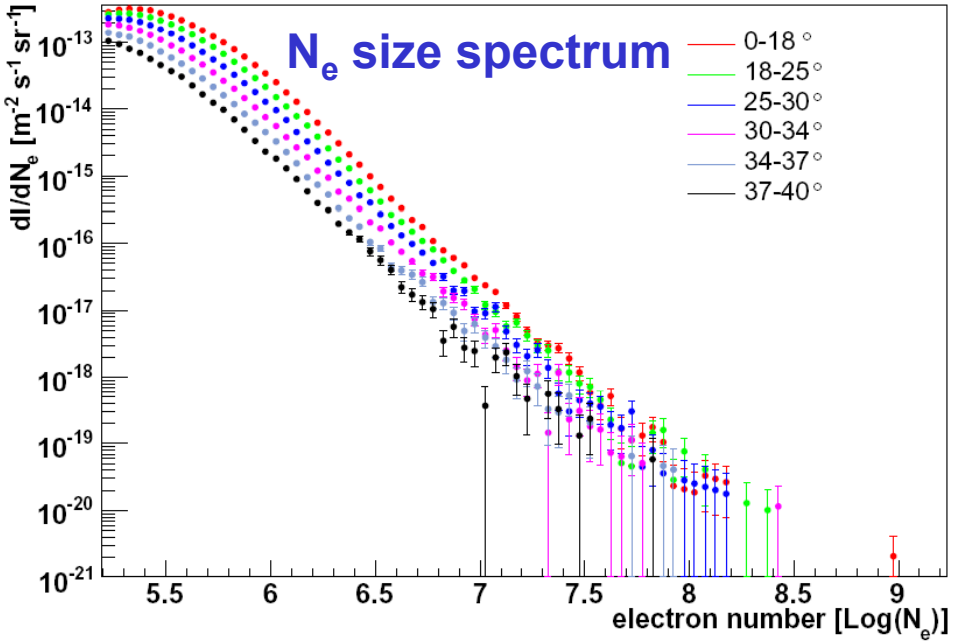
$p+\gamma_{3K} \rightarrow p+e^+ +e^-$

Berezinsky astro-ph/0702488

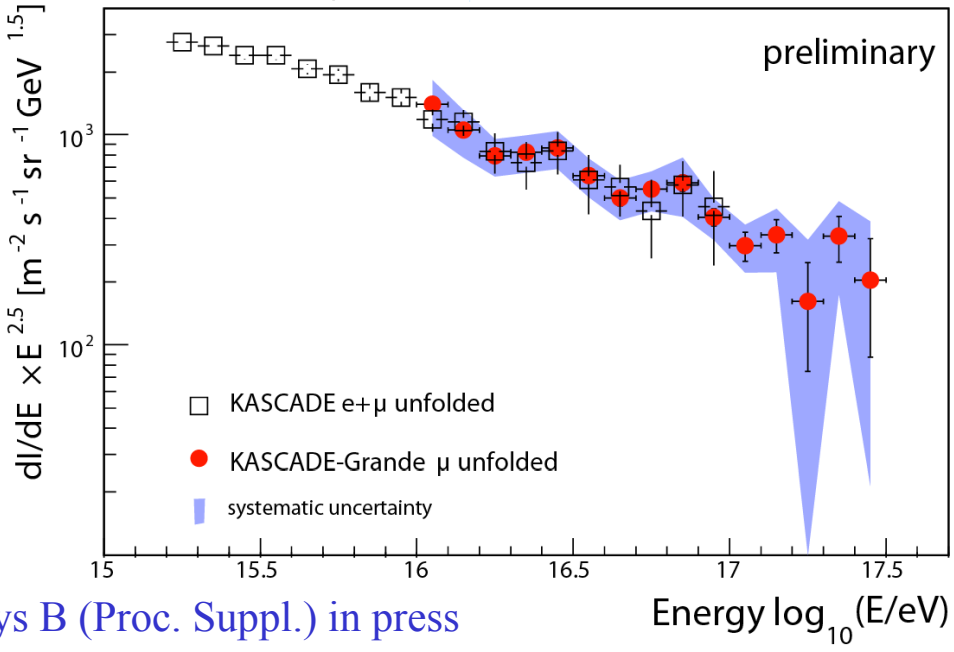

KASCADE
GRANDE Array
37 detector stations
370 m² e/γ:
scintillation counter
SIEBAU Material-Container
ASCADE
0 m x 200 m
700 m
700 m
G. Navarra et al., Nucl Instr & Meth A 518 (2004) 207

KASCADE-Grande First Results





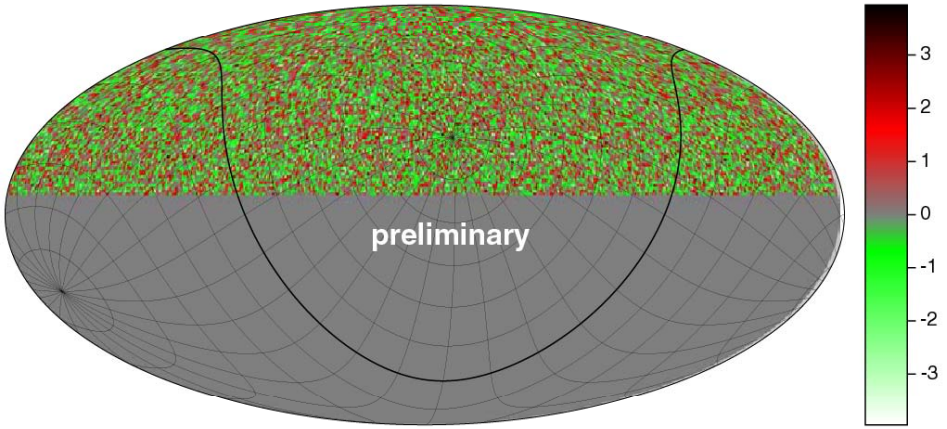
Energy spectrum
N_μ unfolded

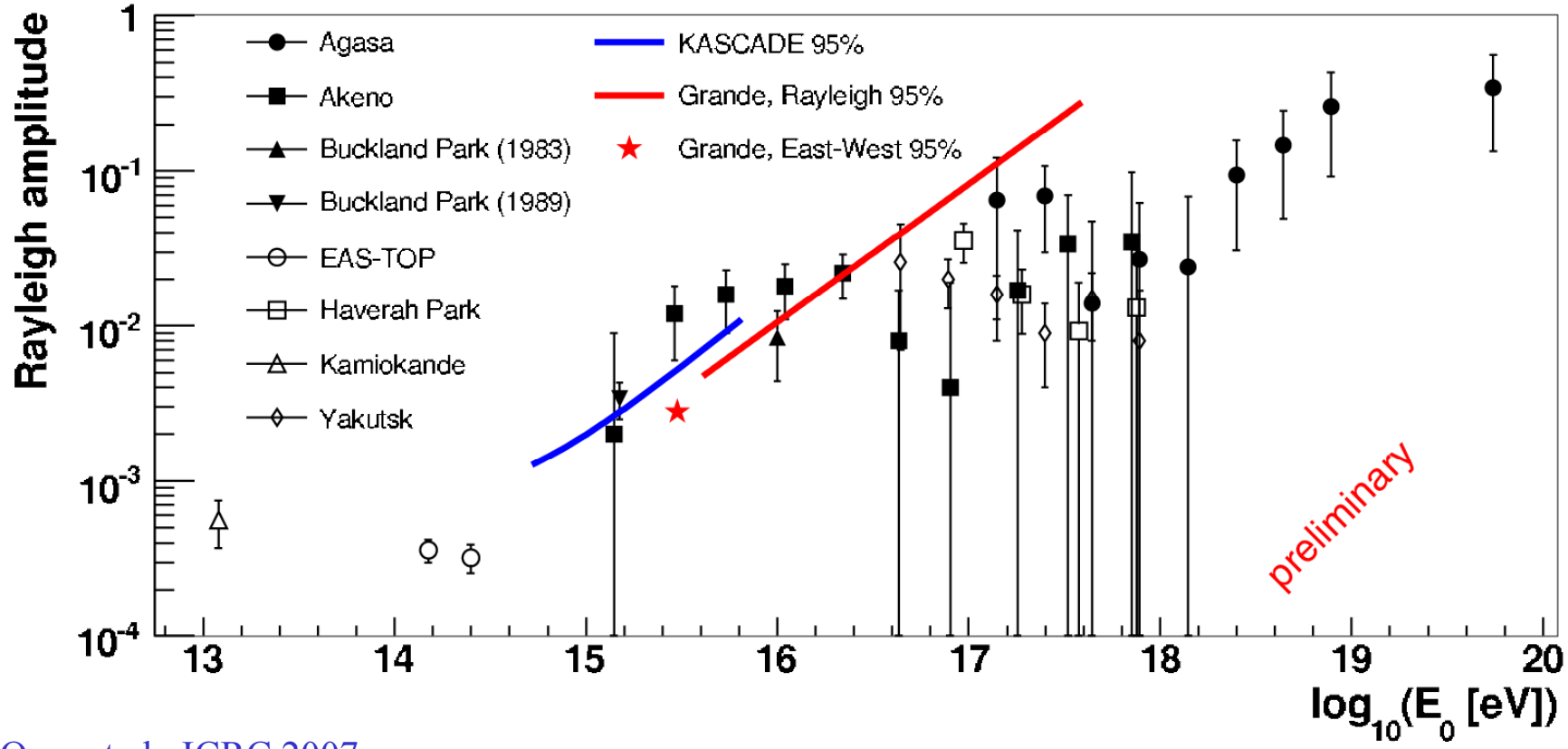


A. Haungs et al., Nucl. Phys B (Proc. Suppl.) in press

F. Cossavella

KASCADE-Grande Anisotropy Studies

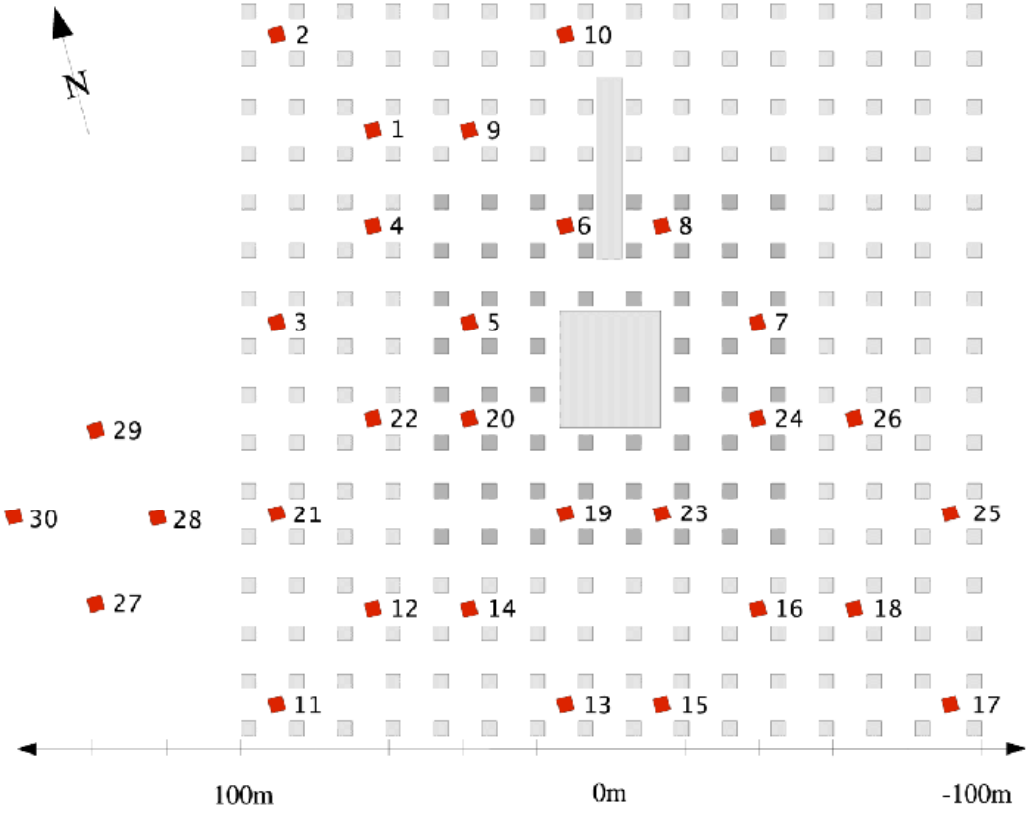


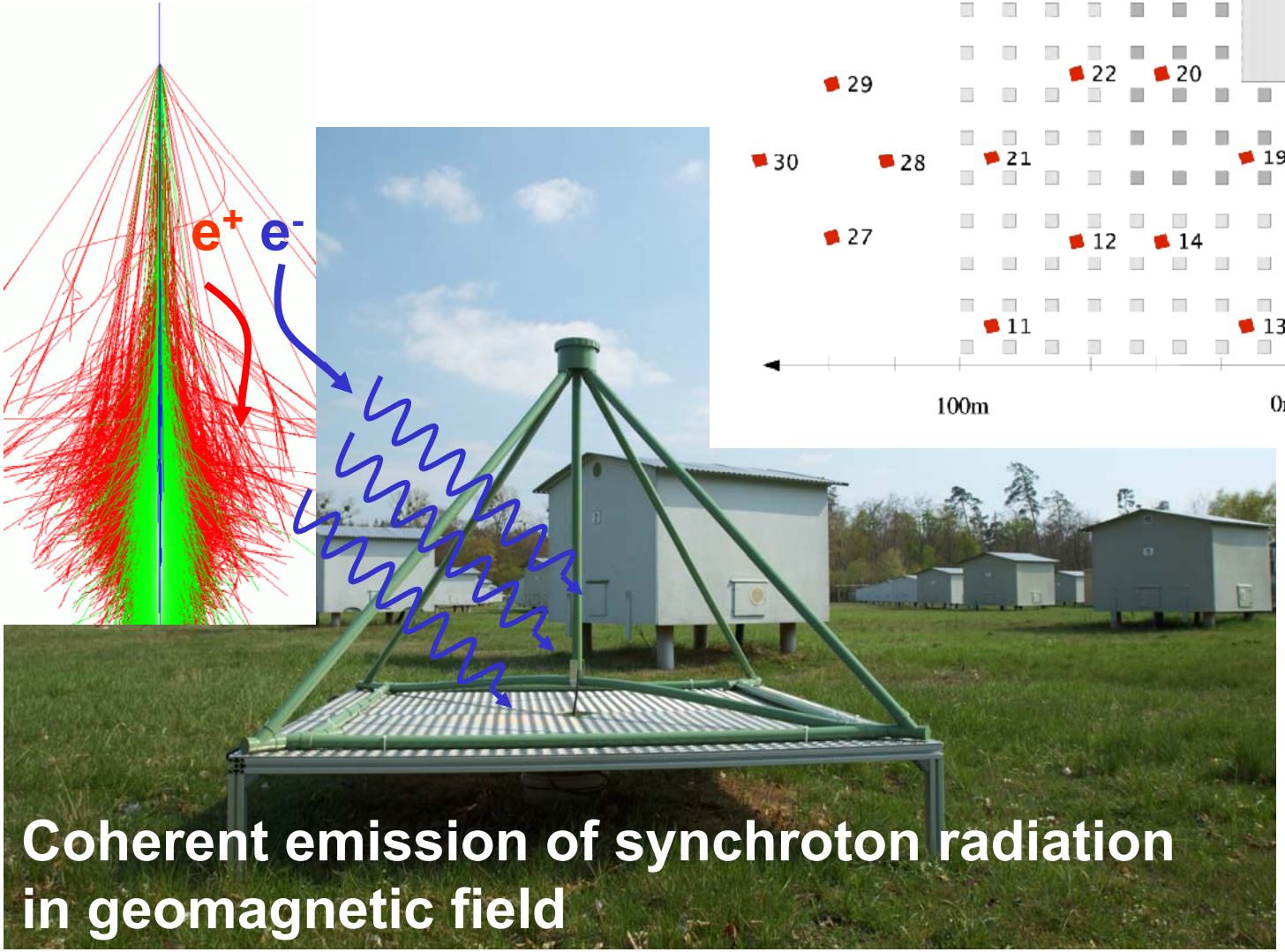


S. Over et al., ICRC 2007

LOPES

30 antennas operating at KASCADE-Grande



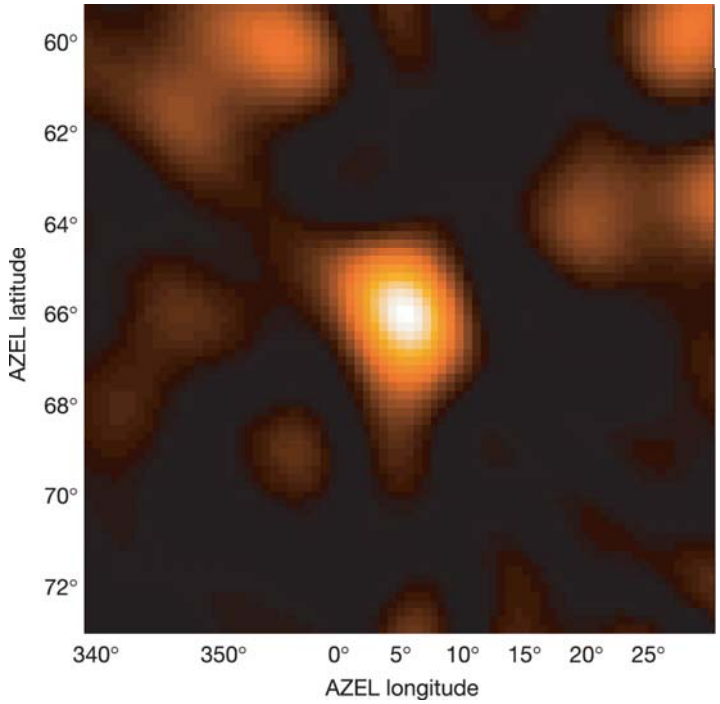


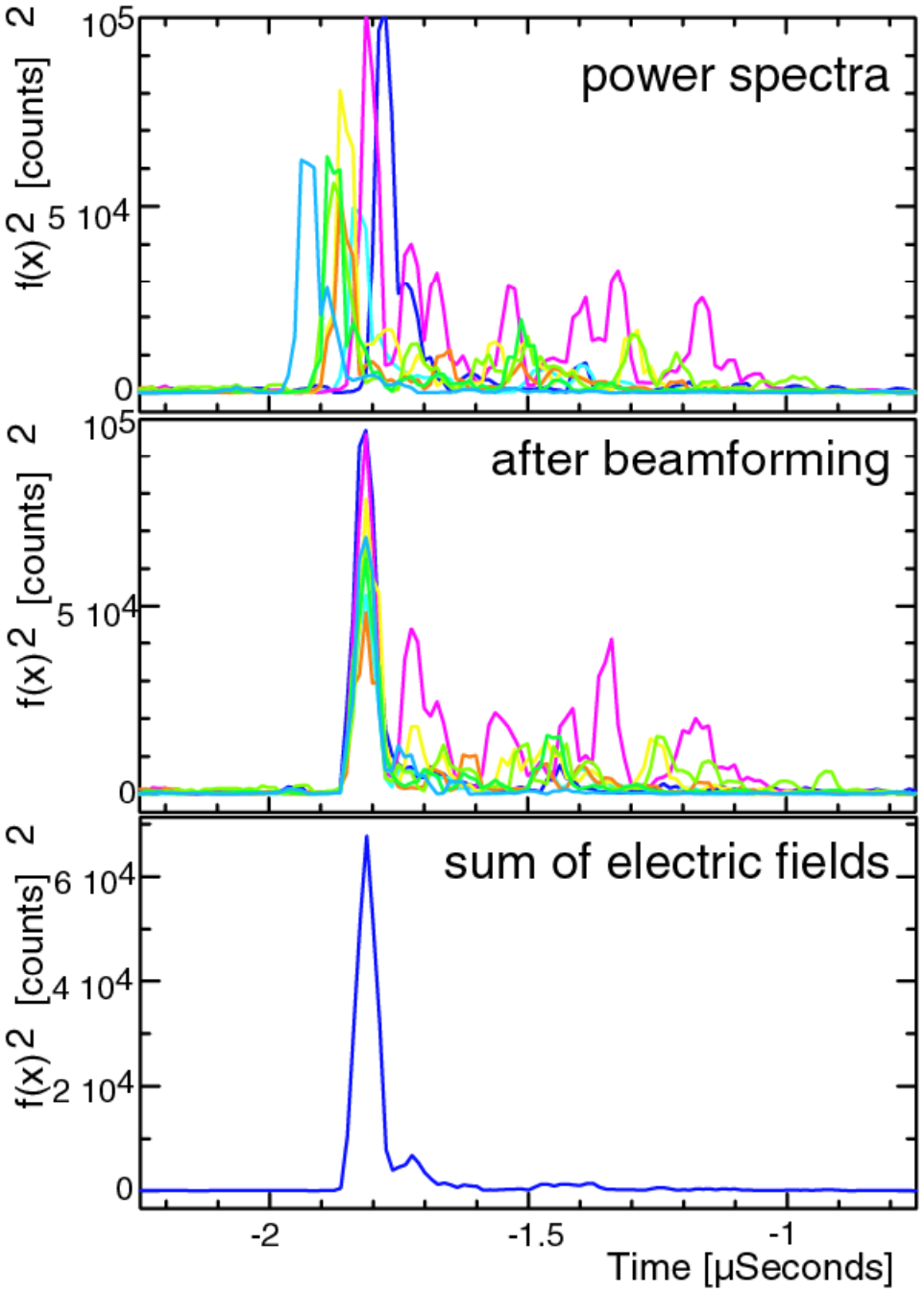
Coherent emission of synchroton radiation in geomagnetic field

LOPES
RADIO EMISSION FROM COSMIC RAY AIR SHOWERS

LOPES
first signals

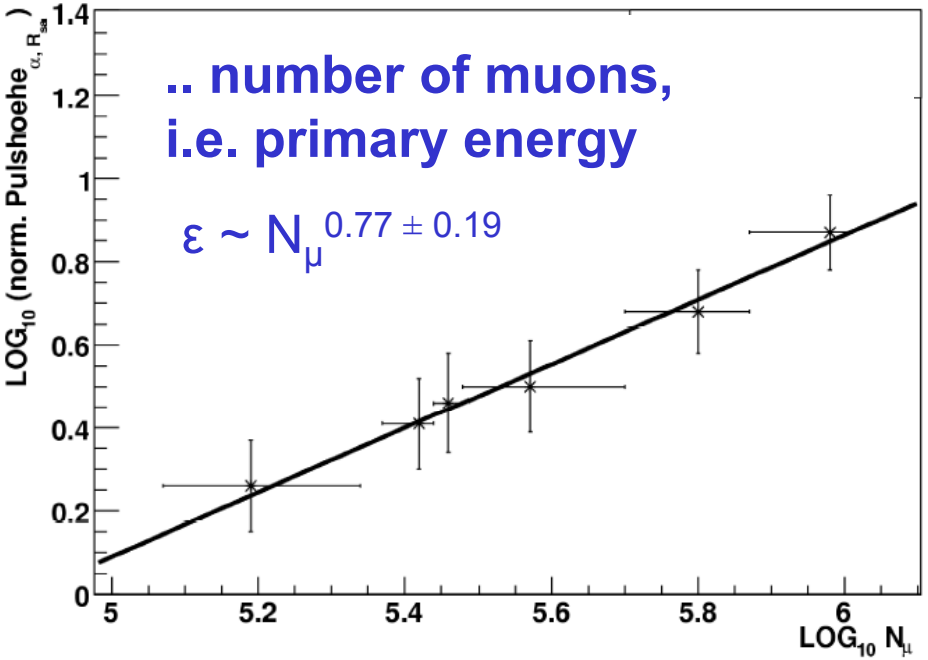
Position of shower in sky

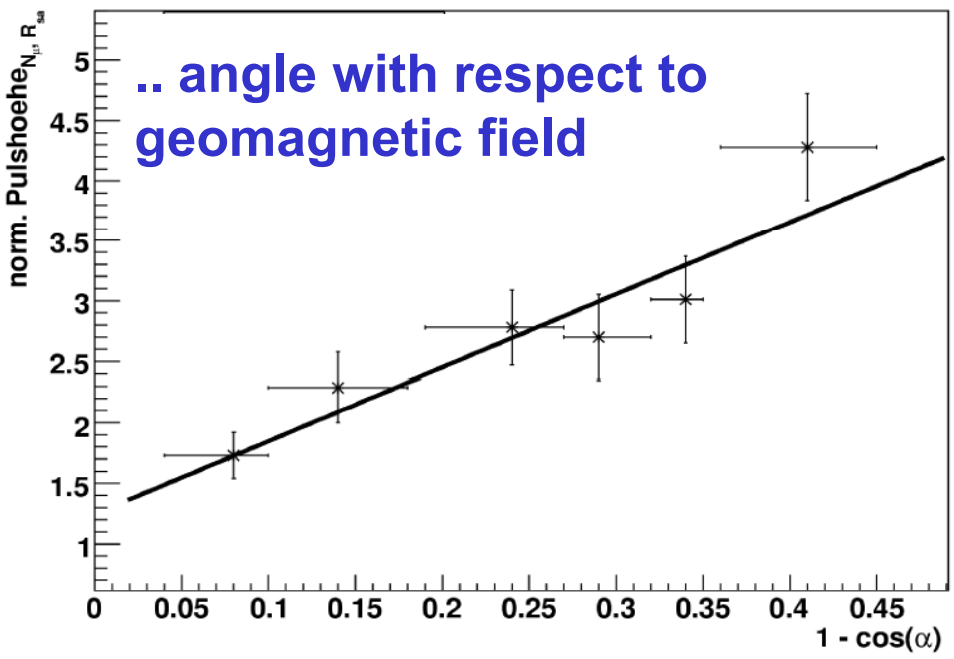


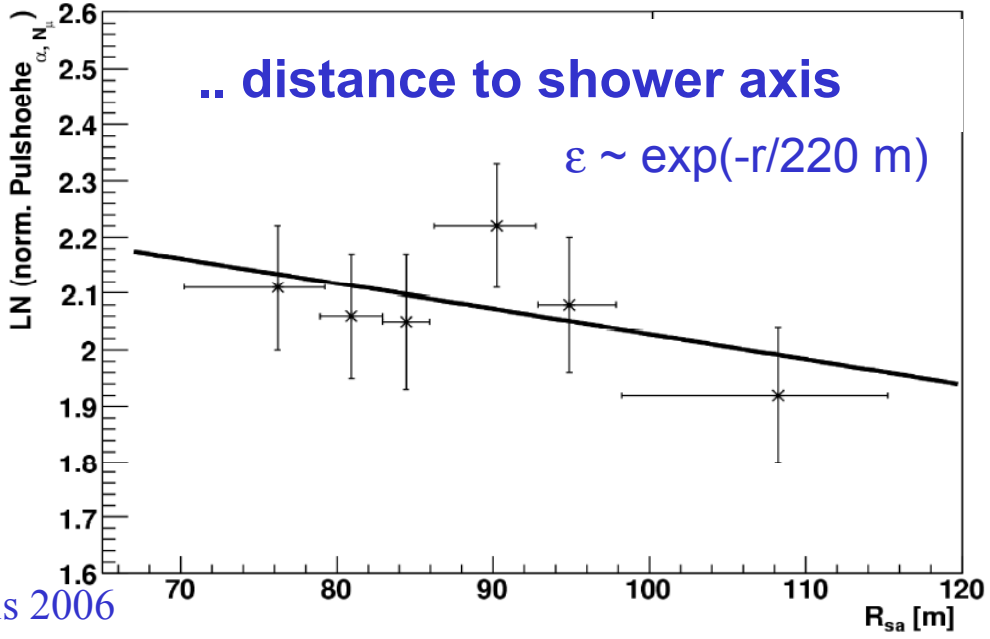


Nature 435 (2005) 313

LOPES – KASCADE-Grande dependence of radio signal on ..







E_0>5 10^{16} eV

E. Bettini Diploma Thesis 2006

ARIADNE Rome International Conference on Astro-Particle Physics
University "Sapienza" June 20th - 22nd 2007 Roma - Italy

The origin of galactic cosmic rays

Galactic cosmic rays:

- Most likely accelerated in supernova remnants
- Knee caused by cut-off for light elements
- Most likely, knee due to combination of acceleration and propagation processes, exotic ideas most likely excluded
- Astrophysical interpretation of air shower data limited by understanding of hadronic interactions in atmosphere
- Qualitative agreement of data with „standard picture“
  However, details not yet clear

Transition region to extragalactic CRs:

- Key experiments take data/are under construction
- Interesting results expected in next five years

Jörg R. Hörandel
Radboud University Nijmegen, The Netherlands www-ik.fzk.de/~joerg