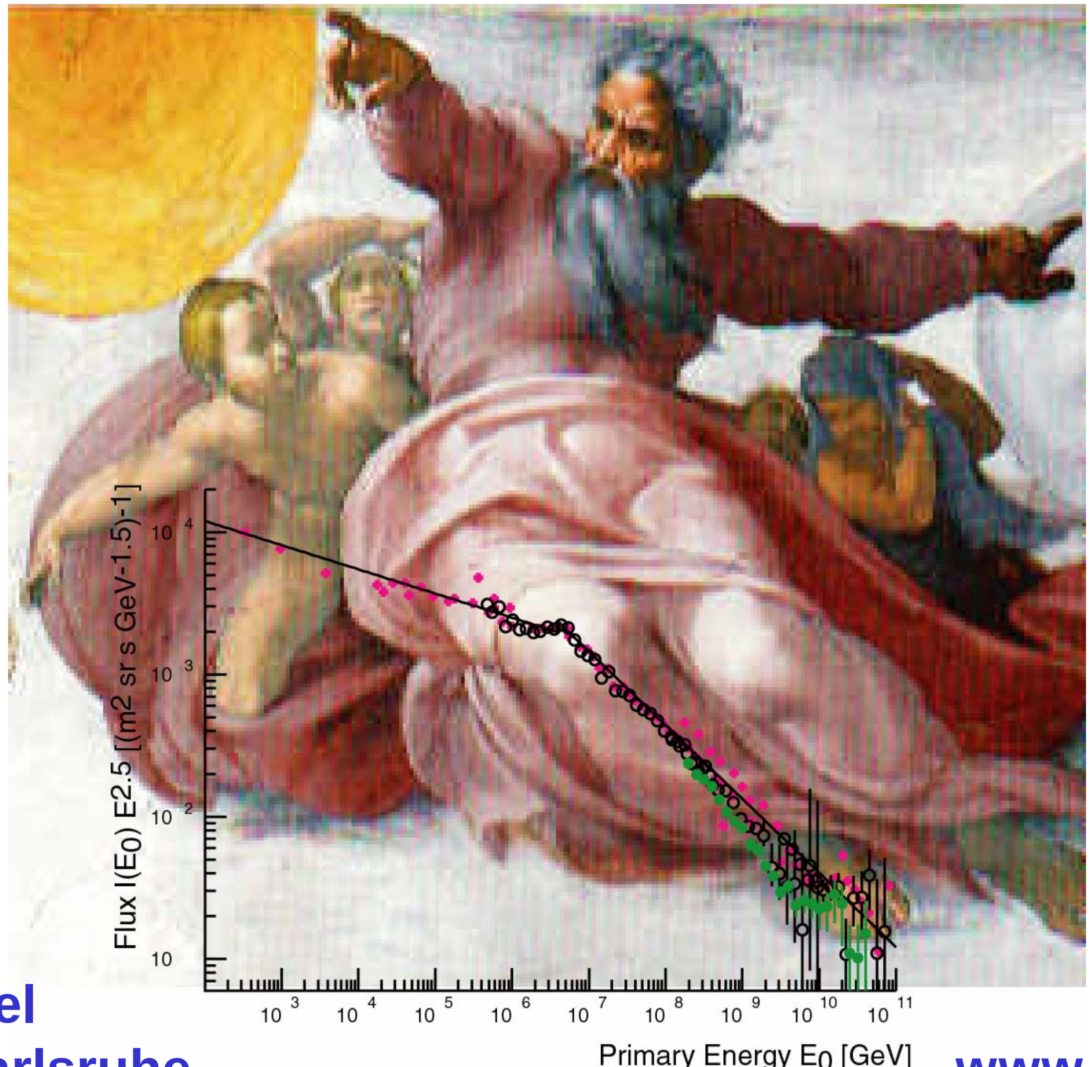
From the Knee to the toes:

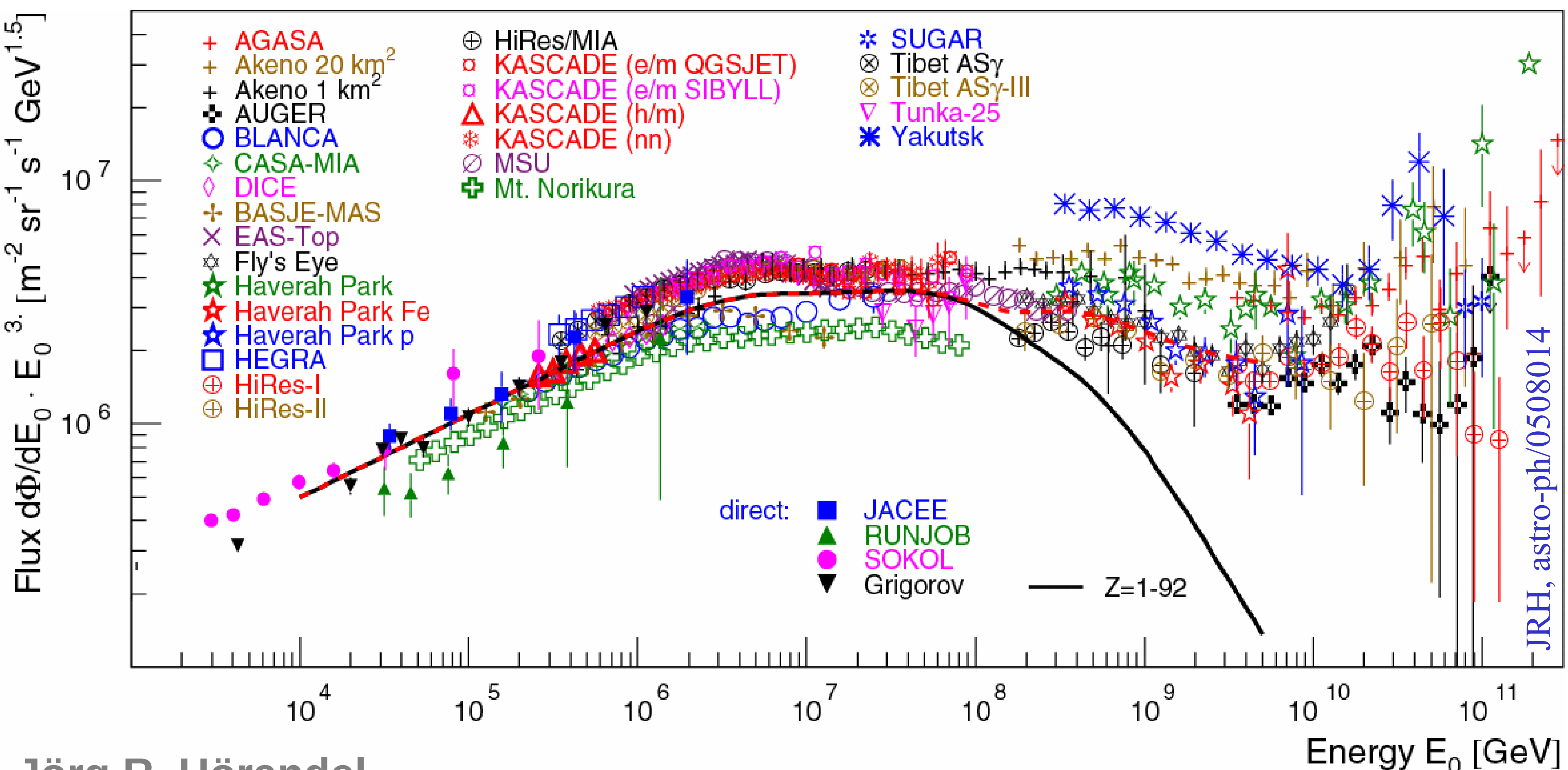
The challenge of cosmic-ray composition



Jörg R. Hörandel
University of Karlsruhe
www-ik.fzk.de/~joerg

From the Knee to the toes:

The challenge of cosmic-ray composition



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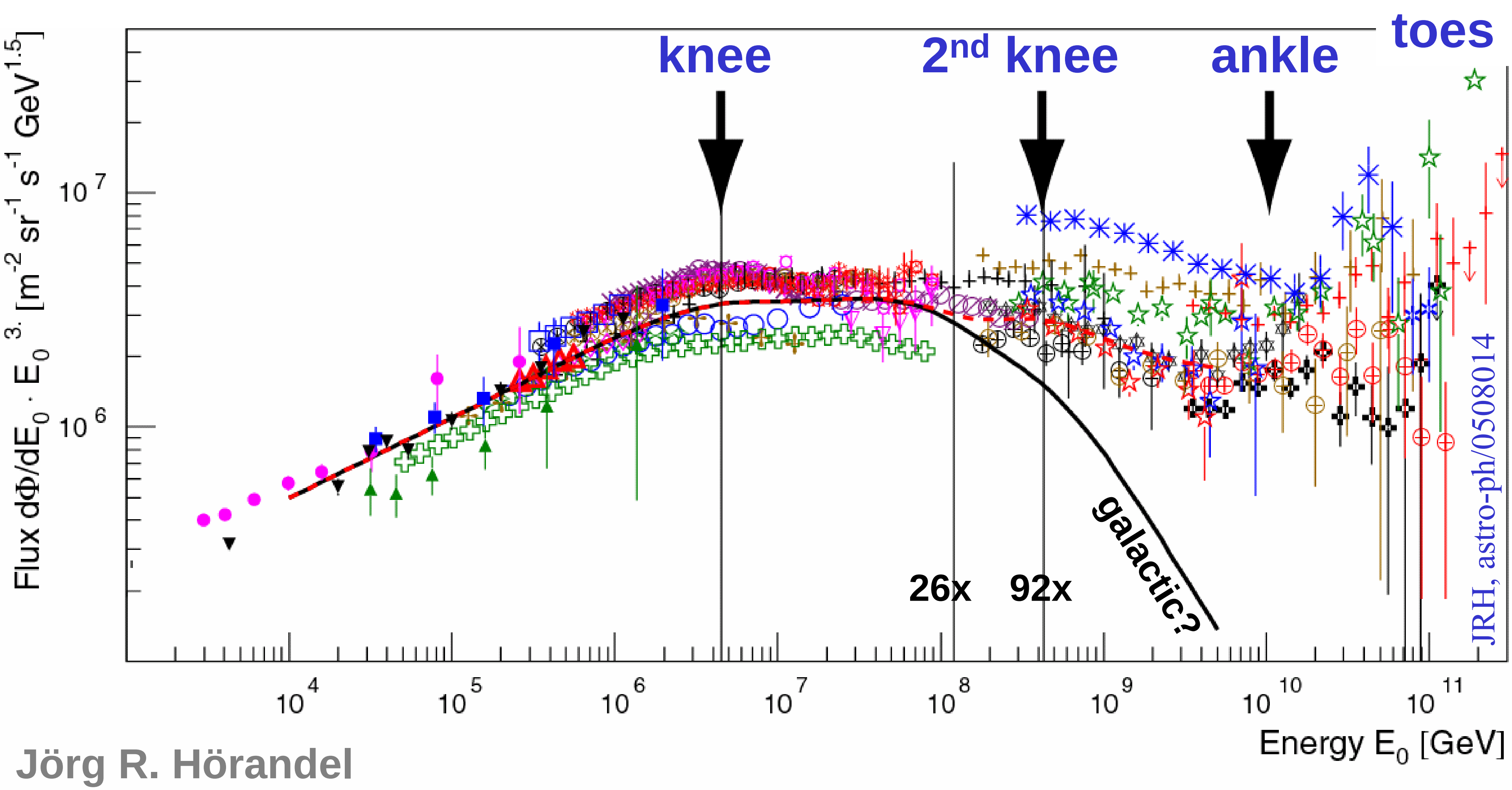
New Views of the Universe

December 8th – 13th, 2005, Chicago

From the Knee to the toes:

The challenge of cosmic-ray composition



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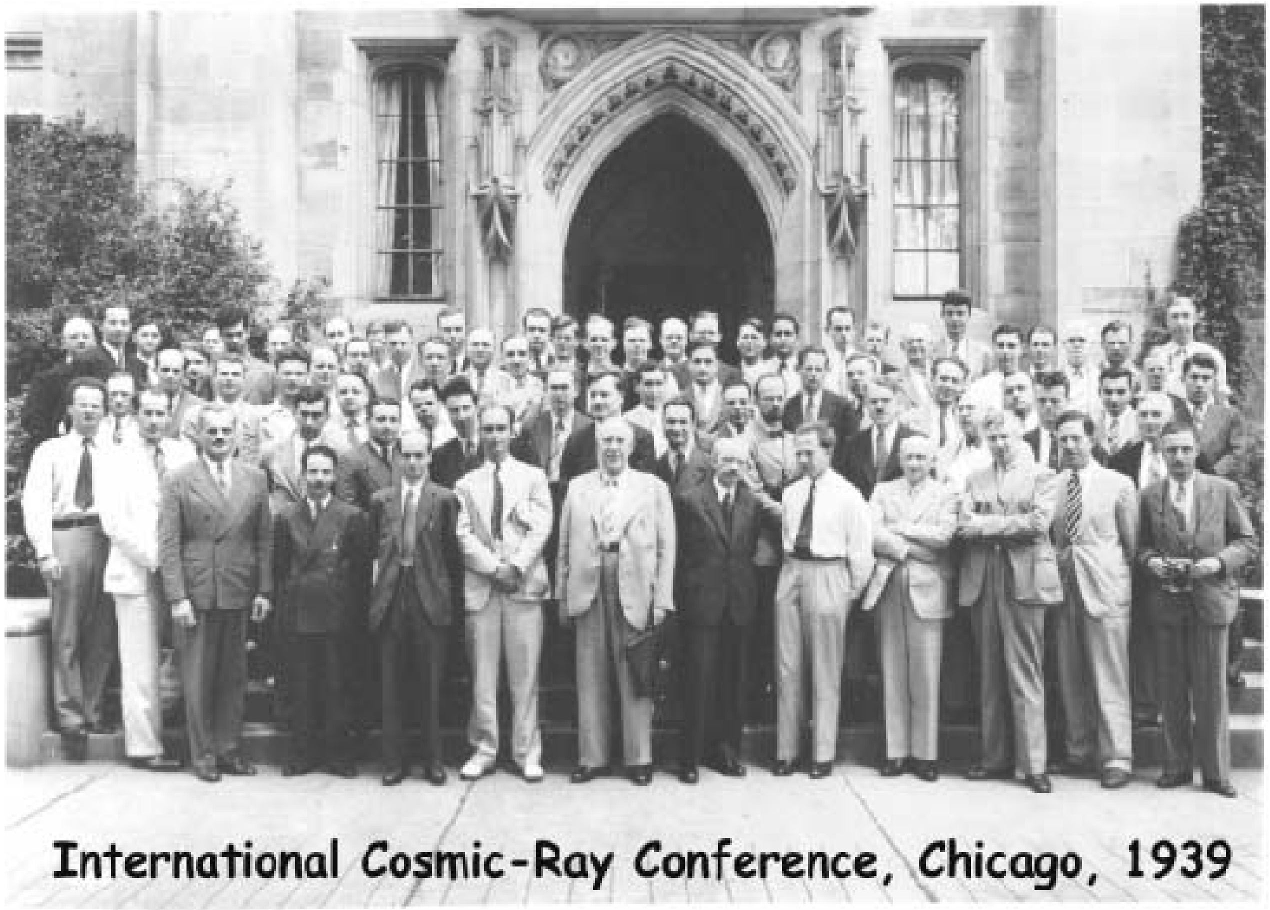
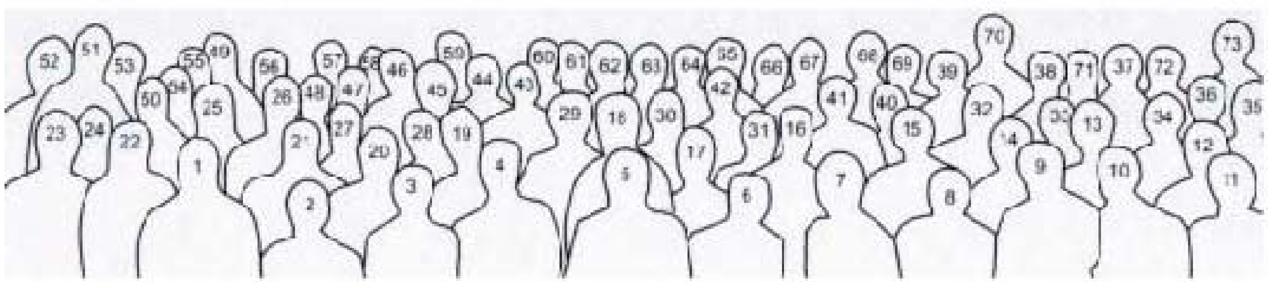
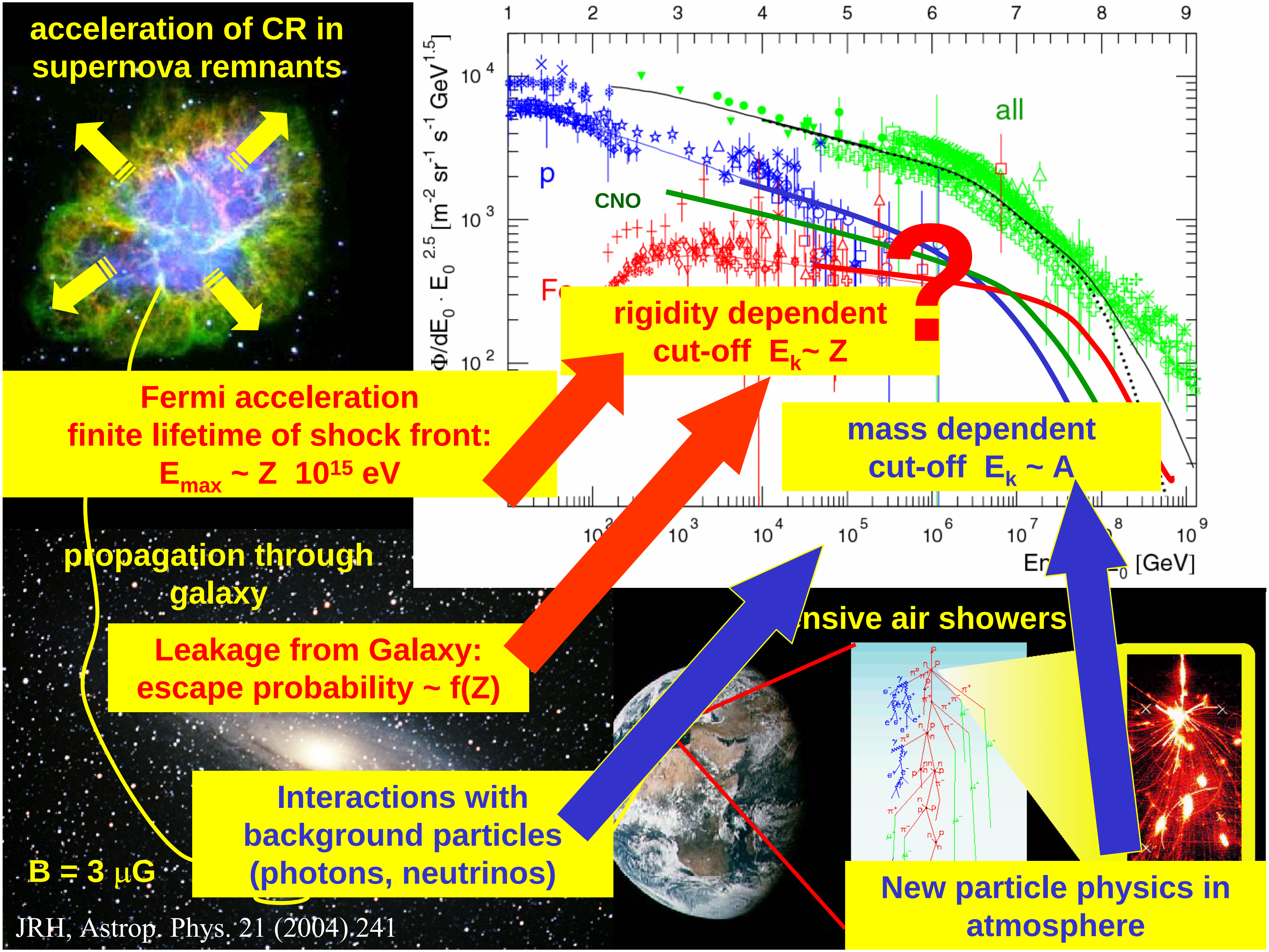




1. A, H, Compton
2. A. Baños
3. M. S. Vallarta
4. C. Anderson
5. V. F. Hess
6. W. Bothe
7. W. Heisenberg
8. J. Clay
9. W. F. G. Swann
10. G. Herzog
11. Beutler
12. W. D. Harkins
13. S. Neddermeyer
15. T. H. Johnson
16. P. Auger
17. B. Rossi
19. J. R. Oppenheimer
20. S. Goudsmit
21. E. Teller
22. R. Brode
23. H. Bethe
25. C.G. Montgomery
26. W. Bostick
28. L. Nordheim
29. S.E. Forbush
30. V. Wilson
33. J. Wheeler
34. M. Pomerantz
37. Dereshem
41. R. Serber
43. E. Wollan
51. M. M. Shapiro
57. C. Eckart
61. D. Hughes
62. W. Jesse
64. J.B. Hoag
65. N. Hilberry
67. P. Gilli
60. A. Snell


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
rigidity dependent cut-off $E_k \sim Z$
mass dependent cut-off $E_k \sim A$
nsive air showers
New particle physics in atmosphere
p
CNO
Fe
all
?
$d\Phi/dE_0 \cdot E_0^{2.5}$ [$m^{-2} sr^{-1} s^{-1} GeV^{1.5}$]
[GeV]
JRH, Astrop. Phys. 21 (2004) 241

TRACER Experiment - Mc Murdo, Antarctica

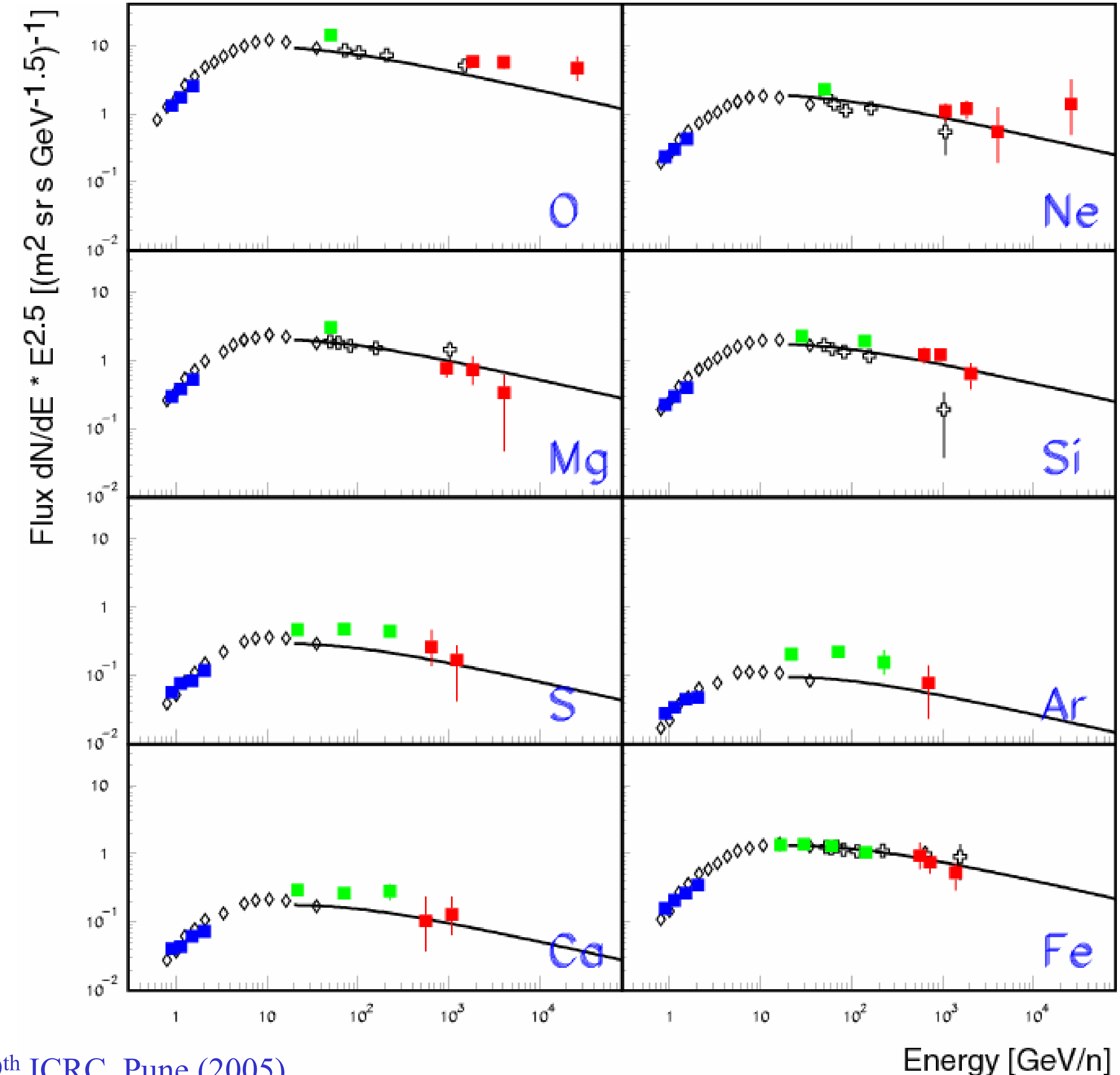
LDB flight: December 12th – 26th, 2003

~ 40 km (3-5 g/cm^2)

Z = 8 - 26

E = 1 GeV/n - ~10 TeV/n

TRACER
energy spectra for individual elements



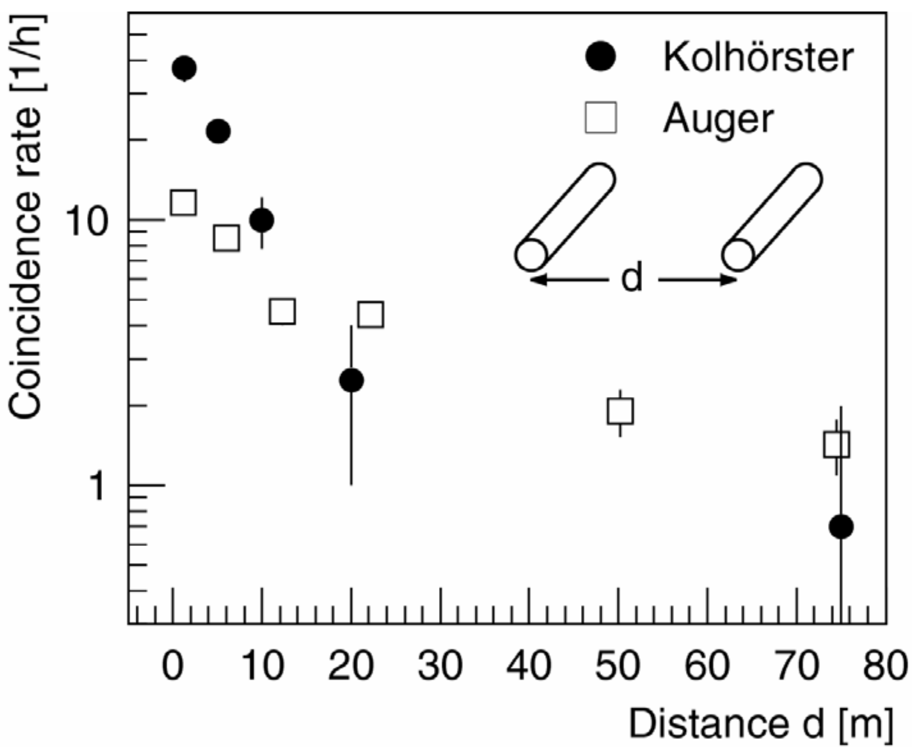
D. Müller et al., Proc. 29th ICRC, Pune (2005)

Extensive air showers

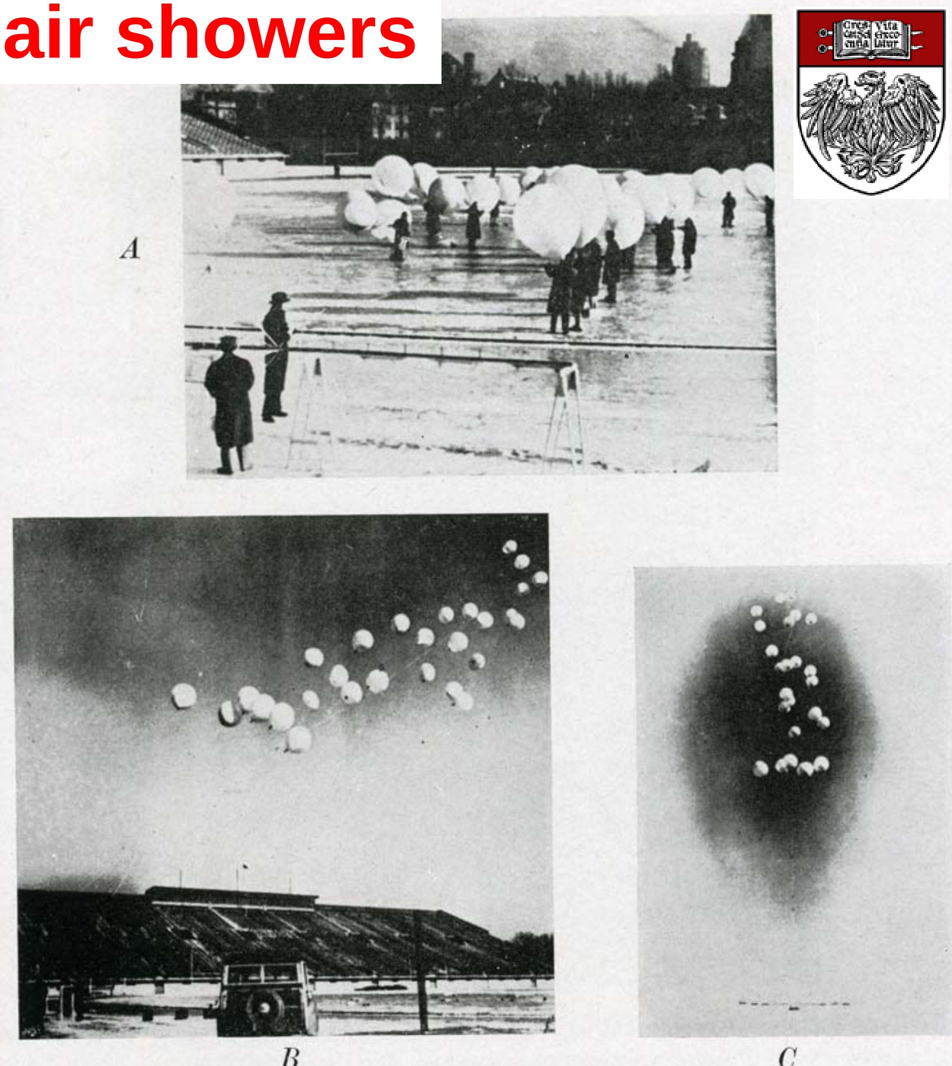
Measuring Cosmic Rays in the Swiss Alps

The author (*left*) and his collaborator, P. Ehrenfest, set up their apparatus in the Jungfraujoch.

P. Auger
Jungfraujoch



W. Kolhörster et al., Naturwiss. 26 (1938) 576
P. Auger et al., Comptes renduz 206 (1938) 1721



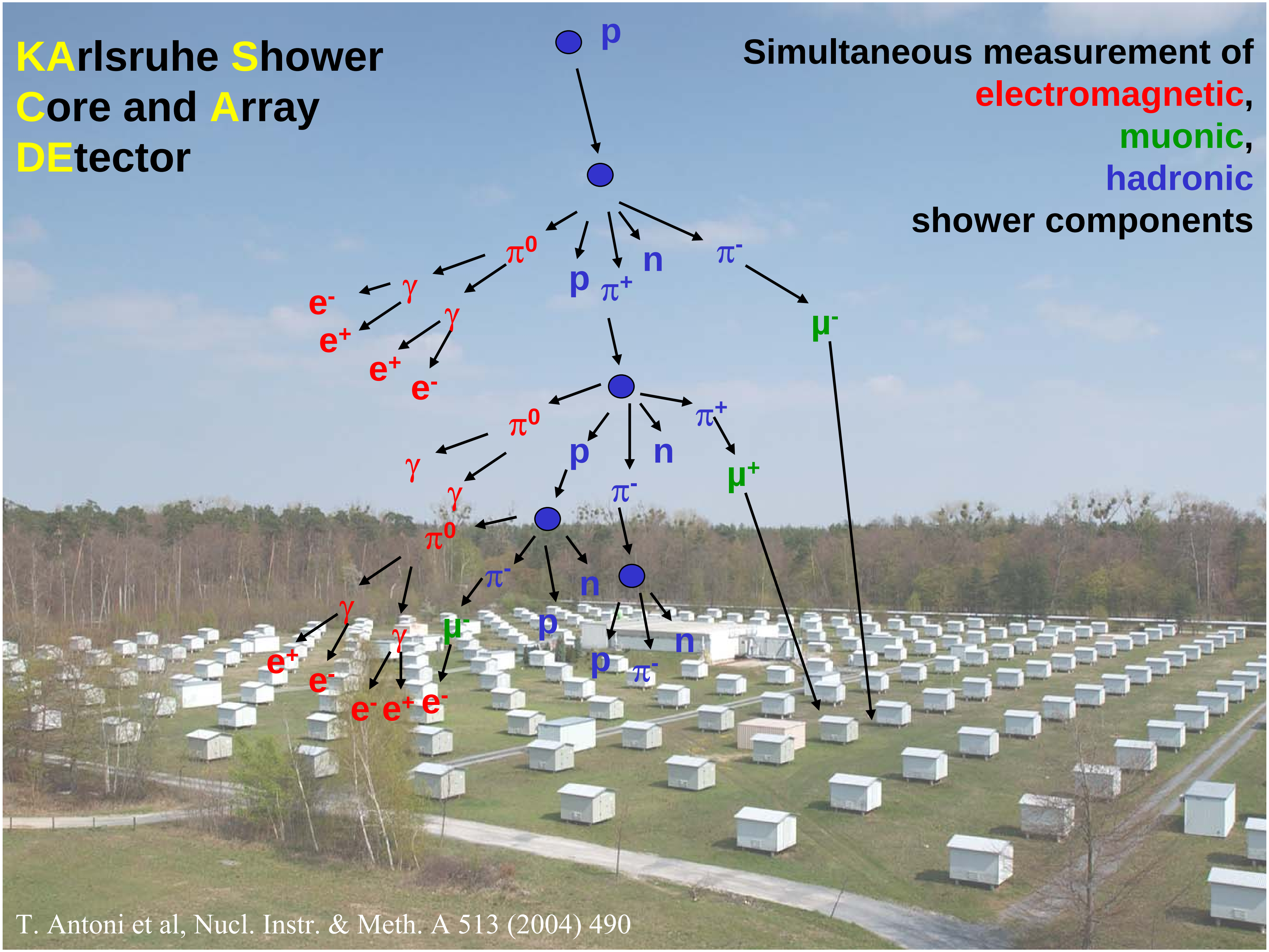
P. Auger

Balloon Flight of January, 1943, Conducted by the Author, Schein, and Rogozinski for the Measurement of Extensive (or Auger-) Showers in the Stratosphere

A. The balloons are assembled on Stagg Field at the University of Chicago, Chicago, Illinois. In the foreground can be seen the long frame which was required for the wide separation of the cosmic-ray counters.

B. The large cluster of balloons as it is about to be released.

C. The balloon train sails into the sky after its release. Suspended below the balloons is the frame supporting the counters and recording apparatus.


KArlsruhe Shower
Core and Array
DEtector
Simultaneous measurement of
electromagnetic,
muonic,
hadronic
shower components
p
π0
p
π+
n
π-
γ
γ
e-
e+
e+
e-
μ-
π0
p
n
π+
γ
γ
π-
μ+
π0
π-
n
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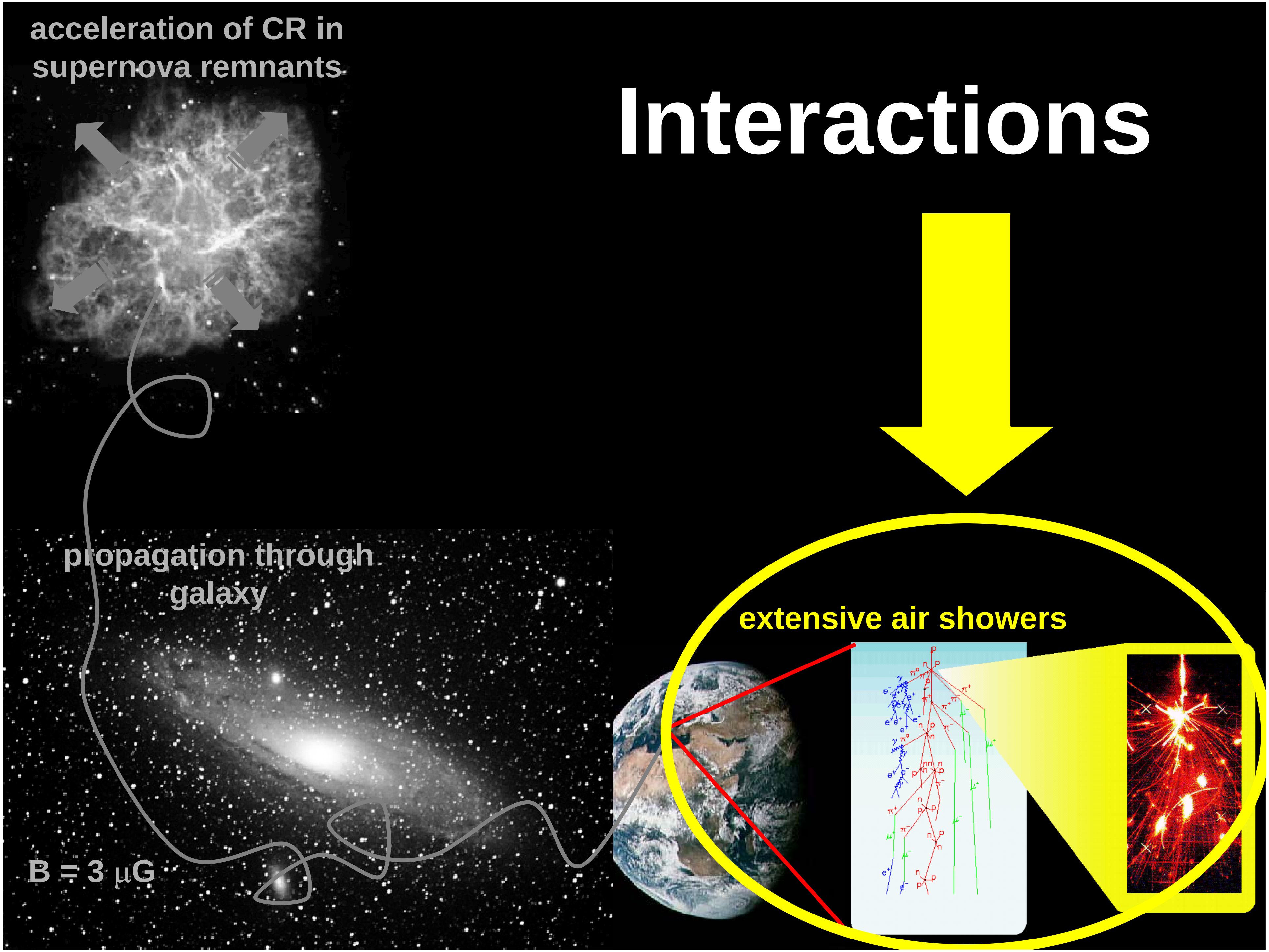
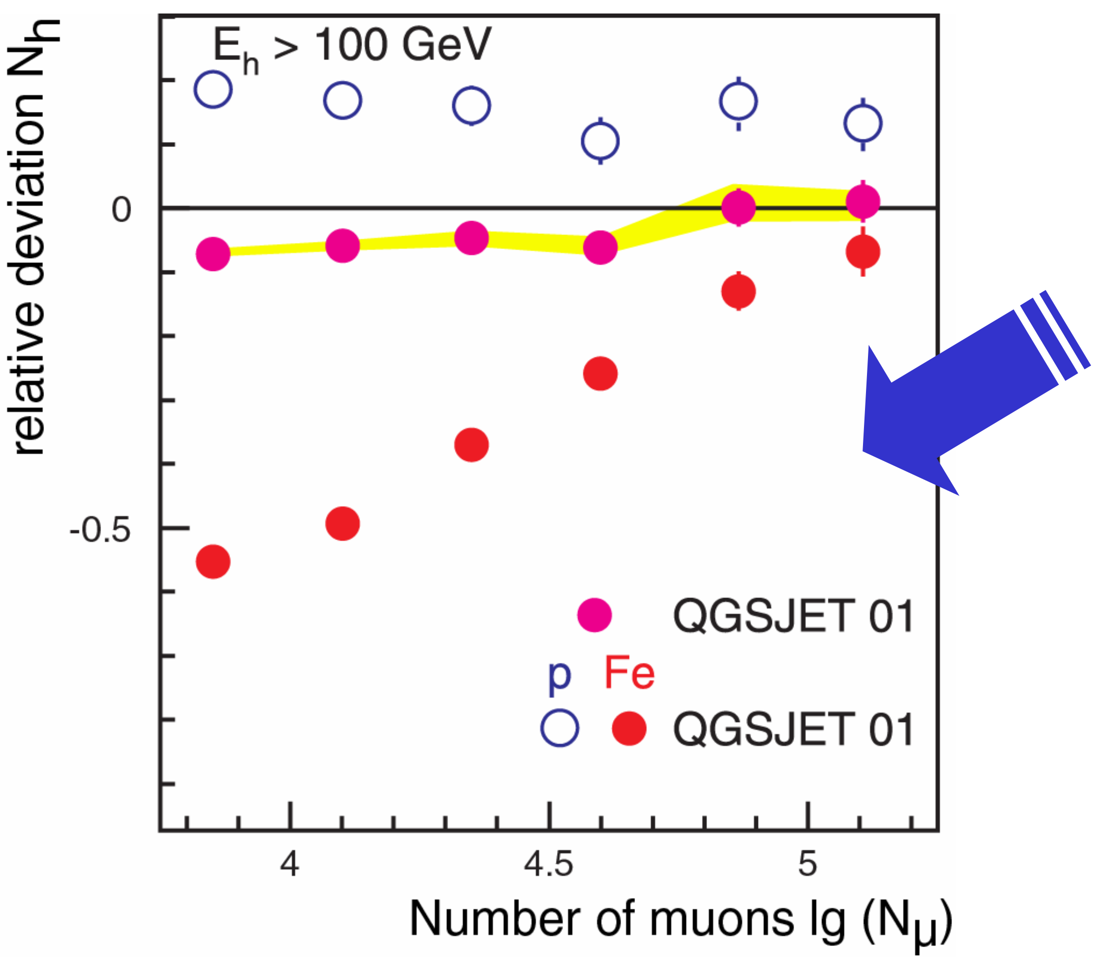
T. Antoni et al, Nucl. Instr. & Meth. A 513 (2004) 490


acceleration of CR in supernova remnants
Interactions
propagation through galaxy
B = 3 μG
extensive air showers

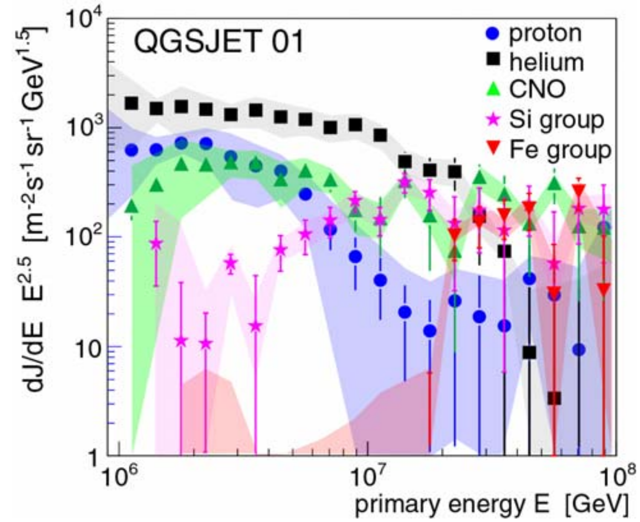
KASCADE: Test of interaction models

QGSJET 01

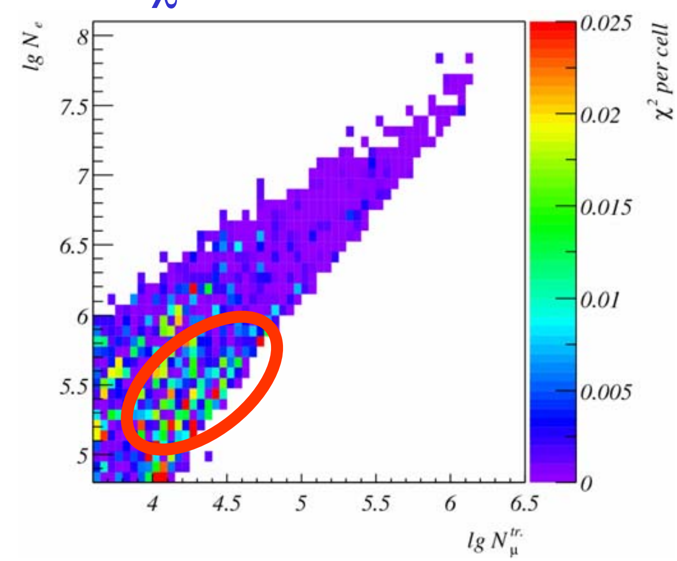
Number of hadrons vs. number of muons



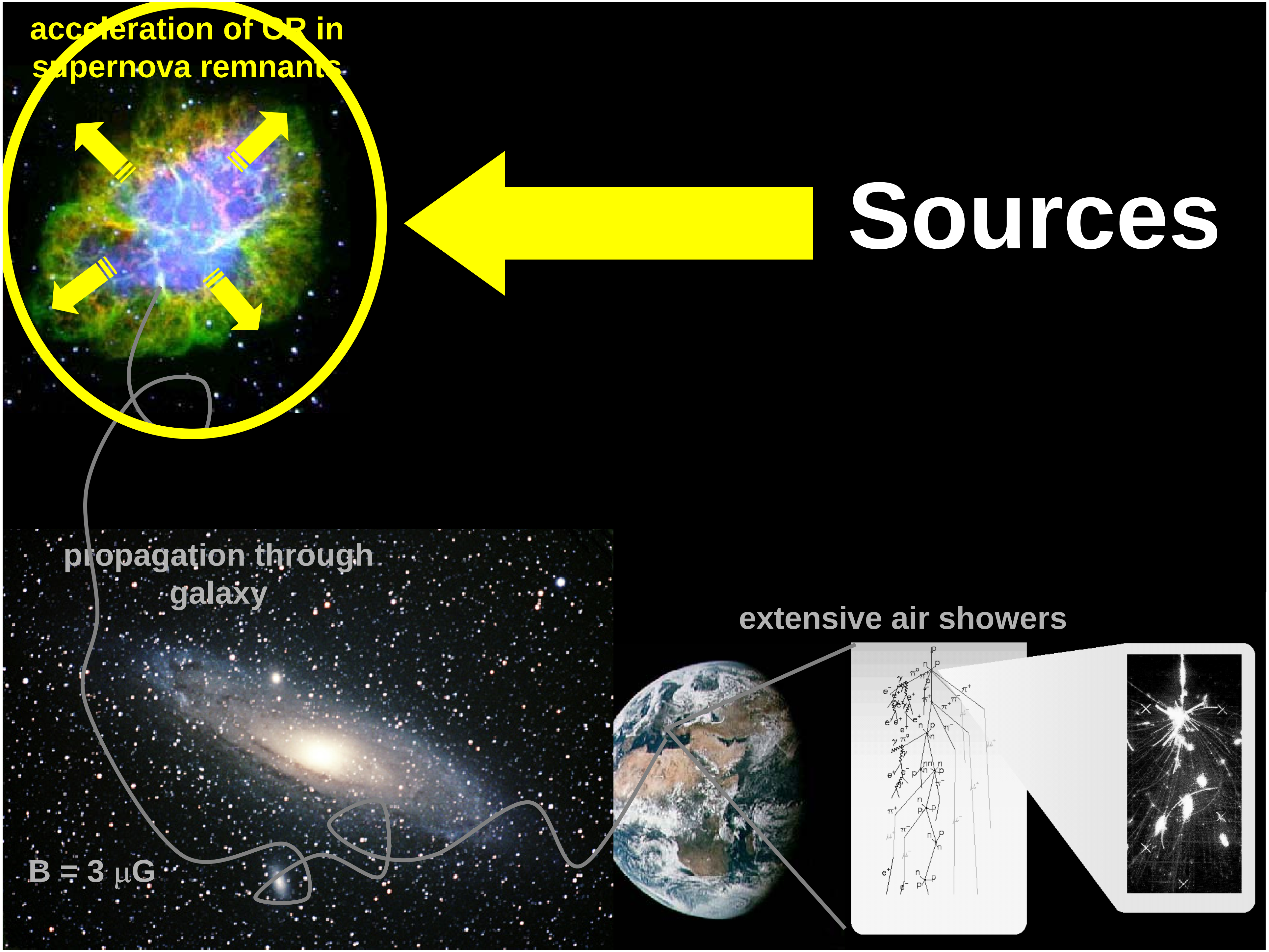
N_e-N_μ analysis



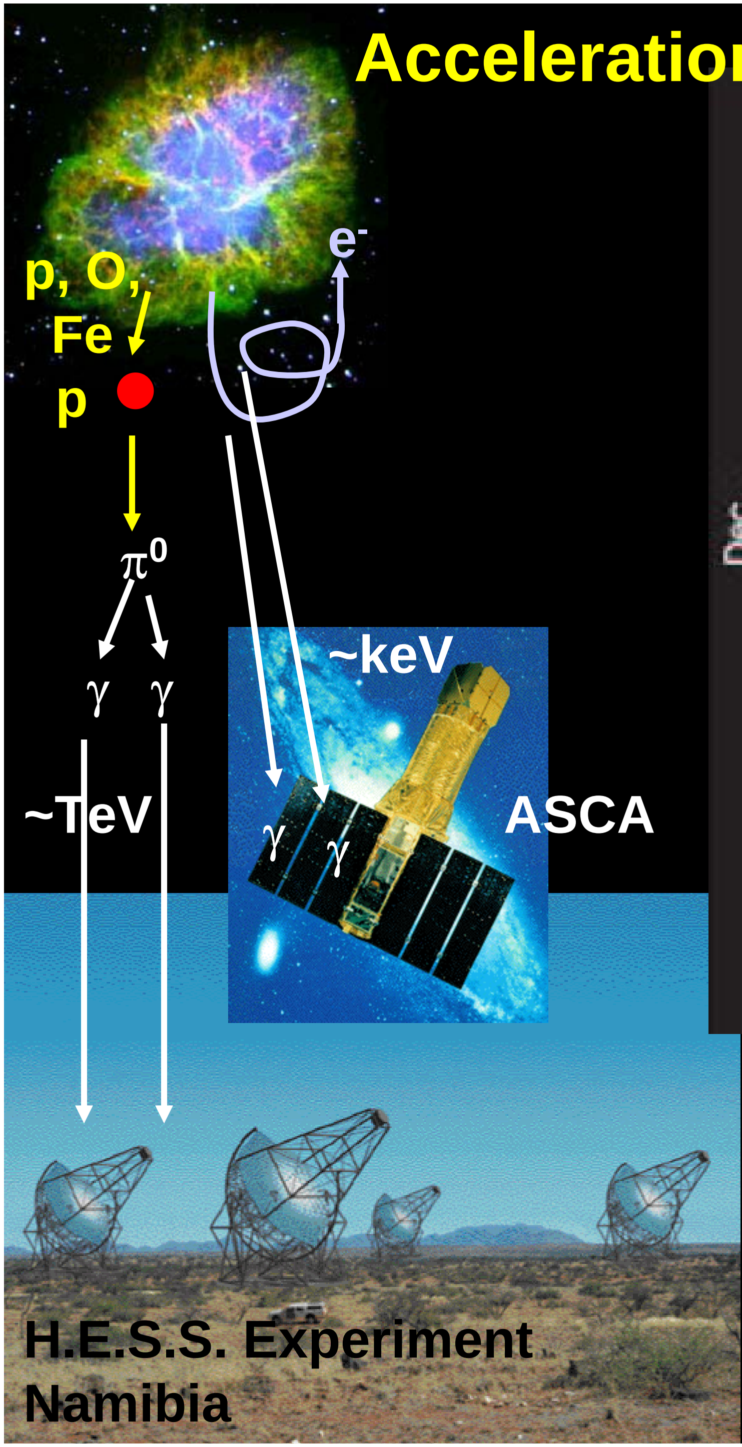
χ^2 distribution

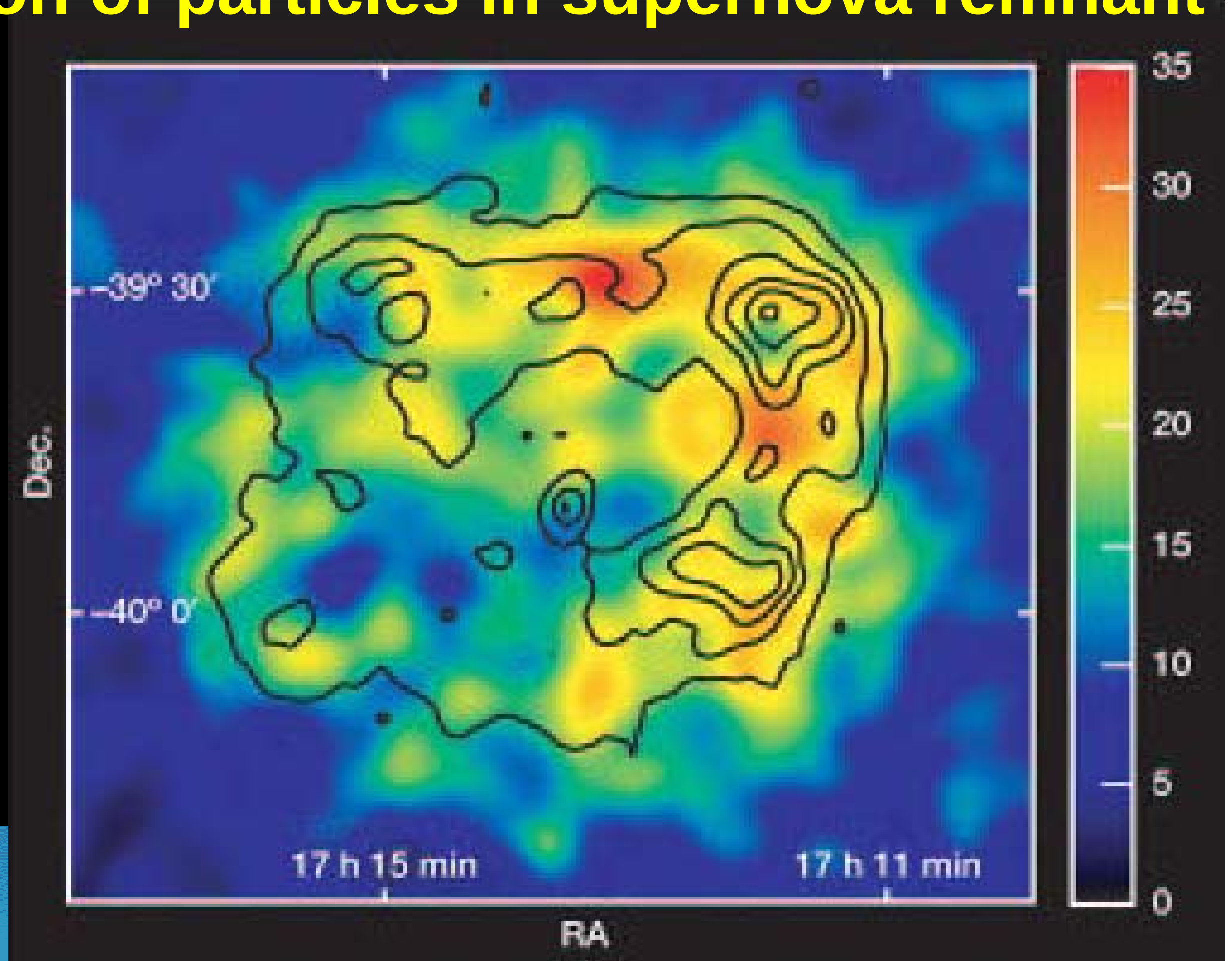


J. Milke et al., 29th ICRC, Pune (2005)


acceleration of CR in
supernova remnants
Sources
propagation through
galaxy
B = 3 μG
extensive air showers

Acceleration of particles in supernova remnant

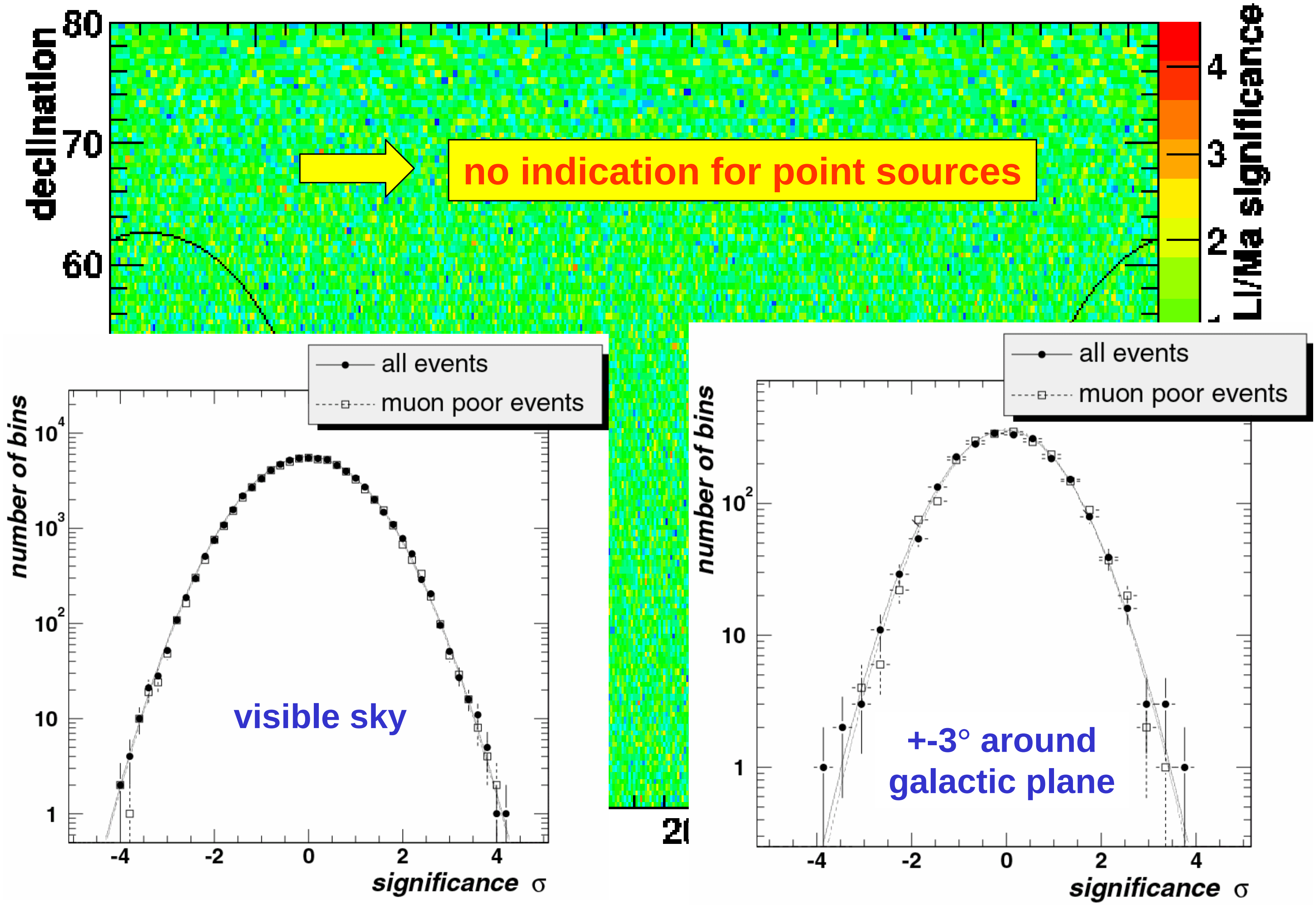




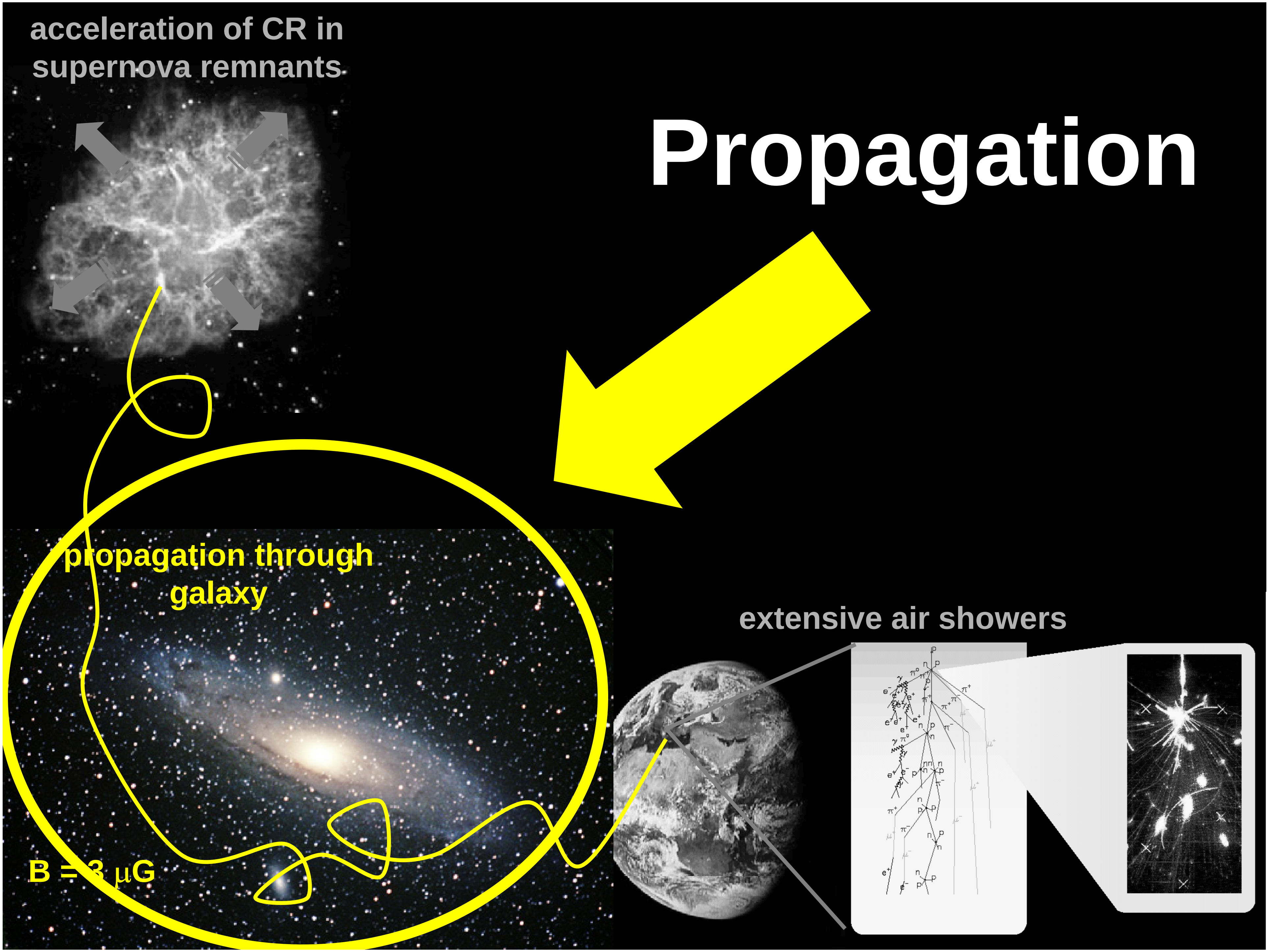
SN R RX J1713.7-3946
H.E.S.S.: TeV-Gamma rays
ASCA: X-rays (keV)

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

KASCADE: Small scale anisotropy – point source search

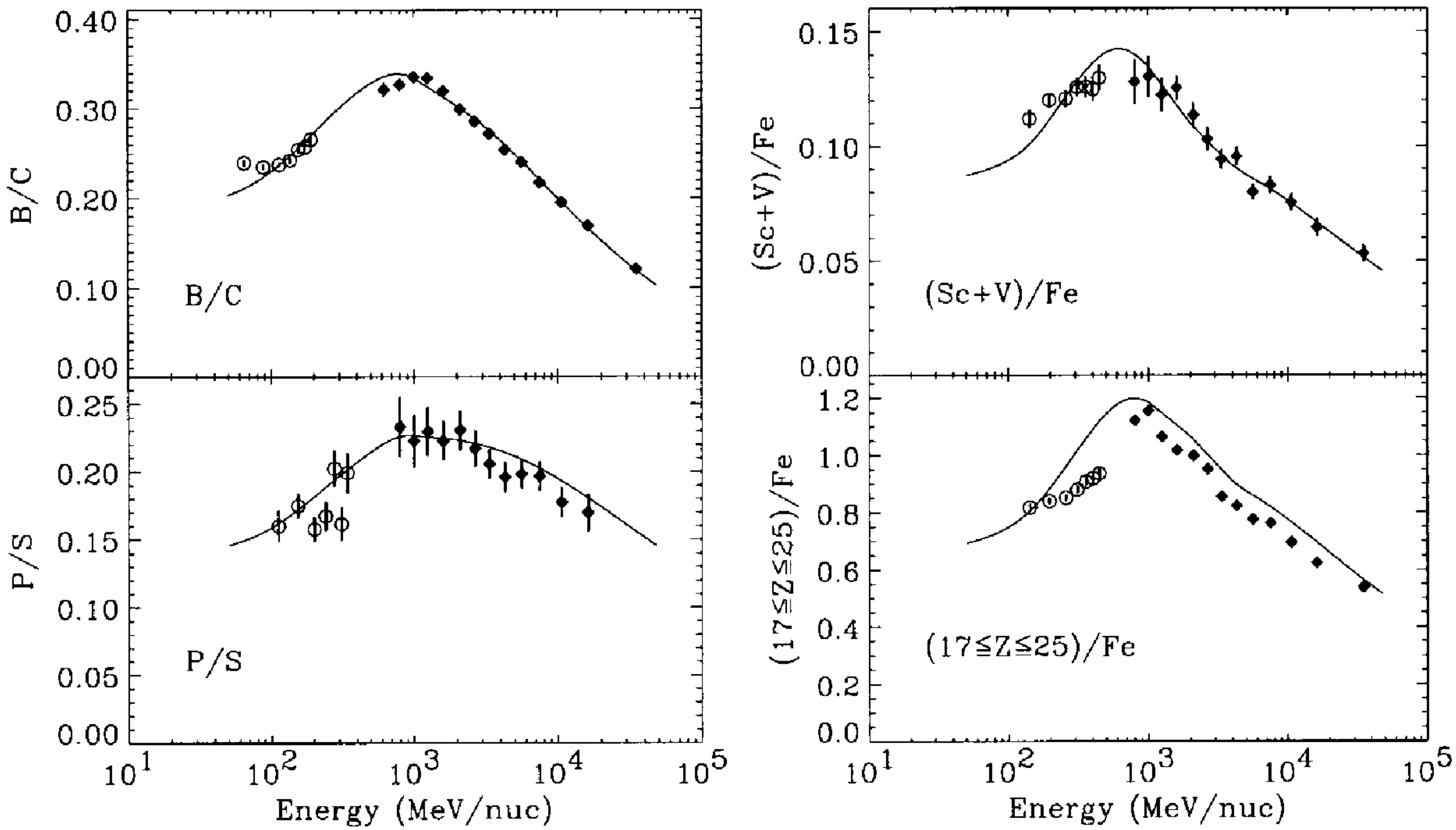


T. Antoni et al., ApJ 608 (2004) 865


Propagation
acceleration of CR in supernova remnants
propagation through galaxy
B = 3 μG
extensive air showers

Ratio of secondary to primary nuclei

ACE/CRIS

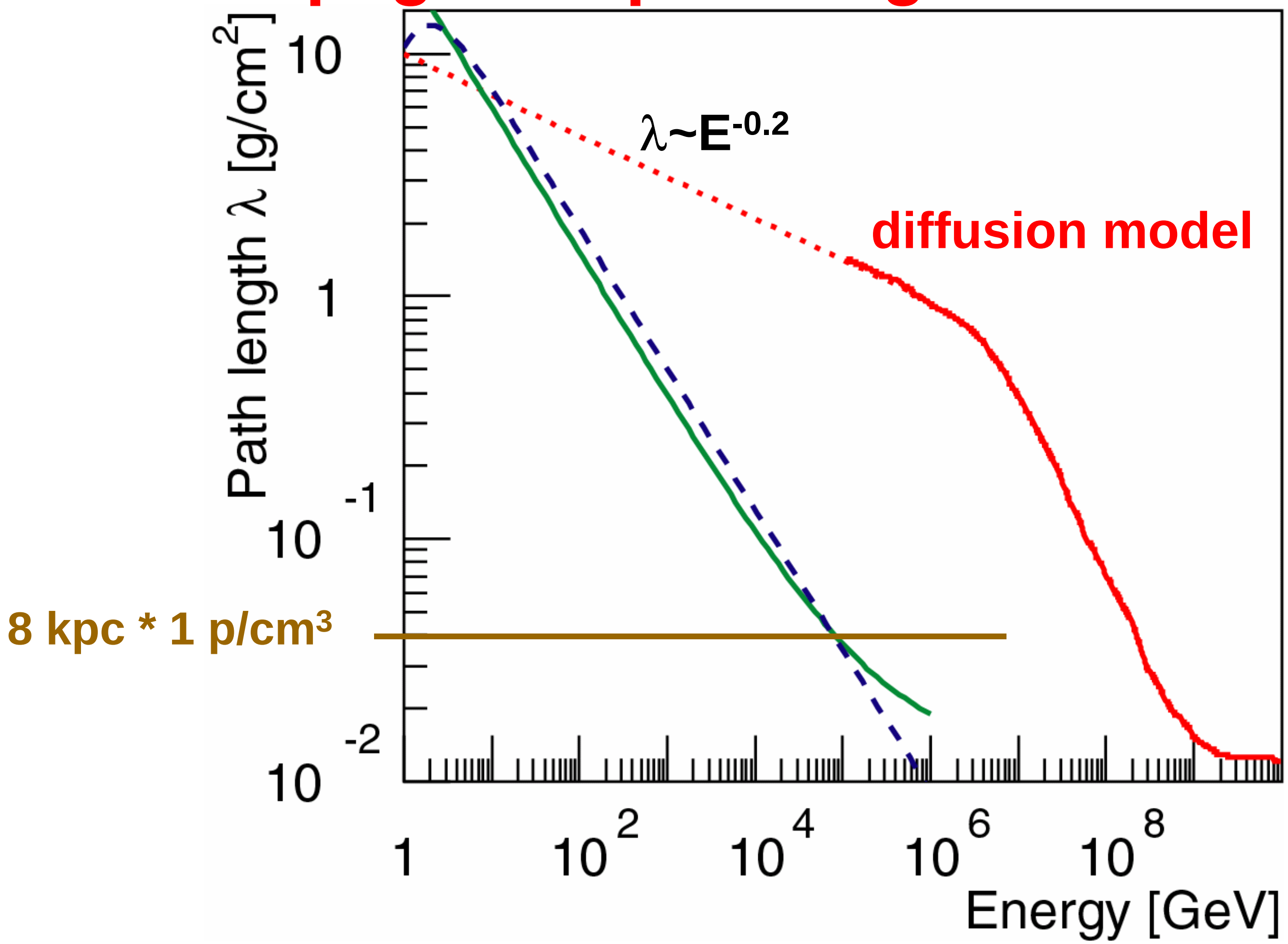


Leaky box model

$$\lambda_{esc} = \frac{26.7\,\beta\,g/cm^2}{(\beta R/1.0\,GV)^{0.58} + (\beta R/1.4\,GV)^{-1.4}}$$

N. E. Yanasak, ApJ 563 (2001) 768

Propagation pathlength in Galaxy



leaky box model

$$\lambda = \frac{26.7\,\beta\,\mathrm{g/cm^2}}{(\beta R/1.0\,\mathrm{GV})^{0.58} + (\beta R/1.4\,\mathrm{GV})^{-1.4}}$$

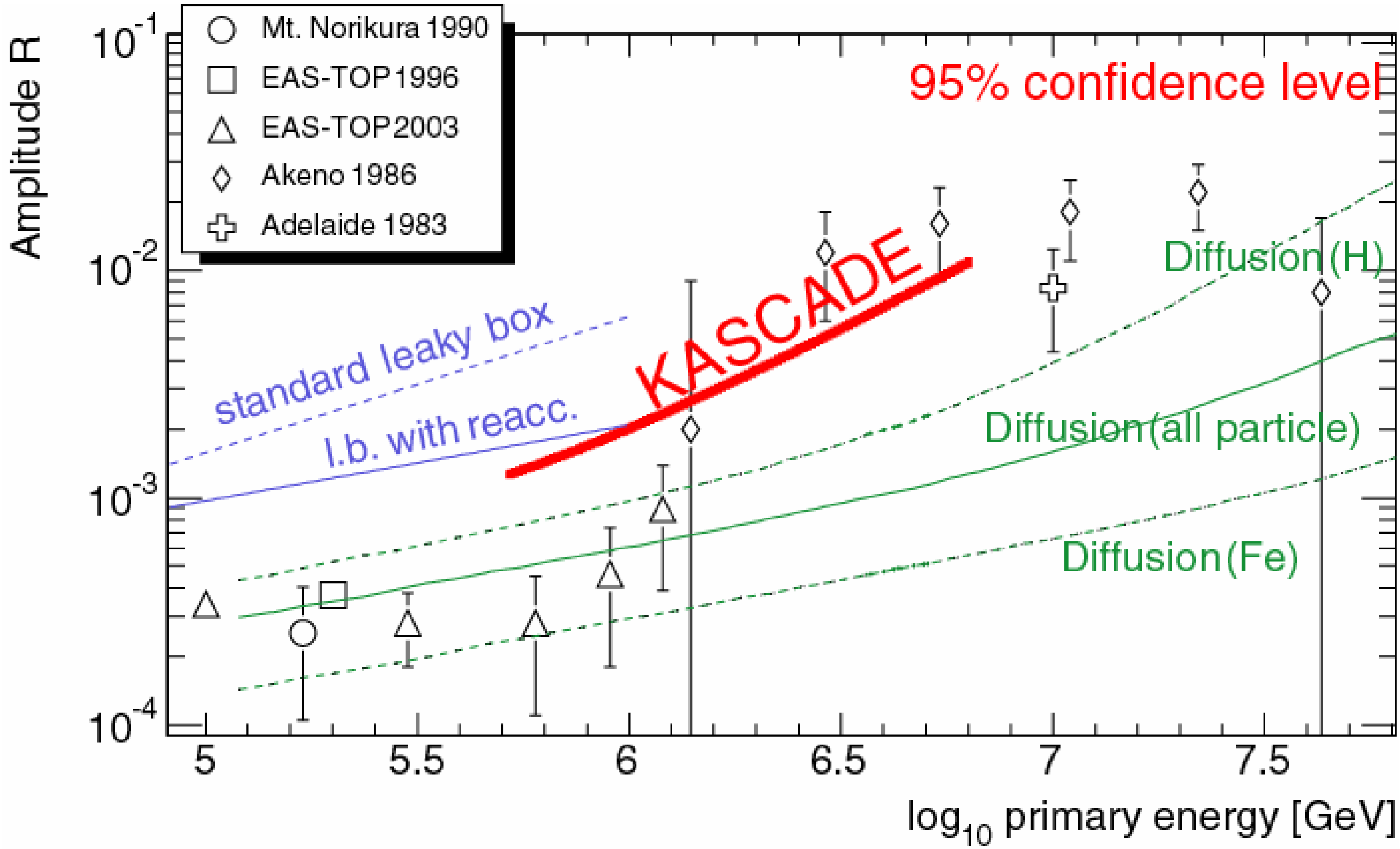
N. E. Yanasak, ApJ 563 (2001) 768

residual pathlength model

$$\lambda = \left[6.0 * \left(\frac{R}{10\,\mathrm{GV}}\right)^{-0.6} + 0.013\right]\mathrm{g/cm^2}$$

S.P. Swordy, 24th ICRC, Rome 2 (1995) 697

Anisotropy amplitude vs energy

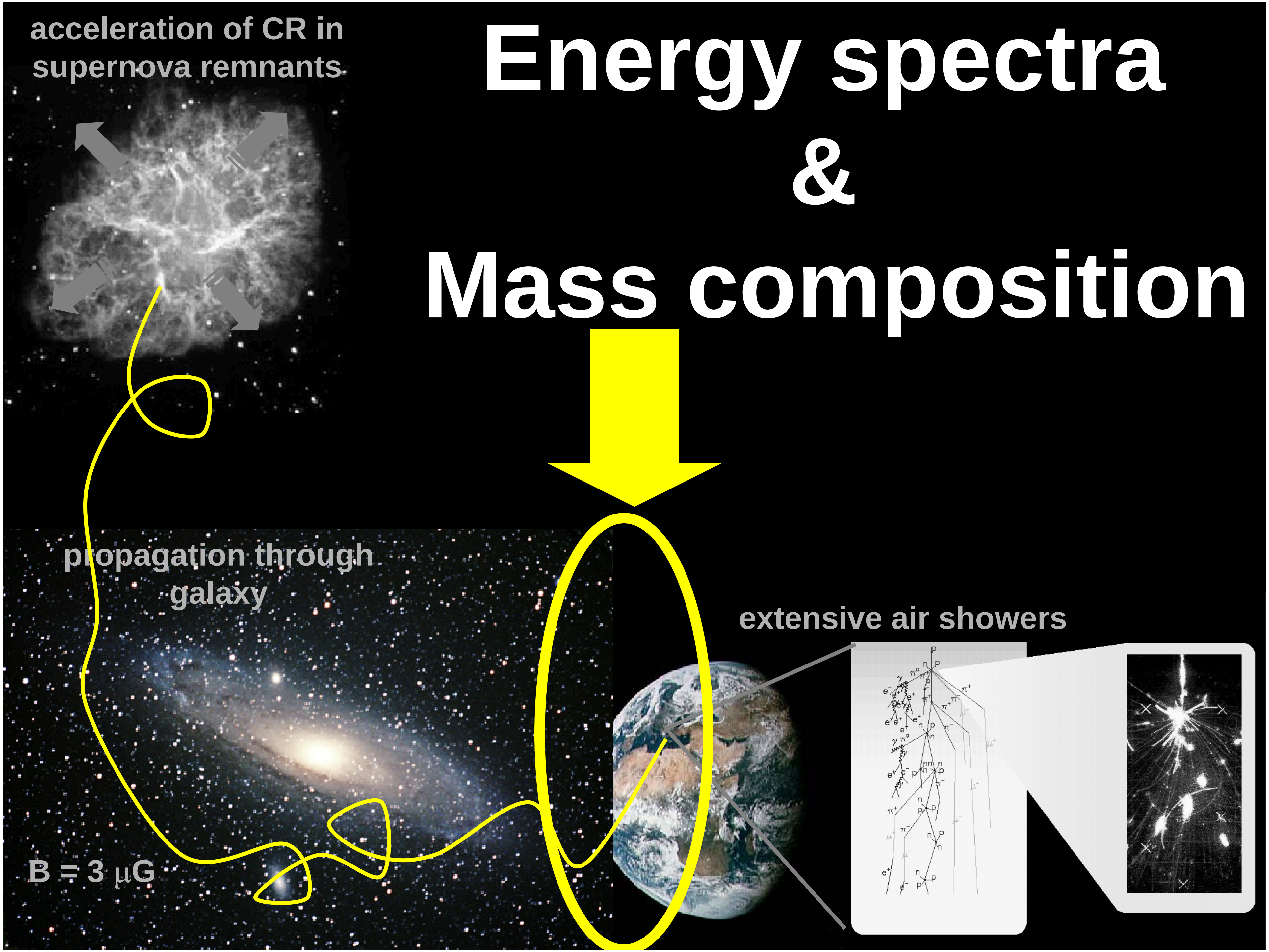


Rayleigh vector $$|\vec{R}| = \left(\frac{2}{n}\sum_{i=1}^{n}\sin\alpha_i\right)^2 + \left(\frac{2}{n}\sum_{i=1}^{n}\cos\alpha_i\right)^2$$

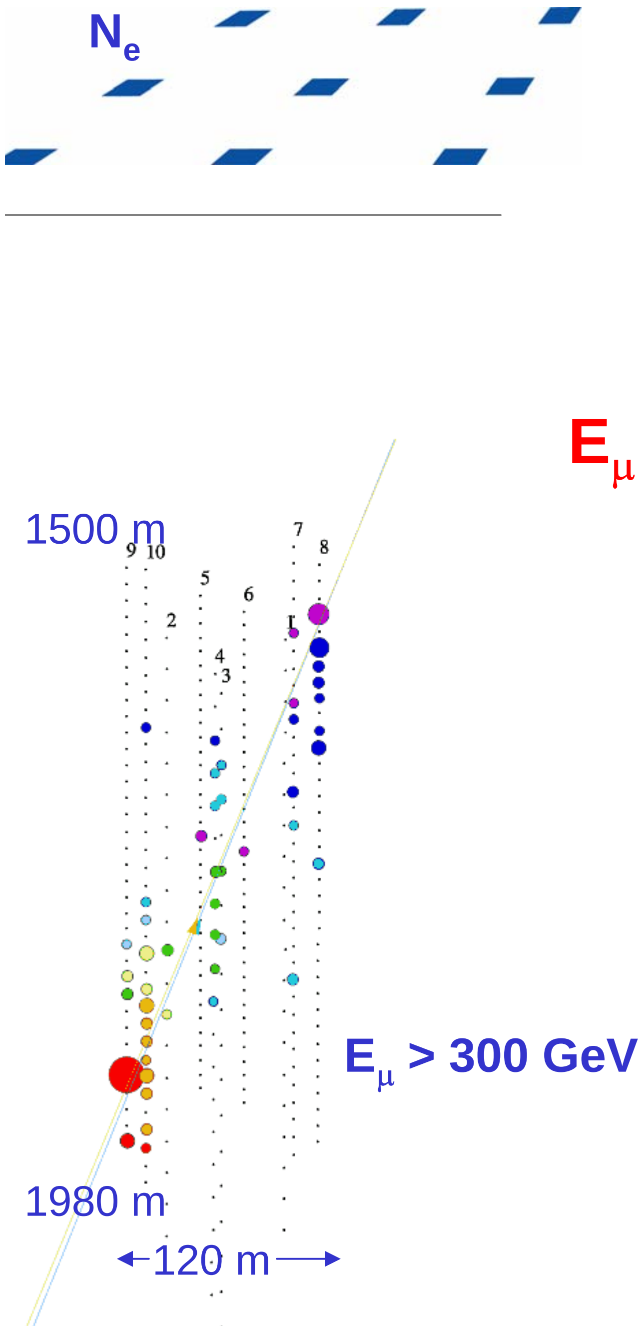
V.S. Ptuskin, Adv. Space Res. 19 (1997) 697

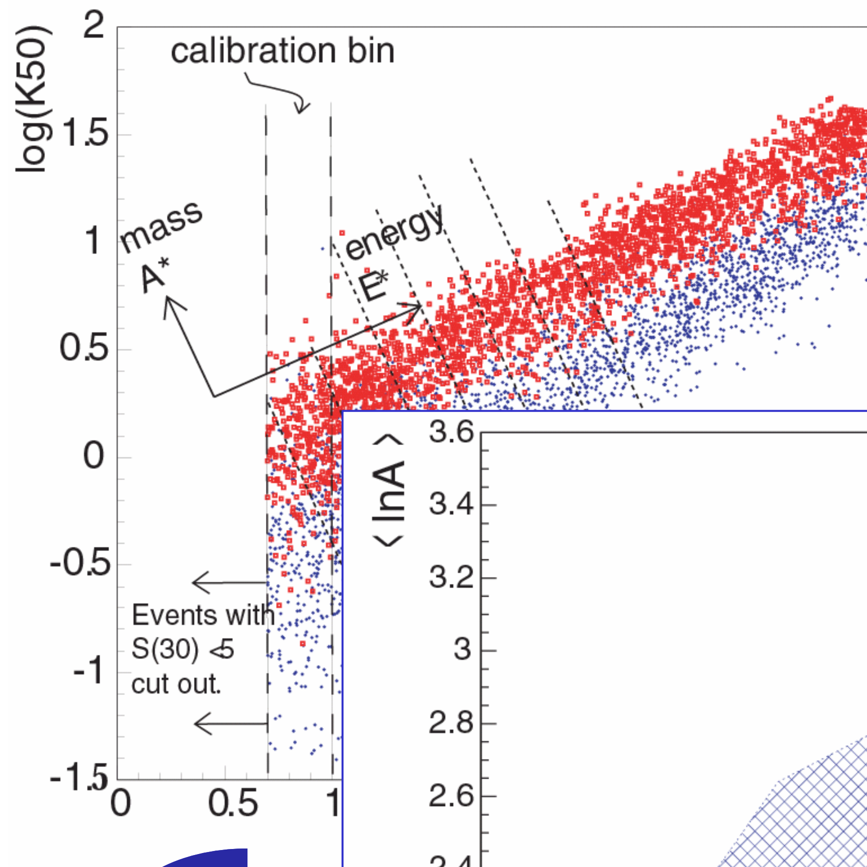
J. Candia et al., J. Cosmol. Astropart. Phys. 5 (2003) 3

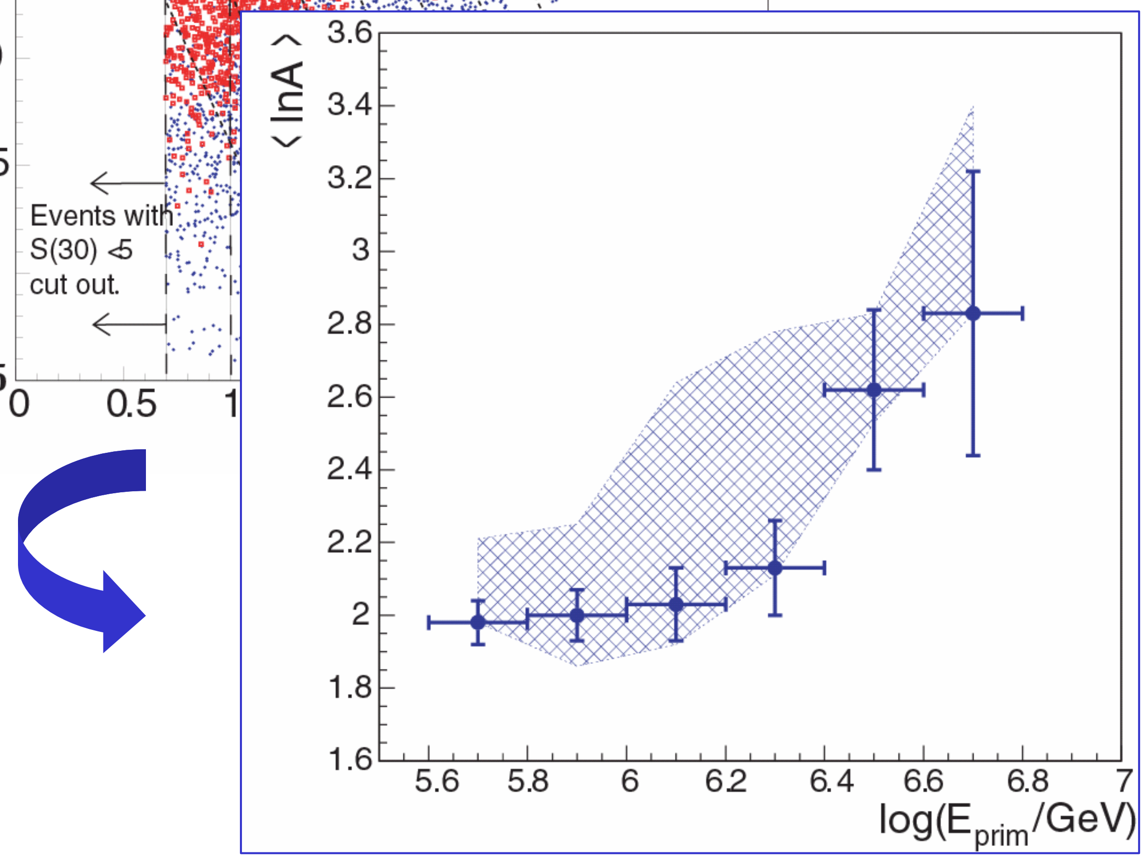
T. Antoni et al, ApJ 604 (2004) 687


acceleration of CR in supernova remnants
Energy spectra
&
Mass composition
propagation through galaxy
B = 3 μG
extensive air showers

SPASE-2 / AMANDA-B10 (South Pole)



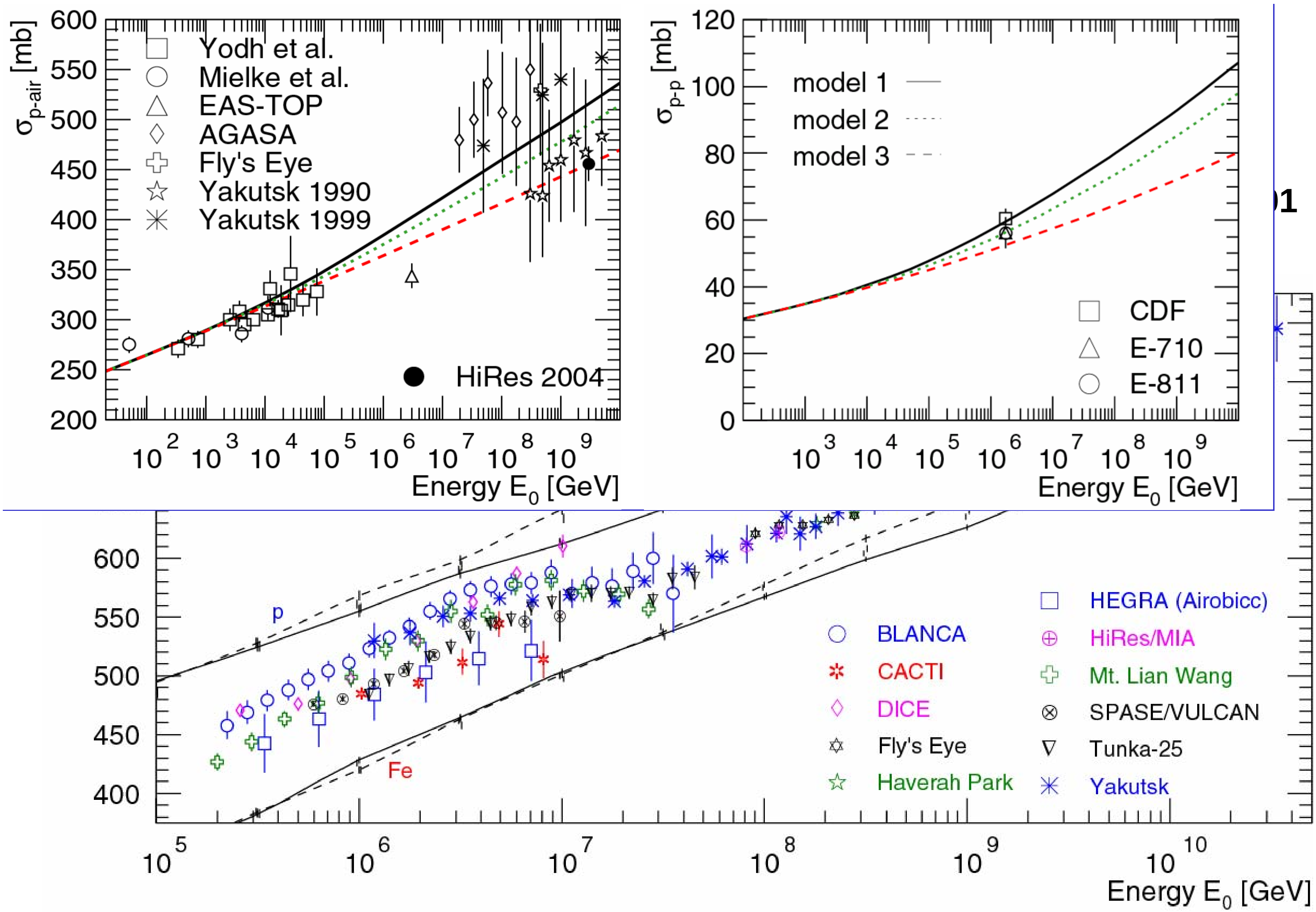




Rawlins et al, Proc. 28th ICRC, Tsukuba 1 (2003) 173

p-air cross section

p-p cross section

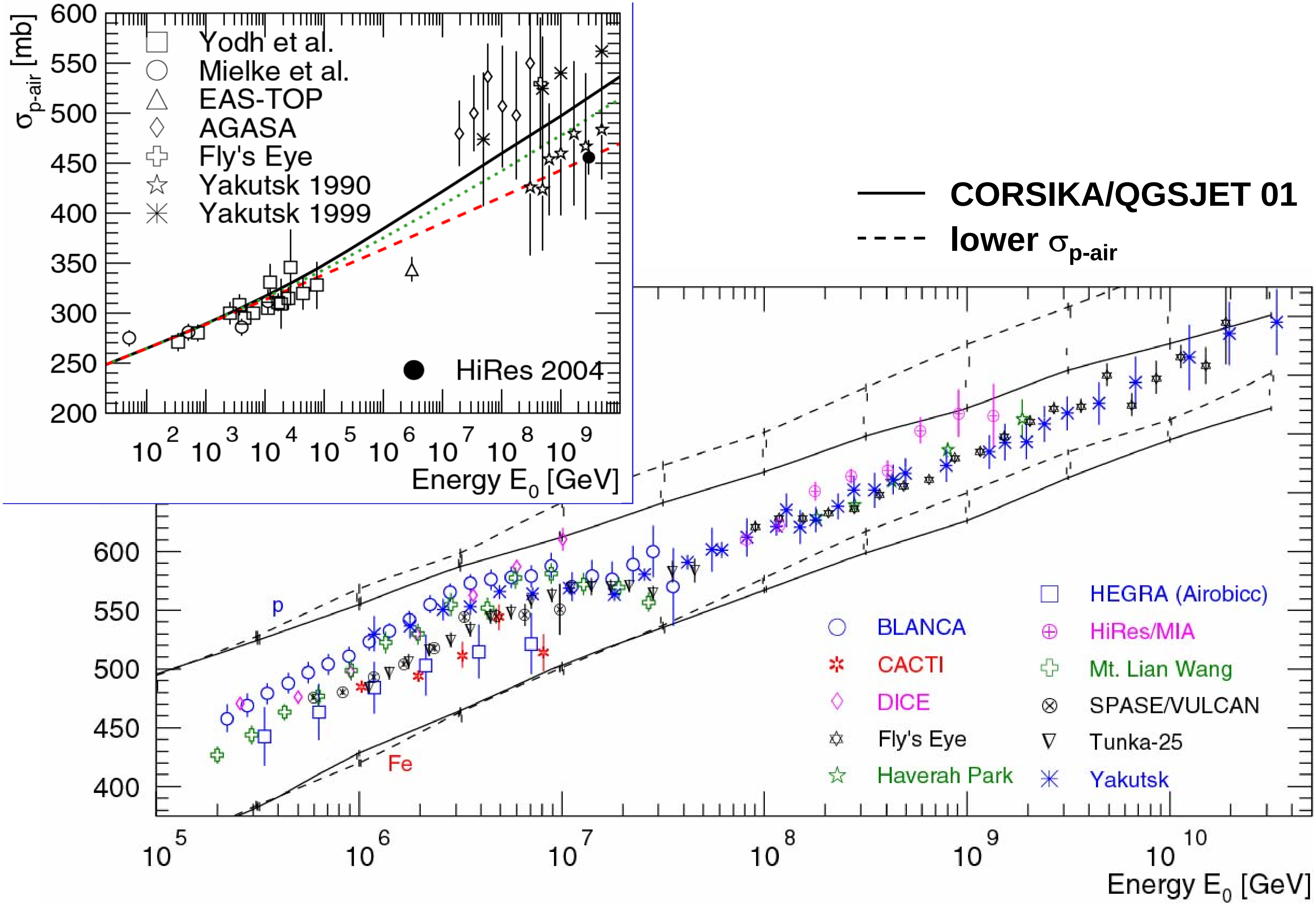


Nucl. Phys. B (Proc. Suppl.) 151 (2006) 75

JRH, J. Phys. G 29 (2003) 2439

p-air cross section

Average depth of shower maximum



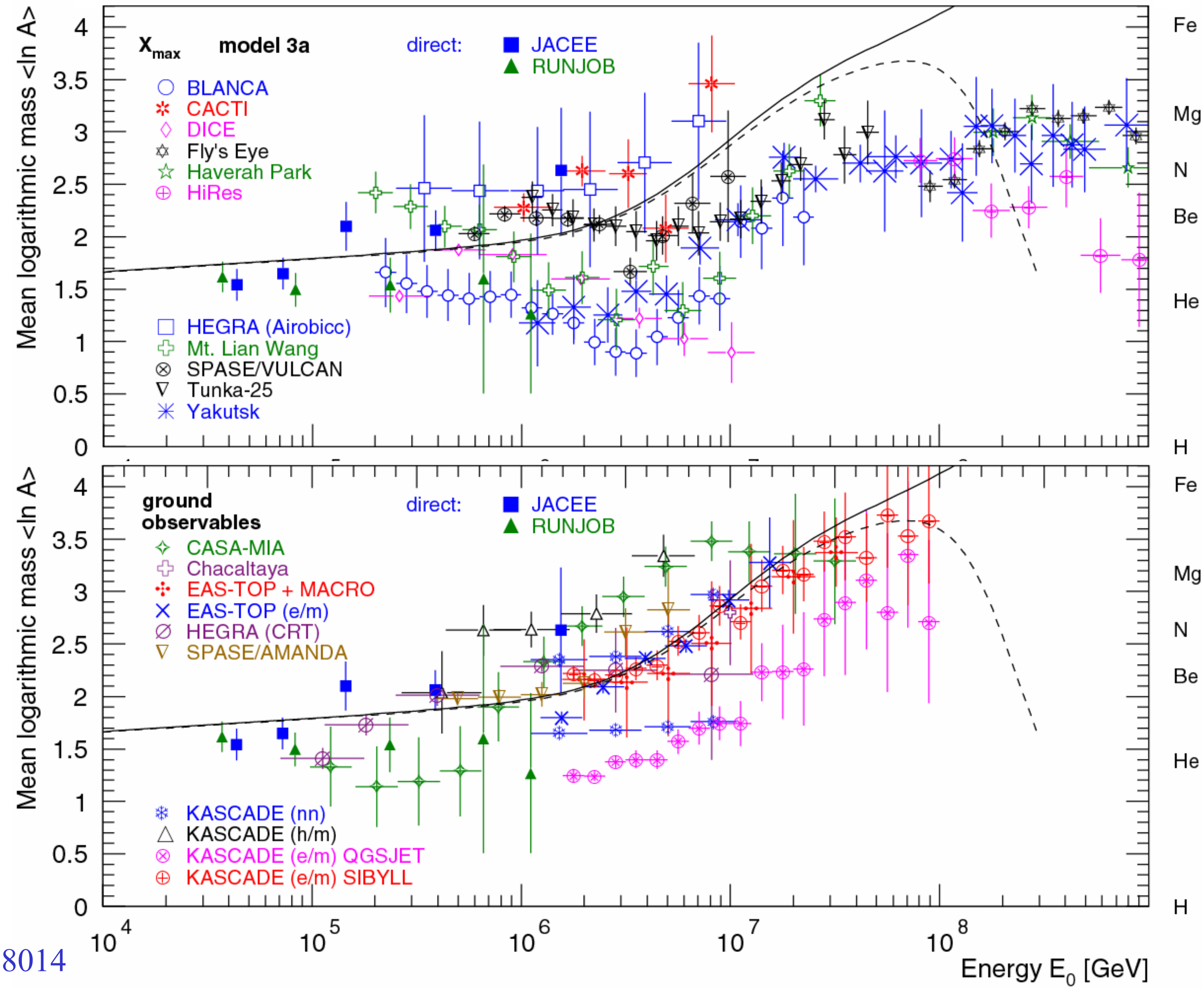
Nucl. Phys. B (Proc. Suppl.) 151 (2006) 75

JRH, J. Phys. G 29 (2003) 2439

Mean logarithmic mass

X_{max}

e, μ, h

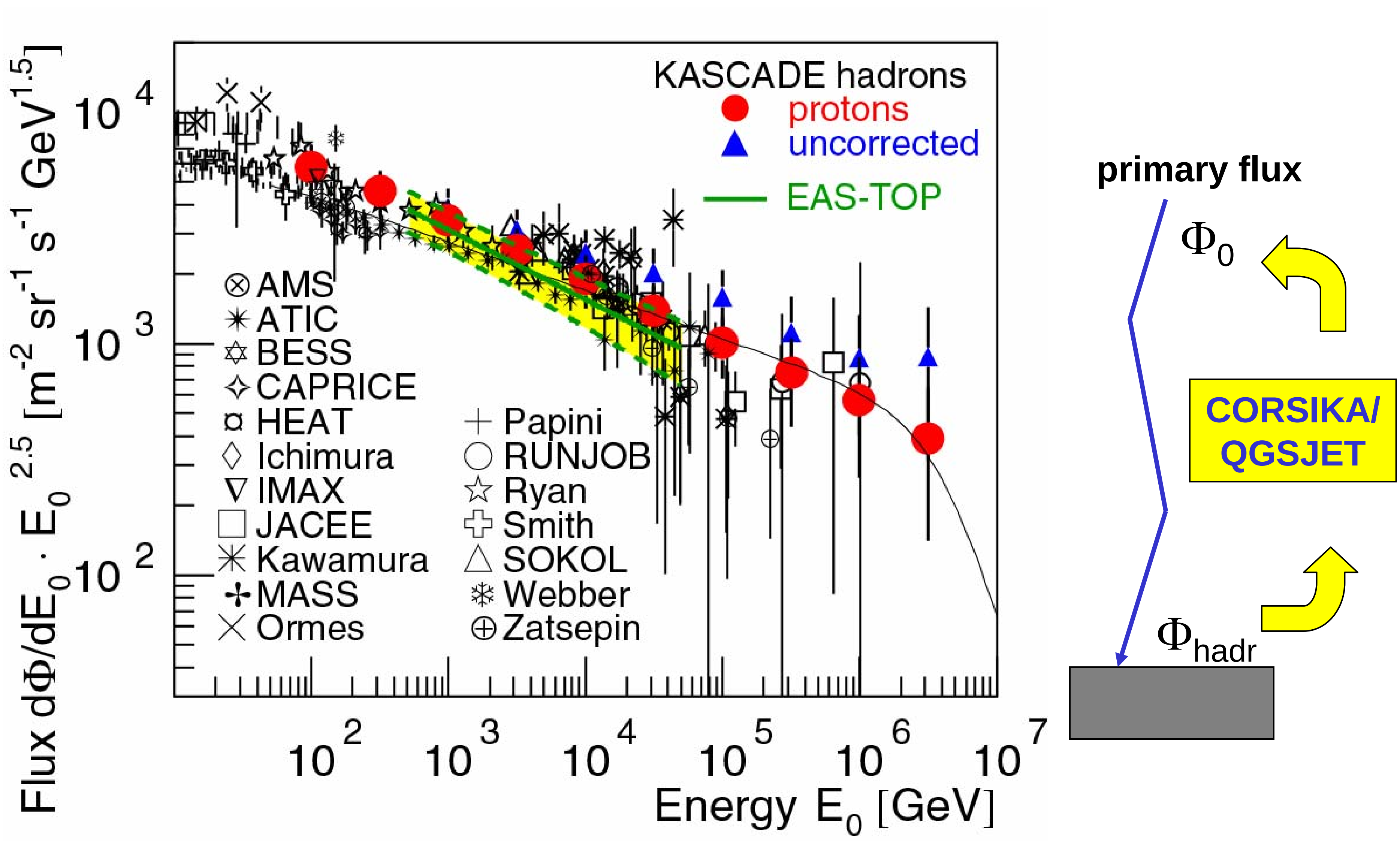


$< \ln A >= \sum r_i * \ln A_i$

JRH astro-ph/0508014

Primary proton spectrum

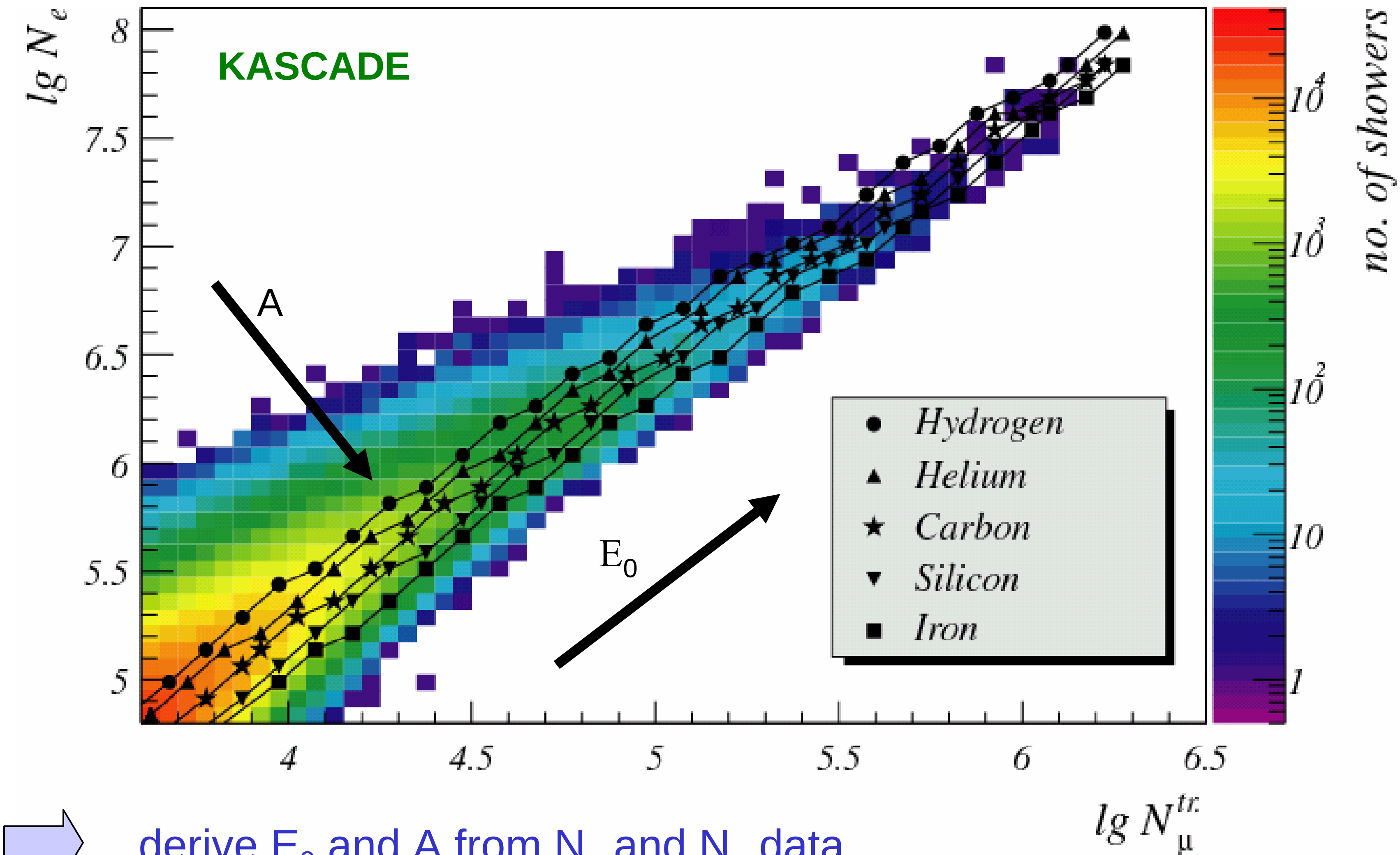
reconstructed from unaccompanied hadrons



T. Antoni et al, ApJ 612 (2004) 914

M. Aglietta et al., Astrop. Phys. 19 (2003) 329

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:

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

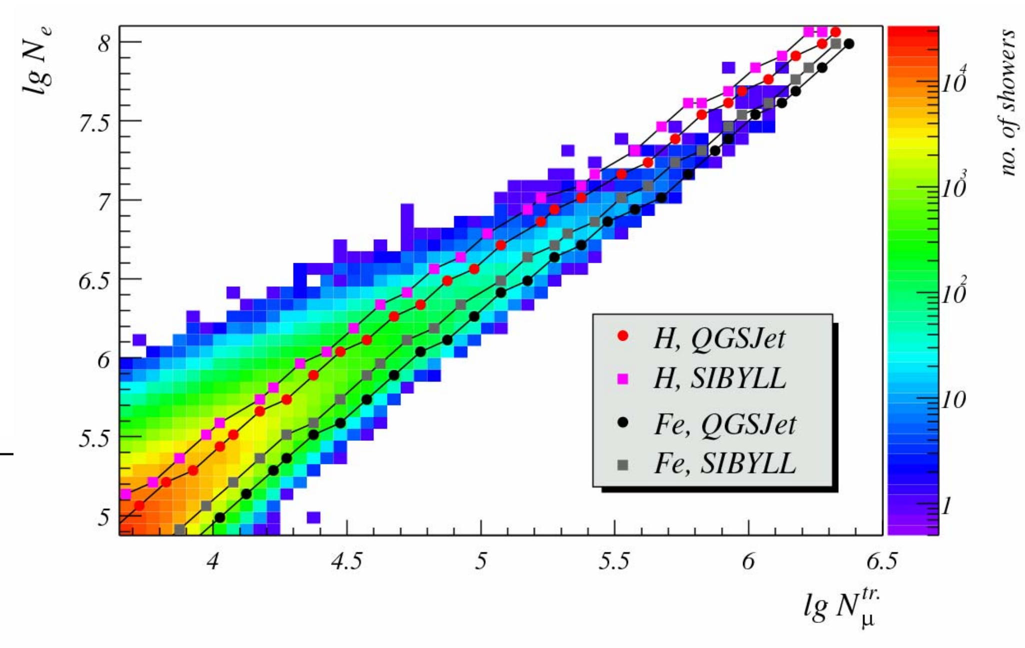
M Roth et al, 28th ICRC, Tsukuba 1 (2003) 139

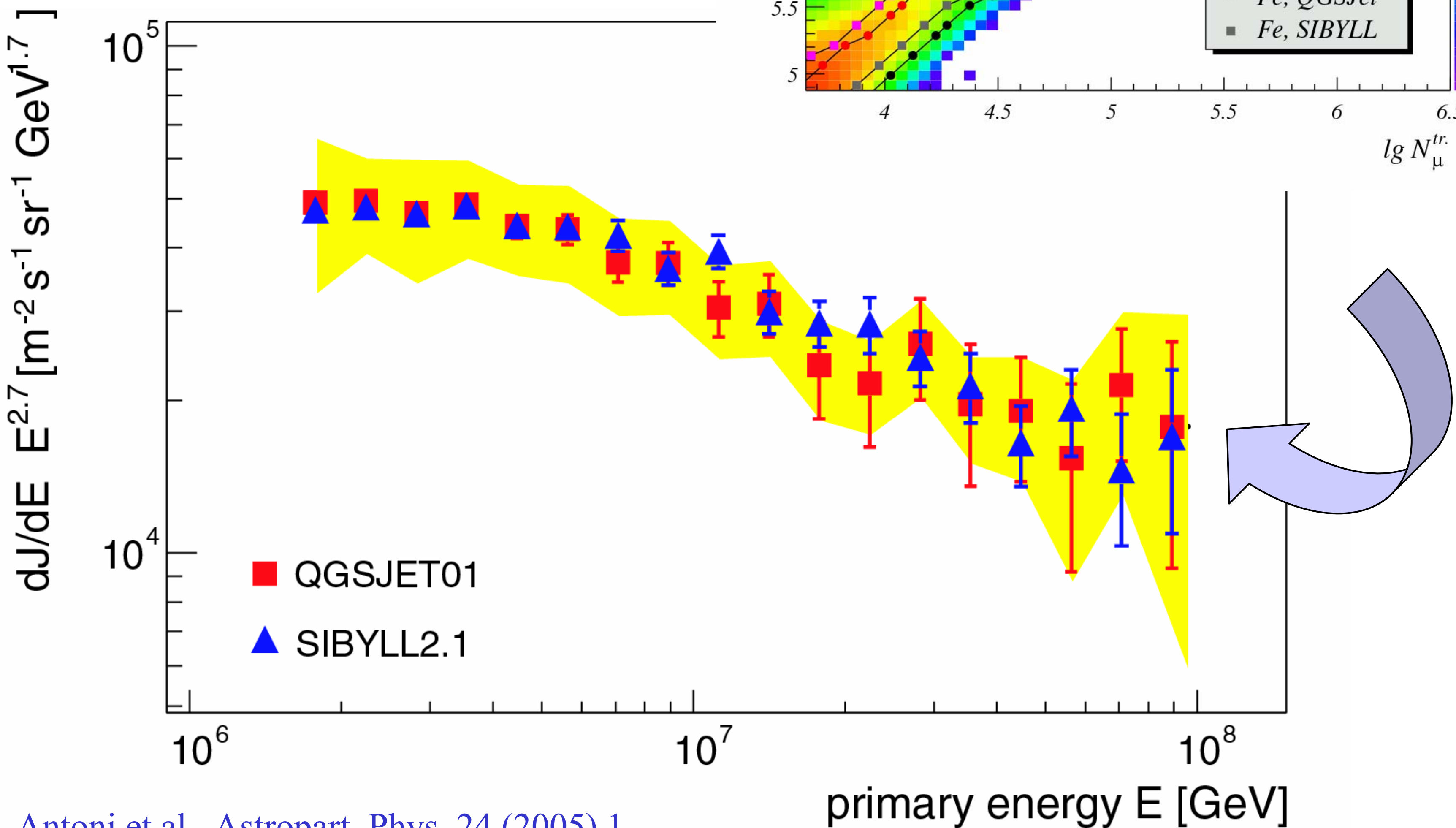
All-particle energy spectrum

two hadronic interaction models:

CORSIKA 6.018/GHEISHA 2002

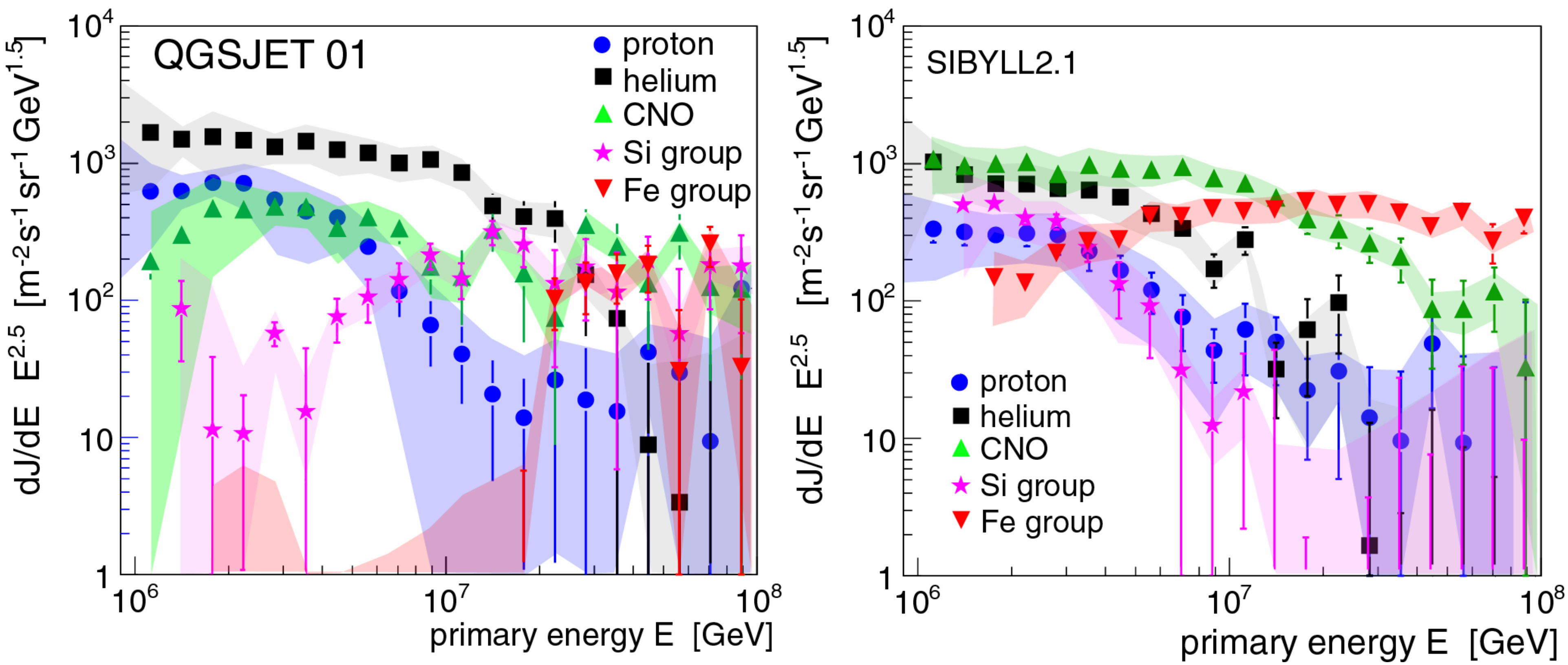
- **QGSJET 01**
- **SIBYLL 2.1**





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

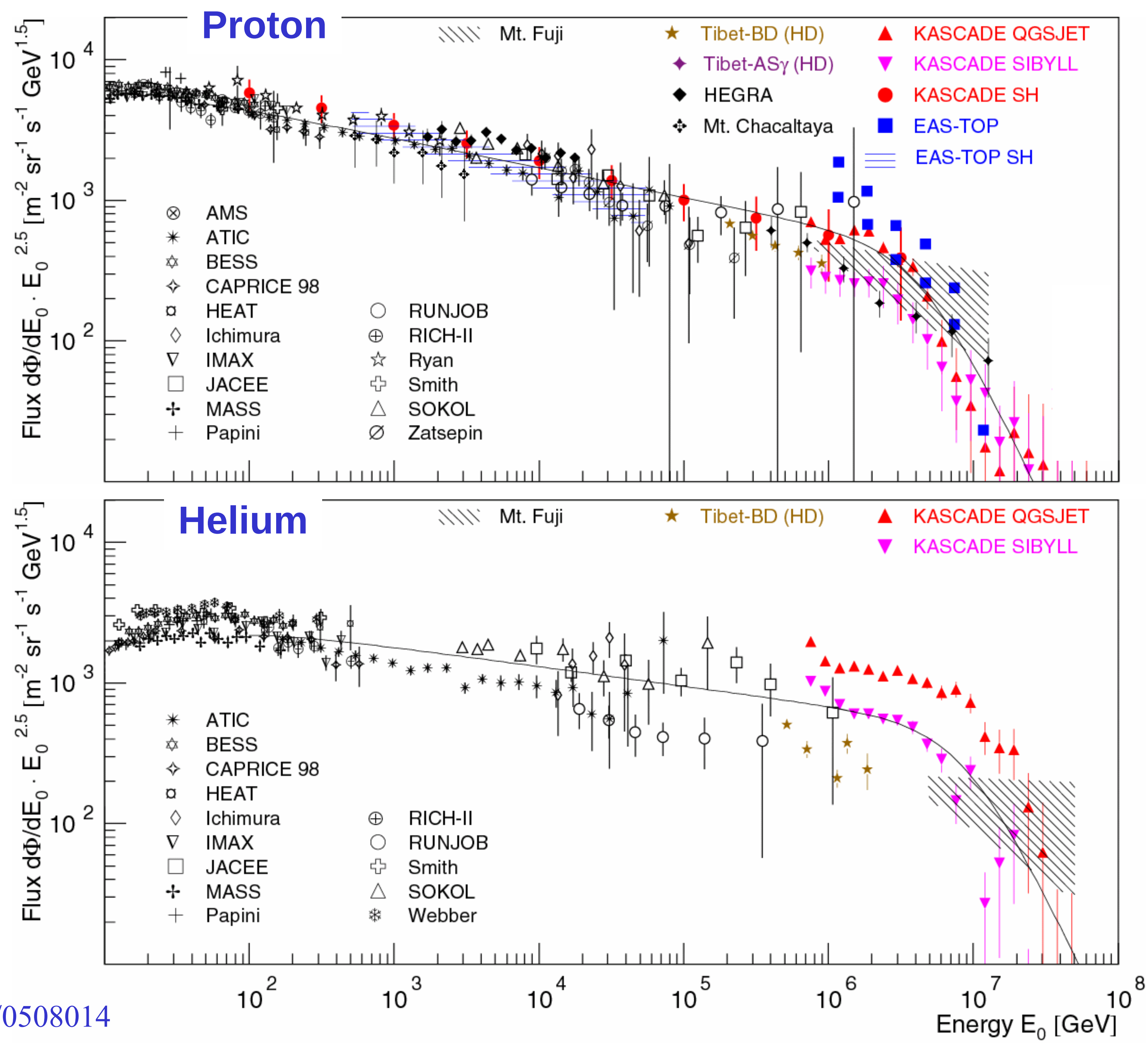
KASCADE: Energy spectra for elemental groups



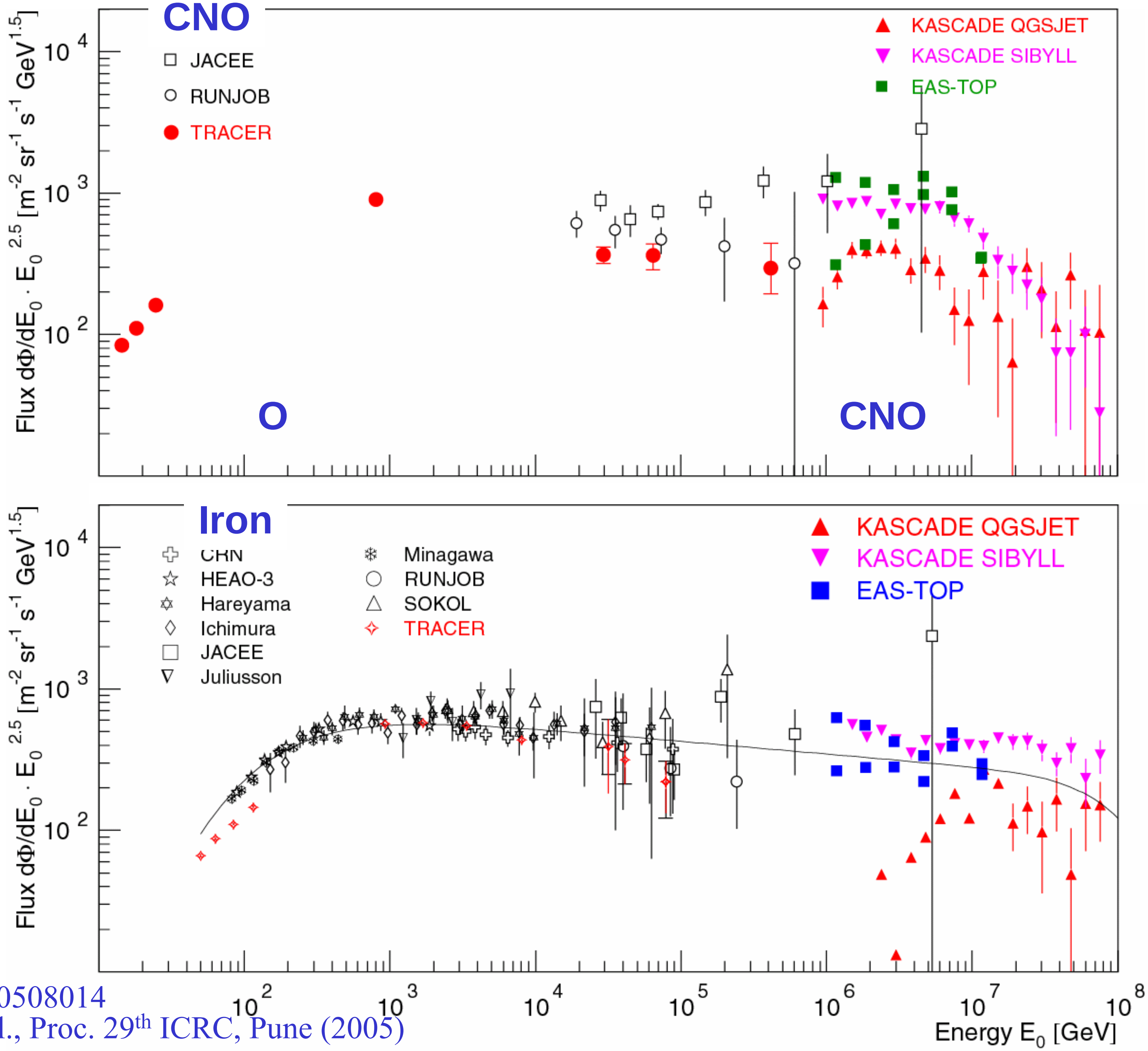
Knee caused by cut-off for light elements

Astrophysical interpretation limited by description of interactions in the atmosphere

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

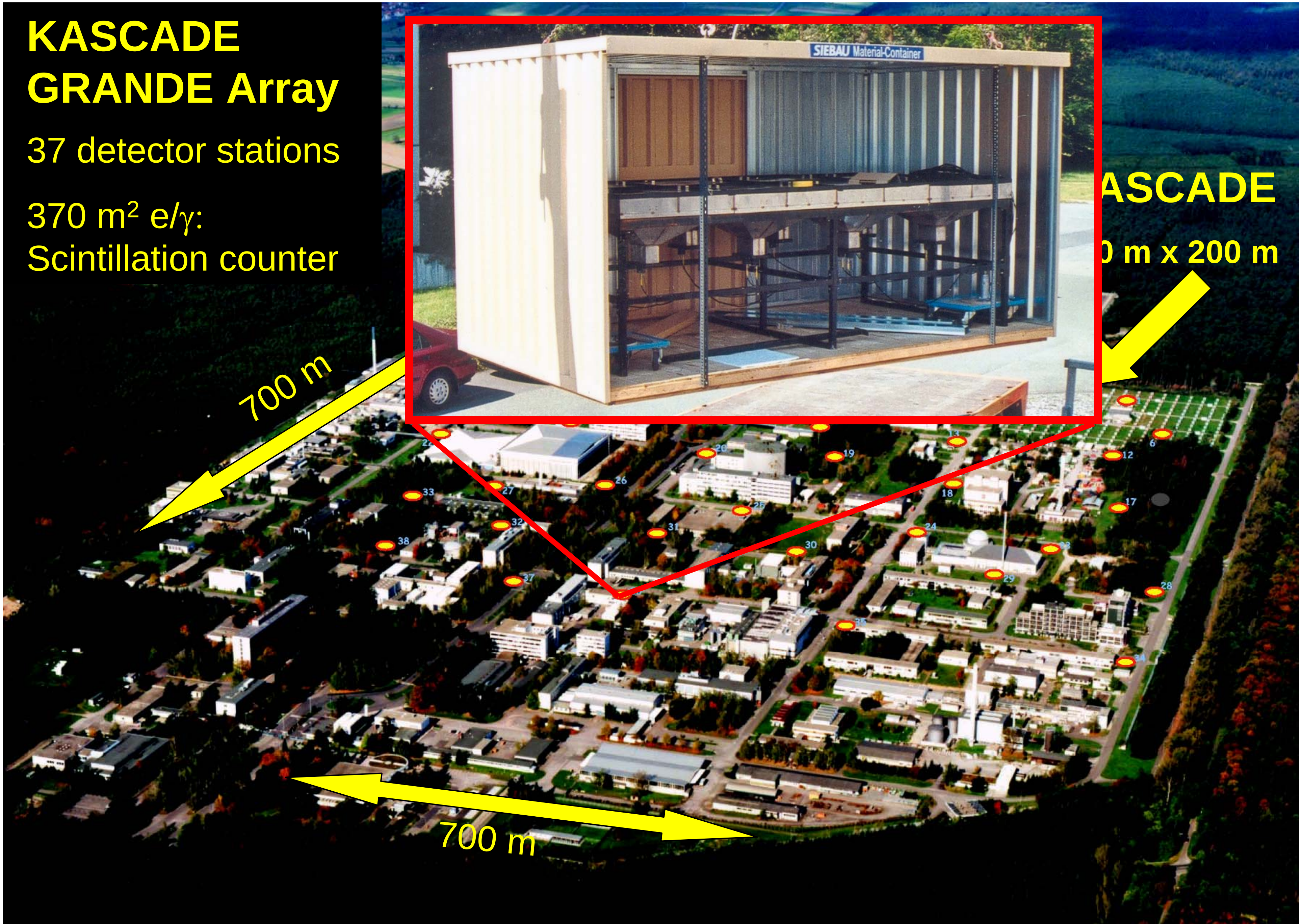


JRH astro-ph/0508014



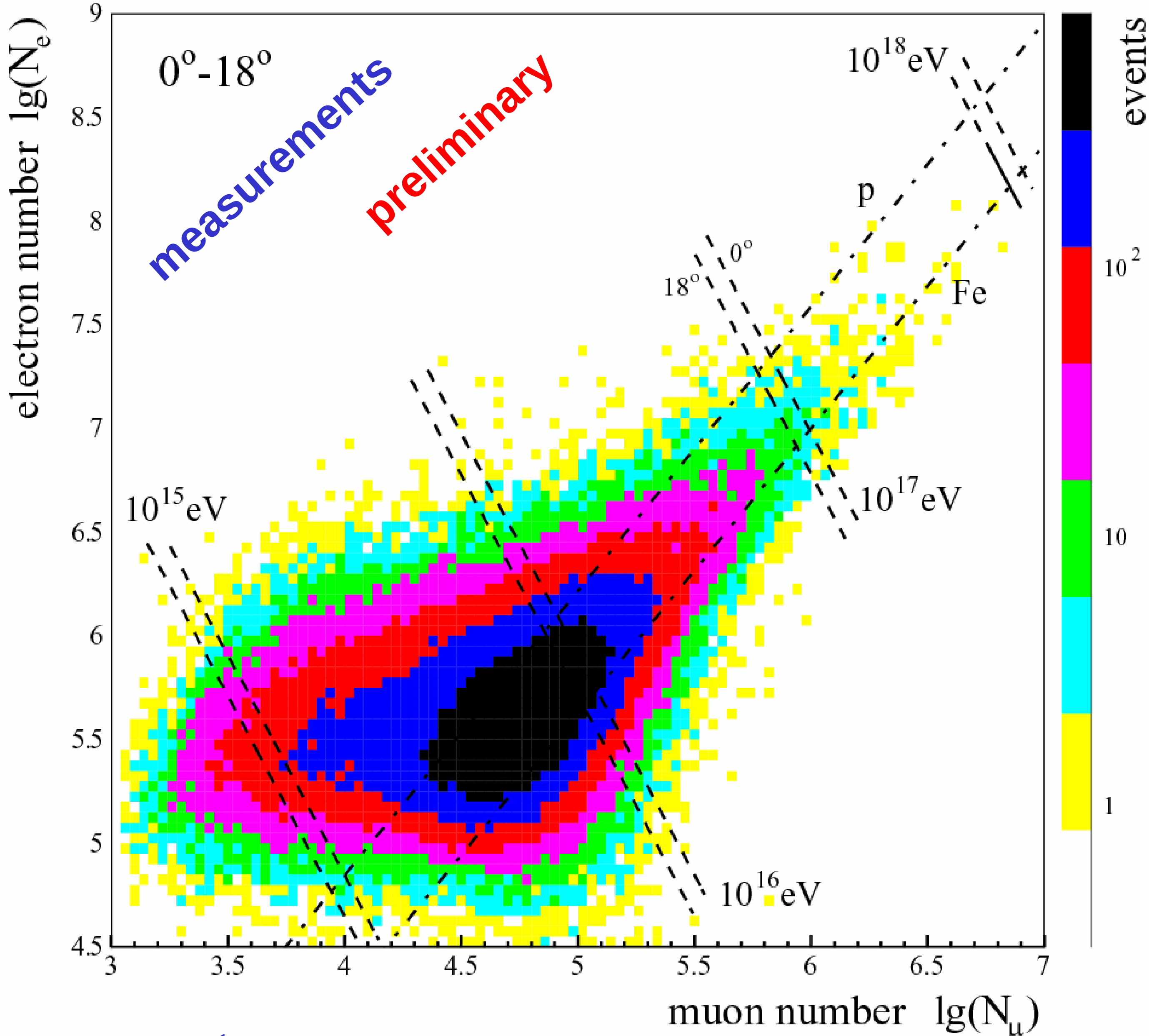
JRH astro-ph/0508014

D. Müller et al., Proc. 29th ICRC, Pune (2005)



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

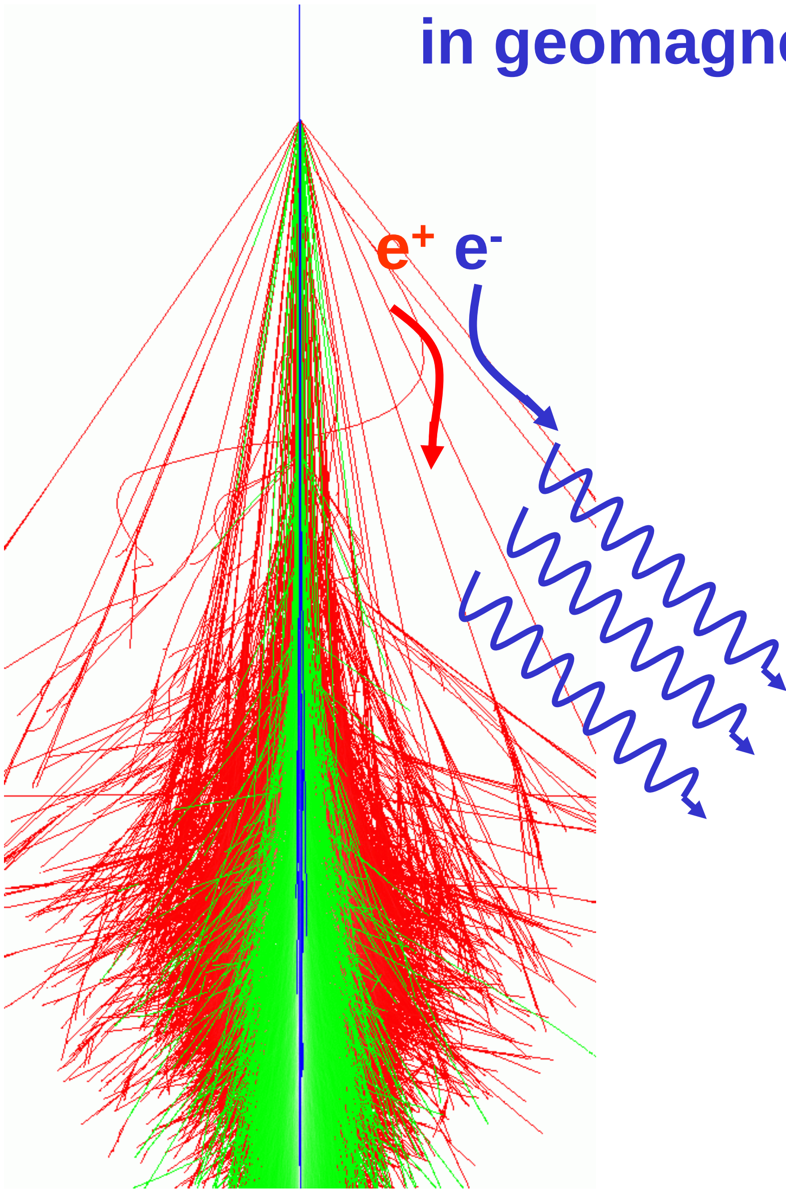
KASCADE-Grande – N_e-N_μ correlation

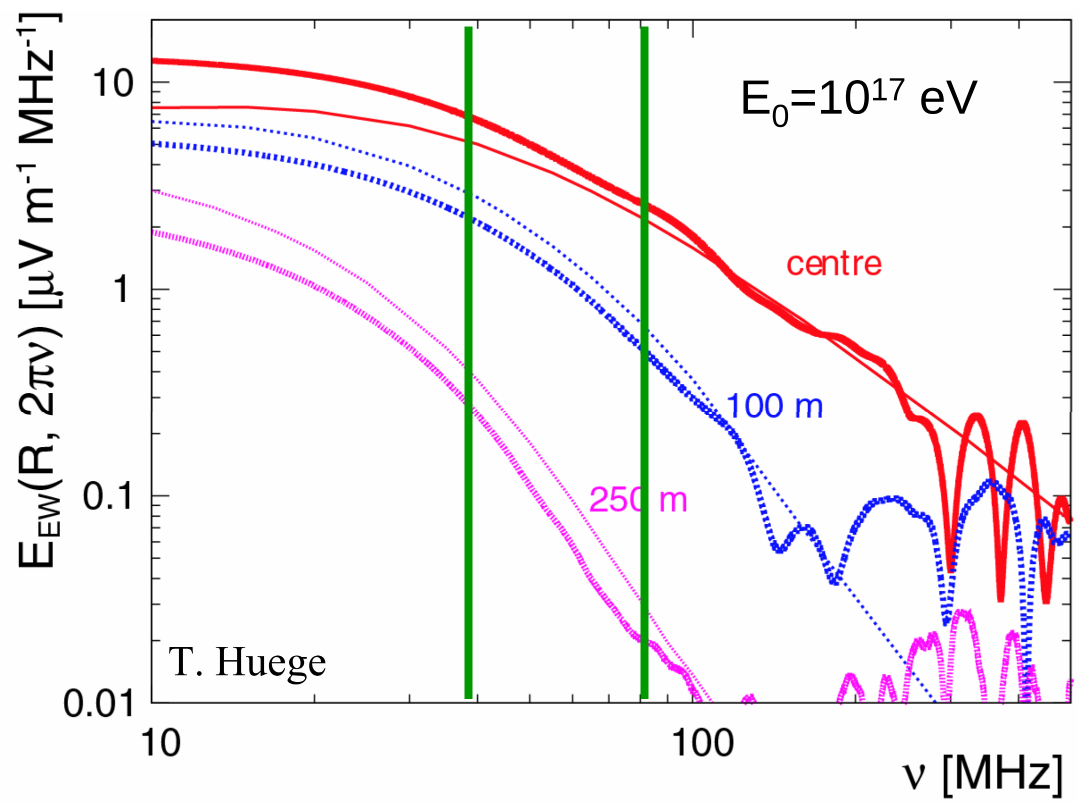


R. Glasstetter et al., Proc. 29th ICRC, Pune (2005)

Radio emission from air showers - LOPES

Coherent emission of synchroton radiation in geomagnetic field

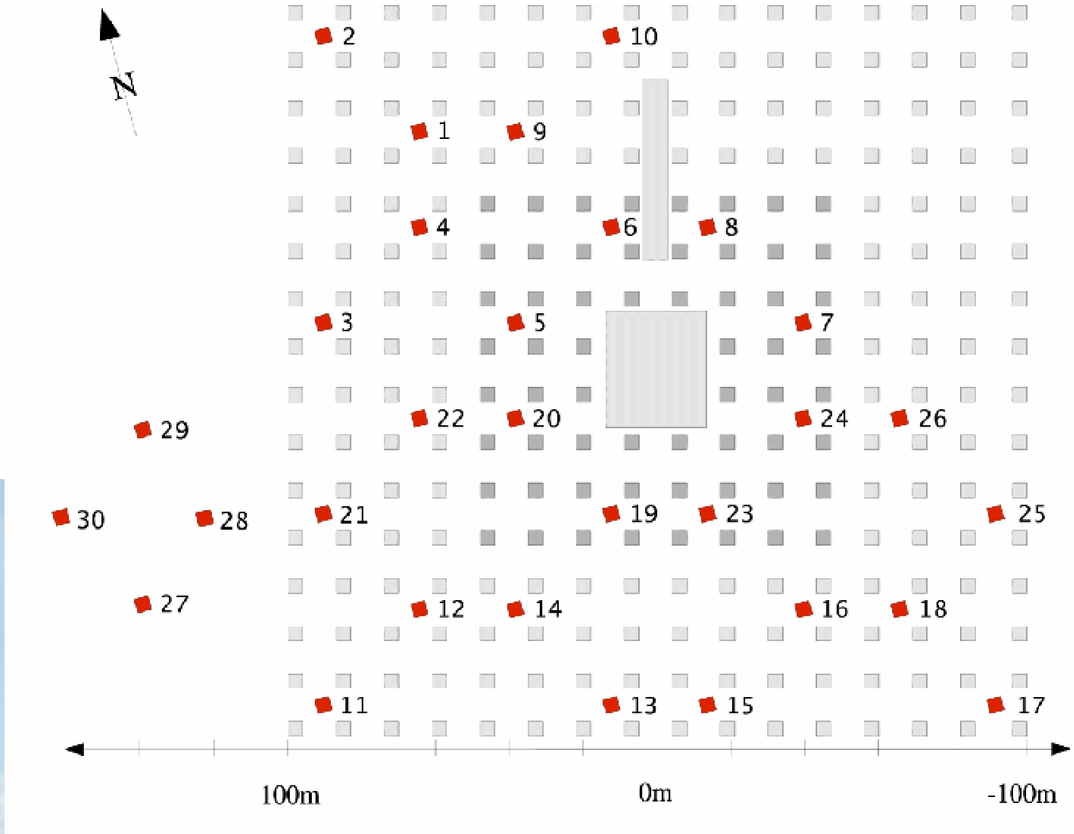


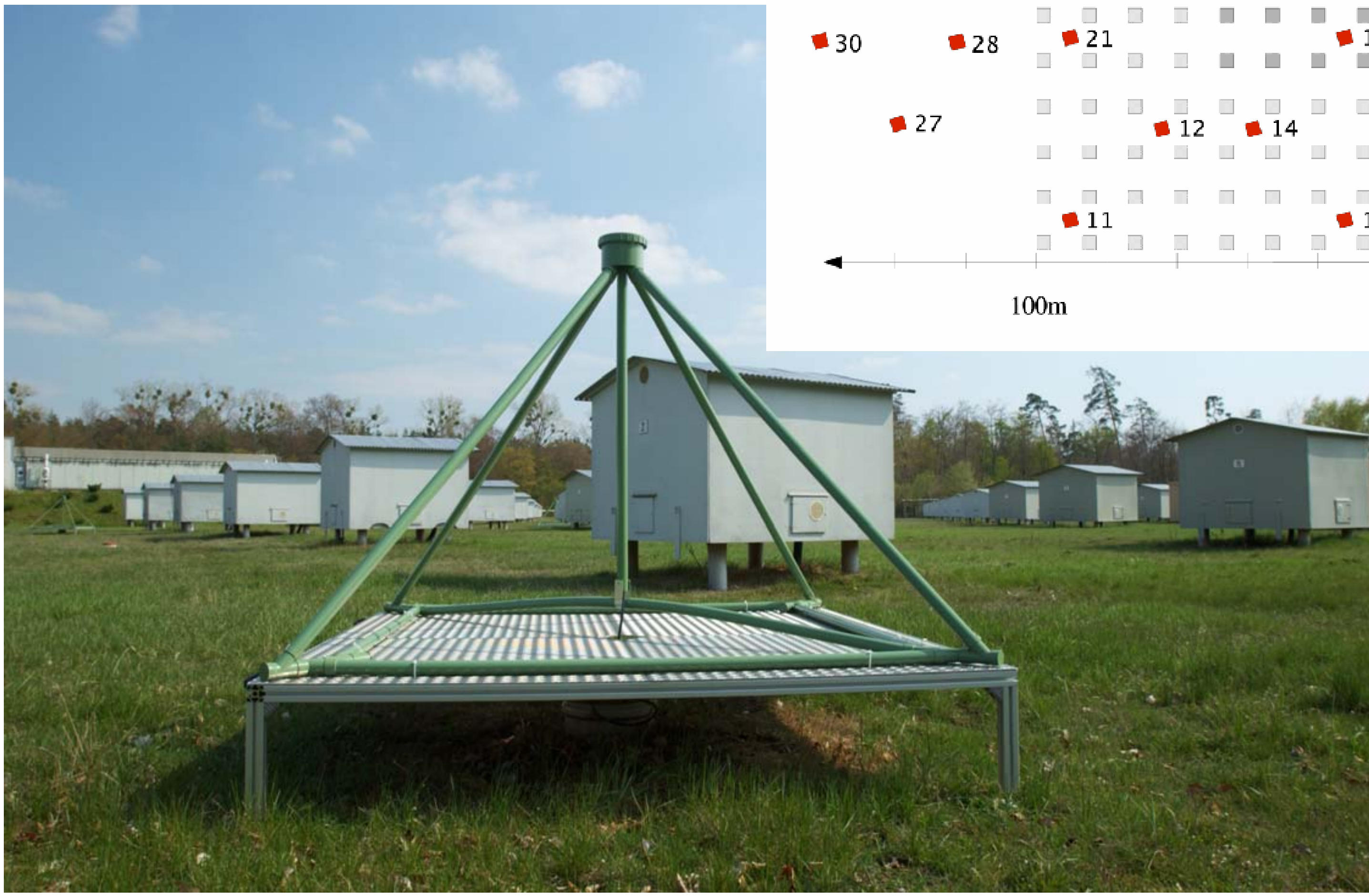


expect signals ~ μV/(m MHz)

LOPES

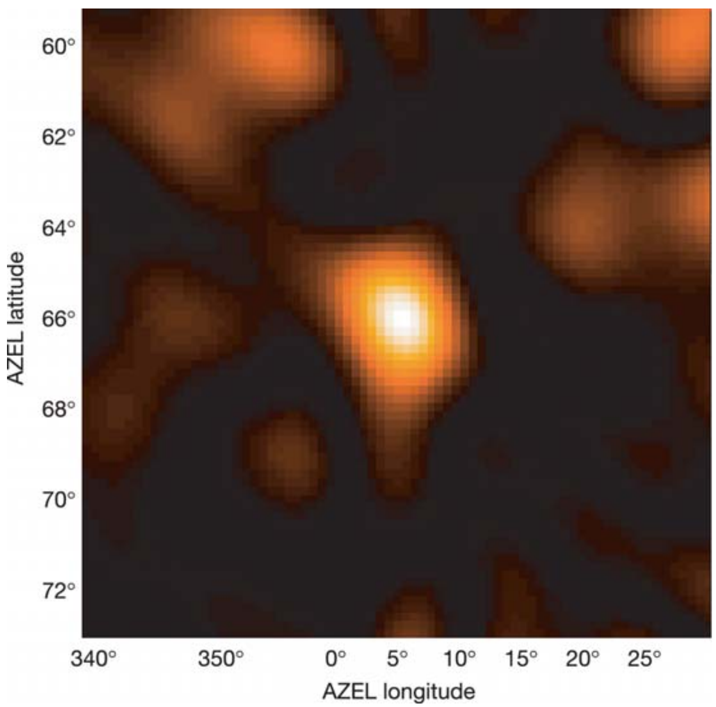
30 antennas operating at KASCADE-Grande



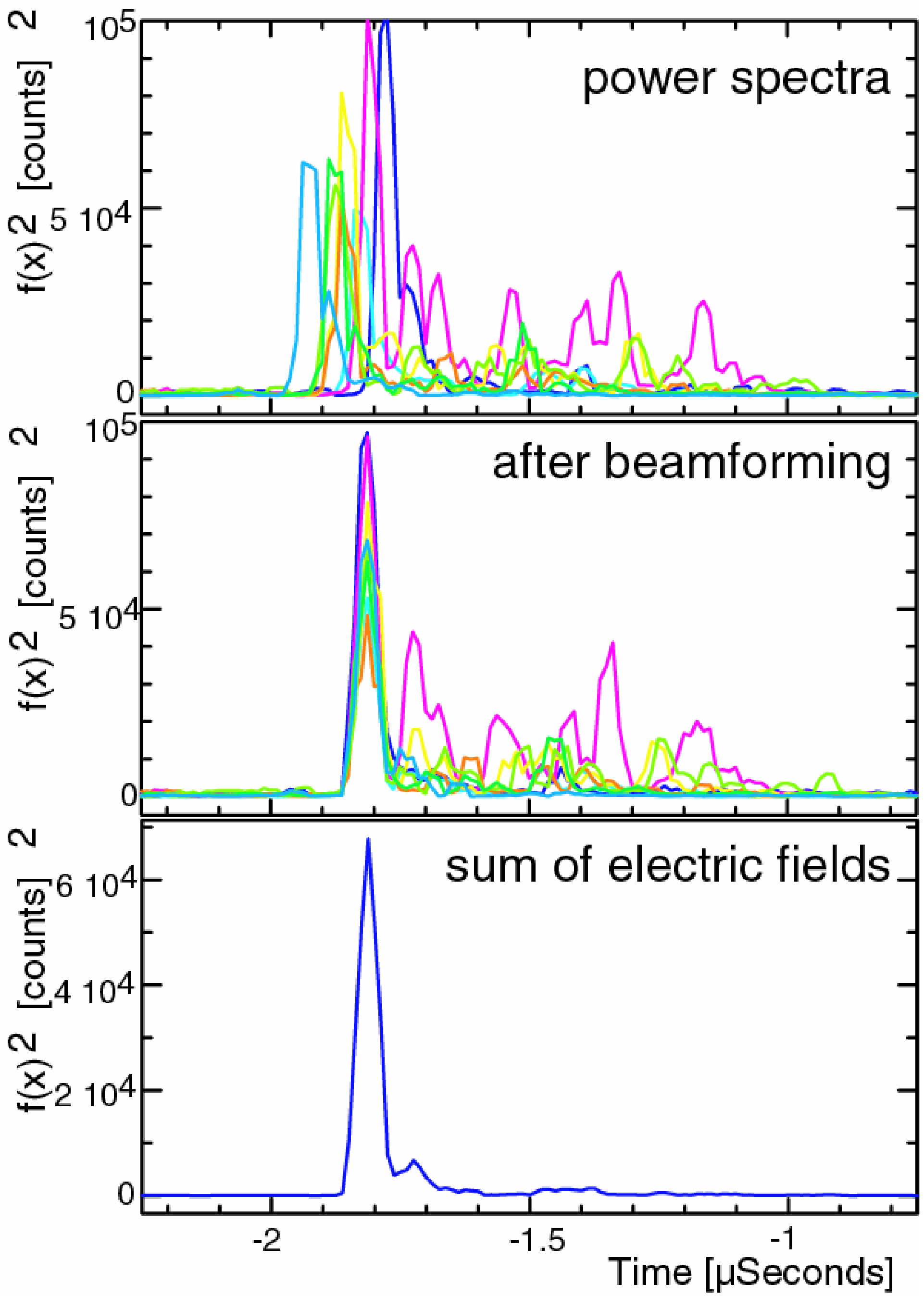


LOPES
first signals

Position of shower in sky

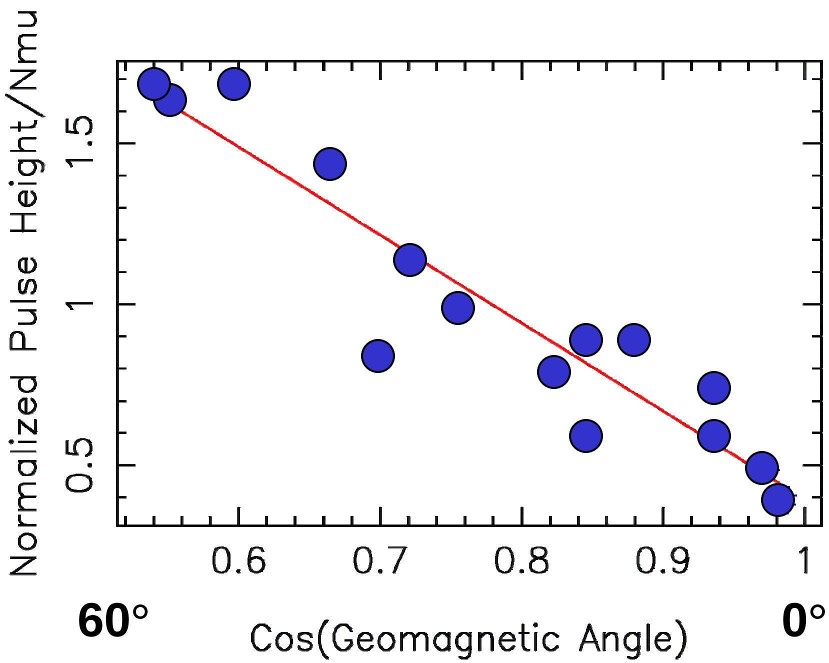


Nature 435 (2005) 313



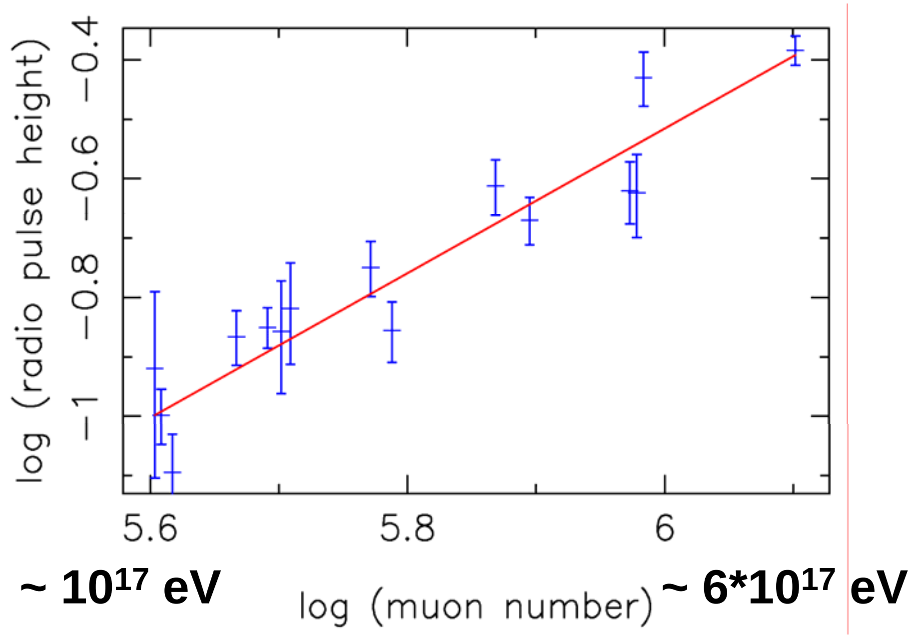
Radio signal – dependence on

angle with respect to geomagnetic field



Geosynchroton emission

number of muons (i.e. primary energy)



Radio signal increases with energy

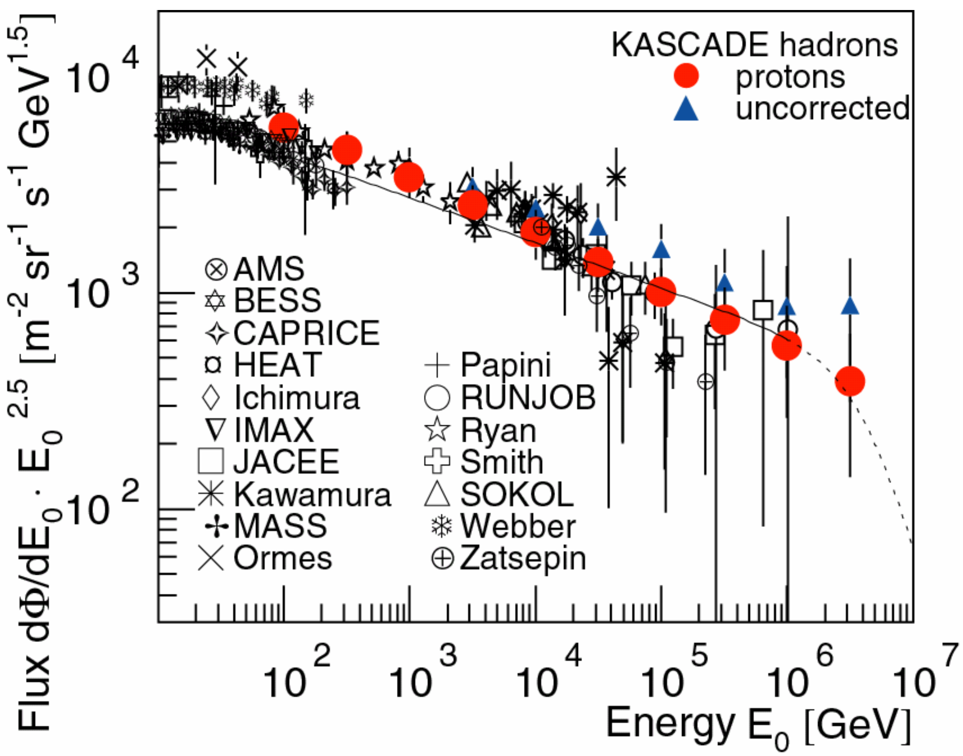
Nature 435 (2005) 313

Hadrons at high altitude → surviving protons

calorimeter @ 500 g/cm^2 — **1 PeV: ~ 6.5 λ_i**

320 m^2 sr ➡ **0.5 m^2 sr effective**

ideal: combination with air Cerenkov detector for calibration



From the Knee to the toes:

The challenge of cosmic-ray composition

Status:

- **Description of interactions in atmosphere improved**
- **Mean mass increases as function of energy** (knee region)
- **Knee is caused by subsequential cut-offs for individual elements**
- **Astrophysical interpretation of EAS measurements limited by understanding of interactions in the atmosphere**

Perspectives:

- **KASCADE-Grande (2nd knee)**
- **LOPES (radio signals)**

} **galactic → extragalactic 10^{18} eV**

- **Radio in AUGER** **>10^{20} eV**

- **Hadrons at large altitude → Proton spectrum** } **direct ←→ indirect 10^{15} eV**

Thanks to my colleagues ...

TRACER Experiment

tracer.uchicago.edu

KASCADE-Grande Collaboration

WWW-IK.FZK.DE/KASCADE_home.html

LOPES

RADIO EMISSION FROM COSMIC RAY AIR SHOWERS