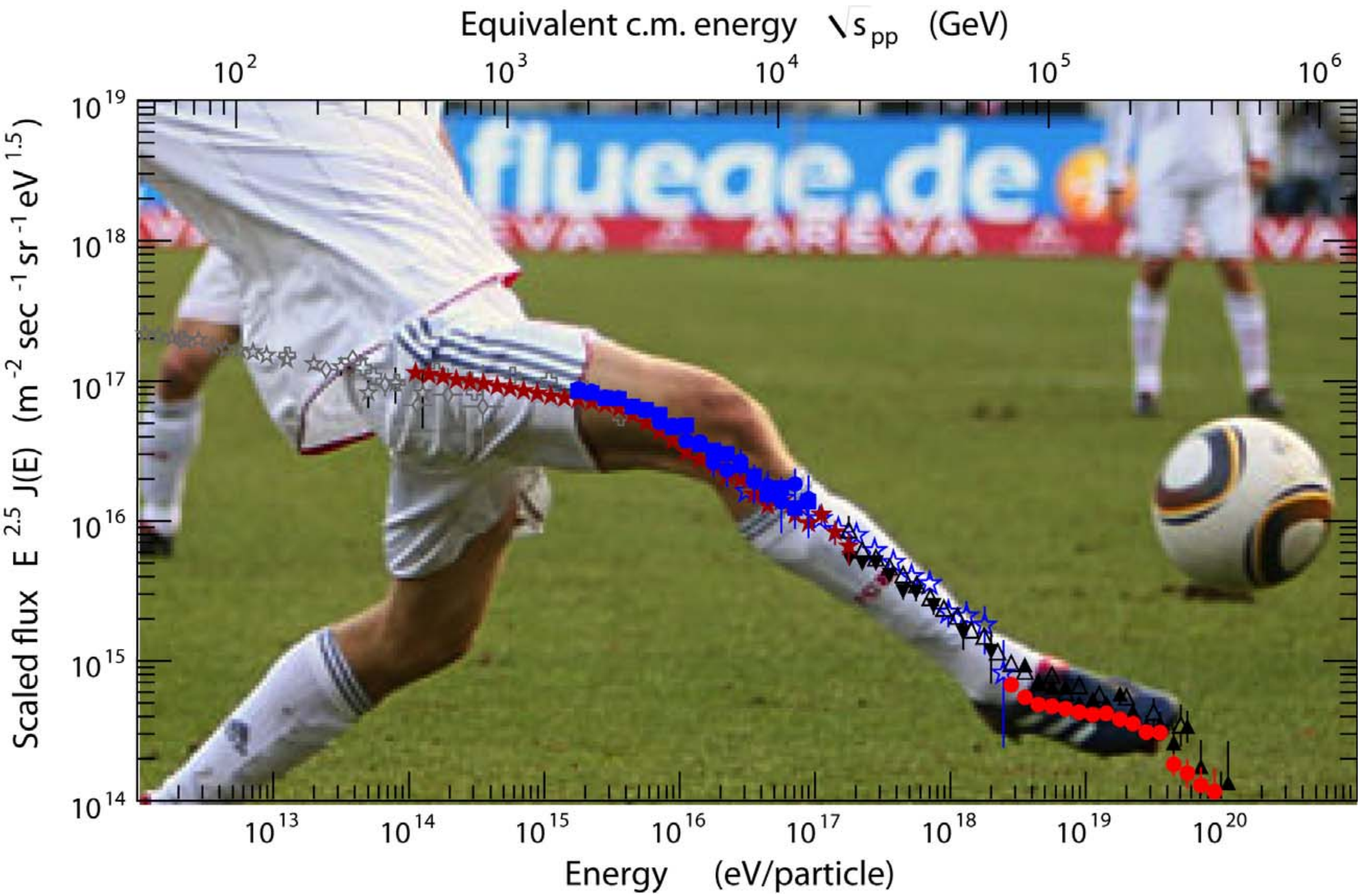
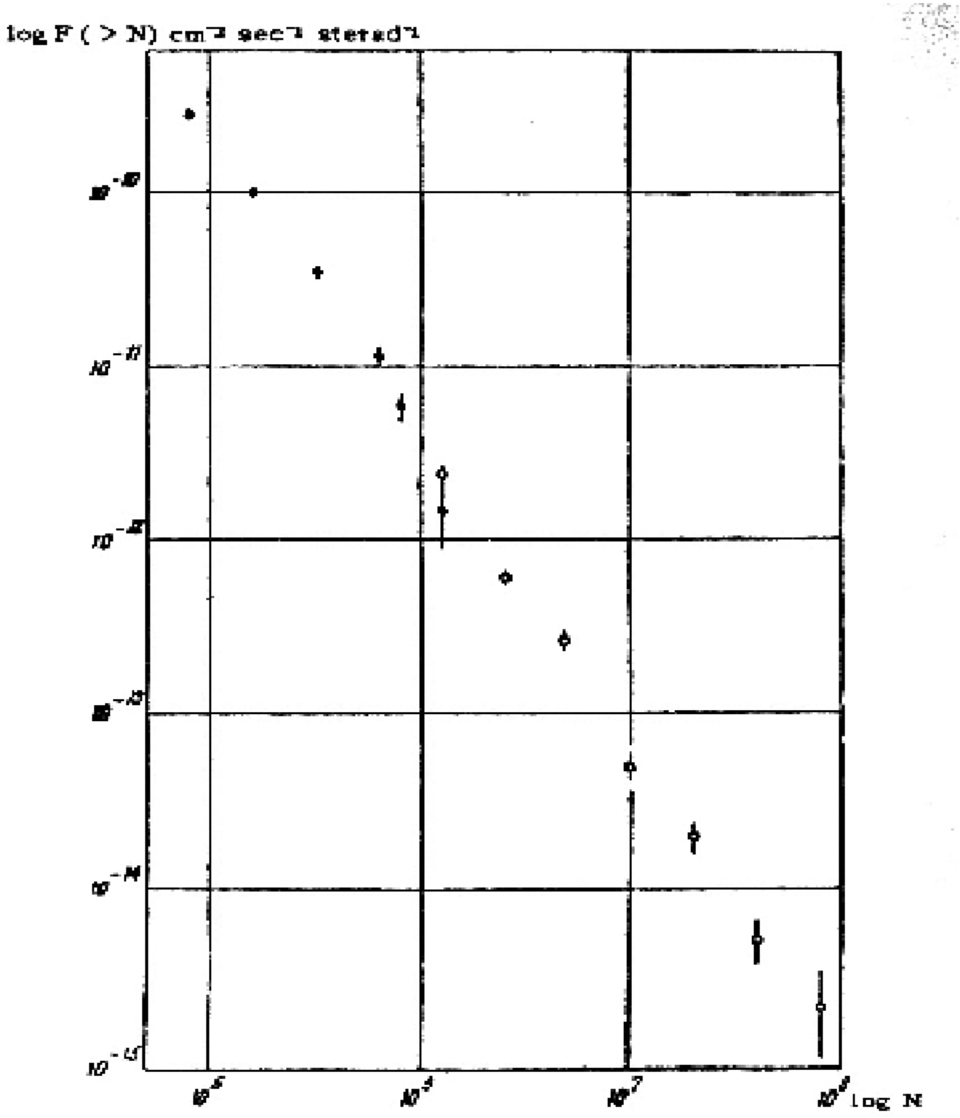
Cosmic Rays
in the Knee Energy Range



The "first knee"



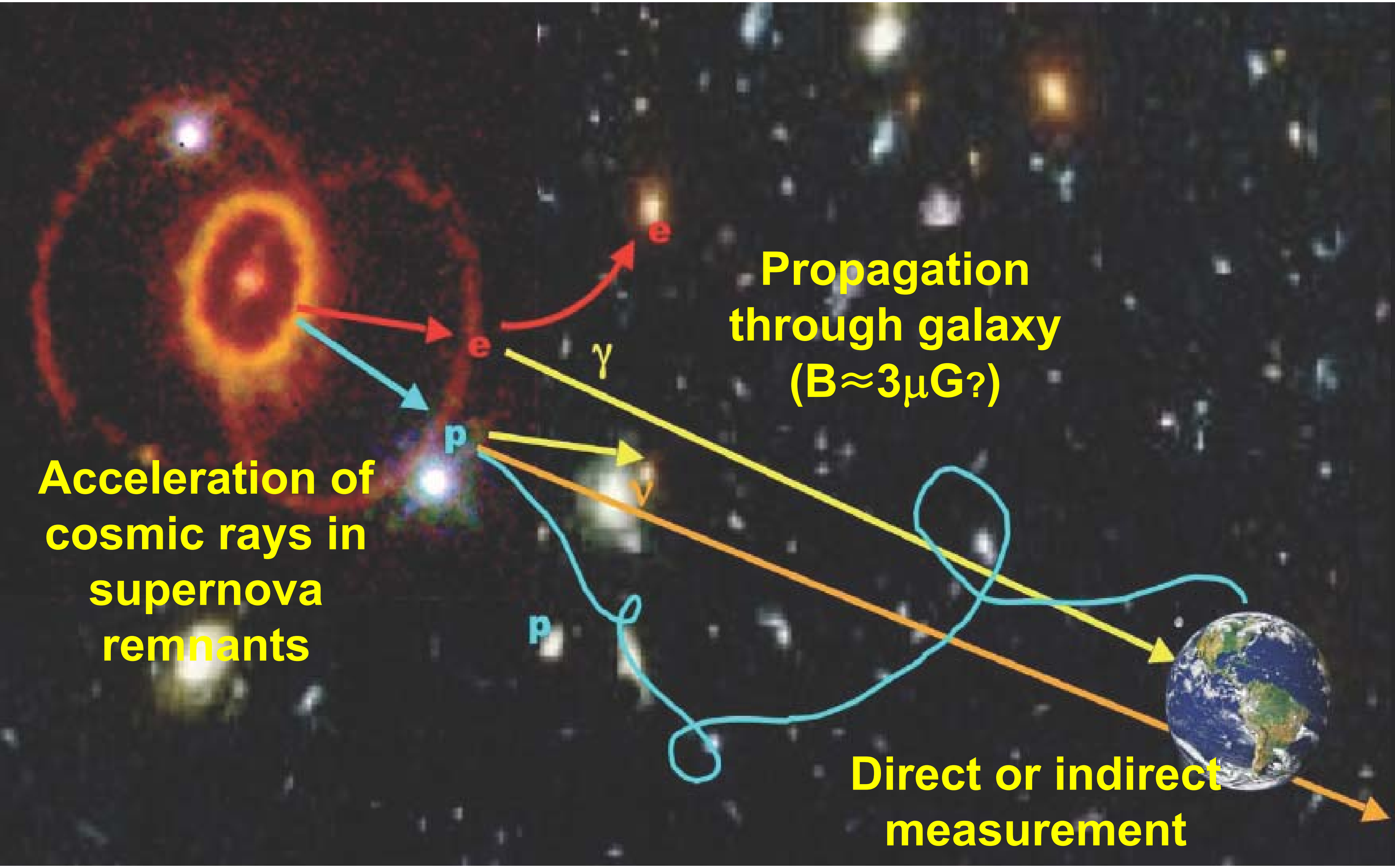
measured N_{ch} spectra

hodoscope counters in a $20x20\ m^2$ array

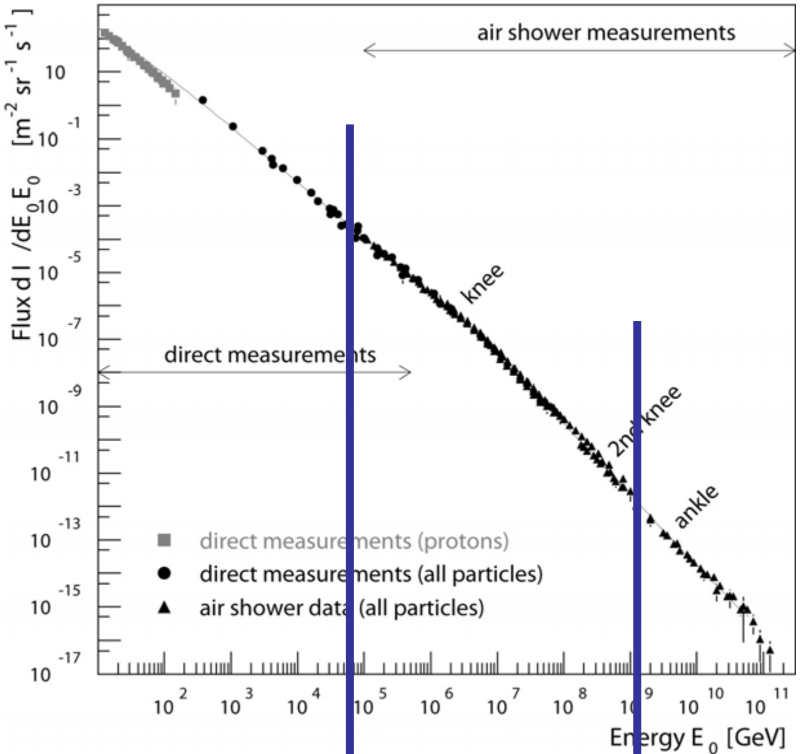
„the observed spectrum is a superposition of the spectra of particles of galactic and metagalactic origin"

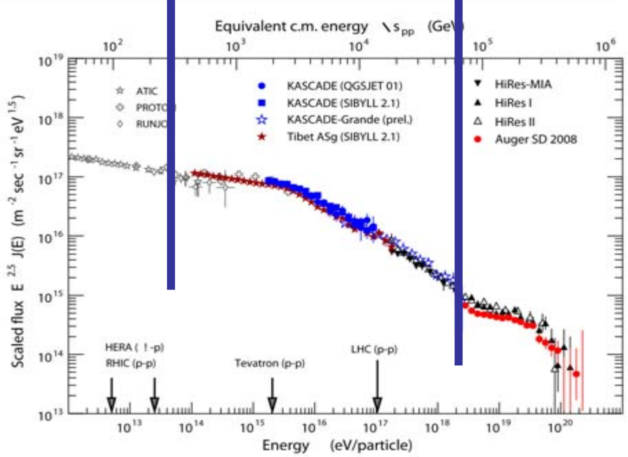
G.V.Kulikov, G.B.Khristiansen, Soviet Physics JETP 35(8) 3 March 1959

Galactic cosmic rays



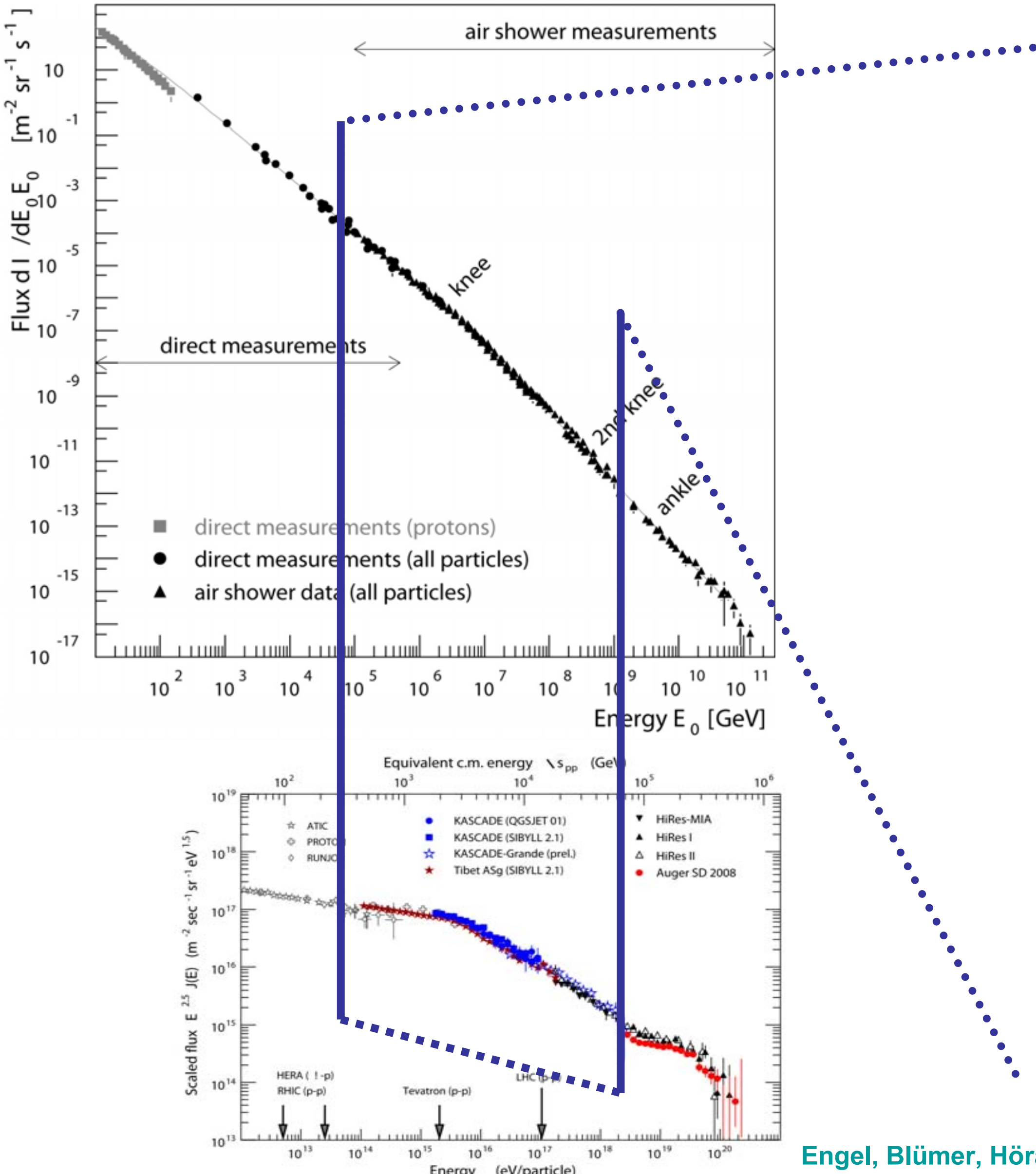
Questions to the knee energy range





Engel, Blümer, Hörandel:
Progress in Particle and Nuclear Physics 63 (2009) 293

Questions to the knee energy range



Overlap direct-indirect measurements?

Hadronic interaction models?

Rigidity dependent knee?

Sharpness of knee?

Composition at knee?

Iron knee?

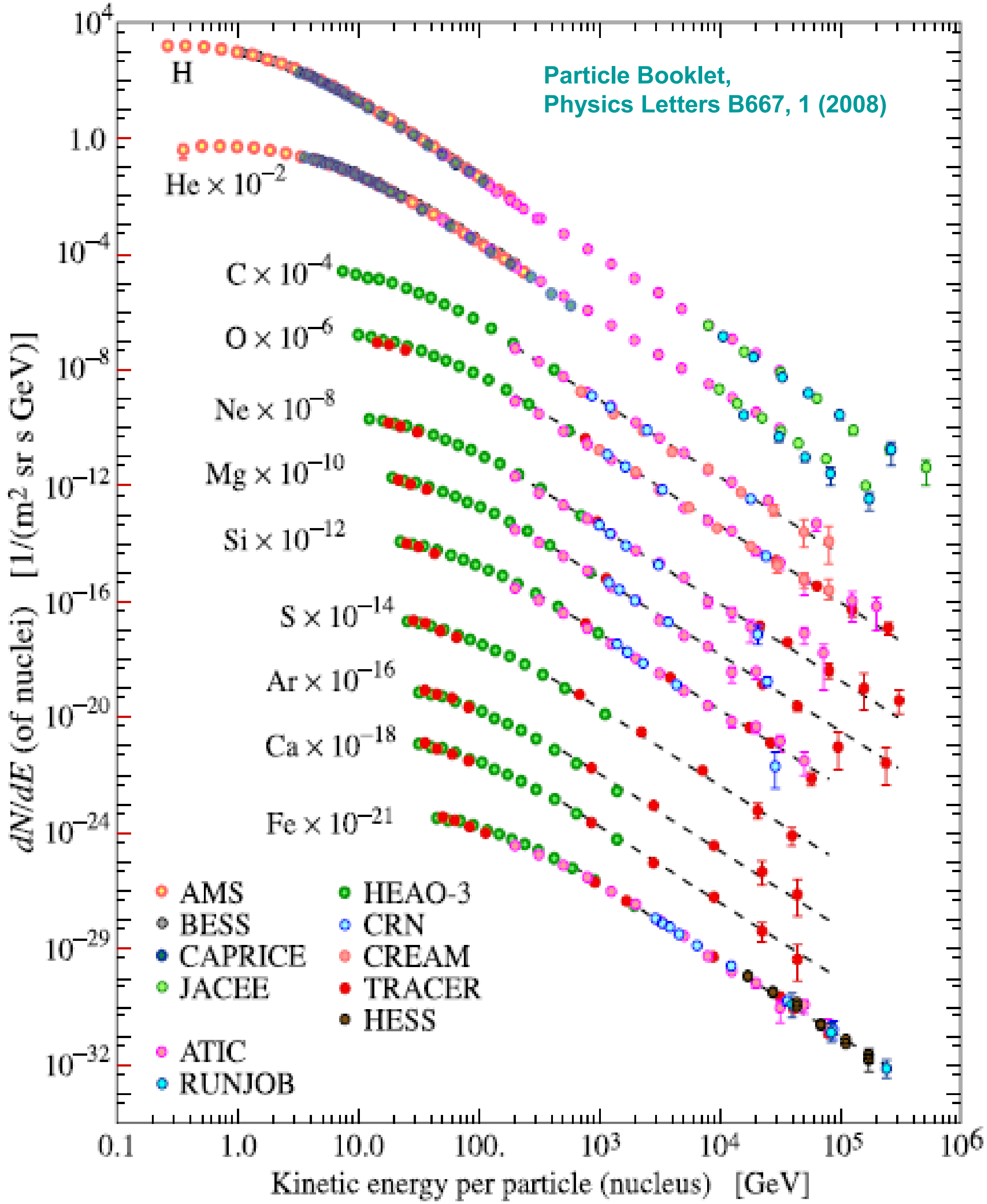
End of Galactic Spectrum?

Second knee?

Transition galactic – xgalactic?

Anisotropy?

Engel, Blümer, Hörandel:
Progress in Particle and Nuclear Physics 63 (2009) 293



Direct measurements

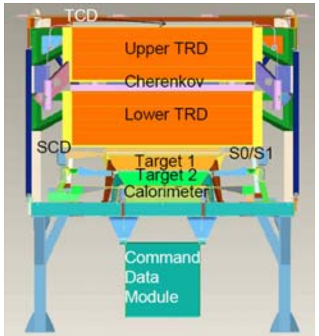
- $dN / dE \sim E^{-\gamma}$
  with $\gamma \sim 2.7$
- Acceleration by Supernova Remnants, only?

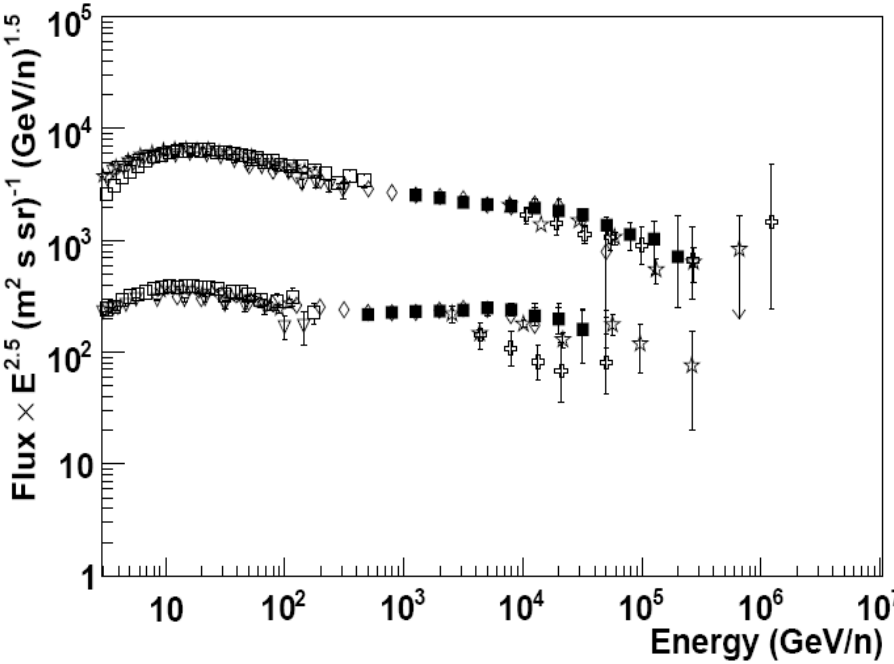
CREAM

Cosmic Ray Energetics And Mass

- **Measurements of elemental spectra for Z = 1 – 26 nuclei**
- **Energy ranges from 10^{11} to 10^{15}eV**
- **CREAM-III 12/07 – 1/08 (29 days)**
  Five succesful flights 2004 – 2010
  ~ 156 days cumulative exposure
- **Combines calorimeteric and transition radiation detector (TRD) techniques**

- **Data shows p and He spectra different in slope**
- **p and He spectra show hardening**
- **Different type of source or acceleration mechanism?**

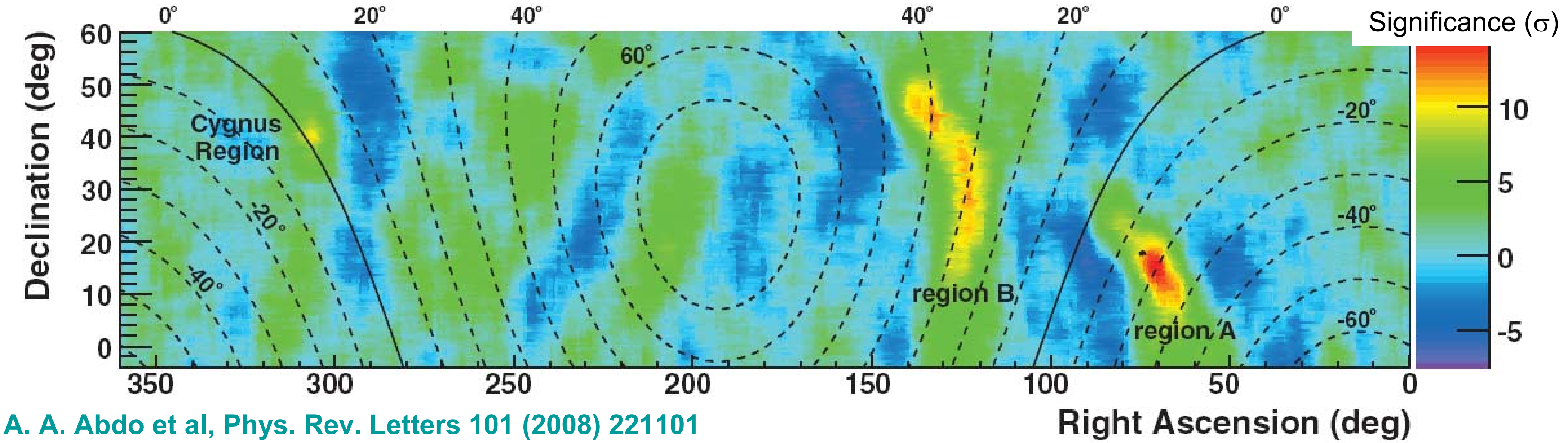




H.S. Ahn et al., Astrophysical Journal 714 (2010) L89.

Large-Scale Anisotropy: MILAGRO

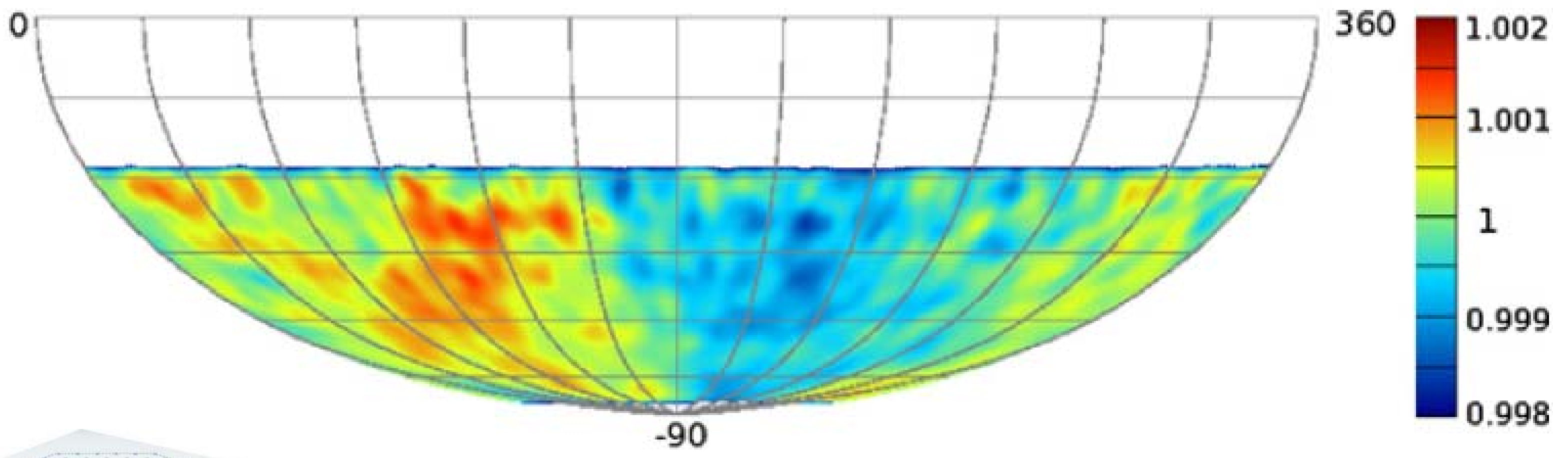
- Water Cherenkov detector in New Mexico, US
- 2600 meters altitude
- 4000 m^2 pond / 40000 m^2 outtrigger coverage
- 0.4° – 1.0° angular resolution
- Sensitivity 100GeV – 100TeV

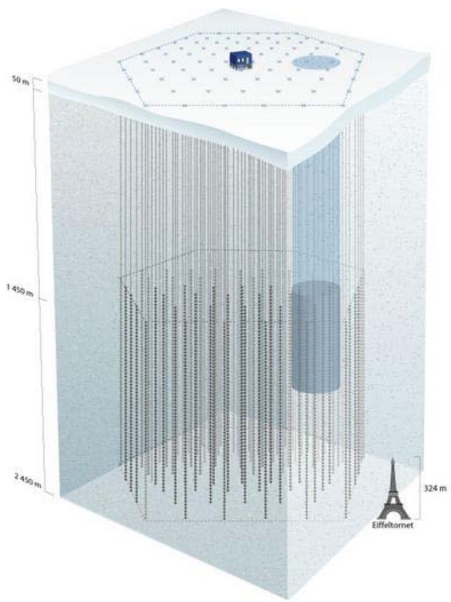


A. A. Abdo et al, Phys. Rev. Letters 101 (2008) 221101

- 7 years: 10^{11} events.
- Map dominated by charged cosmic rays of ~10 TeV
- Two regions of excess 15.0σ and 12.7σ.
- Nearby accelerator? Local magnetic fields?
- Also seen by Super-Kamiokande and ARGO!

ICECUBE





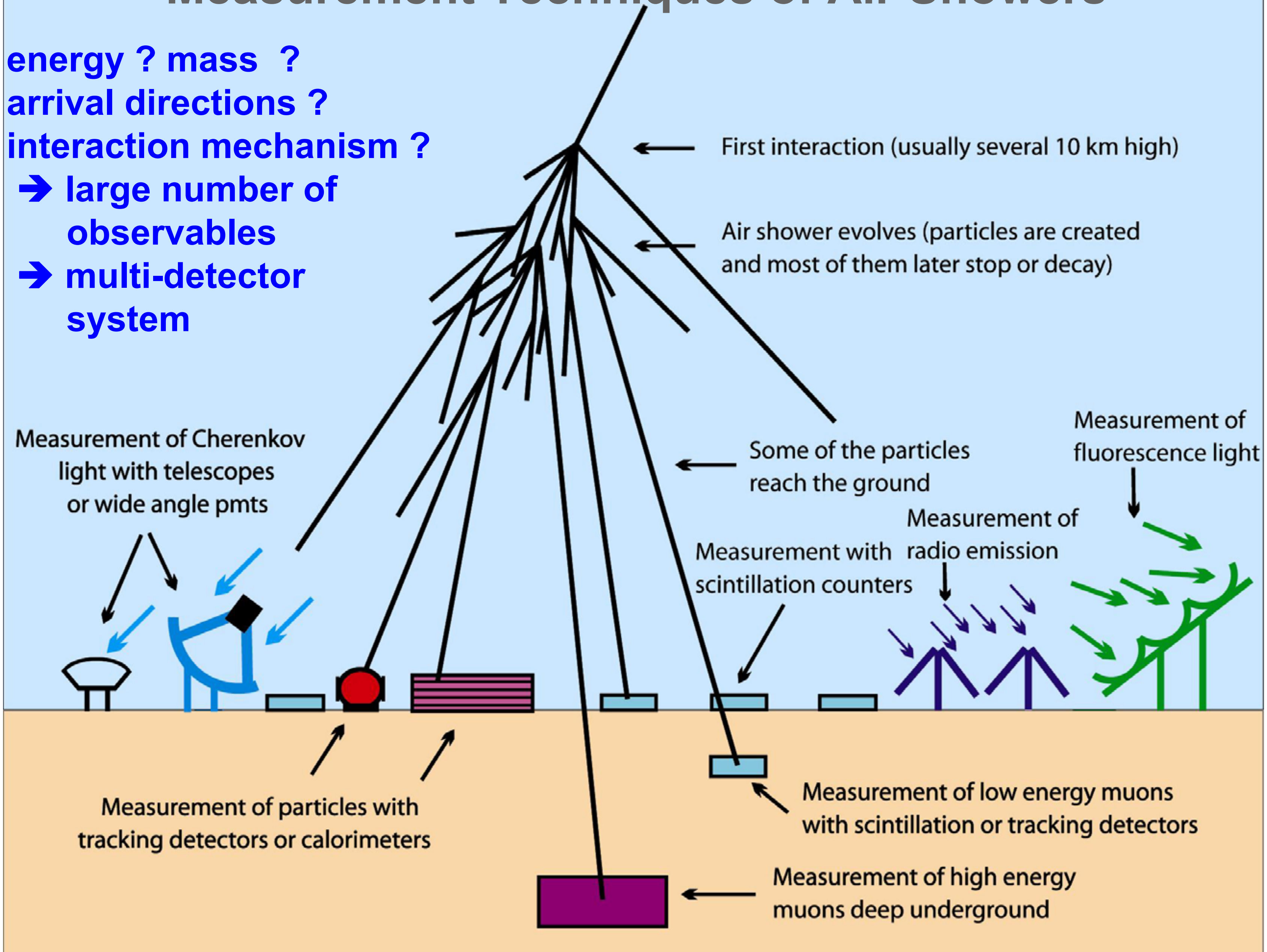
- under-ice (southpole) Cherenkov neutrino detector
- 22 strings: 4.3 billion muons

- Map dominated by charged cosmic rays of ~20 TeV
- Continuation of northern hemisphere anisotropy
- Not by motion of solar system or by heliospheric magnetic field!
- Feature of local interstellar or galactic magnetic fields?
- Nearby source (such as Vela)?

Abbasi, R. et al, The Astrophysical Journal Letters 718, L194, 2010

Measurement Techniques of Air Showers

energy ? mass ?
arrival directions ?
interaction mechanism ?
➔ large number of observables
➔ multi-detector system



KASCADE

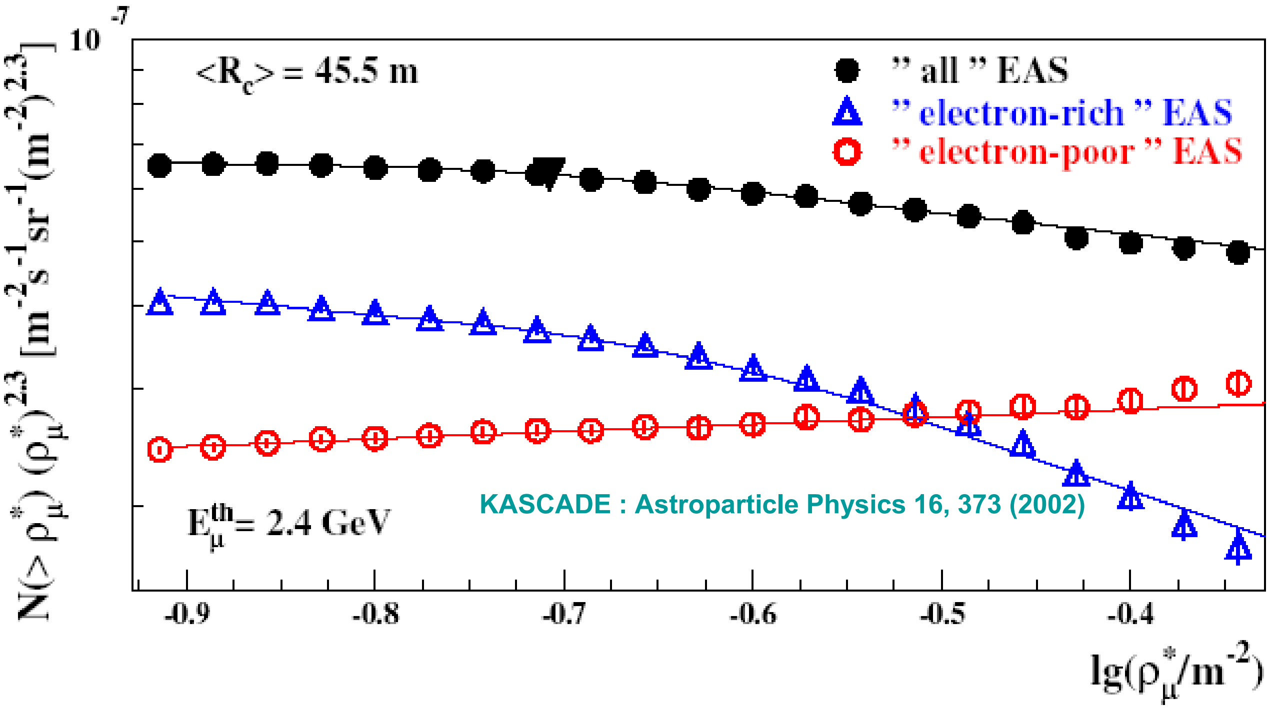
KArlsruhe Shower Core and Array DEtector

- Energy range 100TeV – 80PeV
- Since 1995
- Large number of observables: electrons, muons@4 thresholds, hadrons

T.Antoni et al. NIM A513 (2003) 490

Model independent multi-parameter analysis

Use of three observables:
- high-energy local muon density ➔ energy estimator
- Total muon number and electron number ➔ mass estimator

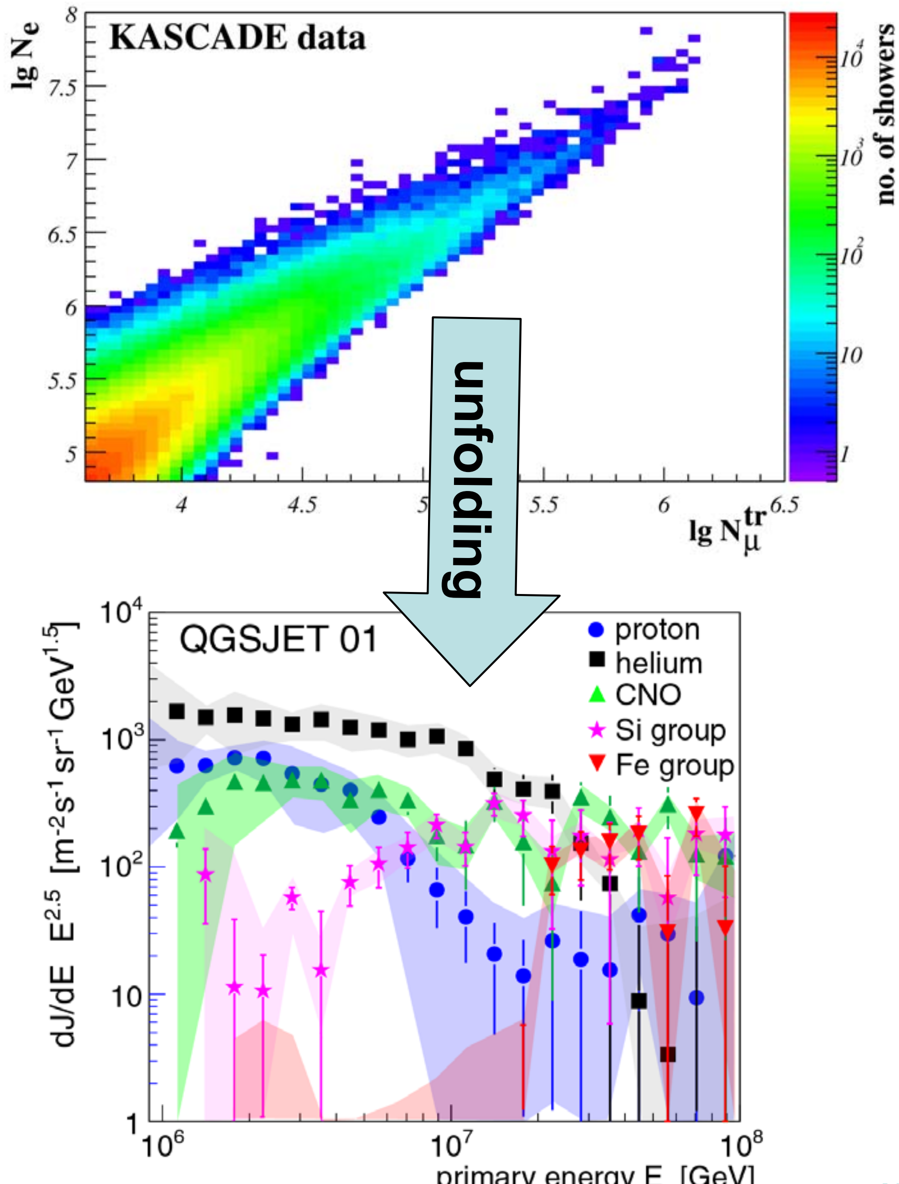


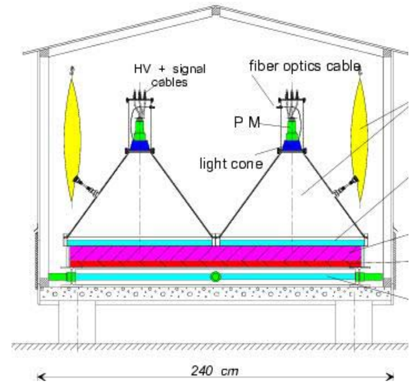
- **KNEE CAUSED BY DECREASING FLUX OF LIGHT ELEMENTS**
- **Do we need hadronic interaction models?**

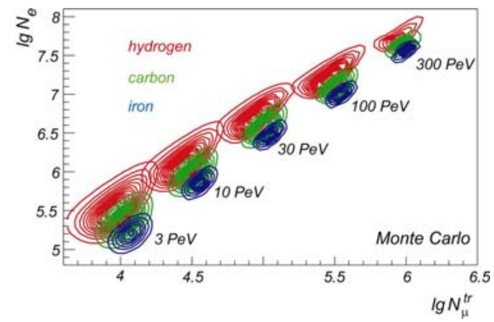
➔ yes, for normalization of absolute energy and mass scale!!

T.Antoni et al. Astroparticle Physics 16 (2002) 373

KASCADE : energy spectra of single mass groups







Searched:

E and A of the Cosmic Ray Particles

Given:

N_e and N_μ for each single event

➔ solve the inverse problem

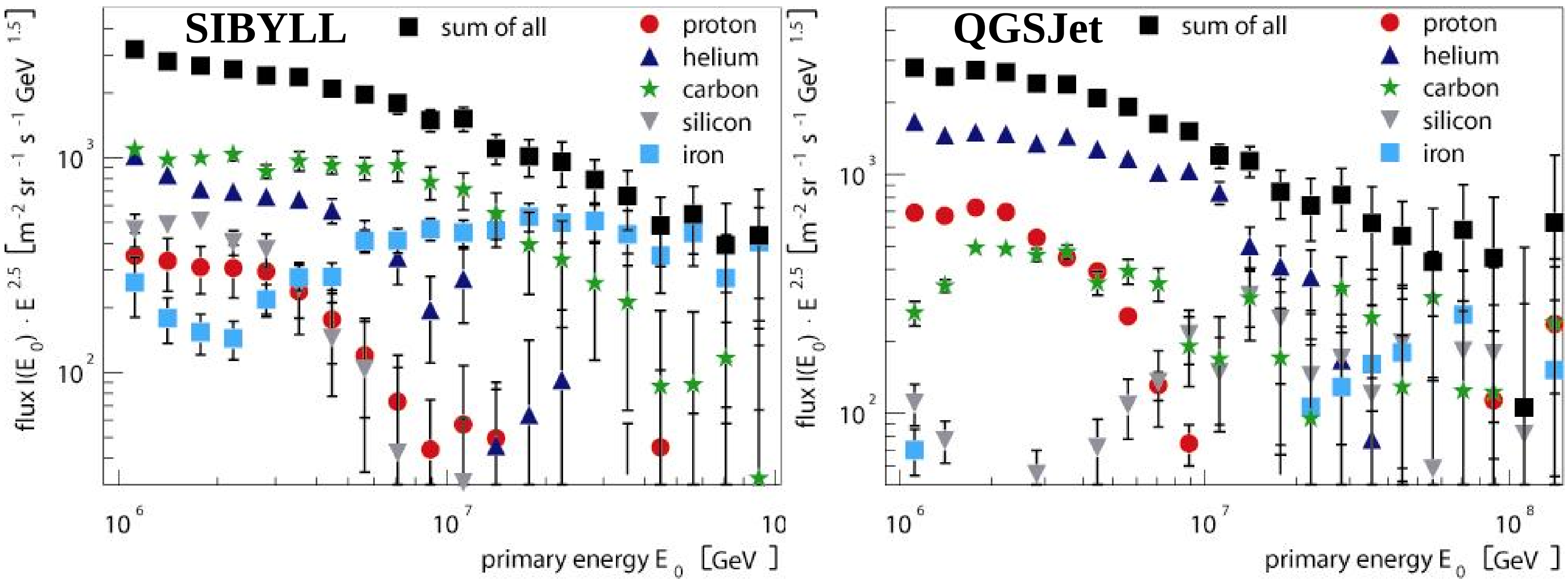
$$\frac{dJ}{d\lg N_e \, d\lg N_\mu^{tr}} = \sum_A \int_{-\infty}^{+\infty} \frac{dJ_A}{d\lg E} \, p_A(\lg N_e, \lg N_\mu^{tr} \mid \lg E) \, d\lg E$$

- **kernel function obtained by Monte Carlo simulations (CORSIKA)**
- **contains: shower fluctuations, efficiencies, reconstruction resolution**

KASCADE collaboration, Astroparticle Physics 24 (2005) 1-25

KASCADE results

- same unfolding but based on different hadronic interaction models embedded in CORSIKA

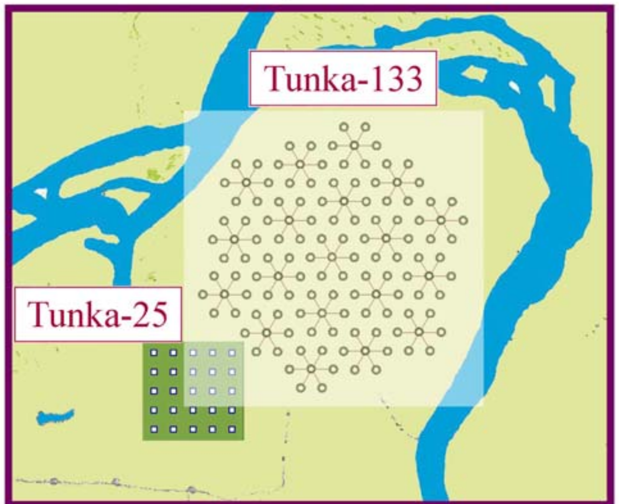


- all-particle spectrum similar
- general structure similar: knee by light component
- relative abundances very different **for different high-energy hadronic interaction models**

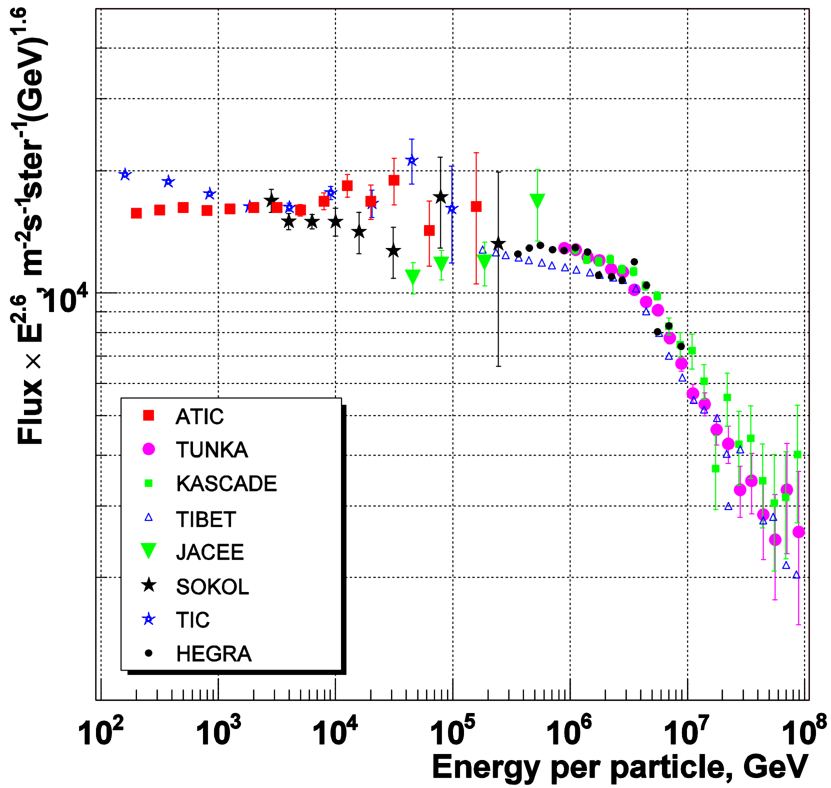
KASCADE collaboration, Astrop.Phys. 24 (2005) 1 , Astrop.Phys. 31 (2009) 86

TUNKA

Tunka-133 – 1 km² dense EAS Cherenkov light array



51° 48' 35" N
103° 04' 02" E
675 m a.s.l.

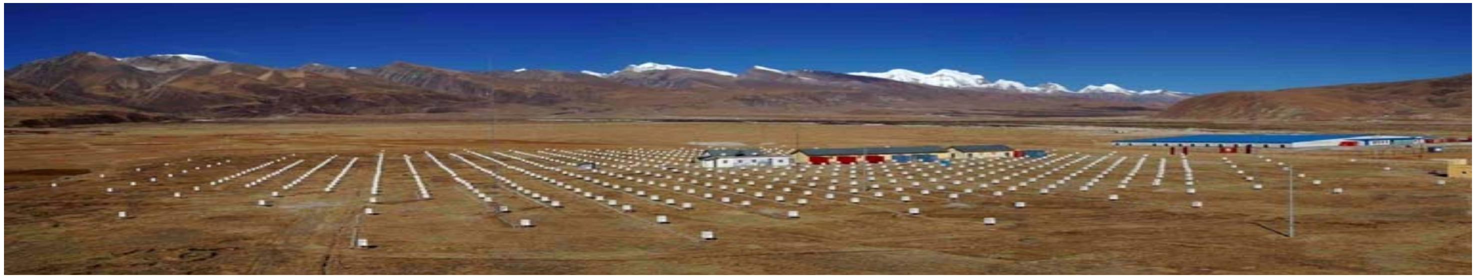


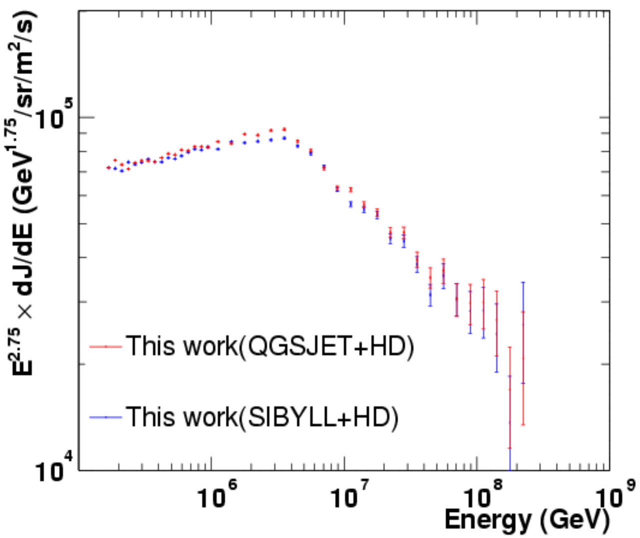
- **A sharp knee around 4 PeV**
- **First 'Cherenkov' spectrum with similar flux**

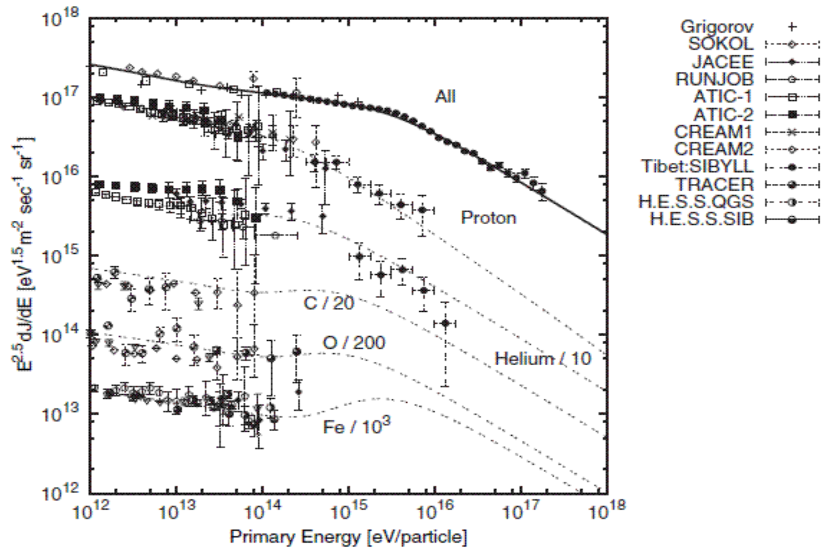
V. Prosin, Tunka workshop 2009

Extension plans: muon counters, Scintillators, Radio net

Tibet ASγ







- **A sharp knee around 4 PeV**
- **Heavy particle dominance at knee**

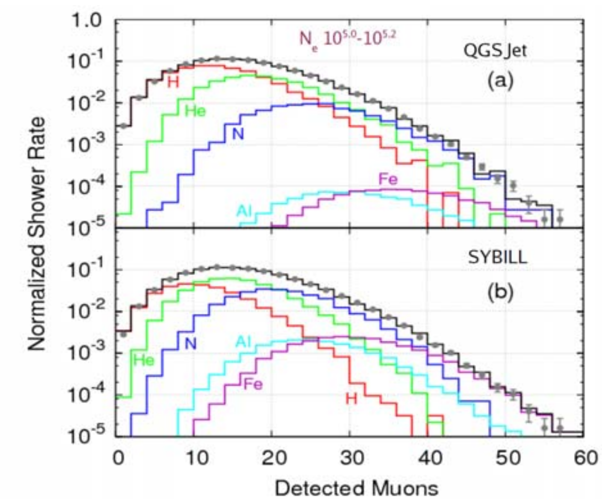
Extension plans:

- **Tibet-AS: scintillator array**
- **YAC (Yangbajing Air shower Core): Burst Detector**
- **Tibet-MD: muon detector**

➔ Spectrum of heavy primaries

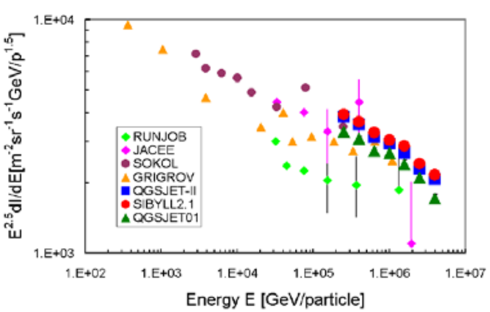
GRAPES

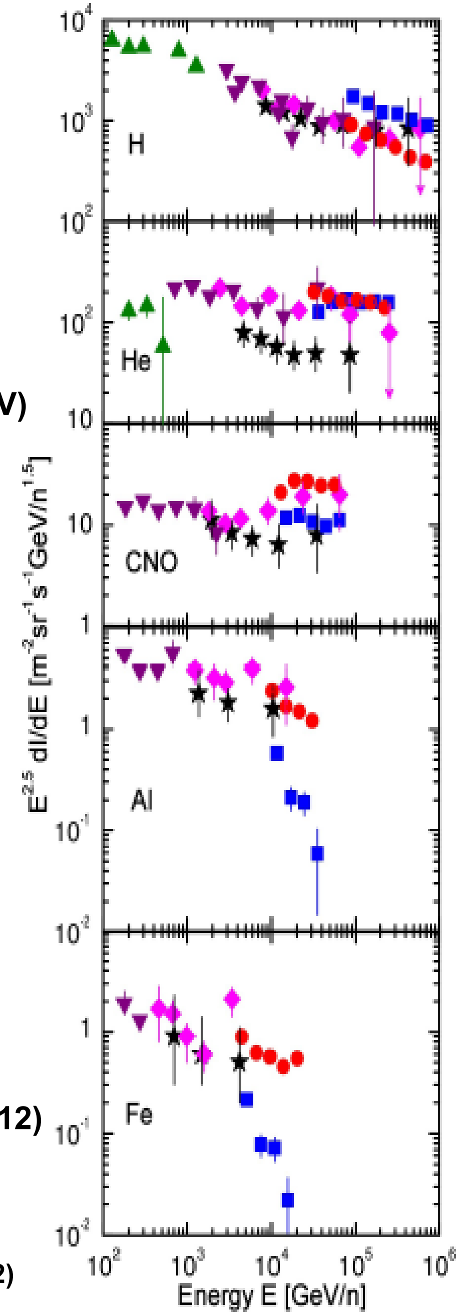
- GRAPES-3, Ooty, India
- at 2200 masl
- 400 scintillators
- $560 m^2$ tracking μ detector ($E_\mu > 1$GeV)
- E from 3×10^{13} eV to 3×10^{16} eV



- **knee by light primaries**
- **overlap with direct measurements!!**

All-particle Spectrum





Future Expansion Plans:

Double muon detector 560 ---> 1120 m^2 (2012)

Wide-angle Cerenkov telescope (2012)

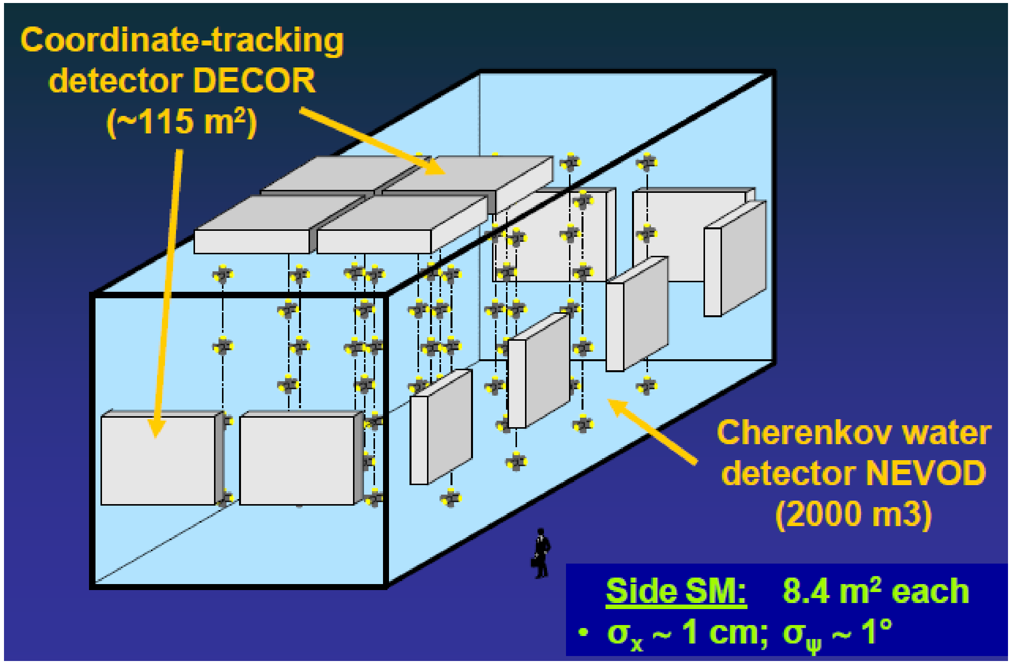
Expansion to ~1 km^2 (2015)

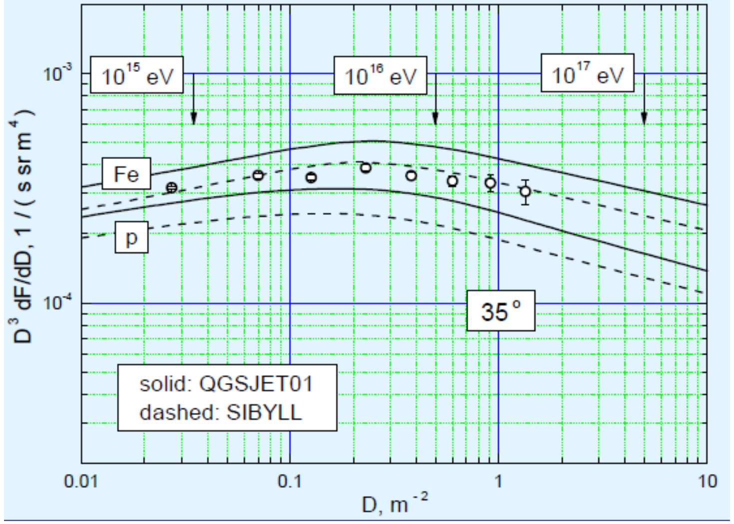
Neutron monitors for solar studies (2012)

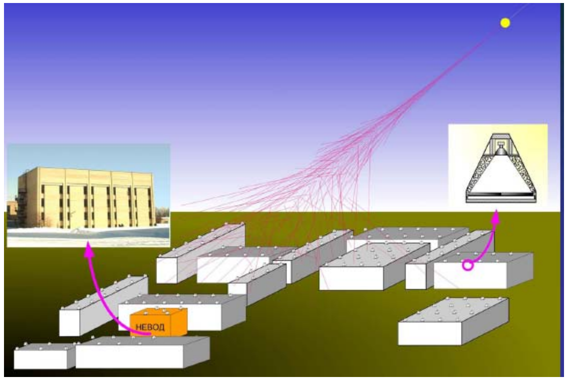
Radio antenna array (?)

Sunil Gupta, ISVHECRI 2010

NEVOD-DECOR







- **large water cherenkov detector, Russia**
- **position detector**

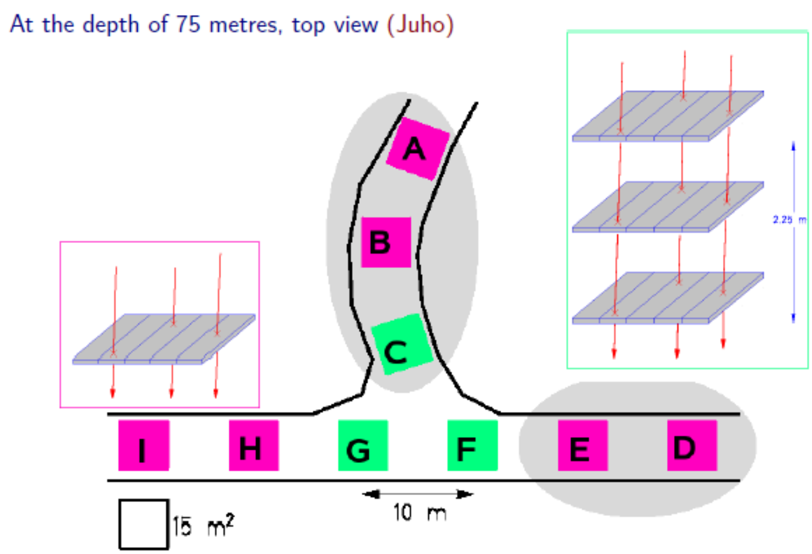
➔ Muon bundles (under large zenith angles)
➔ Sensitivity to energy and composition

- **extension plans: array around**

Petruhkin, KASCADE Symposium 2009

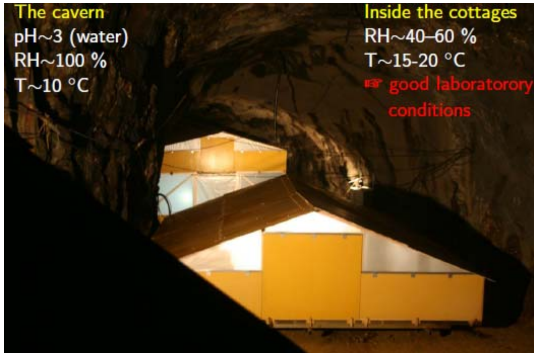
EMMA

Experiment with Multi Muon Array



- 9 x 15 m^2 muon detectors
- 75m depth of Pyhäsalmi mine, Finland
- muon bundles (E_μ > 50GeV)

➔ **muon multiplicity and lateral distribution**
➔ **sensitivity to energy and composition around knee**



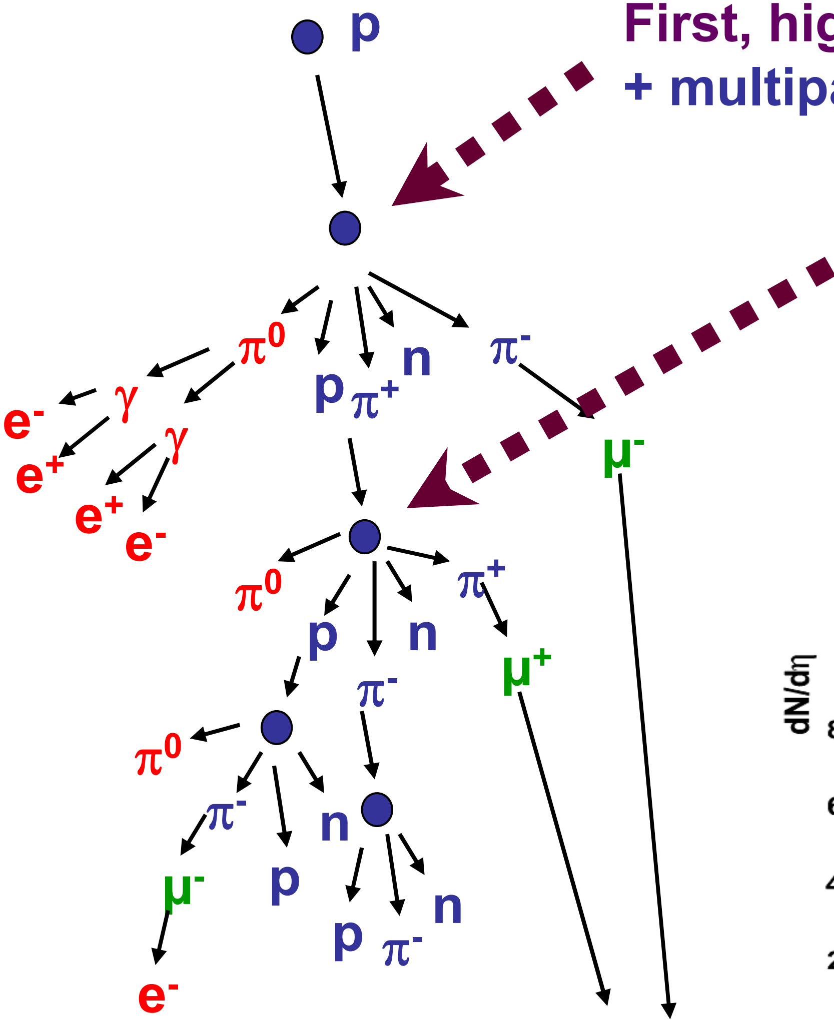
- **extension plans: scintillators in mine (and on top?)**

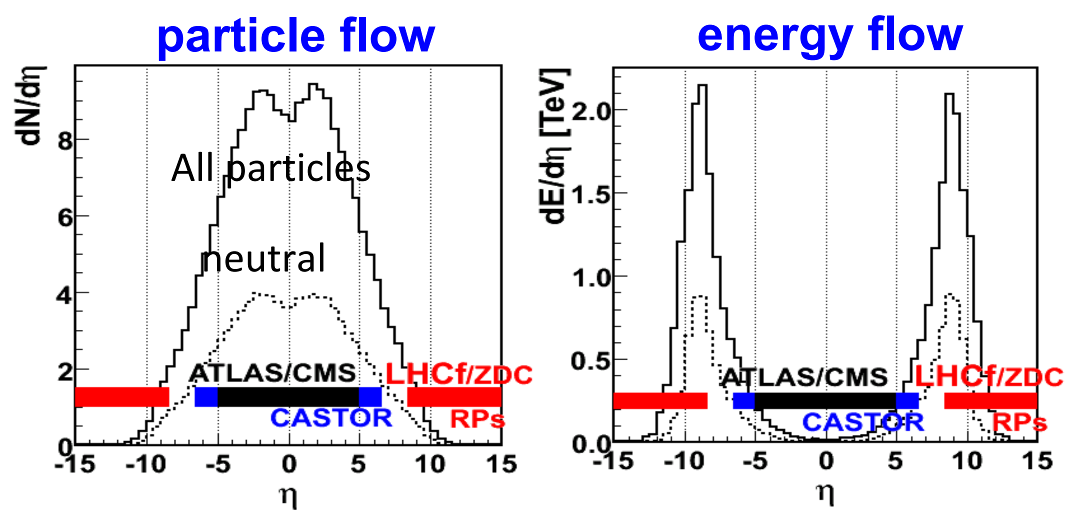
EMMA Collaboration, ICRC2009

Validity of Hadronic Interaction Models

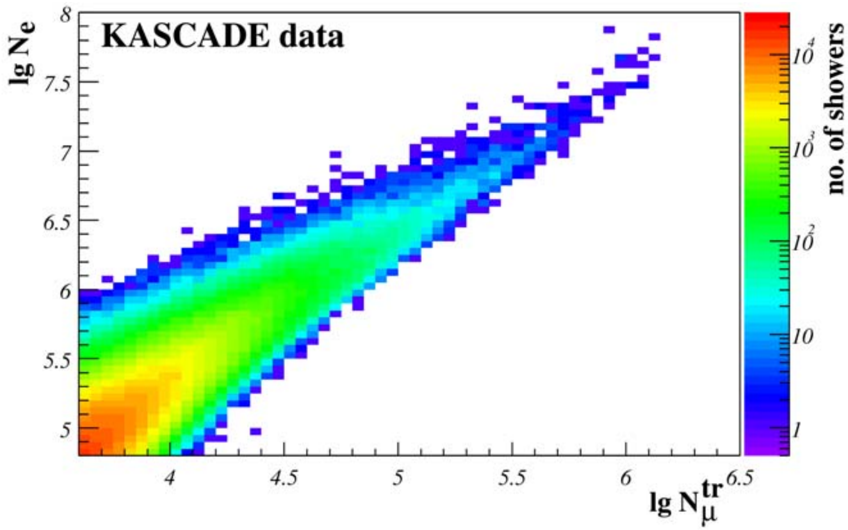
First, high energy interaction: LHC
+ multiparameter measurements EAS

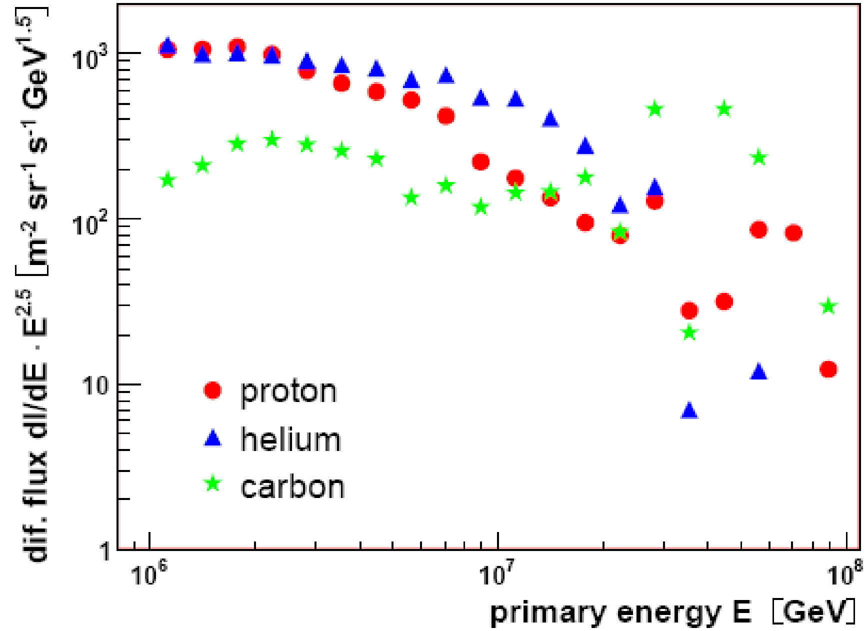
Secondary interactions:
Fix target experiments
+ multiparameter measurements EAS

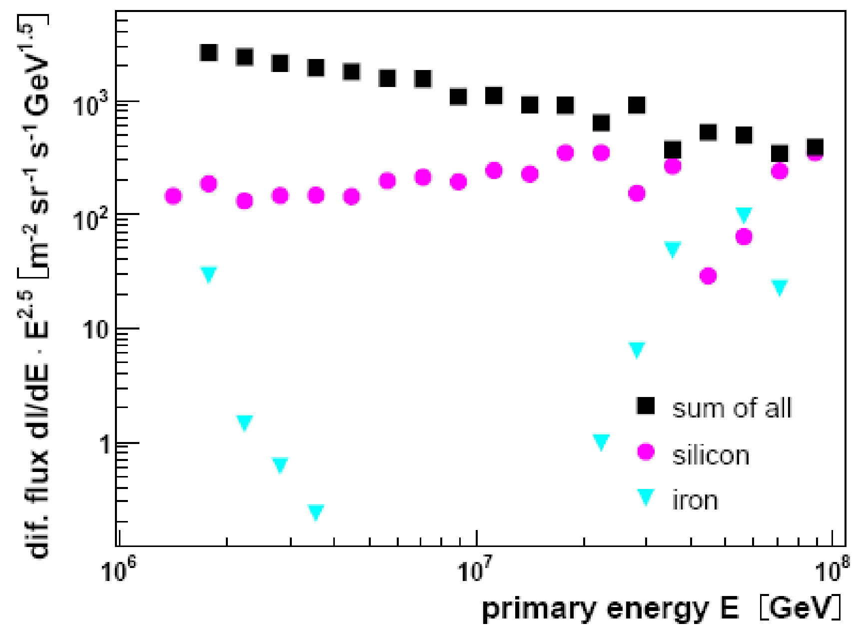




KASCADE
tests new models: EPOS 1.99





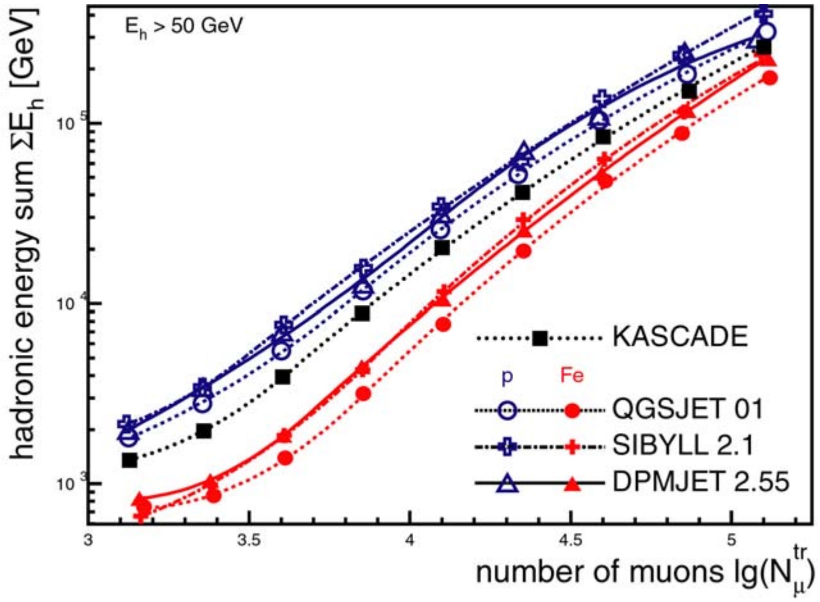


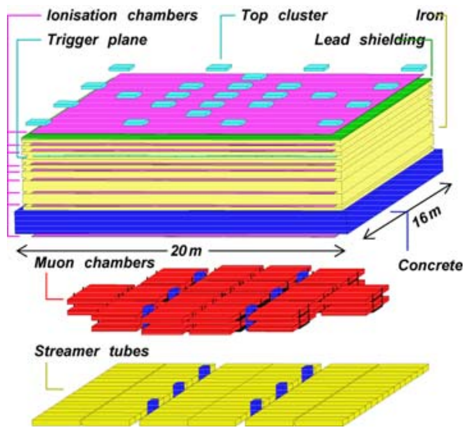
- EPOS 1.99 + FLUKA:
- composition light dominant
- Knee caused by light elements
- all-particle spectrum okay

- the case for EPOS 1.61:
  all-particle spectrum not okay
  very proton dominant

EPOS 1.99: Phys.Rev.C74(2006)044902 // KASCADE analysis: Marcel Finger PhD(2010)

hadronic interaction model tests with EAS data





**Example:
hadrons vs. muons**

correlation of observables:

<u>no hadronic interaction model describes data consistently !</u>

➔ tests and tuning of hadronic interaction models !

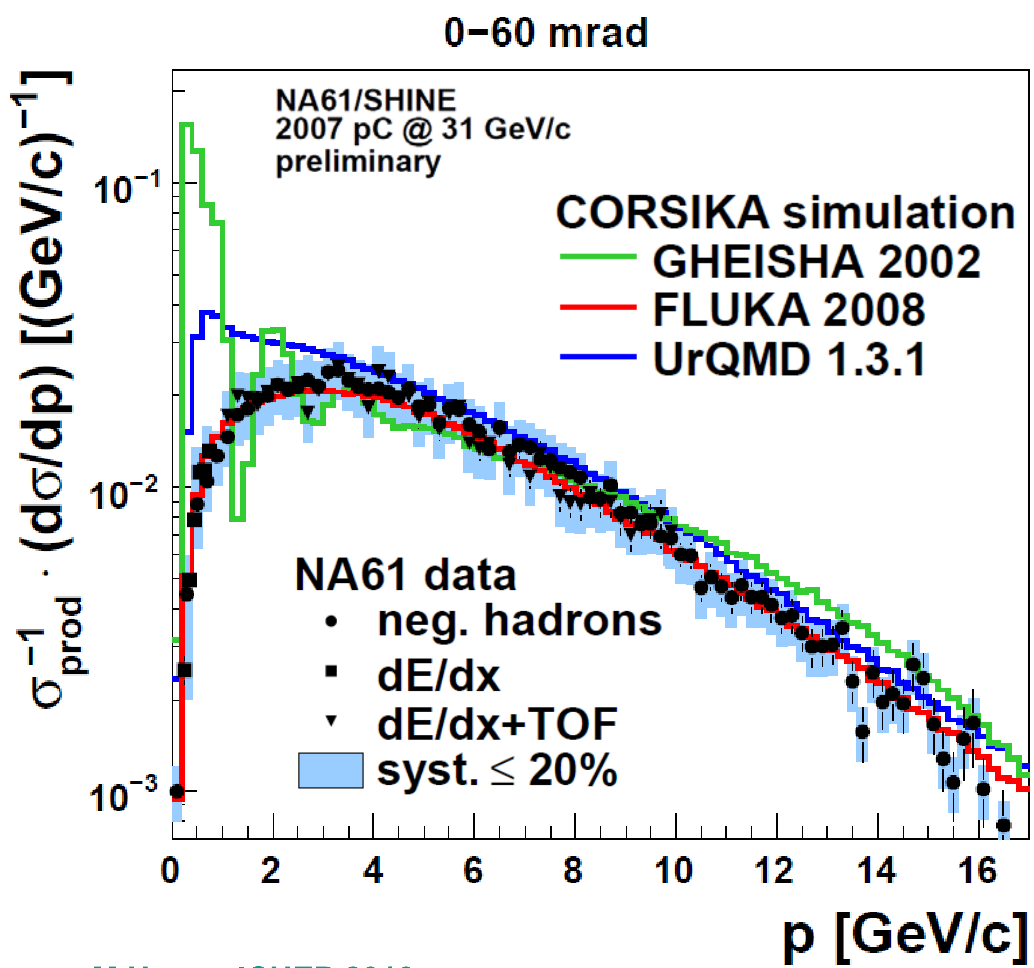
➔ close co-operation with theoreticians (CORSIKA including interaction models)

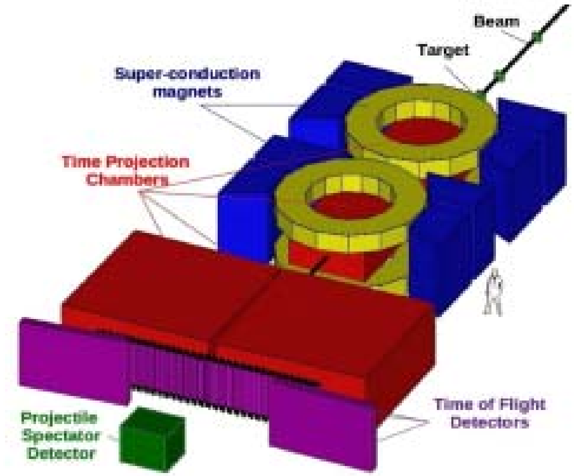
➔ e.g.: •**EPOS 1.6 is not compatible with KASCADE measurements**
•**QGSJET 01and SIBYLL 2.1still most compatible models**

KASCADE collaboration, J Phys G (3 papers: 25(1999)2161; 34(2007)2581; (2009)035201)

SHINE (NA61) @ SPS/CERN

- had (and will have) dedicated cosmic ray runs
  pp (13-158GeV), pC (31-158GeV), πC (158-350GeV)
- particle identification with TDC and ToF



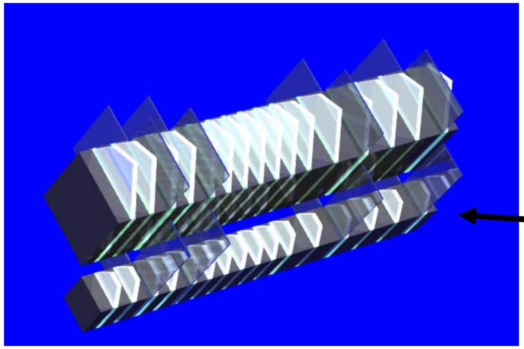


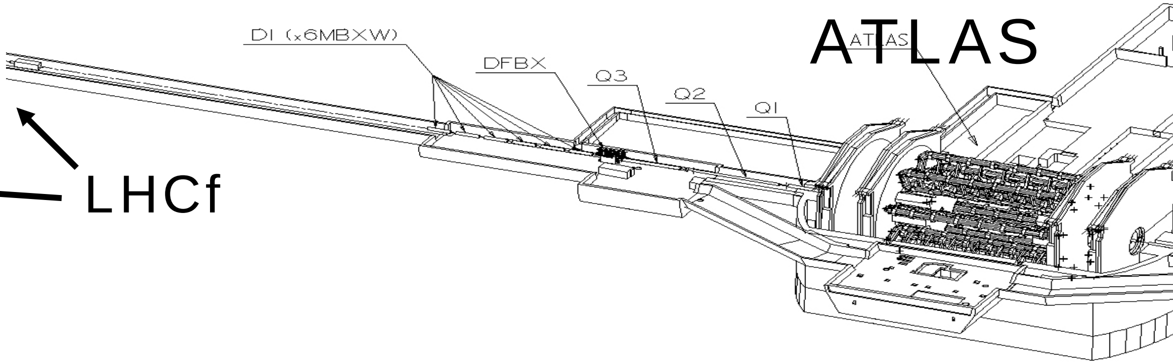
Inclusive π^- - spectra

(pilot run 2007)
p + C at 31 GeV/c

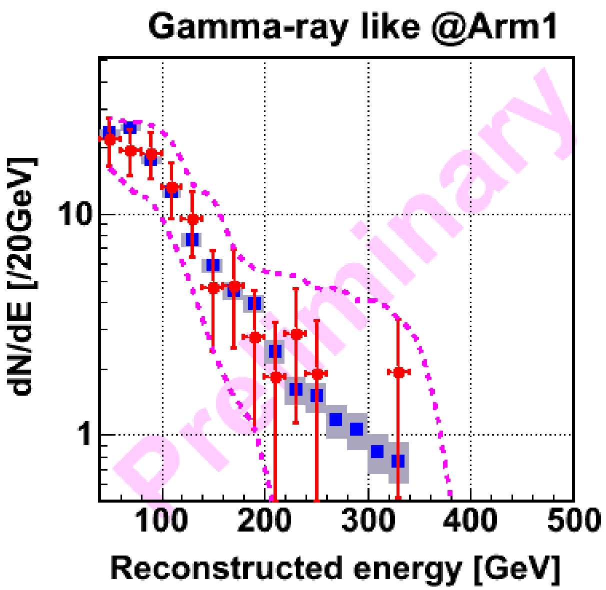
M.Unger, ICHEP 2010

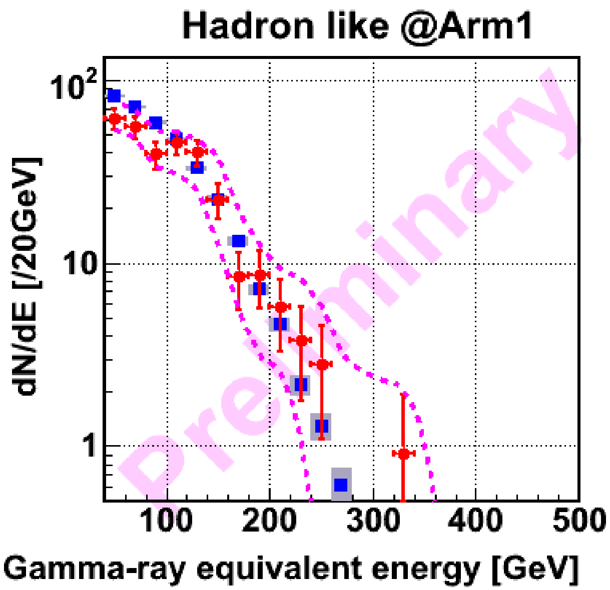
LHCf @ LHC





- Measures very forward (η >8.4; including 0 degree)
- Measures neutral particles at LHC p-p (ion-ion) collisions
- Tungsten calorimeter with plastic scintillators

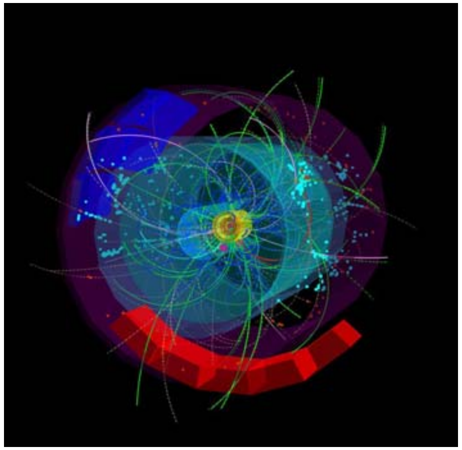




Spectra Comparison with MC (QGSJET2)

Sako, ISVHECRI 2010

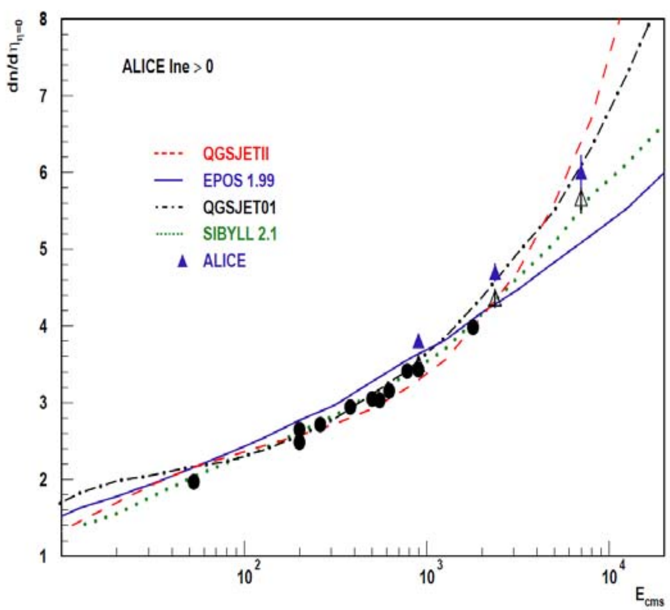
ALICE @ LHC

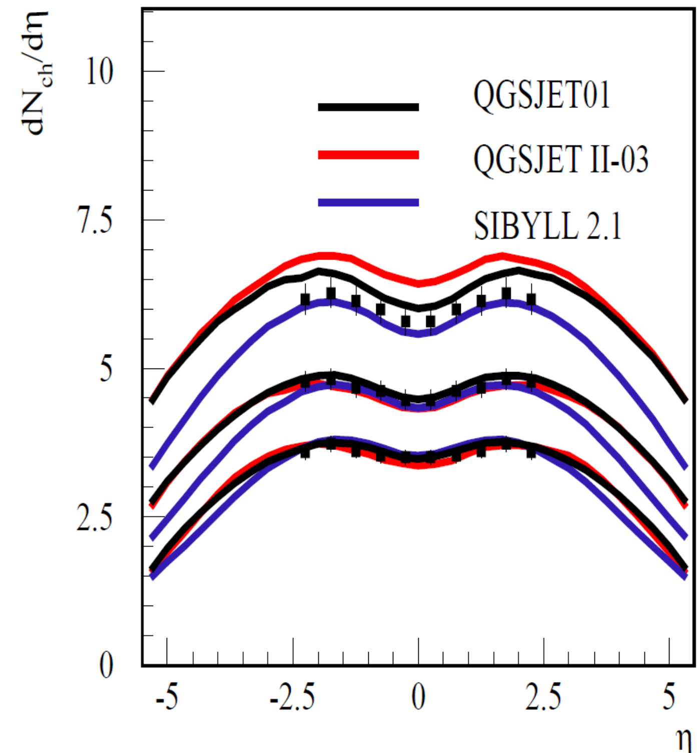


- **Multiplicity distributions and dNch/d η at 0.9, 2.36 and 7 TeV**

➔ significantly larger increase from 0.9 to 7 TeV than in HEP- MCs

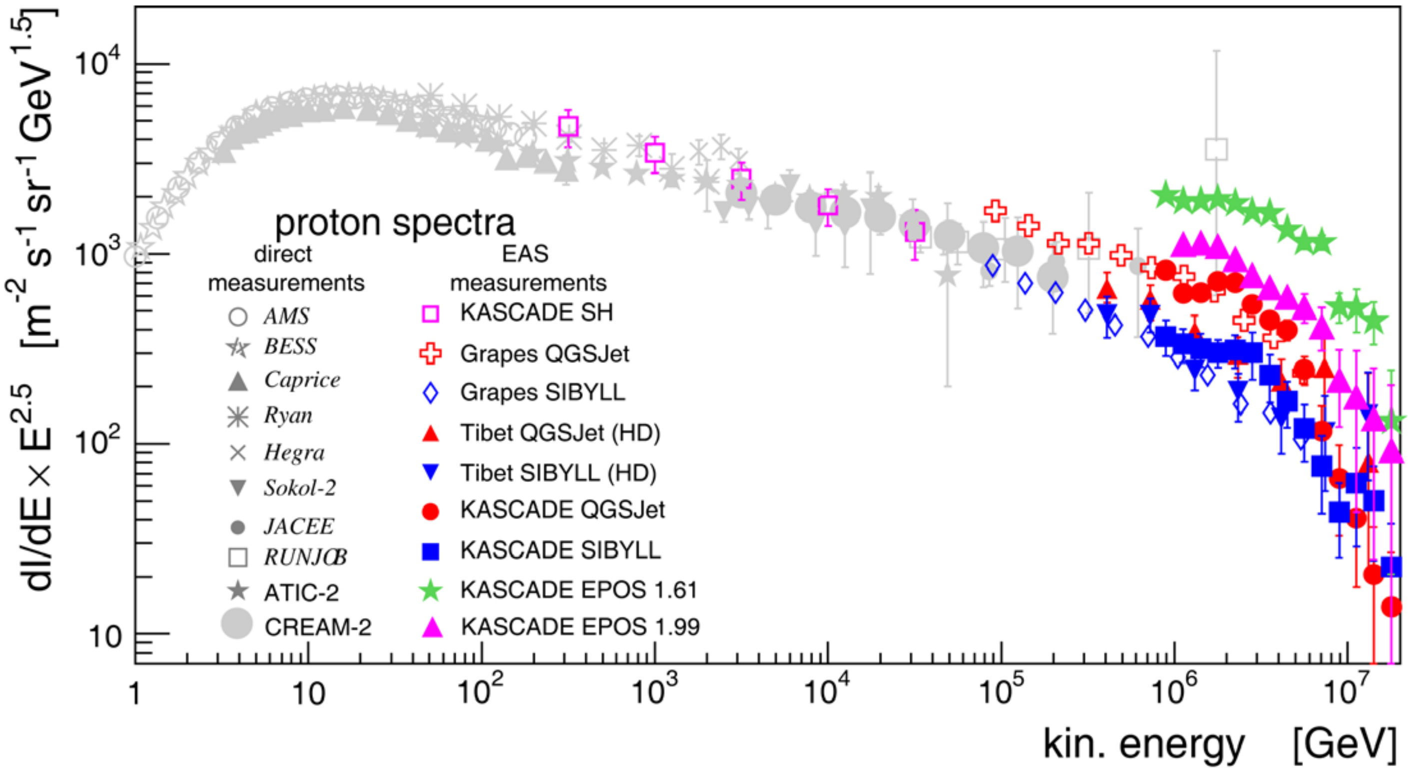
➔ CR- MCs seems to better agree





Henner Büsching, ISVHECRI 2010 // Sergey Ostapchenko (CR-MC)

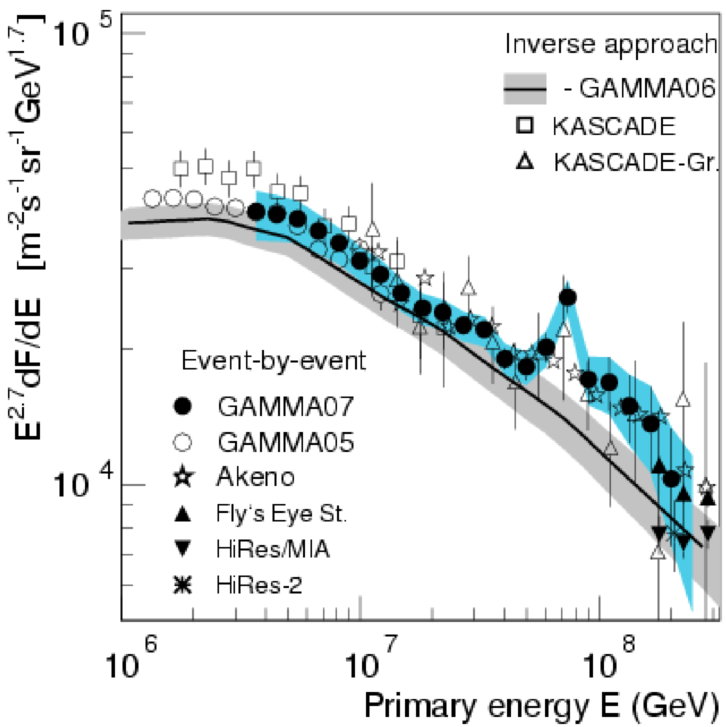
Status of the (1st) Knee



- -) knee caused by light primaries ➔ composition gets heavier across knee
- -) positions of knee vary with primary elemental group
- -) relative abundancies depend strongly on high energy interaction model
- -) no (interaction) model can describe the data consistently (KASCADE)
- -) all-particle spectra agree inside uncertainties (different sharpness?)
- -) proton spectra agree with direct measurements (not for EPOS1.6)
- -) ➔ protons are not the dominant primary at the knee!

GAMMA

- Mt. Aragats, Armenia, 3200 m a.s.l.
- scintillator array + μ-detectors (5GeV threshold)
- energy estimator: $Ln(E_0) \approx Ln(E_1) = f(N_{ch}, N_\mu, s, cos\theta)$

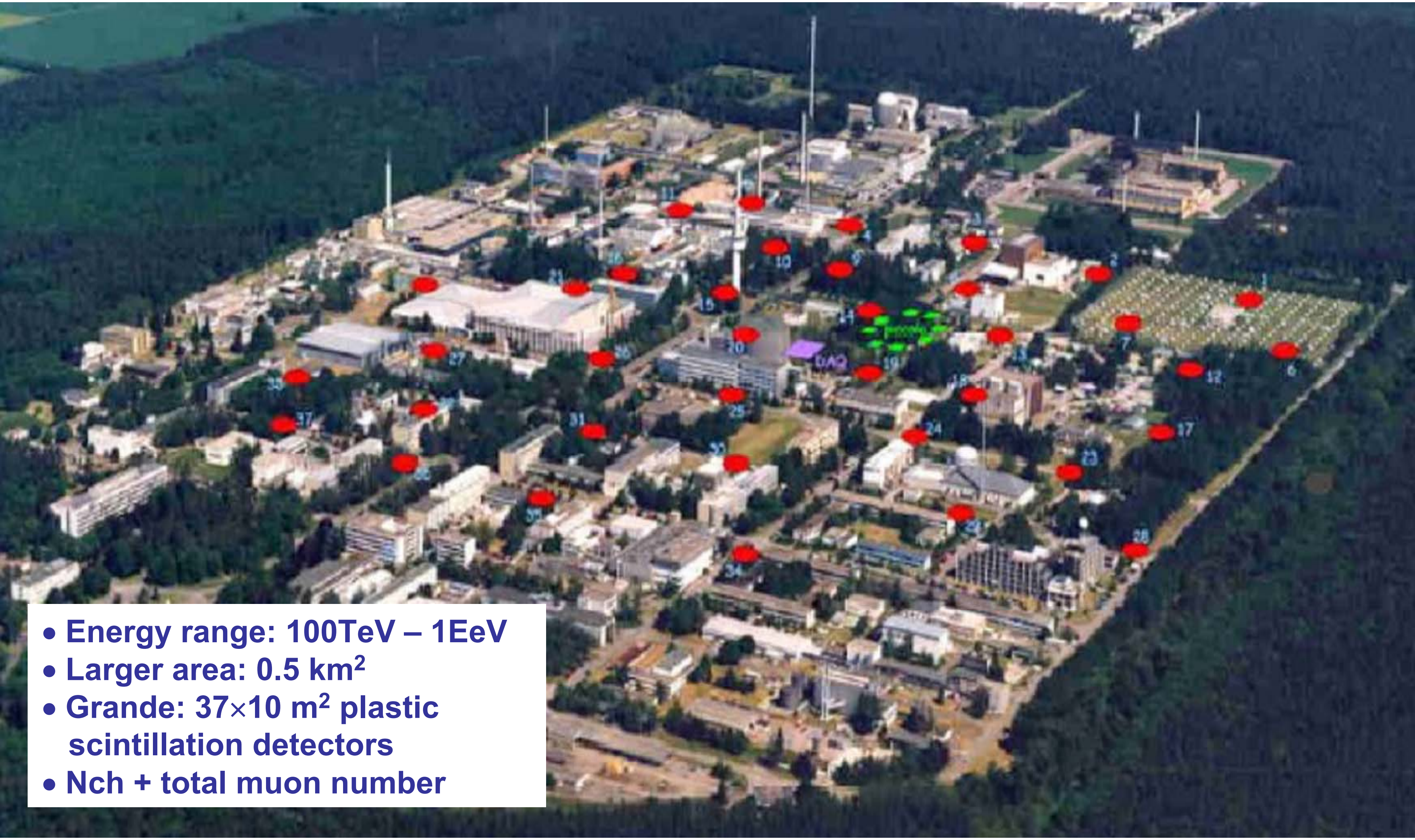


➔ Sharp bump close to 10^{17}eV
* probably heavy primary (age distribution)
* local origin (sharpness)

Planned enhancement:
μ-detectors from 150m² to 250m² using scintillation detectors and Geiger counters

GAMMA coll., J.Phys. G: Nucl. Part. Phys. 35 (2008) 115201

KASCADE-Grande

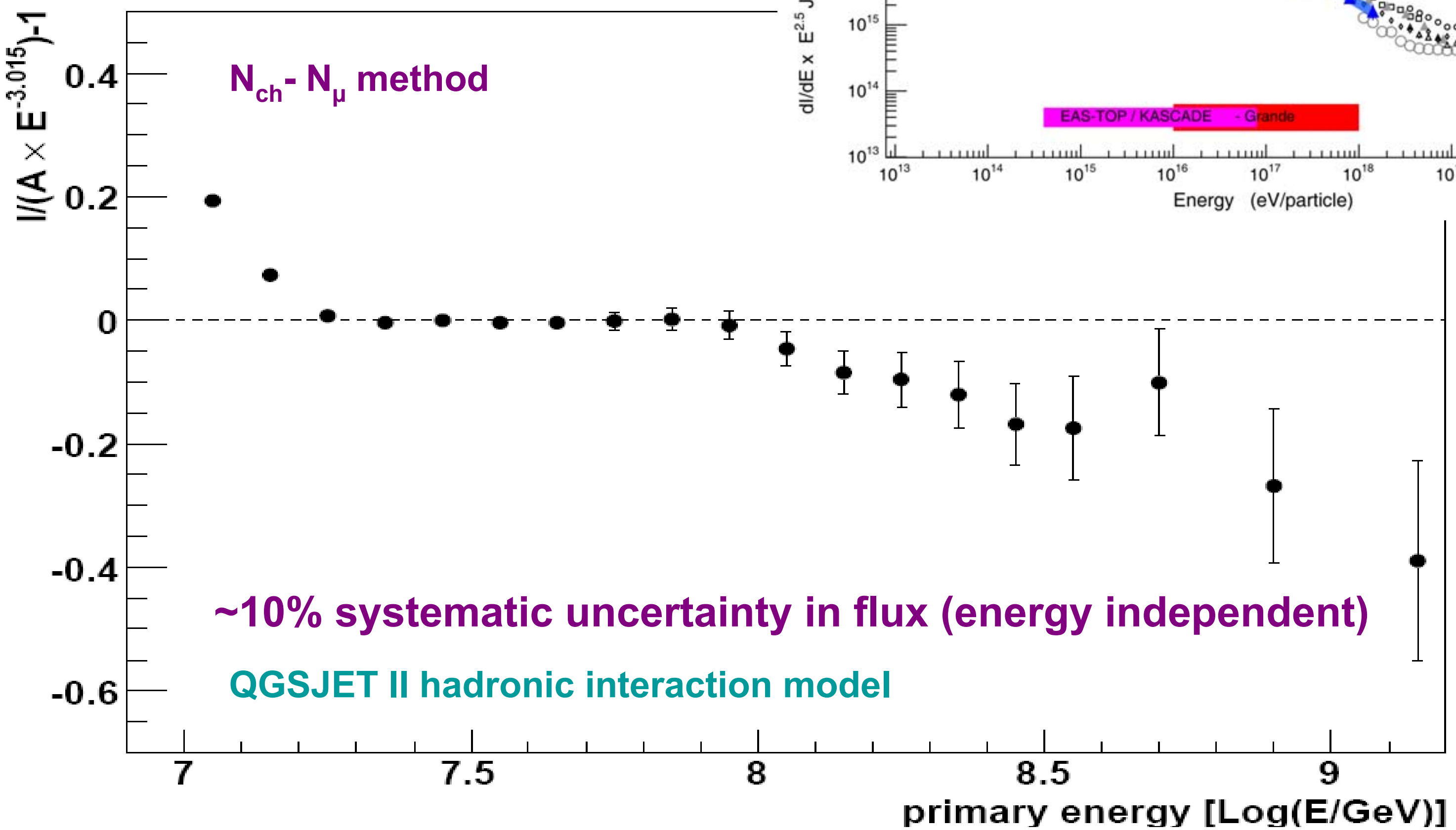


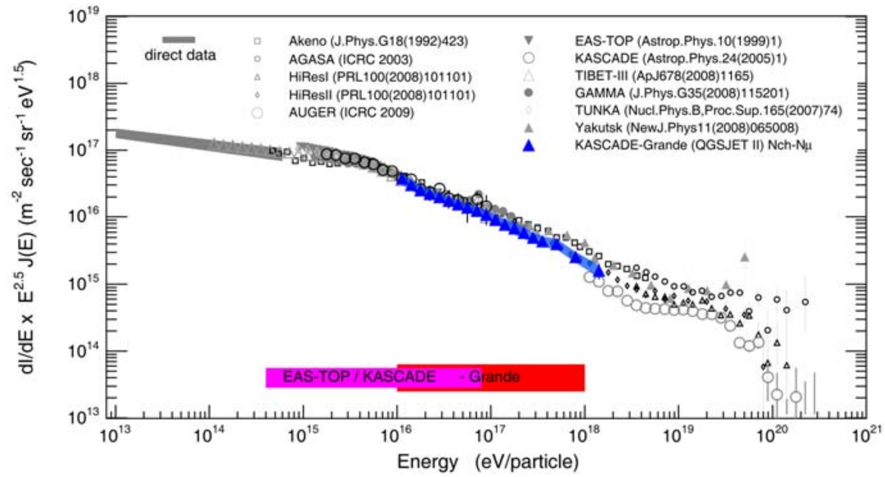
- Energy range: 100TeV – 1EeV
- Larger area: 0.5 km^2
- Grande: 37×10 m^2 plastic scintillation detectors
- Nch + total muon number

W.D.Apel et al, Nucl.Instr. and Meth. A620 (2010) 202

KASCADE-Grande

all-particle energy spectrum



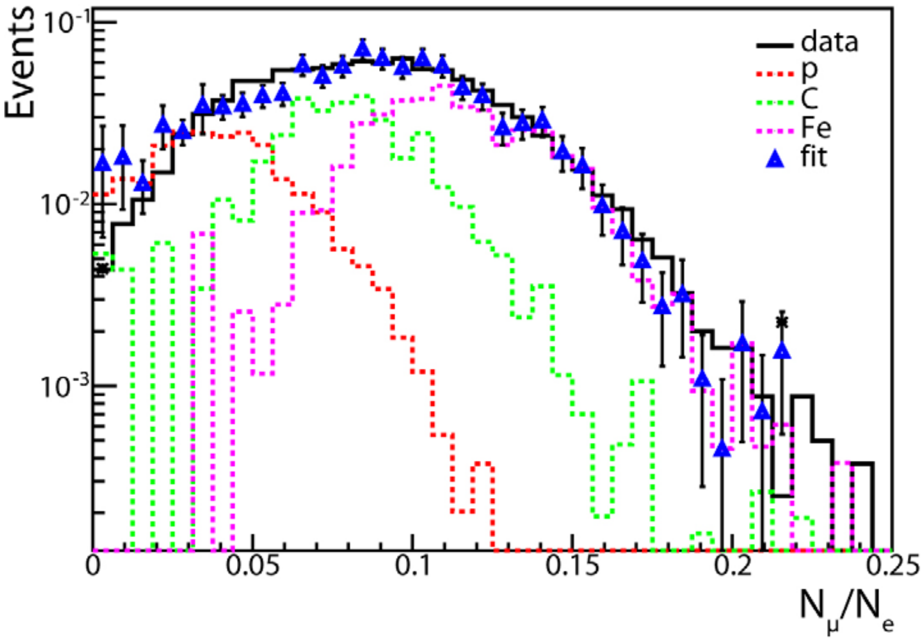


- spectrum not describable by a single power law at 10^{16}-10^{18}eV
- hardening of the spectrum above 10^{16}eV
- small, but significant steepening close 10^{17}eV

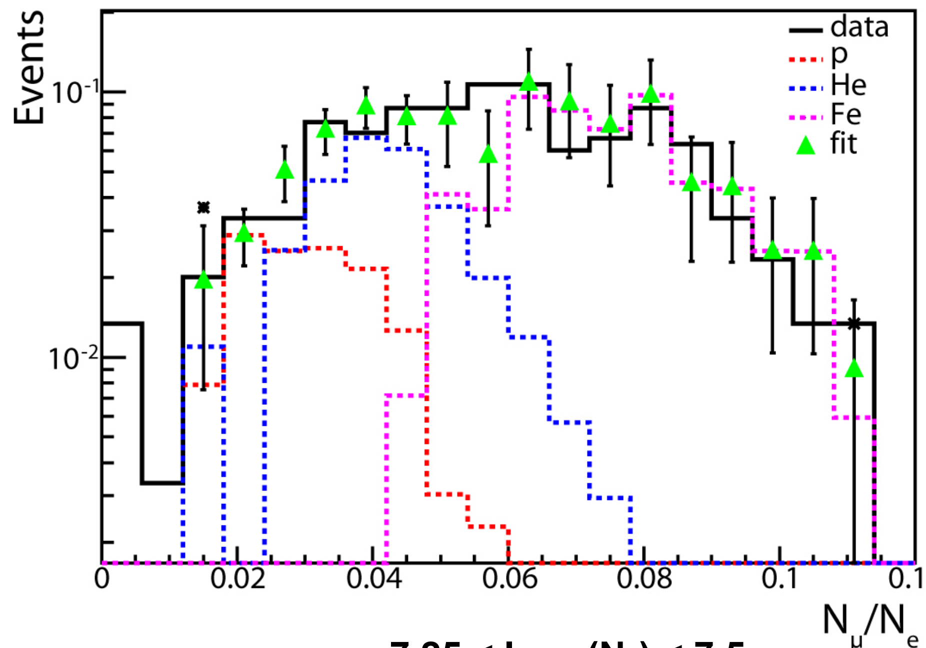
M.Bertaina et al, ECRS 2010

KASCADE-Grande composition: N_μ / N_e-ratio

QGSJET II hadronic interaction model



$6.5 < \log_{10}(N_e) < 6.75$



$7.25 < \log_{10}(N_e) < 7.5$

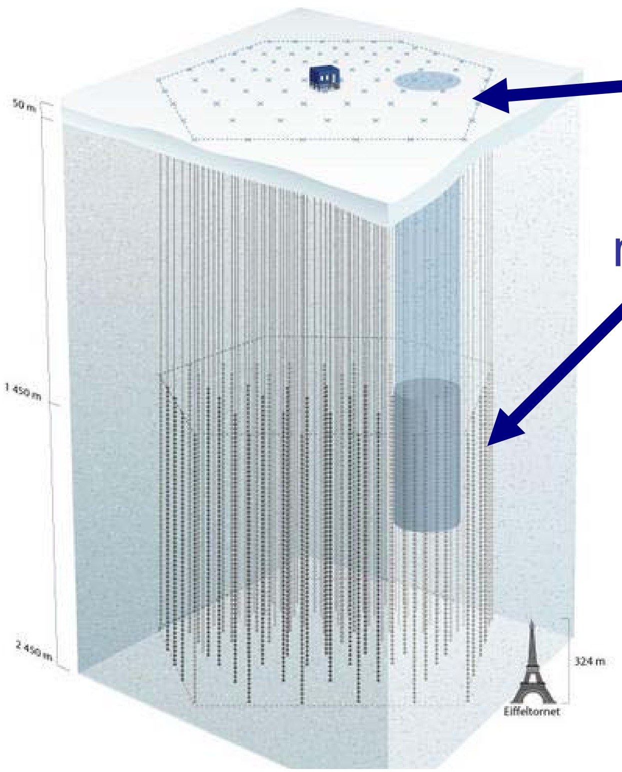
- shower size ratio: investigation of mean and rms

➔ rms of simulated distributions less model dependent than mean

➔ composition: more than 2 components needed at 10^{17}eV

KASCADE-Grande collaboration (E. Cantoni), ICRC 09

IceTop/IceCube



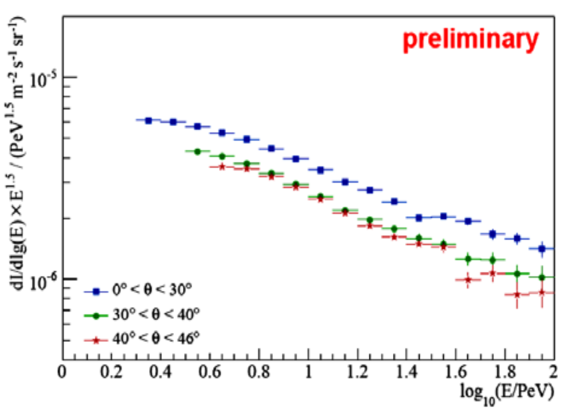
size N_e

muon N_μ

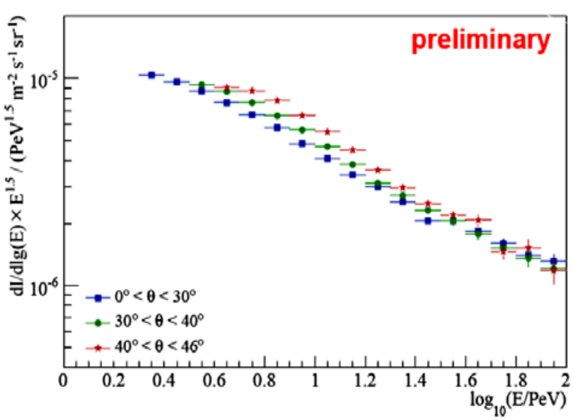
- 2835m altitude
- 80 detector stations / 2 tanks each
- Ice-Cherenkov tanks, area 1 km^2
- Energy range from 2×10^{15} to 10^{17}eV

➔ **Composition sensitive zenith behavior**

PROTON



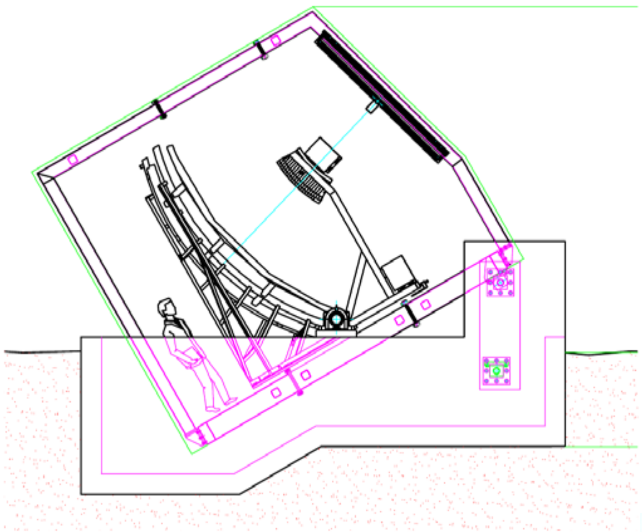
IRON



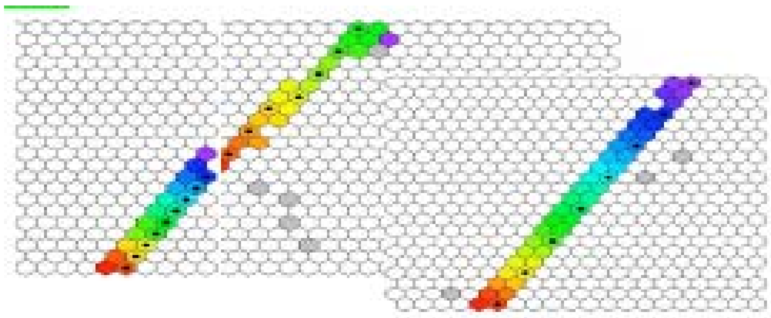
- In future combination with muon information from IceCube

Serap Tilav, ISVHECRI 2010

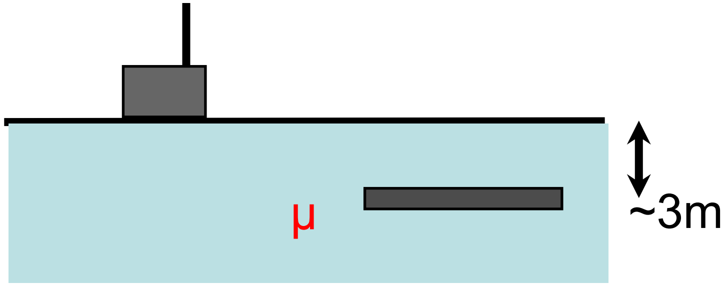
HEAT: High Elevation Auger Telescopes



- 3 ``standard´´ Auger telescopes tilted to cover 30 - 60° elevation
- Sensitivity down to 10^{17}eV

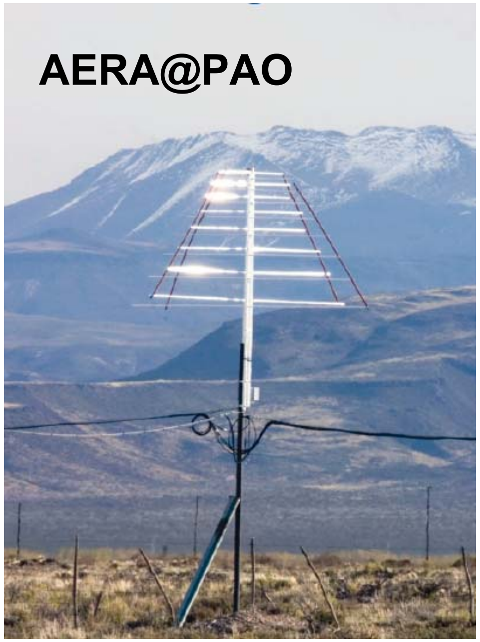


- Also: Infill + AMIGA
  42 additional tanks, 85 μ-detectors



M.Kleifges-Auger Collaboration, ICRC09

EAS Radio detection



- new detection technique $E_{threshold} \approx 10^{17}$eV
- successful and sensitiv to
  - primary energy $\varepsilon \sim E_0^{\gamma}$ ($\gamma \approx 1$) $\Delta E/E \sim 20$-25%
  - arrival direction beam forming resolution better 1^o
  - composition LDF-slope $\Delta A/A$ still unknown

- still many question open to emission mechanism(s)

→ ***suitable for hybrid measurements !***

or stand-alone technique?

Experimental Summary

Below 10^{15} eV :

- p,He shows hardening, He becomes dominant — CREAM
- future: higher energies + heavier particles — CREAM, TIGER, TRACER, …
- anisotropies found (10-20TeV) — Milagro, ARGO, ICECube

Knee region - 10^{15} eV - 10^{16} eV :

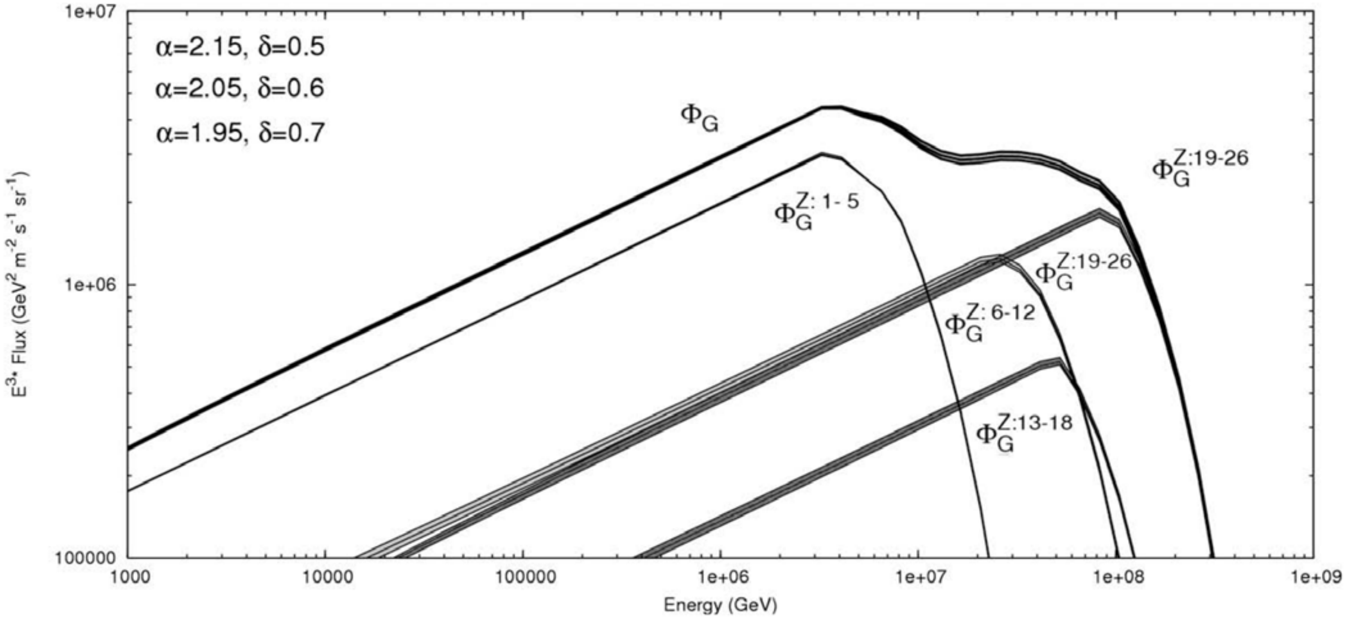
- Knee caused by cut-off for light elements — KASCADE, GRAPES, TIBET
- Proton spectra agree with direct measurements — KASCADE, GRAPES, TIBET
- sharp knee — TIBET, TUNKA
- rigidity dependence of knees — KASCADE, TIBET
- Relative abundancies depend strongly on high energy interaction model
- future: EAS extensions and accelerators — TIBET, GRAPES, LHC, SPS

Transition region 10^{16} eV - 10^{18} eV :

- hardening at 10 PeV — KASCADE-Grande
- steepening at 80 PeV ($=Z \cdot E_{knee}^{proton}$) — KASCADE-Grande
- bump at 80 PeV — GAMMA
- second knee? — Akeno, Hires-Mia
- future experiments: — ICETOP, TUNKA, PAO-Enhancements, Radio, TALE

Comparing data with astrophysical models - I

Simple rigidity dependence: galactic diffuse spectrum from SNR

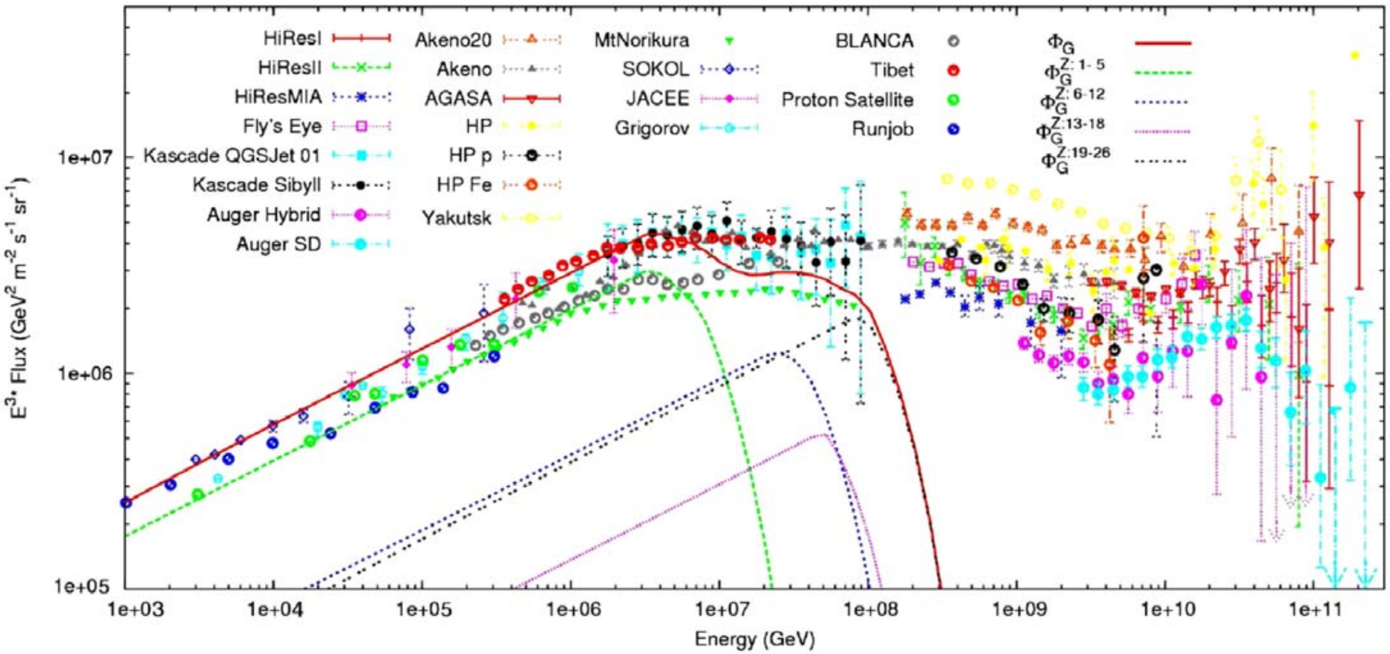


- **Knee by sharp cut-off of light elements!**
- **At knee: He or p dominant, >10^{16}eV heavy dominant!**
- **Hardening at 10^{16}eV!**
- **Sharpness of knee?**
- **What adds above 10^{17}eV?**

C. De Donato, G.A. Medina-Tanco, Astrop. Phys. 32 (2009) 253.

Comparing data with astrophysical models - I

Simple rigidity dependence: galactic diffuse spectrum from SNR



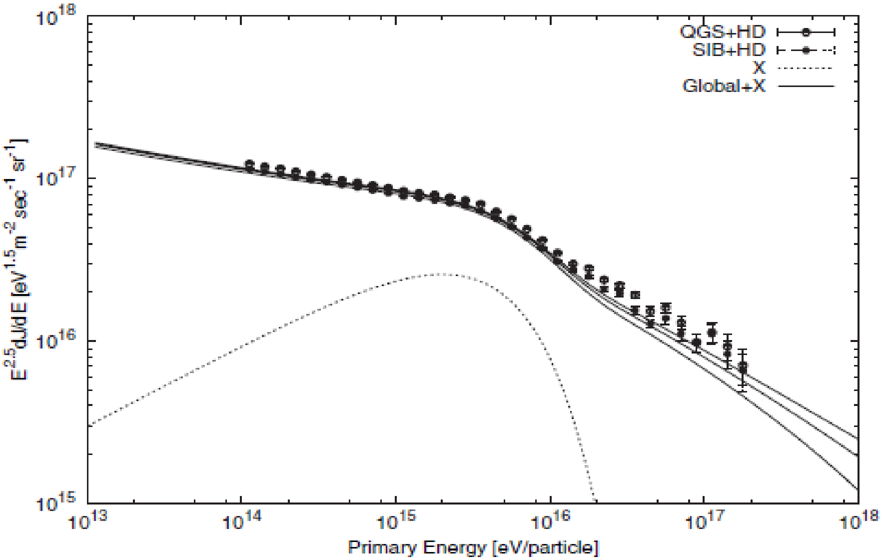
- Knee by sharp cut-off of light elements!
- At knee: He or p dominant, $>10^{16}$eV heavy dominant!
- Hardening at 10^{16}eV!
- Sharpness of knee?
- What adds above 10^{17}eV?

C. De Donato, G.A. Medina-Tanco, Astrop. Phys. 32 (2009) 253.

Comparing data with astrophysical models - II

Modifications to obtain a sharp knee

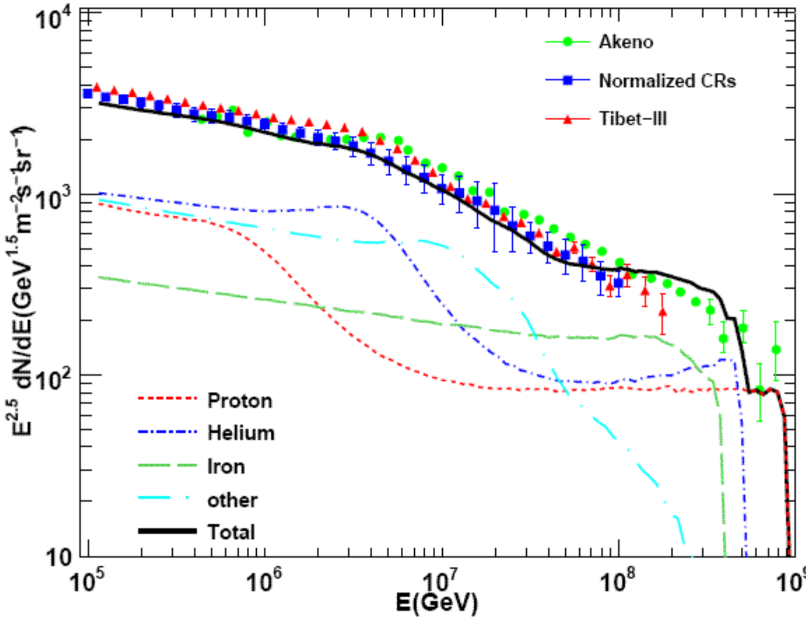
including single source at knee



- •Makes knee sharp
- •Need helium or medium primary
- •Makes hardening at 10^{16}eV weaker
- •What adds above 10^{17}eV?

Erlykin&Wolfendale, J.Phys.G 31(2005)675
Shibata et al., ApJ ,716: 1076 (2010)

nonlinear acceleration effects at SNe shock fronts



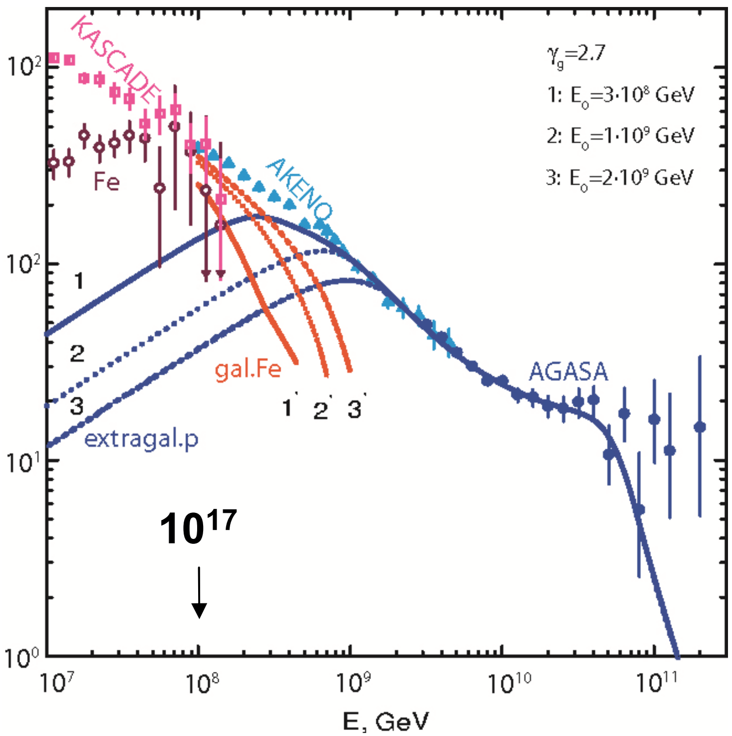
- •Makes knee sharper
- •Helium dominant at knee
- •heavy dominant above knee
- •Makes hardening at 10^{17}eV?

Shibata et al., ApJ ,716: 1076-1083 (2010)
Malkov & Drury 2001; Ptuskin & Zirakashvili 2006

Comparing data with astrophysical models - III

Explaining spectrum around 10^{17}eV

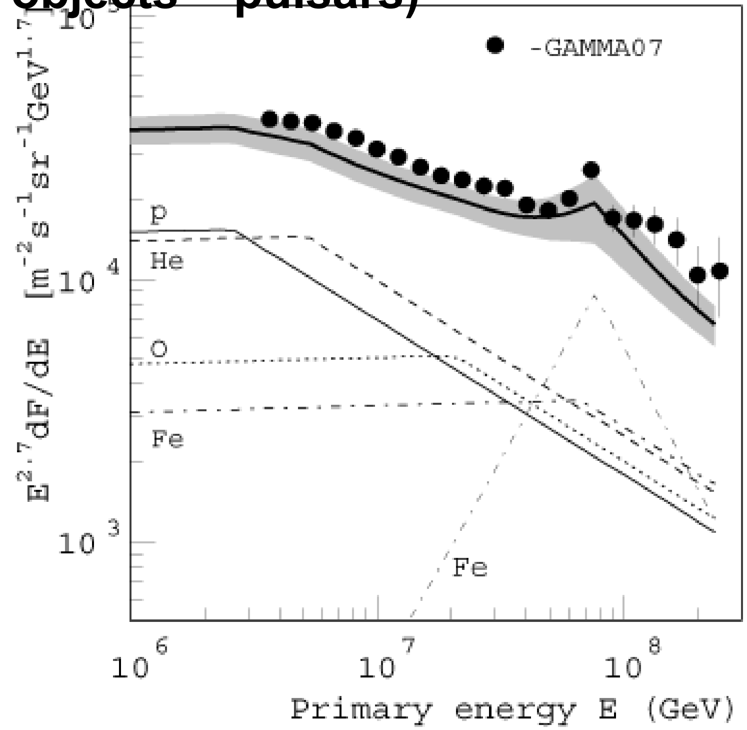
Simple transition from rigidity galactic to proton extragalactic



- **Rigidity knee**
- **Requires 2nd knee?**
- **At 10^{17}eV only proton and iron?**

V.Berezinsky, astro-ph/0403477

Single source at higher energies (e.g. iron component from compact objects = pulsars)

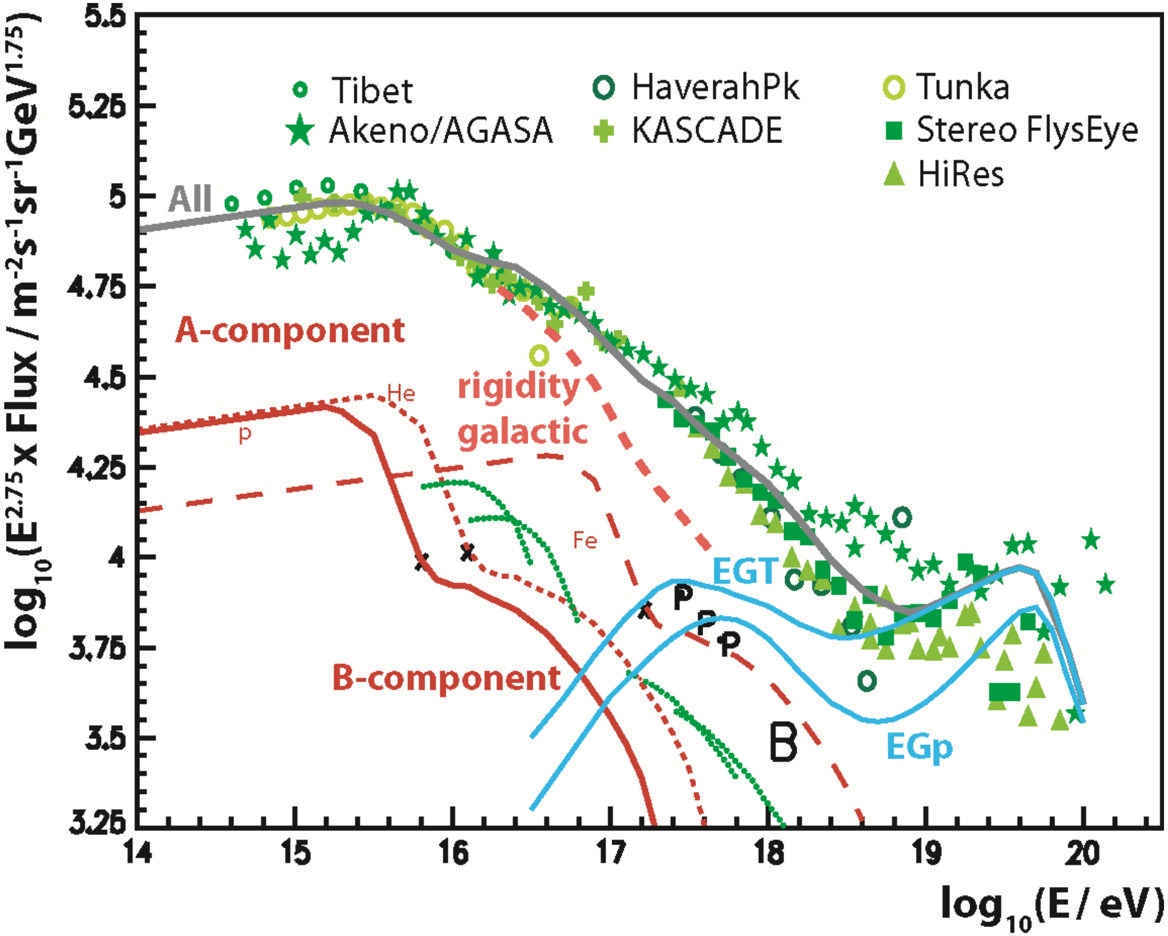


- **Bump at 10^{17}eV**
- **Iron dominant at 10^{17}eV?**

GAMMA coll., J.Phys. G: Nucl. Part. Phys. 35 (2008) 115201

Comparing data with astrophysical models - IV

Inclusion of a galactic component B

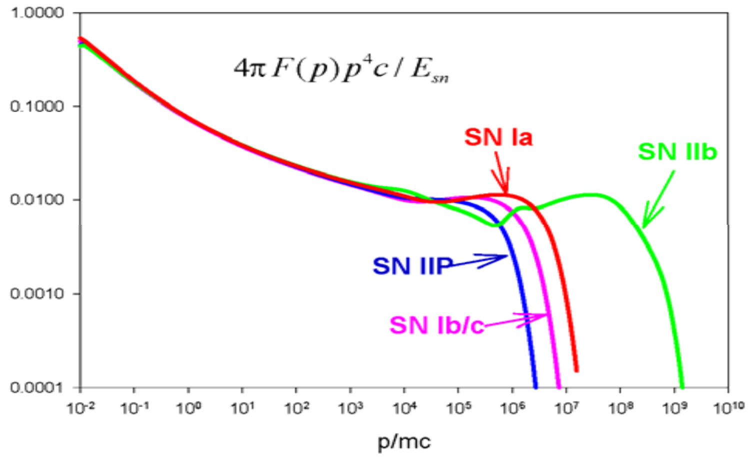


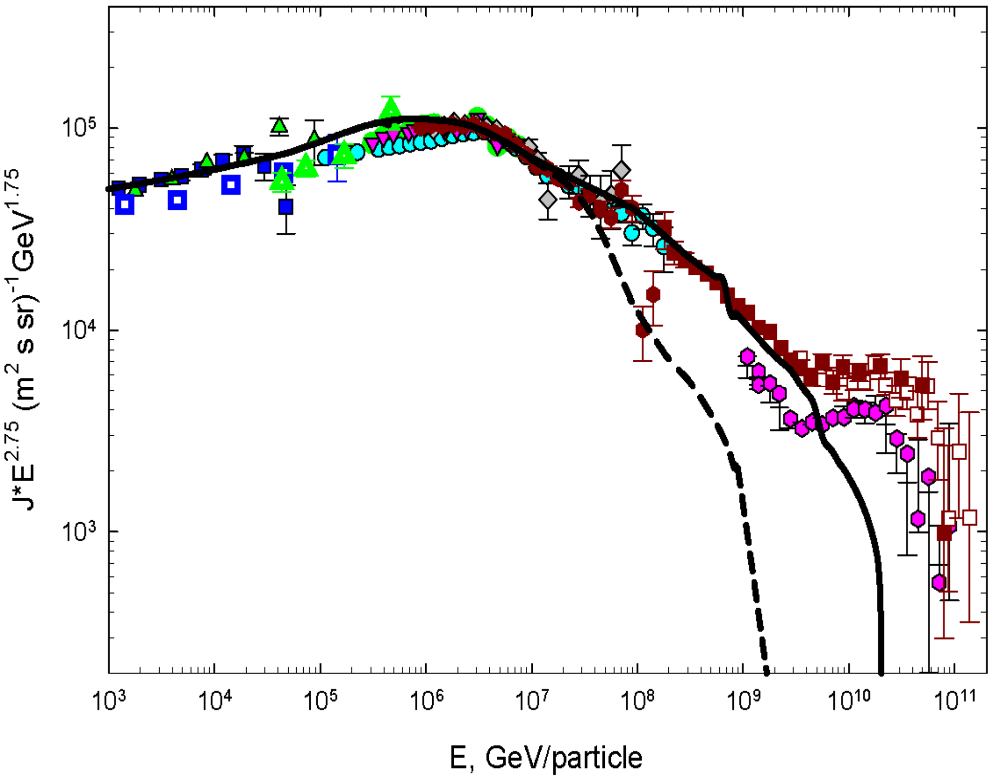
- Light dominance at knee
- Helium at knee
- Rigidity dependent knees
- Hardening at 10^{16}eV
- Weak iron knee at 10^{17}eV
- Mixed composition around 10^{17}eV
- Sharp knee?
- No Bump?
- What is component B?

A.M.Hillas, J. Phys. G: Nucl. Part. Phys. 31 (2005) R95

Comparing data with astrophysical models - IV

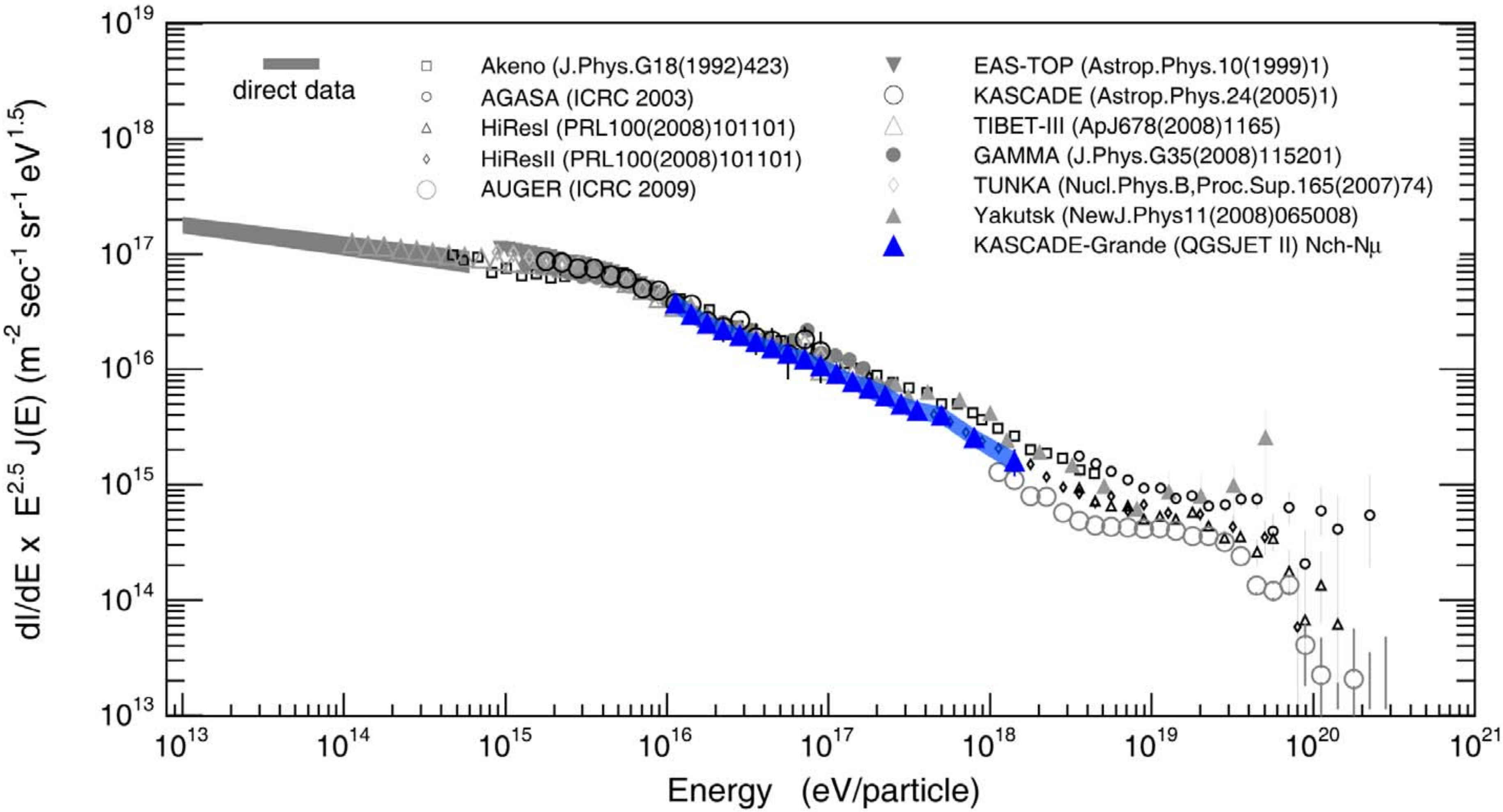
Example for possible component B:
Different types of Supernovae!





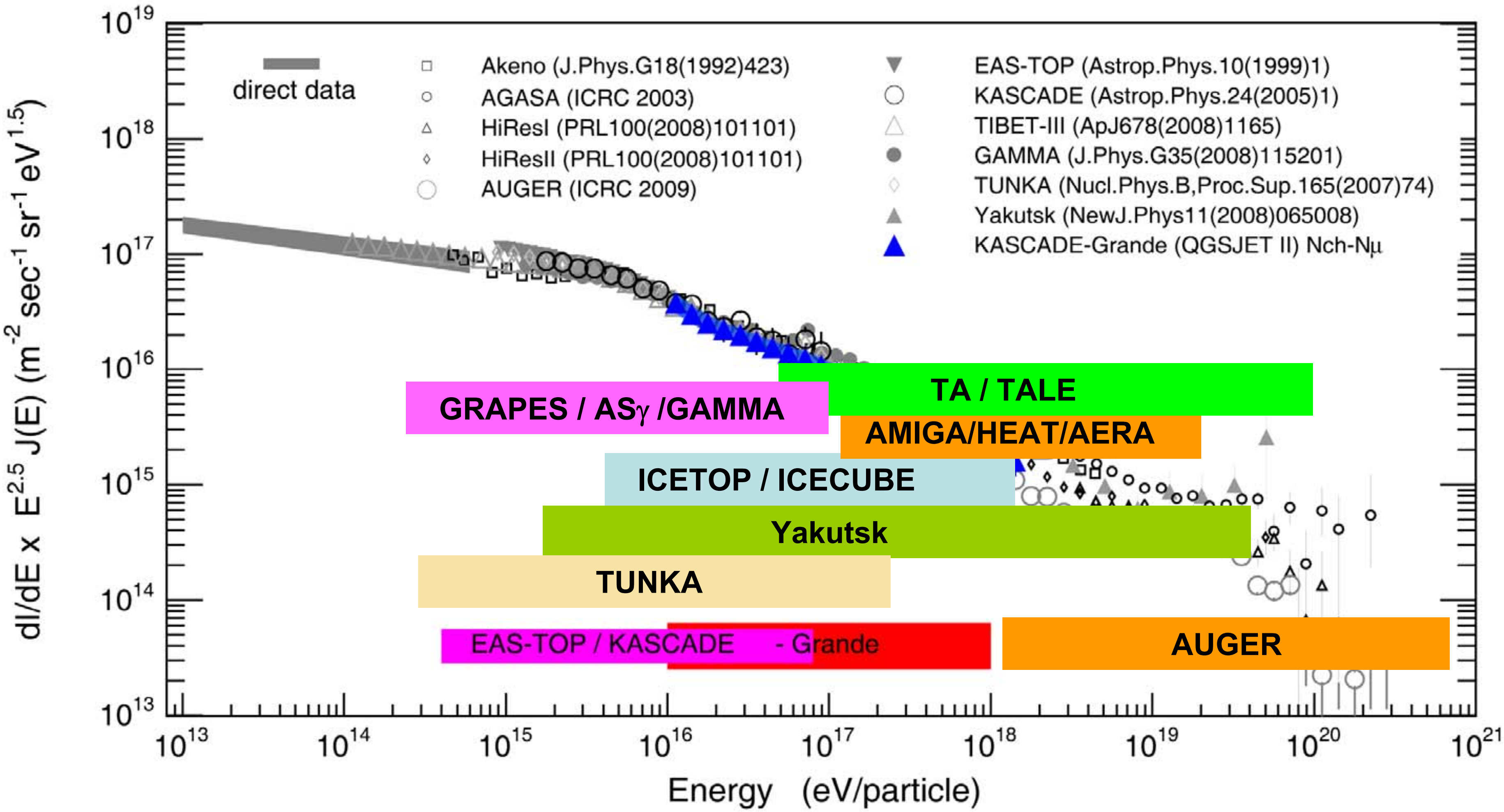
V. Ptuskin et al., Astrophysical Journal 718 (2010) 31.

Summary



Last decade: deeper insight into the spectrum….
….more to come:

Summary



Cosmic ray physics around the knee: STAY TUNED!

Thank you!

Gianni Navarra
12/9/1945 - 24/8/2009