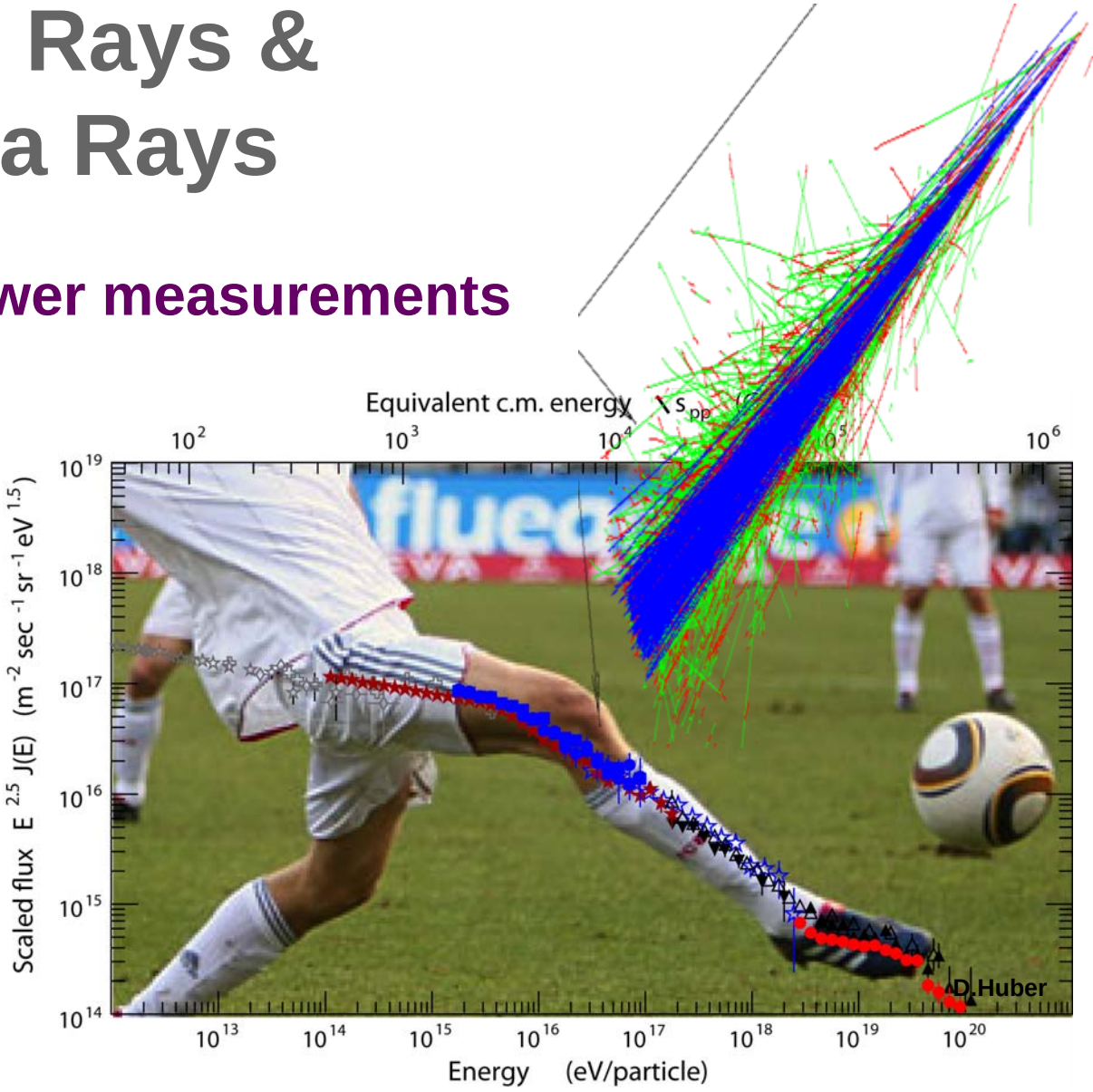
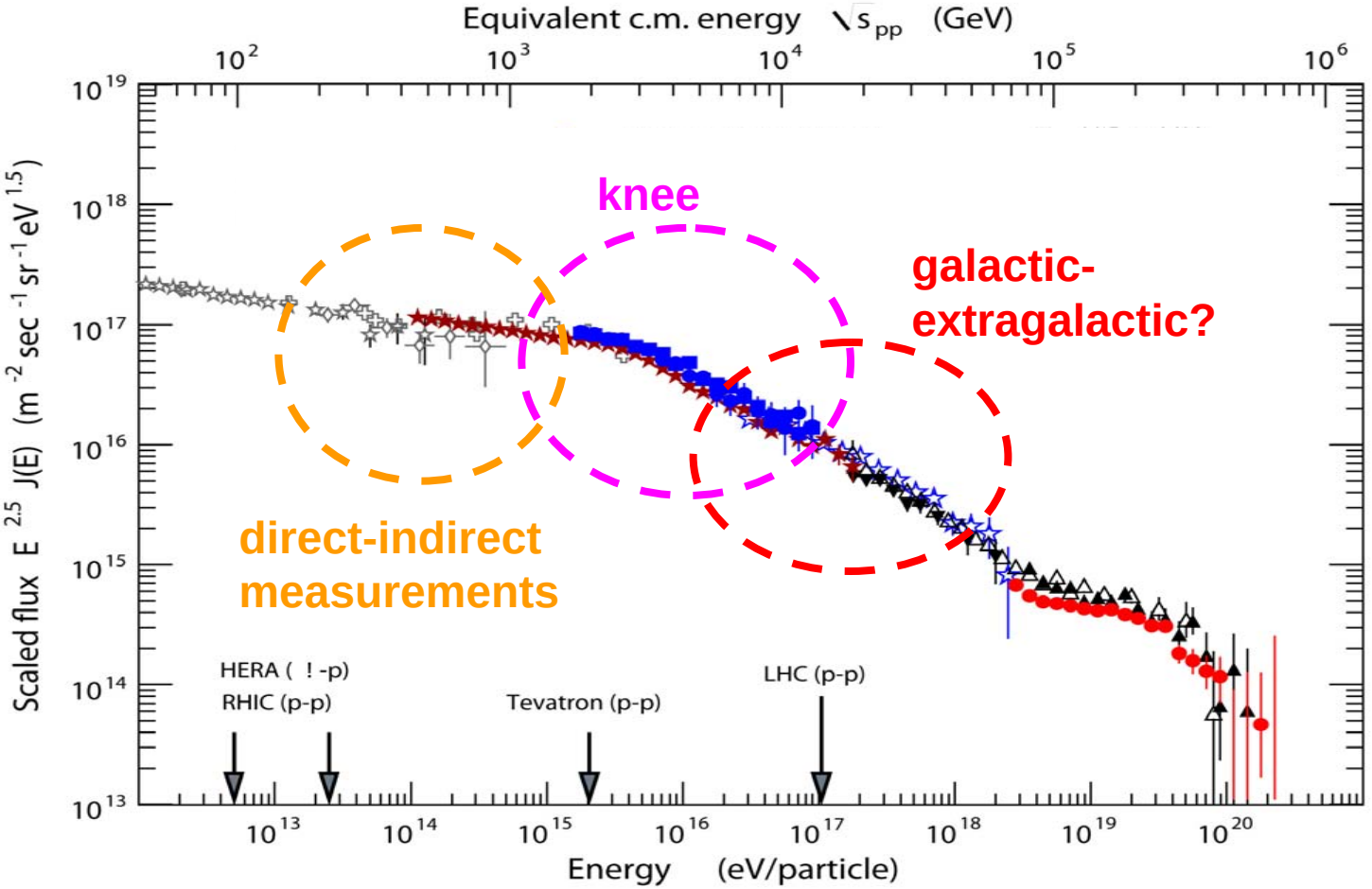
Cosmic Rays & Gamma Rays

via extensive air shower measurements

- CR experiments & CR physics (KASCADE-Grande)
- CR experiments & γ-ray physics
- γ-ray experiments & CR physics
- Synergies & Multi-messenger

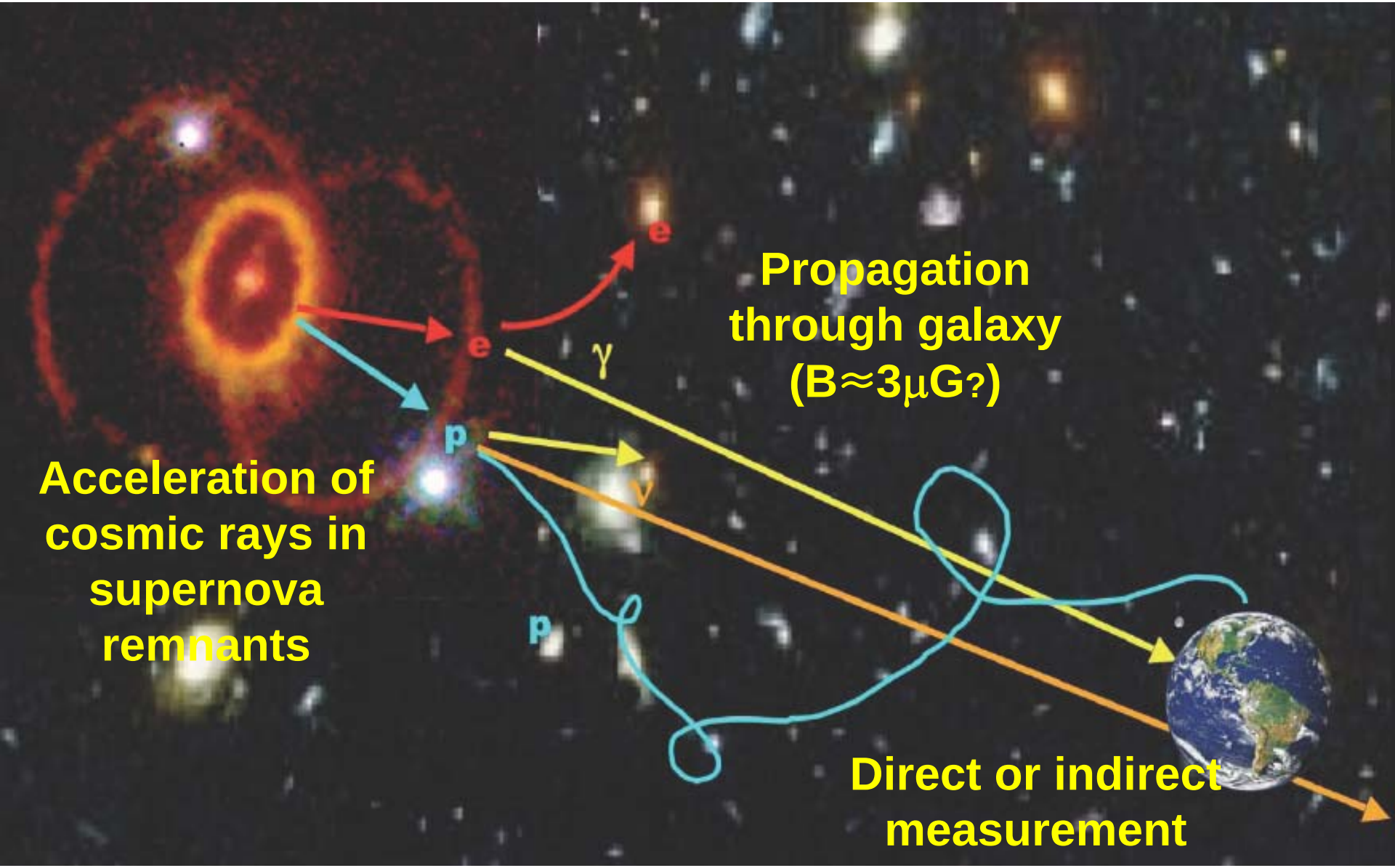


This talk: High-energy galactic(?) cosmic rays



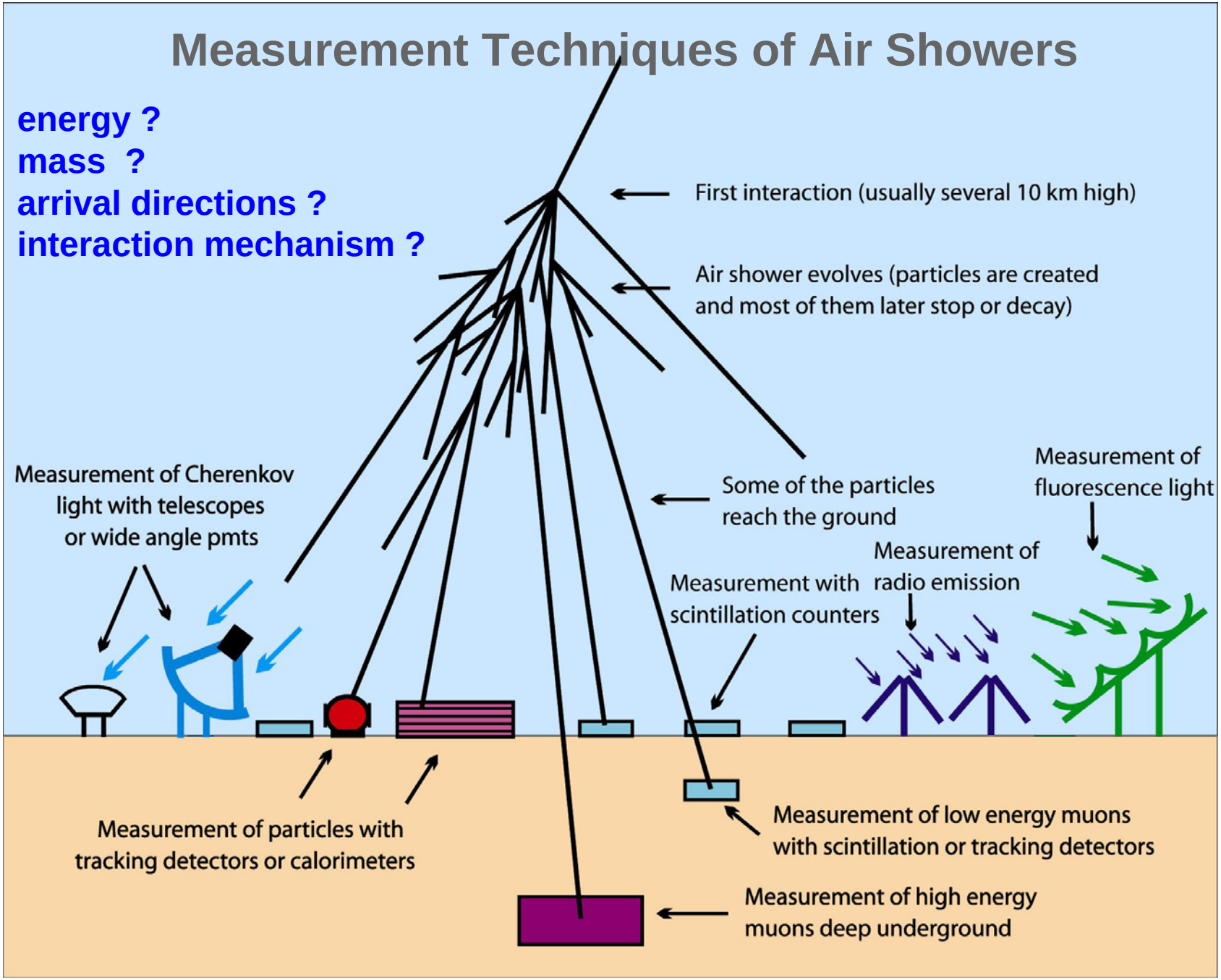
10^{15}-10^{17}eV:	**Origin of the knee?**	**Rigidity dependence?**
10^{16}-10^{18}eV:	**Iron knee (rigidity)?**	**Transition galactic-eg CR?**
10^{13}-10^{15}eV:	**Overlap direct-indirect?**	**γ-rays: are there PeVatrons?**

Galactic cosmic rays: standard picture



Measurement Techniques of Air Showers

energy ?
mass ?
arrival directions ?
interaction mechanism ?



Cosmic Ray Experiments & Cosmic Ray Physics

- **KASCADE**
- **ARGO**
- **KASCADE-Grande**
- **Tunka-133**
- **IceTop**

- **Future: LHAASO, Auger Enhancements, TALE, GRAPES**

- **Not discussing: Highest energy cosmic rays**

  (Pierre Auger Observatory, Telescope Array, Yakutsk, JEM-EUSO, …)

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

25 years KASCADE - Grande

- 49 collaborative papers in reviewed journals (8 still in queue, short author list papers not included)
- 55 PhD thesis
- 86 diploma/master thesis

1992 Proposal
CORSIKA

1996 KASCADE

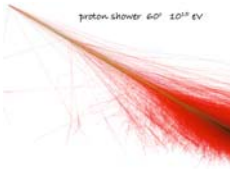
2000 model tests
light knee

2004 KASCADE-Grande
γ limit
(an)isotropy
proof-of-principle radio detection
muon production height
LOPES

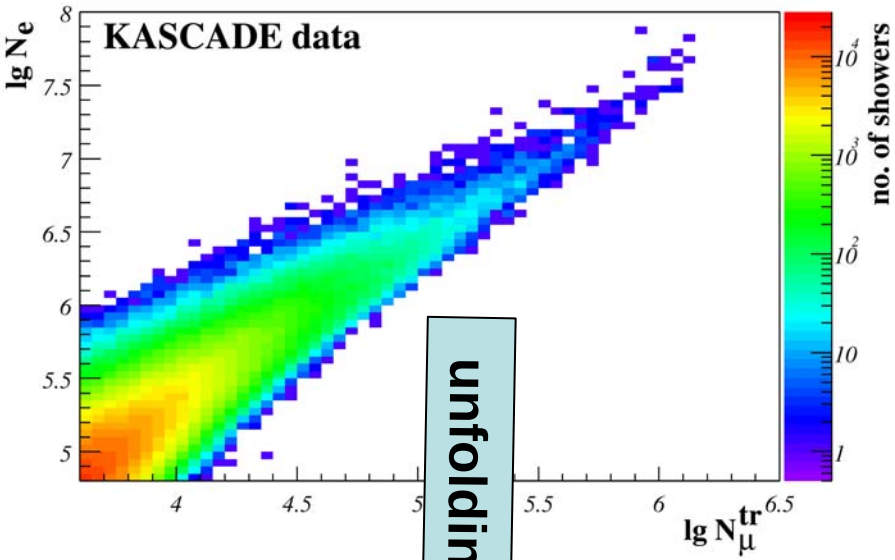
2008 Karlsruhe Air Shower Test Facility
iron knee
CROME
Cosmic Revelation
EAS GHz emission

2012 KCDC
light ankle
Xmax by radio

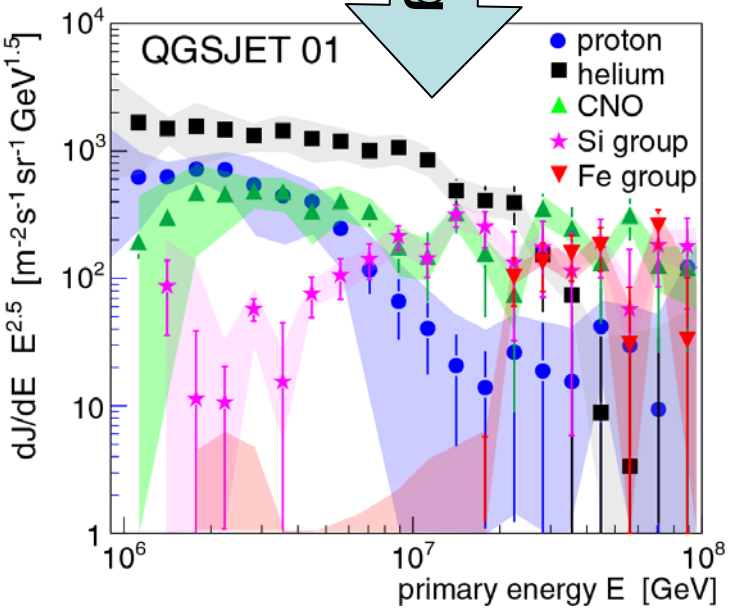
2016

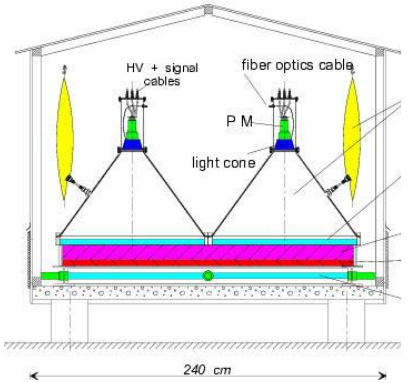


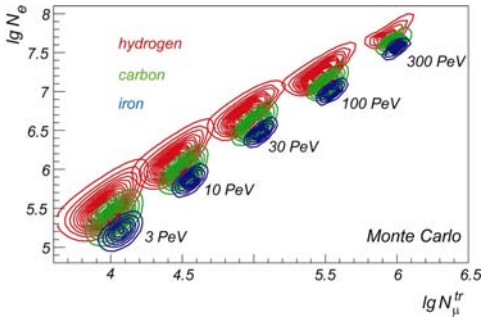
KASCADE : energy spectra of single mass groups



unfolding







Searched:

E and A of the Cosmic Ray Particles

Given:

N_e and N_μ for each single event

➔ solve the inverse problem

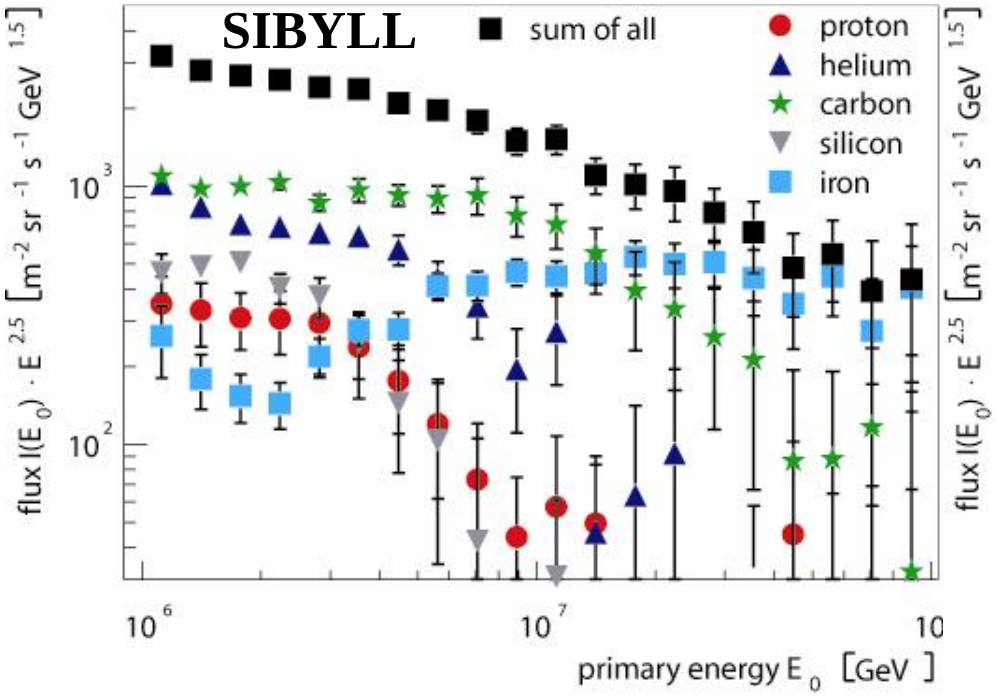
$$\frac{dJ}{d\lg N_e\, d\lg N_\mu^{tr}} = \sum_A \int_{-\infty}^{+\infty} \frac{dJ_A}{d\lg E}\, p_A(\lg N_e, \lg N_\mu^{tr} \mid \lg E)\, d\lg E$$

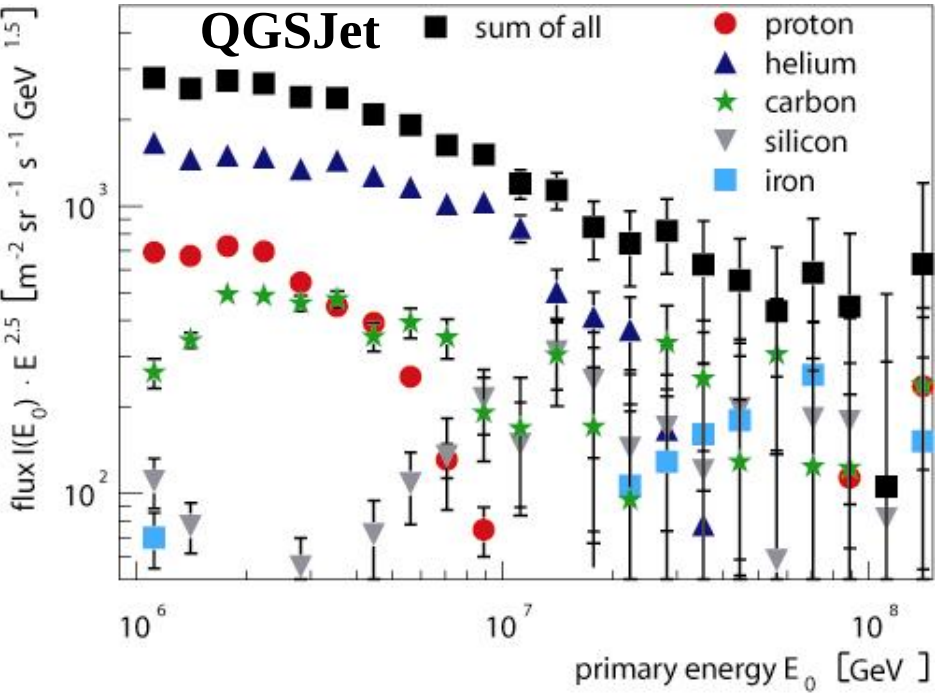
- kernel function obtained by Monte Carlo simulations (CORSIKA)
- contains: shower fluctuations, efficiencies, reconstruction resolution

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

KASCADE results

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





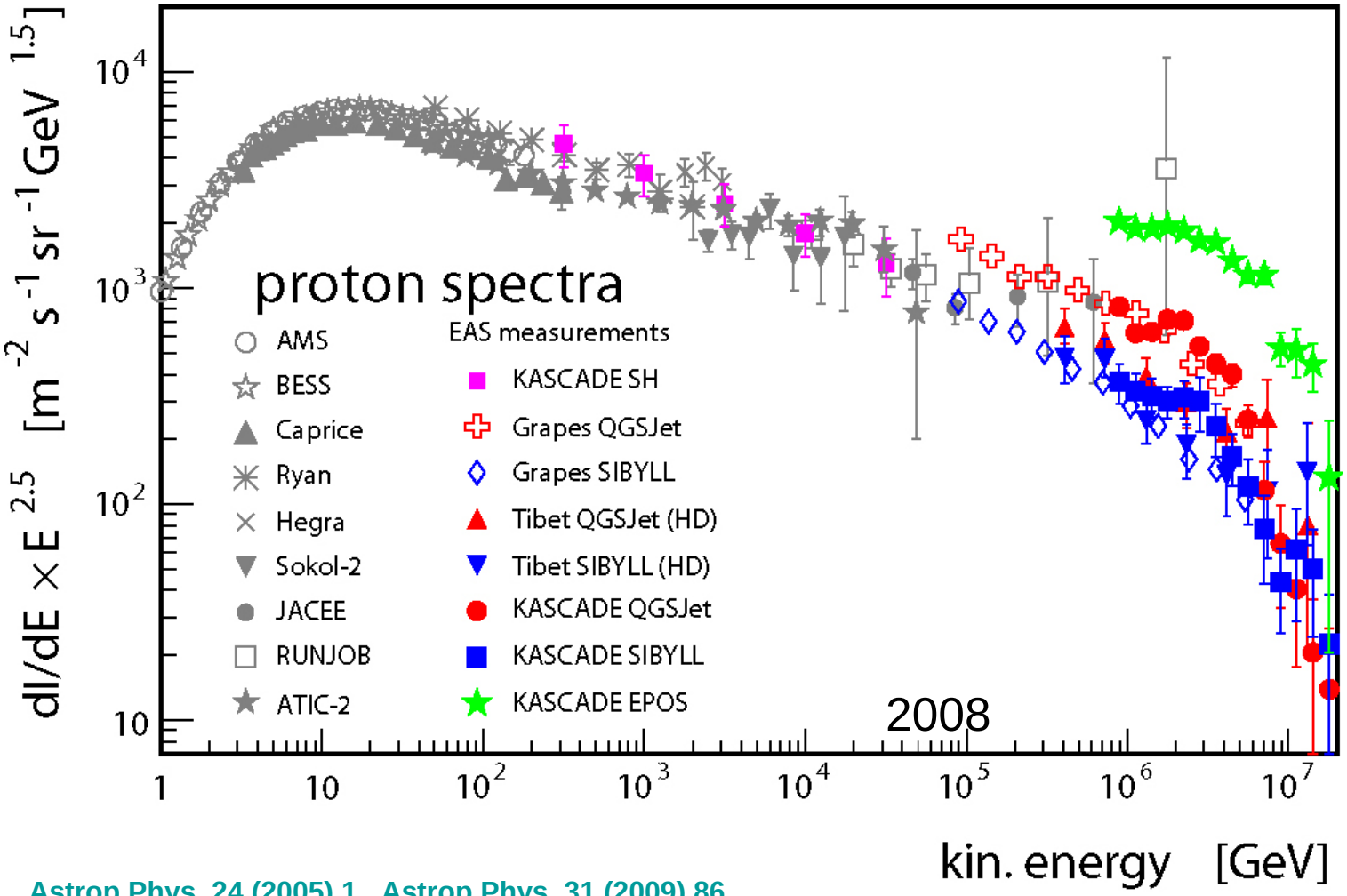
- all-particle spectrum similar
- general structure similar: knee by light component
- relative abundances very different for different high-energy hadronic interaction models

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

observation of a „light“ knee at 2-4·10^{15} eV

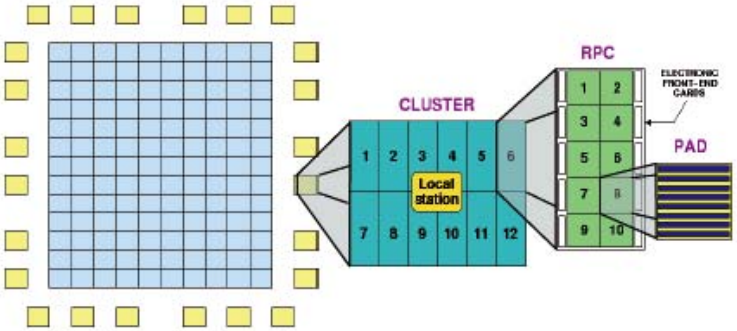
The proton spectrum

- a bit outdated….needs update (new experiments, new hadronic models)



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

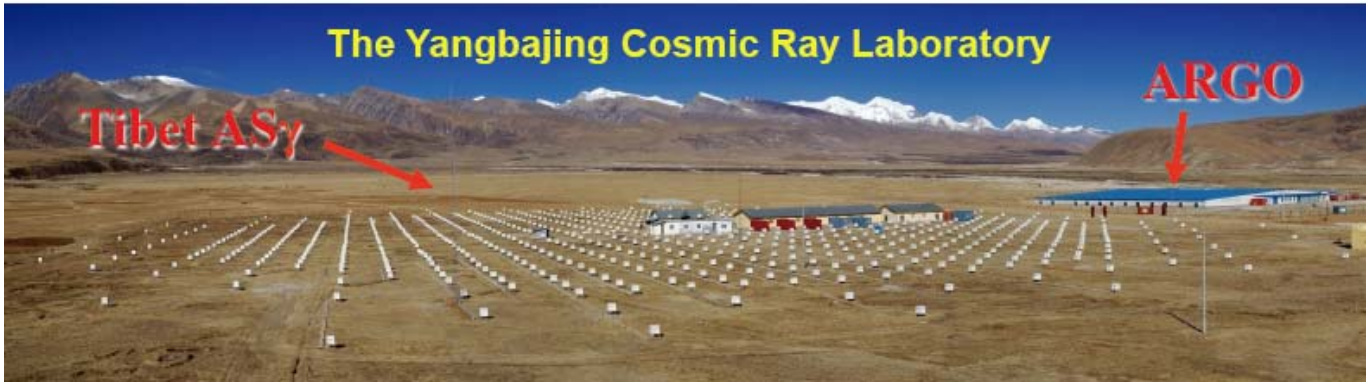
ARGO – YBJ in Tibet

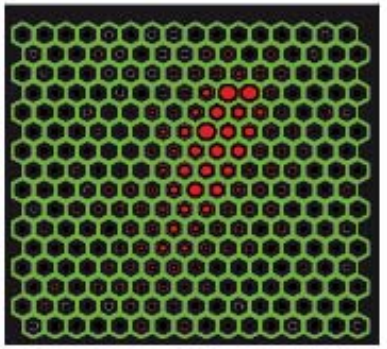


Longitude 90° 31′ 50″ East
Latitude 30° 06′ 38″ North

90 Km North from Lhasa (Tibet)

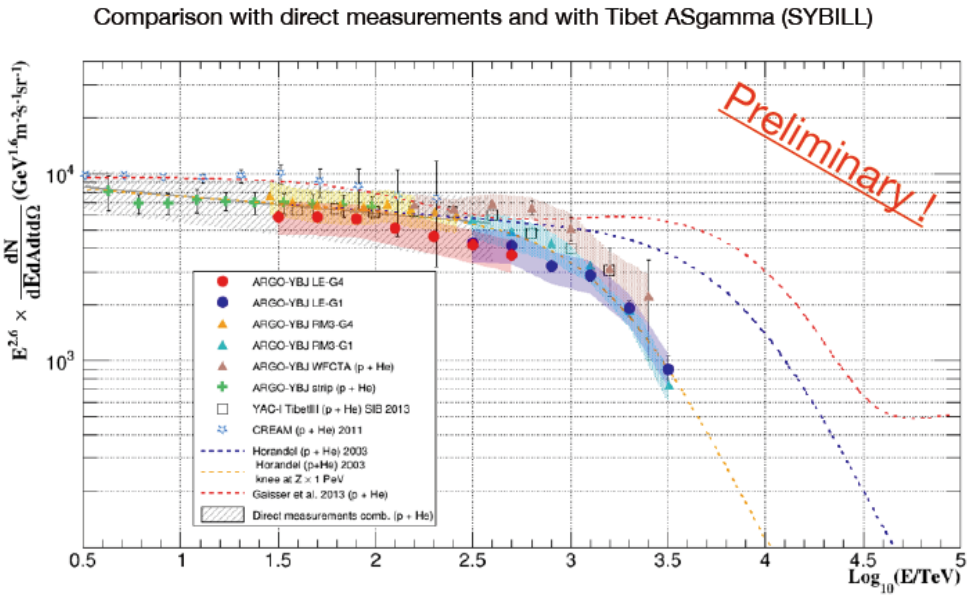
4300 m above the sea level
~ 600 g/cm²

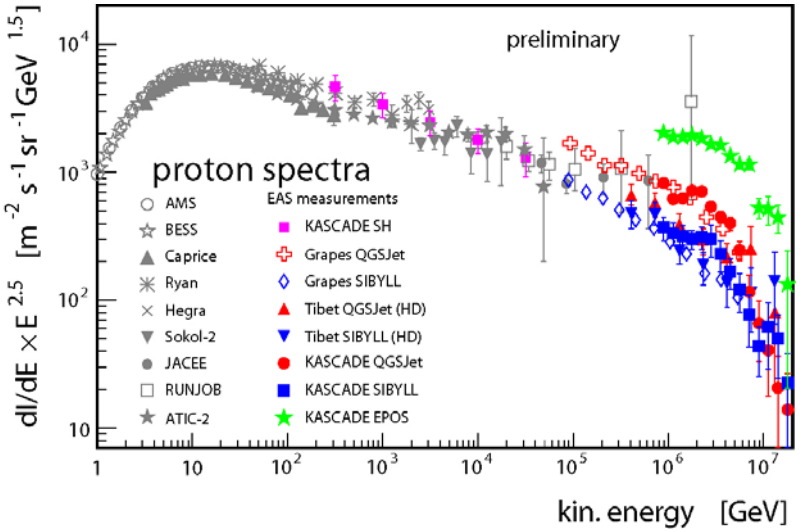




- dense array at high altitude
- Gamma-ray experiment with high sensitivity to low energy EAS
- new: hybrid measurements with a LHAASO prototype WFCTA

ARGO – YBJ in Tibet
spectrum of light primaries

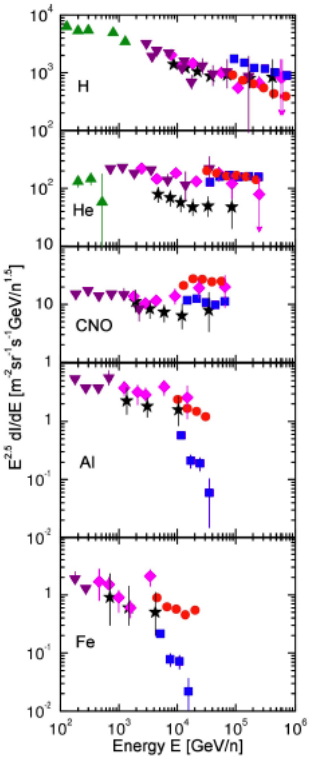




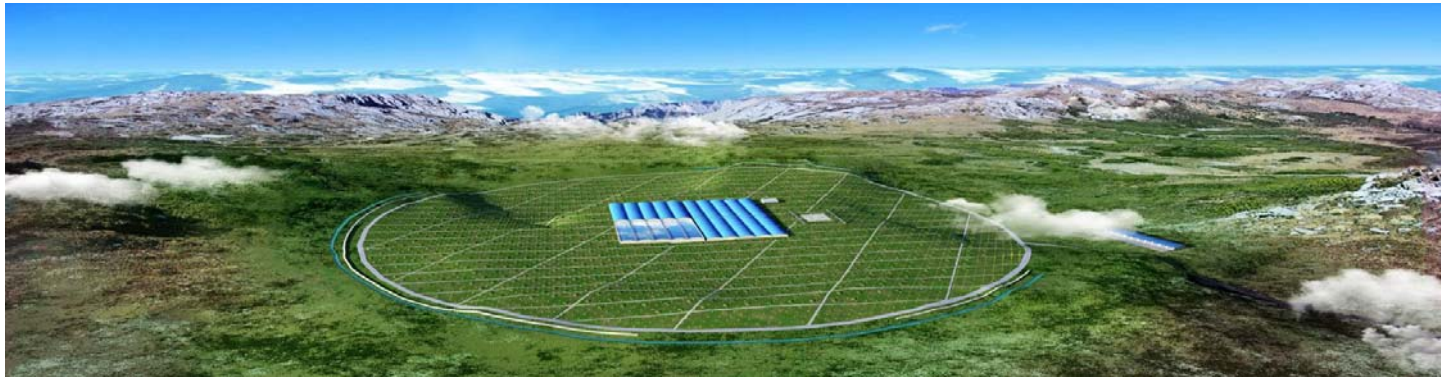
G. Di Scascio, 5th High Altitude workshop, Paris, May 2014

- **new: light spectrum (p+He) below the all-particle knee**
- **different analysis methods applied**
- **further structures in the individual mass group (proton) spectra?**
  or contradiction to KASCADE?

Future CR experiments in the low energy EAS range: GRAPES in India & LHAASO in China



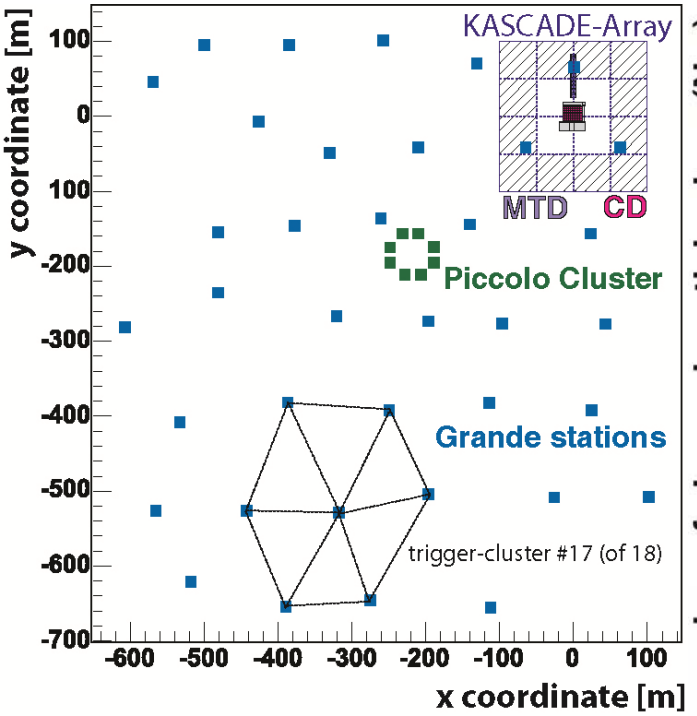
H. Tanaka et al. J. Phys. G: Nucl. Part. Phys. **39** (2012) 025201

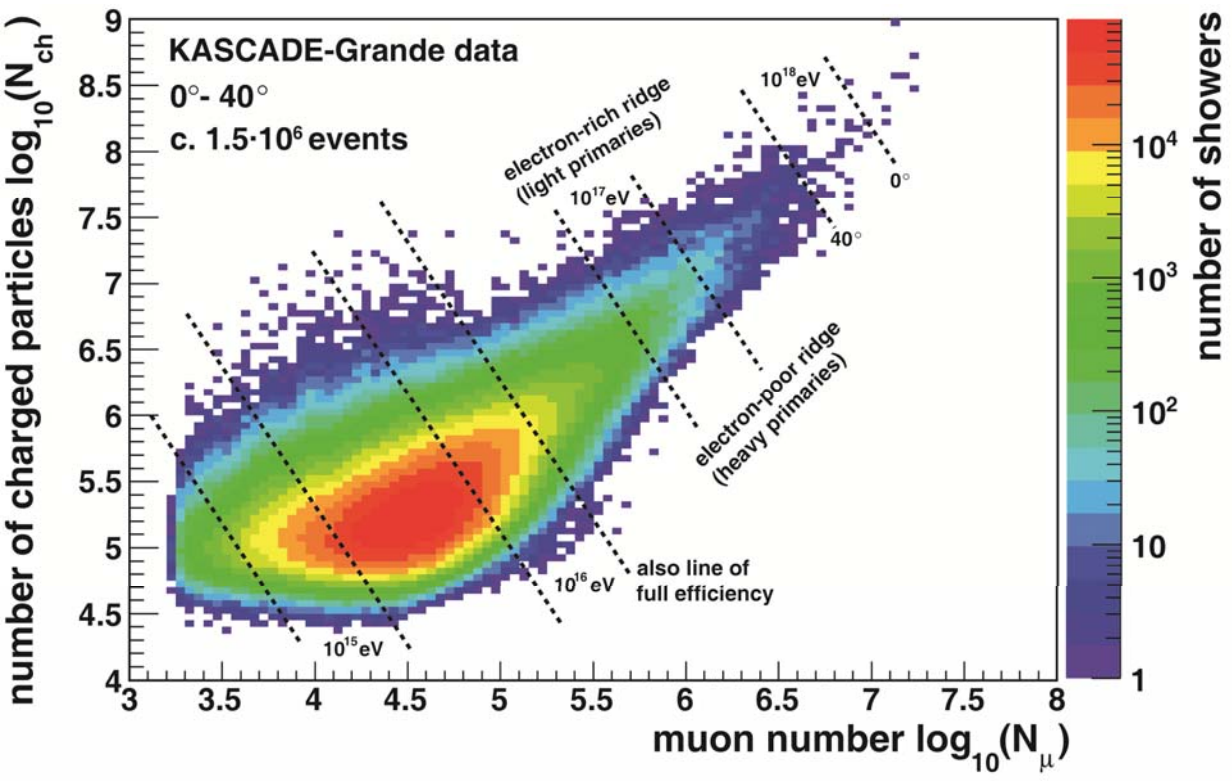


KASCADE-Grande

multi-parameter EAS measurements

KASCADE-Grande: the measurement





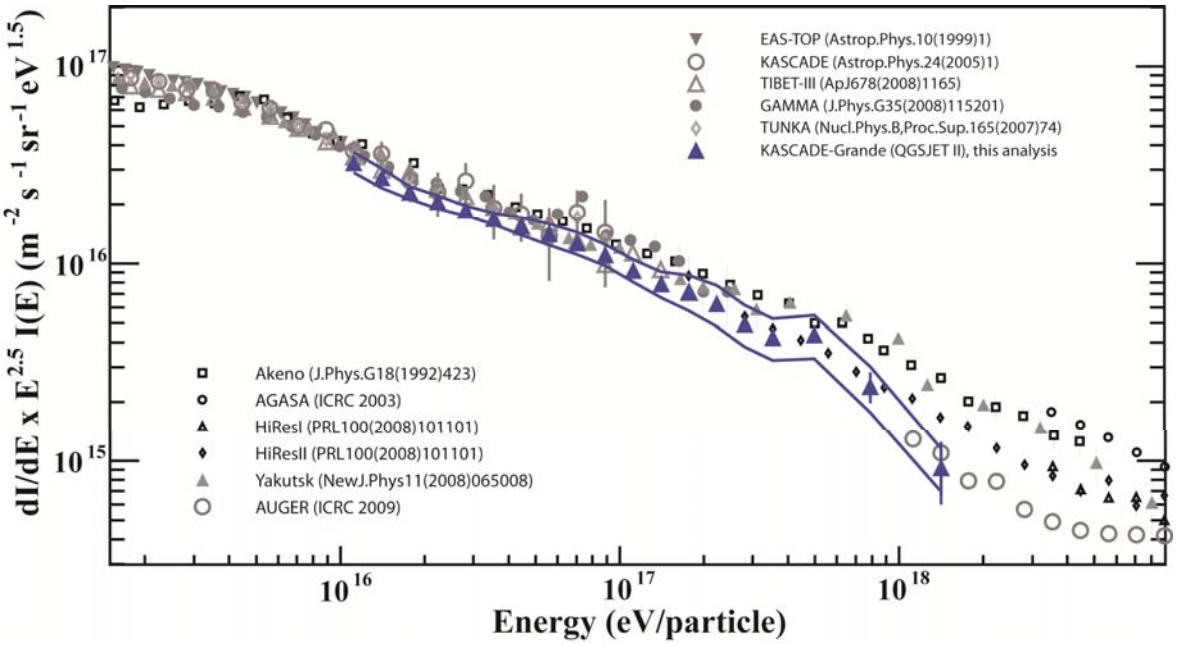
➔ **determination of primary energy**
➔ **separation in “electron-rich” and “electron-poor” event**

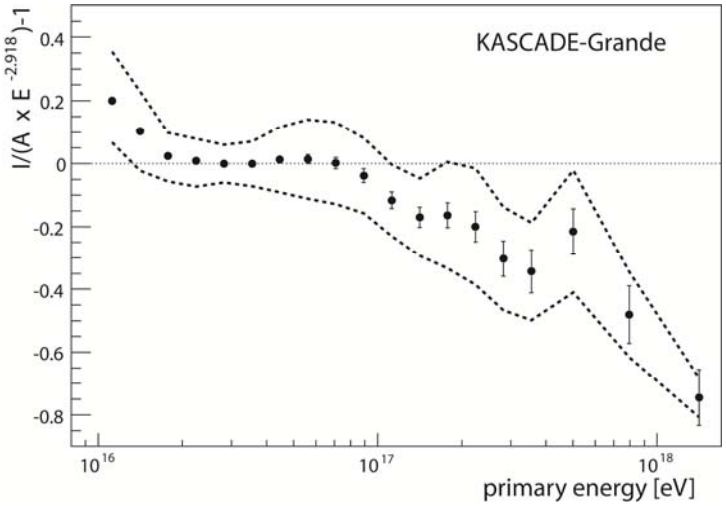
All-particle energy spectrum :

$$\log_{10}(E) = [a_p + (a_{Fe}-a_p)\cdot k] \cdot \log_{10}(N_{ch}) + b_p + (b_{Fe}-b_p)\cdot k$$

$$k = (\log_{10}(N_{ch}/N_\mu) - \log10(N_{ch}/N_\mu)_p) / (\log10(N_{ch}/N_\mu)_{Fe} - \log10(N_{ch}/N_\mu)_p)$$

QGSJET II hadronic interaction model





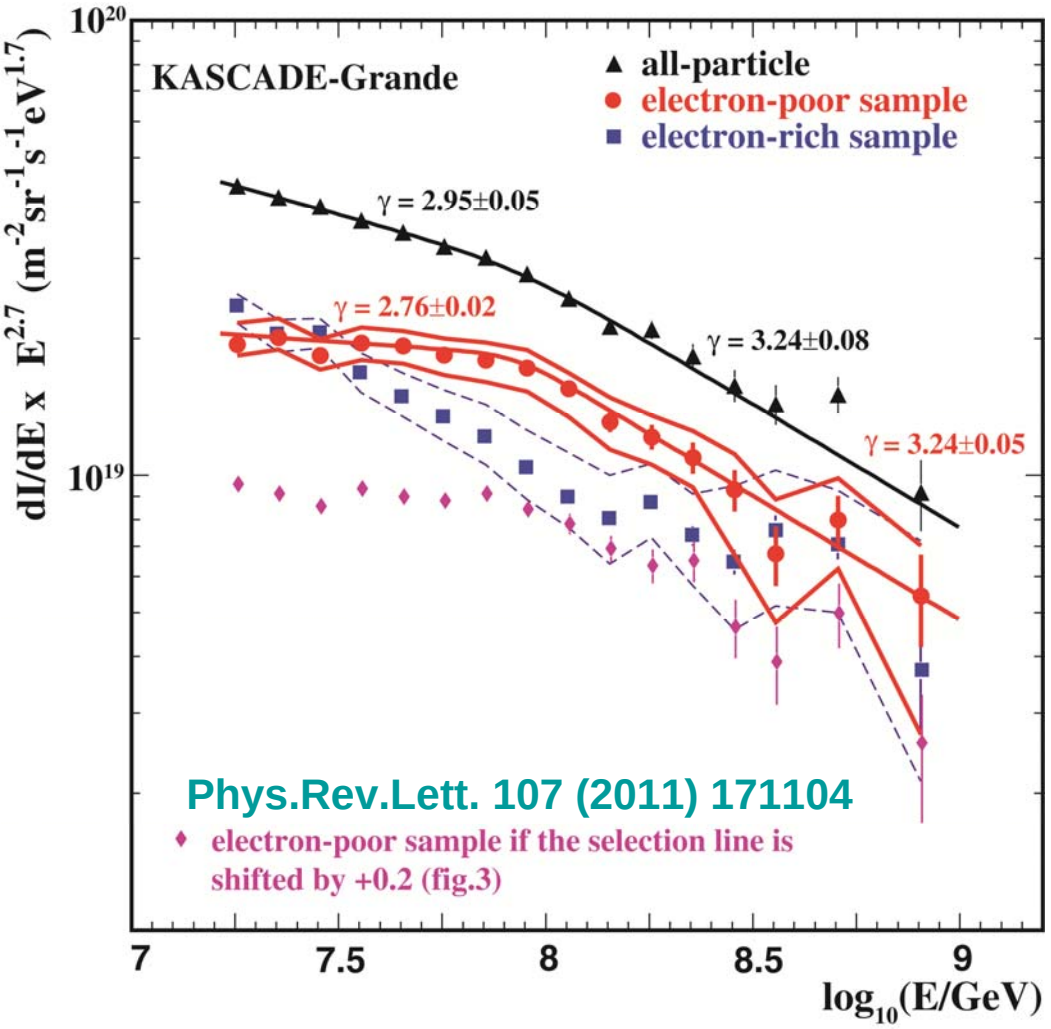
~15% systematic uncertainty in flux (energy independent)

-different zenith angle bins
-no composition dependence

Astroparticle Physics 36 (2012) 183

KASCADE-Grande: Spectra of individual mass groups

$k = (\log_{10}(N_{ch}/N_{\mu}) - \log10(N_{ch}/N_{\mu})_p) / (\log10(N_{ch}/N_{\mu})_{Fe} - \log10(N_{ch}/N_{\mu})_p)$



observation of a „heavy“ knee at 8-9·10^{16} eV

- spectra of individual mass groups:

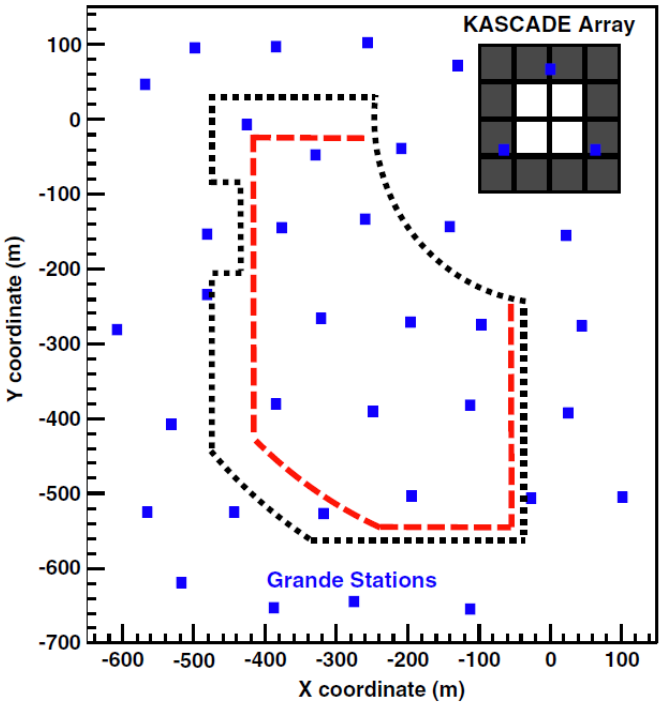
➔ steepening close to 10^{17}eV (2.1σ) in all-particle spectrum

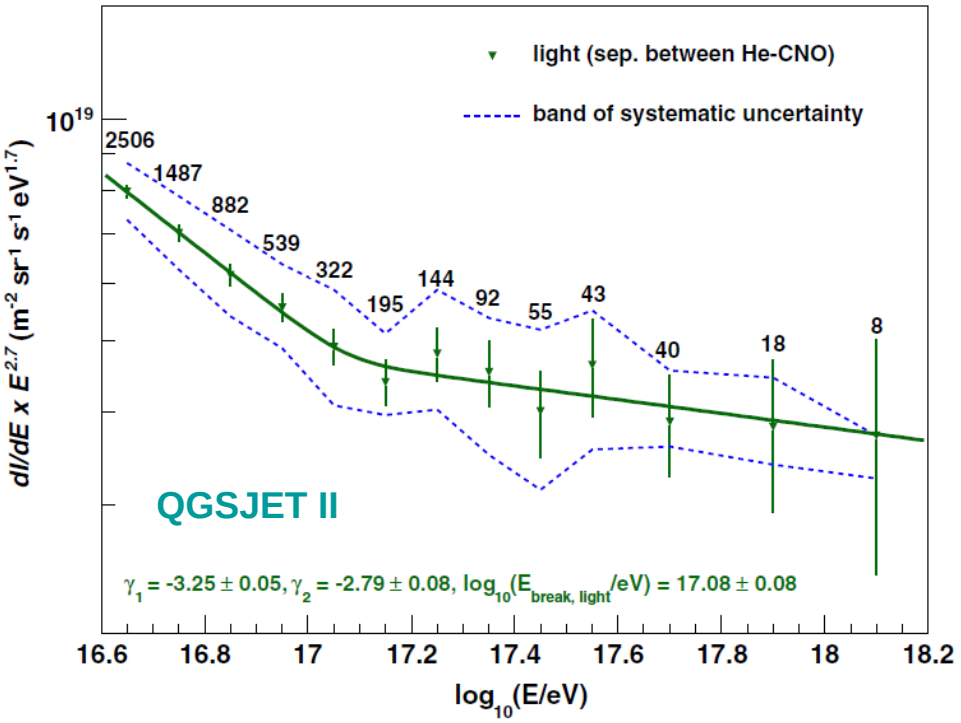
➔ steepening due to heavy primaries (3.5σ)

➔ spectrum of more enhanced heavy sample has harder spectrum before break.

➔ light+medium primaries show steeper spectrum, but fit by power law okay
➔ possibility for hardening above 10^{17}eV

KASCADE-Grande: spectrum of light primaries





- re-investigation of the spectrum of light primaries:

➔ increased area (higher threshold)
➔ 1 year more data
➔ improved selection cut

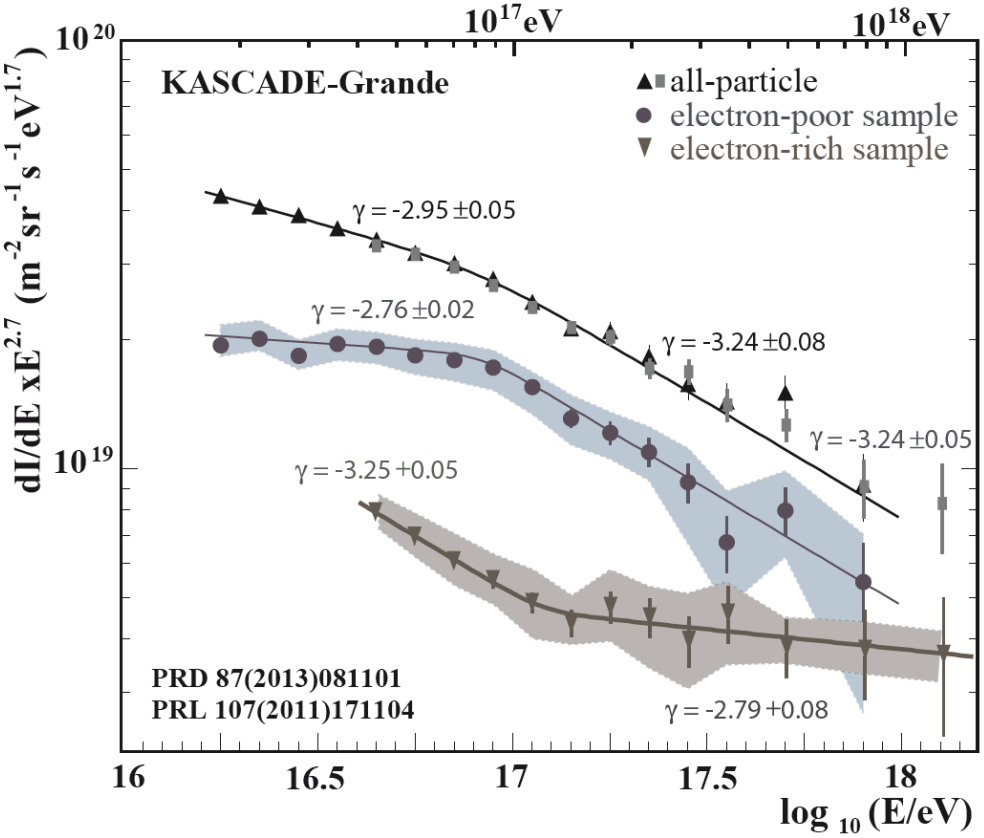
➔ hardening at $10^{17.08}$ eV (5.8σ) in light spectrum

➔ slope change from γ = -3.25 to γ = -2.79!

Phys.Rev.D (R) 87 (2013) 081101

observation of a „light“ ankle at 1-2·10^{17} eV

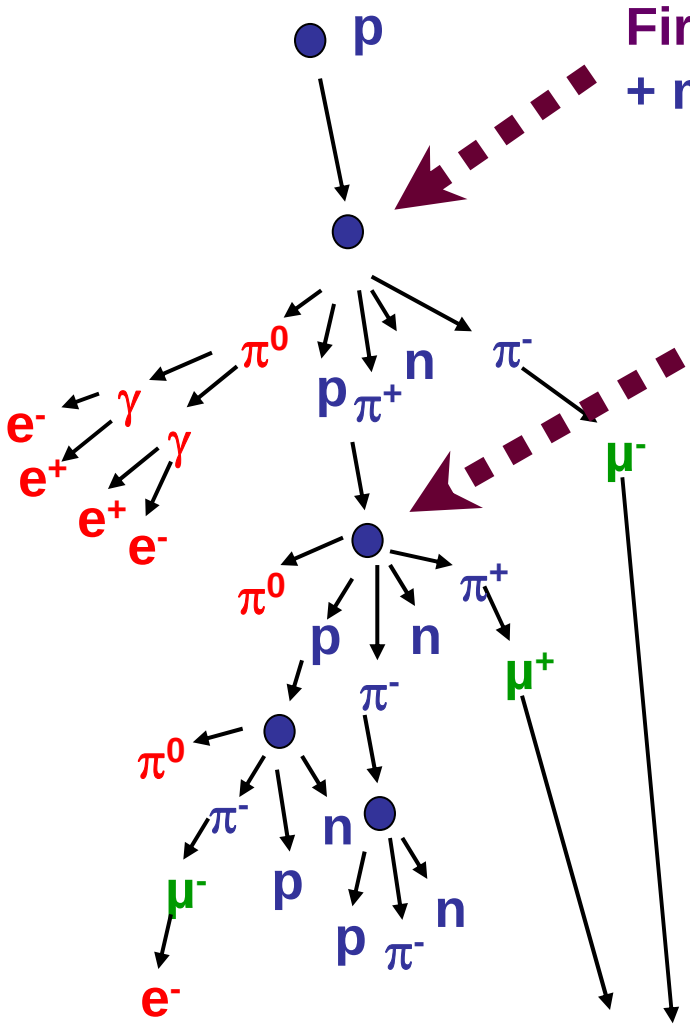
KASCADE-Grande : energy spectra of mass groups



- **steepening due to heavy primaries (3.5σ)**
- **hardening at $10^{17.08}$ eV (5.8σ) in light spectrum**

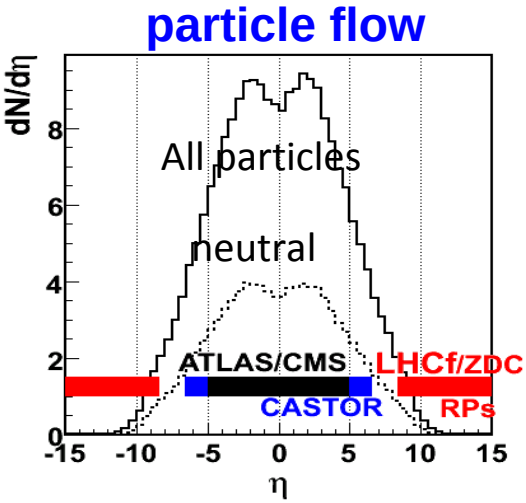
Phys.Rev.Lett. 107 (2011) 171104
Phys.Rev.D (R) 87 (2013) 081101

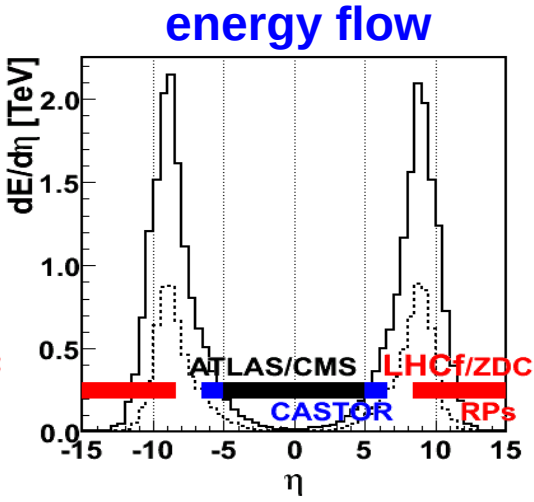
Validity of Hadronic Interaction Models



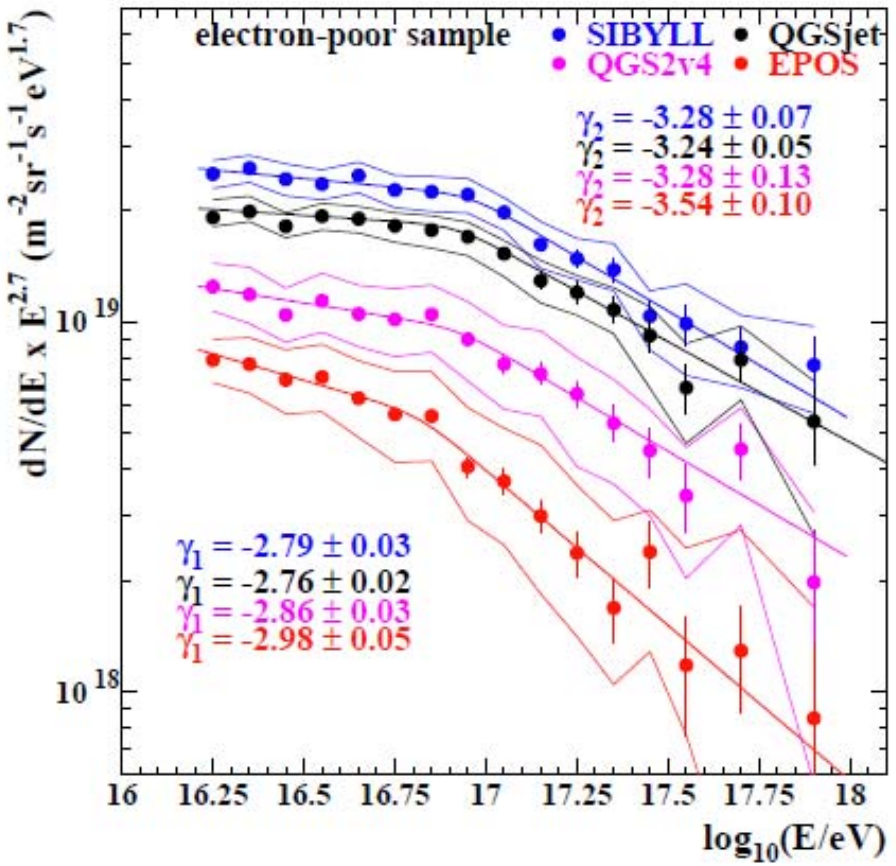
First, high energy interaction: LHC
+ multiparameter measurements EAS

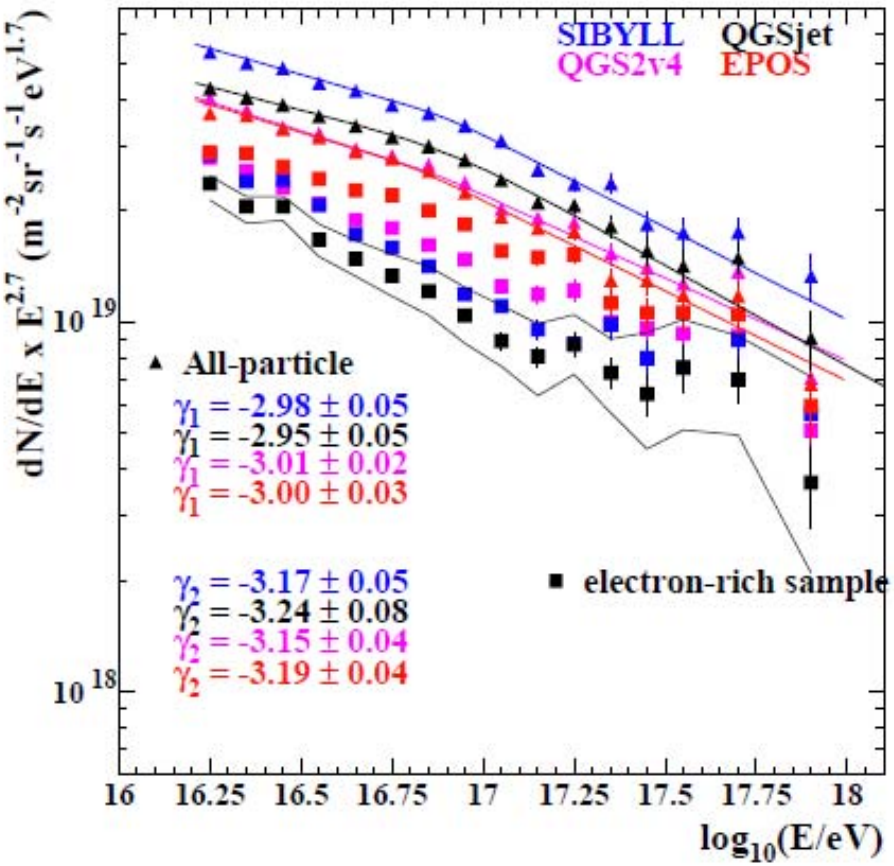
Secondary interactions:
Fix target experiments
+ multiparameter measurements EAS





KASCADE-Grande: model dependence





- Structures of all-particle, heavy and light spectra similar

➔ knee by light component and heavy component; ankle by light component

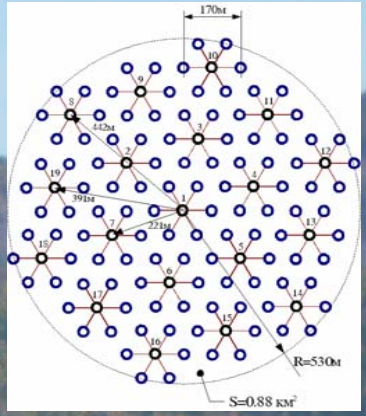
- relative abundances different for different high-energy hadronic interaction models

Advances in Space Research 53 (2014) 1456

Tunka-133

light flux at core distance 200 m Q_{200} ~ Energy

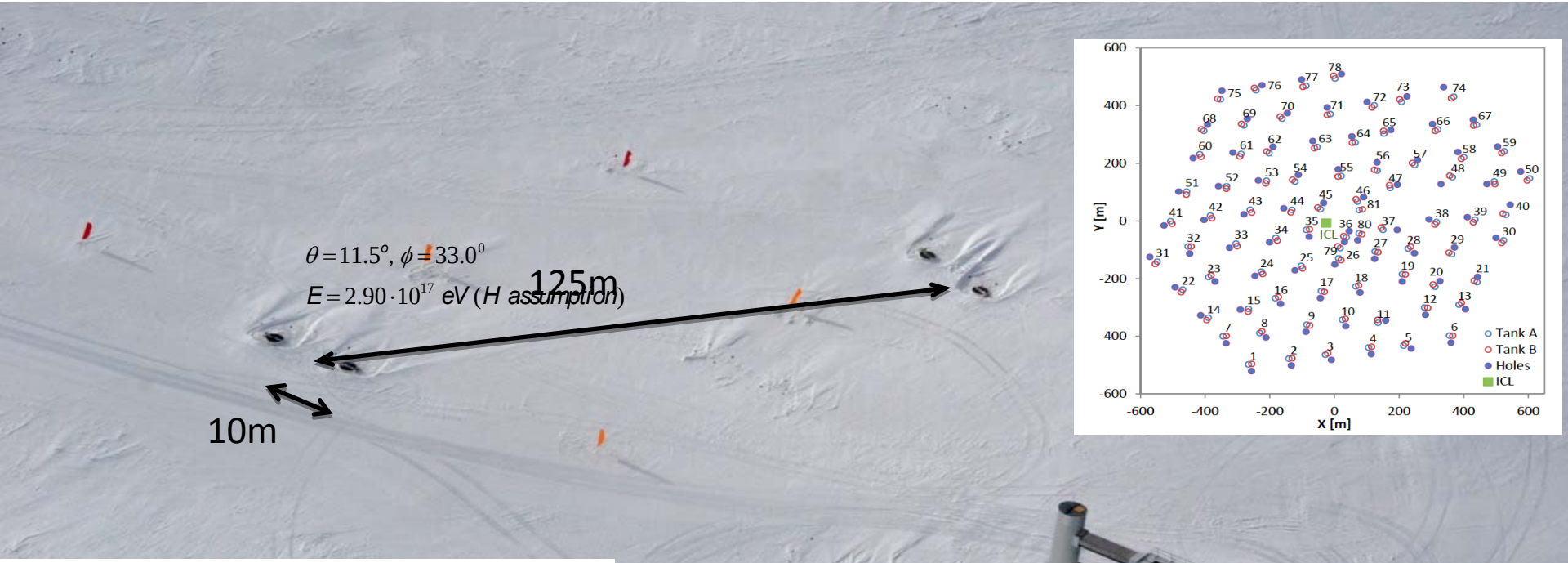
steepness of LDF P = Q(100)/Q(200) ➔ X_{max}

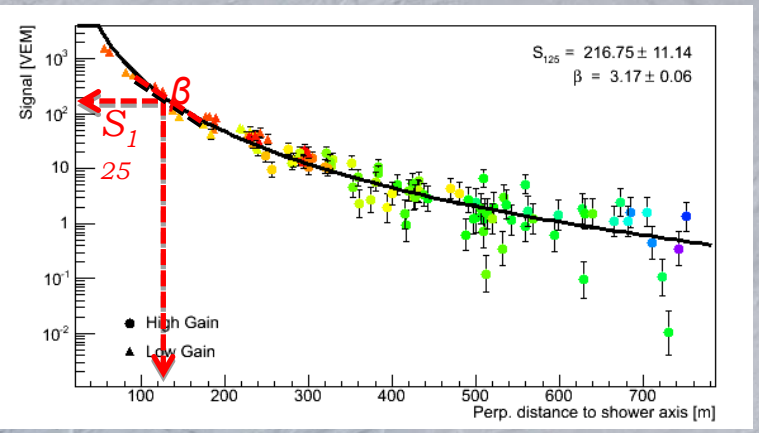


- Energy range: 100TeV – 1EeV
- Area: >1 km^2; 675m asl
- Cherenkov-experiment: LDF
- 2011: Tunka-133 is extended by 6 distant external clusters

NIM A (2013) accepted - http://dx.doi.org/10.1016/j.nima.2013.09.018

IceTop

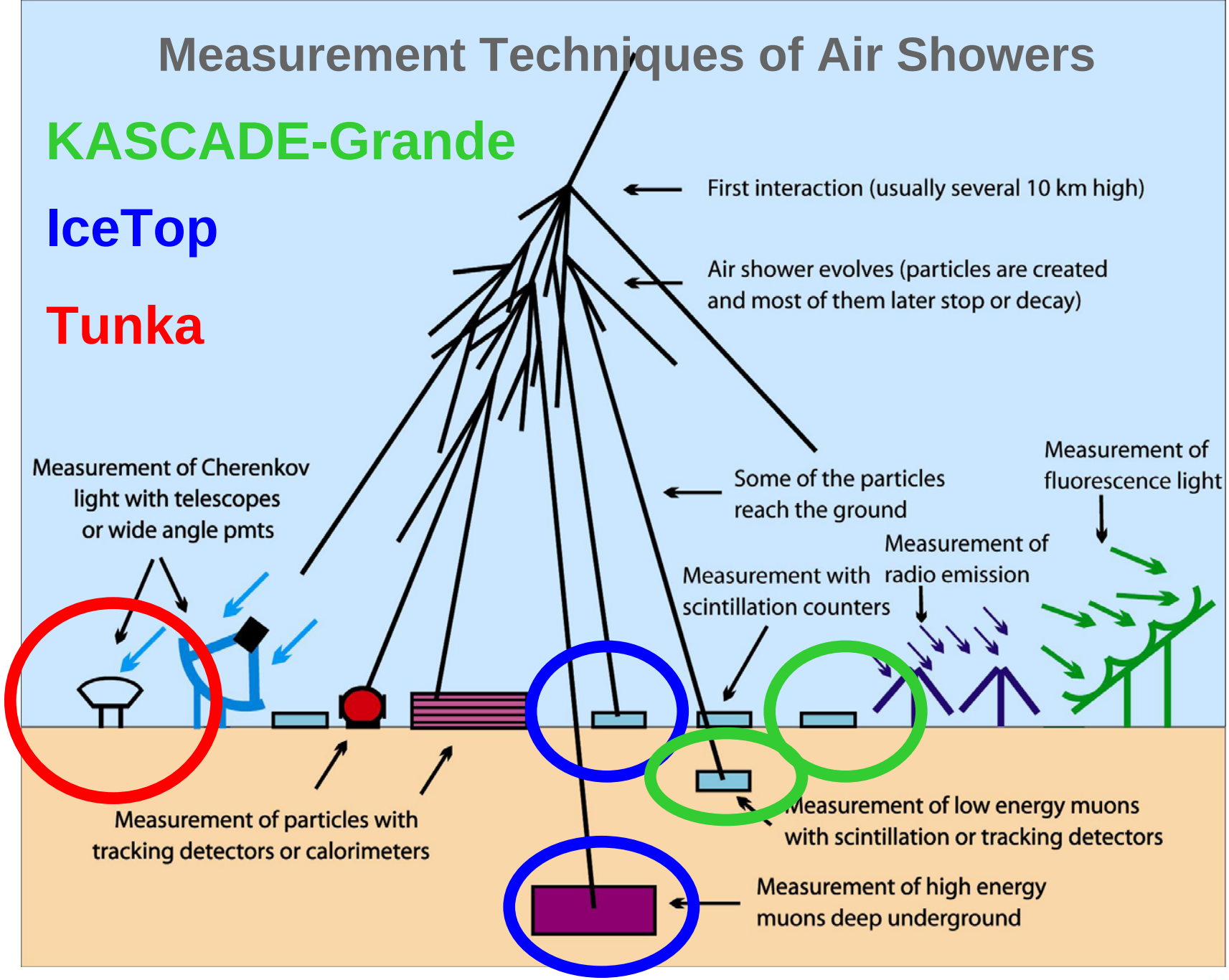


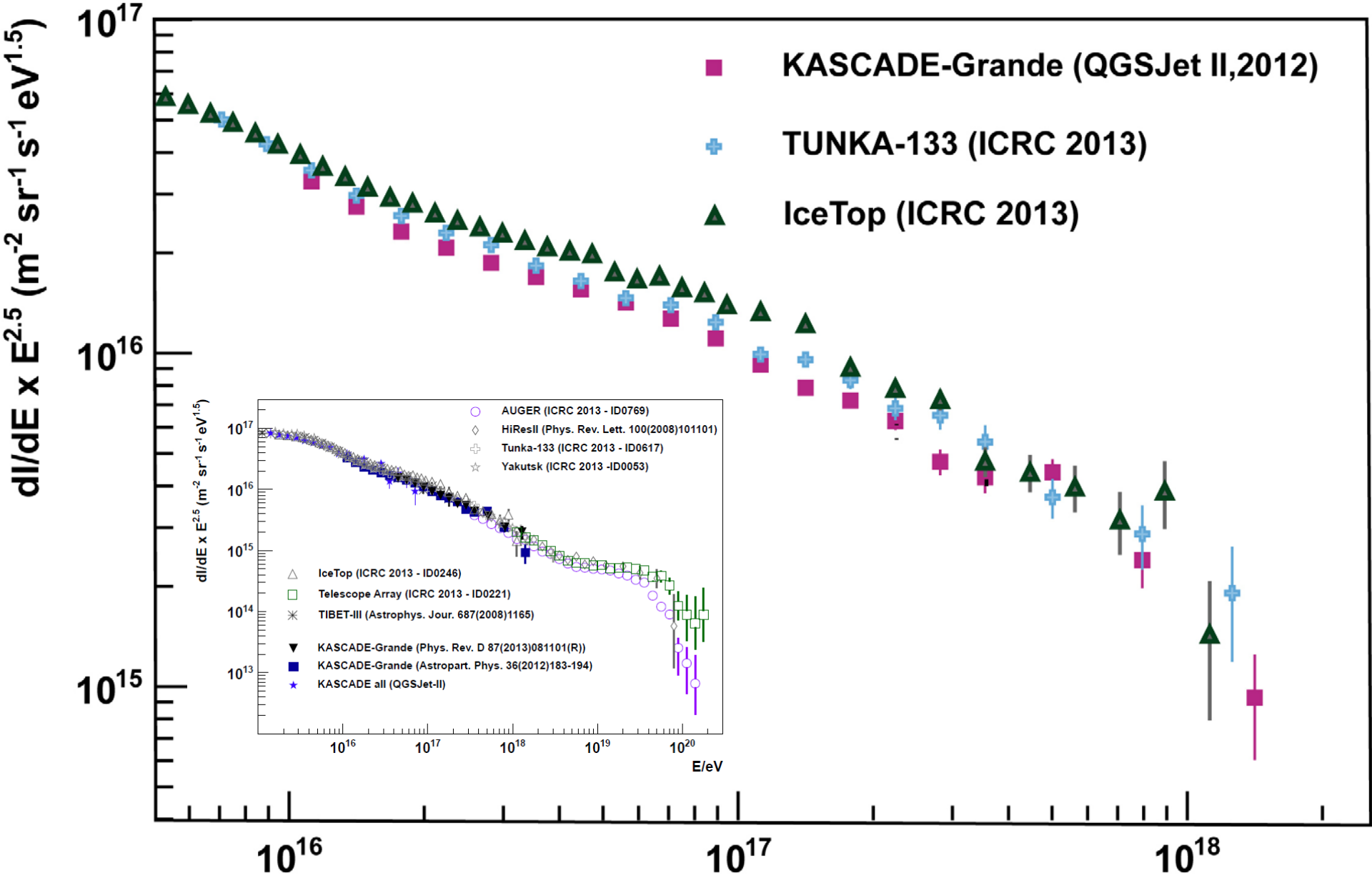


- Energy range: PeV – 1EeV
- Area: 1 km^2
- 2835m altitude (680 g/cm^2)
- 81 ice cherenkov stations
- LDF + particle density at 125m
- in-ice high-energy muons

Phys Rev D 88 (2013) 042004

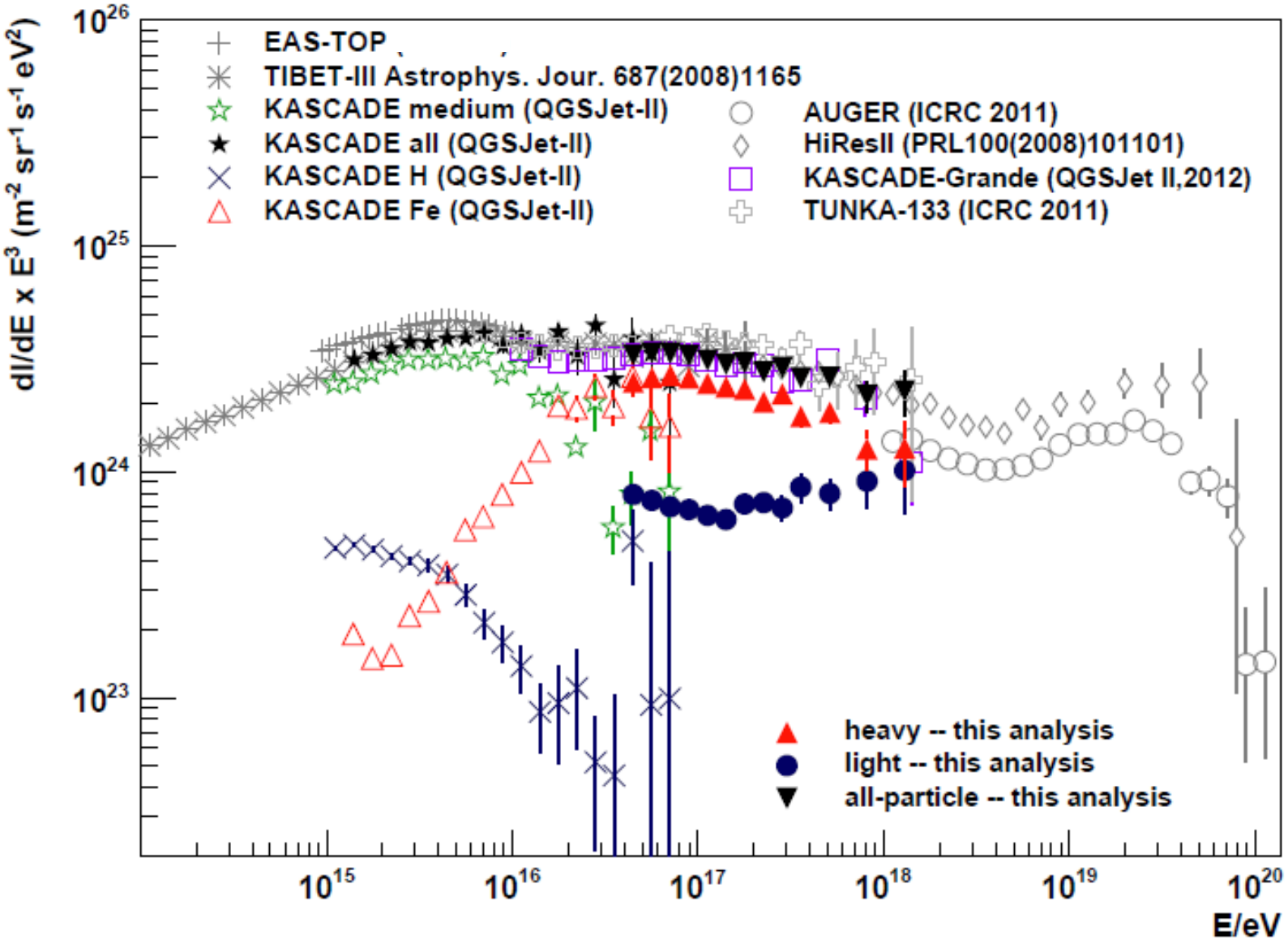
Measurement Techniques of Air Showers





- Structures of all-particle spectra similar (in the level of 15%)
- difference due to hadronic interaction model or reconstruction?

Light and Heavy Knees, Ankles, and Transition



Cosmic Ray Experiments & Gamma-ray Physics

- **KASCADE**
- **Moscow State University array (MSU)**
- **ARGO**

- **Future: GRAPES, Tunka-133, IceTop, Auger Enhancements, TALE**

- **Not discussing:**

  - Search for highest energy Photons = GZK-photons

  (Pierre Auger Observatory, Telescope Array, Yakutsk, JEM-EUSO, …)

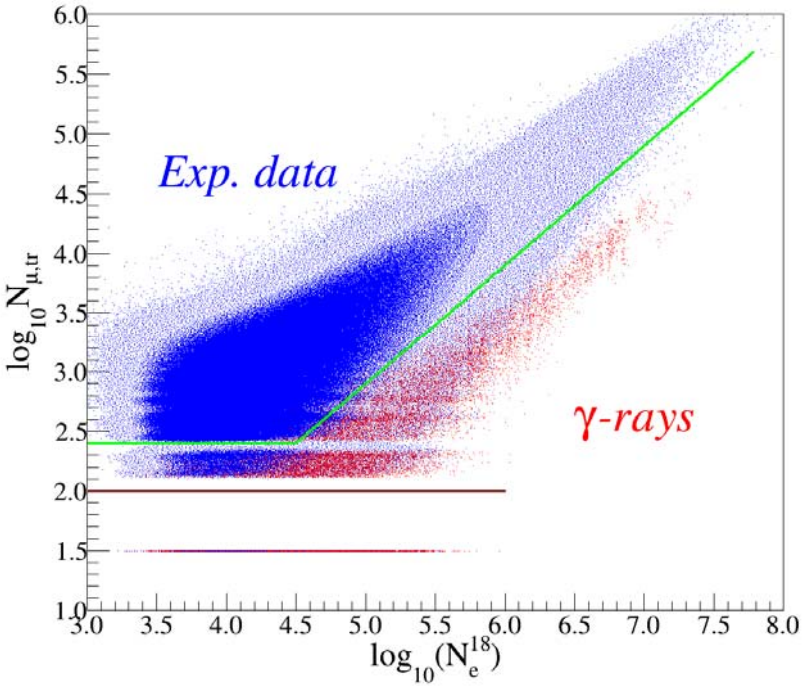
  - Results of EAS-γ-ray Experiments in Gamma-Ray Physics

  (ARGO, Tibet-ASγ, Milagro, HAWC, LHAASO, HiScore, IACTs, CTA, ….)

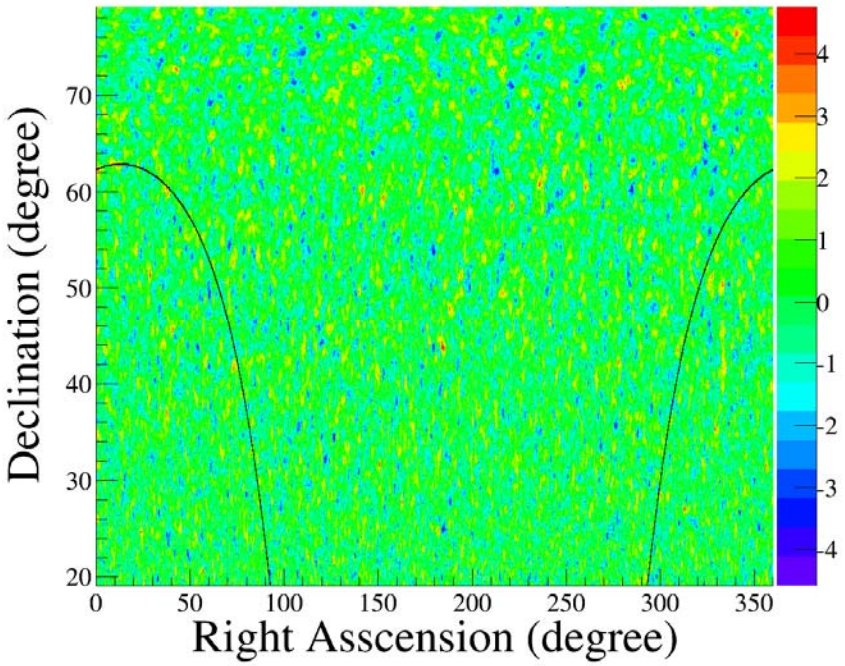
Gamma ray search at KASCADE

KASCADE collaboration,
Zhaoyang Feng, Donghwa Kang,
in preparation

- Data set from 1998.05.11 to 2010.05.14 ; $3 \cdot 10^8$ events



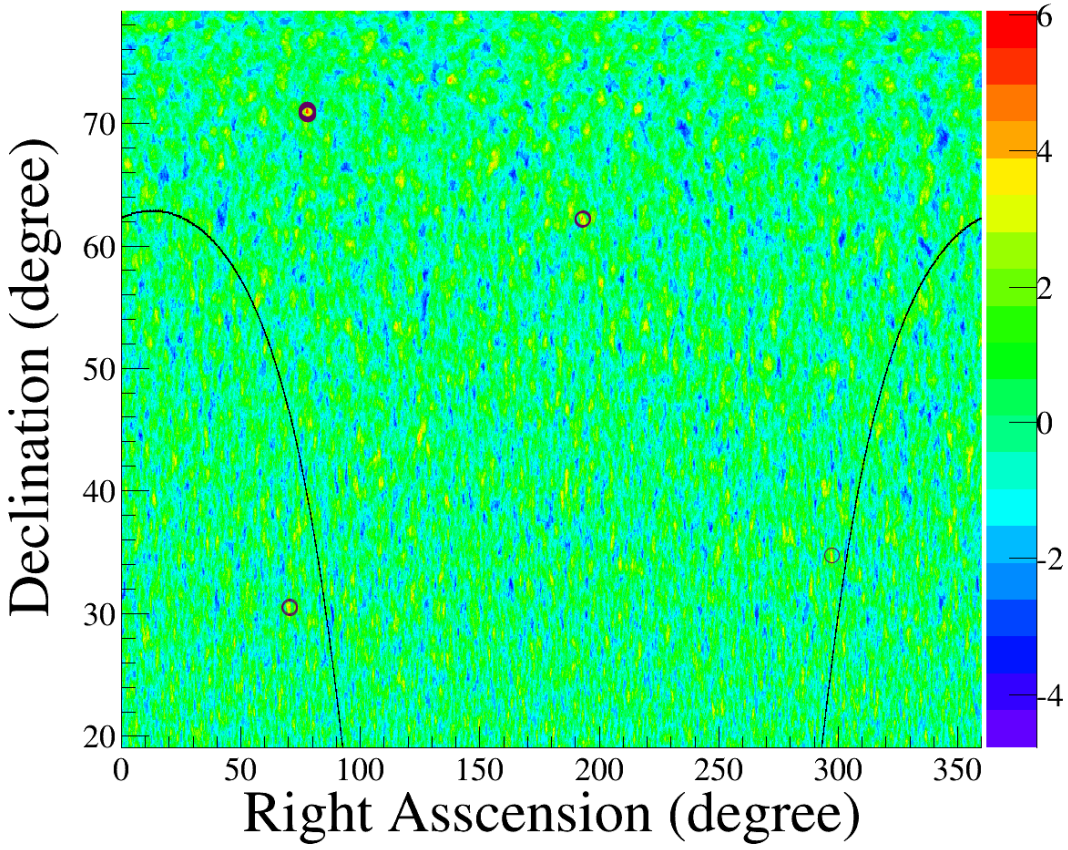
all events

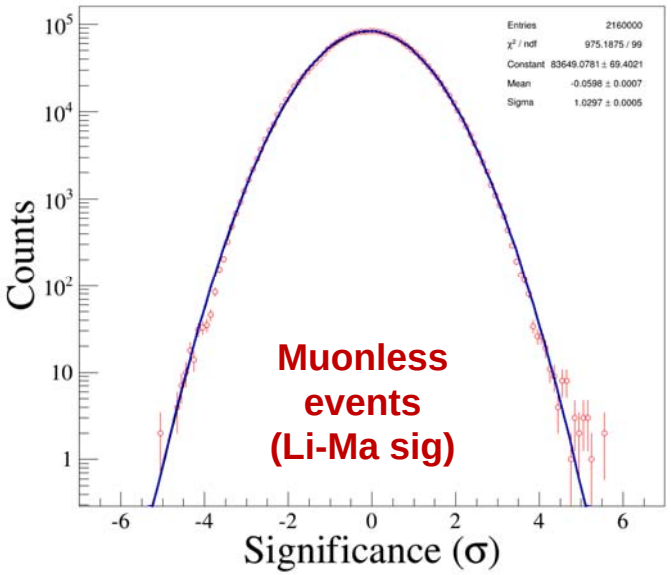


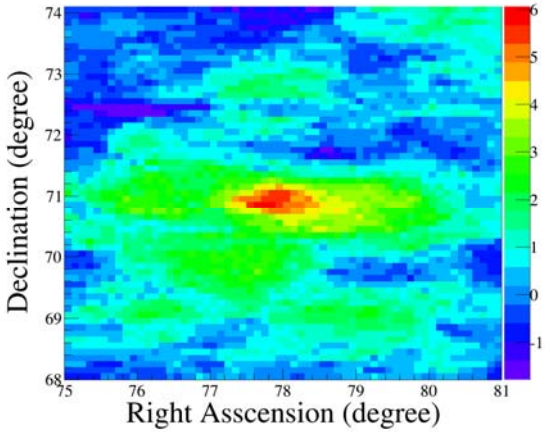
-selection of muon poor events (88170 events)
-Gamma energy: >168 TeV
-Background estimation (equi-distant zenith angles) Anemonori et al.
-Significance estimation (Li-Ma and Poisson significances)
-Diffuse flux limit calculated for different energies (Helene 1983)
-Upper point source limits calculated

Muonless events

Muon poor events



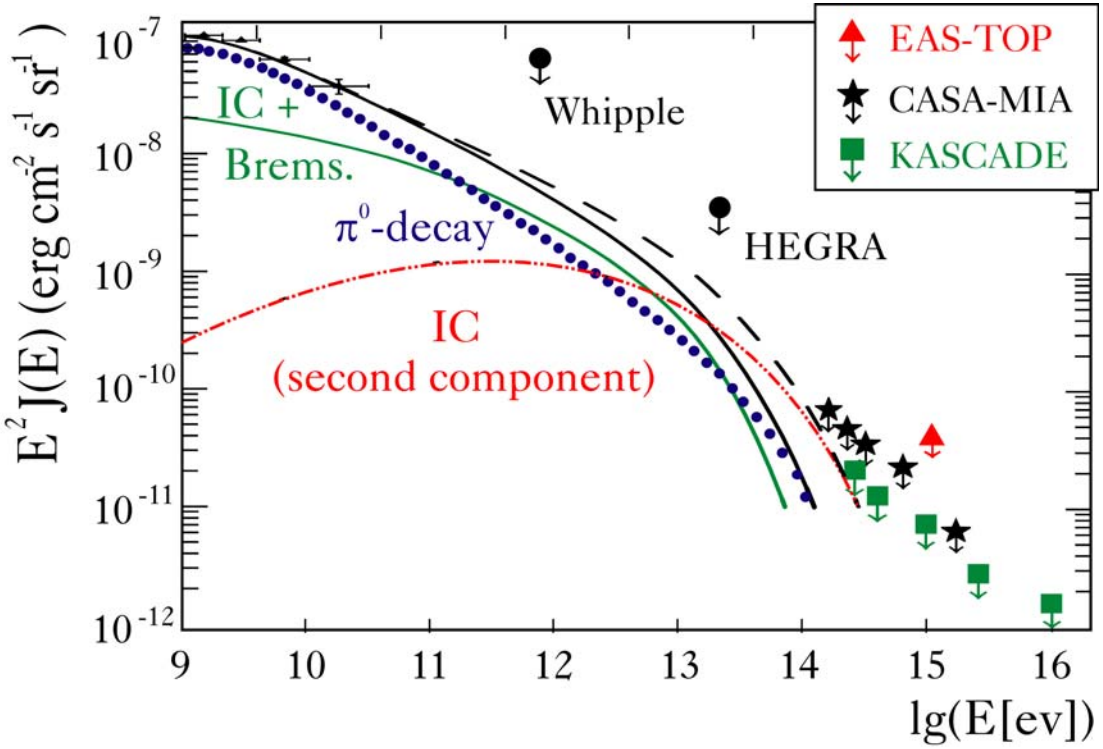




Candidate:
(ra,dec)=(77.75,70.85) Non=25, Noff=5.53
Li-Ma Sig=5.56
Poisson Prob=7.152e-10 Poisson Sig=6.052
27 cells

Search for primary photons (diffuse Gamma-ray flux):

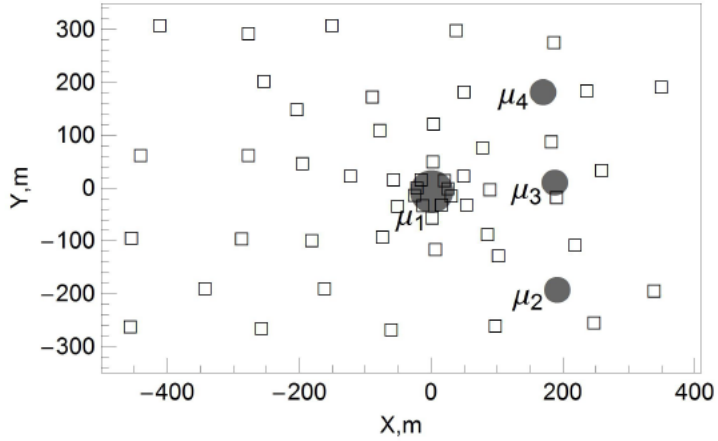
Primary photons: point directly to the source of cosmic rays
air-showers are muon-poor, i.e. small ratio of muon to electron number

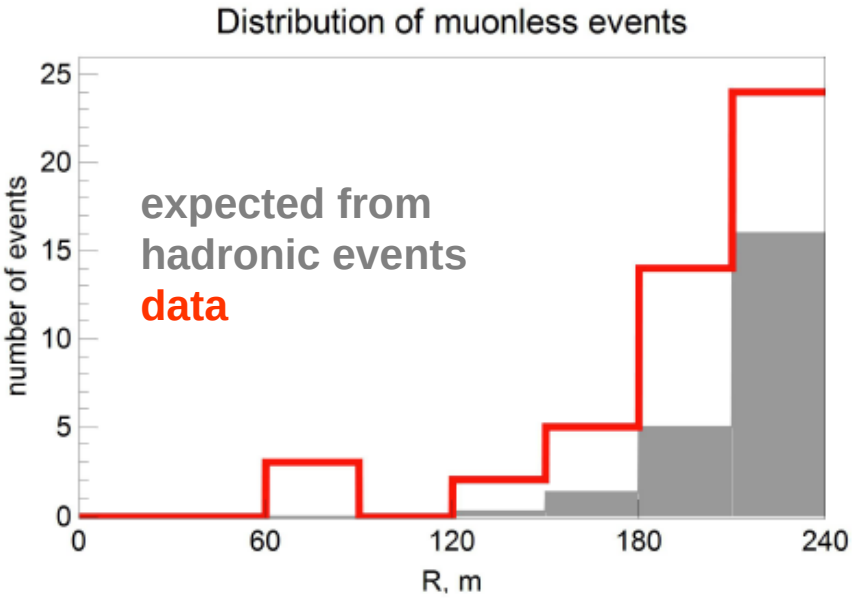


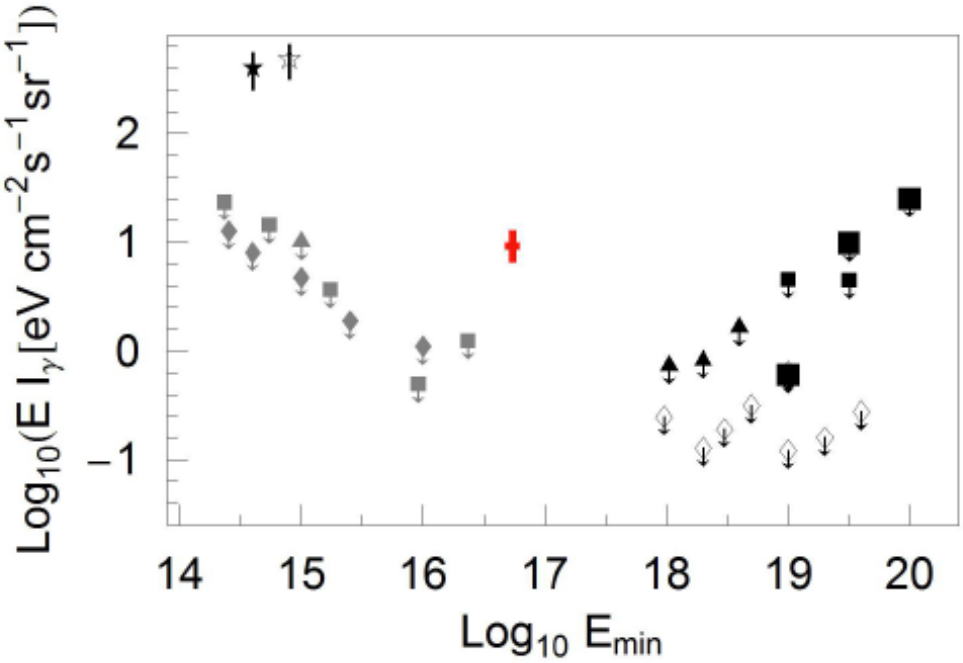
no positive signal observed
best limits for the diffuse flux

KASCADE collaboration,
F.Feßler, ICRC 2003

MSU array: Moscow State University experiment







-Re-analysis of old data
-Claim to have positive signal
-Gamma energy: close to 100 PeV
-KASCADE-Grande is checking

arXiv:1307.4988v1

Gamma-Ray Experiments & Cosmic Ray Physics

- **IACT experiment**
  (H.E.S.S. iron spectrum)
- **Anisotropies**
  (Milagro, HAWC, Tibet, IceTop, ARGO)
- **Low energy cosmic ray spectra**
  (GRAPES, ARGO, Tibet)

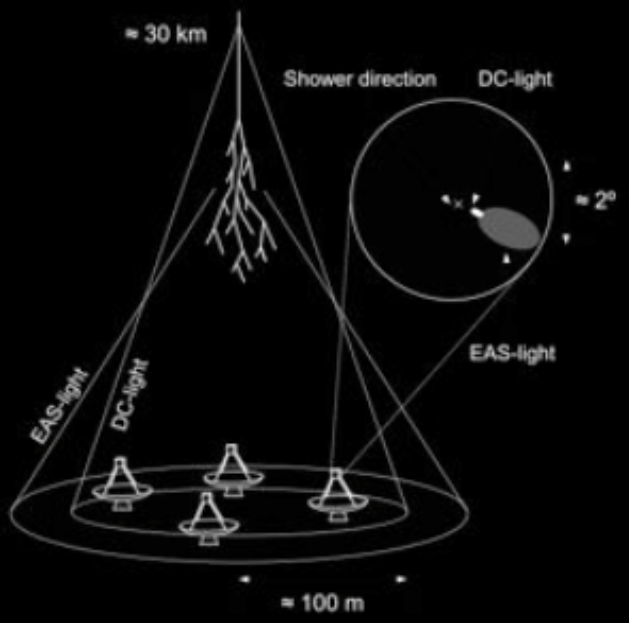
- **Future: LHAASO, HiSCORE, GRAPES, CTA, HAWC**

IACT (HESS)

- **Can we measure the Cosmic Ray Iron spectrum with HESS?**
- **Direct Cherenkov light:**

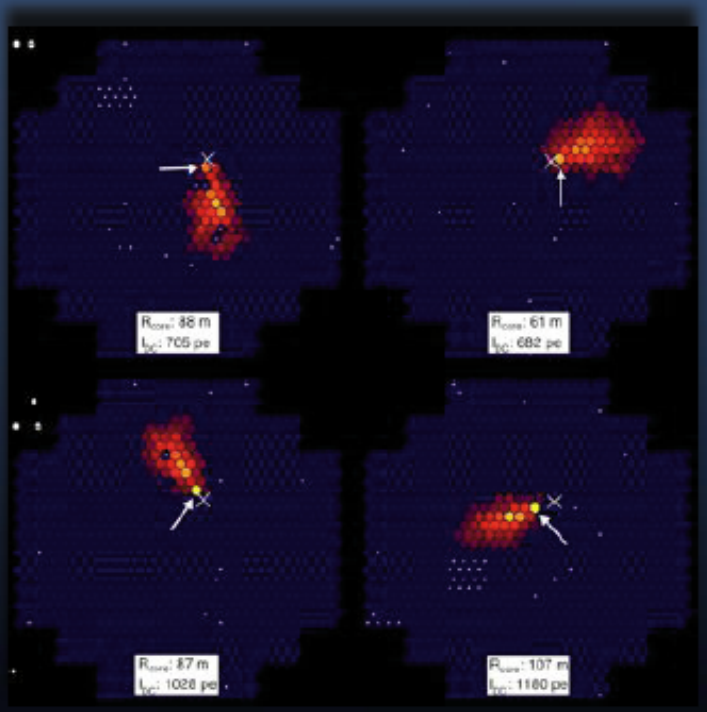
$$I_{\mathrm{DC}} \propto Z^2$$

$$I_{\mathrm{shower}} \propto E$$

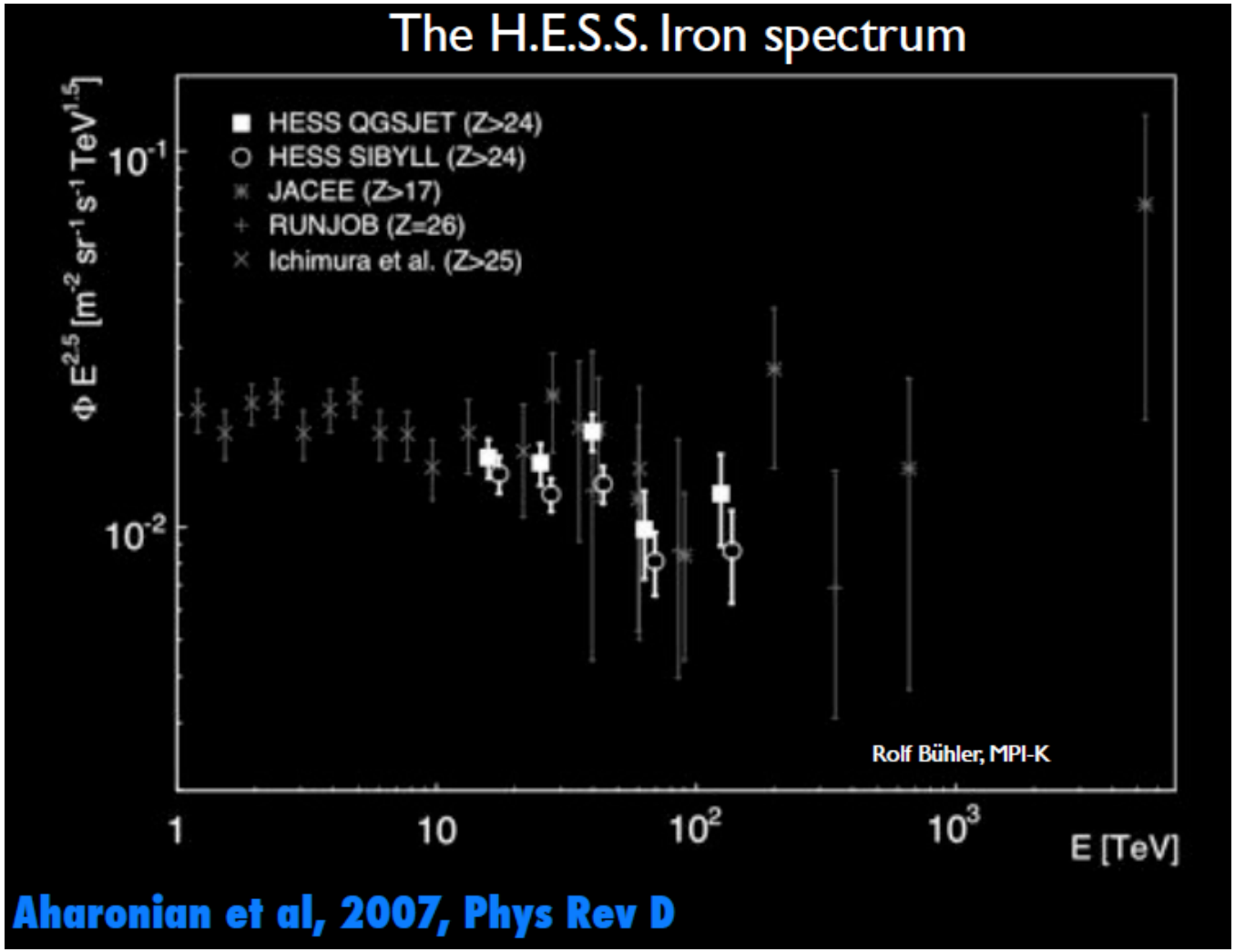


Technique: Keida, Swordy, Wakely. (2002)

DC-light from Cosmic Rays



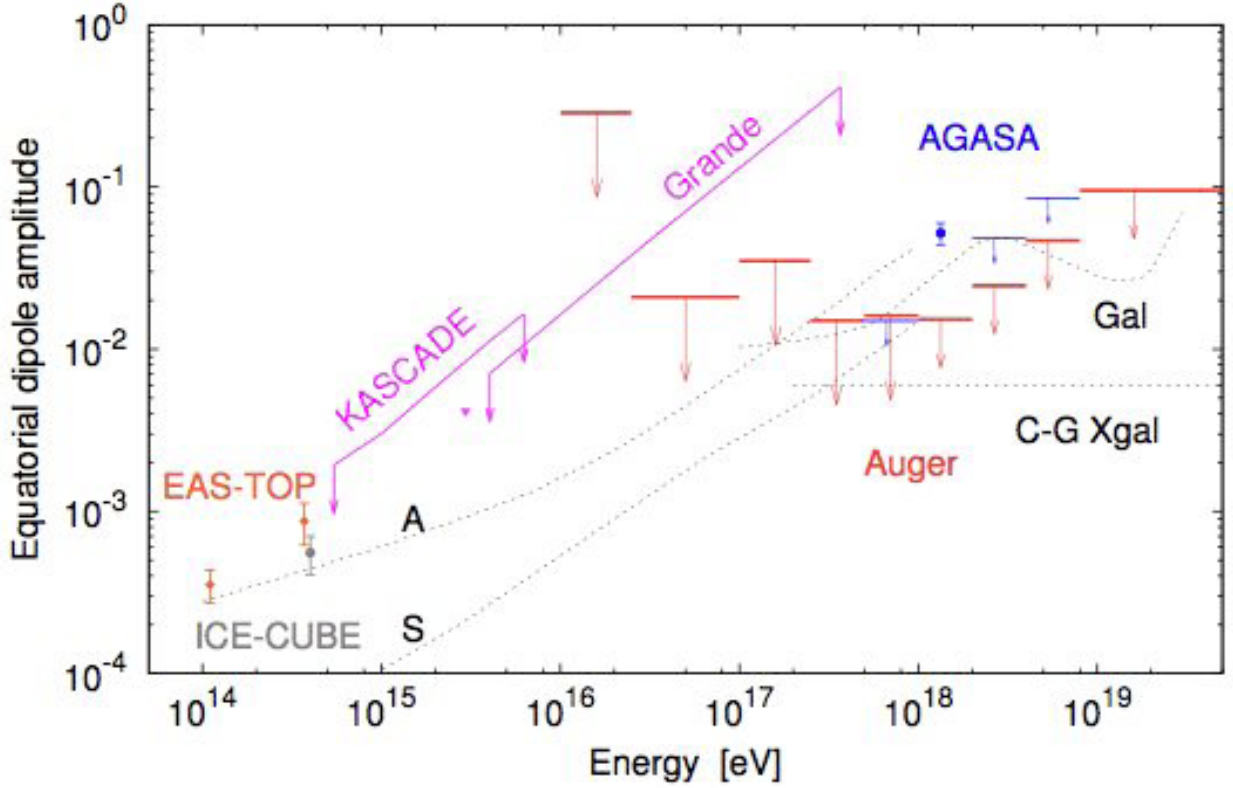
IACT (HESS)



Slides Stolen from talk by Kosack
VERITAS presently looking into data

Analysis of large scale anisotropy of cosmic rays:

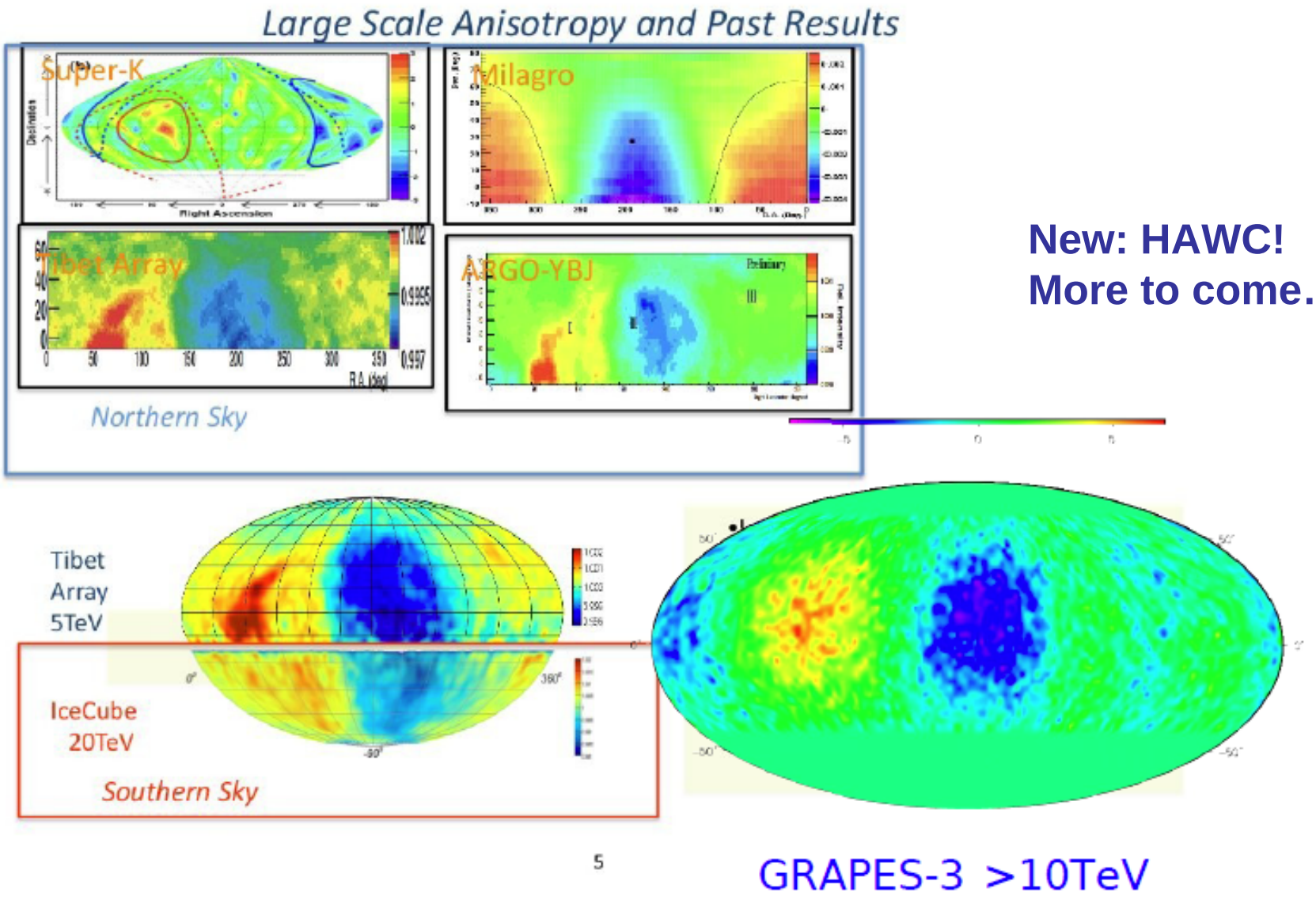
Anisotropy: different astrophysical models for the origin of the knee can be distinguished by their predictions of anisotropy



no large scale anisotropy observed (above PeV)
limits in Rayleigh amplitude

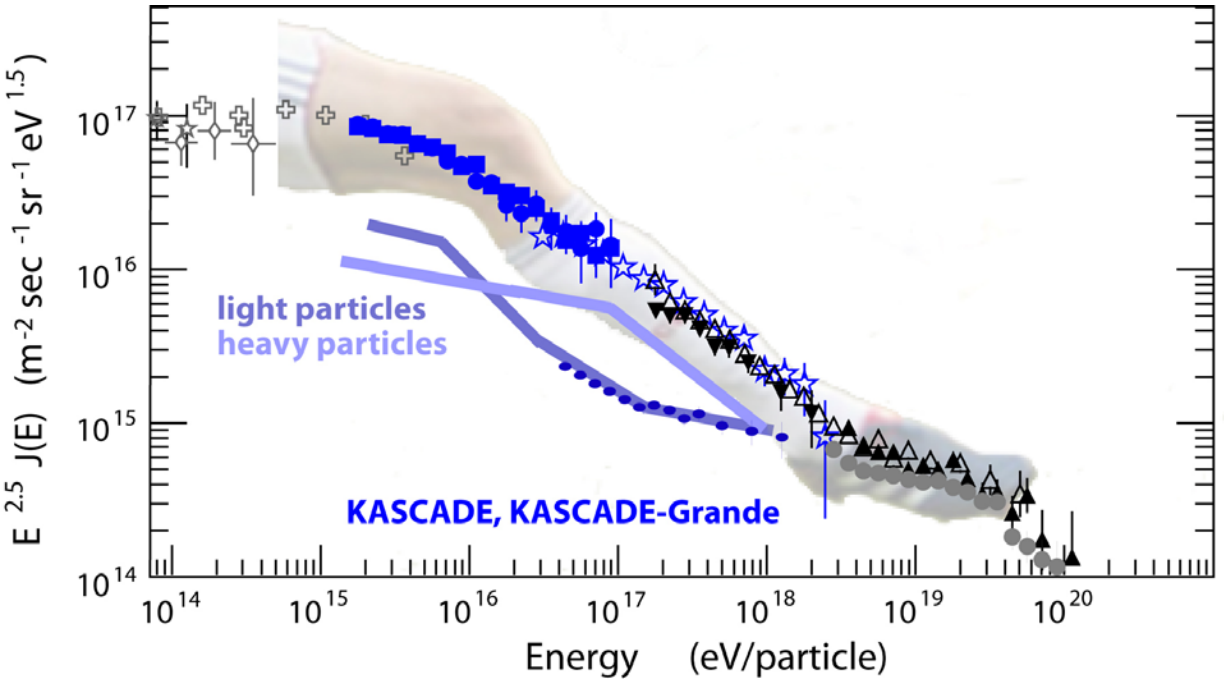
KASCADE collaboration
Astrophysical Journal 604 (2004) 687

Large scale Anisotropies observed (below PeV)



New: HAWC!
More to come…..

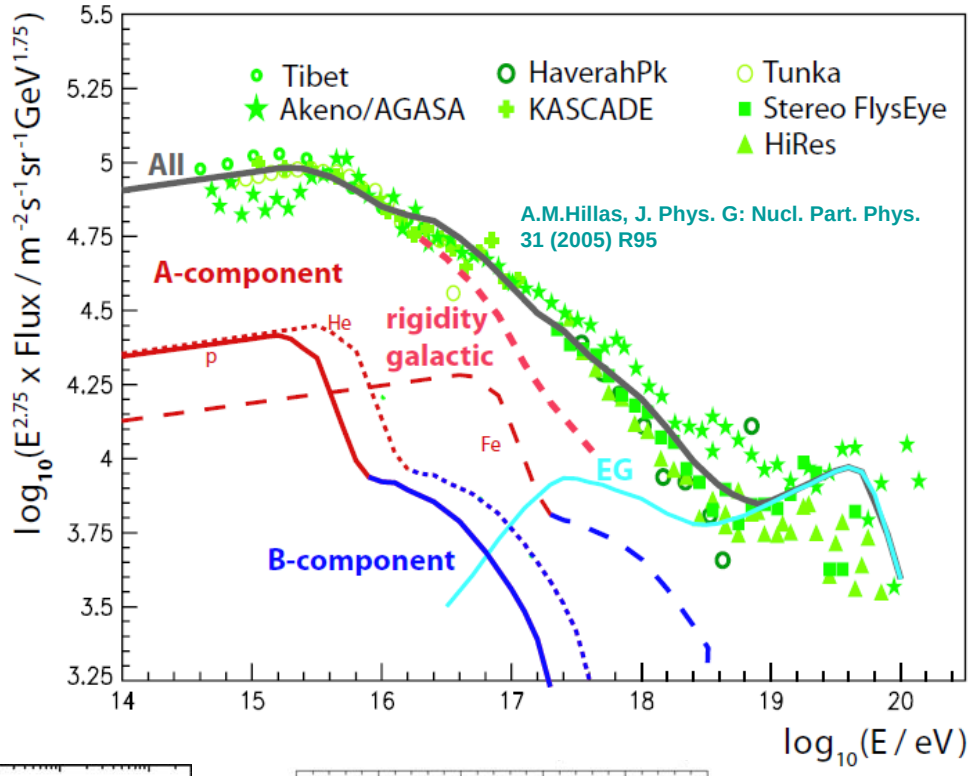
Light and Heavy Knees, Ankles, and Transition Summary (KASCADE-Grande)

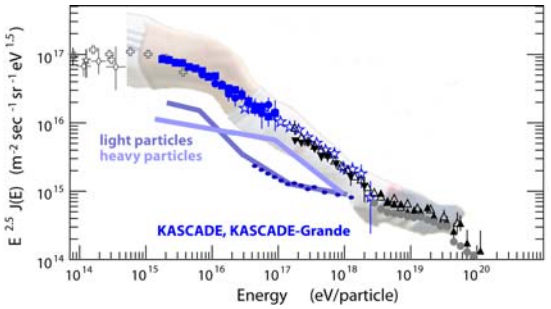


- ➔ KASCADE: knee of light primaries at ~3·10^{15}eV
- ➔ Hardening at 10^{16}eV due to knee of medium component
- ➔ KASCADE-Grande: knee of heavy primaries at ~9·10^{16} eV
- ➔ heavy knee less distinct compared to light knee
- ➔ mixed composition for 10^{15} to ~ 8·10^{17} eV
- ➔ light ankle at 1-2·10^{17} eV

knee position $\propto Z$

Light and Heavy Knees, Ankles, and Transition



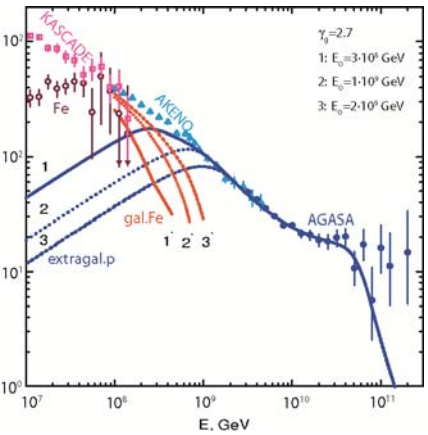


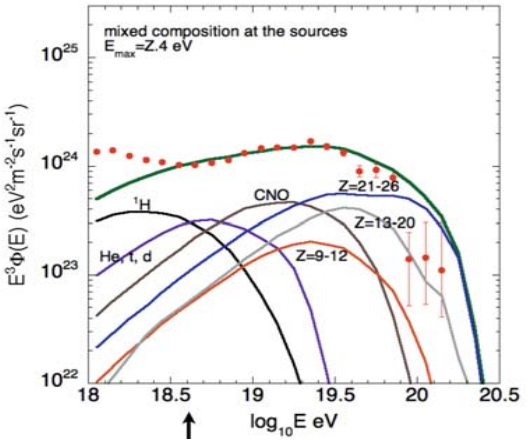
Questions:

- which astrophysical scenario (model) describes the data?

- exact energy and mass scale?

- spectral shape of individual masses?



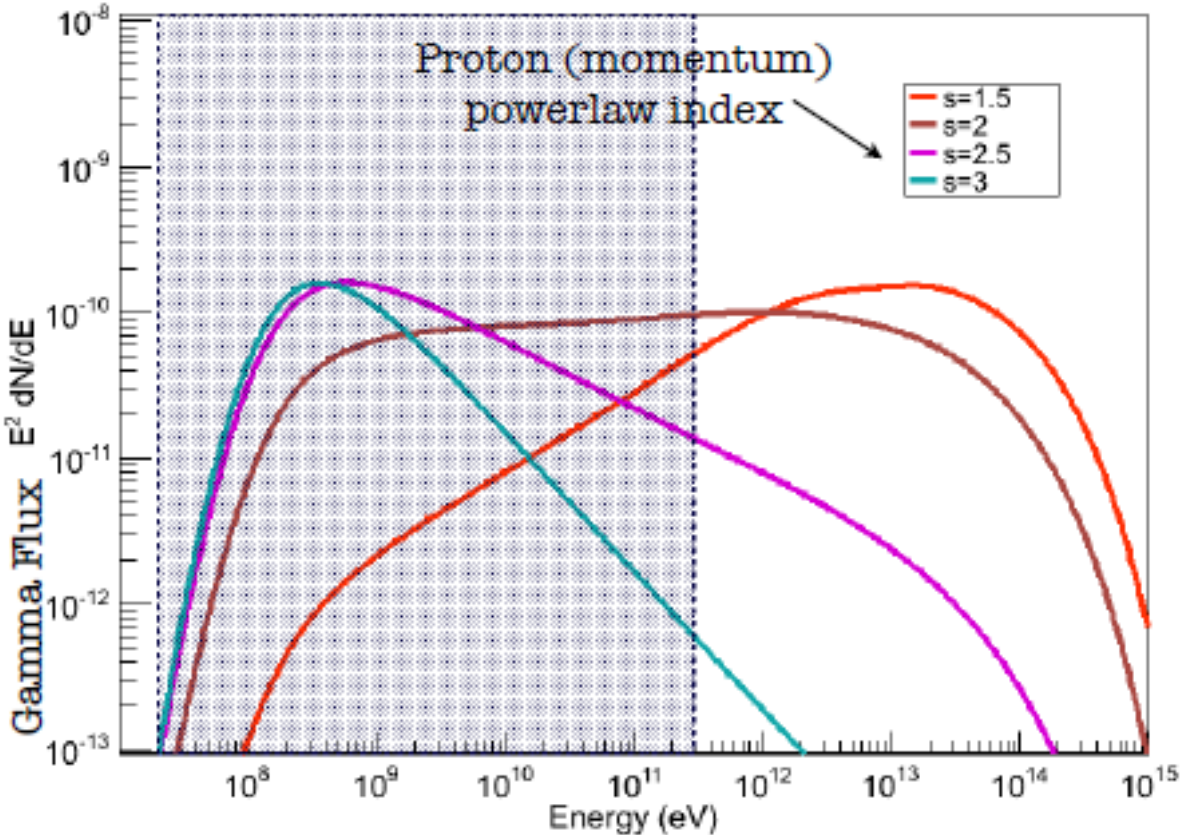


V.Berezinsky, astro-ph/0403477

D.Allard, astro-ph/1111.3290

Synergy with Gamma-ray astronomy

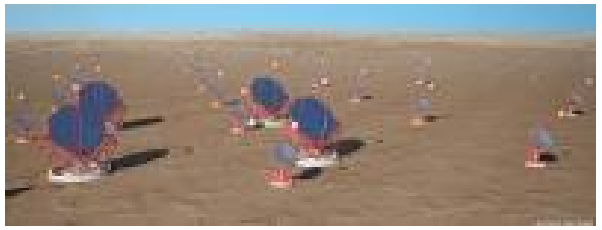
- **Do shell-type SNR accelerate protons? (via π^0-decay!)**
- **To which energy? (up to 10^{15}eV?)**
- **Distinguishable from electron acceleration?**



Stefan Funk, TAUP 2013, Asilomar, CA, US

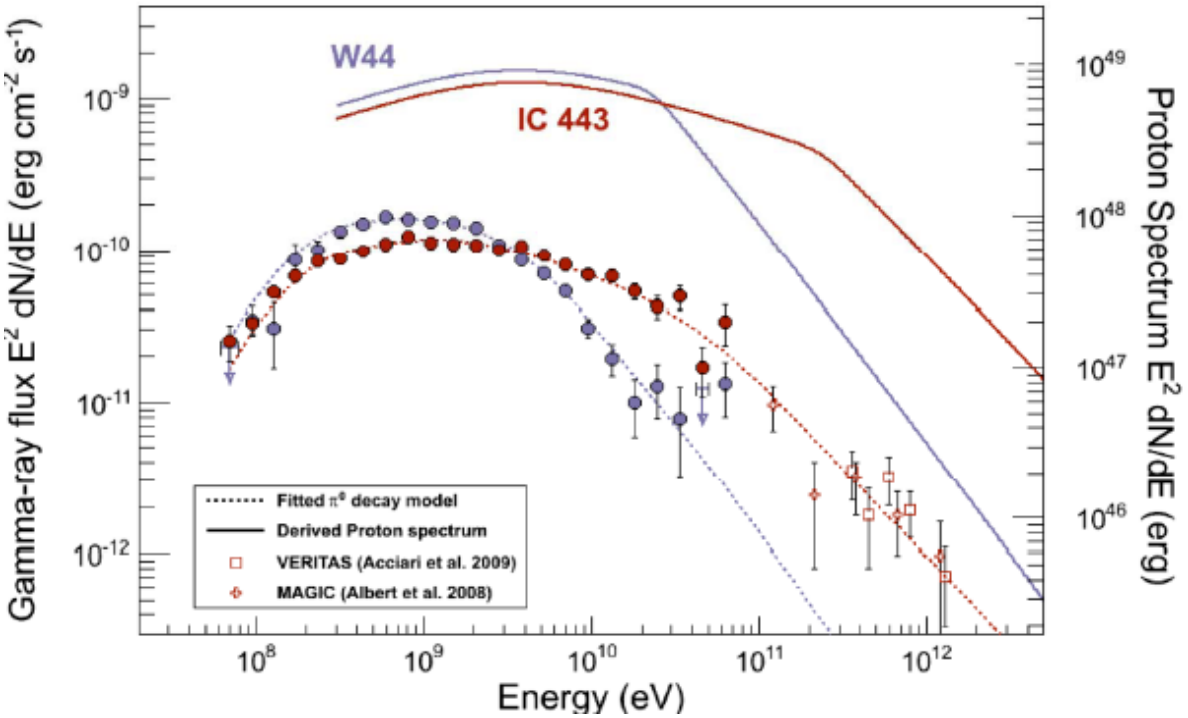
Expected gamma flux (π^0 –bump) for different proton injections

- **Fermi-Lat**
- **TeV γ-ray Cherenkov**



Gamma-ray astronomy: Fermi

- **IC 443 and W44 are the two brightest SNRs in the Fermi-LAT range**



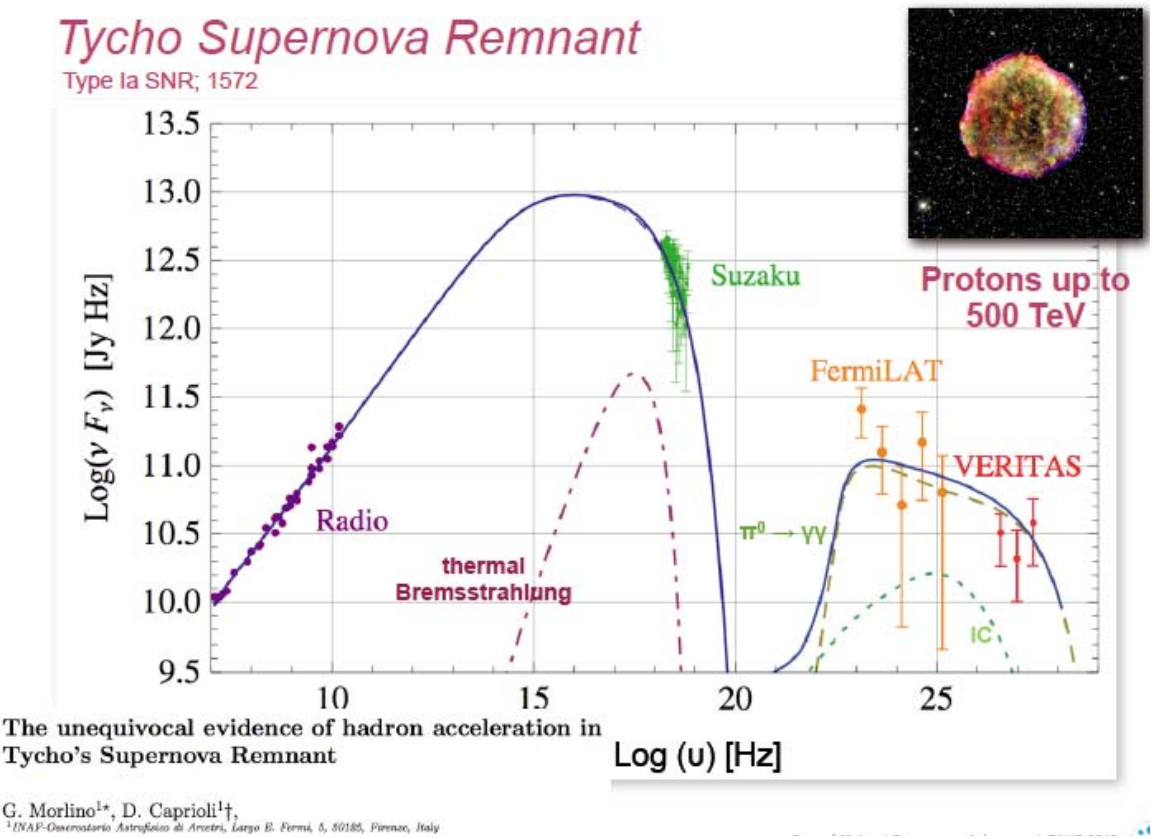
Measured gamma-rays and calculated proton spectrum

Proton acceleration yes
but only up to TeV?
← Dependent on age of SNR?

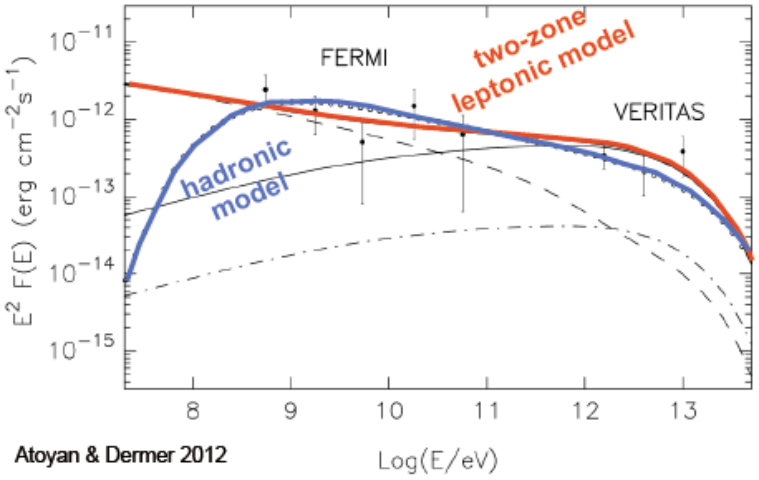
Stefan Funk, TAUP 2013, Asilomar, CA, US

Gamma-ray astronomy: IACT

-problems: gas density for hadronic
magnetic fields for leptonic



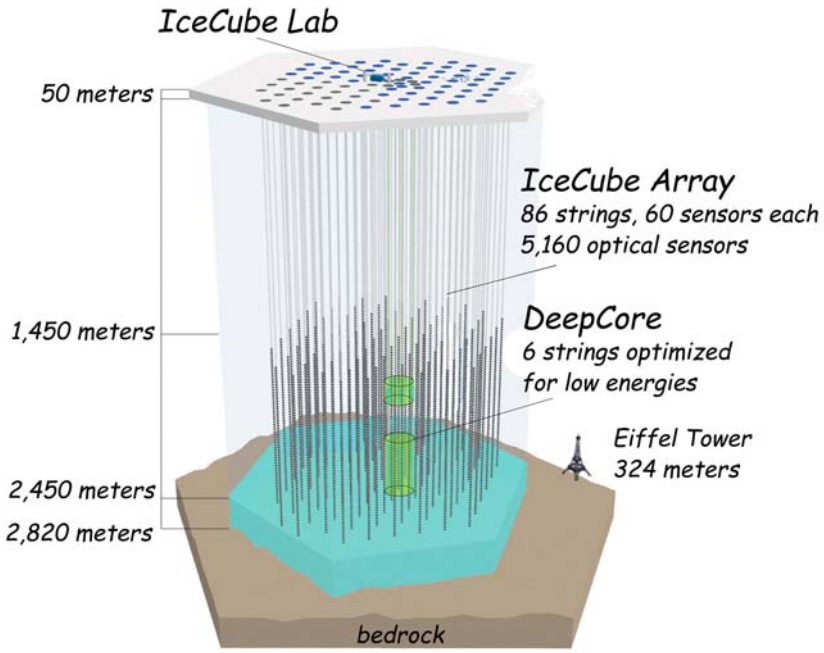
Measurement also explainable by hadronic and leptonic models



← Still no proof that SNR accelerate protons up to the knee, but also no exclusion….

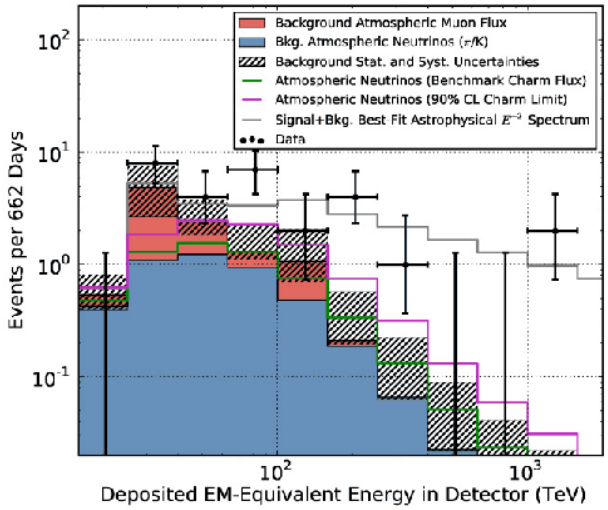
Gernot Maier, TAUP 2013, Asilomar, CA, US

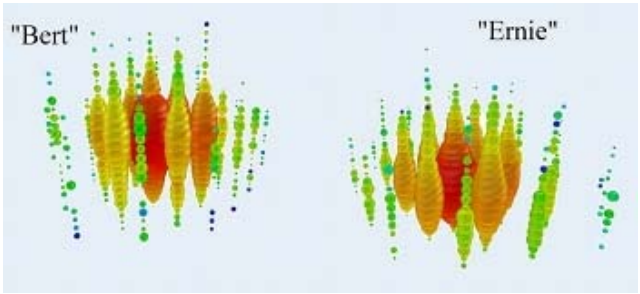
Synergy with Neutrino astronomy: IceCube

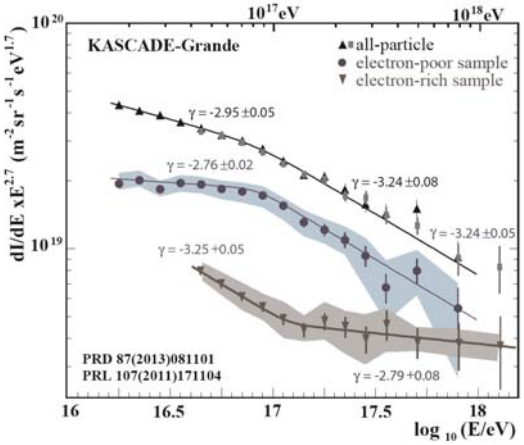


- cosmic neutrinos from IceCube correspond to 10^{17}eV protons

← galactic or extragalactic source?





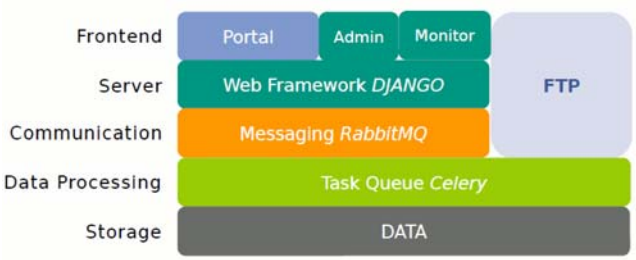


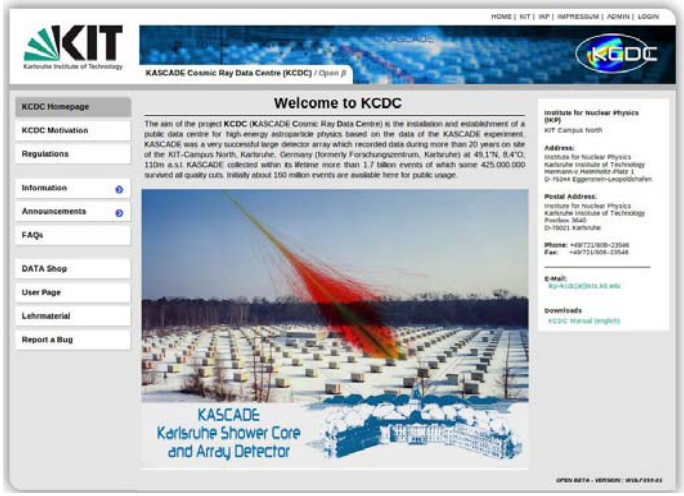
Measured PeV-neutrinos by IceCube

Public Cosmic Ray Data: KASCADE Cosmic ray Data Centre

- **KCDC = publishing research data**
  from the KASCADE experiment
- **Motivation and Idea of Open Data:**
  general public has to be able to access and use the data
  the data has to be preserved for future generations
- **Web portal:**
  providing a modern software solution for publishing KASCADE data for a general audience
  In a second step: release the software as Open Source for free use by other experiments
- **Data access:**
  $1.6 \cdot 10^8$ EAS events of first data release is now available

https://kcdc.ikp.kit.edu/

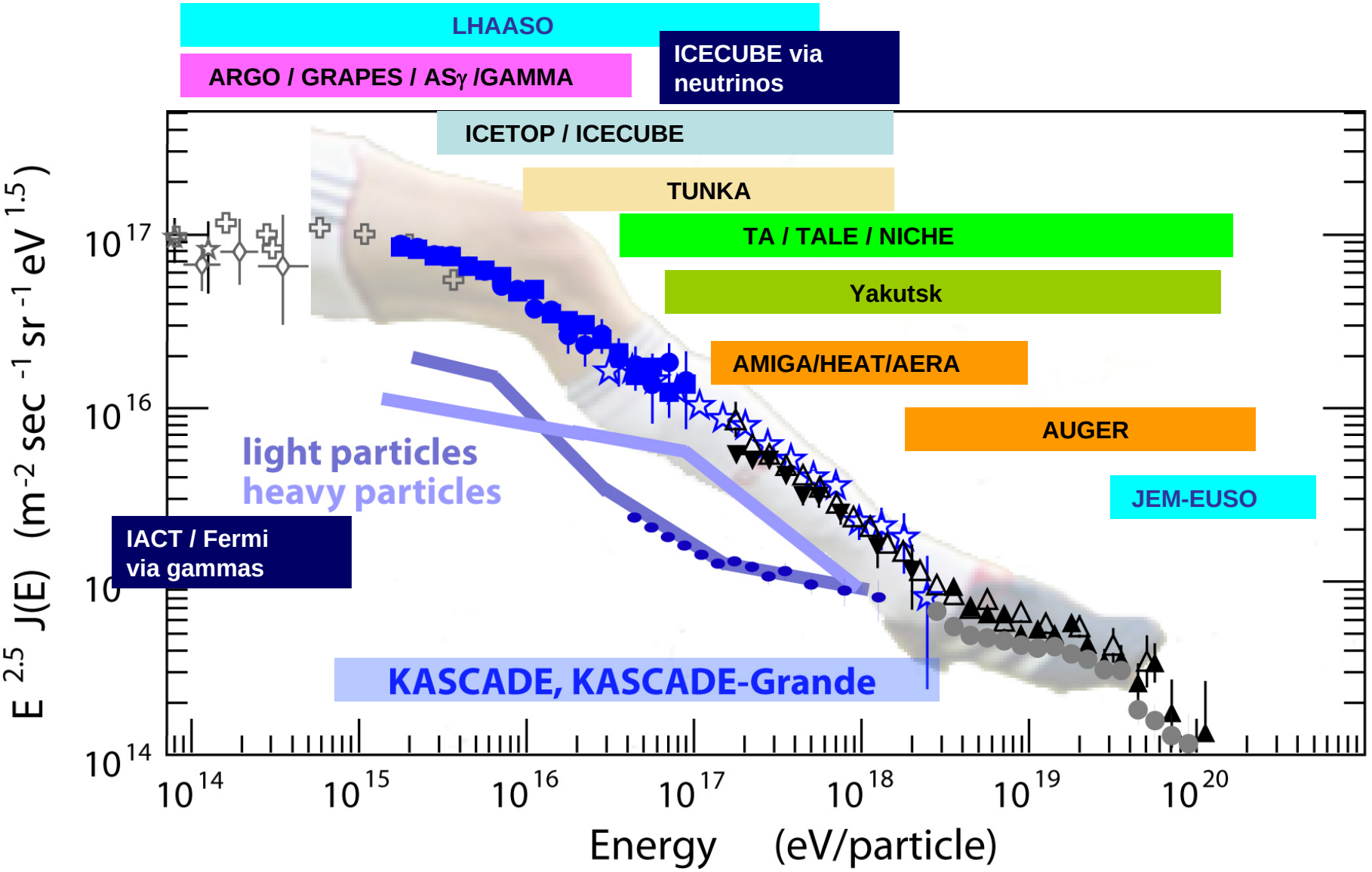




KASCADE-Grande: Mission Accomplished !!

open access to research data
https://kcdc.ikp.kit.edu

Summary



answers only by combining all information: stay tuned!

KASCADE:
Contribution to most important question!

©Claus Grupen

Hopefully not another
100 years (since V.Hess)
or even 25 years (since KASCADE)
needed to finally answer
this question