Present status of the experimental high-energy cosmic ray research

J.C. Arteaga Velázquez

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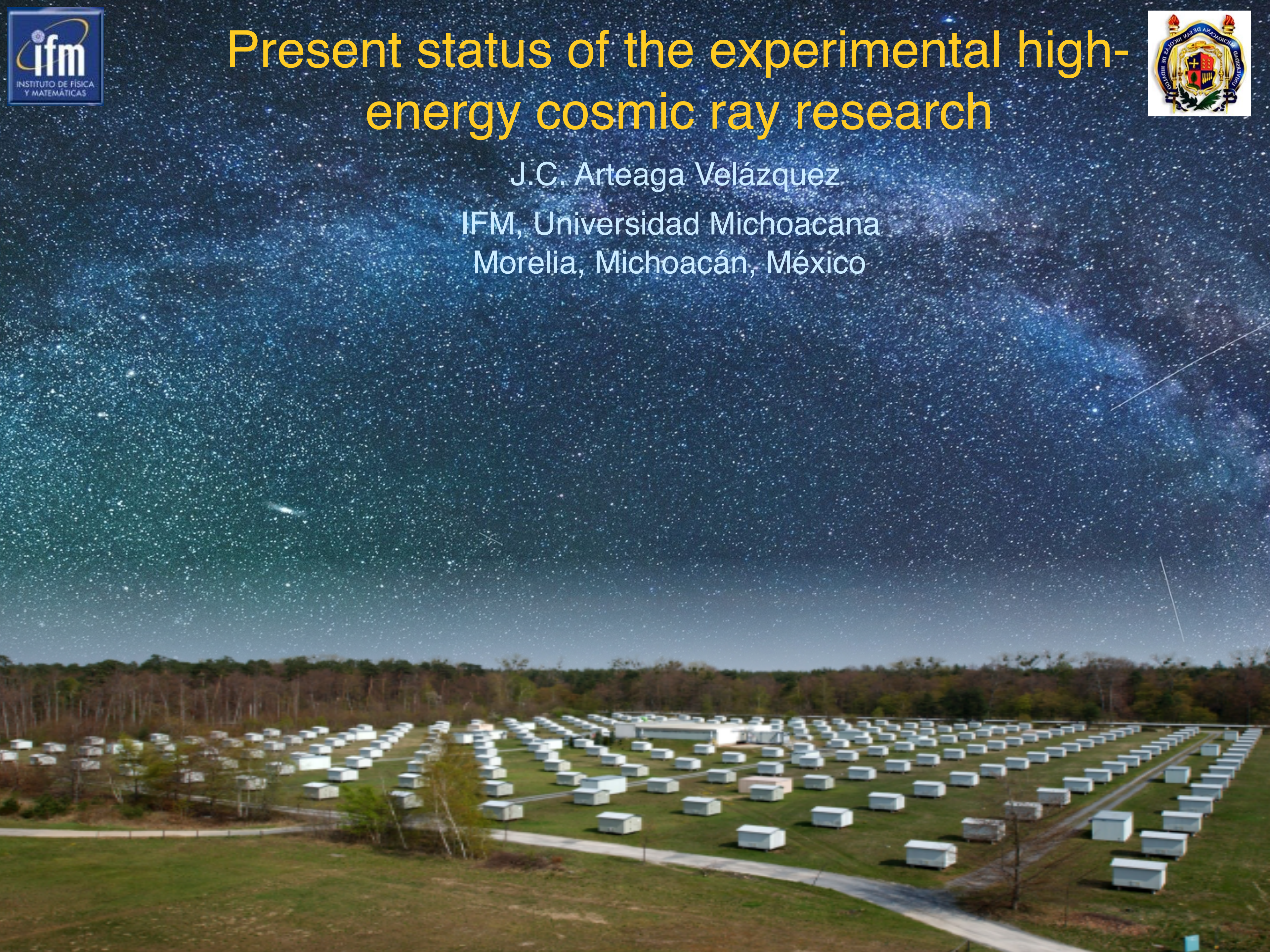

Present status of the experimental high-energy cosmic ray research

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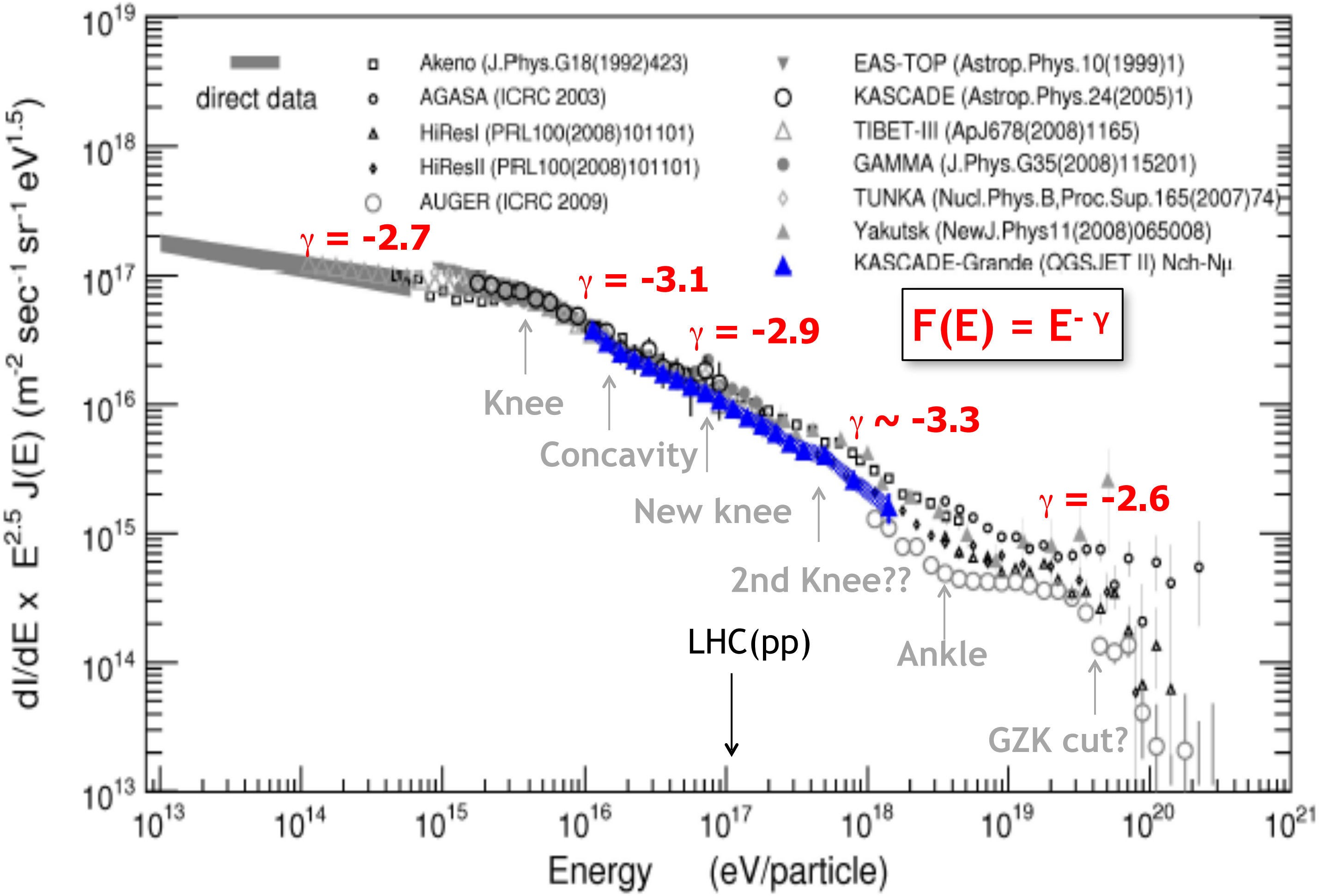
Overview

1) Introduction
2) The energy spectrum of Cosmic Rays
3) Detectors & Results
4) Astrophysical interpretation
5) Summary

2) Energy spectrum



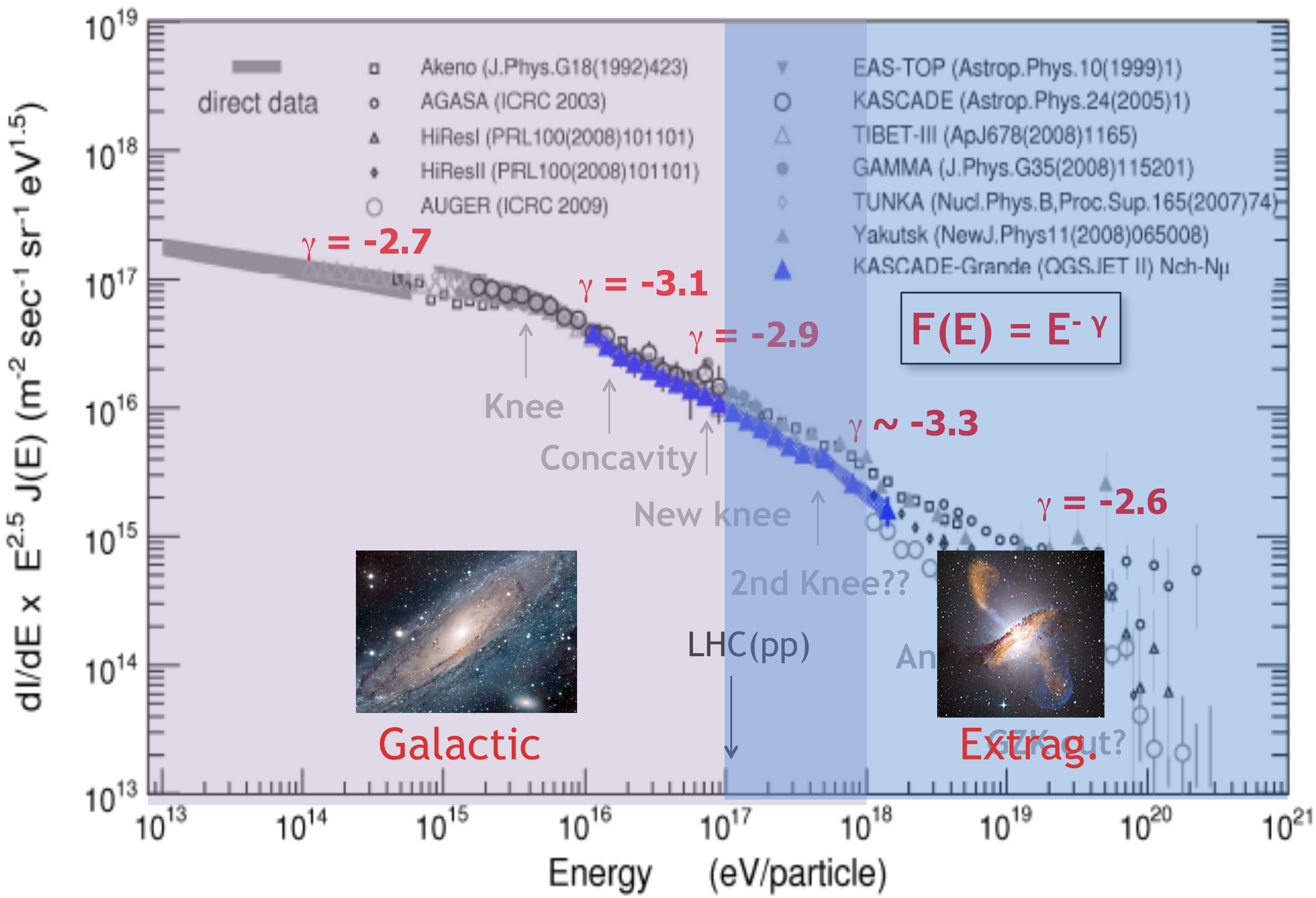
Questions

- Sources
- Acceleration
- Propagation
- Spectral features origin
- Composition
- Galactic-extragalactic transition

Data

- Spectrum
- Composition
- Arrival direction
- γ/ν

2) Energy spectrum



Questions

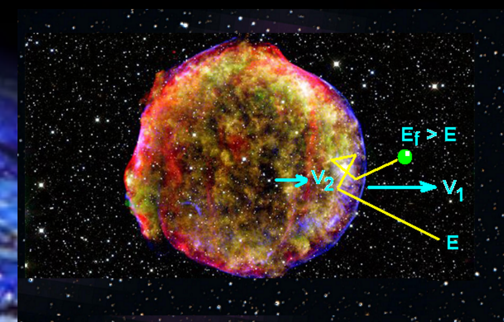
- Sources
- Acceleration
- Propagation
- Spectral features origin
- Composition
- Galactic-extragalactic transition

Data

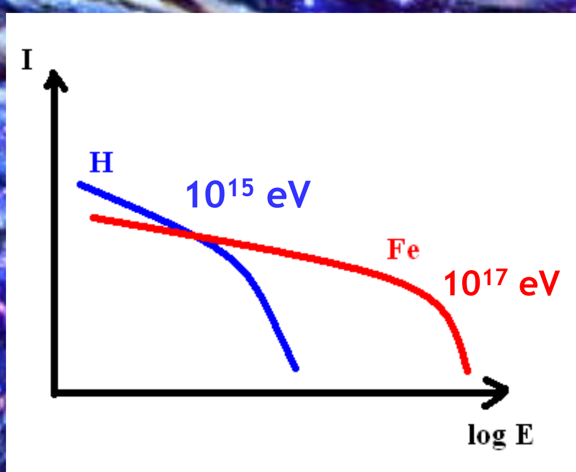
- Spectrum
- Composition
- Arrival direction
- γ/ν

Problem with galactic confinement:
$E_{max} \sim Ze \times B \times R$

G. Giacinti et al., Phys. Rev. D 91, (2015)



$L_{cr} \sim 10^{40}$ erg/s = 10% L_{SNR}



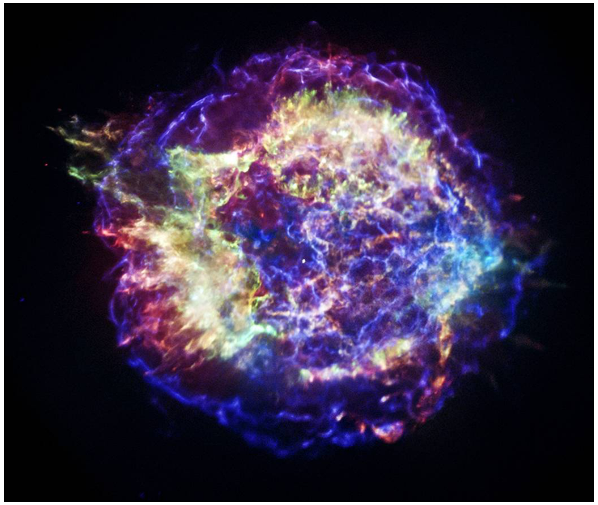
Problem with efficiency of accelerators (Fermi mechanism):

$$E_{\max}(Z) = Ze \times R_c = Z \times E_{\max}(Z=1)$$

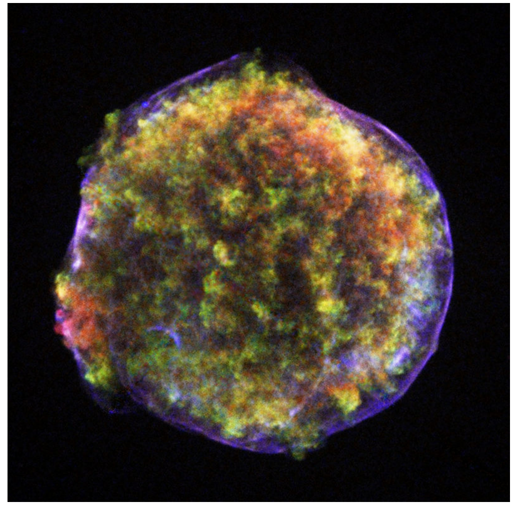
$E^{H}_{max} = 4 \times 10^{15}$ eV & $E^{Fe}_{max} = 10^{17}$ eV

T.K.Gaisser et al., Frontiers of Phys. 8 (2013)

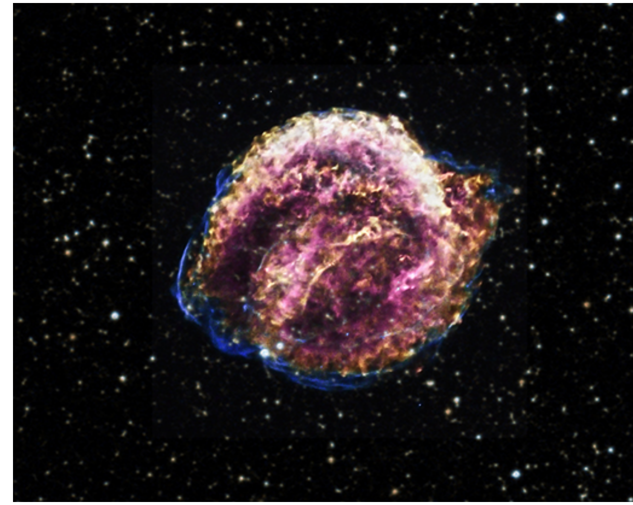
2) Energy spectrum



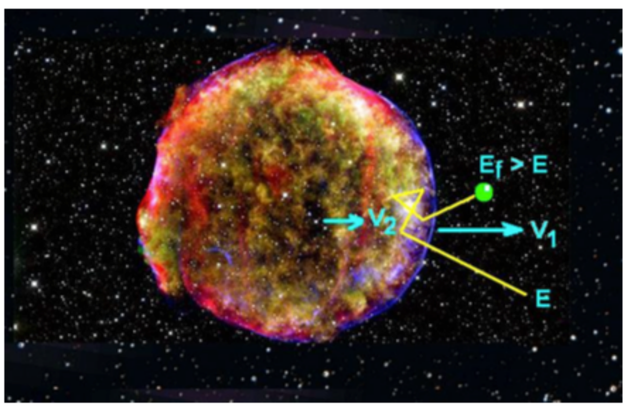
Cassiopea A



Tycho



Kepler



Modelo Remanente de Supernova:

- Mecanismo fermi 1er Orden

  $\Delta E/E \sim (v_2/c) = \beta$

- Energía máxima

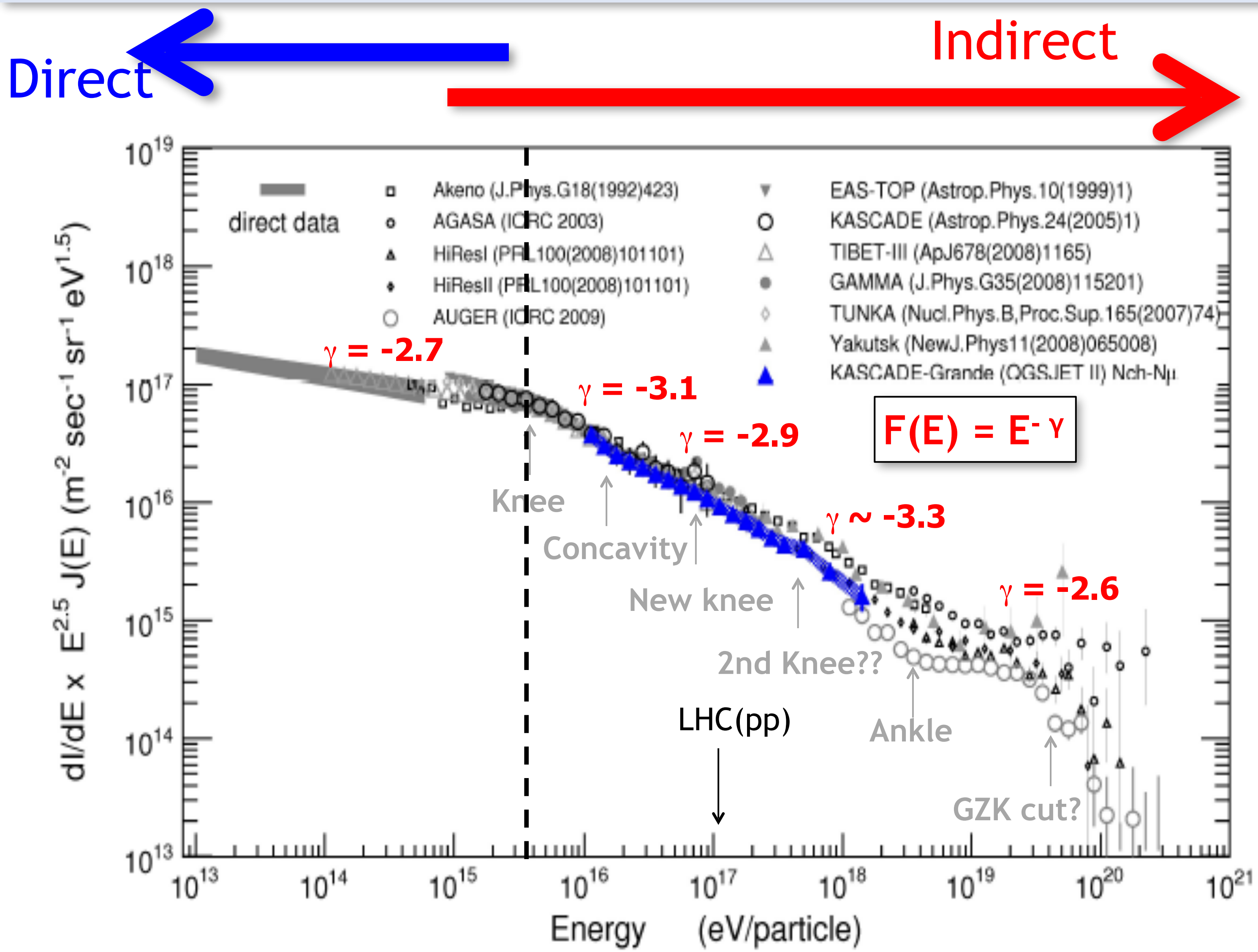
  $E_{max} \sim Ze \cdot \beta_s \cdot B \cdot R$

- Espectro de la forma

  $dN/dE \sim E^{-(\gamma_o + \varepsilon)}$

  donde $\gamma_o = 2$ y $\varepsilon < 1$

2) Energy spectrum

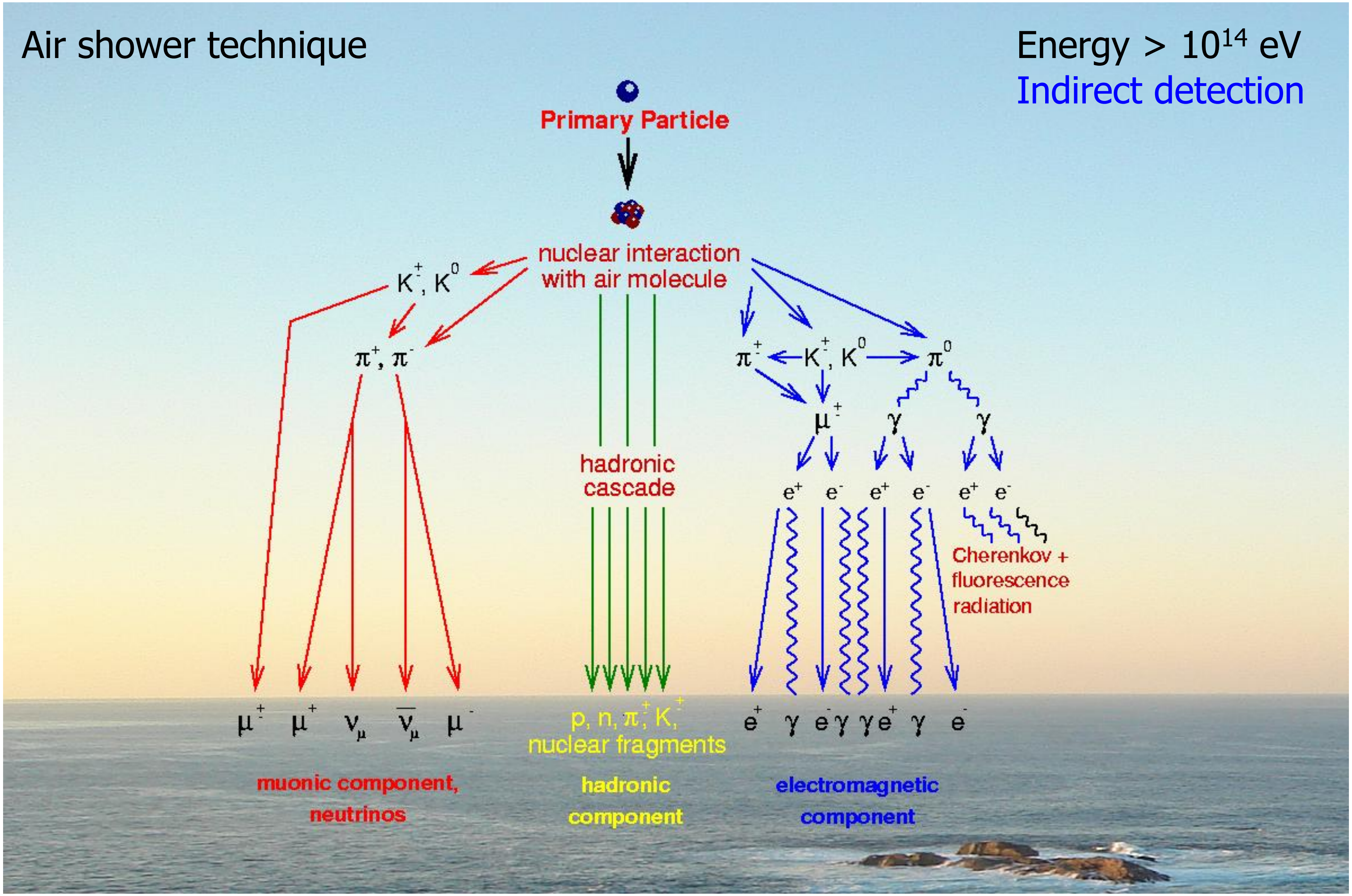


2) Energy spectrum

Air shower technique

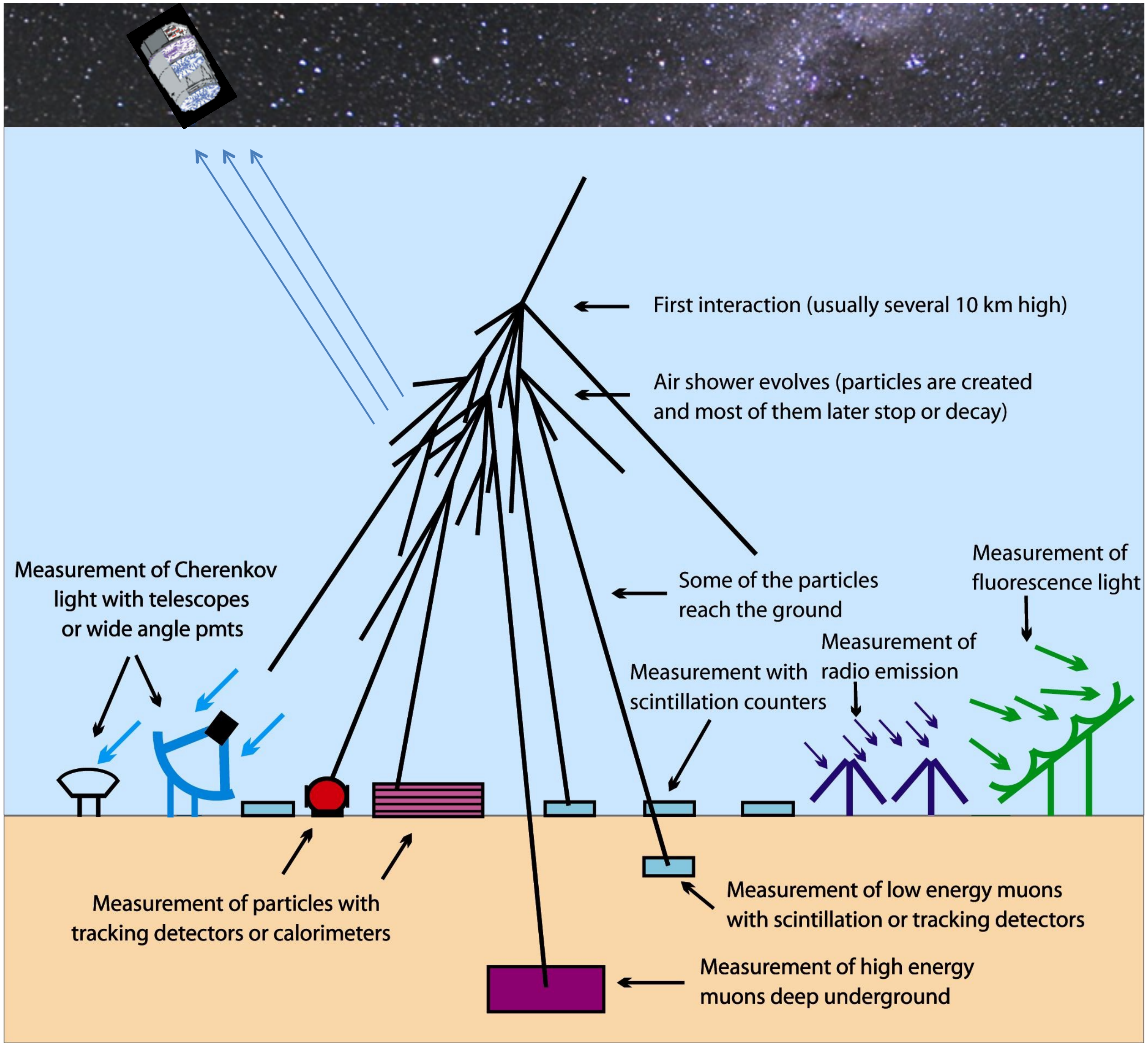
Energy > 10^{14} eV

Indirect detection

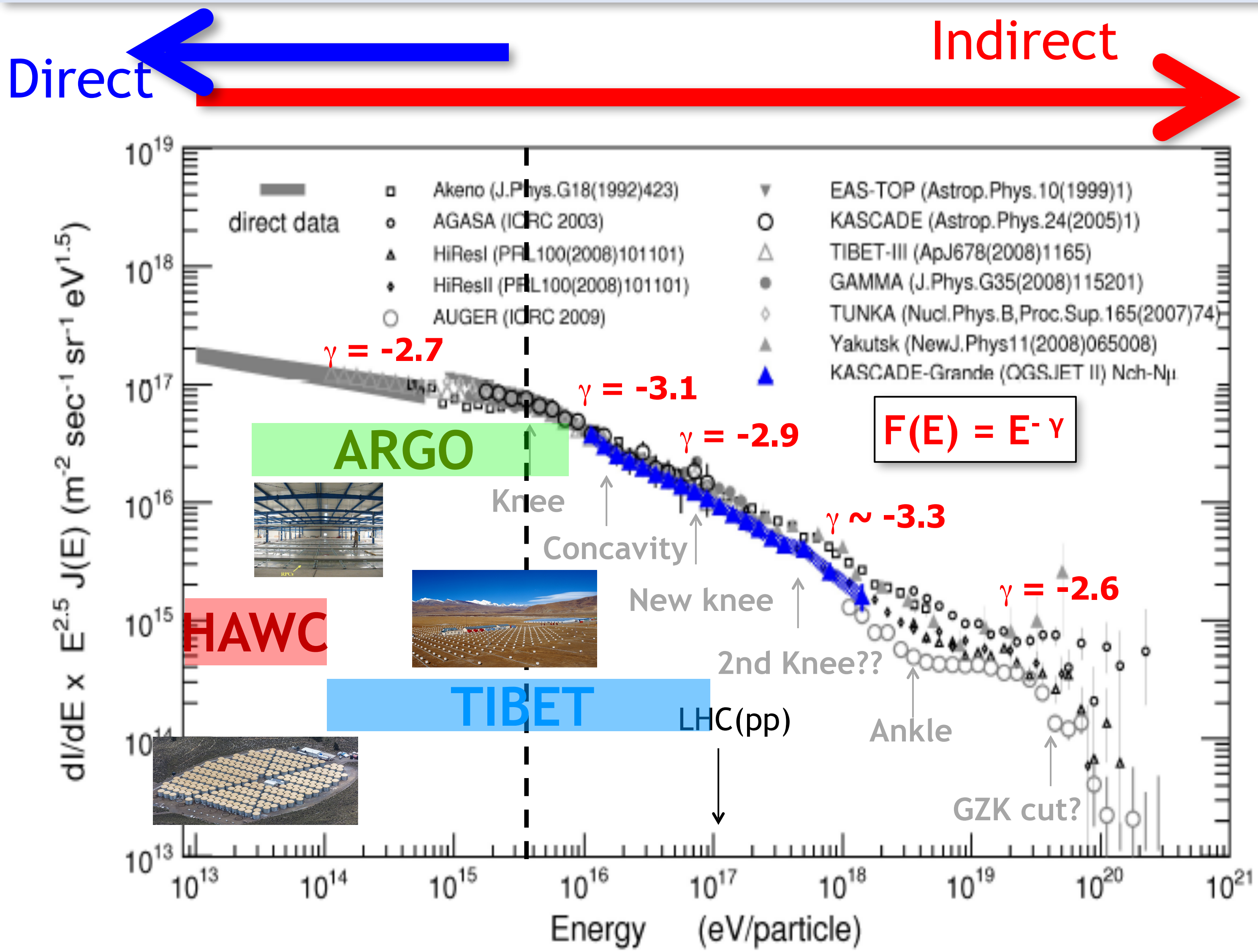


2) Energy spectrum

Detection



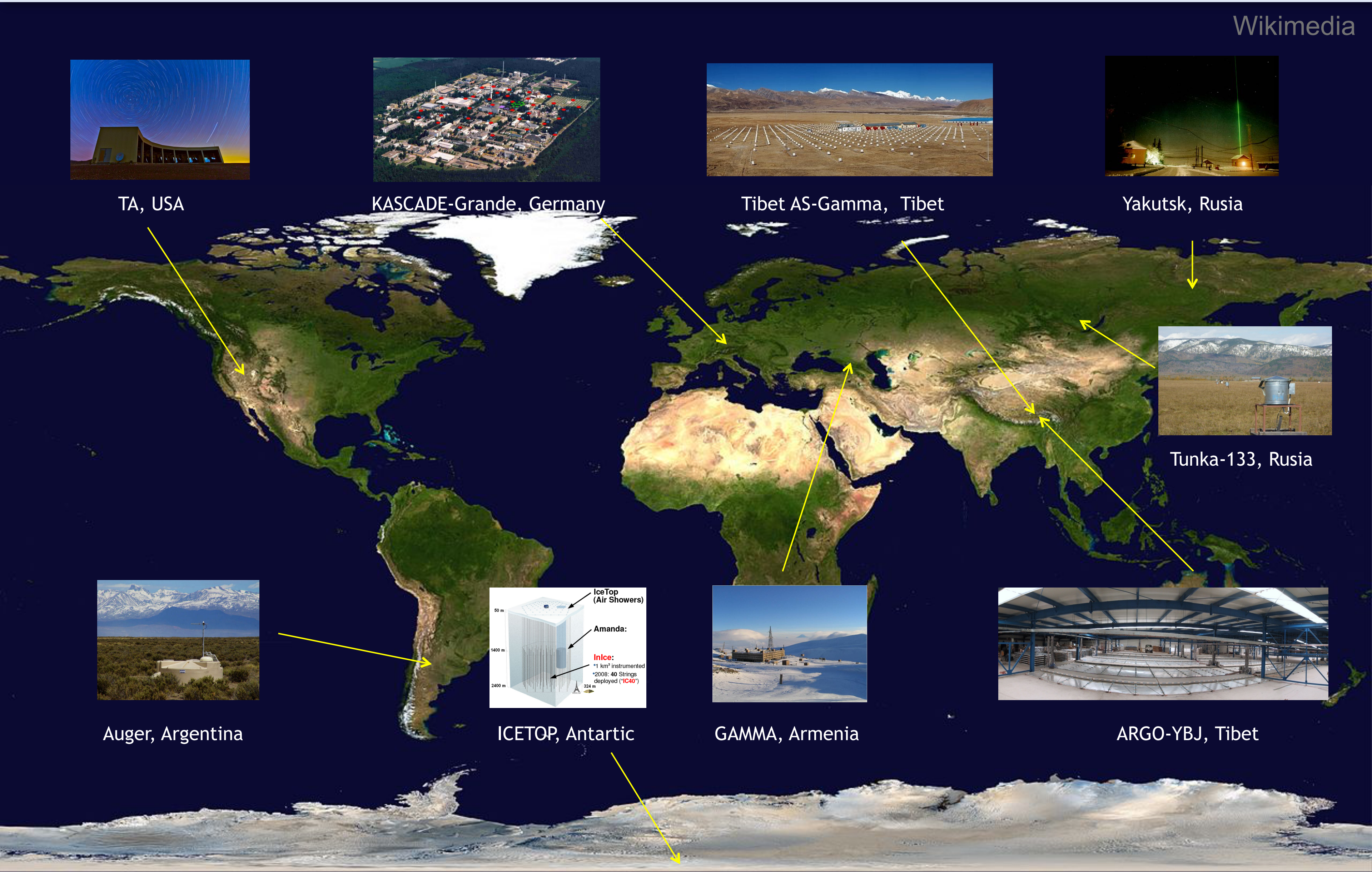
2) Energy spectrum

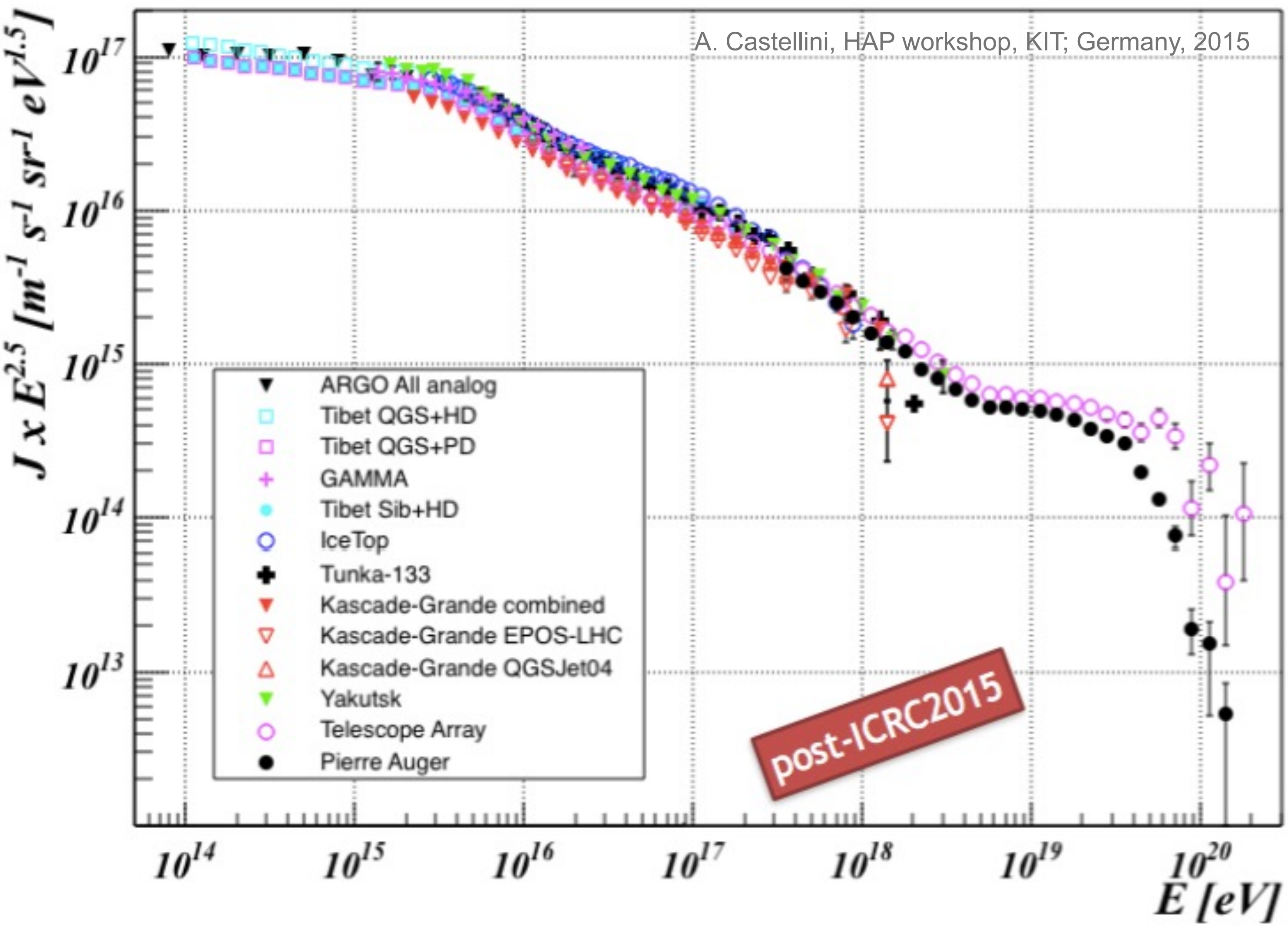


Indirect measurements extended below 1 PeV

2) Energy spectrum

Wikimedia



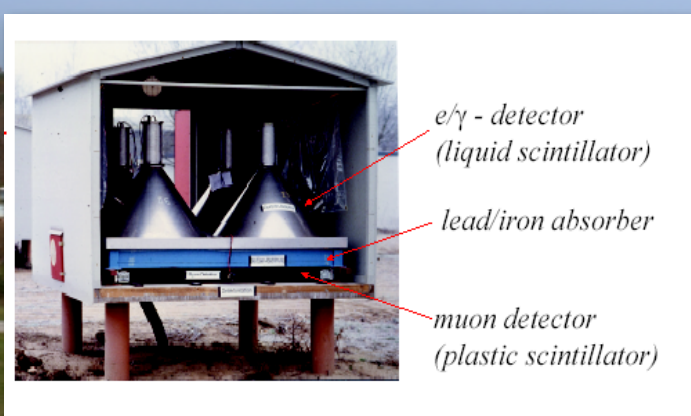


In general, good agreement regarding main features of the all-particle spectrum

The KASCADE experiment

Karlsruhe Shower Core and Array Detector

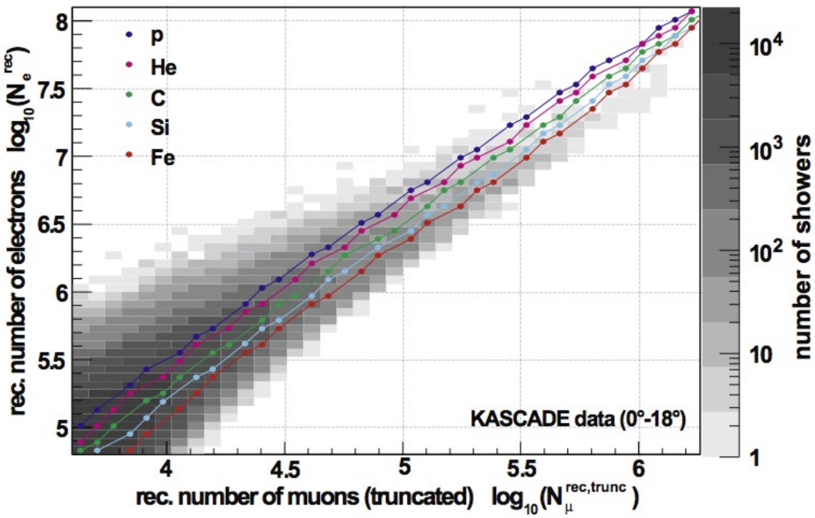
- Components:
  - Ground array with 252 e/γ and μ scintillator detectors
  - Central detector (Calorimeter, μ detectors)
  - Muon tracking detector
- Observables:
  N_e, N_μ, N_{hadron}
- $E = 10^{14} - 10^{17}$ eV



3) Detectors & Results

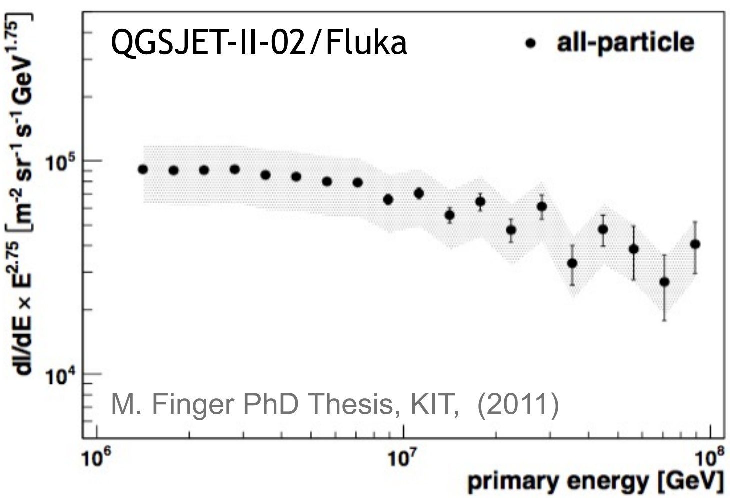
Unfolding: $n_A(\lg N_e, \lg N_\mu) = \int_0^\infty p_A(\lg N_e, \lg N_\mu \,|\, E)\, f_A(E)\, dE$

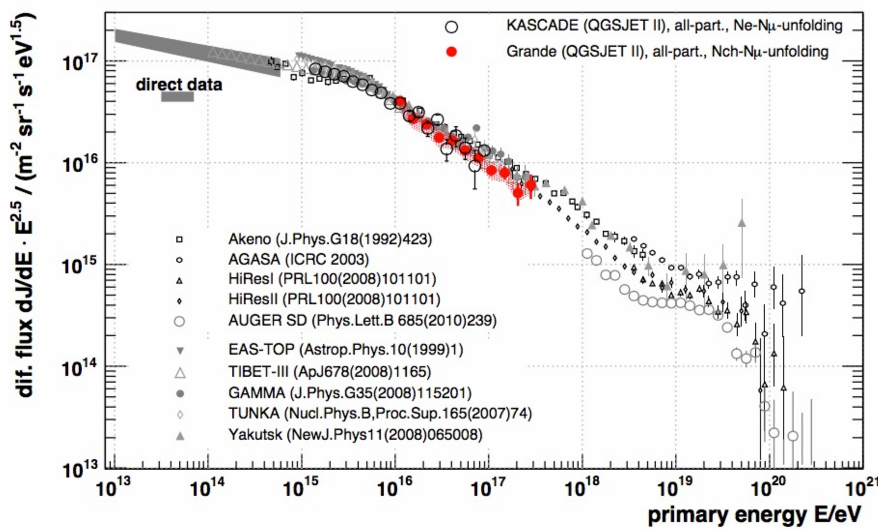
E = 10^{15} - 10^{17} eV



- Knee at 4 - 5 x 10^{15} eV
- Agreement with experiments at lower and higher energies

D. Fuhrmann, PhD Thesis, KIT, (2012)





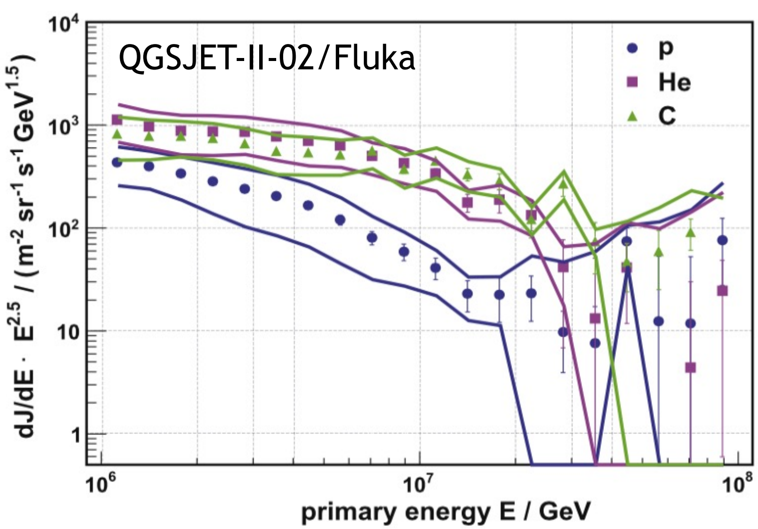
3) Detectors & Results

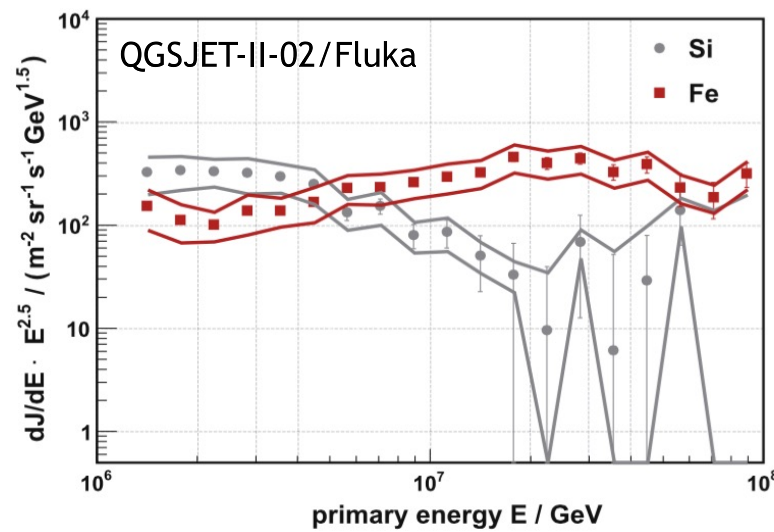
Spectra of elemental groups: E = 10^{15} - 10^{17} eV

- Knee produced by light component
- Knee position change with composition
- E_{knee} α Z or A?
- E^{Fe}_{knee} ~ 10^{17} eV?

Z	Knee (10^{15}eV)
H (Z = 1)	4
He (z = 2)	7-8
C (Z = 6)	20-30

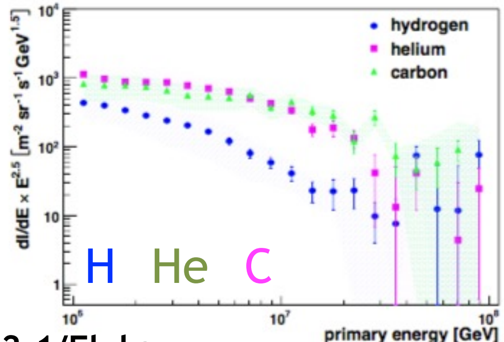
D. Fuhrmann et al., Astrop. Phys. 47 (2013)

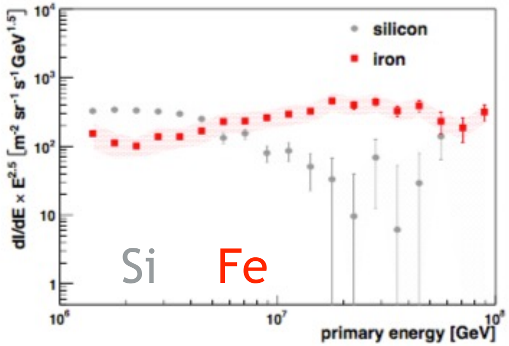




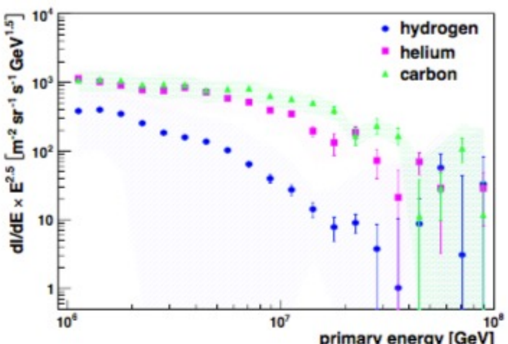
3) Detectors & Results

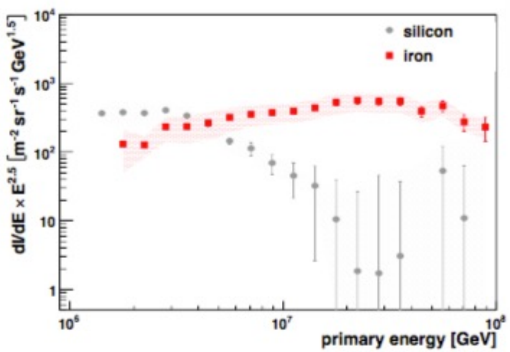
QGSJET-II-02/Fluka



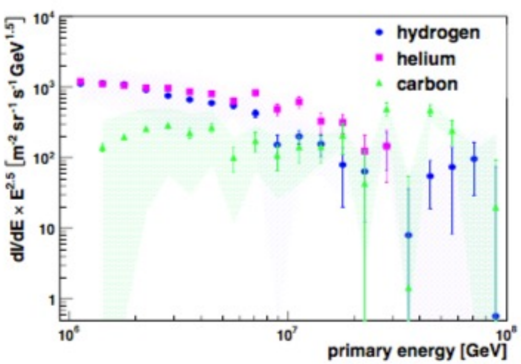


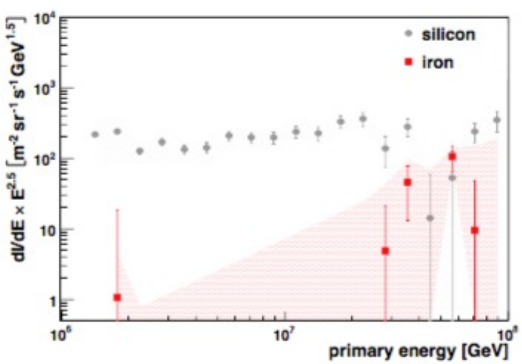
SIBYLL 2.1/Fluka





EPOS 1.99/Fluka



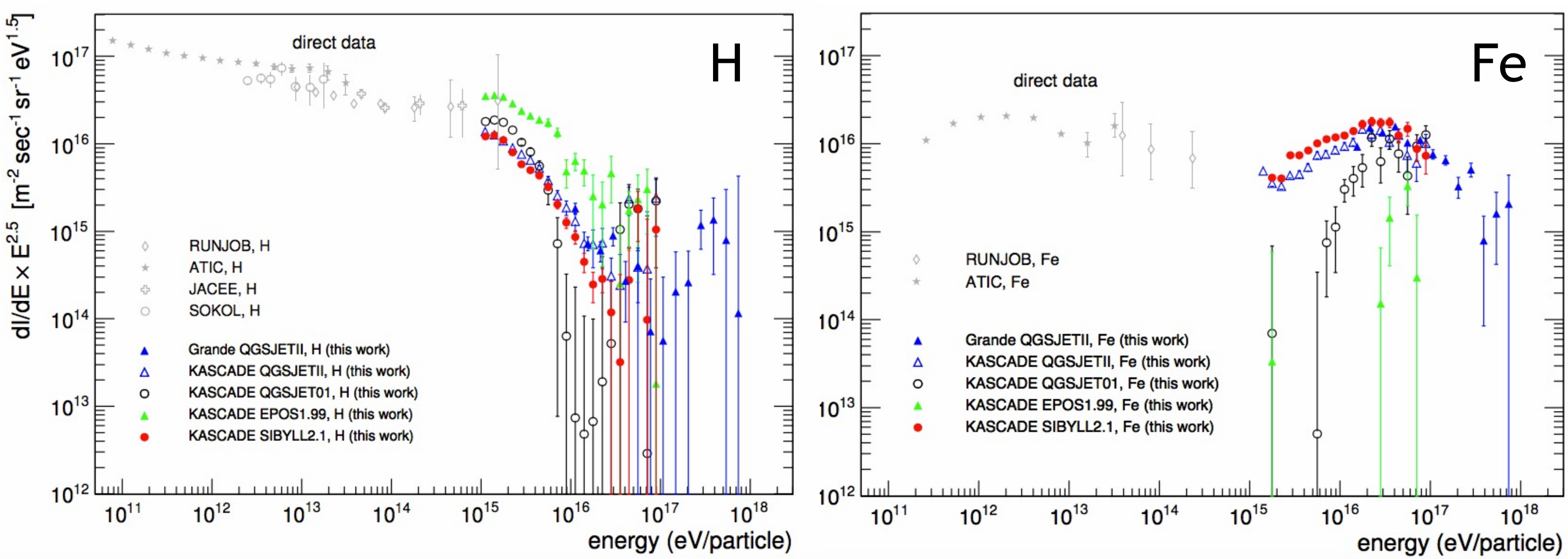


Effect of hadronic interaction models:

- Relative abundances change.
- Main results for light mass groups independent of both result and model.

M. Finger PhD Thesis, KIT, (2011)

Composition: Comparison with direct measurements



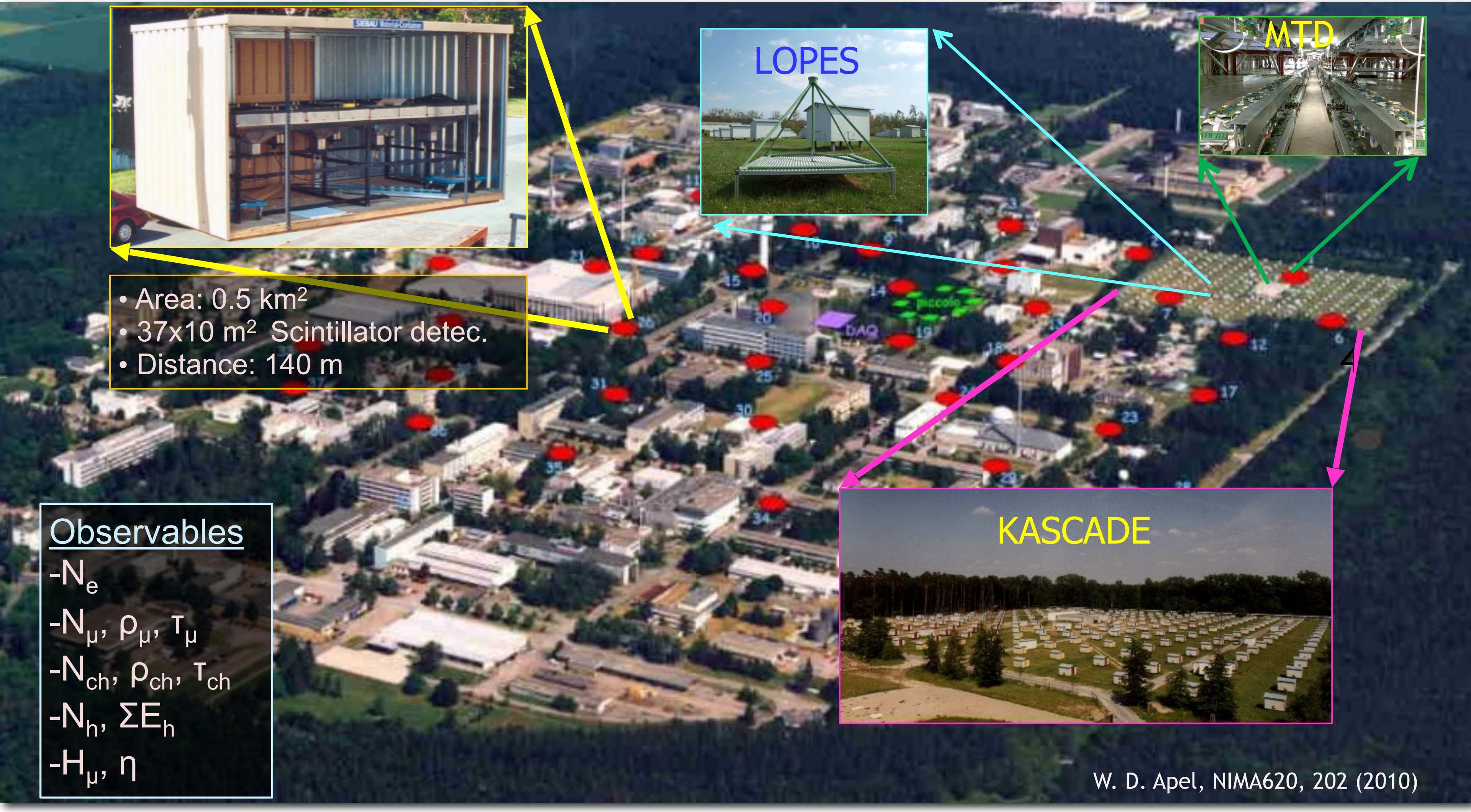
Good agreement with direct measurements

M. Finger PhD Thesis, KIT, (2011)

3) Detectors & Results

KASCADE-Grande detector

$E = 10^{16} - 10^{18}$ eV



- Area: 0.5 km^2
- 37x10 m^2 Scintillator detec.
- Distance: 140 m

Observables

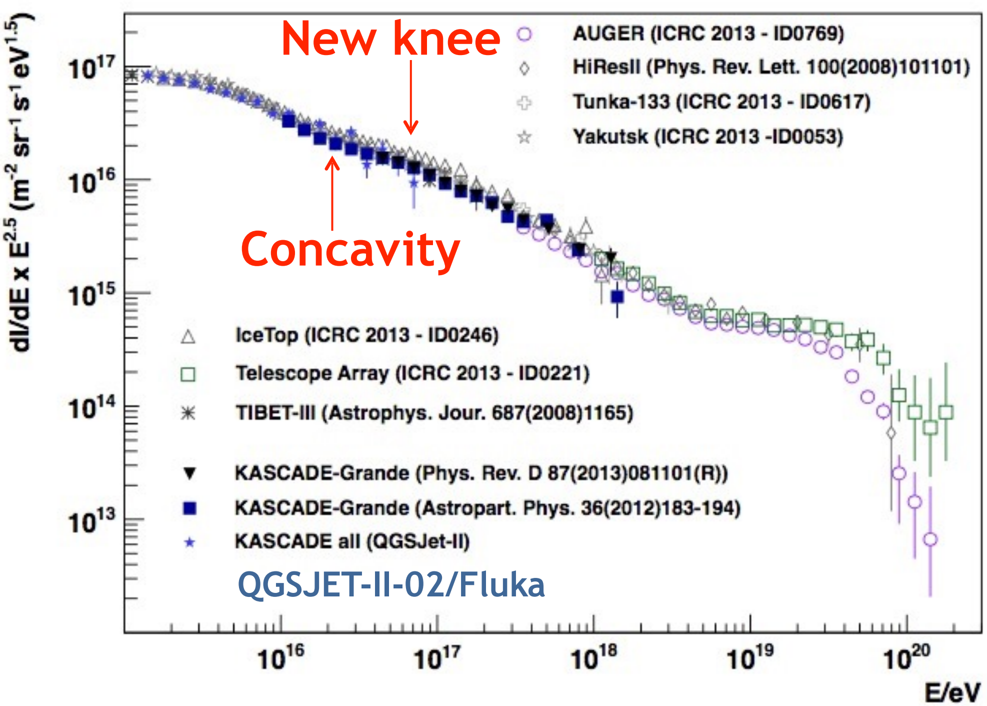
- N_e
- N_μ, ρ_μ, τ_μ
- N_{ch}, ρ_{ch}, τ_{ch}
- N_h, ΣE_h
- H_μ, η

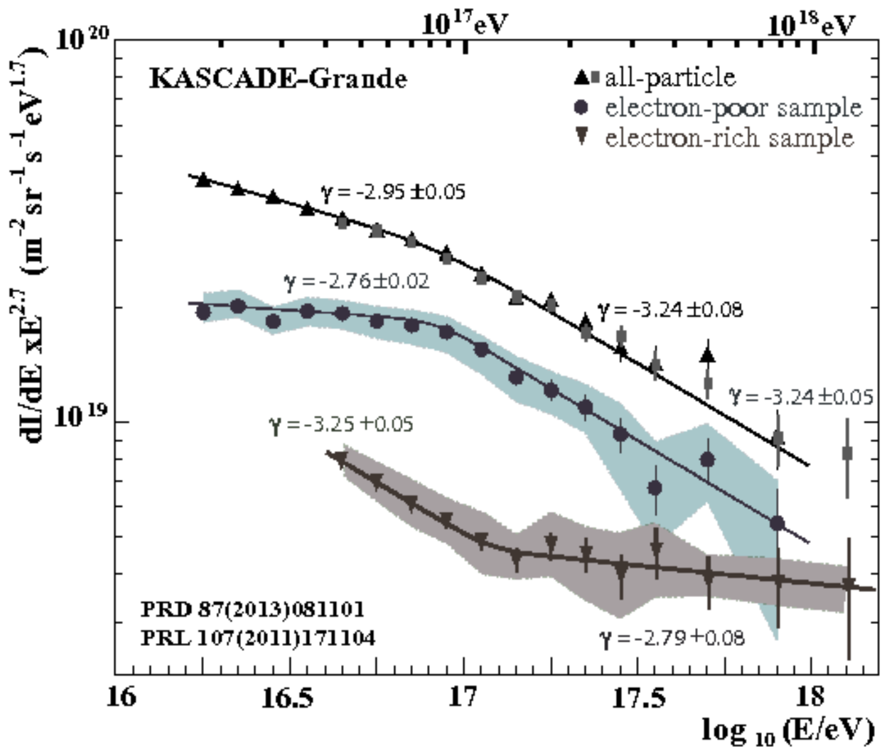
W. D. Apel, NIMA620, 202 (2010)

3) Detectors & Results

All-particle energy spectrum: E = 10^{16} - 10^{18} eV

Light/heavy mass groups



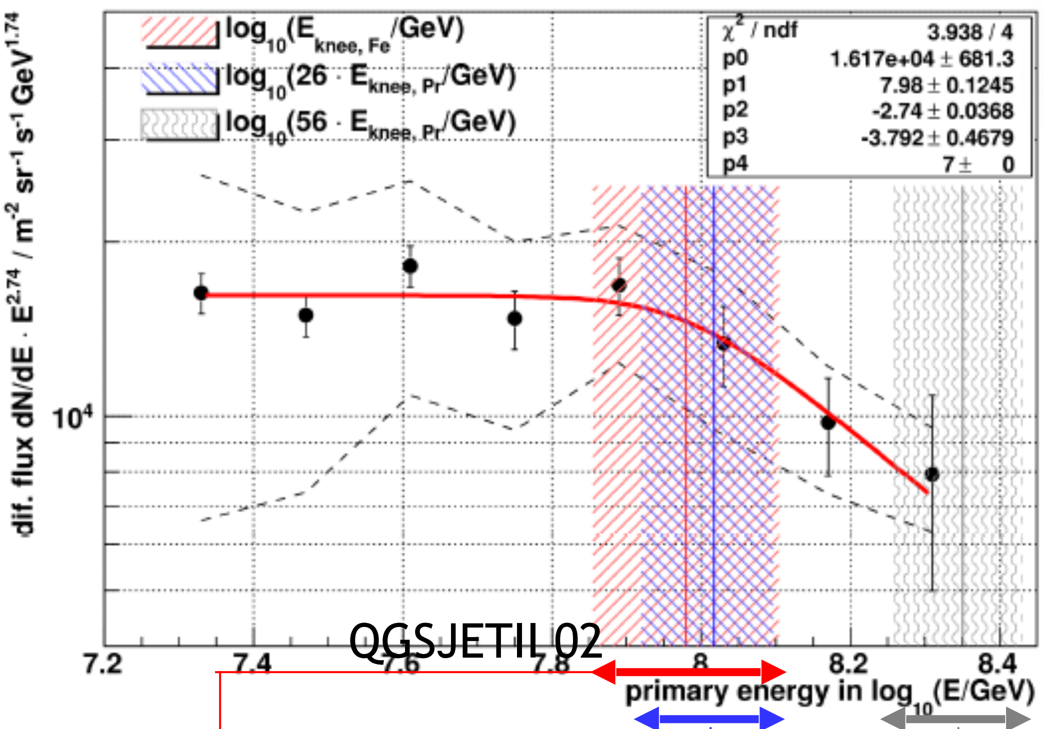


Observation of two new features

Heavy Knee: 8 x10^{16} eV

Light Ankle: 10^{17} eV

Energy spectrum of the iron component



In favor of rigidity dependent scenario of galactic CR's

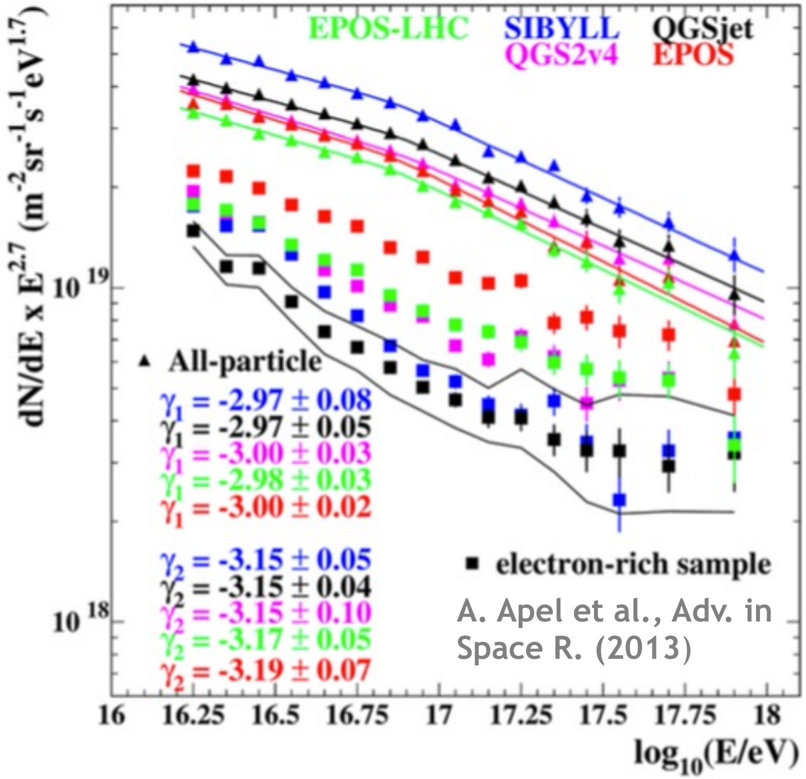
A. Apel et al., Astropart. Phys. 47 (2013)

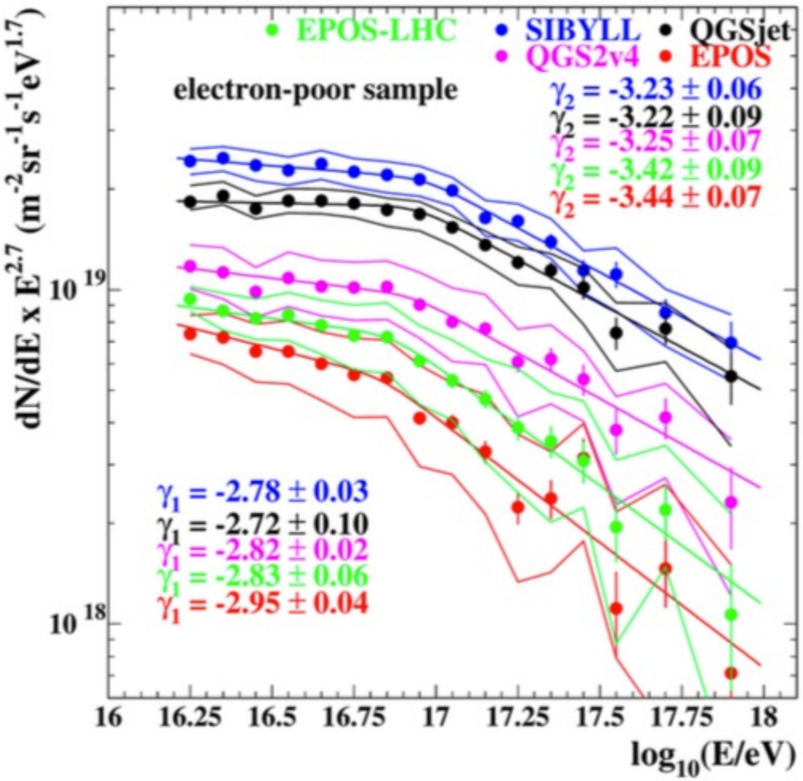
Expected if $E_k \propto A$

KASCADE-Grande

Expected from the KASCADE data if $E_k \propto Z$

Spectra of light/Heavy groups: Effect of hadronic interaction models



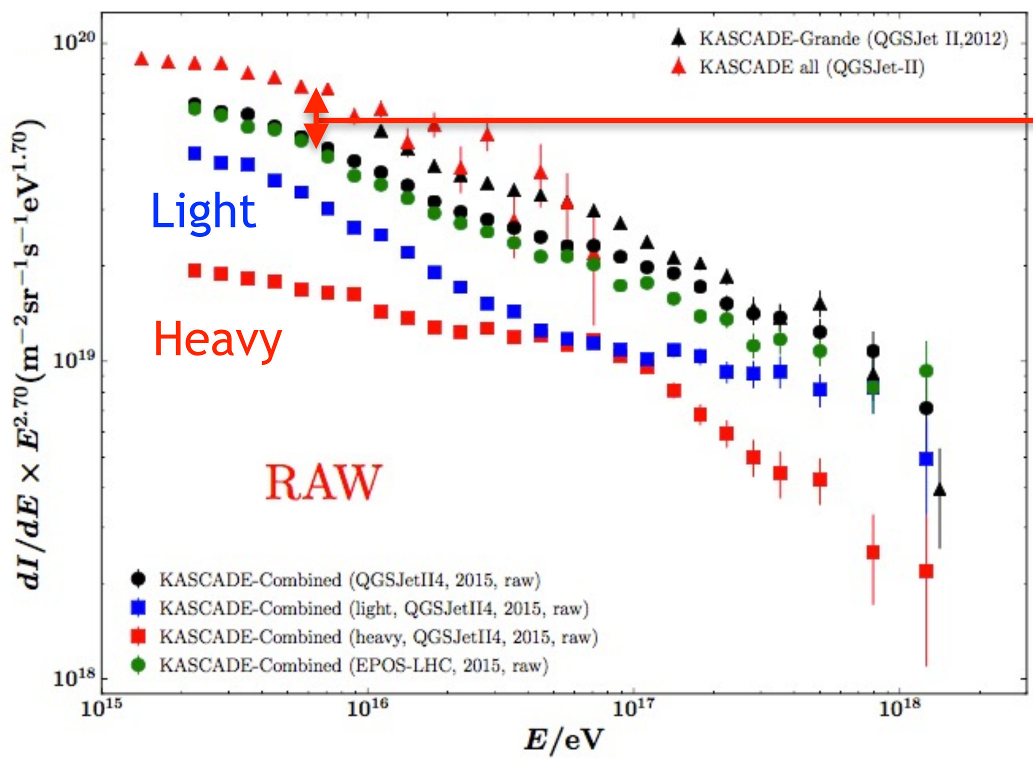


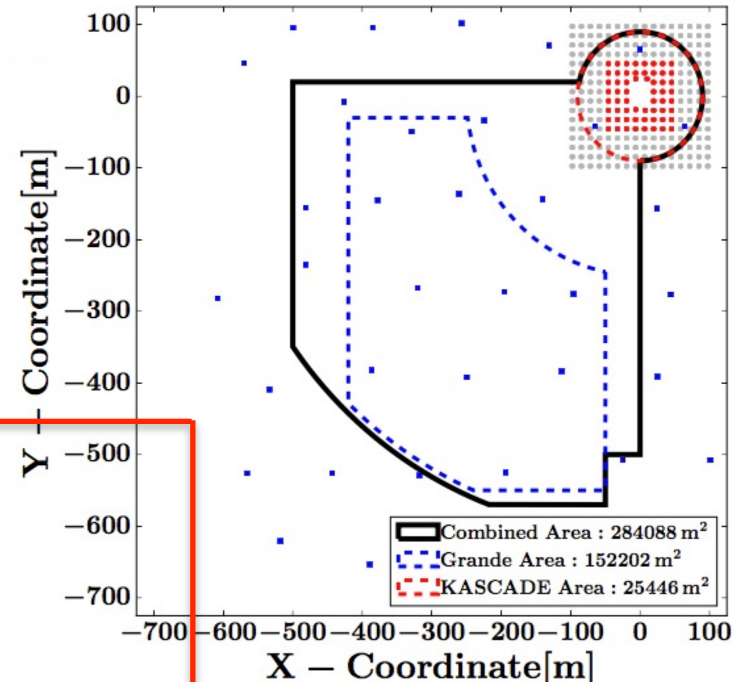
- Main features are retained.
- Location of features slightly dependent of model.
- Relative abundances sensitive to hadronic models.

3) Detectors & Results

All-particle energy spectrum: E = 10^{15} - 10^{18} eV

- KASCADE/KASCADE-Grande combined analysis in progress

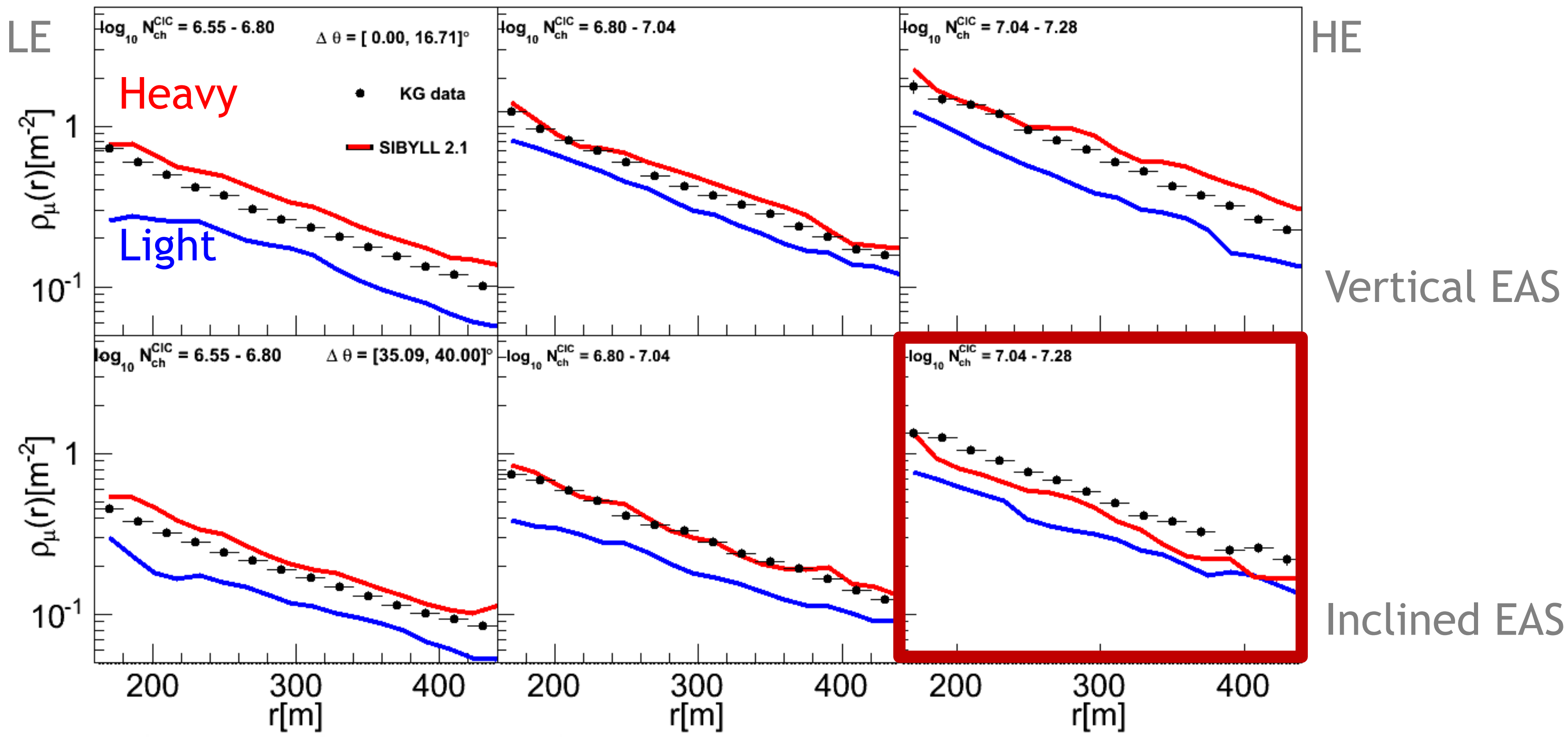




All-particle: Variation between post-/pre-LHC models

S. Schooi, HAP workshop, KIT; Germany, 2015

3) Detectors & Results

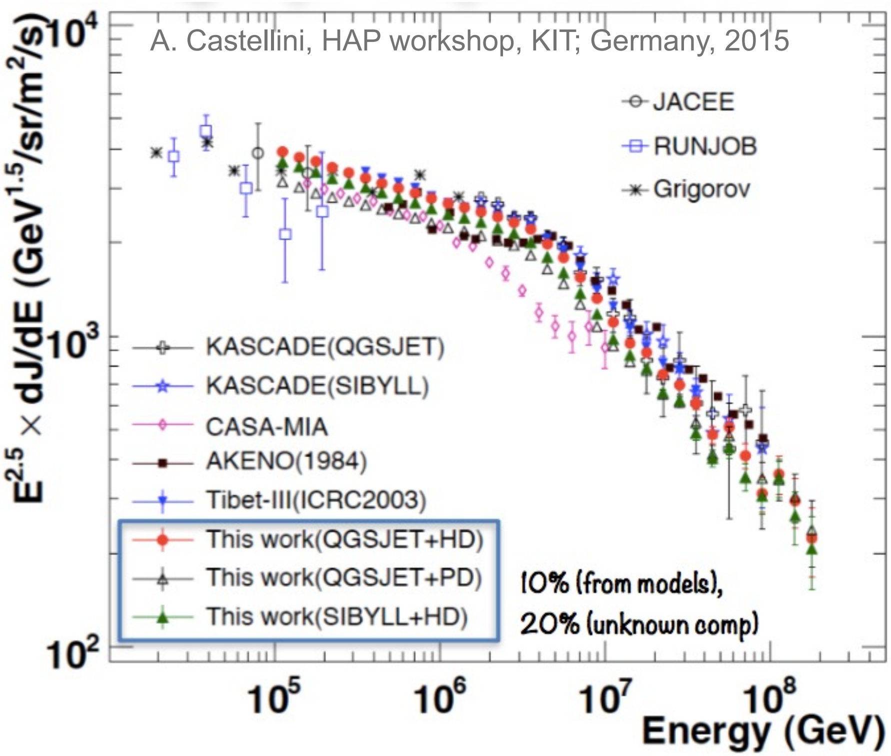


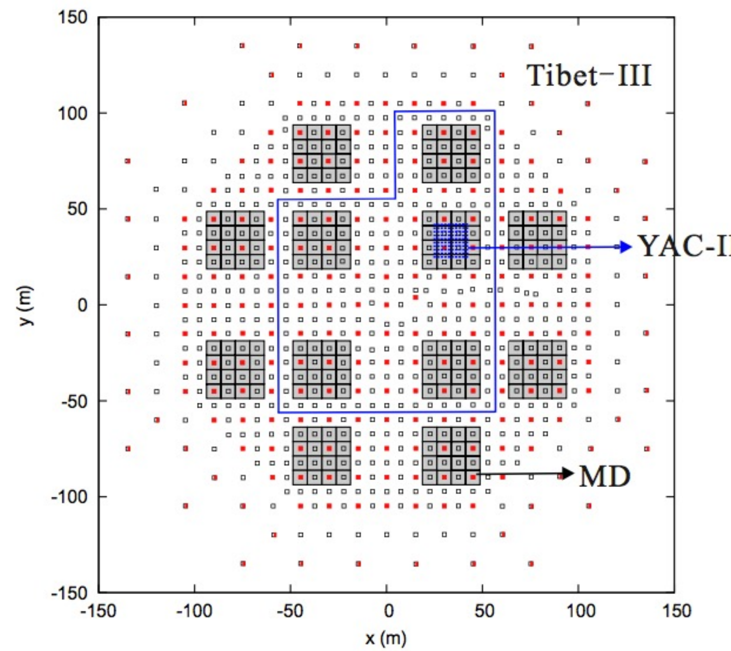
SIBYLL 2.1 predictions for Fe+Si/H+He are **smaller than the measured data** at HE for inclined EAS

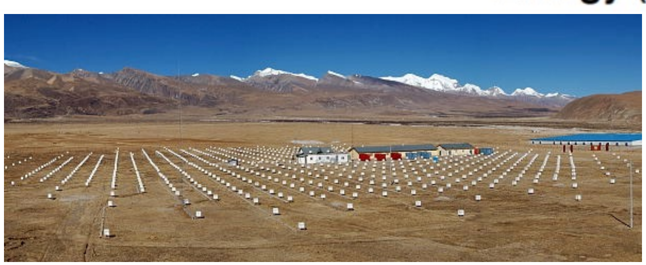
3) Detectors & Results

Tibet AS-gamma: All-particle flux (10^{14}-10^{17} eV)

L- Jin-Sheng et al., arxiv: 1501.06327
J. Huang, et al., Astop. Phys. 66 (2015)







Hybrid detector, 606 g/cm^2, China

Instrument	*Area (m^2)*	*Detectors*	*Type*
Tibet-III	*5,000*	*789 particle counters*	N_e
YAC-II	*500*	*124 shielded scintillator counters*	*e.m.*
MD array	*4,500*	*5 underground water Cherenkov tanks*	N_μ

3) Detectors & Results

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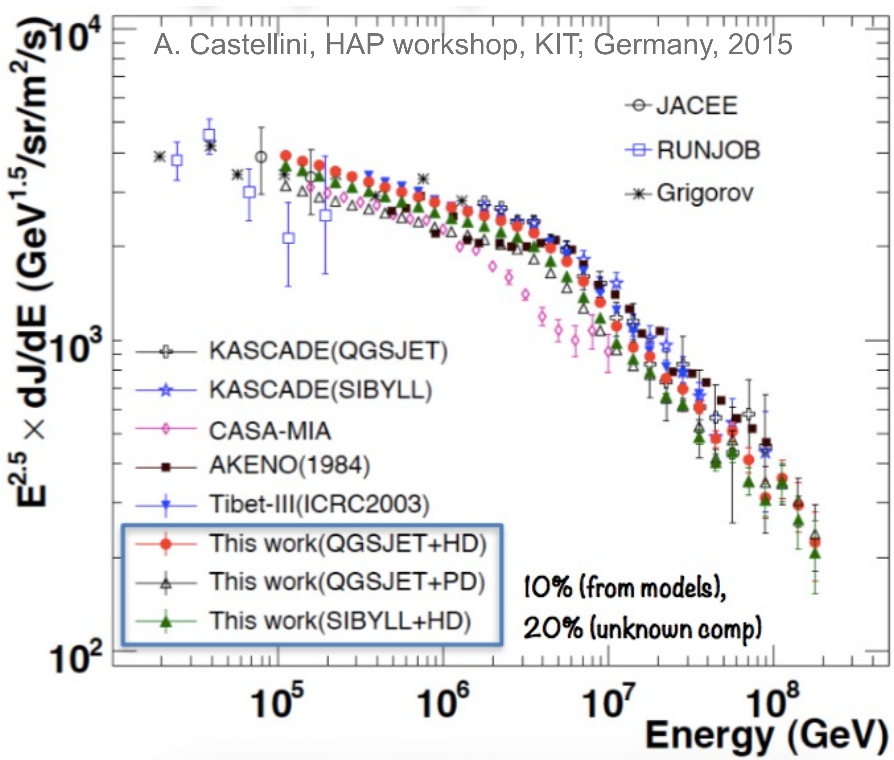
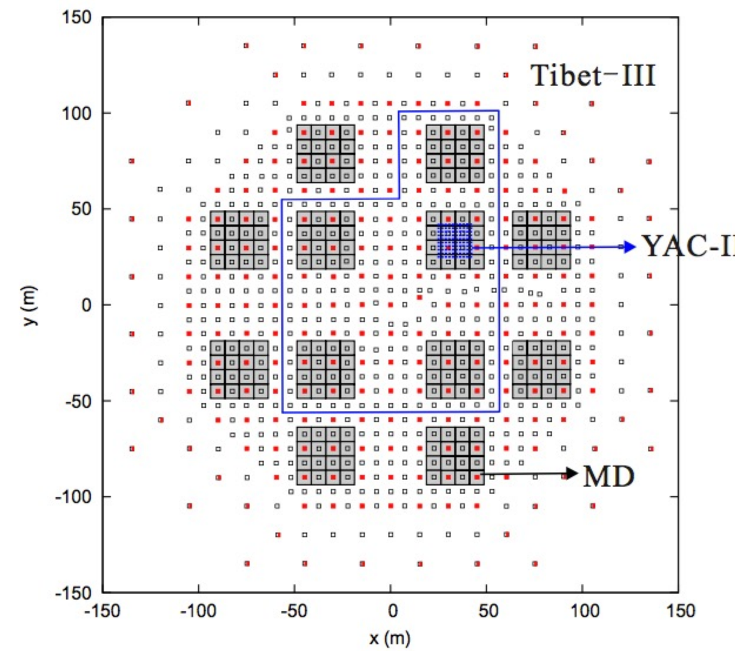
J. Huang, et al., Astop. Phys. 66 (2015)





Good agreement with direct measurements at low energies

Knee position in agreement with KASCADE results

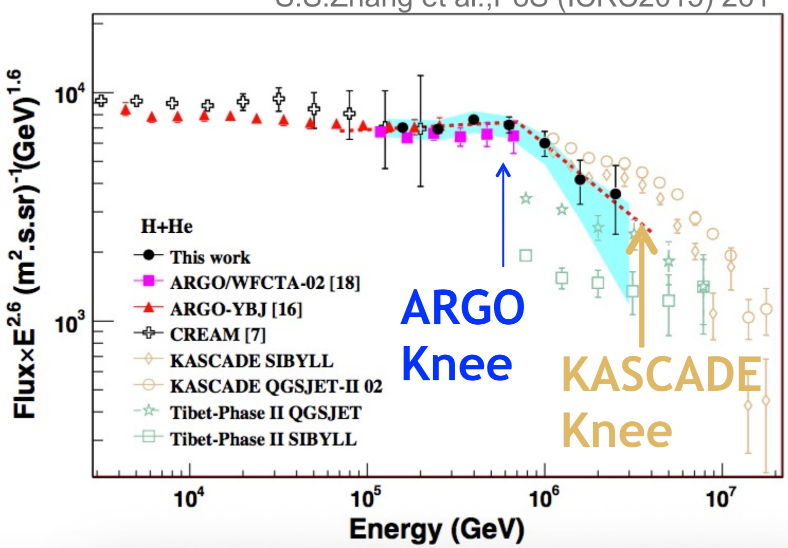
Model	Knee
QGSJET+Heavy D.	*4.0 ± 0.1*
QGSJET+Proton D.	*3.8 ± 0.1*
SIBYLL + Heavy D.	*4.0 ± 0.1*

3) Detectors & Results

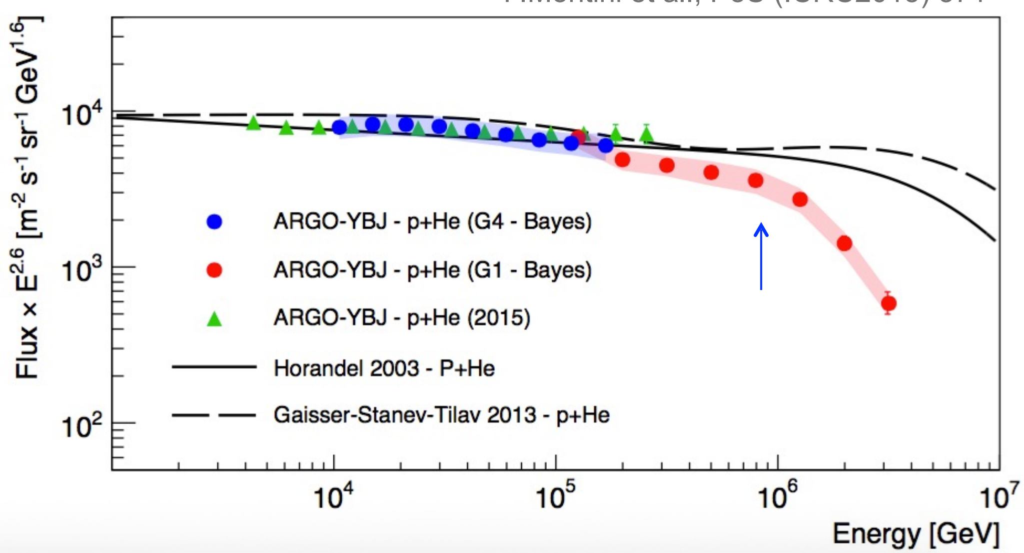
Argo-YBJ/LHAASO CTA: P&He spectrum (3 x 10^{12} - 3 x10^{15} eV)

- Argo-YBJ: 6700 m^2, 1836 Resistive Plate chambers
- Cherenkov telescope: 256 pixels, 1º x 1º each

S.S.Zhang et al.,PoS (ICRC2015) 261

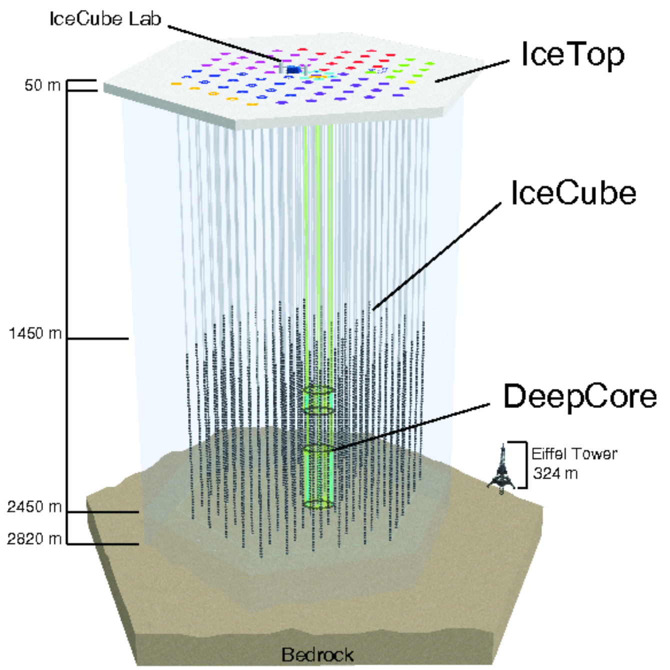


P.Montini et al., PoS (ICRC2015) 371

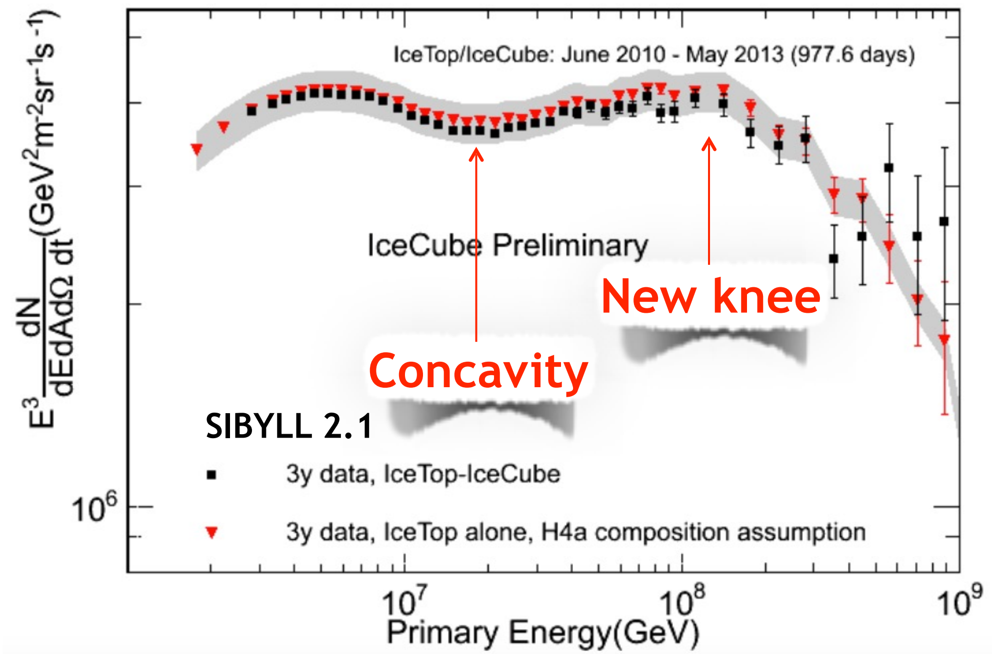


Location of light knee from ARGO (700 TeV) in disagreement with KASCADE

ICETOP/ICECUBE: All-particle spectrum (10^{15}-10^{18} eV)



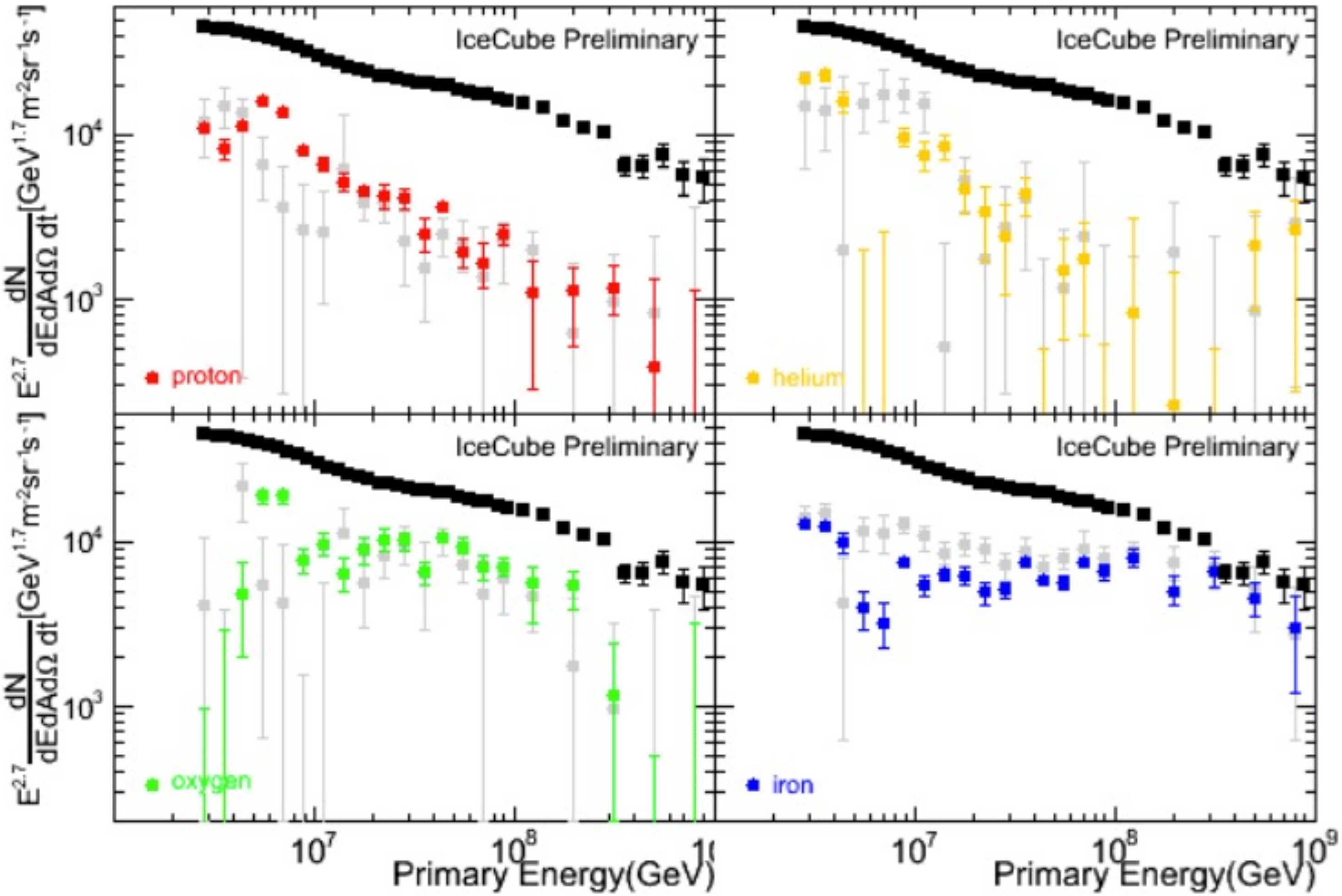
K.Rawlins et al., PoS (ICRC2015) 334



IceTop (Antartic, 2835 m a.s.l.)
- 81 Cherenkov detectors
- 1 km^2 of effective area
- Cherenkov light in ice.
- S(125m).

ICETOP/ICECUBE: Elemental mass group spectra (10^{15}-10^{18} eV)

K.Rawlins et al., PoS (ICRC2015) 334



Color:

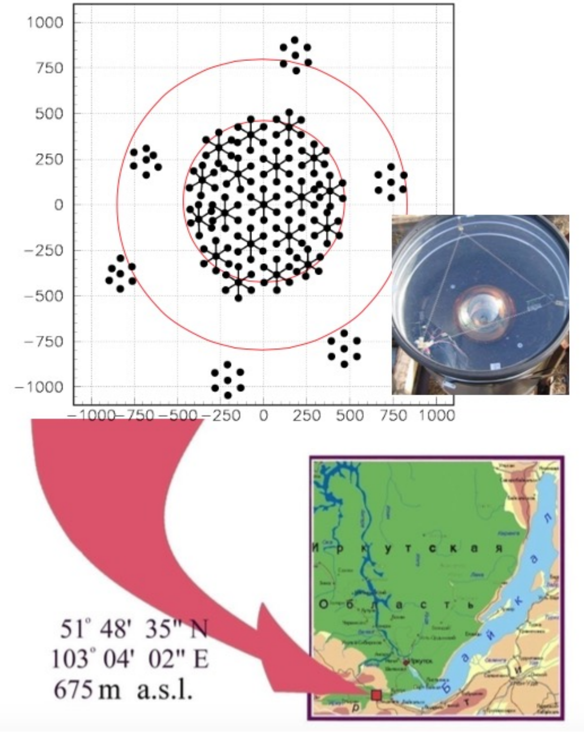
SIBYLL 2.1

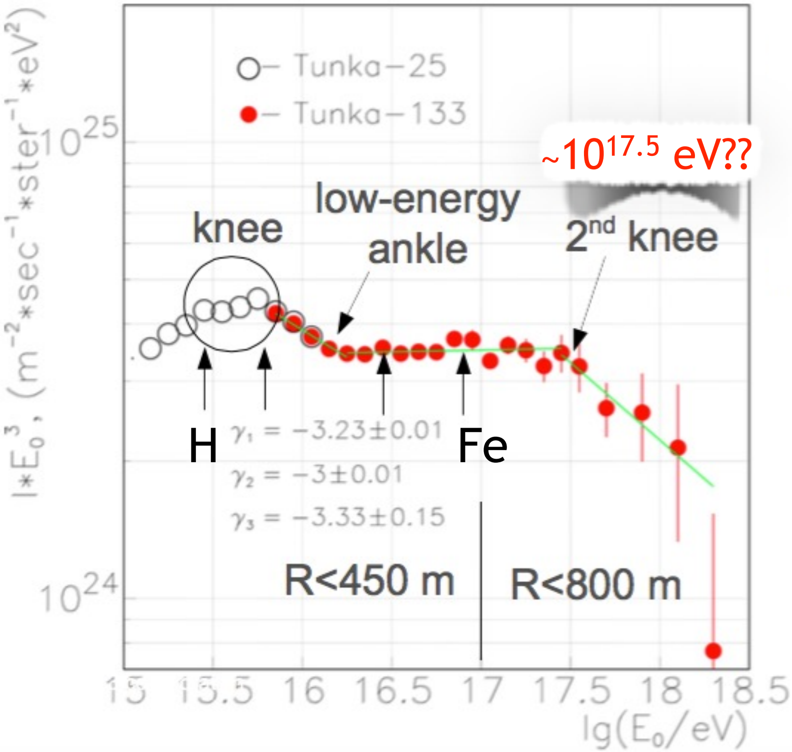
Grey:

QGSJET-II—03

3) Detectors & Results

ICETOP/ICECUBE: All-particle spectrum (10^{15}-10^{18} eV)





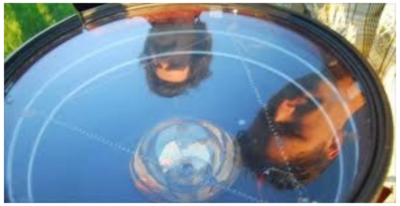
TUNKA-133 (Rusia, 675 m a.s.l.)

-175 optical detectors

-1 km^2 of effective area

-Cherenkov light in atmosphere

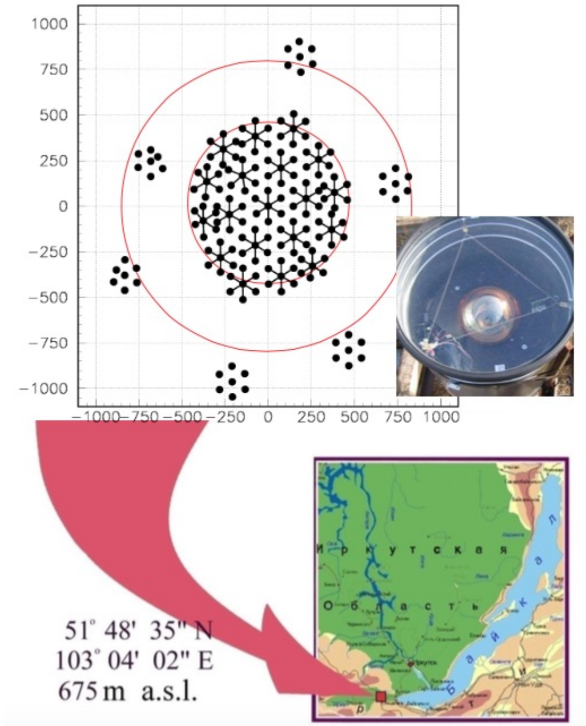
-Q(175 m).

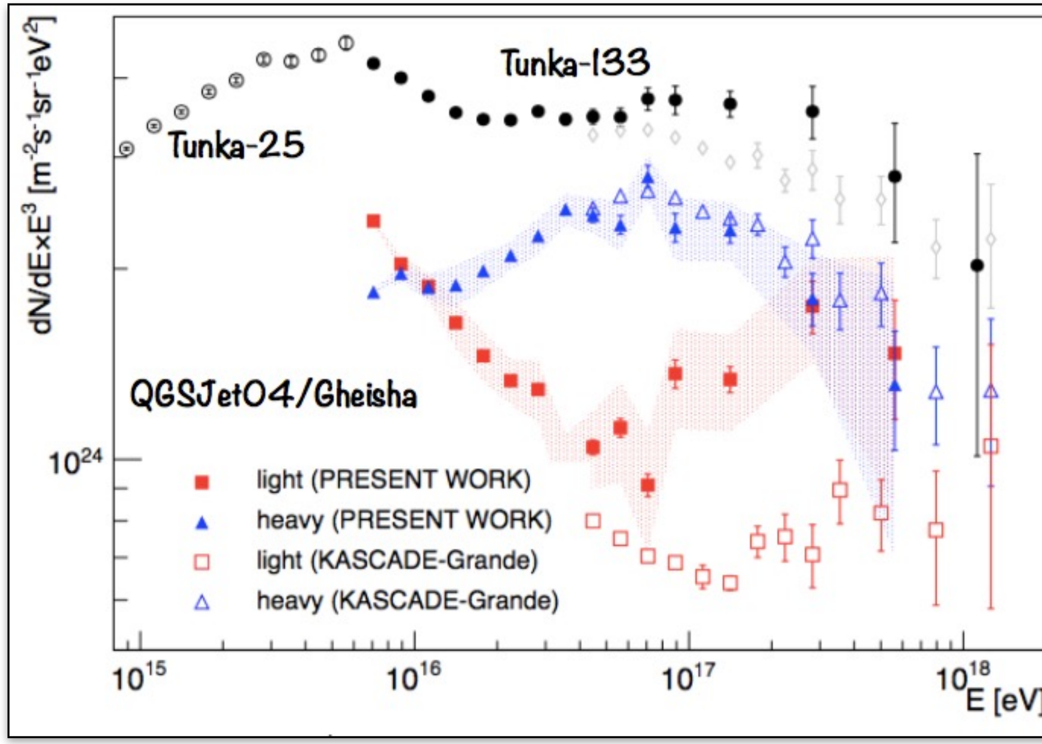


S. Epimakhov, HAP workshop, KIT; Germany, 2015

V.V. Prosin et al., NIMA 756 (2014)

ICETOP/ICECUBE: All-particle spectrum (10^{15}-10^{18} eV)





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S. Epimakhov, HAP workshop, KIT; Germany, 2015

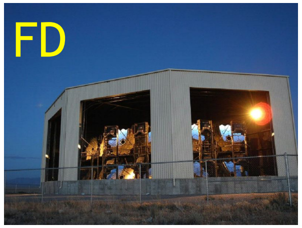
V.V. Prosin et al., NIMA 756 (2014)

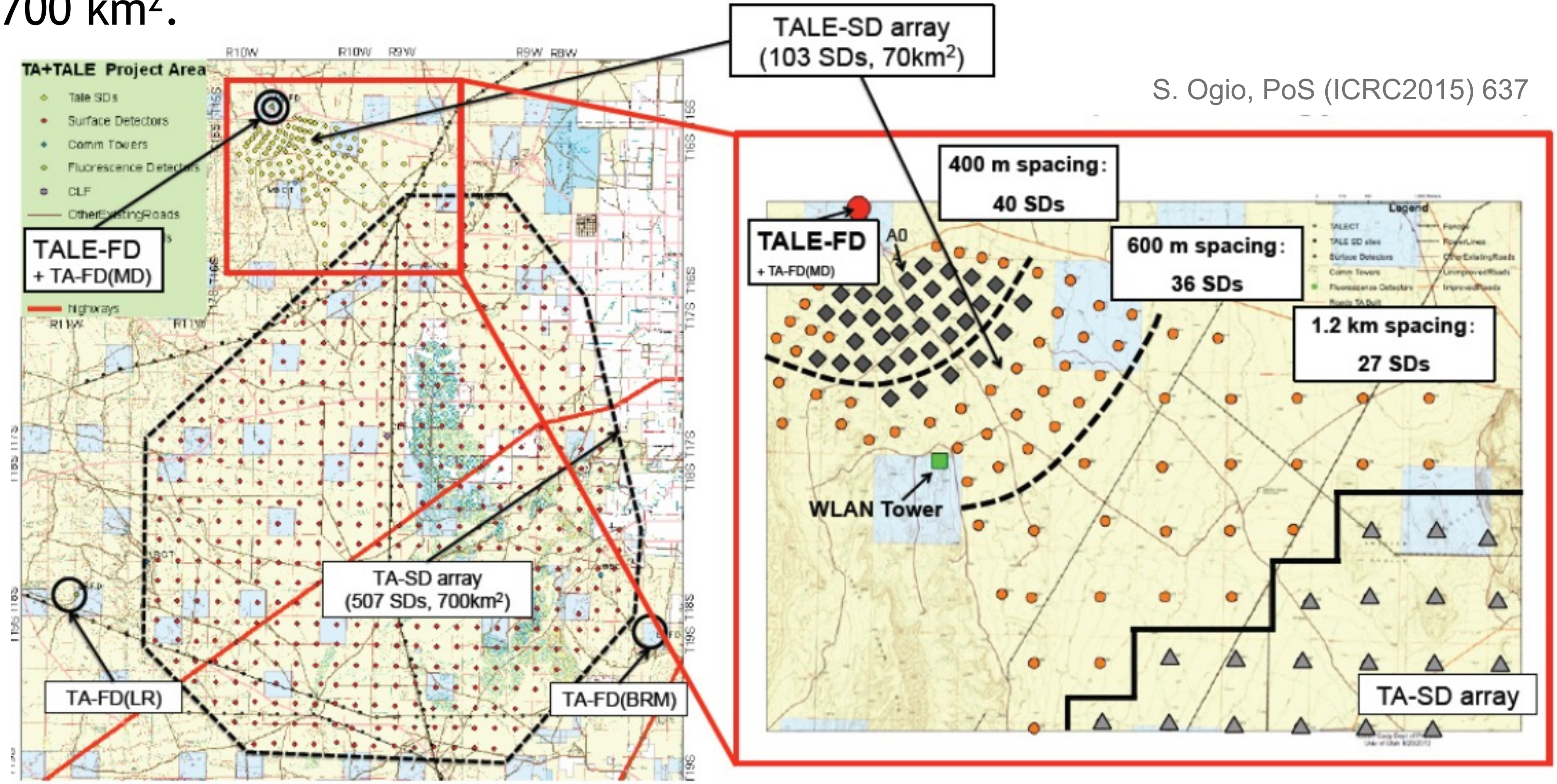
Telescope Array/TALE: All-particle spectrum (10^{15}-10^{18} eV)

Hybrid detector (USA, 1400 m a.s.l.)

E> 10^{18} eV

- FD: 3 fluorescence stations.
- SD: 507 scintillation detectors, 700 km^2.





S. Ogio, PoS (ICRC2015) 637

3) Detectors & Results

Telescope Array/TALE: All-particle spectrum (10^{15}-10^{18} eV)

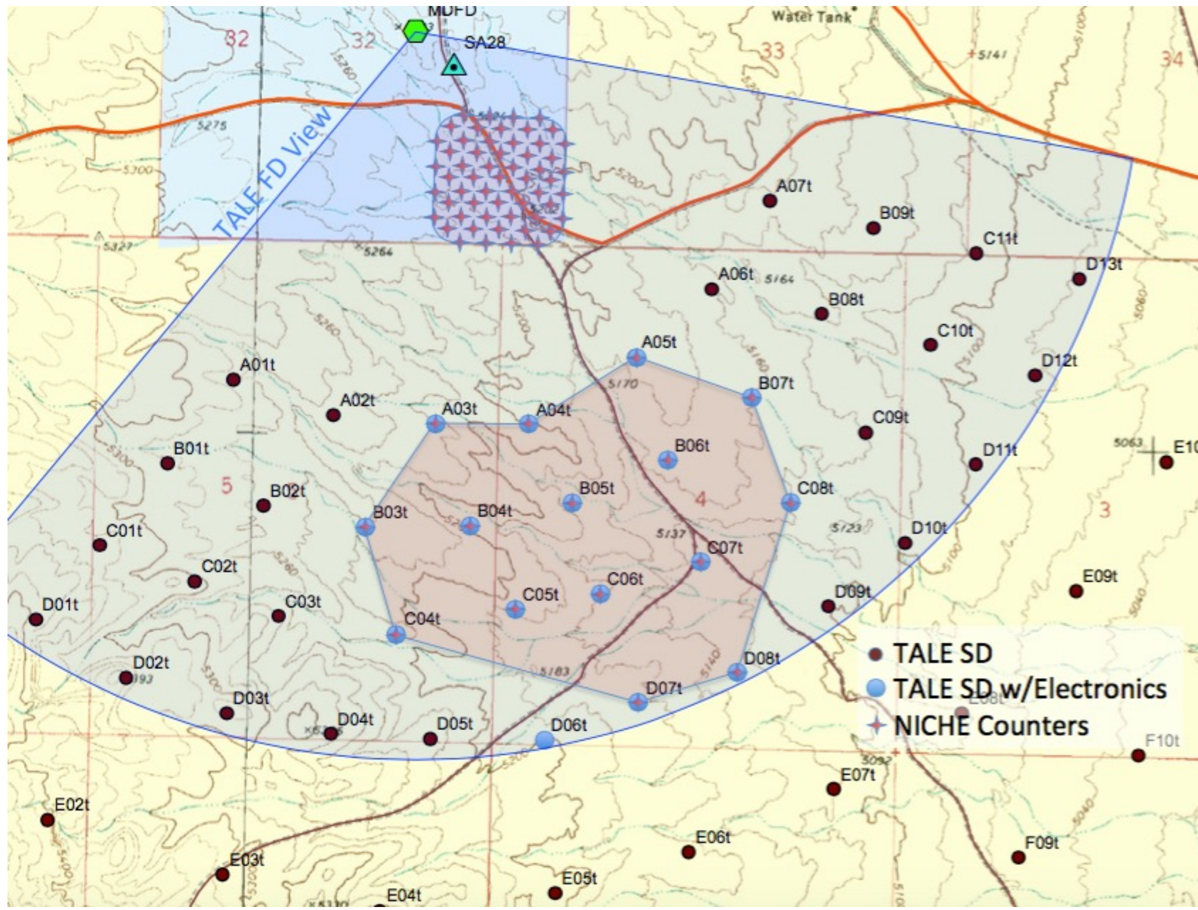
Hybrid detector (USA, 1400 m a.s.l.)

E> 10^{15} eV

TALE
- 103 SD's, 70 km^2.
- 10 HiRes FD's.

T. AbuZayyad, UHECR 2014 meeting

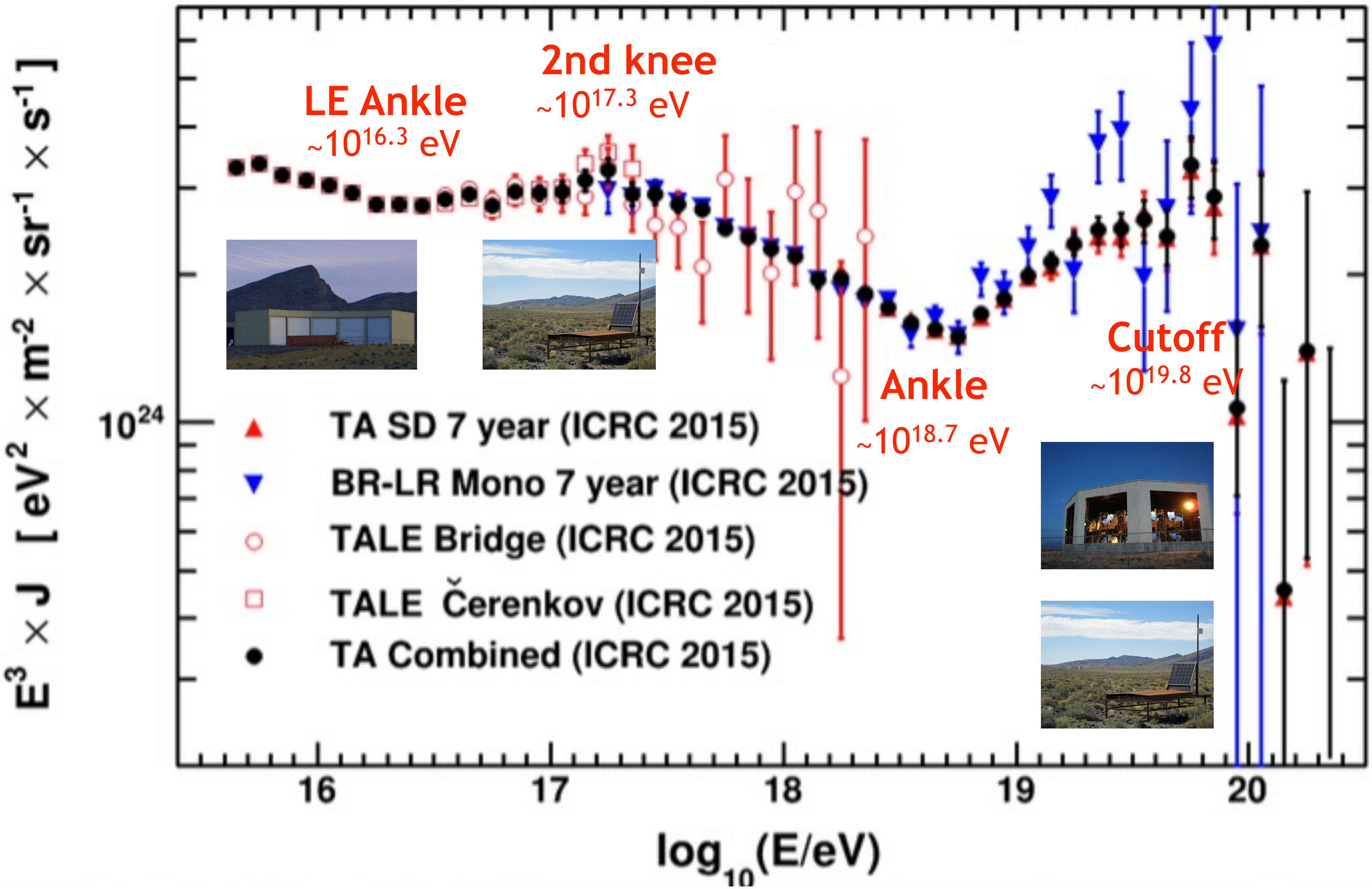
S. Ogio, PoS (ICRC2015) 637



3) Detectors & Results

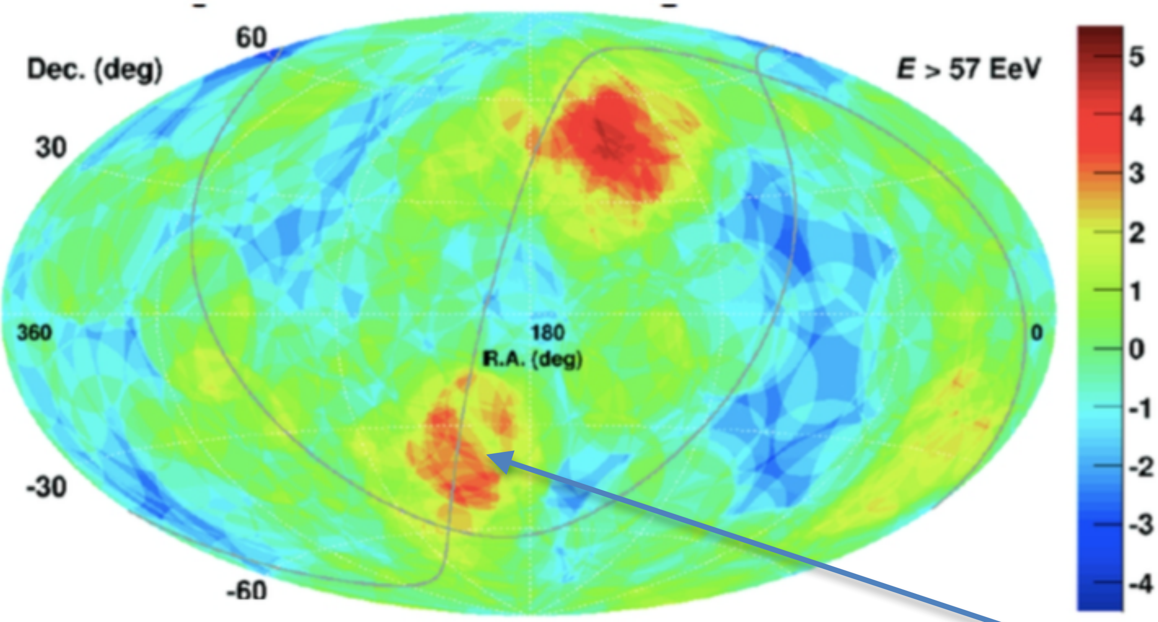
Telescope Array/TALE: All-particle spectrum (10^{15}-10^{18} eV)

C. Jui, ICRC 2015



3) Detectors & Results

Telescope Array & Auger: Hot spots at ultra-high energies



P. Lipari, HAP workshop, KIT; Germany, 2015

TA

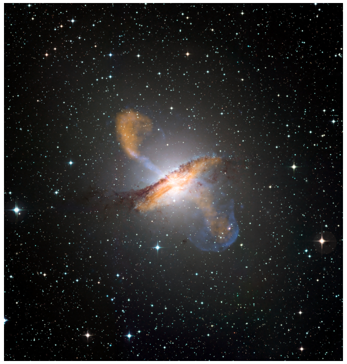
7 years, 109 Events (> 57 EeV)

Northern Hemisphere: hot spot seen by TA (3.4 σ) near the Ursa Major cluster

Auger

10 years 157 events (> 57 EeV)

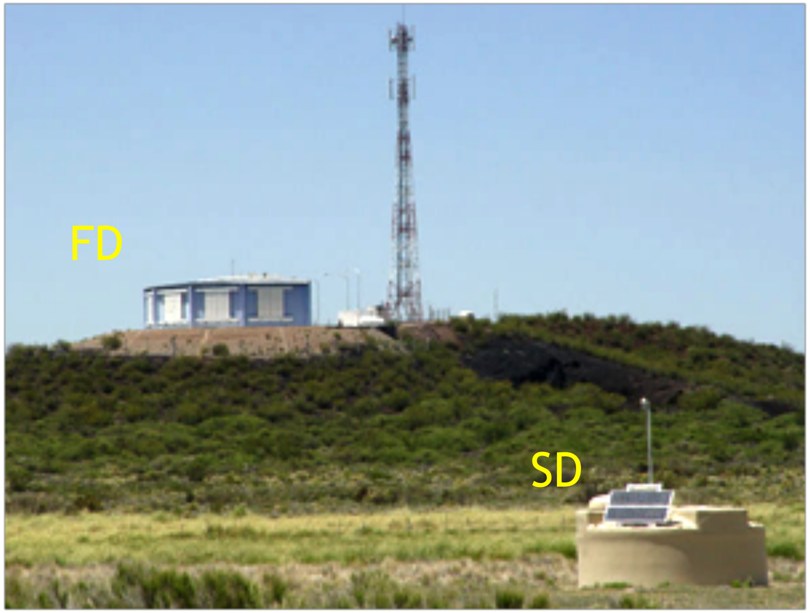
Southern Hemisphere: hot spot seen by Auger (post-trial prob 1.4%) near to Cen A



3) Detectors & Results

Pierre Auger Observatory

See L. Villaseñor talk



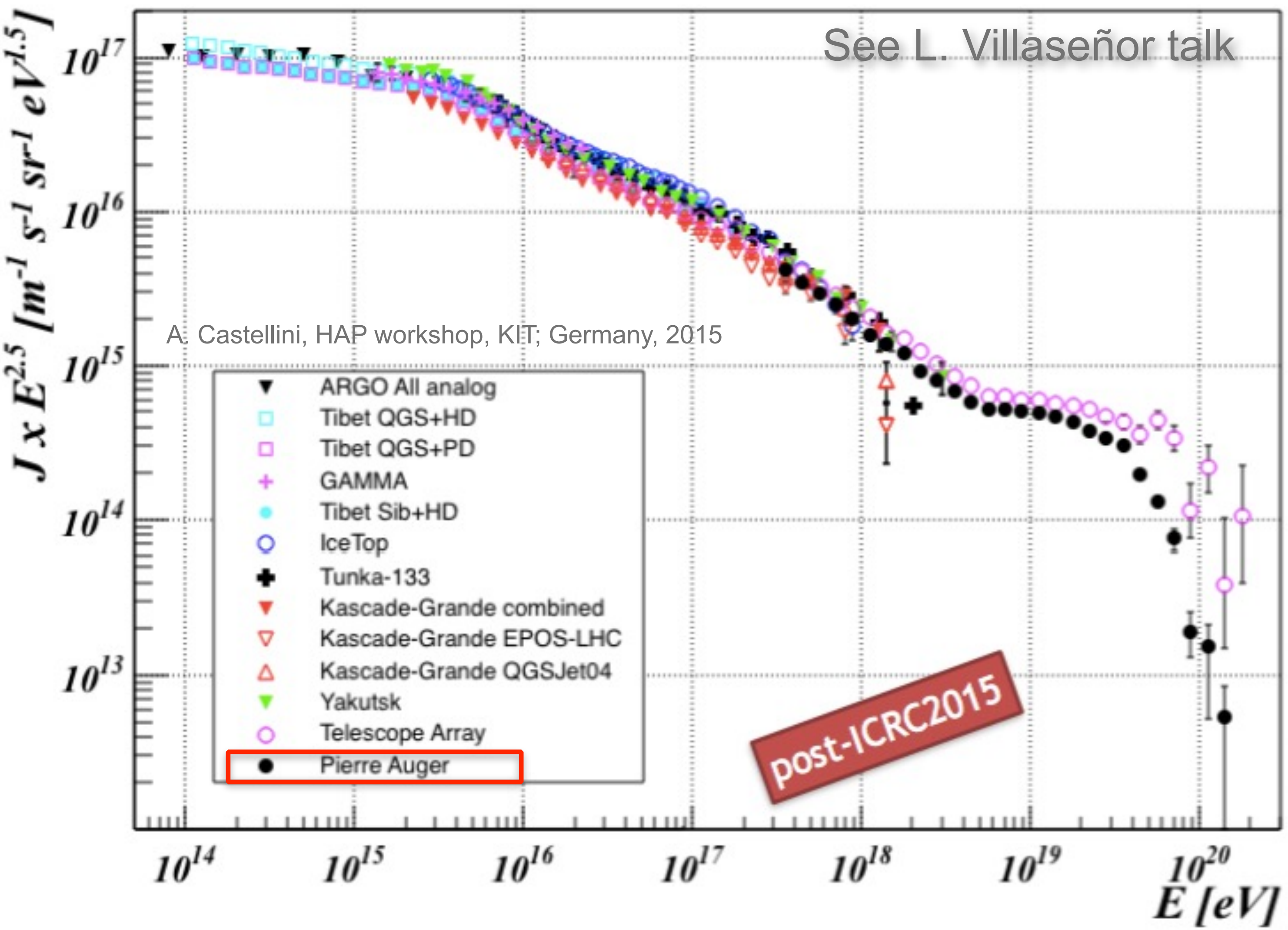
Hybrid detector, Argentina (1340-1610 m a.s.l.)

E> 10^{18} eV
- FD: 24 fluorescence stations.
- SD: 1660 WCD's, 3000 km^2.
- AERA: 124 radio stations, 6 km^2.

E> 10^{17} eV
- HEAT: 3 fluorescence telescopes.
- AMIGA: Underground muon counters.

3) Detectors & Results

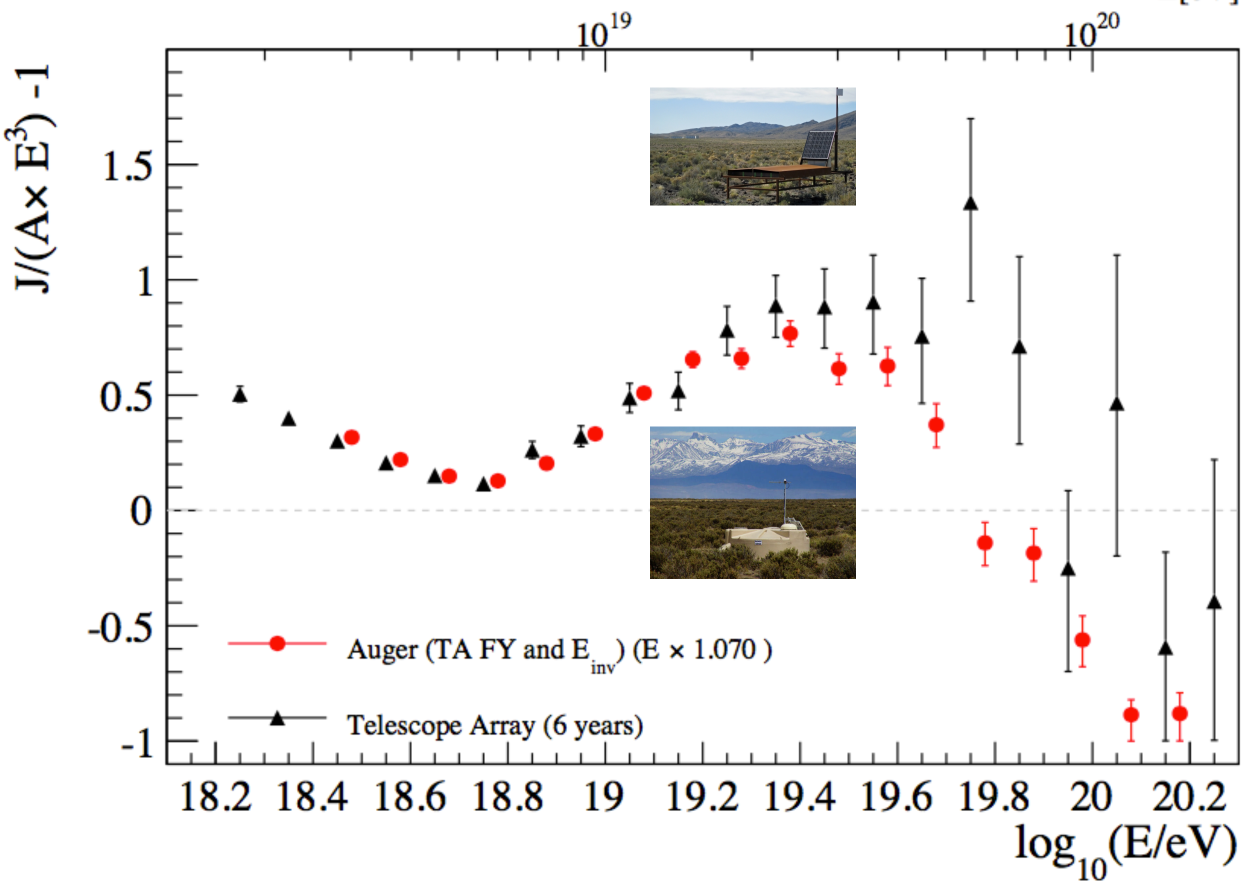
Pierre Auger Observatory: All-particle spectrum (2 x 10^{17}-10^{20} eV)



3) Detectors & Results

Pierre Auger Observatory: All-particle spectrum

M. Roth, HAP workshop, KIT; Germany, 2015



GZK cut-off or loss of efficiency at source?

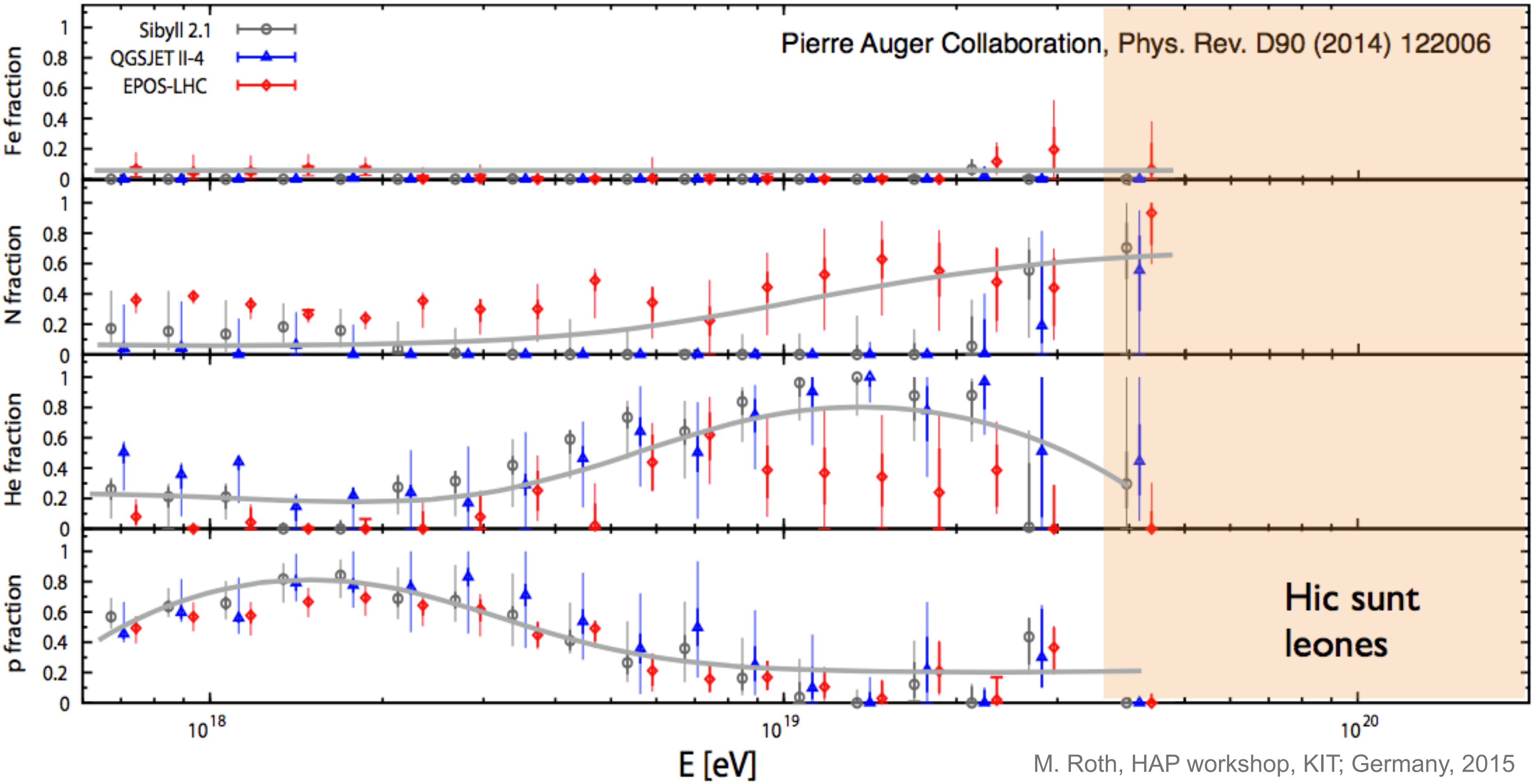
Different fluxes at extreme energies at North and South hemispheres?

See L. Villaseñor talk

3) Detectors & Results

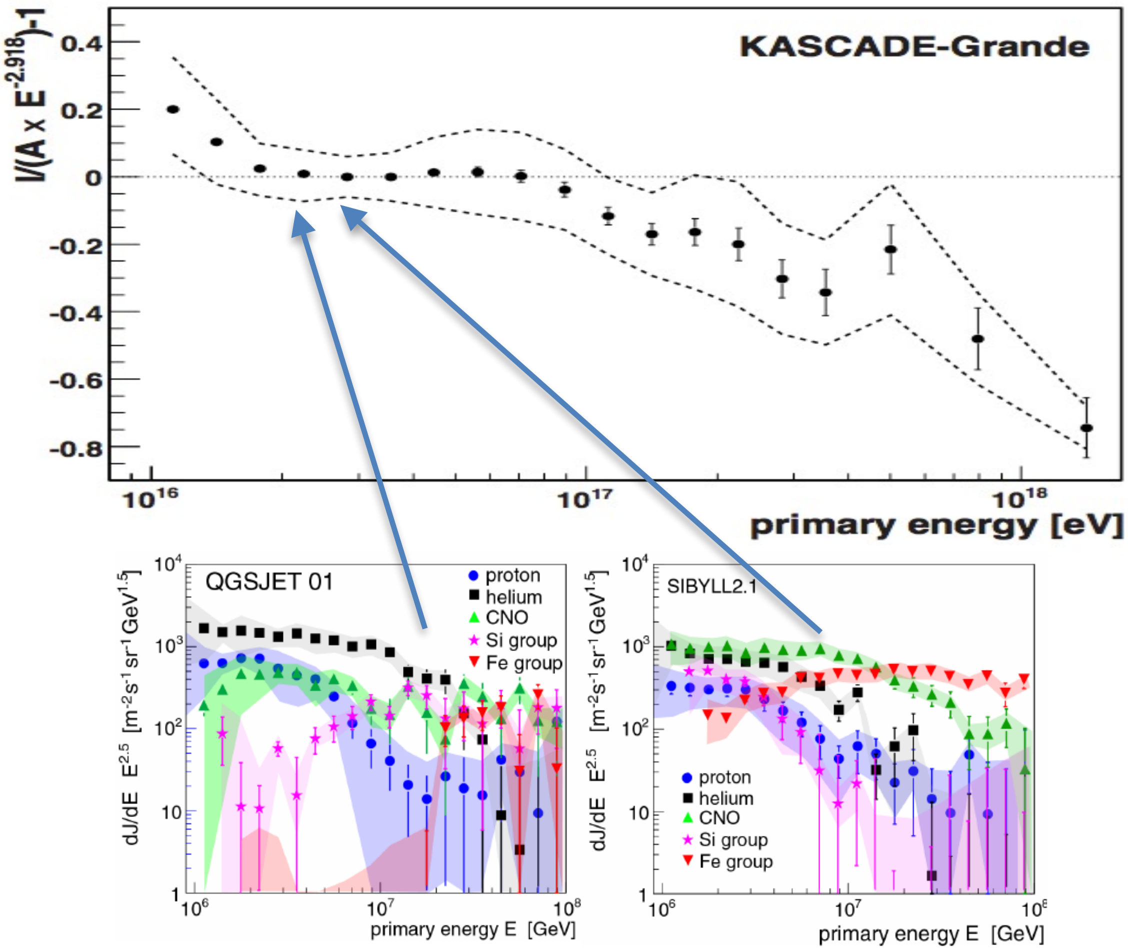
Pierre Auger Observatory: Composition (6 x 10^{17}-10^{20} eV)

See L. Villaseñor talk



M. Roth, HAP workshop, KIT; Germany, 2015

5) Astrophysical interpretation



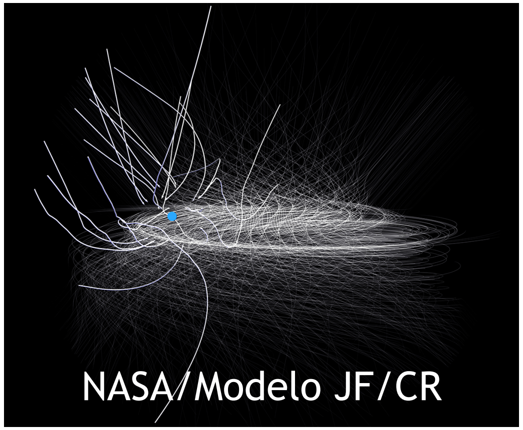
Hardening of spectrum due to to a GAP between CNO and Fe groups? or transition from one type of source to another one?

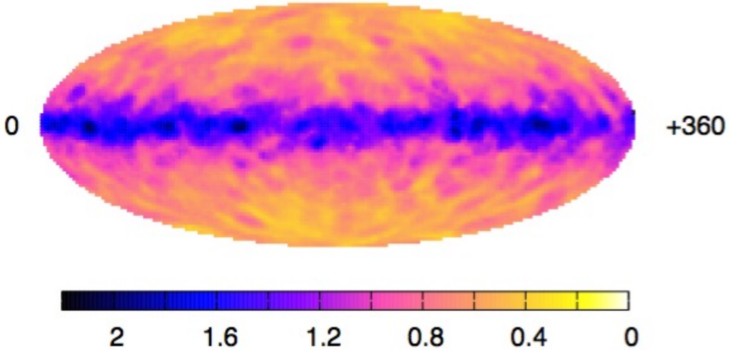
5) Astrophysical interpretation

Escape model: Diffusion in galactic magnetic field (GMF)

Components: Regular + Random

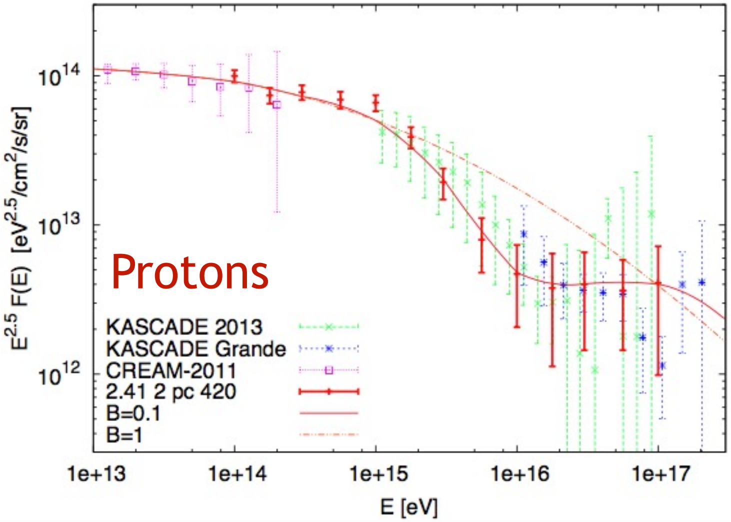
G. Giacinti et al., Phys. Rev. D 91, (2015)





Deflection of protons (40 EeV) in a turbulent GMF.

Fits to elemental spectra to constrain magnitude of B_{rand} in GMF.

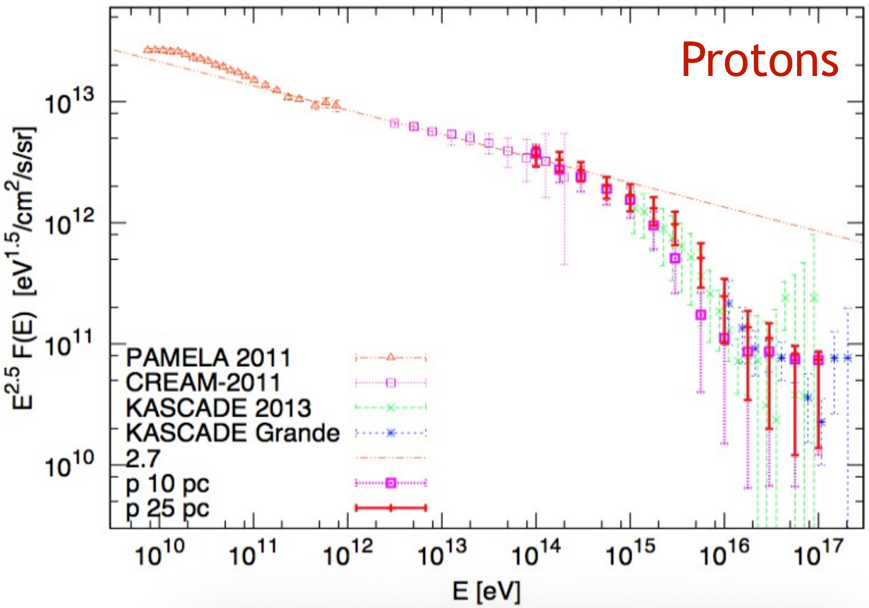


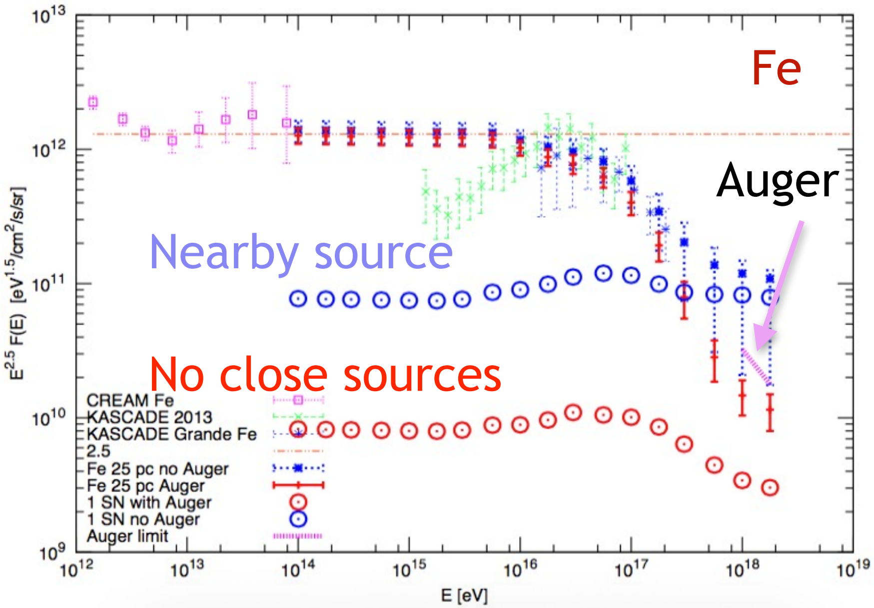
Reduced turbulence (β small) is preferred.

5) Astrophysical interpretation

Escape model: Diffusion in galactic magnetic field (GMF)

G. Giacinti et al., Phys. Rev. D 91, (2015)





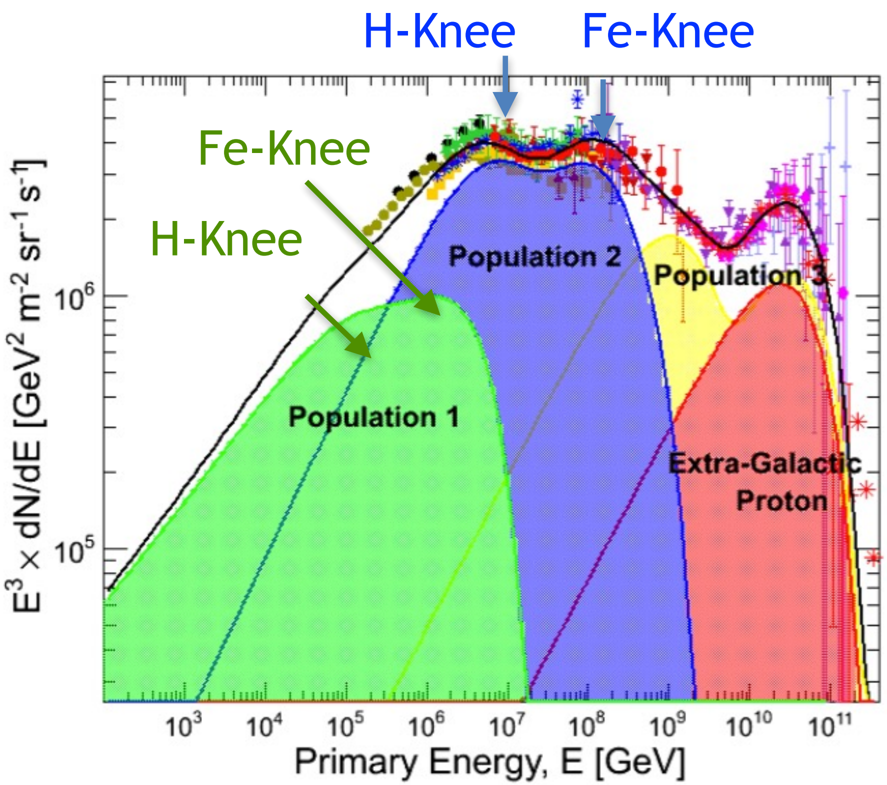
Specific shape of elemental spectra is modeled by escape rate from galaxy

Auger data on Fe exclude presence of recent nearby sources

- $E_{knees} \propto Z$
- Explain recovery of protons at 10^{17} eV.

4) Astrophysical interpretation

Different type of sources

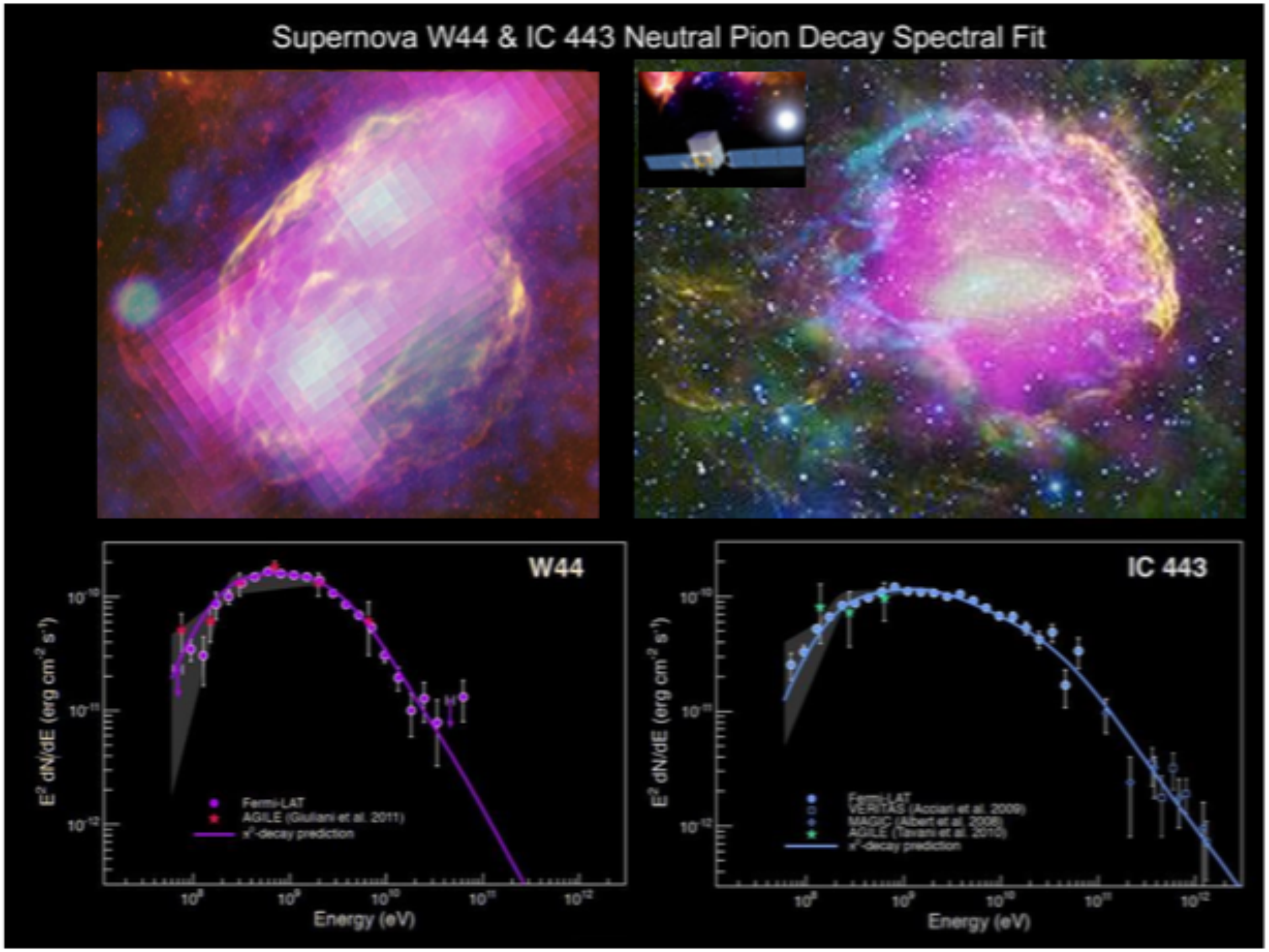


- $E_{knees} \propto Z$ for populations 1&2.
- Population 1: Classical SN: Emax ~ 100 TeV
- Population 2: Galactic Pevatron (PWN/Hypernovae, etc.)
- Population 3: Galactic Eevatron. (Hypernovae/GRB's in the past)
- Population 4: Extragalactic.

S. Tilav, ISVHECRI (2014)
T.K.Gaisser et al., Frontiers of Phys. 8 (2013)

4) Astrophysical interpretation

γ–ray emission at GeV's detected by FERMI–LAT from two SNR's confirms cosmic ray acceleration up to 100 TeV



Ackerman, arxiv:1302.3307

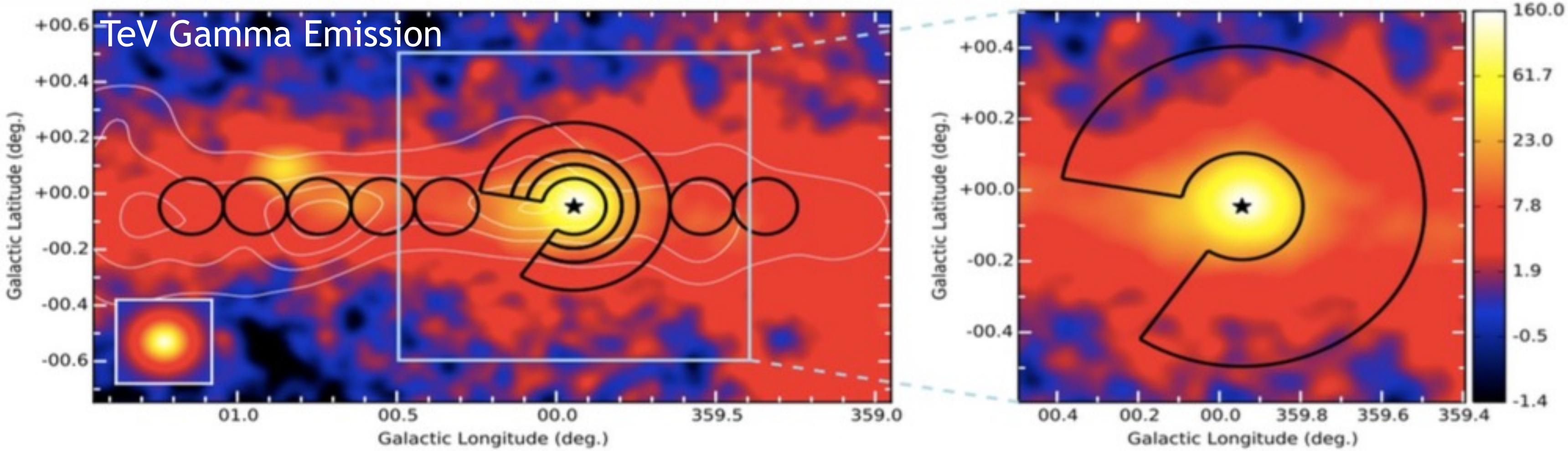
Scientific American 19-02-2013

NASA Press Release Feb. 14, 2013

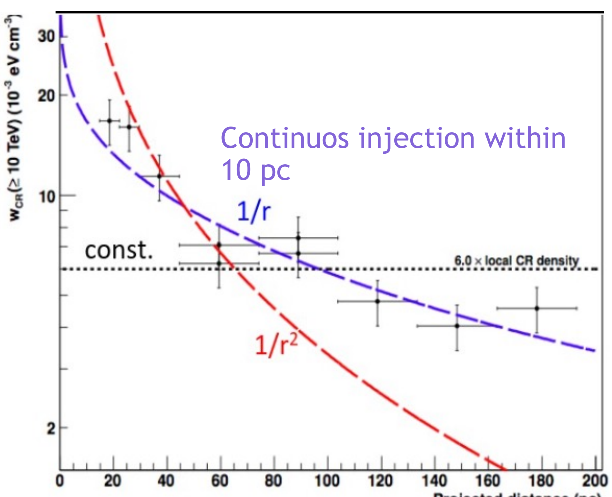
4) Astrophysical interpretation

PEVATRON at the galactic center?

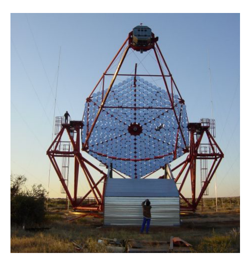
A. Viana, ICRC, 2015

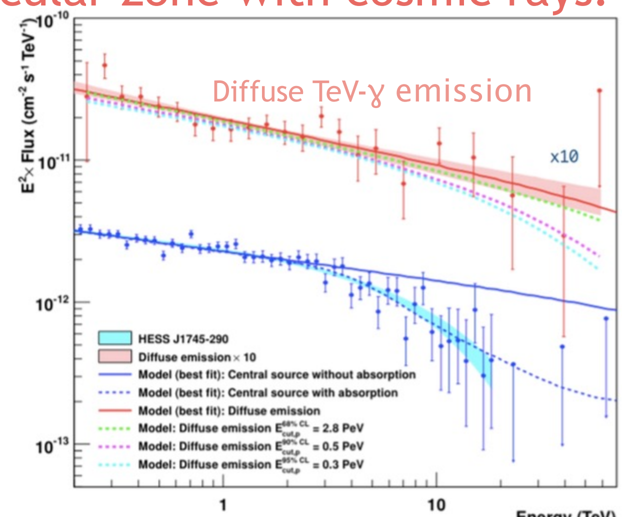


Diffuse TeV emission from interactions of molecular zone with cosmic rays?

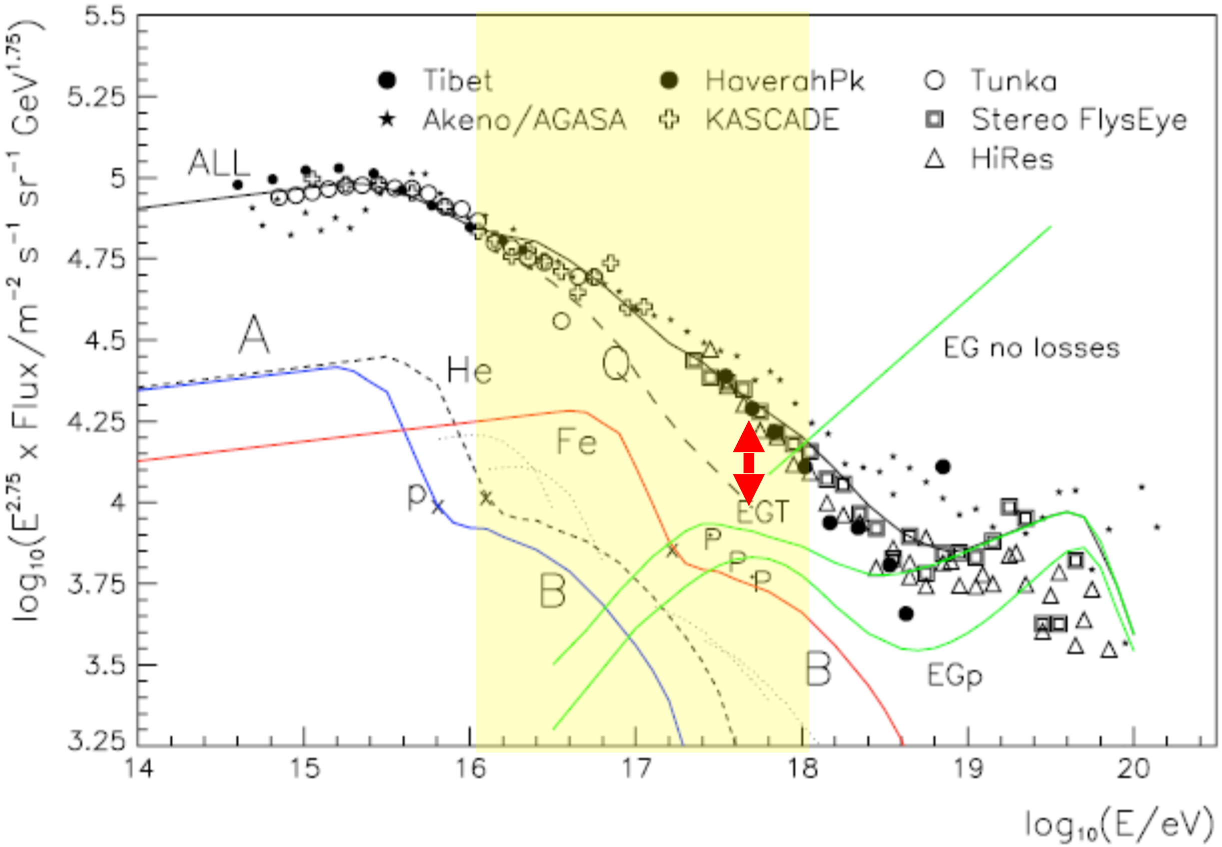


HESS





4) Astrophysical interpretation



Hillas: Extrapolation is not enough to explain the all-particle energy spectrum of cosmic rays.

➢ Contribution from ultra-heavy elements (> A^{Fe})?

➢ New galactic sources?

6) Summary

• The origin, propagation, acceleration mechanism and composition of high-energy cosmic rays is still not known.

• First measurements of the spectra of elemental mass groups have been done.

• Composition results on relative abundances affected by uncertainties in hadronic interaction models.

• Rigidity dependent scenario of galactic cosmic rays.

• First look at the galactic-extragalactic transition at the ankle of the light component?

6) Summary

Thank you!