Overview of Galactic Cosmic Ray Detection

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Outline

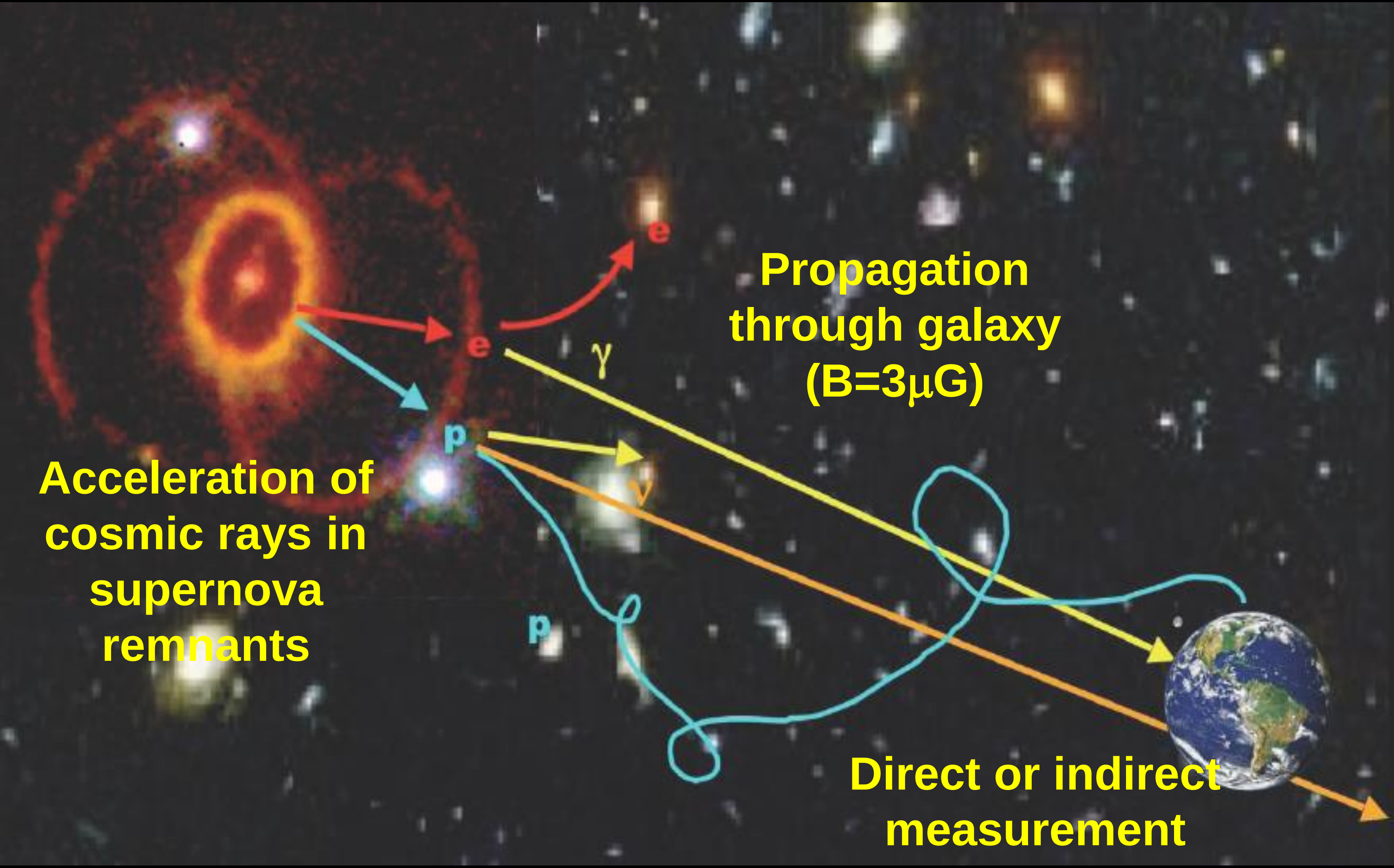
- Introduction

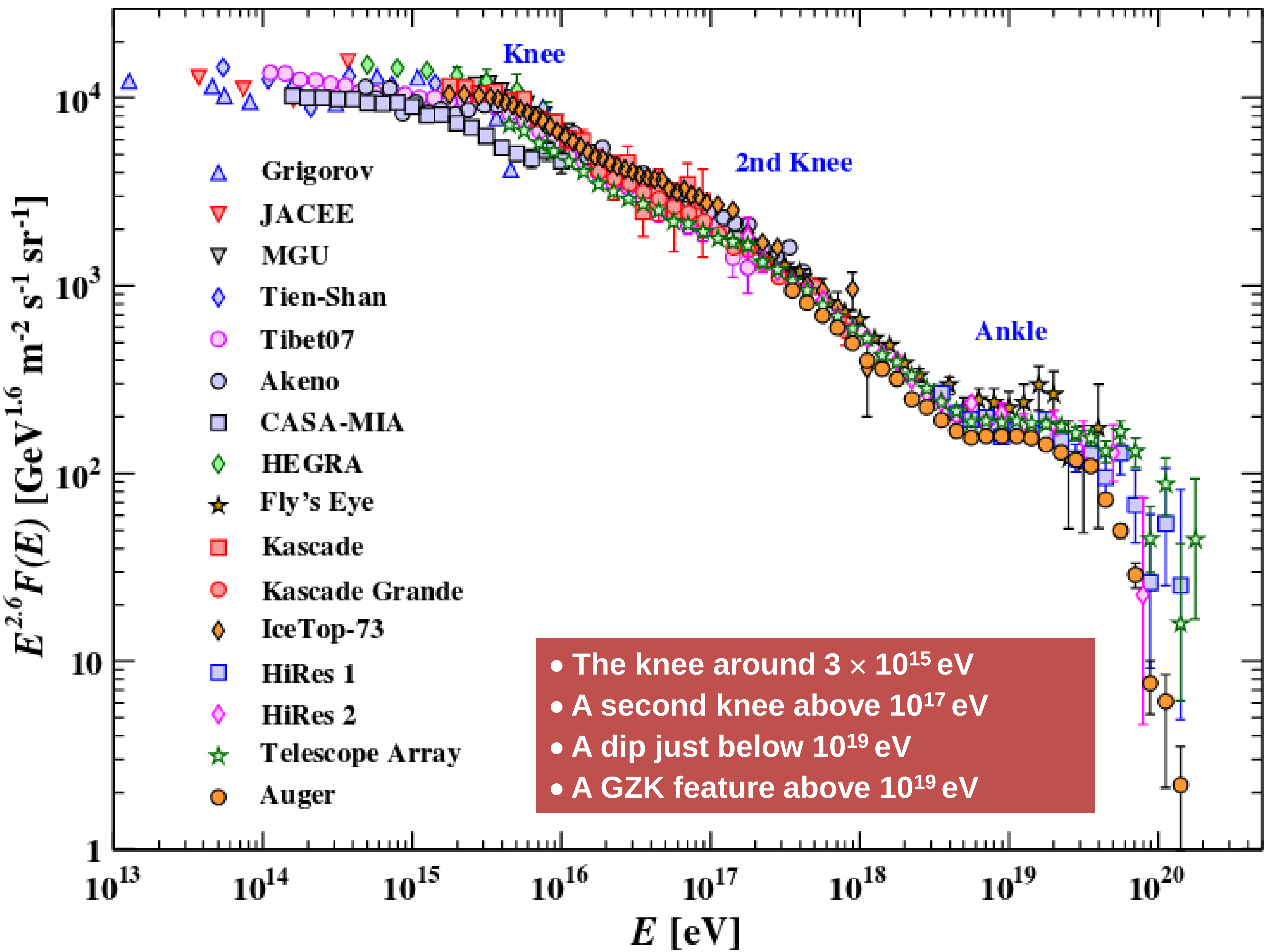
- Selected science results on galactic cosmic rays
  - all-particle energy spectrum
  - elemental composition
  - energy spectra based on different hadronic models

- Extensive air shower measurements of PeV to EeV
  - knee and transition region:
    KASCADE, KASCADE-Grande, Tunka, IceTop
  - TA Low Energy Extension: TALE
  - Auger to lower energy: HEAT

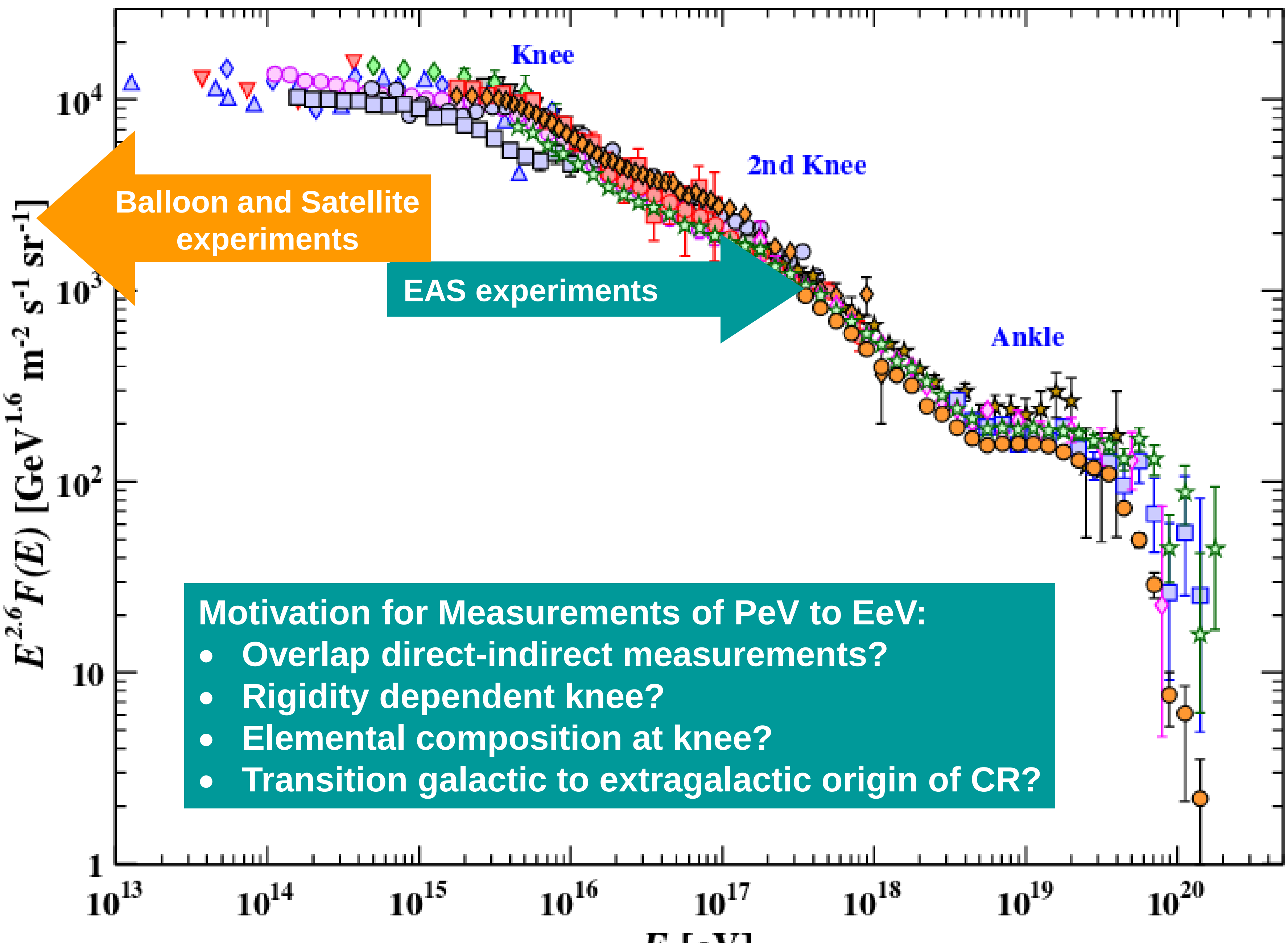
- Conclusion

Galactic Cosmic Rays





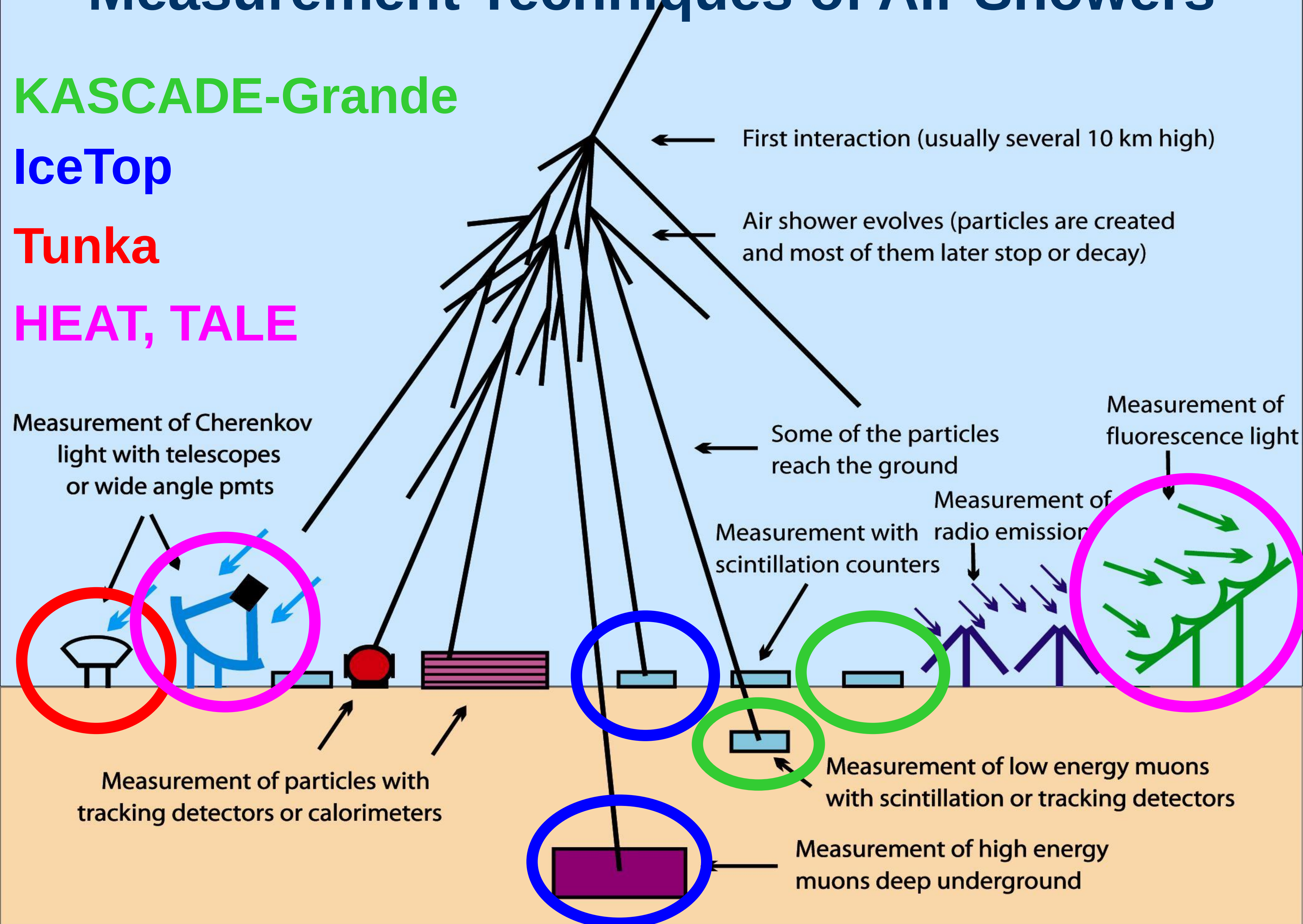
[Particle Data Group 2015]



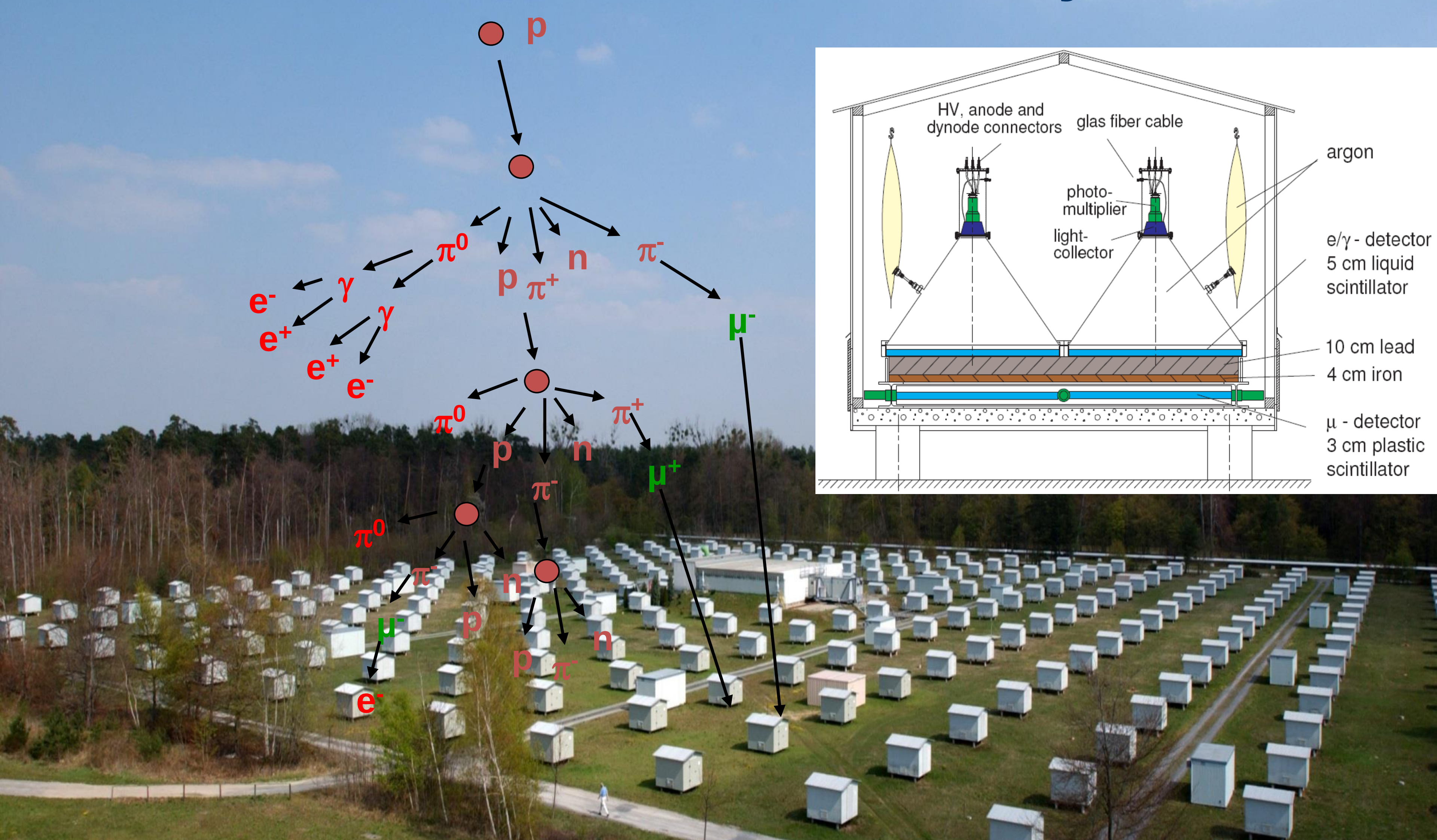
[Particle Data Group 2015]

Present Experiments $10^{16} – 10^{18}$ eV

Measurement Techniques of Air Showers

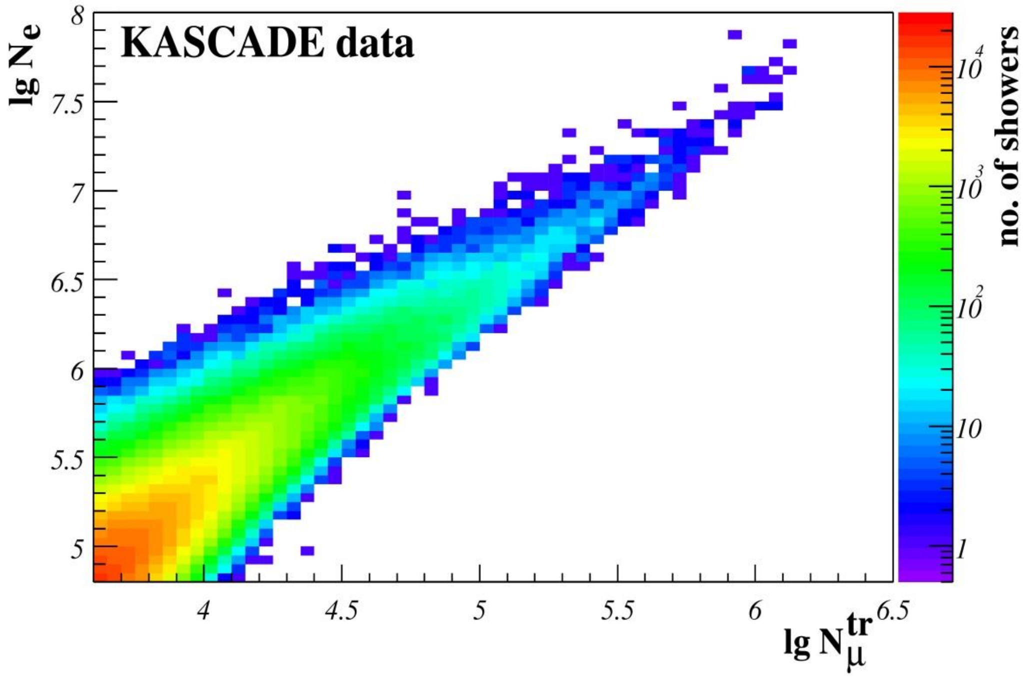


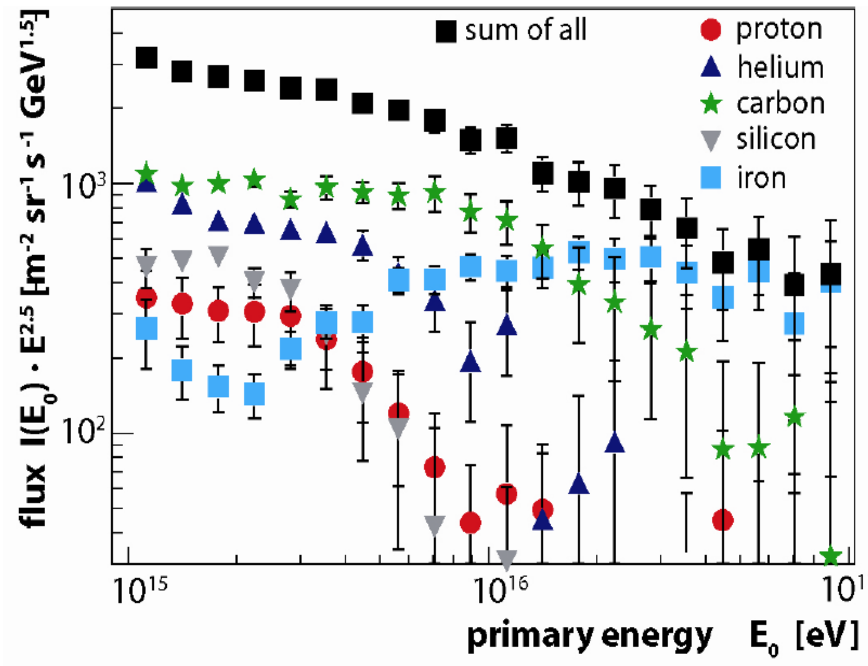
KArlsruhe Shower Core and Array DEtector



- Energy range 100TeV – 80PeV
- Since 1995
- Large number of observables

KASCADE Energy Spectra of Single Mass Groups





<u>Searched:</u> energy and mass of the cosmic ray particles

<u>Given:</u> 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

- **Knee caused by light primaries**
- **Relative abundancies depend strongly on high energy interaction model**

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

- **KCDC (KASCADE Cosmic ray Data Centre)**
  = 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

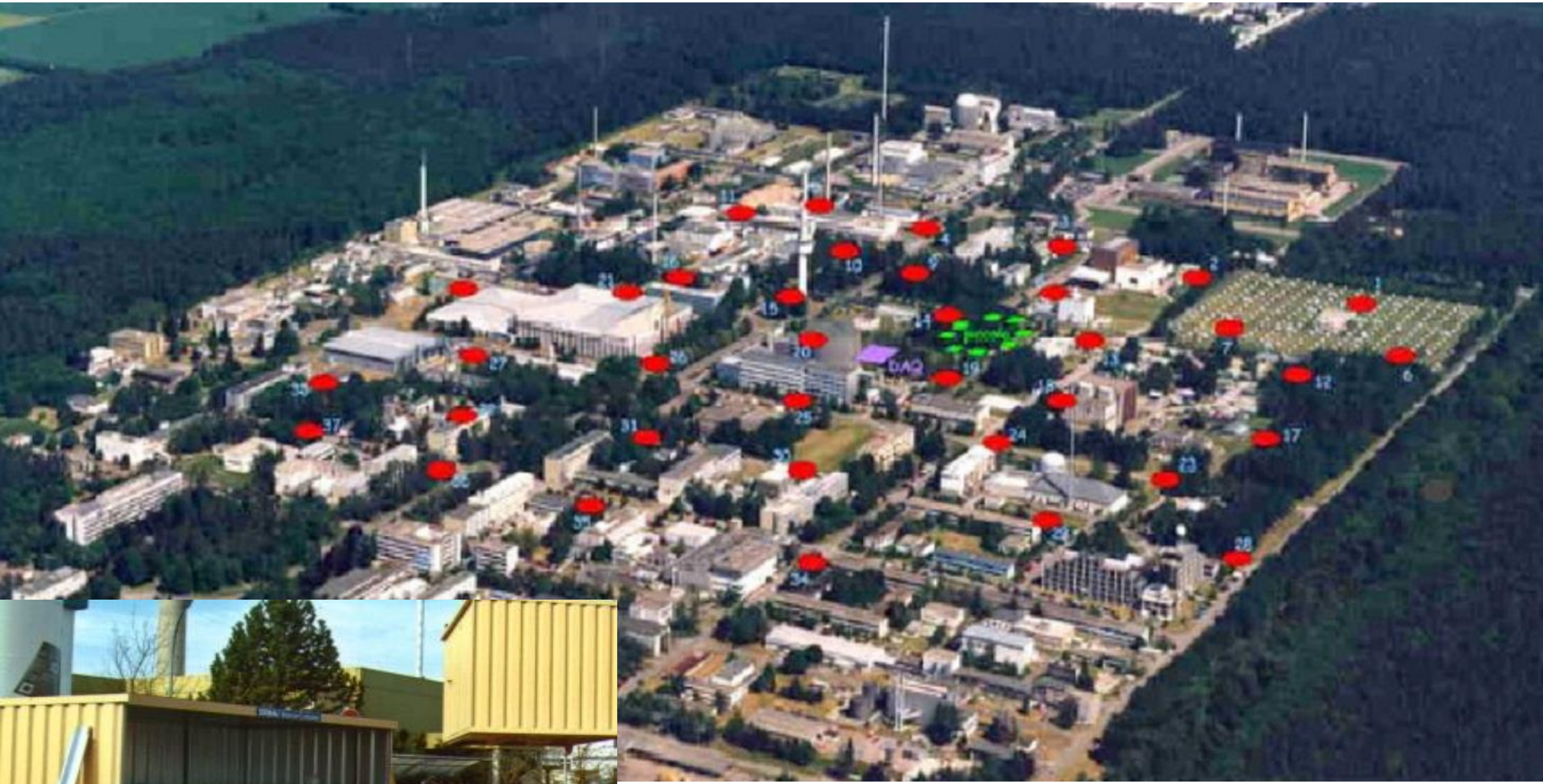
- **Web portal:**
  - providing a modern software solution
  for publishing KASCADE data
  for a general audience
  - In a second step: release the software
  as Open Source for free use by
  other experiments

- **Data access:**
  $1.6 \cdot 10^8$ EAS events of first data release is now available

Paper in preparation

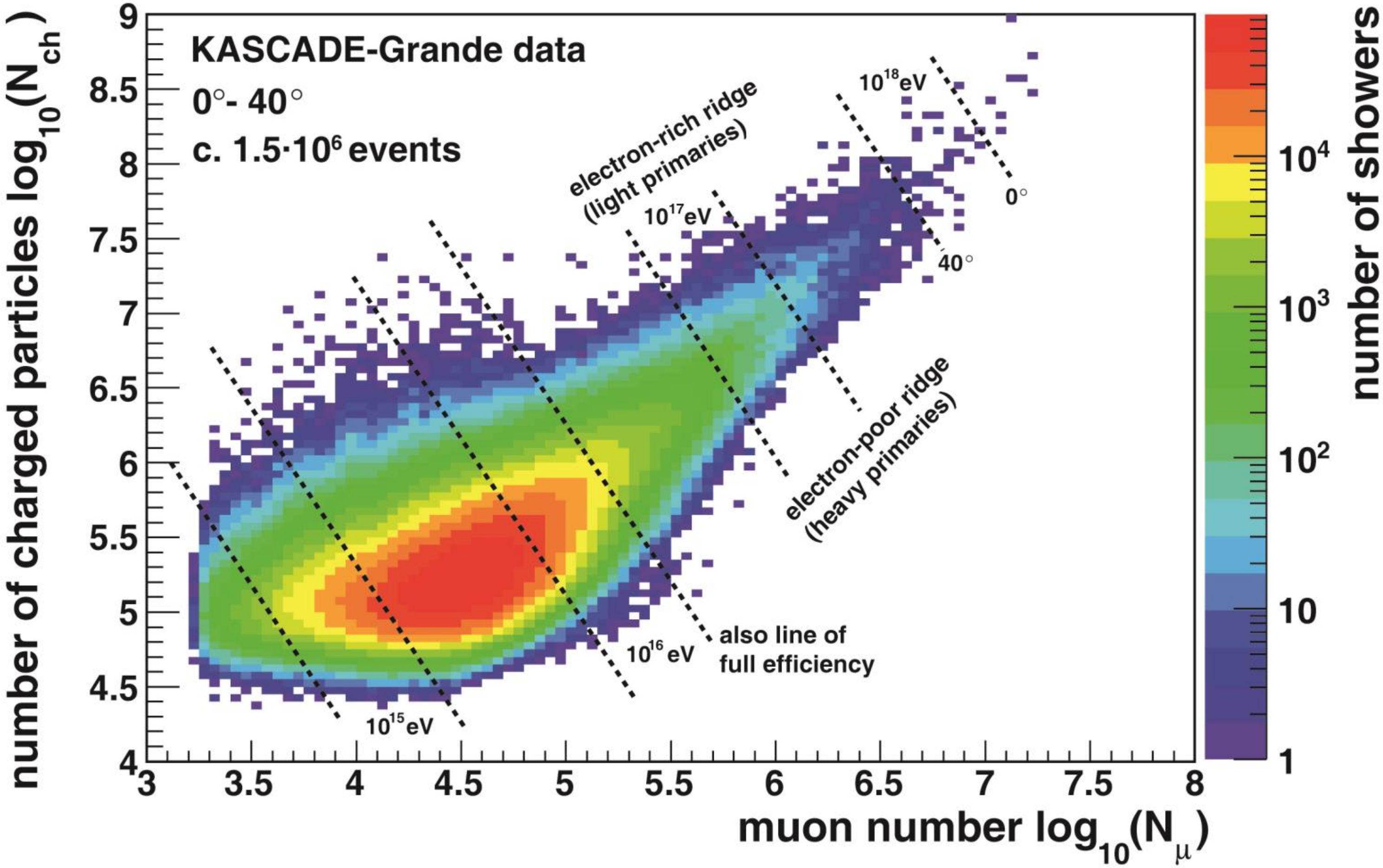
KASCADE-Grande

(**KA**rlsruhe **S**hower **C**ore and **A**rray **DE**tector + **Grande**)



- **Total effective area: 0.5 km^2**
- **Large array of 37 stations with 137m spacing**
- **Each station has a plastic scintillation detector of 10 m^2**
- **18 trigger clusters (0.5Hz)**

Energy and Elemental Composition

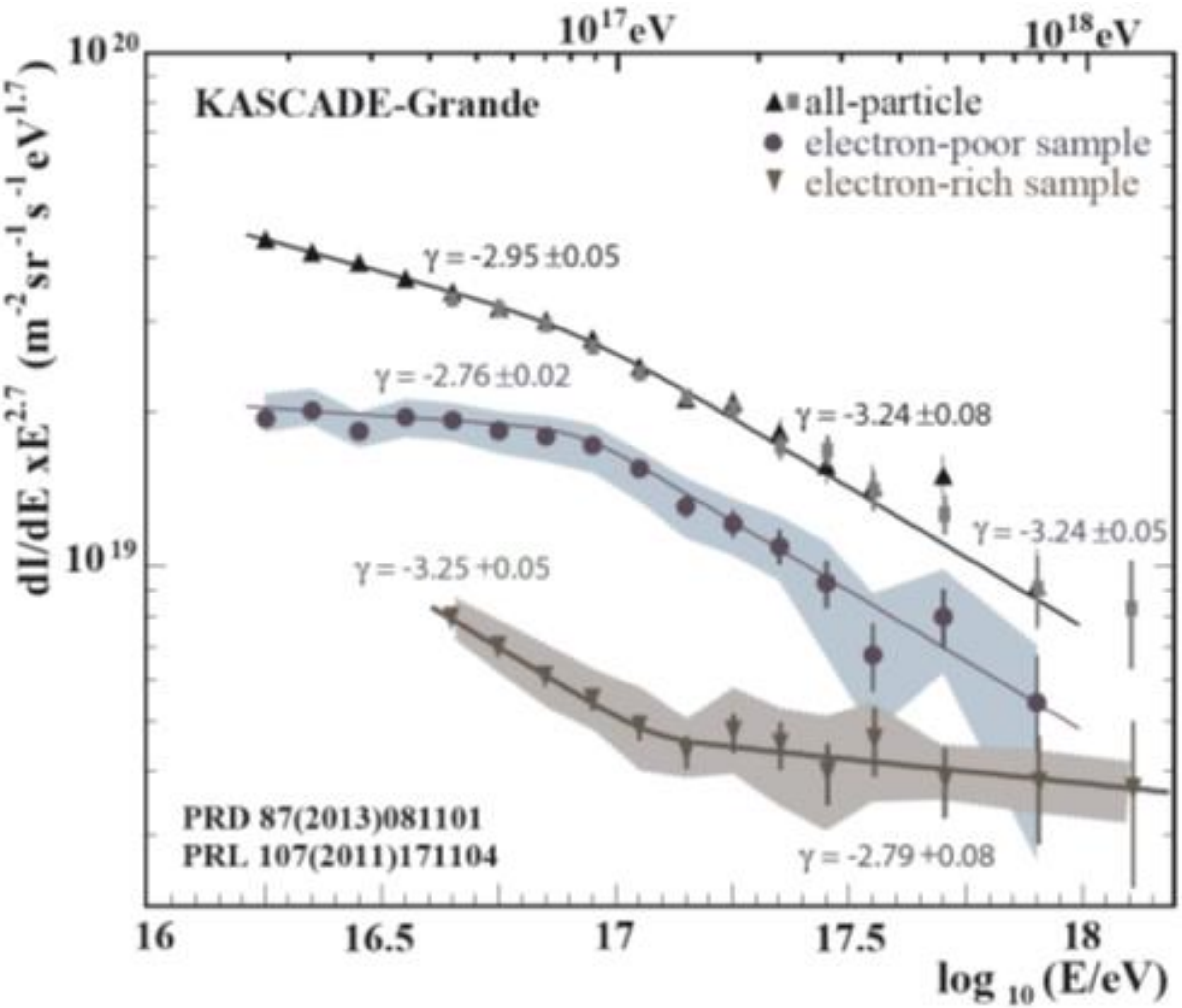


- **2-dim. shower size distribution → determination of primary energy**
- **Separation in “electron-rich” and “electron-poor” events**

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

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

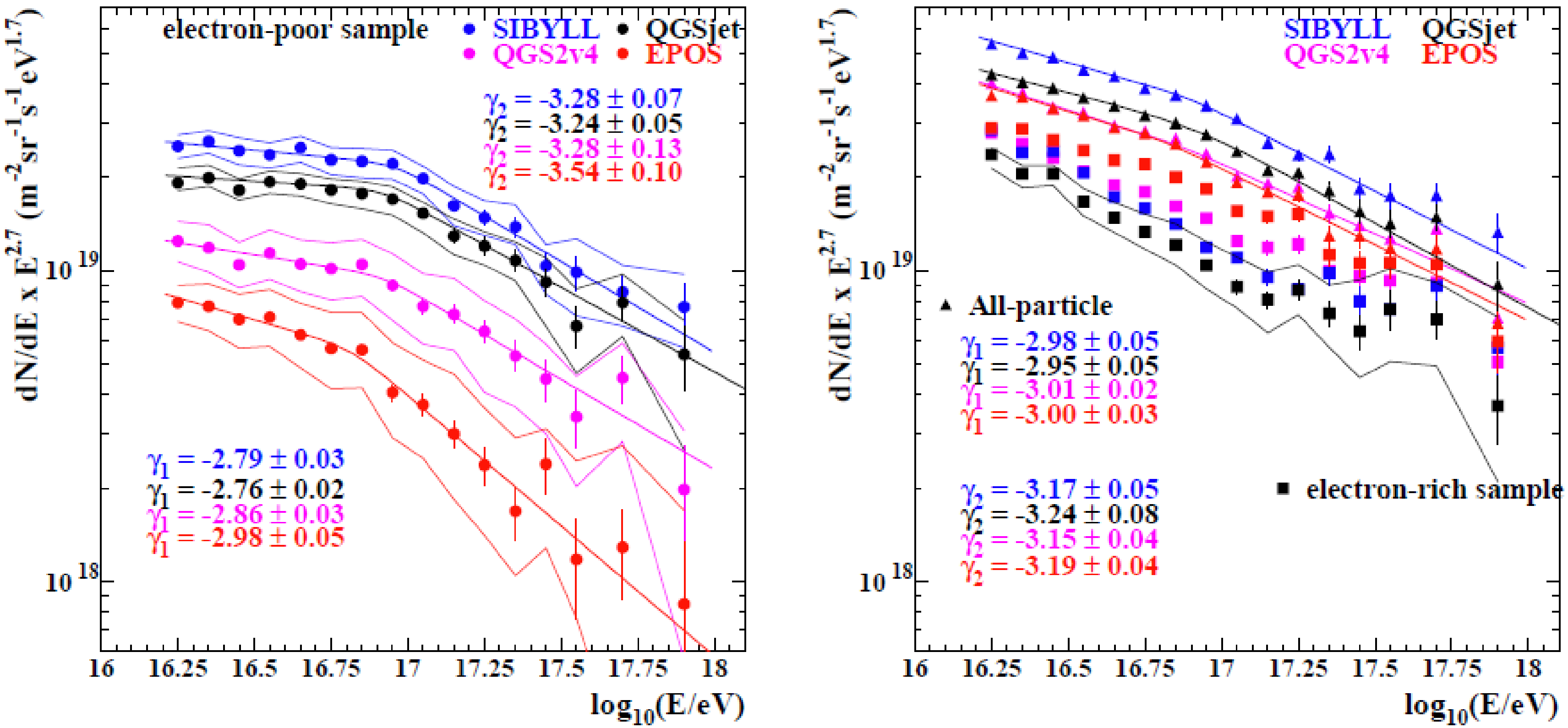
Spectra of Individual Mass Groups



- **steepening close to 10^{17}eV (2.1σ) in all-particle spectrum**
- **steepening due to heavy primaries (3.5σ)**
- **hardening at $10^{17.08}$eV (5.8σ) in light spectrum**
- **Slope change from γ = -3.25 to γ = -2.79**

[PRL107 (2011) 171104, PRD (R) 87 (2013) 081101]

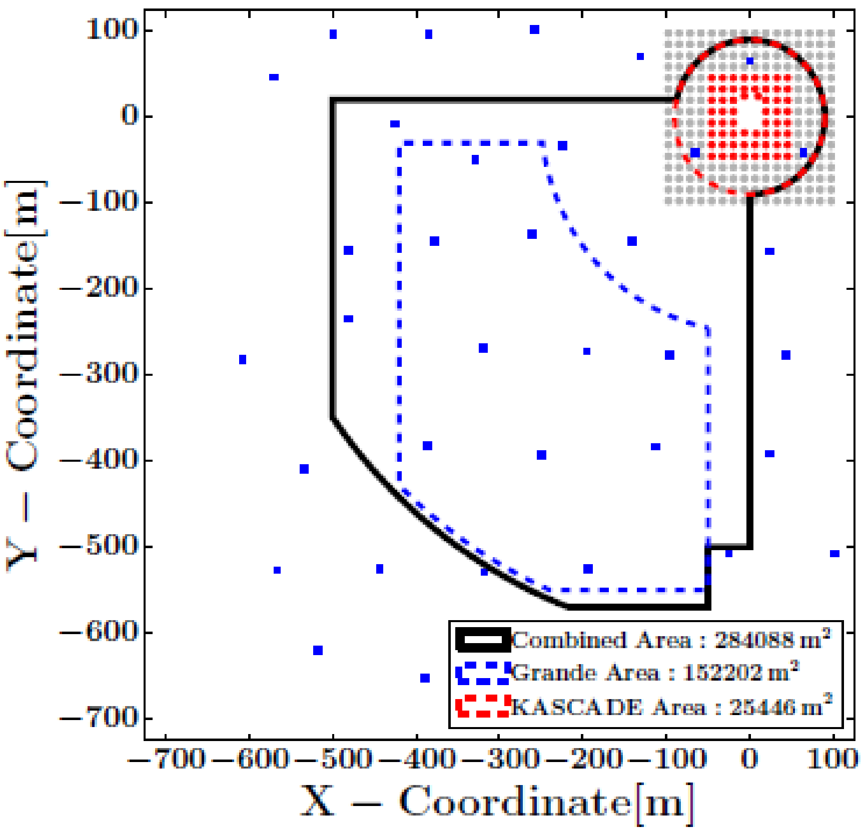
KASCADE-Grande: Model Dependence

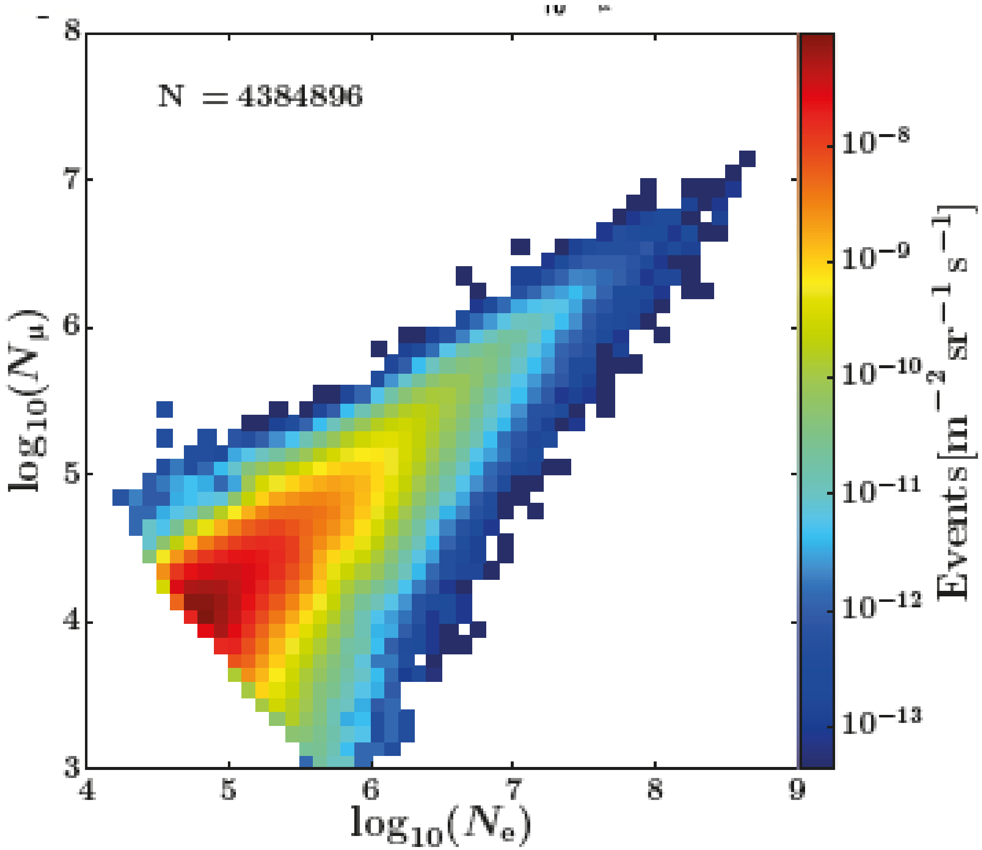


- **Structures of all-particle, heavy and light spectra similar**
  → knee by heavy component; ankle by light component
- **Relative abundances different for different high-energy hadronic interaction models**

[Advances in Space Research 53 (2014) 1456]

Combined Analysis

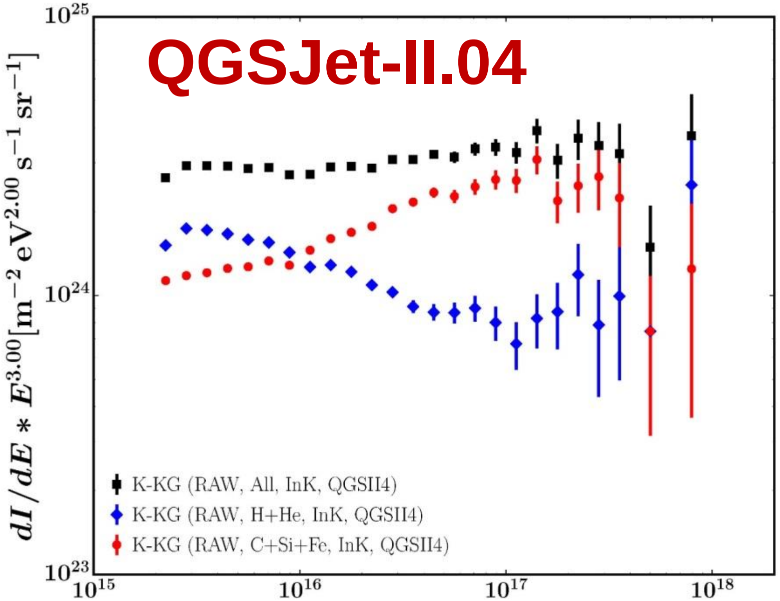


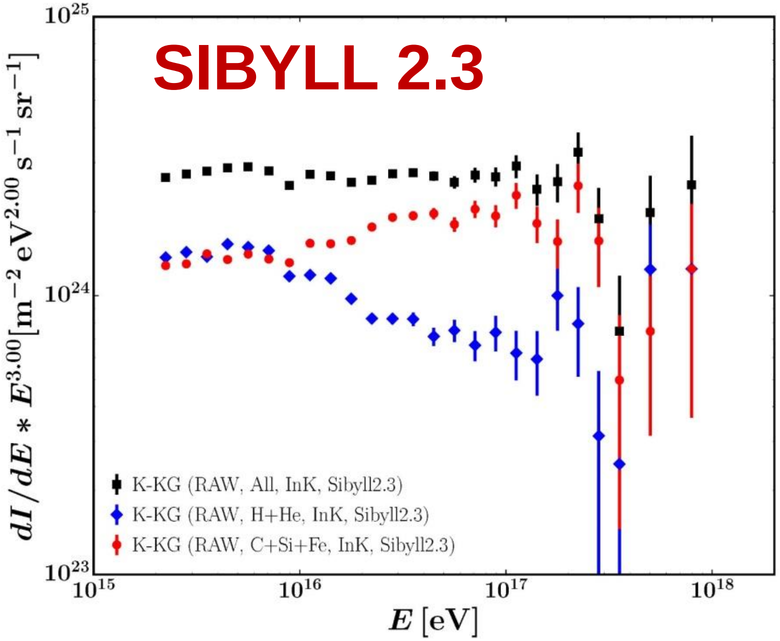


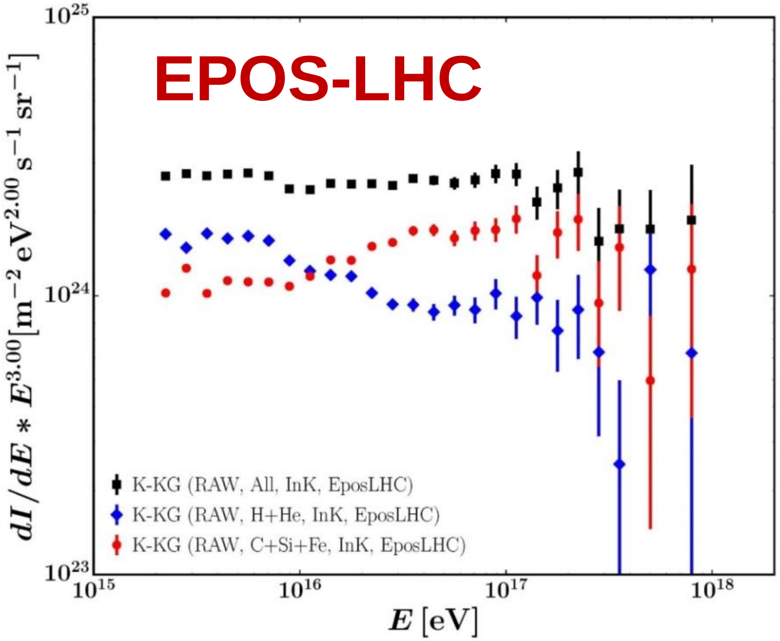
- For KASCADE: additional stations at larger distances → higher energies
- For Grande: additional 252 stations → higher accuracy

[Dissertation of Sven Schoo]

Combined Analysis: Energy Spectra



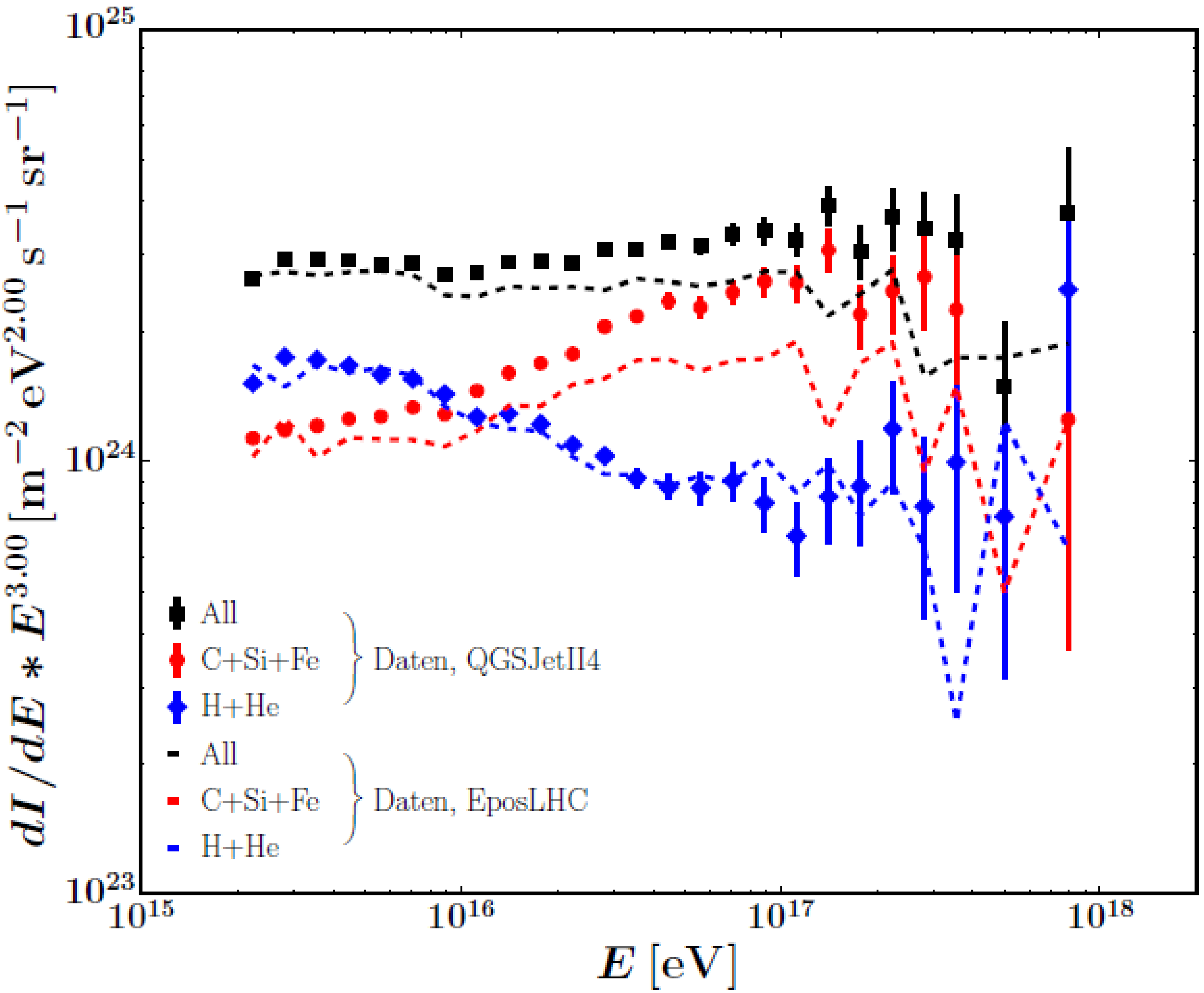




- **Energy spectra based on different hadronic interaction models**
- **All structures confirmed**
- **All-particle spectrum good agreement**
- **Relative abundance of light and heavy quite different**

Spectra not corrected for uncertainties

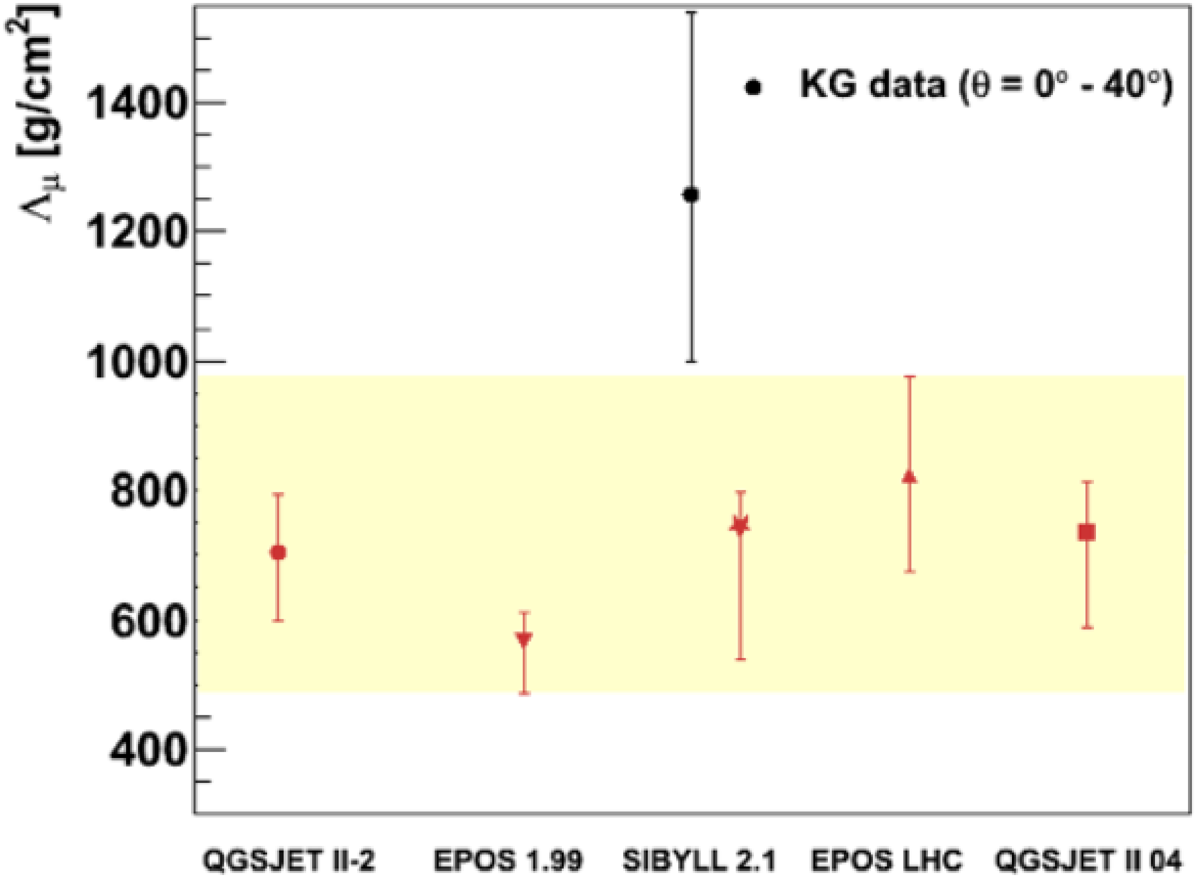
Combined Analysis: QGSJet-II.04 vs EPOS-LHC



- **Light primary interactions okay?**
- **Heavy primary interactions show differences**

← Muon component not sufficiently described
(Distance from shower core covered by muon detectors limited)

KASCADE-Grande: Muon Attenuation Length



Total muon number:

$$N_\mu = N_{\mu,0} \exp[- X_0 \sec(\theta) / \Lambda_\mu]$$

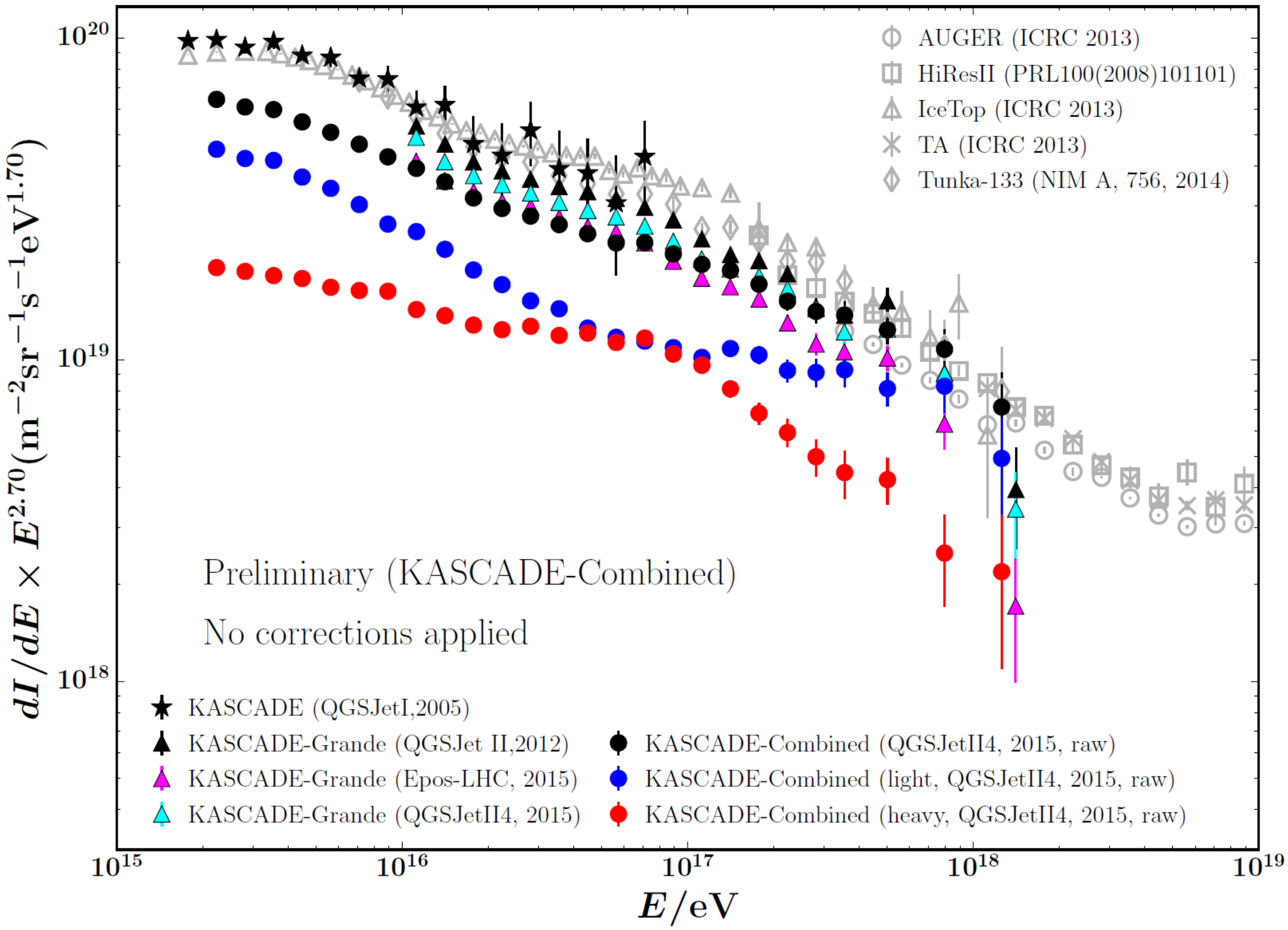
Attenuation length measured is different from the predictions of Monte Carlo

→ Observed evolution of the muon content of EAS in the atmosphere is not described by the hadronic interaction models

→ Influences absolute energy and mass scale, but not spectral features

[Juan Carlos Arteaga, Submitted to Astropart. Phys.]

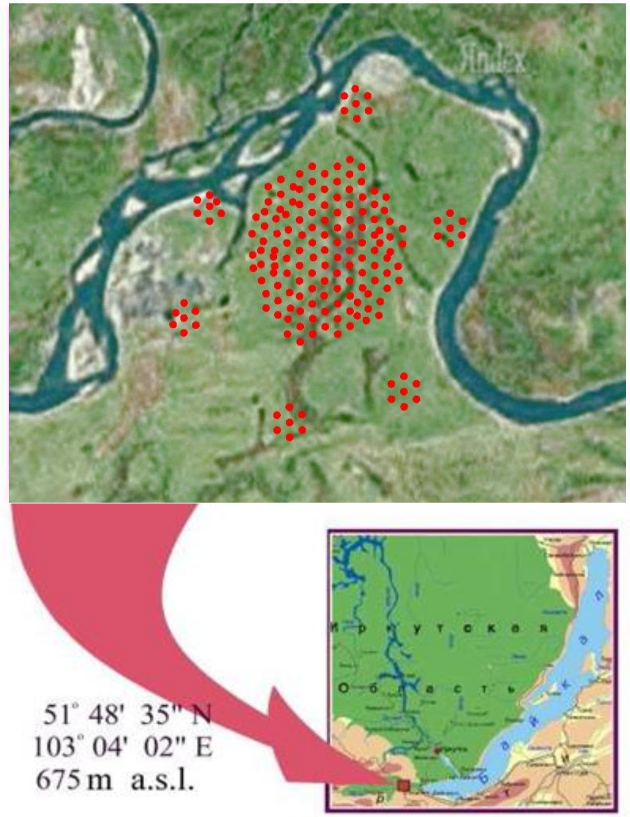
Conclusion Combined Analysis



- **Structures of spectra confirmed**
- **Models still do not agree to each other and to data**
- **Light component seems to agree better than heavy**
- **Problem probably in the muons (known due to special selection)**
- **Around 10^{15} eV still (again) no clear picture**

[Dissertation of Sven Schoo, Paper in preparation]

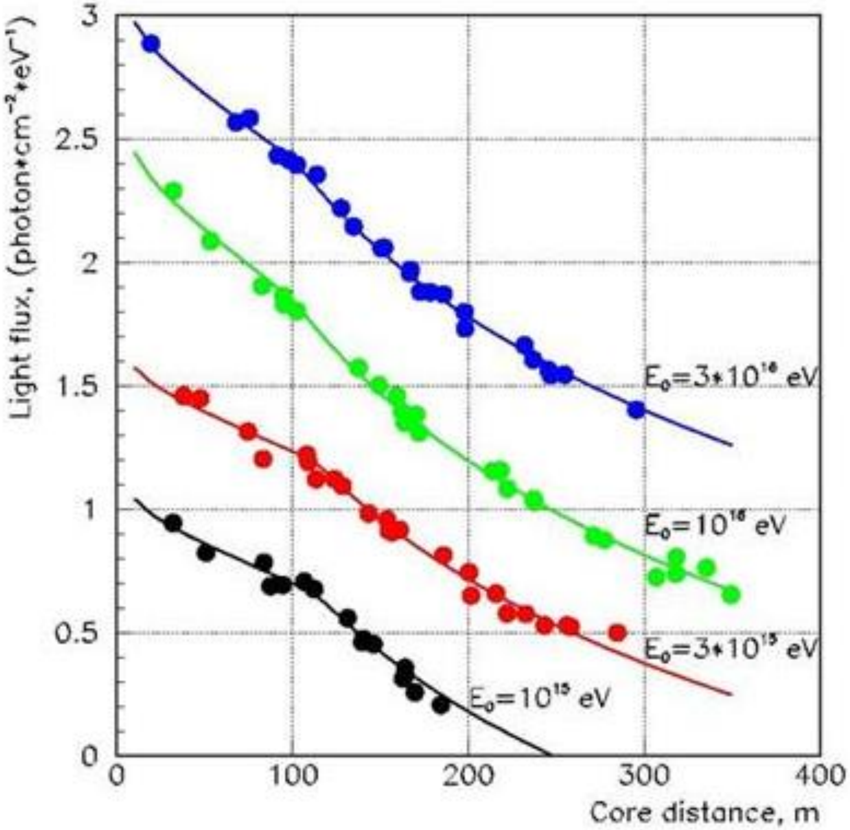
Tunka



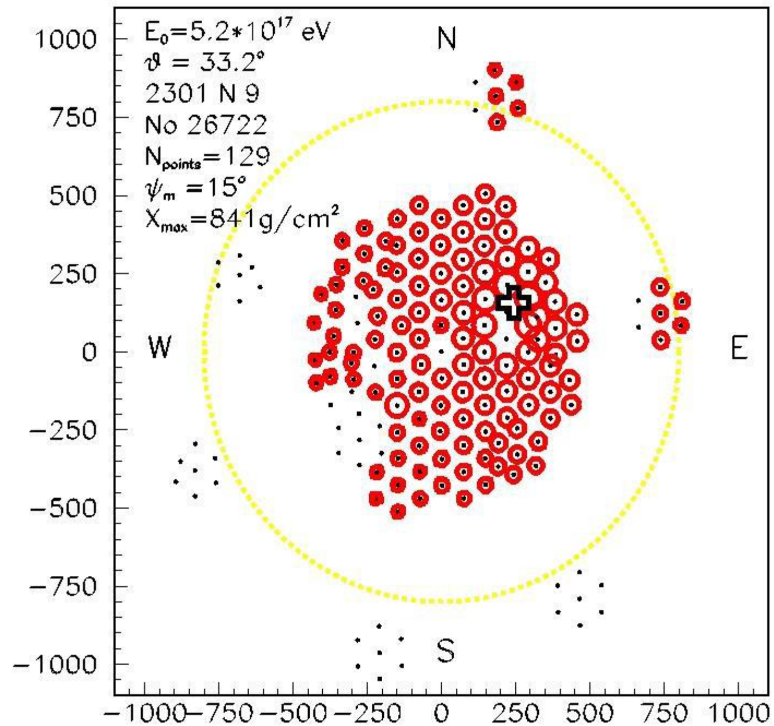
- **Energy range: 100TeV – 1EeV**
- **Area: >1 km²; 675m a.s.l.**
- **Cherenkov-experiment: LDF**
- **2011: Tunka-133 is extended by 6 distant external clusters**

Tunka: Reconstruction

Experimental data fitting with LDF

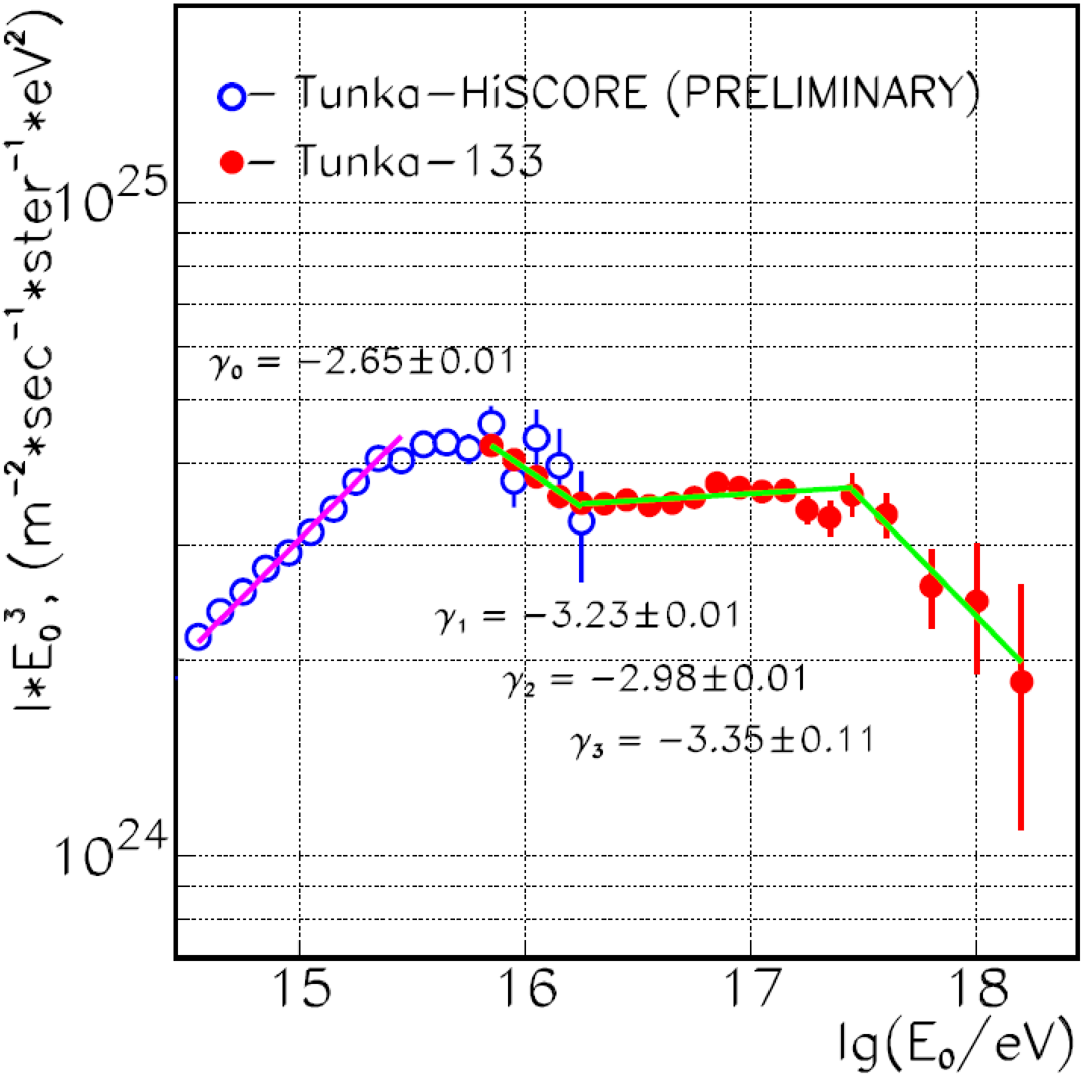


- **E_0 ~ $(Q_{200})^g$ (LDF function, g depends on composition)**
- **X_{max} reconstruction: Steepness of LDF**



- **Core accuracy ~ 10 m**
- **Energy resolution ~ 15%**
- **Energy threshold at 10^{15} eV**

Tunka: All-particle Energy Spectrum

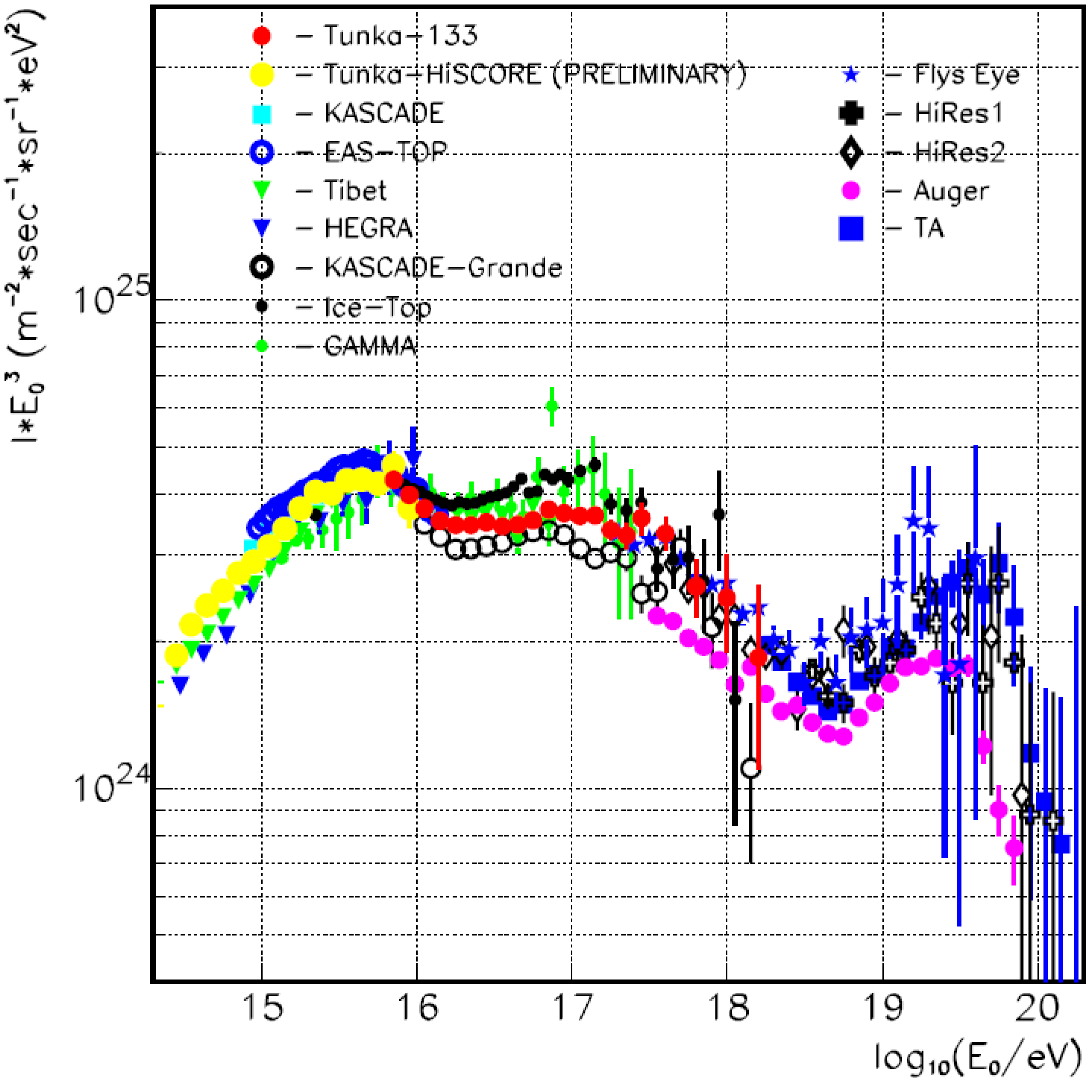


- **Two sharp feature at energies:**
  - $2 \cdot 10^{16}$ eV (first announced by KASCADE-Grande in 2010)
  - $3 \cdot 10^{17}$ eV (similar to that announced by Yakutsk and Fly's Eye in 90th)

- **Tunka-HiSCORE:**
  - prototype 9 optical stations
  - 80 h during 13 clean moonless nights from February to March in 2014

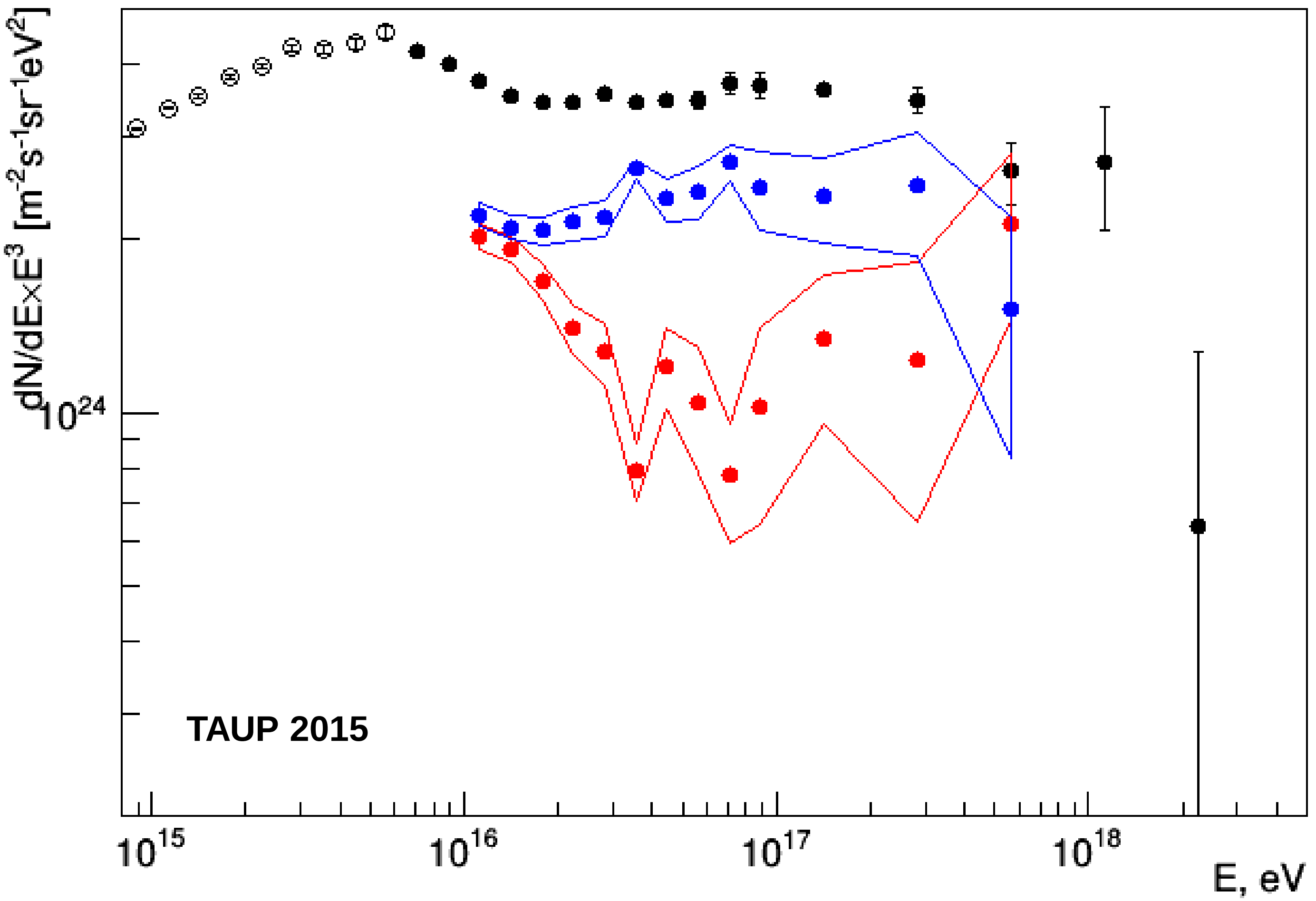
[V. Prosin et al, EPJ Conf. 121 (2016) 03004]

Tunka: Comparison With Others



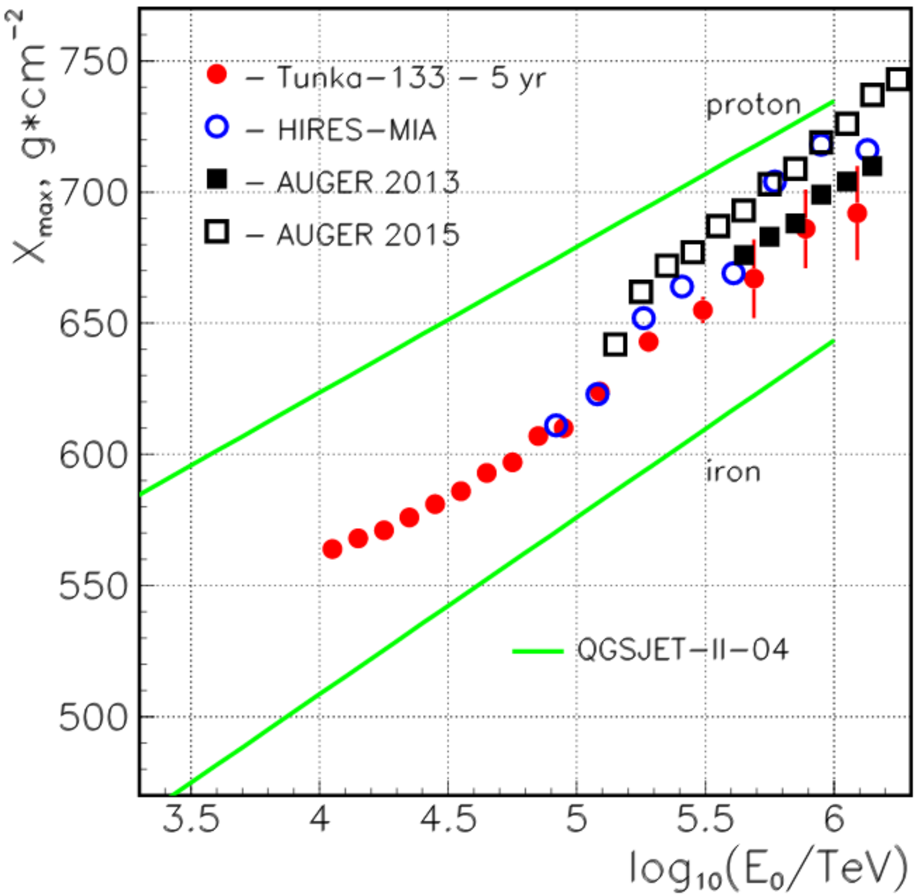
- Agreement with KASCADE-Grande and IceTop
- All the spectra coincide with Tunka-133, if energy of KASCADE-Grande is increased by 3% and energy of IceTop is decreased by 3%
- This shift is less than announced experimental accuracy
- Agreement with old Fly's Eye, HiRes and TA spectra

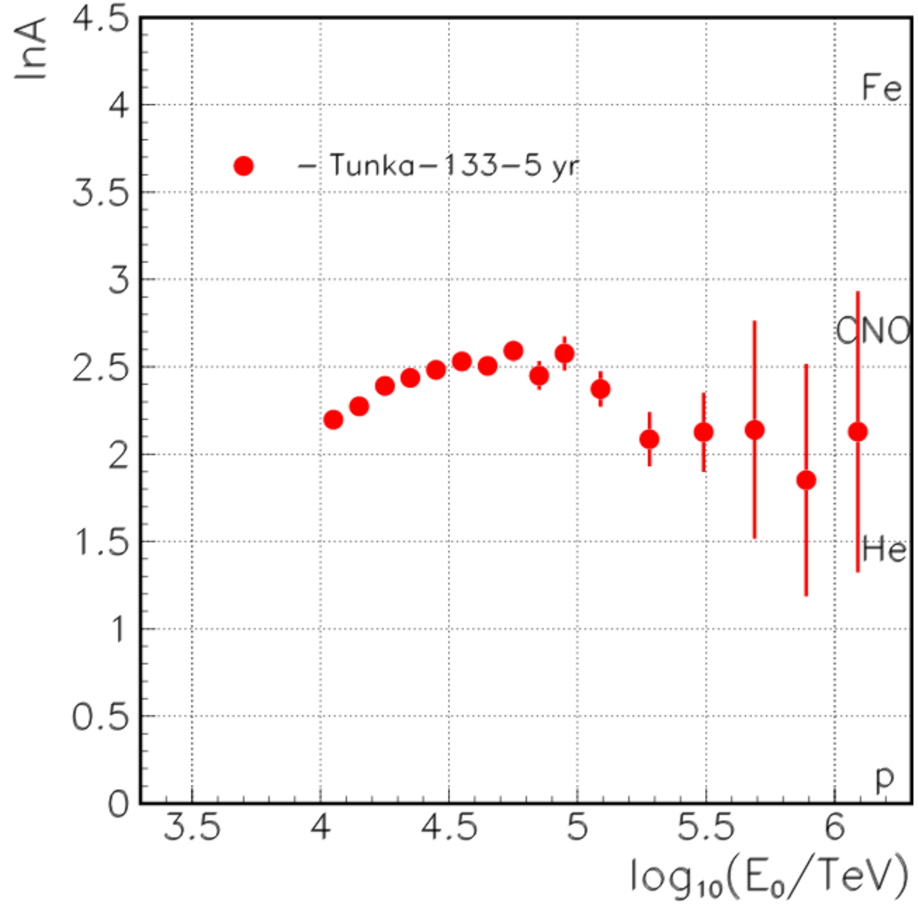
Tunka: Light and Heavy Components



- **The heavy component (all other) has a break at 10^{17} eV**
- **The light component (p+He) starts to rise again above 10^{17} eV**

Tunka-133: Composition

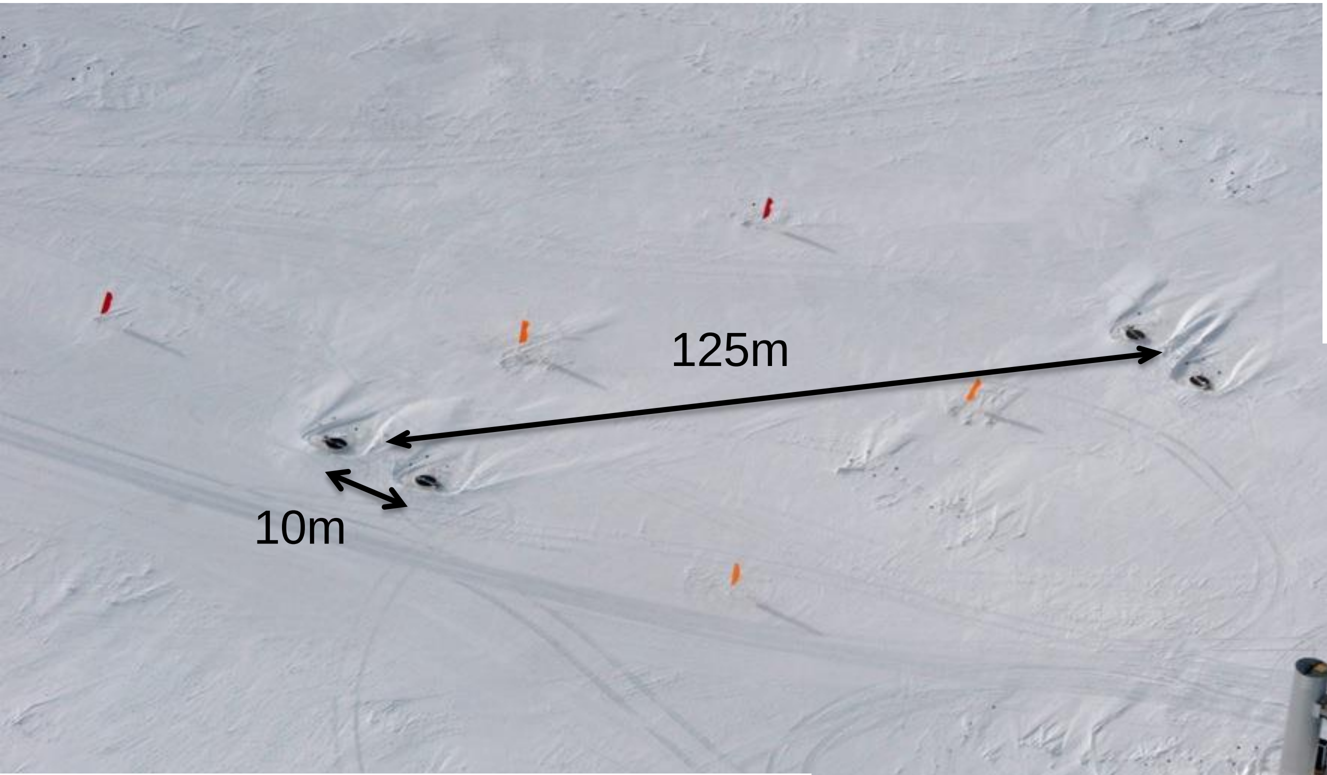


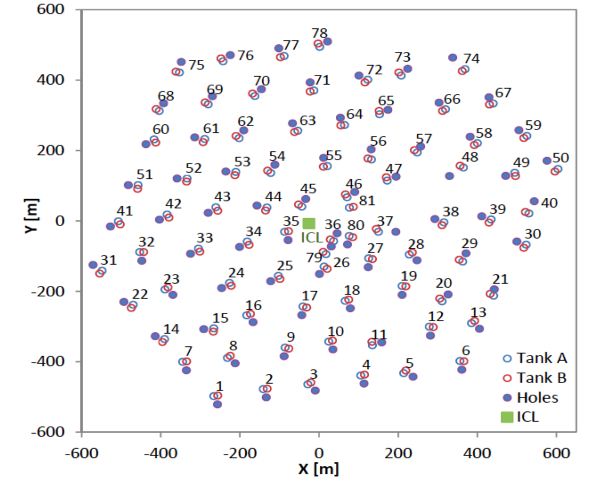


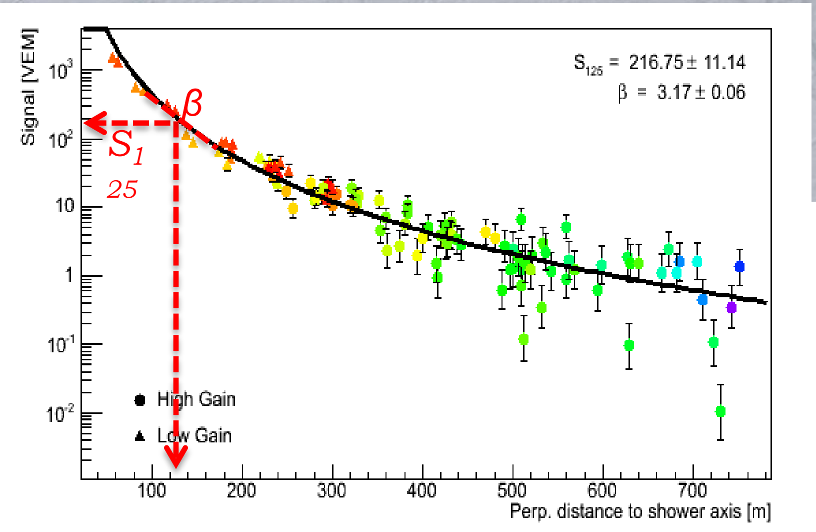
- **An agreement with previous Auger 2013**
- **But no enough statistics to discuss the discrepancy with the current Auger results**

[J. of Phys.: Conf. Series 718 (2016) 052031]

IceTop

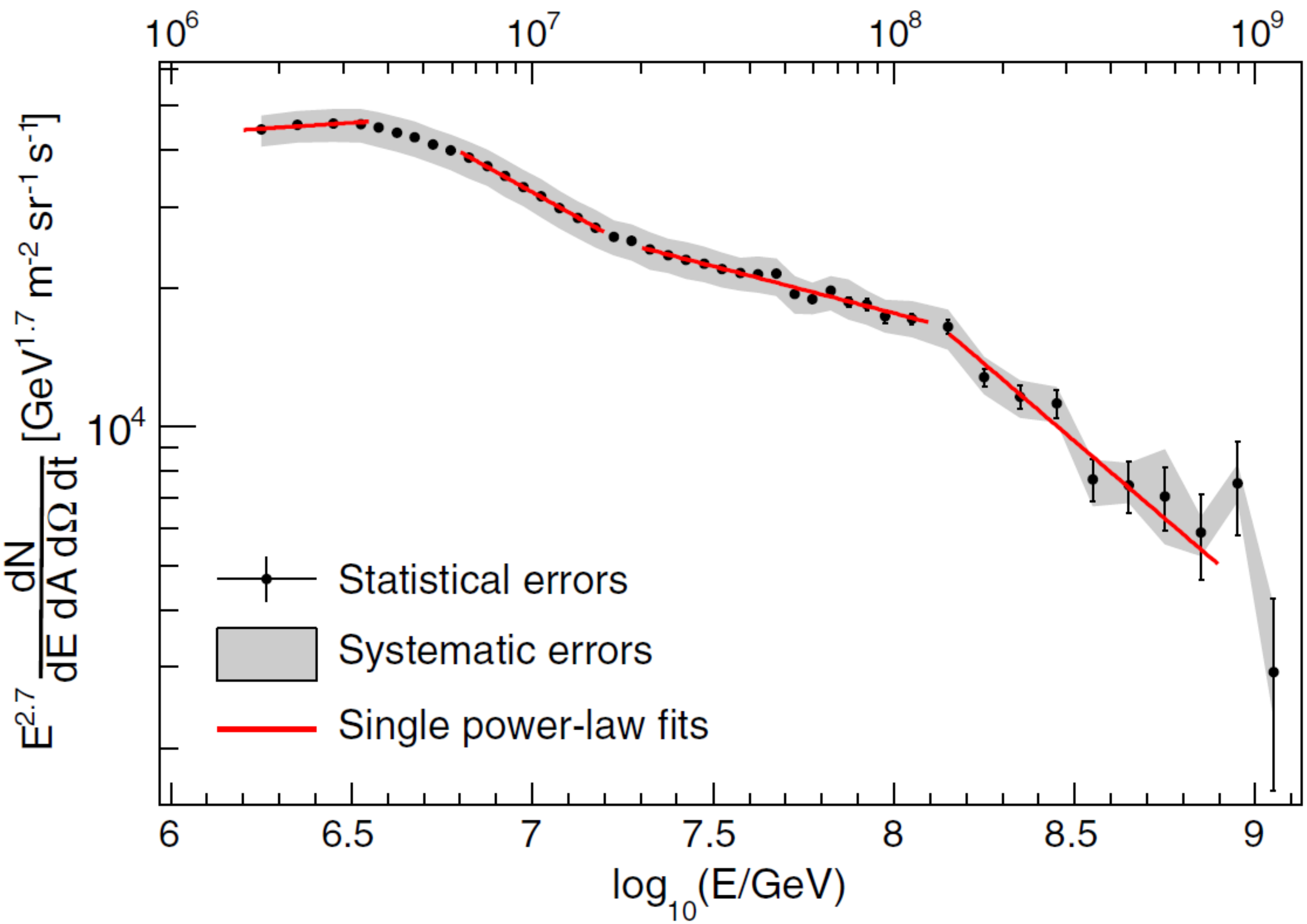






- Energy range: PeV – 1EeV
- Area: 1 km^2
- 2835m altitude (680 g/cm^2)
- 81 ice cherenkov stations
- LDF + particle density at 125m
- in-ice high-energy muons

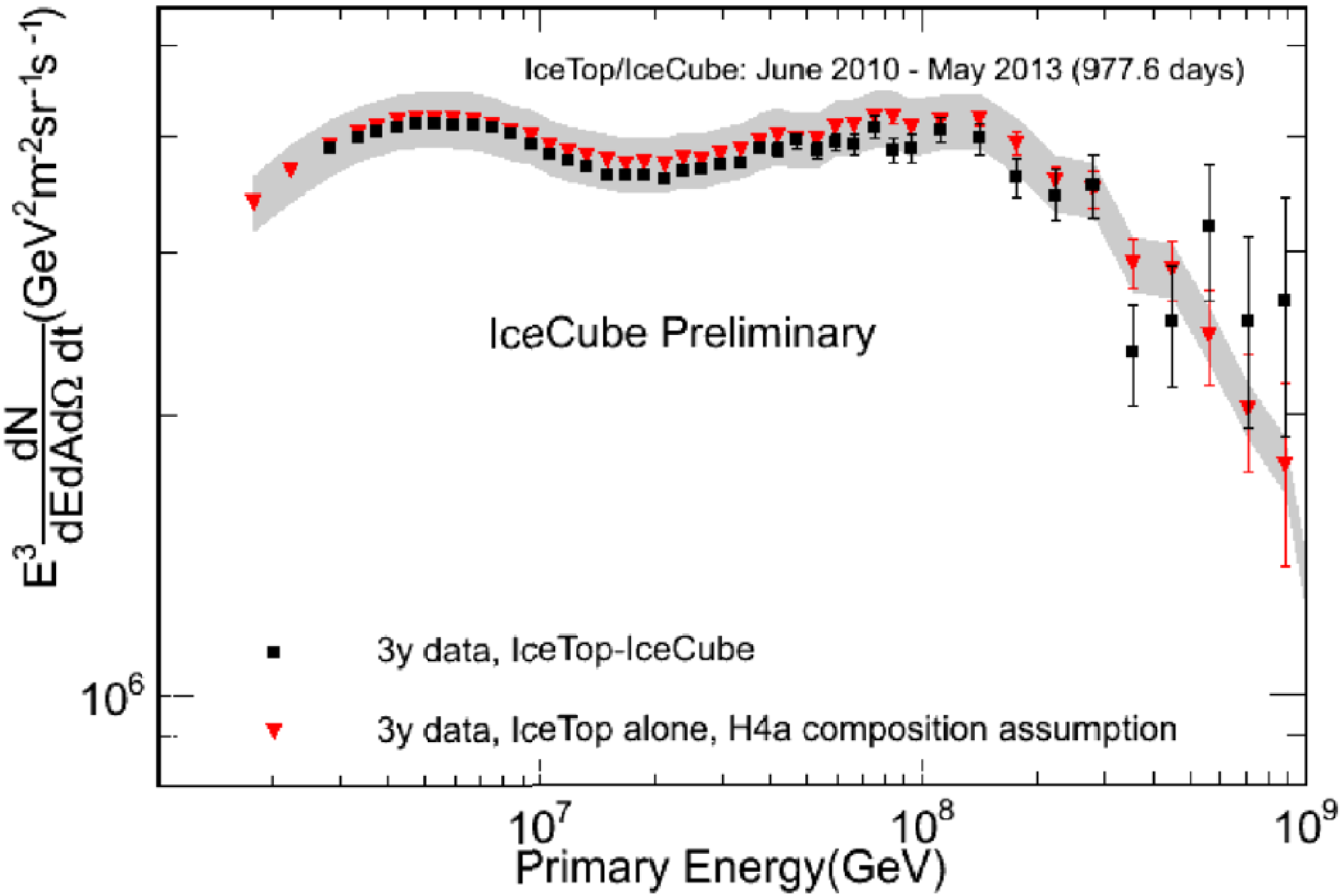
IceTop: Energy Spectrum (remind)



- **The spectrum does not follow a simple power law above the knee up to 1 EeV**
- **Observed a spectral hardening at 18 $\pm$ 2 PeV**
- **The spectrum steepens at 130 $\pm$ 30 PeV**

[PRD88 (2013) 042004]

IceTop / IceTop+IceCube Compared

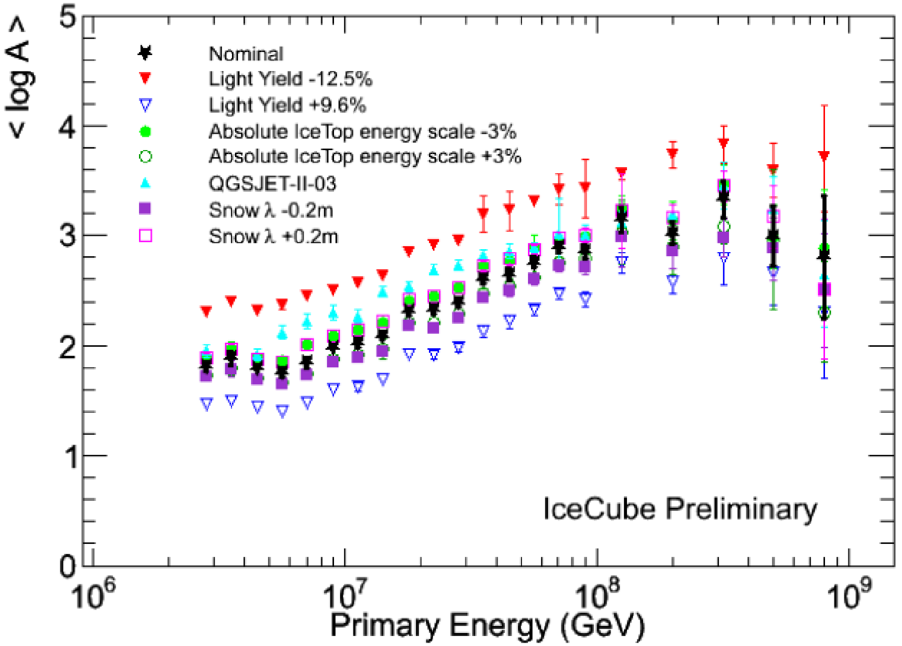


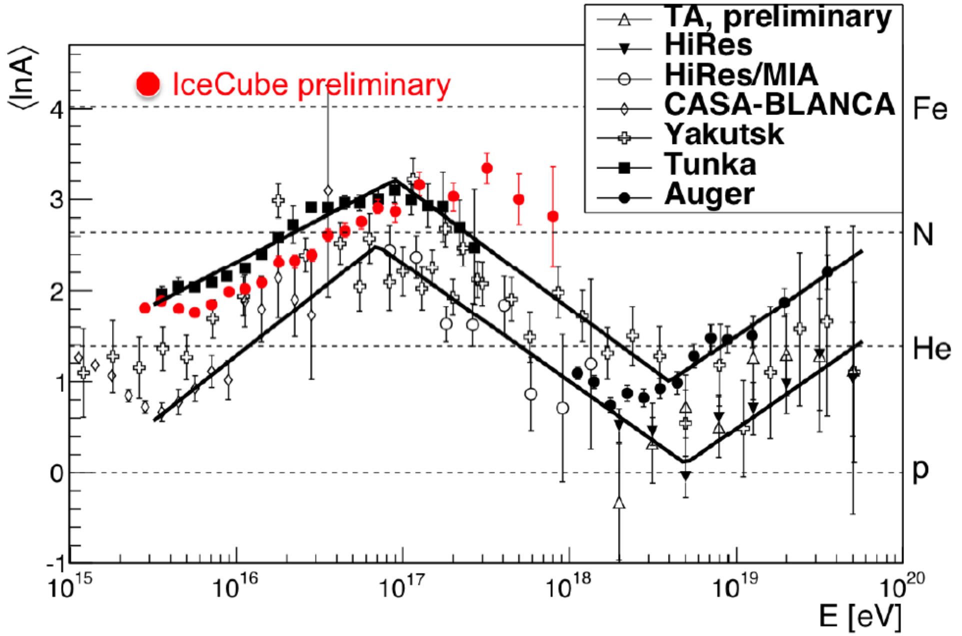
Systematic error band showed corresponds to 7% composition systematic

- **Coincident event analysis uses a neural network to determine both energy and composition**
- **Improvements in snow attenuation calculation and in light propagation models**

[Nucl. Phys. B Proc. Supp. (2016) 1]

IceTop+IceCube: Composition

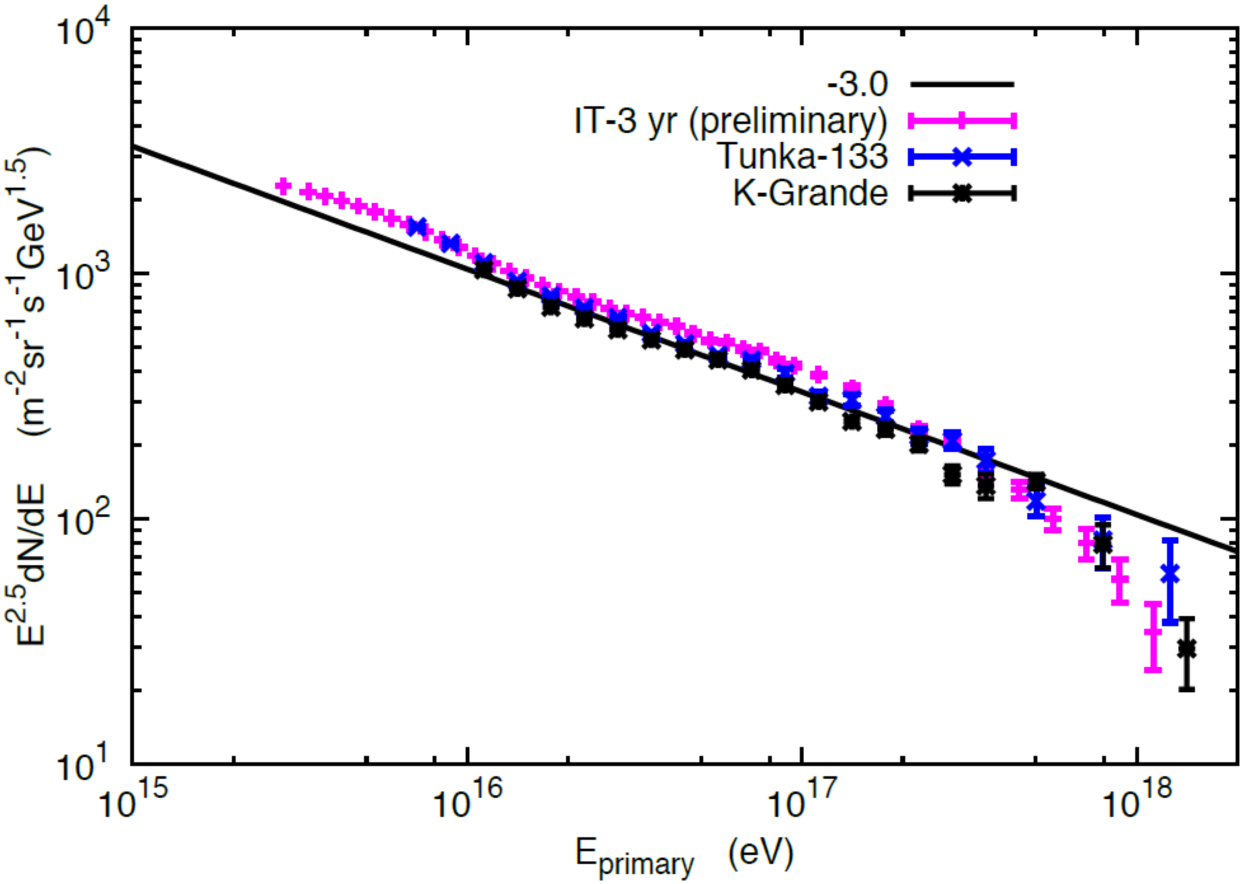




- **Energy dependence of <ln(A)> from the coincident analysis and its systematic effects**
- **The combined IceTop+IceCube analysis shows a clear trend toward heavy primaries in average <ln(A)>**
- **The heavy knee is at higher energies and above the models**

[Nucl. Phys. B Proc. Supp. (2016) 1]

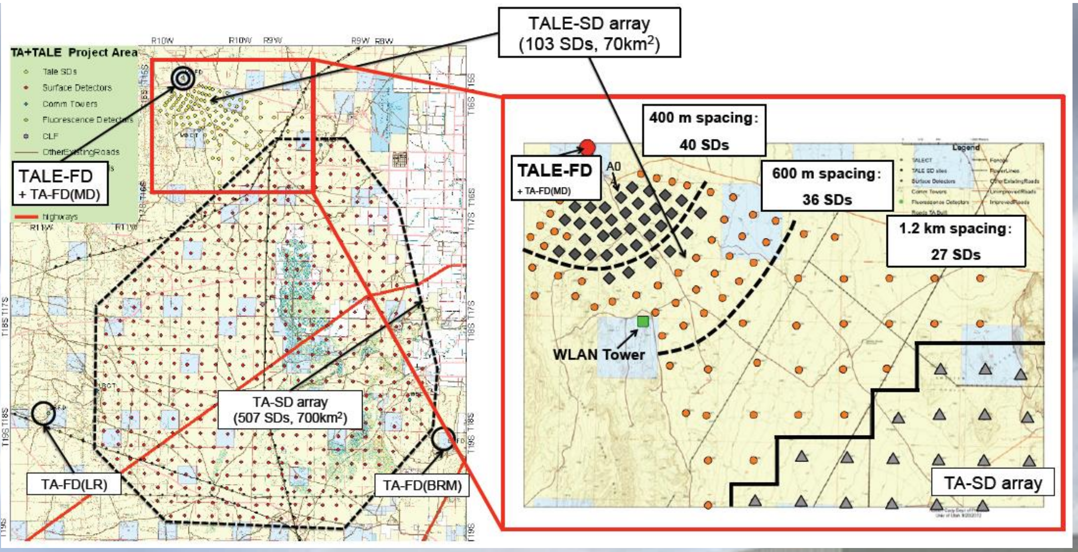
All-particle Energy Spectrum
KASCADE-Grande – Tunka – IceTop

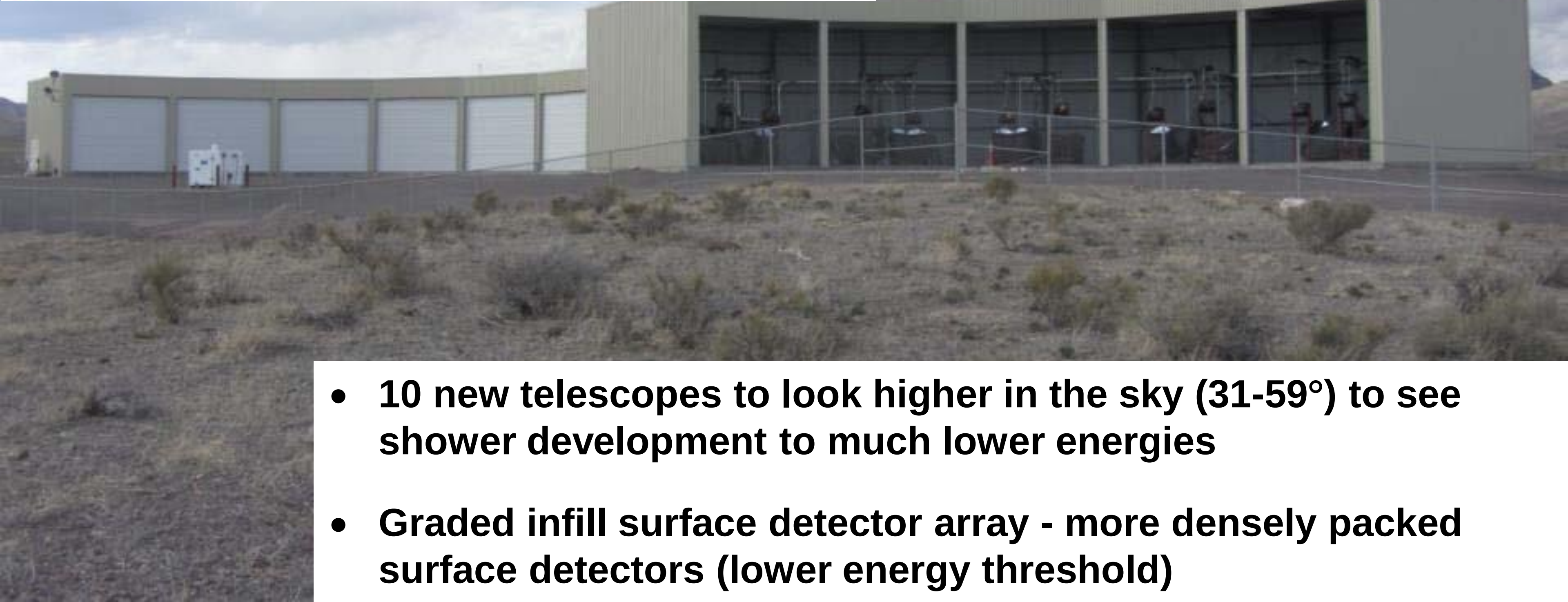


Differences between the experiments for same hadronic interaction model are in the same order of the difference between results based on different hadronic interaction models at one experiment

- **Same structures observed in spite of different observables and observation levels**
- **Absolute scale difference: < 20% within systematics (by method and composition sensitivity)**

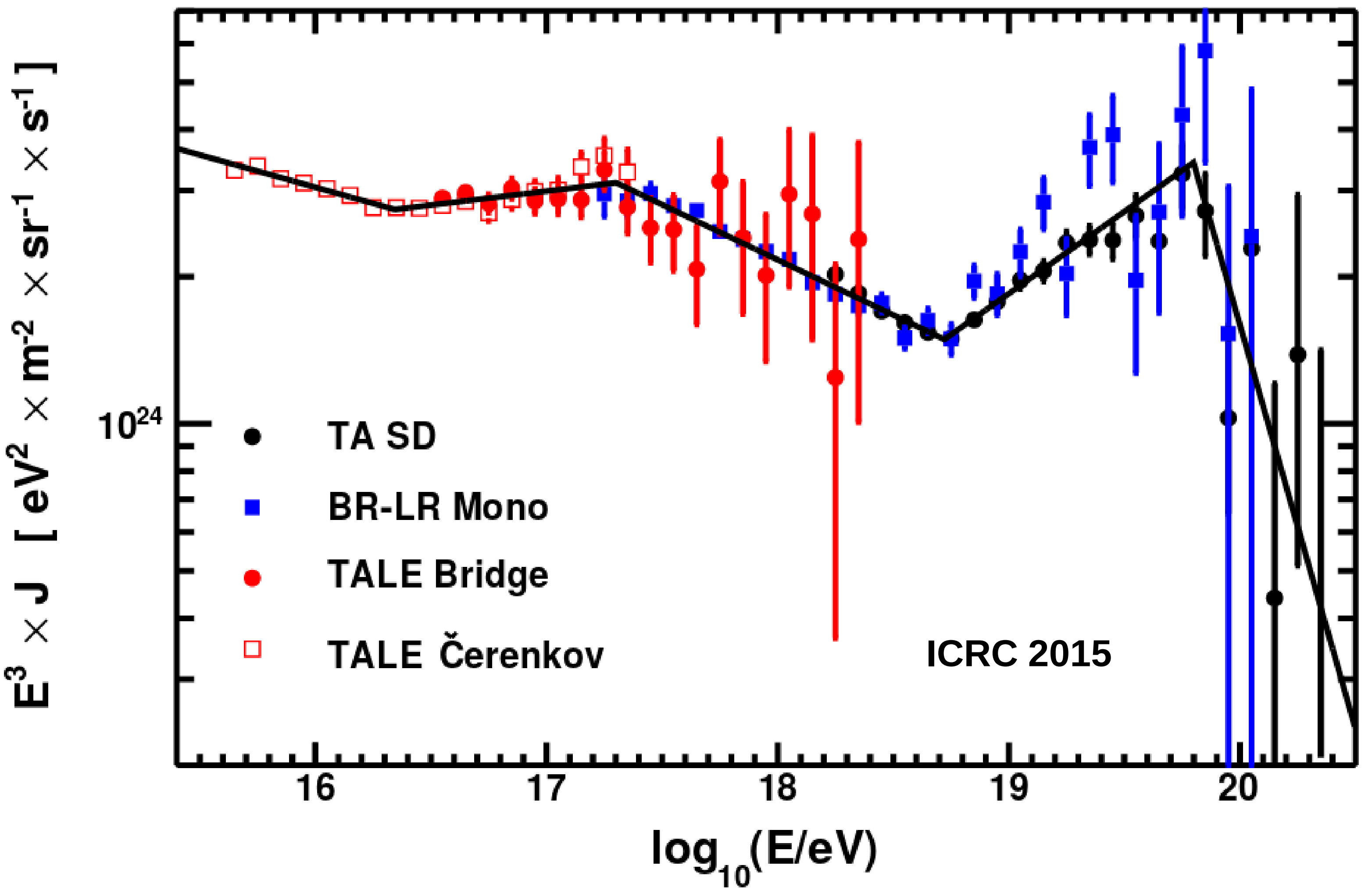
TA Low Energy Extension (TALE)





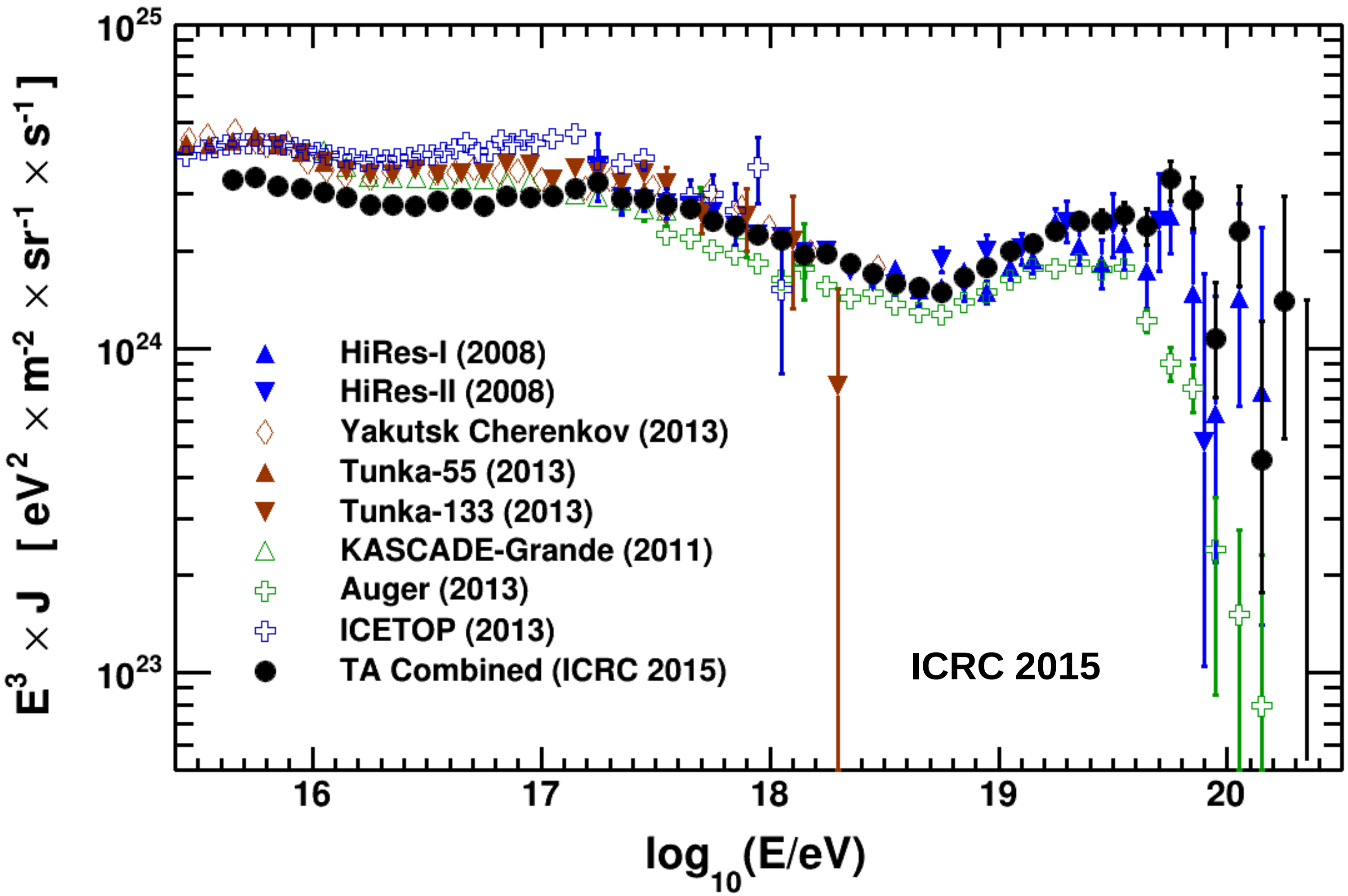
- **10 new telescopes to look higher in the sky (31-59°) to see shower development to much lower energies**
- **Graded infill surface detector array - more densely packed surface detectors (lower energy threshold)**

Combined TA Energy Spectrum



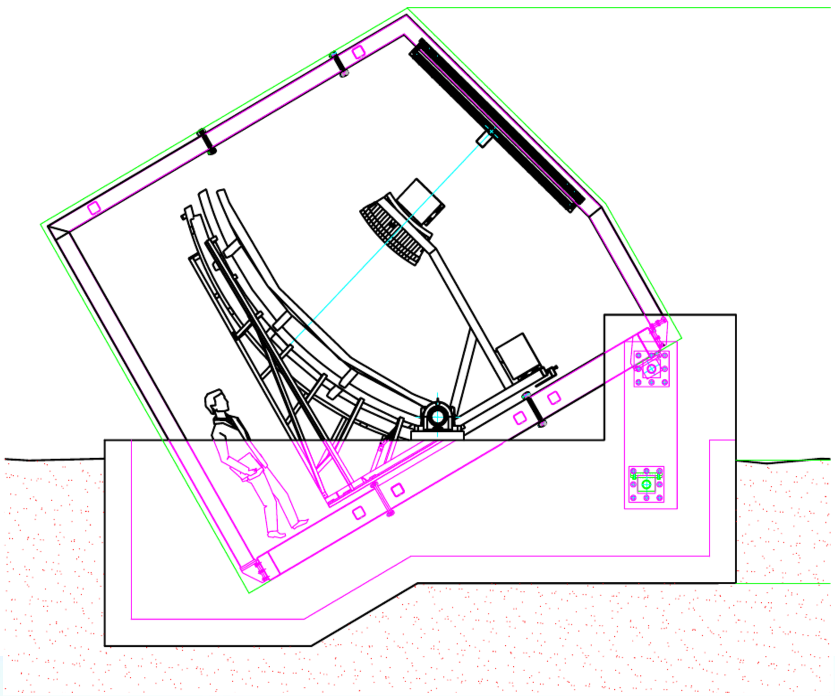
- TALE FD ($10^{16.5} < E < 10^{18.4}$ eV)
- TALE FD reconstructed using only the Cherenkov light ($10^{15.6} < E < 10^{17.4}$ eV)
- Two features: a low energy ankle at $10^{16.34}$ eV and a second knee at $10^{17.3}$ eV

Comparison With Others



- **Strong composition dependence and still large systematic errors**
- **Discrepancy between TA Combined and the ground based experiments due to systematic effects?**

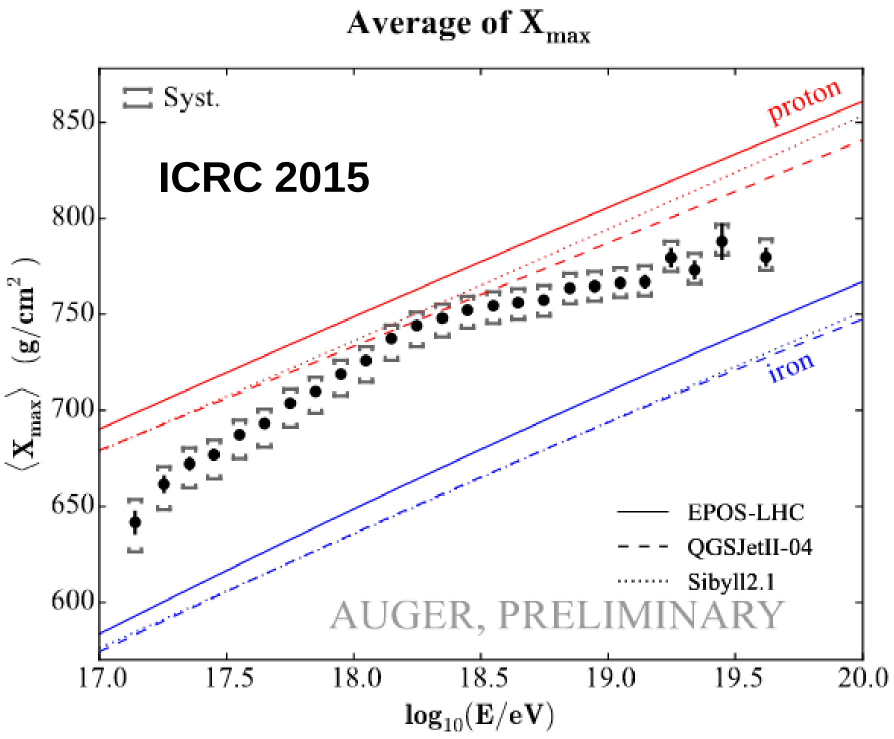
High Elevation Auger Telescope (HEAT)

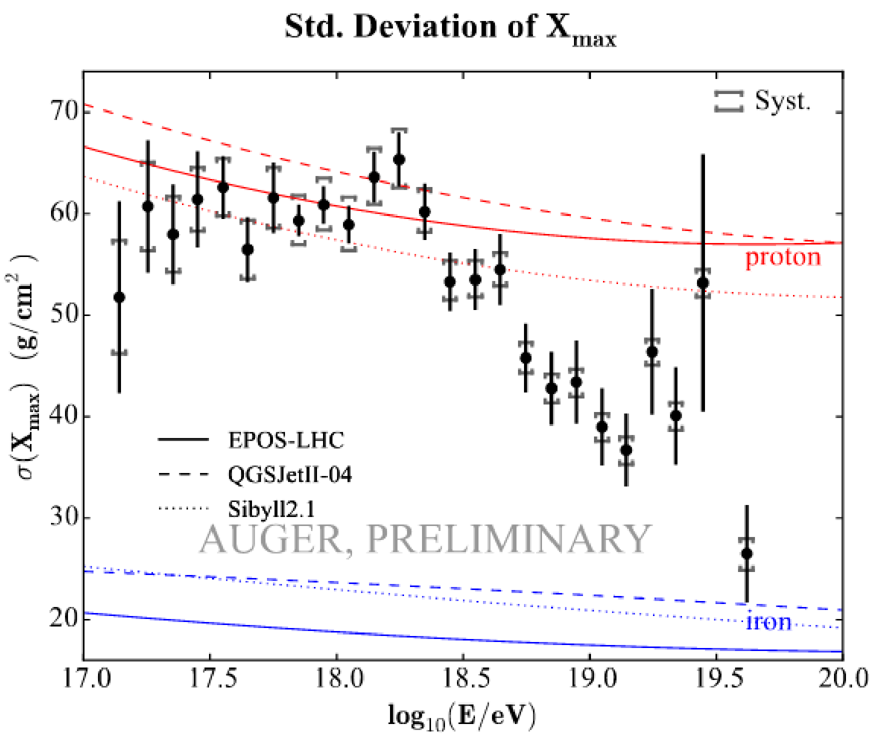


- Low energy extension of Pierre Auger Observatory
- 3 tiltable FD at Coihueco site with FOV of 30 – 60° in upward mode
- Due to the FOV higher in the atmosphere, sensitive down to 10^{17}eV → on decade in energy overlap with KASCADE-Grande

Auger Muons and Infill for the Ground Array (AMIGA):
SD Infill + Muon Counter
23.5 km^2 with 750 m spacing

HEAT: Composition





- **Energy range: $10^{17} – 10^{18.3}$ eV**
- **Data between 01.06.2010 and 15.08.2012**
- **Mean of the shower maxima as well as their fluctuations indicate a composition becoming lighter up to $10^{18.3}$ eV**
- **Transition from light to heavier primaries above $10^{18.3}$ eV**

Conclusion

- Features of the energy spectrum found by KASCADE-Grande have been confirmed by Tunka, IceTop and TALE with improved statistics and analysis technique:
  - A steepening at 10^{17} eV dominated by heavy components
  - A hardening at about $2 \cdot 10^{16}$ eV
  - A flattening of the light component around 10^{17}eV = Maybe the first sign of an extra-galactic component

- The mass composition of KASCADE-Grande, Tunka and IceTop shows similar tendencies, however, the absolute scale difference is still large due to hadronic interaction models:
  - Still some contradiction on the composition around 10^{18} eV
  - HEAT indicates a clear transition from heavy to light between 10^{17} eV and 10^{18} eV, while Tunka and IceTop show a less pronounced effect.

- Relative abundancies depend strongly on high energy interaction model and astrophysical interpretation is limited by description of interactions in the atmosphere. Need to improve the hadronic interaction models