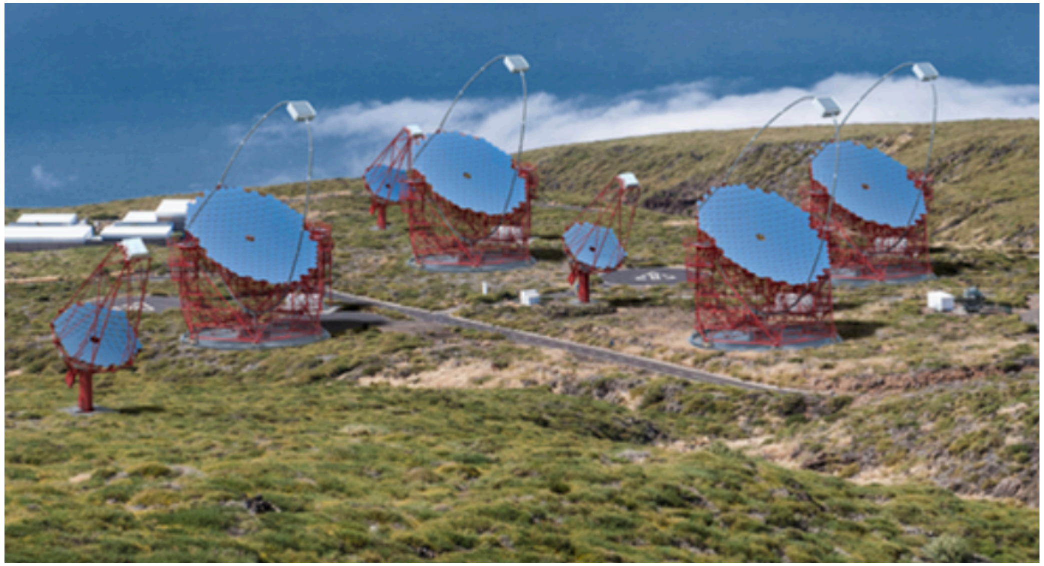
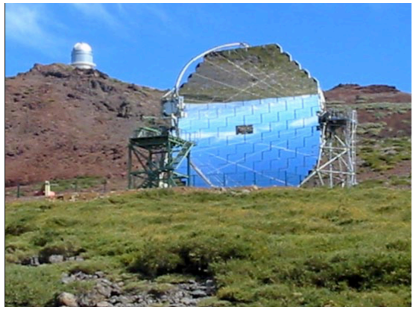
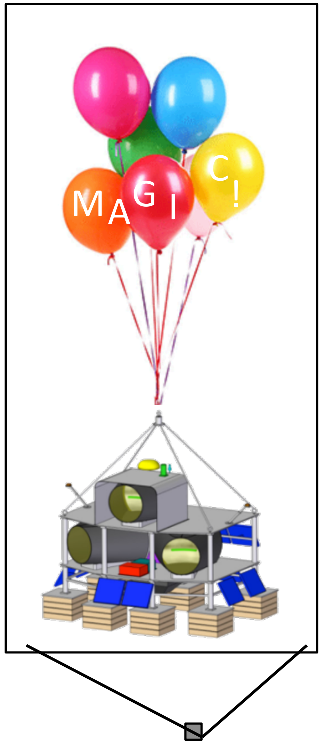
Cosmic ray composition from PeV to 10^{19} eV with IACTs



CTA: LST, MST, SST



MAGIC



Very-Very
Small
Size
Telescope

Andrii Neronov
University of Geneva

Astrophysics + MAGIC, La Palma 2018

Overview

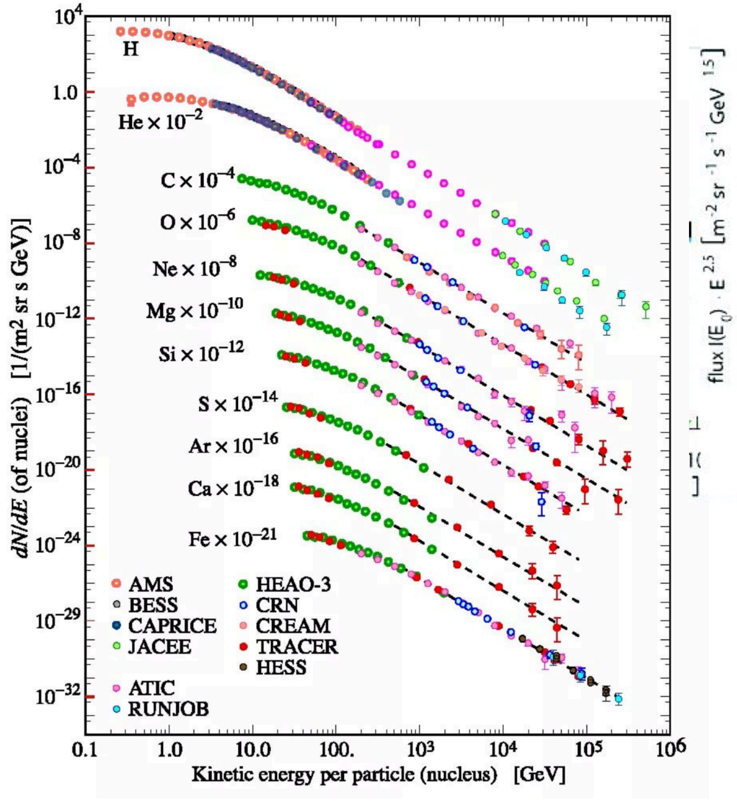
Introduction: Cosmic ray composition data: TeV, PeV, EeV to UHECR

Muon component of strongly inclined air showers

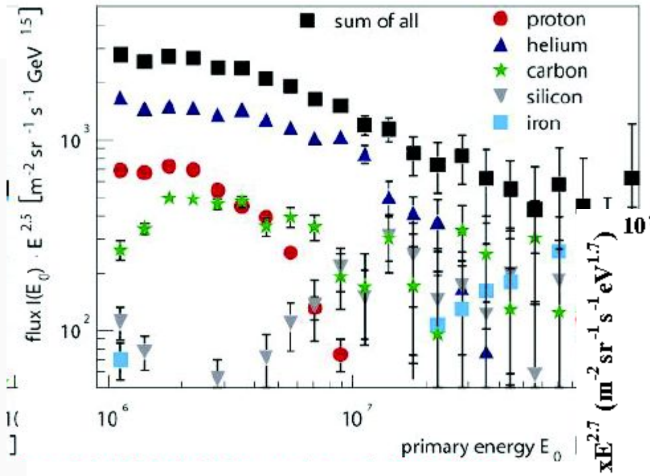
Imaging of muon and electromagnetic component in high zenith angle showers

MAGIC / CTA vs. dedicated small IACT

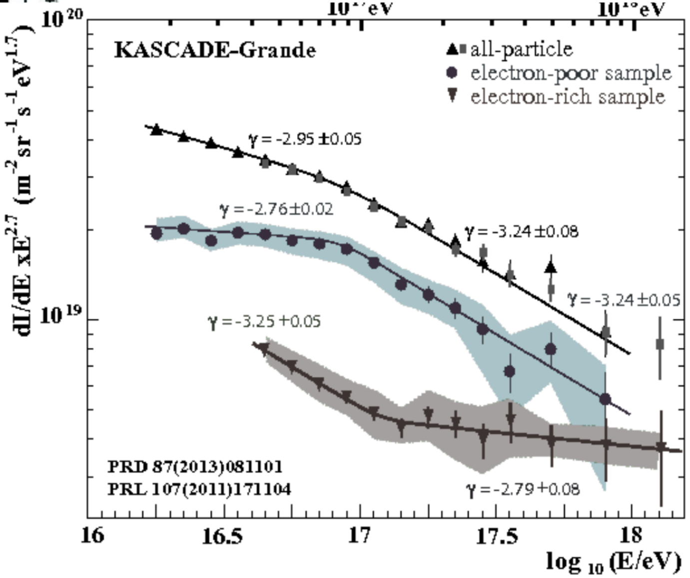
Cosmic ray composition data



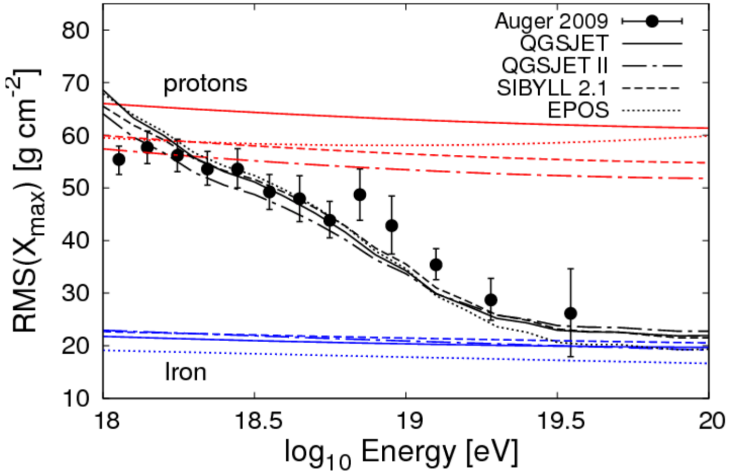
KASCADE



KASCADE-Grande



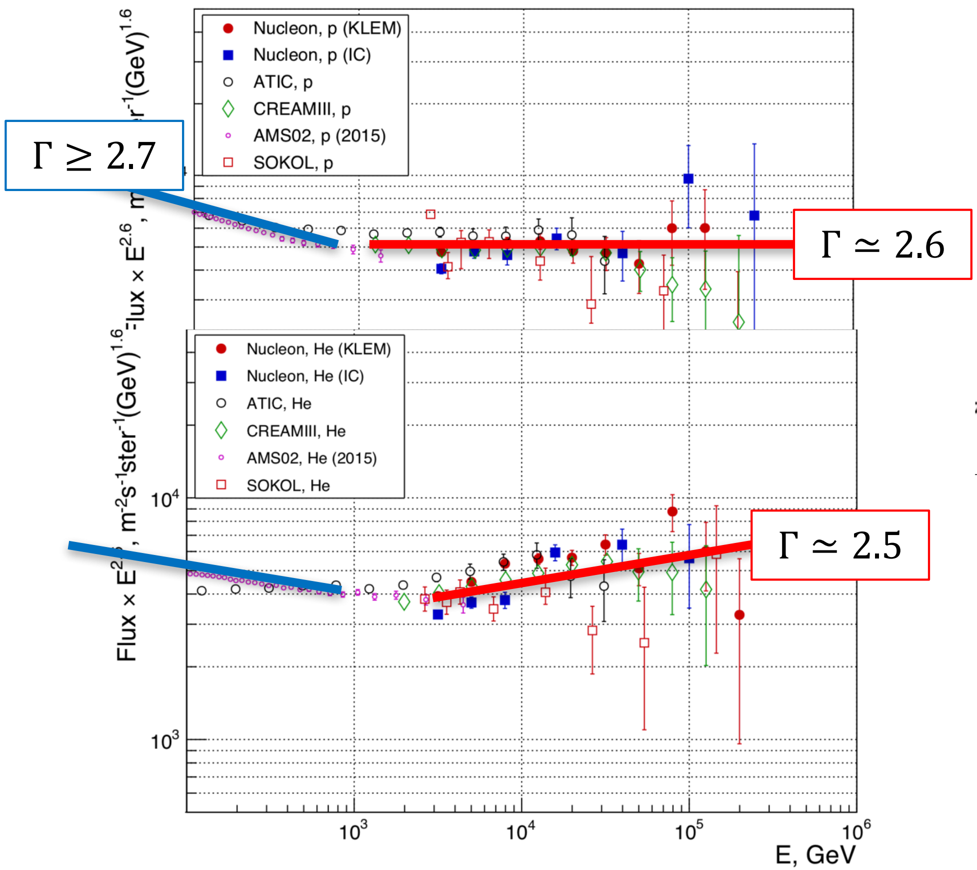
Pierre Auger Observatory

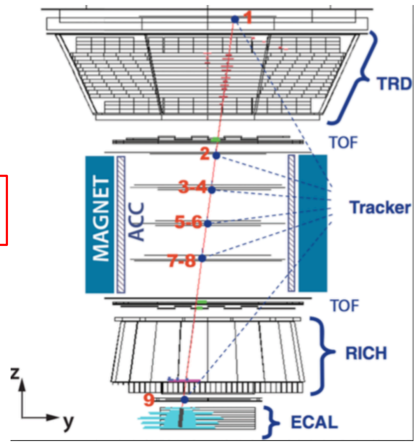


Quality of identification of primary cosmic ray particles degrades with the increase of energy because of the decreasing number of measurable characteristics of the CR events.

CR particle ID in the 1-100 TeV

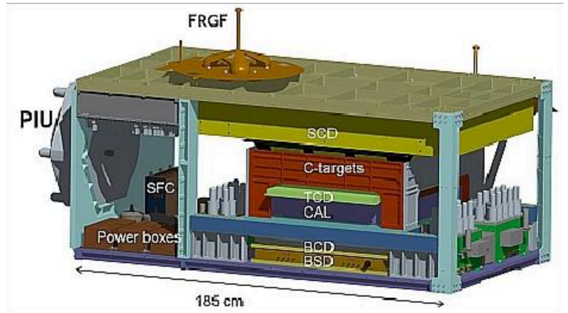
Atkin et al. '17

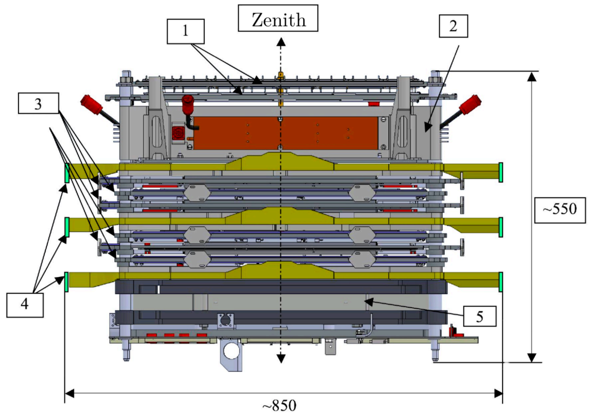




AMS-02

ISS-CREAM





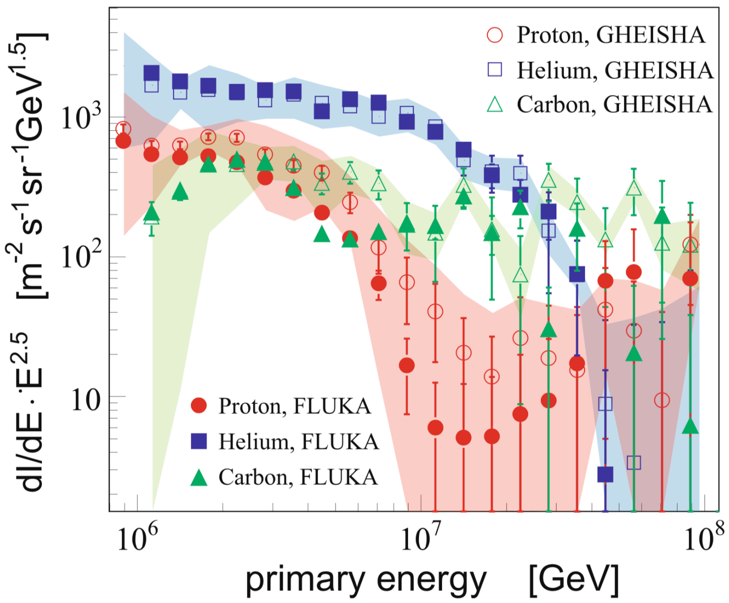
NUCLEON detector at Resurs P-2 sattelite

Direct measurement of CR primary particle ID are done with balloon- or space–based detectors (PAMELA, AMS-02, NUCLEON, CREAM,…..

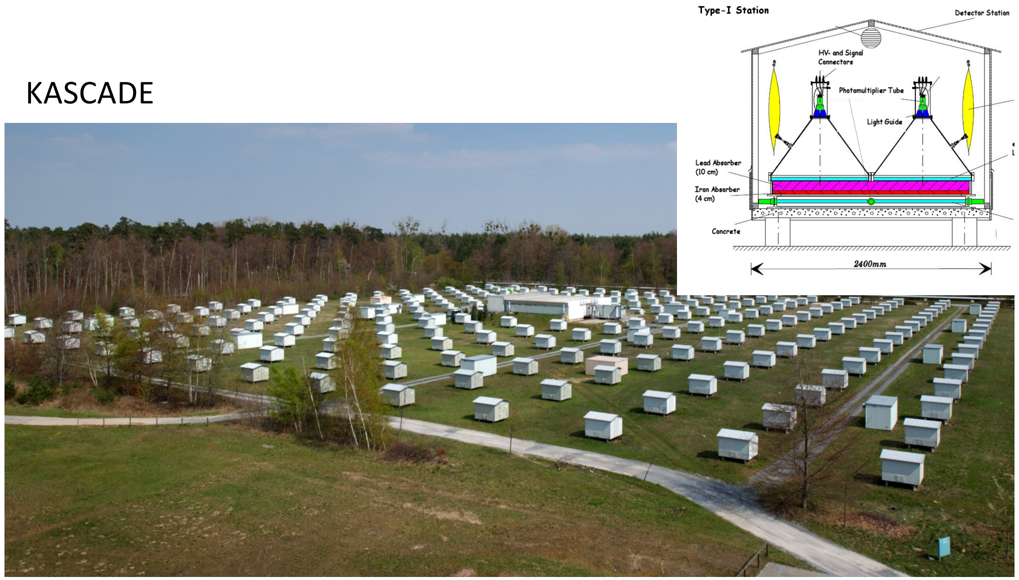
Hardening of the CR spectrum is observed above several hundred GeV, and the spectra of different elements **seem to** have different slopes …..

CR particle ID in the 0.1-100 PeV

Apel et al. '09



KASCADE



Above 100 TeV CR particle ID is measured only indirectly, via its imprint on development of Extensive air showers (EAS):

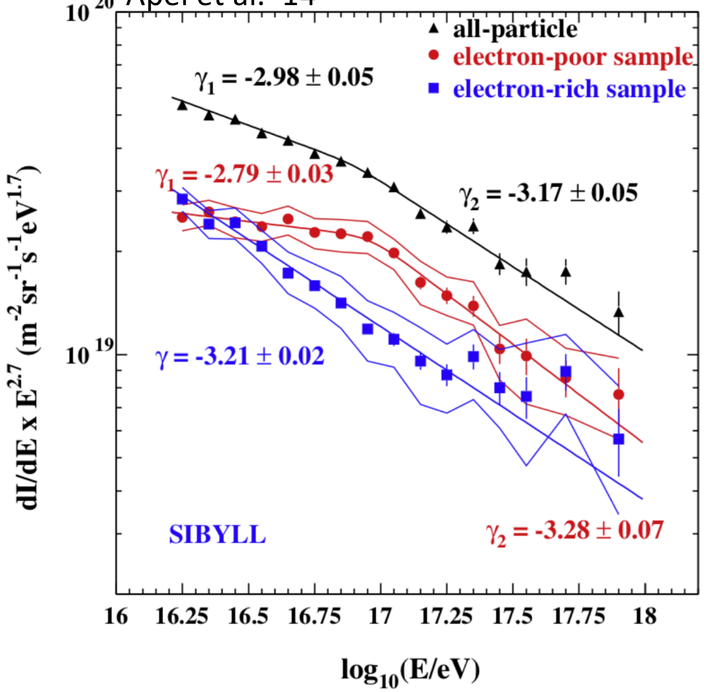
– heavier nuclei primary CR particles produce more muon-rich EAS
– heavier nuclei primary CR particles induce EAS developing at shallower atmospheric depths

Composition of the CR flux rapidly changes above 10^{15} eV (the "knee"). Heavier particles up to iron starts to dominate* the flux at in 10^{16}-10^{17}eV range.

* Details depend on hadronic interaction models used

CR particle ID in the 0.1-100 EeV

Apel et al. ‘14



KASCADE-Grande

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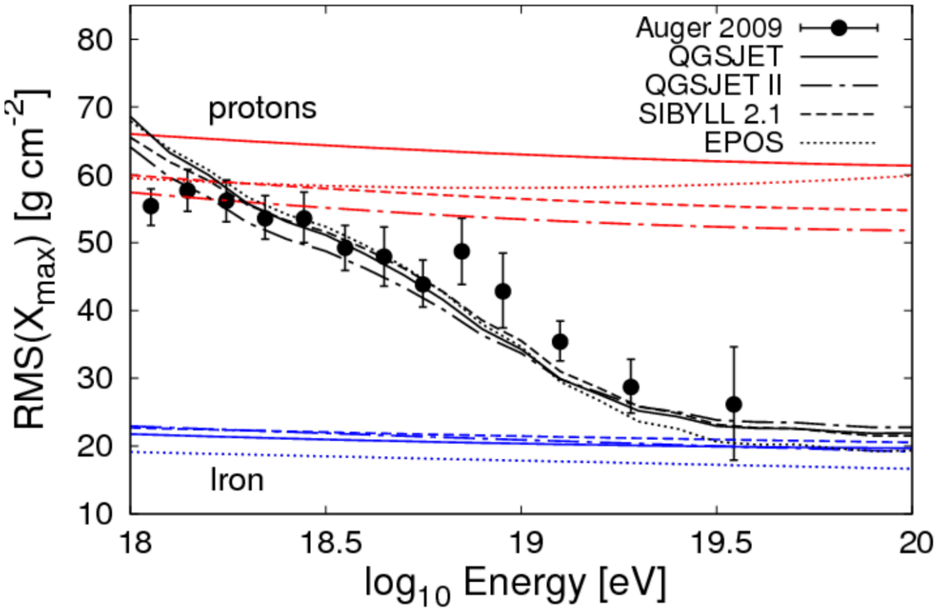
Above $3\text{x}10^{17}$ eV the composition changes back *. The flux is again dominated by lighter nuclei.

* Details depend on hadronic interaction models used

CR particle ID in the 0.1-100 EeV

Pierre Auger Collab. '16



Pierre Auger Observatory

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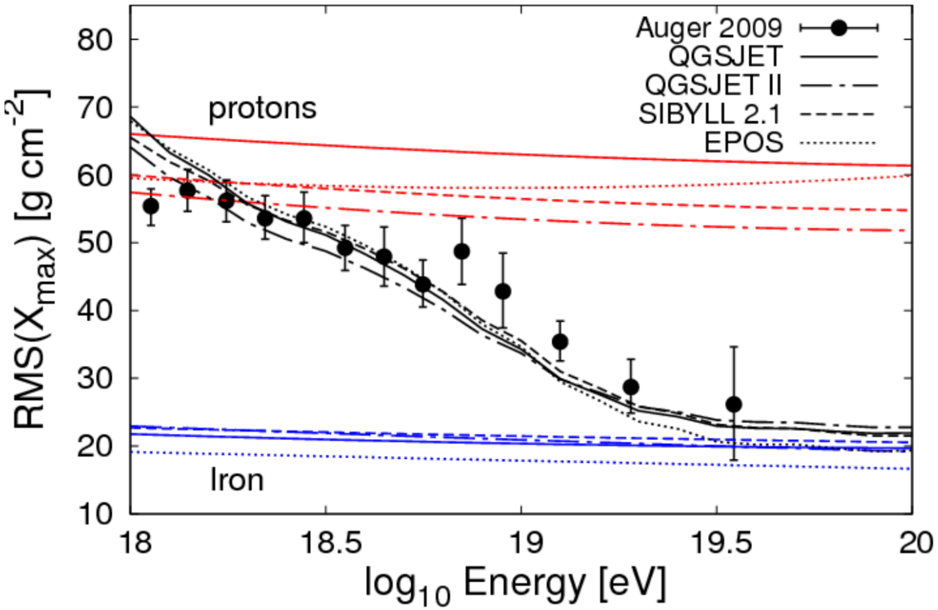
… and above 10^{19} eV the composition seems to change back

* Details depend on hadronic interaction models used

Muon excess in Auger EAS observations at 10^{19} eV

Pierre Auger Collab. '16



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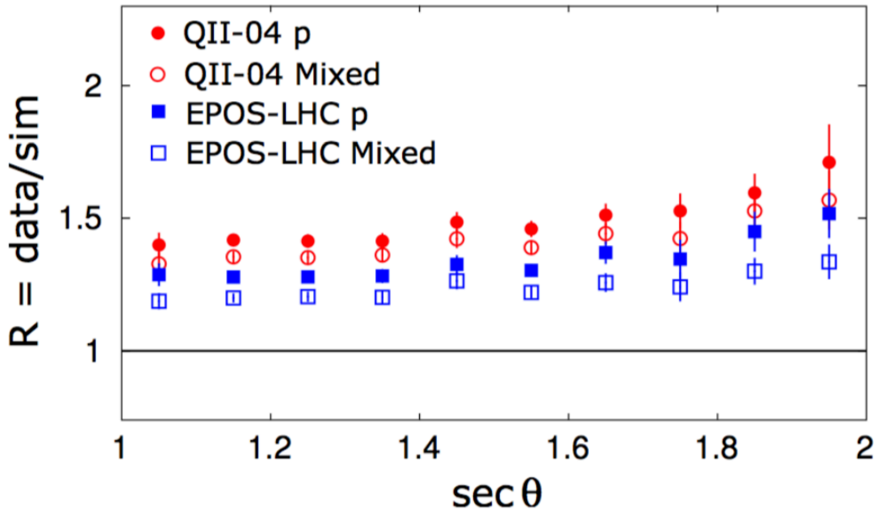
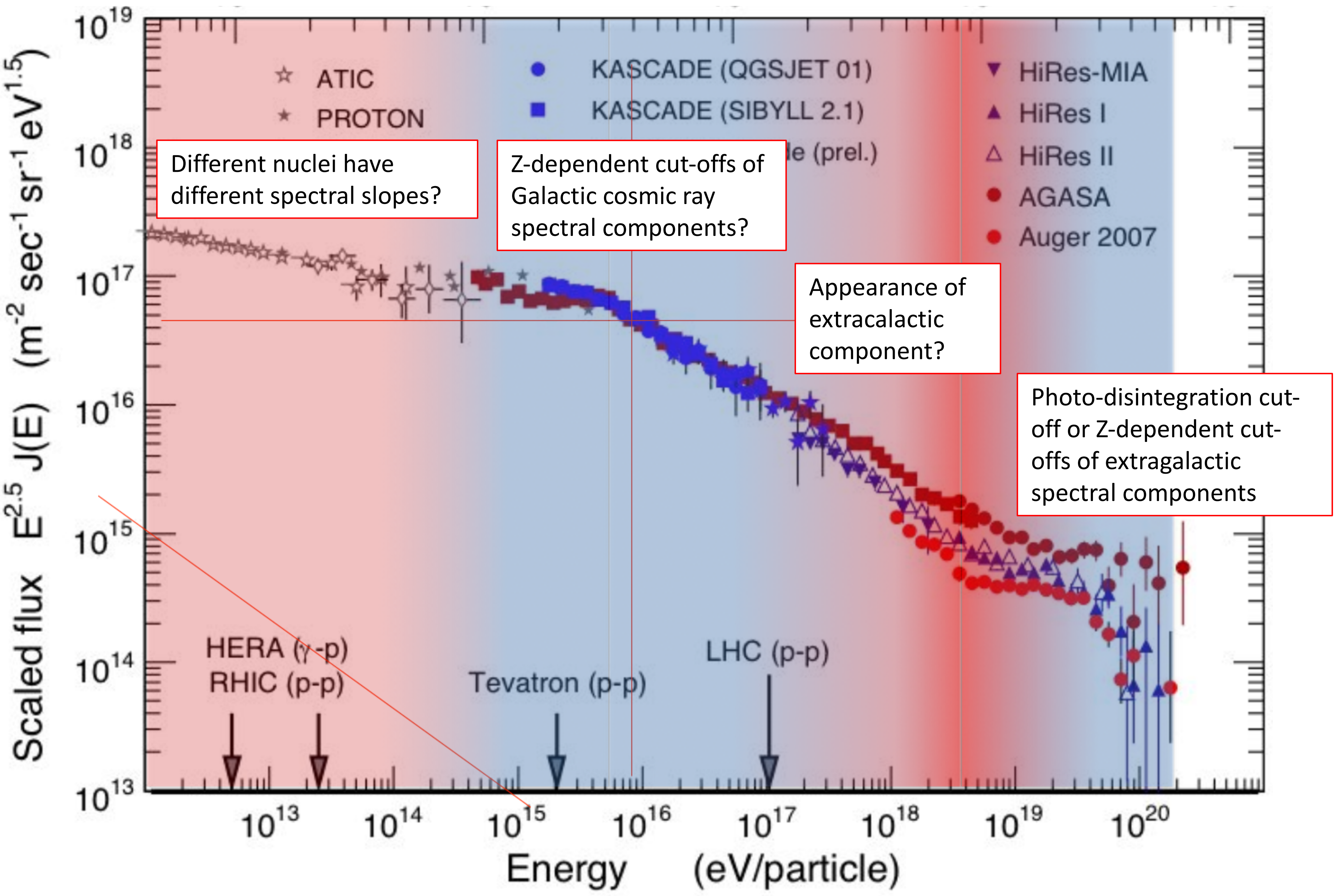


Auger systematically sees over-abundance of muons at about 1e19 eV energy, by 30-50% compared to simulated showers

arXiv:1610.08509

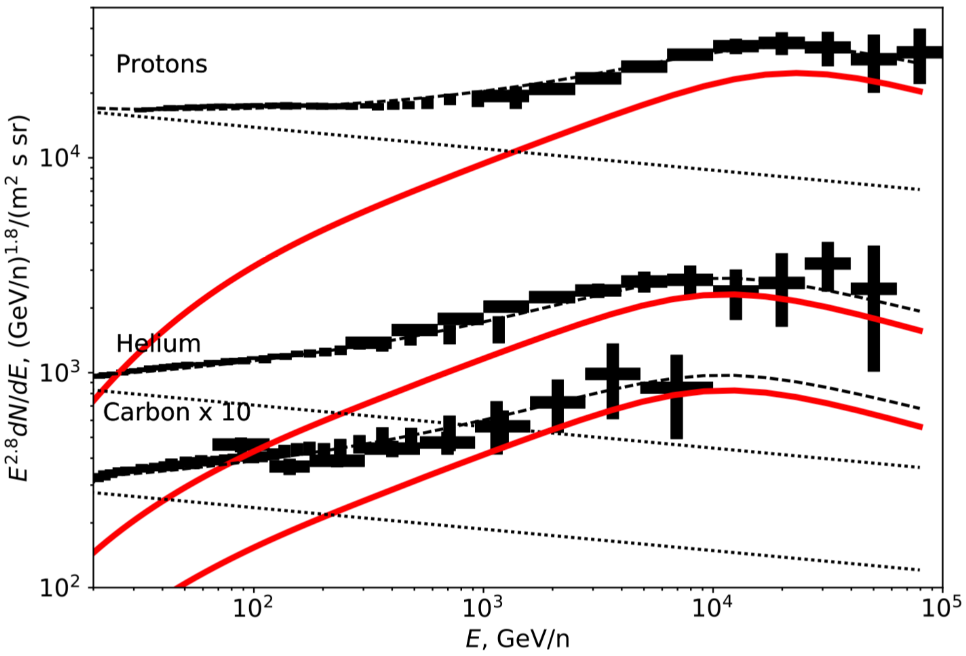
* Hadronic interaction model uncertainties

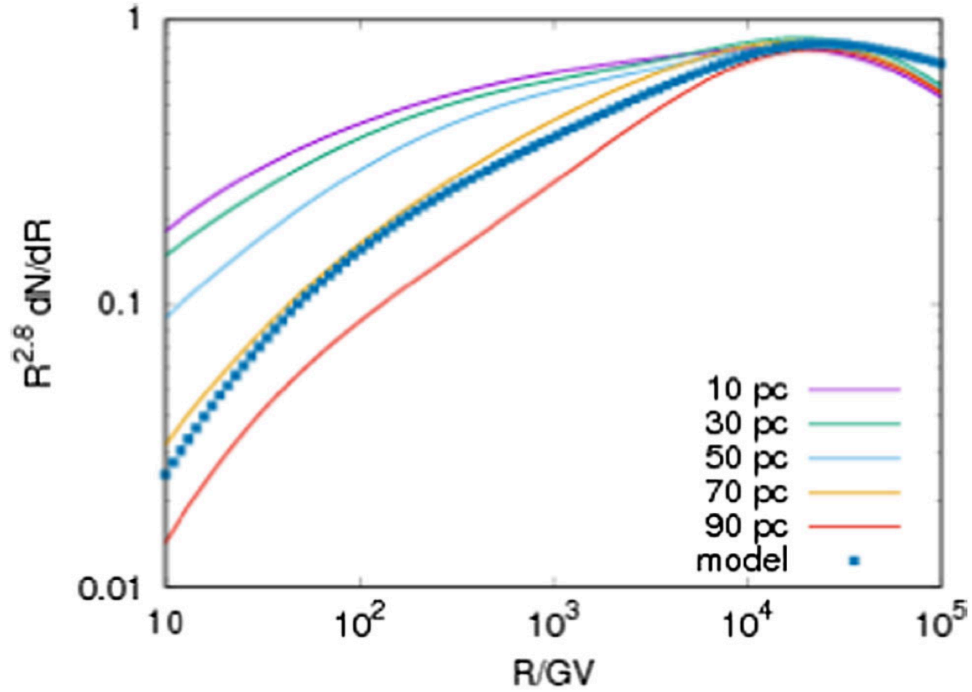
CR composition across energy bands



Theoretical modelling (examples)

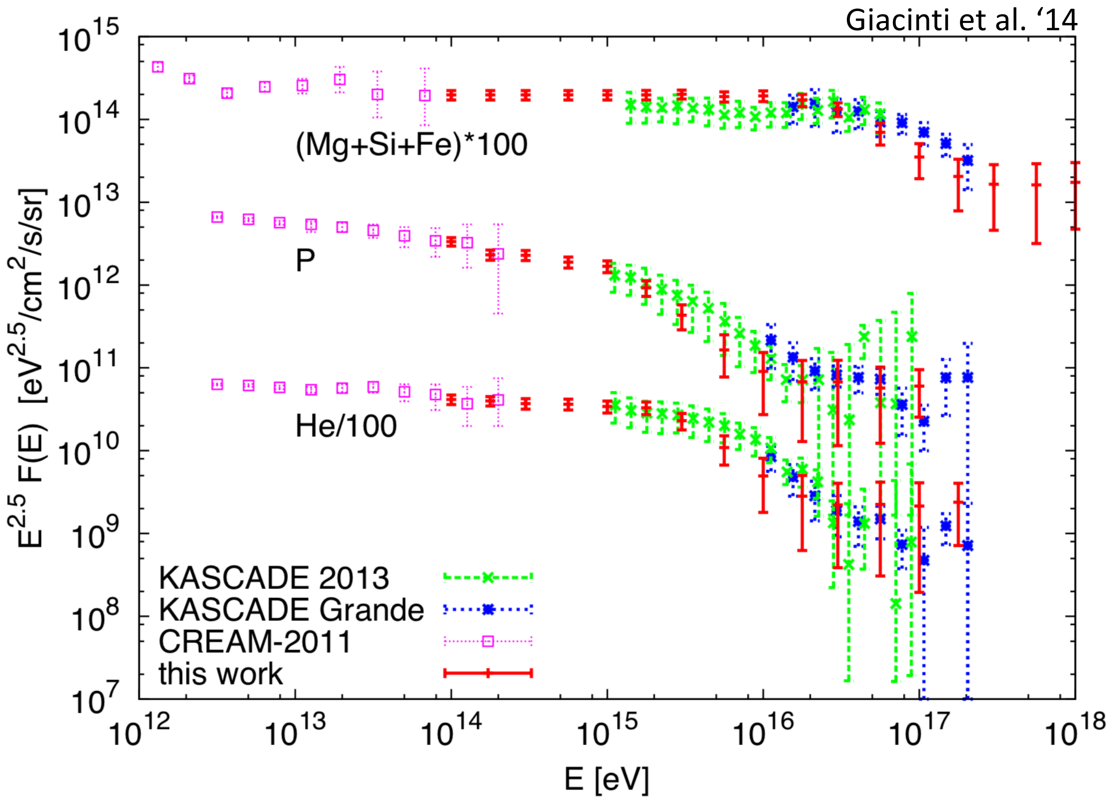
Kacherliess et al. '17





Differences in slopes of spectra of different nuclei could be explained e.g. by the presence of "local" recent cosmic ray injection event (2-3 Myr ago, within 100 pc distance). Lower and lower energy cosmic rays gradually reach the Solar system boundary in rigidity-dependent manner and provide flux components in excess of the average Galactic cosmic ray "sea".

Theoretical modelling (examples)



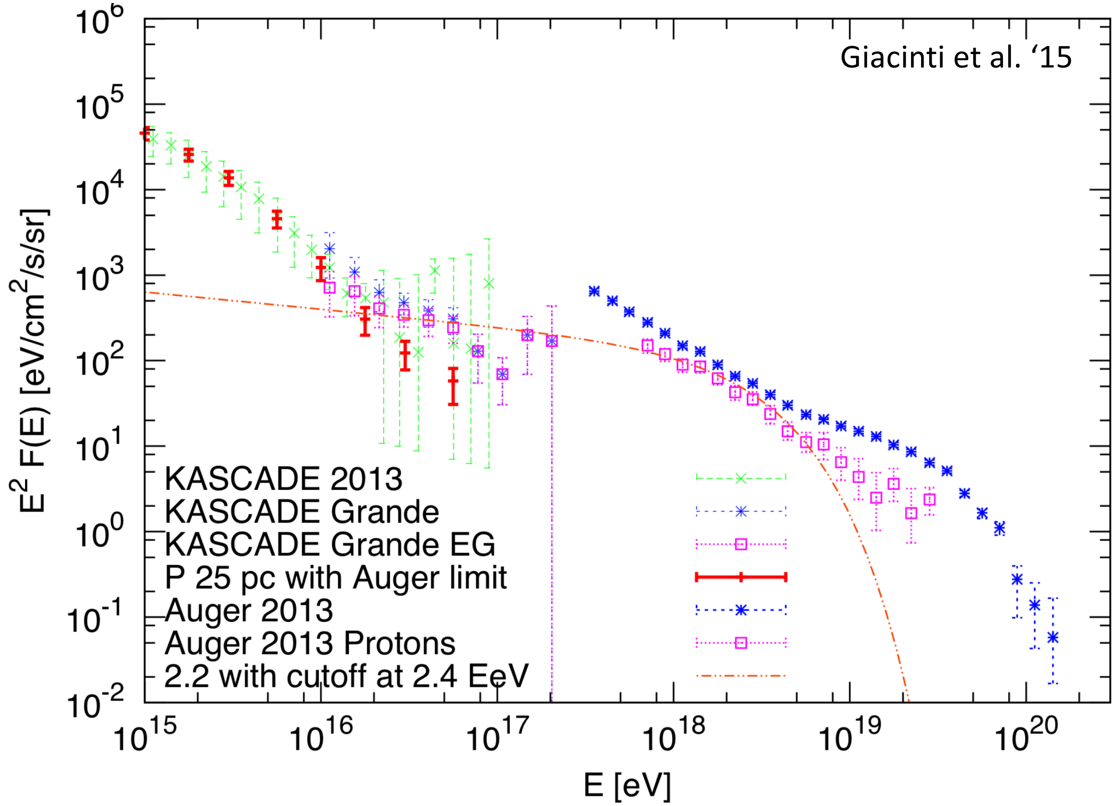
The “knee” feature could be either due to

– high-energy cut-off in the spectrum of single recent nearby dominant CR source

– high-energy cut-off of the average Galactic CR source population

– Change of regime of diffusion of CRs at the energy where CR scattering length becomes longer than the coherence length scale of Galactic magnetic field

Theoretical modelling (examples)

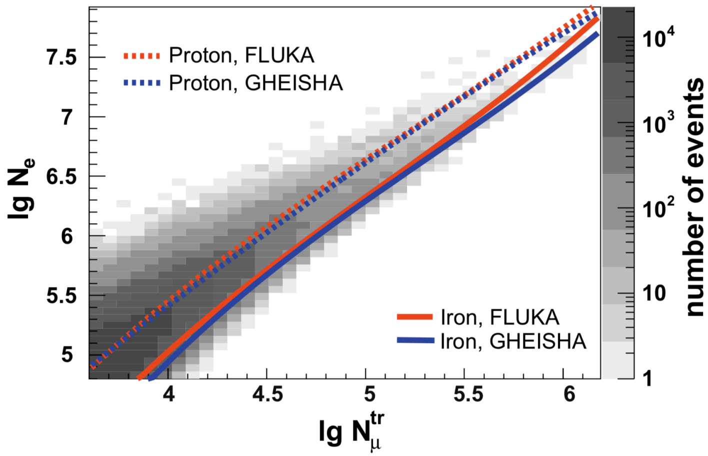


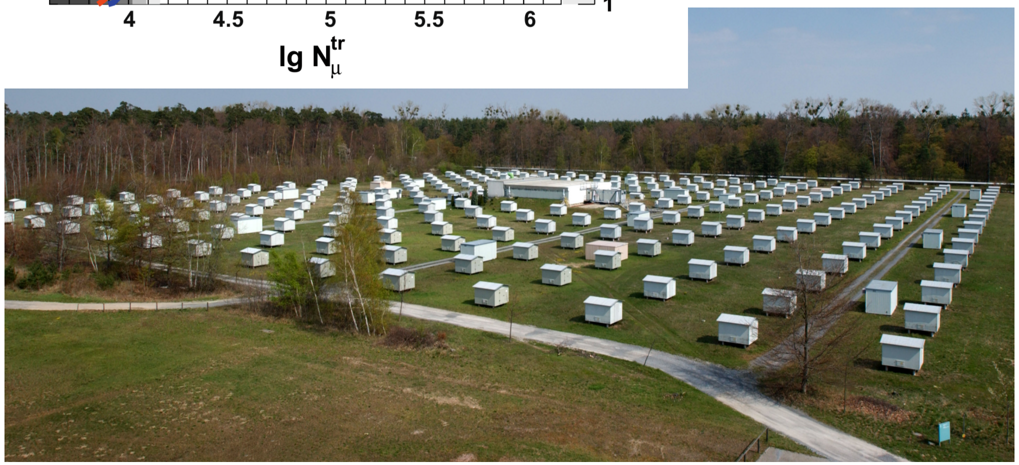
Lightening of the composition above $3x10^{17}$ eV could be due to presence of extragalactic flux component with nearly E^{-2} type spectrum (generically expected) with high-energy cut-off above $\sim 3\times10^{18}$ eV energy.

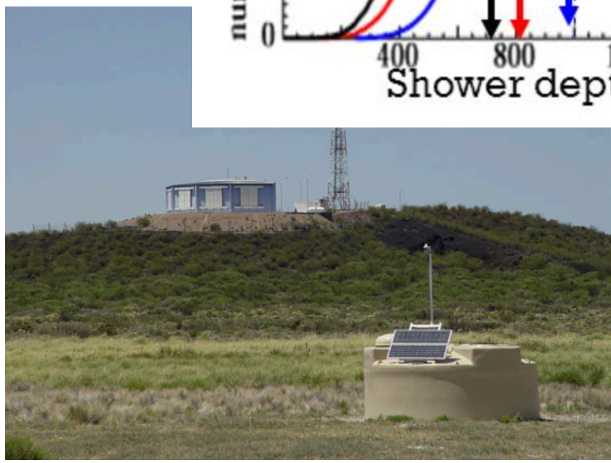
Heavier composition above 10^{19} eV is then due to the Z-dependent high-energy cut-off of extragalactic CR spectrum.

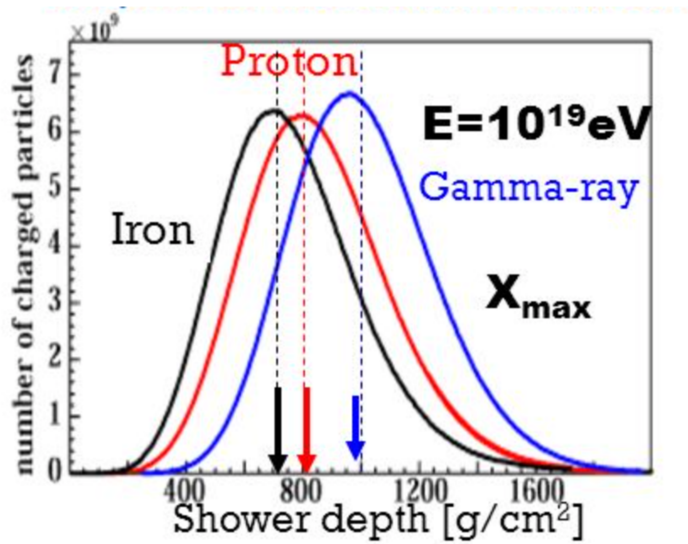
Primary particle ID from EAS measurements

Apel et al. '09









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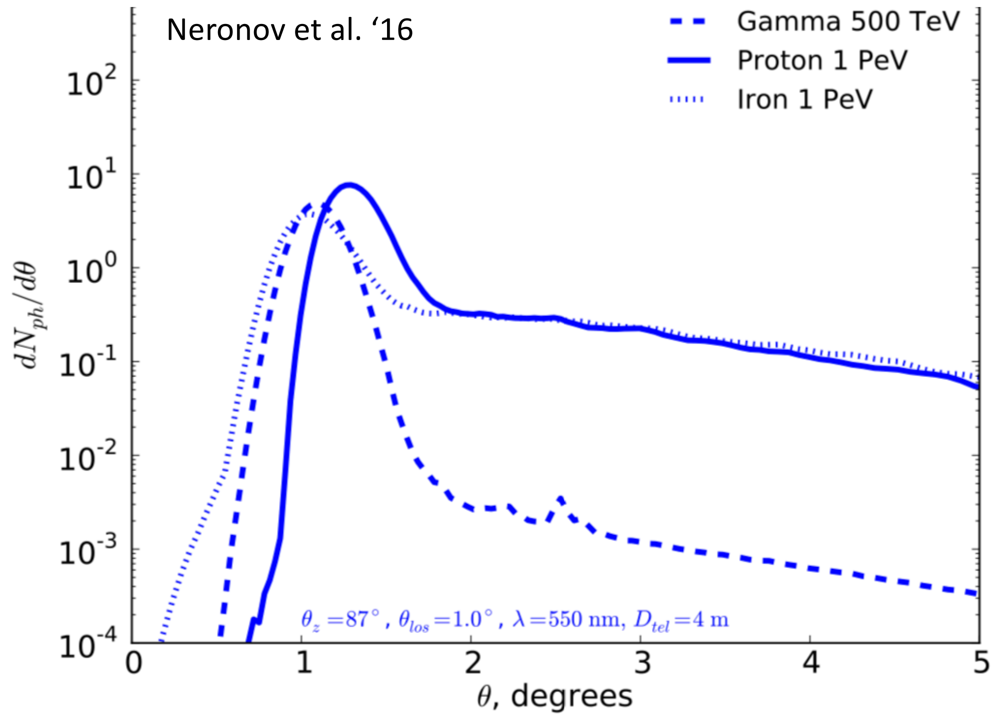
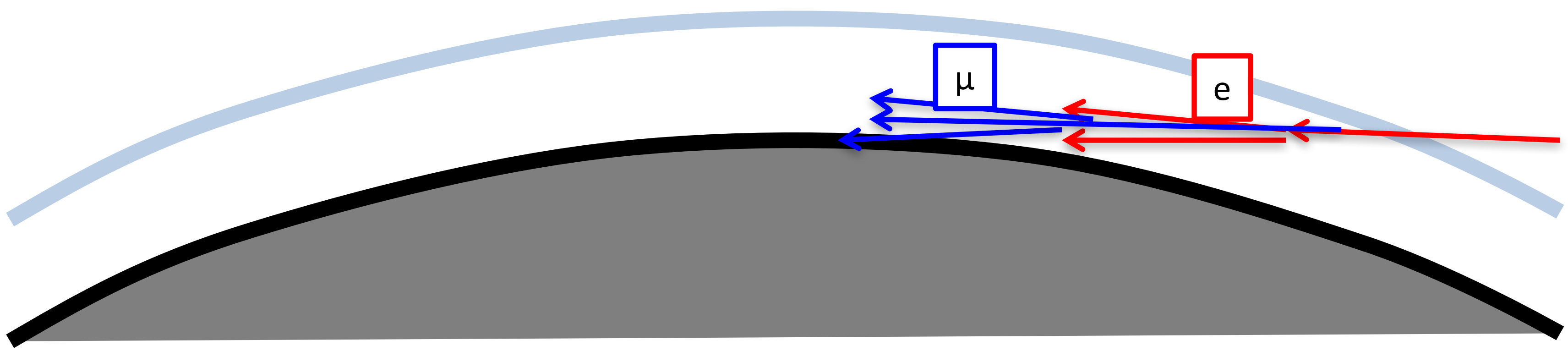
Primary particle ID with IACT

Muon component is largely sub-dominant in the shower maximum region.

It starts to dominate at large depth in the atmosphere.

PeV proton-induced shower incident at 87° zenith angle





Primary particle ID with IACT

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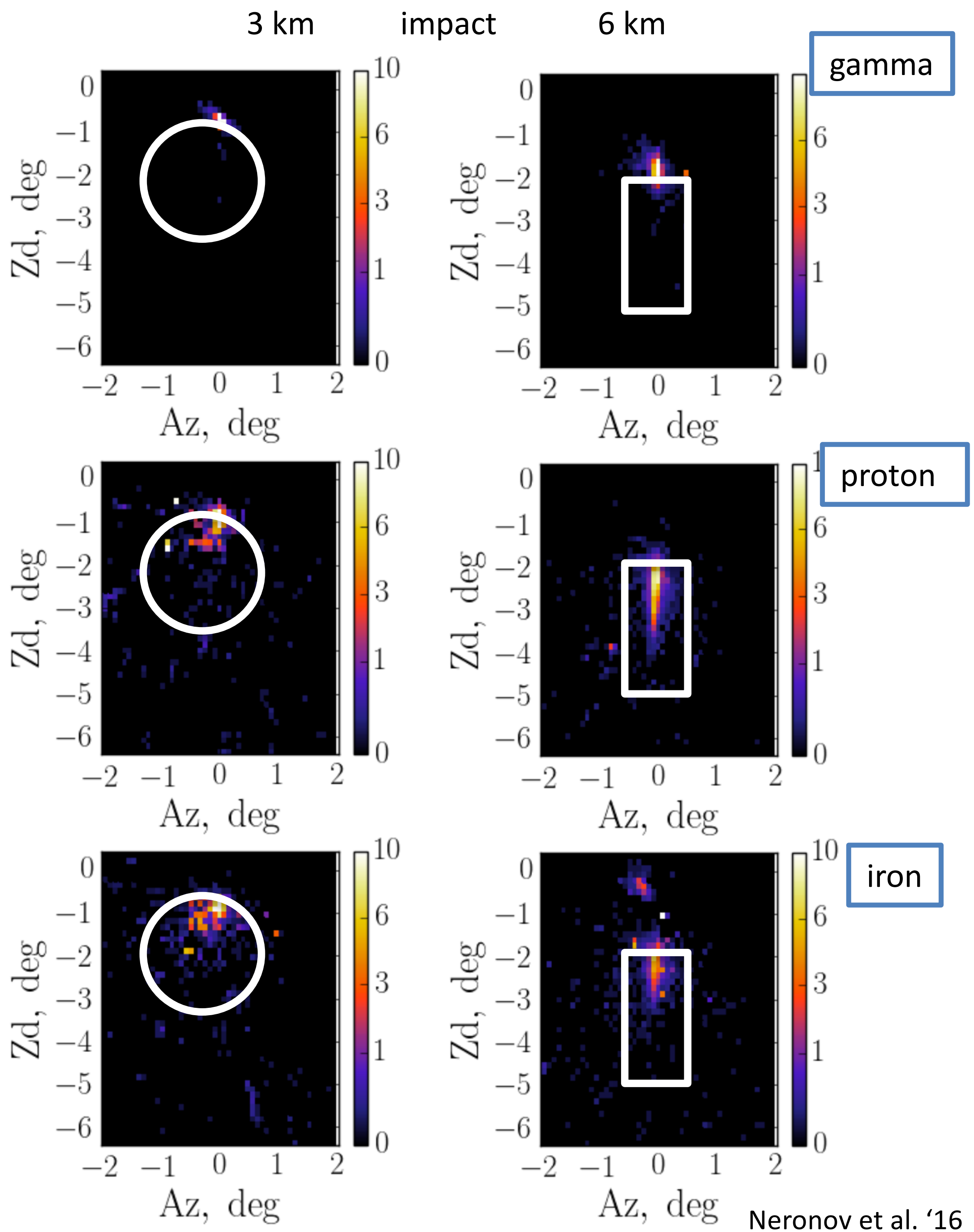
It starts to dominate at large depth in the atmosphere.

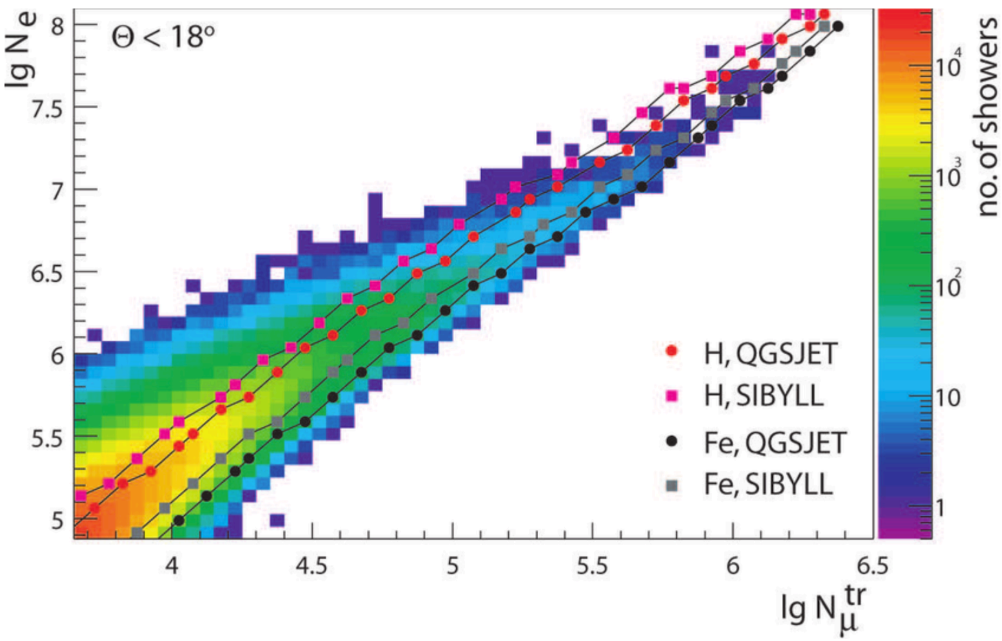
Muon “tail” or “halo” has different appearance in strongly inclined EAS initiated by different particles



Neronov et al. ‘16

Primary particle ID with IACT

KASCADE



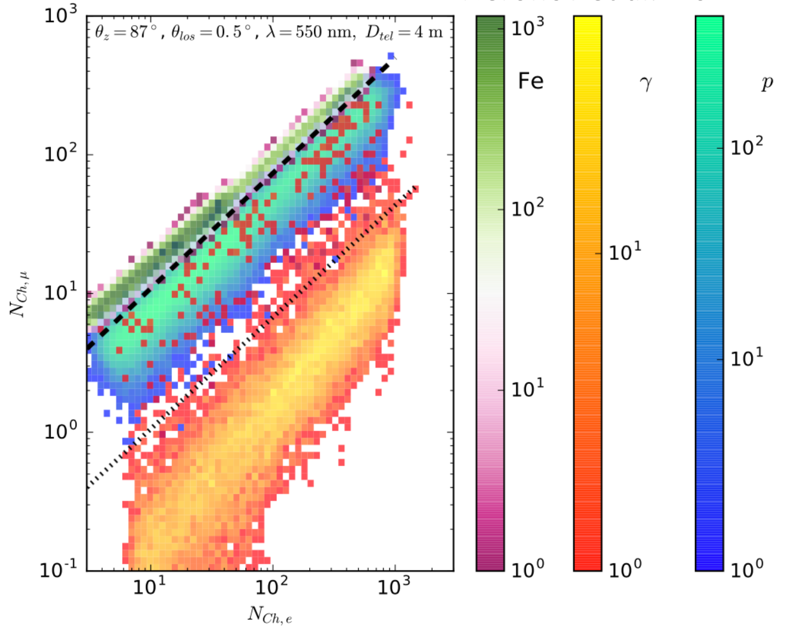
$A_{geom} \sim 4{\times}10^4 \mathrm{m}^2$

$\Omega \sim \pi$

$A_{geom}{\times}\Omega \sim 0.1\ \mathrm{km^2 sr}$

IACT

Neronov et al. '16



MAGIC

$A_{eff} \sim \Omega_{FoV} D^2 \sim 300 \left(\frac{D}{350\ km}\right)^2 \left(\frac{\Omega_{FoV}}{2{\times}10^{-3}}\right)$ km²

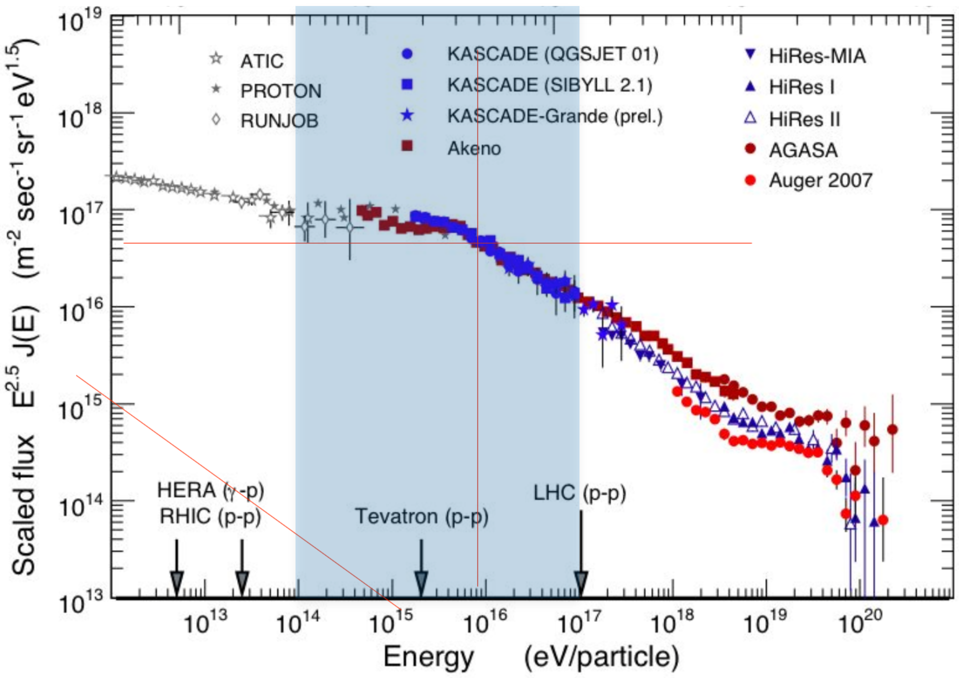
$\Omega \sim \pi \left(\frac{1.4\pi}{180}\right)^2 \simeq 2{\times}10^{-3}$

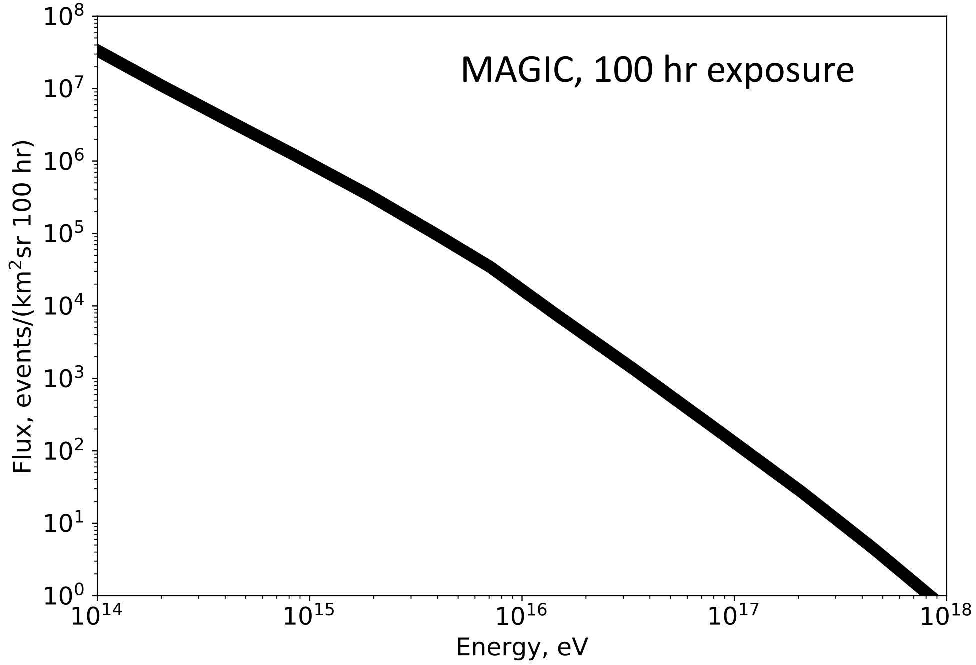
$A_{eff}{\times}\Omega \sim 0.5\ \mathrm{km^2 sr}$

IACT imaging of strongly inclined showers provides data needed for measurement of primary particle ID via muon content measurements.

Distance to top-of-Troposphere: $\sqrt{2R_E H} \simeq 350 \left(\frac{H}{10\ km}\right)^{1/2}$ km

Primary particle ID with MAGIC





IACT imaging of strongly inclined showers provides data needed for measurement of primary particle ID via muon content measurements.

– with larger “Grasp” ($A \times \Omega$), even for IACT not optimized for composition studies

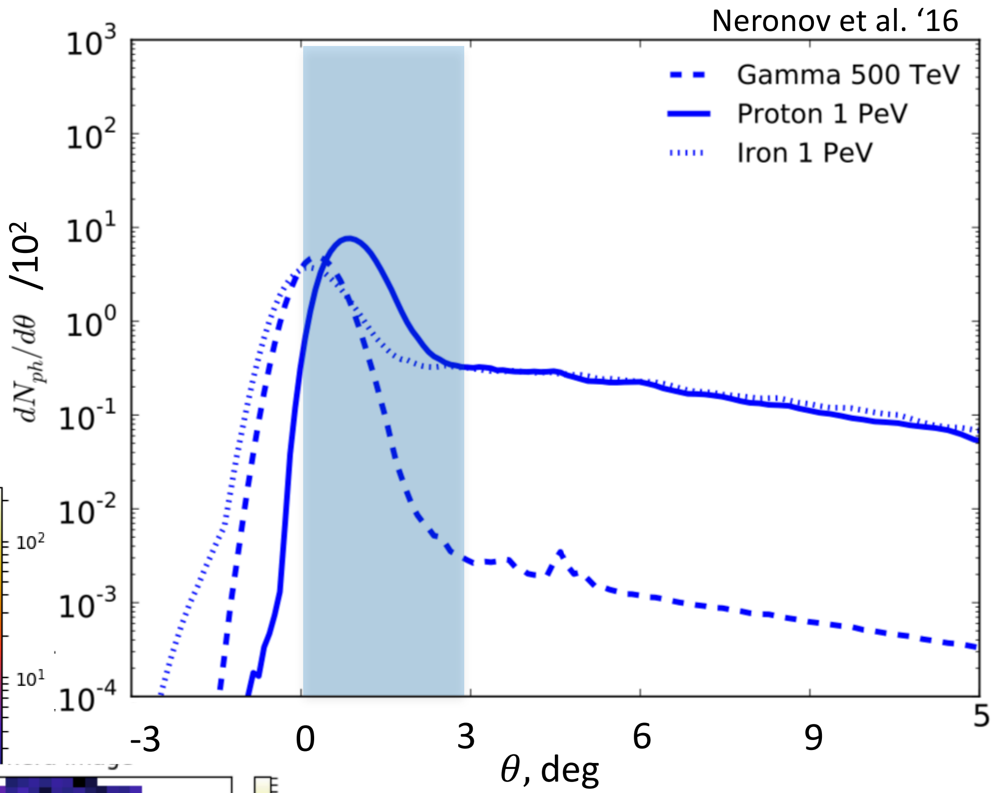
High-zenith angle observations with MAGIC could provide composition data across the knee energy range.

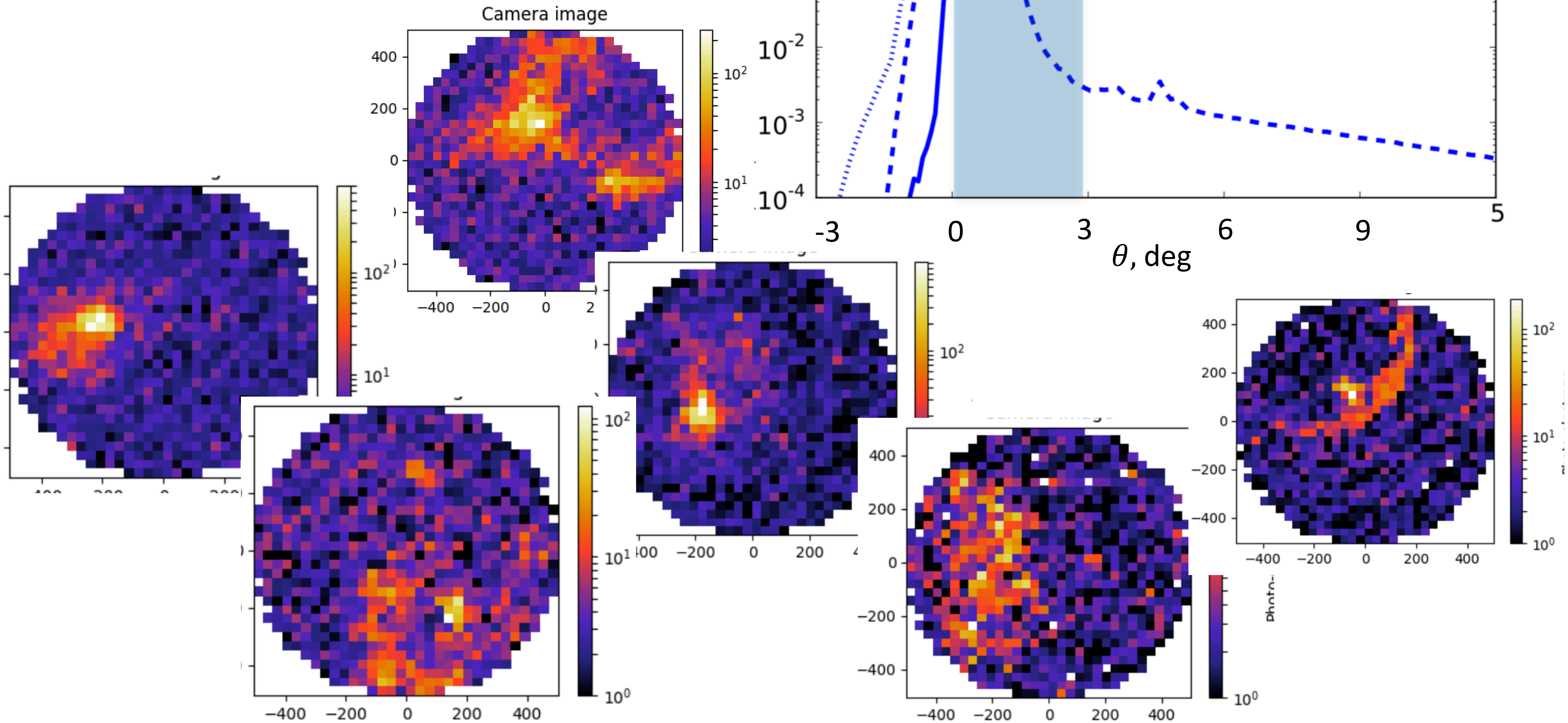
First look at MAGIC data at 80º zenith angle

– MAGIC FoV is somewhat too narrow for detection of muon halo / tail at 80º zenith.

– Electromagnetic core +muon halo / tail seems to be present in $\sim PeV$ energy scale shower images.

– Next step: Monte-Carlo convolving CORSIKA simulations with camera response are needed.





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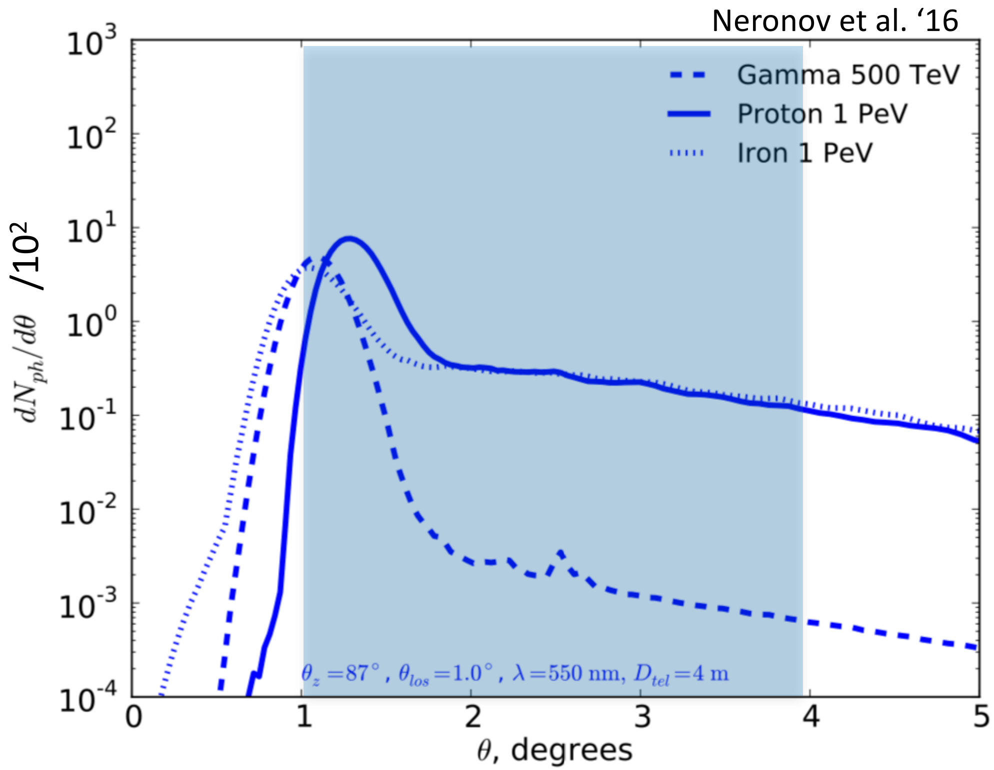
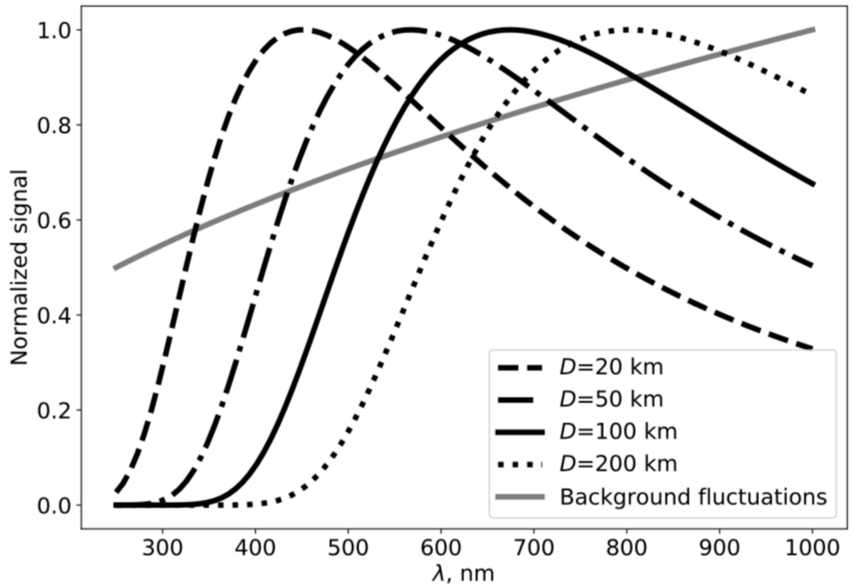
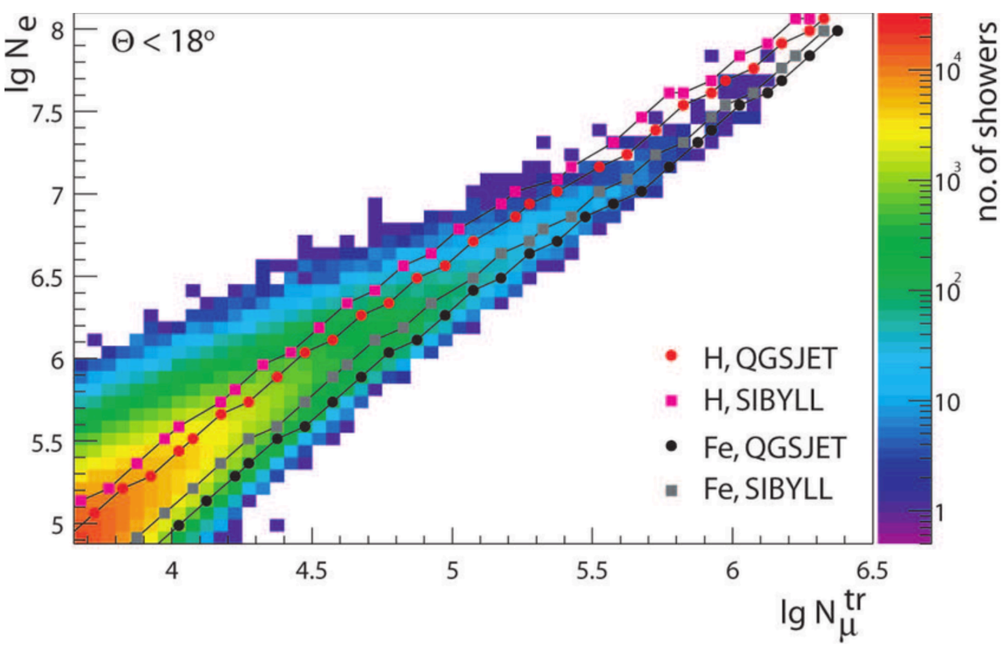
– Observing at still larger zenith angles would make electromagnetic / muon component separation more clear.





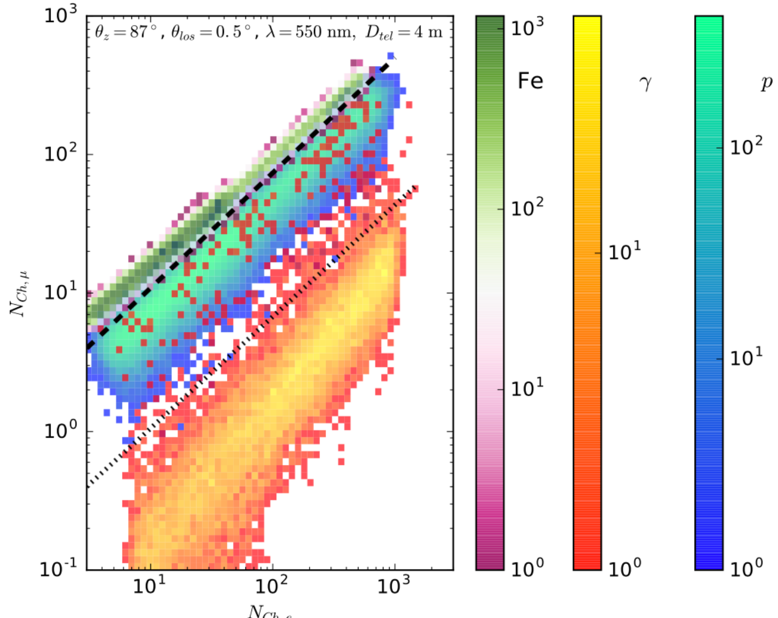
Primary particle ID with an optimized IACT

KASCADE



$A_{geom} \sim 10^4 \text{m}^2$
$\Omega \sim \pi$
$A_{geom} \times \Omega \sim 0.03 \text{ km}^2\text{sr}$

IACT

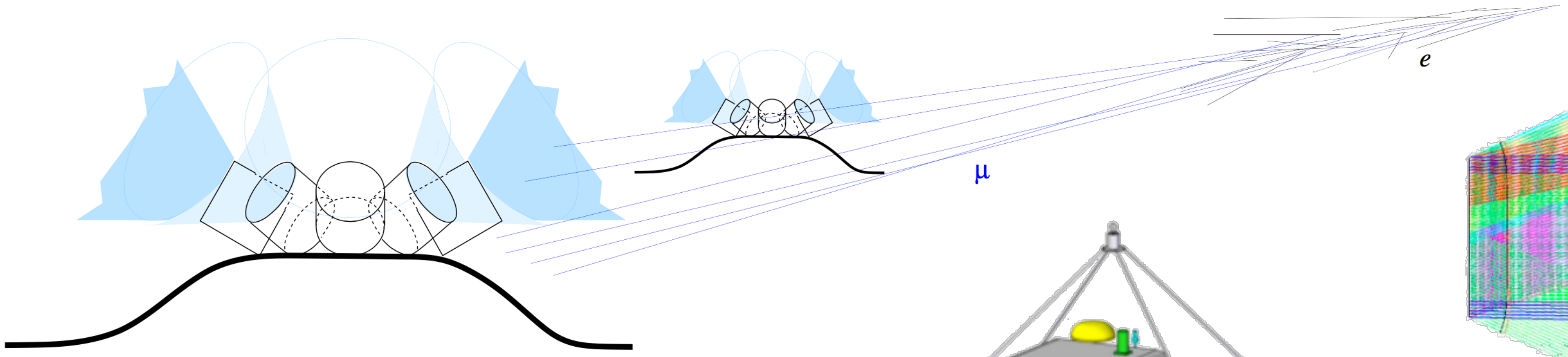


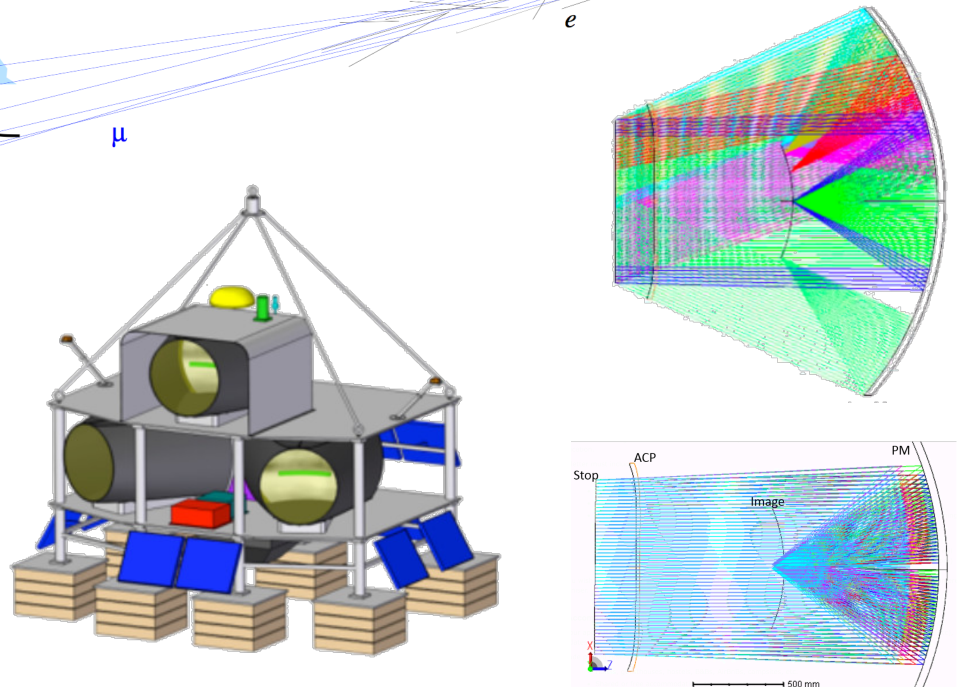
$A_{eff} \sim \Omega_{FoV} D^2 \sim 10^5 \left(\frac{D}{350\ km}\right)^2 \left(\frac{\Omega_{FoV}}{1}\right) \text{km}^2$
$\Omega \sim \pi \left(\frac{1.4\pi}{180}\right)^2 \simeq 2\times10^{-3}$
$A_{eff} \times \Omega \sim 200 \text{ km}^2\text{sr}$

IACT system with very wide FoV, e.g. monitoring a 10° x 360° strip at large zenith angle, could provide large statistics of measurement of muon content of EAS.

Distance to top-of-Troposphere: $\sqrt{2R_E H} \simeq 350 \left(\frac{H}{10\ km}\right)^{1/2}$ km

Primary particle ID with an optimized IACT





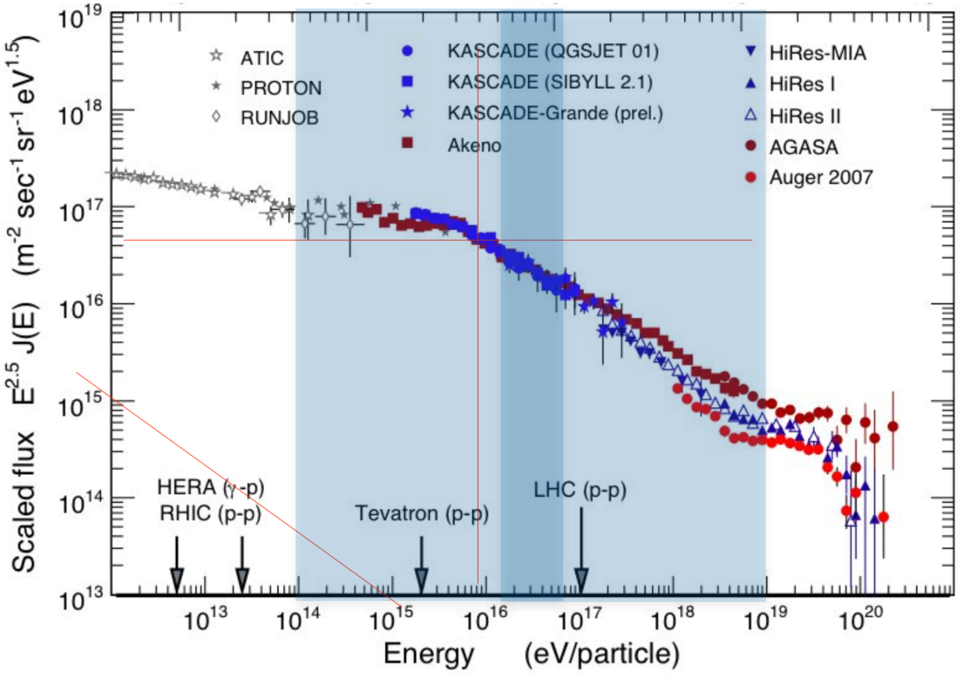
Very-Very Small Size Telescopes for EUSO-SPB2

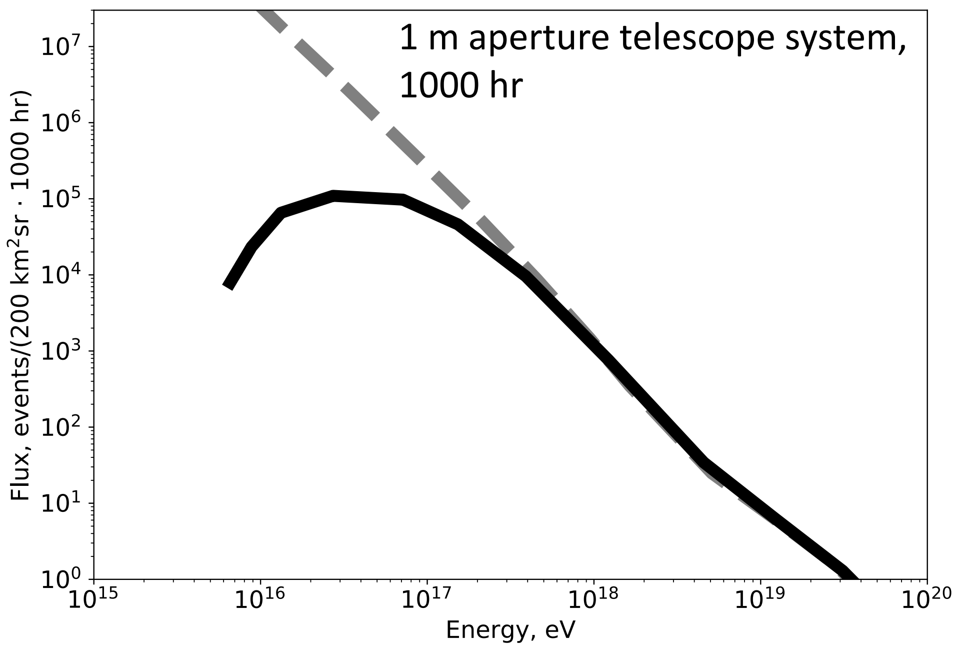
IACT system with very wide FoV, e.g. monitoring a 10° x 360° strip at large zenith angle, could provide large statistics of measurement of muon content of EAS.

Example: EUSO-SPB2: Small (1 m aperture) wide FoV (40°) Cherenkov telescope system for deployment on a Super-Pressure high-altitude balloon (could be used on ground as well).

arXiv:1703.04513

Primary particle ID with an optimized IACT





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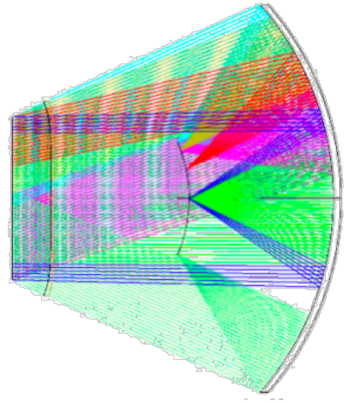
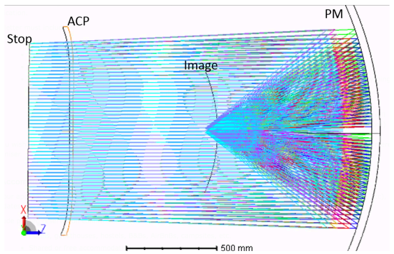
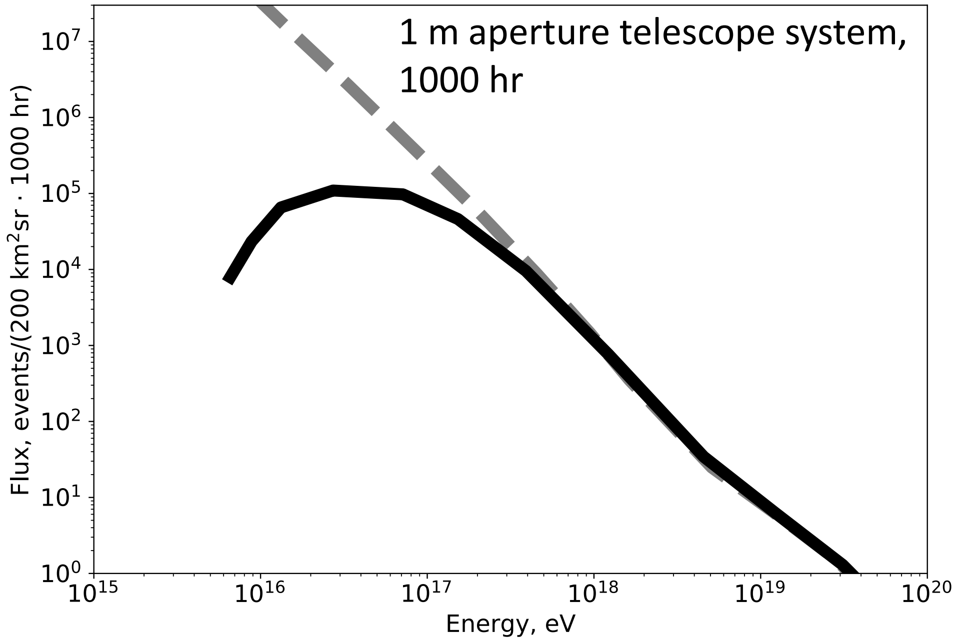
Muon excess in Auger EAS observations at 10^{19} eV

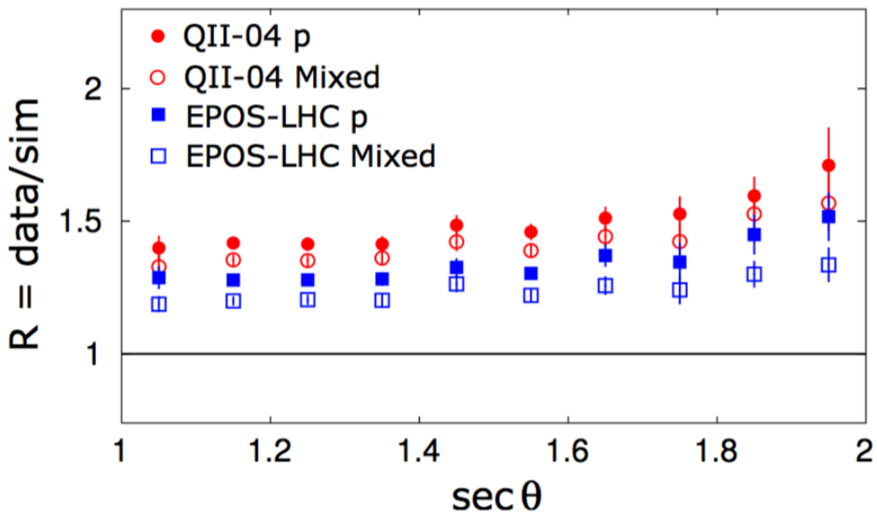




EUSO-SPB2



Lifting telescopes on a balloon would allow to see shower development in shallow atmosphere, to test hadronic interaction models



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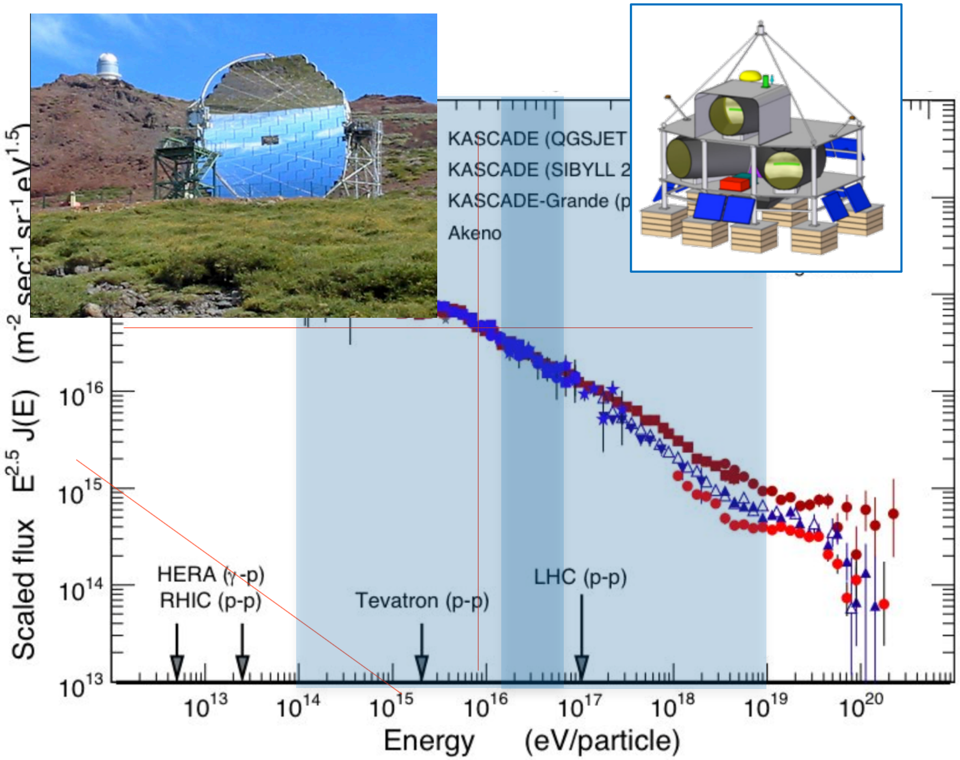
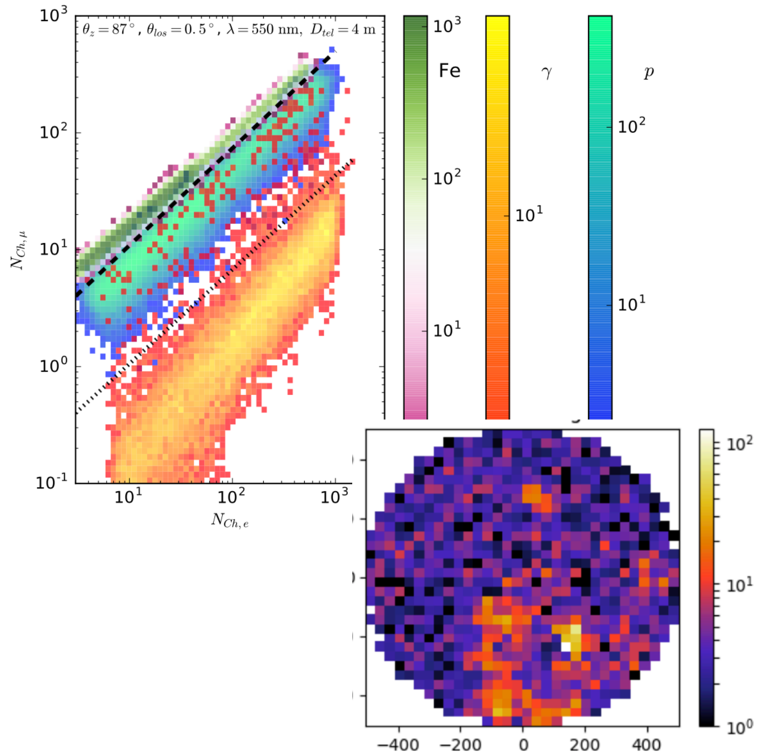
arXiv:1610.08509

* Hadronic interaction model uncertainties

Summary





Measurement of muon content of EAS is possible with IACT systems

Different telescope configuration optimisations could be found for the measurements in different energy ranges: knee, ankle, Galactic-to-extragalactic transition.

Very small size IACTs with very wide FoV are needed for measurement of composition in the energy range ≥EeV