Karlsruhe Institute of Technology

Measurements of High-Energy Cosmic Particles

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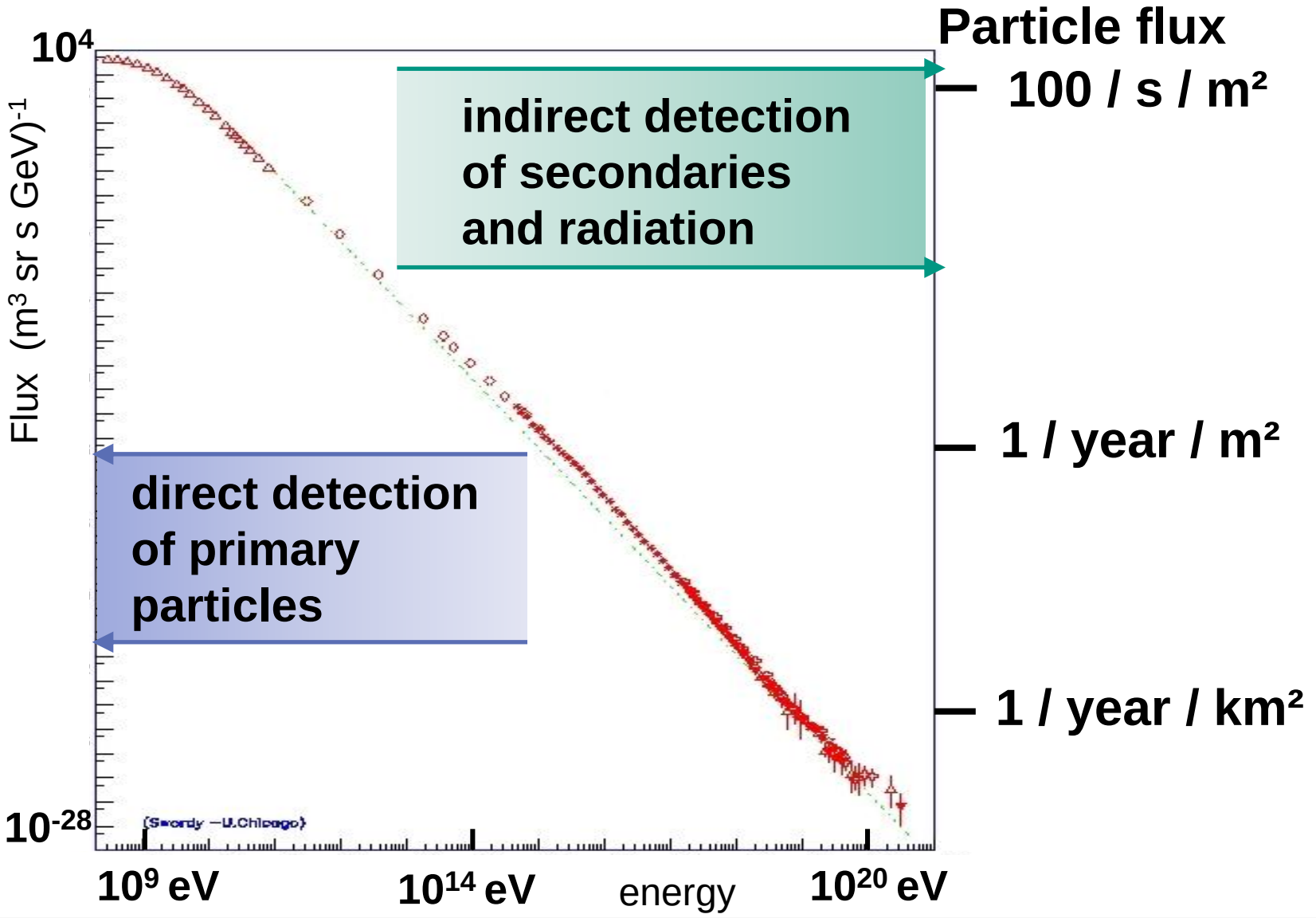
Content

- Ultra-high-energy cosmic rays
  - Energy range: direct and indirect measurements
  - Quest of the highest energies
- Cosmic-ray activities at KIT
  - Direct measurements: AMS
  - Air-shower heritage: KASCADE-Grande and CORSIKA
  - Current main project: Pierre Auger Observatory
- Developments for future experiments
  - IceCube-Gen2 includes surface upgrade → see posters
  - Air-shower from space JEM-EUSO pathfinders
  - Radio technique AERA, Tunka-Rex, GRAND

Cosmic-ray energy spectrum

- **98 % Nuclei**
  - protons
  - helium nuclei
  - few heavier nuclei
- 2 % others
  - charged
    - electrons
    - positrons
    - anti-protons
  - neutral
    - photons
    - neutrinos



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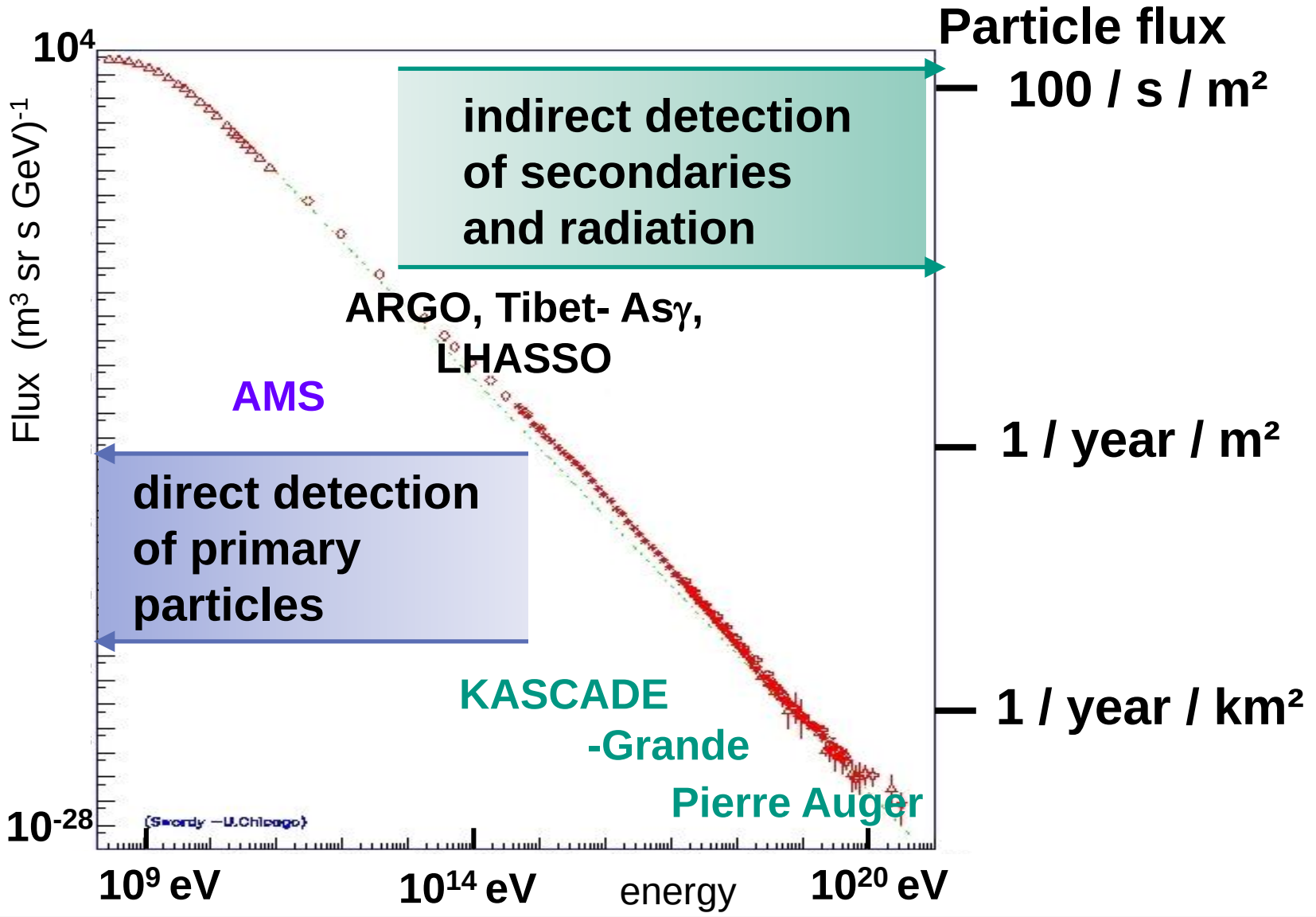
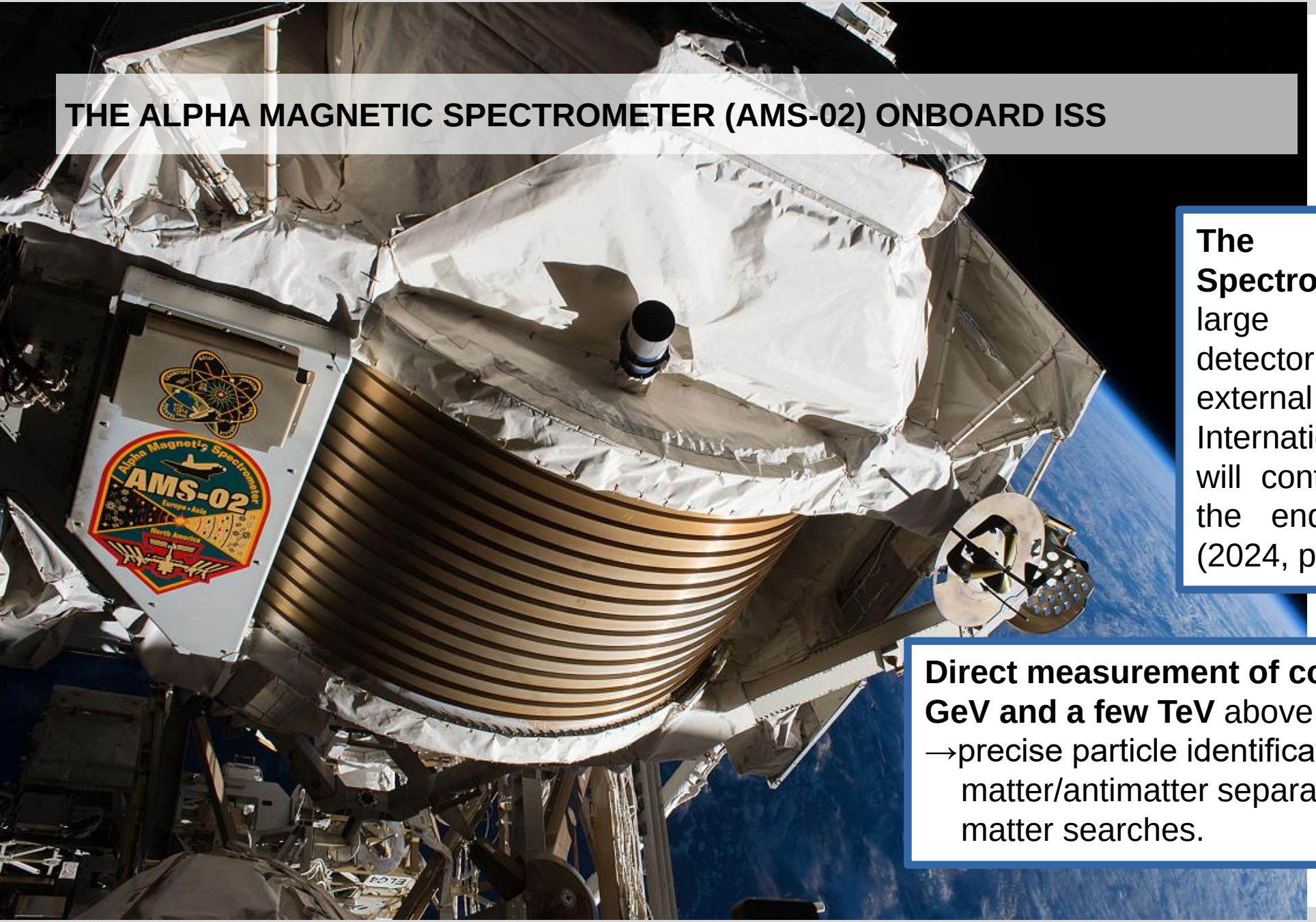


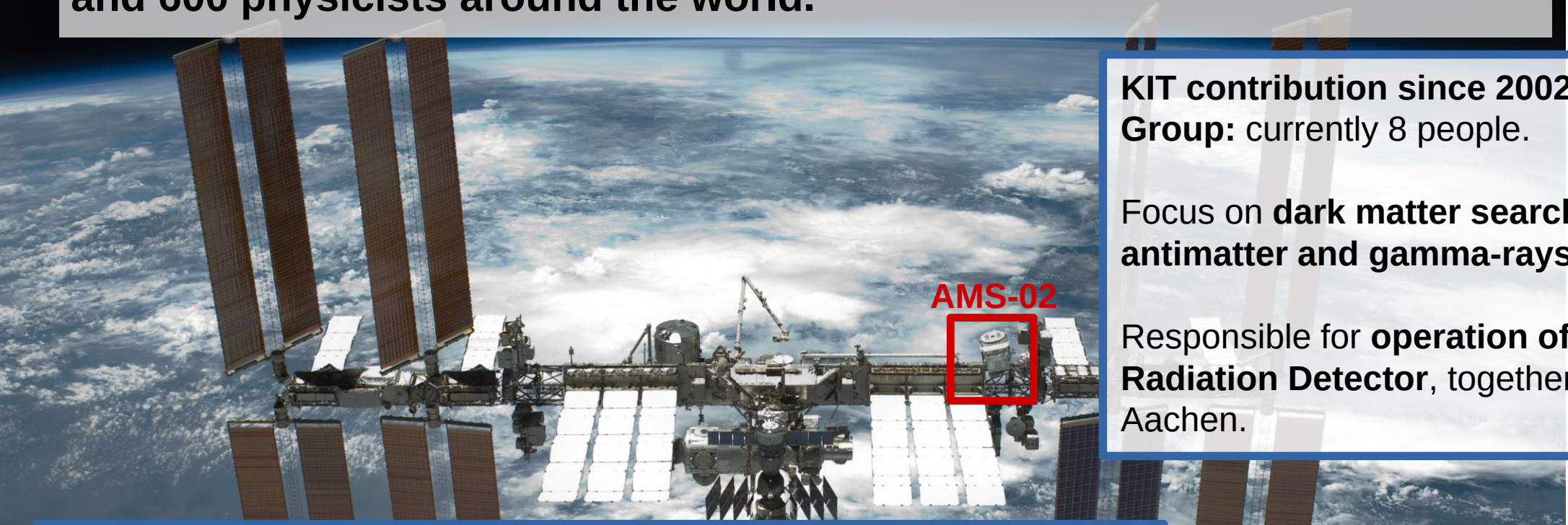
THE ALPHA MAGNETIC SPECTROMETER (AMS-02) ONBOARD ISS



The Alpha Magnetic Spectrometer (AMS-02) is a large acceptance particle detector installed in 2011 as an external module on the International Space Station. It will continue to take data until the end of station operation (2024, possibly 2028).

Direct measurement of cosmic rays between **0.5 GeV and a few TeV** above the atmosphere
→precise particle identification,
matter/antimatter separation for dark matter searches.

AMS is an international collaboration with 56 institutes from 16 countries and 600 physicists around the world.



KIT contribution since 2002.
Group: currently 8 people.

Focus on **dark matter searches in antimatter and gamma-rays**.

Responsible for **operation of Transition Radiation Detector**, together with RWTH Aachen.

Strong contribution from China:

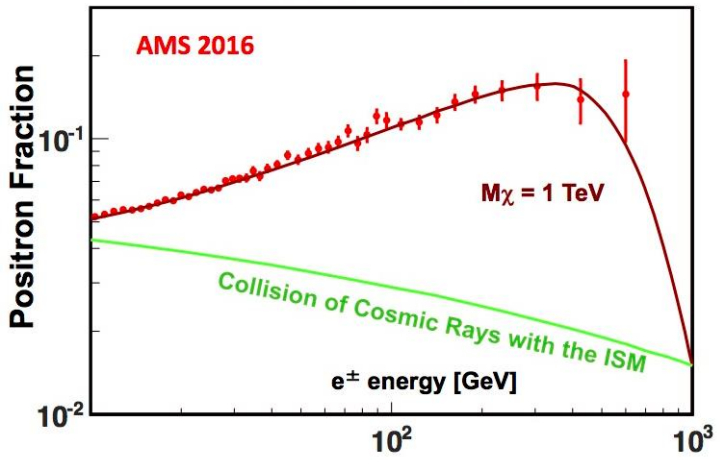
Institute of Electrical Engineering (IEE), Chinese Academy of Sciences, Bejijng
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing
Jiao Tong University, Department of Physics, Shanghai
National Laboratory of Aeronautics and Astronautics, Beijing
Shandong University, Tsinan
Southeast University, Nanjing
Sun Yat-Sen University, School of Physics and Engineering, Guangzhou

AMS@SJTU: **Wei Li,** Zhi-Ming Zhen, Baosong Shan and Kaiyuan Wu.

gebauer@kit.edu

AMS-02 @ KIT

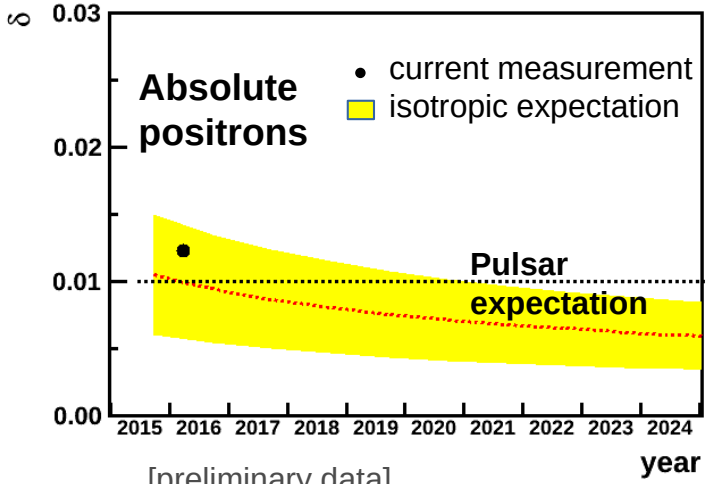
Positron fraction $e^+/(e^+ + e^-)$



[Phys. Rev. Lett. 110, 141102 (2013)]

An unexpected rise in the positron fraction could be explained by dark matter annihilation...
...or new astrophysical point sources.

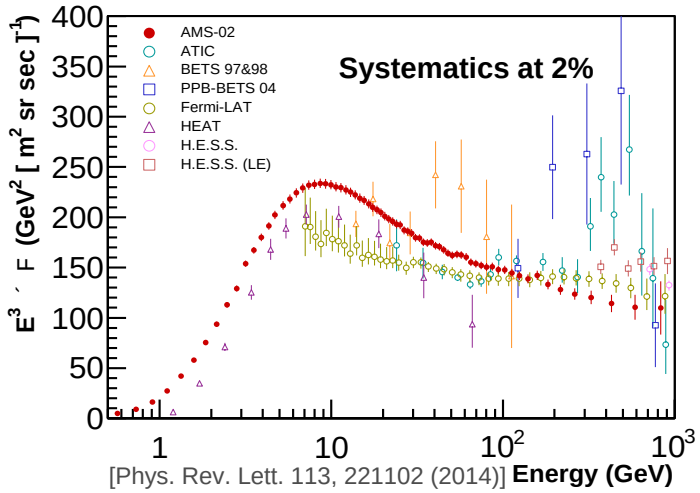
Search for anisotropies



[preliminary data]

Astrophysical point sources might imprint position information on cosmic ray arrival directions.

Combined electron flux $(e^+ + e^-)$

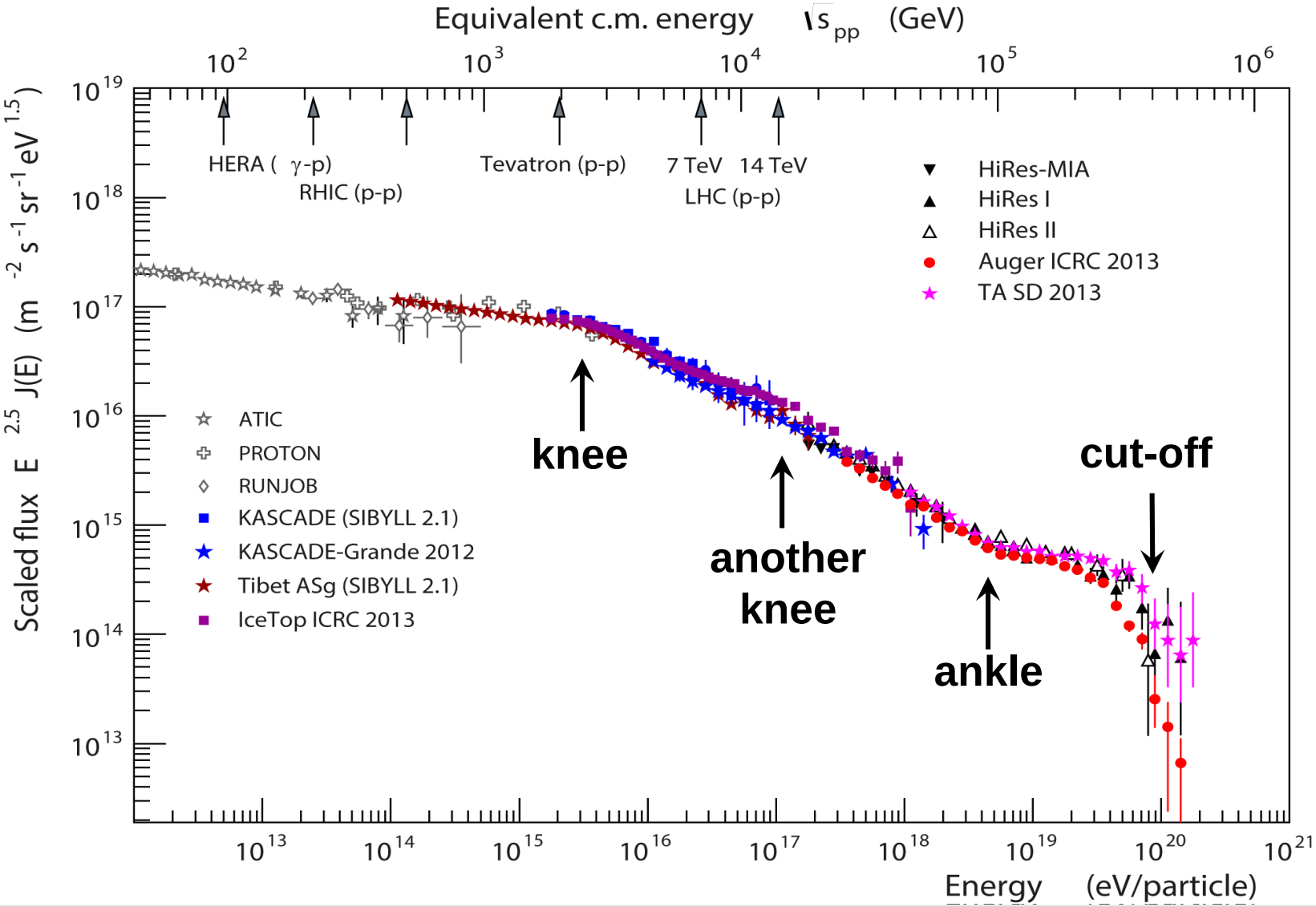


[Phys. Rev. Lett. 113, 221102 (2014)]

The accuracy of the AMS data allows for the first time to disentangle astrophysical uncertainties from a possible exotic source.

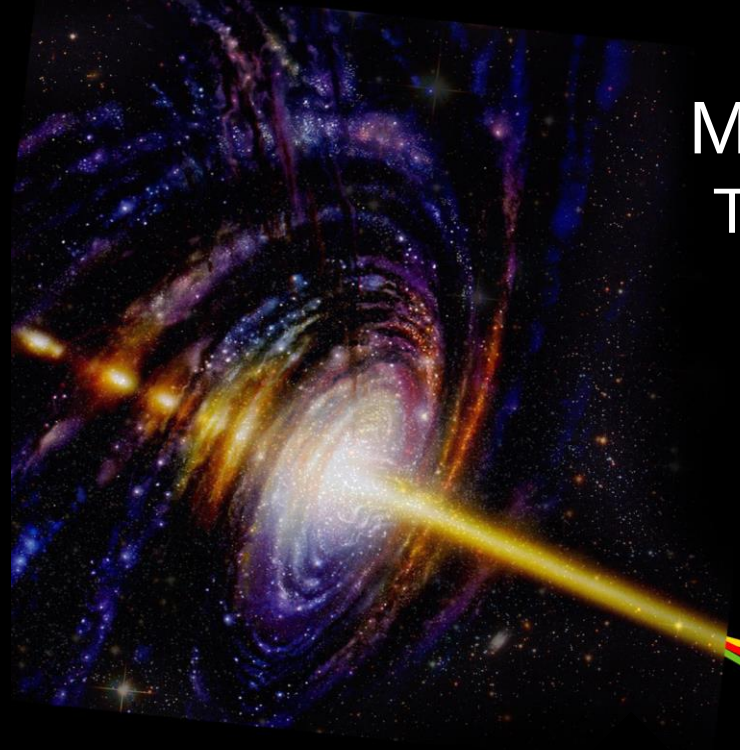
Each of these measurements is directly linked to the search for dark matter in cosmic rays.
So far none of the AMS measurements could be explained within our current understanding of cosmic ray transport.

Cosmic ray energy spectrum - scaled



Multi-messanger approach to find origin:

Though detected γ + ν might be from different sources than highest energy CR…



ν ~10^{15} eV

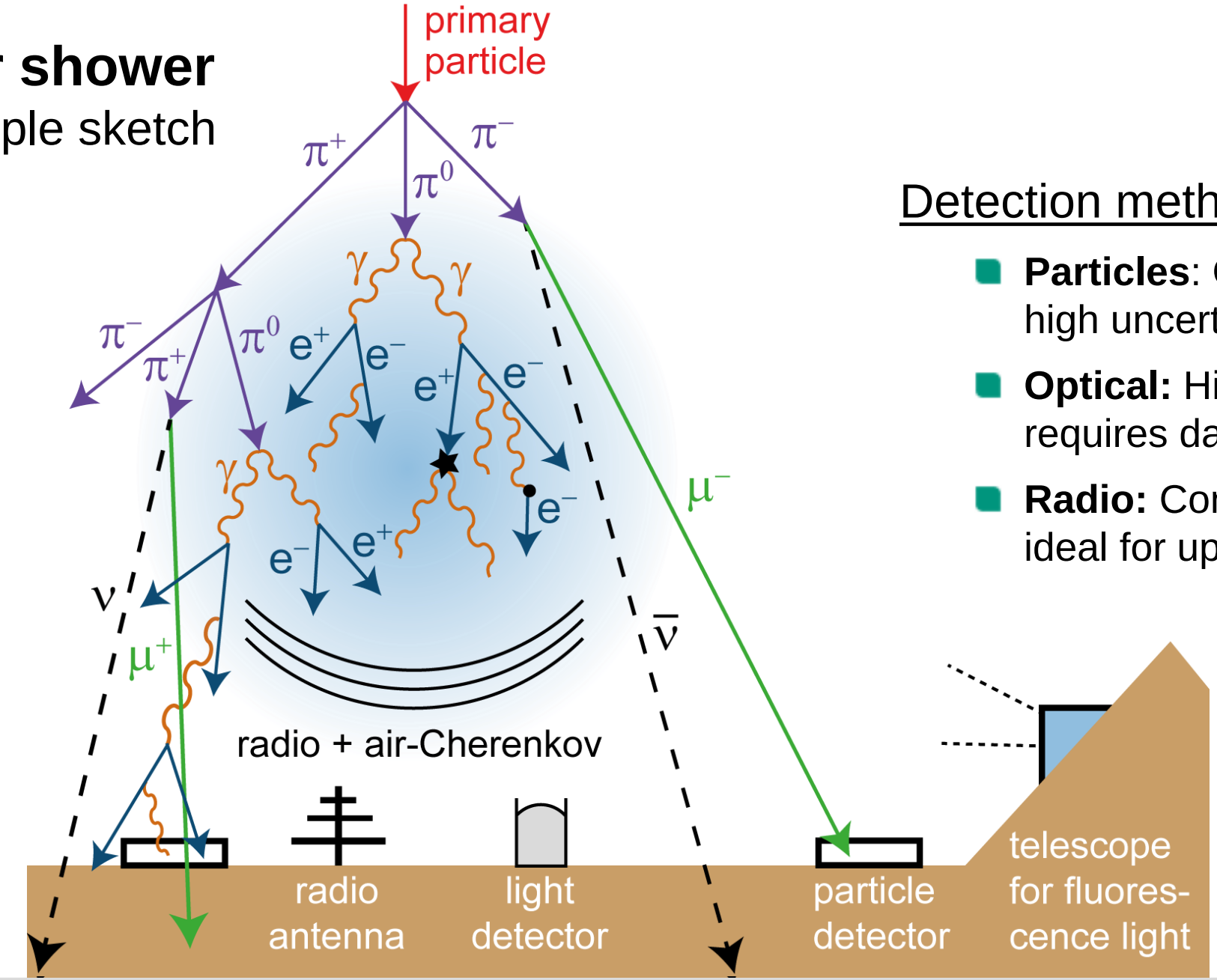
γ

~10^{14} eV

p, He, …, Fe

~10^{20} eV

Air shower
simple sketch



Detection methods of air showers:

- **Particles**: Classical approach, but high uncertainties in interpretation
- **Optical:** Highest accuracy, but requires dark and clear nights
- **Radio:** Combines advantages, ideal for upgrades and future arrays

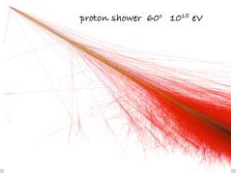
Prog. Part. Nucl. Phys.
93 (2017) 1-68
arXiv: 1607.08781

KIT heritage: KASCADE-Grande

- **56 collaborative papers in reviewed journals** (4-5 still in queue, short author list papers not included)
- **57 PhD thesis**
- **86 diploma/master thesis**

1989 Proposal

1996 KASCADE



2000 CORSIKA

model tests

2004 KASCADE-Grande

light knee

2008 LOPES

γ limit

(an)isotropy

proof-of-principle radio detection

muon production height

2012 Cosmic Revelation

heavy knee

CROME

CROME

Karlsruhe Air Shower Test Facility

2016 End of operation

light ankle

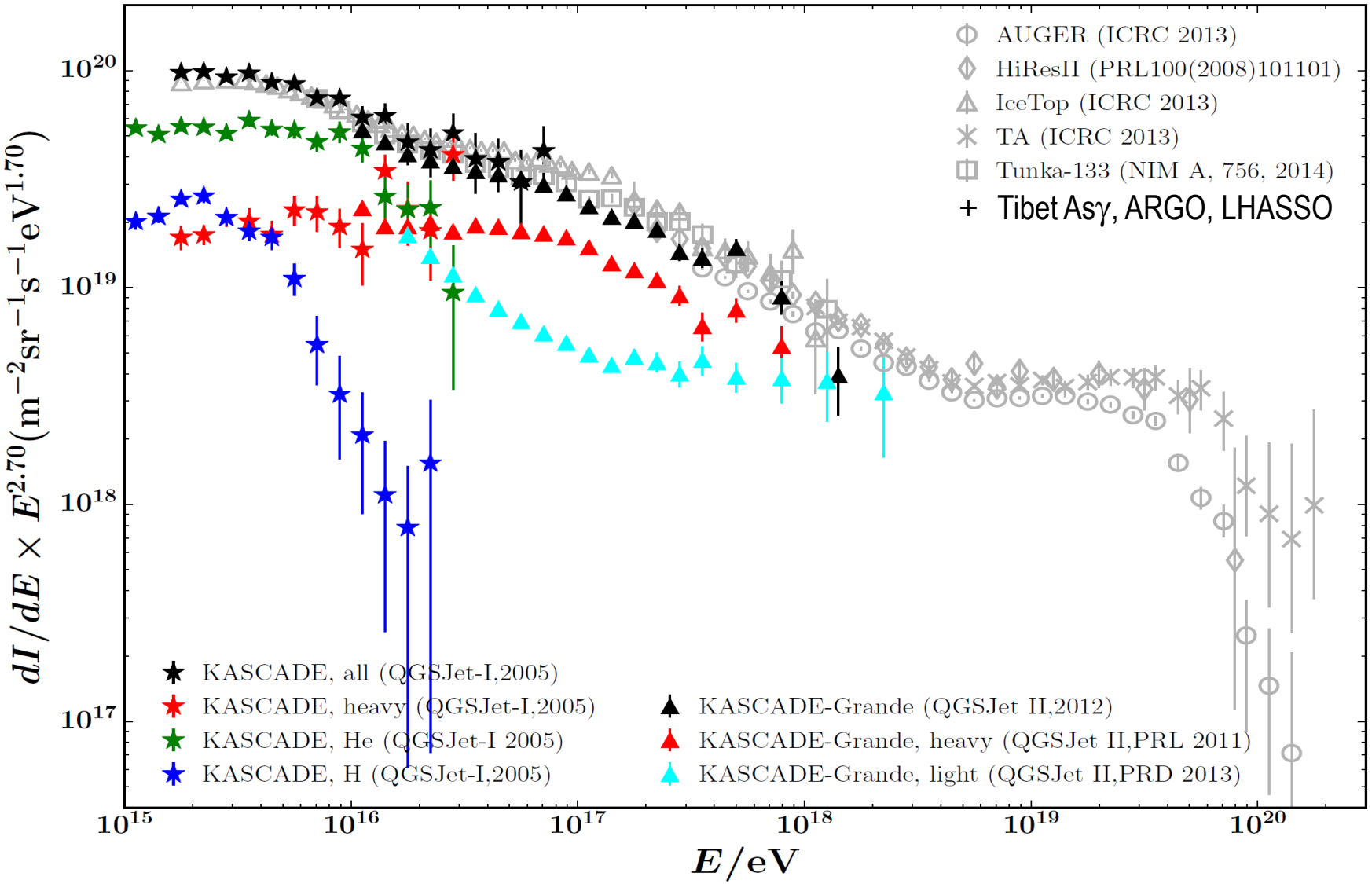
EAS GHz emission

Xmax by radio

A. Haungs, et al., ICRC 2017


KASCADE
KCDC
Cosmic ray Data Centre
KASCADE data available at:
https://kcdc.ikp.kit.edu
A. Haungs, et al., ICRC 2017

KASCADE-Grande: New component at 10^{17} eV



- Light and heavy knees consistent with scaling by Z
- Extragalactic CR above 10^{17} eV?
- More accurate measurements + analyses needed:
  - KCDC
  - IceCube-Gen2
  - LHASSO
  - GRAND-300

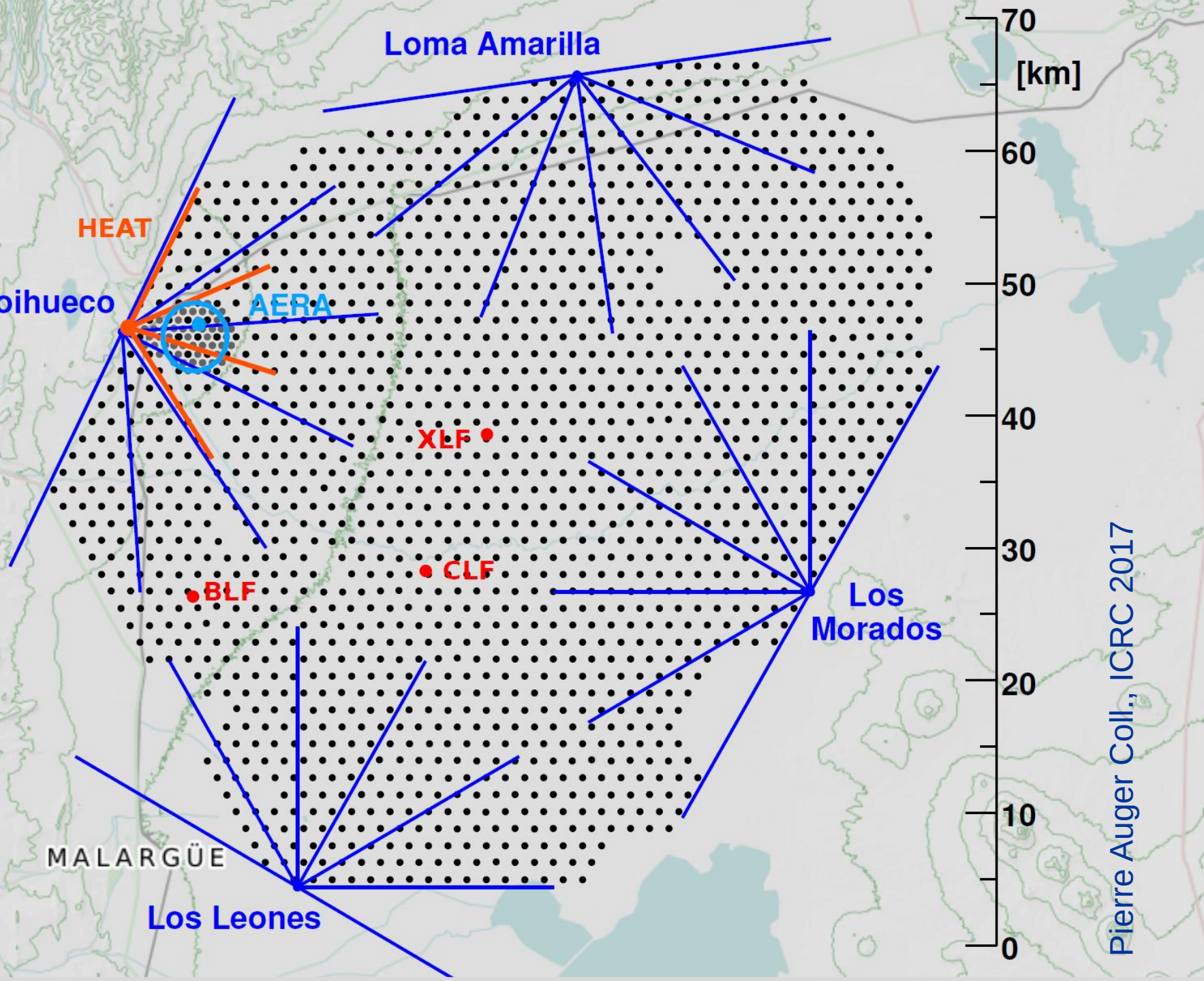
Pierre Auger Observatory

- International Collaboration
  - 16 countries
  - about 70 institutions
  - about 400 scientists
- In Argentina since 2002, full size since 2008
- World-largest array with 3000 km²
- Combination of different detection techniques

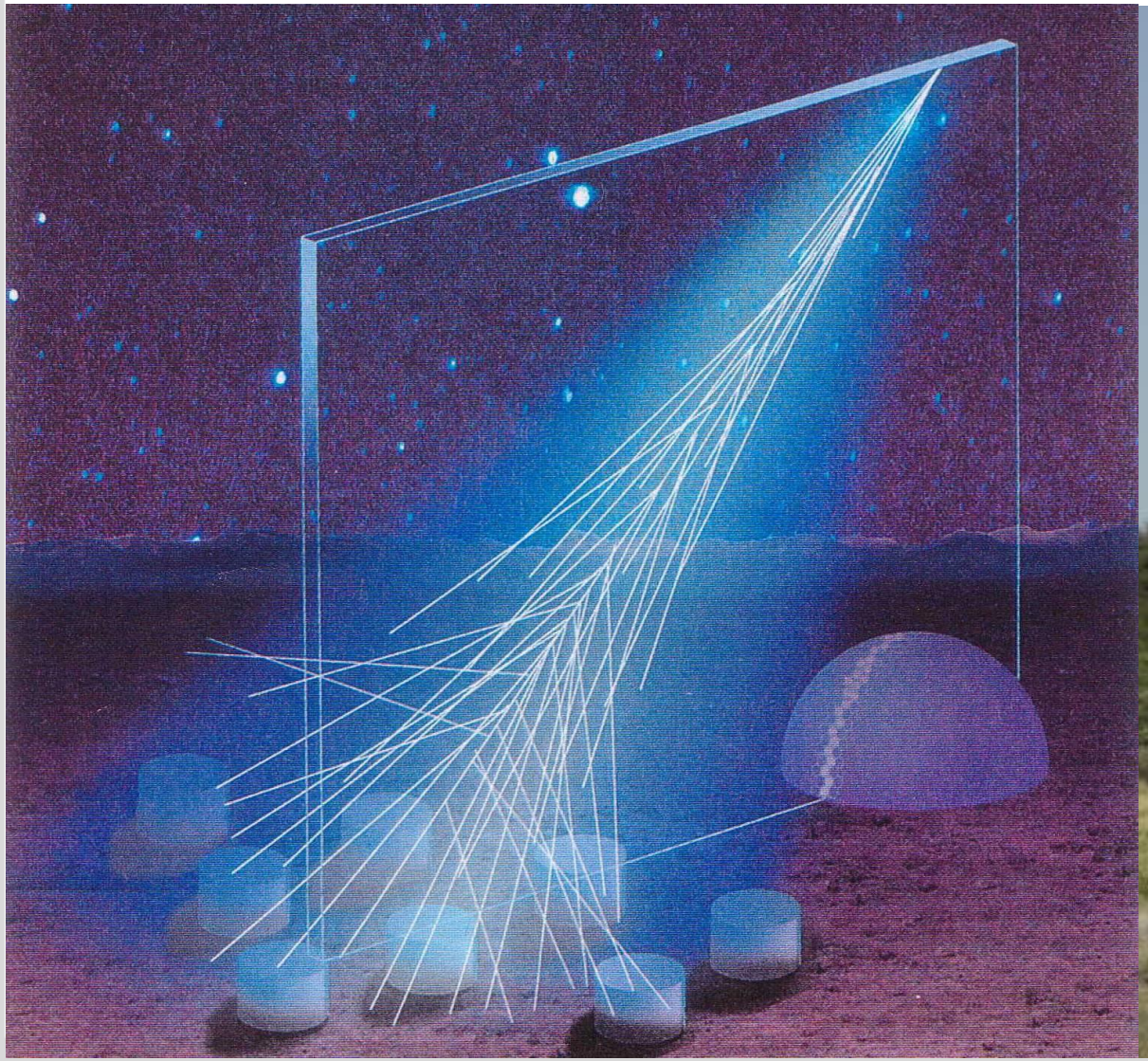
PIERRE AUGER OBSERVATORY

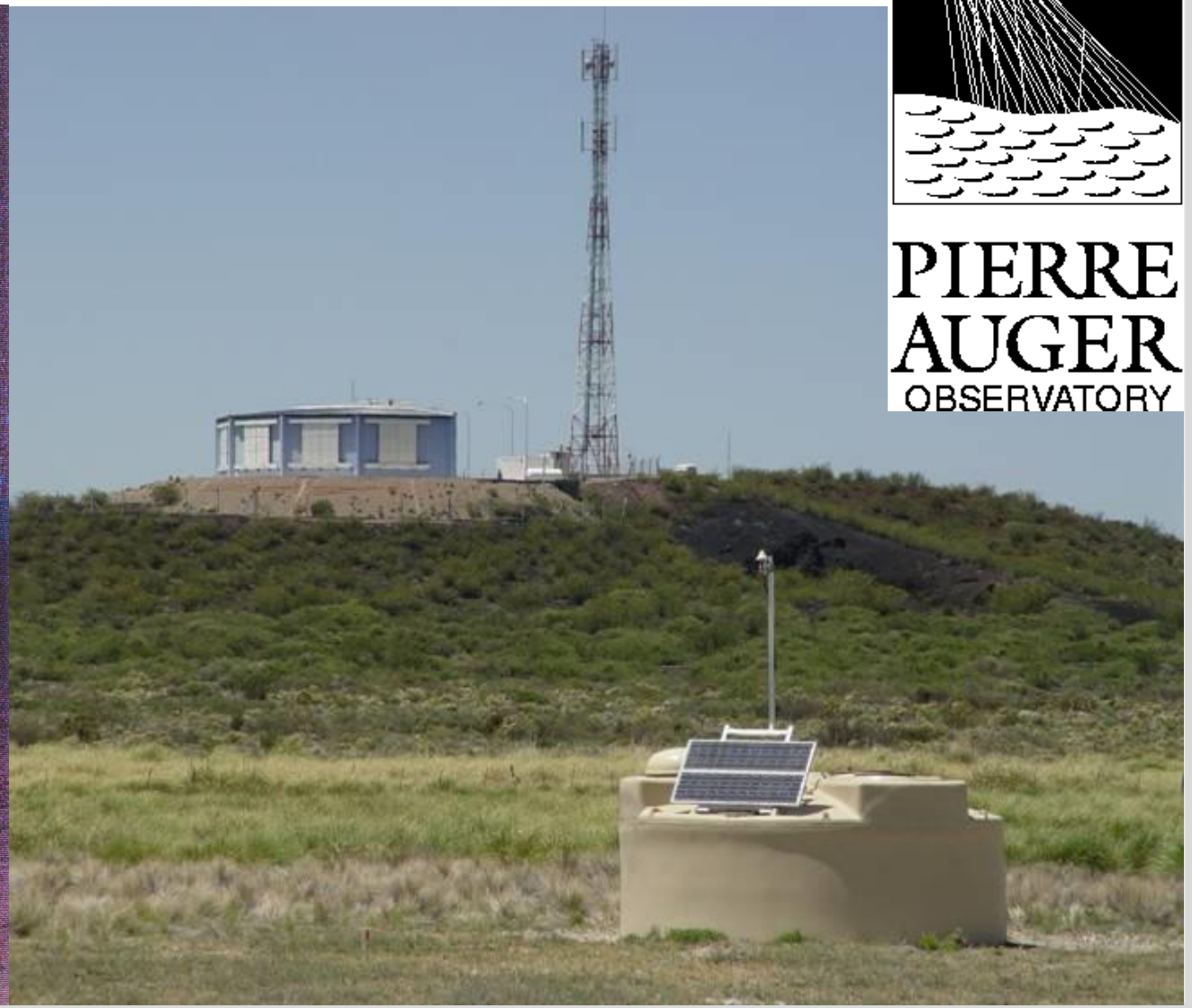
Pierre Auger Observatory

3000	km²
1660	particle detectors
27	fluorescence telescopes
153	radio stations (AERA)



Hybrid detection for highest accuracy

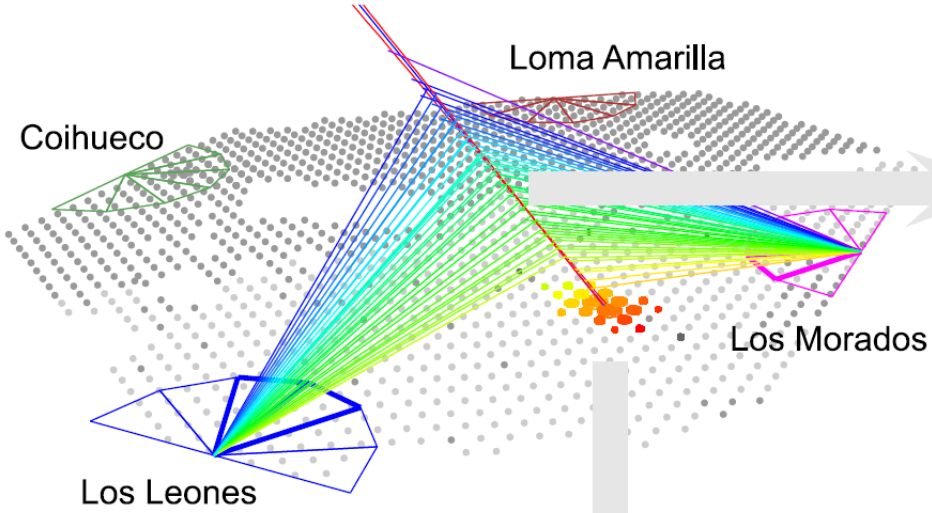


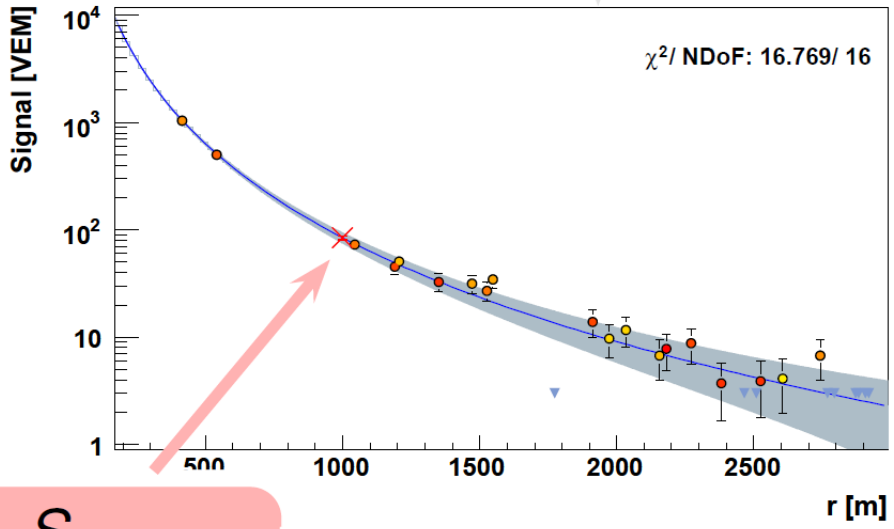


PIERRE AUGER OBSERVATORY

Hybrid Measurements

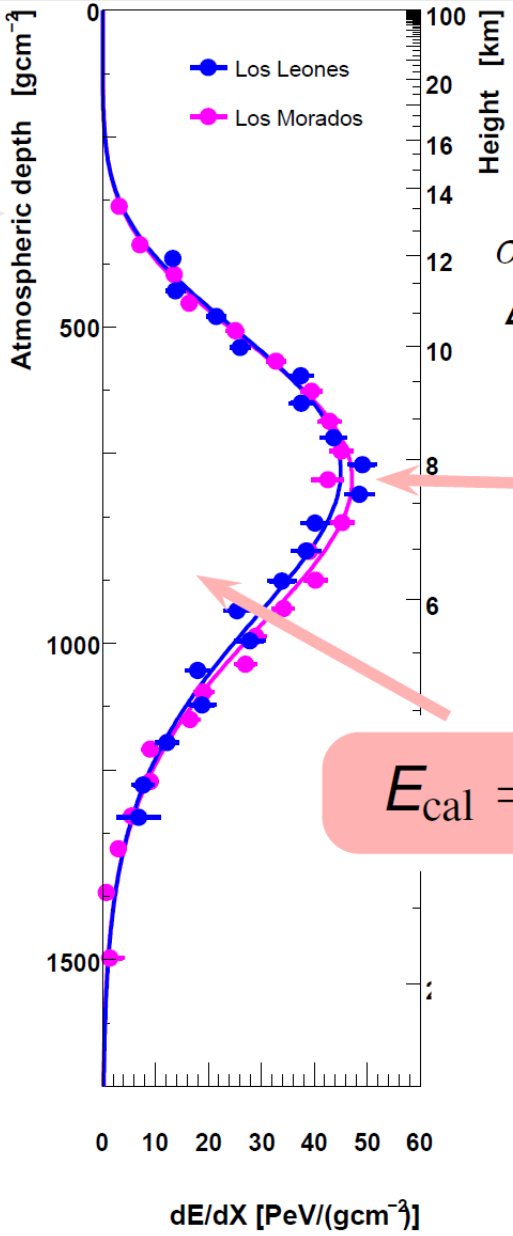
- Calibrate particle detection against fluorescence light
- High accuracy of energy spectrum
- High per-event accuracy only with 10% duty cycle





S_{1000}

$E_{\text{surface}} = f(S_{1000}, \theta)$



$\sigma_{X_{\max}} \leq 20\,\mathrm{g/cm^2}$
$\Delta_{\text{sys}} \leq 10\,\mathrm{g/cm^2}$

$X_{\max}$

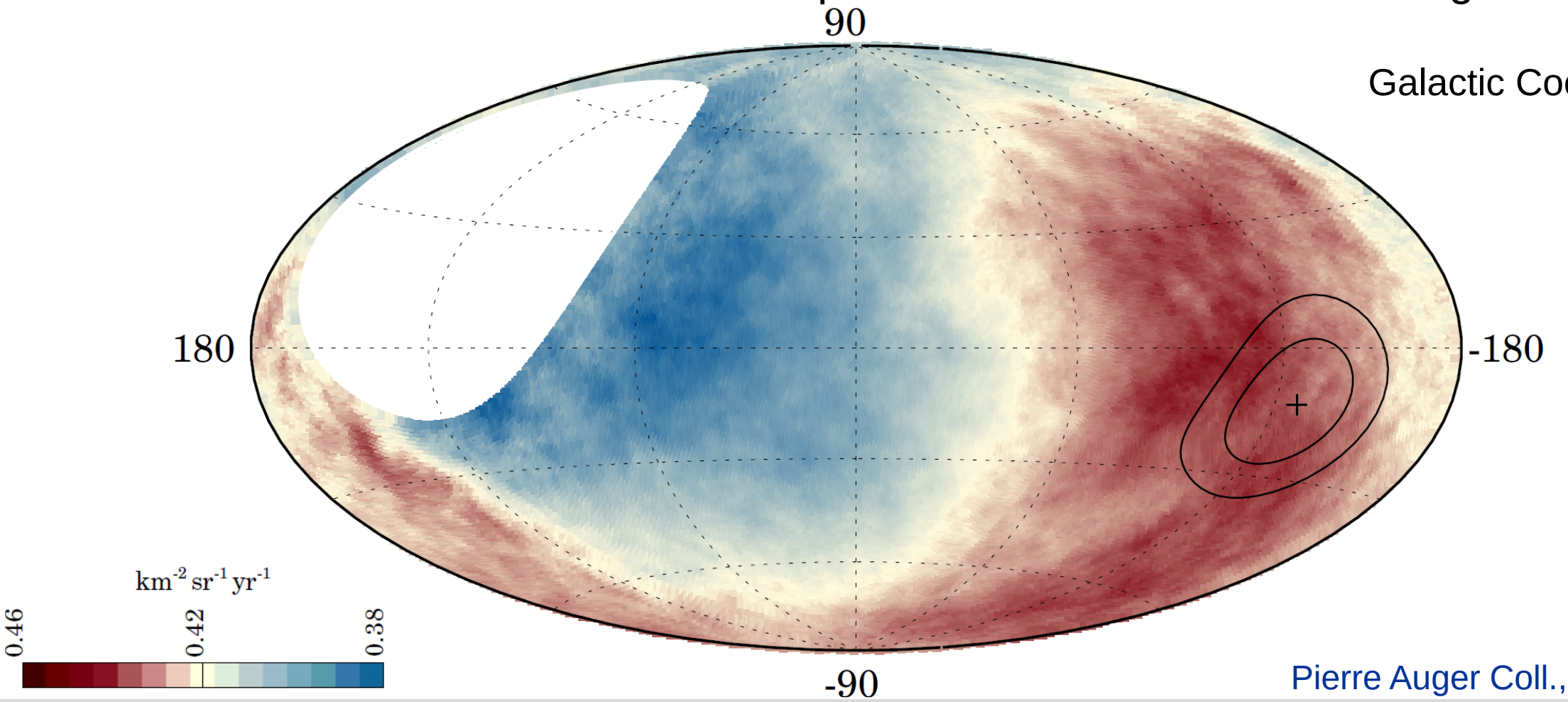
$E_{\text{cal}} = \int \frac{dE}{dX}\, dX$

$\sigma_E / E \sim 8\,\%$
$\Delta_{\text{sys}} \approx 15\,\%$

Pierre Auger Coll., ICRC 2017

Dipole Anisotropy above 8 EeV

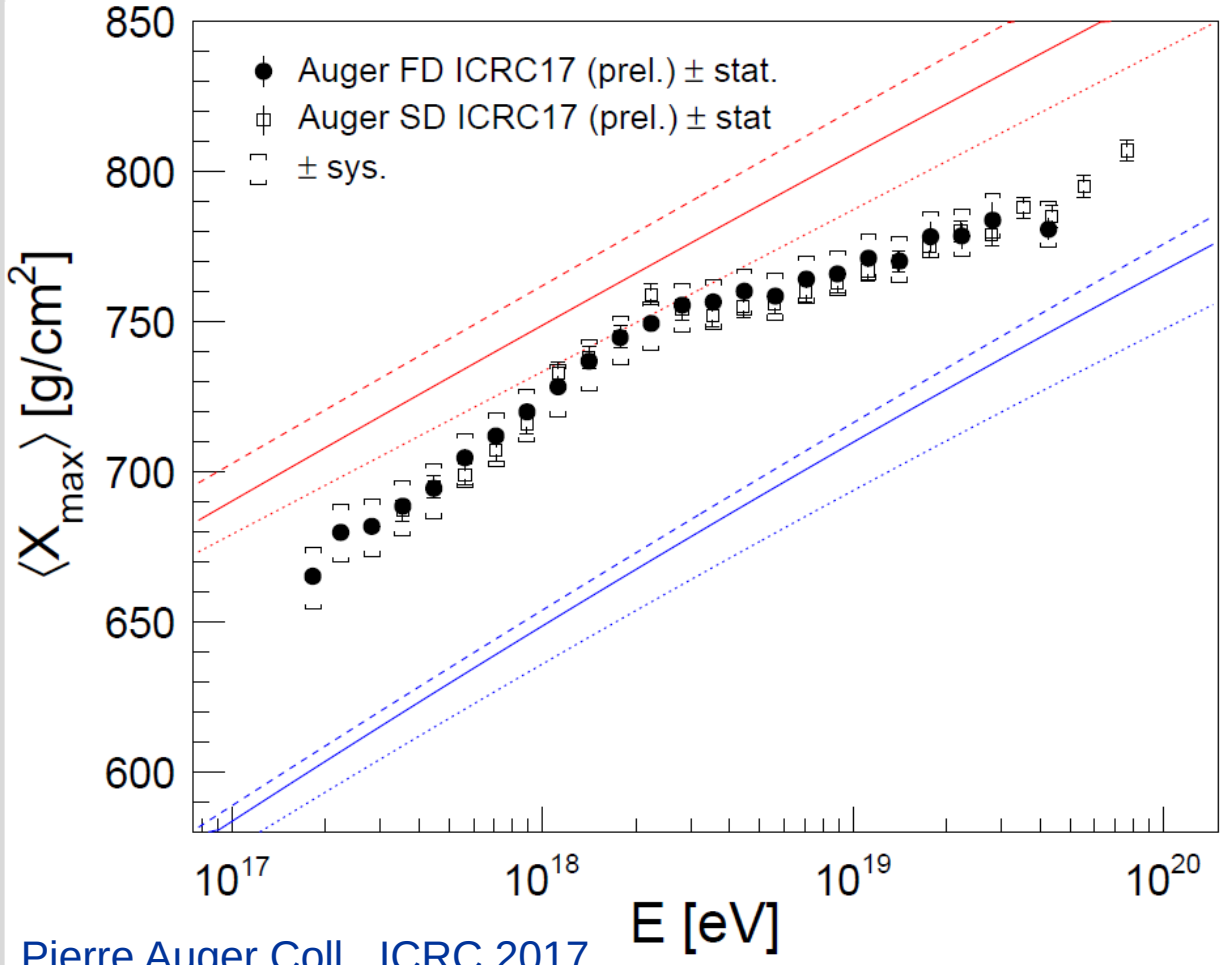
- Consistent with several extragalactic sources of mixed nuclei
- Needs to be resolved into mass components for better understanding

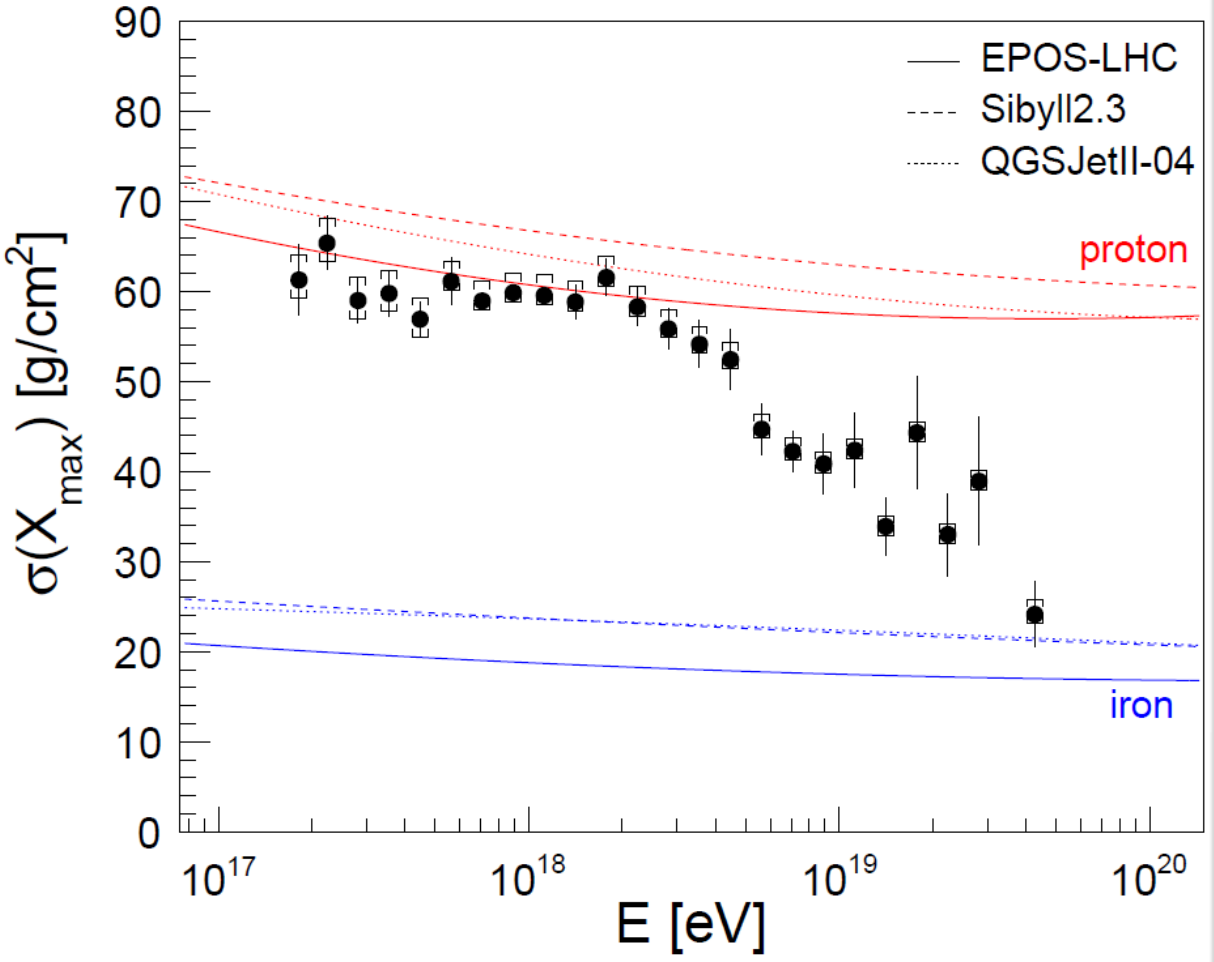


Pierre Auger Coll., ICRC 2017

Mass composition

- Mixed nuclei at all energies, no composition data at 10^{20} eV





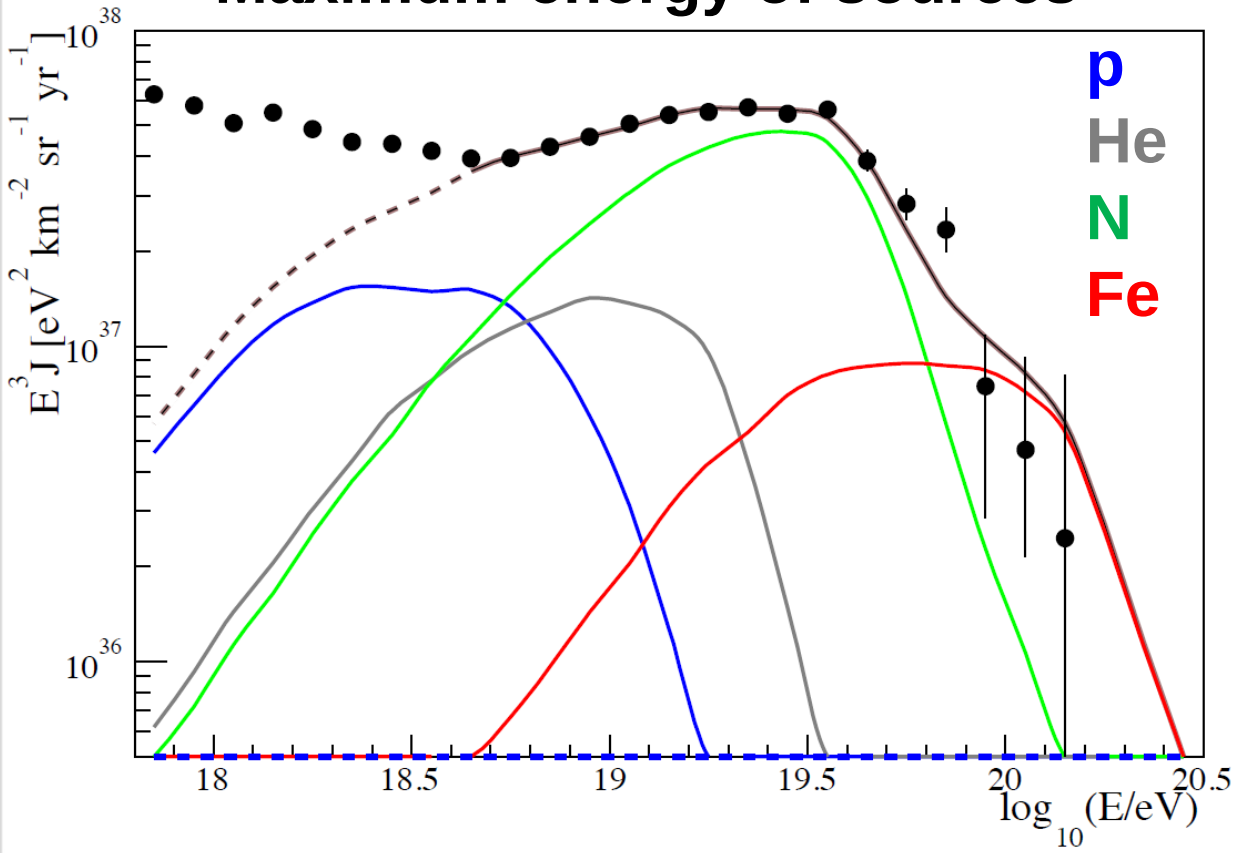
Pierre Auger Coll., ICRC 2017

Mass separation critical for many physics questions

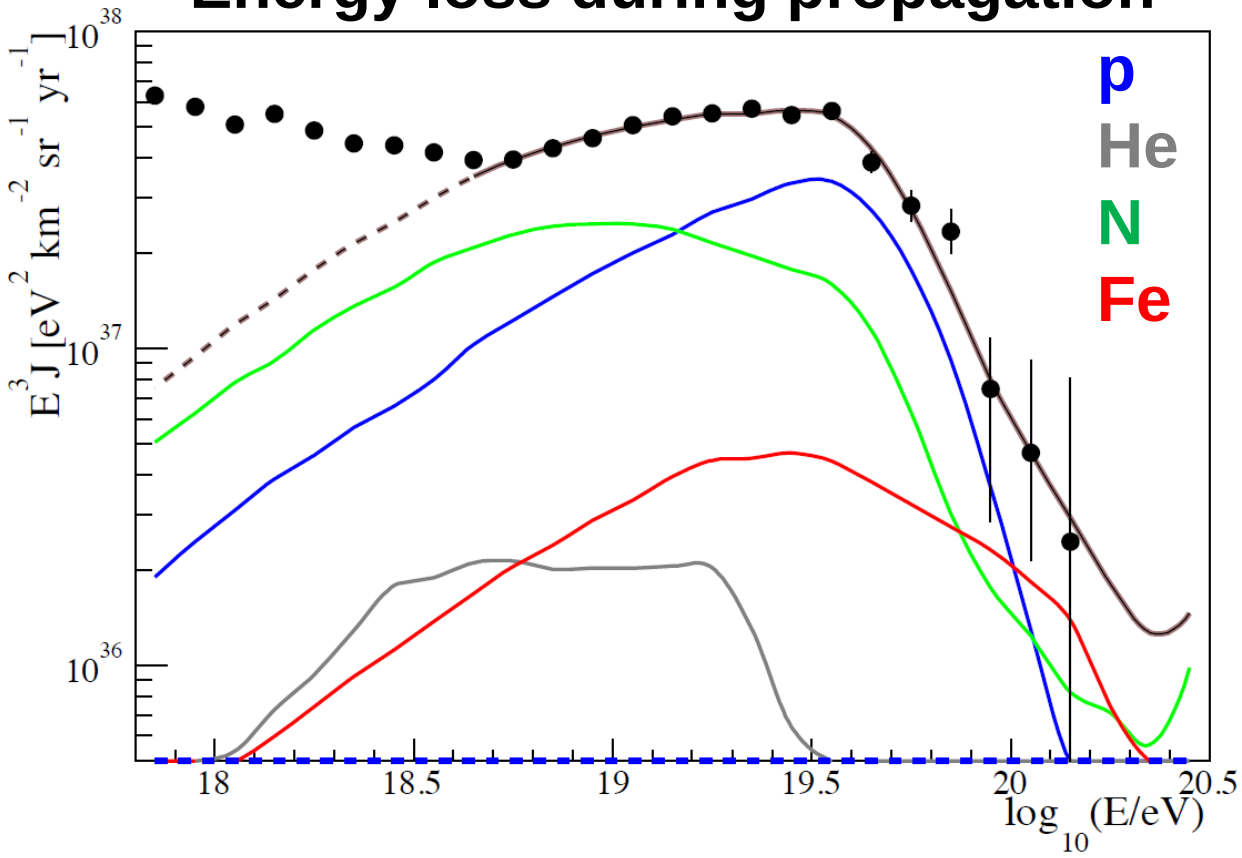
- What is the maximum energy in the Universe?

Pierre Auger Coll., arXiv:1604.03637

Maximum energy of sources



Energy loss during propagation

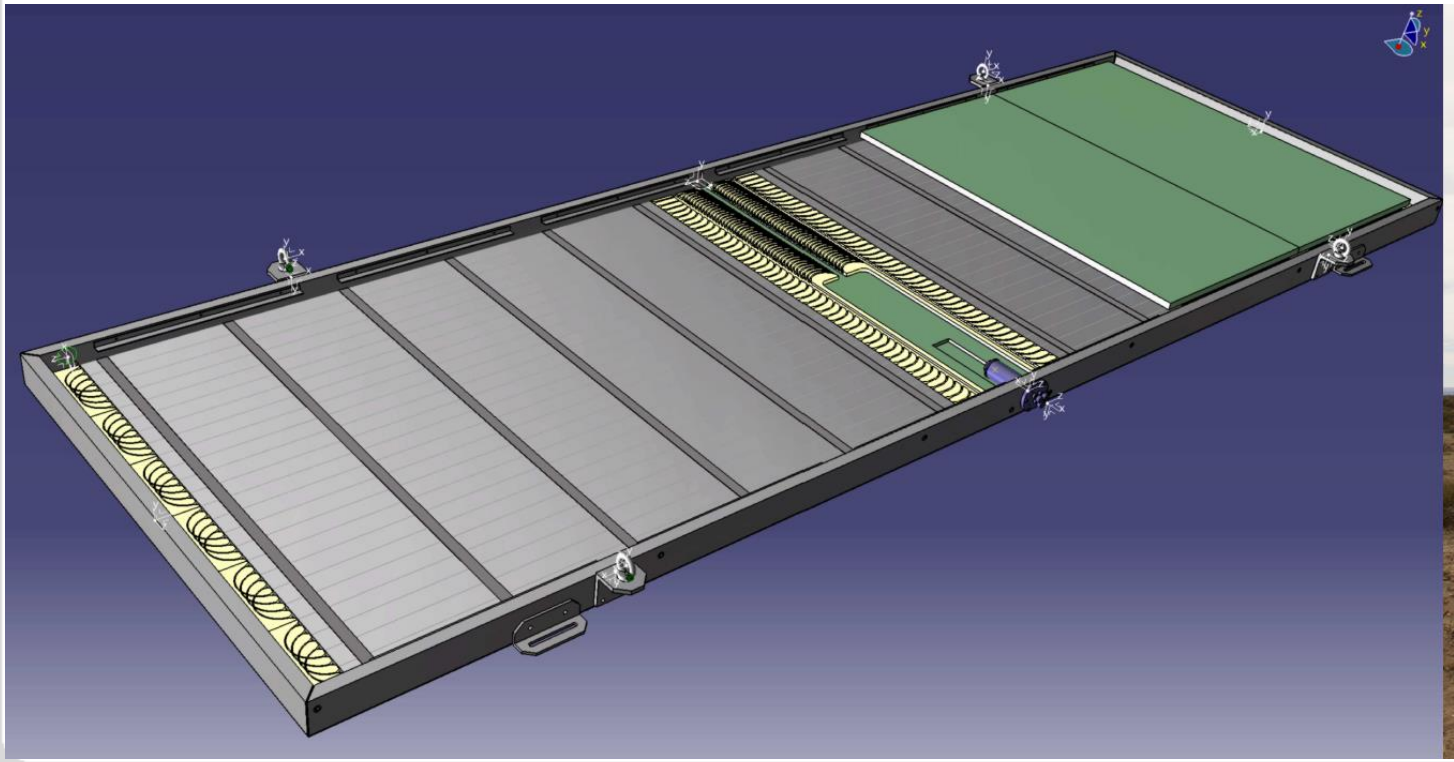


→ **Accurate measurement of mass composition as function of energy required!**

Upgrade: AugerPrime

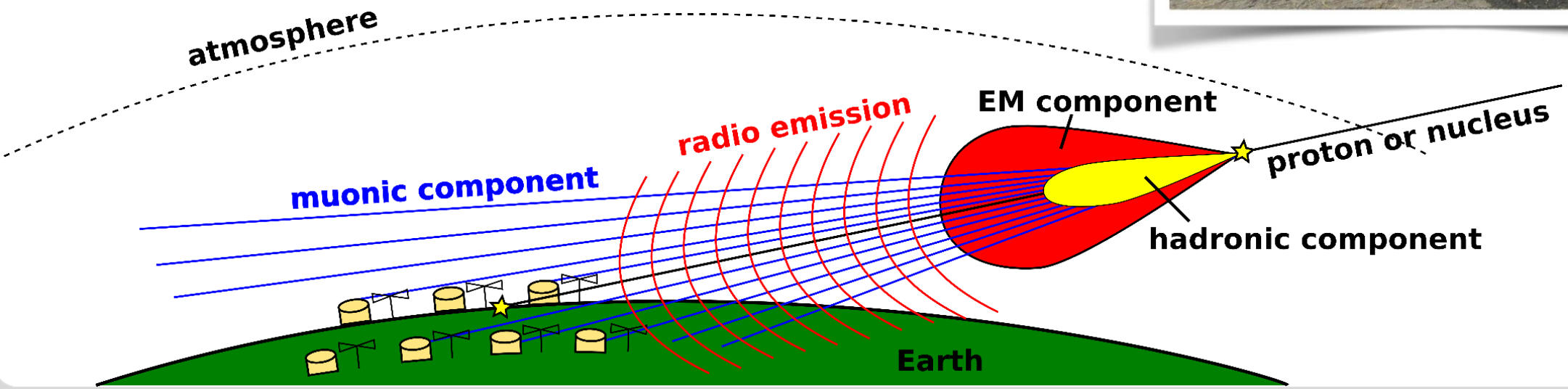
- Main component: Scintillator Surface Detectors on top of each tank
  - Electron-Muon separation
  - Distinguish light and heavy primary particles for each air-shower event

Pierre Auger Coll., ICRC 2017



Radio for the future

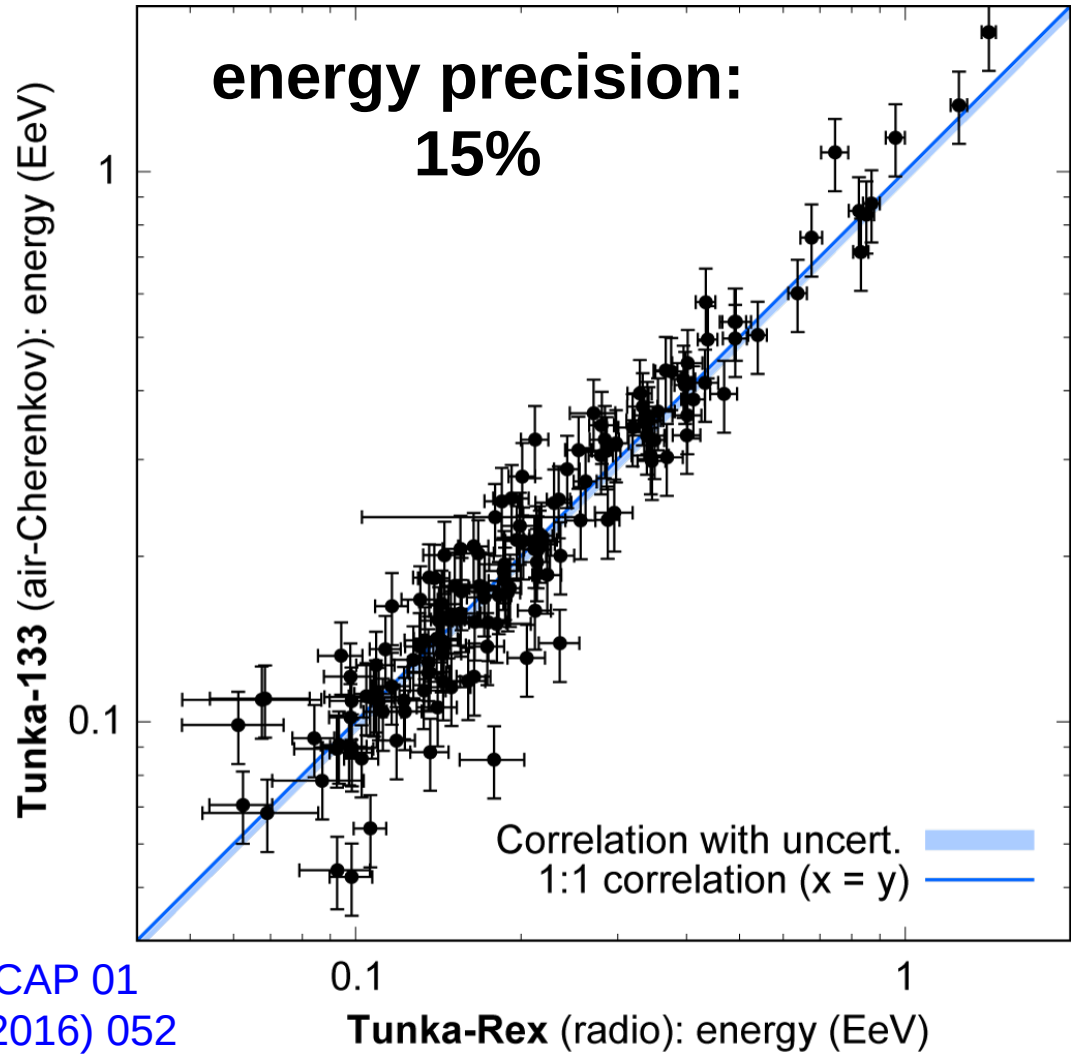
- Possible idea for next upgrade after AugerPrime
  - Mass-sensitivity for inclined showers
  - Search for neutrinos + photons
  - Pathfinder for GRAND



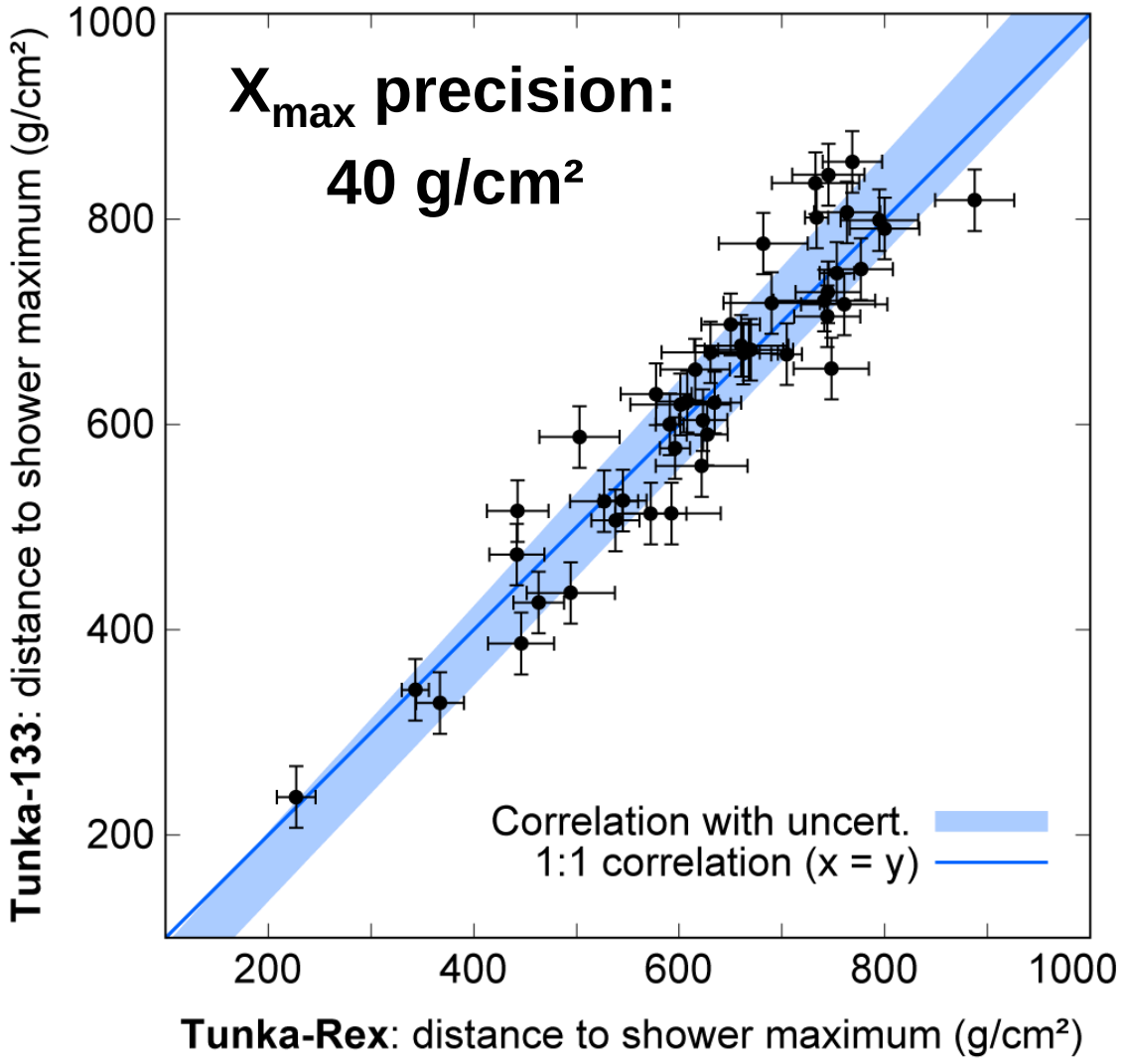
Tunka Radio Extension in Siberia

Correlation of Radio and Cherenkov-light measurements

- Experimental proof that radio is sensitive to distance to shower maximum

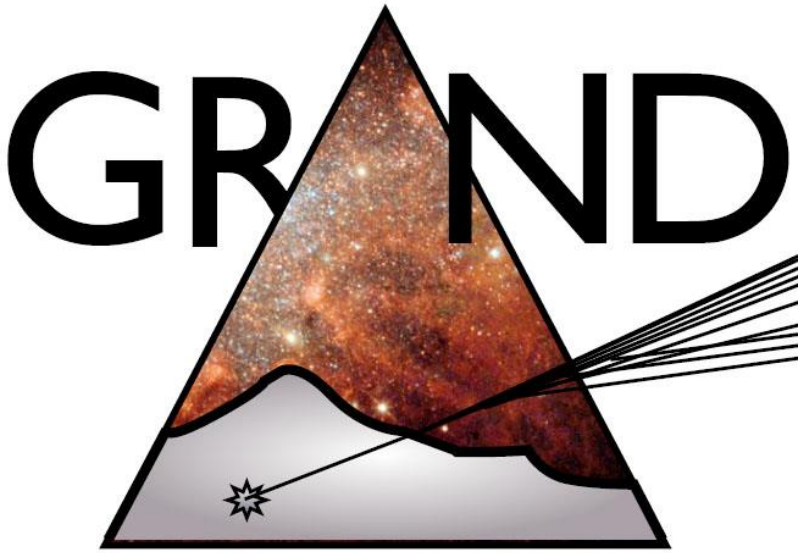


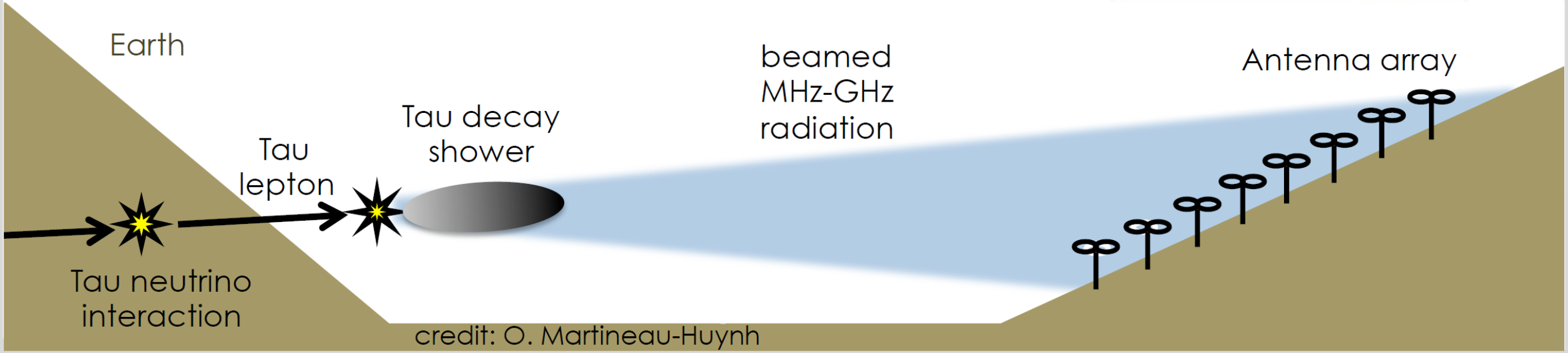
JCAP 01 (2016) 052



Giant Radio Array for Neutrino Detection (GRAND)

- Huge array of 200,000 km² for cosmic particles
  - First prototype under construction in Ulastai, Xinjiang, China
  - 2020 leading array for most energetic Galactic CR
  - 2025 world-largest array for cosmic-ray air showers
  - 2030's neutrino detection at 10^{18} eV with full extension





Conclusion

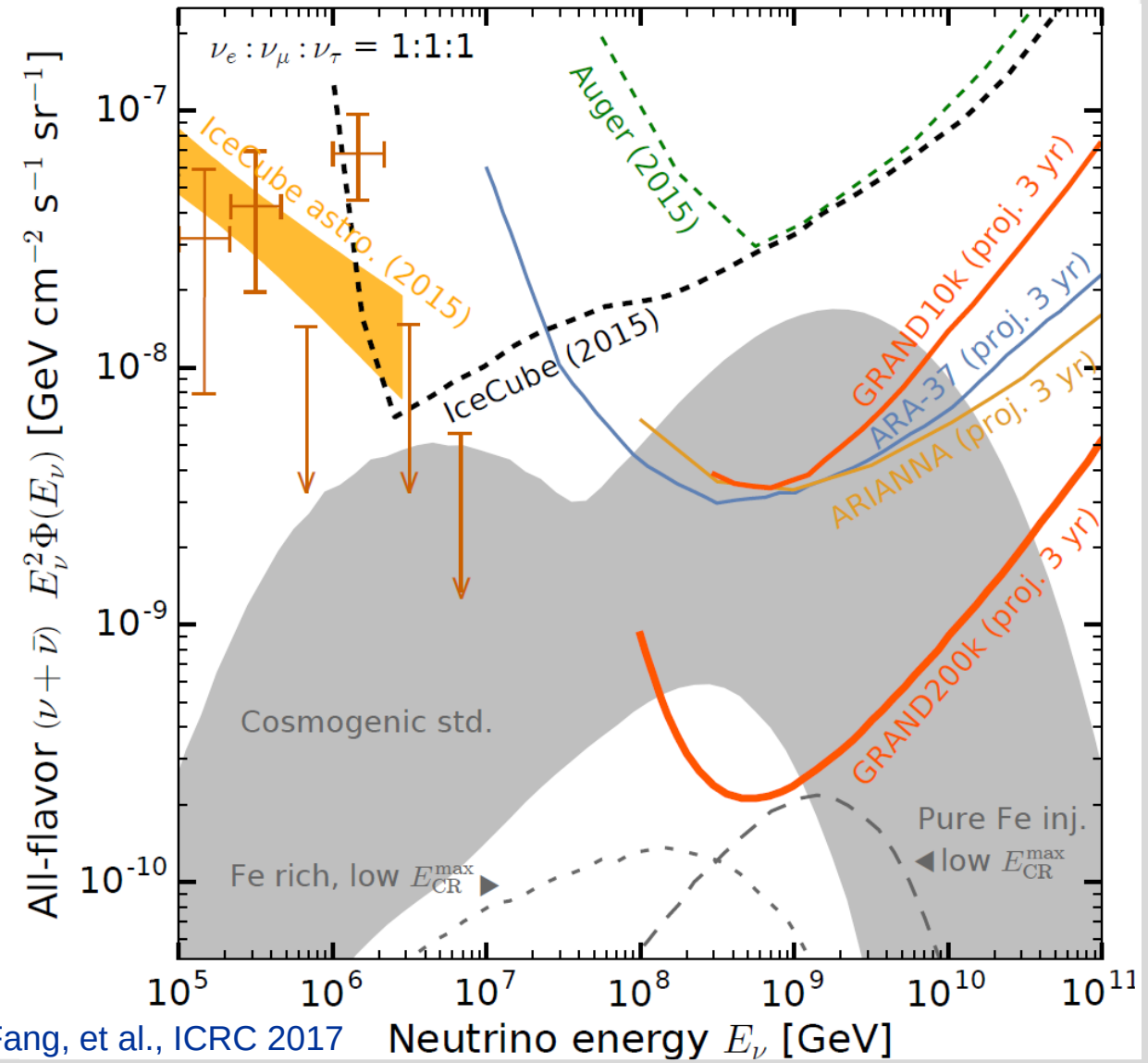
- Cosmic rays: extrasolar nuclei with energies up to > 10^{20} eV
  - Several hints for transition from Galactic to Extra-Galactic origin around 10^{17} eV
  - Unprecedented detail in measurements, but sources still unknown
  - More accurate and larger arrays needed!
- KIT competences in Cosmic Rays
  - Detector development, operation, and management
  - World-wide used standard code for Monte Carlo simulations: CORSIKA
  - Analyses and physics results leading in many aspects of the field
- Future activities in Cosmic Rays
  - AMS until 2024, AugerPrime until 2025
  - IceCube-Gen2
  - Technology development for future space missions + radio arrays

TREND and the 21CMA in Ulastai, Xinjiang, China

→ Site for first prototype of GRAND (under construction)

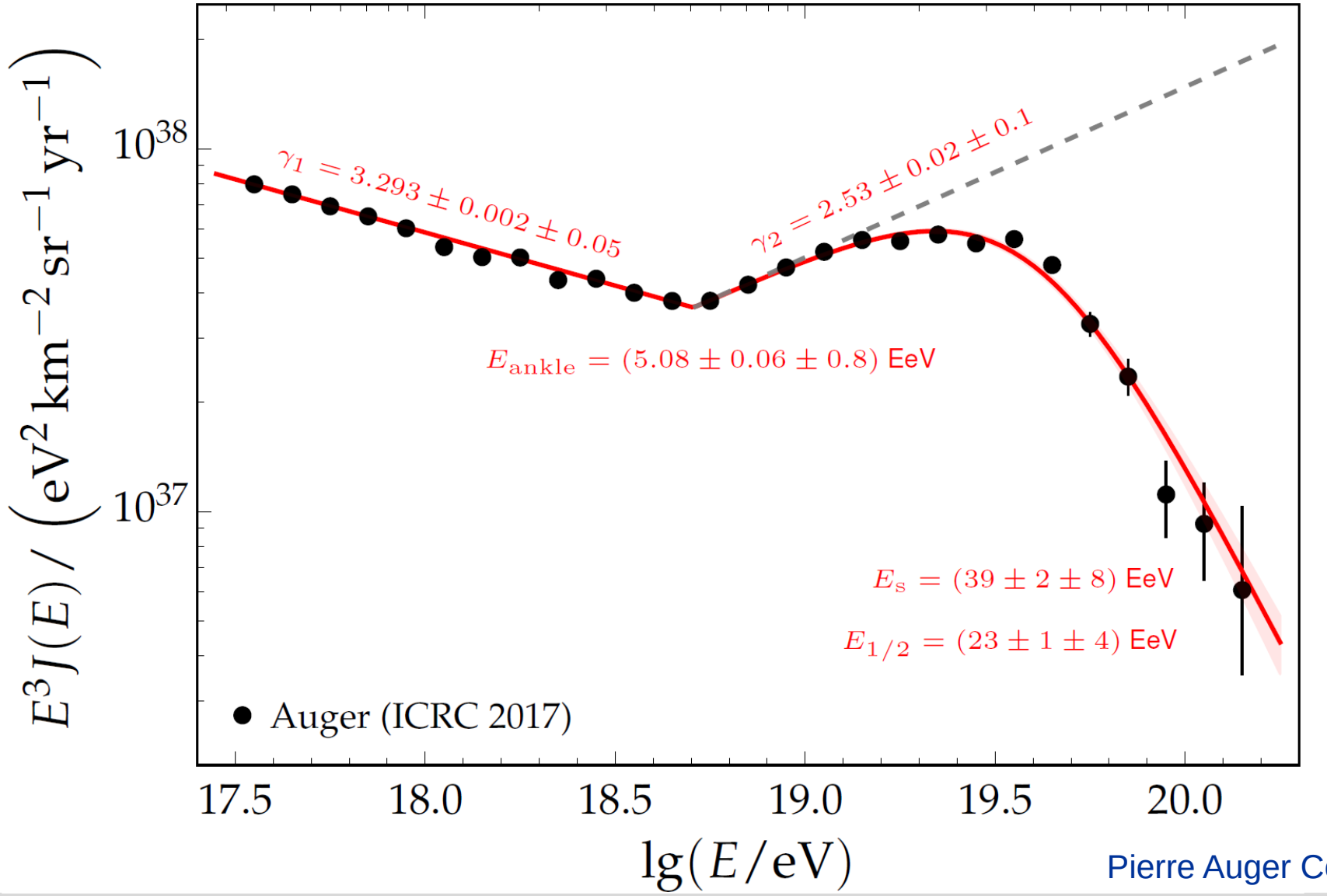
GRAND: schedule and sensitivity

- Phase 1 under construction in Xinjiang
  - 35 antenna stations as prototype
- Phase 2 starting 2020 in China
  - 300 antennas on 100 km²
  - most energetic Galactic cosmic rays
  - world-leading, if radio + muon detectors
- Phase 3 in 2020's
  - 10,000 km², larger aperture than Auger
- Phase 4 in 2030's
  - 200,000 km² internationally distributed
  - Guaranteed neutrino detection at 1 EeV



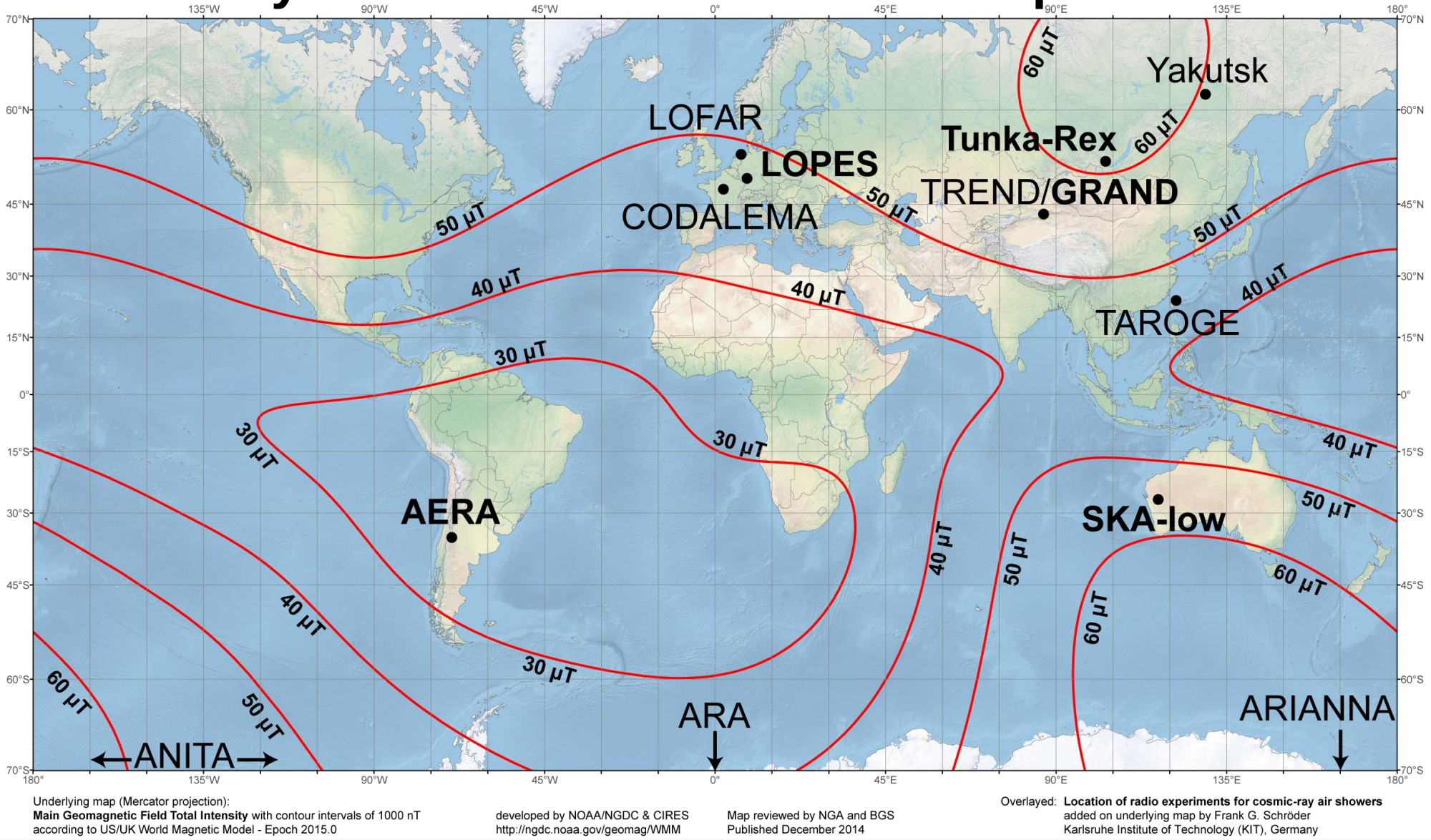
Ke Fang, et al., ICRC 2017

Most accurate spectrum at highest energies



Pierre Auger Coll., ICRC 2017

Radio arrays for air showers: the technique for the future



Underlying map (Mercator projection):
Main Geomagnetic Field Total Intensity with contour intervals of 1000 nT
according to US/UK World Magnetic Model - Epoch 2015.0

developed by NOAA/NGDC & CIRES
http://ngdc.noaa.gov/geomag/WMM

Map reviewed by NGA and BGS
Published December 2014

Overlayed: **Location of radio experiments for cosmic-ray air showers**
added on underlying map by Frank G. Schröder
Karlsruhe Institute of Technology (KIT), Germany

Prog. Part. Nucl. Phys.
93 (2017) 1-68
arXiv: 1607.08781

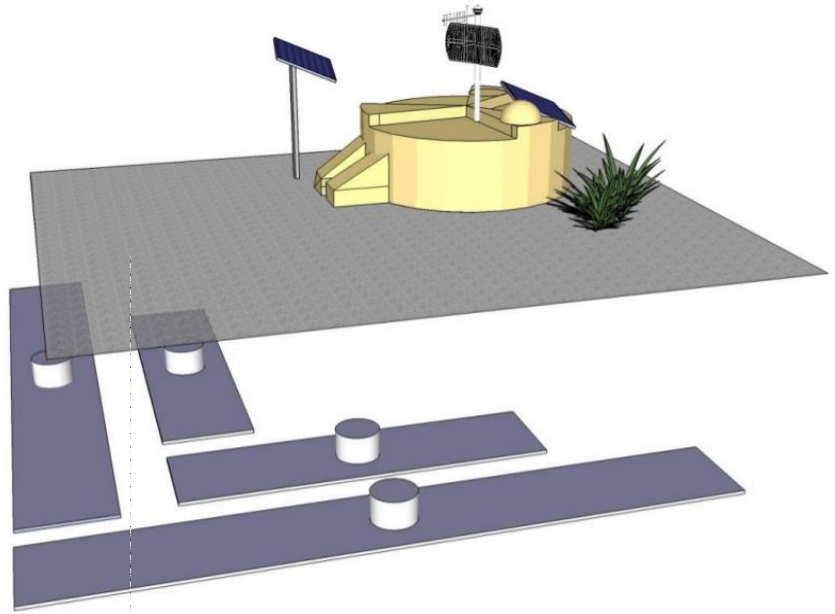
frank.schroeder@kit.edu

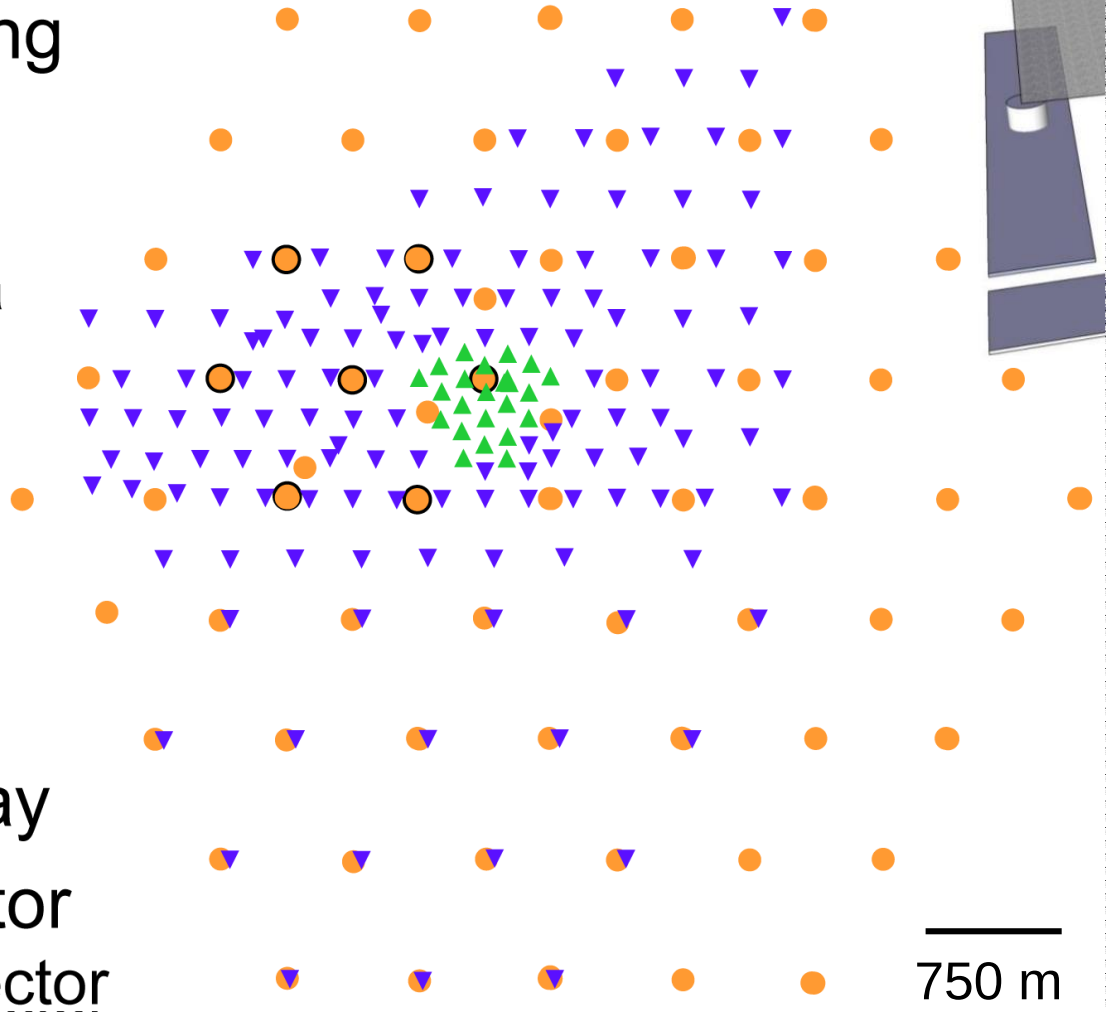
Auger Engineering Radio Array (AERA)

- 153 autonomous stations on 17 km²

Auger **E**ngineering
Radio **A**rray

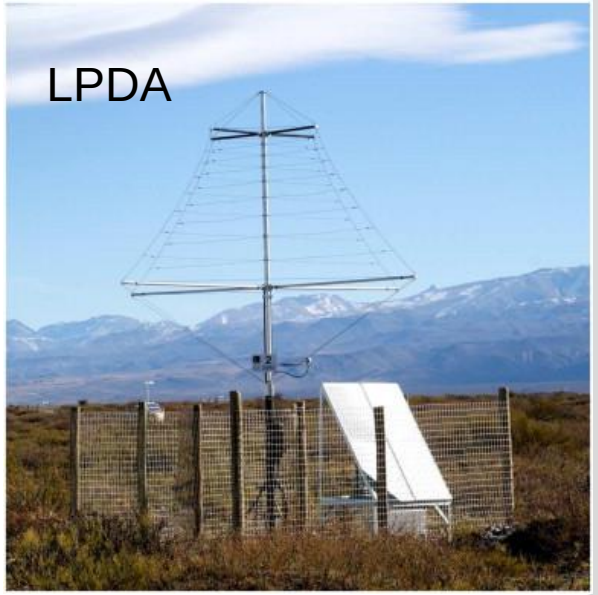
- ▲ LPDA antenna
- ▼ Butterfly antenna





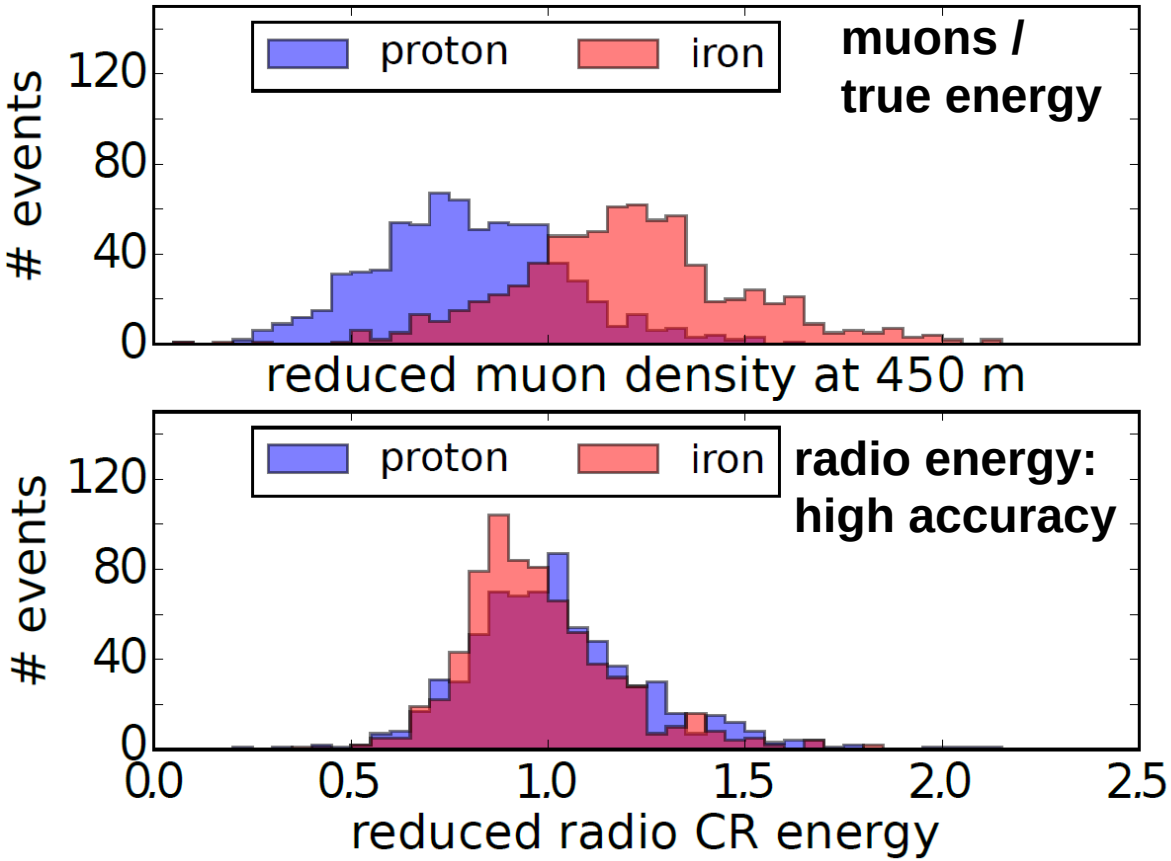
Auger **M**uon and
Infill **G**round **A**rray

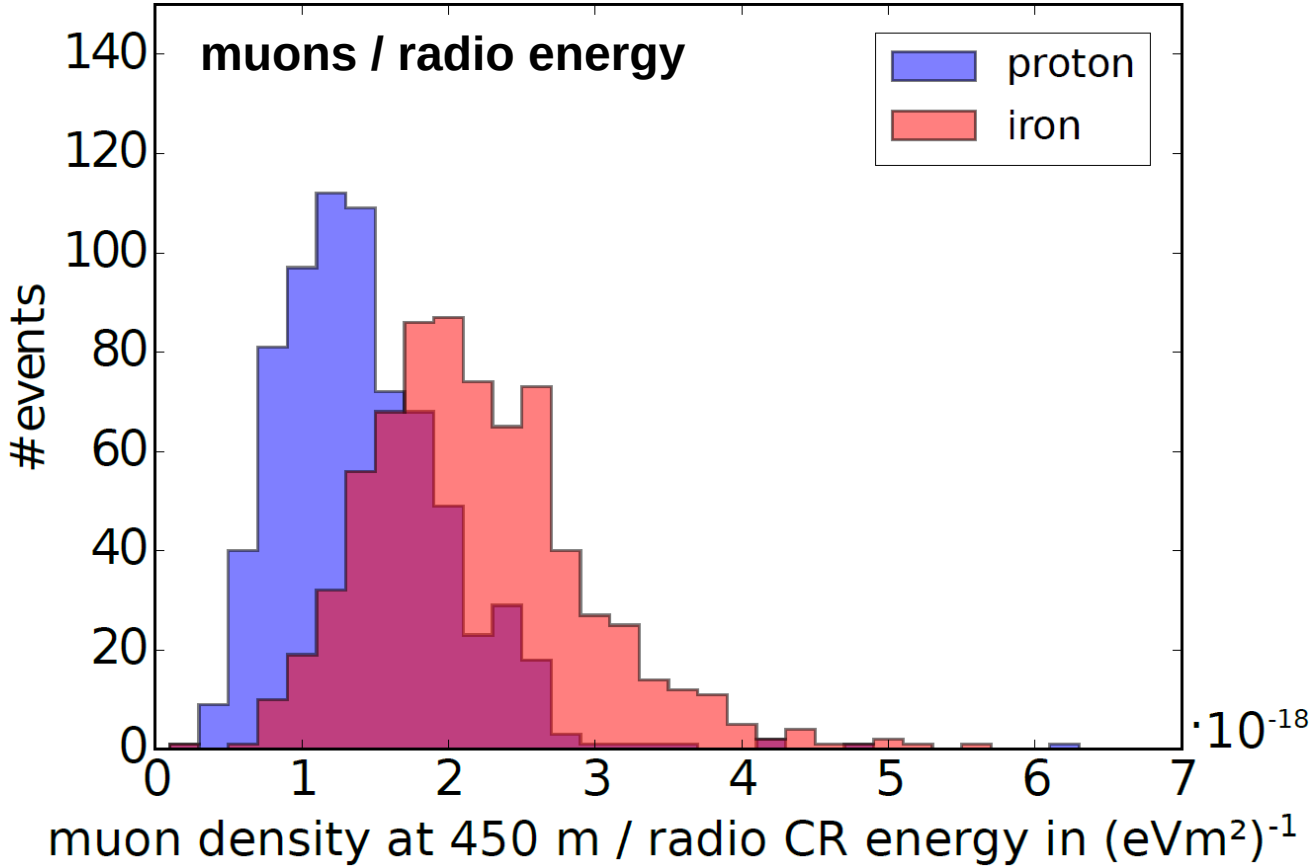
- **S**urface **D**etector
- with **M**uon **D**etector



Mass separation by radio + muon detection

- Preliminary simulation study for current AERA + buried AMIGA scintillators
- Complementary to shower maximum → maximize accuracy for composition



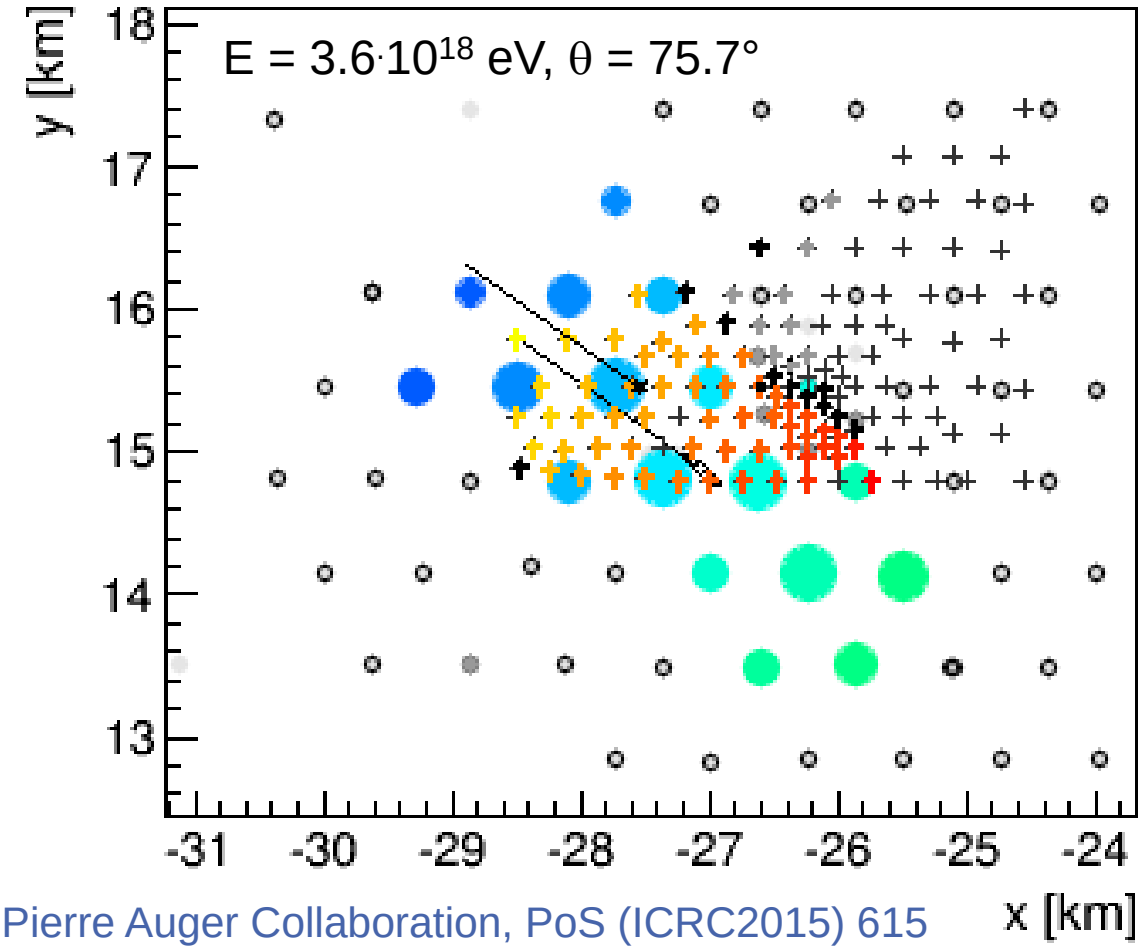


E. Holt (Auger Coll.), ICRC 2017 → best poster prize

Huge footprint for inclined showers

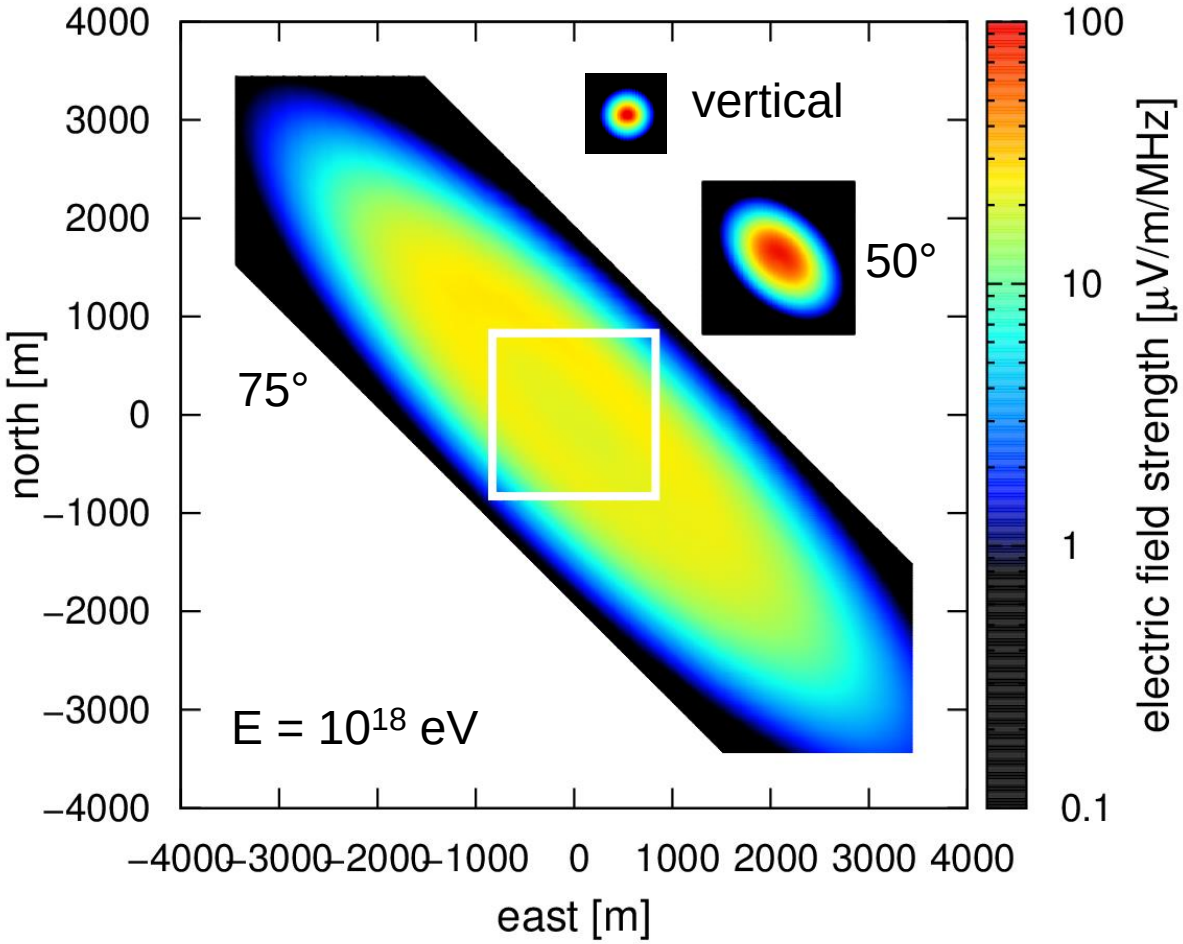
- Enables sparse antenna arrays for highest energies at reasonable costs

Auger measurement



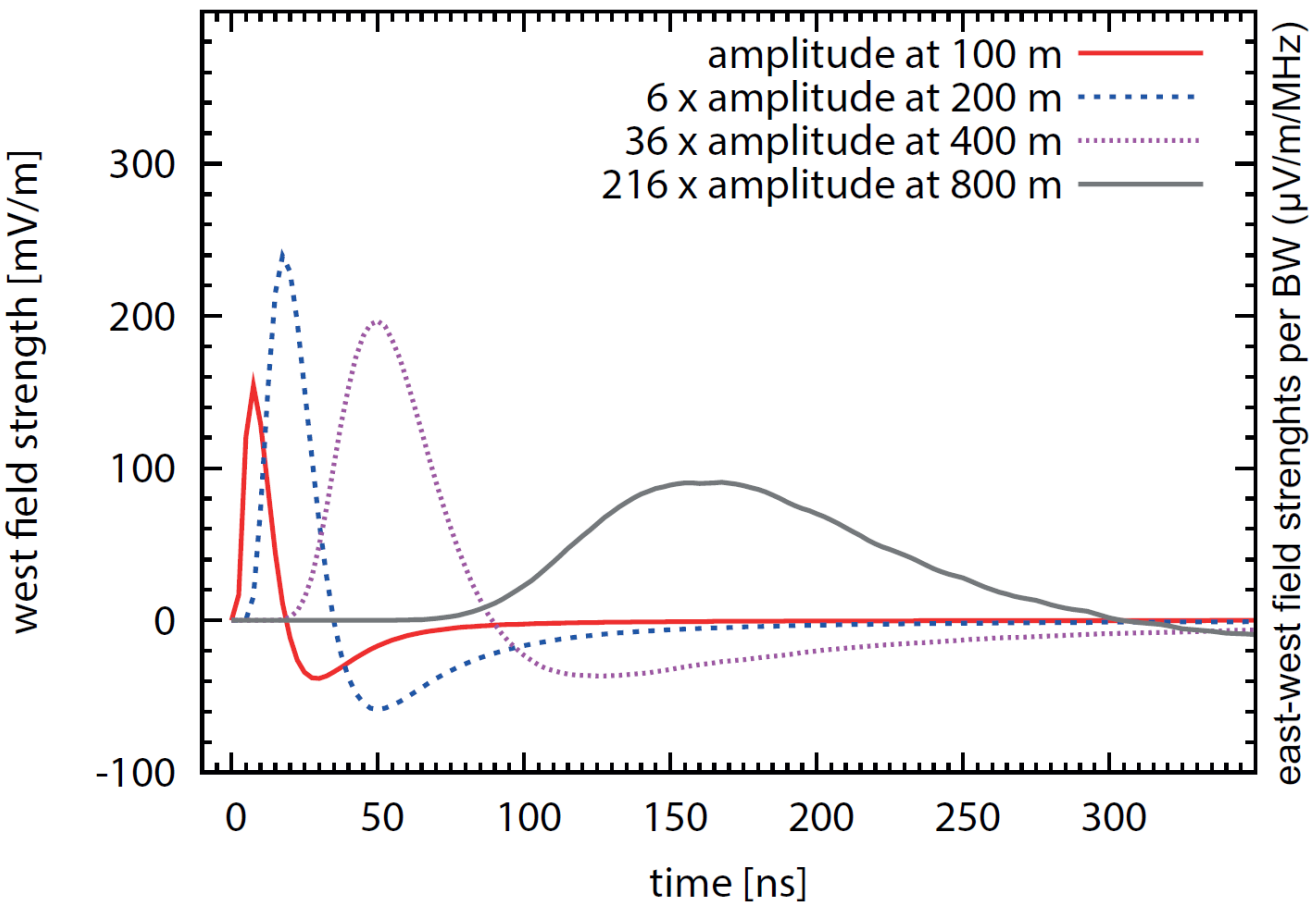
Pierre Auger Collaboration, PoS (ICRC2015) 615

CoREAS simulation

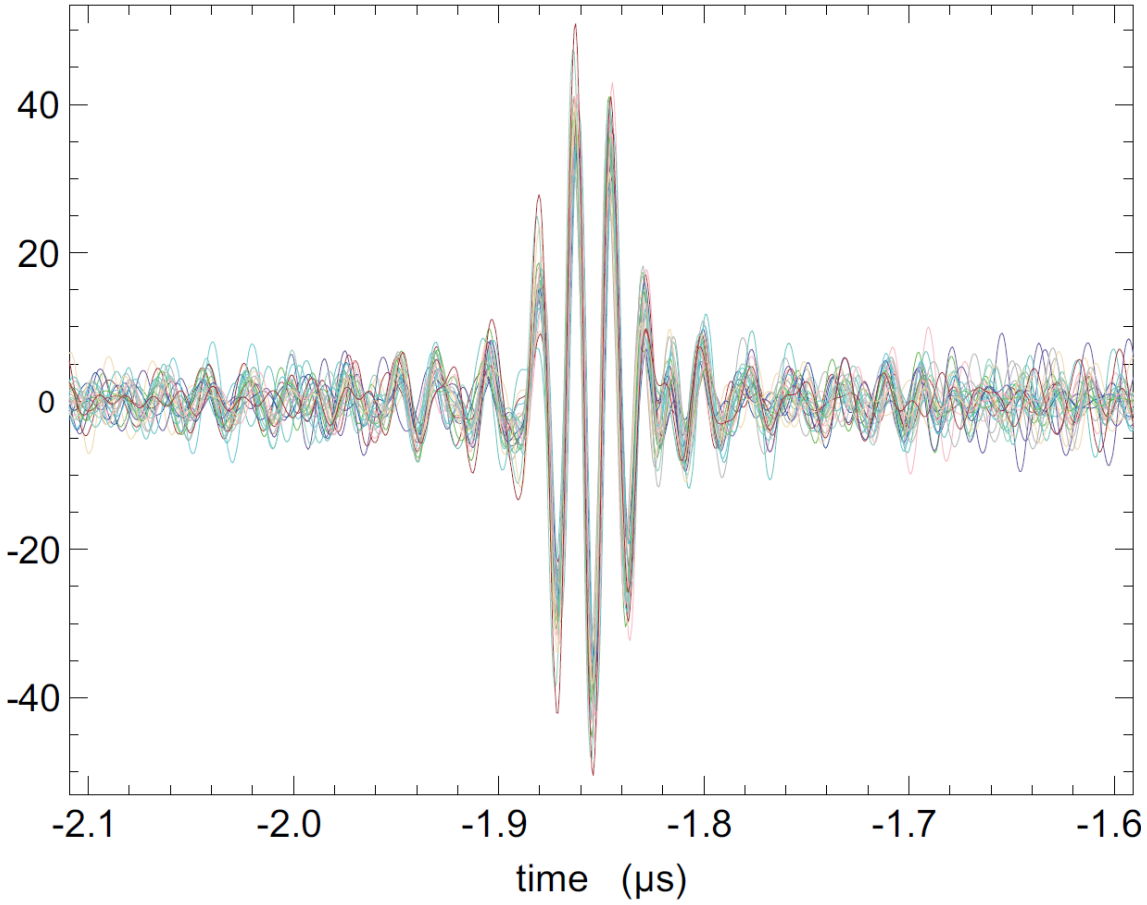


Radio pulse

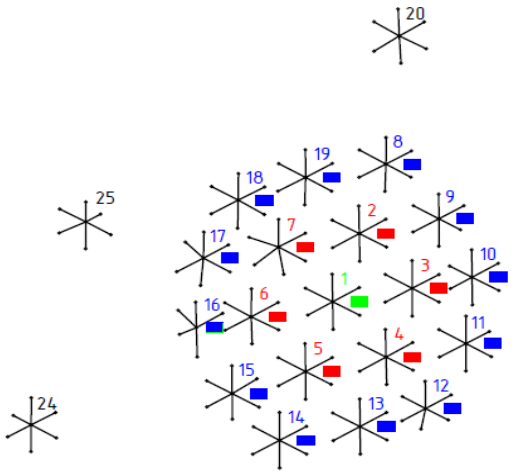
CoREAS simulation, full bandwidth

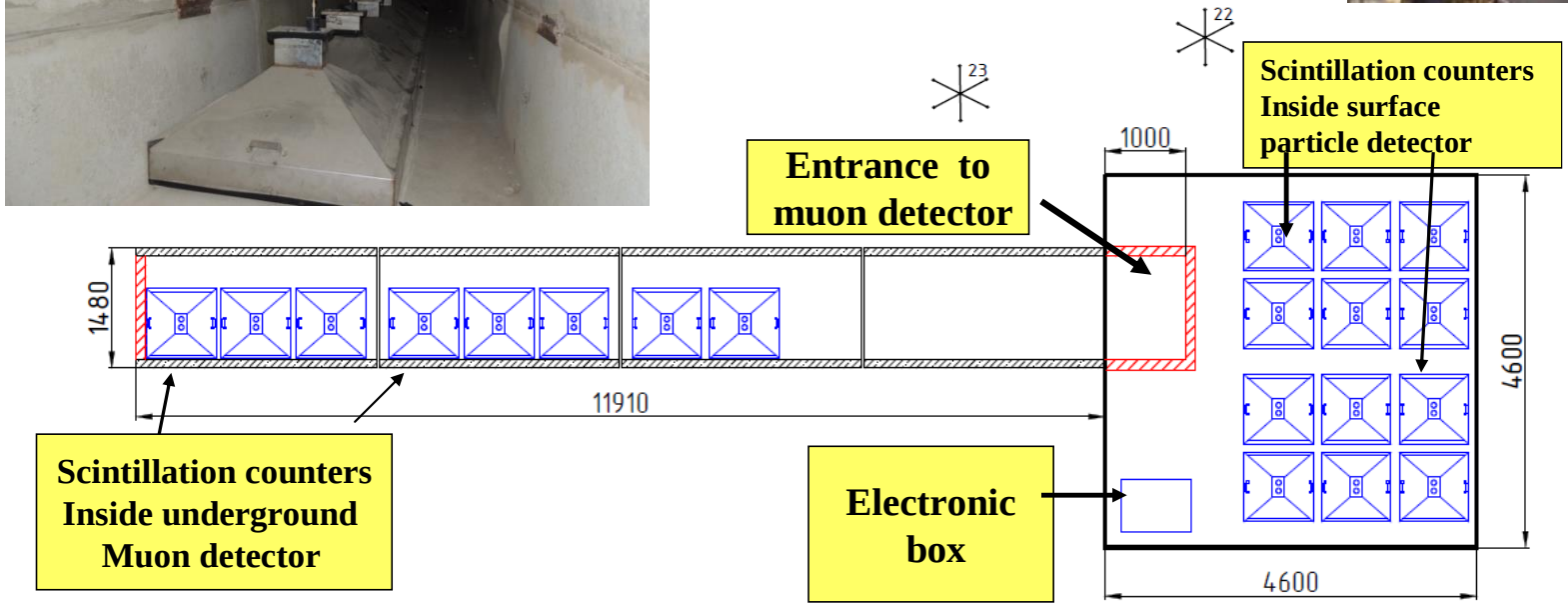


LOPES measurement, 43-74 MHz



Tunka-133 and Tunka-Grande at TAIGA

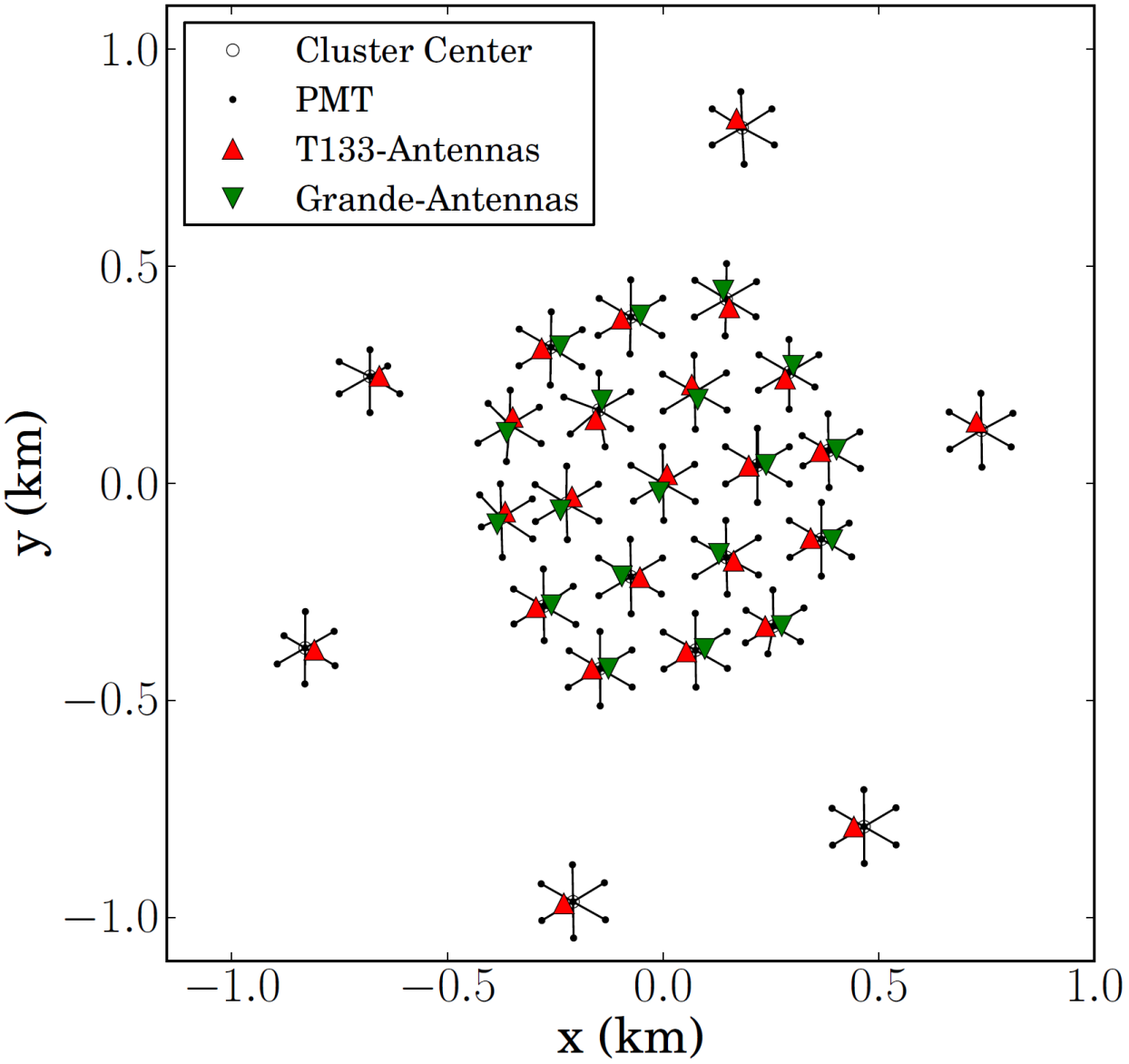




- Cosmic Rays
  - Tunka-133
  - Tunka-Grande
  - Tunka-Rex
- Gamma Rays
  - HiSCORE
  - IACT
  - Muon detectors as veto

ECRS 2014
Tunka Coll.

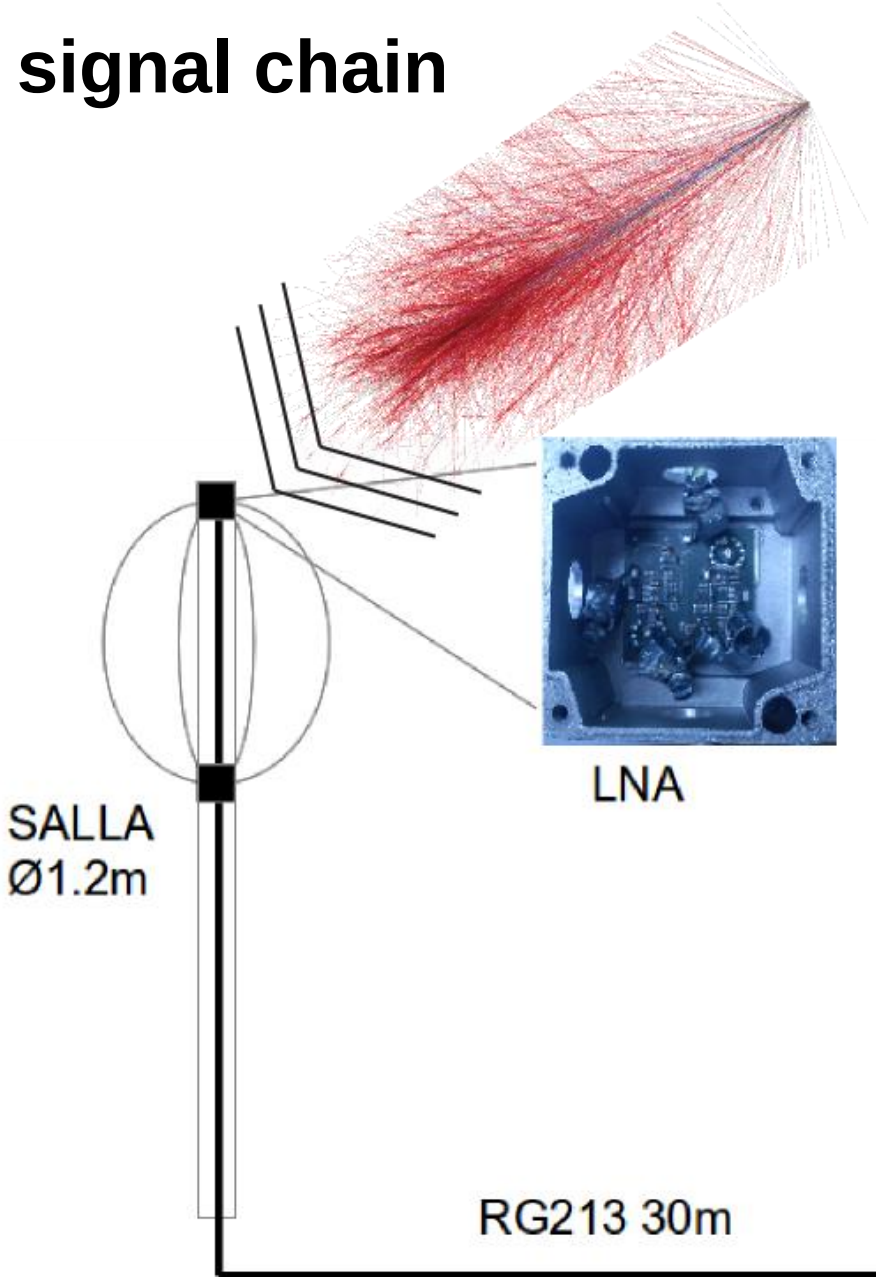
Layout of Tunka-Rex



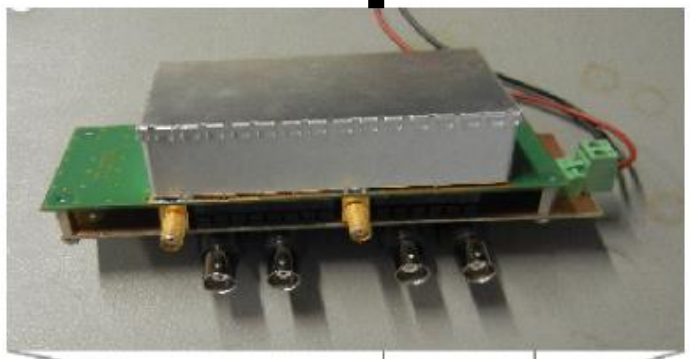
- Array layout
  - 200 m spacing in 1 km² inner area
- Fully analyzed: Oct 2012 – Apr 2014

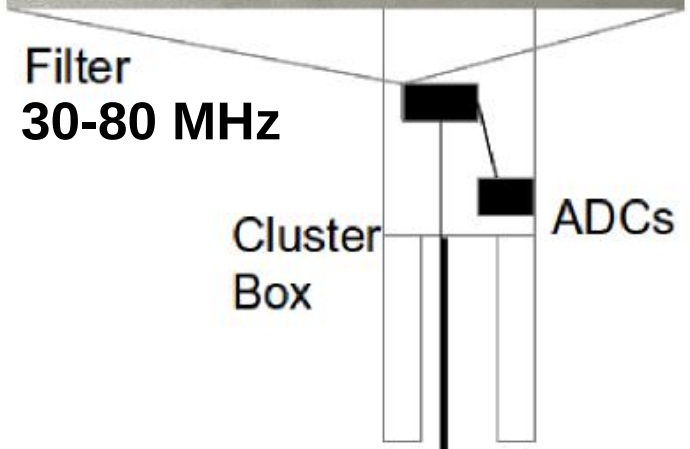
Year	Stations	Trigger
2012	19	Tunka-133
2013	25	Tunka-133
2014	timing problem	
2015	44	Tunka-133 + Grande
2016	63	Tunka-133 + Grande

Tunka-Rex signal chain



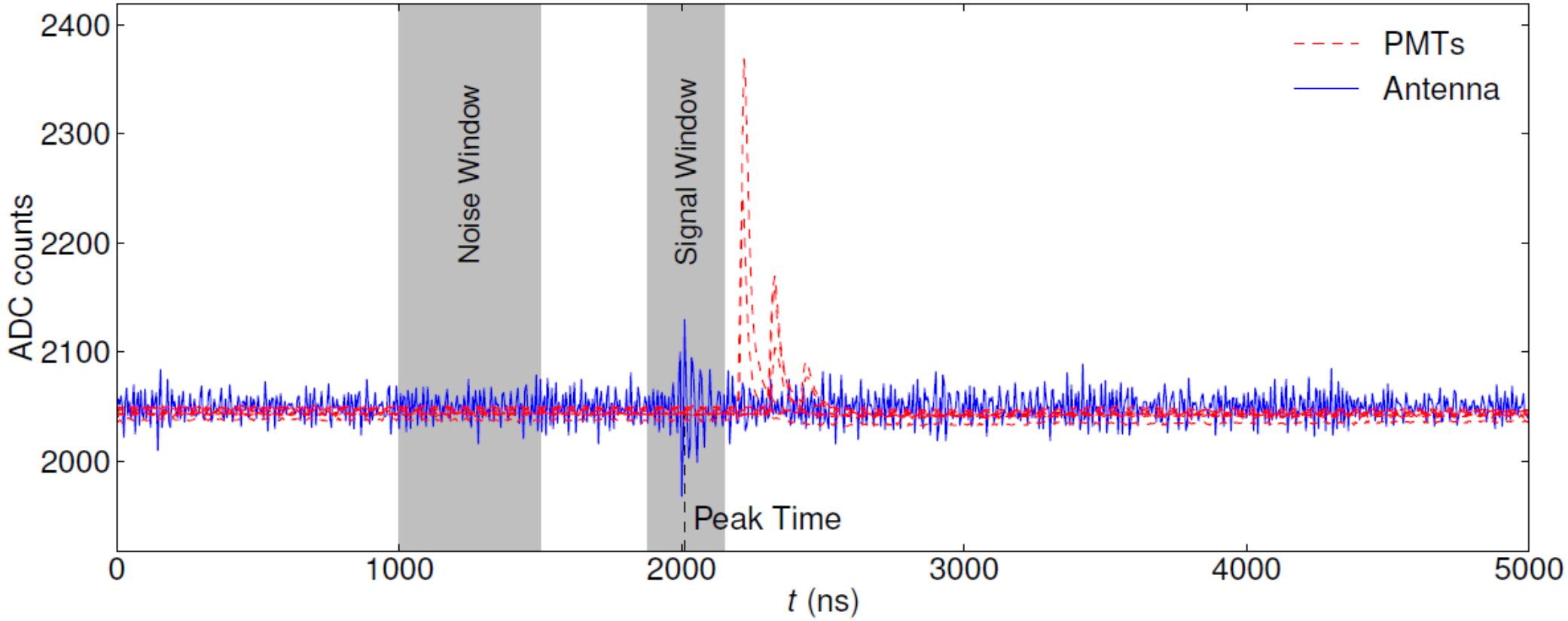
Using data acquisition of Tunka-133 / Tunka-Grande



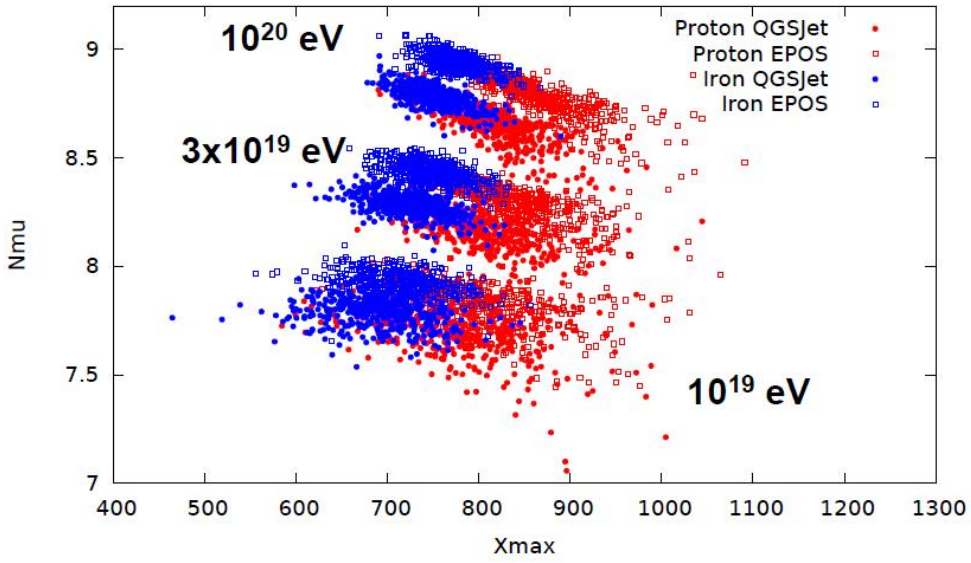


Reconstruction of Tunka-Rex event

- Signal-to-noise ratio (in power) > 10
  - 5% chance probability of false-positive detection in a single antenna
- 3 antennas + direction agreement with Tunka-133 required

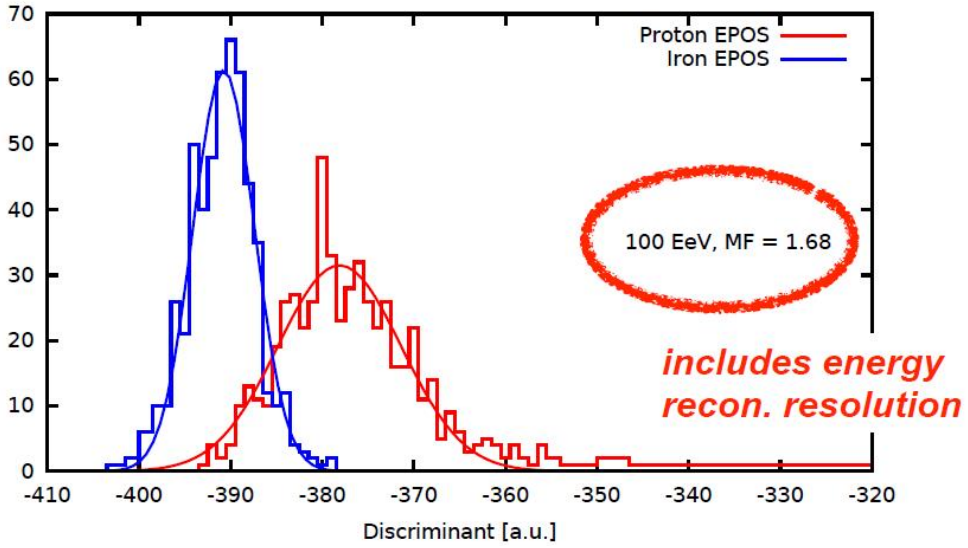


AugerPrime: Upgrade for better mass separation

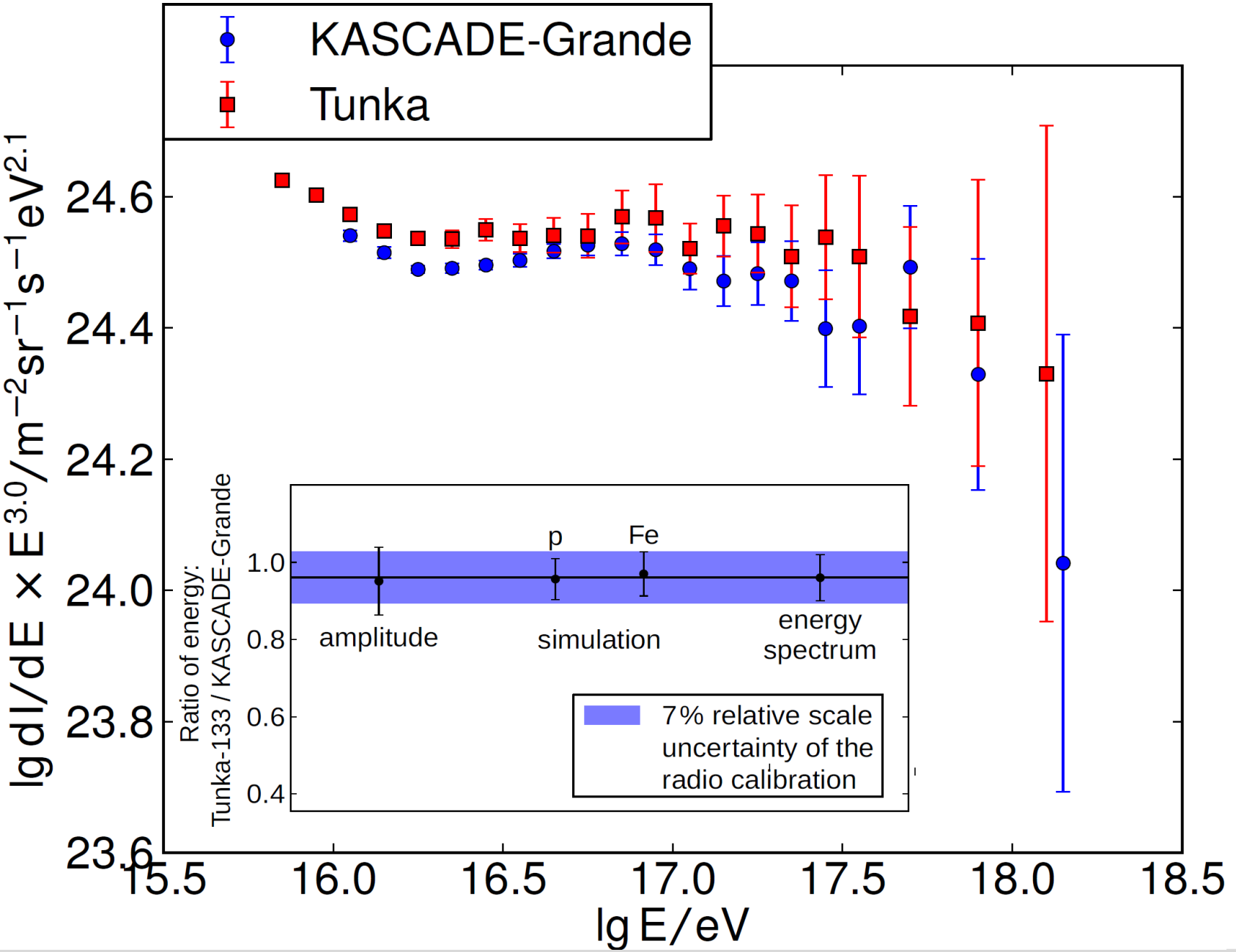


Merit factor
(discrimination power)

$$f_{\mathrm{p,Fe}} = \frac{|\langle S_{\mathrm{Fe}}\rangle - \langle S_{\mathrm{p}}\rangle|}{\sqrt{\sigma^2_{\mathrm{Fe}} + \sigma^2_{\mathrm{p}}}}$$



Comparing energy scales via radio

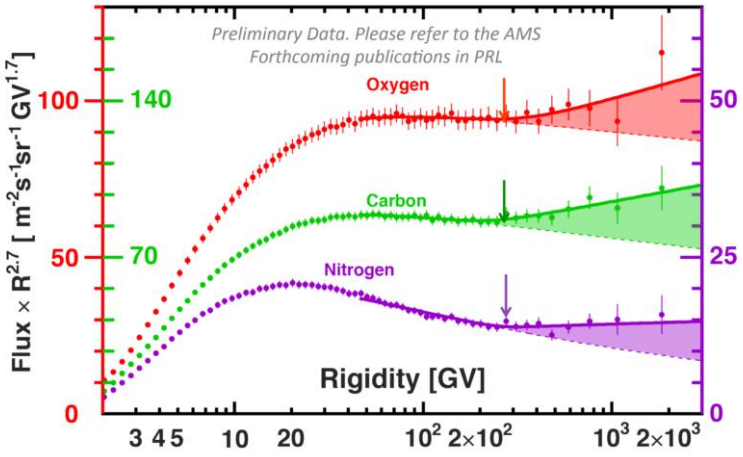


Tunka-Rex + **LOPES** Colls., accepted by PLB

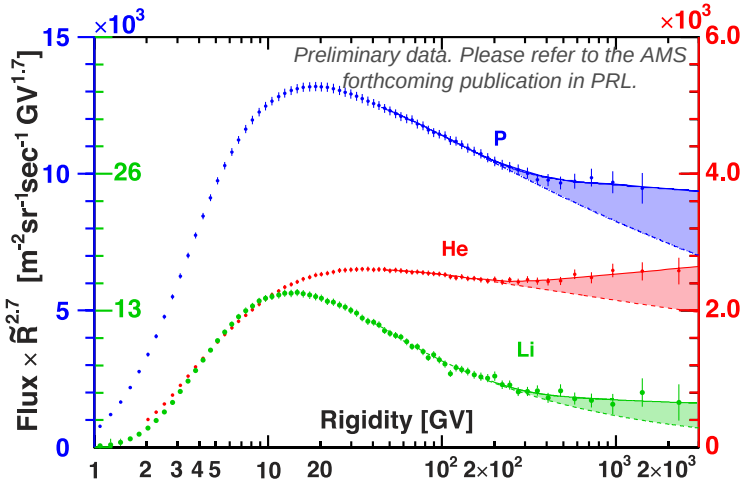
Other AMS-02 results: new, precise, and unexpected

The accuracy of the AMS data reveals a number of unexpected features, almost all of which are currently not understood.

The spectra of oxygen, carbon and nitrogen do not follow the traditional single power law



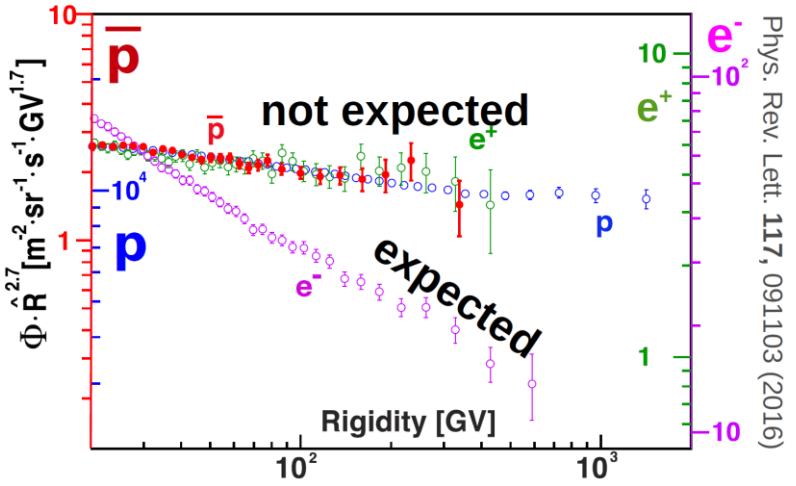
...as do the fluxes of protons, helium and lithium.



Possibly point to local cosmic ray accelerator.

The understanding of these features is crucial to dark matter searches in cosmic rays.

The rigidity dependences of e^+, $\bar{p}$, p are identical from 60-500 GV.



Possibly points to secondary production in sources very close to Sun.

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