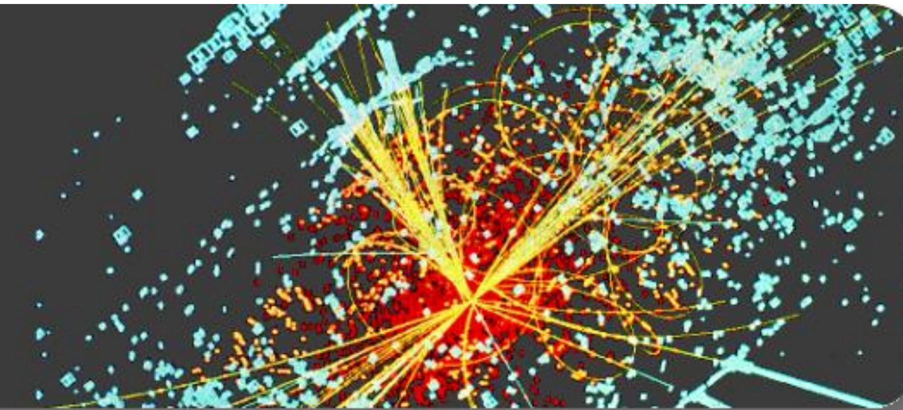


(UHE) Cosmic Ray Physics

B7 – neutrino physics (cosmic messengers)

Plan of the talk:
- UHECR Cosmic Ray Physics
- Multi-Messenger Astroparticle Physics
- Particle Physics Connection

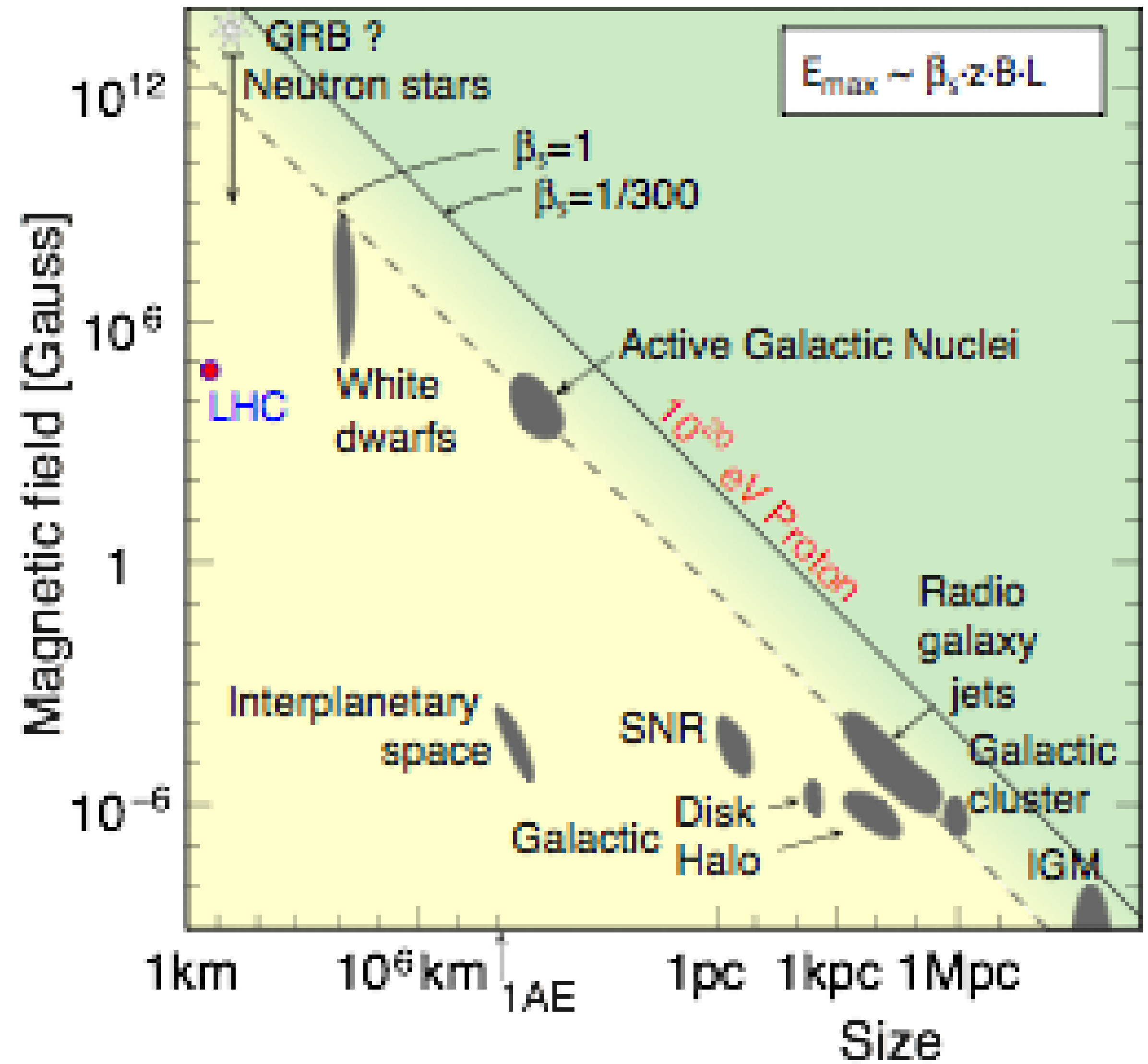
#117: Auger
#119: GRAND
#014: NEVOD
#084: APPEC

Andreas Haungs
Karlsruhe Institute of Technology
andreas.haungs@kit.edu

The puzzle of UHECR

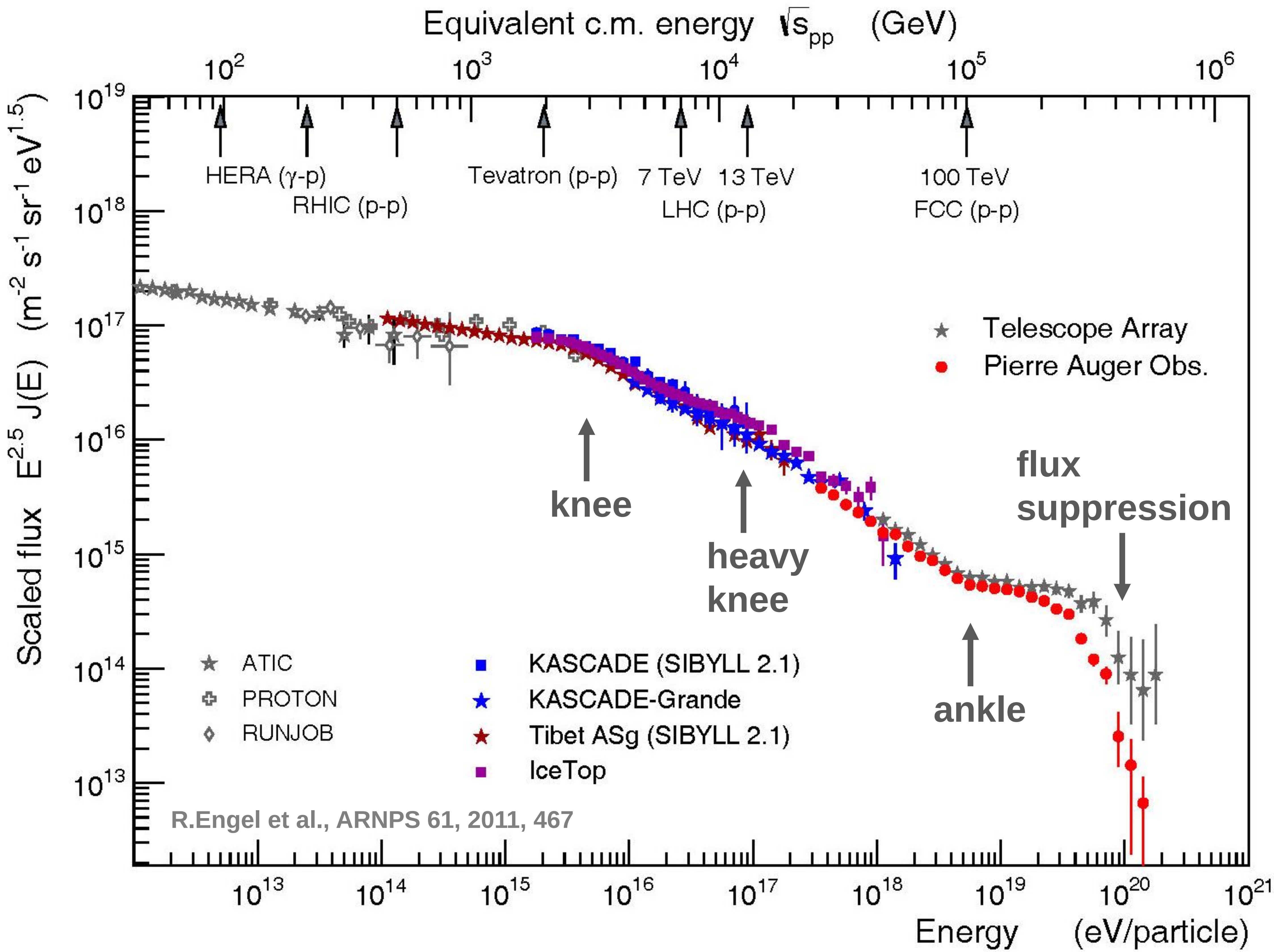
Need accelerator of size of Mercury orbit to reach 10^{20} eV with LHC technology

Hillas plot (1984)



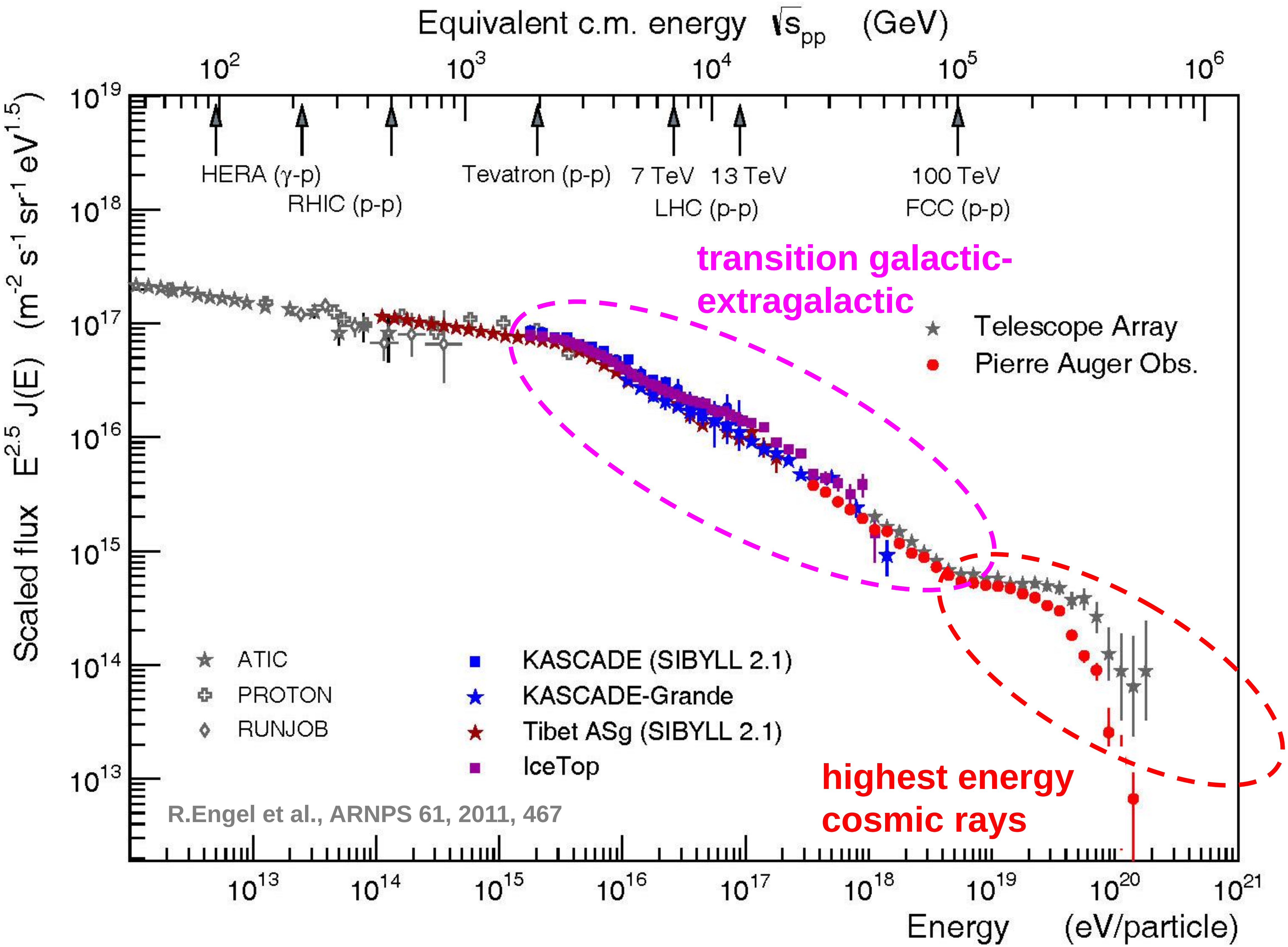
- **Source of cosmic rays**
- **Acceleration mechanisms of cosmic rays**
- **Propagation processes of cosmic rays**
- **Interaction physics and cross-sections at $\sqrt{s_{pp}}$ > 100TeV**

Ultra-High Energy Cosmic Rays



European Strategy Update

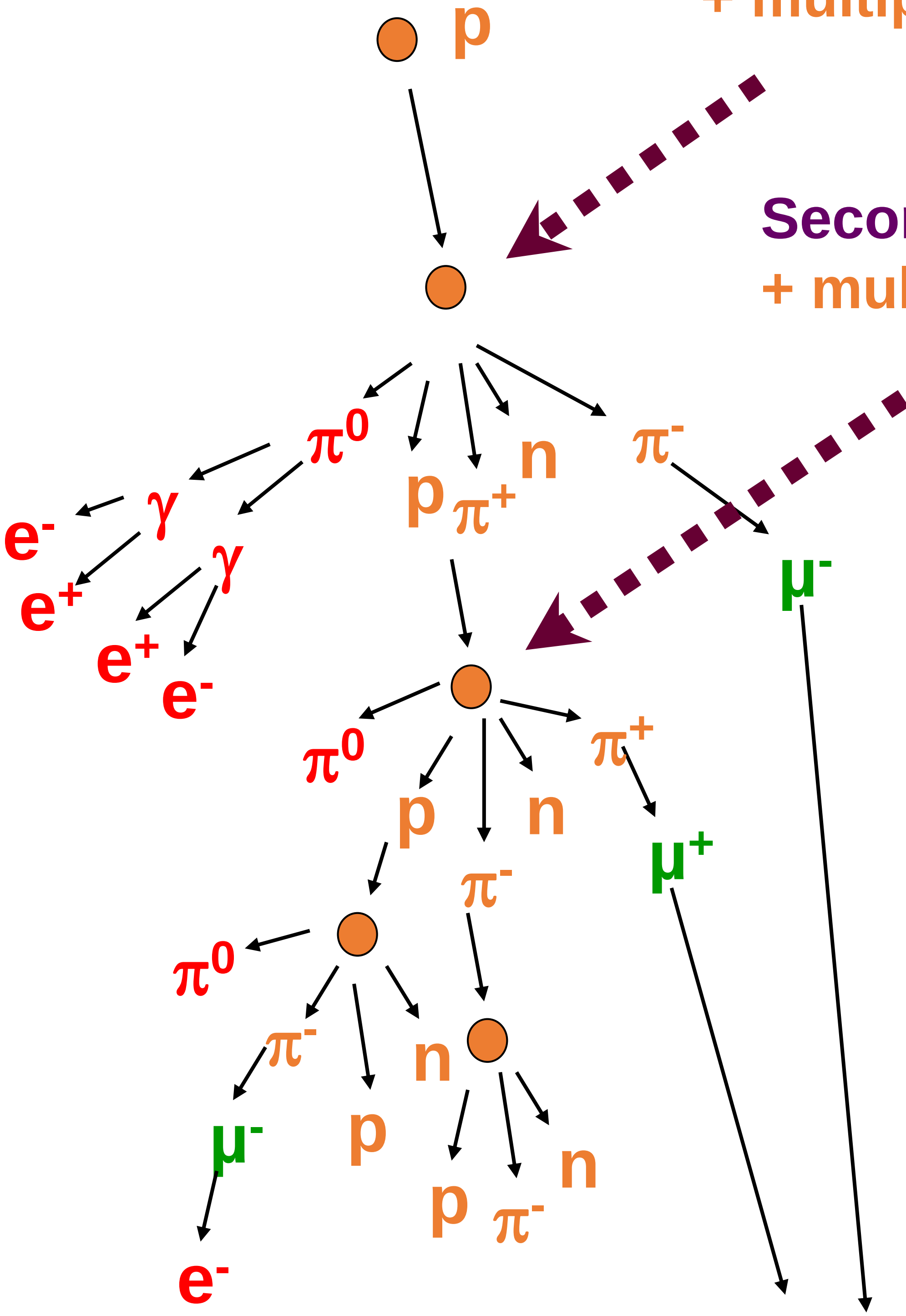
Ultra-High Energy Cosmic Rays



European Strategy Update

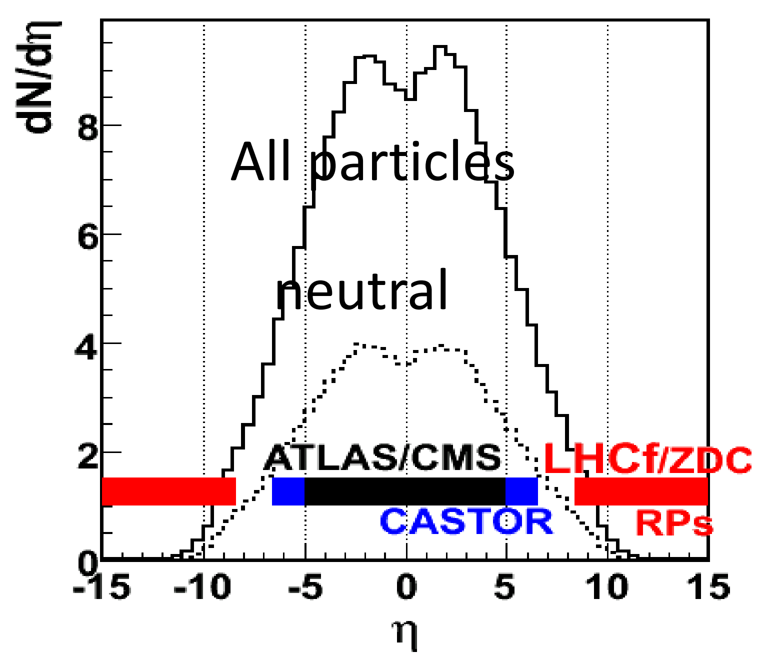
UHECR: >10^{15} eV ; Air-Shower Measurements

First, high energy interaction: LHC
+ multiparameter measurements EAS

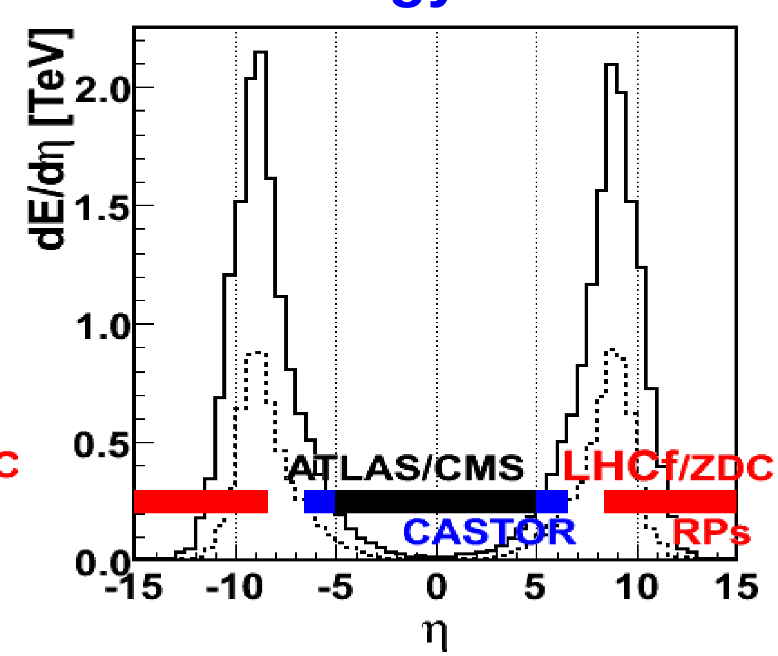


Secondary interactions: Fix target experiments
+ multiparameter measurements EAS

particle flow



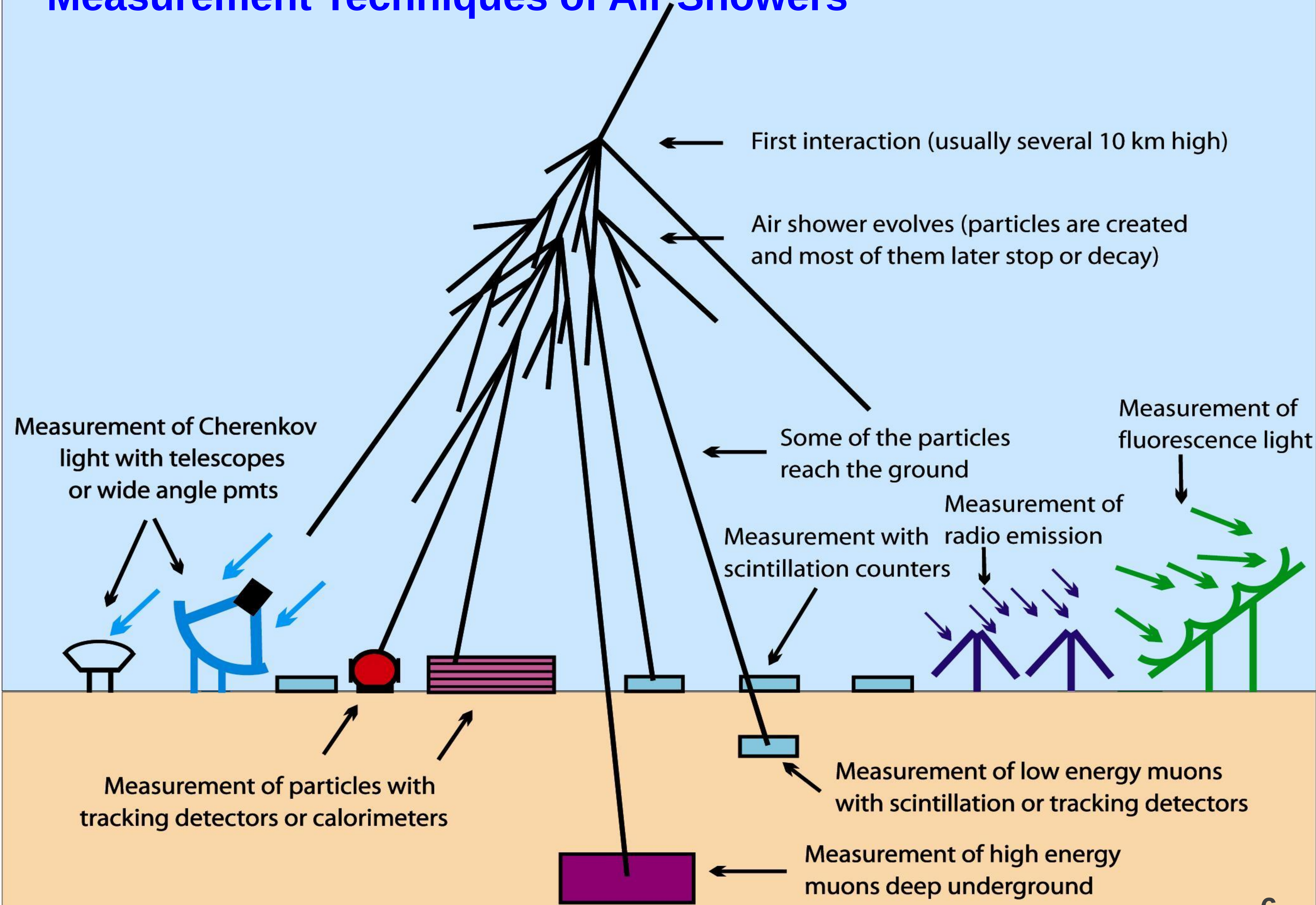
energy flow



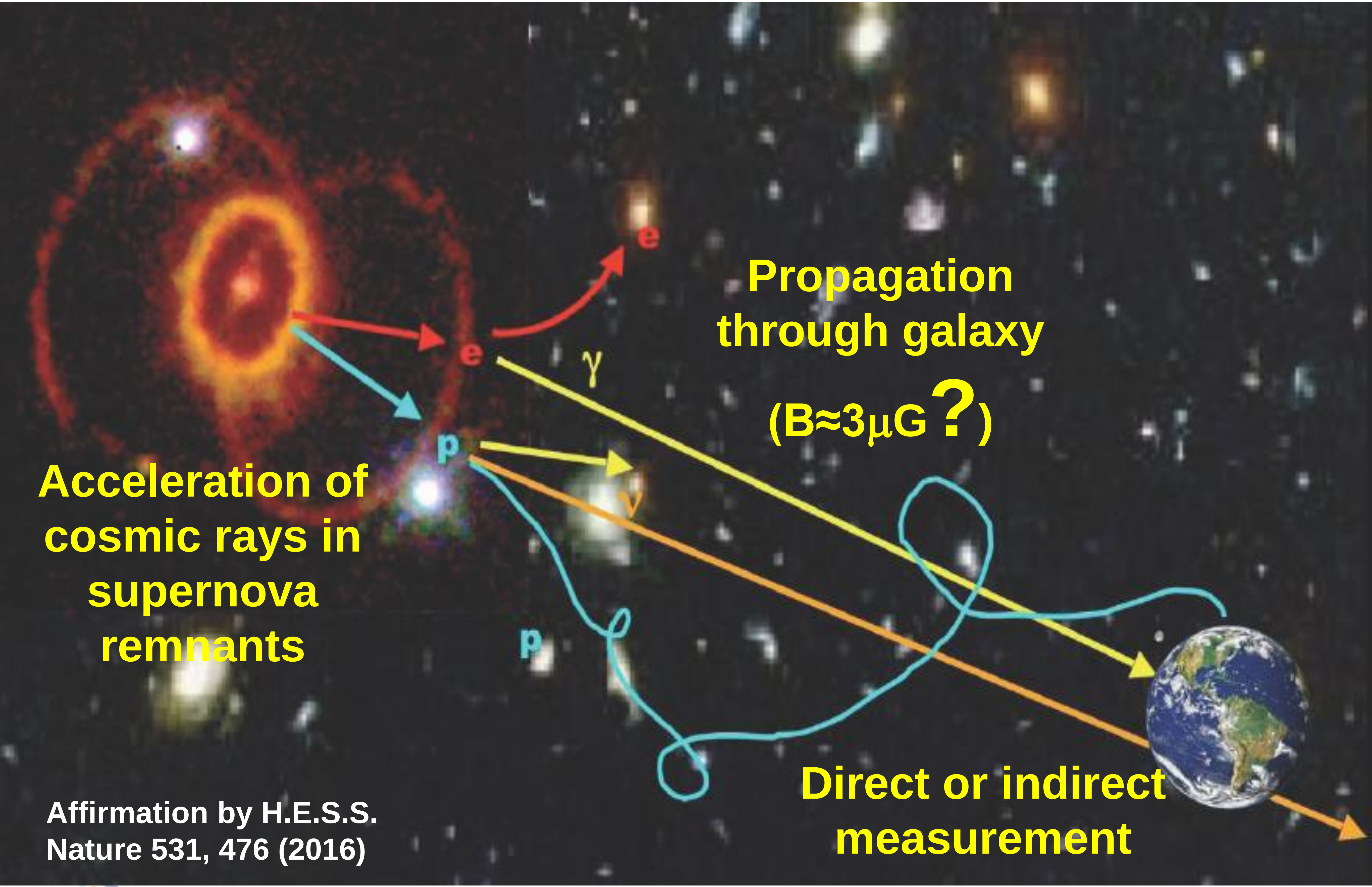
EAS measurement and reconstruction:

- energy ?
- mass ?
- arrival directions ?
- interaction mechanism ?

Measurement Techniques of Air Showers



Galactic Cosmic Rays: standard picture (charge dependent knees)

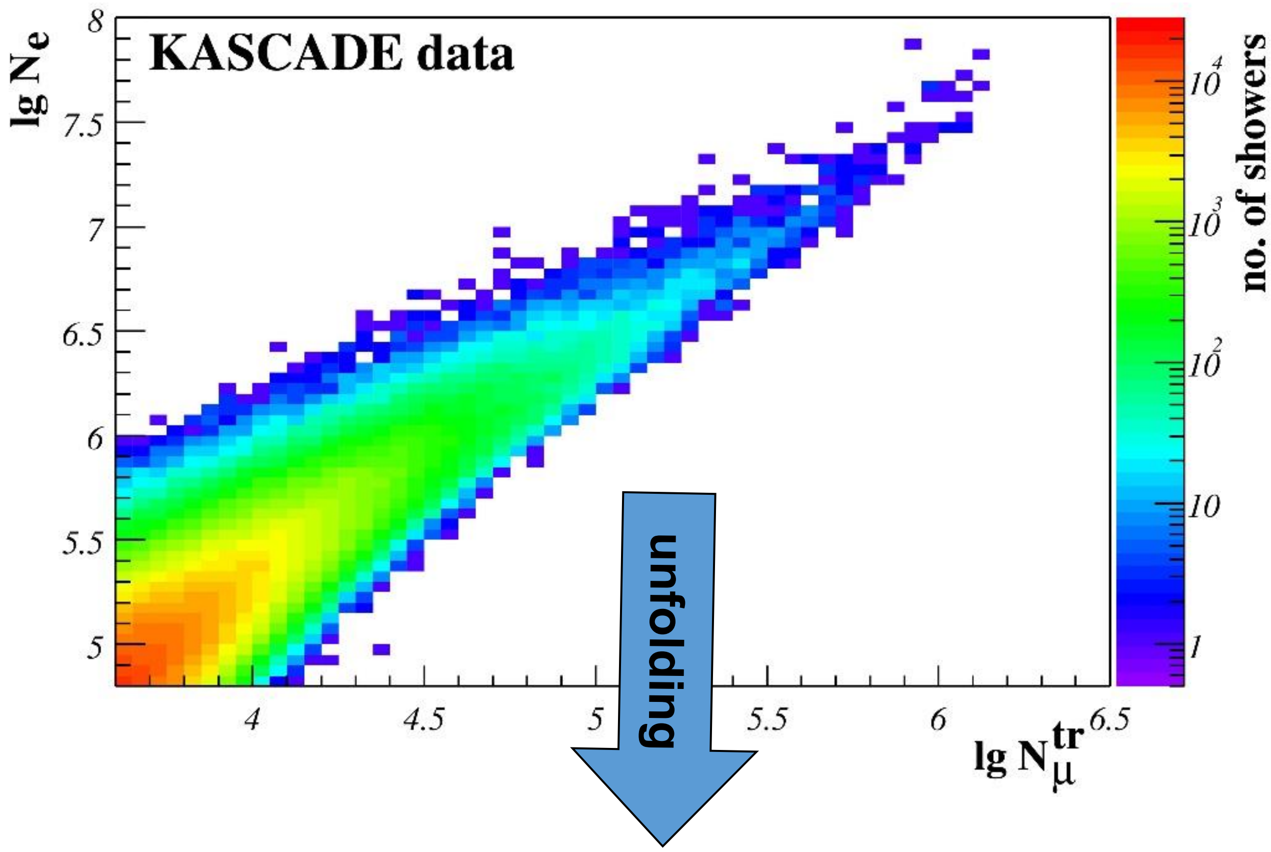


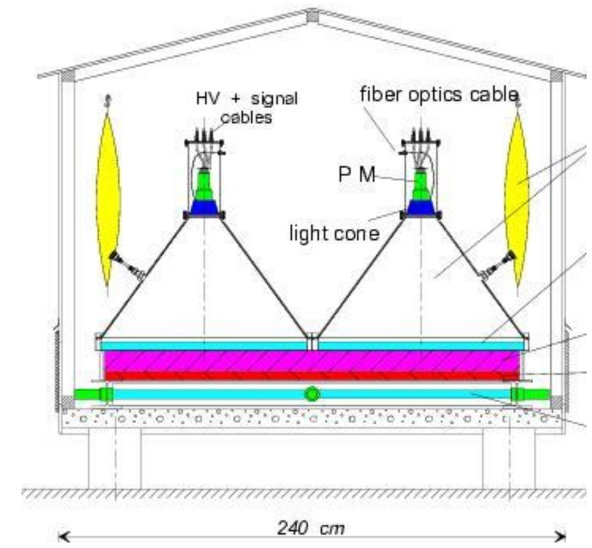
KASCADE-Grande

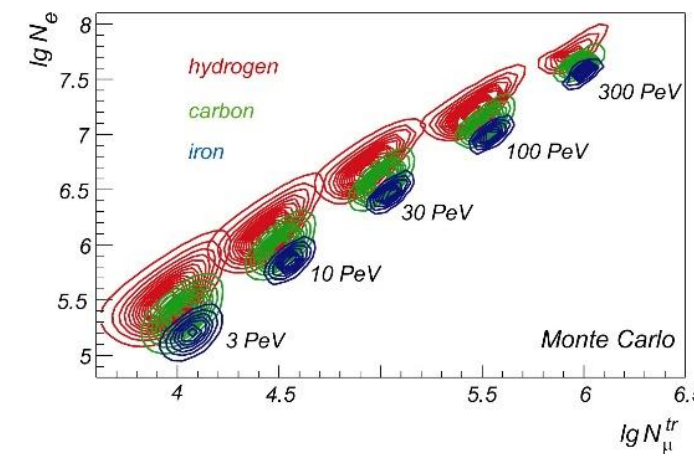
KASCADE
KCDC
Cosmic ray Data Centre

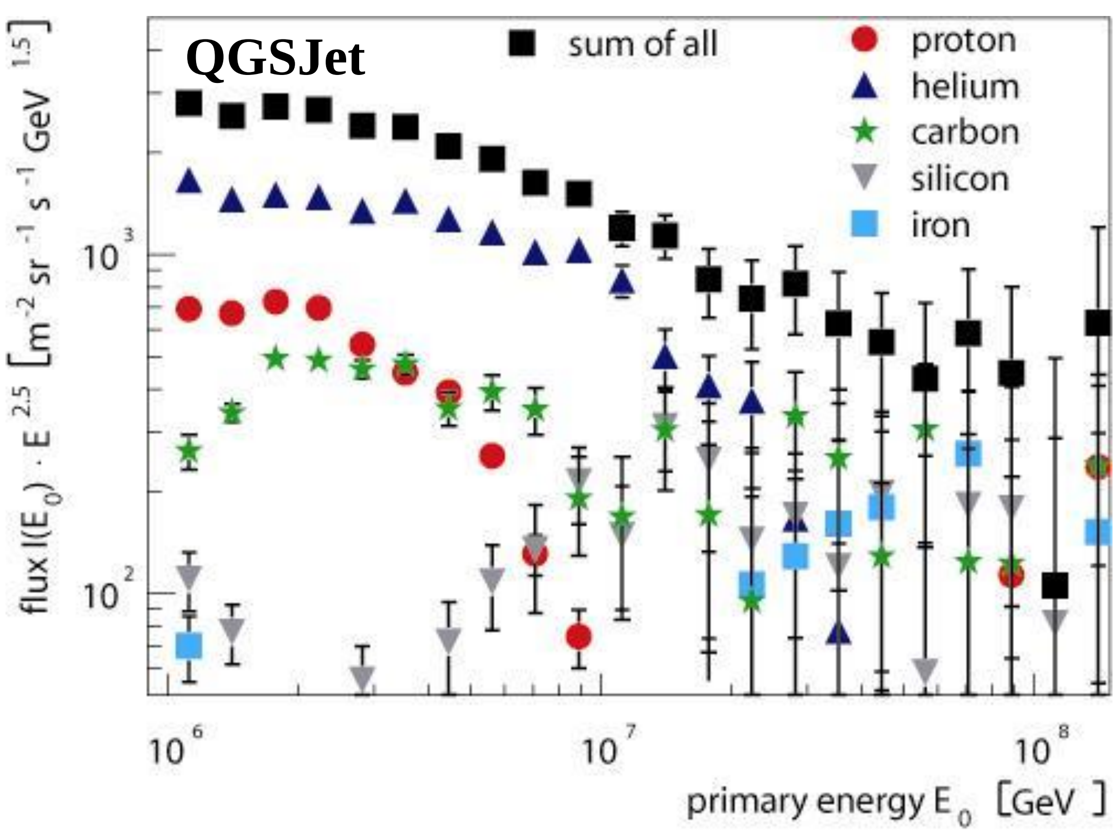
https://kcdc.ikp.kit.edu

KASCADE: energy spectra of single mass groups









Searched:

E and A of the Cosmic Ray Particles

Given:

N_e and N_μ for each single event

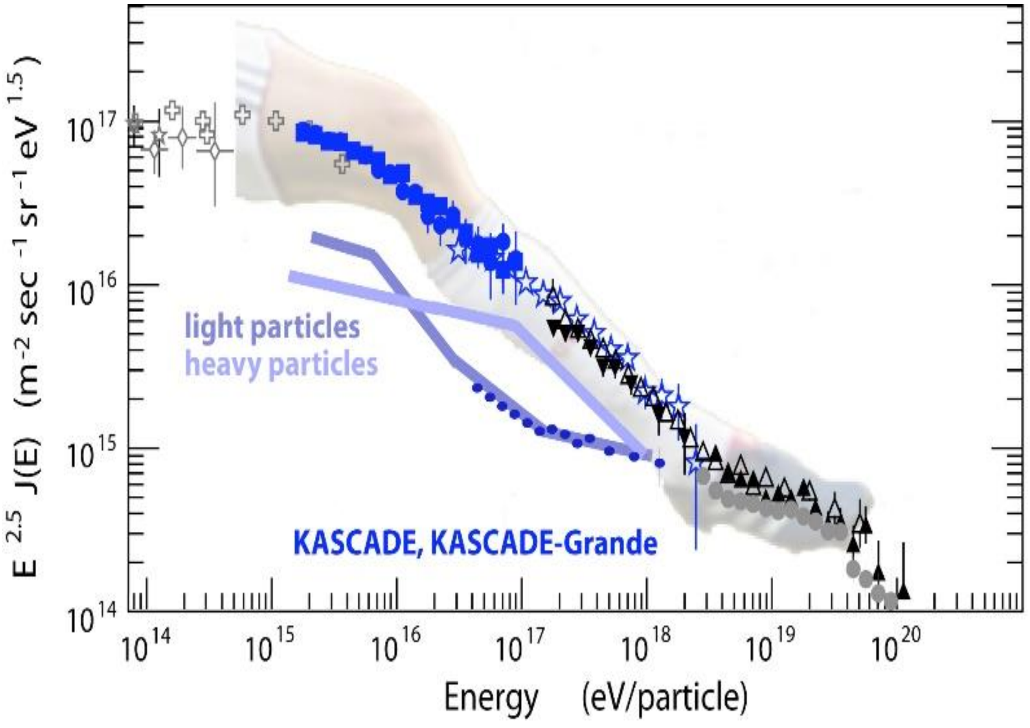
➔ solve the inverse problem

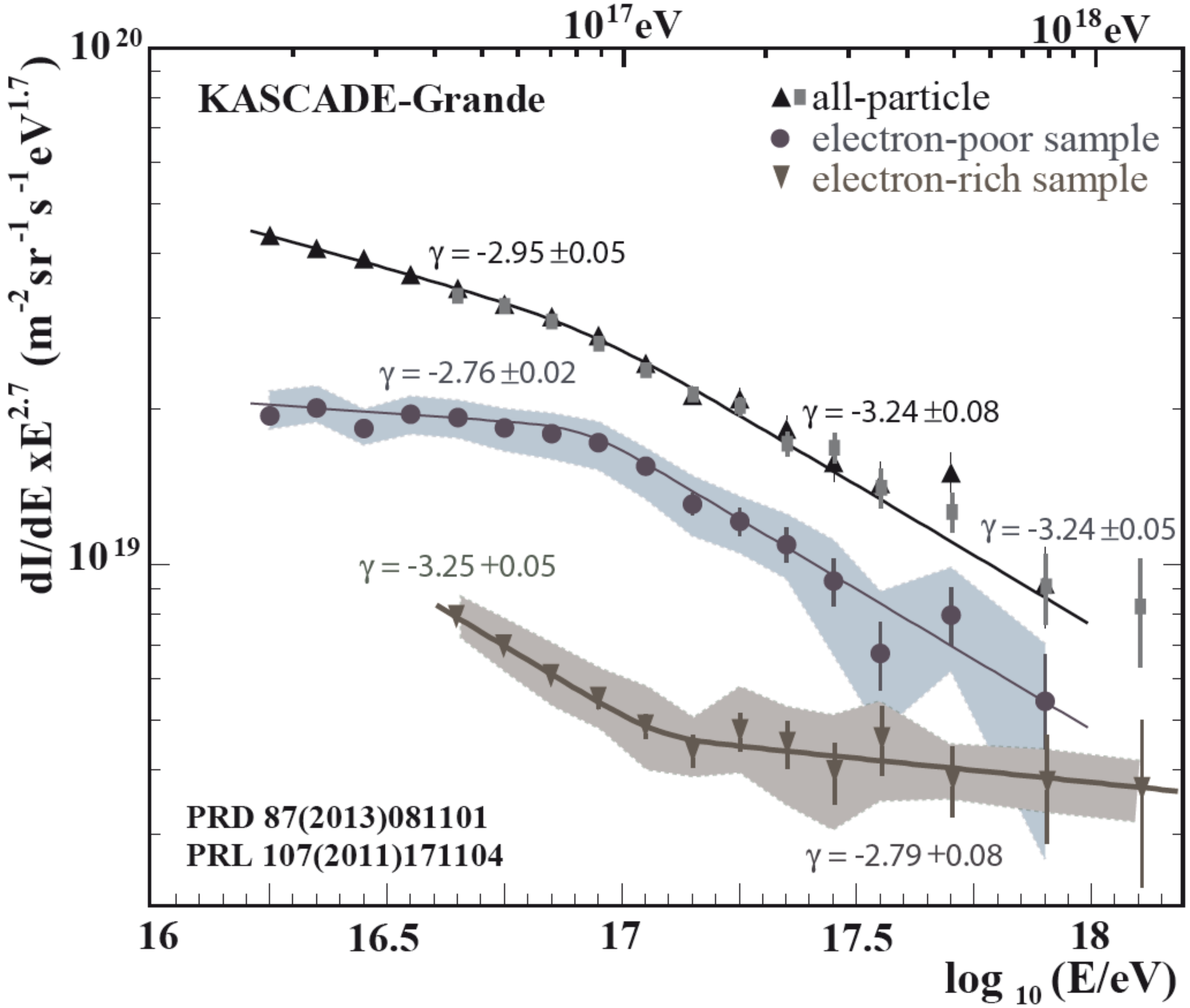
$$\frac{dJ}{d\lg N_e \, d\lg N_\mu^{tr}} = \sum_A \int_{-\infty}^{+\infty} \frac{dJ_A}{d\lg E} \, p_A(\lg N_e, \lg N_\mu^{tr} \mid \lg E) \, d\lg E$$

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

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

KASCADE-Grande: transition to extragalactic origin



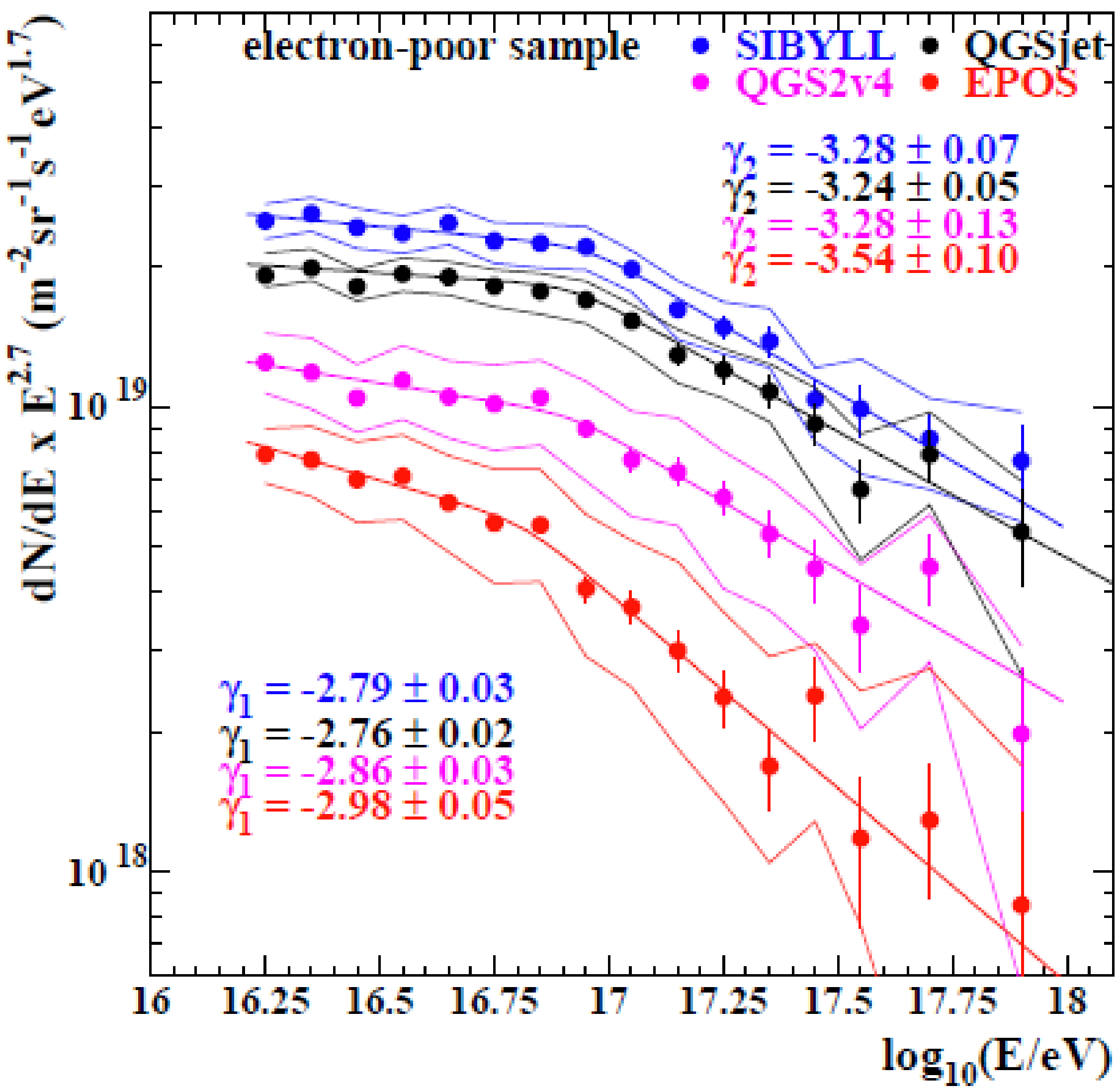


- **steepening (knee) due to heavy primaries (3.5σ) ➔ charge dependent knees**
- **hardening (ankle) in light spectrum (5.8σ) ➔ onset of extragalactic CR?**

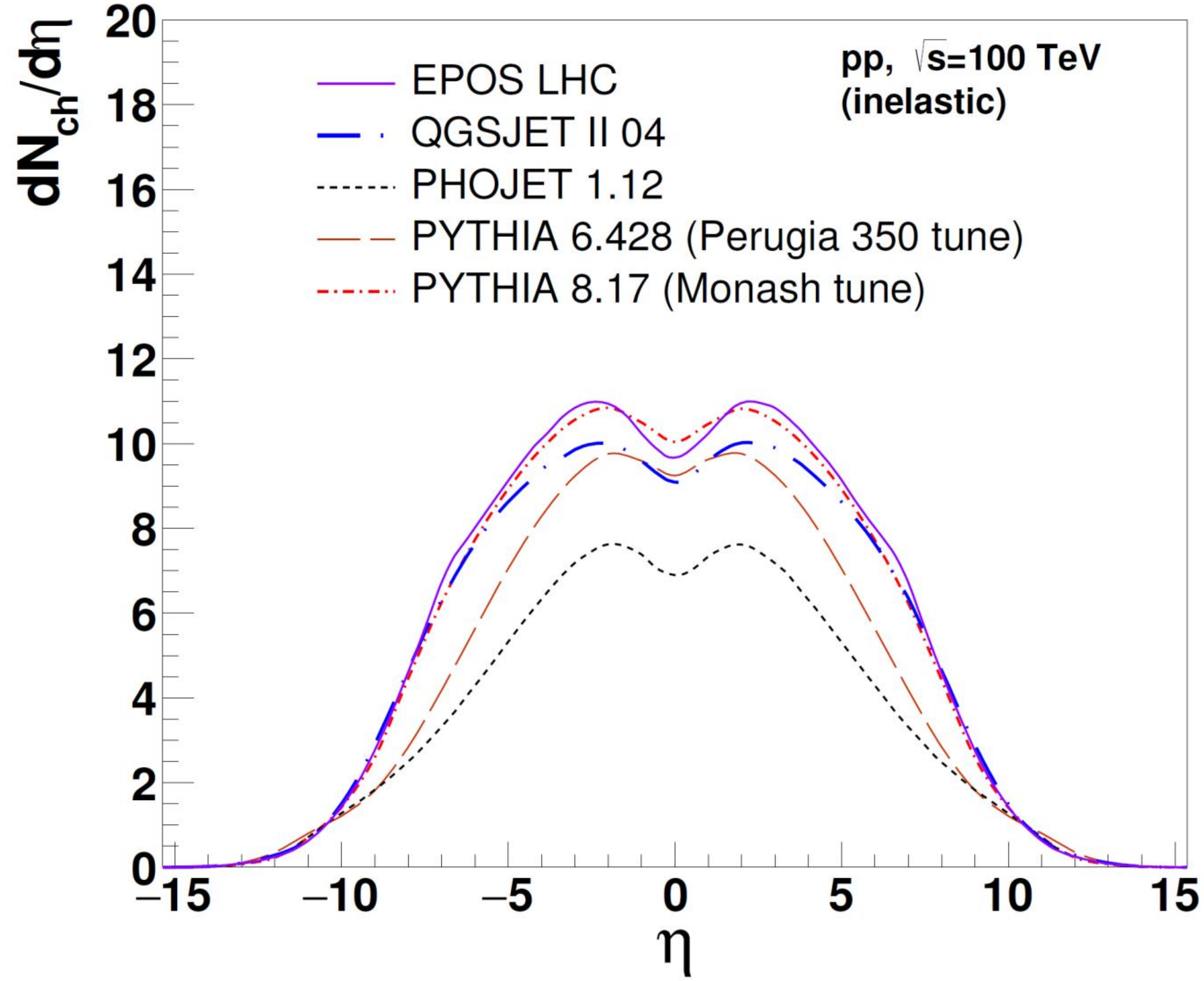
Phys.Rev.Lett. 107 (2011) 171104
Phys.Rev.D (R) 87 (2013) 081101

Dependence on Hadronic Interaction Models

KASCADE-Grande



Protons: E_{lab} = 8 x 10^{18} eV



- **Spectra of heavy primary induced events based on different interaction models**
- **relative abundances different for different high-energy hadronic interaction models**

- **Simulated pseudorapidity distributions for pp interactions**
- **Significant differences in models**

Advances in Space Research 53 (2014) 1456

D‘Enterria, Pierog, JHEP 08 (2016) 170

European Strategy Update

Main Experiments 10^{16}-10^{18}eV

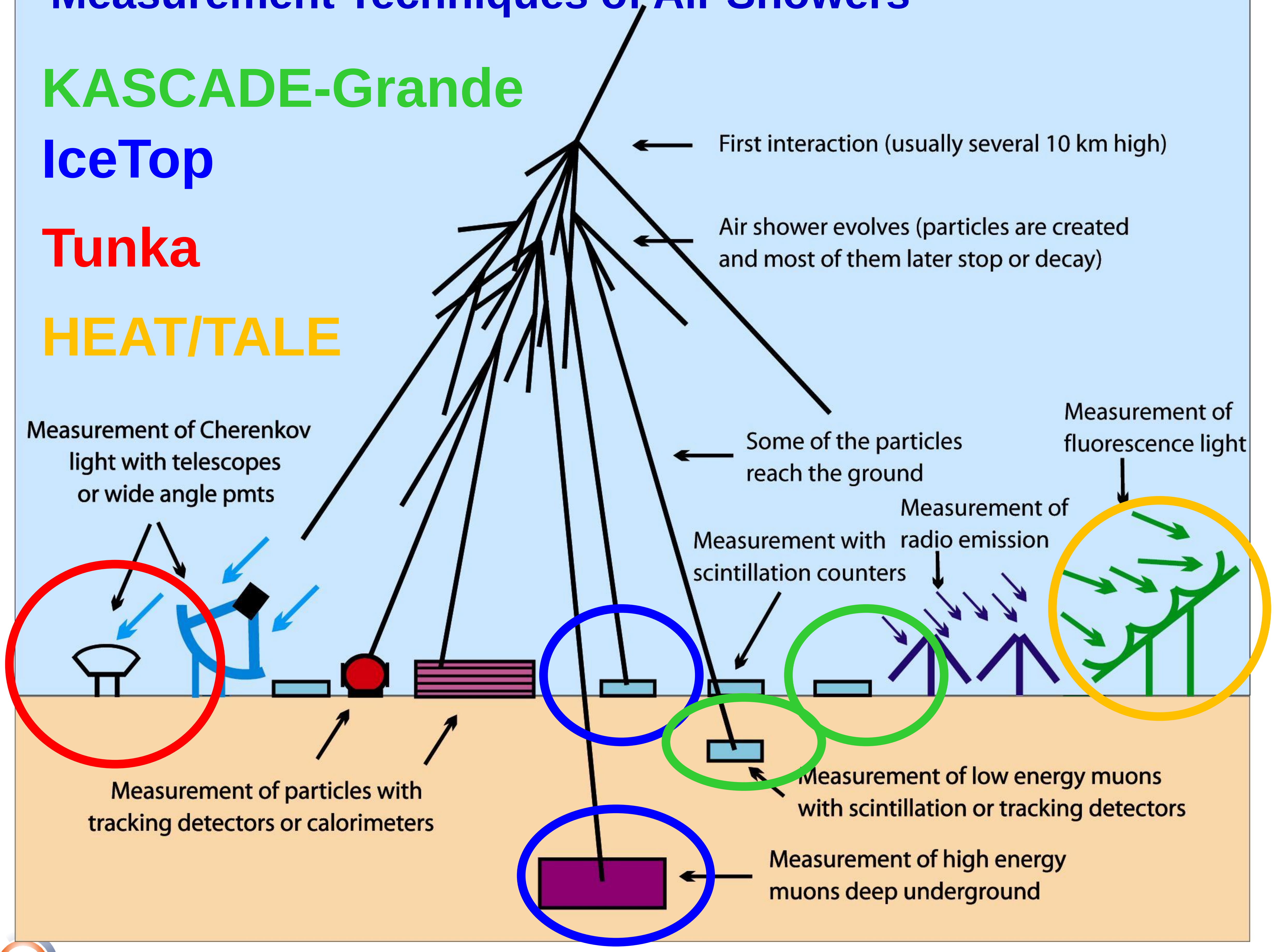
Measurement Techniques of Air Showers

KASCADE-Grande

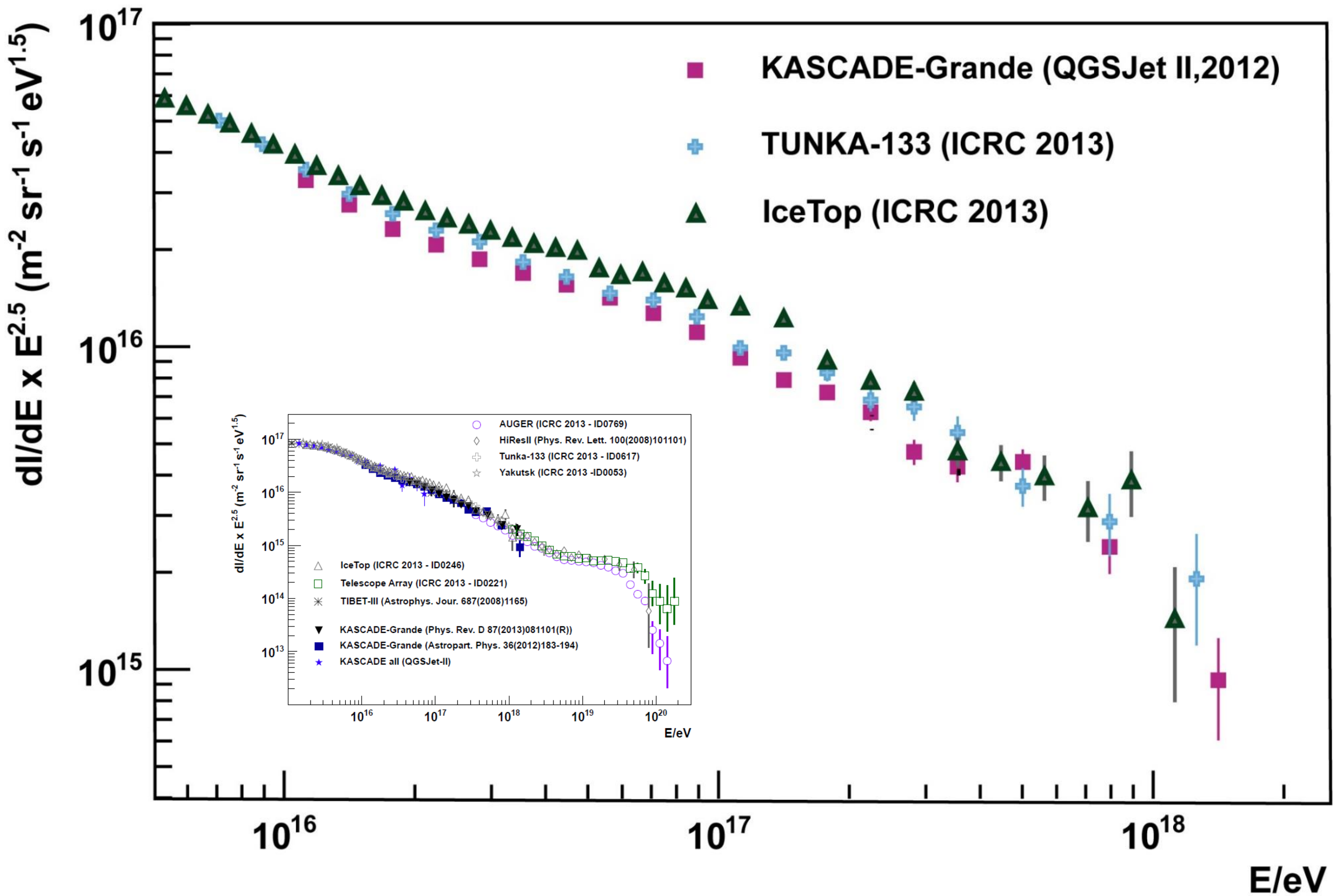
IceTop

Tunka

HEAT/TALE



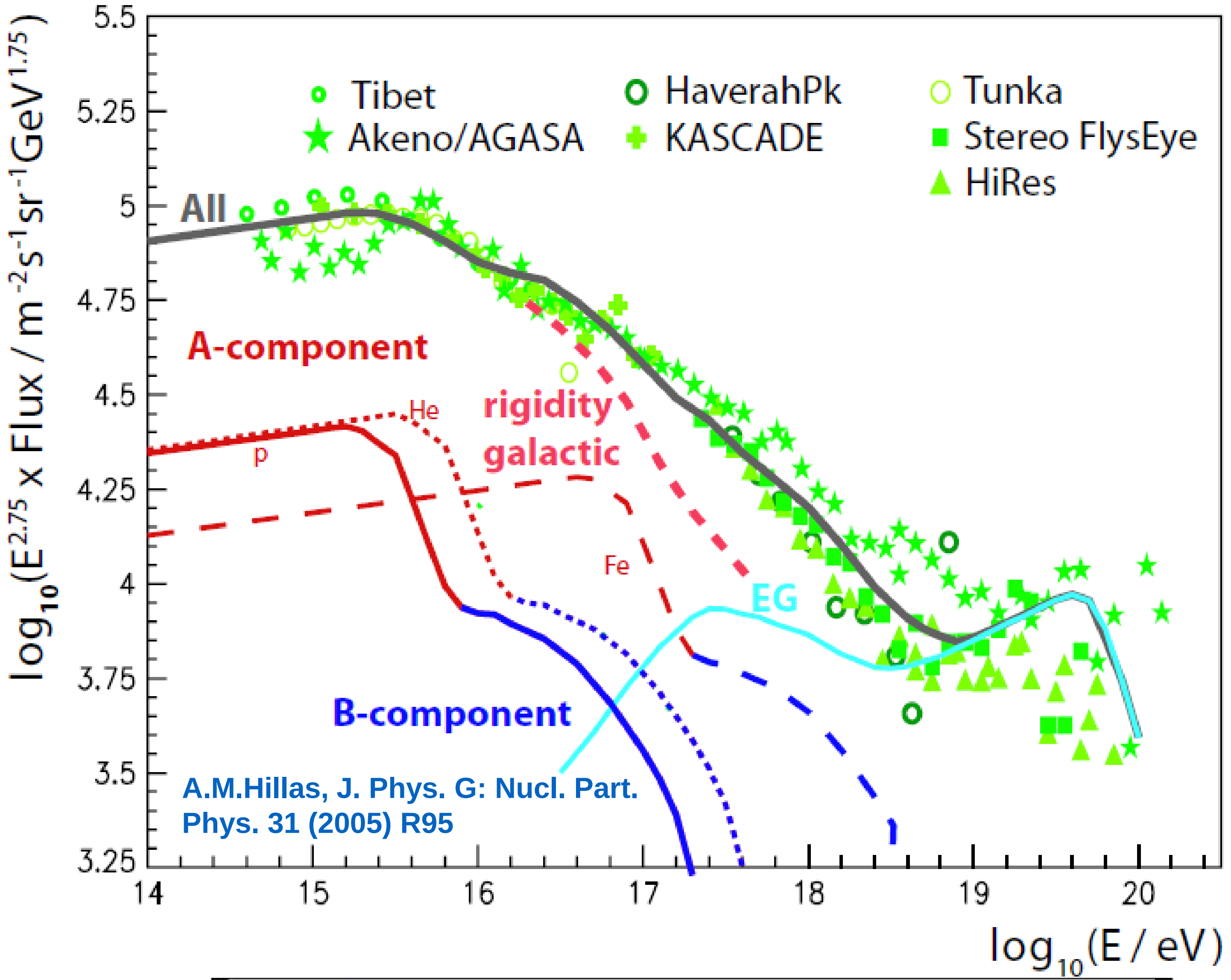
Cosmic Rays

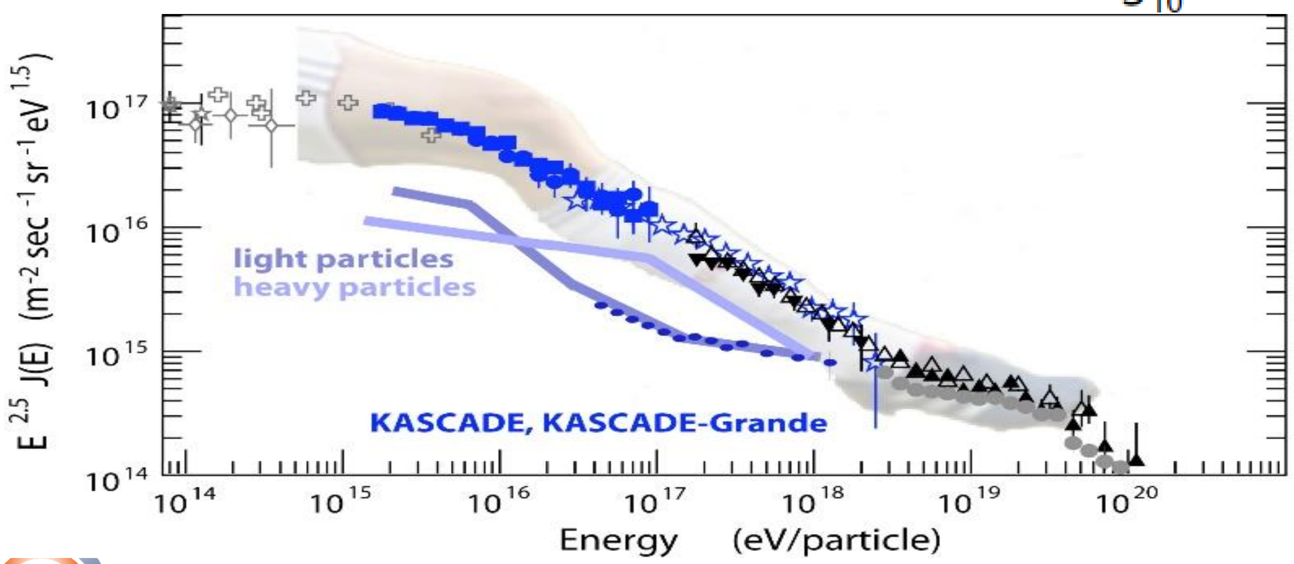


- Structures of all-particle spectra similar (in the level of 15%)
- composition results are still uncertain

European Strategy Update

Light and Heavy Knees, Ankles, and Transition





Most probable rigidity dependent knees (A component)

(galactic) B-component needed to explain all-particle spectrum

Highest energy extragalactic (Auger)

(mass dependent) Anisotropies in arrival direction?

➔ One has to understand the transition region to understand the UHECR

Strategy:

Multi-component analyses = Combine data of various experiment to

- **Validate \ improve hadronic interaction models**
- **Validate astrophysical models**

European Strategy Update

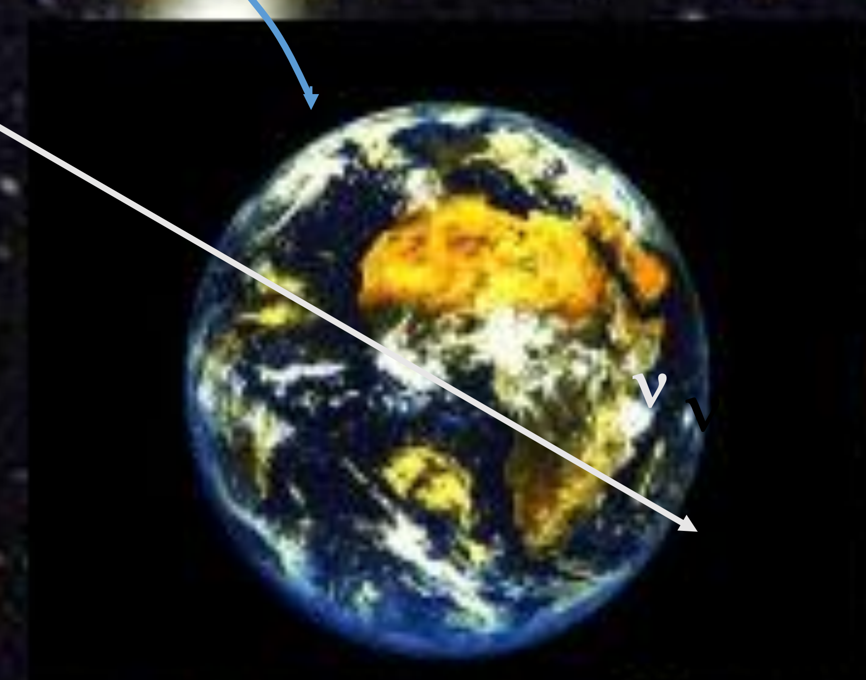
Extragalactic Cosmic Rays

$$p + \gamma_{2.7K} \rightarrow \Delta^{+}(1232)$$
$$\rightarrow p + \pi^{0} \rightarrow p\gamma\gamma$$
$$\rightarrow n + \pi^{+} \rightarrow pe^{+}\nu$$

GZK-Cutoff

$p+\gamma_{CMB}$ -> $p+\pi^{0}$ (>50EeV)

γ3K **(400 cm^{-3})**



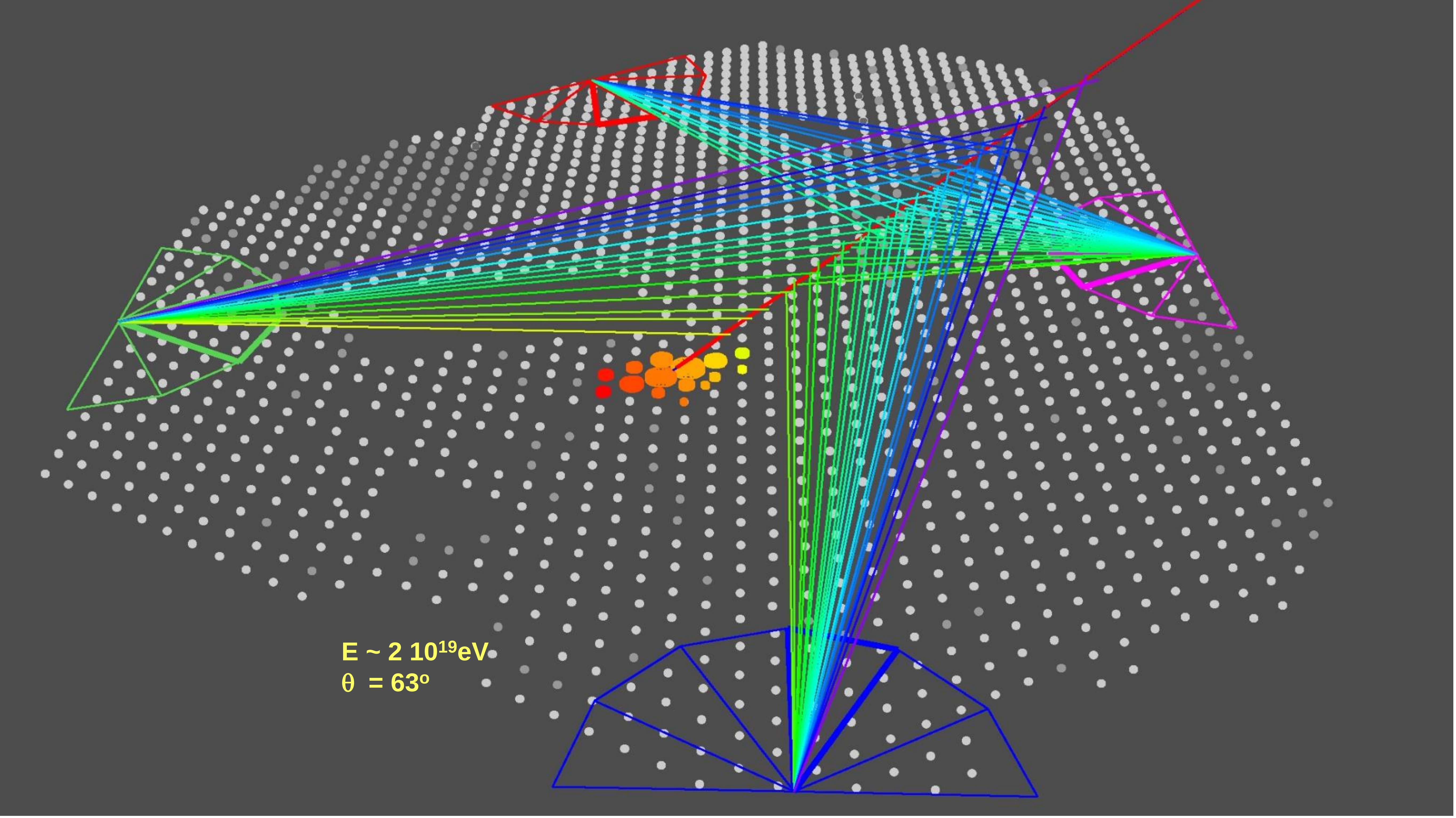
Acceleration mechanism is unknown (strong extragalactic processes which happens very close are necessary)

Pierre Auger Observatory

Photo: Steven Saffi

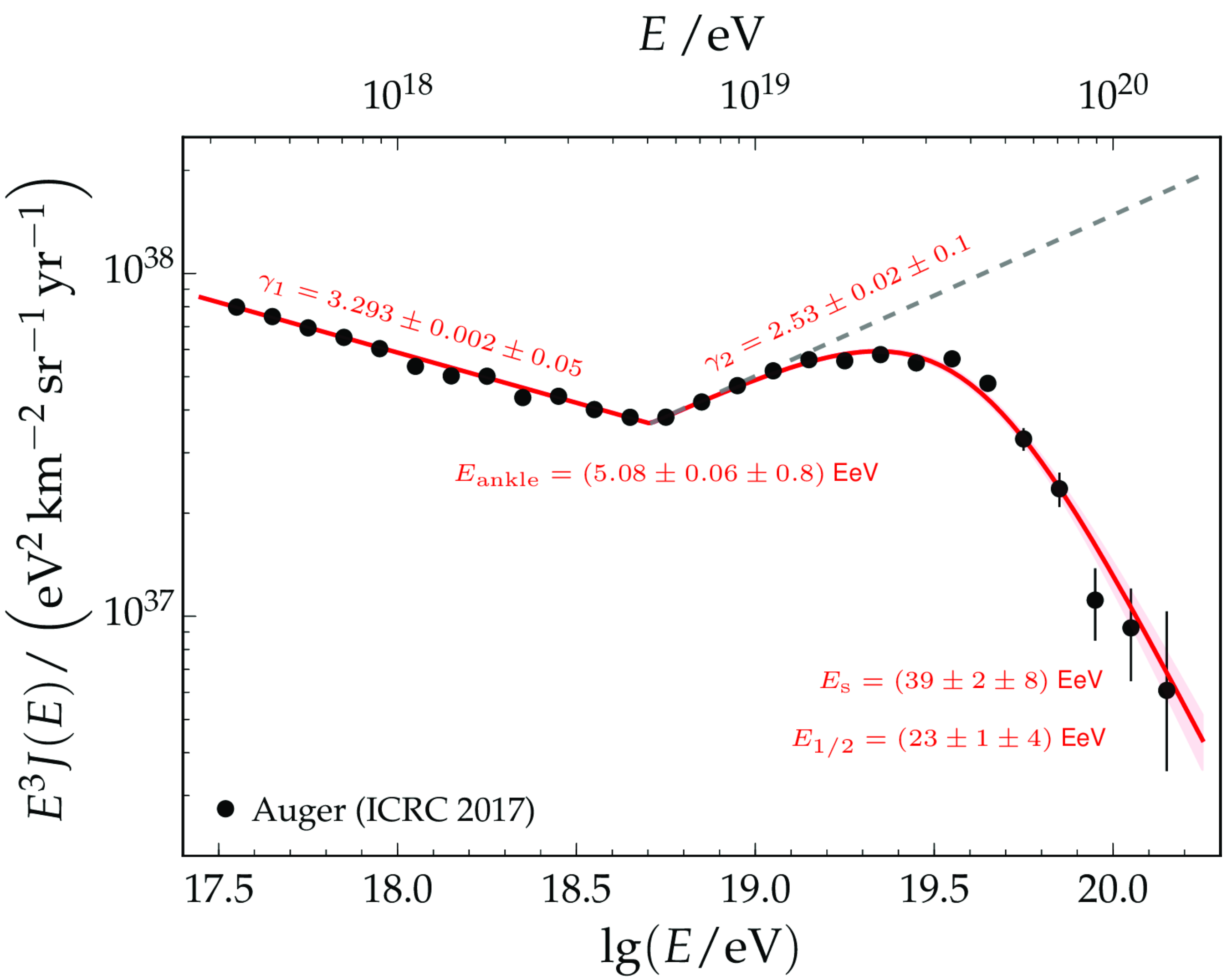
#117: Auger

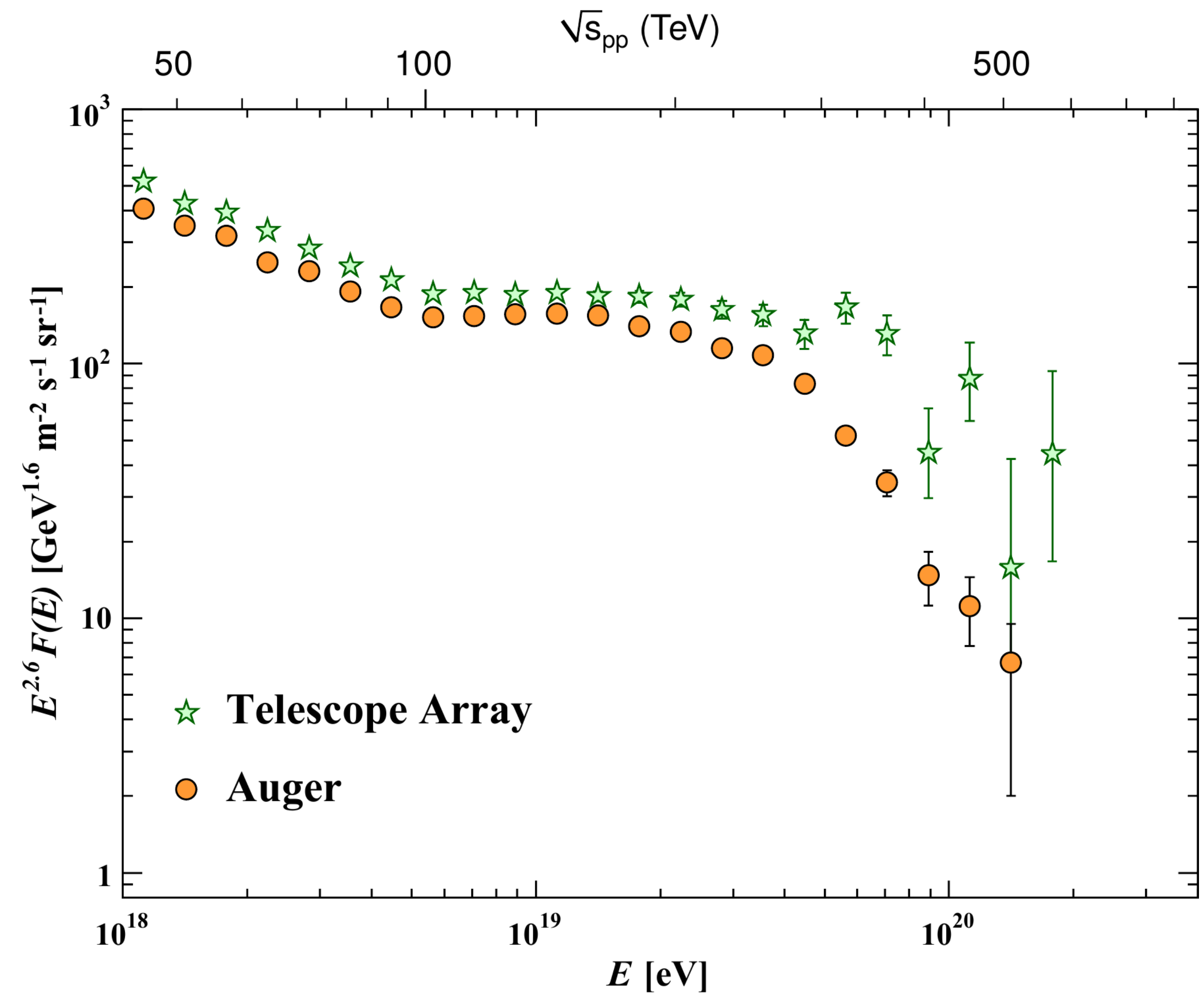
Hybrid Events



Telescope Array

UHECR: Energy Spectrum



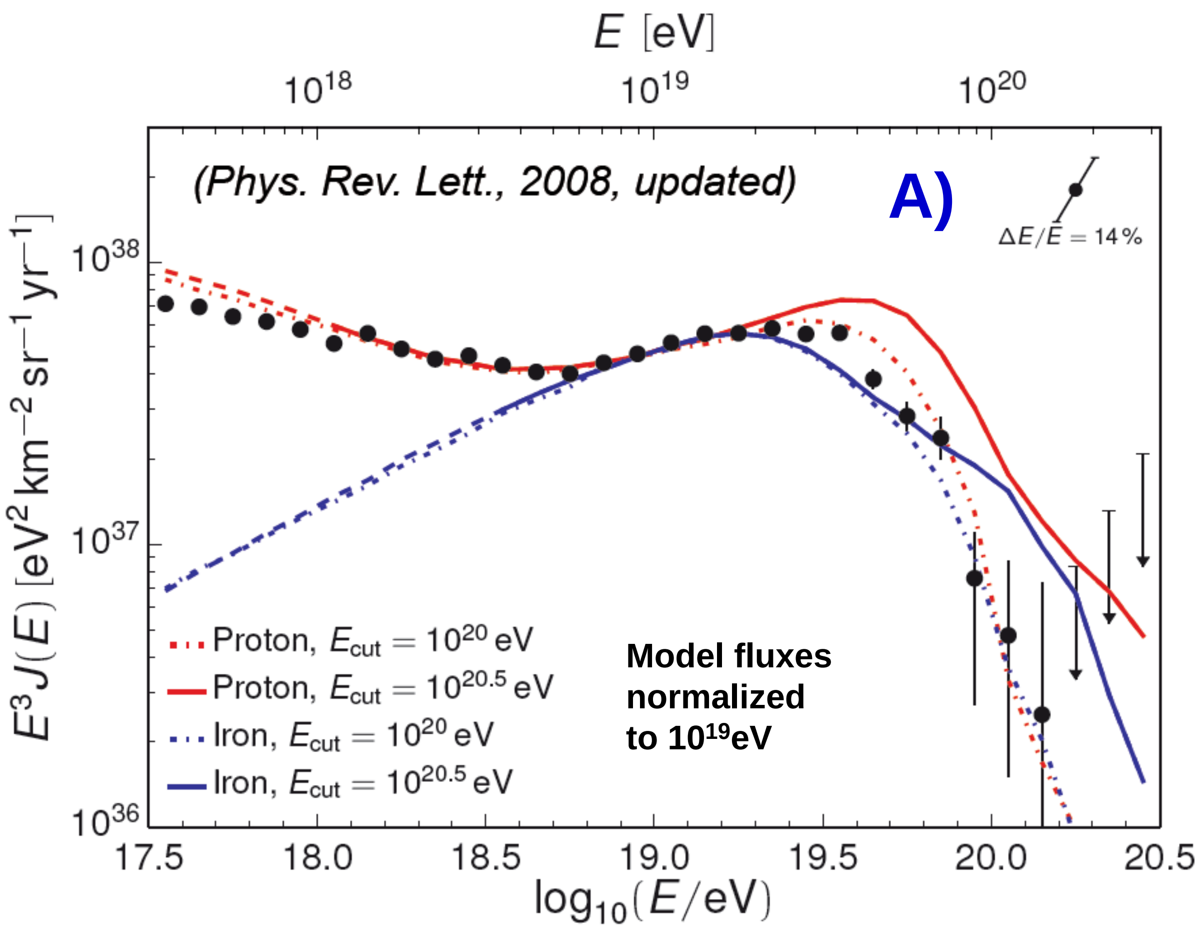


R. Alves Batista et al., MIAPP 2019, 1903.06714

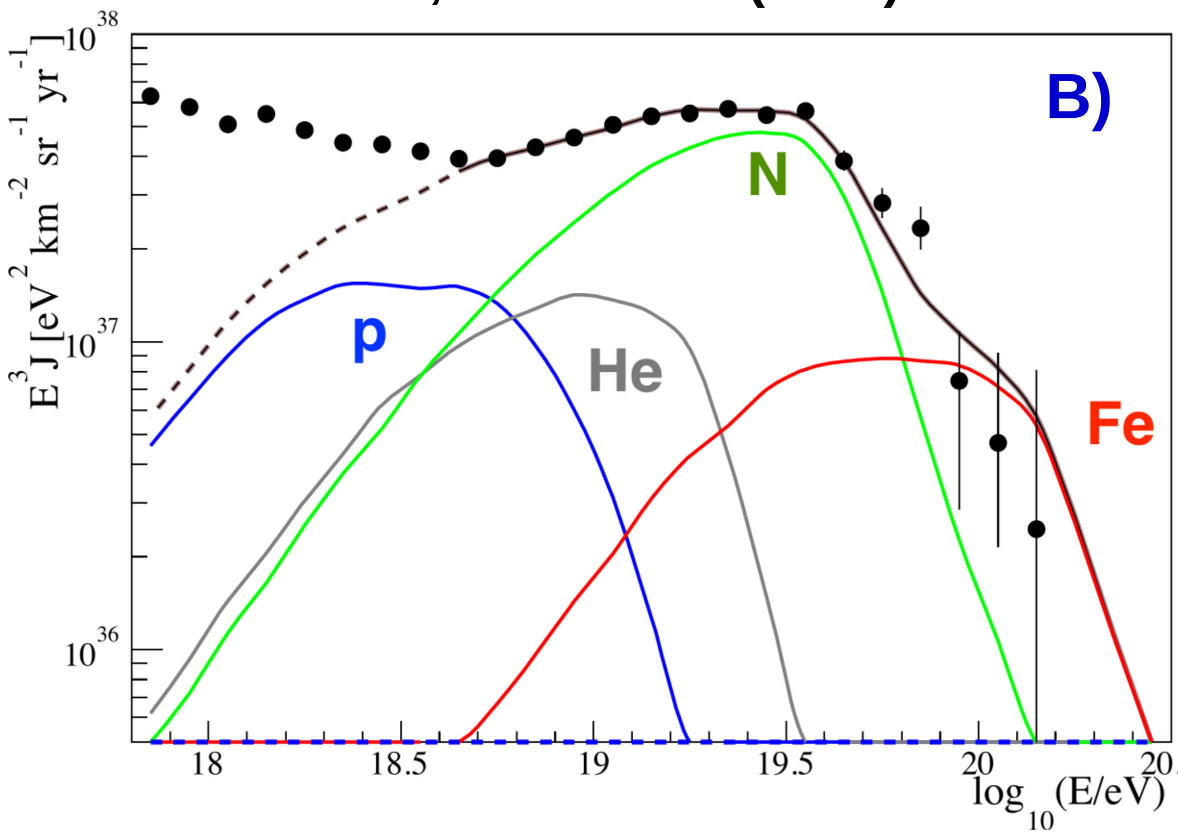
- ankle feature with very high precision
- flux suppression
- very rare events above 10^{20} eV
- at highest energies difference in hemispheres?

European Strategy Update

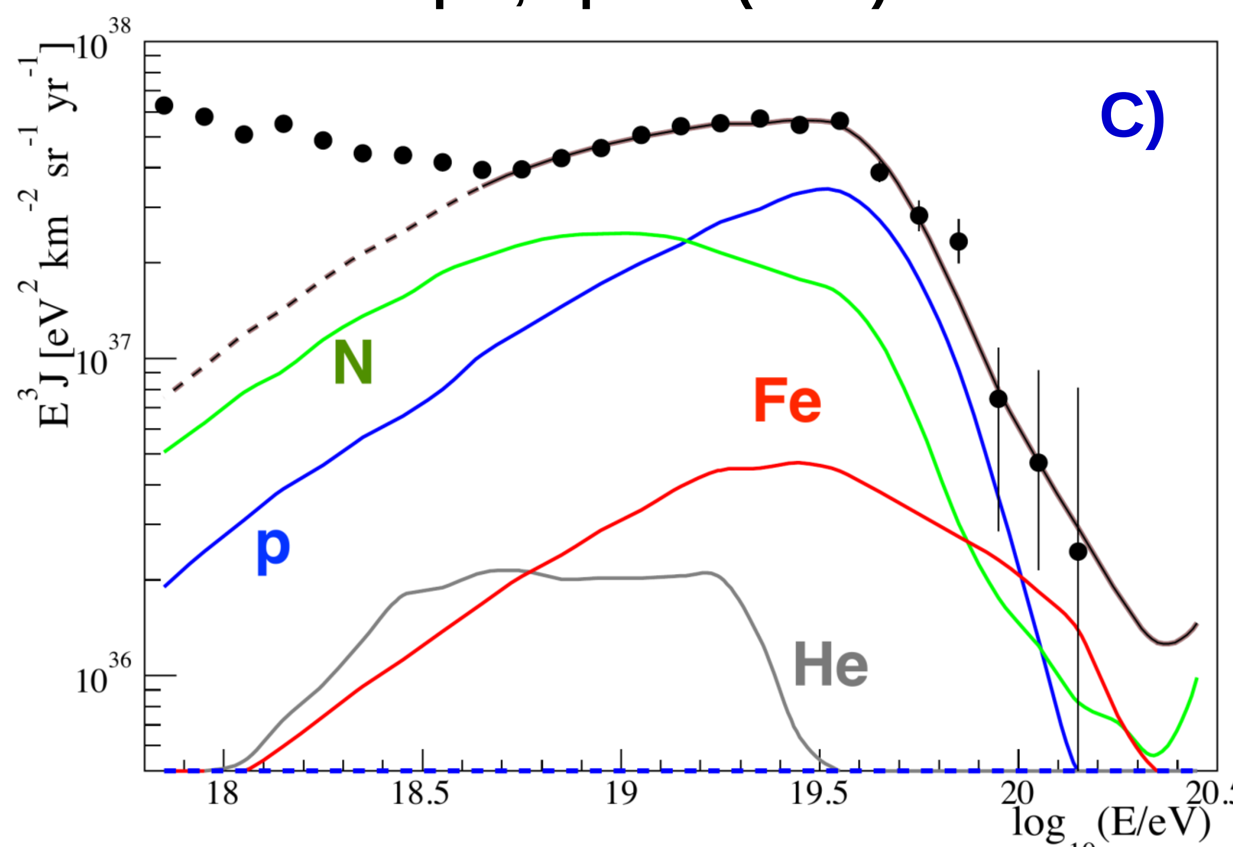
UHECR: Energy Spectrum Interpretation



Allard, JCAP 0810 (2008) 033



Hooper, ApP 33 (2010) 151



A) p-dominated "dip" scenario

B) sources accelerate to maximum rigidity ("tired" sources)

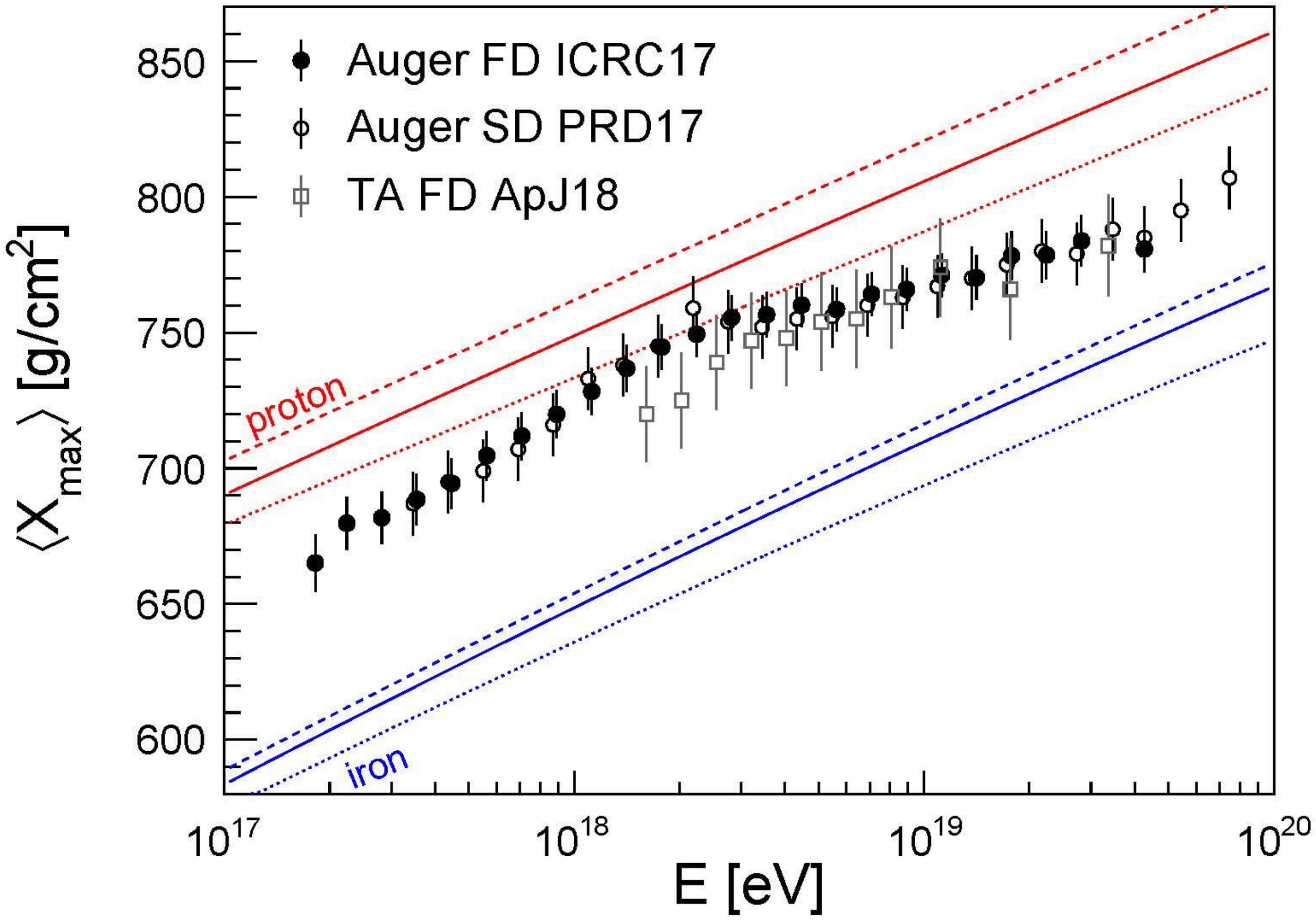
C) (mostly) photo-disintegration, energies shifted down

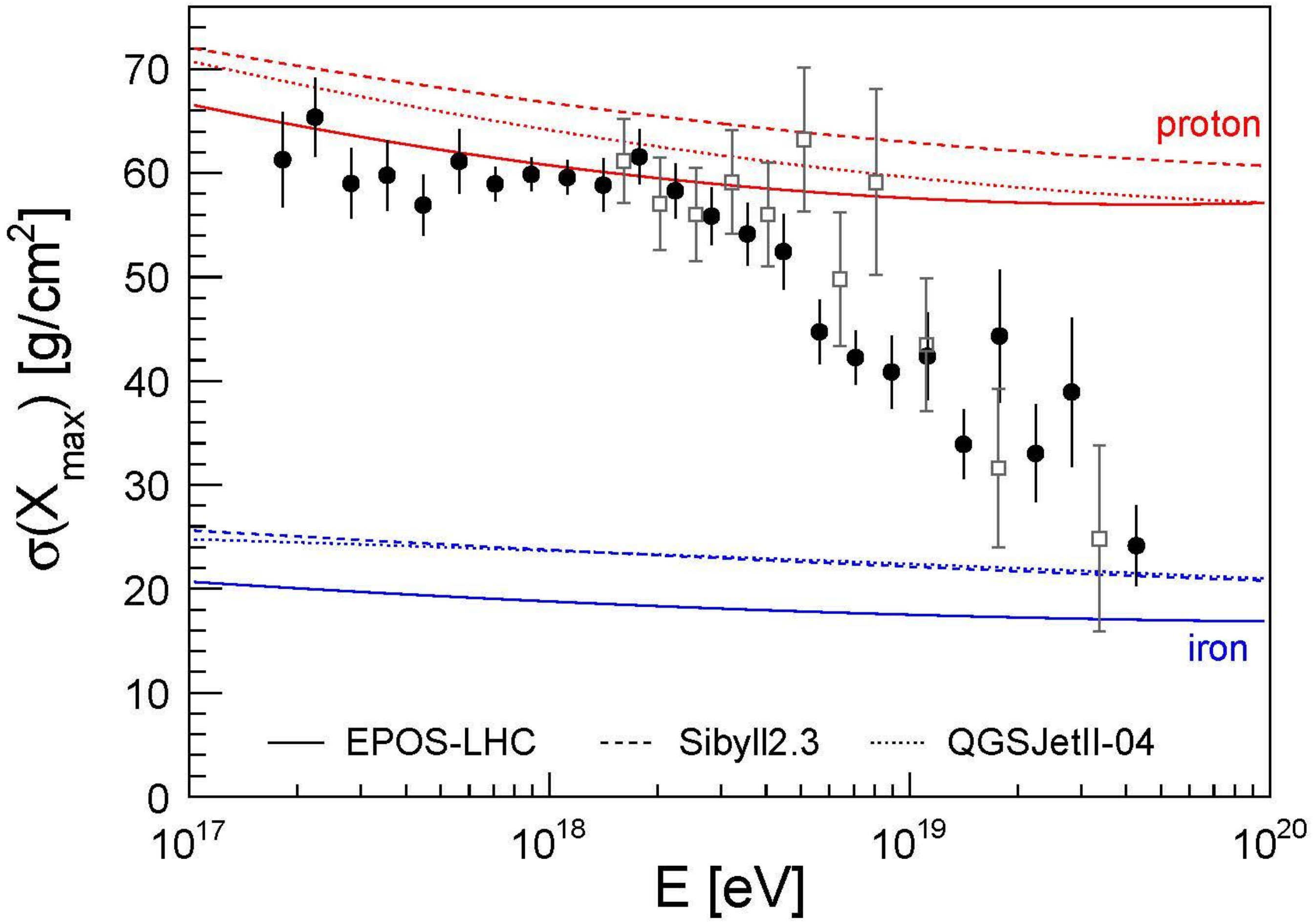
➔ Composition needed!

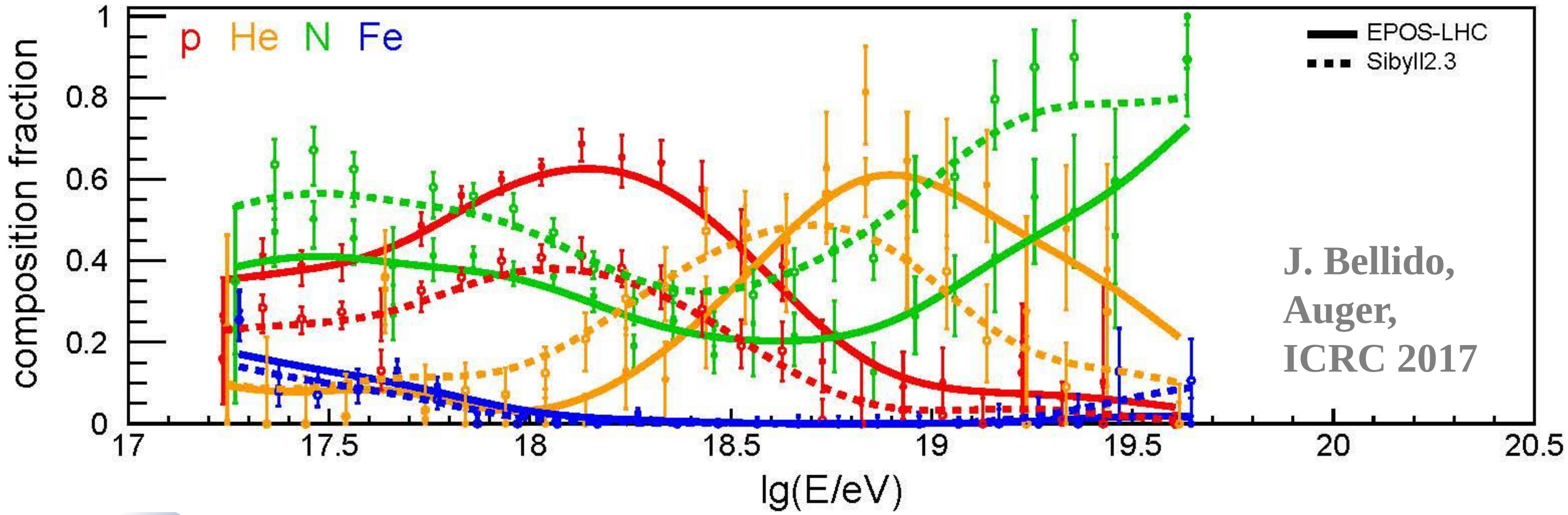
Pierre Auger Collab., JCAP 1704 (2017)

Composition: mean depth and rms of shower maximum

R. Alves Batista et al., MIAPP 2019, 1903.06714



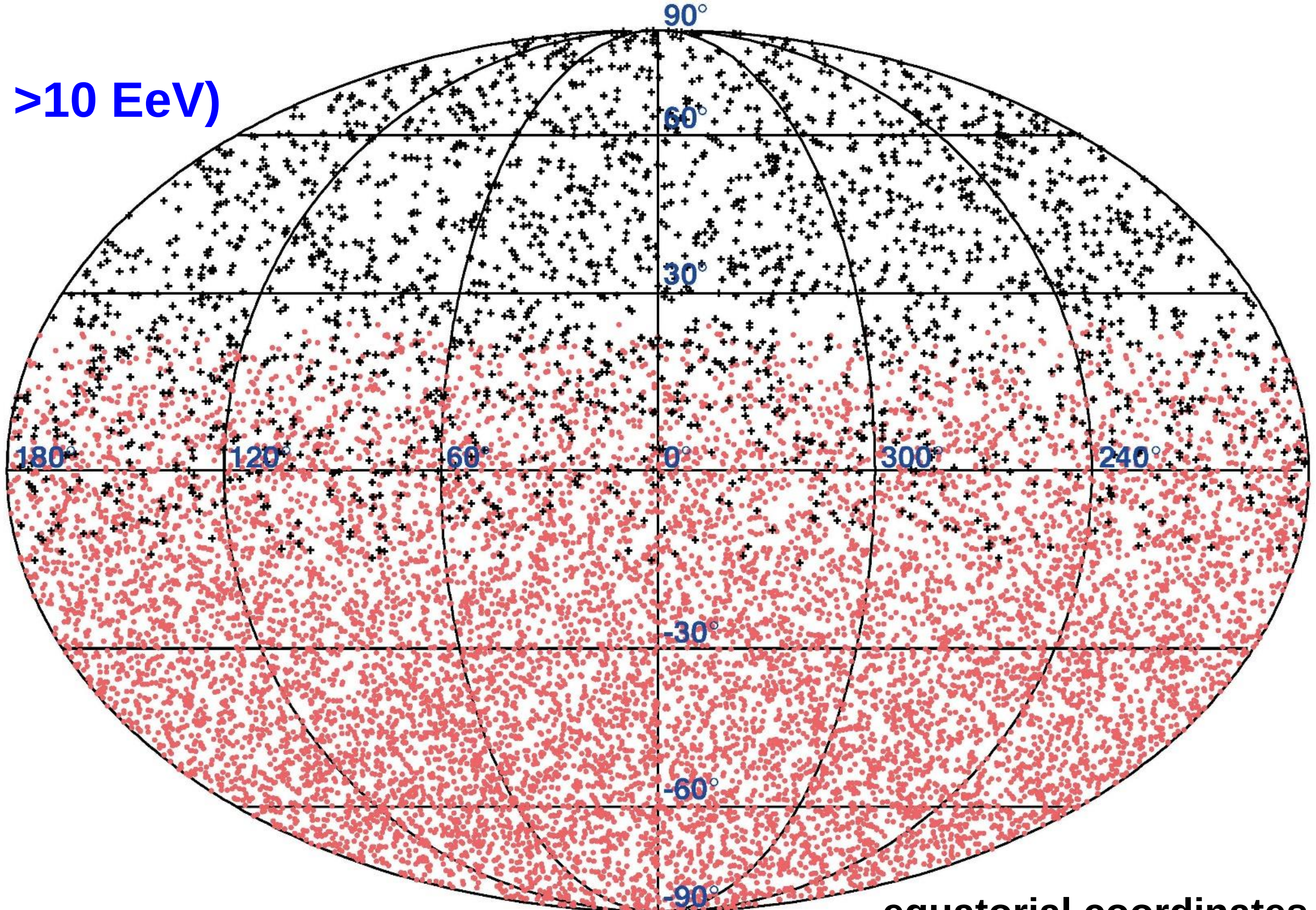




- **Composition is getting heavier with energy**
- **Measurements only applicable up to 50 EeV due to statistics**
- **Absolut composition scale model dependent**

Arrival Distribution: Anisotropies at different scales

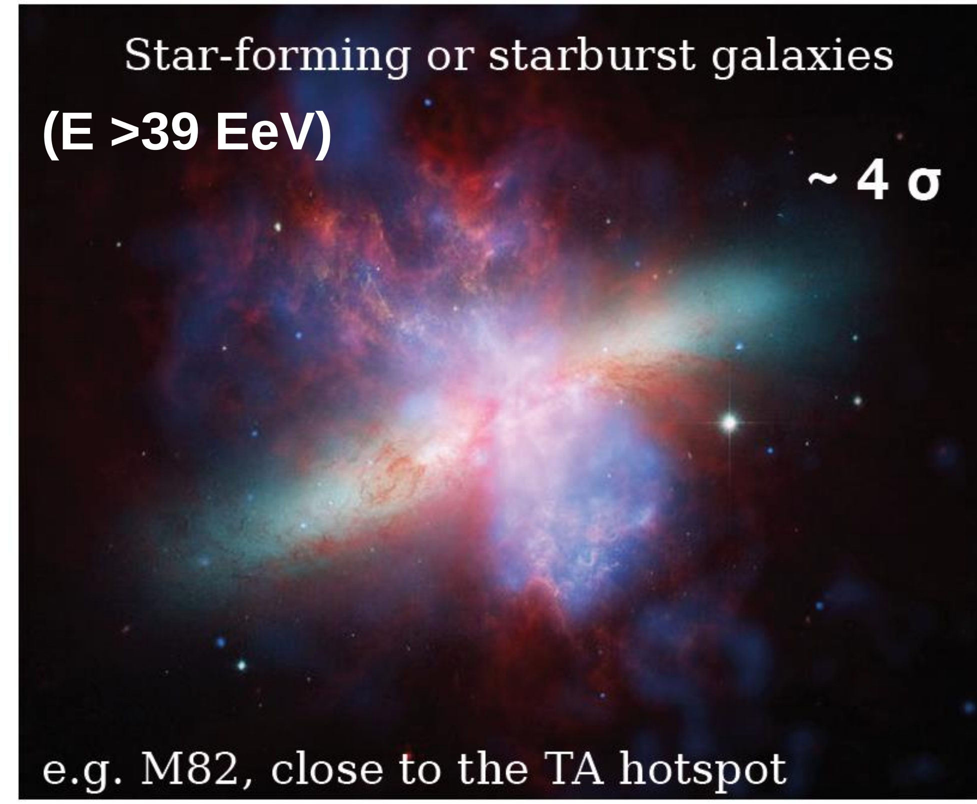
(E >10 EeV)



equatorial coordinates

Pierre Auger and TA Collaborations, ApJ **794** (2014) 2, 172

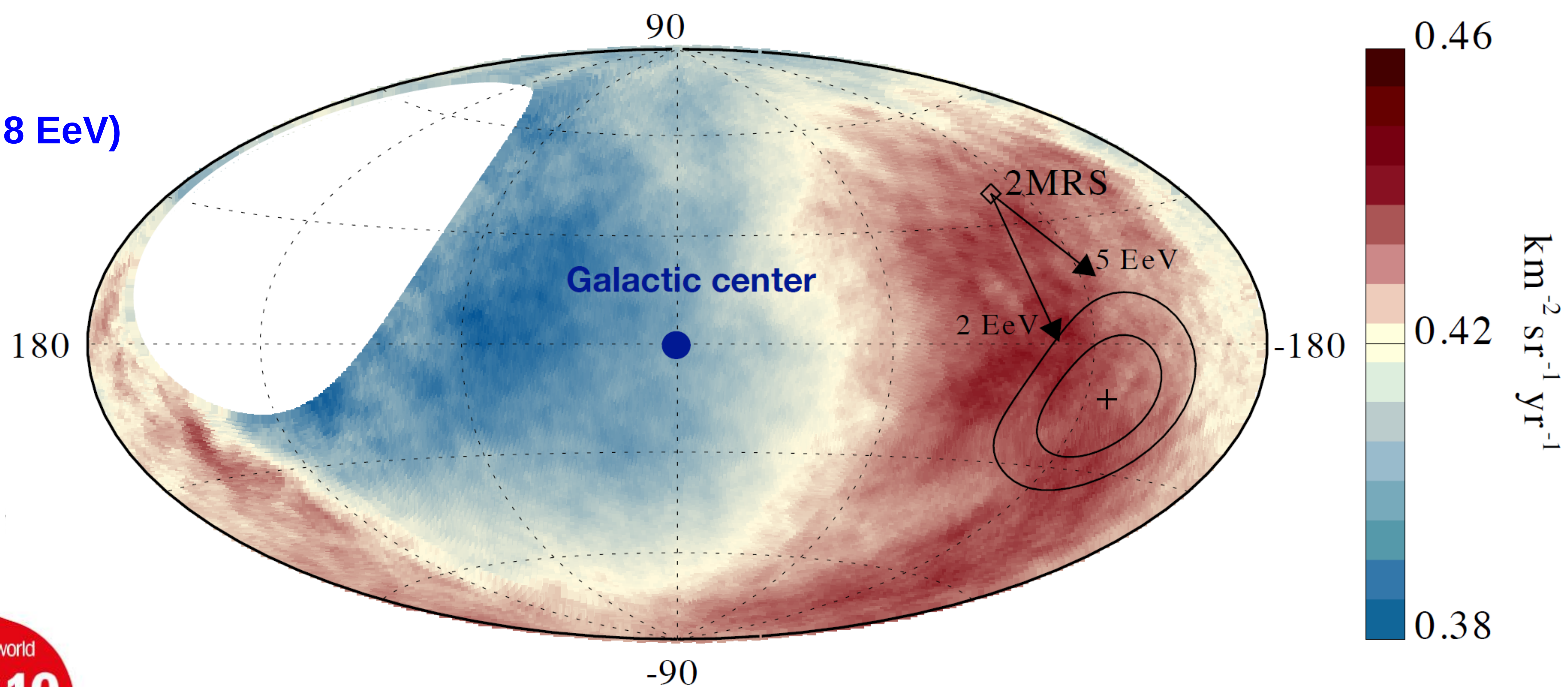
- **Indications for anisotropy**
- **Correlation with catalogues: best for Starburst-Galaxies**



Pierre Auger Collab., Astrophys.J. 853 (2018) L29

European Strategy Update

Arrival Distribution: Dipole at E > 8 EeV



physicsworld TOP 10 BREAKTHROUGH 2017

Dipole above 8 EeV with 5.2σ and an amplitude of 7%
➔ Particles are indeed of extragalactic origin

Science 357 (2017) 1266

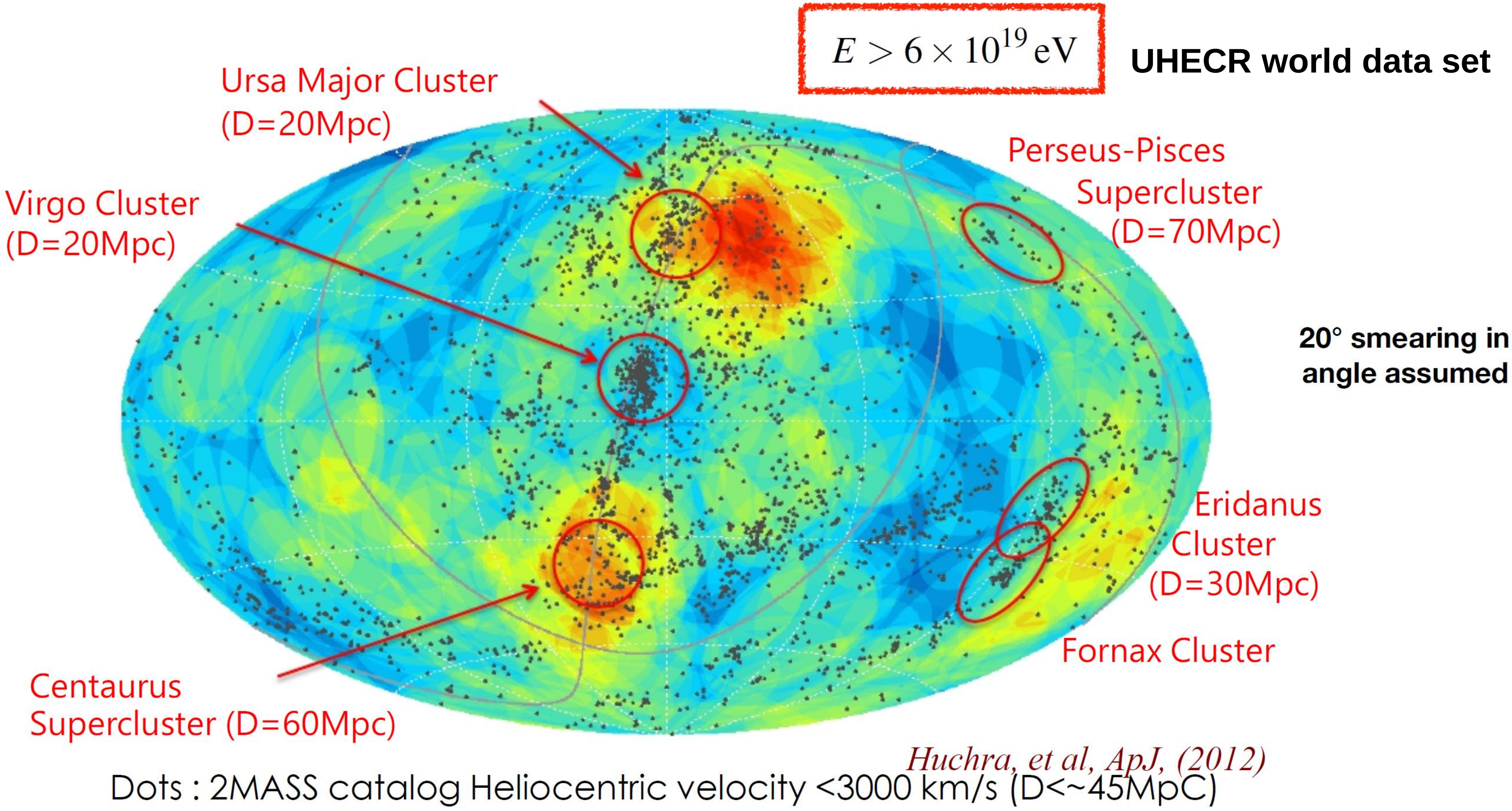
Deflection of UHECR in magnetic fields:

$$\delta \simeq 3^o \frac{B}{3\,\mu G} \frac{L}{kpc} \frac{6\times10^{19}\,eV}{E/Z}$$

Arrival directions follow mass distribution of near-by galaxies (2MASS Redshift Survey)

European Strategy Update

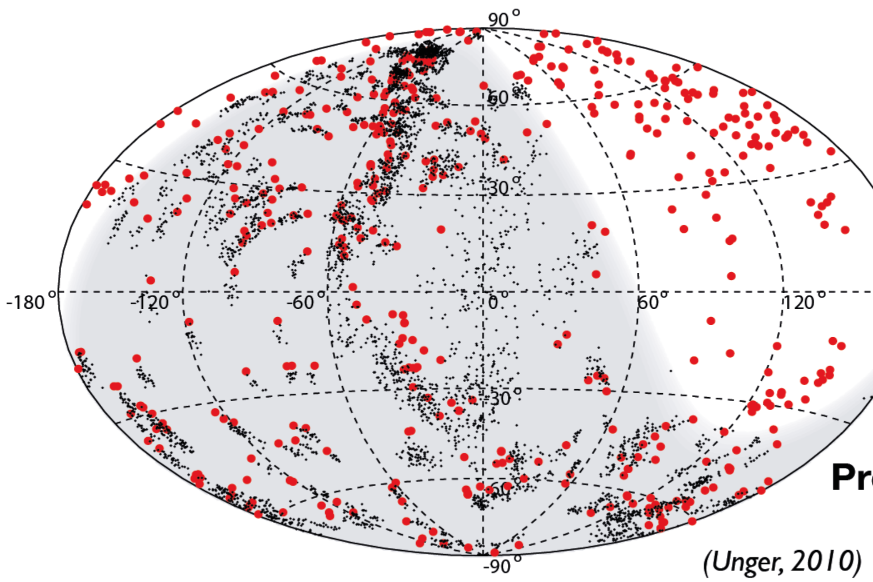
Anisotropy at highest energies ($E > 6 \cdot 10^{19}$ eV)



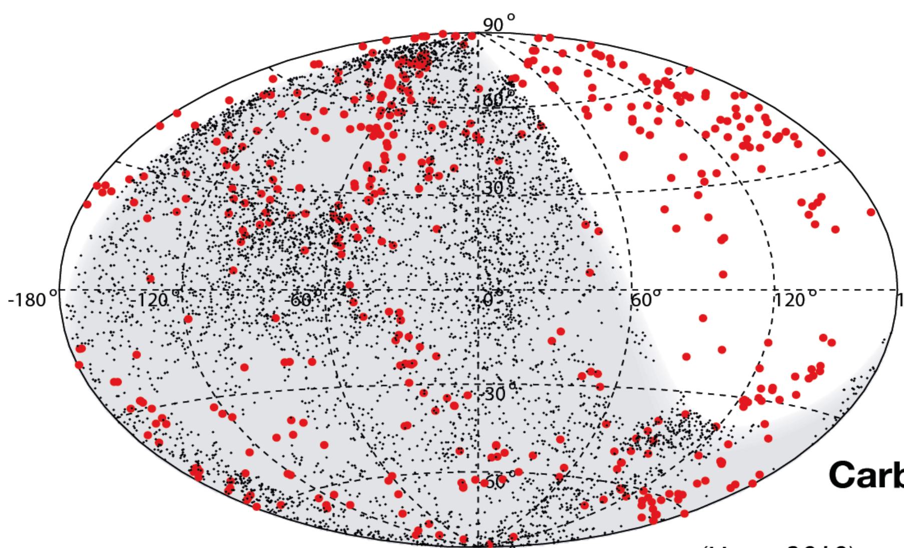
Ogio et al. ISVHECRI 2018

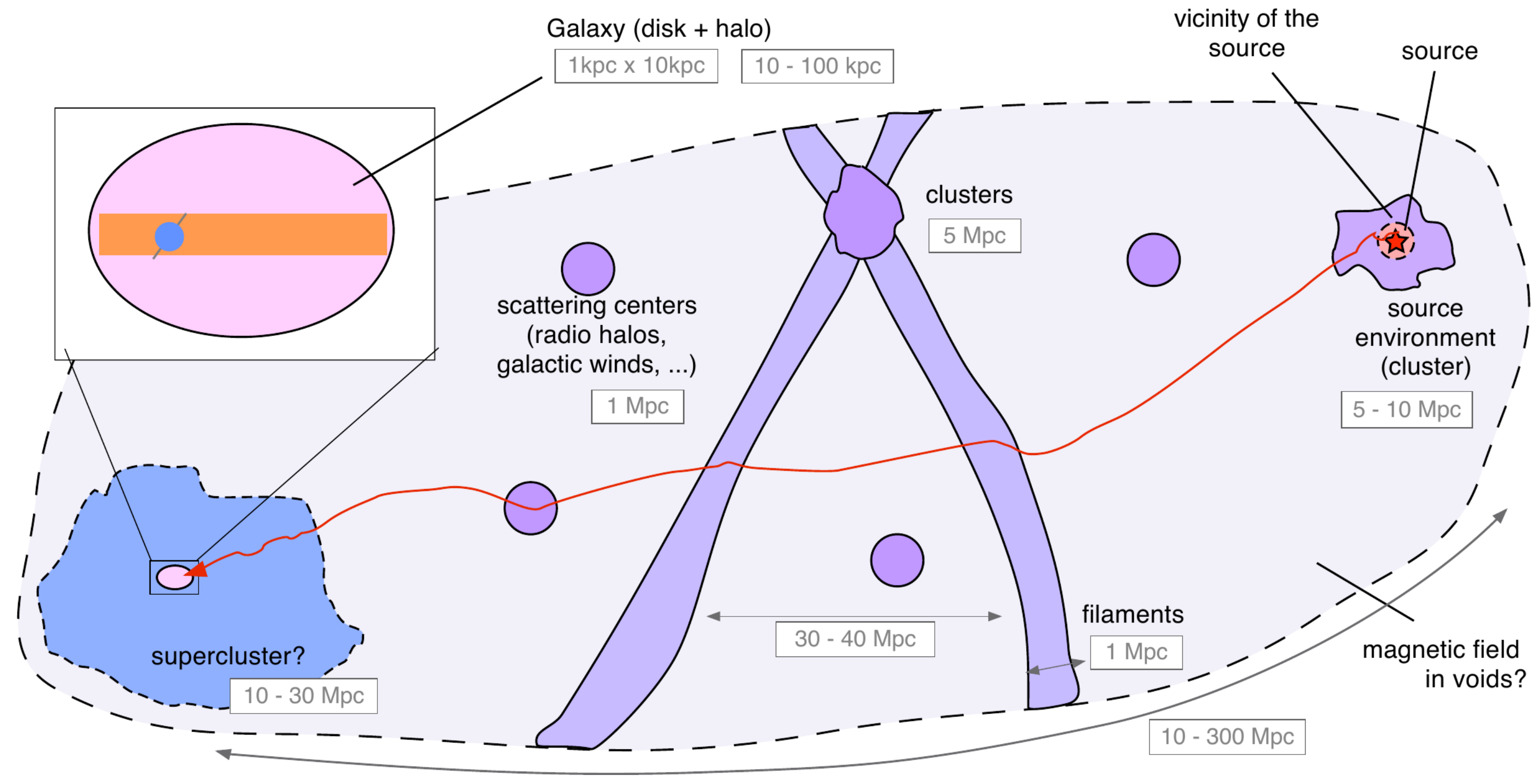
- **Hotspots found**
- **Distribution not directly correlated with matter distribution in close Universe**
- **Deflection in magnetic fields?**

Strategy: source identification by arrival distribution



Simulation





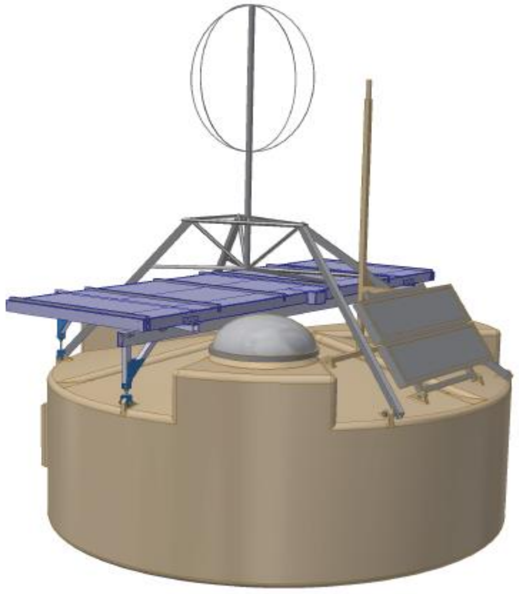
$$\delta \simeq 3^{o} \frac{B}{3\,\mu G} \frac{L}{kpc} \frac{6\times 10^{19}\,eV}{E/Z}$$

- **Assumption of sources**
- **Simulation of propagation**
- **Galactic magnetic field as spectrometer to fit GMF models** *M. Unger & G. Farrar et al. 2017 & 2019*

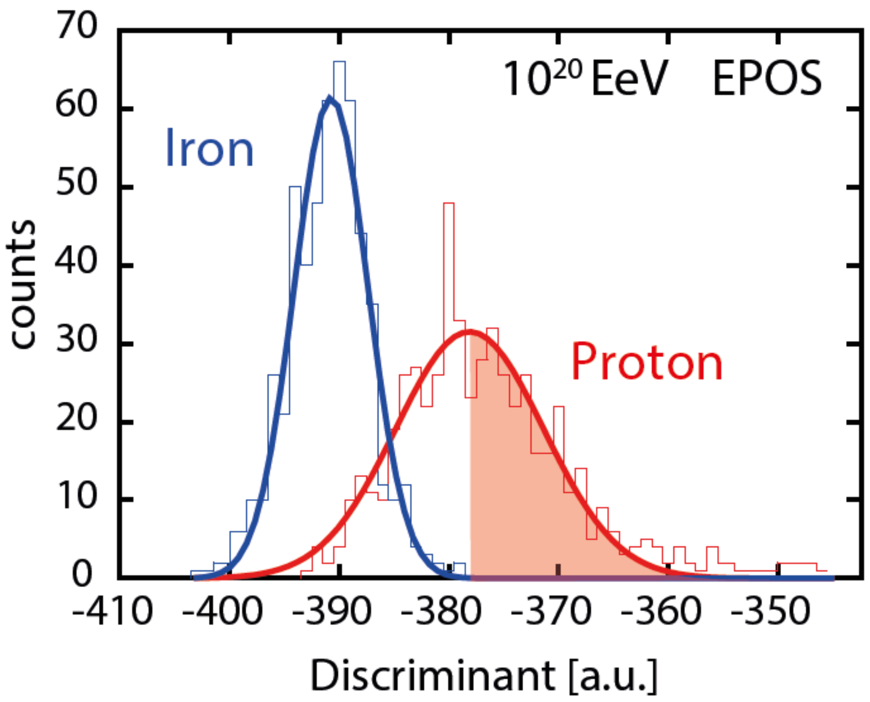
➔ composition and magnetic fields have to be known

(for composition determination the interactionphysics have to be known)

Next: AugerPrime



- Scintillators (3.8 m²) and radio antenna on top of each array detector
- Composition measurement up to 10^{20} eV
- Composition selected anisotropy
- Particle physics with air showers



- **Installation finished 2021**
- **Operation AugerPrime until 2030**

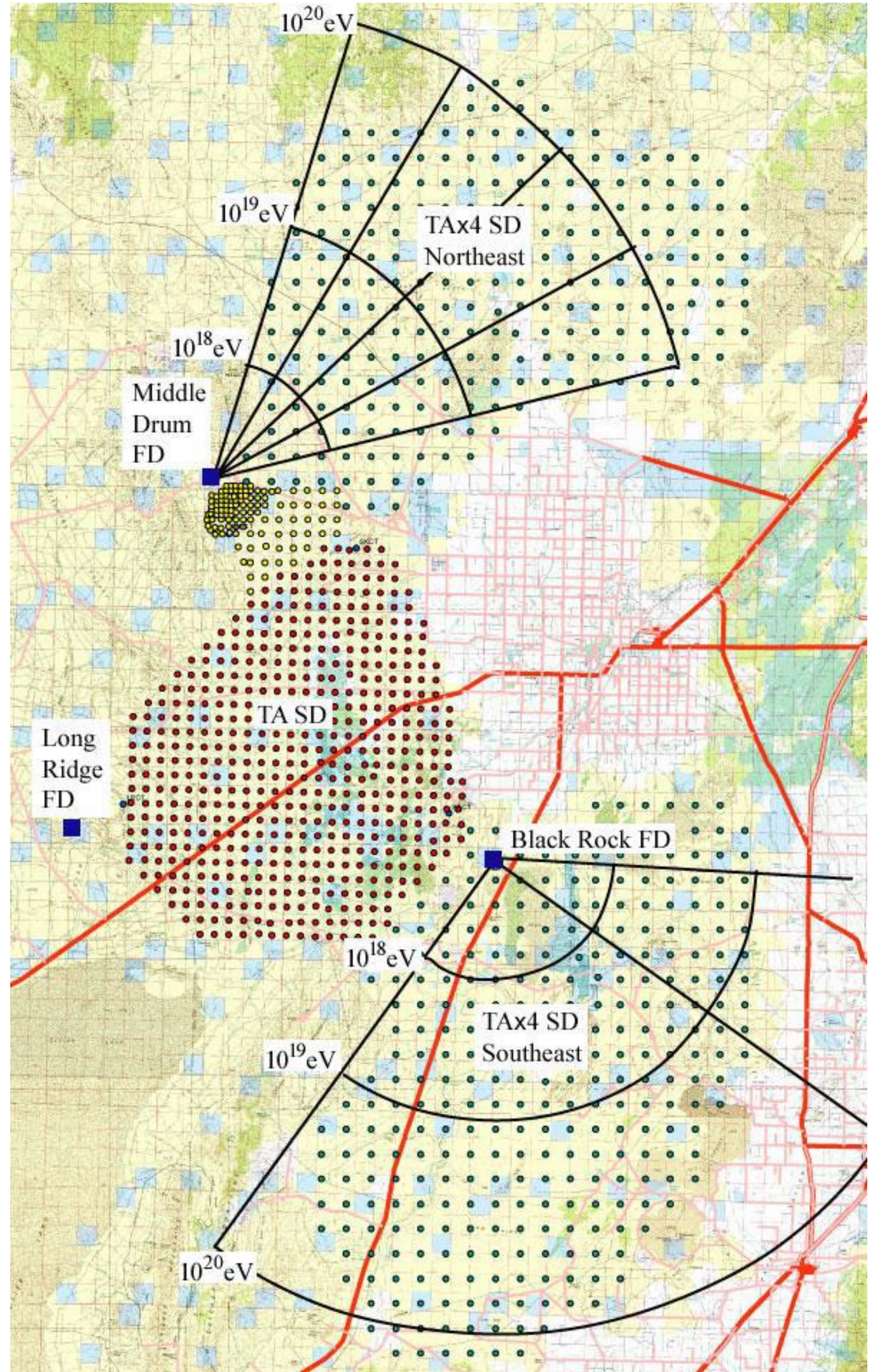
➔ **Composition!**

(AugerPrime design report 1604.03637)

Next: Telescope Array x 4

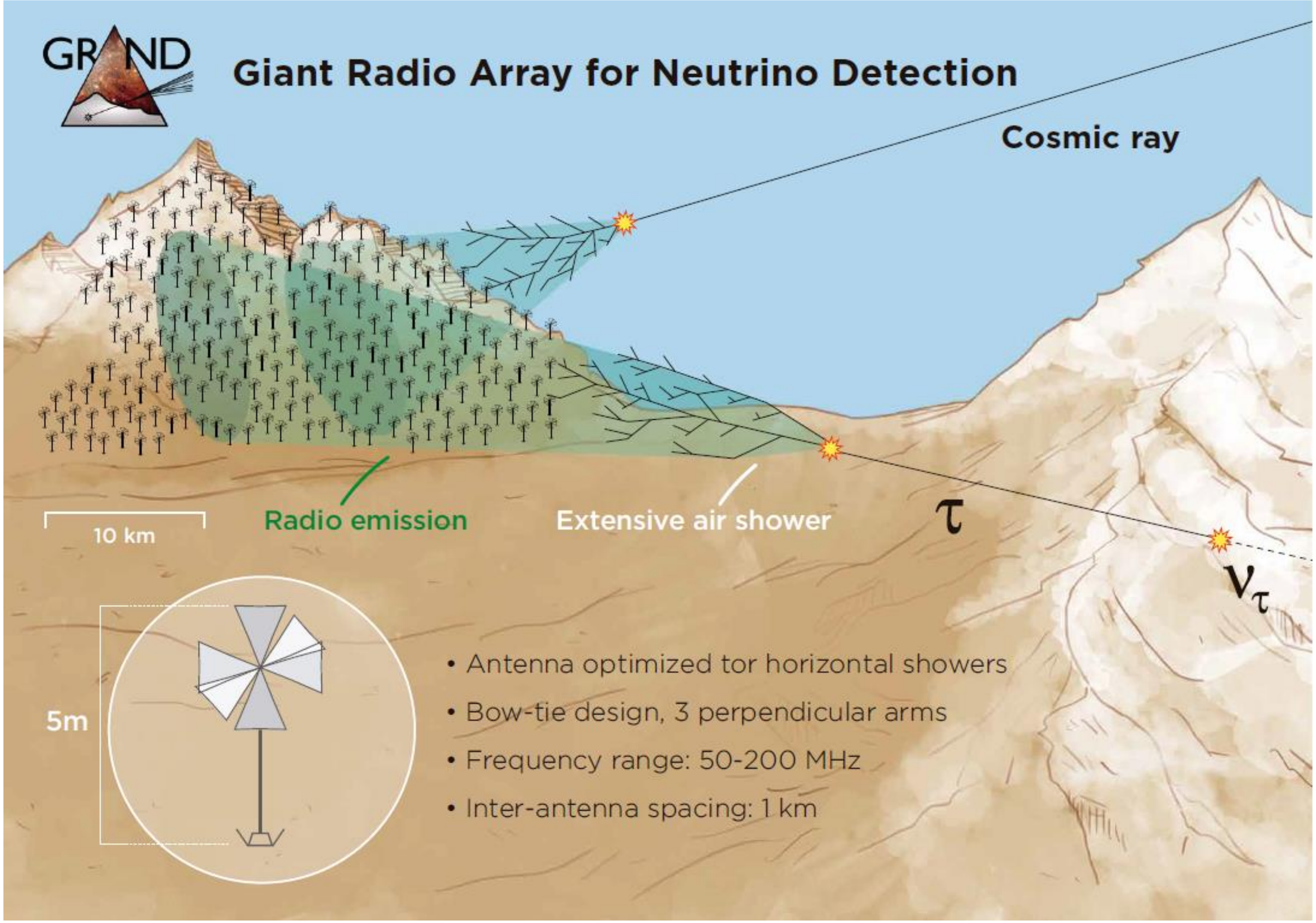
- **500 new SDs with 2.08 km spacing and TA SDs cover 4×TA SD detection area (~3000 km²)**
- **2 new Fluorescence Detector (FD) stations (4+8 HiRes Telescopes)**
- **First light was observed by north FD station**
- **Construction of south FD station is ongoing**

- **➔ Statistics!!**



European Strategy Update

Next: GRAND

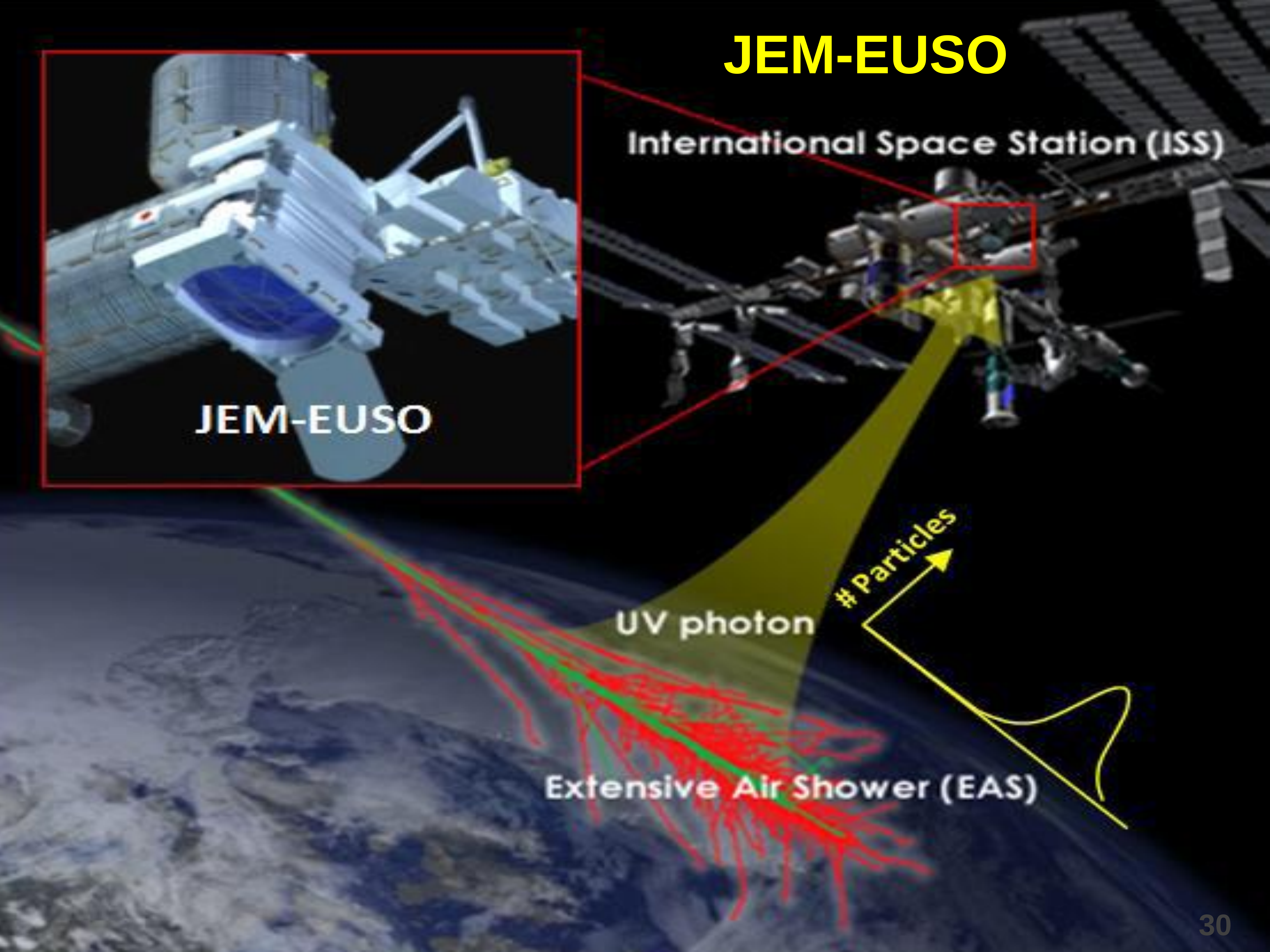


#119: GRAND

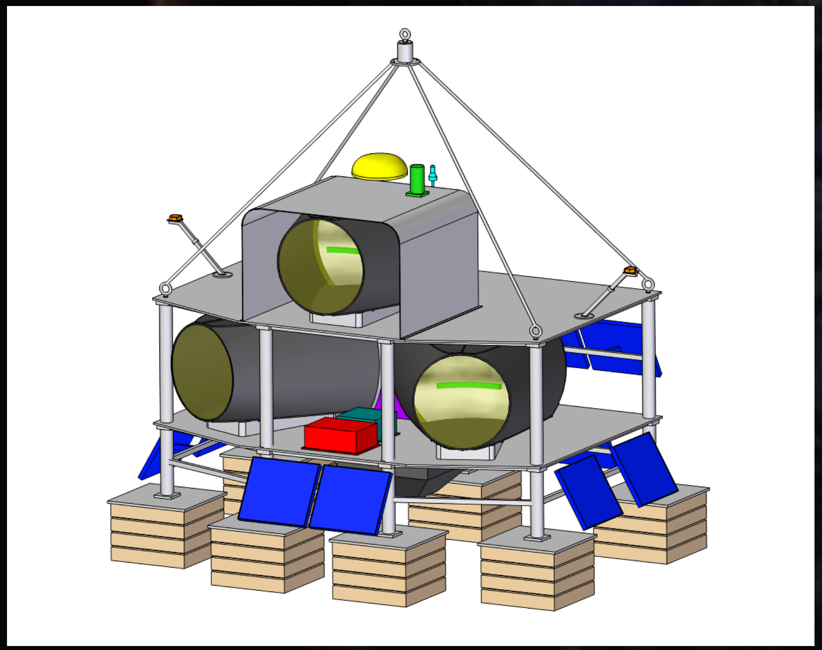
- $200.000\ km^2$ arranged in ~10 independent arrays across the globe
- Strong support form China; prototype until 2021 in China
- Sensitive to Neutrinos and UHECR
  - ➔ Statistics!! + EHE Neutrinos

European Strategy Update

JEM-EUSO

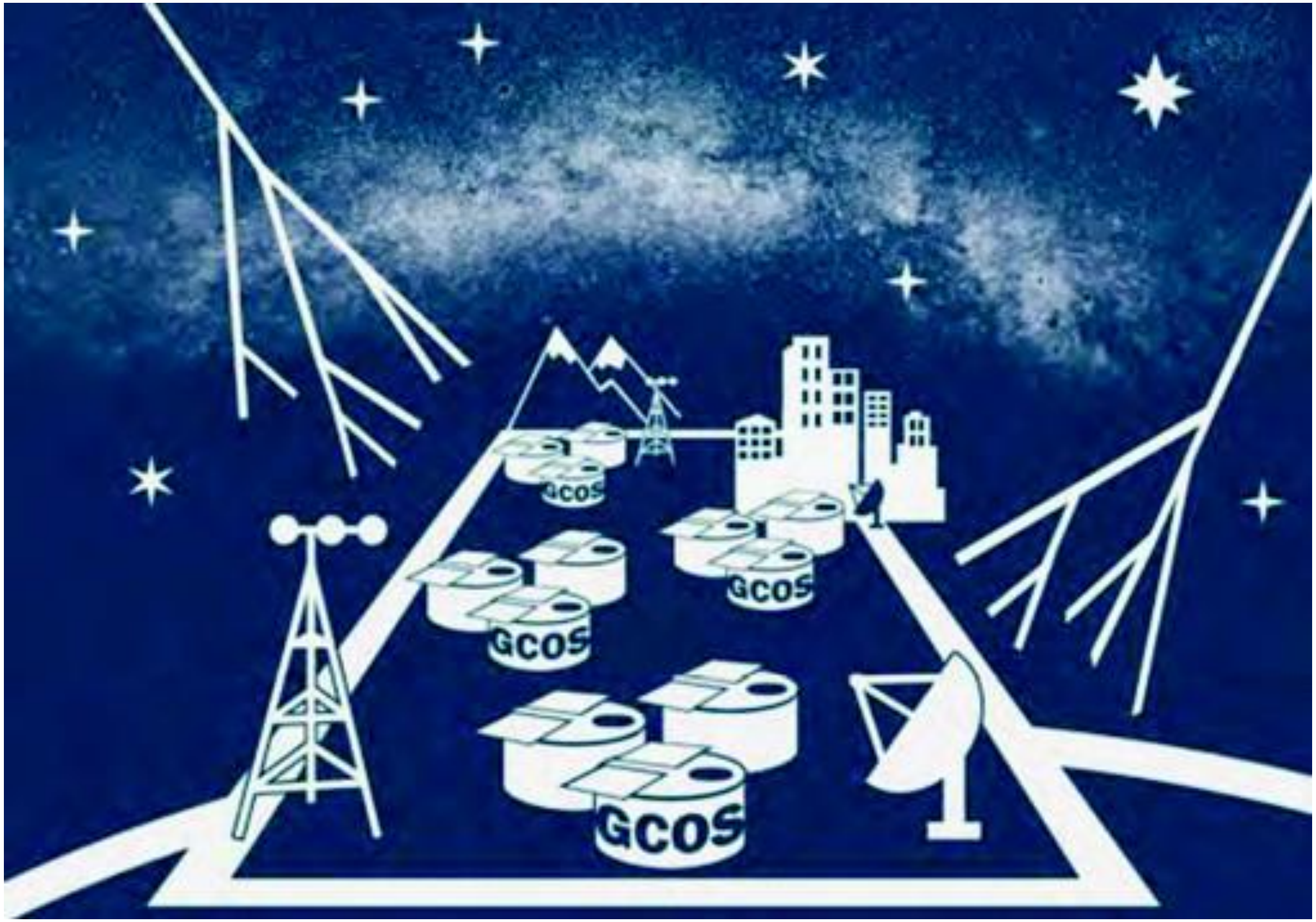

JEM-EUSO
International Space Station (ISS)
UV photon
#Particles
Extensive Air Shower (EAS)

EUSO-SPB2



➔ **Statistics!! + EHE Neutrinos**

GCOS = Global COSmic ray observatory



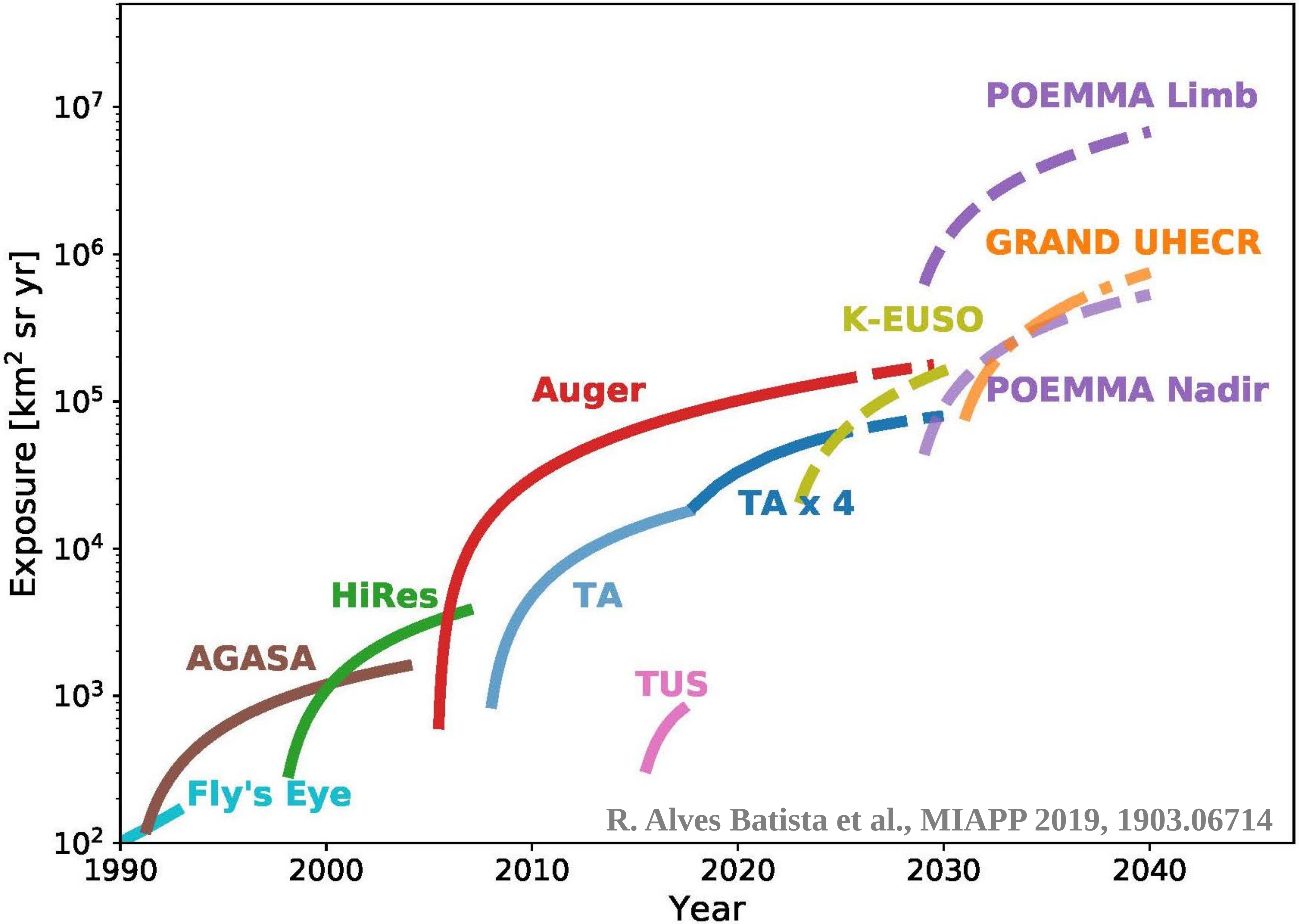
Auger
TAx4
GRAND
POEMMA

p-astronomy with sources

- Global, few sites, N+S
- ca. 90,000 km^2 (x30 Auger)
- Optimal detector for composition sensitivity

European Strategy Update

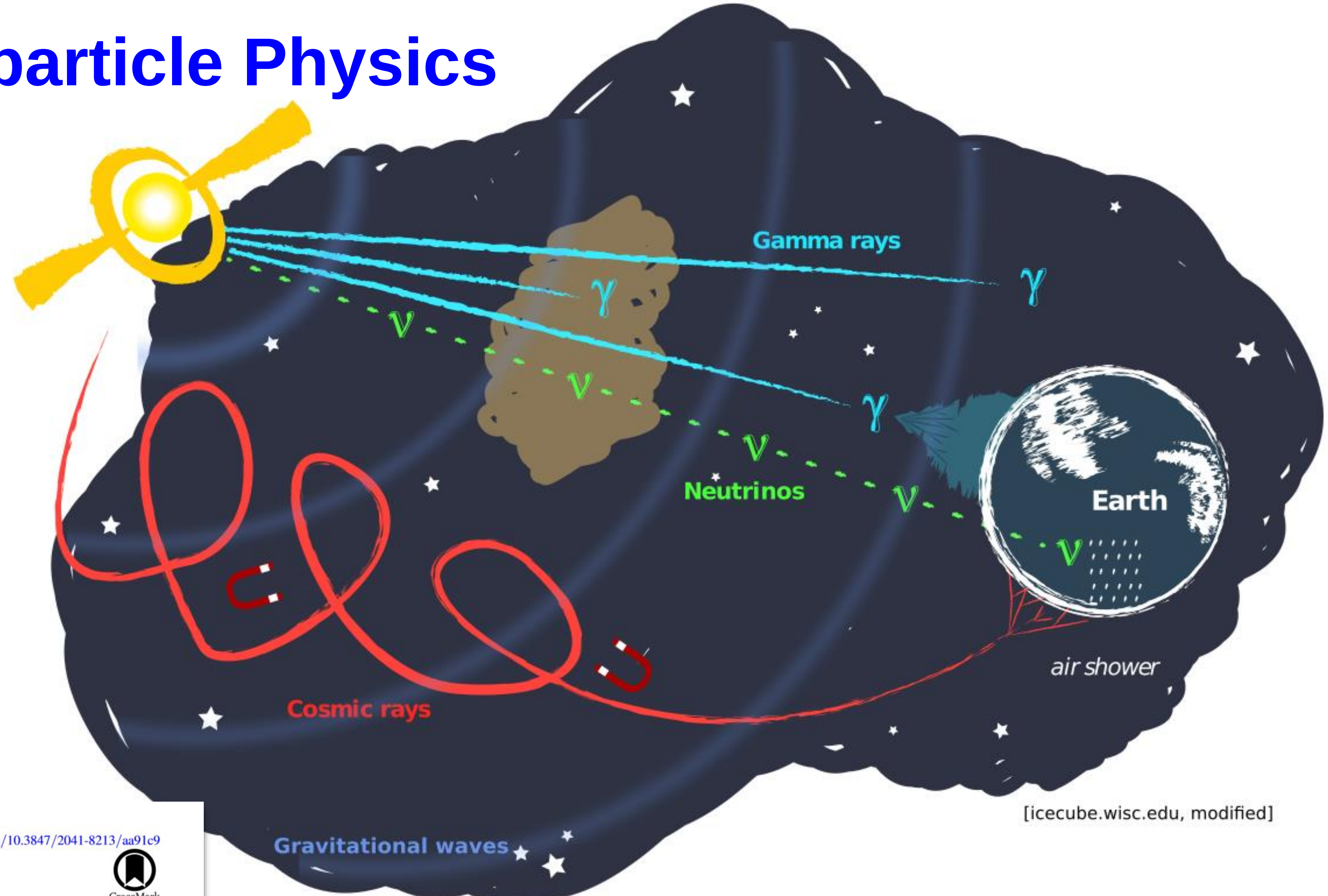
UHECR: Exposure



…..higher statistics!!! **(we cannot change the luminosity…)**

European Strategy Update

Multi-Messenger Astroparticle Physics



<u>The multi-messenger era:</u>

- Cosmic rays,
  detected in 1912
- Gammy rays,
  detected in ~1950
- High-energy neutrinos,
  detected in 2013
- Gravitational waves,
  detected in 2015

The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9

Multi-messenger Observations of a Binary Neutron Star Merger*

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-HXMT Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
(See the end matter for the full list of authors.)

Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 October 16

Abstract

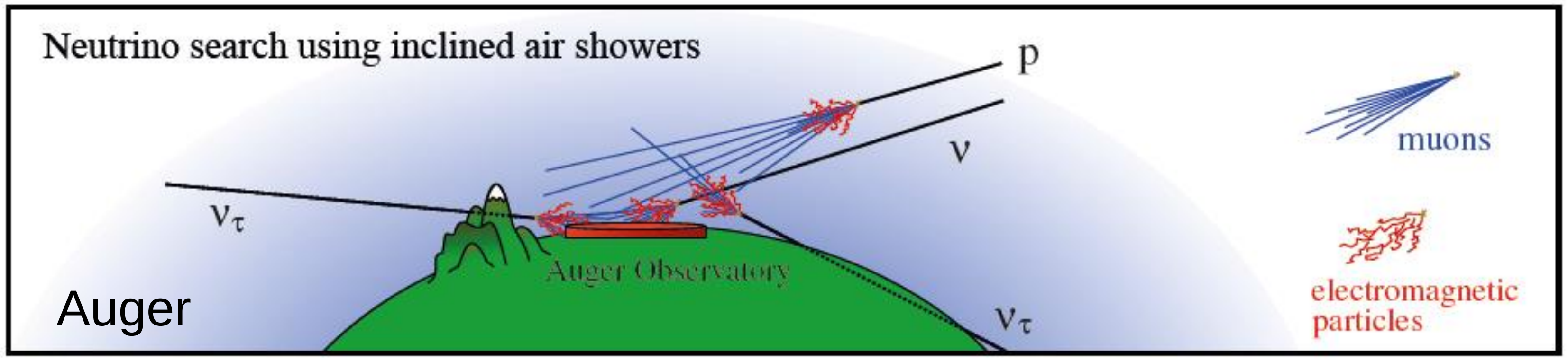
On 2017 August 17 a binary neutron star coalescence candidate (later designated GW170817) with merger time 12:41:04 UTC was observed through gravitational waves by the Advanced LIGO and Advanced Virgo detectors. The

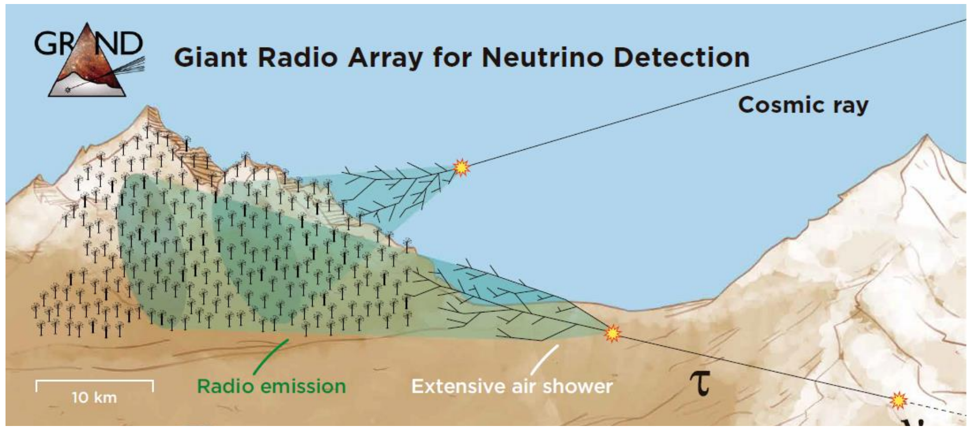
3000 authors / 70 observatories
Astrophys.J. 848 (2017) 2, L12

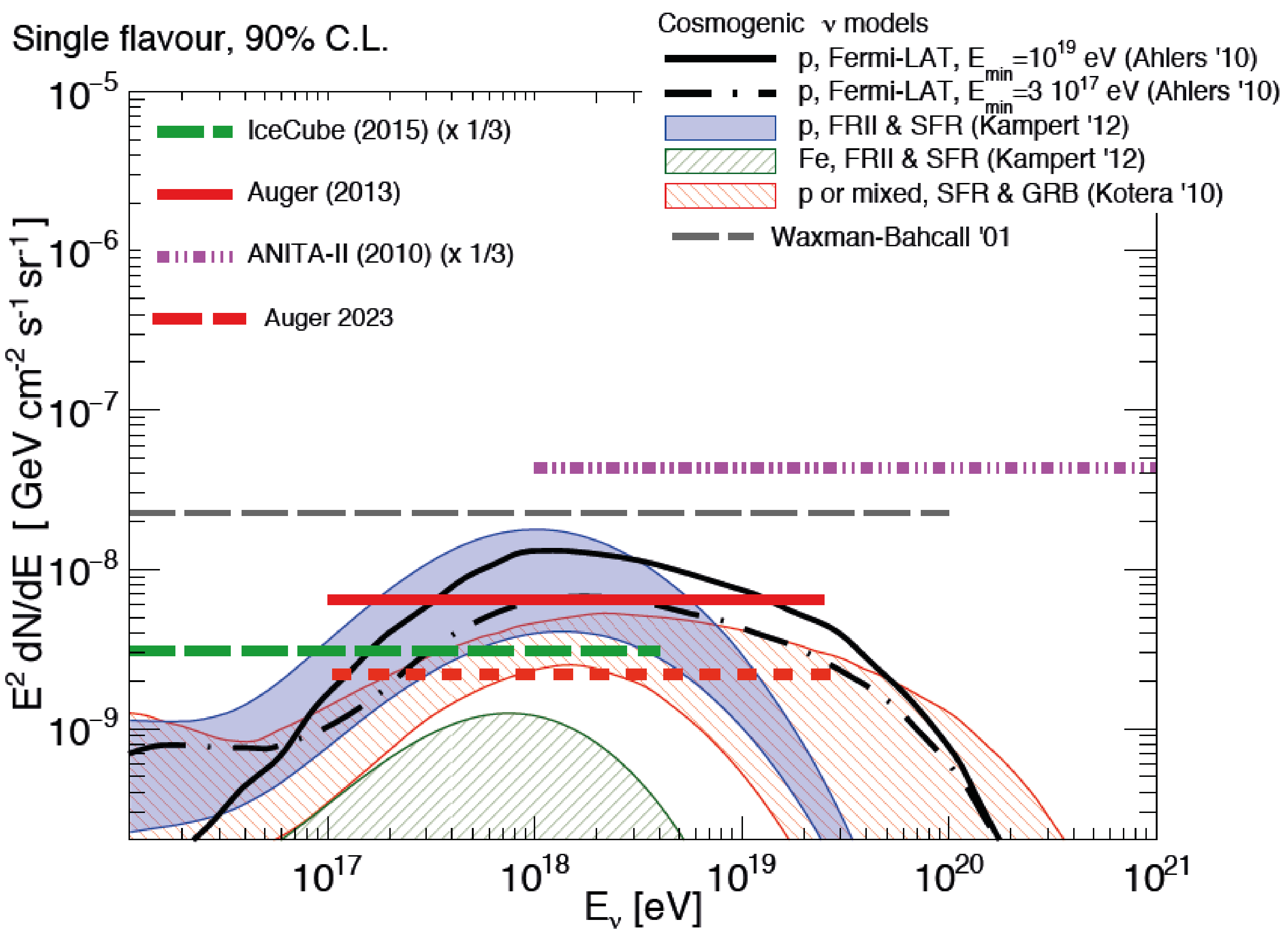
➔ Learn more about the High-Energy Universe by combining information from the different tracers

➔ see talk Marek Kowalski

CR observatories are also Neutrino Detectors





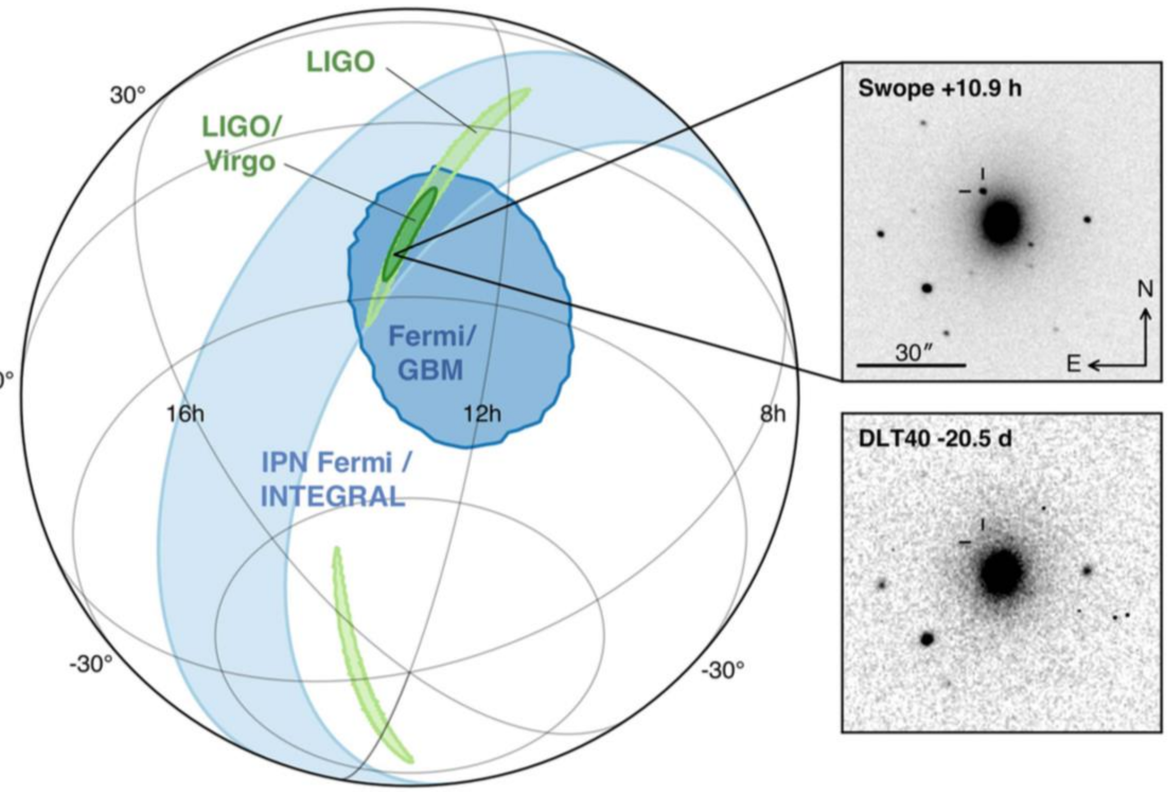


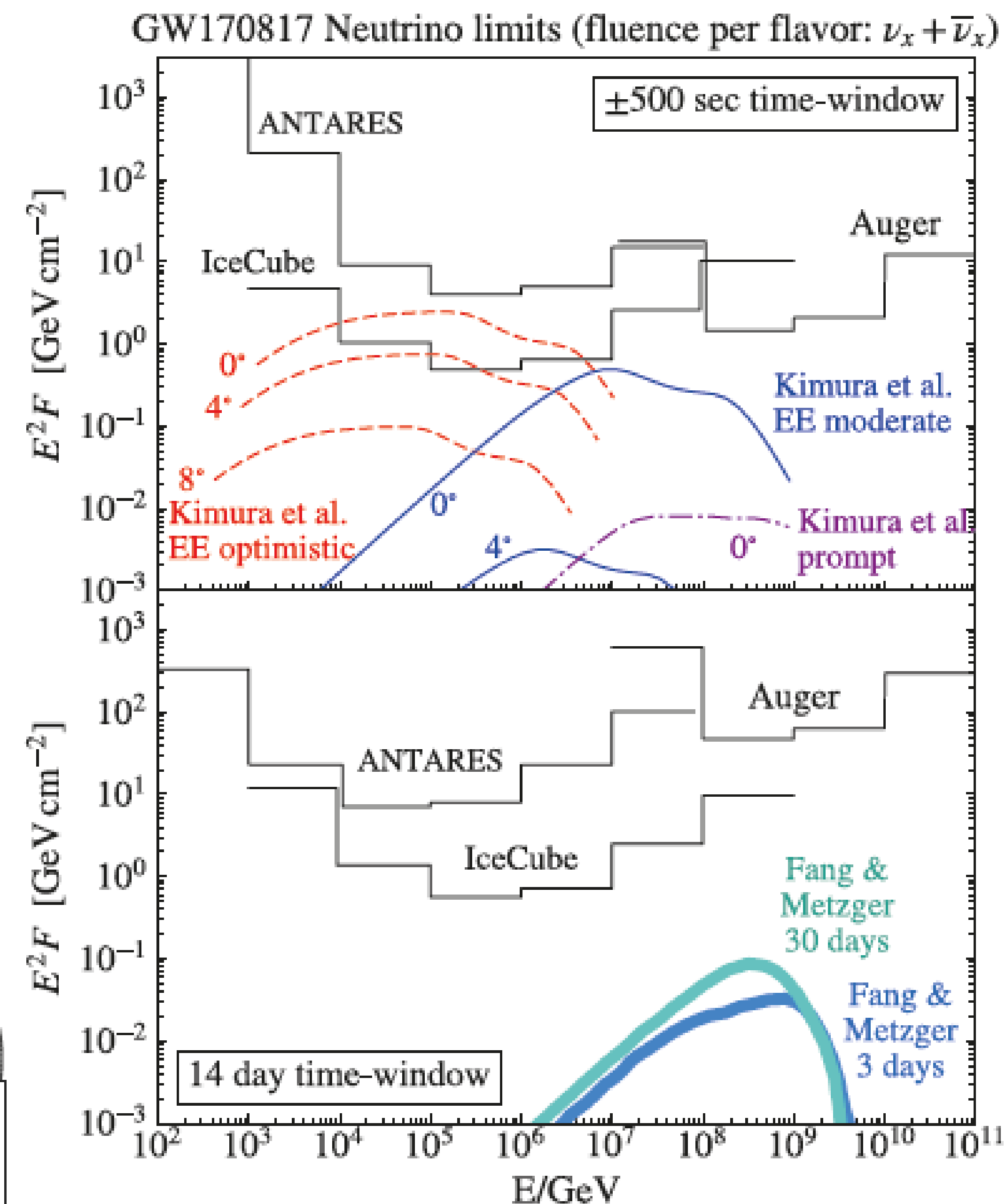
AugerPrime 1604.03637

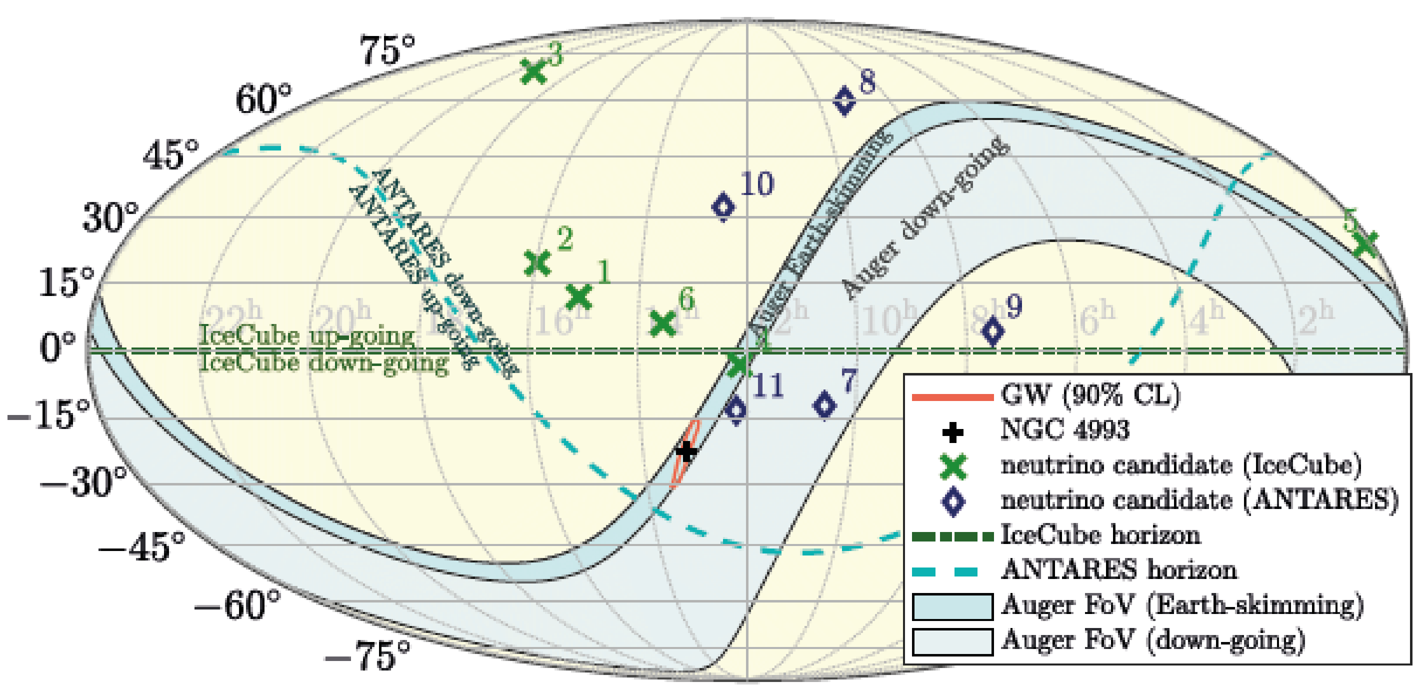
the first EeV-neutrino should be 'just around the corner'

European Strategy Update

The Dawn of Multi-Messenger Astroparticle Physics





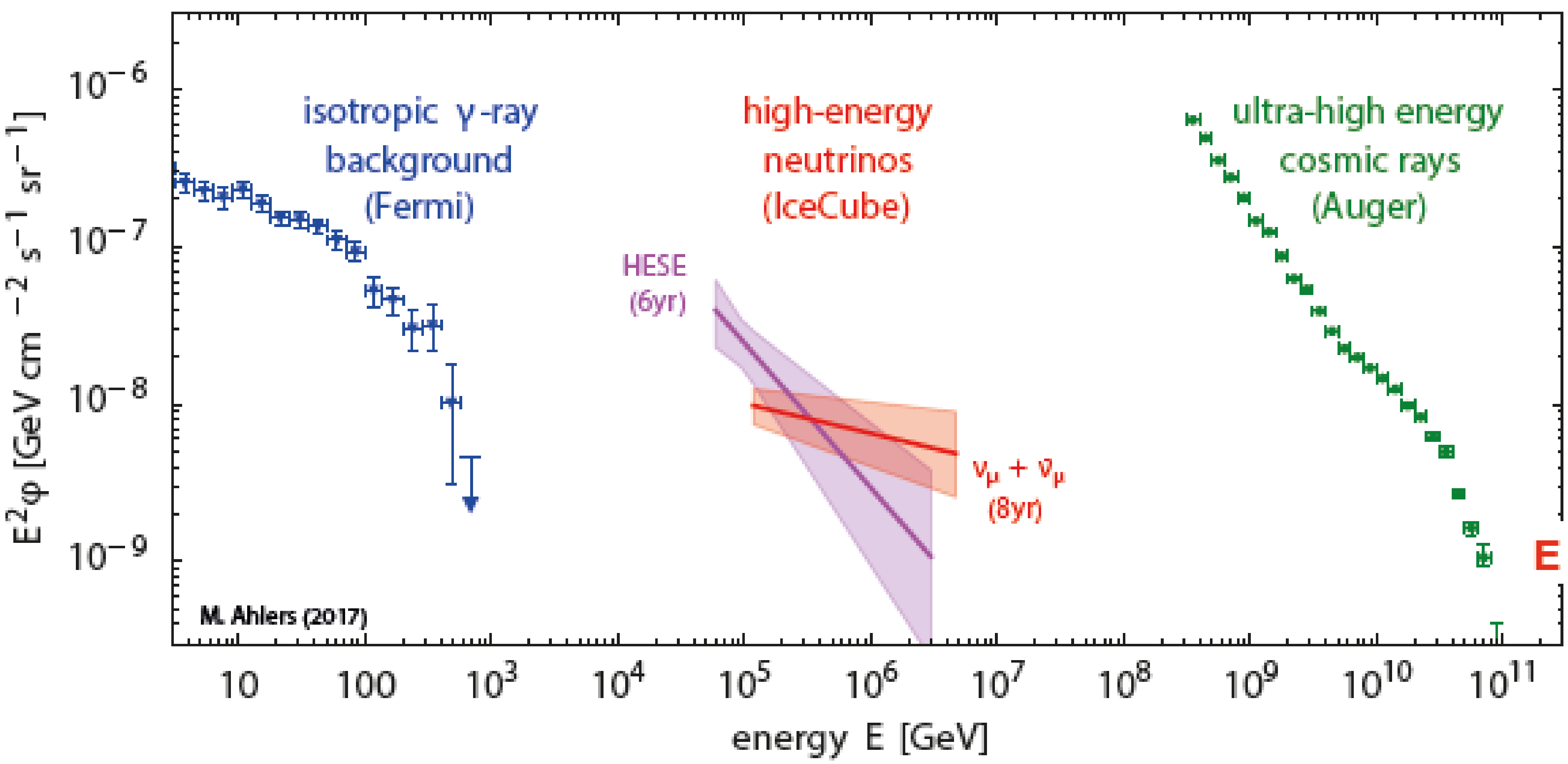


Astrophys.J. 848 (2017) 2, L12

Multi-Messenger Astroparticle Physics

Particle flux multiplied by E²

$$E^2 \frac{dN}{dE} = E \frac{dN}{d\ln E}$$



Energy density per decade

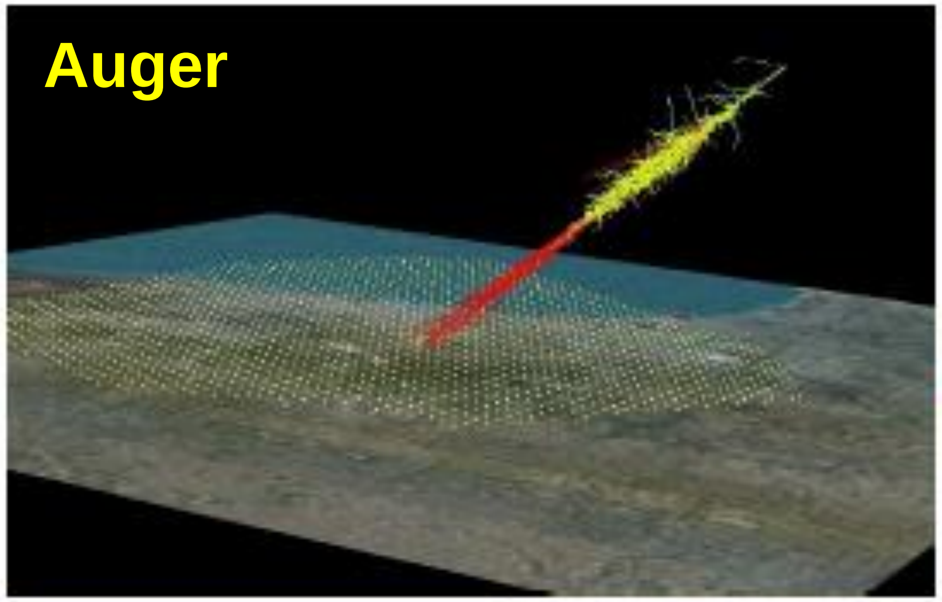
$$\rho_{\rm decade} = \int_{\rm decade} E \frac{dN}{d\ln E}\, d\ln E$$

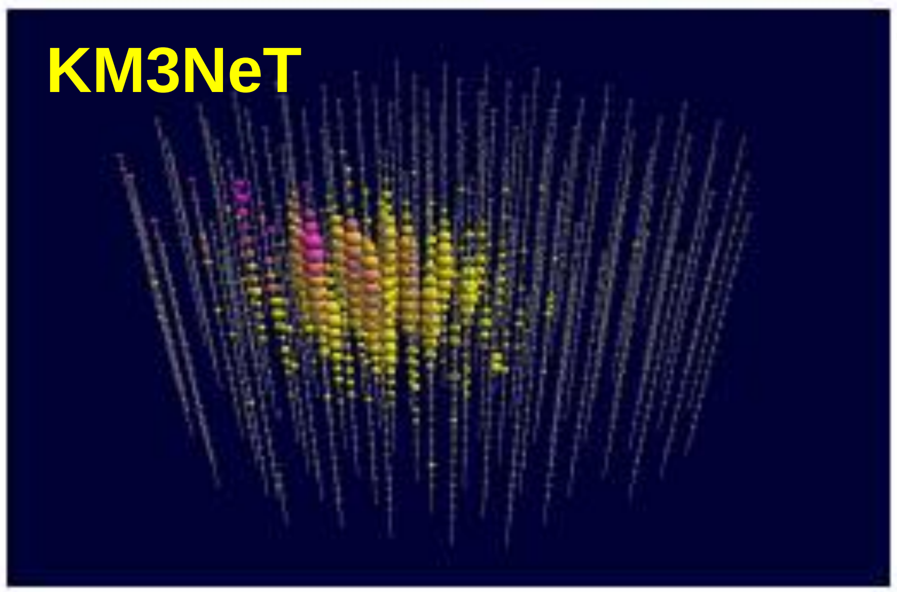
Energy density per decade similar in all three messenger particles

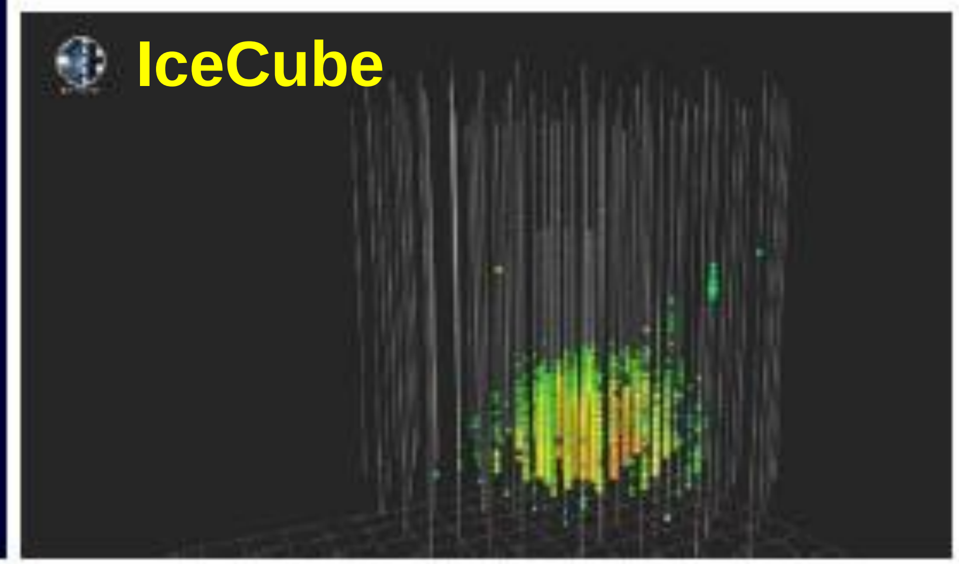
- **Study the high-energy Universe**
- **Explore the correlation / connection between various tracers**

European Strategy Update

Multi-Messenger Astroparticle Physics



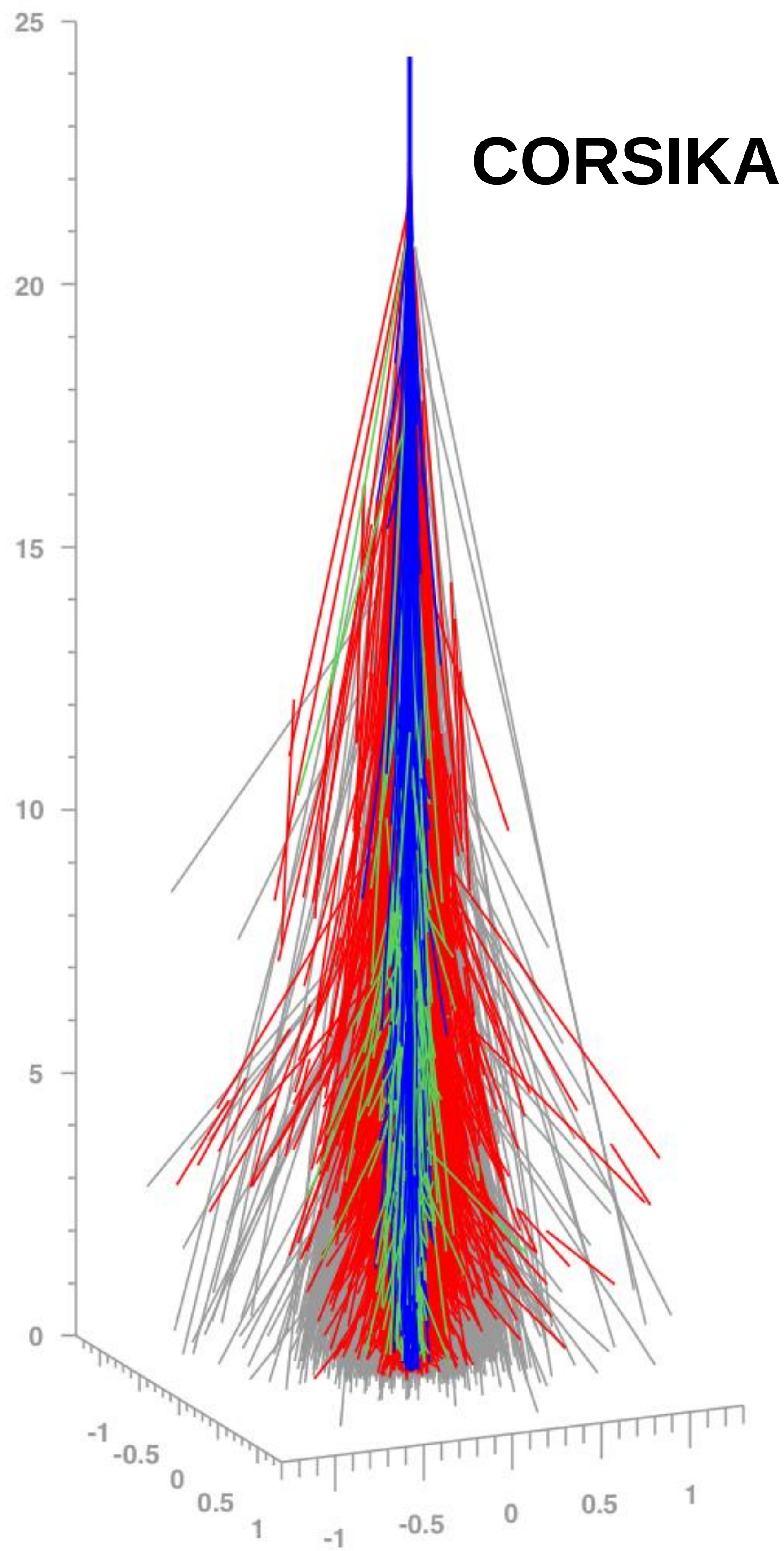




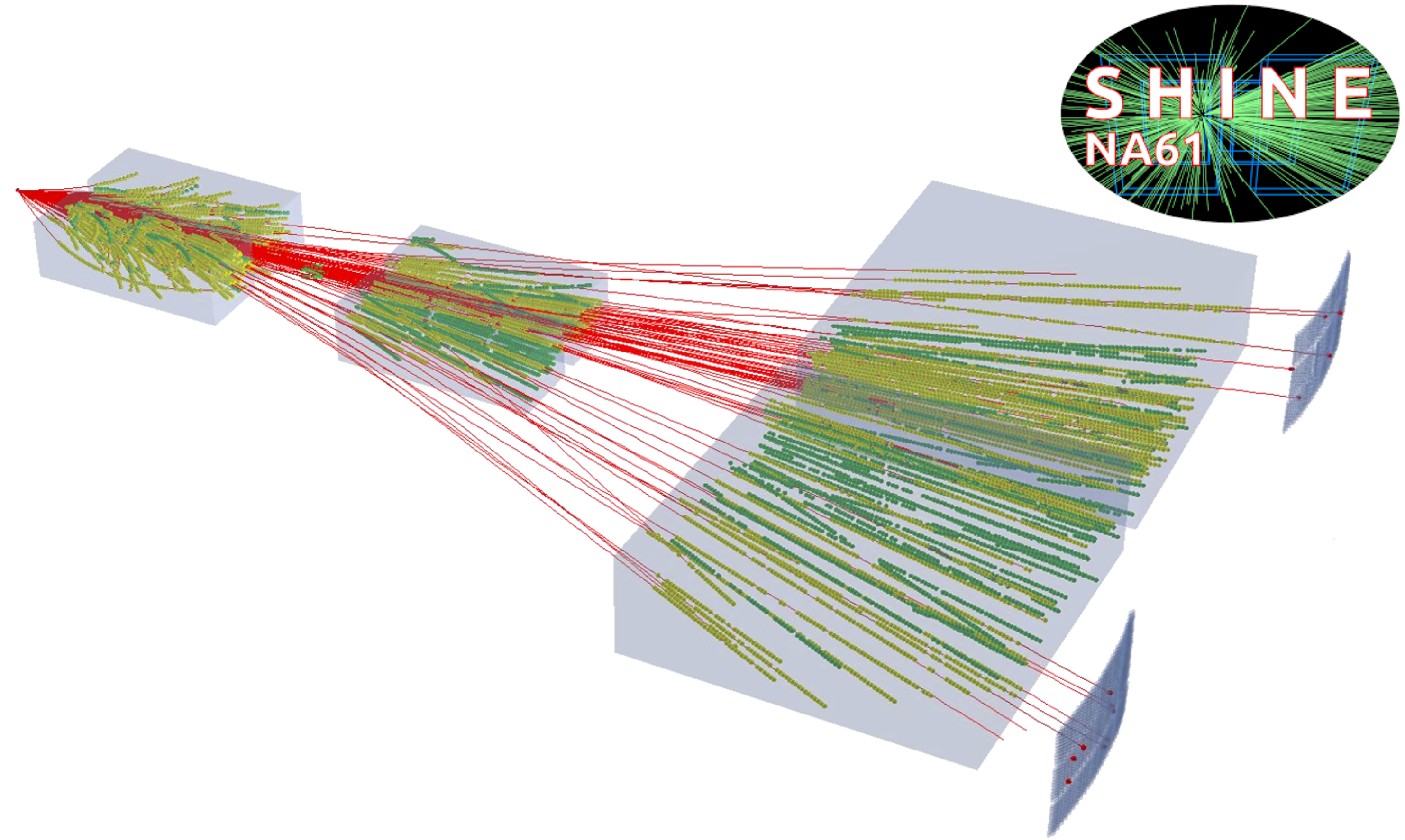
Strategy:

- **long-term operational observatories for ‘Shower-Measurements’**
- **synergies in detection technologies**
- **synergies in simulation and reconstruction of showers (Big Data Analytics)**
- **for MM-analyses common data format and access (Research Data Management)**
- **for Open Data common platforms (Data Curation)**

Particle Physics



- **Validity of hadronic interaction models**
- **Measuring cross sections**
- **Search for BSM physics**



CORSIKA: world-leading tool for air shower modeling
CORSIKA 8: global community effort to

- **improve software**
- **improve shower simulations & hadronic event generators** *see talk Tanguy Pierog*
- **improve computational efficiency**
- **provide more flexibility for future experiments**
- **increase stability: debugging, testing facilities, automation**

LHC measurements for Cosmic Ray

After exploiting pp collisions up to 13TeV it remains to study physics effects most relevant in EAS:

Nuclear effects of light ions:

Oxygen-proton, oxygen-oxygen collisions

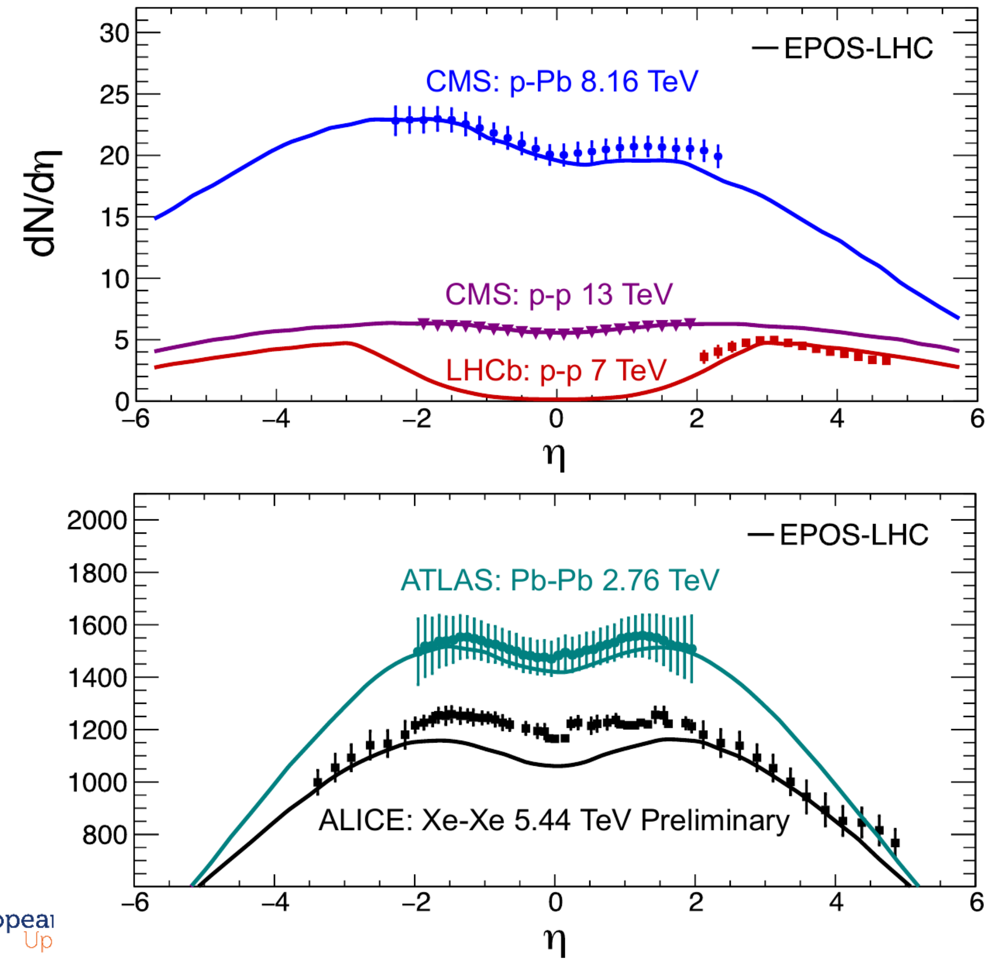
Extrapolation from pp and PbPb systems to light ions is non-trivial and remains one of the large uncertainties in EAS simulations.

Planned in Run 3, see arXiv:1812.06772 [hep-ph]

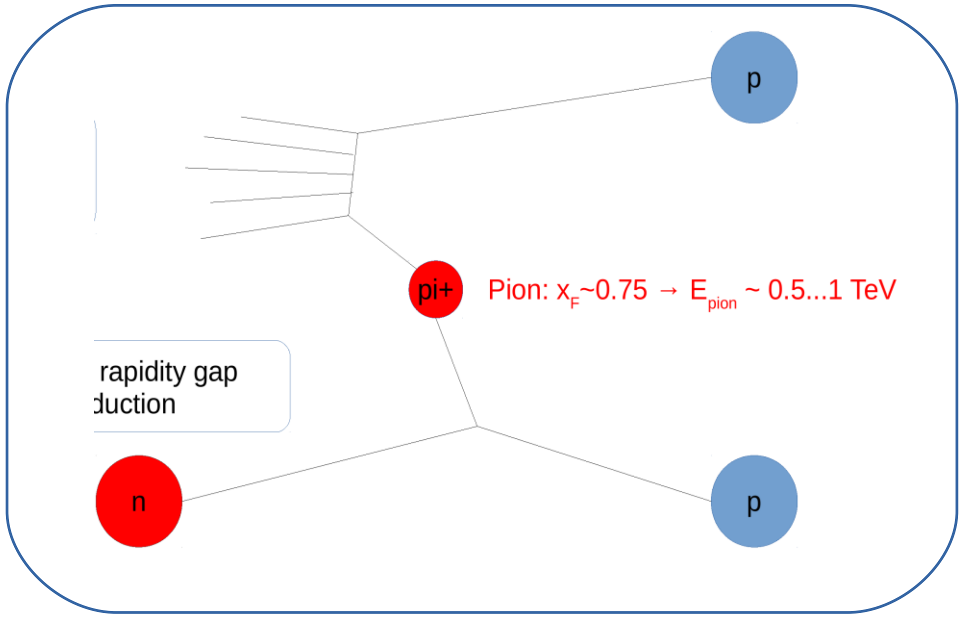
Pions (mesons) as projectile particles:

By far most collisions in EAS are meson-air, the description of pion-air based on LHC pp data is the largest source of uncertainty in EAS simulations.

Tagging charge-exchange reactions where a O(0.1TeV) pion collides with a proton will be the most significant remaining help for CR physics.

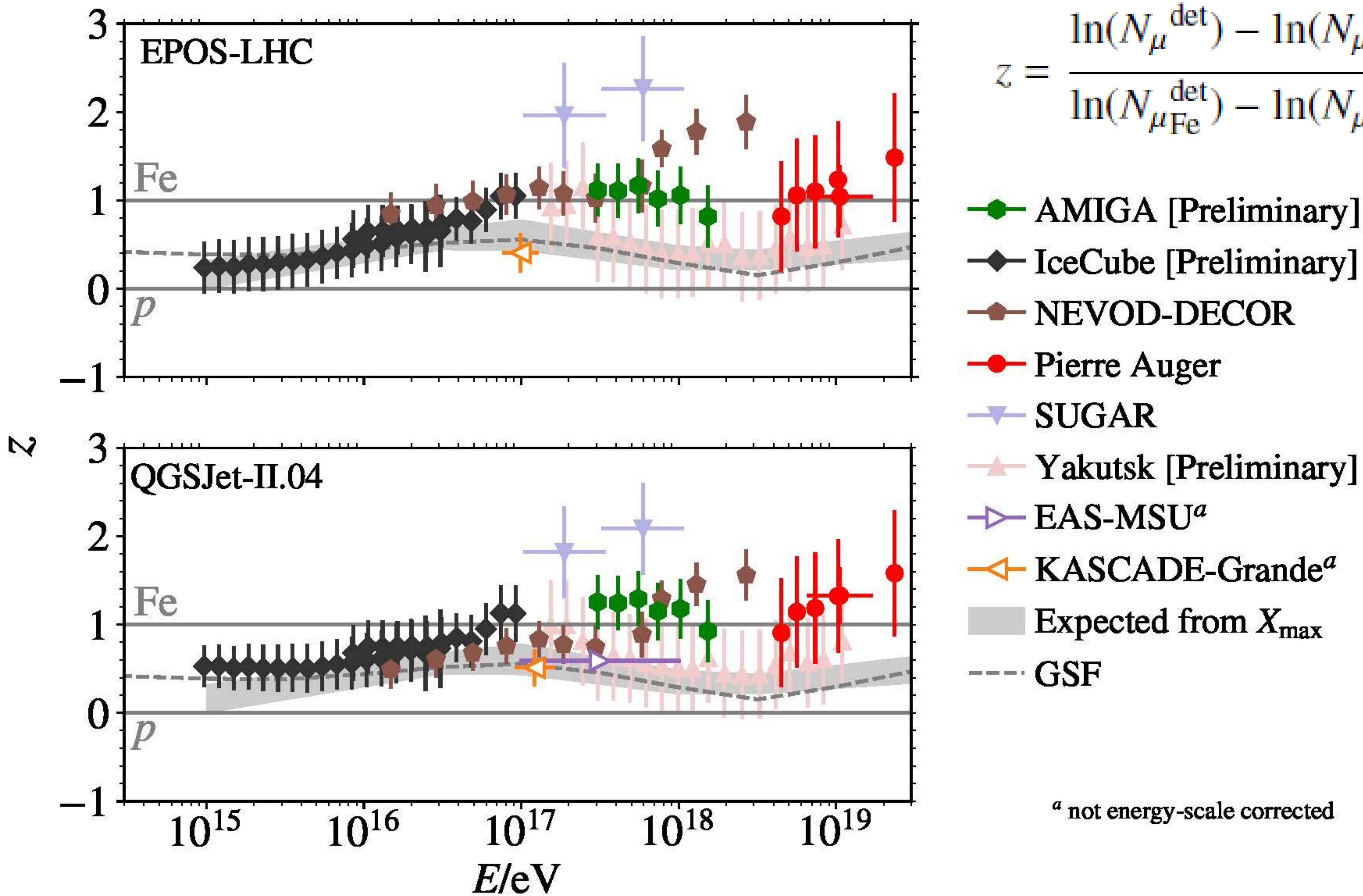


pp and PbPb data well described, **but XeXe not!**



Ralf Ulrich

Muon Deficit in Air Shower Simulations

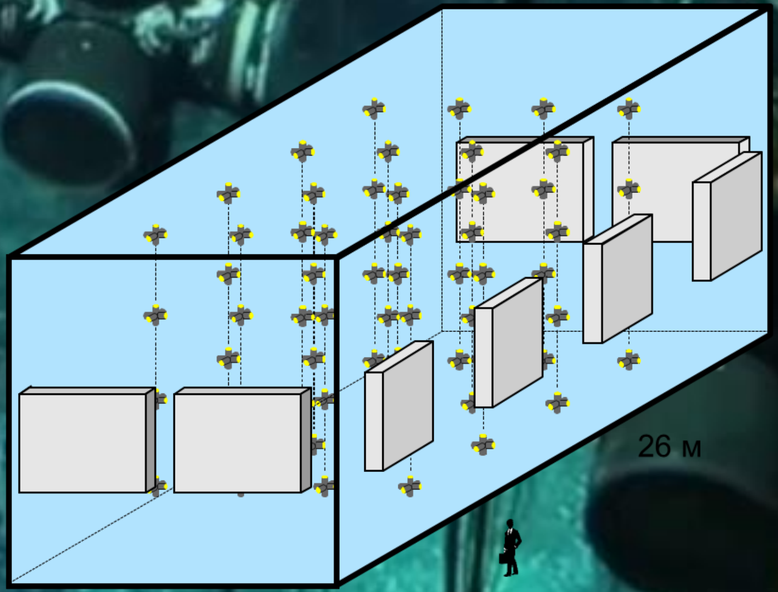


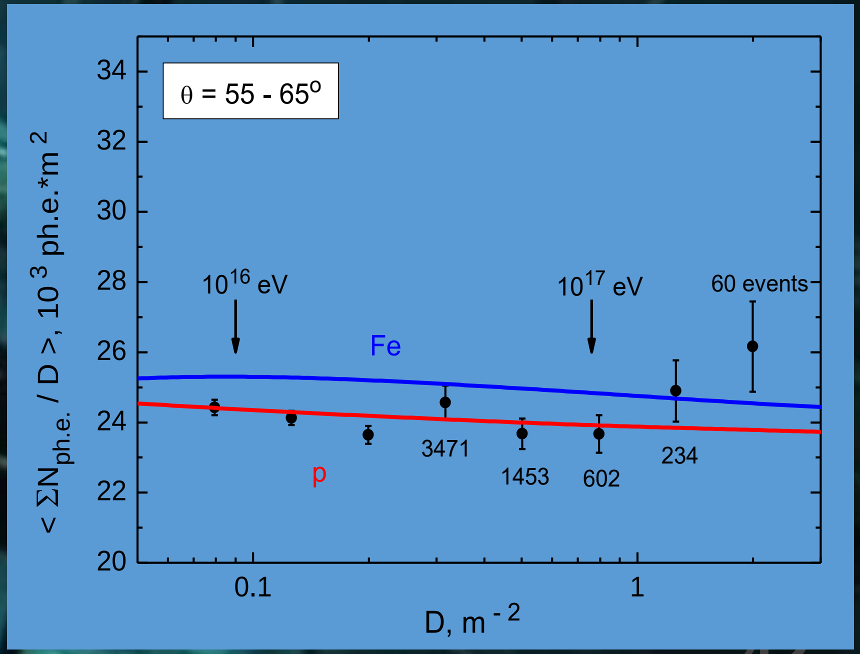
$$z = \frac{\ln(N_\mu^{\text{det}}) - \ln(N_{\mu p}^{\text{det}})}{\ln(N_{\mu\text{Fe}}^{\text{det}}) - \ln(N_{\mu p}^{\text{det}})}$$

[a] not energy-scale corrected

Dembinski et al., arXiv:1902.08124

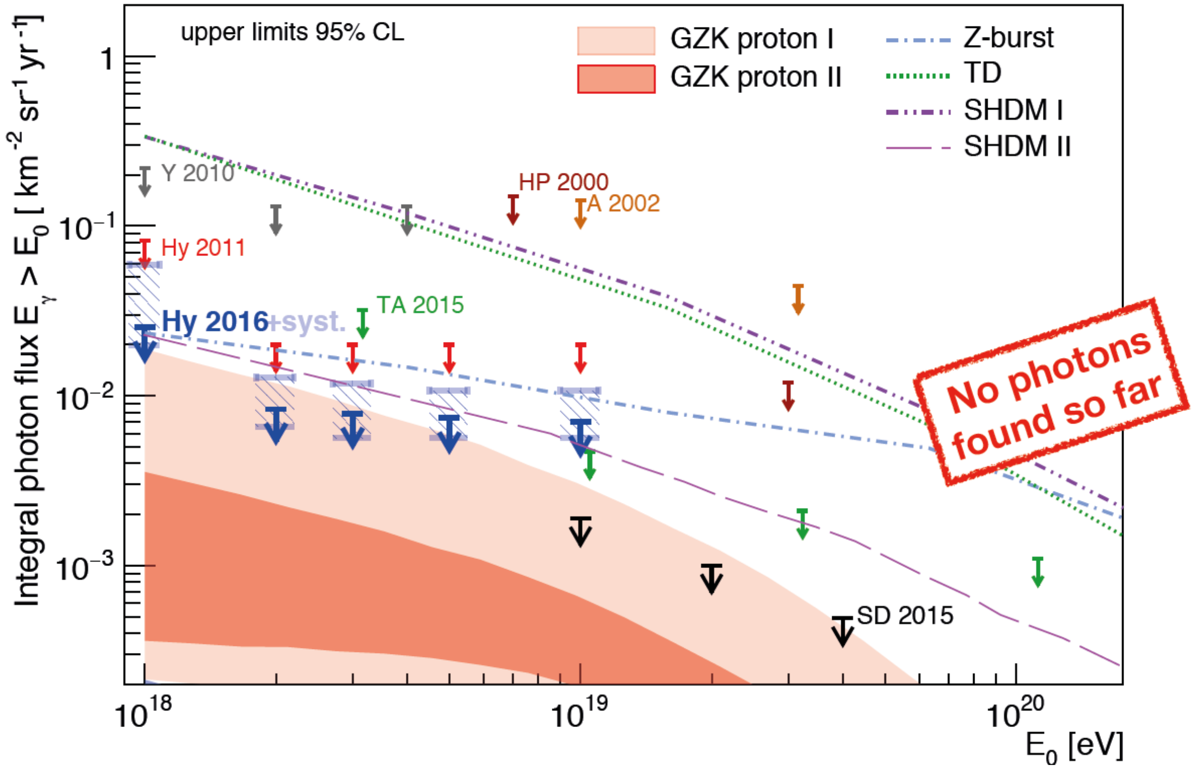
Nevod / Decor


26 м


θ = 55 - 65°
< ΣN_ph.e. / D >, 10^3 ph.e.*m^2
D, m^-2
10^16 eV
10^17 eV
60 events
Fe
p
3471
1453
602
234
34
32
30
28
26
24
22
20
0.1
1

Beyond Standard Model

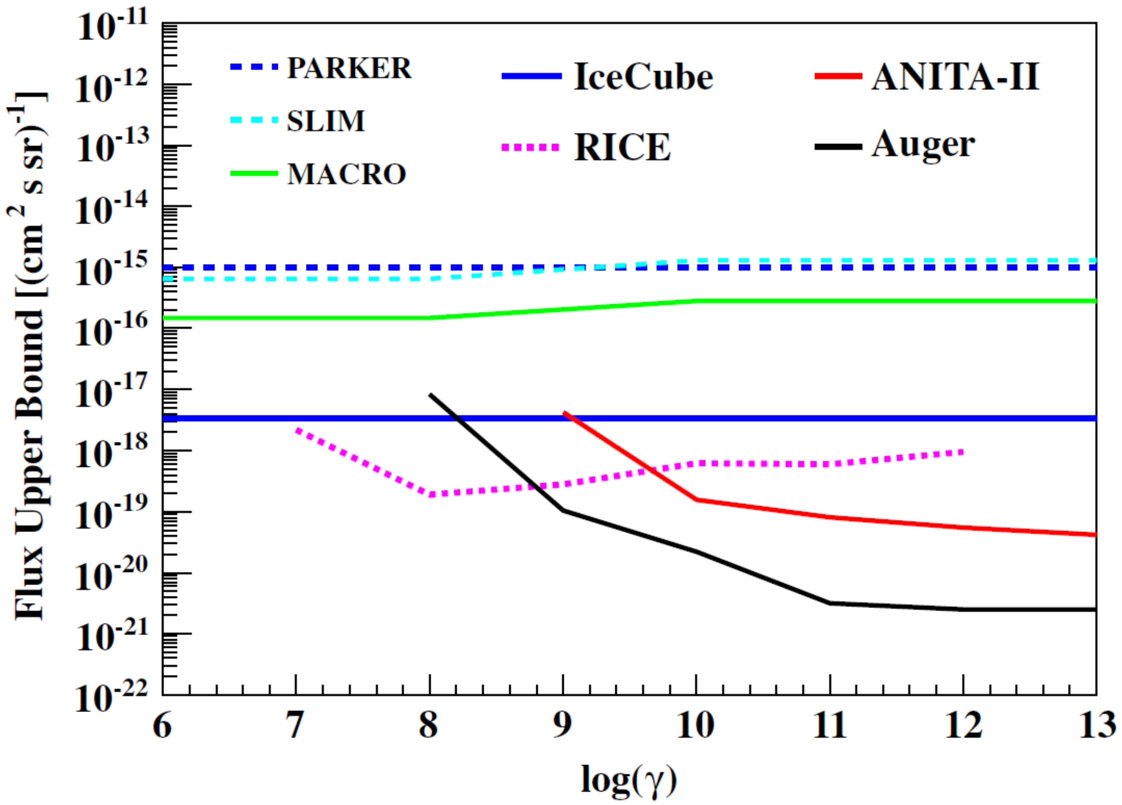
….of Acceleration



Most models of UHECR from exotic sources are ruled out:

- topological defects
- monopoles
- cosmic strings
- cosmic necklaces
- HE neutrinos create Z-bursts in resonant interactions
- …..

….of Particle Physics e.g., Monopoles



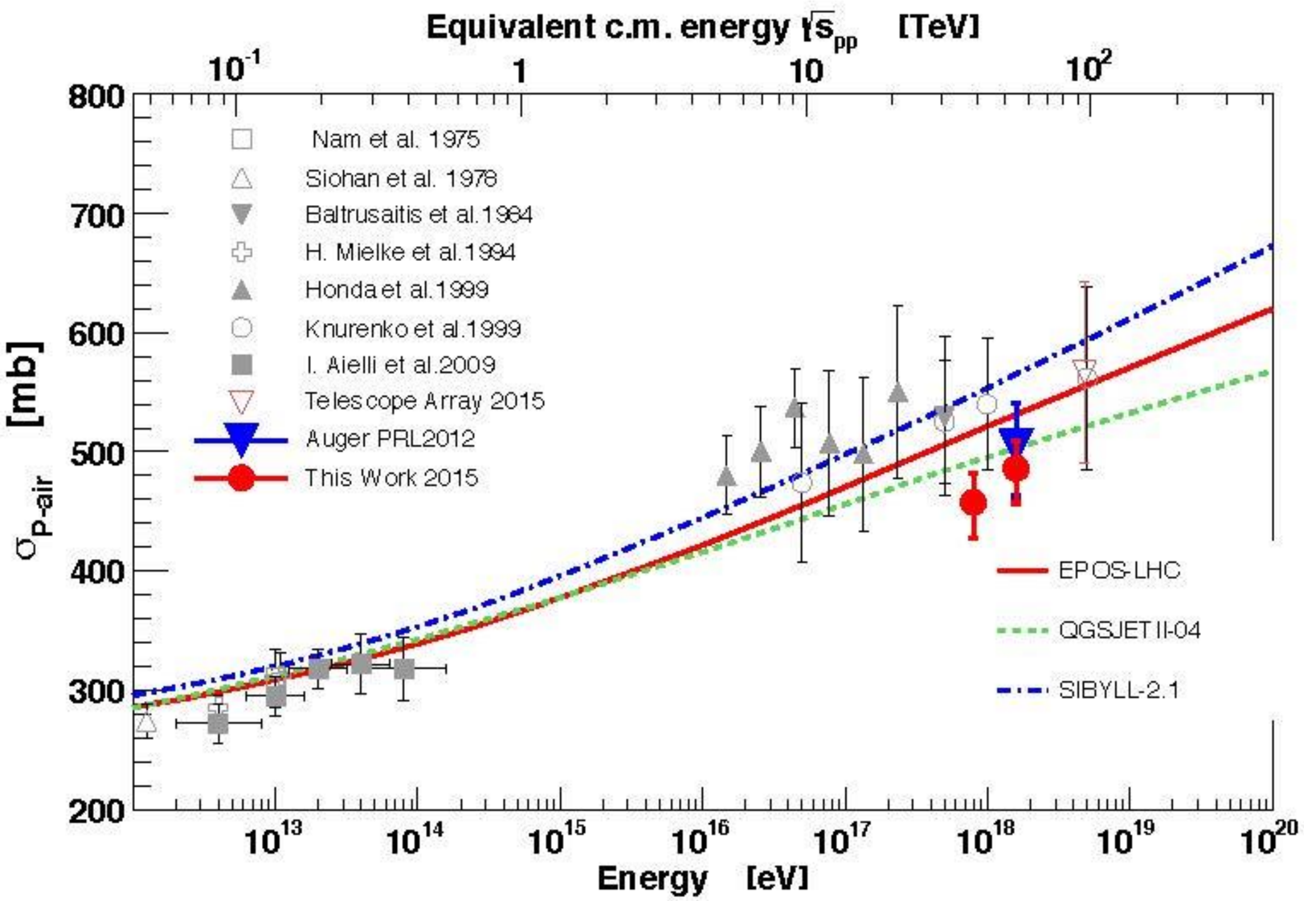
The particle showers produced by an ultrarelativistic monopole with similar energy deposit than UHECR, but different profile.

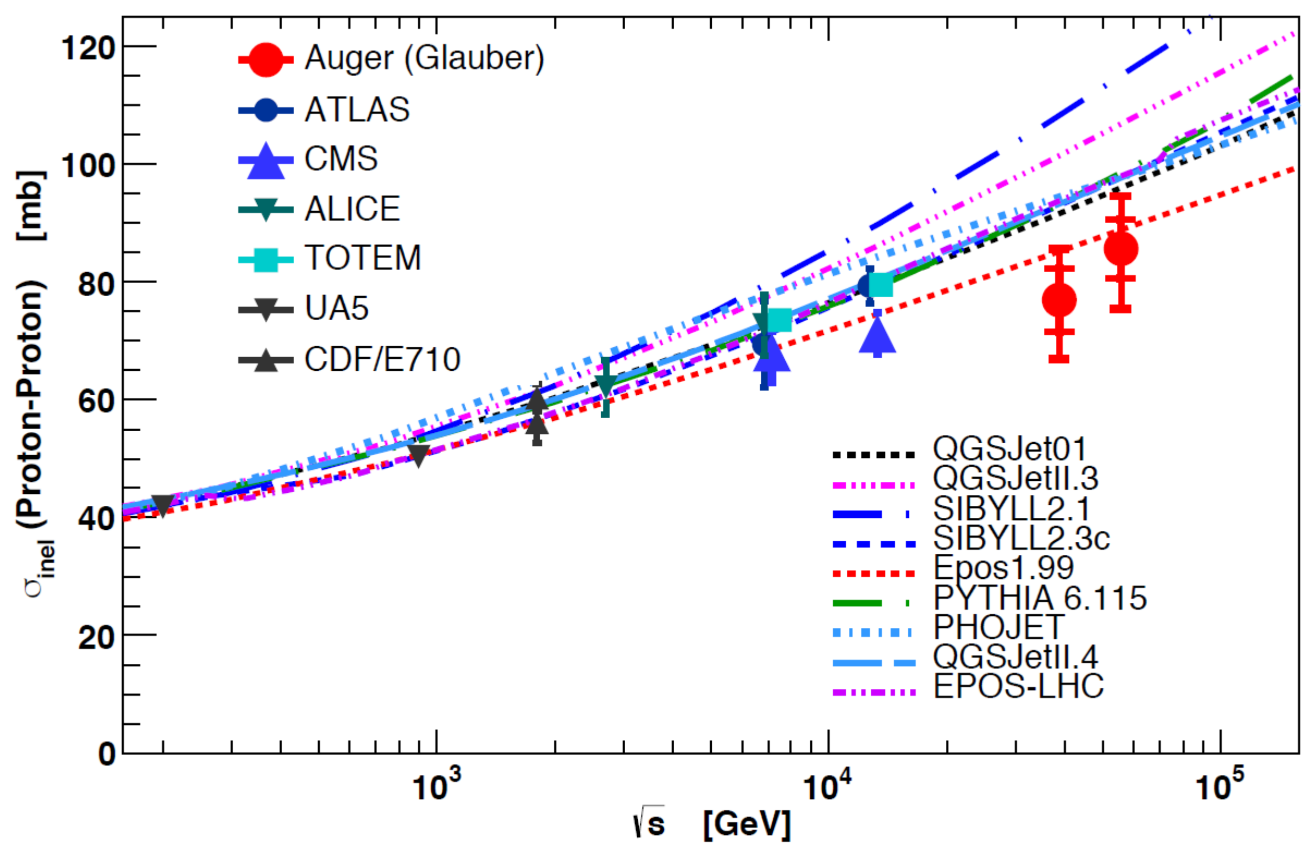
➔ Fluorescence measurements

Auger, PRED 94, 082002 (2016)

Hot topic: Plasma Wakefield Acceleration in the Lab and in the Universe?

Cross-section





Glauber model (multiple scattering approximation)

(Ulrich, Auger, ICRC 2017)

Connection Cosmic Ray – Particle Physics

Interaction physics:

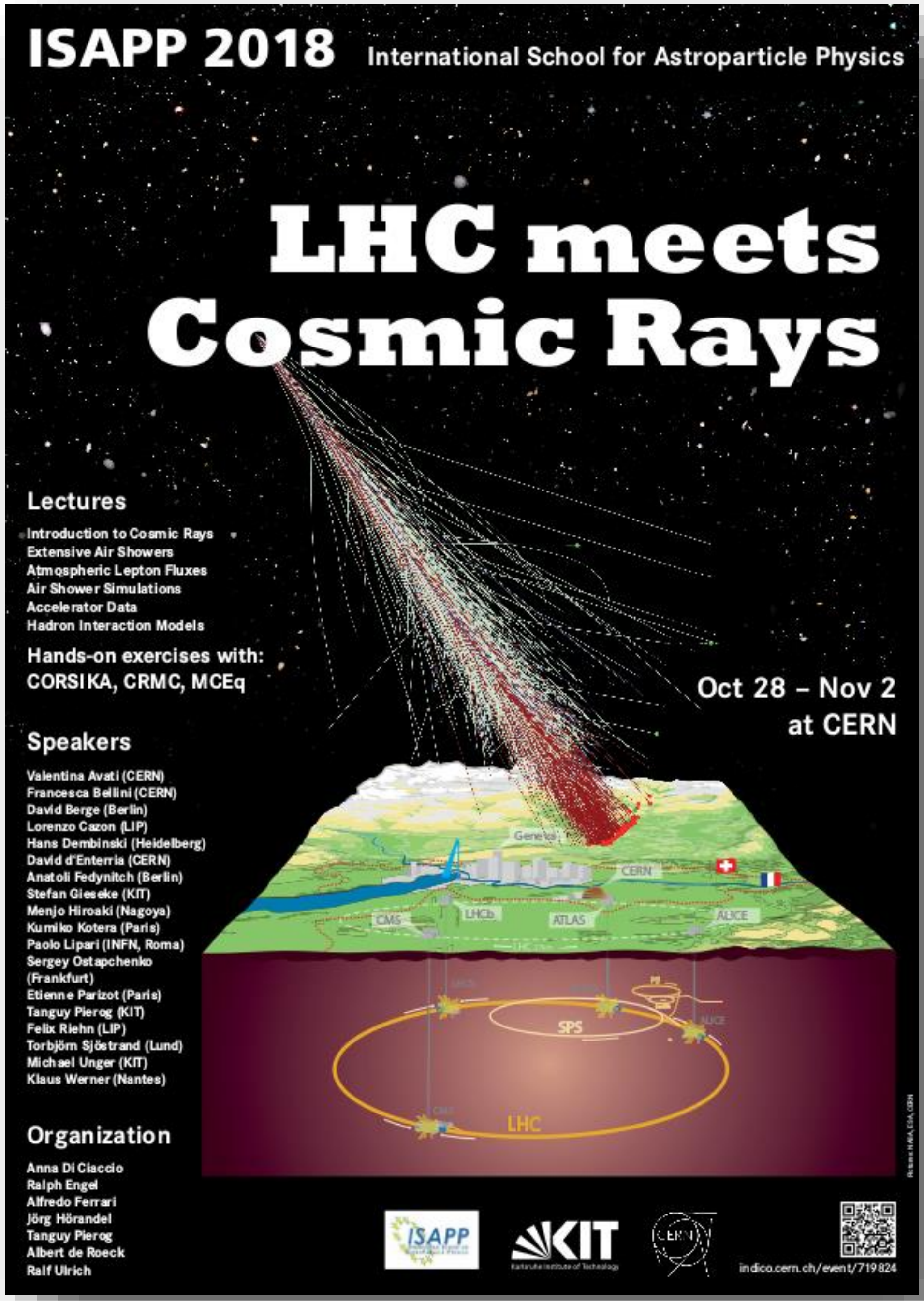
→ higher energies, forward direction
→ validation of models
→ beyond standard model physics
→ (proton-proton) cross-sections

Technology:

→ detector developments
→ readout electronics
→ Monte-Carlo software
→ handling large infrastructures
→ computing models
→ Big Data Analytics

Society:

→ ‚FAIR' data life cycle
→ outreach
→ education / training



➔ Sources of UHECR
➔ Understanding the high-energy Universe
➔ UHE particle physics

see talk Teresa Montaruli
#084: APPEC