



Ultra-high-energy Cosmic Rays in the next Decade(s): a personal summary of the Snowmass CF7 Whitepaper on UHECR

Frank G. Schroeder (coordinators and coauthors of Whitepaper on next slide)

Bartol Research Institute, Department of Physics and Astronomy, University of Delaware, Newark, DE, USA,
 and Karlsruhe Institute of Technology (KIT), Institute for Nuclear Physics, Karlsruhe, Germany

Experiment	Feature	Cosmic Ray Science*	Timeline
Pierre Auger Observatory	Hybrid array: fluorescence, surface e/μ + radio, 3000 km ²	Hadronic interactions, search for BSM, UHECR source populations, σ_{p-Air}	AugerPrime upgrade
Telescope Array (TA)	Hybrid array: fluorescence, surface scintillators, up to 3000 km ²	UHECR source populations proton-air cross section (σ_{p-Air})	TAx4 upgrade
IceCube / IceCube-Gen2	Hybrid array: surface + deep, up to 6 km ²	Hadronic interactions, prompt decays, Galactic to extragalactic transition	Upgrade + surface enhancement → IceCube-Gen2 deployment → IceCube-Gen2 operation
GRAND	Radio array for inclined events, up to 200,000 km ²	UHECR sources via huge exposure, search for ZeV particles, σ_{p-Air}	GRANDProto 300 → GRAND 10k → GRAND 200k multiple sites, step by step
POEMMA	Space fluorescence and Cherenkov detector	UHECR sources via huge exposure, search for ZeV particles, σ_{p-Air}	JEM-EUSO program → POEMMA
GCOS	Hybrid array with X_{max} + e/μ over 40,000 km ²	UHECR sources via event-by-event rigidity, forward particle physics, search for BSM, σ_{p-Air}	GCOS R&D + first site → GCOS further sites

*All experiments contribute to multi-messenger astrophysics also by searches for UHE neutrinos and photons; several experiments (IceCube, GRAND, POEMMA) have astrophysical neutrinos as primary science case.

2025 2030 2035 2040

arXiv:2205.05845

Snowmass Whitepaper

- UHECR whitepaper prepared for U.S. Snowmass survey which is about *particle physics* in the next decade(s)
 - WP covers particle and astrophysics aspects of UHECR
 - almost 100 authors + 200+ endorsers
 - 283 pages (with front- and back-matter)
 - to be published in Astroparticle Physics
- Input from the community via workshops and via topical conveners
- WP makes general recommendations and outlines a plan for experiments over the next decades
 - caveat: Snowmass targets U.S. funding agencies and particle physics community

see references in WP for material shown here:

<https://arxiv.org/pdf/2205.05845>

Ultra-High-Energy Cosmic Rays

The Intersection of the Cosmic and Energy Frontiers

CONVENERS

A. Coleman¹, J. Eser², E. Mayotte³, F. Sarazin^{†3}, F. G. Schröder^{†1,4}, D. Soldin¹, T. M. Venters^{†5}

TOPICAL CONVENERS

R. Aloisio⁶, J. Alvarez-Muñiz⁷, R. Alves Batista⁸, D. Bergman⁹, M. Bertaina¹⁰, L. Caccianiga¹¹, O. Deligny¹², H. P. Dembinski¹³, P. B. Denton¹⁴, A. di Matteo¹⁵, N. Globus^{16,17}, J. Glombitza¹⁸, G. Golup¹⁹, A. Haungs⁴, J. R. Hörandel²⁰, T. R. Jaffe²¹, J. L. Kelley²², J. F. Krizmanic⁵, L. Lu²², J. N. Matthews⁹, I. Maris²³, R. Mussa¹⁵, F. Oikonomou²⁴, T. Pierog⁴, E. Santos²⁵, P. Tinyakov²³, Y. Tsunesada²⁶, M. Unger⁴, A. Yushkov²⁵

CONTRIBUTORS

M. G. Albrow²⁷, L. A. Anchordoqui²⁸, K. Andeen²⁹, E. Arnone^{10,15}, D. Barghini^{10,15}, E. Bechtol²², J. A. Bellido³⁰, M. Casolino^{31,32}, A. Castellina^{15,33}, L. Cazon⁷, R. Conceição³⁴, R. Cremonini³⁵, H. Dujmovic⁴, R. Engel^{4,36}, G. Farrar³⁷, F. Fenu^{10,15}, S. Ferrarese¹⁰, T. Fujii³⁸, D. Gardiol³³, M. Gritsevich^{39,40}, P. Homola⁴¹, T. Huege^{4,42}, K. -H. Kampert⁴³, D. Kang⁴, E. Kido⁴⁴, P. Klimov⁴⁵, K. Kotera^{42,46}, B. Kozelov⁴⁷, A. Leszczyńska^{1,36}, J. Madsen²², L. Marcelli³², M. Marisaldi⁴⁸, O. Martineau-Huynh⁴⁹, S. Mayotte³, K. Mulrey²⁰, K. Murase^{50,51}, M. S. Muzio⁵⁰, S. Ogio²⁶, A. V. Olinto², Y. Onel⁵², T. Paul²⁸, L. Piotrowski³¹, M. Plum⁵³, B. Pont²⁰, M. Reininghaus⁴, B. Riedel²², F. Riehn³⁴, M. Roth⁴, T. Sako⁵⁴, F. Schlüter^{4,55}, D. Shoemaker⁵⁶, J. Sidhu⁵⁷, I. Sidelnik¹⁹, C. Timmermans^{20,58}, O. Tkachenko⁴, D. Veberič⁴, S. Verpoest⁵⁹, V. Verzi³², J. Vícha²⁵, D. Winn⁵², E. Zas⁷, M. Zotov⁴⁵

[†]Correspondence: fsarazin@mines.edu, fgs@udel.edu, tonia.m.venters@nasa.gov

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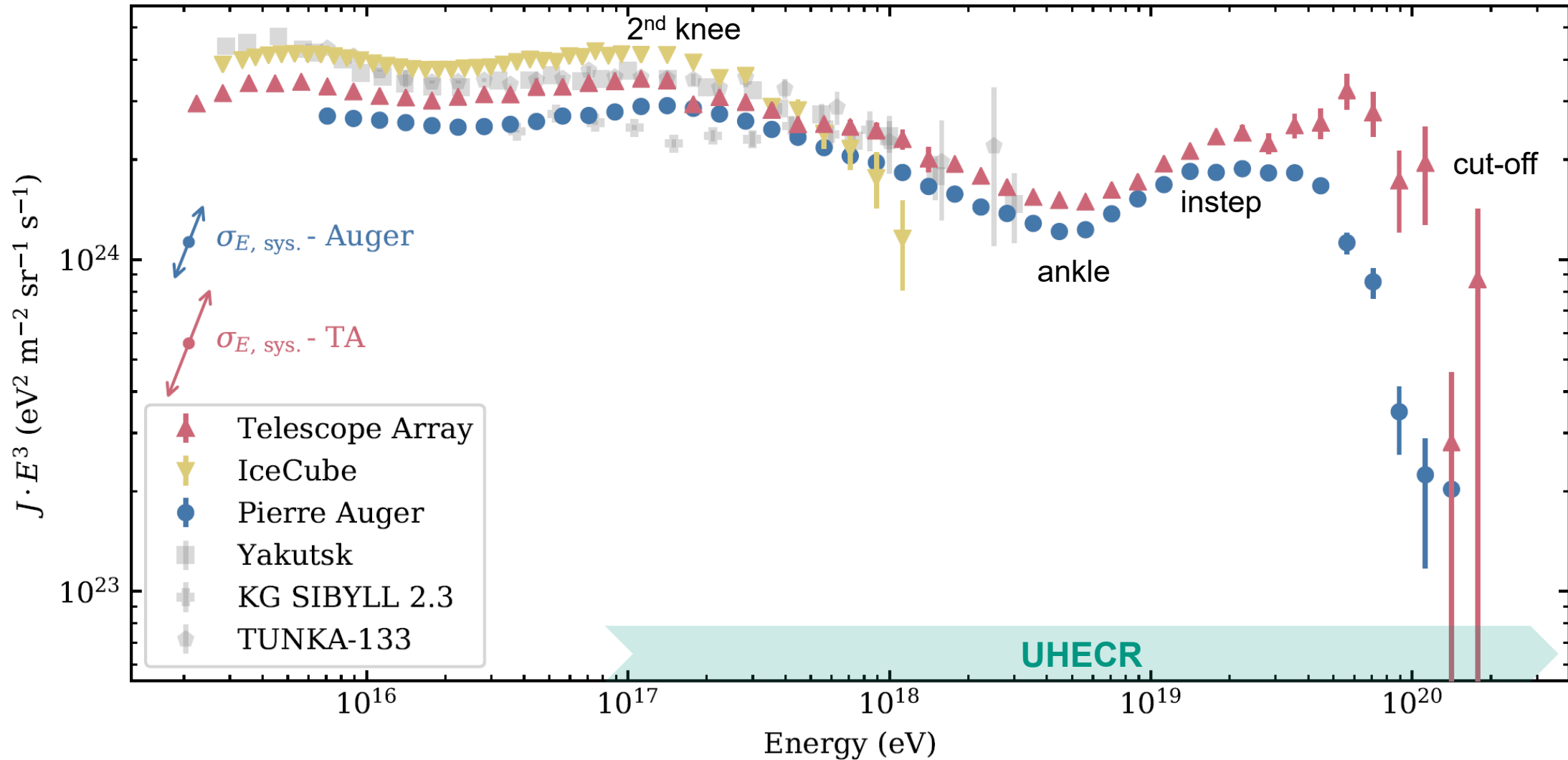
Acknowledgements

Bibliography

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Cosmic-Ray Energy Spectrum: UHECR above 100 PeV*



*100 PeV threshold for UHECR motivated by start of extragalactic component and by muon problem

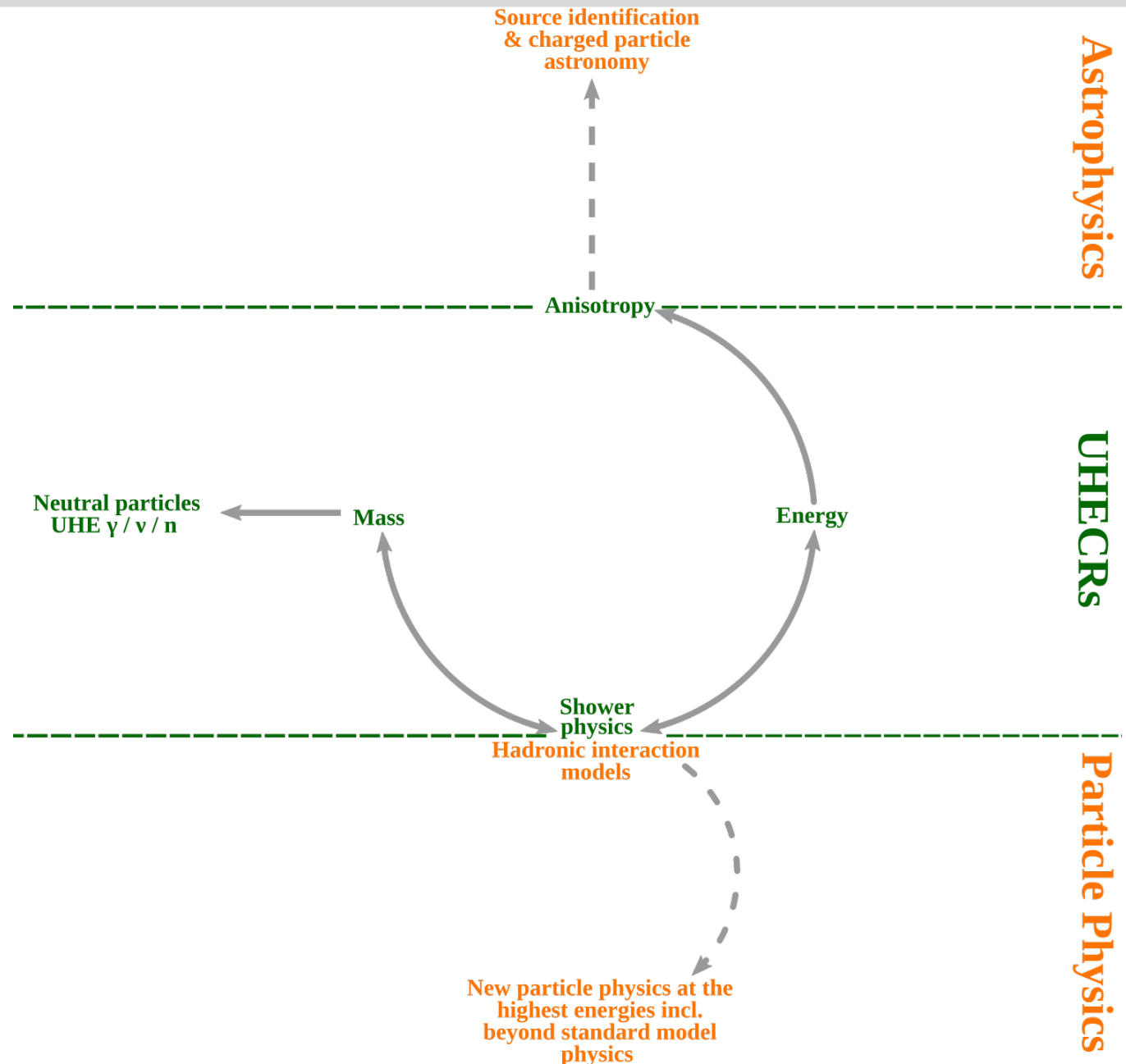
Big UHECR Picture

■ astrophysics

- source (classes)
- via anisotropy
- via test of models against observed mass and energy

■ particle physics

- shower physics
- physics in sources and during propagation
- search for BSM



Big UHECR Picture

■ astrophysics

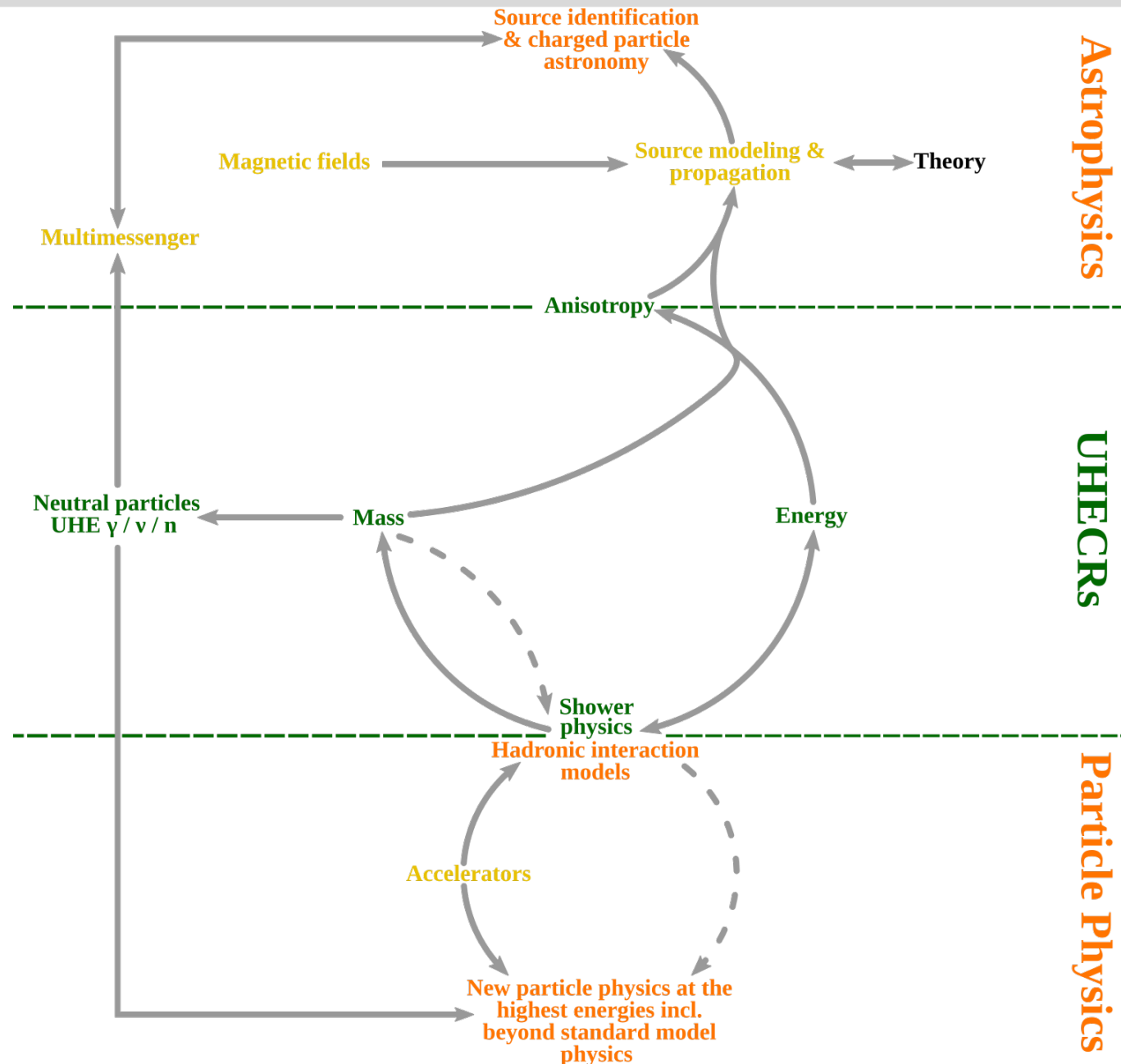
- source (classes)
- via anisotropy
- via test of models against observed mass and energy

■ particle physics

- shower physics
- physics in sources and during propagation
- search for BSM

■ connection to other fields

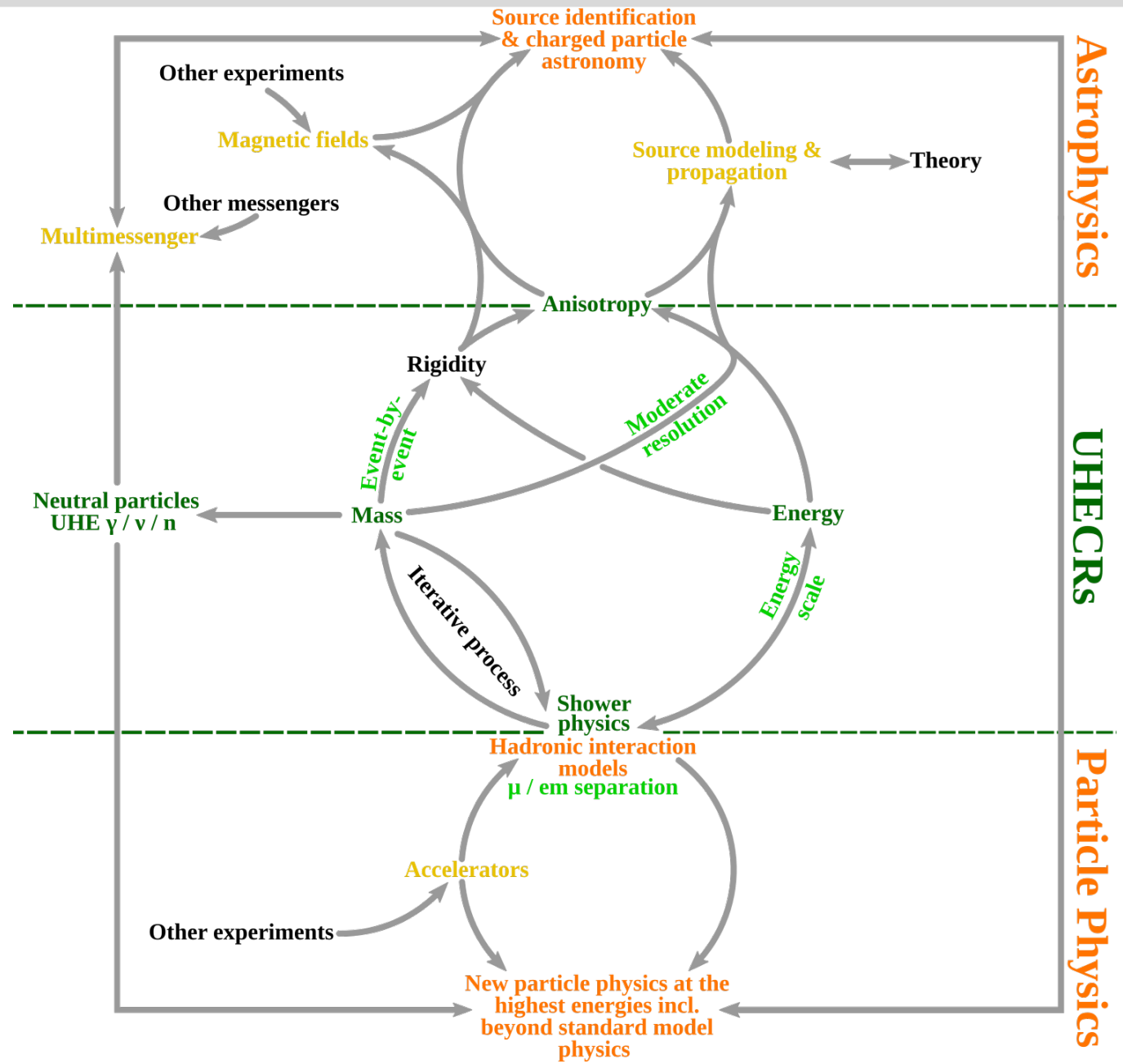
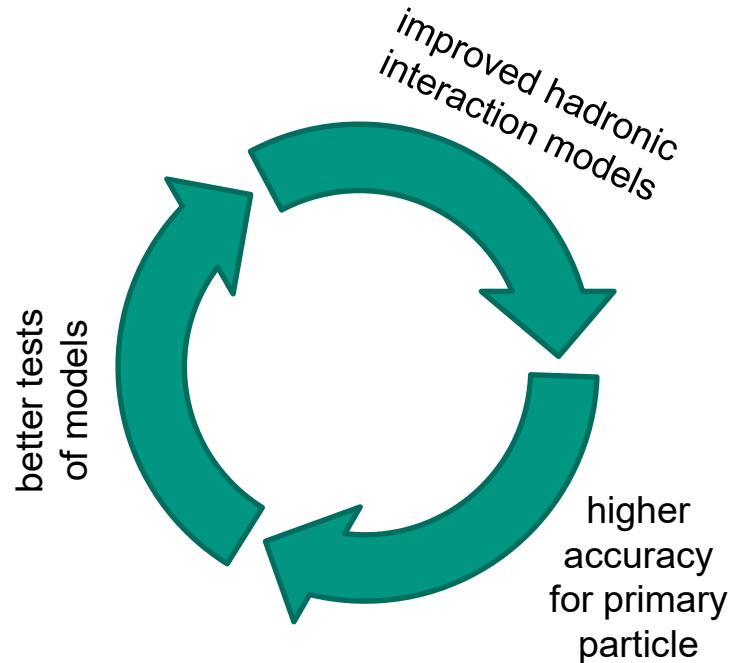
- multimessenger
- magnetic fields in space
- accelerator experiments



Big UHECR Picture

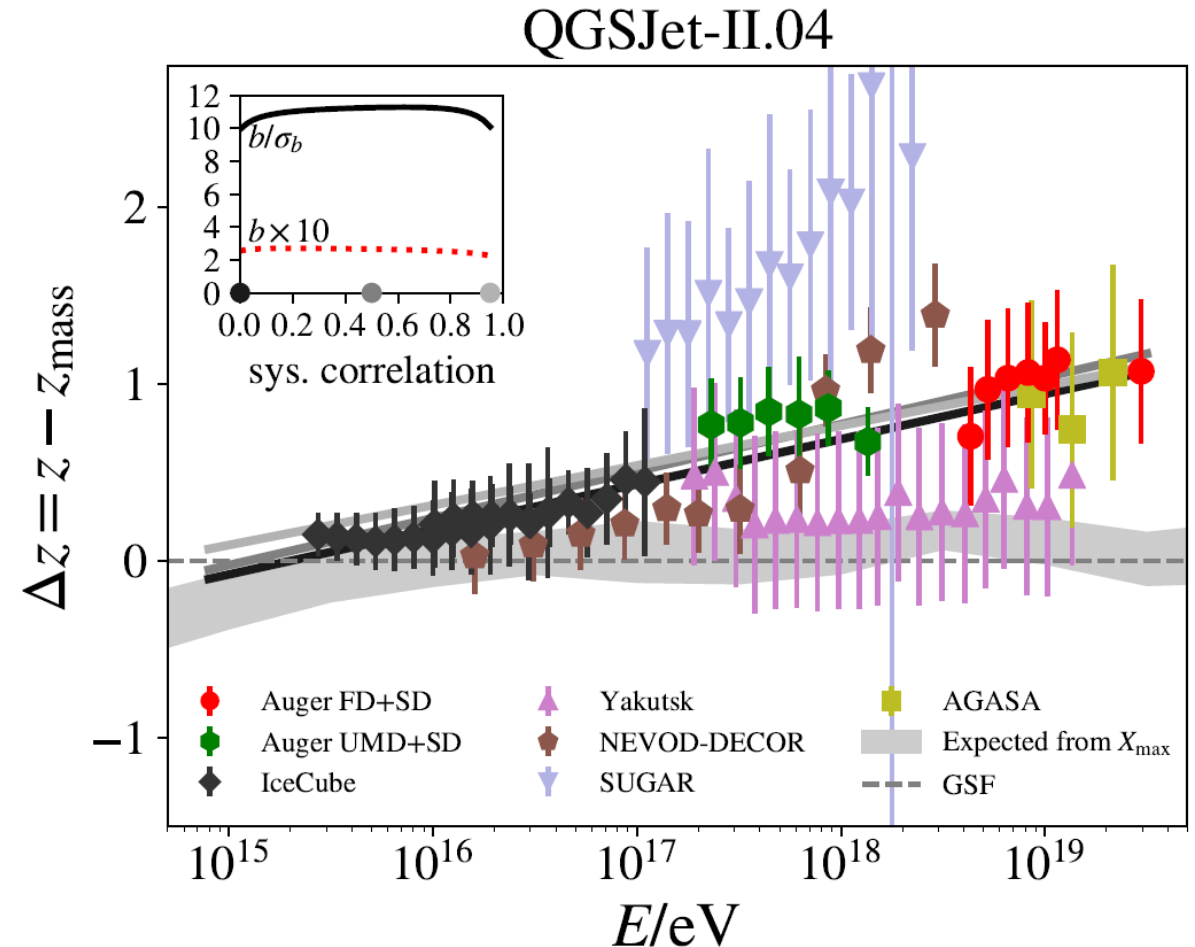
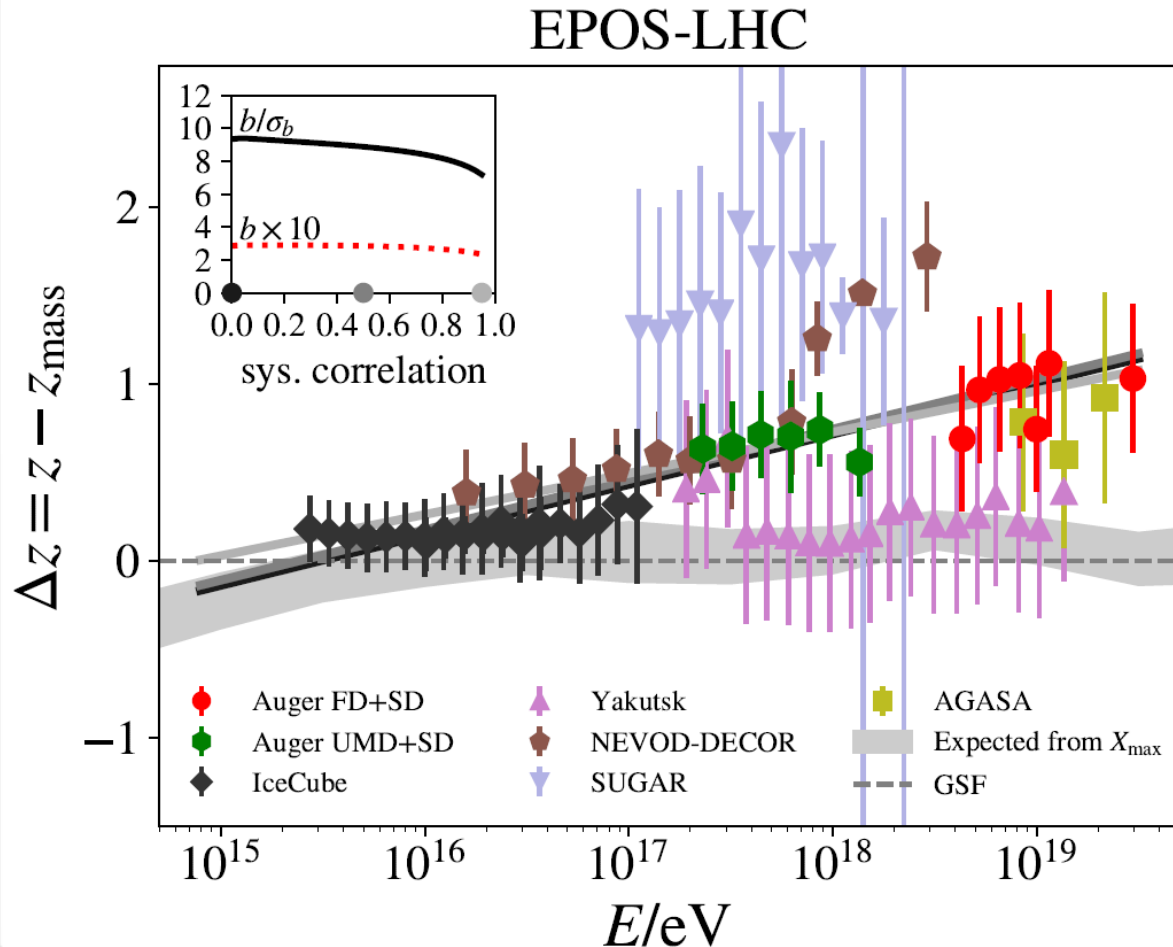
- interplay between particle and UHECR astrophysics
- higher accuracy for rigidity

virtuous circle of cosmic-ray physics



Particle Physics: Muon Problem in Hadronic Interaction Models

- Hadronic models predict too few muons above PeV energies
- Tensions also for other muon observables (production height, dependence on shower inclination)



Particle Physics: Test of various BSM scenarios, SHDM, LIV, ...

- UHECR: guaranteed progress in astrophysics *and* search for dark matter, LIV, ...

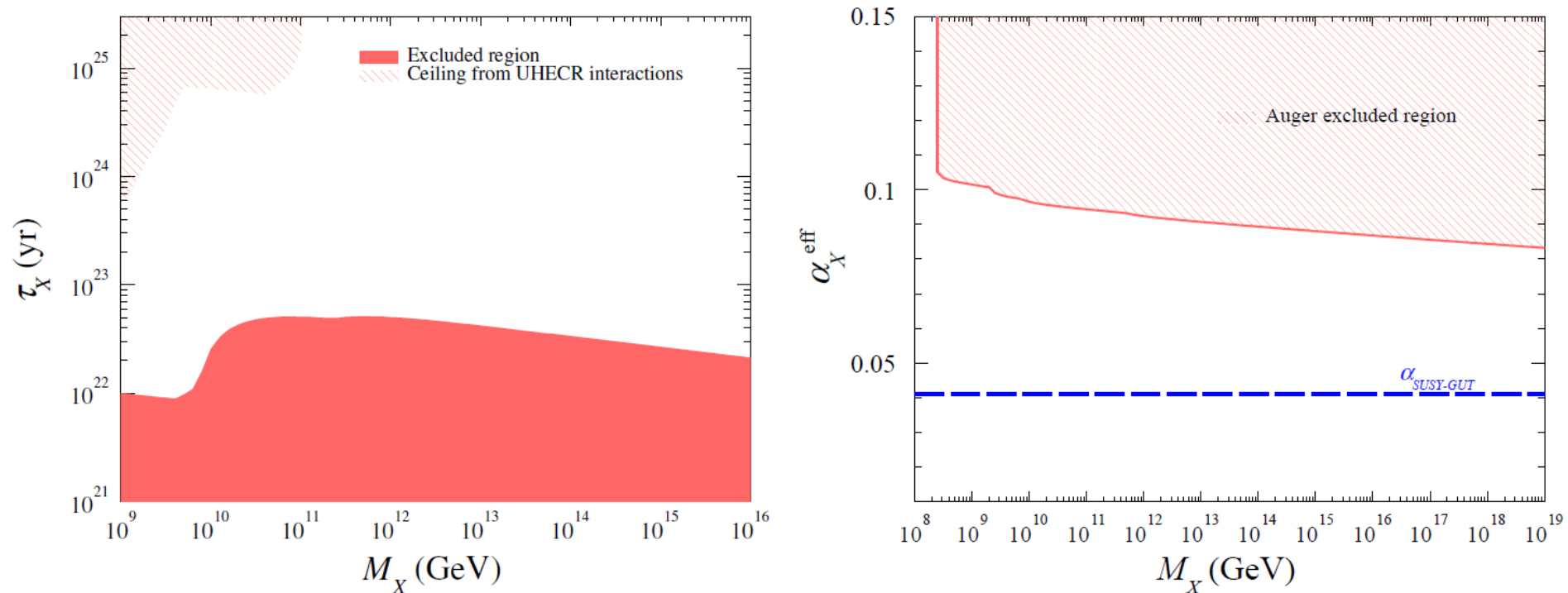


Figure 3.8: Constraints on the mass and lifetime of SHDM particles as obtained from the upper limits on photons [375] (left) and upper limits at 95% C.L. on the effective coupling constant of a hidden gauge interaction as a function of the mass for a dark matter particle decaying into $q\bar{q}$ [18] (right). For reference, the unification of the three SM gauge couplings is shown as the blue dashed line in the framework of supersymmetric GUTs [376]. Figures taken from Refs. [18, 375].

Big UHECR Picture

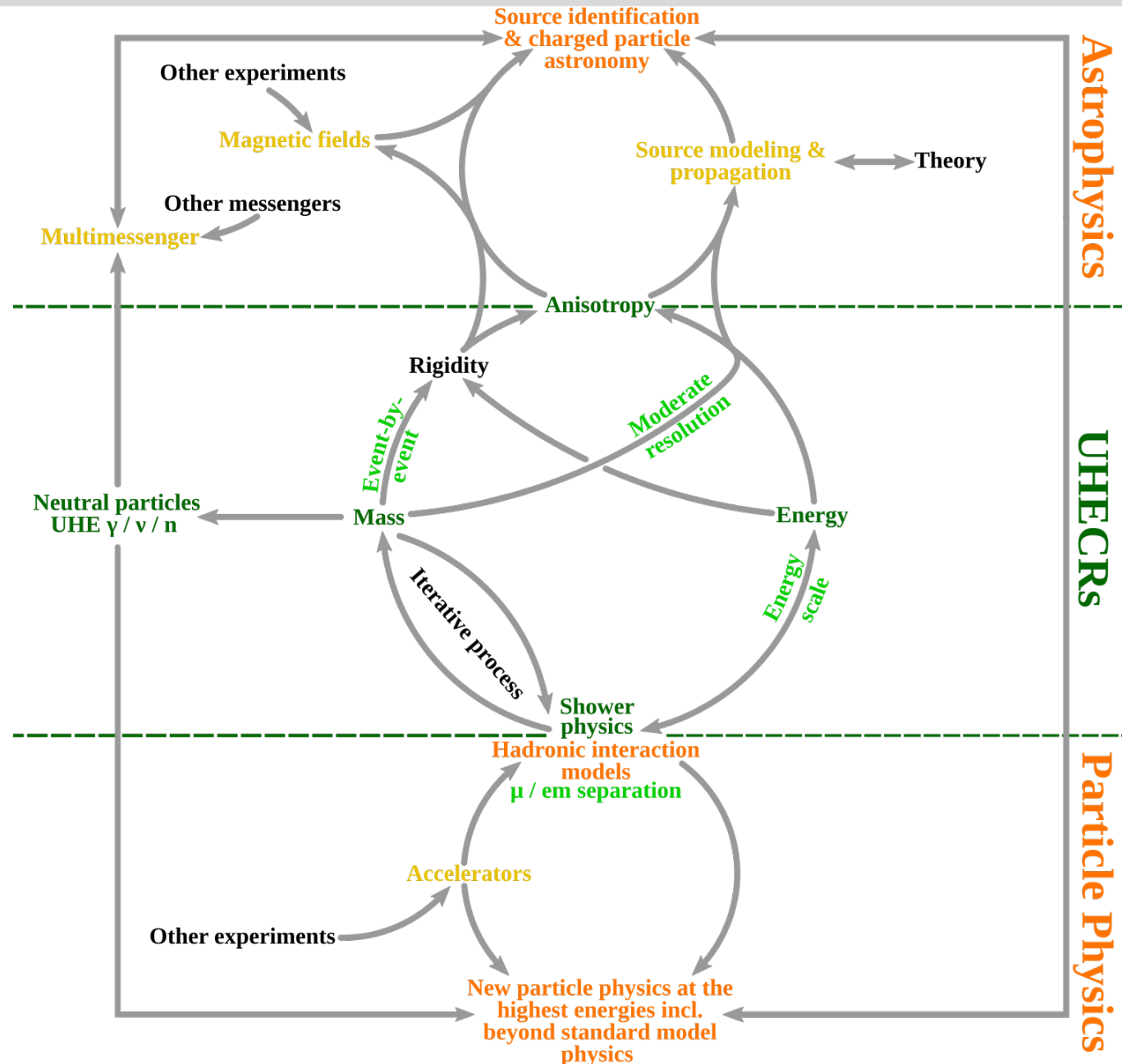
Two types of future experiments:

■ Event-by-event Rigidity

- requires high accuracy for mass and energy of primary particle
- enables rigidity selection to search for sources in distribution of arrival directions
- promising if rigidities $R > 10$ EV stem from mixed composition

■ Huge Exposure

- anisotropy measurements with very high statistics
- requires only average mass composition for interpretation
- promising if composition is pure at highest energies, or if ZeV particles could be discovered



Big UHECR Picture

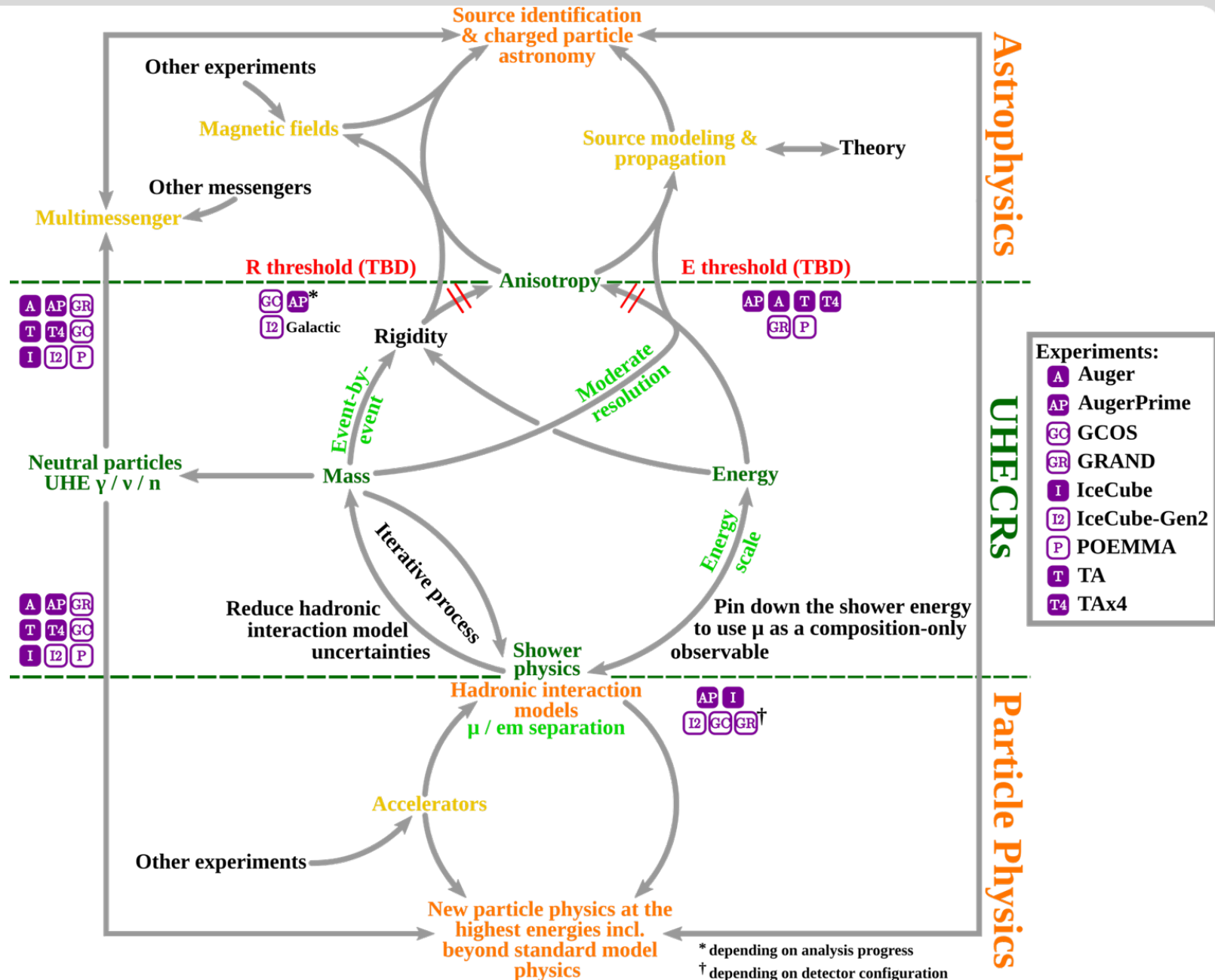
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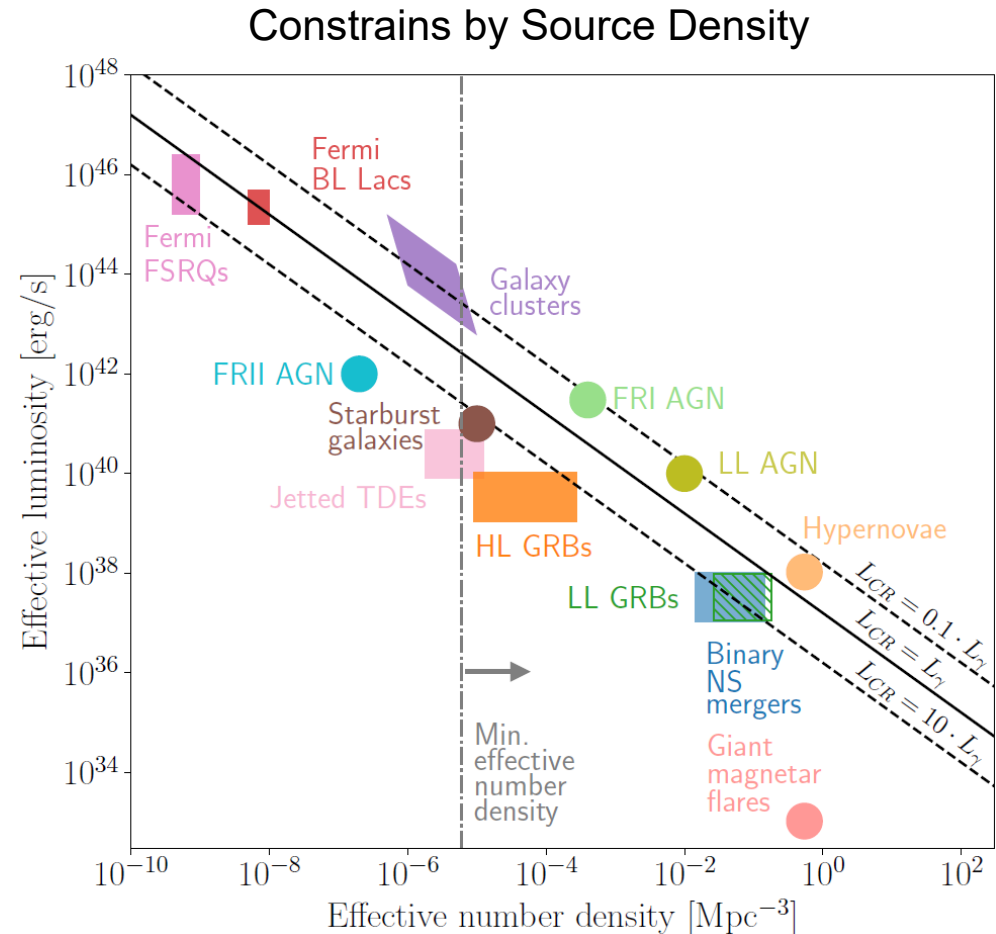
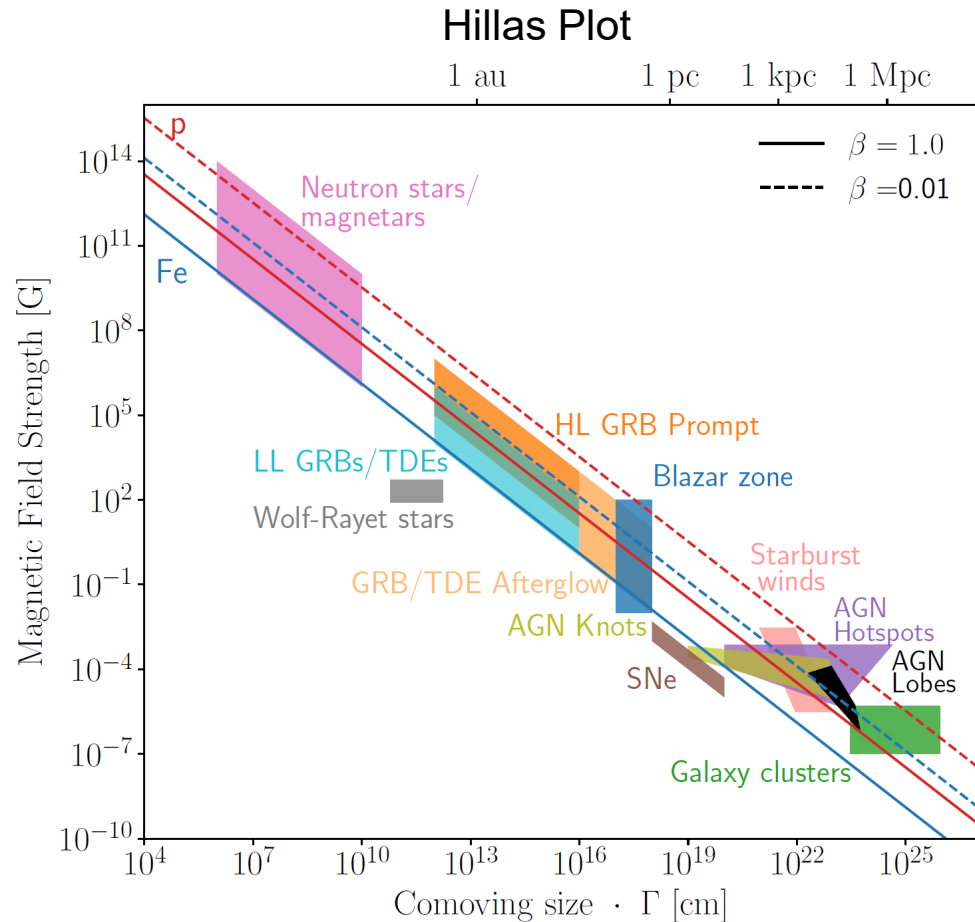
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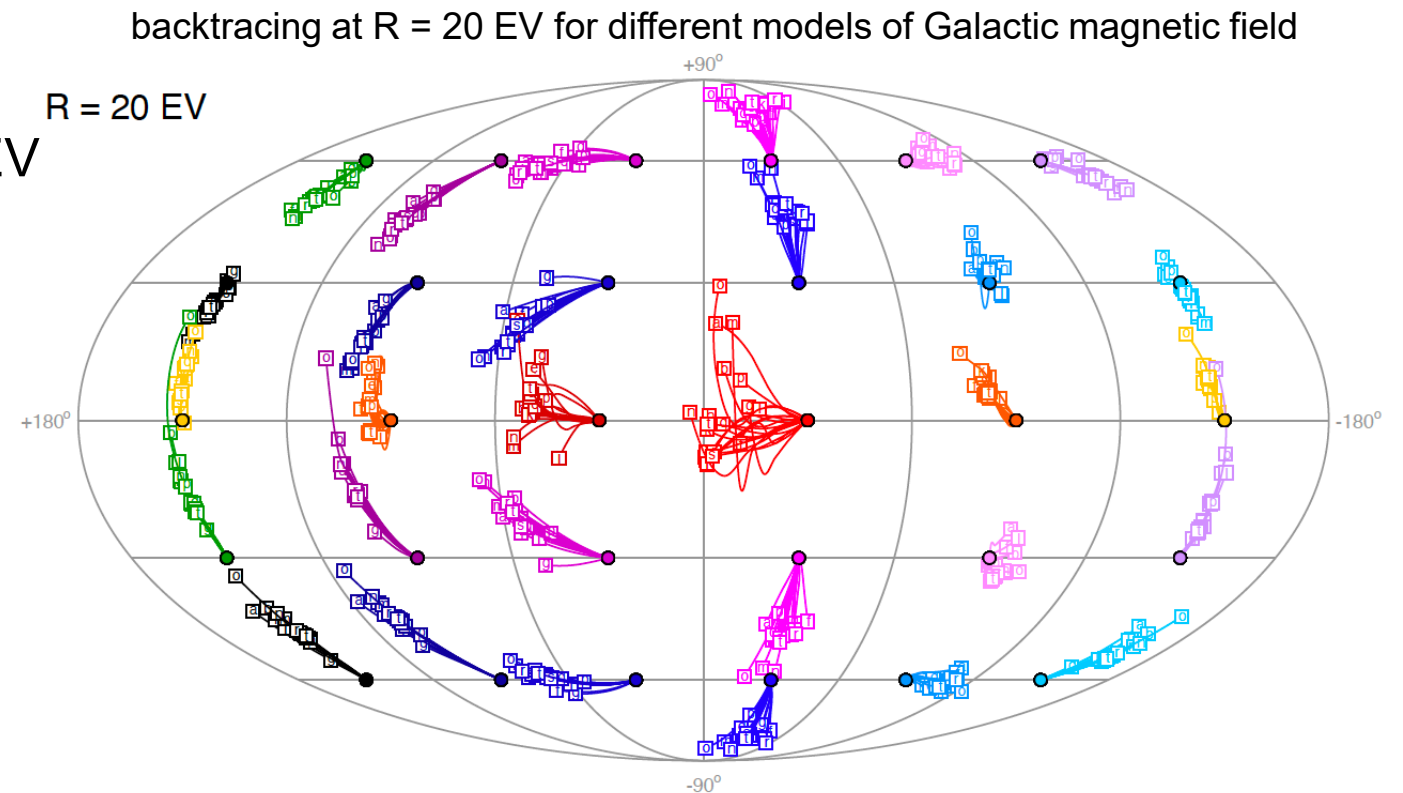
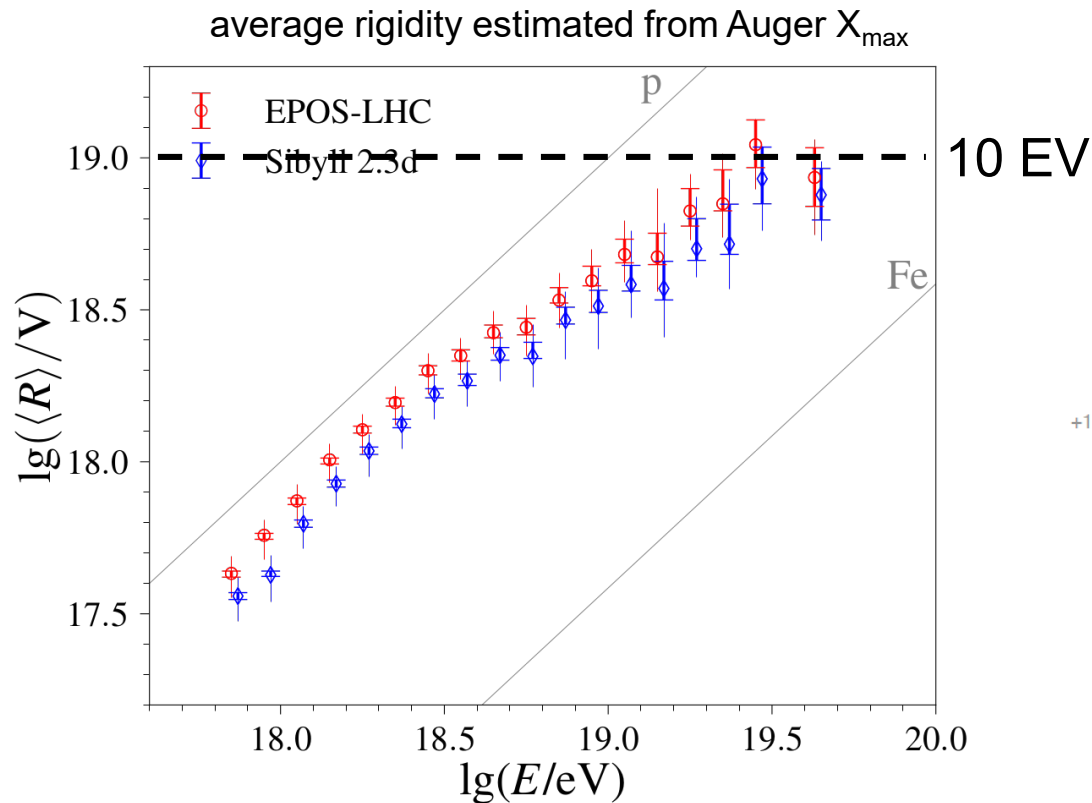
Astrophysics: What are the sources of UHECR?

- Are there Galactic EeV cosmic rays?
- Are there different populations and classes of extragalactic UHECR sources?



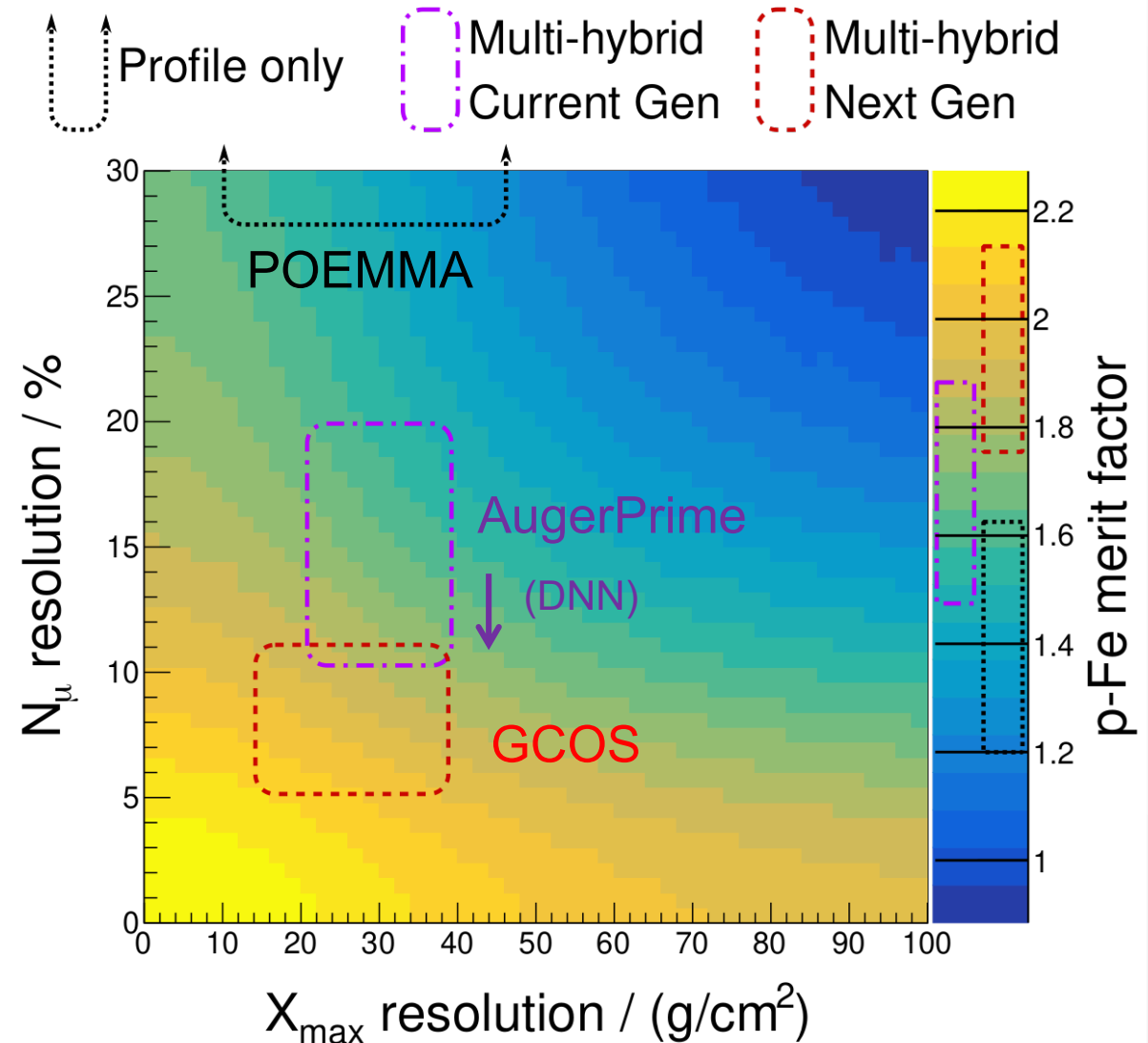
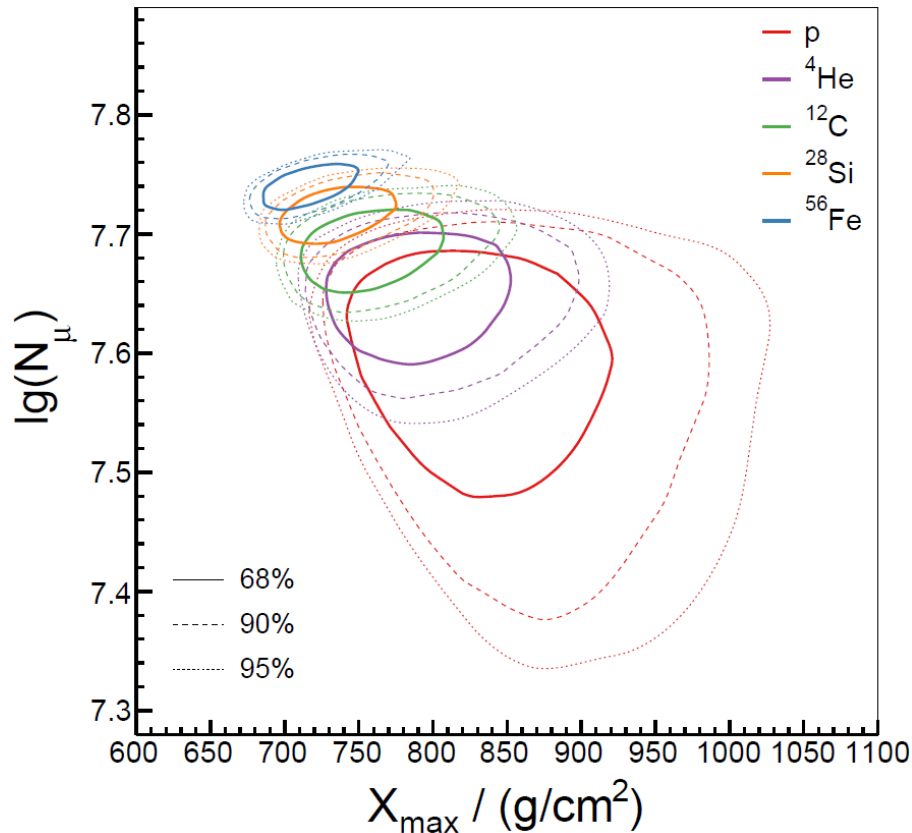
Particle Astronomy with Rigidities $R > 10$ EV

- Rigidity required for astronomy depends on knowledge of magnetic fields
- With current knowledge about 20 EV or higher desirable
- Likely, but not certain whether cosmic rays with $R > 10$ EV exist



How to improve the accuracy of rigidity measurements?

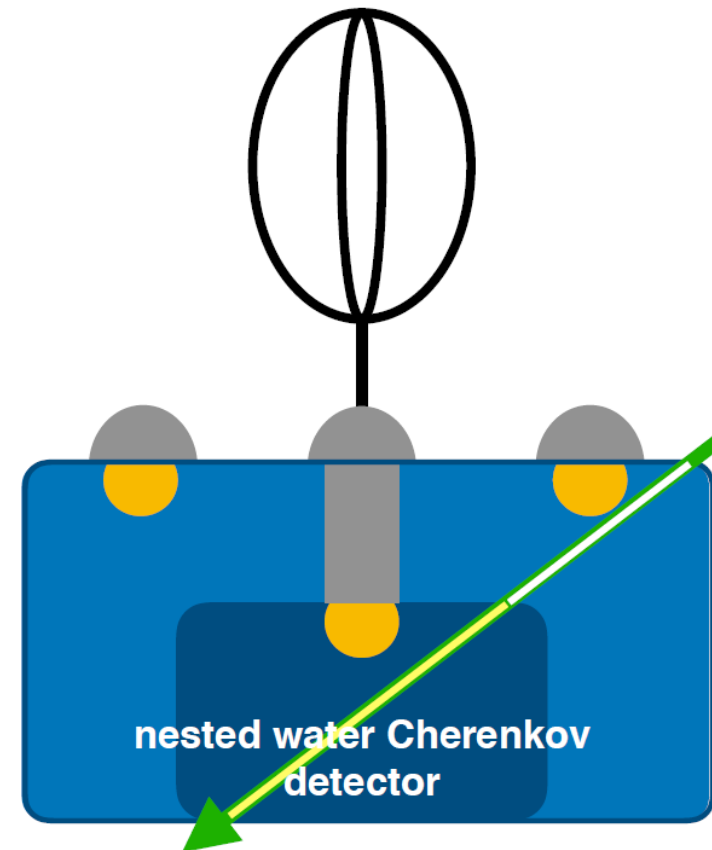
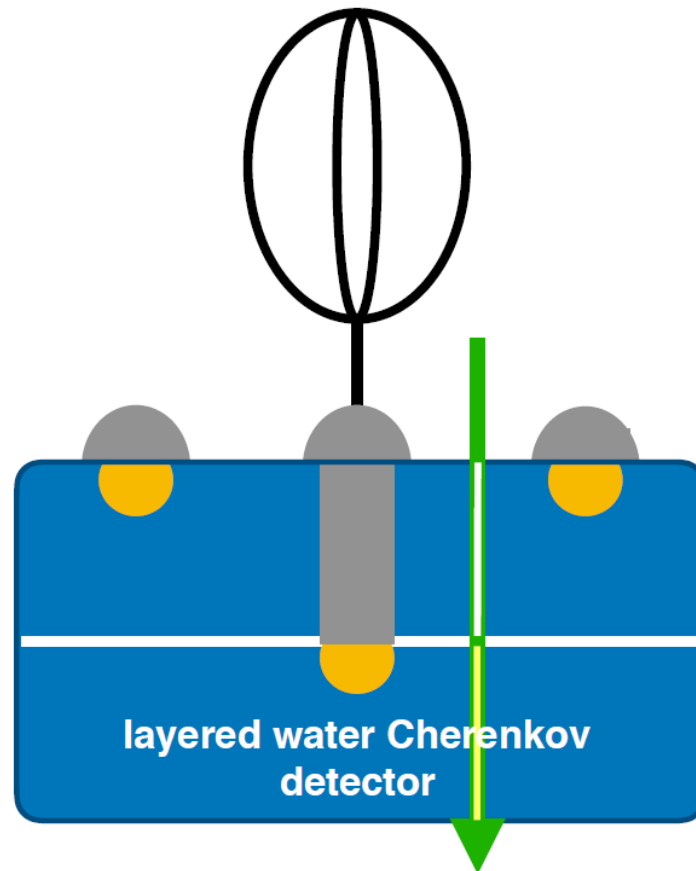
- Paradigm of shower universality tells us there are only few independent shower observables
- Need to measure all of them, if possible: combining muons and X_{\max} for mass resolution



How to improve muon measurements for rigidity?

- Goal: 10% muon number resolution with next generation particle detectors
- Need to have accurate measurement of electromagnetic component at the same time for rigidity
- New reconstruction techniques, e.g., neural networks, can provide X_{\max} with the same detectors

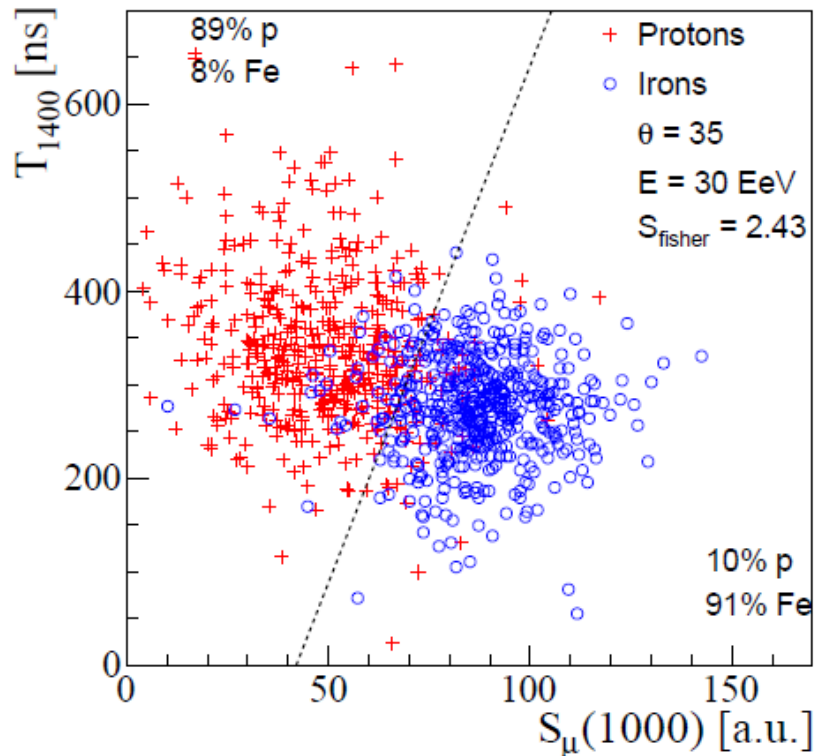
possible detector layout for GCOS



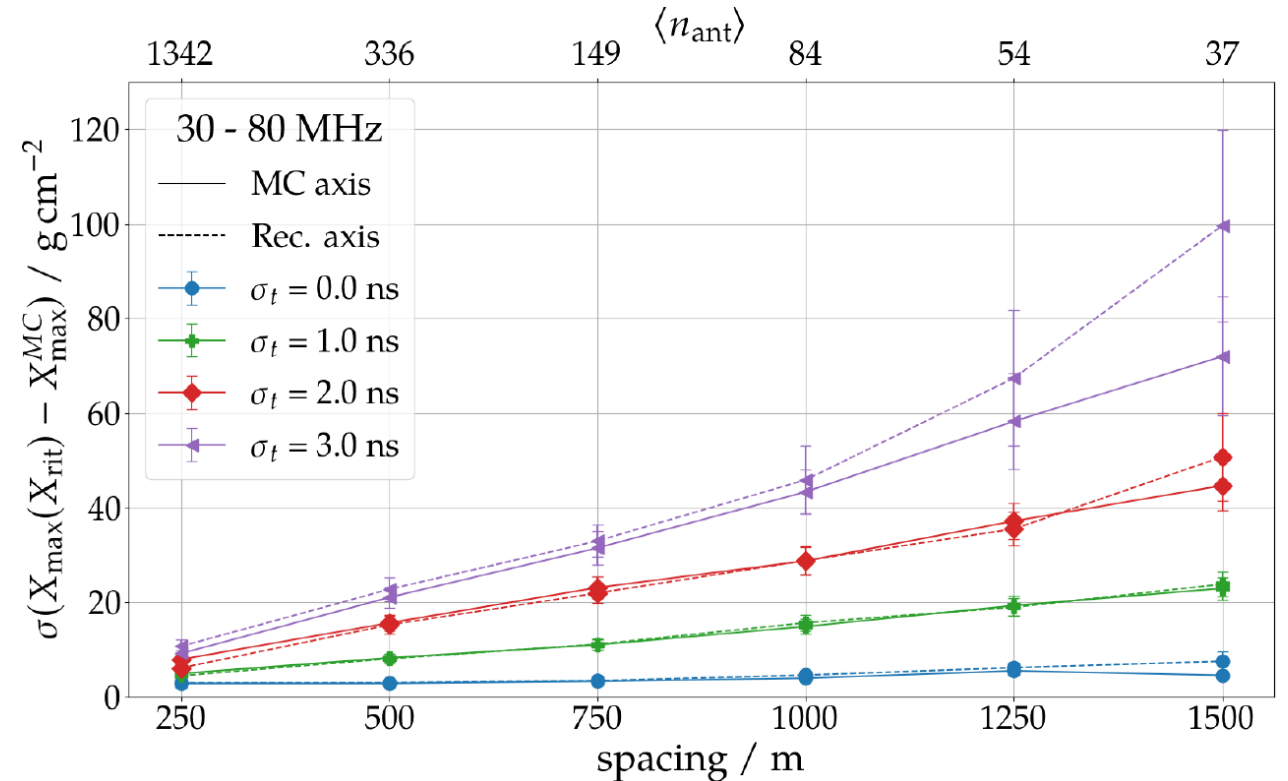
How to improve X_{\max} measurements?

- Higher X_{\max} accuracy than the about 20 g/cm² achieved today is unnecessary due to fluctuations
- Further development of fluorescence technique to provide huge exposure at affordable cost
- 24/7 duty cycle possible from particle detector or radio antennas with similar accuracy

X_{\max} from time distribution in layered tank



simulation study: X_{\max} with radio interferometry for inclined showers

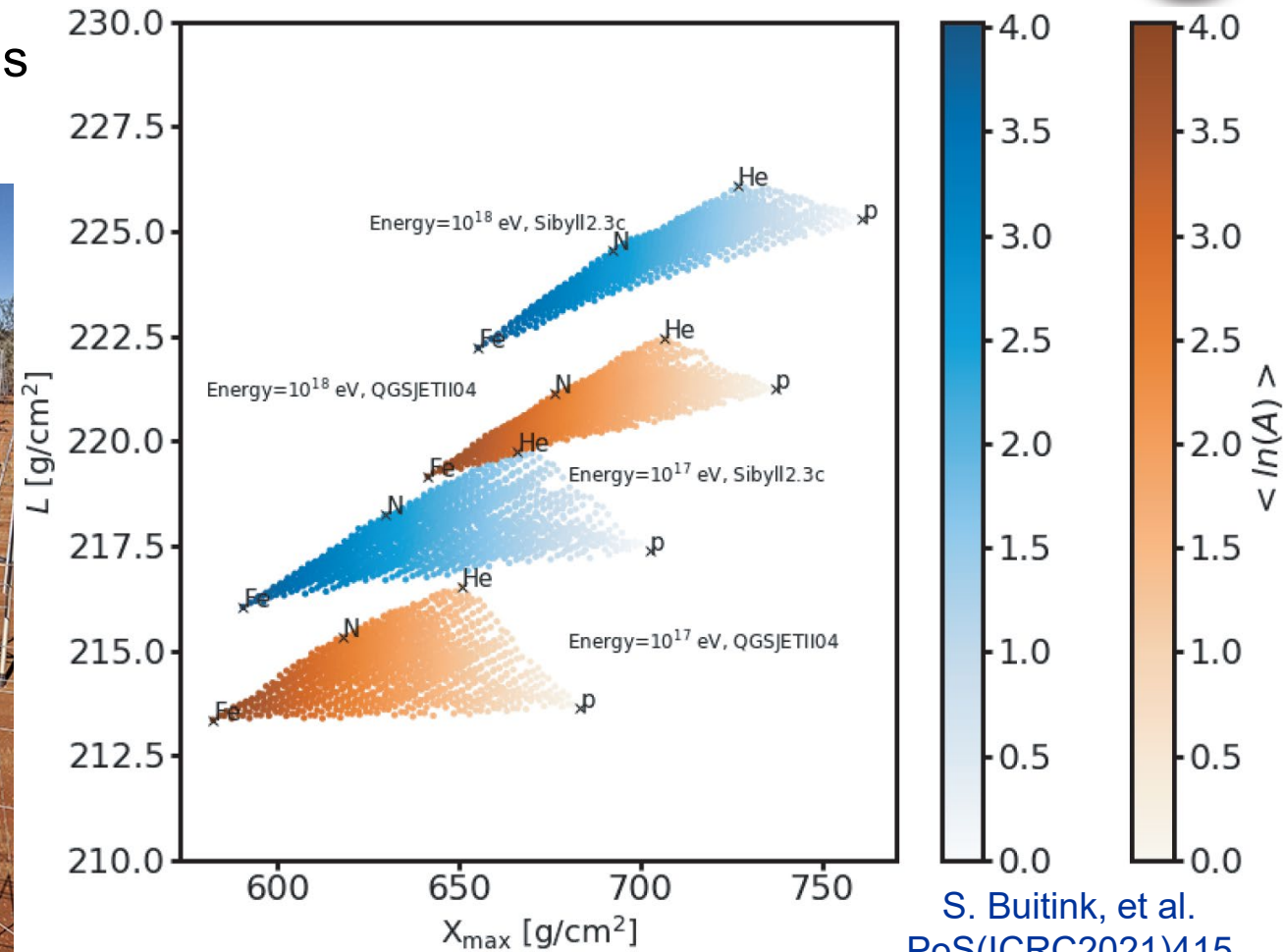


Other possibilities for higher mass accuracy?

- SKA: 10 PeV to 1 EeV air shower detection in parallel to radio astronomy
- Shower profile beyond X_{\max} for higher mass sensitivity and new tests of interaction models



Artist impression of SKA-low in Australia:
60,000 antennas on $\frac{1}{2}$ km²



S. Buitink, et al.
PoS(ICRC2021)415

Experiments of the next two decades

- Auger and TA upgrades will lead the field for the next 10 years
- 4 main experiments identified for the decade afterwards that complement each other
 - 3 of them designed also (mainly) as neutrino observatories: IceCube-Gen2, GRAND, POEMMA
 - GCOS (Global Cosmic Ray Observatory) will be designed to deliver event-by-event rigidity for UHECR

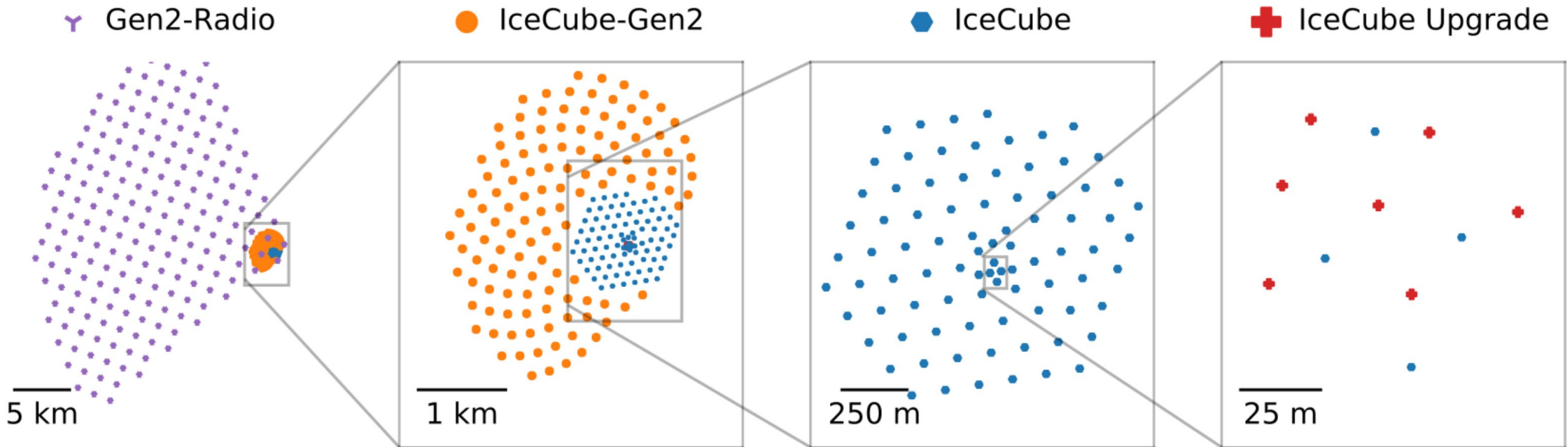
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2025 2030 2035 2040

IceCube-Gen2 – the planned extension of IceCube

- an order of magnitude larger optical array in the ice for PeV neutrinos and a sparse *in-ice radio* array for the detection of ultra-high-energy neutrinos
- complemented by a surface array above the in-ice optical array



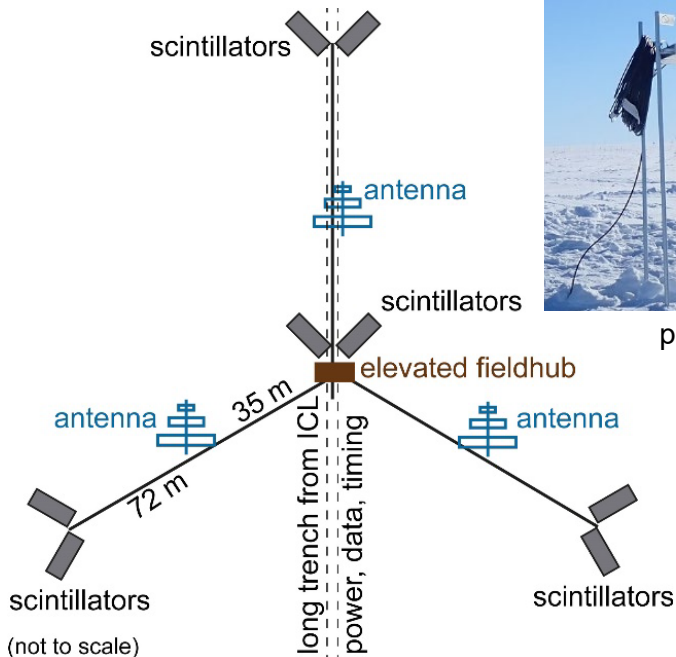
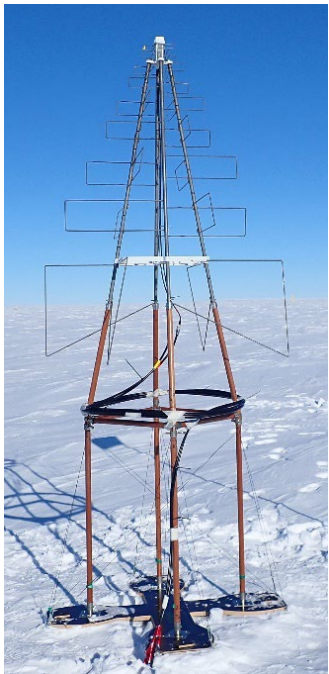
[arXiv:2008.04323](https://arxiv.org/abs/2008.04323)

IceCube-Gen2 and its Surface Array

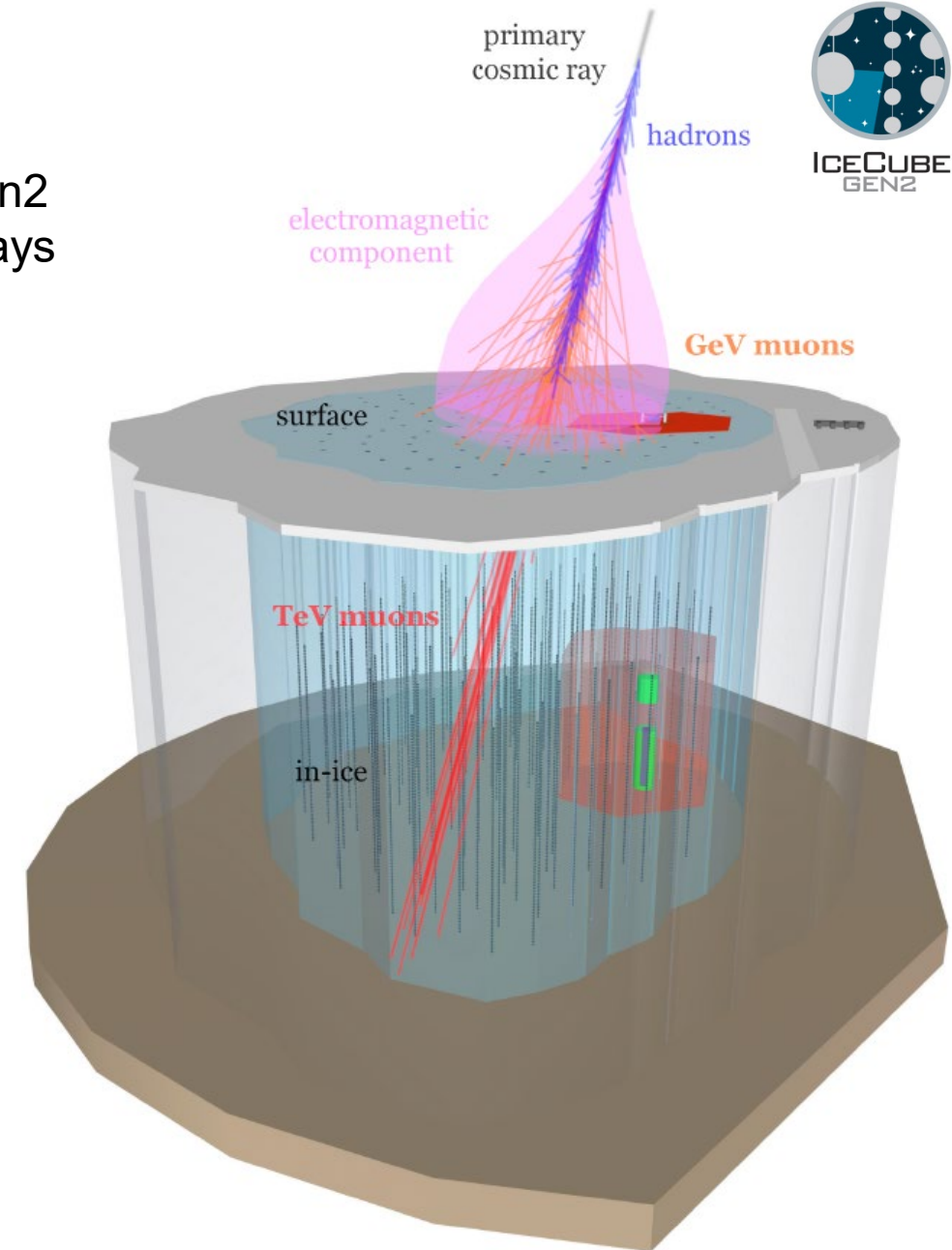
- Combination of deep and surface detector will make IceCube-Gen2 a unique laboratory for air-shower physics and Galactic cosmic rays
- 8x larger area, 30x larger aperture for in-ice coincidences

Surface Array of approx. 150 stations:

4 pairs of scintillators + 3 antennas

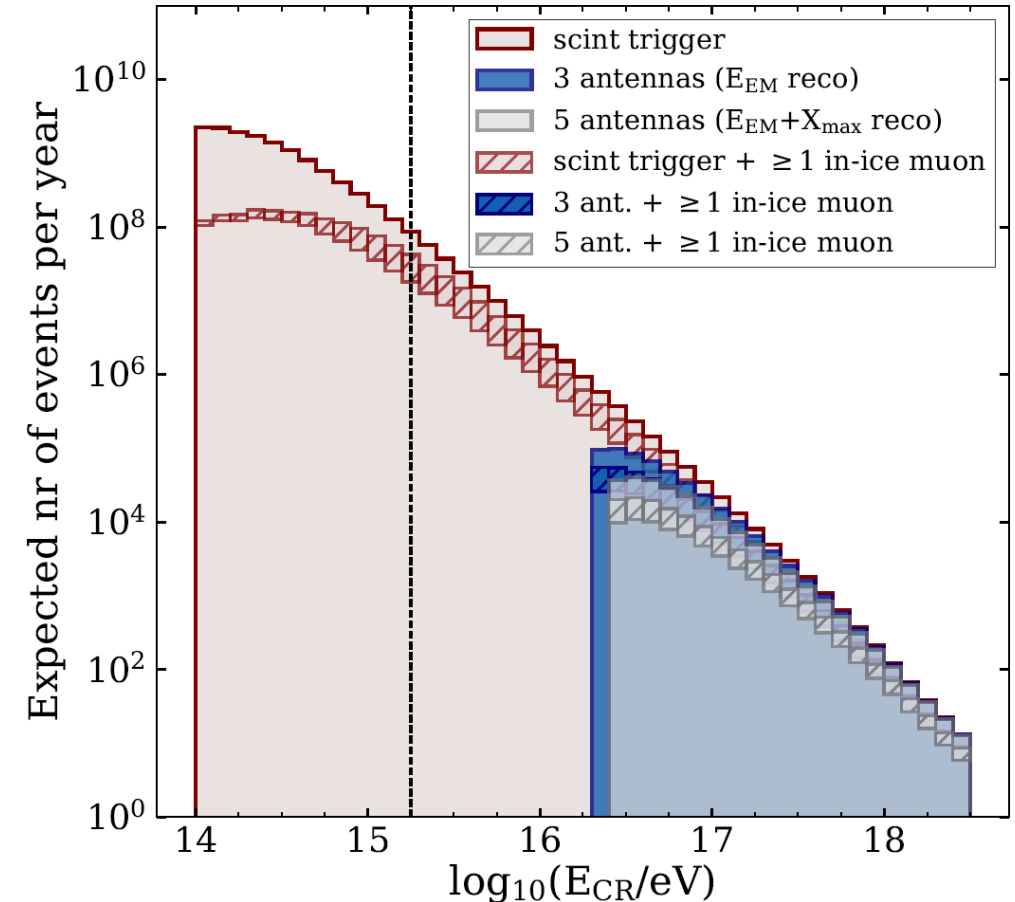
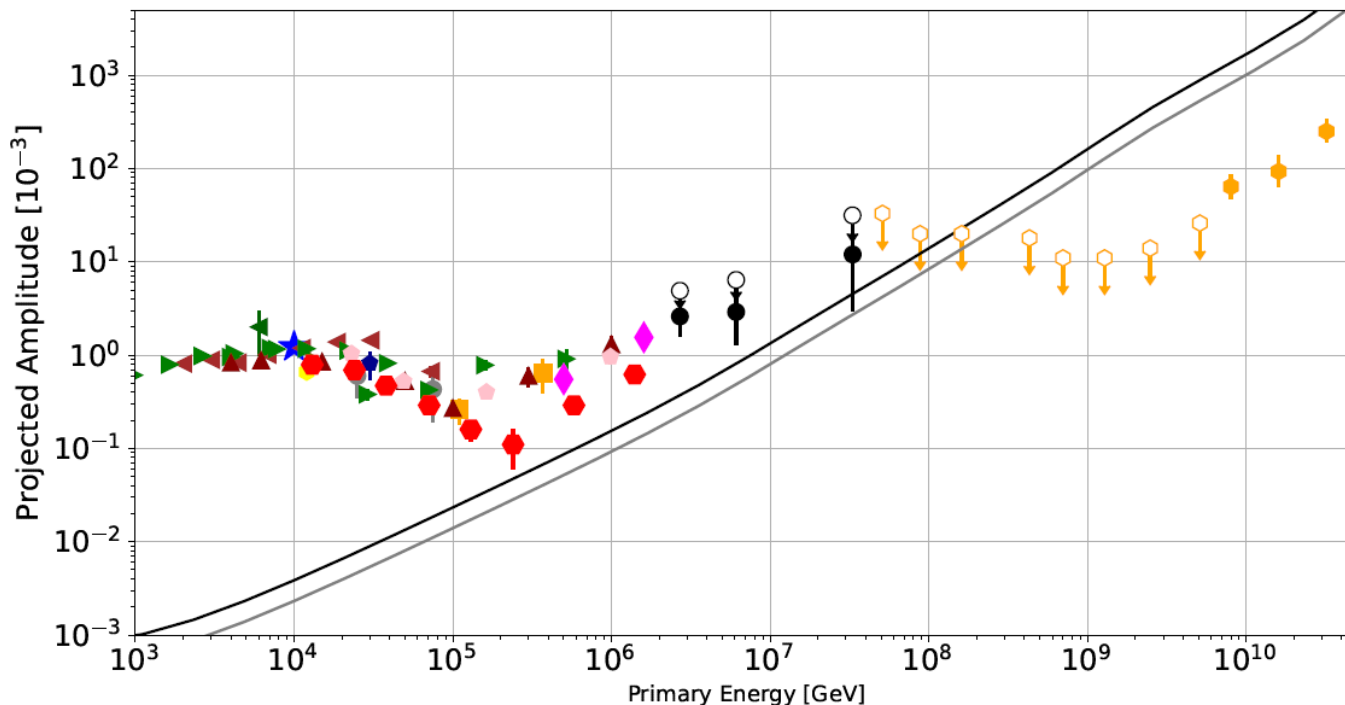
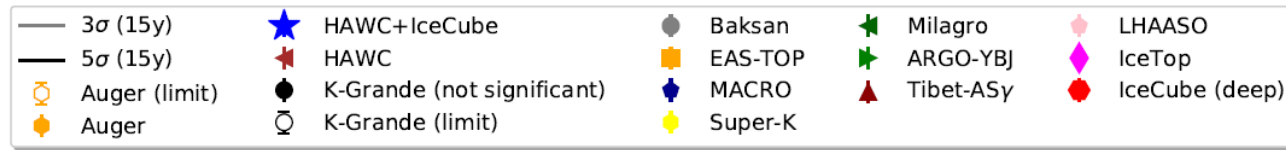


photos: prototype station at South Pole



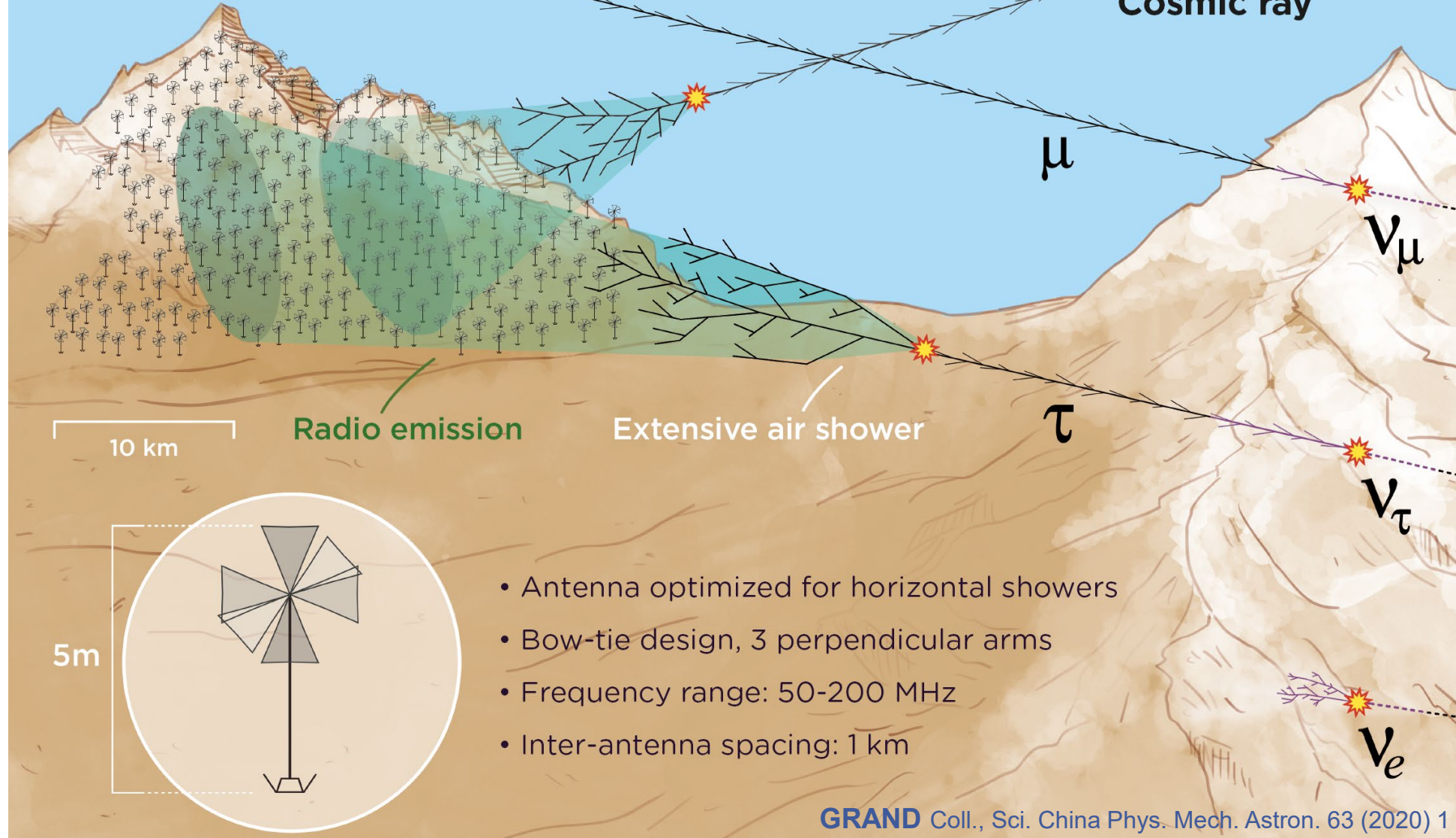
IceCube-Gen2: Cosmic-Ray Energy Range

- Radio + in-ice muons: unprecedented accuracy for mass from 30 PeV to several EeV
- Anisotropy measurements up to second knee (around 200 PeV)
 - also important improvements for energy range of knee and below, e.g., by addition of IceAct telescopes



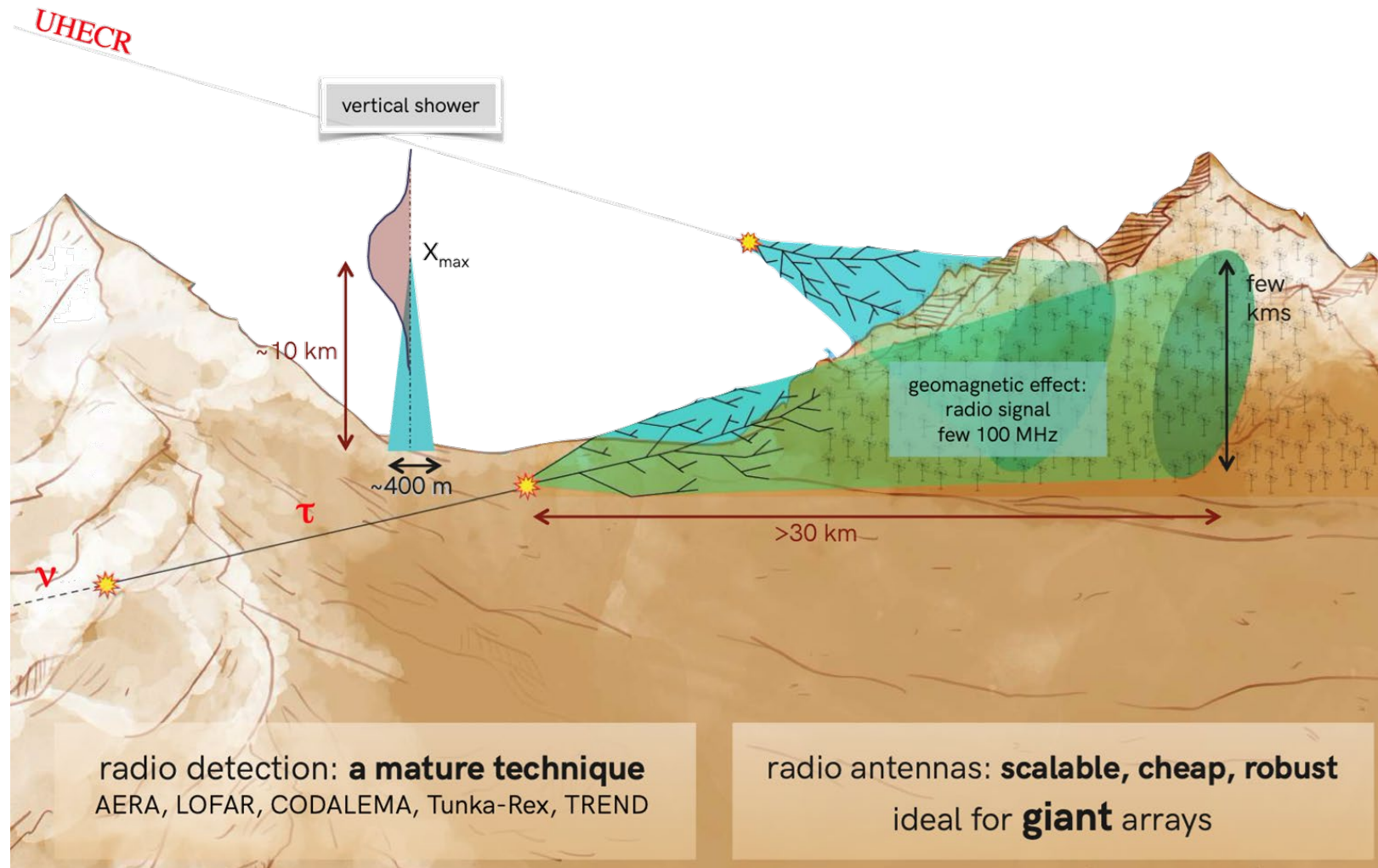


Giant Radio Array for Neutrino Detection



Giant Radio Array for Neutrino Detection

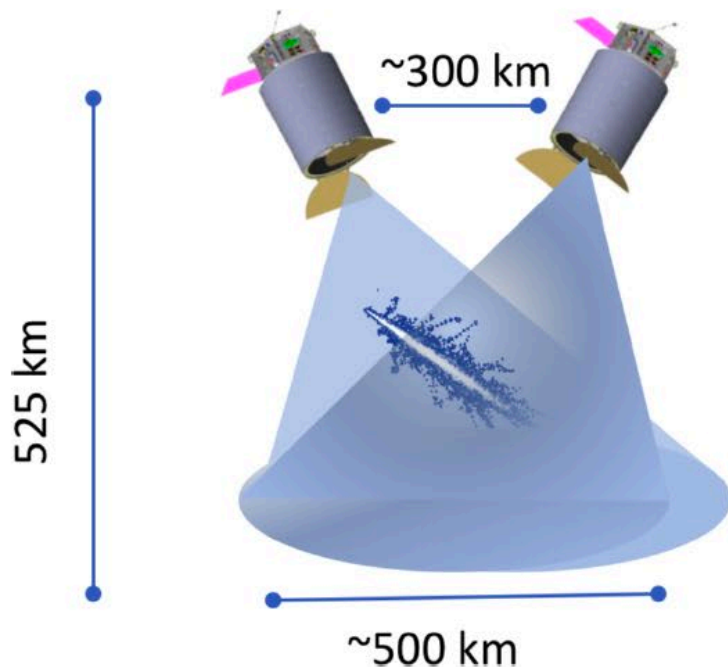
- UHECR as important second science case next to neutrinos
- various sites worldwide
 - main ones in China
- 200,000 km² total
 - inclined showers only
 - **aperture of 100,000 km² sr**
- Possibly X_{\max} measurement in addition to energy, but no muon detection at most sites
 - mediocre mass resolution
- strengths is the high statistics
- common sites with GCOS possible, but different requirements on accuracy



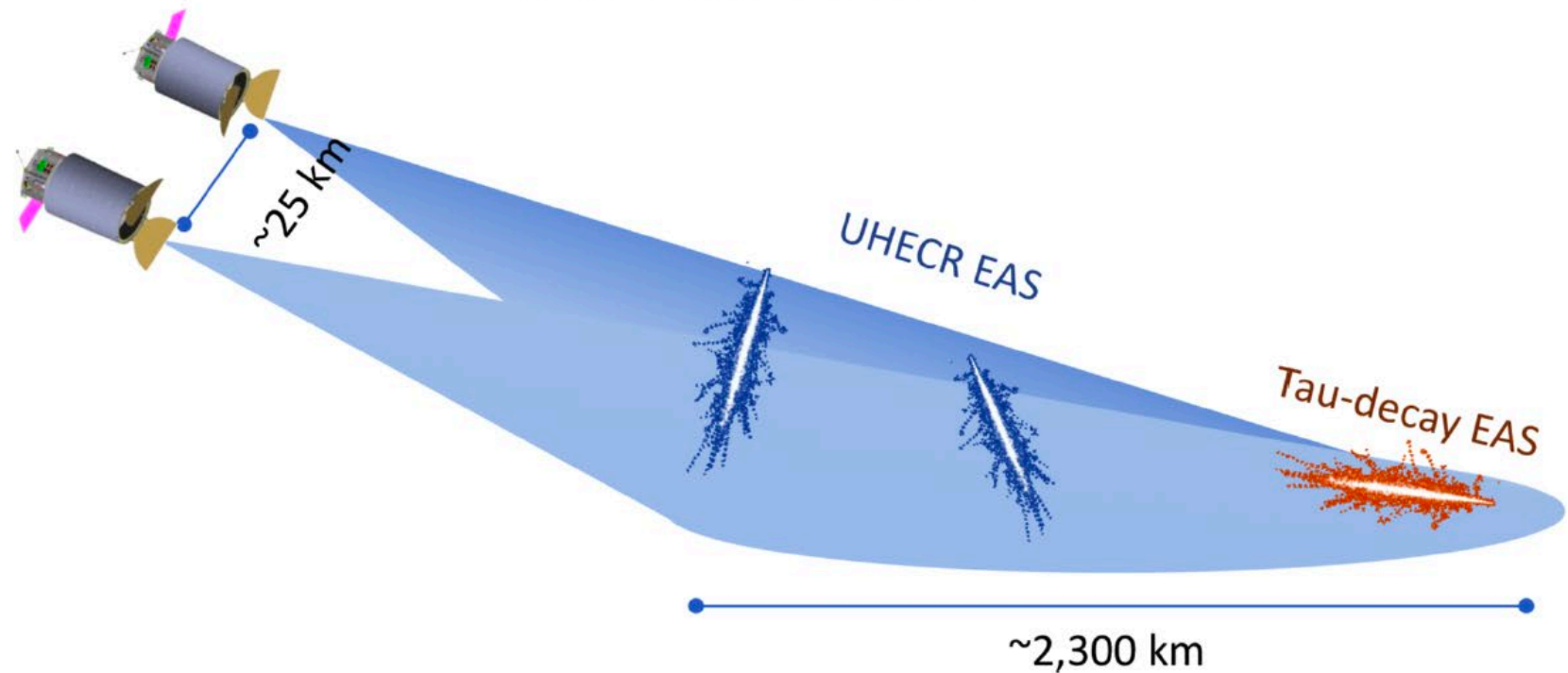
POEMMA: stereo fluorescence observation from space

- Two science cases: UHECR and neutrinos, both with full sky coverage
- Good X_{\max} and ok energy resolution (\rightarrow mediocre rigidity resolution) and very high aperture
- Complementary to GRAND in many aspects: technology, space vs. ground, ...

POEMMA-Stereo

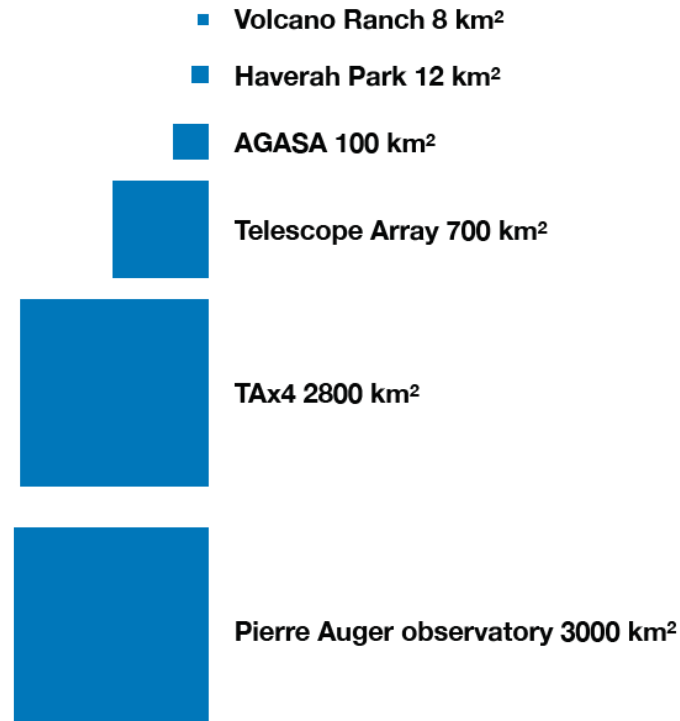


POEMMA-Limb

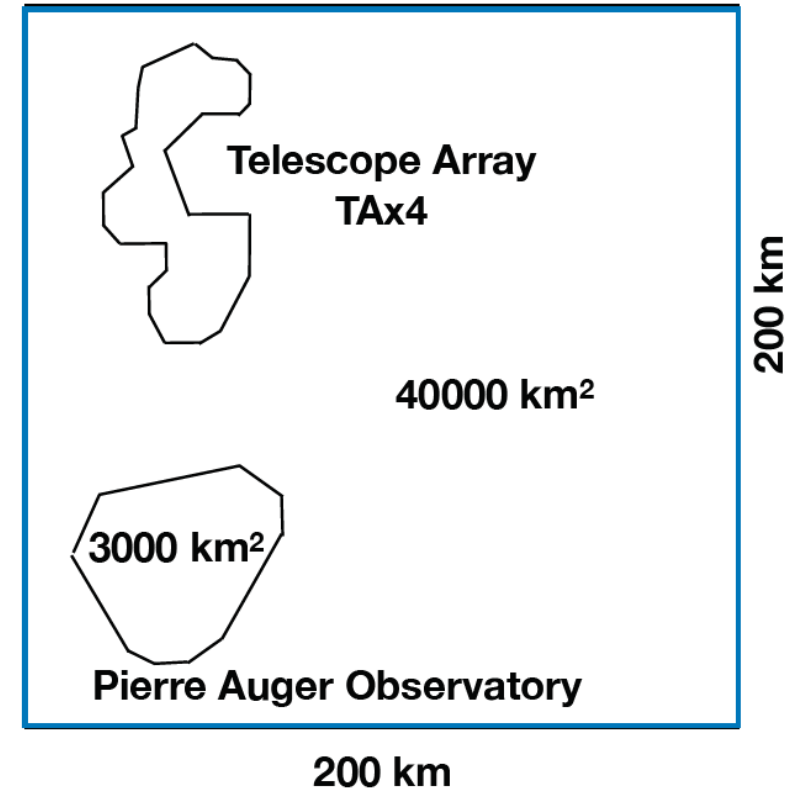


Global Cosmic Ray Observatory (GCOS)

- Dedicated observatory for UHECR
 - Several sites for full-sky coverage
 - Detector design and science under discussion at dedicated workshop
 - GCOS aims at highest achievable accuracy for mass and energy
 - event-by-event rigidity
 - High accuracy also beneficial for particle physics science goals
- GCOS can be *the* common project of our community in the next decade!

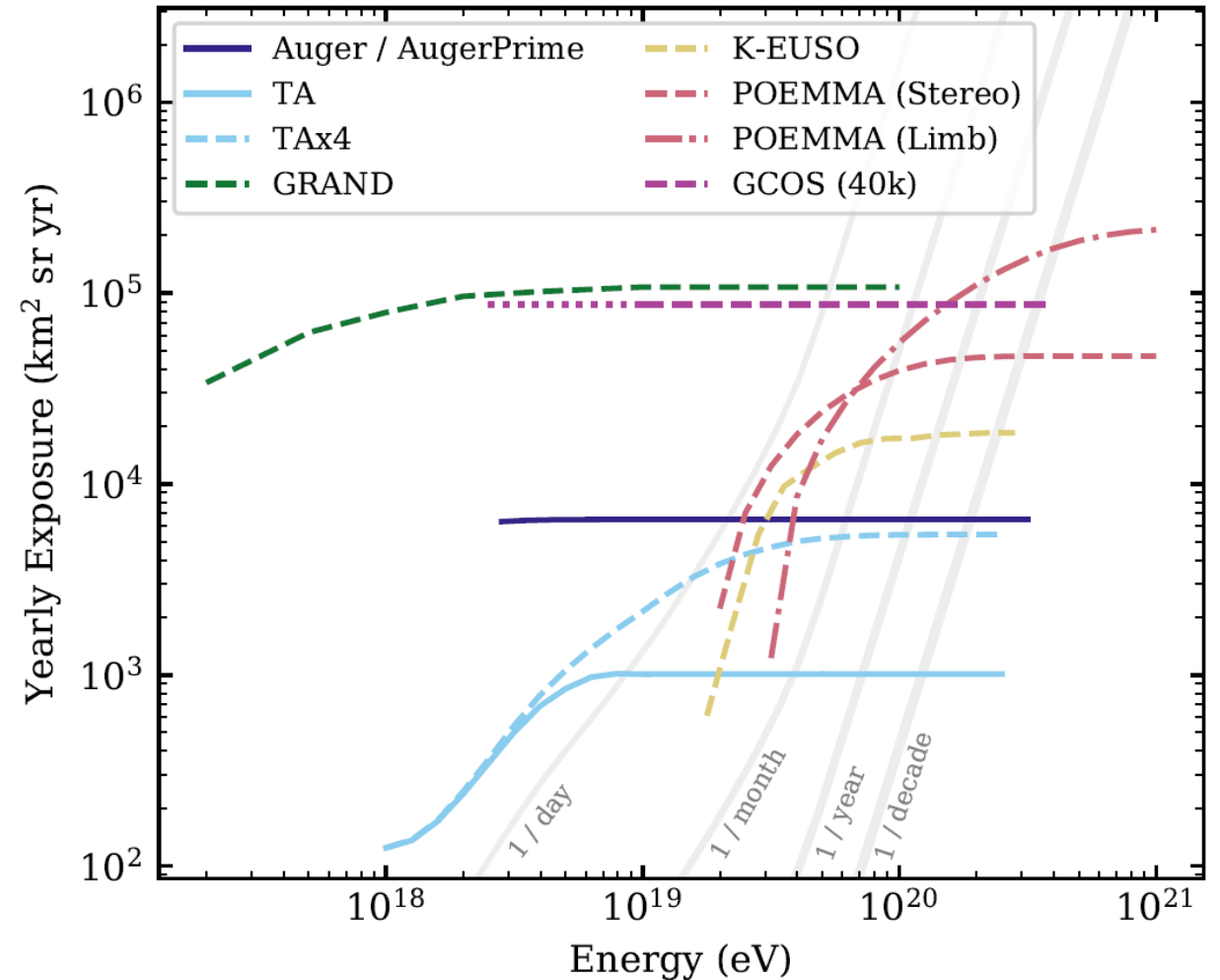
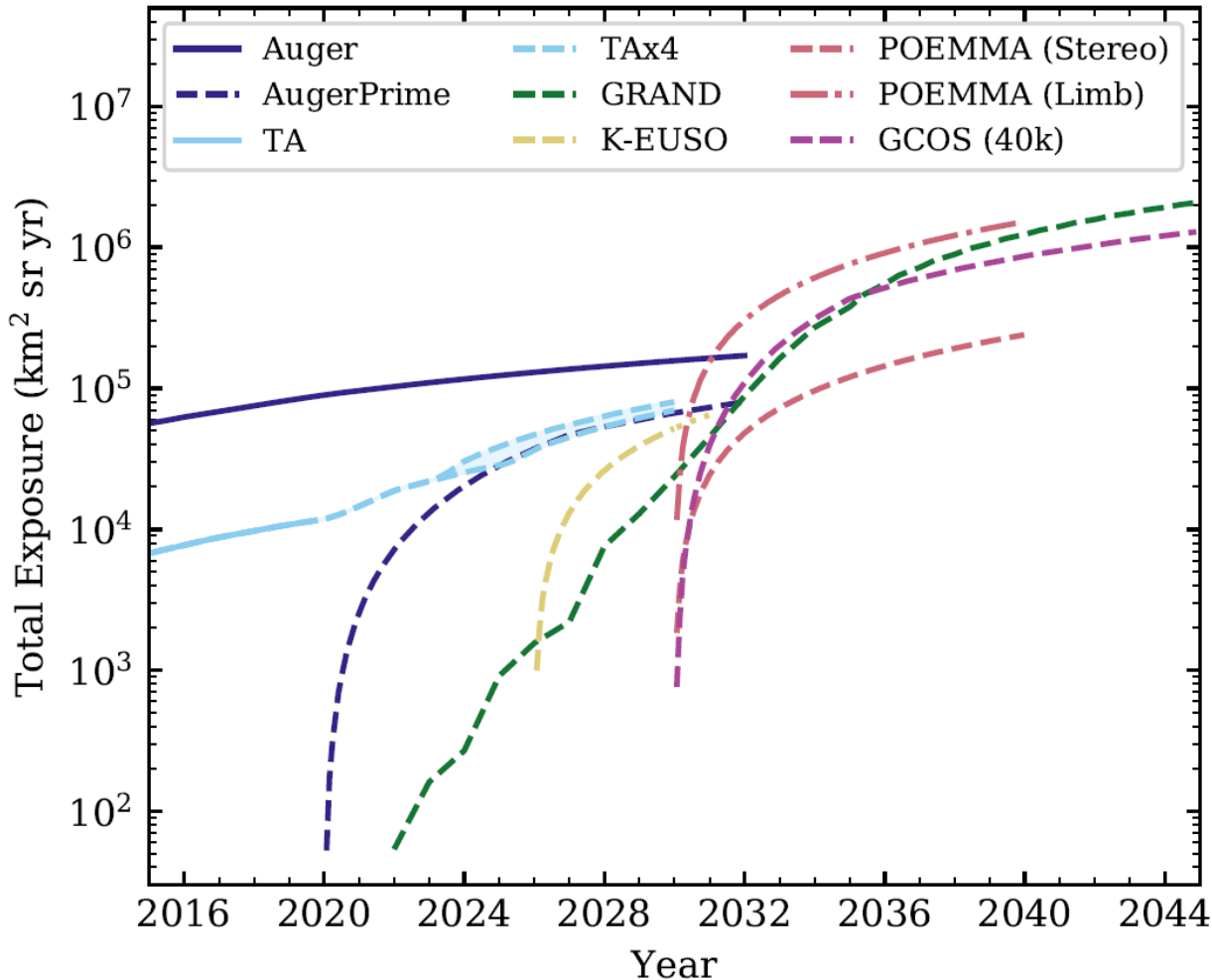


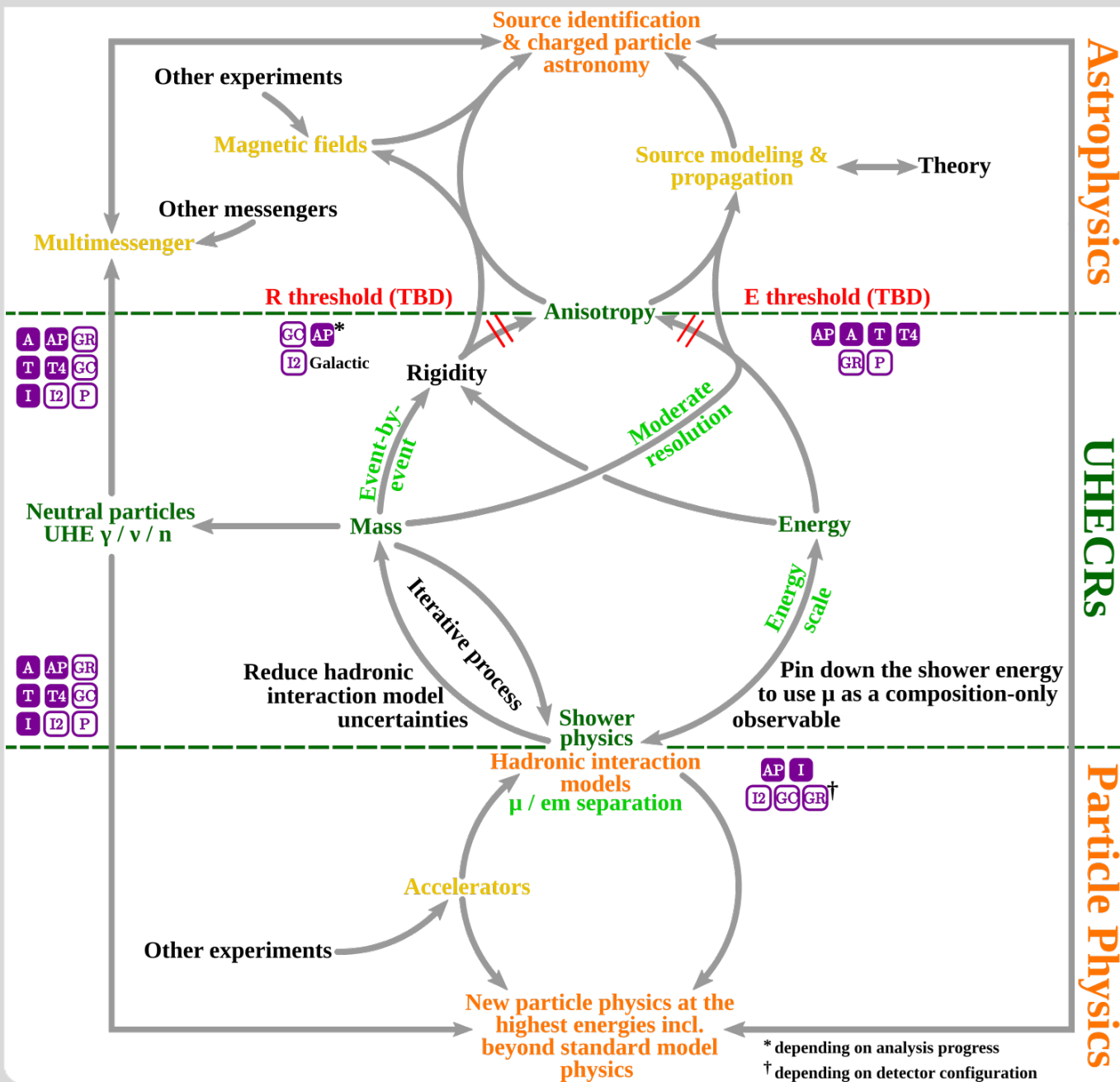
Size of past and current ground arrays and possible size of GCOS (all sites combined)



Comparing Exposures of UHECR experiments

Keep in mind: exposure is only one dimension, accuracy for mass and energy is the other one





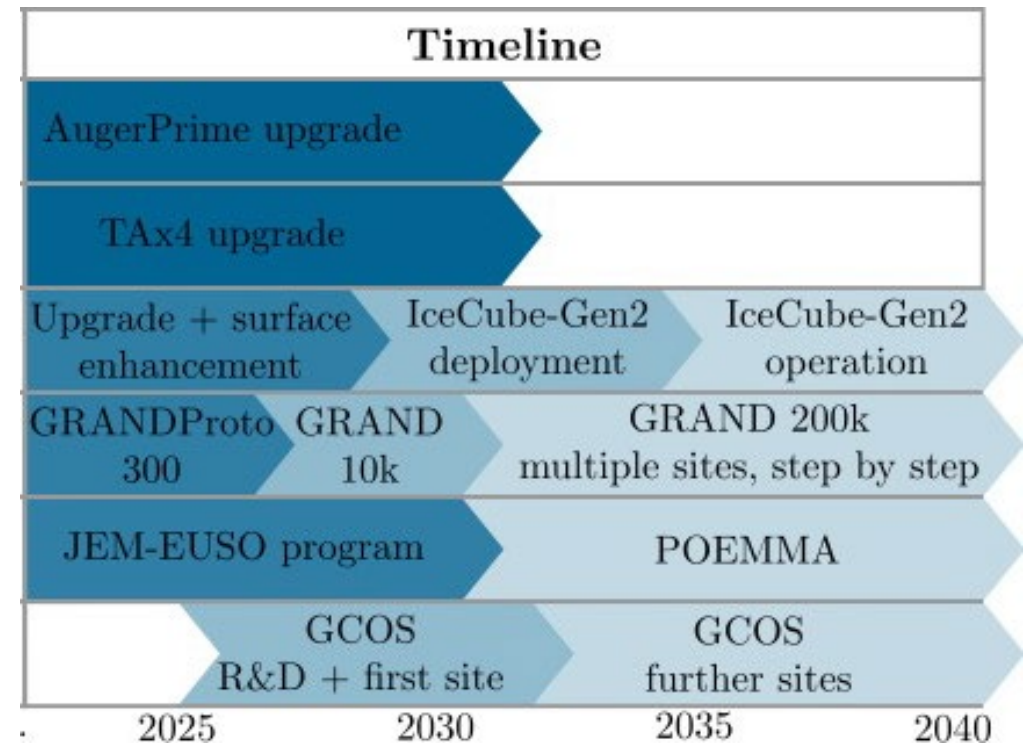
- Experiments:
- A Auger
 - AP AugerPrime
 - GC GCOS
 - GR GRAND
 - I IceCube
 - I2 IceCube-Gen2
 - P POEMMA
 - T TA
 - T4 TAx4

Conclusion

Two types of future experiments

- event-by-event rigidity
- huge exposure

provide the chance for break-through discoveries and guarantee exciting astrophysics *and* particle physics



Additional Slides

Personal Conclusion: Ultra-high-energy Cosmic Rays

■ Recent results

- New features in cosmic-ray energy spectrum (many features known by now)
- Mixed mass composition of cosmic rays varies over energy
- Various experiments mostly consistent within systematic uncertainties

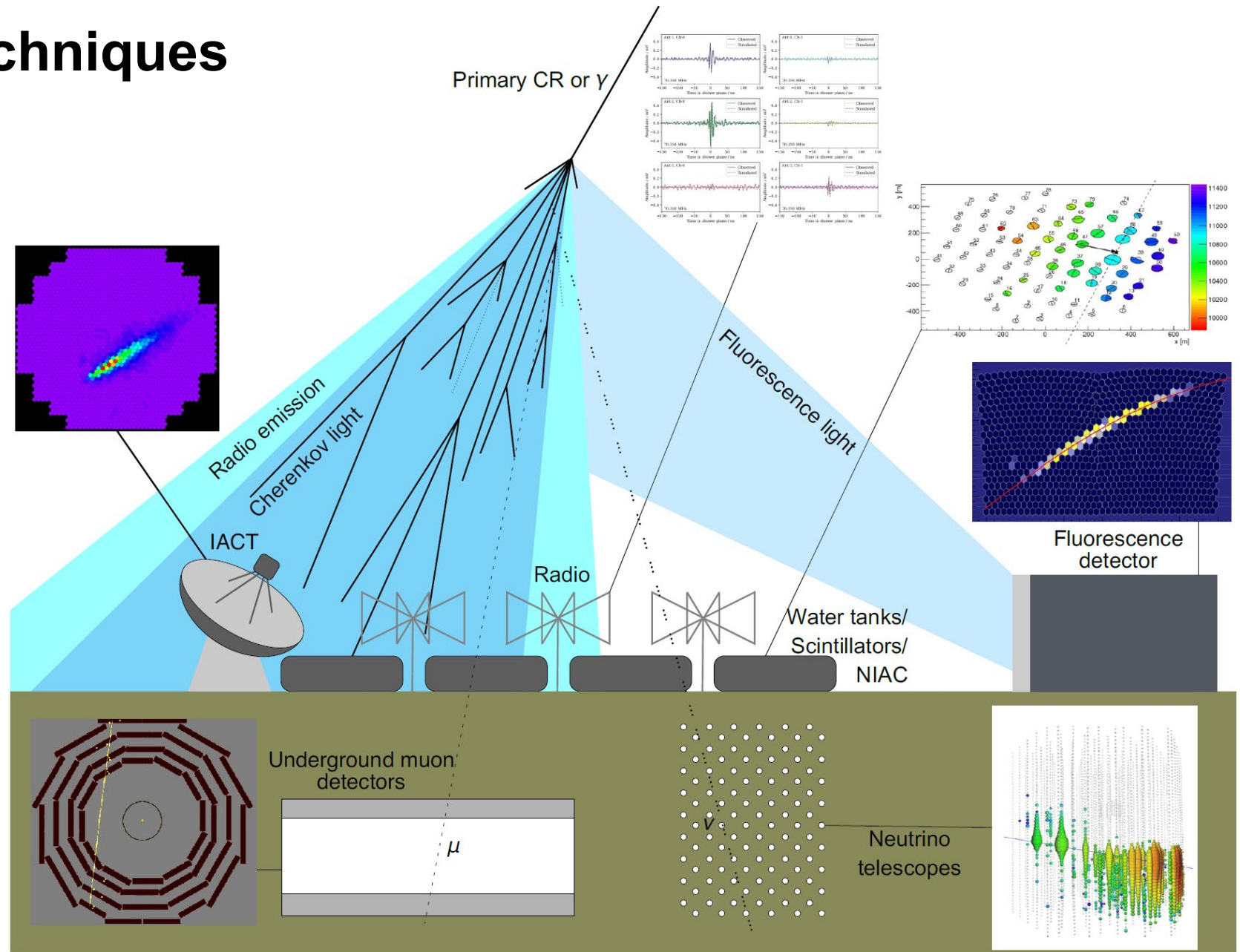
■ Open questions

- What is the origin and maximum energy of the most energetic *Galactic* cosmic rays?
- What are the *extragalactic* sources at the highest energies?
- What causes the mismatch between muon measurements and predictions by models?

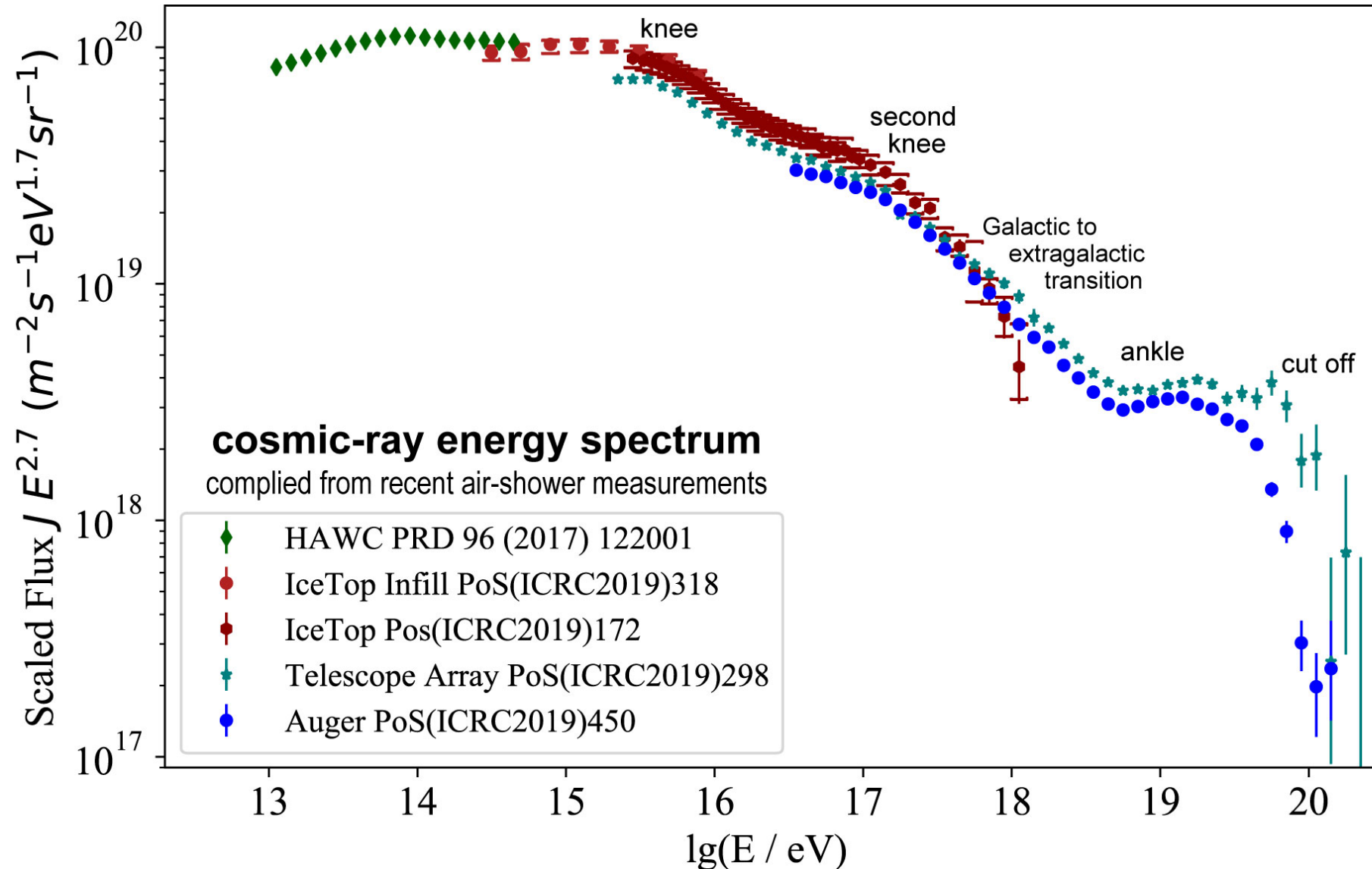
■ Future plans: *statistics and accuracy*

- Upgrades of current ground arrays aim at per-event estimation of primary particle type
- Proposals for new ground arrays: GRAND, GCOS, and IceCube-Gen2 (for PeV – EeV)
- Future space experiments important to increase exposure at highest energies

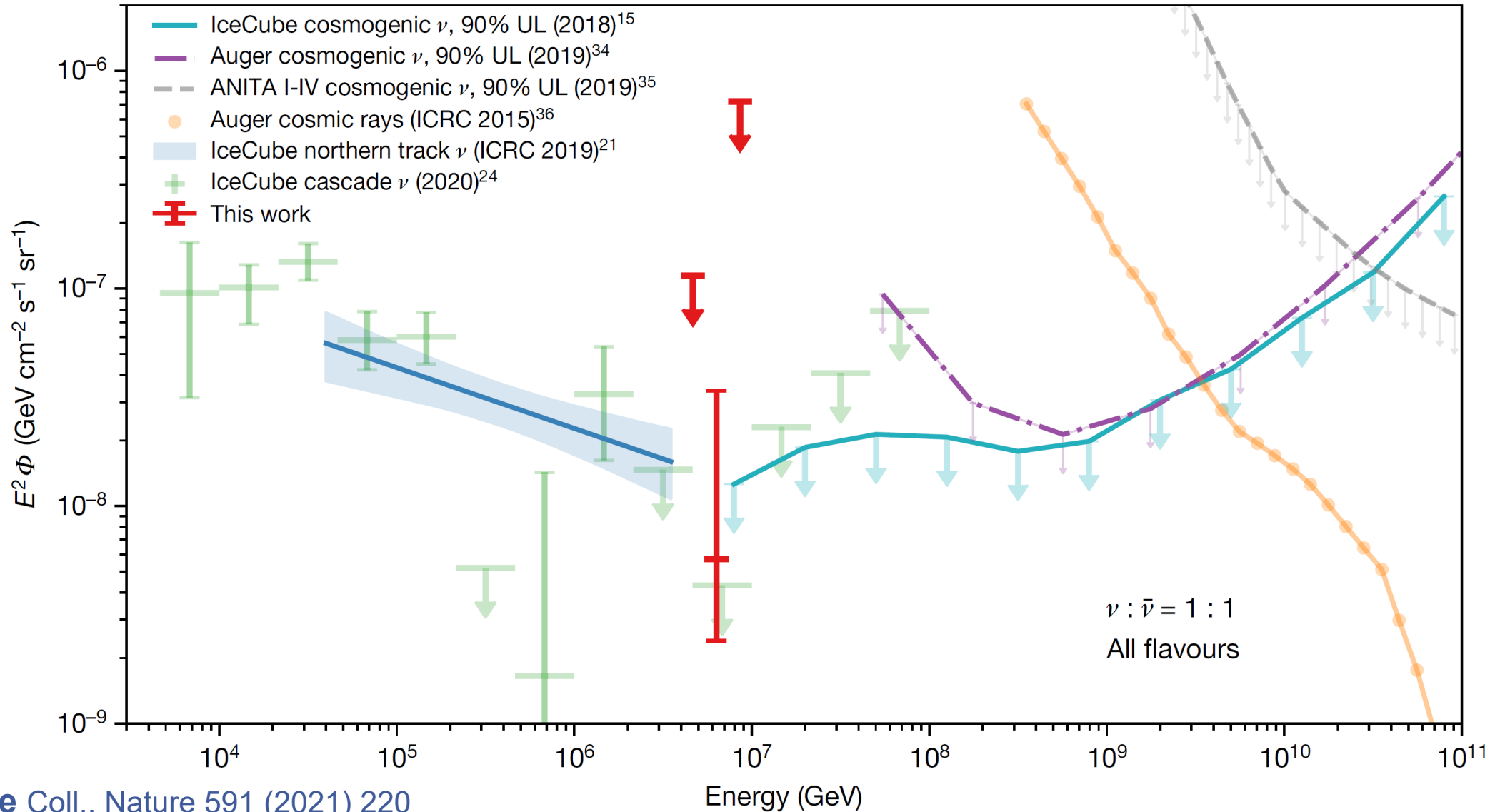
Instrumentation Techniques



All-particle Energy Spectrum by Air-Shower Arrays

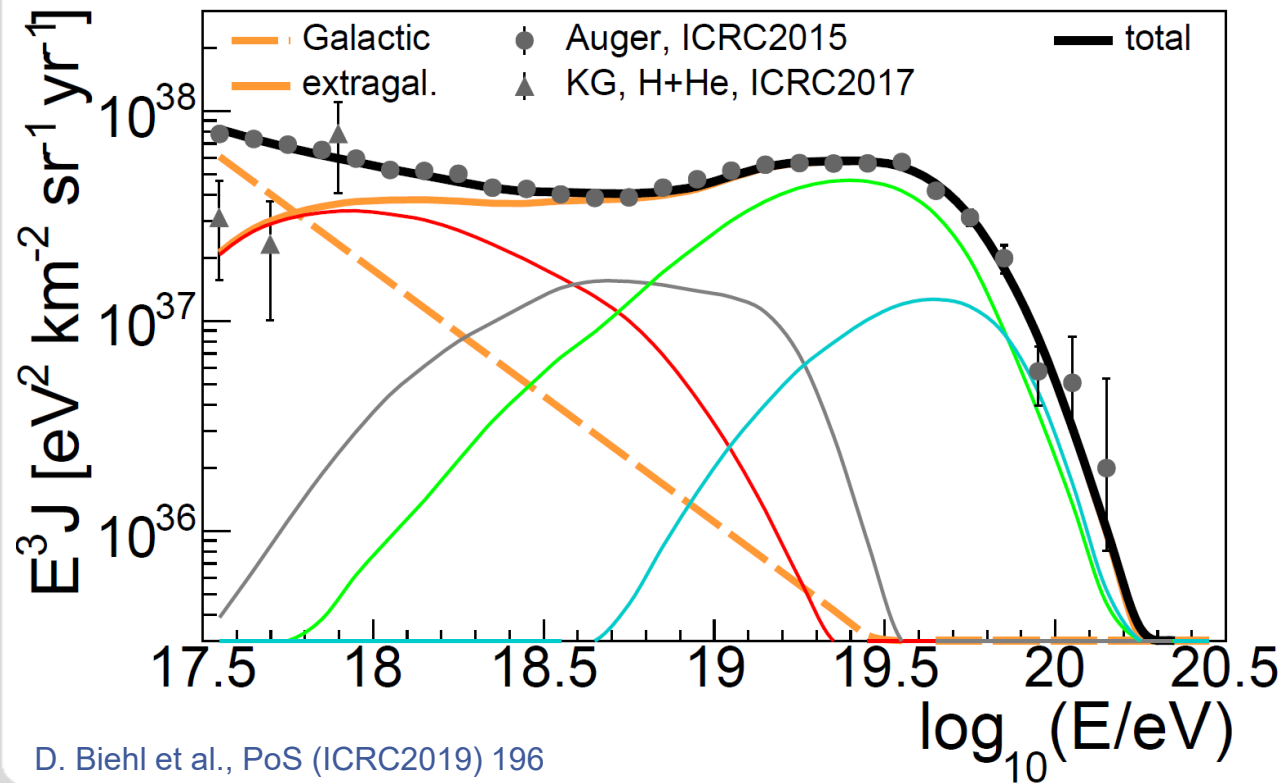


Almost 10 PeV neutrino (at Glashow resonance of 6.3 PeV)

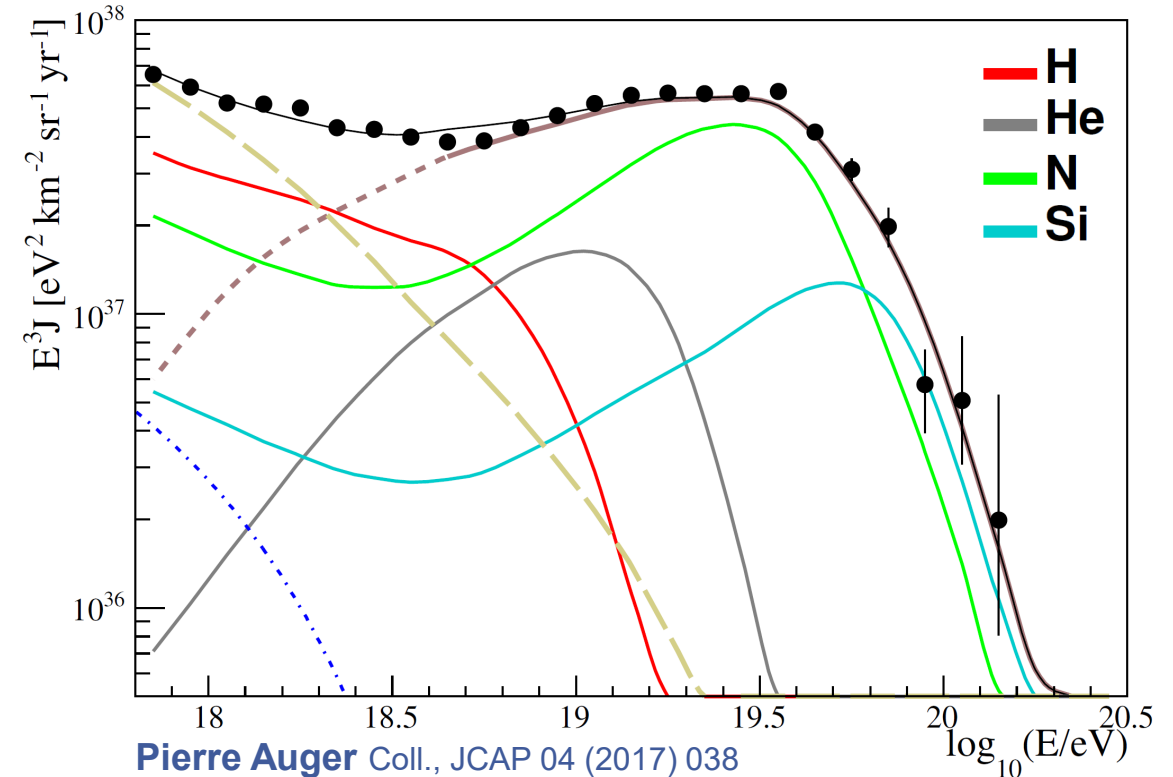


Interpretations of UHECR flux and open questions

- Cut-off due to maximum acceleration energy and/or due to propagation?
 - Need to determine proton fraction at highest energies
- Ankle likely a mixture of propagation effects and transition between components
 - Is this the transition from Galactic to extragalactic CR, or different extragalactic components?



D. Biehl et al., PoS (ICRC2019) 196

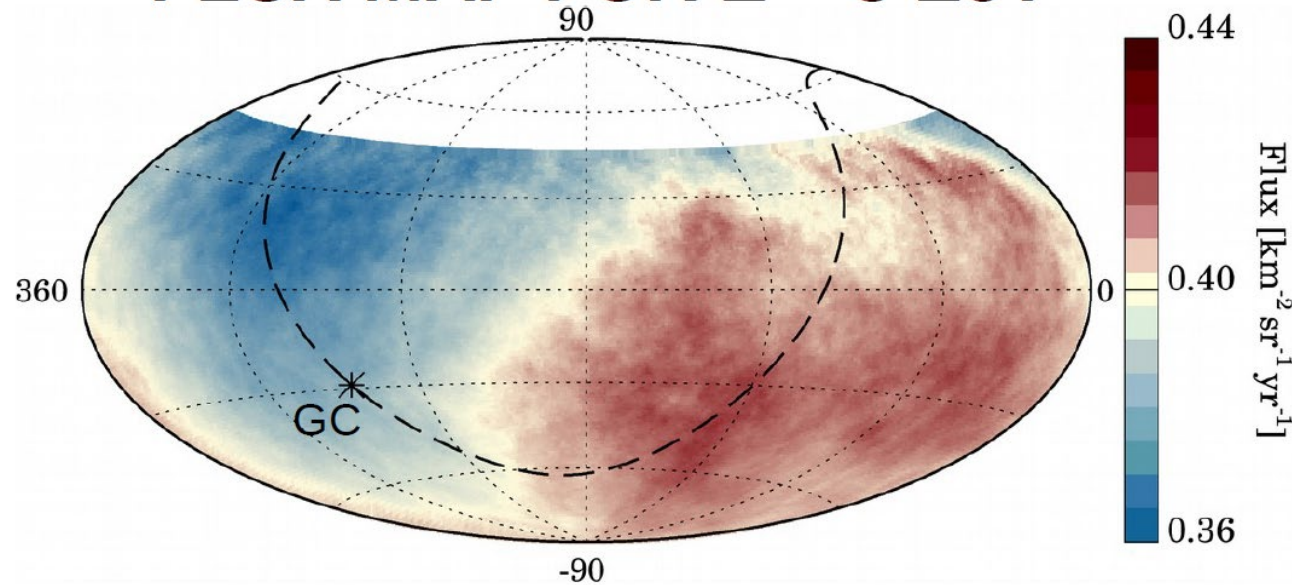


Pierre Auger Coll., JCAP 04 (2017) 038

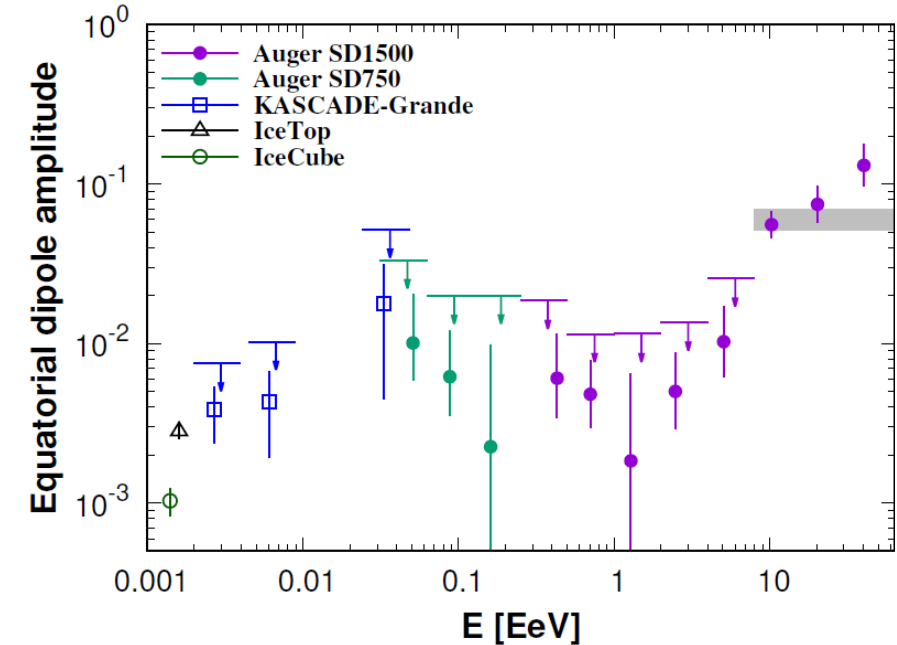
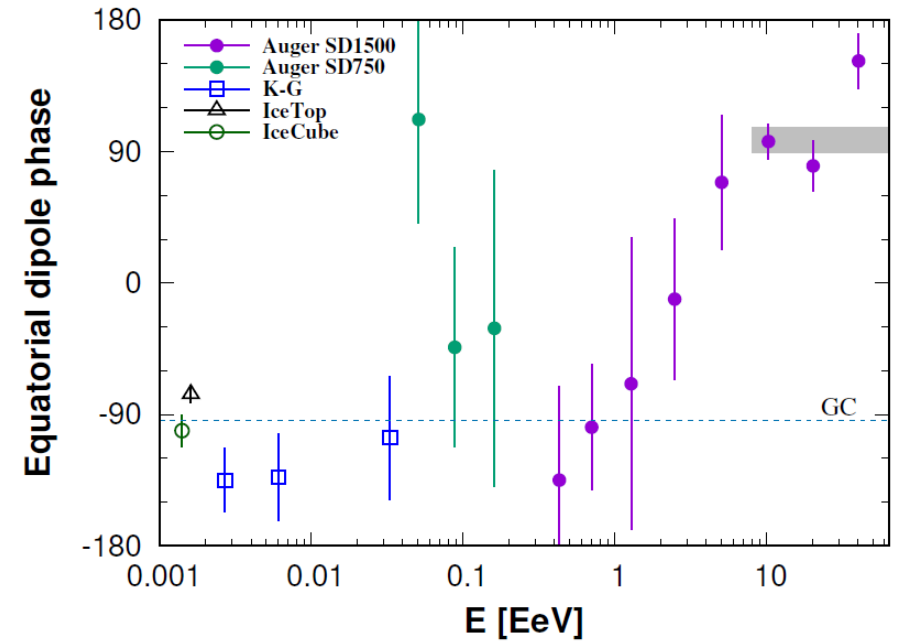
Auger Dipole – UHECR Anisotropy

- Dipole strengths increases with energy
- Direction consistent with extragalactic origin
- Transition of dipole phase around 1 EeV: hint for Galactic-to-extragalactic transition

FLUX MAP FOR $E > 8$ EeV

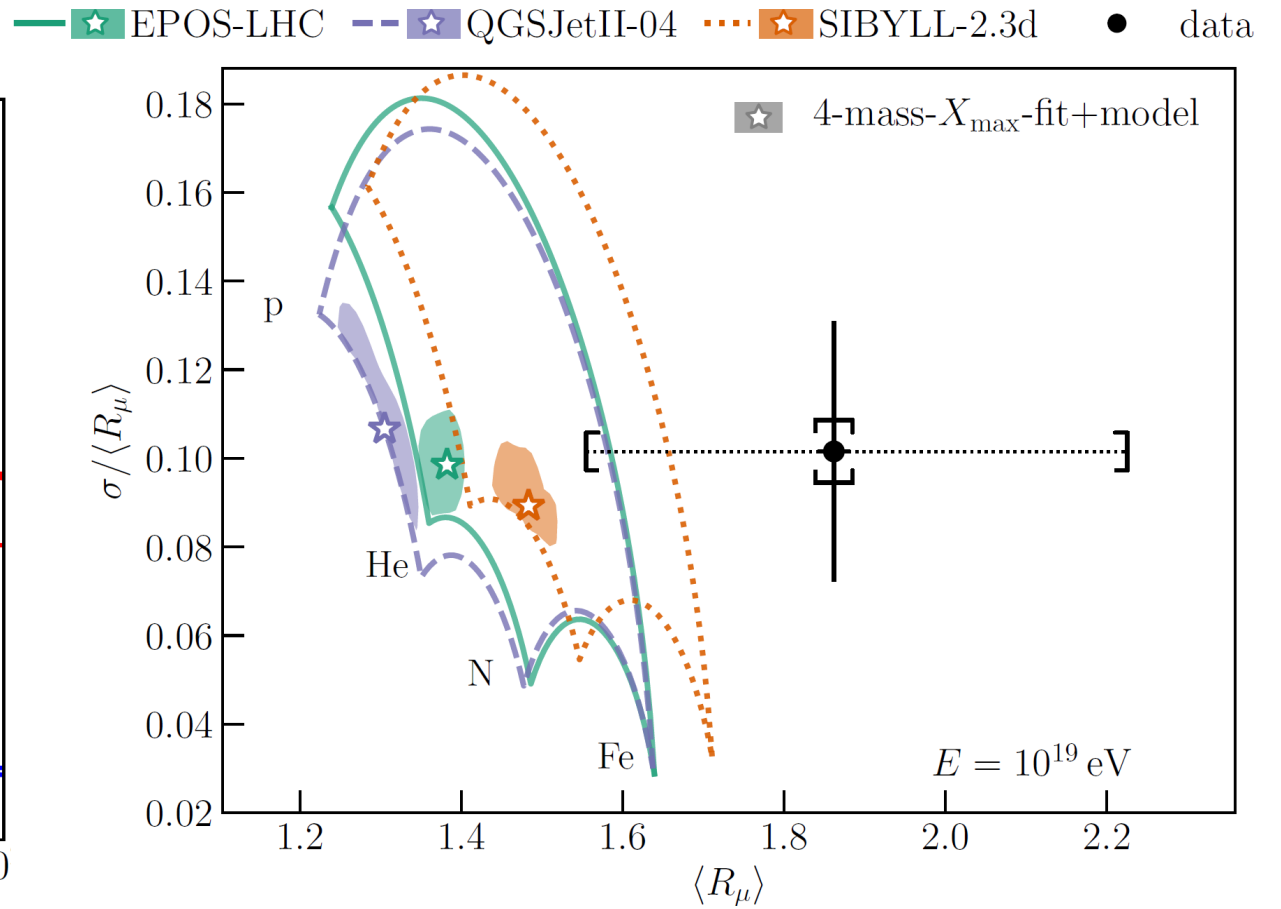
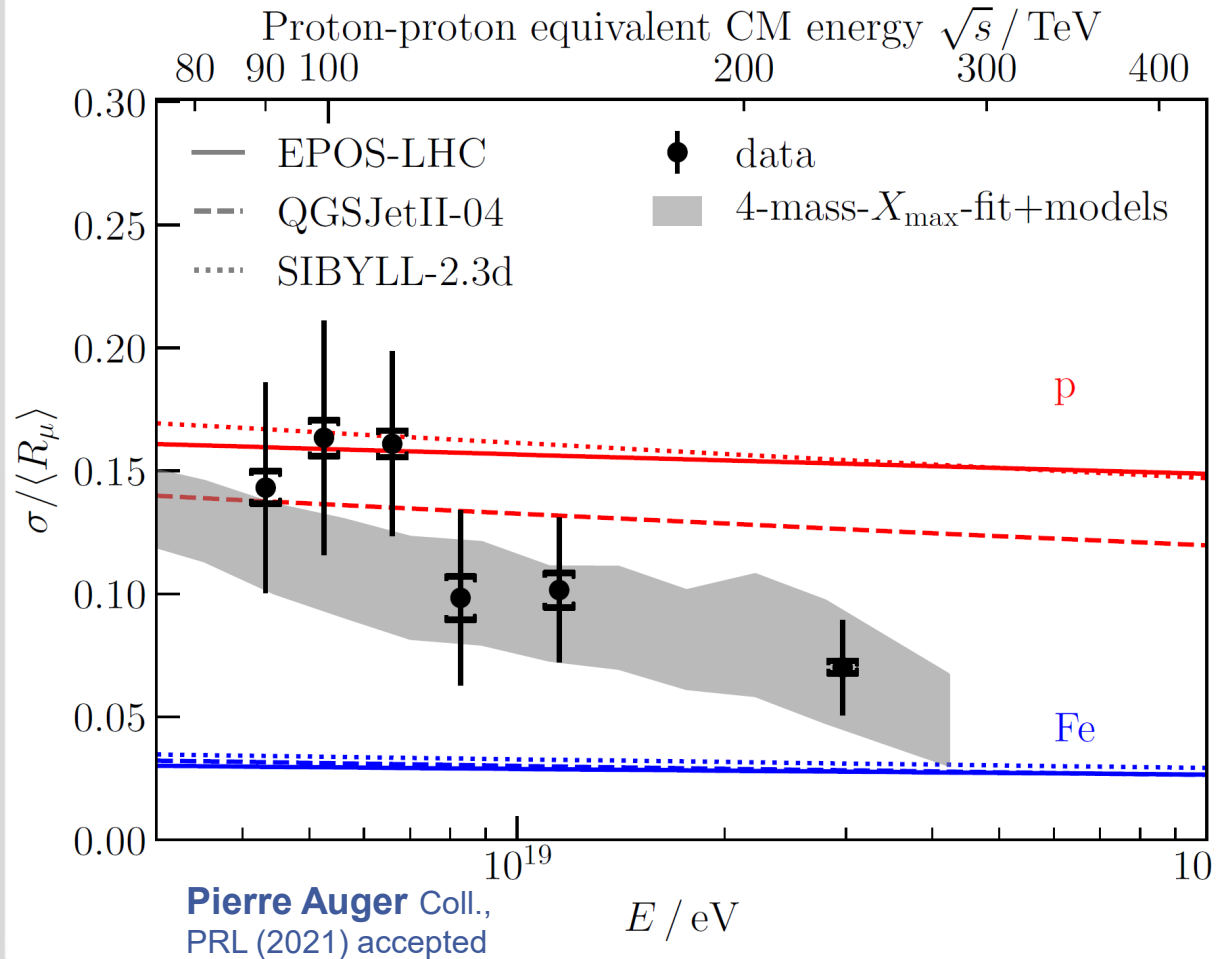


equatorial coordinates, smoothed on 45° radius windows



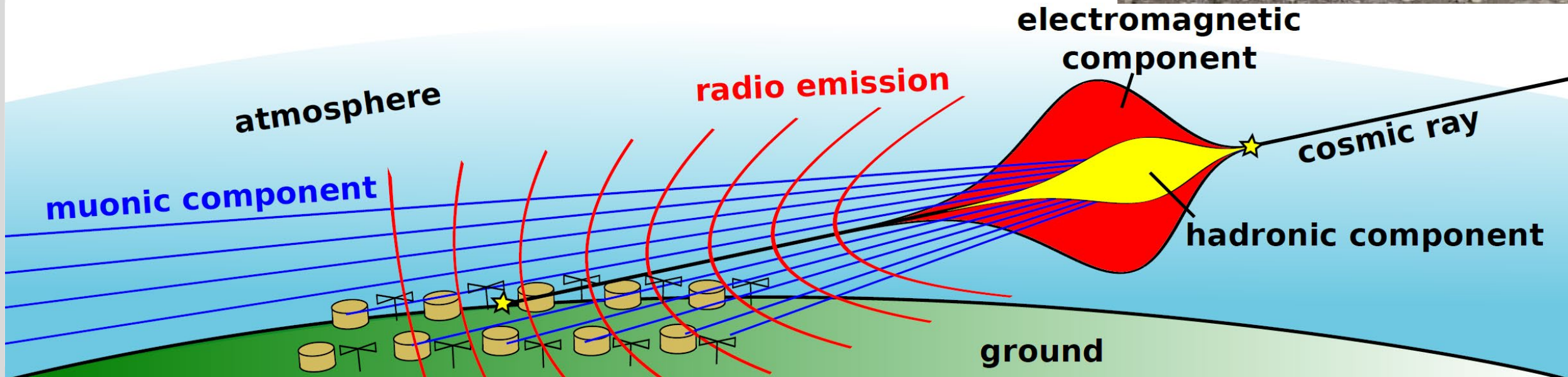
Fluctuation of muon number measured by Auger

■ Hadronic interaction models can describe variations in muon number, but not absolute number



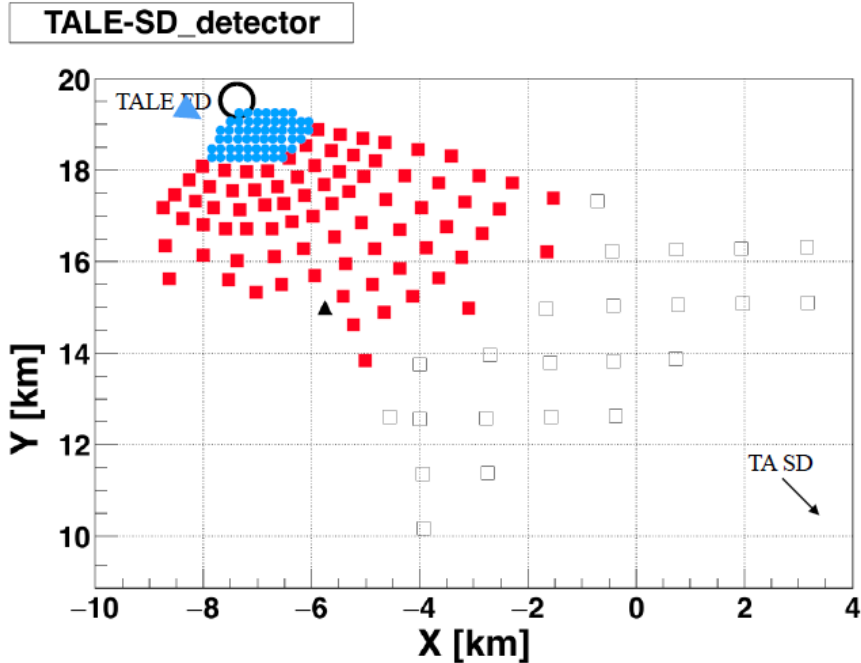
AugerPrime: Upgrade of the Pierre Auger Observatory

- Improved quality of surface detector:
 - scintillators + radio antennas
 - underground muon detectors
 - better electronics
- Enables *per-event mass discrimination*

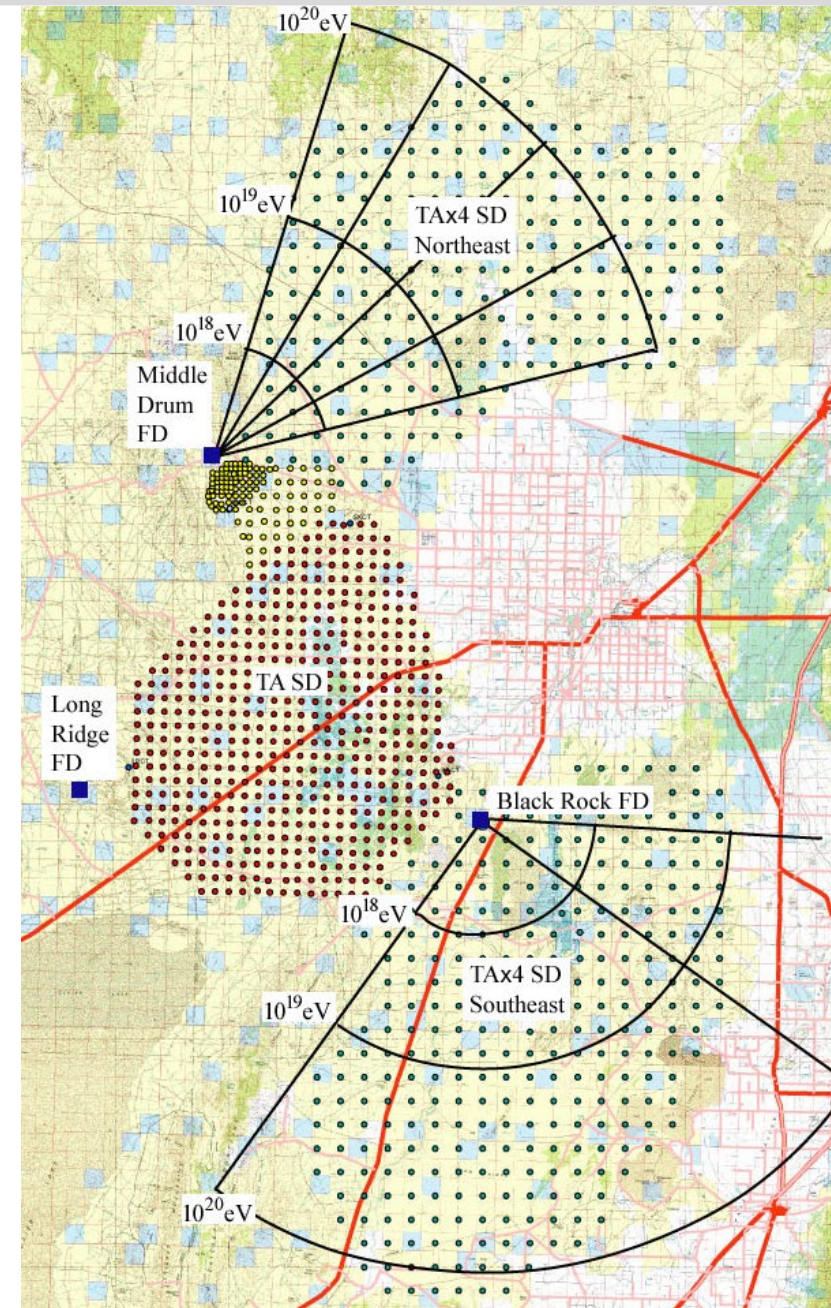


Telescope Array: Upgrades

- Highest energies ($E > 10^{19.8}$ eV)
 - TAx4 \rightarrow 3000 km² scintillator array
 - new fluorescence telescopes
- Lower energies ($E > 10^{15.5}$ eV):
 - TALE SD array complementing NICHE and FD



Telescope Array Coll.,
PoS (ICRC2019) 013 + 375



LHAASO – a 1 km² multi-hybrid detector in China

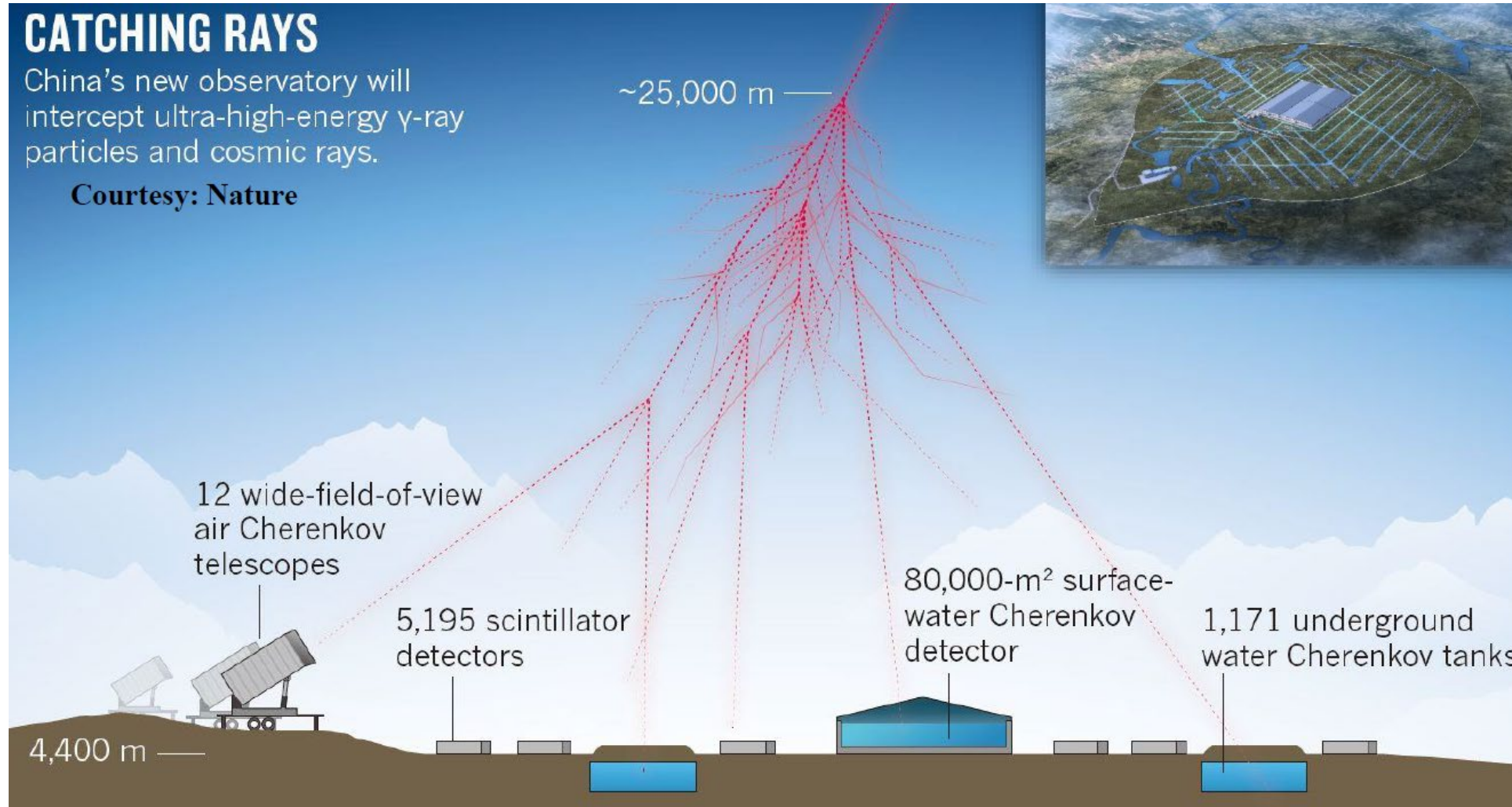


Primary goal are gamma-rays, but also excellent cosmic-ray detector

CATCHING RAYS

China's new observatory will intercept ultra-high-energy γ -ray particles and cosmic rays.

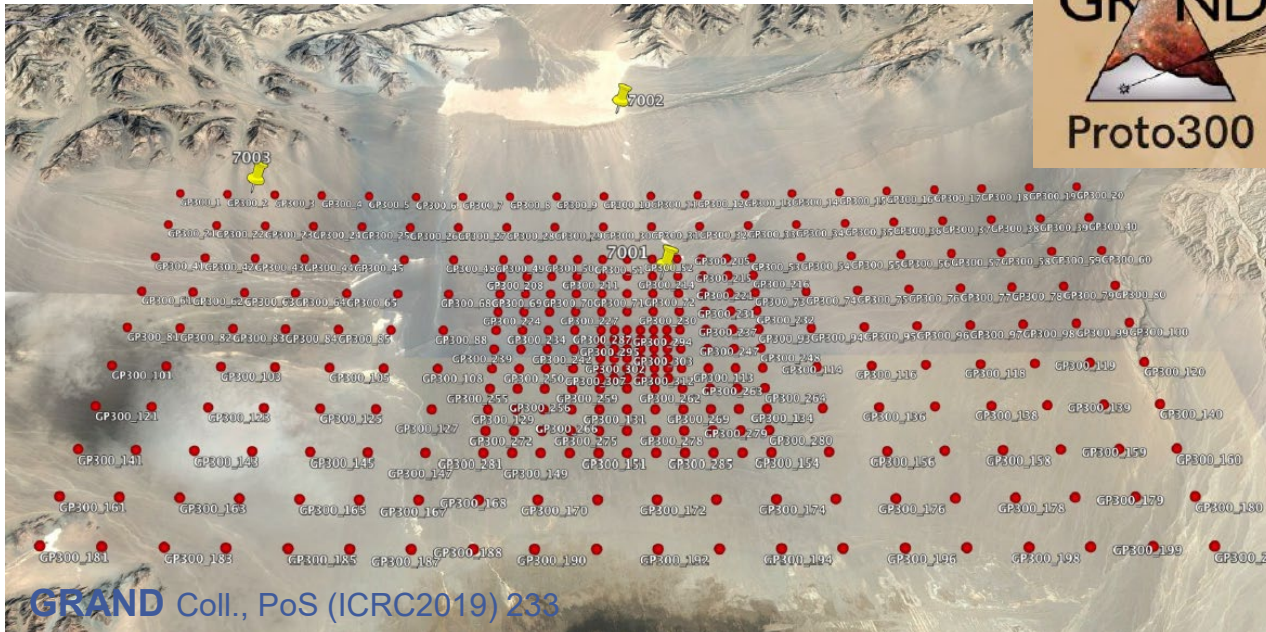
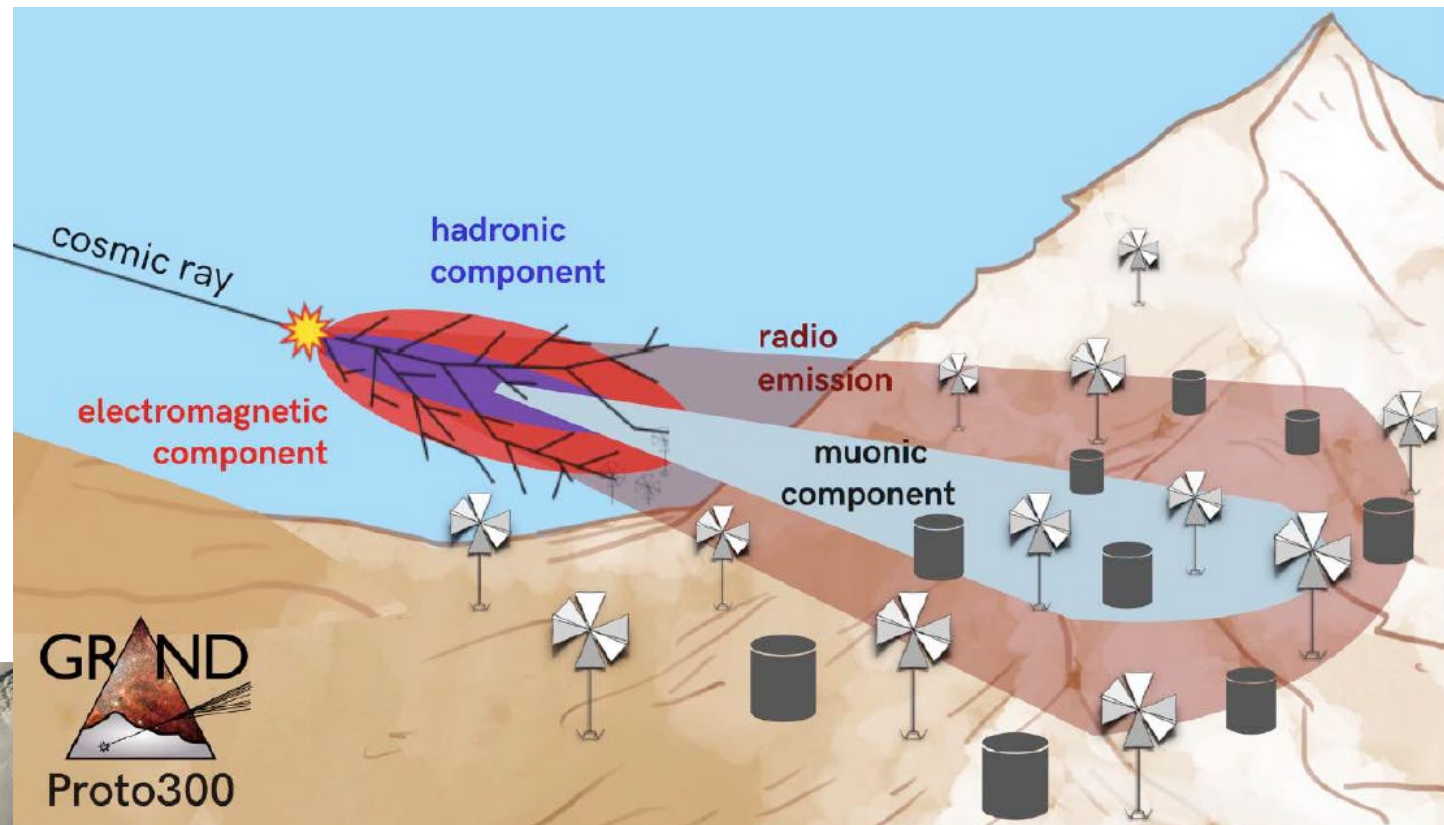
Courtesy: Nature



LHAASO Coll.,
PoS (ICRC2019) 693

GRANDproto300

- Cosmic-Ray science in EeV range with inclined air showers
 - 300 antennas on 200 km²
 - Auger-like water-Cherenkov detectors for muons
 - future stages will be antennas only

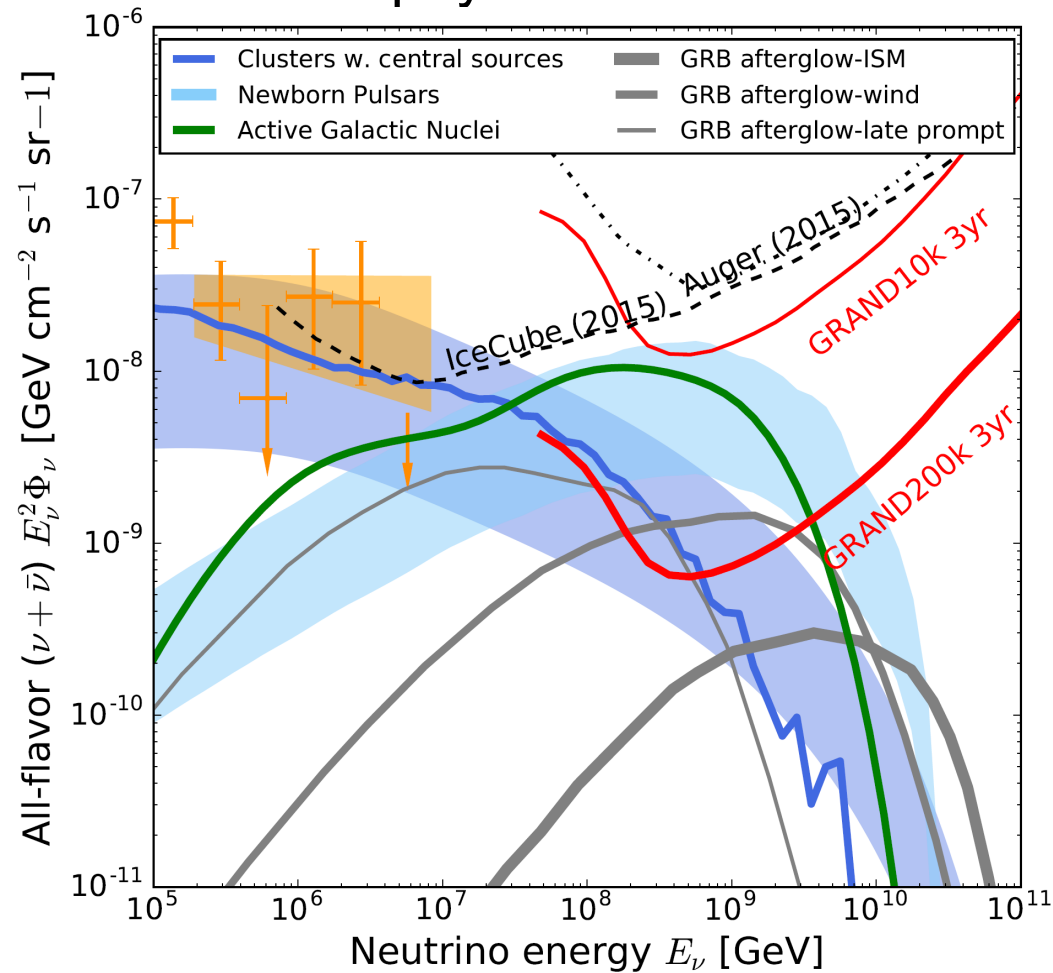


■ Prototype for next stages of GRAND

- GRAND 10k will have comparable exposure to Auger for cosmic rays
- GRAND 200k (if build) may complement future space missions for UHECR

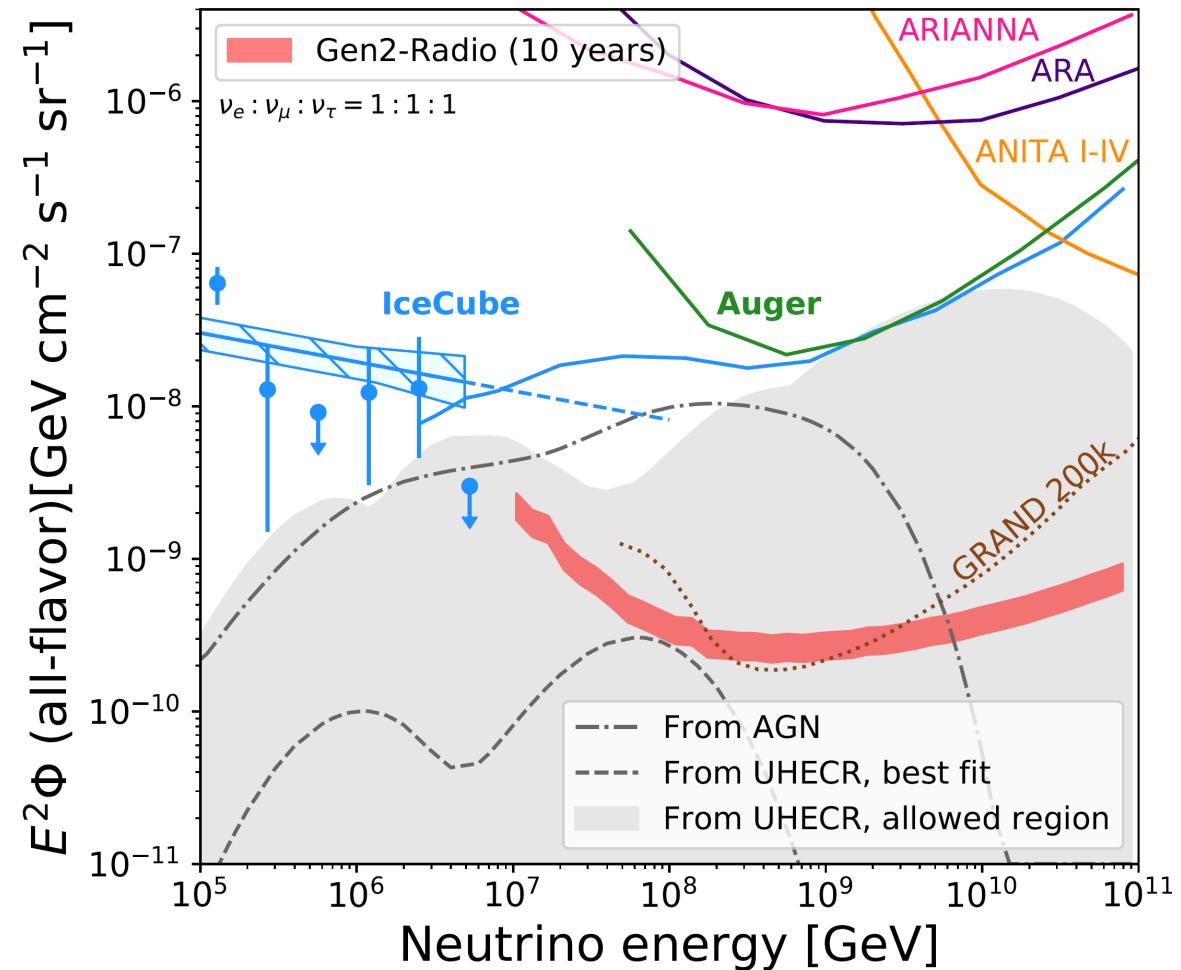
GRAND and IceCube-Gen2 sensitivities for EeV neutrinos

Astrophysical Neutrinos



GRAND Coll., Sci. China Phys. Mech. Astron. 63 (2020) 1

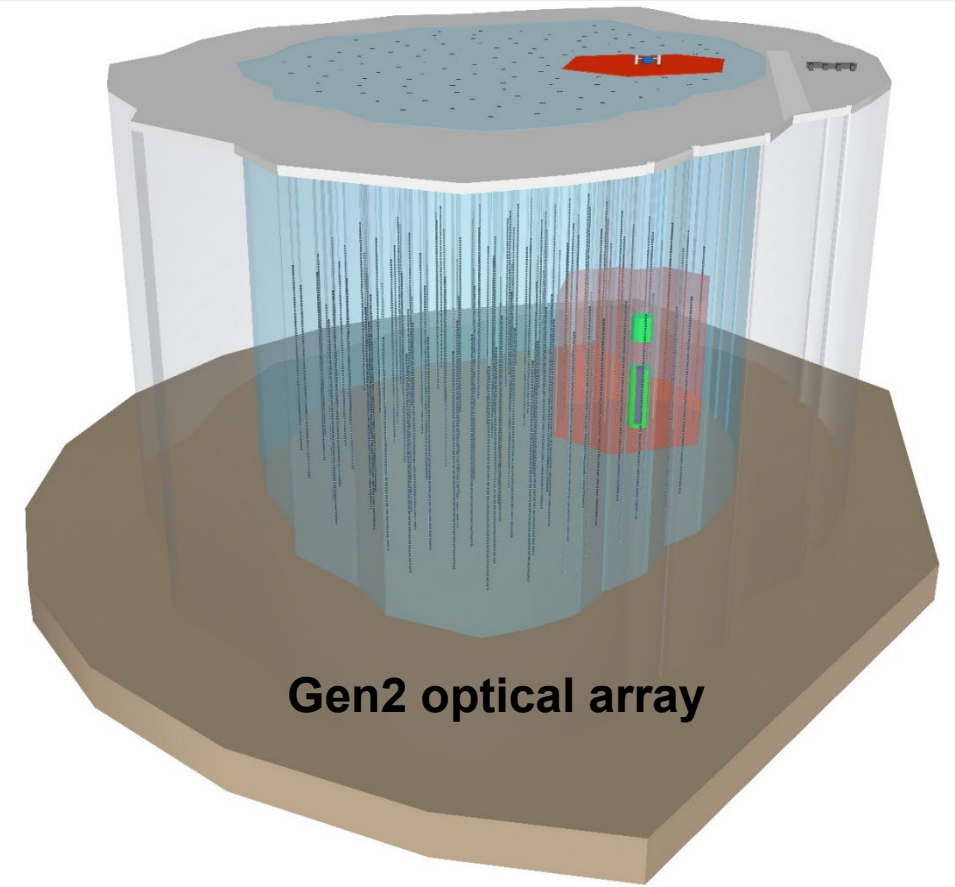
Cosmogenic Neutrinos



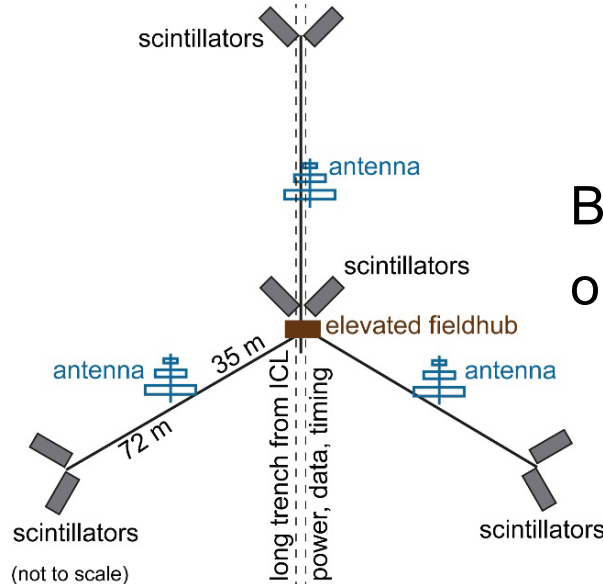
IceCube-Gen2 Whitepaper, arXiv:2008.04323

IceCube-Gen2 Surface Array

- Enhancement of IceTop surface array continued for IceCube-Gen2 surface array
- High accuracy for most energetic Galactic cosmic rays in the PeV to EeV region



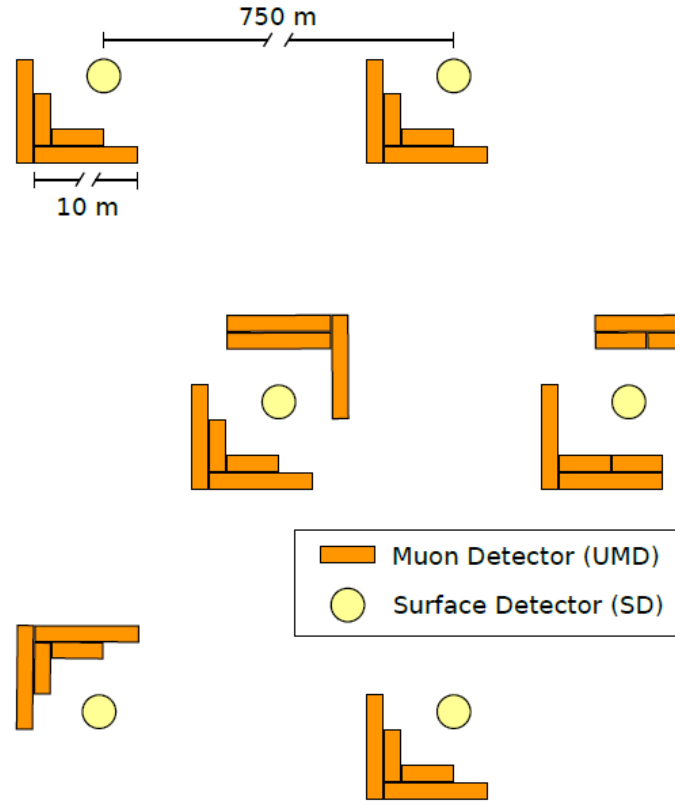
Gen2 optical array



Baseline design of Gen2 Surface Array:
one station per optical string (122)

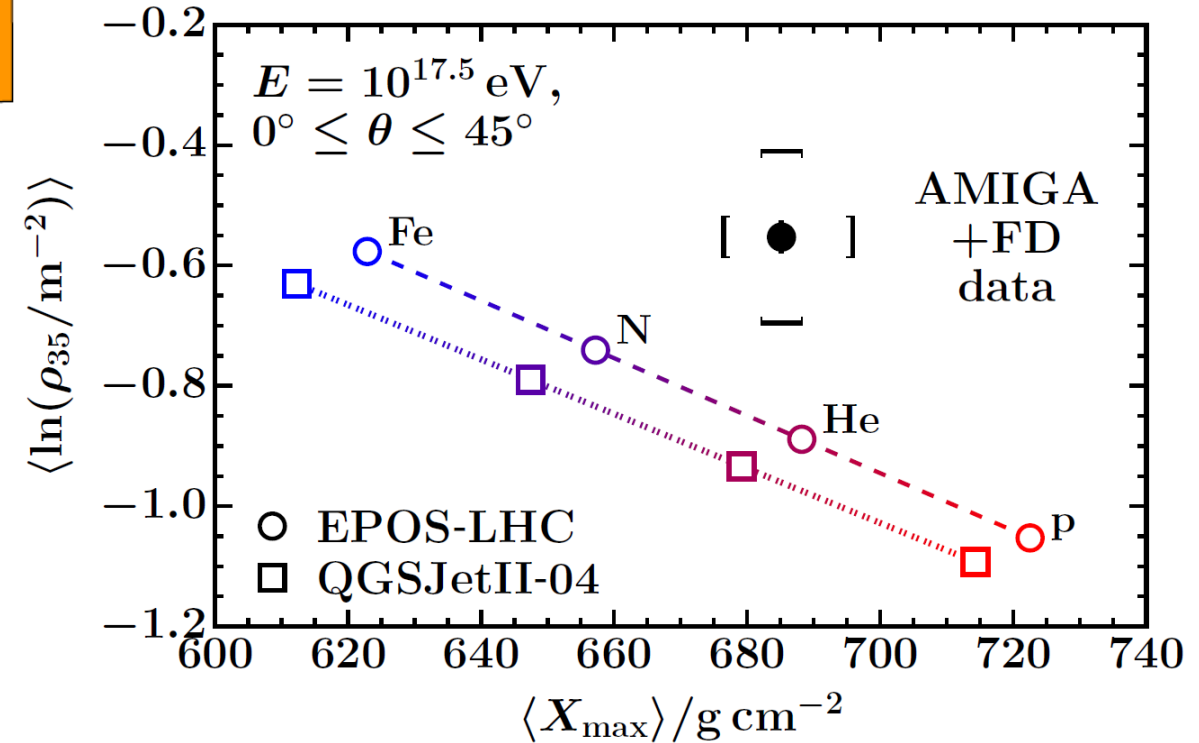
- 4 pairs of scintillators enabling low threshold for veto
- 3 radio antennas increasing accuracy at high energies

Muon Measurements of AMIGA Engineering Array



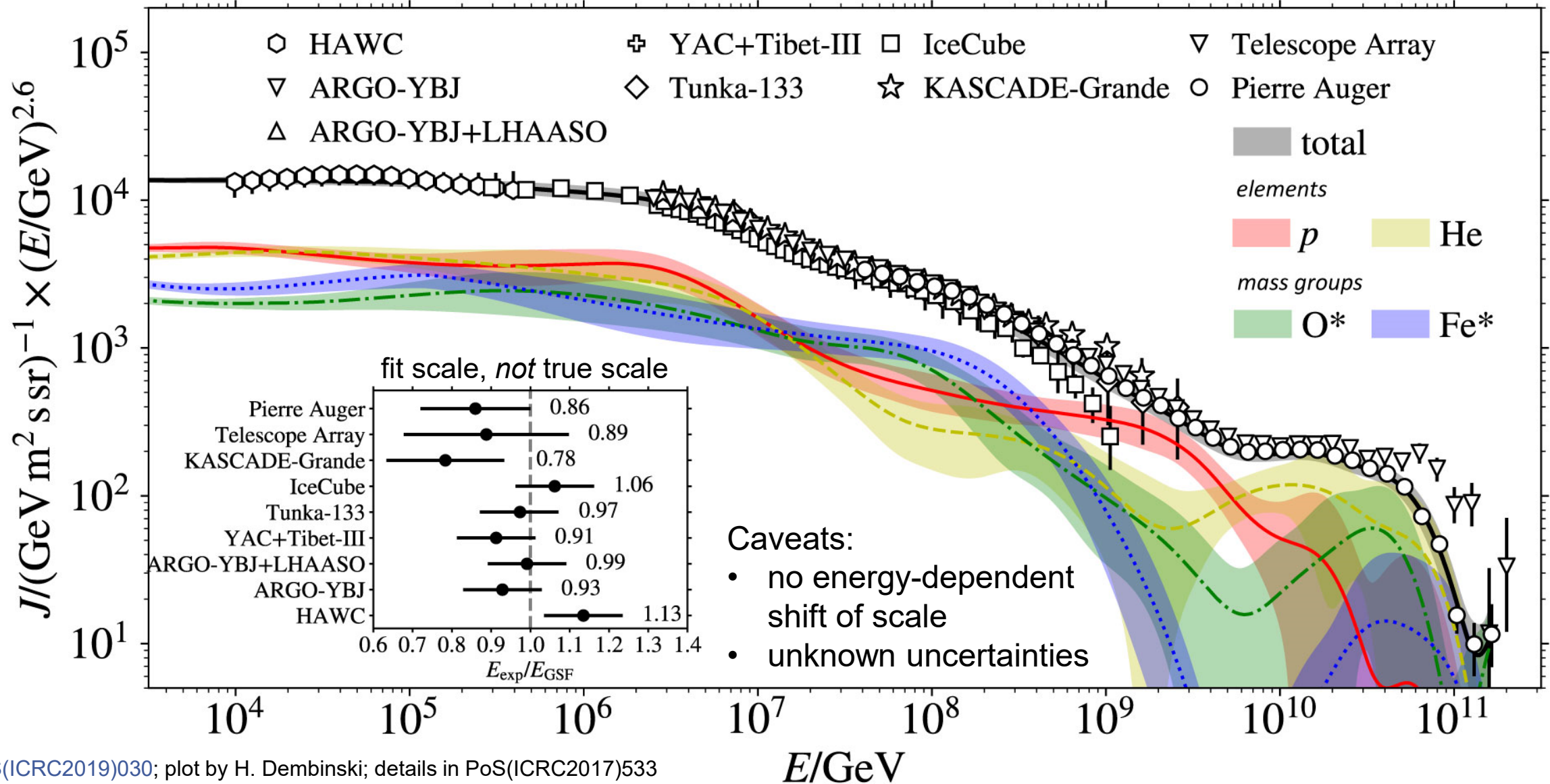
UMD-750m
 23.5 km²
 61x30m² Plastic Scintillators
 buried 2.3m triggering from WCDs

Combination of pure muon and pure electromagnetic measurement (by fluorescence) confirms muon deficit in simulations



Pierre Auger Coll., PoS (ICRC2019) 411

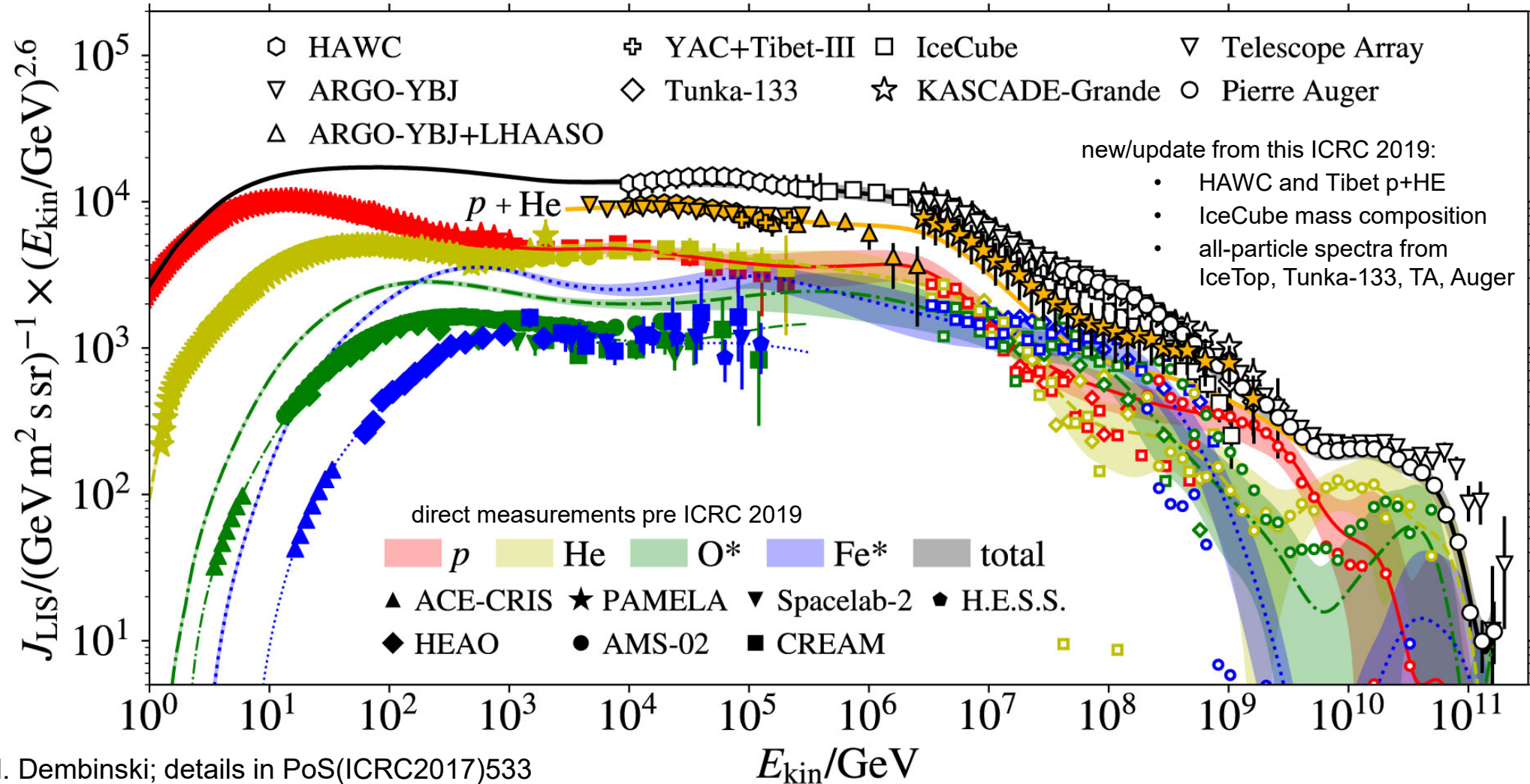
Cosmic-Ray Energy Spectrum and Mass Composition



PoS(ICRC2019)030; plot by H. Dembinski; details in PoS(ICRC2017)533

Global Spline Fit (Composition and Energy Spectrum)

Fit of spectra *within experimental uncertainties*, allowing for constant shift in energy scales



plot by H. Dembinski; details in PoS(ICRC2017)533