UNIVERSITY OF DELAWARE
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Ultra-high-energy Cosmic Rays in the next Decade(s):

a personal summary of the Snowmass CF7 Whitepaper on UHECR

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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, $\sigma_{\text{p-Air}}$	AugerPrime upgrade
Telescope Array (TA)	Hybrid array: fluorescence, surface scintillators, up to 3000 km^2	UHECR source populations proton-air cross section ($\sigma_{\text{p-Air}}$)	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, $\sigma_{\text{p-Air}}$	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, $\sigma_{\text{p-Air}}$	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, $\sigma_{\text{p-Air}}$	GCOS R&D + first site → GCOS further sites
			2025 · 2030 · 2035 · 2040

*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.

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

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Contents of Snowmass UHECR Whitepaper

Contents

see references in WP for material shown here:

https://arxiv.org/pdf/2205.05845

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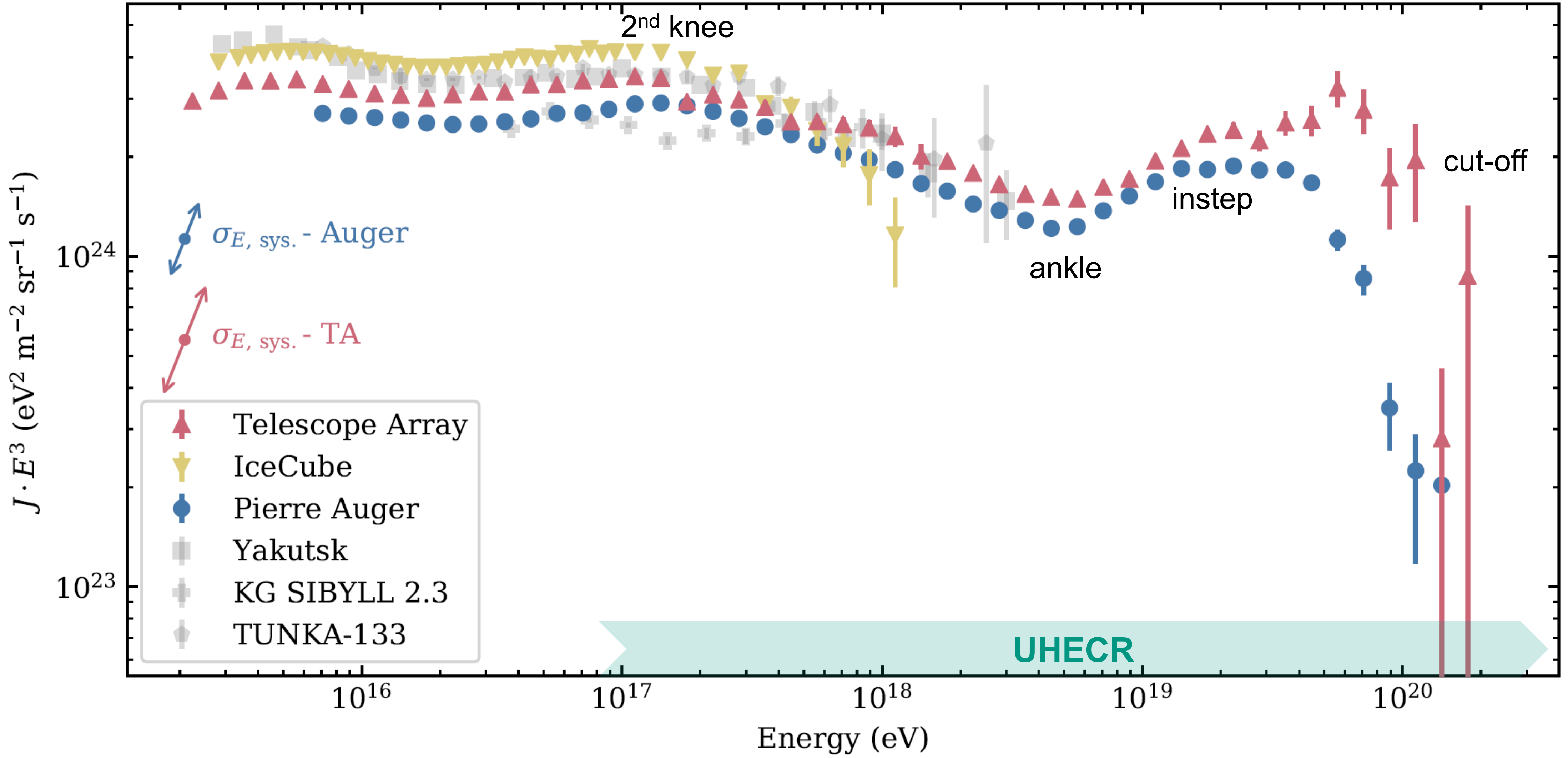
Cosmic-Ray Energy Spectrum: UHECR above 100 PeV*



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

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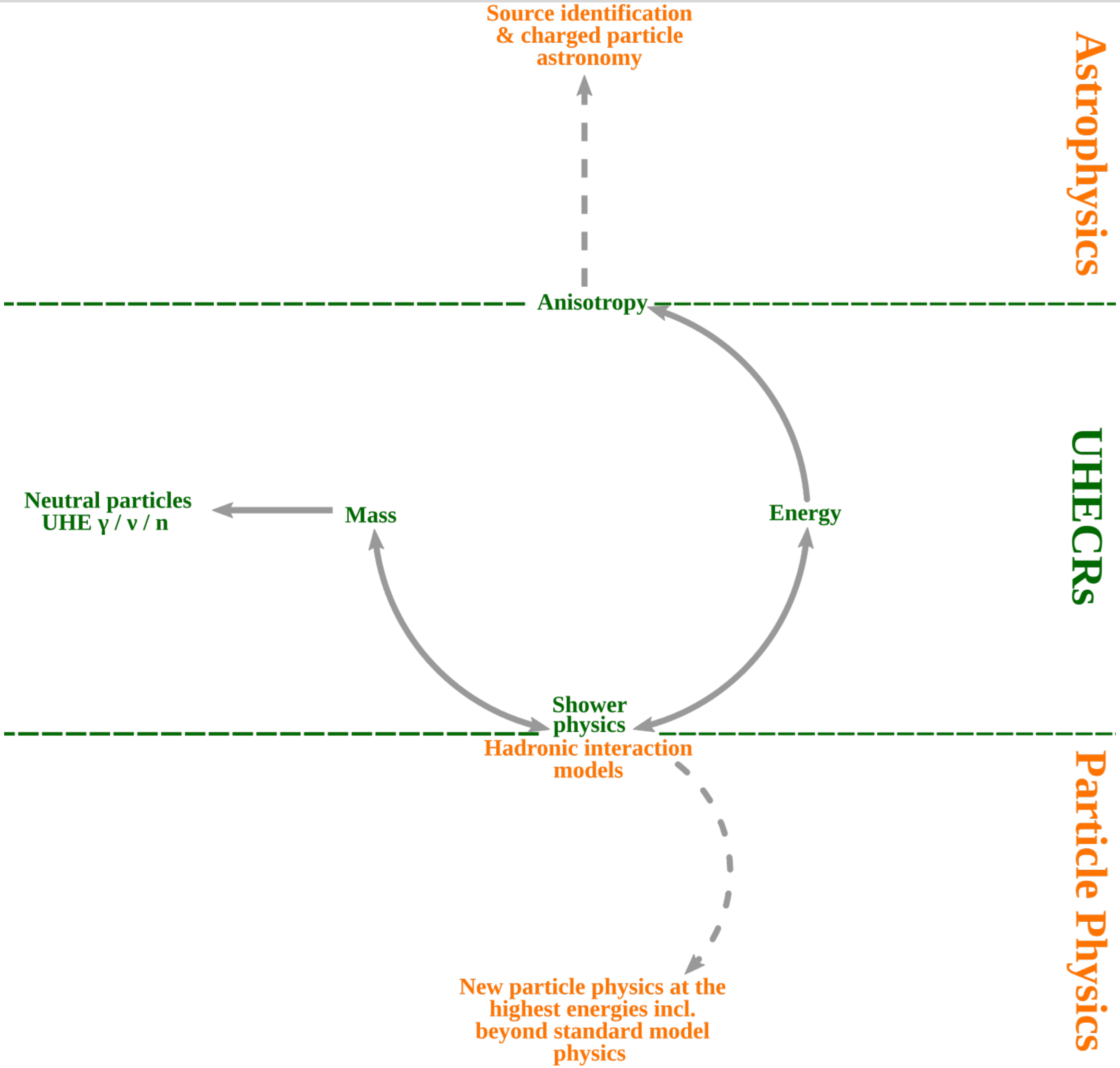
Big UHECR Picture

- 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



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- astrophysics
  - source (classes)
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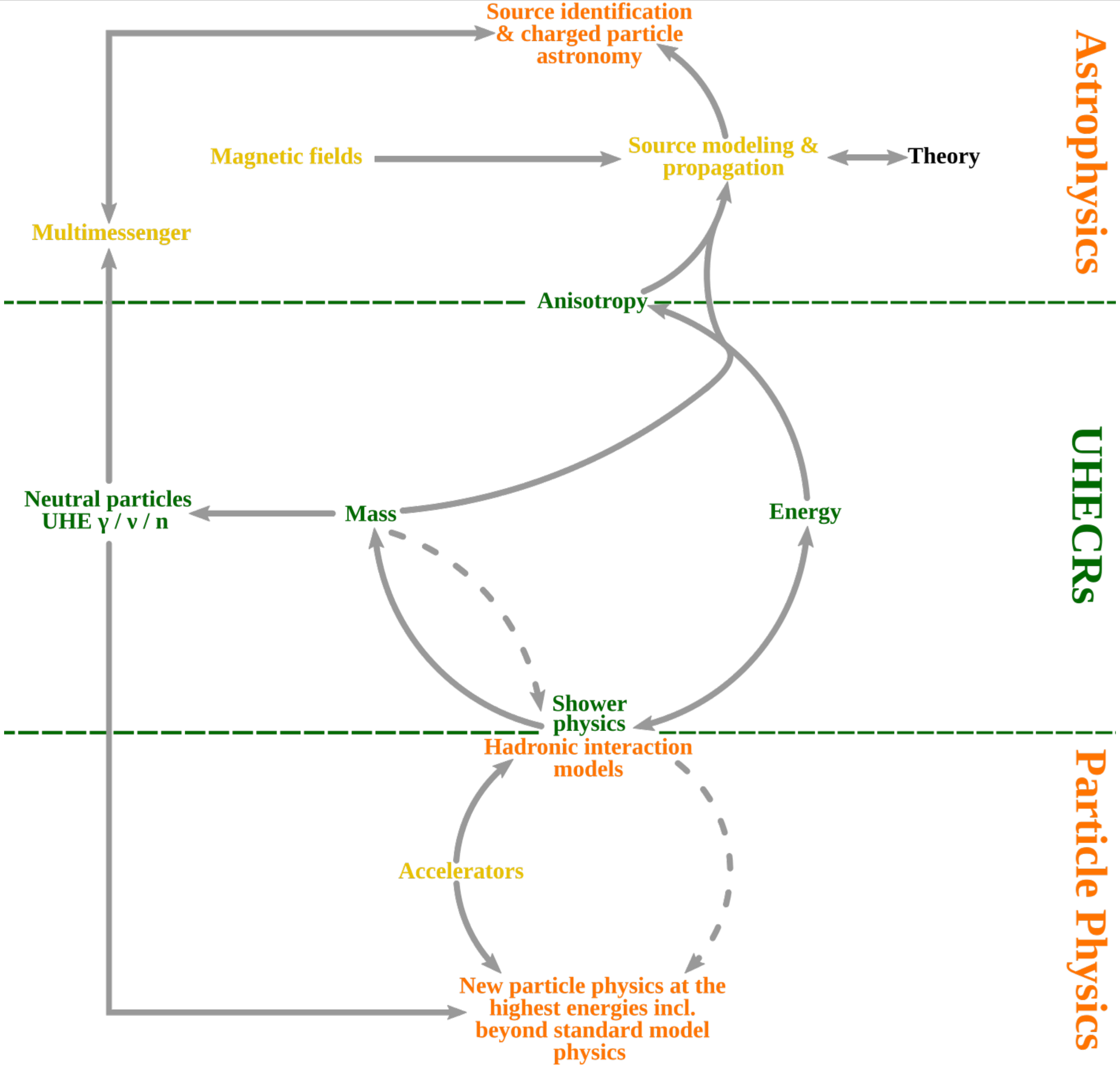
  - physics in sources and during propagation
  - search for BSM
- connection to other fields
  - multimessenger
  - magnetic fields in space
  - accelerator experiments



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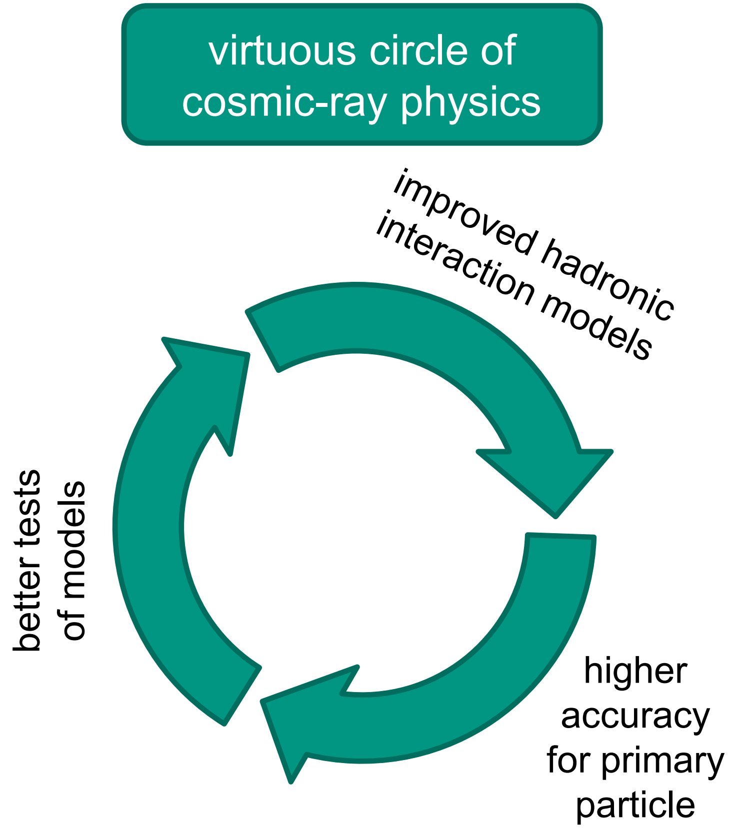
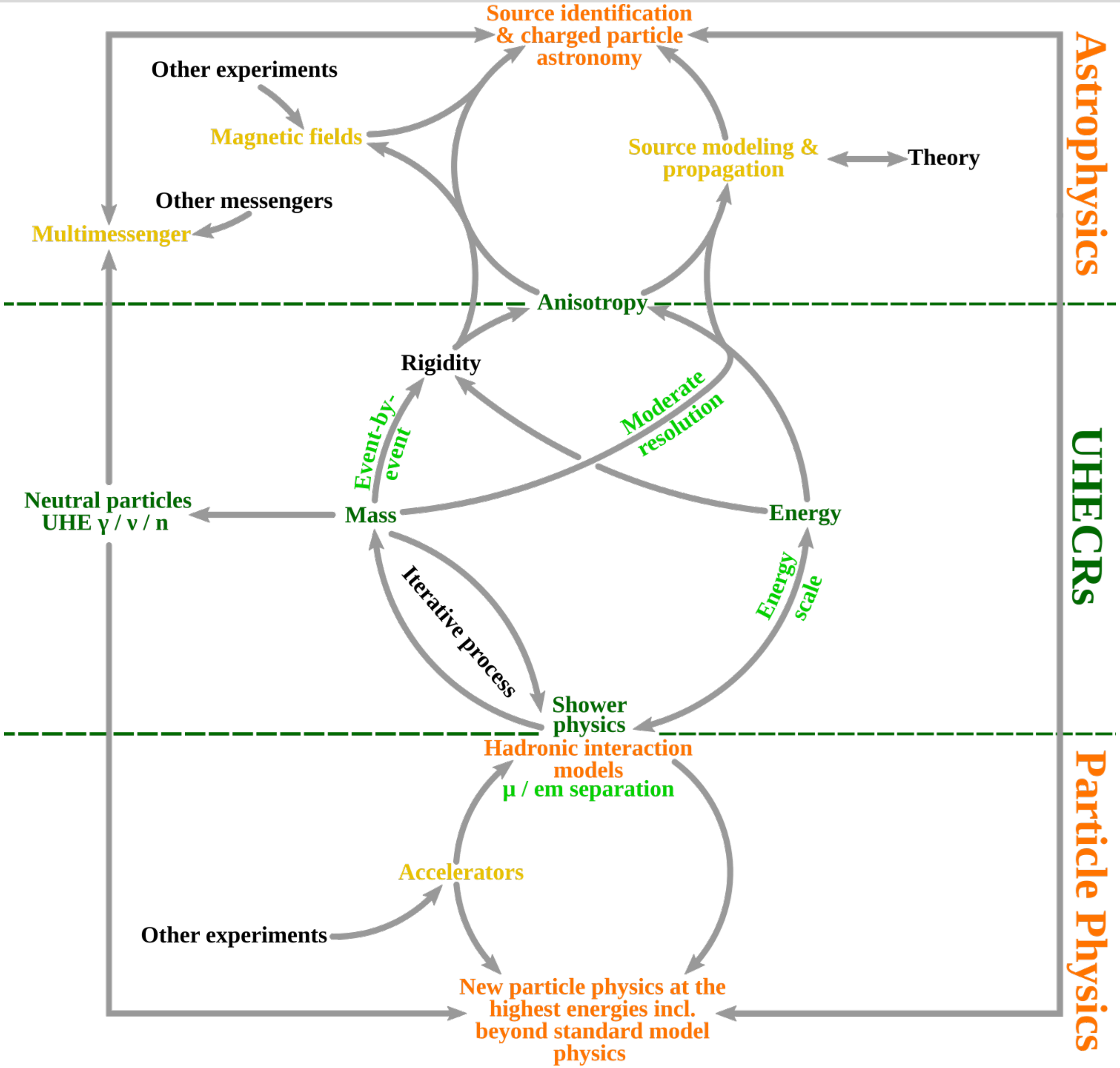
Big UHECR Picture

- interplay between particle and UHECR astrophysics

→ higher accuracy for rigidity





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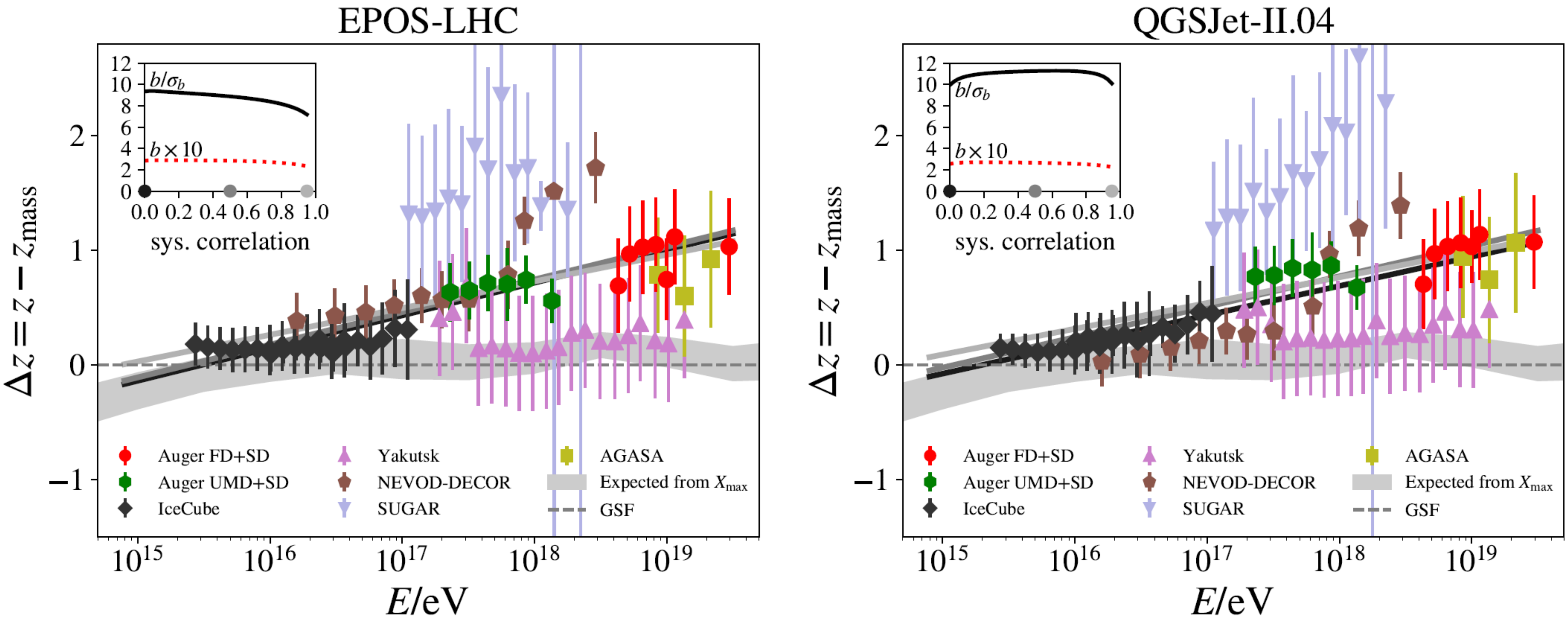
Particle Physics: Muon Problem in Hadronic Interaction Models

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



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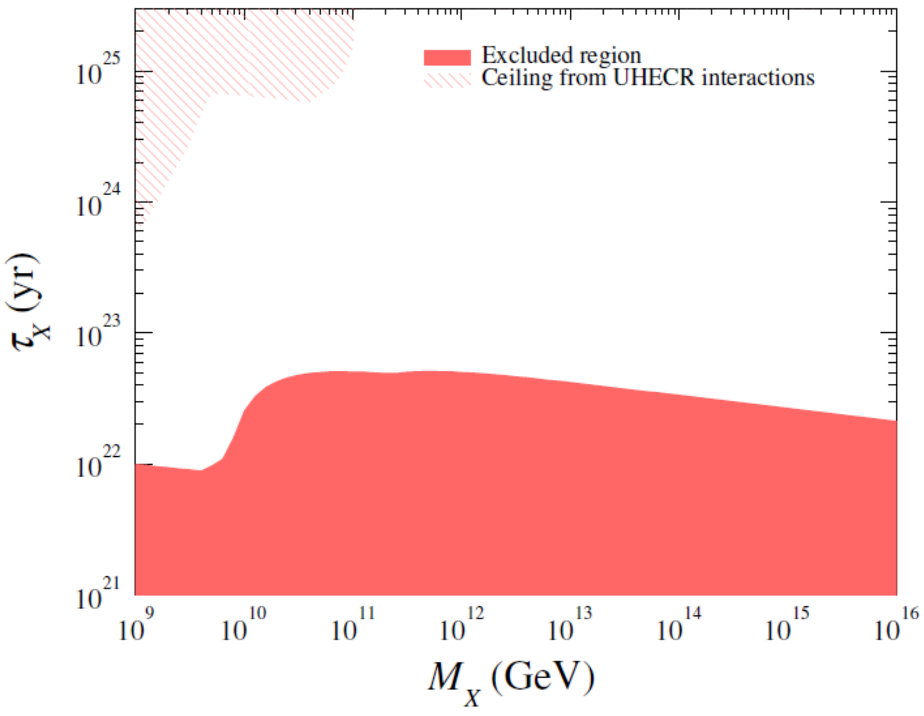
Particle Physics: Test of various BSM scenarios, SHDM, LIV, …

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



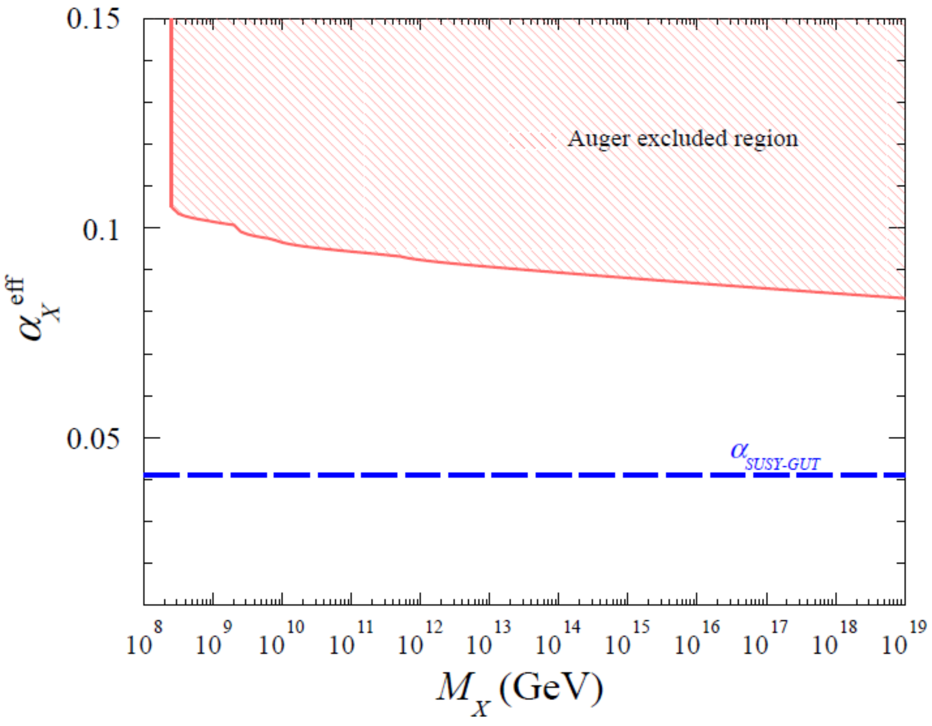


Figure 3.8: Constraints on the mass and lifetime of SHDM particles as obtained from the upper limits on photons [375] (left) and upper limits at 95% C.L. on the effective coupling constant of a hidden gauge interaction as a function of the mass for a dark matter particle decaying into $q\bar{q}$ [18] (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].

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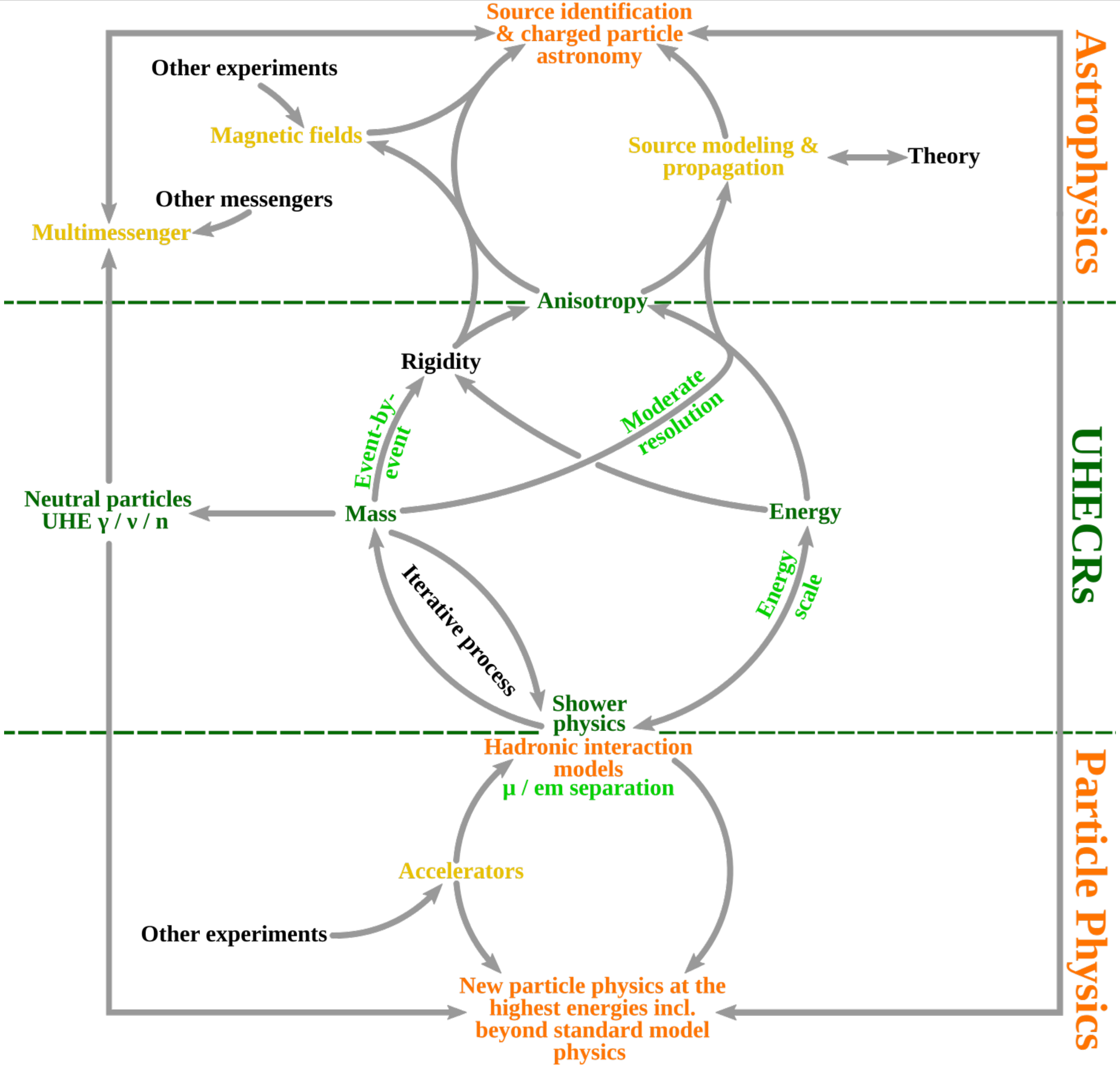
Big UHECR Picture

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



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Big UHECR Picture

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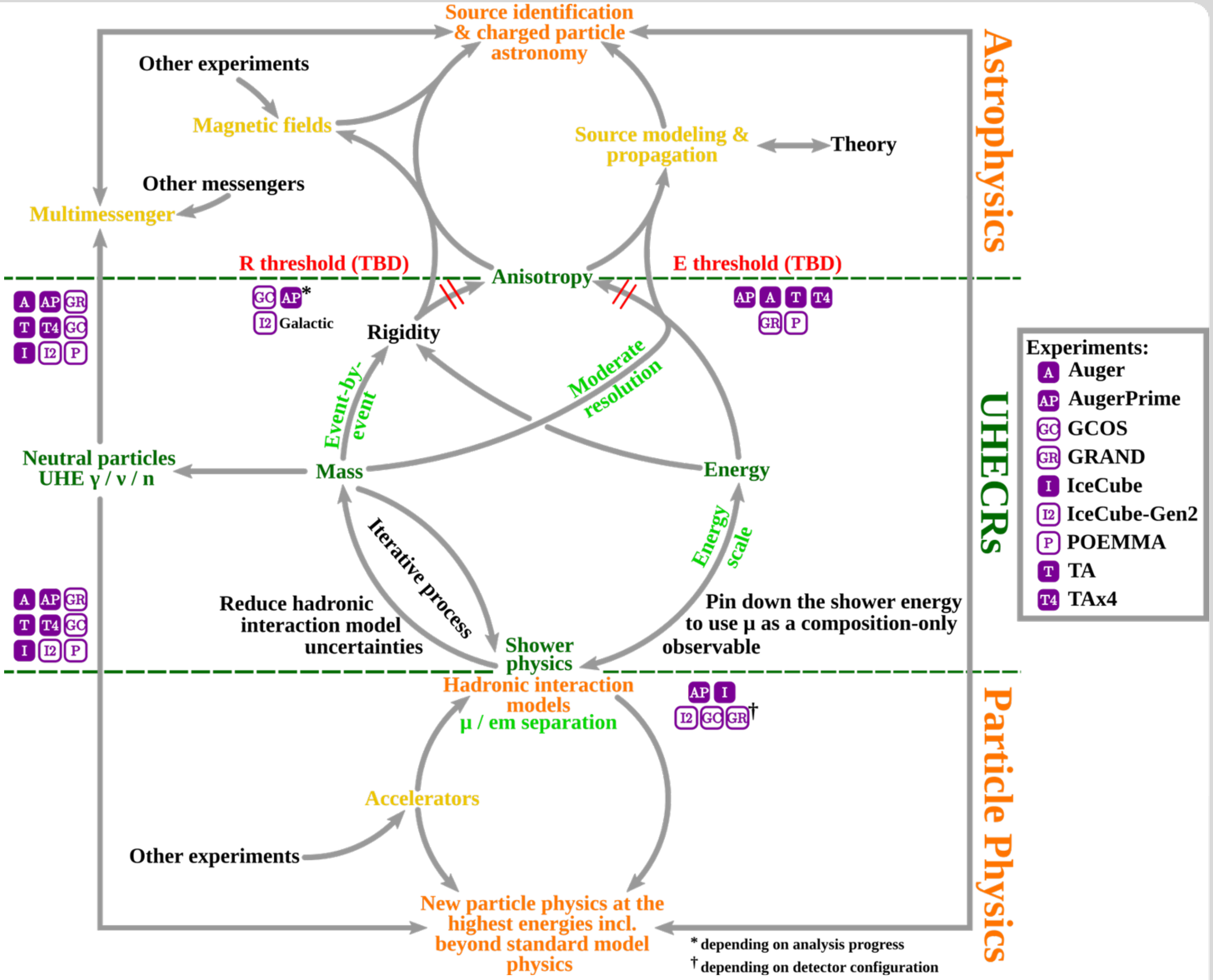

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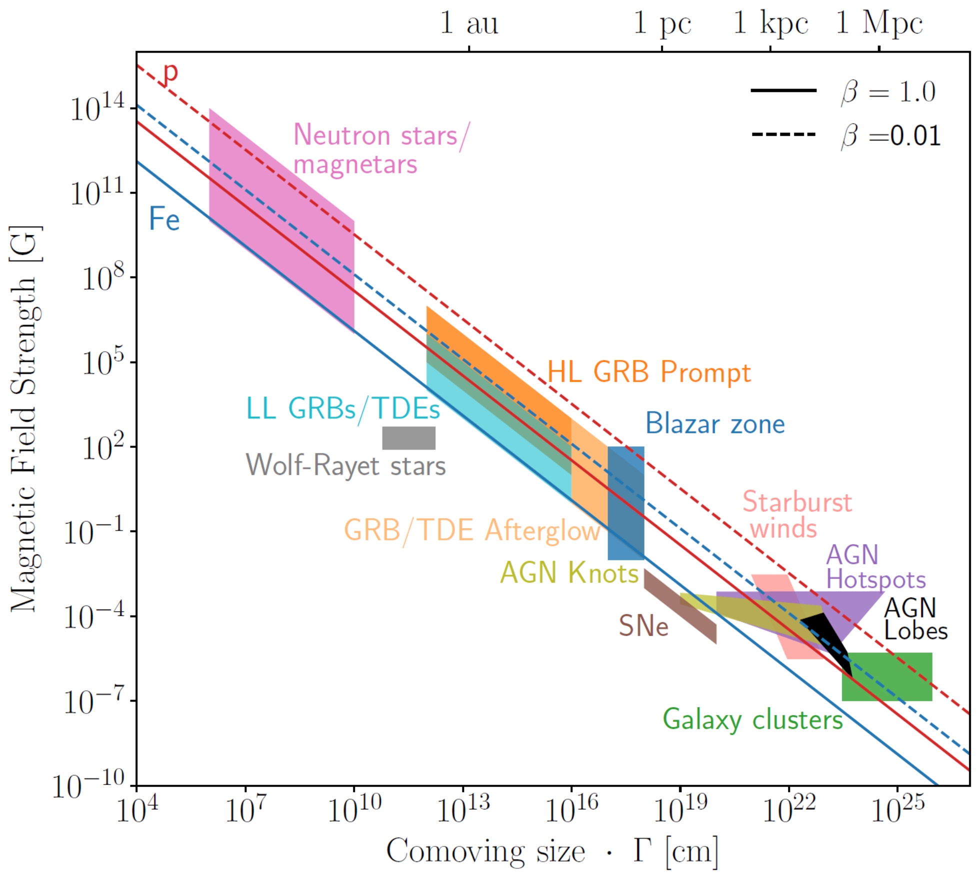
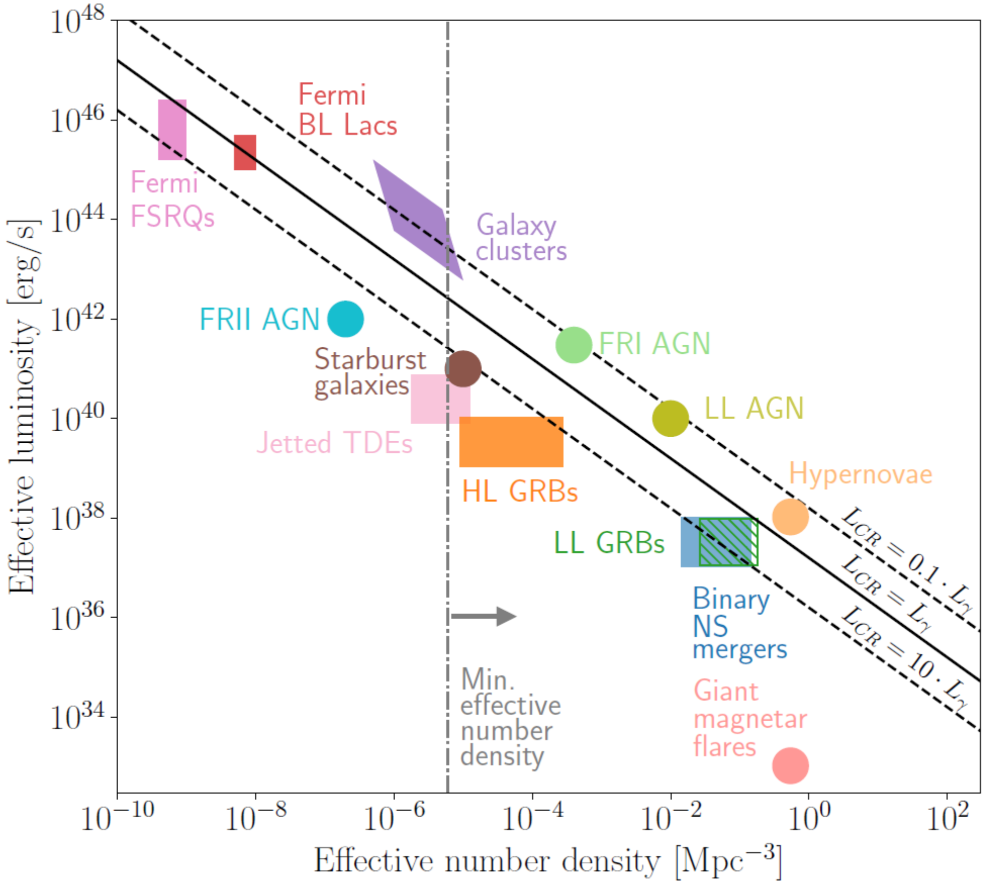
Astrophysics: What are the sources of UHECR?

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

Hillas Plot



Constrains by Source Density



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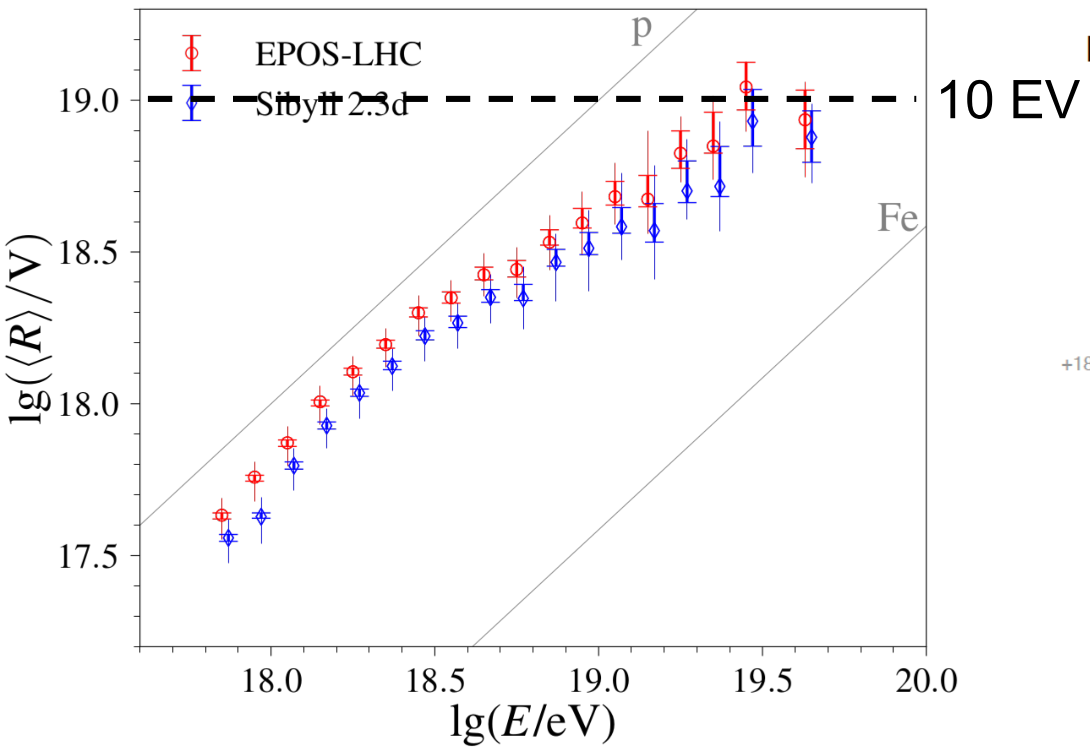
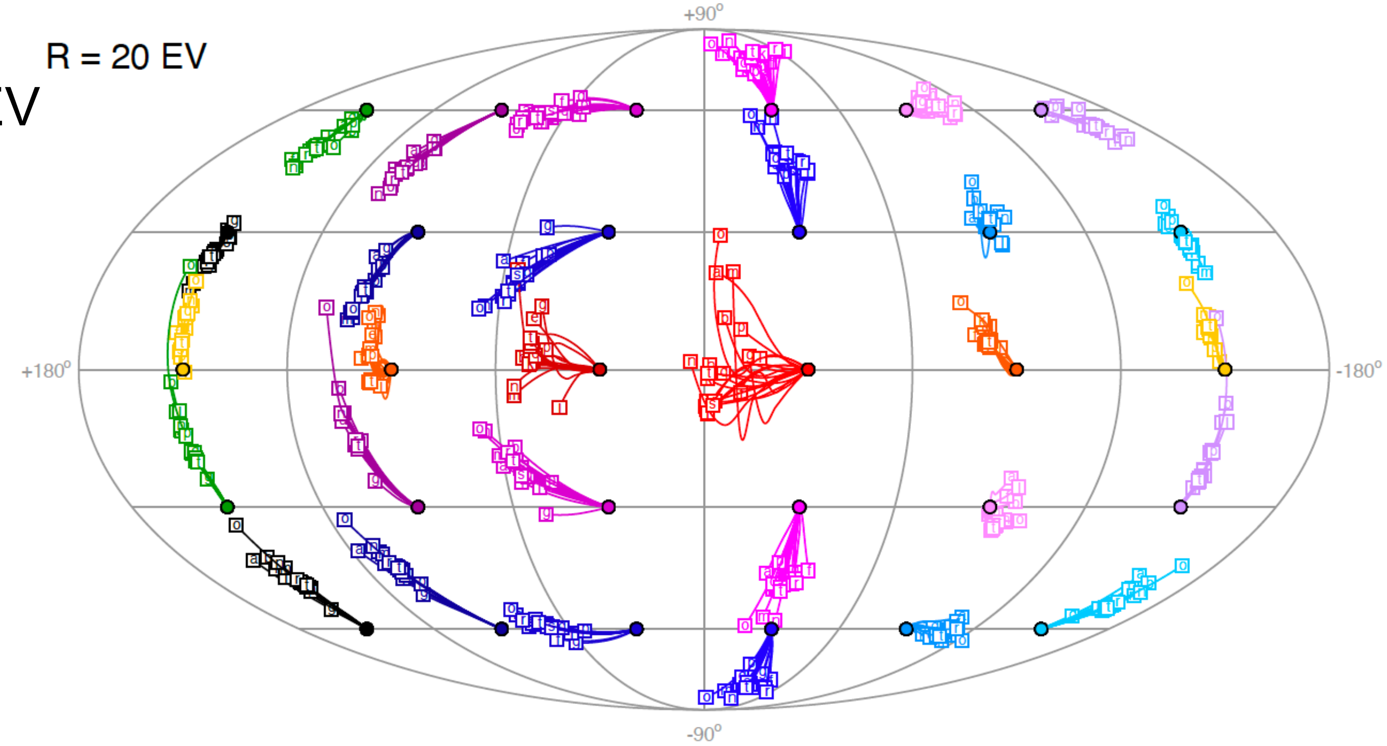
Particle Astronomy with Rigidities R > 10 EV

- 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

average rigidity estimated from Auger X_{max}



backtracing at R = 20 EV for different models of Galactic magnetic field



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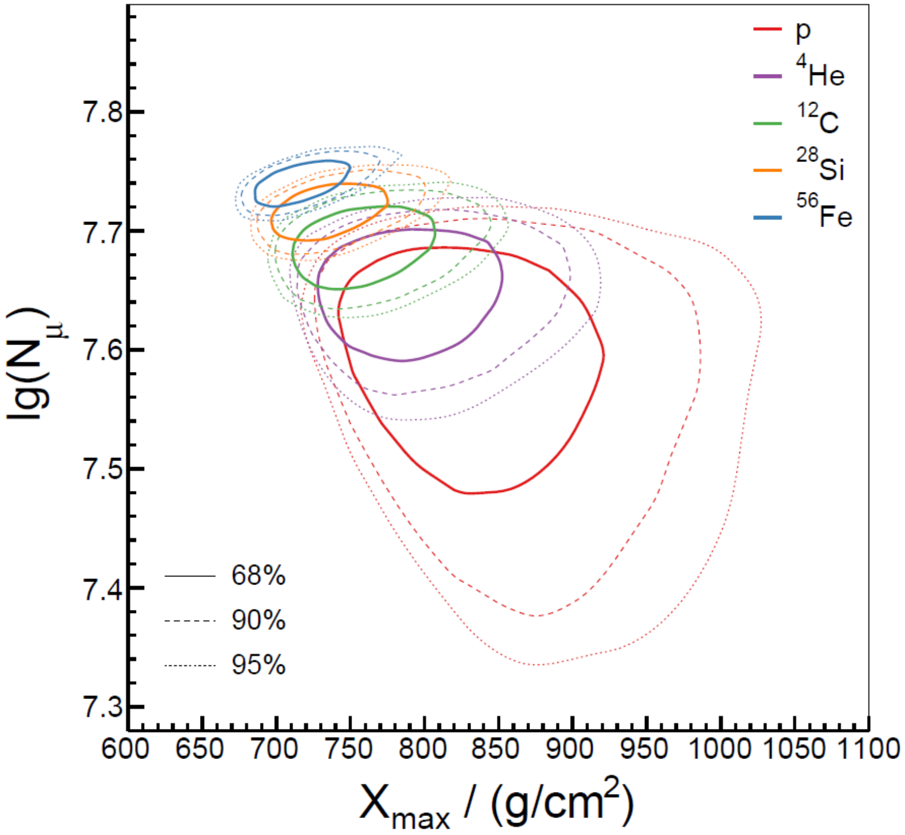
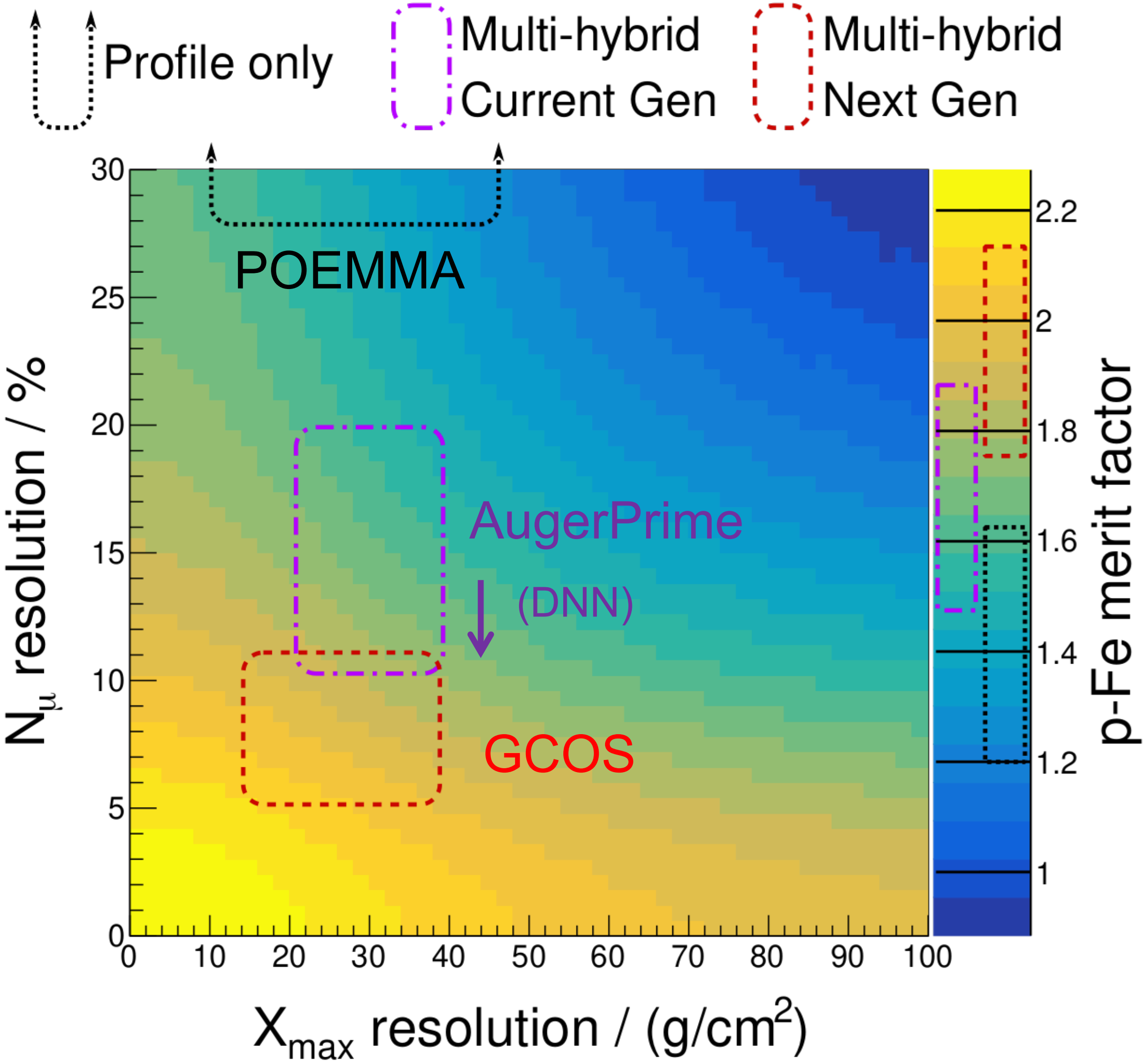
How to improve the accuracy of rigidity measurements?

- 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





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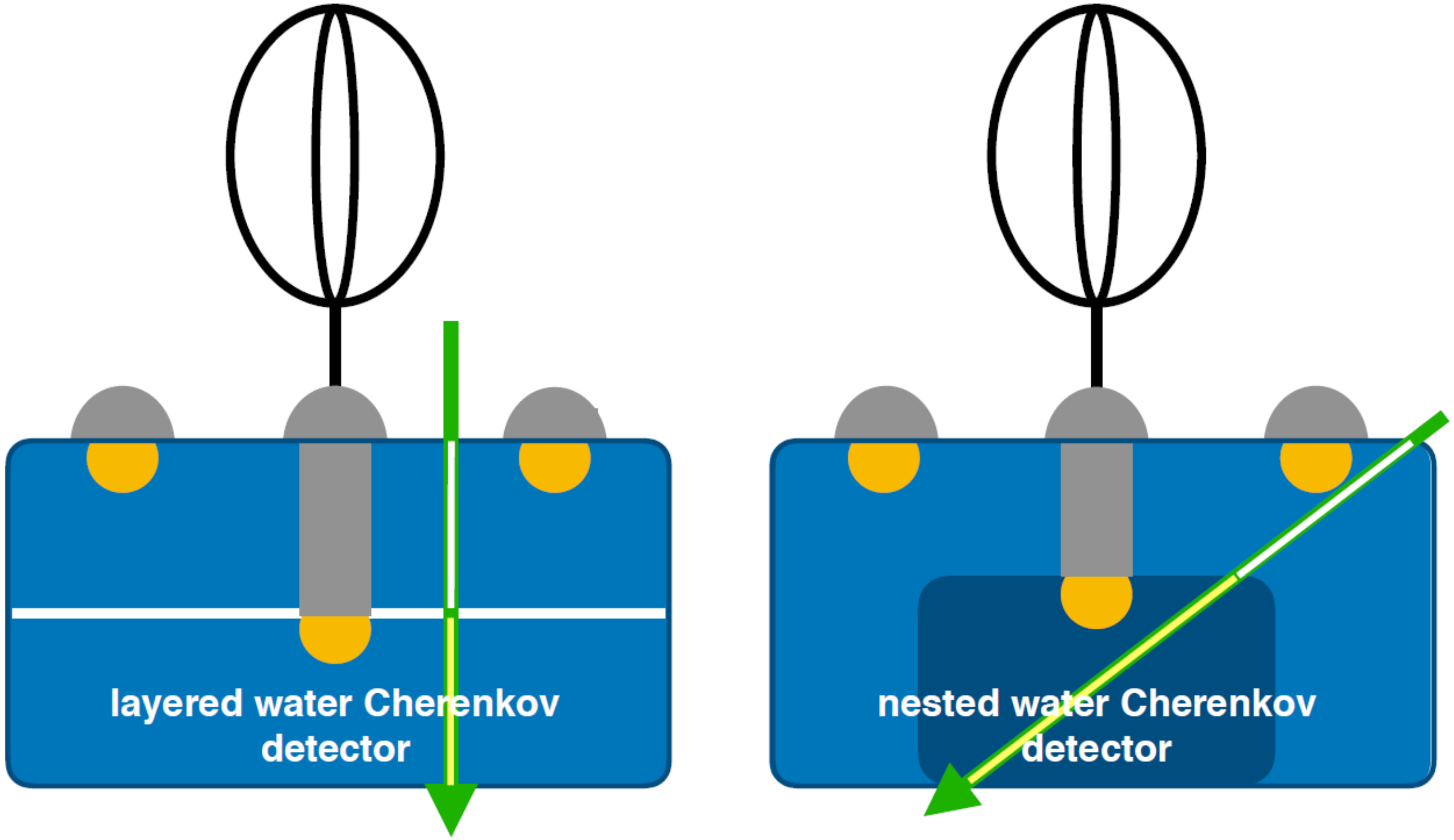
How to improve muon measurements for rigidity?

- 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



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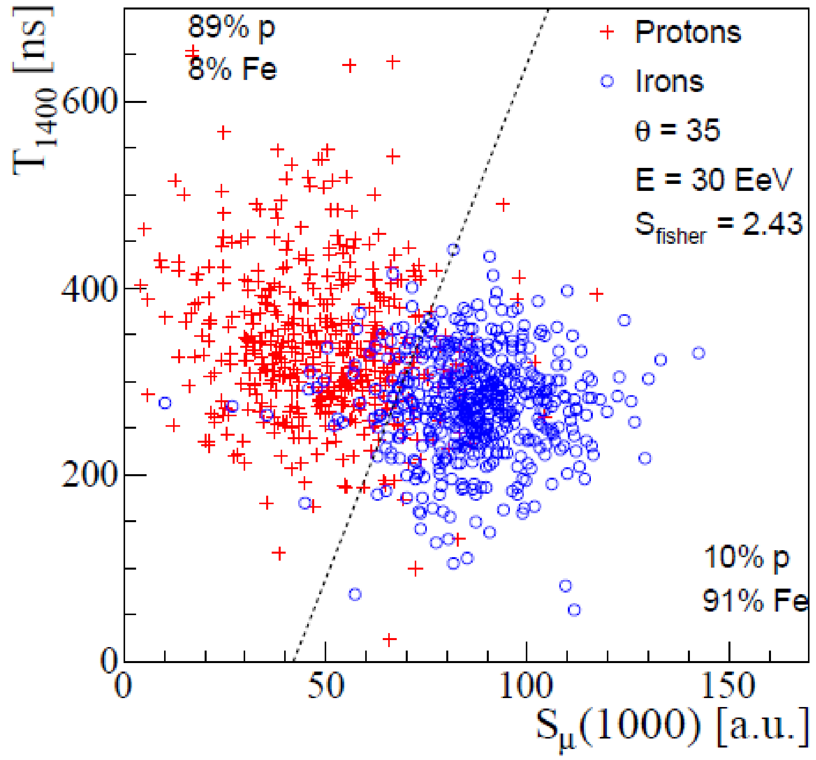
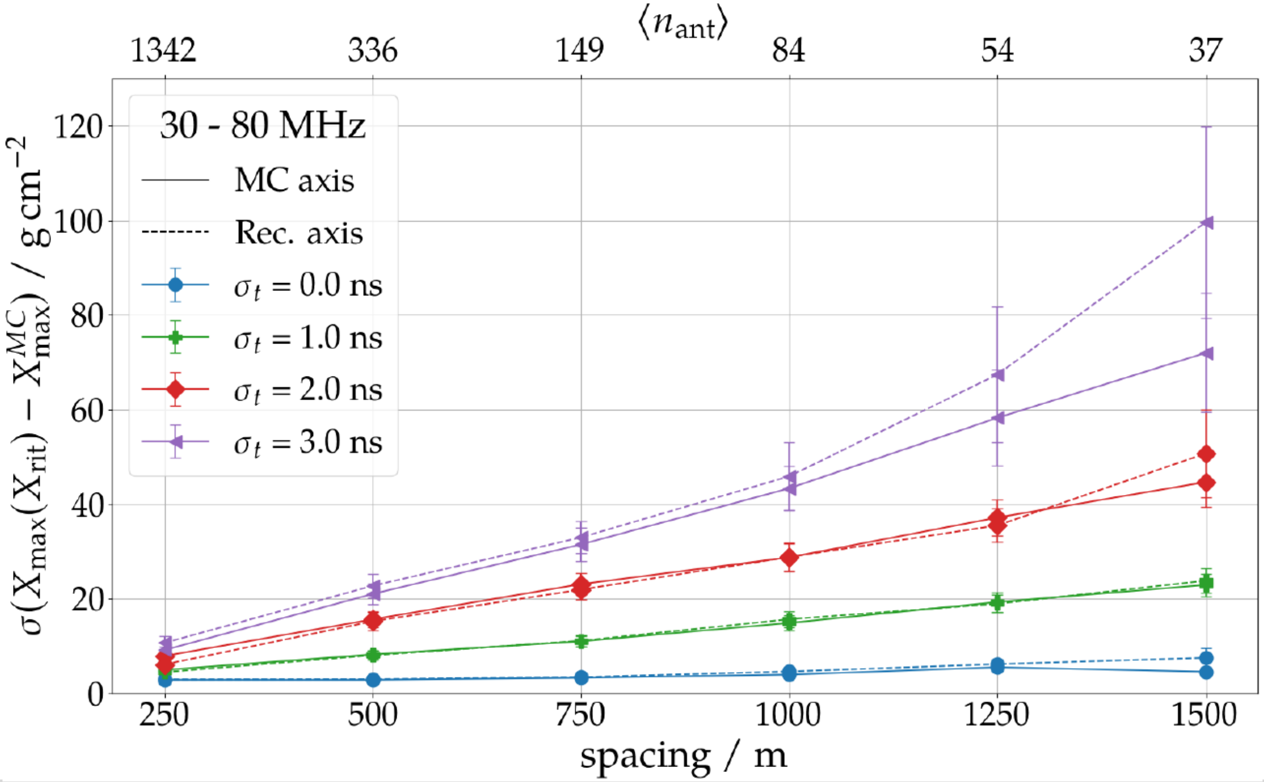
How to improve X_{max} measurements?

- 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



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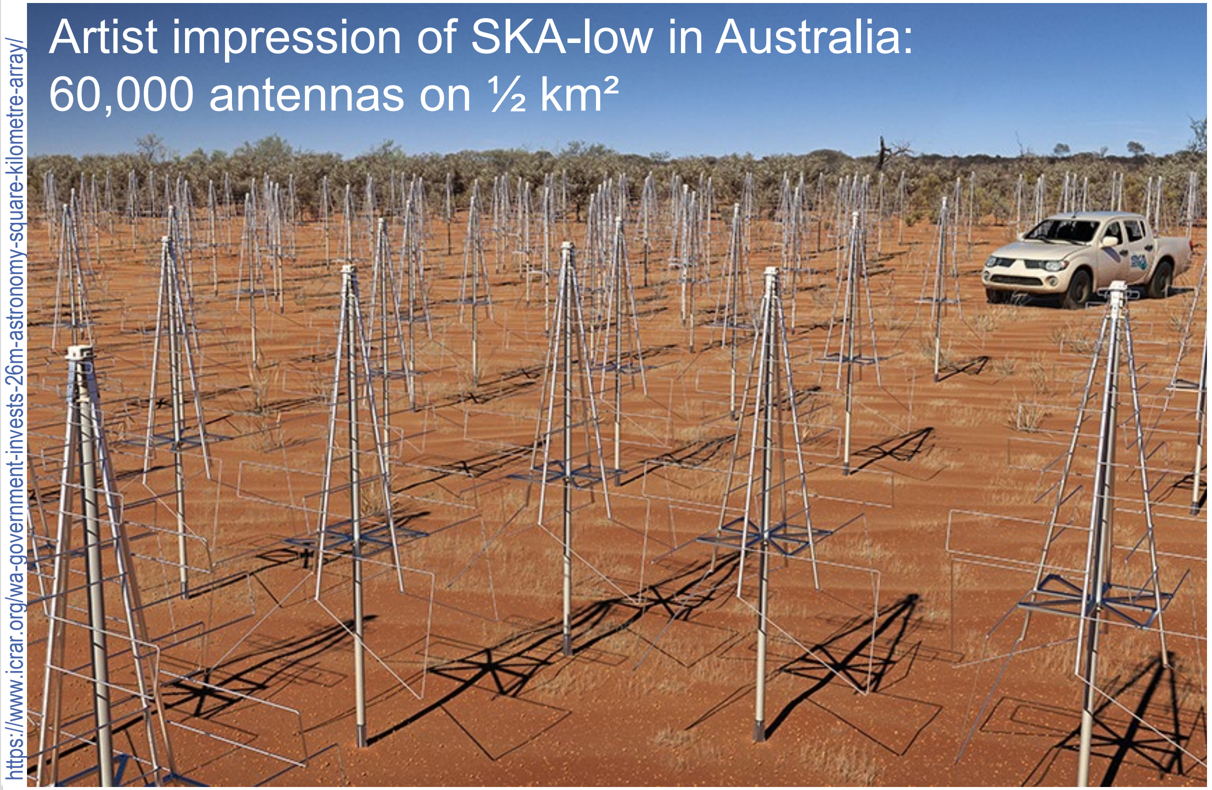
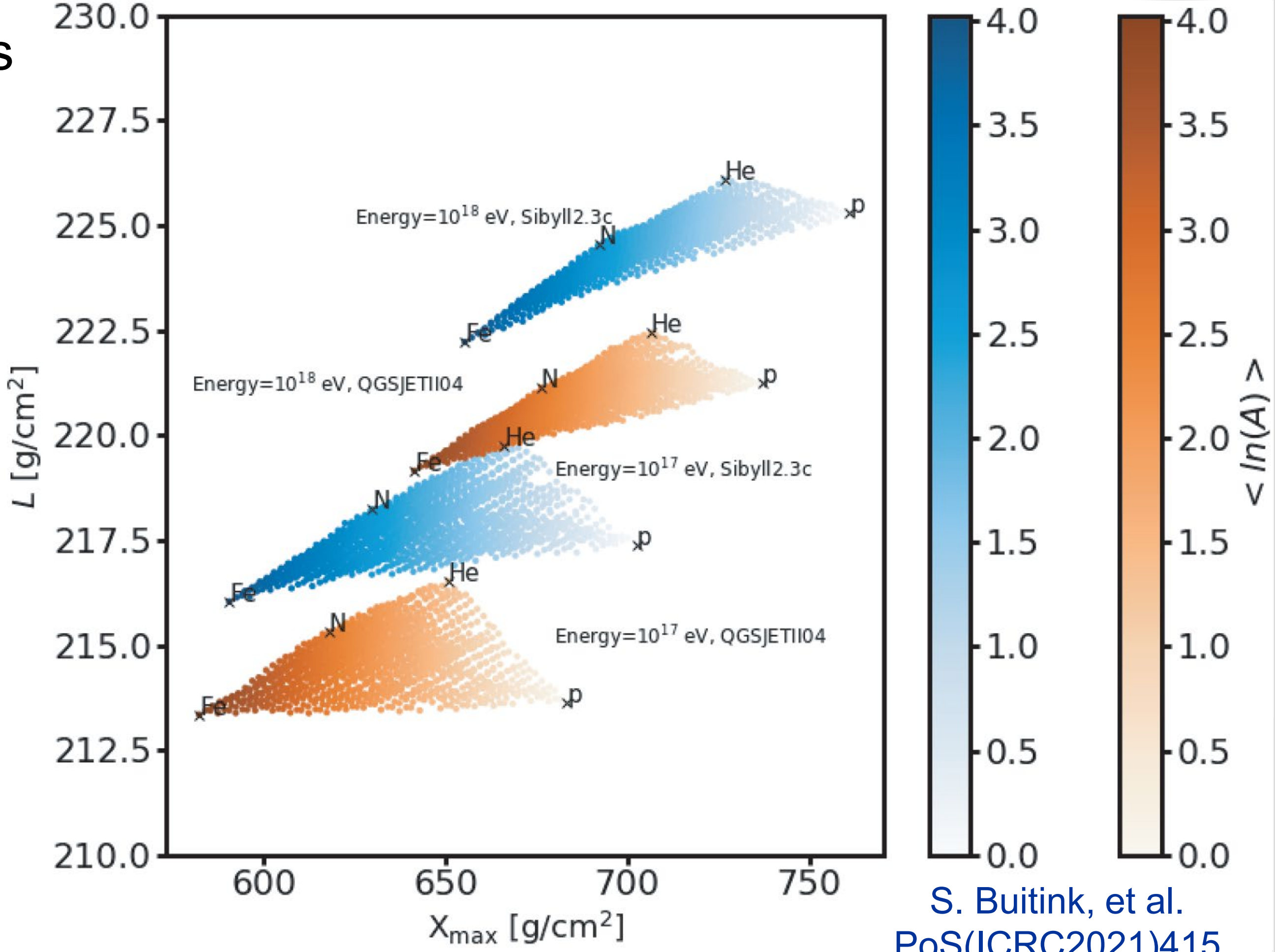
Other possibilities for higher mass accuracy?

- 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



https://www.icrar.org/wa-government-invests-26m-astronomy-square-kilometre-array/



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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

Experiment	Feature	Cosmic Ray Science*	Timeline
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Timeline: 2025 2030 2035 2040

*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.

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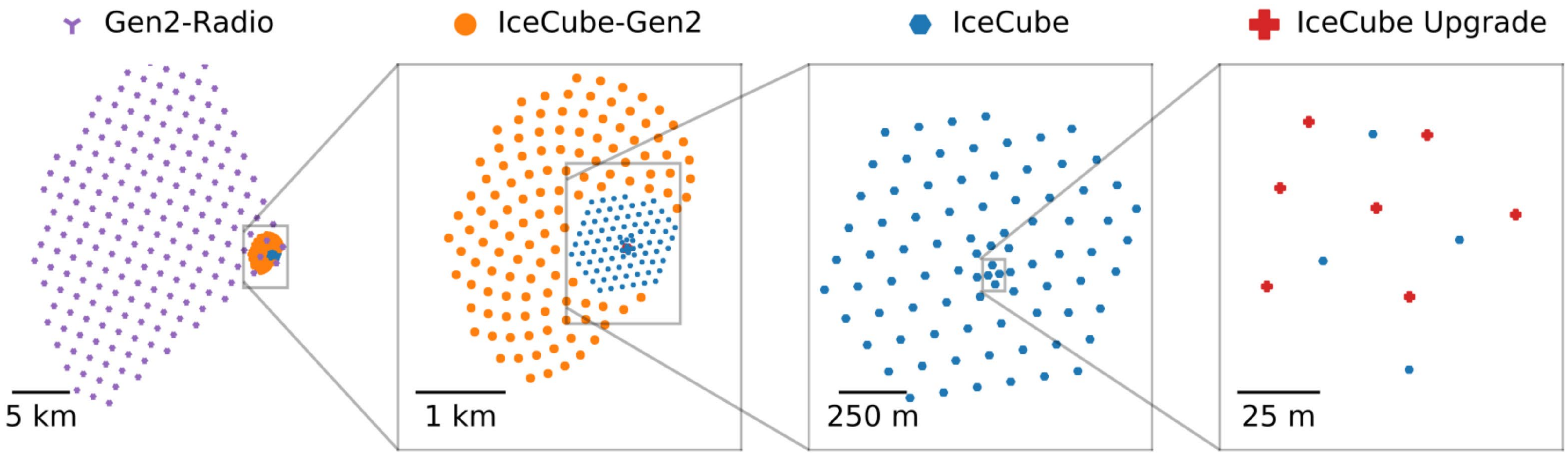
IceCube-Gen2 – the planned extension of IceCube

- 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 neutrions
- complemented by a surface array above the in-ice optical array



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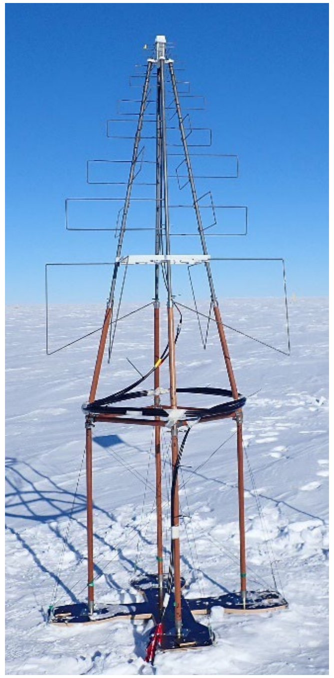
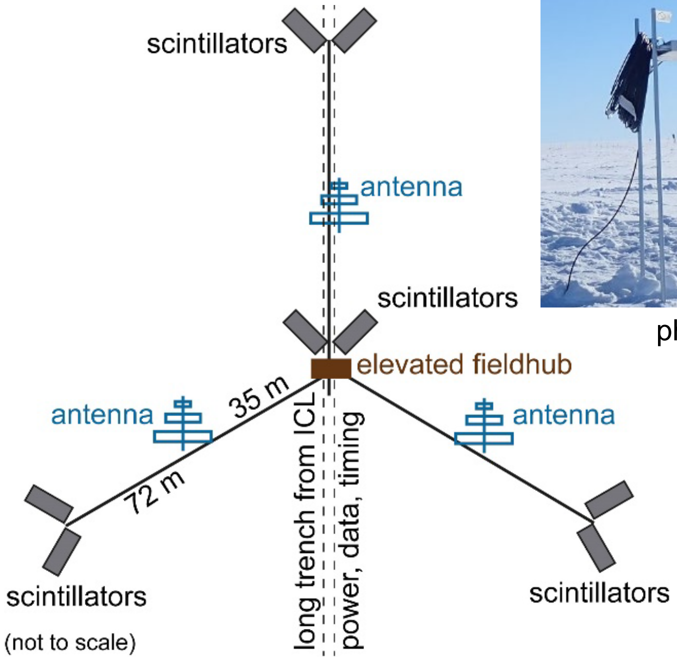
IceCube-Gen2 and its Surface Array

- 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

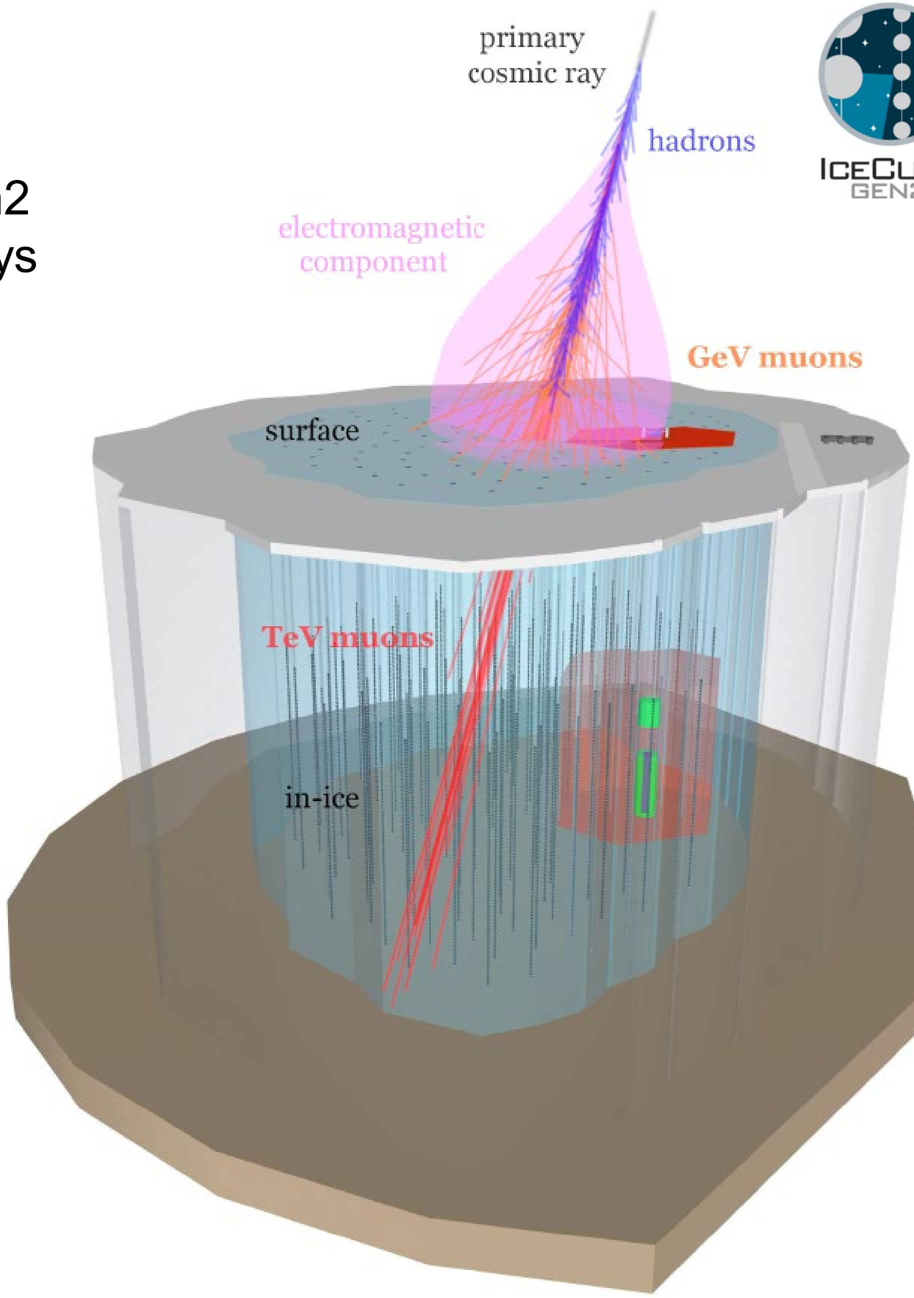
Surface Array of approx. 150 stations:

4 pairs of scintillators + 3 antennas





photos: prototype station at South Pole



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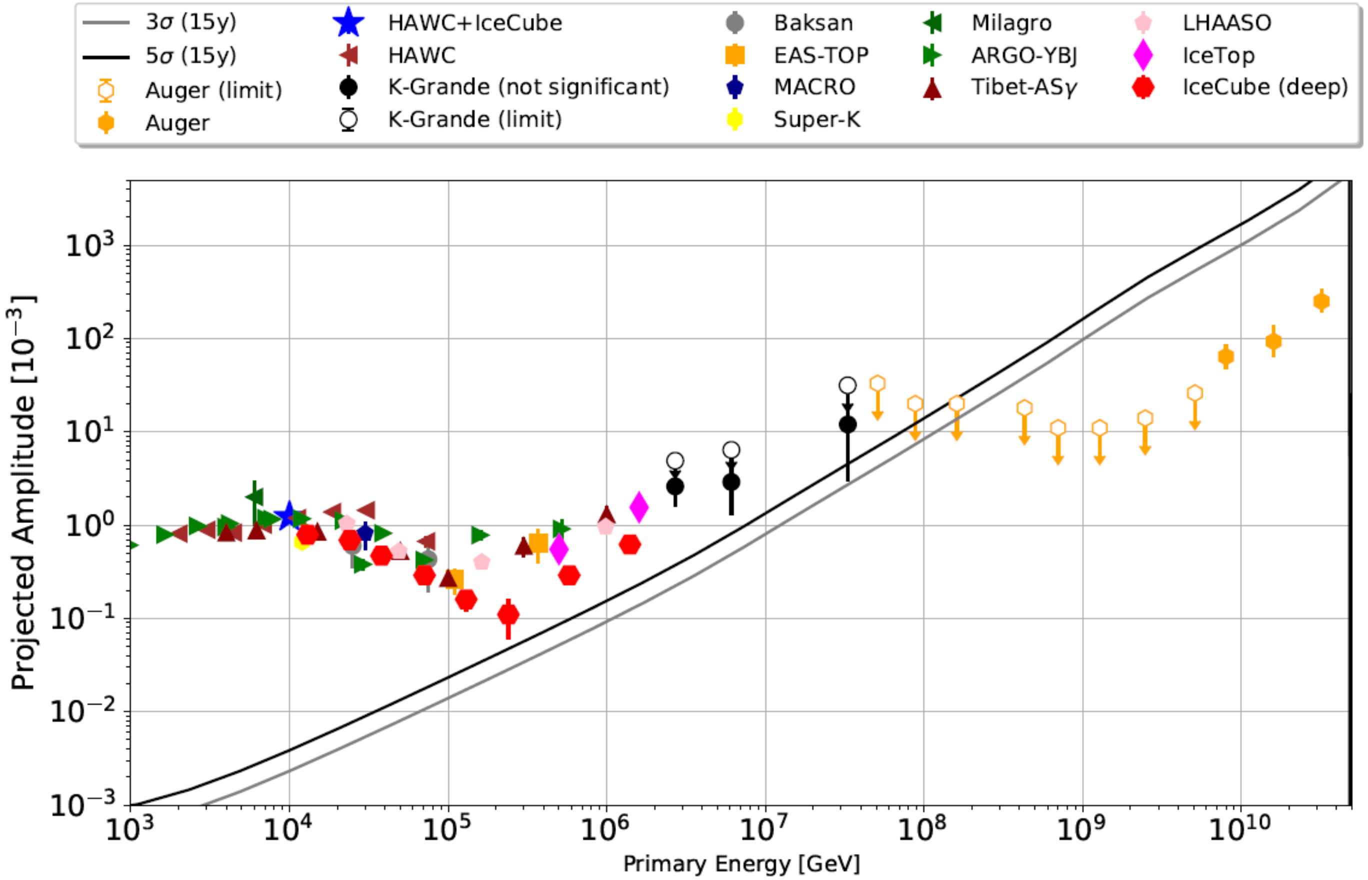
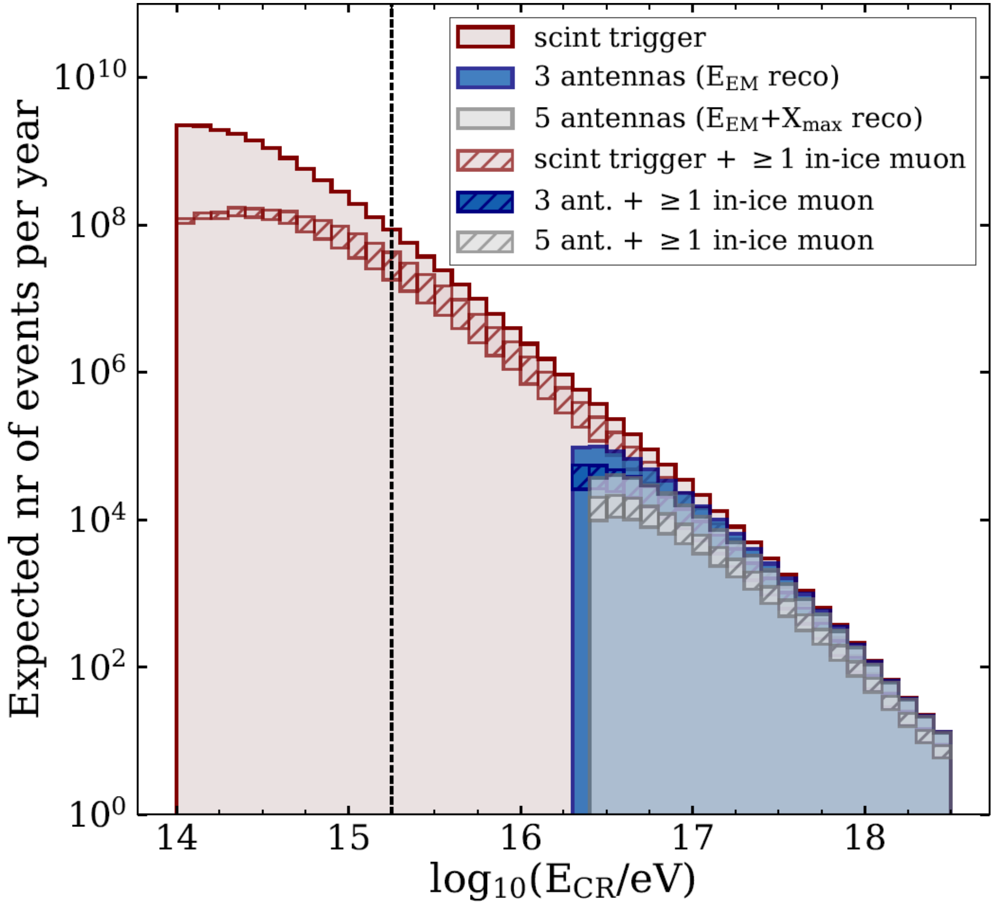
IceCube-Gen2: Cosmic-Ray Energy Range

- 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





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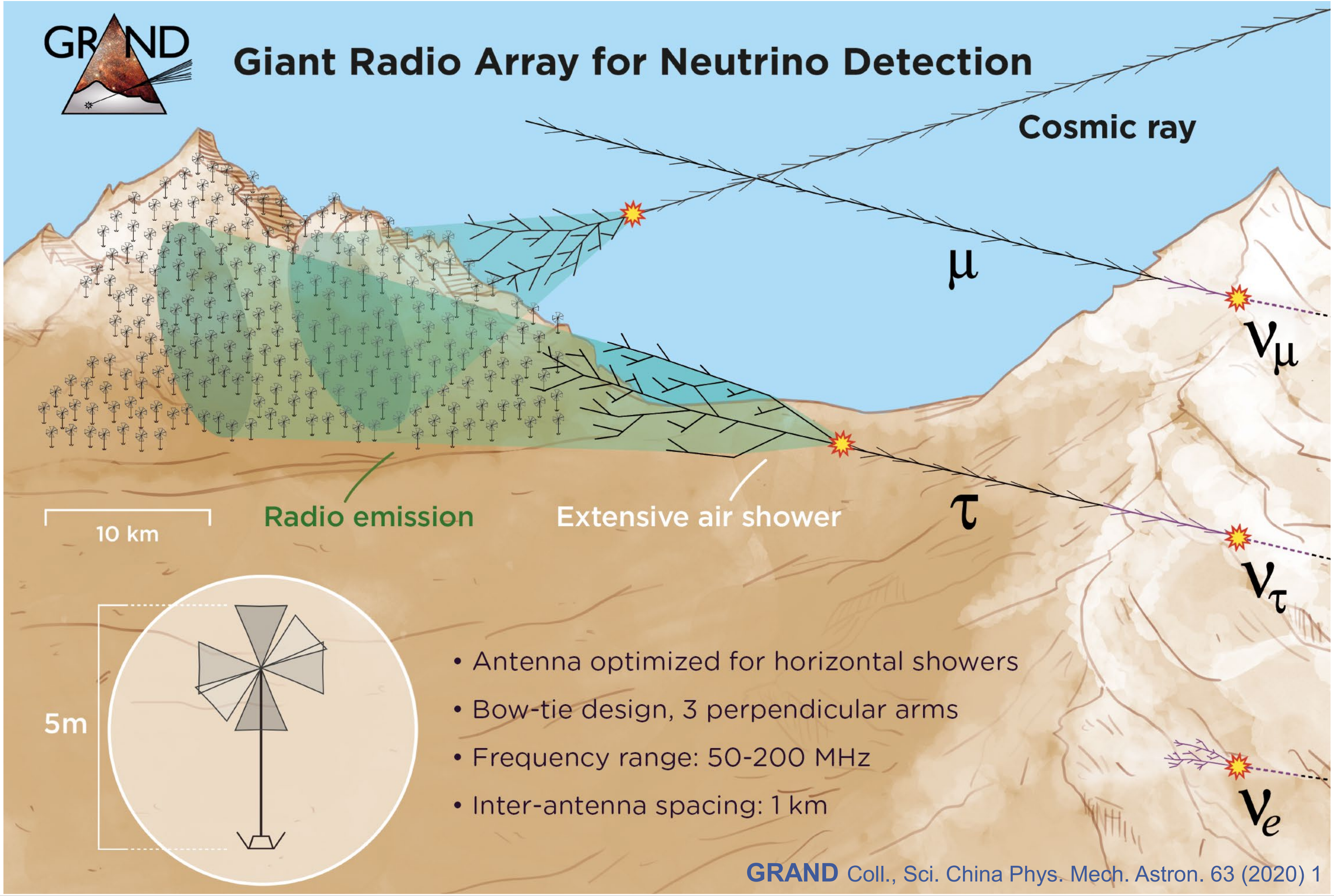

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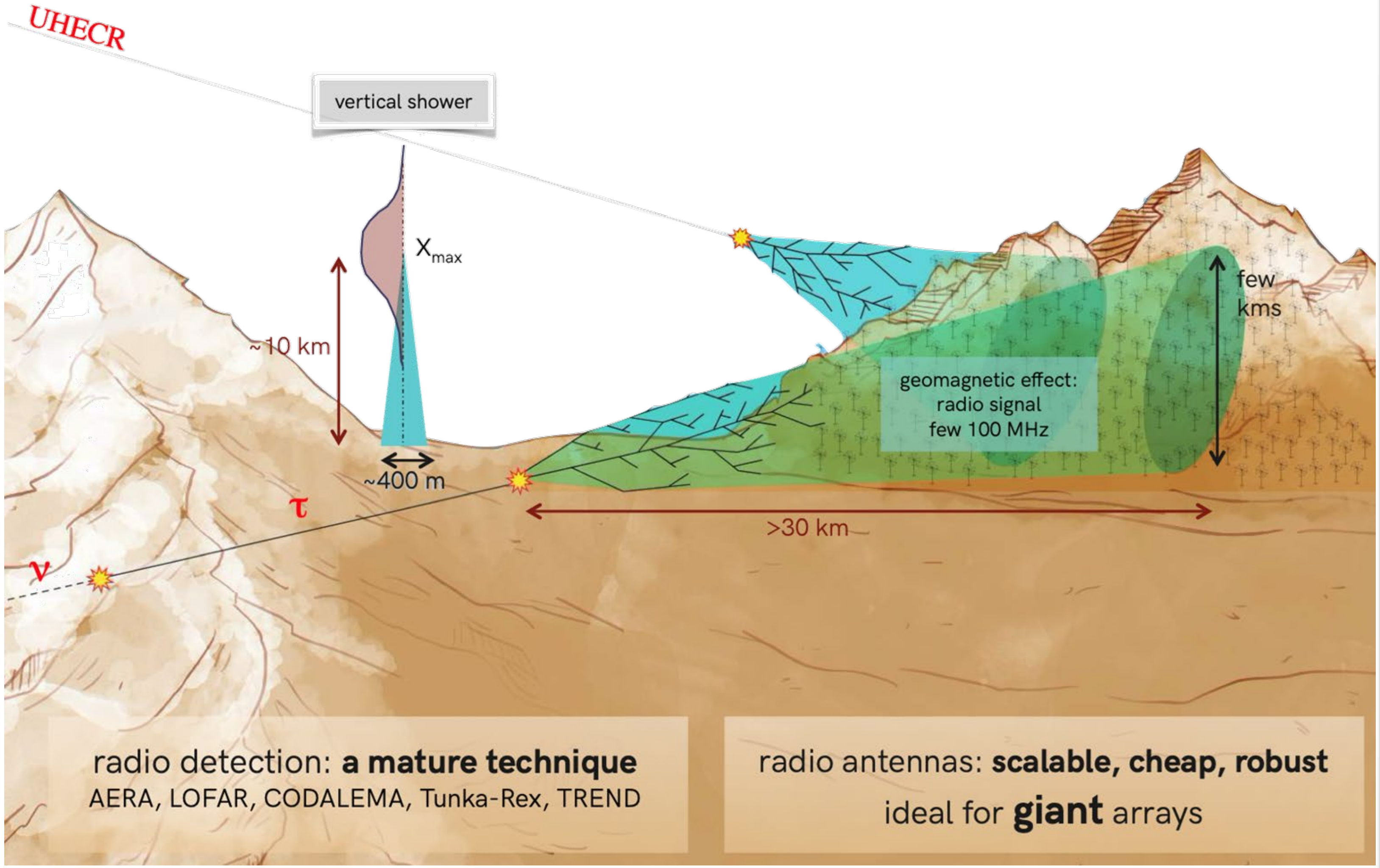
Giant Radio Array for Neutrino Detection

- UHECR as important second science case next to neutrinos
- various sites worldwide
  - main ones in China
- 200,000 km^2 total
  - inclined showers only
  - **aperture of 100,000 km^2 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



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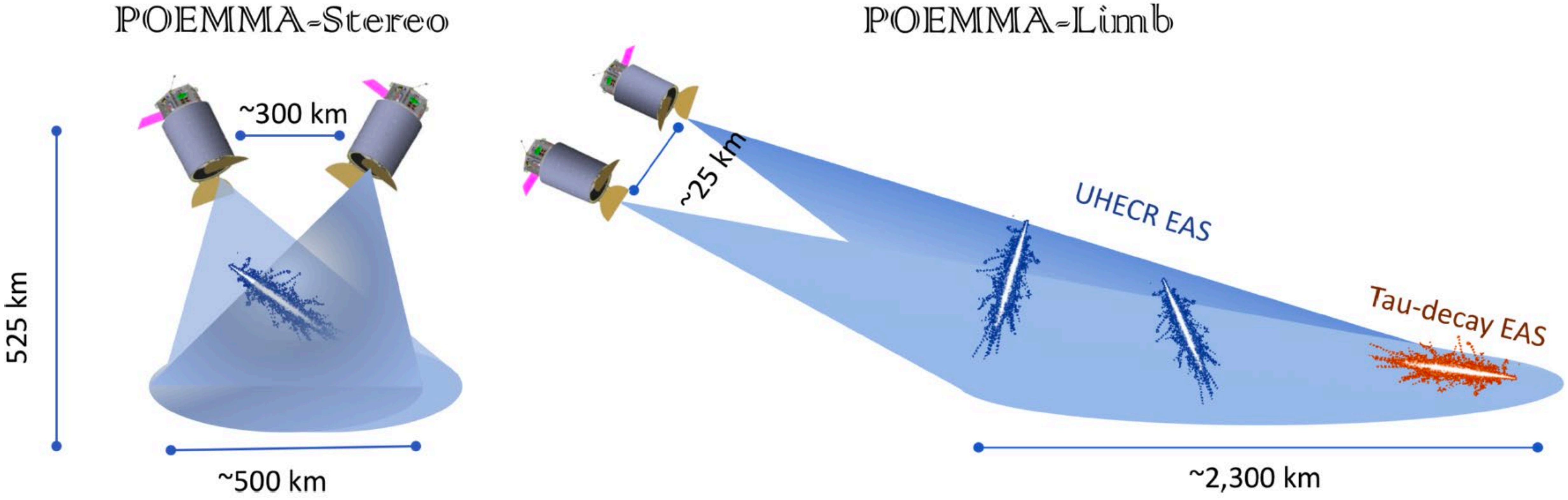
POEMMA: stereo fluorescence observation from space

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



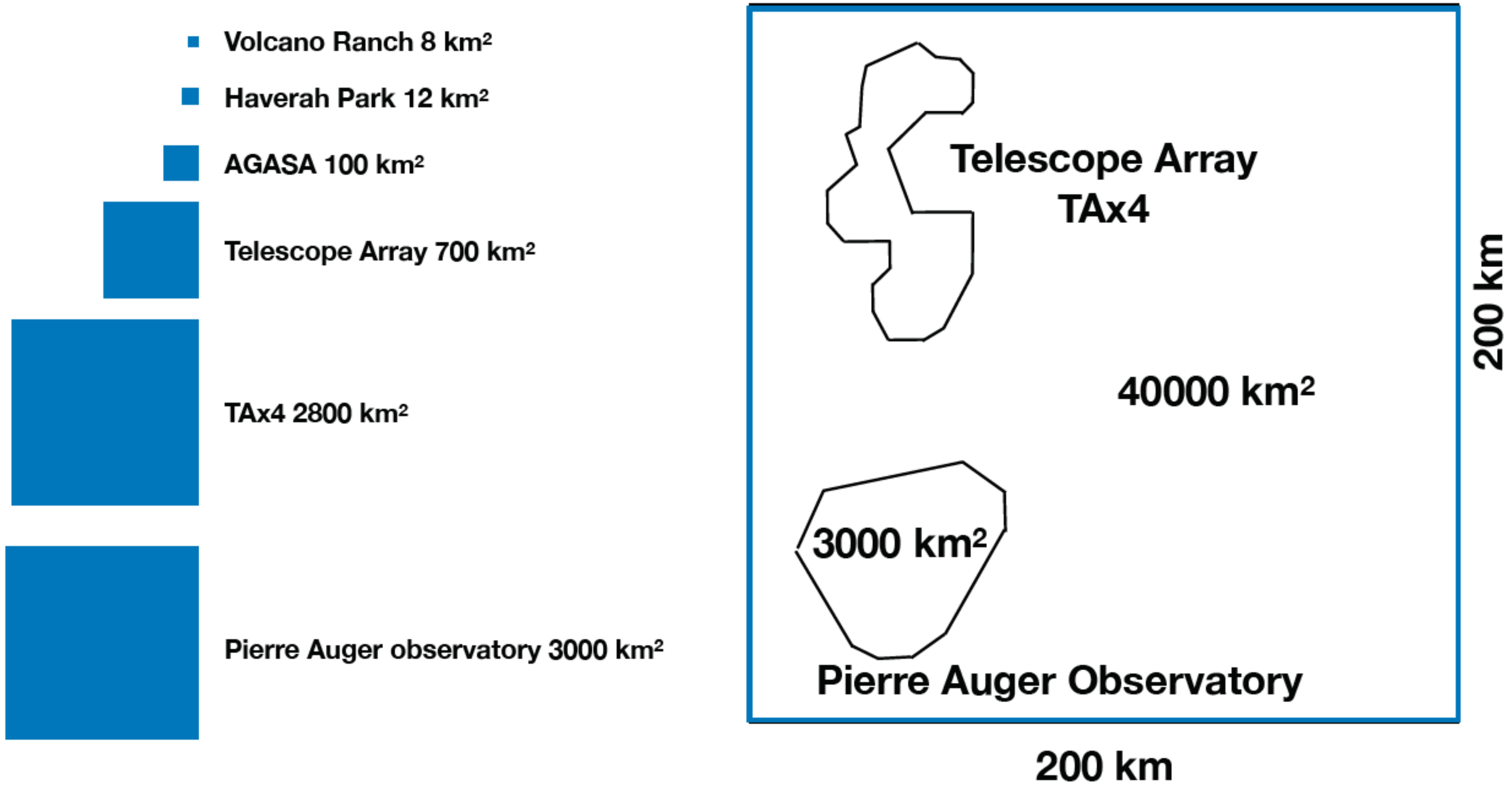
Global Cosmic Ray Observatory (GCOS)

- 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)



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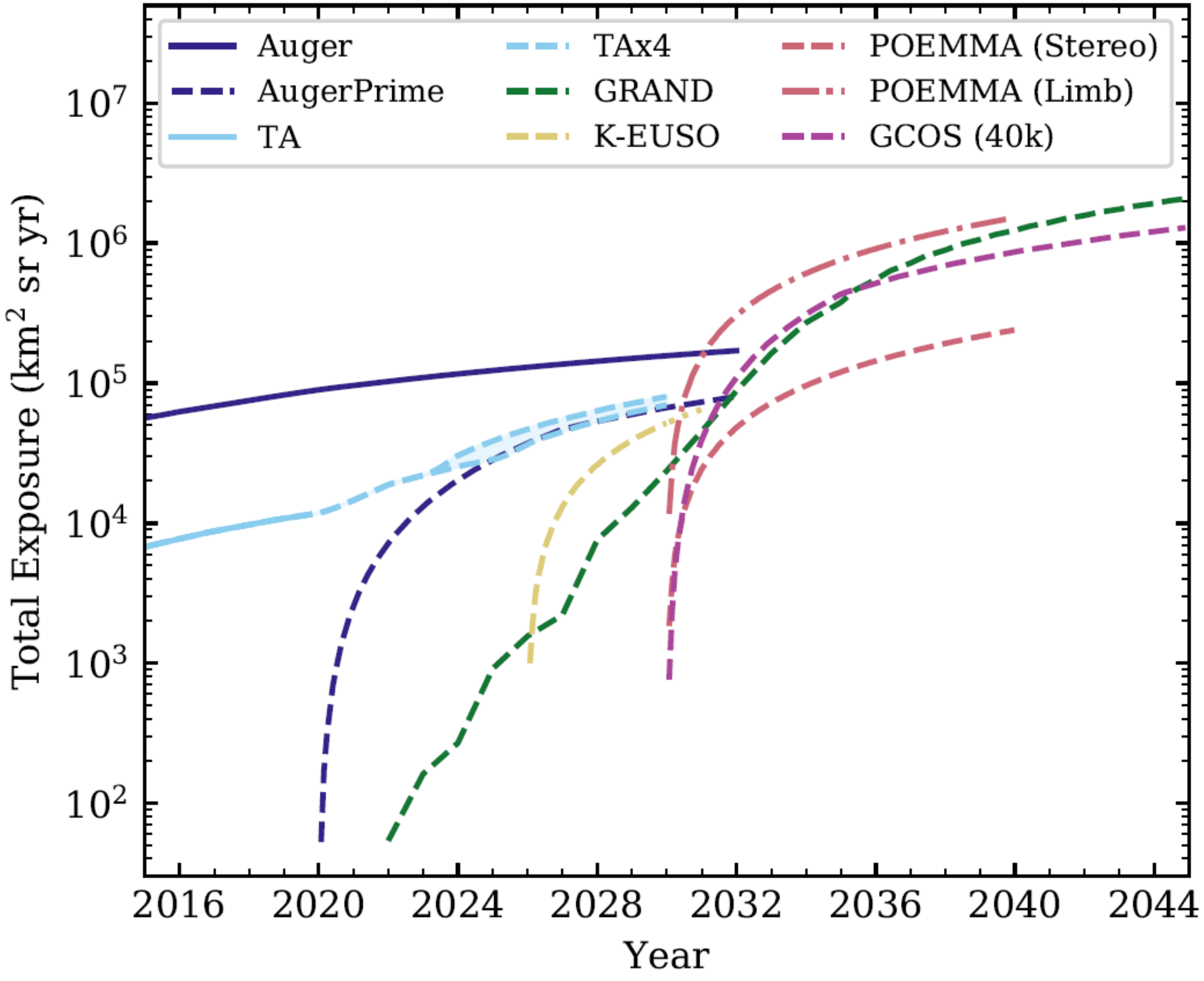
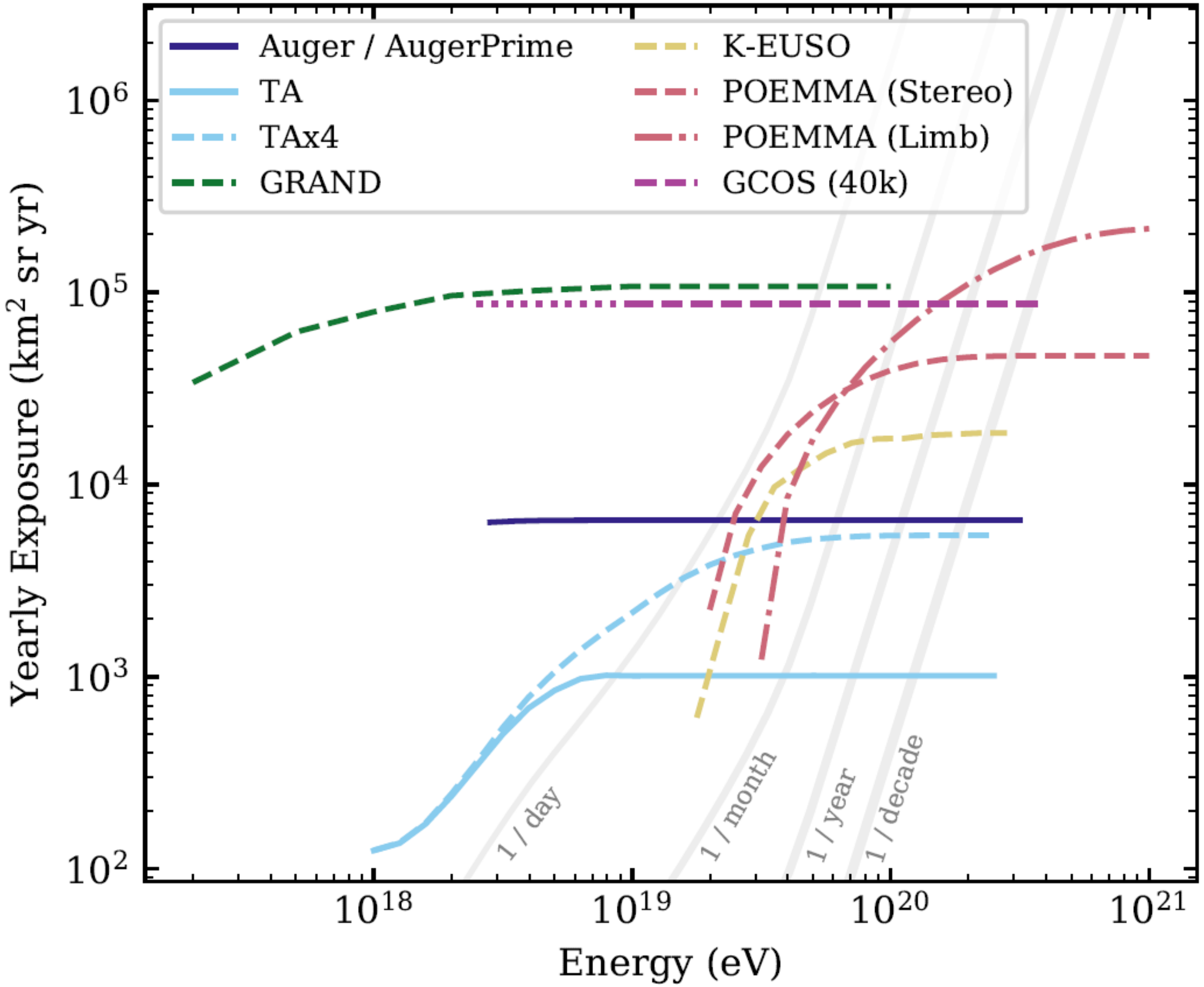
Comparing Exposures of UHECR experiments

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





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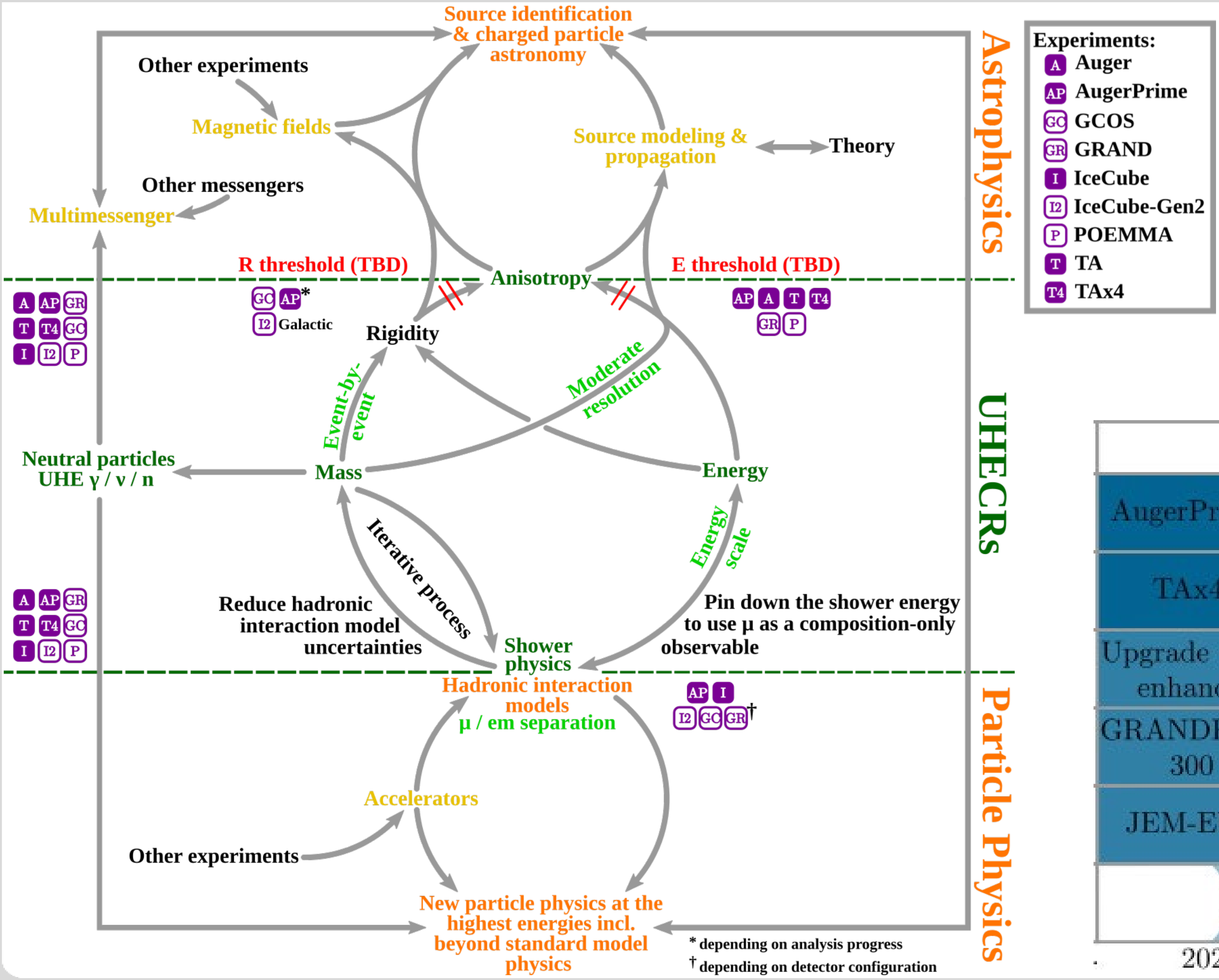
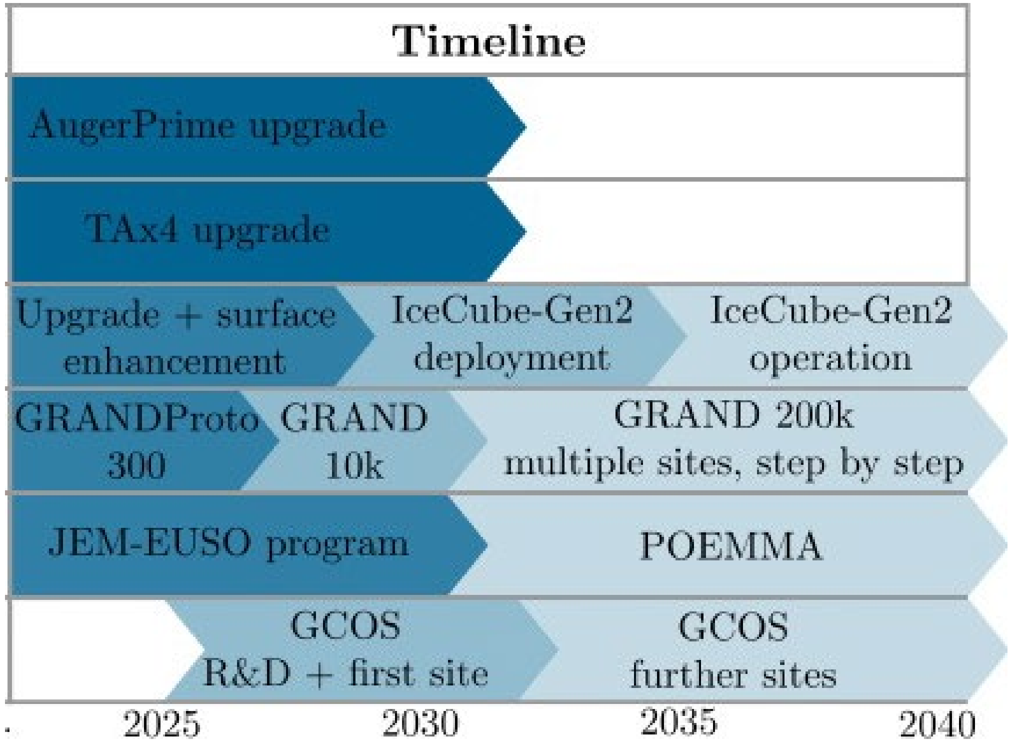


Conclusion

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



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Additional Slides

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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

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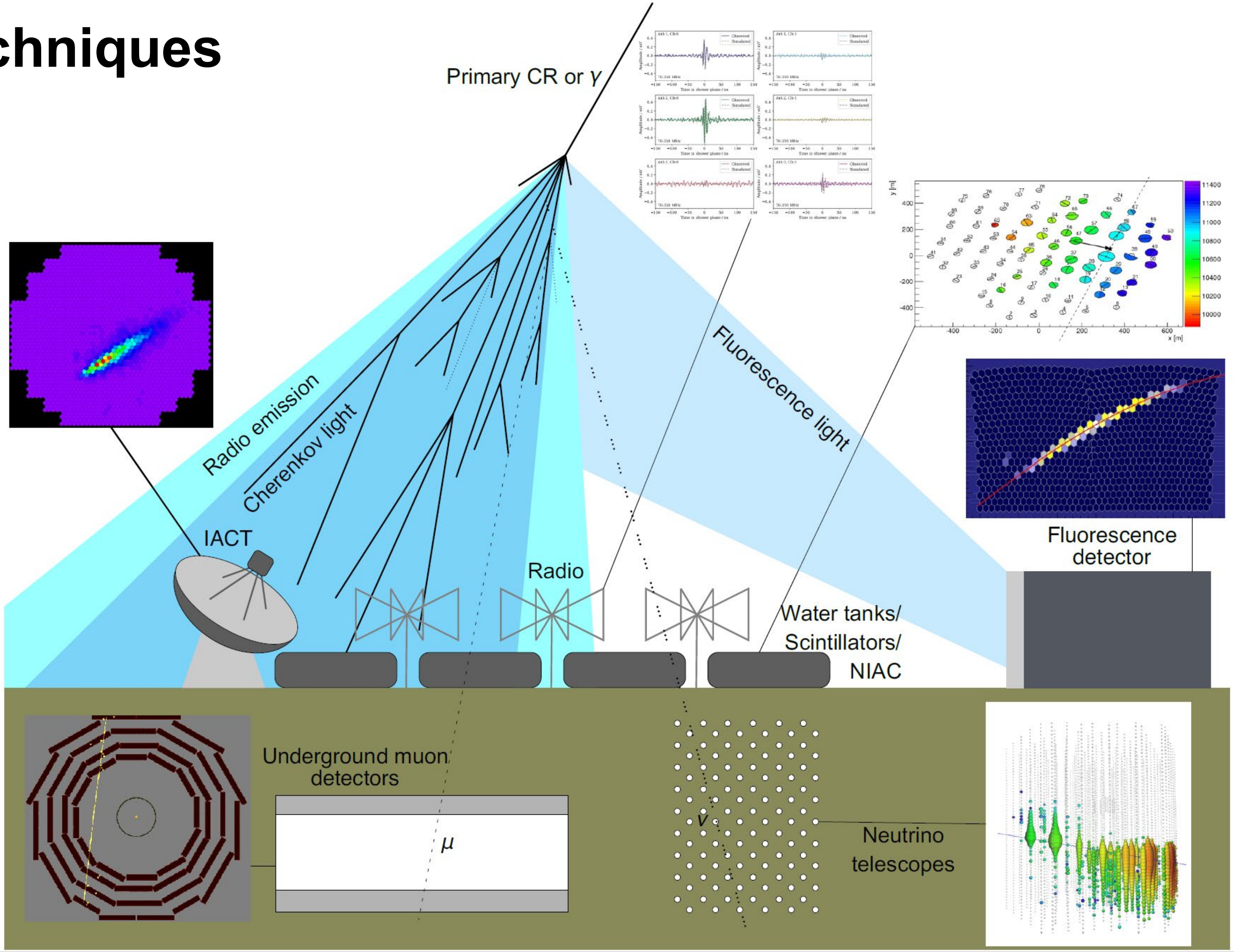
Instrumentation Techniques



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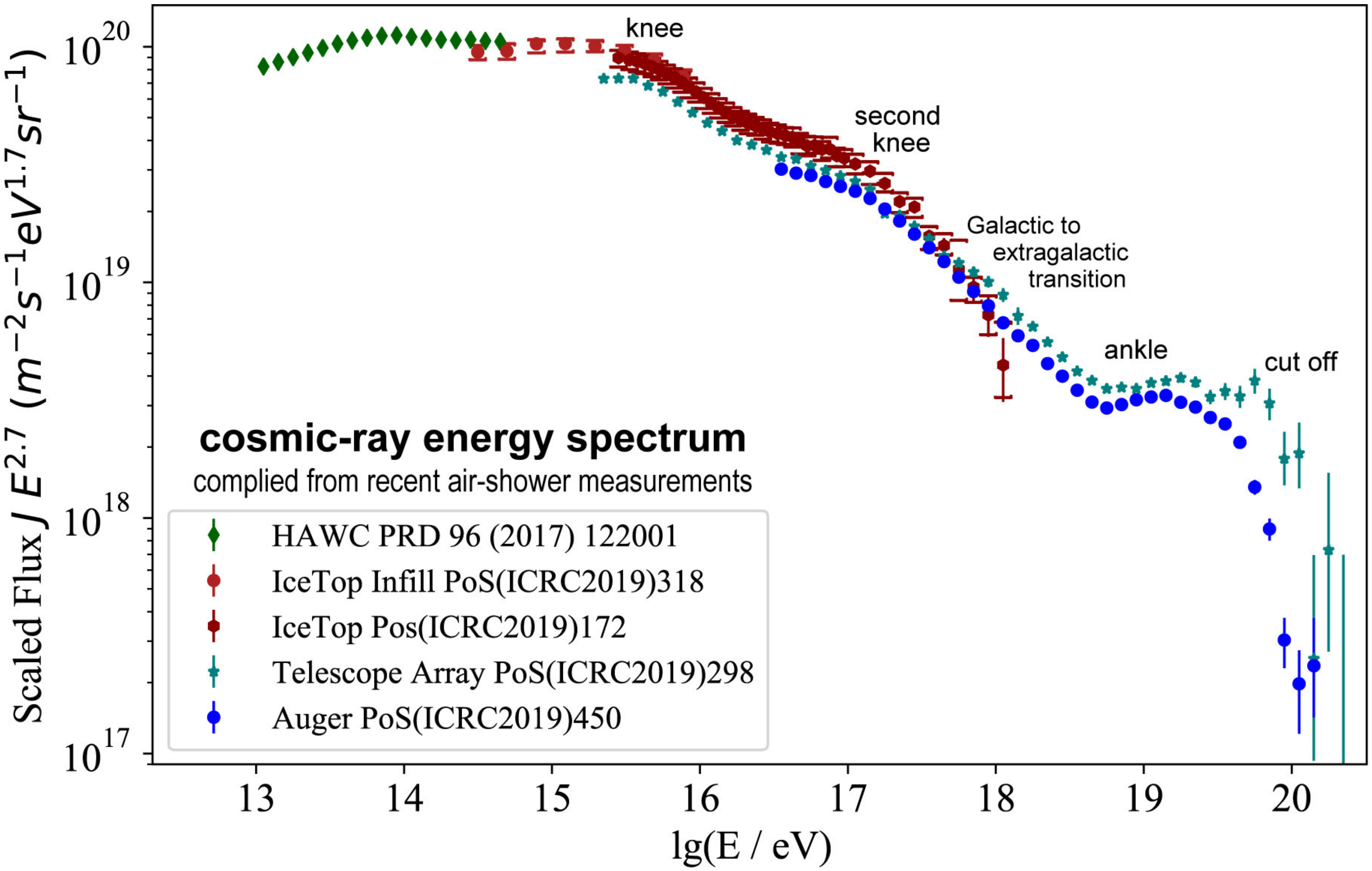
All-particle Energy Spectrum by Air-Shower Arrays



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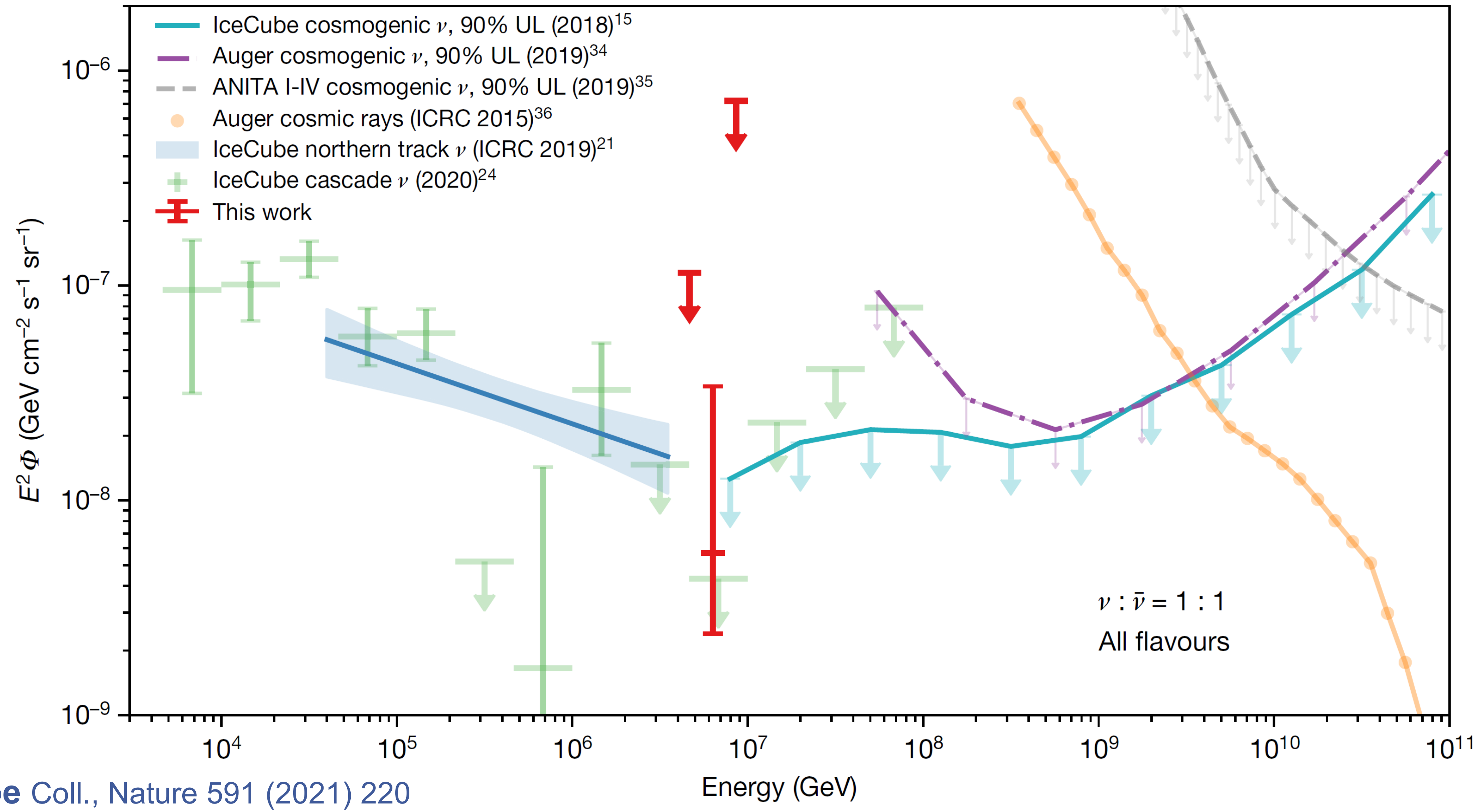
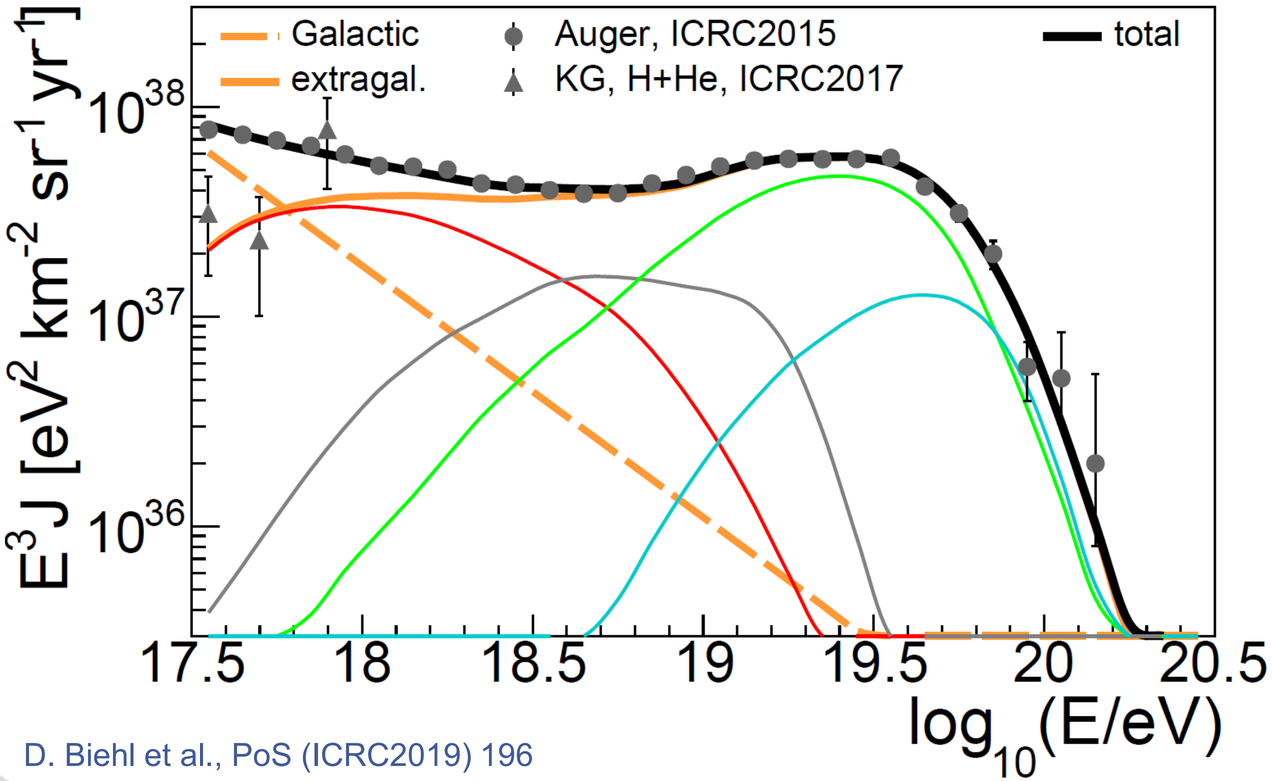
Almost 10 PeV neutrino (at Glashow resonance of 6.3 PeV)



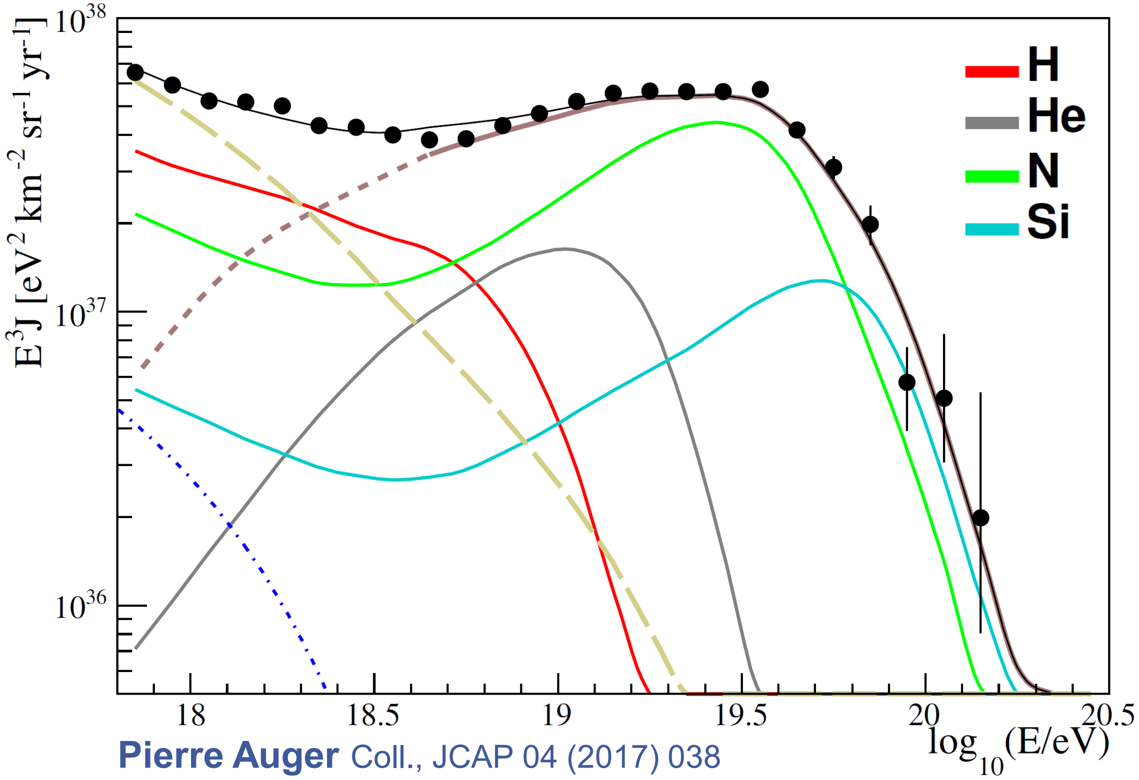
IceCube Coll., Nature 591 (2021) 220

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

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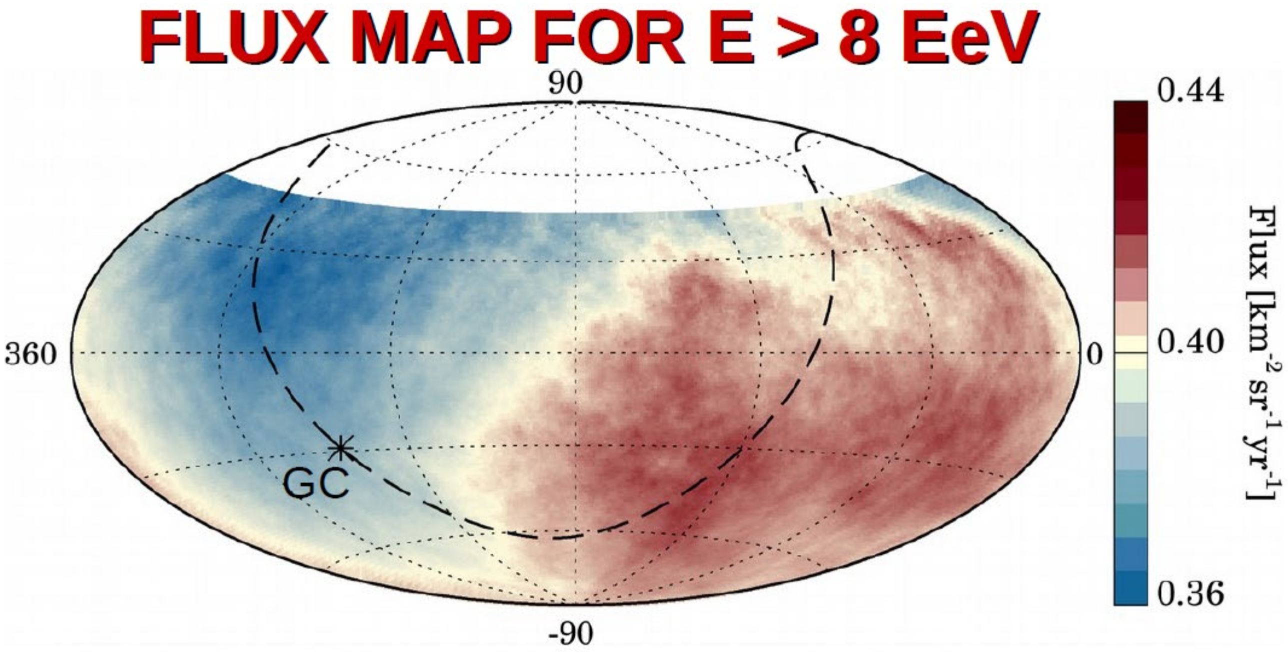
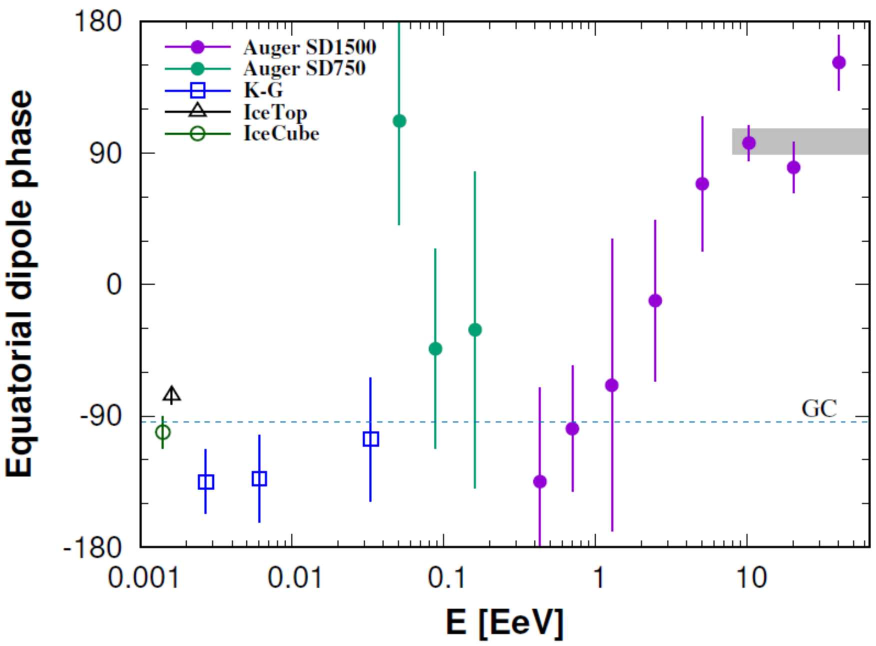
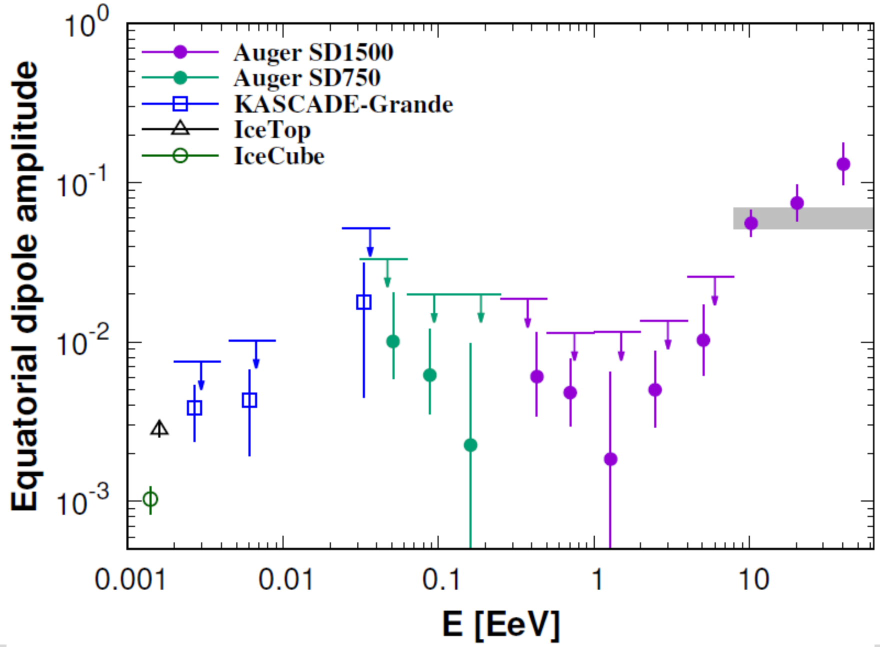
Auger Dipole – UHECR Anisotropy

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



equatorial coordinates, smoothed on 45° radius windows





Pierre Auger Coll., ICRC 2019 / APJ 891 (2020) 142

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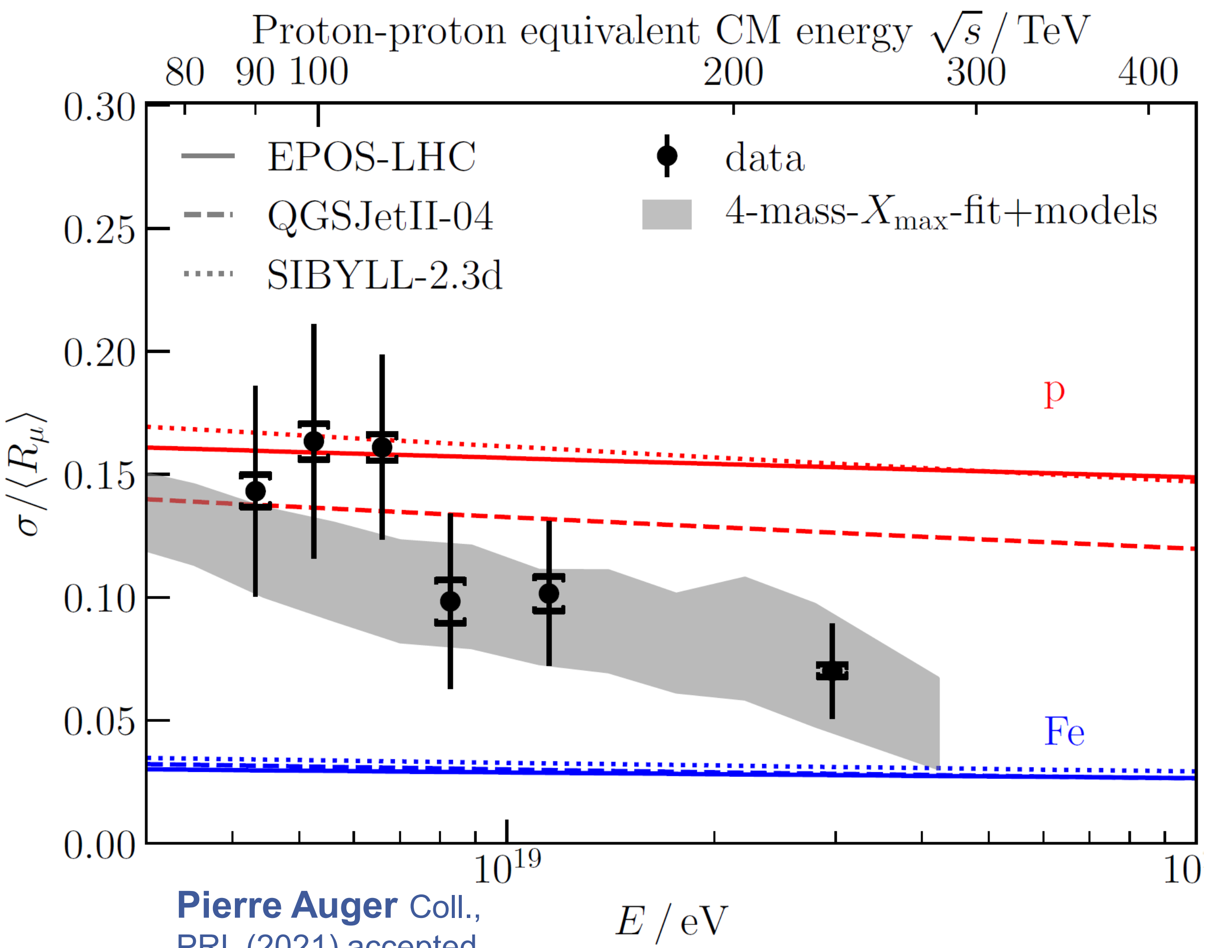
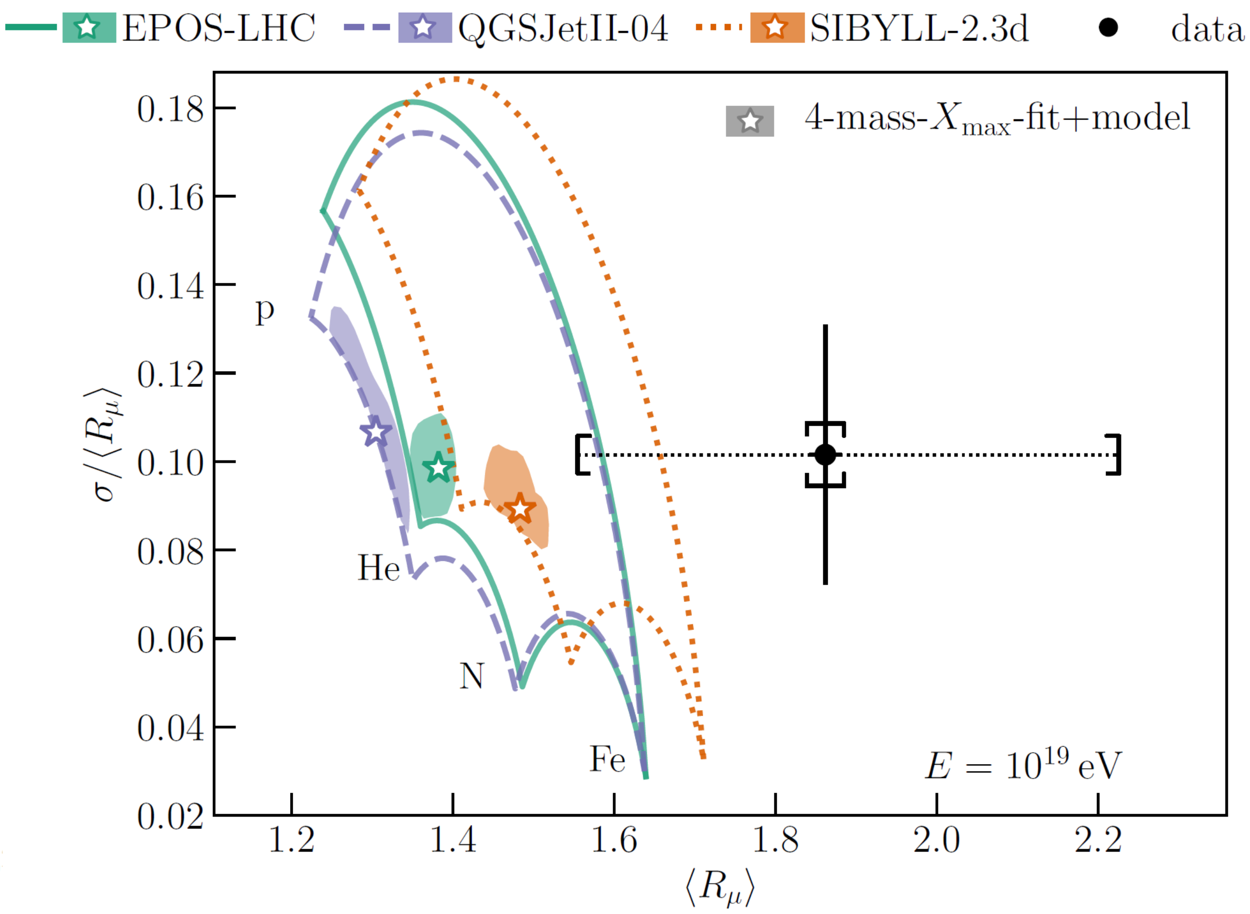
Fluctuation of muon number measured by Auger

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



Pierre Auger Coll.,
PRL (2021) accepted



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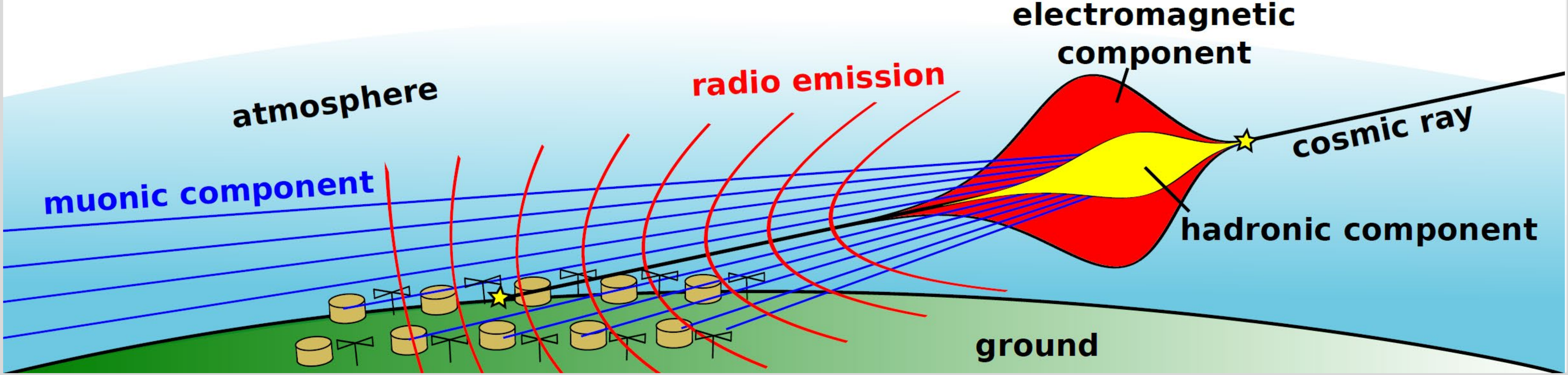
AugerPrime:
Upgrade of the Pierre Auger Observatory

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



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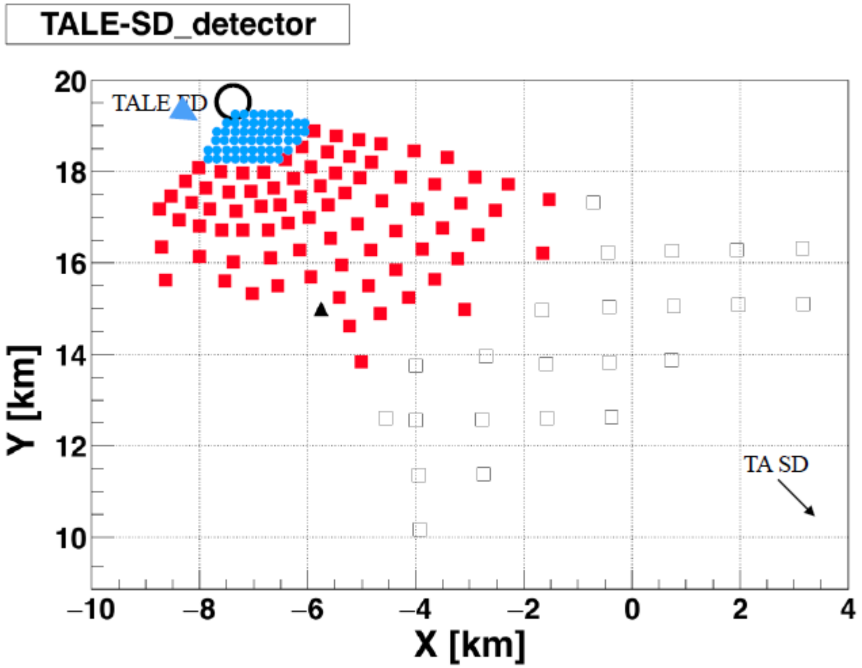
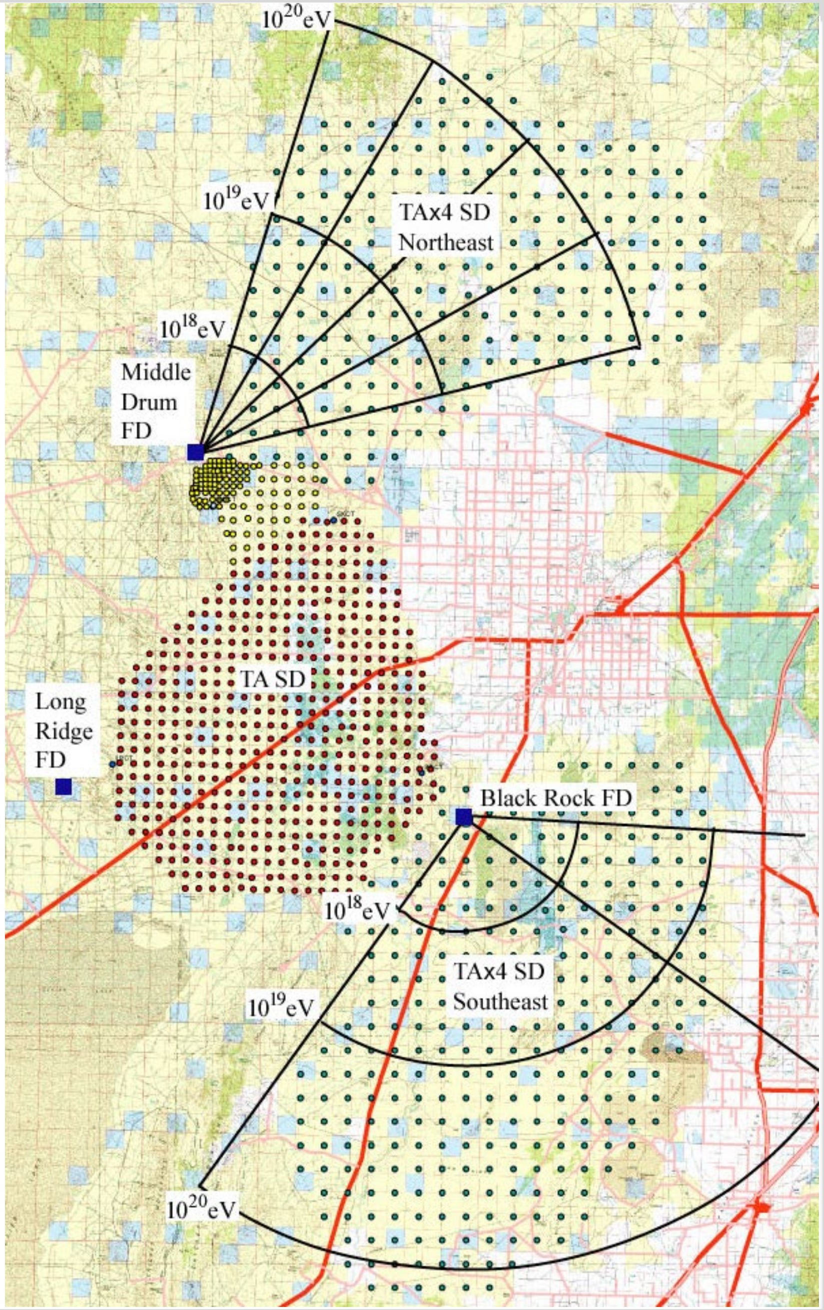
Telescope Array: Upgrades

- Highest energies ($E > 10^{19.8}$ eV)
  - TAx4 → 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

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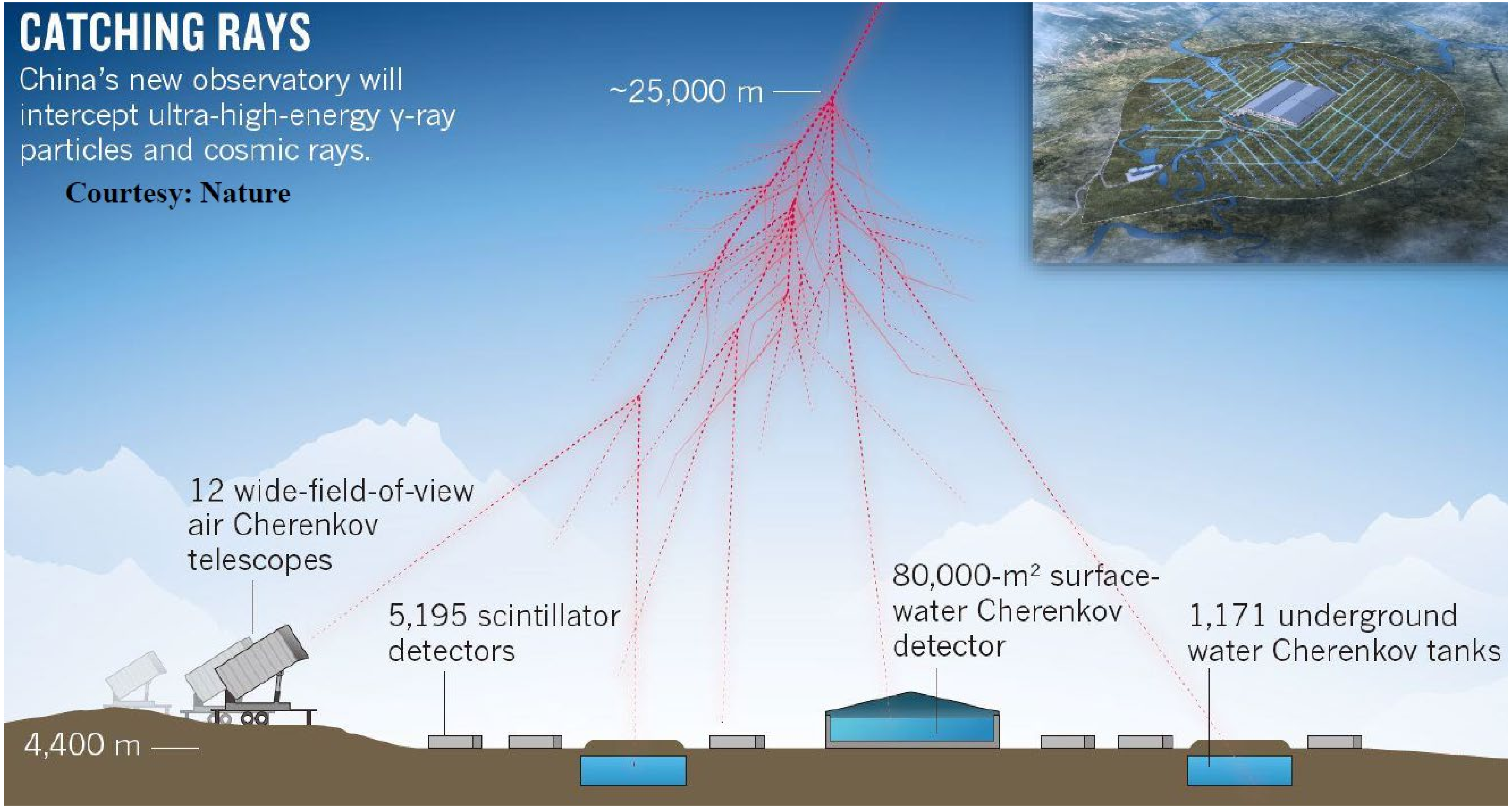
LHAASO – a 1 km^2 multi-hybrid detector in China

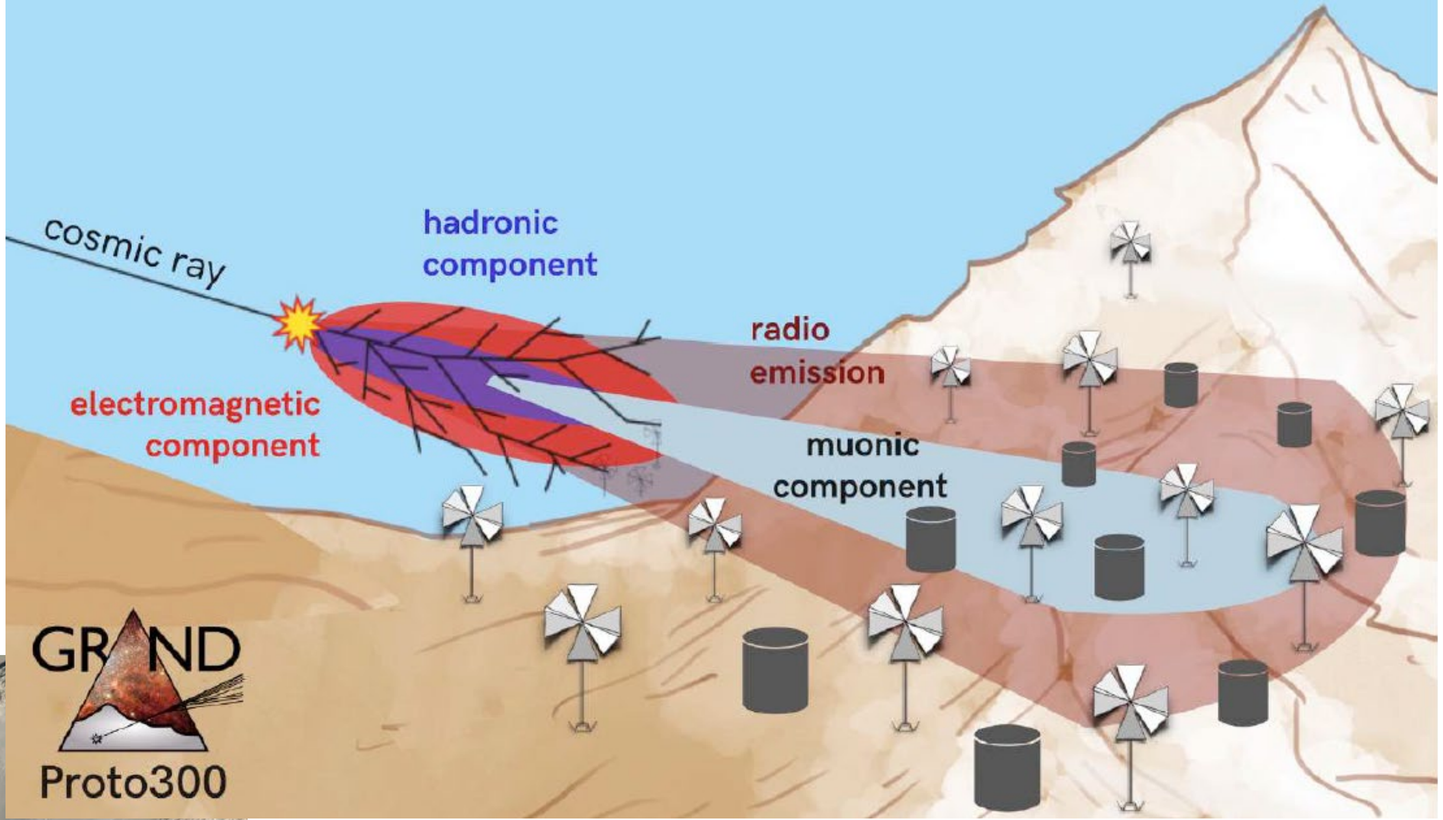
Primary goal are gamma-rays, but also excellent cosmic-ray detector

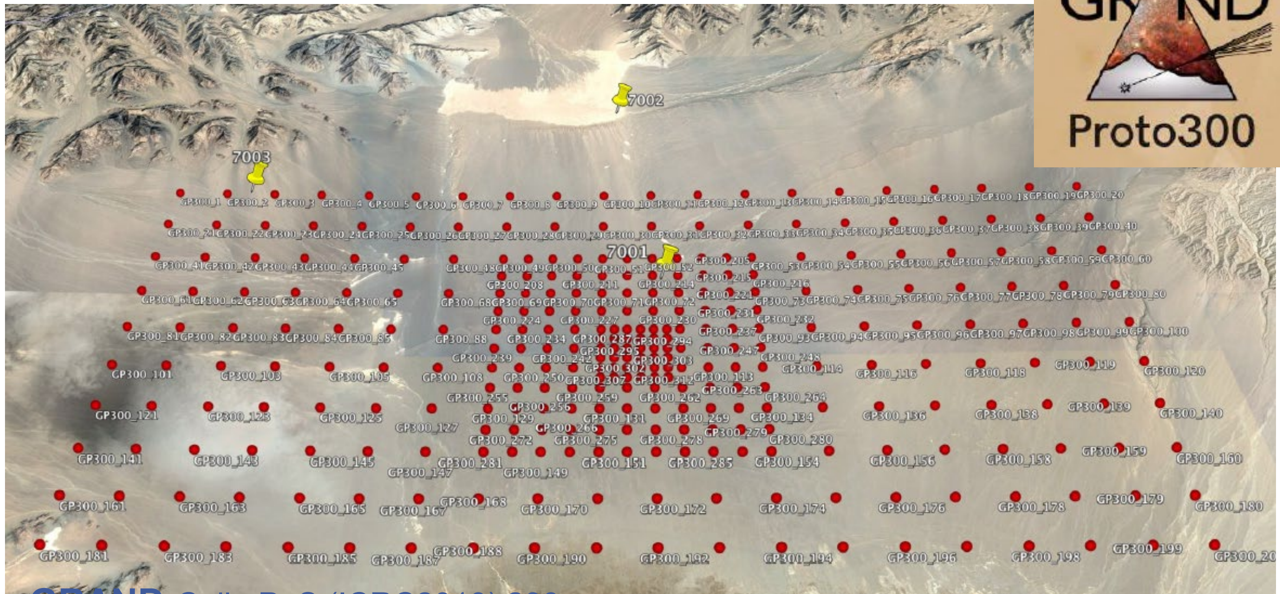


LHAASO Coll.,
PoS (ICRC2019) 693

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





GRAND Coll., PoS (ICRC2019) 233

- 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

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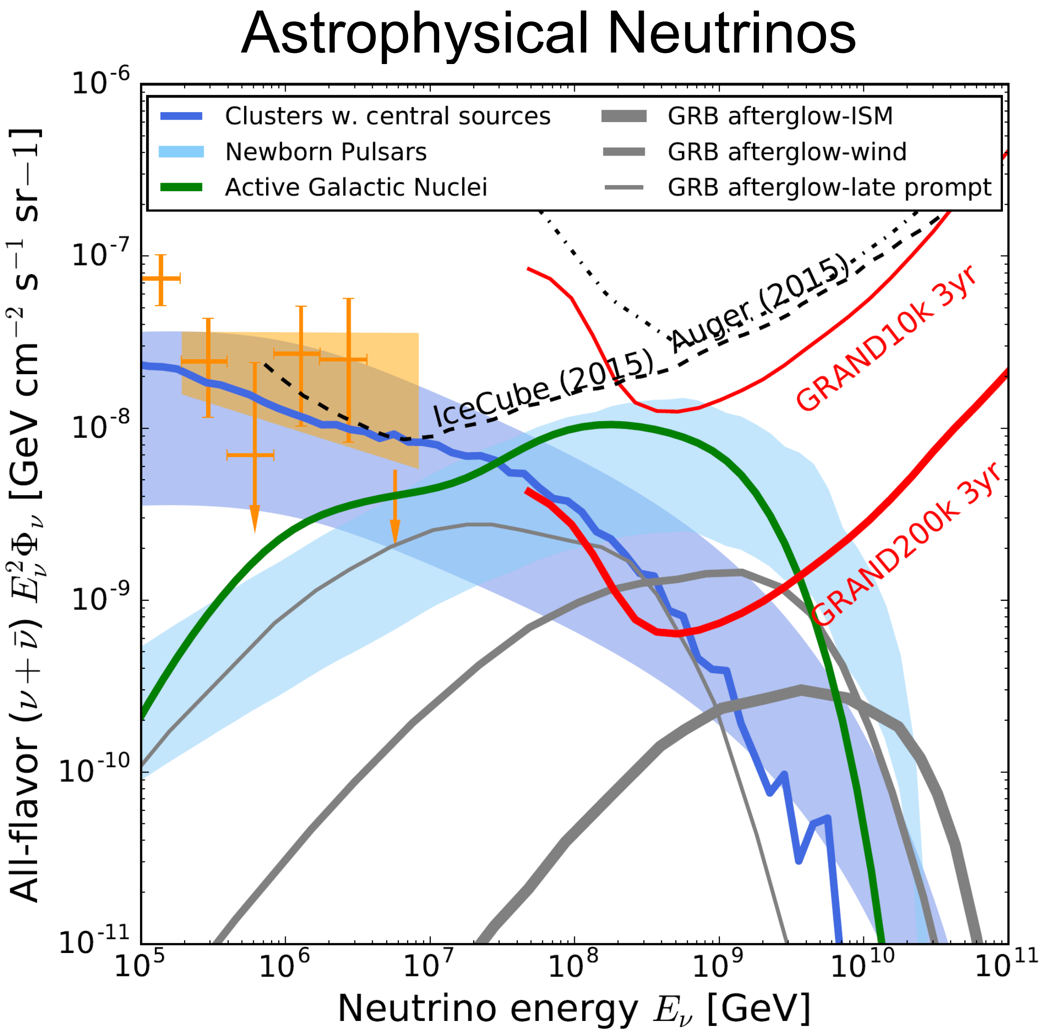
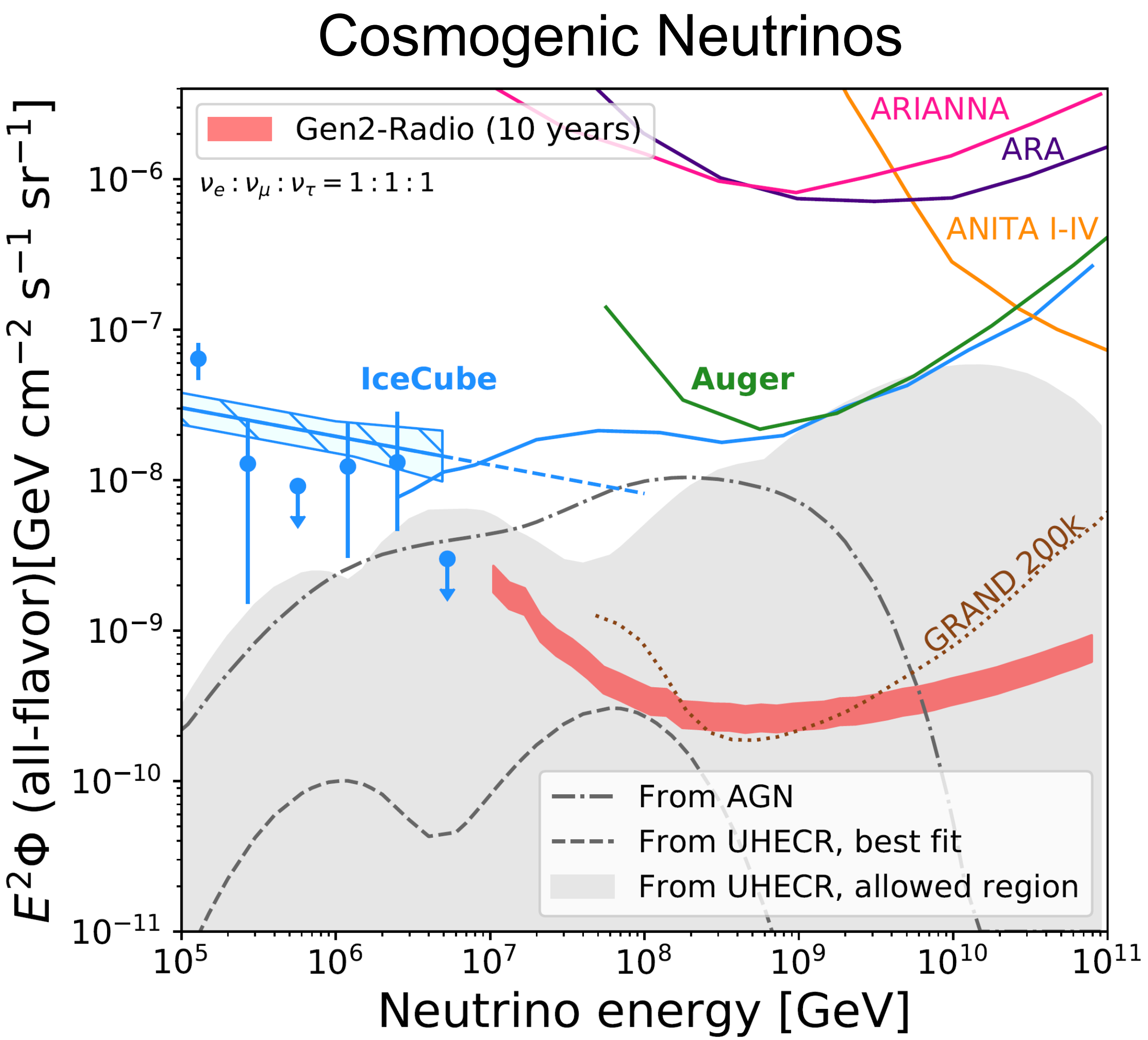
GRAND and IceCube-Gen2 sensitivities for EeV neutrinos



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



IceCube-Gen2 Whitepaper, arXiv:2008.04323

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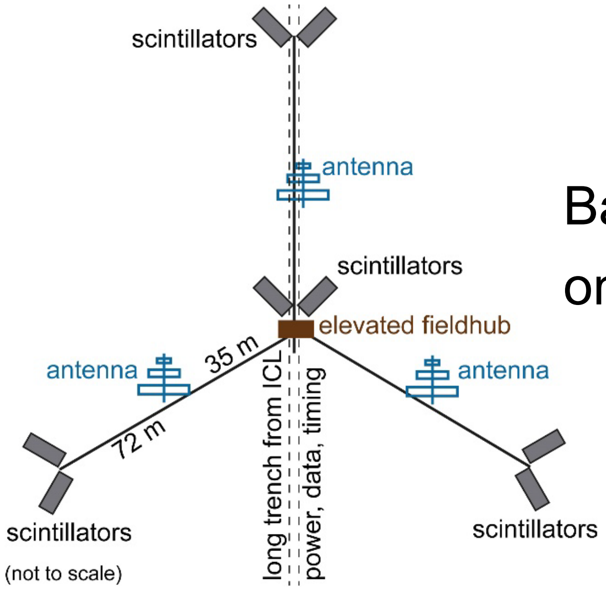
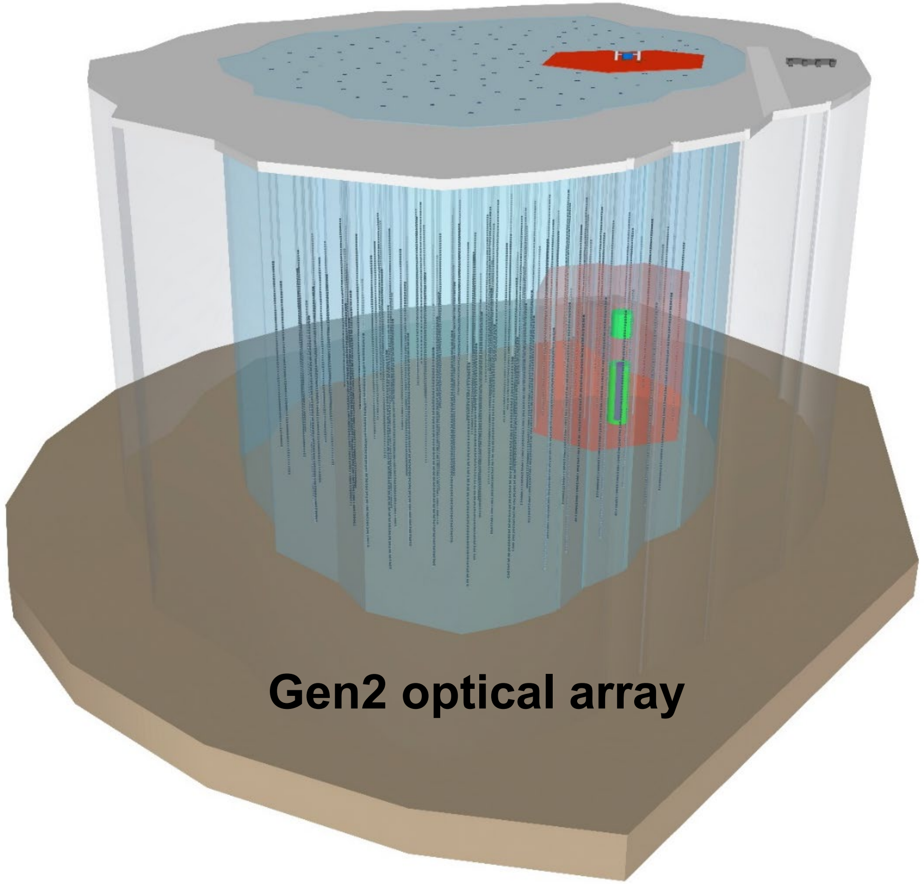
IceCube-Gen2 Surface Array

- 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





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

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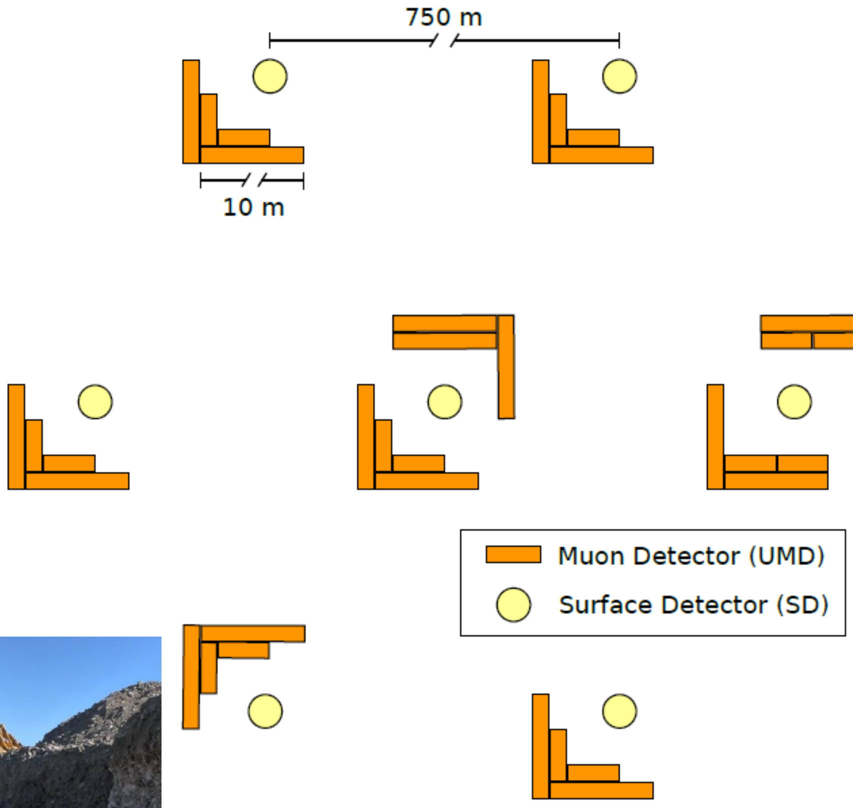
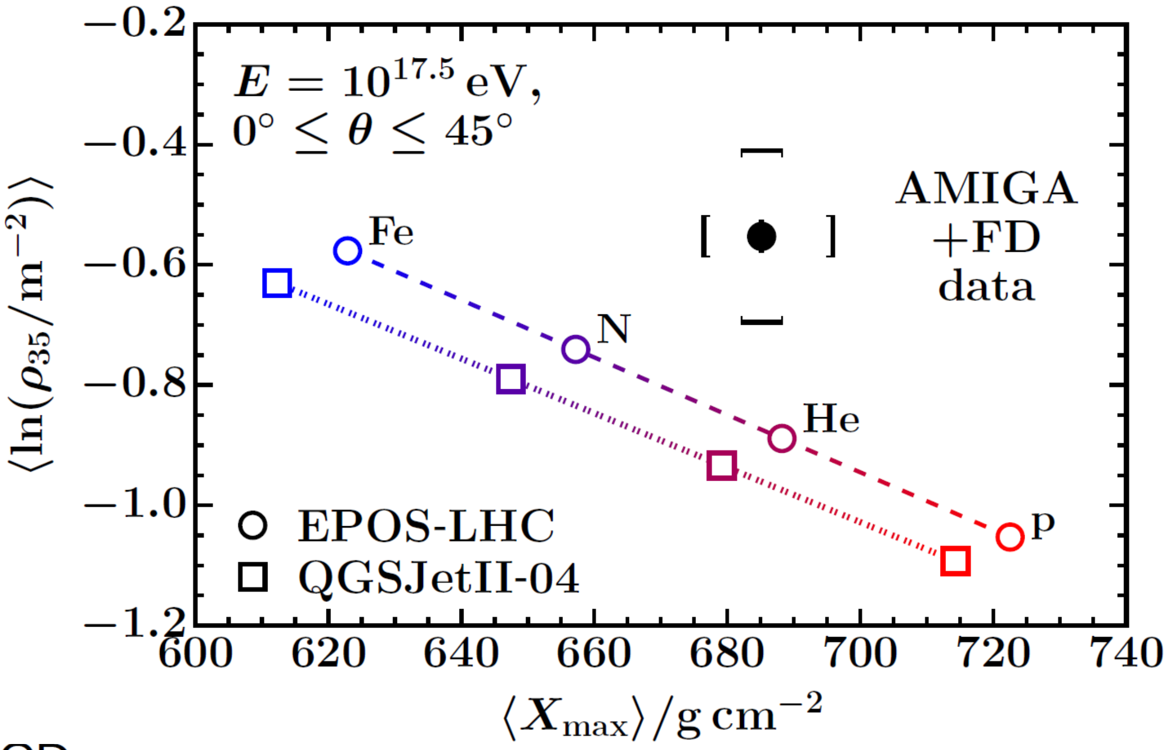
Muon Measurements of AMIGA Engineering Array



Combination of pure muon and pure electro-magnetic measurement (by fluorescence) confirms muon deficit in simulations



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

Pierre Auger Coll., PoS (ICRC2019) 411

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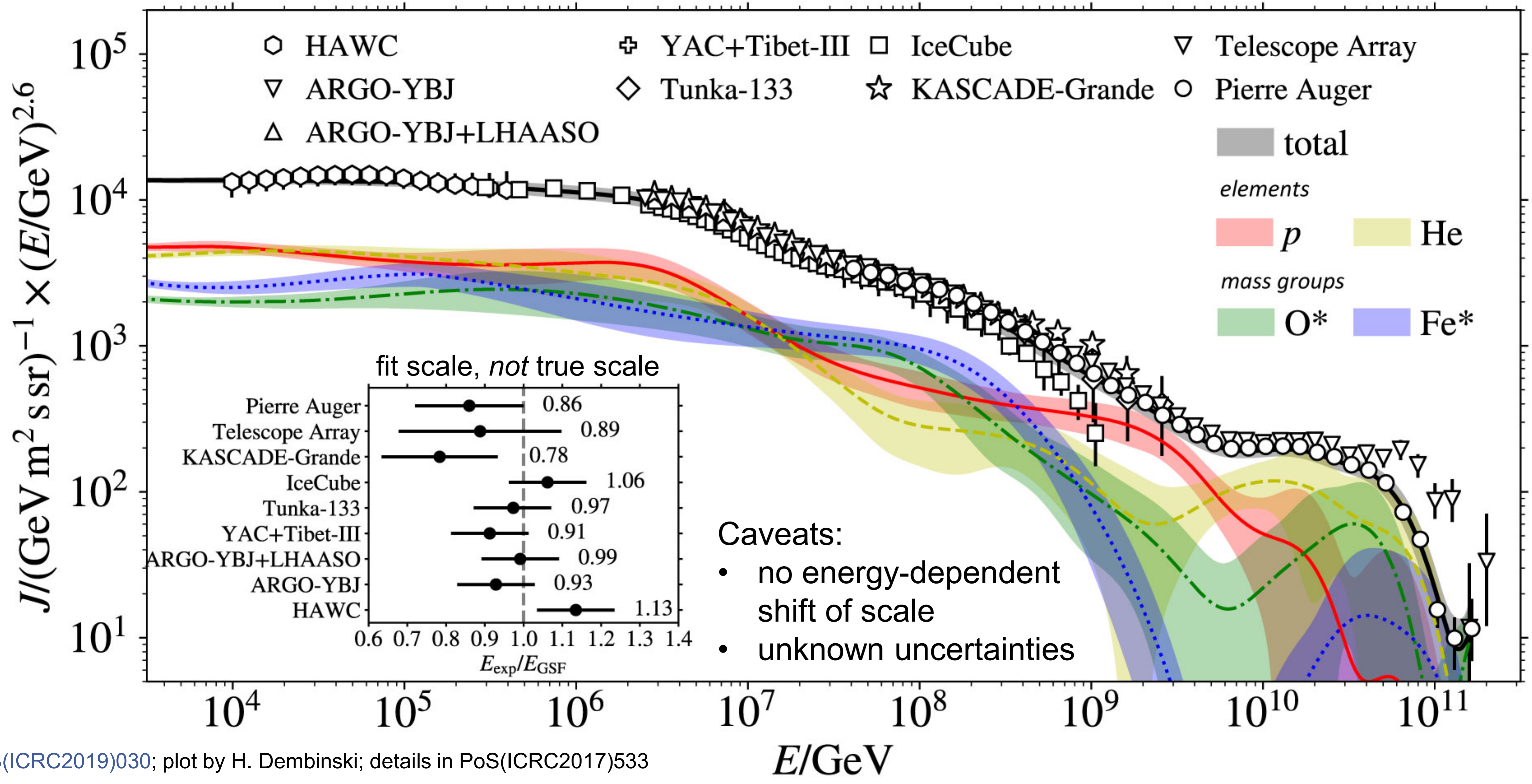
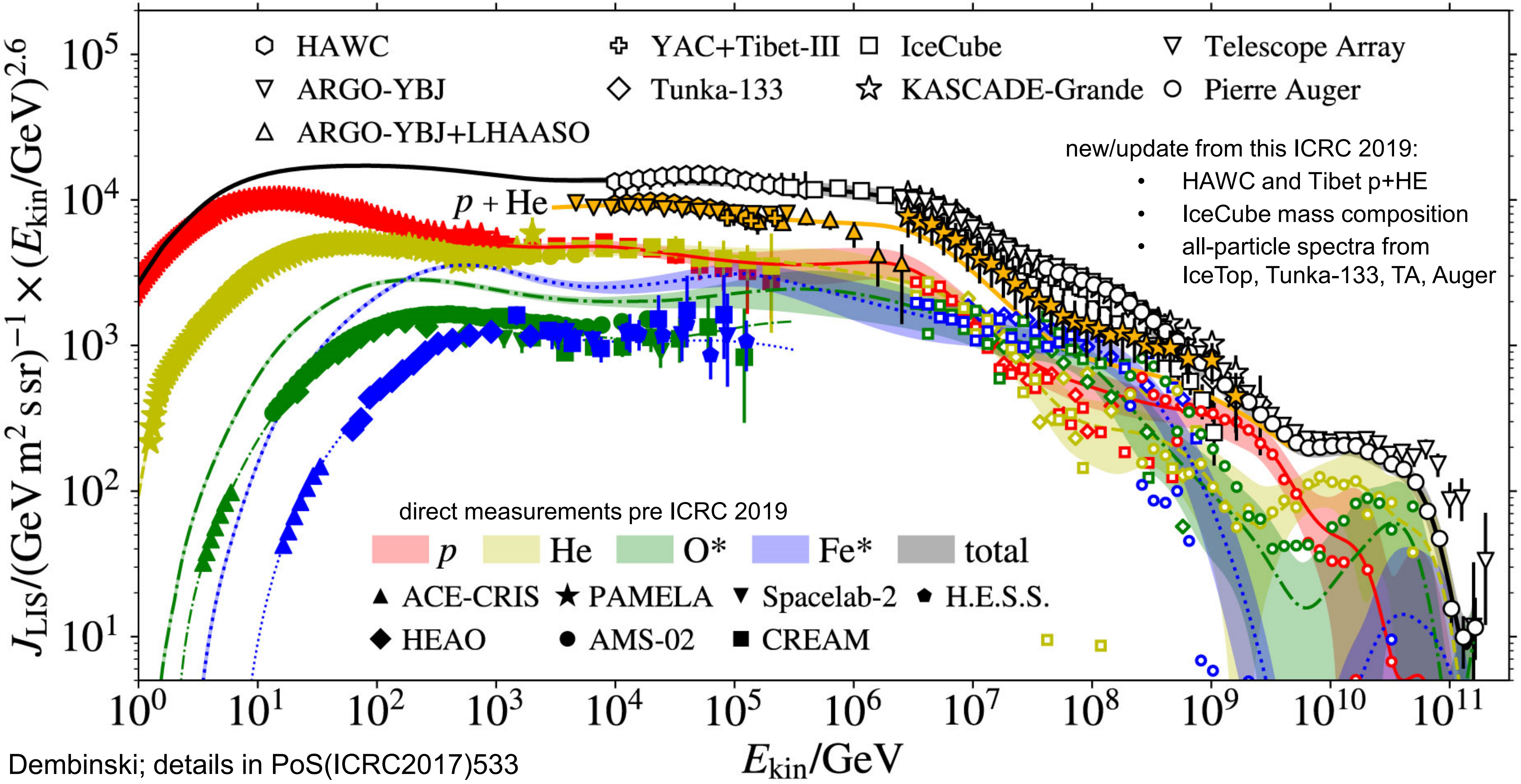
Cosmic-Ray Energy Spectrum and Mass Composition



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

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