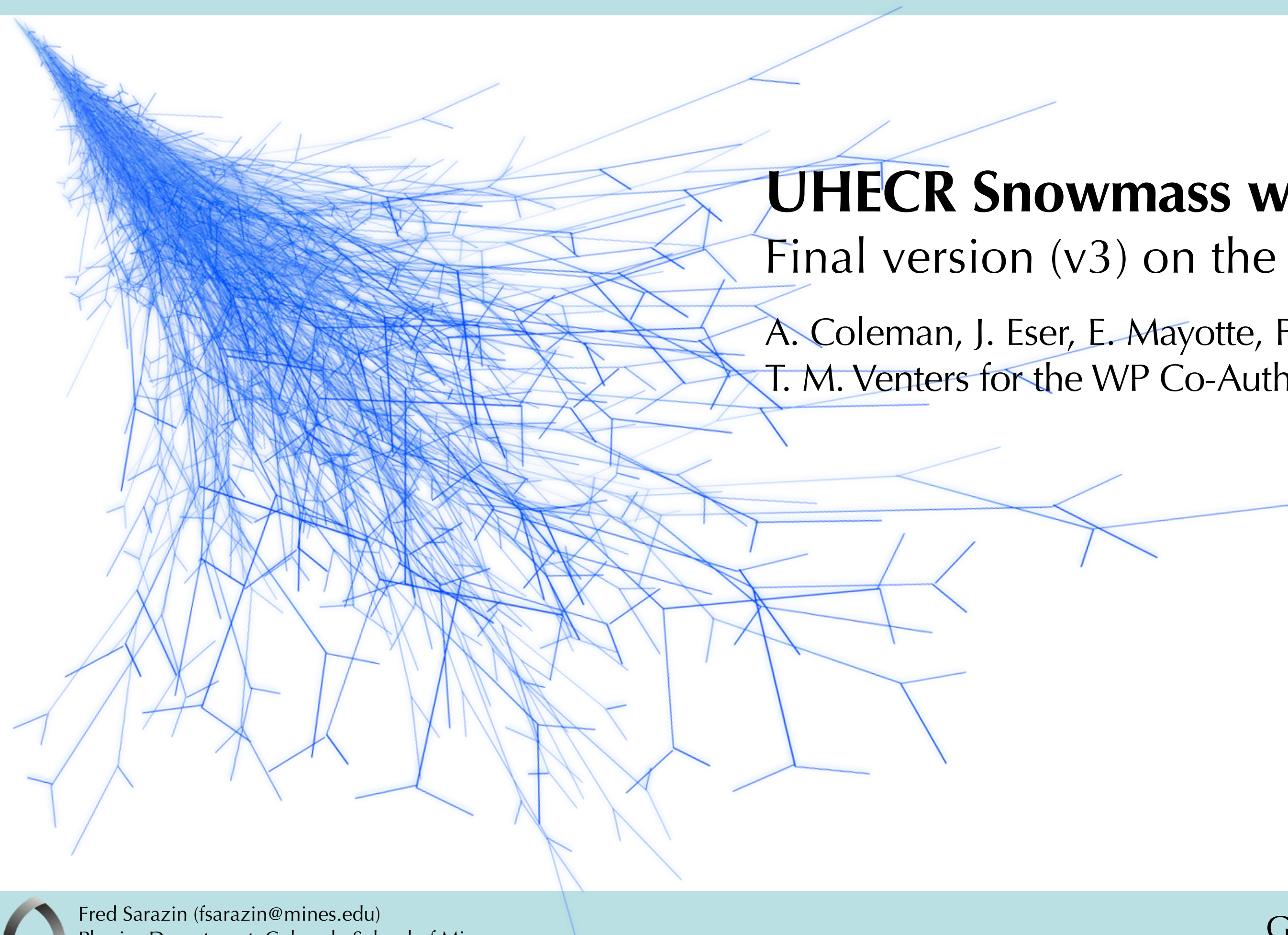

UHECR Snowmass white paper overview

Final version (v3) on the arXiv*

A. Coleman, J. Eser, E. Mayotte, F. Sarazin, F. G. Schröder, D. Soldin, T. M. Venters for the WP Co-Authors

*https://arxiv.org/pdf/2205.05845

Snowmass flow

The **Snowmass Process** is a US particle physics community planning exercise sponsored by the Division of Particles and Fields of the American Physical Society. During this process, scientists develop a collective vision for the next seven to ten years for **particle physics research** in the US.

- **White papers** like this one inform the Frontier Topical reports (CF7 in this case)
- **Frontier topical** reports inform Frontier reports (Cosmic Frontier in this case)
- **Frontier reports** inform the Snowmass report
- **Snowmass report** eventually informs the P5 report
- **P5 report** is the guide for HEP funding in the US for the next decade

Fred Sarazin (fsarazin@mines.edu)
Physics Department, Colorado School of Mines

First UHECR workshop
Oct 20, 2021

- The **UHECR** Snowmass white paper aims at identifying the scientific goals of the community looking out **two decades** in the future.
  - **UHECR:** for the purpose of this document E > 100 PeV
  - **Why two decades?** Current experiments are going to operate for another decade, while most planned experiments are about one decade out and will need to operate 5-10 years.
- The white paper also aims at being a **baseline roadmap** for the community and therefore need to be **international** and (reasonably) thorough. We are aiming for a 70 - 100 pages document.

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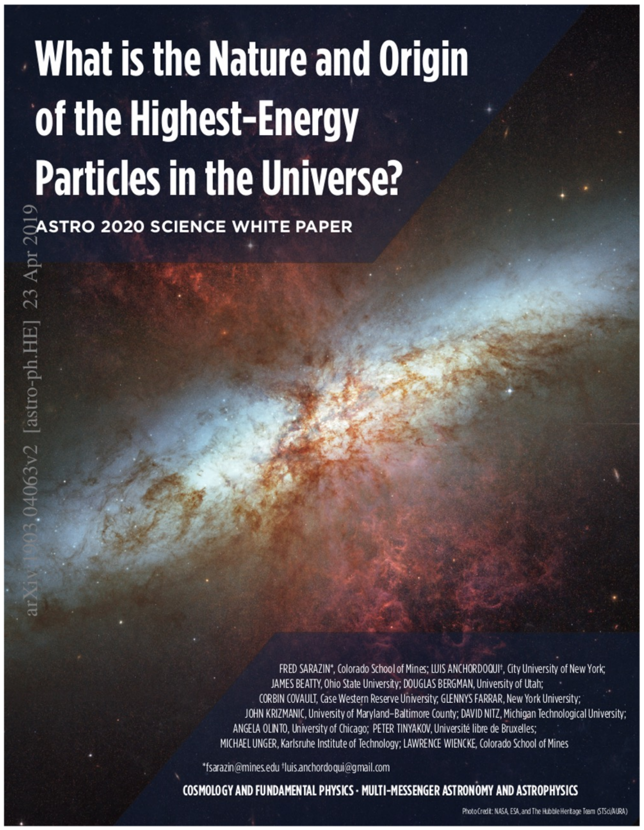


Astro 2020 was a NASEM exercise aimed at identifying the key scientific challenges for astronomy and astrophysics in the next decade.

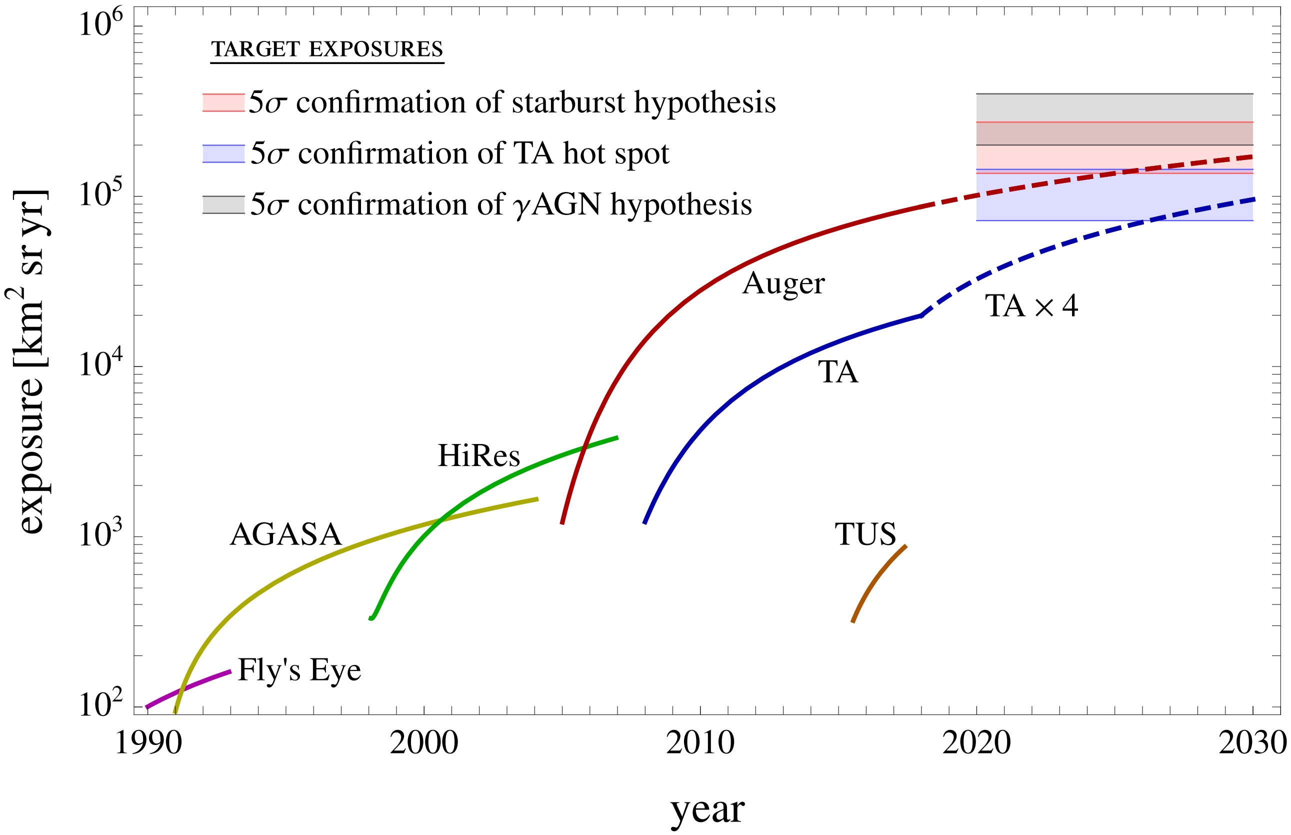
Astro 2020 science white papers:

- 5-page strict limit for all science white papers regardless of the breadth of topic covered
- UHECR white paper (arXiv:1903.04063) focused solely on the science with a distinct focus on astroparticle physics
- Another white paper on lower energy (galactic) CRs (by Frank Schroeder et al. – arXiv:1903.07713)

Activities, Projects, or State of the Profession Consideration (APC)

- 10-page strict limit for all APC white papers
- Only POEMMA (arXiv:1907.06217) represented

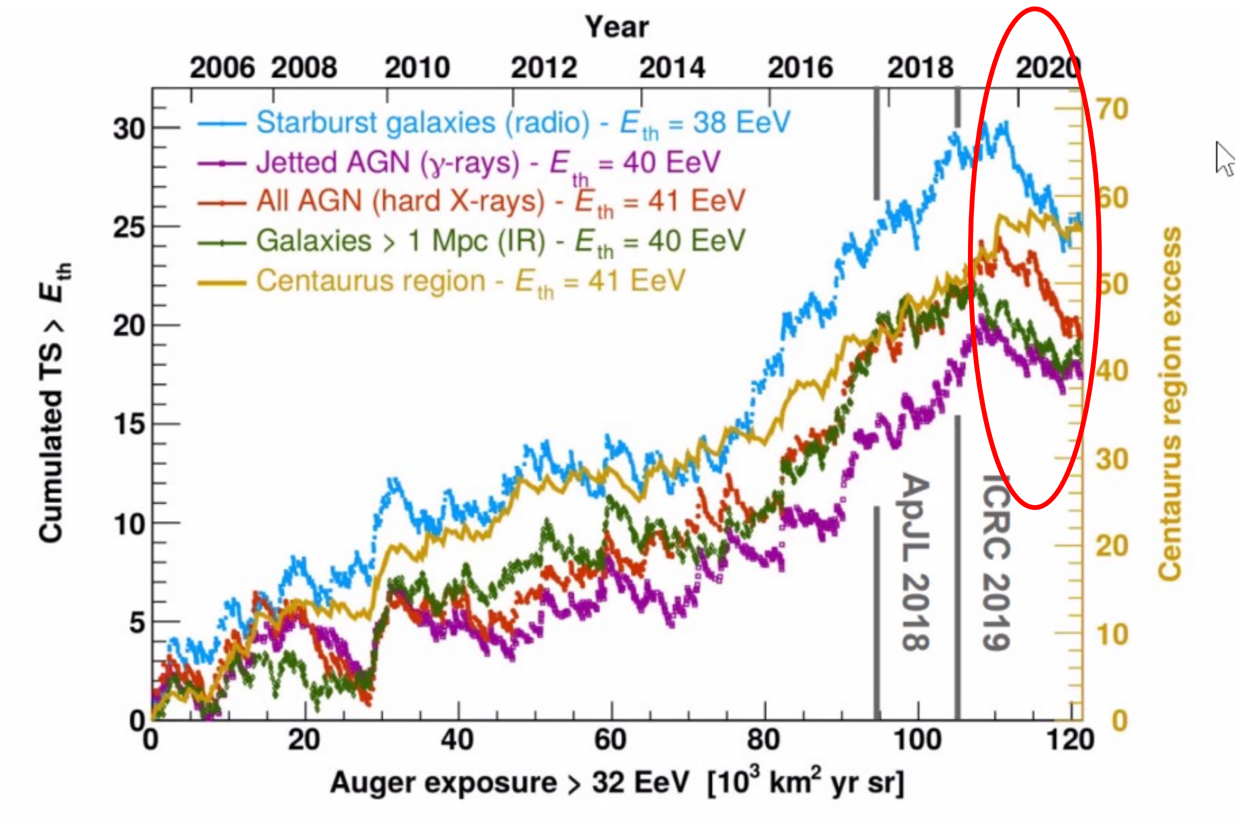
Note: more documents were submitted as Notice of Intents (incl. Auger if I recall).



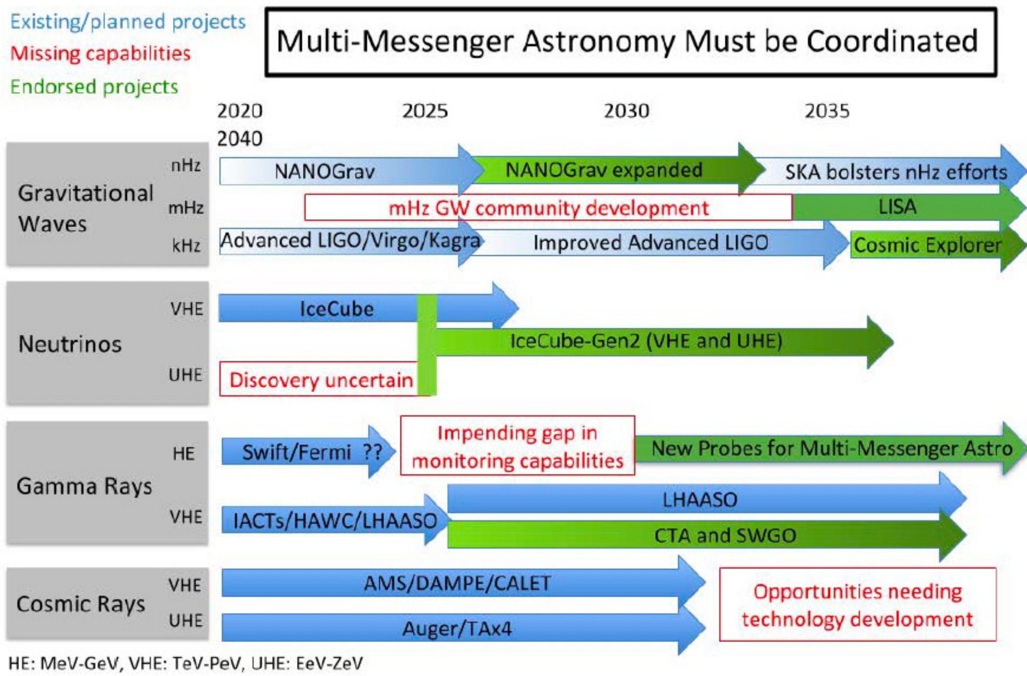
By 2030:

- The TA hot spot may be confirmed at 5σ level (but what sources hide behind the hot spot may remain a mystery!)
- One or more classes of UHECR sources may be discovered by Auger.

F.Sarazin, L.Anchordoqui et al.
2020 Decadal Survey UHECR white paper
arXiv:1903.04063



- May take longer?



UHECR beyond 2030?

FIGURE L.4 Schematic high-level view of capabilities in different messengers over decades (blue: existing or planned, red: missing capabilities, green: endorsed new projects, dated by construction starts). Gradient shading indicates projects that can start taking data as construction proceeds. Not shown are many promising potential projects for which technology development is needed. With each messenger, the discovery prospects are outstanding; with multi-messenger observations, they could be transformative.

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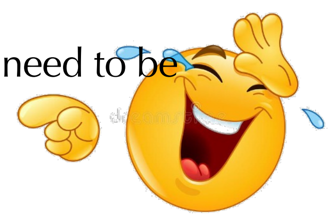

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Submitted to the US Community Study
on the Future of Particle Physics (Snowmass 2021)

arXiv:2205.05845v2 [astro-ph.HE] 16 May 2022

Ultra-High-Energy Cosmic Rays

The Intersection of the Cosmic and Energy Frontiers

Abstract: The present white paper is submitted as part of the "Snowmass" process to help inform the long-term plans of the United States Department of Energy and the National Science Foundation for high-energy physics. It summarizes the science questions driving the Ultra-High-Energy Cosmic-Ray (UHECR) community and provides recommendations on the strategy to answer them in the next two decades.

Conveners

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Final arXiv version (v3): https://arxiv.org/pdf/2205.05845

Wide community involvement:

- 7 conveners
- 29 topical conveners
- 62 contributors
- 200+ endorsers

Document:

- 190+ pages of content and discussion (283 with front- and back-matter)
- Spread over 8 chapters, 38 sections and 78 subsections
- 132+ figures, 25+ of which are unique
- 1,114 unique references cited

Content

Contents

- **In the last 20 years,** UHECR science has come of age and now informs particle- and astrophysics with precision measurements at energies beyond those obtainable with terrestrial (accelerator) experiments.

- **Over the next 10 years,** it is critical that the shortcomings of modern Hadronic interaction models (e.g., the muon puzzle) be addressed and a clearer picture of primary composition at the highest energies be obtained using observations from the upgraded Pierre Auger Observatory and Telescope Array Project.

- **Looking out to 20 years,** to progress UHECR science both an expansion of full-sky exposure and shower-by-shower sensitivity to critical observables will be required, providing a clear opportunity for synergistic partnerships between space and ground based observatories.

From: Report of the first GCOS workshop (to the EUSO collaboration)

Extrapolating beyond 2030 is a (very) risky exercise

- Current differences (spectrum, mass composition…) between Auger and TA will be understood

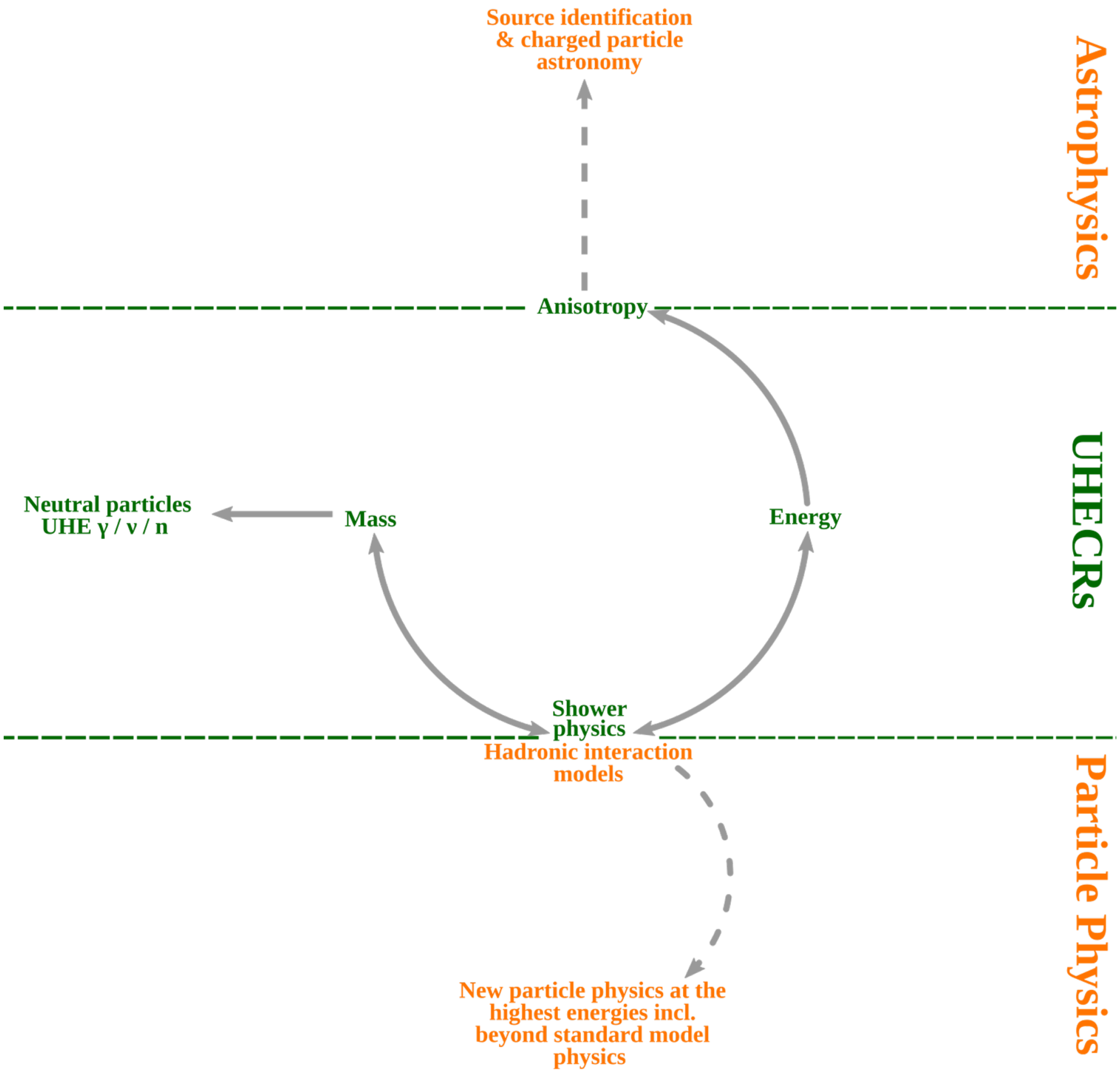
- At least one class of UHECR sources will be identified (Auger), confirmation of hot spot(s) in the northern hemisphere, but may not provide insights on sources (TA)

- Source and acceleration models will be strongly constrained by (V)HE γ/ν and UHE CR observations (simultaneous or not)
  - Narrow the number of source class candidates

- Hadronic interaction / muon excess will be (better) understood (e.g. p-O LHC run)
  - Convergence of hadronic interaction models → Better handle on mass composition
  - Hadronic interactions at the highest energies

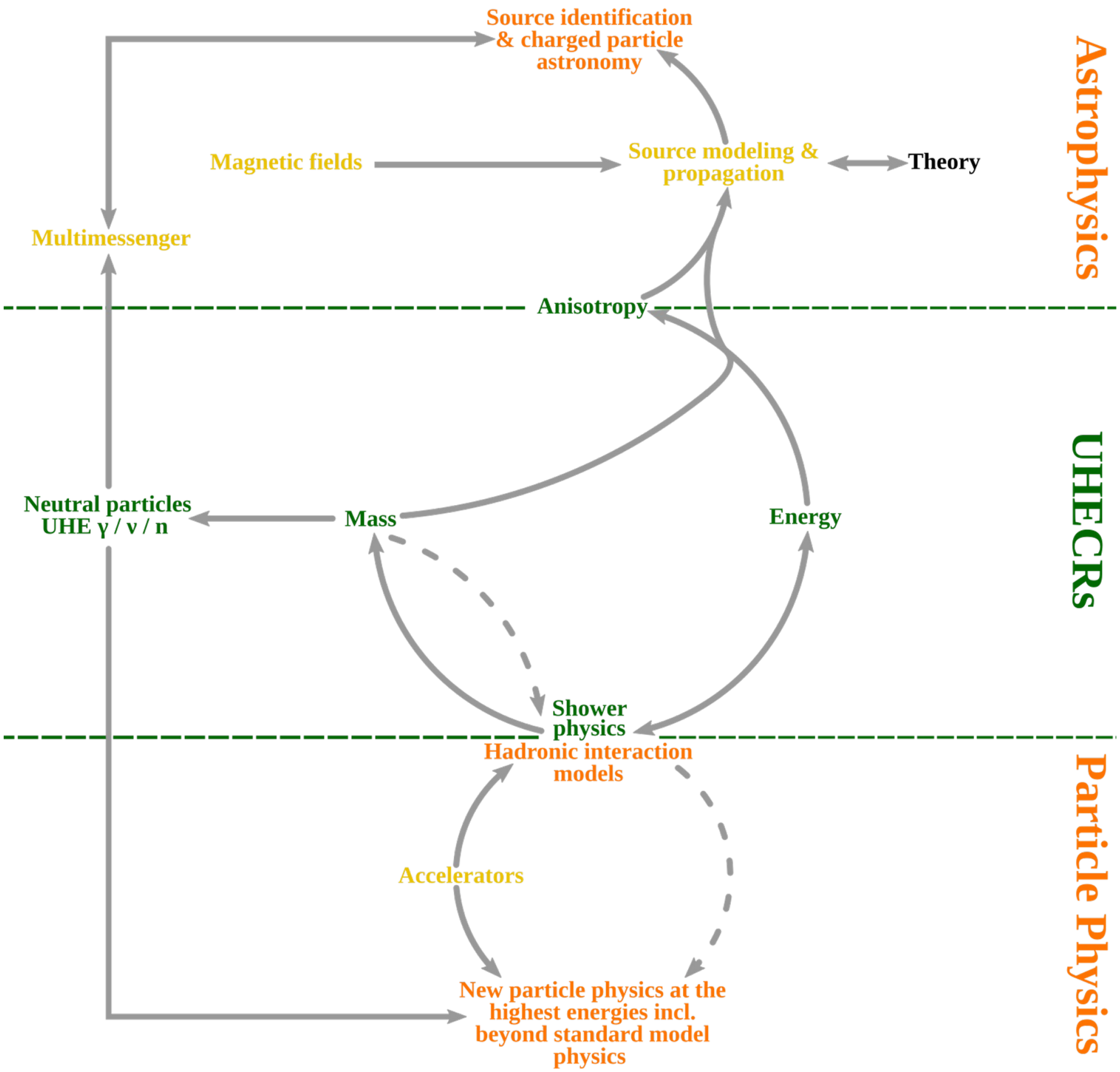
- Galactic Magnetic Field will be better understood (IMAGINE…)
  - Source search with heavier primaries (He, CNO) / still depends on source location and composition
  - Charged-particle astronomy feasible (but not demonstrated) with heavier-than-proton primaries?
  - Are Extra-galactic Magnetic Field contributions too small to matter?

- Improvement in current detector techniques (SD, FD, Radio…), but newer ones as well (Radar…)



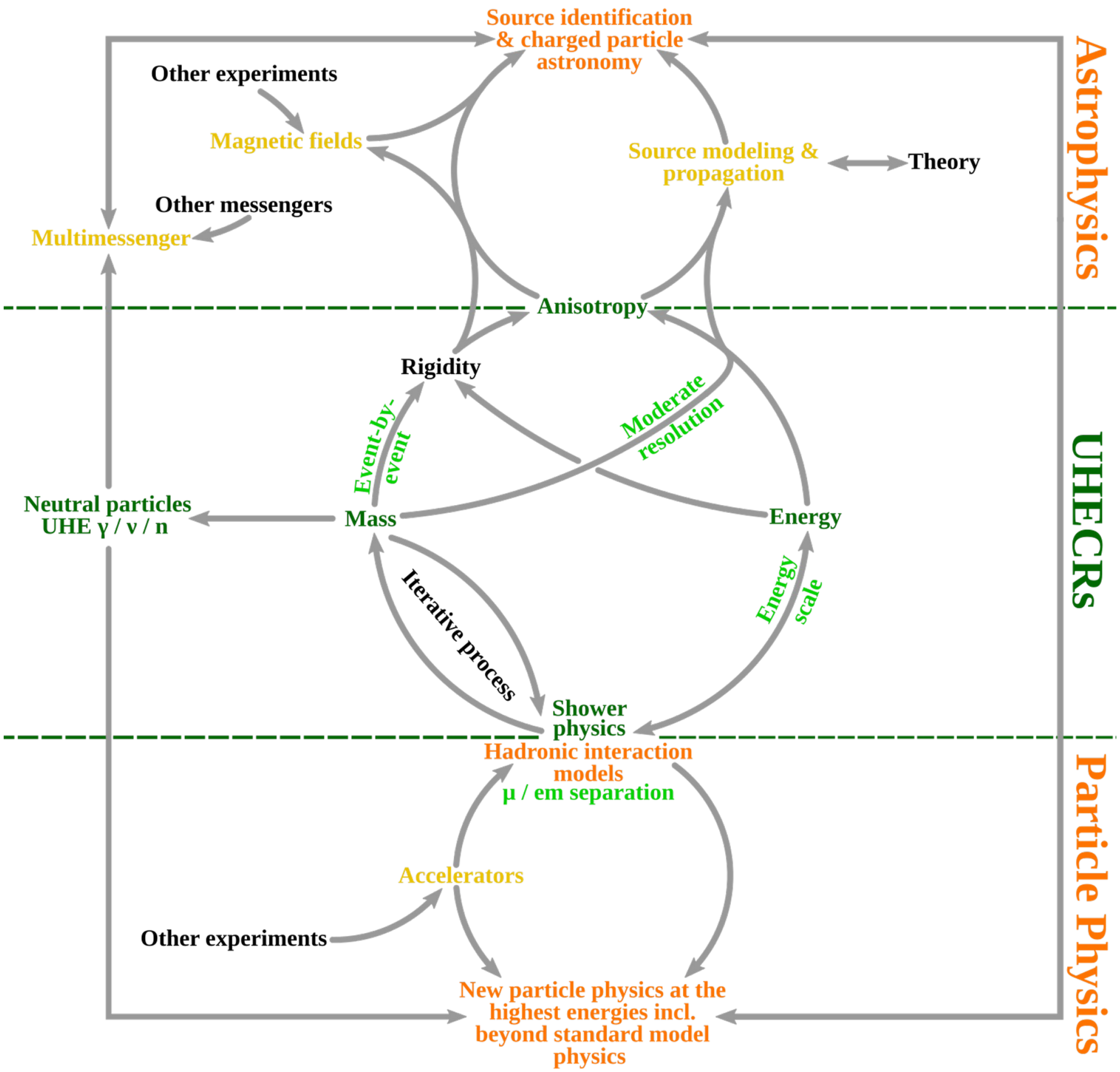
Articulating the white paper

- UHECR science sits at the **intersection of the Cosmic and Energy Frontiers** and can contribute to both.
- In the context of the Snowmass process, it was important to **highlight the opportunities to study particle physics at the highest energies** (well beyond human-made accelerators). Only mentioned briefly in Astro 2020 UHECR white paper.
- **Win over the (US) HEP community** to gain support for future UHECR observatories.



Articulating the white paper

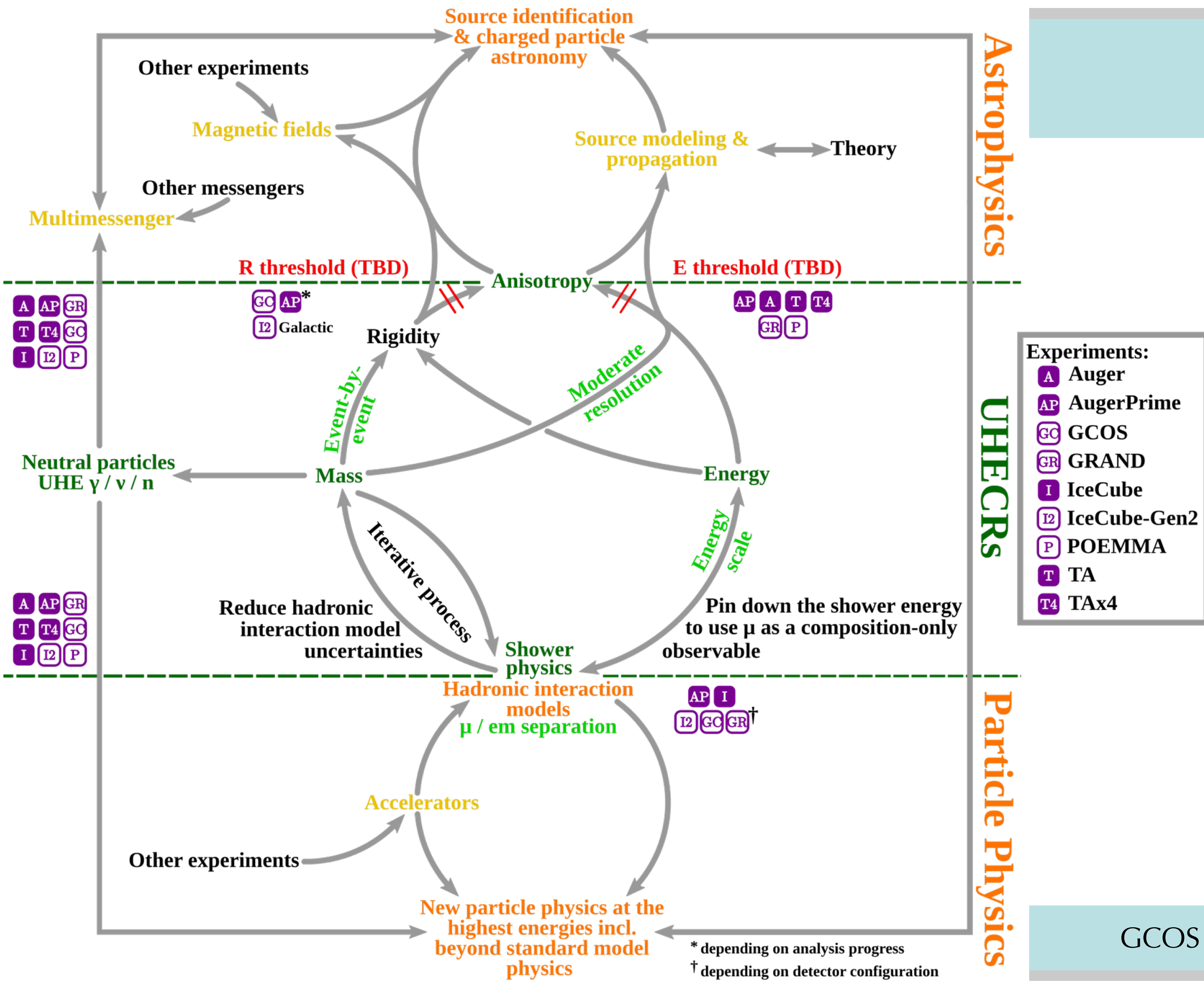
- **Identify the connections and synergies with other fields**, both experimental and theoretical, to achieve the primary goals.
- How do we currently attempt to reach the primary goals?



Articulating the white paper

- **Understand what is needed** to achieve the primary goals (driven by current knowledge, planned upgrades, new analyses…).
- **Better understanding of hadronic interactions** (e.g. muon puzzle) driving shower physics is a key to progress further → Obvious connection to Particle Physics.
- **Pinning down hadronic interactions** will in turn help with primary mass identification → Critical for Astroparticle Physics.

Articulating the white paper



- The final step is to **identify the experiments** that are contributing or will contribute to achieving the science goals.
- AugerPrime and **GCOS** (and IceCube Gen 2 at lower energy) have a **critical role** to play.

- Even in the most optimistic scenario, the first next-generation experiment will not be operational until around 2030. AugerPrime and TA×4 should continue operation until at least 2032.
- IceCube and IceCube-Gen2 provide a unique laboratory to study particle physics in air showers. For this purpose, the deep detector in the ice should be complemented by a hybrid surface array for sufficiently accurate measurements of the air showers.
- A robust effort in R&D should continue in detector developments and cross-calibrations for all air-shower components, and also in computing techniques. This effort should include, whenever possible, optimized triggers for photons, neutrinos and transient events.

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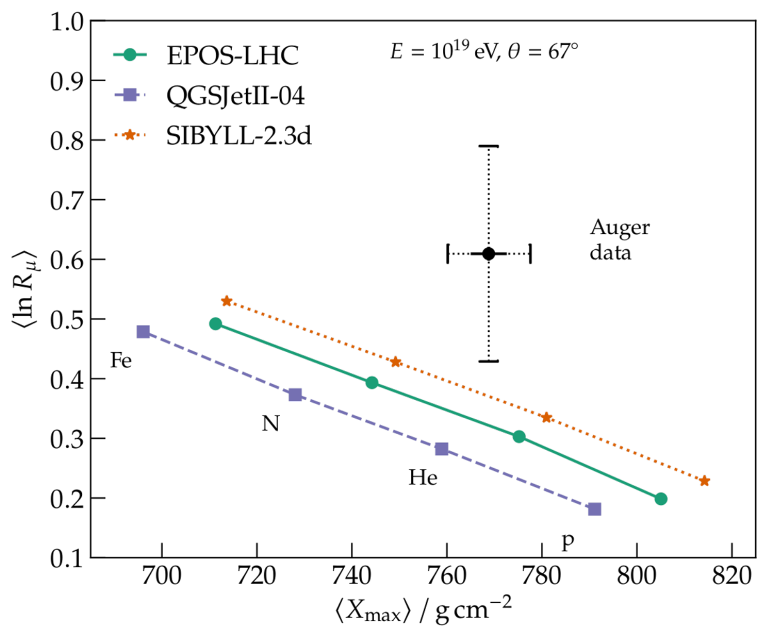
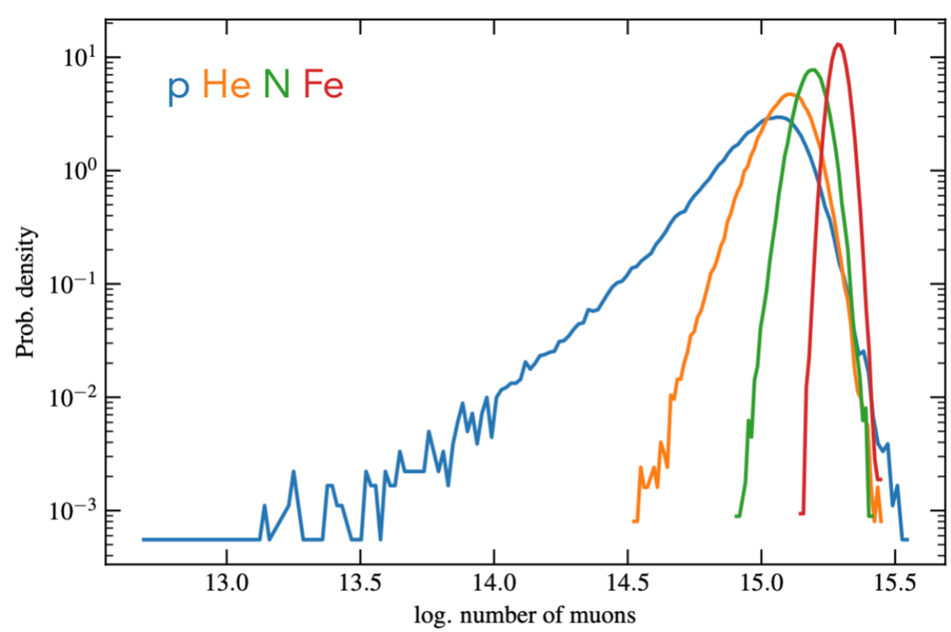
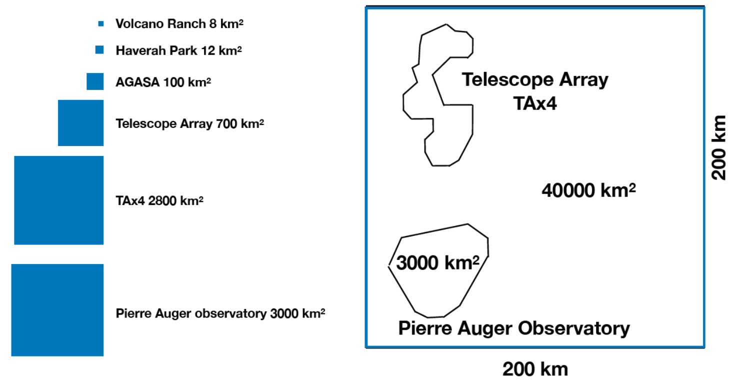
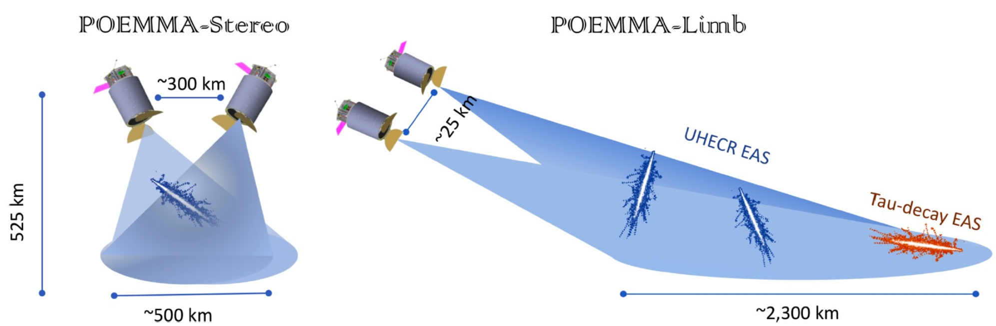
- To achieve the high precision UHECR particle physics studies needed to provide strong constraints for leveraging by accelerator experiments at extreme energies, even finer grained calibration methods, of the absolute energy-scale for example, should be rigorously pursued.

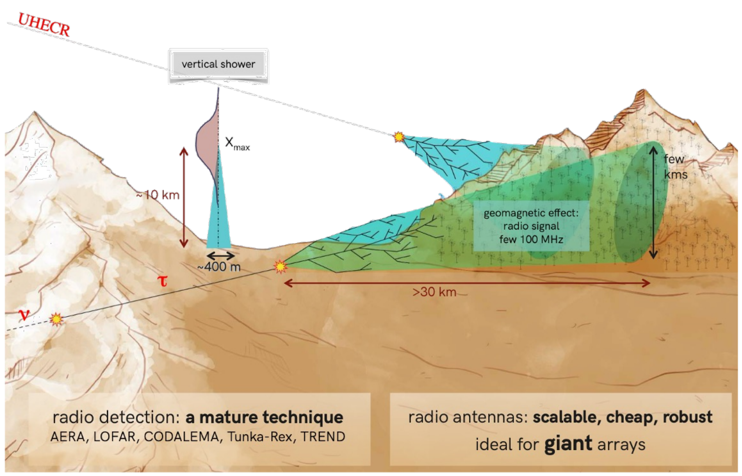




- The next-generation experiments (**GCOS**, GRAND, and POEMMA) will provide complementary information needed to meet the goals of the UHECR community in the next two decades. They should proceed through their respective next stages of planning and prototyping.



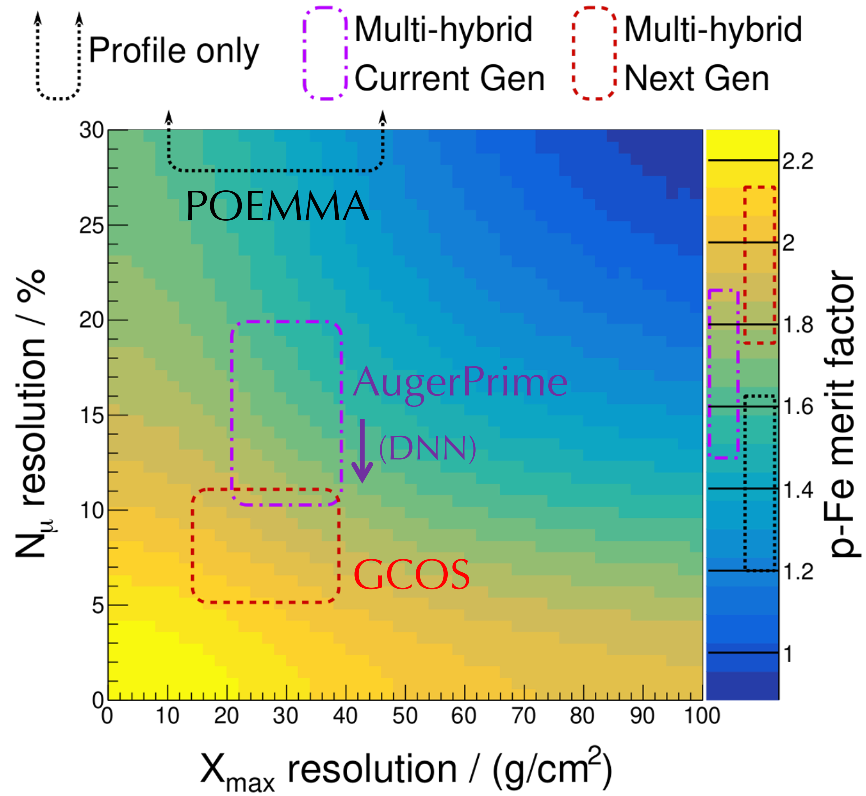




- At least one next-generation experiment needs to be able to make **high-precision measurements to explore new particle physics** and measure particle rigidity on an event-by-event basis. Of the planned next-generation experiments, **GCOS** is the best positioned to meet this recommendation.

See talk by D.Soldin

GCOS: in principle, a "small" high-precision array is possible for some hadronic interaction studies. However, such an array would not be appropriate for hadronic interaction studies and BSM searches post suppression (see next two slides as well).



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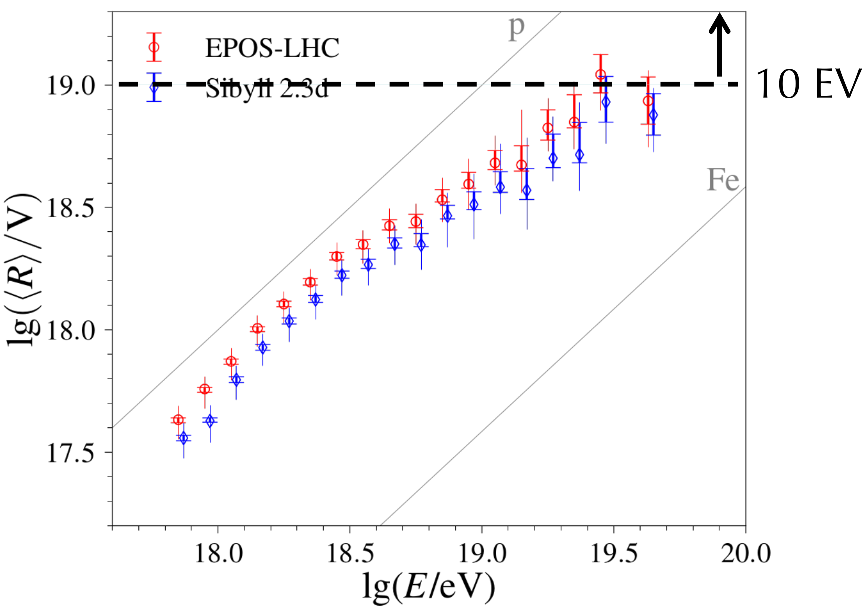
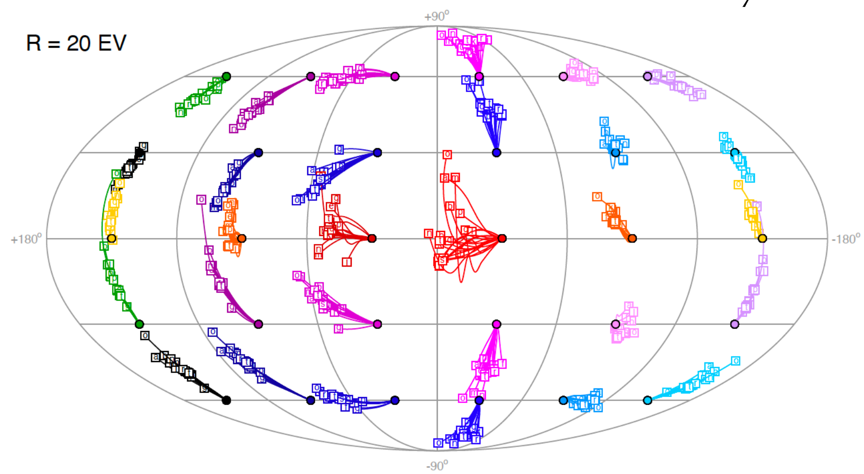
- At least one next-generation experiment needs to be able to make **high-precision measurements to** explore new particle physics and **measure particle rigidity on an event-by-event basis.** Of the planned next-generation experiments, **GCOS** is the best positioned to meet this recommendation.

See talk by M. Unger





GCOS: large exposure needed to collect events beyond 10 EV.

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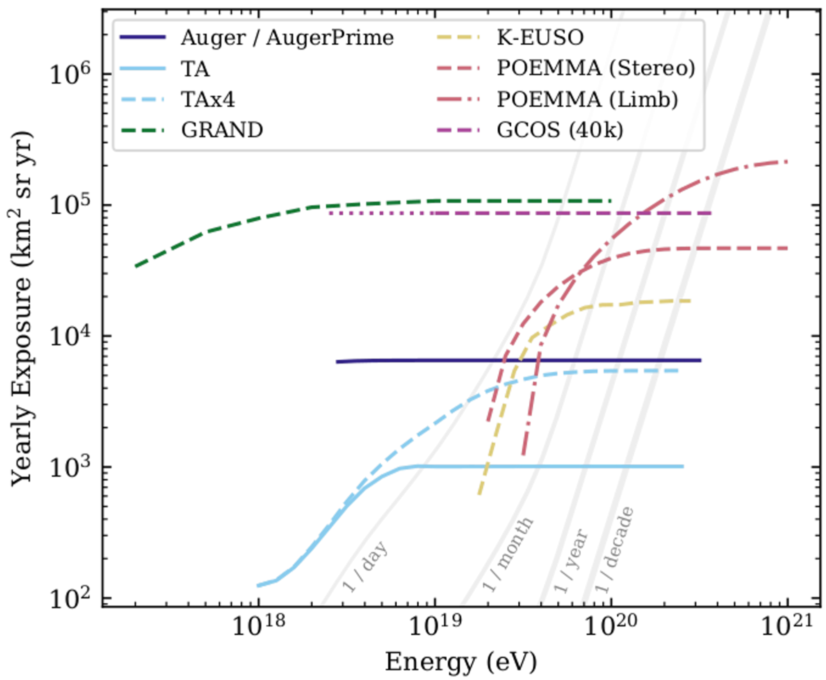
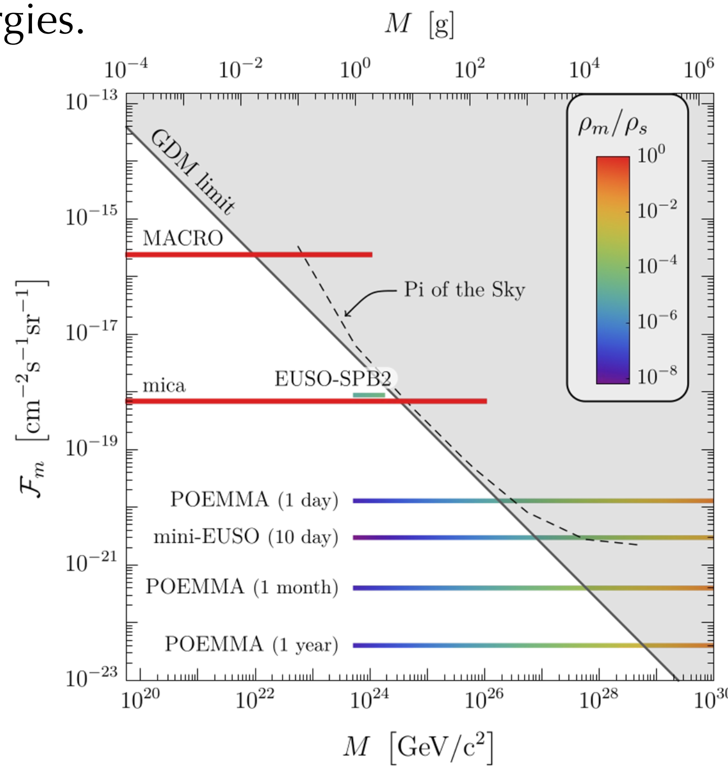
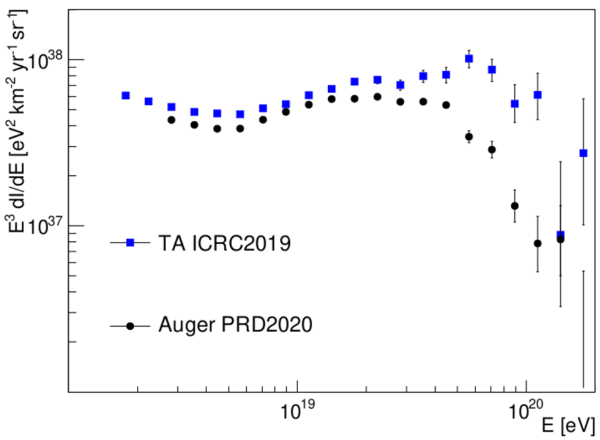
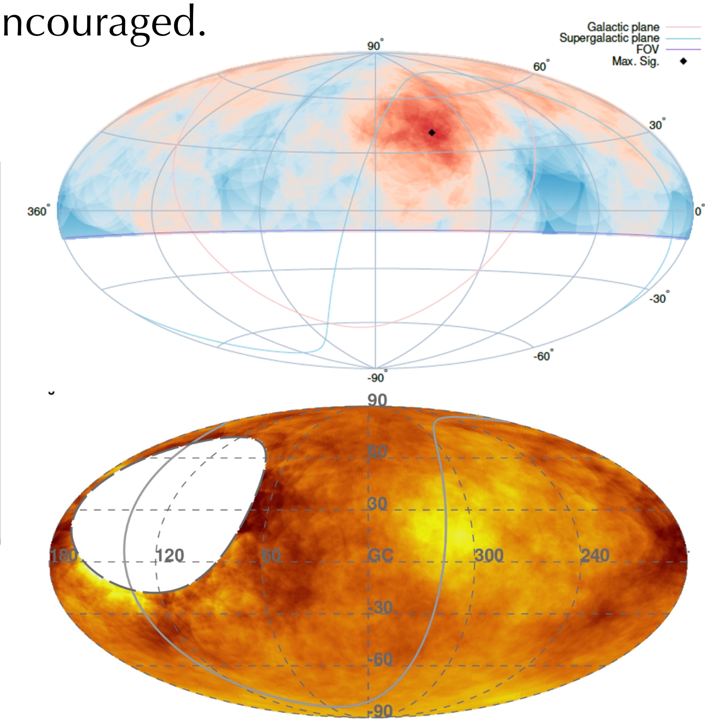
- As a complementary effort, experiments with sufficient exposure (> 5×10^5 km^2 sr yr) are needed to search for Lorentz-invariance violation (LIV), SHDM, and other BSM physics at the Cosmic and Energy Frontiers, and to identify UHECR sources at the highest energies.

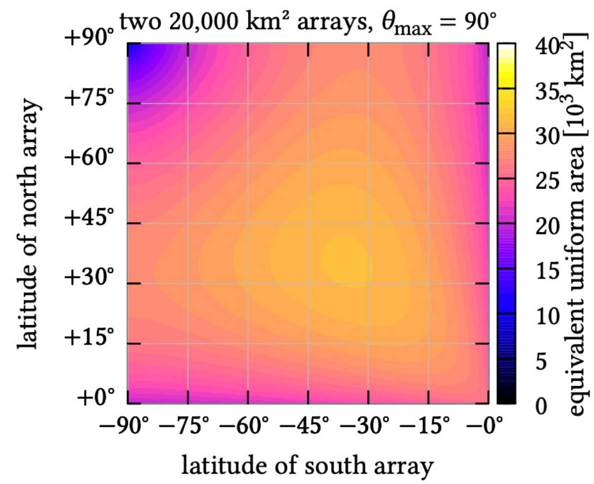




- Full-sky coverage with low cross-hemisphere systematic uncertainties is critical for astrophysical studies. To this end, next generation experiments should be space-based or multi-site. Common sites between experiments are encouraged.







A.DiMatteo, INFN Torino (GCOS workshop #1)

- Based on the productive results from inter-collaboration and interdisciplinary work, we recommend the continued progress/formation of joint analyses between experiments and with other intersecting fields of research (e.g., magnetic fields).

- The UHECR community should continue its efforts to advance diversity, equity, inclusion, and accessibility. It also needs to take steps to reduce its environmental impacts and improve open access to its data to reduce the scientific gap between countries.

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Beyond 2030 →

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.

THANK YOU