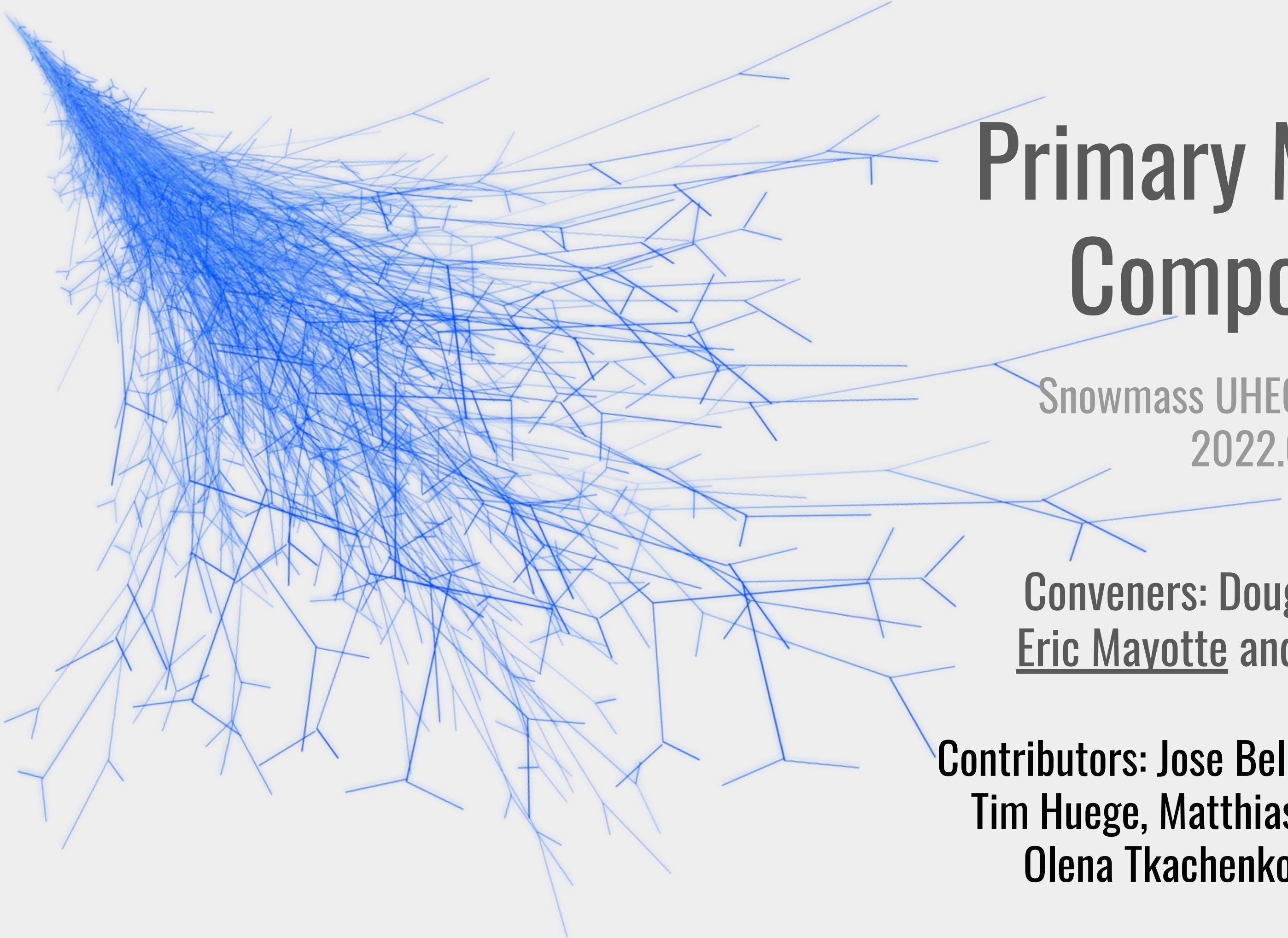
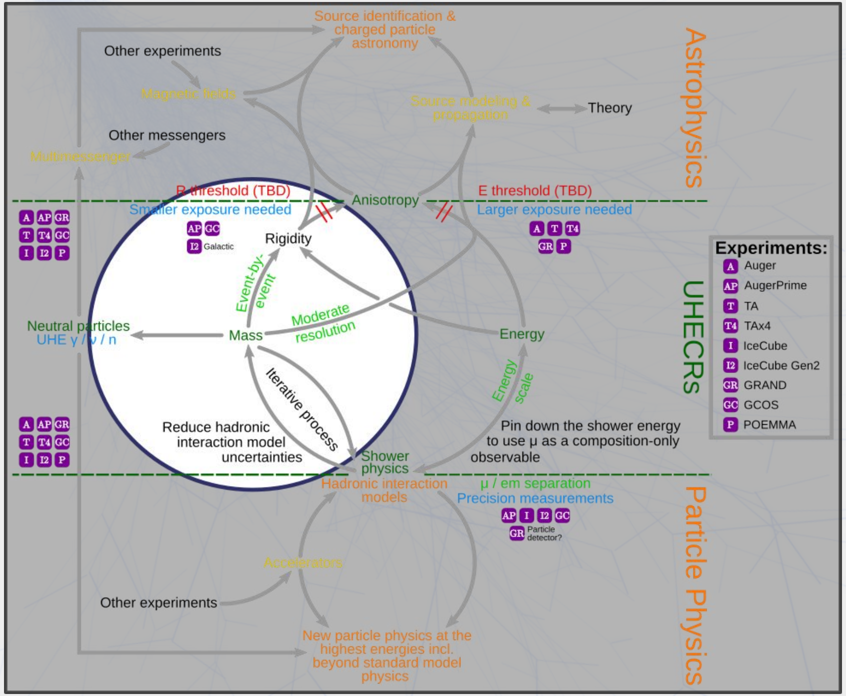


Primary Mass and Composition

Snowmass UHECR Workshop II
2022.01.25

Conveners: Douglas Bergmann, Eric Mayotte and Alexey Yushov

Contributors: Jose Bellido, Jonas Glombitza, Tim Huege, Matthias Plum, Bjarni Pont, Olena Tkachenko, Michael Unger



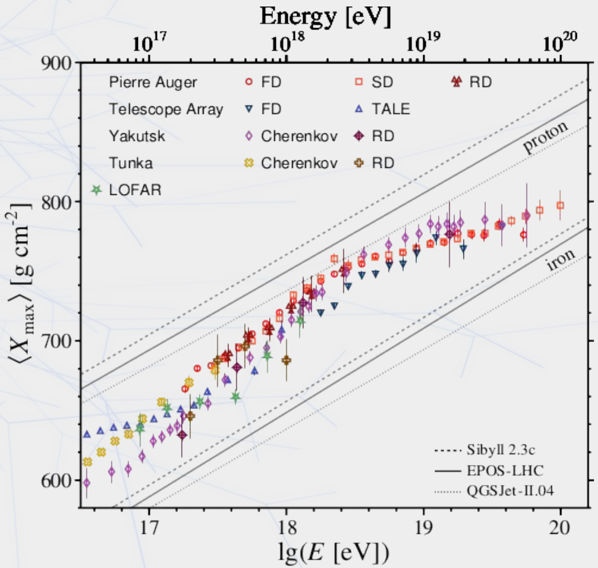
Synopsis:

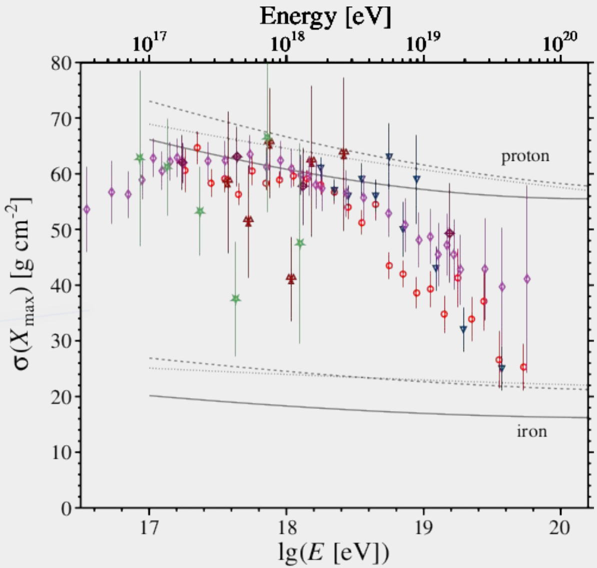
All aspects of UHECR physics are closely tied to primary composition and therefore stand to benefit greatly from the increasing resolution and statistics.

However, above the suppression the current picture is unclear and much of what can we hope to achieve in the next 20 years hinges on what we will find in the next 10.

Current Status: X_{max} measurements

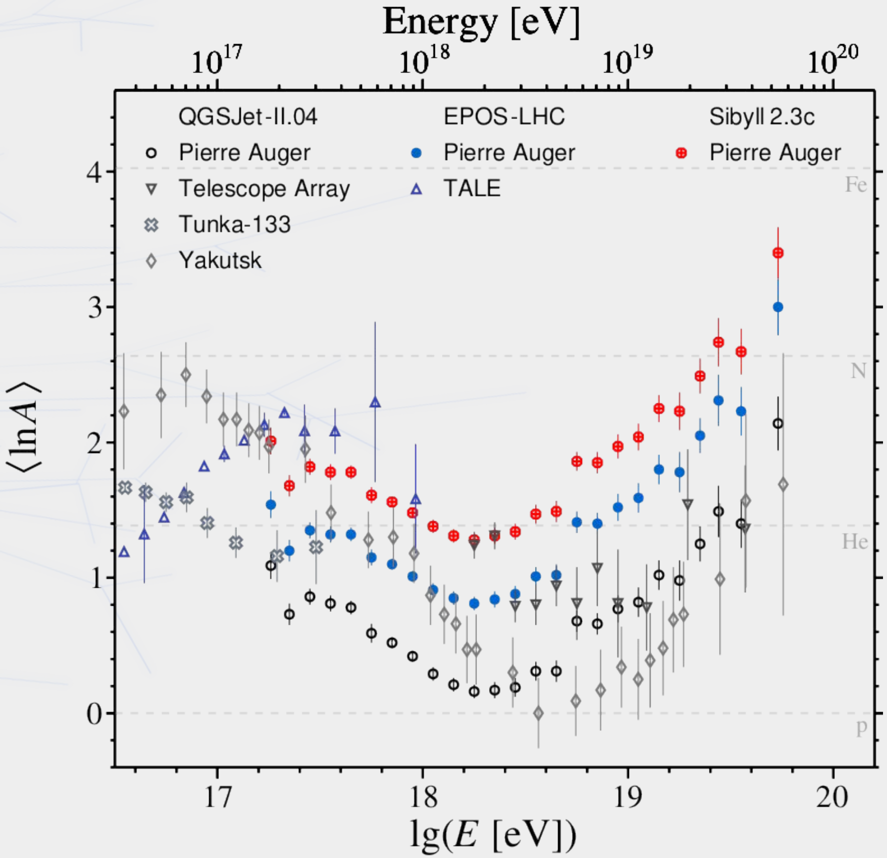
- **Shower profiles and X_{max}:** FD X_{max} measurements and analyses have provided the most reliable mass measurements to date.
- **Picture unclear past the cutoff:** Low duty cycle of the FD (~14%) and complicated quality cuts mean statistics at the highest energies are low (<100 events E > 40 EeV).
- **SD methods on the rise:** SDs make indirect measurements, but machine learning methods are already taking advantage of the 100% duty cycle SD.





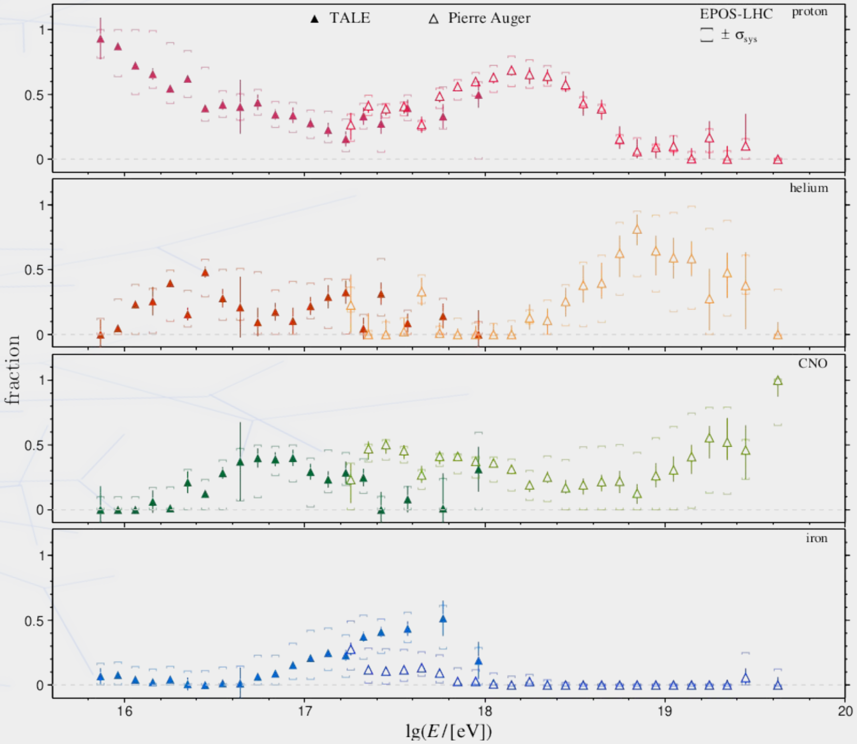
Current Status: Mean primary mass

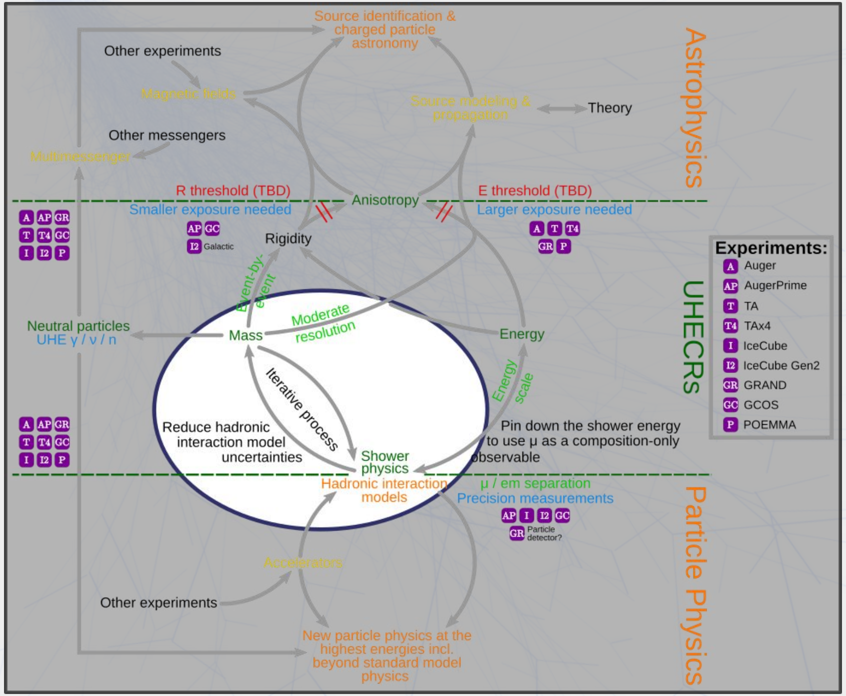
- **Moments of $\ln A$**
  The first 2 moments of X_{max} are closely related to the first 2 moments of $\ln A$.
- **FD and SD trends agree**
  Mass scales however differ greatly due to model uncertainties.
  - **100 PeV - 1 EeV:** The flux starts heavy and mixed but gradually lightens.
  - **1 EeV - 2 EeV:** The lightest mean mass is reached with a large proton fraction.
  - **2 EeV - 40 EeV:** Statistics run low, as energy grows a mixed flux increases in mean mass also, generally, in purity.
  - **$E > 40$ EeV:** Uncertain.



Current Status: Mass fractions

- **First and second knee?**
  - The knee is mainly protons;
  - mass increases with energy as expected;
  - second knee fractions do not look right.
- **Extragalactic kick in:**
  - Just below the ankle protons dominate;
  - at 8 EeV its helium and too rigid for a galactic source of the dipole.
- **The highest energies:**
  - Mass increases further CNO dominates, no sign of iron or protons;
  - above ~40 EeV FD statistics die out;
  - will post suppression be pure iron, heavy and mixed or have a light component?

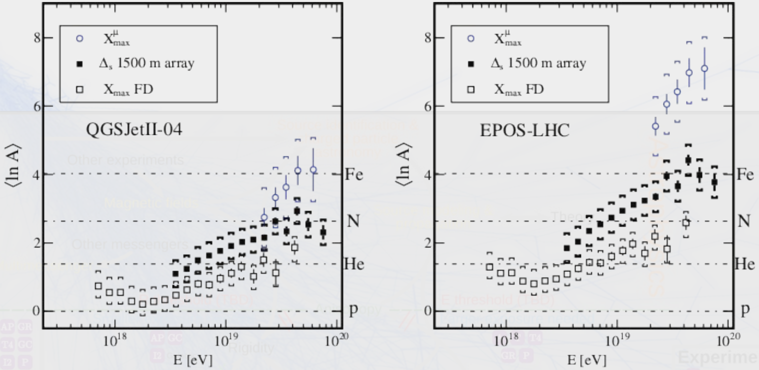


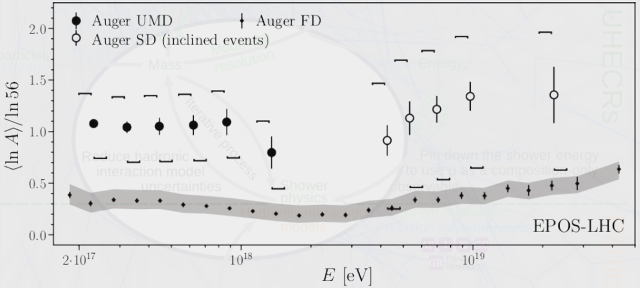


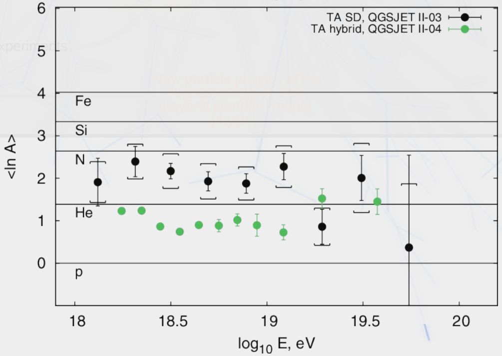
Connections: Hadronic Interactions

Mass and hadronic interactions are deeply intertwined. Improvements in one will lead to improvements in the other.

- N_μ and X_{max} scale uncertainties complicate mass interpretations.
- Lack strong of N_μ and X_{max} constraints for specific mass groups makes improving models difficult.
- If Fe can be isolated and a N_μ can be measured, low shower-to-shower fluctuations mean progress is assured.







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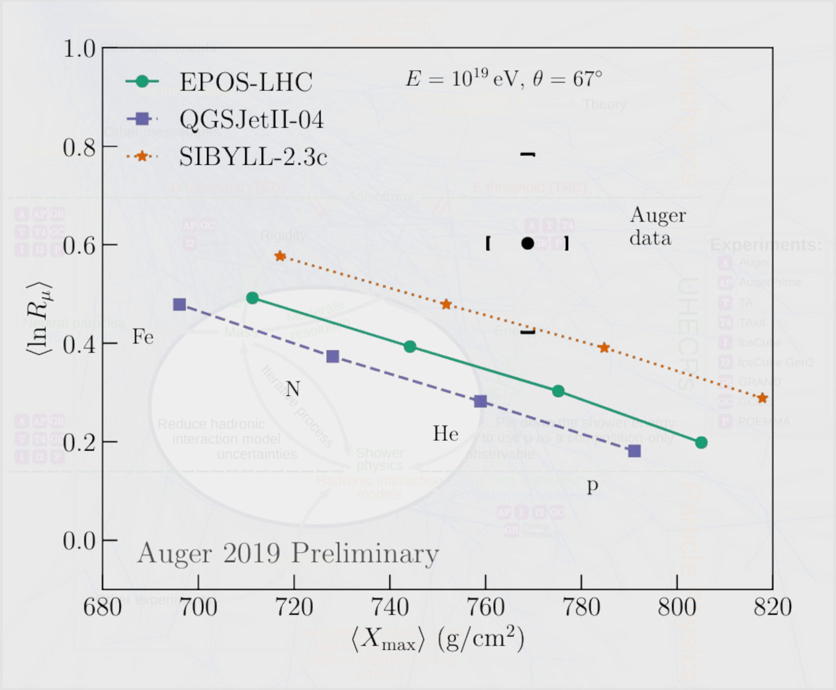

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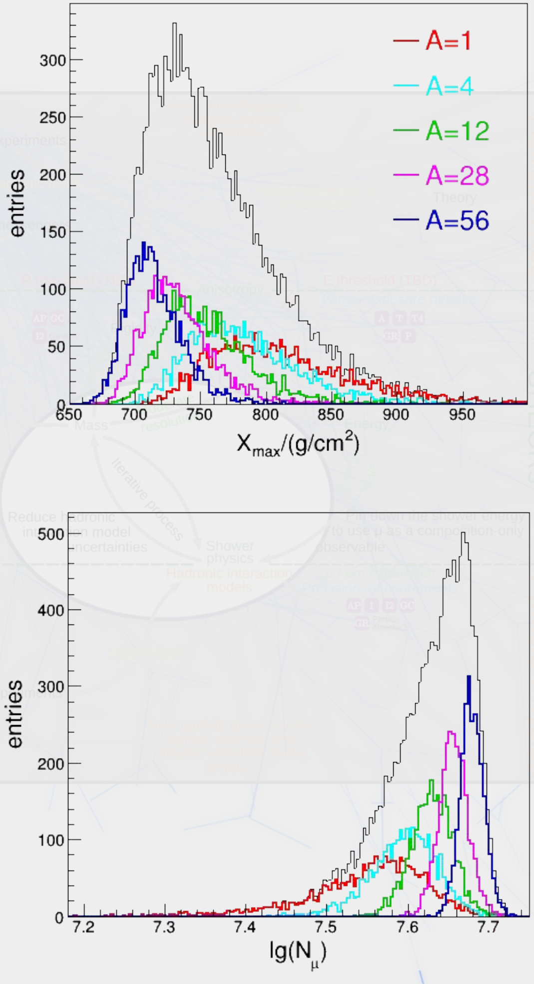

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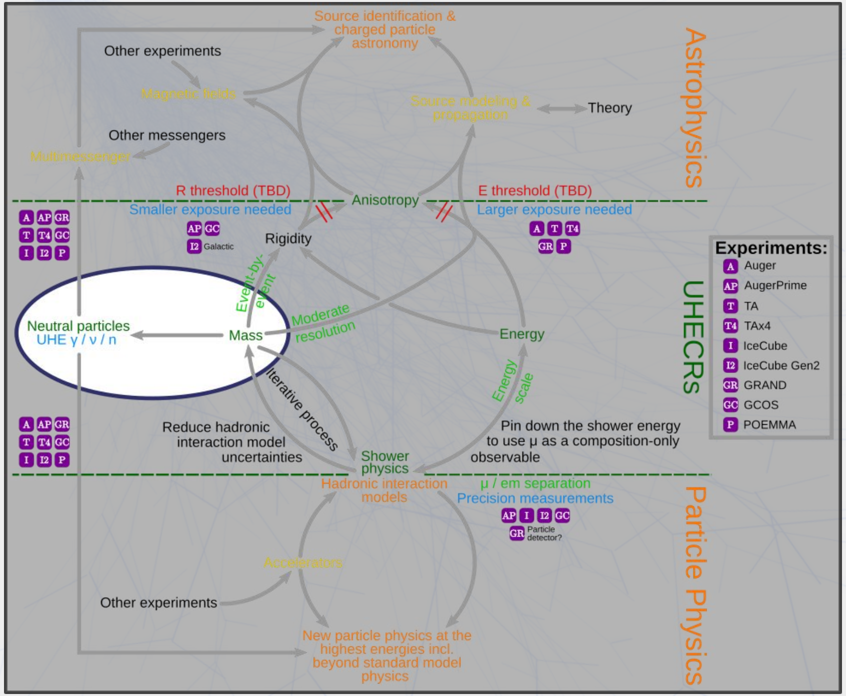
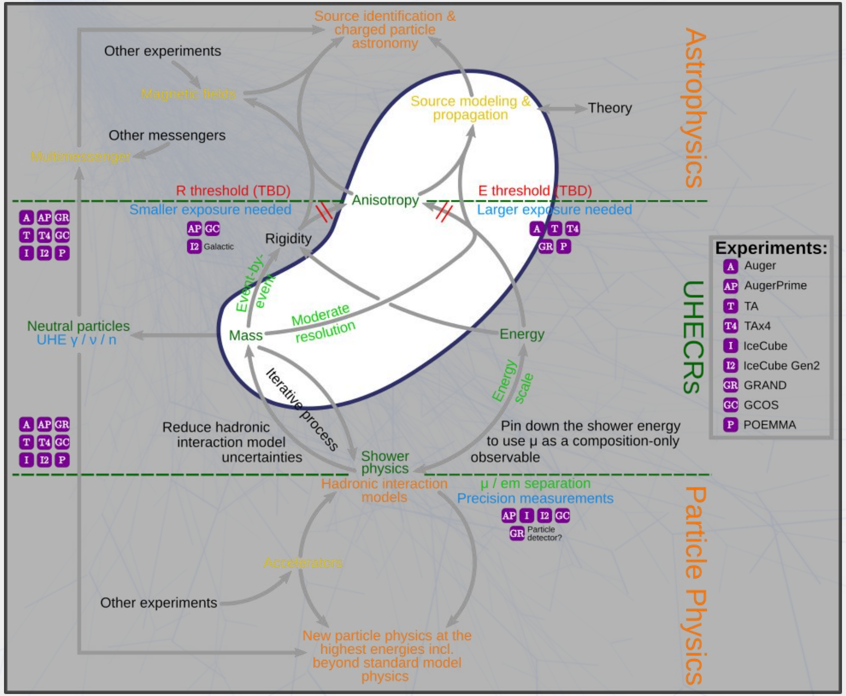
Connections: Neutral Particles and Exotics



The identification of the primary type is critical to searches for UHE neutral particles

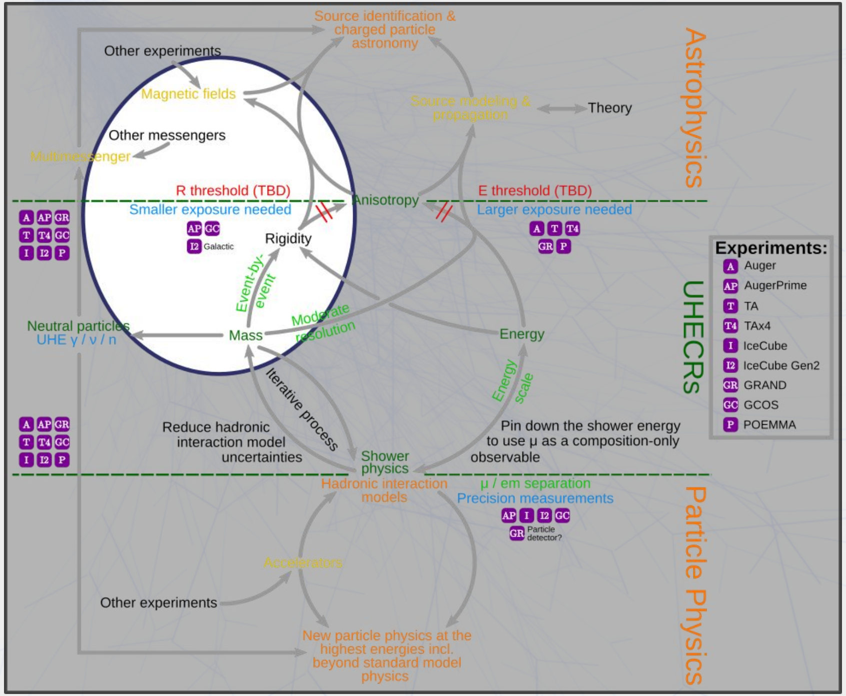
- Increased N_μ and X_{max} resolutions lead to lower backgrounds and higher efficiencies in searches.
- Measurement of UHECR mass critticle to calculation of expected γ, v and n flux.
- UHECR composition related uncertainties in atmospheric neutrino rates equal to uncertainties from QCD, decrease them.

Connections: Combined Fits and Mass Anisotropy



A moderate degree of mass resolution and large statistics offers many avenues for progress on sources. Particularly post-cutoff.

- Mass + Spectrum combined fits
- Multiplet studies
- Split sky composition measurements
- Light-tail only anisotropy searches
- Composition Sky Mapping
- Tomographic studies
- Mass + Spectrum + AD combined fits



Connections: Rigidity and Magnetic Fields

Resolutions high enough for event-by-event mass sensitivity will be very powerful at energies where the composition is mixed.

- Event-by-event mass, charge and energy measurements give direct access to each event's lorentz factor and rigidity.
- At high enough rigidities this info allows for events to be backtracked to sources,
- but only if magnetic field models are good enough…

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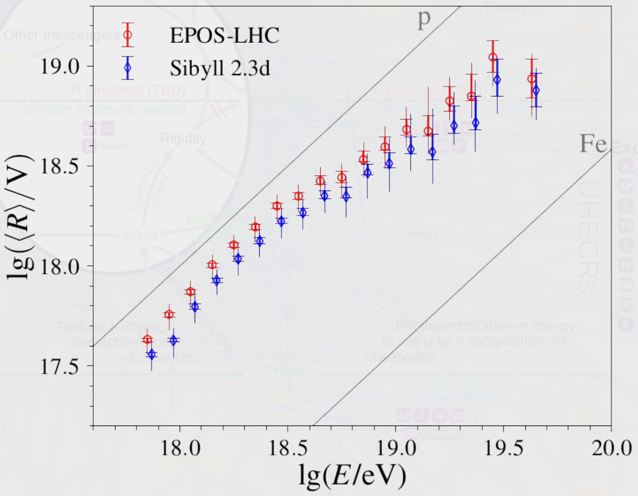

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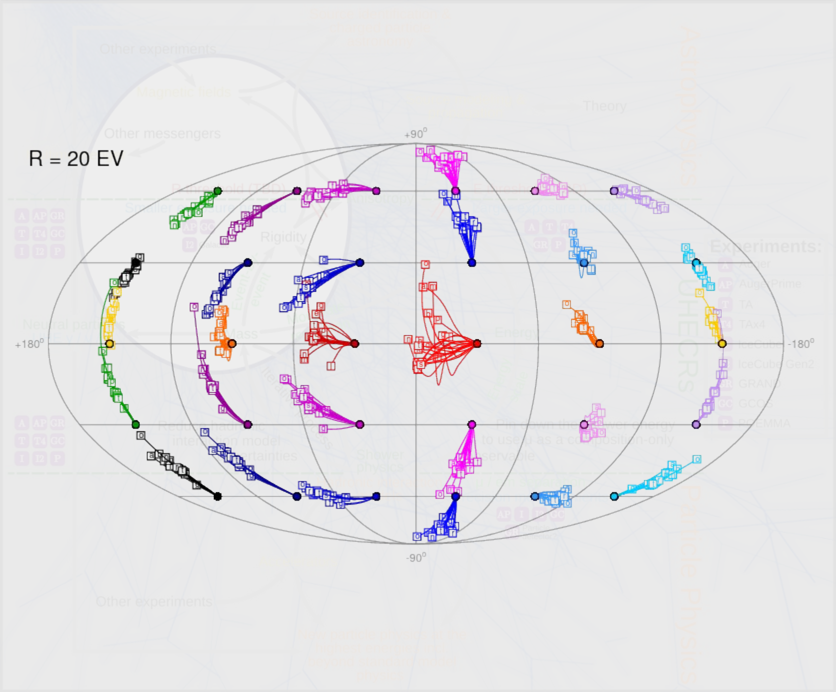

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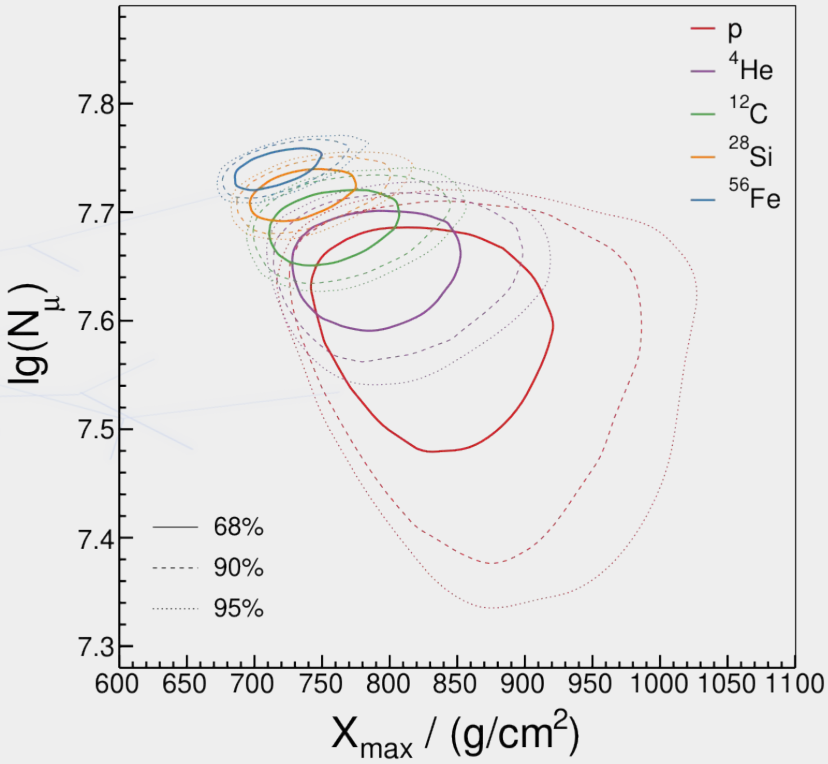
Goals: 10-Years

- **Increase statistics at the highest energies:**
  - TAx4 will collect statistics in the Northern hemisphere to clarify the full sky picture;
  - machine learning will unleash the SD and probe mass past the cutoff and quantify beam purity.
- **Solve the muon puzzle:**
  - Multi-hybrid events at AugerPrime, IceCube Gen2 and SKA to isolate Fe and set the N_μ and X_{max} scales;
  - help will come from astrophysics via multiplet studies and the high energy spallation products.
- **Event-by-event resolution:**
  - Devorce N_μ and X_{max} interpretations to enable event-by-event mass reconstructions.
- **Combine mass, energy and arrival directions:**
  - Leverage all observables simultaneously to narrow source candidates and learn about magnetic fields.



Outlook: 20-Years

Difficult to say. Very different possibilities present at different energies…

- **100 PeV - 1 EeV:**
  - Hunt down the highest energy galactic sources proton only anisotropy searches
  - reveal the transition to the extragalactic flux via high resolution mass spectra,
- **1 EeV - 40 EeV:** Use event-by-event mass sensitivity to:
  - probe particle physics beyond the reach of accelerators;
  - isolate light components and backtrack magnetic deflections.
- ***E* > 40 EeV:**
  - If beam is highly pure, mass sensitivity unneeded. Leverage anisotropy and spectrum to probe the extreme universe;
  - if flux is bimodal, isolate rigid components and image sources,
  - if flux is mixed and heavy, huge event-by-event exposure will be required to progress.