Energy Spectrum

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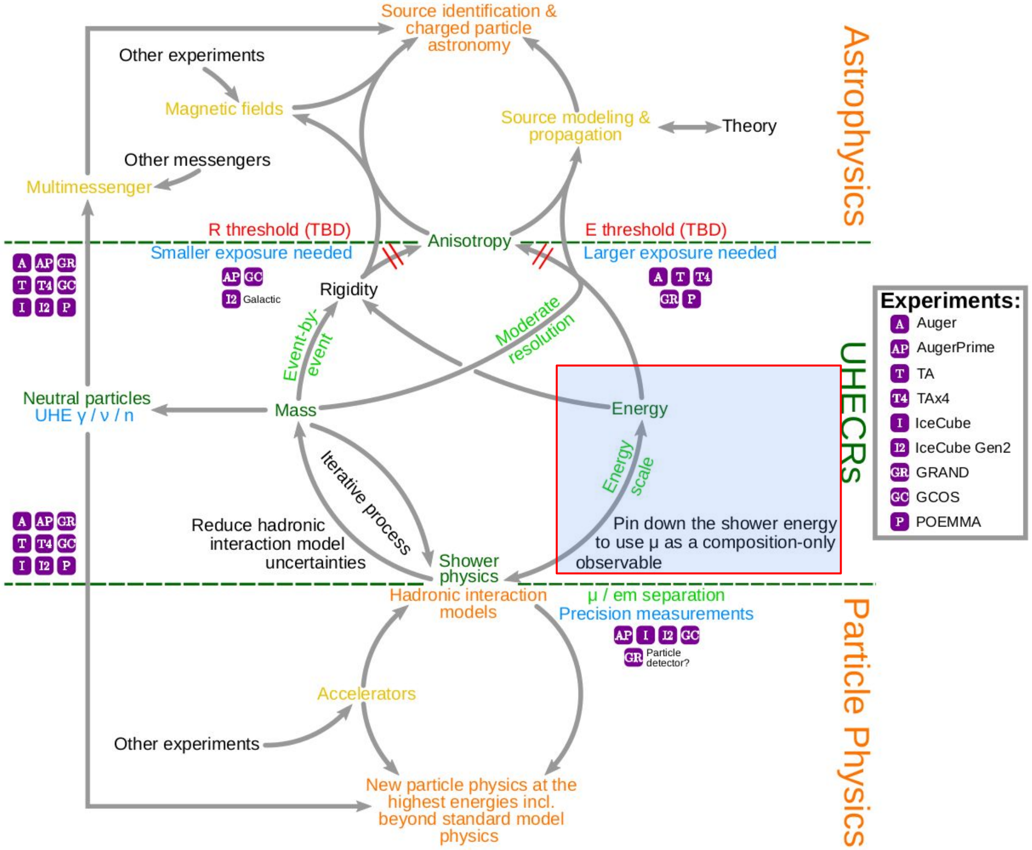


Successes of the Current Generation of Experiments

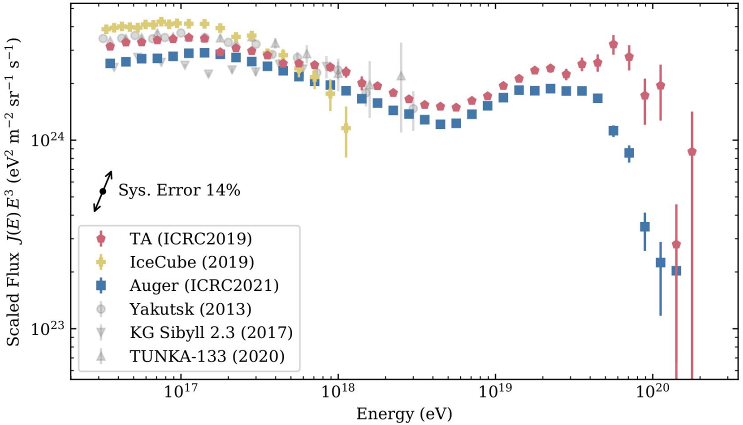
At UHE, very statistically precise measurements of the spectrum

Shape:

Measured well over several ord. of mag.

Confirmed ankle and suppression

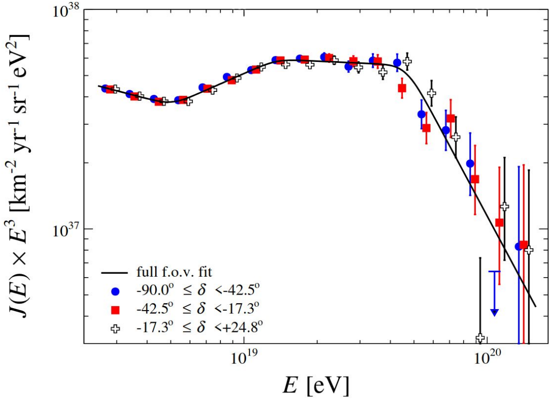
First measurement of instep

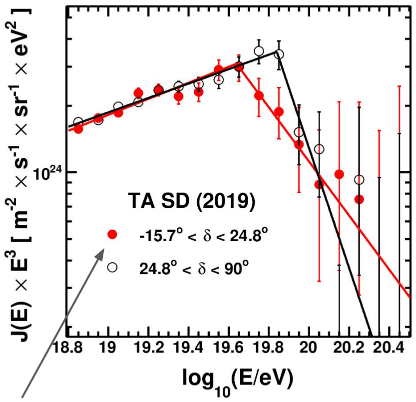


Directionality:

Above ~30 EeV, evidence of arrival dependence in the northern hemisphere

Southern sky arrival dependence is consistent with dipole >8 EeV





Approx. common band

Careful Comparison through Joint Work

Studies, such as arrival direction, require a careful understanding of the energy scale shifts. Spectra are useful for this purpose

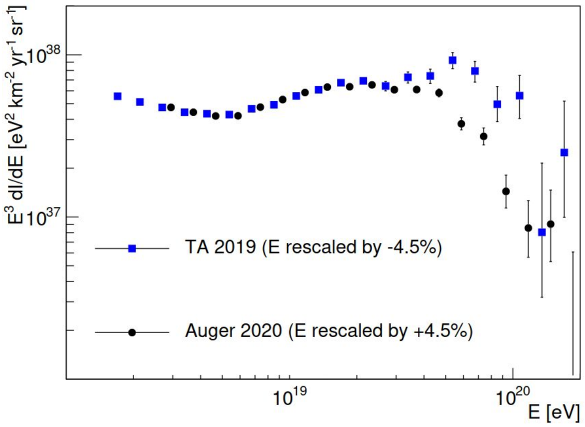
Energies below the instep can be brought into agreement with a 9% energy scale shift.

Above instep, a comparison in the common declination band yields better agreement.

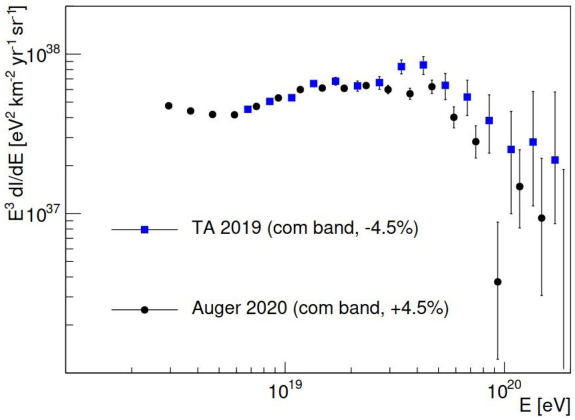
A further 20% shift per decade yields better agreement. Beyond the range of known systematics.

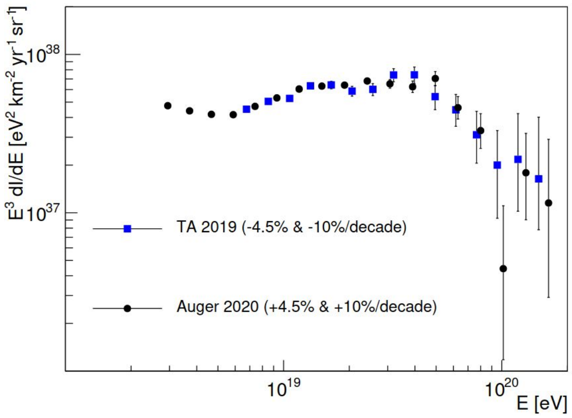
Would benefit from the increased exposure that will come from TAx4.

All sky



Common sky





Cosmic Ray Energy in the Next Decade(s)

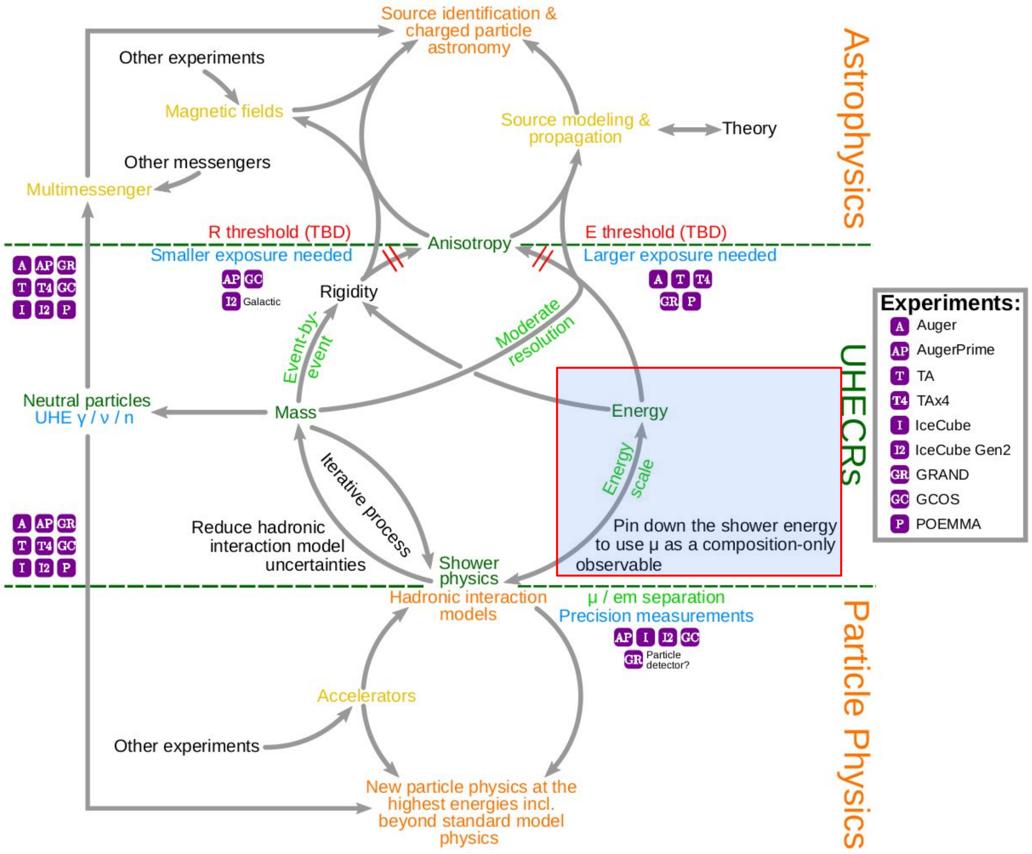
The scaling with energy is important for studying the sources of cosmic rays and hadronic interactions.

Need to make improvements on both energy resolution and energy scale uncertainties to make major progress

Major improvement will be tied to better understanding of hadronic interaction models.

Will result in better energy resolution for individual events, by breaking mass/energy degeneracy. For energy scale, by better understanding the hadronic-to-EM energy flow during shower development

Will need experiments that can best exploit a better understanding of these interactions



Upgrades to the Current Experiments (~2020s)

Differences in the spectra seen by TA/Auger are at the highest energies. Continued study over the next decade.

All-particle spectrum:

Auger-Prime ⇒ continued operation, same aperture

TAx4 ⇒ 2800km^2 array, targeting highest energies

→ Further confirm declination dependence? Discovery?

Mass-dependent spectra:

AugerPrime ⇒ new hardware to improve energy/mass assignment

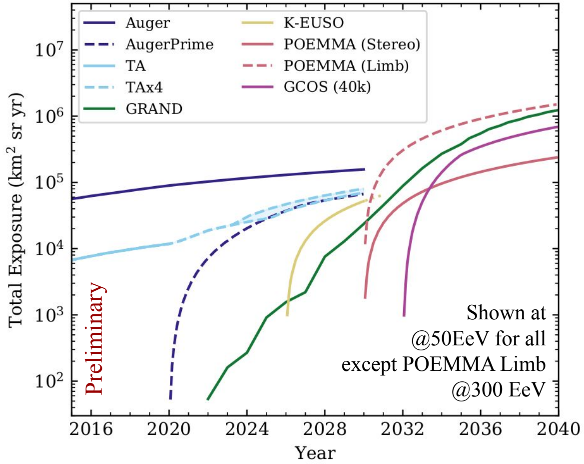
→ Better understand what *causes* the features in the spectrum

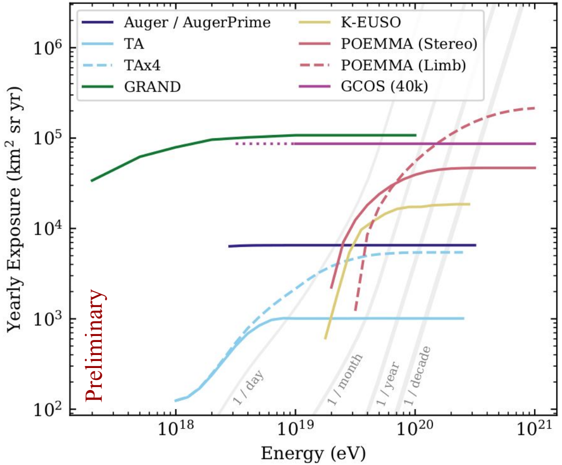
Both studies:

Better understanding of hadronic interaction models

Improved analysis methods ex: machine learning

Dedicated efforts to directly cross-calibrate energy scales





Next Generation Experiments (~2030s)

The next generation of experiments will target the highest energy cosmic rays, in particular.

K-EUSO/POEMMA: fluorescence-based with large exposures, useful for studying all-sky with single detector

GRAND: largest exposure over whole UHE range, limited particle detectors ⇒ measurements of EM

GCOS: large exposure, muli-detector →best energy/mass resolution

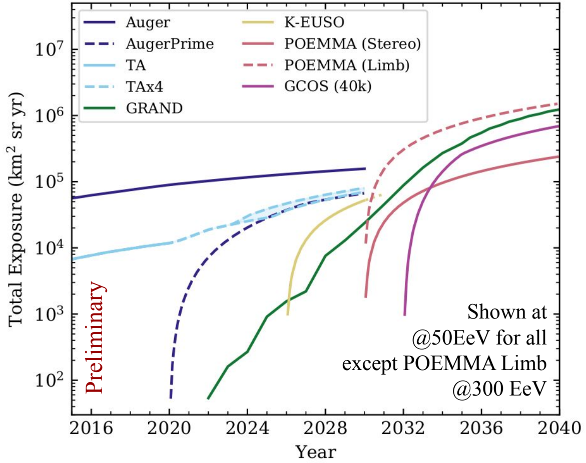
Probably all-sky coverage

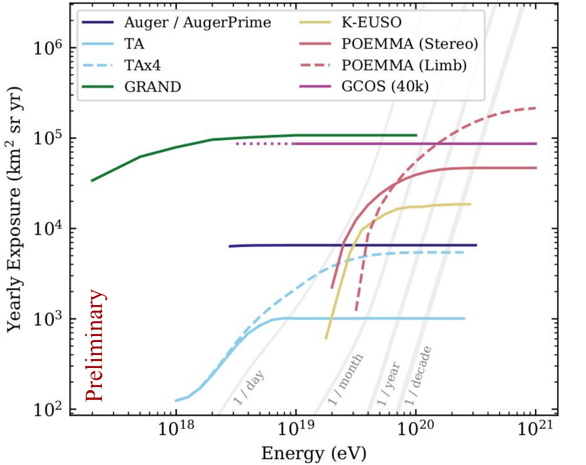
Will make much stronger conclusions about the features at the end of the spectrum than we can with today's experiments:

Caused by ex: GZK vs maximum-acceleration

Look for recovery beyond the observed suppression

Need for improved calibration of hardware (telescopes, antennas) which dominate the systematic uncertainties of the energy scale!





Connection to Galactic Cosmic Rays

Important to understand the transition between galactic and extragalactic sources. Strong constraints on models will come from mass-dependent spectra.

Expected improvement from multi-detector approach

AugerPrime:

433m and 750m arrays with scintillators and muon detectors, overlap with AERA antennas

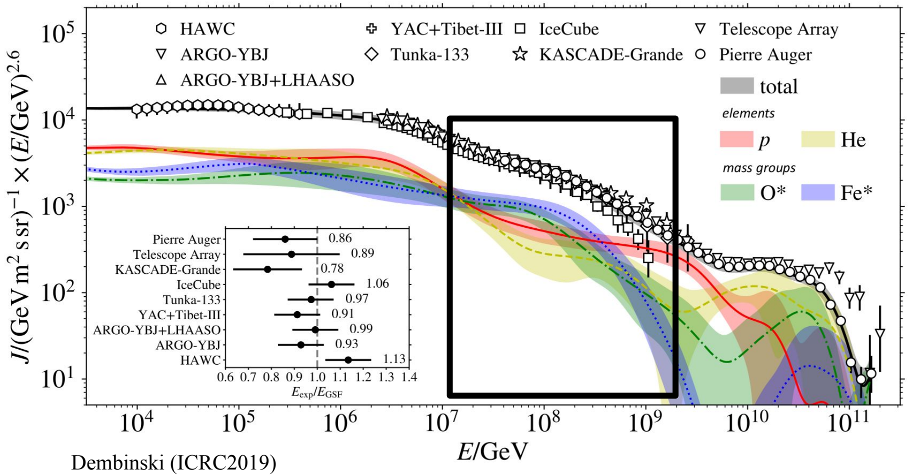
IceCube-Gen2:

Scintillator panels and antennas
>300GeV muons in the deep ice

GCOS?:

Energy threshold not yet known

Also will be important for constraining/validating hadronic models



Dembinski (ICRC2019)