Global Cosmic Rays Observatory (GCOS)

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based on the GCOS workshop contributions

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A subjective view of GCOS

1. Why?
   - I don't know
2. When?
   - I don't know
3. How?
   - I don't know

A subjective view of GCOS

1. Why?
   - I don't know Depends on other experimental/theoretical results
2. When?
   - I don't know Depends on the community (after 2030)
3. How?
   - I don't know Depends on expected performances

Let us dream (or the very optimistic view)

Ingredients from the experimental point of view: energy, mass composition, direction, large statistics

Expected results for 2030 from current experiments:

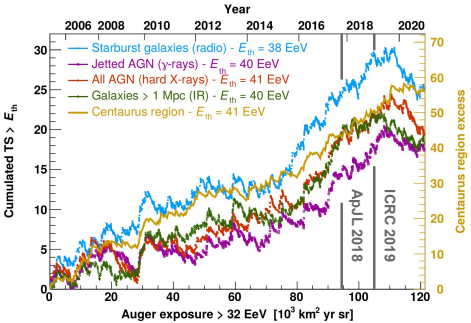
- very good agreement between the air-shower measurements and simulations
- classes of sources are revealed
- mass composition dependency on the sky
- very good limits on UHE neutrinos productions

Impossible measurements for 2030 from current air-shower detectors

- measurement of the UHE neutrinos
- measurement of the UHE photons
- charged particle spectra for individual sources
- dark matter
- extragalactic and galactic magnetic fields

Anisotropies at small scales: correlations with catalogues

Catalog	$E_{\rm th}$ [EeV]	Ψ [deg]	α [%]	TS	Post-trial p-value
All galaxies (IR)	40	24^{+16}_{-8}	15^{+10}_{-6}	18.2	6.7×10^{-4}
Starbursts (radio)	38	25^{+11}_{-7}	9^{+6}_{-4}	24.8	3.1×10^{-5}
All AGNs (X-rays)	41	27^{+14}_{-9}	8^{+5}_{-4}	19.3	4.0×10^{-4}
Jetted AGNs (γ-rays)	40	23^{+9}_{-8}	6^{+4}_{-3}	17.3	1.0×10^{-3}



4.0σ

3.1σ

Current exposure: $120,000\,\mathrm{km}^2\mathrm{sr}\,\mathrm{yr}$

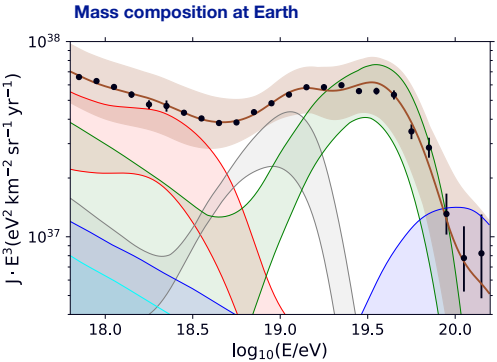
Assuming linear growth of the TS:

Expected 5σ reach in 2025-2030

We need large exposure, can we reach Auger(2021) each year?

1)

Energy spectra of sources?

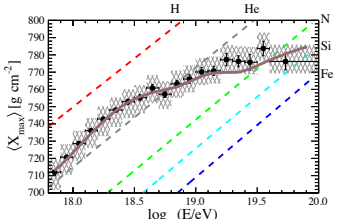


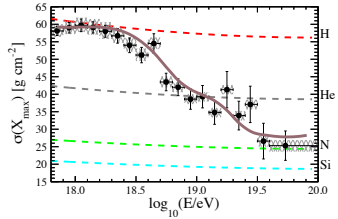
A = 1
1 < A < 5
4 < A < 23
22 < A < 39
38 < A < 57

Bands:
Experimental uncertainties
(model uncertainties smaller)

Energy scale: $\sigma_{sys}(E)/E = 14\,\%$

X_{max} scale: $\sigma_{sys}(X_{max}) = 6 \div 9$ g cm^{-2}





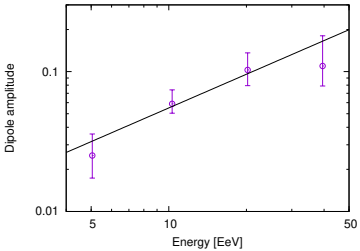
Different model scenarios considered for low-energy part
(transition to galactic component), similar results for total composition obtained

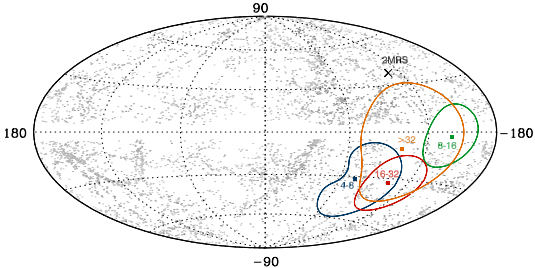
Including also the arrival direction information, a better constrain on the spectra at the source and on magnetic fields

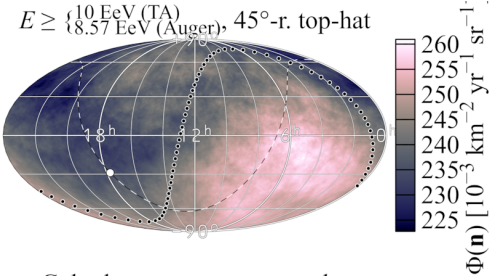
Requirements: very good energy resolution and mass composition

Large scale anisotropies

Energy-independent dipole amplitude disfavored at the level of 3.7σ





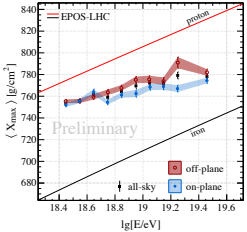


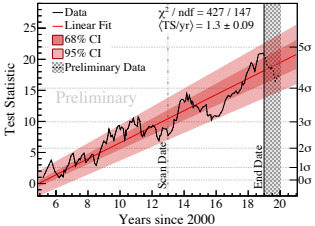
Combined analysis with Telescope Array collaboration: better constrain on the dipole direction

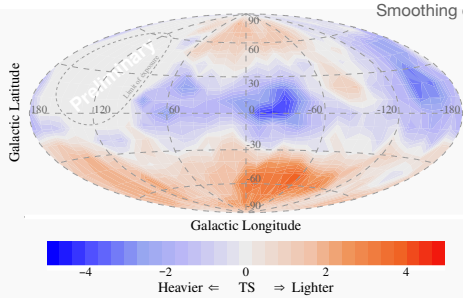
By 2030 also the phase will be measured (TA$\times$ 4 + Auger)

Can we go further? Inclusion of the mass composition information?

Mass composition distribution over the sky







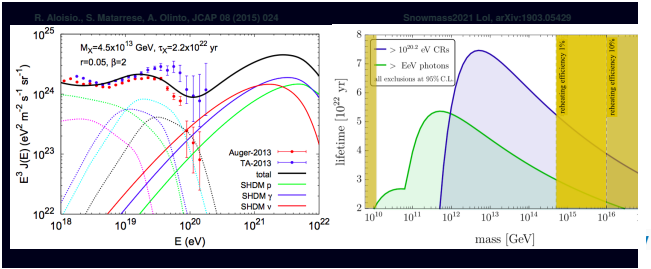
Mass dependent horizon effect?

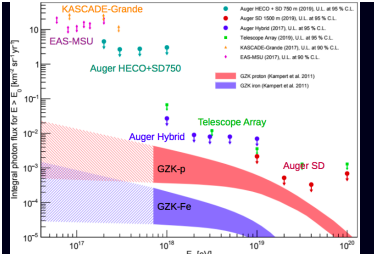
No confirmation from other variables yet

More data are needed (and more sensitivity), reach 5σ by 2030

Very good sensitivity to mass composition (at least as good as current FD)

Photons and Dark matter searches at 100 EeV

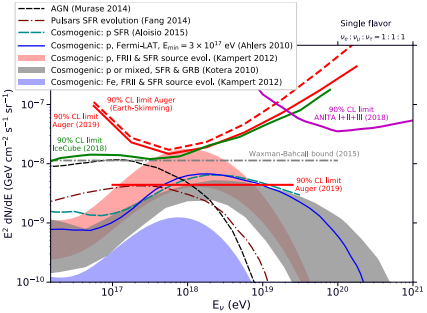


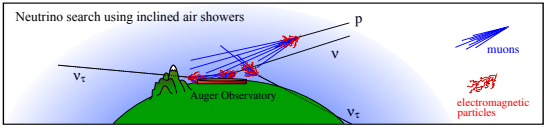


- Current upgrades will not improve too much the limits
- SHDM constrained but not completly excluded
- Photon sesitivity is needed (and exposure)
- Coverage towards the galactic center (one of the main signatures)

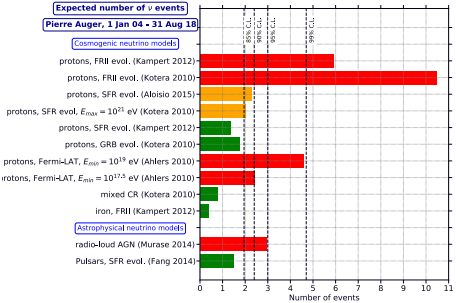
Ultra high energy neutrinos

GRAND/IceCube will be leading on neutrinos messengers





(JCAP 10 (2019) 022, JCAP 11 (2019) 004)



We need mountains

Searches of neutrinos in coincidence with GW/photons

Sources searches in preferential directions

The shopping list

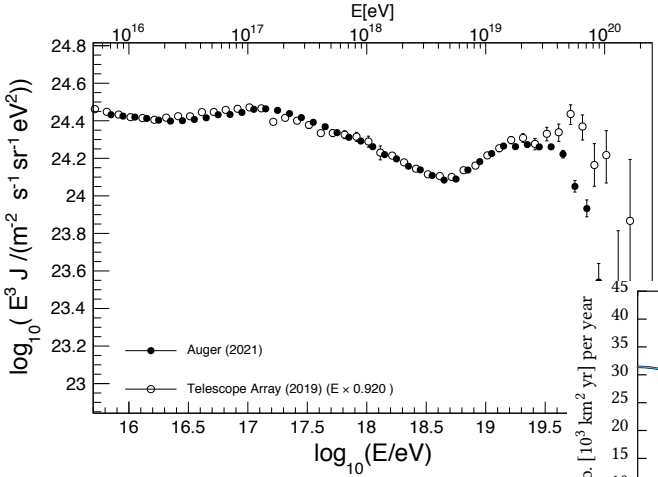
Extras on the list of wishes

- Particle interactions at the highest energies (p-Air cross-section)
- Lorentz invariance tests (via air-showers development or cosmic rays propagation)
- Geophysics and atmospheric science: elves, gamma ray flashes, lightning
- (Understand magnetic fields and if there are any preferential directions)

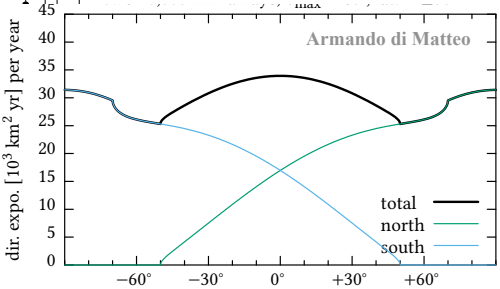
Experimental requirements

- A nice site near high mountains
- Huge exposure and full coverage
- Angular resolution better than 2 degrees and good energy resolution
- Mass composition measurements with (at least) FD precision
- Separate measurements of the electromagnetic and muonic components

Which energy range?



We need a good compromise between HUGE exposure and very good resolution



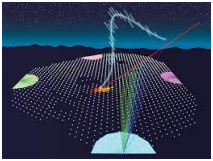
Build $60,000\,\mathrm{km}^2$ array? (20 times Auger?)

Towards a ground array

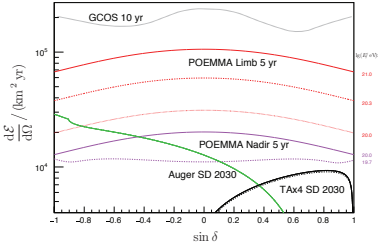
Complementarity of approaches

Space - ground

POEMMA:
intrinsic full-sky coverage



GCOS:
particles, radio, fluorescence
better resolution (E, X_{max})
study (hadr.) interactions



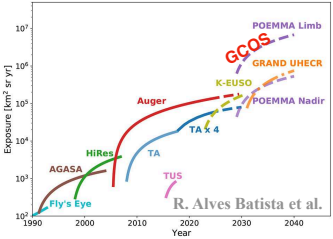


FIGURE 16 | Evolution of the exposure of past, current, and upcoming (solid lines) UHECR experiments as a function of time for ground-based and space experiments. Proposed experiments are also shown (dashed lines). F. Oikonomou and M. Panasyuk for this review.

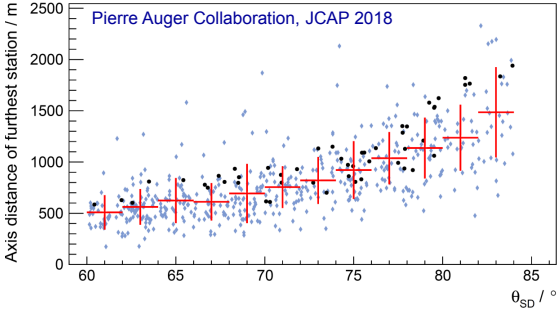
Complementarity of techniques

The Giant Radio Array for Neutrino Detection

200'000 radio antennas over 200'000 km^2
~20 sub-arrays of 10'000 antennas
over favorable sites in China and worldwide

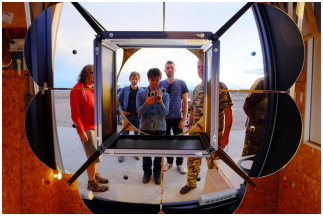
Radio measurements?

- GRAND will (hopefully) lead the path in the radio-only measurements
- AERA measured inclined air-showers with footprints of 2 km
- AugerPrime upgrade to confirm the solid angle for which reasonable mass composition and energy resolution can be achieved at alrge detector spacing



- AERA results: energy resolution 10%
- Needs another detector for large spacing > 1.5 km (even with radio-interferometric methods and very good GPS synchronisation)

Flourescence detector Array of Single-pixel Telescopes(FAST)?

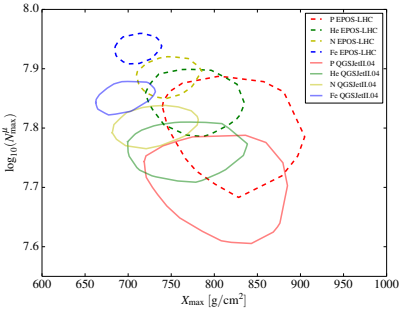


- Low cost fluorescence telescopes tested at Auger and TA sites
- 100% efficiency above 30 EeV for 3-fold coincidences
- Resolutions: 8% for energy, 30 $\mathrm{g/cm^2}$, 4.2 degrees
- Near future: stand-alone operations of FAST array in the field
- (small duty cycle, atmospheric condition, hard to stand alone in the field, absolute calibration, energy systematics) Might need an extra detector

A ground particle detector?

- Needs separation between the muonic and electromagnetic components and time structures
- Energy can be taken from simulations, still intrinsic fluctuations are at around 10% on energy (depends on distance to $X_{\max}$)
- Scintillators are too flat, a 3D detector might help

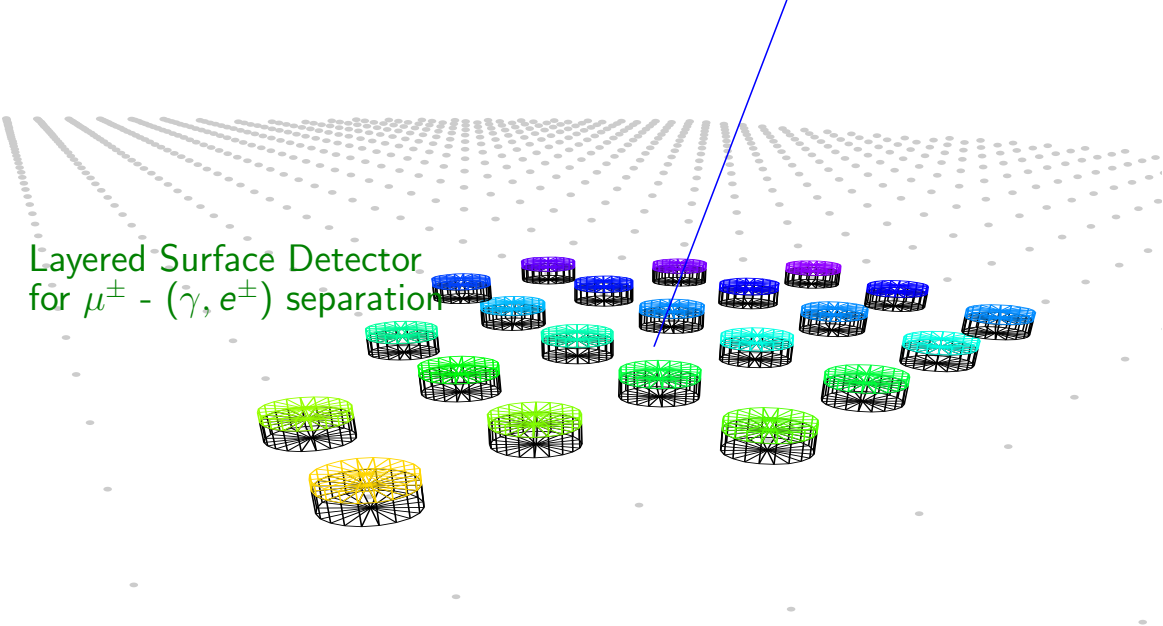
10 EeV, 38 degrees



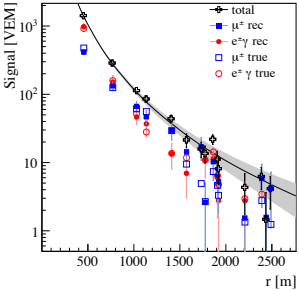
If we can obtain N_μ and $X_{\max}$ we win

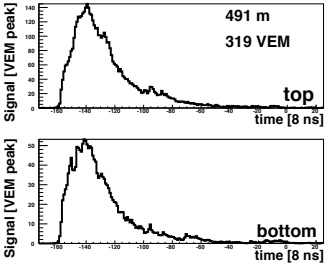
(i.e. separate the electromagnetic and the muonic components)

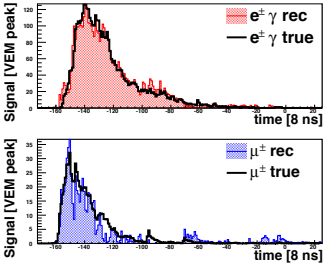
Layered Surface Detector for $\mu^{\pm}$ - $(\gamma, e^{\pm})$ separation



Good resolution for muonic and electromagnetic signals at station level







- Prototypes tested in the field (at Auger)
- Based on the different response of the Water Cherenkov tank to em and muons
- Robust and well-known detectors
- Needs simulations for the energy calibration (or a different detector to cross calibrate)

The Future of Cosmic Ray Observatories

To be written by the cosmic rays community:
dream big and realistic