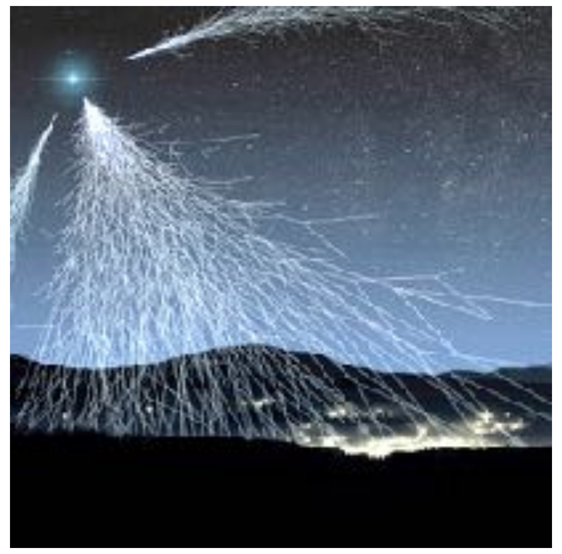
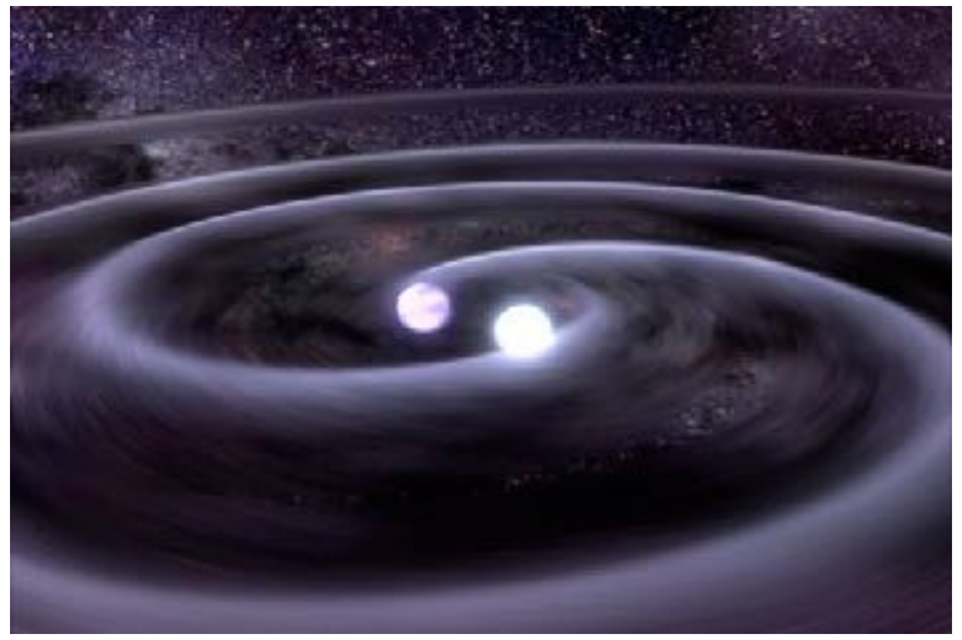
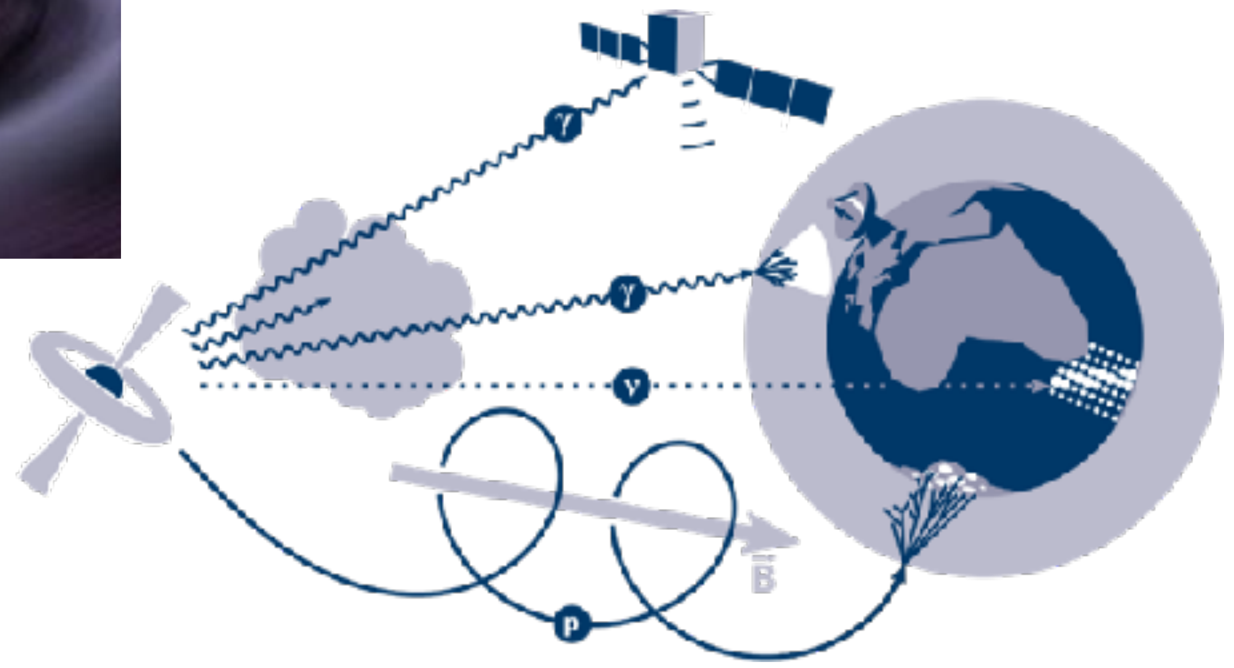


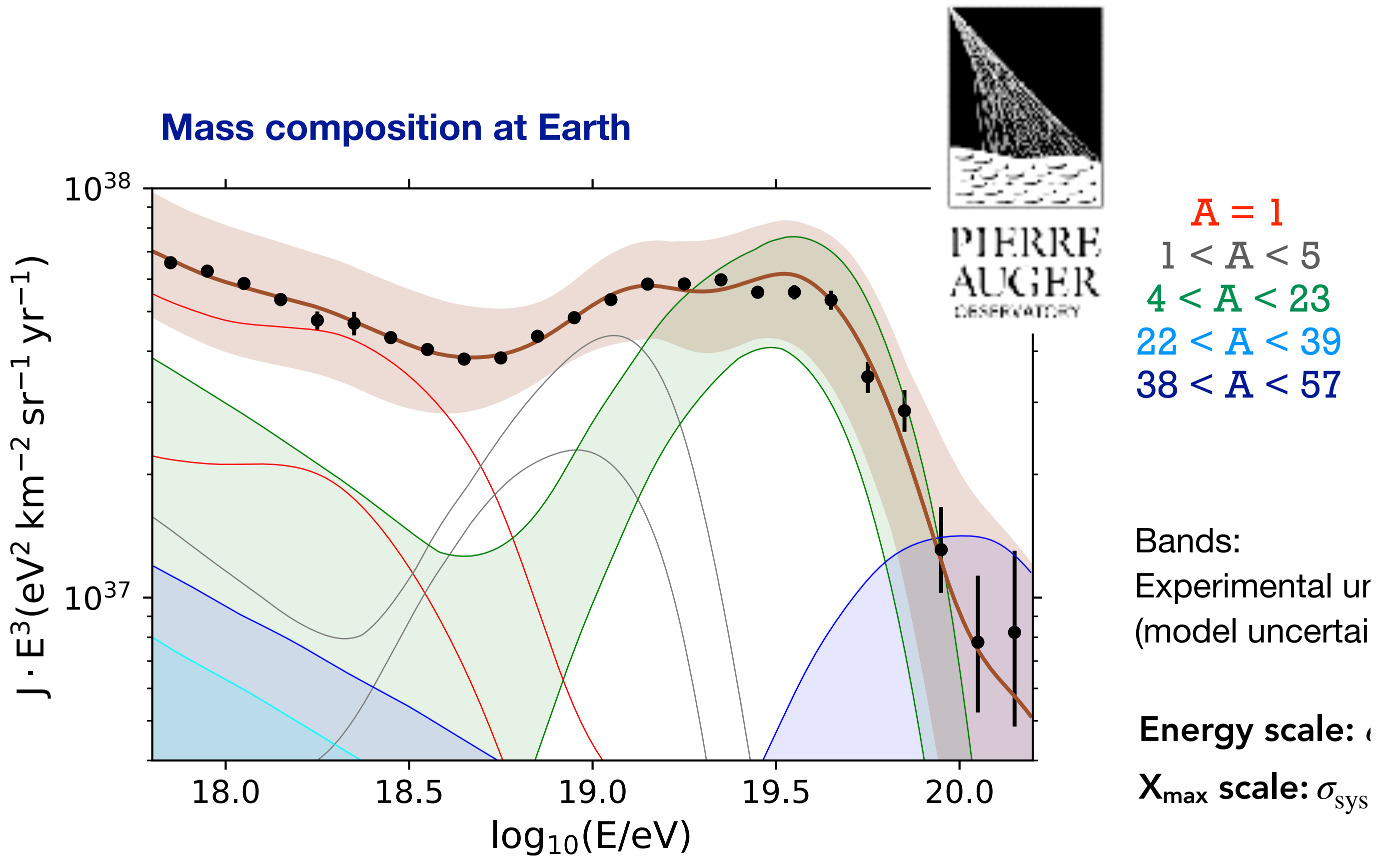
GCOS
The Global Cosmic Ray Observatory

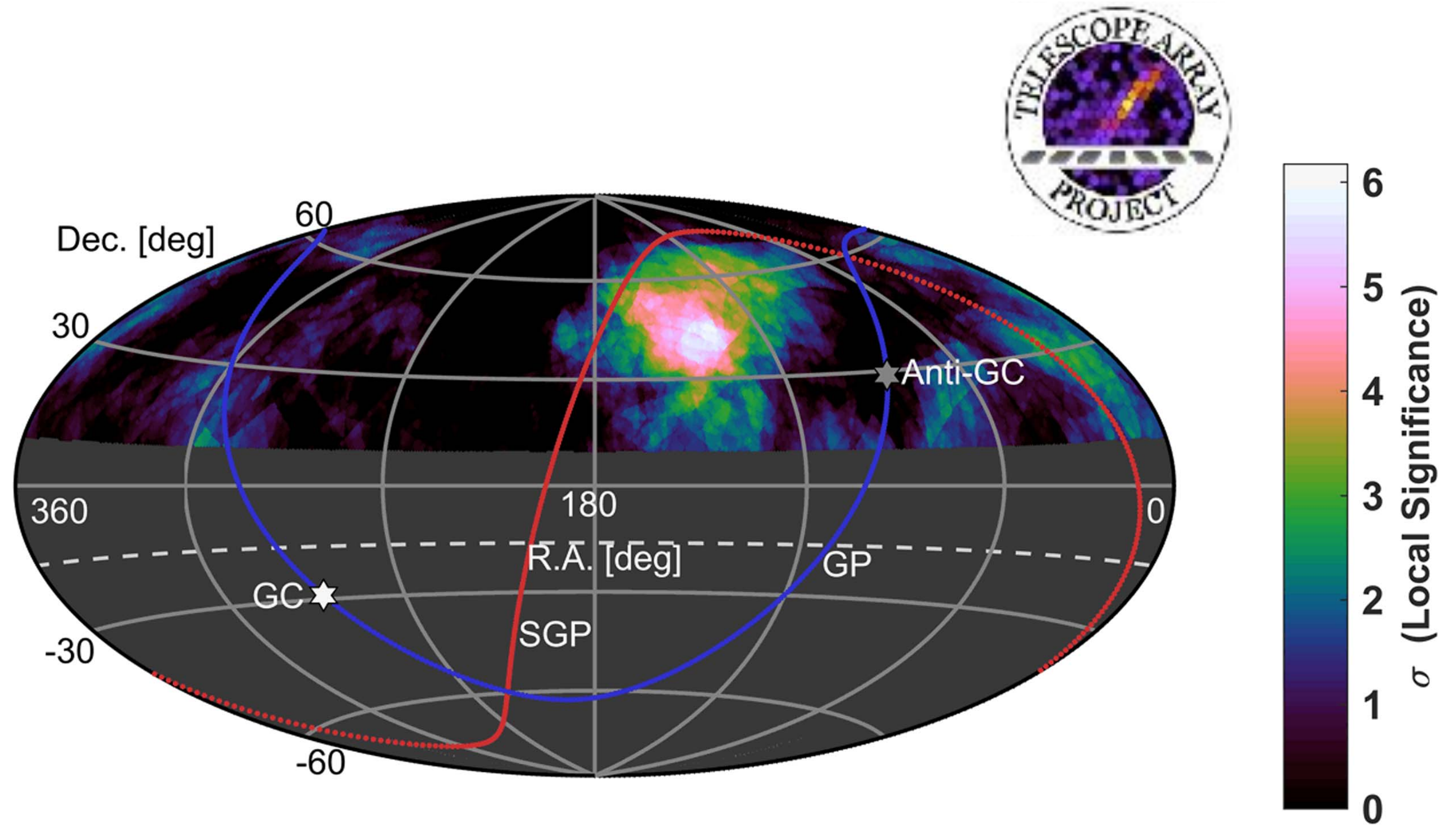
ONLINE ICRC 2021 THE ASTROPARTICLE PHYSICS CONFERENCE Berlin | Germany
37th International Cosmic Ray Conference 12–23 July 2021

Multi-messenger astroparticle physics beyond 2030
protons, nuclei, gamma rays, neutrinos, (gravitational waves)









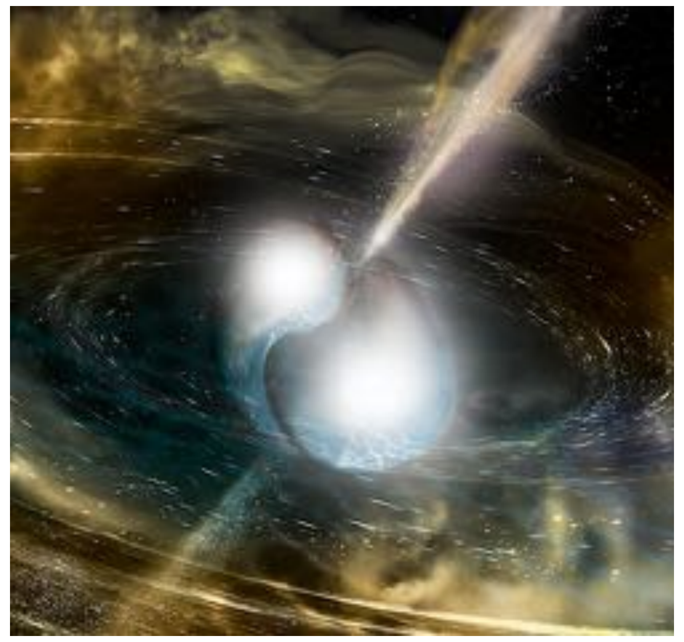
workshop with >200 participants in May 2021
to discuss path to define physics case and develop concepts for detection technologies

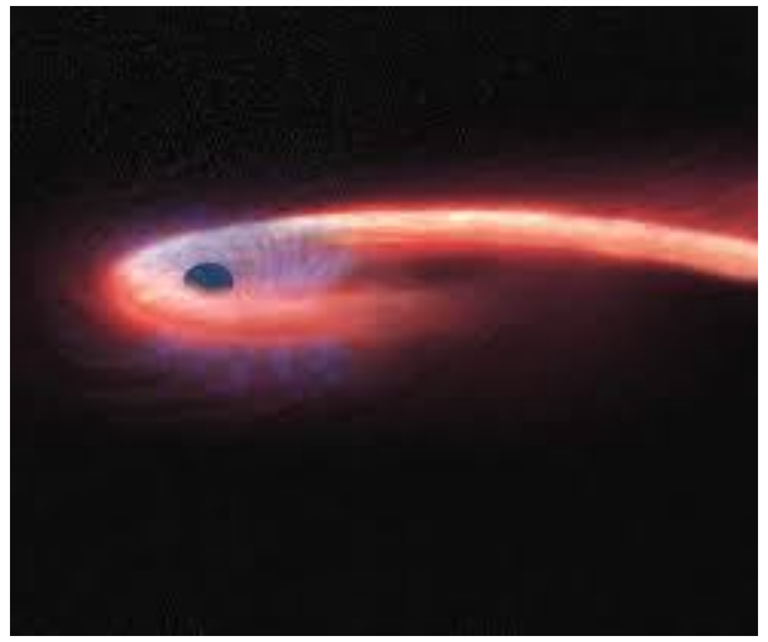
GCOS homepage: http://particle.astro.ru.nl/gcos

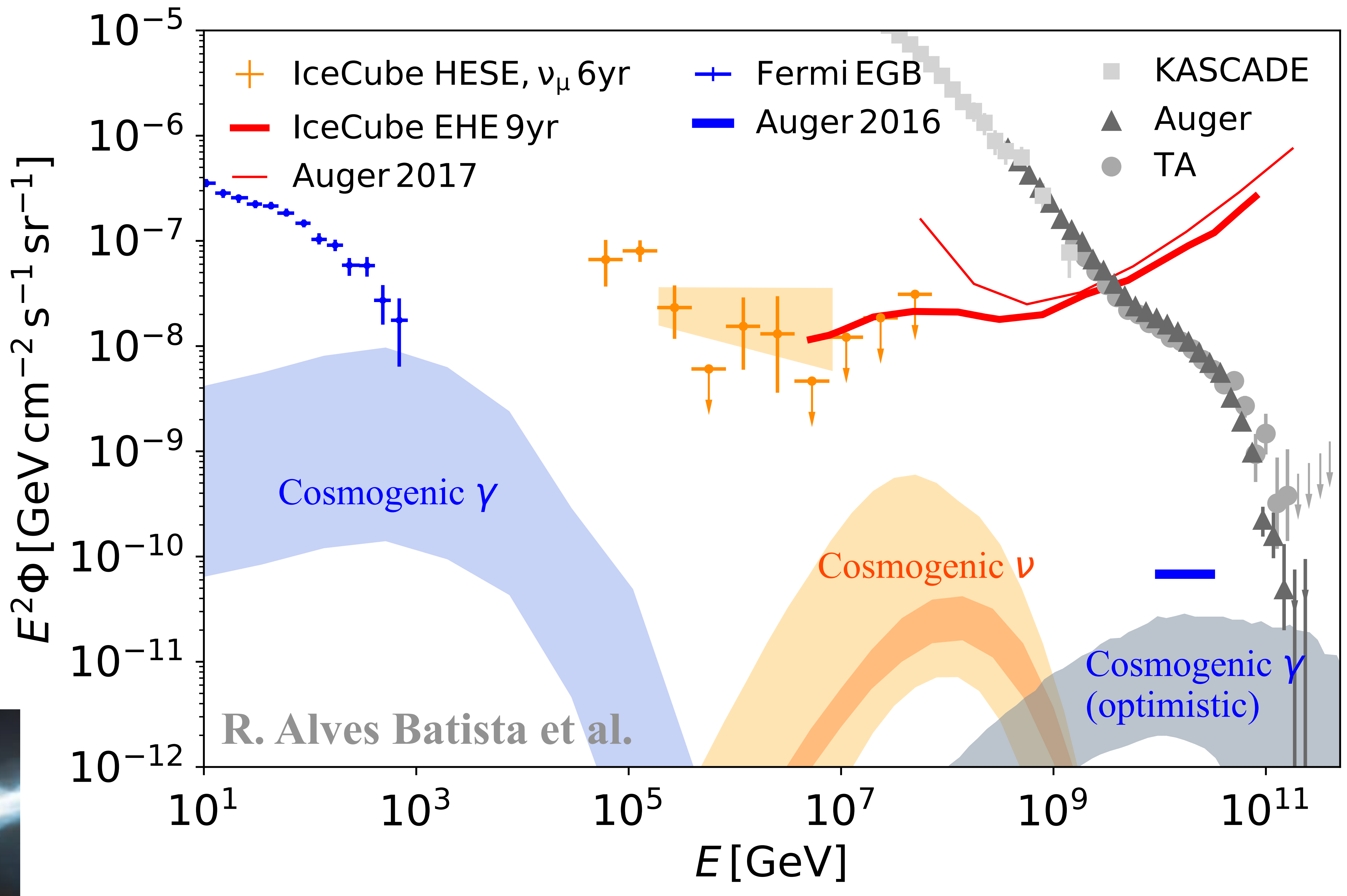
Jörg R. Hörandel on behalf of GCOS
Radboud Universiteit Nijmegen - Vrije Universiteit Brussel - http://particle.astro.ru.nl

Towards a science case for UHE particles

- **Find and study sources of UHE particles (protons, nuclei, gamma rays, neutrinos)**
- **Explore multi-messenger connections to understand transient events, such as mergers of compact binaries, tidal disruption events, gamma-ray bursts**
  —> provide insight to most violent processes in Nature
  —> understand connection with GW sources





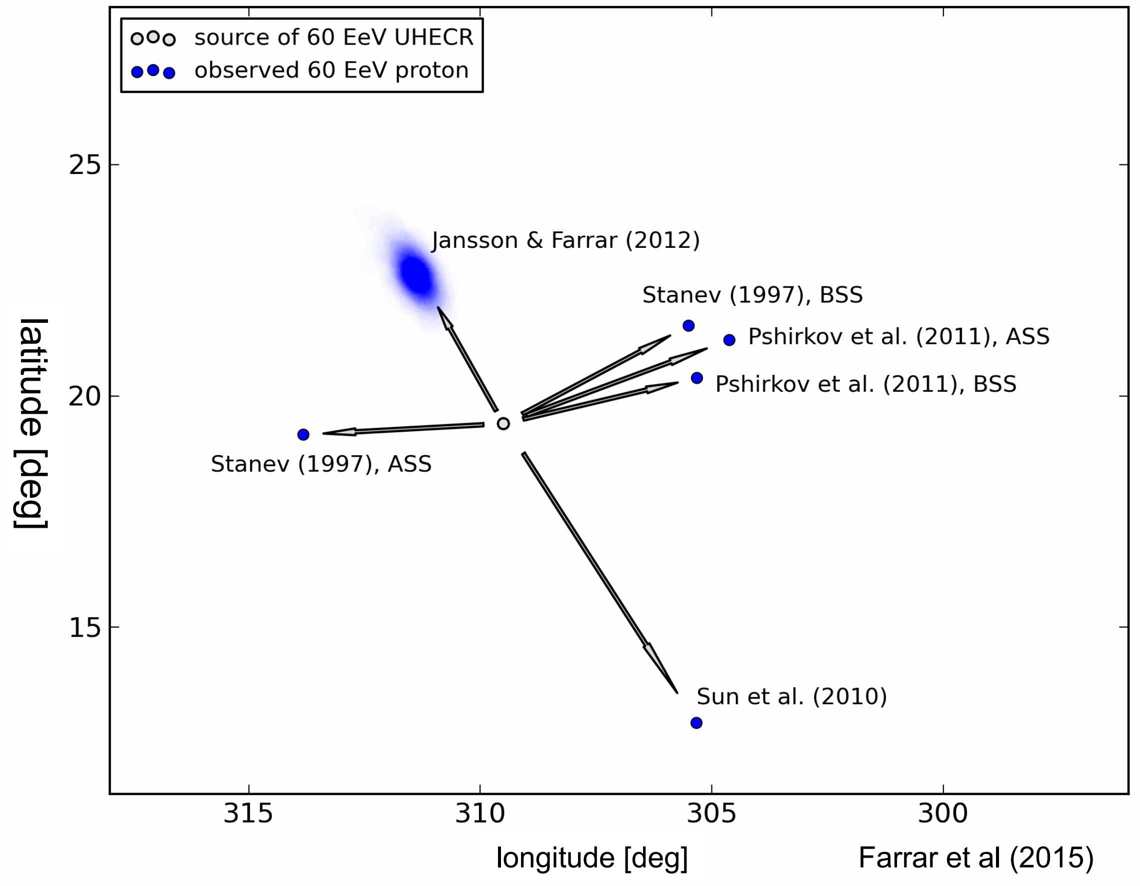


—> develop **model scenarios** for different source classes and extract measurable features

Understanding the effects of Galactic and extra-galactic magnetic fields

current models predict completely different deflection angles of UHE CRs

Ultra-high energy cosmic ray arrival direction:



Farrar et al (2015)

The future:

Small-scale magnetic fields:

- Correlations between magnetic field orientations as measured with different tracers, in different media.
- Modeling is slowly going beyond gaussian random fields

→ Models include 'proper' turbulent fields and their correlations to CRs, thermal electrons, etc.

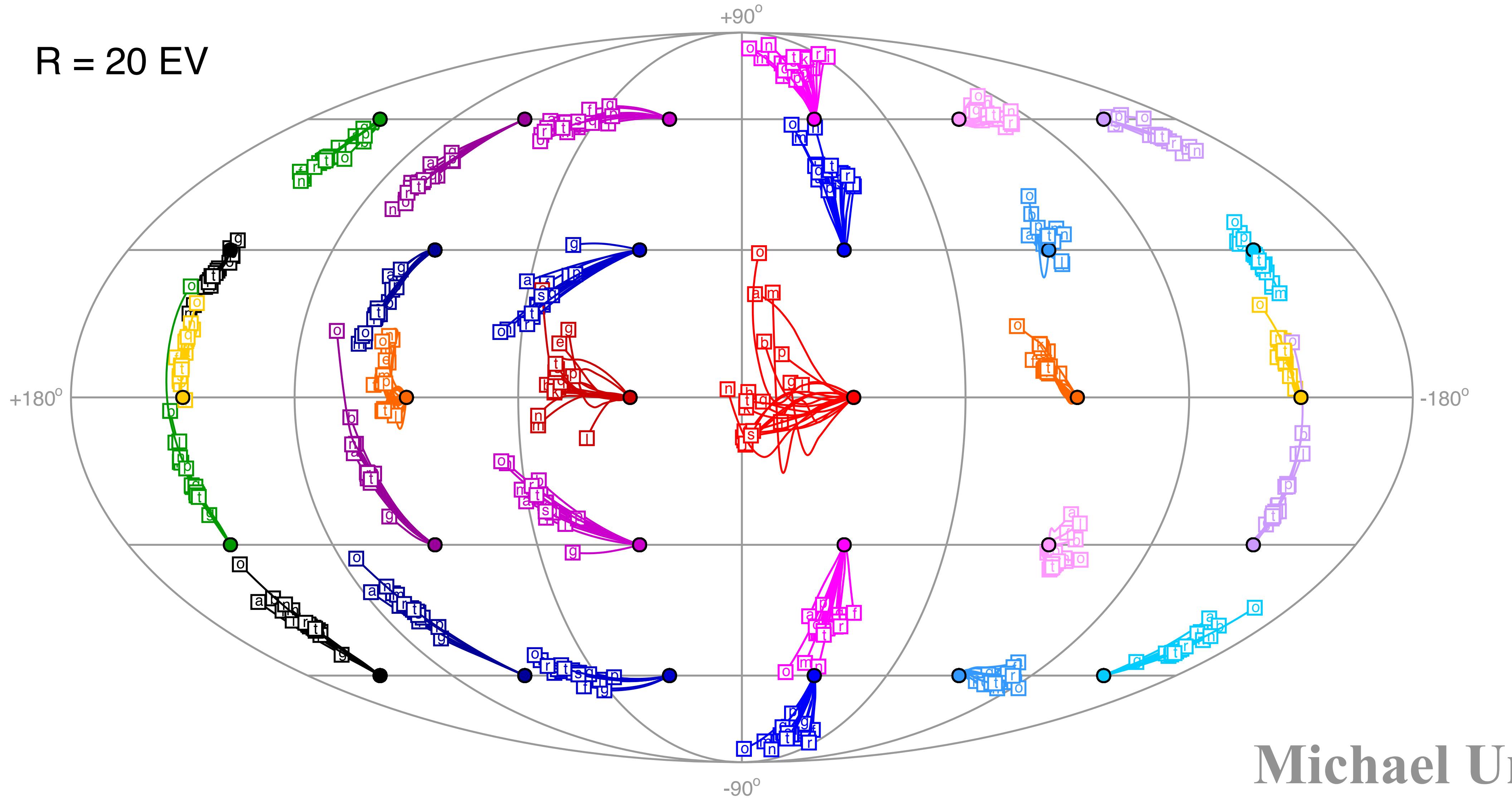
Large-scale magnetic fields:

- IMAGINE will model Galactic magnetic fields *and* compare models quantitatively

→ IMAGINE produces THE best-fit large-scale Galactic magnetic field model and UHECR arrival directions can be corrected.

Marijke Haverkorn

Charged particle astronomy with GCOS



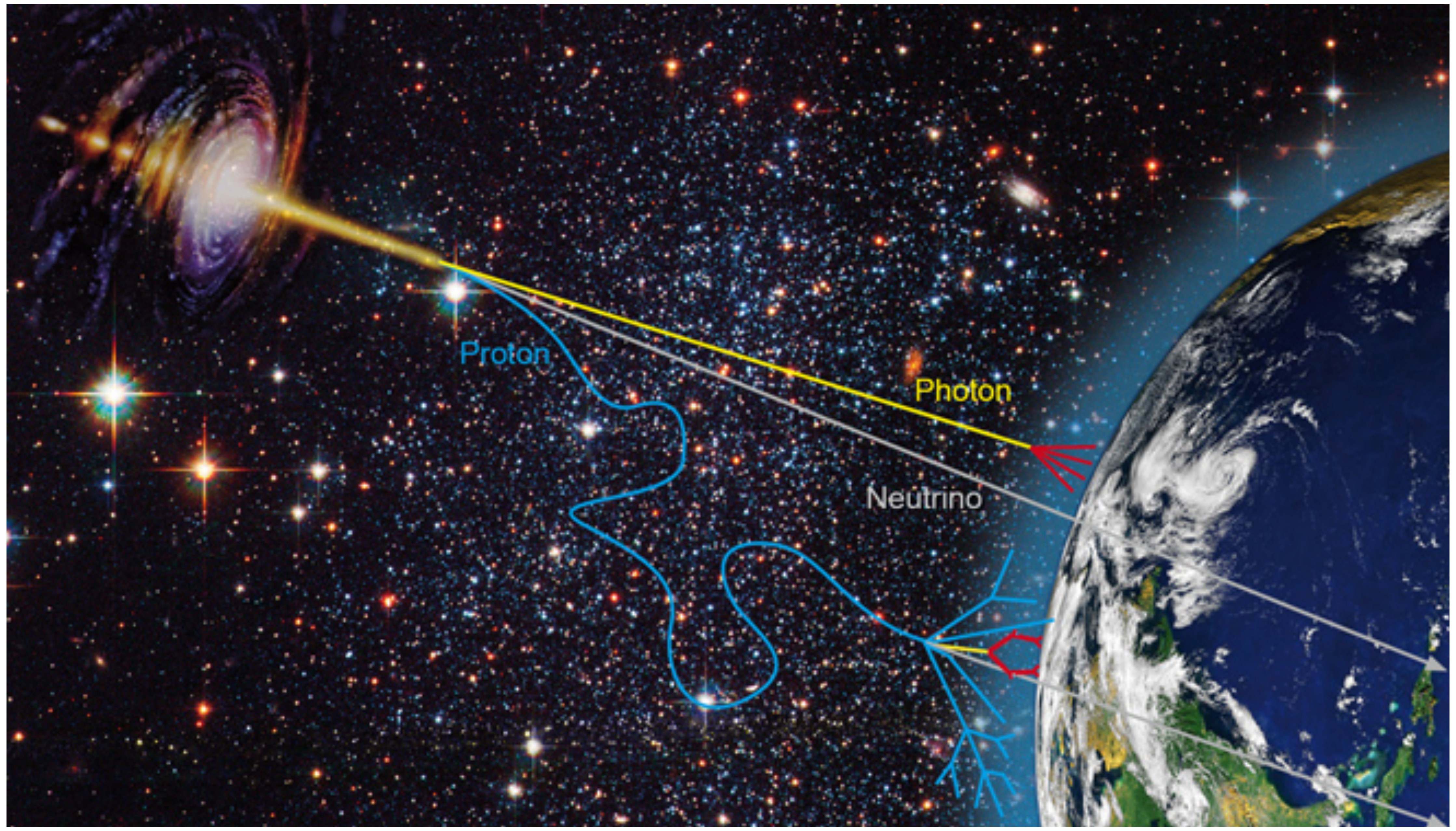
Michael Unger

How to treat extragalactic magnetic fields?

(e.g. R. Alves Batista et al)

- **need to isolate lightest air showers**
- **complicated interplay *R* (deflections) and *E* (attenuation)**

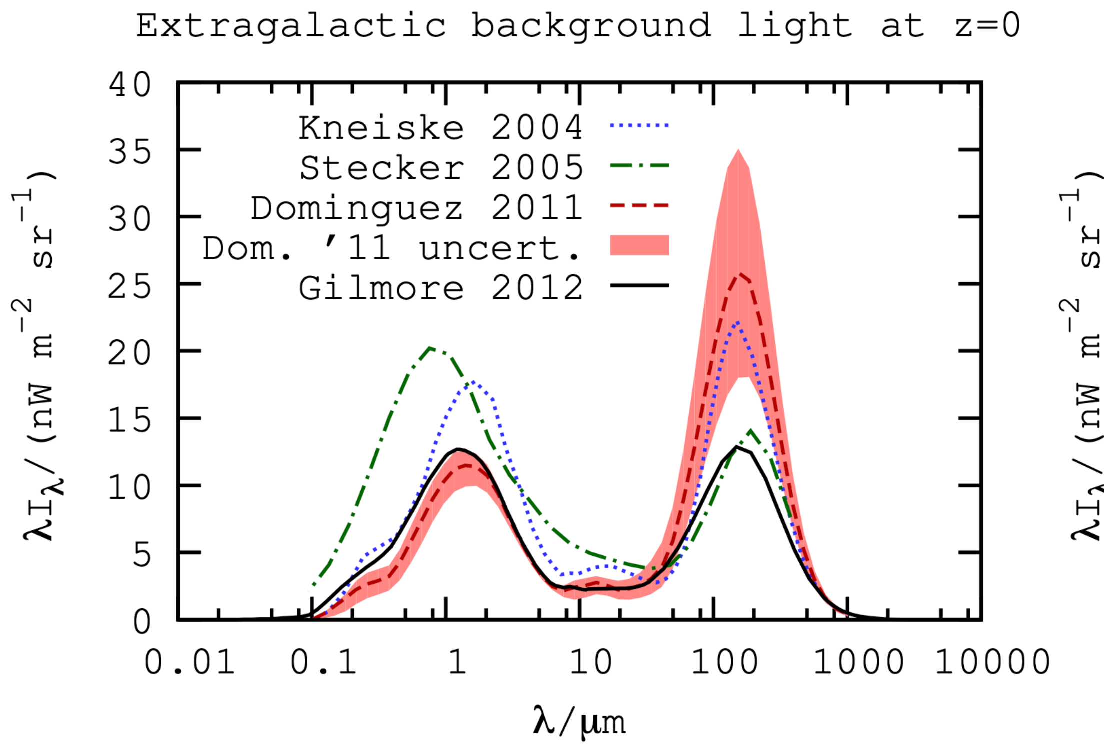
Interaction properties



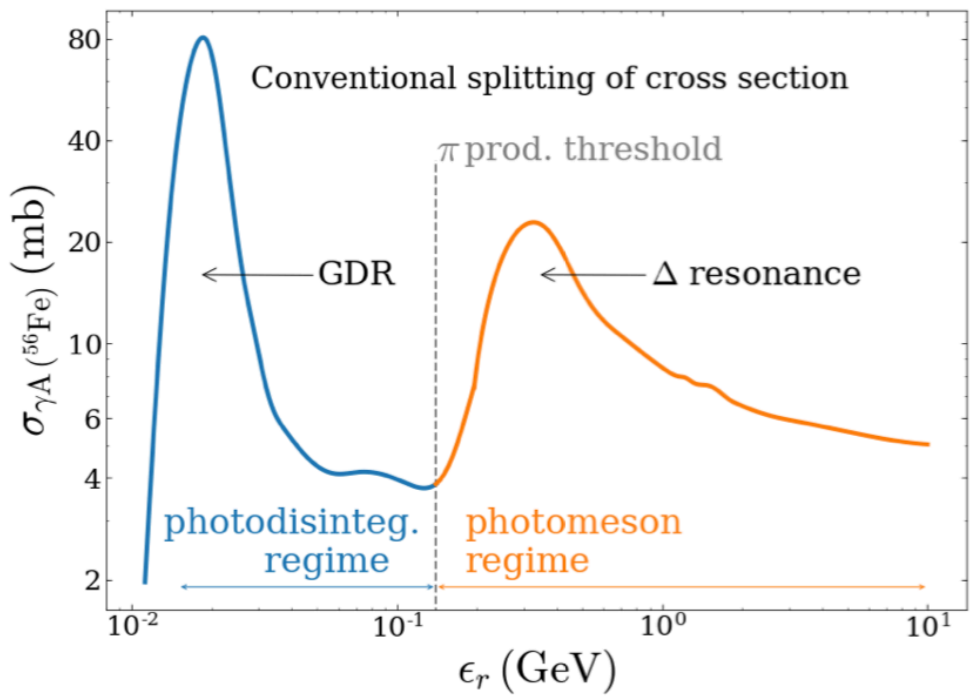
interpretation of data requires good understanding of interaction properties

- **at the sources**
- **during propagation**
- **within the atmosphere (-> air showers)**

Alves Batista, **DB**, di Matteo, van Vliet & Walz, JCAP 2015



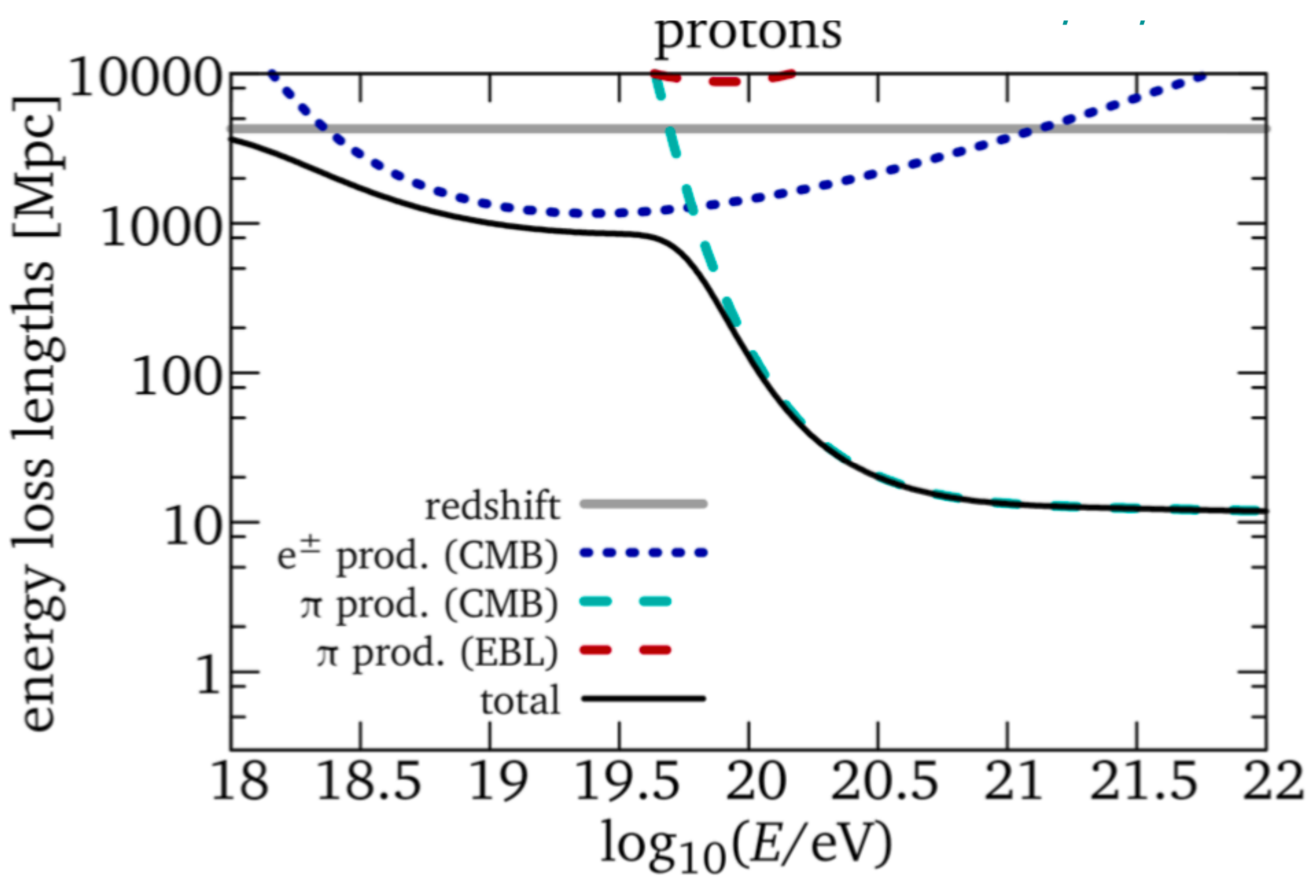
Morejon, Fedynitch, **DB**, Biehl & Winter, JCAP 2019



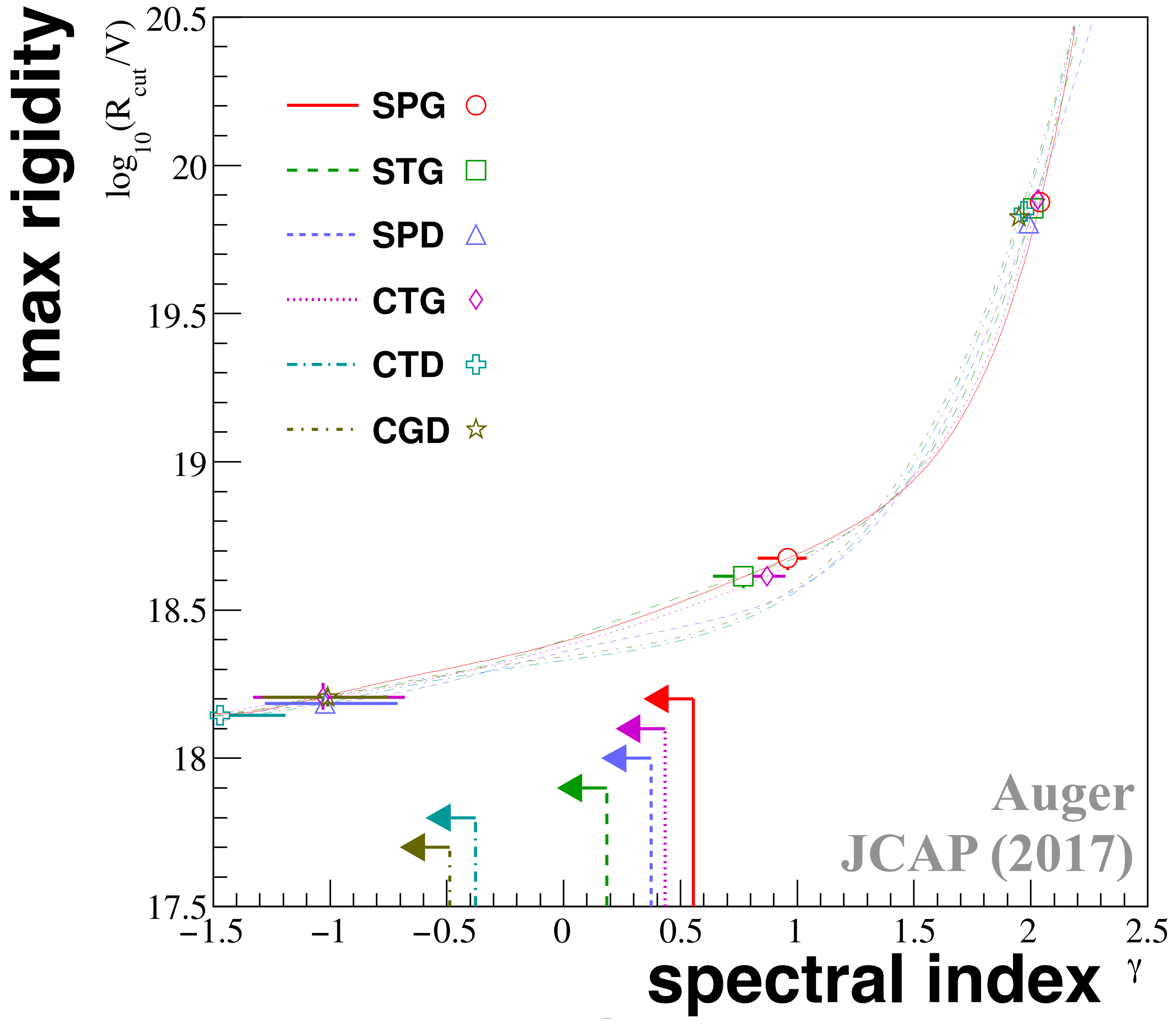
astro-physics

nuclear physics

interaction lengths of UHECRs

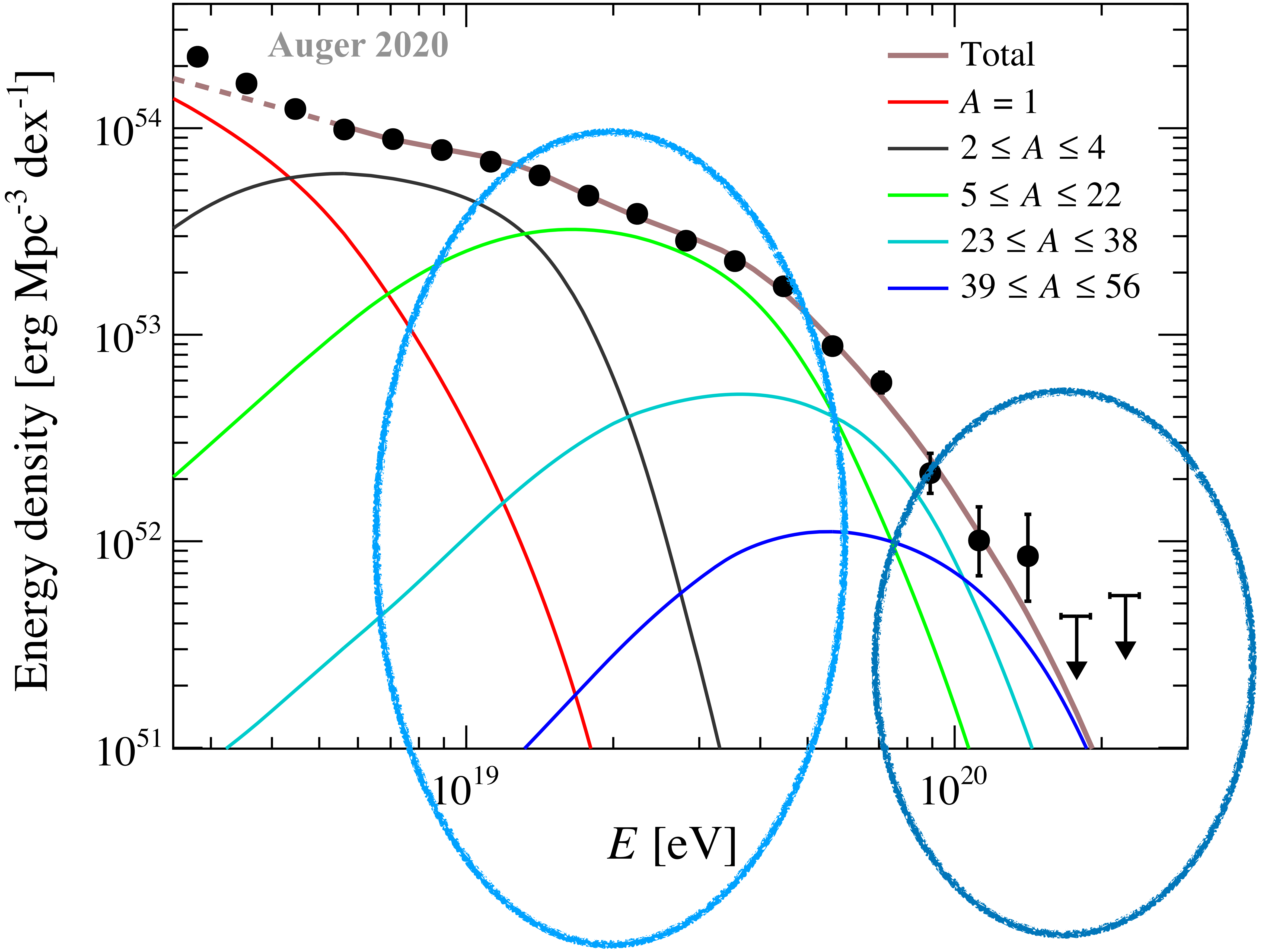


propagation models influence the predicate power of astrophysical models used to interpret UHECR data



Denise Boncioli

Optimal target energy range to find UHE sources



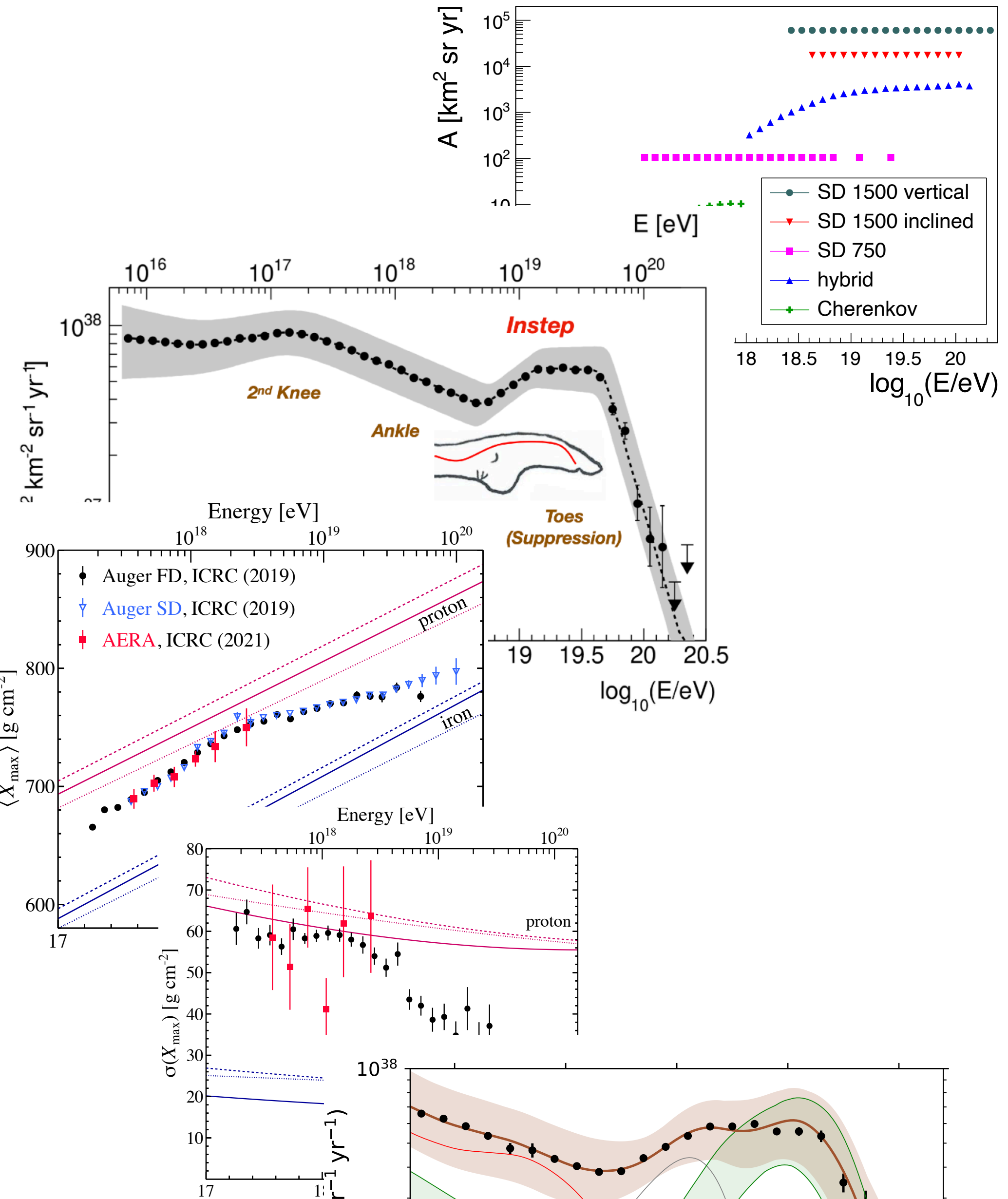
focus on highest E and isolate light (low Z) particles?

if understanding of Galactic B fields is sufficient:
—> backtrack particles with moderate Z
—> focus on slightly lower E?

total number of detection units ~const.
—> need to decide:
- huge aperture?
or
- smaller array with higher density and better resolutions (E, A)

What will we learn in the next decade from TAx4 and AugerPrime?

PIERRE AUGER OBSERVATORY



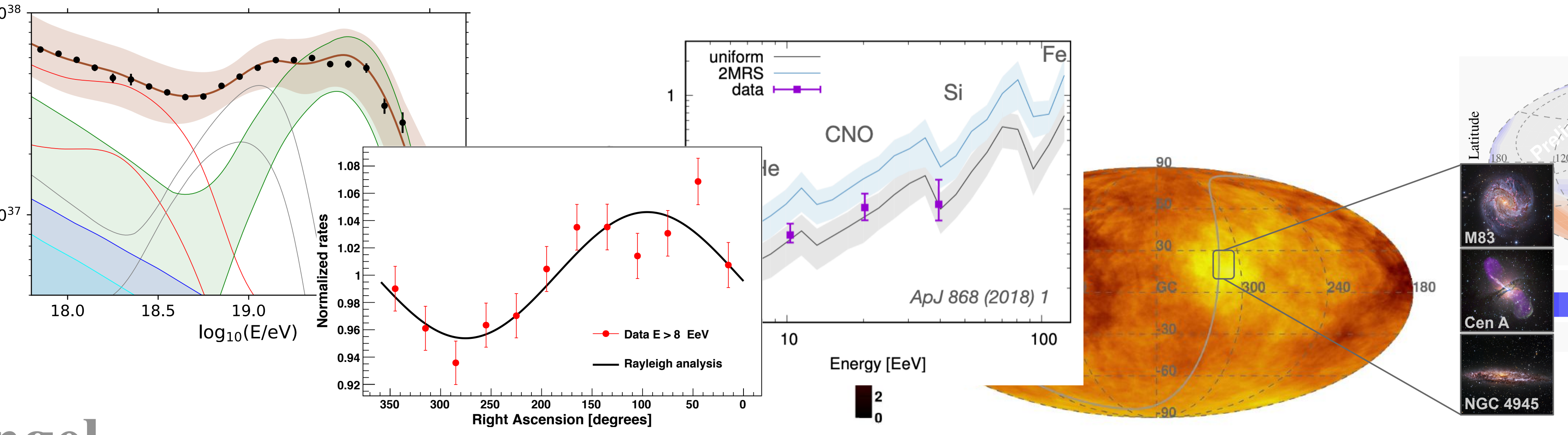
Summary

Phase I:

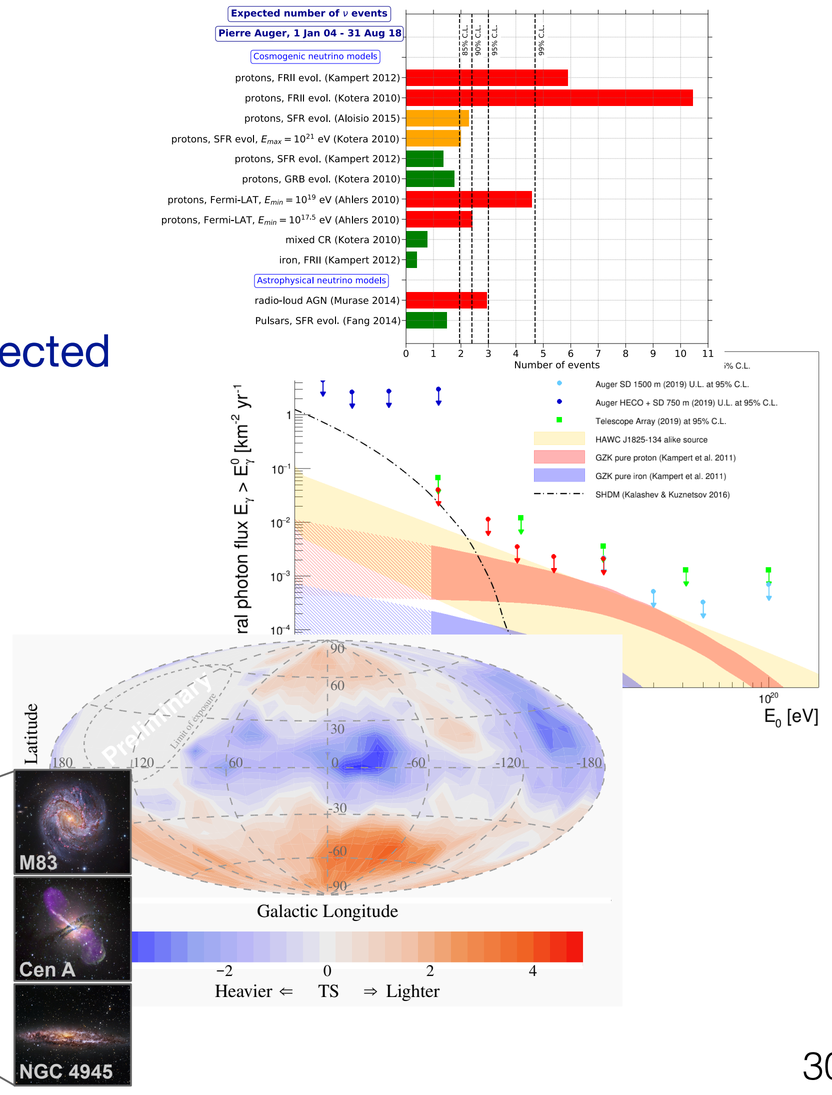
- Exposure 80,000 km² sr yr (vertical, highest quality), up to 120,000 km² sr yr (loose cuts, combined)
- Change of composition established
- Composition tightly linked to hadronic interactions
- Anisotropy observations very challenging
- **Increasingly consistent picture is emerging**

Phase II:

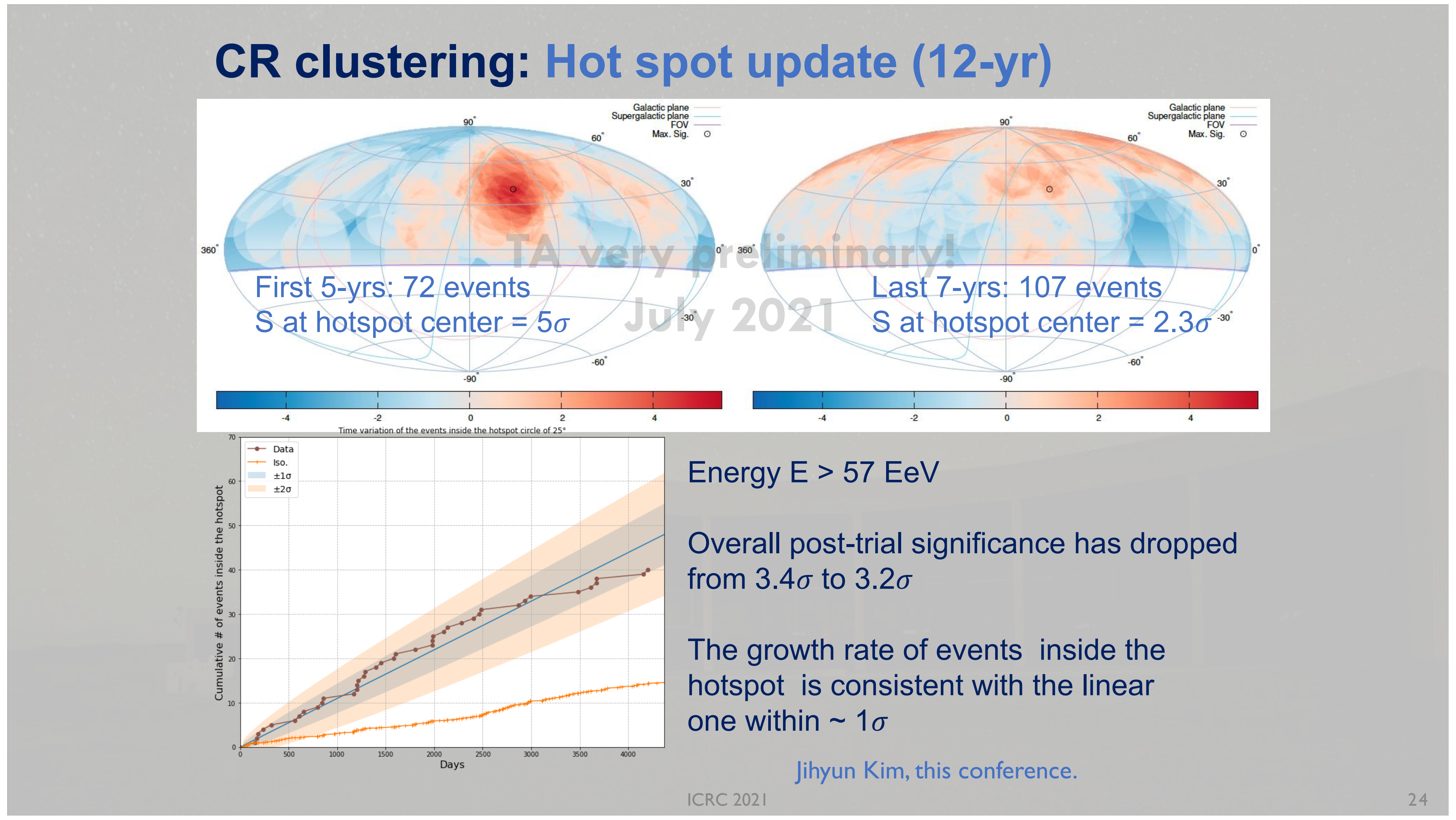
- Upgrade AugerPrime in progress
- Additional exposure 40,000 km² sr yr (vertical) expected
- Enhanced composition and hybrid information
- Re-analysis of all data planned



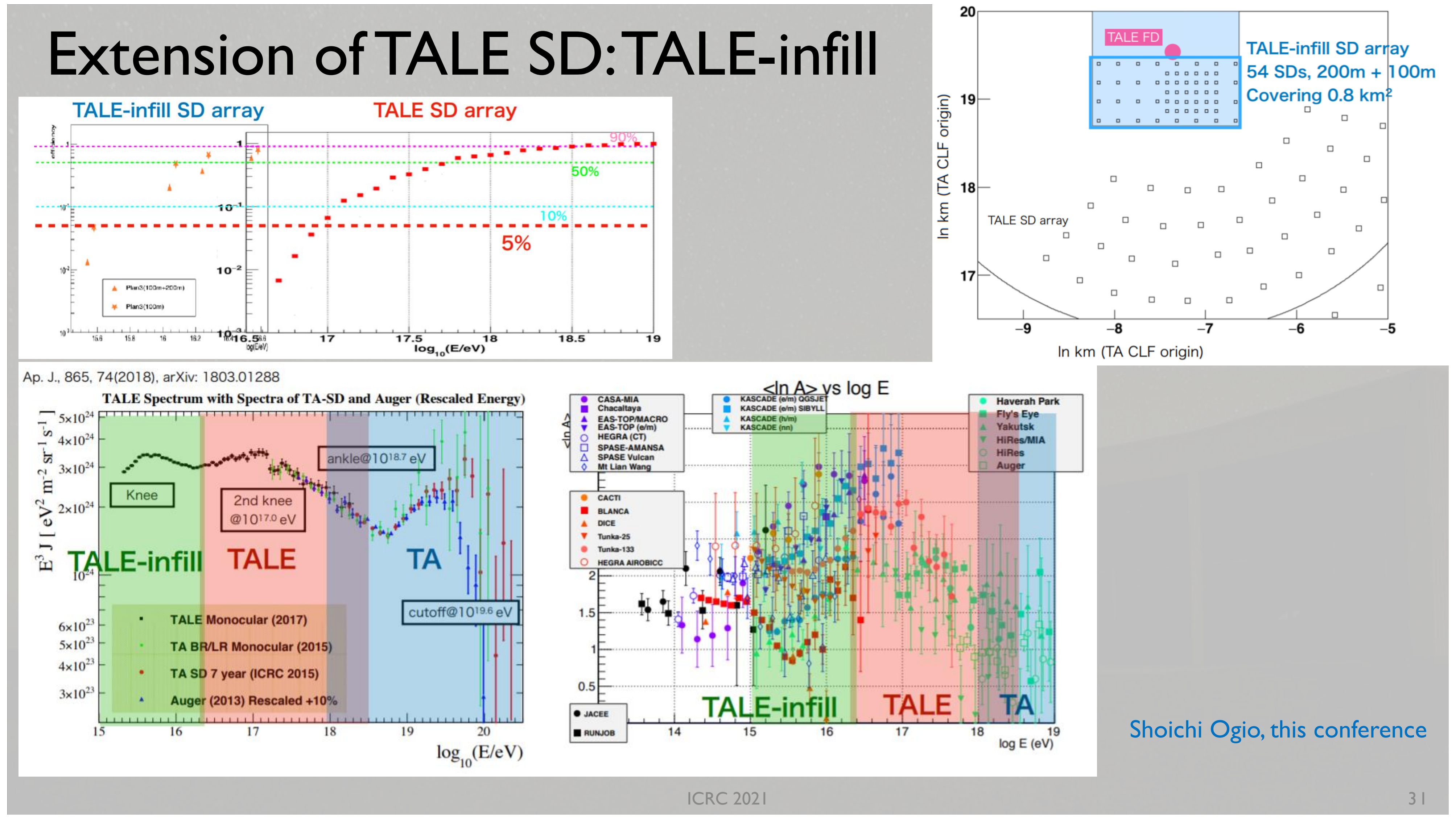
TELESCOPE ARRAY PROJECT

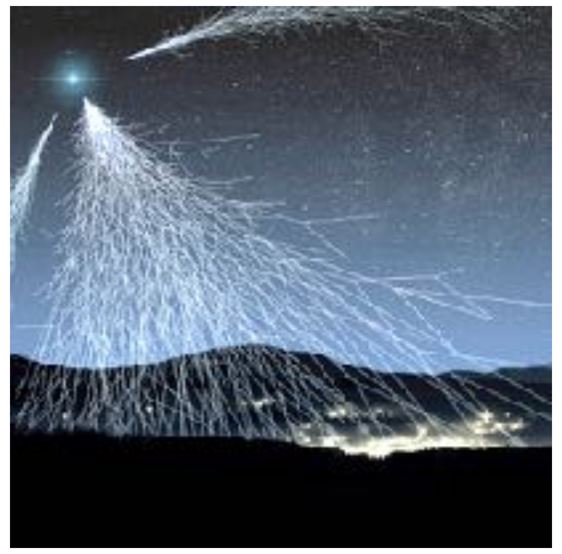


Ralph Engel



Grigory Rubtsov





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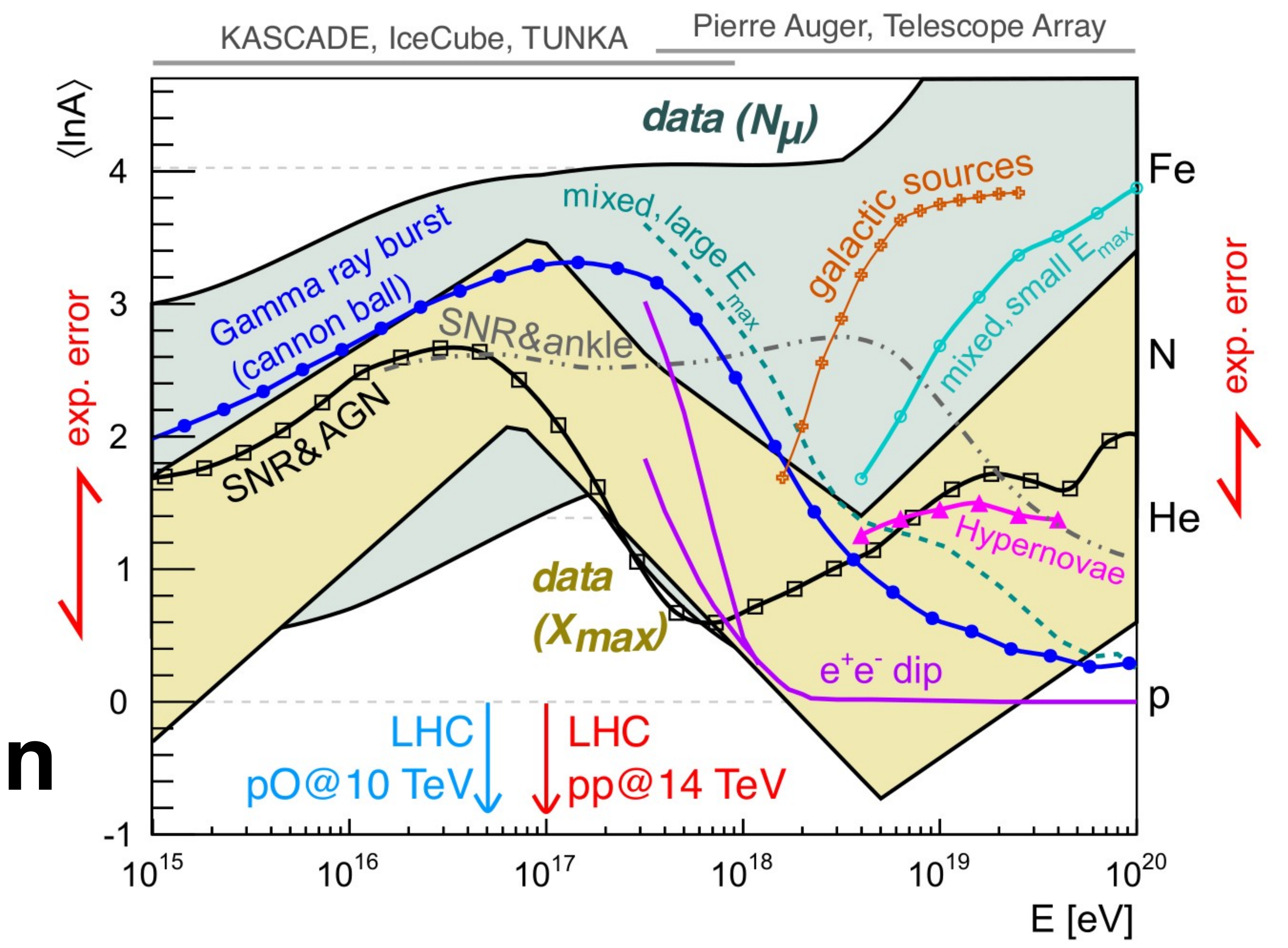
Additional science cases

Particle physics

UHE particles are detected via extensive air showers
—> degeneracy between mass and hadronic interactions
—> hadronic interactions are the key for proper air-shower simulations and appropriate interpretation of data

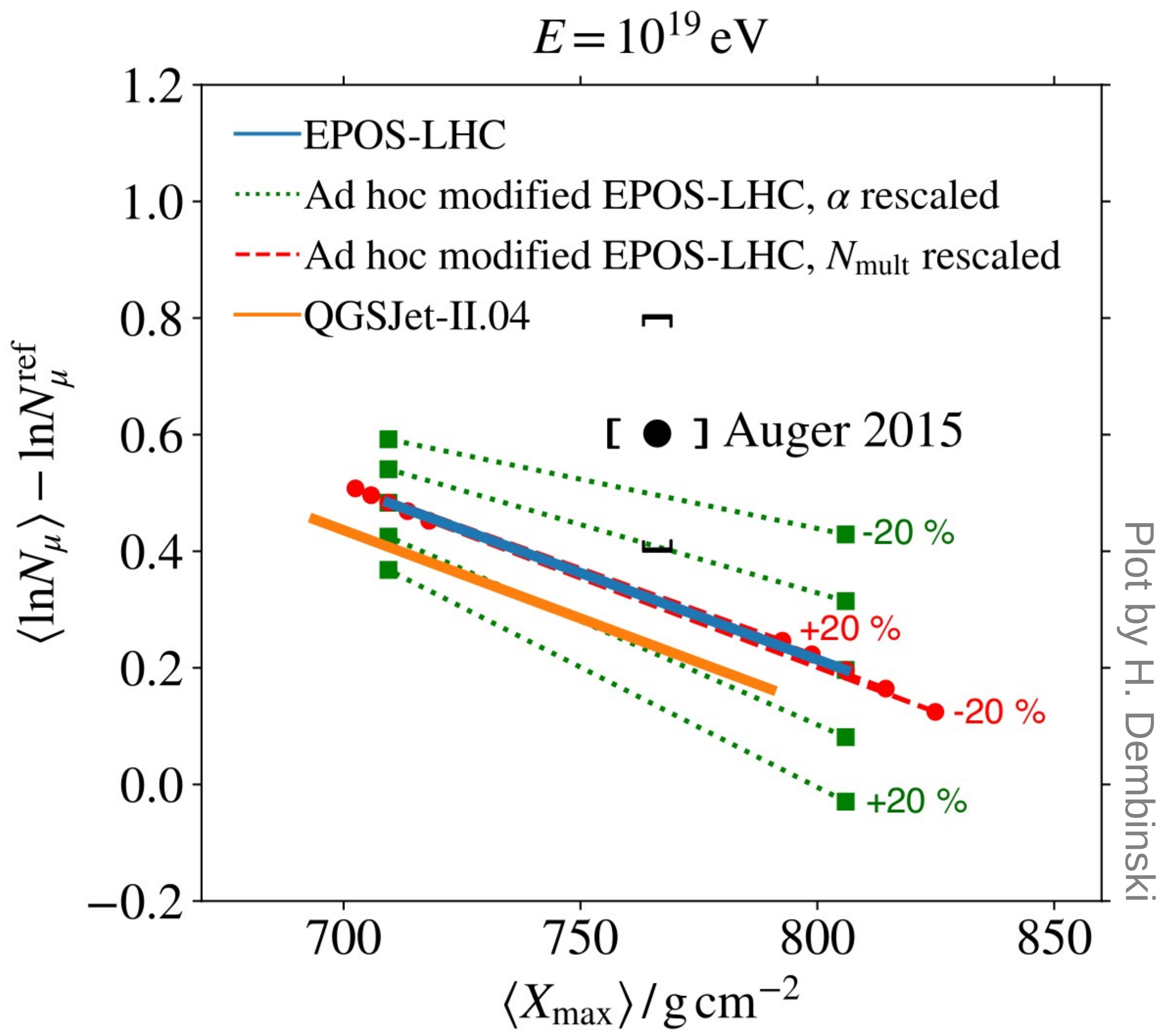


Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

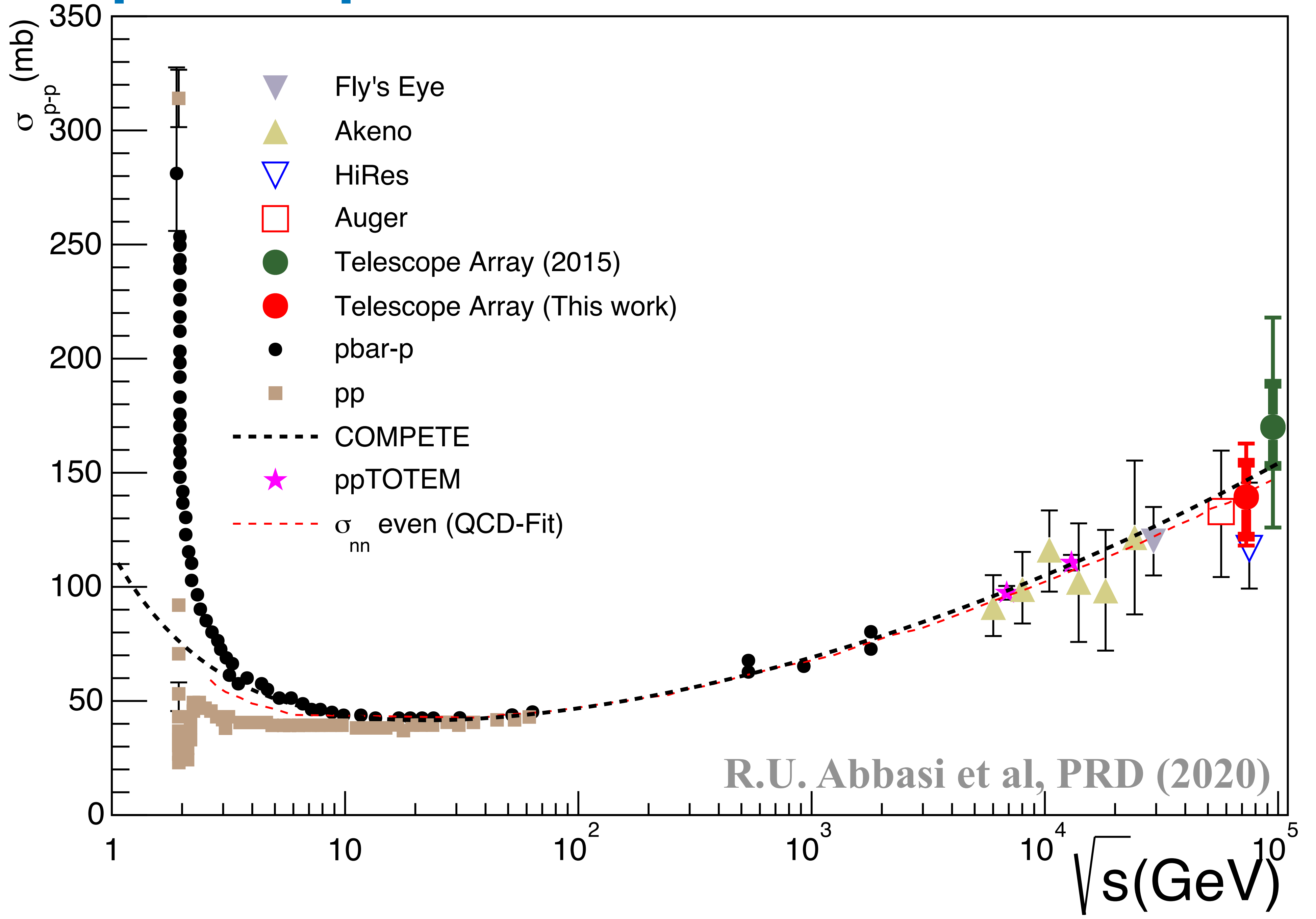
inconsistent mass composition measurements point to weaknesses in hadronic interaction models (e.g., Hörandel 2003, Kampert&Unger 2012)
—> GCOS needs to provide hybrid measurements of air showers

—> use air shower data to constrain models

to reduce muon discrepancy,
—> change energy dependence of μ production



proton-proton cross section



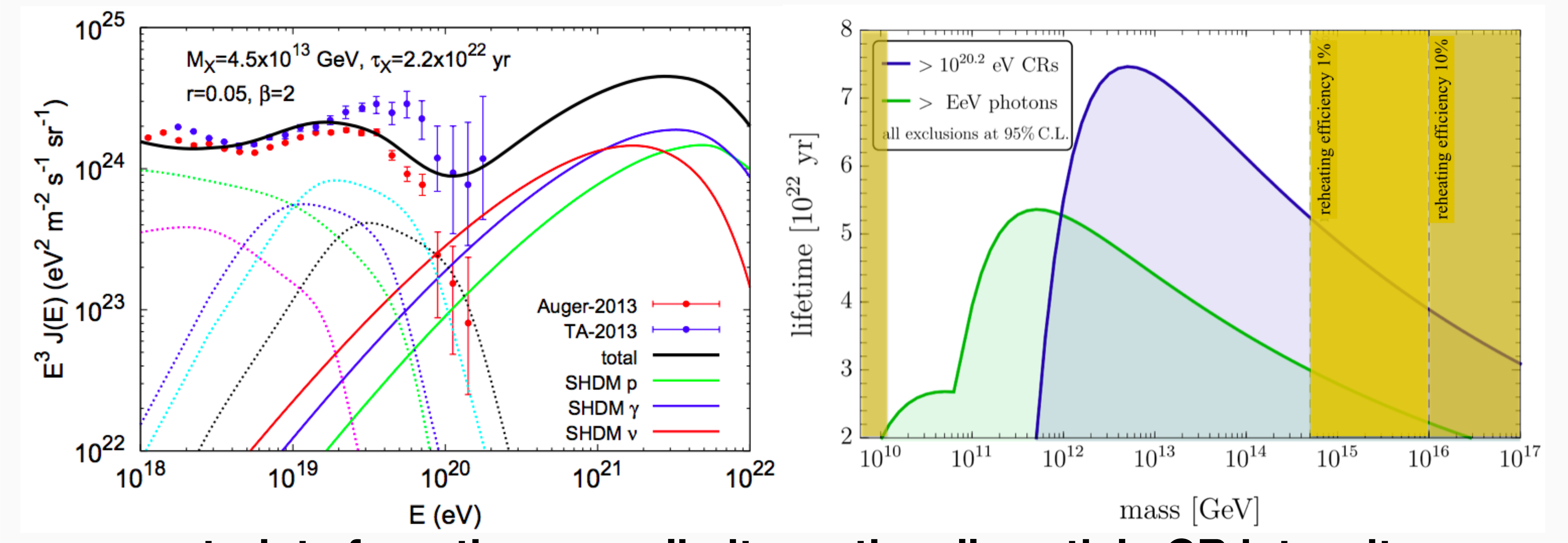
X_{max} uncertainties mostly due to nuclear collision extrapolations
-> precise measurements (inelastic cross-section, multiplicity, diffraction) needed in pA and AA (A<20) at LHC

Tanguy Pierog

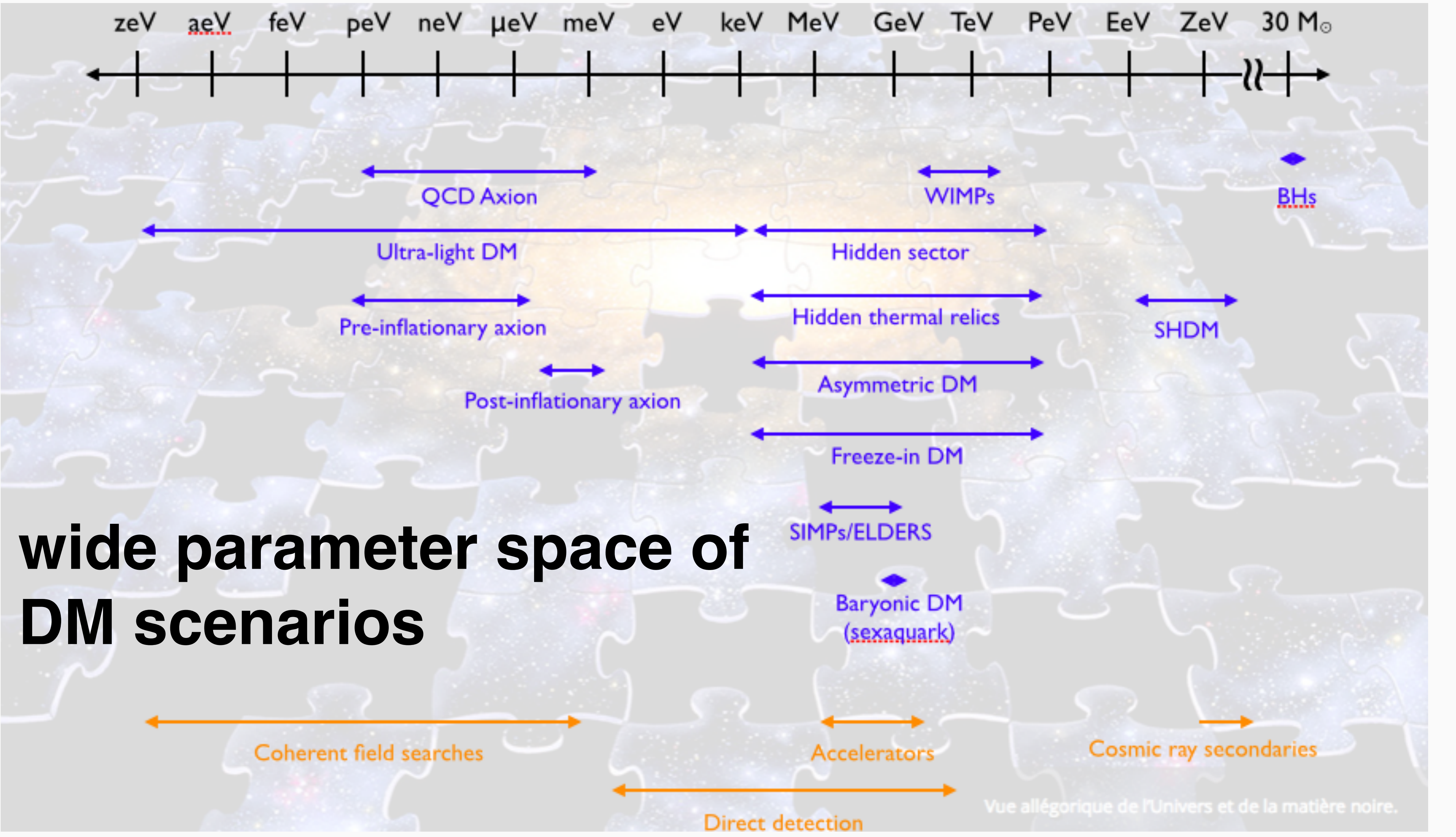
Dark-matter searches

R. Aloisio., S. Matarrese, A. Olinto, JCAP 08 (2015) 024

Snowmass2021 LoI, arXiv:1903.05429



constraints from the upper limits on the all-particle CR intensity



wide parameter space of DM scenarios

Olivier Deligny

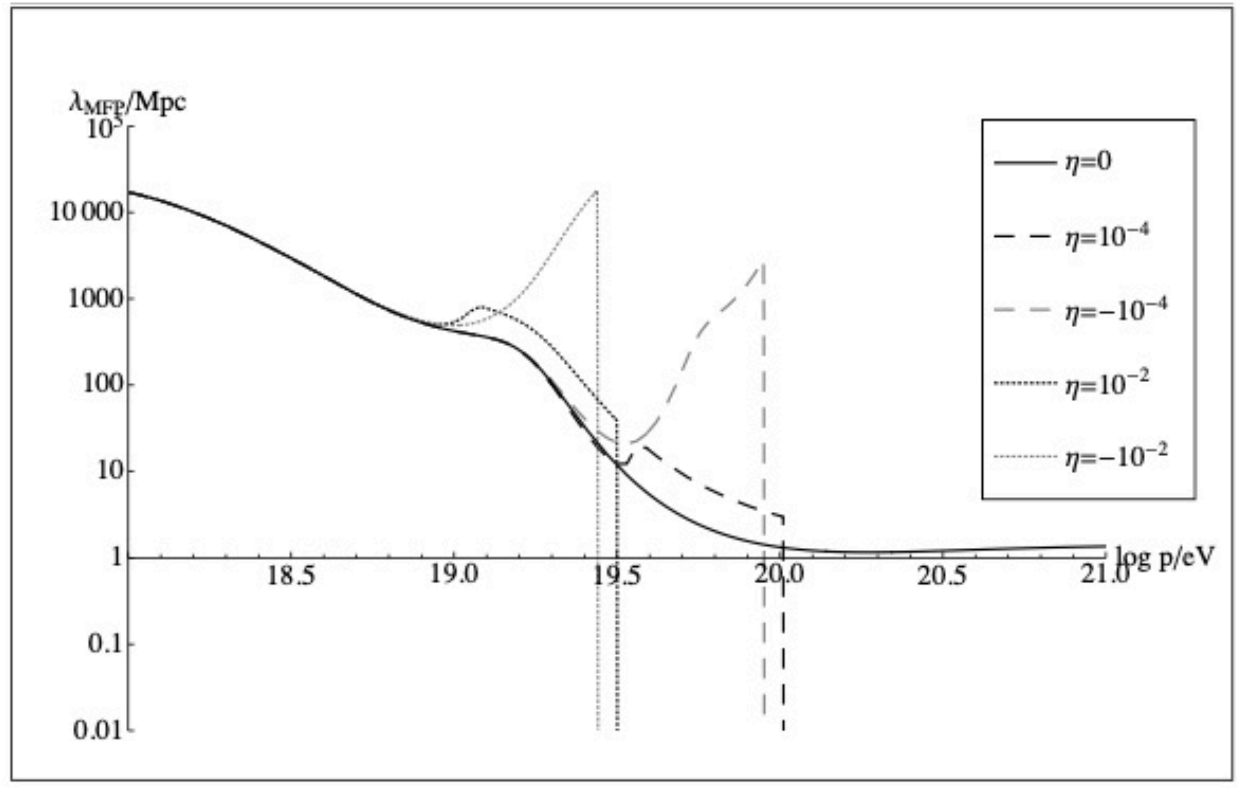
Fundamental physics and quantum gravity

Lorentz symmetry violations

- could affect cosmic-ray propagation and air shower development
- could exist in the nucleon or photon sector

—> influence on nuclei mean free path

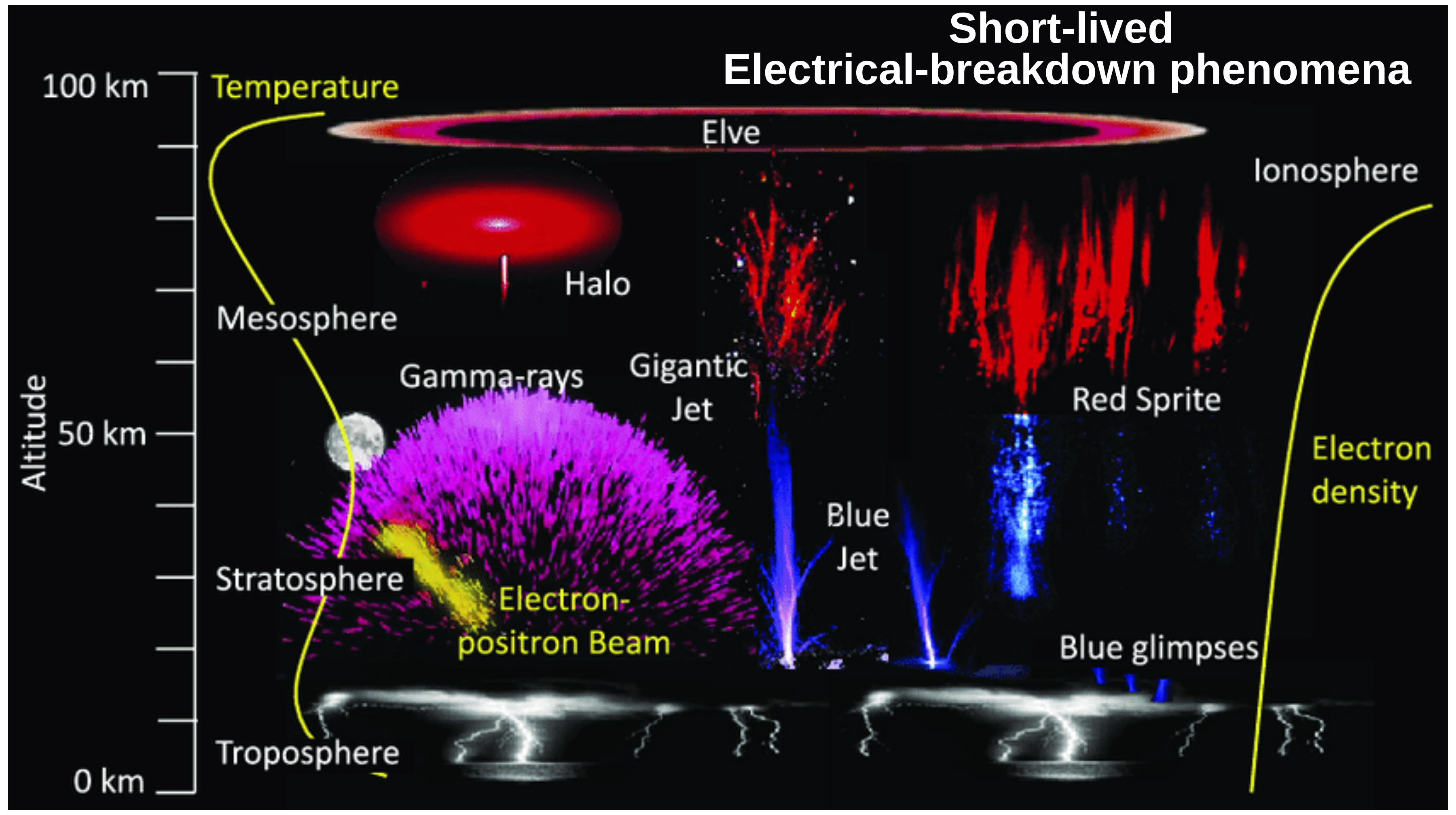
—> possible effects also on neutrino dispersion relation —> neutrino decay



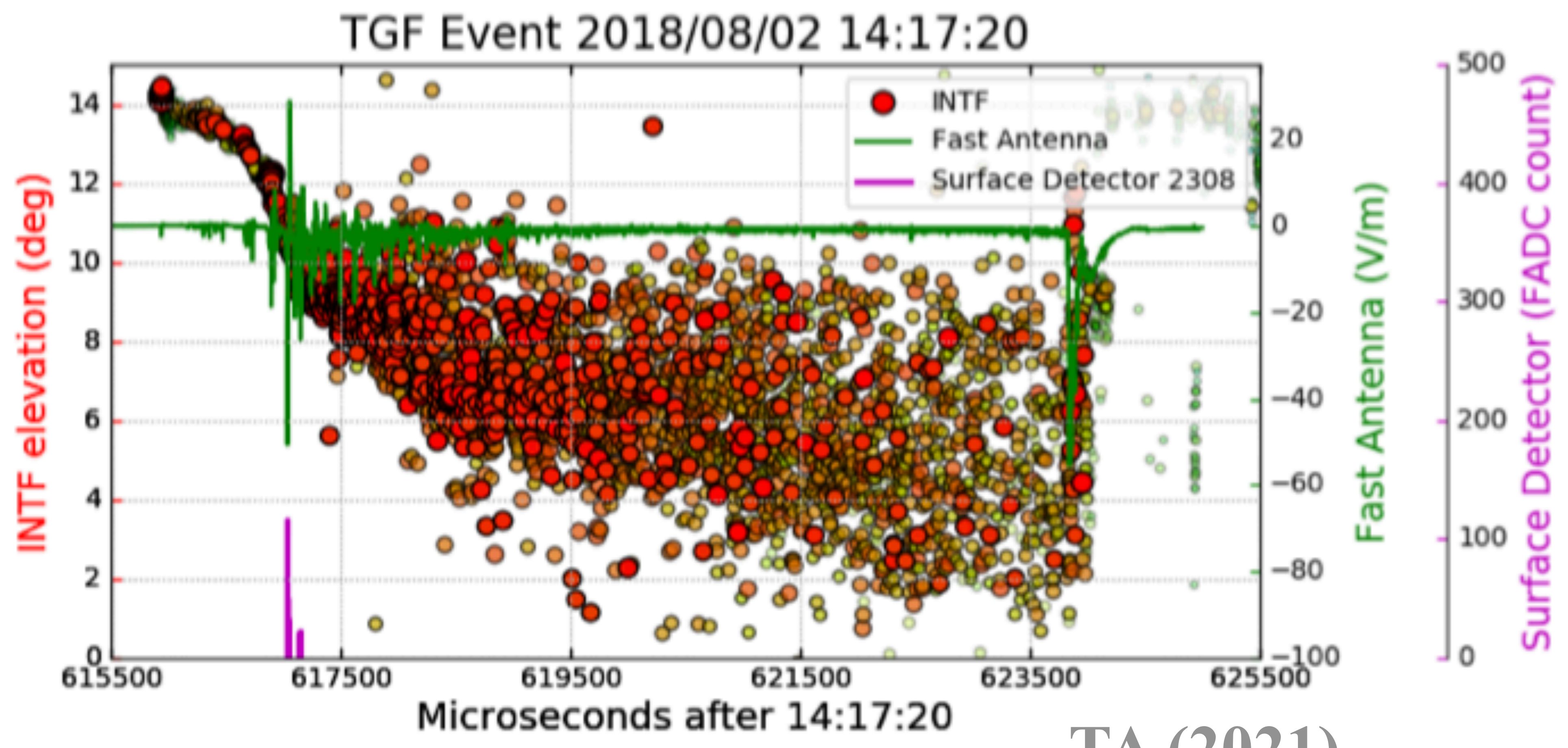
Günter Sigl

—>GCOS needs good sensitivity for UHE photons & neutrinos

Geophysics and atmospheric science

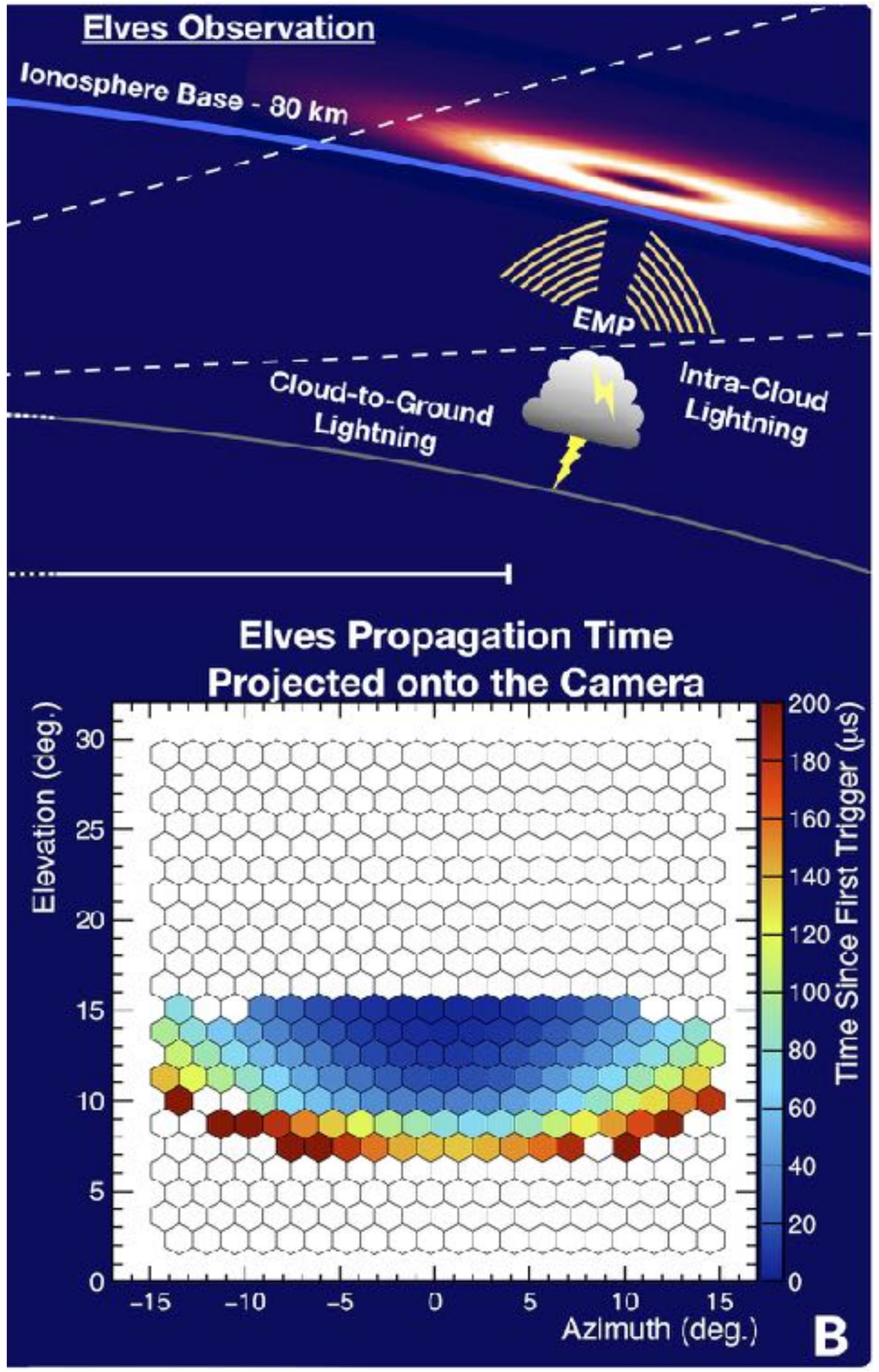


observing terrestrial gamma-ray flashes with TA



TA (2021)

studying ELVES with Auger



Auger (2020)

precise mapping of lightning with LOFAR

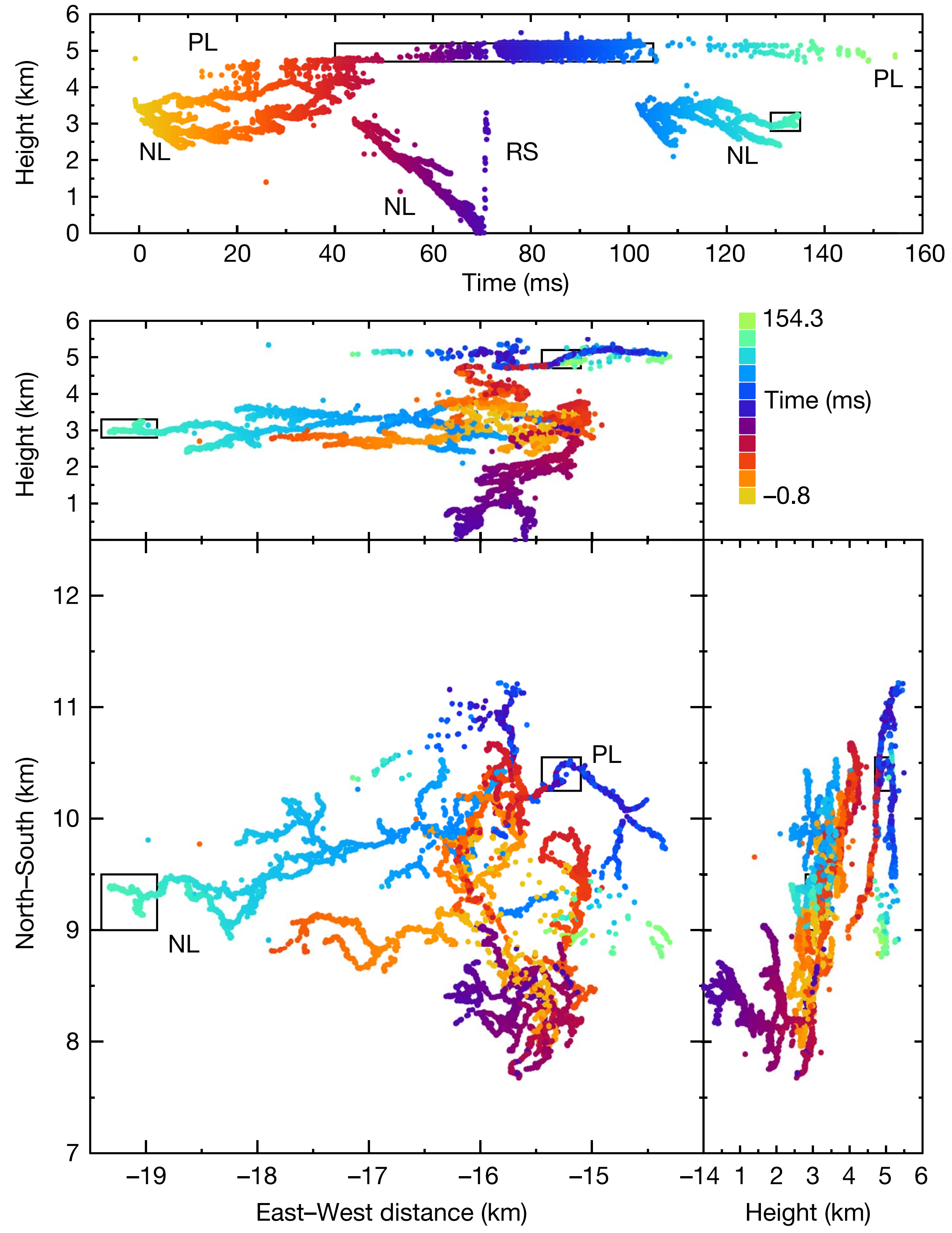
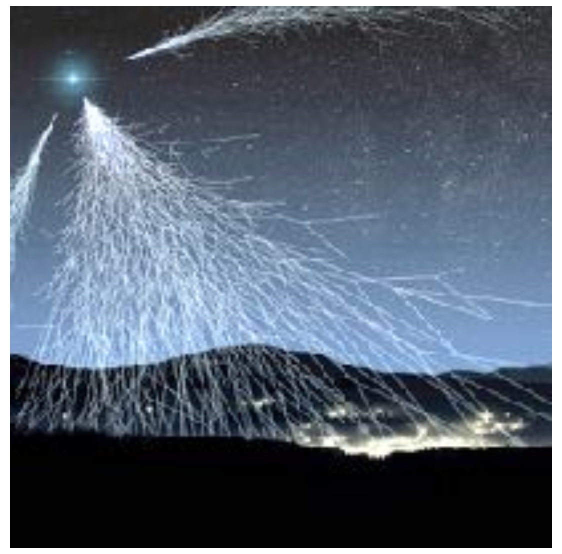


Fig. 1 | Map of the 2017 flash. Each dot is the location of a radio source. Sources from the positive leaders (PL) and negative leaders (NL) are shown. When the negative leader connects to ground, it creates a 'short' that propagates up the lightning channel called a return stroke (RS). The boxes indicate the areas that are shown in Fig. 2. Distances are relative to the LOFAR core.

LOFAR, Nature (2019)

Roberta Colalilo Rasha Abbasi



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Detection concepts

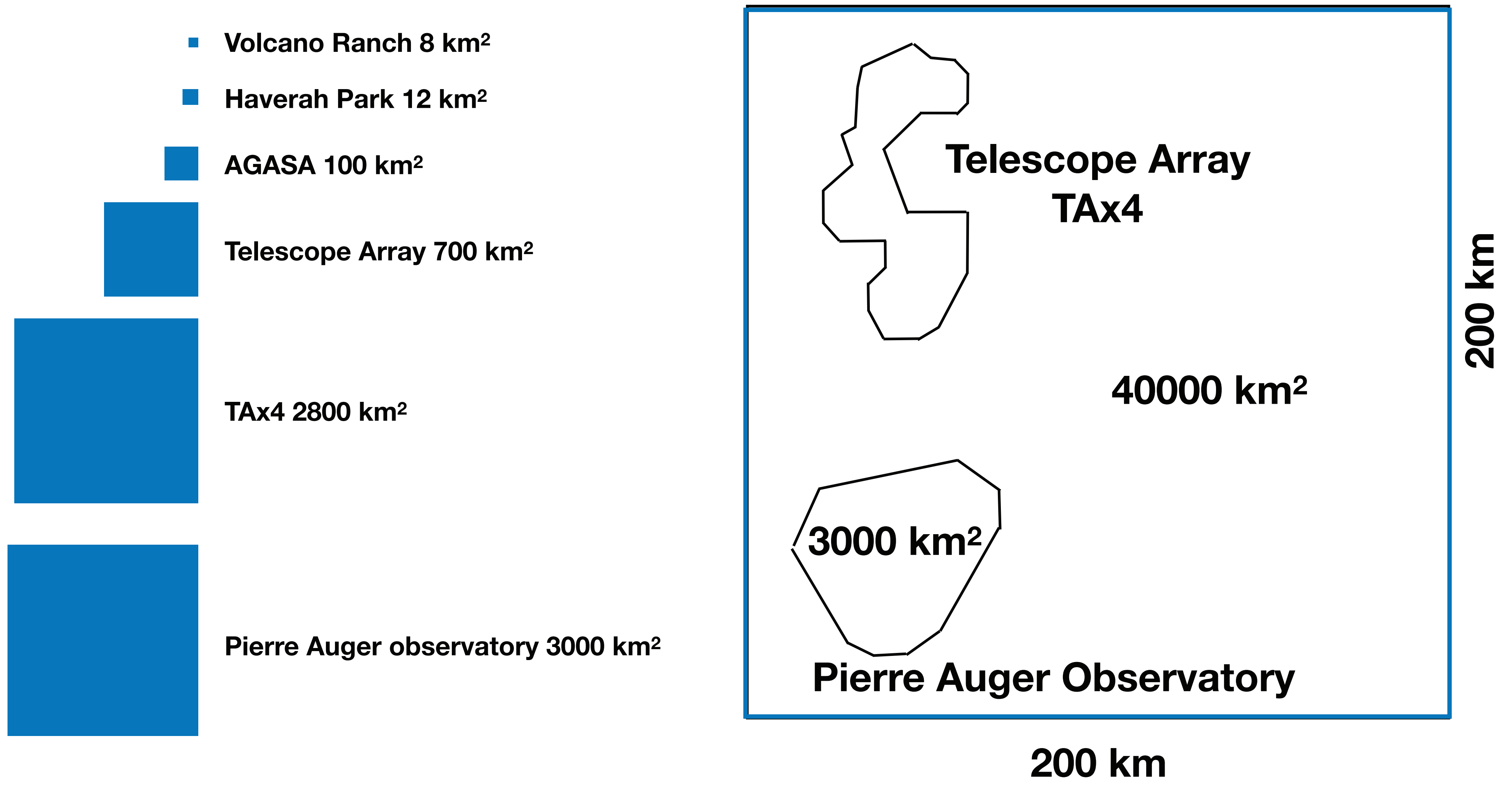
How to reach the physics case with a ground array?

Acceptance/exposure?
What statistics will we need?

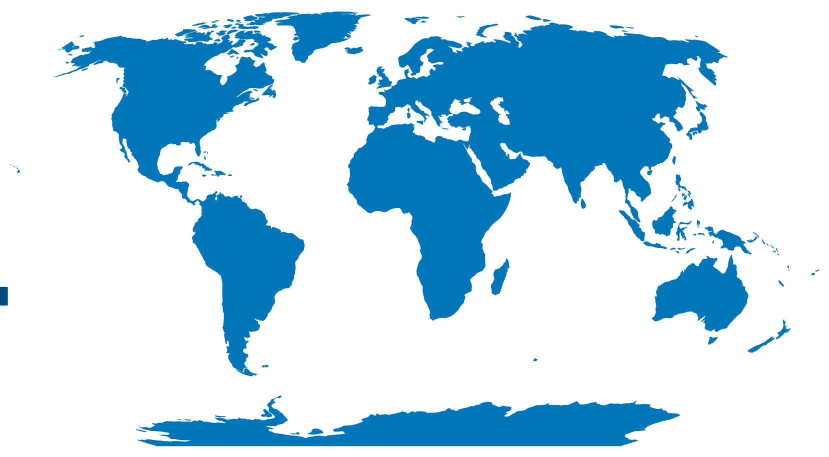
$E > 10^{19.6}$ eV ~500 /yr (1000 km² and 2π)

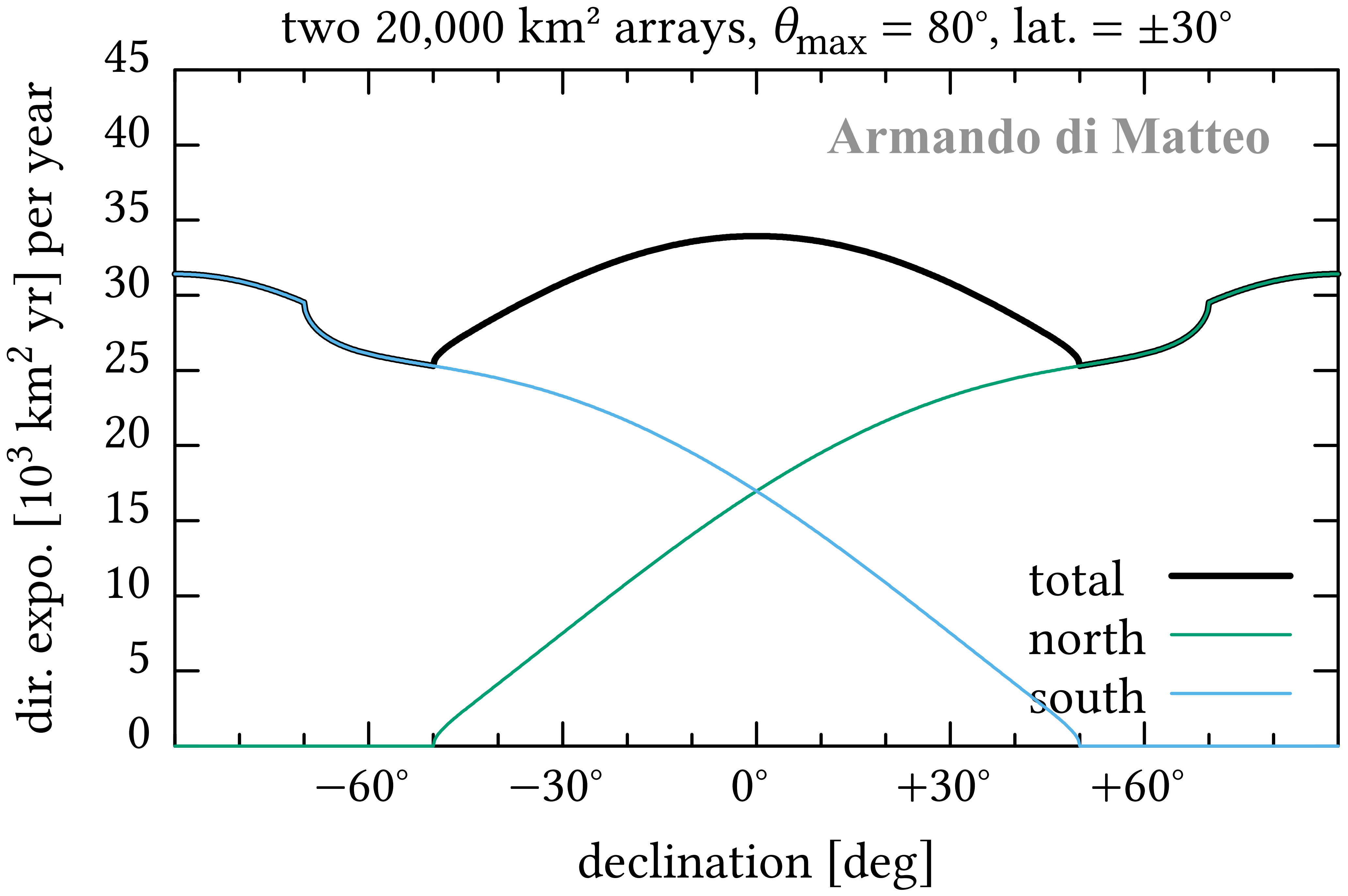
~5% light particles
~50% efficiency
40000 km²

—> 5000 light particles/decade ($E > 10^{19.6}$ eV)



Where: full sky coverage?
—> equator, several sites, …



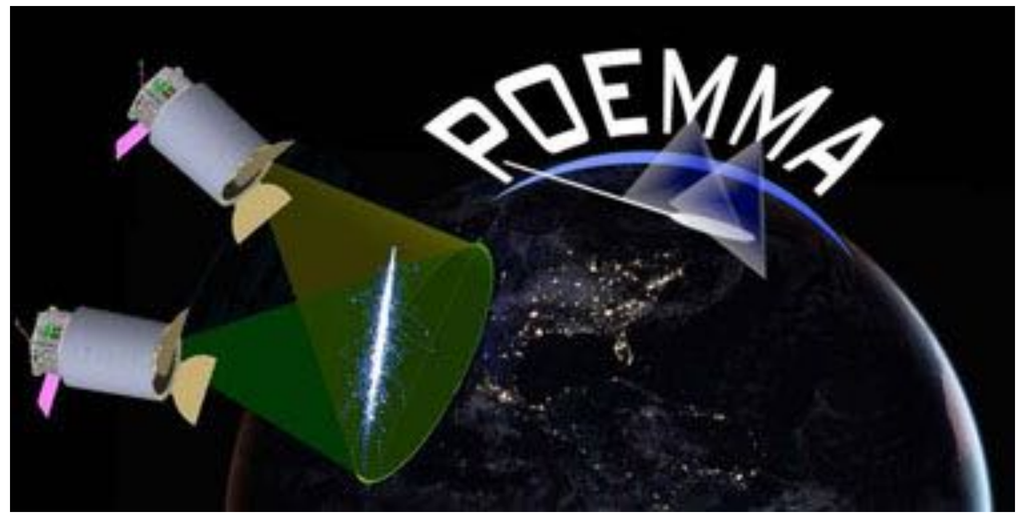


What is realistic in terms of area and number of detectors?

10x existing arrays? —> 40 000 - 50 000 km²
10x number of units? —> 10 000 - 20 000 detectors
1.6 - 2 km spacing

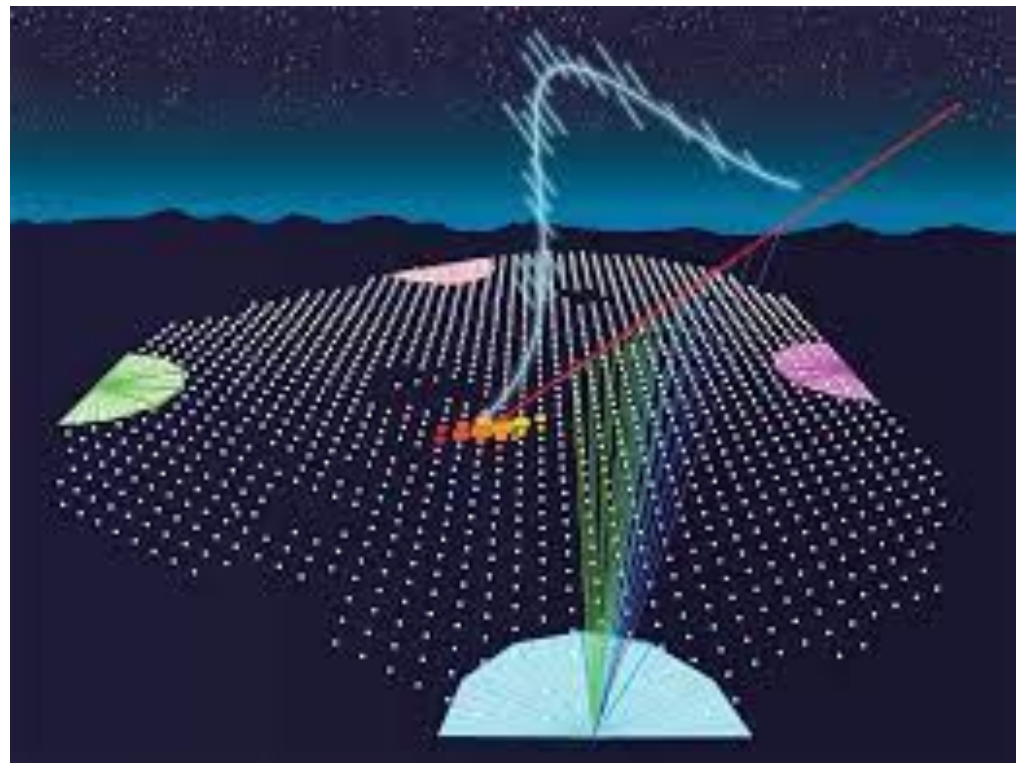
Complementarity of approaches

Space - ground



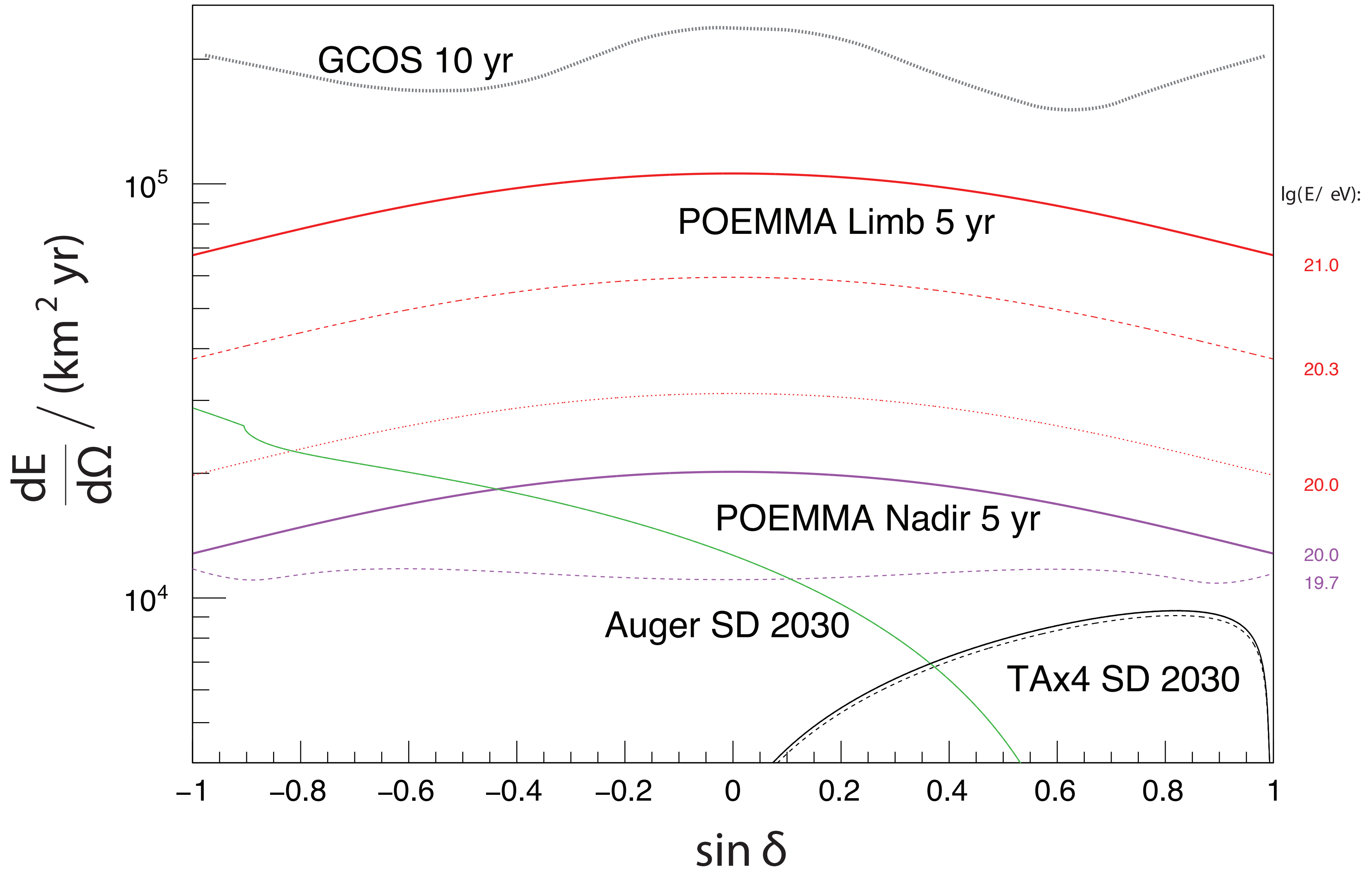
POEMMA:

intrinsic full-sky coverage



GCOS:

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



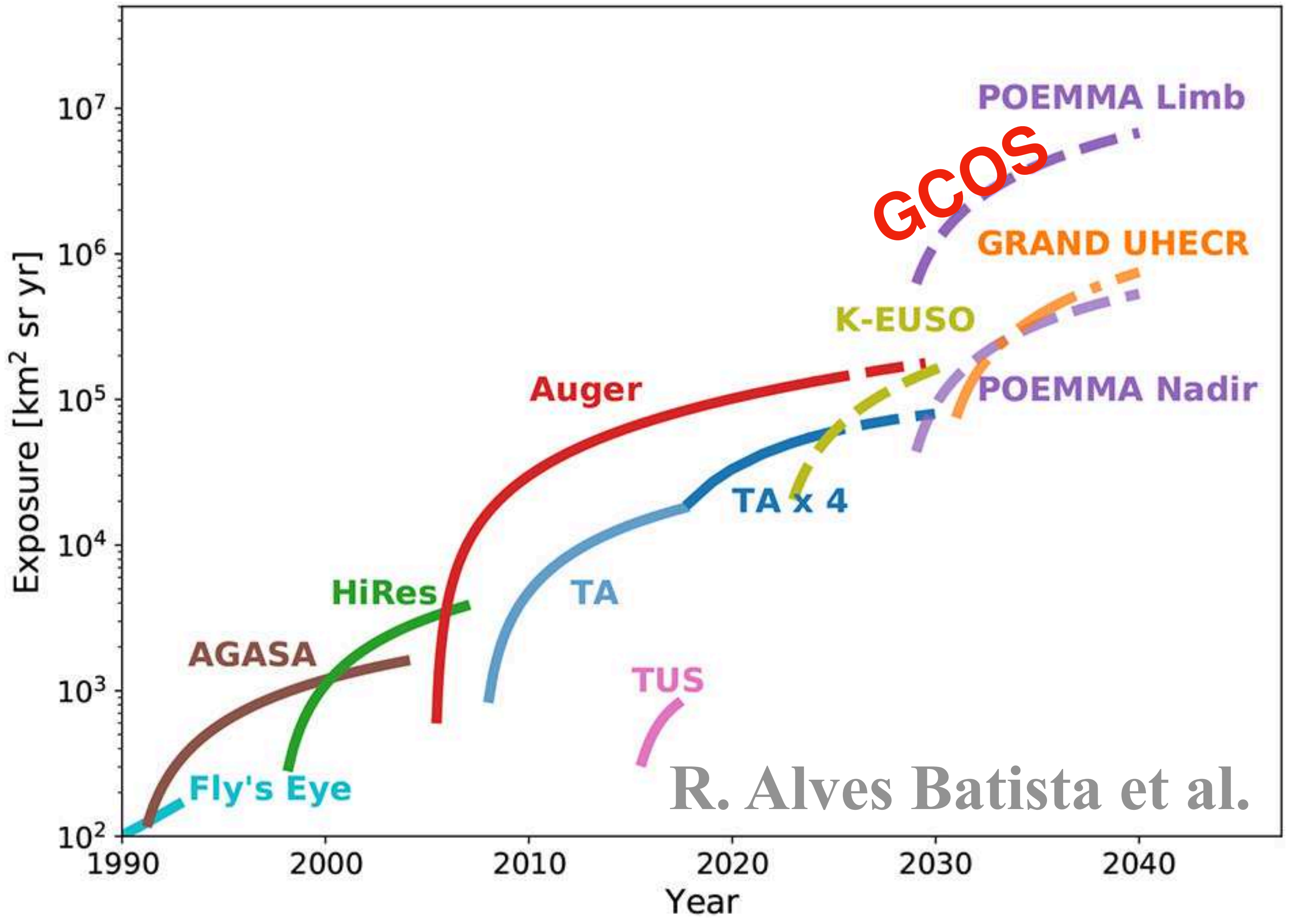


FIGURE 16 | Evolution of the exposure of past, current, and upcoming (solid lines) UHECR experiments as a function of time for ground-based and space experiments. Proposed experiments are also shown (dashed lines). F. Oikonomou and M. Panasyuk for this review.

Complementarity of techniques

The Giant Radio Array for Neutrino Detection

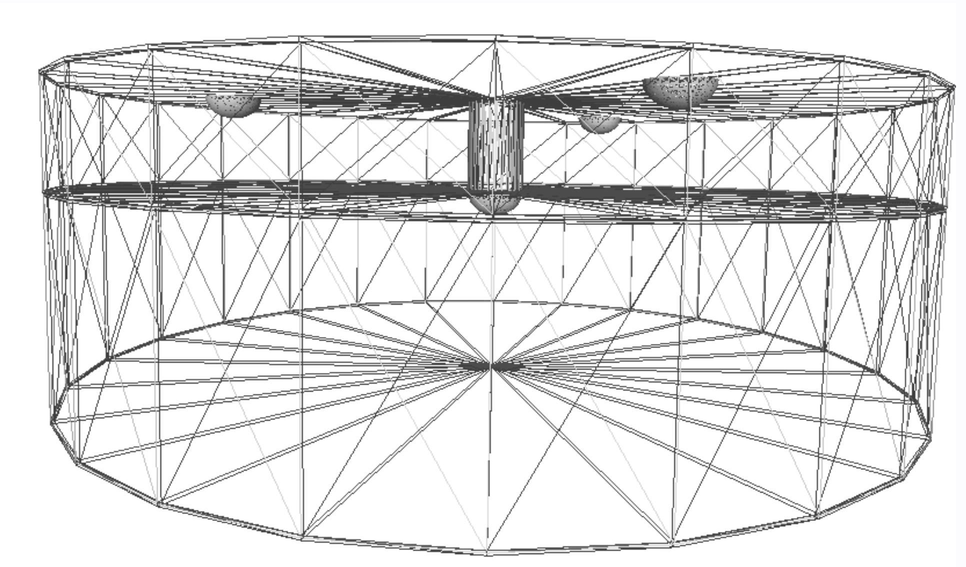
GRAND

200'000 radio antennas over 200'000 km²
~20 sub-arrays of 10'000 antennas
over favorable sites in China and worldwide

Advanced water Cherenkov detectors

The idea: optical separation of a Water Cherenkov Tank

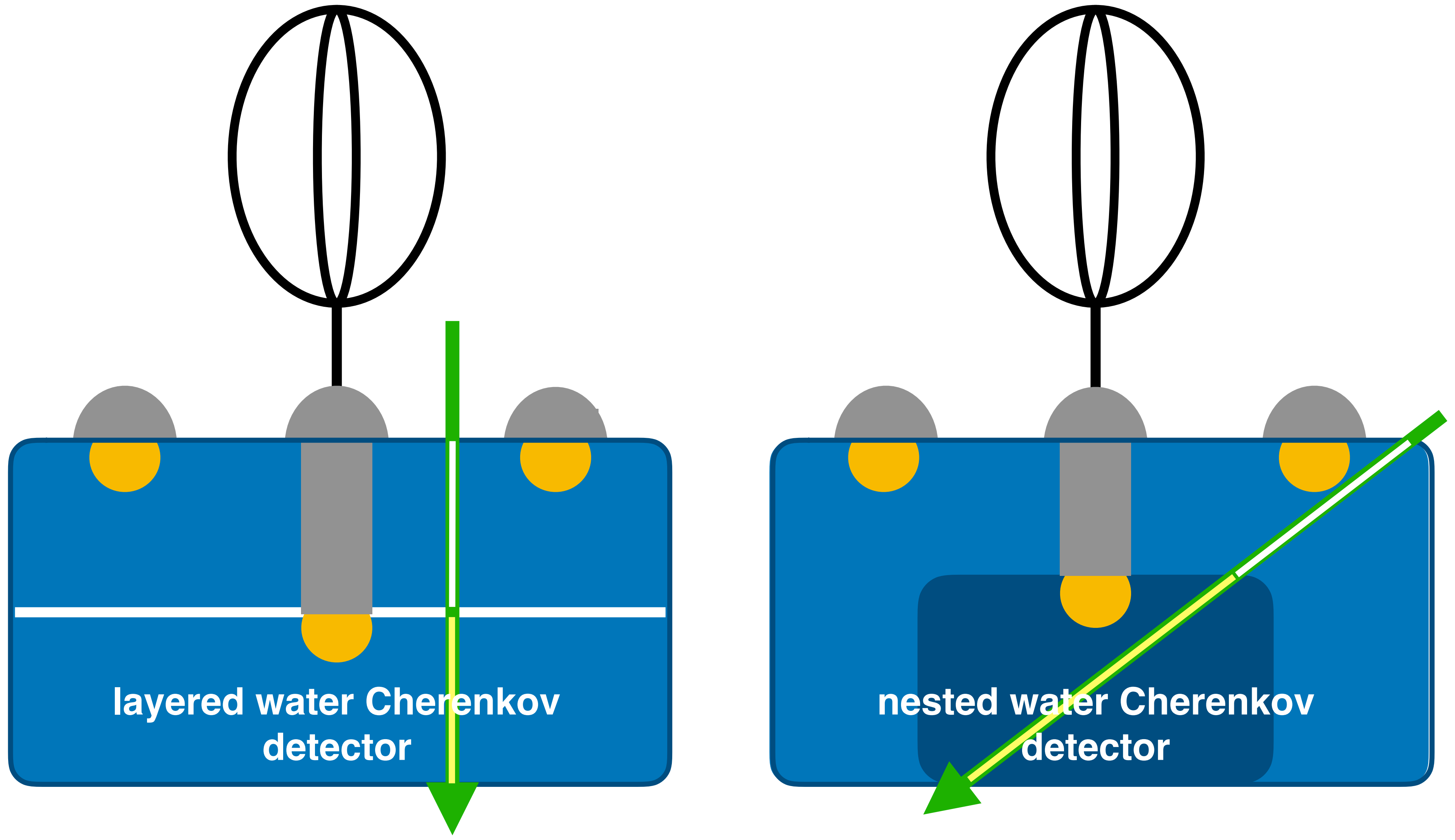
A water volume responds different to photons, $e^{\pm}$ and $\mu^{\pm}$



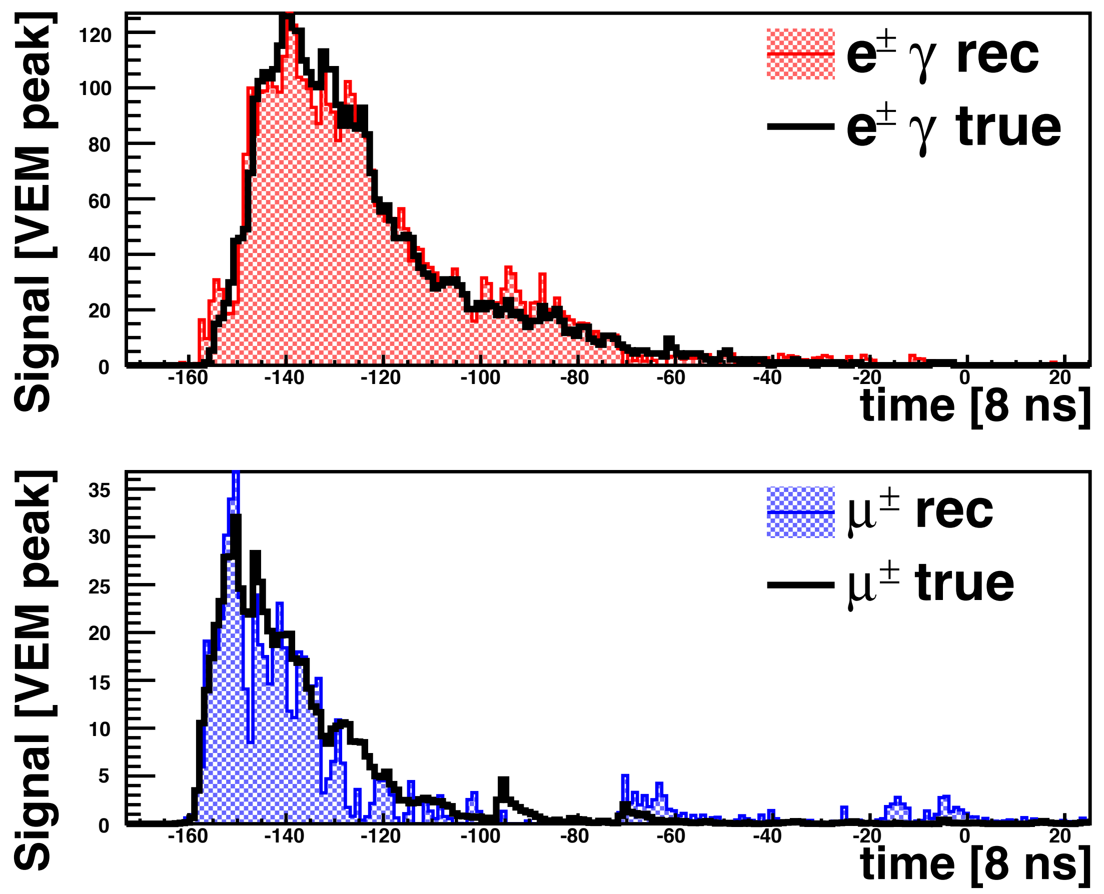
$$\begin{pmatrix} S_{\rm top} \\ S_{\rm bot} \end{pmatrix} = \mathcal{M} \begin{pmatrix} S_{\rm EM} \\ S_{\mu} \end{pmatrix} = \begin{pmatrix} a & b \\ 1-a & 1-b \end{pmatrix} \begin{pmatrix} S_{\rm EM} \\ S_{\mu} \end{pmatrix}$$

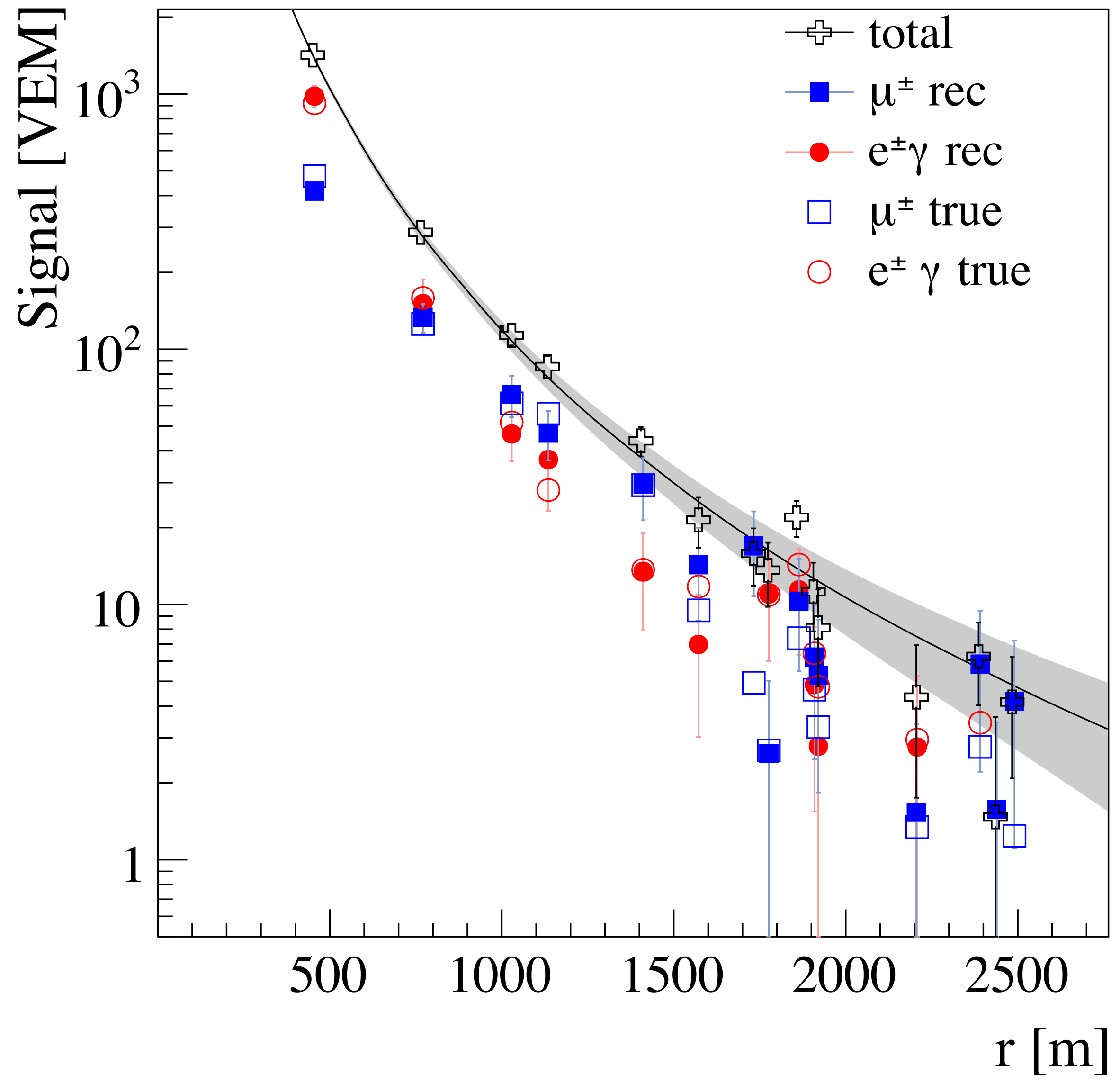
$$\begin{pmatrix} S_{\rm EM} \\ S_{\mu} \end{pmatrix} = \mathcal{M}^{-1} \begin{pmatrix} S_{\rm top} \\ S_{\rm bot} \end{pmatrix}$$

2



Not only total signal, but also time distributions





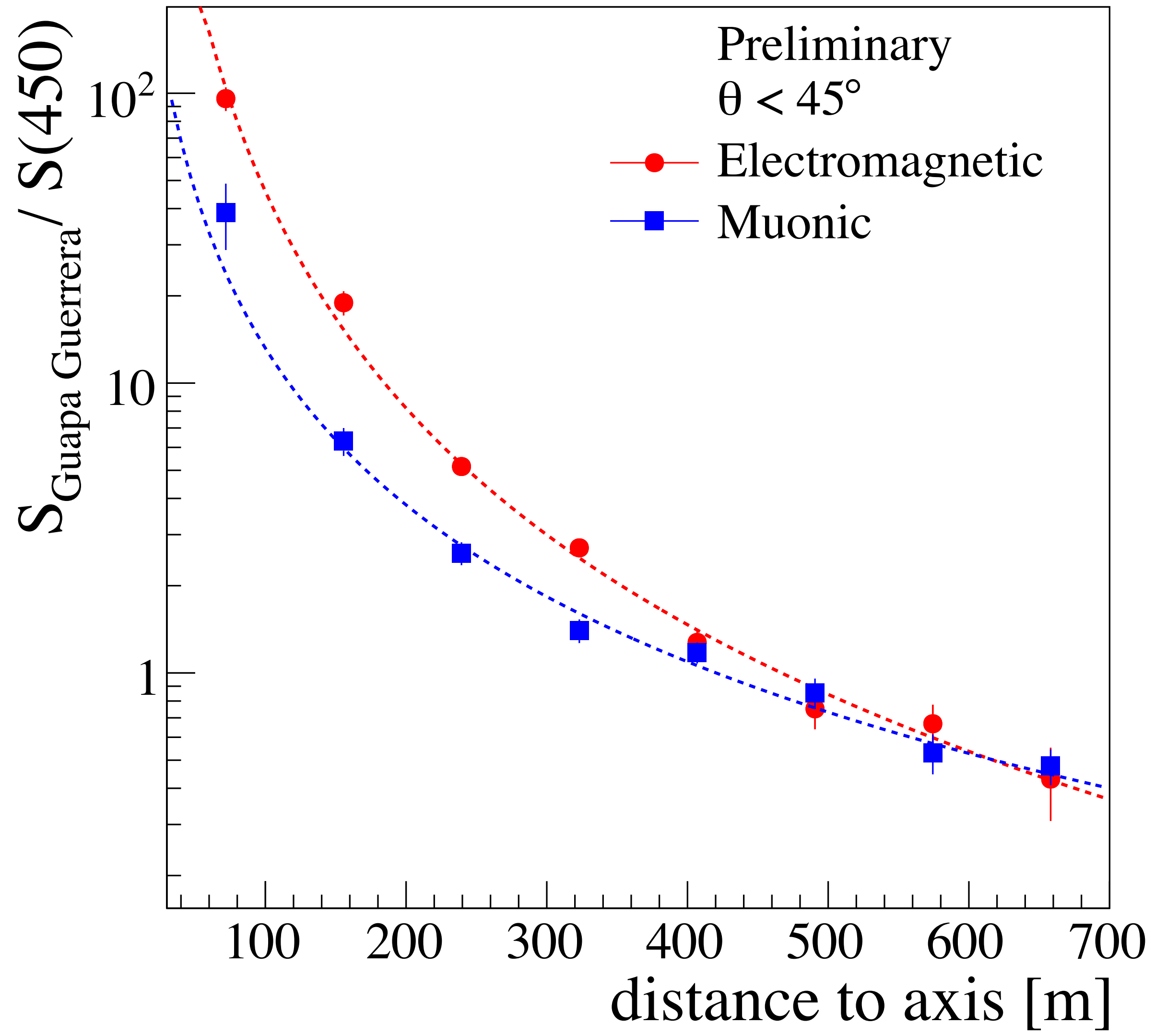
Based on Universality or DNN we can get $X_{\rm max}$

5

prototype measurements at Auger Observatory

Mean LDFs for the electromagnetic and muonic components

900 events ($E > 0.03\,{\rm EeV}$, $\theta < 45^{\circ}$)



13

Ioana Maris   Antoine Letessier-Selvon et al., Nucl. Instr. Meth. A 767 (2014) 41–49

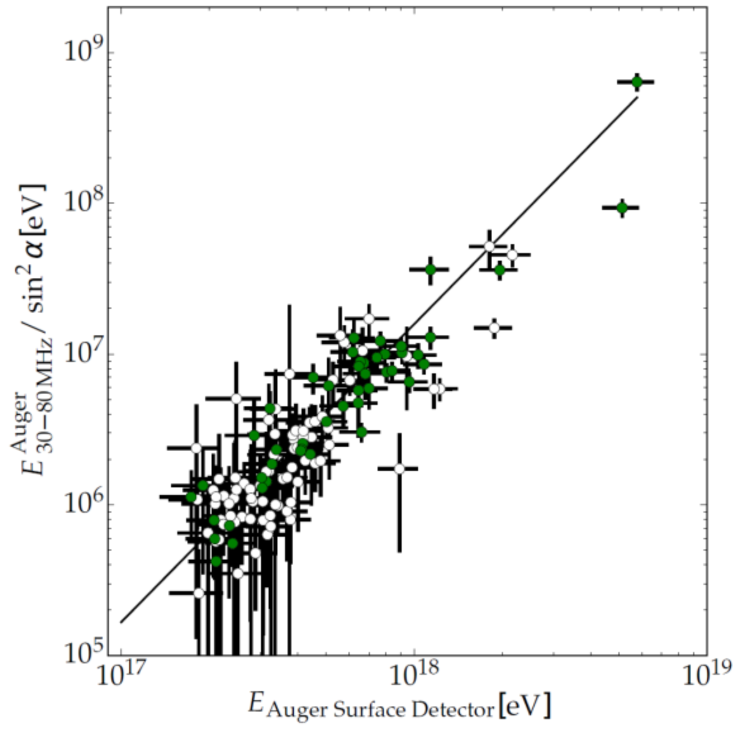
Radio detection

Radio detection today

Karlsruhe Institute of Technology

- The radio detection technique is mature
  - External triggering works very reliably
  - Radio self-triggering works in radio-quiet areas
- Radio emission phyics is understood at 10% level
- We have reached very competitive measurement performance
  - Energy resolution 10-15%
  - Xmax resolution 15-20 g/cm^2 (LOFAR, AERA)
  - Angular resolution well below 0.5°
- Radio can be used to calibrate absolute energy scale of cosmic ray detectors

For a review, see
TH, Physics Reports 620 (2016) 1

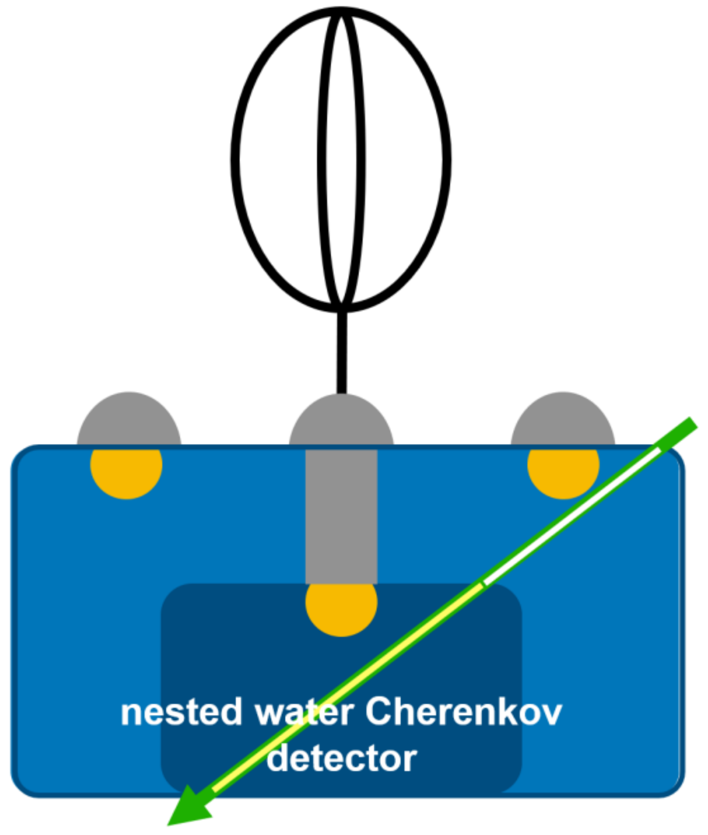


Pierre Auger, PRL 116 (2016) 241101

What to do in a next-generation experiment?

Karlsruhe Institute of Technology

- „Nested detector“ plus Radio antenna
  - Extra cost for Radio is small, likely well below 1000 EUR per station
  - Provides data for mass composition studies, energy scale calibration
- If possible, go beyond 80 MHz, for potential „single-station analysis“ à la ANITA, ARIANNA, lowering thresholds
- If possible, try time synchronization on 1 ns scale (differential GPS, …?)
- Grid beyond 1.5 km seems unfavorable



J. Hörandel, introductory talk

Conclusions

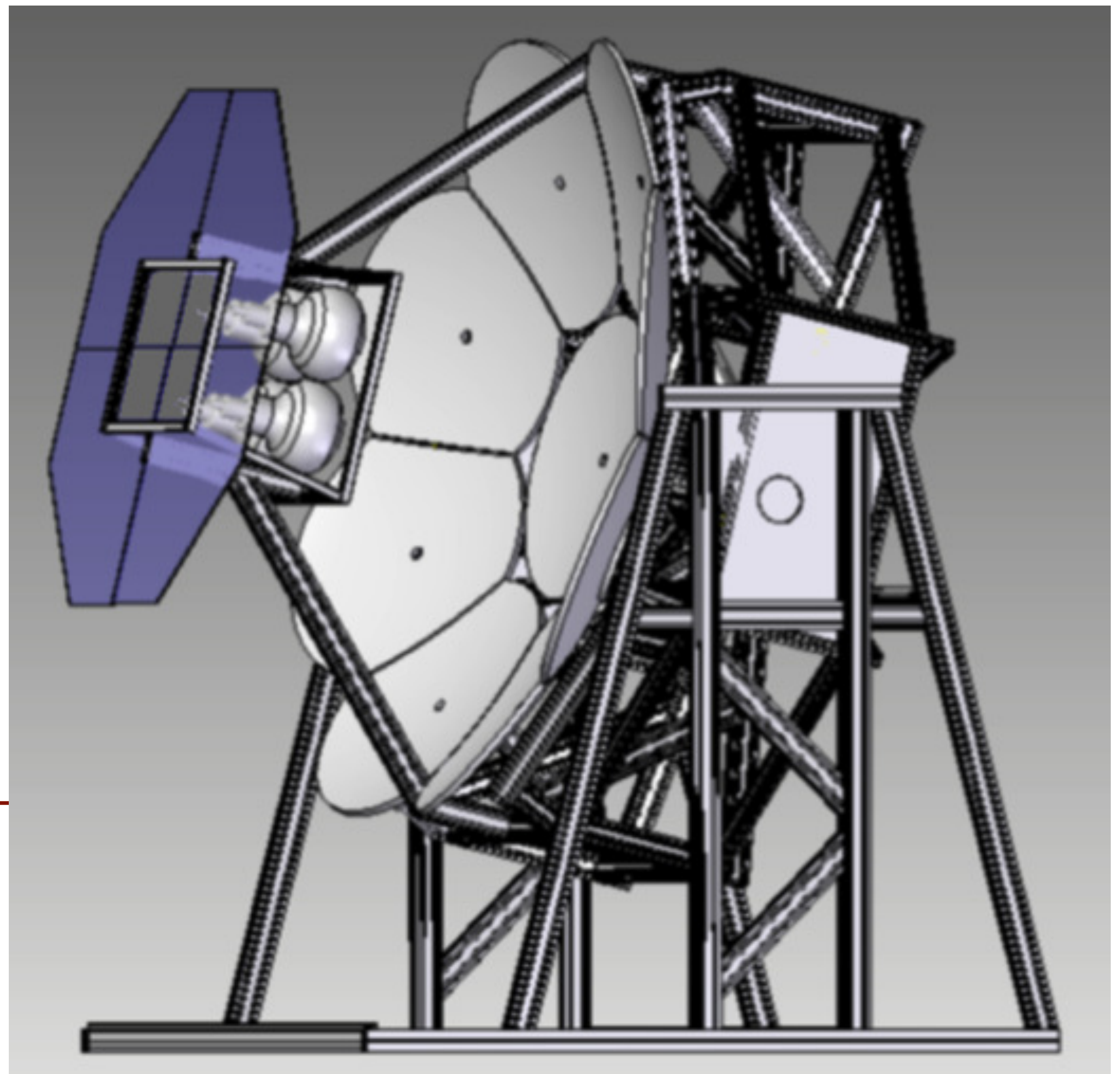
Karlsruhe Institute of Technology

- Radio detection is mature and delivers valuable information
  - „Electromagnetic energy“ within 10%
  - Xmax for vertical showers (AERA@ICRC), possibly for inclined with RIT
  - Independent calibration of absolute energy scale
- Larger antenna spacing -> higher zenith angles -> smaller solid angle
  - 1.5 km grid for AugerPrime RD will work
  - 2.0 km grid seems like stretching it

Tim Huege

Fluorescence light telescopes

array of low-cost telescopes



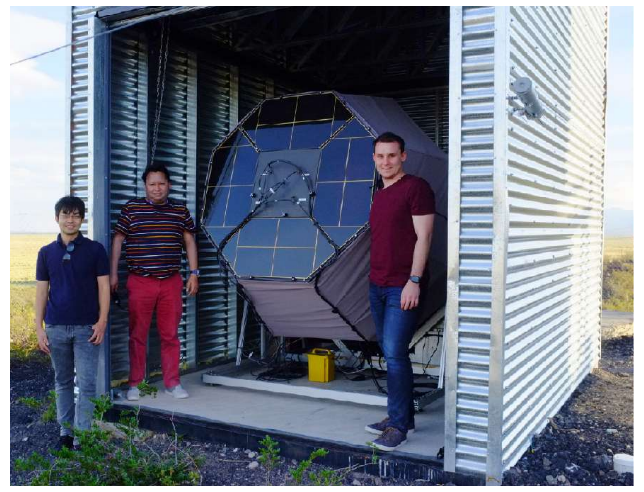
Fluorescence detector Array of Single-pixel Telescopes

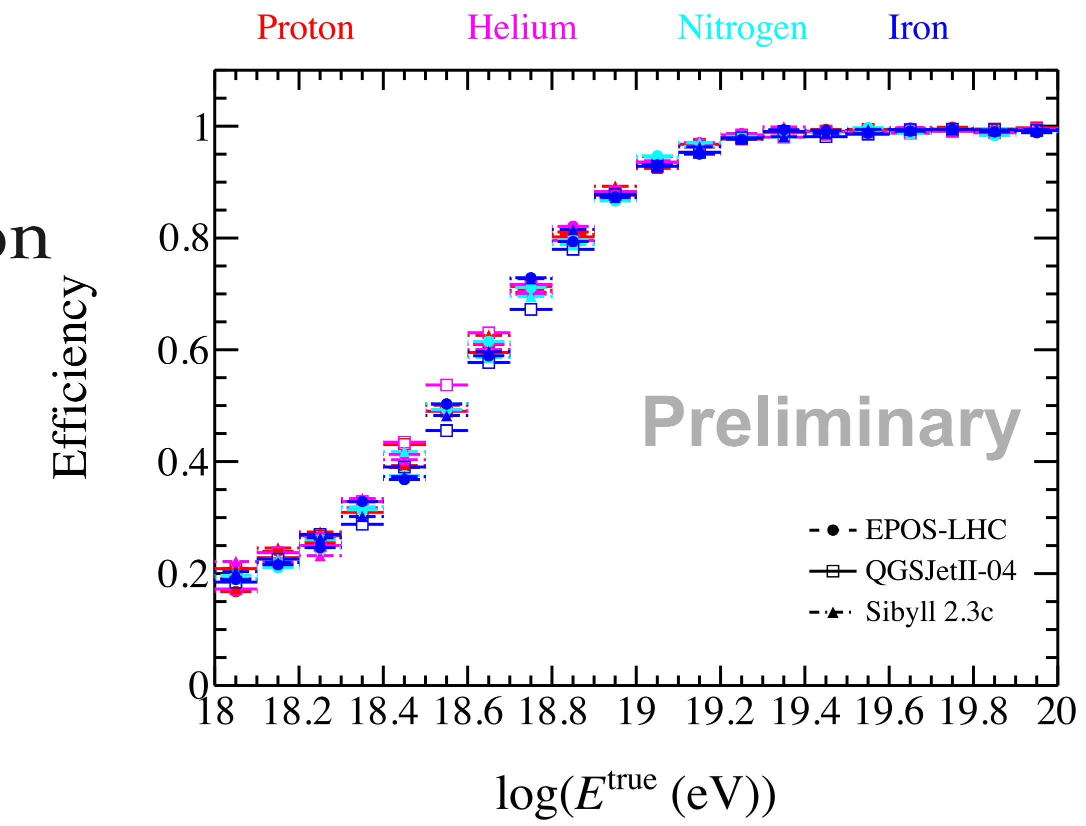
Summary and future plan

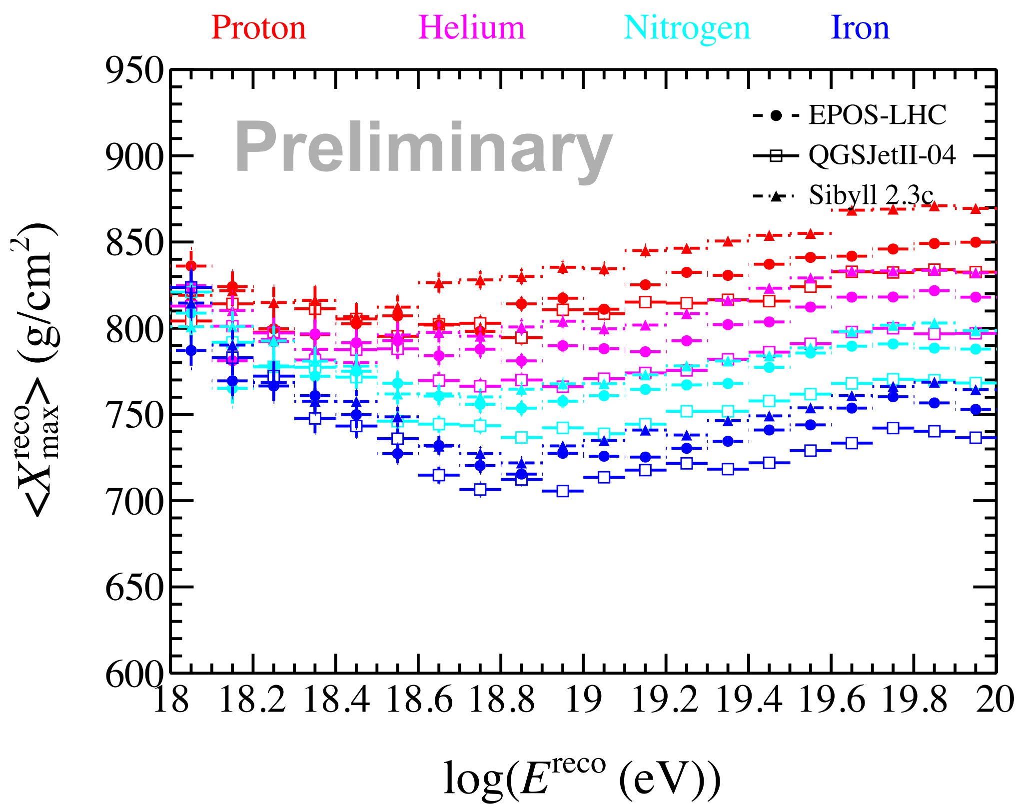
- **Fluorescence detector Array of Single-pixel Telescopes (FAST)**
  - Low-cost fluorescence telescope array
  - Promising concept as next-generation cosmic ray observatory to fulfill requirements
- **Preliminary performance estimation**
  - 100% efficiency above $10^{19.3}$ eV
  - Resolution of neural network reconstruction
    - Arrival direction: 4.2 deg, Core: 465 m
    - Energy: 8%, Xmax: 30 g/cm^2 ($\Delta\ln A$ ~ 1)
- **Next step and challenges**
  - Stand-alone operation of FAST "array" in field

FAST@TA

FAST@Auger







https://www.fast-project.org

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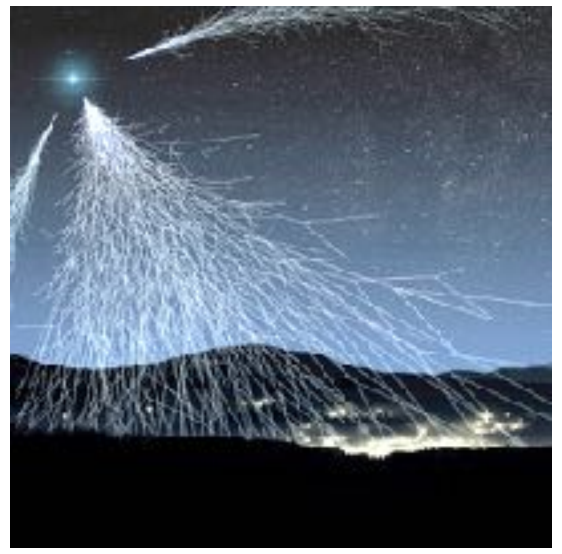
Toshihiro Fujii



GCOS
The Global Cosmic Ray Observatory

Multi-messenger astroparticle physics beyond 2030

Based on the experience and scientific results which we have obtained and which we will obtain in the next decade, in particular with the Pierre Auger Observatory and the Telescope Array, we will be in a position to make accurate estimates of what is required to build GCOS.

next steps:

- workshop end 2021/begin 2022 to further define science case and to further specify technical requirements
- write a roadmap towards a science case for UHE multi-messenger astroparticle physics beyond 2030

GCOS homepage: http://particle.astro.ru.nl/gcos