Astroparticle Physics

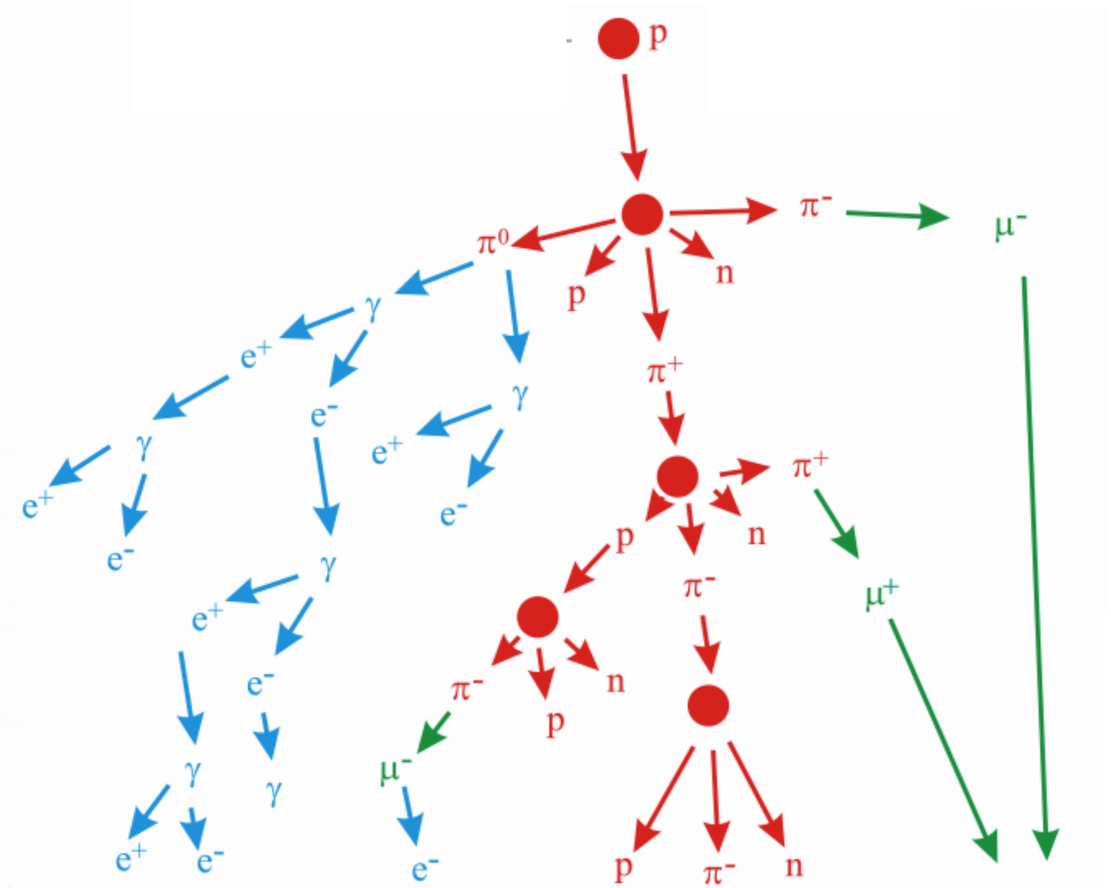
Cosmic Rays, Gamma-rays, (Neutrinos),
and the multi-messenger approach

Ruben Conceição

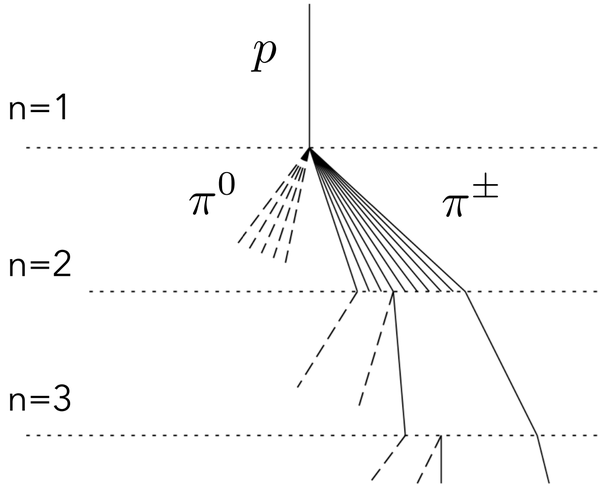
10th IDPASC school, Nazaré, September 16th 2021

EAS engine - *(discussed yesterday)*

Monte Carlo EAS simulation [CORSIKA]



Heitler-Matthews model



$$\langle X_{\max} \rangle \propto \ln\left(\frac{E_0}{A}\right)$$

$$\langle N_\mu \rangle \propto A^{1-\beta} E_0^{\beta}$$

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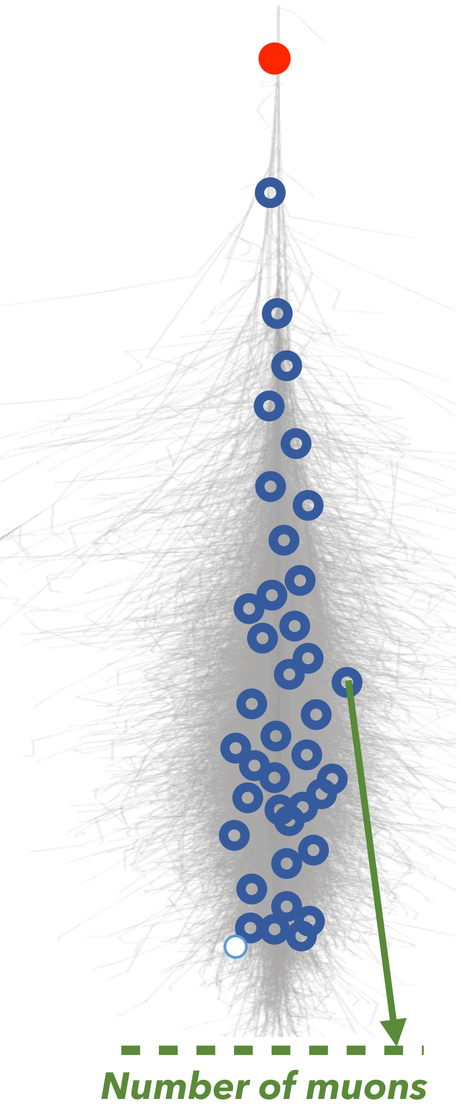
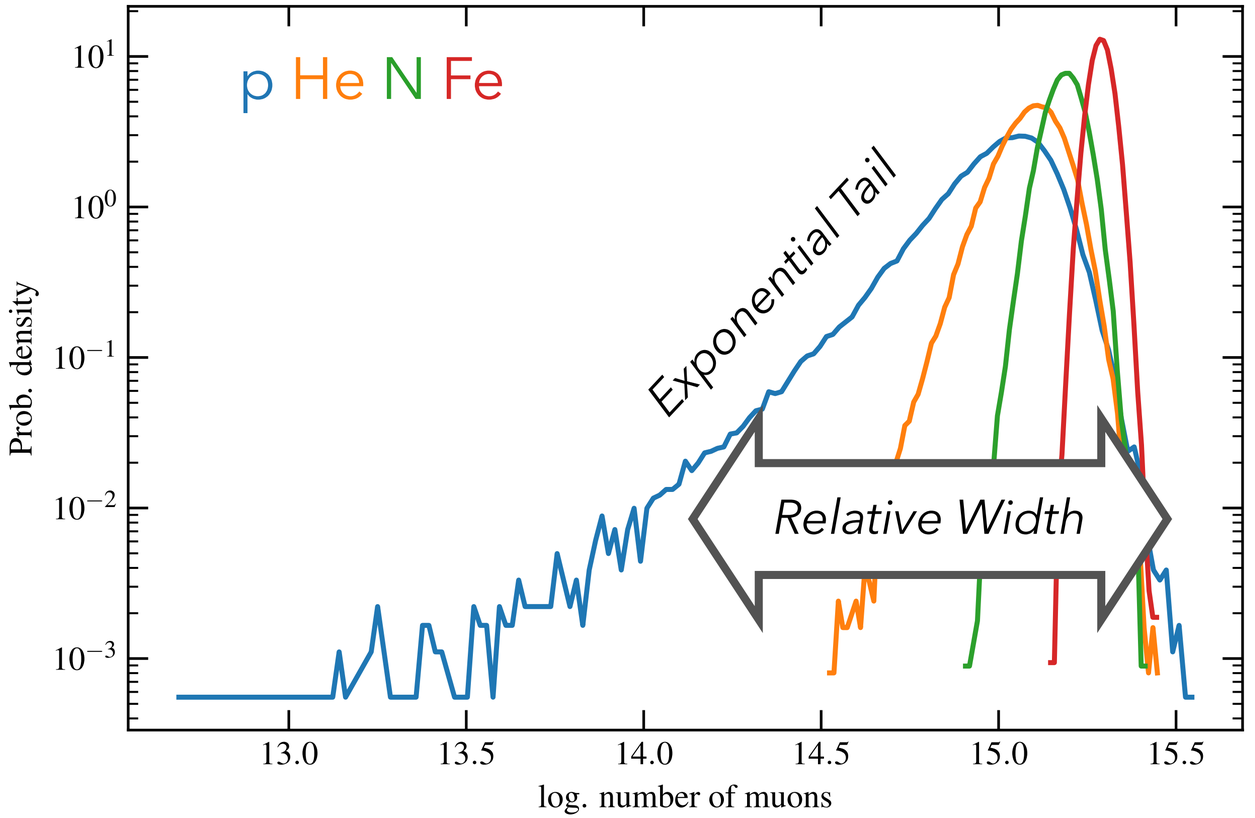
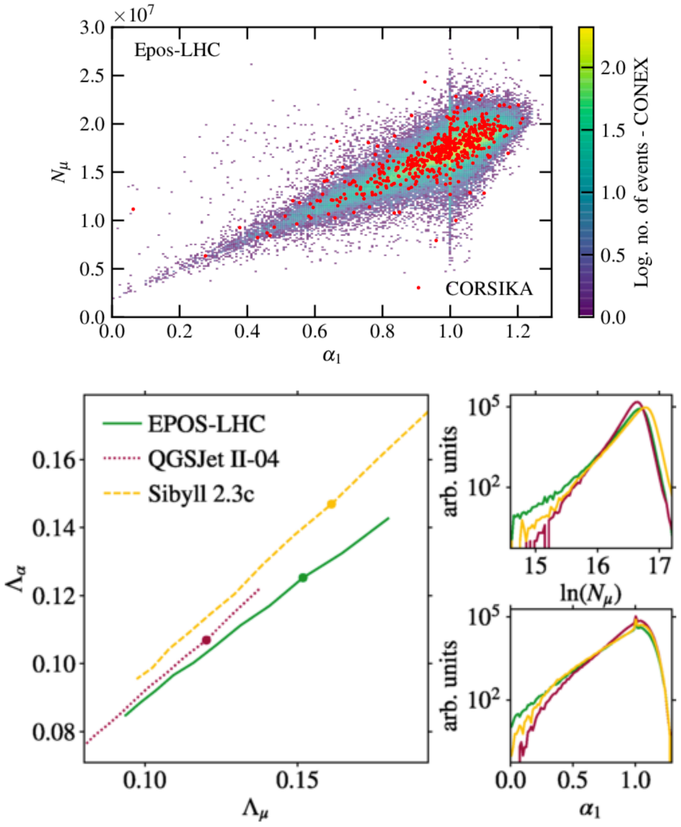
Accessing the first interaction

L. Cazon, RC, F. Riehn, PLB 784 (2018) 68-76

L. Cazon, RC, M. Martins, F. Riehn,Phys.Rev.D 103 (2021) 2, 022001







The shape and relative fluctuations of the muon number distribution gives access to the properties of the **FIRST hadronic interaction** (fraction of energy carried by neutral pions)

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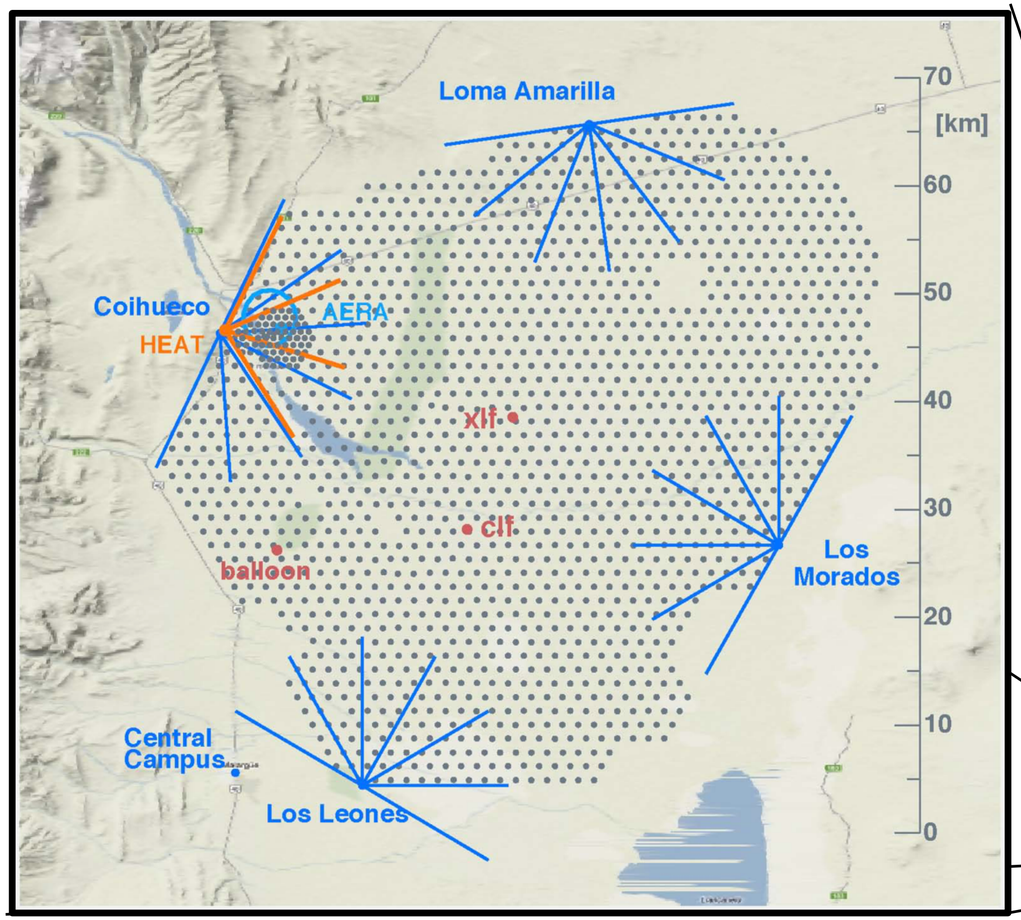
Detection Techniques

The Pierre Auger Observatory as a case study for the Cosmic Ray indirect detection field

Pierre Auger Observatory



Area: 3000 km^2

Pampa Amarilla, Mendoza, Argentina

Altitude: 1400 m a.s.l.

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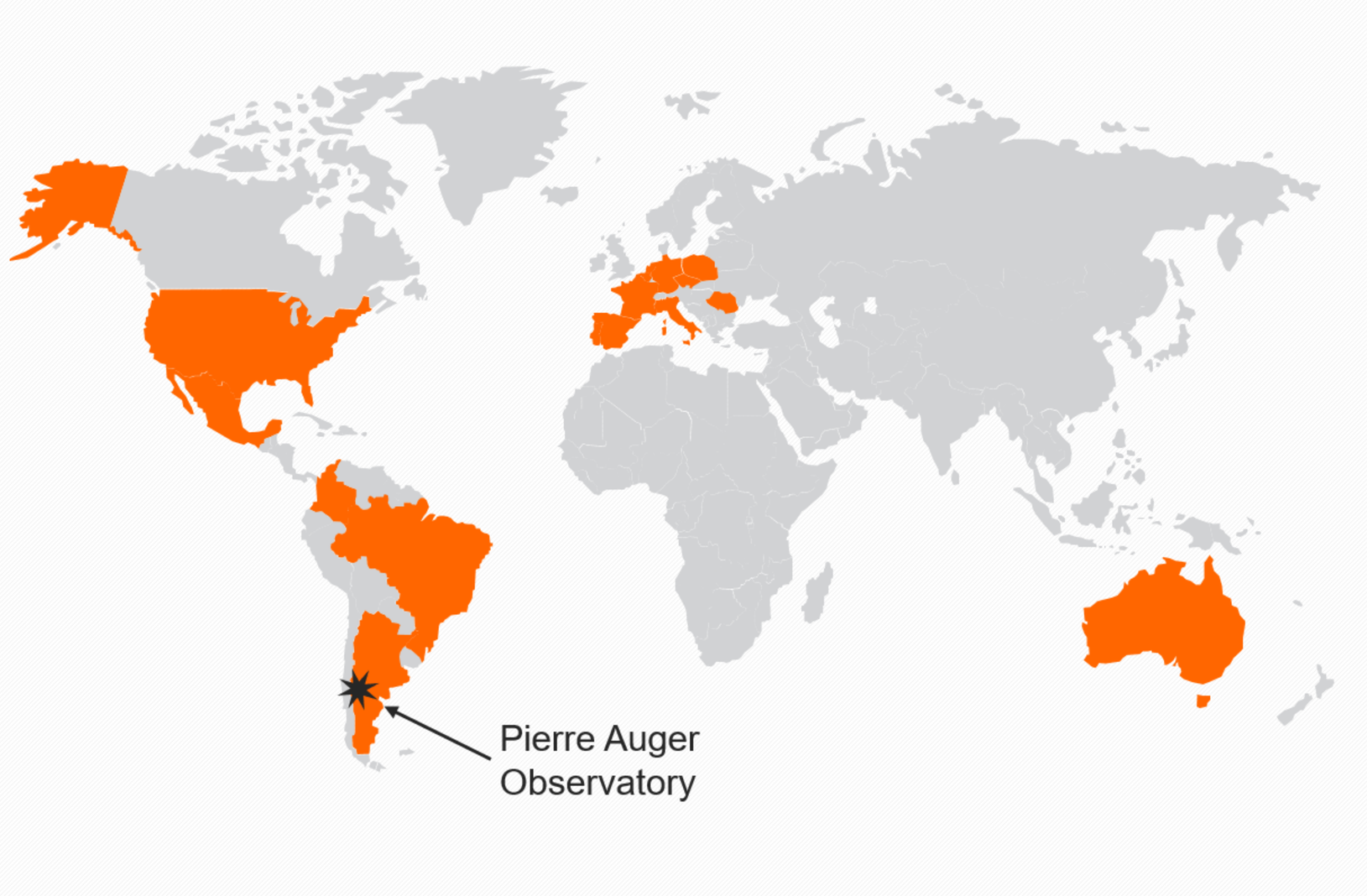
Pierre Auger Collaboration

Argentina
Australia
Belgium
Brazil
Colombia
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Romania
Slovenia
Spain
USA



International collaboration of 17 Countries and ~ 400 scientists

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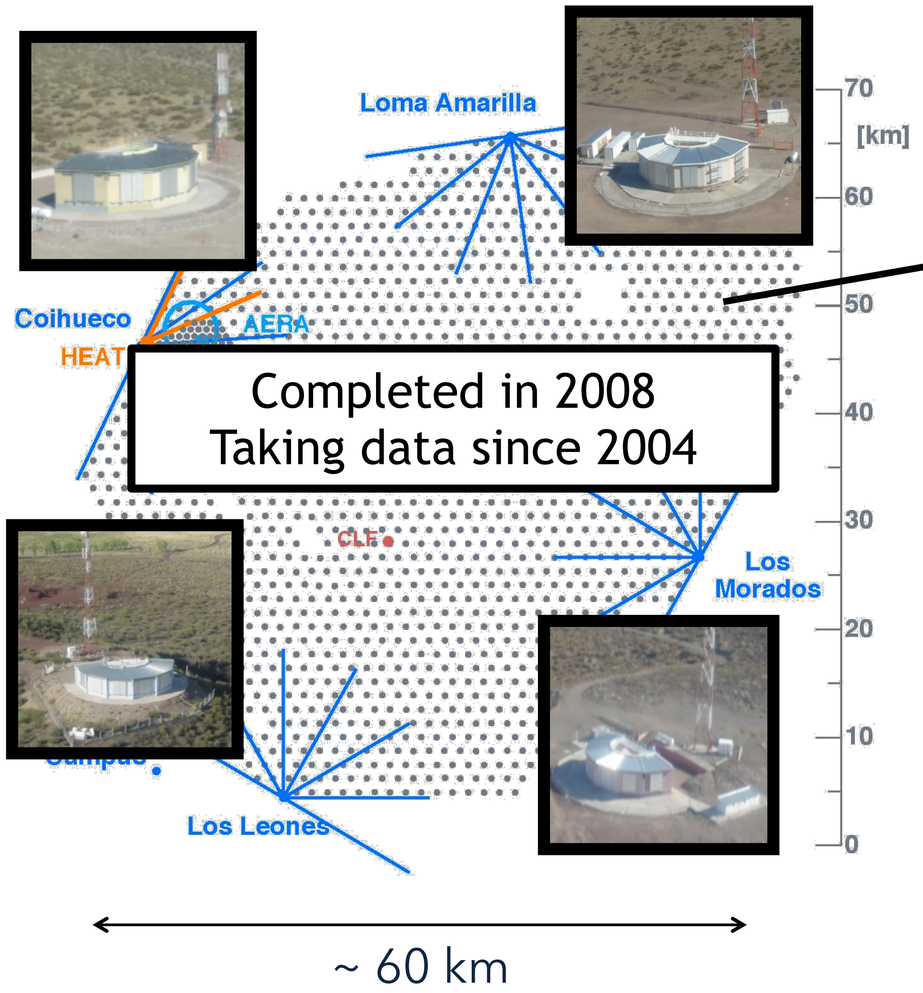
Pierre Auger Observatory



- ~ 1600 Surface detectors (SD)
- In a 1.5 km hexagonal grid
- 3000 km^2

- 4 Fluorescence Detectors (FD)
- 6 x 4 + 3 Fluorescence Telescopes

Built to detect and study the extremely rare UHECR

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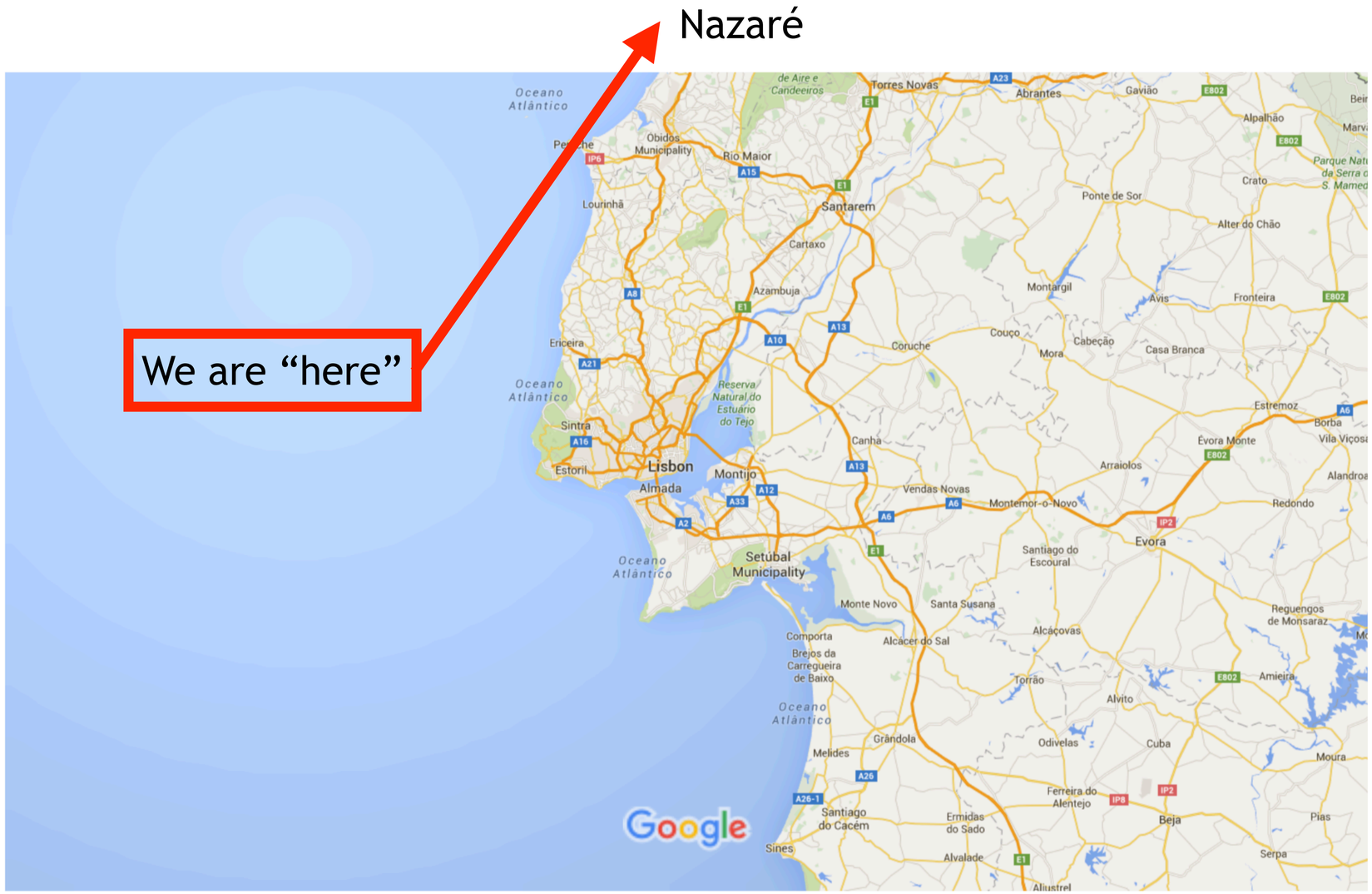
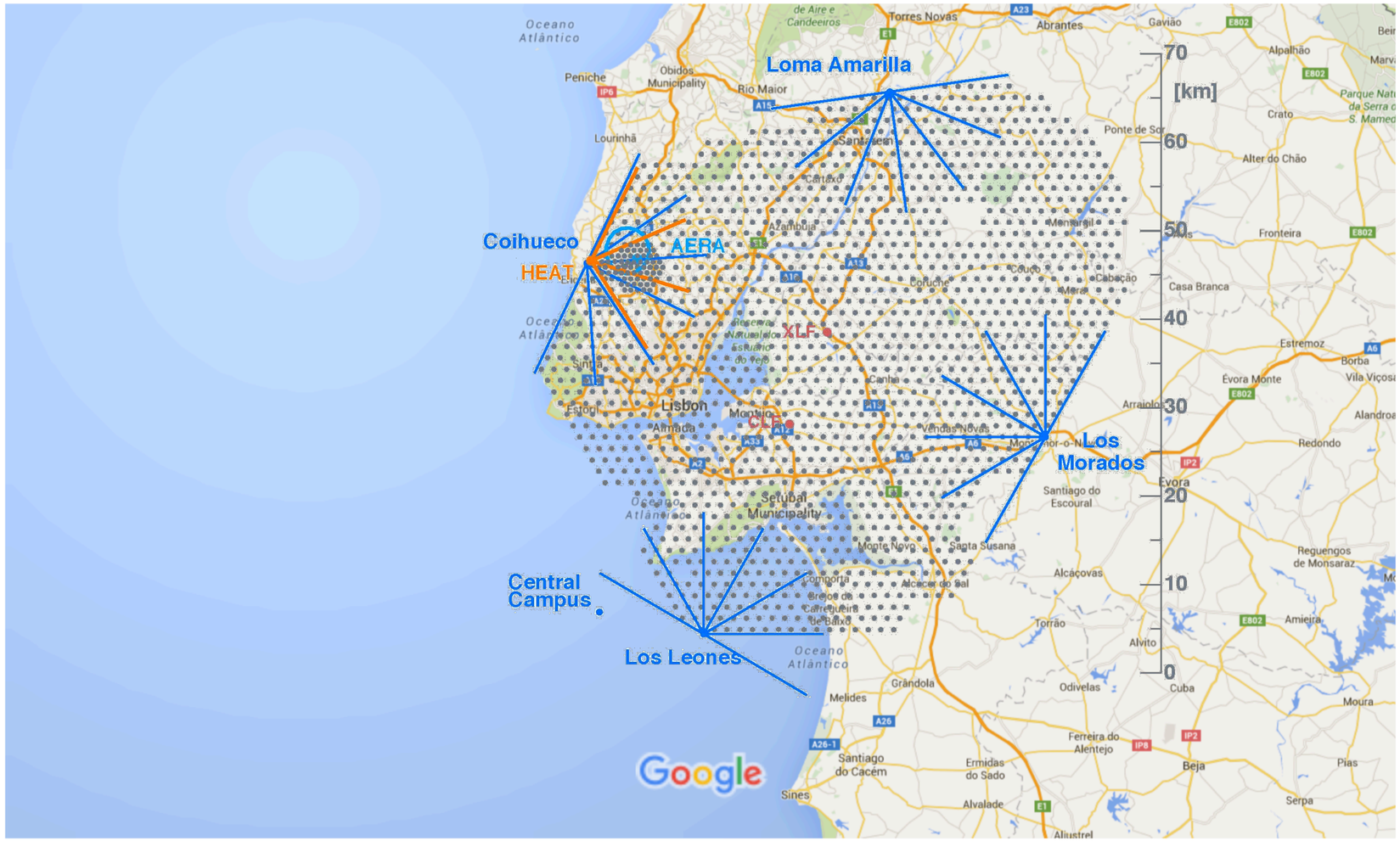
What’s the size of the Observatory?



Really big!!



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Pierre Auger Observatory

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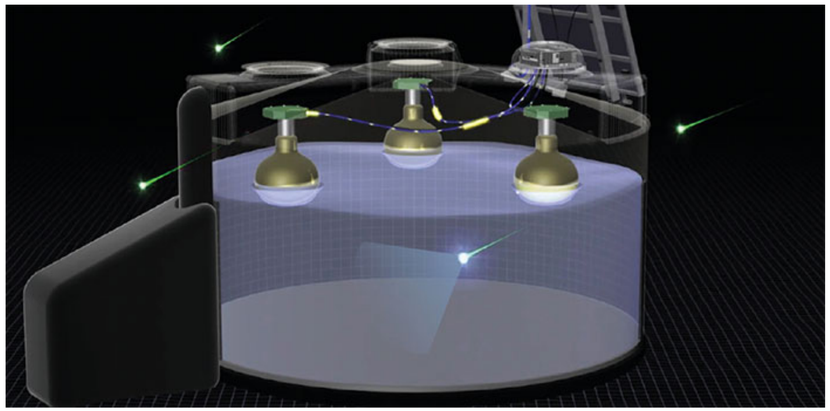
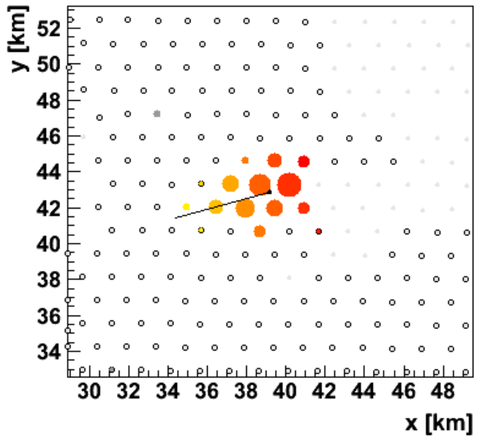
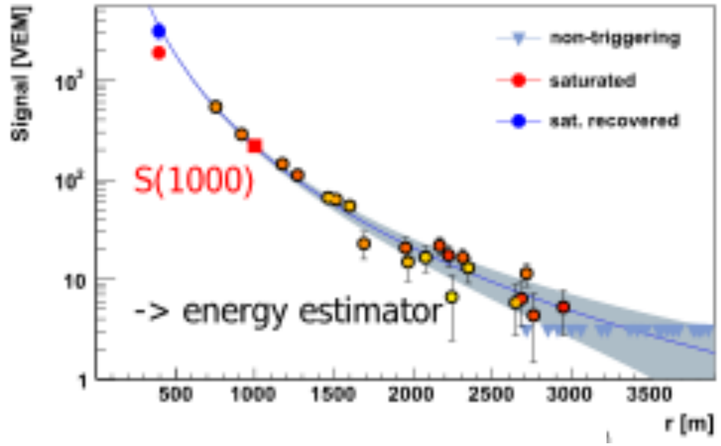
Surface Detectors (SD)

Surface Detectors

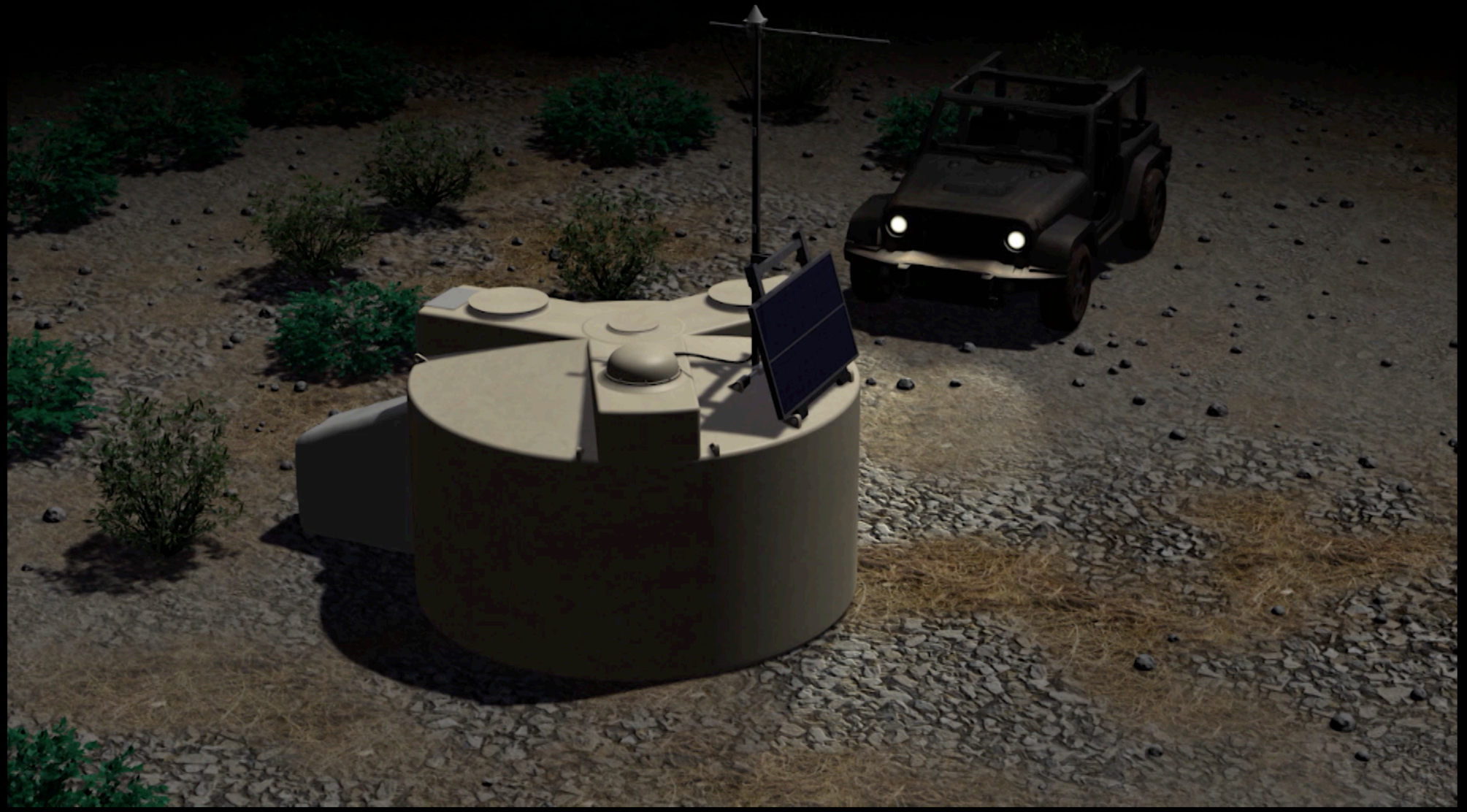
- Sample shower secondary particles reaching the ground
  - 100% duty cycle
  - Arrival time → primary cosmic ray direction
  - Energy estimation: signal at 1000 meters from the shower core







Water Cherenkov Detector (WCD)



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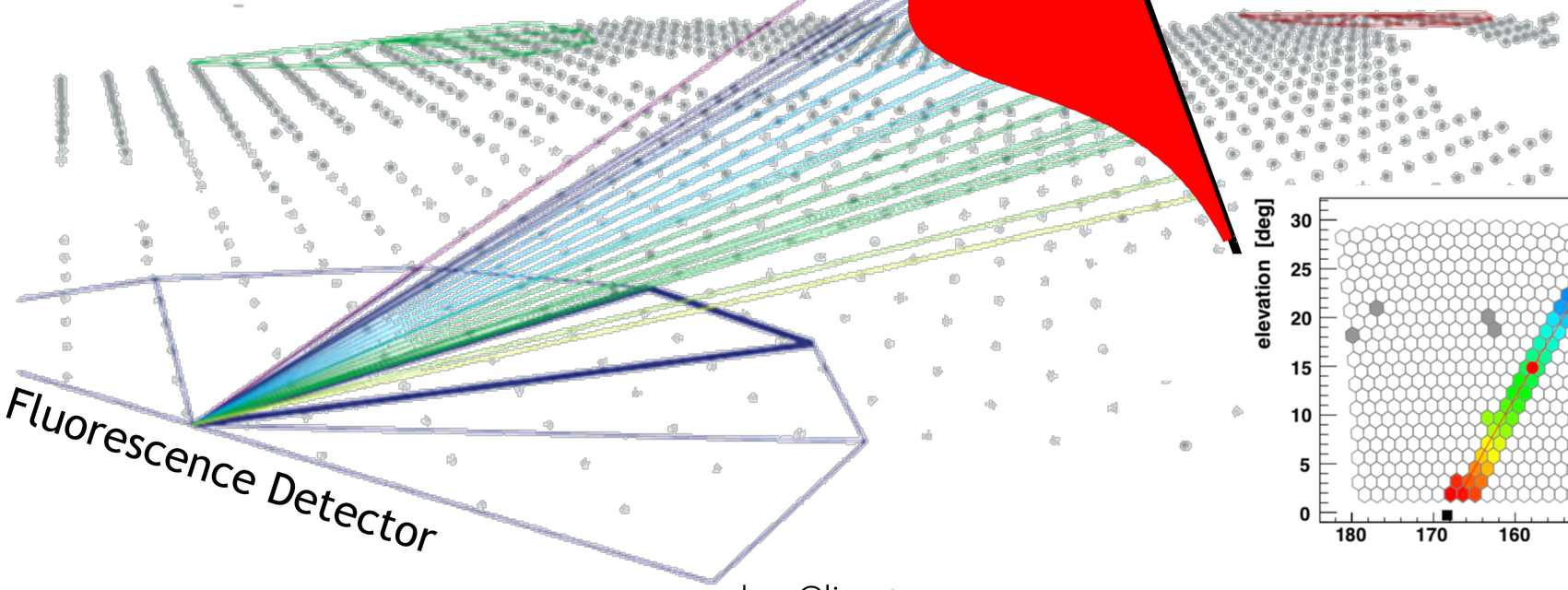
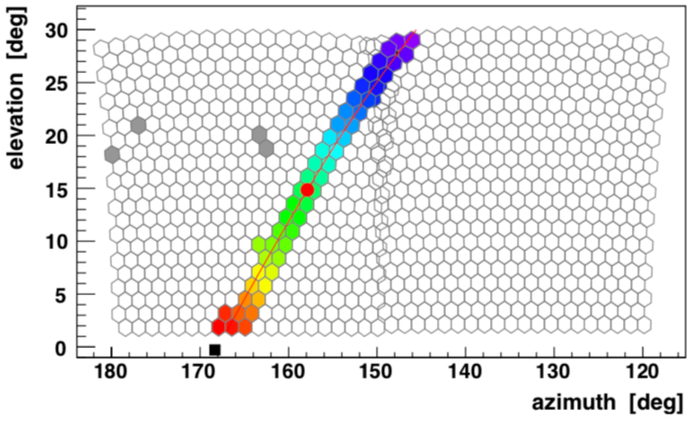
Fluorescence Detector

- FD: collects the fluorescence light produced by the shower development
- Only operate in moonless clear sky nights (~15% duty cycle)
  - Energy → integral of the collected photons
  - Primary composition → Shower maximum depth





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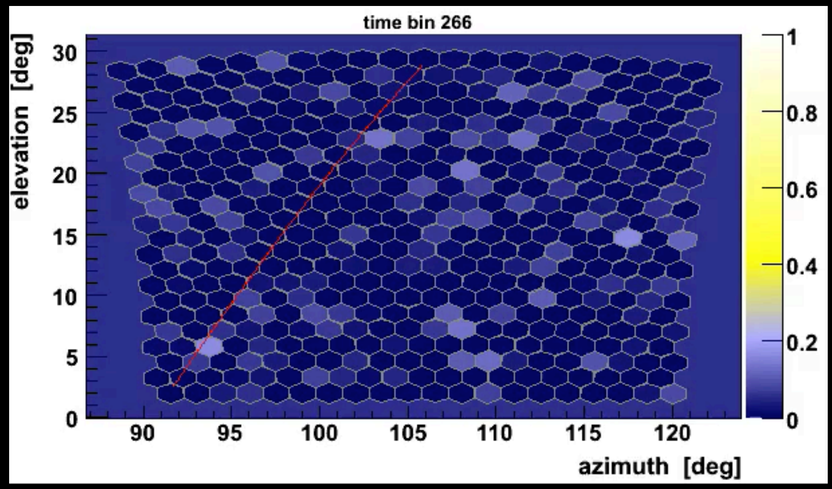
Fluorescence Detector



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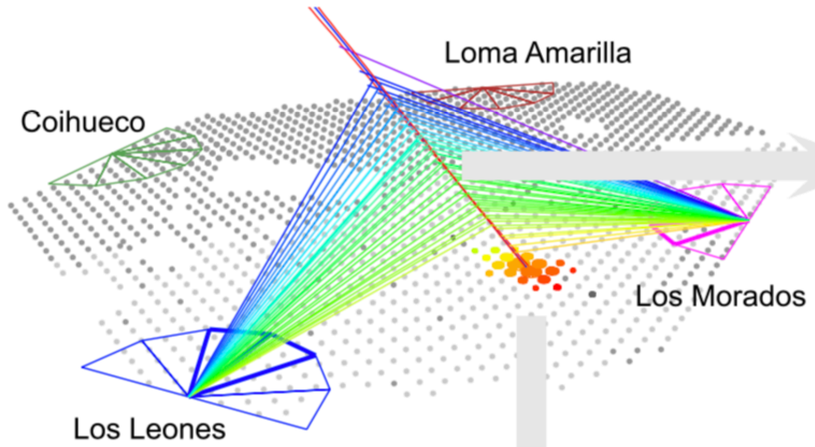
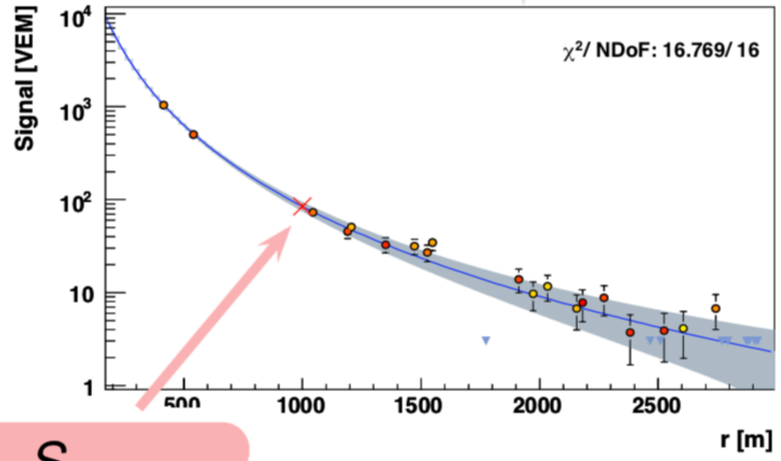
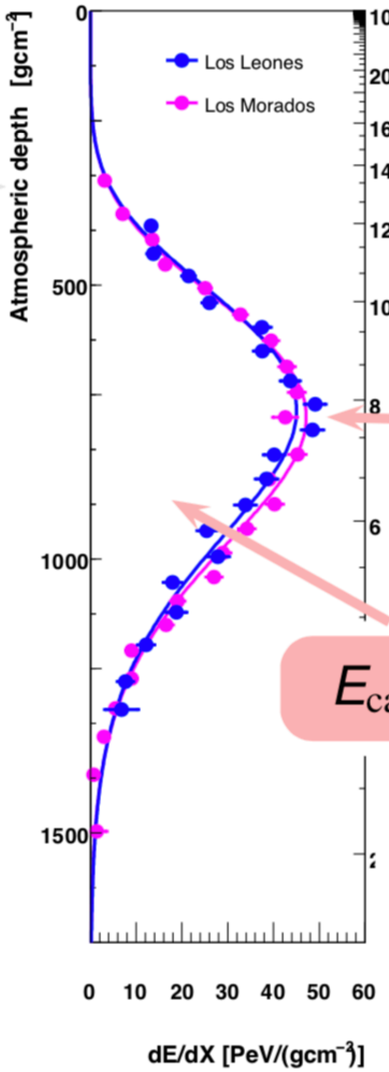
Hybrid Technique (FD + SD)





S_{1000}

$E_{\text{surface}} = f(S_{1000}, \theta)$

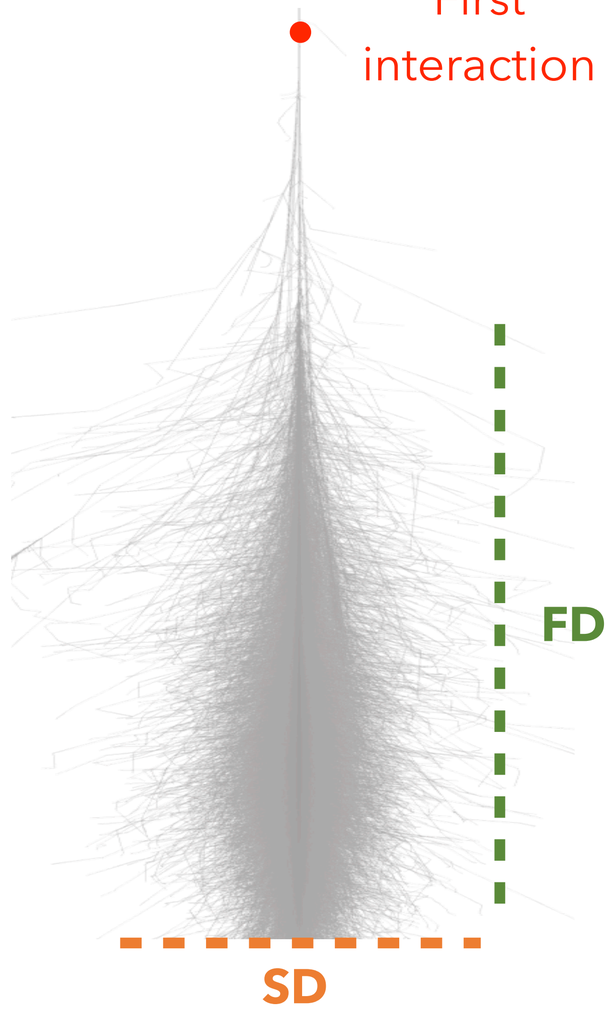


$\sigma X_{\max} \leq 20\ \mathrm{g/cm^2}$
$\Delta_{\text{sys}} \leq 10\ \mathrm{g/cm^2}$

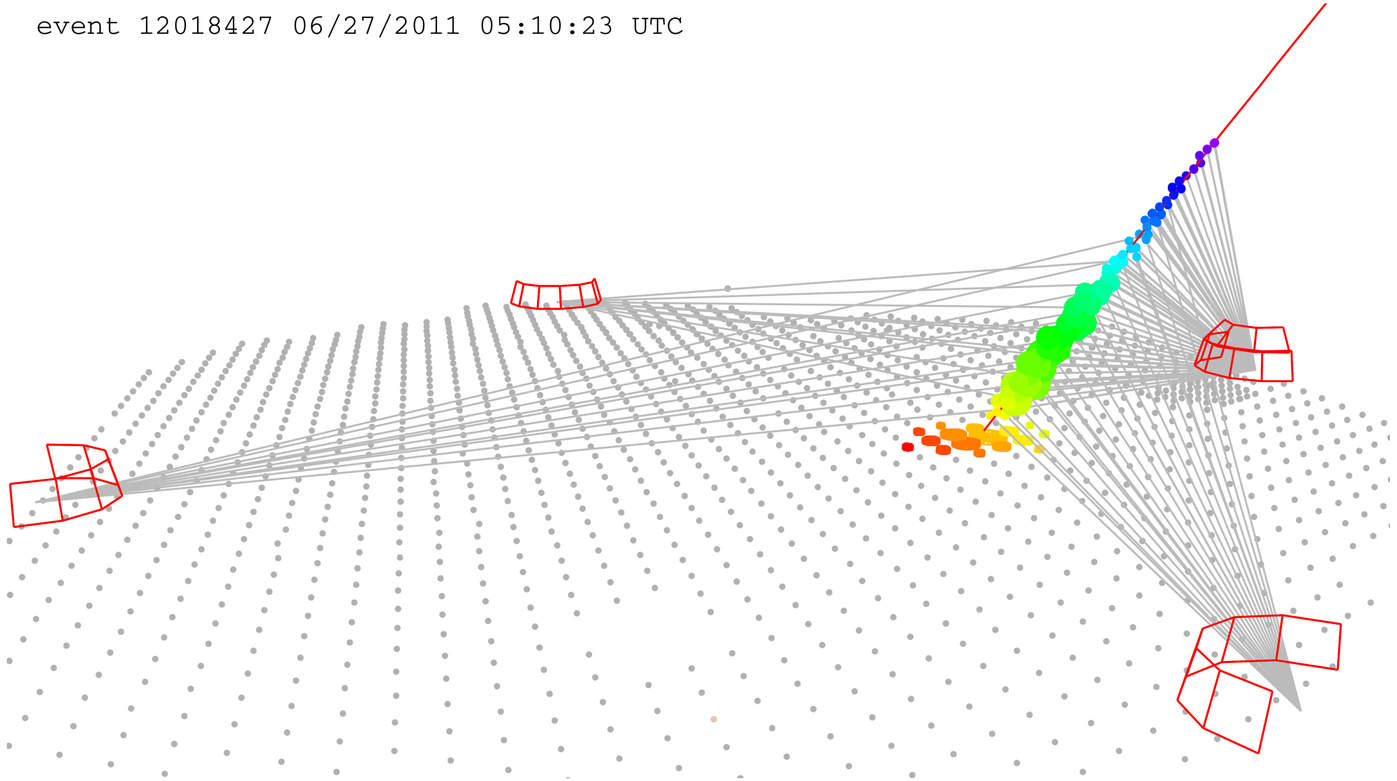
$X_{\max}$

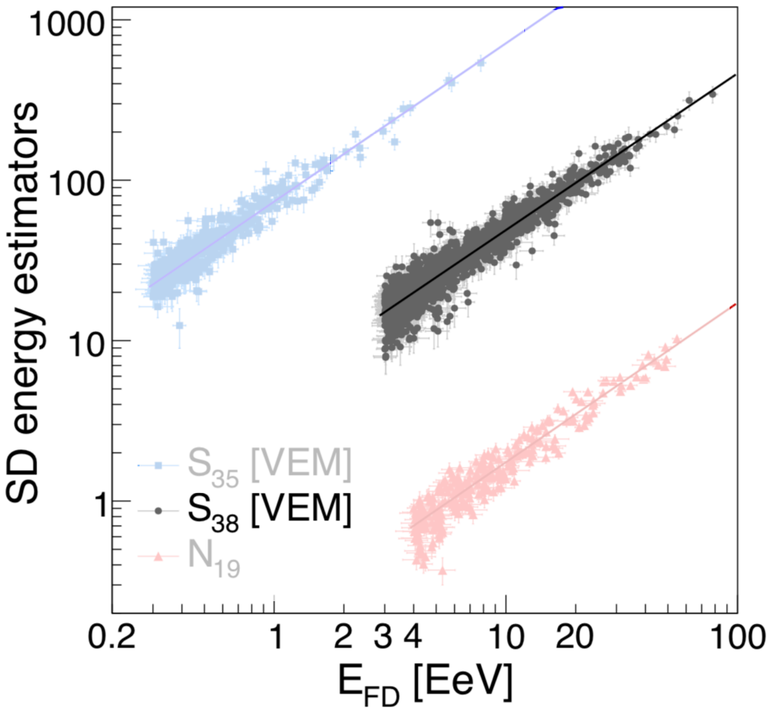
$E_{\text{cal}} = \int \frac{dE}{dX}\, dX$

$\sigma_E/E \sim 8\,\%$
$\Delta_{\text{sys}} \approx 15\,\%$



Hybrid technique (FD + SD)





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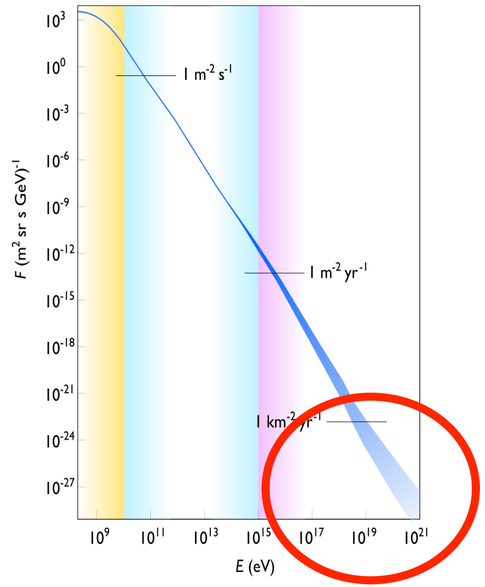
Ultra High Energy Cosmic Rays

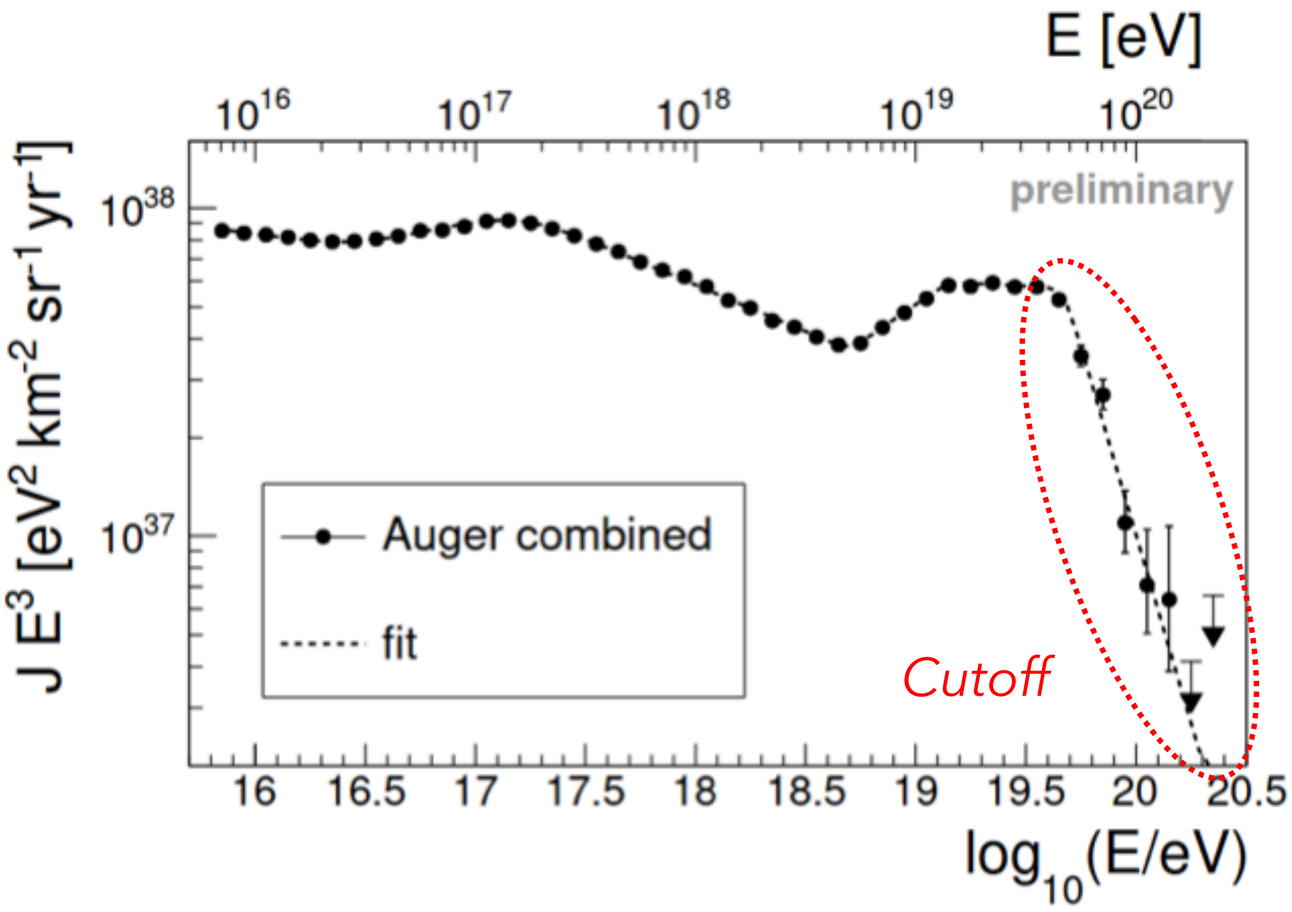
What have we learned so far?

UHECR energy spectrum

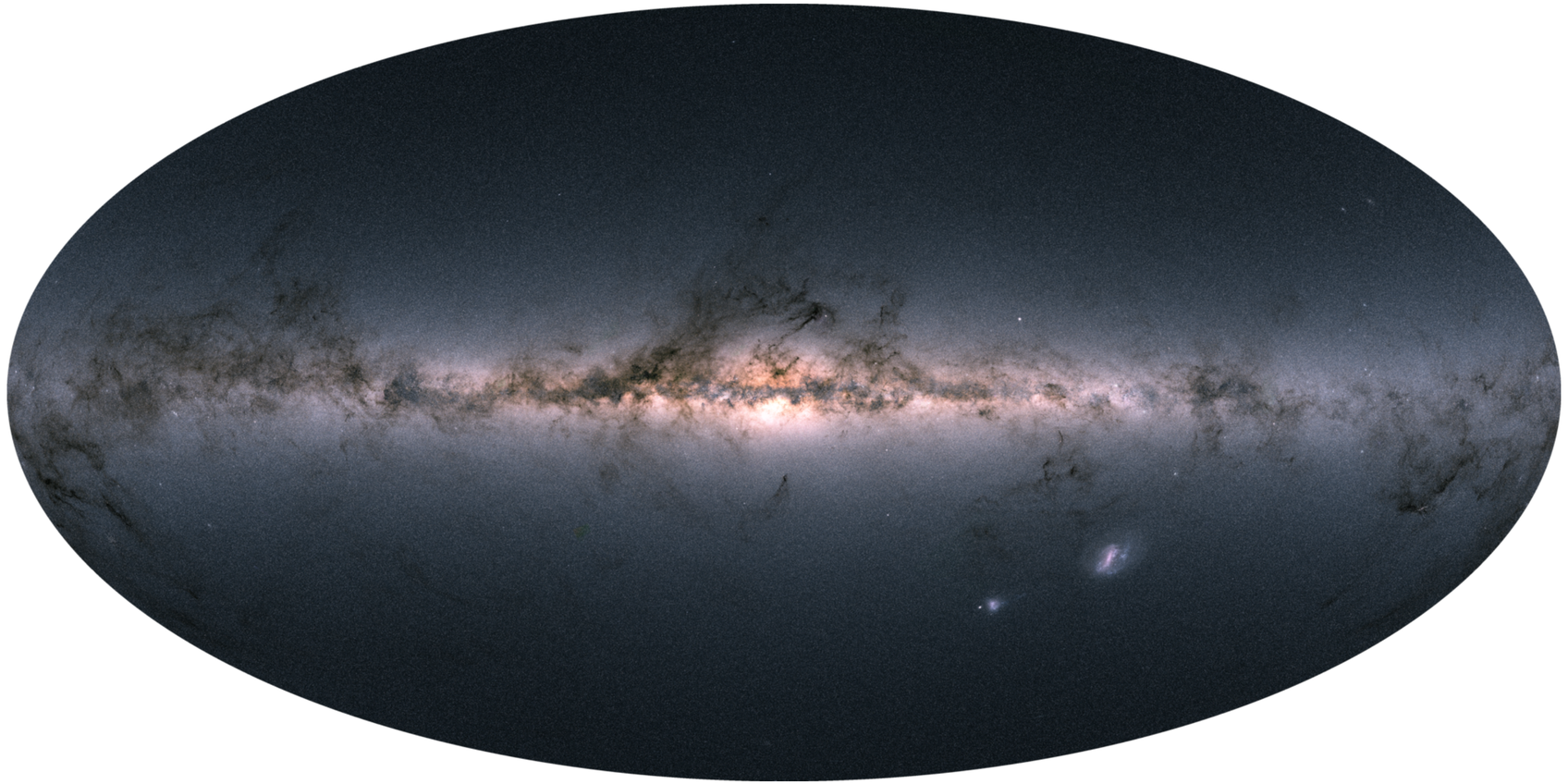


Put strong constraints on UHECR production and propagation

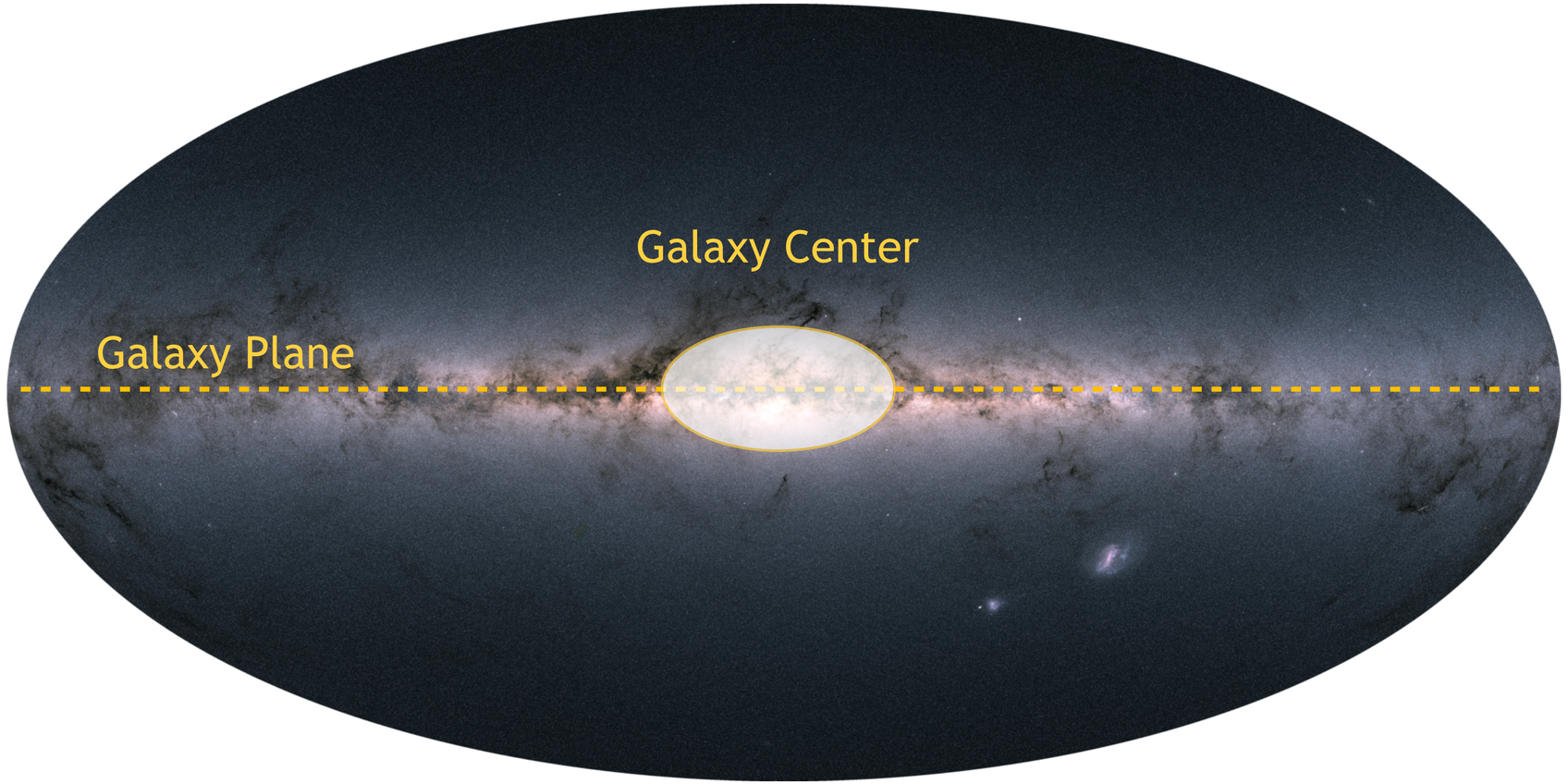
Pierre Auger Collaboration, ICRC this year



Are UHECRs produced in our galaxy?



Are UHECRs produced in our galaxy?



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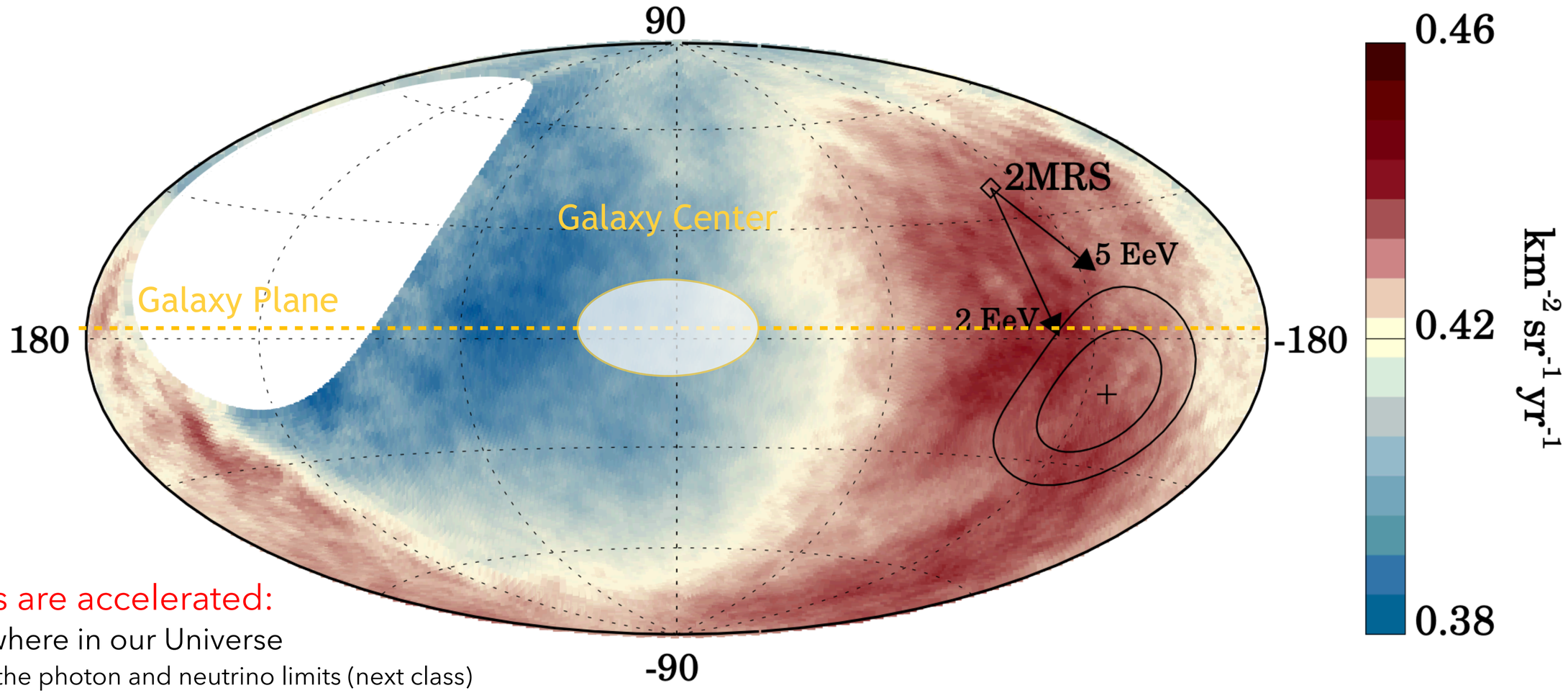
UHECR have an extra-galactic origin

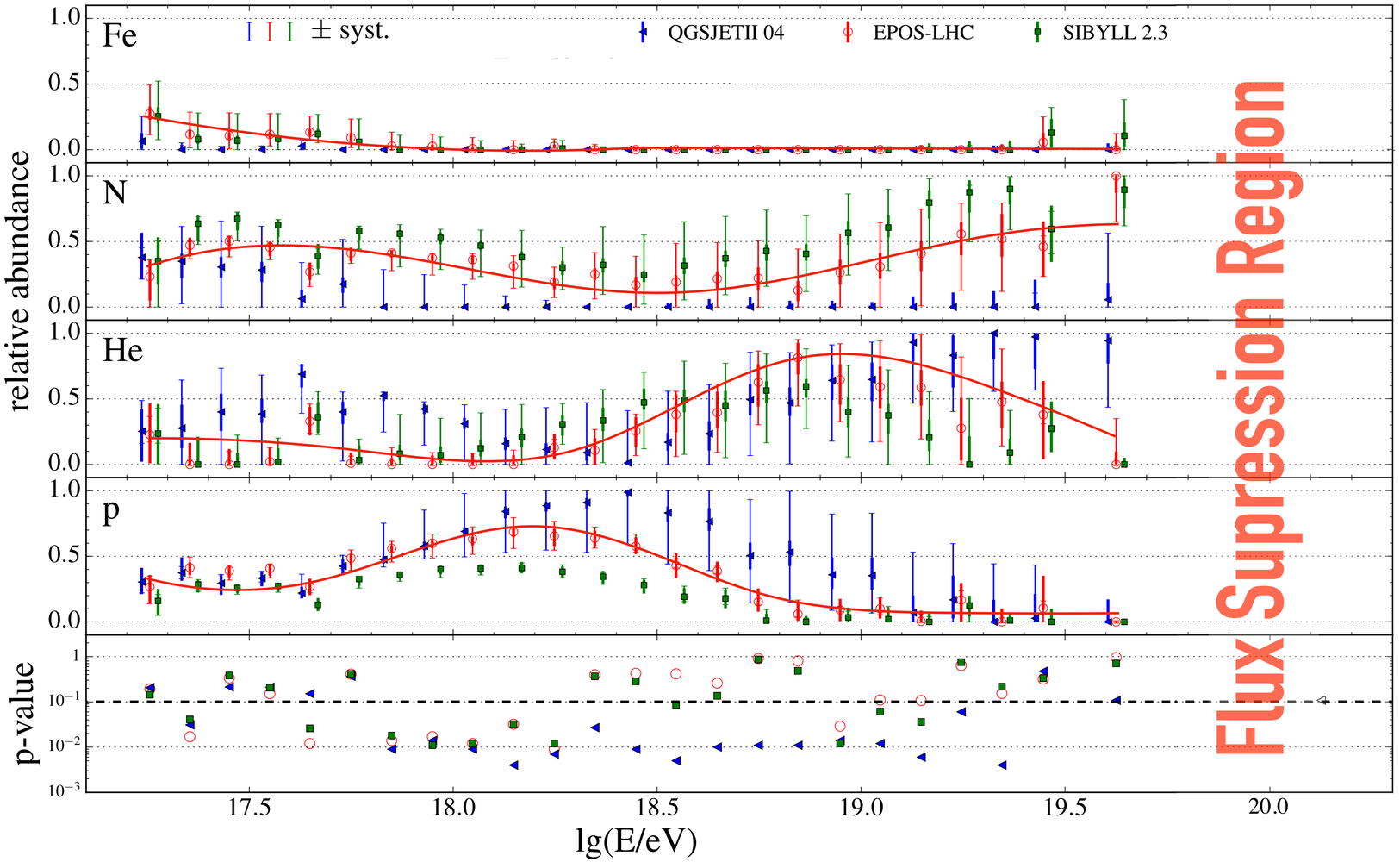
Science 357 (2017) no.6537, 1266-1270

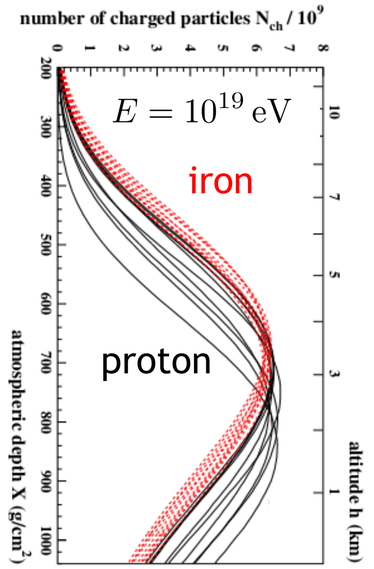


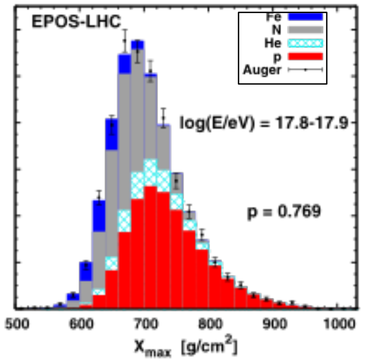
- UHECRs are accelerated:
  - somewhere in our Universe
    - from the photon and neutrino limits (next class)
  - Outside the galaxy

Composition fits to X_{max}

35th ICRC, PoS (2017) 506







*The primary **composition** goes from **light to heavier** as its energy increases*

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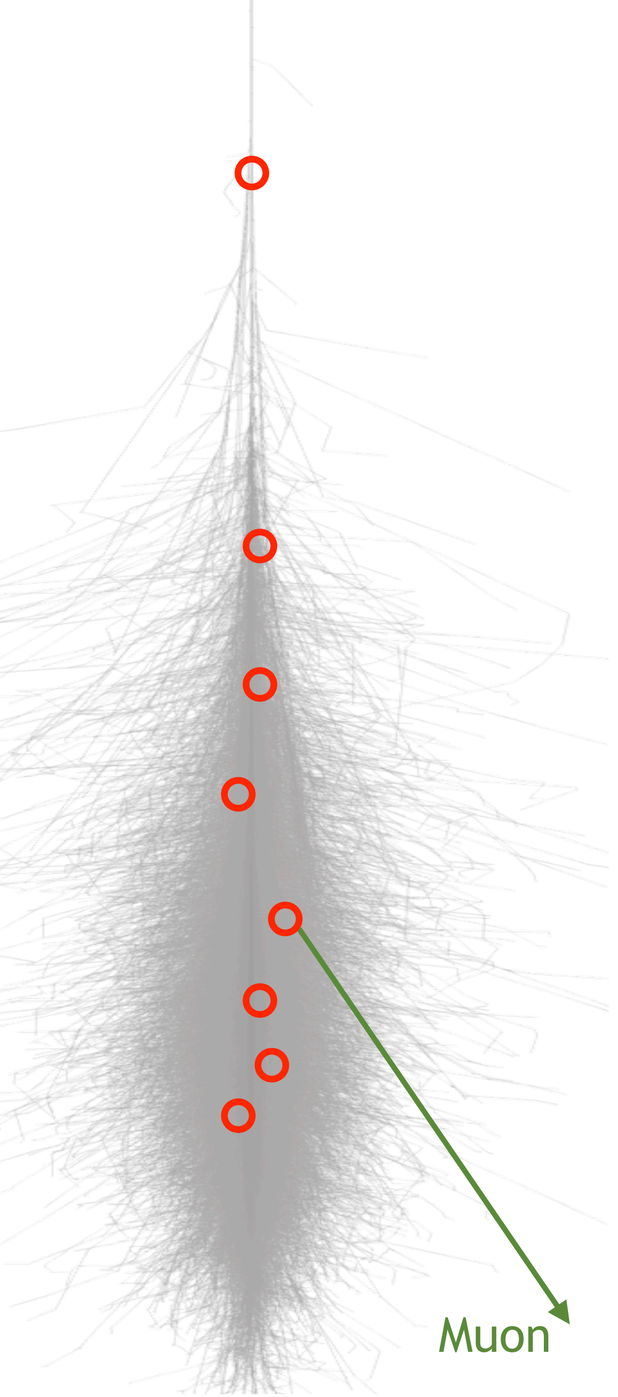
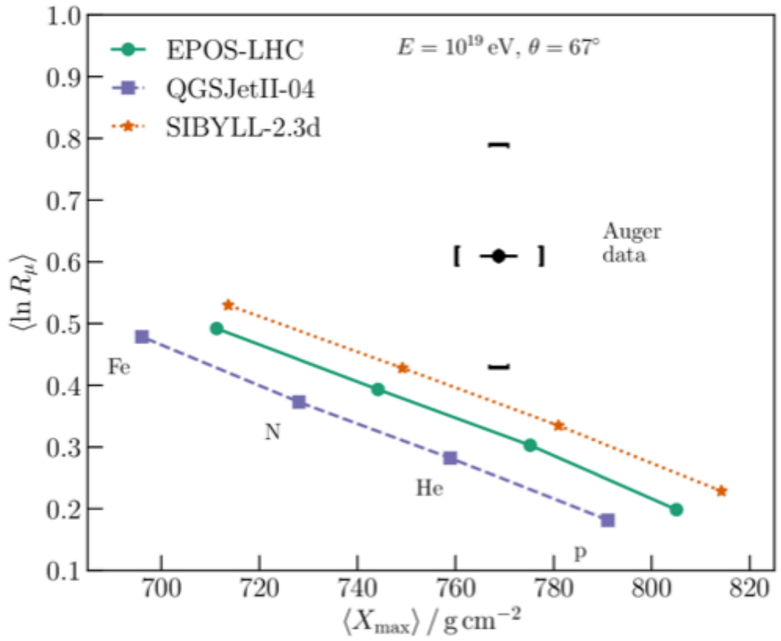
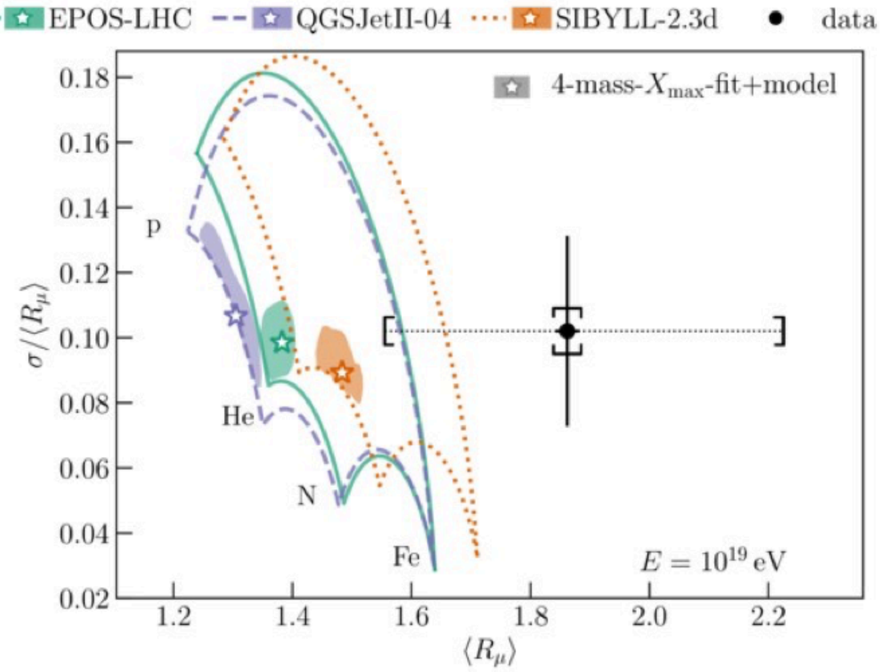
Shower description



Phys.Rev.Lett. 126 (2021) 15, 152002





Combination of different measurements **reveals tension between data and all hadronic interaction models**

Relative fluctuations suggests that **discrepancy** might be related to hadronic **low energy interactions** in the shower

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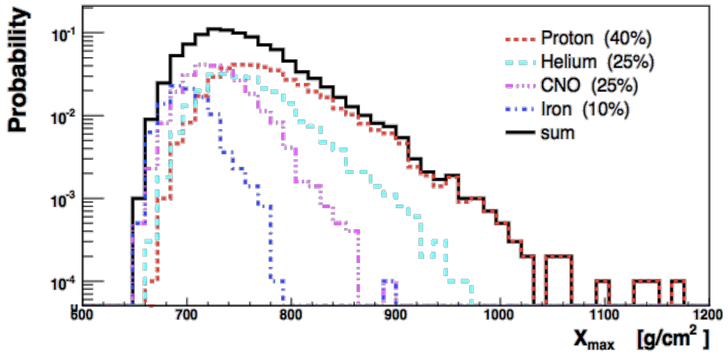
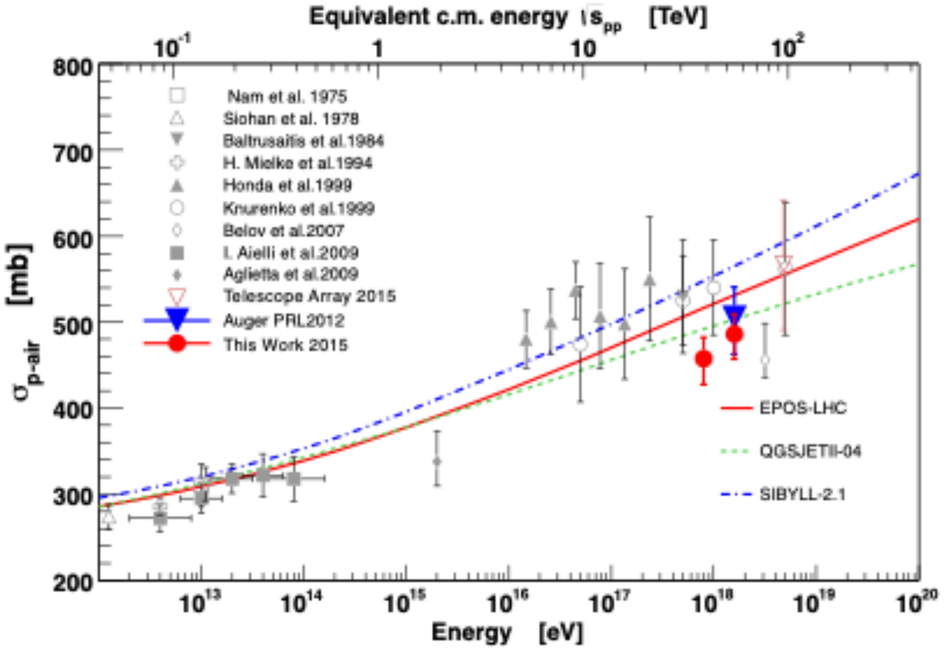
Proton-air cross-section

34th ICRC, PoS (2015) 401

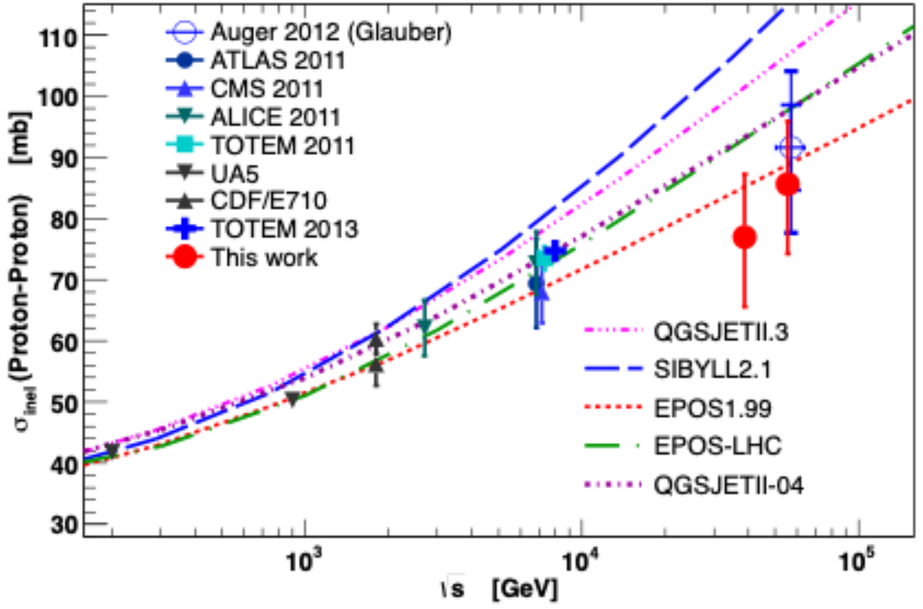
- p-Air cross-section can be extracted from the X_{max} distribution tail
  - If there is a large fraction of protons



Proton-Air Cross-section



Proton-proton Cross-section



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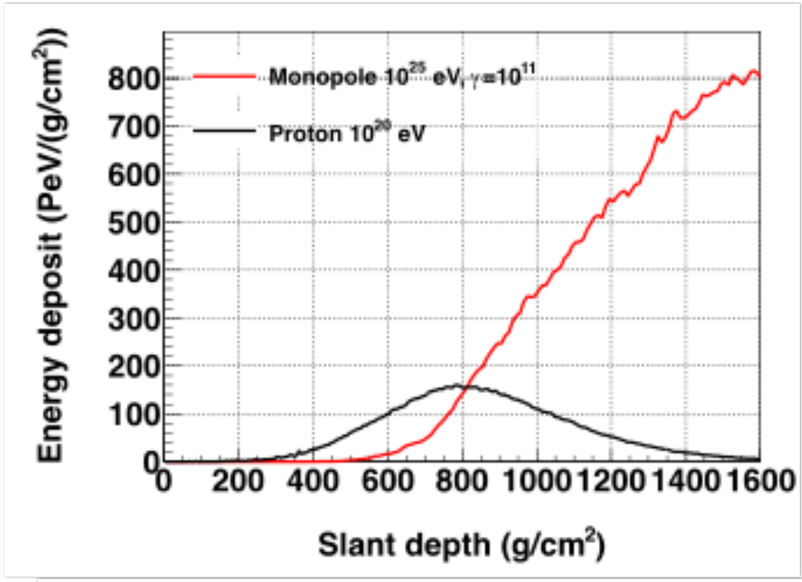
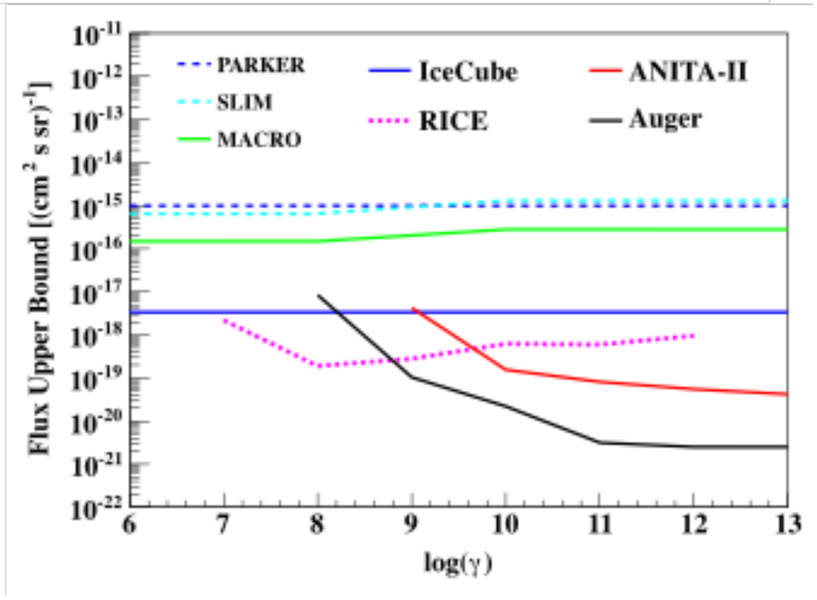
Testing exotic scenarios

Phys.Rev. D94 (2016) no.8, 082002

- Put the strongest limit on the existence of ultra-relativistic magnetic monopoles (MM)
  - Test on fundamental particle physics exotic scenarios
    - Relics of phase transitions in the early universe

- MM produce air showers with a distinct signature from standard ones
  - Should be easily observed by the Auger FD
  - $E_{mon} \approx 10^{25}\,\mathrm{eV}$
  - $M_{mon} \in [10^{11}; 10^{16}]\,\mathrm{eV/c^2}$





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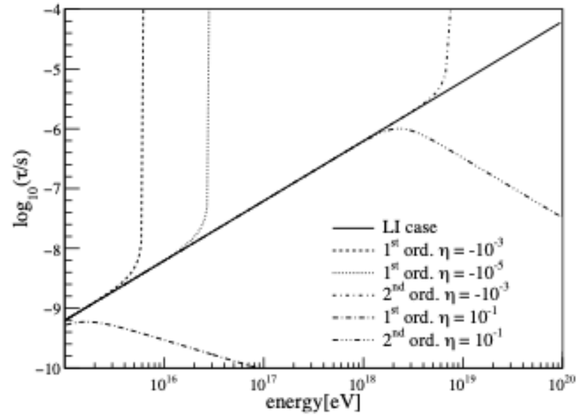
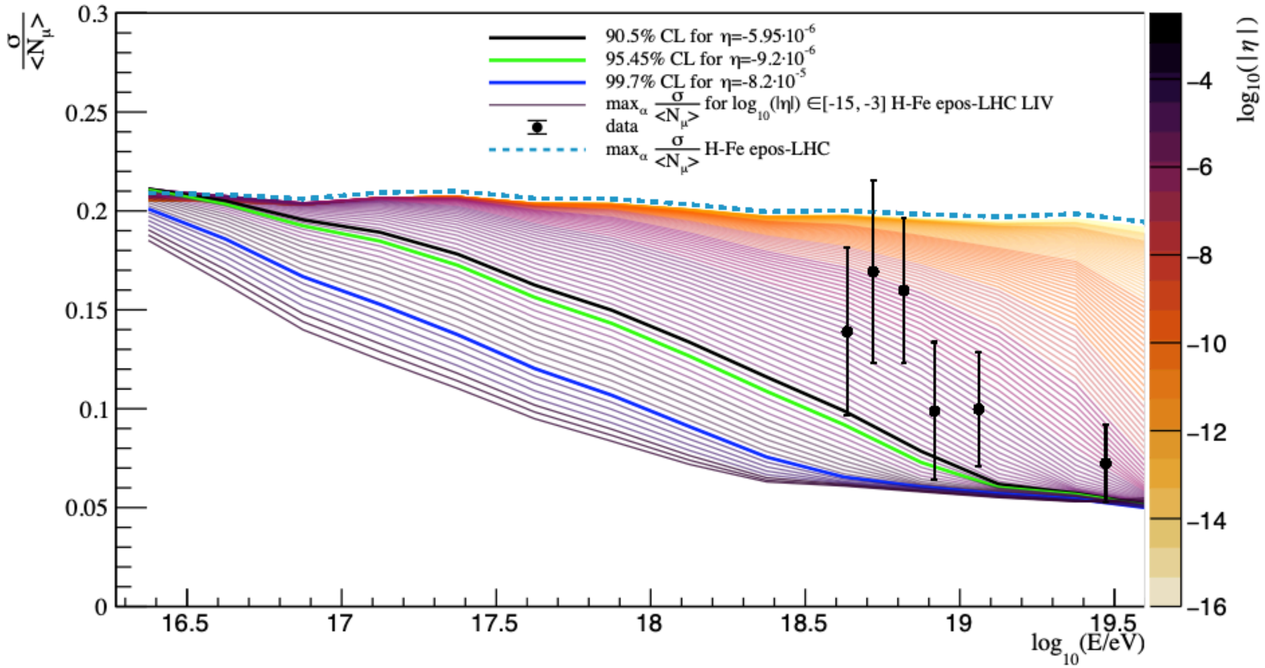
Lorentz Invariance Violation

- LIV is predicted by many Quantum Gravity theories
- Change the dispersion relation in a phenomenological way and see impact in shower observables

$$E^2 - p^2 = m^2 + \eta^{(n)} \frac{p^{n+2}}{M_{\mathrm{Pl}}^{n+2}}$$

  - LIV doesn't allow the pi0 to decay immediately
- The fluctuations of the number of muons at the ground shows a high sensitivity to LIV
- Stringent cut for high energy interactions





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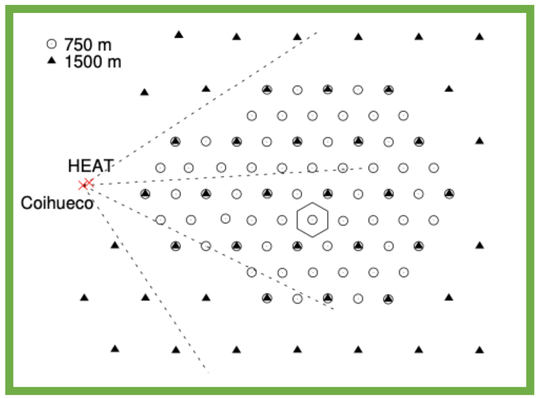
Next years of the Pierre Auger Observatory

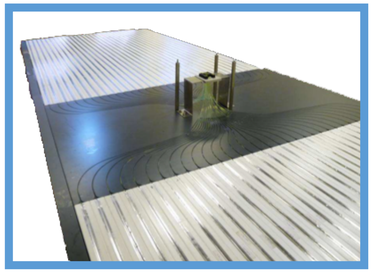
(A plethora of measurements to fully understand the shower)

HEAT

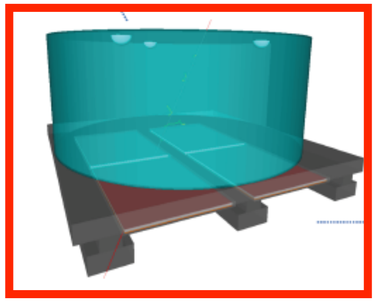


LHC c.m. energy equiv to first interaction

Radio



AMIGA



MARTA

Infill

Auger Prime (SSD)

10^{16} 10^{17} 10^{18} 10^{19} 10^{20} Energy [eV]

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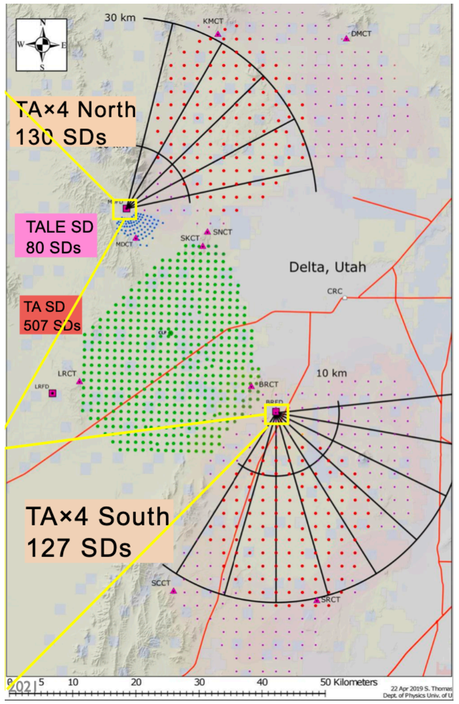
Other planned experiments…

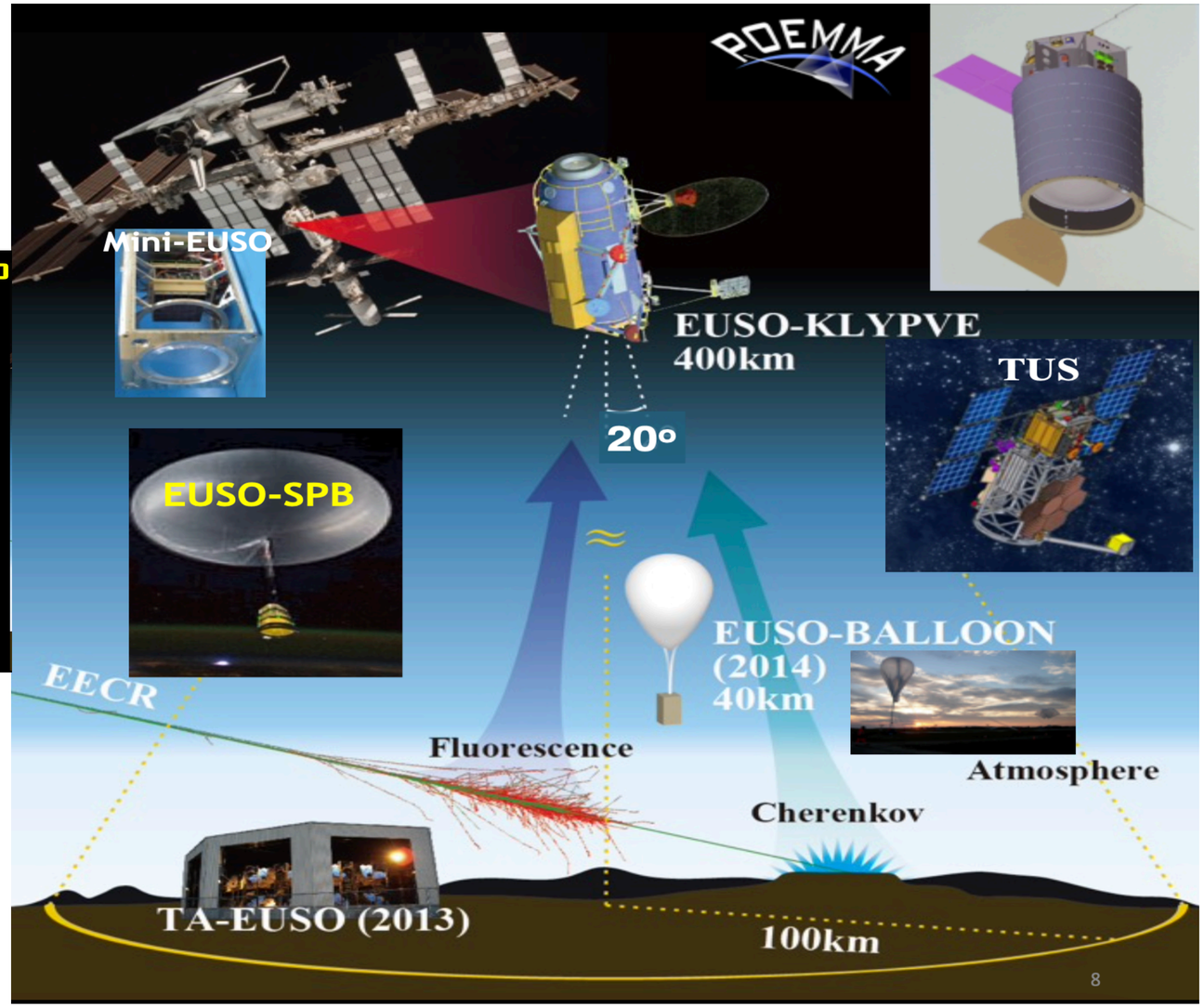
Dramatically increase the effective area

Full coverage of the sky



JEM-EUSO PROGRAM

- EUSO-TA (2013-)
- EUSO-Balloon (2014)
- TUS (2016-17)
- EUSO-SPB1 (2017)
- Mini-EUSO (2019 -)
- EUSO - SPB2 (2023)
- K-EUSO (2023+)
- POEMMA (2029+)



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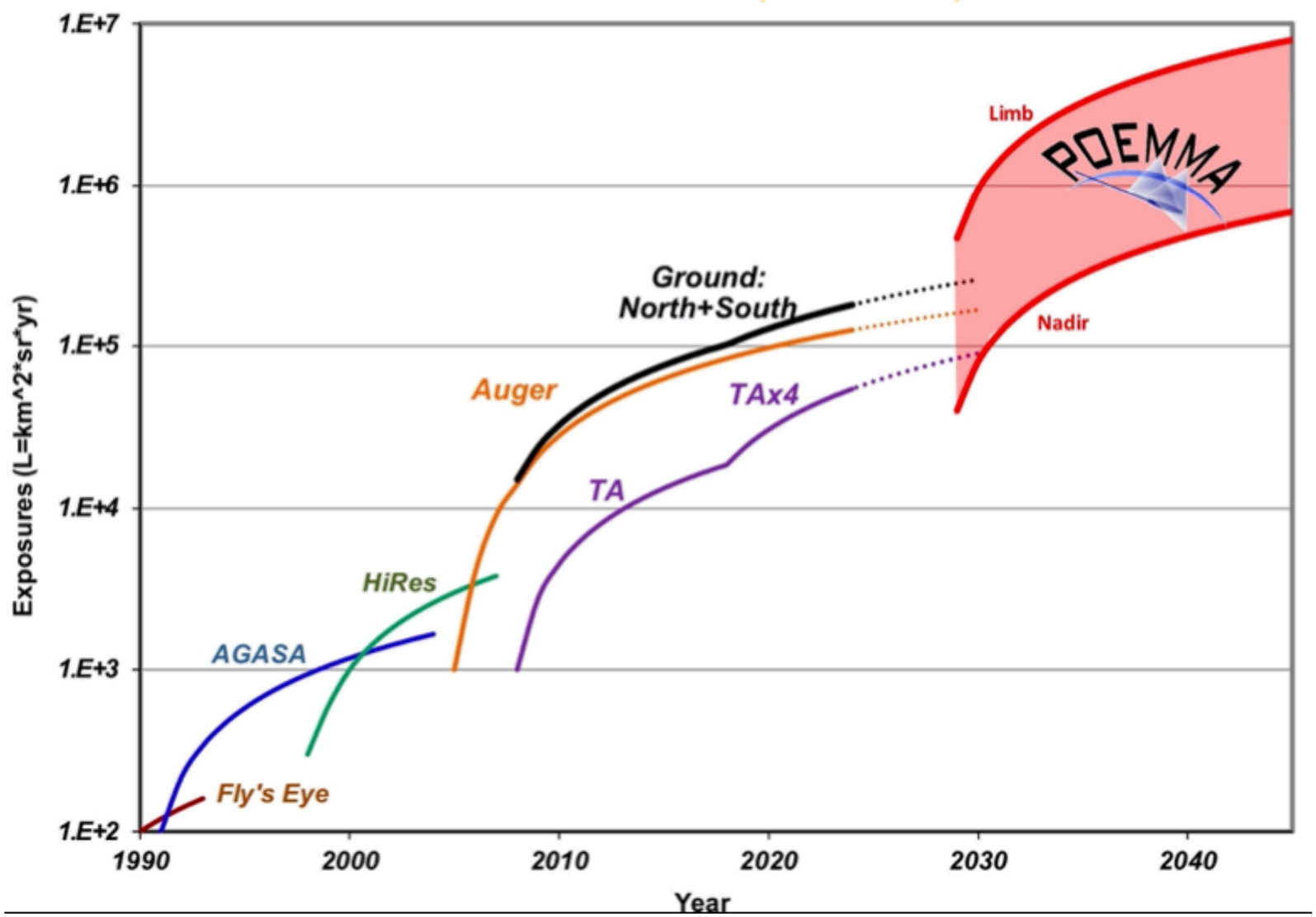
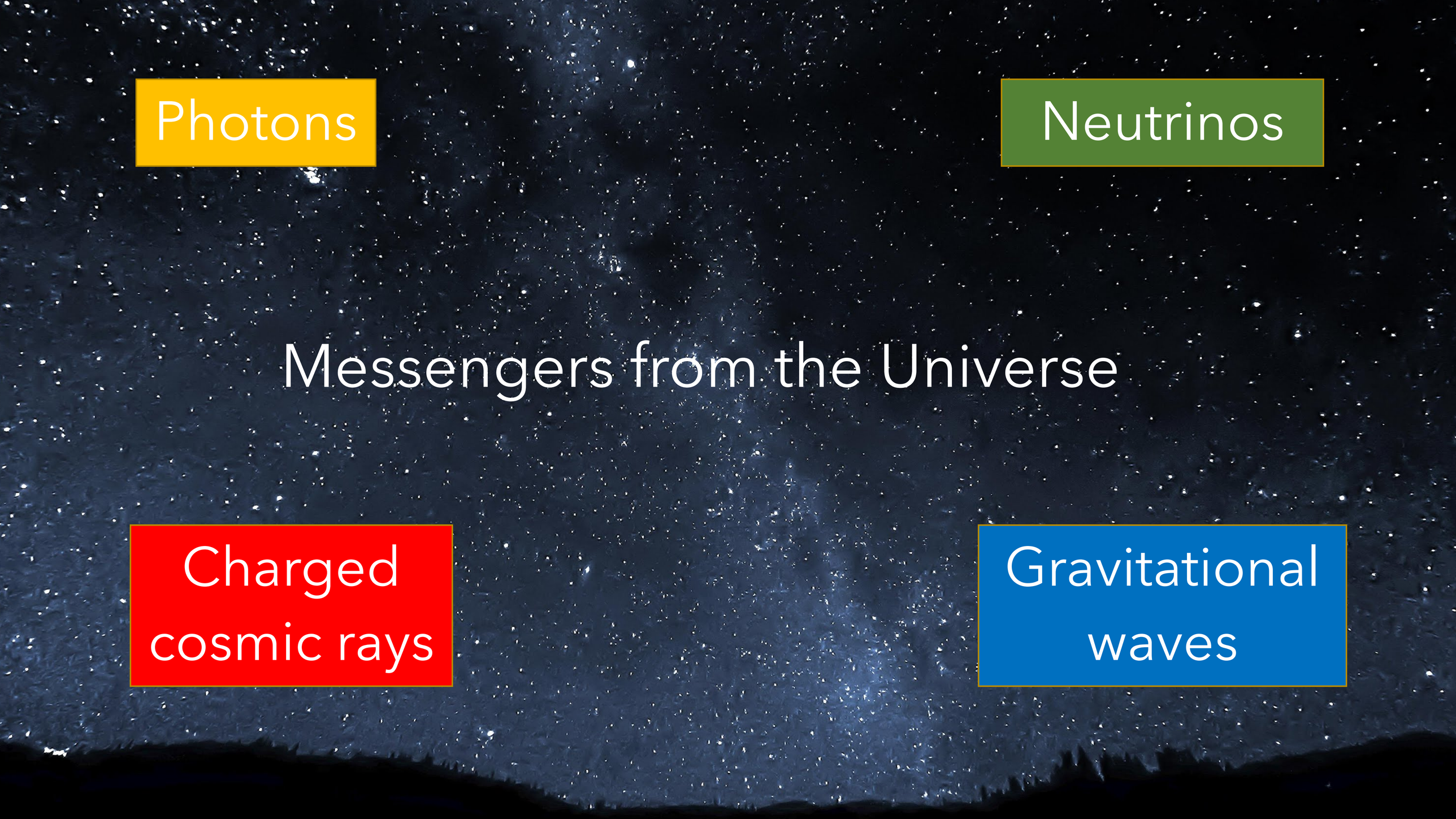
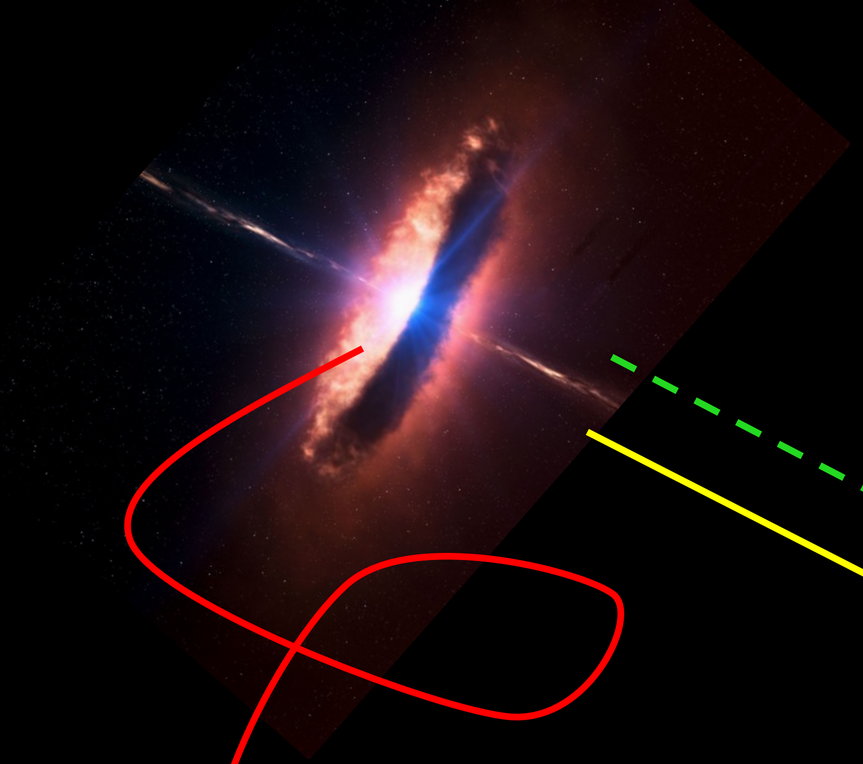
All about exposure…




Photons
Neutrinos
Messengers from the Universe
Charged cosmic rays
Gravitational waves

Complementarity



protons are deflected by the galactic magnetic fields

gammas travel in straight lines but can be absorbed in the way

neutrinos travel in straight lines b
are very difficult to detect

ν

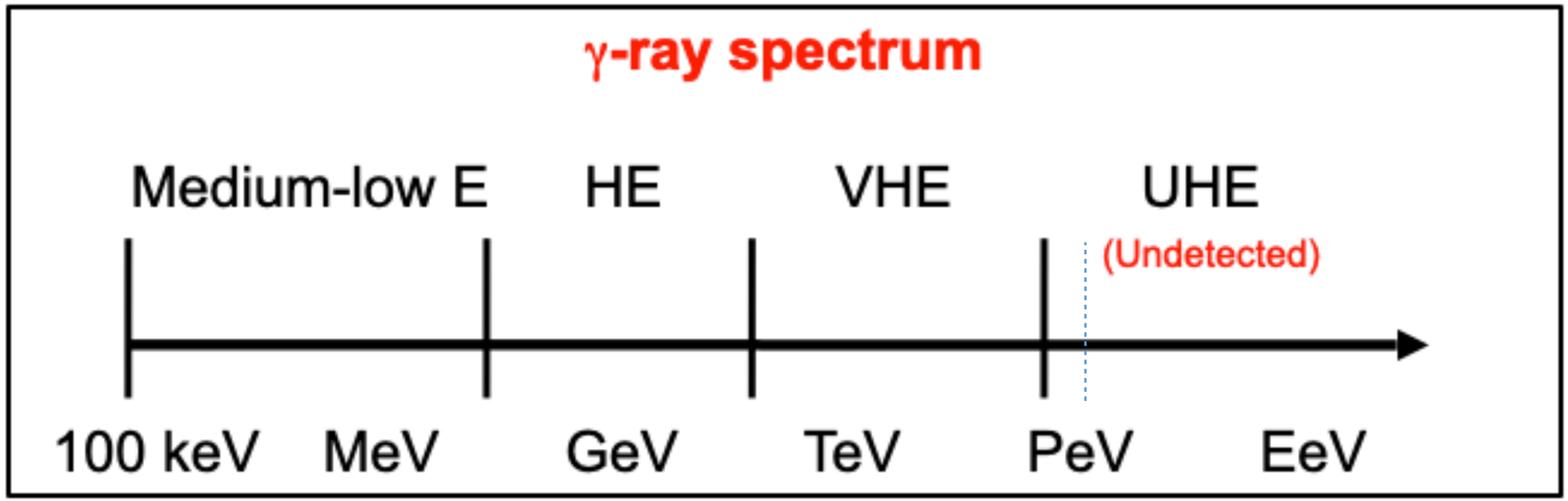
γ

p

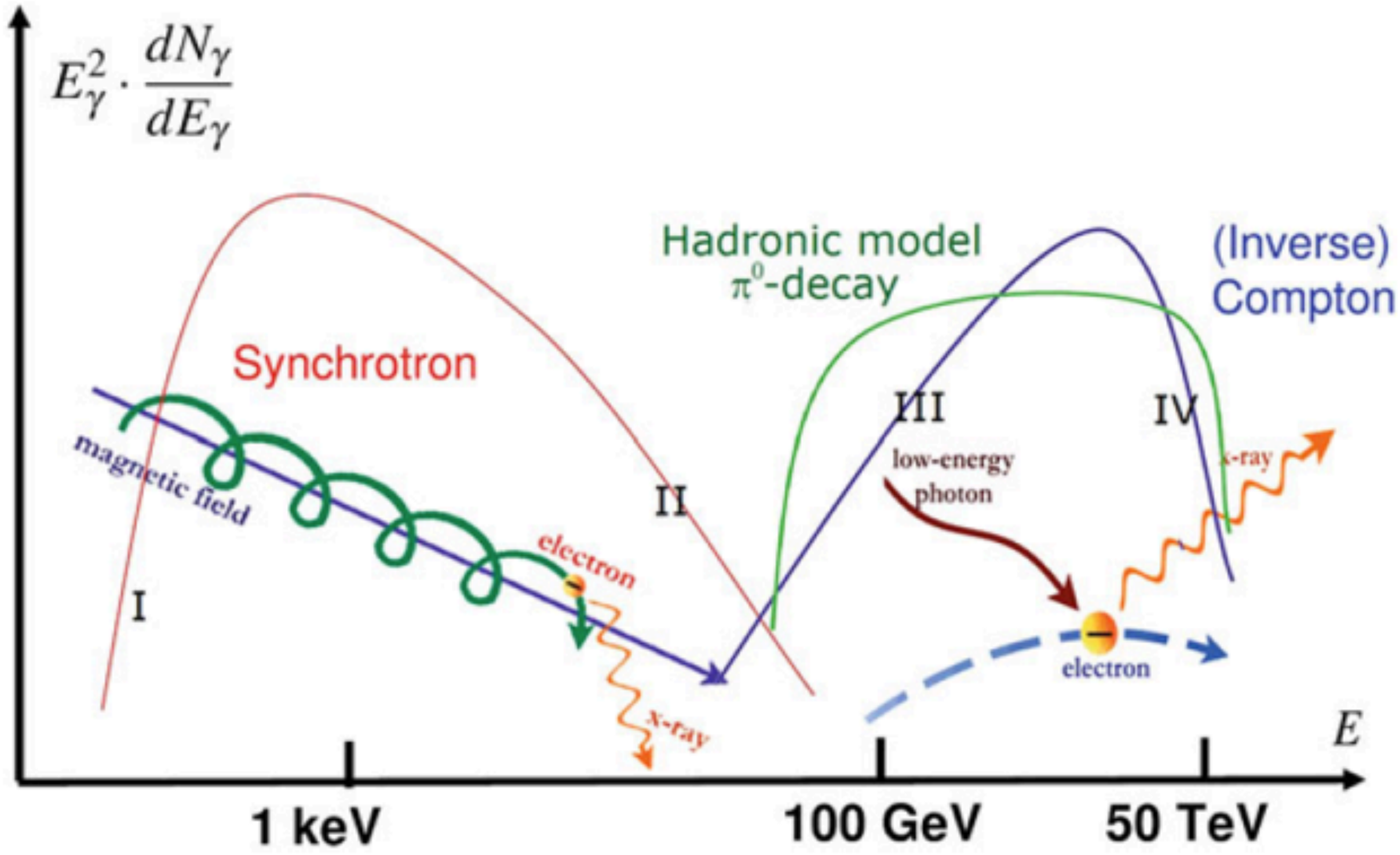
Photons

Focus on gamma-rays

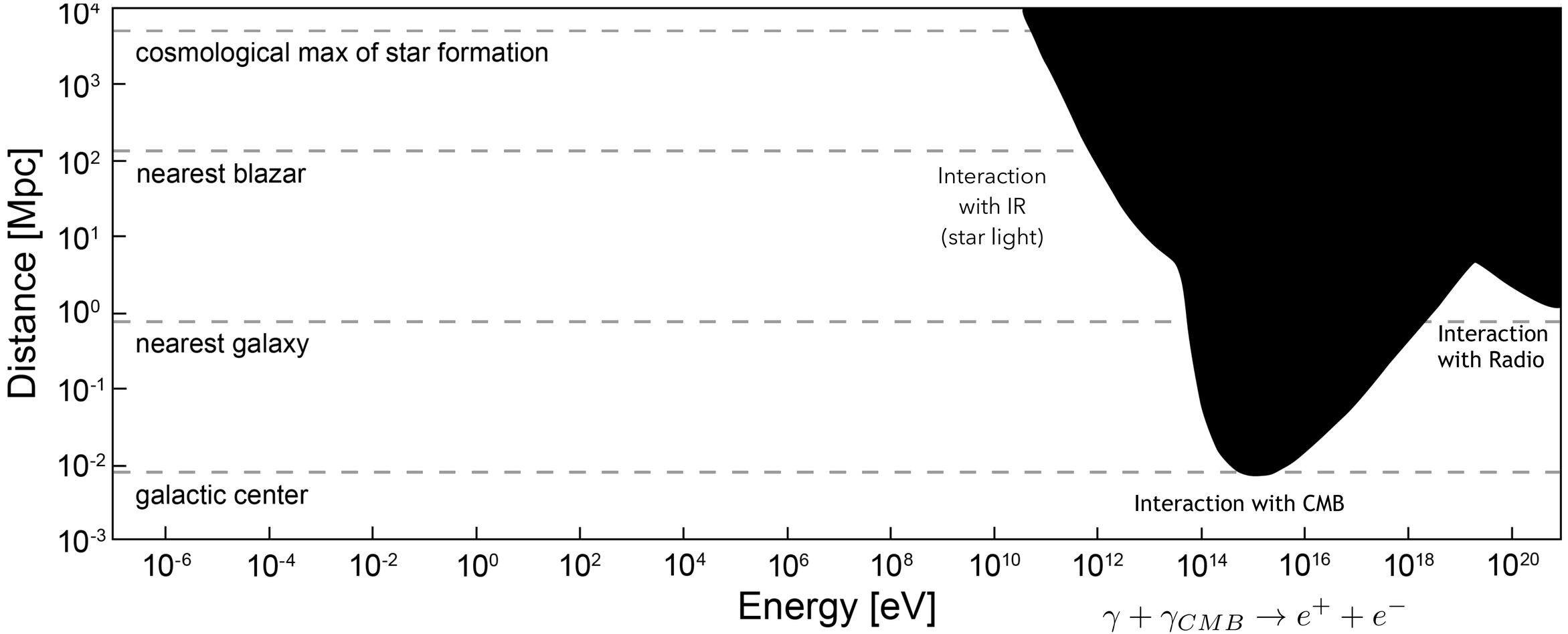
Nomenclature



Acceleration



Propagation



(Very) High Energy Gamma Rays

- Astrophysical gamma rays
  - Energy region of interest from GeVs to hundreds TeVs
- Scientific interest:
  - Key to understand the **acceleration mechanism** of cosmic rays in our galaxy
  - Violent astrophysical phenomena: pulsars and black holes
  - Galactic magnetic fields
  - Photon radiation fields in the Universe
  - Indirect search of **dark matter** (WIMP interactions)
  - Test fundamental properties of quantum gravity
  - …

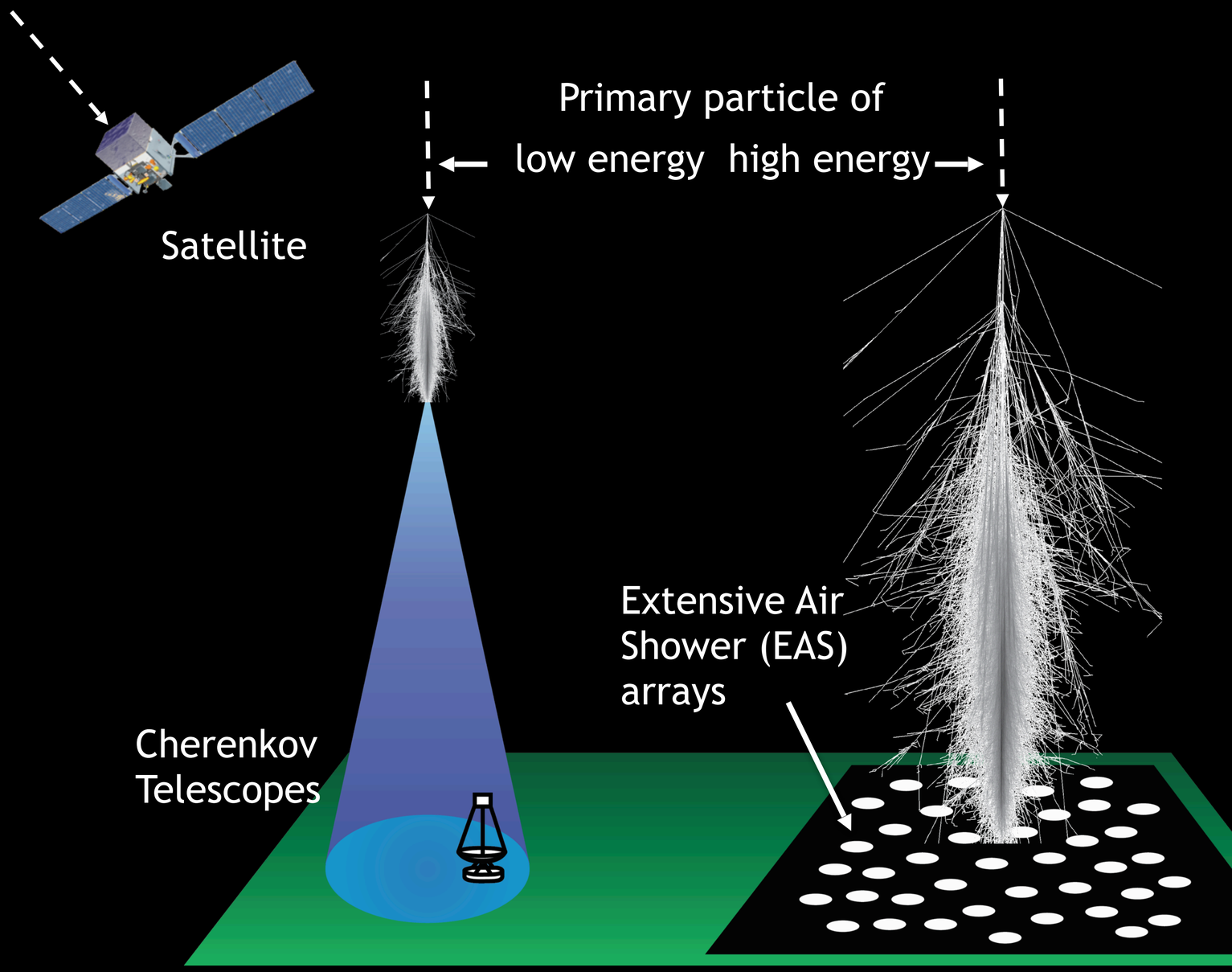
How to detect?

High-energy gamma rays

- ✦ 10 MeV - 100 GeV
- ✦ **Satellites**

Very-high-energy gamma rays

- ✦ 100 GeV - 100 TeV
- ✦ **Cherenkov telescopes**
  - ✦ Small duty cycles
  - ✦ Small field-of-view
  - ✦ Good energy and direction reconstruction
- ✦ **EAS arrays**
  - ✦ Large field of view
  - ✦ Duty cycle ~100%
  - ✦ Poorer energy and direction reconstruction



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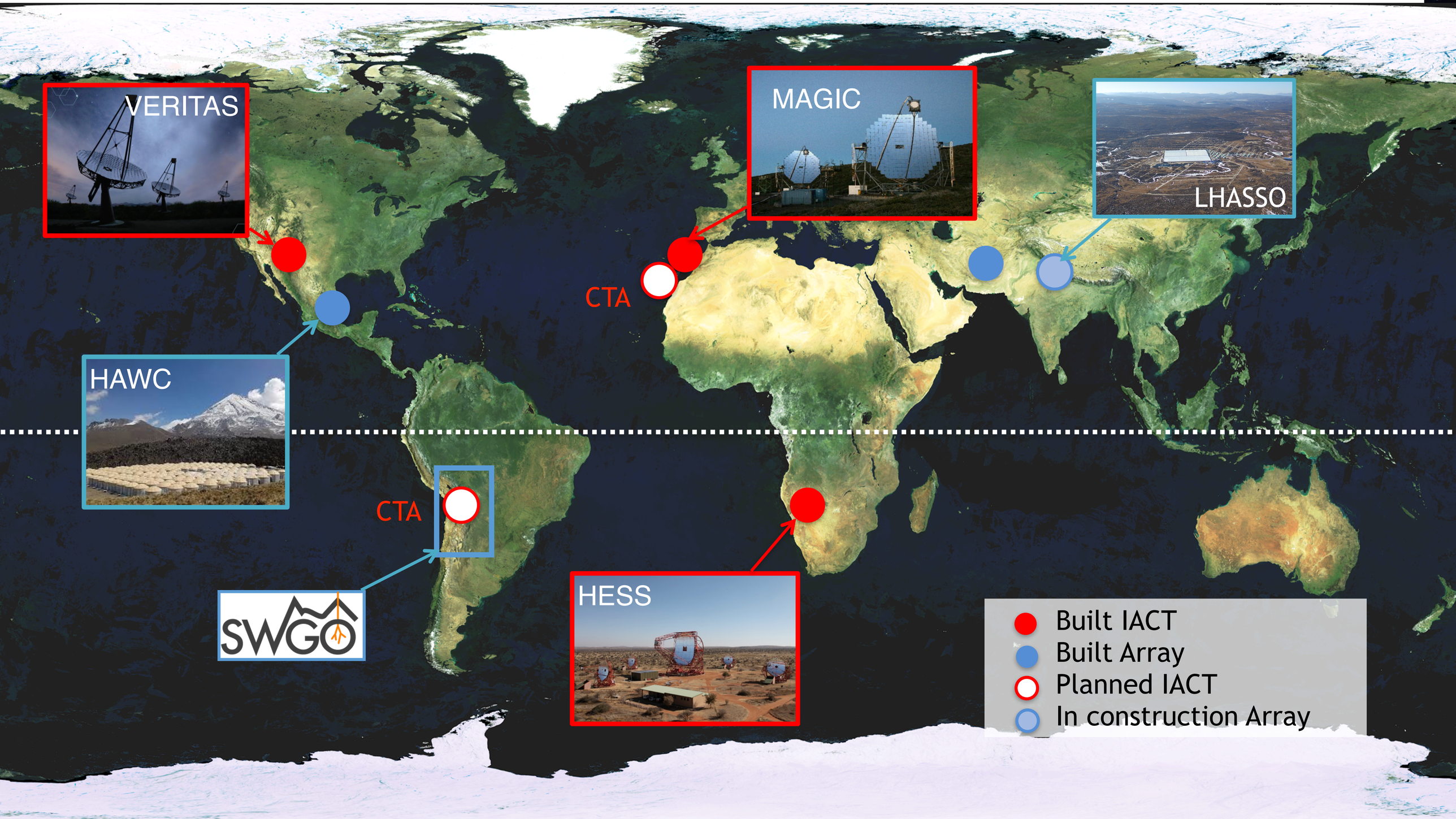
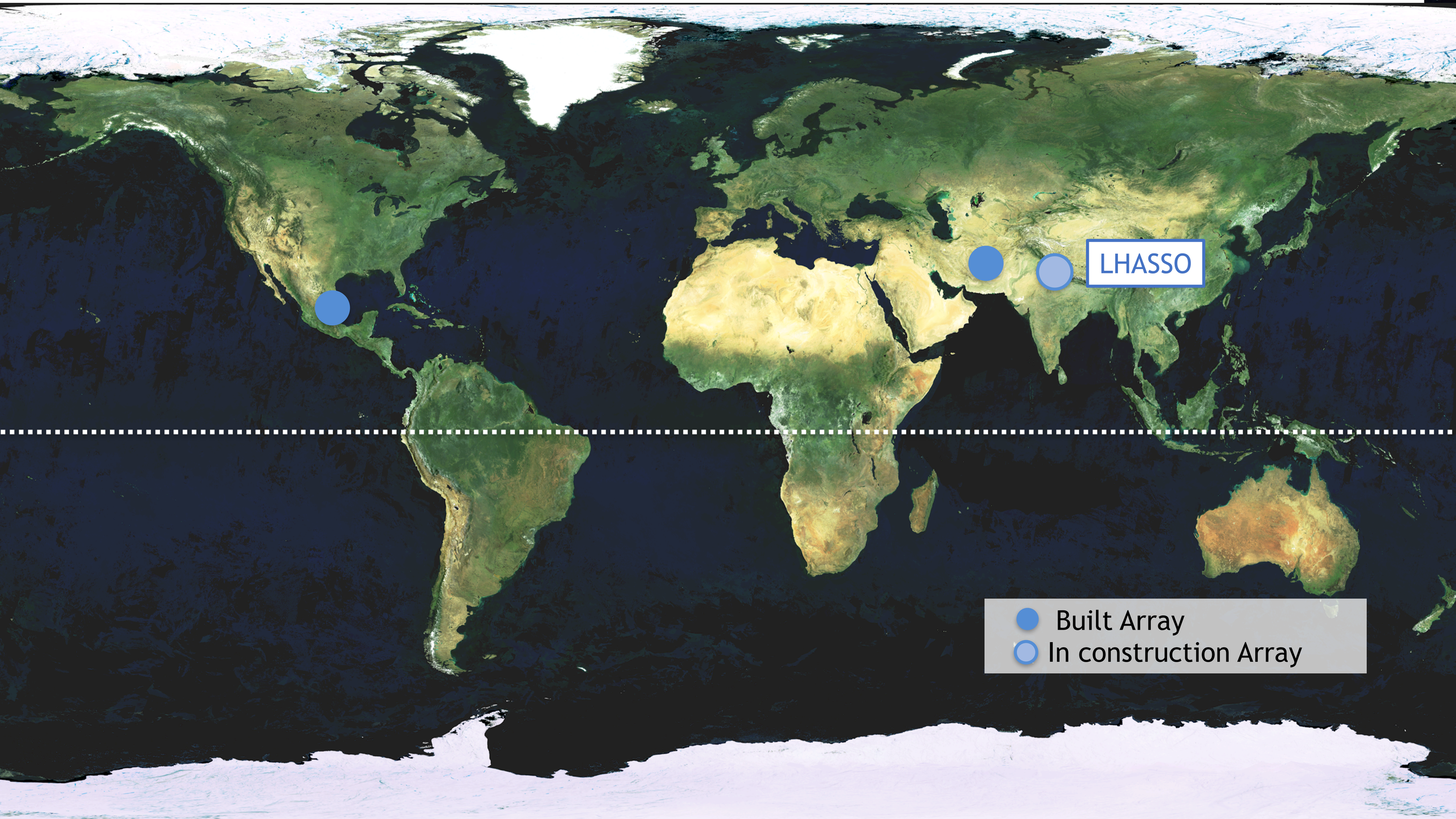
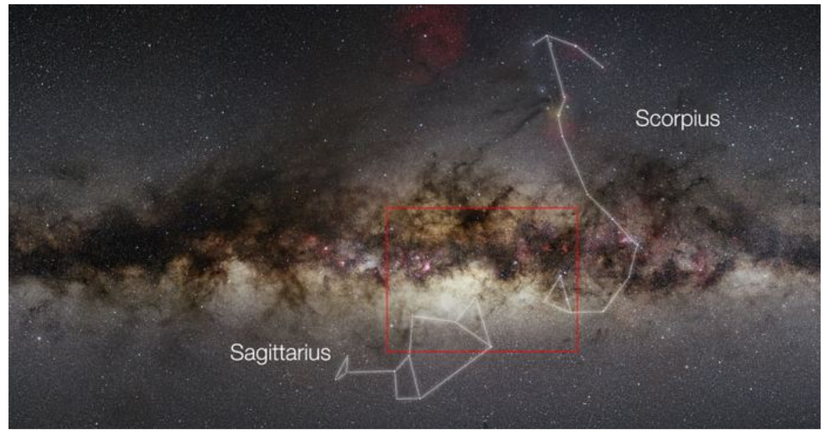

VERITAS
MAGIC
LHASSO
CTA
HAWC
CTA
SWGO
HESS
Built IACT
Built Array
Planned IACT
In construction Array


LHASSO
Built Array
In construction Array

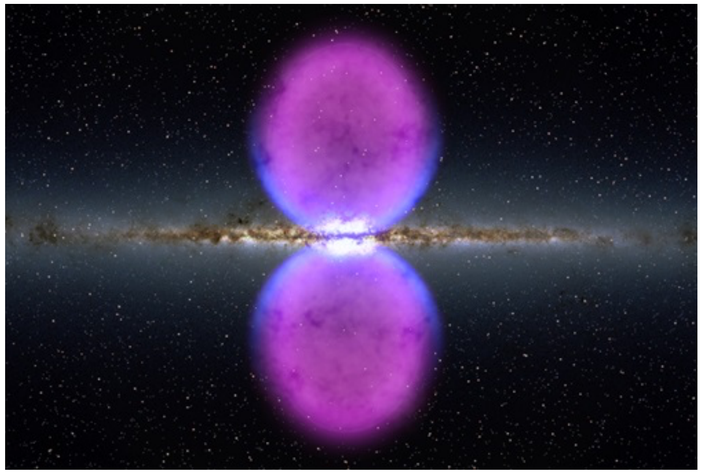
Complementary to the powerful Cherenkov Telescope Array project

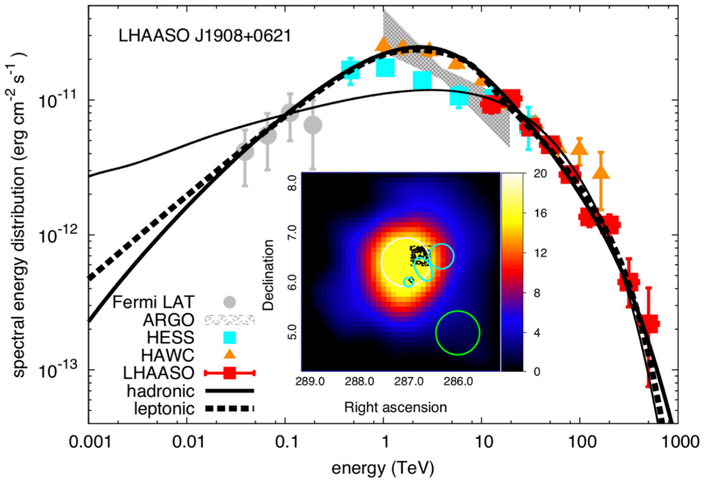


CTA

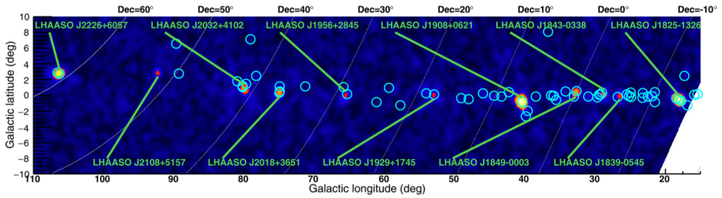
SWGO

Some interesting highlights…

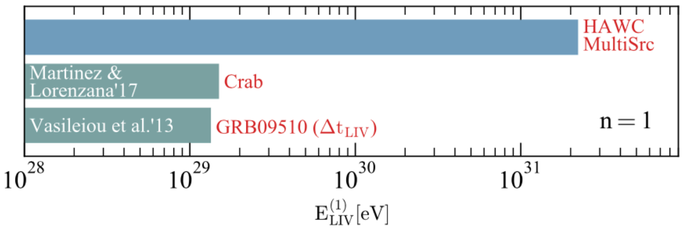




Sources > 100 TeV



Lorentz invariance limits



Fermi bubbles - gamma ray emission (up to ~100 GeV) in outbursts from our Galaxy

LHAASO has observed several PeV (10^{15}eV) photon sources being in our Galaxy

Observation of photons with E ~ 1.8 PeV can be used to put stringent limits to LIV above the Planck scale

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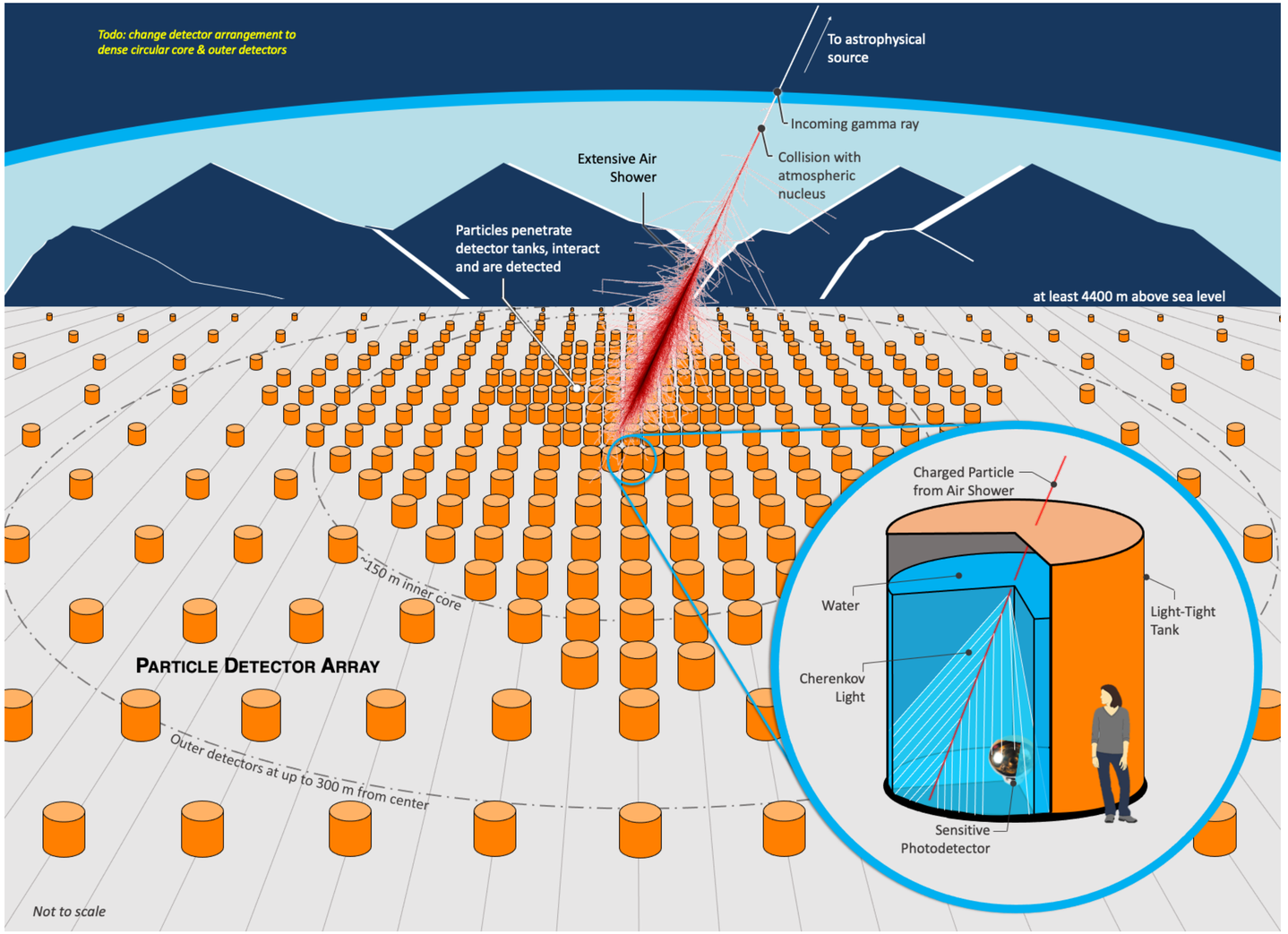
The challenge for SWGO…

- To design an experiment able to fulfil the following requirements:
  - **Muon tagging**/counting capability
  - Lower energies
    - to be placed at **high altitude** (~5000 m a.s.l.)
    - **Compact array**
  - Higher energies
    - **Large area** (~ few km^2)



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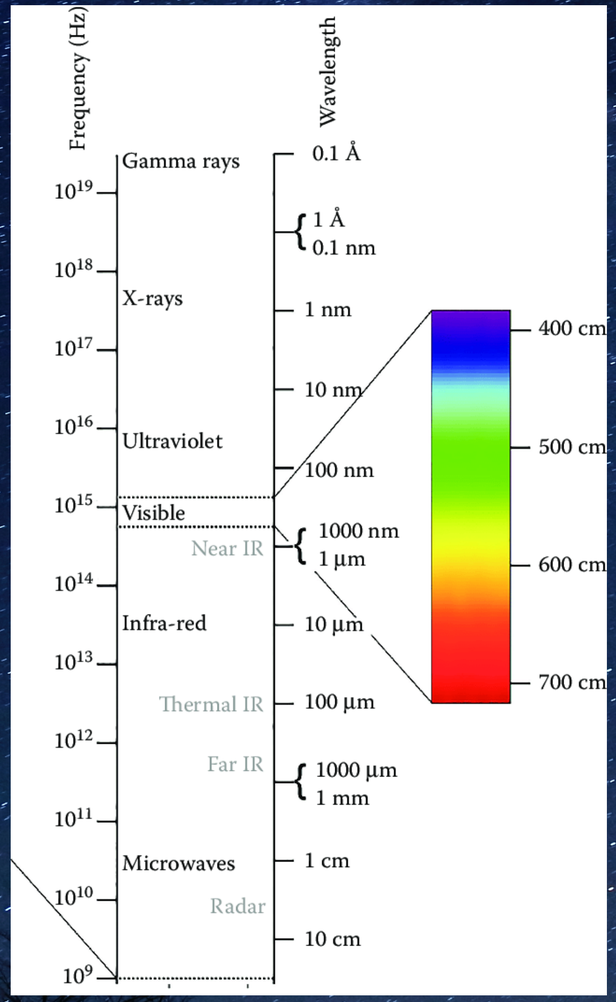
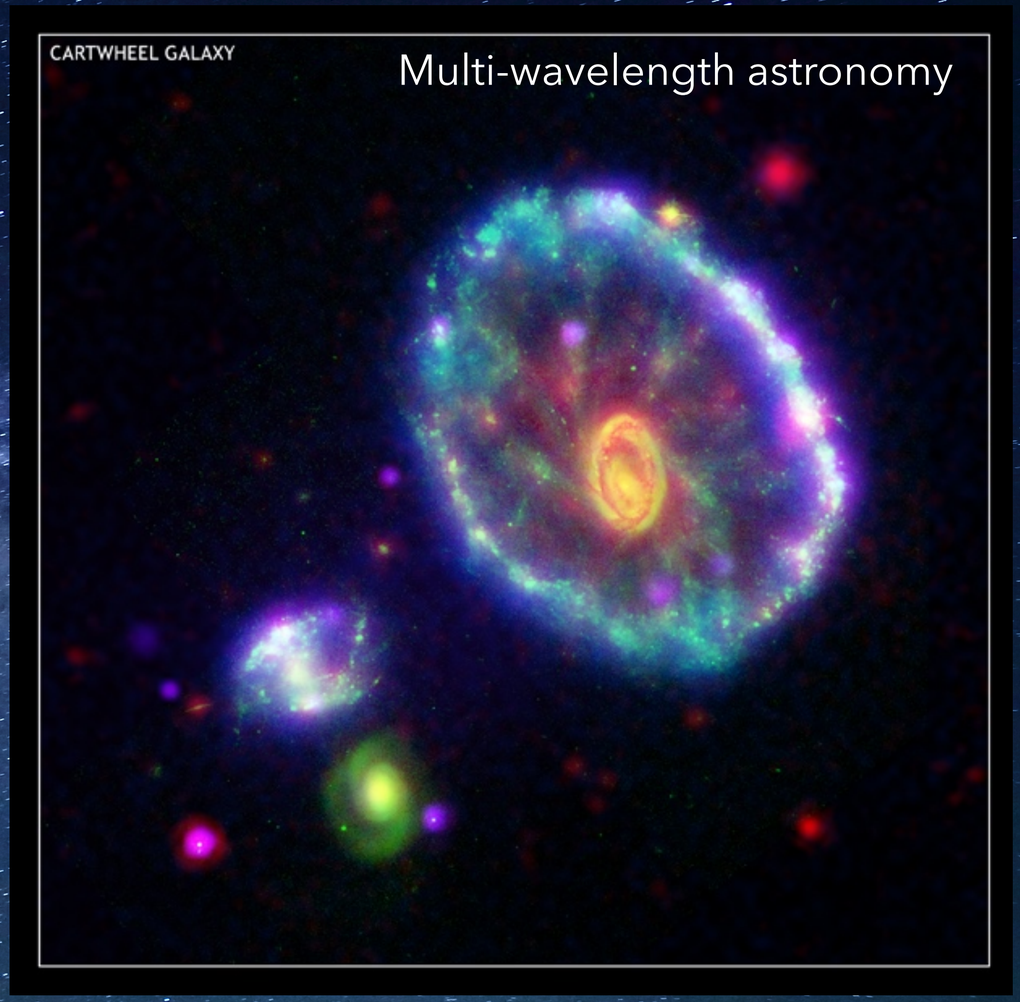
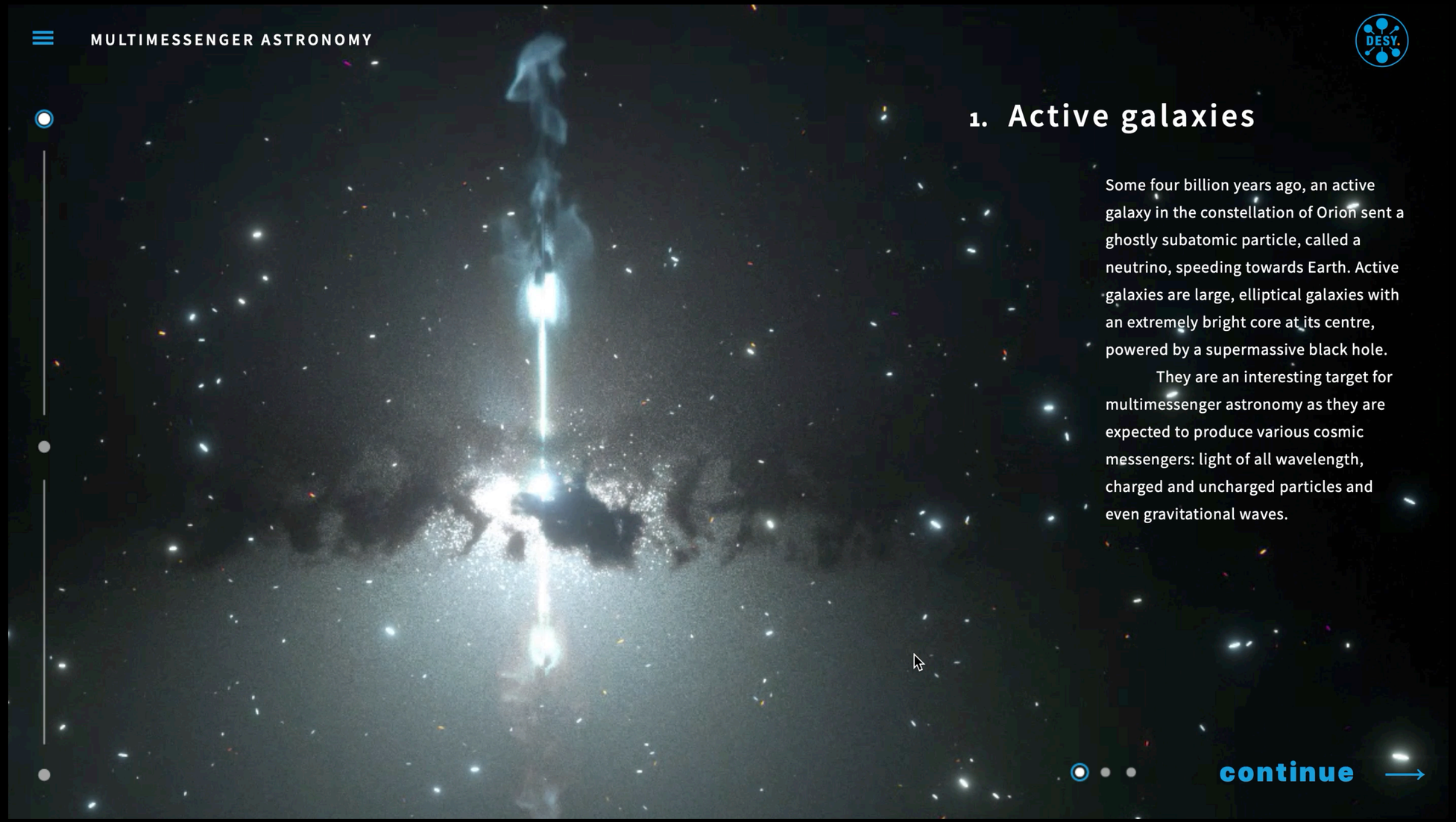
Multi-messengers

The opening of a new era…

Photons (different wavelengths)



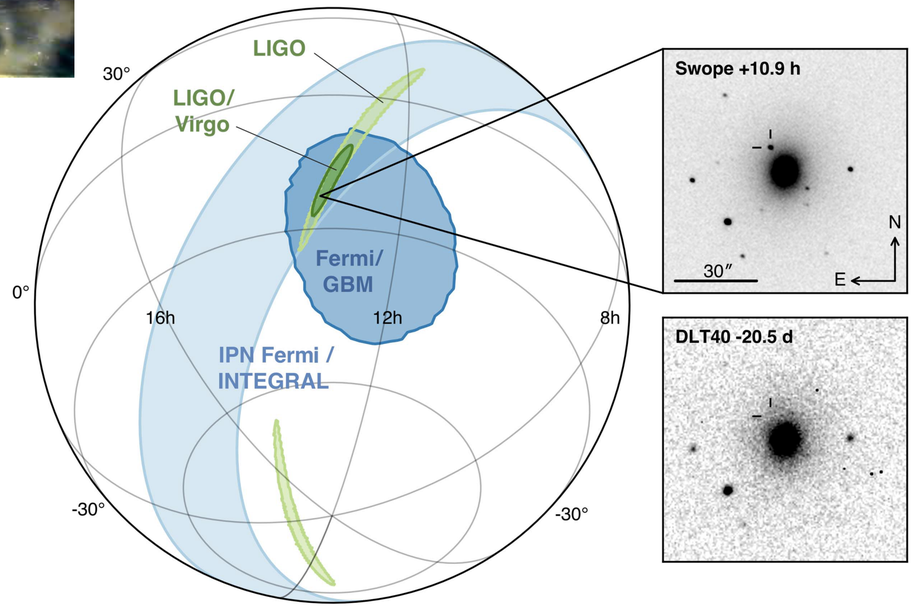




https://multimessenger.desy.de

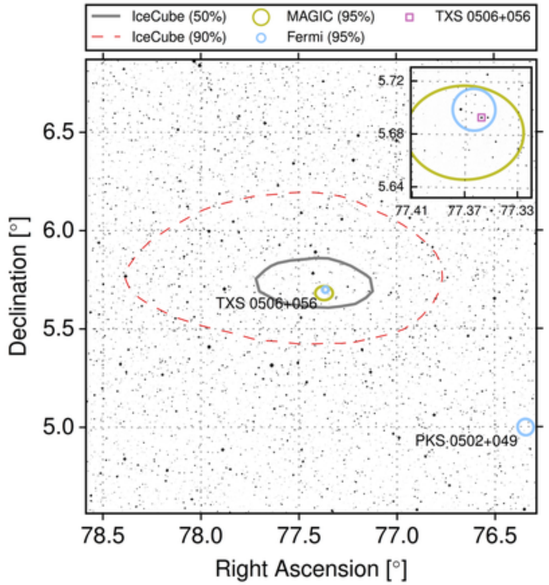
Recent Multi-messenger Observations

Observation of a Binary Neutron Star Merger



LIGO, VIRGO, INTEGRAL, Fermi, IceCube, Pierre Auger … (2017) [1946 citations]

Observation of a neutrino and a gamma-ray flare from the same source



Icecube, MAGIC, Fermi-LAT … (2018) [407 citations]

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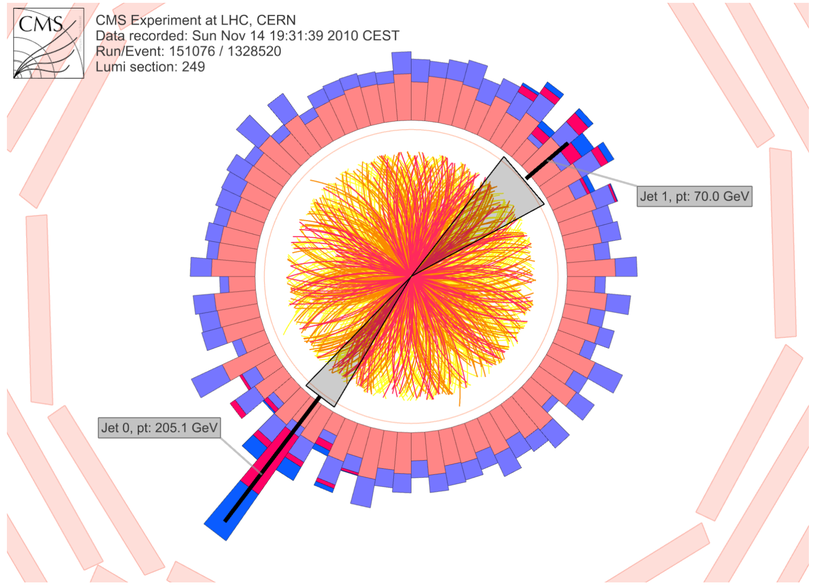
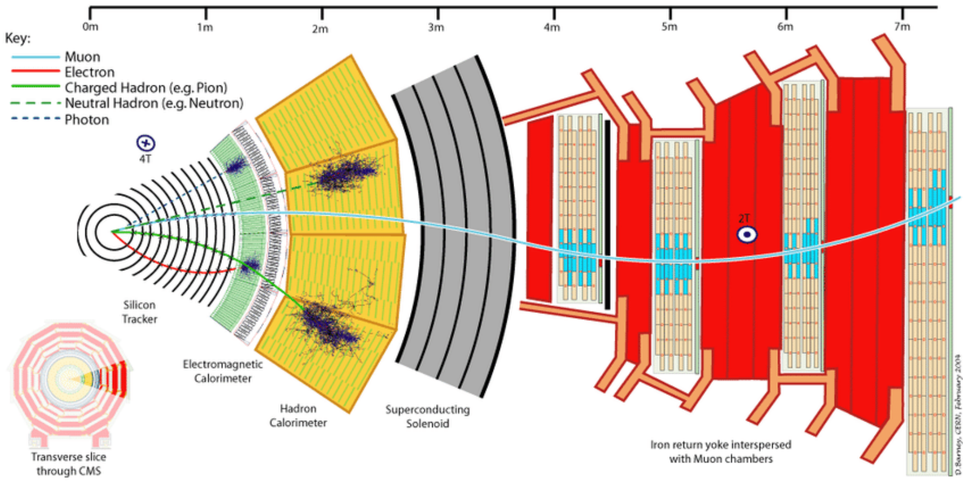
A plethora of measurements…

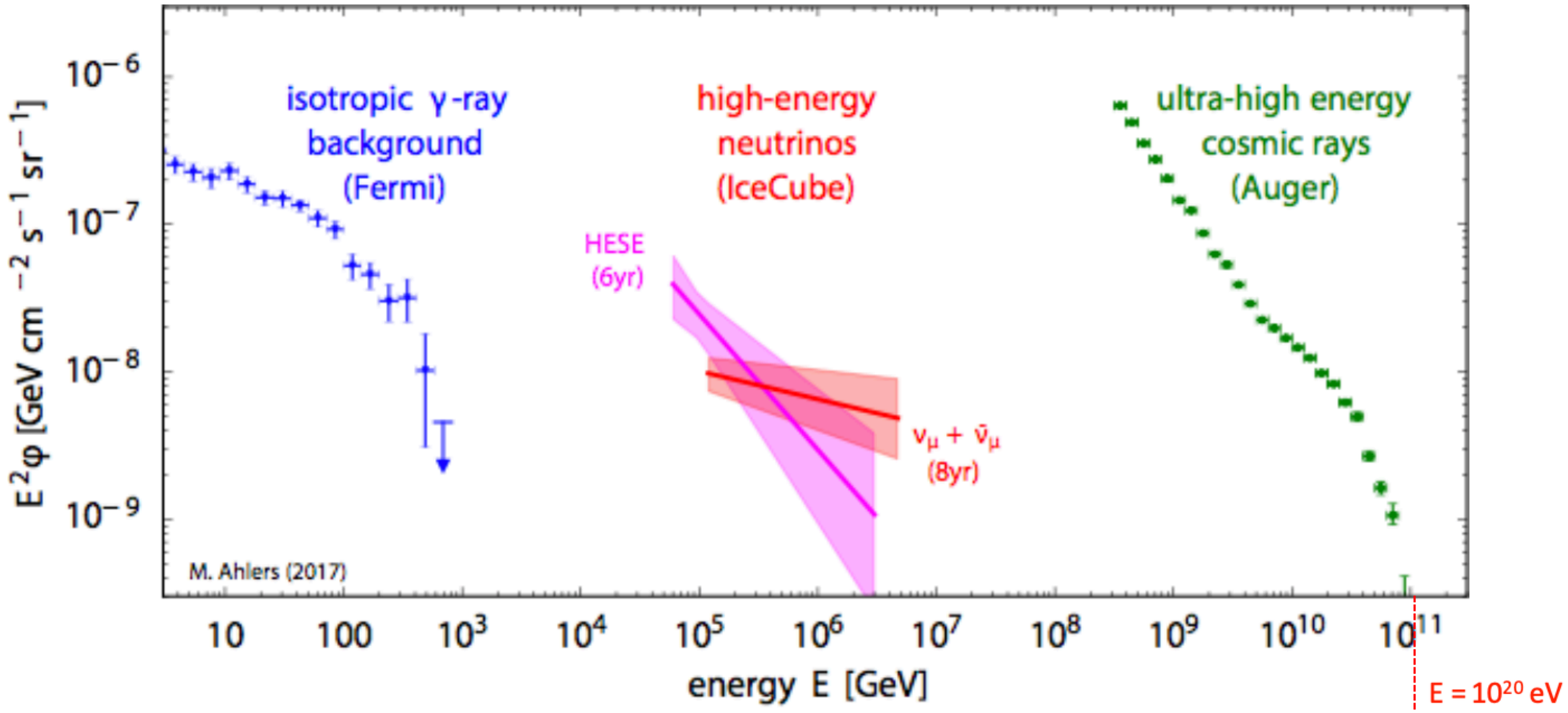
- The importance of complementary and calibrated measurements
  - An example at the LHC





- Observation of jet-quenching phenomena using ***Z0 + jet*** measurements

The multi-messenger approach



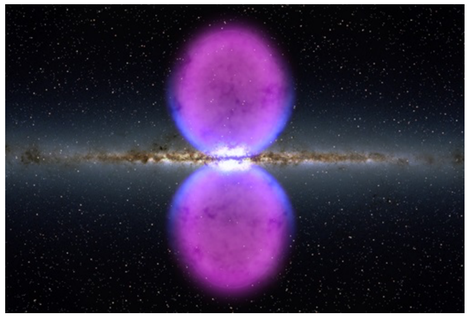
$$E^2\frac{dN}{dE} = E\frac{dN}{d\ln E}$$

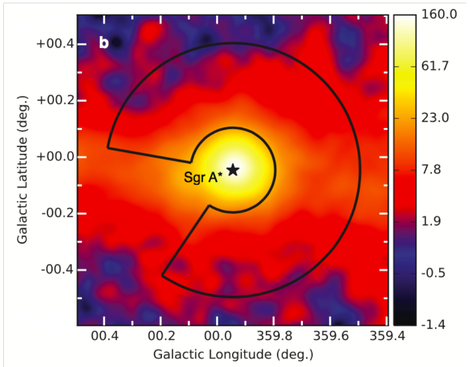
$$\rho_{\text{decade}} = \int_{\text{decade}} E\frac{dN}{d\ln E}\, d\ln E$$

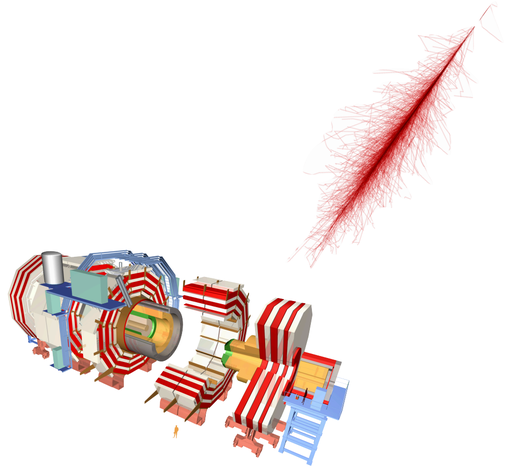
Summary

Again a biased view :-)

A strong effort to cover all messengers at all energies…







SWGO
The Southern Wide-field Gamma-ray Observatory

PIERRE AUGER OBSERVATORY

10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20} Energy [eV]

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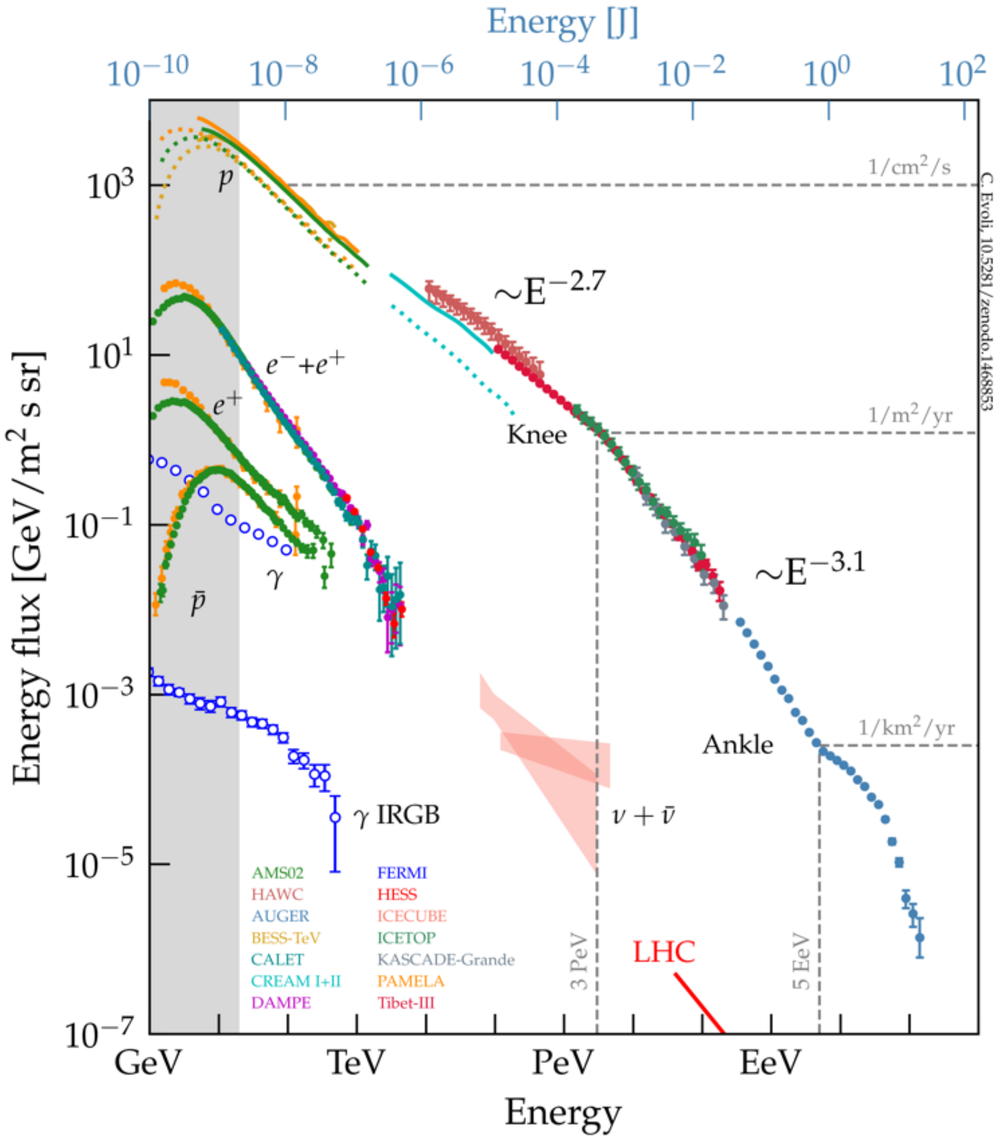
A multitude of measurement to understand our Universe



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PORTUGAL 2020

UNIÃO EUROPEIA
Fundo Europeu de Desenvolvimento Regional

LIP

TÉCNICO LISBOA

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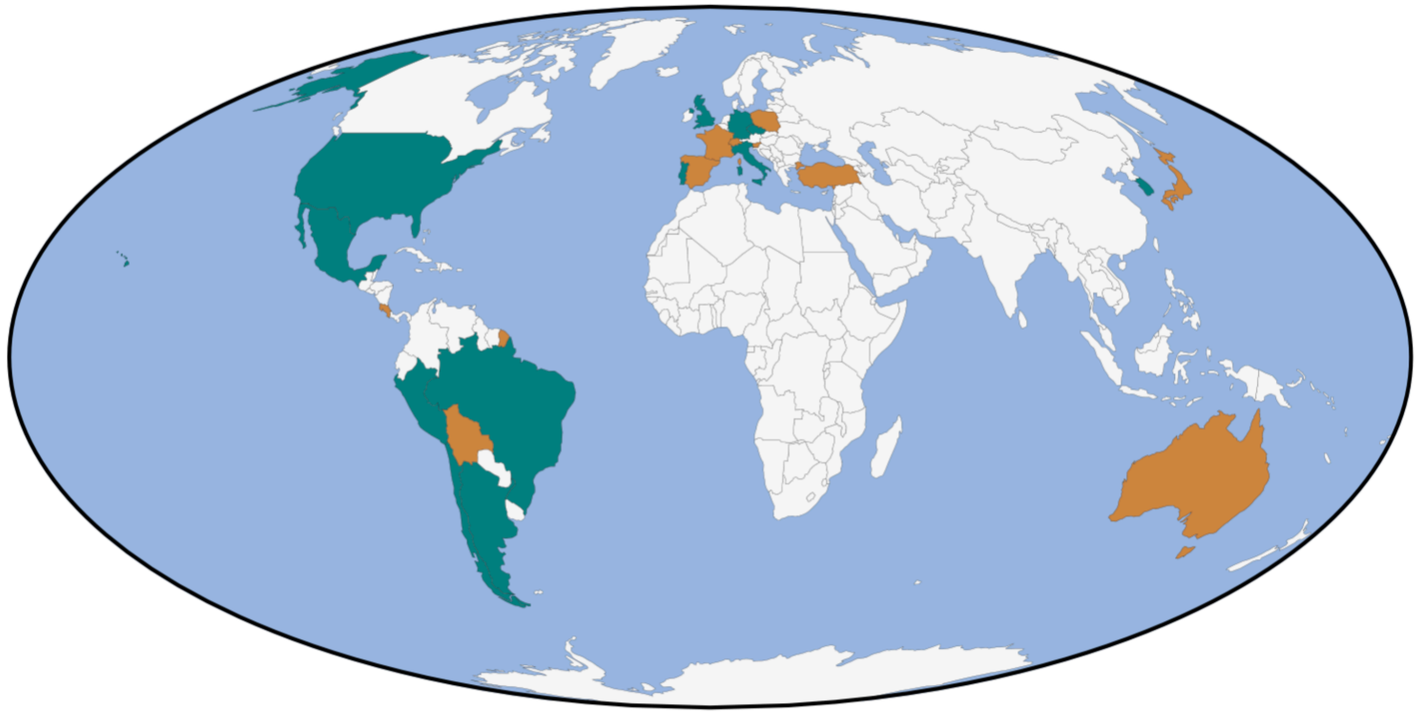
Backup slides

SWGO

(Southern Wide-field Gamma-ray Observatory)

3 year R&D project to design the next gamma-ray wide field of view experiment

- 53 institutes
- > 100 scientists
- 13 countries
- 32 supporting scientists



Countries in SWGO

Institutes

Argentina*, Brazil, Chile, Czech Republic, Germany*, Italy, Mexico, Peru, Portugal, South Korea, United Kingdom, United States*

Supporting scientists

Australia, Bolivia, Costa Rica, France, Japan, Poland, Slovenia, Spain, Switzerland, Turkey

**also supporting scientists*

Goal: to cover the high energy Southern gamma-ray sky from ~100 GeV to ~10 PeV

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