Exploring the extreme energy Universe

Ruben Conceição

LIP   TÉCNICO LISBOA

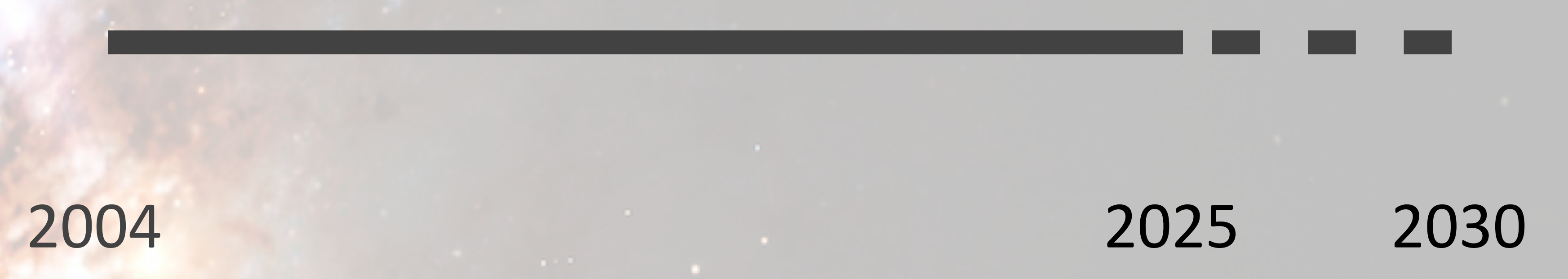
LIP researcher position call, Lisboa, November 3rd 2022

Exploring the extreme Universe

✧ **Pierre Auger Observatory**

PIERRE AUGER OBSERVATORY

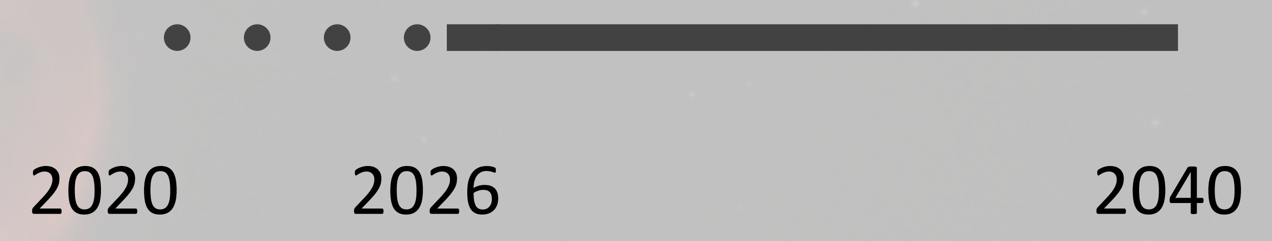
UHE Cosmic Rays



✧ **Southern Wide-field Gamma-ray Observatory**

SWGO The Southern Wide-field Gamma-ray Observatory

VHE-UHE Gamma Rays



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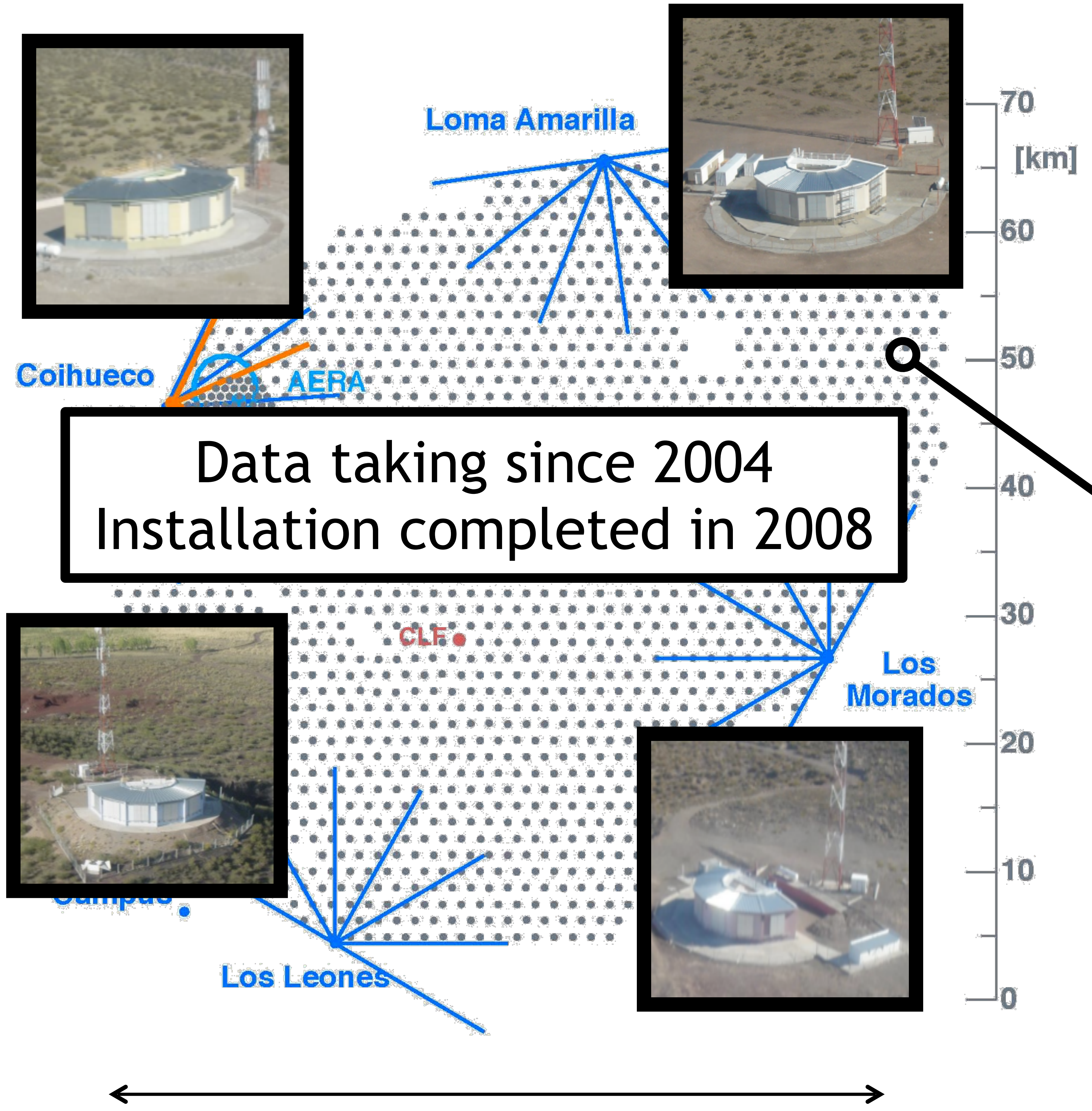
Ultra-high-energy cosmic rays

Pierre Auger Observatory - Auger Prime

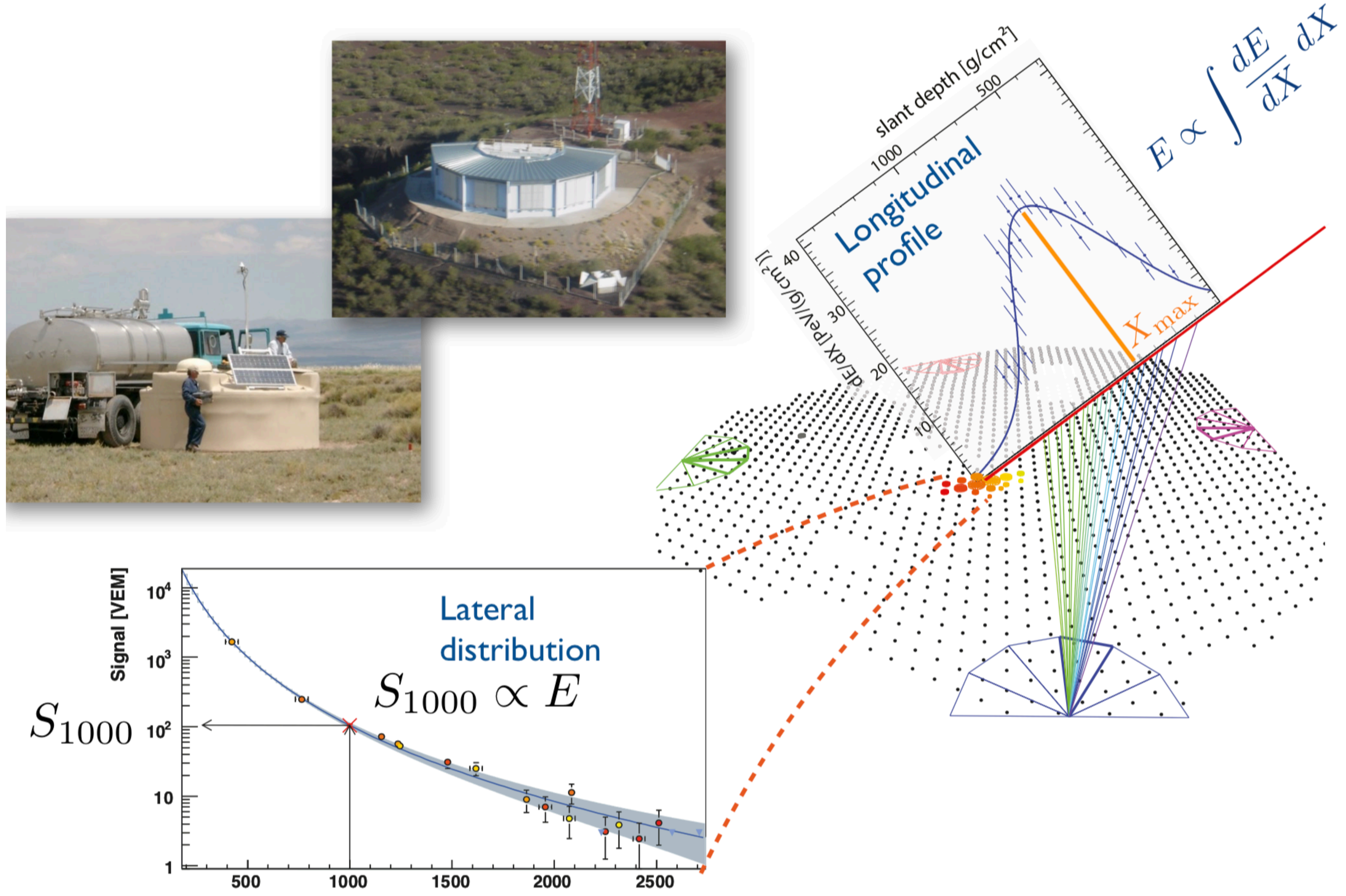
Pierre Auger Observatory



~ 60 km

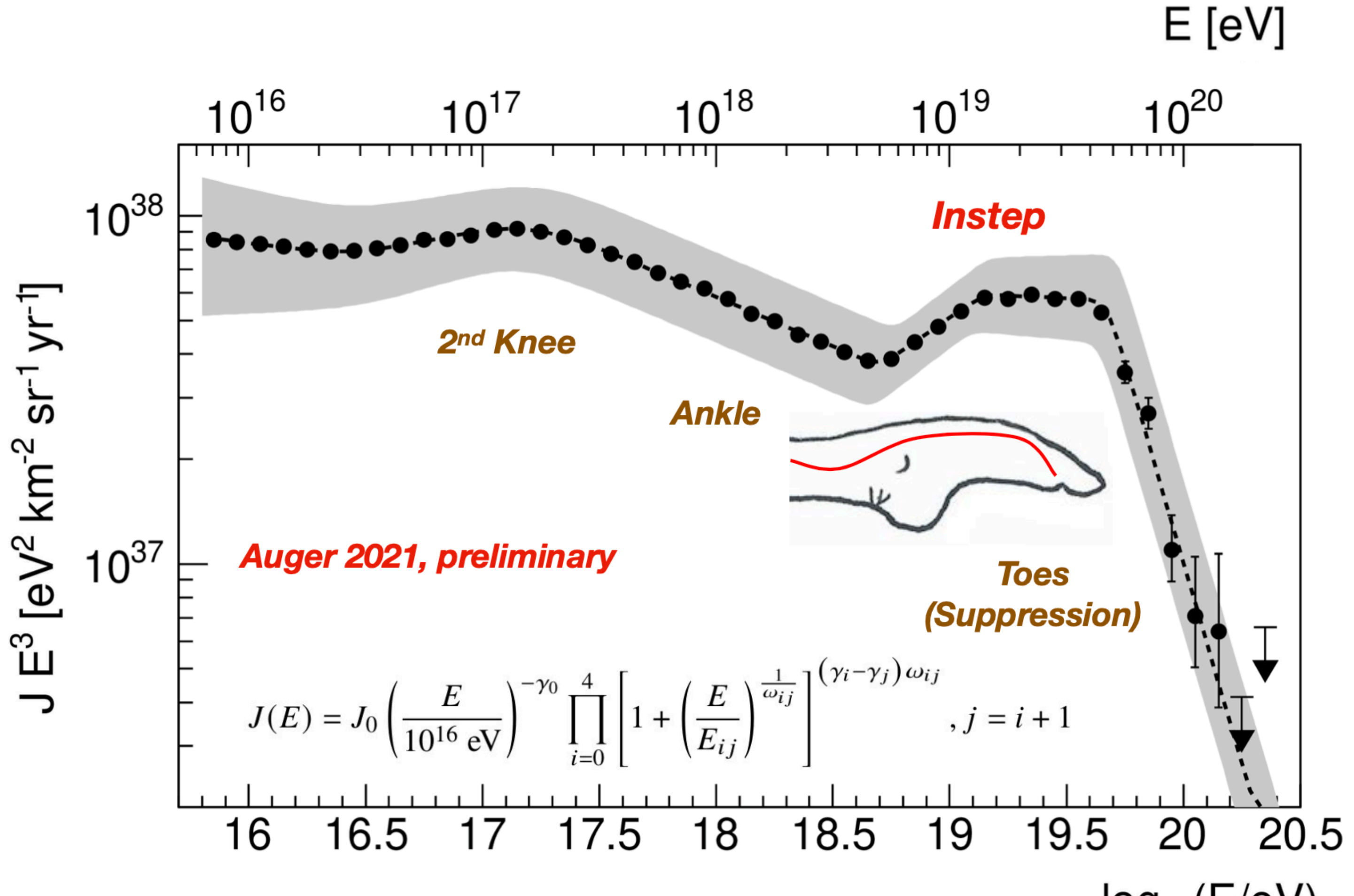
- 4 Fluorescence Detectors (FD)
- 6 x 4 Fluorescence Telescopes

- ~ 1600 Surface Detectors (SD) Stations
- SD stations spaced by 1.5 km
- Covering an area of 3000 km²



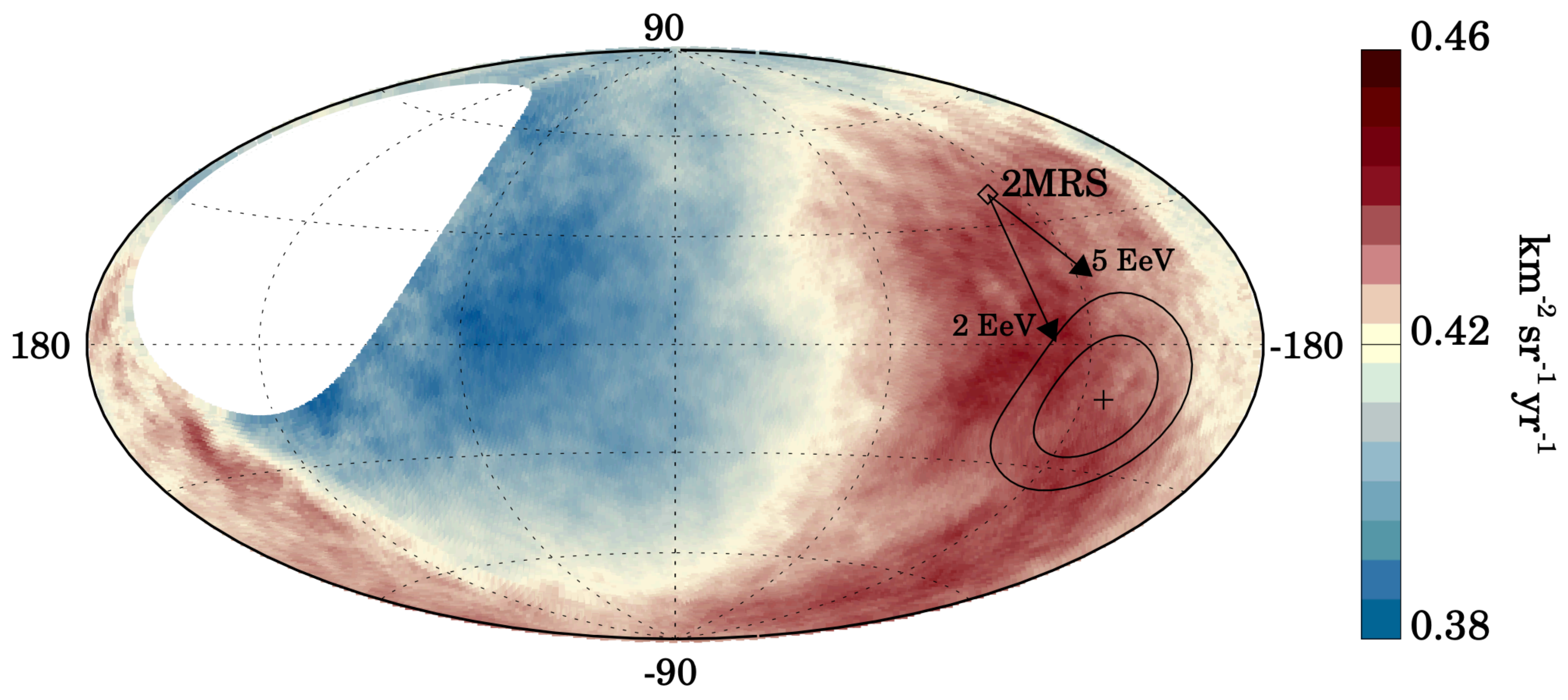
Pierre Auger collaboration results in a nutshell

UHECR energy spectrum features



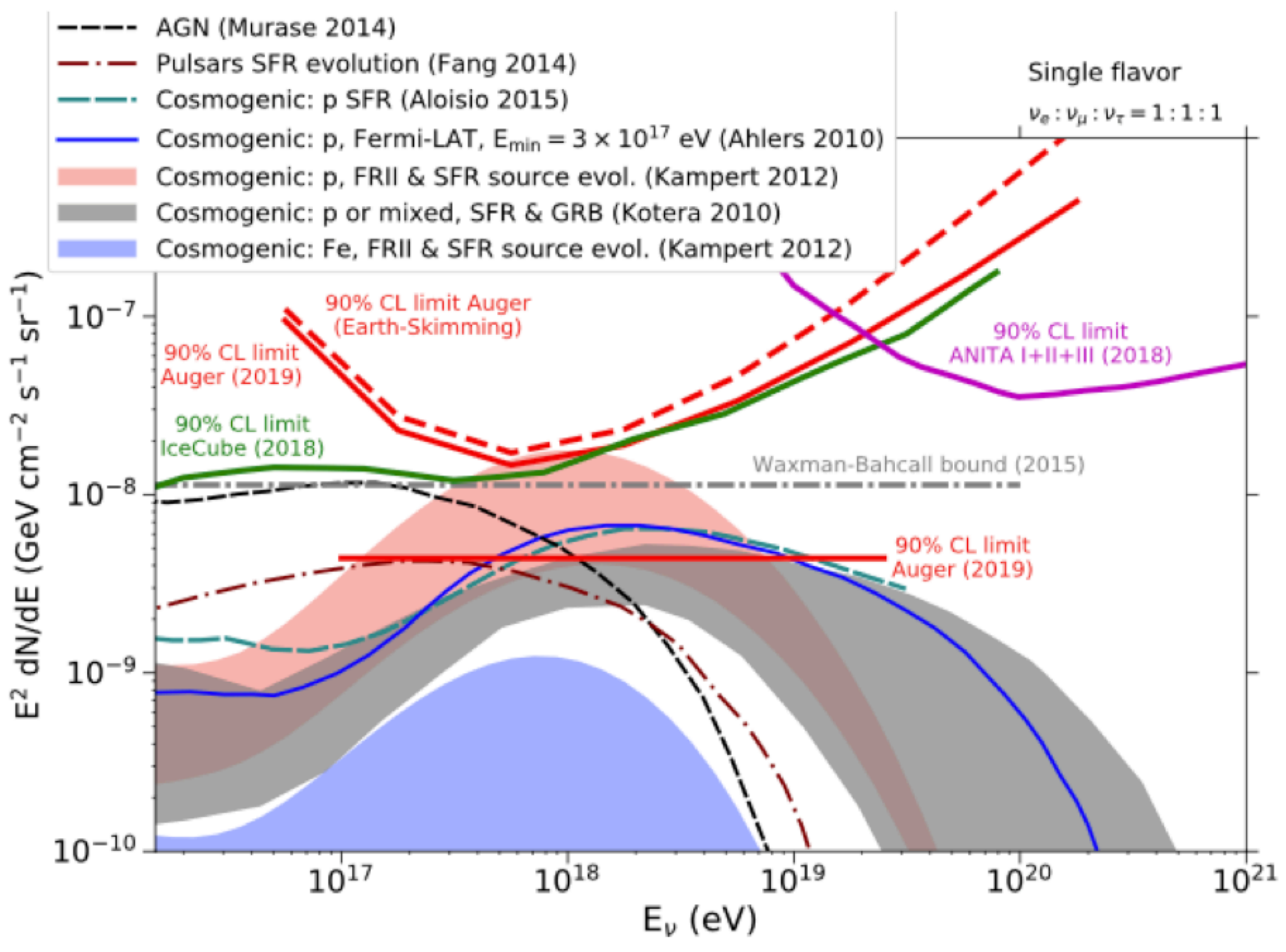
Phys. Rev. Lett. 125 (2020) 121106

UHECR have an extra-galactic origin



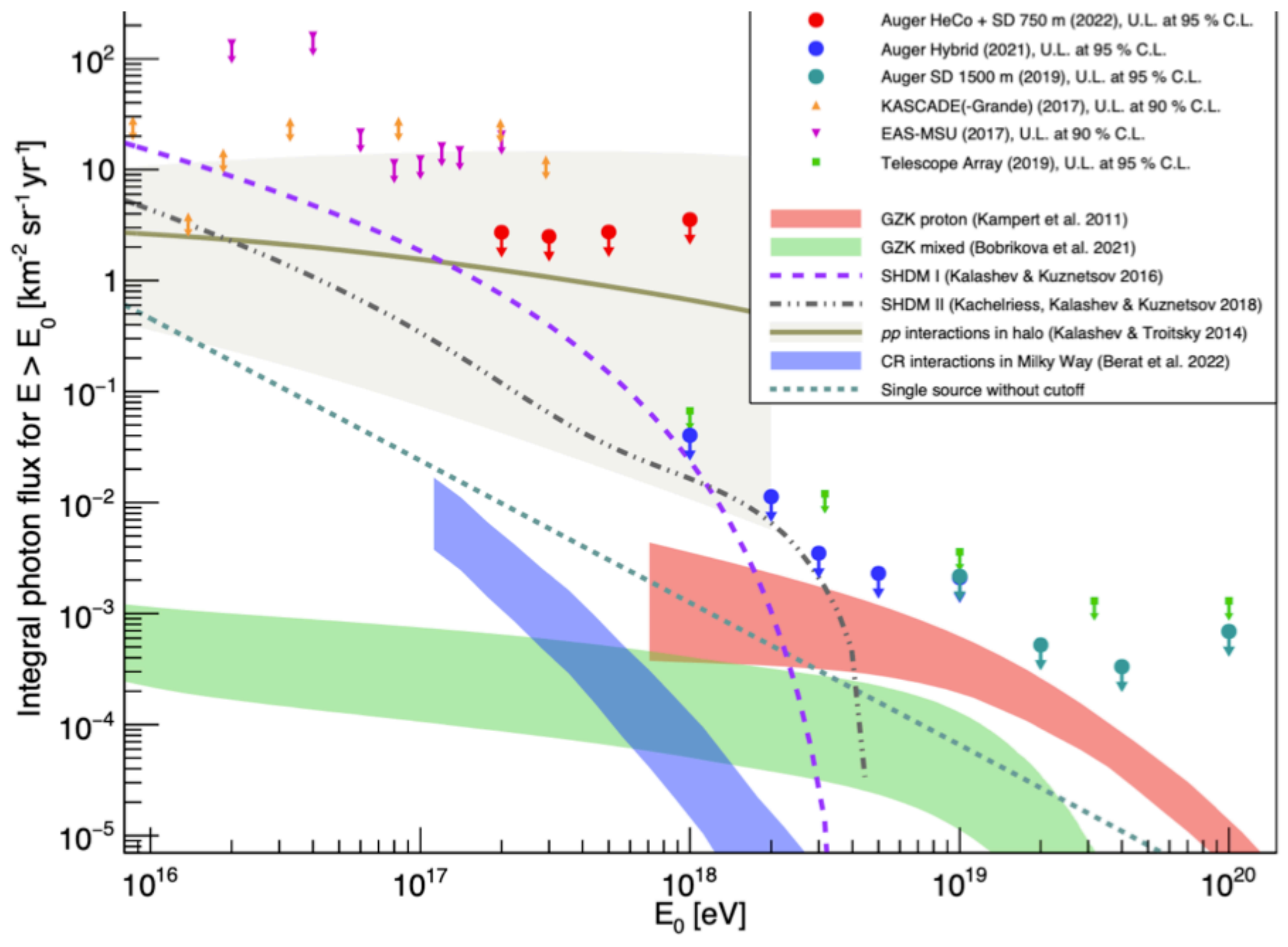
Science 357 (2017) 6537, 1266-1270

Stringent limits on UHE neutrinos



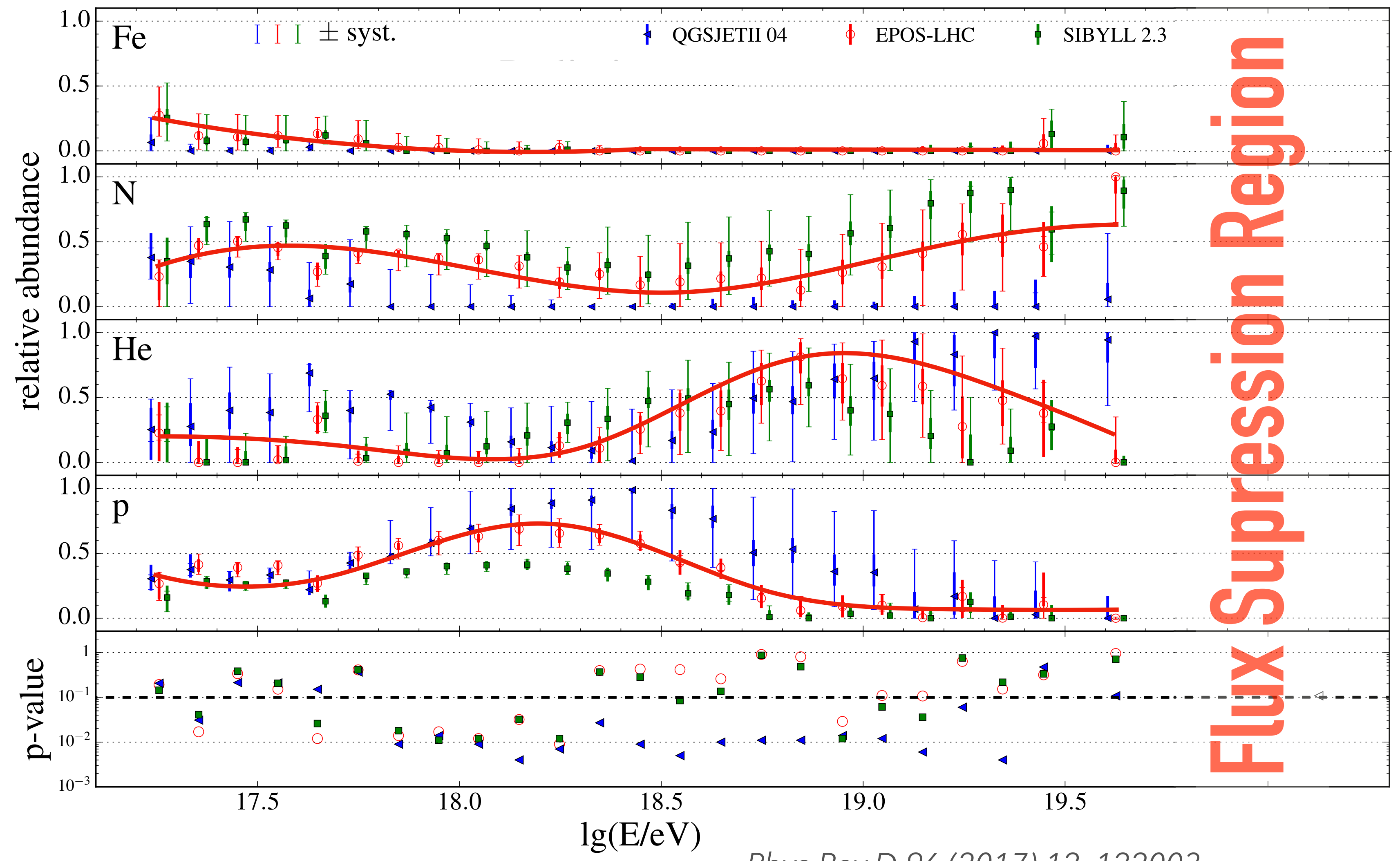
ApJ 902 (2020)105

Stringent limits on UHE photons



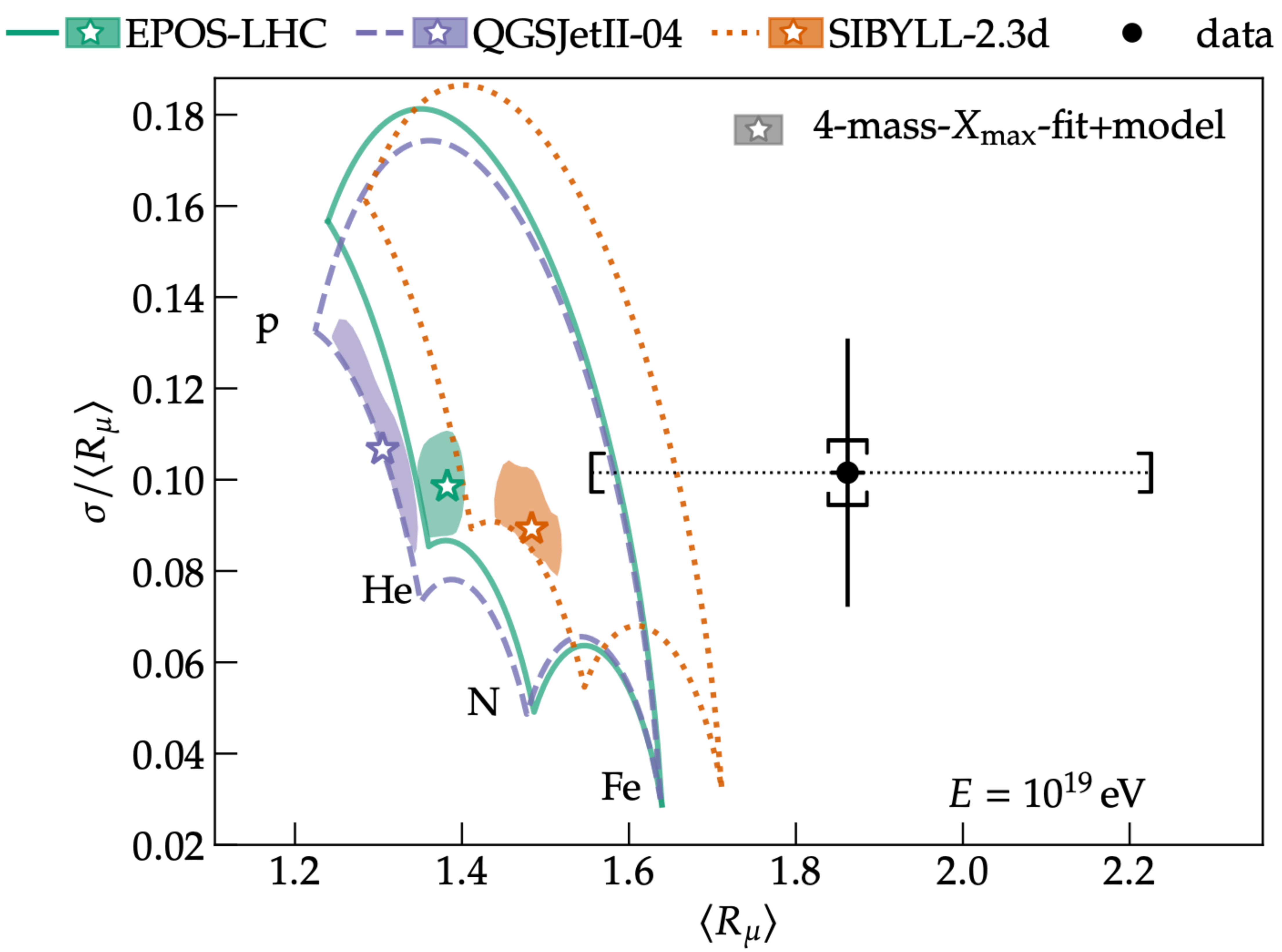
Astrophys.J. 933 (2022) 2, 125

Mass composition evolution towards heavier elements



Phys.Rev.D 96 (2017) 12, 122003

The muon puzzle



- **Post-LHC** tuned hadronic interaction models **unable to consistently explain** the muon number measurements
  - Muon number scale off even accounting the huge uncertainties on the energy scale
  - The muon number relative fluctuations are consistent with model expectations

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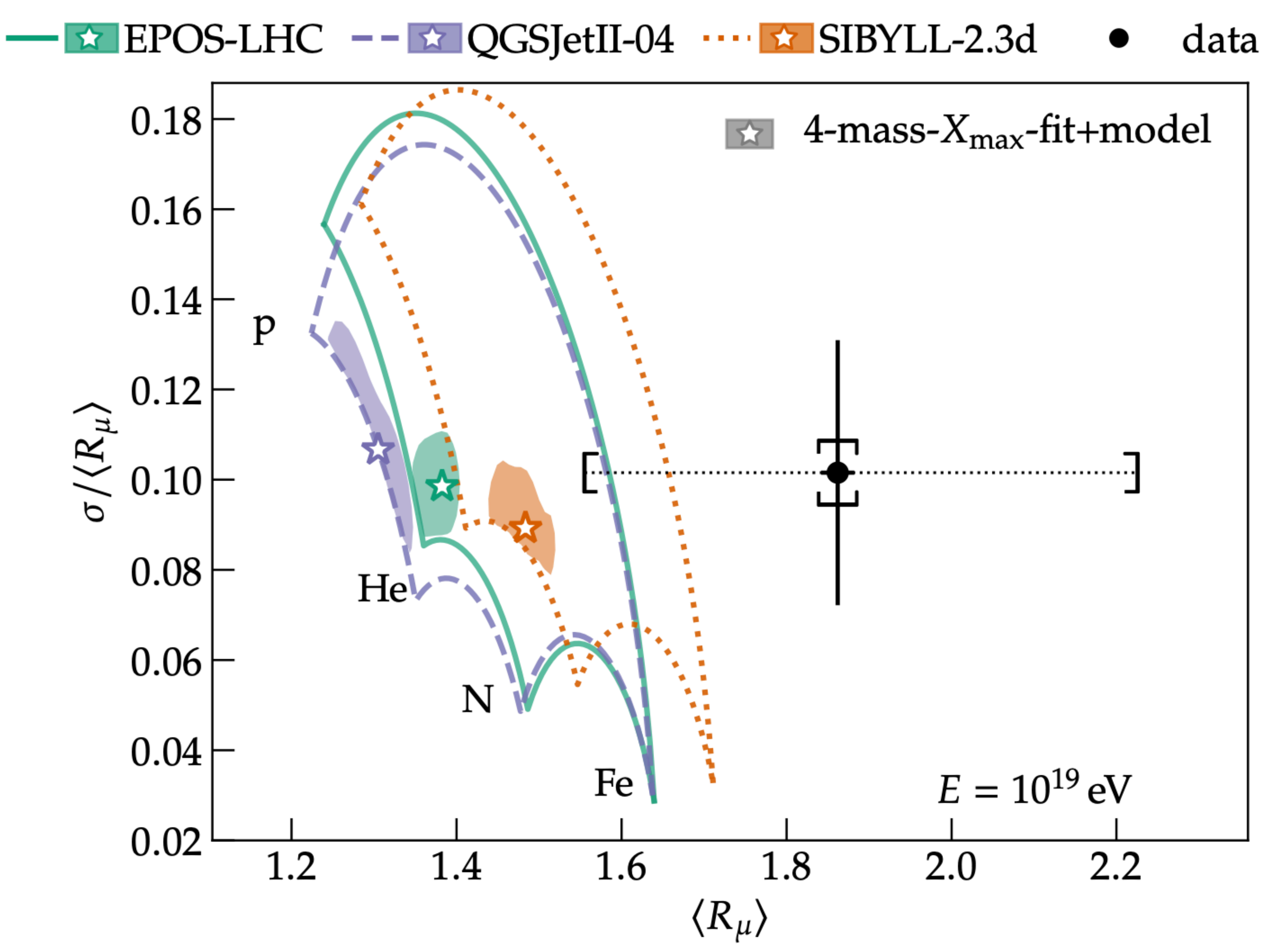
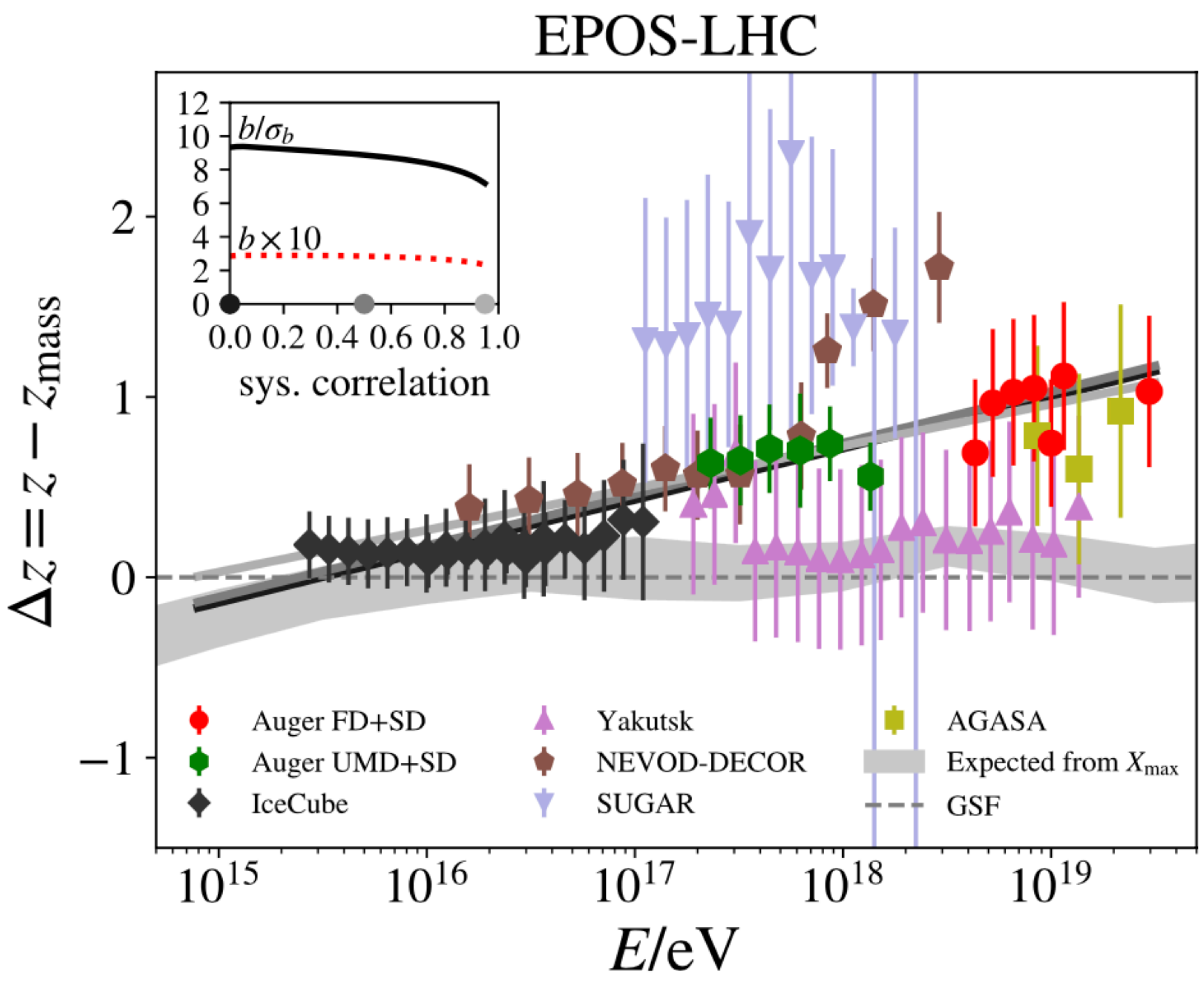
The muon puzzle





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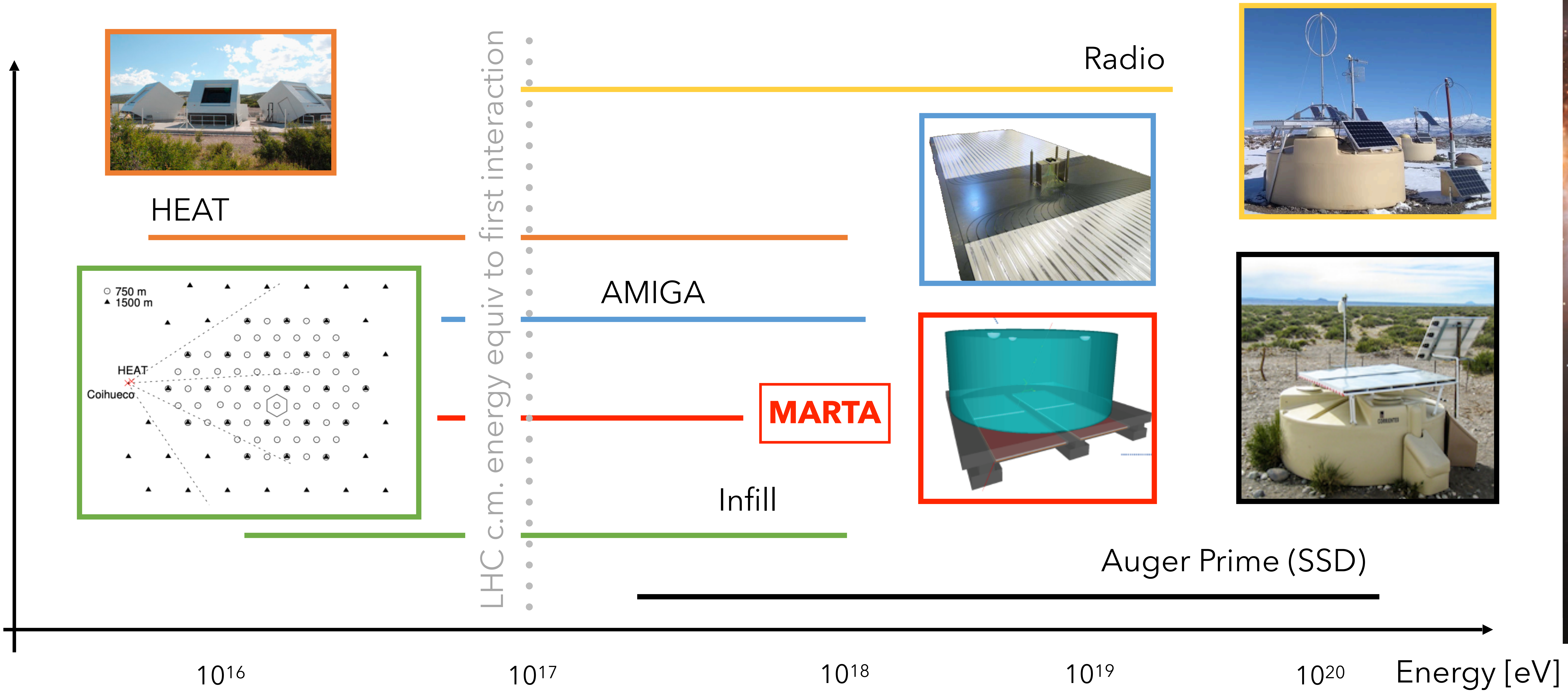
Multi-hybrid shower events

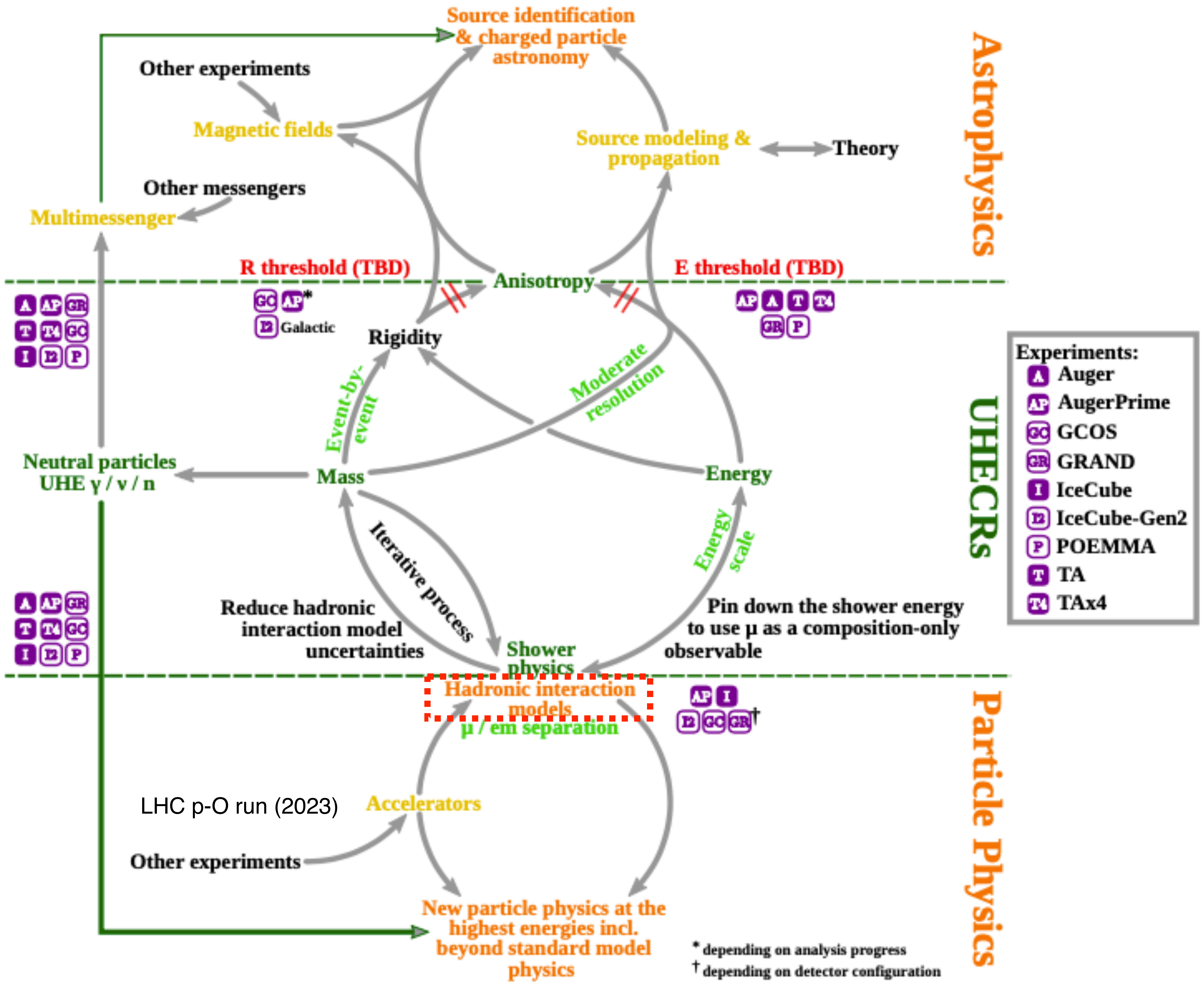
(A plethora of measurements to fully understand the shower)



The coming golden age of UHECR physics

- *"UHECR observations have so far provided a complex observational picture that makes the field more exciting"* – referee of the white paper
- Diagram summarising the strong connections of UHECRs with particle physics and astrophysics, and the strategies to attain the **fundamental objectives (in orange)** in the next two decades
- The understanding of **hadronic interactions** is vital!

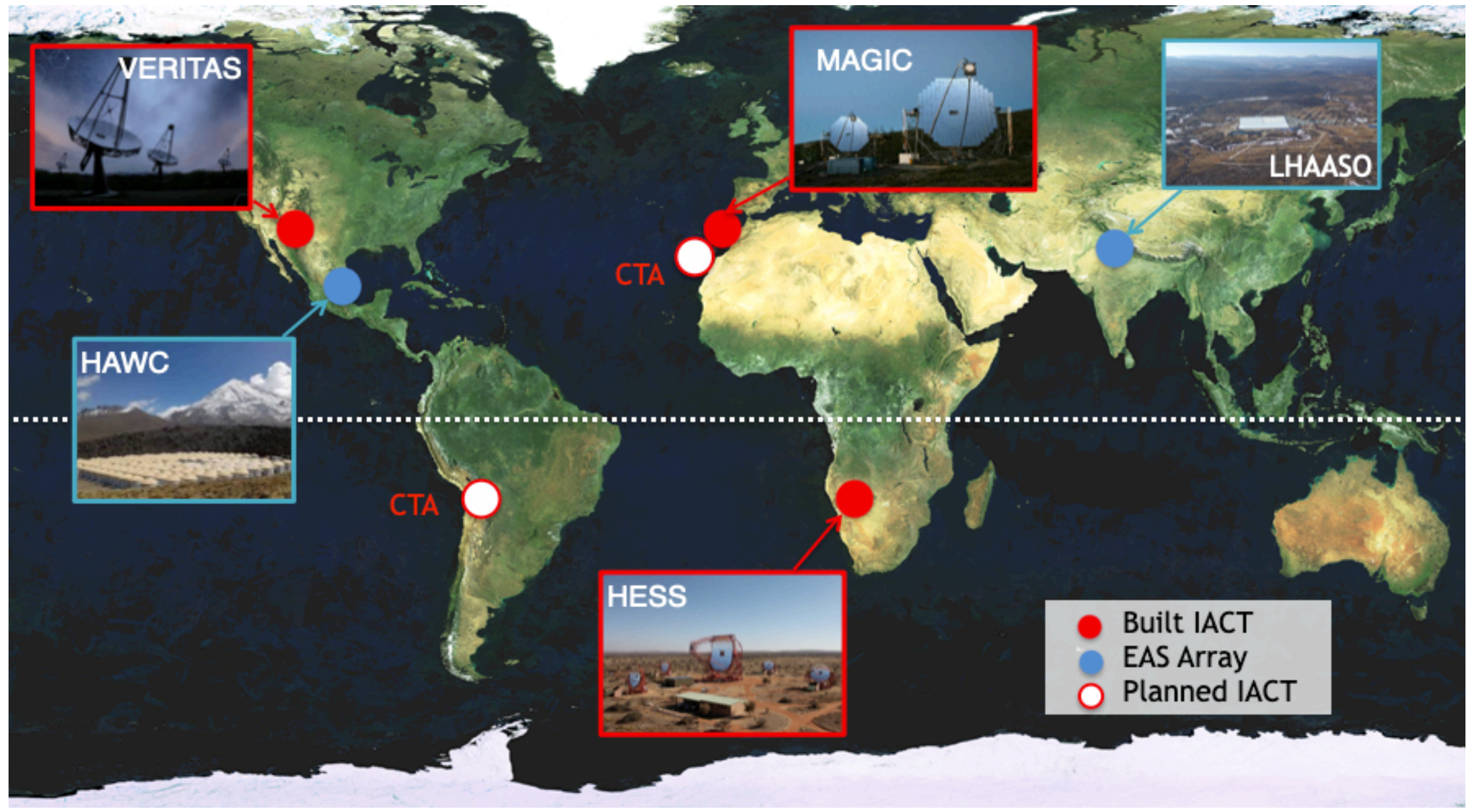
UHECR white paper, arXiv:2205.05845 [astro-ph.HE] ,submitted to Astropart. Phys. Journal

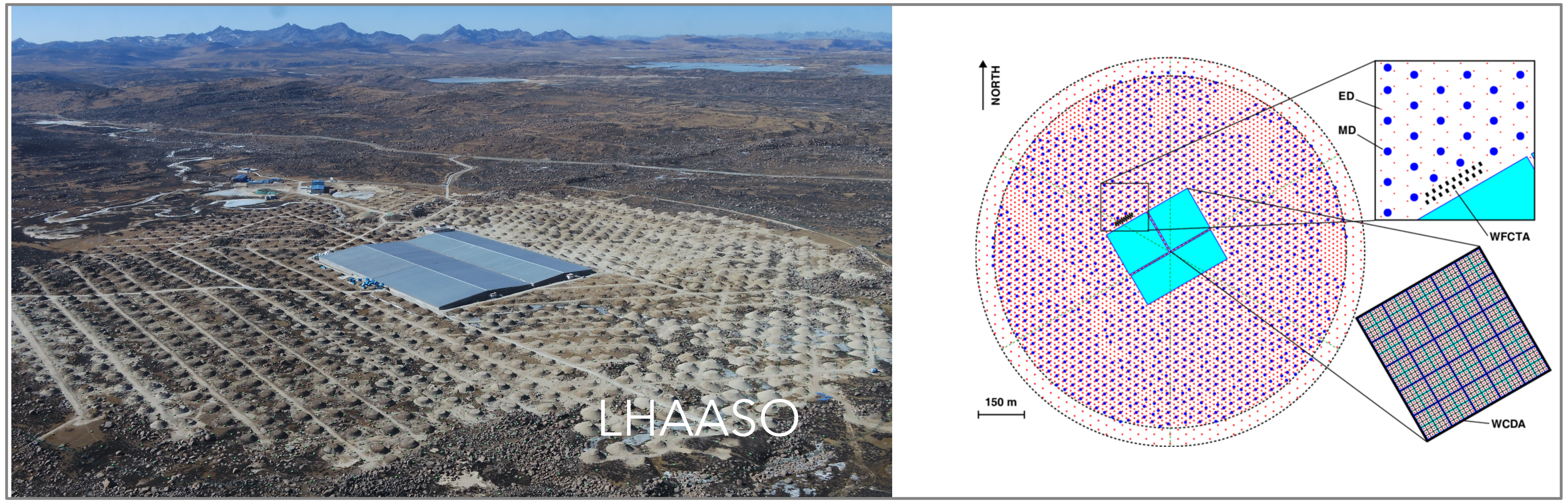


VHE-UHE
Gamma rays

Southern Wide Field Gamma Ray Observatory (SWGO)

The discovery of PeV photons





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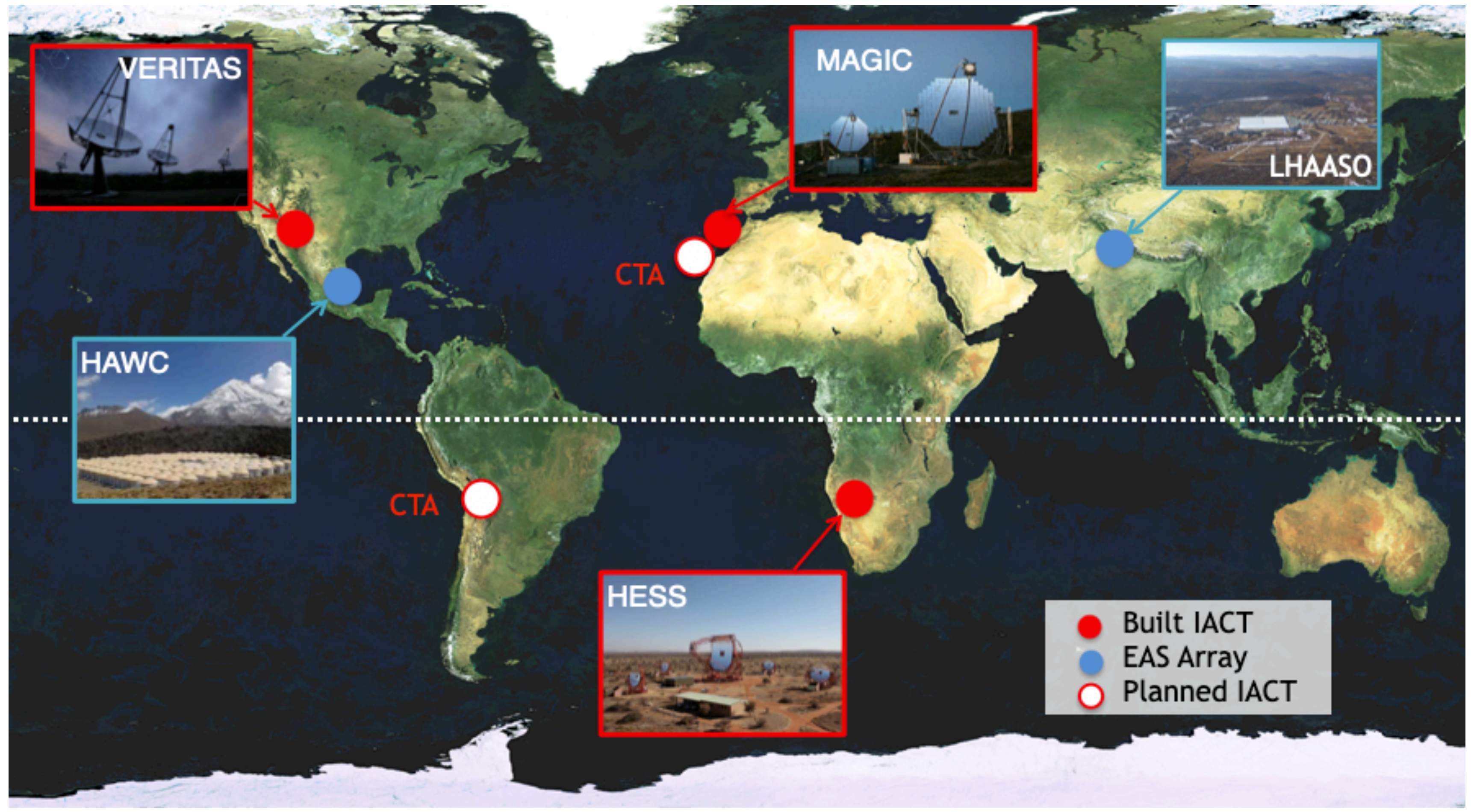

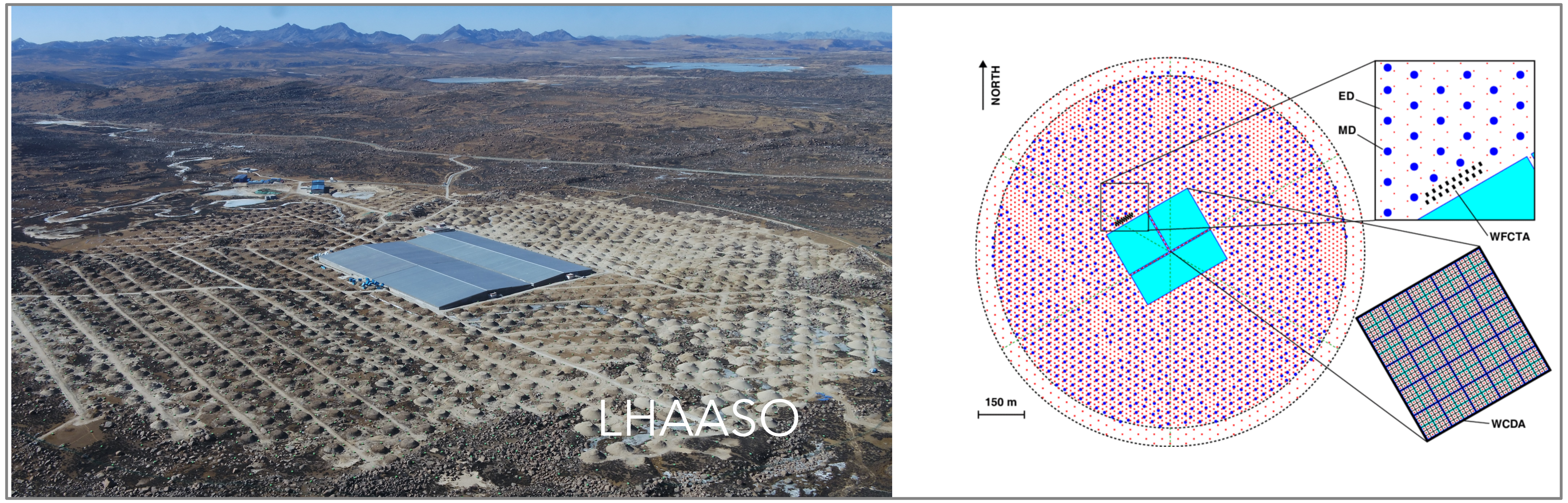

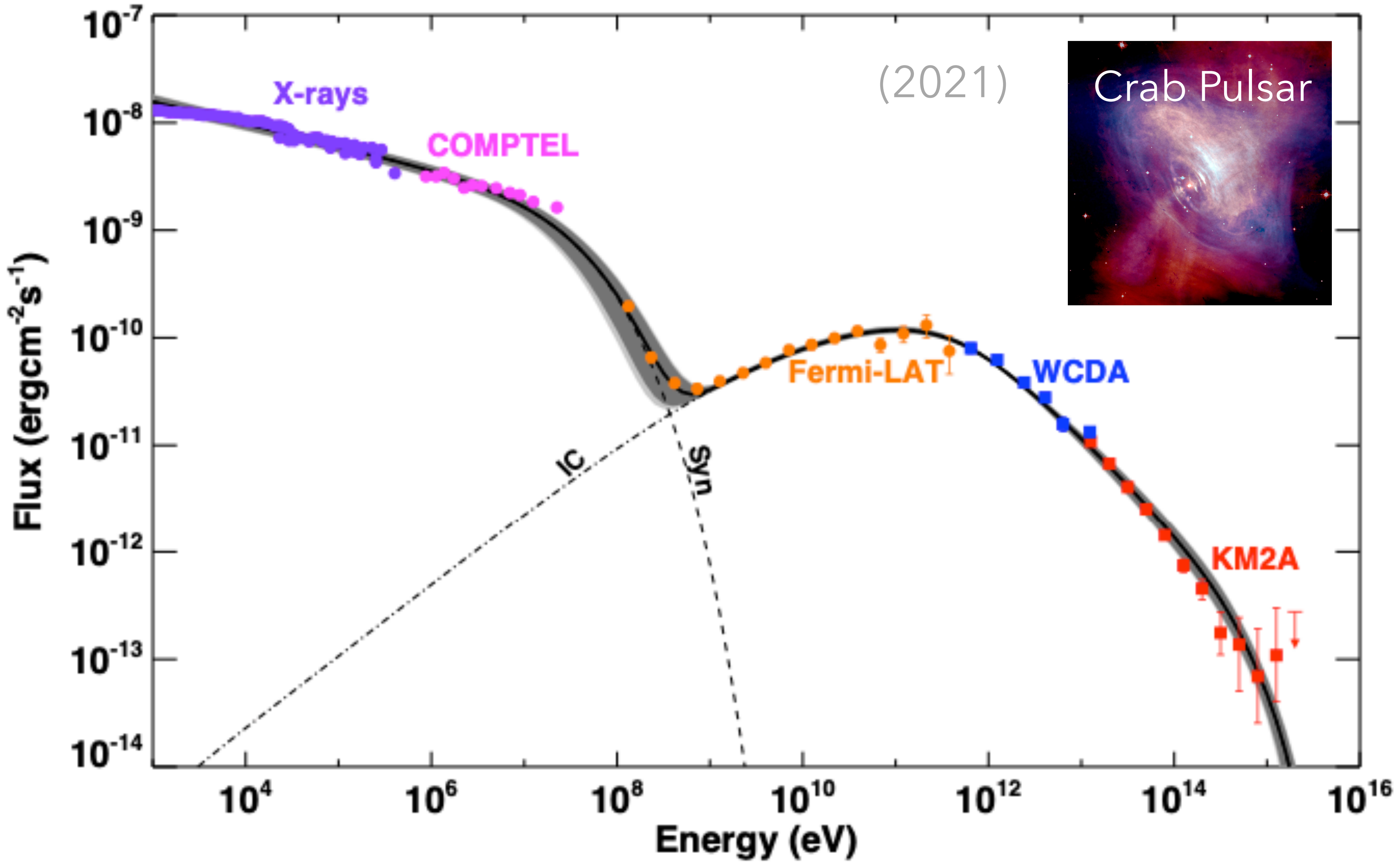

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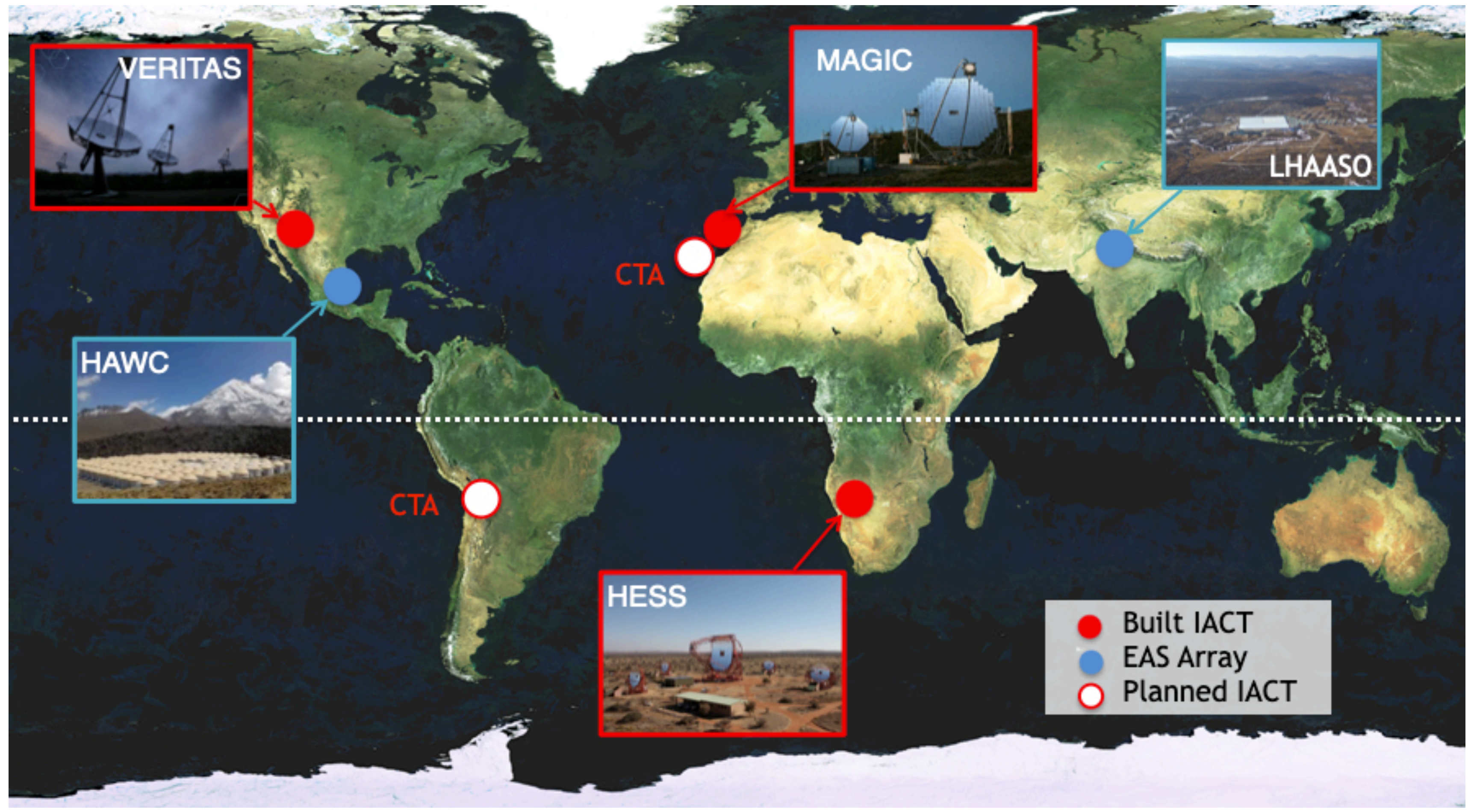
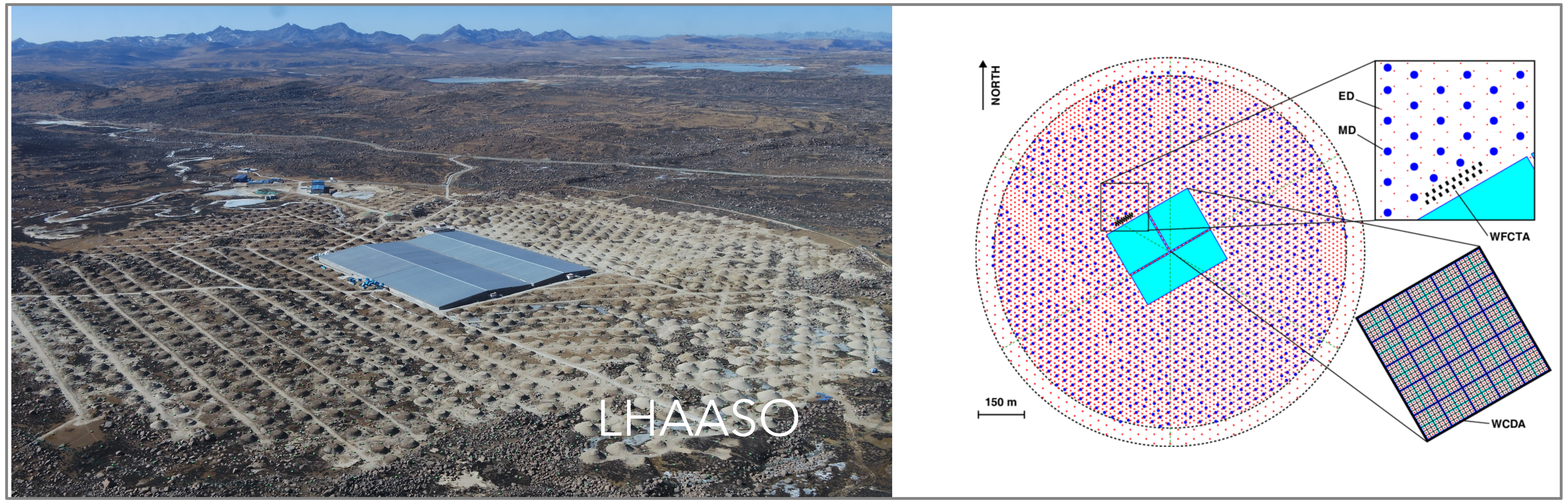
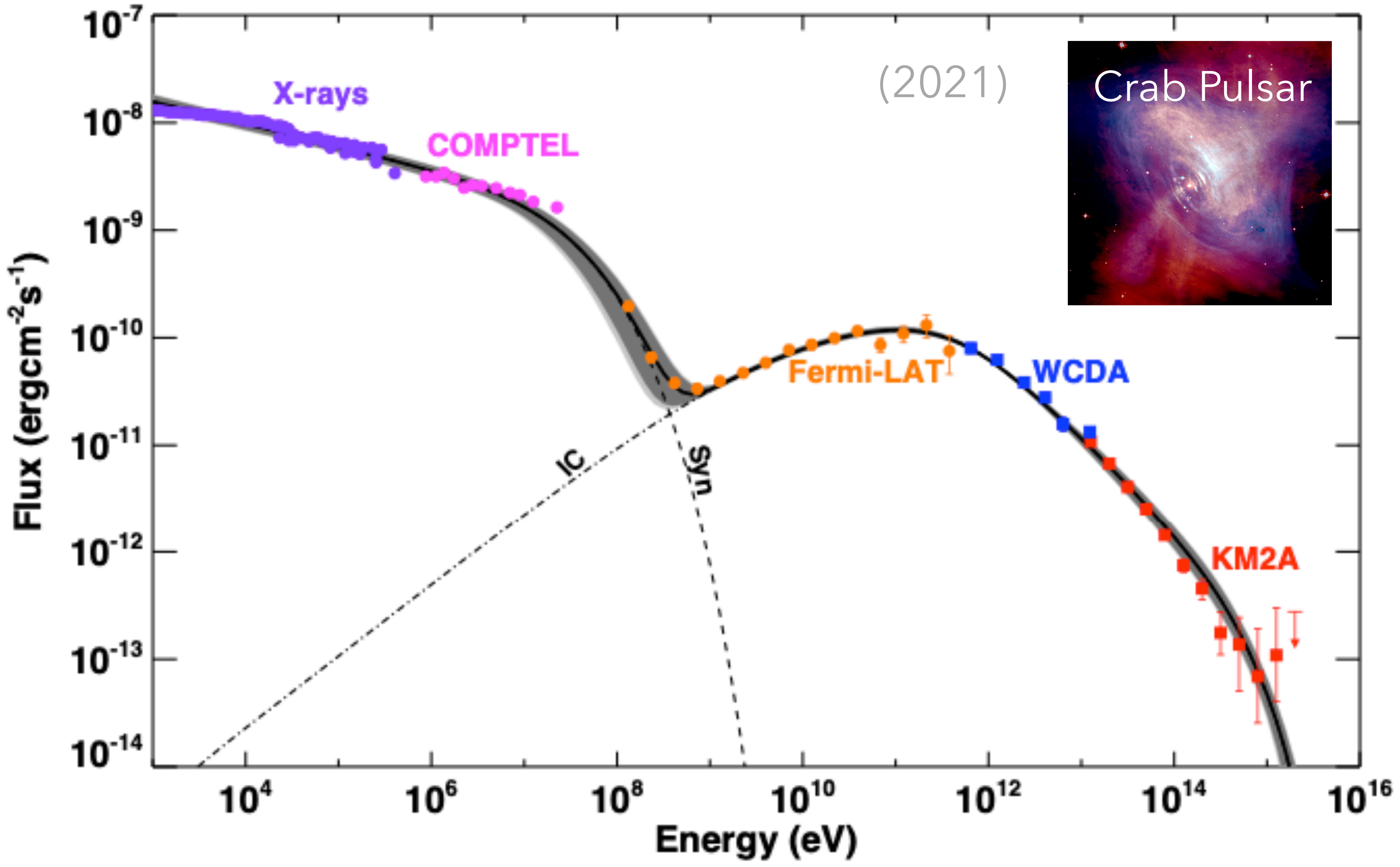
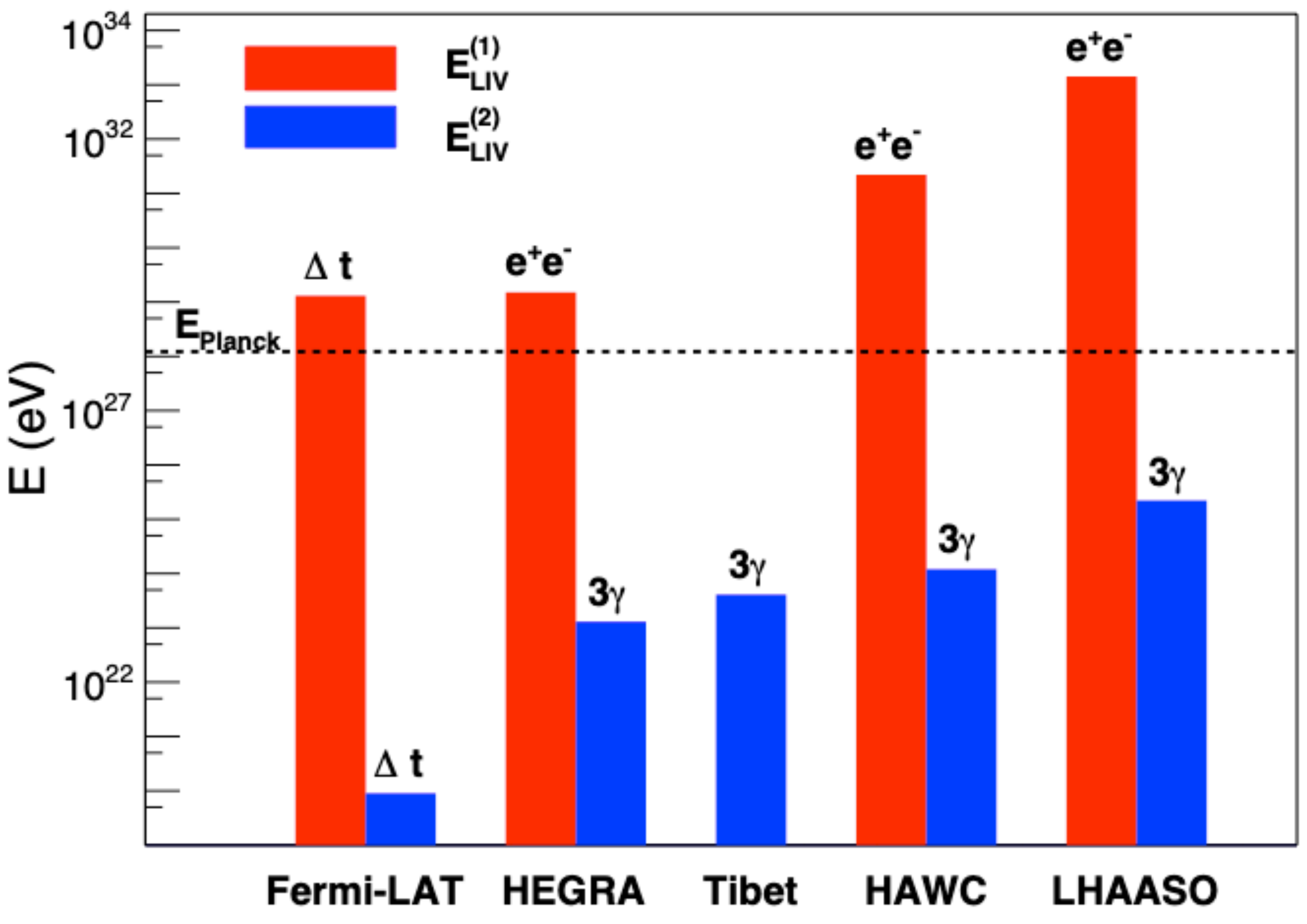






LIV studies



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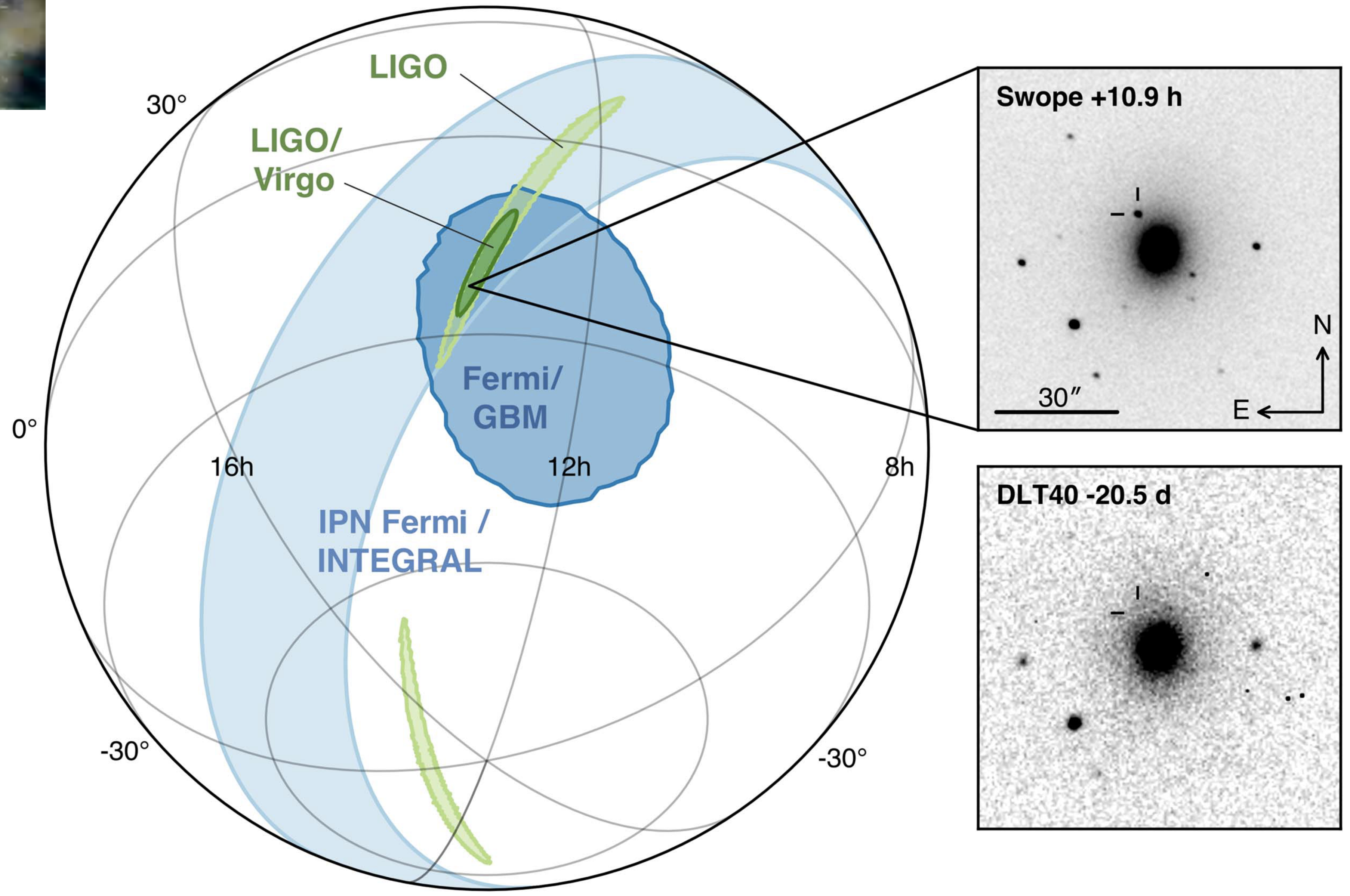
Astroparticle Multimessenger Era

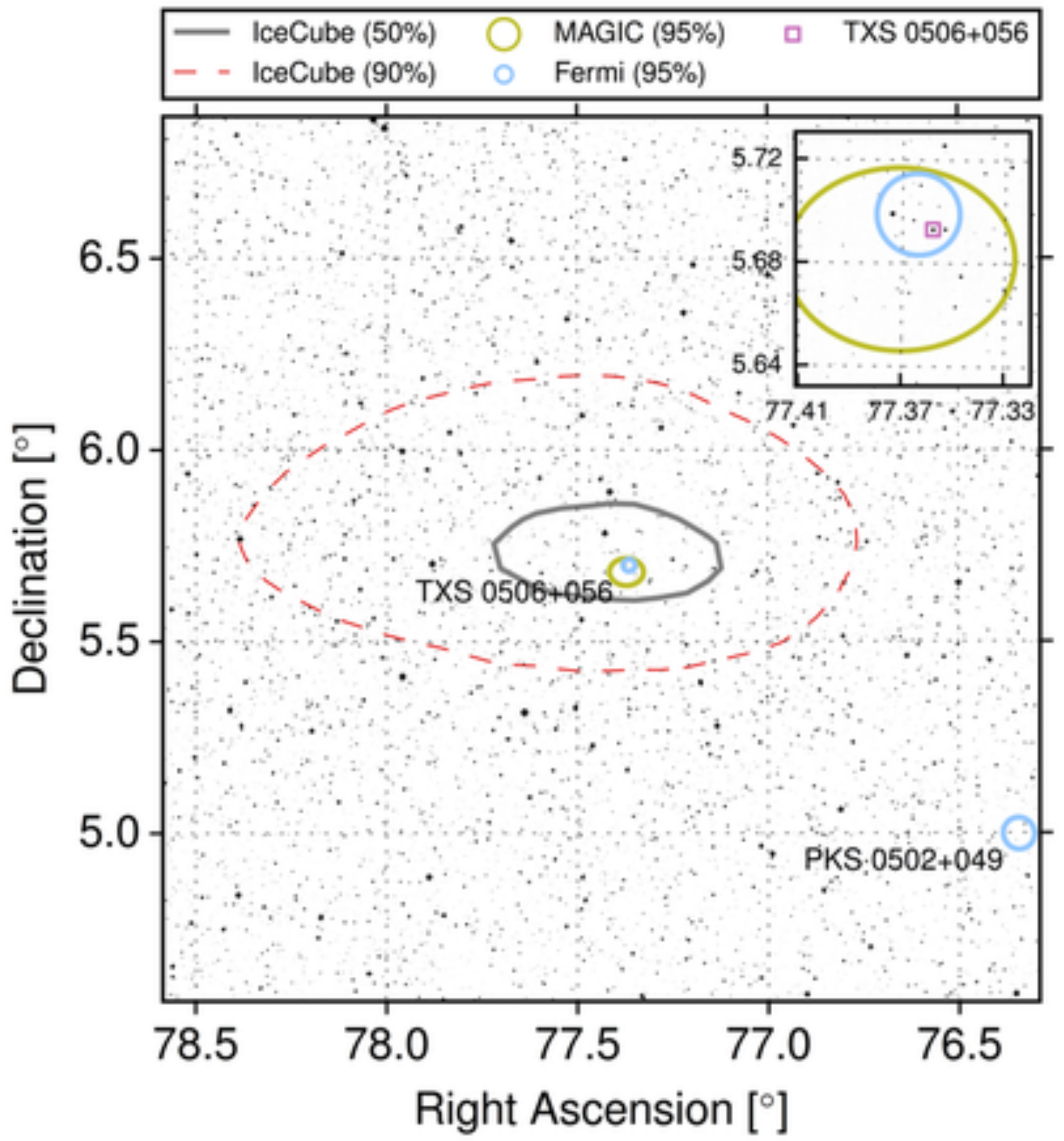
Observation of a Binary Neutron Star Merger

LIGO, VIRGO, INTEGRAL, Fermi, IceCube, Pierre Auger … (***2017***)



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

IceCube, MAGIC, Fermi-LAT … (***2018***)



Energy [eV]

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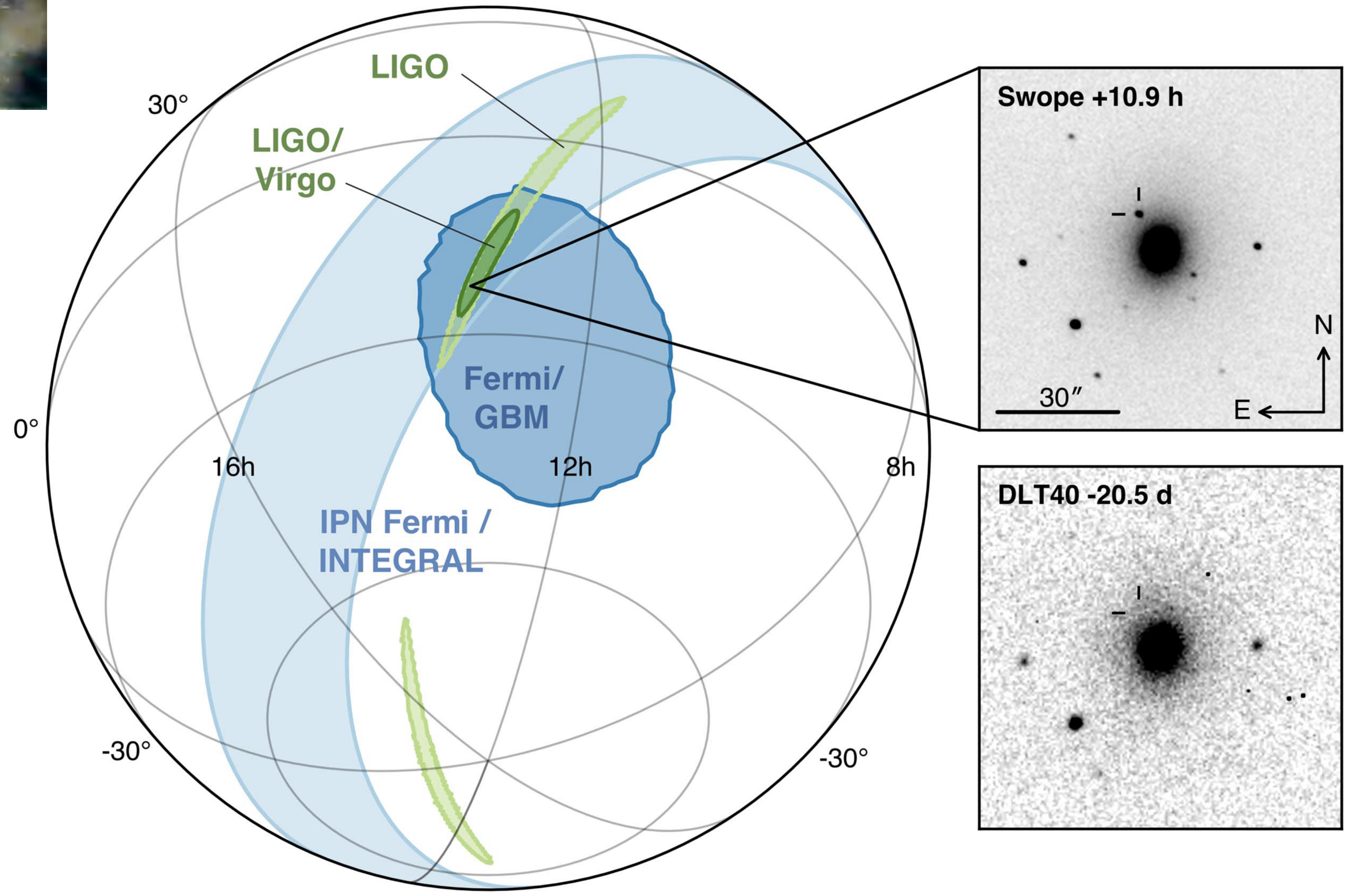

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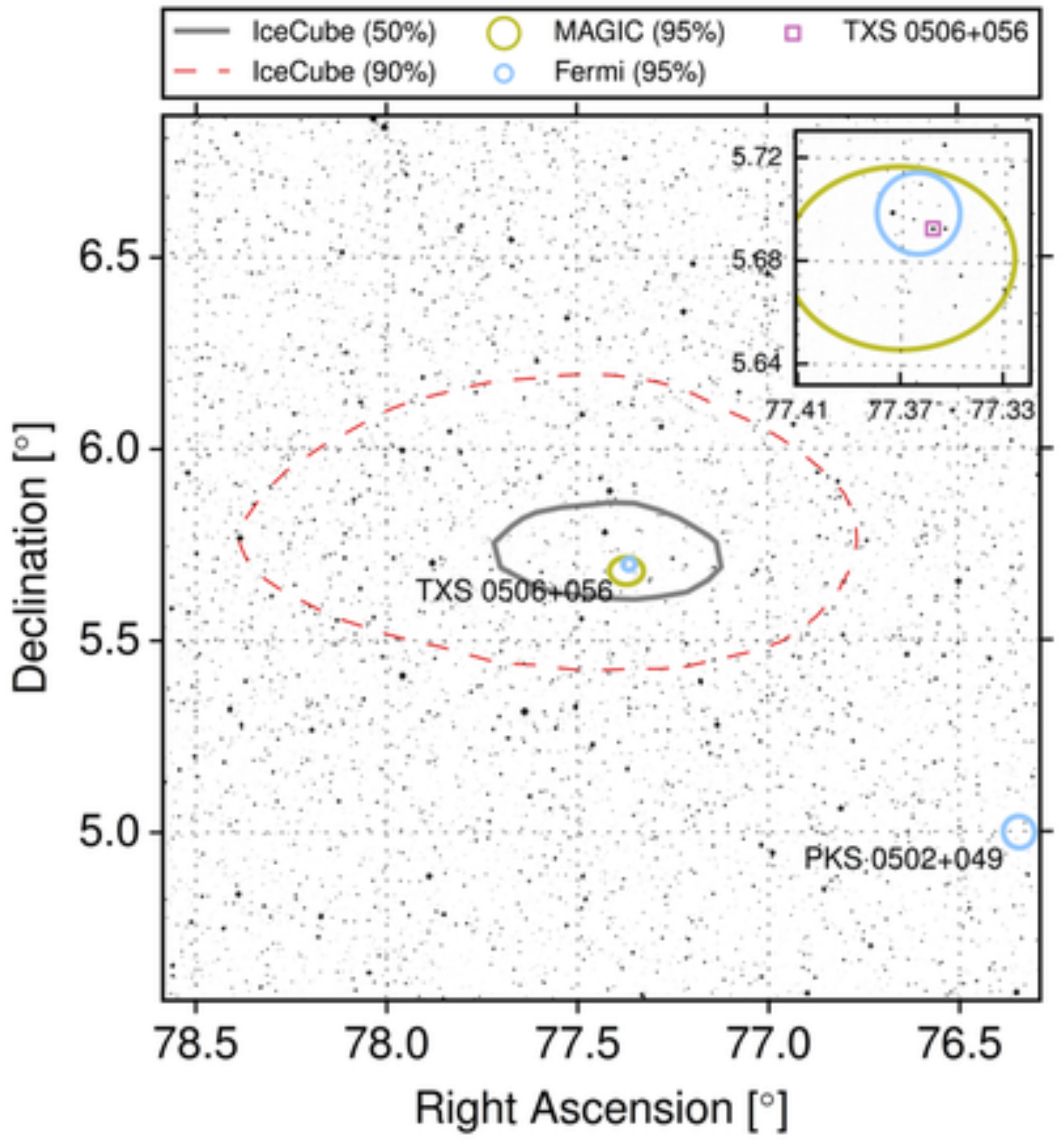
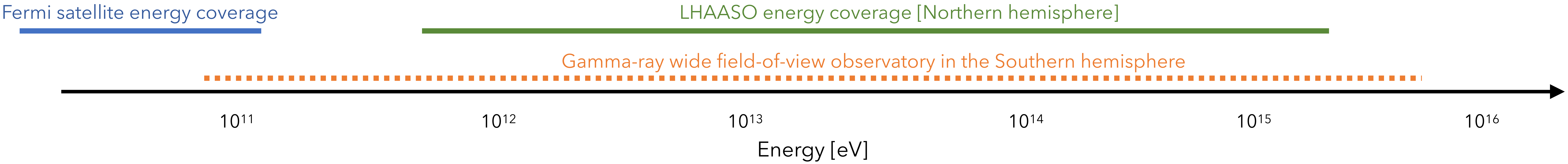


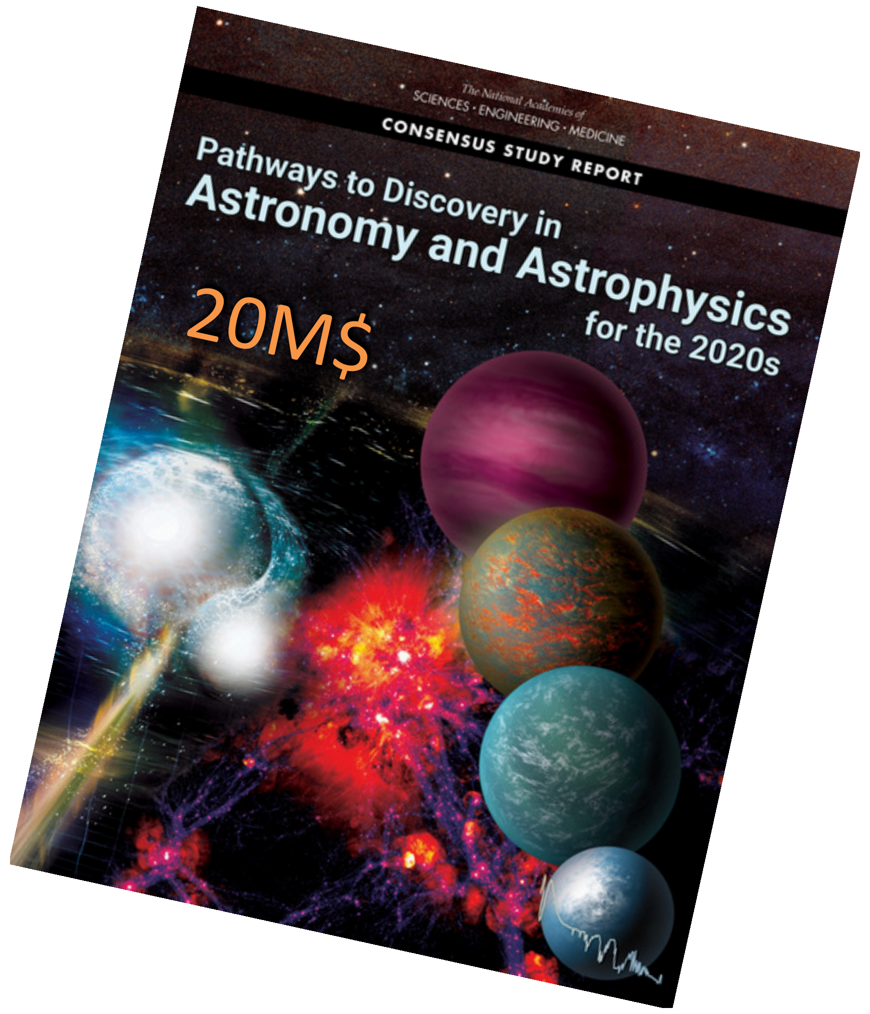


SWGO collaboration

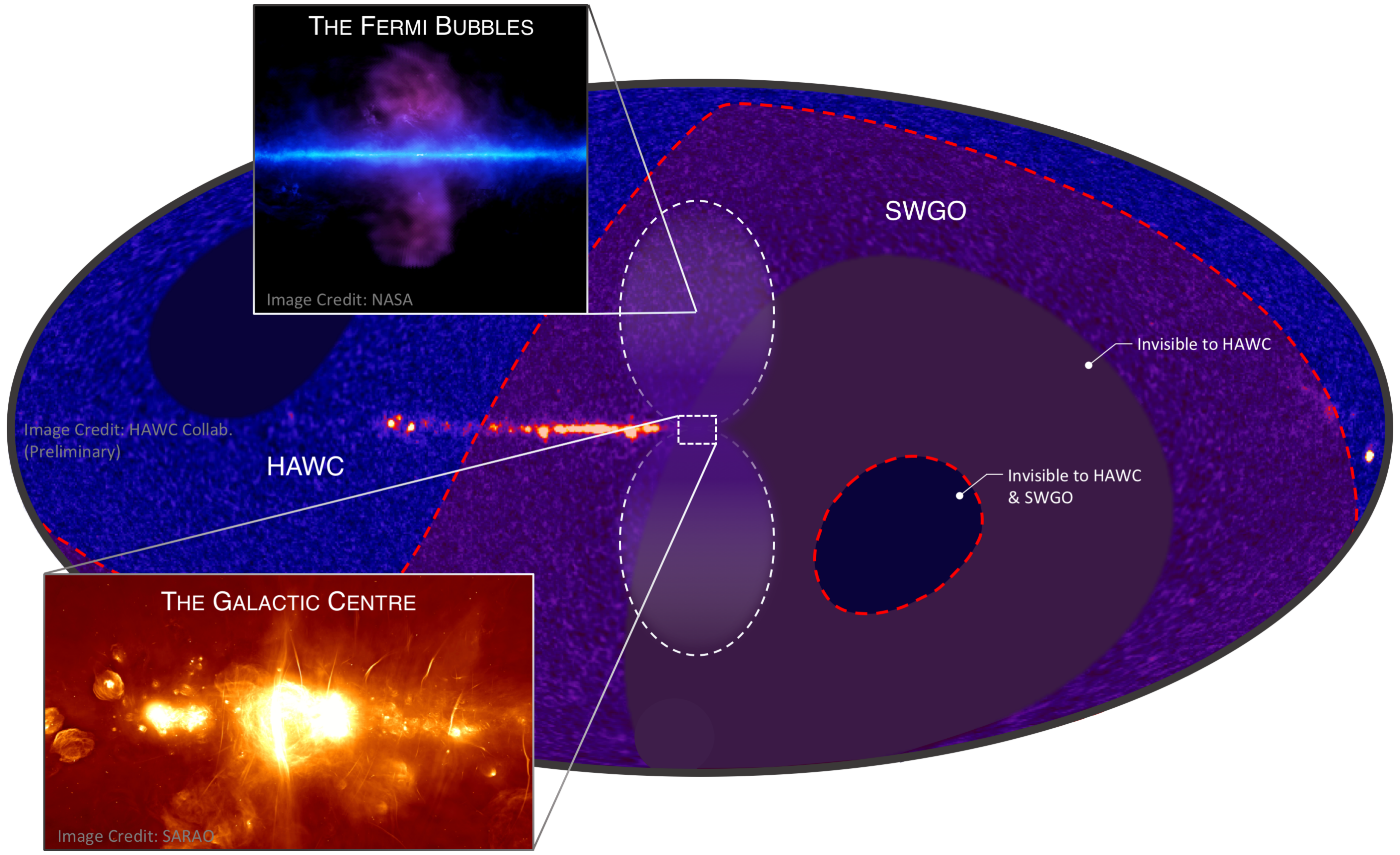
~3-year R&D project to design and plan the next generation wide field-of-view gamma-ray able to survey and monitor the Southern sky

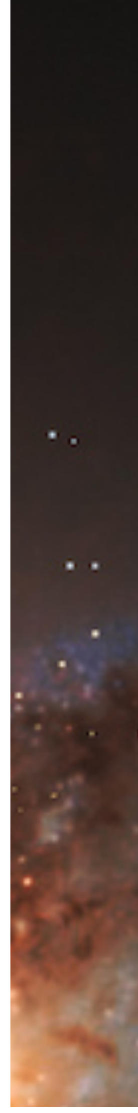
- **S**outhern **W**ide-field **G**amma-ray **O**bservatory
  - Formed at *July 1st 2019*
- 14 Countries / ~ 50 institutes / More than 100 scientists

	SWGO R&D Phase Milestones	
✓	M1	R&D Phase Plan Established
✓	M2	Science Benchmarks Defined
✓	M3	Reference Configuration & Options Defined
✓	M4	Site Shortlist Complete
✓	M5	Candidate Configurations Defined
	M6	Performance of Candidate Configurations Evaluated
	M7	Preferred Site Identified
	M8	Design Finalised
	M9	Construction & Operation Proposal Complete



The scientific goal





www.swgo.org

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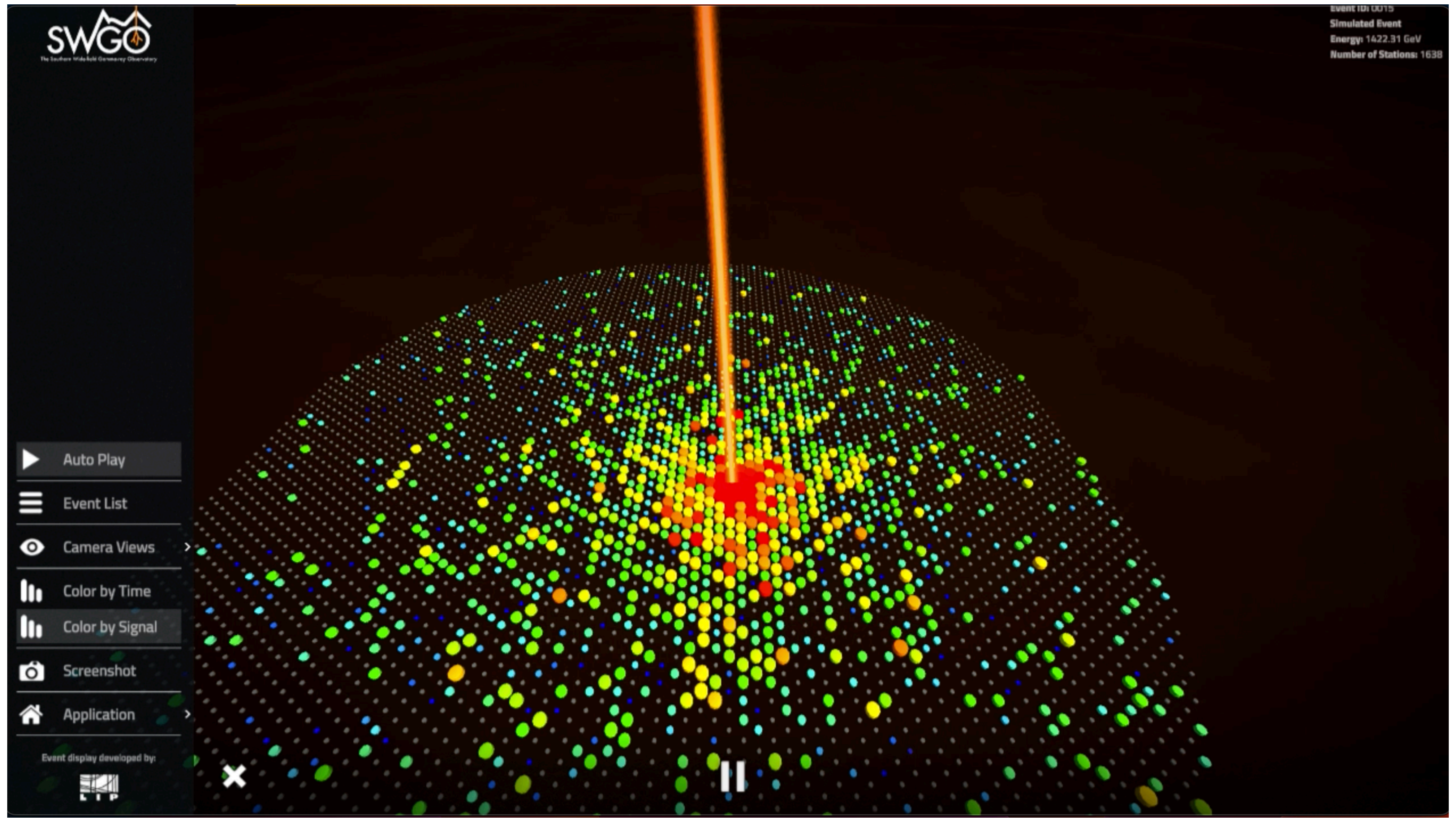
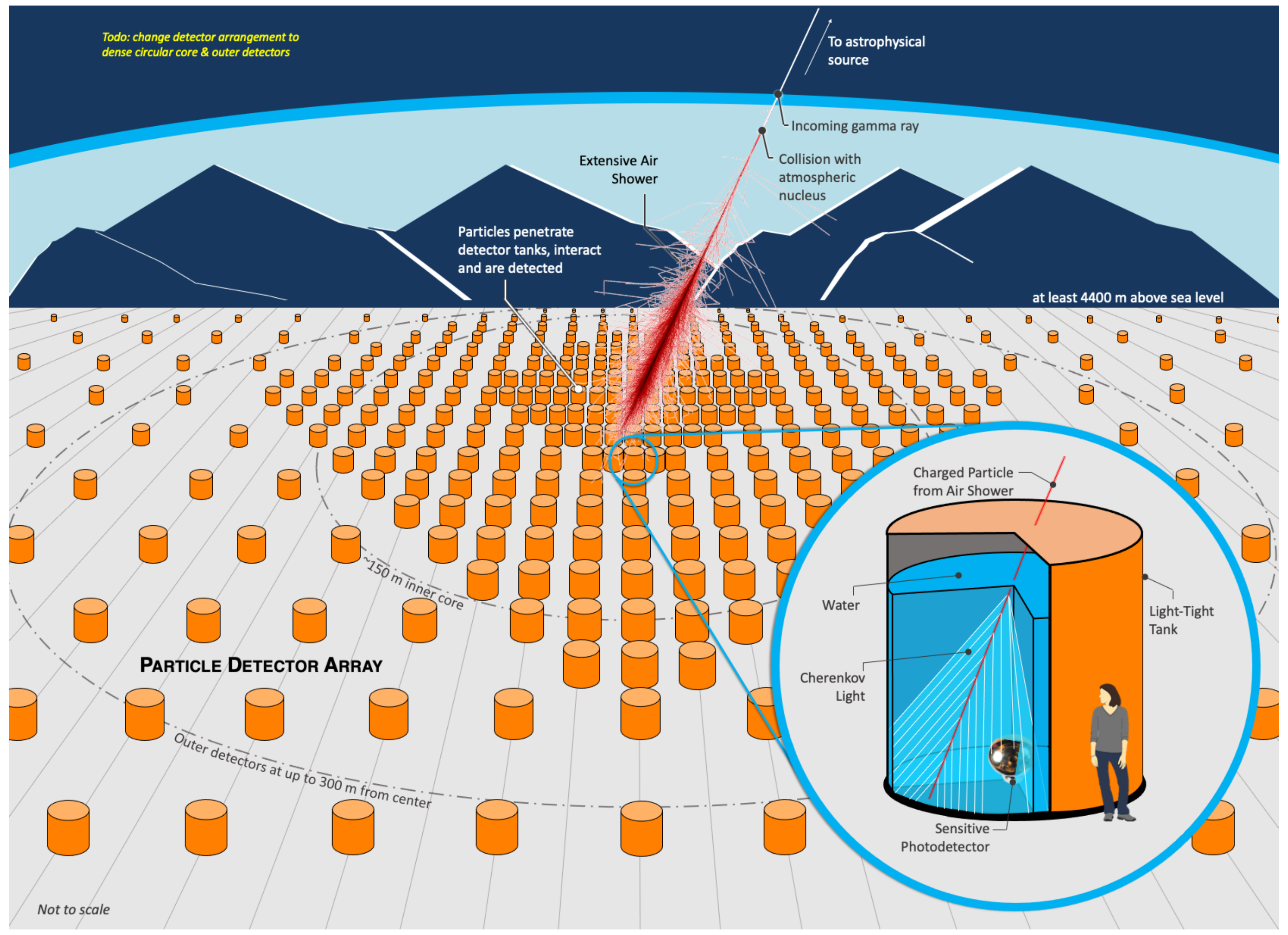
The challenge…

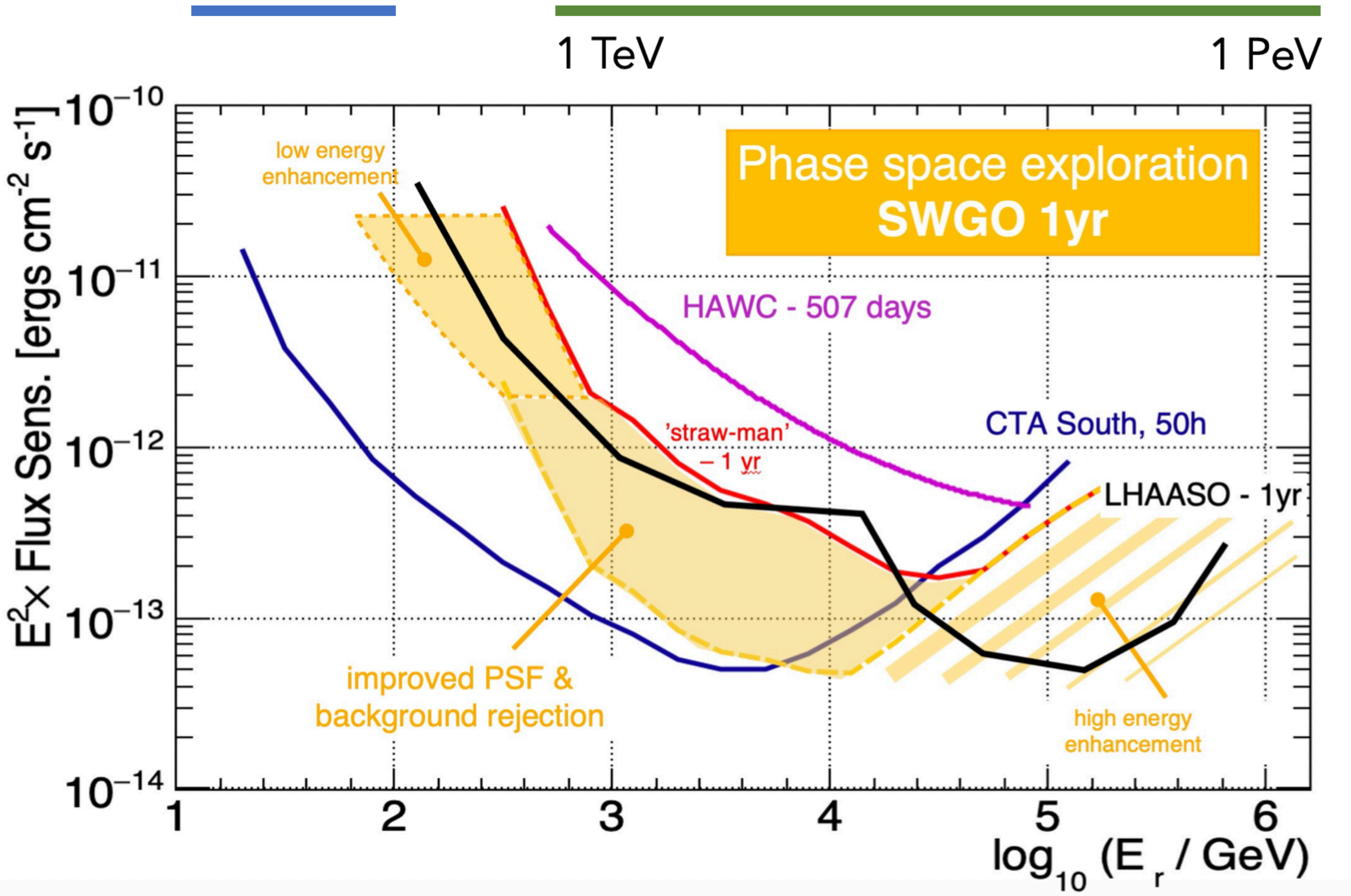
- To design an experiment able to fulfil the following requirements:
  - **Muon tagging**/counting capability
  - Lower energies
    - to be placed at **high altitude** (~5000 m a.s.l.)
    - **Compact array**
  - Higher energies
    - **Large area** (~ few km^2)

LIP-SWGO event visualizer of the compact array - γ induced shower of 1.4 TeV





Experiments:
- Satellite
- Ground-based



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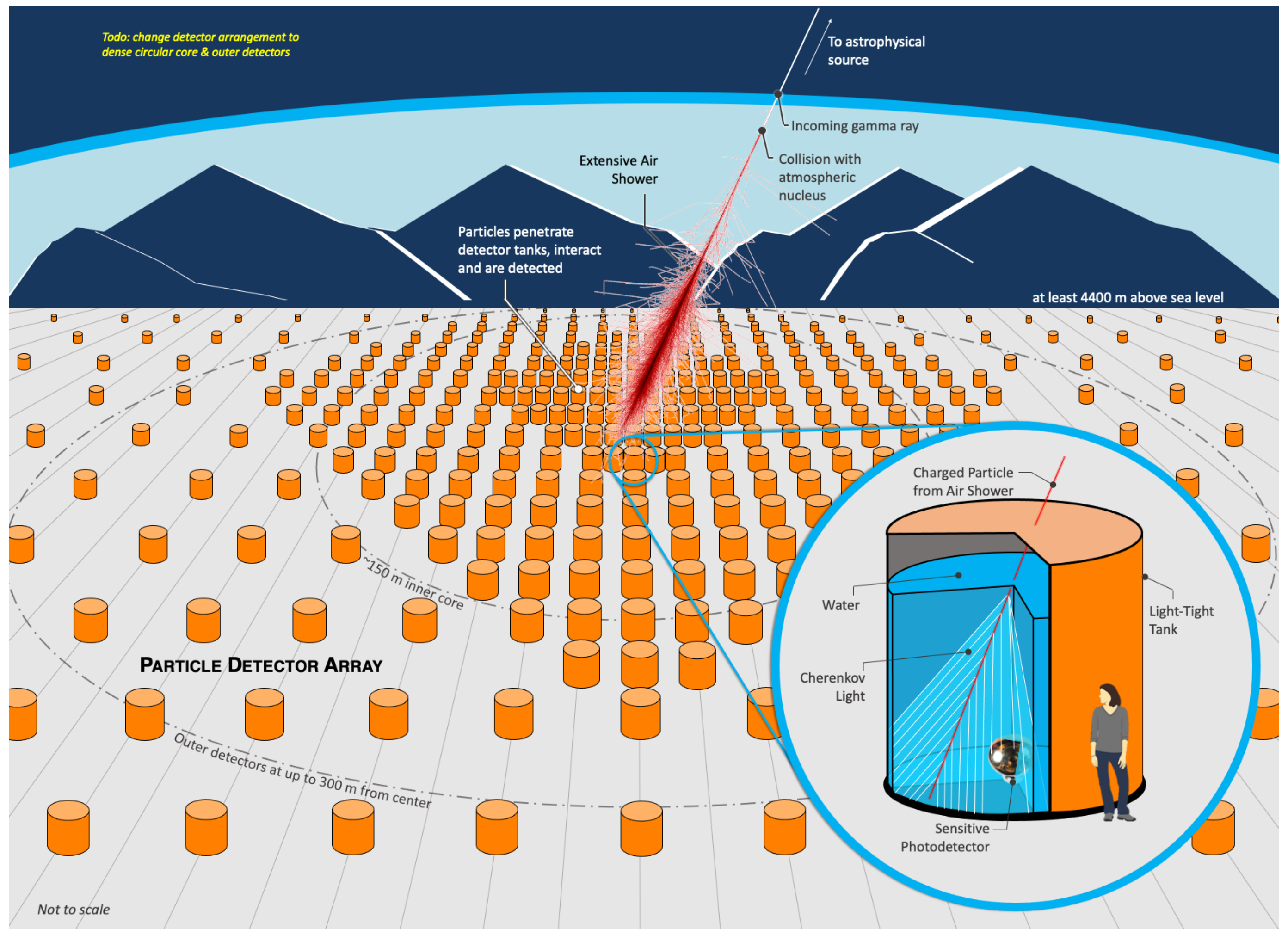
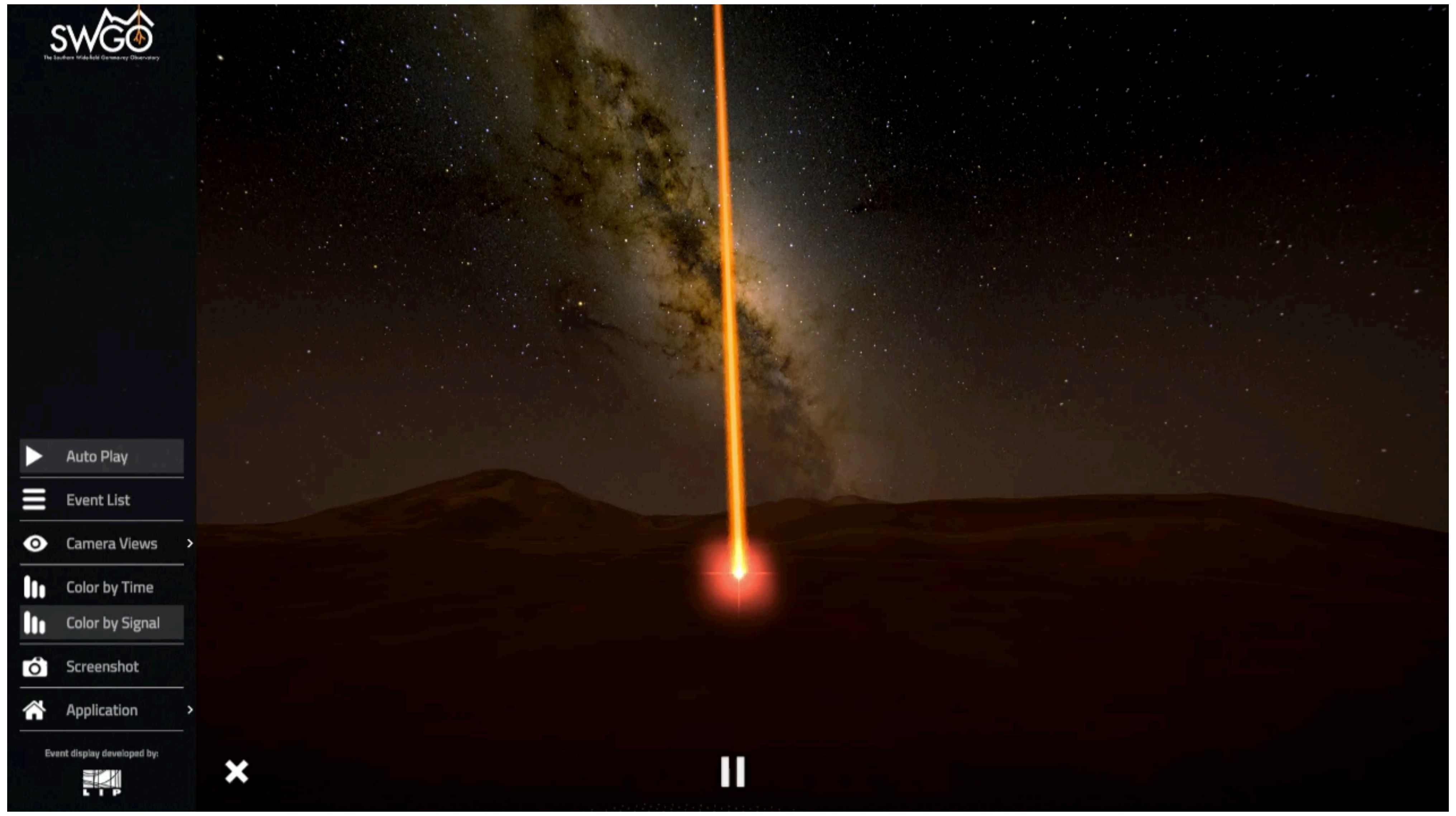


LIP-SWGO event visualizer of the compact array - γ induced shower of 1 - 60 TeV



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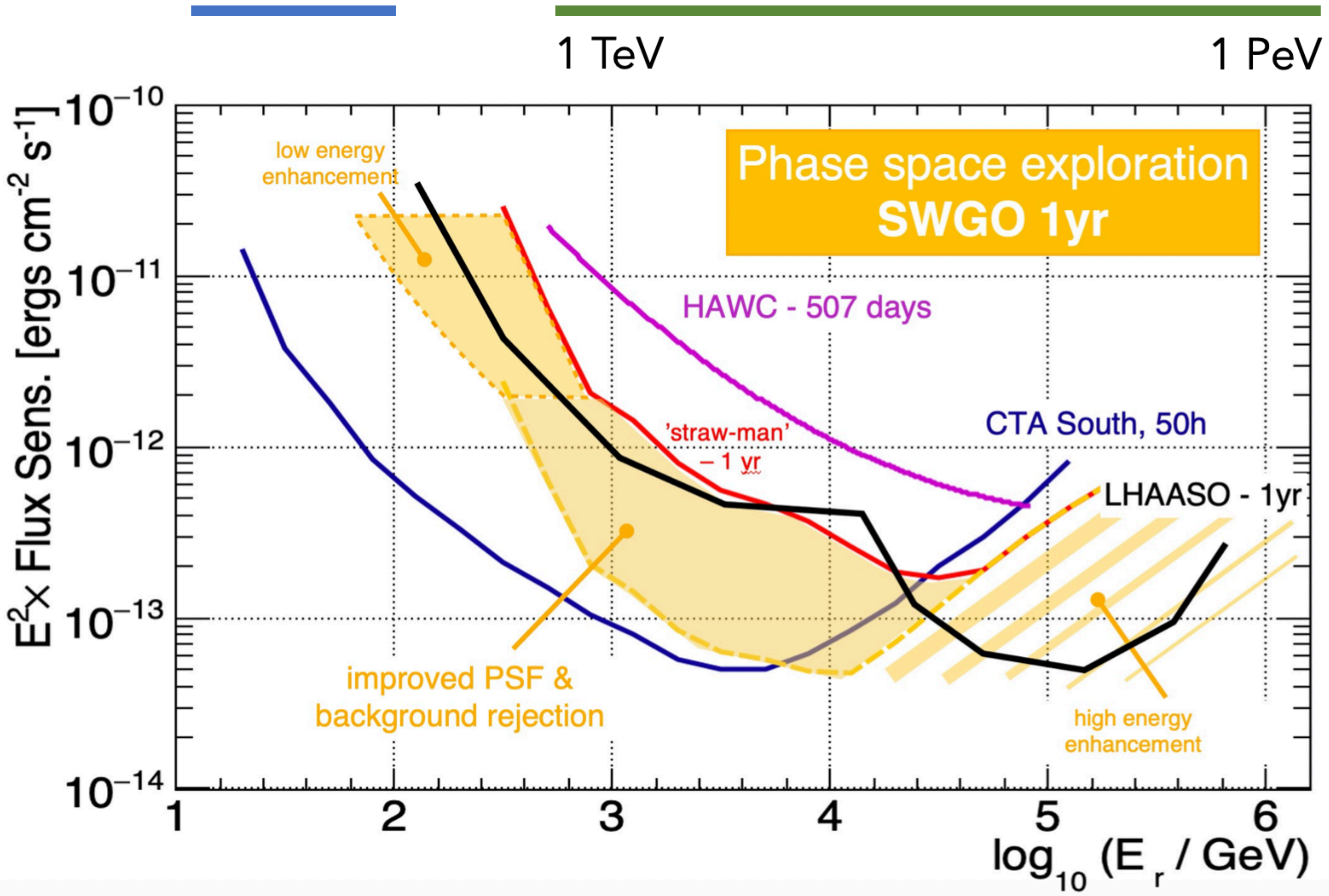

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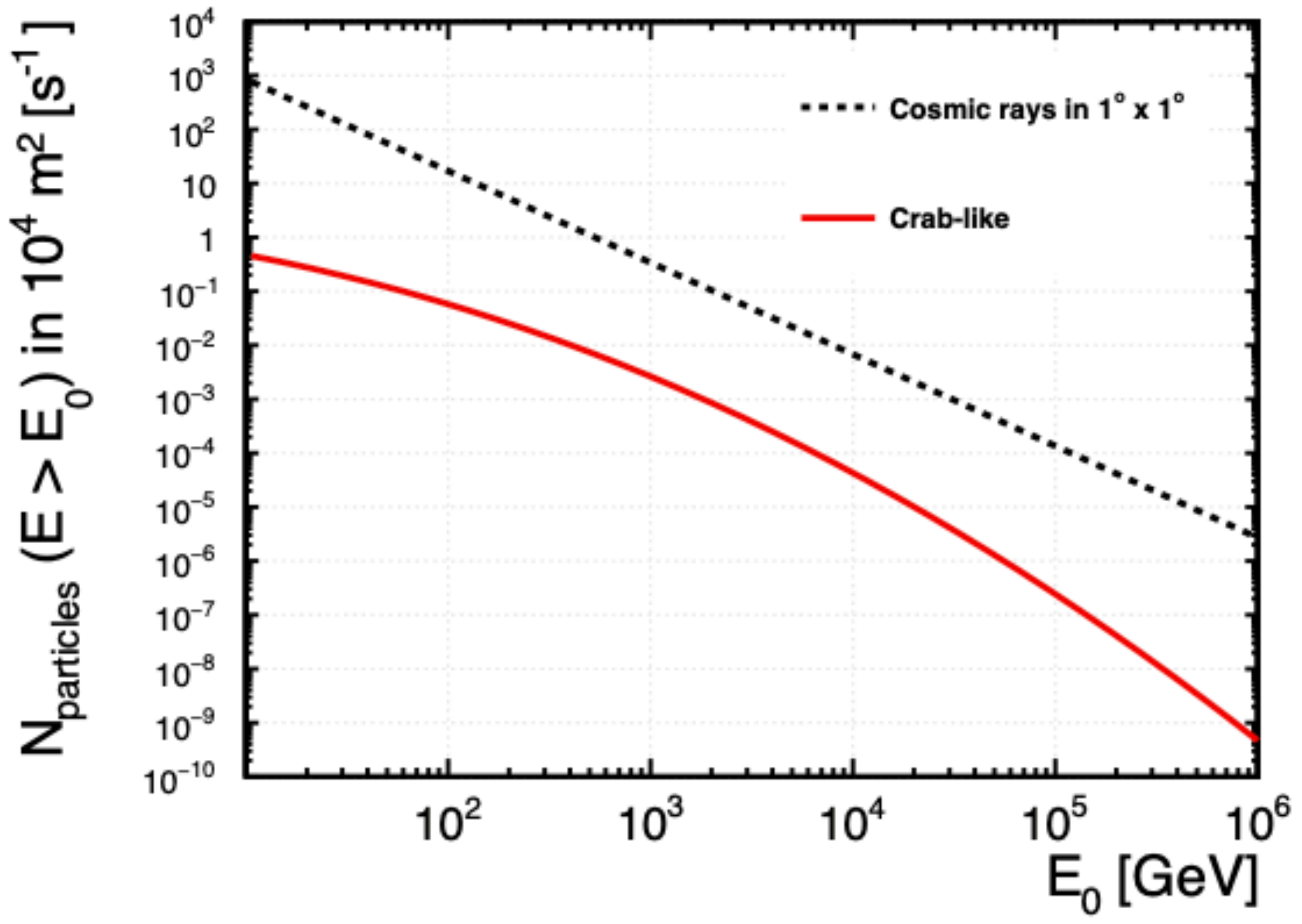
Uncertainties on EAS description at lower energies



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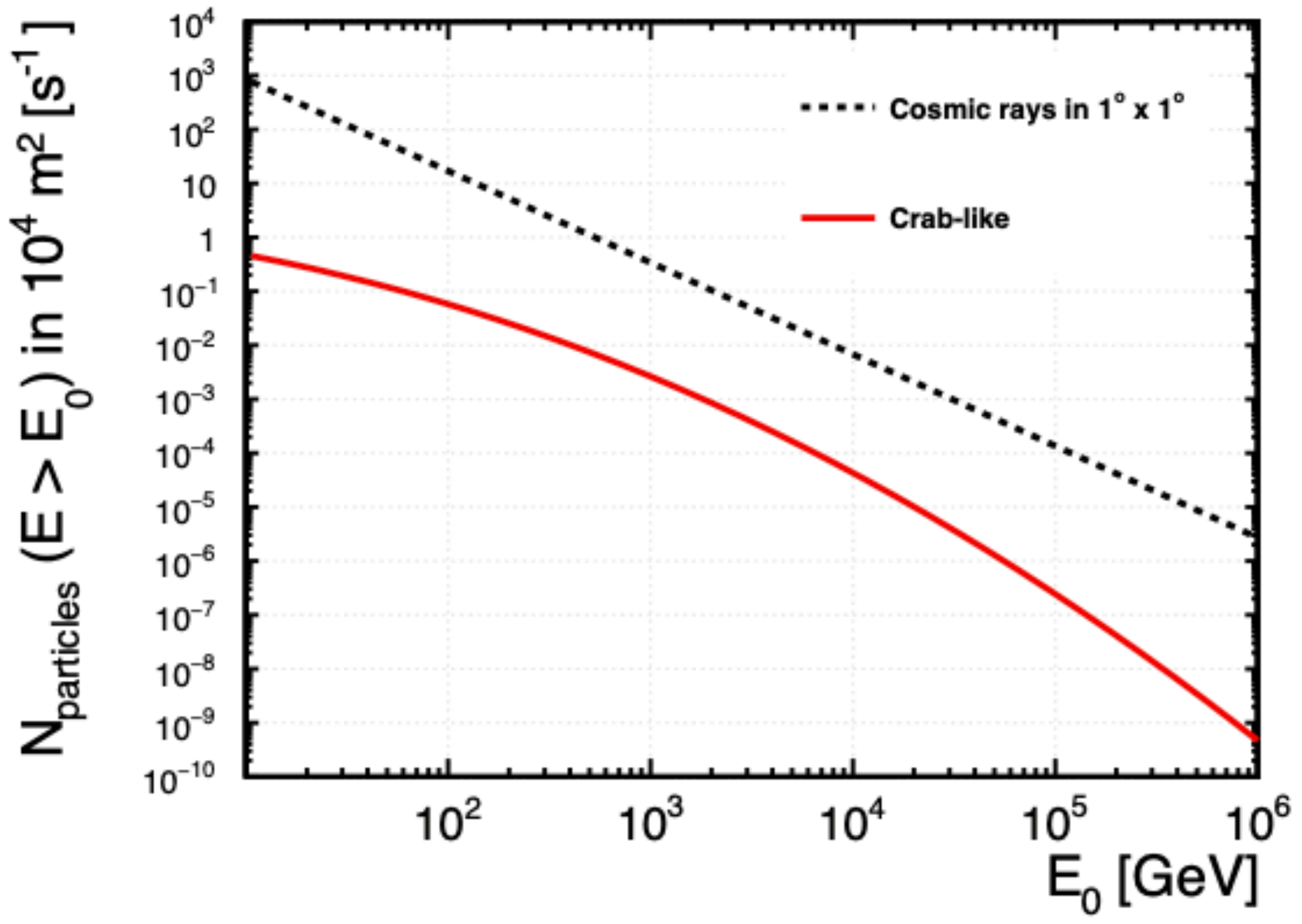

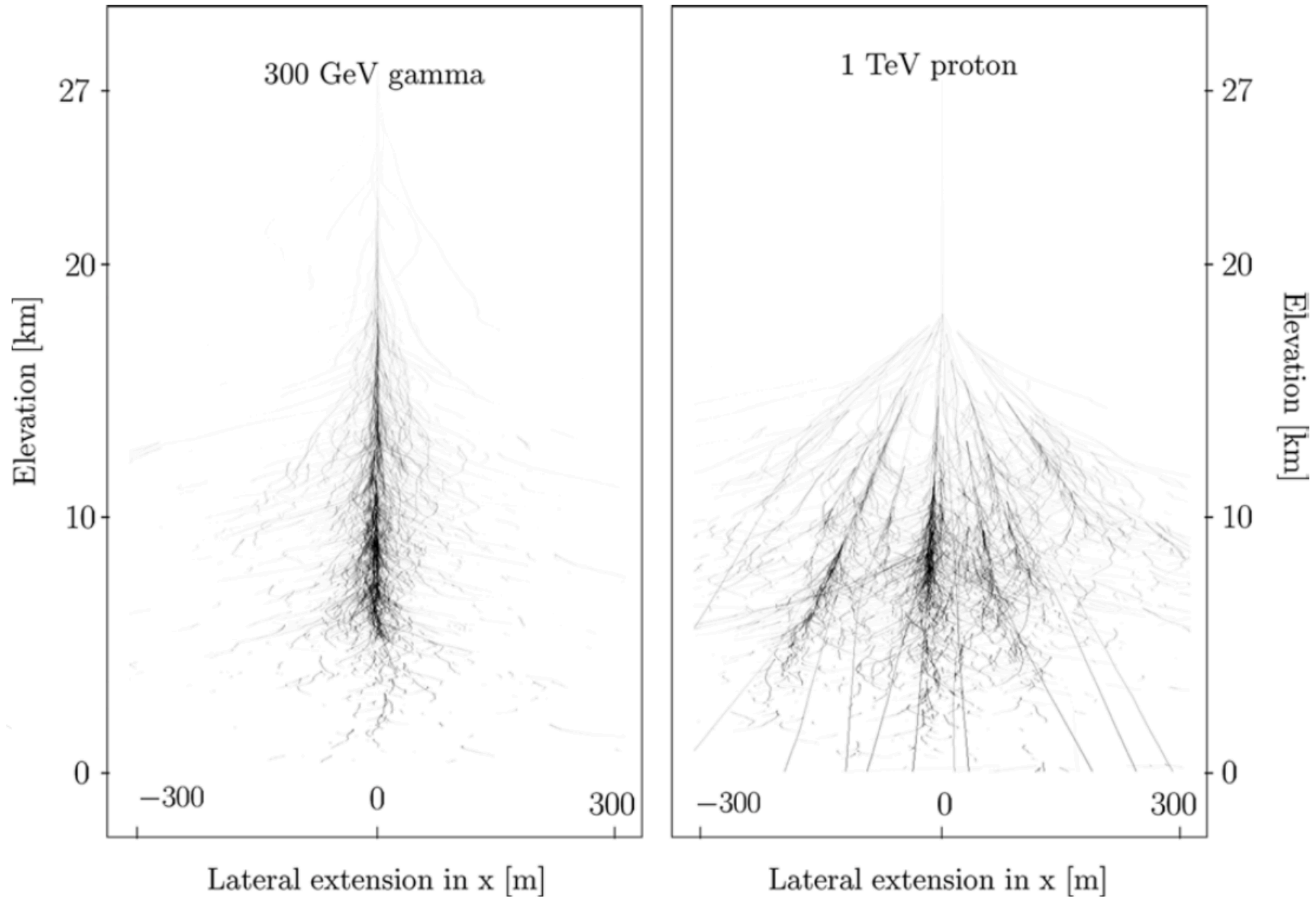

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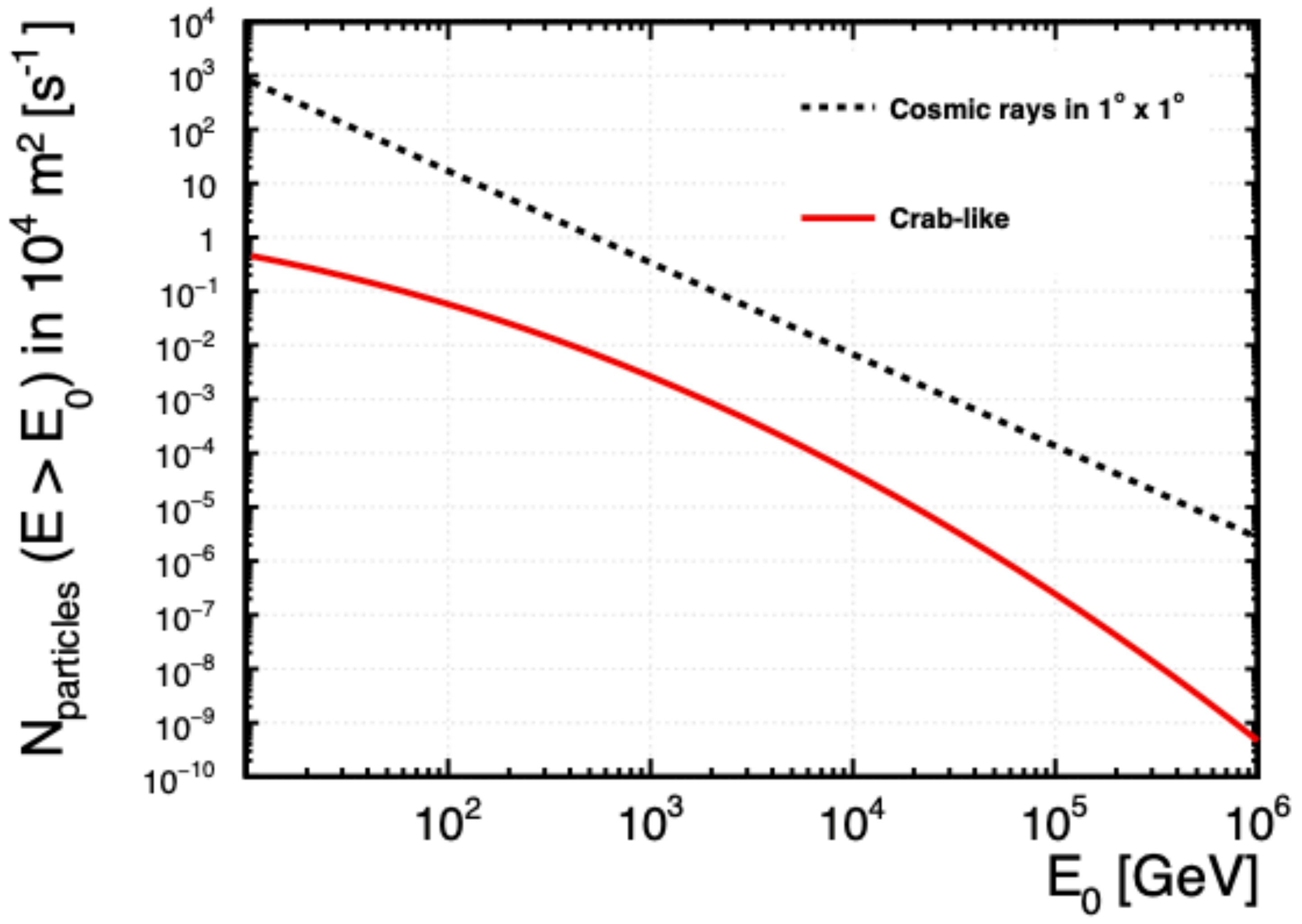
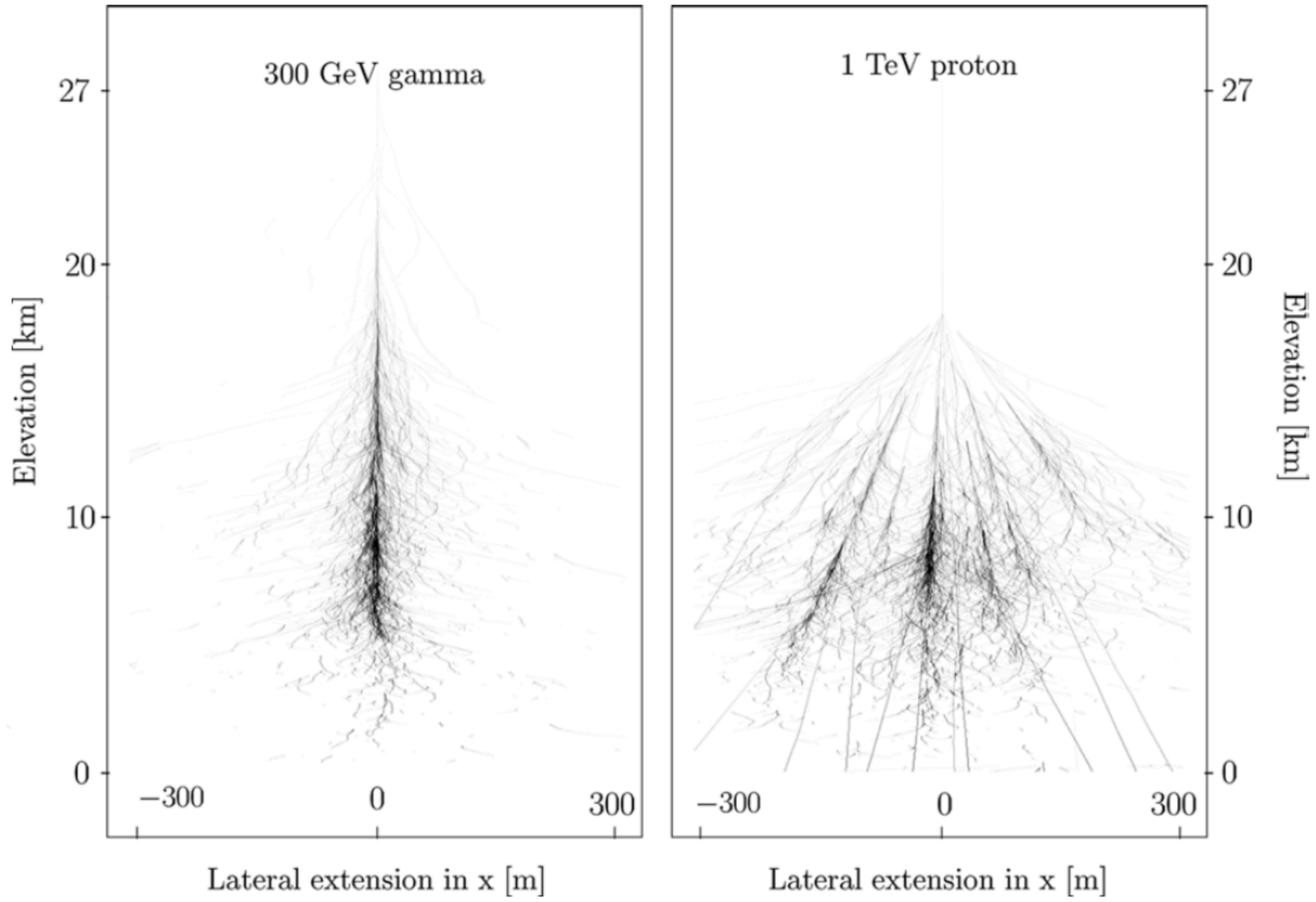
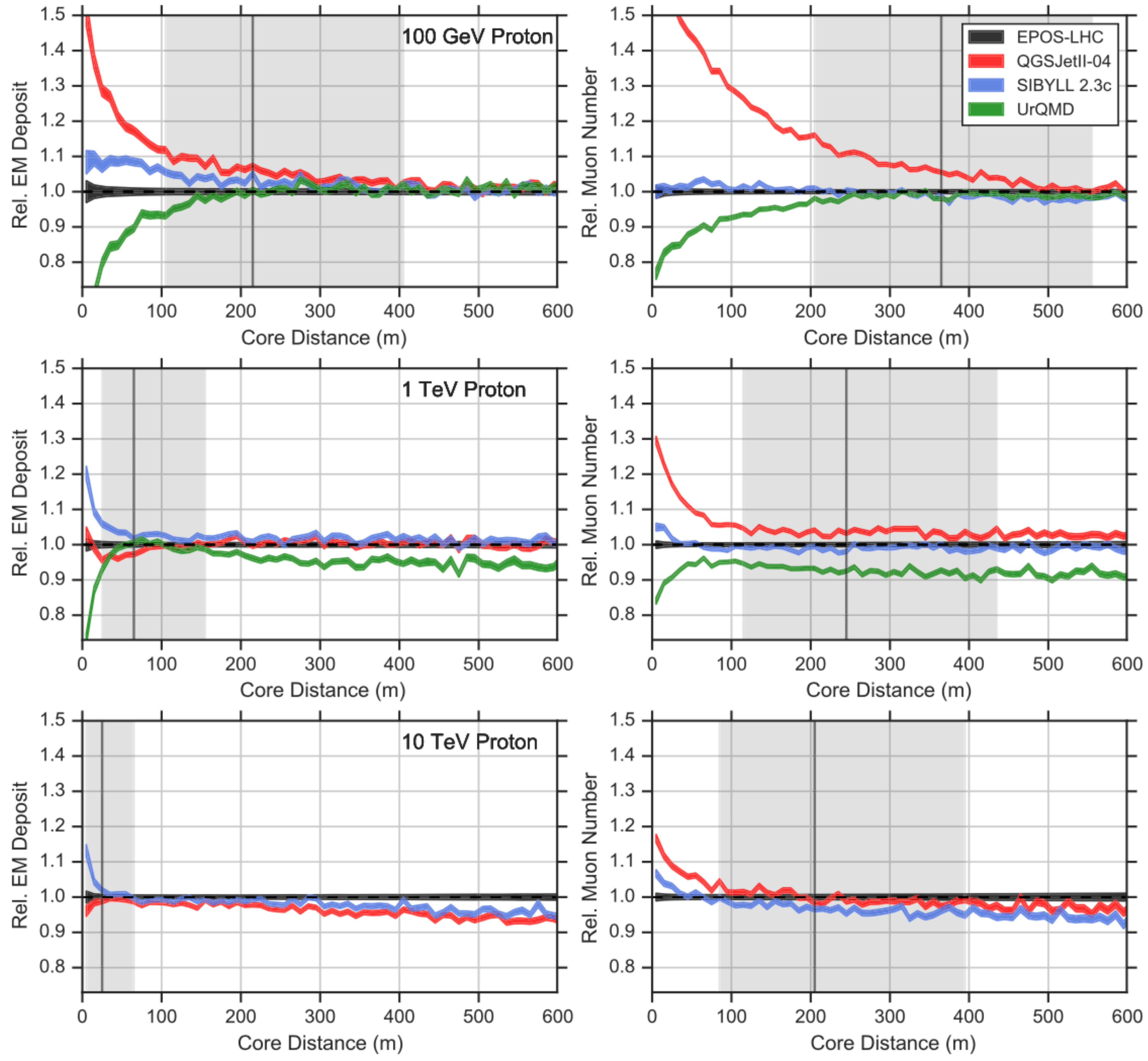




Phys.Rev.D 100 (2019) 2, 023010



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My view…

Towards a consistent description of Extensive Air Showers

Significant enhancement of primary mass composition capabilities

Perform stringent tests to the UHE universe

The path

Assess the shower
multi-scale behaviour
exploring the muon
distribution features

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Assess the shower multi-scale behaviour exploring the muon distribution features

Advance detector R&D for cosmic ray experiments to enhance inter-calibrations and redundancy

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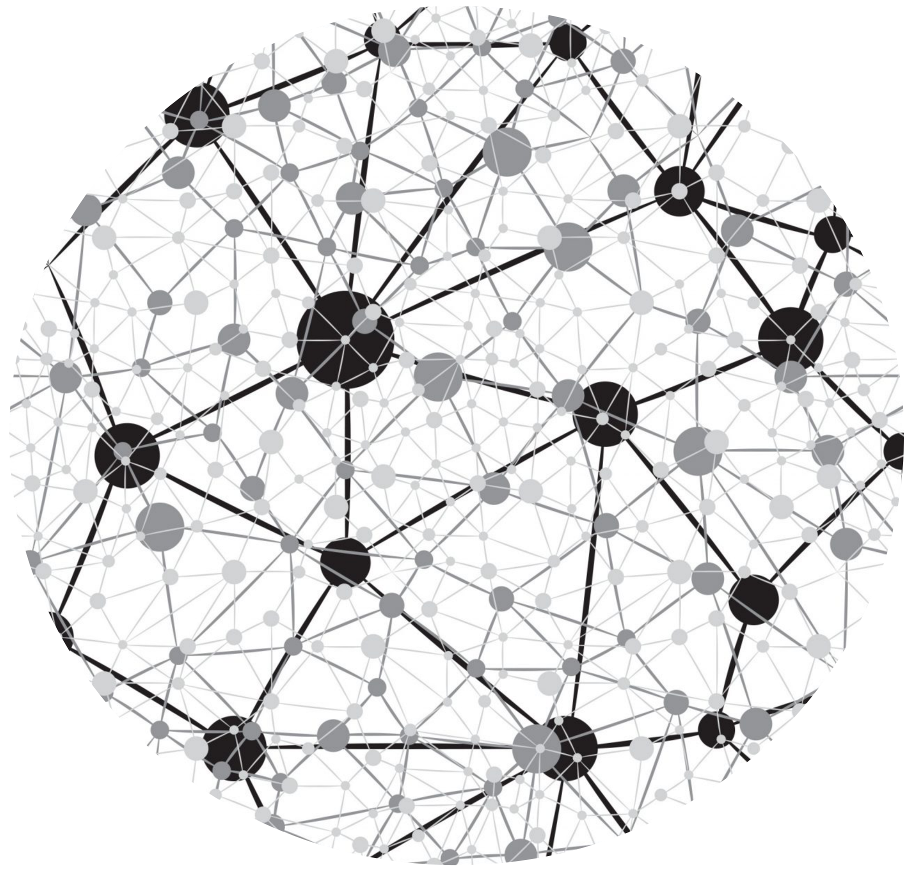

Develop new shower observables and sophisticated analyses

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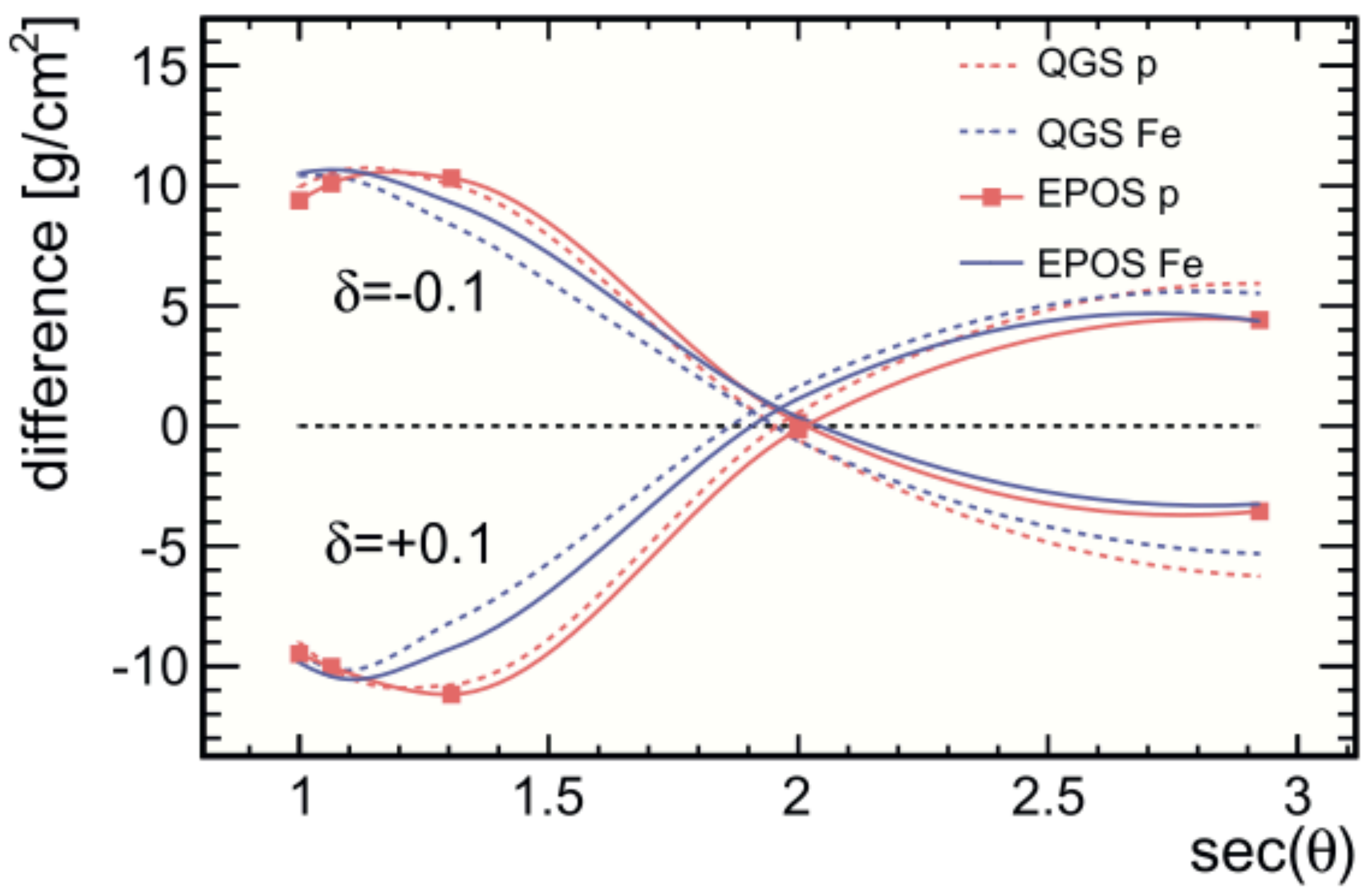
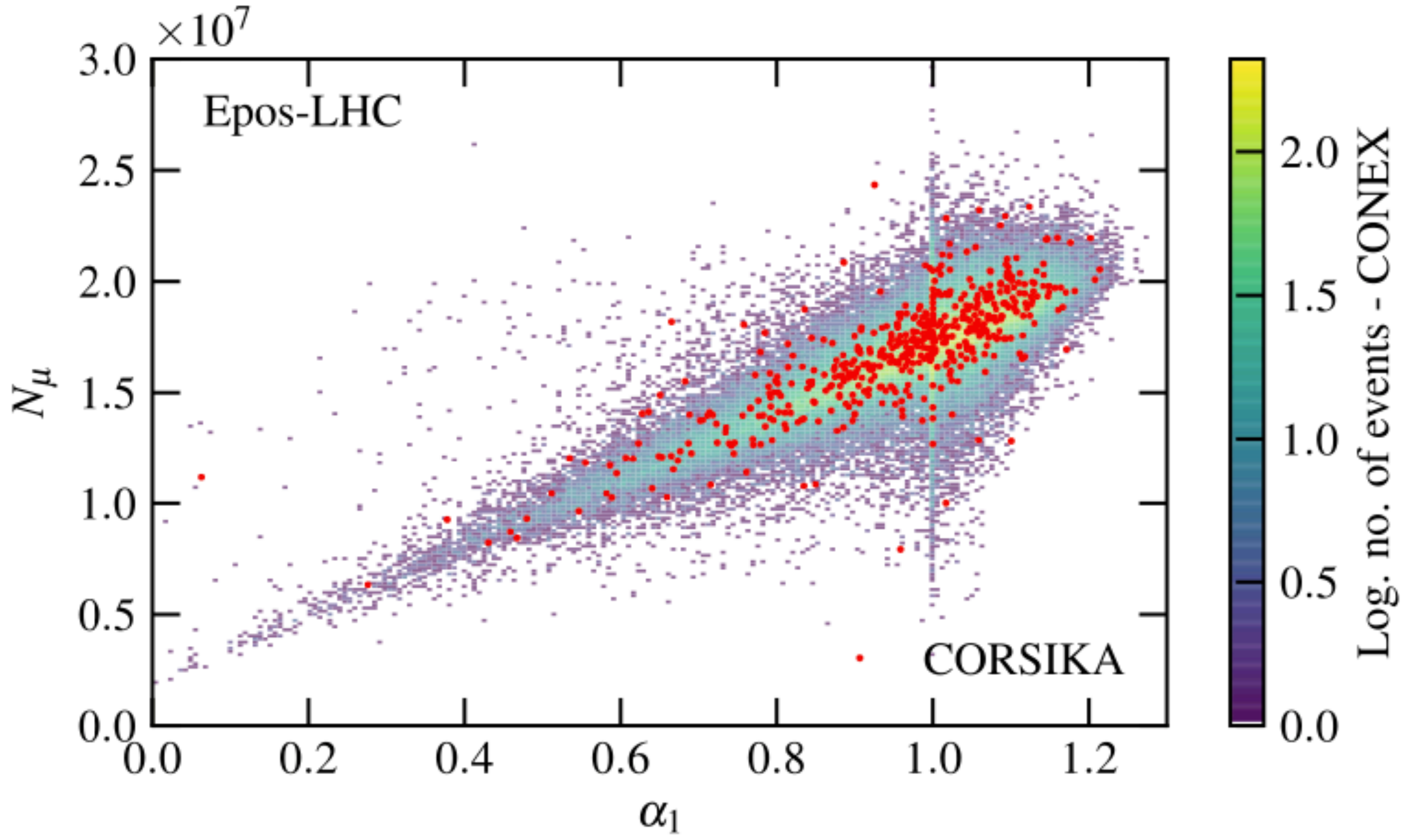
Assessing the muon distributions

Astropart.Phys. 86 (**2017**) 32-40



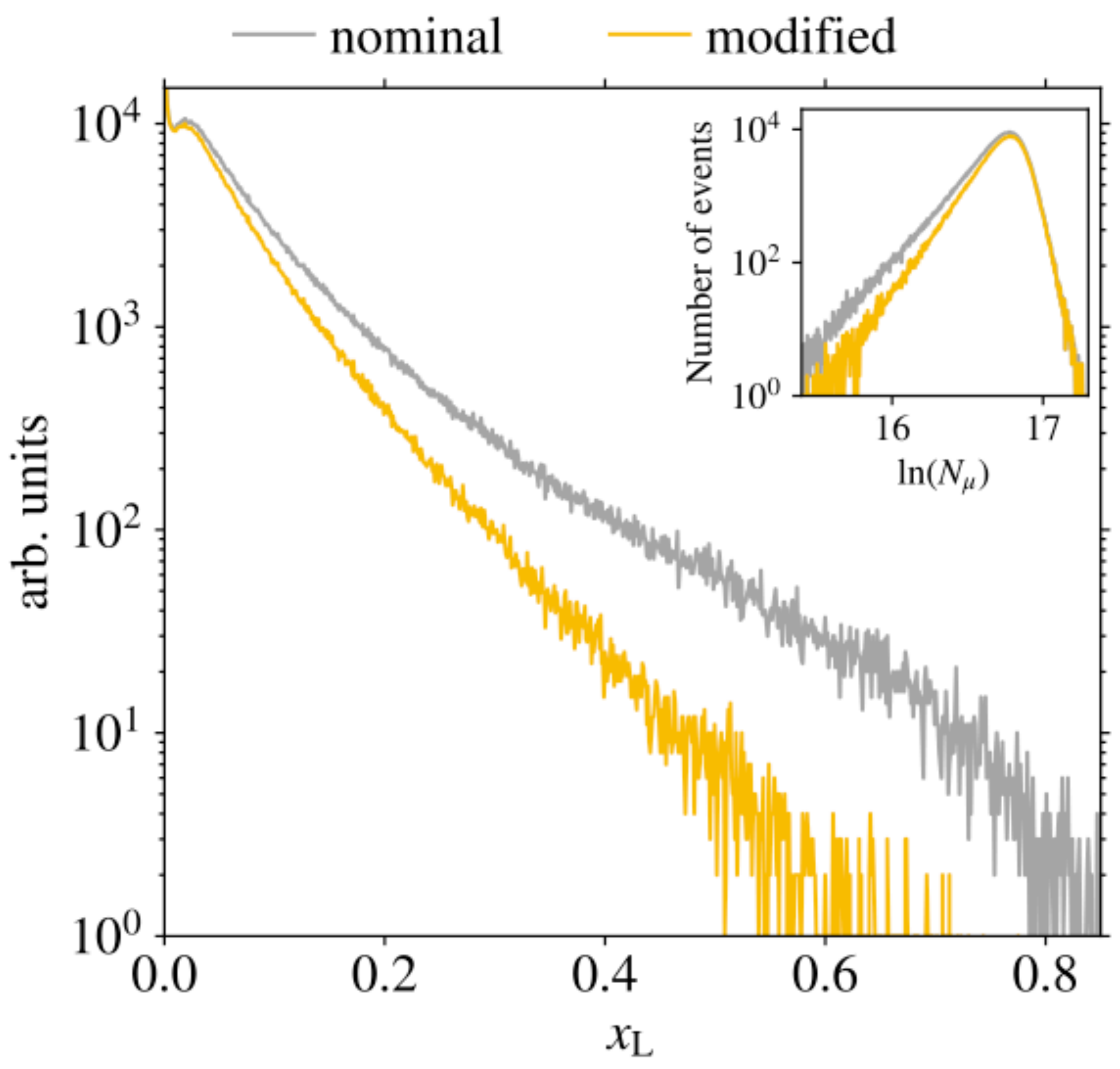
(Variation of the energy spectrum by $\pm 10\,\%$)

*Phys.Lett.B 784 (**2018**) 68-76*



E=10^{19} eV proton showers

Phys.Rev.D 103 (**2021**) 2, 022001



First interaction π^0 energy spectrum

$X^\mu_{\max}$ is highly sensitive to the EAS muon energy spectrum

Muon number fluctuations controlled by fraction of energy going into the hadronic sector in the first interaction - α_1

The tails of the π^0 energy spectrum and the muon number distribution are connected

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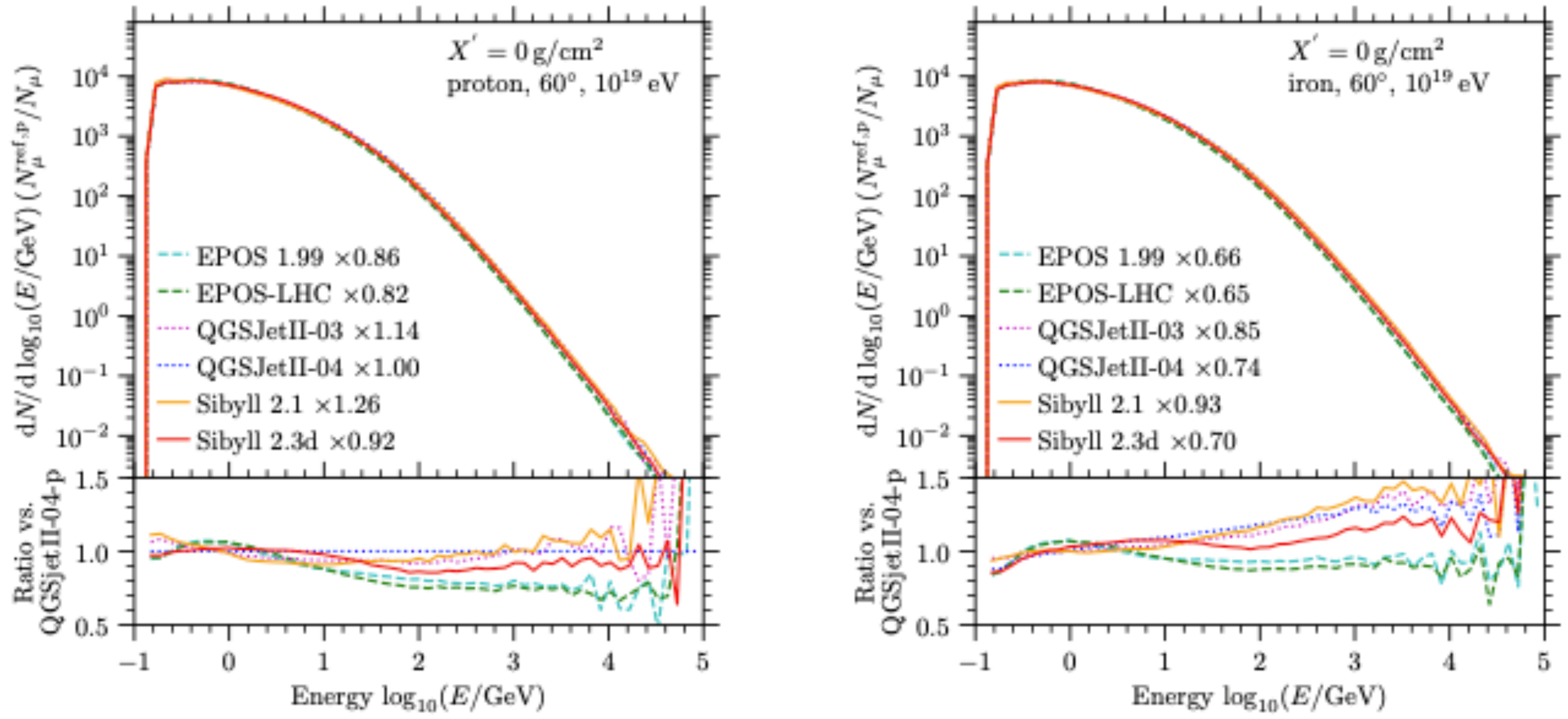
Assessing the muon distributions

arXiv:*2210.13407 [hep-ph]* (***2022***), *submitted to JCAP*



	Absolute (relative) variation in median under				
varying:	HE model		primary		
fixing:	p	Fe	EPOS-LHC	QGSJetII-04	Sibyll 2.3d
$\langle \mathcal{X}^{\mu}_{\max} \rangle$ (g/cm^2)	28 (4.5)	26 (4.7)	73 (12.0)	74 (12.8)	82 (13.6)
$\langle \mathcal{N}^{*}_{\mu} \rangle$	1.7×10^7 (16)	1.9×10^7 (14)	2.8×10^7 (21)	2.6×10^7 (23)	2.7×10^7 (23)
$X^{\mathrm{L}}\|_{80}$ (g/cm^2)	5 (1.8)	5 (1.9)	11 (4.1)	13 (4.9)	13 (4.8)
$E_{\mu}\|_{50}$ (MeV)	29 (3.6)	51 (5.8)	54 (6.7)	77 (9.1)	72 (8.5)
$p_{\mathrm{T}}\|_{50}$ (MeV)	1 (0.6)	2 (0.9)	3 (1.3)	4 (1.8)	3 (1.6)

- The EAS muon distribution can be described using only 3 features: universal longitudinal profile, transverse momentum, energy spectrum
- The simulation display a strong universality, independently of the models
- The models are only distinguishable on the muon energy spectrum for $E_{\mu} \gtrsim 10\,\mathrm{GeV}$
  - explore through inclined showers (collaboration with Santiago de Compostela group)

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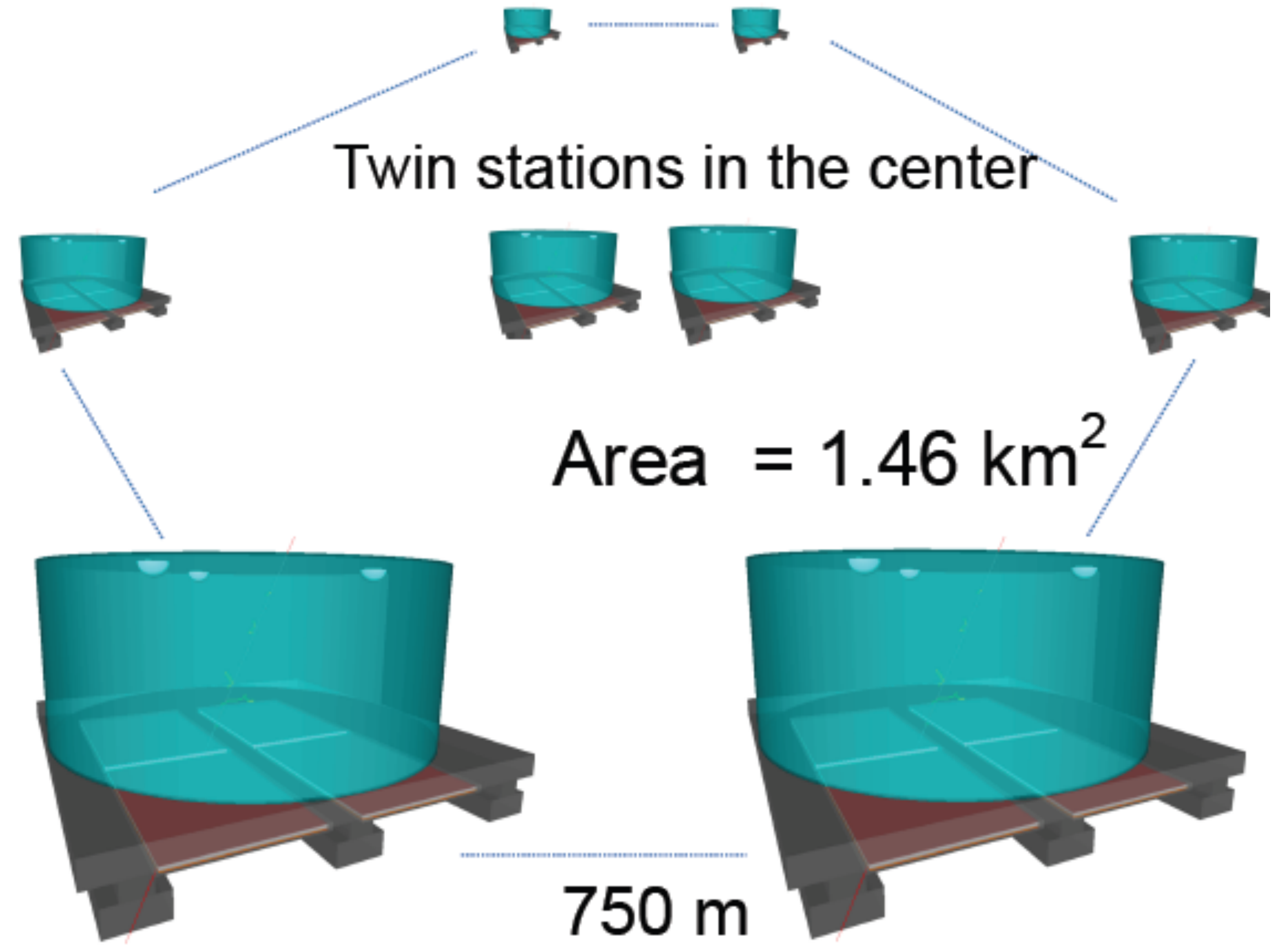
Novel detector concepts

*Eur.Phys.J.C 78 (**2018**) 4, 333*

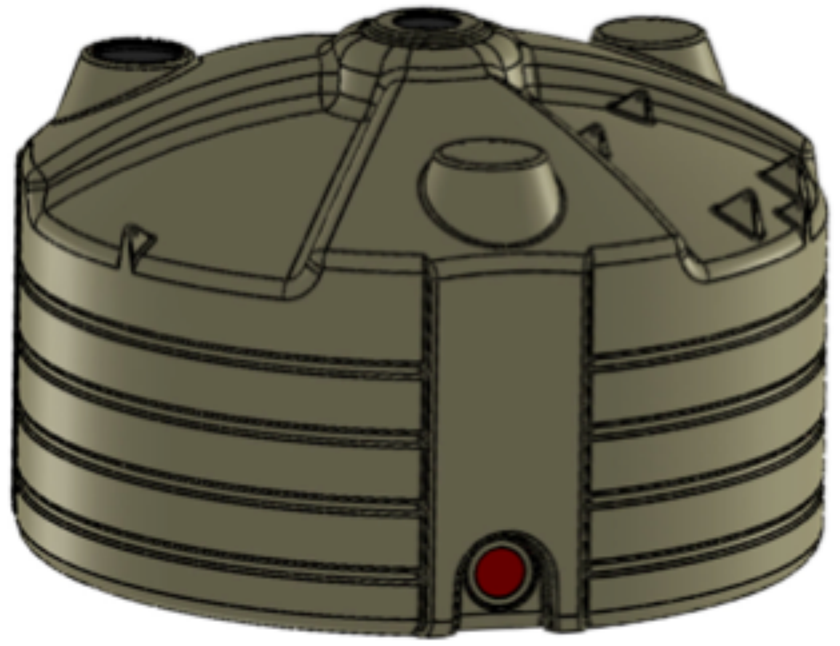


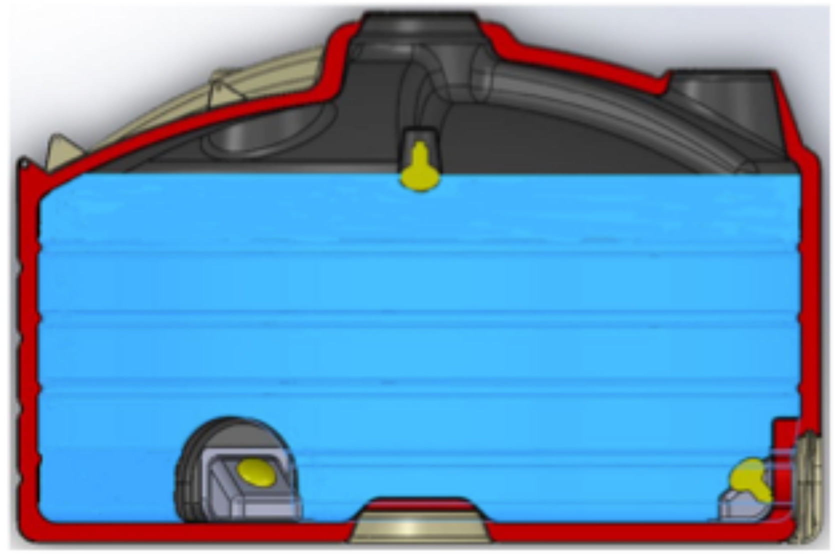
- **MARTA engineering array (R&D)**
  - Water Cherenkov Detectors + Resistive Plate Chambers
  - Take advantage of good time resolution and RPC high segmentation
- Direct measurement of the shower muon component
- Potential to very interesting (inter-)calibrations

Pierre Auger Collab., JINST 15 (**2020**) 09, P09002 - RPC hodoscope @ Auger WCD

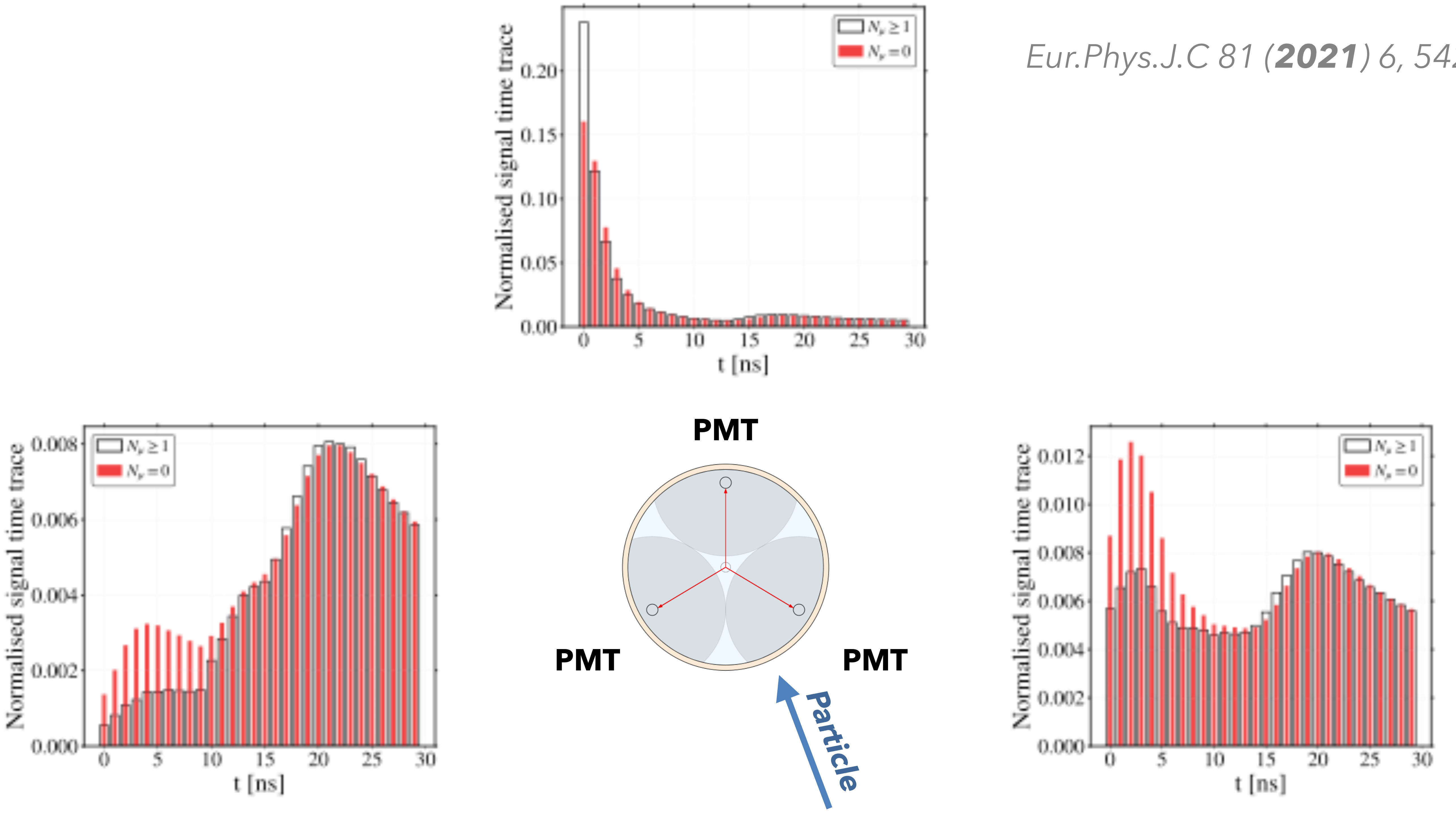
- **Mercedes WCD station**
  - Trade water volume by number of photo-sensors + Neural Networks
  - High physics performance suitable to the future gamma-ray observatories
  - New engineering standards with PMT deployment and resilience to environmental harshness

*Eur.Phys.J.C 82 (**2022**) 10, 899*





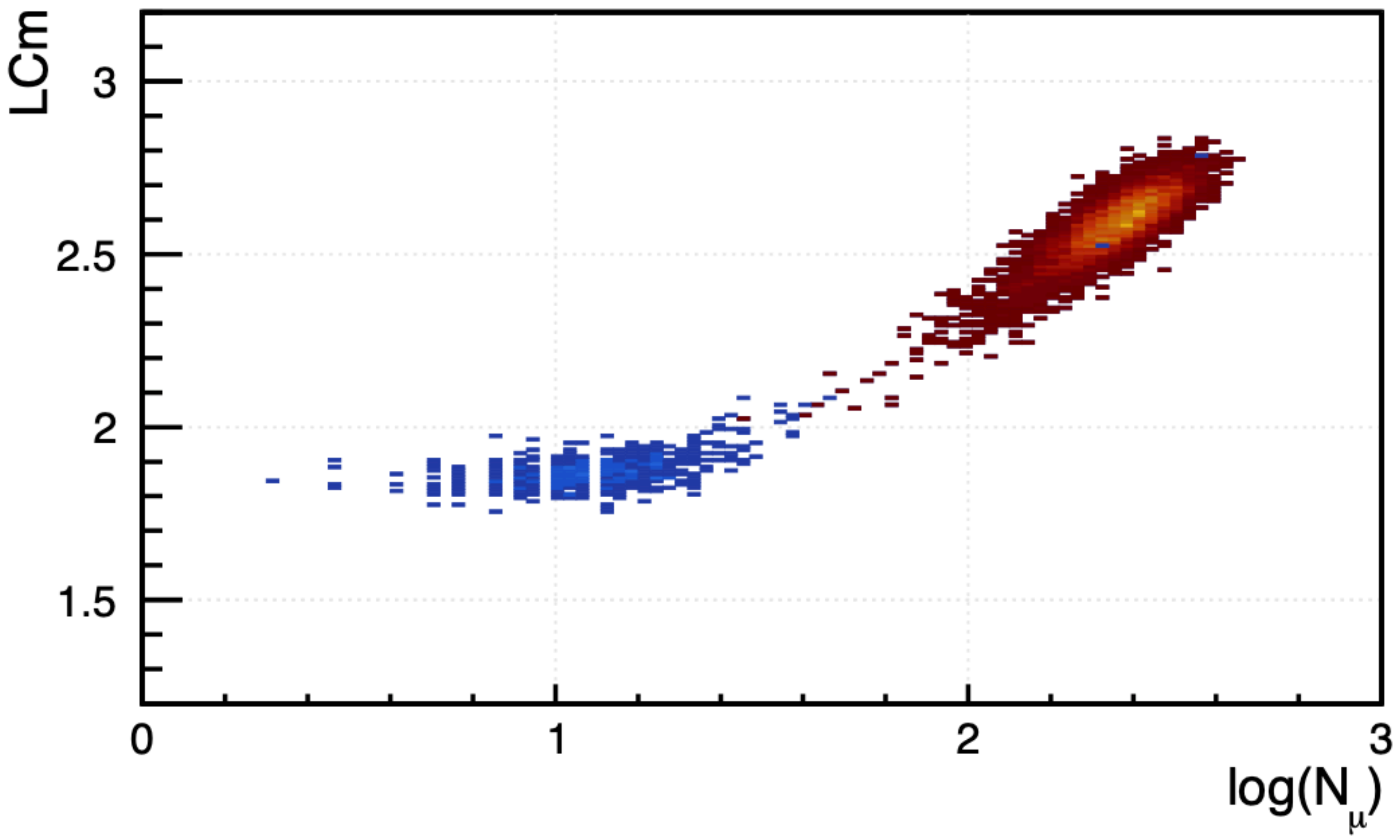
New observables & analyses



*Eur.Phys.J.C 81 (**2021**) 6, 542 - Eur.Phys.J.C 82 (**2022**) 10, 899*

- Use the power of **neural networks** combined with **detector design** to identify the presence of muons through the analysis of the PMT signal time trace

*JCAP 10 (**2022**) 086*



- LCm - gamma/hadron discriminator based on the analysis of the **azimuthal fluctuations of the shower footprint**
- It has been shown at EeV energies that even the e.m. component of the shower is sensitive to the hadronic activity

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My role…

Accumulated experience and future goals

Contributions to the field

Development of shower observables & new measurements

USP shape parameters: *Astropart.Phys.* 34 (**2011**) 360-367 ; J.Phys.Conf.Ser. 632 (**2015**) 1, 012087 ; JCAP 03 (**2019**) 018

Muon Production Depth: Astropart.Phys. 35 (**2012**) 821-827 ; Astropart.Phys. 86 (**2017**) 32-40 ; Phys.Rev.D 90 (**2014**) 1, 012012

Muon number fluctuations: Phys.Lett.B 784 (**2018**) 68-76 ; Phys.Rev.D 103 (**2021**) 2, 022001 ; Phys.Rev.Lett. 126 (**2021**) 15, 152002

Gamma/hadron discriminators : JCAP 10 (**2022**) 086

Short author publication ; Related collaboration publication

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New experiments and detectors

Cosmic-ray experiments: Eur.Phys.J.C 78 (**2018**) 4, 333 **(MARTA)** ; JINST 15 (**2020**) 09, P09002 **(RPC hodoscope)**

Gamma-ray experiments: Astropart.Phys. 99 (**2018**) 34-42 **(LATTES)** ; Eur.Phys.J.C 81 (**2021**) 6, 542 ; Eur.Phys.J.C 82 (**2022**) 10, 899 **(Mercedes)**

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New reconstruction algorithms and future measurements

Gamma-ray energy reconstruction: Eur.Phys.J.C 81 (**2021**) 1, 80

Gamma-ray background mitigation: Phys.Lett.B 827 (**2022**) 136969

Neutrino detection in gamma-ray arrays: arXiv:2208.11072 [hep-ph] ; accepted in Phys.Rev.D (**2022**)

Interpretation of muon measurements: Astropart.Phys. 36 (**2012**) 211-223 ; Astropart.Phys. 83 (**2016**) 40-52 ; Phys.Rev.Lett. 117 (**2016**) 19, 192001;
Phys.Rev.D 96 (**2017**) 12, 122003 ; Eur.Phys.J.C 80 (**2020**) 8, 751

Machine learning algorithms: IEEE Access PP(99):1-1 (**2019**); Neural Computing and Applications 34, 5715–5728 (**2022**)

Short author publication ; Related collaboration publication

Positions and achievements

Pierre Auger Collaboration

Leader of the Air Shower Physics task

Auger Physics tasks: Arrival directions, Mass composition, Air Shower Physics

Scientific coordinator of the MARTA R&D project

SWGO Collaboration

Coordinator of the Analysis and Simulation Working Group

WGs@SWGO: Science, A&S, Detector, Site, Outreach

ruben@lip.pt

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LIP Auger group

Co-Pi of the Auger-LIP group
PI of the Project UHECR@Auger
Currently supervising of 1 PhD student (IST)
and Co-supervisor of 2 PhD student (U. Minho / U. Santiago de Compostela)
Currently supervising 2 Master students (IST)

LIP SWGO group

Co-Pi of the SWGO-LIP group
Co-Pi of the LATTES-LIP group
Currently supervising of 2 PhD students (IST)
Co-supervisor 2 Master students (U. Granada)

PI/Co-PI of several projects won in competitive calls - in the last 5 years managed more than 750 k€

ruben@lip.pt

Positions and achievements

Teaching activities

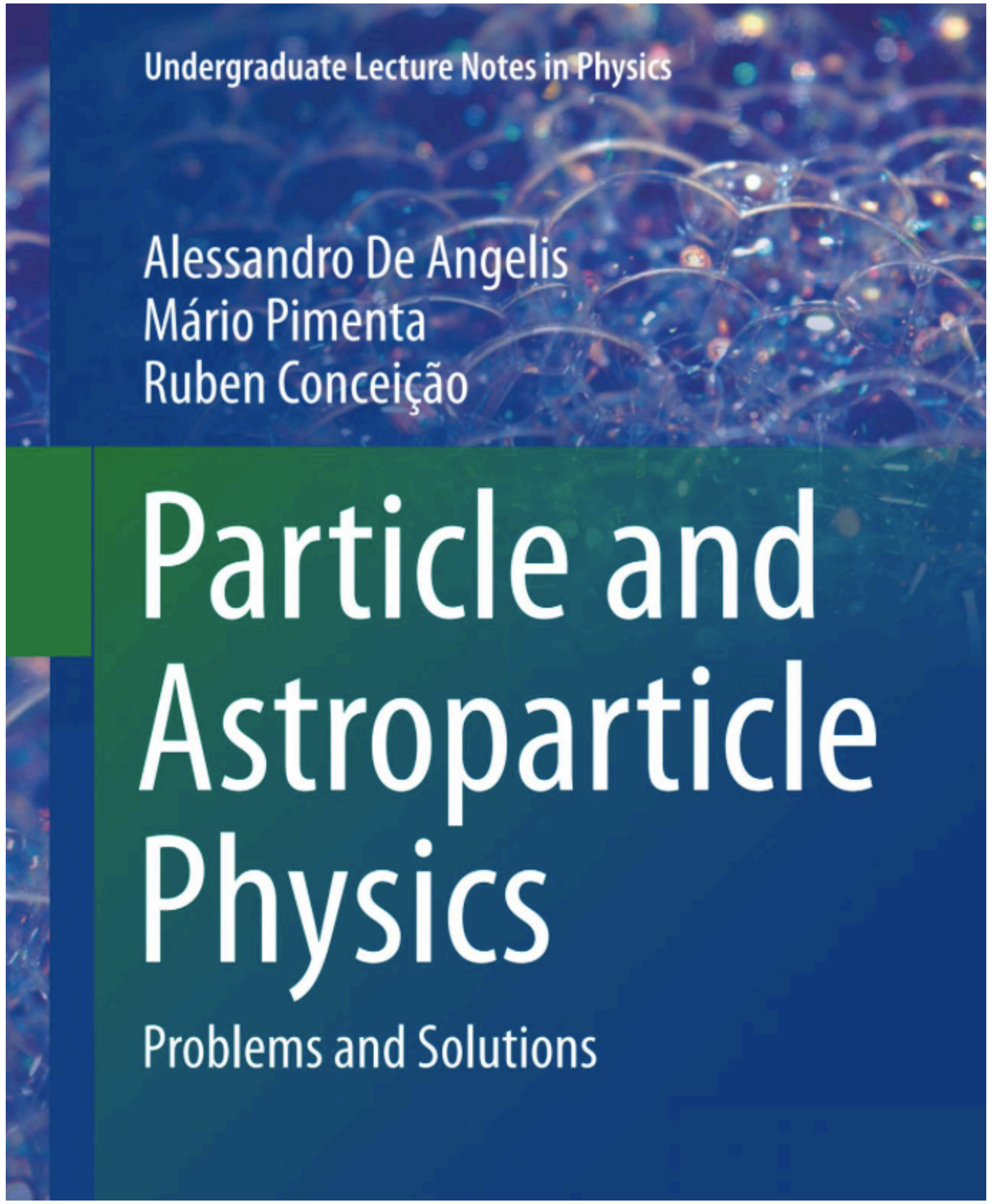
Invited Assistance Professor at Physics Department of IST
Senior Lecturer of Topics on Particle and Astroparticle Physics I
Senior Lecturer of Astroparticle Multimessengers
Senior Lecturer of Astroparticle Physics (PhD course)

Award of excellence in Teaching on Topics on Particle and Astroparticle Physics I (2022)
Award of excellence in Teaching on Particle Physics (2021)
Award of excellence in Teaching on Mechanics (2020)
Award of excellence in Teaching on Electromagnetism and Optics (2019)

Author of the Book Particle and Astroparticle Physics: Exercises and Solutions

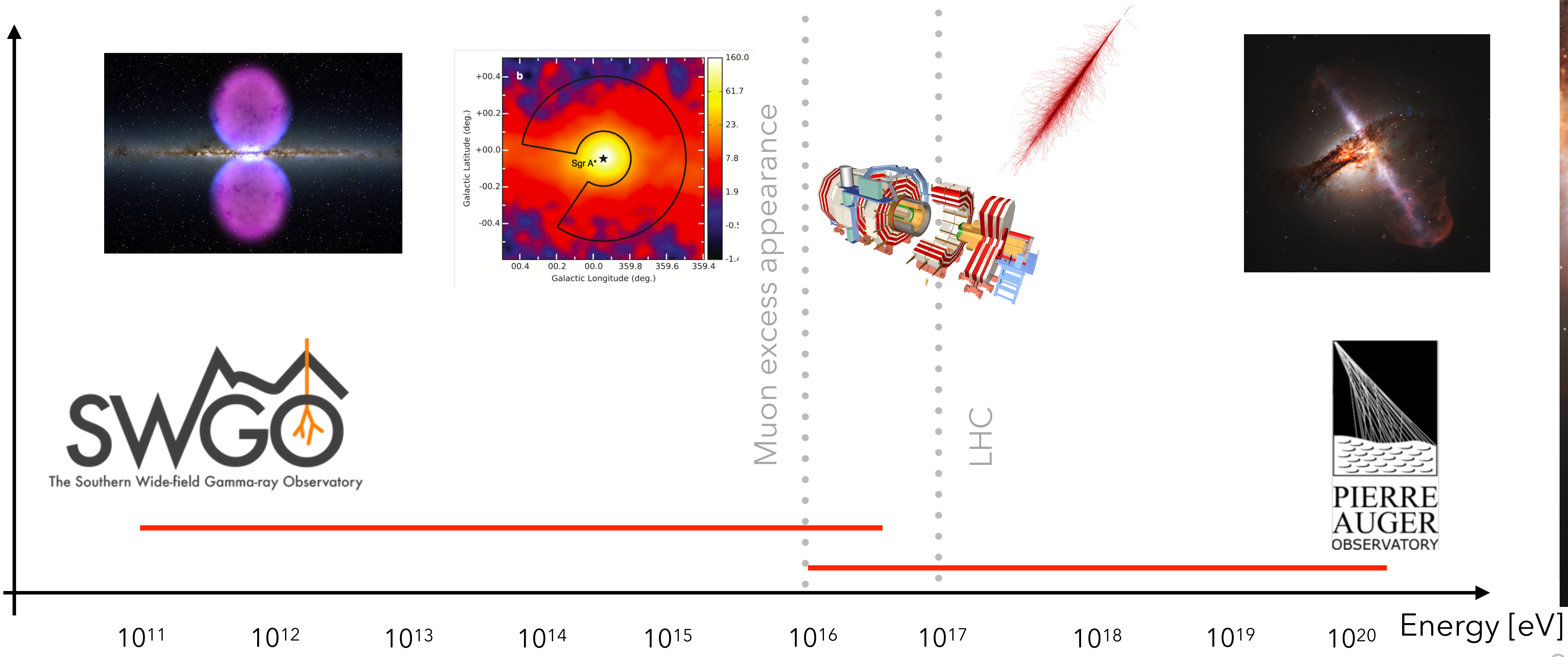
Supervisor of 3 PhD students
Co-supervisor of 2 PhD students
Supervisor of 8 Master students
Supervisor of 19 students on LIP summer internships
Coordination of 2 Junior researchers

Lecturer in several PhD international courses: IDPASC (2013; 2017; 2021)



Astroparticle Physics

A unique opportunity to explore the extreme energy Universe



Acknowledgements

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Backup slides