The Context of Ground-based Gamma-ray Astronomy

Ulisses Barres de Almeida
CBPF

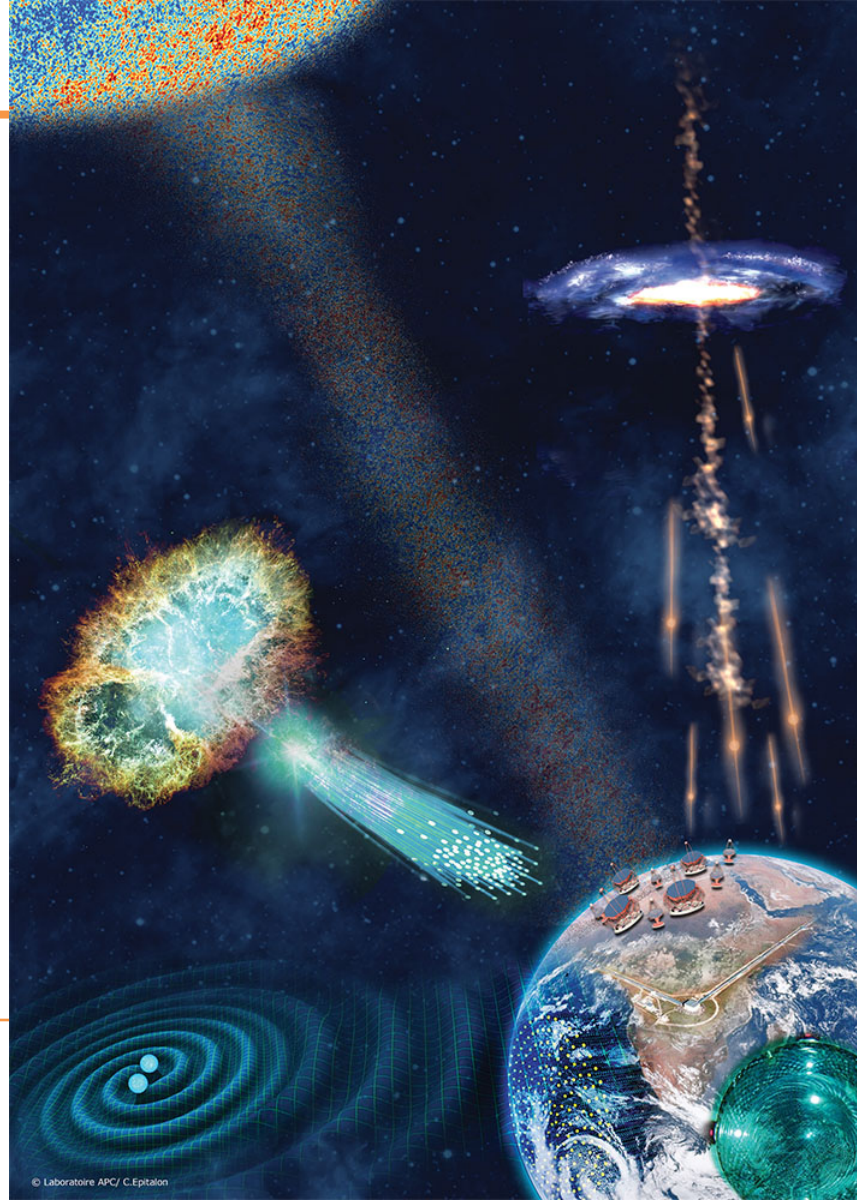


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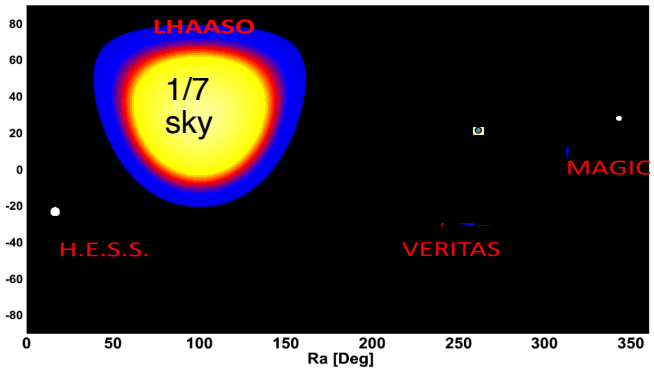
— RPCs 2026 | 18th September | UERJ, Rio —

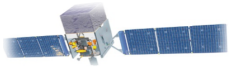
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2. Prelude to a new era
3. CTAO is coming online
4. EAS arrays in the south
5. The future in South America



Ground-based Techniques



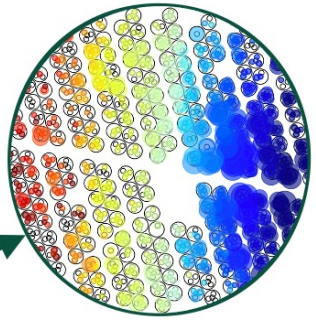


Air-shower particle arrays

High Duty Cycle

Wide-Field of View

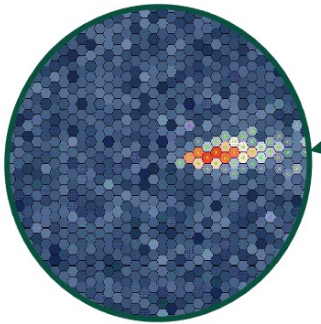
UHE Performance



Few ns spread in particle arrival at each detector

Electro-Magnetic Cascade

Few ns light flash



Cherenkov Light

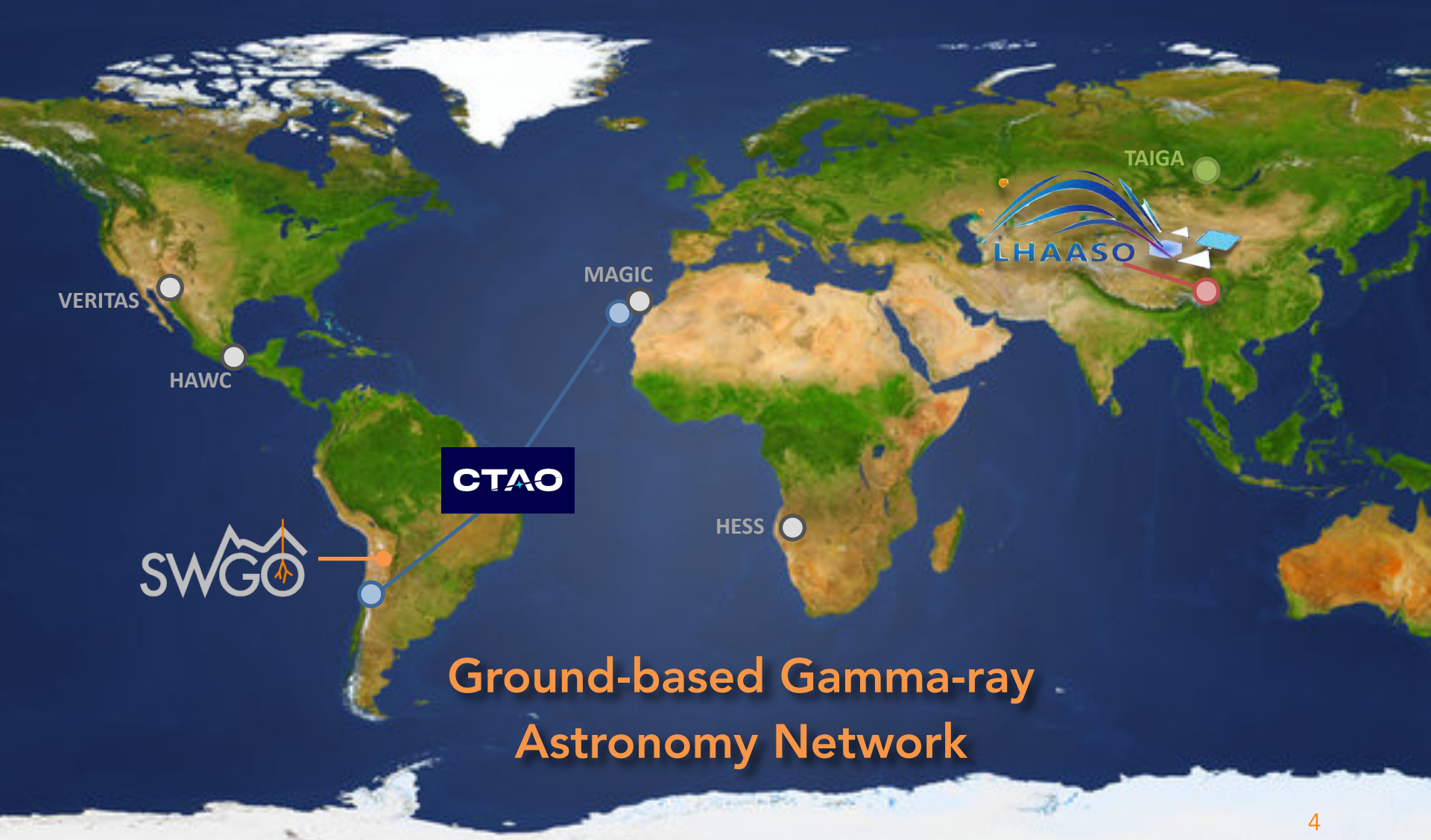
© Armelle Jardin-Blicq

Air-Cherenkov Telescopes

Low Duty Cycle

Pointing instruments

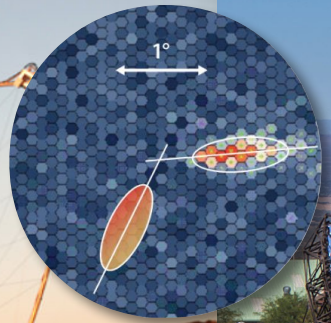
Precision Astronomy



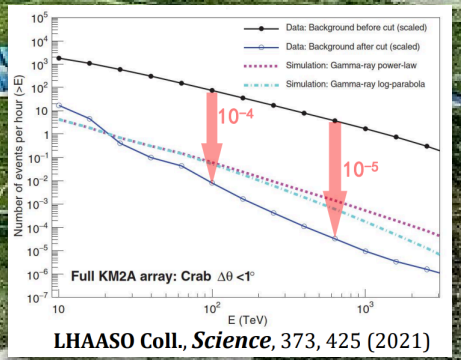
Ground-based Gamma-ray Astronomy Network

Precision Astronomy at VHEs

- Large reflectors + Fine-pixel camera
- Wide field of view for imaging and background
- Stereoscopy → excellent shower reconstruction

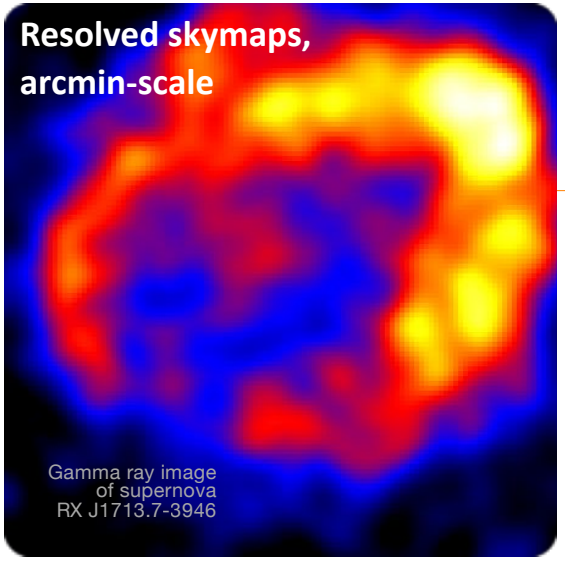


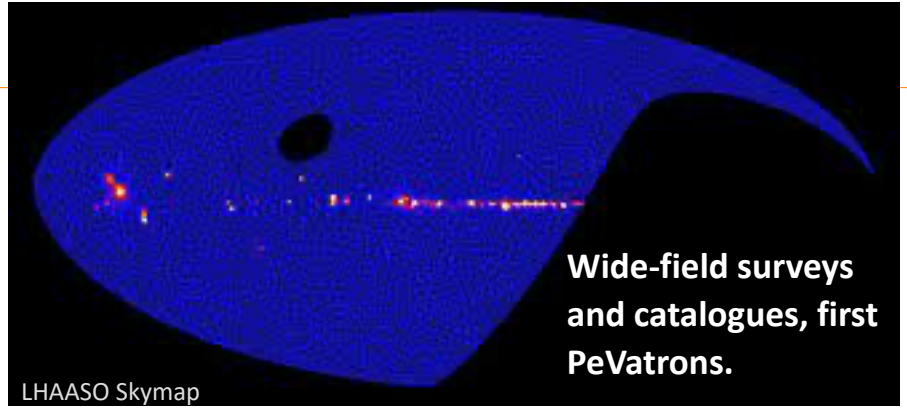
- High altitude & fill factor → dense shower front sampling
- Large array areas for efficient shower detection
- Large Muon Effective Areas

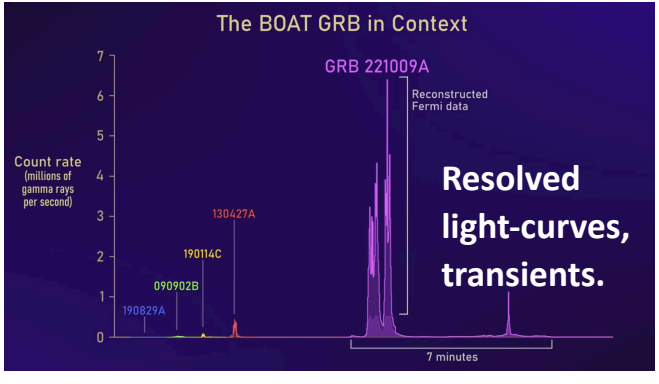


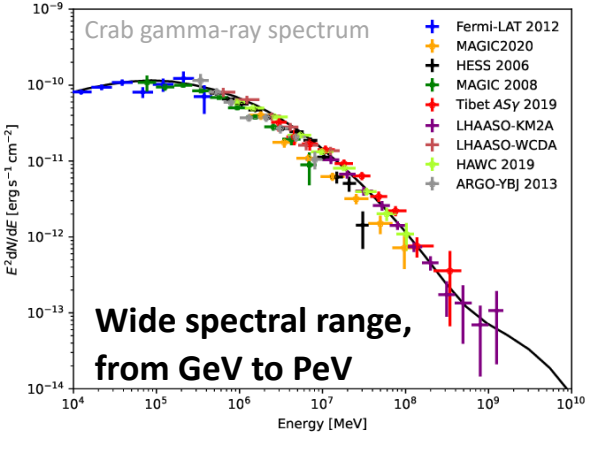
LHAASO Coll., ***Science***, 373, 425 (2021)

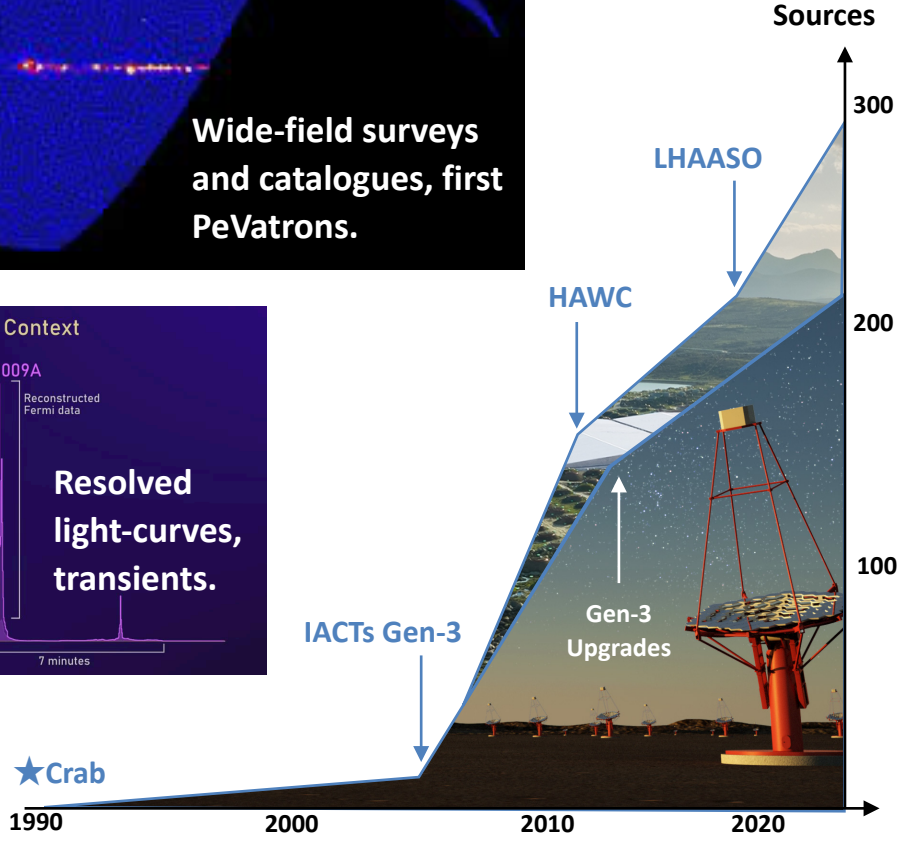
VHE Astronomy in the 2020s











CTAO will:

- Reach the limits of angular resolution
- Push the boundaries of survey capabilities
- Expand energy coverage towards the 100 TeV+

Next Frontiers?

→ Hybrid Techniques

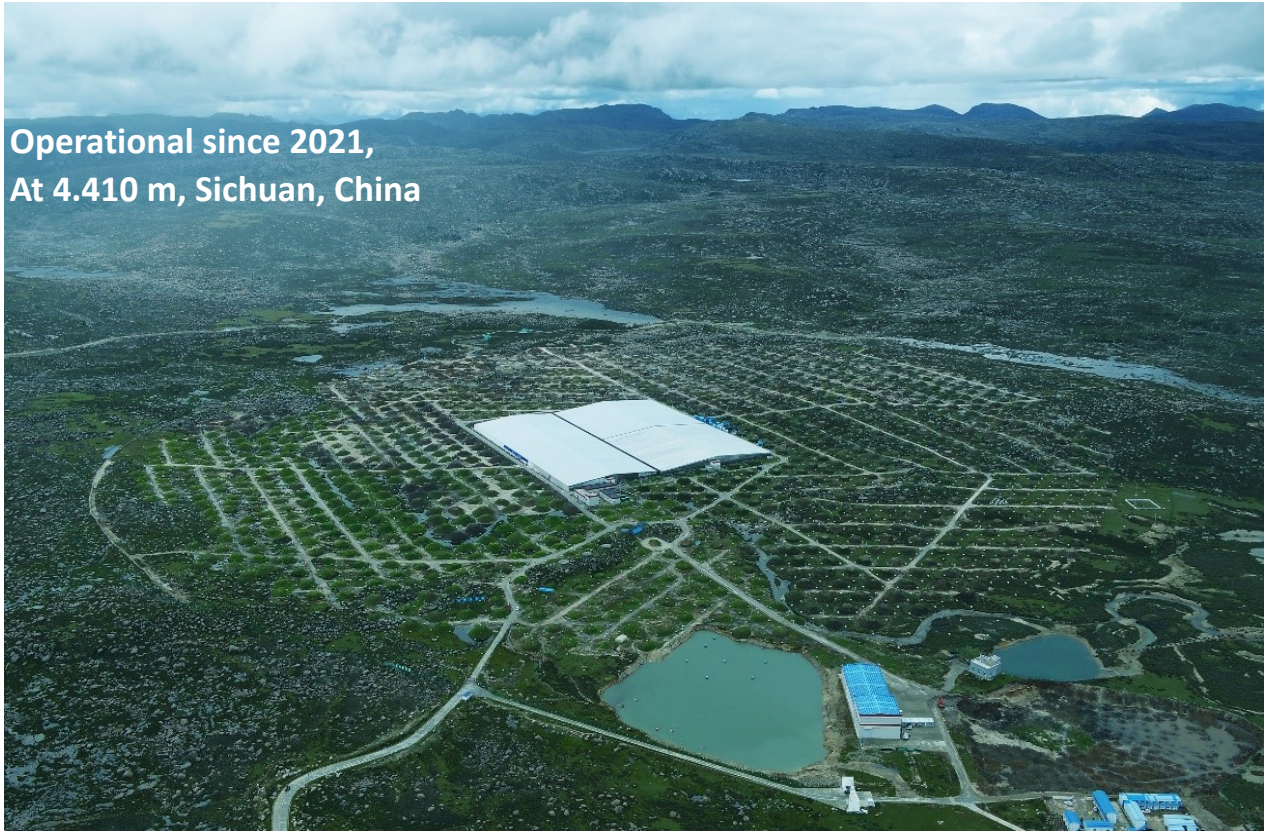


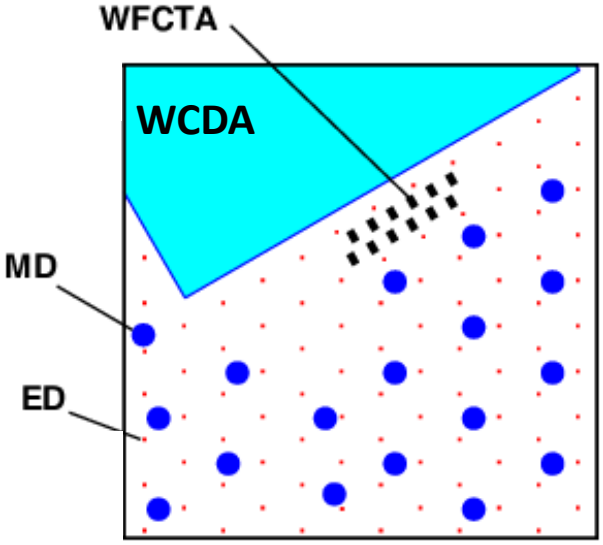
Improved angular resolution

Towards lower energies

Cost-effective CR suppression

LHAASO

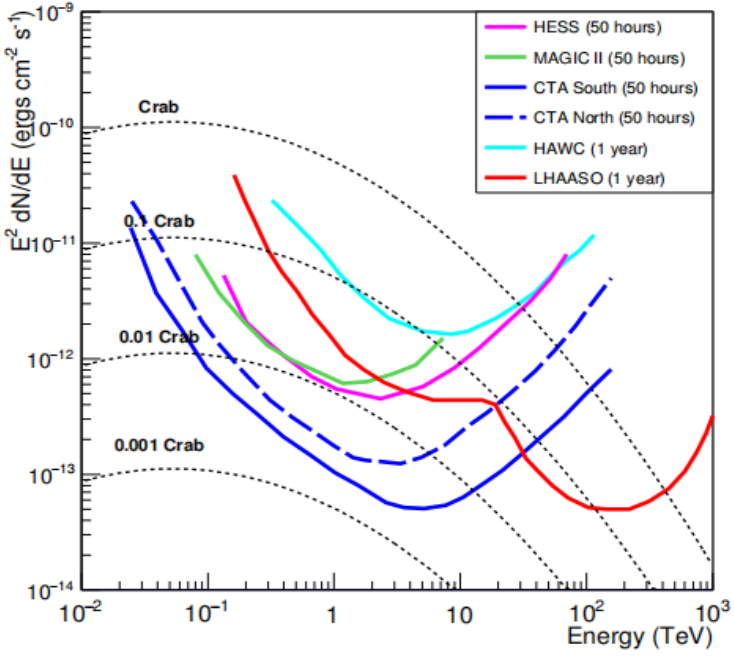


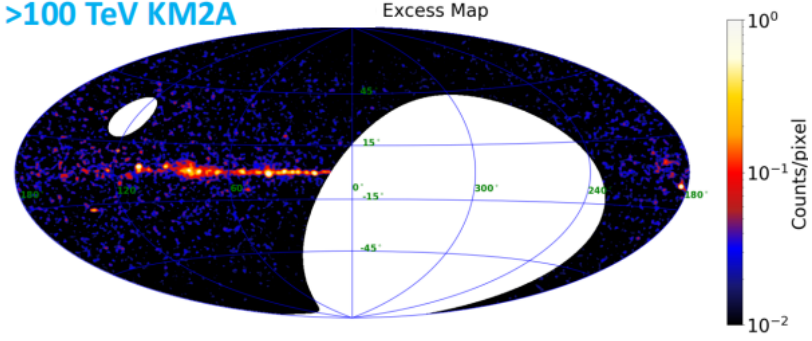


- **WCDA,** 80,000 m^2, operating < 10 TeV
- **ED** x 5,216 units, covering 1.3 km^2
- **MD** x 1,188 units, with 4% FF
- **WFCTA,** Cherenkov imaging of air-showers

LHAASO

- **LHAASO has expanded the catalogue of UHE sources into the PeV range**
- **Plurality of source types,** dominated by PWN and Halos with UHE emission & SNRs
- Morphology : CR interaction with surrounding MCs
- YMSCs, including the Cygnus super-pevatron
- mQSOs as potential PeV accelerators
- **Diffuse emission up to PeV**, excess flux towards inner GP
- **Potential for study of GRBs and fast transients demonstrated with the BOAT**

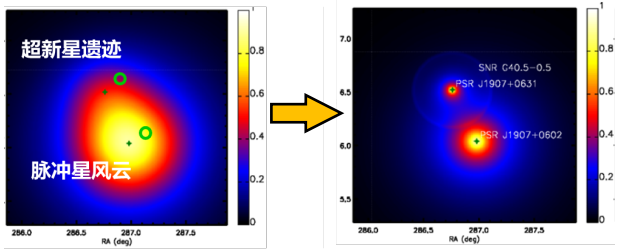


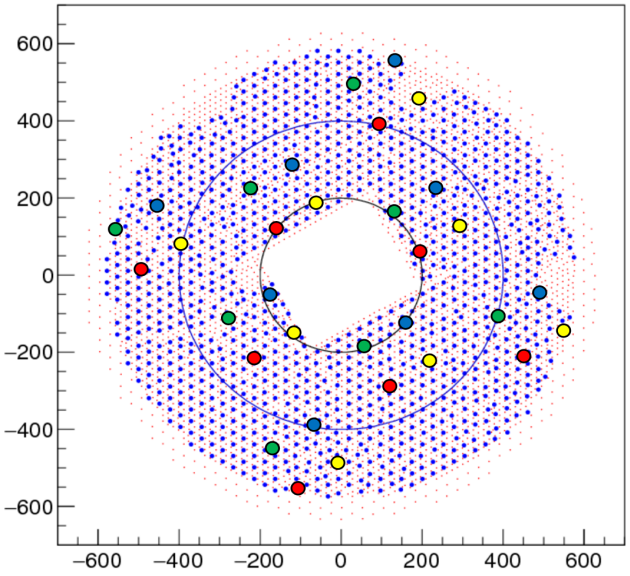


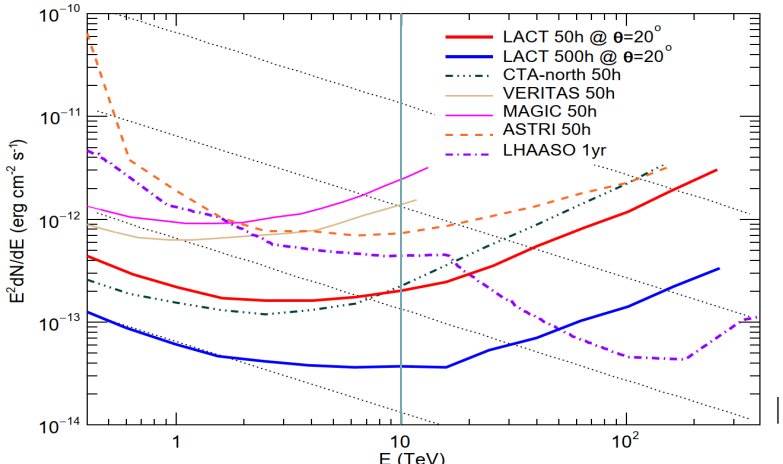
90 sources, 43 > 100 TeV

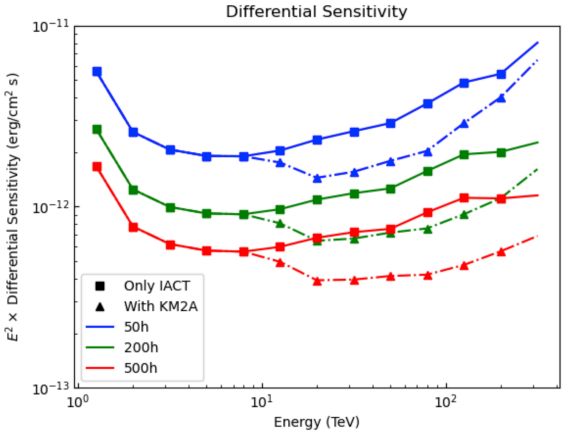
LACT

- Installation of 32 6-m IACTs in LHAASO site
- Project status:
  - 2025 - first telescope
  - 8 telescopes exp. 2026
  - Full-array in 2028





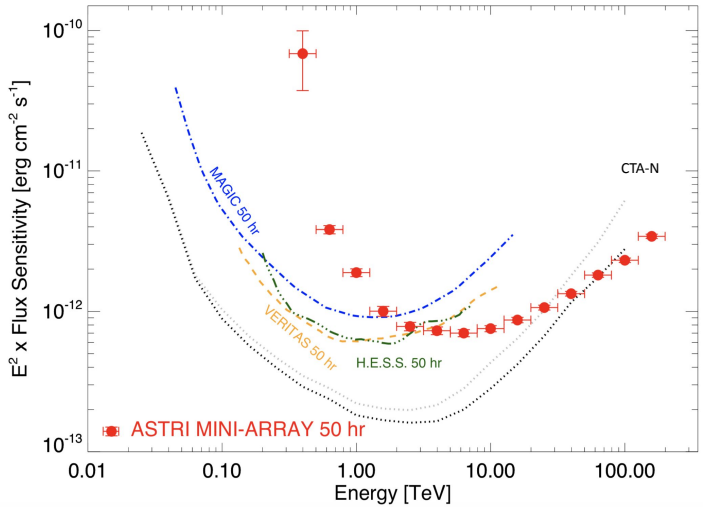




Improved sensitivity
when operating in conjunction
with LHAASO particle array

ASTRI

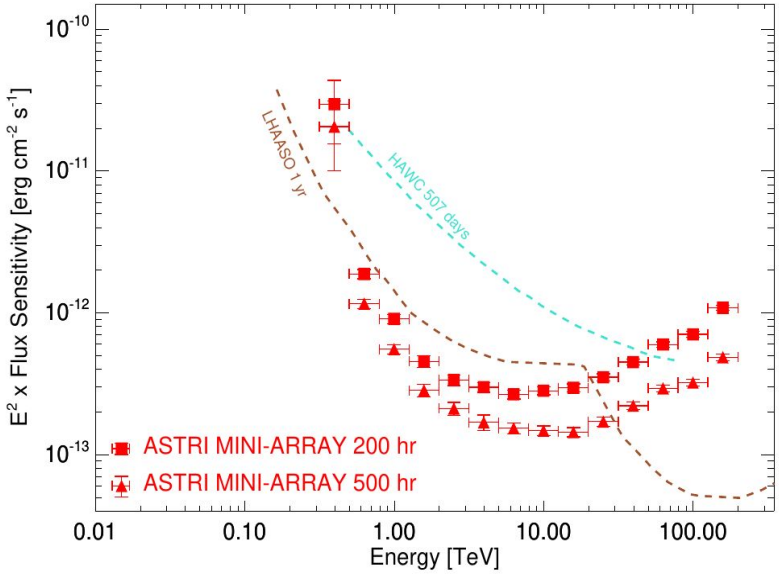
- The array will be completed this year
- Successful Blazar Monitoring with ASTRI-1
- First Stereo Crab Observations performed in 2026



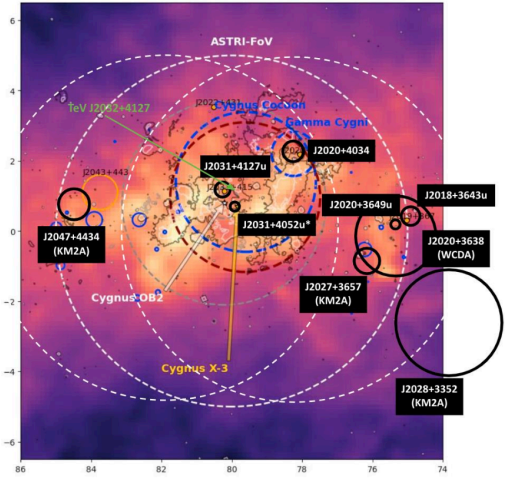


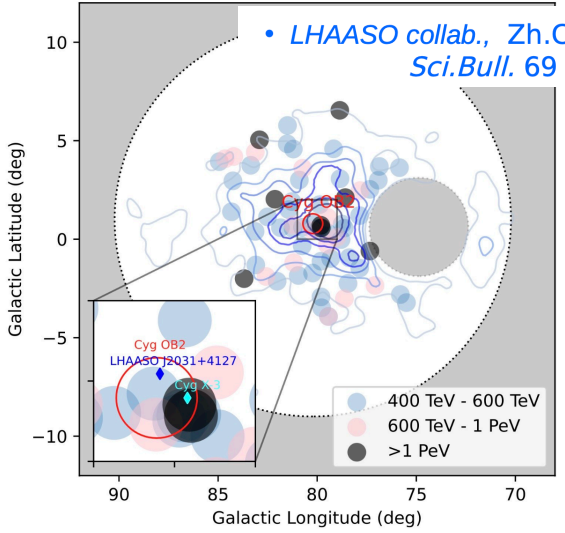
ASTRI-LHAASO Synergies

- The ASTRI-LHAASO synergies are a prelude to gamma-ray astronomy in the coming decade
  - → Exploiting the complementarity of the two observational techniques
- ASTRI observing strategy will allow for a deep study of the most interesting LHAASO sources



The Cygnus region





- *LHAASO collab.*, Zh.Cao et al, 2310.10100, *Sci.Bull.* 69 (2024) 4, 449

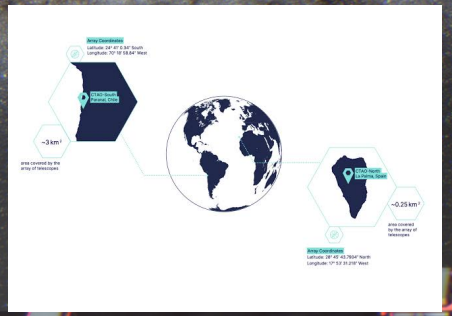
The arrival of CTAO

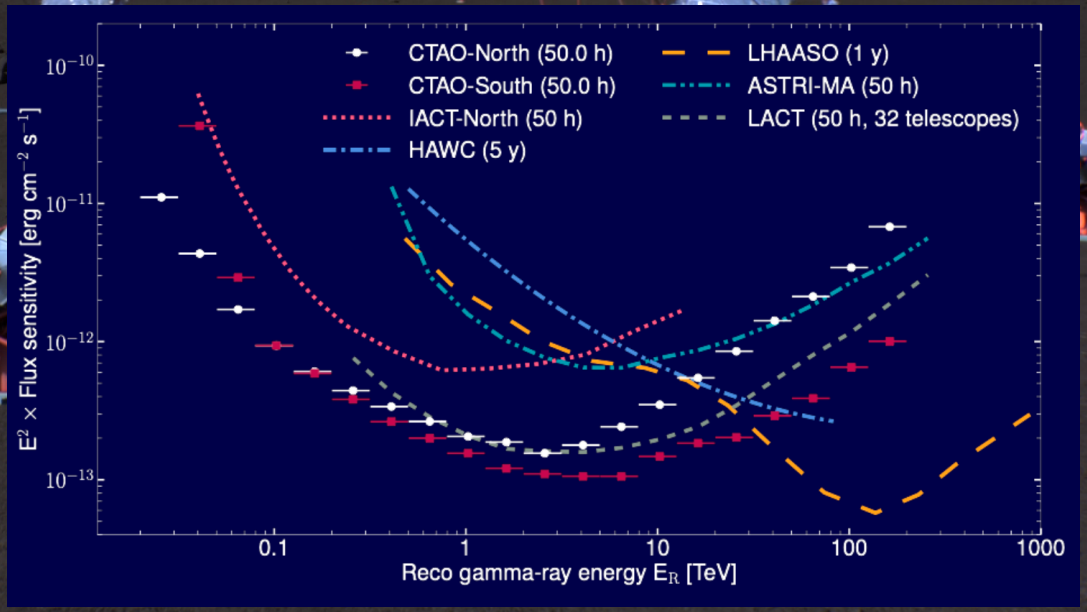


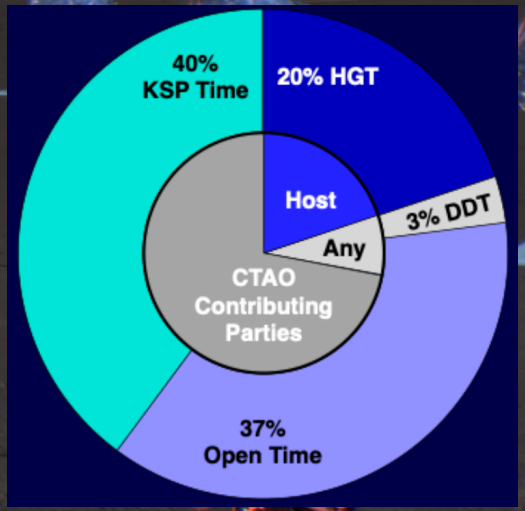
—RPC 2026 | UERJ, Rio —

CTAO is the definitive IACT array

- Ultimate instrumental performance
- Alert and follow-up capabilities
- A proposal-driven observatory
- Multiple observing modes
- Full-sky coverage



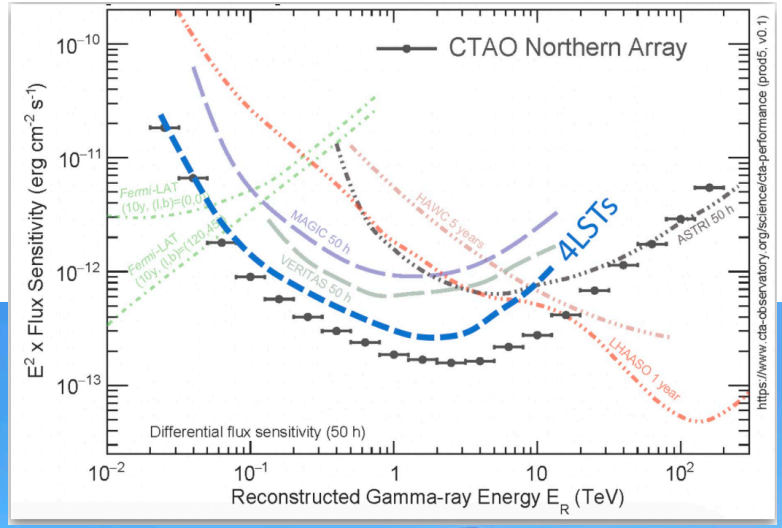


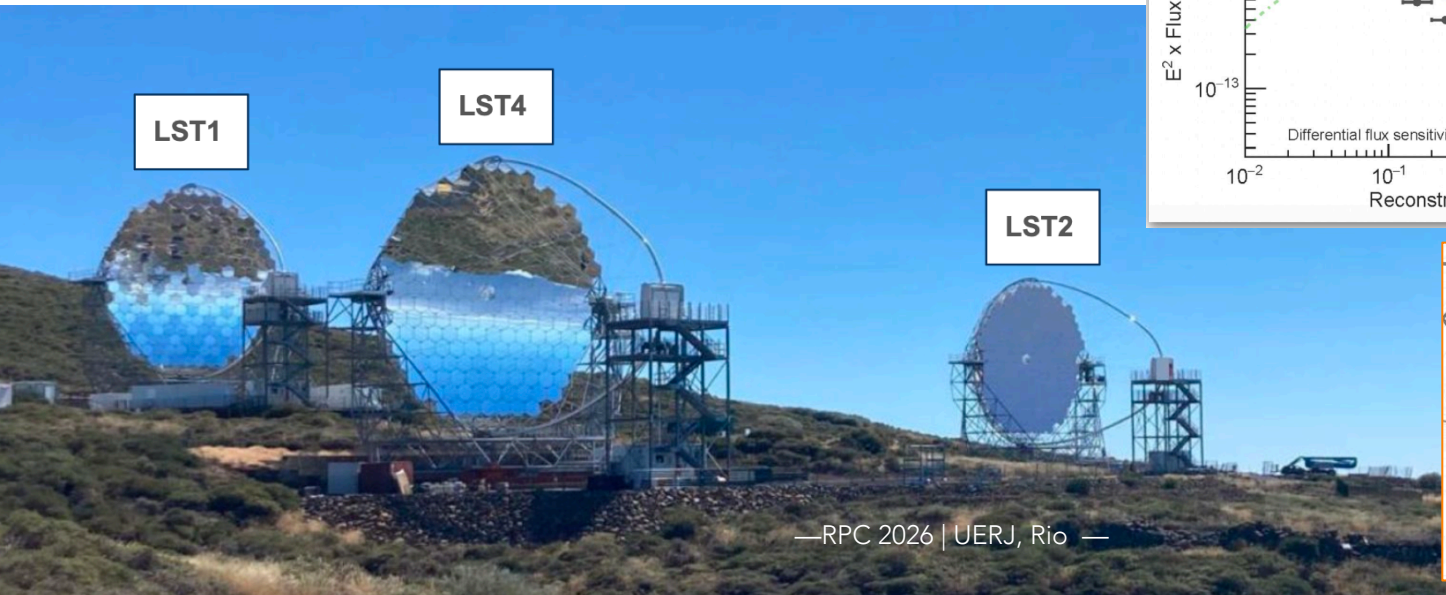


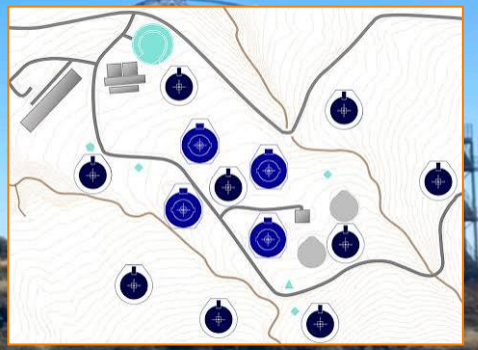
CTAO | LST COLLABORATION

The LST Array

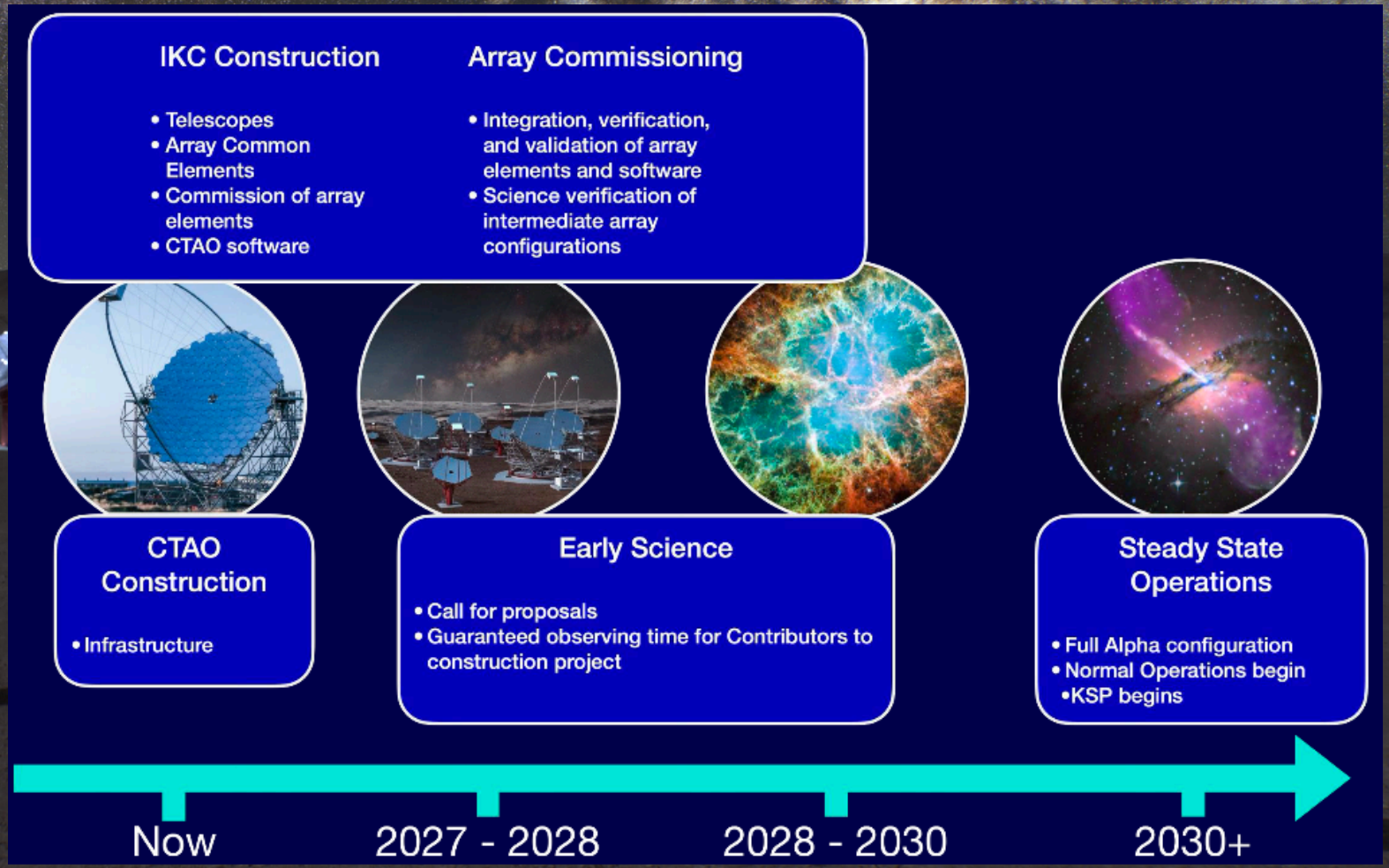
- LST-1 operating since several years
- Inauguration and Commissioning in the next months
- Fast slewing and low-energy threshold of ~ 20 GeV
- Ideal instrument for soft, transient sources







Future Perspective



Future Perspective





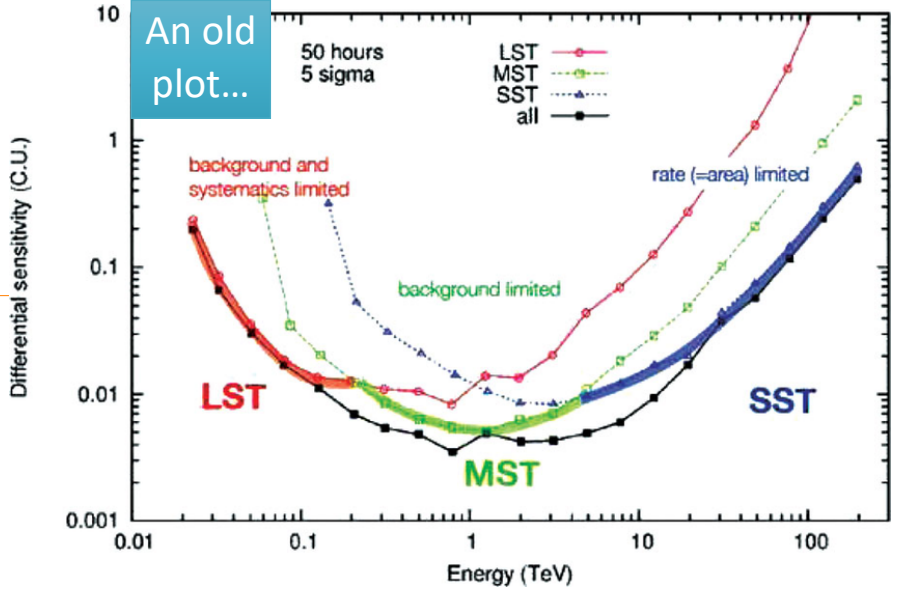
2028	2029	2030	2031	2032
4x LST 1x MST	4x LST 5x MST	4x LST 9x MST	4x LST 9x MST	4x LST 9x MST
Observatory Release 2	Observatory Release 3	Observatory Release 4	Official Start of Operations	
Verified in 2028 AO Call in 2029	Verified in 2029 AO Call in 2030	Verified in 2030 AO Call in 2031	AO Call in 2032	
2x MST 5x SST	TBD + 2 LST (CTA+ project)	14x MST 37x SST	14x MST 37x SST	
Early Science OP 1	Early Science OP 2	Early Science OP 3	OP1	

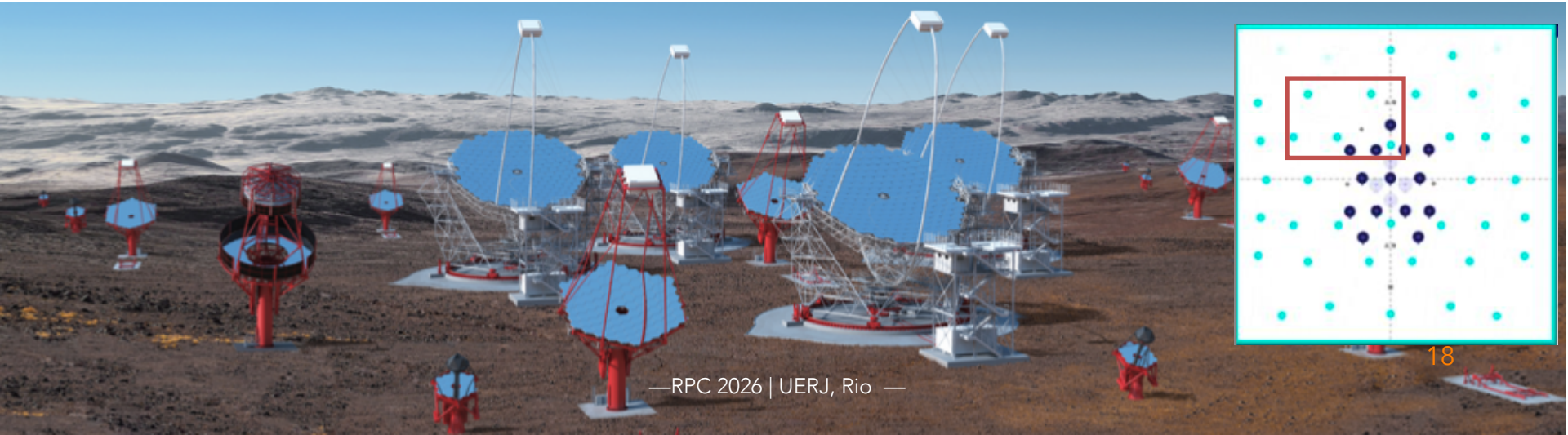
PRELIMINARY



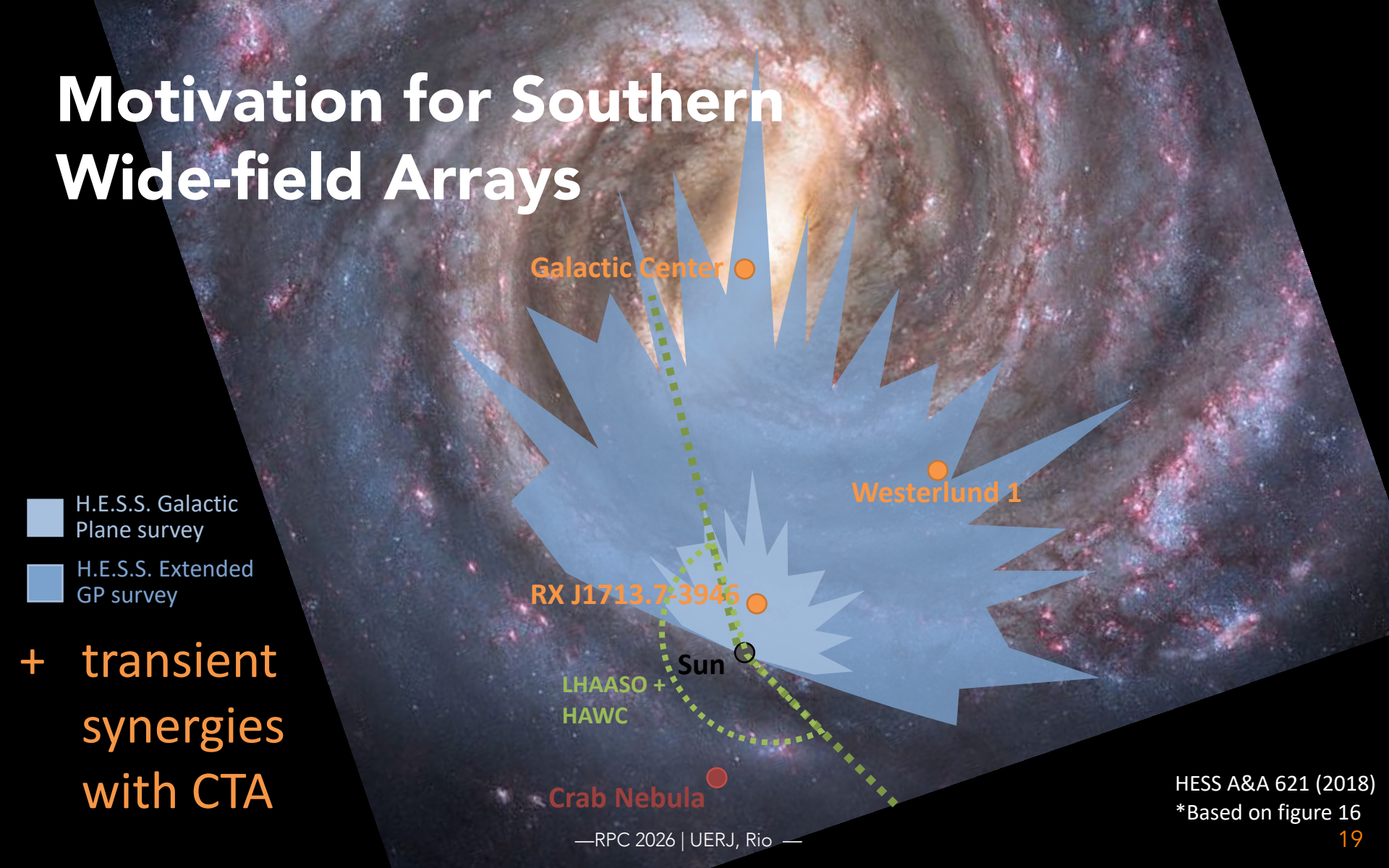
CTAO-Alpha

- SST sub-array expected for 2031 (37 tels)
- Intermediate configuration operations from 2028
- SSTs will bridge CTA with wide-field arrays, such as SWGO, in the Southern Hemisphere





Motivation for Southern Wide-field Arrays



\+ transient synergies with CTA

HESS A&A 621 (2018)
*Based on figure 16



EAS Arrays in the South

ALPACA

Andes Large Area Particle Array for Cosmic rays and Astronomy

SWGO

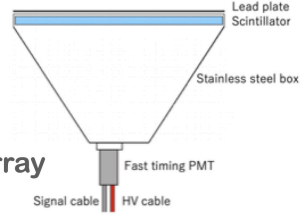
Southern Wide-Field Gamma-ray Observatory

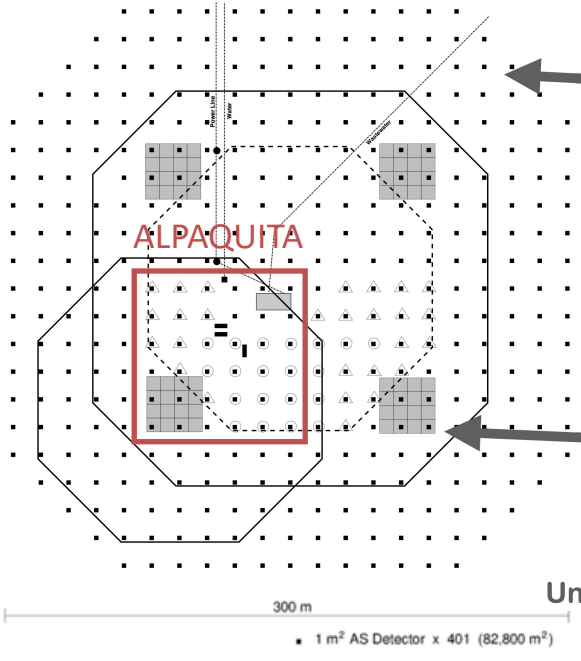
ALPACA (2028+)

Thanks to Takashi Sako & Kato Sei

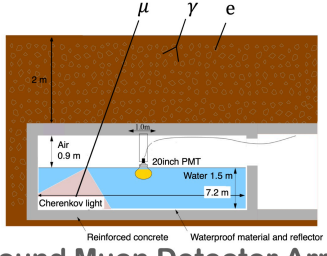
- 400 x 1 m² plastic scintillator SD
  - → 15-m spacing; 82,800 m²







Air Shower Array

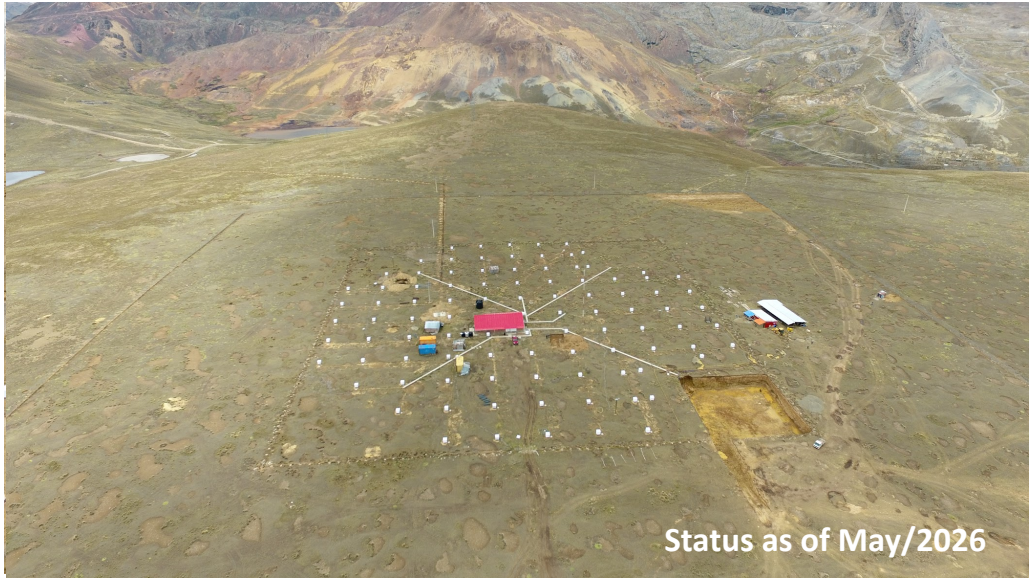


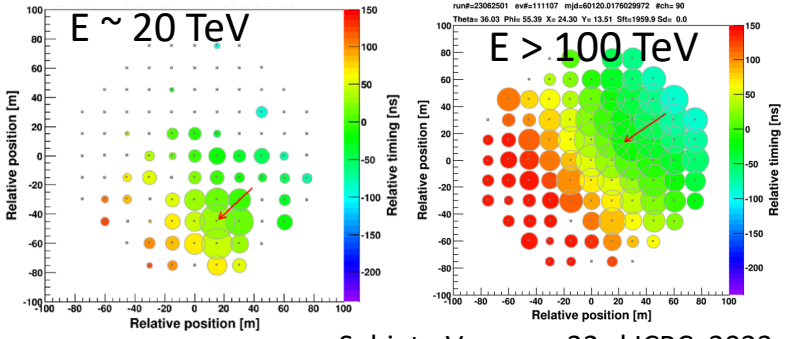
Underground Muon Detector Array



- 64 x 56 m² WCD muon array
  - → 4 x 16 cell clusters; 4% FF

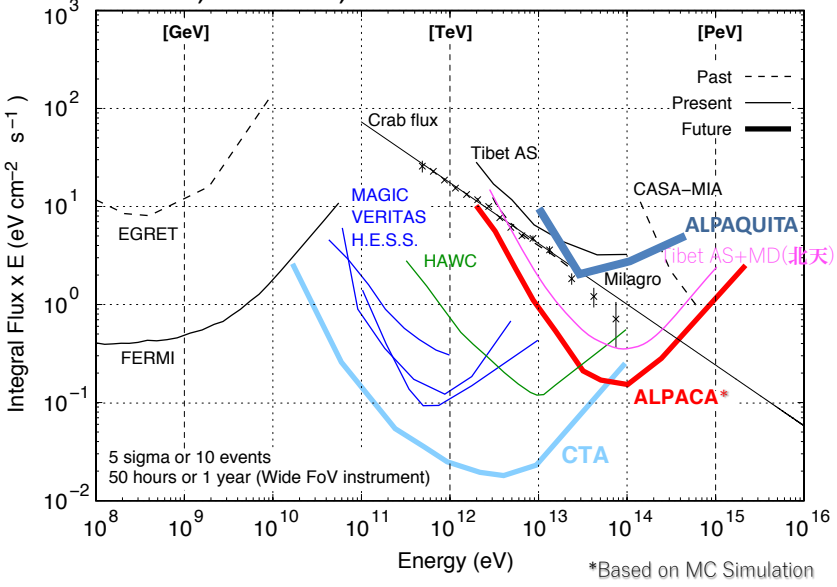
ALPAQUITA





Subieta-Vasquez, 33rd ICRC, 2023

Kawata, 33rd ICRC, 2023



*Based on MC Simulation

- 1/4 ALPACA array
  - → 97 SD units;18,450 m^2
  - → muon array under construction, exp. 2027

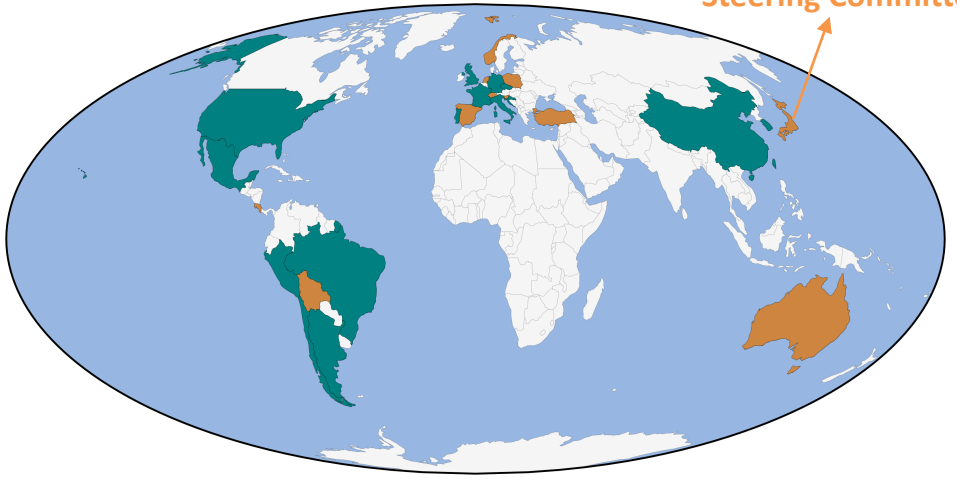
- Angular resolution ~0.2^o @100TeV
- Energy resolution ~20% @100TeV

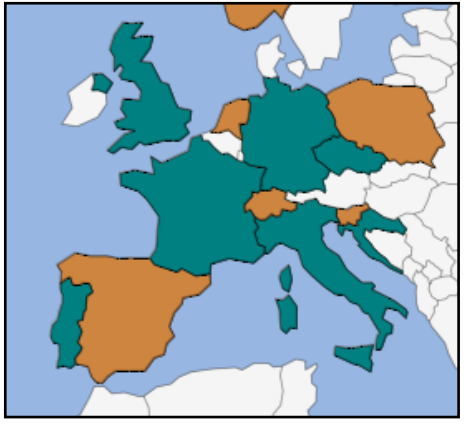
SWGO Collaboration

Member Institutes

Supporting Scientists

ICRR-Tokyo now an invited member of the Steering Committee





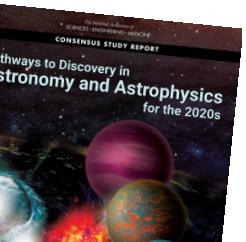
- SWGO partners
  - → 16 countries, circa 100 institutes
  - → + supporting scientists

Argentina	Italy
Brazil	Mexico
Chile	Netherlands
China	Peru
Croatia	Portugal
Czech Republic	South Korea
France	United Kingdom
Germany	United States

Project Status

		SWGO R&D Phase Milestones
2019 ✓	M1	R&D Phase Plan Established
✓	M2	Science Benchmarks Defined
2020 ✓	M3	Reference Configuration & Options Defined
✓	M4	Site Shortlist Complete
2022 ✓	M5	Candidate Configurations Defined
✓	M6	Performance of Candidate Configurations Evaluated
2024 ✓	M7	Preferred Site Identified
→	M8	Design Finalised
→	M9	Construction & Operation Proposal Complete

- Roadmaps
  - → US Decadal Review
  - → SNOWMASS, APPEC, Astronet
  - → LASF4RI, in Latin-America



Science Prospects for the Southern Wide-field Gamma-ray Observatory: SWGO

P. Abreu[1,2], R. Alfaro[3], A. Alfonso[4], M. Andrade[5], E. O. Angüner[6], E. A. Anita-Rangel[7], O. Aquines-Gutiérrez[8], C. Arcaro[9], R. Arceo[10], J. C. Arteaga-Velázquez[11], P. Assis[1,2], H. A. Ayala Solares[12], A. Bakalova[13], E. M. Bandeira[14], P. Bangale[12], U. Barres de Almeida[14,15], P. Batista[16], I. Batković[9,17], J. Bazo[18], E. Belmont[3], J. Bennemann[19], S. Y. BenZvi[20], A. Bernal[7], W. Bian[21], C. Bigongiari[22], E. Bottacini[9,17], R. Branada[23], P. Brogueira[1,2], A. M. Brown[64], T. Bulik[24], K. S. Caballero-Mora[10], P. Camarri[25,26], W. Cao[27], Z. Cao[27], Z. Cao[28]

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https://arxiv.org/abs/2506.01786

Project Status

		SWGO R&D Phase Milestones
2019 ✓	M1	R&D Phase Plan Established
✓	M2	Science Benchmarks Defined
2020 ✓	M3	Reference Configuration & Options Defined
✓	M4	Site Shortlist Complete
2022 ✓	M5	Candidate Configurations Defined
✓	M6	Performance of Candidate Configurations Evaluated
2024 ✓	M7	Preferred Site Identified
→	M8	Design Finalised
→	M9	Construction & Operation Proposal Complete

- Funding
  - → 10 MUSD Approved from FNDCT
  - → Production of WCD units for PeVatron array



Science Prospects for the Southern Wide-field Gamma-ray Observatory: SWGO

P. Abreu[1,2], R. Alfaro[3], A. Alfonso[4], M. Andrade[5], E. O. Angüner[6], E. A. Anita-Rangel[7], O. Aquines-Gutiérrez[8], C. Arcaro[9], R. Arceo[10], J. C. Arteaga-Velázquez[11], P. Assis[1,2], H. A. Ayala Solares[12], A. Bakalova[13], E. M. Bandeira[14], P. Bangale[12], U. Barres de Almeida[14,15], P. Batista[16], I. Batković[9,17], J. Bazo[18], E. Belmont[3], J. Bennemann[19], S. Y. BenZvi[20], A. Bernal[7], W. Bian[21], C. Bigongiari[22], E. Bottacini[9,17], R. Branada[23], P. Brogueira[1,2], A. M. Brown[64], T. Bulik[24], K. S. Caballero-Mora[10], P. Camarri[25,26], W. Cao[27], Z. Cao[27], Z. Cao[28]

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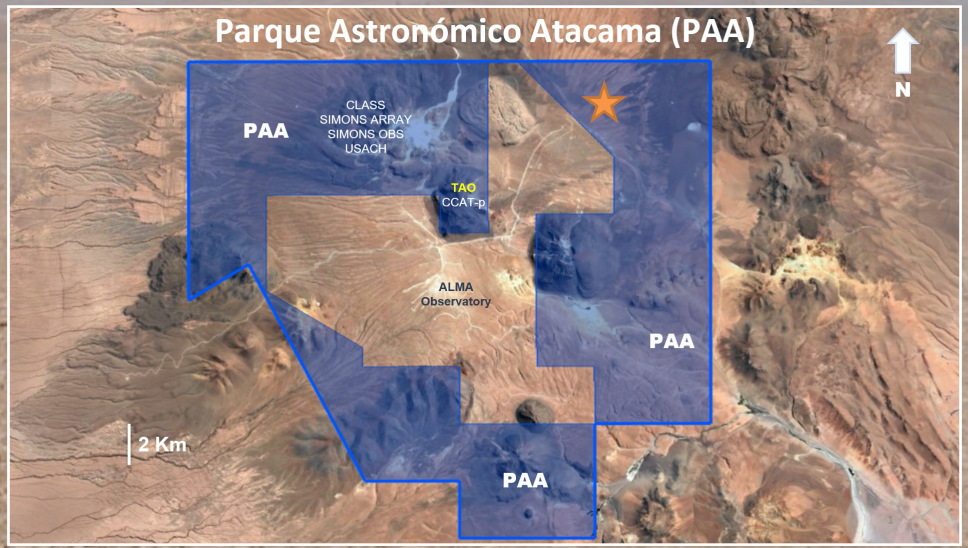
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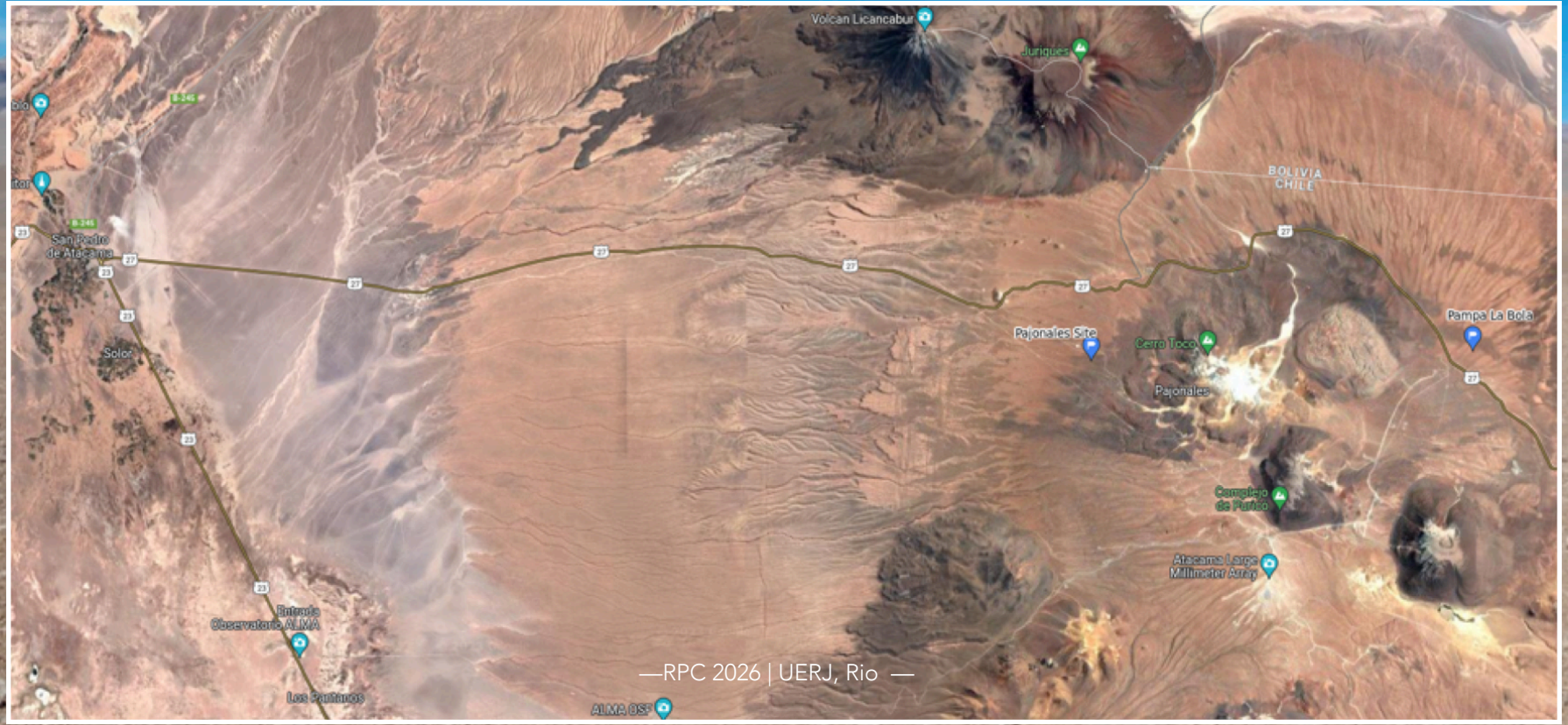
Site Selection

- Preferred and back-up site announced on 12th August 2024
- Pampa La Bola, Atacama Astronomical Park (Chile)
  - Vast plateau at 4,770 m a.s.l.
  - 23° South, 68° West
  - Available area superior to 1 km^2
  - At the international road Chile-Argentina
    - ✓ Few km from ALMA
    - ✓ 40 min from San Pedro de Atacama
    - ✓ 2 hours from Calama (airport)



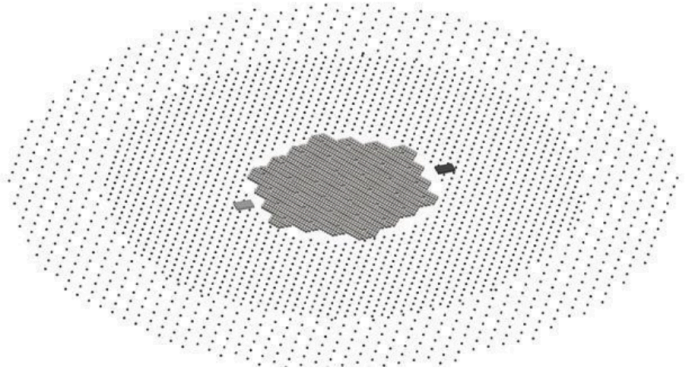
Site Selection

- Pampa La Bola, Atacama Astronomical Park (Chile)



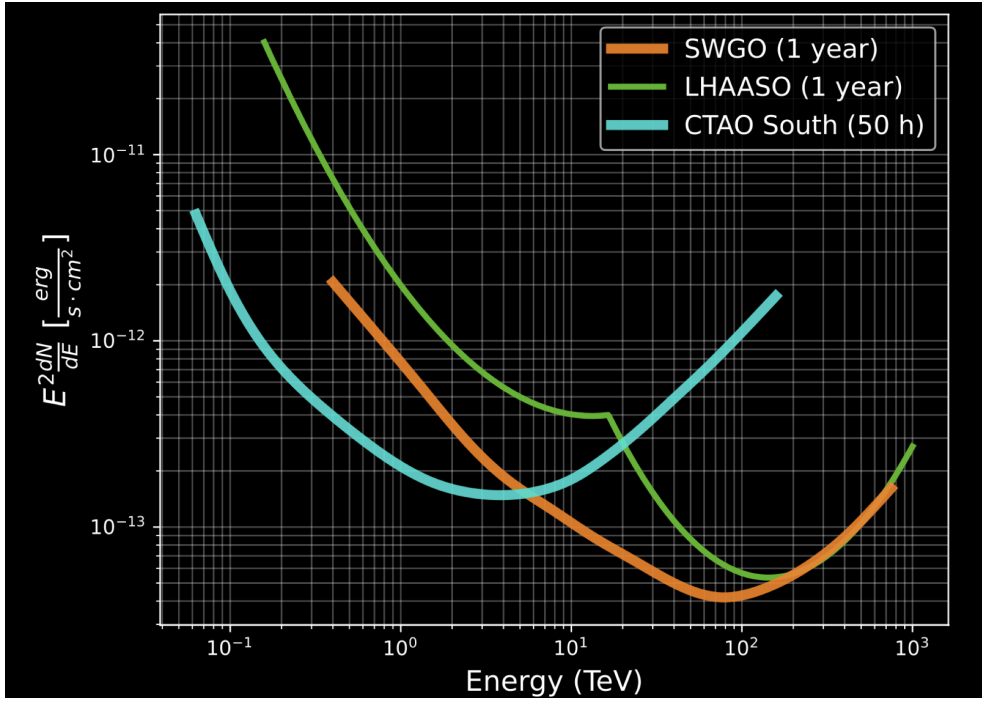
The baseline array layout

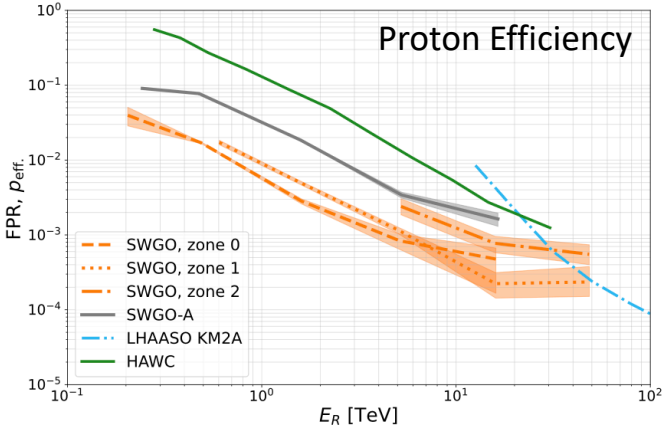
- Graded fill-factor from core to outer-array
  - Inner array: FF=65%, 80,000 m^2, 2,450 tanks (90 m^3)
  - Outer array:
    - Zone 1: FF=4%, R=400 m, 1,660 tanks (15 m^3)
    - Zone 2: FF=1.6%, R=560 m, 760 tanks (15 m^3)

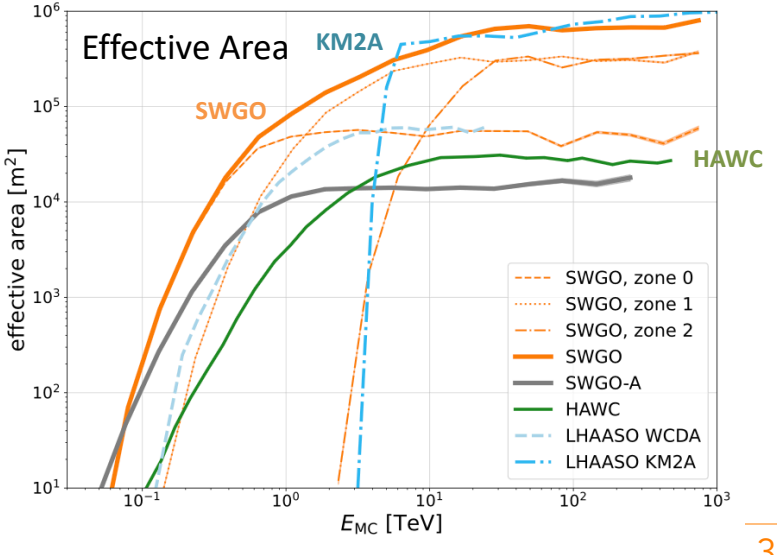




Expected Sensitivity



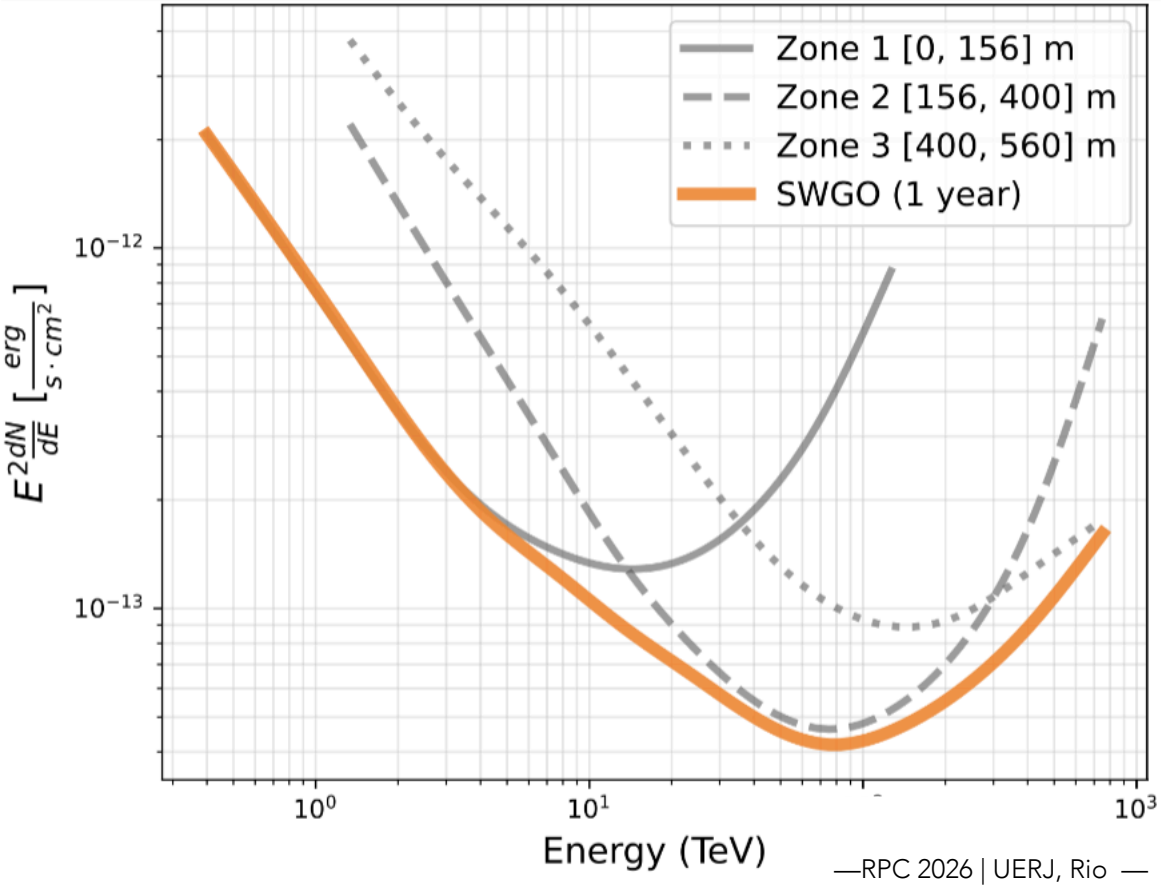


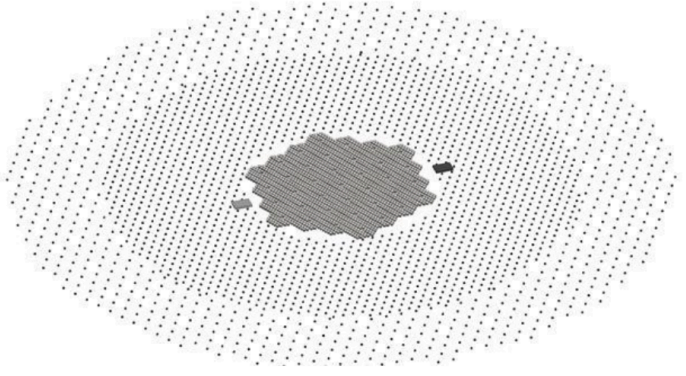


At 4,770 m a.s.l.

arxiv:2506.01786

Expected Sensitivity - Stages

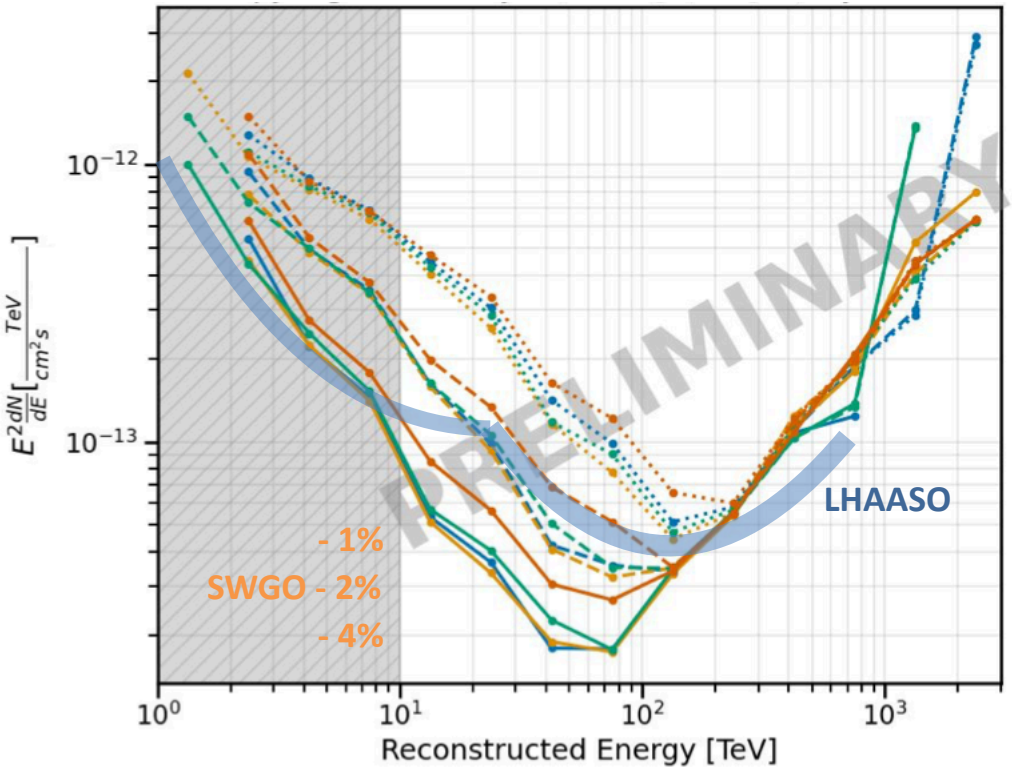




At 4,770 m a.s.l.

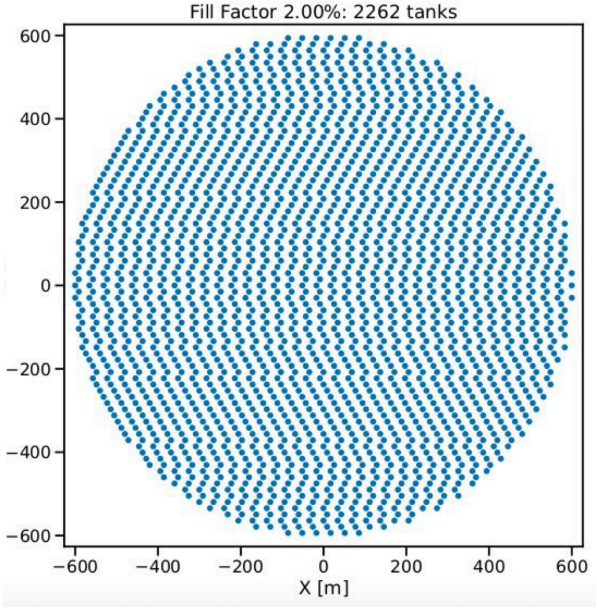
arxiv:2506.01786

Expected Sensitivity - PeV Array



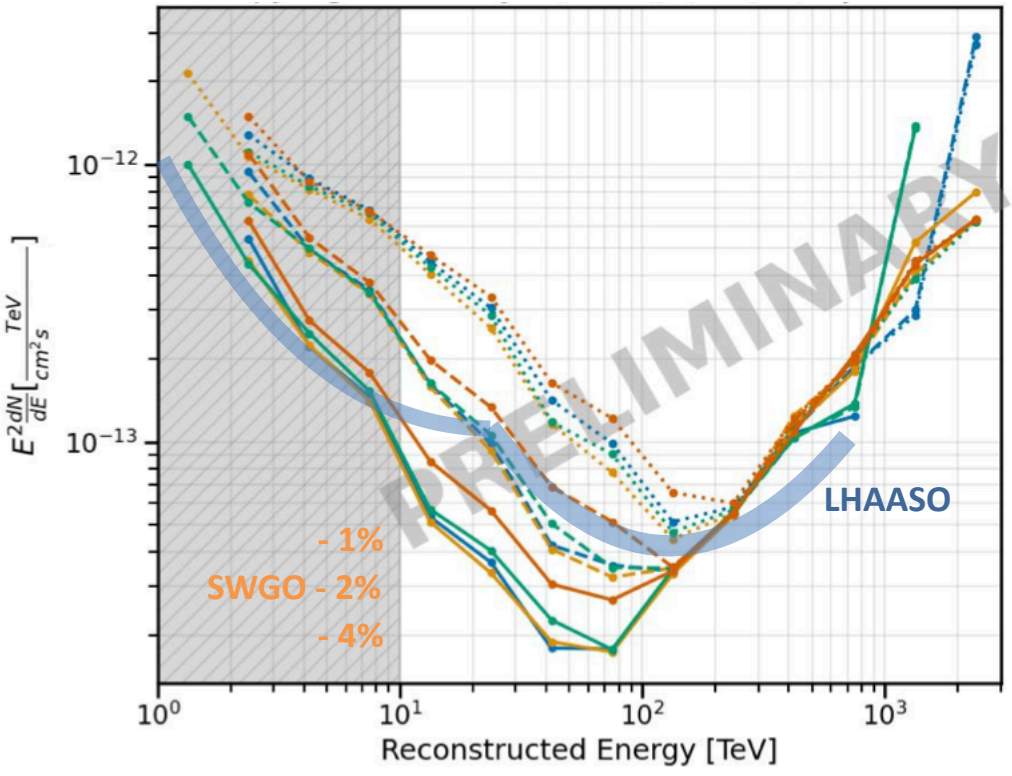
SWGO-PeV (Preliminary)

1.0 km2
2,100 tanks
FF 2%



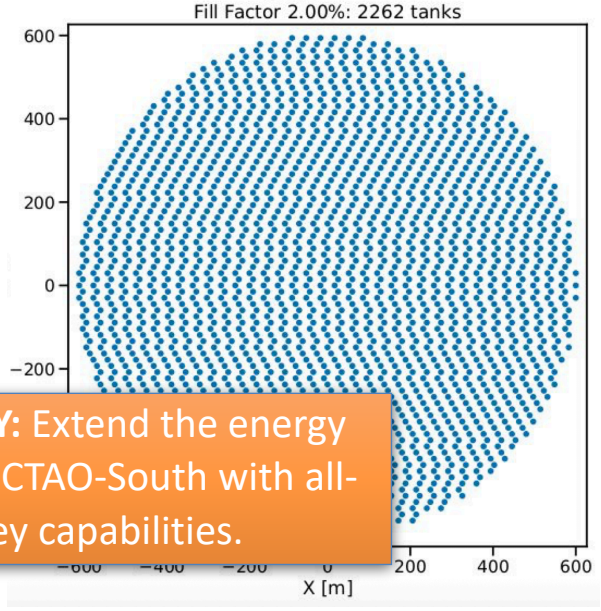
Preliminary Results

Expected Sensitivity - PeV Array



SWGO-PeV (Preliminary)

1.0 km2
2,100 tanks
FF 2%

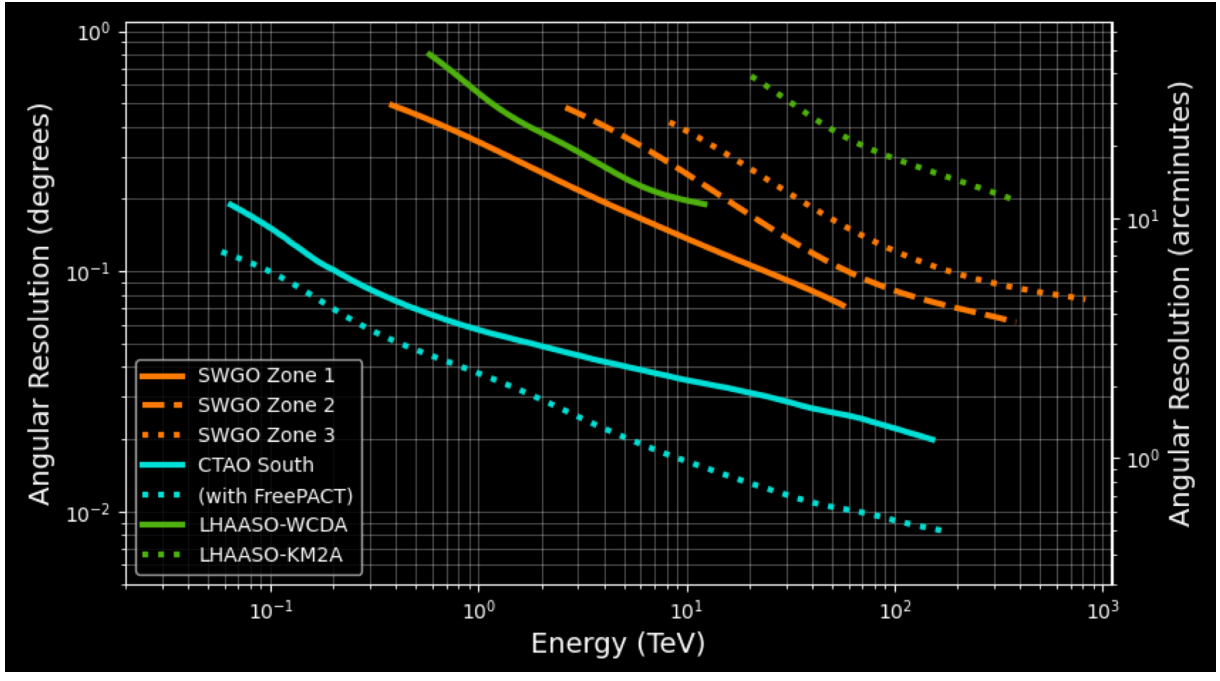


SYNERGY: Extend the energy reach of CTAO-South with all-sky survey capabilities.

Preliminary Results

Target Angular Resolution
Unprecedented for wide-field instrument

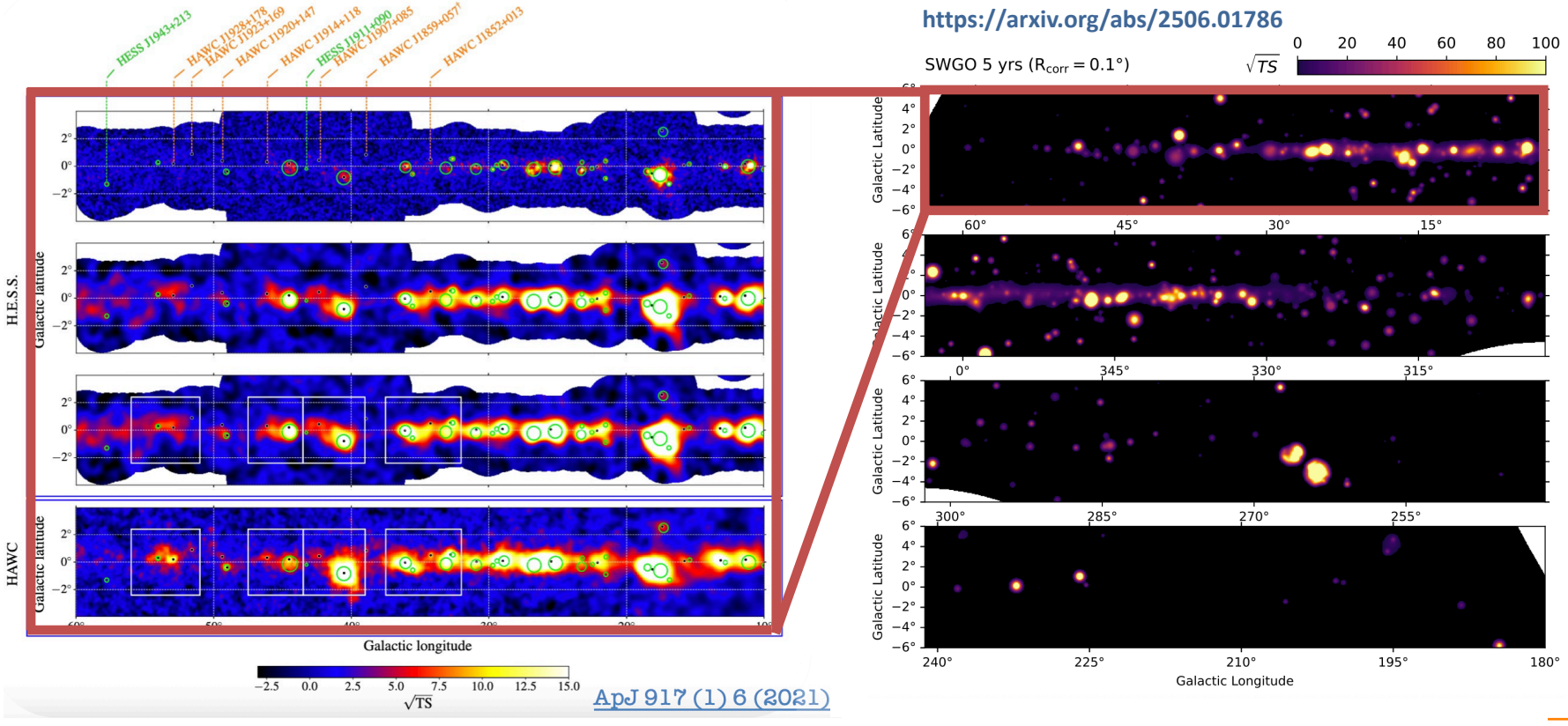
- Key for:
  - → Source morphology for astrophysical modeling above 10 TeV
  - → Extreme transient alerts, e.g. GRBs and AGN flares
  - → Reduction of error regions for MM events



SYNERGY: A transient alert and MM survey instrument for CTAO.

Target Angular Resolution

Unprecedented for wide-field instrument

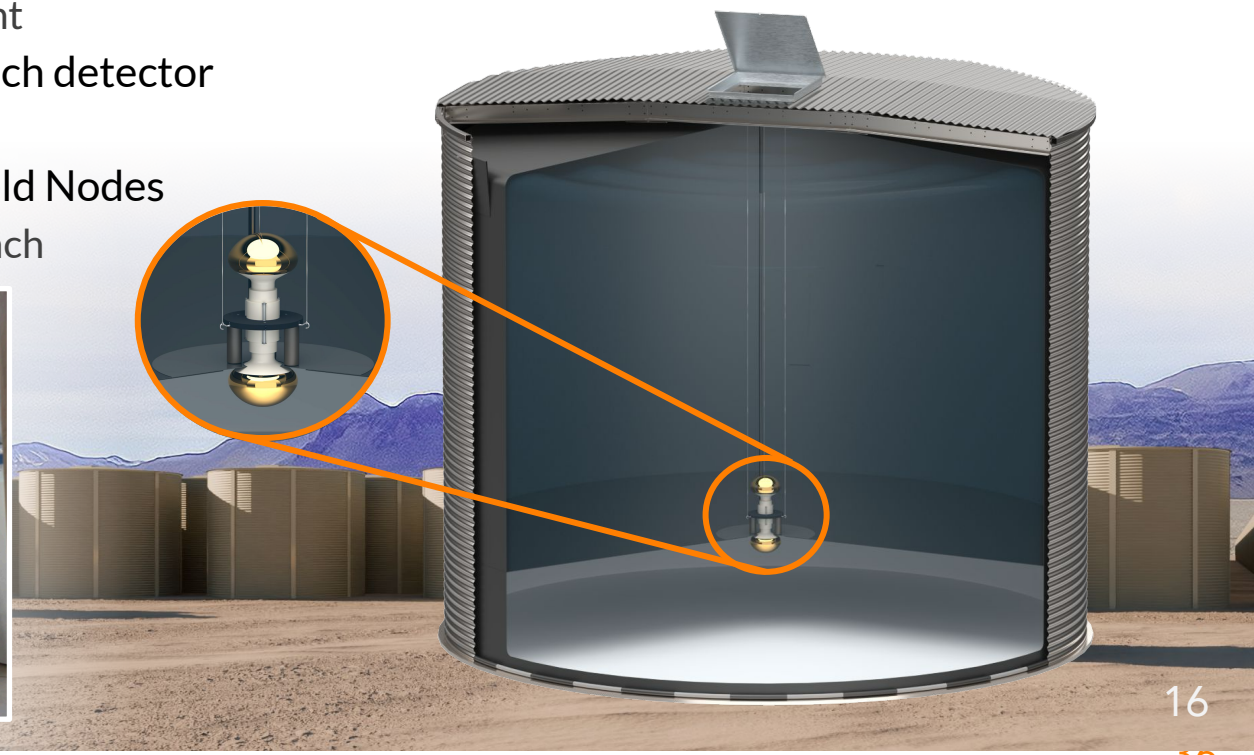


ApJ 917 (1) 6 (2021)

Design of Inner Array

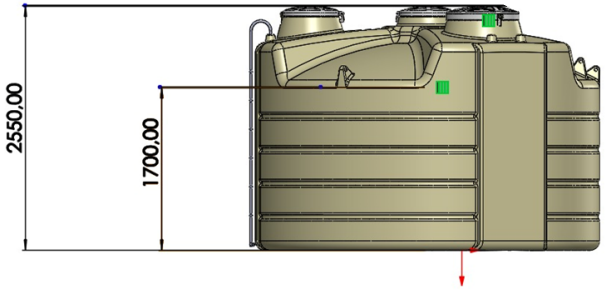
- Steel tanks assembled on site
  - 5.2 m ⌀, 4.1m height
- Double-PMT unit in each detector
  - 10-inch PMTs
- Signals collected at Field Nodes
  - Serve 55 WCDs each





Outer array WCD unit desing

- Design principles
  - → Compact design to minimize water usage
  - → Simplification of logistics, installation and maintenance
  - → Robustness and reliability for long-term operations
  - → Flexibility of unit and array design options
  - → Inexpensive: $ 5kUSD/unit







Extensive previous experience with the Pierre Auger Surface Detector Array.

Outer array WCD unit desing

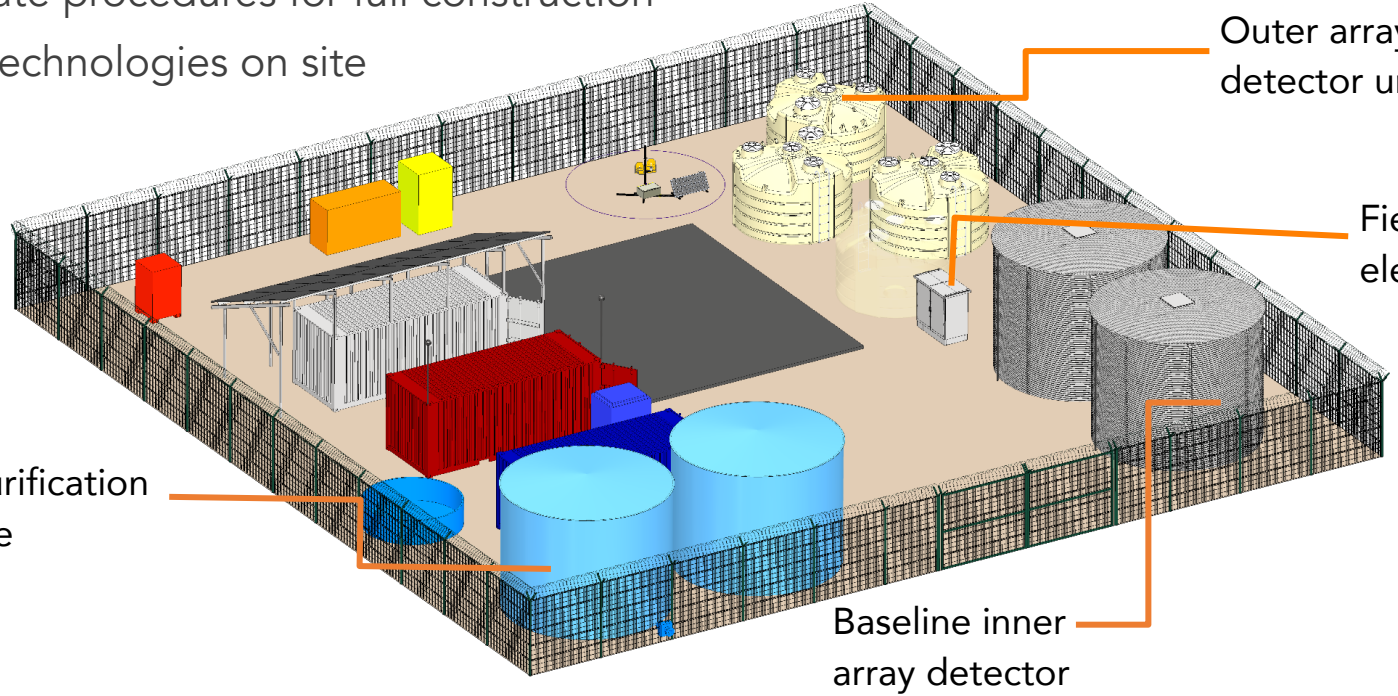
- Innovations
  - Higher UV protection resin (UV-30 vs. UV-15 in Auger)
  - Thermal insulation for high-altitude operation
  - Rotomolding Patent BR1020210266902
  - Inner wall resin layer for Cherenkov light reflection
  - Substitute of costly and complex Tyvek bags



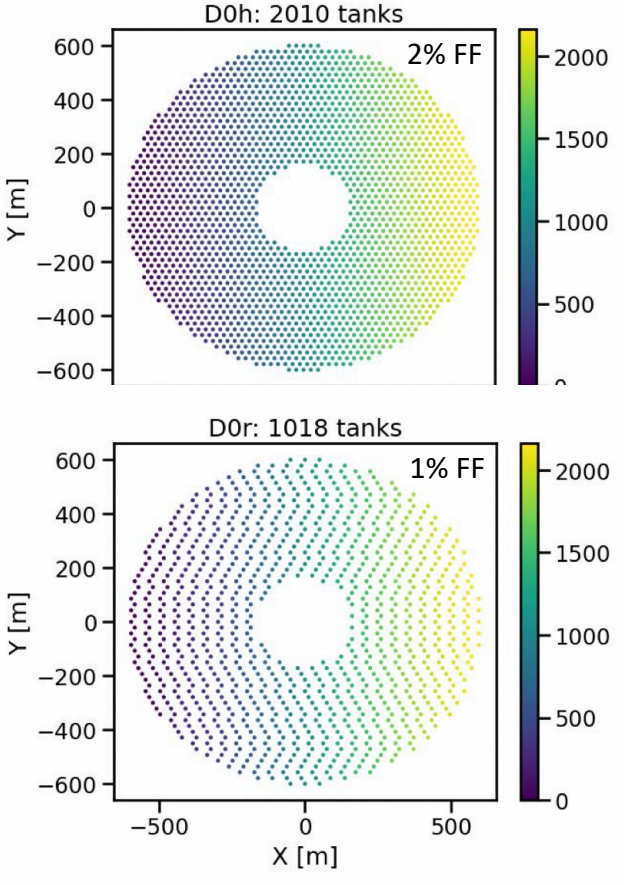


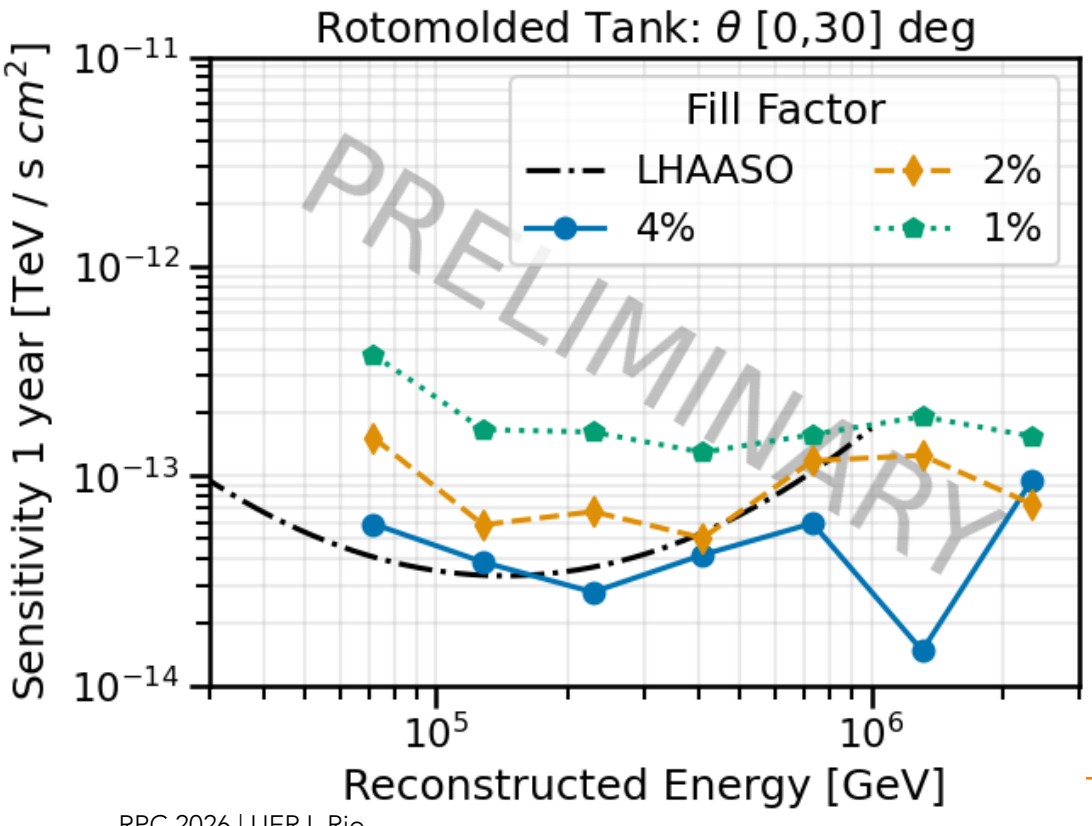
Towards Construction
An SWGO Pathfinder, exp. 2027

- 30 x 30 m fenced area within the future array location
  - → To validate procedures for full construction
  - → To test technologies on site



An SWGO PeVatron Array





Summary

- Ground-based gamma-ray Astronomy will reach its full maturity in the 2030's
- The context of the field will be dictated by the interplay of large IACTs and Wide-Field Particle Arrays
  - LHAASO-ASTRI + LSTs in the North
  - SWGO-CTAO in the South
- Some aspects I left out of this talk:
  - TAIGA high-score exploring synergies in particle / Cherenkov-light EAS detection
  - Auger upgrade to explore the 10^{17} eV photon range
  - ERC-funded radio extension to SWGO (TURBO)
- Common tools and the integration between facilities is key to maximize returns


Thank you!
Ulisses Barres de Almeida
CBPF
CBPF
Centro Brasileiro
de Pesquisas Físicas
— RPCs 2026 | 18th September | UERJ, Rio —