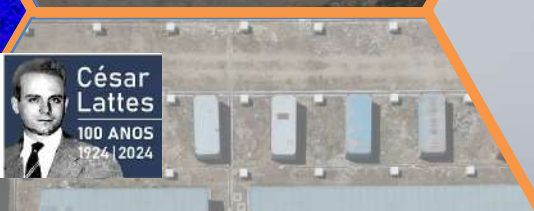
Future TeV-PeV Gamma-ray Instruments

Ulisses Barres

CBPF - IAG/USP



1949 | 2024 75 ANOS CBPF

César Lattes 100 ANOS 1924 | 2024

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2. **IACTs beyond CTA**
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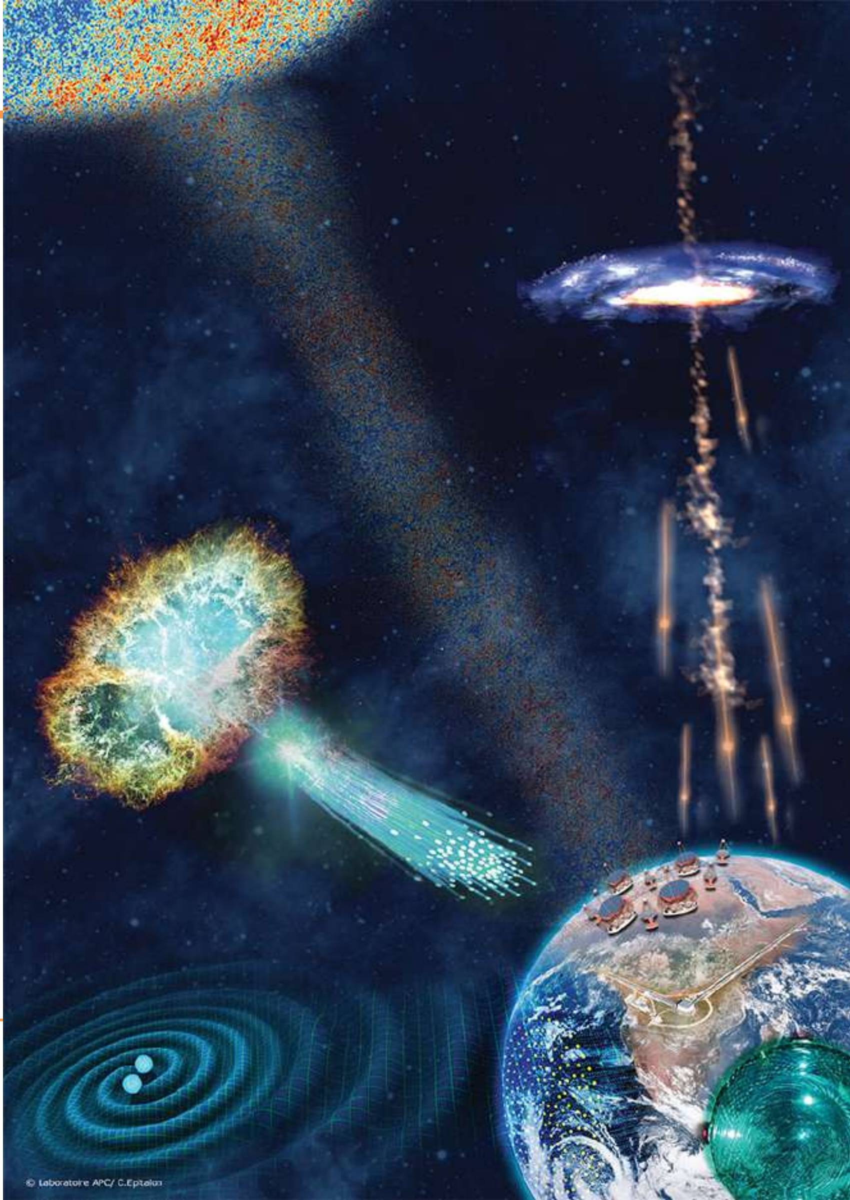
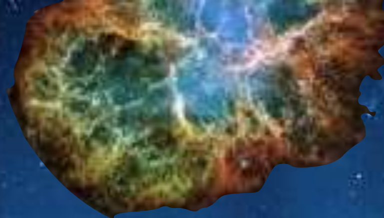
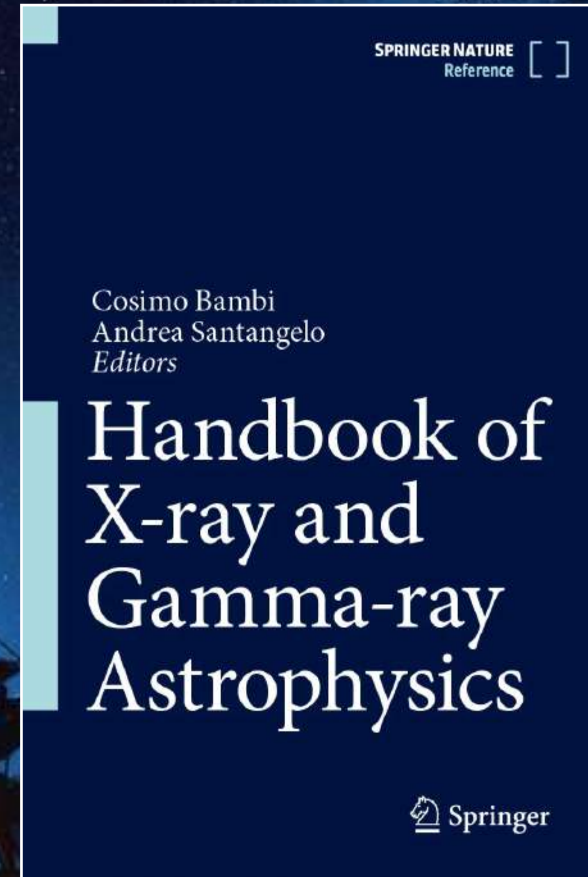
4. **SWGO**



Current context





arXiv:2307.02976

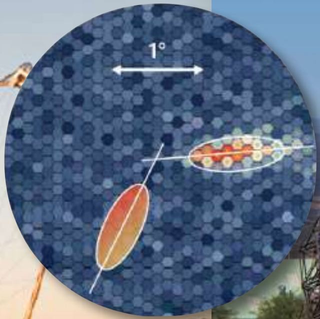
Future developments in ground-based gamma-ray astronomy

Ulisses Barres de Almeida * and Martin Tluczykont

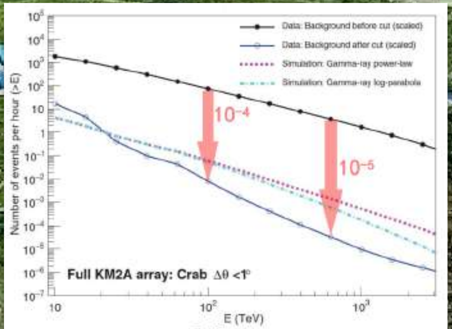
Ground-based Gamma-ray Astronomy Network

'Real Astronomy' at VHEs

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

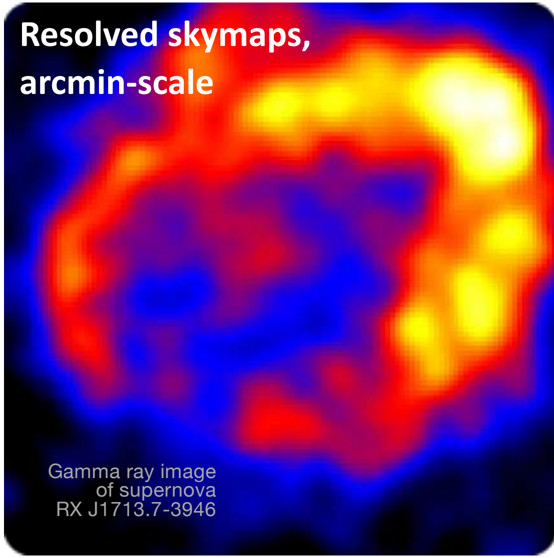


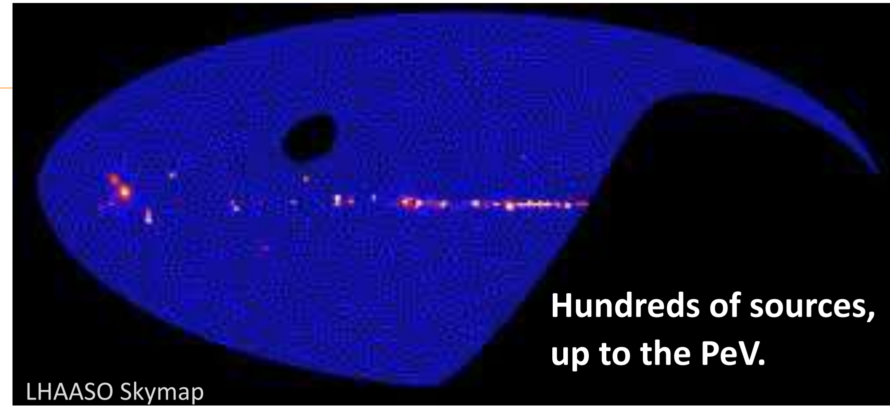
- High altitude & fill factor → dense shower front sampling
- Large array areas for efficient shower detection
- Large Muon Effective Areas

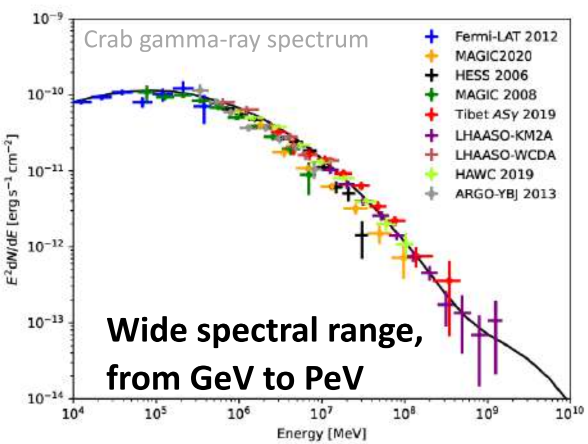


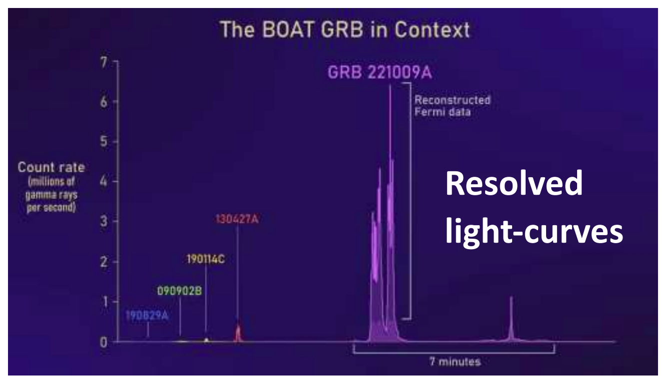
LHAASO Coll., *Science*, 373, 425 (2021)

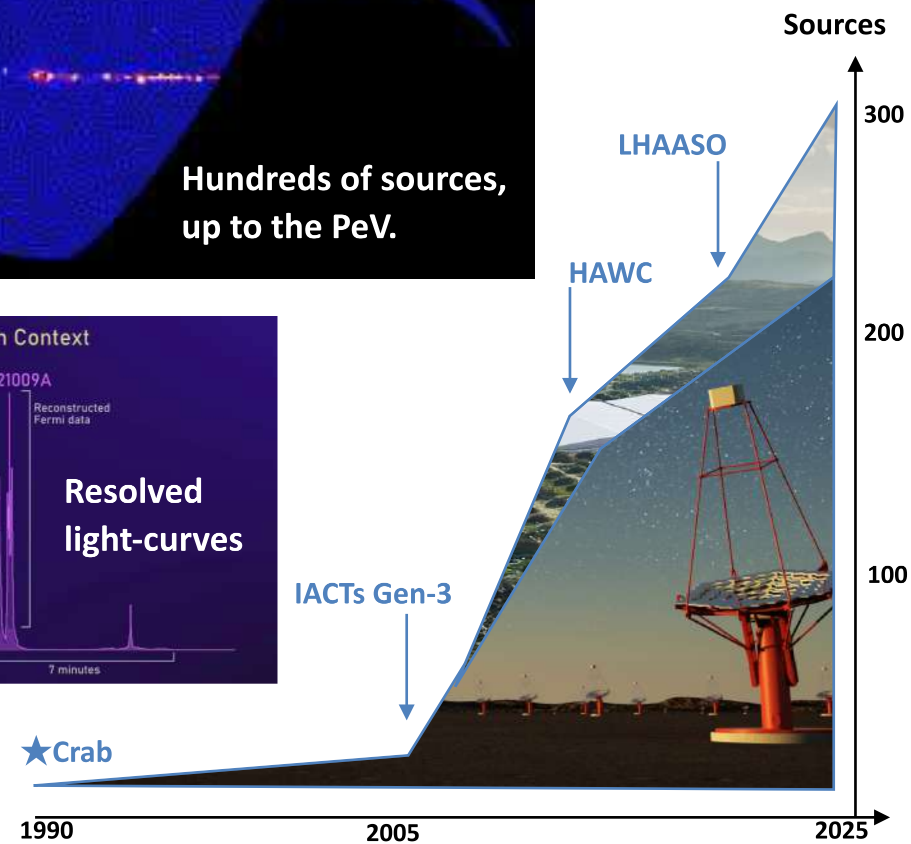
'Real Astronomy' at VHEs



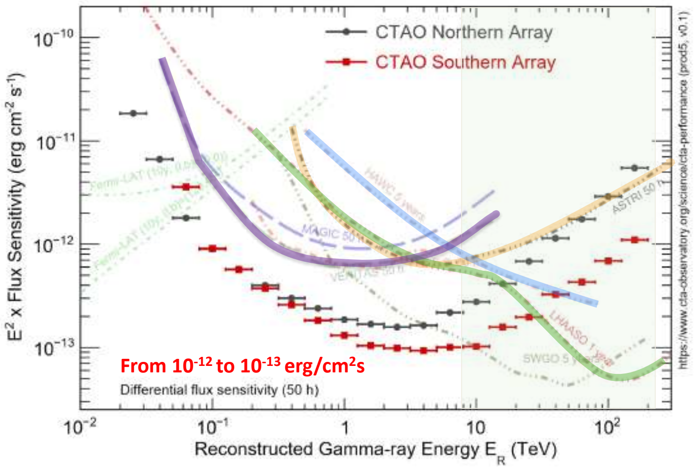








Two techniques

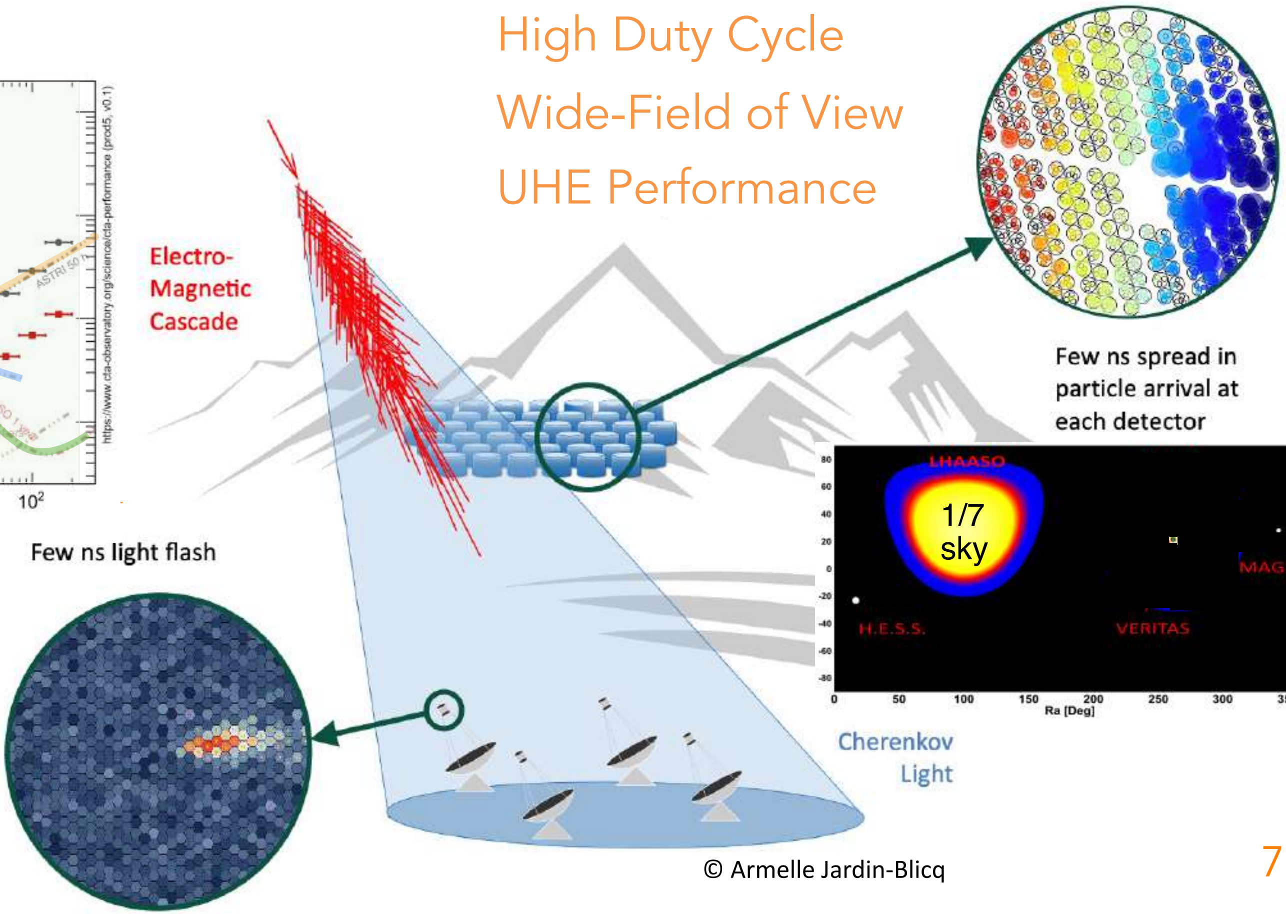


Air-shower particle arrays

High Duty Cycle

Wide-Field of View

UHE Performance



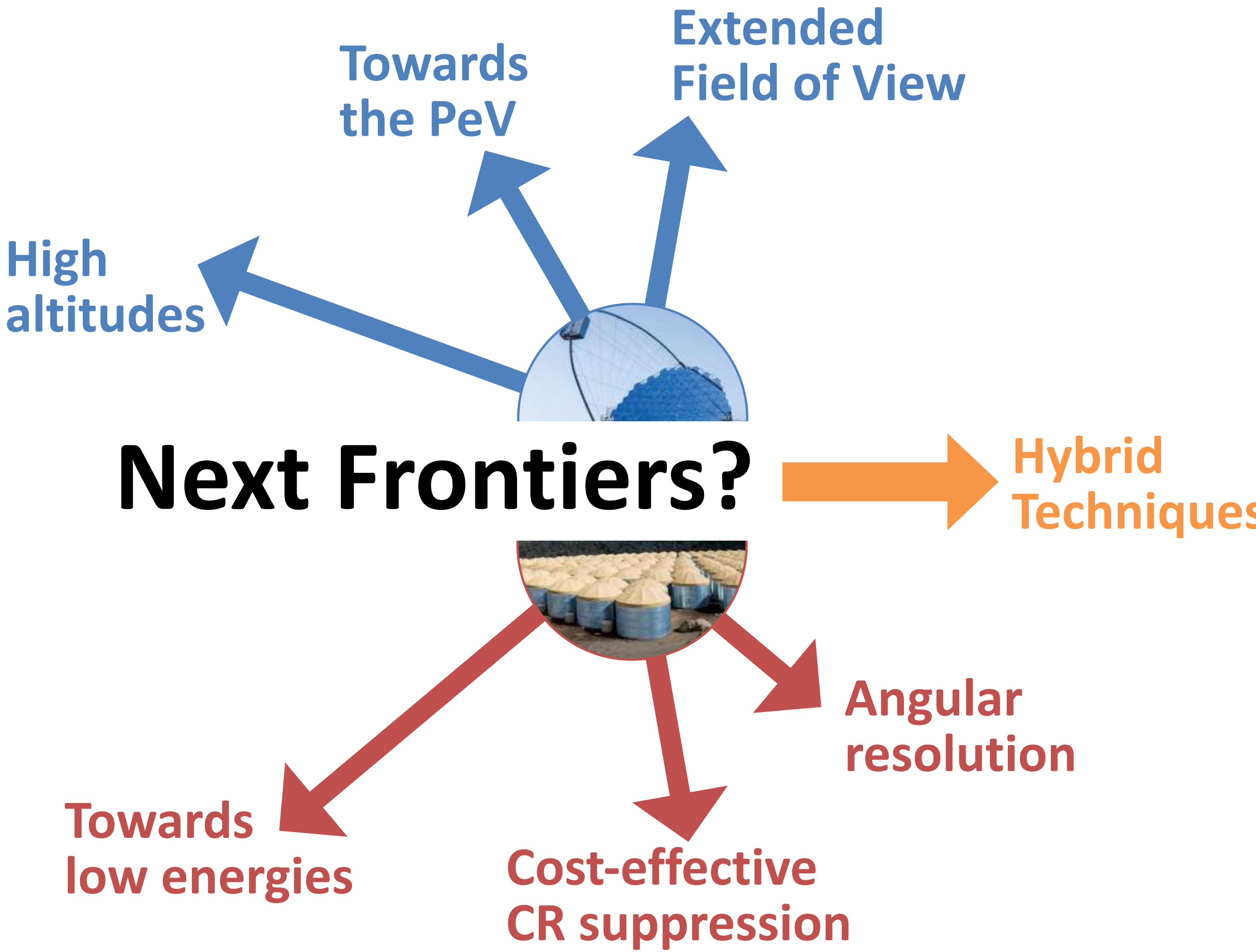
Air-Cherenkov Telescopes

Low Duty Cycle

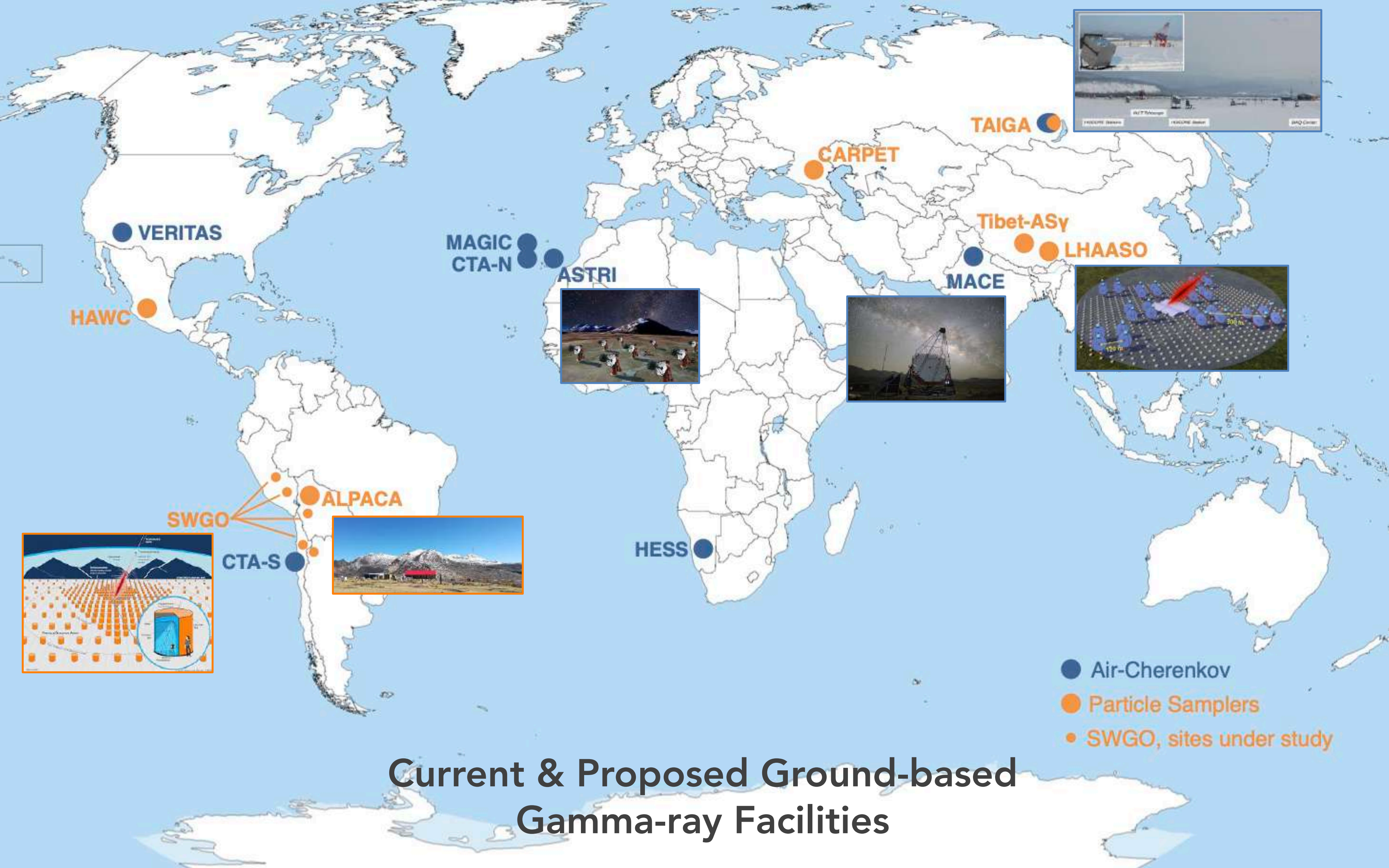
Pointing instruments

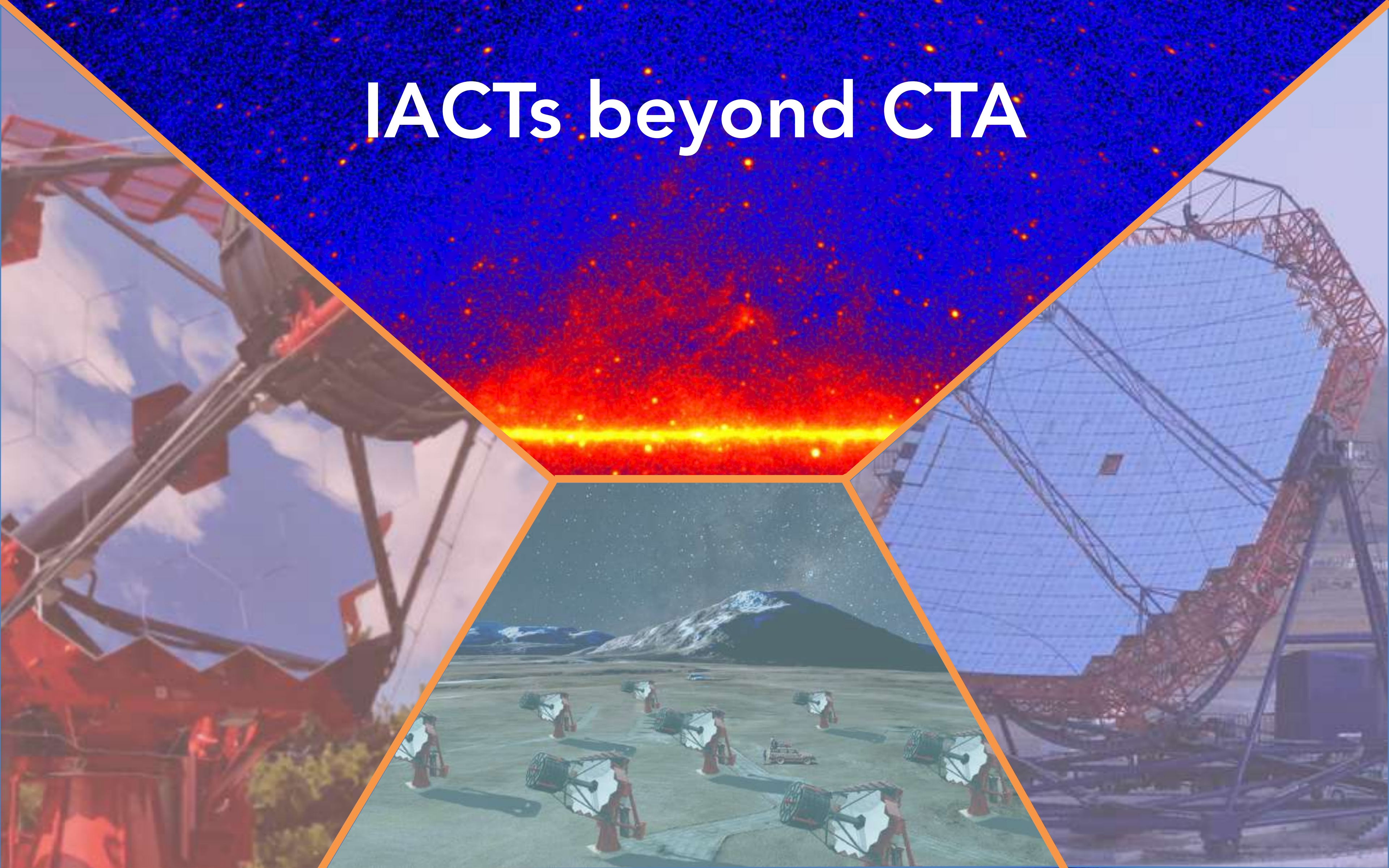
Precision Astronomy at VHE

© Armelle Jardin-Blicq

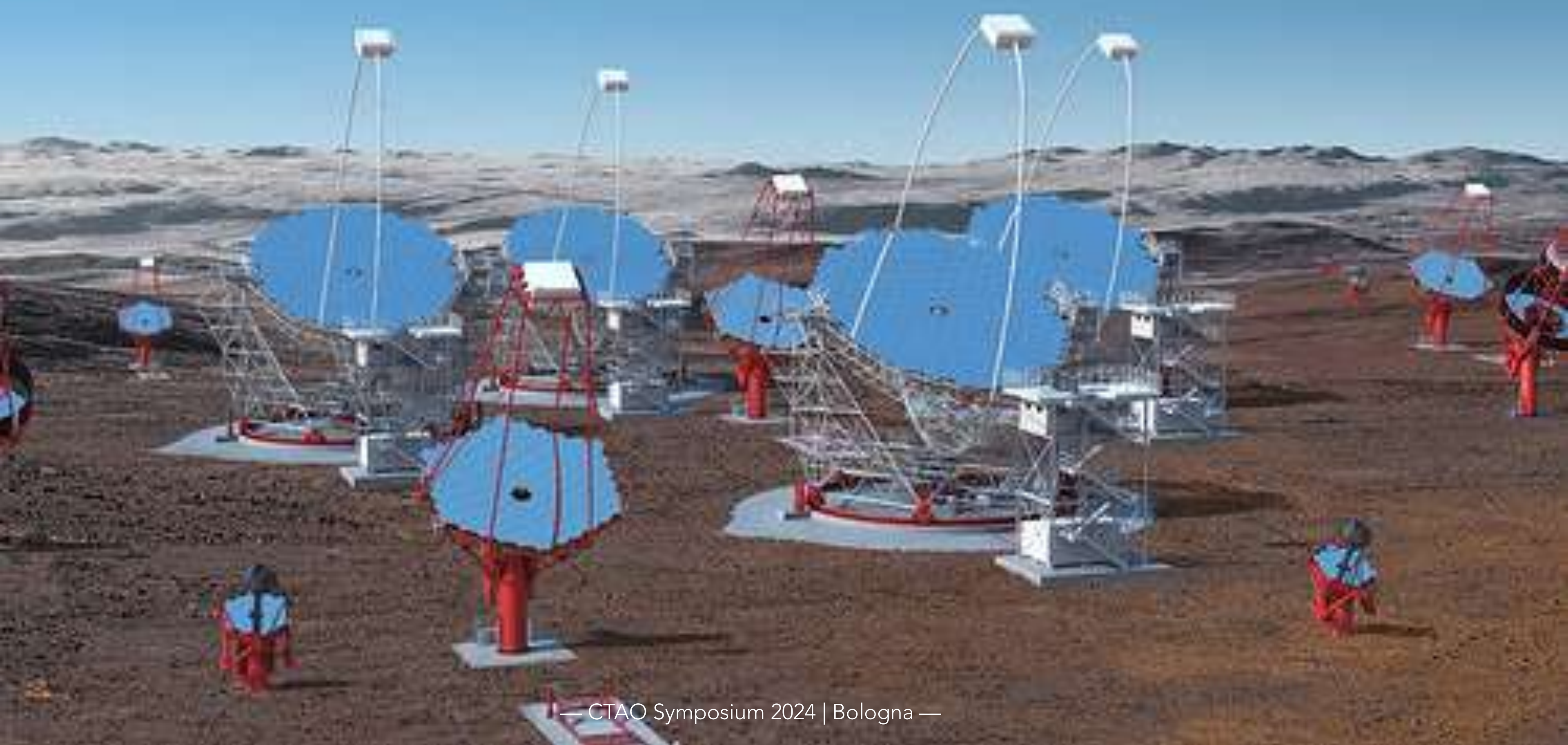

Towards the PeV
Extended Field of View
High altitudes
Next Frontiers?
Hybrid Techniques
Angular resolution
Towards low energies
Cost-effective CR suppression

Current & Proposed Ground-based Gamma-ray Facilities

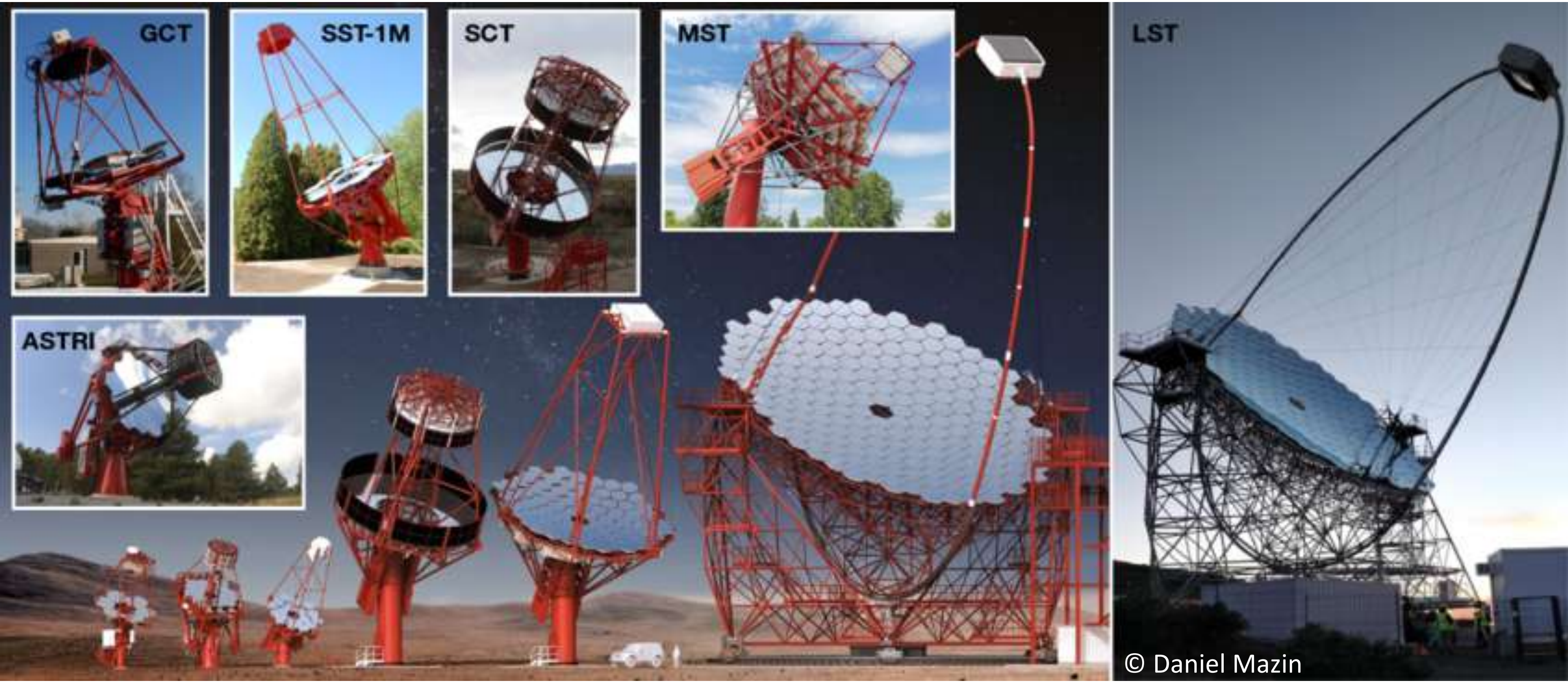



IACTs beyond CTA

The Definitive IAC Array



Large projects are rich R&D environments



ASTRI Telescope

Thanks to Giovanni Pareschi

- Advancing novel IACT optics
  - → Pioneering dual-mirror design for the SSTs
    - ✓ compact telescopes and reduced focal length (7 mm pixel size)
    - ✓ good angular resolution over a wide-field of view (> 10°)
    - ✓ "aplanatic" optics for aberration correction
  - → Developing SiPM camera technology and associated electronics
  - → Expanded into a full "mini-array" proposal
- "Mini-Array" with science exploiting
  - → the CTA timeline and LHAASO synergies
  - → flexible schedule for deep observation programme

ASTRI camera

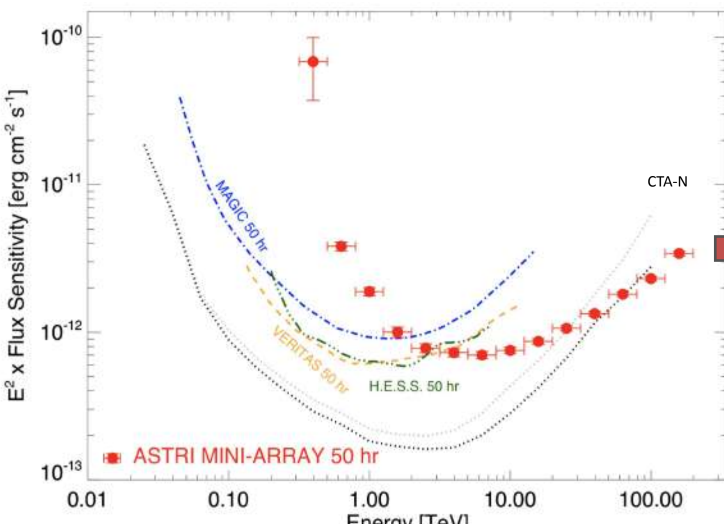
ASTRI Array

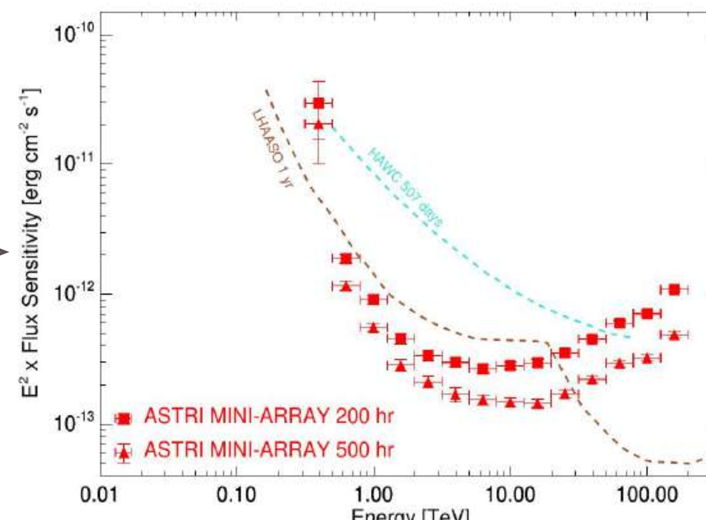
- Array of 9 x 4-m class telescopes at the Teide Observatory, in Tenerife
  - → ASTRI-1 telescope installed in June 2022 → full array by end 2025
  - → Early science from 2025
- Science Programme
  - → deep-field observations, surveys and extended sources
  - → characterise the morphology of extended UHE sources
  - → extend spectra of known sources and measure cut-offs

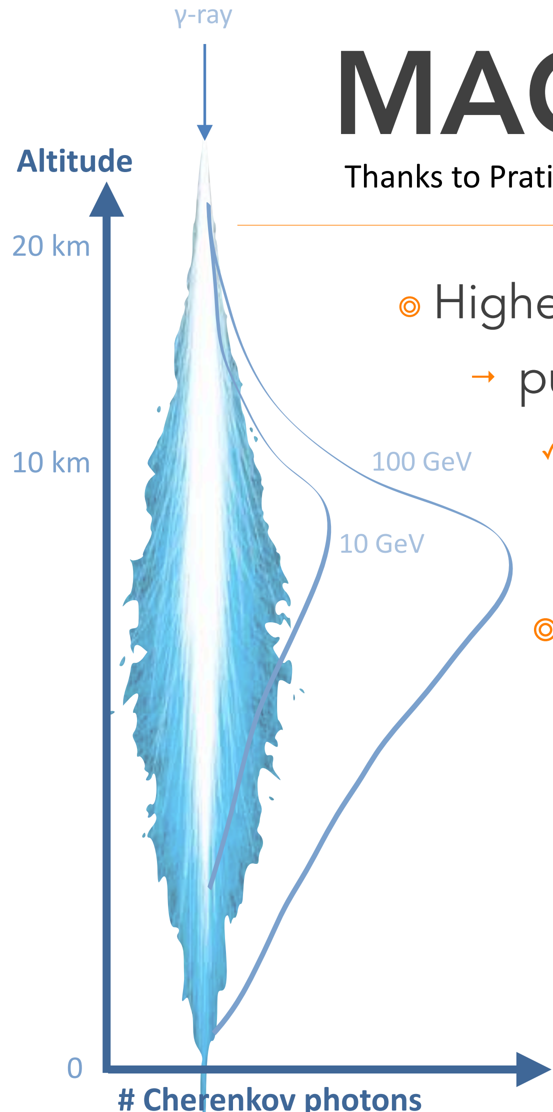
	ASTRI Mini-Array	H.E.S.S.	HAWC	LHAASO
Altitude [m]	2,390	1,800	4,100	4,410
FoV	$\sim 10°$	$\sim 5°$	2 sr	2 sr
Angular Res.	0.05° (30 TeV)	0.06° (1 TeV)	0.15° (10 TeV)	(0.24–0.32)° (100 TeV)
Energy Res.	12% (10 TeV)	15% (1 TeV)	30% (10 TeV)	(13–36)% (100 TeV)
Energy Range	(0.3-200) TeV	(0.02-30) TeV	(0.1-200) TeV	(0.1-1,000) TeV

ASTRI Array

- Science Operations
  - → 4+4 years of science, from 2026
  - → first 4 years: run as an experiment, with key science projects
  - → after which: move towards an observatory model with open time

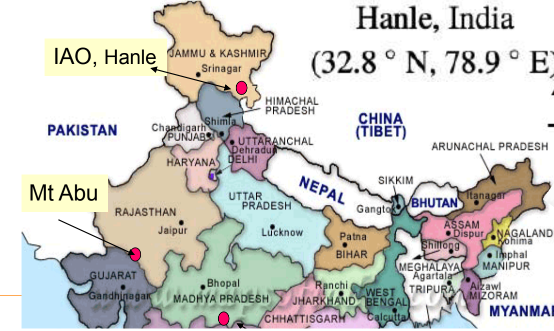






MACE

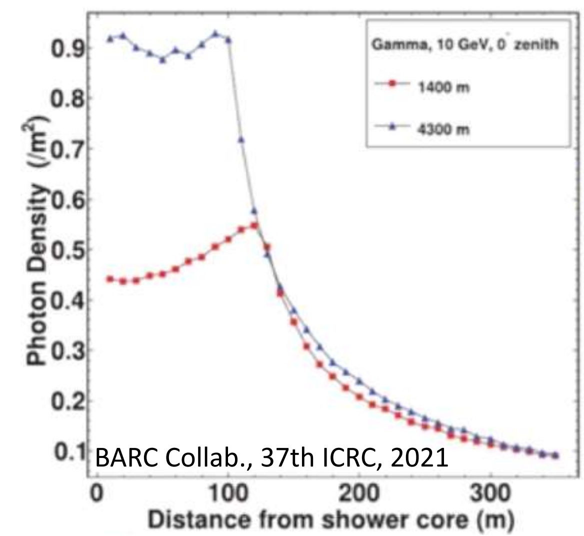
Thanks to Pratik Majumdar



- Highest altitude IACT ever built, at 4,720 m a.s.l. (Hanle, India)
  - → push the energy threshold of observations close c. 20 GeV
    - ✓ Cherenkov light produced only by first few generations of electrons

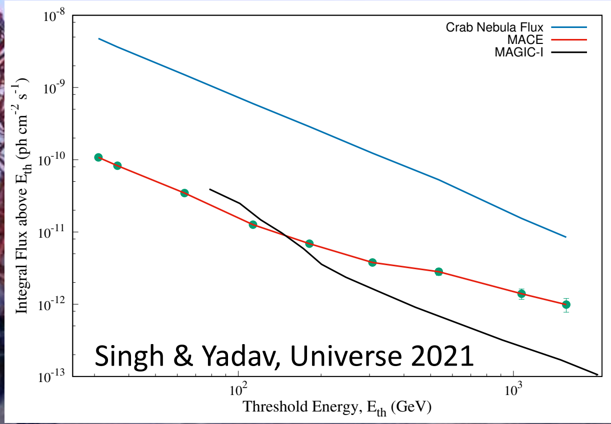
- Challenges
  - → Cherenkov imaging
  - → PSF degradation
  - → Energy resolution
  - → High-energy shower reconstruction / calorimetry

1 ph/m² @ 10 GeV

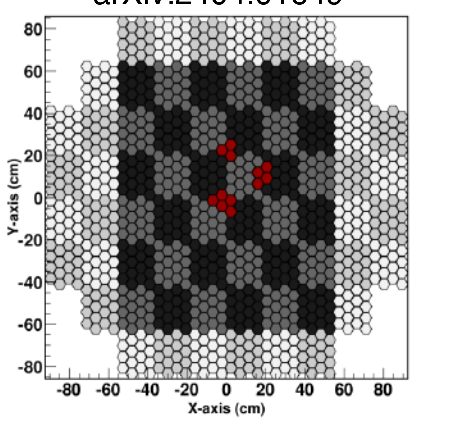


MACE

- ◎ Design Features
  - → Large optical reflector, 21-m ø + AMC
  - → Small on-axis spot size at focal length
  - → Compact camera, 1088 x 1.5″ PMTs
  - → FoV ~ 4°, pixel size = 0.125°
  - → GHz signal processing and trigger strategy



arXiv:2404.01649



MACE

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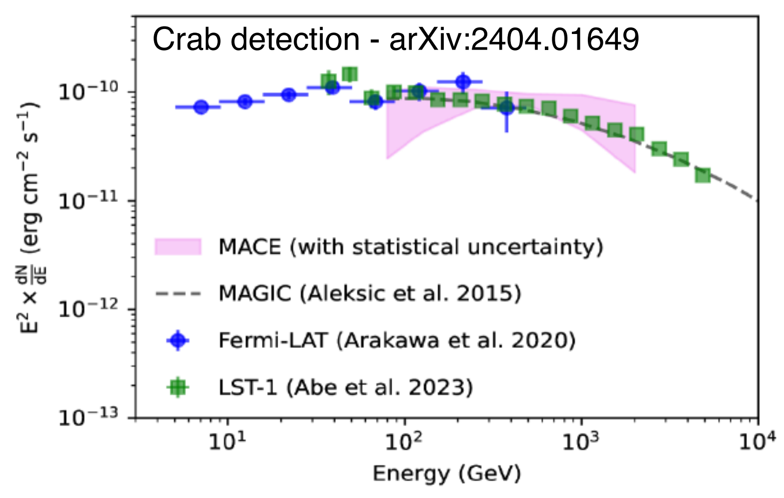
  - → Large optical reflector, 21-m ø + AMC
  - → Small on-axis spot size at focal length
  - → Compact camera, 1088 x 1.5” PMTs
  - → FoV ~ 4°, pixel size = 0.125°
  - → GHz signal processing and trigger strategy
- Simulations ongoing for a stereoscopic MACE-2



MACE detection of very high energy gamma-ray flare from the radio galaxy NGC 1275

ATel #15823; *K. K. Yadav (Bhabha Atomic Research Centre, Mumbai, India)*
on ***23 Dec 2022; 13:02 UT***
Distributed as an Instant Email Notice Transients
Credential Certification: Kuldeep Yadav (kkyadav@barc.gov.in)

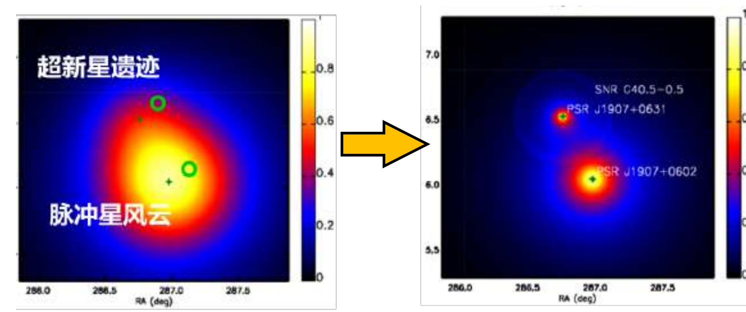
Detection of Very high energy gamma-ray flare from the blazar Mrk 421 with MACE

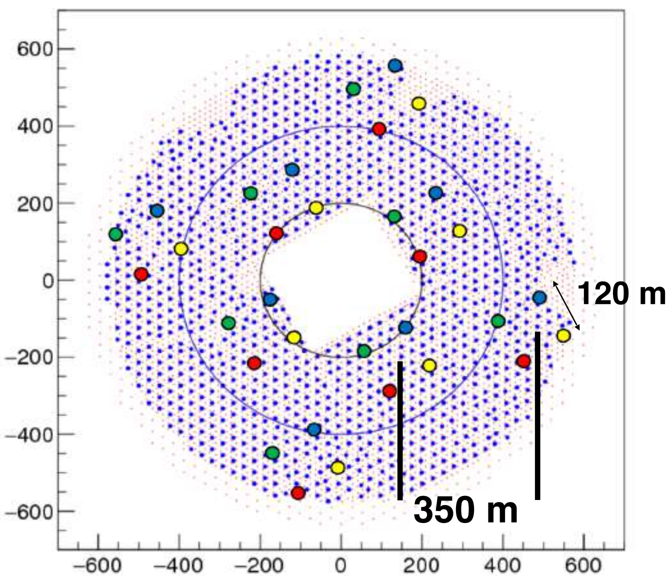
ATel #16537; *K K Yadav on behalf of MACE team (Bhabha Atomic Research Centre, Mumbai, India)*
on ***18 Mar 2024; 13:51 UT***
Credential Certification: Kuldeep Yadav (kkyadav@barc.gov.in)

LACT: LHAASO's IACT Array

Thanks to Hao Zhou

- UHE PeVatrons discovered by LHAASO call for an improved angular resolution down to a few arc-min:
  - → Resolved morphology of extended sources
  - → Better establish counterparts at lower energies

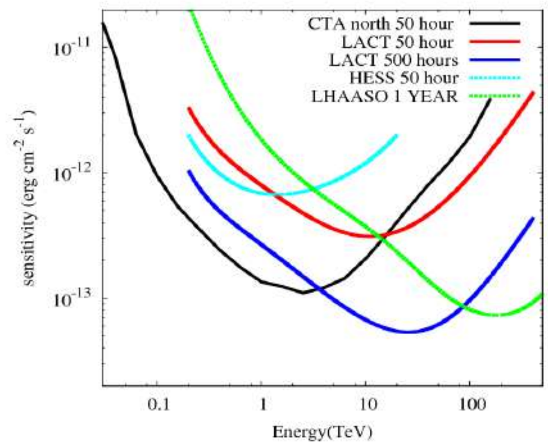




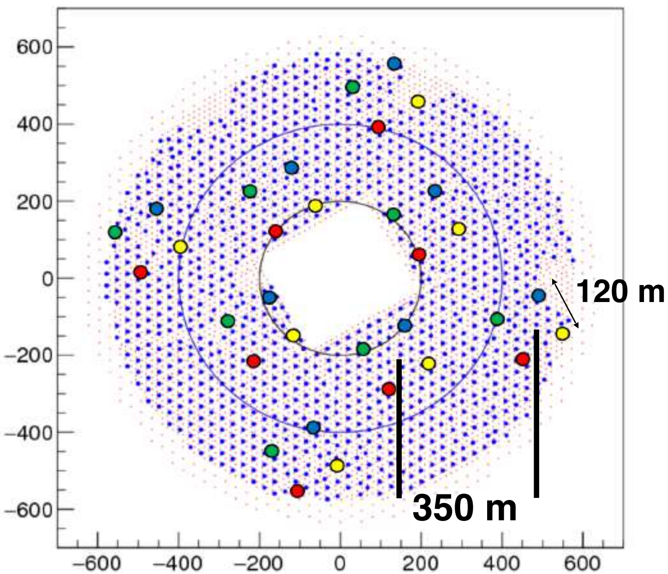
- Proposal for an IACT array at LHAASO site
  - → Operating > 300 GeV, up to UHEs
  - → 32 telescopes in 8 x 4-IACT arrangements
  - → 6-m ø reflector; 9.6° wide-field of view
  - → 500-hr sensitivity @ 100 TeV similar to LHAASO array
  - → First full prototype by end 2024
  - → Complete array expected ~ 2028

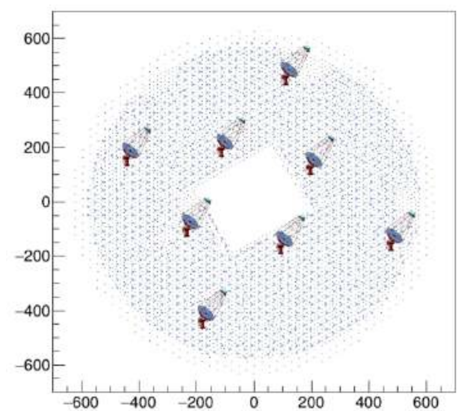
LACT: LHAASO's IACT Array

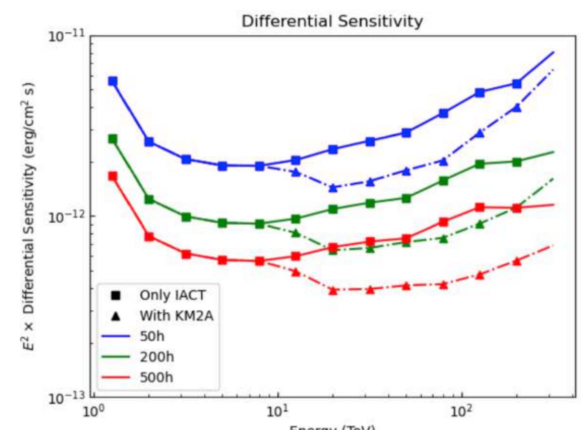
- Expected performance
  - Effective area few-km^2 > 1 TeV
  - Angular resolution better than 3′ > 1 TeV
  - Ground-array hybrid hadron rejection > 10 TeV



On-site prototype at LHAASO

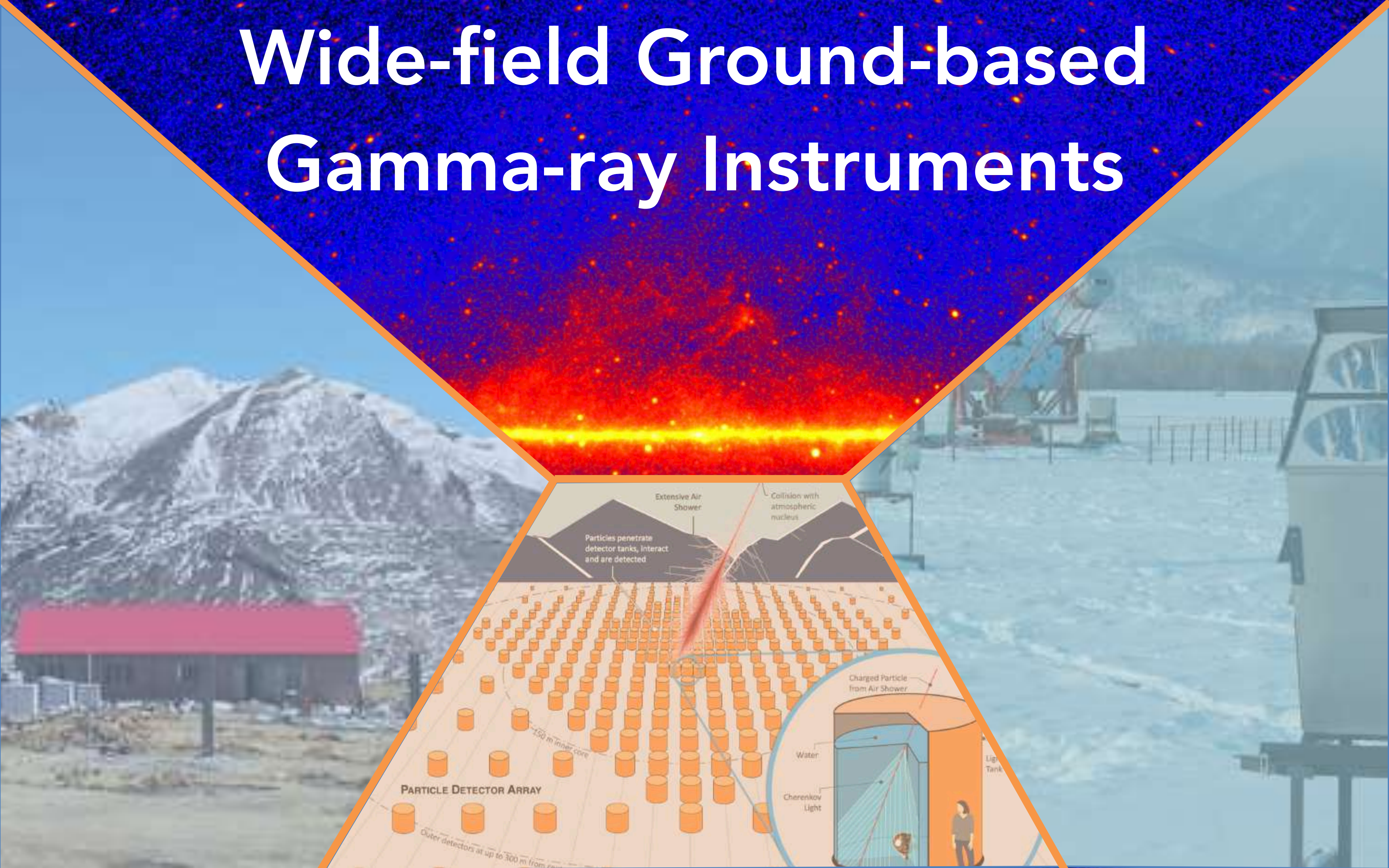




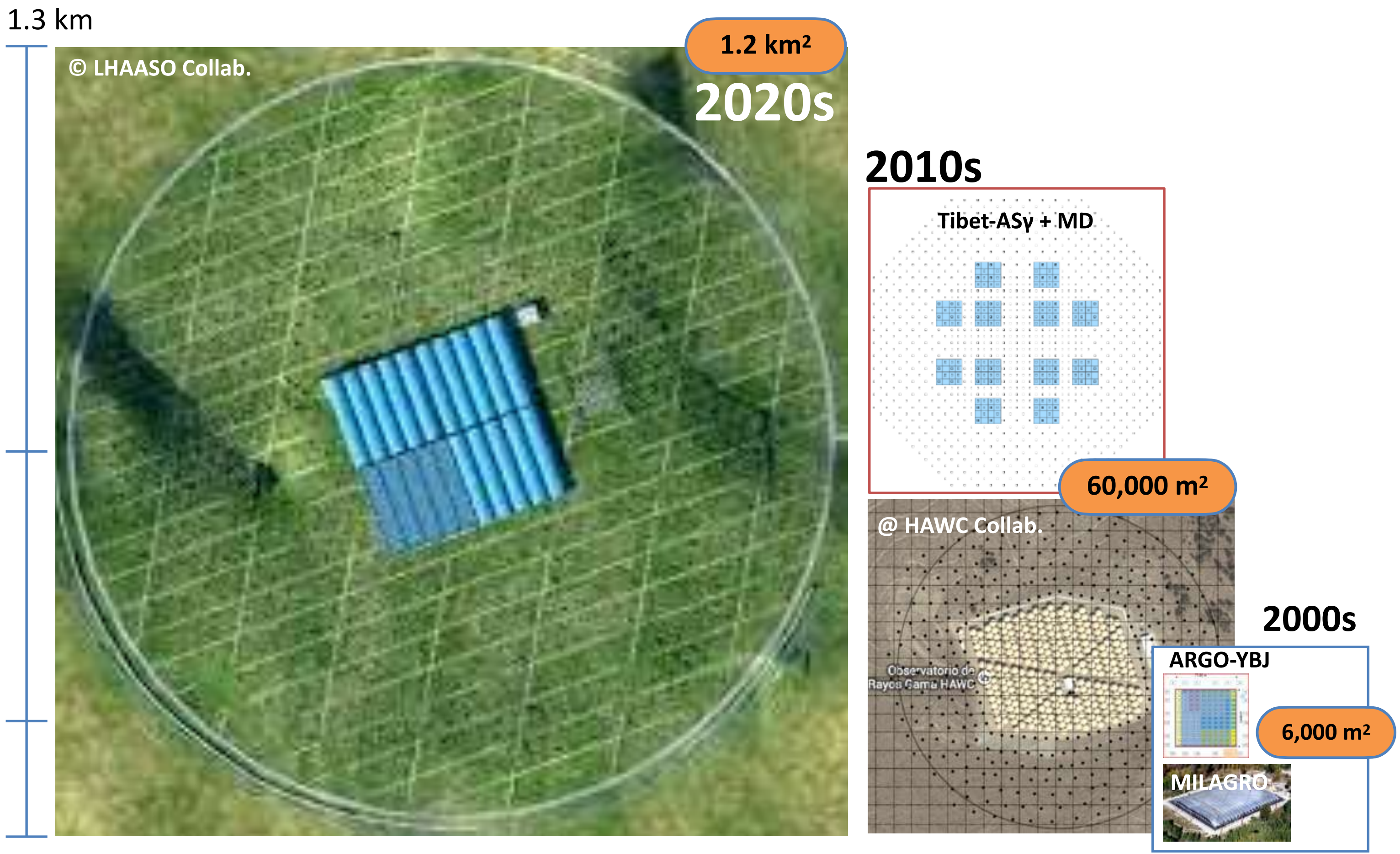


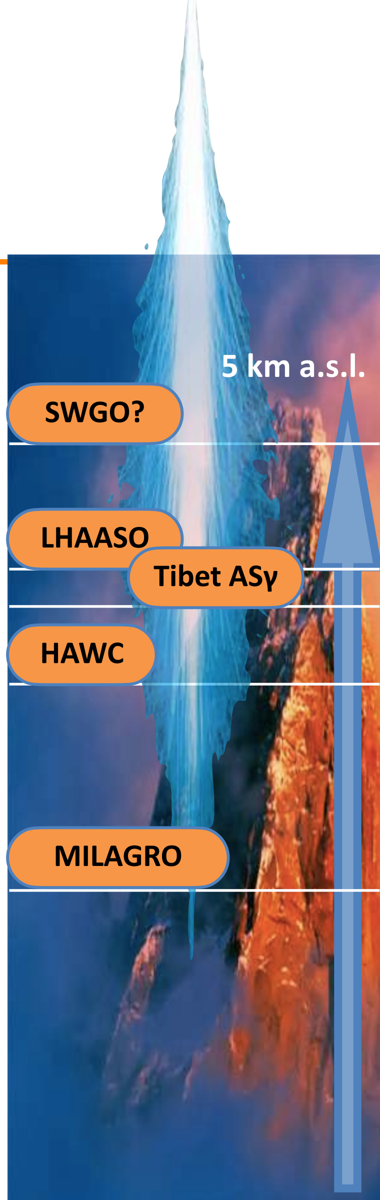
LHAASO + LACT (Zhang et al. 2024, [2402.11286])

Wide-field Ground-based Gamma-ray Instruments



Larger and higher...





TAIGA

Thanks to Martin Tluczykont

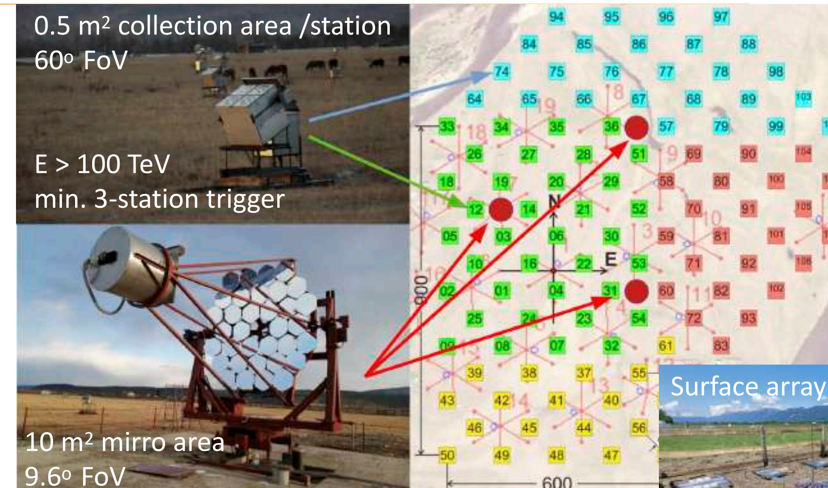
Tunka Advanced Instrument for Gamma Astronomy

- Tunka Valley hosts a long-standing CR facility
  - Tunka-133: 3 km^2 air-Cherenkov array; 175 stations
  - Tunka-Grande: underground muon scintillator array
  - Tunka-Rex: 3 km^2 EAS radio array; 63 antennas
- TAIGA is a novel hybrid facility
- The pilot TAIGA-1 (km^2) stage is in operation
  - HiSCORE: 120 air-Cherenkov timing stations
  - TAIGA-IACT: 3 IACTs
  - TAIGA-Muon: surface and underground scintillator array

TAIGA-1 Hybrid array

TAIGA

- HiSCORE
  - 120 stations, in average 100 m apart
  - Low cost, ~ 1 MEUR/km^2
  - Good core location (~5-10 m) and angular resolution ~ 0.15°
  - Poor γ/hadron separation

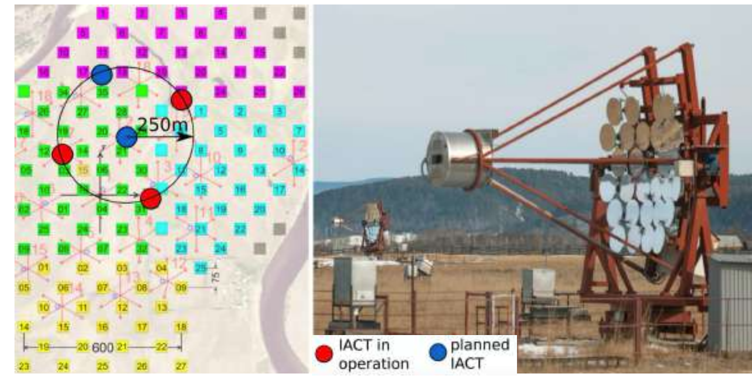


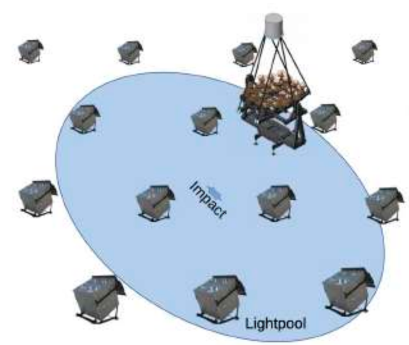
- IACTs
  - 3 x 600-m apart
  - 4.3-m ø, Davies-Cotton IACTs
  - Energy threshold ~ 6 TeV standalone; 10 TeV stereoscopic
  - γ/hadron separation improvement

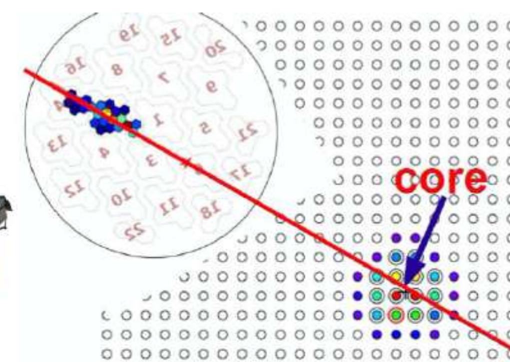
- TAIGA muon
  - Currently based on Tunka-Grande
  - γ/hadron separation > 100 TeV
  - ~ 0.3% fill-factor

TAIGA-1 Hybrid reconstruction

- Typically EAS is seen by 1 IACT + surrounding HiSCORE stations
  - Taking advantage of the full effective area of the single IACT
  - Optimal core-distance reconstruction ~ 250 m
- Core and direction reconstruction is done with HiSCORE.
- Matched to the IACT image size to derive a hybrid scaled width parameter
  - Trigger: 1 IACT + 3 HiSCORE station
  - Combined energy threshold ~ 40 TeV
  - Q-factor (= $\gamma_{eff}/\sqrt{CR_{eff}}$) ~ 4-5







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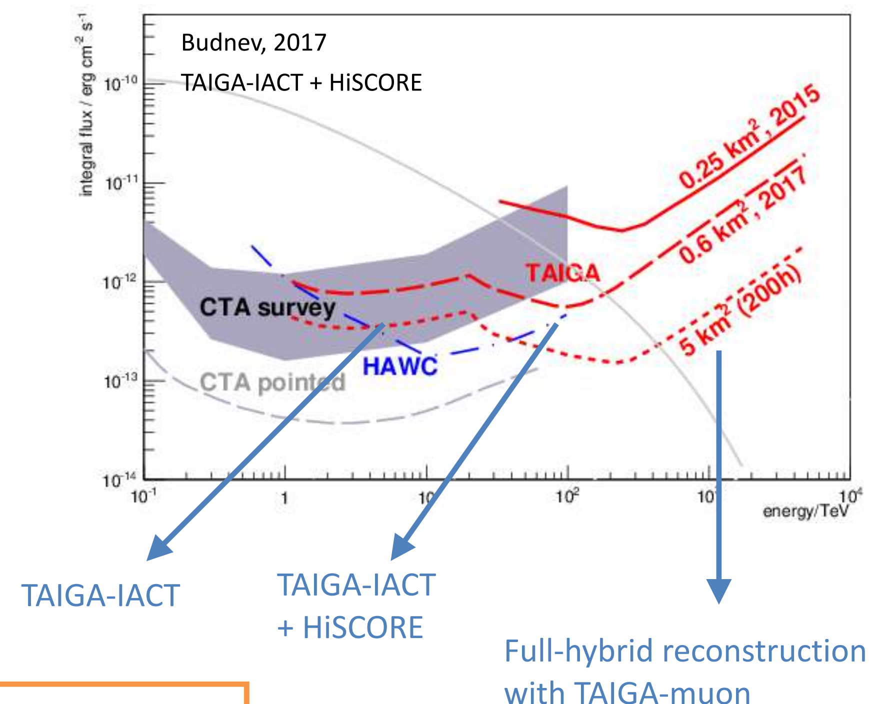


Crab Detection:
arXiv: 2301.11002

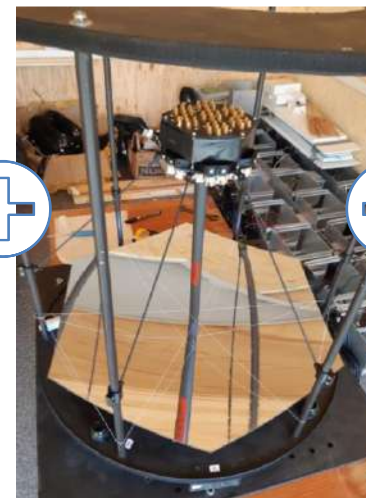
TAIGA

TAIGA 10 km² Array

- Future of expansion of TAIGA, beyond the Tunka site
- Operations from ~ 10 TeV to the PeV range

- 1000 HiSCORE stations
- 100-m spacing
- EAS reconstructions

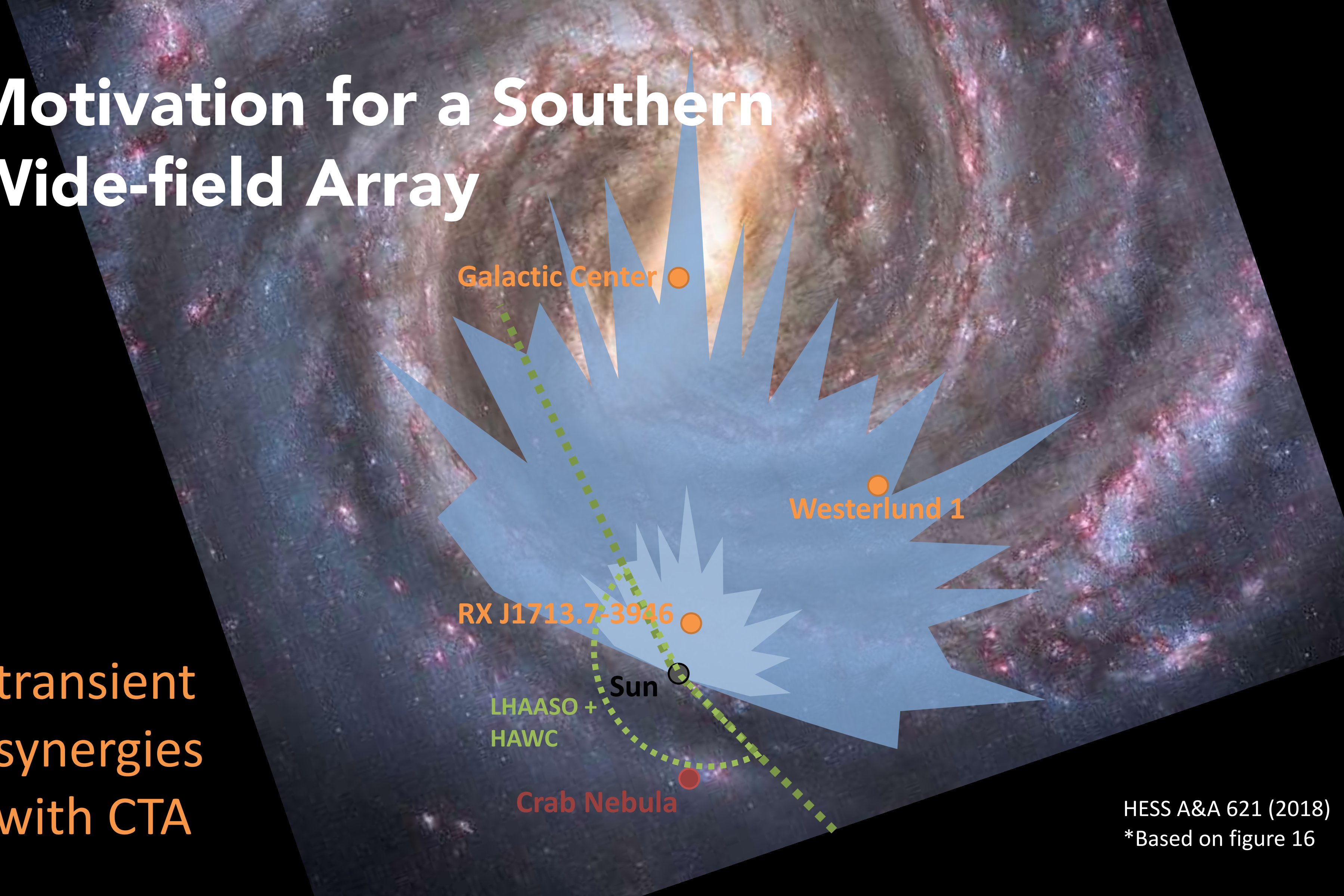
- Up to 10 IACTs
- 4.3-m ø class



- Up to 100 small-imaging telescope
- Wide, 30° FoV
- SiPM-based camera

- Muon-scintillator array
- Surface + underground stations
- Up to 3,000 m^2

Motivation for a Southern Wide-field Array



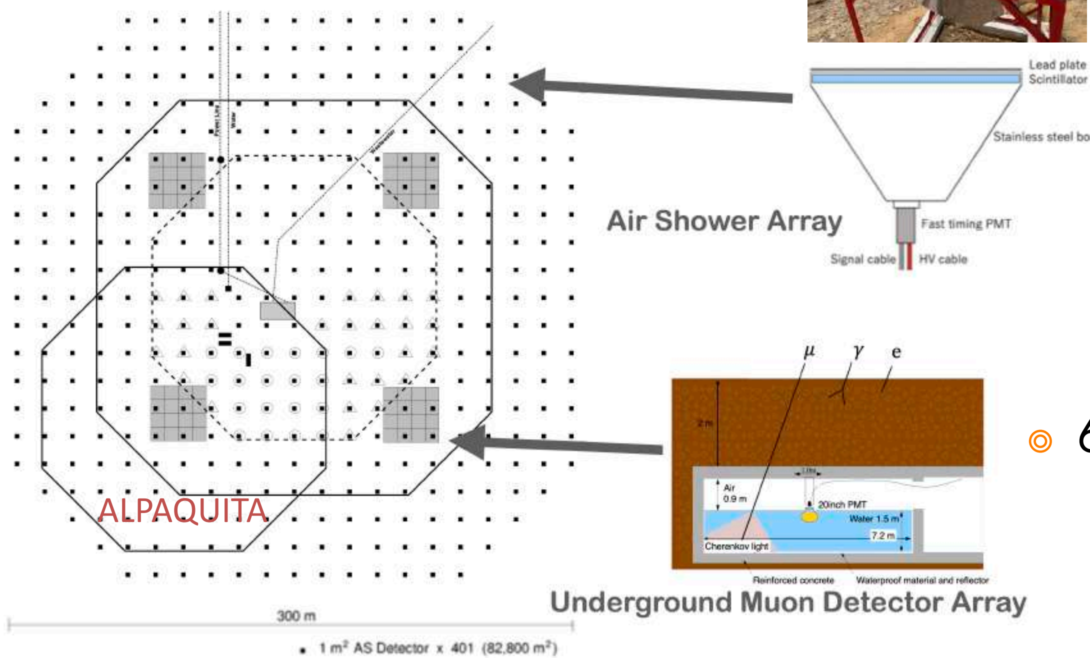
+ transient synergies with CTA

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

ALPACA (2025+)

Thanks to Keto Sei

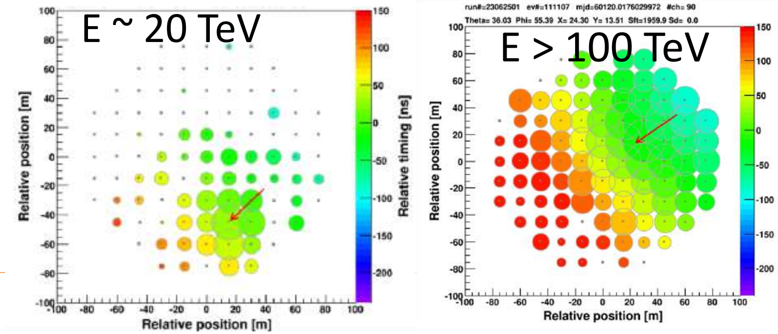
- 400 x 1 m² plastic scintillator SD
  - → 15-m spacing; 82,800 m²



- 64 x 56 m² WCD muon array
  - → 4 x 16 cell clusters; 3,600 m²

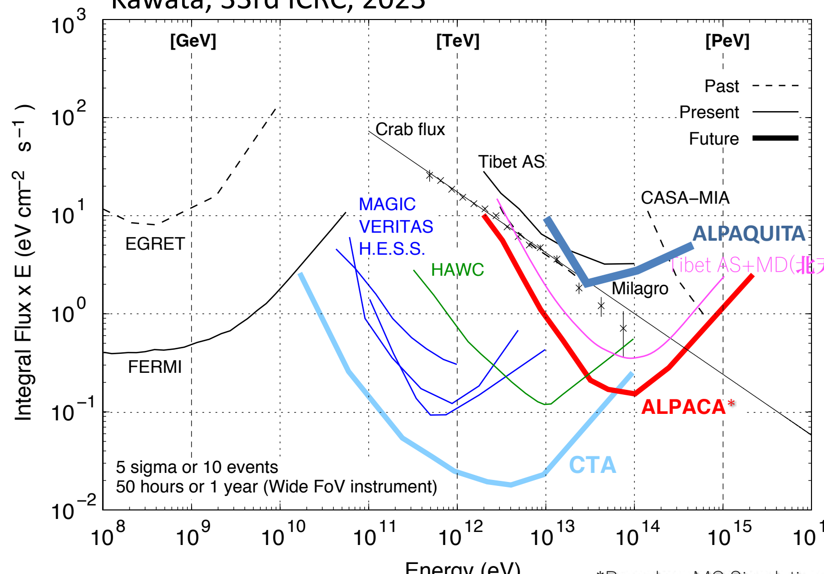
ALPAQUITA

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



Subieta-Vasquez, 33rd ICRC, 2023

Kawata, 33rd ICRC, 2023



*Based on MC Simulation

- Angular resolution ~0.2° @100TeV
- Energy resolution ~20% @100TeV

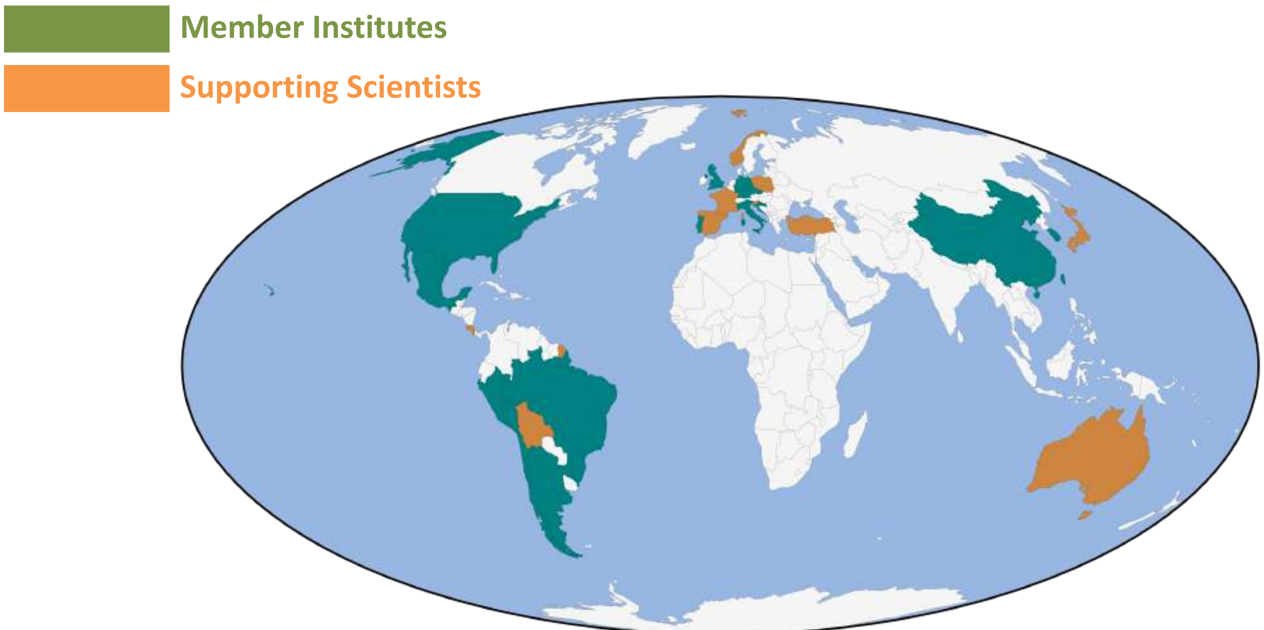
SWGO

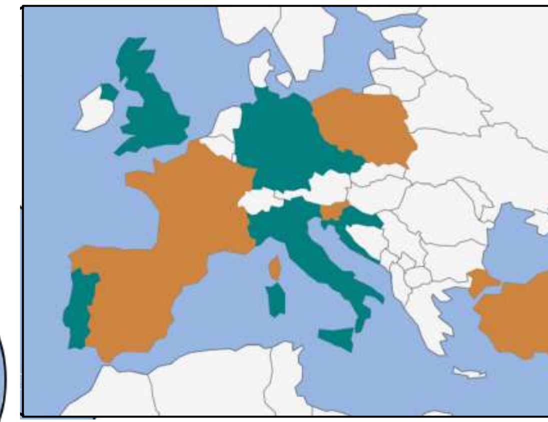
Southern Wide-Field Gamma-ray Observatory

CONTACT:
swgo_spokespersons@swgo.org

www.swgo.org

SWGO Collaboration





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

- SWGO partners
  - → 14 countries, over 80 institutes*
  - → + supporting scientists

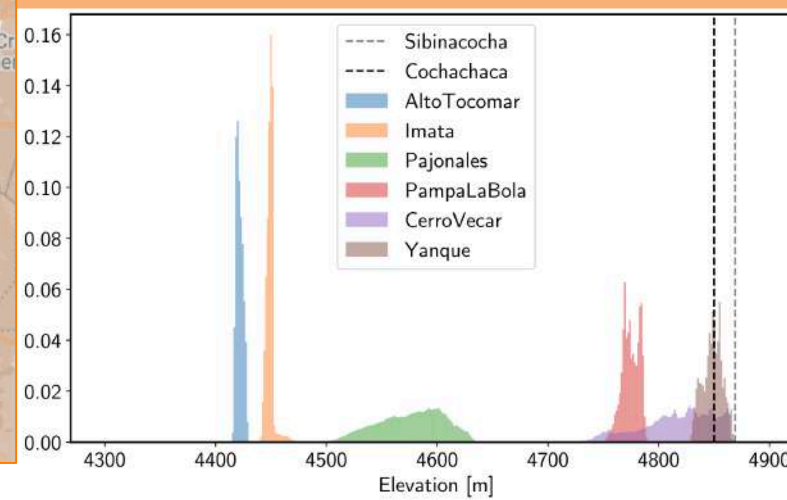
Primary Site Candidates

The Southern Wide-field Gamma-ray Observatory

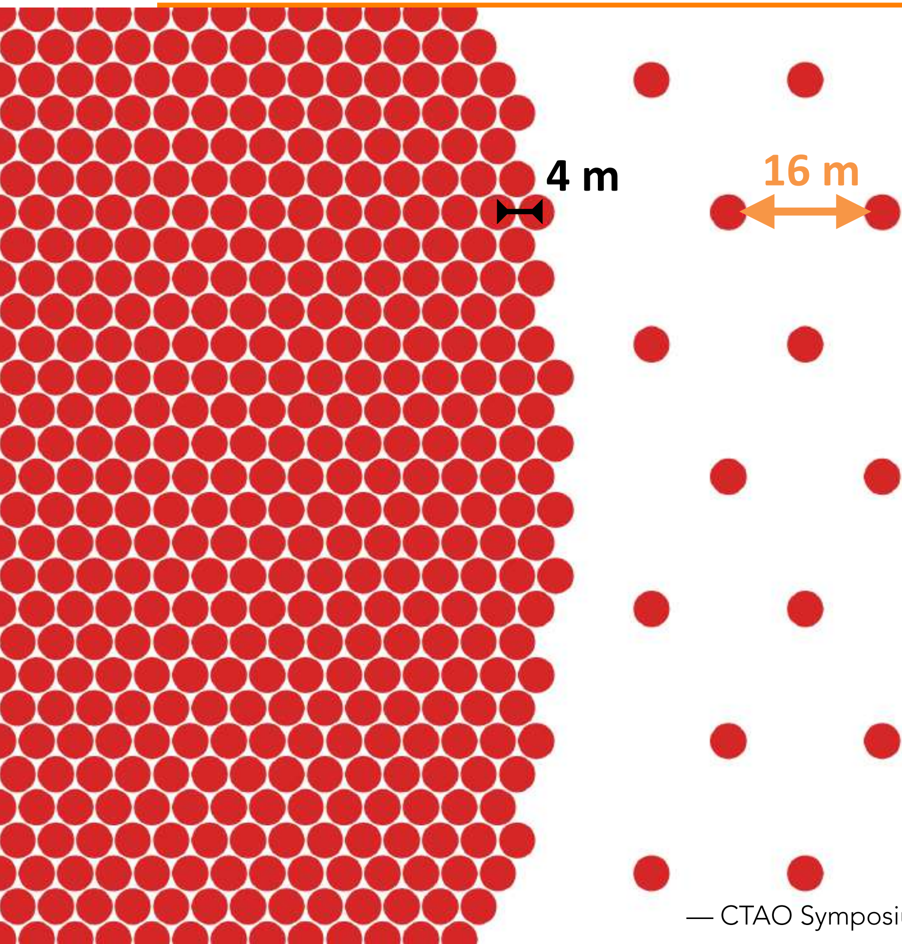
2020-21: Site Candidacies

2022-23: Site Characterization

2024 (July): Site Selection!



The reference detector concept

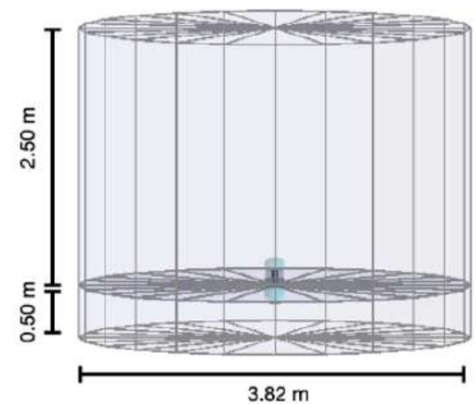


Core: Ø 320 m, FF = 80%
5,700 WCD units

Outer: Ø 600 m, FF = 5%
880 WCD units

Altitude: 4,700 m a.s.l.

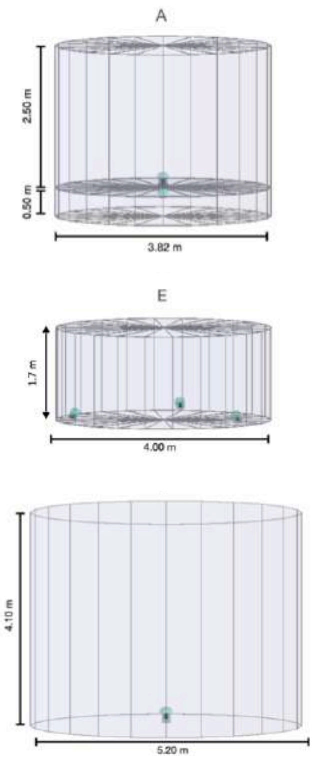
✧ muon counting

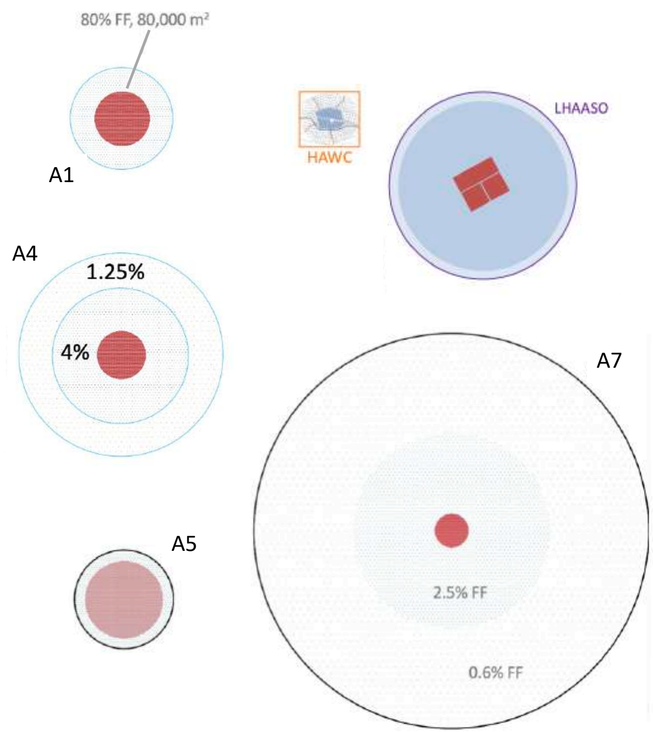


A next generation observatory

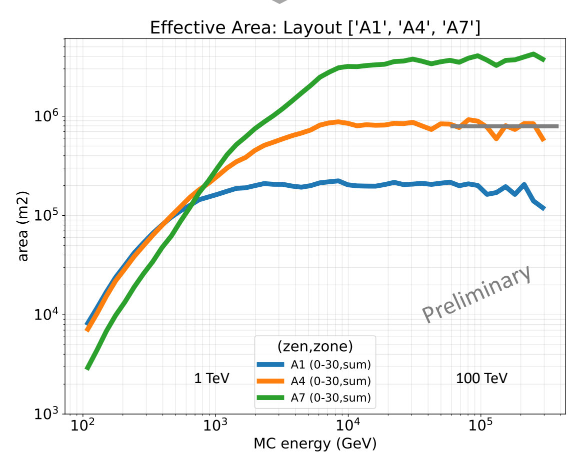
Comprehensive **simulations of 13 configurations** completed; several **reconstruction** and **γ/hadron** separation passes.

All layouts present in the SWGO simulation framework





- **CORSIKA** — Simulation of extensive air showers
- **AERIE** — Detector simulation
- **SWGO-RECO** — Shower reconstruction
- **PYSWGO** — High-level reconstructions (IRFs)



LHAASO approx

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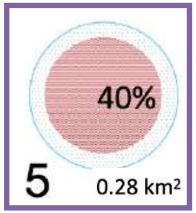
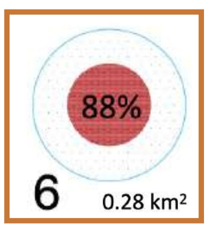
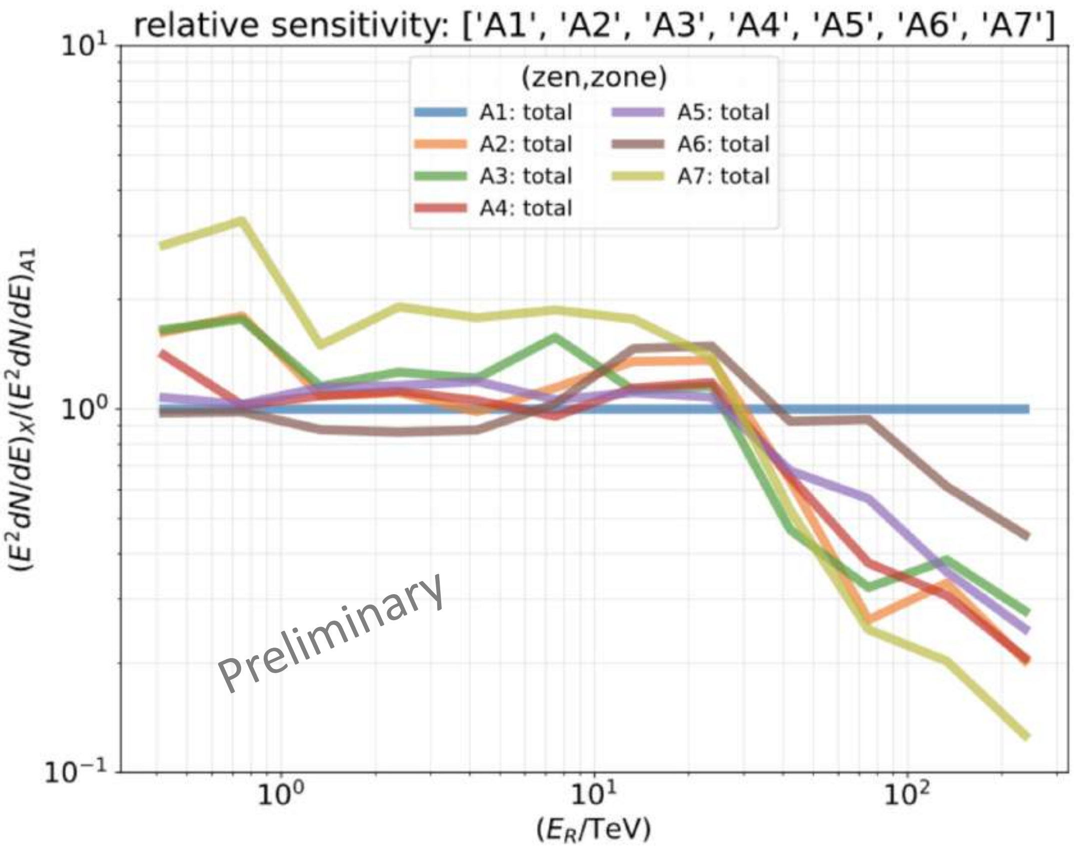


Exploring trade-off between dense core footprint and fill-factor.





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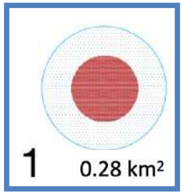
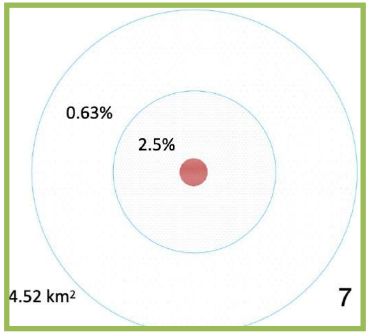
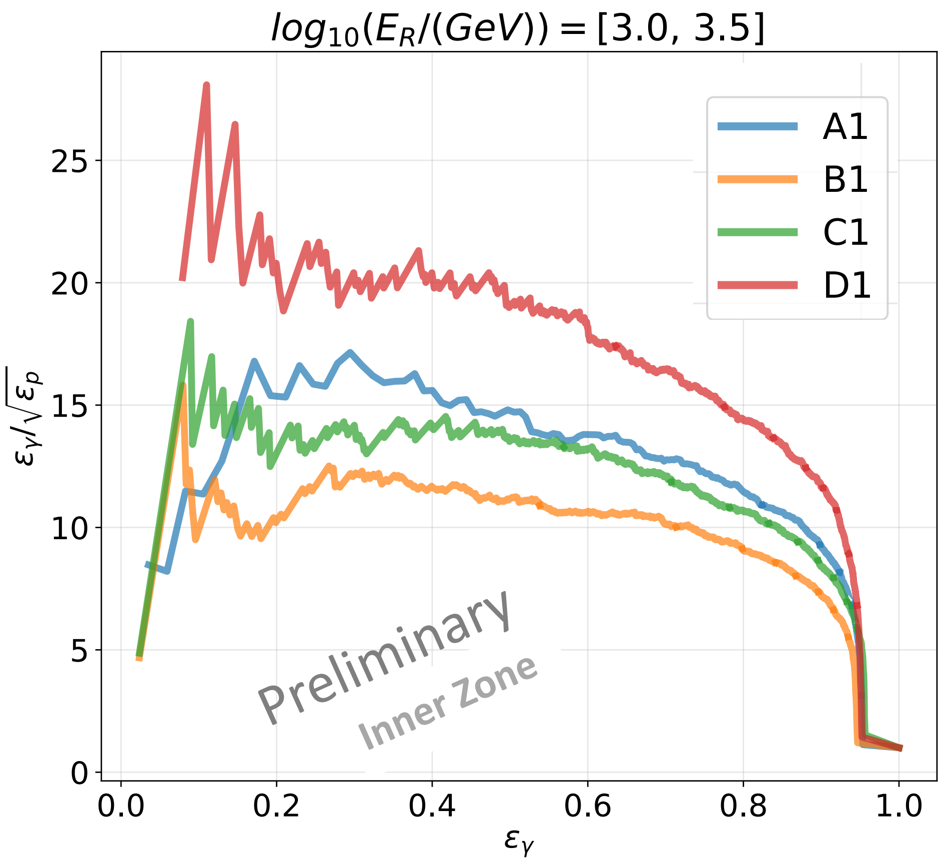


Exploring very large areas and low fill-factors

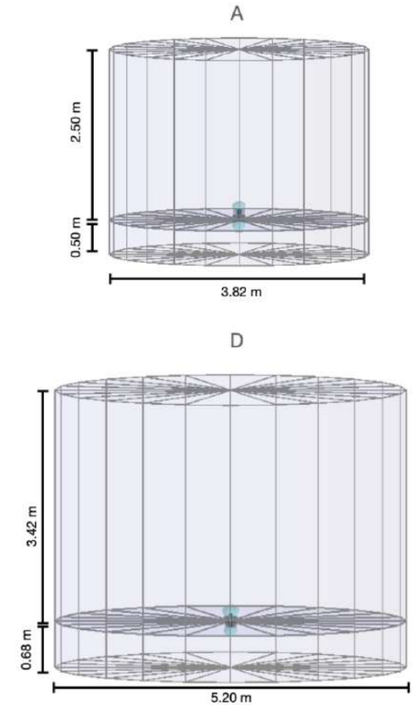


A next generation observatory



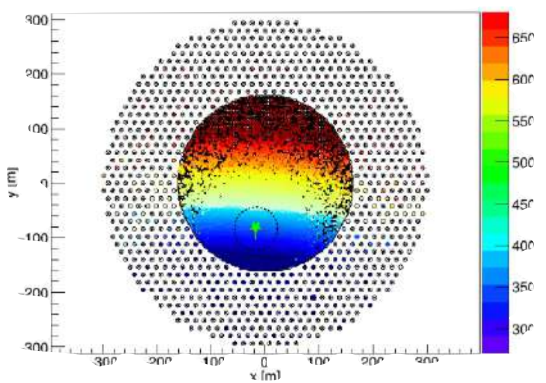
Double-layer WCD unit concept

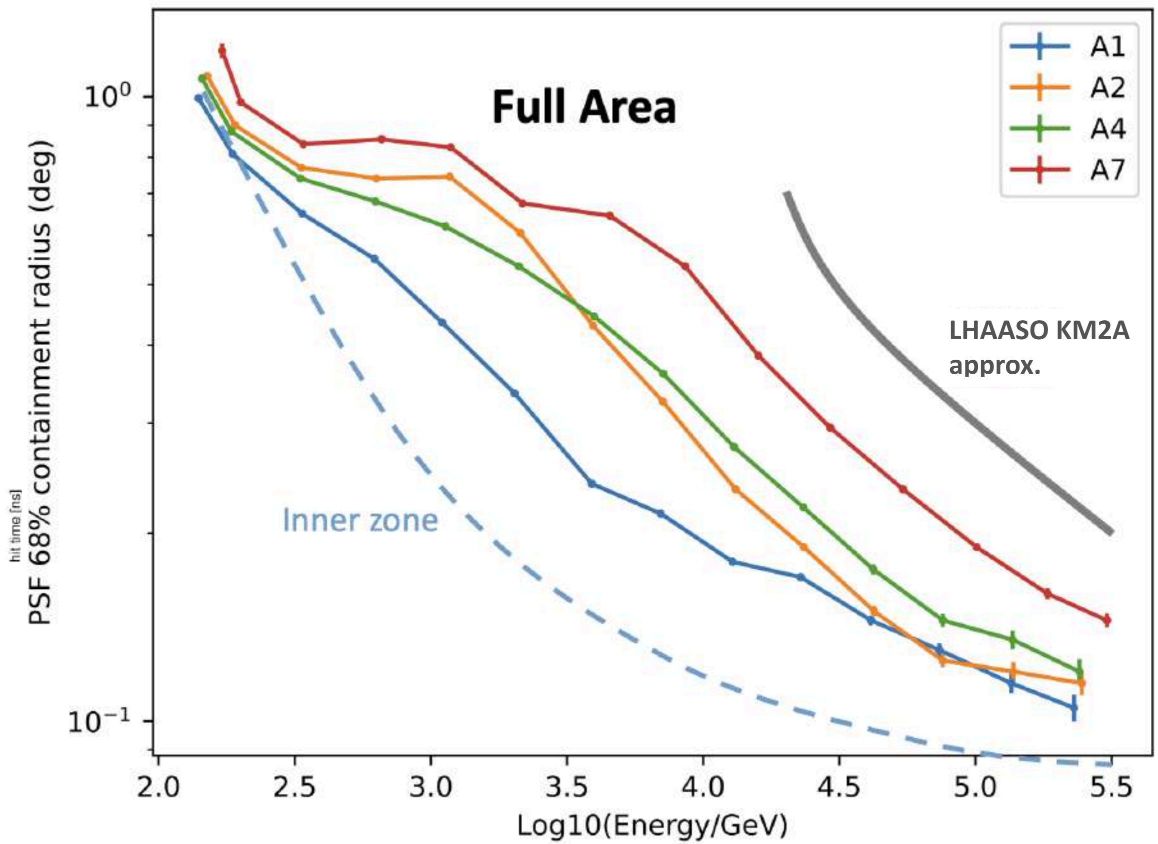
Large background rejection power > 1 TeV 400, with 50% gamma efficiency



A next generation observatory
Angular Resolution

Angular reconstruction methods still being refined

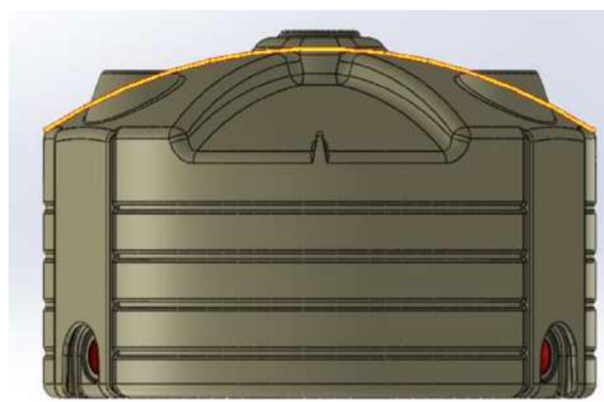




Exploring different WCD concepts

Development of new concepts and approaches

WCD Unit

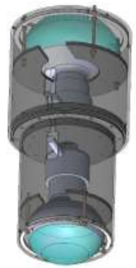


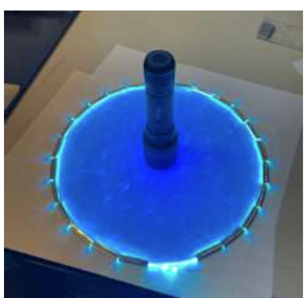
R&D Towards a Lake Array

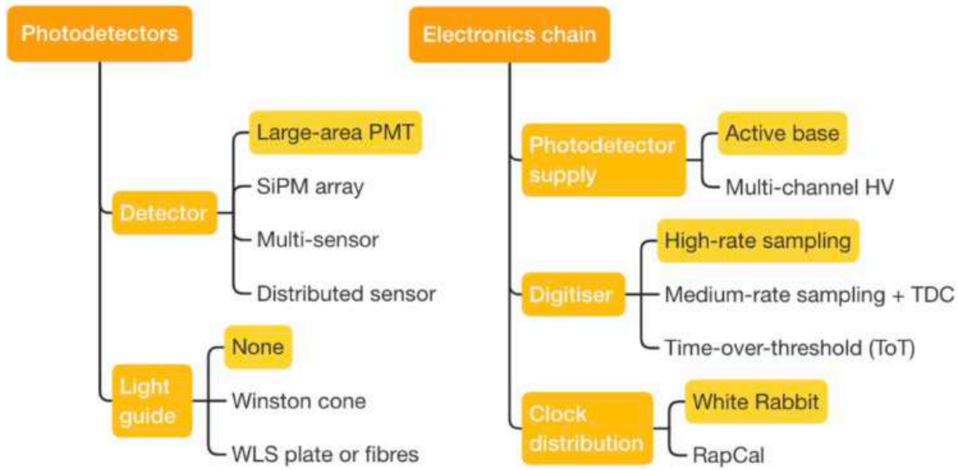
SWGO
The Southern Wide-field Gamma-ray Observatory

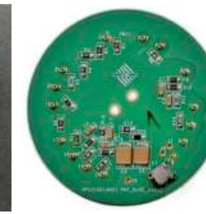
Detector options and prototyping

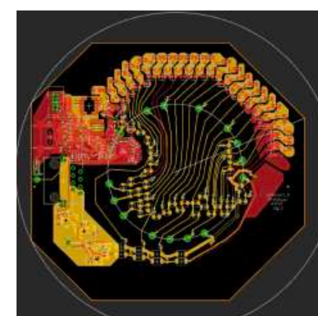
Development of new concepts and approaches







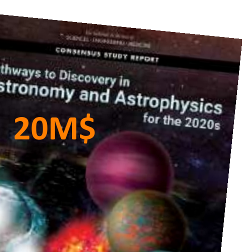




Status & Plan

		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

- R&D Phase
  - → Kick off meeting Oct 2019
  - → Expected completion early 2025
    - ✓ Site and Design Choices made
  - → Then:
- Preparatory Phase
  - → Detailed construction planning
  - → **Engineering Array**
- (Full) Construction Phase
  - → From 2027



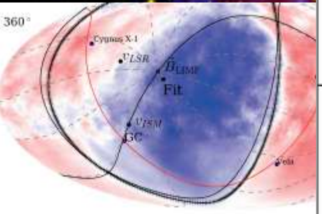
- Roadmaps
  - → US Decadal Review
  - → SNOWMASS, APPEC, Astronet

SWGO
The Southern Wide-field Gamma-ray Observatory

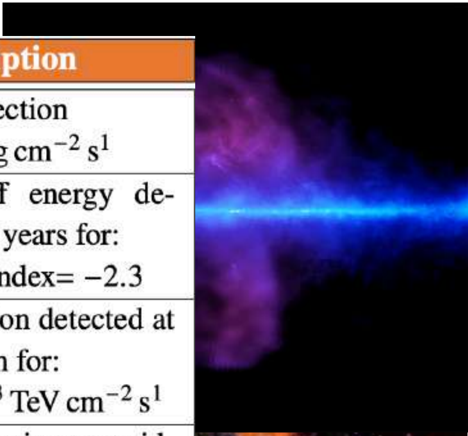
Science

6 core benchmark science cases

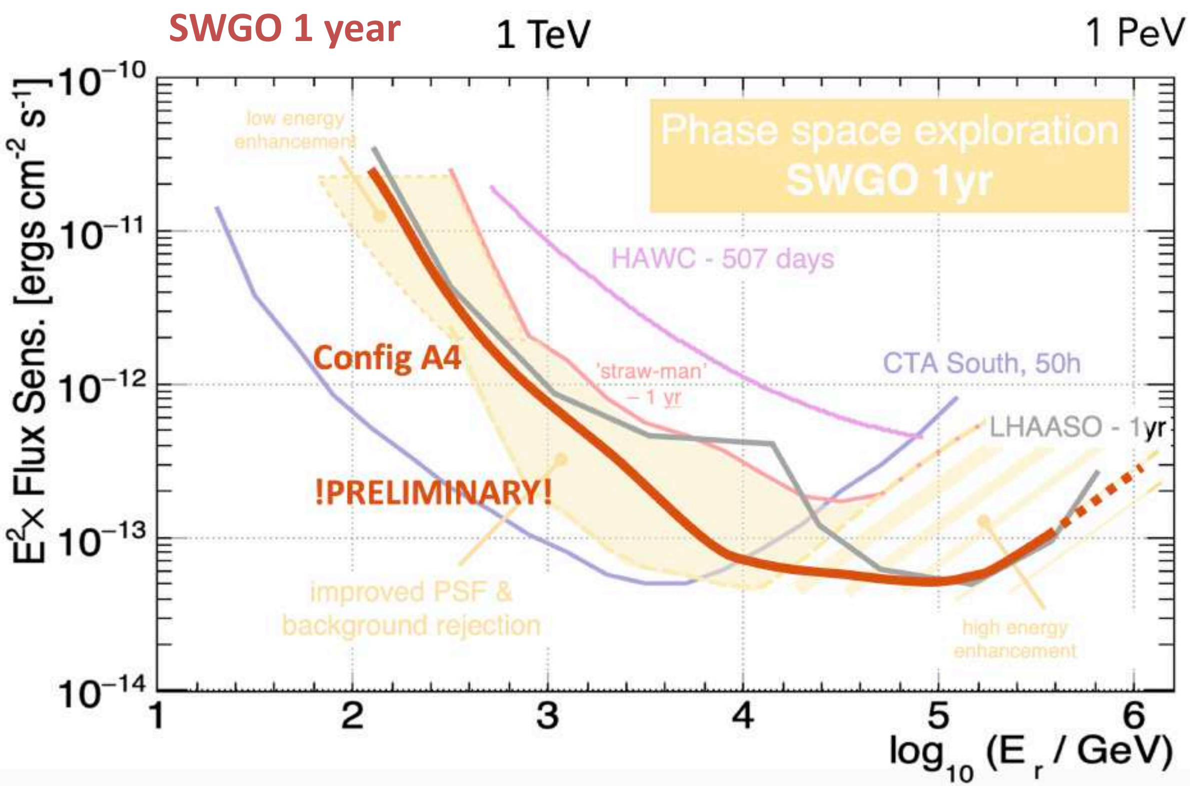
Science case studies using gammapy ongoing.

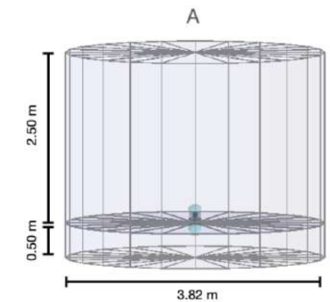


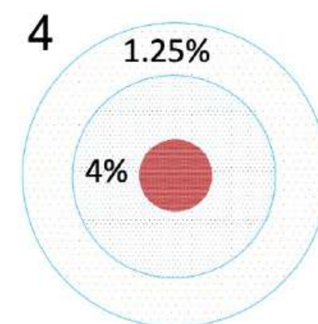
Core Science Case	Design Drivers	Benchmark Description
Transient Sources: Gamma-ray Bursts	Low-energy Site altitude	Min. time for 5σ detection $F(100\,\text{GeV}) = 10^{-8}$ erg cm^{-2} s^{1}
Galactic Accelerators: PeVatron Sources	High-energy sensitivity Energy resolution	Maximum exp-cutoff energy detectable 95% CL in 5 years for: $F(1\,\text{TeV}) = 5$ mCrab, index$= -2.3$
Galactic Accelerators: PWNe and TeV Halos	Extended source sensitivity Angular resolution	Max. angular extension detected at $5\,\sigma$ in 5-yr integration for: $F(>1\,\text{TeV}) = 5 \times 10^{-13}$ TeV cm^{-2} s^{1}
Diffuse Emission: Fermi Bubbles	Background rejection	Minimum diffuse cosmic-ray residual background level. Threshold: $< 10^{-4}$ level at 1 TeV.
Fundamental Physics: Dark Matter from GC Halo	Mid-range energy sensitivity Site latitude	Max. energy for $b\bar{b}$ thermal relic cross-section at 95% CL in 5-yr, for Einasto profile.
Cosmic-rays: Mass-resolved dipole Multipole anisotropy	Muon counting capability	Max. dipole energy at 10^{-3} level. Log-mass resolution at 1 PeV – goal is $A = 1, 4, 14, 56$; Maximum multipole scale > 0.1 PeV.



SWGO target sensitivity







Point-source differential sensitivity
5 bins/decade, 5 sig.

Transients with SWGO

The Southern Wide-field Gamma-ray Observatory

- Short-timescale sensitivity of ground-particle detectors is much worse than IACTs at low E! But room for improvement < 1 TeV

- And a number of other advantages…
  - **100% duty cycle** → higher rate and monitoring capability of transients → bridging the gap with satellite facilities
  - **Serendipitous view** - observation of onset / prompt emission of GRBs
  - **A trigger instrument**!
    - Blind searches and offline checks for afterglow triggers
      - Critical synergy with IACTs and other MWL + MM instruments

✧ **SWGO can bring the 10s deg^2 error boxes (GBM, GW) down to ~ deg^2**

Thanks

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"The history of science can be summarized as the developing of ever more perfect eyes, in a world where there is always more to see"

— Theillard de Chardin