



Multi-Messenger Programme

Ground-based gamma-rays:
Notes on the role of CTA and SWGO

Ulisses Barres de Almeida



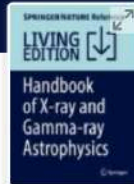
Two new review collections



High-Energy Gamma-Ray Astronomy

Results on Fundamental Questions after 30 Years of Ground-Based Observations

Edited by
Ulisses Barres de Almeida and Michele Doro
Printed Edition of the Special Issue Published in *Universe*



Living reference work | © 2022

Handbook of X-ray and Gamma-ray Astrophysics

[Home](#) > [Living reference work](#)

Editors: [Cosimo Bambi](#), [Andrea Santangelo](#)

Provides comprehensive coverage of X-ray and Gamma-ray astrophysics by outstanding scientists in the field

Serves as both a book for graduate students and a valuable reference resource for researchers

Includes the latest data analysis techniques

5323 Accesses | **24** Citations | **9** Altmetric

Initial Remarks

— Principia MM Programme | May-June 2023 —



MM Scenario of Astroparticle Physics

sub-mm IR-UV X-rays **Gamma-rays** \longrightarrow

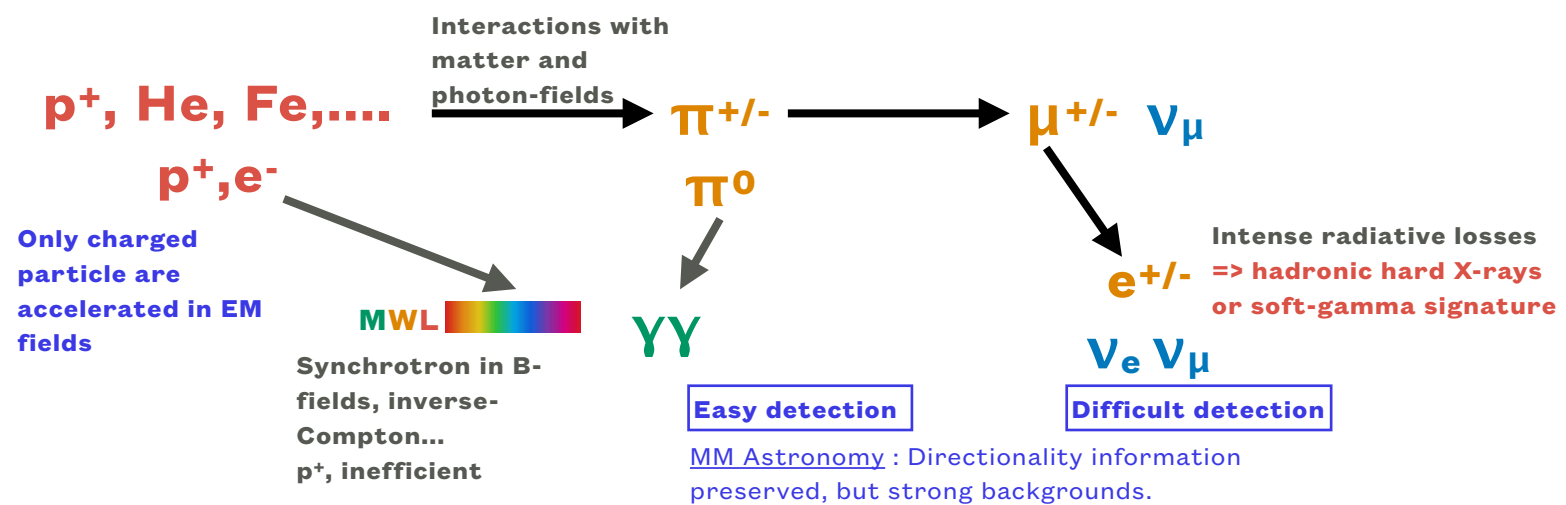
meV ... eV ... keV ... MeV ... GeV ... TeV ... PeV ... EeV ... ZeV

Realm of Astroparticle Physics

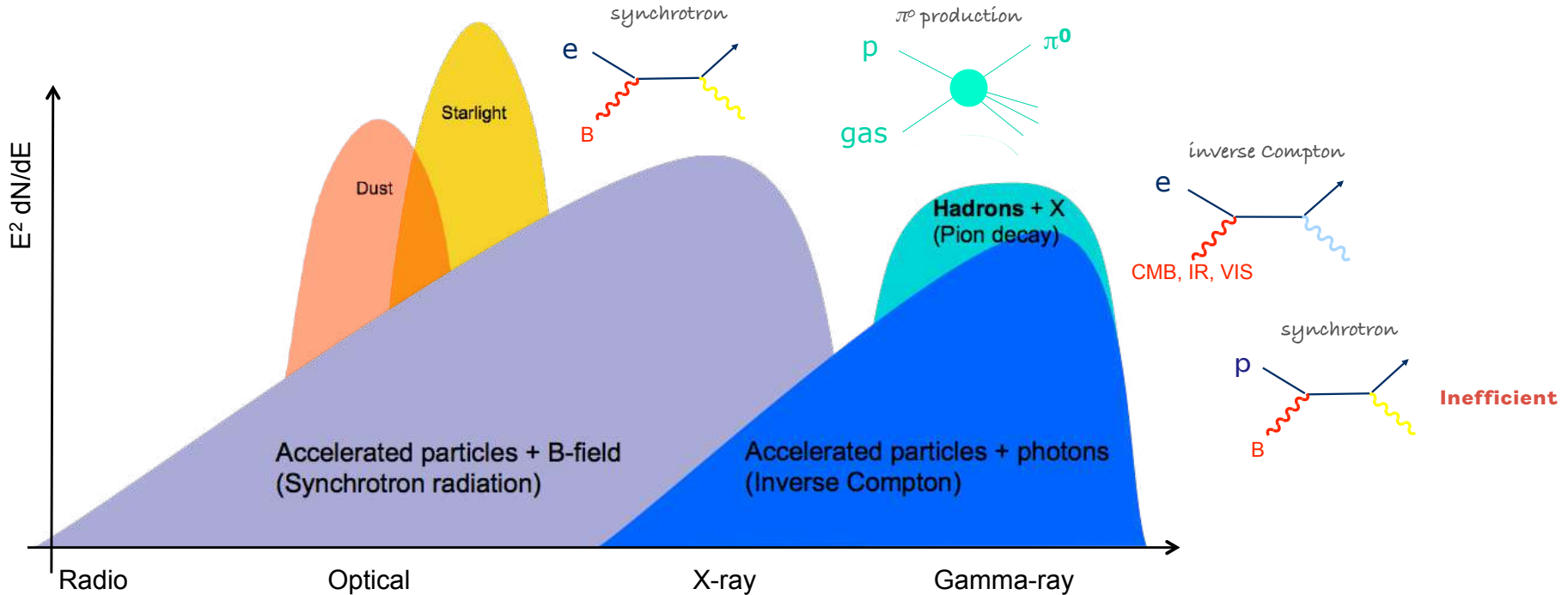
Astronomy with photons

Charged cosmic-ray physics: p, e-, He, Fe, ...

Neutrino signals



Anatomy of a relativistic astrophysical source



© plot by Christian Stegmann, DESY, MG XIV Meeting 2015 (modified)

Ground-based Gamma-ray Astronomy Network

VERITAS

HAWC

MAGIC

LHAASO

cta

SWGGO

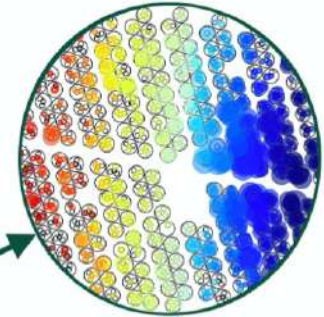
HESS

Status **summary** of the field

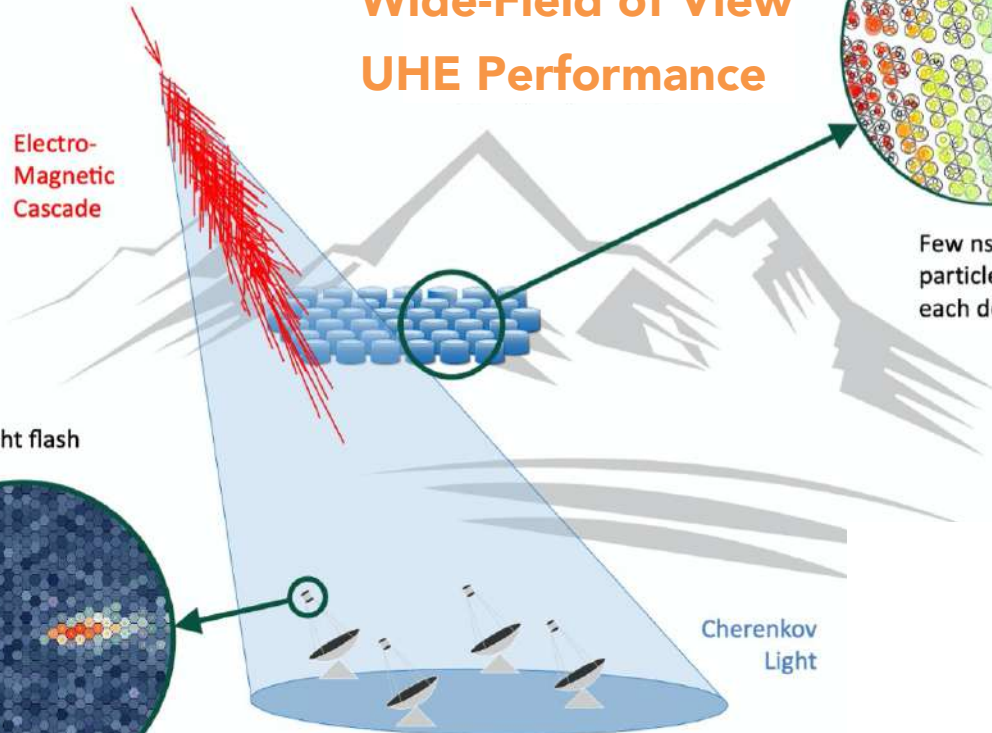
Two techniques

- 1. Air-Cherenkov telescopes
- 2. Altitude particle arrays

High Duty Cycle
Wide-Field of View
UHE Performance



Few ns spread in particle arrival at each detector



Low Duty Cycle
Pointing instruments
Precision Astronomy at VHE



Cost ~ 330 MEuro for construction (cash + in-kind)
All construction funds available!

CTA Observatory (CTAO)

- CTA-North La Palma (1st telescope operating!)
- CTA-South in Chile
- CTA HQ, Bologna
- CTA Data Centre, Berlin

CTA Arrays "alpha" Configuration

- Northern Array: 4 LSTs + 9 MSTs
- Southern Array: 14 MSTs + 37 SSTs

<https://www.cta-observatory.org/>

Expansion
**Medium Sized
SC Telescope
USA (10m)**

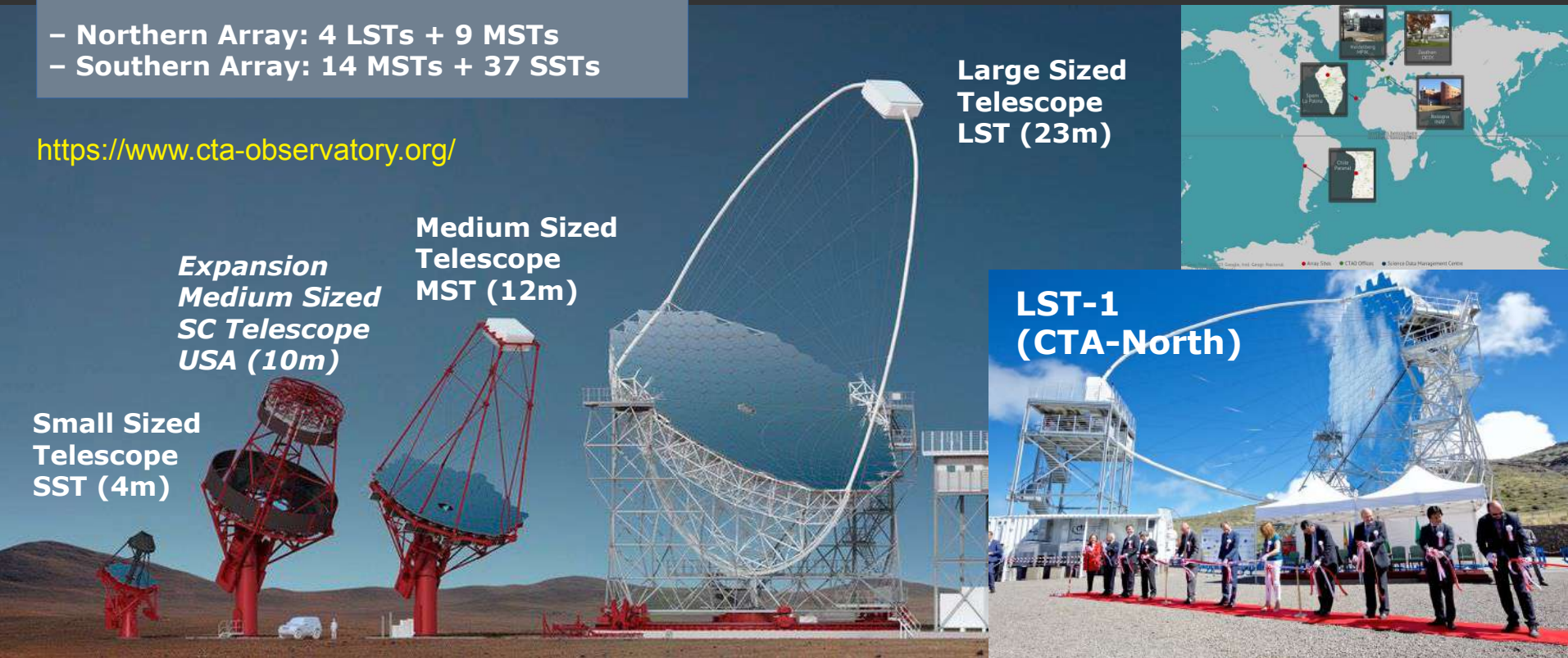
**Small Sized
Telescope
SST (4m)**

**Medium Sized
Telescope
MST (12m)**

**Large Sized
Telescope
LST (23m)**

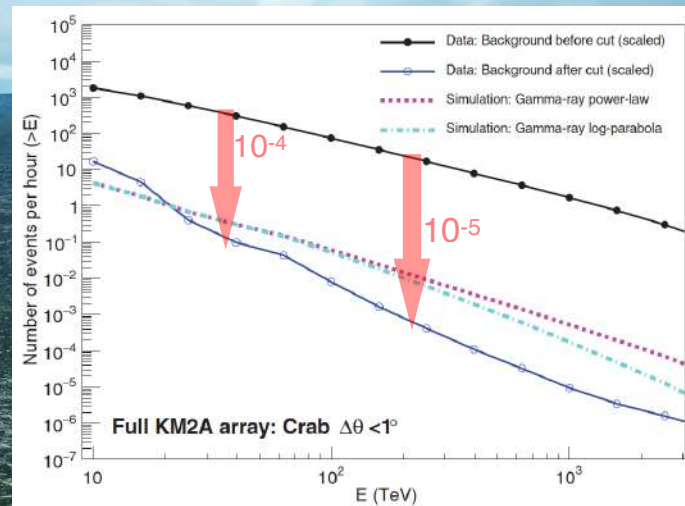


**LST-1
(CTA-North)**



Bird's eye view of LHAASO, 2021-08

- **Location:** 29°21' 27.6" N, 100°08' 19.6" E
- **Altitude:** 4410 m
- **2021-07 completed built and in operation**



Area:
1.3 km²

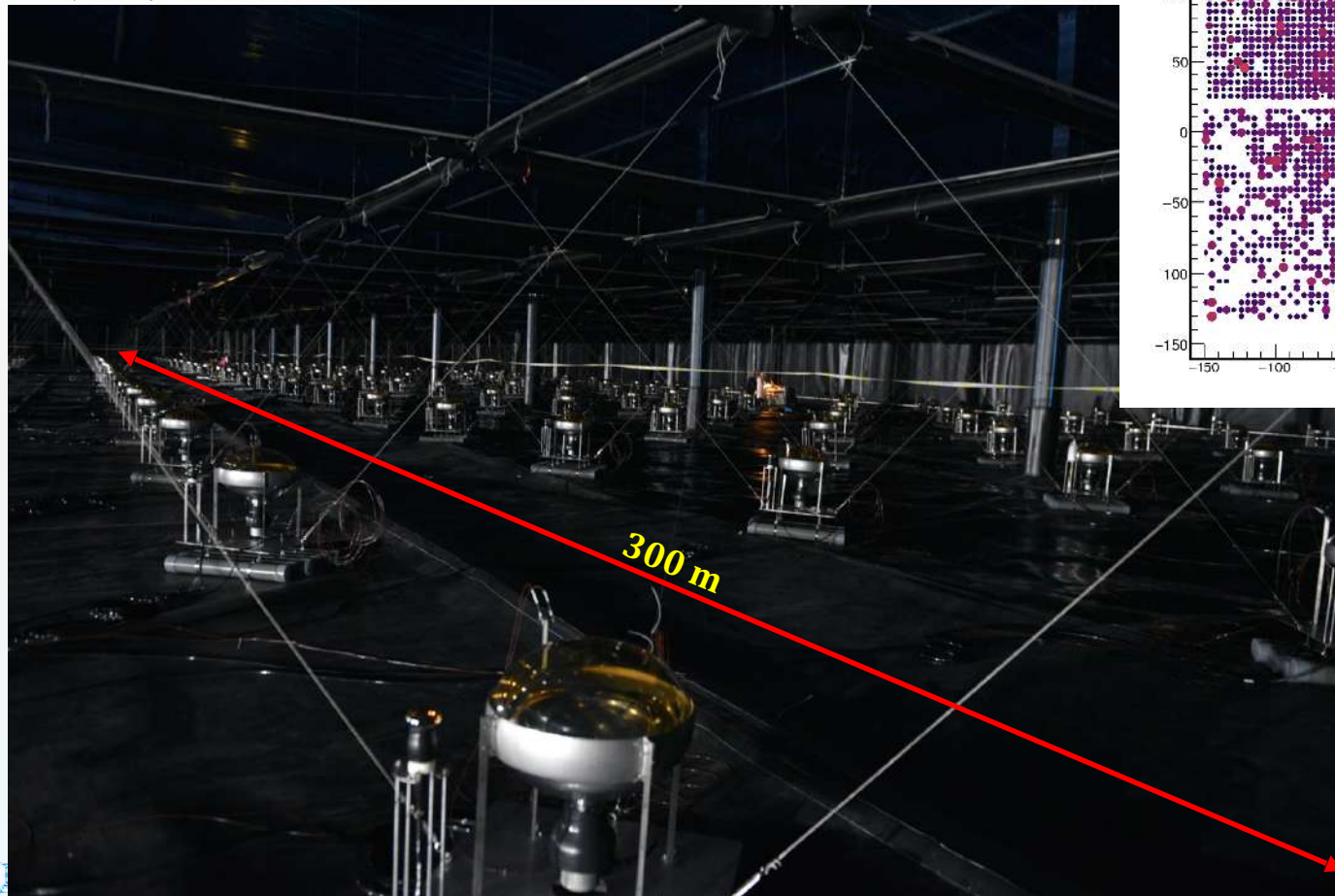
Detectors:
5195 ED
1188 MD

Energy Range:
0.01-10 PeV

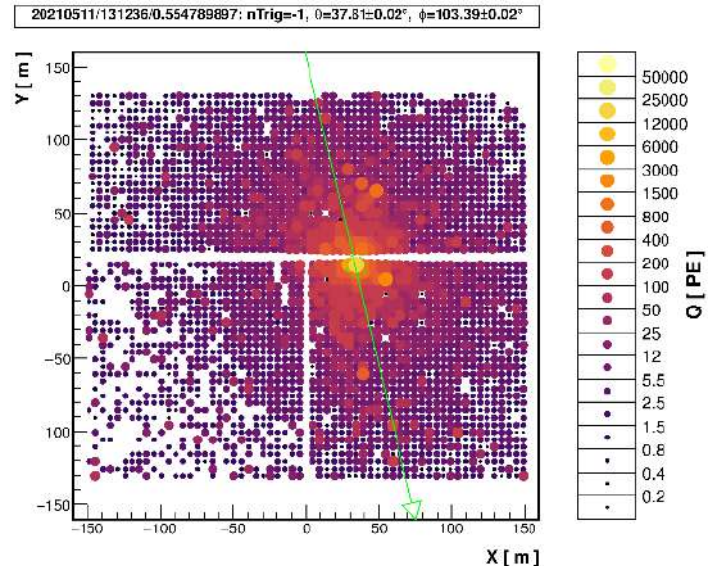




Water Cherenkov Detector Array (WCDA)



300 m



- ◆ Area:
78,000 m²
- ◆ Detector units:
3120
- ◆ Energy Range:
0.1-10 TeV

Larger and higher...

© LHAASO Collab.

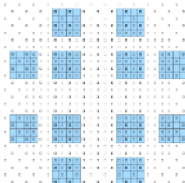
0.01 Crab

2020s



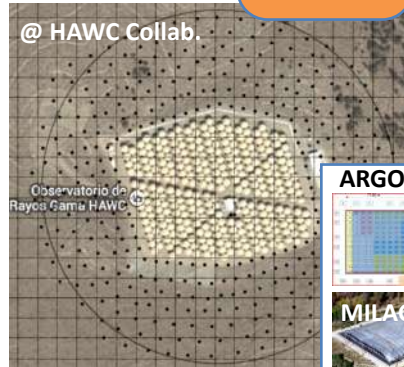
2010s

Tibet-ASy + MD



0.05 Crab

@ HAWC Collab.



2000s

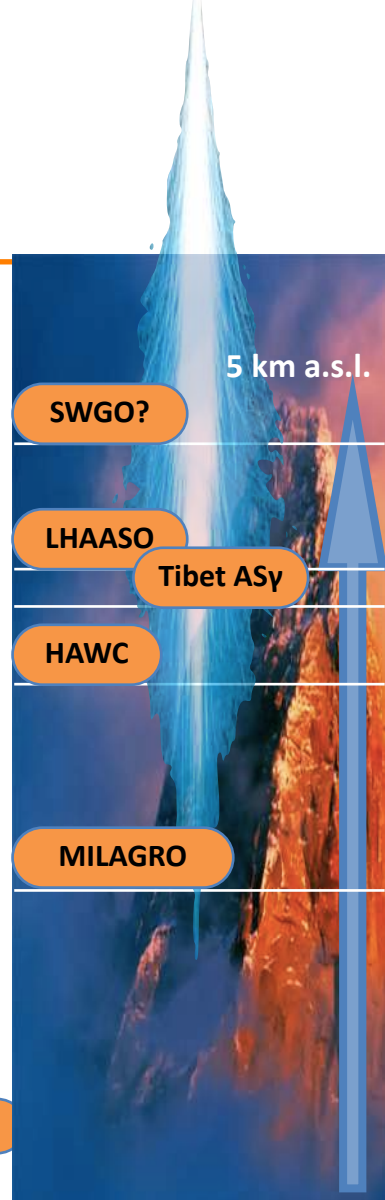
ARGO-YBJ

0.5 Crab



MILAGRO

1.0 Crab



5 km a.s.l.

SWGO?

LHAASO

Tibet ASy

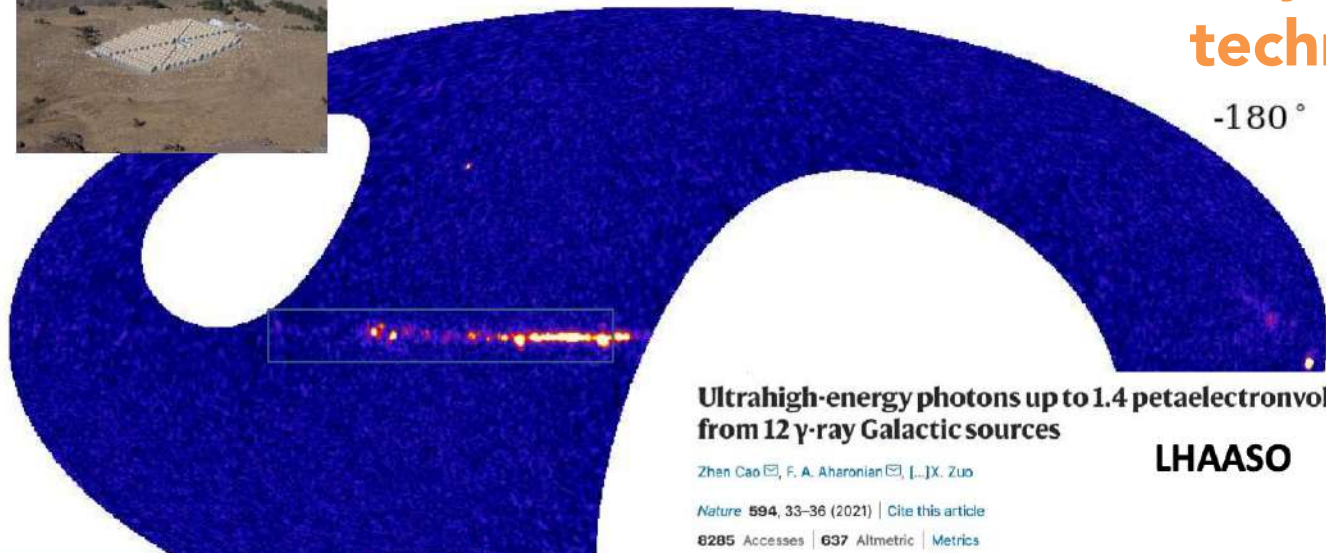
HAWC

MILAGRO

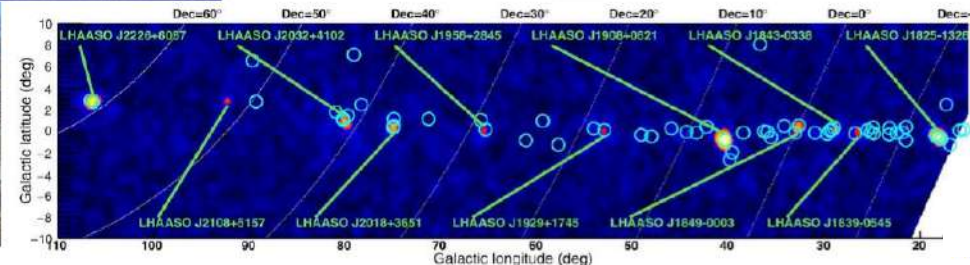
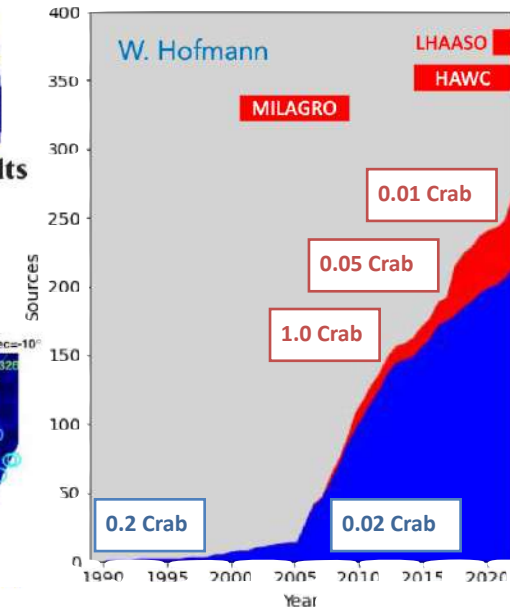
A new window for the UHE sky



HAWC



Major observational
technique > 10s TeV



Neutrino

<https://github.com/ChrisCFTung/FIRESONG>



CTA strategy: Neutrino Target of Opportunity (NToO):

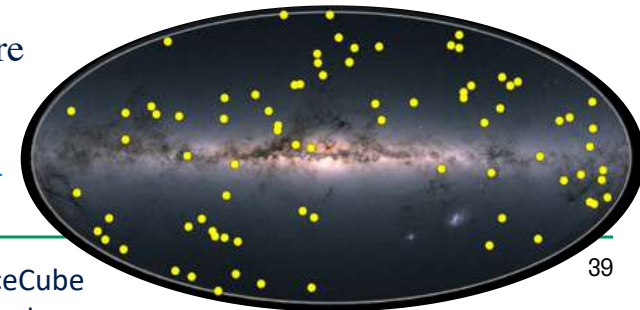
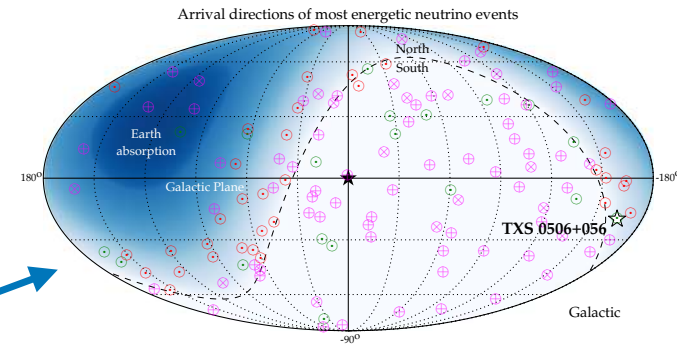
- Transients: CTA search for gamma-ray counterpart from a neutrino alert
- Steady sources: monitor hotspots exceeding IceCube sensitivity

FIRESONG

- Simulate a neutrino population according to source evolution and luminosity function

Density vs. Luminosity plot

- Steady sources: sources/Mpc³ vs. neutrino luminosity
- Transient sources: burst rates/Mpc³ (%flaring blazars) vs. neutrino flare luminosity



- **IC-170922A**: TXS 0506+056 ($z = 0.3365$)
- **IC-190730A**: PKS 1502+106 ($z = 1.84$)
- **IC-200107A**: 3HSP J095507.9+355101 ($z = 0.557$)
- **IC-141209A**: GB6 J1040+0617 ($z = 0.7351$)

IceCube Collab. 2018

IceCube Collab. 2019

IceCube Collab. 2020

Garappa et al. 2019

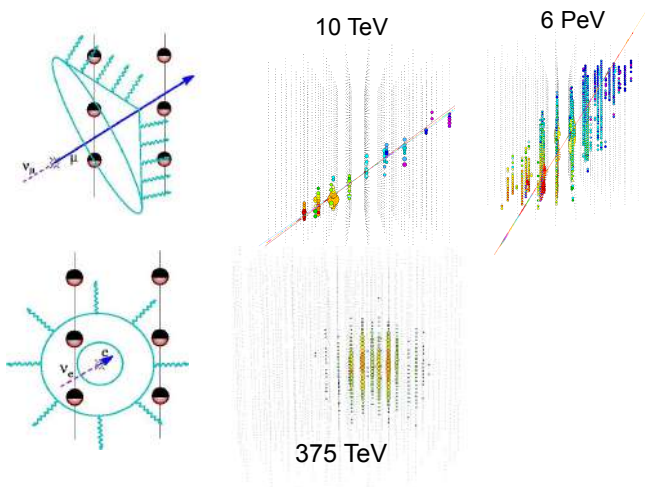
IceCube
neutrino alerts

Neutrino

<https://github.com/ChrisCFTung/FIRESONG>

VHE (IceCube) neutrinos originate in decay process from mesons produced in hadronic interactions:

- $\pi^+ \rightarrow \mu^+ + \nu_\mu$ or $\pi^- \rightarrow \mu^- + \nu_\mu$ from pion decay.
- $\mu^+ \rightarrow e^- + \nu_\mu + \nu_e$ or $\mu^- \rightarrow e^- + \nu_e + \nu_\mu$ from muon decay.



Neutrinos create charged particles in interactions, which then produce the Cherenkov radiation detected.

Muon-tracks

better type of event for astronomy, with good localization ($< 1^\circ$)
most common type of event, thanks to the long trajectories which cross the detector.

Cascade events

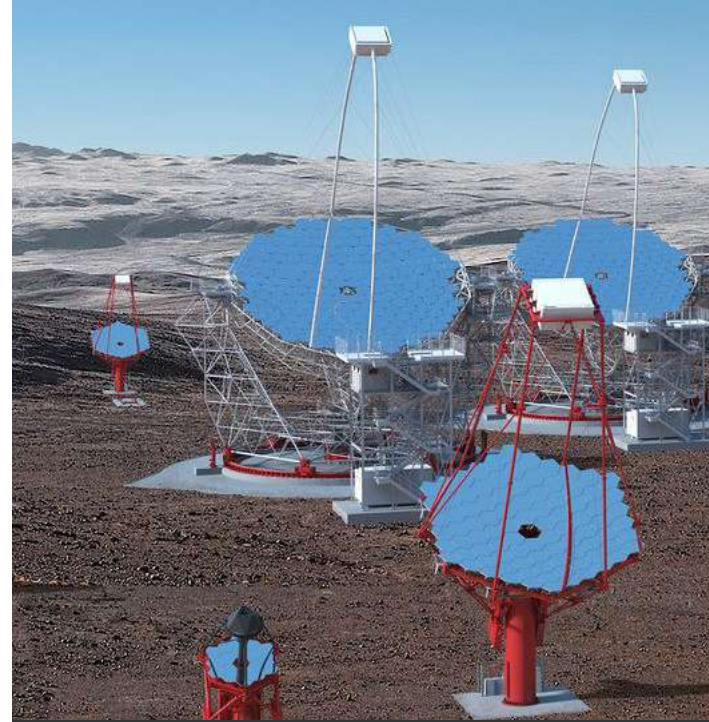
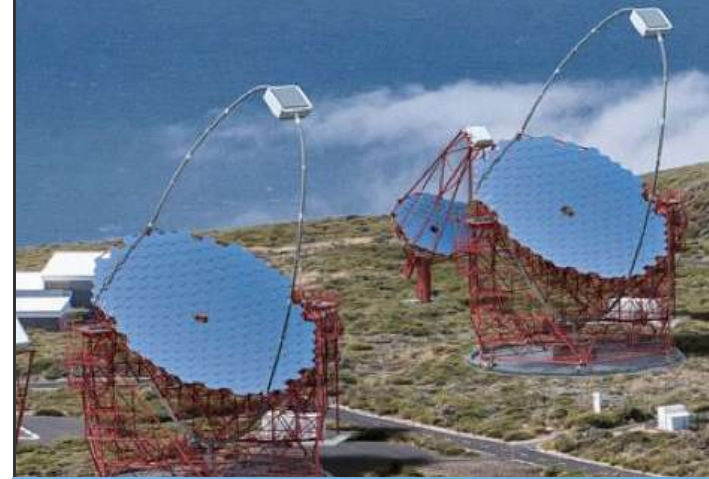
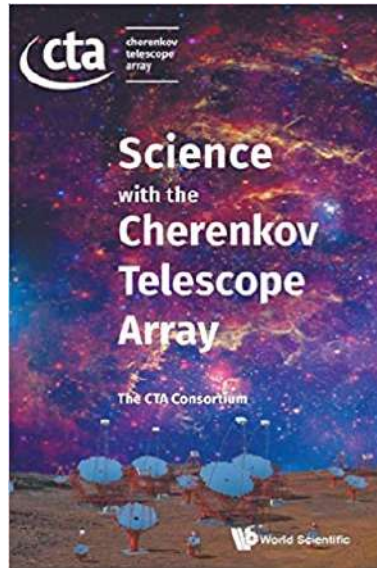
results from electron and tau neutrino interactions

Event has poor localization but good energy resolution and lower background



cherenkov
telescope
array

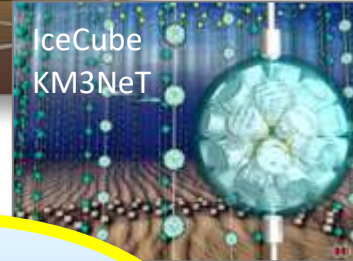
Multi-band & Multi-Messenger outlook



CTA SYNERGIES WITH MWL INSTRUMENTS



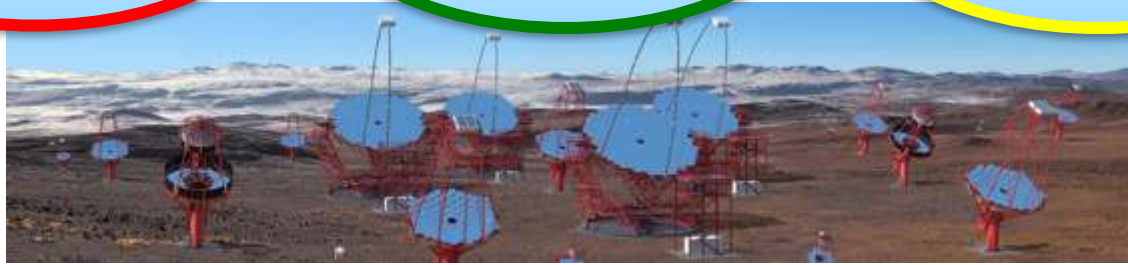
© slide by Werner Hofmann



Target selection & ToOs

Object characterization

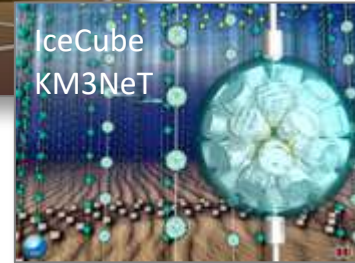
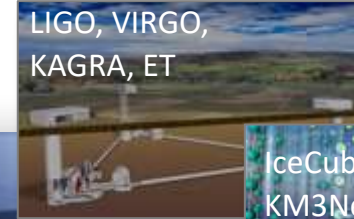
Wide-band / MM SED



CTA SYNERGIES WITH MWL INSTRUMENTS



© slide by Werner Hofmann, modified



- **Non-thermal emission in radio**
- **High-resolution VLBI to image emission zones**
- **Mapping of the diffuse gas (CR targets) to complement CTA view of diffuse emission around accelerators**

- **Detection of fast-variability signals from compact sources**
- **Optical polarimetry to isolate non-thermal component in mixed emission scenarios**

- **X-ray study of shock regions, accretion, high-speed outflows, which connect back to particle acceleration**
- **Soft gamma-ray telescopes for detection of high-energy transients**

MWL



CTA as a player in the MWL+MM arena



CTA will be the largest (open) observatory in the VHE range (20 GeV - 300 TeV), with two sites in both hemispheres for full sky access

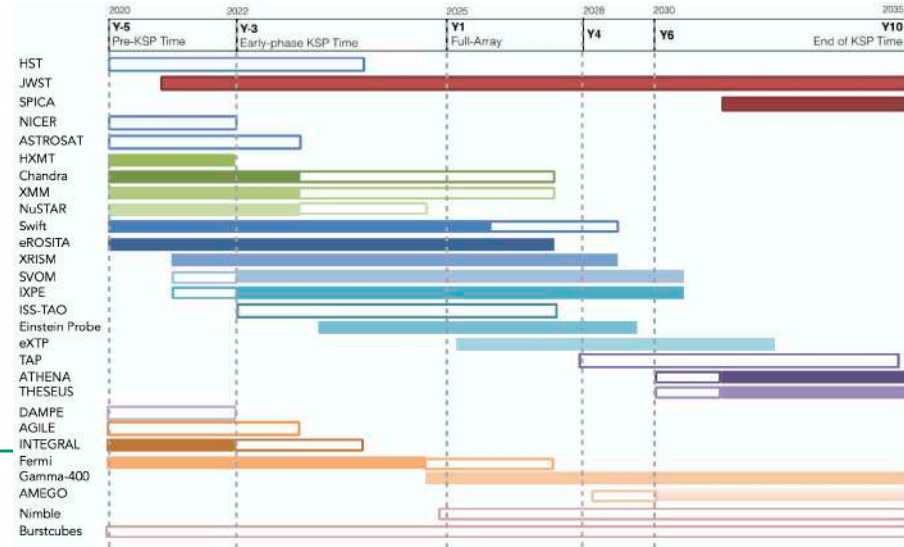
- most sensitive in the range below $< 10\text{s TeV}$
- unique short timescale sensitivity ($> 10^3 \times$ Fermi-LAT) $< 300\text{ GeV}$
- unique angular resolution $< 0.01^\circ$ in entire energy range
- largest FoV in a pointing instrument ($\sim 8^\circ$), ideal for surveys
- rapid response of LSTs ($< 30\text{ s}$)



A powerful and large precision instrument in the TeV range

Operations expected to start between 2025-27 :
contemporaneous to a new generation of MWL and MM instruments

ULISSES BARRES DE ALMEIDA - MARCH 2022

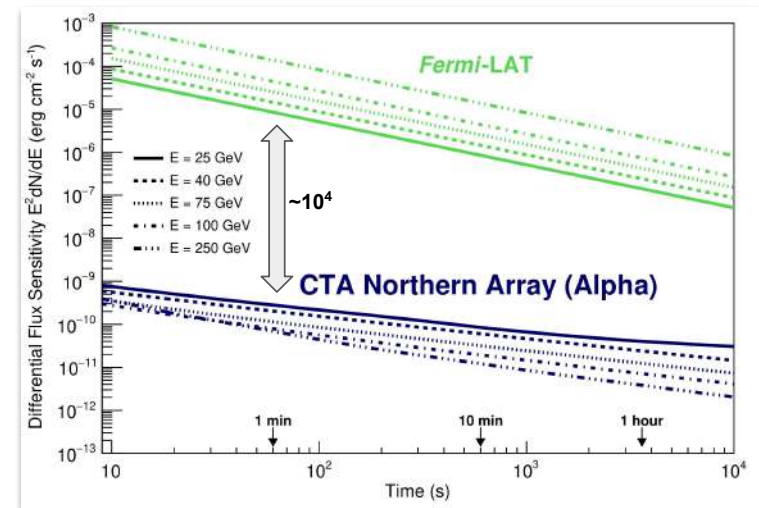


CTA Transient and MM Programme



CTA will have a strong transient and multi-messenger programme, following its unique short-timescale sensitivity in the multi-GeV range, $\sim 10^4$ x superior to Fermi-LAT for timescales our to several ks.

- **Gamma-ray bursts (GRBs)**, external alerts from monitoring facilities. Simulations of a realistic GRB populations estimate CTA detection prospects to few GRBs per year.
- **Galactic transients**, serendipitous detection of a wide range of galactic transients expected from CTA regular Galactic Plane Survey monitoring: flares from pulsar wind nebulae (PWN), X-ray binaries, novae, microquasars, magnetars, etc.
- **High-energy neutrino transients**, CTA strategy is to follow-up (golden) neutrino to maximize the chance of detecting a VHE counterpart.
- **GW transients**, follow-up by CTA can play a unique role to ID counterparts thanks to large FoV and divergent pointing strategy.
- **Core-collapse Supernovae**, investigation of CTA prospects in detecting a wide range of different types of CCSNe and their different signature in the VHE regime.

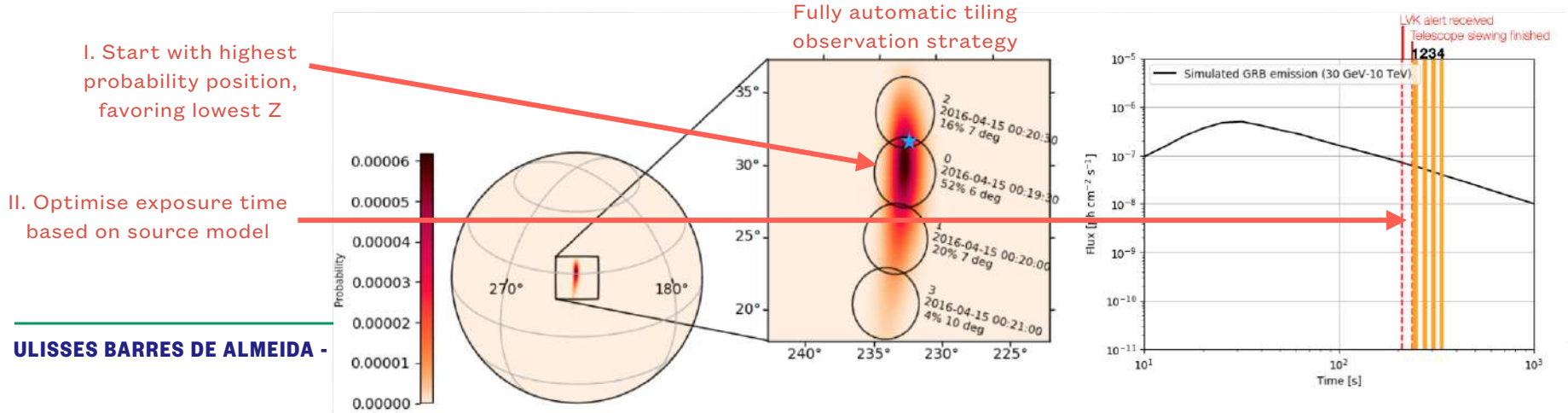


<https://www.cta-observatory.org>

CTA follow-up observation strategy



- CTAO will perform regular (1-3x per week) follow-up observations of GW-GRB and (golden) ν alerts
- The observational strategy is a key element for the success of the programme
 - Optimal pointing pattern to cover the largest total alert uncertainty region (10-1000 deg²) (*Patricelli+2018, Bartos+2019*)
 - Optimal pointing cadence: exposure time tailored to achieve 5σ detection
 - Site coordination to prioritize best observational conditions (sky brightness and quality, zenith angle) and to guarantee lowest energy threshold
 - Divergent array pointing mode to increase the FoV



CTA MWL & MM Coordination Task Force



The achievement of the **CTA core Science Goals** depends on a wealth of MWL and MM data (often involving intense coordination between facilities), and the purpose of the MWL&MM Coordination Task Force is to identify, plan and secure those.

Band or Messenger	Astrophysical Probes	Galactic Plane Survey	LMC & SFRs	CRs & Diffuse Emission	Galactic Transients	Starburst & Galaxy Clusters	GRBs	AGNs	Radio Galaxies	Redshifts	GWs & Neutrinos
Radio	Particle and magnetic-field density probe. Transients. Pulsar timing.	●	●	●	●	●	●	●			●
(Sub)Millimetre	Interstellar gas mapping. Matter ionisation levels. High-res interferometry.	●	●		●	●	●	●	●		
IR/Optical	Thermal emission. Variable non-thermal emission. Polarisation.	●	●		●	●	●	●	●	●	●
Transient Factories	Wide-field monitoring & transients detection. Multi-messenger follow-ups.				●		●	●			●
X-rays	Accretion and outflows. Particle acceleration. Plasma properties.	●	●	●	●	●	●	●	●		●
MeV-GeV Gamma-rays	High-energy transients. Pion-decay signature. Inverse-Compton process	●	●		●	●	●	●	●		●
Other VHE	Particle detectors for 100% duty cycle monitoring of TeV sky.	●	●		●	●	●	●			●
Neutrinos	Probe of cosmic-ray acceleration sites. Probe of PeV energy processes.	●	●	●		●	●	●			●
Gravitational Waves	Mergers of compact objects (Neutron Stars). Gamma-ray Bursts.						●				●

Spatial Coordination for Surveys

Extension of Spectral Coverage

Catalogue cross-matching for resolving counterparts and source ID

Temporal coordination for variable sources

Alerts for Transient Phenomena

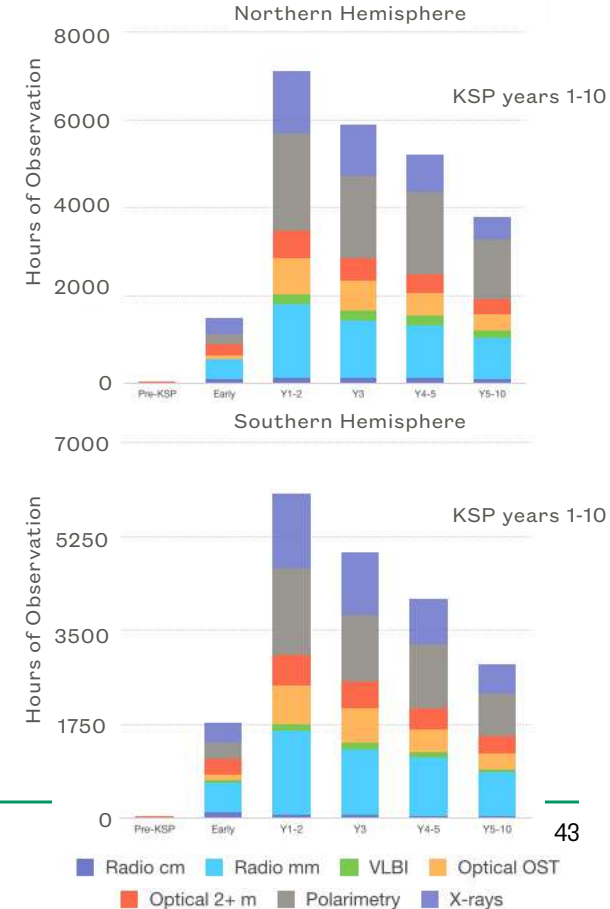


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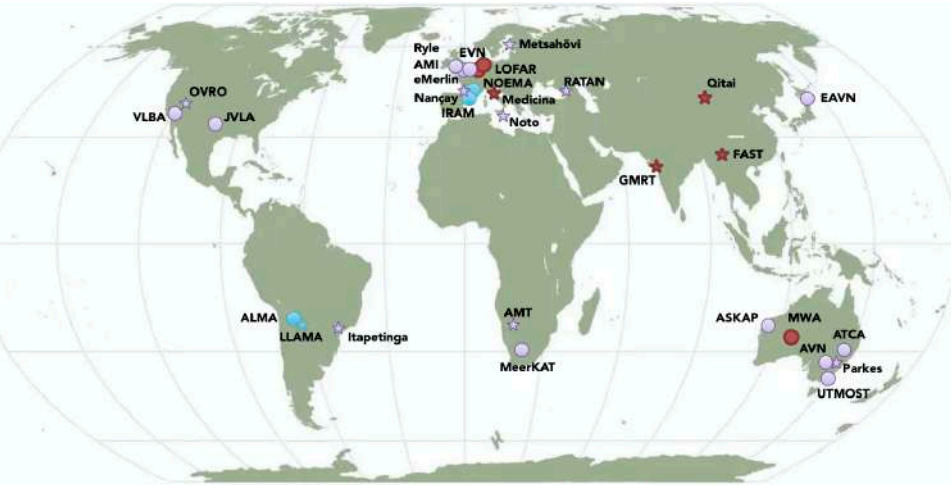
Band or Messenger	Astrophysical Probes	Galactic Plane Survey	LMC & SFRs	CRs & Diffuse Emission	Galactic Transients	Starburst & Galaxy Clusters	GRBs	AGNs	Radio Galaxies	Redshifts	GWs & Neutrinos
Radio	Particle and magnetic-field density probe. Transients. Pulsar timing.	●	●	●	●	●	●	●			●
(Sub)Millimetre	Interstellar gas mapping. Matter ionisation levels. High-res interferometry.	●	●		●	●	●	●	●		
IR/Optical	Thermal emission. Variable non-thermal emission. Polarisation.	●	●		●	●	●	●	●	●	●
Transient Factories	Wide-field monitoring & transients detection. Multi-messenger follow-ups.				●		●	●			●
X-rays	Accretion and outflows. Particle acceleration. Plasma properties.	●	●	●	●	●	●	●	●		●
MeV-GeV Gamma-rays	High-energy transients. Pion-decay signature. Inverse-Compton process	●	●		●	●	●	●	●		●
Other VHE	Particle detectors for 100% duty cycle monitoring of TeV sky.	●	●		●	●	●	●			●
Neutrinos	Probe of cosmic-ray acceleration sites. Probe of PeV energy processes.	●	●	●		●	●	●			●
Gravitational Waves	Mergers of compact objects (Neutron Stars). Gamma-ray Bursts.						●				●



An ecosystem of ground-based facilities

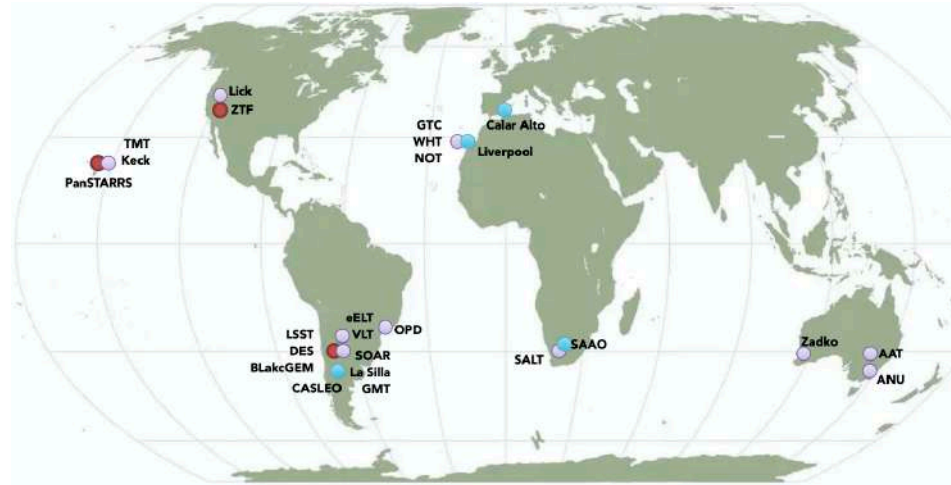


Radio Facilities Map



- Low Frequency Radio
- mm /sub-mm Radio
- Mid-Hi Frequency Radio
- ★ ☆ ★ monitoring / follow-up?

Optical Facilities Map



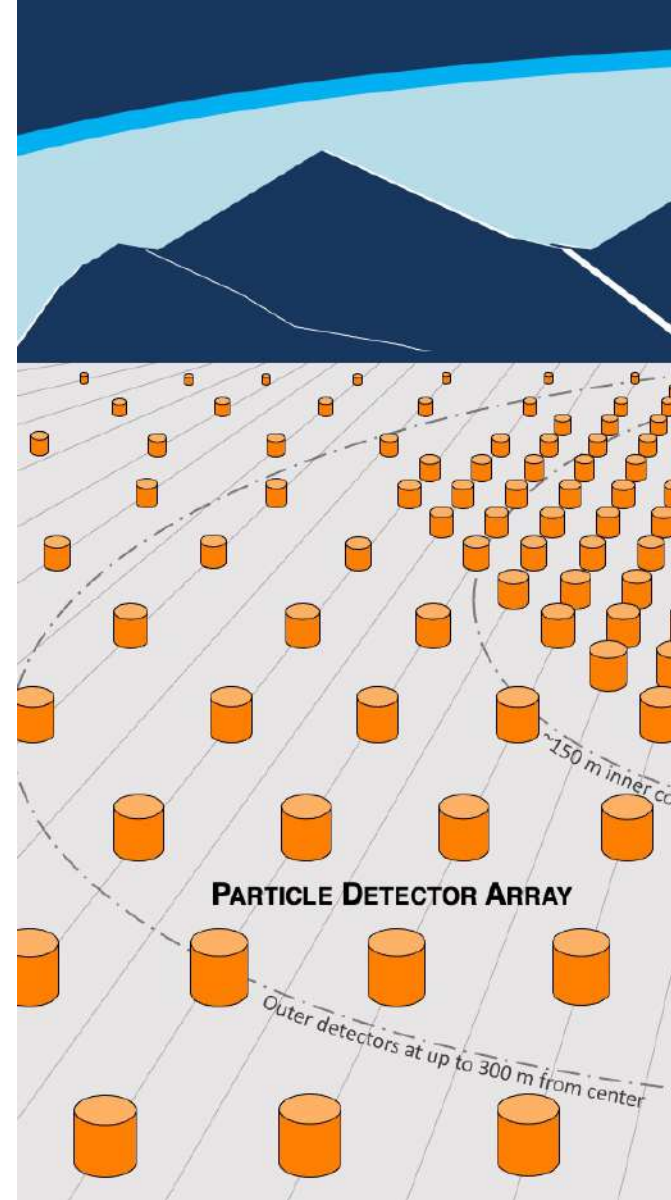
- Transient Factories
- Polarimetric Capability
- Major OIR Facilities



Status of Project Research & Development



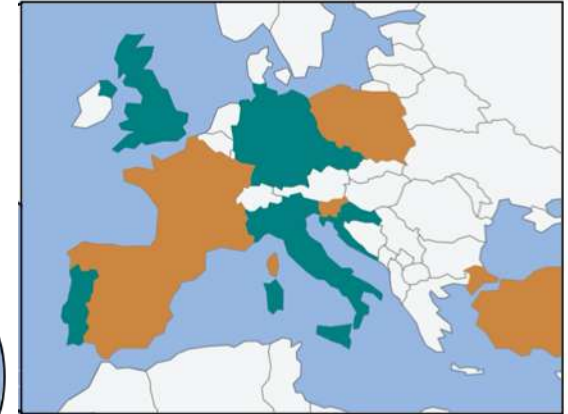
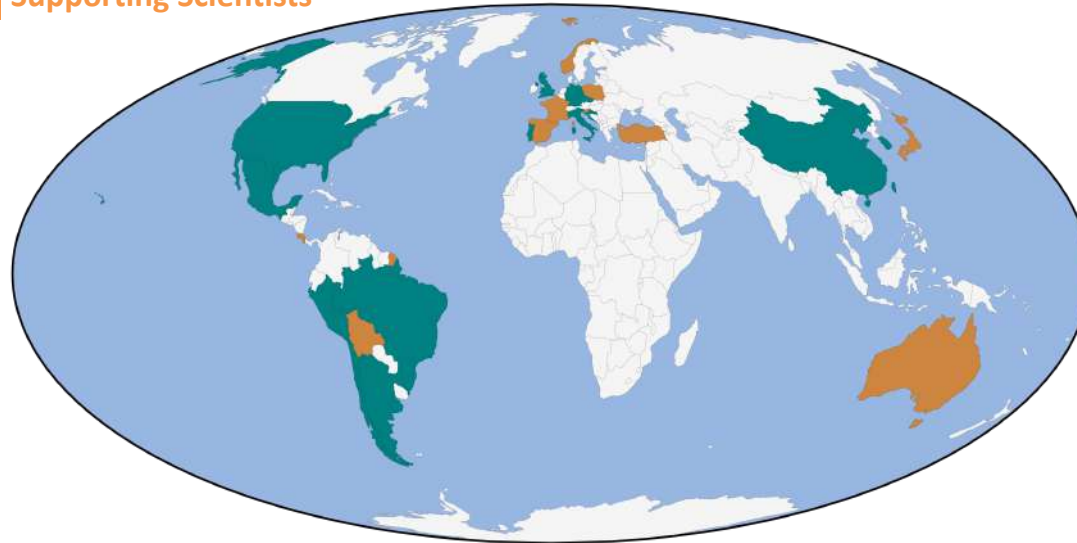
www.swgo.org



SWGO Collaboration

Member Institutes

Supporting Scientists



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

SWGO partners

- 14 countries, 66 institutes, c. 200 scientists*
- + supporting scientists

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 2024
 - ✓ Site and Design Choices made
- Then:

◎ Preparatory Phase

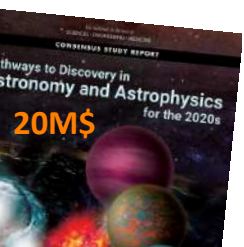
- Detailed construction planning
- **Engineering Array**

◎ (Full) Construction Phase

- 2026+

◎ Roadmaps

- US Decadal Review
- SNOWMASS, APPEC, Astronet



A Wide-field Gamma-ray Observatory in the South

Bolivia 4.7k

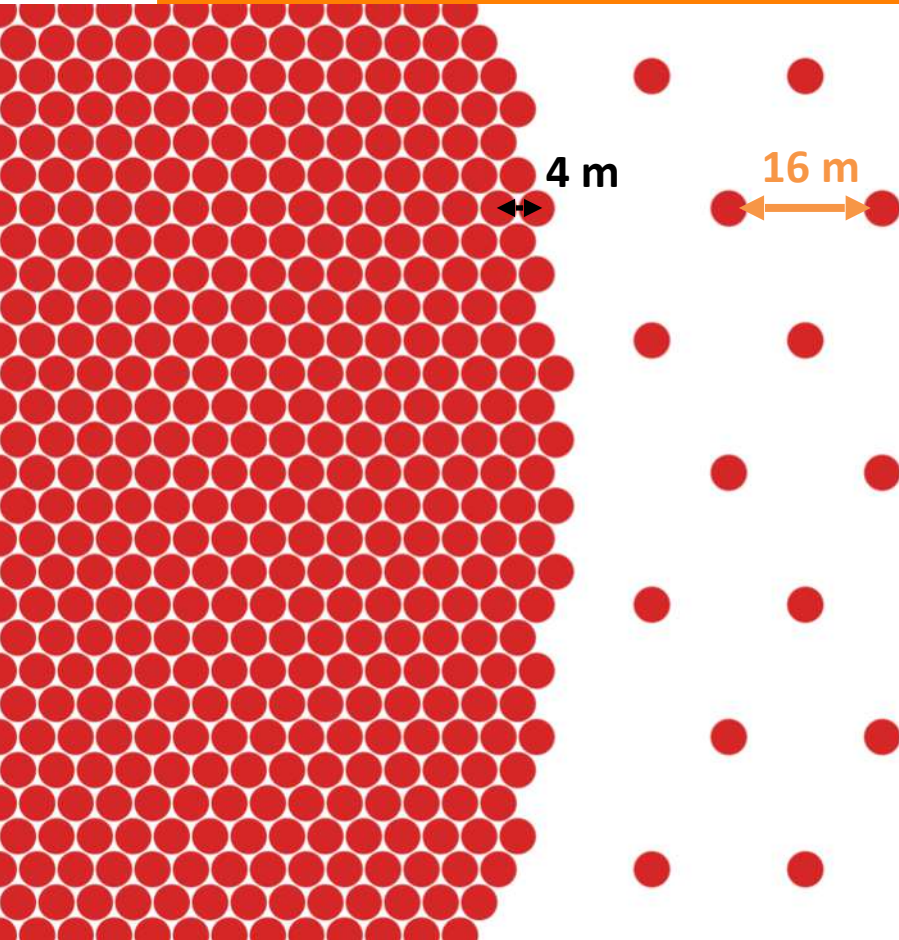
Chile 4.8 k



Argentina 4.8 k

Peru 4.9 k

The baseline detector concept

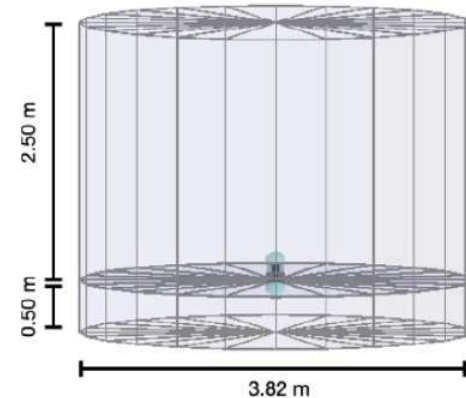


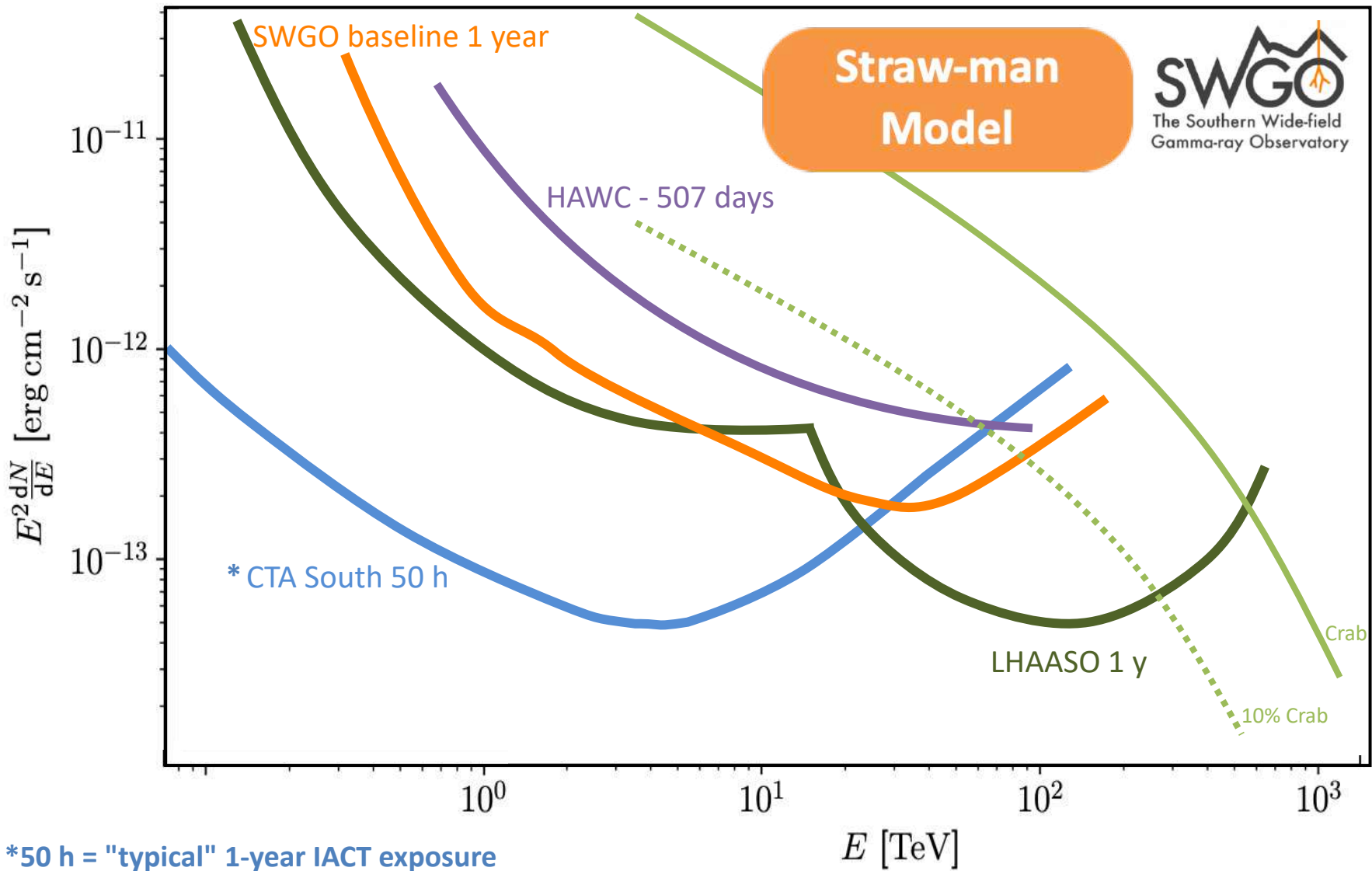
Core: \varnothing 320 m, FF = 80%
5,700 WCD units

Outer: \varnothing 600 m, FF = 5%
880 WCD units

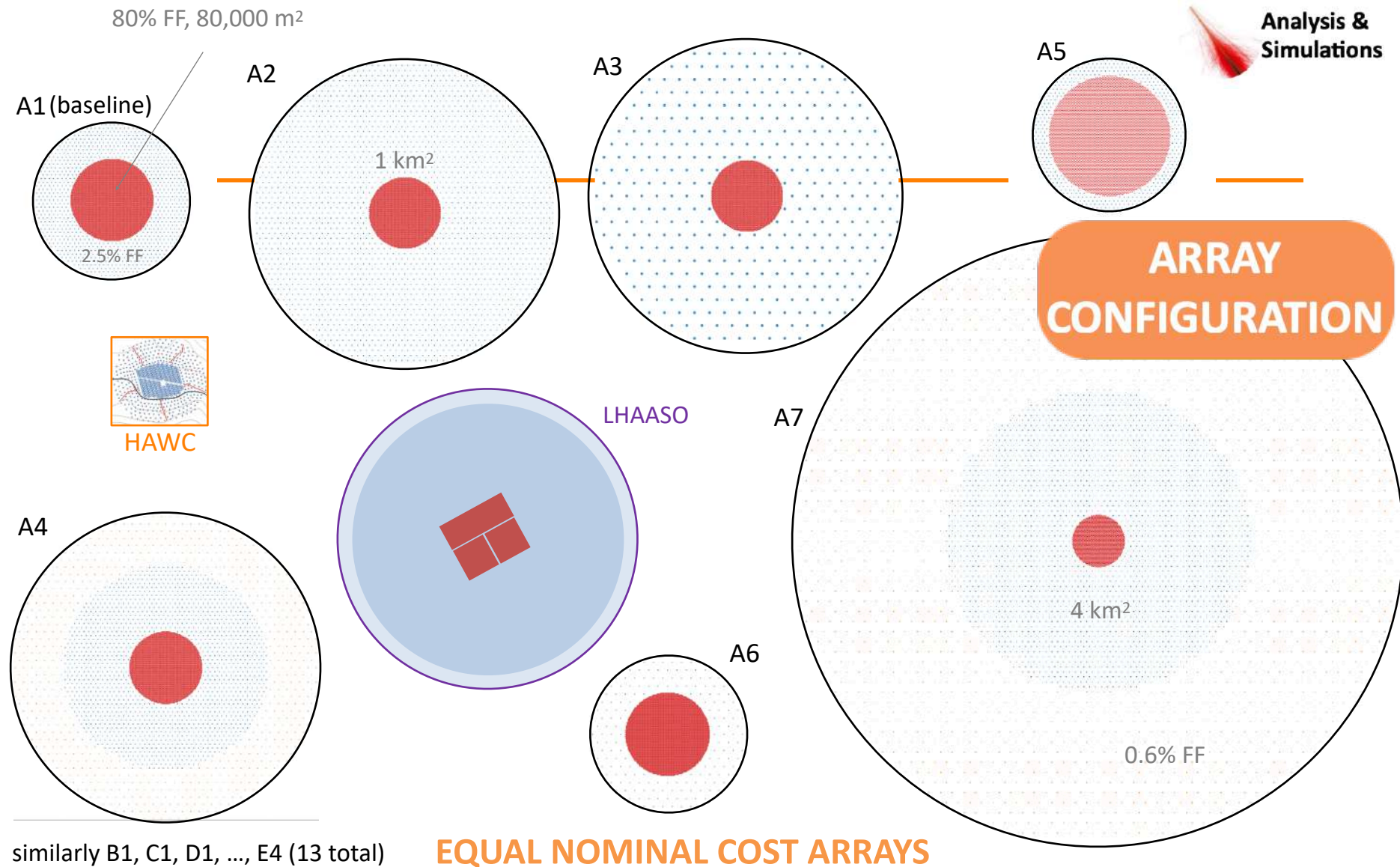
Altitude: 4,700 m a.s.l.

✧ muon counting

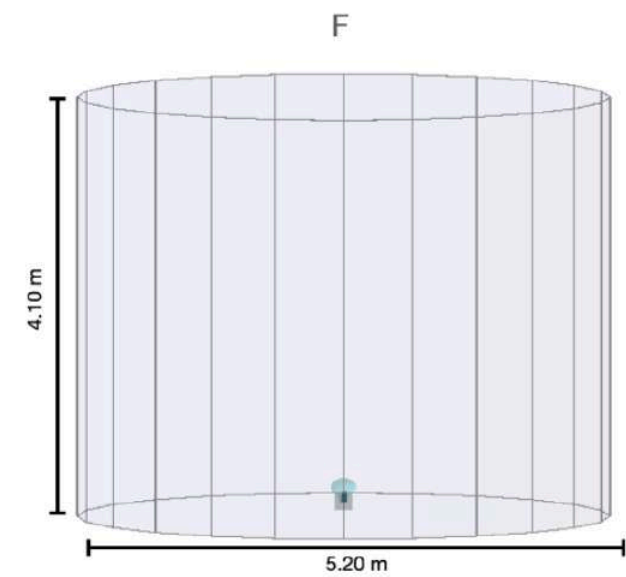
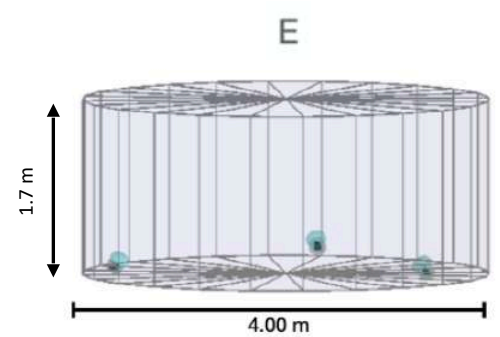
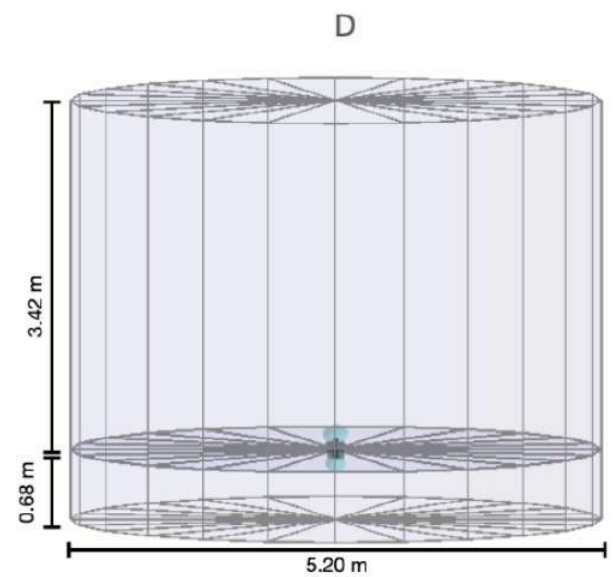
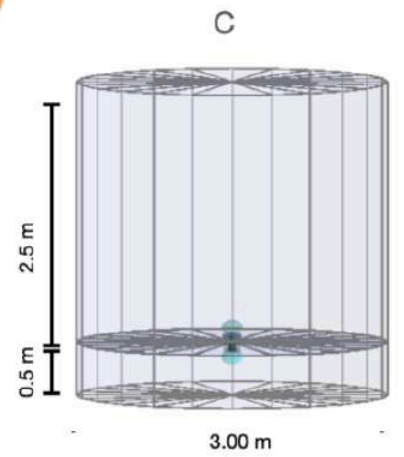
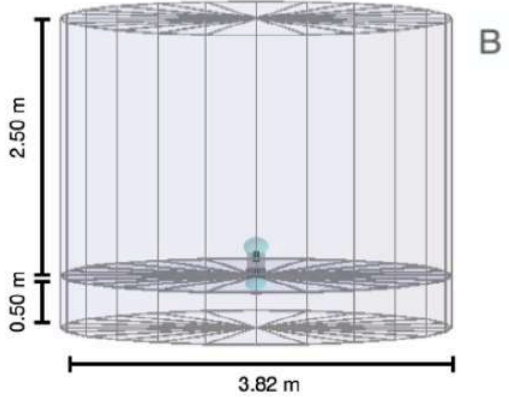
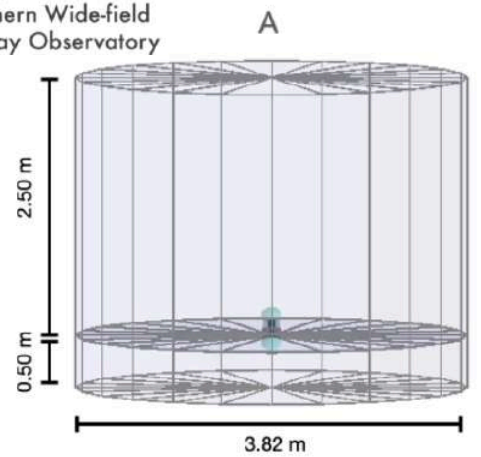




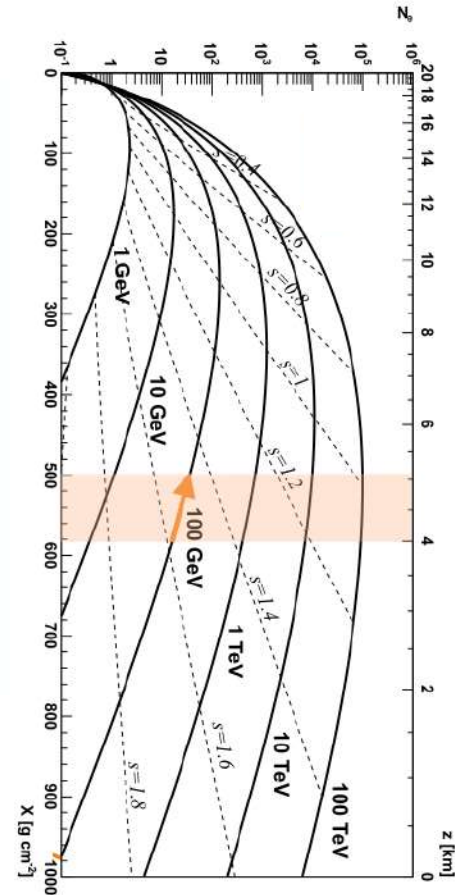
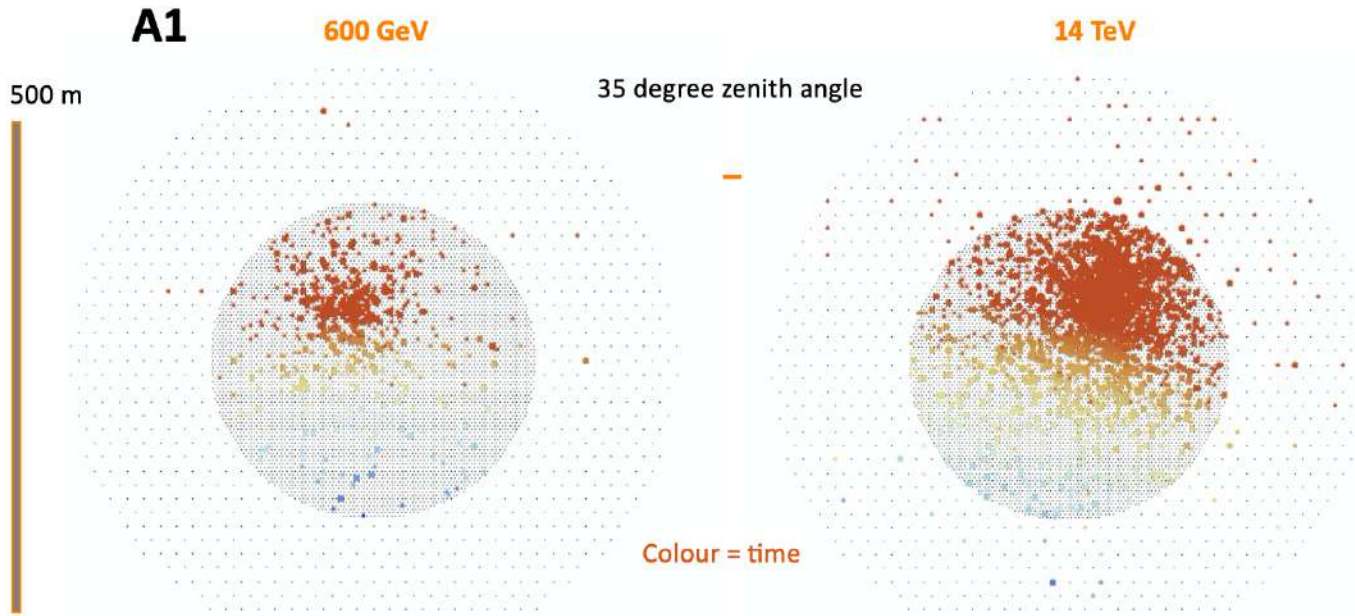
*50 h = "typical" 1-year IACT exposure



WCD unit designs



SWGGO Baseline Requirements



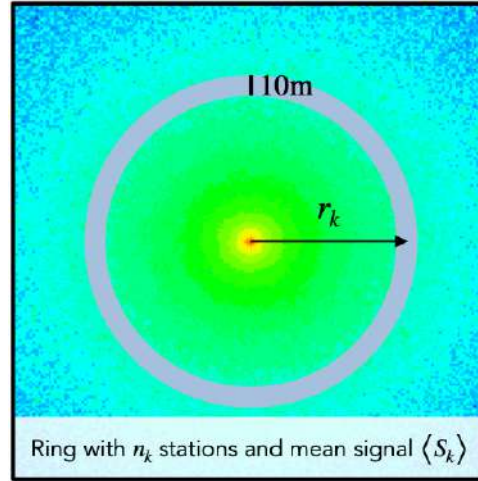
- ⦿ Larger and dense detector array at increased altitude with respect to HAWC
 - Very precise measurements possible below 1 TeV

Shower
footprint

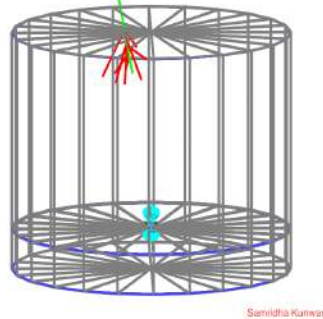
γ /CR
selection

μ detection

Shower azimuthal asymmetries

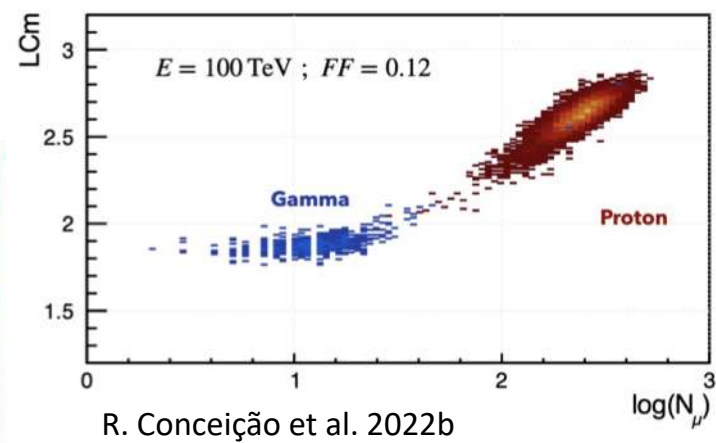


Double-layer WCDs



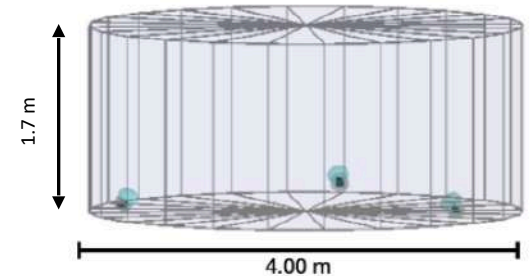
Sannidha Kunwar

F. Bisconti & A. Chiavassa 2022
S. Kunwar et al. 2022

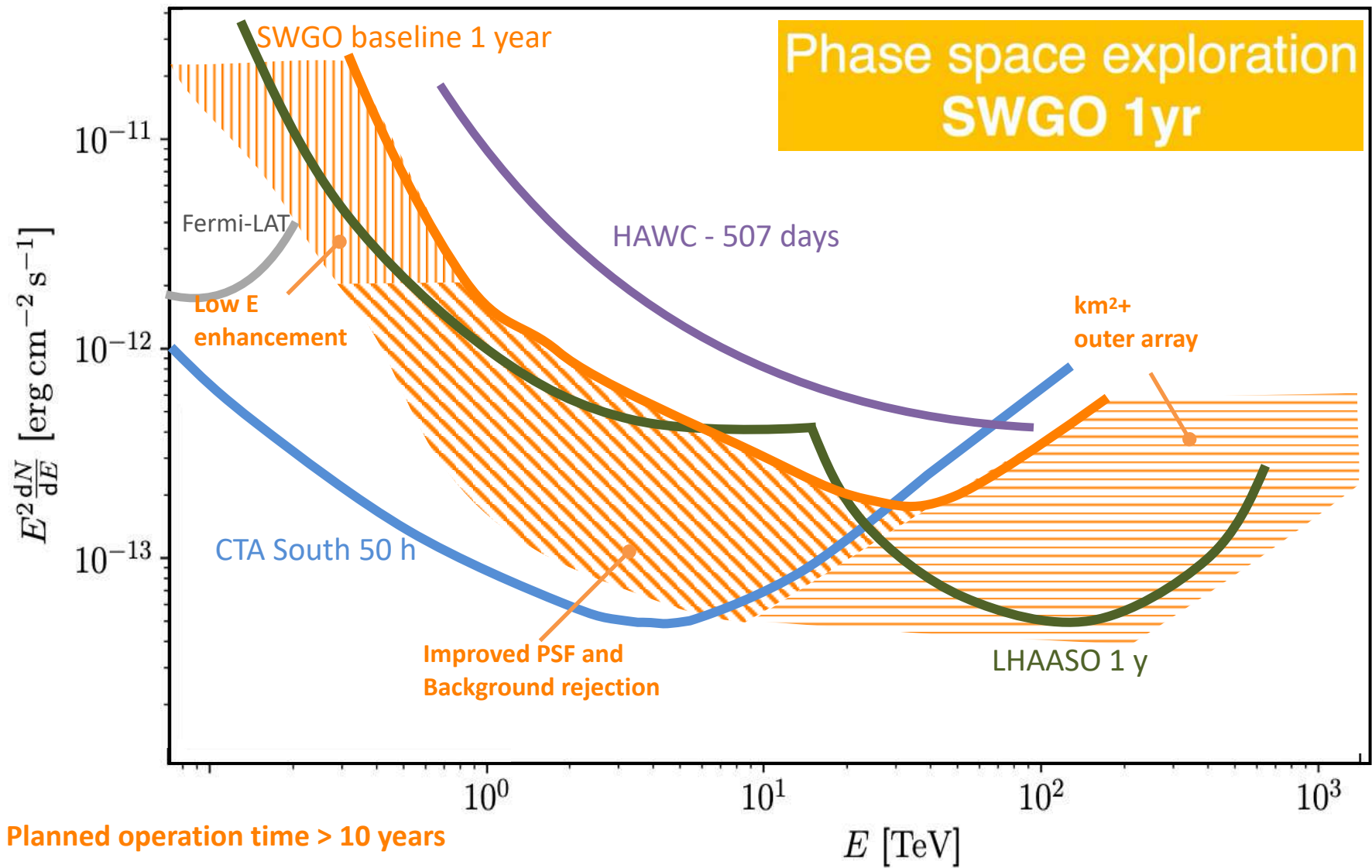


$$C_k = \frac{2}{n_k(n_k - 1)} \frac{1}{\langle S_k \rangle} \sum_{i=1}^{n_k-1} \sum_{j=i+1}^{n_k} (S_{ik} - S_{jk})^2$$

Multi-PMT WCDs

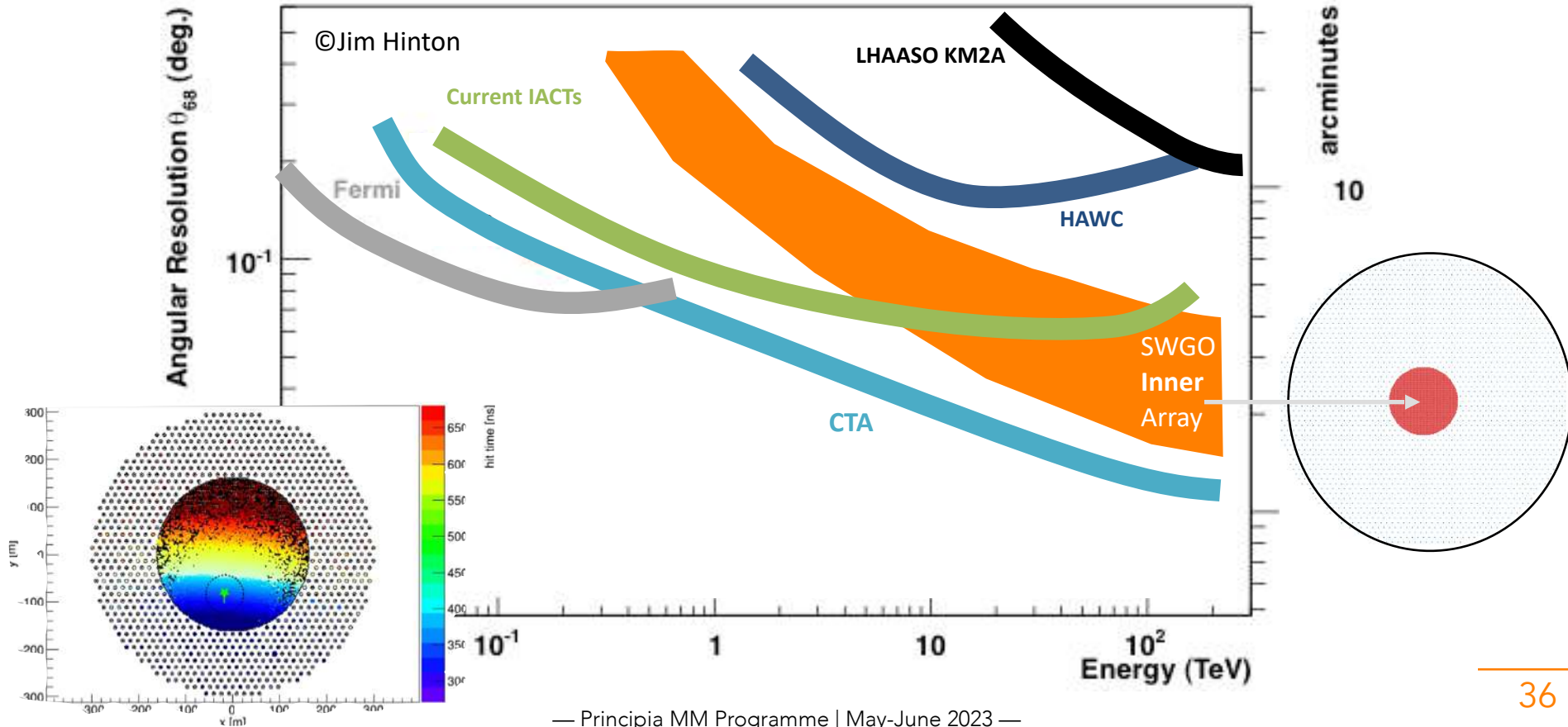


R. Conceição et al. 2022a

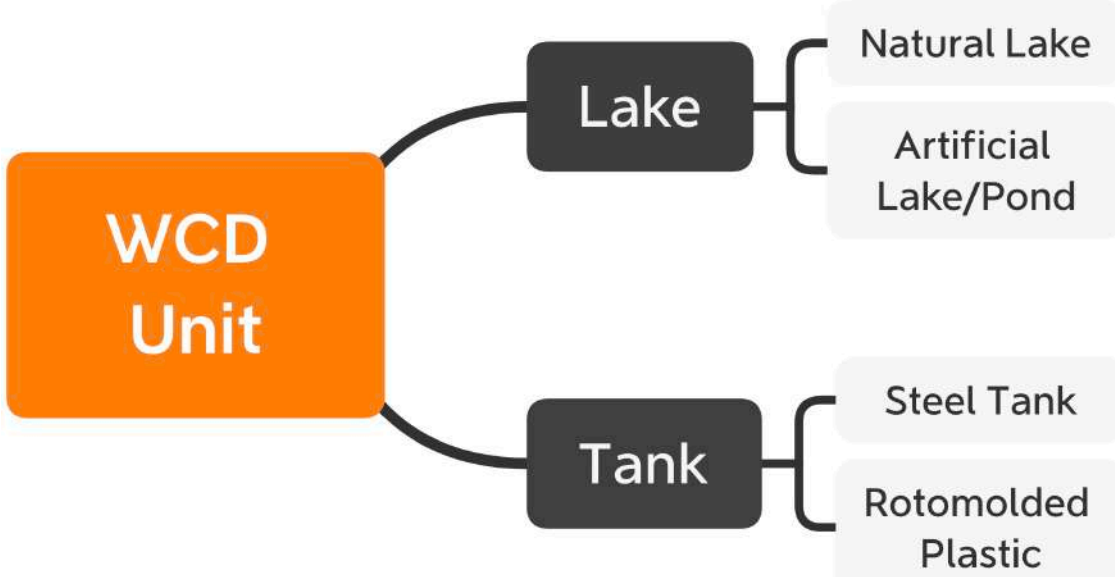
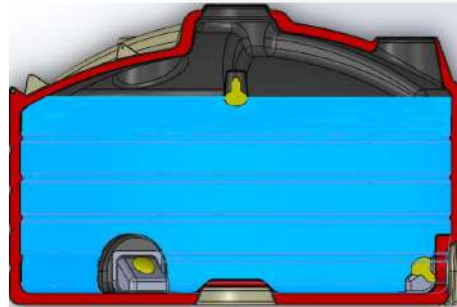
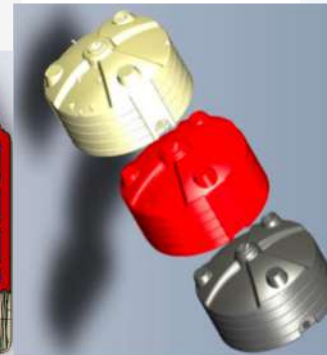


SWGGO Performance Goal

Angular Resolution



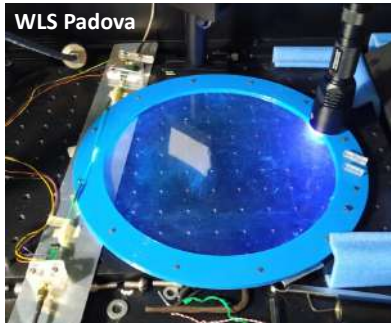
WCD unit Solutions



More Detector Options and Prototyping



PMT module MPIK

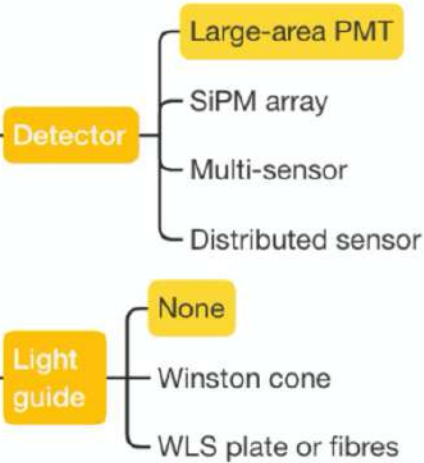


WLS Padova

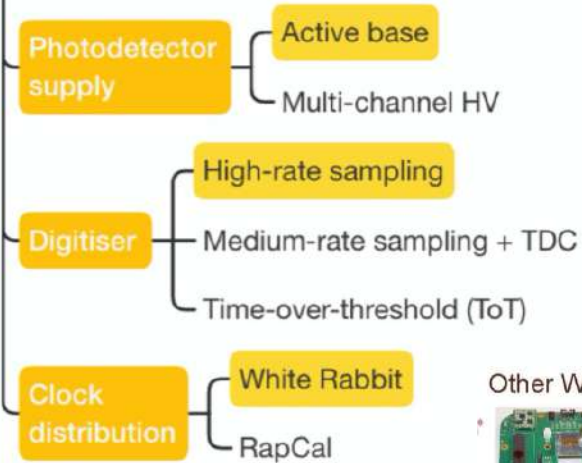


PMTs Naples

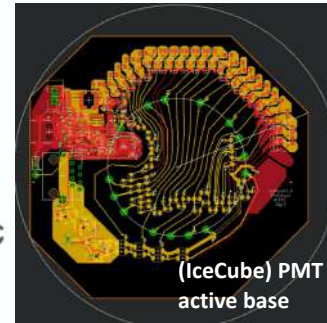
Photodetectors



Electronics chain



HAWC Bladders



(IceCube) PMT active base

Other White Rabbit Node examples:



Central Logic Board (KM3NeT)



CUTE-WR (LHAASO)



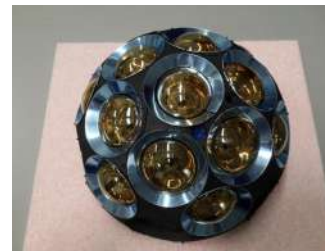
SVEC (CERN)



SPEXI (CERN)

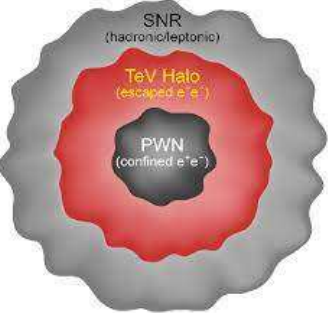
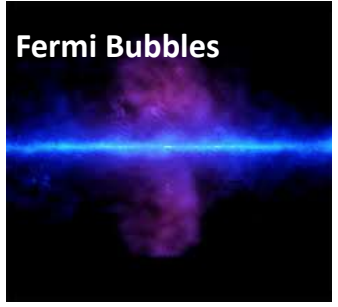


CRIO-WR (CERN)

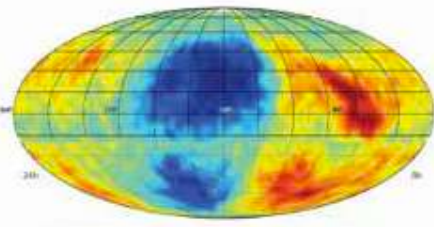


HyperK-style multi-PMT

Scientific Outlook



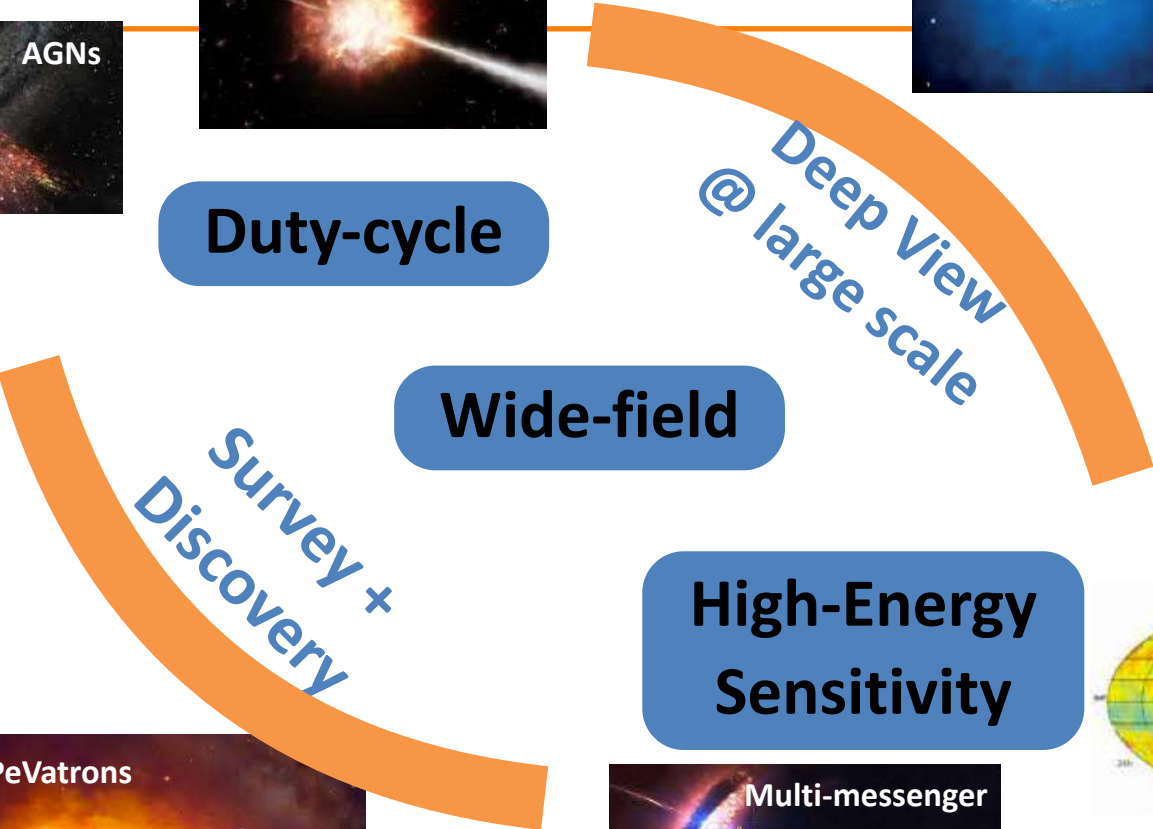
Halos



Duty-cycle

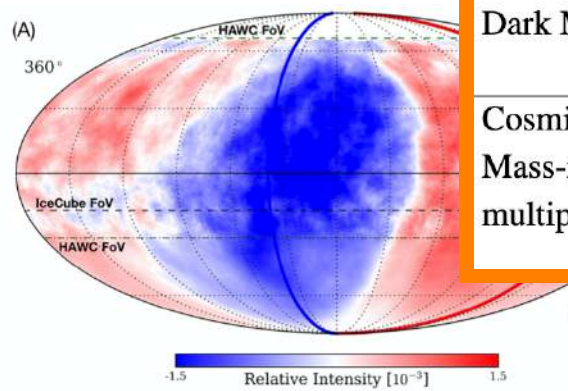
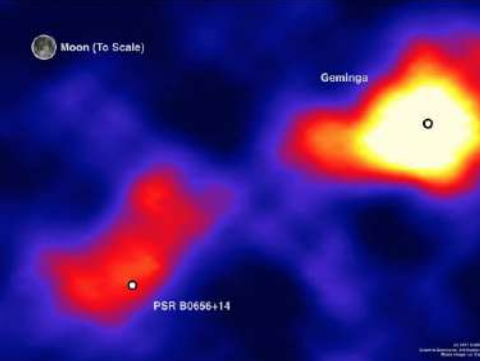
Wide-field

High-Energy Sensitivity





Science



Science Case	Design Drivers
Transient Sources: Gamma-ray Bursts	Low-energy sensitivity & Site altitude ^a
Galactic Accelerators: PeVatron Sources	High-energy sensitivity & Energy resolution ^b
Galactic Accelerators: PWNe and TeV Halos	Extended source sensitivity & Angular resolution ^c
Diffuse Emission: Fermi Bubbles	Background rejection
Fundamental Physics: Dark Matter from GC Halo	Mid-range energy sensitivity Site latitude ^d
Cosmic-rays: Mass-resolved dipole / multipole anisotropy	Muon counting capability ^e

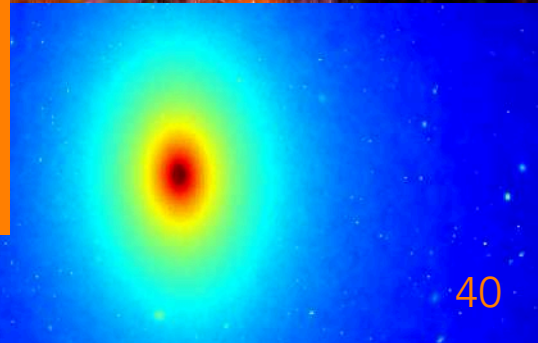
PRELIMINARY DESIGN TARGETS

$E_{th} \rightarrow 100 \text{ GeV}$

$E_{res} < 20\%$

$\Theta_{res} \sim 0.1^\circ$

$CR_{res} @ 10^{-4}$



Transients with SWGO

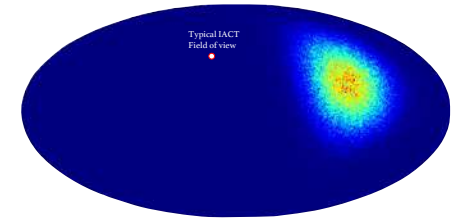
- Short-timescale sensitivity of ground-particle detectors is much worse than IACTs at low E! **But room for improvement < 1 TeV**

1 min sensitivity:

- Fermi-LAT: 10^{-7} erg/cm²/s @ 1 GeV
- SWGO: 10^{-9} erg/cm²/s @ < 500 GeV
- CTA: 10^{-11} erg/cm²/s @ 100 GeV

- And a number of other advantages...

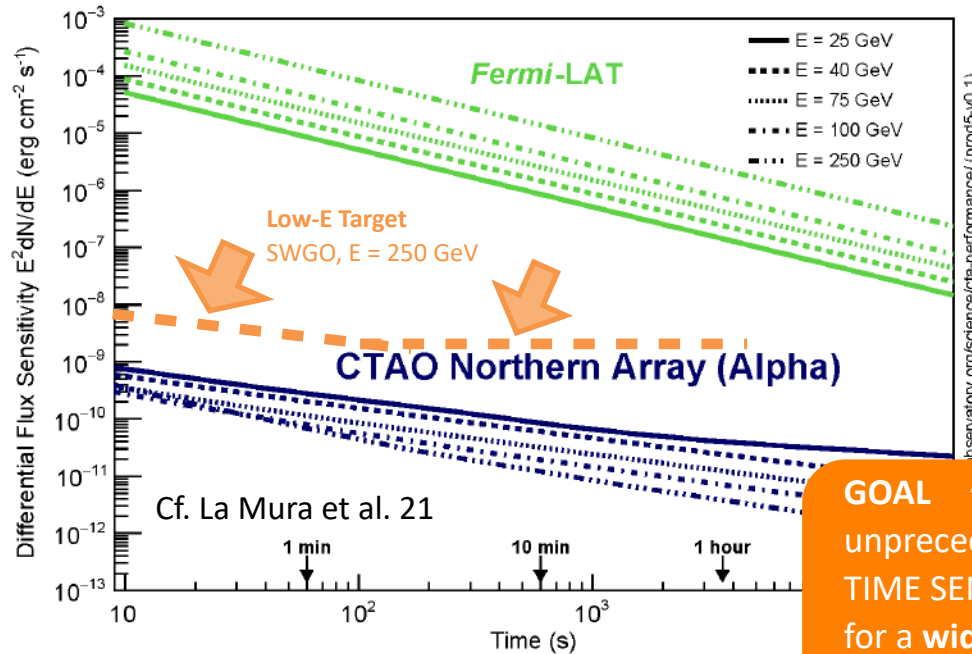
- **100% duty cycle** → higher rate and monitoring capability of transients
→ bridging the gap with satellite facilities
- **Serendipitous view** - observation of onset / prompt emission of GRBs
- **A trigger instrument!**
 - ✓ Blind searches and offline checks for afterglow triggers
 - Critical synergy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



- ✧ **SWGO can bring the 10s deg² error boxes (GBM, GW) down to \sim deg²**

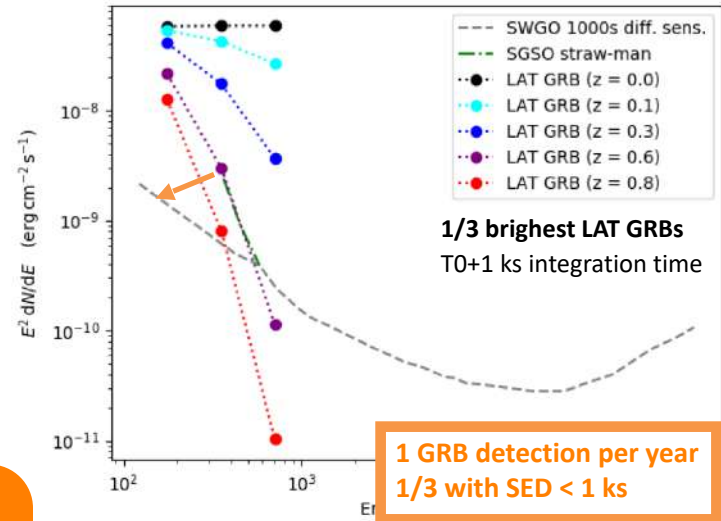
Transients with SWGO

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



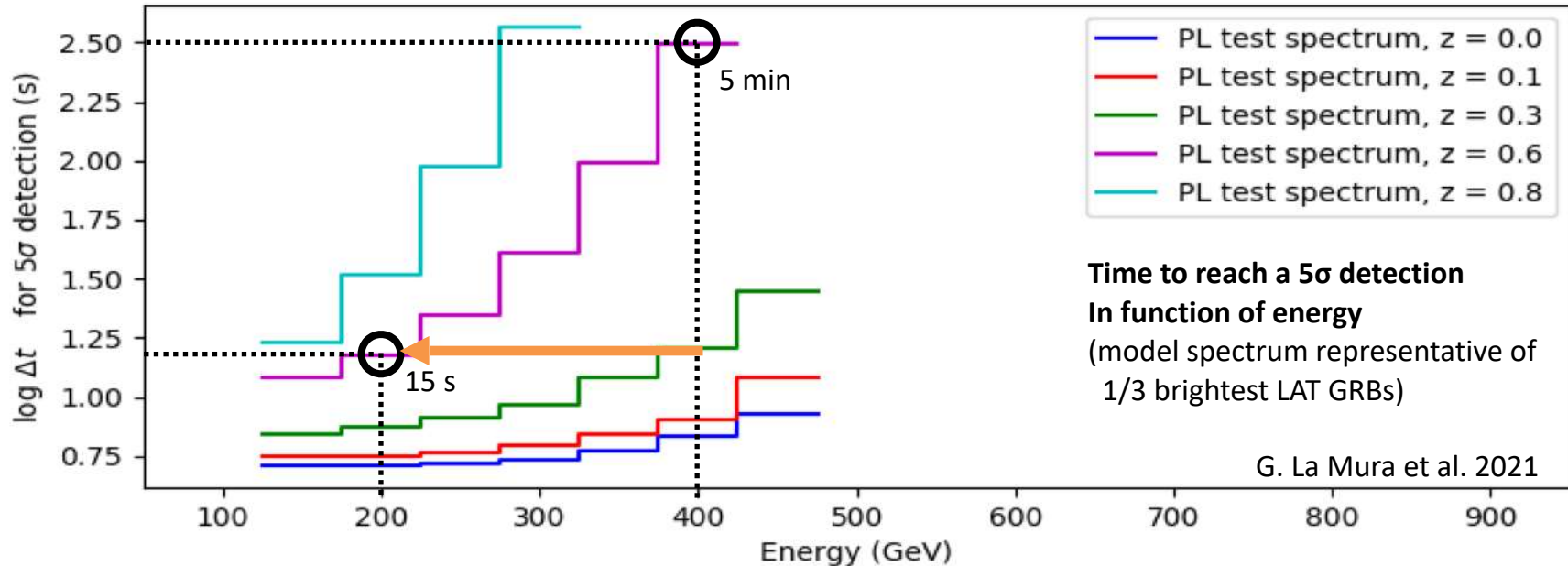
observatory.org/science/cta-performance/ (prod5-v0.1)

GOAL → unprecedented TIME SENSITIVITY for a wide field VHE instrument



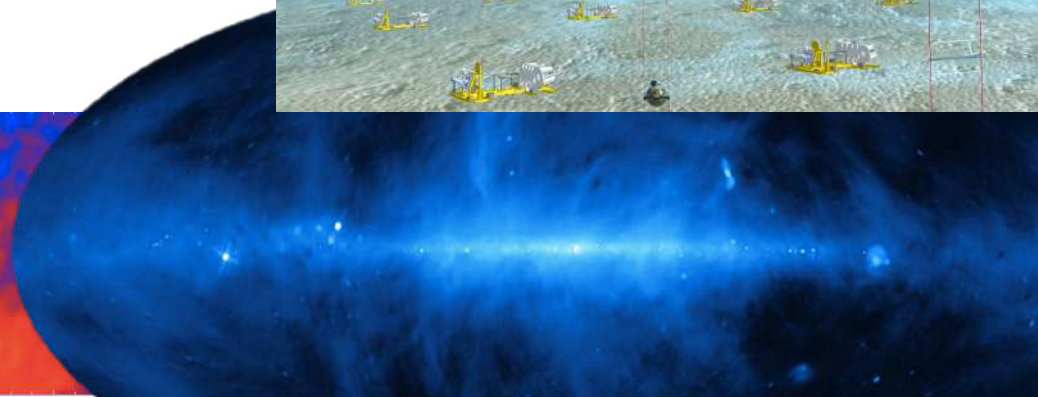
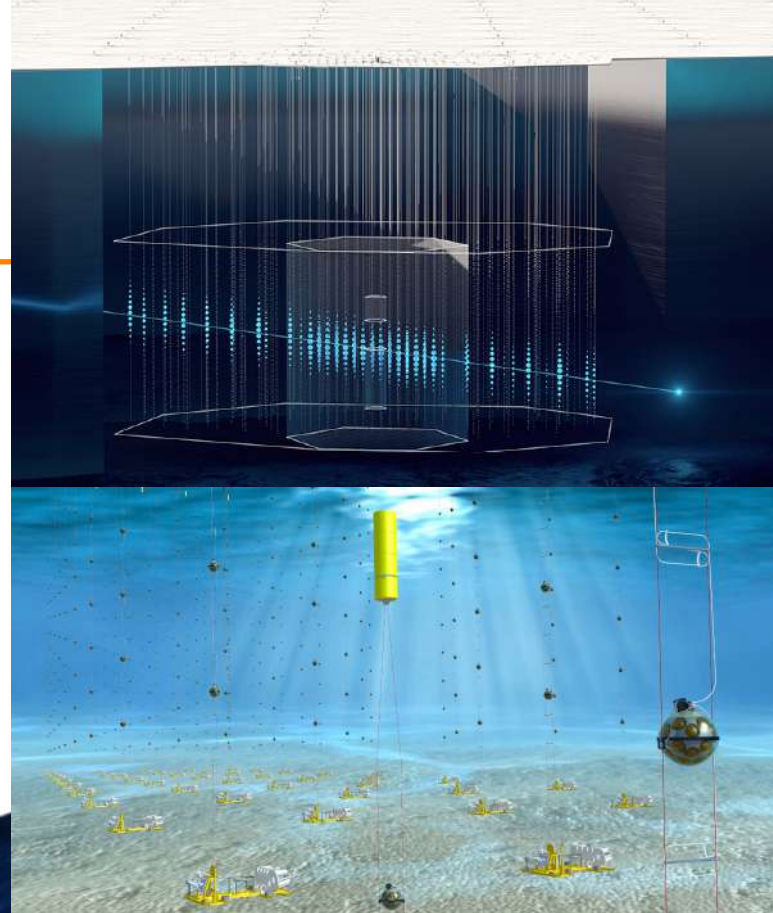
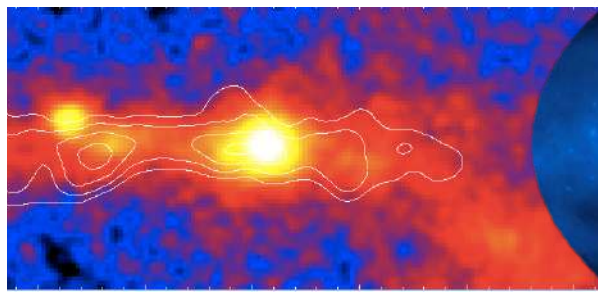
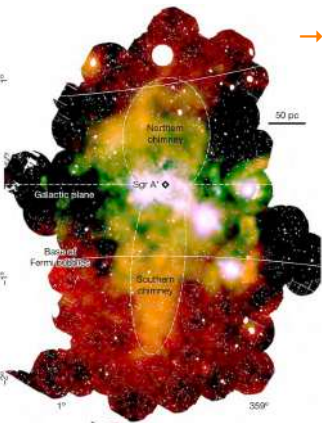
Transients with SWGO

- Energy threshold is crucial for variability studies, in particular short-transient events such as GRBs



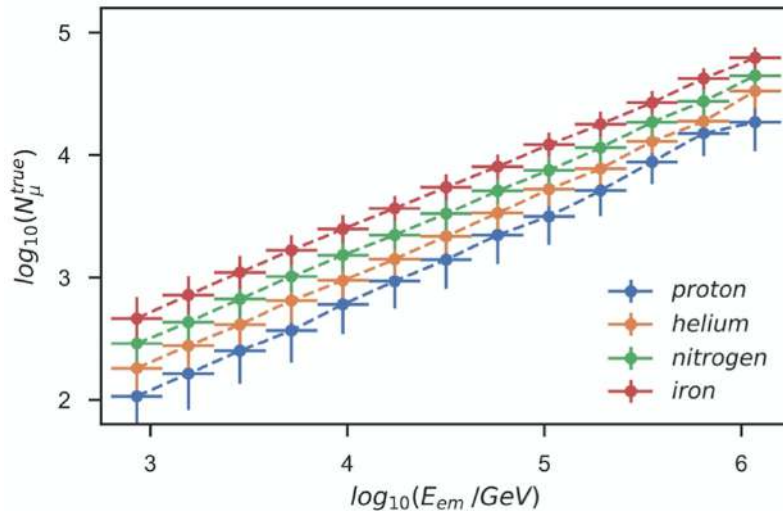
Neutrino Synergies

- ⊙ SWGO+LHAASO
 - Full sky map of TeV-PeV γ emission
- ⊙ Strongly complements new generation of **neutrino instruments**
 - Mapping out diffuse emission / separating IC from pion decay emission, **Dark Matter search** +++
 - Nearby transients/flares

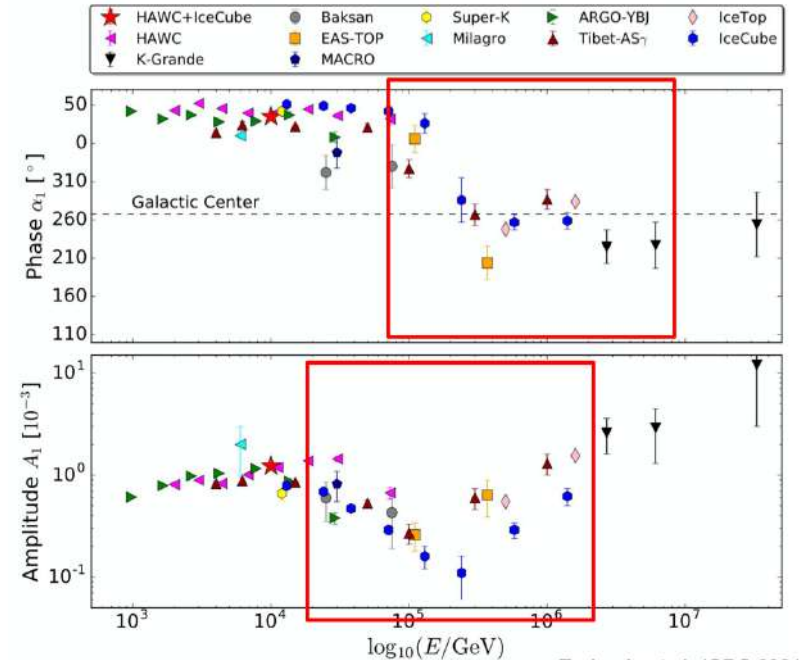


Cosmic rays

- ◎ Charged cosmic ray physics at the knee
 - **Mass-resolved anisotropy studies**
- ◎ Measuring μ -content with WCDs
 - Tagging of single muons at detector unit



Taylor, A. et al., ICRC 2021



Taylor, A. et al., ICRC 2021

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SWGO Collaboration Meeting — Rio de Janeiro — April 2023

