Muon identification and gamma/hadron discrimination using compact single-layered water Cherenkov detectors powered by Machine Learning techniques

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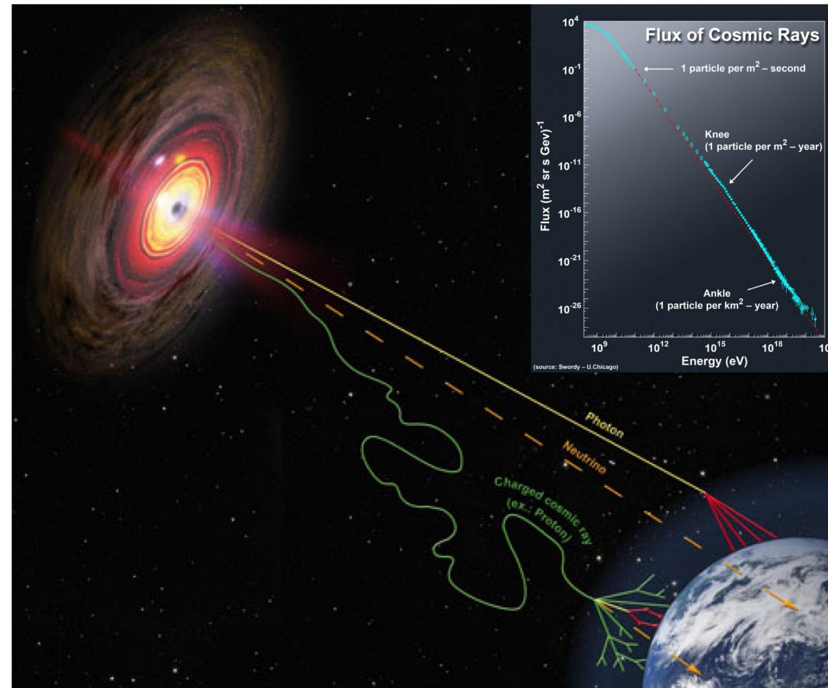
Second MODE Workshop on Differentiable Programming for Experiment Design
Kolymbari, Crete, Greece, September 14th , 2022

Very high-energy gamma-rays

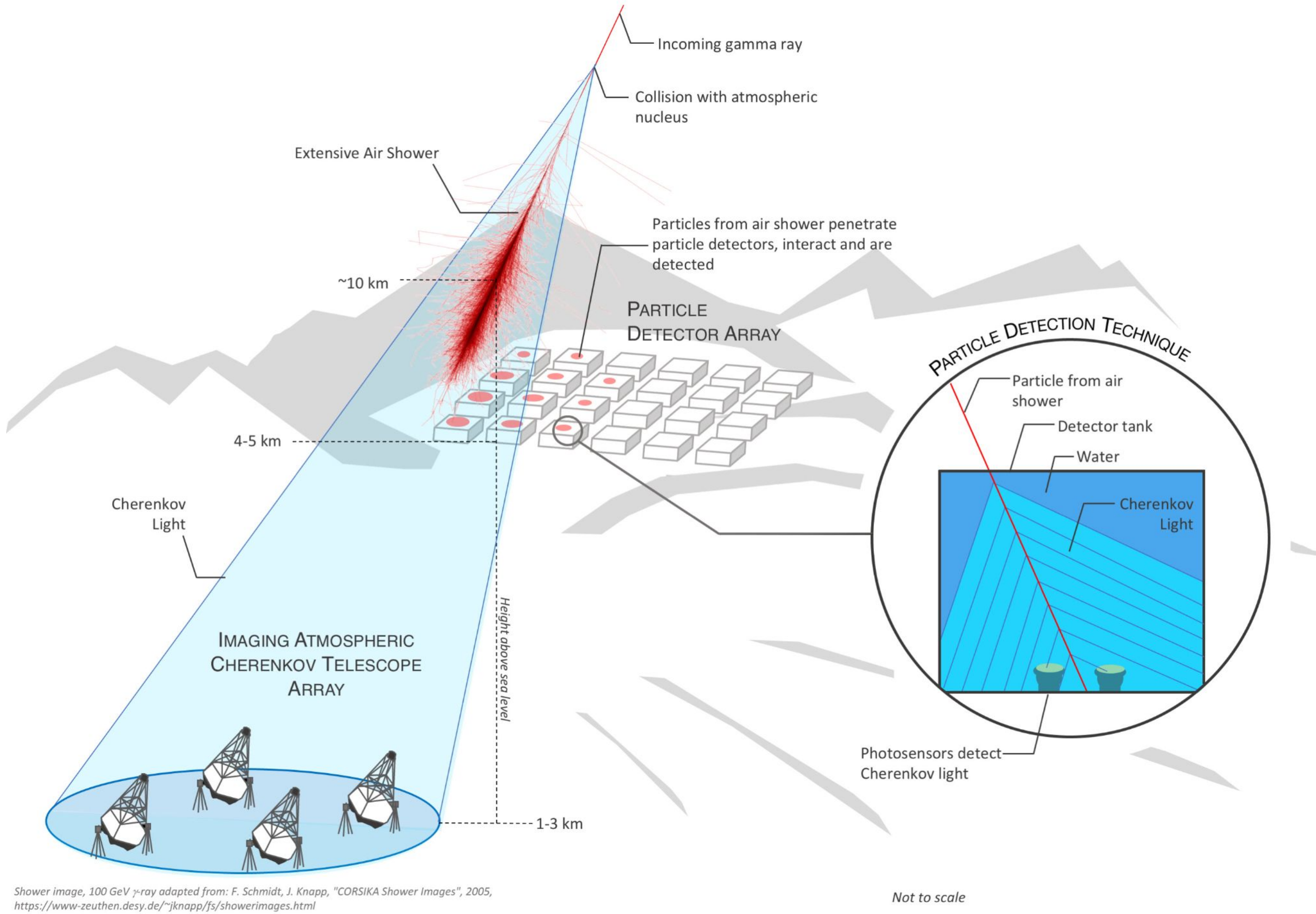
- Extremely energetic photons.
  - From few hundreds of GeVs up to the PeVs.
  - They point to their production source.

- Gamma-rays are related to some of the most extreme and energetic non-thermal events taking place in the Universe.
  - Gamma-Ray Bursts (GRBs)
  - Active Galactic Nuclei (AGNs).
  - Supernovae.

- Essential to prove the existence of new physics at fundamental scales beyond the standard model.
  - Dark matter indirect searches; Lorentz invariance; Quantum gravity; …

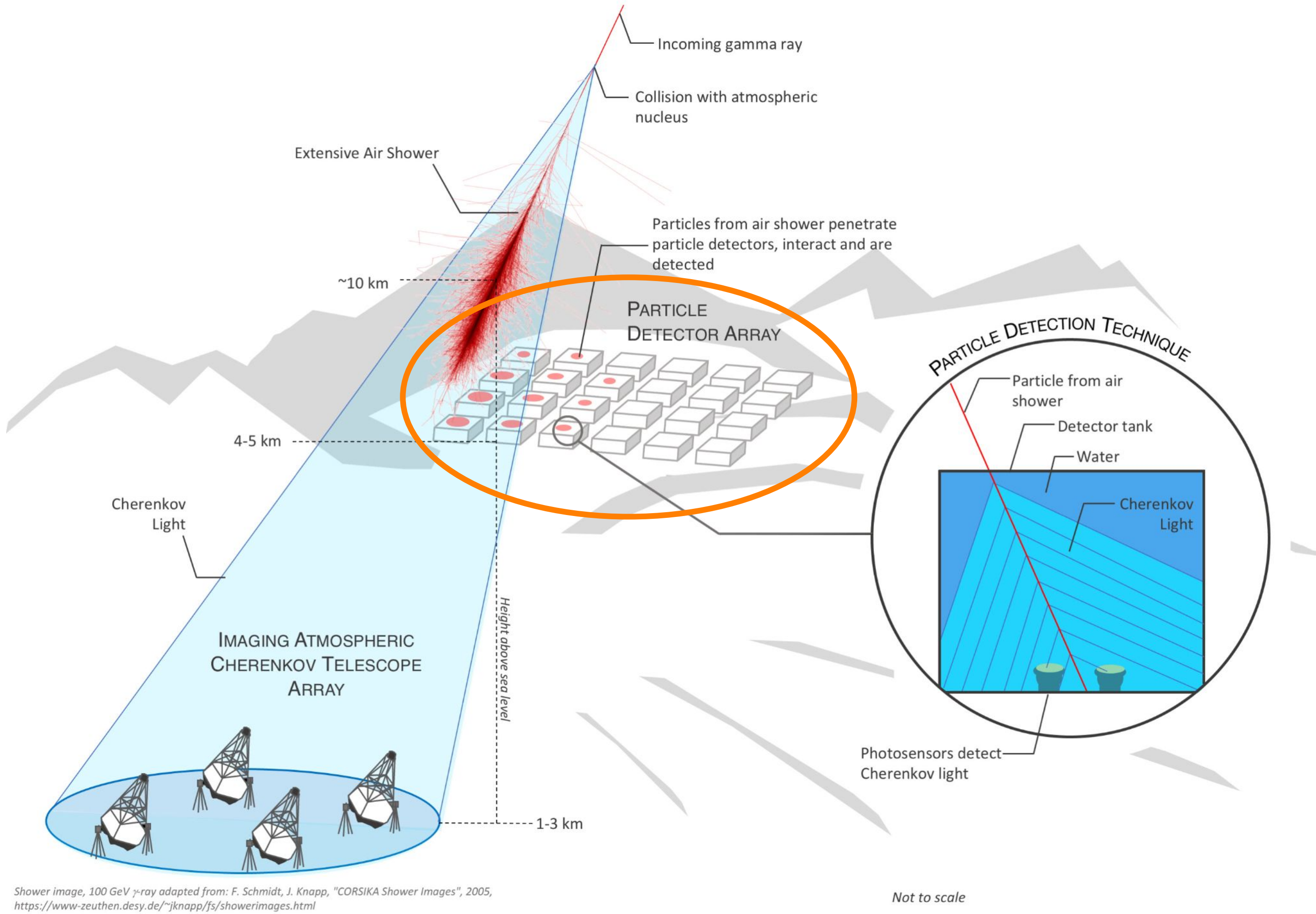


Indirect gamma-ray detection techniques



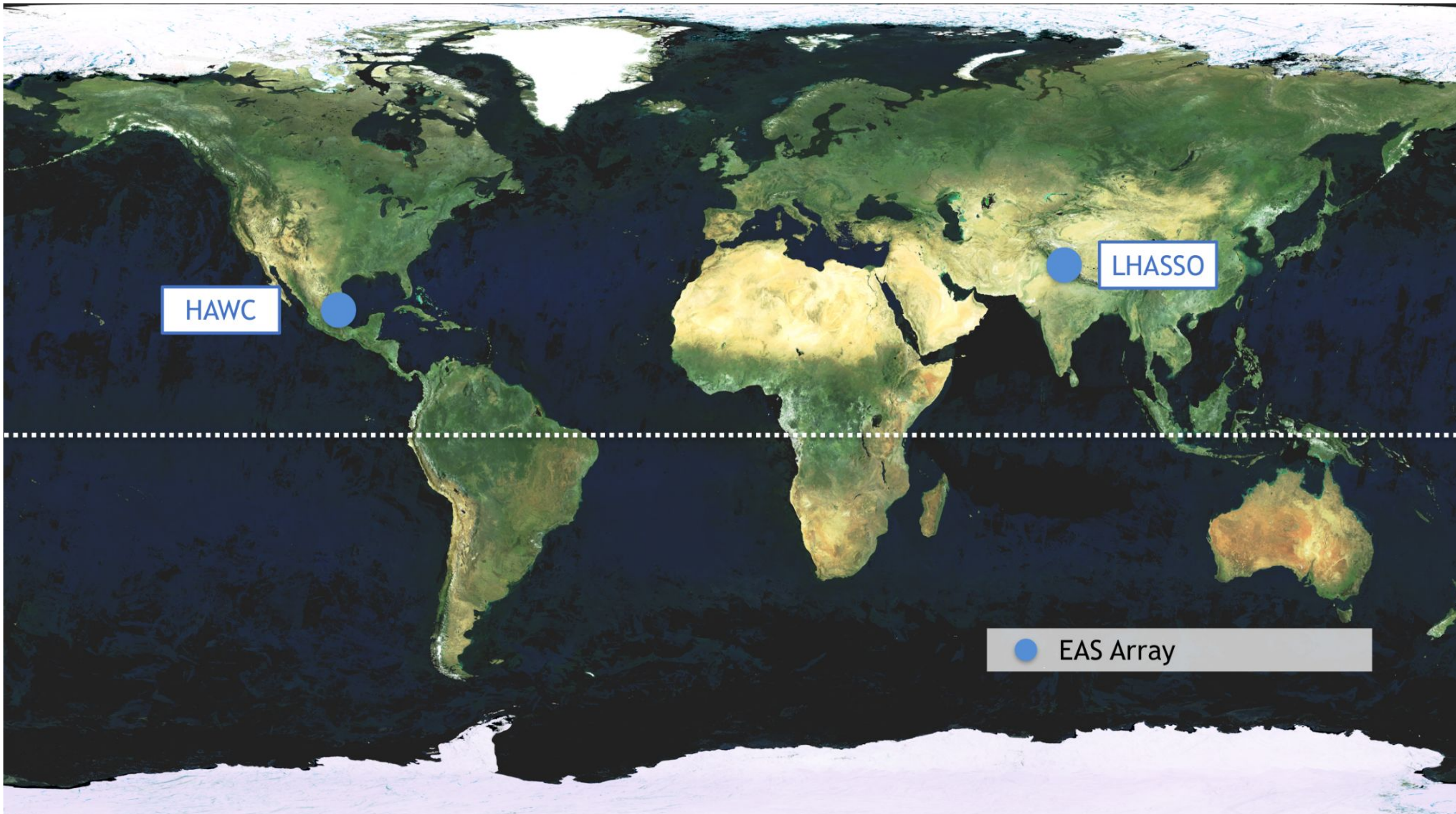
Source: https://www.swgo.org/

Indirect gamma-ray detection techniques



Source: https://www.swgo.org/

Current EAS arrays



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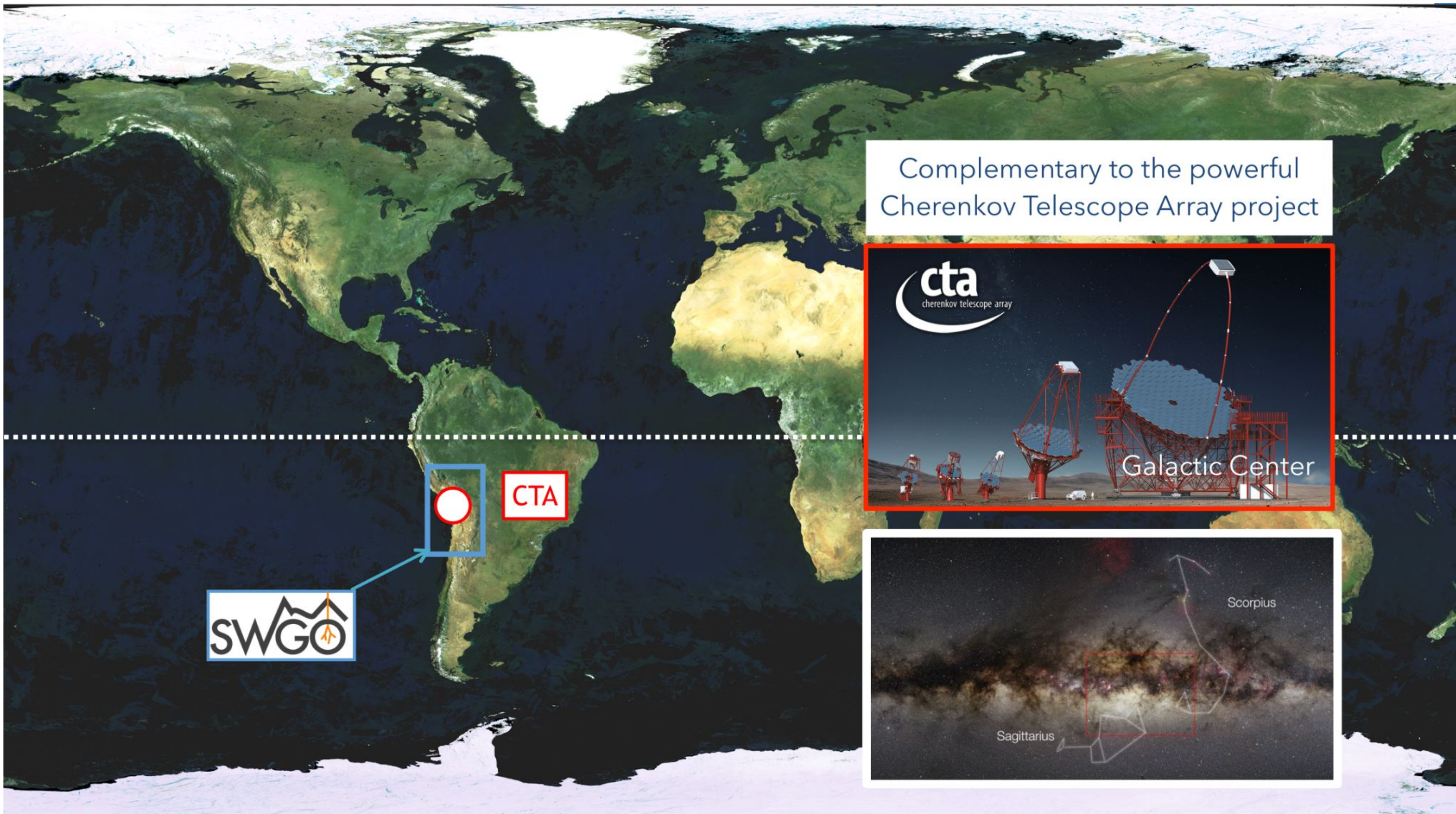
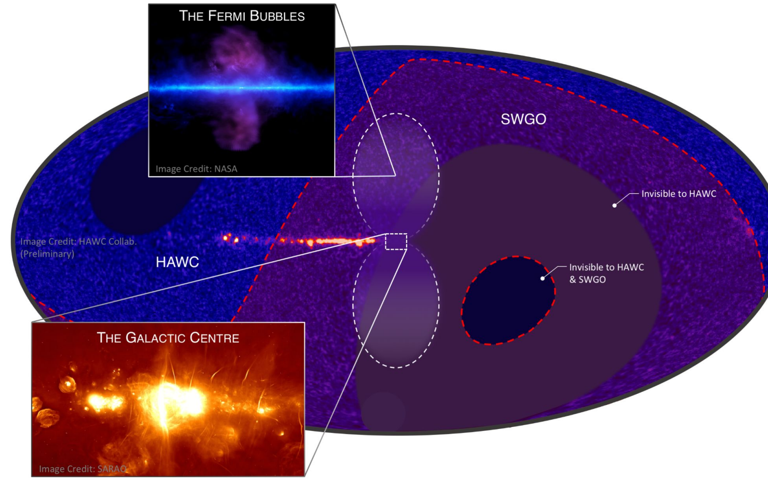
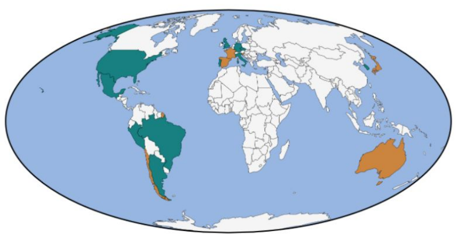


Southern Wide-field Gamma-ray Observatory (SWGO)

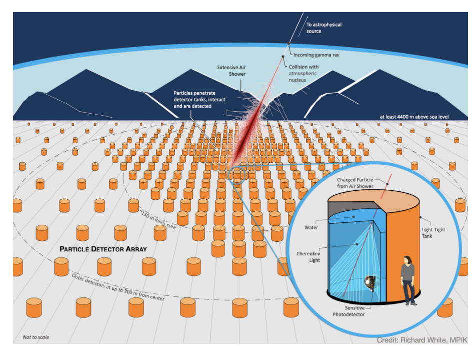
~3-year R&D project to design and plan the next generation wide field-of-view gamma-ray able to survey and monitor the Southern sky

- **S**outhern **W**ide-field **G**amma-ray **O**bservatory (SWGO)
  - Formed at July 1st 2019
  - 13 Countries
  - ~50 institutes
  - More than 100 scientists
  - To be built in South America at a latitude between 10 and 30 degrees south.





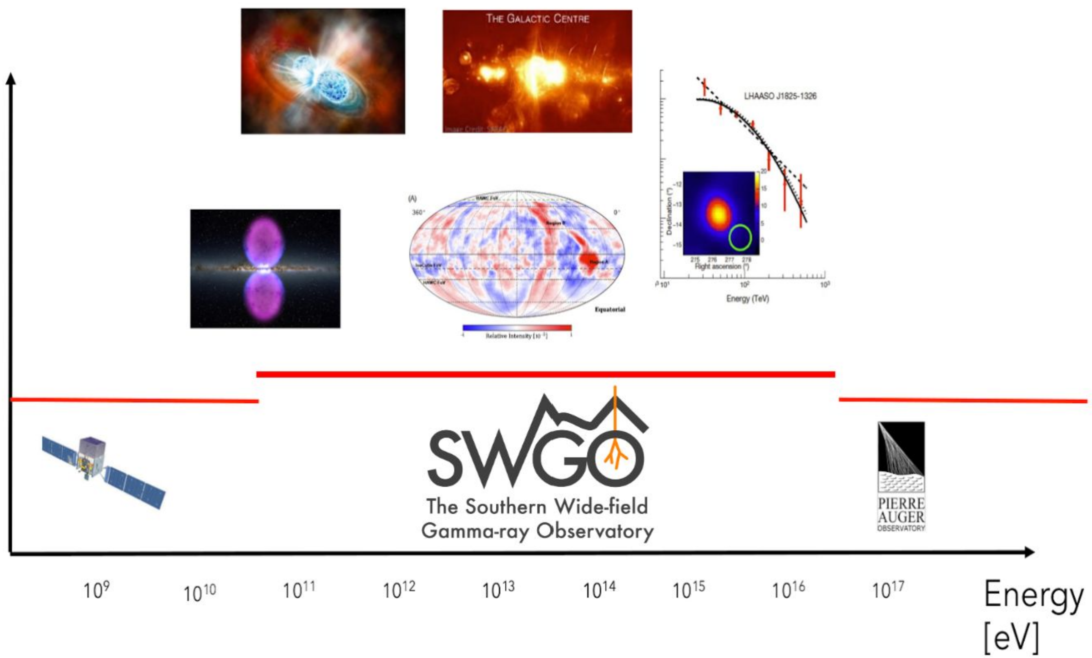
	SWGO R&D Phase Milestones	
✓	M1	R&D Phase Plan Established
✓	M2	Science Benchmarks Defined
✓	M3	Reference Configuration & Options Defined
	M4	Site Shortlist Complete
✓	M5	Candidate Configurations Defined
	M6	Performance of Candidate Configurations Evaluated
	M7	Preferred Site Identified
	M8	Design Finalised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



Source: https://www.swgo.org/

The Southern Wide-field Gamma-ray Observatory

Energy range covered with SWGO

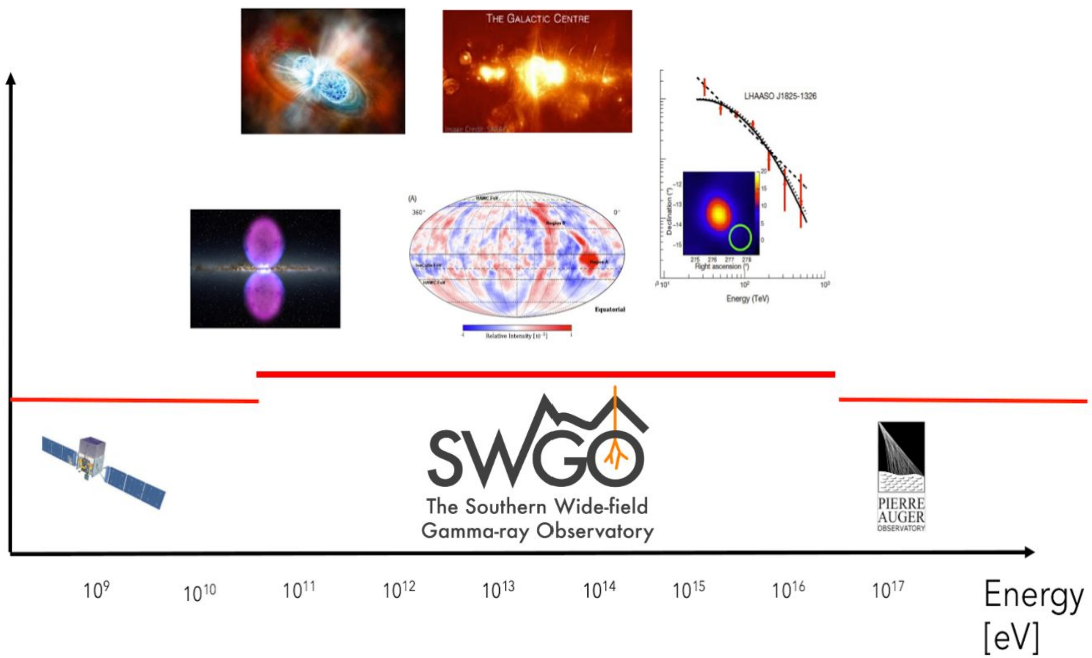


From many tens of GeV to many tens of PeV.

Energy range covered with SWGO

<u>Lowest energies:</u>

- High altitude
- Compact array
- Dedicated ground detector design



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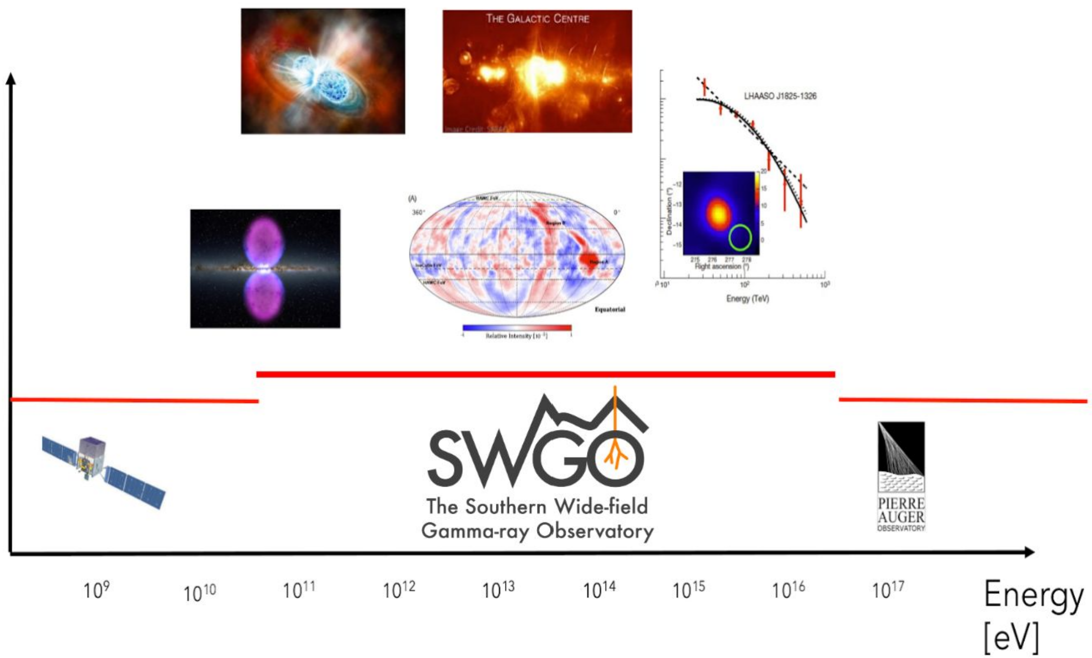
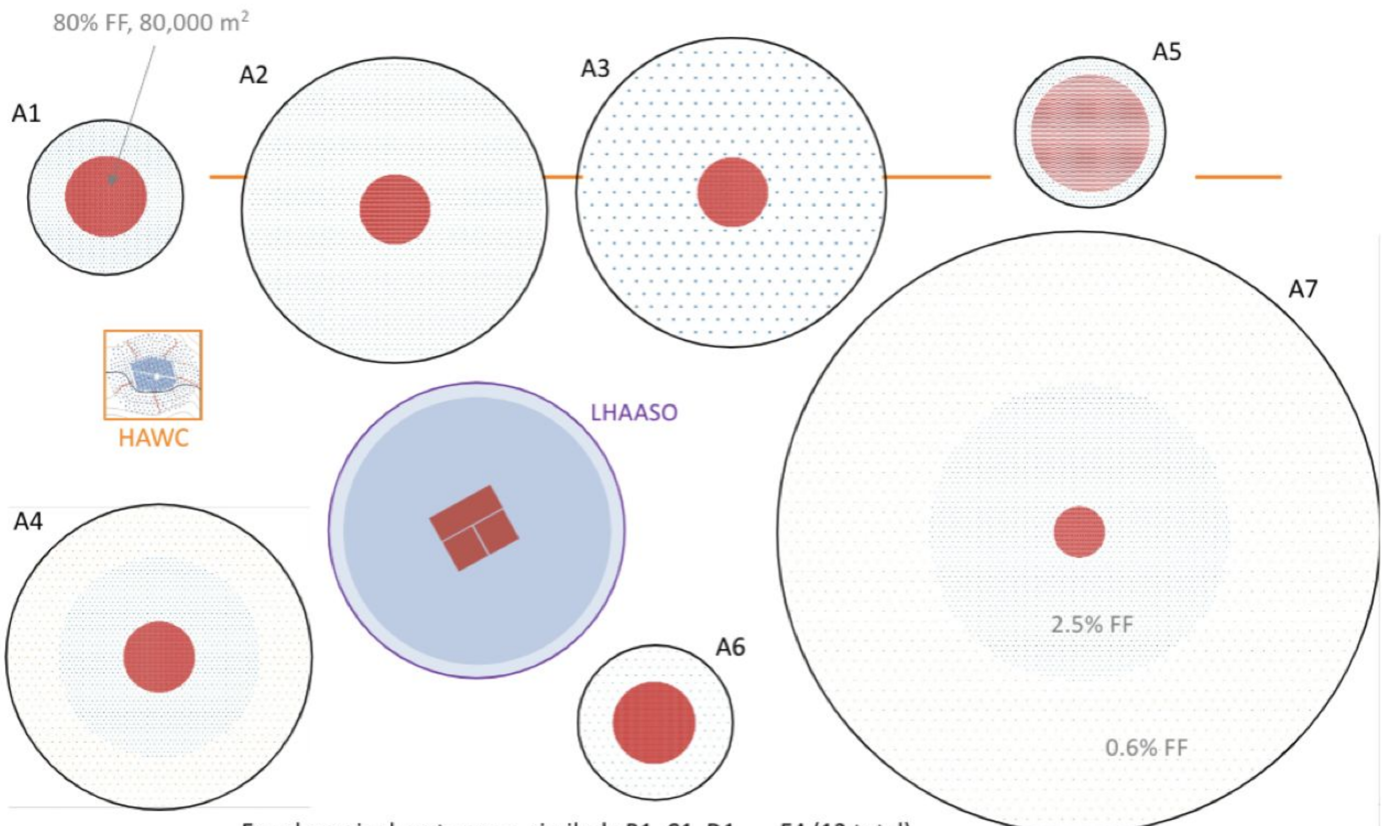


<u>Highest energies:</u>
- Large array area (~1 km² or more)
- Modular
- Sparse array

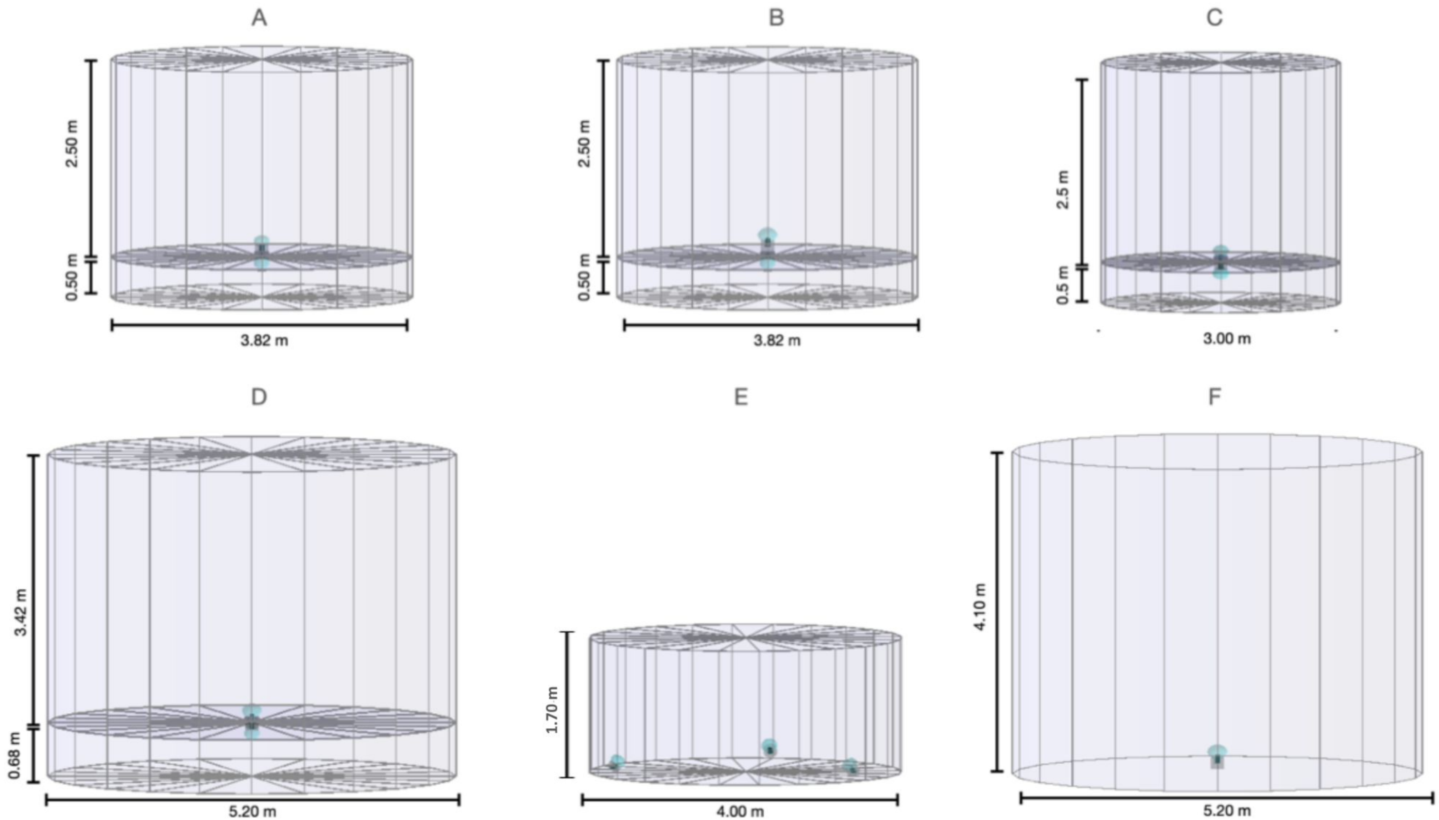
From many tens of GeV to many tens of PeV.

Explore different array layout configurations



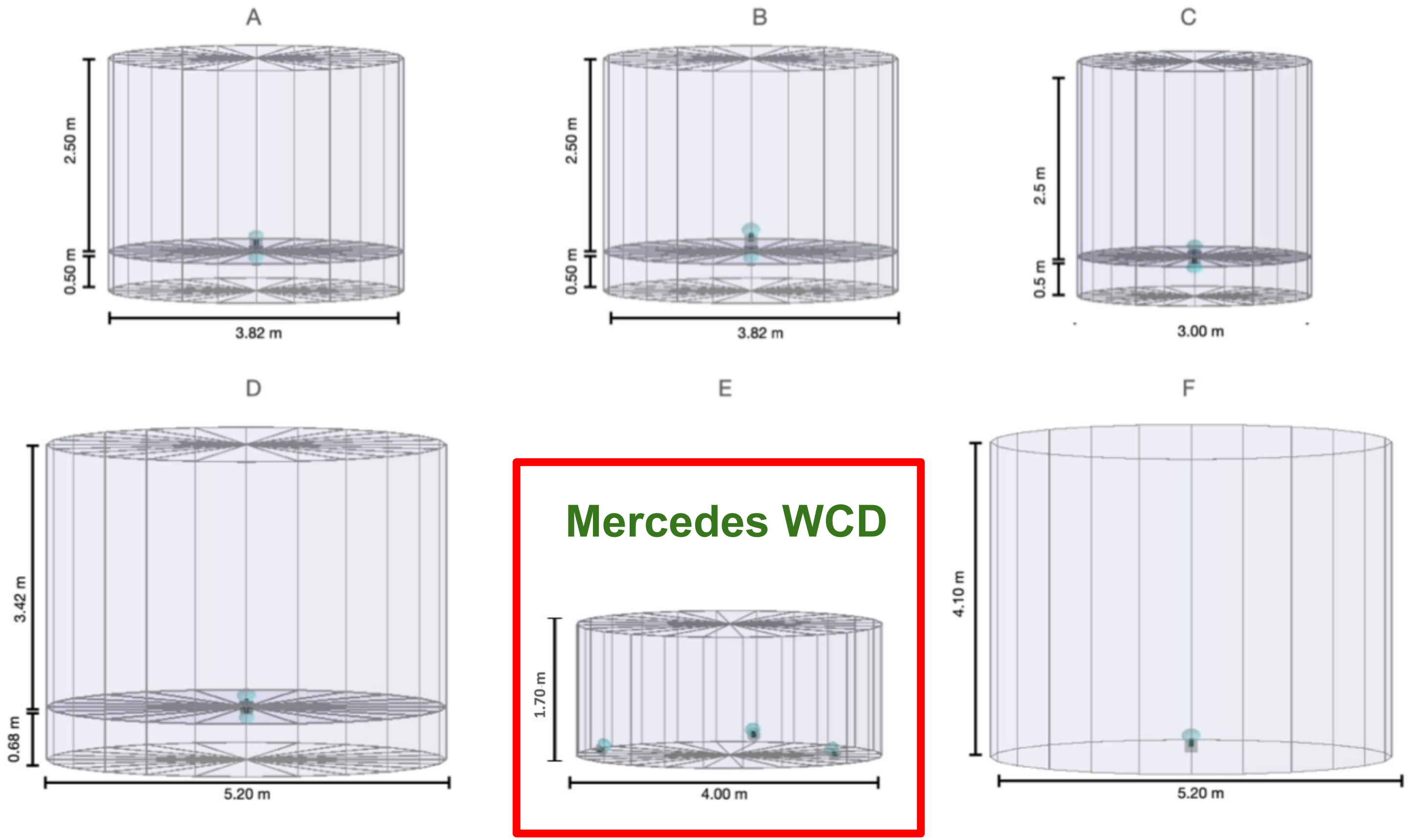
Equal nominal cost arrays, similarly B1, C1, D1, ..., E4 (13 total)

Possible WCD options



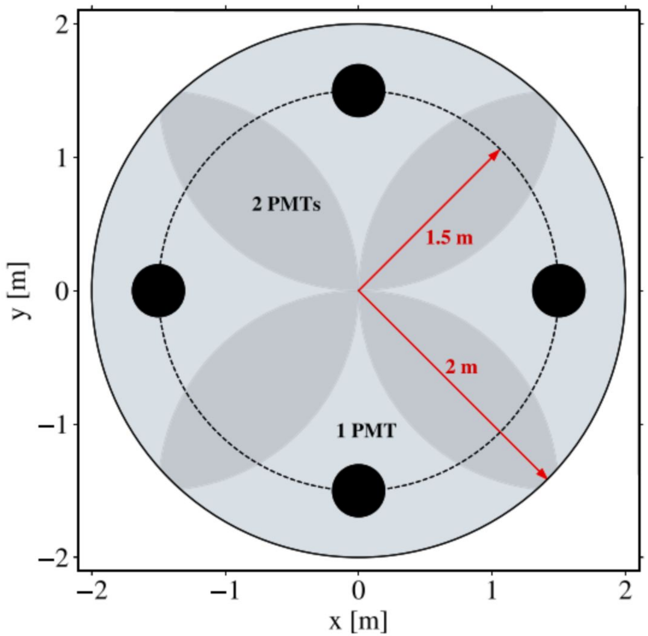
WCD design is essential for muon tagging and gamma/hadron discrimination

Possible WCD options



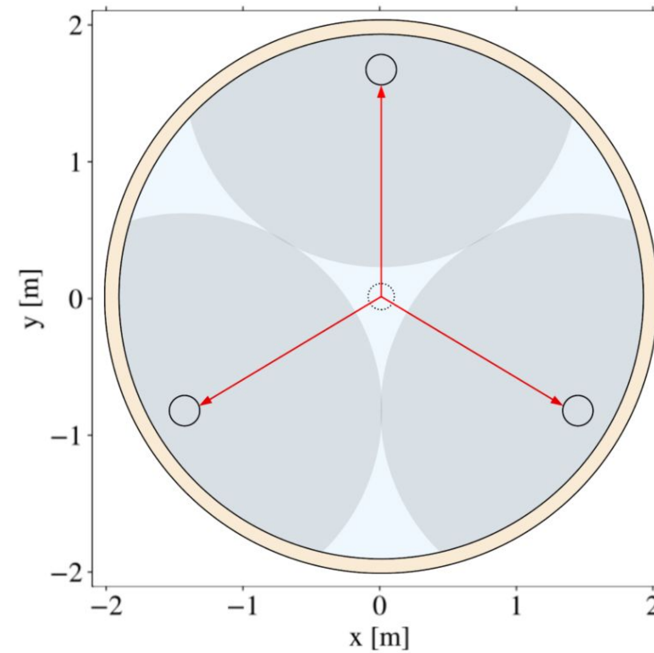
WCD design is essential for muon tagging and gamma/hadron discrimination

Explore asymmetries to tag muons



4x 8-inch PMTs
Water height 1.7 m
Tyvek walls

References:
Eur.Phys.J.C 81 (2021) 6, 542.
Neural Comput & Applic 34, 5715–5728 (2022).
Physics Letters B 827, 136969 (2022)



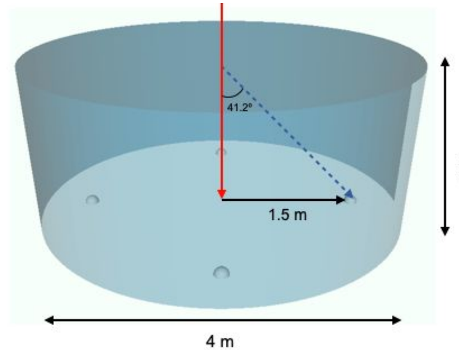
3x 8-inch PMTs
Water height 1.7 m
Tyvek walls

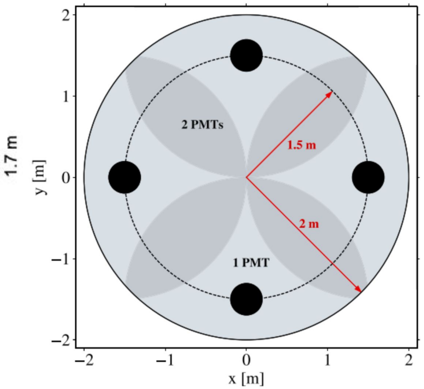
References:
arXiv:2203.08782

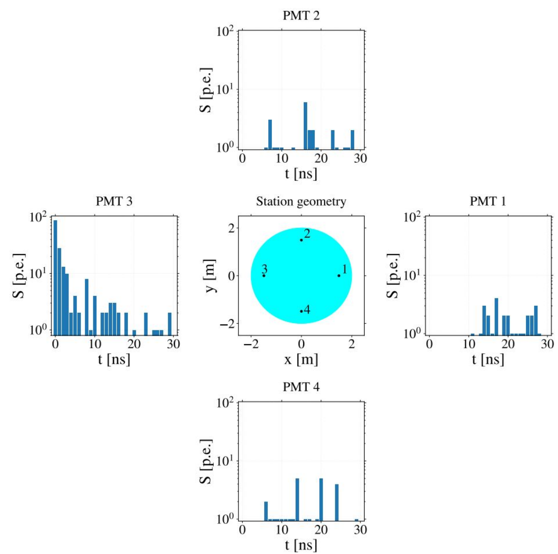
WCD with 4 photo-sensors

Approach using 4 PMTs

- Dimensions based on Single Muon identification.
  - No blind spots.
  - SM seen at most by 2 PMTs.
  - Maximisation of the signal asymmetry to find muons.
- Taking a base diameter: 4 m
  - Height: 1.7 m.
  - PMTs to center: 1.5 m.
  - Less water.
- White walls.
  - Lower the energy threshold.
  - Shower geometry reconstruction taken from the direct Cherenkov light

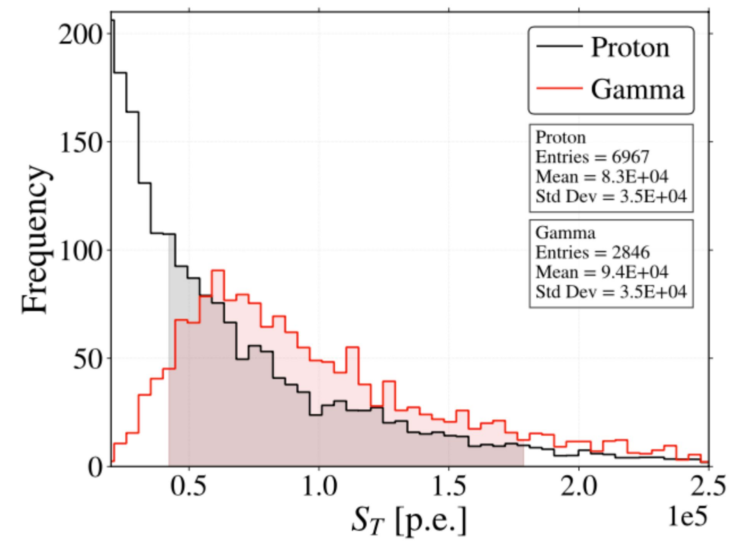






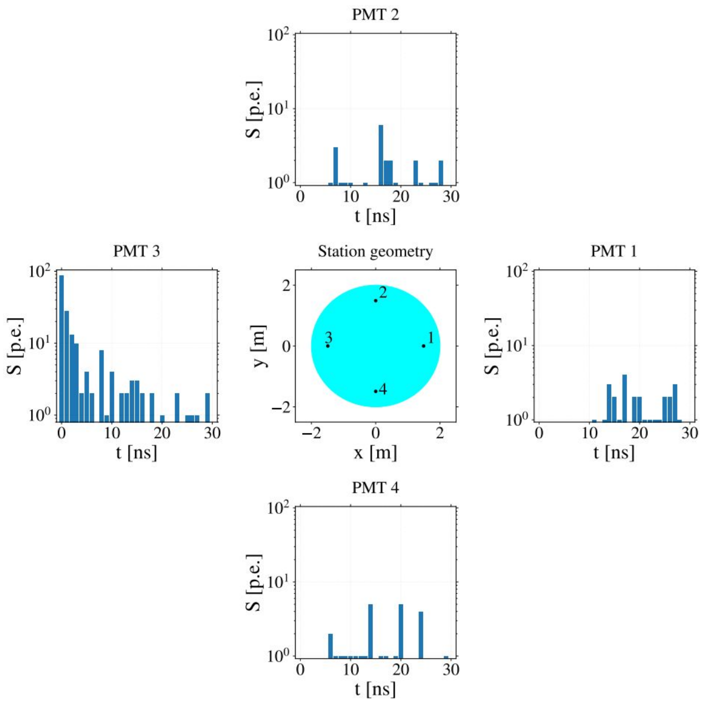
Simulation (4 PMTs)

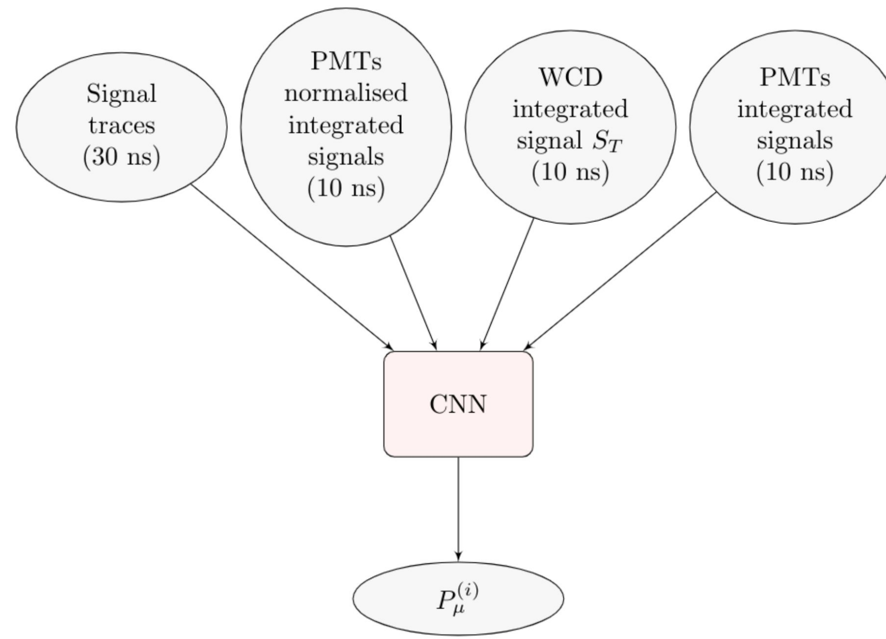
- Simulations:
  - Detector sim. done with Geant4
  - CORSIKA showers at 5200m.
  - Proton: $E_0 \in [0.7,6]$ TeV.
  - Gammas: $E_0 \in [1,1.6]$ TeV.
  - Events with similar signal at the ground.
  - $\theta \in [5°, 15°]$ and [25°,35°].
  - Dense and sparse array.



Events with similar reconstructed energy ~ 1 TeV

ML model (4 PMTs)

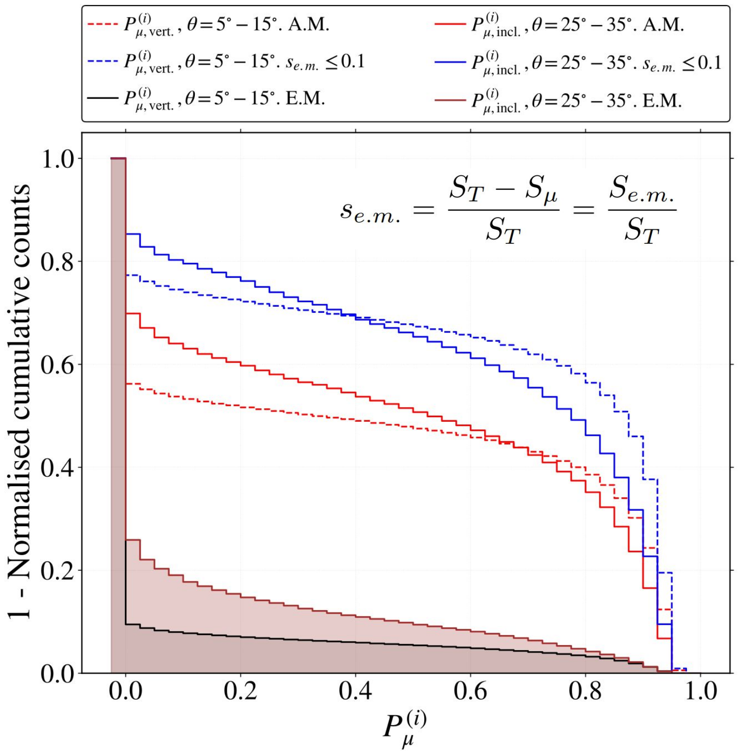


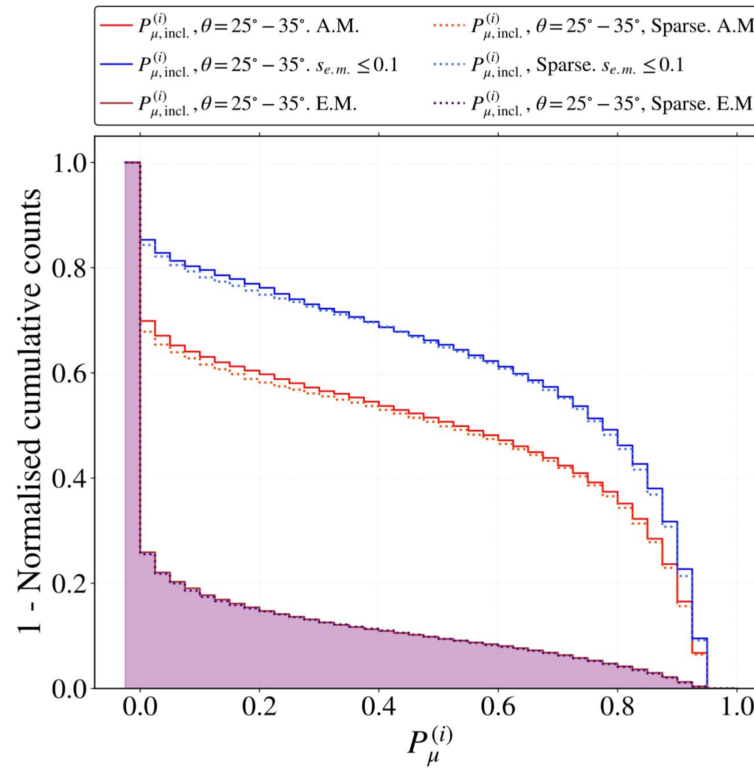


Analyse signal to get the probability that a muon has passed through the WCD.

- Convolutional Neural Network (CNN)
  - Eur.Phys.J.C 81 (2021) 6, 542 (arXiv:2101.10109 [physics.ins-det])
- Several other models tested
  - Neural Comput & Applic 34, 5715–5728 (2022). (arXiv:2101.11924 [physics.ins-det])

Inclined showers and sparse array





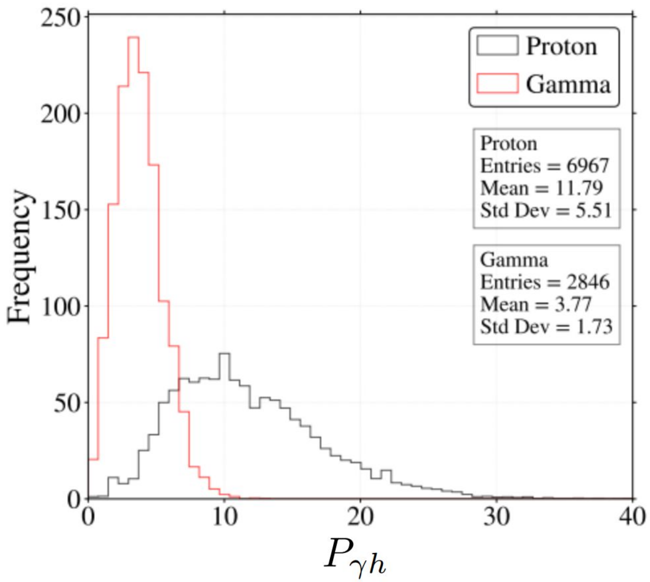
The model was retrained for inclined showers.
Performances nearly independent of the shower inclination

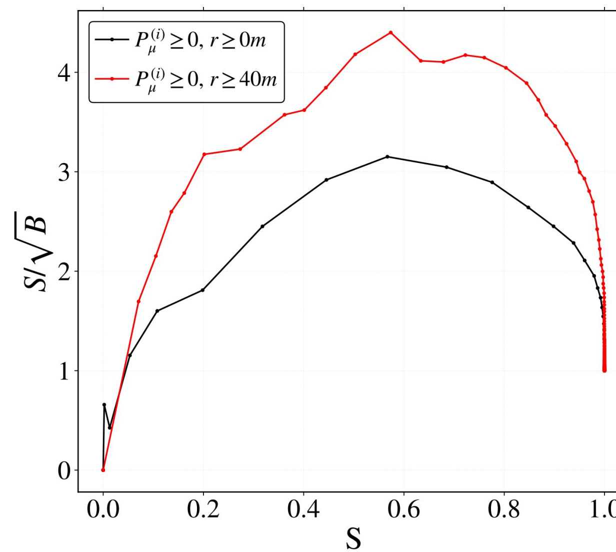
Stations in the sparse and dense array have the same performance.

Muon tagging - G/H discrimination (E_0~1 TeV)

- Build a quantity to evaluate the gamma/hadron discrimination power and the muon quantity in the shower.

$$P_{\gamma h} = \sum_{k=i}^{n_{stations}} P_{\mu,i}$$

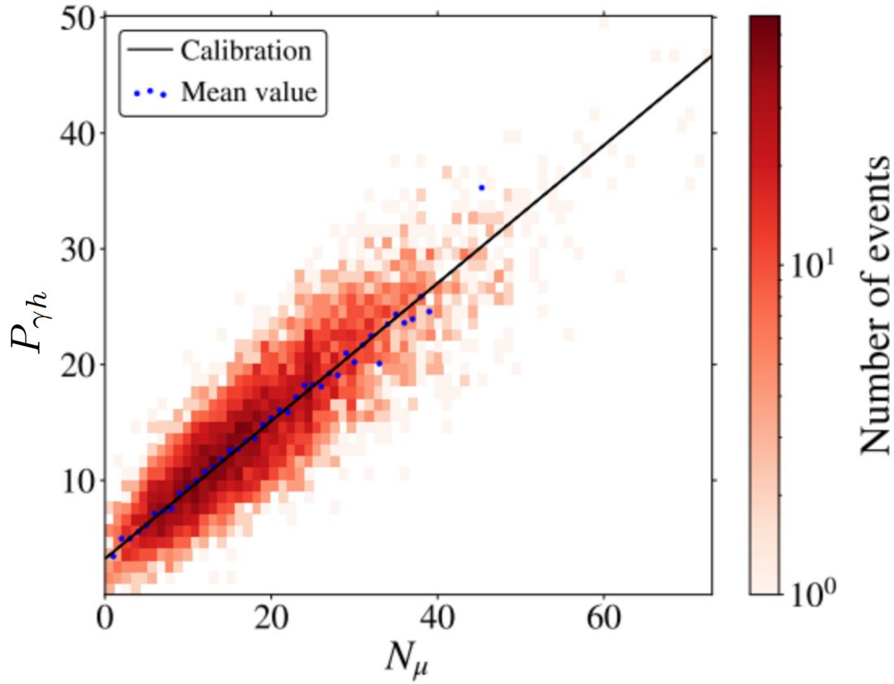


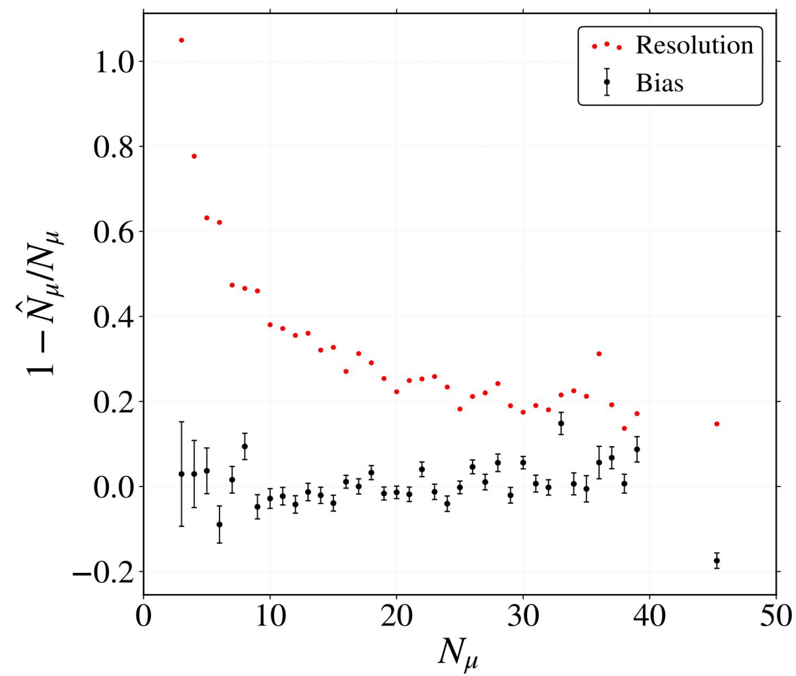


Good gamma/hadron discrimination at E ~1TeV

S/sqrt(B) ~ 4 (similar to LATTES and HAWC)

Muon tagging - G/H discrimination (E_0~1 TeV)





Sensitive to the overall number of muons in the shower event

Small bias and the method has an intrinsic resolution of 2%

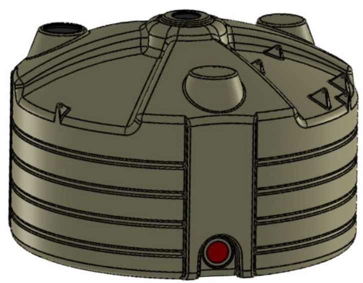
$$\hat{N}_\mu = 1.67\, P_{\gamma h} - 3.22$$

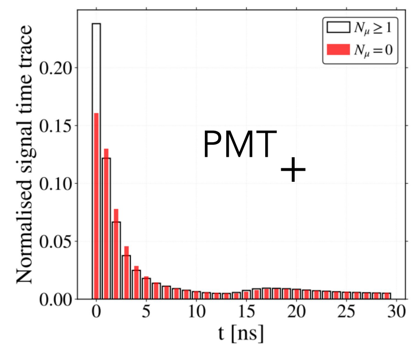
WCD with 3 photo-sensors

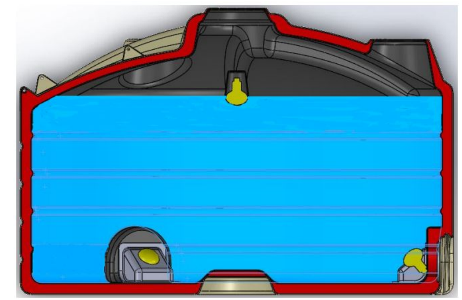
The Mercedes station

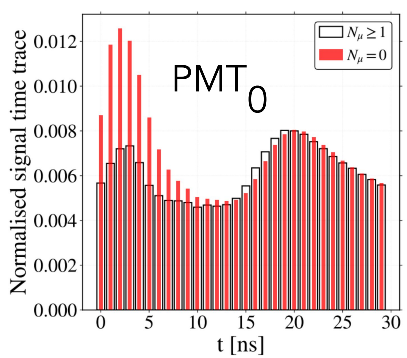
The Mercedes WCD (3 PMTs)

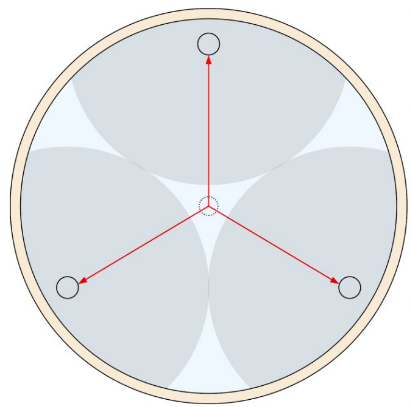
Analyse signal to get the probability that a muon has passed through the WCD.

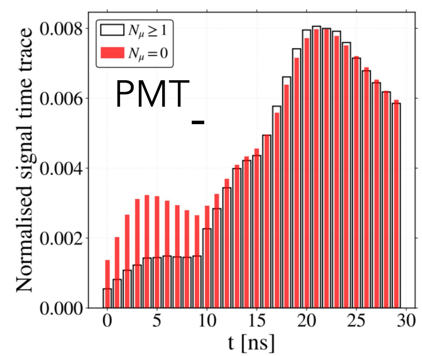






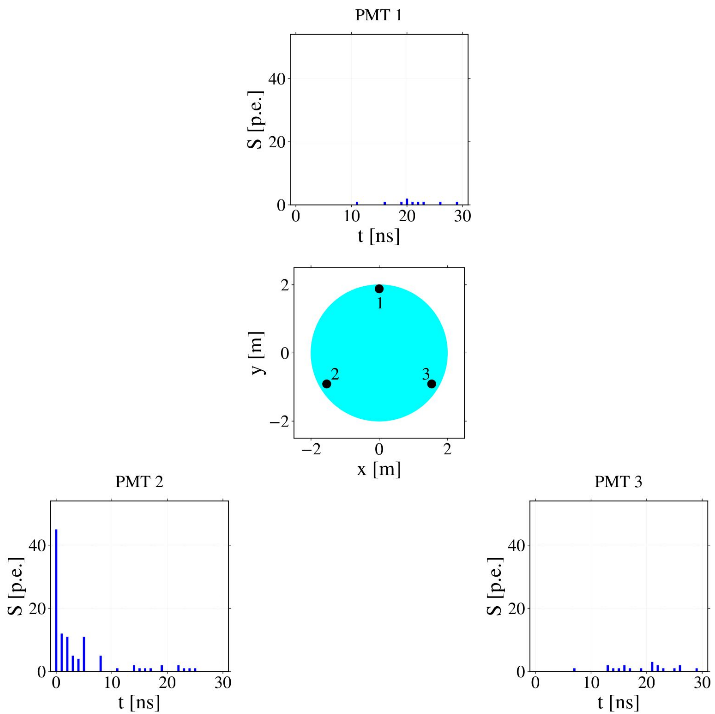


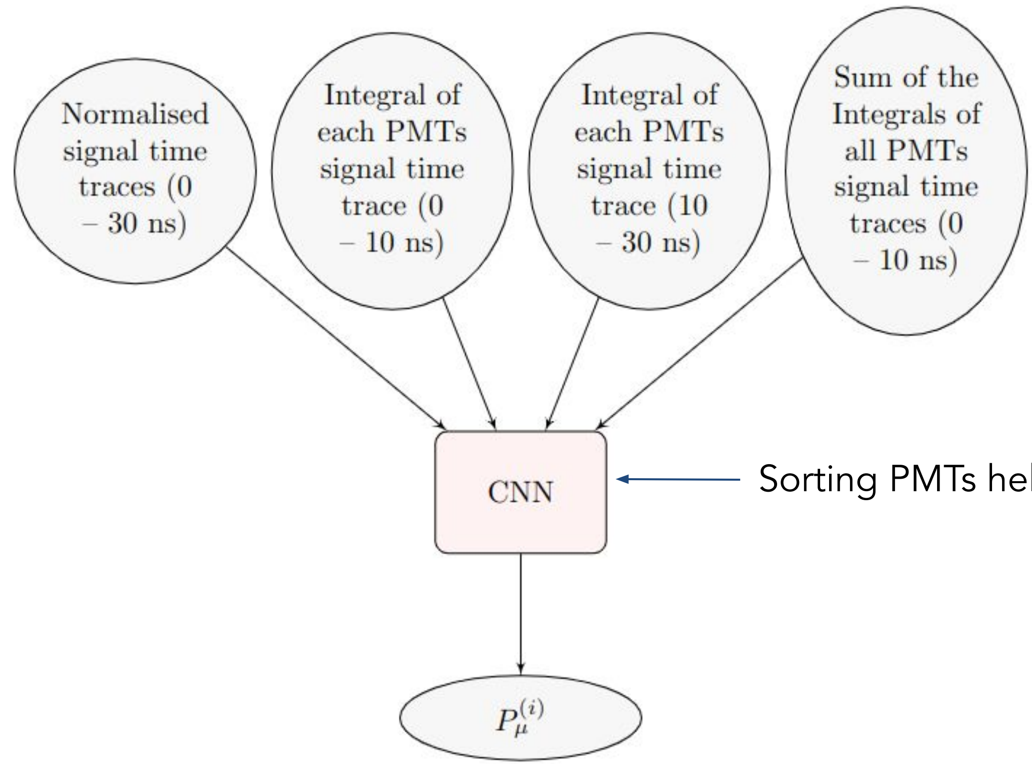




arXiv:2203.08782

ML model (3 PMTs)





Sorting PMTs helps!

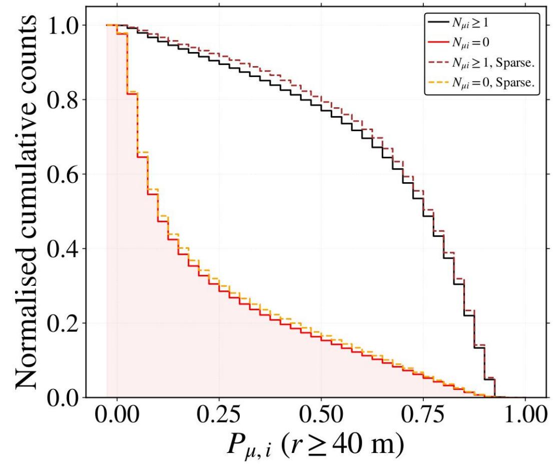
Analyse signal to get the probability that a muon has passed through the WCD.

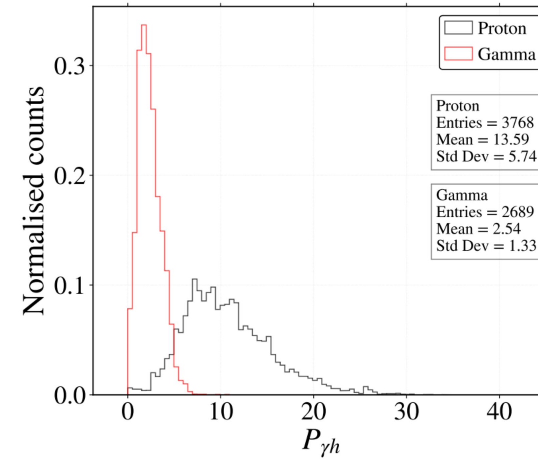
Simulation and ML model (3 PMTs)

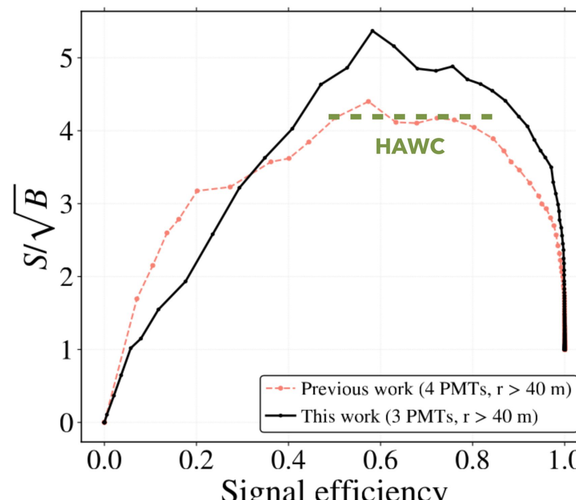
- Variable to evaluate the gamma/hadron discrimination power and the muon quantity in the shower.

$$P_{\gamma h} = \sum_{k=i}^{n_{stations}} P_{\mu,i}$$

- Excellent gamma/hadron discrimination at E ~ 1TeV.
  - S/sqrt(B) ~ 5.
  - Submitted to EPJC (arXiv:2203.08782).
  - Previous work with 4 PMTs: Eur.Phys.J.C 81 (2021) 6, 542.







Conclusions

- Studies at few TeV show that it is possible to perform an excellent muon tagging/counting using a small WCD with multiple PMTs provided that the analysis is performed using ML techniques.
  - → Excellent gamma/hadron discrimination using both stations.
  - → The method works in vertical/inclined showers and compact/sparse array making it interesting for SWGO.
- On-going work and next steps:
  - → γ/h discrimination combining the WCD muon info with shower patterns.
  - → Optimisation studies to be conducted: WCD dimensions, array fill factor.
- This method is still far from being fully explored and optimised.
  Very open for new partners and new ideas!

Thanks for your attention!

Acknowledgements:
IDPASC PhD grant PRT/BD/151553/2021

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Reference configuration for SWGO

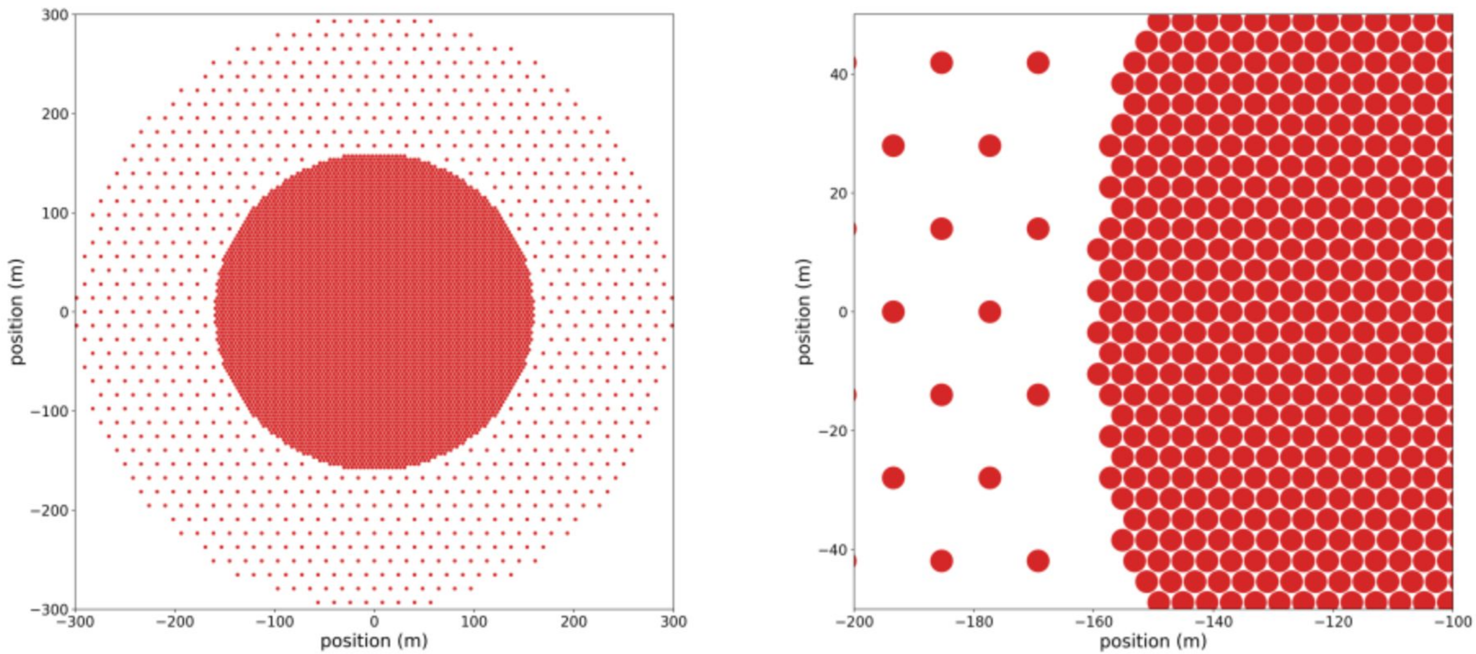


Fig. 1. Left: Reference Configuration layout. Right: zoom of the boundary between core array and outriggers.

Anticipated schedule for SWGO

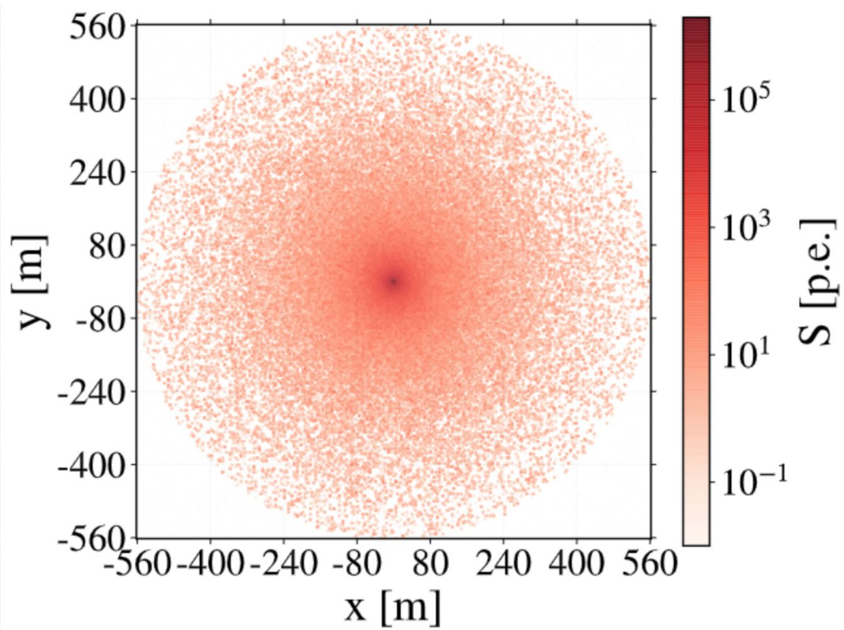
Figure 5 illustrates the anticipated R&D project schedule in terms of expected dates for milestones to be met. In case of slippage, original dates are marked with a →.

Milestone	2019	2020				2021				2022				2023				2024			
	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
R&D Phase Plan		M1																			
Science Benchmarks			M2																		
Reference Configuration				→	M3																
Site Shortlist Complete					→						M4										
Candidate Configurations							→			M5											
Perf. of Candidates Evaluated								→						M6							
Preferred Site Identified									→							M7					
Design Finalised											→							M8			
CDR Ready													→						M9		

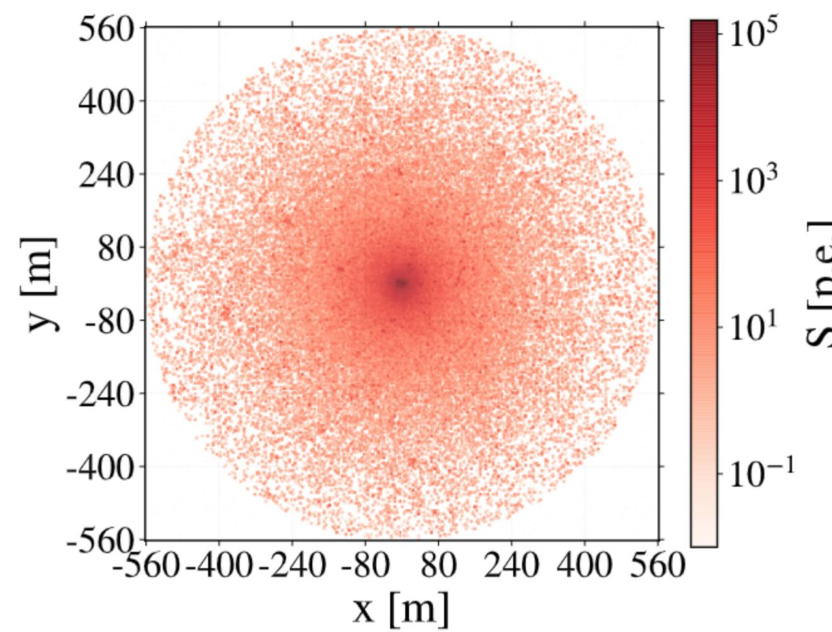
Figure 5: Indicative schedule for the milestones of the R&D phase. An arrow indicates a shift from the originally indicated date. Those milestones in orange are complete as of this revision of the R&D Plan.

Future steps: Enhance γ/hadron separation

Gamma



Proton



Combine muon info at WCD with the shower footprint.

EAS vs IACTs

	EAS-D	IACT
Duty-Cycle	High (≈100%)	Low (≈10-15%)
Field-of-View	Large (2 sr)	Small (4-5 deg)
Sensitivity	Good Sensitivity (5-10% Crab flux)	High Sensitivity (< mCrab flux)
Maximum Energy	~ PeV	<100 TeV
Energy Resolution	Modest (~30-40%)	Very Good (~15%)
Energy Threshold	High (~TeV)	Very Low (~10 GeV)
Angular resolution	Good (0.2-0.8 deg)	Excellent (≈0.05 deg)
Effective Area	decrease with zenith	increase with zenith
Background rejection	Good (~80%)	Excellent (>99%)
Zenith dependence	Very Strong ($[\cos\theta]^7$)	Weak ($[\cos\theta]^{2.7}$)

Source: *CTA & future astroparticle experiments.* D. della Volpe. LHC days 2018.