The Detector Design of the Southern Wide-Field Gamma-Ray Observatory

- Science Benchmarks & Performance Requirements
- Design Drivers
    - Southern Sky
    - Energy Range
    - Background Rejection
- Detector Options – R&D
    - Mechanics
    - Photosensors
    - Electronics
- Design Constraints & Considerations
    - Cost
    - Risk
    - Mitigation
- Detector Deployment & Operation
    - Design Consolidation
    - Construction
    - Analysis, Calibration and Validation
- Summary

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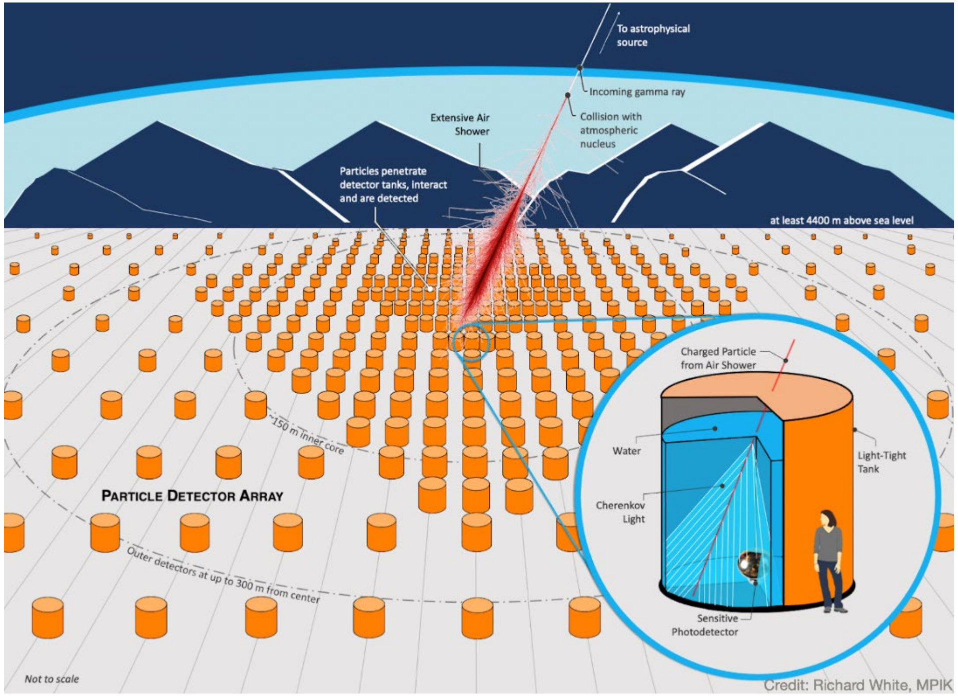
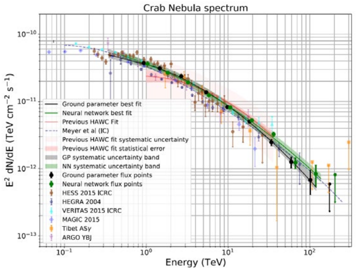
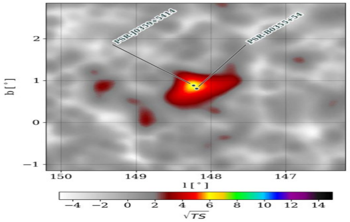
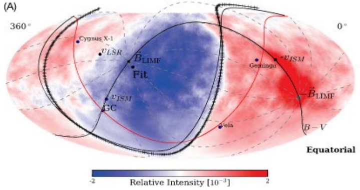


Credit: Richard White, MPIK

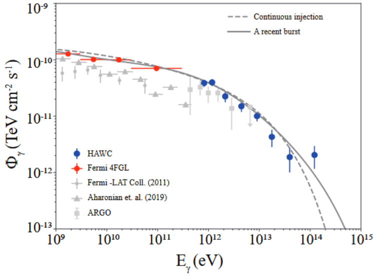
SWGO Science Cases – Design Drivers & Benchmarks

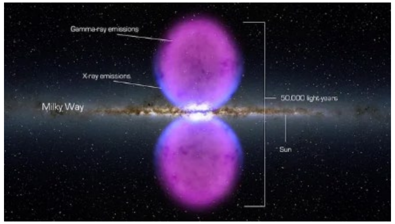


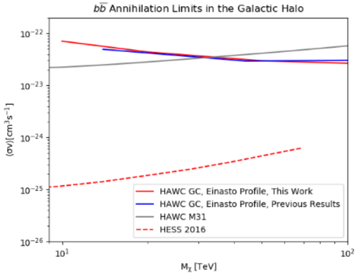




Science Case	Design Drivers	Benchmark Description
Transient Sources: Gamma-ray Bursts	Low-energy sensitivity & Site altitude[a]	Minimum integrated flux (E >100 GeV) for 5σ detection using a PWL index = -2., F(t) $\propto (t/t_{peak})^{-1.2}$ two redshift values (z = 0.3, z = 0.8), 20° from zenith
Galactic Accelerators: PeVatron Sources	High-energy sensitivity & Energy resolution[b]	Flux normalisation at 1 TeV in 5 yr, ensuring 5σ cutoff detection, for: ECPL Index = -2.0, Cutoff = 200 TeV
Galactic Accelerators: PWNe and TeV Halos	Extended source sensitivity & Angular resolution[c]	Maximum source angular extension detectable at 5σ in 5-yr integration for: F(>1TeV) = 5×10^{-13} cm^{-2}.s^{-1}
Galactic Accelerators: Source Confusion	Angular resolution	Minimum angular separation detectable between two sources at 5σ level in 5-yr integration.
Diffuse Emission: Fermi Bubbles	Background rejection	Achievable background rejection power at 3 – 10 TeV whilst keeping 80% of gamma-rays that remain after quality cuts.
Fundamental Physics: Dark Matter from Galactic Halo	Mid-range energy sensitivity Site latitude[d]	100 TeV $b\bar{b}$ thermal-relic cross-section limit at 95% CL in 5-years, for Einasto profile.
Cosmic-rays: Mass-resolved dipole/multipole anisotropy	CR mass-group sensitivity	Muon counting accuracy to enable log-mass CR reconstruction accuracy into 4 groups A={1, 4, 14, 56}; Maximum dipole energy at 10^{-3} level; Maximum multipole scale > 0.1 PeV

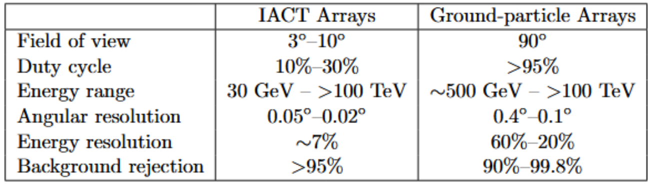






SWGO Science Performance Requirements

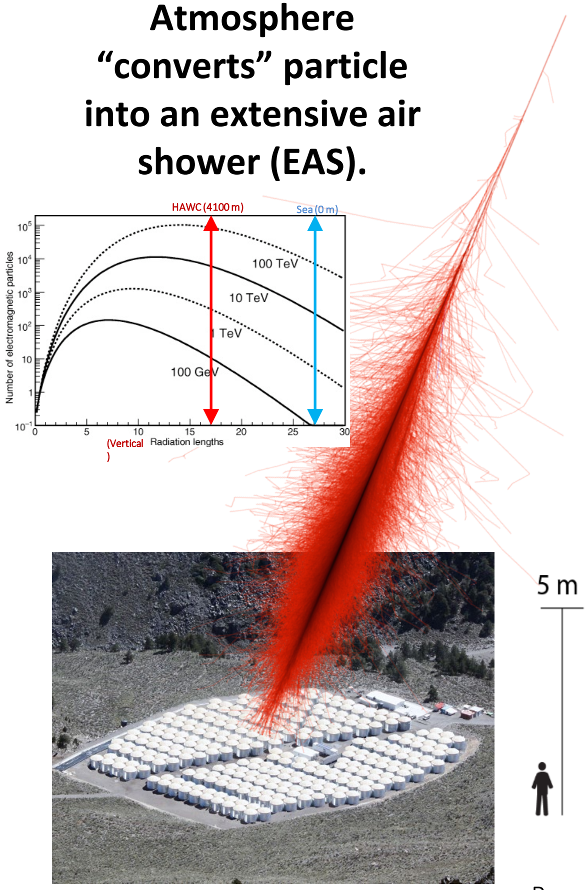
- Wide Instantaneous Field-of-view of the Southern Sky (including GC)
- Continuous Monitoring with minimal downtime
- Low Energy Threshold for Transient Monitoring
- Excellent Differential Point-Source Sensitivity
- Extended Source sensitivity
- Good Measurement of Energy & Arrival Direction
  - Energy resolution better that 20% which improves with energy
  - Sub-degree (<0.3^0) angular resolution which improves with energy
- Excellent Background rejection via Gamma-Hadron Separation
  - Ability to detect Shower "Clumpiness"
  - Muon Tagging/Counting with single WCDs



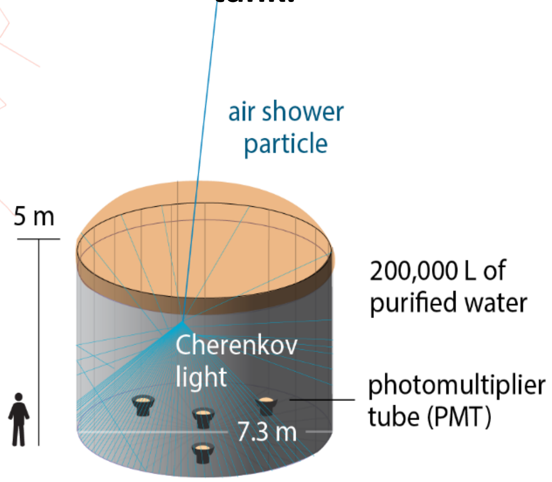
	IACT Arrays	Ground-particle Arrays
Field of view	3°–10°	90°
Duty cycle	10%–30%	>95%
Energy range	30 GeV – >100 TeV	~500 GeV – >100 TeV
Angular resolution	0.05°–0.02°	0.4°–0.1°
Energy resolution	~7%	60%–20%
Background rejection	>95%	90%–99.8%

Design Principles - Water Cherenkov Detector Surface Array

Atmosphere “converts” particle into an extensive air shower (EAS).



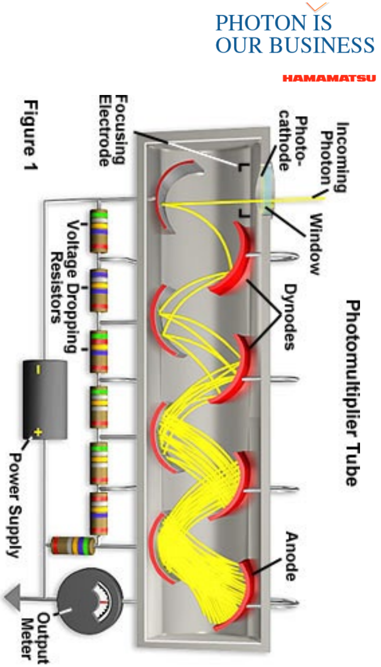
Water Cerenkov Detector Samples Extensive Air Shower particles by measuring their Cerenkov light emitted in water tank.



Based upon Milagro Experiment

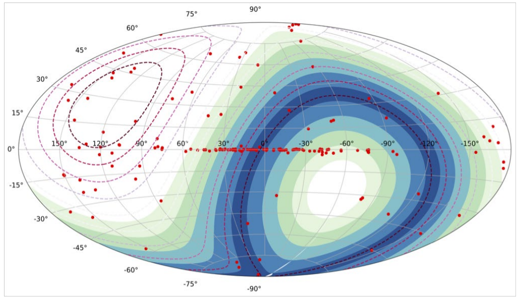
PMT

Converts Cerenkov light into electrical signal.



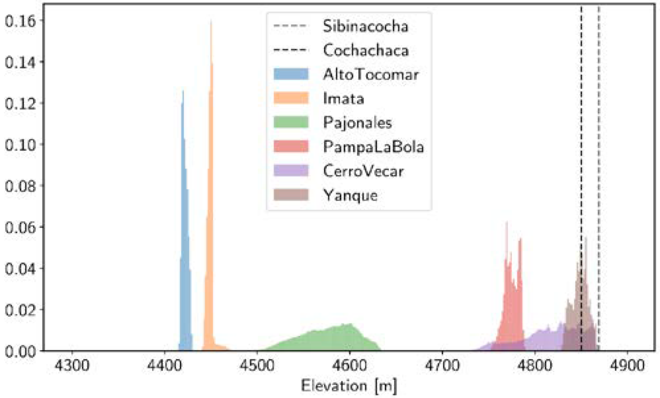
Design Driver – View Southern Sky – High Altitude Candidate Sites

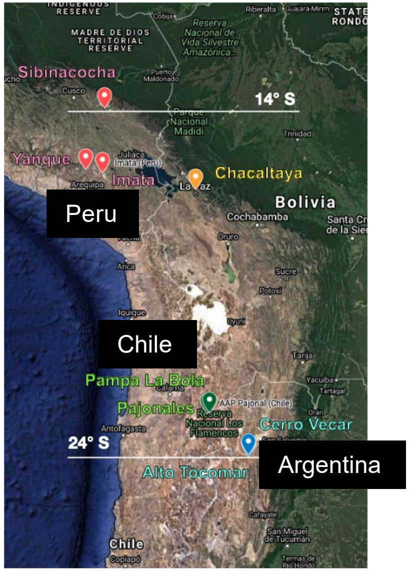
- ☐ **Candidate sites in Argentina, Chile & Peru**
- ☐ **Latitudes – 14^0 S – 24^0 S**
- ☐ **Altitudes – 4450 m – 4800 m**



Exposure at 25 S latitude https://arxiv.org/pdf/1902.08429

Country	Site Name
Argentina	Alto Tocomar
	Cerro Vecar
Chile	Pajonales
	Pampa La Bola
Peru	Imata
	Sibinacocha
	Yanque



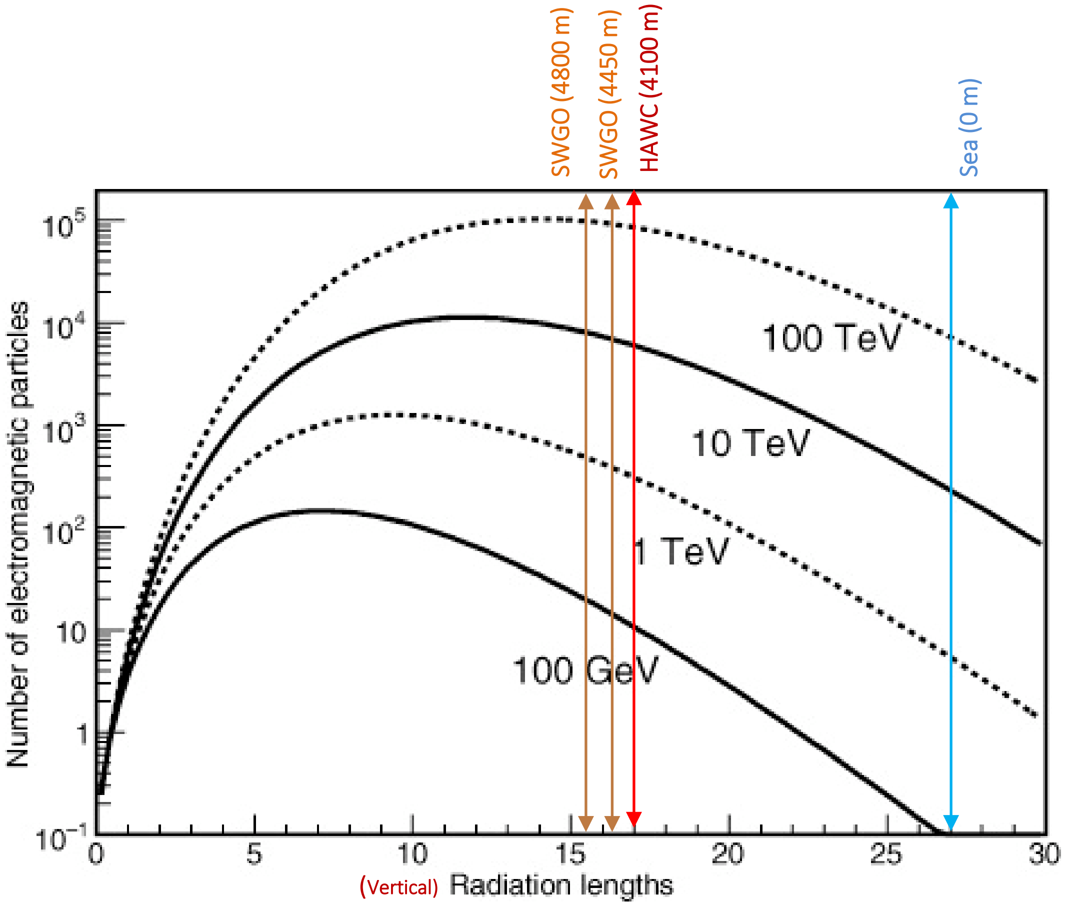


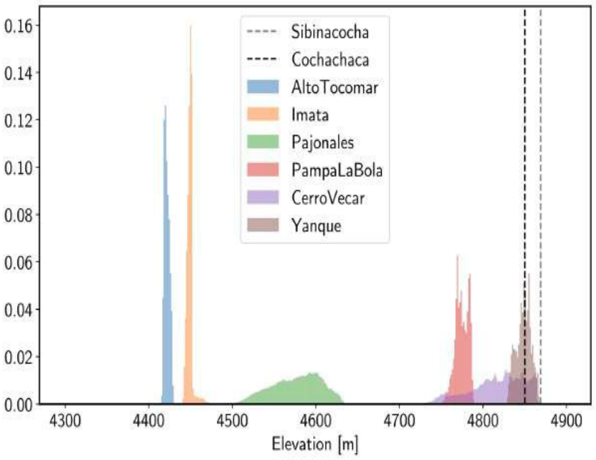
Alto Tocomar, Argentina – 4450 m

Pampa La Bola, Chile - 4770 m

Imata, Peru - 4450 m

Design Driver – High Altitude ➔ Lower Energy Threshold





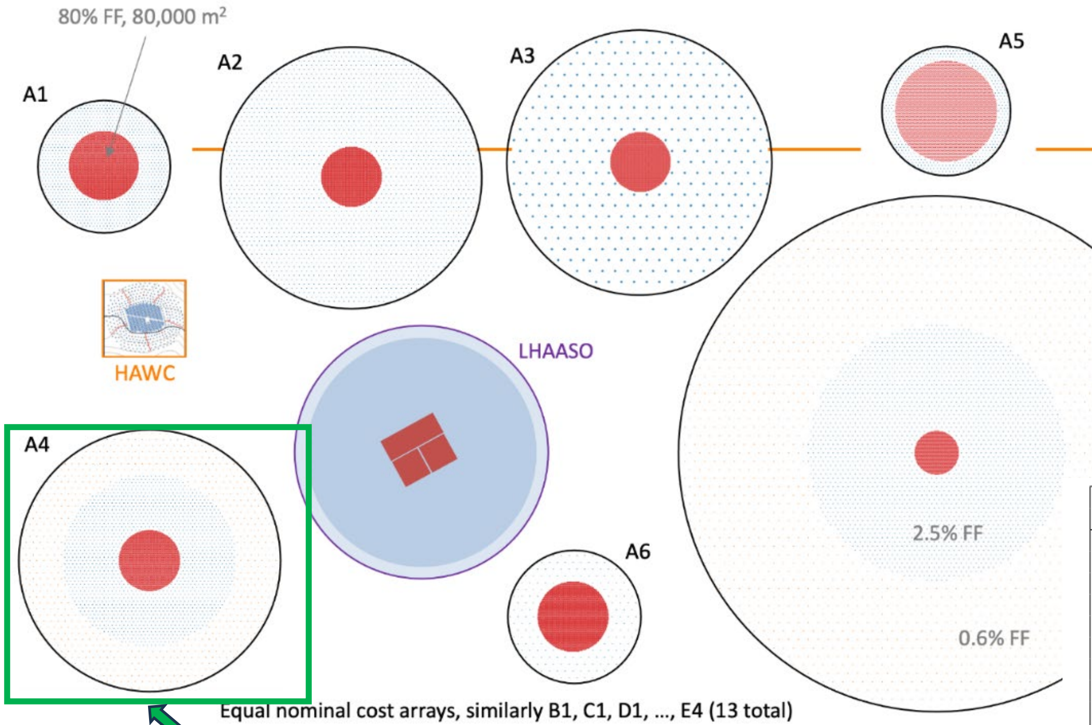
Higher Altitude Site

⬇

Better sample lower energy EAS

Design Driver – Large Area→ High Energy (>PeV) Sensitivity

- ☐ Denser Core Array – up to 80% Fill Factor
- ☐ Sparser Outer Array
- ☐ Graded Array
- ☐ Clustering for practicality
- ☐ Simulations to optimize

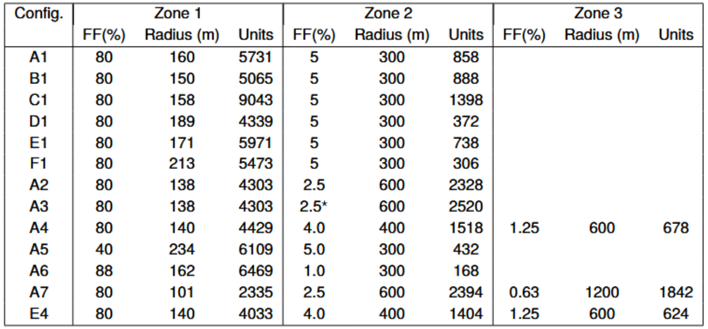


Equal nominal cost arrays, similarly B1, C1, D1, ..., E4 (13 total)

Baseline Configuration

(credit Jim Hinton - MPIK)

Practical Considerations will dictate final choices



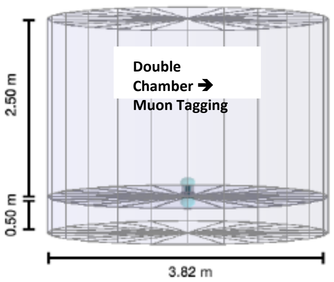
Config.	Zone 1			Zone 2			Zone 3		
	FF(%)	Radius (m)	Units	FF(%)	Radius (m)	Units	FF(%)	Radius (m)	Units
A1	80	160	5731	5	300	858			
B1	80	150	5065	5	300	888			
C1	80	158	9043	5	300	1398			
D1	80	189	4339	5	300	372			
E1	80	171	5971	5	300	738			
F1	80	213	5473	5	300	306			
A2	80	138	4303	2.5	600	2328			
A3	80	138	4303	2.5*	600	2520			
A4	80	140	4429	4.0	400	1518	1.25	600	678
A5	40	234	6109	5.0	300	432			
A6	88	162	6469	1.0	300	168			
A7	80	101	2335	2.5	600	2394	0.63	1200	1842
E4	80	140	4033	4.0	400	1404	1.25	600	624

Tab. 2 Summary of the configurations, detailed in the following subsections. * formed from 7-unit clusters.

WCD Unit Design Configuration

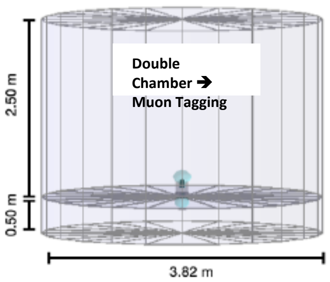
- Unit Configurations with varying diameter, height, compartmentalization, photosensor deployment
- Double Chamber ➔ Muon Tagging
- Smallest Dimension < 2.6 m? "Easily" Realizable in Plastic
- Larger ➔ Special Transport Permits
- "Mercedes"➔ Plastic Tank with 3 Photosensors at wall

A



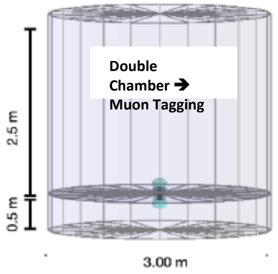
Double Chamber ➔ Muon Tagging

B



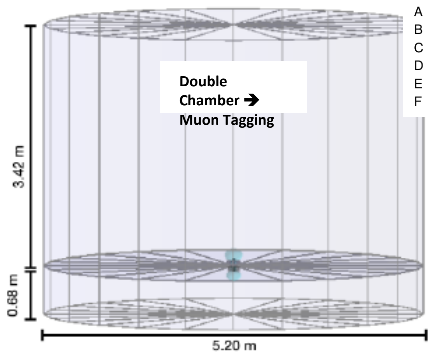
Double Chamber ➔ Muon Tagging

C



Double Chamber ➔ Muon Tagging

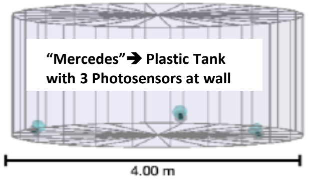
D



Double Chamber ➔ Muon Tagging

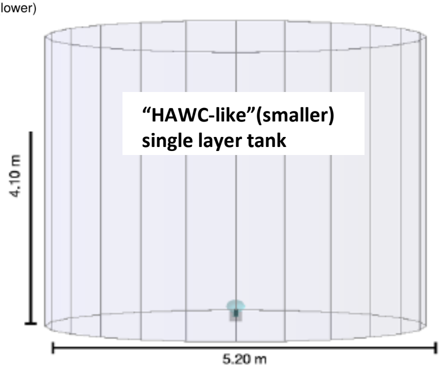
E

Label	Layers	PMT (upper + lower)	Diameter (m)	Depth (upper)	Depth (lower)
A	2	8"HQE +8"	3.82	2.50	0.50
B	2	10"HQE + 8"	3.82	2.50	0.50
C	2	8" +8"*	3.00	2.50	0.5
D	2	10"HQE + 8"	5.20	3.42	0.68
E	1	3×8"	4.00	1.70	-
F	1	10"HQE	5.20	4.20	-



"Mercedes"➔ Plastic Tank with 3 Photosensors at wall

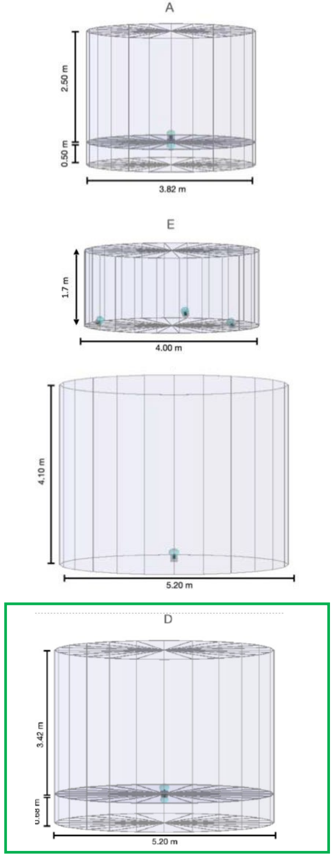
F



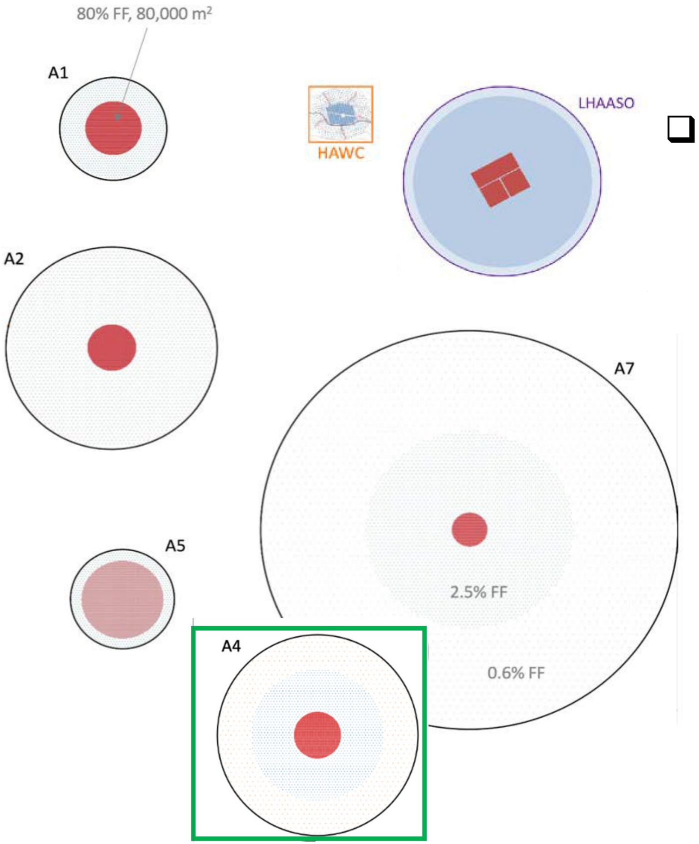
"HAWC-like"(smaller) single layer tank

Optimization of Detector Unit & Array Configuration

Unit Configurations



Array Layout



- ☐ **Fixed Cost Unit & Array Configuration**
  - ○ **Choose Unit Configuration**
  - ○ **Choose Array Layout**
  - ○ **Vary number of units to maintain fixed cost**
- ☐ **Simulate Performance for Various Choices**

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

Optimal Performance Unit & Array Configuration

The "baseline" detector- array and unit configuration

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

Outer: **Ø 600 m, FF = 5%**
880 WCD units

Altitude: **4,400 - 4,800 m a.s.l.**

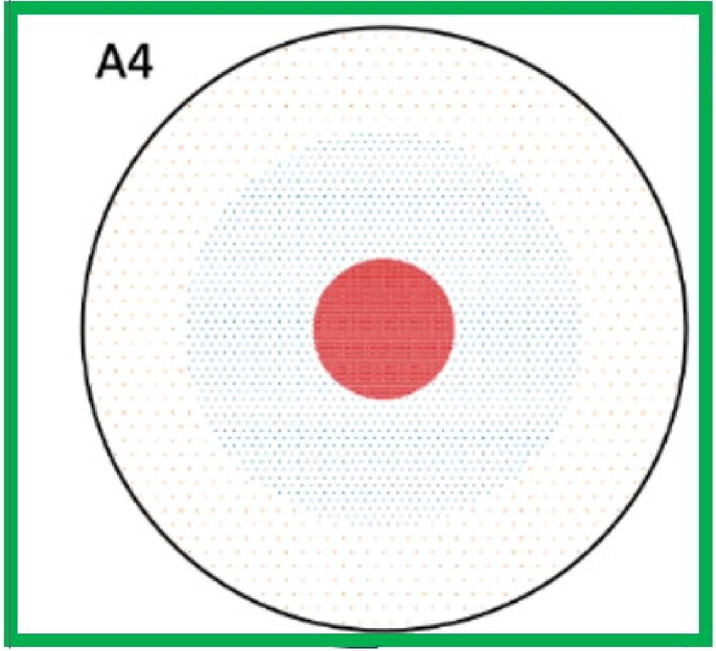
- ☐ Denser core to improve measurement and gamma/hadron separation
- ☐ Sparse outer array to enlarge area to improve high-energy sensitivity

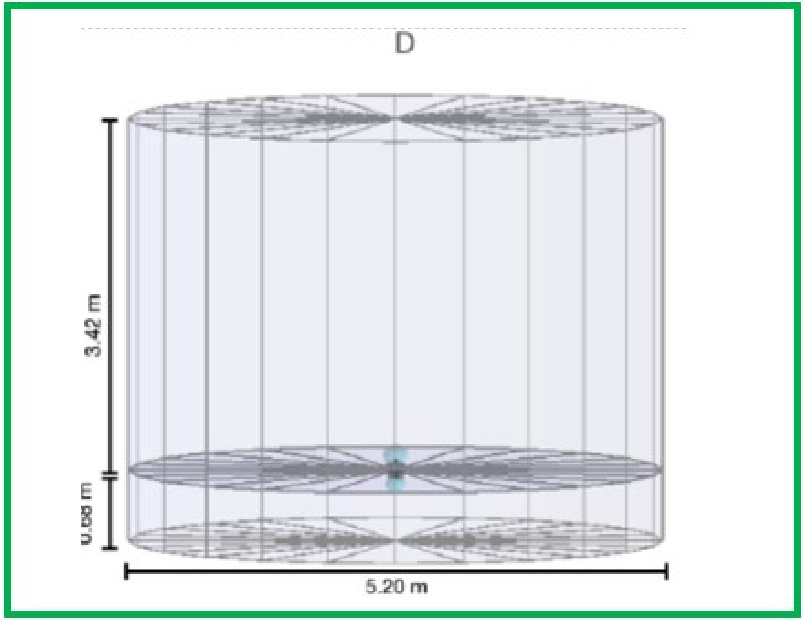
Diameter: **5.2 m**

Double Layer:
Upper: 3.42 m depth
Lower: 0.68 m depth

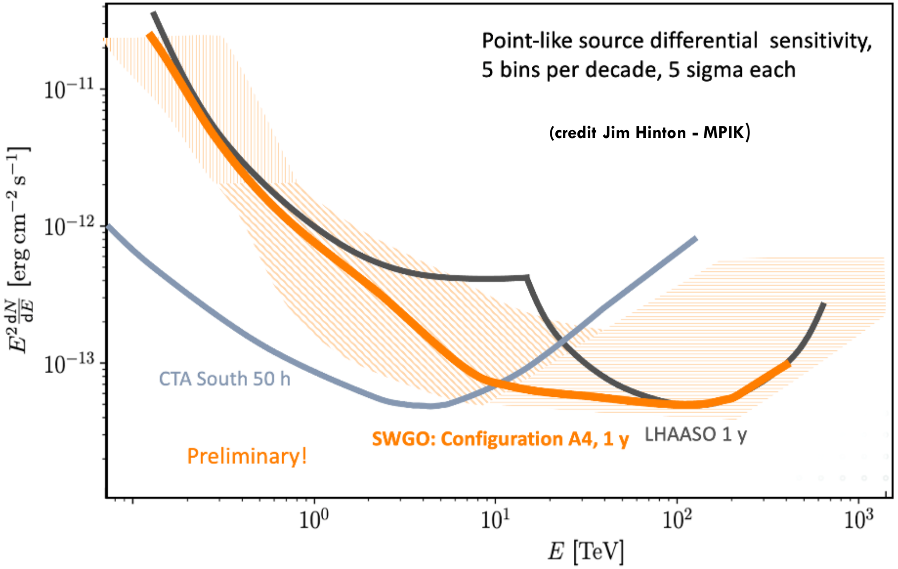
- ☐ Wide for better sampling of EAS
- ☐ Deep/Double Layer

➔ Muon tagging





The "baseline" detector concept - Sensitivity/Angular Resolution

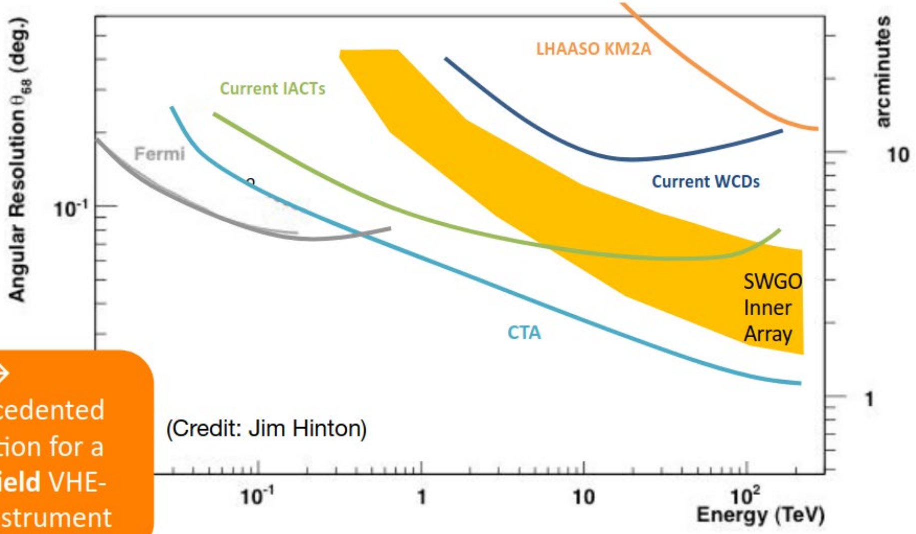


- ☐ High-Altitude to improve sensitivity at low energies
- ☐ Sparse outer array to enlarge area to improve high-energy sensitivity

Dense Sampling and Long Lever Arm of EAS Sampling

↓

Improved Angular Resolution

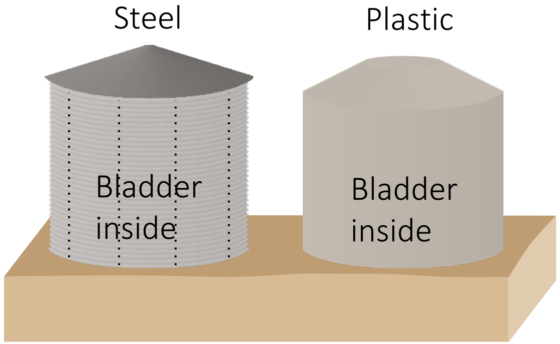


(Credit: Jim Hinton)

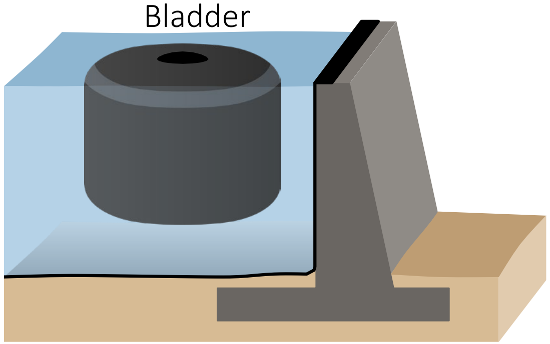
Goal → unprecedented resolution for a **wide field** VHE-UHE instrument

SWGO WCD Deployment Options

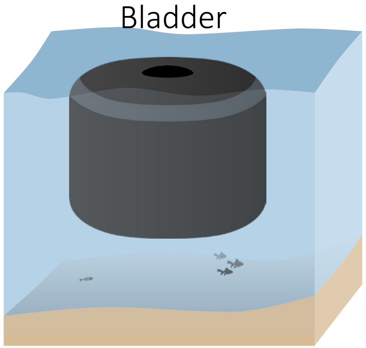
- Several water containment options. Tanks, Pond and Lake.
- Significant Experience with both steel (HAWC) and plastic (Auger) tanks.
- Pond/Lake options eliminate container costs…not as much experience at scale.
- Plastic tanks more easily deployed but limited in size due to transport issues.
- Bladder film and construction developed for use in all options.



Tank Option

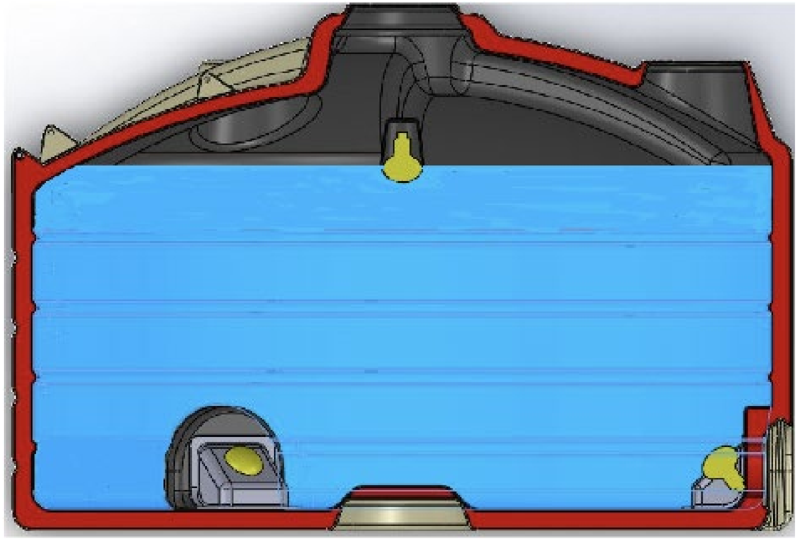


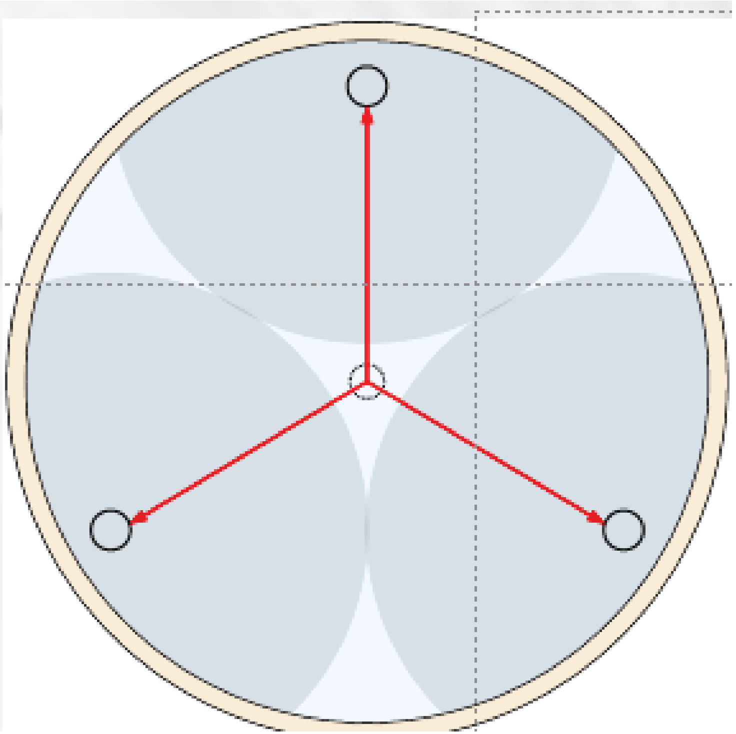
Pond Option



Lake Option

Plastic Tank Option – “Mercedes”





- ☐ Shallow, 3 or 4 PMTS
- ☐ Working with industry
- ☐ Roto-molded
- ☐ Thermal insulation integrated
- ☐ Reduced water requirement
- ☐ Possible Fabrication “nearby”

SWGO Steel Tank Option

- **Fabricated from Galvanized Steel Panels**
- **Larger Dimensions possible**
- **"Compact" Shipping – transportable via road**
- **Water contained in bladder**
  - **Single/Double Compartment**
  - **White (Tyvek)/Black Walls**

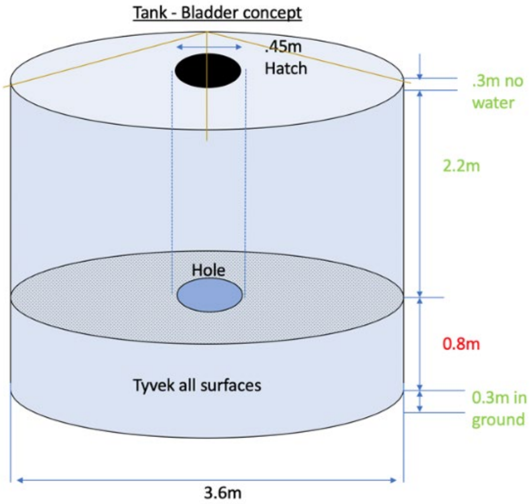
(credit Michael Schneider - UMD)

3.6 m diameter – 4.3 m height

5.2 m diameter – 4.3 m height

Bladders

- Water-Tight
- Light-Tight
- Does not contaminate water
- Lower Chamber - Tyvek used to reflect photons
- Upper Chamber – non-reflective to improve timing
- Working with industrial partners
- film development
- Fabrication



Double Chamber Bladder Concept

Double chamber

Top down inside view with double chamber

Double-PMT Mechanics

Photosensors need to be positioned to view the upper and lower chambers. Weights to balance and reduce buoyancy as well as positioning and surveying mechanisms are being developed. Shown here is an MPIK design to hold an 8” downward-looking and 10” upward-looking PMT. This particular design would be supported from above.

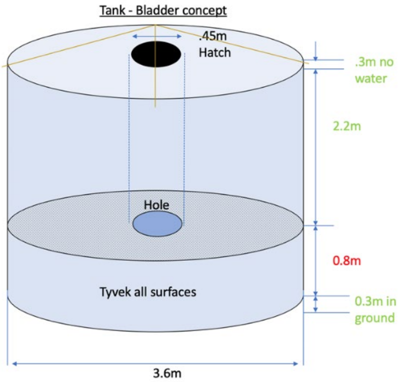
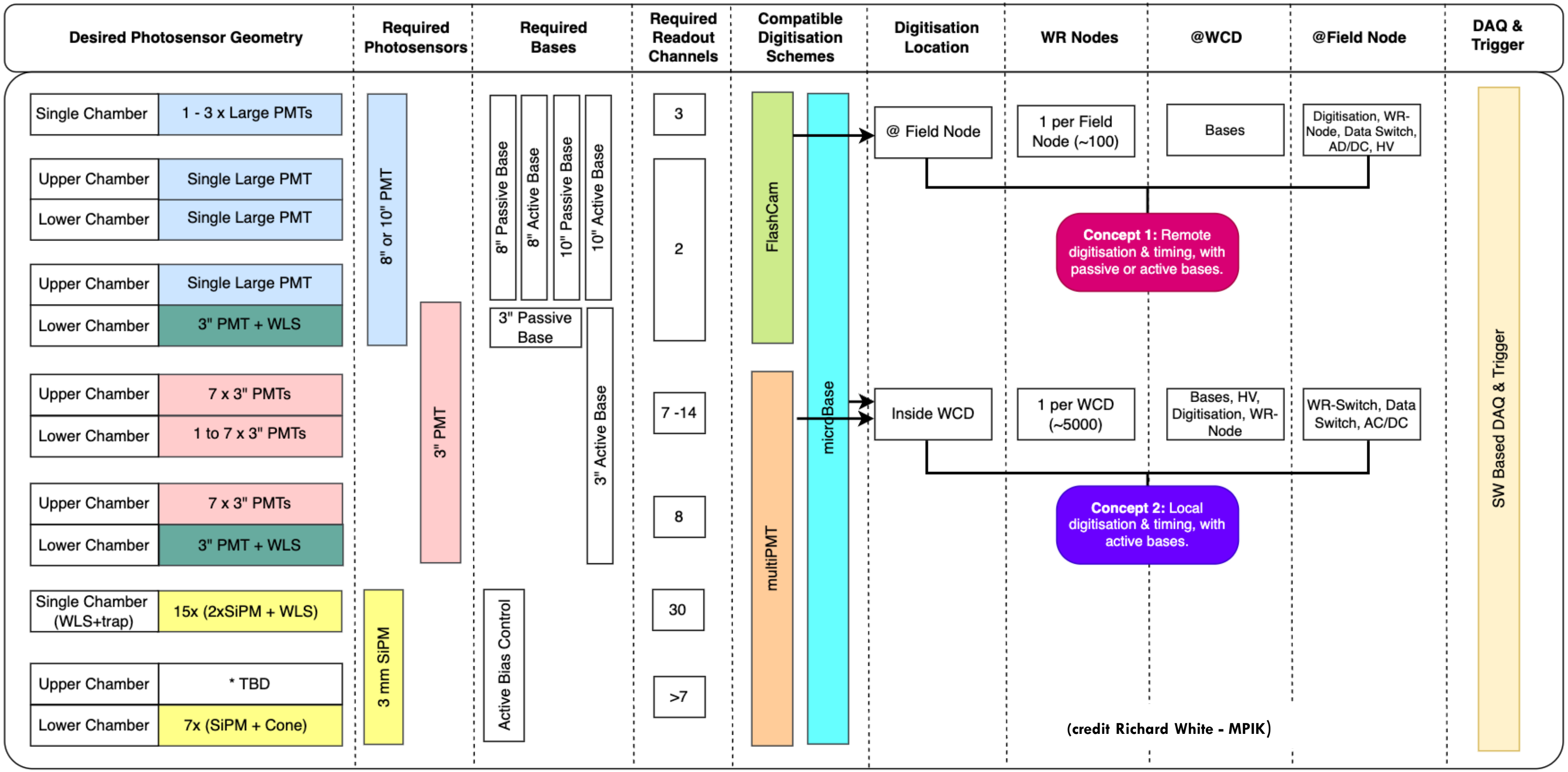


Fig. 1 Prototype double-PMT mechanics developed at MPIK. Due to the modular approach PMTs of different diameters can be combined. Weights are attached to the bottom to make the assembly float or sink under water. This particular implementation combines an 8-inch PMT with a 10-inch PMT and can be hung from the top hatch of a DLWCD bladder. It weighs approximately 23 kg.

Electronics Chain Options



Desired Photosensor Geometry

- Single Chamber – 1 - 3 x Large PMTs
- Upper Chamber – Single Large PMT; Lower Chamber – Single Large PMT
- Upper Chamber – Single Large PMT; Lower Chamber – 3" PMT + WLS
- Upper Chamber – 7 x 3" PMTs; Lower Chamber – 1 to 7 x 3" PMTs
- Upper Chamber – 7 x 3" PMTs; Lower Chamber – 3" PMT + WLS
- Single Chamber (WLS+trap) – 15x (2xSiPM + WLS)
- Upper Chamber – * TBD; Lower Chamber – 7x (SiPM + Cone)

Required Photosensors

8" or 10" PMT

3" PMT

3 mm SiPM

Required Bases

8" Passive Base

8" Active Base

10" Passive Base

10" Active Base

3" Passive Base

3" Active Base

Active Bias Control

Required Readout Channels

3

2

7 -14

8

30

>7

Compatible Digitisation Schemes

FlashCam

microBase

multiPMT

Digitisation Location	WR Nodes	@WCD	@Field Node
@ Field Node	1 per Field Node (~100)	Bases	Digitisation, WR-Node, Data Switch, AD/DC, HV
Inside WCD	1 per WCD (~5000)	Bases, HV, Digitisation, WR-Node	WR-Switch, Data Switch, AC/DC

Concept 1: Remote digitisation & timing, with passive or active bases.

Concept 2: Local digitisation & timing, with active bases.

DAQ & Trigger

SW Based DAQ & Trigger

(credit Richard White - MPIK)

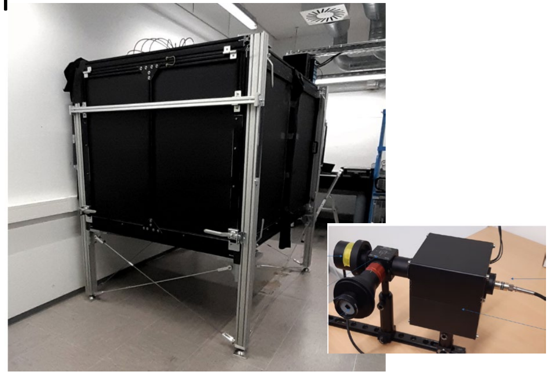
Photosensors

- ☐ Large-Area (8”-10” PMTs)
- ☐ MultiPMT (3”-4” PMTs)
- ☐ WLS,SiPM (Category B)

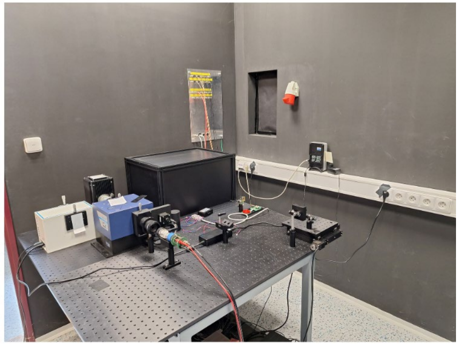
- ☐ Need good timing → Improved Angular Resolution
- ☐ Effective Surface Area/€ → **Greater Sensitivity**
- ☐ Exchange Rates?

Diameter	Model	Sensor Area (cm^2)	QE(390 nm)	Euro/cm^2	Transit Time (ns)
3”	R14374	41	27.5%	14.6	1.3 ns
8”	R5912	283	25%	18.4	2.4
8”	R5912-100	283	35%	15.7	2.4
8”	R14688-100	283	35%	17.8	0.9
8”	NVT N6082	283?	28%	16.8	1.8
9”	HZC XP1805	358?	27%	~10.0	2.4
10”	R7081	379	25%	16.4	3.4
10”	R7081-100	379	35%	14.2	3.4
4”	R16293	?	?	?	proprietary
4”	N2041 (NNVT)	?	?	?	proprietary
Others from old experiments					

(**credit Felix Werner - MPIK**)



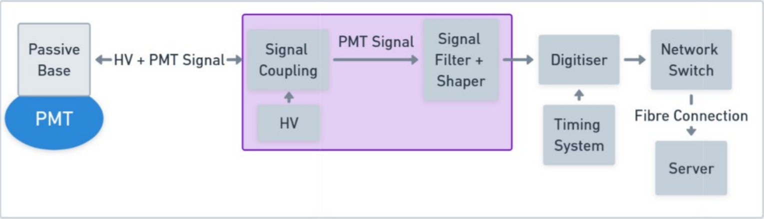
PMT Test facility at MPIK

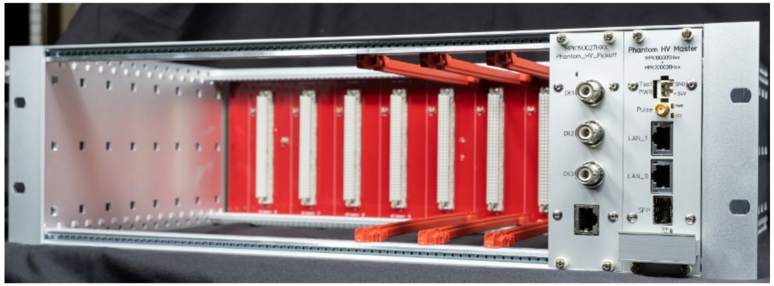


PMT Test facility in Prague

Remote Digitization with FlashCAM ADCs

- ☐ CTA-based design
- ☐ Modified & Developed for SWGO by MPIK Group
- ☐ “Phantom_ HV Supply & Pick-off
- ☐ FlashCam mainboards with two 12-channel ADC





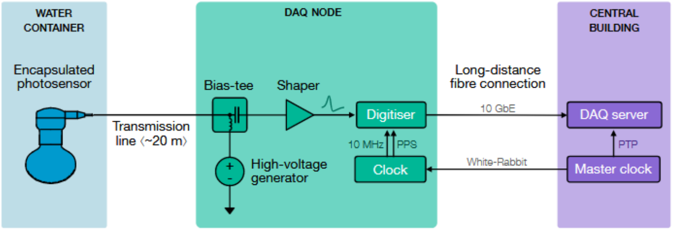


Figure 3: Architecture of the node-based design with encapsulated, passive-base photosensors phantom-powered via a coaxial transmission lines. Signal pick-offs (bias-tees), HV supplies, digitisers, and array timing modules are housed in DAQ nodes distributed throughout the array, each serving several tens of WCDs. A node is connected to the central infrastructure merely with single-mode fibres and AC power.

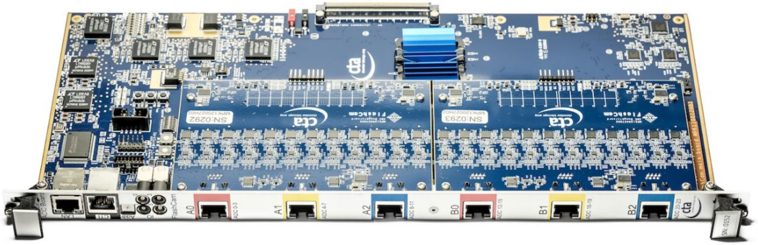
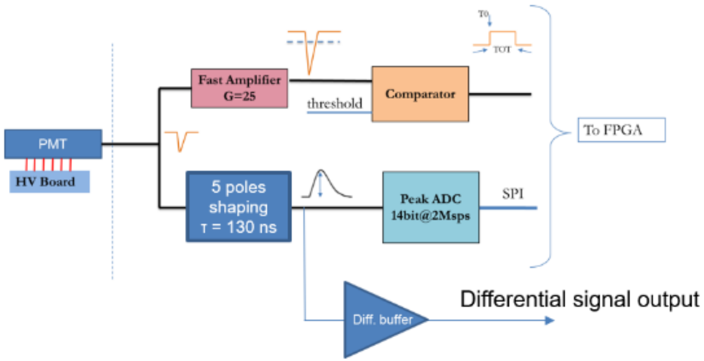
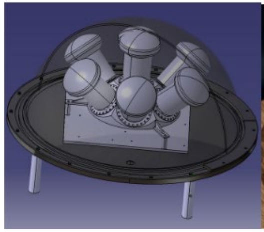


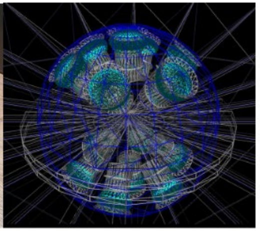
Fig. 1 Photograph of a FlashCam ADC module: a FlashCam mainboard equipped with two 12-channel ADC boards.

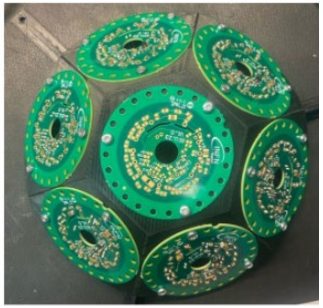
INFN-Napoli Multi-PMT Mechanics/Electronics

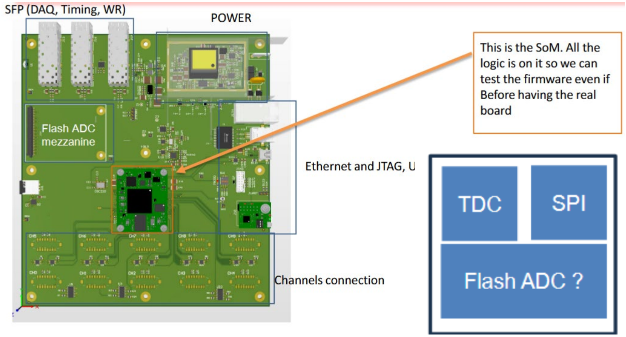
- KM3Net-based design
- Modified & Developed for SWGO by INFN-Napoli Group
- Local digitization of 7 upward-facing 3” XXXX PMTs
- White Rabbit Timing incorporated into mainboard
- Linux-based mainboard to facilitate development



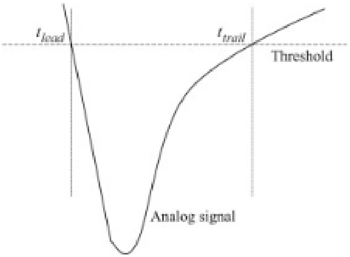


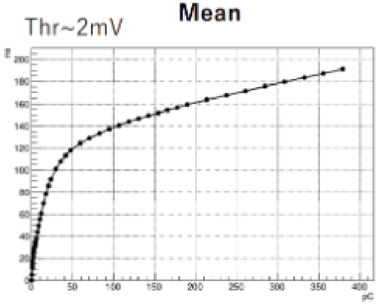






This is the SoM. All the logic is on it so we can test the firmware even if Before having the real board





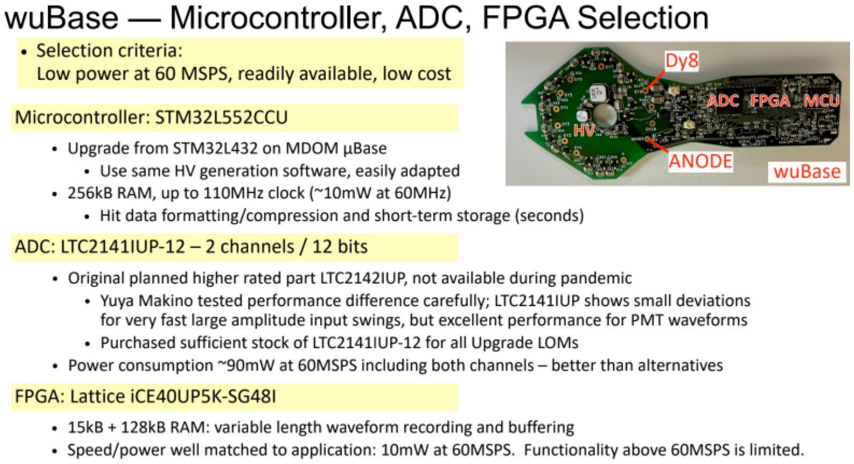
From the ToT we can have hint on the charge of the event

(credit – INFN - Napoli)

IceCube-based Optical Module with Digitizing Active Base

- ☐ IceCube-based design
- ☐ Modified & Developed for SWGO by WiPac Group
- ☐ Cockcroft Walton Active HV Base
- ☐ Local Digitization on Base
- ☐ Existing Optical Modules with 16 PMTs
- ☐ 8 upward, 8 downward looking
- ☐ 32-bit ARM based Mini-mainboard

(credit Mike Duvernois – UW Madison)



wuBase — Microcontroller, ADC, FPGA Selection

- Selection criteria:
  Low power at 60 MSPS, readily available, low cost

Microcontroller: STM32L552CCU

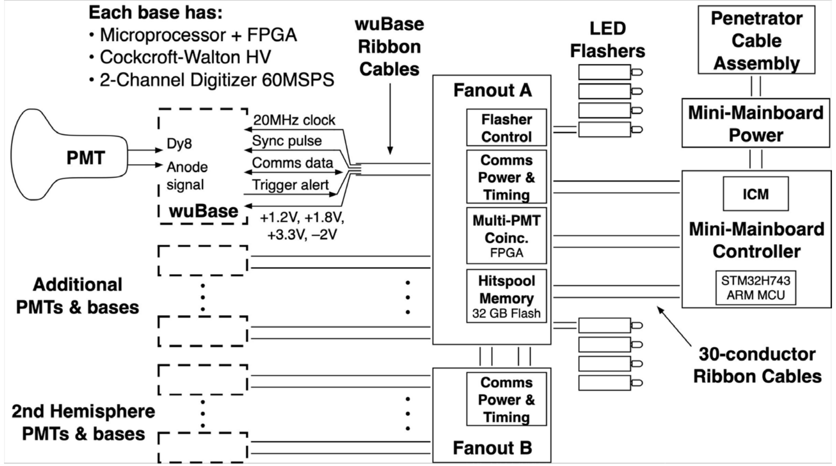
- Upgrade from STM32L432 on MDOM µBase
  - Use same HV generation software, easily adapted
- 256kB RAM, up to 110MHz clock (~10mW at 60MHz)
  - Hit data formatting/compression and short-term storage (seconds)

ADC: LTC2141IUP-12 – 2 channels / 12 bits

- Original planned higher rated part LTC2142IUP, not available during pandemic
  - Yuya Makino tested performance difference carefully; LTC2141IUP shows small deviations for very fast large amplitude input swings, but excellent performance for PMT waveforms
  - Purchased sufficient stock of LTC2141IUP-12 for all Upgrade LOMs
- Power consumption ~90mW at 60MSPS including both channels – better than alternatives

FPGA: Lattice iCE40UP5K-SG48I

- 15kB + 128kB RAM: variable length waveform recording and buffering
- Speed/power well matched to application: 10mW at 60MSPS. Functionality above 60MSPS is limited.

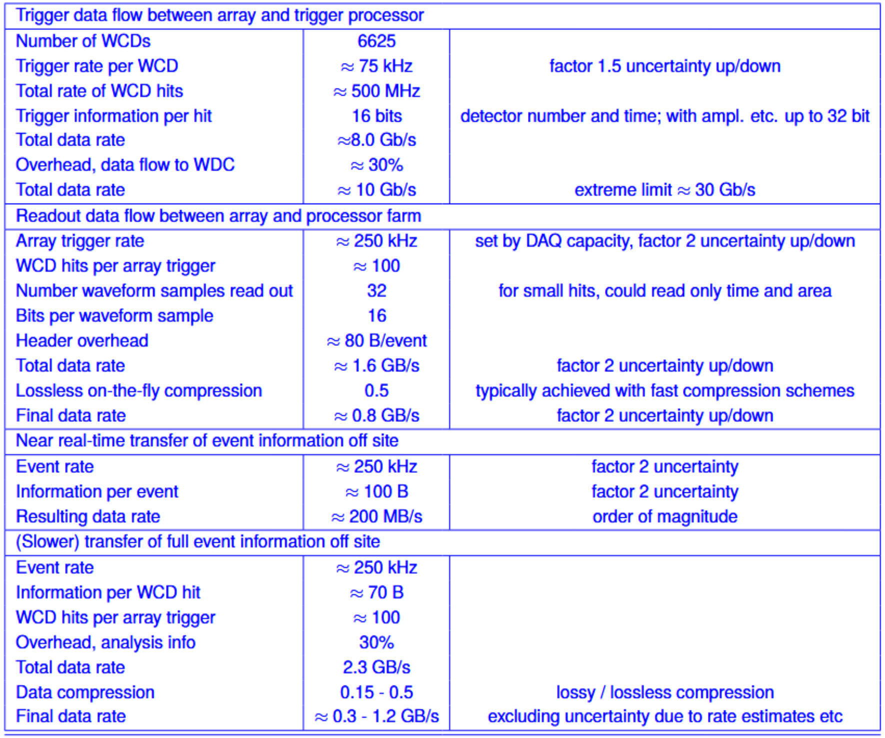


Each base has:

- Microprocessor + FPGA
- Cockcroft-Walton HV
- 2-Channel Digitizer 60MSPS

Data Acquisition Requirements & Online Processing

Tab. 1 Assumptions towards estimate of data rates



Trigger data flow between array and trigger processor		
Number of WCDs	6625	
Trigger rate per WCD	≈ 75 kHz	factor 1.5 uncertainty up/down
Total rate of WCD hits	≈ 500 MHz	
Trigger information per hit	16 bits	detector number and time; with ampl. etc. up to 32 bit
Total data rate	≈8.0 Gb/s	
Overhead, data flow to WDC	≈ 30%	
Total data rate	≈ 10 Gb/s	extreme limit ≈ 30 Gb/s
Readout data flow between array and processor farm		
Array trigger rate	≈ 250 kHz	set by DAQ capacity, factor 2 uncertainty up/down
WCD hits per array trigger	≈ 100	
Number waveform samples read out	32	for small hits, could read only time and area
Bits per waveform sample	16	
Header overhead	≈ 80 B/event	
Total data rate	≈ 1.6 GB/s	factor 2 uncertainty up/down
Lossless on-the-fly compression	0.5	typically achieved with fast compression schemes
Final data rate	≈ 0.8 GB/s	factor 2 uncertainty up/down
Near real-time transfer of event information off site		
Event rate	≈ 250 kHz	factor 2 uncertainty
Information per event	≈ 100 B	factor 2 uncertainty
Resulting data rate	≈ 200 MB/s	order of magnitude
(Slower) transfer of full event information off site		
Event rate	≈ 250 kHz	
Information per WCD hit	≈ 70 B	
WCD hits per array trigger	≈ 100	
Overhead, analysis info	30%	
Total data rate	2.3 GB/s	
Data compression	0.15 - 0.5	lossy / lossless compression
Final data rate	≈ 0.3 - 1.2 GB/s	excluding uncertainty due to rate estimates etc

- ☐ **GPS-GNSS Timing Master**
- ☐ **Photosensor Signals Digitized Remotely or Locally**
- ☐ **Timing Distribution provided by White Rabbit (-like?) Switches**
- ☐ **CPU Server-based Online Software Processing**

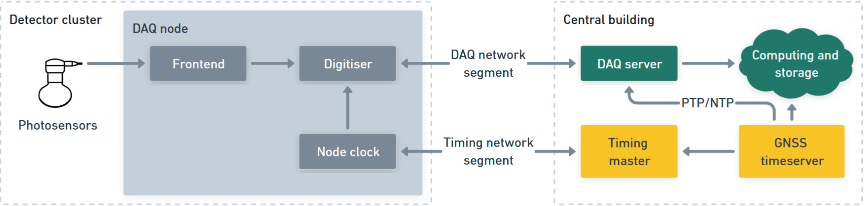
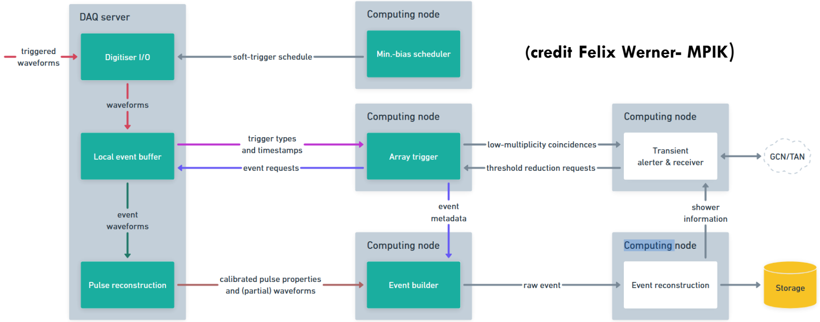


Fig. 1 Physical view of relevant detector components and central infrastructure.



(credit Felix Werner- MPIK)

Fig. 2 Flow diagram for event data. Grey boxes correspond to server hardware (DAQ servers or generic computing nodes) in the computing centre; white boxes correspond to software components; arrows represent information flow.

Design constraints – Cost, Risk & Mitigation

☐ Design Constraints

- ☐ Affordability
- ☐ Durability
- ☐ Feasibility
- ☐ …

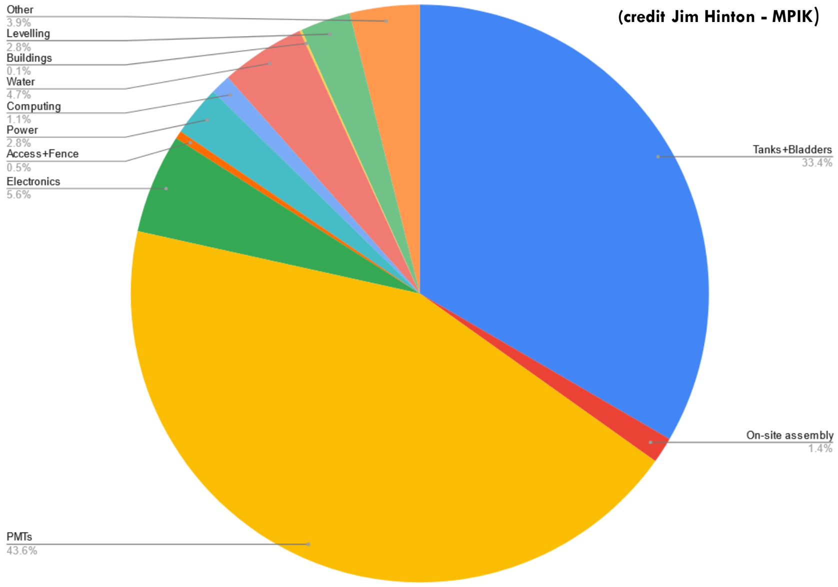
☐ Major Cost Drivers

- ☐ PMTs
- ☐ Tanks & Bladders
- ☐ Water (site-dependent?)
- ☐ ???

☐ Risks

- ☐ Technical
- ☐ Environmental
- ☐ Managerial
- ☐ Political
- ☐ Resources
  - ○ Water
  - ○ Labor
  - ○ Material (PMTs, Electronics, …)

A costing exercise for a representative site



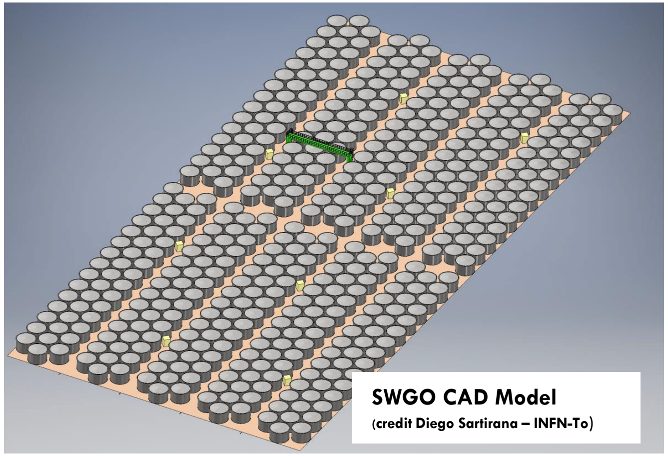
(credit Jim Hinton - MPIK)

☐ Mitigation Examples

- ☐ Lightning protection, grounding
- ☐ Establish Legal Entity
- ☐ Multiple Vendors & Vendor Engagement
- ☐ Early purchase of critical items
- ☐ ….

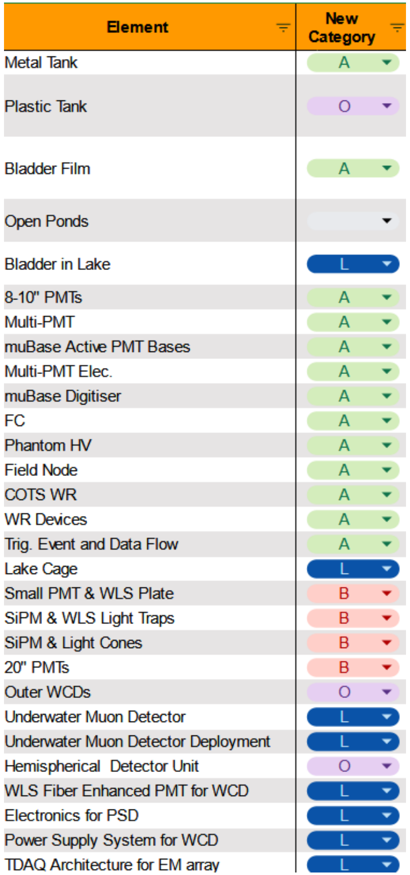
Design Consolidation, Future Expansion & Construction Planning

- **Categorization of detector options proceeding.**
- **Focus on land-based detector option to start construction as soon as possible.**
- **Site selection to occur by end of 2024**
- **Final Detector Design Early 2025**
- **Detailed Site-Specific Deployment plan Mid 2025**
- **Planning for construction and deployment of SWGO is starting.**



SWGO CAD Model

(credit Diego Sartirana – INFN-To)



Element	New Category
Metal Tank	A
Plastic Tank	O
Bladder Film	A
Open Ponds	
Bladder in Lake	L
8-10" PMTs	A
Multi-PMT	A
muBase Active PMT Bases	A
Multi-PMT Elec.	A
muBase Digitiser	A
FC	A
Phantom HV	A
Field Node	A
COTS WR	A
WR Devices	A
Trig. Event and Data Flow	A
Lake Cage	L
Small PMT & WLS Plate	B
SiPM & WLS Light Traps	B
SiPM & Light Cones	B
20" PMTs	B
Outer WCDs	O
Underwater Muon Detector	L
Underwater Muon Detector Deployment	L
Hemispherical Detector Unit	O
WLS Fiber Enhanced PMT for WCD	L
Electronics for PSD	L
Power Supply System for WCD	L
TDAQ Architecture for EM array	L

(credit Richard White – MPIK)

- **Development of novel detector technologies such as the use of SiPMs and Wavelength shifting plates no longer actively pursued for use in baseline design of SWGO**
- **Work by Ultra High energy Task Force on outer array and possible large area lake deployment as a future expansion is ongoing.**

Summary

☐ Design Drivers
- Southern Sky ➔ Go South
- Lower Energy Range ➔ Go High
- Higher Energy Range ➔ Go Big
- Background Rejection ➔ Go Deep

☐ Design Constraints & Considerations
- Cost
- Risk

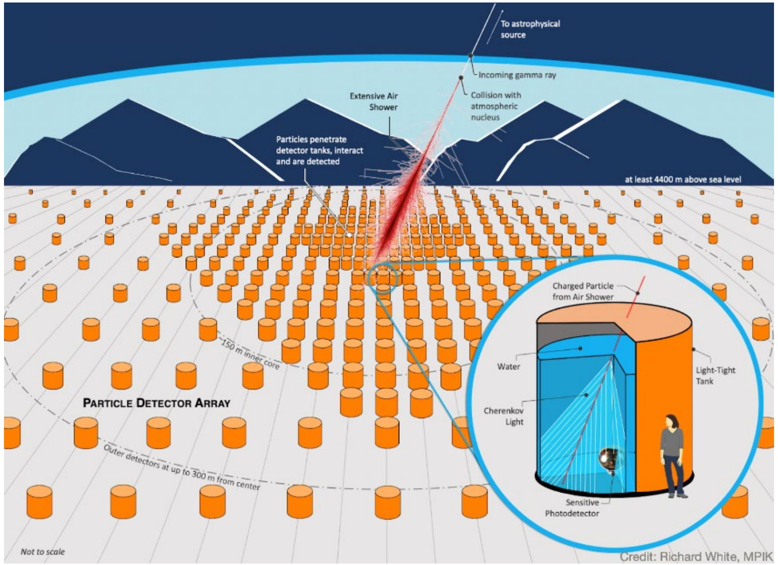
➔ **Emphasize Availability, Affordability, Durability, Feasibility**

☐ Detector Options – R&D
- Mechanics
- Photosensors
- Electronics

➔ **Array of WCD units and DAQ with robust autonomous performance**

☐ Detector Deployment & Operation
- Construction
- Analysis
- Calibration & Validation

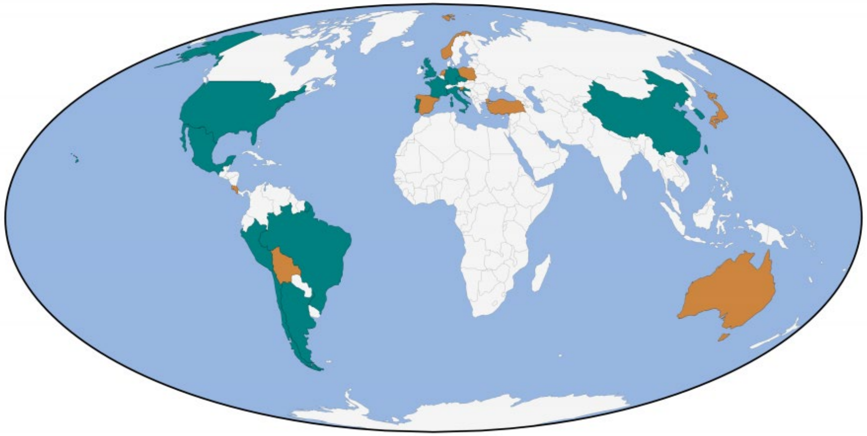
➔ **Make Decisions and Get Started!**



Credit: Richard White, MPIK

The SWGO Collaboration

https://www.swgo.org/SWGOWiki/doku.php?id=collaboration



- ☐ Growing Collaboration
- ☐ More than 270 collaborators on Author List
- ☐ 92 Affiliated Institutions

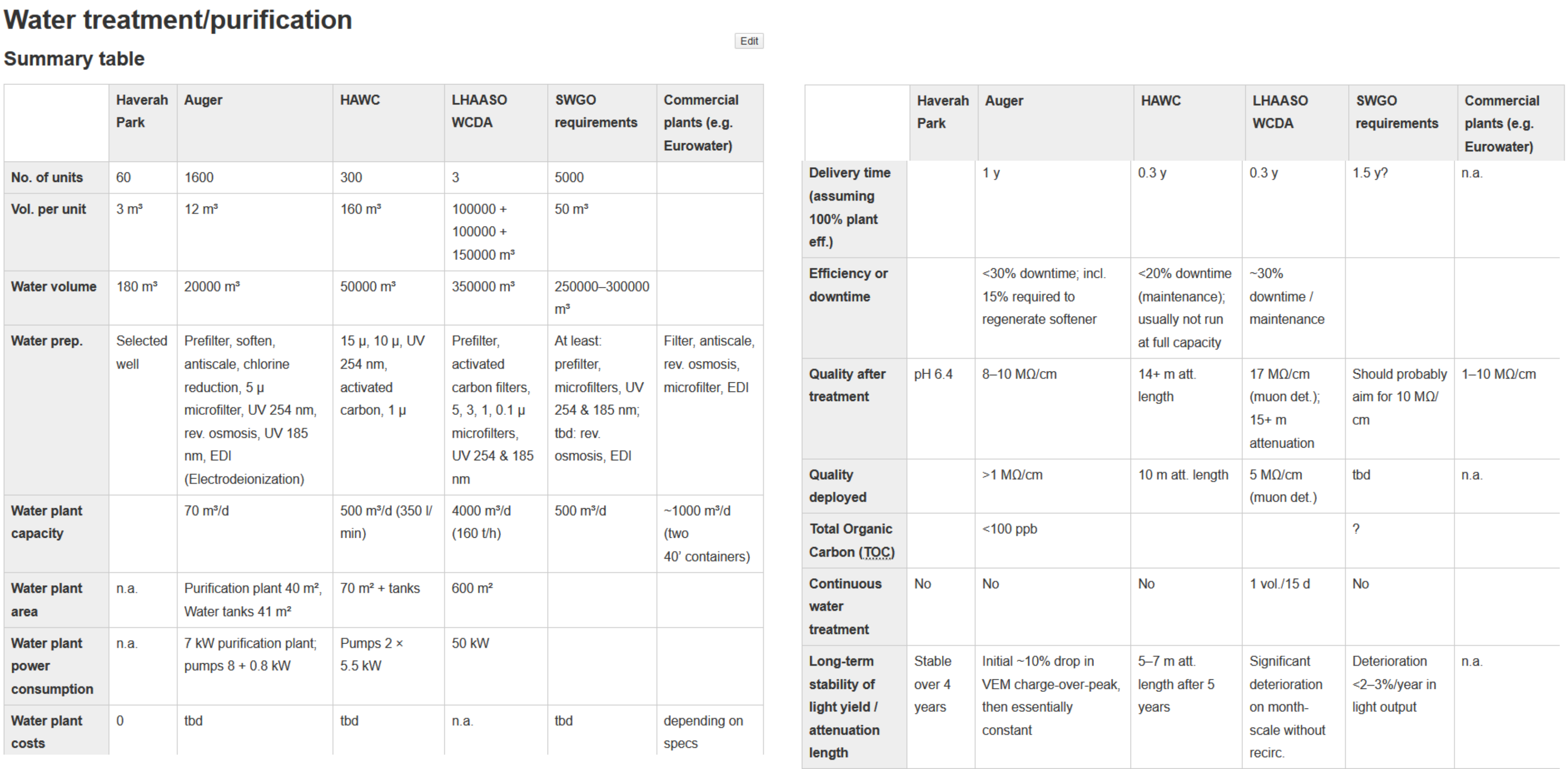
Institutional Member States:
Argentina, Brazil, Chile, China, Croatia, Czech Republic, France, Germany, Italy, Mexico, Peru, Portugal, UK, USA

Associate Members also from
Poland, Slovenia, Sweden

CDMX Meeting April 2024

Backup Slides

Water Treatment - Requirements



Water treatment/purification

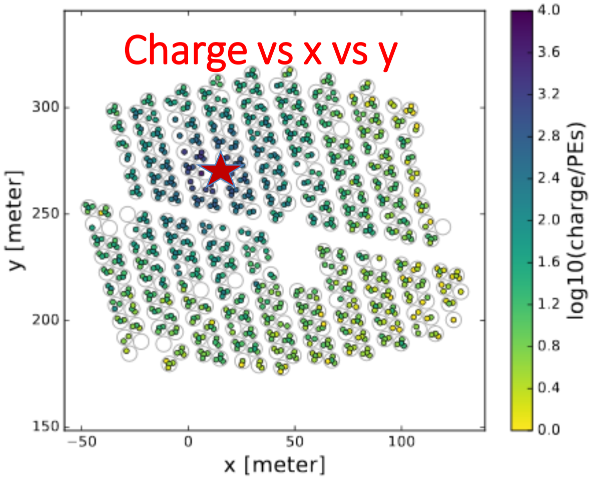
Summary table

	Haverah Park	Auger	HAWC	LHAASO WCDA	SWGO requirements	Commercial plants (e.g. Eurowater)
No. of units	60	1600	300	3	5000	
Vol. per unit	3 m^3	12 m^3	160 m^3	100000 + 100000 + 150000 m^3	50 m^3	
Water volume	180 m^3	20000 m^3	50000 m^3	350000 m^3	250000–300000 m^3	
Water prep.	Selected well	Prefilter, soften, antiscale, chlorine reduction, 5 μ microfilter, UV 254 nm, rev. osmosis, UV 185 nm, EDI (Electrodeionization)	15 μ, 10 μ, UV 254 nm, activated carbon, 1 μ	Prefilter, activated carbon filters, 5, 3, 1, 0.1 μ microfilters, UV 254 & 185 nm	At least: prefilter, microfilters, UV 254 & 185 nm; tbd: rev. osmosis, EDI	Filter, antiscale, rev. osmosis, microfilter, EDI
Water plant capacity		70 m^3/d	500 m^3/d (350 l/min)	4000 m^3/d (160 t/h)	500 m^3/d	~1000 m^3/d (two 40' containers)
Water plant area	n.a.	Purification plant 40 m^2, Water tanks 41 m^2	70 m^2 + tanks	600 m^2		
Water plant power consumption	n.a.	7 kW purification plant; pumps 8 + 0.8 kW	Pumps 2 × 5.5 kW	50 kW		
Water plant costs	0	tbd	tbd	n.a.	tbd	depending on specs

	Haverah Park	Auger	HAWC	LHAASO WCDA	SWGO requirements	Commercial plants (e.g. Eurowater)
Delivery time (assuming 100% plant eff.)		1 y	0.3 y	0.3 y	1.5 y?	n.a.
Efficiency or downtime		<30% downtime; incl. 15% required to regenerate softener	<20% downtime (maintenance); usually not run at full capacity	~30% downtime / maintenance		
Quality after treatment	pH 6.4	8–10 MΩ/cm	14+ m att. length	17 MΩ/cm (muon det.); 15+ m attenuation	Should probably aim for 10 MΩ/cm	1–10 MΩ/cm
Quality deployed		>1 MΩ/cm	10 m att. length	5 MΩ/cm (muon det.)	tbd	n.a.
Total Organic Carbon (TOC)		<100 ppb			?	
Continuous water treatment	No	No	No	1 vol./15 d	No	
Long-term stability of light yield / attenuation length	Stable over 4 years	Initial ~10% drop in VEM charge-over-peak, then essentially constant	5–7 m att. length after 5 years	Significant deterioration on month-scale without recirc.	Deterioration <2–3%/year in light output	n.a.

Reconstruction of Energy & Arrival Direction:

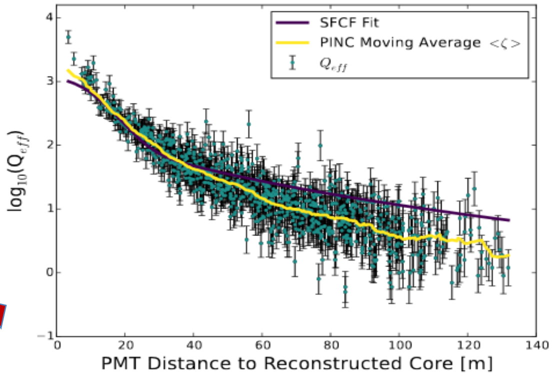
Core Location , Lateral Distribution, Plane Fit



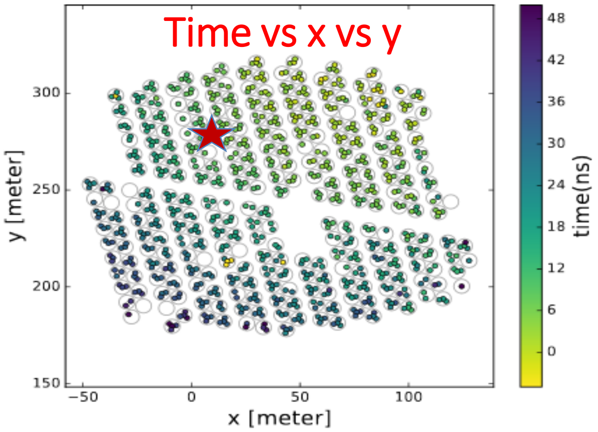
$$x_{COM}, y_{COM} = \frac{\sum_{i=1}^{Nhit} x_i N_{pe,i}}{\sum_{i=1}^{Nhit} N_{pe,i}}, \frac{\sum_{i=1}^{Nhit} y_i N_{pe,i}}{\sum_{i=1}^{Nhit} N_{pe,i}}$$

Location of Maximum Charge Density

Core Location

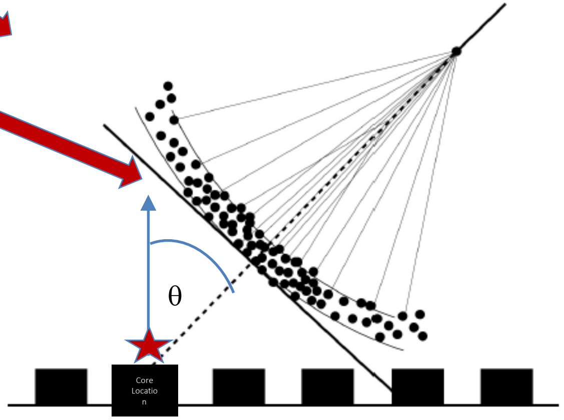


Lateral Distribution Function



Shower Plane

Zenith θ
Azimuth ϕ



Calibration – Dedicated Calibration Hardware and/or Use of Extensive Air Shower & Muons

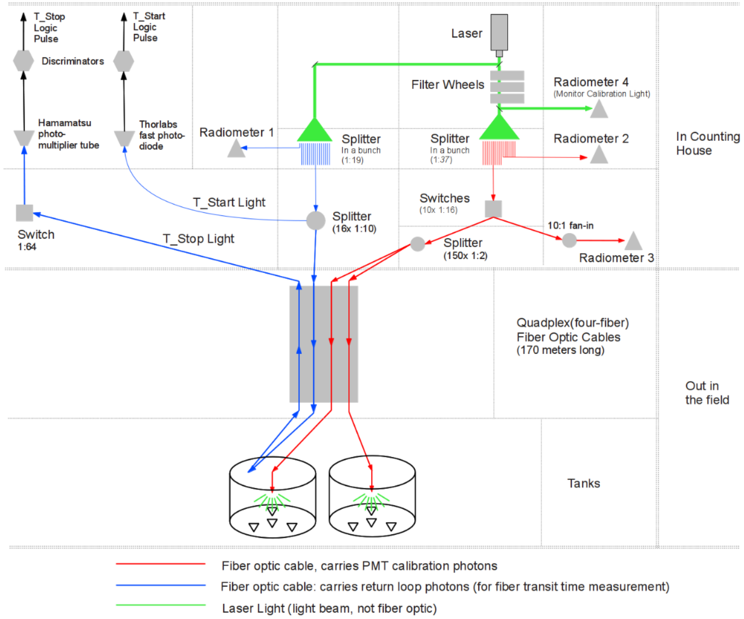
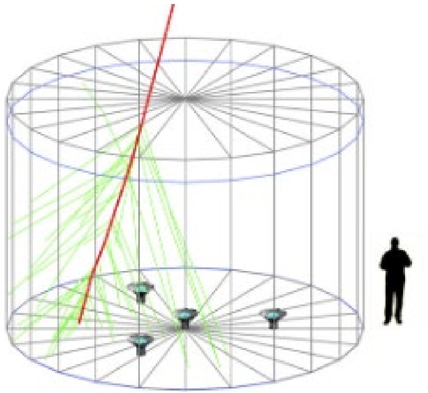


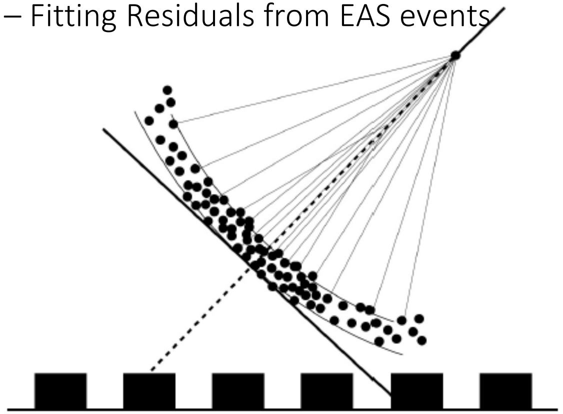
Figure 1: Schematic of the calibration setup for HAWC.

https://arxiv.org/pdf/1508.04312

Charge – Vertical Equivalent Muon Studies



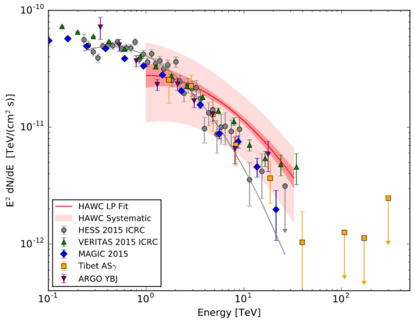
Time – Fitting Residuals from EAS events



Validation - Energy Calibration using The Moon & The Crab!

Validation can be performed using known phenomena:

- ☐ the energy dependent deflection of cosmic rays in the known magnetic field of the earth.
- ☐ The known energy spectrum of the Crab Nebula



2017 HAWC Measurement of the energy spectrum of the Crab
https://iopscience.iop.org/article/10.3847/1538-4357/aa7555/pdf

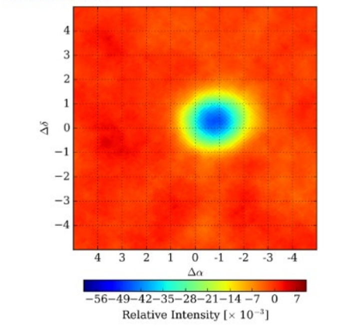
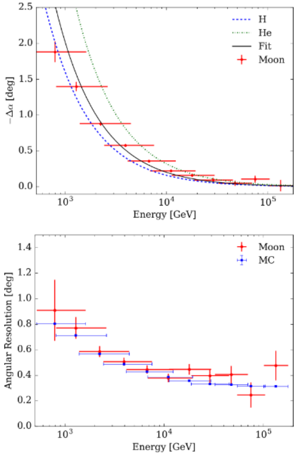
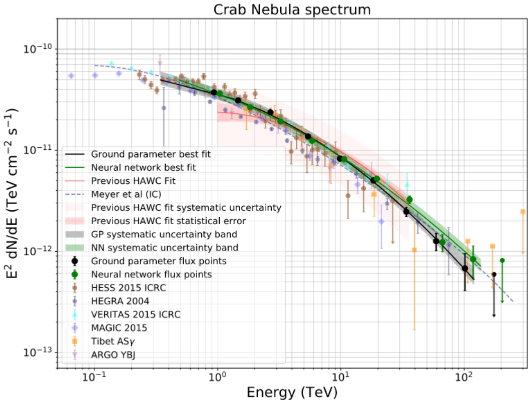


FIG. 5. Relative intensity of the Moon shadow at a mean energy of 4.3 TeV. The map has been smoothed with a top-hat function by 1° to enhance the shadow visually. A two-dimensional Gaussian was fit to the unsmoothed maps.



https://journals.aps.org/prd/abstract/10.1103/PhysRevD.96.122001



2019 HAWC Measurement of the energy spectrum of the Crab
https://iopscience.iop.org/article/10.3847/1538-4357/ab2f7d