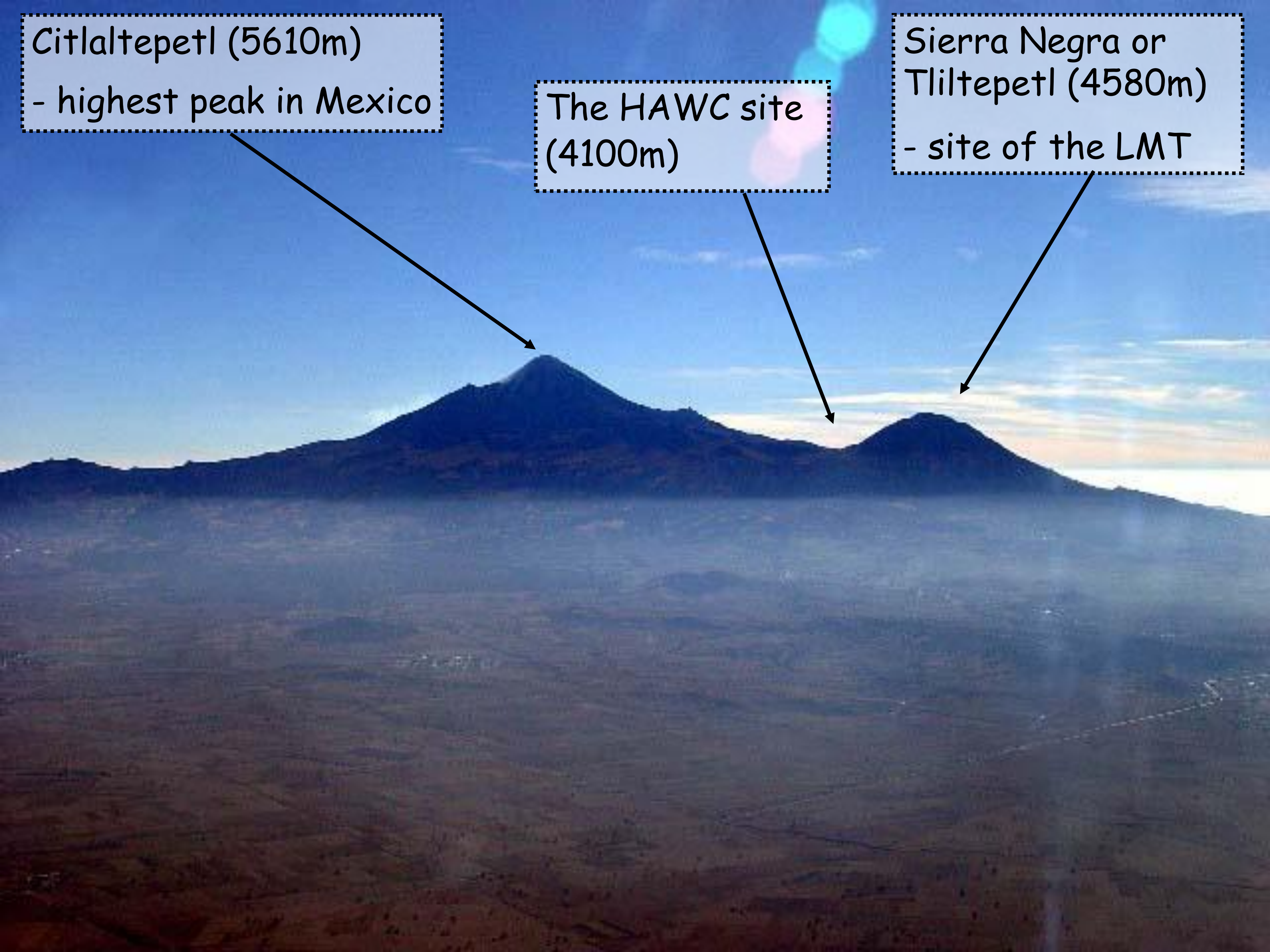
Instrumentation for VHE γ-ray Astrophysics

HAWC — *Michael Schneider*

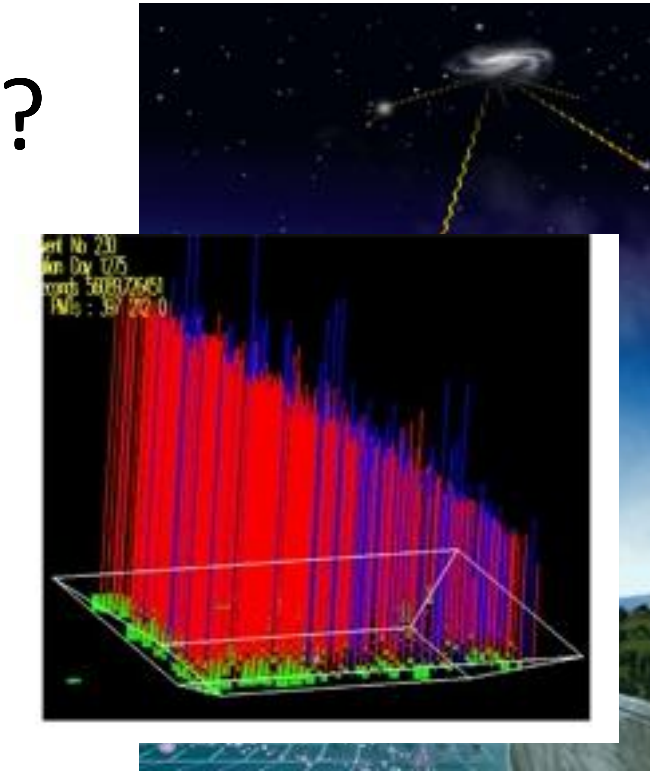
Photosensors for VERITAS Upgrade and AGIS — *Nepomuk Otte*

AGIS — *David Williams*

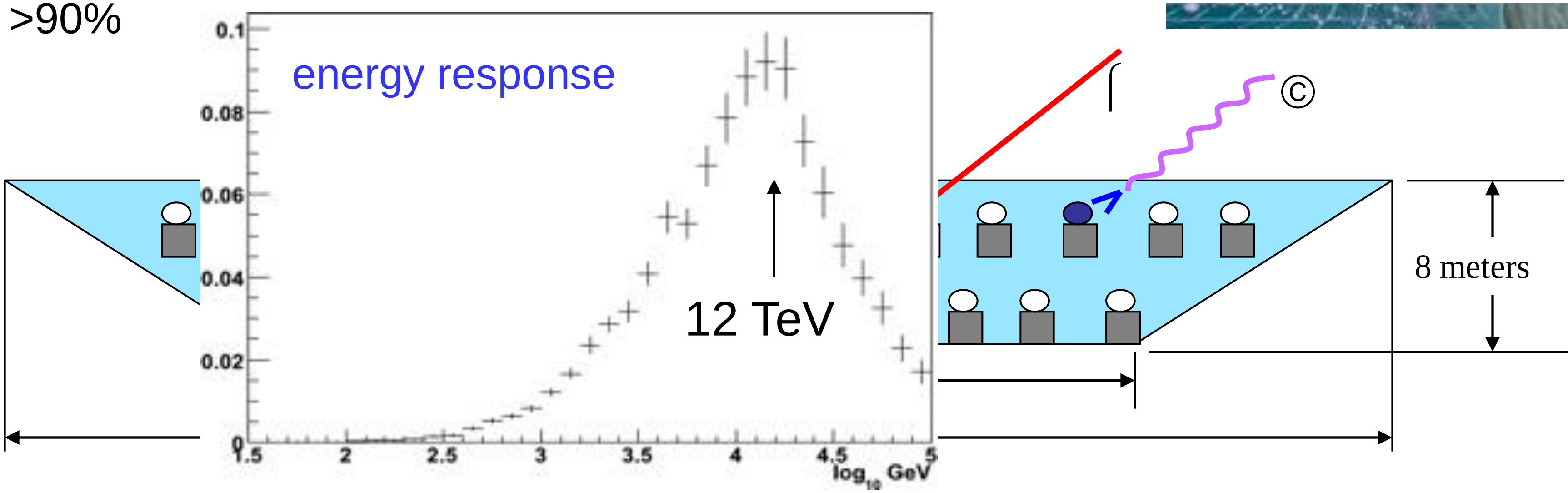

The HAWC
(High Altitude Water Cherenkov)
Observatory


Citlaltepetl (5610m)
- highest peak in Mexico
The HAWC site
(4100m)
Sierra Negra or
Tliltepetl (4580m)
- site of the LMT

How Does Milagro Work?

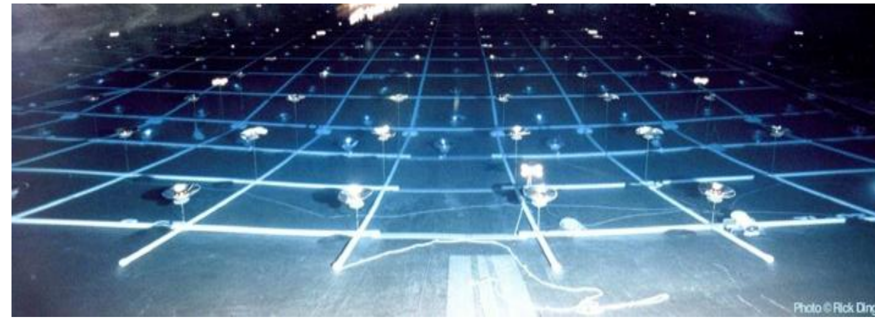


- Detect Particles in Extensive Air Showers from Cherenkov light created in 60m x 80 m x 8m pond containing filtered water
- Reconstruct shower direction to ~0.5° from the time different PMTs are hit
- 1700 Hz trigger rate mostly due to Extensive Air Showers created by cosmic rays
- Field of view is ~2 sr and the average duty factor is >90%

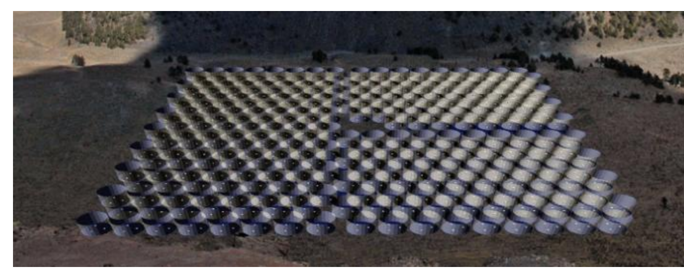


Milagro and HAWC

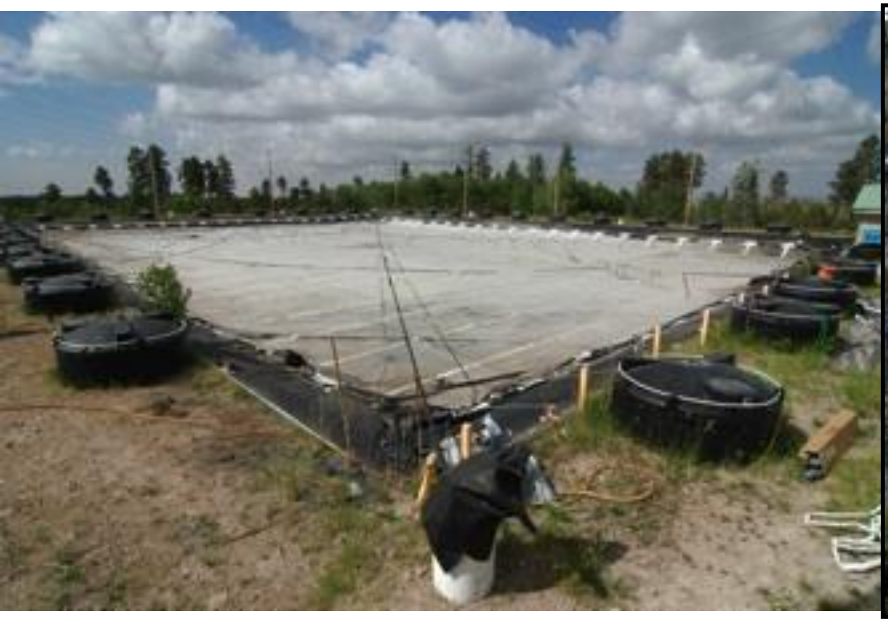
- Milagro was a *first generation* wide-field gamma-ray telescope:
  - Proposed in 1990
  - Operations began in 2001/04
  - Developed γ/h separation

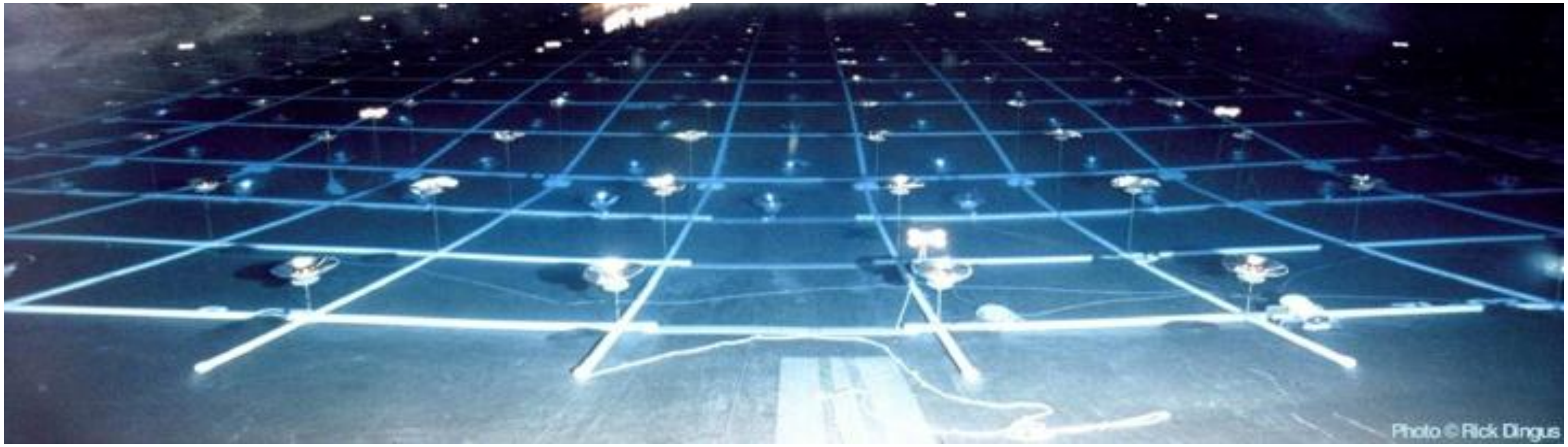


- Discovered:
  - more than a dozen TeV sources
  - diffuse TeV emission from the Galactic plane
  - a surprising directional excess of cosmic rays
- Showed that most bright galactic GeV sources extend to the TeV
- Best instrument for hard spectrum and extended sources
- HAWC is the next logical step
  - It will be 15x more sensitive than Milagro
  - It can be running in 3 yrs (with Fermi)



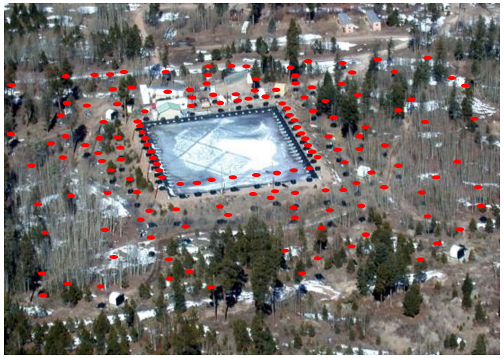
How do you make Milagro better?

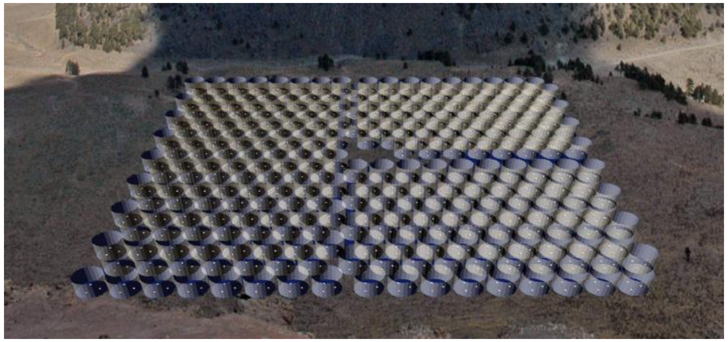




From Milagro to HAWC

- Move it to higher altitude
- Improve optical isolation
- Cover more area with water





- Milagro
- 2630m asl
- One big pond
- Pond area 4,000 m^2

- HAWC
- 4150m asl
- Individual Cherenkov detectors
- Tank area ~20,000 m^2

Science Goals

Understand **particle acceleration** in astrophysical jets by -

triggering **Multi-Messenger** (GWs, neutrino experiments)**/**

Multi-Wavelength Target of Opportunity programs;

- **observing** GRBs (> 30 GeV with scalers);

Discover the **origin of Galactic Cosmic Rays** by

- - measuring gamma-ray spectra to about 100 TeV: gamma spectra from Inverse Compton of electrons cut-off at ≈10-30 TeV,
- harder spectra require **hadronic components**;
- - mapping the multi-TeV **Galactic diffuse gamma ray emission** looking for strong emission regions correlated to matter in the Galaxy;
- - acceleration sites: **extended SNRs** close to molecular clouds and **pulsar winds**
- - understanding the **hadronic anisotropies** at energies > 10 TeV (local CR sources?).

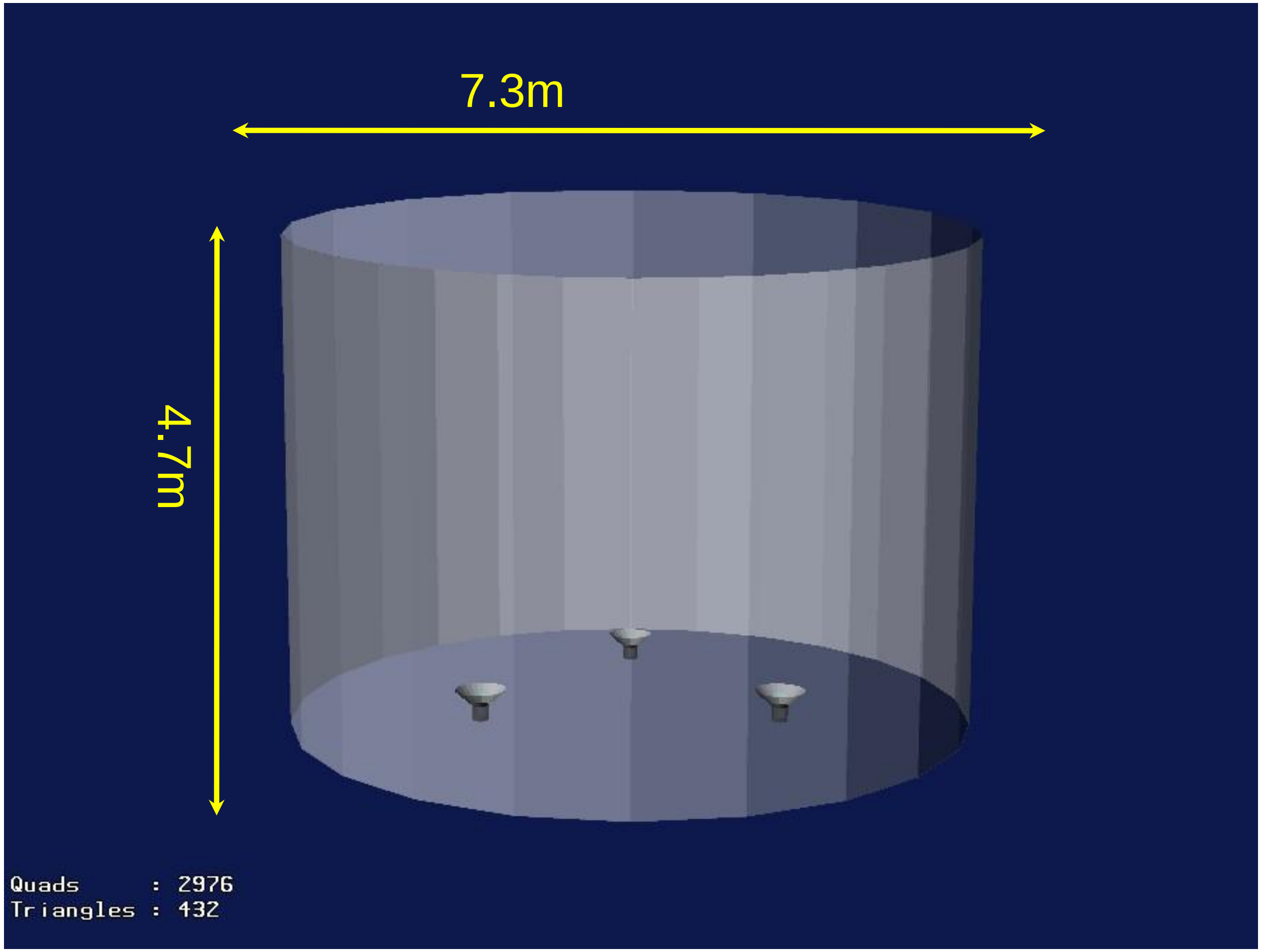
Science Goals

★**New Physics** and **exotic phenomena**:

- understanding the astrophysical background for **Dark Matter** searches requires understanding sources of "backgrounds";
- **axion-like** particles may explain the lower attenuation of 100 TeV distant AGN spectra than what expected by EBL
- heavy Dark Matter (Kaluza-Klein, Wimpzillas,...);
- Highly ionizing and slow particles (Monopoles, Q-balls);
- Study of energy dependent delays from GRBs: hint of **Violation of Lorentz Invariance (photon speed depends on energy) or energy dependent particle acceleration?**

HAWC Tanks

UCSC contribution



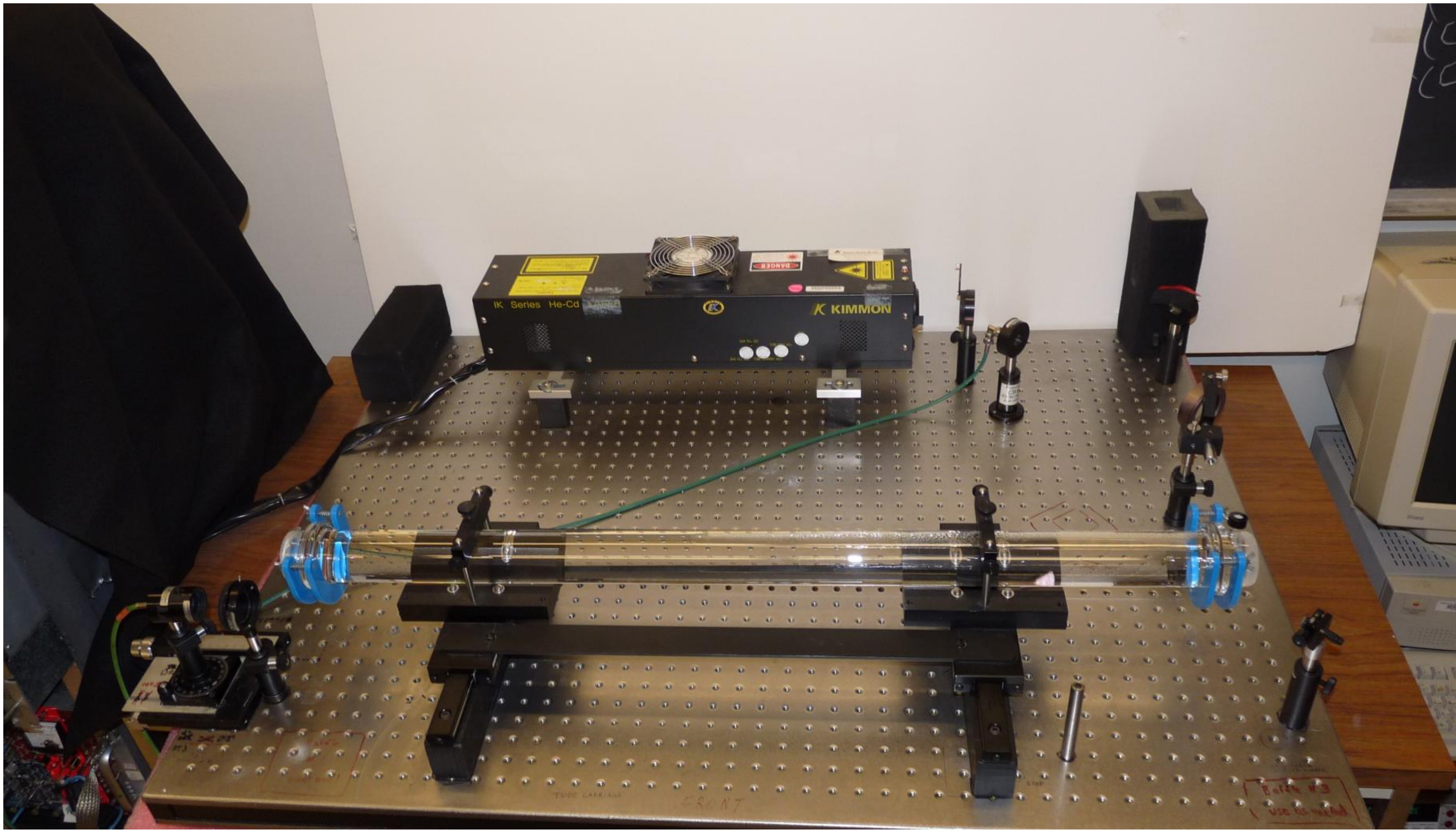
HAWC Bladder and Tank (300)

UCSC contribution

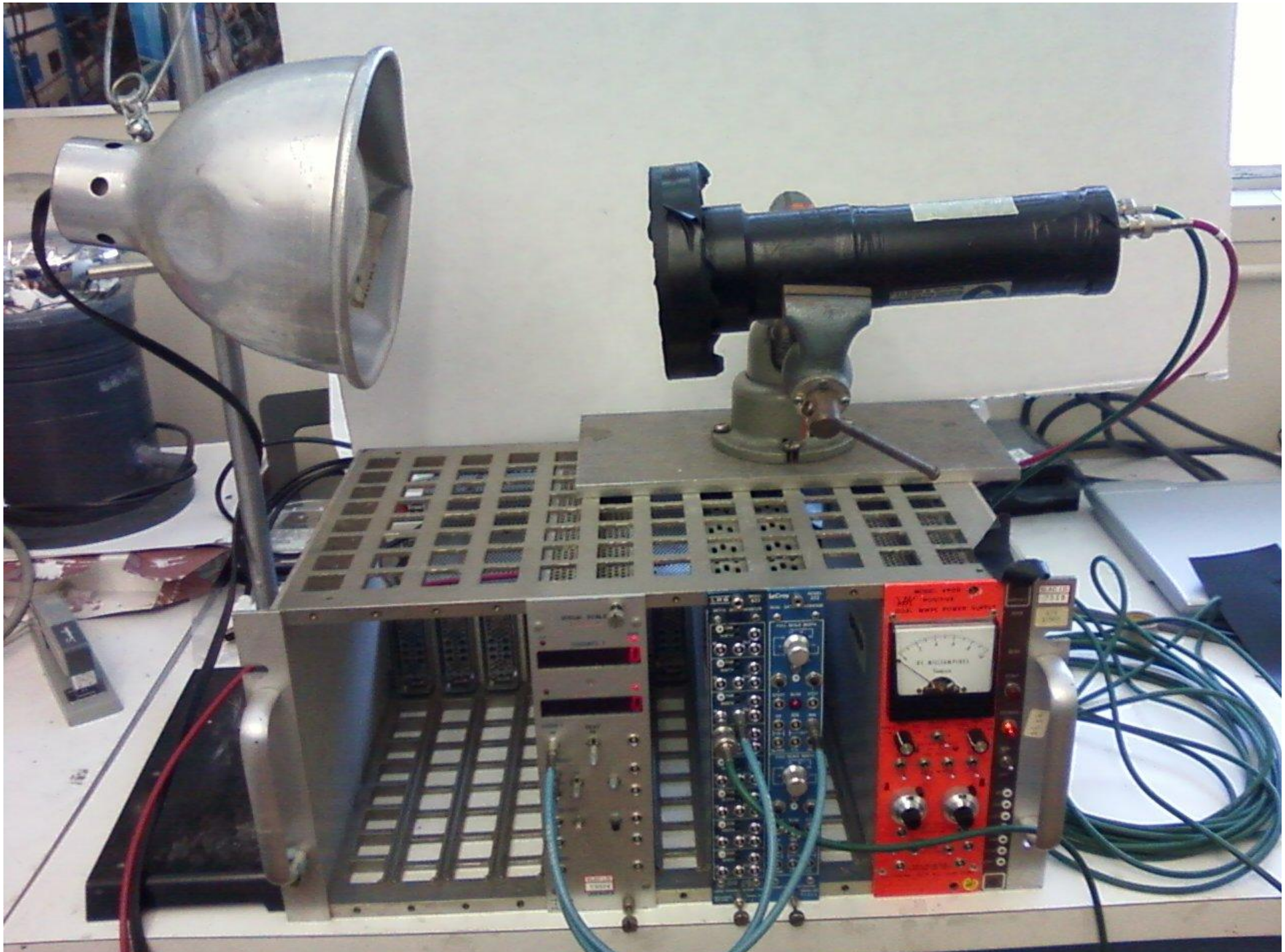
- 7.3m diameter and 5m high
- 190,000liter of purified water
- 3 x8” Hamamatsu PMTs

Inside HAWC Bladder

UCSC contribution : Material / Water Test



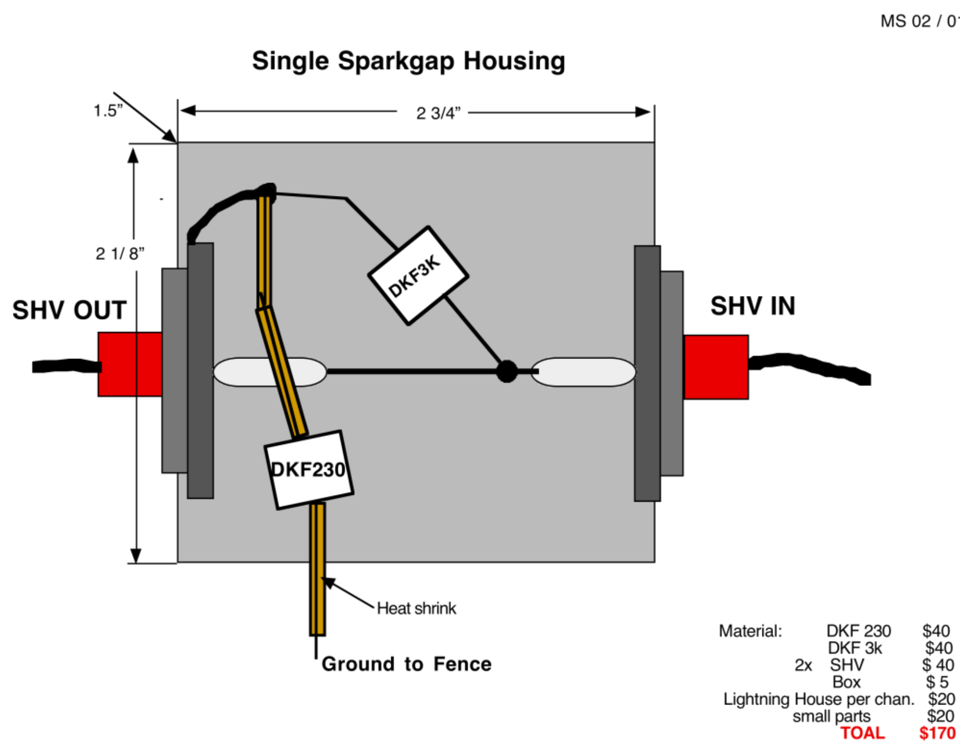
UCSC contribution : Bladder Material Light Test



UCSC contribution : Water Filtration System

UCSC contribution : Lightning Protection

will be built at UCSC ($120k)



HAWC Construction Management

Executive Committee

NSF PI: Jordan Goodman (UMD), DOE PI: Brenda Dingus (LANL)

CONACyT PIs: Andres Sandoval (IF-UNAM), Alberto Carramiñana (INAOE)

All positions are members of the Tech Board

Project Manager

Brenda Dingus (LANL)

Project Office

Project Engineer:
Michael Schneider (UCSC)

Site Engineer:
TBD (IF-UNAM)

Logistics & Safety:
Janina Nava(INAOE)

Budget Analyst:
Dawn Meyers (UMD)

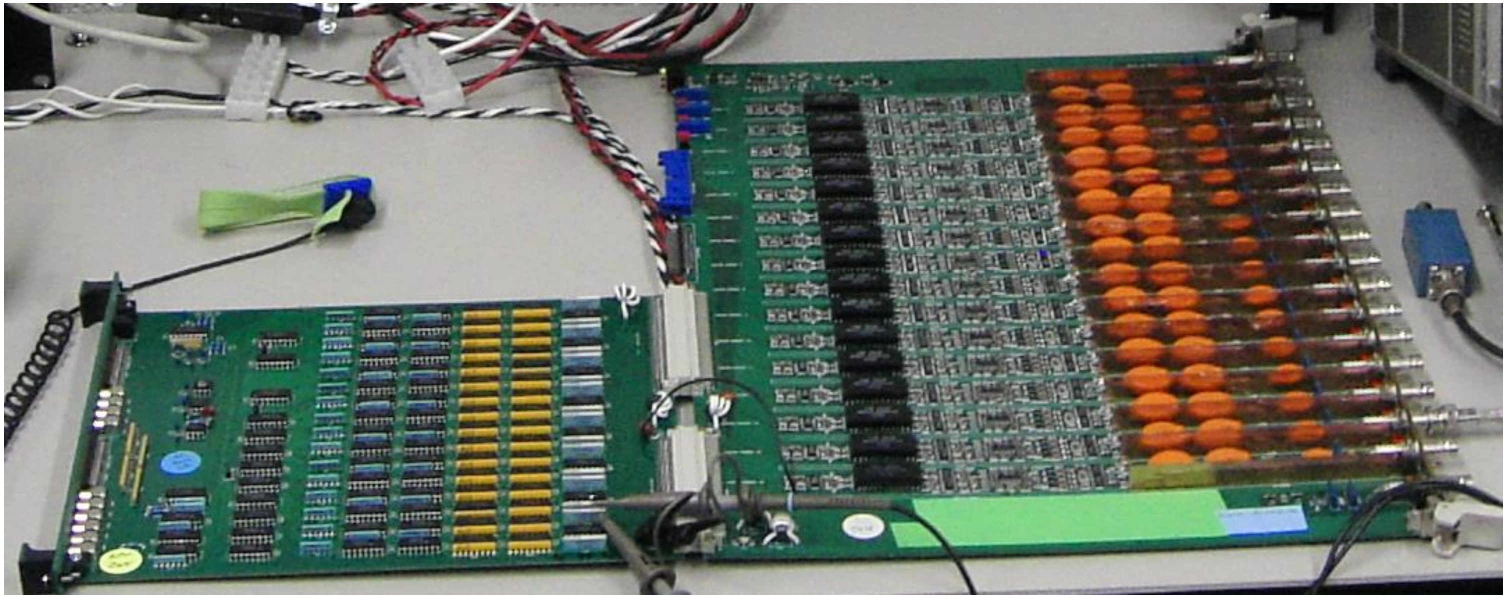
Technical Working Groups

Site	Chair: Alberto Carramiñana (INAOE) Deputy: Humberto Salazar (BUAP)
Instrumentation	Chair: Rubén Alfaro (IF-UNAM) Deputy: Miguel Mostafa (CSU)
Electronics	Chair: Jim Linnemann (MSU) Deputy: Arturo Iriarte (IA-UNAM)
Software	Chair: Andrew Smith (UMD) Deputy: Lukas Nellen (IN-UNAM)
Science	Chair: Magda González (IA-UNAM) Deputy: Petra Hüntemeyer (MTU)

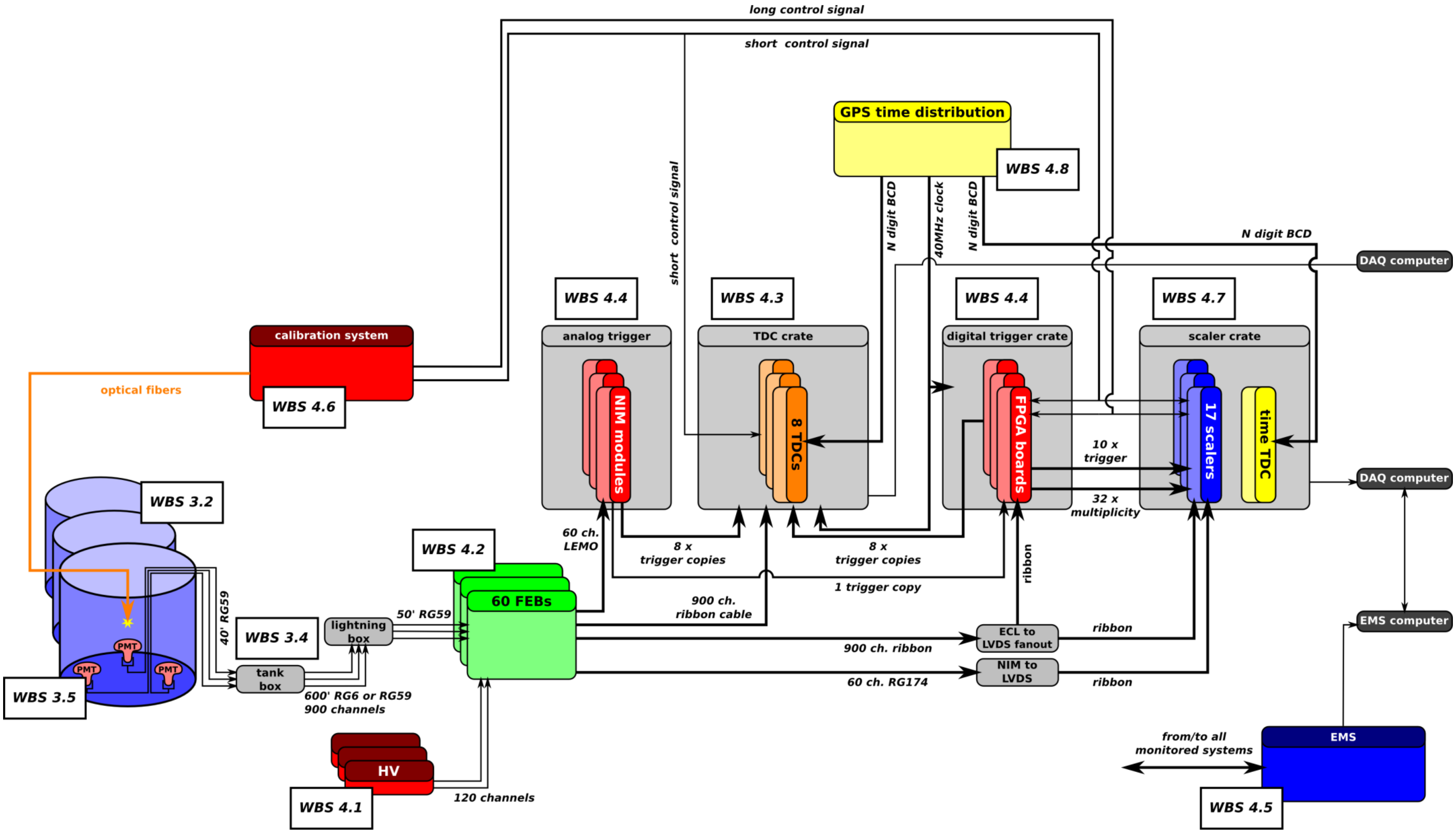
UCSC contribution : Front End Boards

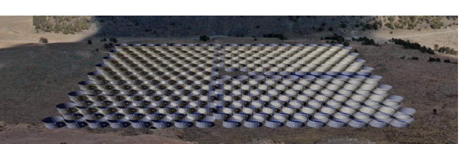
Re-used from Milagro

16 channels: use 5 tanks = 15 tubes/board



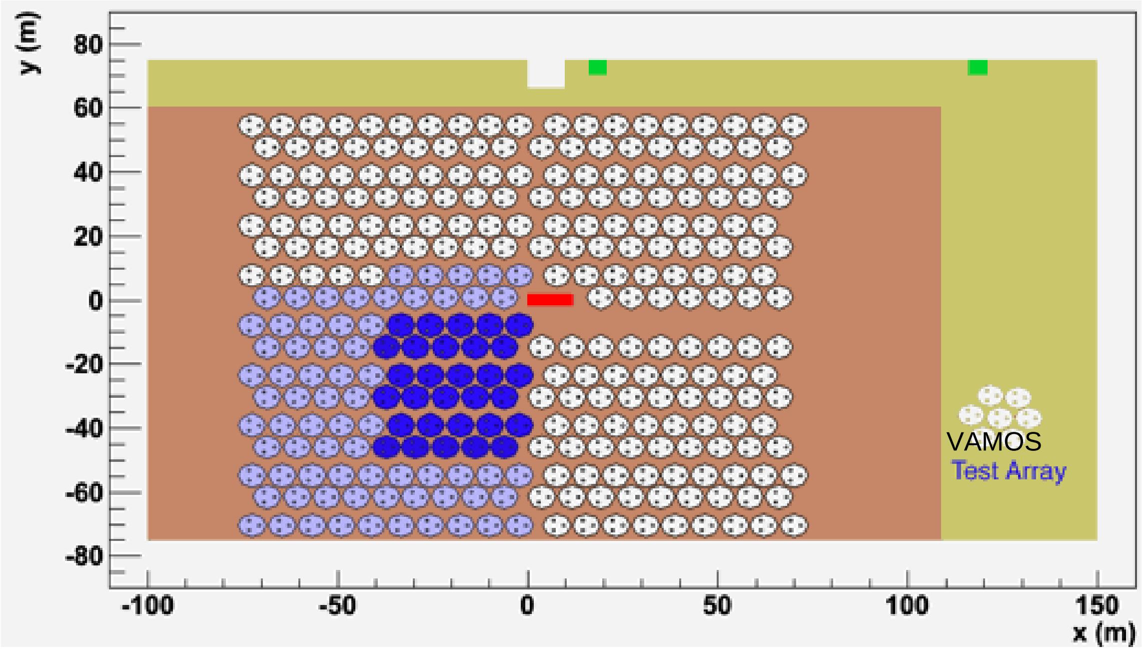
HAWC Electronics Overview





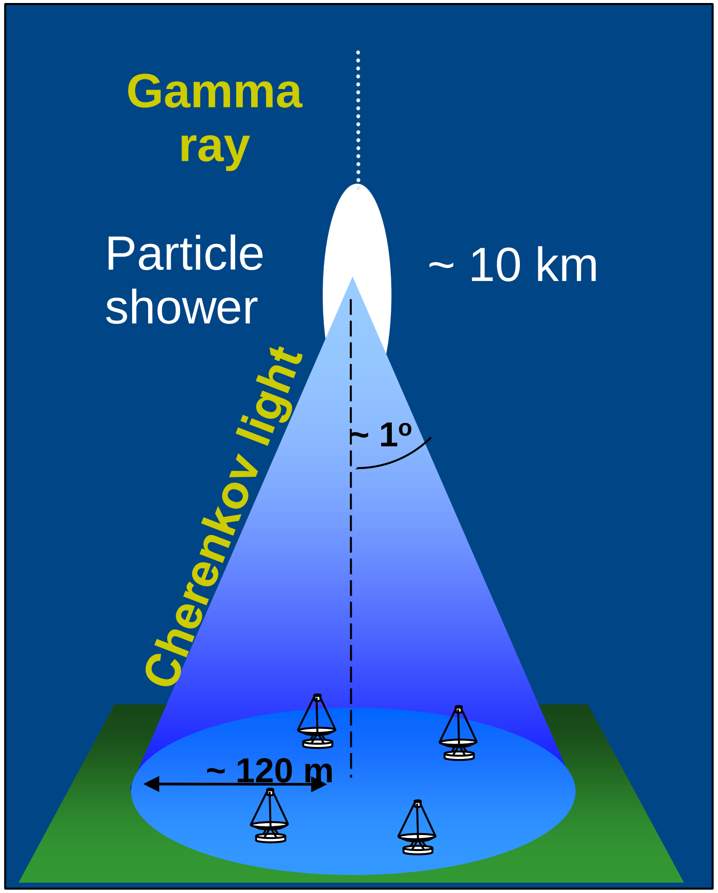
HAWC Construction Phases

- VAMOS
  - Verification Assessment Measuring Observatory Subsystems
- HAWC-30
  - Implementation of All Subsystems
- HAWC-100
  - Science Operations with 2 times Milagro's Sensitivity
- HAWC-300



Milestone	Date
Site construction began.	Fall 2009
VAMOS tanks installed.	Summer 2010
HAWC-30 tanks installed.	Funding Start + 9 months
HAWC-100 tanks installed.	Funding Start + 18 months
Detect Crab at 5 sigma.	Funding Start + 24 months
HAWC-300 tanks installed.	Funding Start + 36 months

Working Environment



Cherenkov Light

- ~1° opening angle
- 5 photons / m^2
- 2-3 ns duration

Night Sky Background Light

- Isotropic
- 10^8 photons sec^{-1} cm^{-1}

Photondetector Requirements

Highest possible photon detection efficiency

- Lower energy threshold
- Better event reconstruction

Minimize non-Poisson tails in pulse height distribution (Afterpulsing / Optical Crosstalk)

- Ensure low energy threshold

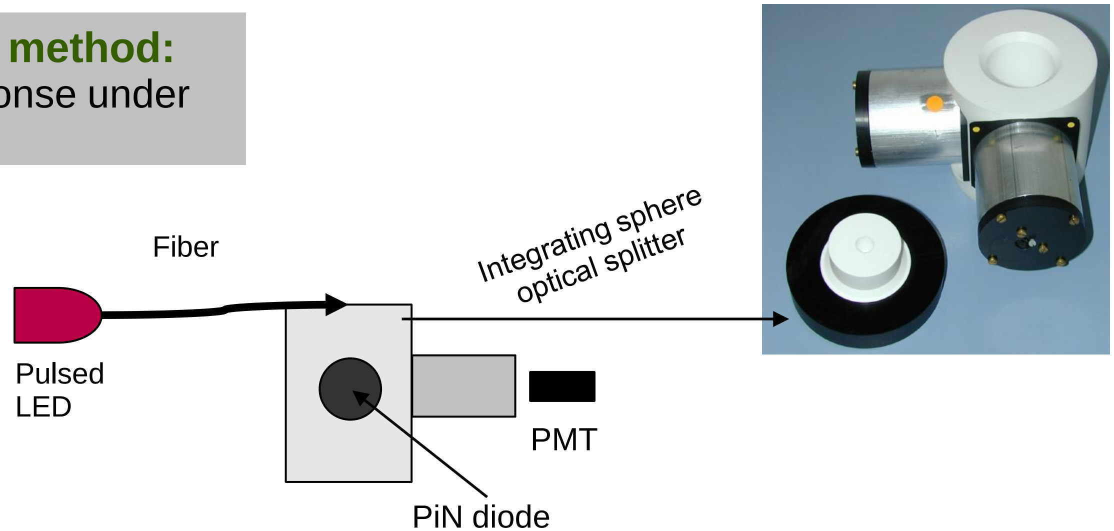
Other Characteristics::

- Aging
- Temperature dependence of parameters
- ...

PDE Measurements

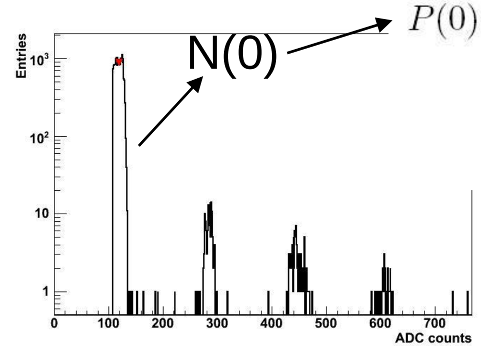
Otte et al., NIM A 567, 1 (2006), pp 360-363

Advantage of the method:
Measure PMT response under "real life" conditions



Procedure:

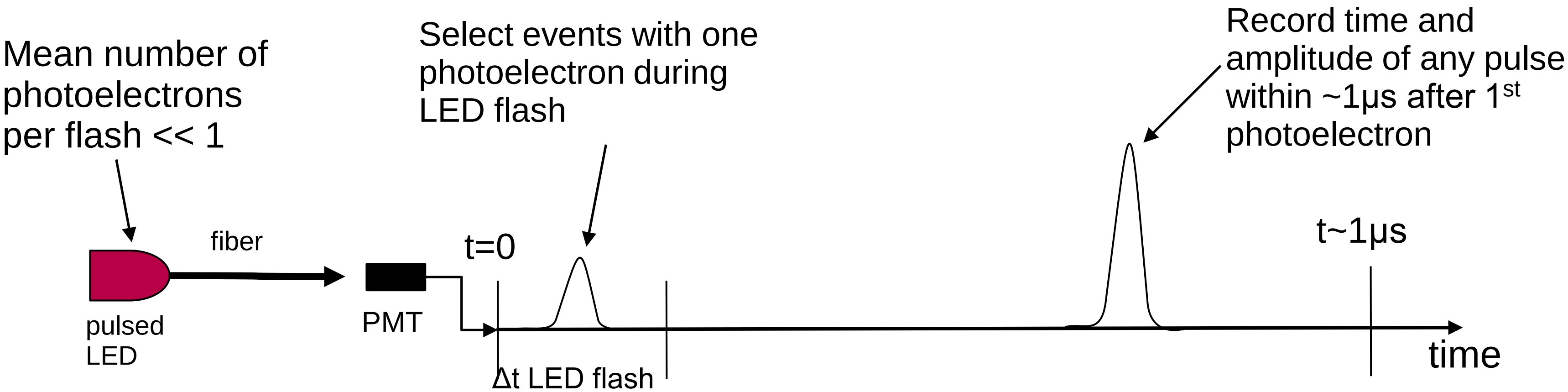
1. Flash setup with fast LED Pulses (~10ns long)
2. Convert PiN signal to photoelectrons and calculate number of **photons at PMT exit**
3. Use Poisson statistics to calculate number of **photoelectrons μ detected with the PMT**
4. PDE = photoelectrons / photons



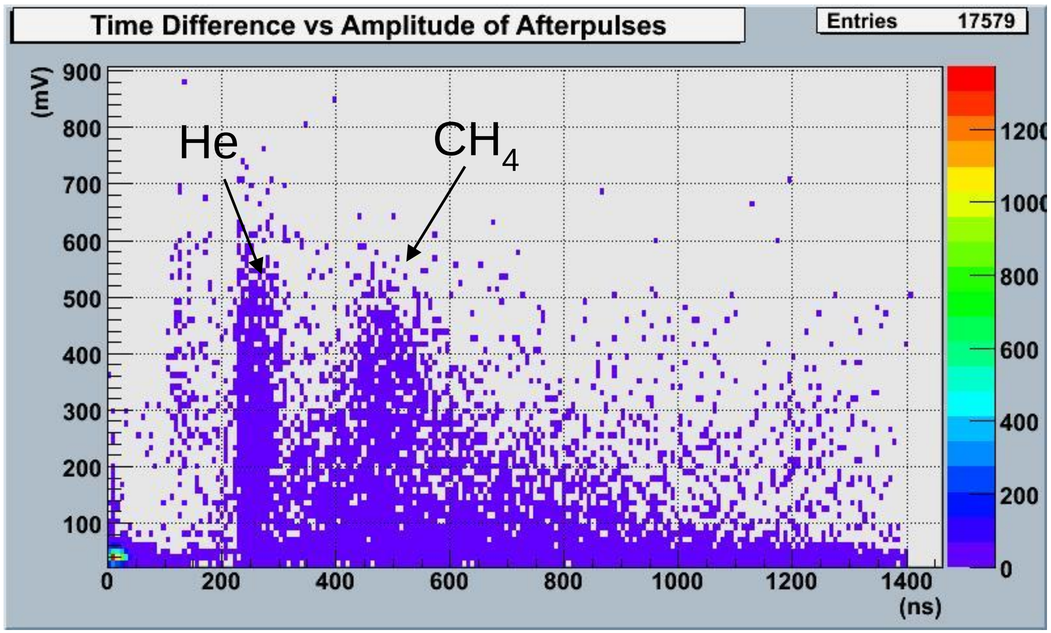
$$P(0) = e^{-\mu} = \frac{N(0)}{N_{total}}$$

$$\Rightarrow \mu = -\ln\frac{N(0)}{N_{total}}$$

Afterpulsing Measurements I



Example: R10408



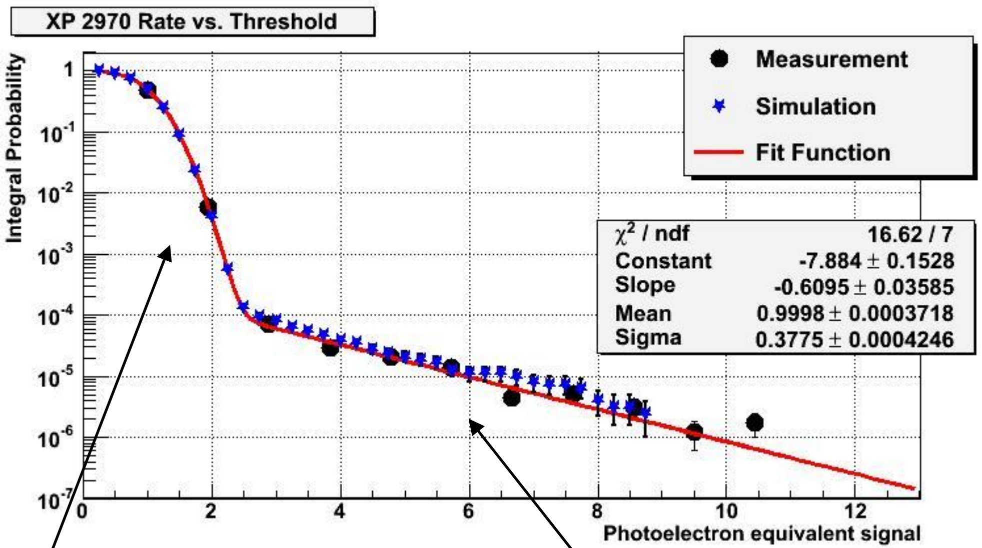
Afterpulsing Measurements II

PMT illuminated with steady
low light level source

Measure:

trigger rate
vs.
discriminator threshold

i.e. integral pulse height distribution



Single pe's

Afterpulses

$$\frac{1}{2}\left[1+\operatorname{erf}\left(\frac{\mu-x}{\sqrt{2\sigma^2}}\right)\right]+\exp(a+b\times x)$$

VERITAS Upgrade

Aiming at:

Lower energy threshold
Better gamma/hadron suppression

Two high-QE candidate tubes

R10408

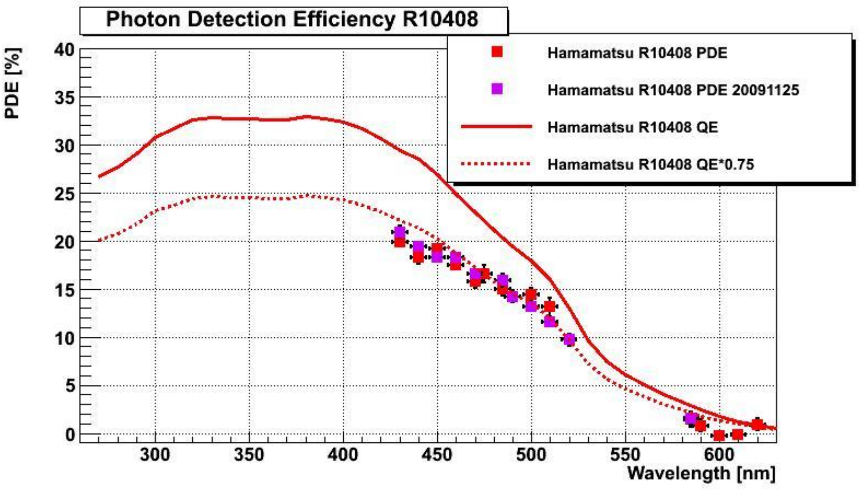
- Hemispherical window, 1”
- 6 stages
- Gain ~25,000
- Used in MAGIC II telescope

R10560-100

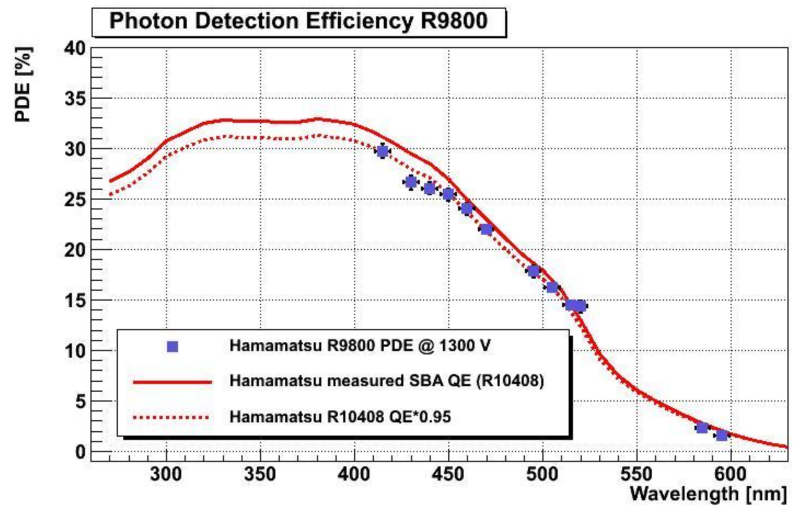
- Flat window, 1”
- 8 stages
- Gain ~1,000,000

VERITAS Upgrade: PDE Measurements

R10408



R9800 / R10560-100



Expected Increase in Cherenkov photon yield:

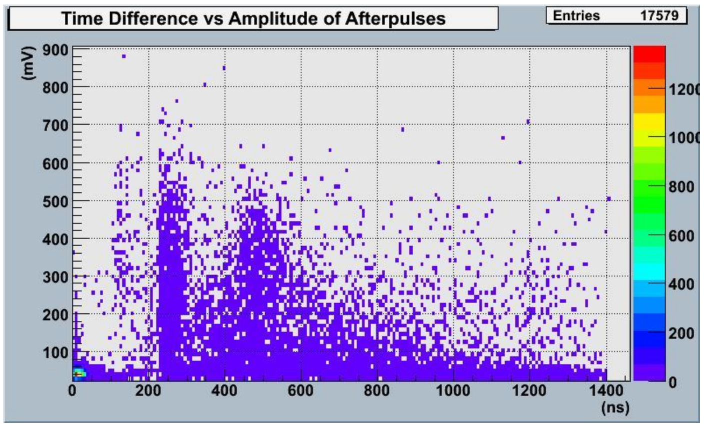
21%

56%

Both PMTs have comparable QE's
but
significantly lower collection efficiency (CE) for R10408
~80%

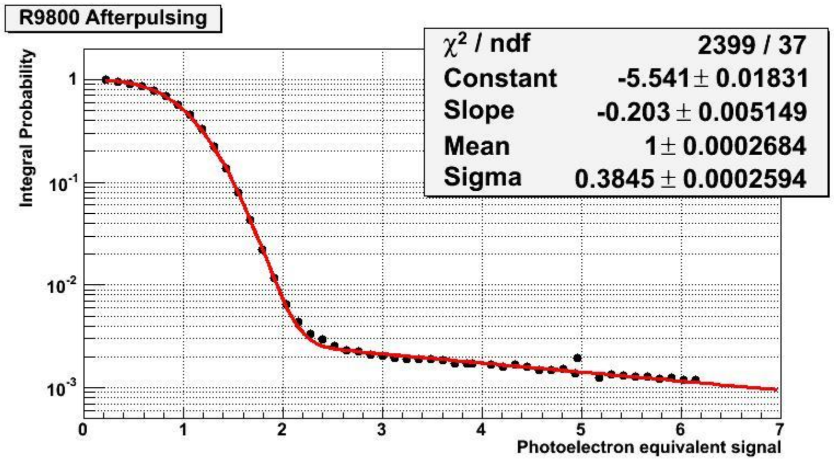
VERITAS Upgrade: Afterpulsing Measurements

R10408



5* 10^{-4} >6pe

R9800



10^{-3} >6pe

Back on the envelope ->: Afterpulsing level in the R9800 is critical

Two approaches to come to a final conclusion:

1. Building of a cluster with R10560-100 and test it in VERITAS
2. Simulations

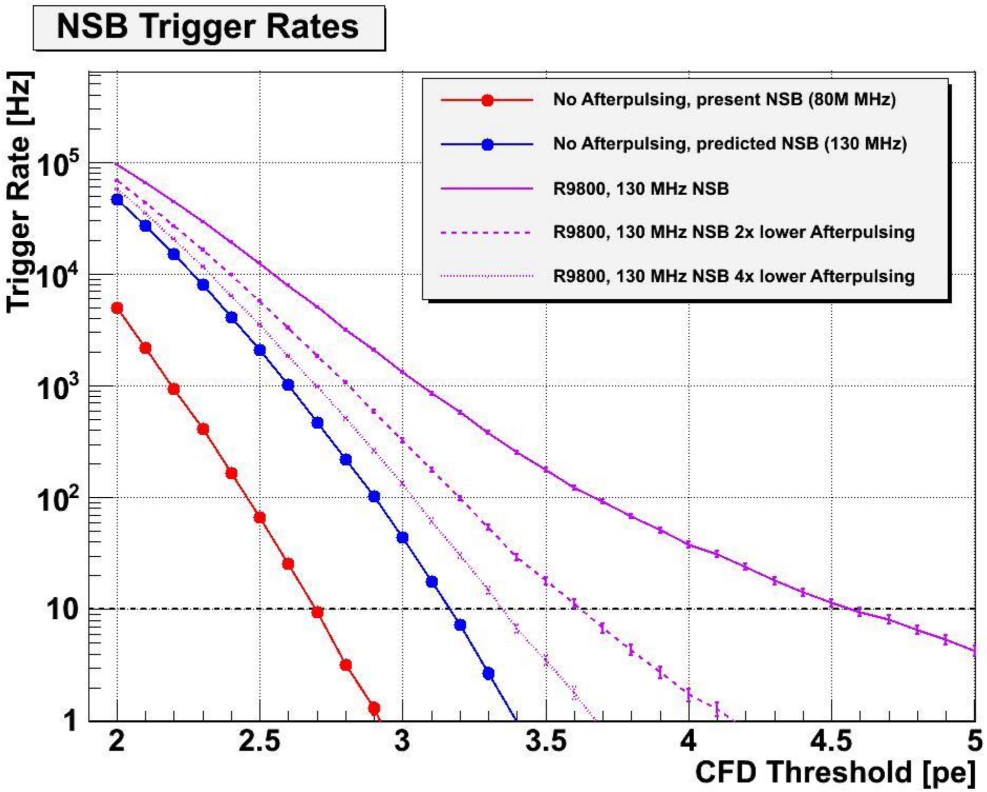
Simulations of Accidental Trigger Rates

CFD threshold setting determined by:

Keeping deadtime low
Keeping data volume low

-> 10 Hz NSB rate

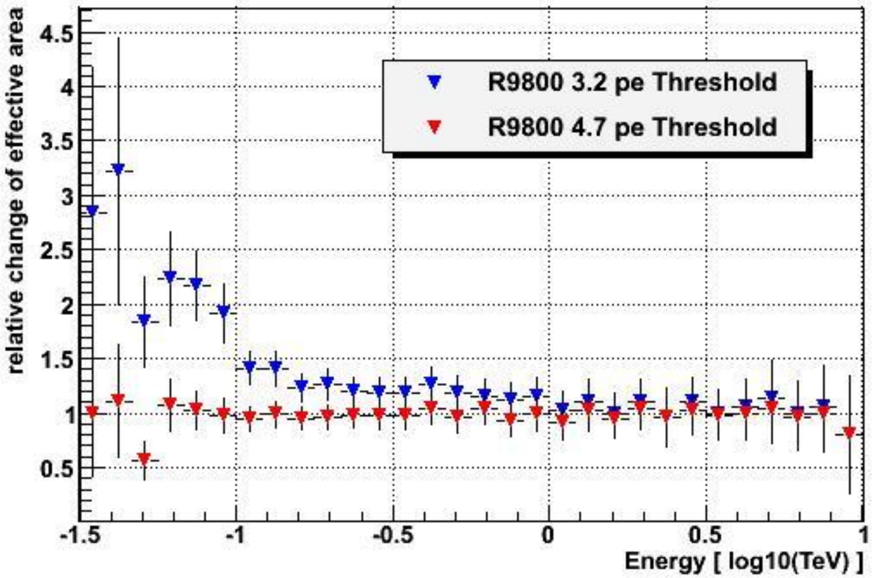
Afterpulsing in R9800 requires 2 times higher CFD thresholds

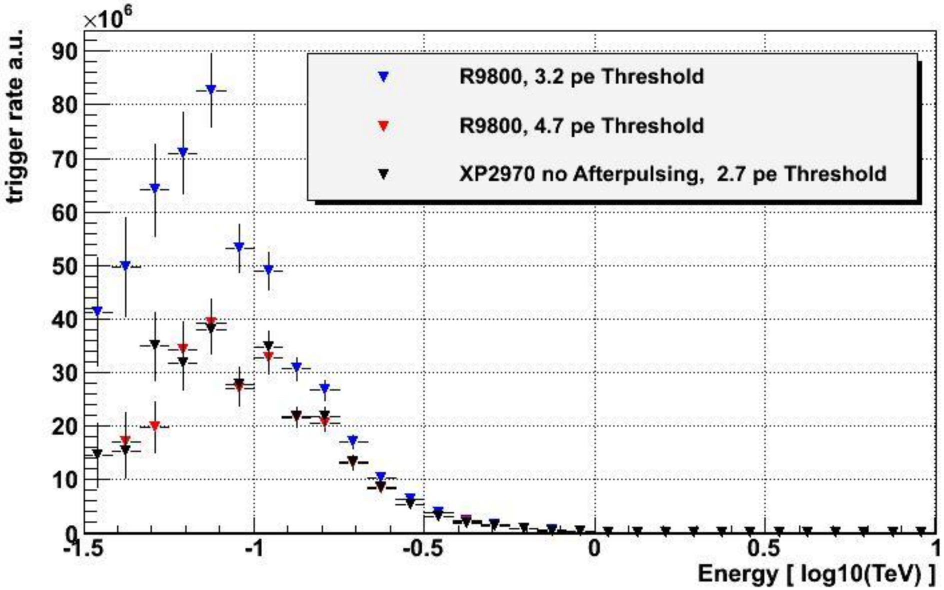


4 times lower AP -> almost no impact on Threshold levels

Effective Areas

Afterpulsing has
significant impact on the effective area





Threshold energy shifts from
80 GeV (Afterpulsing dominated)
to
60 GeV (Afterpulsing free)

present threshold energy ~ 110 GeV

AGIS

UCSC contributions:

- Focal plane instrumentation
- Simulations

Key studies to understand instrument performance

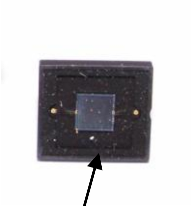
Baseline:

H8500 MAPMT in SBA version

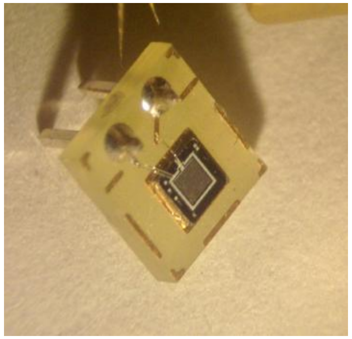
64 pixel
a 5x5 mm^2

Maybe possible in the future:

Geiger Mode APDs or SiPM



3x3 mm^2



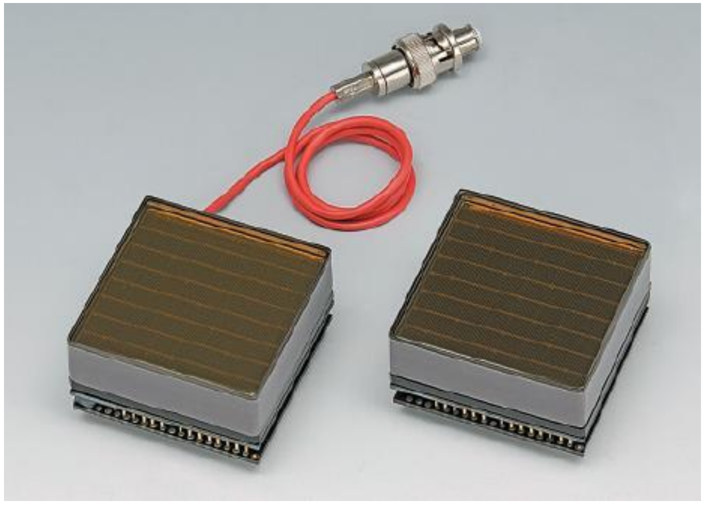
1x1 mm^2

MAPMT Measurements

One H8500 in our group

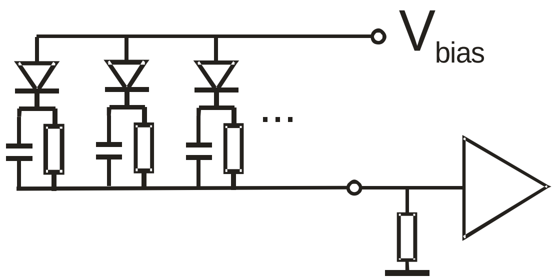
First round of measurements ongoing

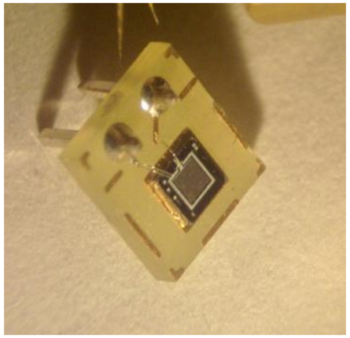
- Photoelectron collection efficiencies
- Homogeneity over pixel and MAPMT
- response as function of incident angle
- Afterpulsing
- Crosstalk
- Response to NSB

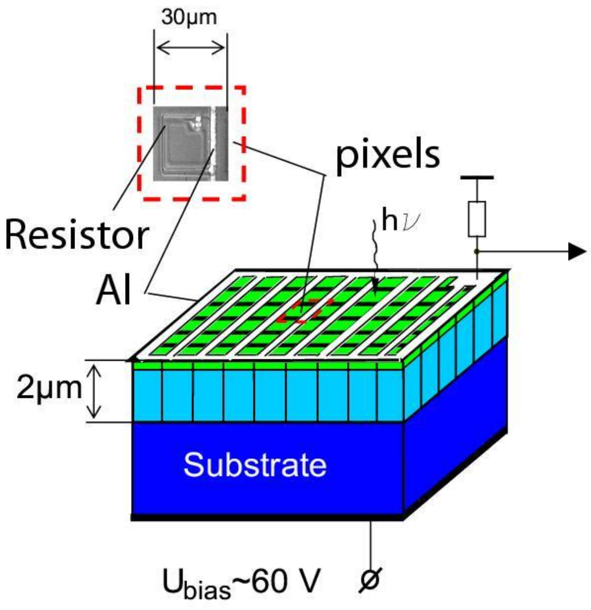


The G-APD

a promising photon detector concept invented in Russia in the 80's
available now in large quantities and from many producers







Major advantages:

- High intrinsic QE of a semiconductor
- Geiger mode operation → sensitive to single photons
- Bias voltage < 100 V
- High intrinsic gain
- Is not damaged in daylight
- Mechanical and electrical robust

Geiger Mode APDs

Continuous evaluation of new devices

Hamamatsu 3 year old MPPC is still the most sensitive devices

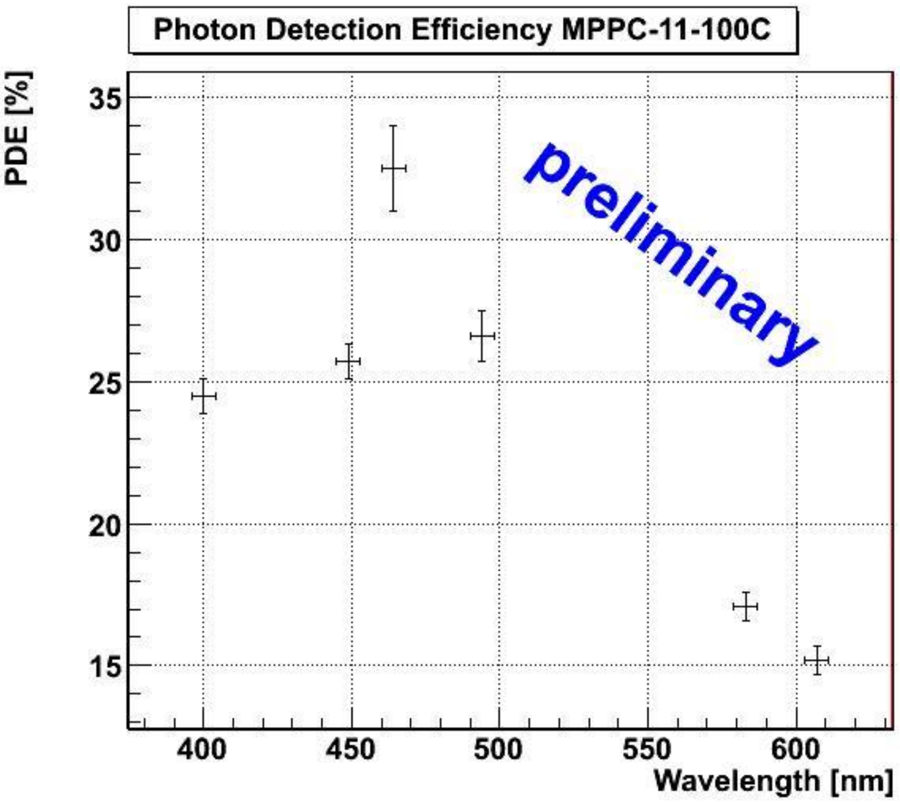
Two main concerns with available devices

- price

PMT is still 5 times cheaper

- blue efficiency

Similar to R10408



AGIS –
The Advanced Gamma-Ray Imaging System

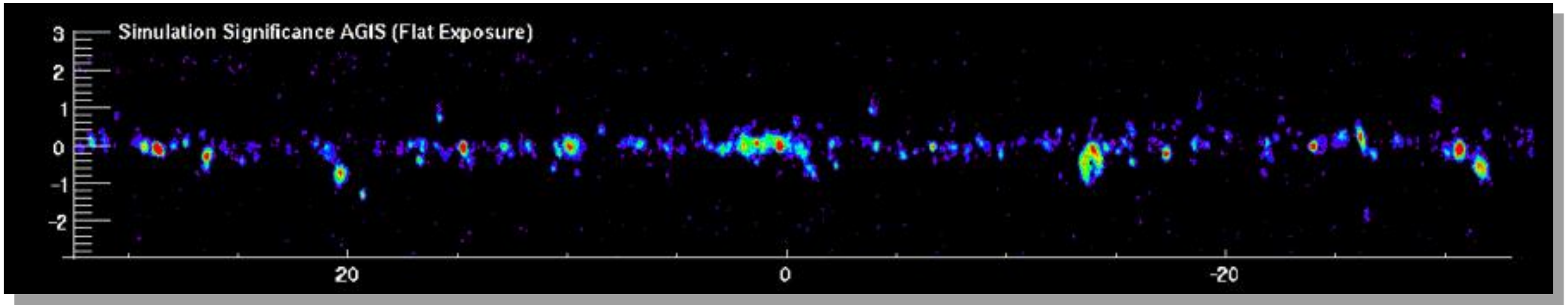
http://www.agis-observatory.org

Institutions:

ADLER	MSFC	UCLA
ANL	Penn State	UCSC
Barnard	Pittsb. State	U. Chicago
Delaware	Purdue	U. Iowa
IAFE	SAO	U. Utah
INAF (Brera)	Stanford/SLAC	Yale
Iowa State	UNAM	Washington U
McGill		

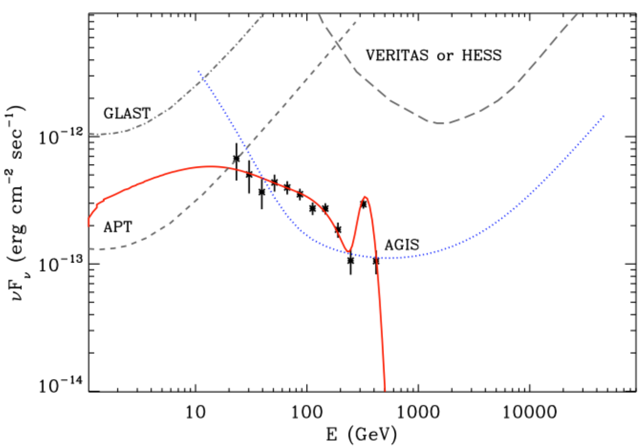
AGIS Science Drivers

Galactic Sources: Angular Resolution, FoV, Southern site



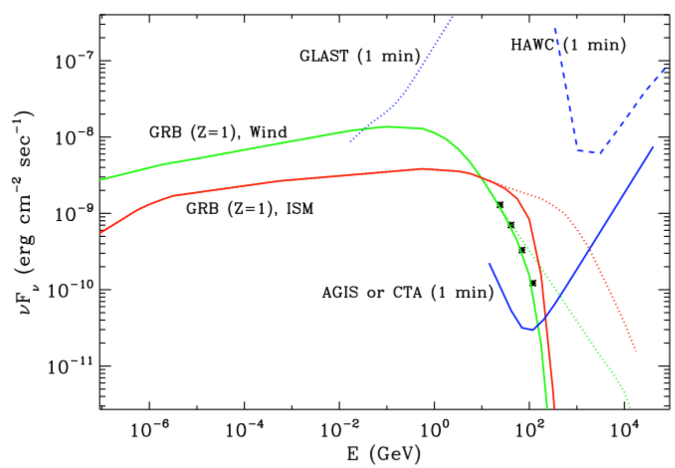
Digel, Funk and Hinton

Dark Matter: Sensitivity and Energy Resolution



Aharonian, Buckley, Kifune and Sinnis 2008

GRBs: Energy threshold, FoV and slew speed



APS White Paper., 2008

AGIS Instrument Concept

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

AGIS

Major Steps to advance the **100 GeV - 10 TeV** regime:

- 36 element array
- Wide FOV
- high resolution imaging

-> angular resolution

-> better background rejection

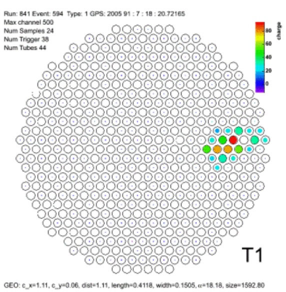
-> better sensitivity

Approaching the limit of the IACT technique in mid Energy regime, where it works best!

Large IACT array technology

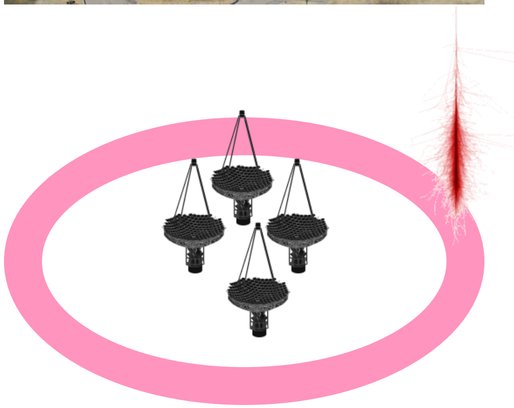
Whipple 10m, MAGIC

Imaging

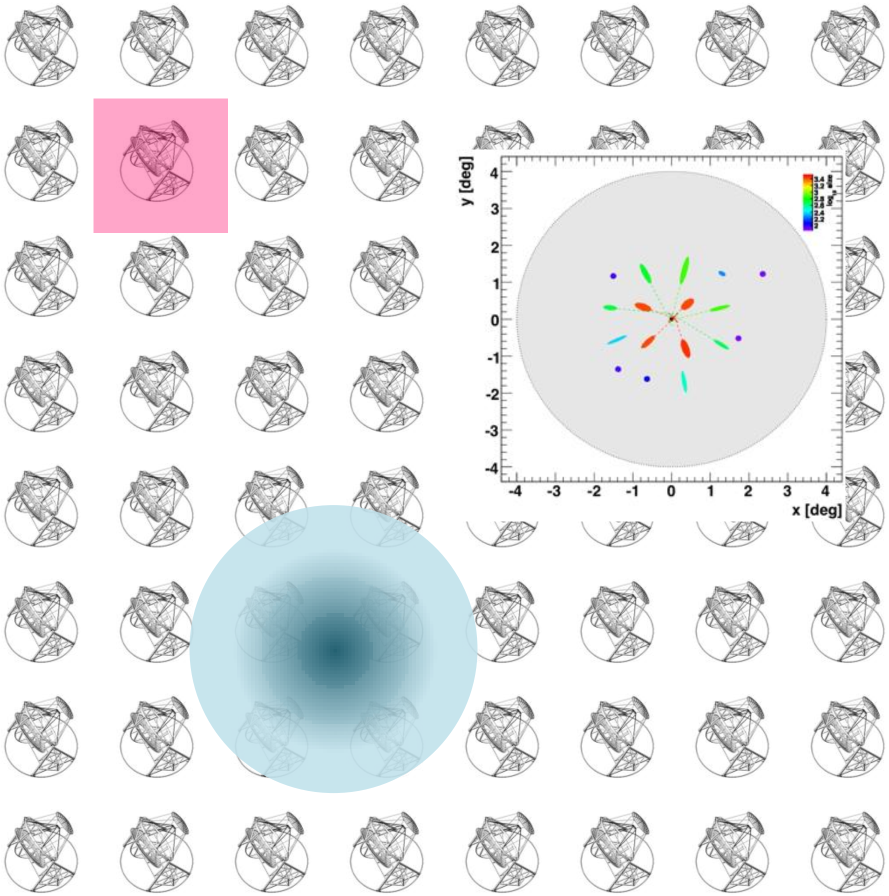


VERITAS, HESS

Stereoscopy



...but collecting area is well outside of the array footprint



AGIS/CTA

Event Containment

IACT Array Natural Scales

Change from “event non-containment” to “event containment” operation regime occurs when ….

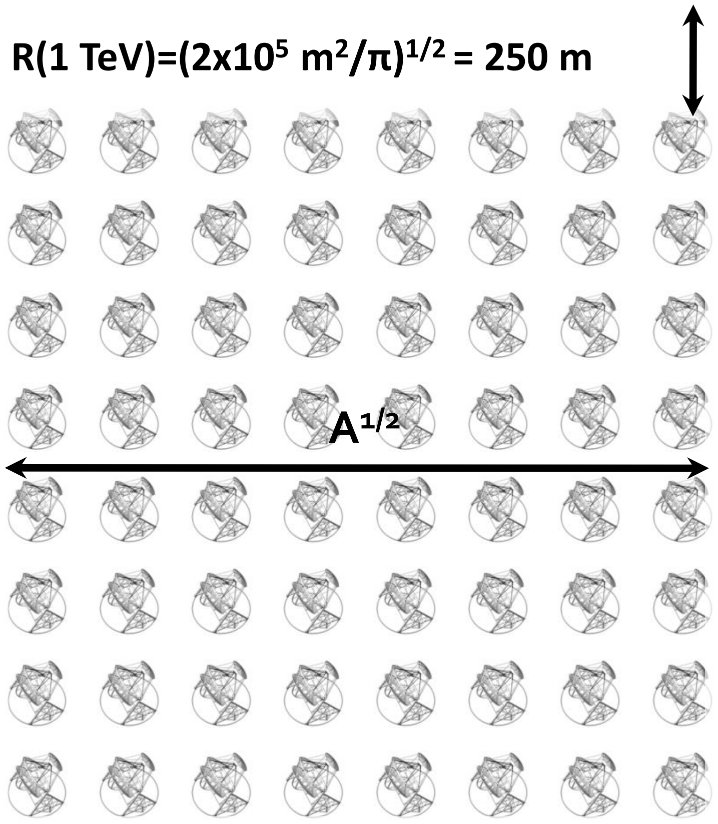
$A \approx 4A^{1/2} * R(1\ \text{TeV})$ ->

$A \approx 1\ \text{km}^2$

$A^{1/2} \approx 1\ \text{km}$

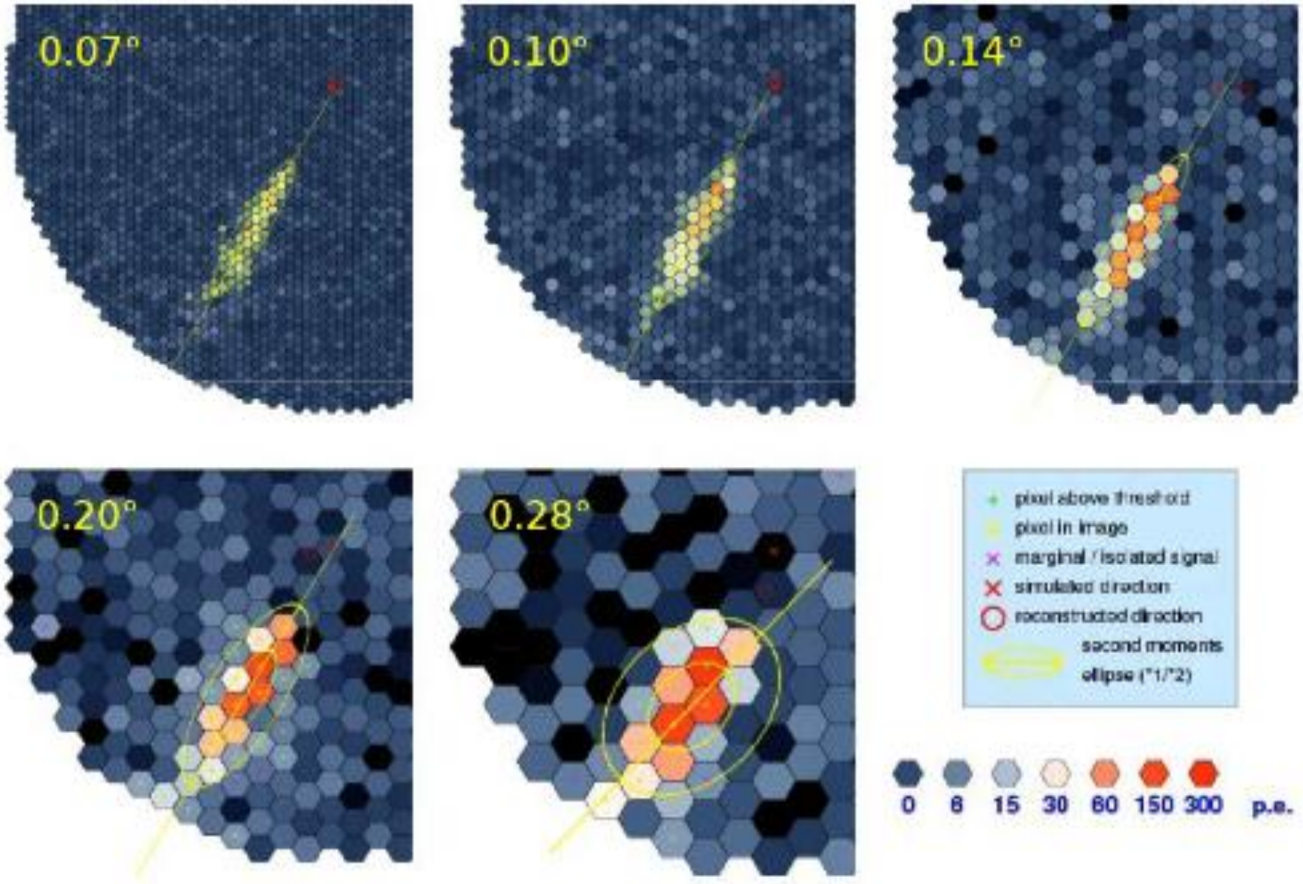
$N_{tel} \approx (A^{1/2}/125\text{m}+1)^2 \approx 80$

If $A \ll 1\ \text{km}^2$,
containment is inefficient,
collective effects are not fully utilized.
If $A \gg 1\ \text{km}^2$,
cost inefficient,
sensitivity improves only as $N^{-1/2}$.



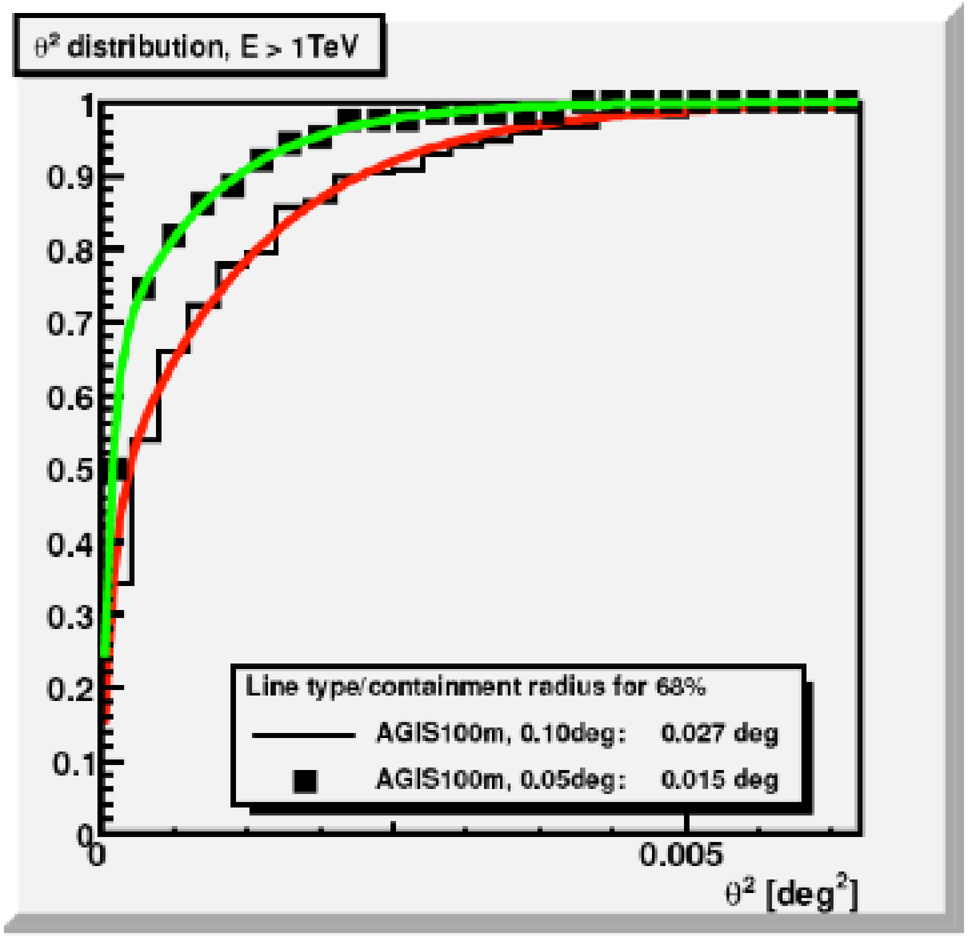
AGIS-36 is 50% contribution toward world-wide AGIS/CTA observatory (either N or S)

Pixel Size Effects

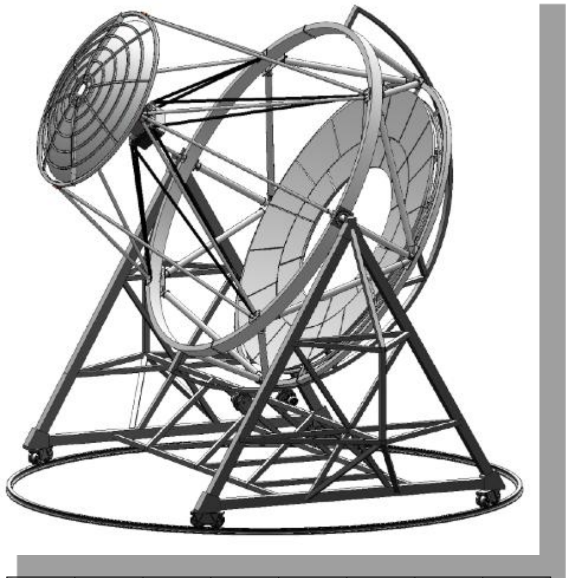


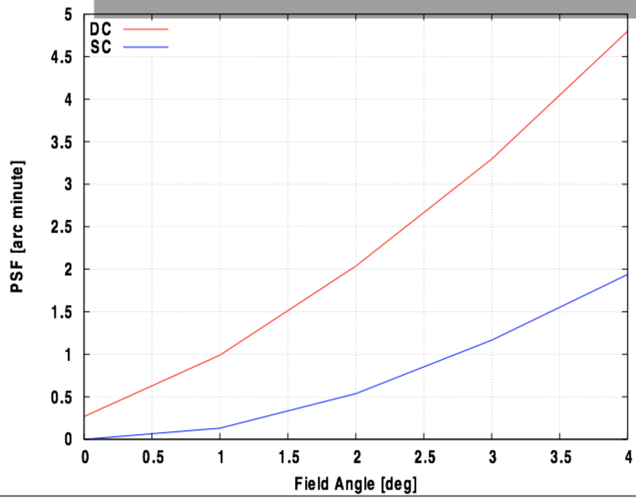
Angular resolution

- Smaller pixels (0.05deg) can give substantially better angular resolution than larger pixels (0.1 deg).



AGIS Optical Design





- Demagnifying 2-mirror (Schwarzschild-Coulder) provides *plate scale reduction*, *aberration correction*, isochronous optics for *fast timing*, *lower moment of inertia* for fast slewing.
- Initial design for R&D telescope has a diameter D=11.5m, and f/D=0.56
- Both rail-style (HESS) and pedestal based (VERITAS) mount designs will be studied for ease of deployment, reliability and cost.

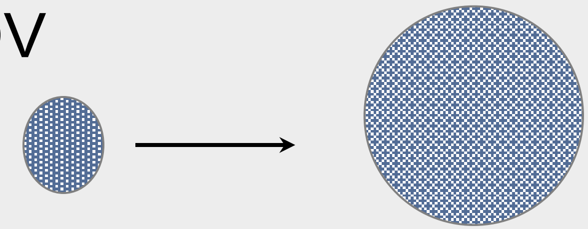
AGIS Telescope Concept

Pixelation

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

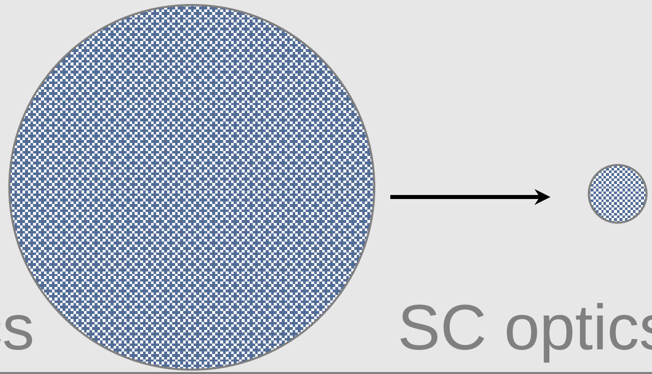
0.28° 0.20° 0.07°

FOV



3.5 deg. 8 deg.

Relative Size



DC optics SC optics

AGIS Element:
Schwarzschild-Couder optics
☐

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

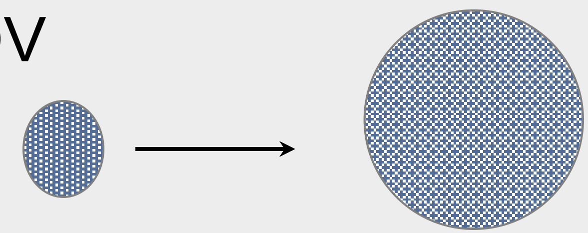
AGIS Telescope Concept

Pixelation

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

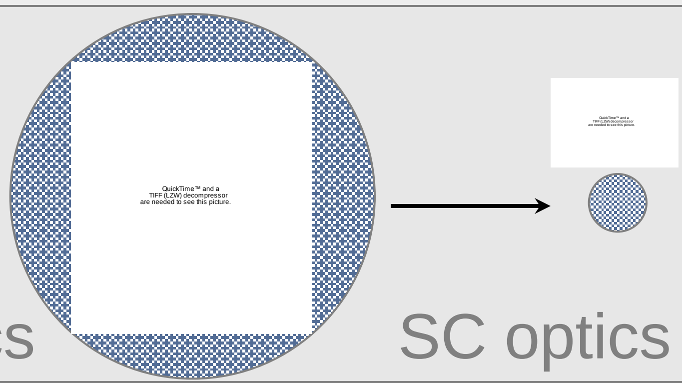
0.28°   0.20°   0.07°

FOV



3.5 deg.   8 deg.

Actual Size



DC optics   SC optics

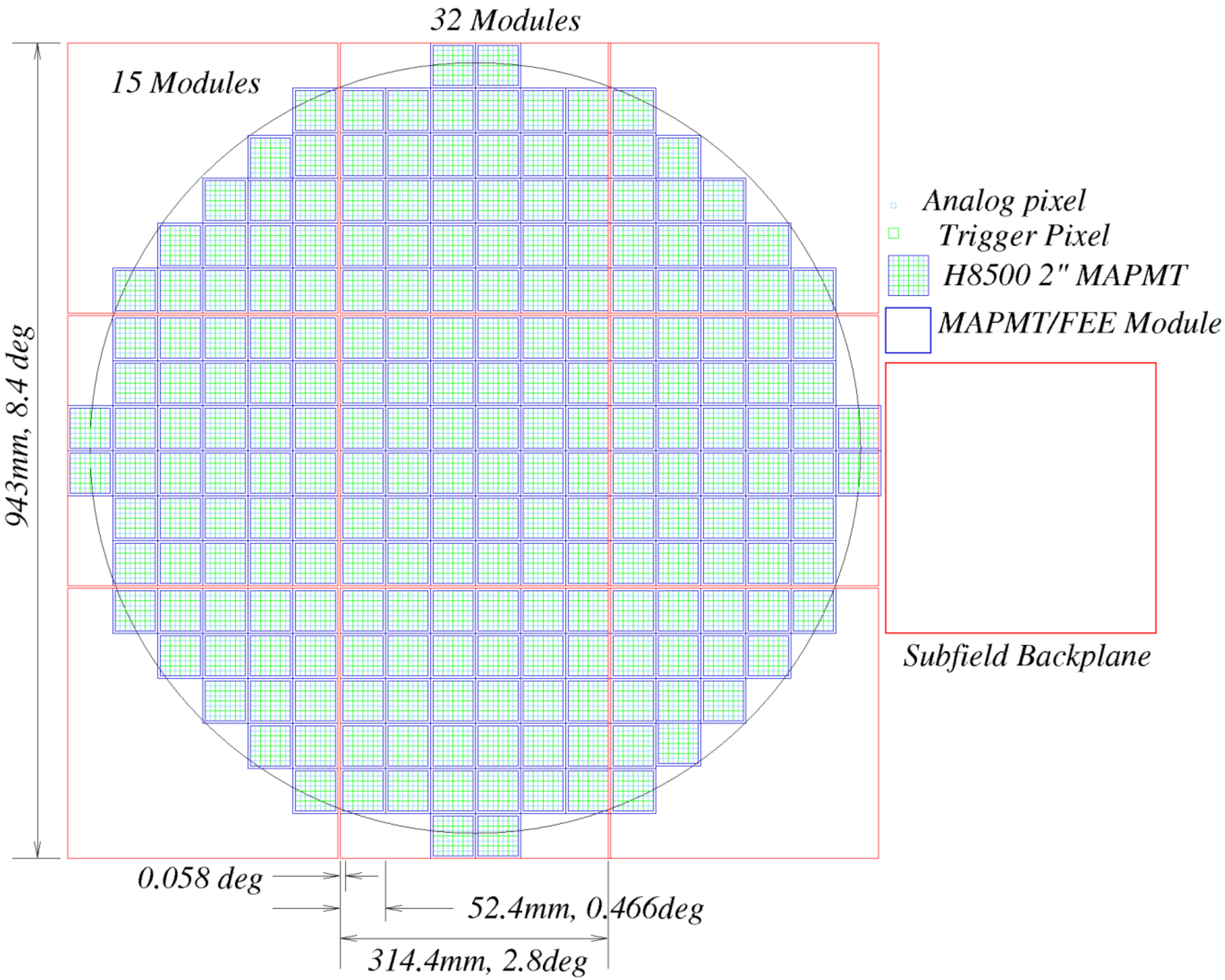
AGIS Element: Schwarzschild-Couder optics

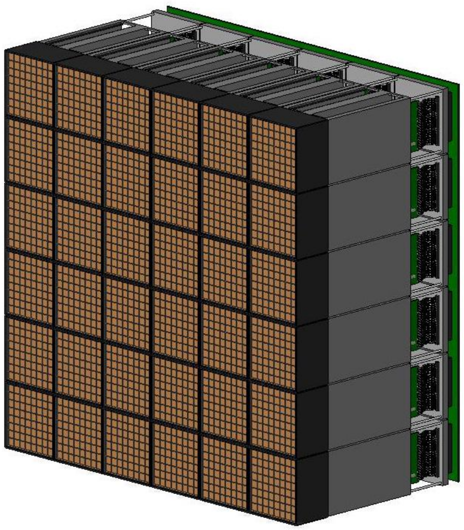
□

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

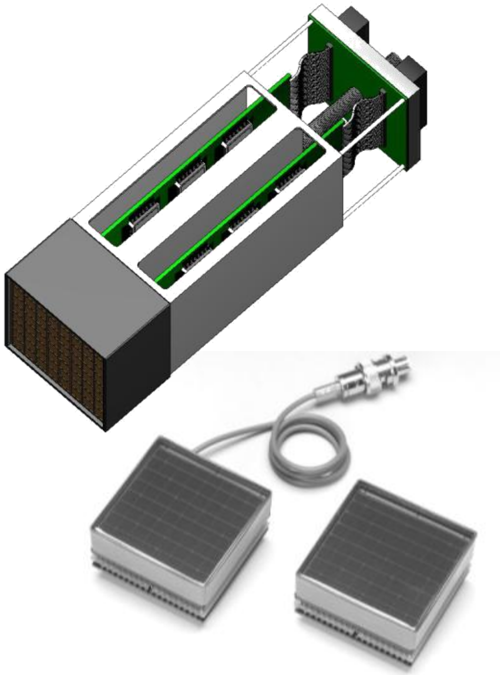
Secondary optics, but telescope with short f/D & compact high resolution, wide FOV cameras!

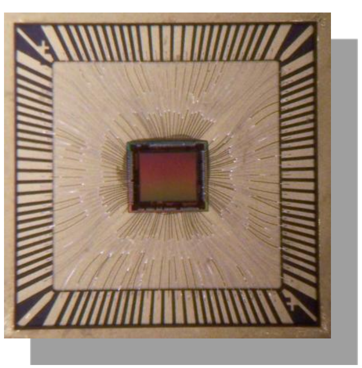
Camera Strawman





Camera





- 224 2” Hamamatsu MAPMTs
- 14,336 0.058° pixels
- 14,336 1 Gsps analog pipeline channels
- 16 channel x 4k 1 Gsps TARGET ASIC (following up on many generations of the U. Hawaii BLAB/Labrador design)
- 3,586 trigger channels
- Total electronics cost $1.36M/camera, $80.7/channel
- Power estimate: 2.3kW/telescope
- Assuming a 5kHz event rate (TBD) a compression ratio of 10:1, the total data rate will be 4PB/year

R&D timelines & management

Goal:
Build Prototype

...

Test

Prototype

Minimize cost
OSS, mirrors

Prototype R&D

Conceptual R&D

Done!

Project management: procurement, reviews, site, WBS, …

2007 2008 2009 2010 2011 2012 2013

UC Dark Matter Initiative

- Successful MRPI (Multicampus Research Programs & Initiatives) that grew out of INPAC, the Instutite for Nuclear and Particle Astrophysics and Cosmology
- Bernard Sadoulet (Berkeley) is PI
- \$1.8M over 5 years
- Nurturing the development of next-generation dark-matter experiments
- ~\$135/yr for AGIS in first three years