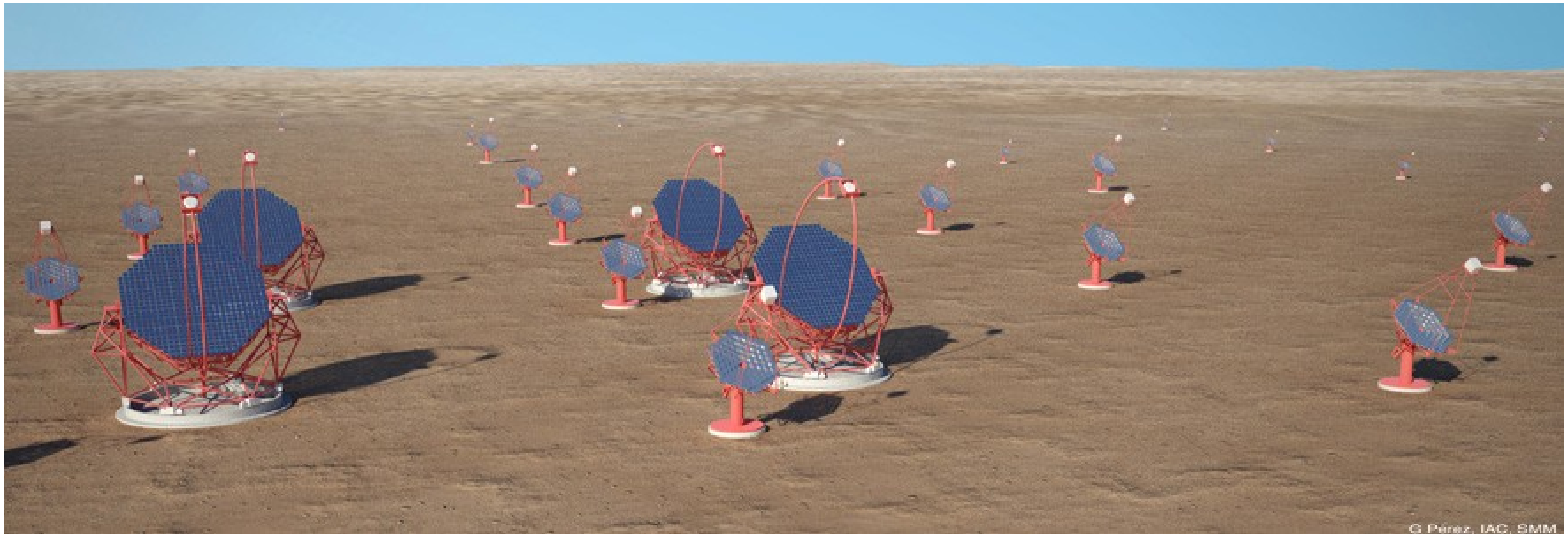
A Silicon Photomultiplier Camera for Use in the Cherenkov Telescope Array



Caitlin Johnson for the CTA Consortium

15 August 2013

Meeting of the Division of Particles and Fields

American Physical Society

Santa Cruz, CA

Acknowledgments

UCSC: David Williams, Aurelien Bouvier, Andrey Kuznetsov, Lloyd Gebrehmedin, David Chinn

CTA SC camera group:

J. Anderson, M. Bogdan, A. Bouvier, J. Buckley, K. Byrum, R. Cameron, M. Doert, G. Drake, M. Errando, J. Finley, S. Funk, N. Hidaka, B. Humensky, C. Johnson, D. Kieda, F. Krennrich, A. Kuznetsov, A. McCann, K. Meagher, I. Mognet, P. Moore, R. Mukherjee, D. Nieto, R. Northrop, A. Okumura, N. Otte, J. Rouselle, L. Sapozhkinov, H. Tajima, L. Tibaldo, V. Vandenbroucke, V. Vassiliev, R. Wagner, S. Wakely, A. Weinstein, D. Williams, M. Wood

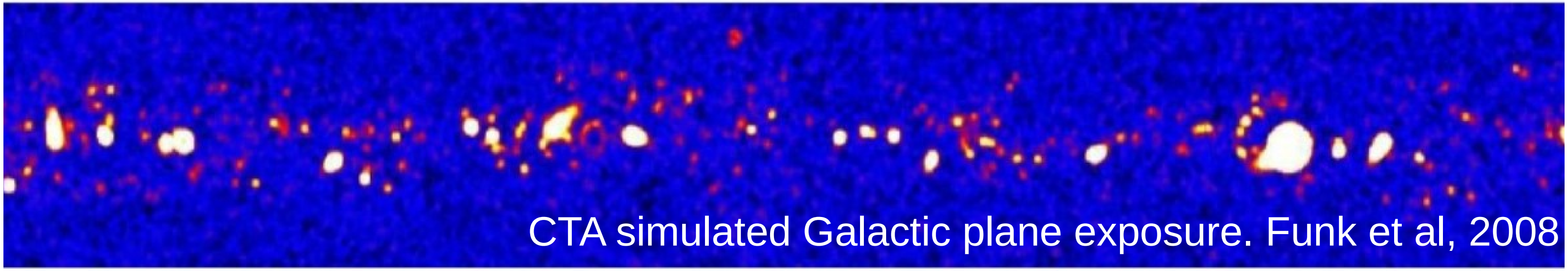
What do we study and why is it relevant to DPF?

Very high energy (VHE) gamma ray astrophysics

~100 GeV – 100 TeV

Unique Imaging Atmospheric Cherenkov Telescopes (IACTs) are used.

Not your typical telescope—particle physics oriented science goals.

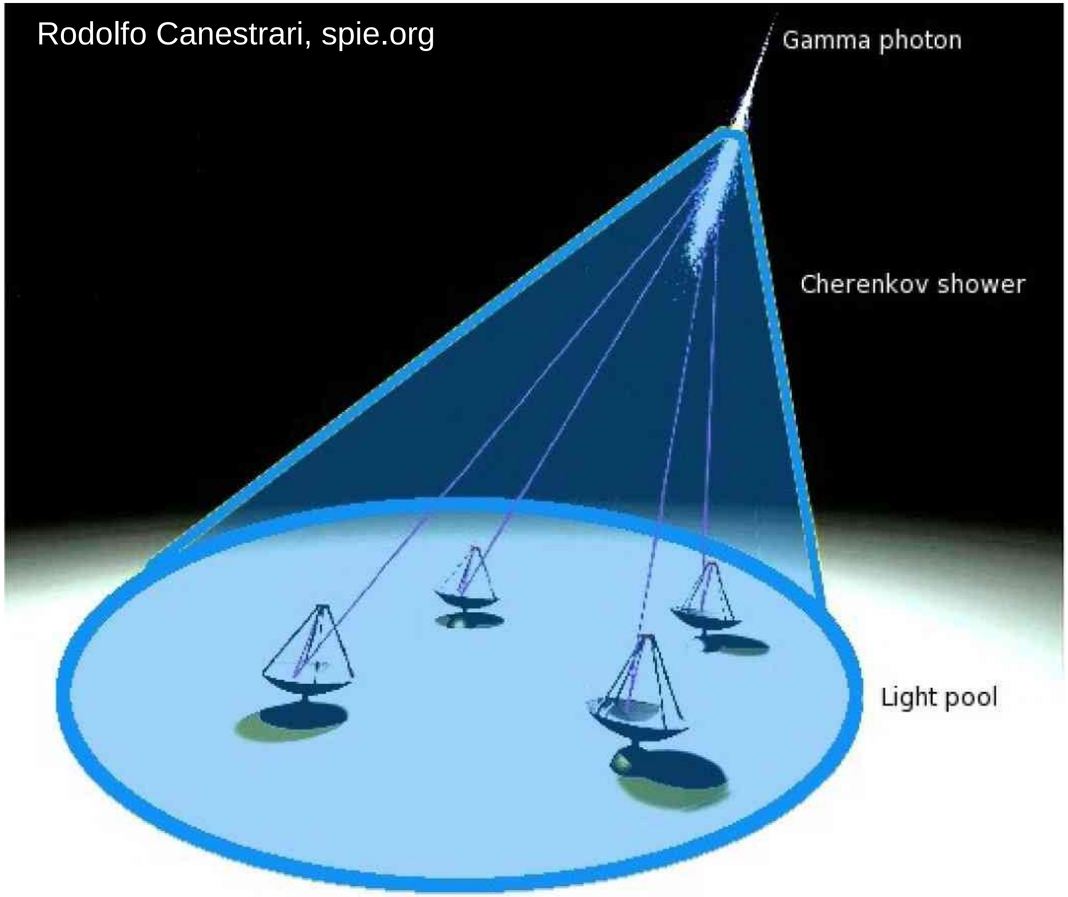


CTA simulated Galactic plane exposure. Funk et al, 2008

Science goals:

- Indirect dark matter detection
- Tests of Lorentz Invariance
- Particle processes in relativistic jets
- Cosmological constraints via the extragalactic background light
- Axion-like particles
- Intergalactic magnetic fields

Gamma rays are imaged via air shower.



Gamma ray induces atmospheric particle shower

↓

Cherenkov radiation is produced by particle shower

↓

Cherenkov **light pool** reaches the ground

↓

Light pool **imaged stereoscopically**

↓

Shower **reconstructed**: ***energy*** and ***direction*** of incident gamma ray

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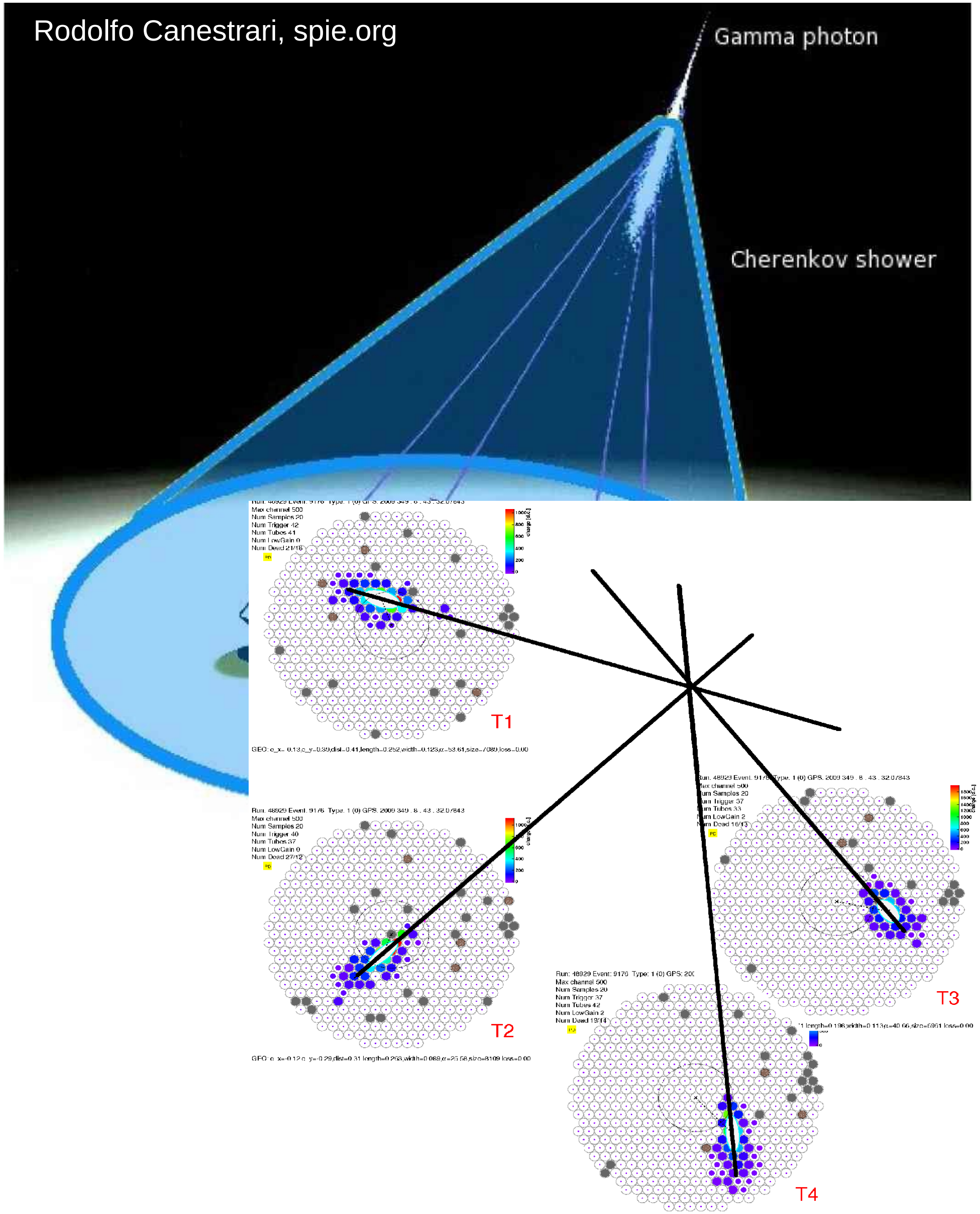

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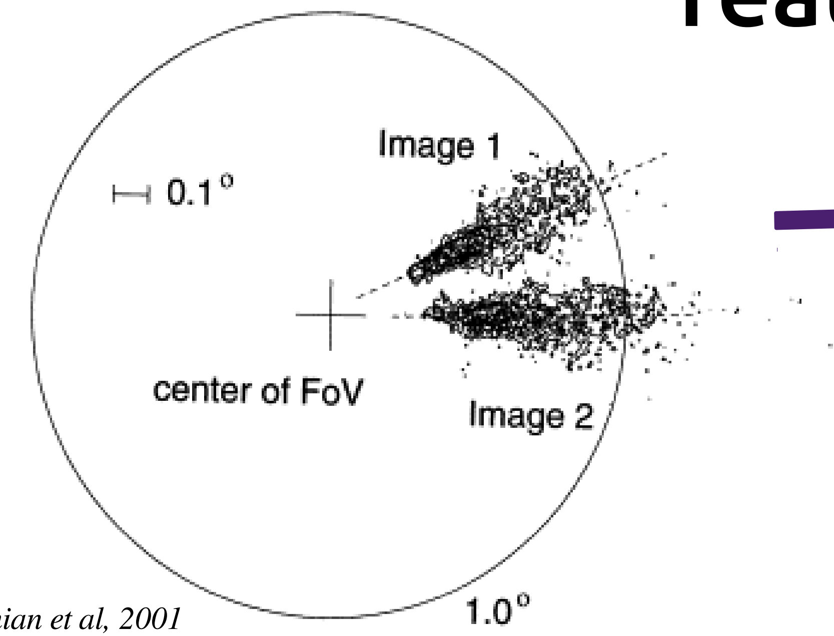
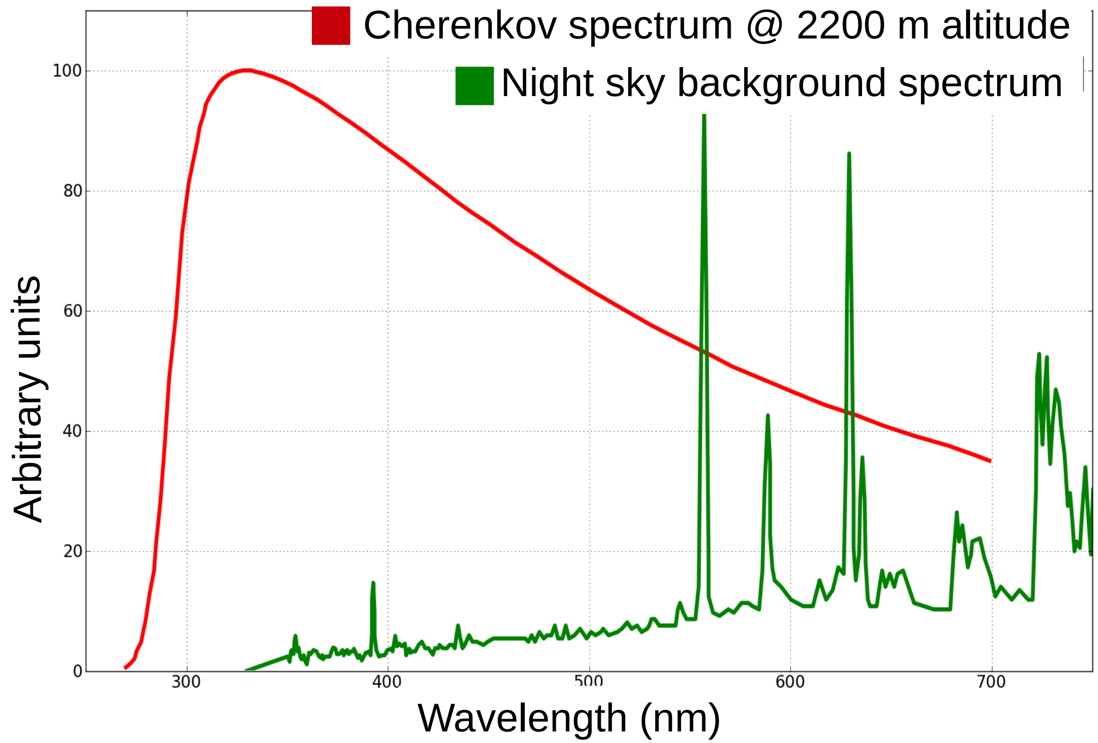
This technique requires specific camera features.



Aharonian et al, 2001

- Linear photon counting
- High gain



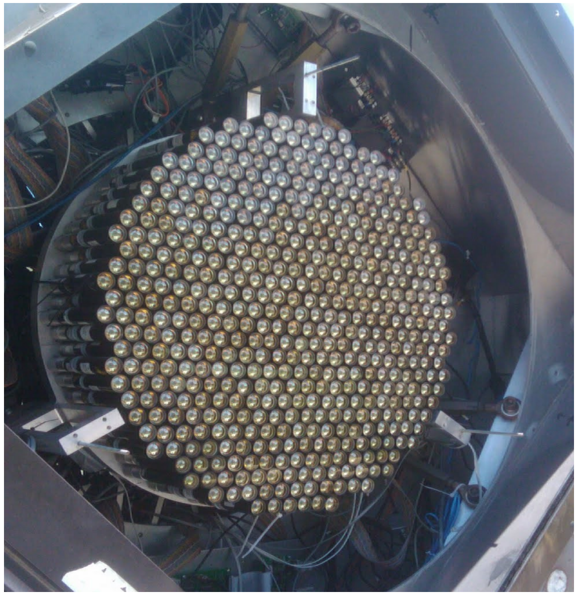
- Low noise
- Sensitive to UV light pool
- Fast triggering (~5 ns Cherenkov light flashes)

Current IACTs use photomultiplier tubes.

VERITAS
Southern Arizona

MAGIC
Canary Island of La Palma

H.E.S.S.
Namibia

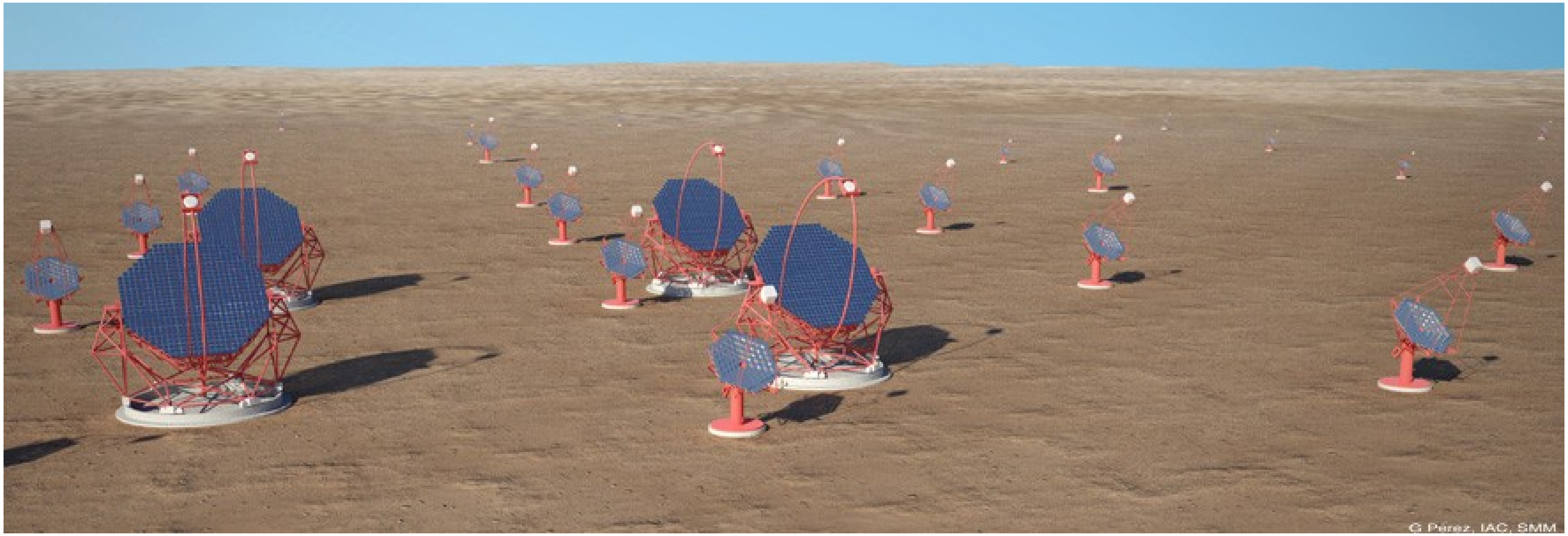


Photomultiplier Tube Camera

~500-2000 PMTs per camera

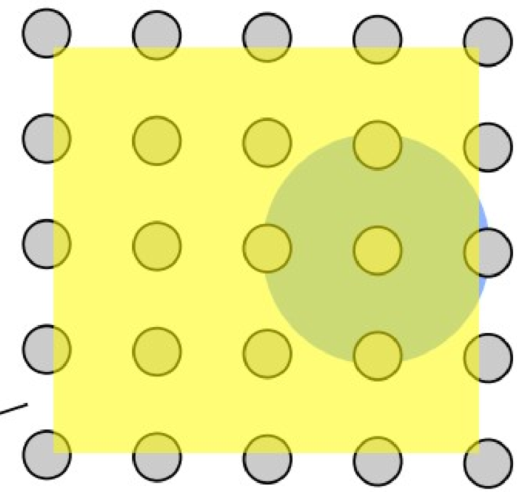
VERITAS pixel size: ~0.15 deg

The next generation IACTs allow for the integration of new designs and new technology.



Next Generation: The Cherenkov Telescope Array

- International effort (> 25 countries)
- 60-100 telescopes with different designs and 3 sizes in the southern hemisphere
- Smaller array in the northern hemisphere
- Energy threshold of 30 GeV
- > 1km^2 array



Large detection area
More images per shower
Lower trigger threshold

Unprecedented Sensitivity for IACT Science goals!

CTA aims to capture transient events and make sky surveys.

these need...

High resolution over a wide FOV

Large light collecting area

New Schwarzschild-Couder telescope design is envisioned for small and medium sized telescopes.

Current:
Davies-Cotton

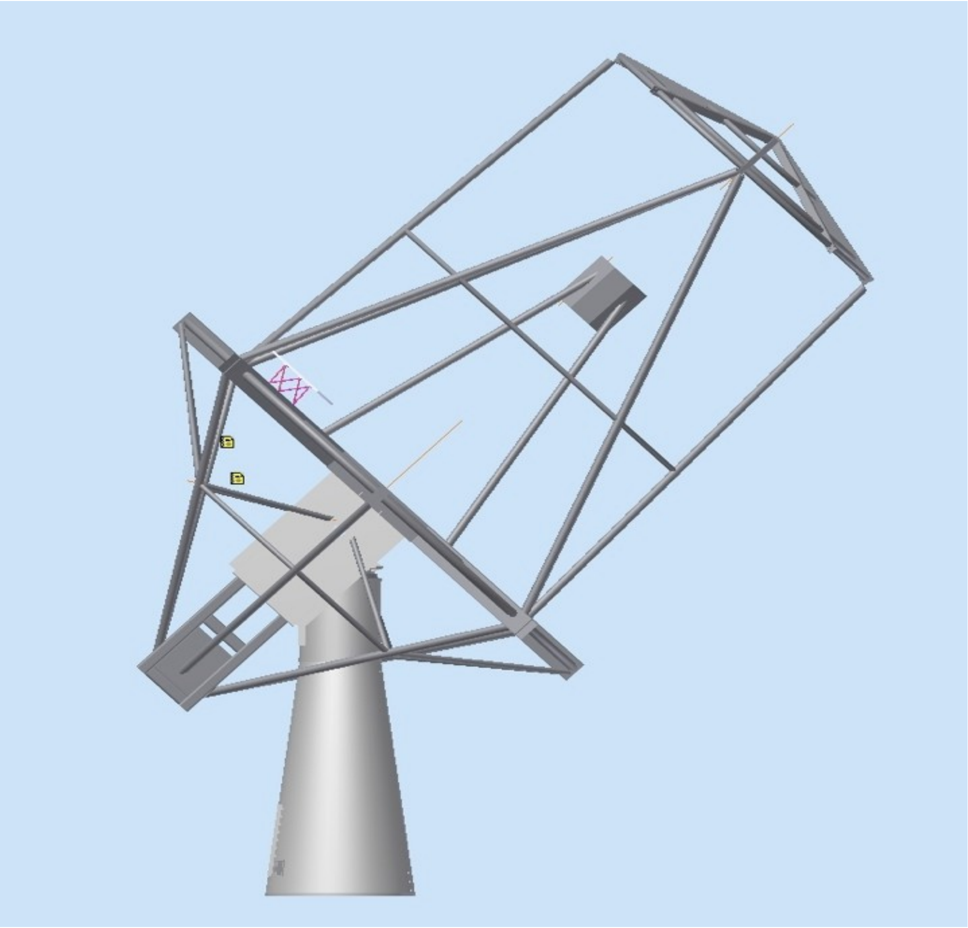
→

Single,
faceted mirror

Schwarszchild-Couder:

→

Never been built!
Characterized by an aplanatic (no spherical aberrations) two-mirror optical design

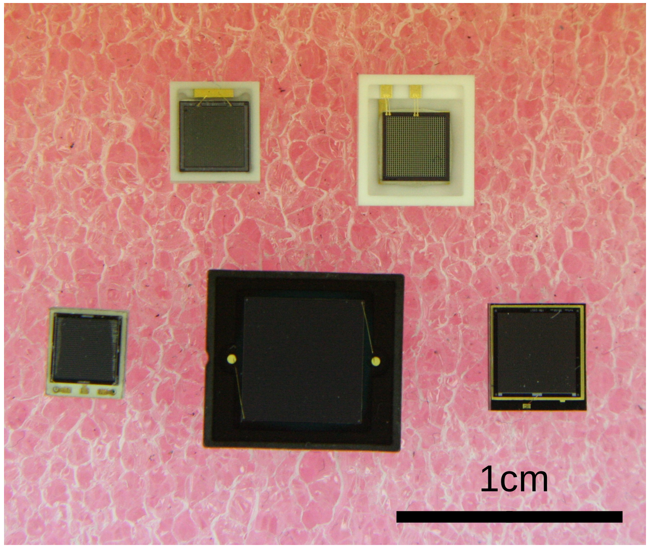


Advantages of the SC Telescope Design

- Comatic aberrations corrected near optical axis provide improved PSF over a wider FoV
- Secondary mirror demagnifies image making plate scale 3-4 times more compact than for the DC design
- Can use high density, low cost novel photosensors
- Simultaneously increases imaging resolution and decreases cost per pixel and signal processing electronics

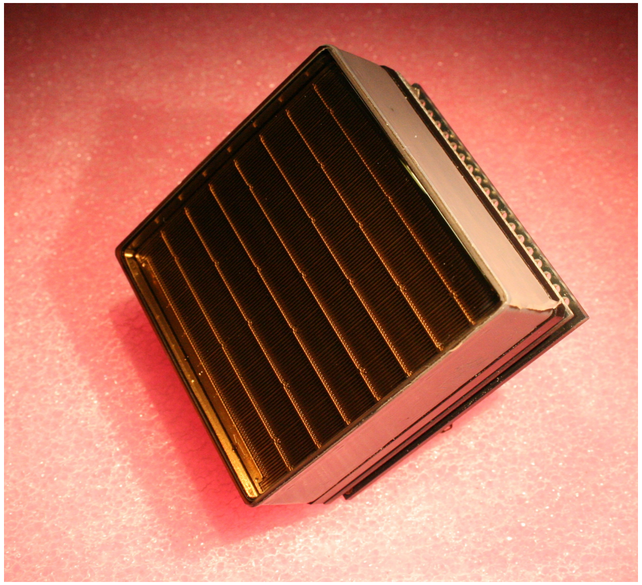
Opens door for two new technologies:

- Silicon Photomultiplier
- Multi Anode PMT



SiPM
L to R, top to bottom:
Excelitas
Hamamatsu
Ketek
SensL
FBK

MAPMT
Hamamatsu
H10966B
52x52 mm^2



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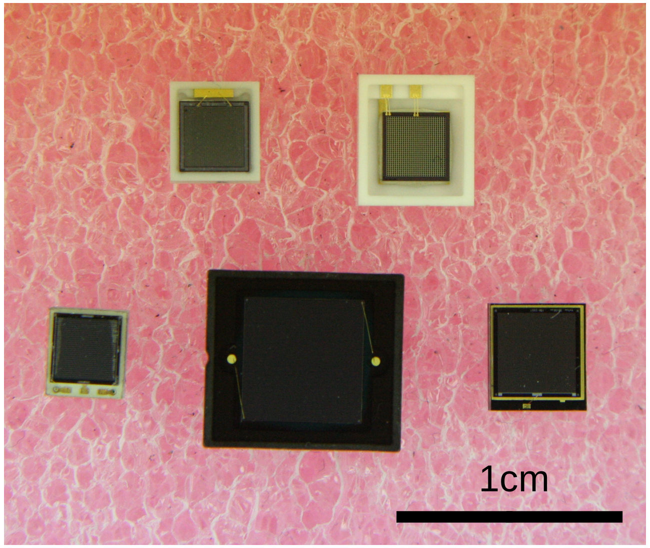

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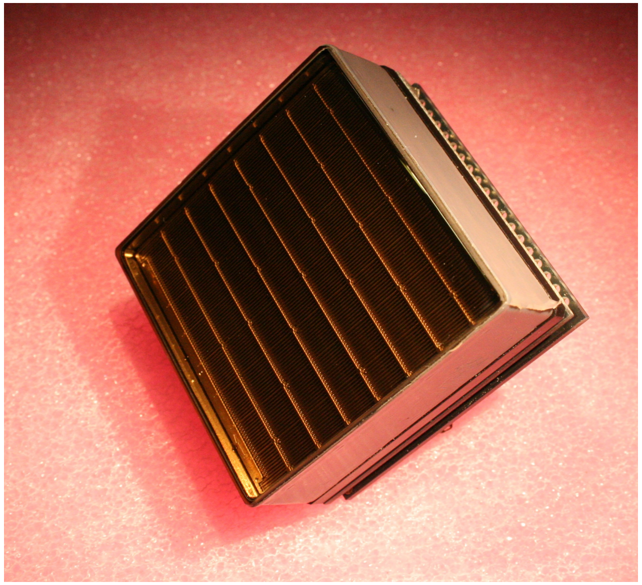
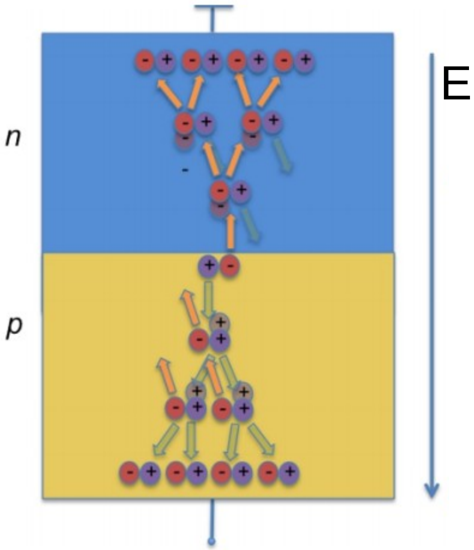


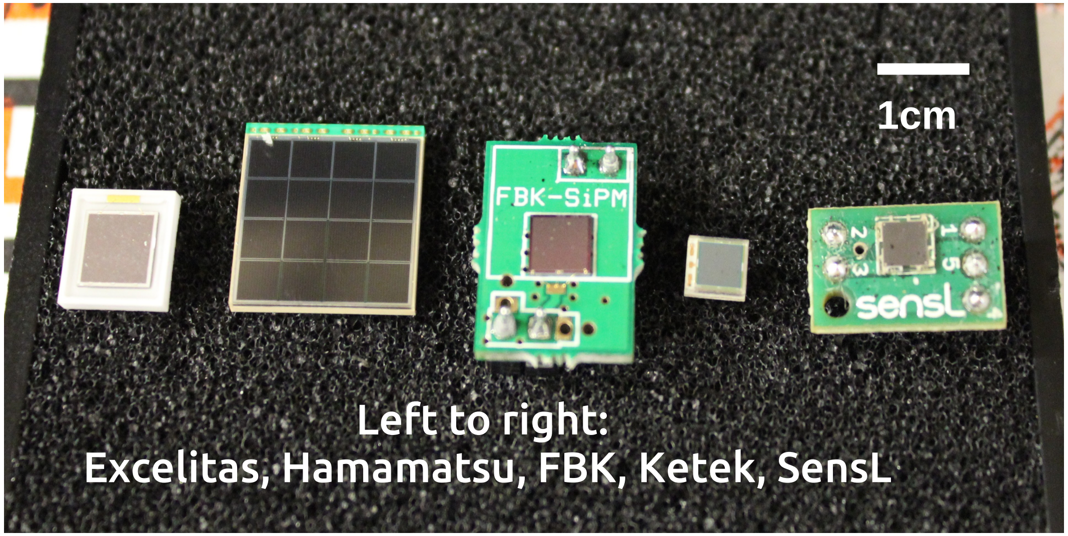
The SiPM is ideal for a small plate scale provided by the SC telescope design.



Schematic of the Geiger Mode used in SiPMs with the direction of the electric field indicated. (www.sensl.com, 2011)

- Utilizes avalanche photodiodes in Geiger mode
- Photon excitation in the depleted region produces a pair of charge carriers
- Electric field accelerates charge carriers
- They trigger an electron-hole avalanche saturating the active area

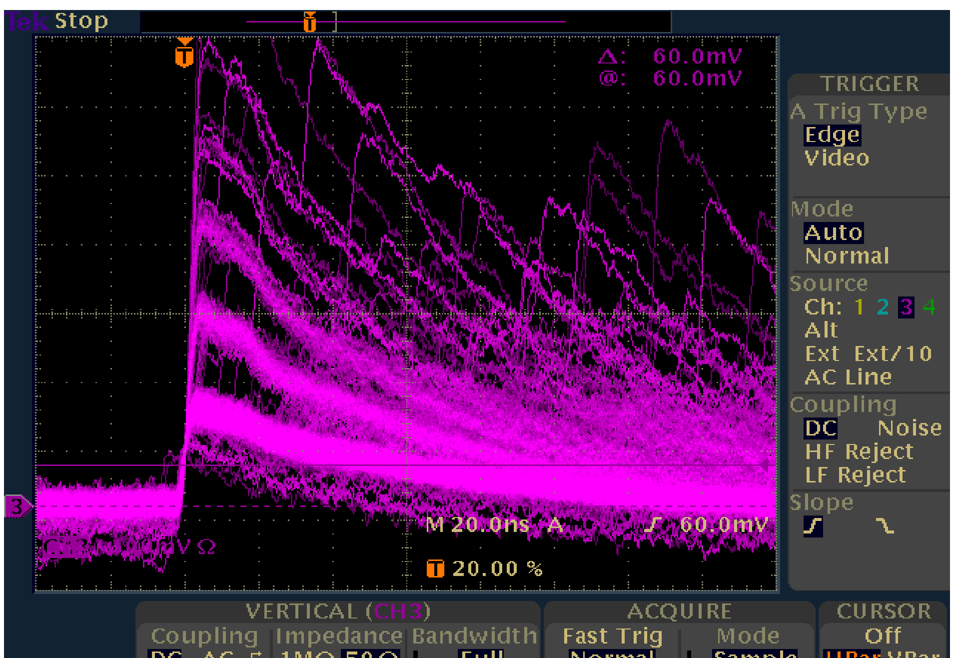
- Pixels formed by a matrix of G-APDs
- Parallel operation allows for single photon counting
- Quenching resistors stop the avalanche and allow the signal producing cycle to repeat.



PMTs are not obsolete, but SiPMs have significant advantages.

PMT Drawbacks:

- Fragile
- High voltage (~1000-1500 V)
- Aging
- Limited detection efficiency



SiPM Advantages:

- More durable
- Low voltage (~20-100 V)
- Low power consumption
- Resistant to high light levels
- Good pulse height resolution
- Continually decreasing cost
- Higher achievable PDE

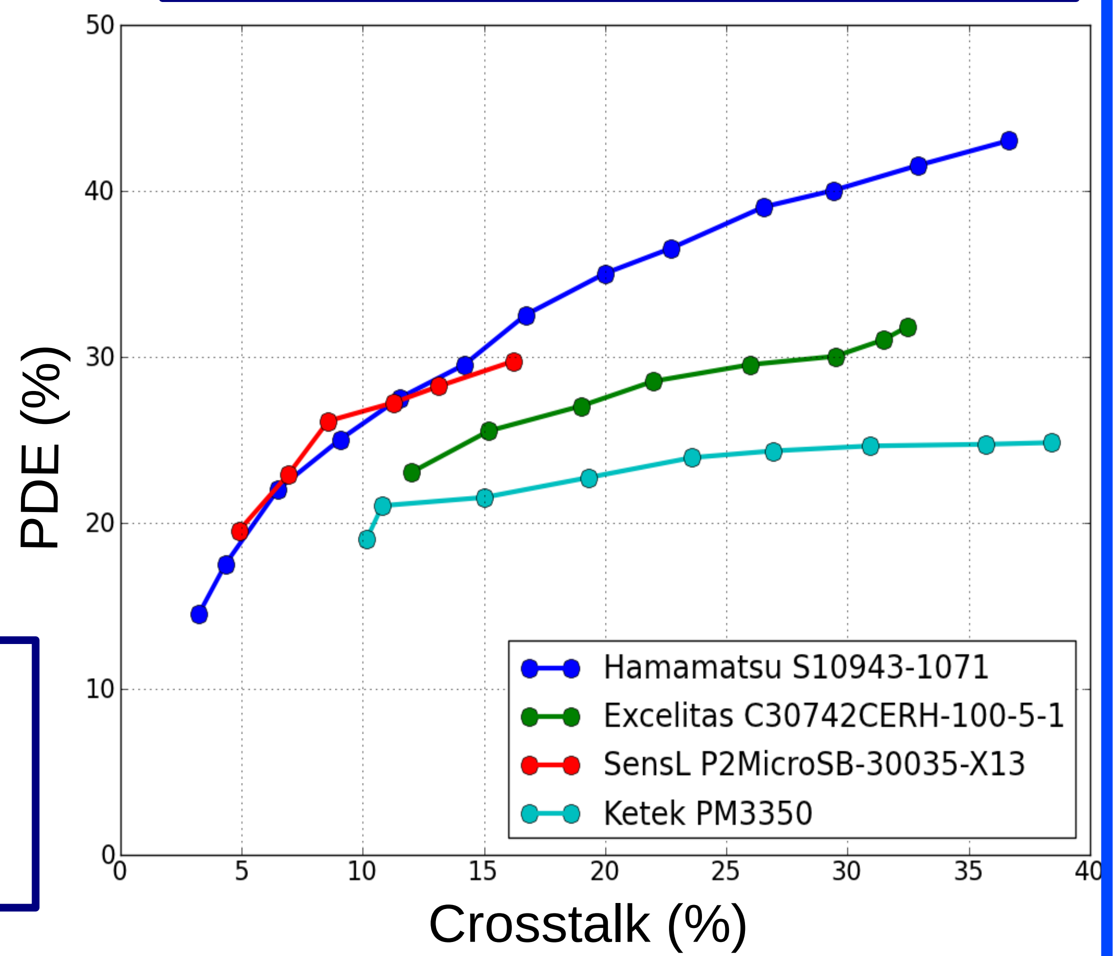
Raw pulse shape from Hamamatsu S10943-1071

Before using SiPMs we must understand how they behave.

Photon Detection Efficiency (PDE): probability for an incoming photon to create a detectable electronic signal

Cross talk: the probability that infrared photons from the Geiger Avalanche discharge travel outside the cell and trigger an avalanche in a neighboring cell.

Both are dependent on operating voltage.



Operating Voltage -V breakdown is temperature dependent

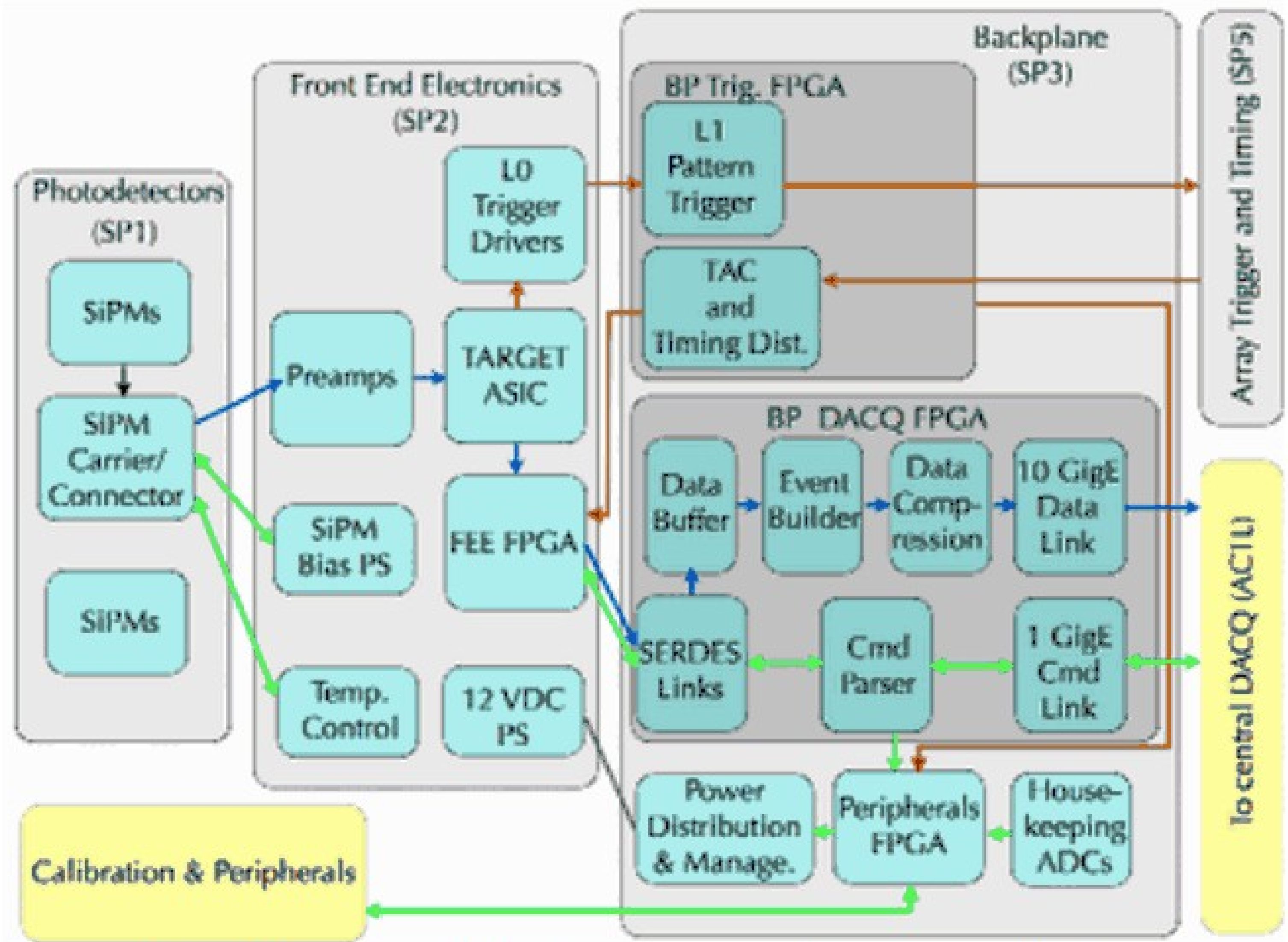
Monitoring temperature and accurately characterizing V breakdown vs. T is crucial!

Fine pixelation → ~11,000 pixels per camera → ~0.067 deg square

SC telescope design and SiPM camera have promising advantages!

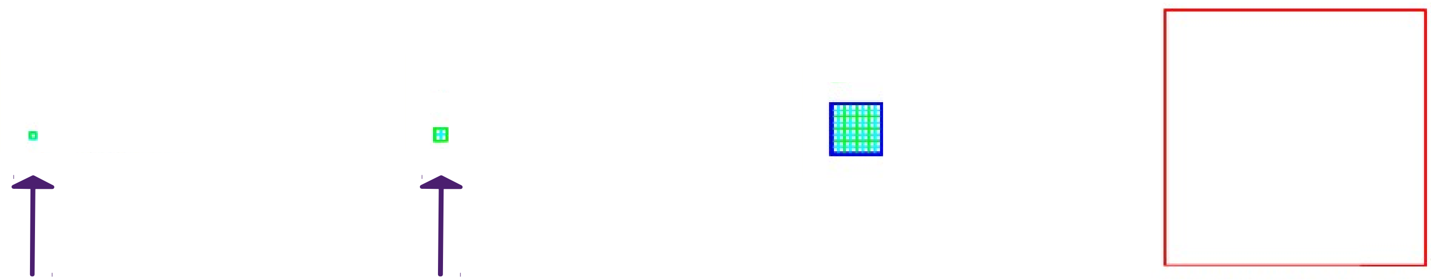
But, how do we efficiently and cost effectively readout from almost 1 million channels??

An integrated and hierarchical camera structure allows for efficient readout.



Overview of SC telescope camera components

The camera pixels themselves are also hierarchical.

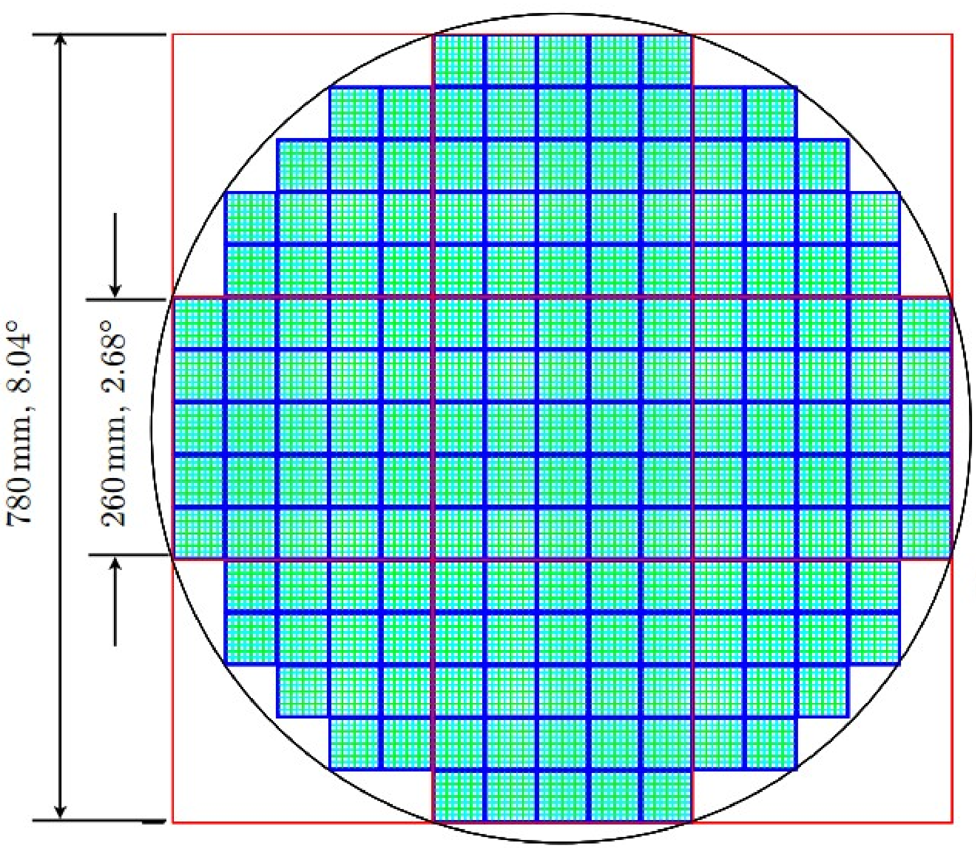


Analog Pixel
(0.067x0.067 deg)

Trigger Pixel
(2x2 Analog Pixels)

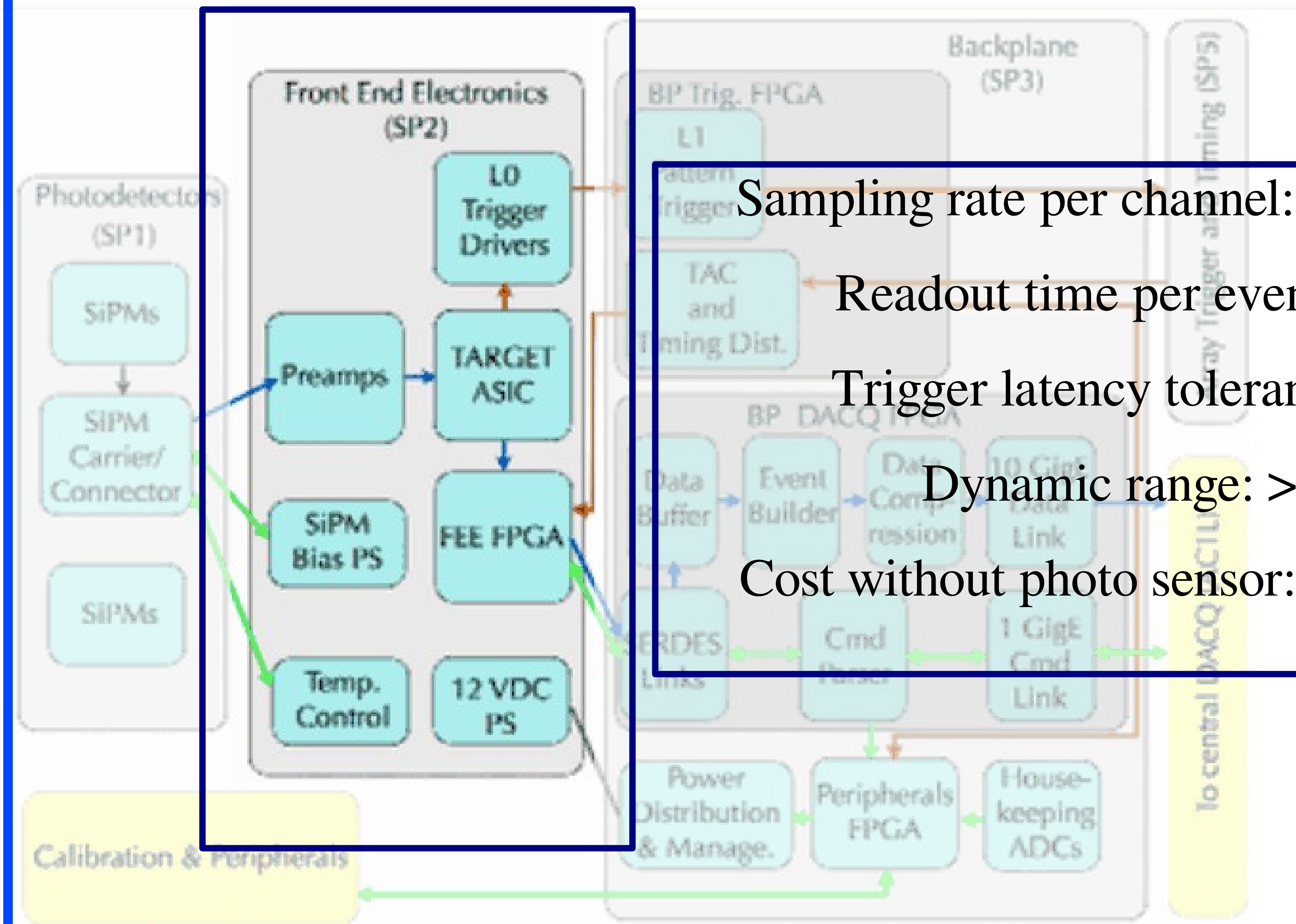
Camera Module
(8x8 Analog Pixels)

Subfield Backplane
(5x5 Camera Modules)



- Merges signals from a large number of pixels into the front-end pattern trigger
- Signal processing and data acquisition happen at the camera level

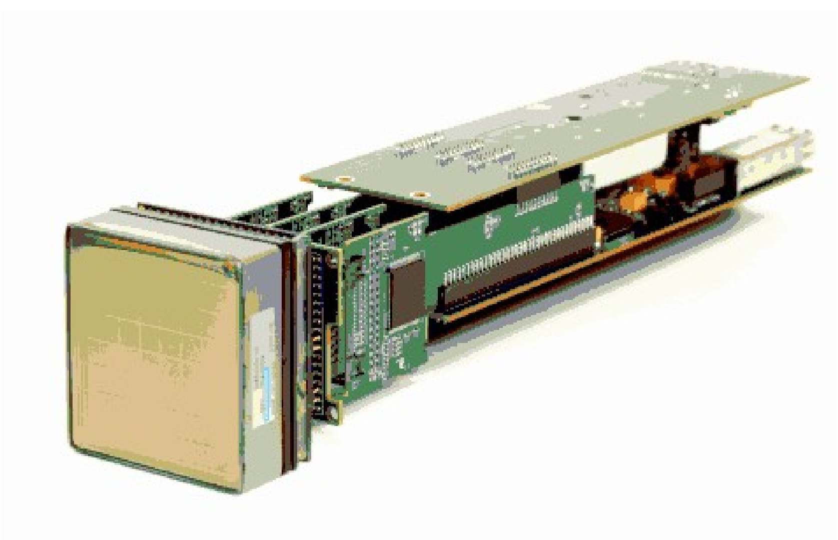
Front end electronics requirements:



- Sampling rate per channel: > 1 Gsample/s
- Readout time per event: < 20 μs
- Trigger latency tolerance: > 2 μs
- Dynamic range: > 8 bits
- Cost without photo sensor: < $20/channel

Accomplished with the TARGET module.

- **T**eV **A**rray **R**eadout with **G**Sa/s sampling and **E**vent **T**rigger
- ASIC: designed specifically for use in CTA
- Programmable SiPM voltage supply and discriminator thresholds
- ADC for monitoring current
- Plugs directly into the subfield backplane



TARGET camera module prototype
(MAPMT version shown,
SiPM version to be used)

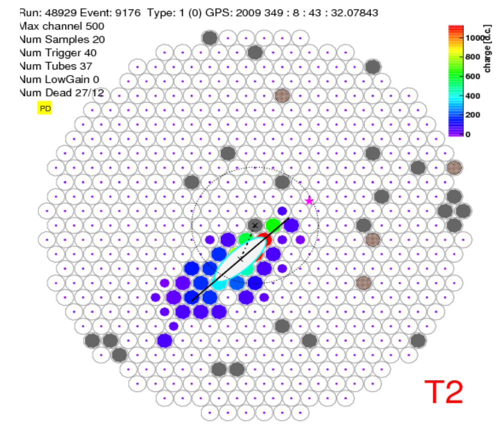
Data is read out to the backplane.

Combines functions into a monolithic board for each camera subfield:

- Data acquisition
- Level-1 pattern trigger (identifies clusters of hits)
- General purpose power distribution & control
- Time synchronization

-Events are built in the camera and tagged with 1 ns precision.

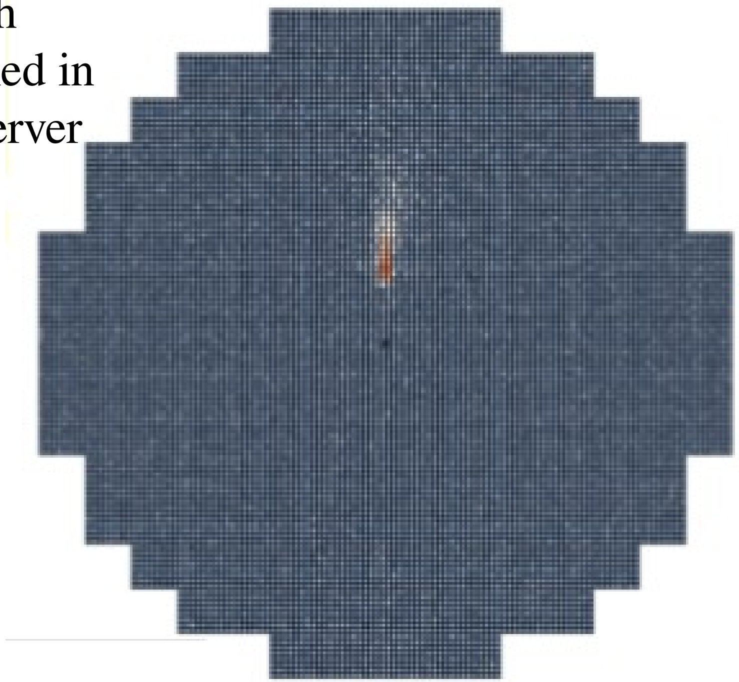
-Data is formatted, compressed and sent out of the camera via a high speed network connection.



VERITAS image for comparison

Data from each subfield is assembled in the camera data server

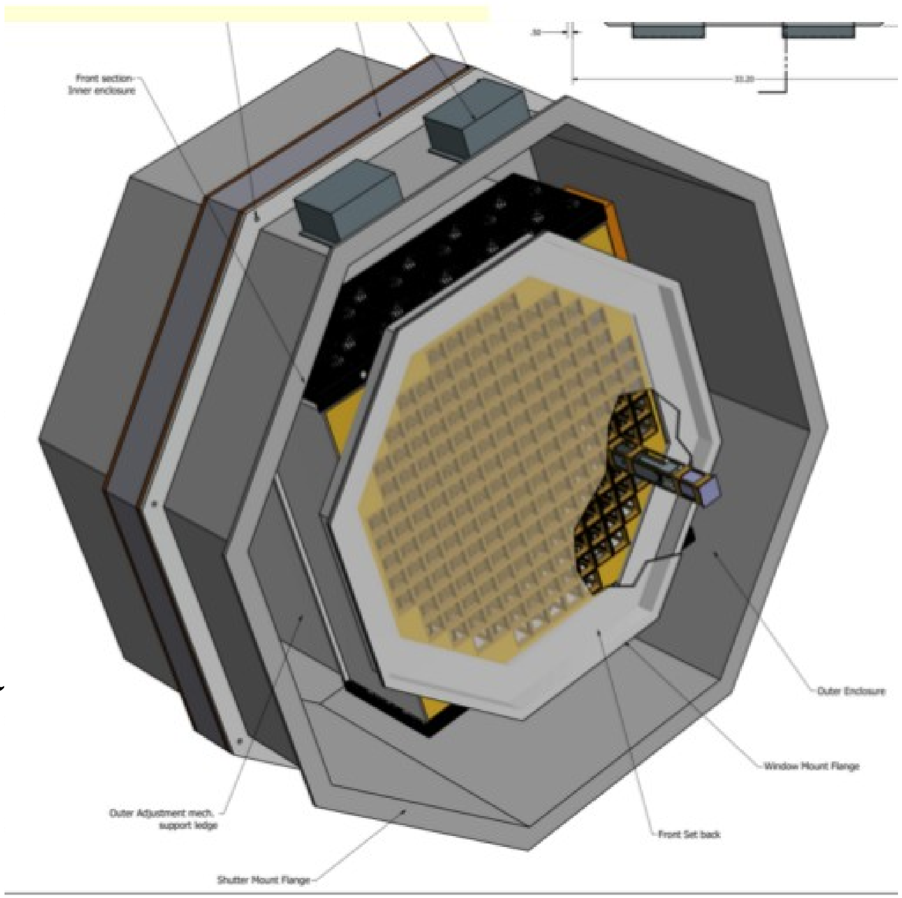
Preliminary backplane layout with parts locations



γ-ray Shower
Energy: 1 TeV
Impact Distance: 100m

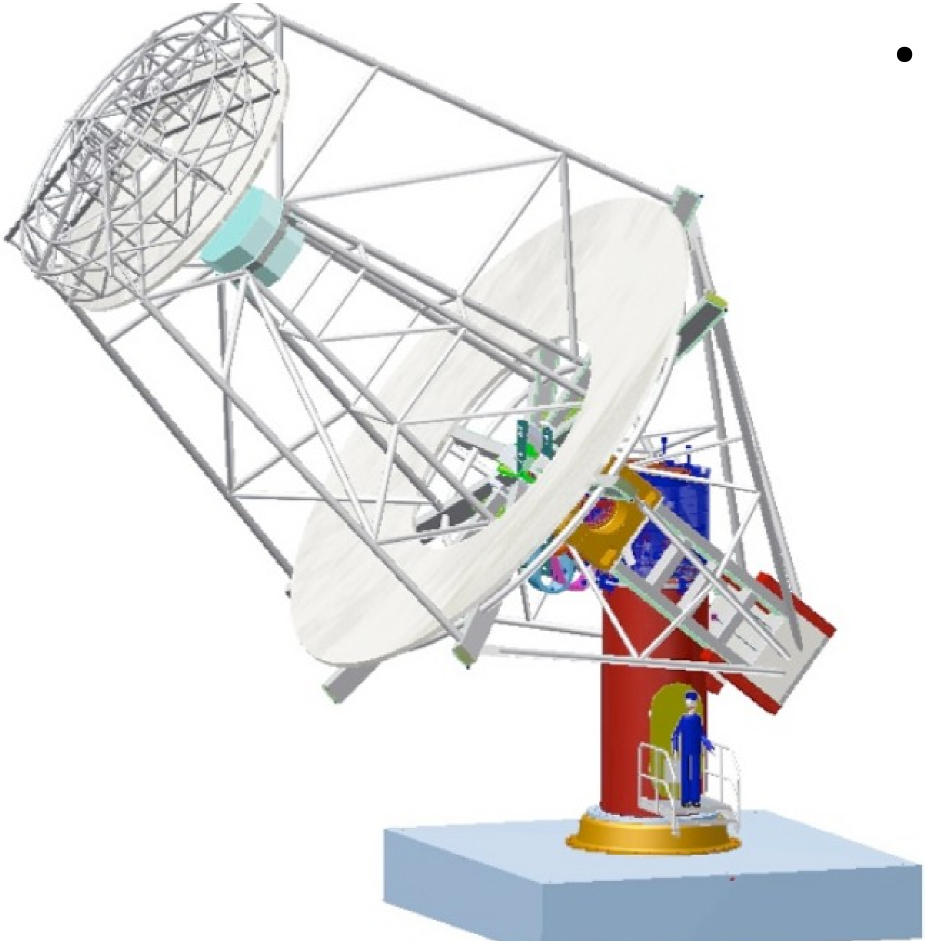
Camera mechanical system

- Houses the electronics, includes the cooling system, the interface to the OSS, and a frame for supporting the focal plane
- Environmental monitoring
  - Important for understanding SiPM performance!
- Allows for replacement of camera subfields or modules in addition to relocating subfields.
  - Easier upgrades and development!



Prototype Schwarzschild Couder Telescope (pSCT) is currently in the development phase.

- Full scale 9.5 m SC telescope to be built at the VERITAS site
- Prototype of the medium sized telescope class for CTA
- First light anticipated fall 2015



- Validate MC simulations and technological approaches for CTA

  In conjunction with VERITAS:

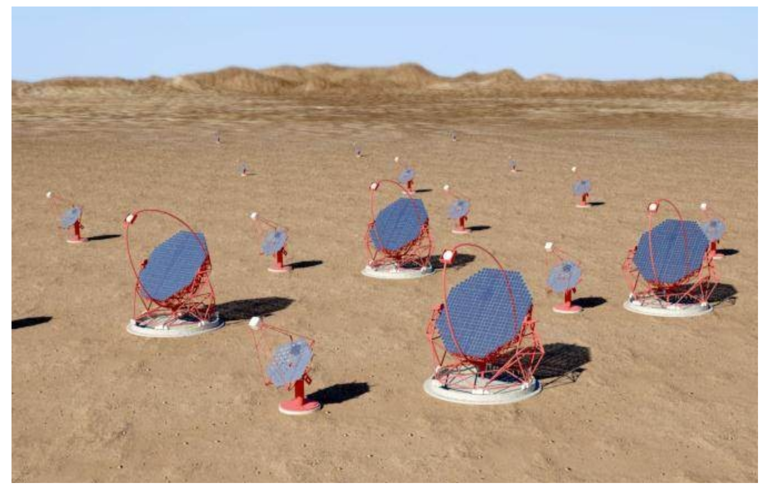
  - Increase array foot print
  - Increase the # of showers imaged by a factor of ~2.5
  - Better distinguish the direct Cherenkov light for cosmic-ray composition studies

  Stand alone telescope:

  - Source monitoring

The future is bright for VHE astrophysics.

CTA will debut new technology and designs to the astrophysics community.



Once completed, the pSCT will contribute to a current, well established experiment and be instrumental in developing the full CTA array.