G-APD Based Imaging Camera for VHE Gamma Ray Telescope : Design Details and Current Status

Varsha Chitnis

DHEP seminar , 25 April 2019

Plan of the talk :

Physics motivation for VHE gamma ray astronomy

Detection technique

HAGAR telescope system : some highlights

G-APD based camera : Design Details

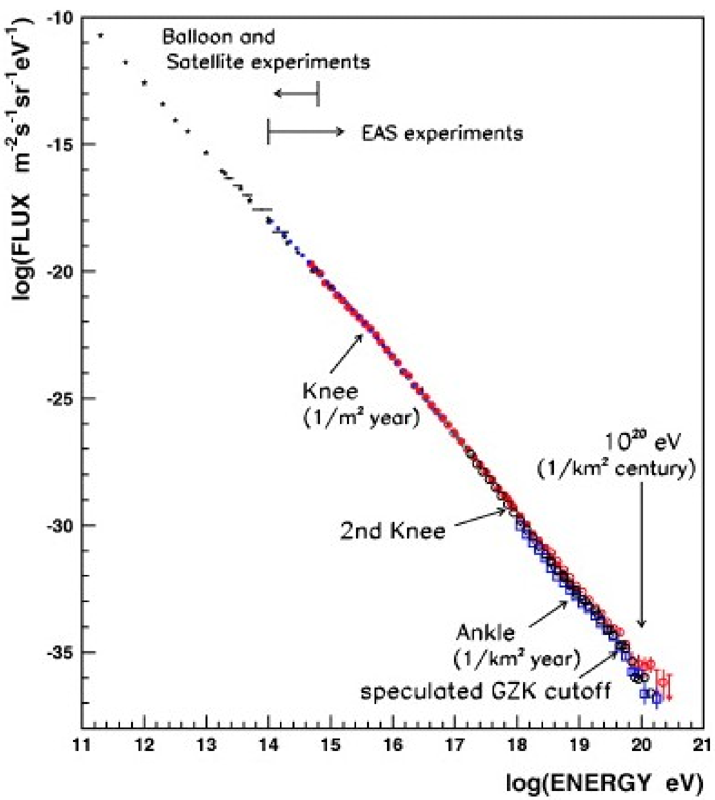
Status and Timeline

Science Goals

Future Directions

Physics Motivation for VHE Gamma Ray Astronomy

- Best window to study non-thermal universe



- Cosmic ray origin and acceleration :
  Supernova remnants likely sites for
  cosmic rays with energies < 10^{15} eV
  Active Galactic Nuclei likely sites for
  cosmic rays with higher energies

- Insight into emission regions and emission processes in various astronomical sources

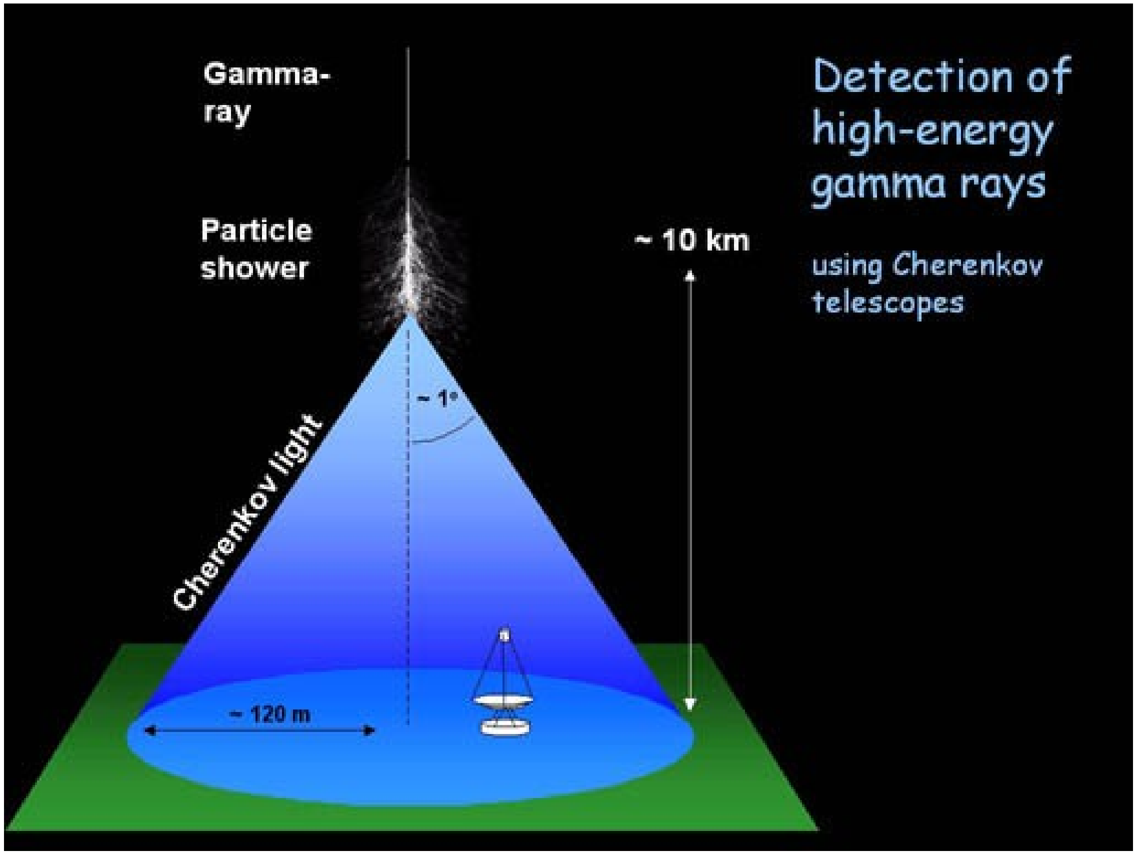
- Physics beyond standard model through searches for dark matter

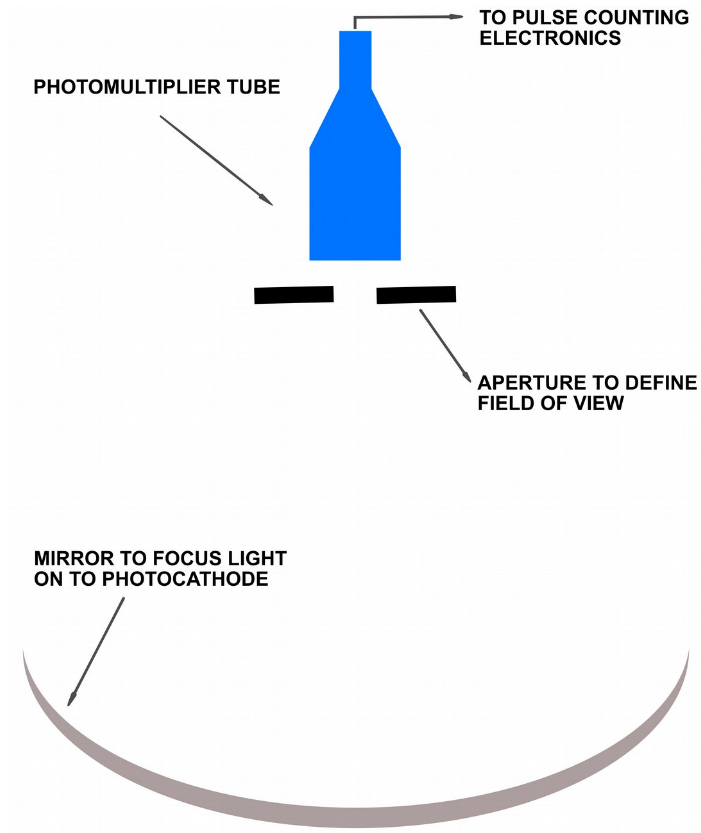
- Tests for Lorentz invariance violation through study of rapid time variations in VHE emission from distant objects

- Indirect estimation of extragalactic background light through VHE emission from AGN

Atmospheric Cherenkov Technique

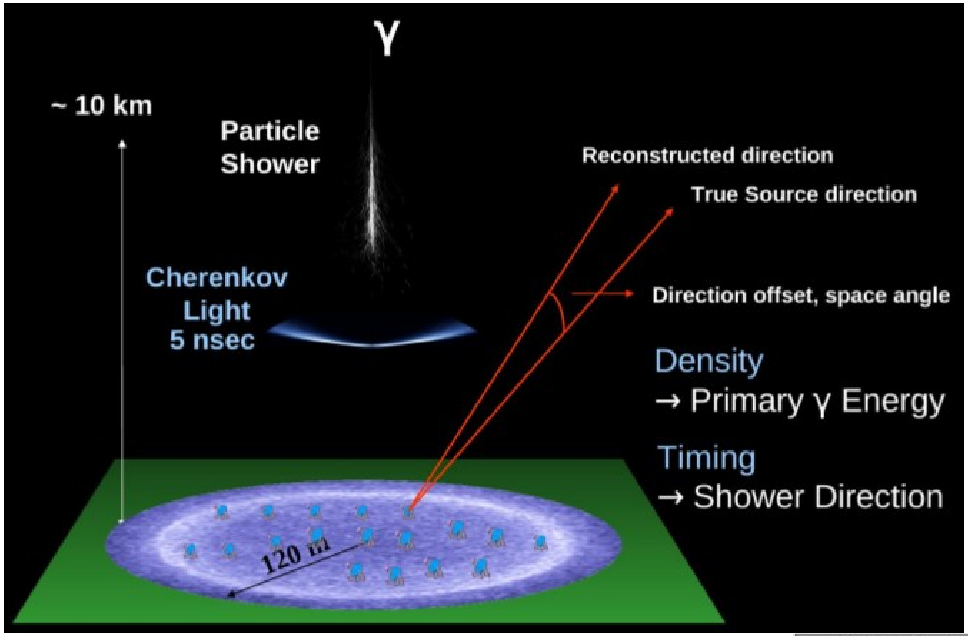
VHE gamma ray band : few 10's GeV to ~ few 10's TeV





	ACT	satellite
Collection area	$10^4 – 10^5$ m^2	~ 1 m^2
Duty cycle	short	long
Detection method	indirect	direct
FOV	3°- 5°	large (~2 sr)

Variants of Atmospheric Cherenkov Technique

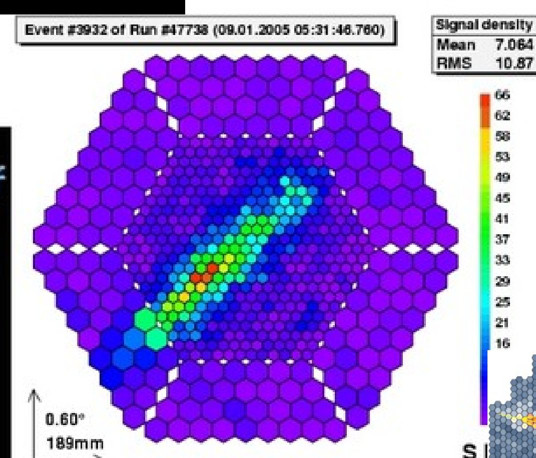


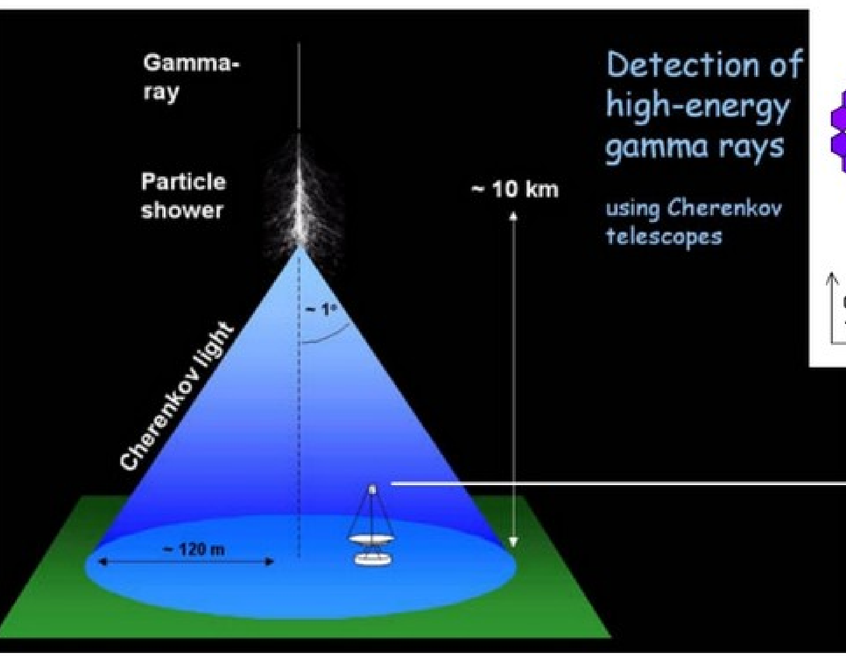
Wavefront sampling technique:

Multiple collectors sample light across Cherenkov pool, record arrival time of shower front and Cherenkov photon density at various locations

Imaging technique :

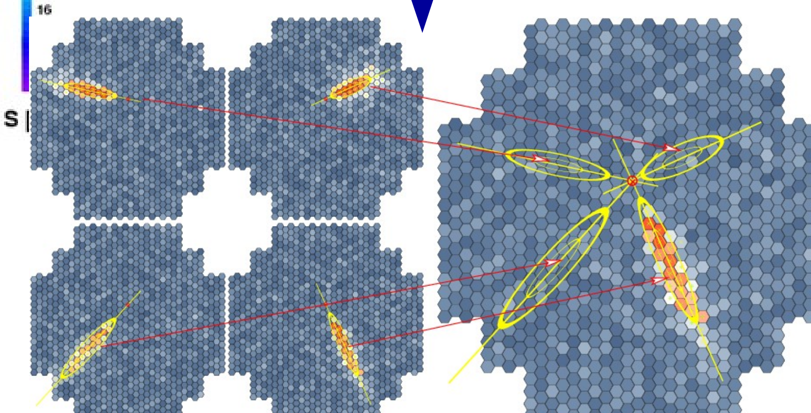
Cluster of PMTs at focus of large reflector, records images of air showers



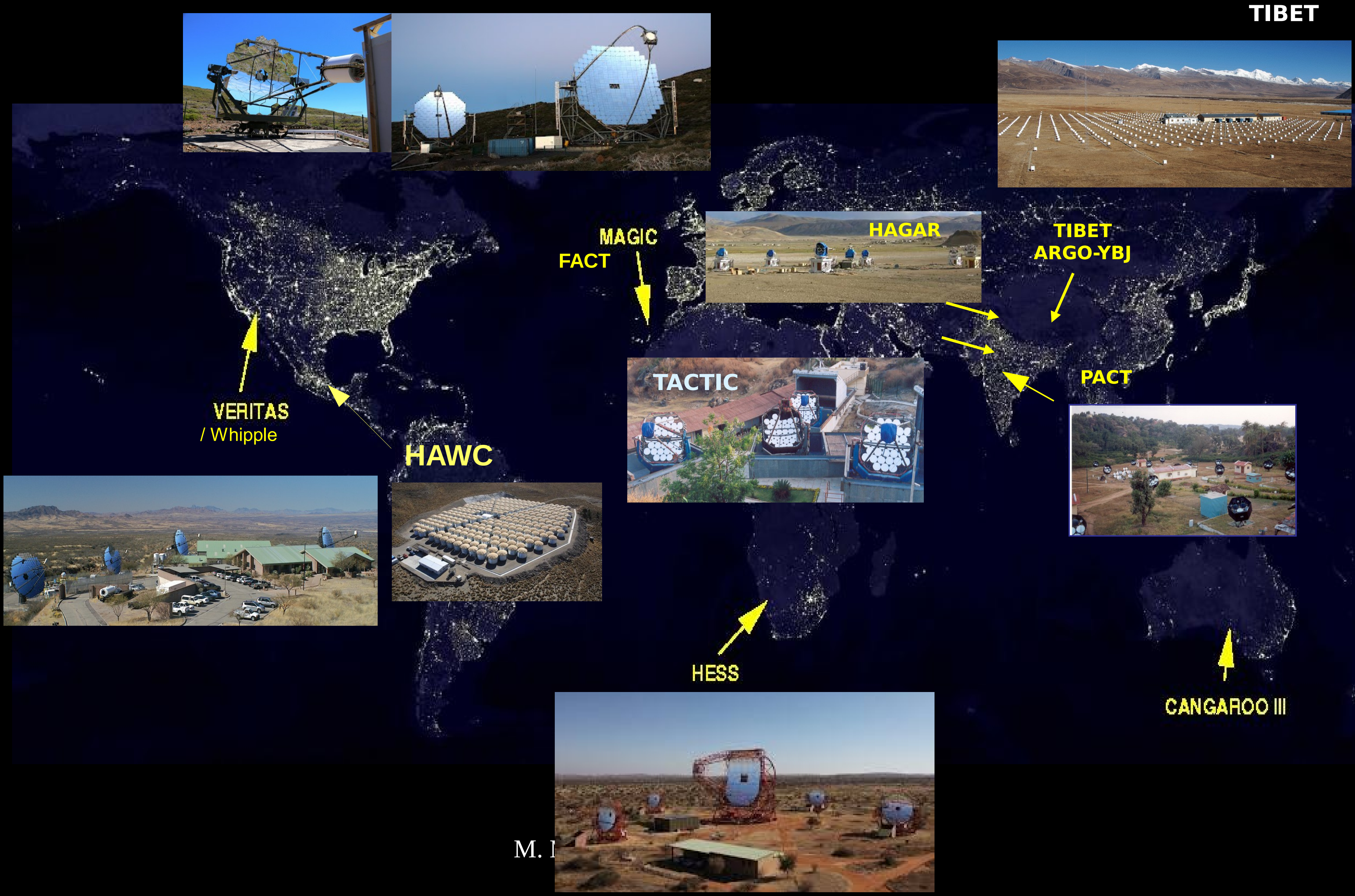


Stereoscopic imaging with multiple imaging telescopes

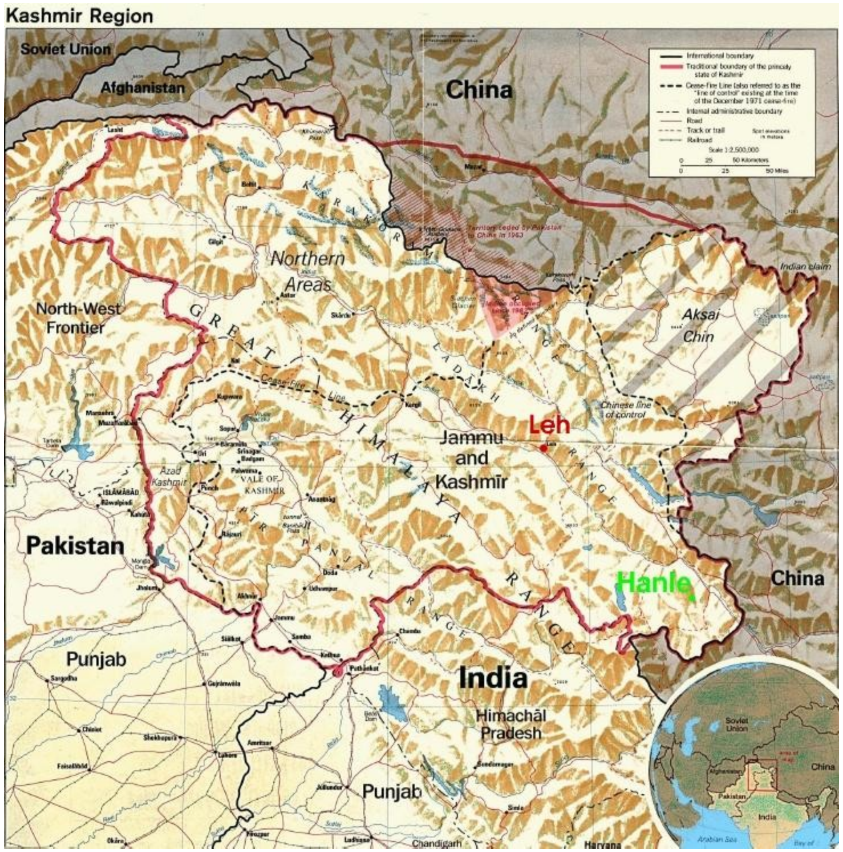
Improved angular and energy resolution



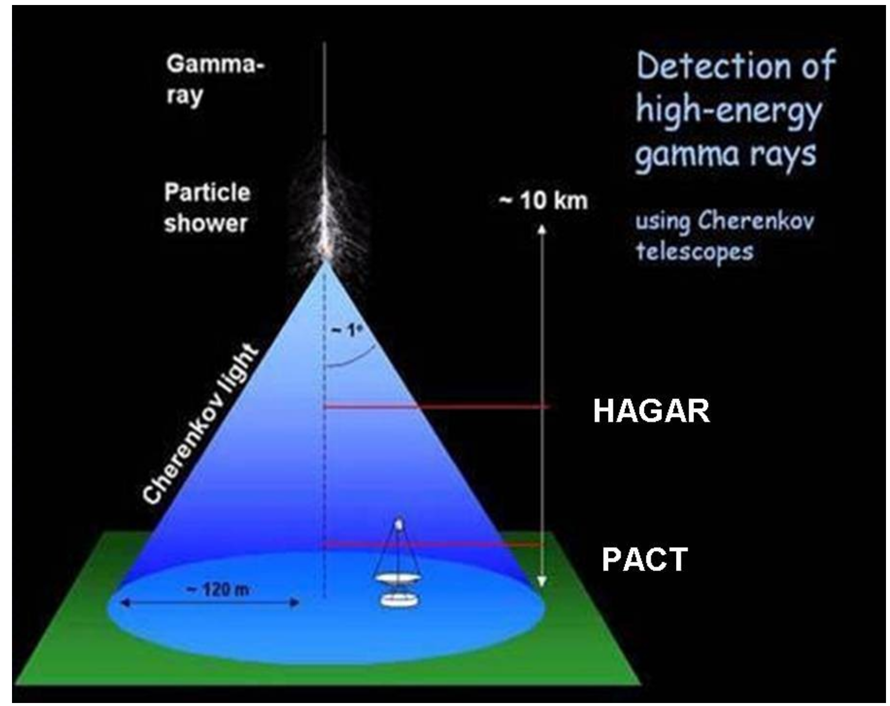
Ground-based γ-ray astronomy in the World



High Altitude GAmma Ray (HAGAR) Telescope Array



Lower energy threshold to study distant AGNs, GRBs, to study pulsed component of pulsars



- **Located at Hanle in Himalayas**
  - **Latitude : 32° 46' 46" N**
  - **Longitude : 78° 57' 51" E**
  - **Altitude : 4270 m**

Higher Cherenkov photon density at higher altitude
Lower atmospheric attenuation of Cherenkov photons

→ Reduction in energy threshold

HiGRO collaboration : BARC, TIFR, IIA, SINP

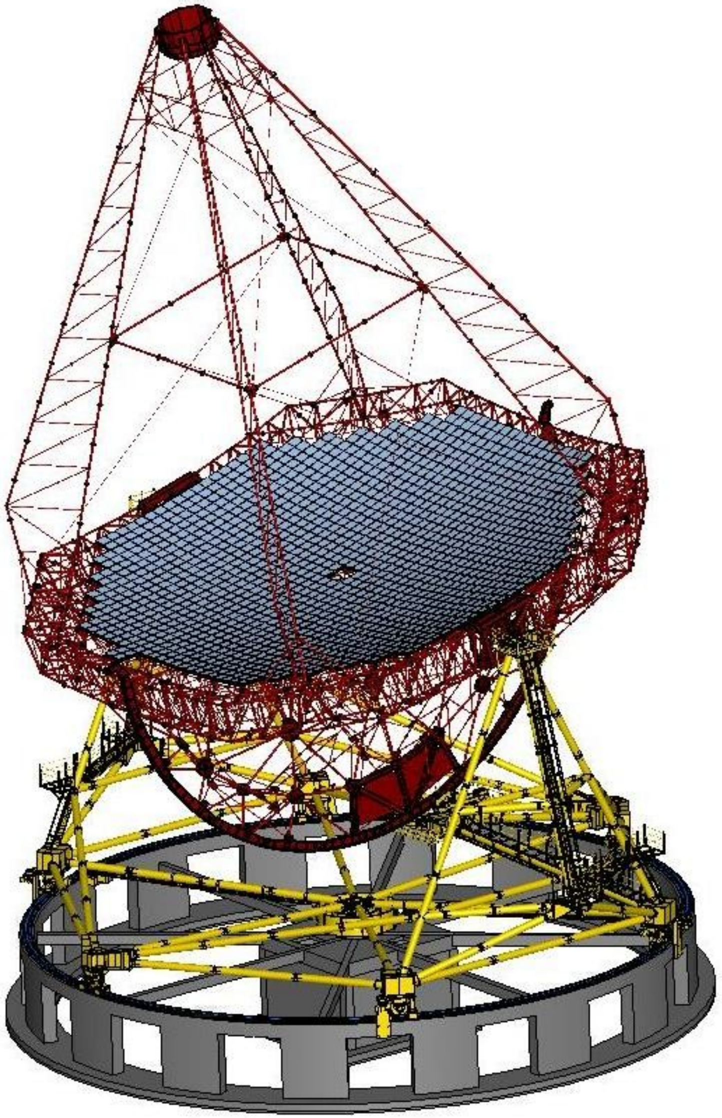
Highlights from HAGAR

Array of seven telescopes based on wavefront sampling technique
Energy threshold : 210 GeV
Operational since September 2008
Observational data duration (September 2008 – March 2019) ~ 7000 hrs

Main targets : Blazar class AGN, pulsars
Detection of Crab nebula at 20.7 σ significance level
Detection of pulsations from Crab at 6.9 σ significance level
Detection of blazar Mkn 421 in flare as well as moderate state of activity
Study of data extended over seven years period
Detection of blazar Mkn 501 in moderate state of activity

Next stage : Telescope with imaging camera

Major Atmospheric Cherenkov Experiment (MACE)



Project led by BARC

Single imaging telescope with large
geometrical area of 340 m^2
(~ 21 m diameter reflector)
Consists of diamond turned aluminum
mirror panels

Mechanical structure ~ 150 tons,
45 m high, 25 m focal length

Imaging camera consisting of 1088 pixels
of size 0.125 deg, total FoV : 4deg x 4deg
camera weight : 1.2 tons

Expected energy threshold ~17 - 40 GeV
depending on zenith angle

Integral flux sensitivity : ~ 2.5% of Crab
nebula flux in 50 hours

Expected to detect Crab nebula at 5σ
level in about 2 minutes

Imaging Telescope

MACE at Hanle

- MACE at an advanced stage of commissioning at Hanle
- First light expected in this year
- Operation mainly in discovery mode
- Need small telescope to monitor known blazars
- Study of time variability of these objects on time scales from minutes to years to understand emission mechanisms
- Small size telescope (4m class) will suffice

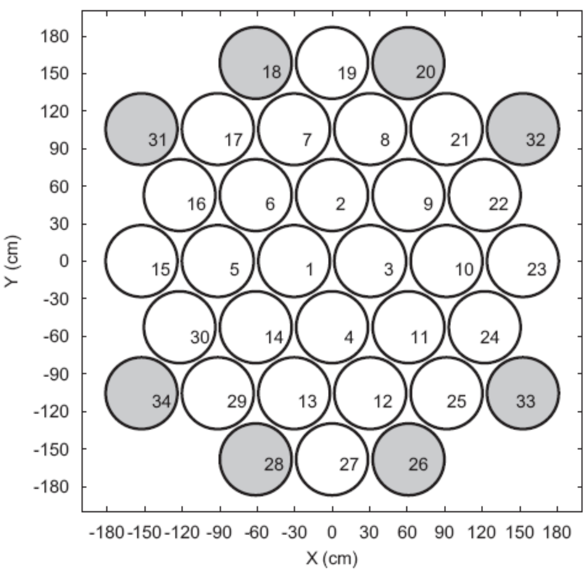
Telescope for imaging camera

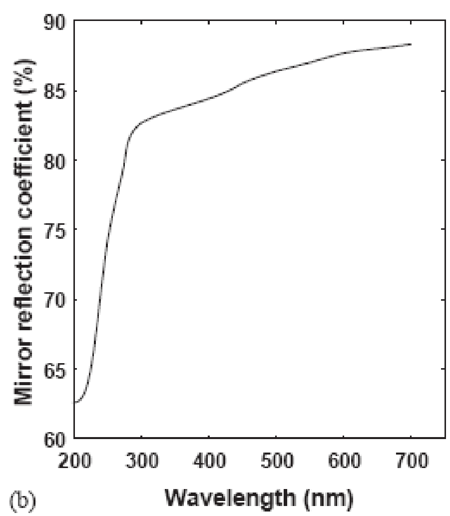
Vertex element of TACTIC operated by BARC at Mt. Abu

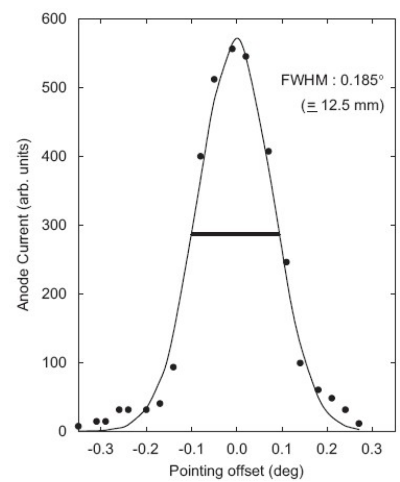
Light collector area 9.5 m^2, consists of 34 spherical mirror facets

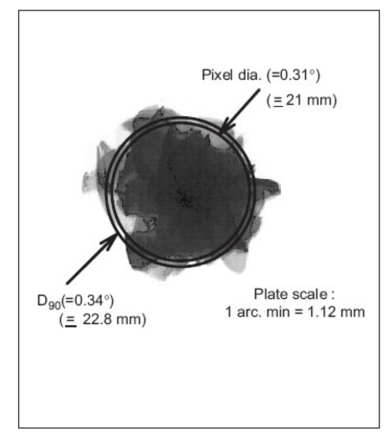
Focal length = 4 m, f/D ~ 1.1

PSF FWHM ~ 0.185° (≡ 12.5 mm)
D_{90} ~ 0.34° (≡ 22.8 mm)









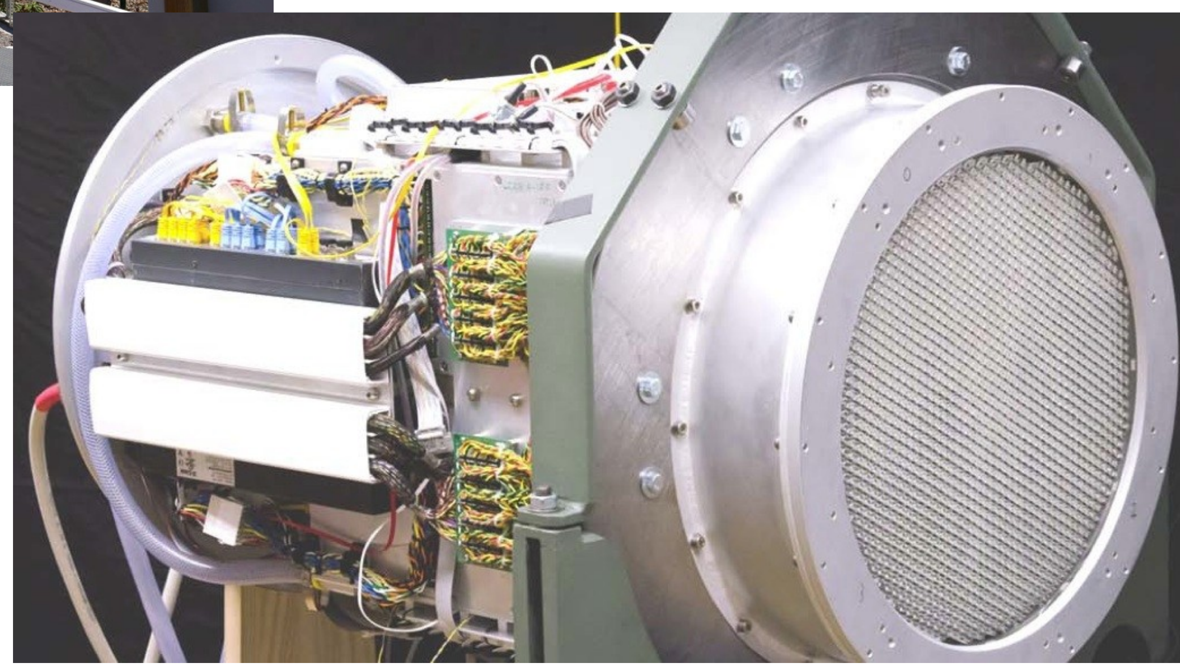
Measured PSF of TACTIC light collector

Photograph of image of Sirius

(Ref : Koul et al., NIM, A 578, 548, 2007,
Tickko et al. NIM, A 539, 177, 2005)

FACT : The First G-APD Cherenkov Telescope

- **Location : La Palma, Canary Islands, Spain**
- **Altitude : 2200 m a.s.l.**
- **Hexagonal mirrors**
- **Mirror area : 9.5 m^2**
- **Energy threshold : 750 GeV**
- **Operational since October 2011**
- **Monitoring bright AGNs**



Camera details :

- **FOV : 4.5°**
- **1440 pixels**
- **Pixel size 0.11°**
- **Photo-sensors : G-APDs**
- **Light concentrators : solid**

(Ref : https://www.isdc.unige.ch/fact)

Imaging camera for small telescopes

Choice of photo-sensors

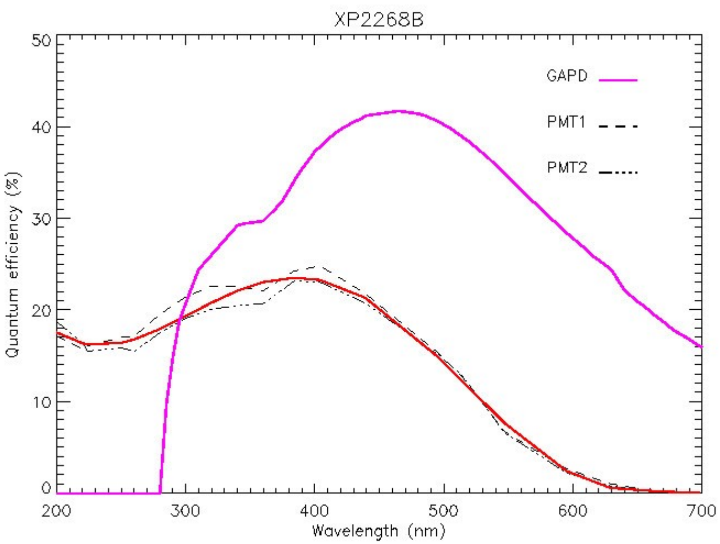
PMTs

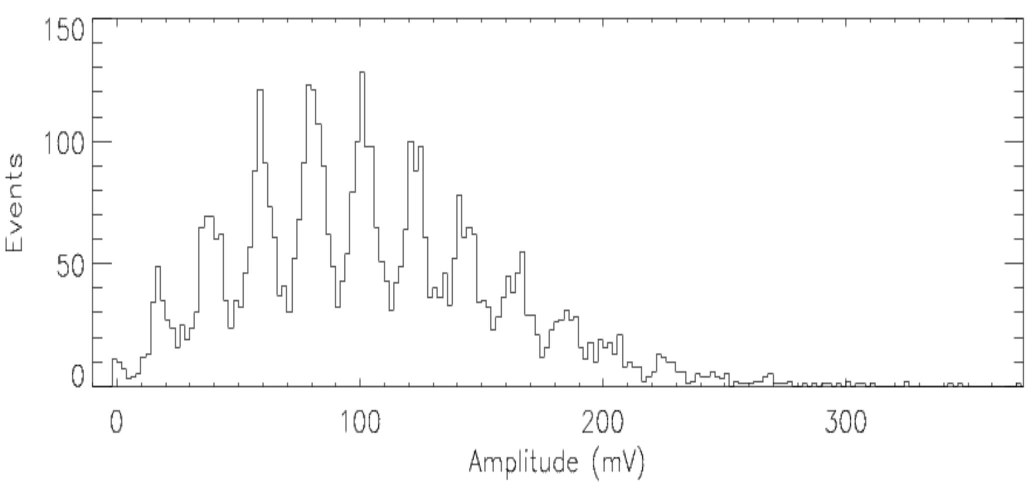
high gain, fast response
low quantum efficiency

Bulky , fragile, heavy
high bias voltage (~kV)
operation only during dark night
magnetic sensitivity

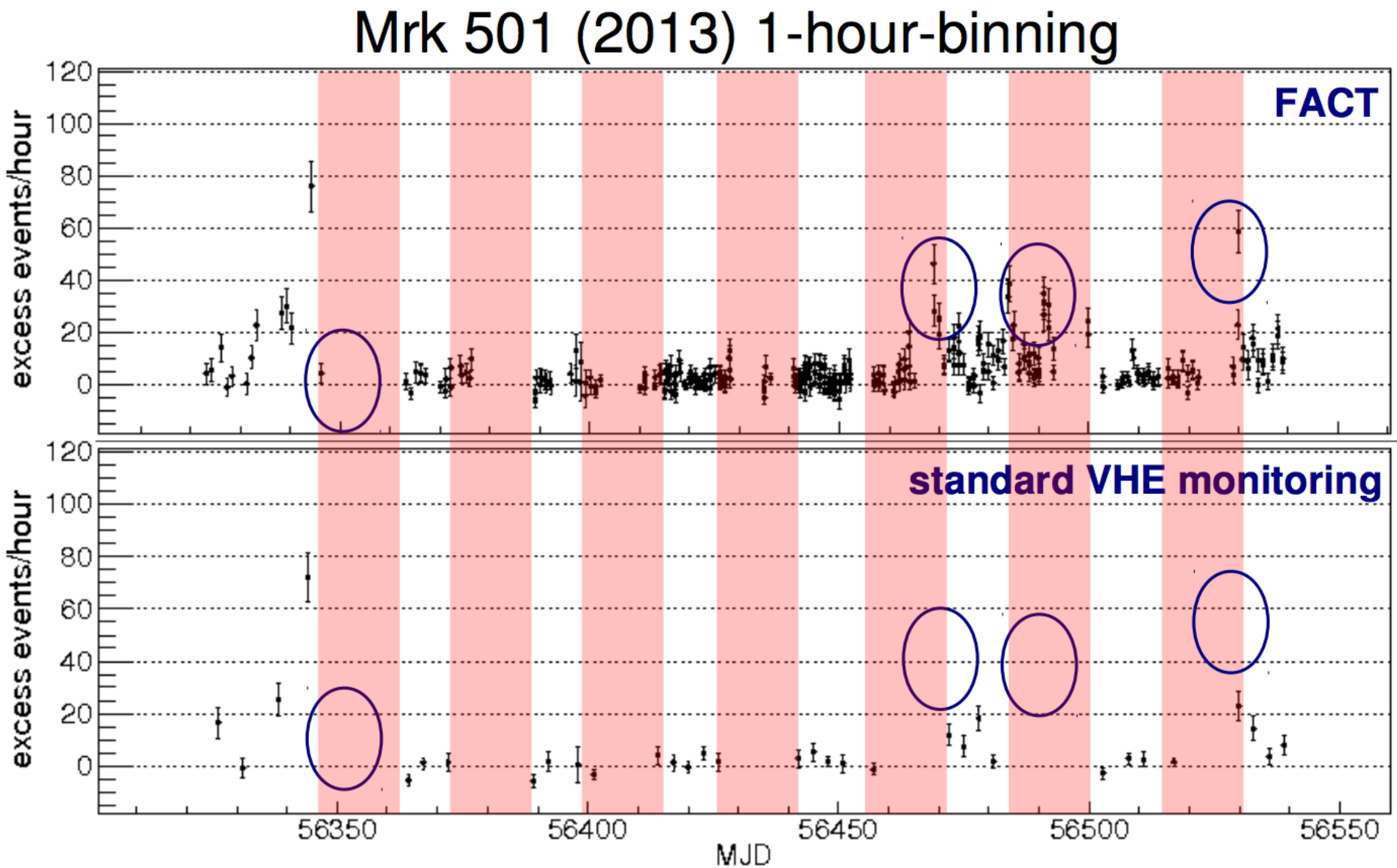
G-APDs

high gain, fast response
high photon detection efficiency
well resolved photo-electron spectrum
compactness, ruggedness, low weight
low bias voltages (< 60 V)
operation possible even during moonlight and twilight
magnetic insensitivity
Cross-talk, temperature dependence of gain





Mkn 501 Light Curve from FACT and MAGIC



All data ~410h

Moon < 65%
1h every
~3rd night
→ ~32h

FACT monitoring strategy → Unbiased data sample

(credits : FACT group)

Design Parameters for Camera

FOV : 5 deg X 5 deg
Physical size : 36 cm X 36 cm
Pixel size : 0.3 deg (21 mm)
no. of pixels : 256
Light concentrators : hollow

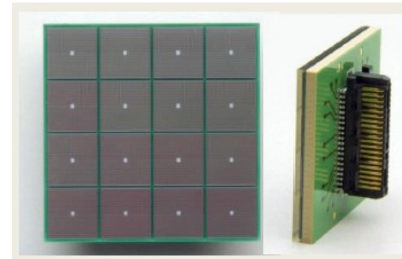
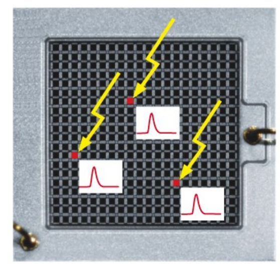
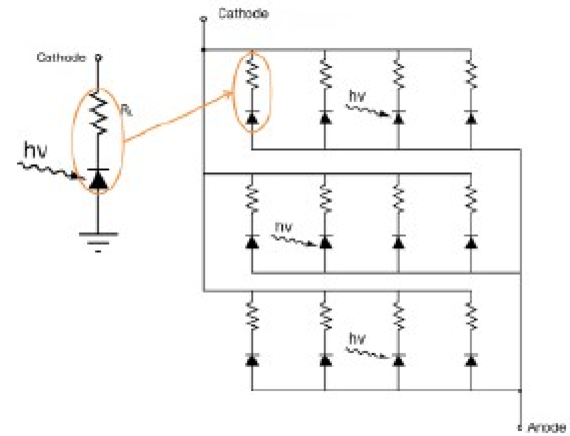


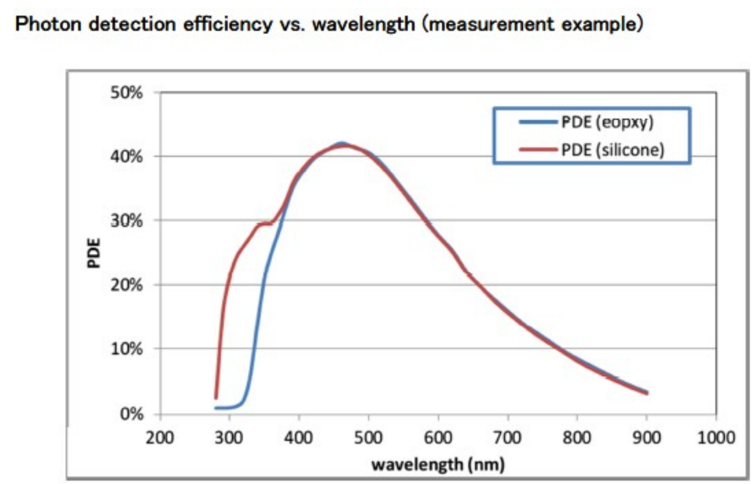
Photo-sensor : 16 channel (4x4) Array of MPPC from Hamamatsu S13361-3050AS-04 with size 12.6 mm X 12.6 mm





Sensor details :

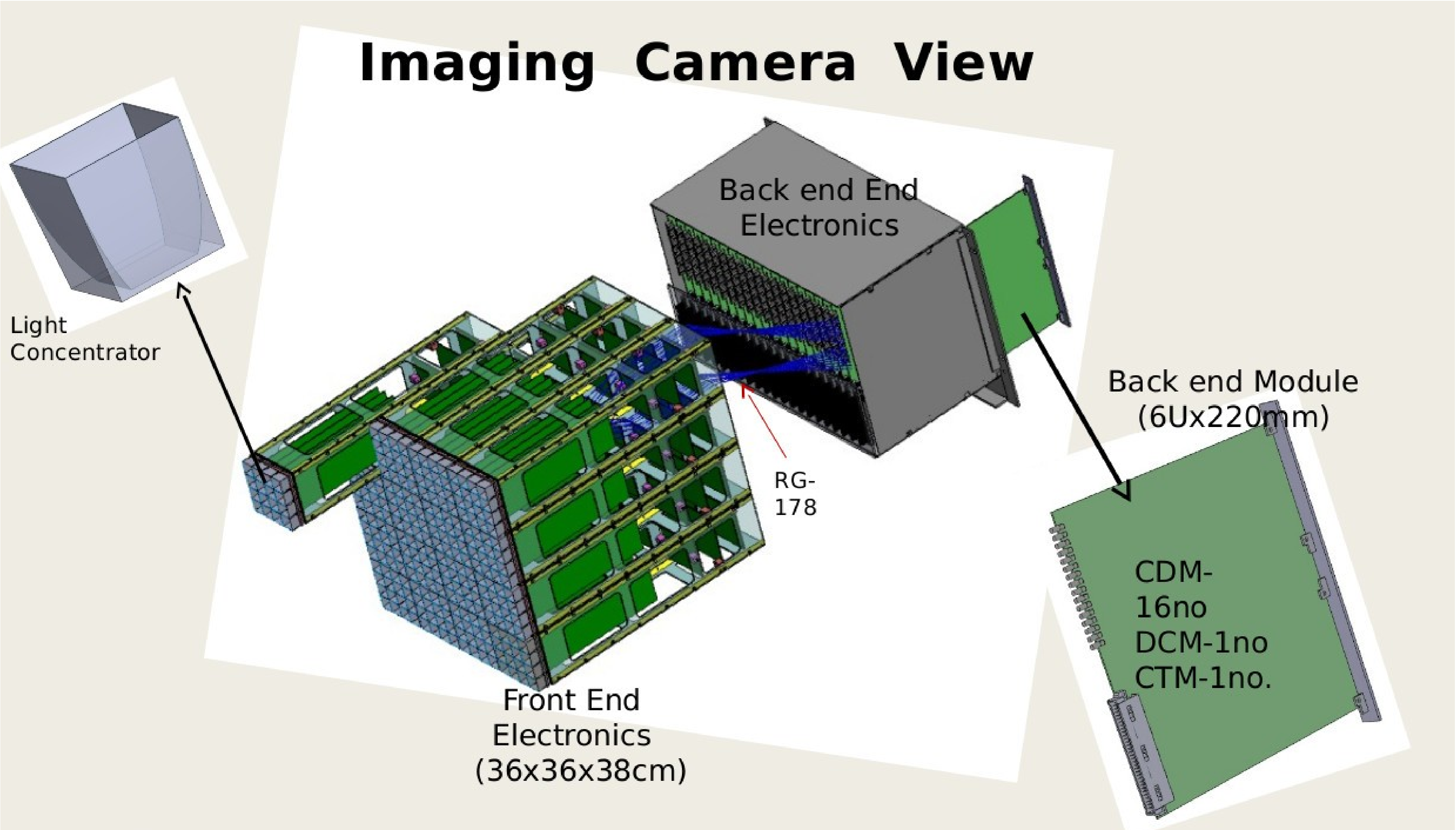
- 4X4 array of 3 mm x 3 mm channels or sub-pixels consisting of 3584 micro-cells of 50 μm pitch
- Fill factor : 74%
- Breakdown voltage : 53$\pm$5 V
- Operating voltage : V_{br}+3 V
- Temperature coefficient for break-down voltage : 54 mV/C
- Gain : $10^5 - 10^6$
- Operating temperature : -20 C to +60 C
- Spectral response over 270-900 nm peaking at 450 nm
- Peak photon detection efficiency : 40%
- Dark count rate : 0.5 MHz at 25C
- Optical cross-talk : 3%



Design Parameters for Camera

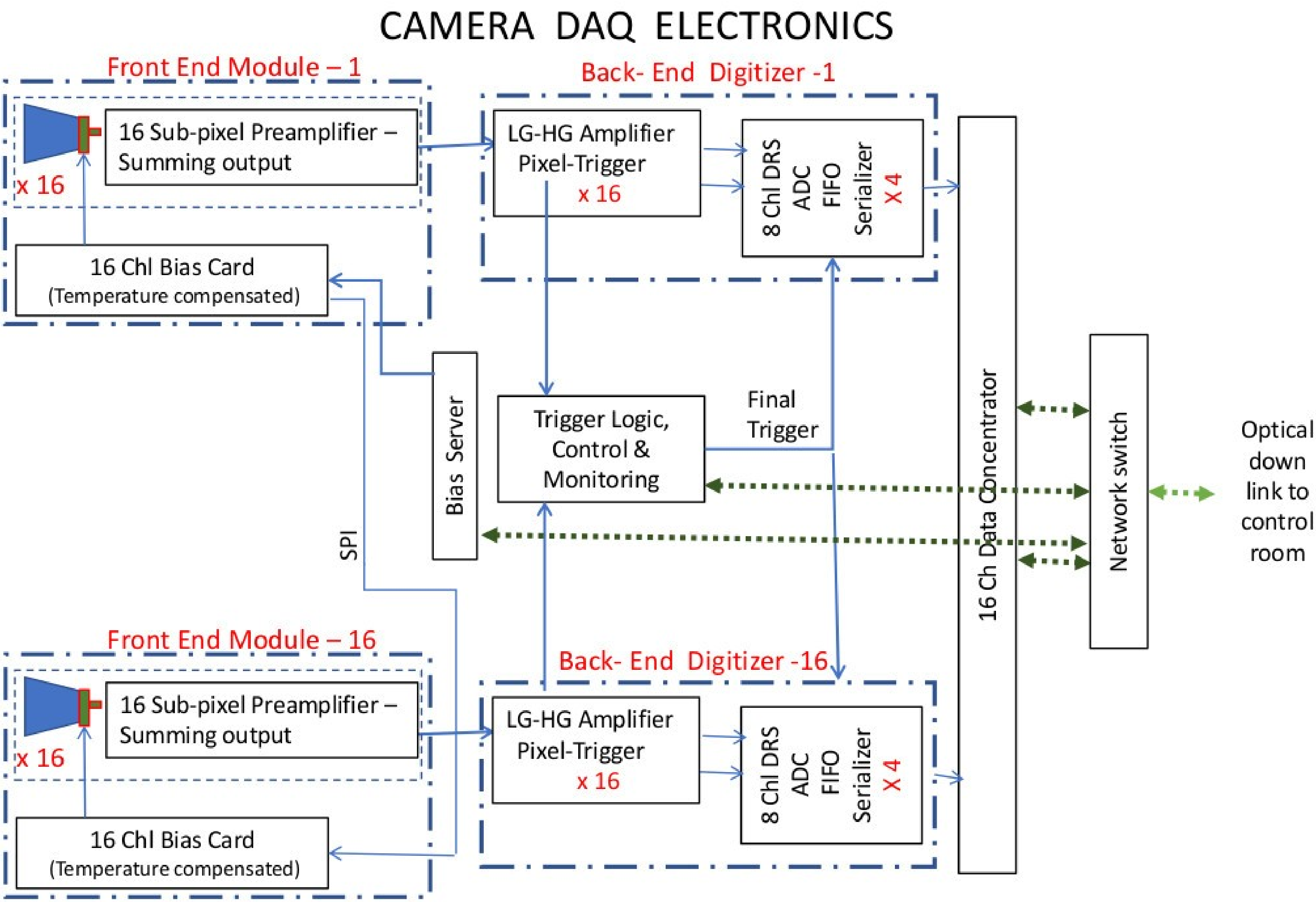
Design criteria for electronics and mechanical structure :

- **Dynamic range : 1 to 2000 pe/pixel with single pe resolution upto few pe**
- **Timing resolution for pulse profile : 1 ns**
- **Operation to be carried on dark nights (background rate 92 MHz/pixel) as well as under twilight/moon (background rate 2-3 orders of magnitude higher)**
- **Event rate : < 100 Hz**
- **Electronics mounted at the back of the camera**
- **Power consumption < 500 W**
- **In-situ calibration setup**
- **Cooling system if required**
- **Weight < 100 kg**



Dimensions : 36 cm X 36 cm sensor area
42 cm X 42 cm X 60 cm camera
Weight : ~ 100 kg
Power : < 2 Watt/pixel
Data size : ~ 65 kbytes/event

Functional Diagram of Camera DAQ



Main Challenges in Design of Camera

1. Maintaining constant gain in view of temperature and light level variation

2. High background flux from night sky even during dark nights and with 2-3 orders of magnitude increase during moonlit nights -> pulse pileup

3. G-APD has significant PDE at longer wavelengths where NSB dominates

4. Huge capacitance of G-APD (320 pF/sub-pixel)

5. Dynamic range of 1-2000 pe

6. Pulse profile recording in 1 ns bins

7. Operation in temperature range -20 C to +30 C

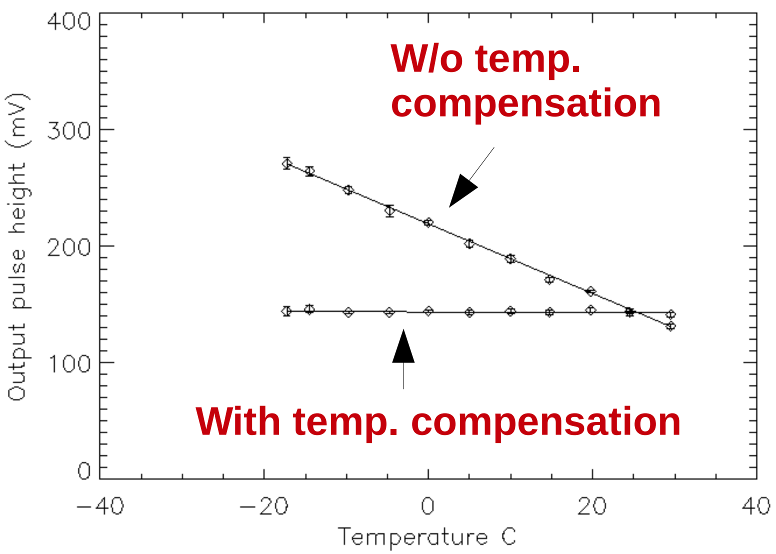
8. Low noise

9. Entire electronics to be mounted in focal plane

Bias Supply for G-APDs

Requirement : **To provide bias voltage of about 52-58 V maintaining constant gain**

Challenge : **Temperature and light level dependency of system gain, maintaining constant gain as temperature varies from -20 C to +30 C throughout the year**



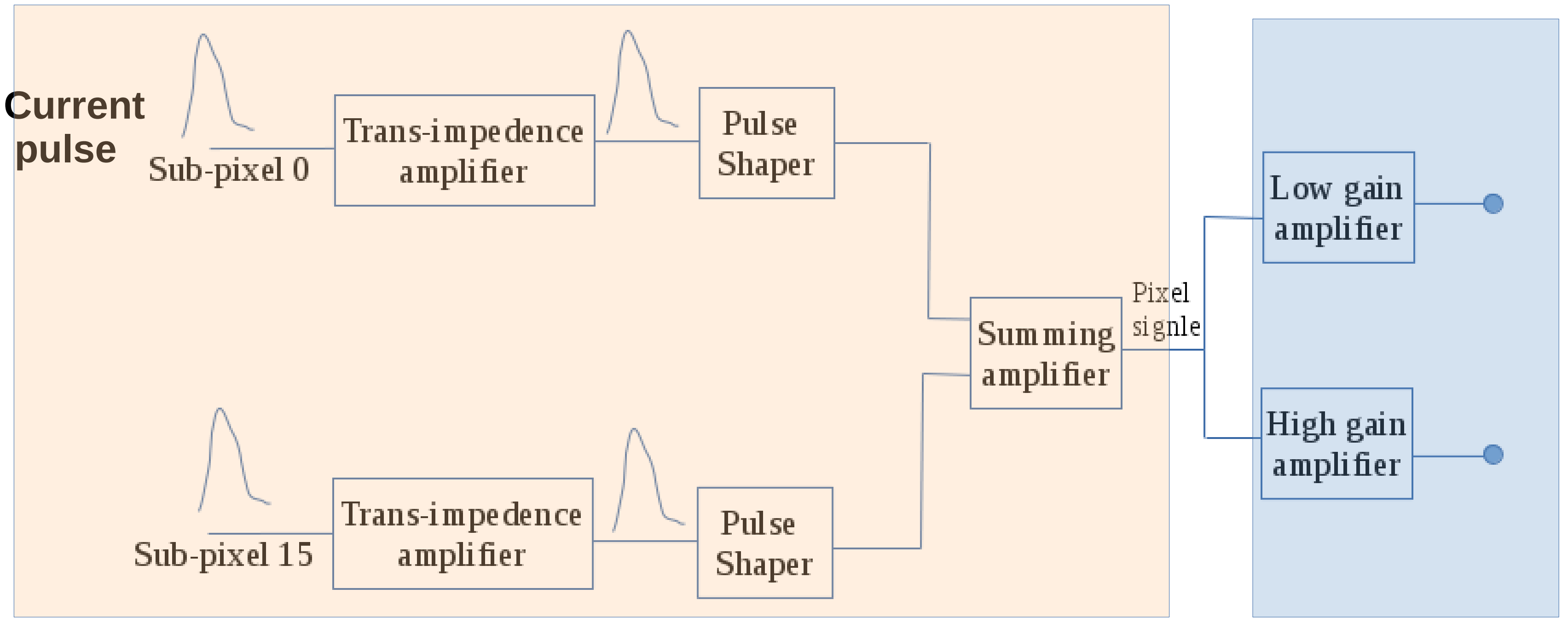
Main features :

- **Based on DC/DC converter HV80 from AiT Instruments**
- **Provides voltage range of 0-80 V with 4 mA load**
- **Bias voltage variation in steps of 5 mV**
- **Low ripple and noise (< 5 mV @ 80 V)**
- **Xmega series micro-controller from Atmel for controlling and monitoring bias**
- **Individual channel ON-OFF facility**
- **Over-current shut-down feature**
- **Each supply board caters to eight pixels, needs +5 V @ 1.3 A supply at full load**
- **Remote access through ESPI communication via Raspberry Pi**
- **G-APD gain stability improved from 97% to 3% over the temperature range -20 C to +30 C**

Pre-amplifier

Challenges : Huge capacitance (320 pF) at the output of G-APD sub-pixel
→ low impedence amplifier
Possibility of pileup of pulses due to length of G-APD pulse (80 ns)
Minimize heat dissipation, single pe resolution, 1-2000 pe dynamic range

Solution : Amplification of sub-pixel pulses using trans-impedence pre-amplifier,
Shaping of amplified sub-pixel pulses followed by addition of pulses

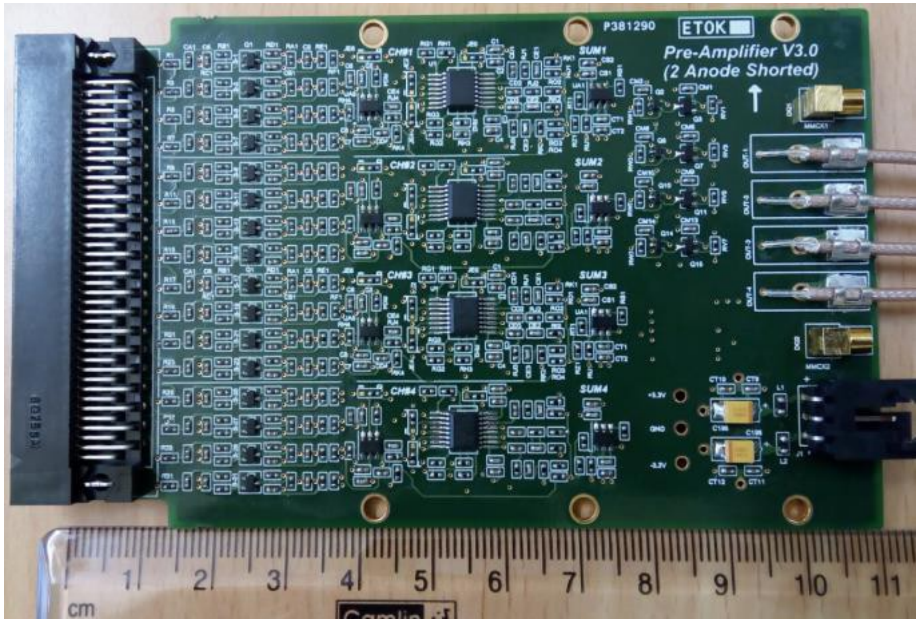


Pre-amplifier : input impedence 6 ohm, TIA gain : 0.64 mV/μ-amp
input pulse to TIA : peak amplitude 12.5 μ-amp/pe
TIA output pulse characteristics : 8 mV peak amplitude, 80 ns base width

Pulse shaper : based on pole-zero cancellation

Output of summing amplifier : Rise time < 6 ns, base width : 20 ns

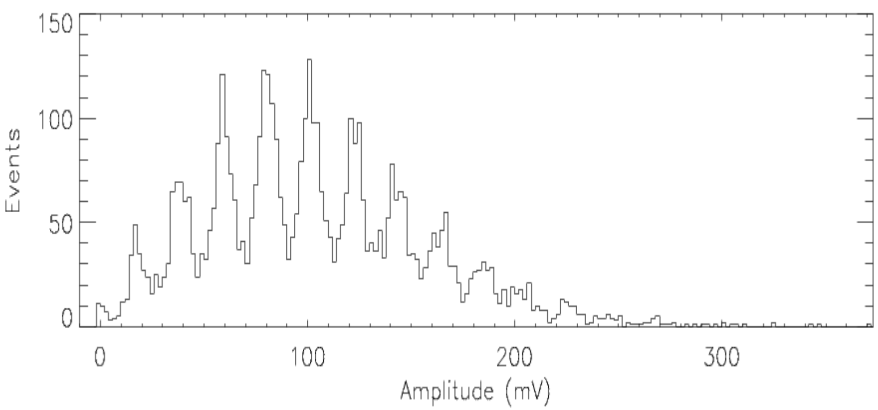
Pre-amplifier

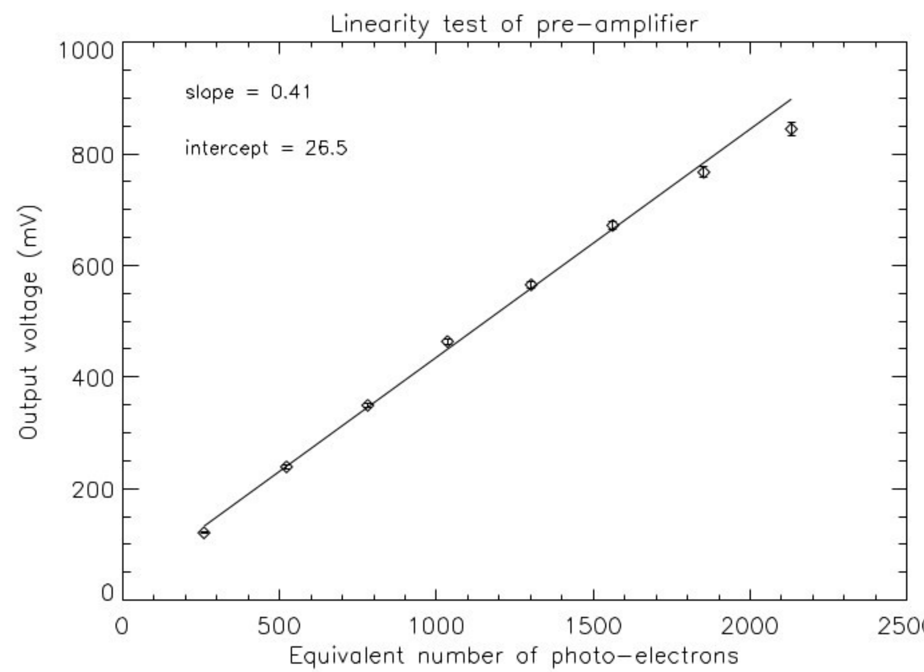


Other features :

Sub-pixel enable/disable
Supply : ± 3.3 V
Power consumption : 0.6 W/pixel
Processing of 64 sub-pixels

Amplitude distribution of G-APD pulses



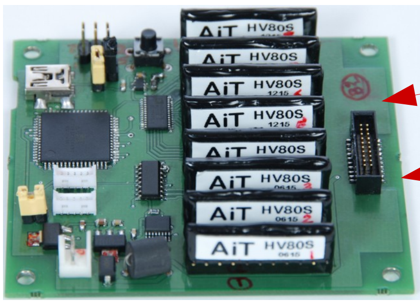


Requirement : Cover the dynamic range of 1-2000 pe with single pe resolution upto few pe

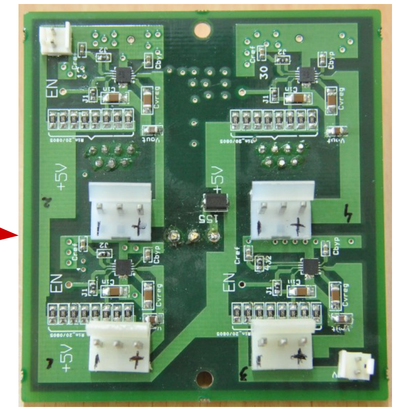
Two channels of amplification
High gain : 1 - 100 pe, Low gain : 1 – 2000 pe

16-Pixel Cluster Module

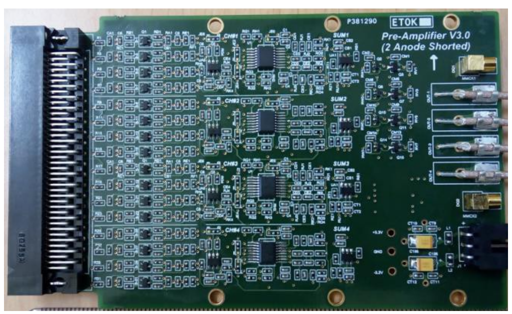
8 ch. Bias Supply Card

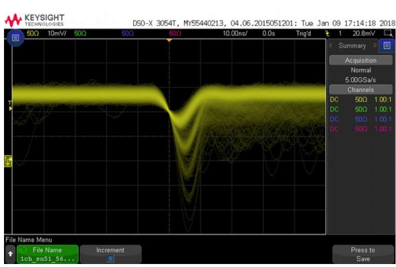


Low Voltage Power Supply Card



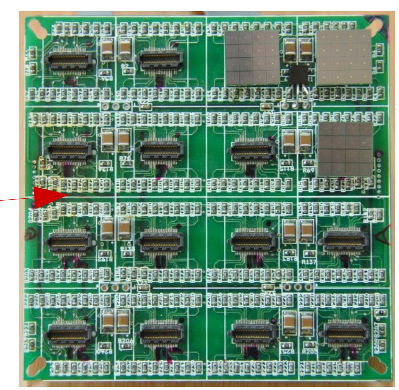
4 Pixel Pre-Amplifier



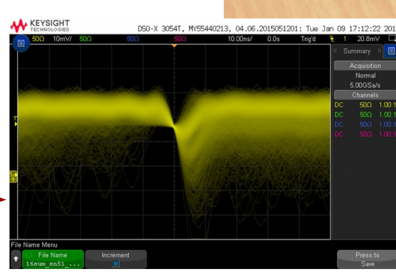


1 ch

G-APD Mount PCB



16 ch sum



Pixel Cluster Module (PCM) Dimensions:
280mm (H) x 88mm (B) x 88mm (W)

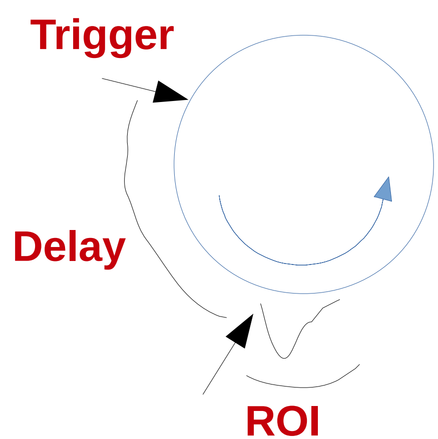
Digitizer Module

Requirement : Recording pixel pulse profiles with resolution of 1 ns

DRS4 chip based design with sampling rate of 1 GSPS

36 channels in board catering to LG and HG of 16 pixels and 4 calibration signals

DRS4 chip : Array of switched capacitors with 1024 cells in ring continuously storing charge information



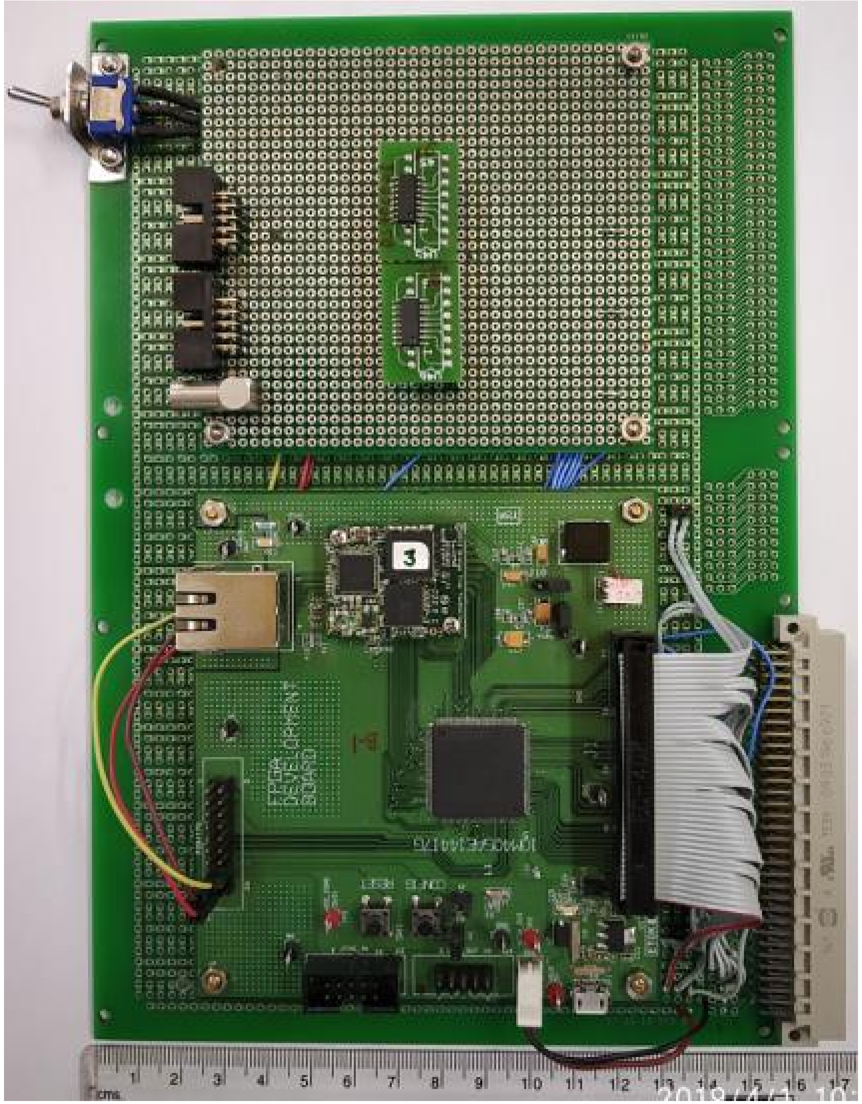
On receipt of trigger, sampling halted after pre-determined delay and information in region of interest (ROI) digitised using 14 bit ADC at 33 MHz rate

Each DRS4 chip caters to high and low gain channels for 4 pixels

Comparators to generate first level trigger (pixel trigger)

FPGA for pixel enable/disable, threshold setting, multiplexed digitization, recording ROI, data transmission over serial link to data concentrator etc

Control and Trigger Module



Control section :

- Sending control / configuration / initialization data to all back end modules
- Recording monitor data from all digitizers
- Processor in FPGA interfaces to all other modules over back panel cSPI as well as remote control room over Ethernet for communication and data transfer

Trigger section :

- Receives first level trigger signals from 16 digitizer modules
- Generates final trigger and sends trigger signal to digitizer modules
- Generates event number and 100 ns resolution time stamp synchronized with GPS
- Sends event number and time stamp to digitizer modules over a common serial link of 20 Mbps

The module also provides 10MHz clock signal to all other back-end modules for synchronization of operations

Trigger Scheme

Two types of triggers NCT and 4NNB under consideration

Pixel threshold for trigger selectable e.g. 4 pe, 5 pe,…
Coincidence window selectable (5 / 10 / 15 / 20 ns)

Blue : 4NNB   Green : NCT

15	31	47	63	79	95	111	127	143	159	175	191	207	223	239	255
14	30	46	62	78	94	110	126	142	158	174	190	206	222	238	254
13	29	45	61	77	93	109	125	141	157	173	189	205	221	237	253
12	28	44	60	76	92	108	124	140	156	172	188	204	220	236	252
11	27	43	59	75	91	107	123	139	155	171	187	203	219	235	251
10	26	42	58	74	90	106	122	138	154	170	186	202	218	234	250
9	25	41	57	73	89	105	121	137	153	169	185	201	217	233	249
8	24	40	56	72	88	104	120	136	152	168	184	200	216	232	248
7	23	39	55	71	87	103	119	135	151	167	183	199	215	231	247
6	22	38	54	70	86	102	118	134	150	166	182	198	214	230	246
5	21	37	53	69	85	101	117	133	149	165	181	197	213	229	245
4	20	36	52	68	84	100	116	132	148	164	180	196	212	228	244
3	19	35	51	67	83	99	115	131	147	163	179	195	211	227	243
2	18	34	50	66	82	98	114	130	146	162	178	194	210	226	242
1	17	33	49	65	81	97	113	129	145	161	177	193	209	225	241
0	16	32	48	64	80	96	112	128	144	160	176	192	208	224	240

Four types of outputs from each digitizer module :

1. **Trigger condition satisfied in module itself (FT)**
   → first level trigger from module and final Trigger from CTM

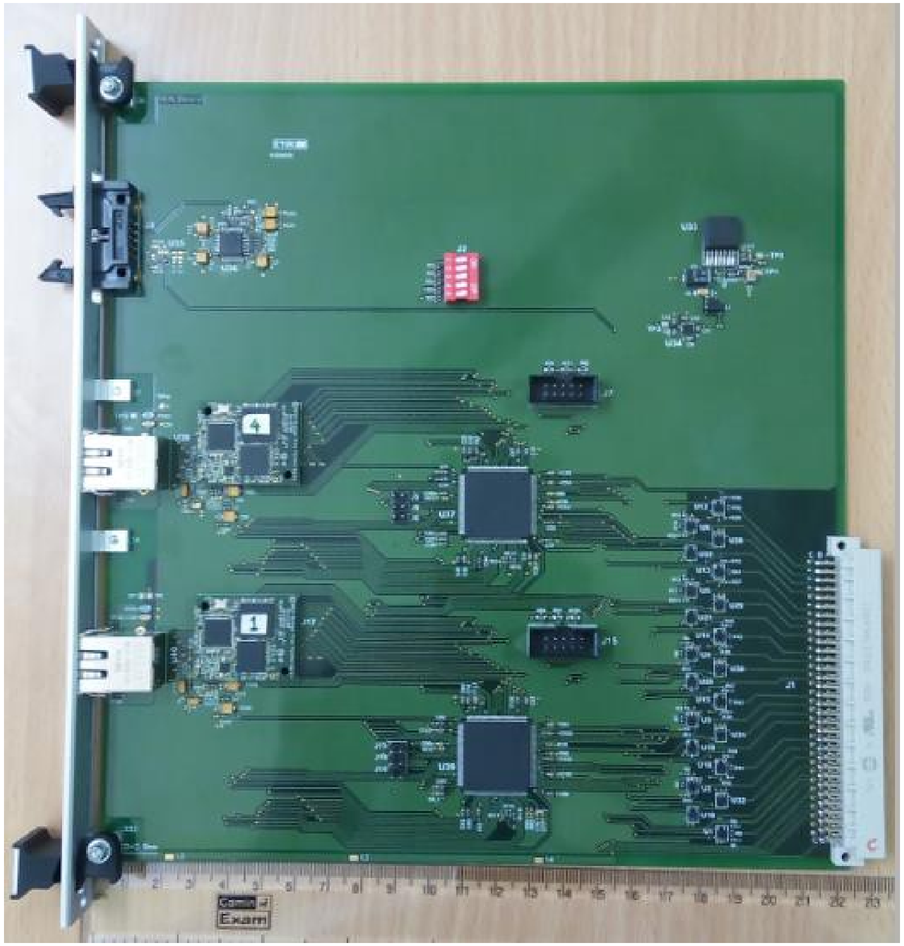
2. **Two adjacent pixels from module boundary triggering (2F)→ first level trigger generation at module and final trigger from CTM after verifying output form neighbouring module**

3. **One pixel from boundary triggering (1F)**
   → Similar to 2F

4. **Bit pattern corresponding to location of triggered pixels → for CTM to check for valid trigger**

Data recording for all digitizers on final trigger from CTM

Data Concentrator Module



Receives data packets from digitizer modules

Sends data to remote PC over two 1 GbPS
Ethernet links

Consists of two identical circuits, each catering
To half of the camera

Throughput rate upto 160 MBPS achieved

Some Photographs

Back end crate

Setup for testing back end electronics

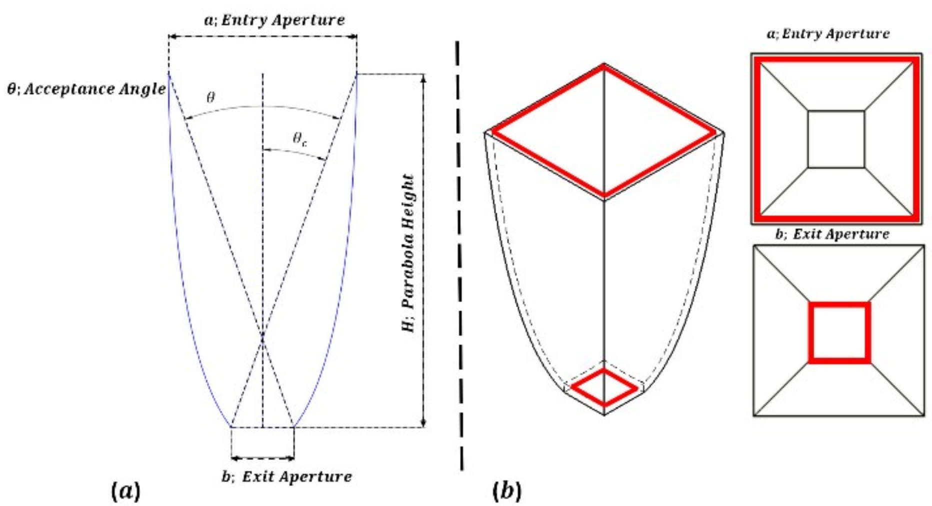
Light Concentrators

Purpose :

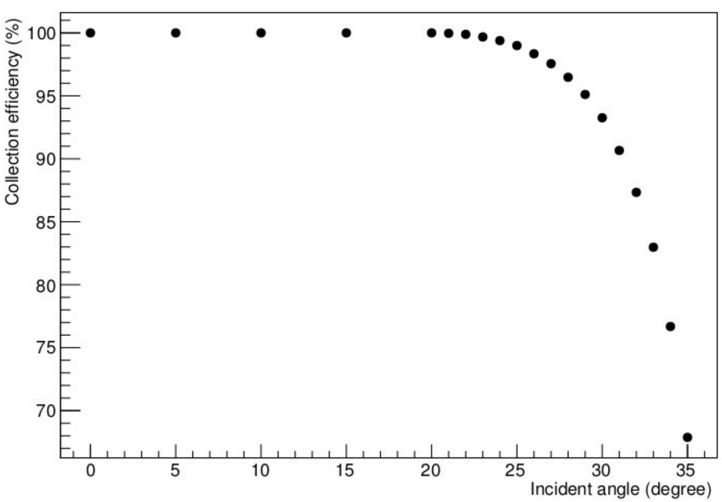
- Concentrate light from larger area to smaller area
- Reduce dead space between photo-sensors
- Cut-off environmental stray light entering photo-sensors

Design details of light concentrators for G-APD camera :

- Square entry – square exit design
- Entry : 21.1 mm X 21.1 mm , Exit : 12.4 mm X 12.4 mm, Length : 23.2 mm
- Acceptance angle : 36 deg



Collection efficiency for surface with 100% reflectivity



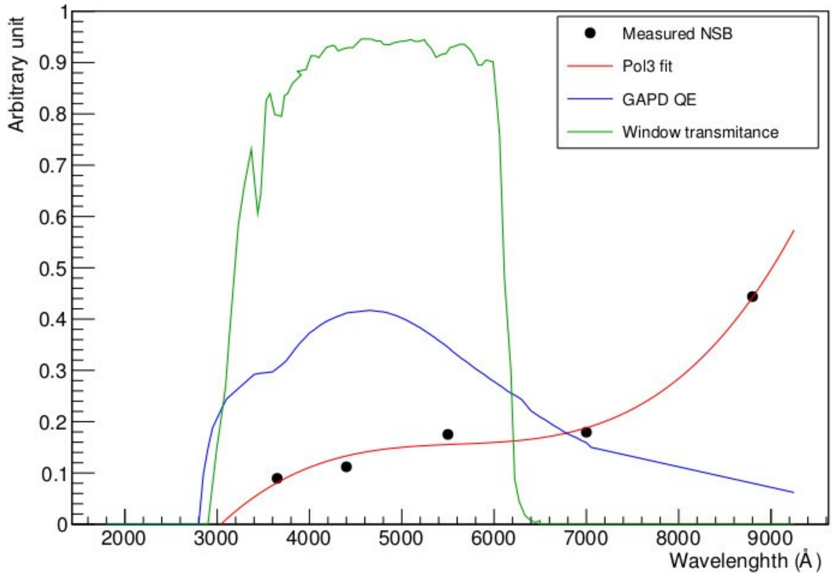
Good collection efficiency upto 28 deg

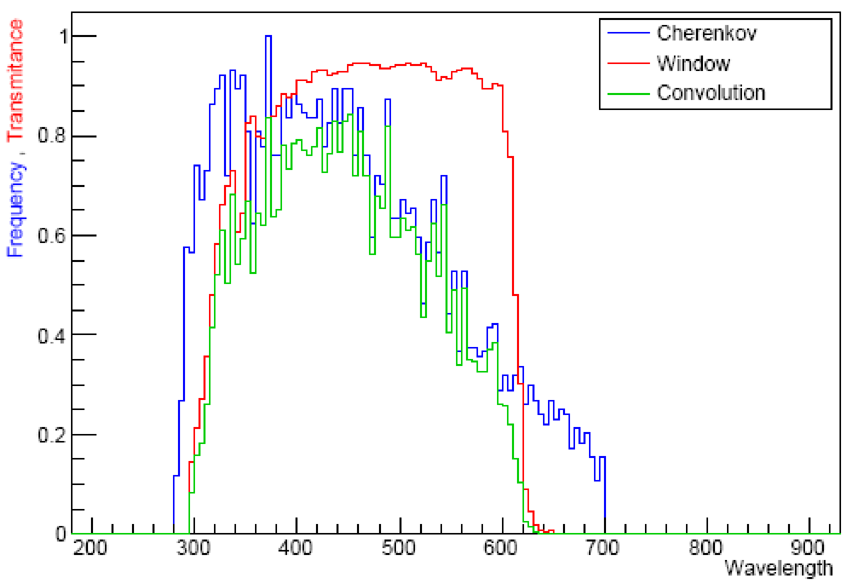
Specifications :

- Material : ABS plastic with aluminum coating on inside surface
- Average collection efficiency > 85%

Reduction in NSB

Estimated NSB rate for dark nights : 92 MHz/pixel





Window in front of LC to cutoff NSB at longer wavelengths

Material : Schott filter glass with dichroic coating

Characteristics :

Transmission in 350-600 nm : 88%
Transmission in 625-900 nm : 0.2%
Transmission beyond 900 nm : 0%

Disadvantage :
Cherenkov photon absorption

49% reduction NSB
25% loss of Cherenkov photons

NSB reduction important considering planned operations under moonlit condition

Other Challenges

Total power consumption < 500 W

Electronics designed to minimize power consumption
Maximum power consumption in pre-amplifier cards ~ 155 W

Low noise design : Components selected accordingly

Temperature variation -20 C to +30 C : Components selected accordingly

Space constraints :

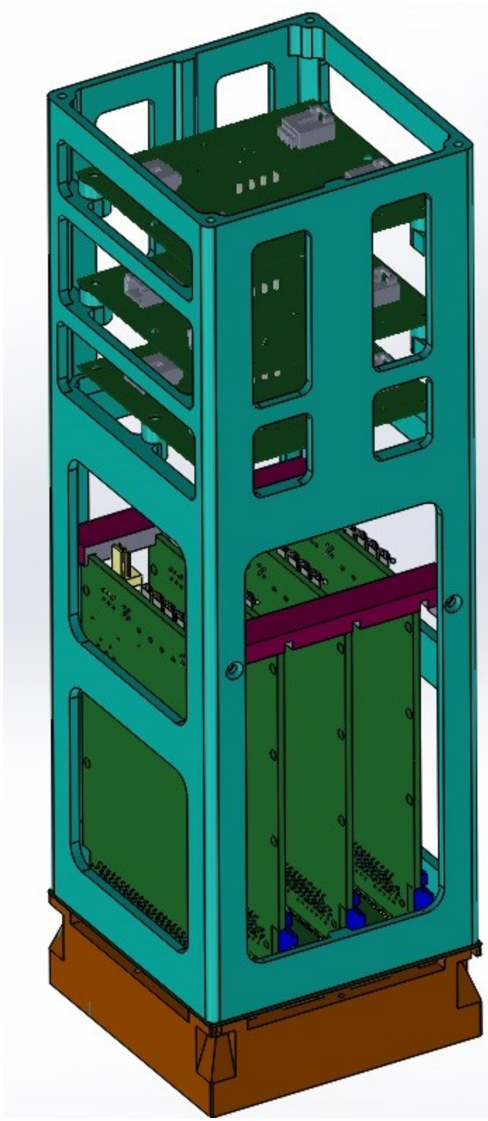
Camera dimensions : 42 cm X 42 cm X 60 cm

Multi-layer PCBs (5-10 layers)
SMD components
In pre-amplifier card with 880 components in 11 cm X 7 cm with 10 layers

Weight < 100 kg

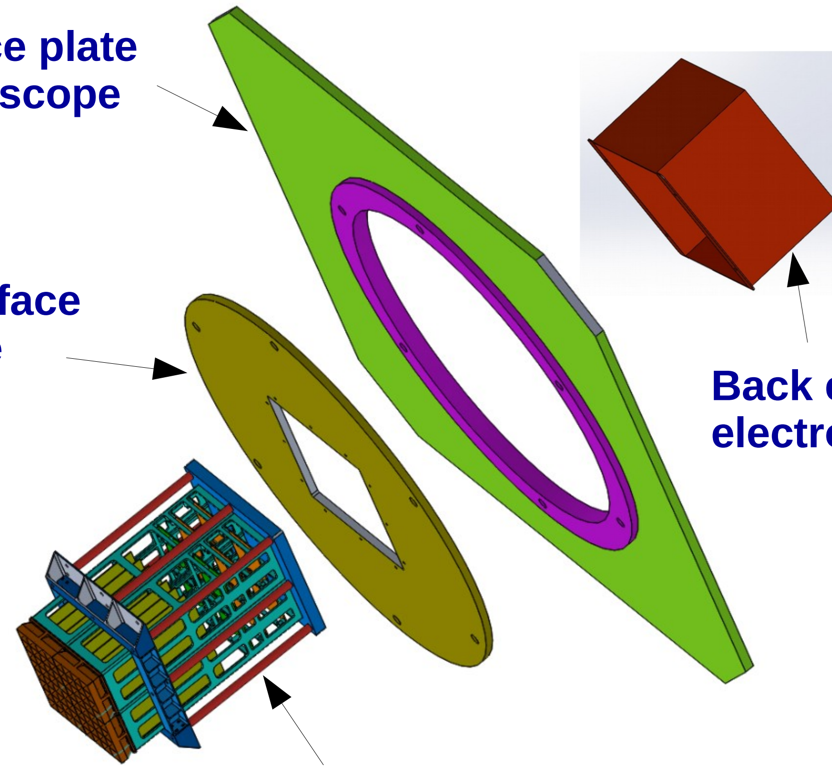
Mechanical Structure

16-pixel cluster module



Dimensions : 88 mm X 88 mm X 28 mm
Weight : 1.5 kg
Material : Nylon

4-module setup to be installed at Mt. Abu

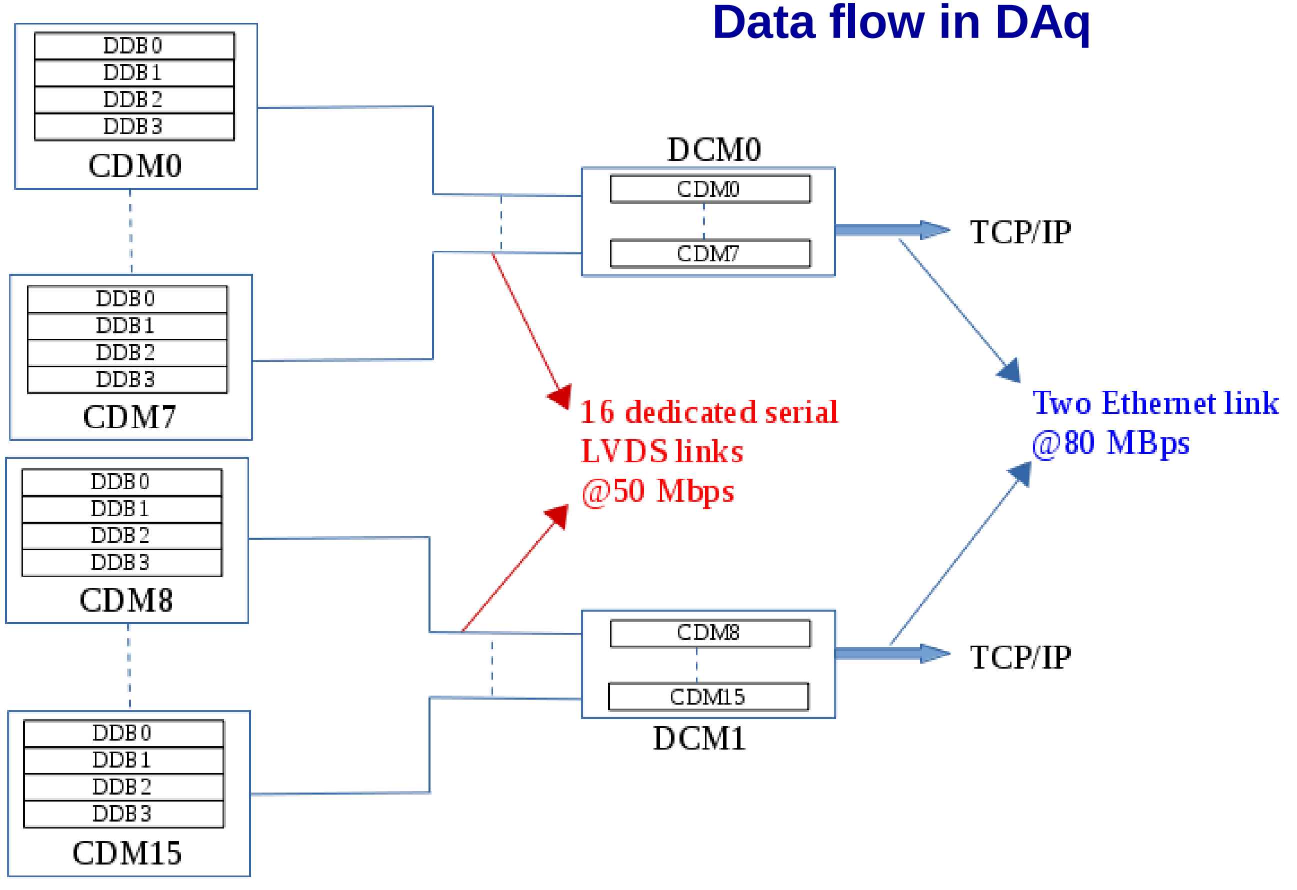


Camera (16 module) enclosure dimensions :
42 cm X 42 cm X 60 cm

Weight < 100 kg

Data Size

Data flow in DAq

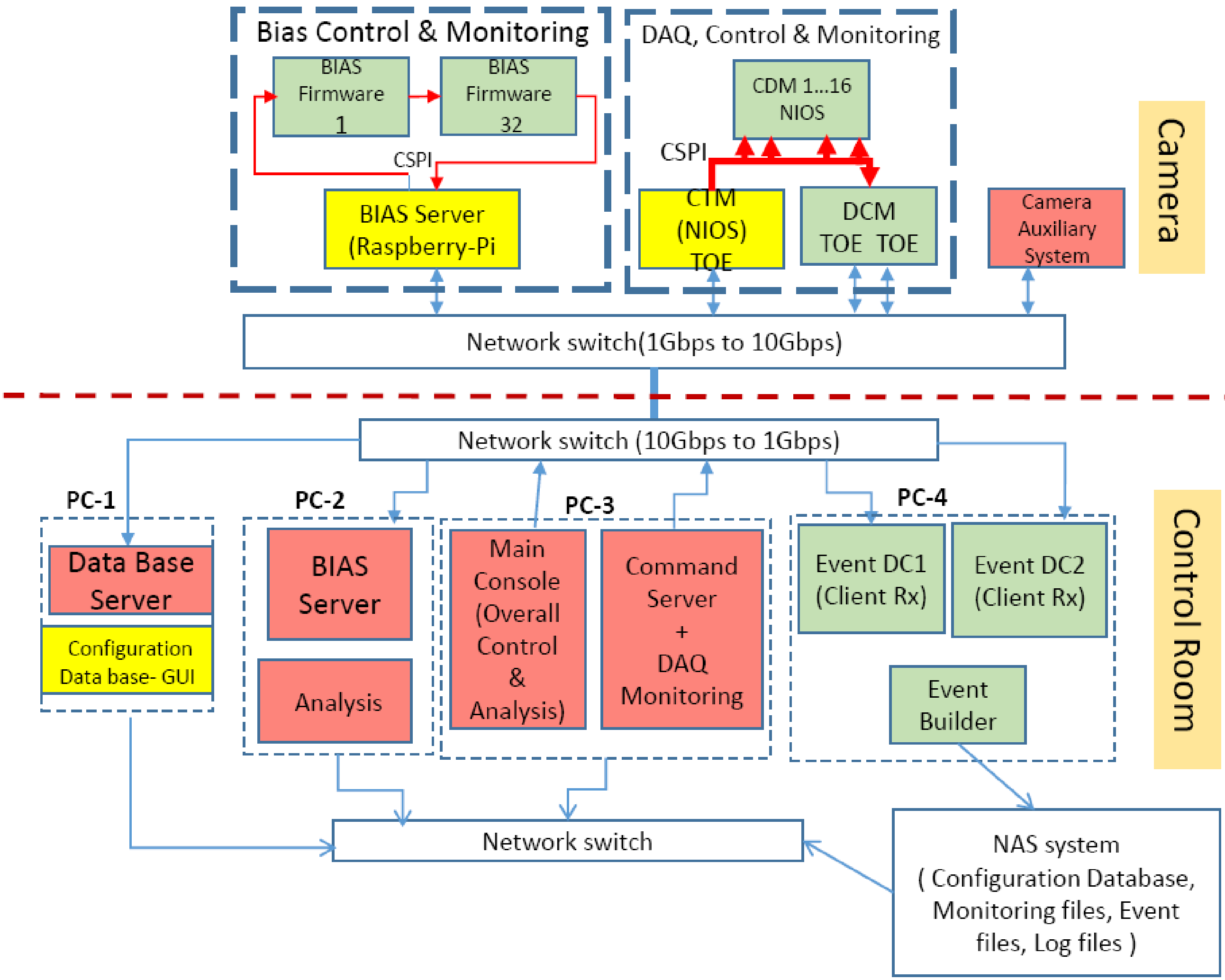


Data will be recorded in binary format initially and will be converted into ROOT format later

Interactive Qt-ROOT based GUI for data monitoring

Data Type	ROI (ns)	Data size /event (kB)	Maximum rate (Hz)	Dead time/DDB (µs)	Data size /hour for 50 Hz rate (GB)
Calibration	1024	1186	84		
Science	100	122	822	30	22
Science	50	64.5	1550	16.5	11.6

Software scheme between Camera Electronics and remote servers in Control Room



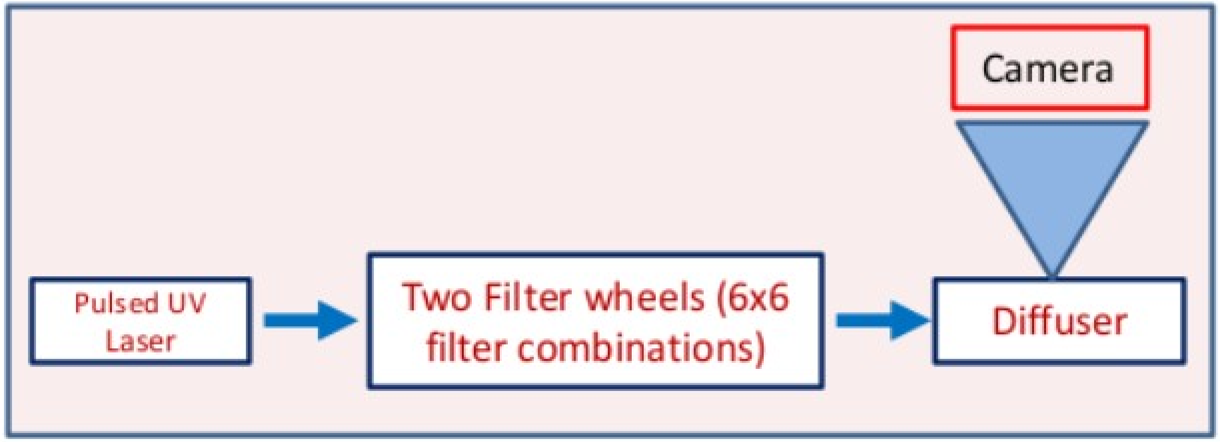
Camera software:

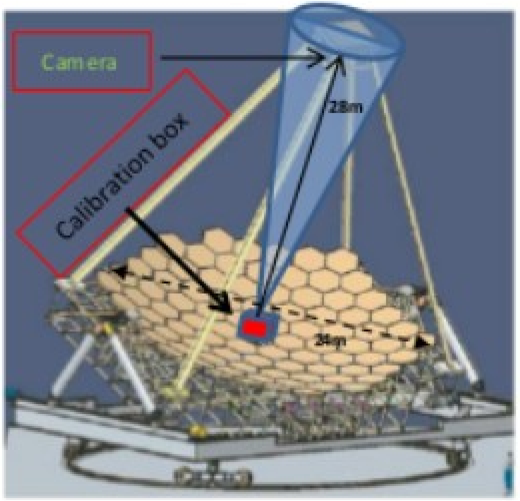
- **Bias control and monitoring : bias card micro-controllers connected to Raspberry-Pi over cSPI**
- **Trigger and digitizer built over NIOS processor**
- **Data concentrator built on FPGA - collects data from digitizers and sends to control room over two Ethernet links**

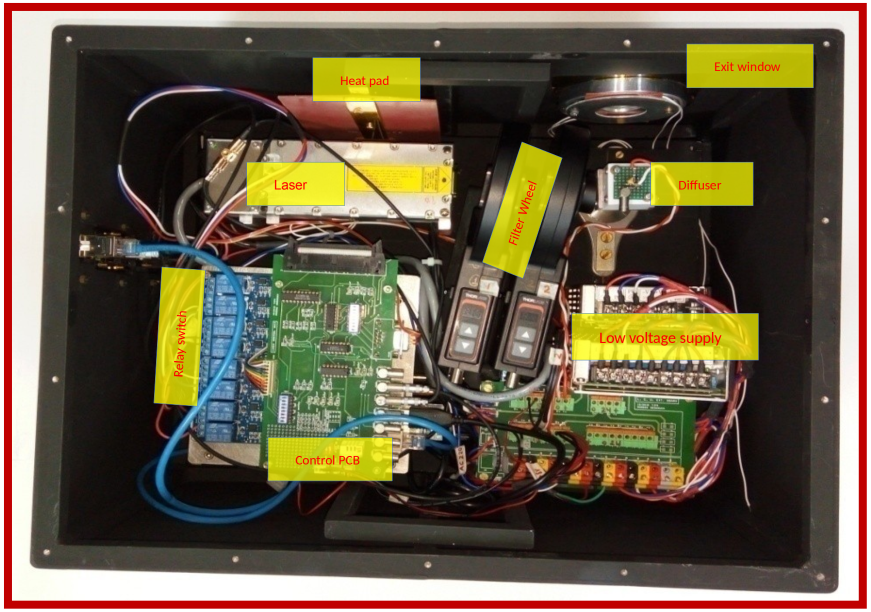
Control room software :

- **Data base : calibration and configuration data**
- **Bias server**
- **Main console for camera control and analysis**
- **Event builder**
- **NAS repository**

In-situ Calibration Setup



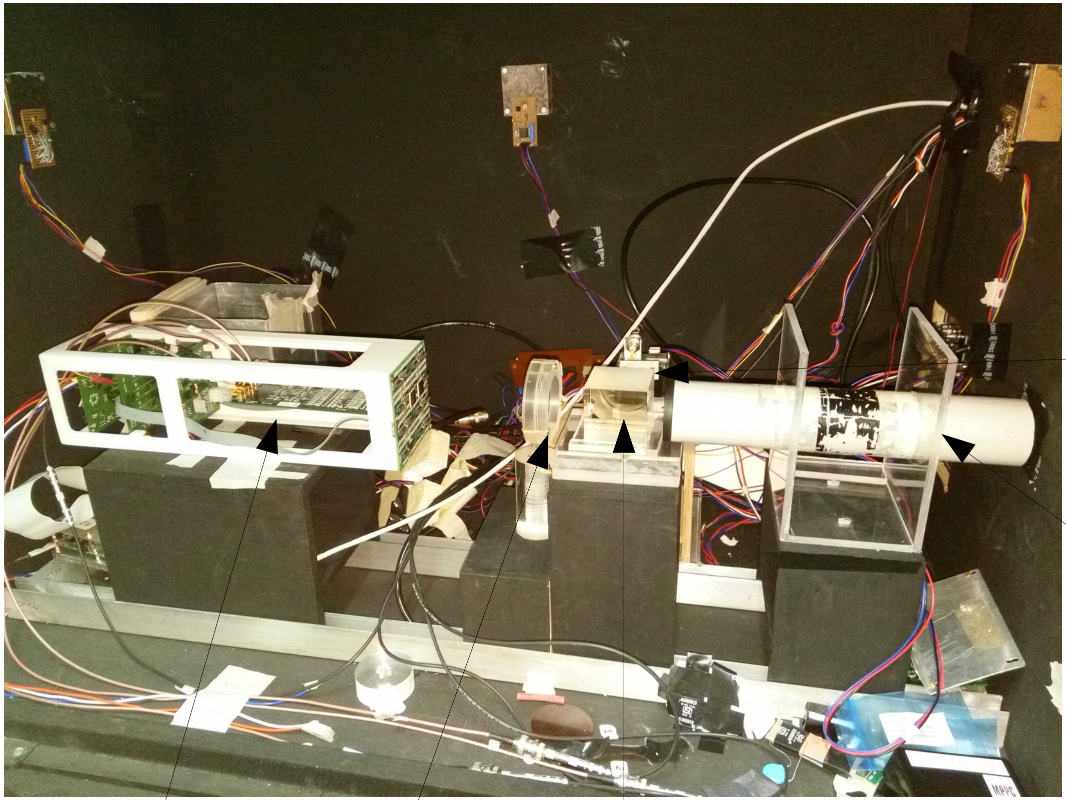




UV laser wavelength : 355 nm
Pulse width : 0.3 ns
Repetition rate : 10 Hz – 2 kHz
Range : 1- 1000 pe
Light intensity distribution and light stability better than 5%

Another LED based calibration system will be installed on camera shutter

G-APD Characterisation Setup



LED flasher :
405 nm, pulse duration : 3.5 ns
with intensity control

Reference detector : Hamamatsu SiPM module

LED output coupled through optical fibre

16 pixel module

Diffuser

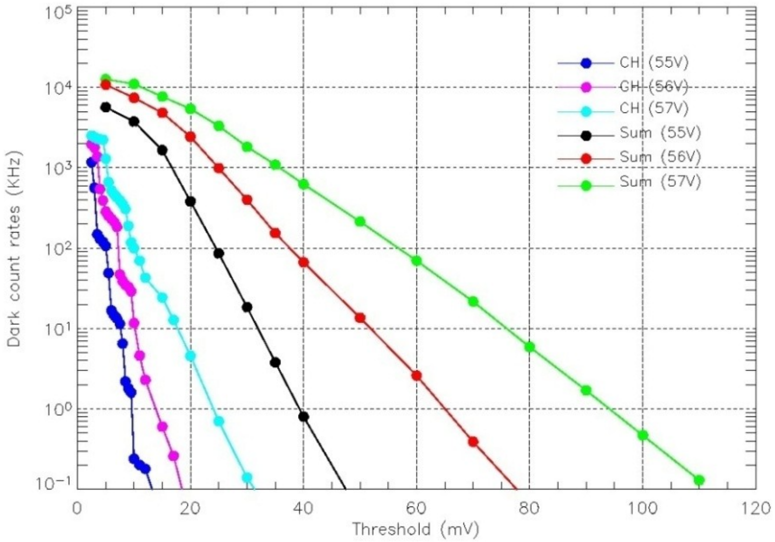
Beam splitter (Non-polarized broad band)

Measurements :

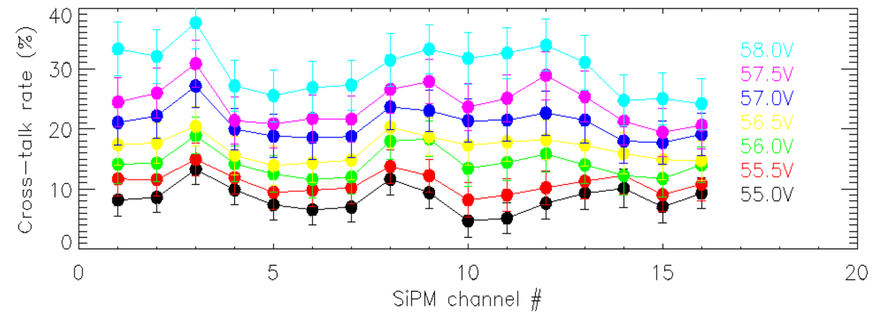
Dark and cross talk count rate
Breakdown voltage
Temperature dependence of breakdown voltage
Measurement of absolute gain and its linearity
Shape of sub-pixel and added pulses
Photon detection efficiency

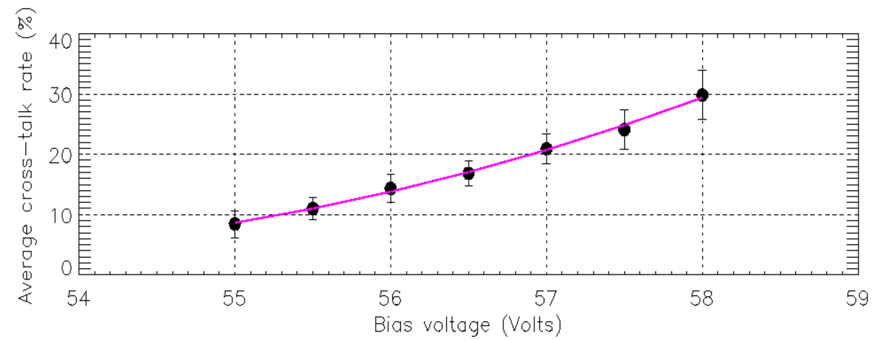
G-APD Characterisation

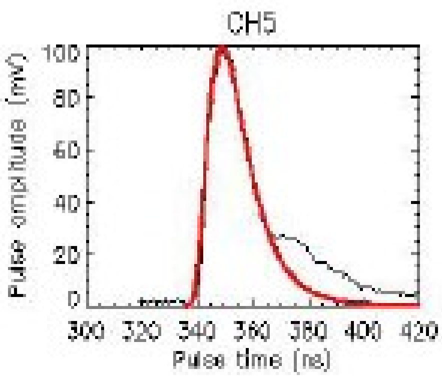
Dark count rate



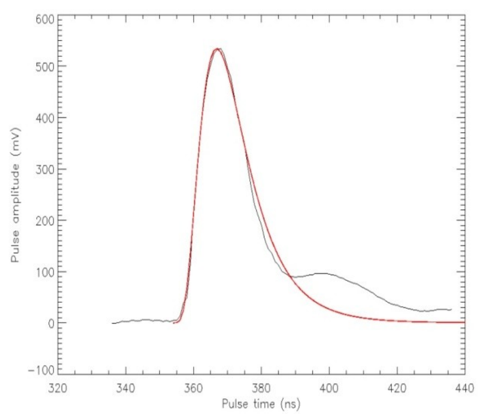
Cross-talk



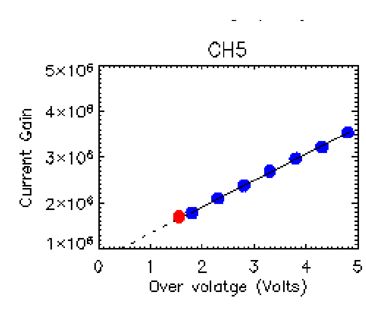




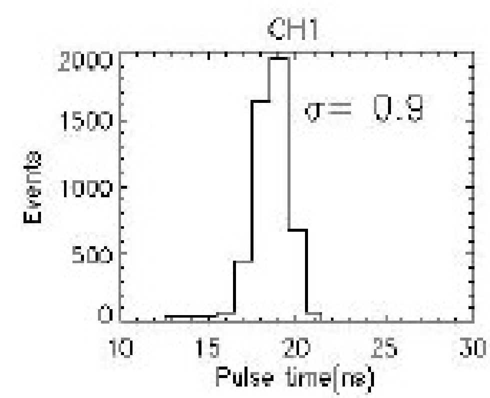
Sub-pixel pulse



Pixel pulse



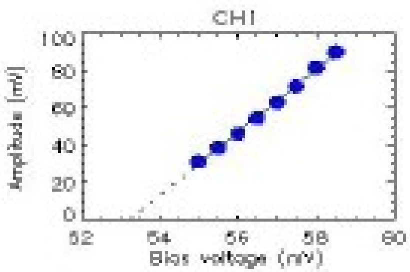
Gain vs over-voltage

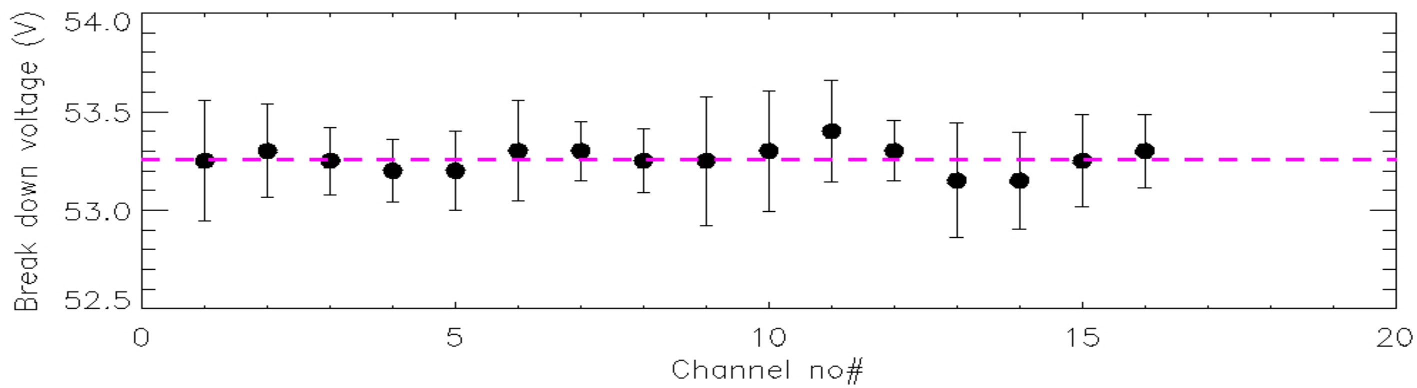


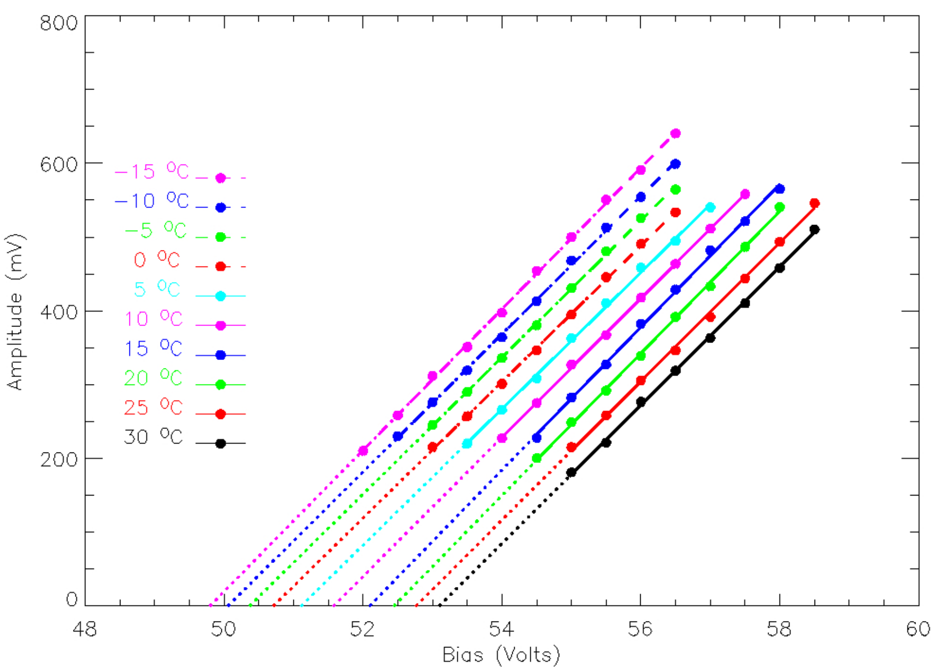
Timing jitter

G-APD Characterisation

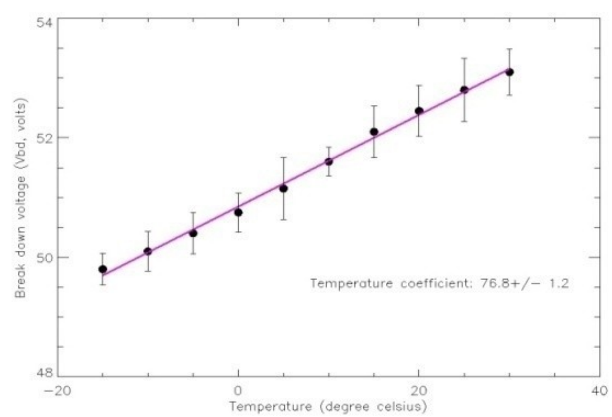
Breakdown voltage







Temperature dependence of breakdown voltage



Estimation of Expected Performance Parameters

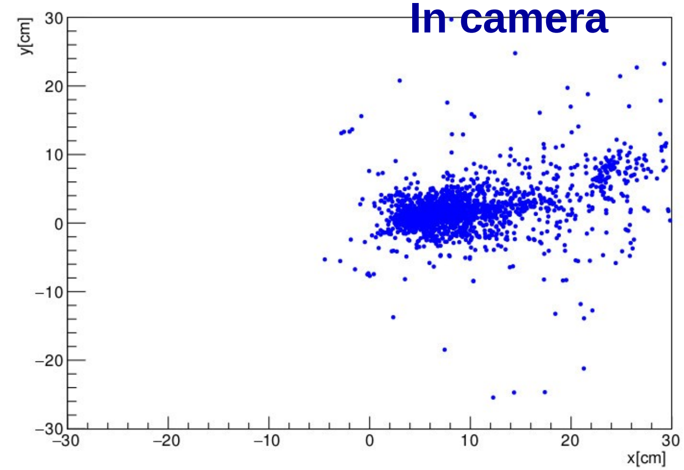
Simulations of extensive air showers initiated by gamma rays and cosmic rays Using CORSIKA package

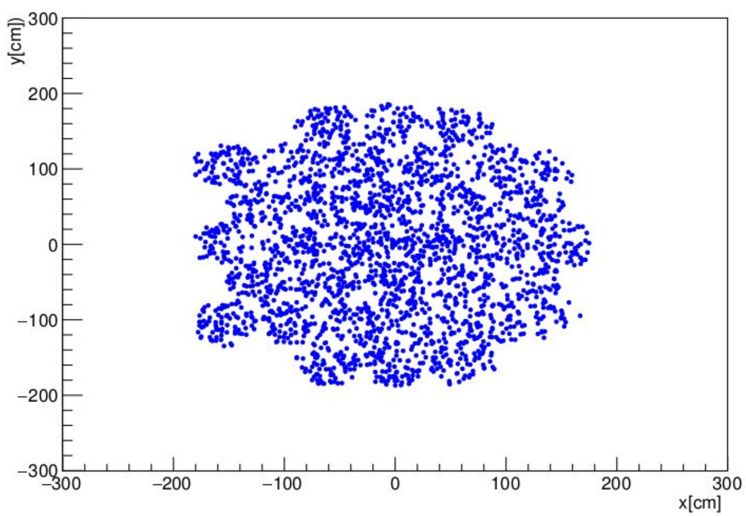
Inputs : **gamma ray and cosmic ray spectral shapes, shower direction, impact parameter range, geomagnetic field and altitude of observation level, telescope details, mirror reflectivity, G-APD photon detection efficiency etc**

Output : **Cherenkov photon distribution at observation level**

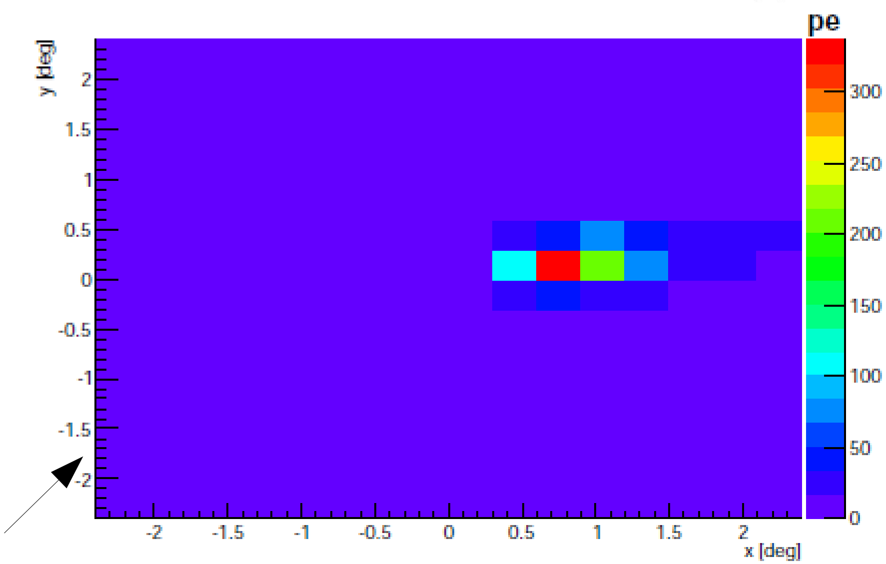
Ray tracing to telescope and camera plane

In camera





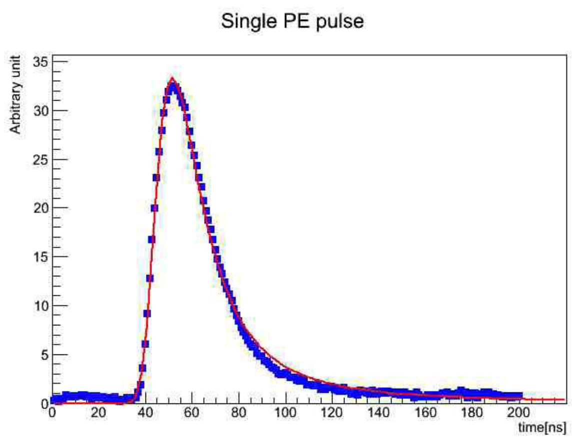
Photon distribution at light collector



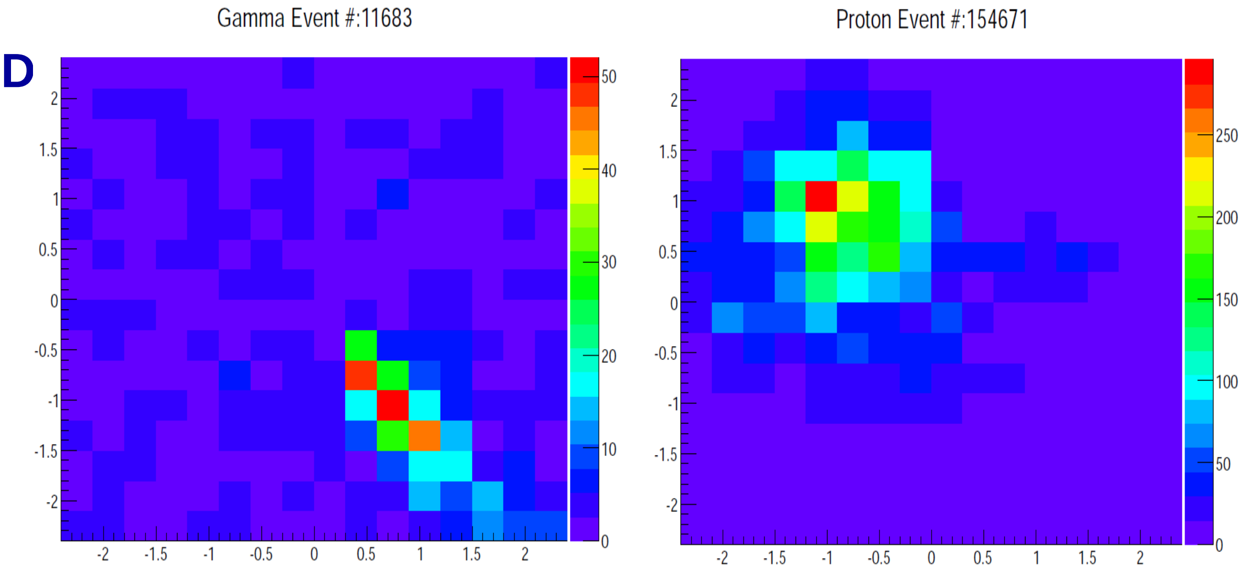
Camera pixels

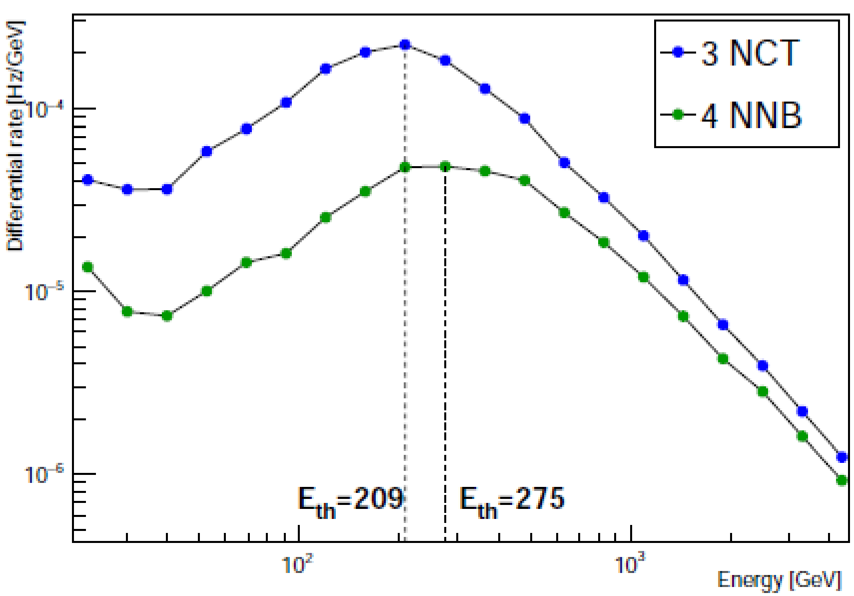
Estimation of Expected Performance Parameters

Detector simulations :
NSB photons
single pe pulse response of G-APD
Trigger criteria



Typical simulated images





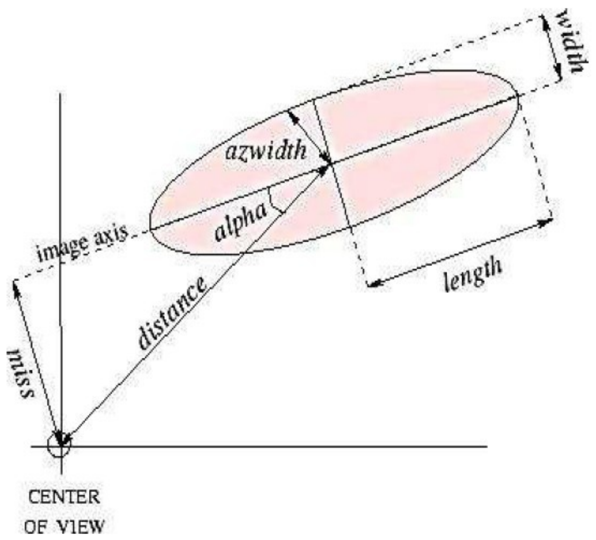
5 ns coincidence width

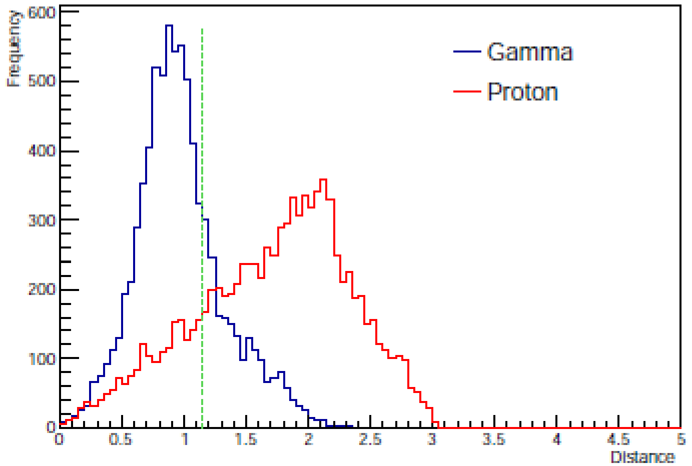
Trigger condition	Trigger rate (Hz)	Gamma ray rate (/min)	Energy threshold (GeV)
8 pe NCT	32	7.4	209
8 pe 4NNB	14.7	2.8	275

Estimation of Sensitivity

Sensitivity : Detection of gamma ray signal in presence of cosmic ray background

Gamma-hadron segregation based on Hillas parameters





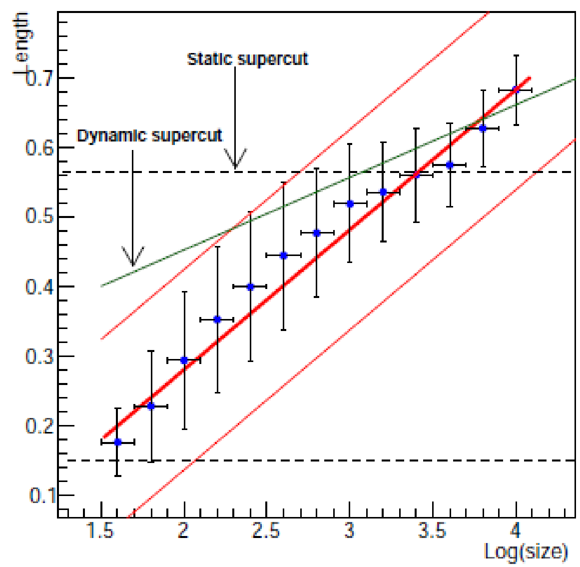
(c) Distance

Static supercuts : Optimization of Hillas parameters to get maximum quality factor

98.6% rejection for cosmic ray showers retaining 37.8% gamma rays

Dynamic supercuts : Further optimization considering energy dependence of parameters

99.0% rejection of cosmic ray showers retaining 39.5% gamma rays



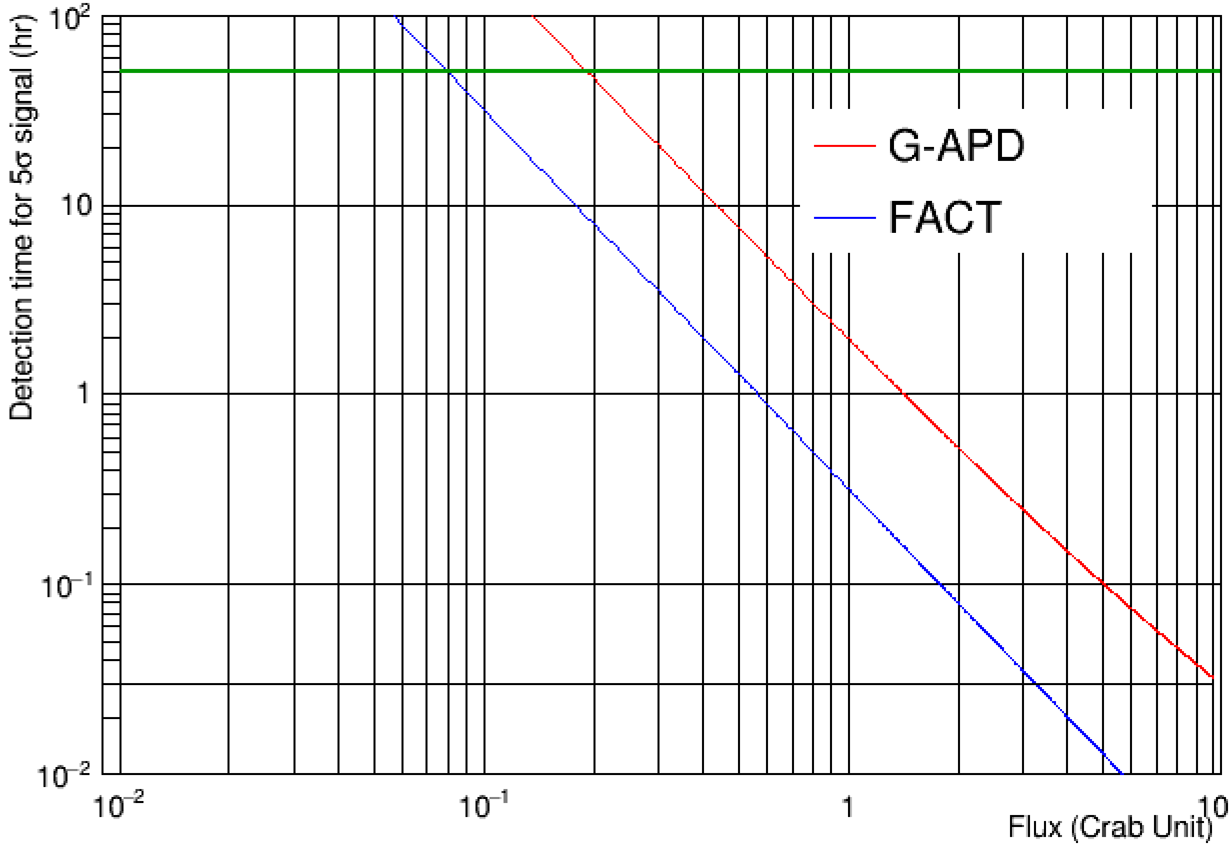
Estimation of Sensitivity

Sensitivity estimate : 20% Crab nebula flux in 50 hours

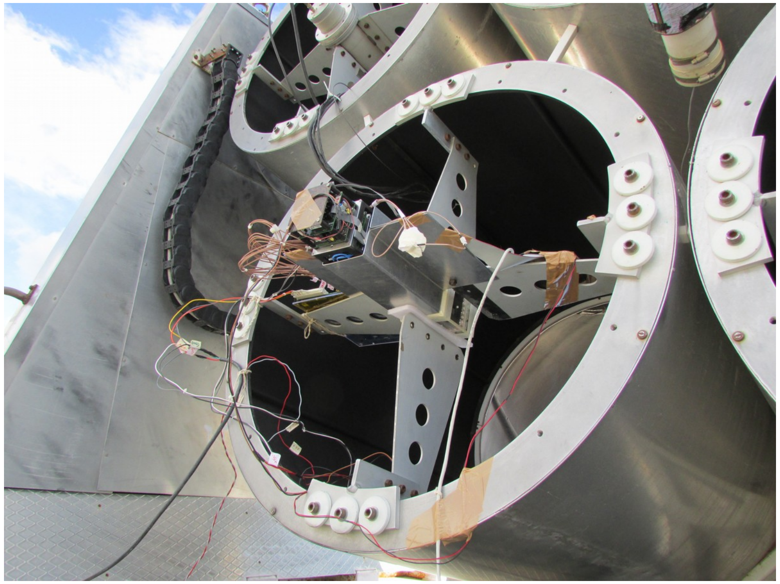
Based on 65% efficiency for light concentrators → 85%
NSB reduction with window not considered

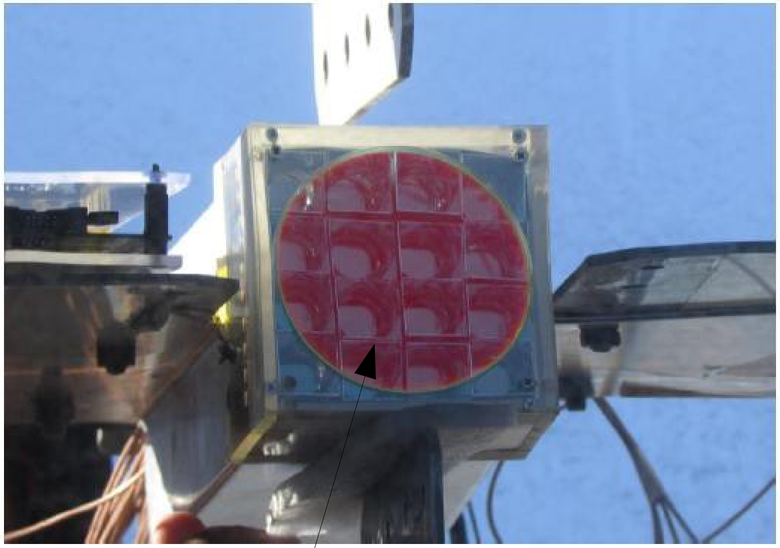
Simulations being revised

Sensitivity of FACT : 8% Crab nebula flux in 50 hours

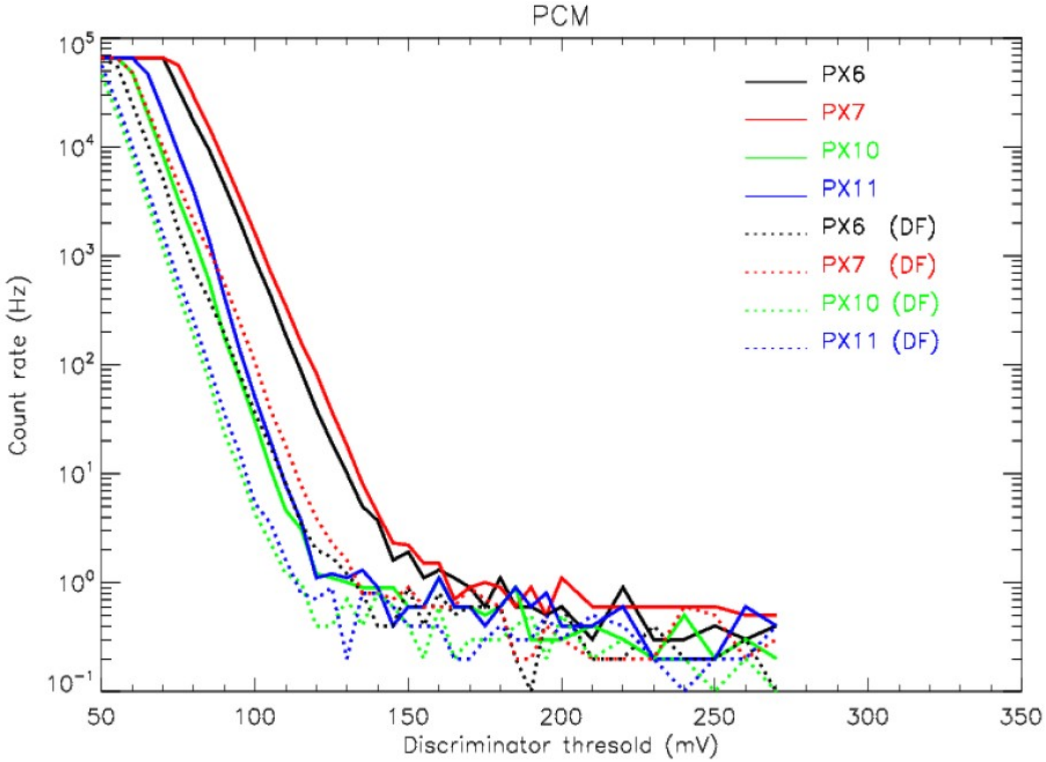


Tests at Hanle with 16-pixel module in October 2018

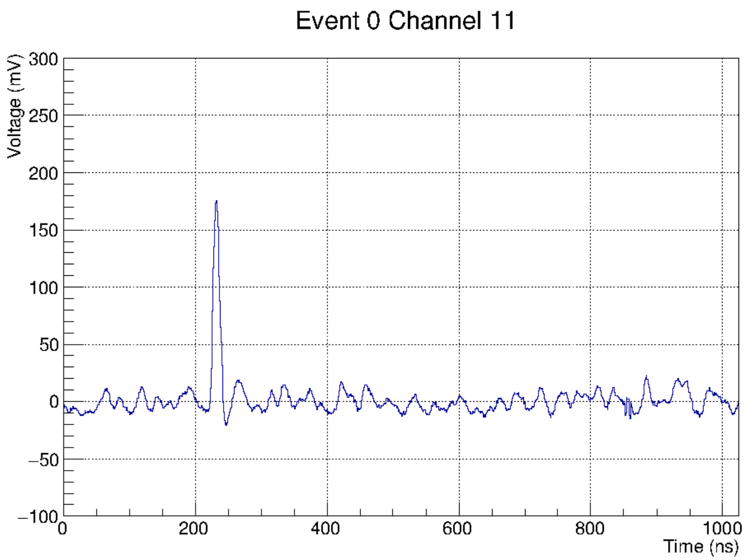


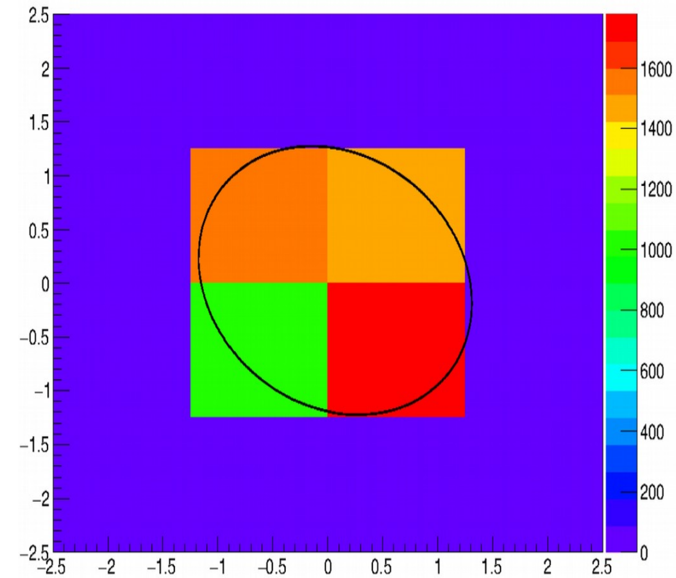


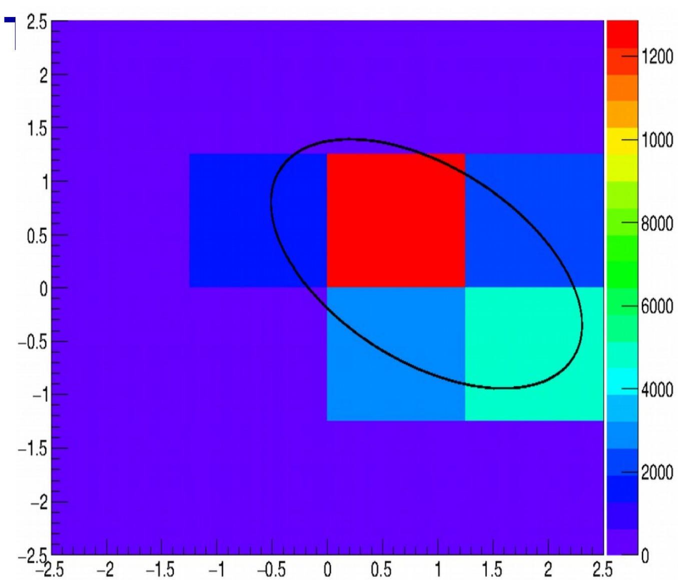
Dichroic plate

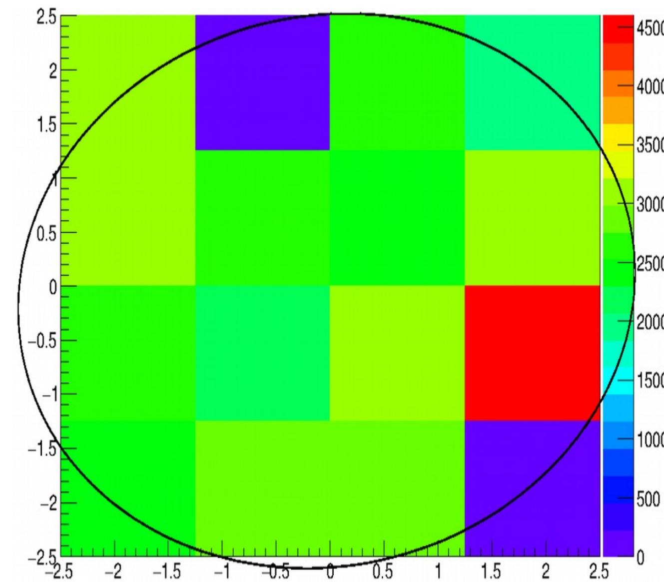


Tests at Hanle with 16-pixel module in October 2018









Status and Timeline

1. Tests with 4 modules at Mt. Abu October-December 2019

Status for 4+1 modules :

G-APD caharacterisation setup ready and characterisation carried out for 10 G-APDs, another 70 by August
Light concentrators : indent in process, by June
Camera housing : indent in process, by May
G-APD mount, Pre-amplifier, LV power supply, bias supply -> manufactured, assembly in progress
Digitizer, trigger modules : manufacturing + assembly by May end
Data concentrator and back-end crate : ready, tested and in use

End to end tests for 4 modules : July-August 2019

2. Production and testing of remaining 12 modules and spares, housing for entire camera etc : January - August 2020

3. Full camera tests at Mt. Abu : November - December 2020

4. Installation of telescope and camera at Hanle : May - August 2021

Comparison of Telescopes with G-APD based Cameras

	FACT	G-APD Telescope	SST-1M
Mirror area (m^2)	9.5	9.5	12.6
f/D	1.4	1.1	1.4
FoV	4.5	5 X 5	9
No. of pixels	1440	256	1296
Pixel size	0.11	0.3	0.24
Sensor size	3 mm X 3 mm	12.6 mm X 12.6mm	10.4 mm width hex
Light concentrator	Solid (PMMA)	Hollow	Hollow
Geometry	Hex entry sq. exit	Sq entry sq exit	Hex entry hex exit
Entry size	9.5 mm width	21.1 mm X 21.1 mm	23.2 mm width
Exit size	2.8 mm X 2.8 mm	12.4 mm X 12.4 mm	9.4 mm width
Length (mm)	19.9	23.2	36.7
Area concentration	10	2.9	6
Pre-amplifier design	Trans-impedence	Trans-impedence	Trans-impedence
Digitizer	DRS 4 with 2GSPS	DRS 4 with 1GSPS	FADC with 250 MSPS
Trigger condition	9 adjacent pixels	NCT/4NNB	Geometric pattern
Coinc. Window (ns)	12	10	
Trigger rate (Hz)	60	20-30	
Rate handling capability	> 230 Hz	1 kHz	32 kHz
Altitude (kms)	2.2	4.3	2.1
Energy threshold (GeV)	750	200-300	

Science Goals of the Telescope

Monitoring of known blazar class AGNs

Understanding variability on time scales of minutes to years

Coordinated observations with MACE and TACTIC

Operation in synergy with FACT and similar telescope coming up in Mexico to have continuous coverage of blazars

Multiwaveband campaigns with AstroSat, HCT, MIRO, ARIES etc

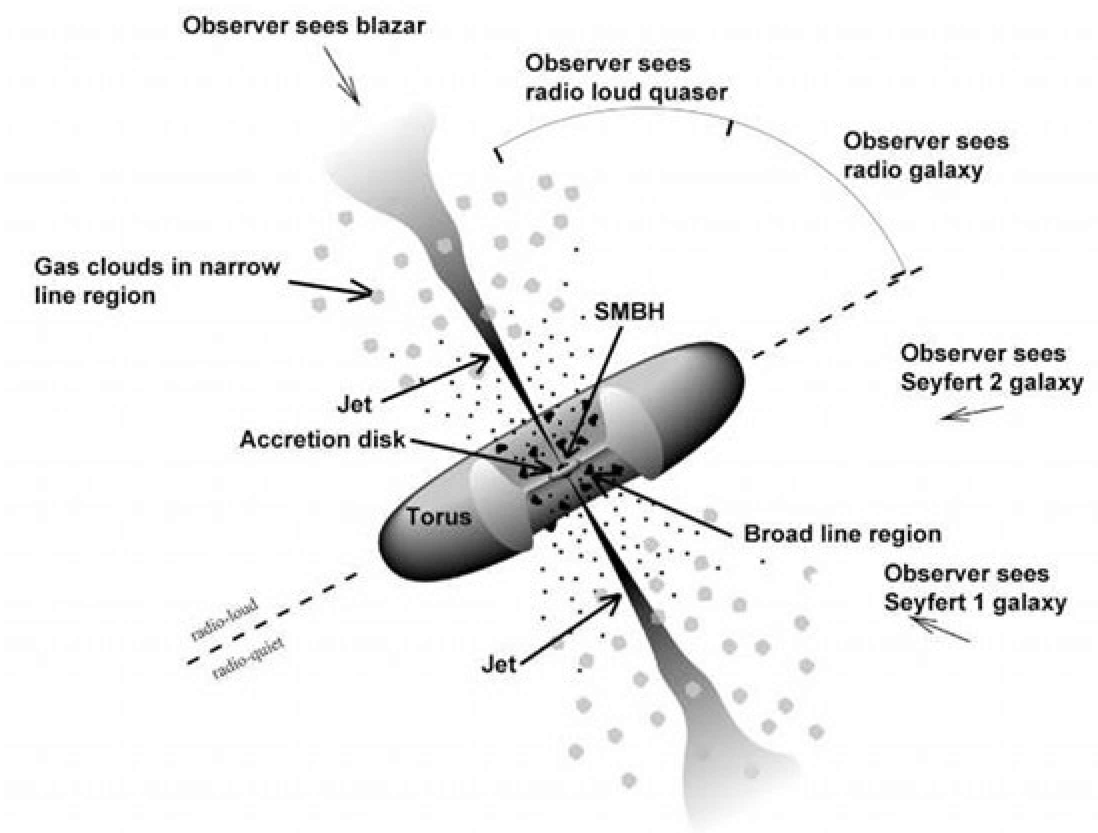
Future possibilities :

Similar telescope at Mt Abu

Adaptation of camera design for 10 m class telescope

Contribution towards G-APD based camera for SSTs of CTA

Active Galactic Nuclei



Blazars have jets directed towards us

Variability in all wavebands on various time scales ranging from minutes to years
Wide range of flux variation

Unanswered questions :

How jets are produced?
How they are collimated?
What are they made of?
How particles are accelerated in jets?

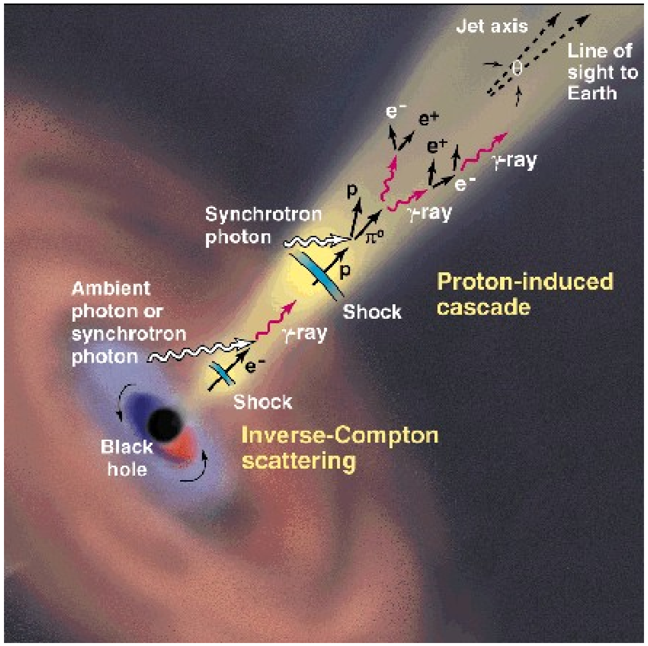
Multwaveband study of blazars

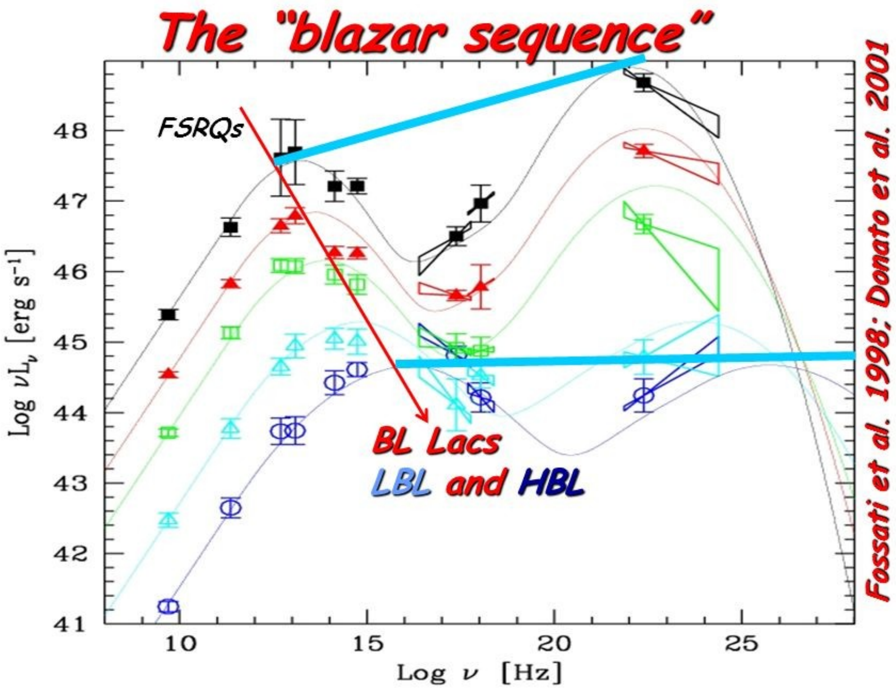
Light curves :
- **Correlation between light curves from various wavebands and lags**
- **Variation of variability amplitude with frequency**
- **Shortest time scale of variability**
- **Flux distributions in various wavebands**

Spectral information :
- **Spectral shape, index, break**

Blazars

Multiwaveband Spectral Energy Distribution (SED)





First peak : Synchrotron emission from electrons

Second peak : leptonic (Synchrotron Self-Compton/ External Compton) or hadronic (Proton synchrotron/ proton induced cascades)

Clues regarding emission processes, size/location of emission region, acceleration mechanism, cooling time scales, disk-jet connection etc.

Group Members

PI : V. R. Chitnis

Electronics Hardware : S. S. Upadhya, K. S. Gothe, S. K. Rao, S. K. Duhan, M. N. Saraf

Software : B. K. Nagesh, Mano Ranjan

Mechanical structure : P. Verma, A. P. Krishnan Kutty

PCB layout, wiring etc : N. K. Parmar, R. L. Deshmukh, V. A. Nikam

Laboratory tests, calibration setup, analysis : B. B. Singh , …

Simulations, data analysis software : S. R. Patel, A. Sarkar, A. Roy

Operations at Hanle : N. Dorji, P. Dorjey

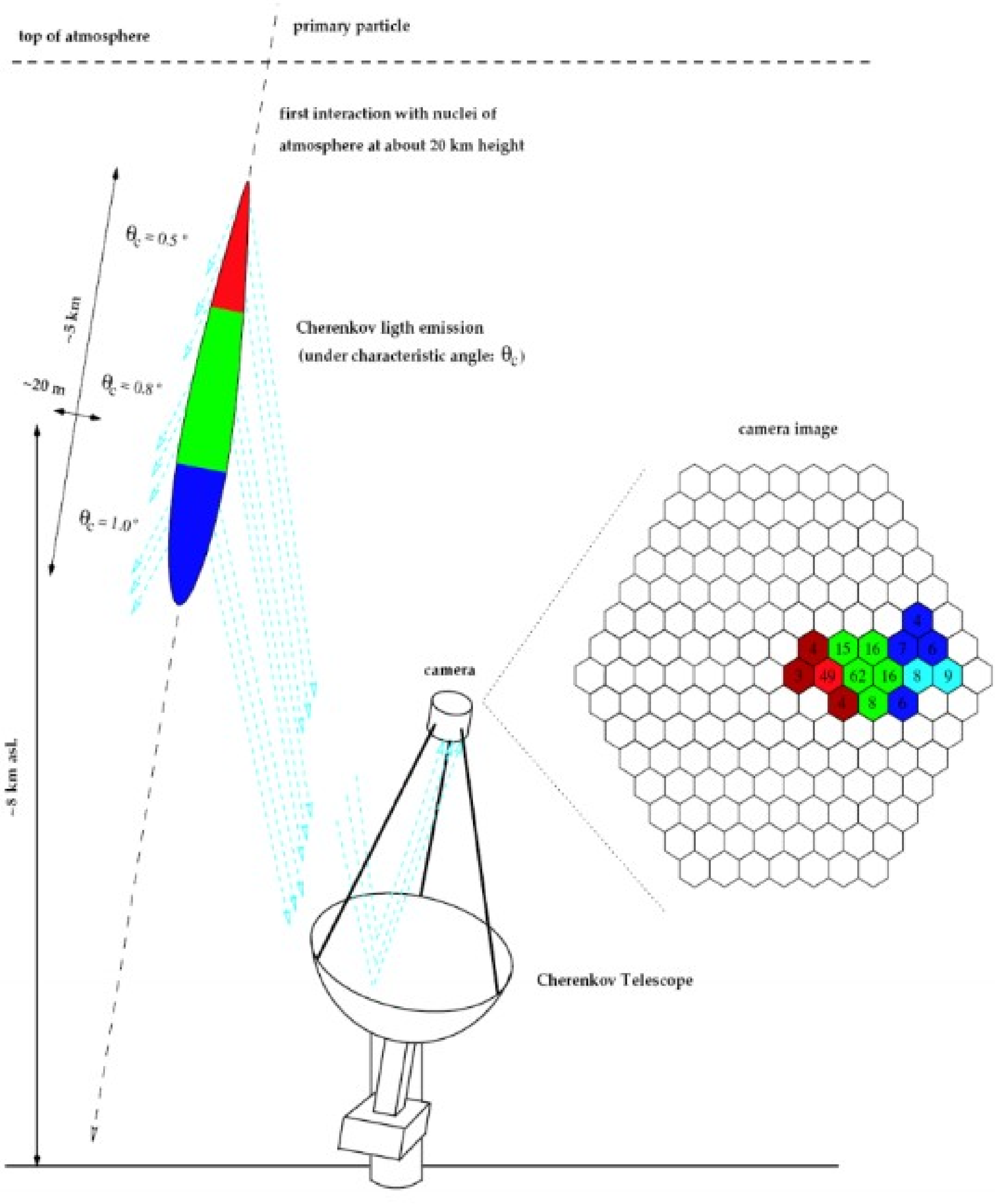
Thanks

Backup Slides

Cost Estimation

1. Cost Amplifier card x 4no…. 18400 (7000 reduction) x4
- Bias card x 2no ….. 50000 (HV80=45K) x2
- ………. 15000 (LT3482)x2
- Power supply card …. 3000
- GAPD card ………. 8000(2000 Assembly)
- ---
- Pixel Cluster Module 184600 ie 11538 per pixel
- --
2. Cluster Digitizer Module
- DDB ….. X 4 21000x4
- CDM ….. 5000
- -------------------------------
- Total……….. 89000 ie 5562/pixel
3. Other Modules
- CTM … 15000
- DCM ….. 20000
4. Power supply + crate .. 50000 + 250000
5. Total cost of DAQ Electronics excluding sensor ….. 47,12,300 or 35,92,600

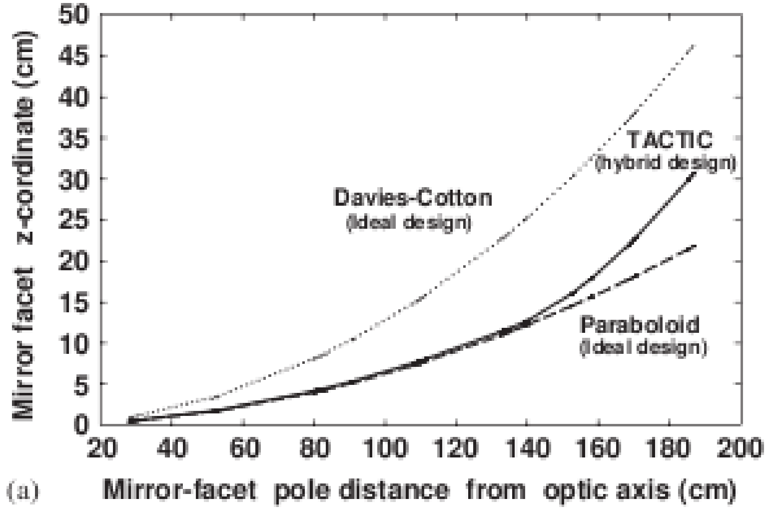
   Cost per pixel is 18400 (17000) or 14000(12600)



top of atmosphere
primary particle
first interaction with nuclei of
atmosphere at about 20 km height
θc ≈ 0.5°
~5 km
Cherenkov ligth emission
(under characteristic angle: θc)
~20 m
θc ≈ 0.8°
camera image
θc ≈ 1.0°
4
4 15 16 7 6
3 49 62 16 8 9
4 8 6
camera
~8 km asl.
Cherenkov Telescope

TACTIC Telescope

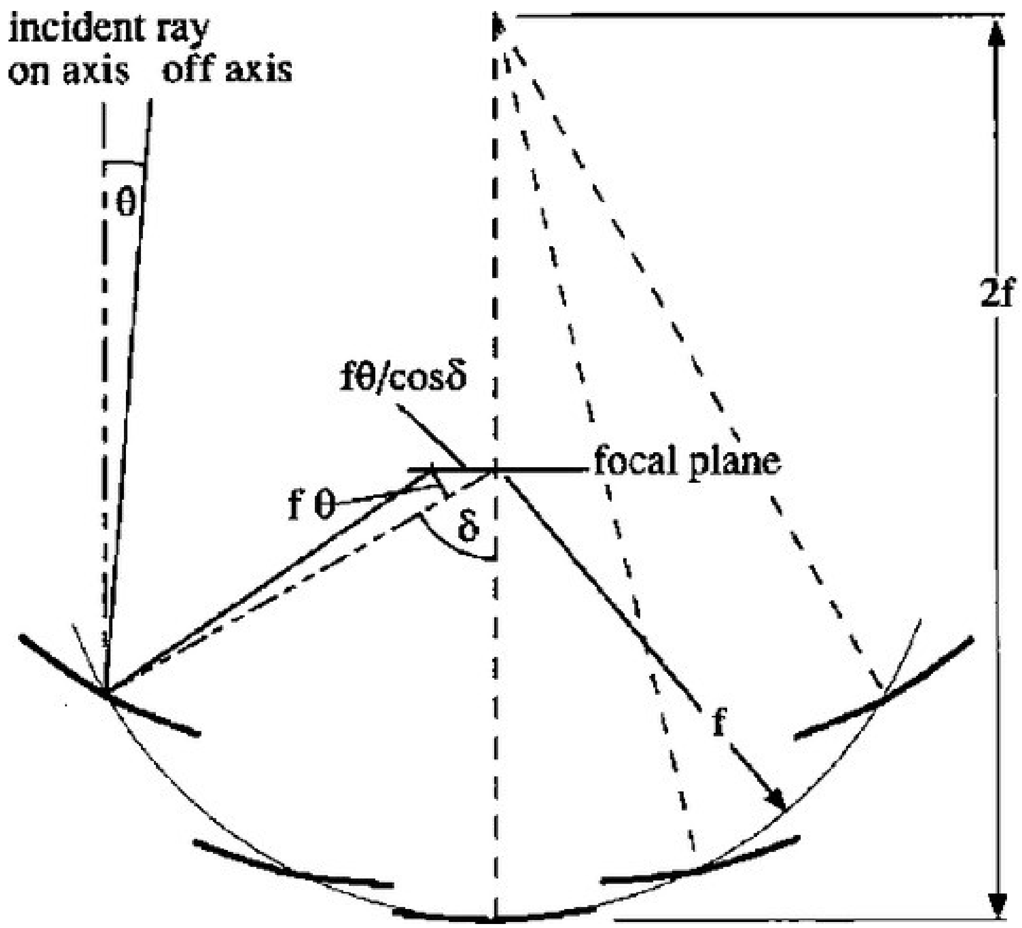
Hybrid design



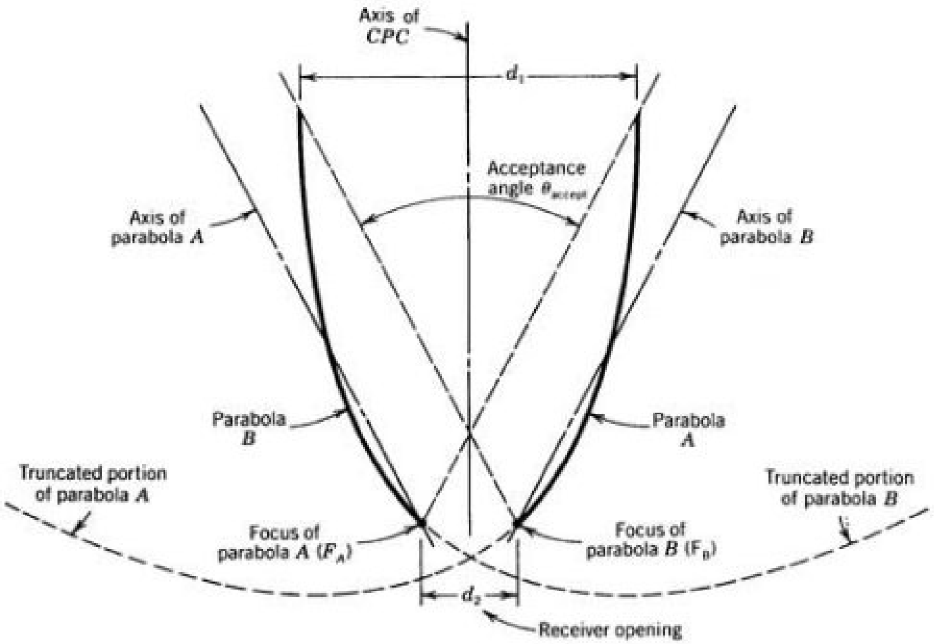
Davies-Cotton : identical mirror facets
Light from different parts of the reflector
Reach focal plan at different times
→ Longer integration time

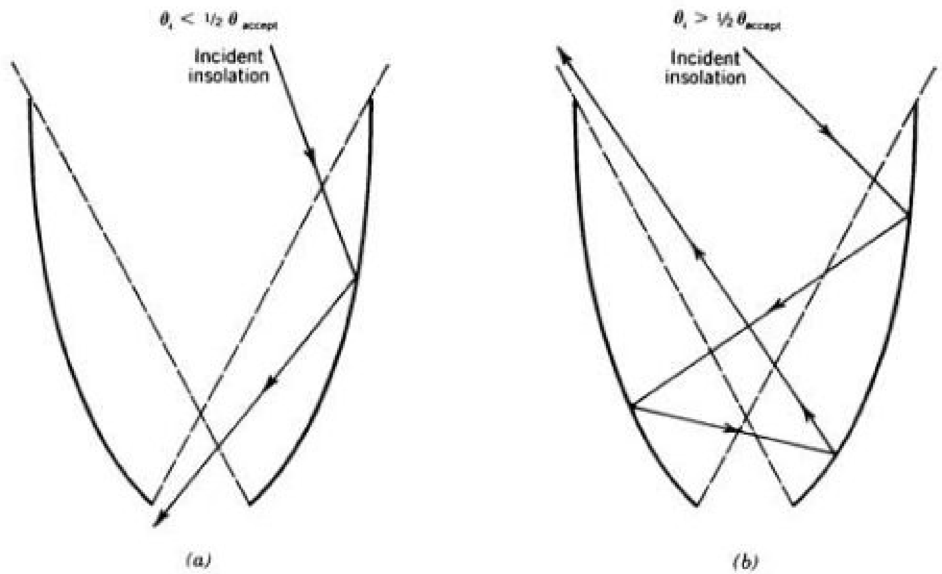
Paraboloid : facets with different radii of
Curvature to fit paraboloid design
Shorter integration time

Davies-Cotton design



Light Concentrator Principle





G-APD Working Principle:

When avalanche is triggered : C_D start discharging through R_s with time constant $\tau_D = C_D \times R_s$ $(500 \times 10^{-15} \times 100 = 50ps)$

The current through quenching resistor (I_{max})

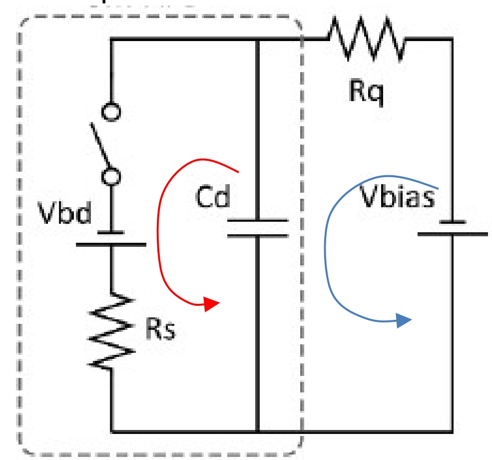
The voltage drop across R_Q reduces diode voltage below the V_{bd} and quenching the avalanche.

The charging of C_D starts with time constant $\tau_Q = C_D \times R_Q$ give the slow exponential decay of the GAPD current/signal and determine the recovery time (20ns to 300ns) of the microcell.

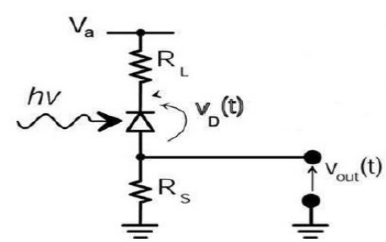
The GAPD gain

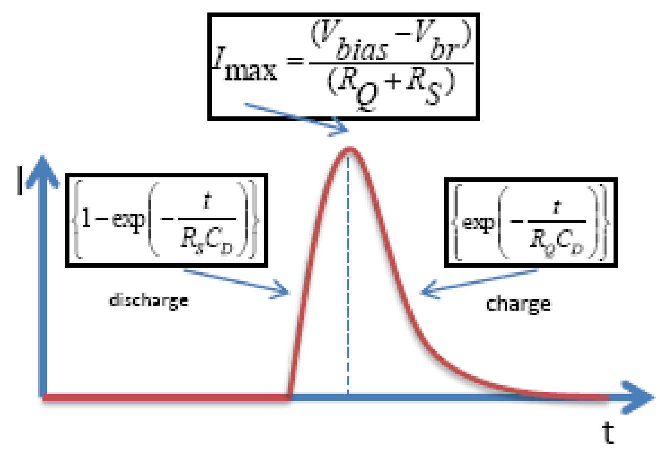
$$G = \frac{Q(\text{single avalanche})}{q_e} = \frac{I_{max} * \tau_Q}{q_e} = \frac{C_D * (V_{bias} - V_{br})}{q_e}$$

The equivalent circuit of GAPD



Simple biasing circuit of GAPD





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Sensitivity Comparison

Telescope	**Cosmic ray rejection**	**Gamma ray retention**	**Sensitivity in Crab units in 50 hours**	**Time to detect Crab at 5σ**	**Energy threshold (GeV)**
G-APD telescope	99%	39.5%	20%	2 hours	250
FACT			8%	20 minutes	750
TACTIC (before upgrade)	99.07%	50%		25 hours	1200
TACTIC (after upgrade)				13 hours	800
HESS	99.9%	50%		~ 2 minutes	~ 100
MACE			2.7%	2 minutes	38

Lightcurve :

Correlations between various wavebands and lags -> information about locations of emission regions, some clue about emission mechanisms for various regions, SSC vs EC/hadronic models in case of orphan flares

Variability amplitude variation with frequency -> emission mechanisms for various regions

Shortest timescale of variability -> location and size of emission region, possible acceleration mechanism

Flux distribution -> lognormality indicates multiplicative process and could be imprint of accretion disk on jet indicating disk-jet connection

Long term variability → emission regions, moving blobs/socks in helical jets, change in Viewing angle

QPO -> helical structure of the jet, binary SMBH, last stable orbit of the black hole, Oscillation modes of accretion disk

Spectral shape and index :

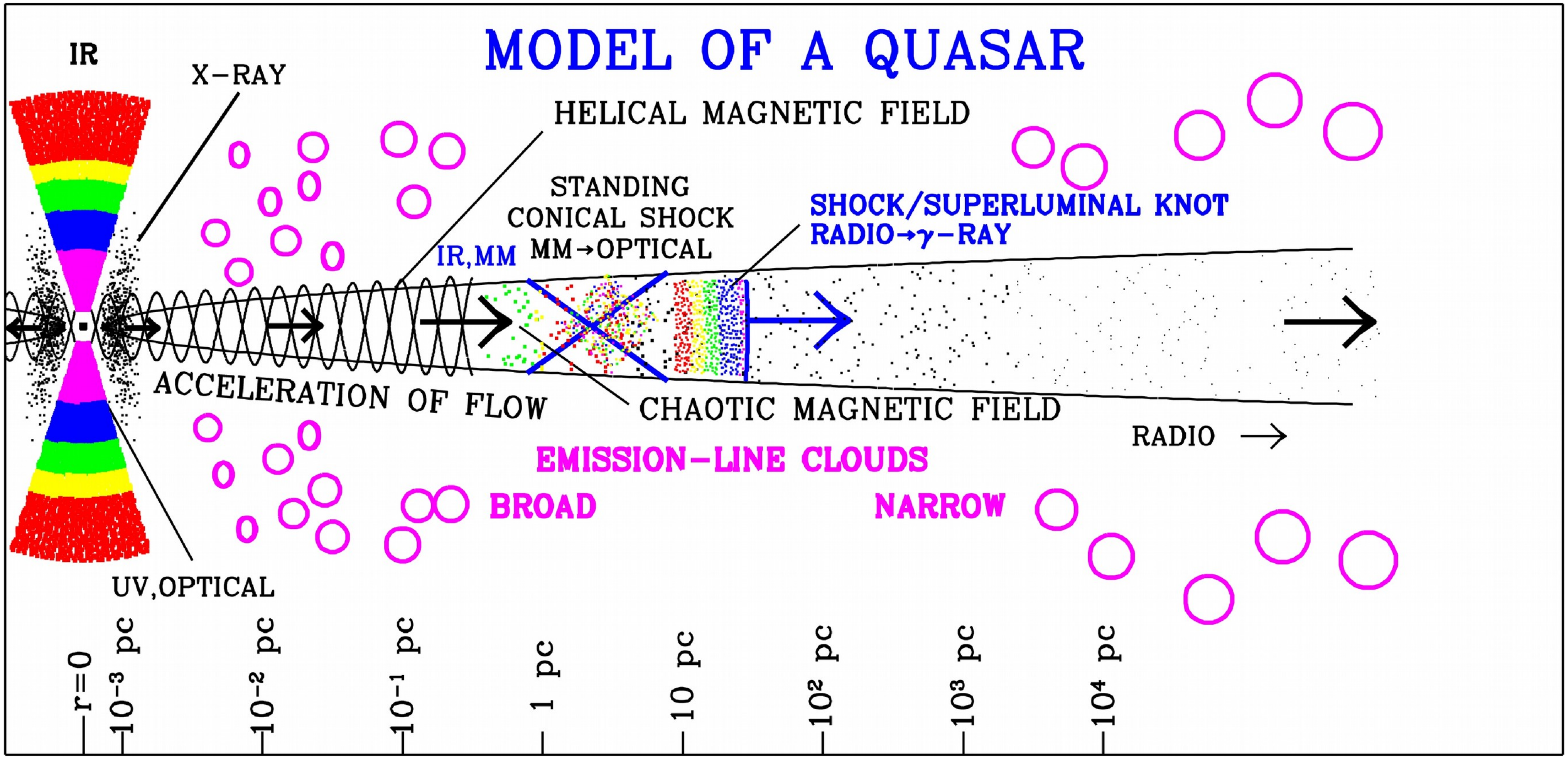
Photon spectrum harder than 1.5 -> indicates something other than Fermi first order mechanism

Spectral break -> cooling time scale

SED modeling :

Whether it can be fitted with a single zone SSC or multiple emission regions needed, whether hadronic model required, whether there is EC component

Acceleration Mechanisms



Fermi first order (diffusive shock acceleration)
Fermi second order (stochastic acceleration)
Relativistic magnetic reconnection