The Terzina instrument onboard the NUSES satellite

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Scuola Universitaria Superiore

INFN LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

(on behalf of the NUSES collaboration)

ASAPP 2023 - Advances in Space AstroParticle Physics
19-23 June 2023, Perugia, Italy

The NUSES mission

A space mission conceived as a pathfinder for new observation methods and technologies in the study of high and low energy radiations enabling new sensors, tools and methodologies. The NUSES satellite hosts two payloads.

- ✓ **Zirè** - Monitor of the variations of the flux of protons and electrons (E<250 MeV) in the ionosphere and magnetosphere possibly correlated with seismic activity. Pathfinder of future missions to measure MeV gamma rays from stable and transient astrophysical sources. (Talk by I. De Mitri, R. Nicolaidis, Poster by R. Pillera).

- ✓ **Terzina** - Path-finder of future missions devoted to the detection of high energy (E>1 PeV) astrophysical neutrinos and cosmic rays through space-based detection of the atmospheric Cherenkov emission.

- ✓ The NUSES mission was approved by the Italian Space Agency (ASI), that funded launch and ground segment of the mission (launch expected by the 2nd half of 2025).

The NUSES mission is a joint project of Gran Sasso Science Institute (GSSI) and Thales Alenia Space Italy (TAS-I), funded by the Italian Government and the Italian Minister for economic development.

The NUSES Collaboration

60+ members of the scientific collaboration from GSSI (PI Institution), INFN, several Universities in Italy, University of Geneva (CH), University of Chicago (USA) and the Italian Space Agency:

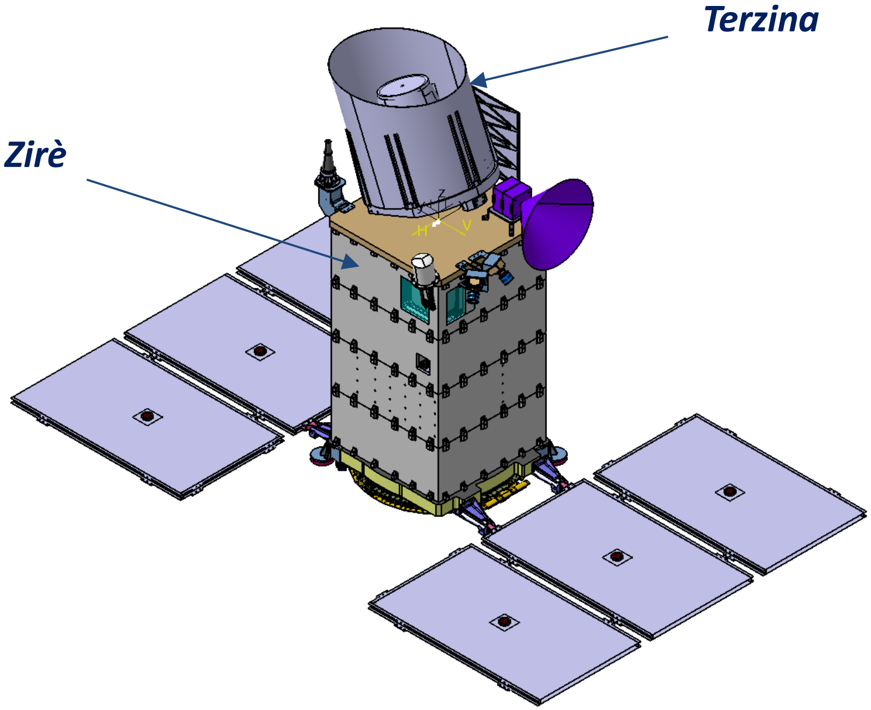
GRAN SASSO SCIENCE INSTITUTE — SCHOOL OF ADVANCED STUDIES — Scuola Universitaria Superiore | INFN Istituto Nazionale di Fisica Nucleare | UNIVERSITÉ DE GENÈVE | THE UNIVERSITY OF CHICAGO | ASI Agenzia Spaziale Italiana

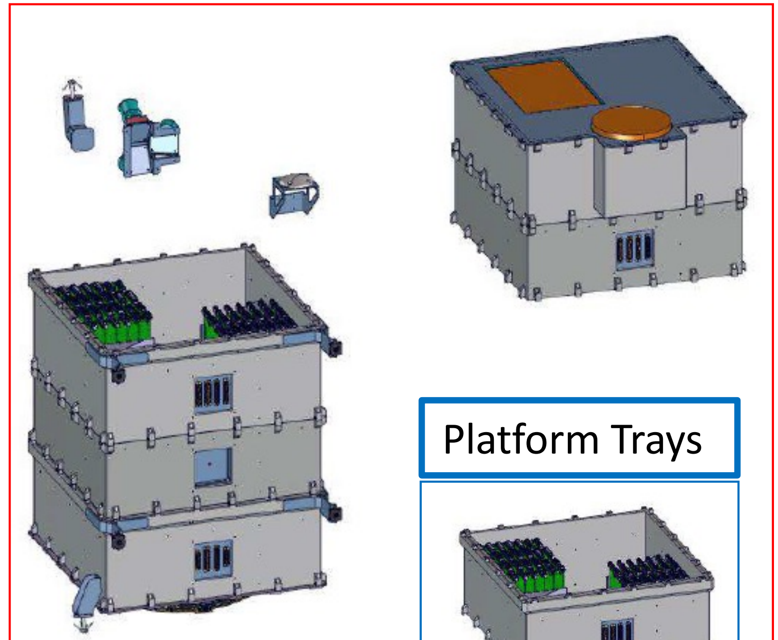
Current list of groups:
- Gran Sasso Science Institute
- INFN – Laboratori Nazionali del Gran Sasso
- L'Aquila University
- Roma "Tor Vergata" University and INFN-Roma2
- Torino University and INFN Torino
- Trento University and INFN-TIFPA
- Bari University and INFN Bari
- Padova University and INFN Padova
- Napoli "Federico II" University and INFN Napoli
- Salento Unviersity and INFN Lecce
- Geneva University (CH)
- University of Chicago (USA)
- Italian Space Agency (Science and Research Di

Industrial partners:

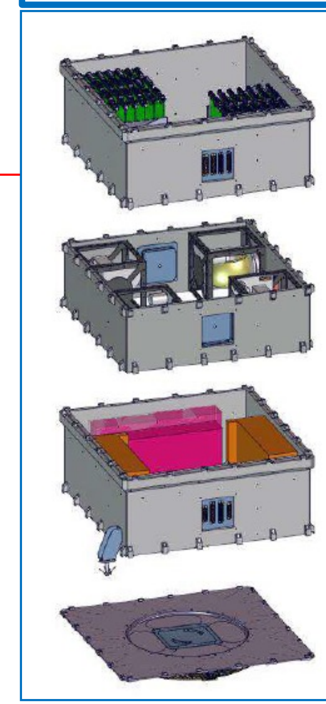
ThalesAlenia Space (a Thales / Leonardo company) | FONDAZIONE BRUNO KESSLER — FUTURE BUILT ON KNOWLEDGE | OFFICINA STELLARE — OUR WORLD, YOUR SPACE

Satellite Platform

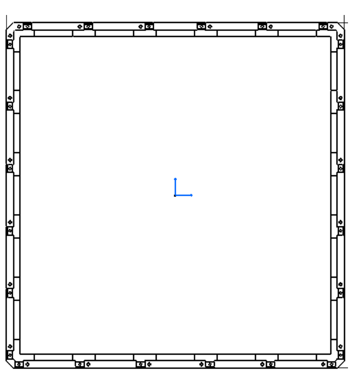


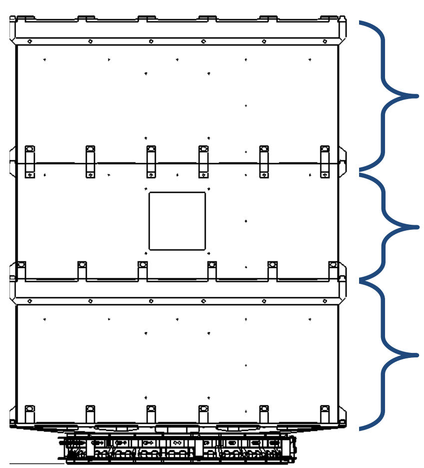


Platform Trays

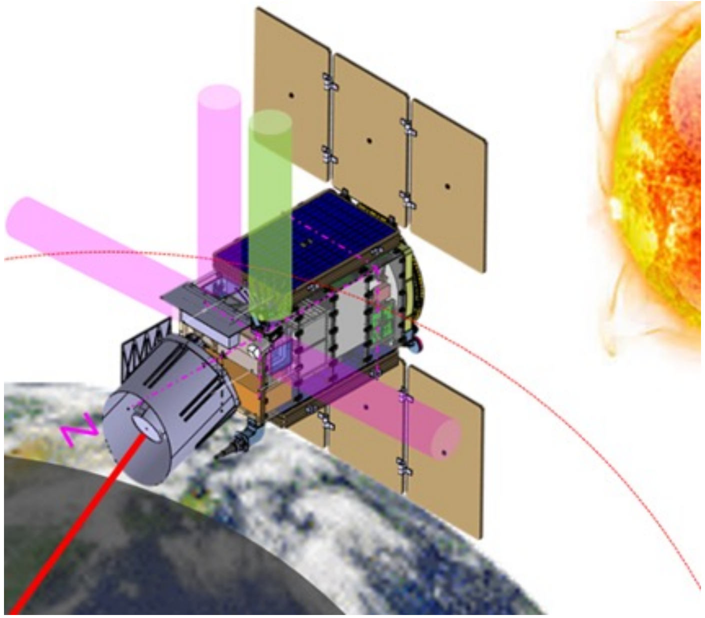


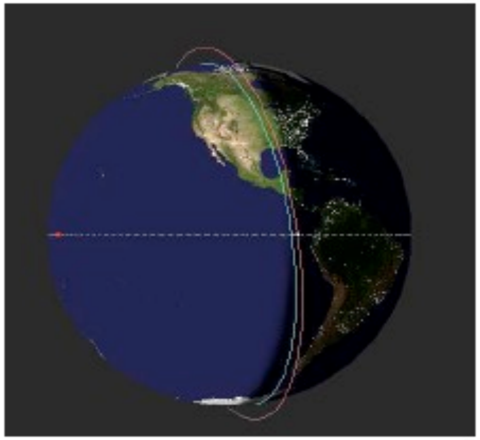
NIMBUS (**N**ew **I**talian **M**icro **BUS**)
is a new Platform concept which foresees a modular approach relying on standard trays.



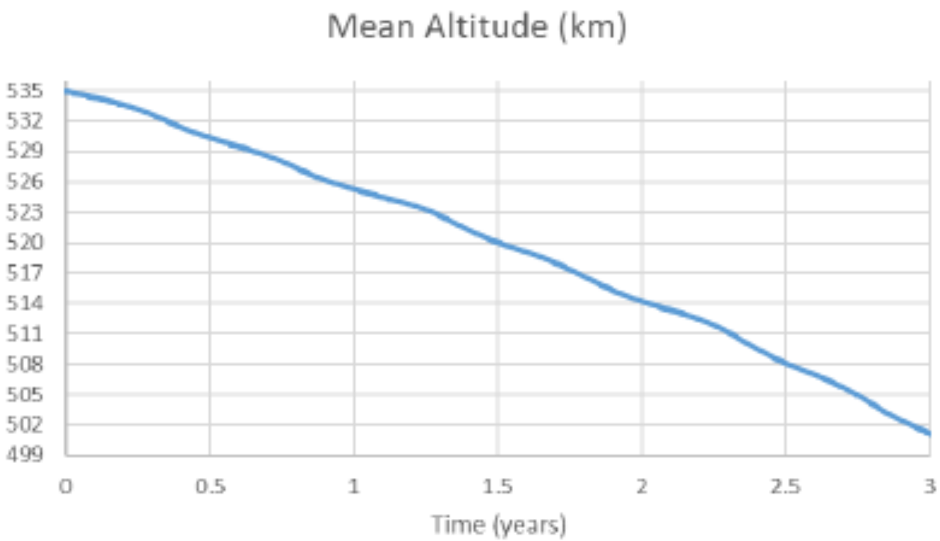


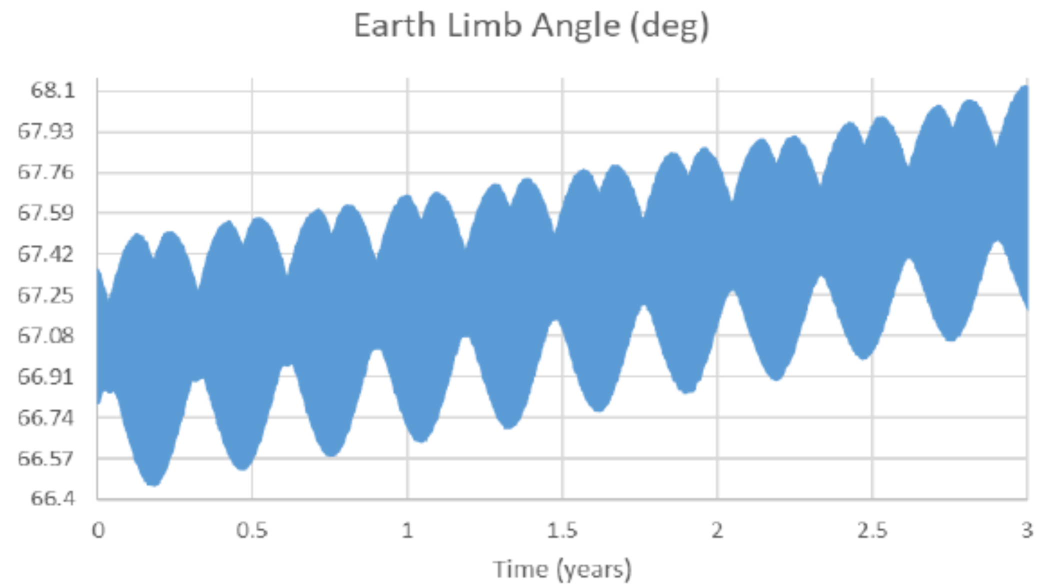
Satellite Orbit





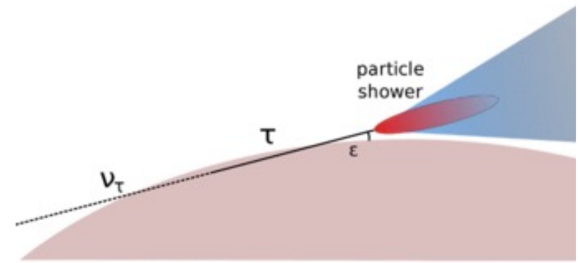
- Low Earth Orbit (LEO) with high inclination, sun-synchronous orbit on the day-night border (BoL altitude 535 Km, inclination = 97.8°, LTAN = 18:00);



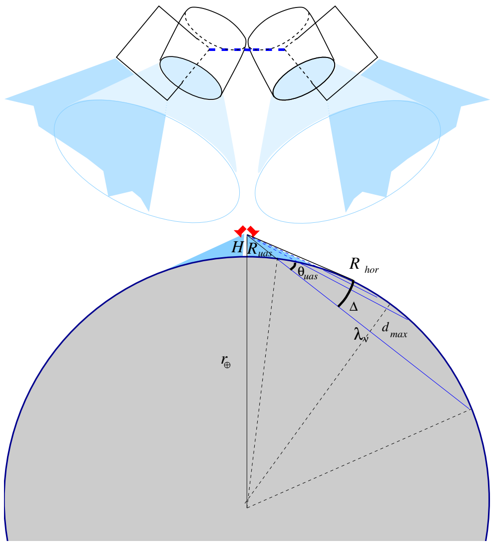


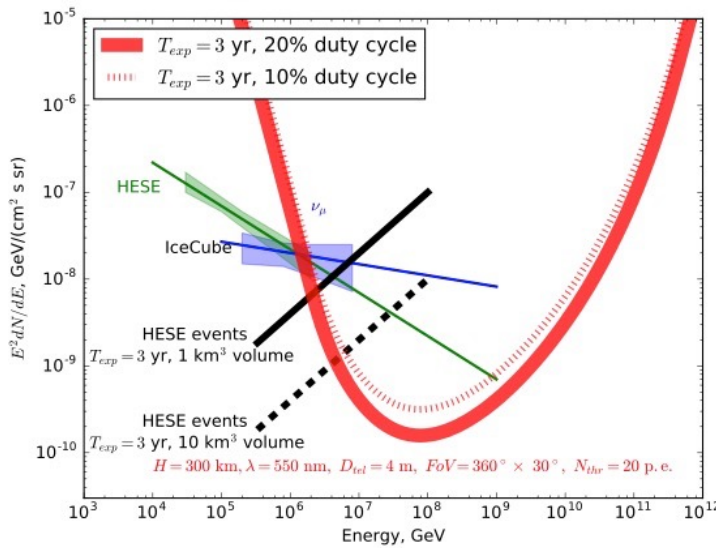
- Orbit optimization for Cherenkov photons detection
- Ballistic mission (no propulsion for orbital control)

Astrophysical neutrinos and HE CR



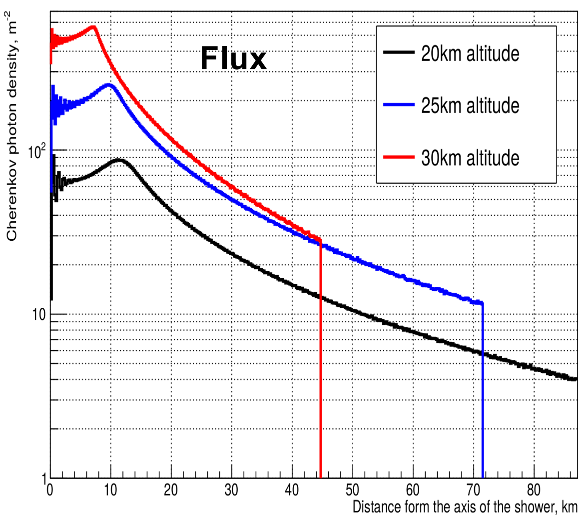
A. Neronov et al. 2017

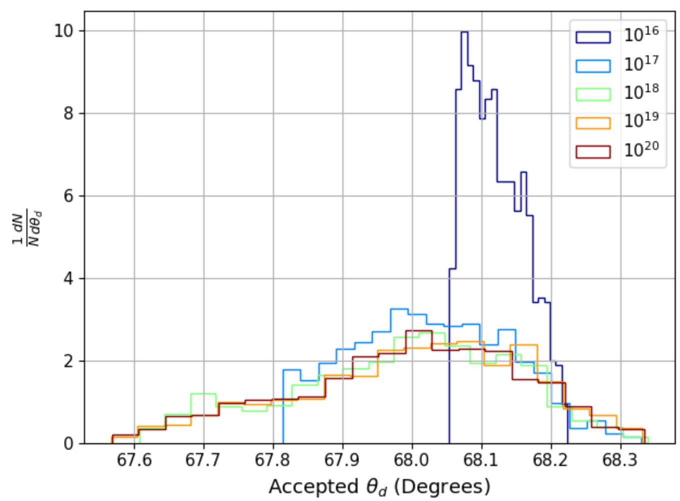


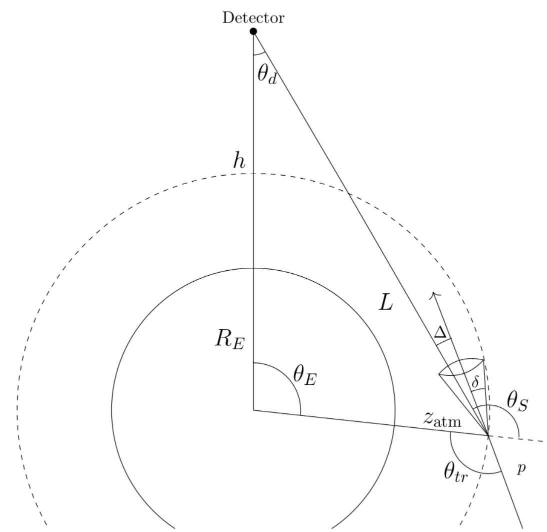


- ✓ The observation of astrophysical neutrinos at energies > few PeV can be achieved only from space.
- ✓ High energy CR (E>1 PeV) can be efficiently observed through EAS Cherenkov emission.

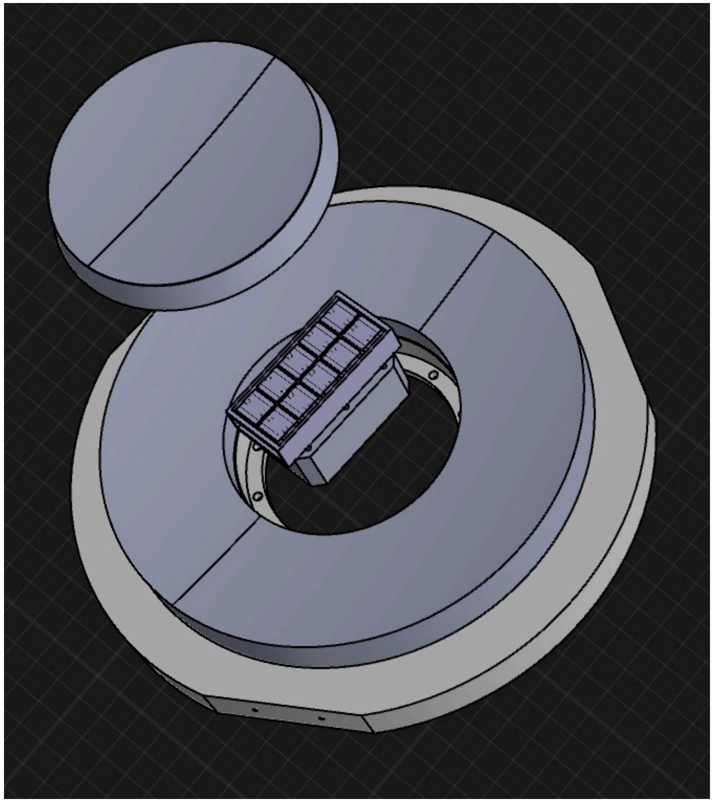
A. Cummings et al. 2021







Terzina telescope



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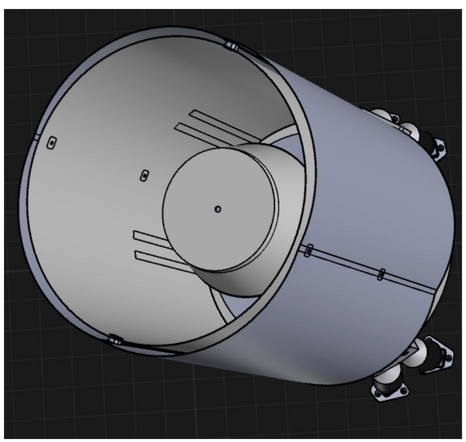
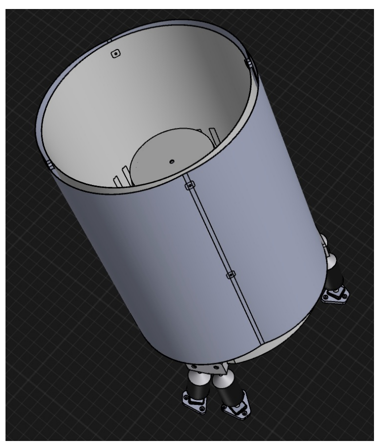
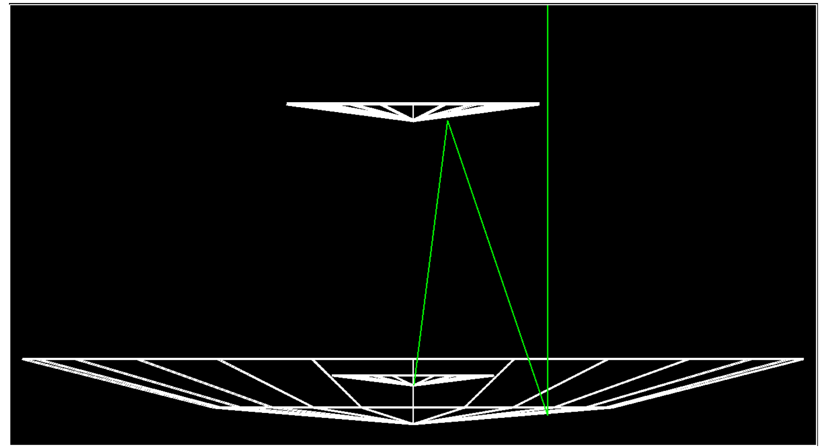


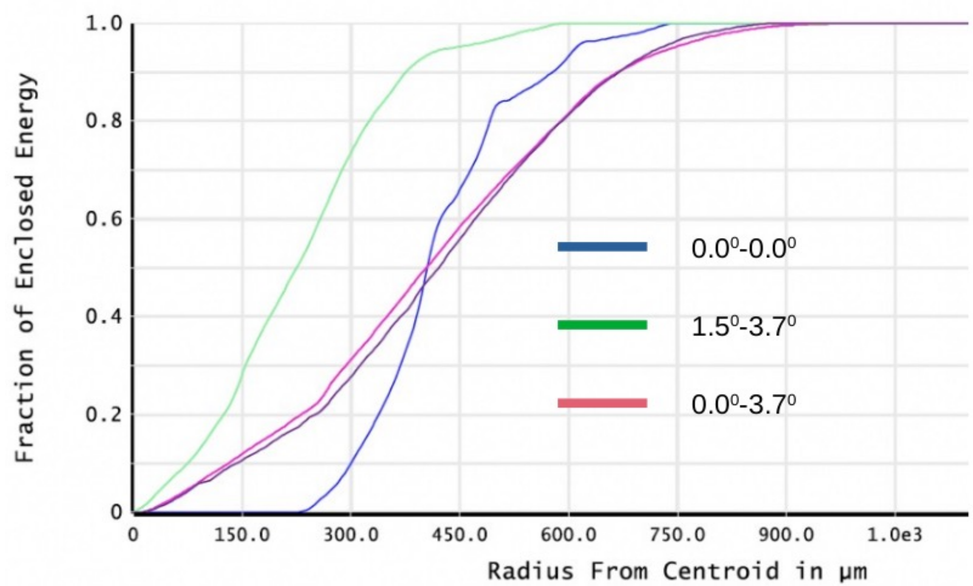


Terzina total weight ~35 kg



- ✓ Equivalent focal length 925 mm
- ✓ Field of View (FoV) : 7.2^o
- ✓ Point spread function (PSF) : <1.0 mm
- ✓ Effective area of the telescope : 0.1 m^2
- ✓ M1 paraboloid, M2 hyperbole

Point spread function for different inclination angles



Full simulation pipeline

Track fast sim → Fast simulation of the tracks to choose potentially interesting events which can be detected.

~10^{13} simulated events

EASCherSim → MC simulation of the Cherenkov emission by HE CR and photon propagation to the telescope

~10^{5} simulated events

Geant4 → MC simulation of the photon propagation in the Telescope.

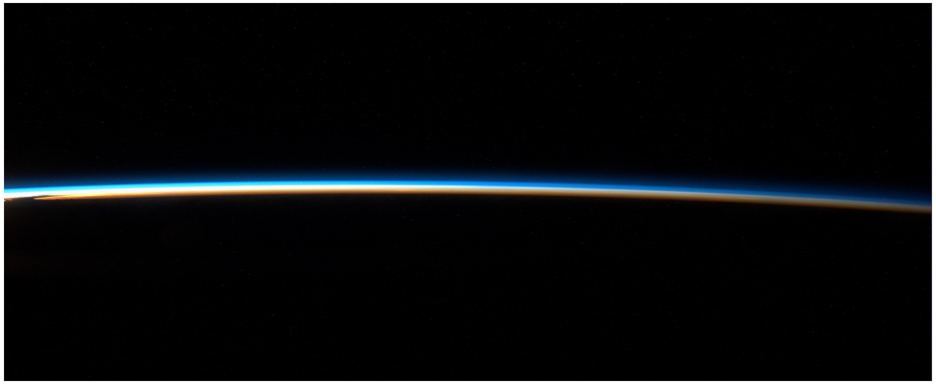
~10^{8} simulated events

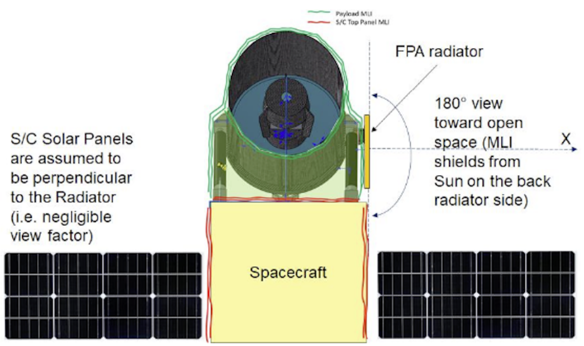
SiPM response → Simulating the SiPM response includes cross-talk, after-pulse, PDE, preamplifier bandwidth

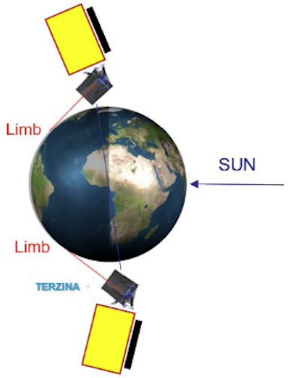
~10^{8} simulated events

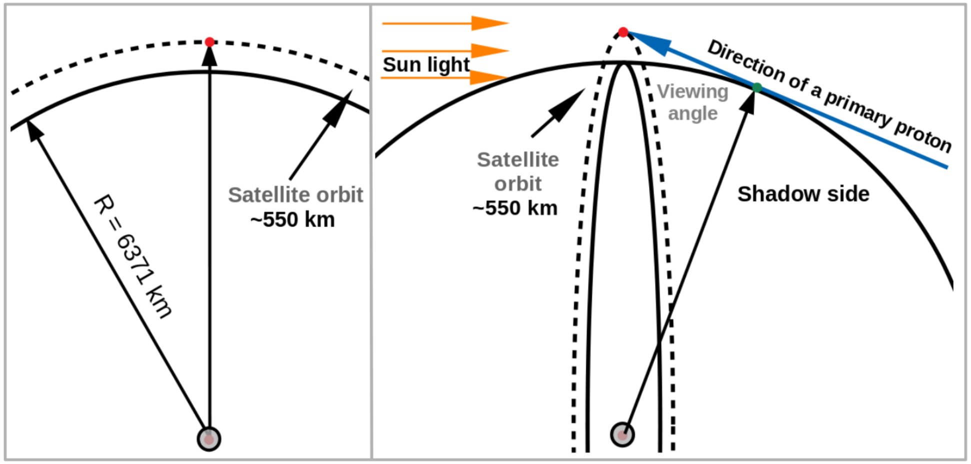
The Cherenkov signal on the telescope

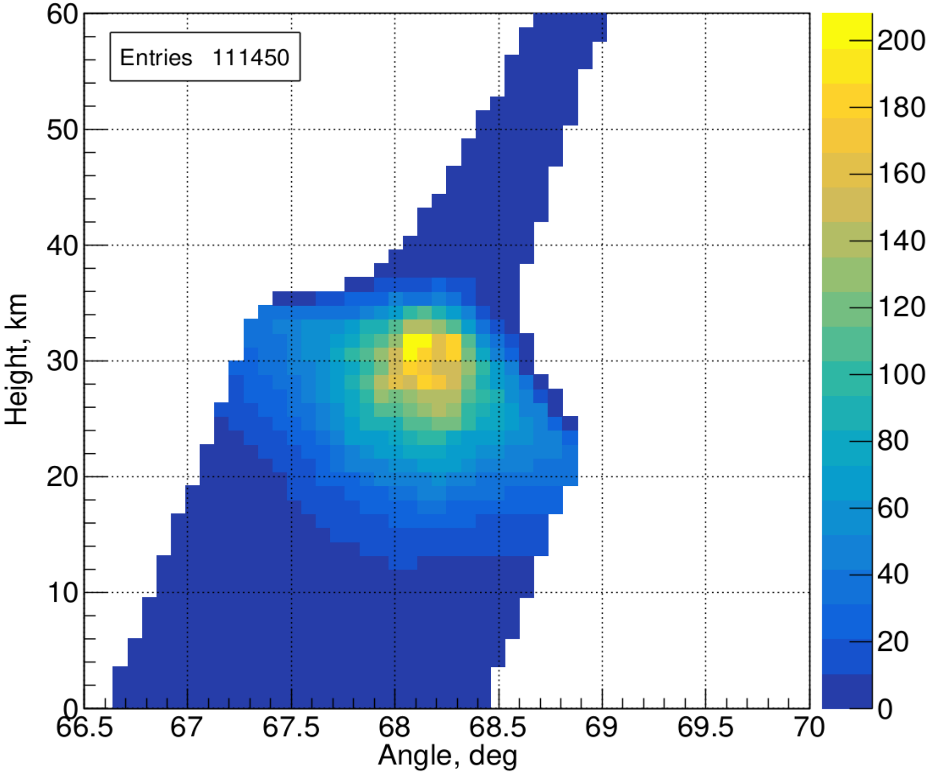
- Looking at the atmosphere limb (just above) for CR detection and (just below) for neutrinos detection.
- Tiny layer of the atmosphere shines in Cherenkov.
- Most contributing layers of the atmosphere around altitudes 20 - 40 km



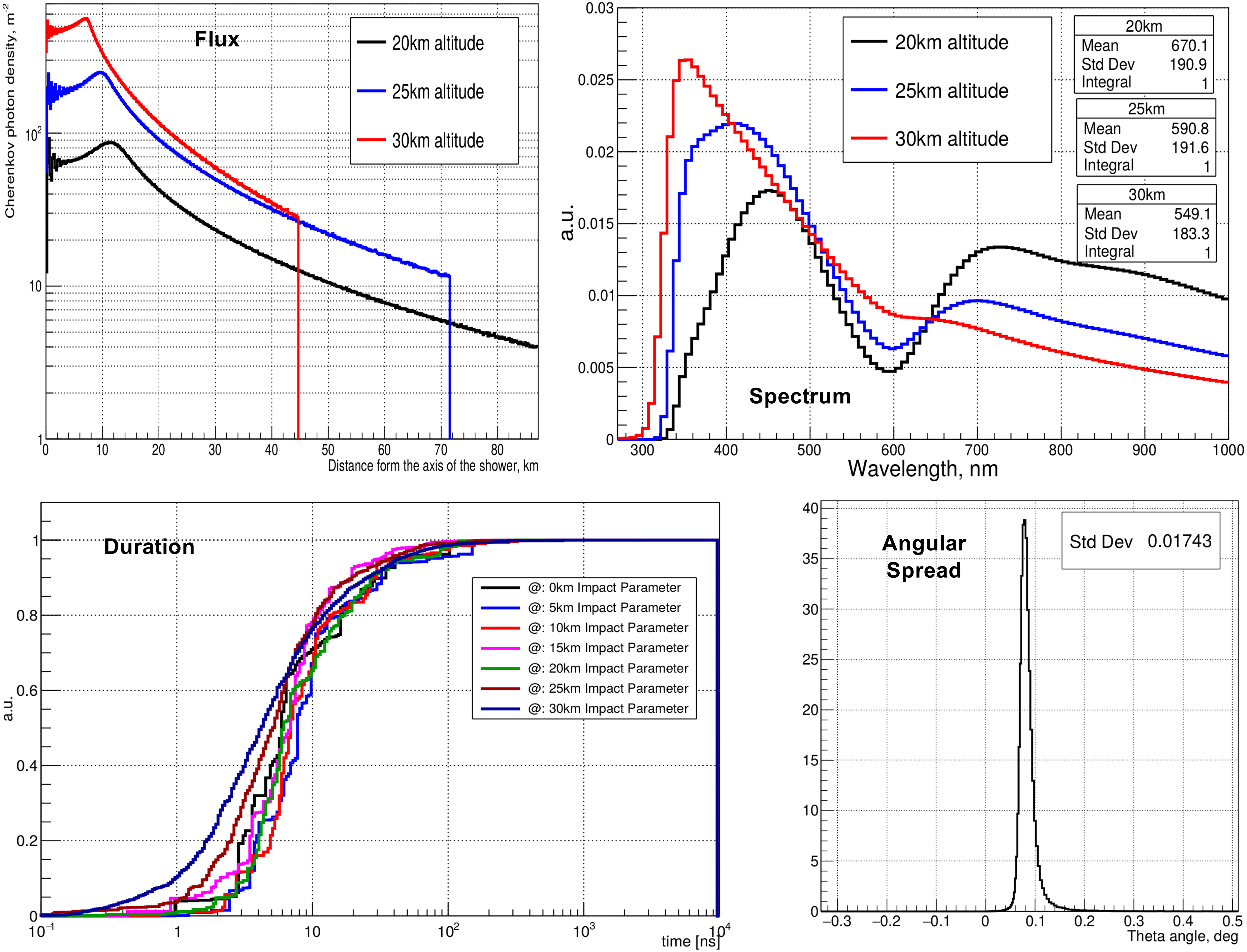








EAS-Cher-sim https://pypi.org/project/easchersim/1.1/



EAS-Cher-sim https://pypi.org/project/easchersim/1.1/

Telescope focal plane

SiPM arrays: **8 x 8 channels**

Pixel: **3 x 3 mm^2**

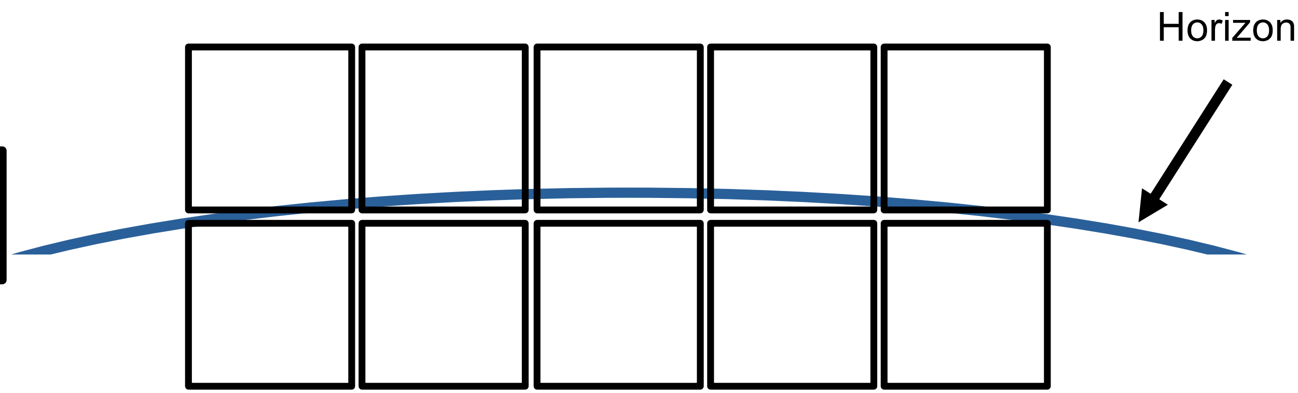
Pixel FoV: **0.18°**

5 x 2 = 10 SiPM arrays In total

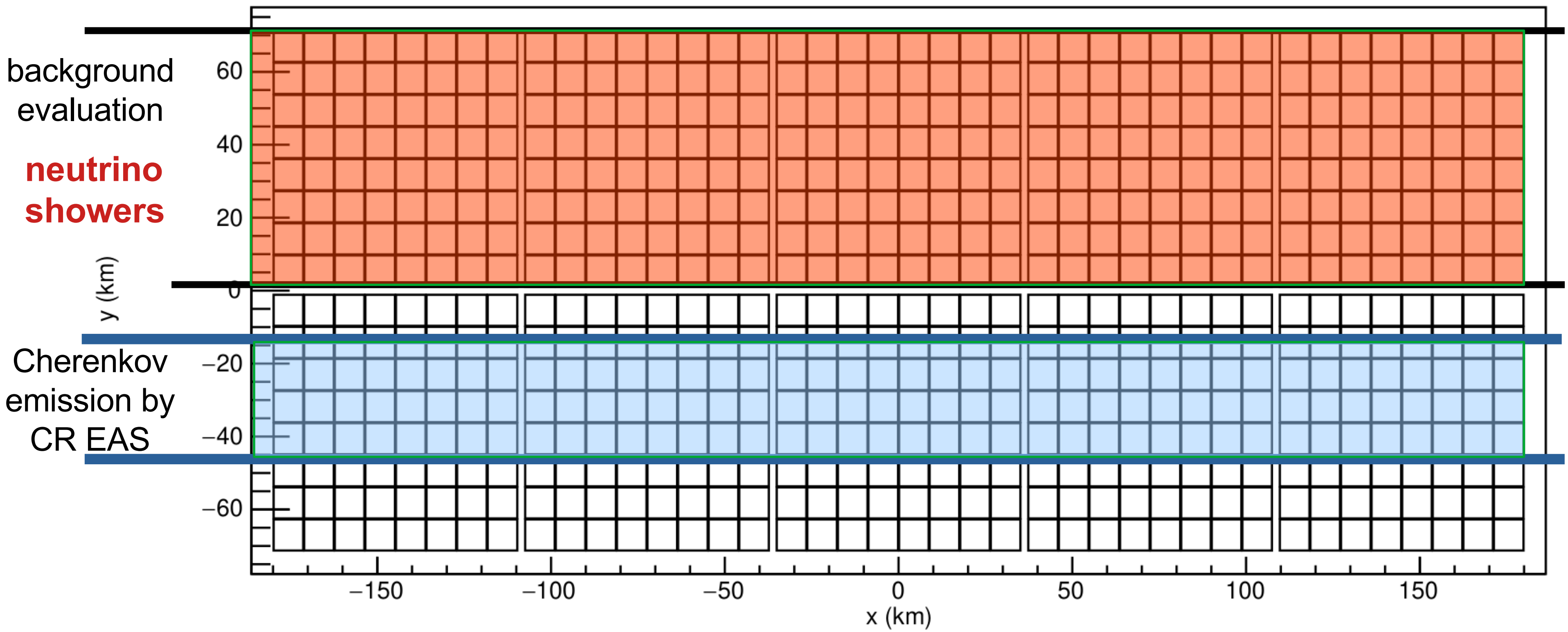
(8 x 8) x 10 = 640 pixels (channels)

Array dim. : 25.3 x 25.3 mm^2

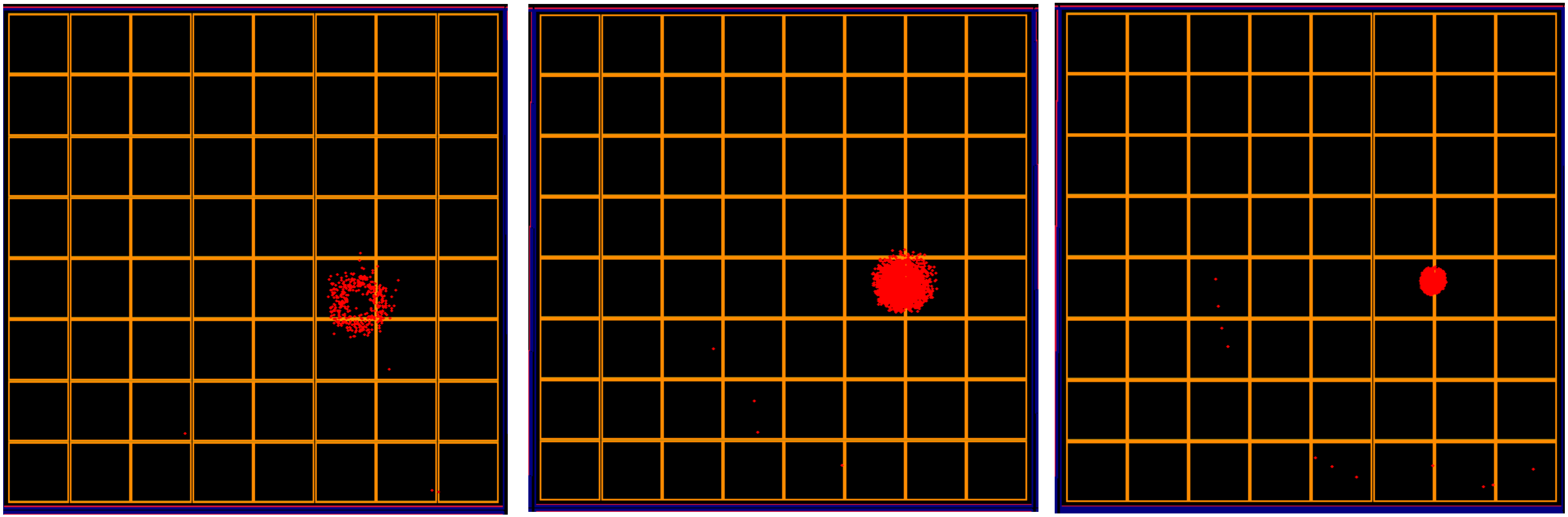
Array Eff. area : 24 x 24 mm^2



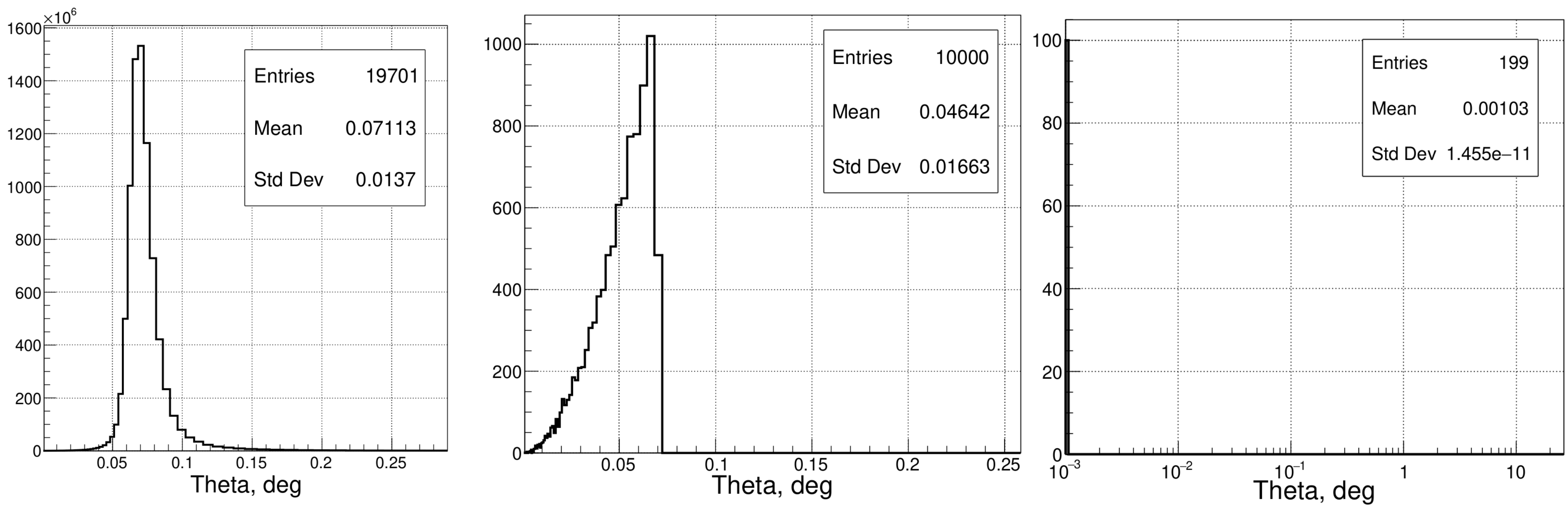
Camera plane with projection on the Earth (total area 360x140 km^2)



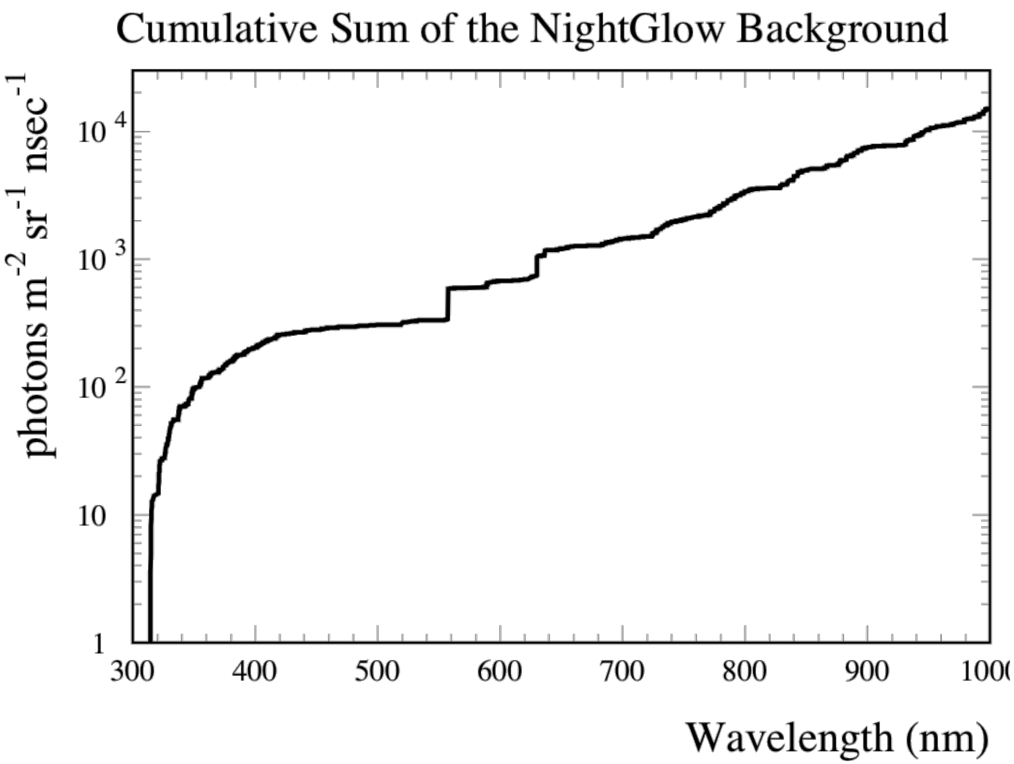
Single shower event looks like a doughnut

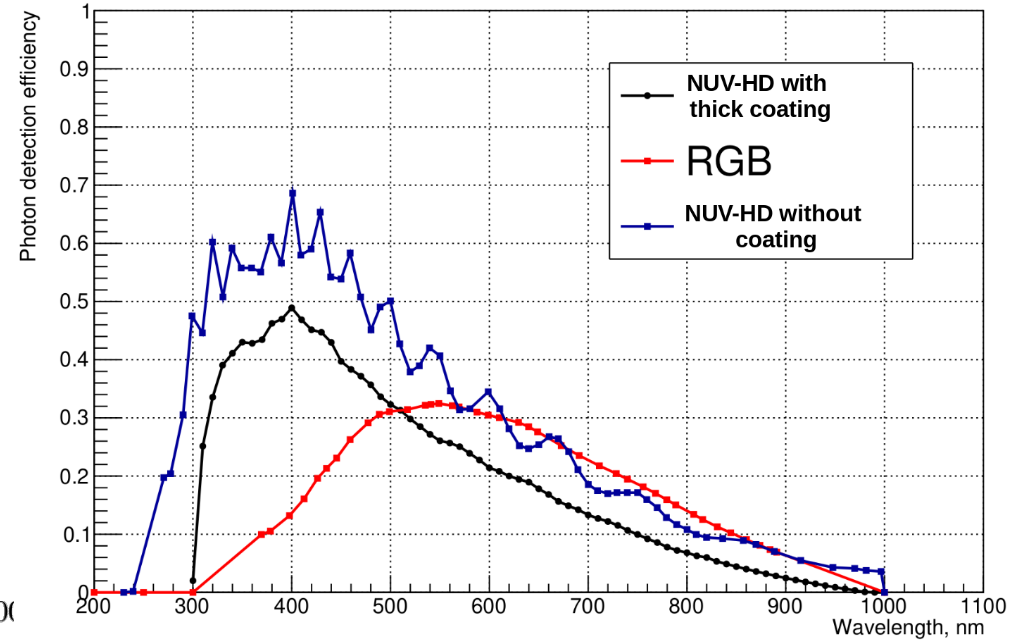


EASCherSim | Spherically uniform | Point like source



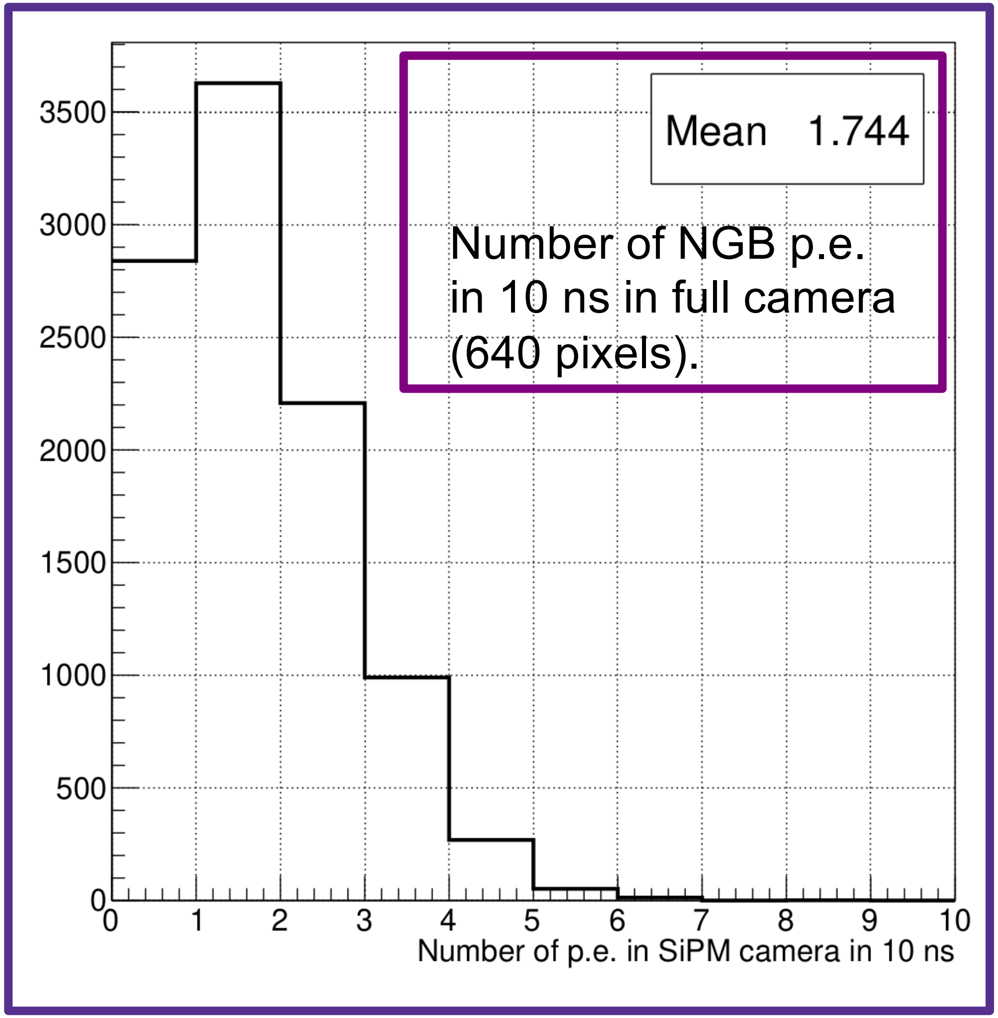
Night Glow Background rate



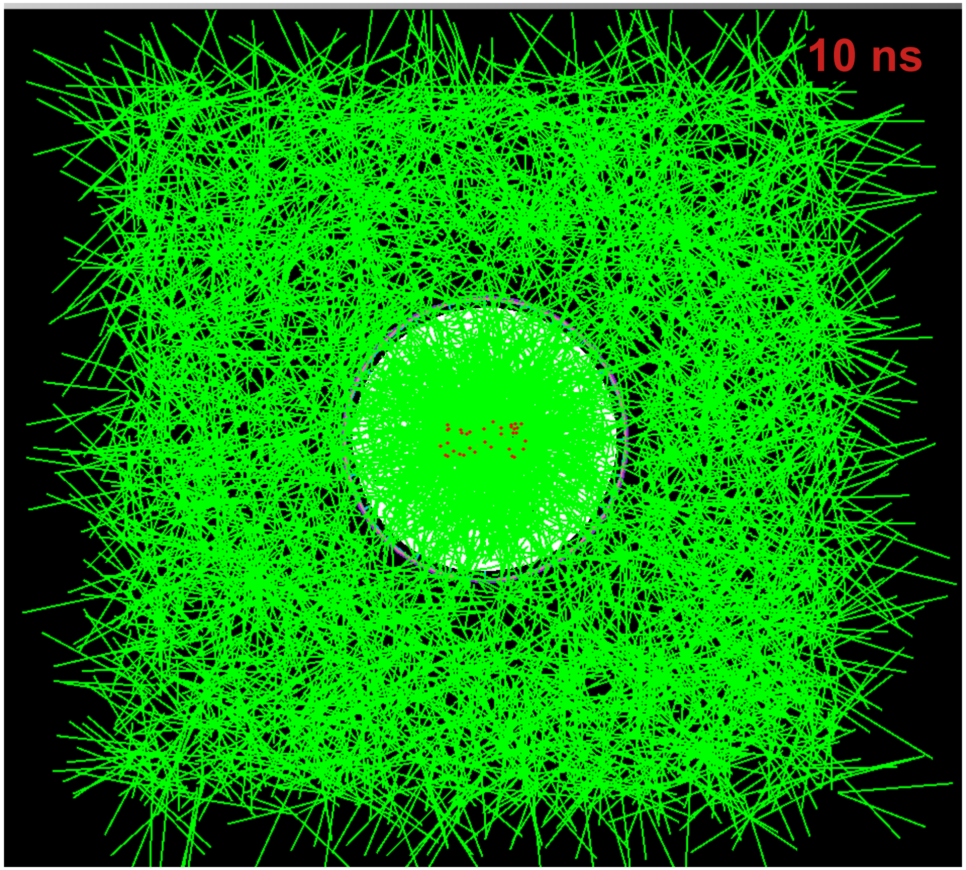


- ✓ Simulations are performed assuming NUV-HD-LowCT SiPM developed by FBK, has typical values (for 35 μm cell-size) of dark count rate (DCR ~ 50 kHz/mm^2), afterpulsing (AP ~ 5%), optical crosstalk (CT ~ 5%–20%) and photodetection efficiency (peak PDE ~ 50%–60%.)

- ✓ We are now testing NUV-HD-MT, which employs metal filling of the Deep Trench Isolation (DTI) that separates adjacent micro-cells in the SiPM, to further reduce optical cross-talk probability without reducing PDE. The NUV-HD-MT technology is a joint effort by FBK and Broadcom.



Spread angle up to **10° (FoV/2 = 3°).**
Phi and cos(Theta) have uniform distribution.



Rate per pixel NGB = 0.86 MHz

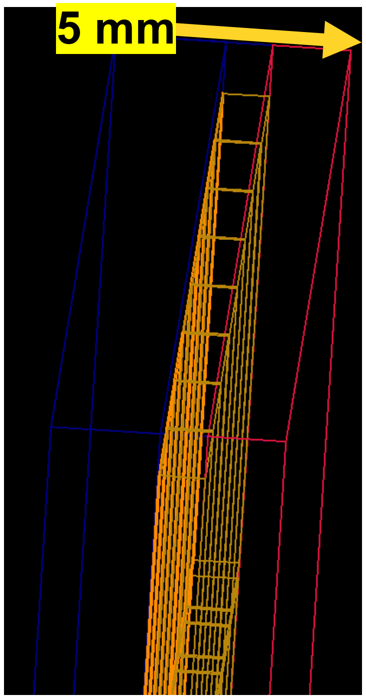
No safety factor included

NGB with safety factor : 0.86 MHz x 8 = 7 MHz **~ 10 MHz**

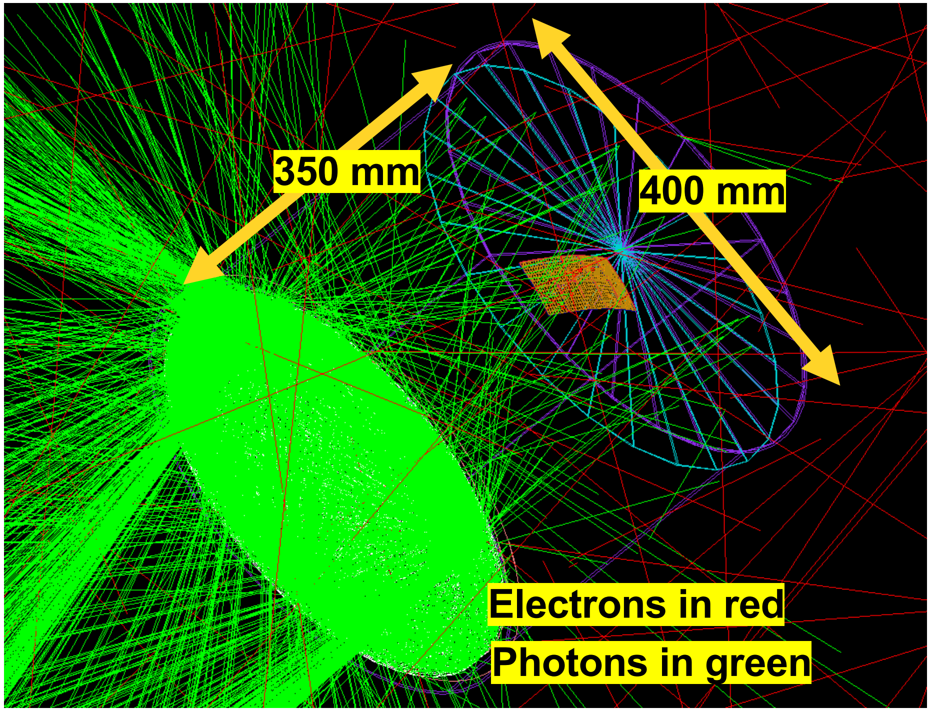
Radiation background (SPENVIS+G4)

- SiPM and electronics will get the radiation damage
- Scintillation, fluorescent materials and Cherenkov radiator materials will produce background optical photons.
- Low energy and high charge ions potentially can induce the signal directly in SiPM.

Radiation dose



Light produced in the optical elements



Electrons
~7 Gray/year

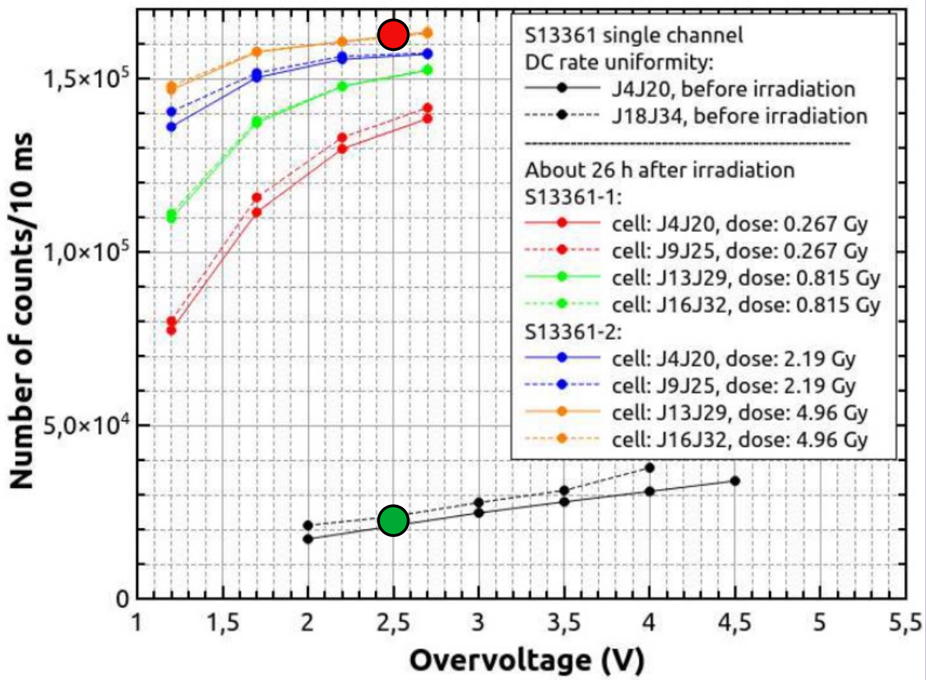
Protons
~3 Gray/year

Total radiation dose
~ 10 Gray/year

- Energy deposition in the volume made of SiPM
- Simulation of the Terzina telescope geometry composed by fused silica and aluminum mechanical structure.

Radiation effects on SiPM Dark Count Rate (DCR)

SiPM Proton Irradiation POLAR-2



S. Mianowski et al, Exp.Astr. 55 (2023) 2, 343 e-Print: 2210.01457

- 🟢 2×10^4 cont/ 10 ms
- 🔴 16×10^4 cont/ 10 ms

✓ DCR increase by factor of 8 for 5 Gray irradiation dose

✓ NUSES Geneva group performed a measurement campaign irradiating the FBK NUV-HD-LowCT SIPM confirming POLAR-2 observation.

Talk by L. Burmistrov

DCR increase by factor of **16 for 10 Gray** irradiation dose

Assuming a DCR of 50 kHz/mm^2 at BoL than at EoL (3 years) DCR will be 2.4 MHz/mm^2

Expected DCR after 3 years of operation in Terzina: **~22 MHz per pixel**

ASIC and trigger logic

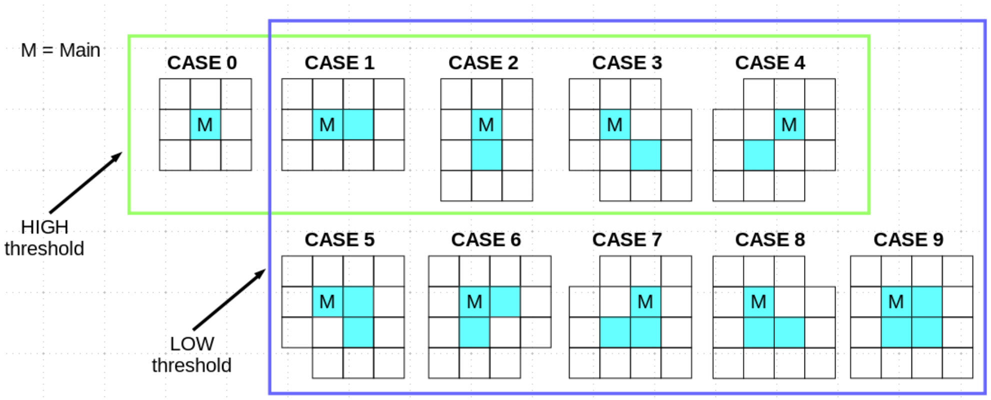
Talk by A. Di Salvo

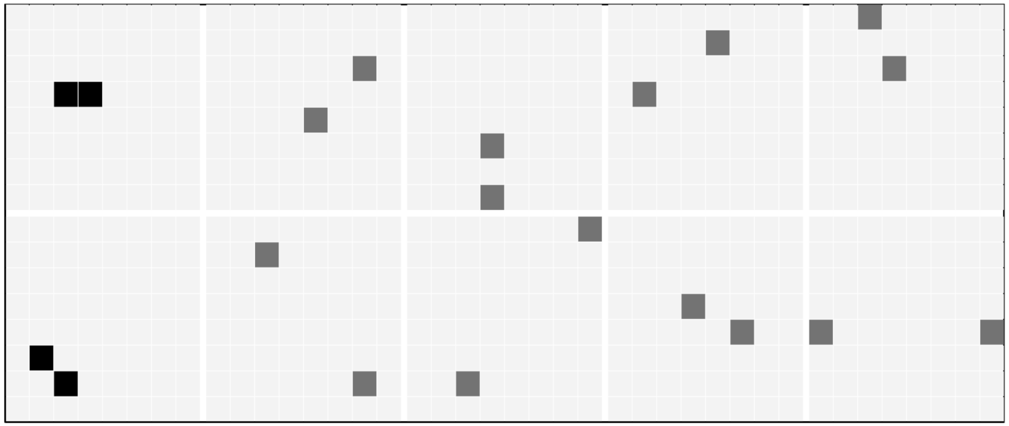
ASIC

- ✓ 64 channels (pixels)
- ✓ Each channel has a memory with a total number of 256 cells with 12bit resolution. Arranged in a programmable number of blocks (1, 4 or 8). Reference configuration: 8 blocks of 32 cells each.
- ✓ Two programmable thresholds: low S_0 and high S_1
- ✓ Two programmable counters: HIGH_CNT and WAIT_CNT
- ✓ Clock cycle: T_{clk}= 5 ns
- ✓ Data transfer to the FPGA: 1 bit in 1.25 ns
- ✓ Power consumption around 2 mW/channel.

If one channel exceeds the low threshold S_0 , during the time frame Δt_c = (HIGH_CNT + WAIT_CNT)*T_{clk} changes to the pixels state are accepted. After the time Δt_c = (HIGH_CNT + WAIT_CNT)*T_{clk} the hitmap is acquired. A single hitmap is composed by 112 bits (98 bit + 14 bit overhead). Data are accepted (event recognition) if:

- S_1 is exceeded in one pixel with at least one adjacent pixel above S_1 (upper row in figure)
- S_0 is exceeded in one pixel with at least two adjacent pixels above S_0 (lower row in figure)

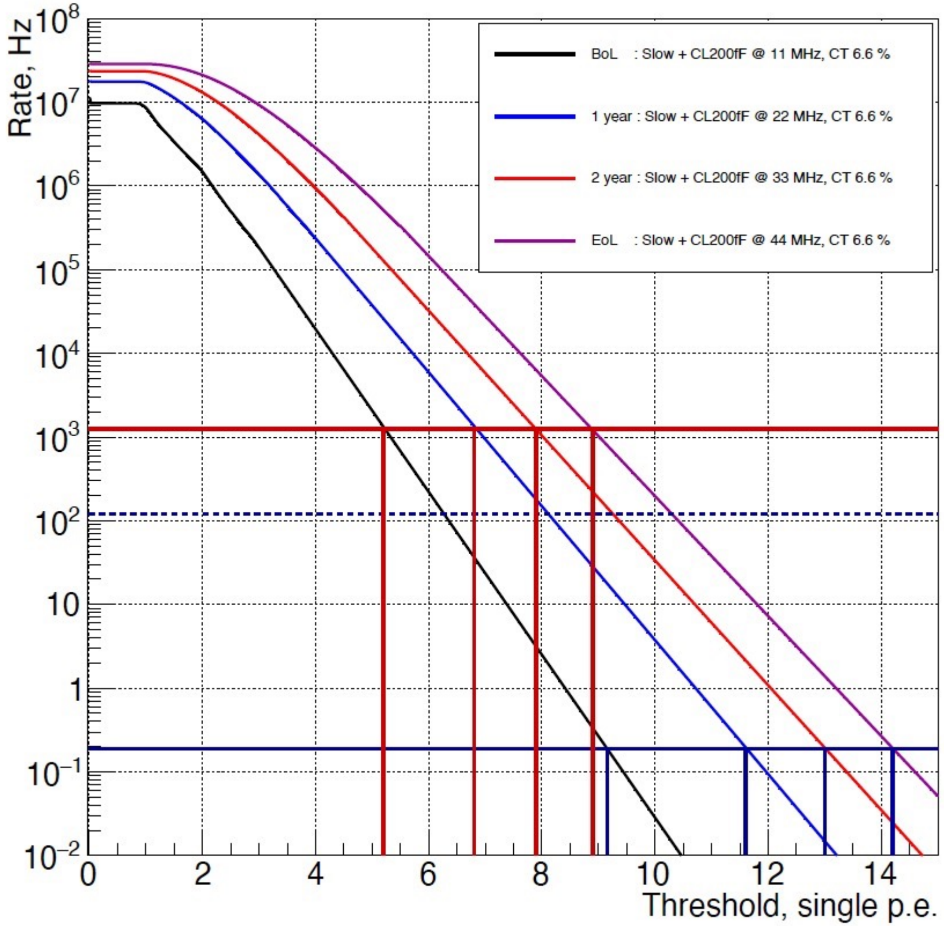




DIGITIZATION (PULSE SHAPE)

Once the event is accepted it will be centred for digitization at t_S the time when the threshold S_0 (S_1) is exceeded. Digitization is obtained through 32 time-samples of the signal spaced by T_{clk}, total sampled time interval 160 ns (t_S-80 ns, t_S+80 ns), occupying one memory block per channel (pixel).

The digitized signal in a single pixel is encoded in a number of bit: 12x32+header+padding = 434 bit. An event in a single ASIC is encoded in 64x434 = 27776 bit.



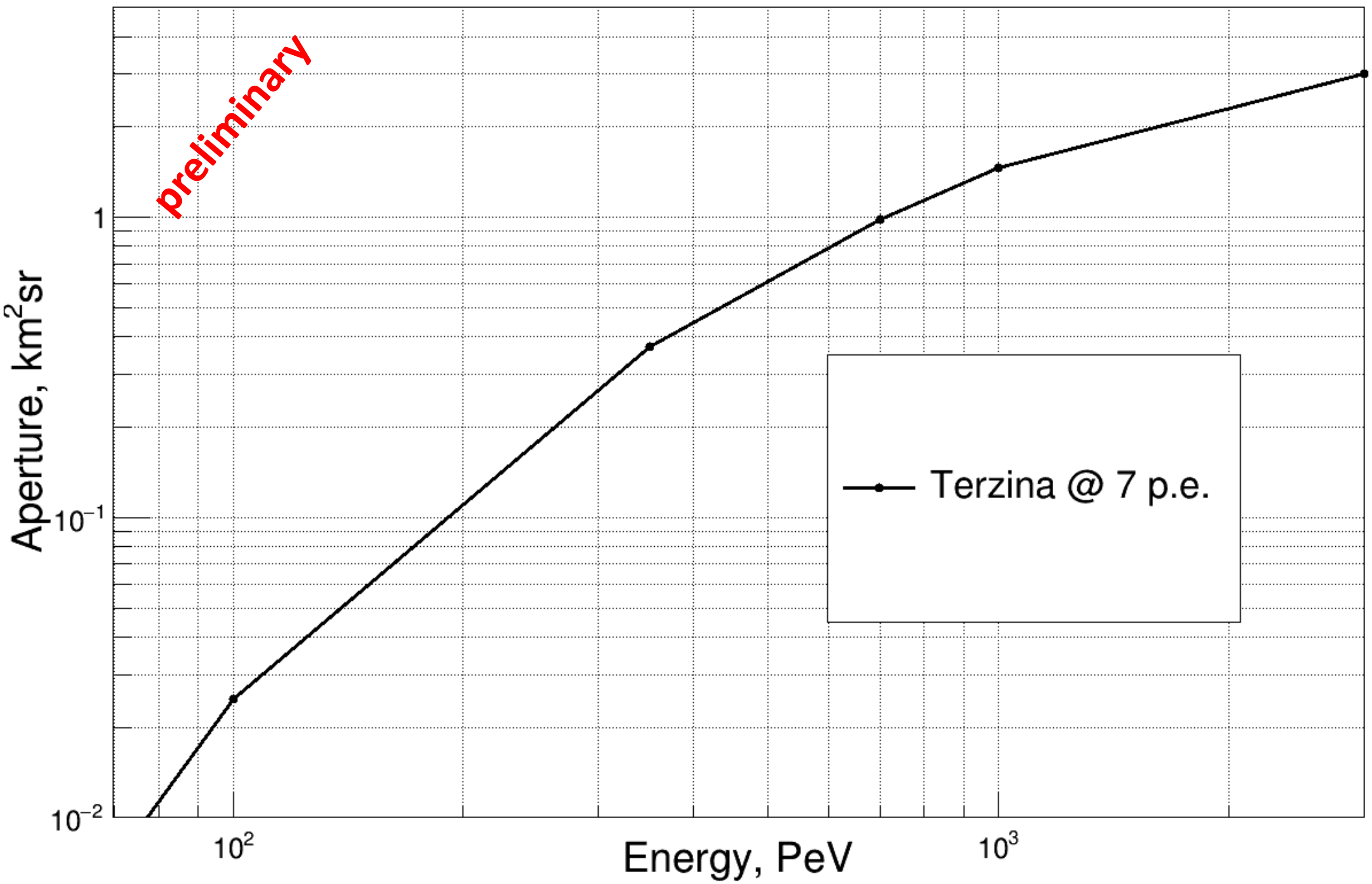
THRESHOLDS AND TRIGGER RATE

Let's consider the intermediate case of the mission after 1 y (blue line), fixing S_0=7 p.e. and S_1= 9 p.e. one has roughly 1 KHz for the S_0 trigger rate per pixel and 30 Hz for the S_1. The hitmap recognition chain has a total duration: Δt_c+140+30 ns. Using Δt_c=20+60 ns one has a hitmap recognition time of 250 ns (deadtime associated to a single memory block of the ASIC)

DOWNLINK AND EVENT RATE

The downlink that the S/C will provide has a stream of maximum 45 Gb/d, being the size of one event 27776 bit = 3472 b, the maximum number of events that can be sent for the offline analysis is 1.29×10^7 events/day. Which corresponds to an event rate of roughly 150 Hz.

Terzina aperture



✓ Around 100 events per year of CR with E>100 PeV will be detected by Terzina

Conclusions

- ✓ First observation of high energy cosmic ray showers from space through Cherenkov signal.
- ✓ Certify HE neutrino detection feasibility through Cherenkov emission in the Earth skimming geometry.
- ✓ UV - near visible background characterization from the Earth limb.

Terzina is a pathfinder for future space missions

- ✓ Super Pressure Balloons (POEMMA-B). Discussions started to a possible scaling of the Terzina design for the POEMMA-B Cherenkov Telescope.
- ✓ Satellites constellations for CR and neutrino detection through Cherenkov emission (POEMMA, Space Cherenkov Telescope)

The NUSES Collaboration

First “in person” Collaboration Meeting GSSI Jun 2022

Thank you

Two years postdoc position:

The GSSI is seeking outstanding candidates to join the High Energy Astroparticle Physics group for the experimental study of cosmic radiation.
The ideal candidate should have a solid background in experimental particle and astroparticle physics with a PhD in the field.
Previous experience in the experimental study of cosmic radiation with space-based missions and in the related activities (R&D, data analysis, and
payload response simulations) would be an asset.
Total gross salary: **45.000,00 eur**. Deadline: July 6th, 2023.
See the position 1.2 at the link below:
https://www.gssi.it/albo-ufficiale-online-gssi/item/download/4396_26fc3b69b46a2d802e2f574daa9c2314

Two years position for a Payload/Satellite engineer:

The ideal candidate should have a solid background in aerospace or electronics engineering.
He/she will contribute to the design and optimization of the mechanical or electronic model of scientific payloads and/or satellite platforms, including the development of test beds used for single subsystems characterization.
Simulations and tests for space qualifications will also be part of the work.
Knowledge of the commonly used software tools for mechanical or electronic design is also required.
The selected candidate will join the High Energy Astroparticle Physics group for the experimental study of cosmic radiation.
See the call at line 313 at this link: https://www.gssi.it/albo-ufficiale-online-gssi

GSSI is also offering **four PhD positions** in the newborn PhD programme for **"Innovative Technologies for Space Missions and Radiation Detection"**, under the Astroparticle Physics area,
Applications from physicists, engineers, and young experts in the field are welcome till July 6th, 2023.
See the call at line 316 at this link: https://www.gssi.it/albo-ufficiale-online-gssi