SPACEMON: SPACE ENVIRONMENT MONITORING WORKSHOP 2025

Performance and Radiation Mitigation for SiPMs in LEO Missions

Paper on ArXiv ePrint: https://arxiv.org/abs/2503.00532 (accepted in JCAP)

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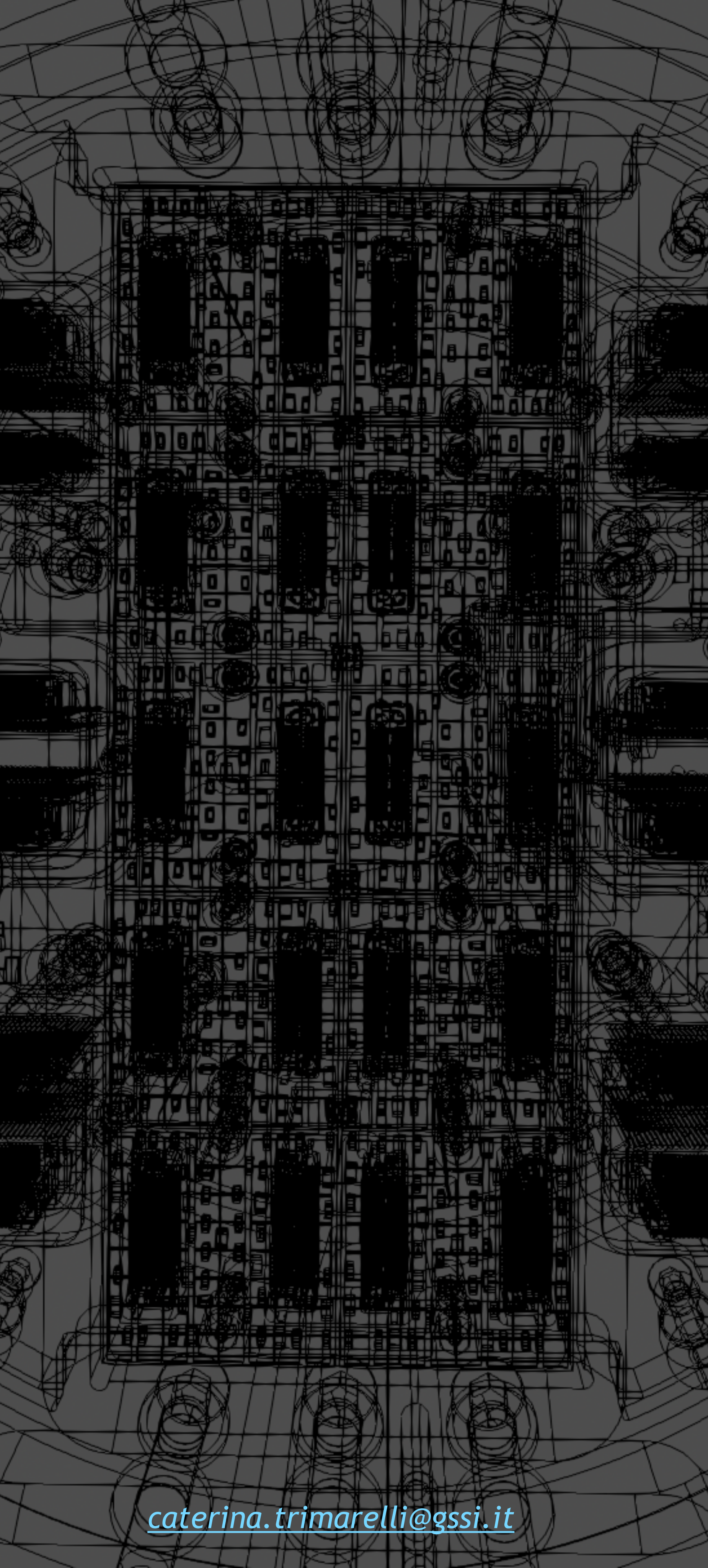

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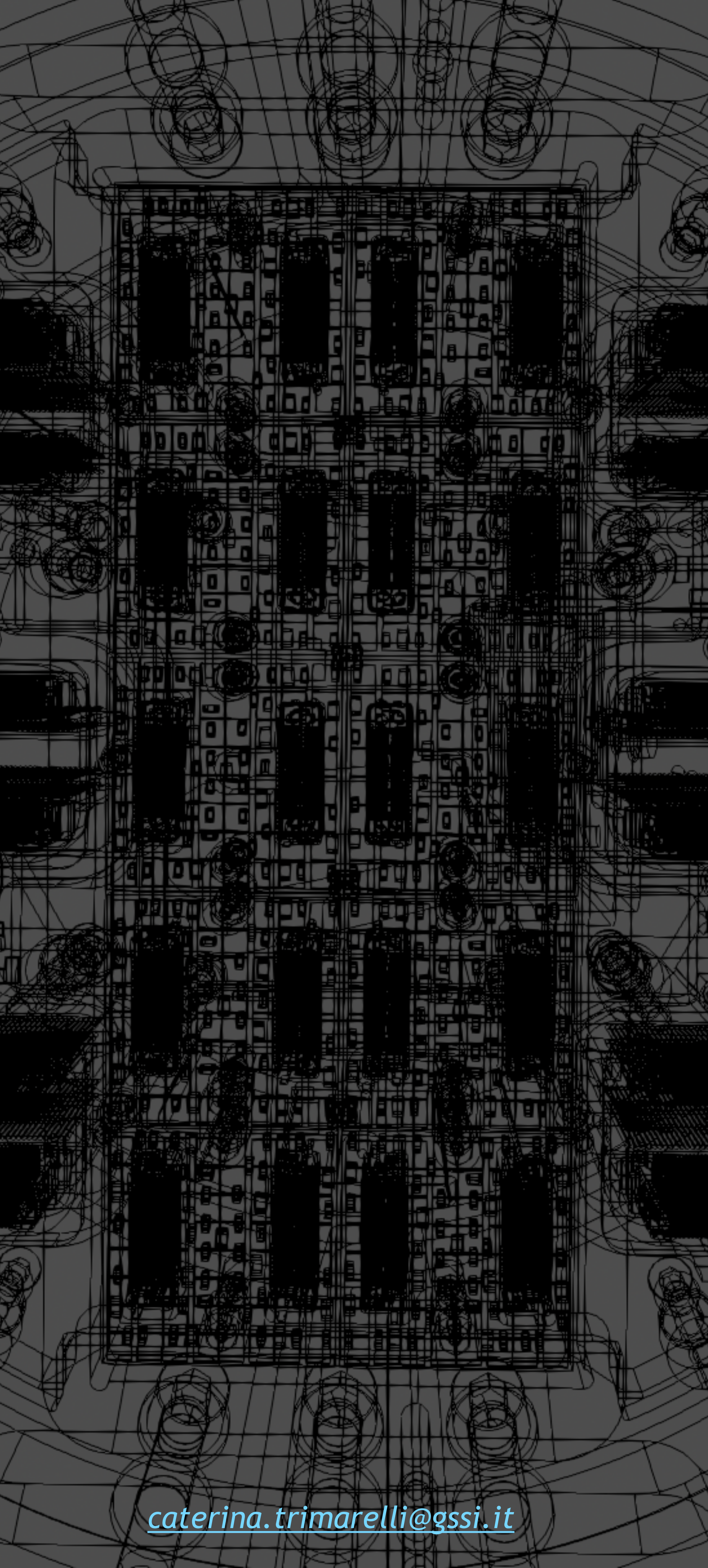
OUTLINE

- Silicon photosensors in space applications
- Terzina: research goals and features
- The NUV-HD-MT SiPMs for Terzina: why MT and characterisation
- The radiation fluxes for a LEO space mission
- Dose estimates from radiation with Geant4
- Radiation damage in silicon with proton and electron irradiation
- DCR prediction during mission and mitigation strategies (annealing)



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SiPM on space missions

Pros

- high photon detection efficiency (PDE)
- low-power consumption*
- operate efficiently in low-light conditions
- compact size and robustness

Cons

- susceptibility to radiation
- sensitive to temperature variations

*~50 W for Terzina

SiPM on space missions

Pros

- high photon detection efficiency (PDE)
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Cons

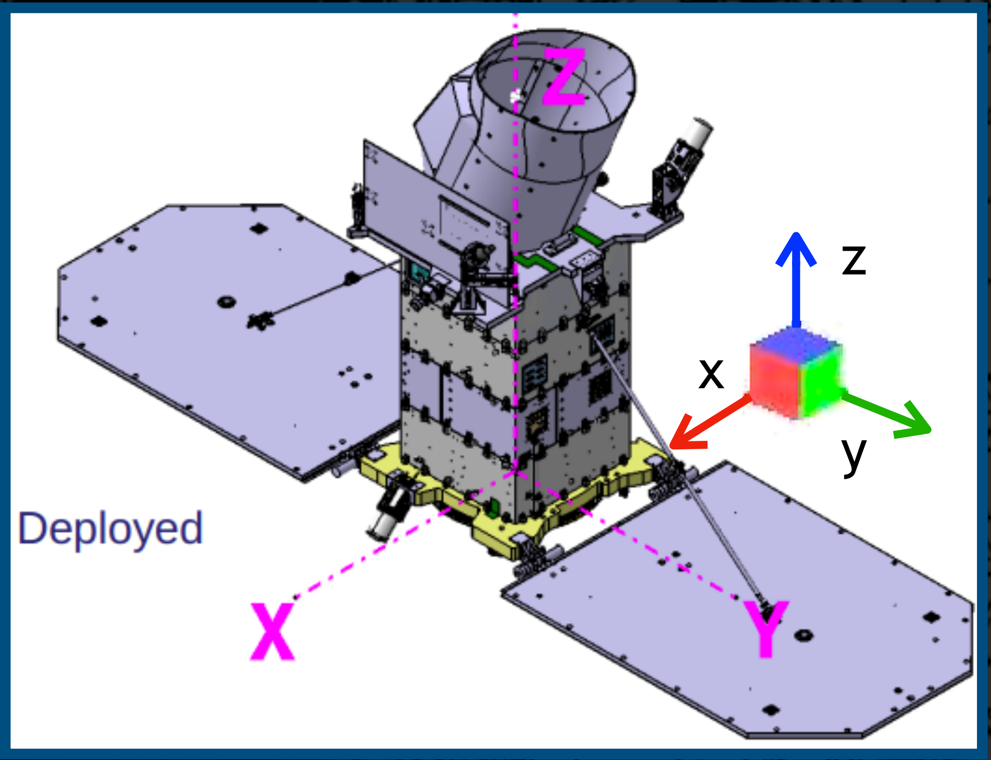
- susceptibility to radiation
- sensitive to temperature variations

all this was studied and taken into account for the NUSES space mission

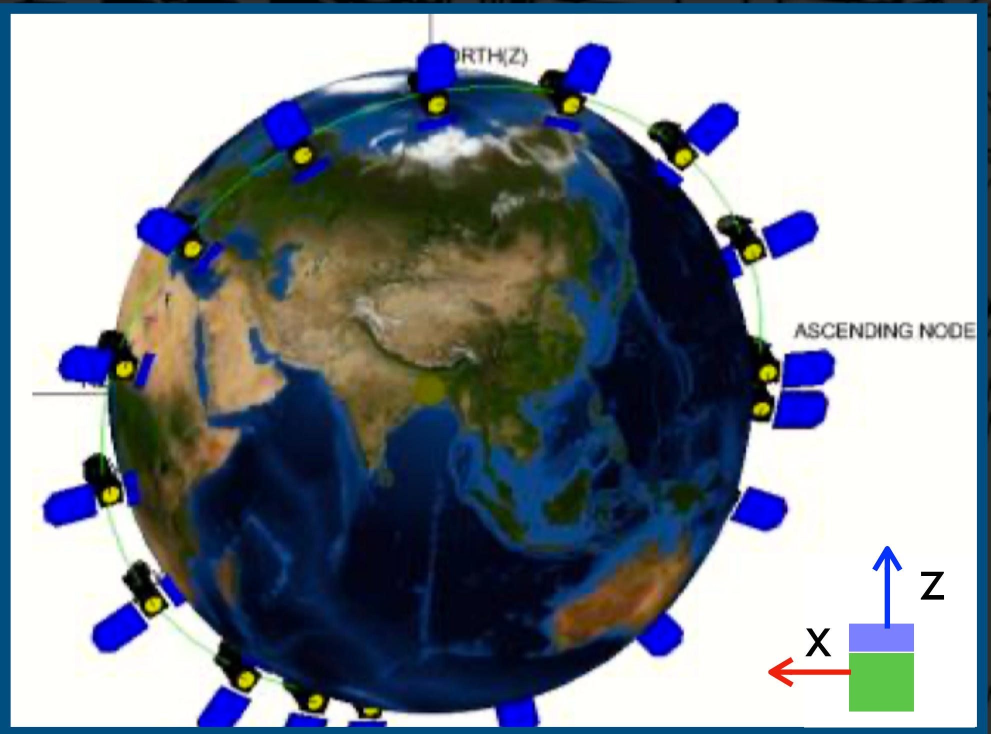
The NUSES project

The NUSES project will employ SiPMs for both of its payloads, Terzina and Ziré

- Ziré, to monitor low-energy (< 250 MeV) cosmic ray fluxes in the Van Allen belts, gamma-ray bursts in the energy region 1-10 MeV, space weather and lithosphereionosphere- magnetosphere couplings
- Terzina telescope, pointing to the dark side of the Earth's limb, to detect the faint Cherenkov light from ultra-relativistic particle showers in the dark atmosphere



Mission Lifetime	3 y
Mean Altitude	550 km, LEO
Semi-major axis (km)	6928 km
Eccentricity	0
Inclination (deg)	97.6 deg, SunSync
LTAN	18:00:00
Pointing	< 0.1 deg



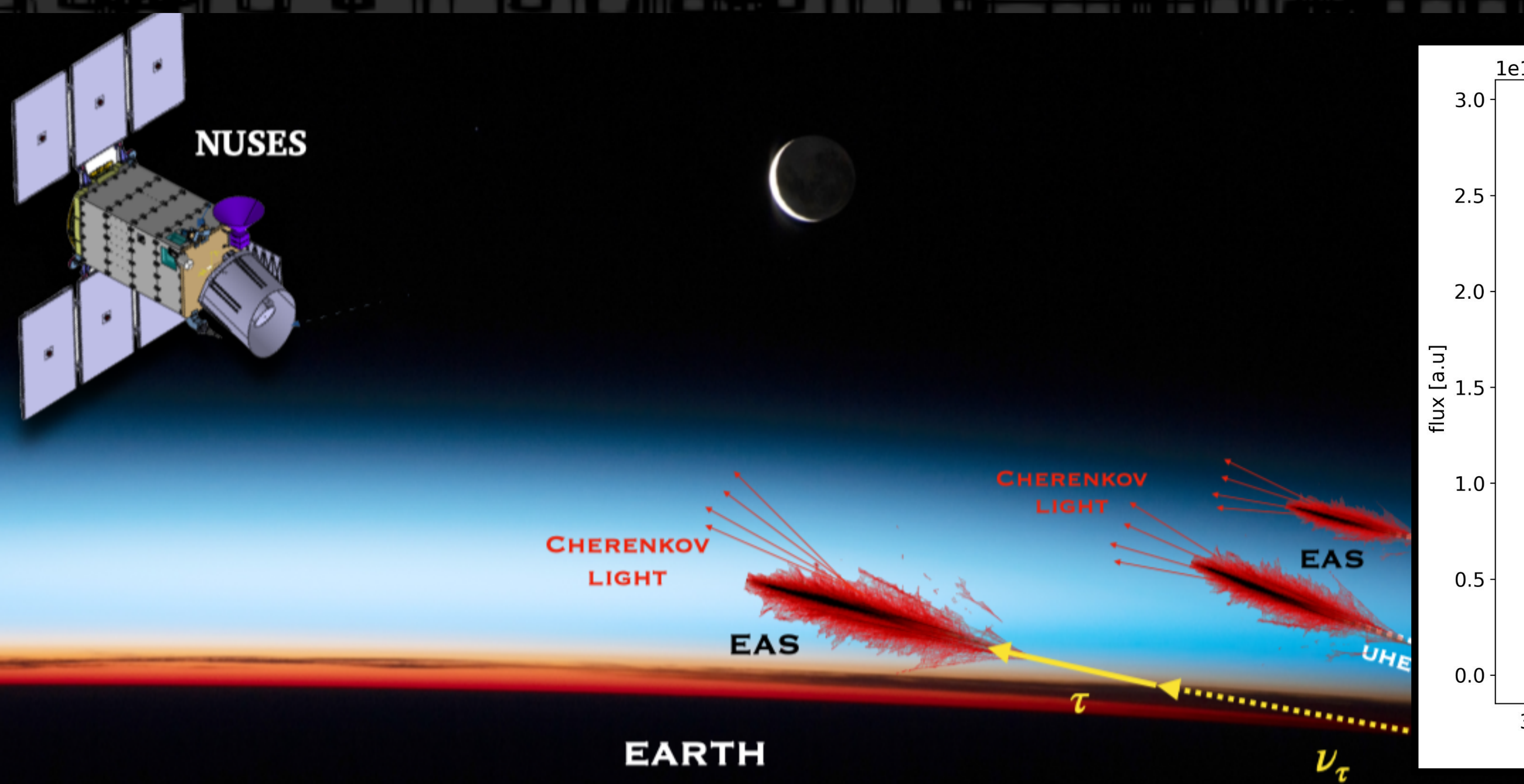
See G. Fontanella talk for more details

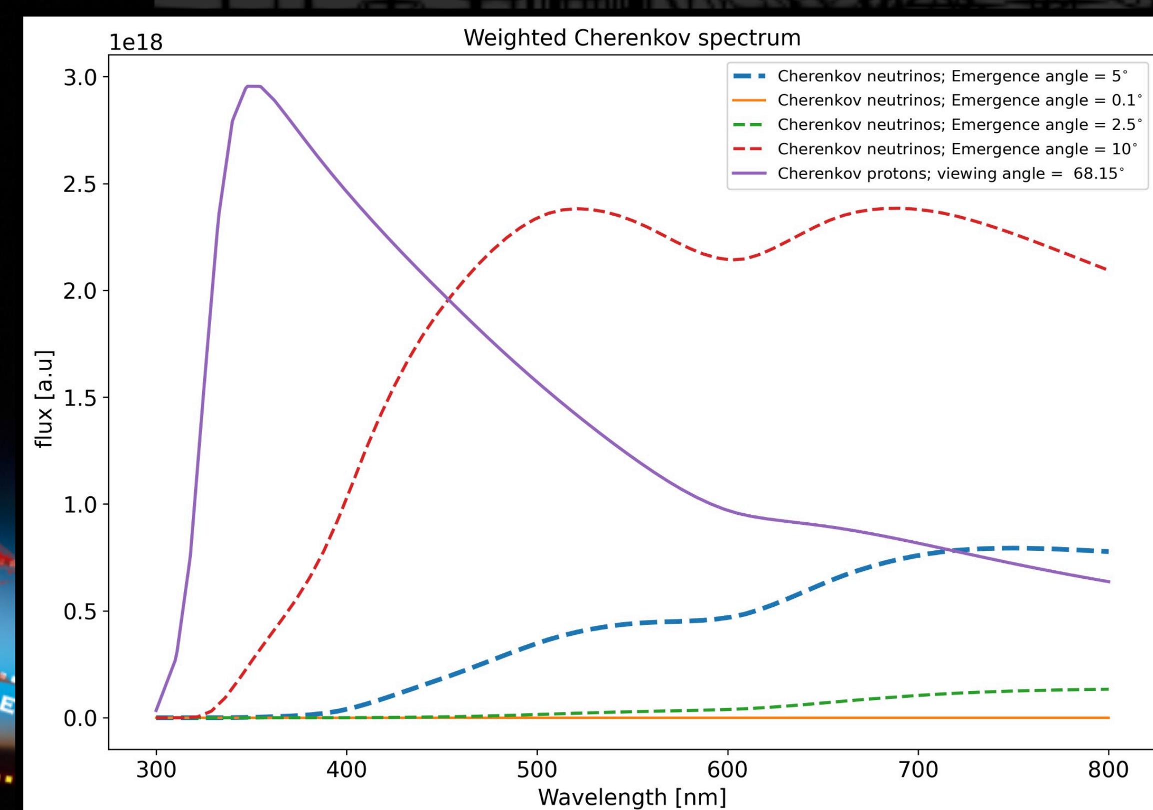
The Terzina Telescope Research goals

Looking at the atmosphere limb:

- Just above: Cherenkov emission of UHECRs induced air showers.
  Primary particles: **CRs** (> 100 PeV) impinging the atmosphere above the Earth's limb.

- Just below: Cherenkov pulse produced by upward-moving EAS.
  Primary particles: τ and μ decay or interactions ($\nu_{\tau,\mu}$ of E> few PeV)



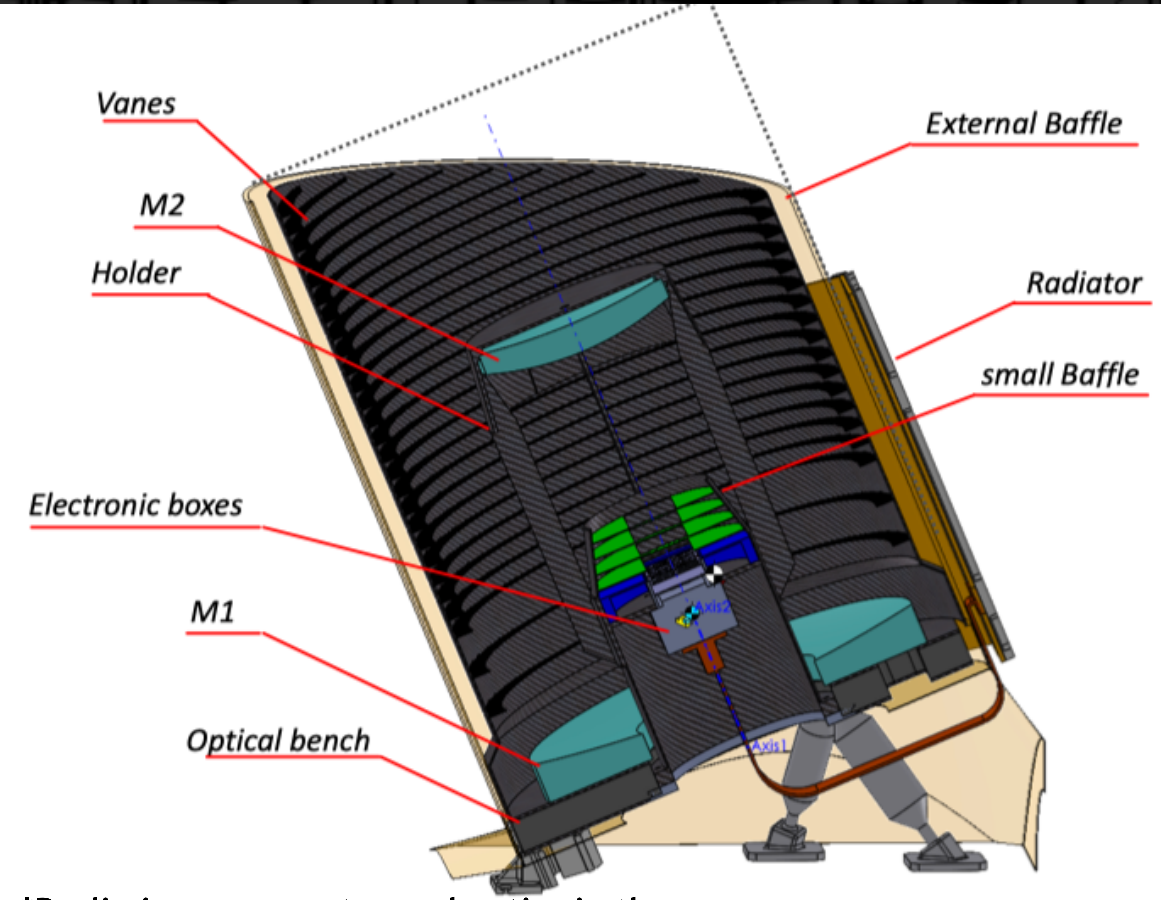


The Terzina Telescope

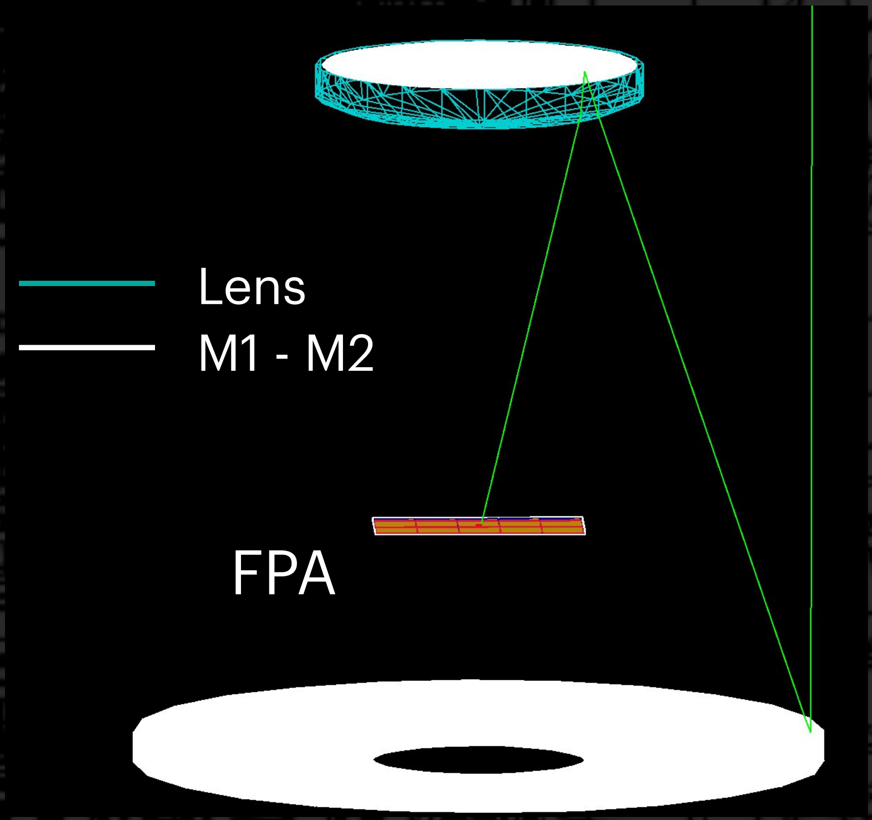
Mass: ~ 40 kg
Dimensions: ~60 cm x 60 cm x 50 cm

The Terzina telescope is composed by:

1. the thermal control system and mechanics;
2. the optical head unit;
3. the focal plane assembly (FPA)



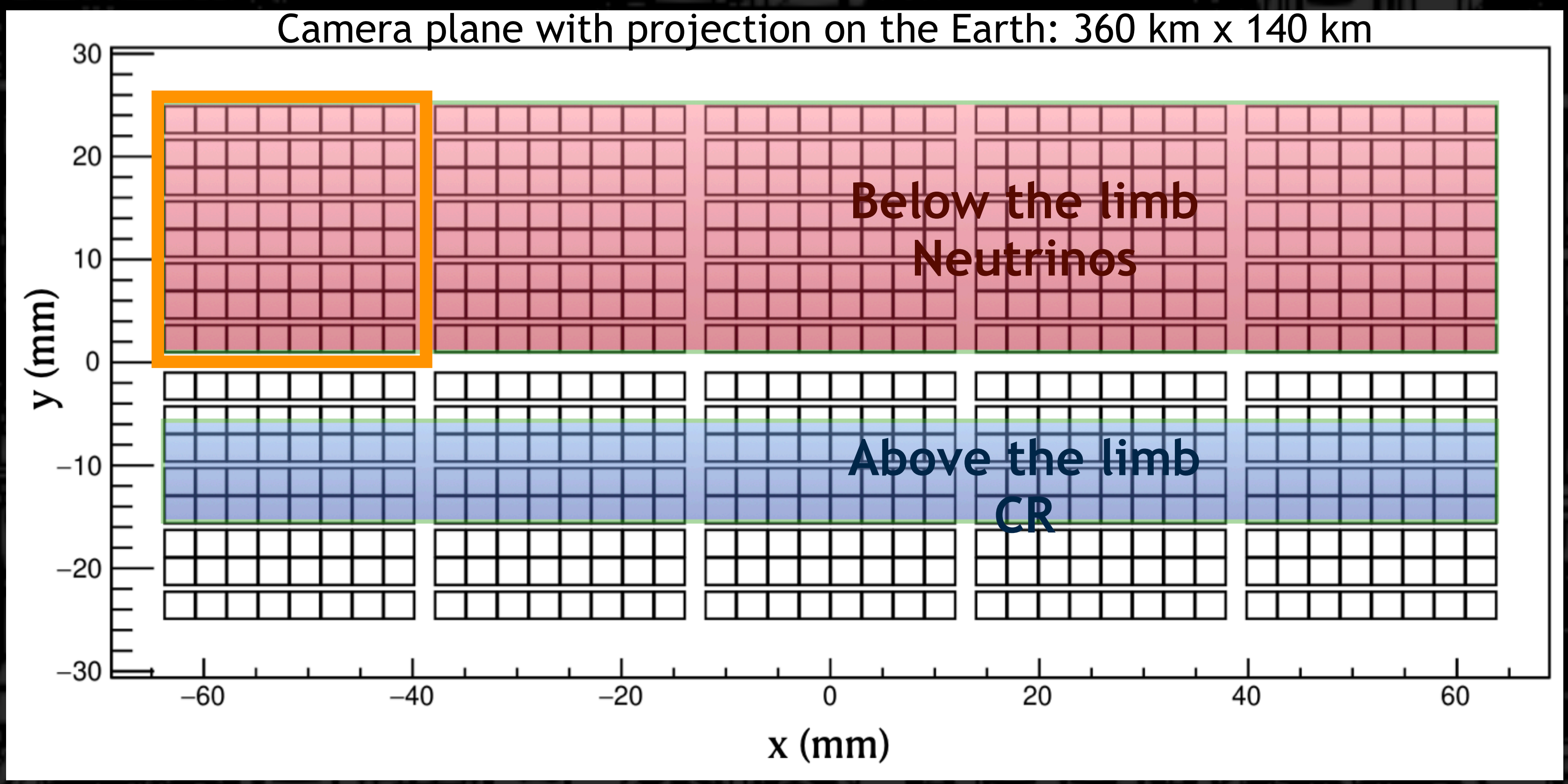
*Preliminary geometry and optics in the paper

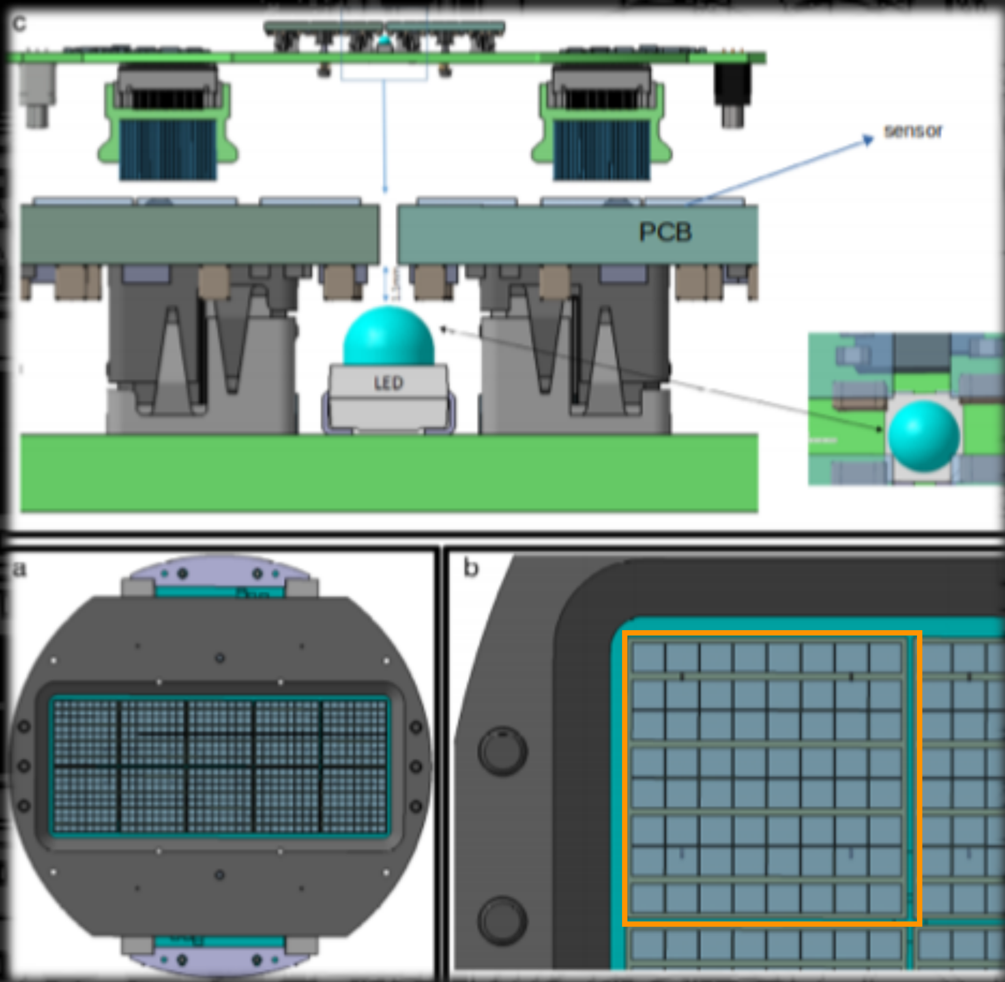


Schmidt-Cassegrain optics

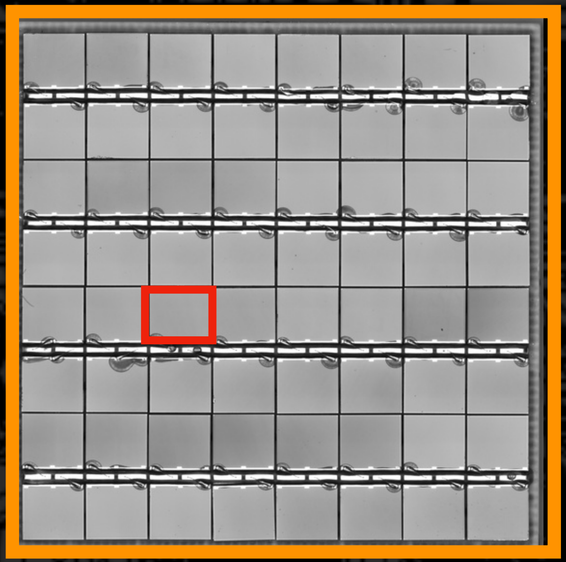
- Equivalent focal length $F_L = 925\,\mathrm{mm}$
- Telescope Field of View: 7.2° along the Earth's limb and 2.9° across it
- Effective area of the telescope: 0.0915 m^2
- 8% of shadowing (baffles and vanes)
- M1 ($D = 430\,\mathrm{mm}$) and M2 ($D = 194\,\mathrm{mm}$) aspherical mirrors

The Focal Plane Assembly





tile dim: 24.9 mm x 24.9 mm



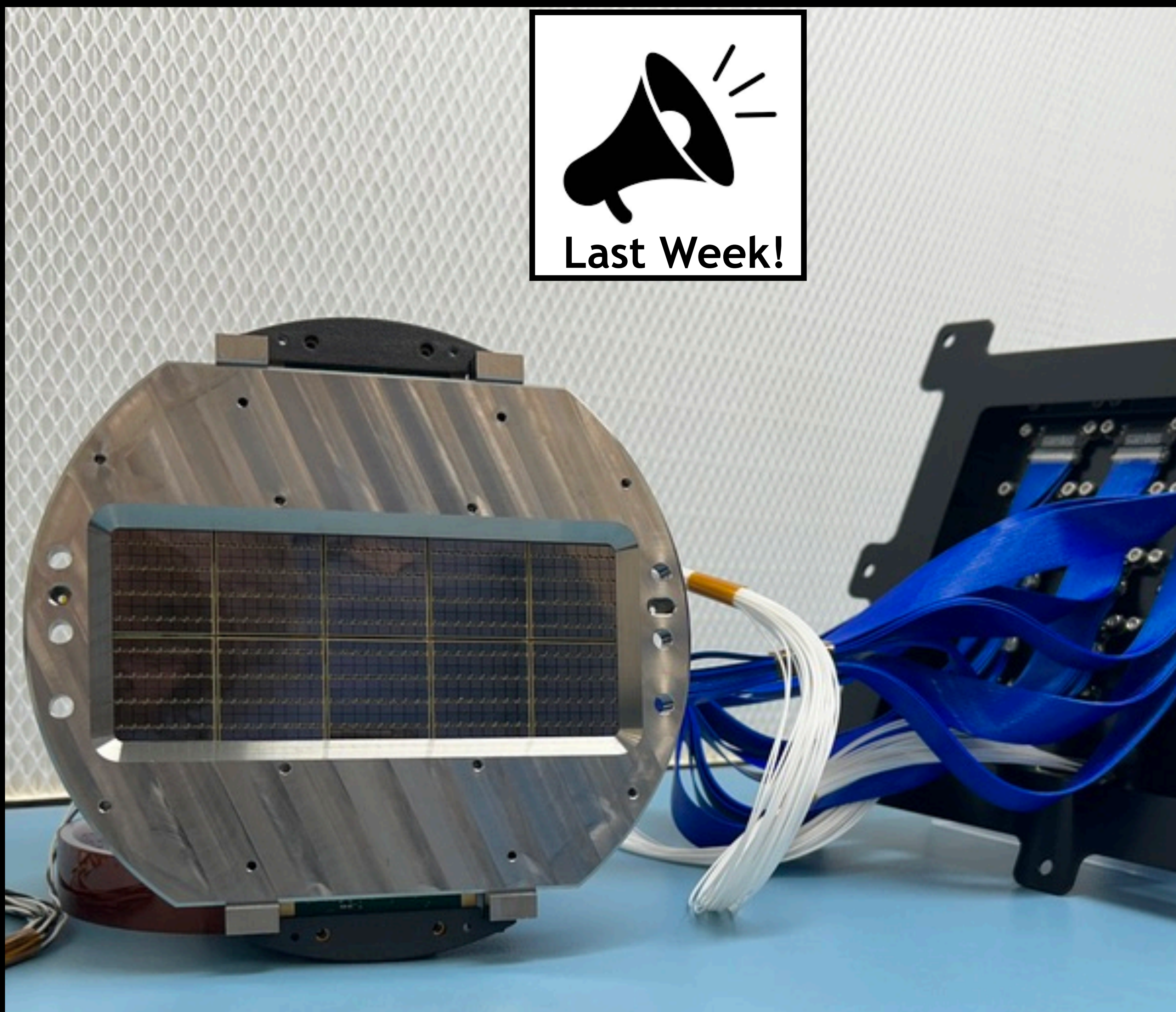
Pixel Information:

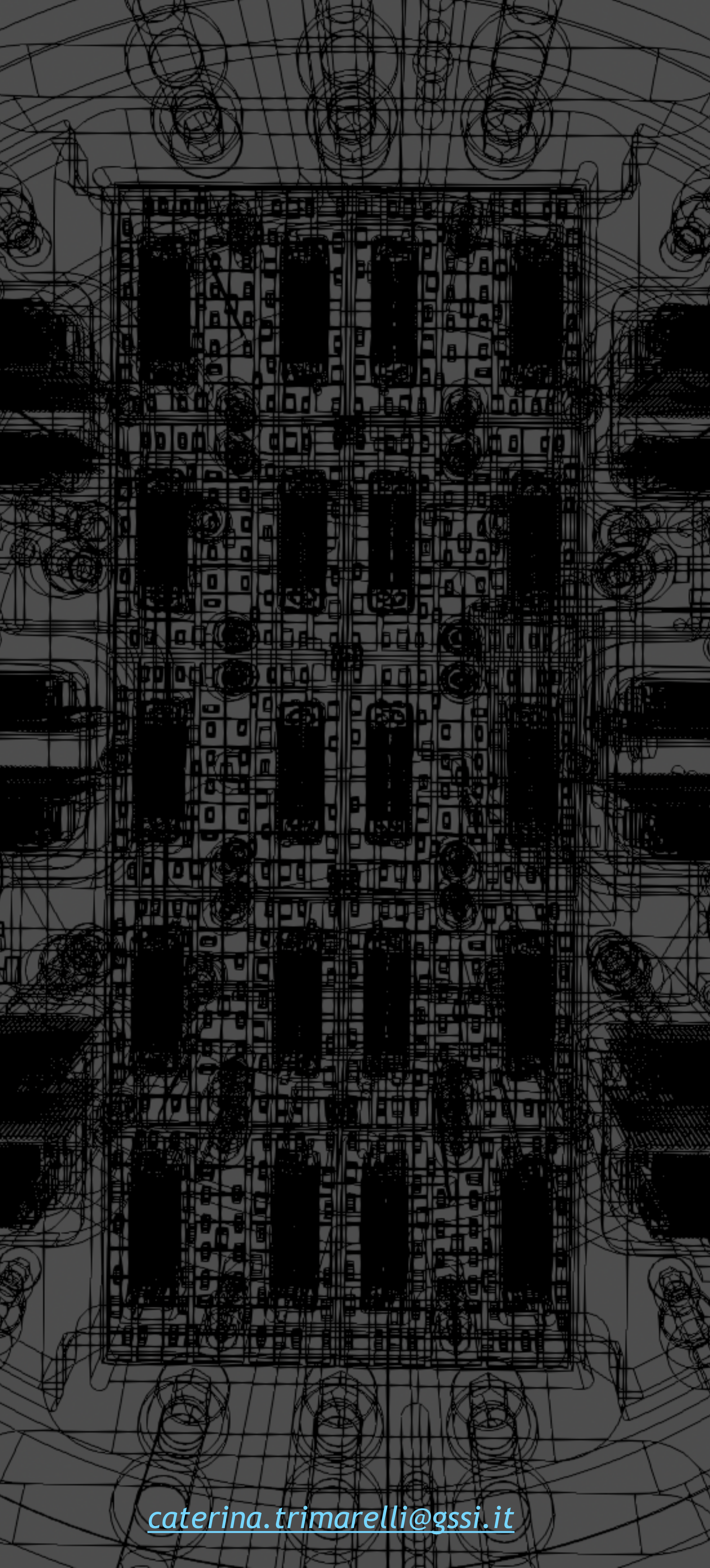
- **Size: 2.3 mm x 2.7 mm**
- $\mathrm{FoV}_{pix} = \arctan(r_{SiPM}/F_L) \simeq 0.18^{\circ}$
- DCR(kHz/mm^2) ~ 100
- CT (%) ~ 7
- PDE% @450 nm ~50
- V_{BD}=32.6 V

SiPM arrays 8x8 pixels
~131 mm x 60 mm
5x2 = 10 SiPM arrays
(8x8) x 10 = 640 pixels

The Focal Plane Assembly

The integration and functionality tests





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The NUV-HD-MT SiPMs

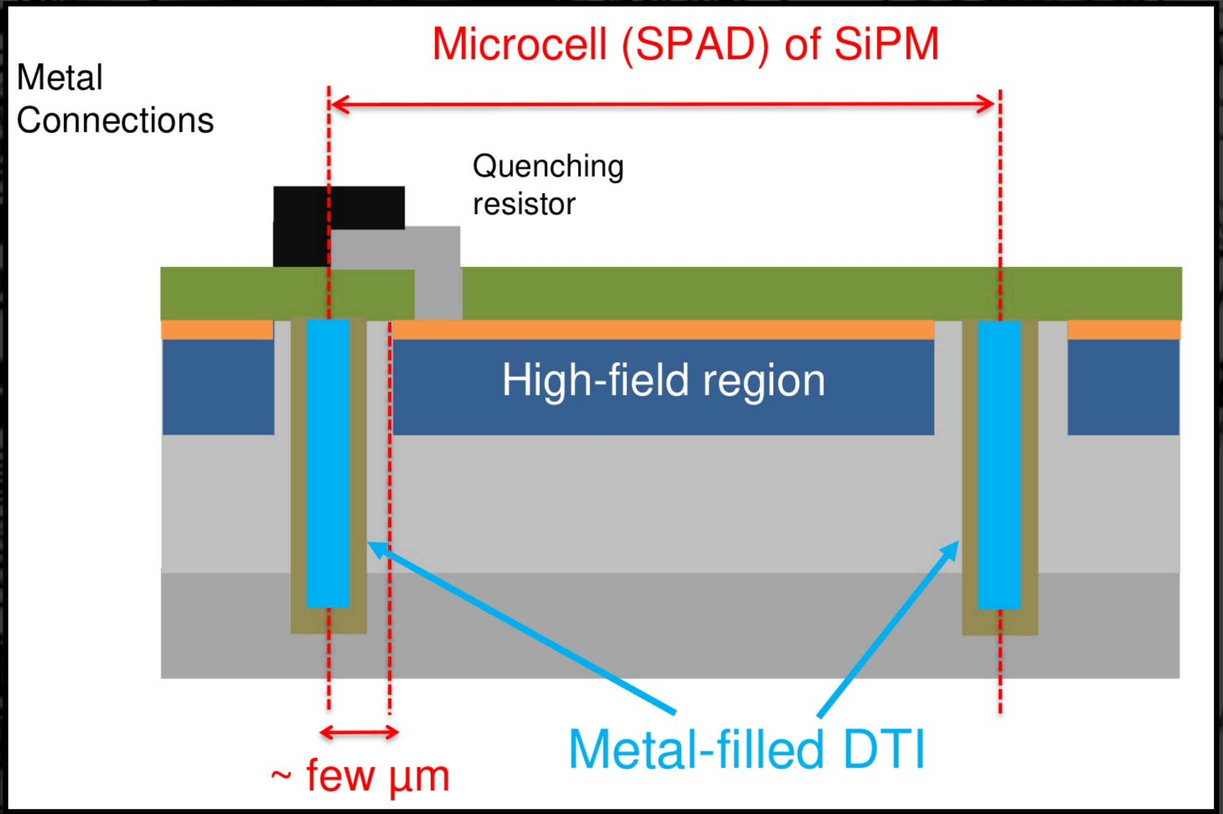
The requirements for the SiPM technology to be adopted by Terzina are:

- to achieve PDE > 50% at 400 nm, namely in the region of the peak of the specific Cherenkov light spectrum;
- optical cross-talk (OCT) of less than 10% at the operation voltage;
- dark count rate (DCR) of less than 100 kHz/mm 2 at BoL of the mission;
- signal duration of less than 40 ns full width half-maximum

The NUV-HD-MT SiPMs

The NUV-HD-MT technology has been developed by FBK adding metal-filled Deep Trench Isolation (DTI) to strongly suppress optical cross-talk.

- technology minimizing the optical cross-talk and the DCR
- Investigation of micro-cell sizes in order to maximize the PDE while keeping the signal duration short.
- to use bare or coated sensors.



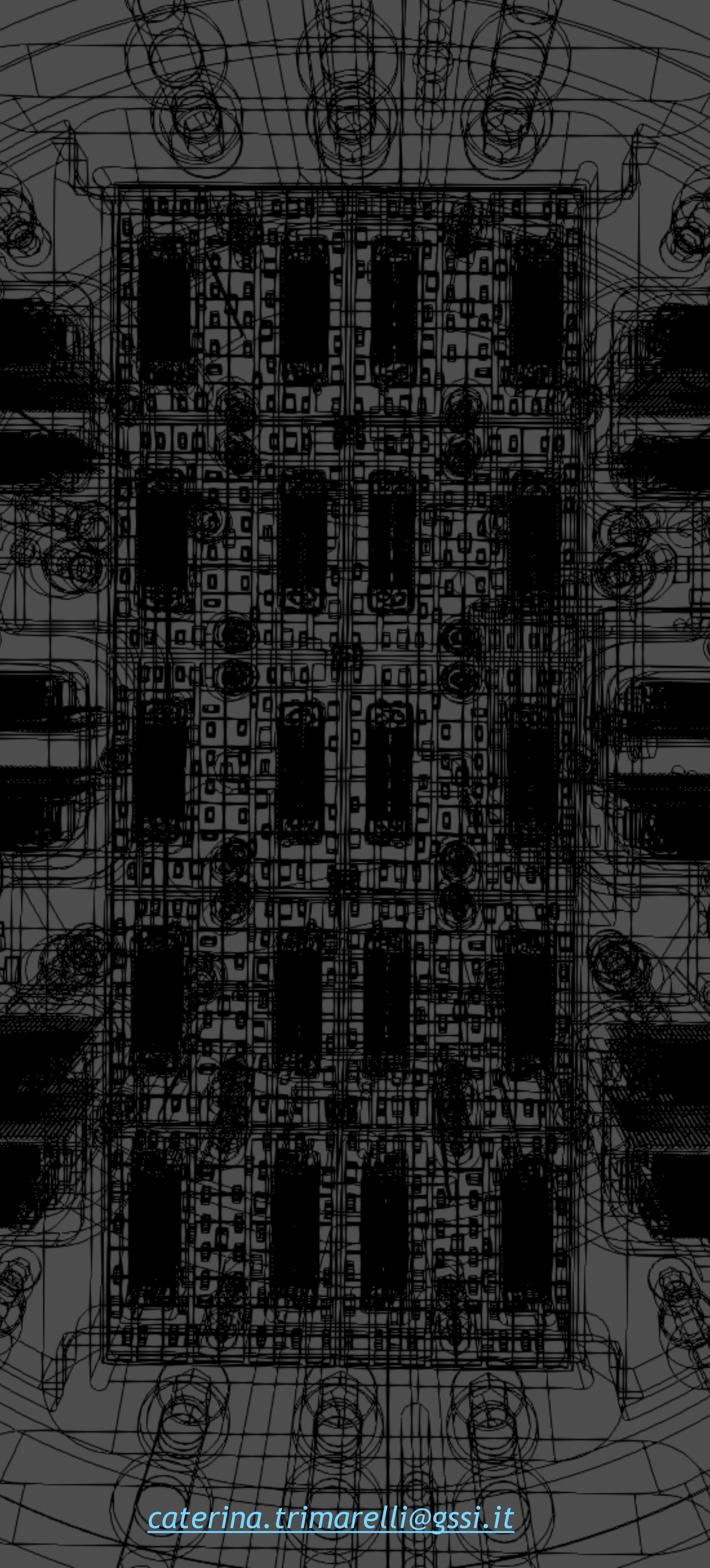
The NUV-HD-MT SiPMs

We have measured the NUV-HD-MT SiPM of 3×3 mm^2 and 1×1 mm^2 with micro-cell sizes of 25, 30, 35, 40, 50 µm:

- Static characterisation ✓
- Dynamic characterisation ✓
- Optical characterisation ✓
- Thermal effect ✓

See paper for details and plots!

OUTLINE



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Radiation Hardness for SiPMs in LEO Missions

SPENVIS

Evaluation of radiation fluxes for LEO space missions

GEANT4

Dose estimates from radiation in space with Geant4

LAB

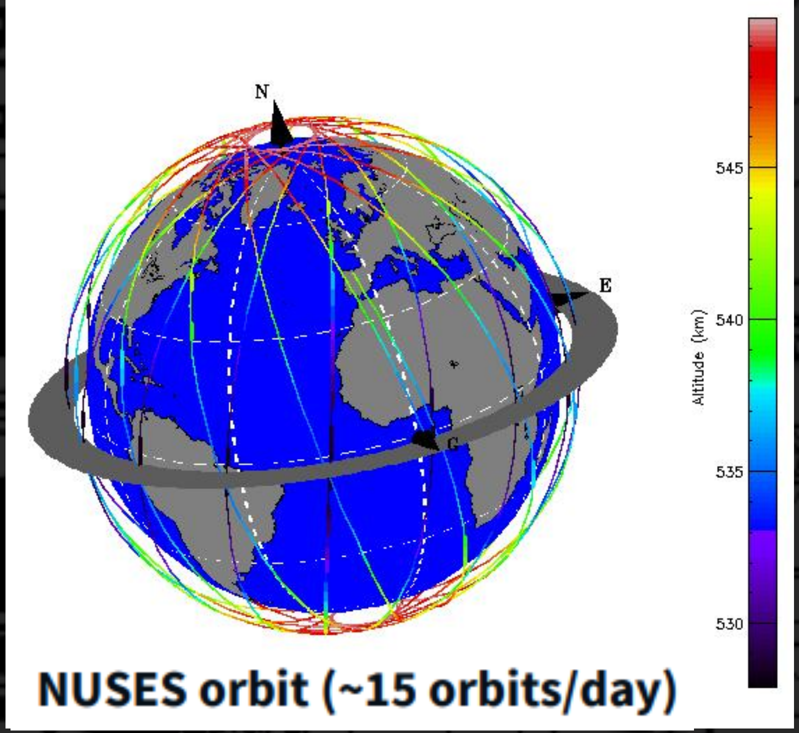
Radiation damage in silicon with proton and electron

SPENVIS: the NUSES project

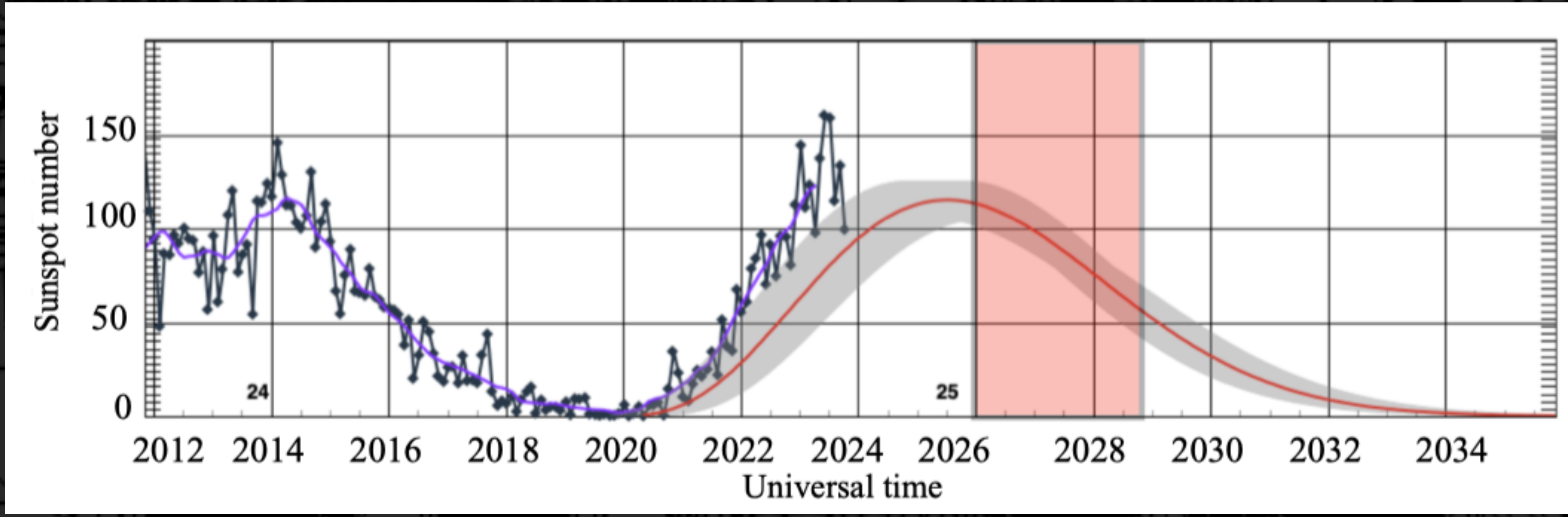
Evaluation of radiation fluxes for LEO space missions

The expected fluxes for the NUSES spacecraft averaged on 15 orbits (1 day) during its operation time for:

- Solar particle events (SPEs)
- Trapped protons and electrons in the Van Allen radiation belts
- Galactic cosmic rays (GCRs)
- Earth's Albedo contribution not taken into account



NUSES orbit (~15 orbits/day)



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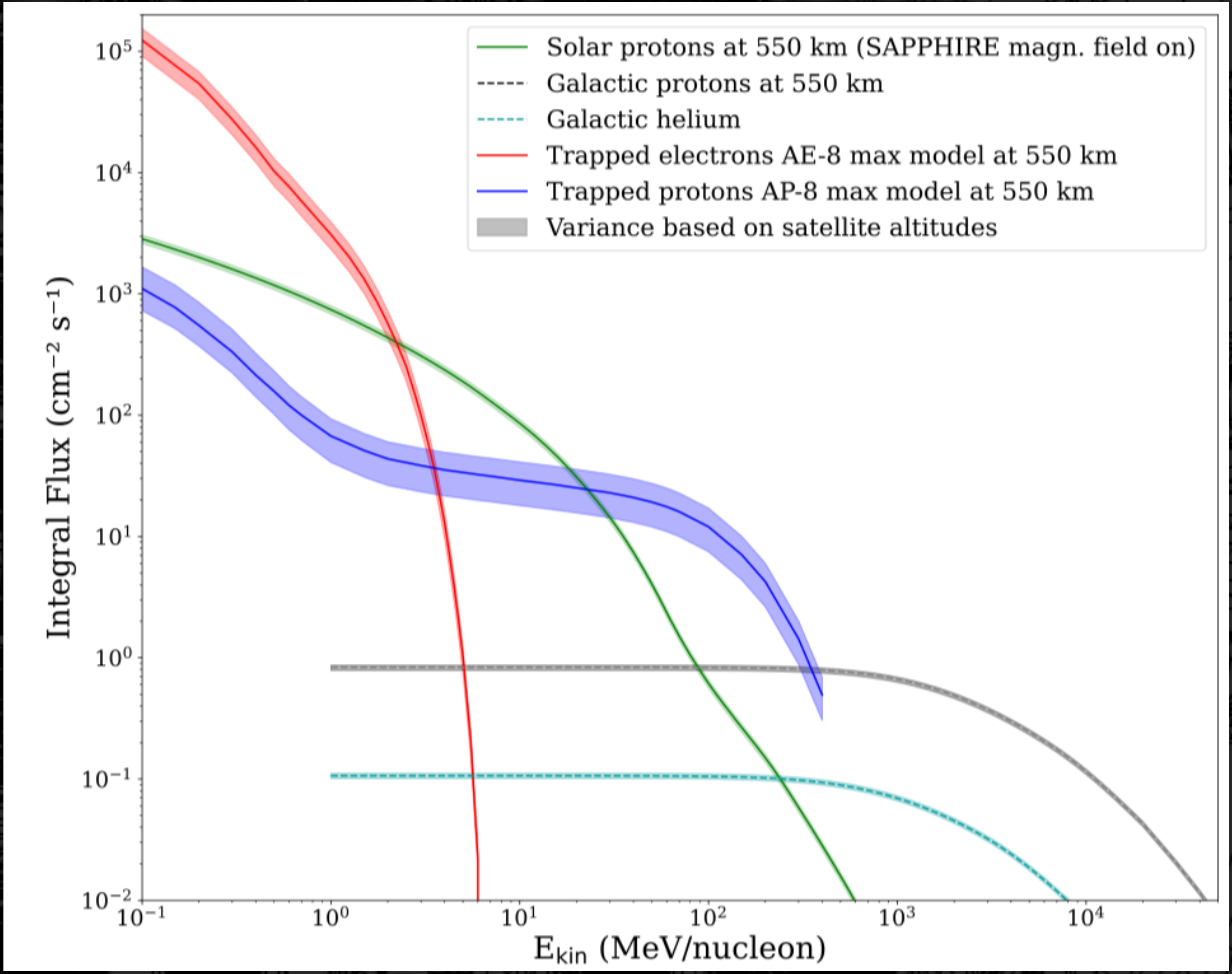

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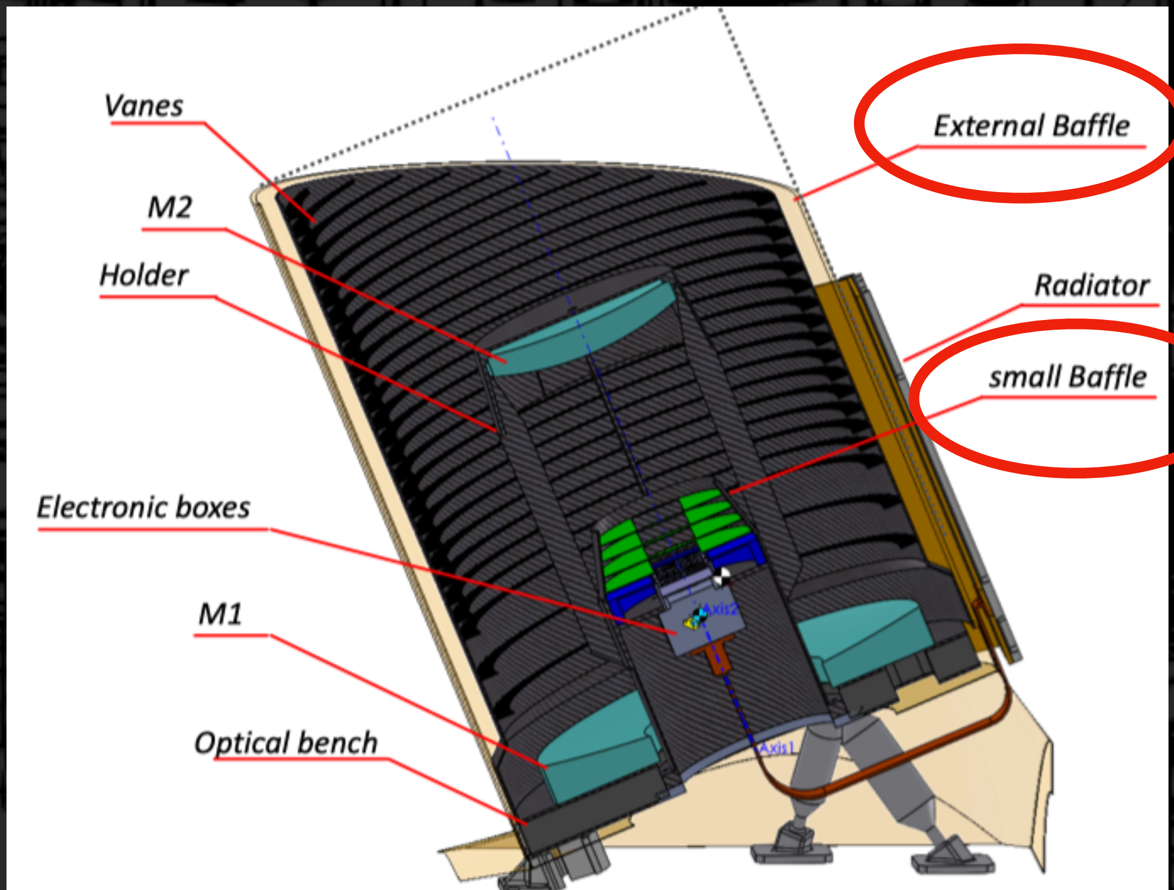
Geant4 simulation

Dose estimates from radiation in space with Geant4

To estimate the dose that we expect on Terzina's camera, we simulated the geometry of the telescope in Geant4

1. The mechanics: we tested different geometrical configurations varying the thickness and height of the external baffle and the thickness of the small baffle



*Preliminary geometry and optics in the paper

baseline geometry

- an external baffle (Carbon fibre)
thickness = 1 mm
maximum height = 730 mm

- the small baffle (Carbon fibre)
thickness = 1 mm

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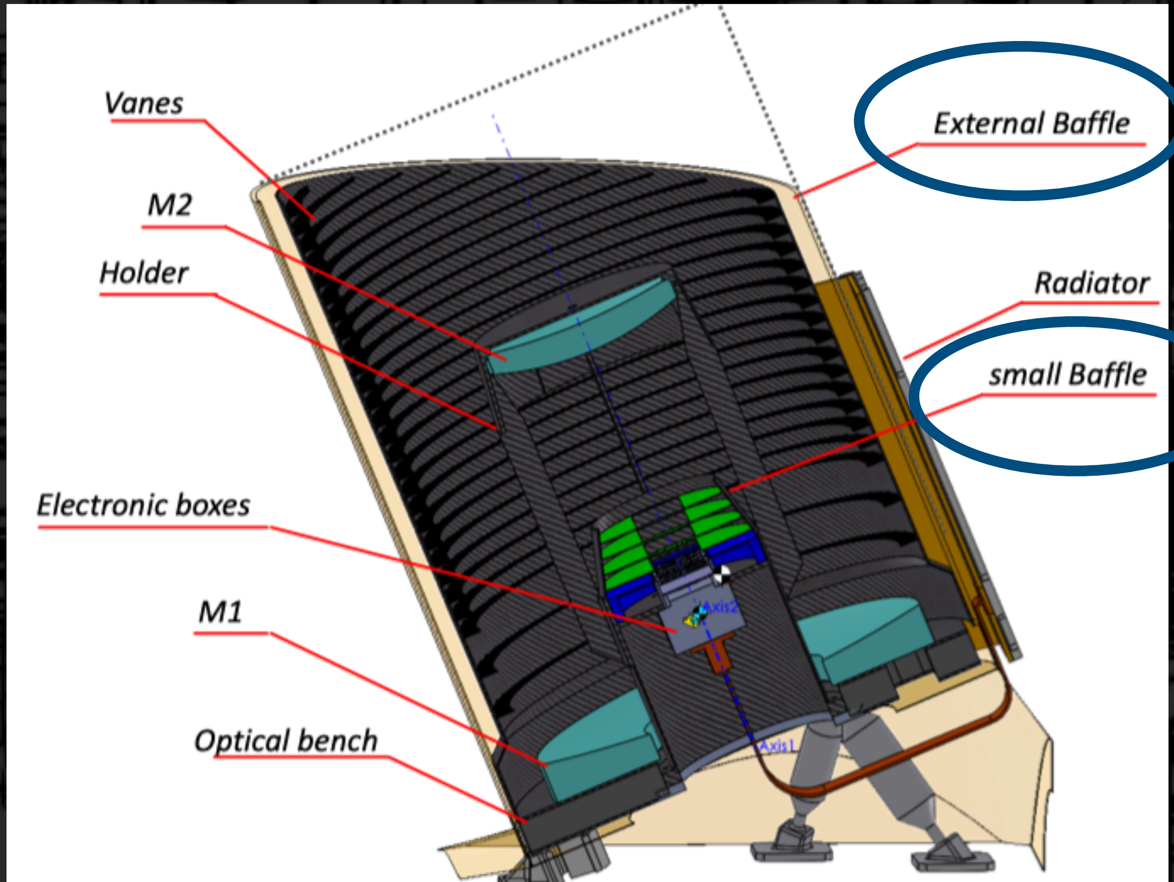

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benchmark geometry

- an external baffle (Carbon fibre)
thickness = 1 mm
maximum height = 730 mm

- the small baffle (Carbon fibre)
thickness = 4 mm

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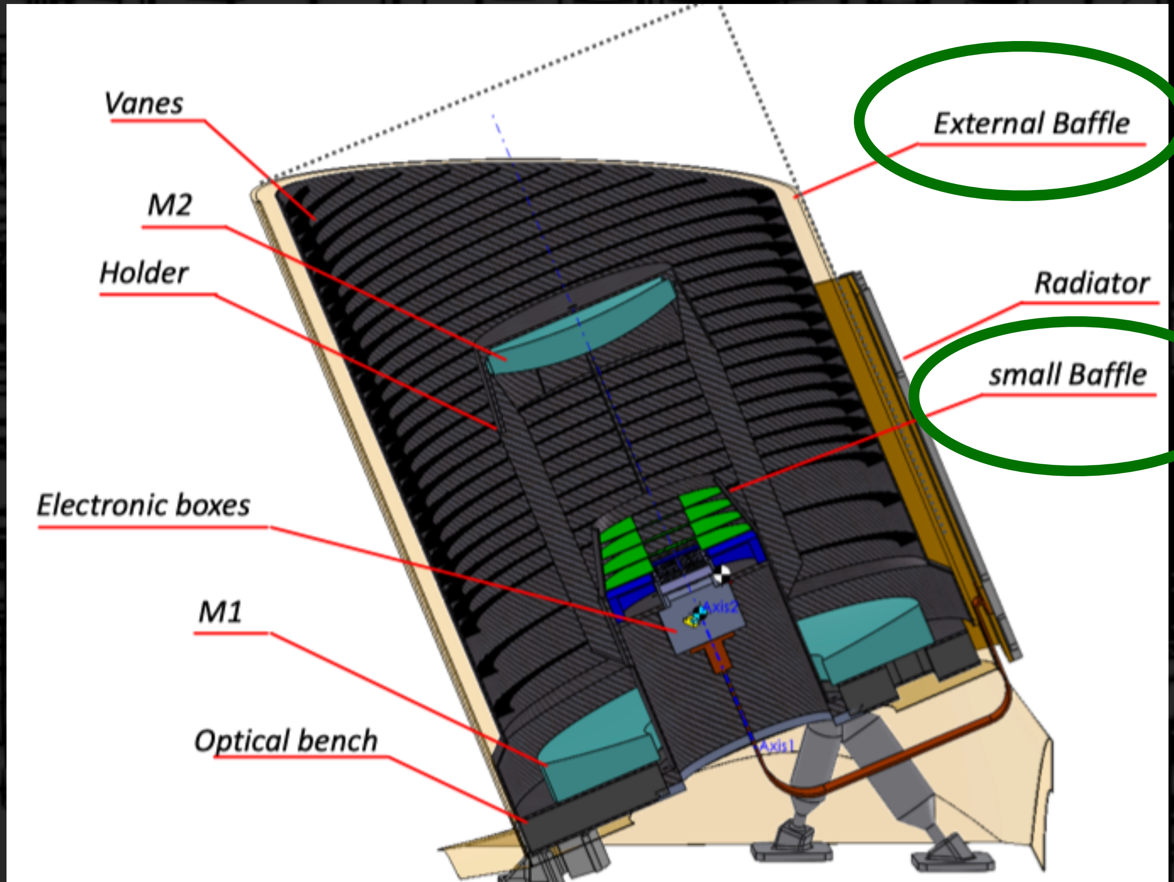

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shielded geometry

- an external baffle (Carbon fibre)
thickness = 2 mm
maximum height = 730 mm (full, without transverse cut)

- the small baffle (Carbon fibre)
thickness = 4 mm

Geant4 simulation

Dose estimates from radiation in space with Geant4

To estimate the dose that we expect on Terzina's camera, we simulated the geometry of the telescope in Geant4

2. The injected particles: electrons and protons considering isotropic direction and energy range of the corresponding SPENVIS candidates fluxes;

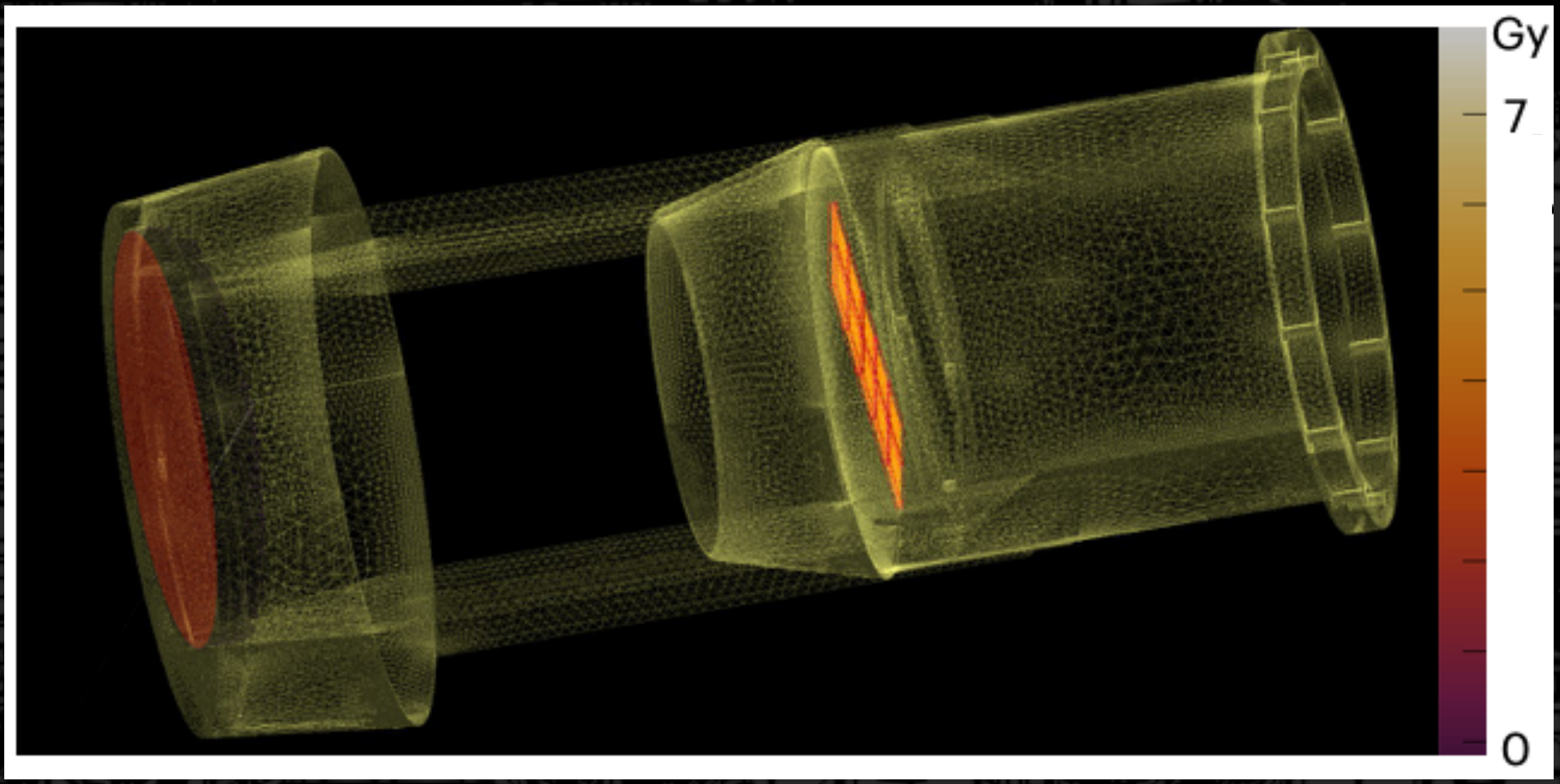
3. The total energy deposited in the sensitive volume of the FPA tiles and in the PCB, $E_{\rm dep}$ returned in MeV, has been calculated by Geant4

Differential fluxes $\frac{d\phi}{dE}$ integrated over a sphere of radius R = 50 cm surrounding the considered volumes and for the duration of the mission $t_{\rm EoL} = 3$ years

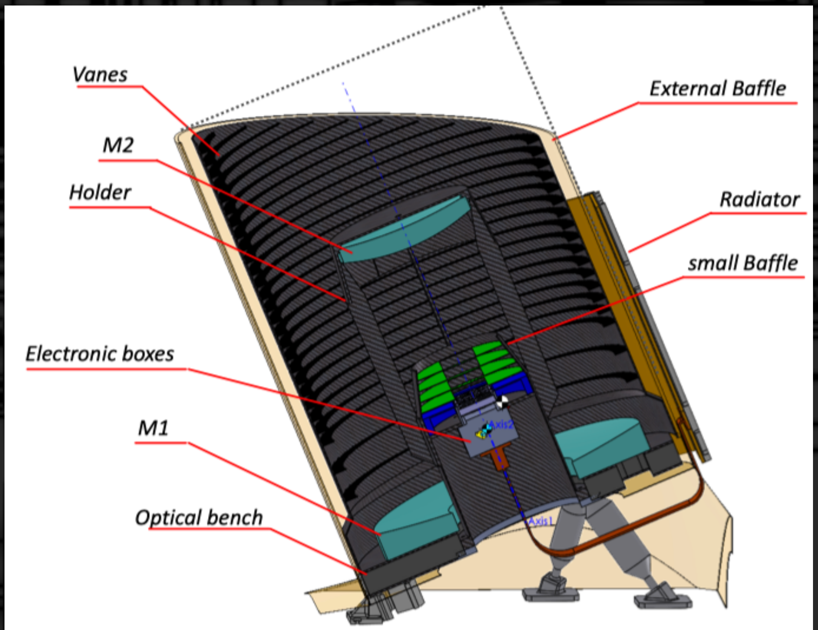
$$\Delta D(E) = \frac{4\pi R^2 t_{EoL}}{2M_{tot}} c_{\rm MeVJ} E_{dep} \Delta\phi(E)$$

Geant4 simulation

Dose estimates from radiation in space with Geant4



The small CF baffle (4 mm) shields most of the expected radiation!



		Trapped e $\mathcal{D}$ (Gy)	Trapped p $\mathcal{D}$(Gy)	solar p $\mathcal{D}$ (Gy)
baseline	sensors	14.4 ± 2.5	0.71 ± 0.28	2.35 ± 0.04
	PCB	5.35 ± 0.82	0.58 ± 0.20	1.32 ± 0.02
benchmark	sensors	10.6 ± 3.3	0.64 ± 0.23	2.06 ± 0.03
	PCB	5.70 ± 0.92	0.52 ± 0.18	1.27 ± 0.02
shielded	sensors	3.65 ± 0.52	0.50 ± 0.17	0.81 ± 0.01
	PCB	2.10 ± 0.28	0.49 ± 0.17	0.64 ± 0.01

Geant4 simulation

Dose estimates from radiation in space with Geant4

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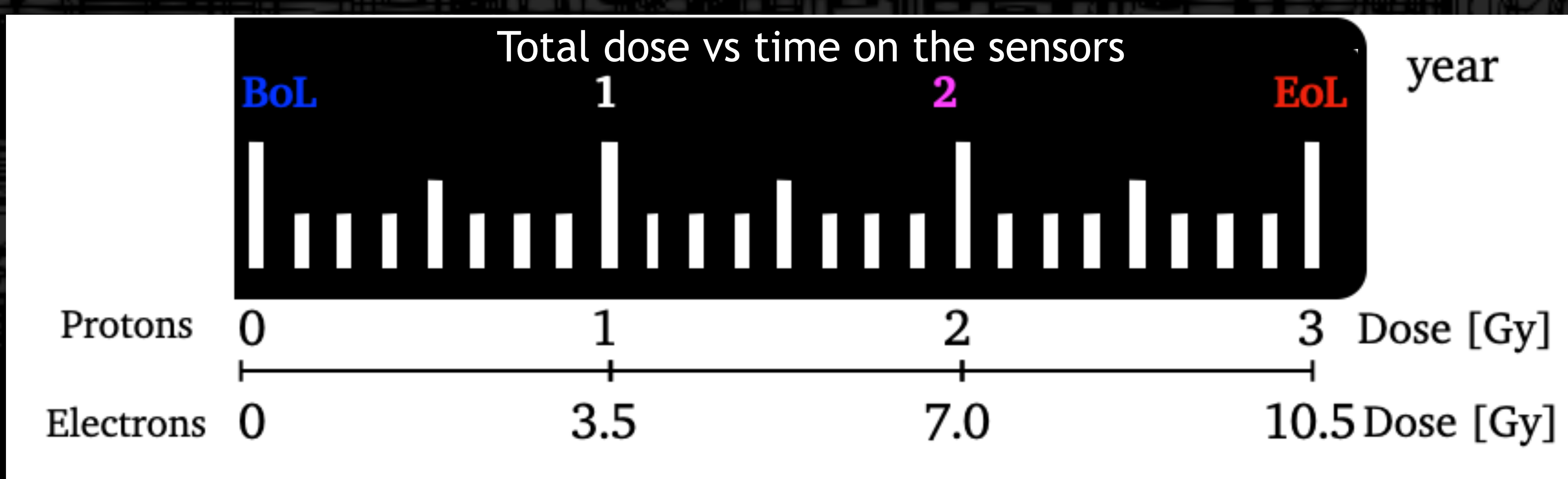
benchmark	sensors	10.6 ± 3.3	0.64 ± 0.23	2.06 ± 0.03
	PCB	5.70 ± 0.92	0.52 ± 0.18	1.27 ± 0.02
shielded	sensors	3.65 ± 0.52	0.50 ± 0.17	0.81 ± 0.01
	PCB	2.10 ± 0.28	0.49 ± 0.17	0.64 ± 0.01

From this simulation we obtain the total dose as a function of the mission time



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how much this dose affects the DCR of our sensors?

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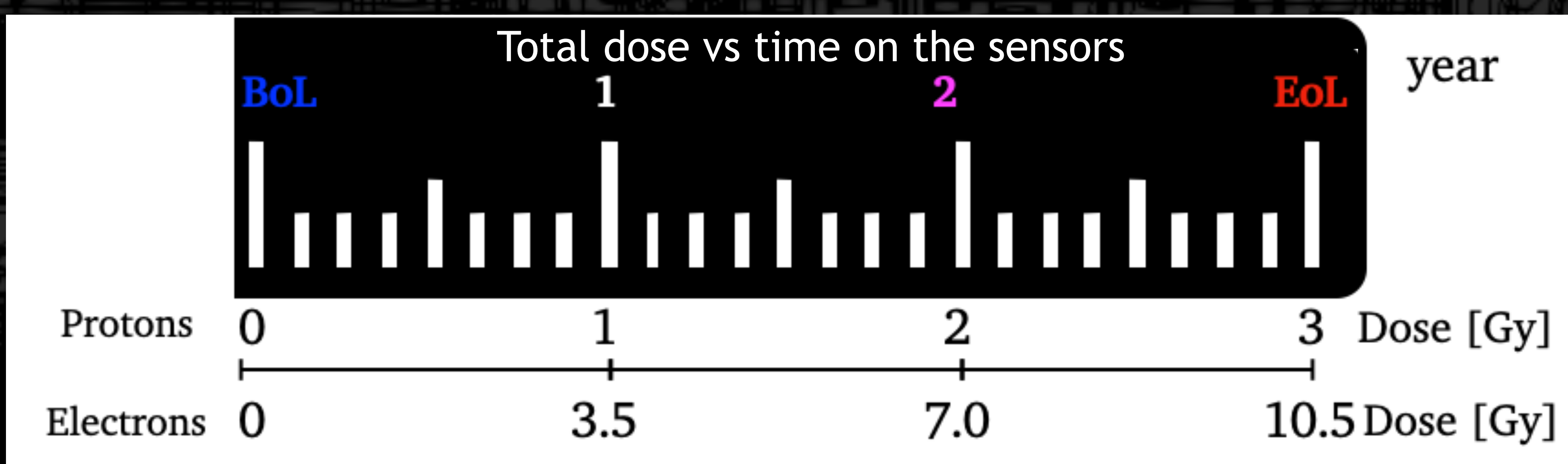

how much this dose affects the DCR of our sensors?

-> When an energetic charged particle hits a SiPM, it deposits energy through both **ionizing** and **non-ionizing** processes;

-> In silicon, bulk damage is due to Non-Ionizing Energy Loss (NIEL) and surface damage by Ionizing Energy Loss (IEL);

-> Bulk damage is due to high-energy particles which can displace atoms out of their lattice creating defects

-> The defects in silicon crystals lead to an increase in leakage current due to the generation of electron-hole pairs from defects in the depletion region

This leads to a temperature-dependent increase in DCR, which is more significant for protons than for electrons, which primarily induce ionisation rather than defects due to their lower mass and less efficient energy transfer to the crystal lattice

Radiation Hardness for SiPMs in LEO Missions

SPENVIS

Evaluation of radiation fluxes for LEO space missions

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LAB

Irradiation campaigns for NUSES

- TID Test
  see G. Fontanella
- Proton test
- Electron test

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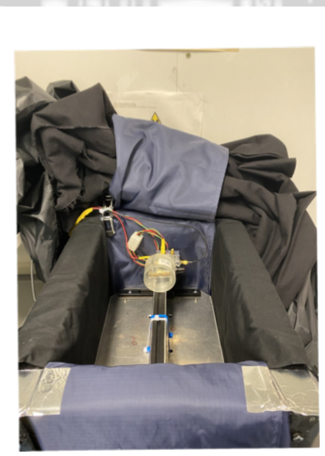
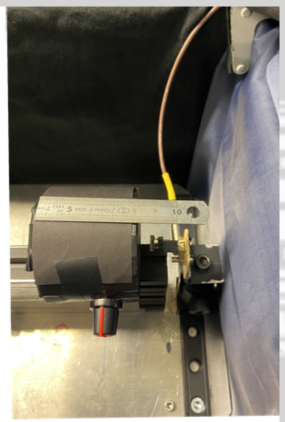
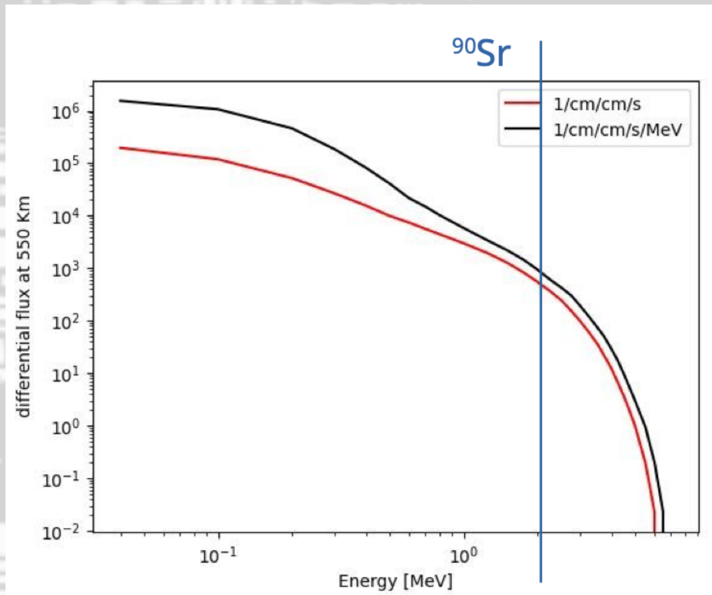
Irradiation measurement

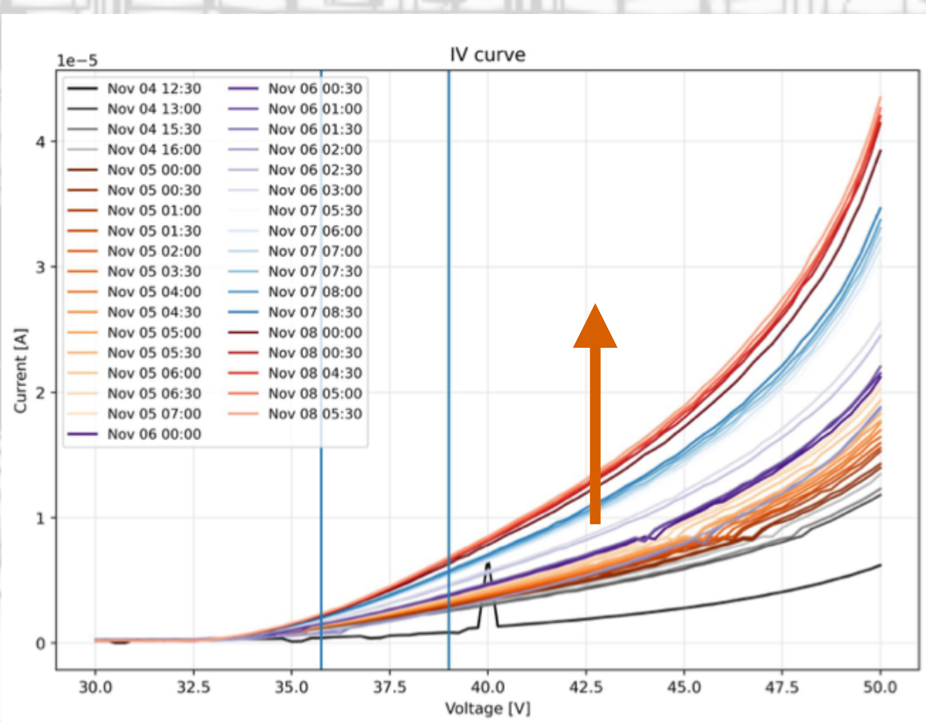
Electrons







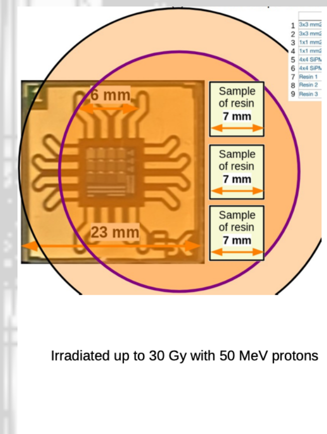
SiPM 3x3 40 μm without resin irradiated by electrons produced by the Sr90 source

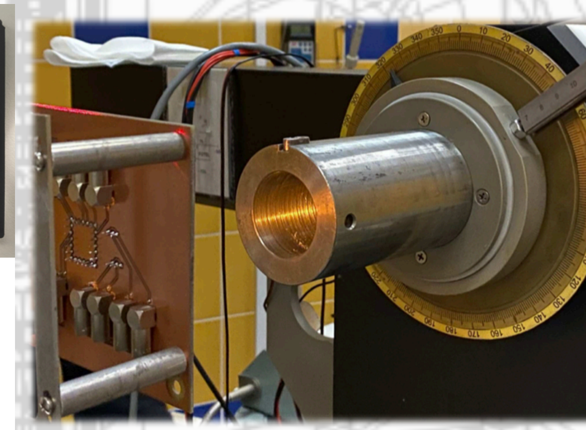


Increase of post-breakdown, multiplied current (Dark counts)

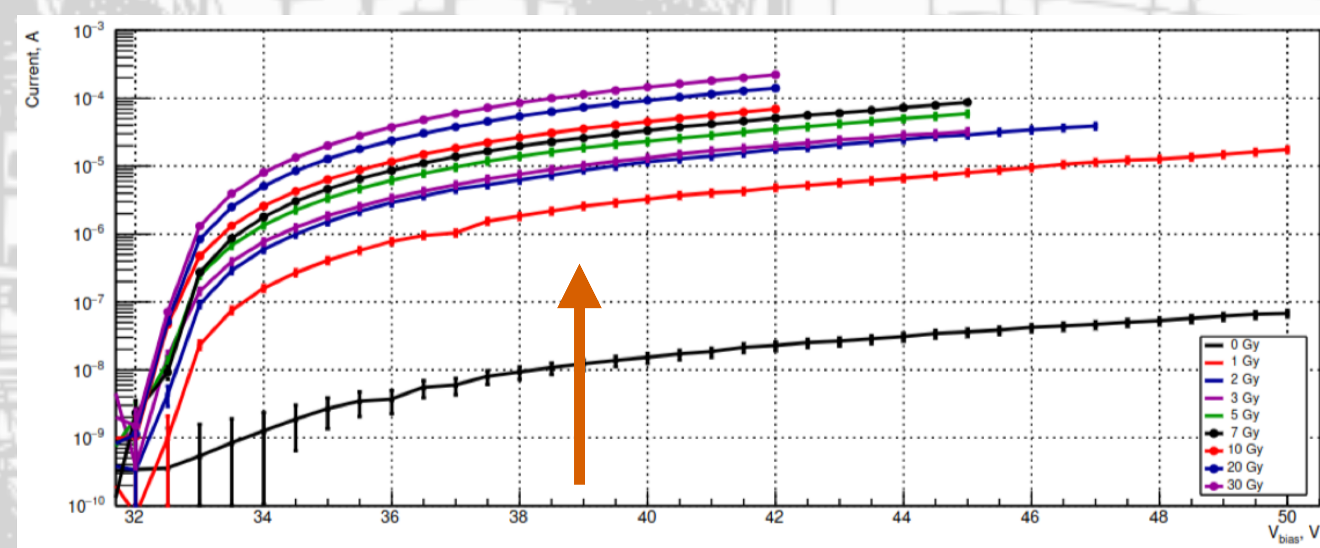
Irradiation

Protons



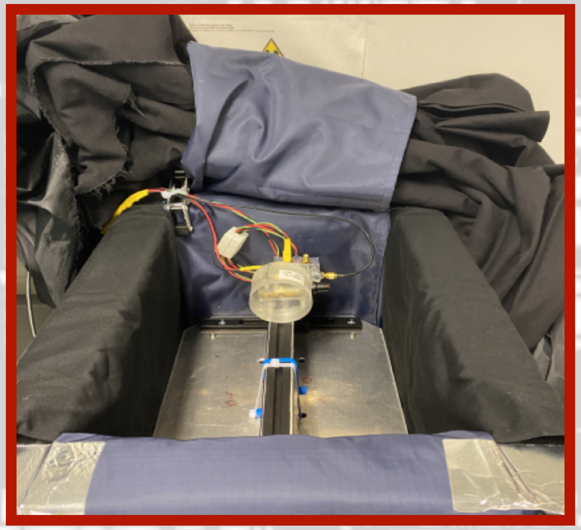


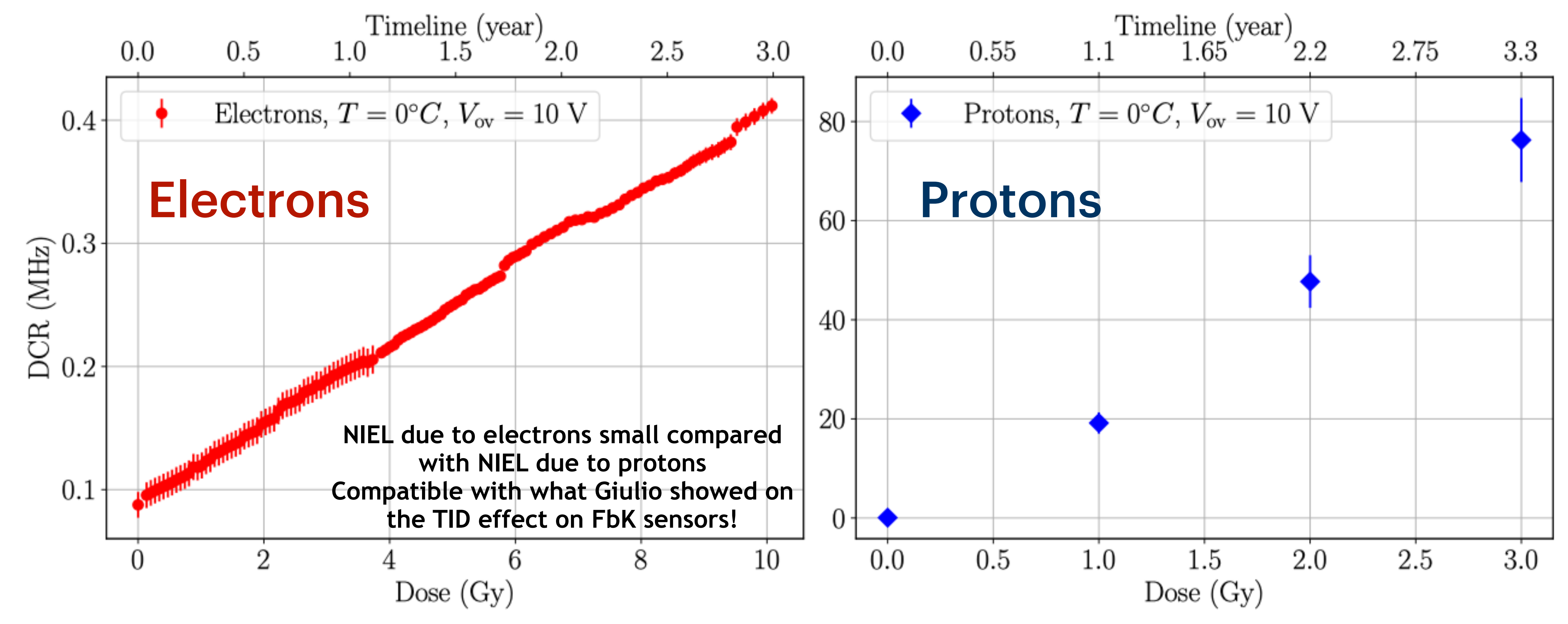
Many SiPM devices have been irradiated with 50 MeV protons up to 30 Gy



Irradiation measurement

Inferred DCR per pixel for Terzina SiPMs sensitive area ~6.58 mm^2 from IV measurements





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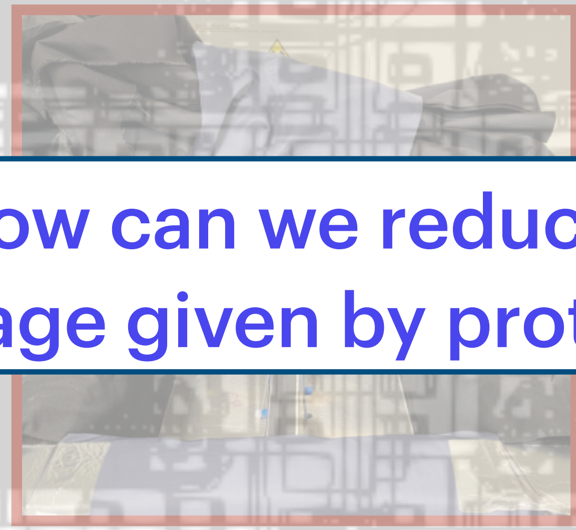
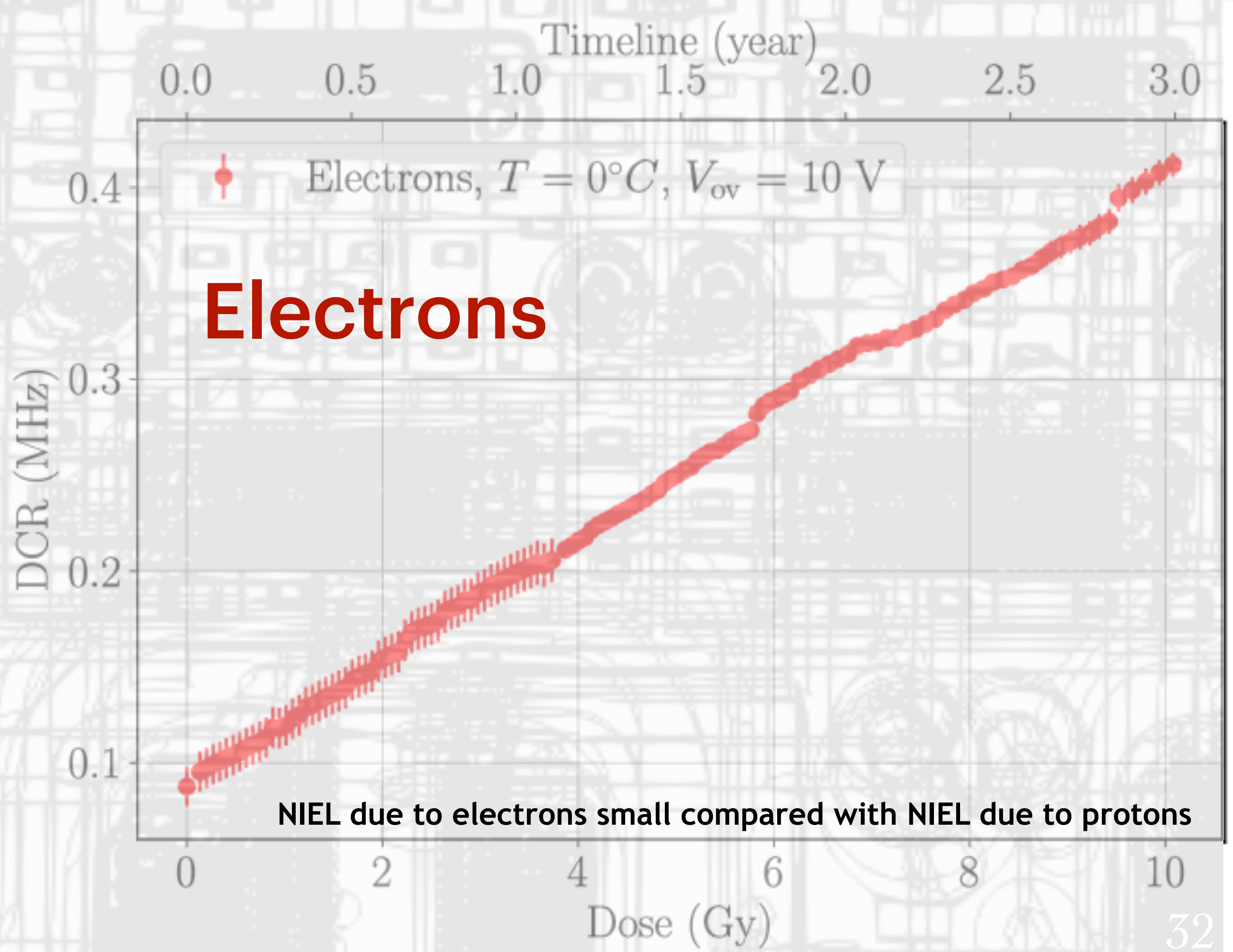
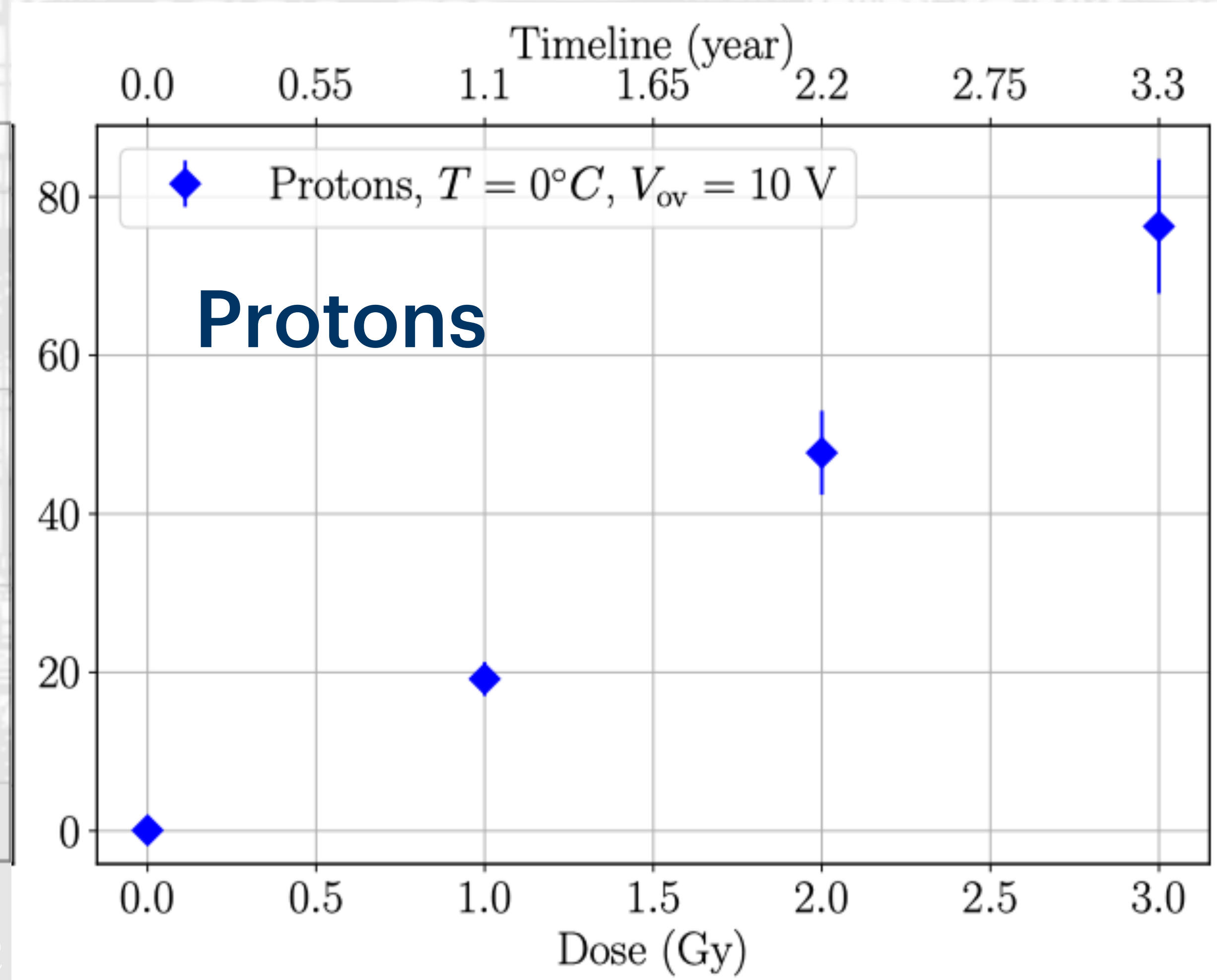


How can we reduce the damage given by protons????





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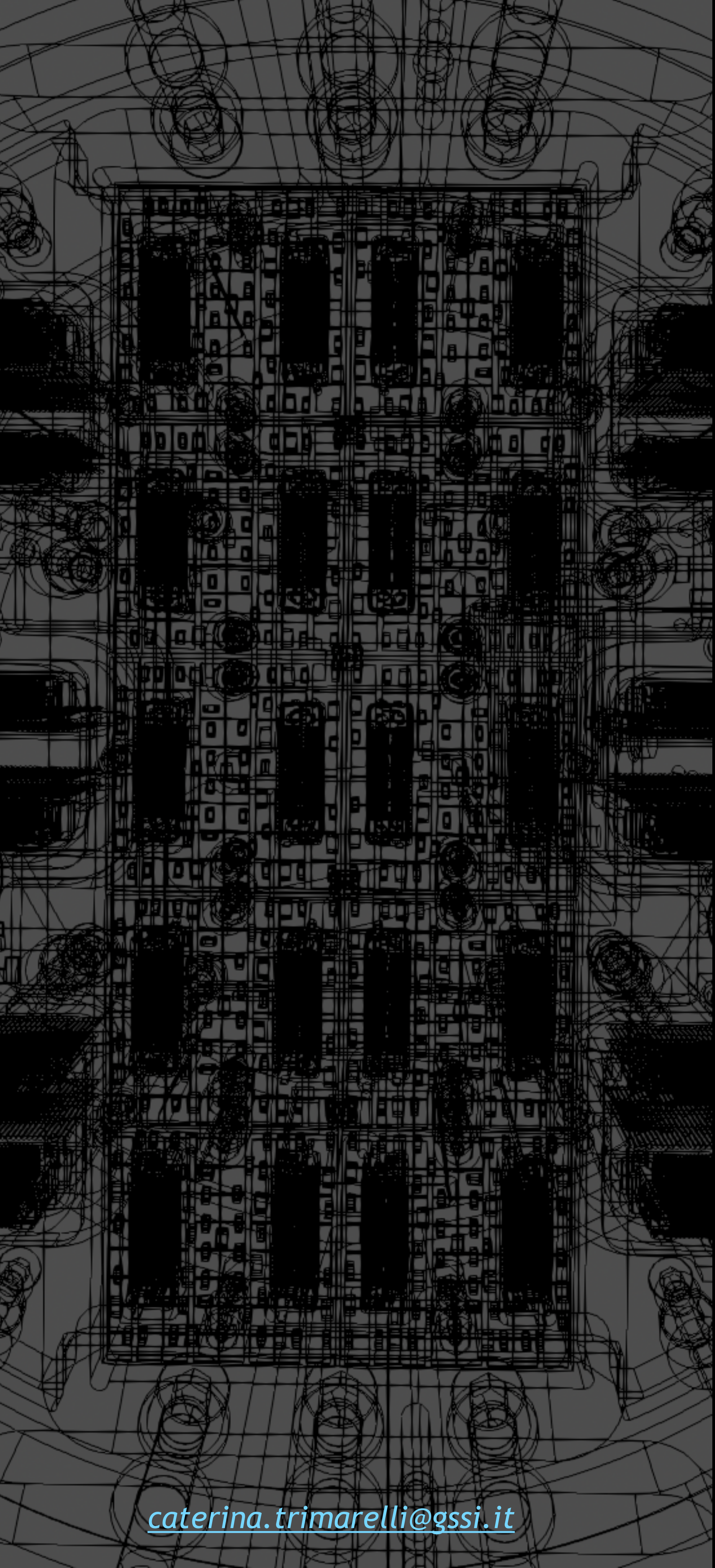

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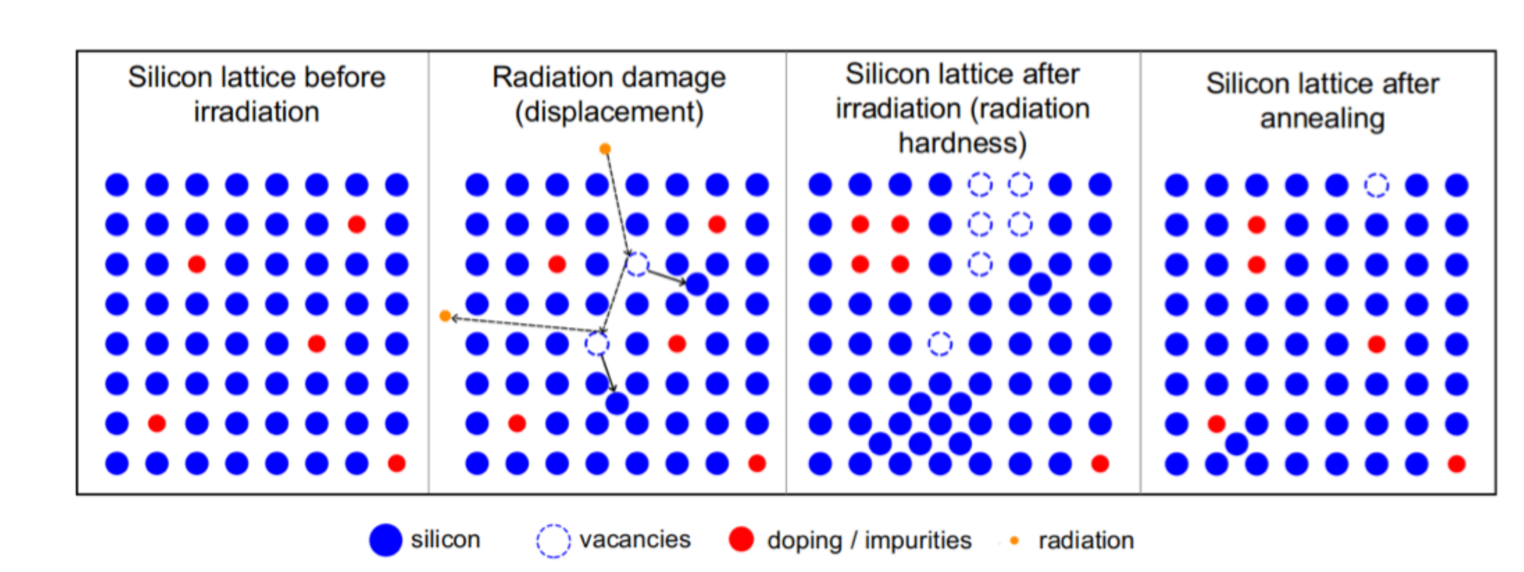
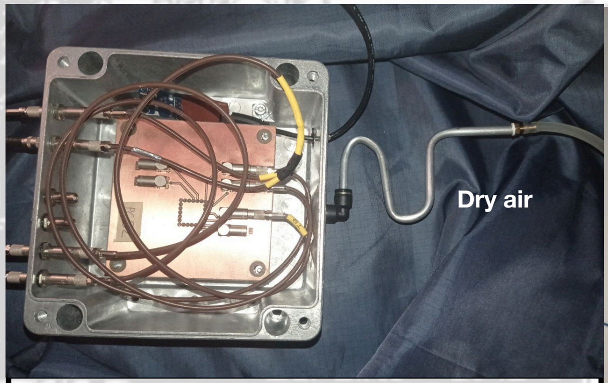
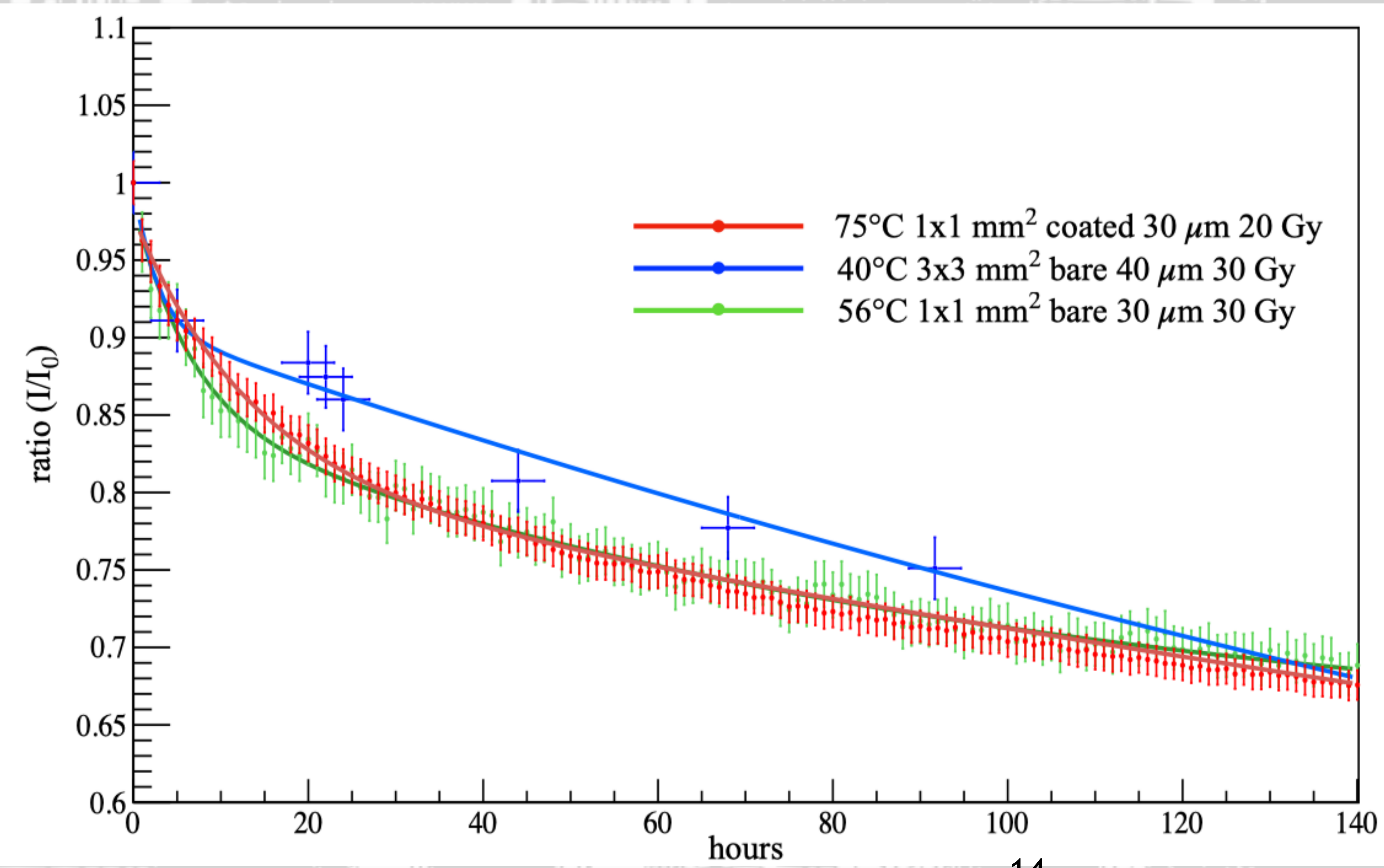
Annealing





Putting the devices in a climatic chamber at a fixed temperature for a certain period of time



We can conclude that for at least $T > 50^{\circ}$ C after 84 hours we recover 40%!

Use this information to do a cycle procedure during the mission

In order to maintain a stable signal-to-noise ratio during the entire mission!

DCR prediction during mission

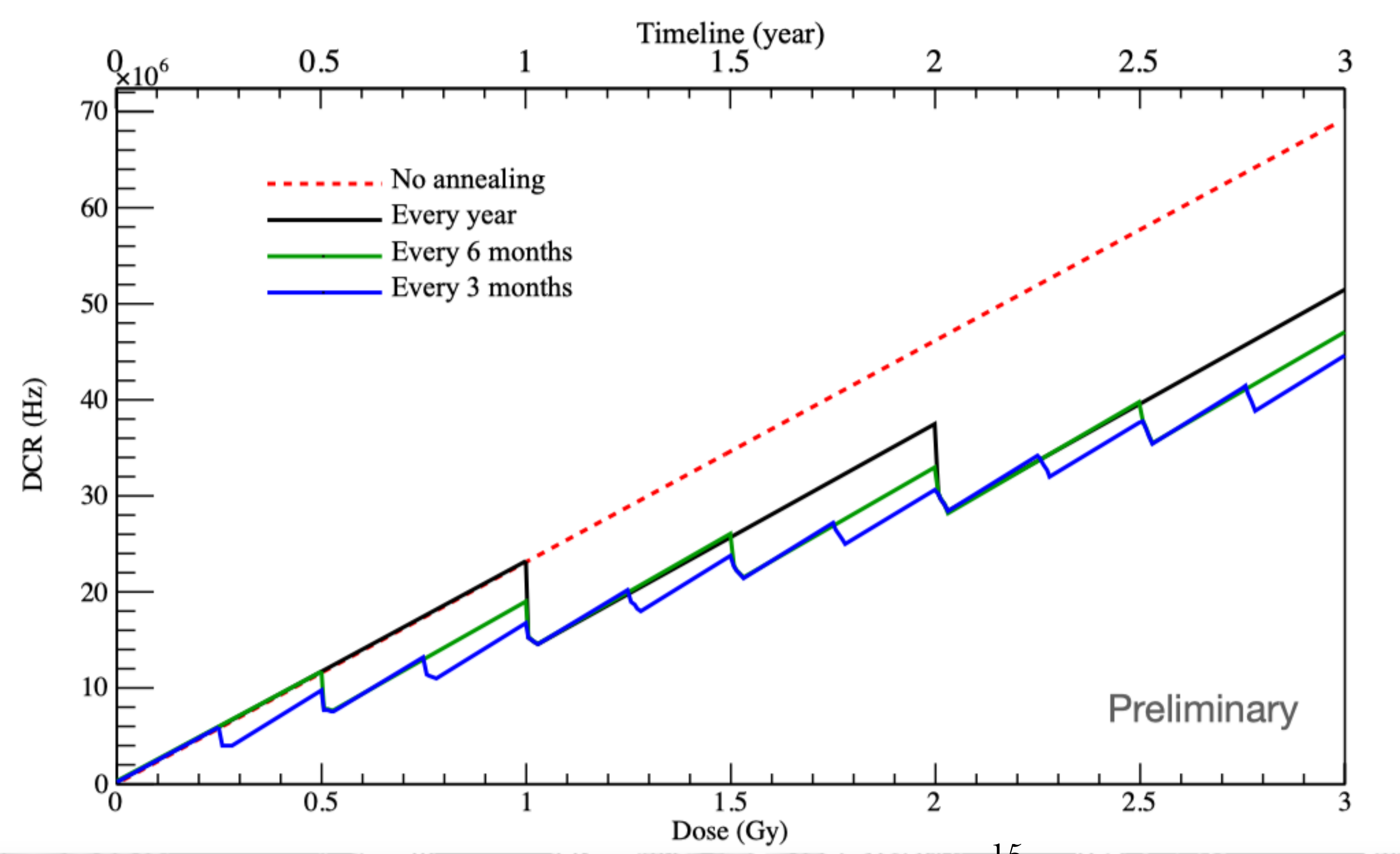
$$\frac{d\mathrm{DCR}}{dt} = C_{\mathrm{ir}} + C_{\mathrm{an}}\mathrm{DCR}$$

1) Pure irradiation cycle

$$\mathrm{DCR} = C_{\mathrm{irr}}t + \mathrm{const}$$

2) Pure annealing cycle

$$\mathrm{DCR} = \exp(C_{\mathrm{ann}}t + \mathrm{const}_1) + \mathrm{const}_2$$



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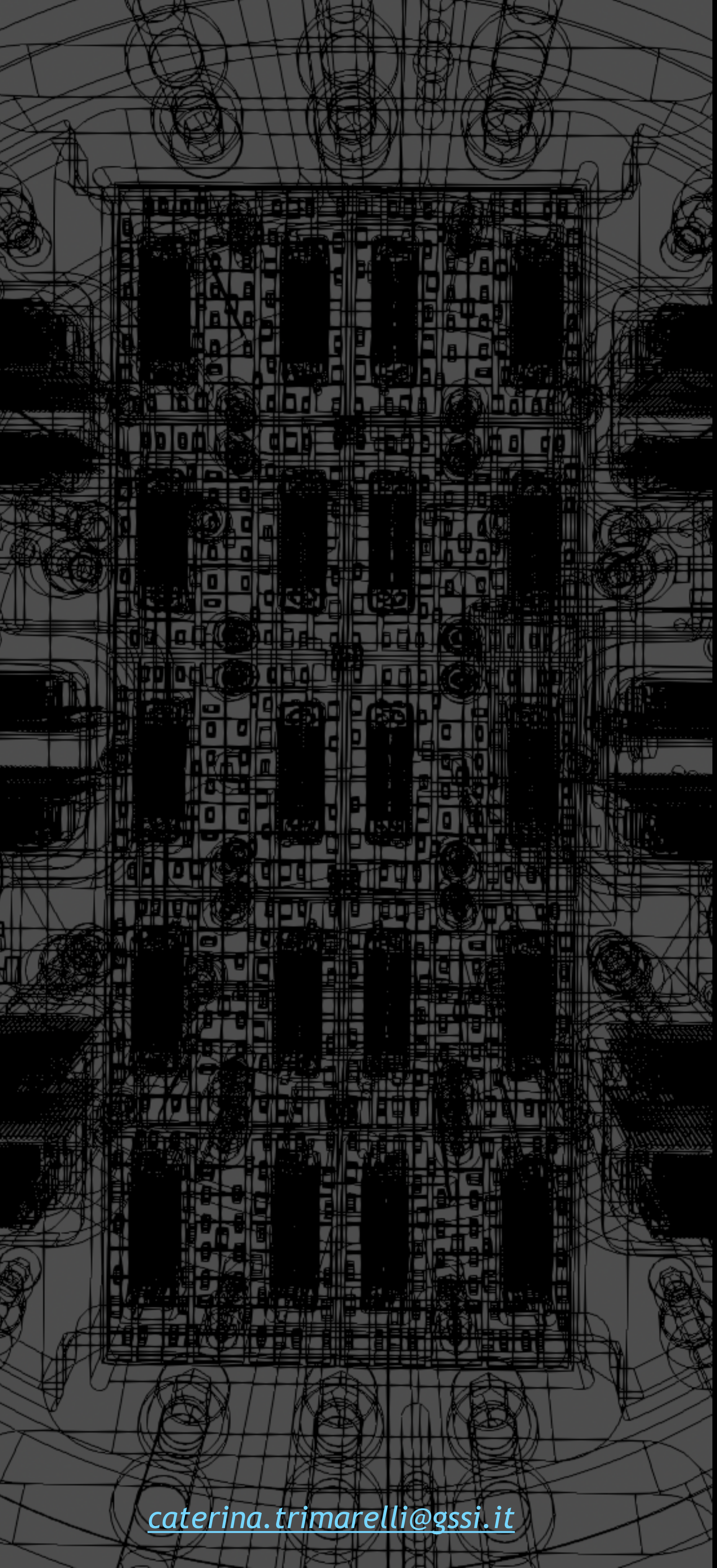

Conclusions

- Full the characterisation of FBK SiPMs which allowed to select the optimal size of the μ -cells of SiPMs to adopt in the Terzina mission;
- Determination of the increase of the power consumption with radiation damage.
- Mitigation strategy based on periodic annealing during the mission.
- Developed model can be used to apply similar mitigation strategies on future LEO missions
- Final terzina tiles have been tested and characterized
- Requirements for Terzina tiles achieved
- FPA finally mounted to do the quality tests!

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THANKS

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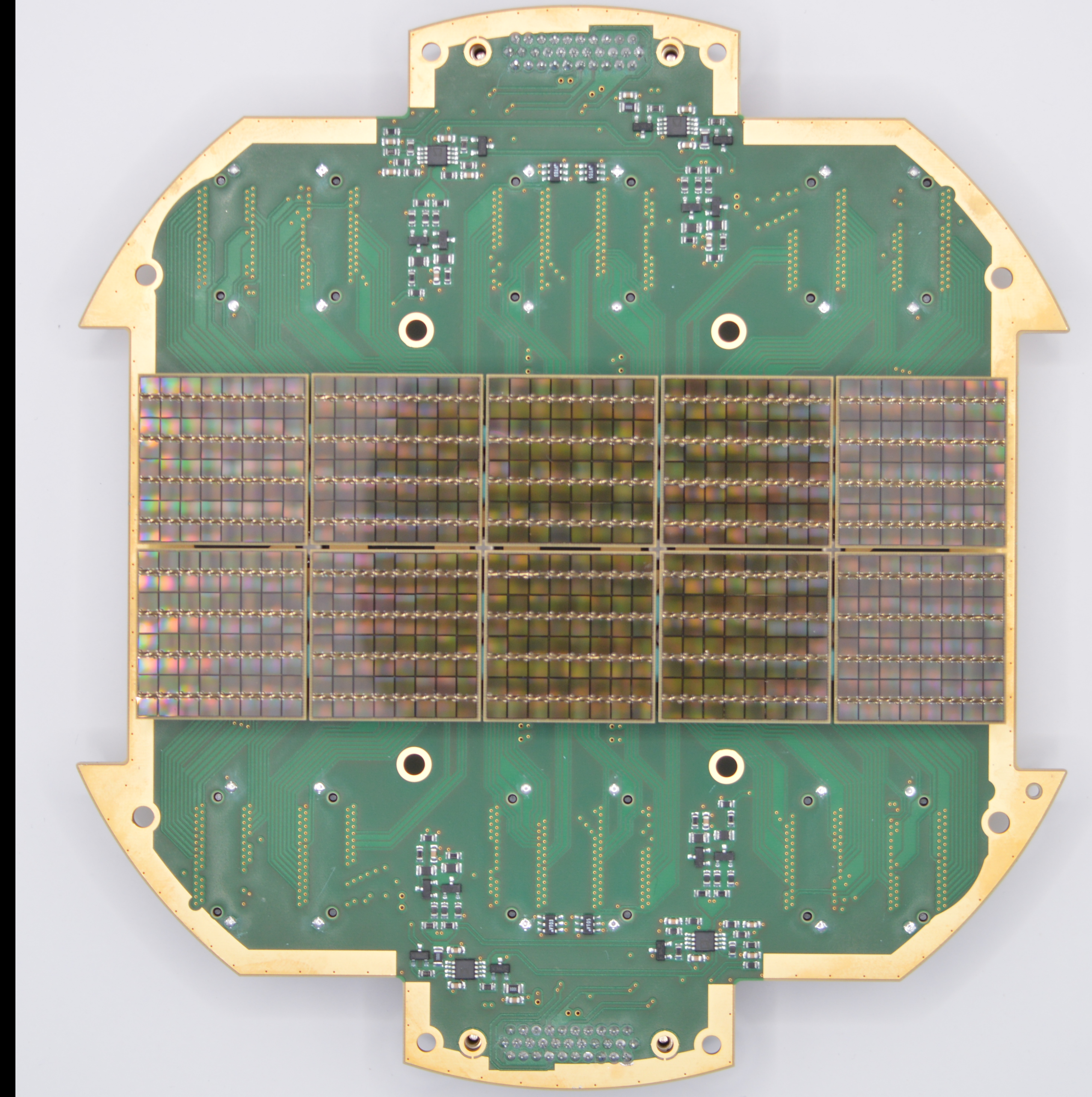

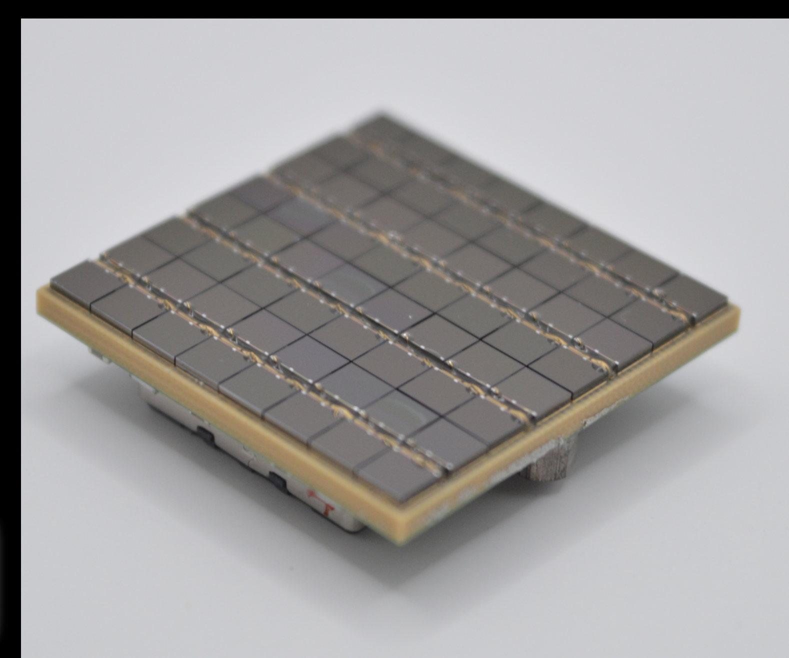

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