Temperature Dependence of Radiation Damage Annealing of Silicon Photomultipliers

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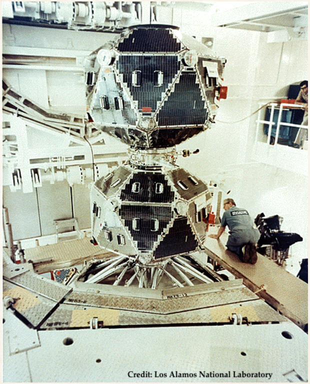
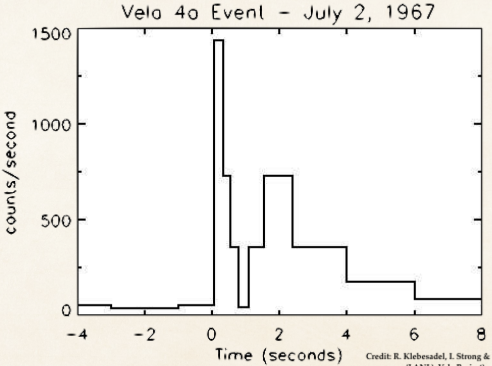
- First GRB discovered by chance in 1967 by the Vela US military satellites monitoring USSR nuclear test activity in space after the signature of Nuclear Test Ban Treaty

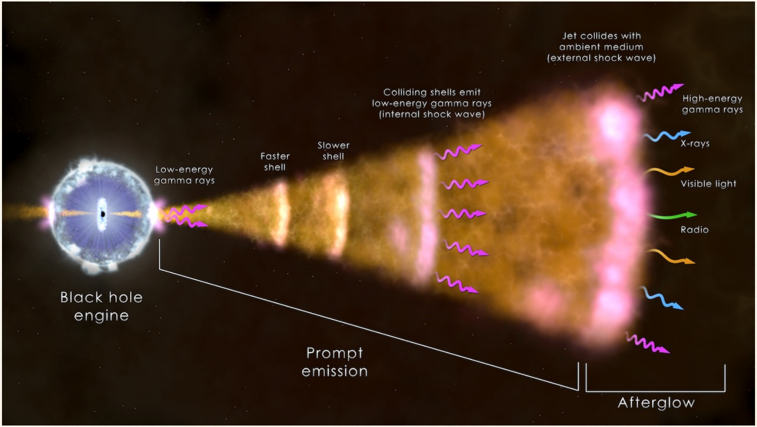




Credit: R. Klebesadel, I. Strong & R. Olson (LANL), Vela Project)

Science framework: The Gamma-Ray Bursts paradigm

- Bright and short transient event in the γ band (**prompt emission**) followed by an **afterglow** spanning the entire EM spectrum



(Credit: NASA's Goddard Space Flight Center)

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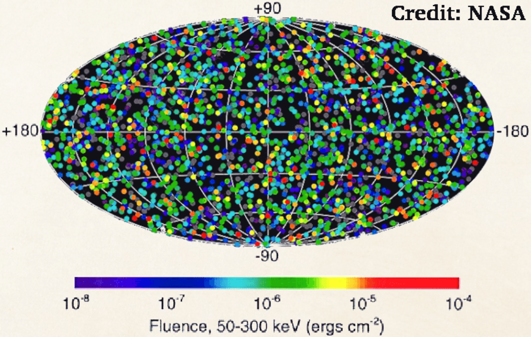
- GRBs are uniformly distributed in the sky, have very diverse spectral properties and fluence, and are of extragalactic origin



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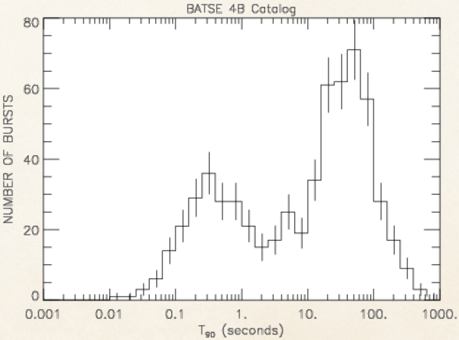
- GRBs are uniformly distributed in the sky, have very diverse spectral properties and fluence, and are of extragalactic origin
- Classified in two categories: short GRBs (T_{90}<2 s) are originated by binary compact object merger, long ones (T_{90}>2 s) are associated with supermassive star explosions

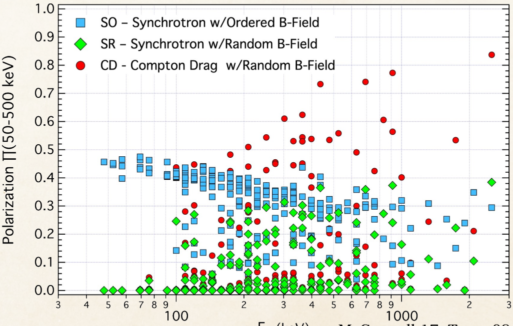


(Credit: BATSE 4B Catalog, Robert S. Mallozzi)

Science framework: Why measuring GRB polarization ?

Spectral information alone does not allow to disentangle the existing emission models.
Measuring polarization is a very powerful tool to probe the physics of GRBs, as it can inform us about:

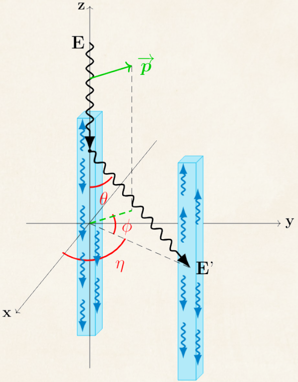
- The emission mechanism at play in the source (synchrotron vs. photospheric)
- The outflow dynamics: Kinetic Energy vs. Poynting Flux Dominated
- The jet angular structure: top hat jet, with smooth edges, truly structured
- The magnetic field configuration (random, ordered)



McConnell 17, Toma 09

Science framework: the POLAR-2 GRB polarimeter

- POLAR-2 is a large scale GRB polarimeter
- It consists of a segmented detector making use of Compton scattering to measure the polarization of incoming γ-rays
- Designed as an array of elongated plastic scintillators (converting γ-rays to optical light) readout by **SiPMs** (Silicon-based light sensors)
- Half sky field-of-view to catch many GRBs, sensitive in the 20-800 keV range
- Planned for a launch to the CSS in 2027



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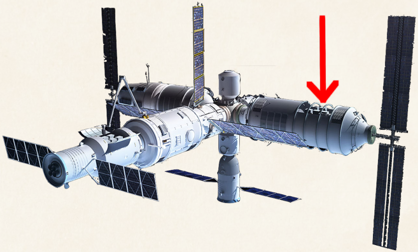
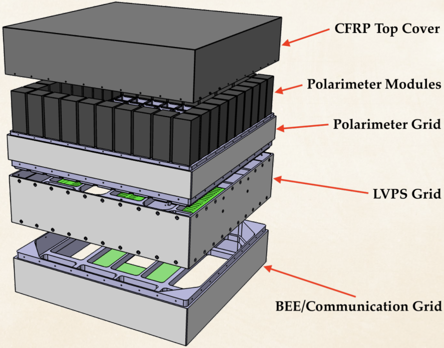
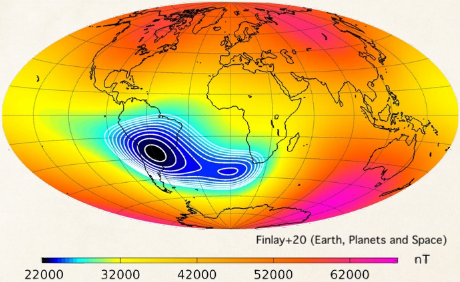




In-orbit radiation environment

In-orbit radiation environment is dominated by protons, which can damage silicon-based technologies operated in-orbit, especially when crossing the SAA



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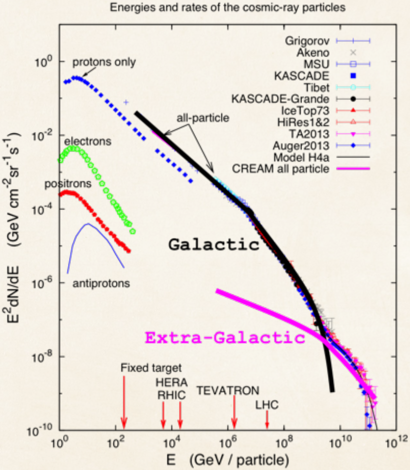
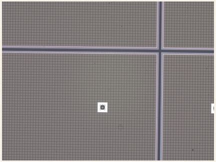
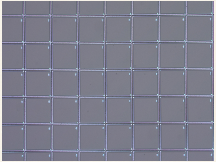
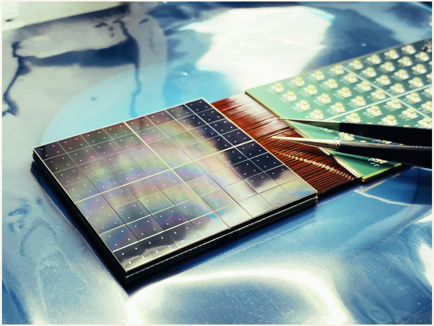


T.K. Gaisser 2016

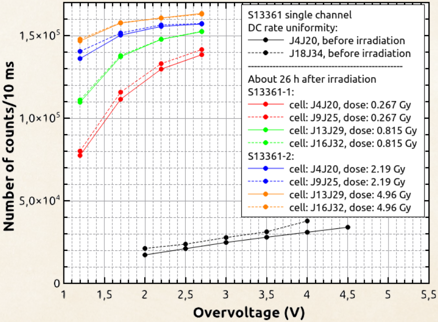
Radiation damages SiPMs by inducing defects in the silicon lattice, leading to a higher DCR and dark current, and therefore degrading the sensitivity of space-based instruments after some operation time





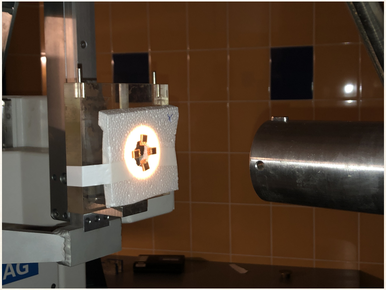


(Credit: Hybrid SA, POLAR-2 collab.)

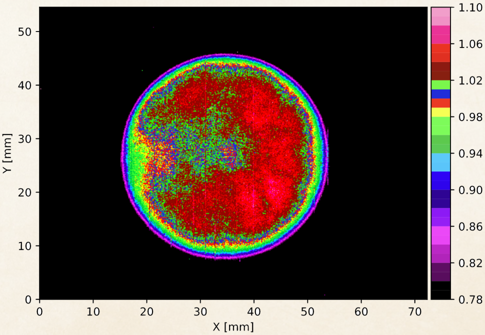


Exp. Astron. 55, p343–371 (2023)

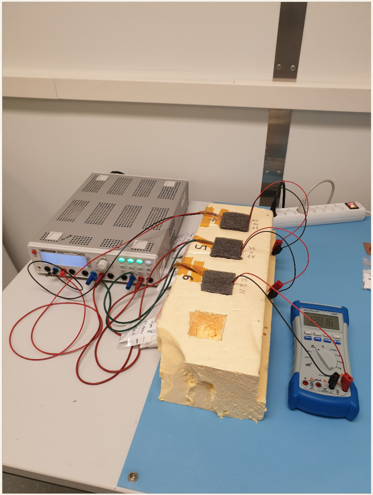
SiPM Thermal Annealing Irradiation Setup

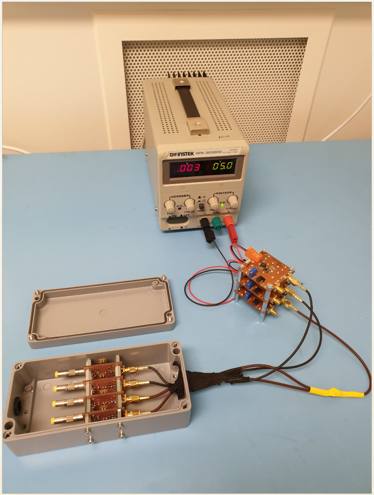


- NIM A 1048 (2023) 167934
- 58 MeV proton beam @IFJ-PAN, Krakow
- Sensors exposed to 0.134 Gy (equivalent to 1.7 yrs on the CSS according to Geant4 simulations)
- Fluence of 10^8 p/cm^2

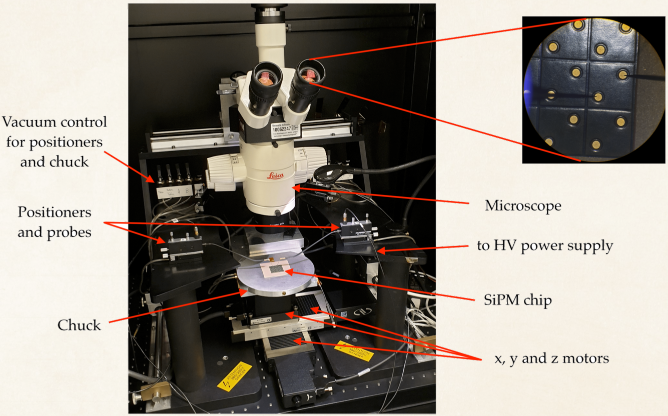


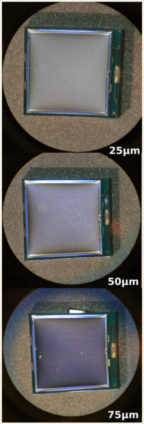
- 21 S13360-60xx SiPMs from Hamamatsu (25, 50, and 75 μm) stored at 6 temperatures ranging from -22.8 ± 1.8°C to 48.7 ± 3.3°C
- 4 of the sensors are stored with a bias ($\Delta V = 3, 8, 12$ V)



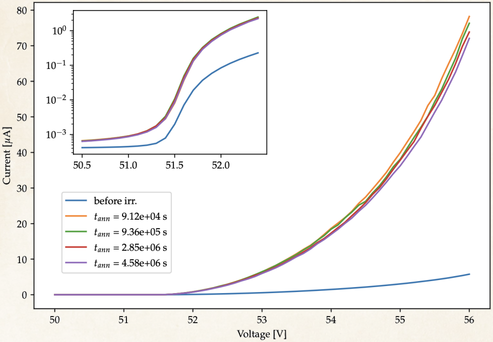


SiPM Thermal Annealing Probe Station Setup





I-V measurement versus time $-22°$C vs. $+20°$C



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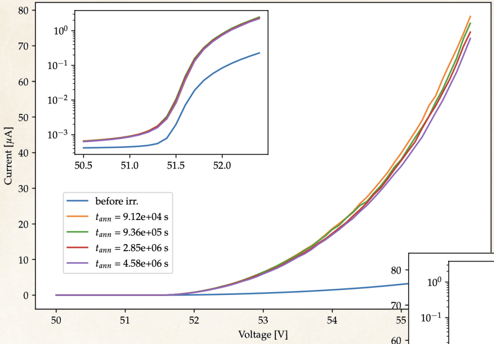
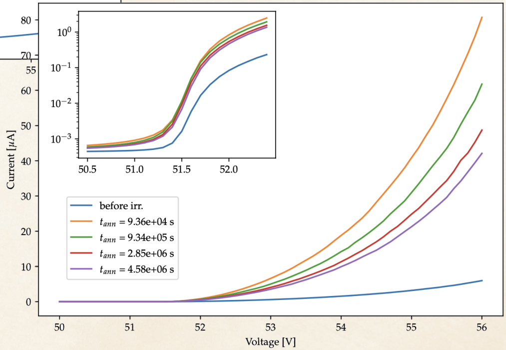
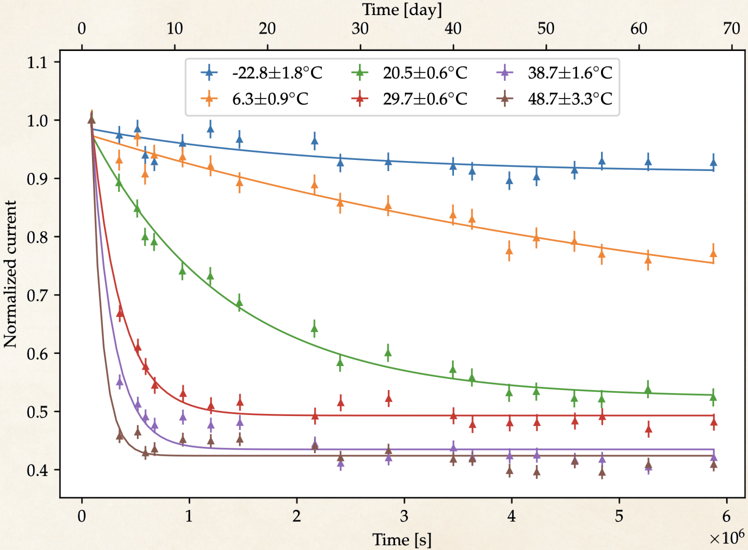
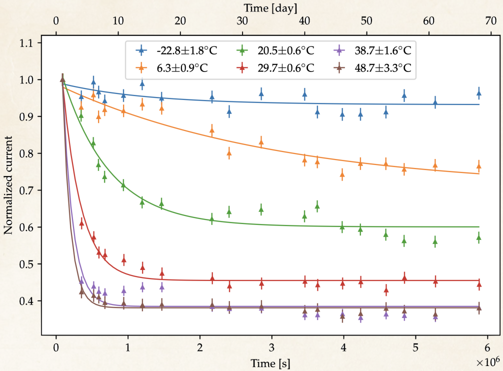




Time evolution of dark current at $\Delta V=3$ V 75 μm microcells



Time evolution of dark current at ΔV=3 V 25 and 50 μm



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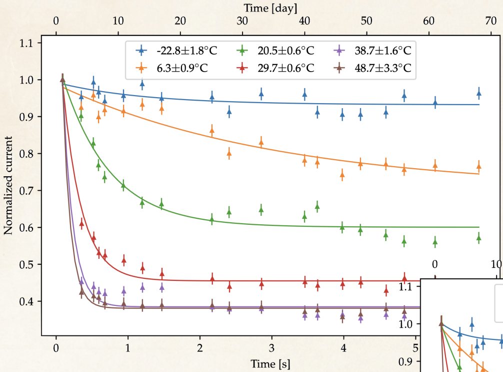
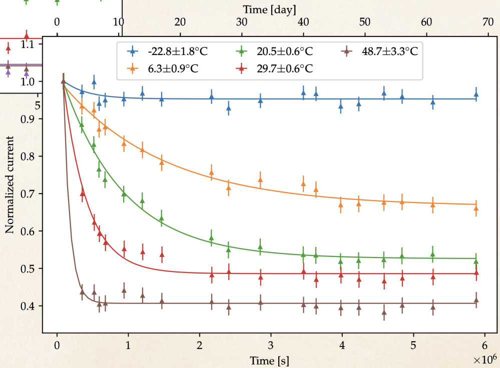
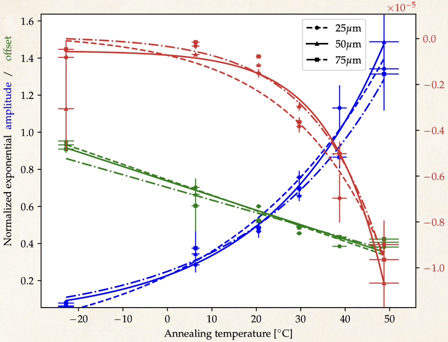
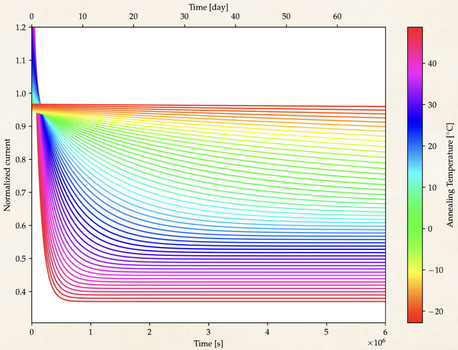




Exponential decay parameters vs. $T_{annealing}$

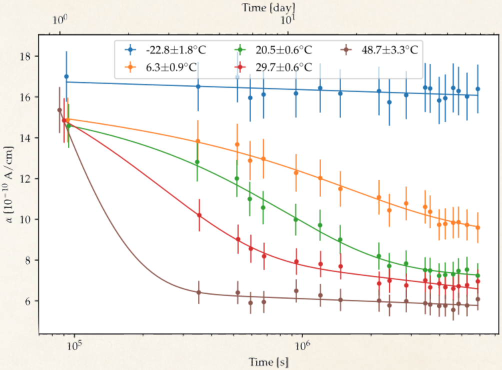
$$a(T) \times \exp(b(T) \cdot t) + c(T)$$





Current-related damage rate α

Current-related damage rate defined as $\alpha = \frac{\Delta I}{\Phi_{eq} V}$.

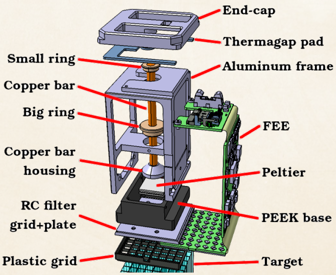


Other formalism to parameterize the thermal annealing effect:
$\alpha(t) = \alpha_I \exp\left(-\frac{t}{\tau}\right) + \alpha_0 - \beta \ln\left(\frac{t}{t_0}\right)$ with the Arrhenius relation that links the decay to thermal energy and defect activation energy: $\frac{1}{\tau} \equiv k(T) = k_0 \exp\left(-\frac{E_a}{k_B T}\right)$

Annealing strategies for POLAR-2

- SiPMs are being operated as cold as possible during scientific data taking thanks to a Peltier based active cooling system
- About once a year, the sensors can be annealed for a couple of days using power resistors (1.98 W @ 9 V) mounted on the back of the PCB
- Without annealing, the DCR is expected to increase by a factor 5 per year. This corresponds to an energy threshold increase of 0.75 keV for a SiPM intrinsic crosstalk of 10%. This number is halved with 1 day of annealing at 50°C every year.

Operating temperature [°C]		-10	0	20
Scenario 1 "No Annealing"	25μm		15.7 ± 0.8	
	50μm		15.4 ± 2.2	
	75μm		7.2 ± 0.9	
Scenario 2 "Continuous annealing"	25μm	13.15 ± 0.73	11.93 ± 0.67	9.49 ± 0.59
	50μm	12.74 ± 1.84	11.61 ± 1.67	9.35 ± 1.36
	75μm	5.80 ± 0.72	5.36 ± 0.65	4.51 ± 0.55
Scenario 3a (1 day) "Continuous + Stimulated annealing"	25μm	8.02 ± 0.45	7.27 ± 0.41	5.79 ± 0.36
	50μm	7.40 ± 1.07	6.75 ± 0.97	5.43 ± 0.79
	75μm	3.59 ± 0.45	3.31 ± 0.40	2.79 ± 0.34



Summary & Outlook

- SiPMs are starting to replace other light sensors for space missions
- Unlike former generation sensors (e.g. PMTs), they are sensitive to radiation induced damage
- Damages in the Silicon lattice can be annealed by heating up the sensors, this effect is temperature-dependent and has been characterized in details in the works below
- The POLAR-2 instrument will be operated from 2027 on the CSS using RadFETs to monitor the radiation environment and heaters to anneal the sensors and mitigate the impact of radiation damage on the science performances

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