SiPM Applications in Novel SmallSat Missions for Gamma-ray Astronomy

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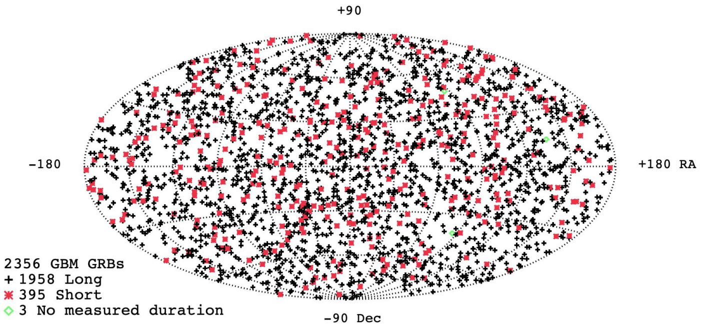
NASA MSFC
April 28, 2022

*** speaker**

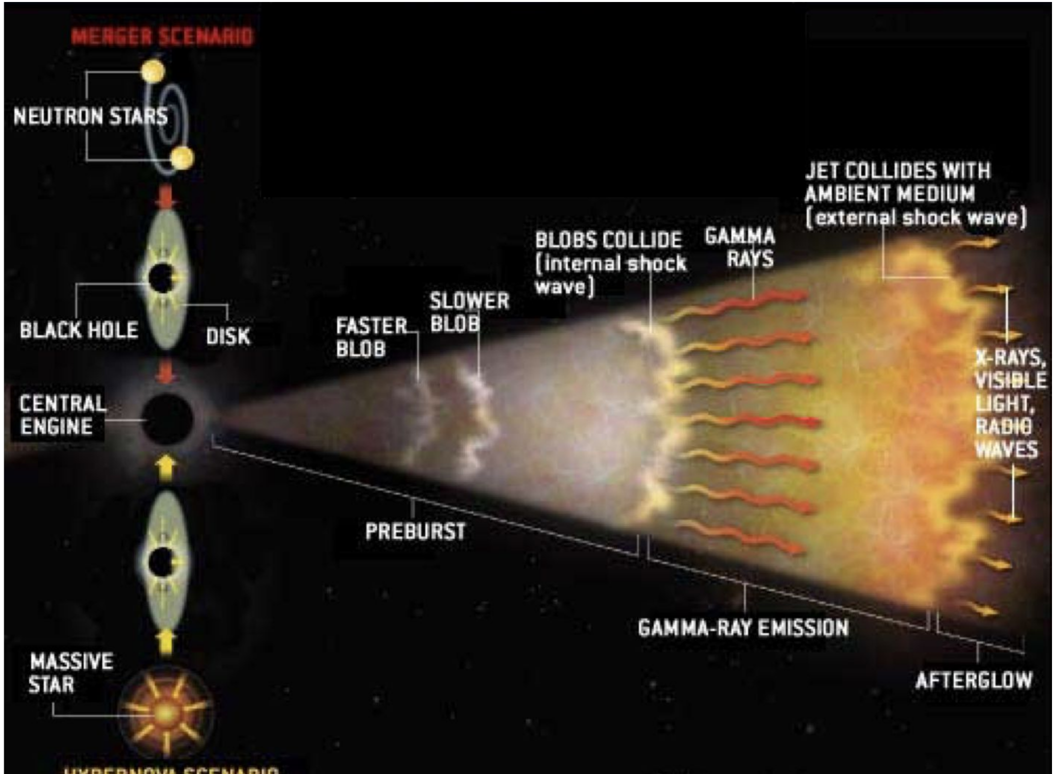
Some background

- Observations of **gamma-ray bursts** date back to the 1970s

- Random nature and short (~1-100 sec) timescales favor wide field-of-view instruments



Von Kienlin et al (2020)



N. Gehrels et al. (2002)

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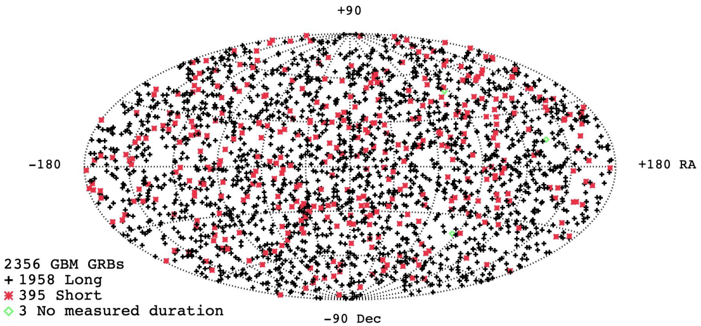

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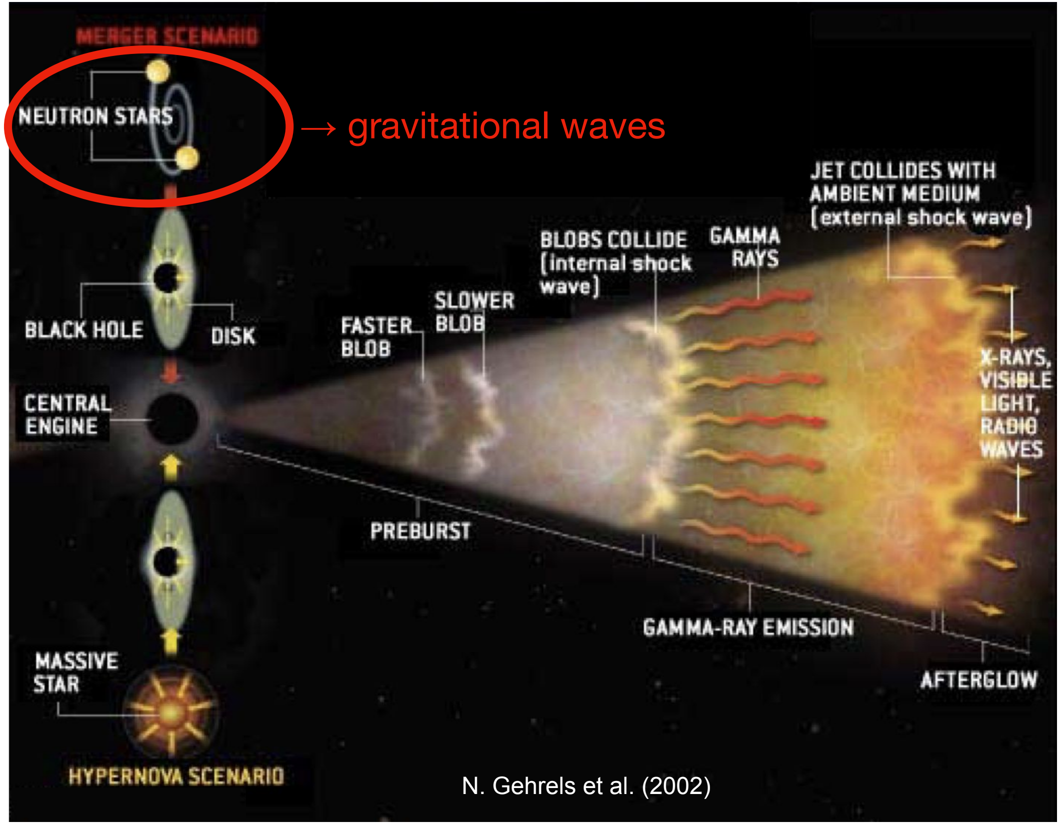

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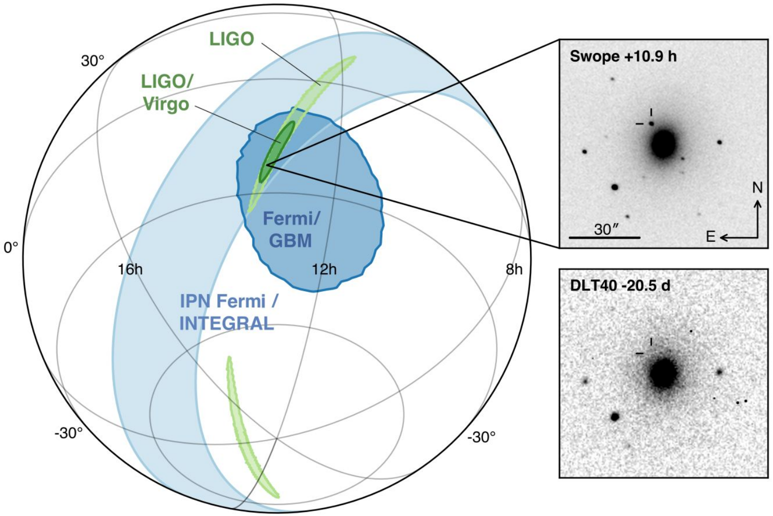
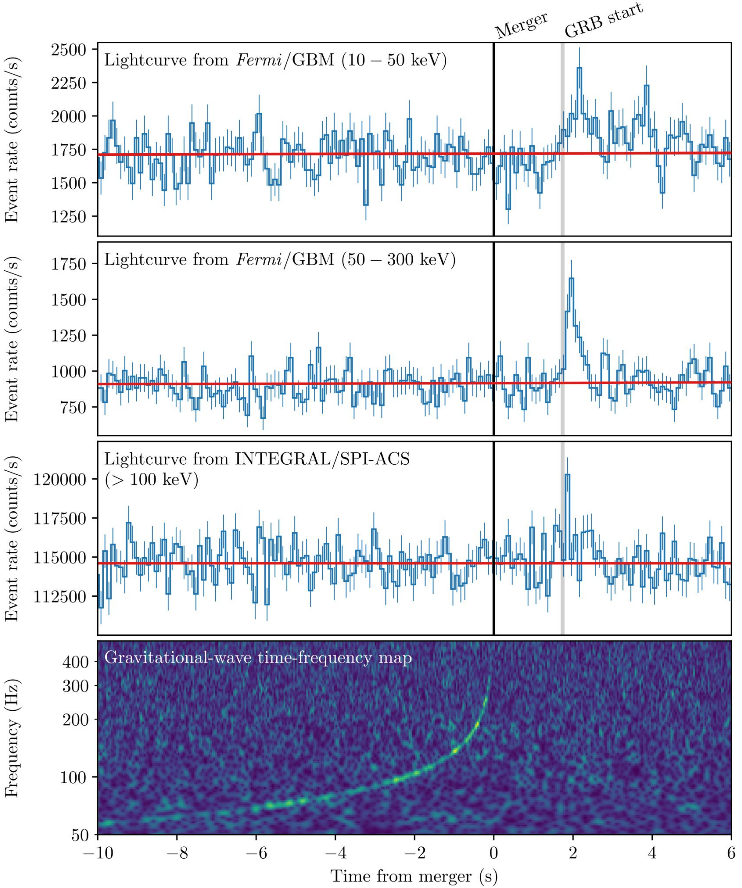
Some background

- GRB 170817A / GW170817 proved that observations of gamma-ray bursts are critical for the field of multimessenger astronomy



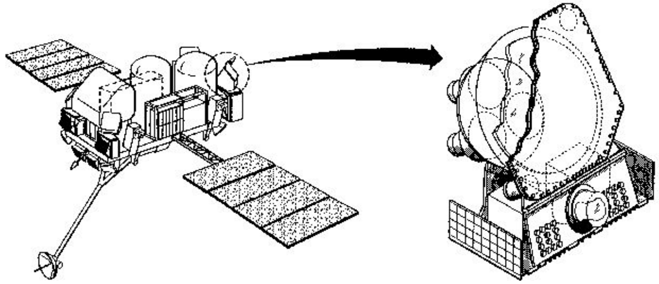


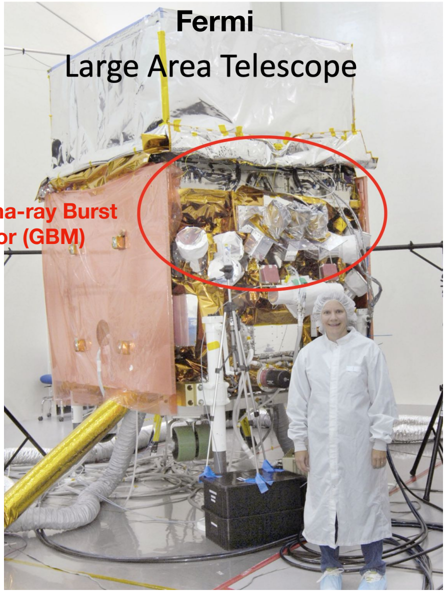
Abbott et al (2017)

Past & Existing “All-sky” GRB Instruments

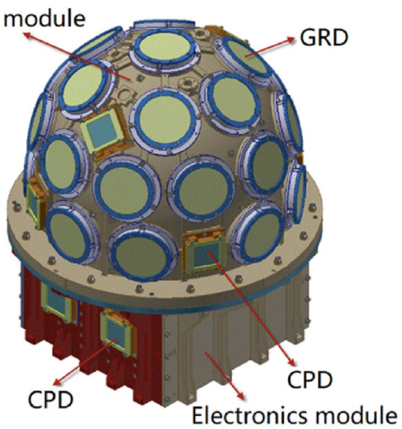
Compton
Gamma-Ray Observatory

BATSE
Detector Module
(1 of 8)





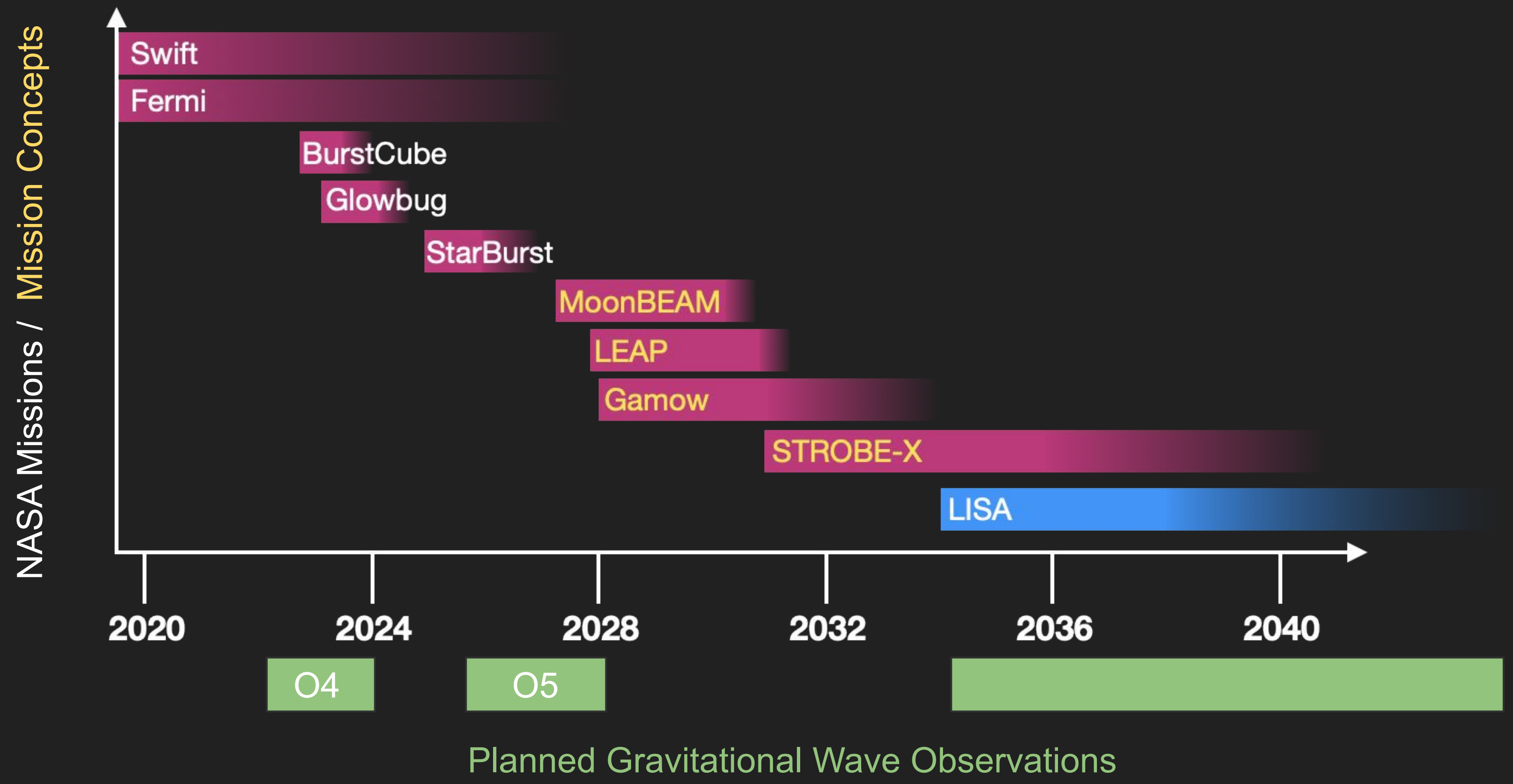
GECAM



Z.H. An et al 2021

- **General idea:** a large set (order 10) of thin scintillation detectors oriented to cover the full sky.
- **The million dollar question:** how do we improve all-sky GRB detection capabilities (sensitivity + angular resolution) <u>in the long term</u>?

Outlook



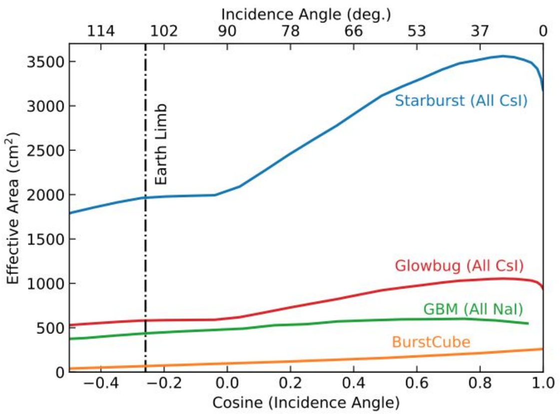
Credit: Michelle Hui

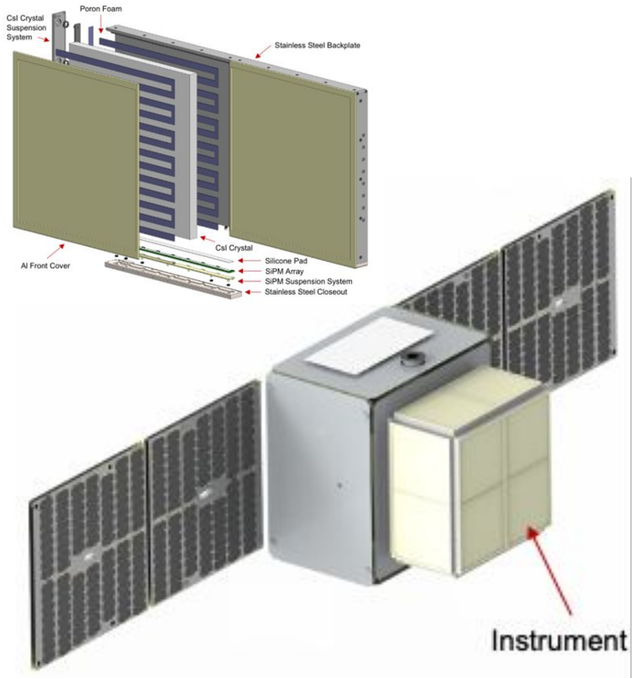
New Mission: StarBurst

- StarBurst is part of the new Pioneers program which seeks to do compelling astrophysics with smaller spacecraft at a lower cost

Quick Facts

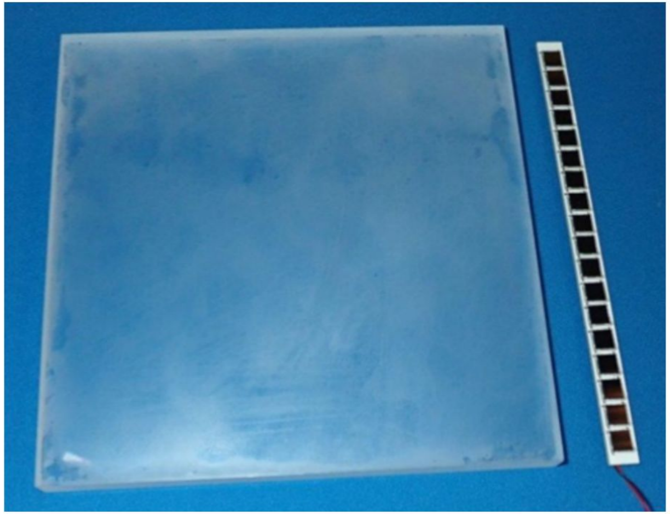
- Pioneer Class ESPA-Grande SmallSat
- Observatory mass (MEV): 300 kg
- Instrument mass (MEV): 150 kg
- Energy Range: 30 keV - 2 MeV
- **Effective Area: 3500 cm^2 (>5x GBM)**
- Field-of-view: > 2π sr
- Based on Glowbug hardware from NRL
- Absolute time resolution: 2 μs
- GRB localization: 3° for GRB 170817
- Mission duration: 1 year
- Orbit: Low inclination (0° - 40°) LEO
- **Detection Rate: 1000 GRBs/yr (200 sGRBs/yr)**
- **Joint Detection Rate: 9.8 GW-sGRBs/yr**

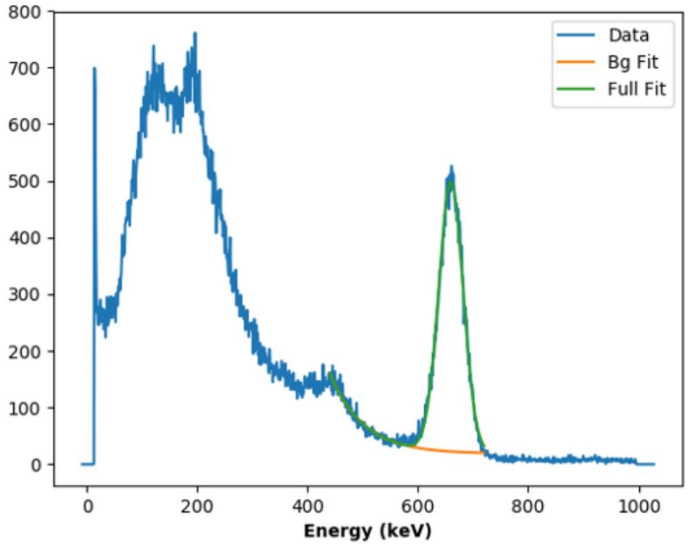




New Mission: StarBurst

- StarBurst uses SiPMs to tile the edges of thin scintillator crystals for efficient packaging, providing more space for the active detection volume





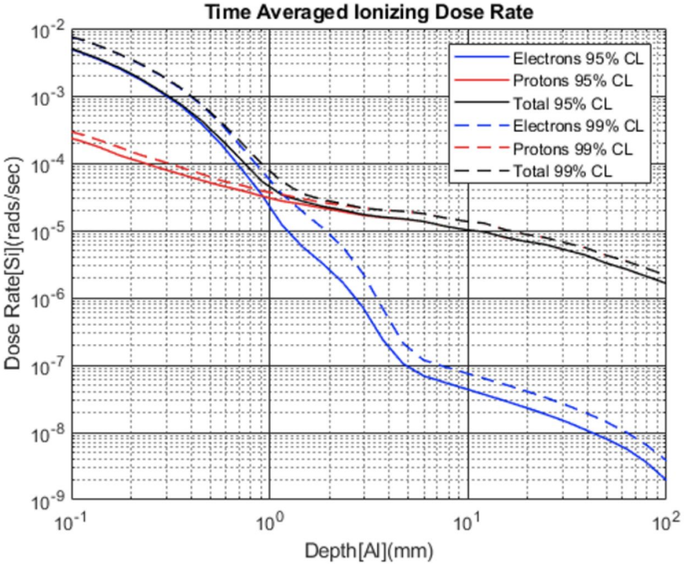
150 mm x 150 mm CsI(Tl) crystal from Glowbug with 6mm SensL J-Series SiPMs

New Mission: StarBurst

- However, there are some notable trade-offs:

  (1) High SiPM capacitance means we use active summation with op-amps to combine the signals from the 76 individual SiPMs viewing each crystal → increased power consumption

  (2) Large increase in operational current with radiation damage over the 1 year mission duration

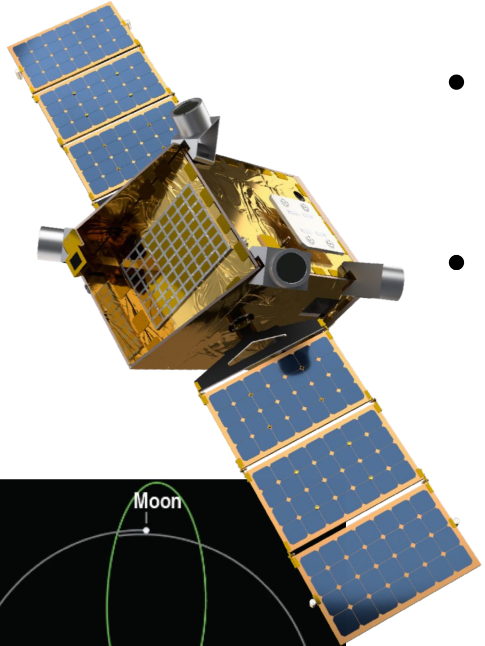


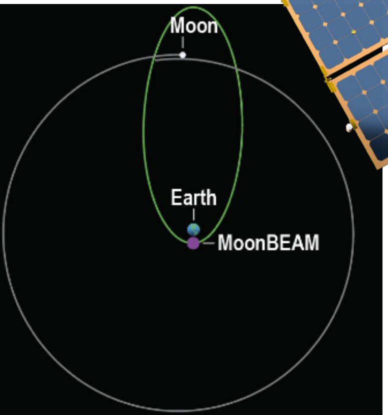
Back of envelope numbers from NRL:

- Mission start: 6 μA current draw per SiPM = 13 mW / detector
- After 1 year: 400 μA current draw per SiPM = 1.0 W / detector
- **Total power increase of ~12 W = limiting factor for instrument lifetime (2 years max compared to 14+ years of GBM).**

Using FJ60035 curves from Lee Mitchell's talk from Tuesday

Proposed Mission: MOON BEAM



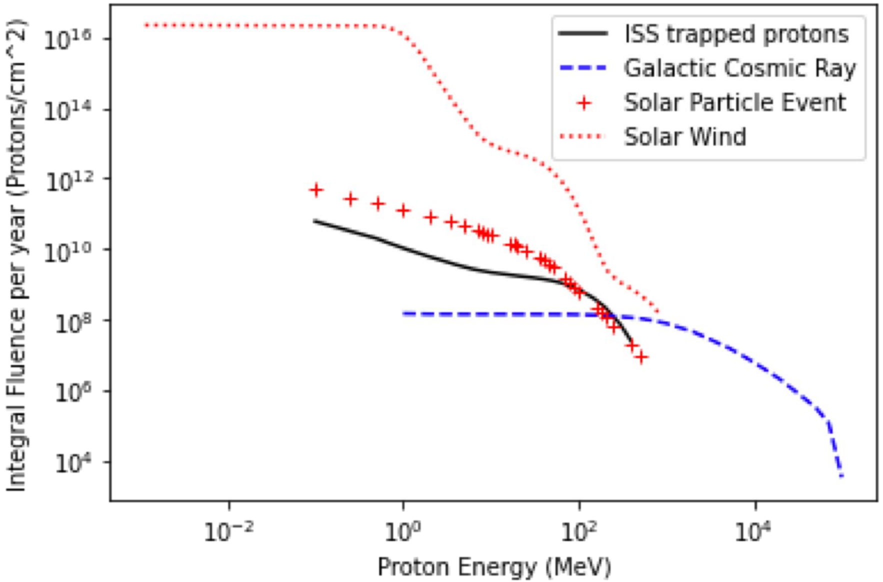


- **3-year gamma-ray SmallSat mission** in cislunar orbit to explore the behavior of matter and energy under extreme conditions by observing relativistic astrophysical explosions.
- MoonBEAM provides key capabilities that are difficult to achieve in Low Earth Orbit:
  - **instantaneous all-sky** field of view from lunar resonant orbit.
  - **13+ days of uninterrupted livetime**.
  - **stable background** for ultra long duration GRBs.
  - sensitive to **prompt GRB emission** energy range, with broad coverage for spectroscopy (10 keV – 5 MeV).
  - **~5° independent localization and longer baseline** for additional localization improvement with other gamma-ray missions.
  - **rapid alerts** to the astronomical community for contemporaneous and follow-up observations.

<u>Question</u>: to SiPM or not to SiPM?

Radiation environment for MoonBEAM

- MoonBEAM largely avoids LEO radiation environment however...
  - 14 day transit passes through radiation belts to reach the planned orbit
  - Advice was given to account for 1 extreme Solar event since they occur every ~10 years)



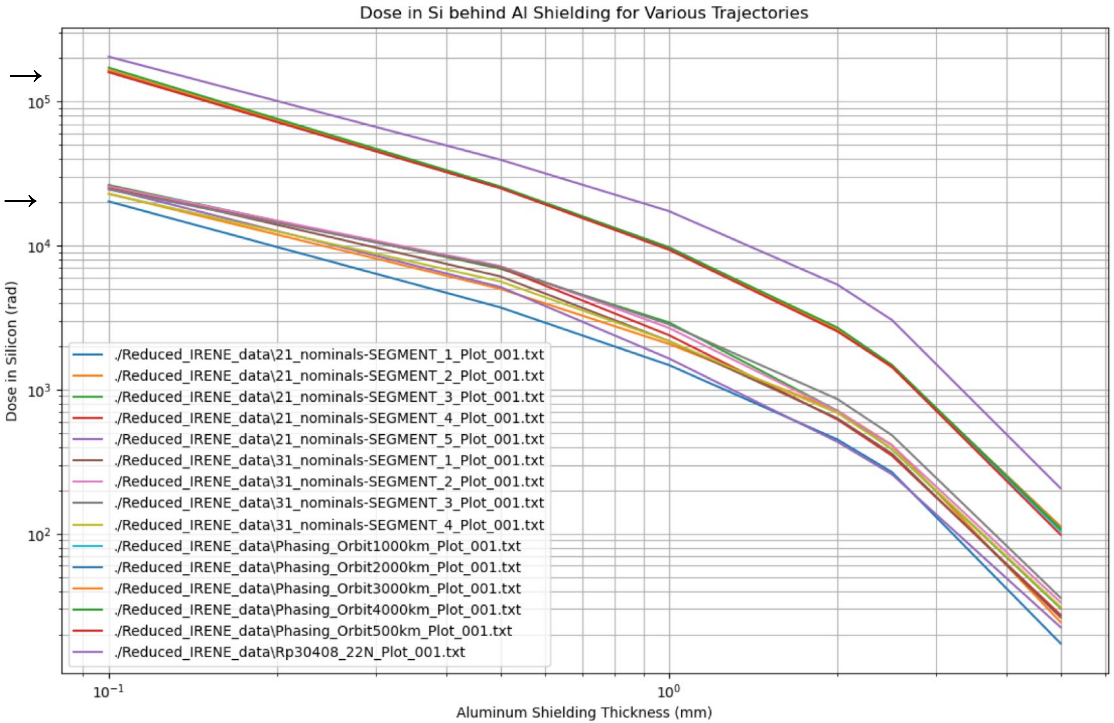
Fine Print:

- Values pulled from the SLS radiation environment document.
- Solar Particle Event (+) is a single extreme solar event that typically occur once every 10 years, in a geomagnetically unshielded environment.
- There is an SPE estimate done per event for ISS but is less than trapped protons.
- Solar wind is done for 15-year integral, probably because this was calculated for the Gateway. This fluence is 95 percentile and corrected for 1 year exposure.
- "should be used for evaluation of thin surface materials on a spacecraft in a near rectilinear halo orbit for 15 years."
- Table 3.3.1.10.2-6 were generated using the L2-Charged Particle Environment (L2-CPE) model (Minow, J.I. et al., AIAA-2007-0910) for a near-rectilinear halo orbit (NRHO) for 15 years. The model includes exposure to the various regions of the Earth's magnetotail as well as the solar wind. These particles could be important for very thin external surface materials with 15 year mission life. Since the environment is directional, the highest fluence of each of the 6 surfaces of a cube was used with the 95th percentile setting of the model.

Radiation environment for MoonBEAM

105 days in science orbit →

These are phasing orbits → heading out to science orbit from GTO

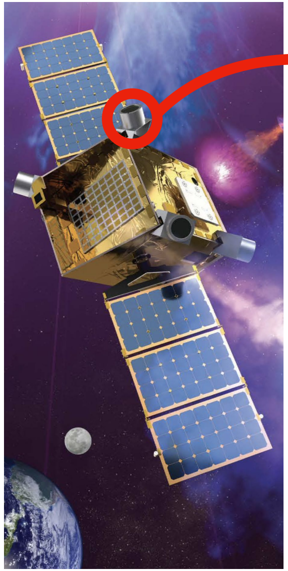


Takeaway: phasing orbit will give us 1e3 to 1e4 rad, depending on how much material we think will be between vacuum and SiPM. Losing performance before we can take advantage of our science orbit.

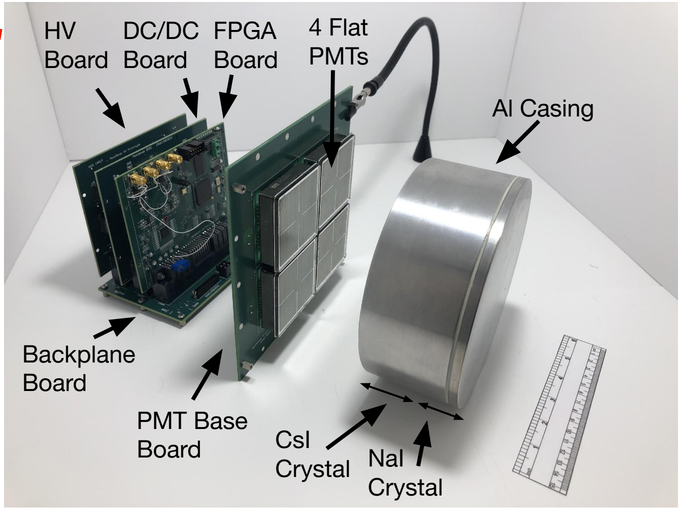
MoonBEAM's solution to volume constraints

- Balanced approach which combines a reduction in detector size and a reduction in number of detectors through the use of phoswich technology.

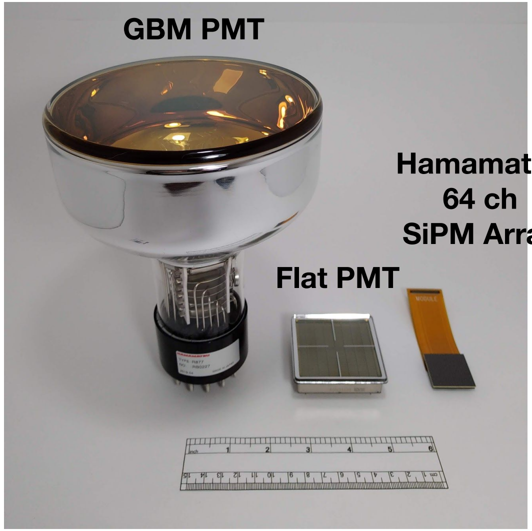
- Would not work for a smaller spacecraft form factor, such as a CubeSat.



components

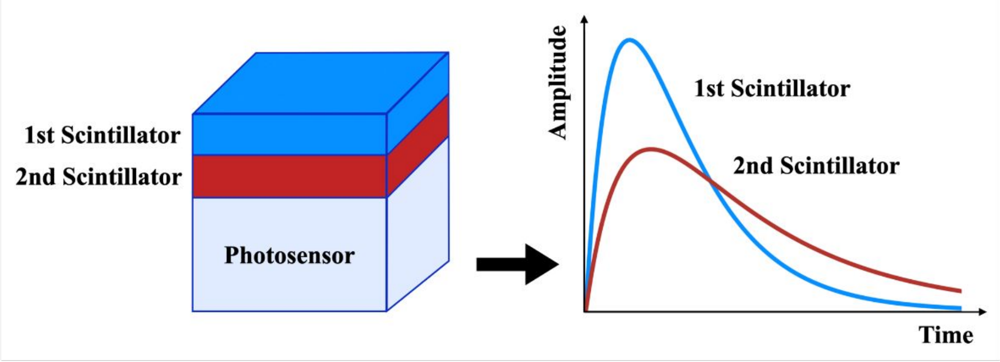


Flat PMT Size Comparison



MoonBEAM's solution to volume constraints

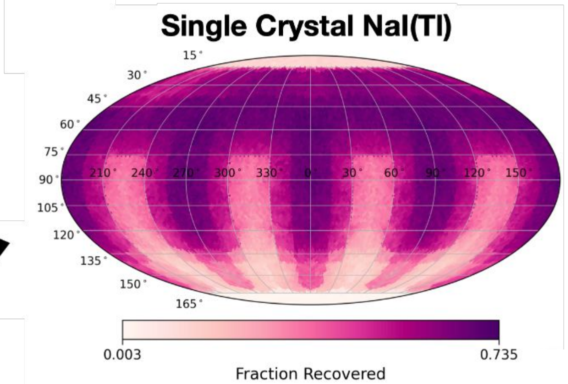
- Phoswich technology couples two scintillators with different decay timescales

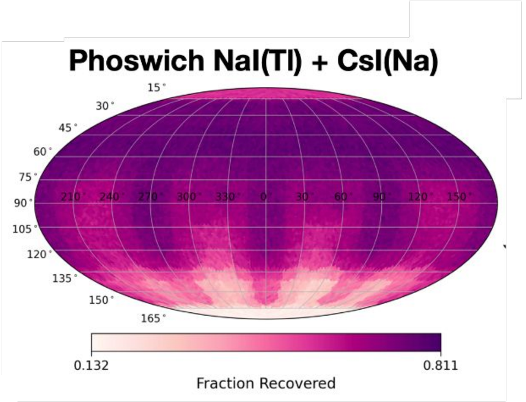


- Allows a single detector to operate via two modes:
    - forward scintillator only → angular response of a thin detector
    - both scintillators → larger off-axis sensitivity

- Net result is the ability to provide better sky coverage with fewer detectors

Fraction of detected GRBs for a single crystal (GBM-like) design versus a phoswich design





Summary

- There's no such thing as a free lunch.
  Both SiPMs and PMTs have their benefits and drawbacks.

- My current thinking:

  Can I fit a flight capable PMT?

  Yes = use a PMT for its robustness, ability for extended science ops
  No = make sure I can complete my science goals in 1-2 years. If yes, use SiPMs

- Ground breaking science like GW170817 often comes during the extended phase of NASA missions
- Radiation damage is the main factor limiting wide-spread adoption outside of short-lived missions. GRB missions can only partially mitigate with shielding due to thin detector designs, need to view the whole sky.

Thanks!

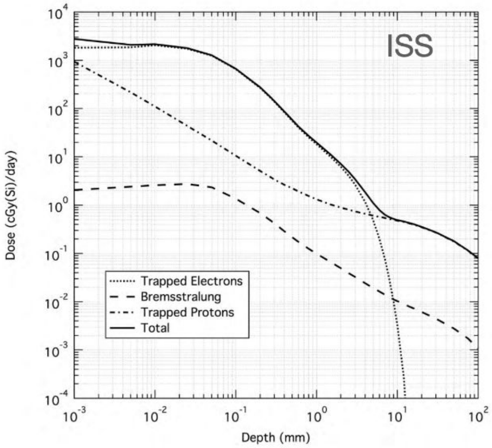


Figure 3.3.1.1-4. Daily Trapped Belts TID Inside Shielding

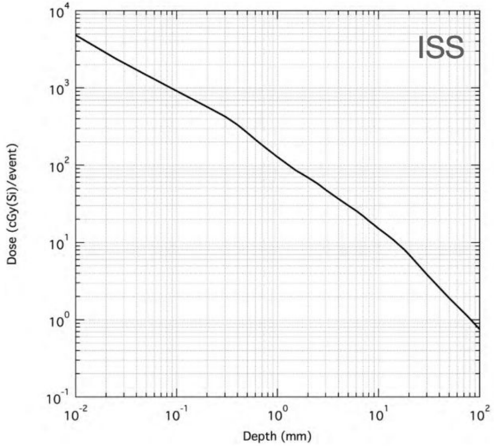


Figure 3.3.1.1-5. Total SPE TID Inside Shielding

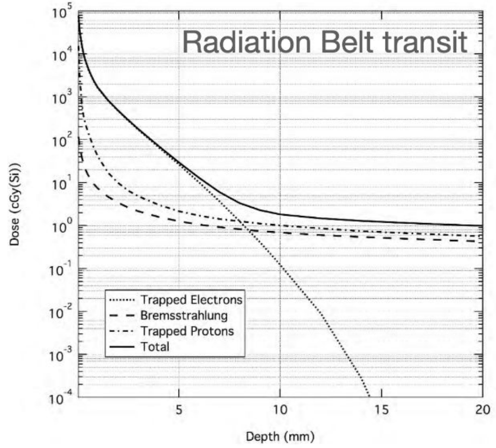


Figure 3.3.1.2.2-3. Trapped Belts TID inside Shielding

GCR is O(1e-2) per day in cGy(Si)

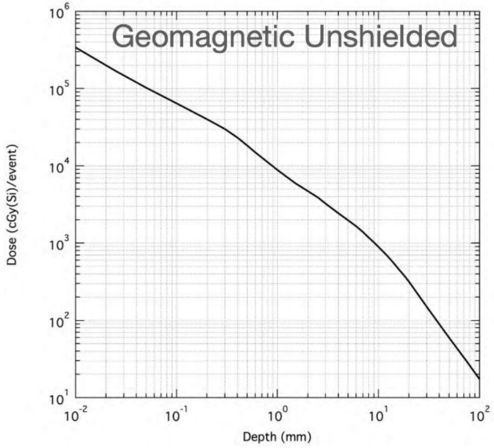


Figure 3.3.1.10.2-3. Total Unshielded SPE TID Inside Al Shielding

Solar particle event and transit via radiation belt dominates the accumulated radiation dose.

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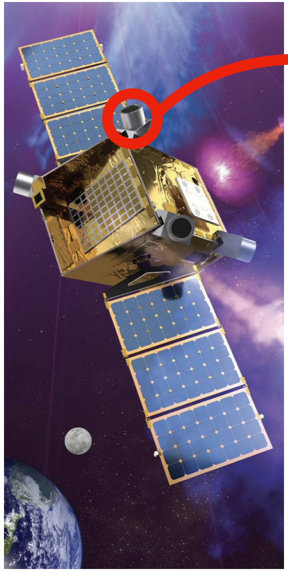

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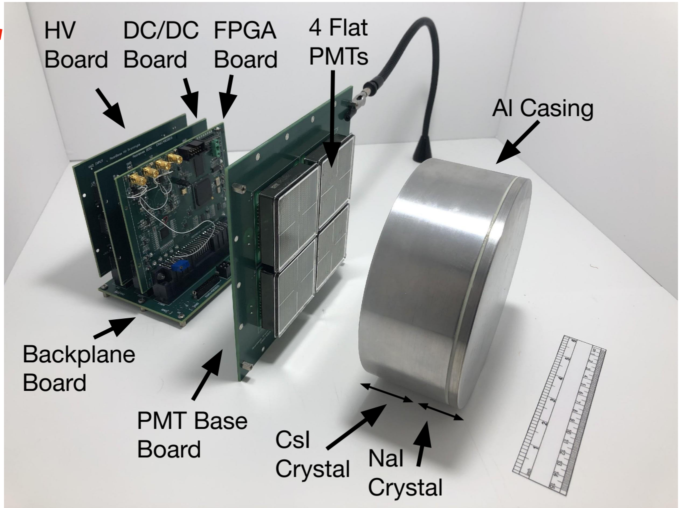

fully assembled