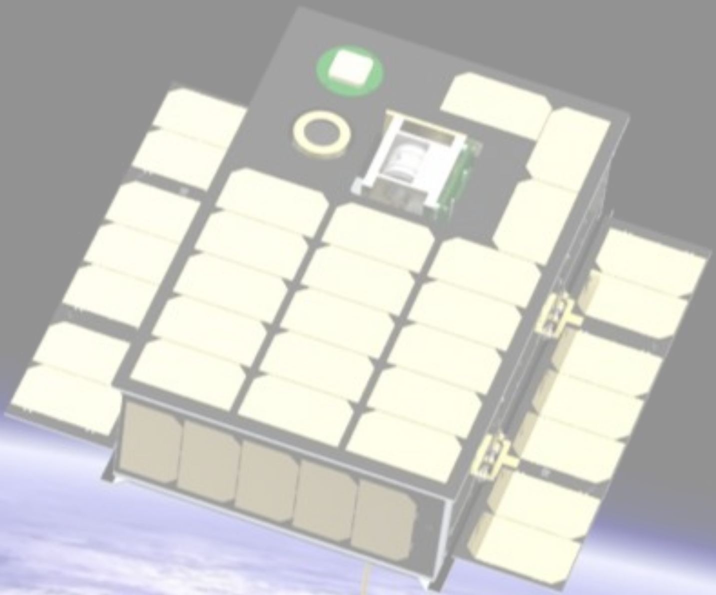
BurstCube: A CubeSat for Gravitational Wave Counterparts



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See ICRC 2017 Proceedings for More Details: https://pos.sissa.it/301/760/

Website: https://asd.gsfc.nasa.gov/burstcube/

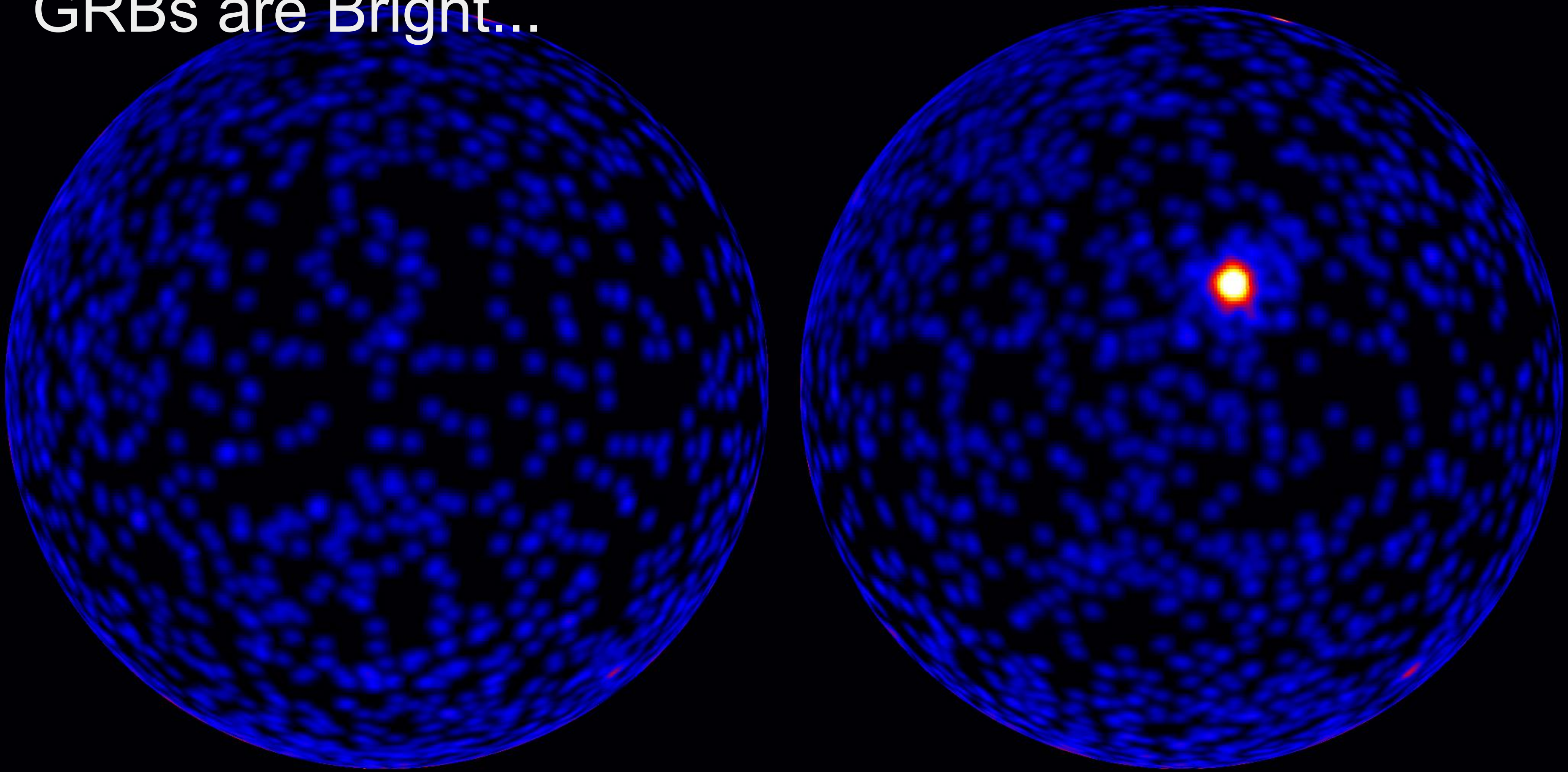
Productive Procrastination

"The secret of my incredible energy and efficiency in getting work done is a simple one," ... "anyone can do any amount of work, provided it isn't the work he is supposed to be doing at that moment."

Robert Benchley

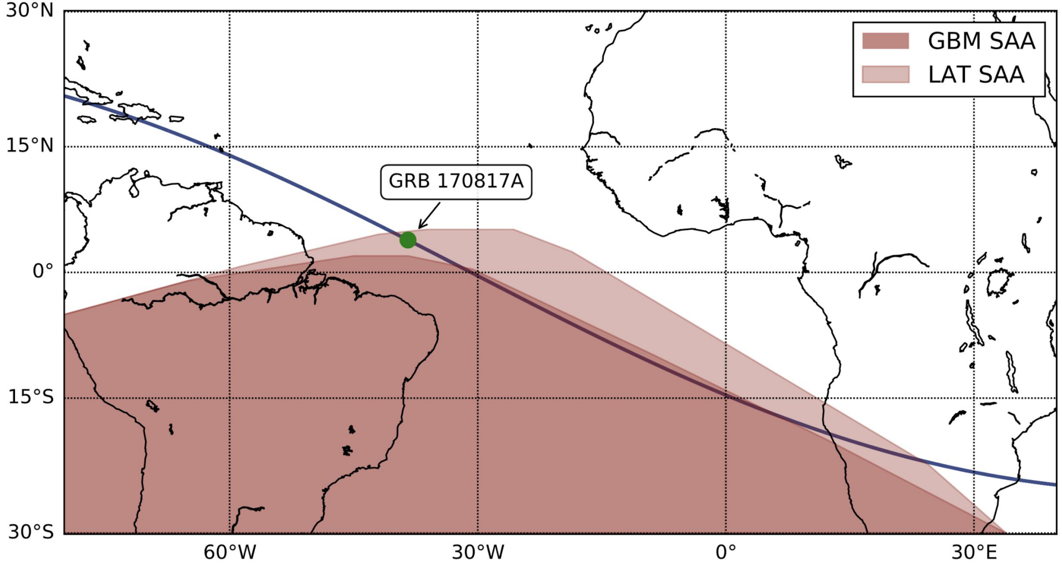
Question: How do you detect gamma-rays on a CubeSat?

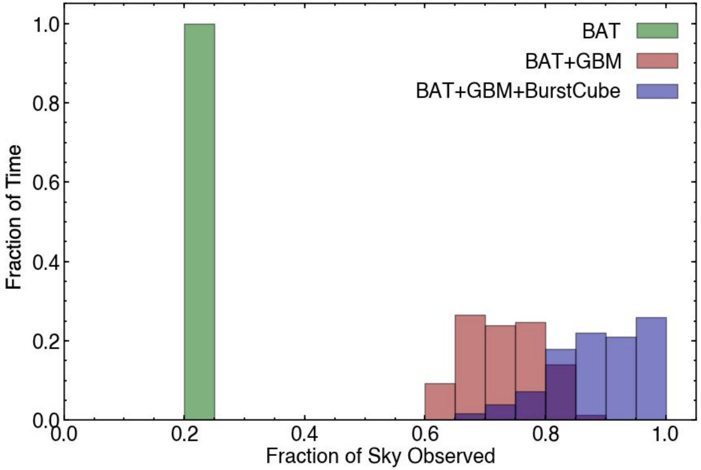
GRBs are Bright...



Before and after Fermi LAT views of GRB 130427A, centered on the north galactic pole

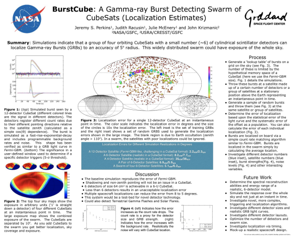
GRBs can happen anywhere at anytime...



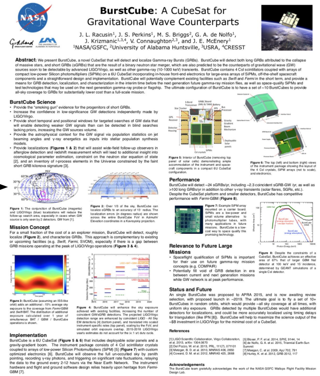


The Path to Mission Acceptance (& eventual Success)

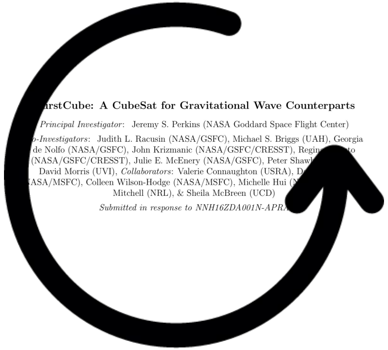
Procrastination: Quick Study in Python (2014)



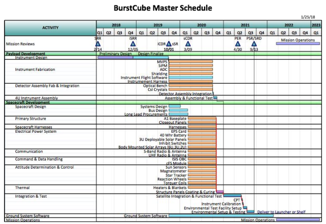
Preliminary Mission Design (2015)



Proposals Fail Until They Don't (2015, 2016, 2017)



(Refine the Details)



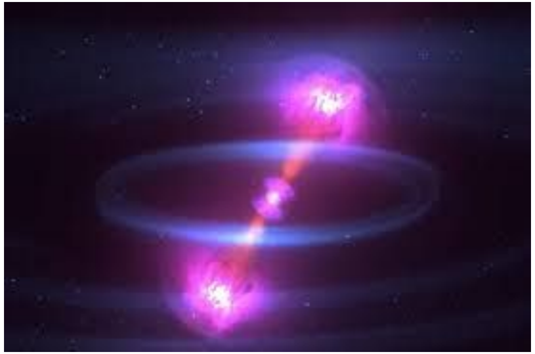
Success! (or, now the real work begins)

Final Preachy Slide: Be Open

- Be open with your ideas
- Be open with your code
- Be open with your results
- Be open with your time
- Be open to other people

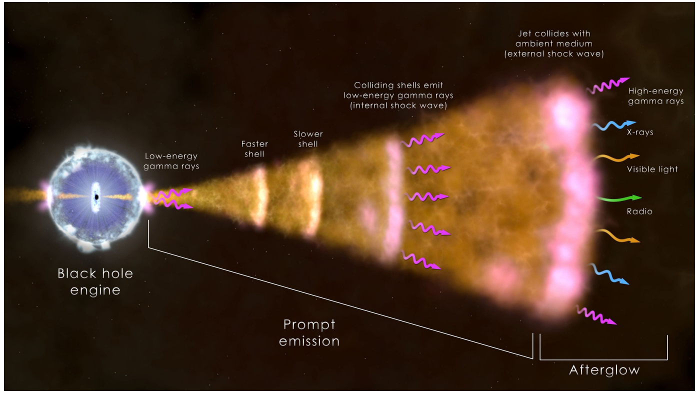
BurstCube Science

- Monitor the sky for transient and variable Gamma-ray sources on timescales of milliseconds to hours
  - Gamma-ray Bursts
  - Gravitational Wave Counterparts
  - Solar Flares
  - Magnetar Outbursts
  - Galactic Binaries Outbursts
- Rare short events are vital to catch, another gamma-ray instrument makes those events less likely to be missed



Gamma-ray Bursts

- Most energetic explosions in the Universe
  - Long duration GRBs (>2 s) produced by collapse of massive stars
  - Short duration GRBs (<2 s) produced by neutron star mergers
- Detectable nearby (10's of Mpc) out to most distant objects in Universe (~500 Million Years after Big Bang)
- Occur somewhere in sky ~1/day
- Increasing coverage to complement existing monitors, trigger ground-based follow-up of interesting subset



Gamma-ray Burst Science

Astrophysical jets occur throughout the universe, throughout time, and on vastly different time and size scales.

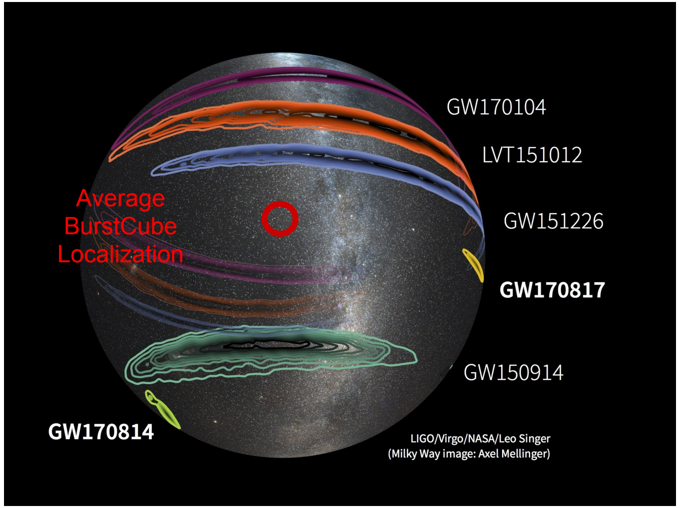
We still don't understand how they work.

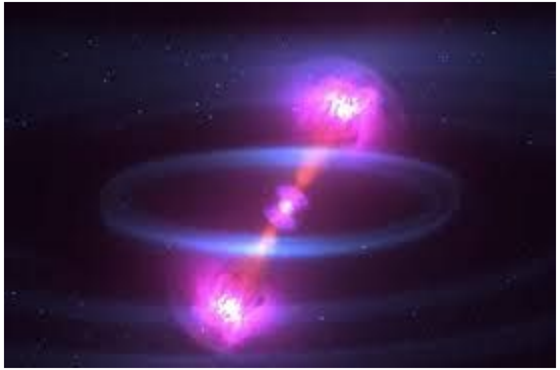
GRB observations allow us to study the birth, growth, and death of a jet in a short period of time over the full E-M spectrum. GW observations give us even more observables.

- BurstCube will provide **triggers, localization**, and gamma-ray **light curves and spectra** of GRB prompt emission for use in conjunction with other ground and space-based broadband (radio to X-ray) observations of GRBs and their afterglows
- BurstCube observations will contribute to **open questions** in the field:
  - Emission mechanisms - role of thermal and non-thermal components
  - Jet composition - matter-dominated versus magnetically dominated
  - Jet structure and role of viewing geometry - top hat, structured jets, cocoon

Gravitational Wave (GW) Counterparts

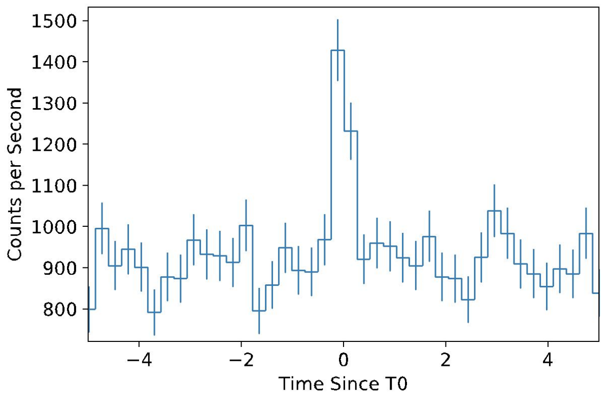
- Neutron Star mergers produce short duration gamma-ray bursts (GRB)
- GW170817/GRB170817A is the first confirmation, though it may be a rare unusual event (very nearby)
- Increasing sky coverage is vital for detecting these rare events
- BurstCube will provide temporal coincidence with GW triggers, temporal and spectral properties, localizations
- GRB detections allow GW searches to lower thresholds, increasing available volume and rate



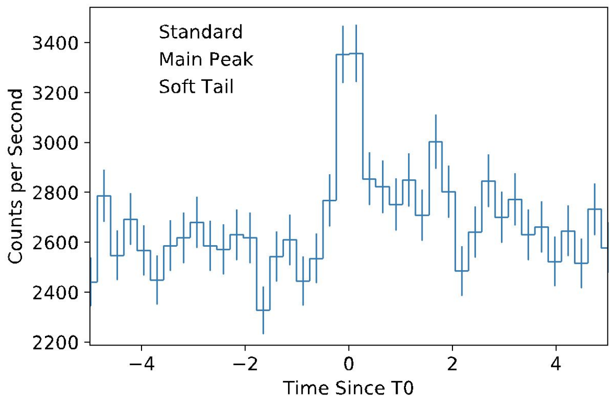


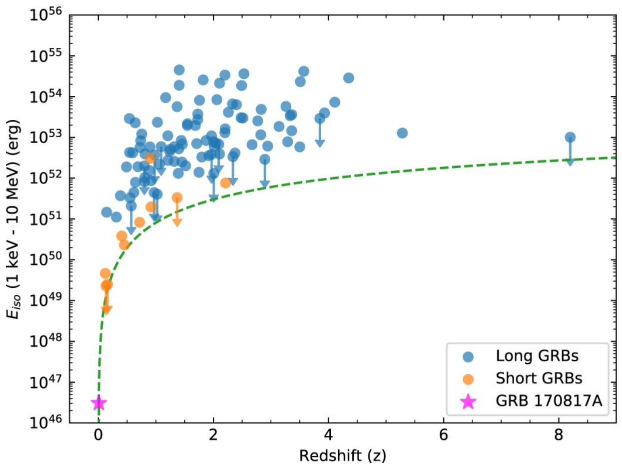
GW170817: Some Expected Results

- Confirms Merging NS origin for short GRBs
- Fundamental physics results, e.g., speed of gravity = speed of light
- At first, it looks like a very typical, even boring short GRB
- Pulse is consistent with GRB emission theories
- Upper limits on the radius of the jet and the emitting region



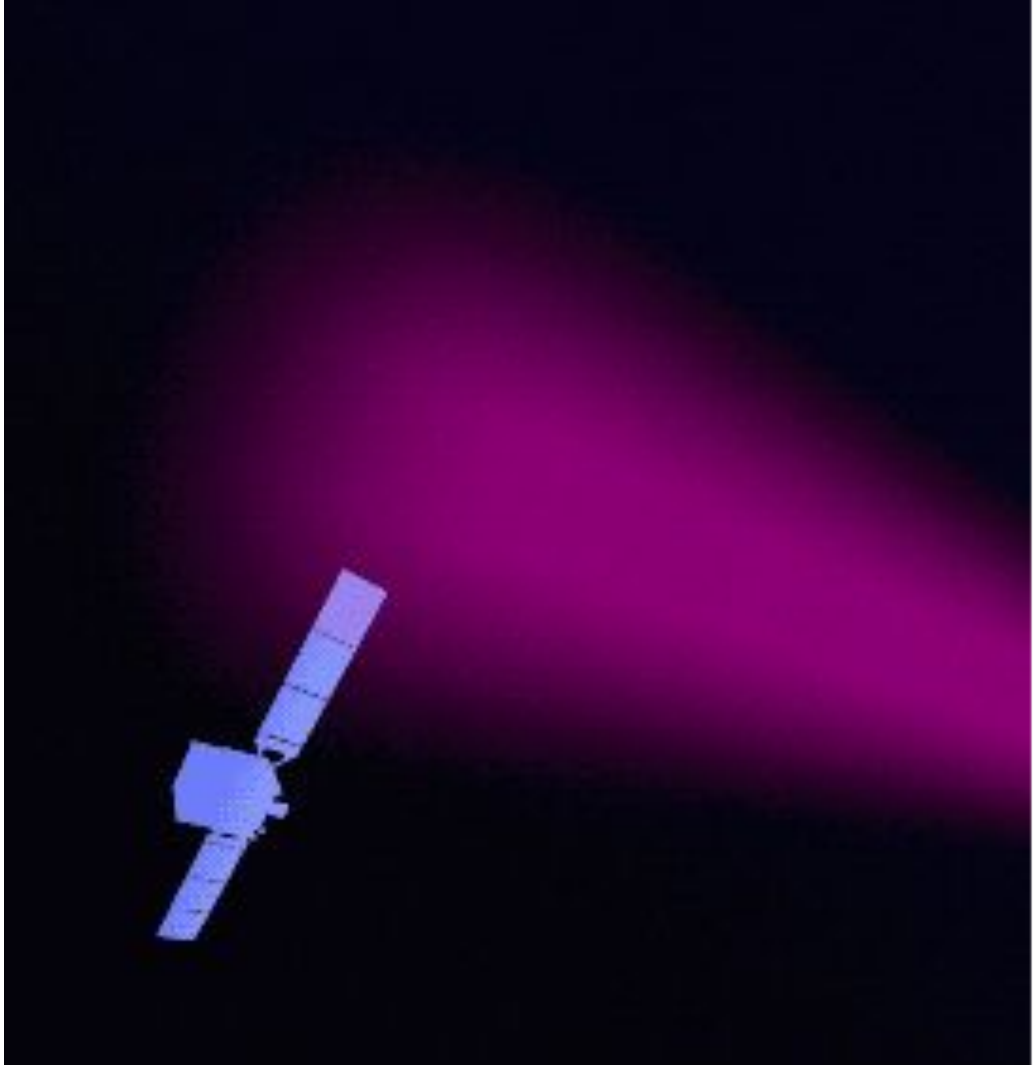
GW170817: Some Unexpected Results

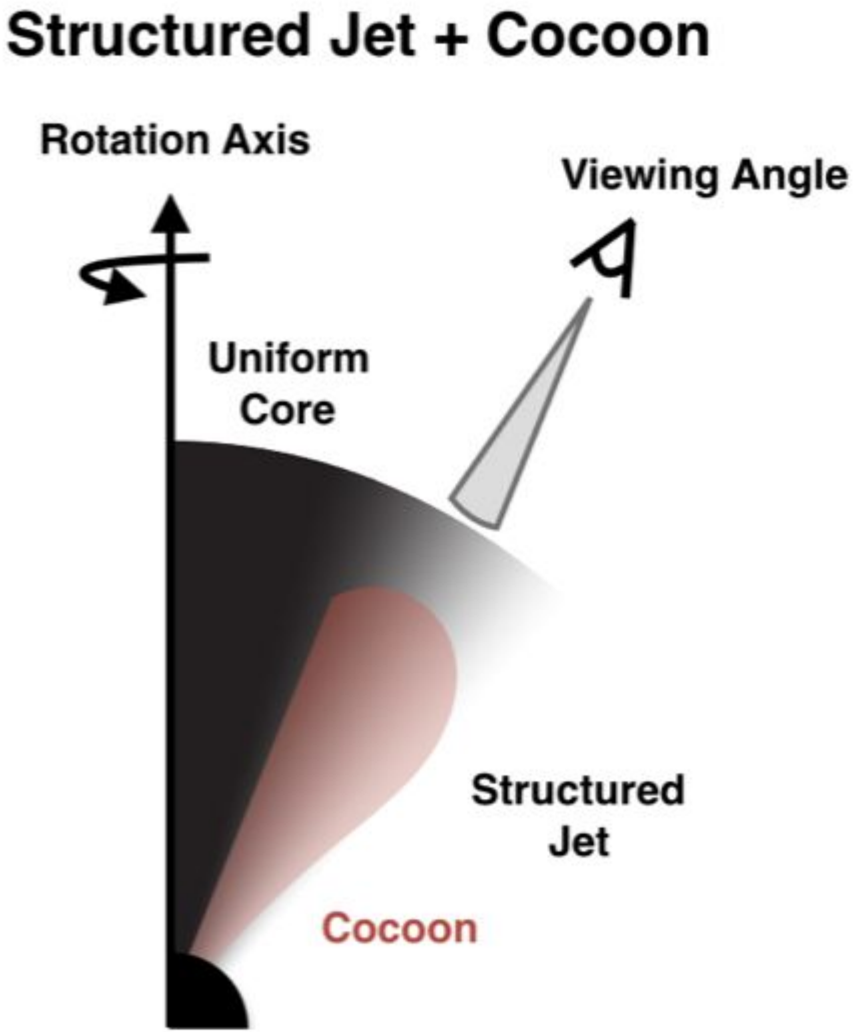




- Thermal tail: photosphere or cocoon emission?
- Viewed from off-axis: structured jet?

- Closest (known) short GRB and very under-luminous
- ➔ Revise upward the expected joint GW / GRB joint detection rate




Structured Jet + Cocoon
Rotation Axis
Viewing Angle
Uniform Core
Structured Jet
Cocoon

Gravitational Wave Counterpart Detection Rates

- The revised joint detection rate between Fermi GBM (triggered short GRBs) and LIGO at its planned sensitivity is 0.3 to 1.7 per year
- One limitation: due to SAA passages and Earth blockage, the average duty cycle for GBM observing a point on the sky is ~60%
- BurstCube will:
  - Increase the joint GW/GRB detection rate by observing GRBs not accessible to Fermi, increasing the duty cycle for observing the sky to 75%,
  - Pioneer low cost, wide field-of-view monitoring of short GRBs.

Gamma-ray Burst Science

- BurstCube will provide triggers, localization, and gamma-ray light curves and spectra of GRB prompt emission for use in conjunction with other ground and space-based broadband (radio to X-ray) observations of GRBs and their afterglows
- BurstCube observations will contribute to open questions in the field:
    - Emission mechanisms - role of thermal and non-thermal components
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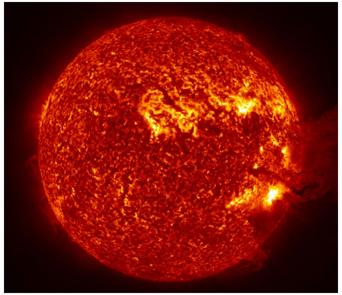
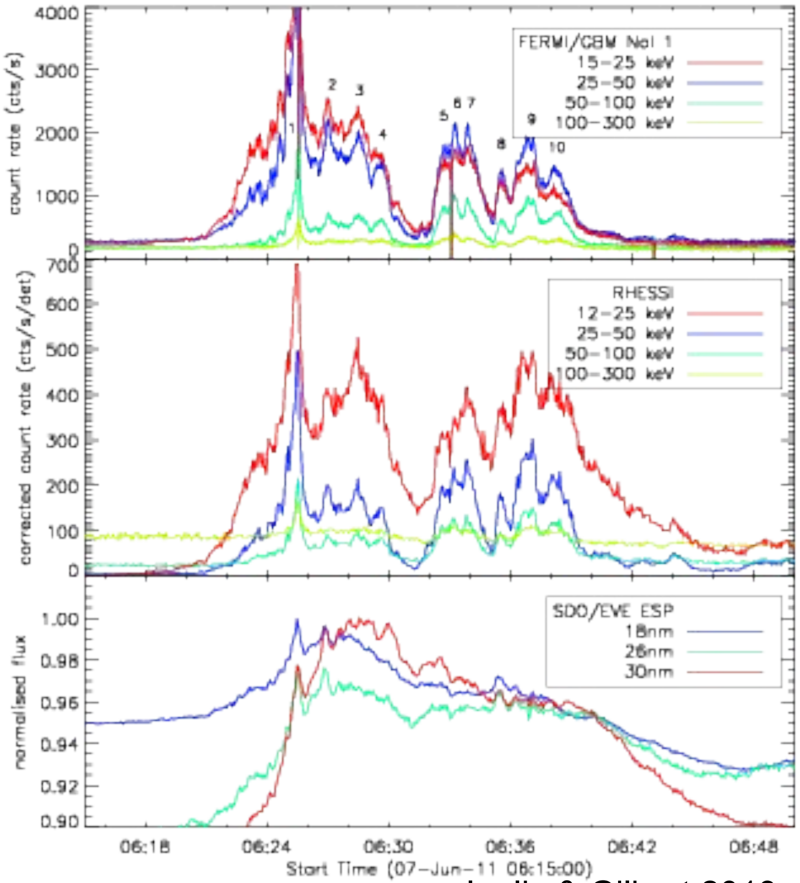
Solar Flares

- BurstCube will observe the Sun during normal operations
- Solar Flare impulsive emission will trigger BurstCube
- Provide temporal and spectral evolution of flares - like RHESSI and Fermi-GBM

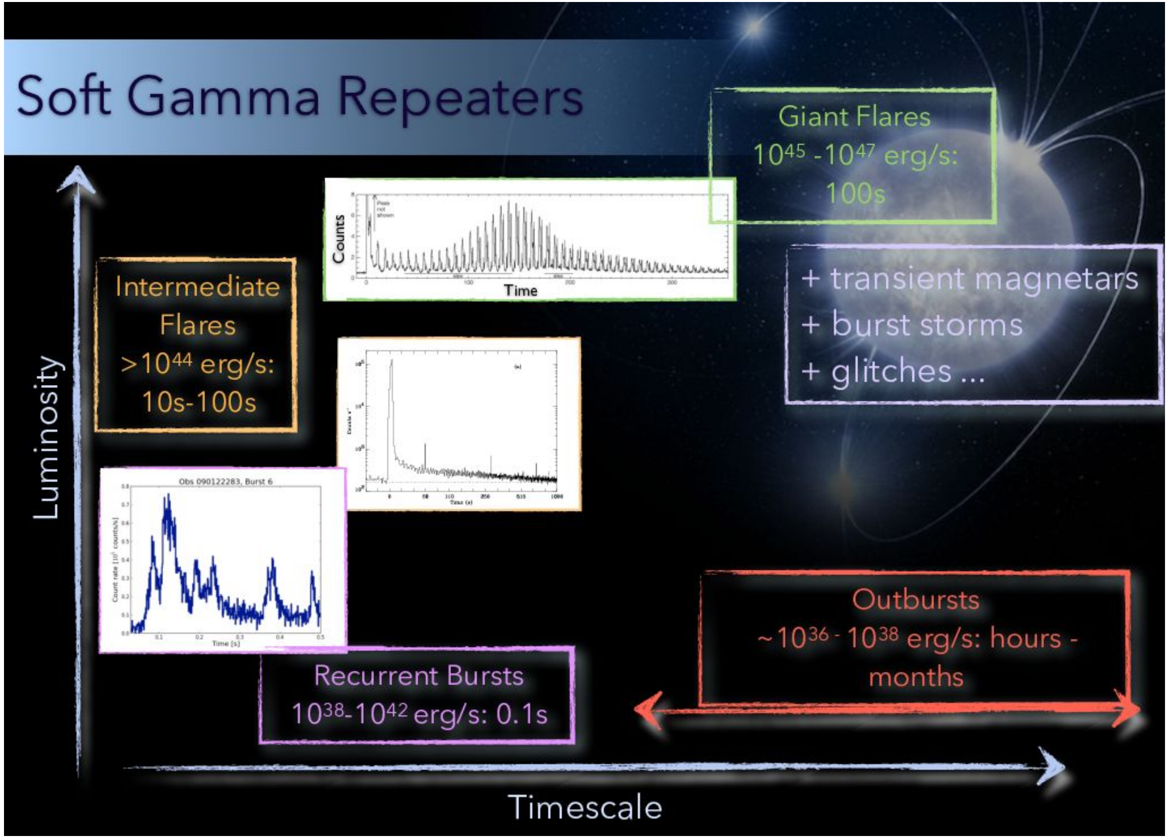




Inglis & Gilbert 2013

Magnetar Flares

- Highly magnetized neutron stars with outbursts on timescales of seconds to months
- Giant flares are rare (last one was in 2004) and extremely luminous

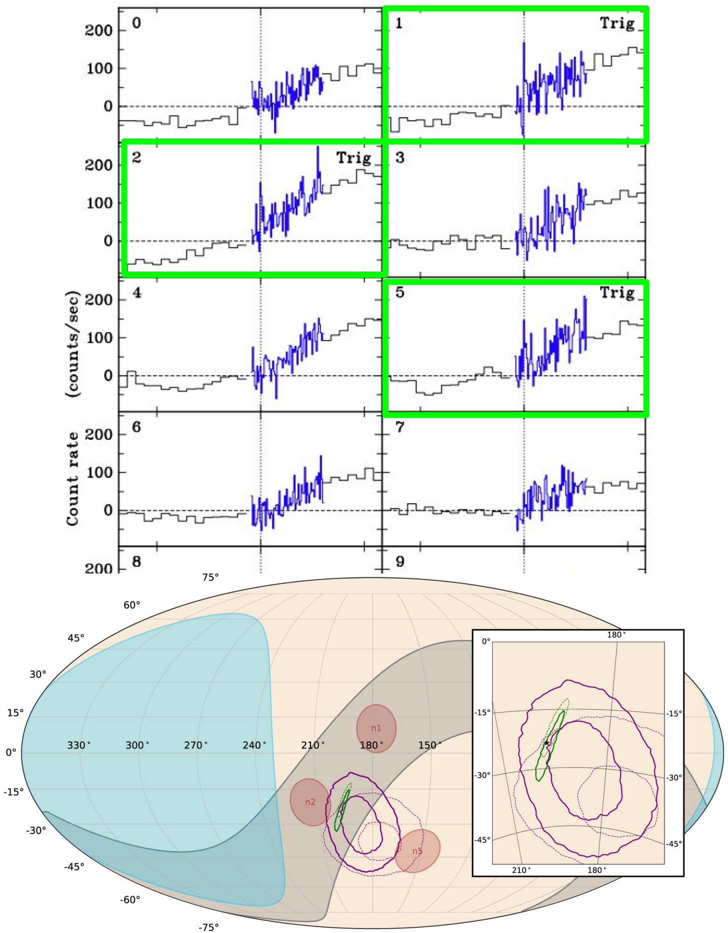


Credit: Daniela Huppenkothen

BurstCube Observations

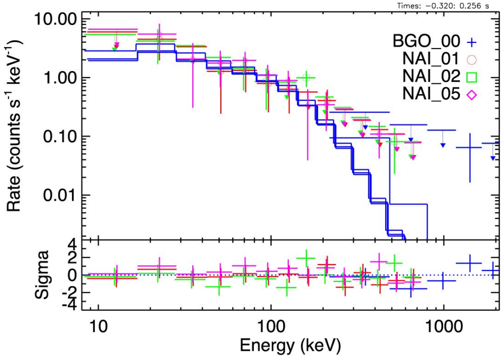
- Detect individual photon time of arrival and energy
- Onboard binning of photons in energy and time
- Trigger on rate increases in energy bins, on different timescales, and phase shifting
- Localize source using relative strength of signals in each detector
- Rapidly transmit alert to ground for distribution to follow-up facilities

Fermi-GBM Observation of GRB 170817A

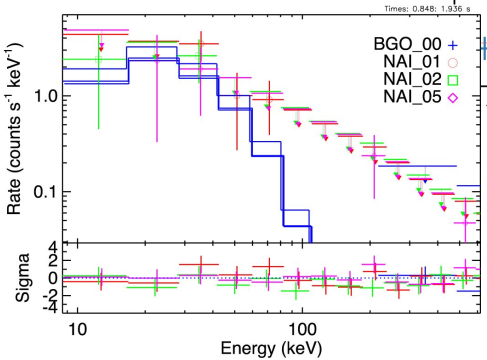


Goldstein et al. (2017)

Data Products



(a)



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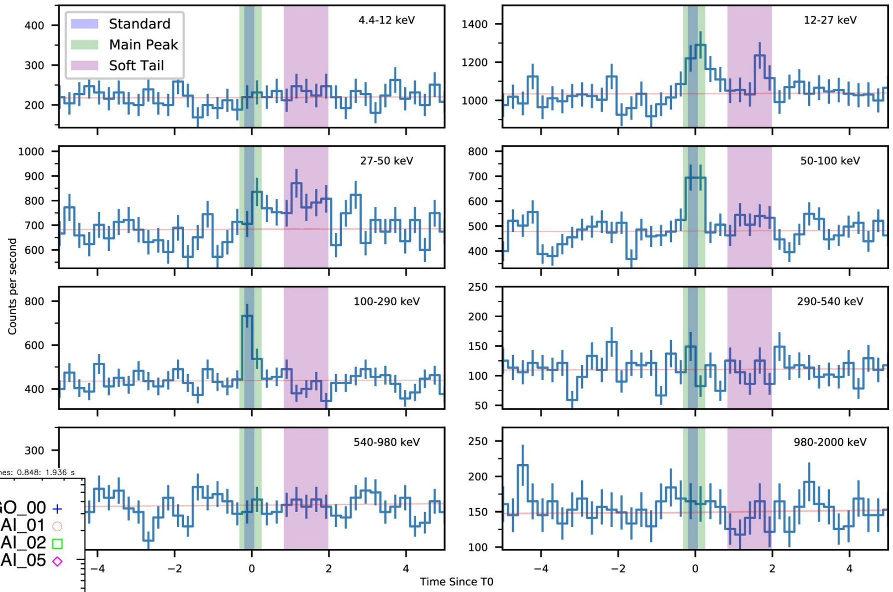
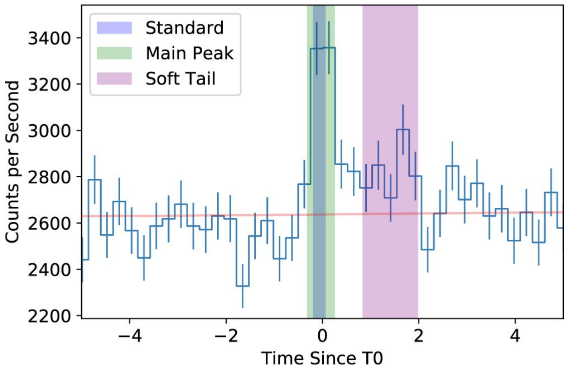
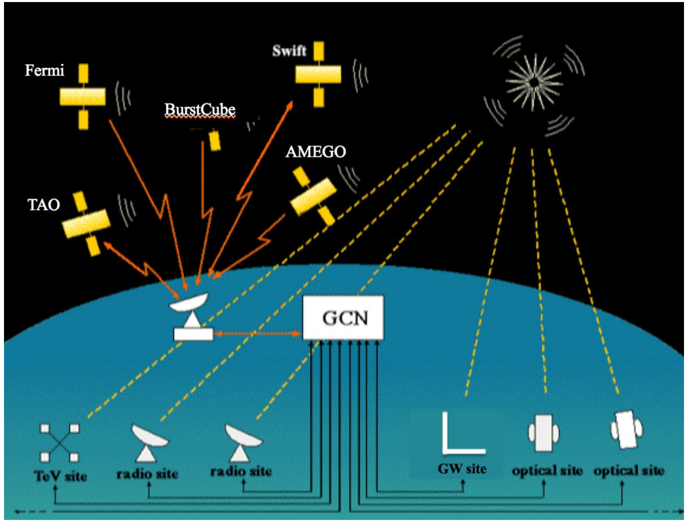




Goldstein et al. 2017

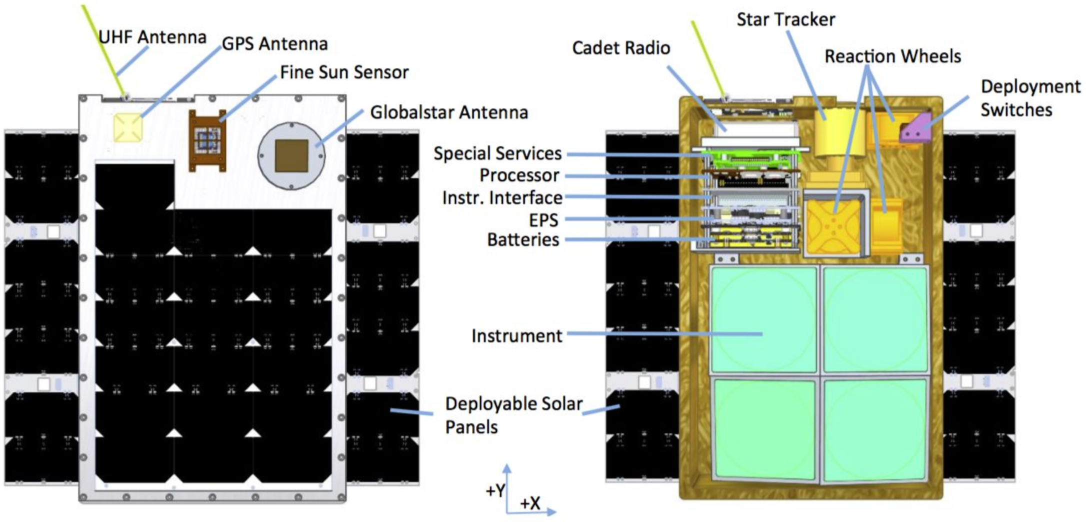
Rapidly Transmit Alert

- If high-bandwidth (via S-band TDRSS)
  - Compute rough onboard localization, transmit to ground
  - Downlink energy and time binned light curves during window around trigger
  - Compute more precise localization on-ground
- If low-bandwidth (via GlobalStar)
  - Compute onboard localization, transmit to ground
  - Downlink full light curves for on-ground improved localizations during next UHF ground station pass (12+ hours latency)
- Either method, send trigger and series of localizations, light curves, spectra to follow-up community via Gamma-ray Burst Coordinates Network (GCN)

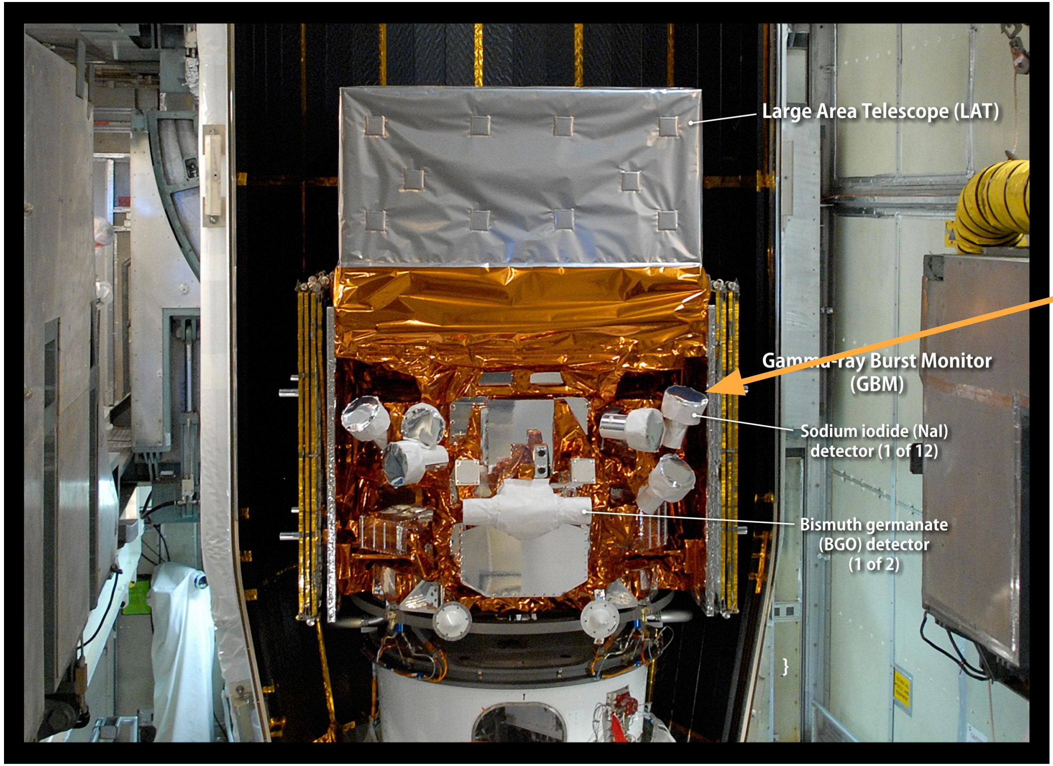


Mission Overview

- Observes the unocculted sky pointed. Records Ɣ-ray photons. Triggers on rate fluctuations.
- 4 year development. 1 year operations.
- Baseline bus is *Dellingr*.
    - 6U CubeSat (PSC standard)
    - 3 axis pointing
    - UHF communication
    - Body mounted solar panels
    - Deployable solar panels
    - Star Tracker
    - Rapid comms (either globalstar or TDRS)



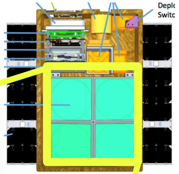
Use of Dellingr platform makes use of prior development and minimizes risk.

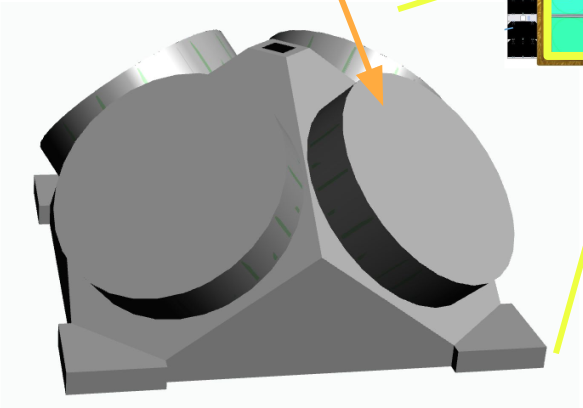


Instrument is based on many previous designs. Most recently, *Fermi*-GBM.

One (of 12) NaI detectors on Fermi.

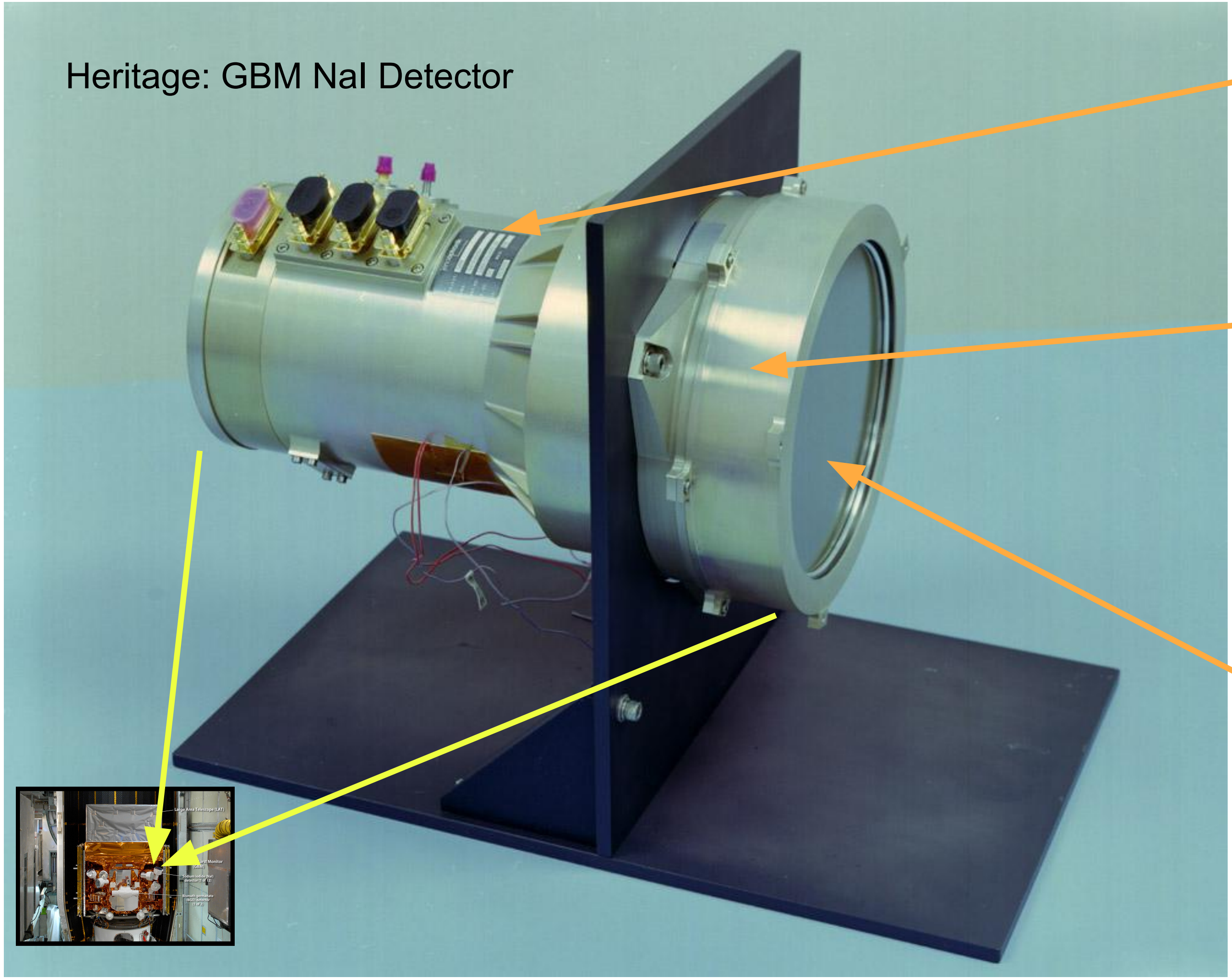
Similar detectors are used on Burstcube (4 smaller CsI detectors).





Gamma-ray transients are localized based on relative rates in each of the 12 detectors.

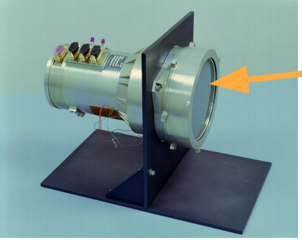
Instrument Heritage and Design



Photomultiplier tube (PMT, converts scintillating light into electric signal).

NaI crystal (ɣ-rays are absorbed and the energy converted into scintillation light)

Be Window (transparent to ɣ-rays and X-rays)

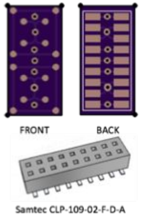


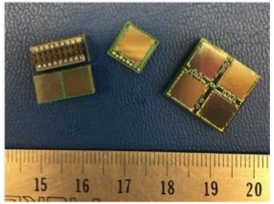
GBM NaI:

- 12.7 cm diameter
- 1.27 cm thick

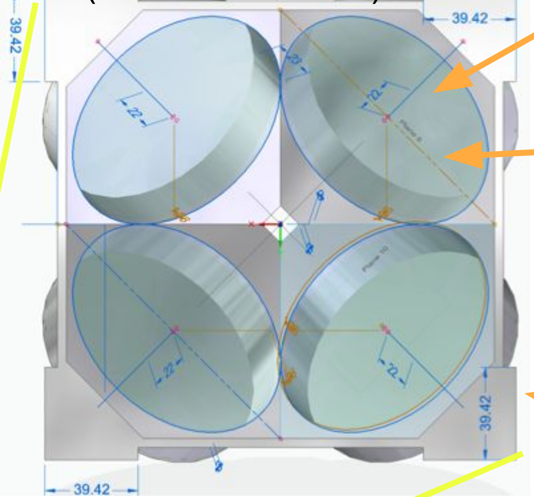
New Capability: Large-area Silicon Photomultipliers (SiPMs) Arrays

- Solid state photodetectors
- Low mass,
- Low power
- Low voltage



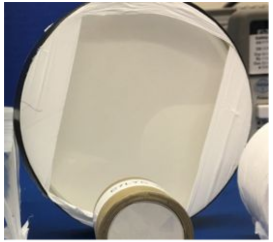


4U Instrument Assembly (from underneath)



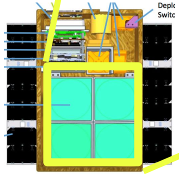
BurstCube:

- CsI crystal has slightly higher energy range than NaI.
- 10.2 cm diameter,
- 2.2 cm thick



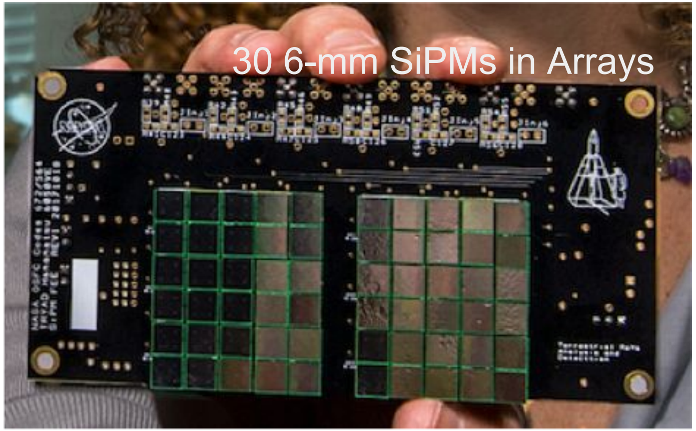
Al Optical Bench

- CsI crystals installed from back.
- View the sky out of the Al Bench
  - Al is reasonably transparent (GBM used Be)
- Sealed in via a 0.3 cm thick quartz optical window



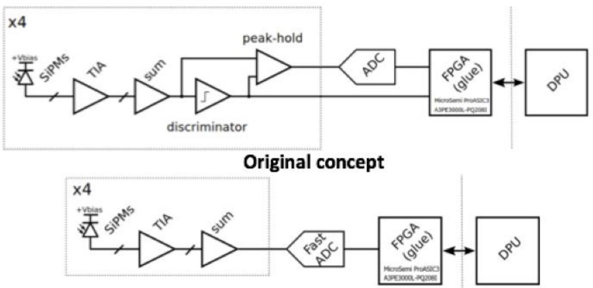
Instrument: SiPMs and Front End

- Crystals mated to arrays of SiPMs via the quartz window.
  - 44(65)% coverage with 100(145) SiPMs
- Low bias voltage (20 - 70 volts). Needs temperature compensation circuit.
- SiPM carrier boards will be mounted to preamp board.
- Different carrier board tiling and summing (both passive and active) schemes will be evaluated.
- Preamp board
  - Sums the signals,
  - Performs amplification,
  - Signal shaping
  - Pulse height analysis (PHA)
- Rad-tolerant 12-bit Analog Digital Converter (ADC) and FPGA. digitizes, time- and detector-tags, and buffers events.
- Data processing will occur as a Core Flight System (cFS) module on the OBC, external to the optical bench to reduce electronic noise pickup.
- On-orbit background ~800 counts/second and median peak flux is ~ 300 counts/second above background.



Modifying FEE boards developed and tested for TRYAD mission (designed for a fast plastic scintillator, need to optimize for slower CsI signals).

Science Signal Processing

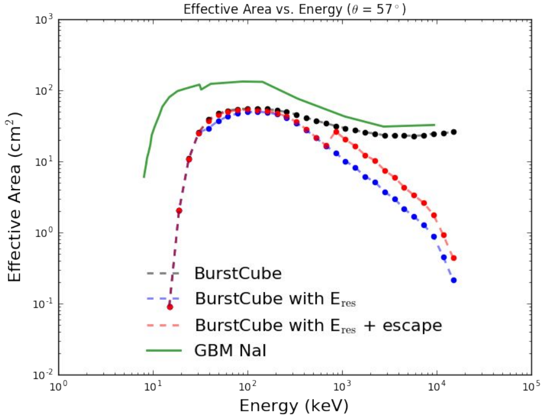


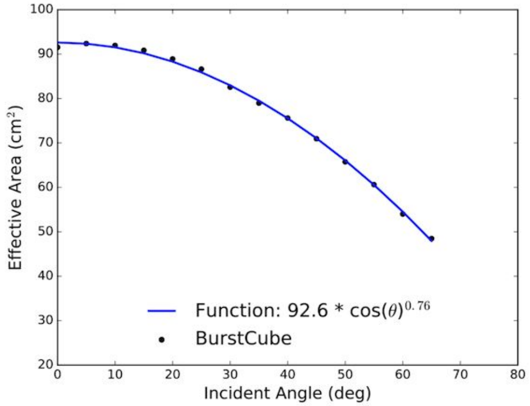
Updated concept (under consideration)

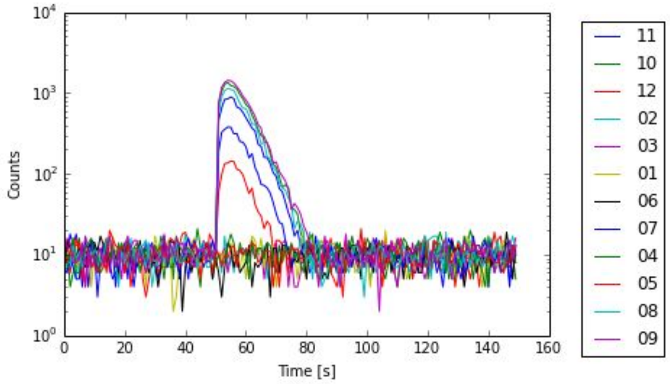
Considering doing peak hold post digitization (increased power but more flexible). Could also use commercial option (IDEAS or WEEROC).

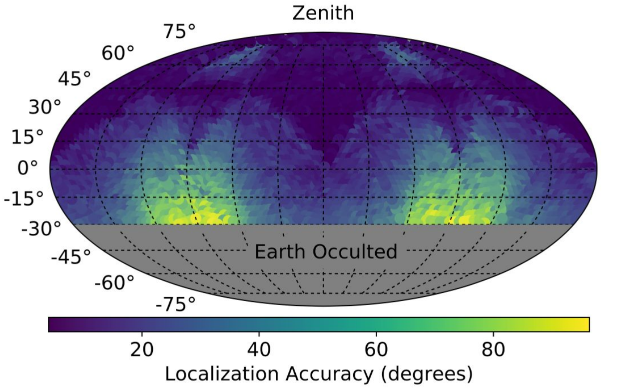
Instrument: Detectors

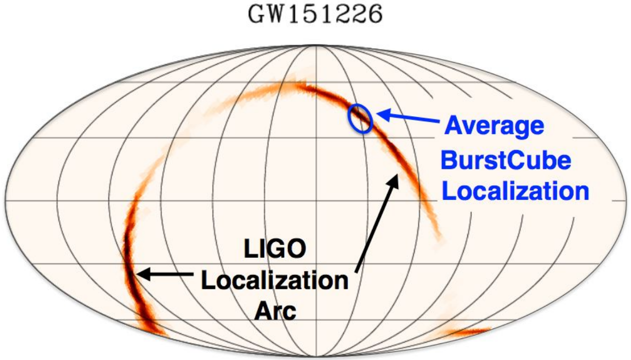
- Main detecting material is CsI in a thin disk format.
  - Has been used many times for space based applications.
- Converts x-rays and gamma-rays from about 20 keV to 1000 keV into scintillation (in the UV).
- Are about 70% as effective as the NaI detectors on GBM.
- Thin disk format enables Cos(θ) directional dependence for incoming radiation
  - Four detectors working in tandem locate gamma-ray transients.

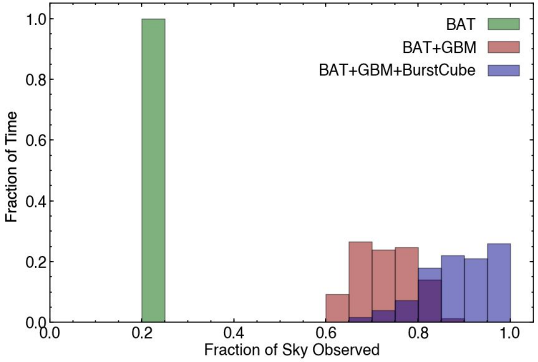


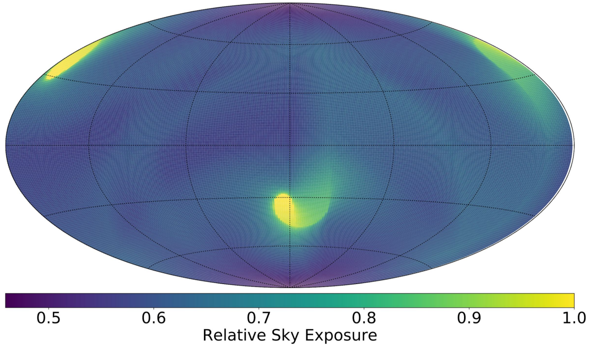


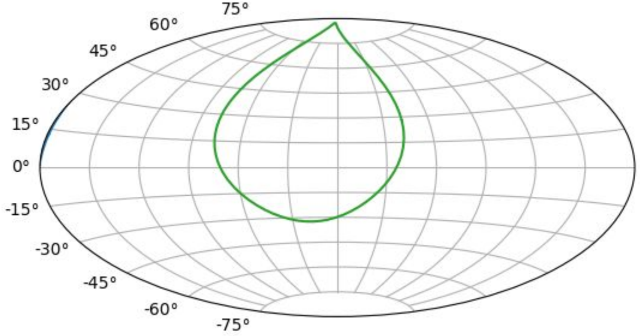


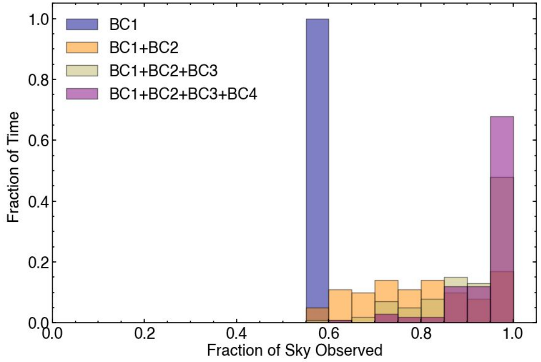












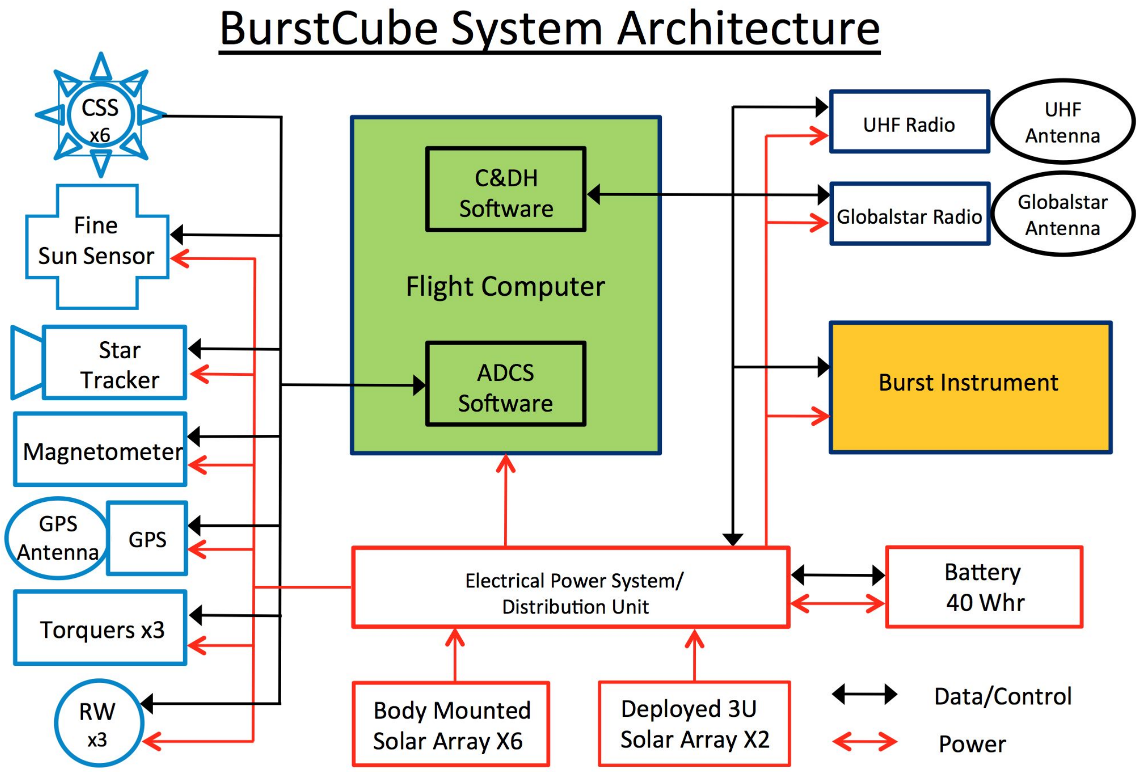
Instrument: Performance

BurstCube Concept of Operations

- Point the 6U face at the zenith direction when in eclipse, and possibly reorient to point the 6U face at the Sun in daylight to charge batteries (instrument has no Sun constraints).
- Monitor the sky in 4 detectors continuously (except SAA), performing sliding search for significant rate increases on temporally binned data (e.g. 50 ms, 250 ms, 1 s) and spectrally binned data (e.g. 50-300 keV, 100-300 keV, 10-1000 keV).
- Transmit trigger information (onboard localization, binned light curve and spectra) to the ground rapidly either via low-rate TDRSS (S-band) or GlobalStar (UHF), distribute notifications via GCN
- During scheduled downlinks (via TDRSS or ground-stations), transmit full dataset of binned or unbinned continuous data

System

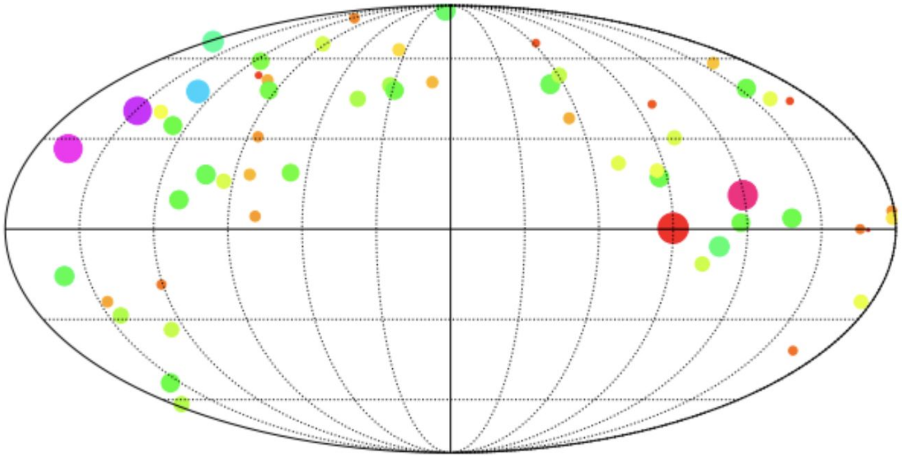
- Solar panels are body mounted on all faces along with two 3U deployable panels.
- UHF uses a deployable antenna system.
- Low latency comms will either be globalstar (or equivalent) or TDRS. Uses patch antenna.
- ADCS is 3-axis pointer:
  - Sun sensors
  - Magnetometer
  - Star tracker
  - Torquer coils (integrated on the solar panels)
  - Three reaction wheels



In [42]:
```
pos = np.array([[grb.eph._ra*180./np.pi,grb.eph._dec*180./np.pi] for grb in real_grbs])

hp.mollview(title="'Real' GRBs with Errors")
hp.graticule()
hp.projscatter(pos[:,0], pos[:,1], lonlat=True, coord='G',
               c=errors, s=np.array(errors)*10, cmap=plt.cm.hsv)
plt.show()
```

```
0.0 180.0 -180.0 180.0
The interval between parallels is 30 deg -0.00'.
The interval between meridians is 30 deg -0.00'.
```



Simulations...