BurstCube: A CubeSat for Gravitational Wave Counterparts

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for the BurstCube team
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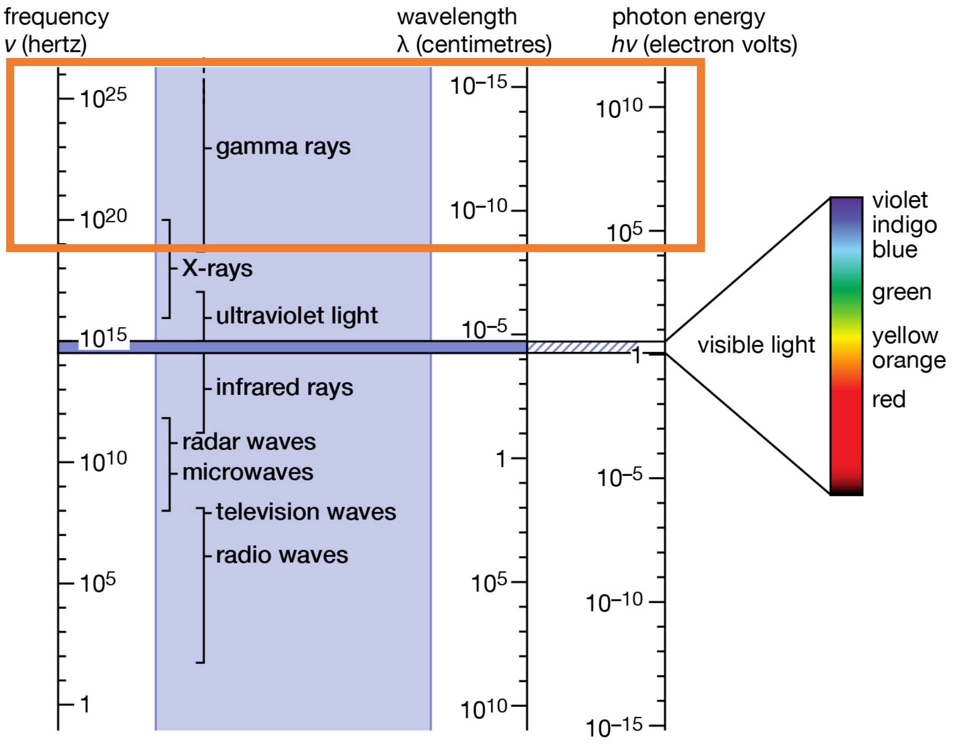
Short Gamma-Ray Burst (SGRB)

- Gamma-ray photons are the highest energy light
- GRBs are groups of gamma-rays that last milliseconds to hours and “outshine the universe”
- Sources of GRBs are ultra-relativistic, highly collimated beamed outflow jets associated with supernova, and binary-neutron stars (BNS), etc…
- GRBs are categorized by the duration of light curves (photon count rate vs time)
- **SGRBs are less than 2 seconds**, otherwise they are long GRBs

>10 keV, $< 10^{-9}$ cm, $>10^{19}$ Hz



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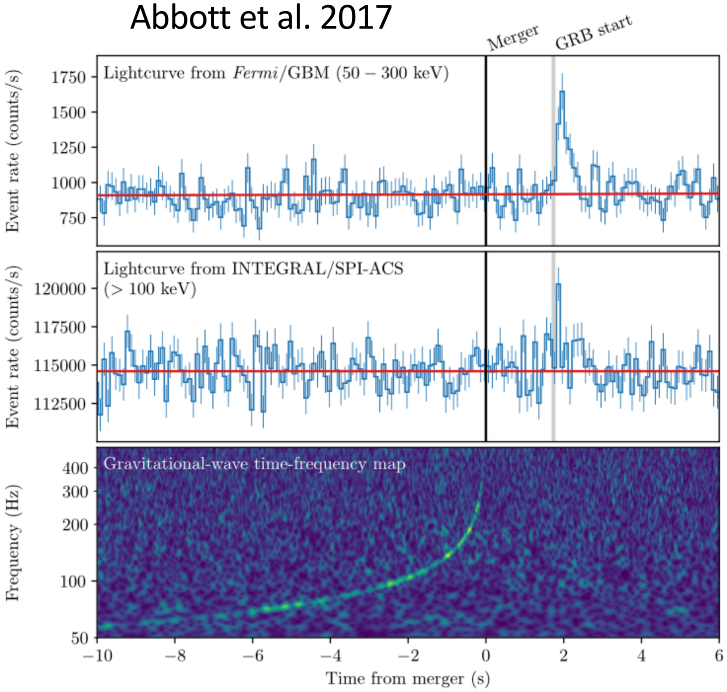
SGRBs Coincident with Gravitational Waves

- Fermi-GBM had the first verified joint detection of a SGRB (GRB 170817A) with a gravitational wave (GW170817)
  - LIGO and Virgo are two GW observatories on earth that detected this GW event
- This coincident detection and subsequent EM follow-up provide direct evidence that BNS are progenitors of SGRBs
- Many questions remain about GRB physics
  - Are the spectral properties observed in GRB 170817A common to all compact object merger events? What about GRB150101B?
  - What is the origin of gamma-ray emission?
  - What angular structure to jets have?

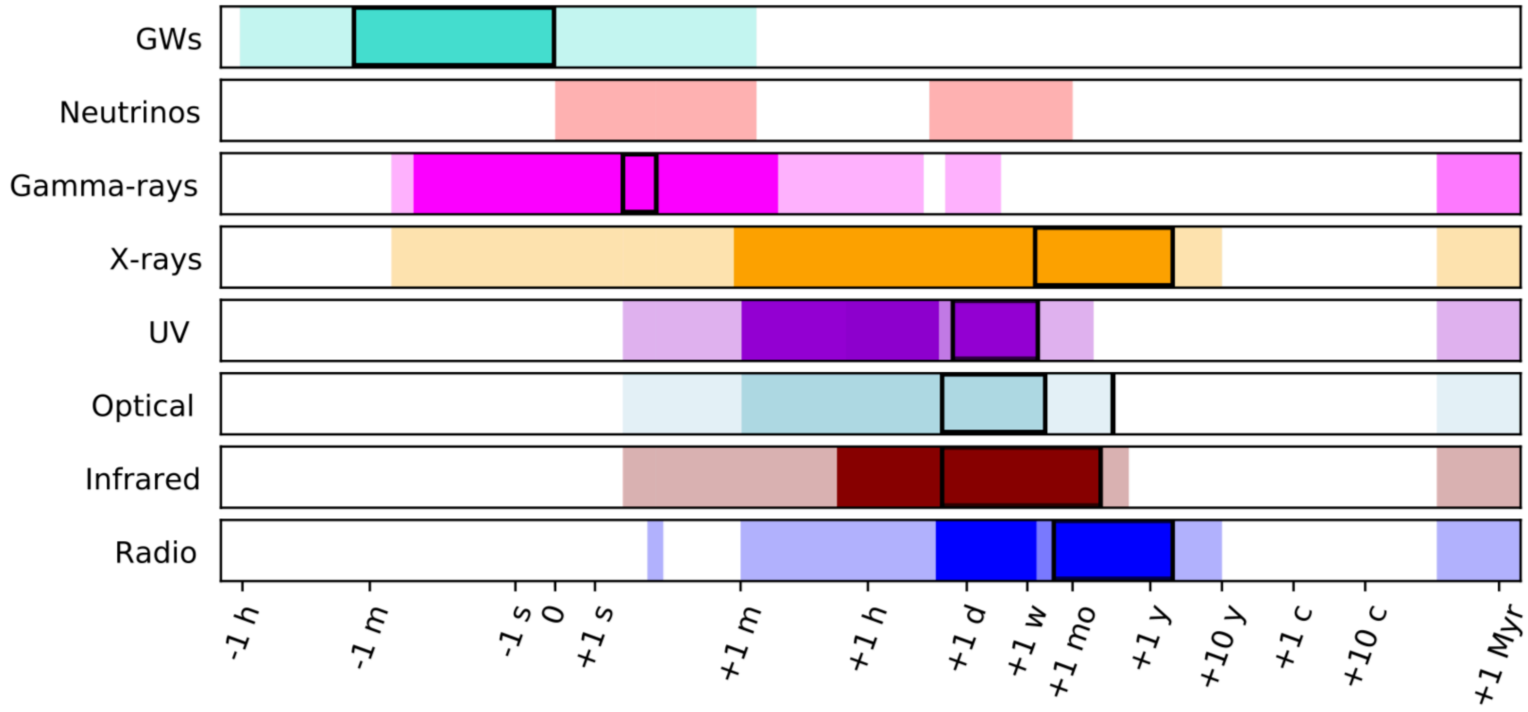
SGRB
1.7 seconds
later

Abbott et al. 2017



Multi-messenger Landscape of 170817

E. Burns 2019, arXiv:1909.06085



Black lines: 170817 observations

Dark regions: other SGRB associated observations

Shaded regions: expected observations

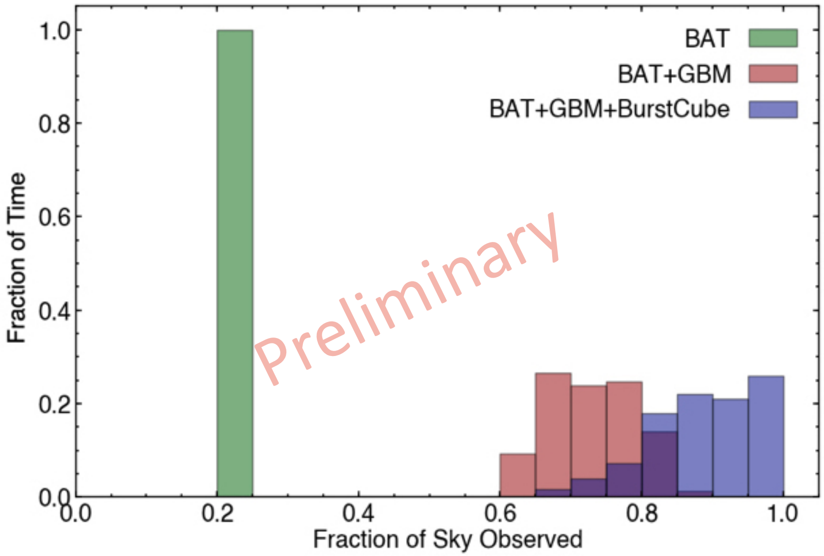
- Science of multi-messenger event 170817 was a triumph of the entire field.
- The coincident detection of a SGRB and association with a GW was the catalyst

BurstCube: A CubeSat for GW Counterparts

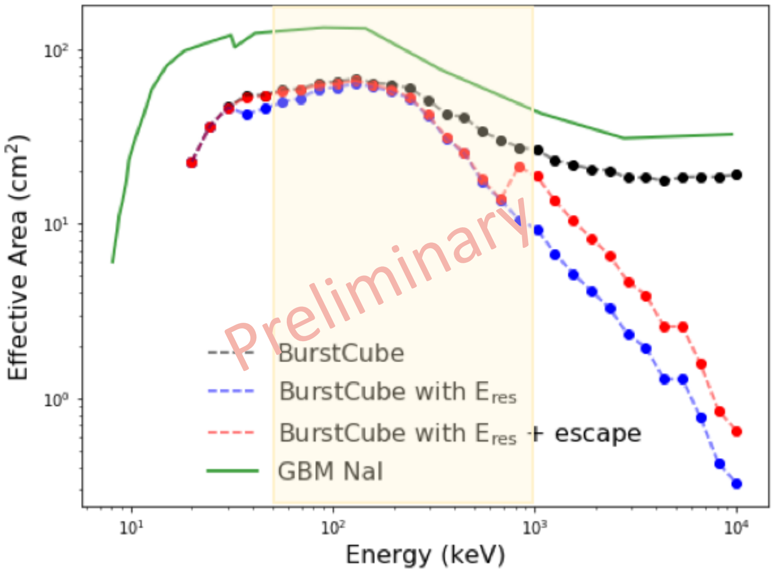
- Needs of the science community from gamma-ray experiments are continued sensitivity, and broad-band sky coverage
  - Results are independent confirmations of GW triggers, localization constraints in real-time, additional NS mergers detected through GWs
- BurstCube will enable and complement future GRB, GW, and BNS science by **detecting, localizing, and characterizing SGRBs**
- BurstCube will measure energy response of GRBs 50 keV - 1 MeV
- BurstCube will provide rapidly available high-resolution temporal, spectral and location data; expecting ~20 SGRB/year
- BurstCube is currently in its development and testing phase to prepare for launch readiness in the fall of 2021

Total sky coverage for GRBs is enhanced with BurstCube

BurstCube's effective area represents sensitivity to gamma-rays and is comparable to Fermi/GBM (green line)

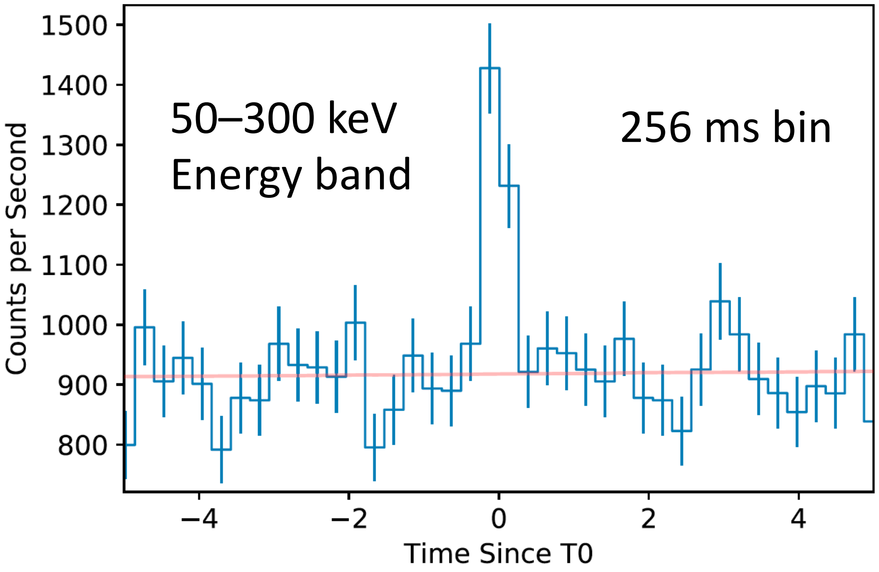


Racusin et al. arXiv:1708.09292v1



BurstCube will produce light curves similar to Fermi/GBM

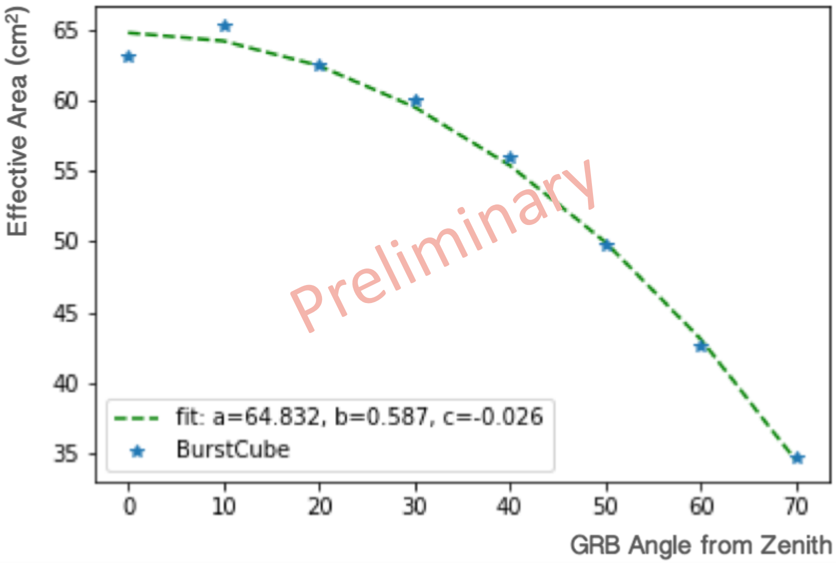
Fermi/GBM light curve of GRB170817A



Goldstein et al. 2017

Response has cosine-like dependence on GRB incident angle.

GRB Localization is based on relative rates between the detectors

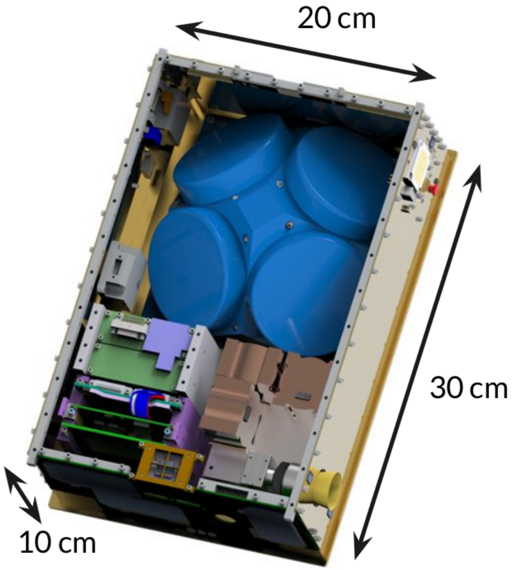


Racusin et al. arXiv:1708.09292v1

BurstCube: Instrument Design

1U ~ 10 cm^3

- BurstCube is a 6U CubeSat
  - Deployable Solar Panels & full ACS
  - Low-earth orbit, Nanoracks deployed (ISS orbit)
- Instrument Package
  - 4 CsI(Tl) scintillator crystals coupled to arrays of low-power Silicon Photo-Multiplier (SiPM)s with custom electronics
  - 90 mm diameter, 19 mm thick
  - 116 SiPMs summed per crystal
- Communications
  - BurstCube will relay data to the ground via TDRSS
    - 5-15 minute goal with an updated Vulcan radio



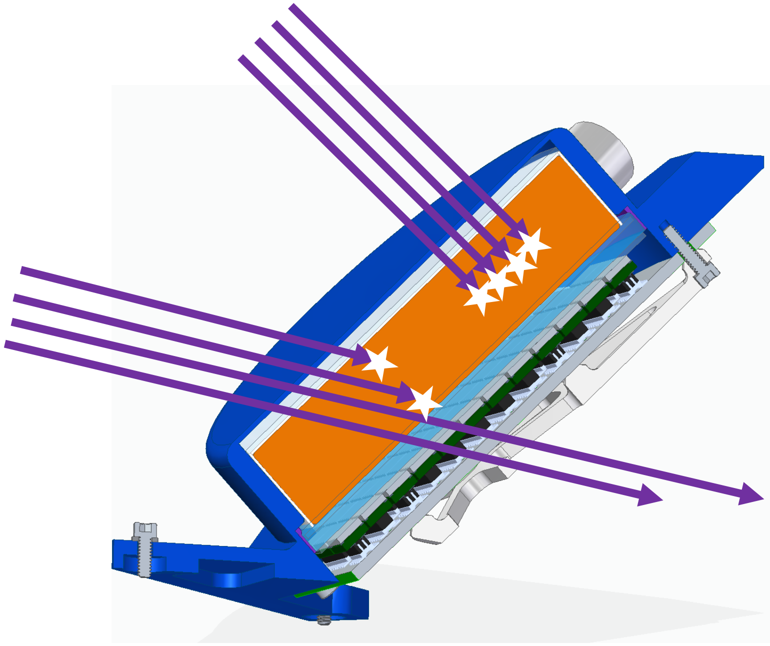
Launch Delivery Goal:
Late 2021

Approx 4.5 W allowed for instrument (4Us)

BurstCube Detector

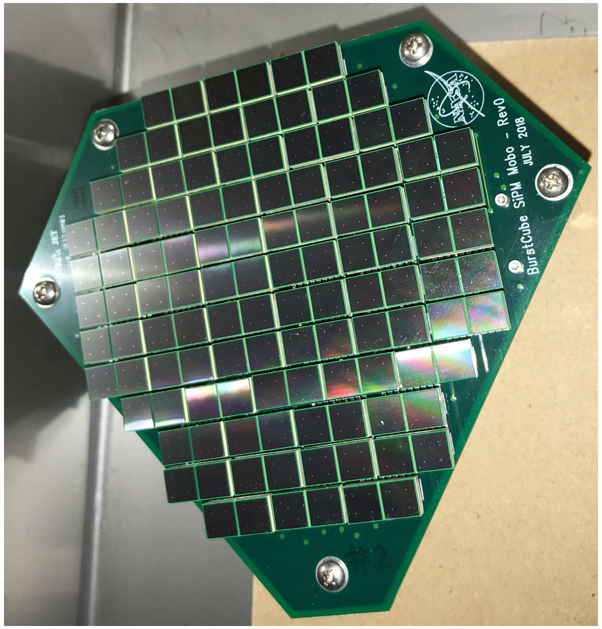
Gamma-rays scintillate in the CsI(Tl)

CsI(Tl) dimensions
90 mm diameter
19 mm thick



Response of CsI(Tl) > 1 µs

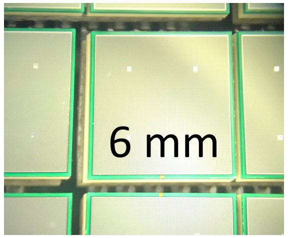
Custom, **in-house designed,** front-end electronics (FEE) -heliophysics group at GSFC



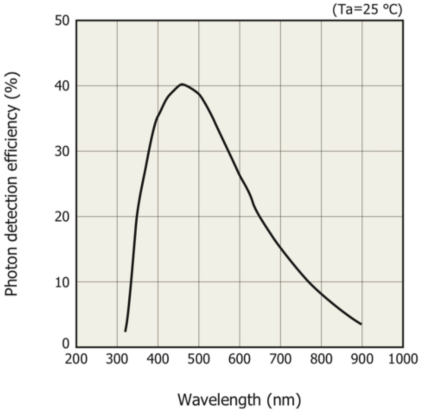
Actively summing SiPMs to shape slow response of CsI

Power less than 1 W for all four boards, < 1 W for digital back-end, approx 2 W for bias

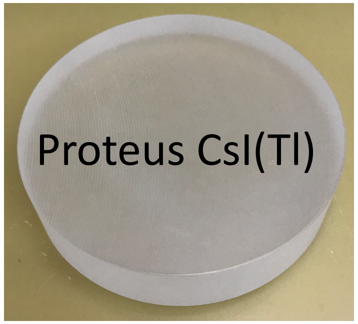
Using SiPMs with Crystal Scintillators



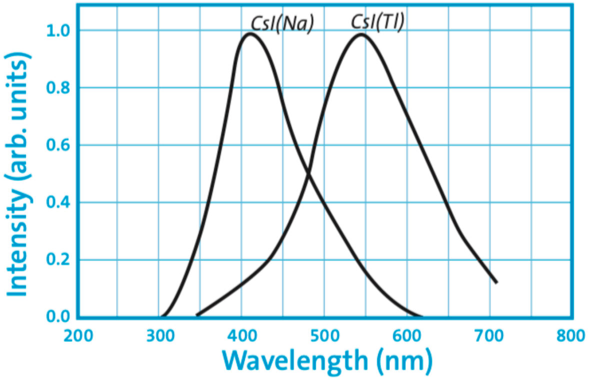
SiPM Detection Efficiency Hamamatsu S13360-6050VE



Half efficiency range: 350 nm – 650 nm
Peak: 450 nm



CsI(Tl) Emission Spectrum



CsI(Tl) Half emission range: 475 nm – 625 nm
Peak: 550 nm

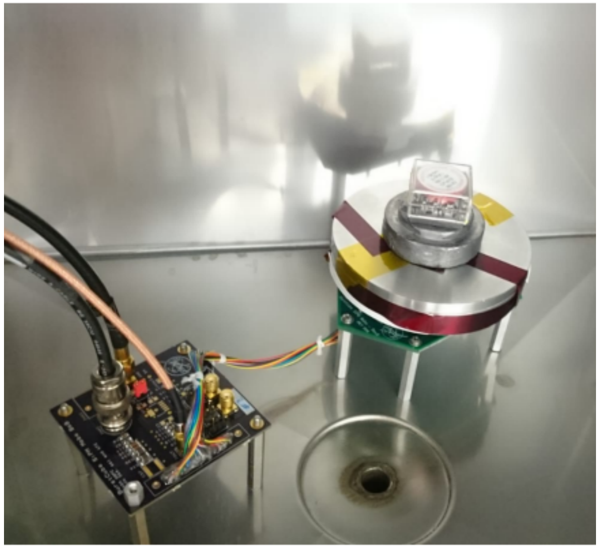
- We performed trade studies with other SiPMs: Hamamatsu best low noise high gain
- Gain: order ~ 10^6
- pixel size: 50 μm
- Dimensions: 6 mm x 6 mm
- V_{BR} = 53 ± 5 V

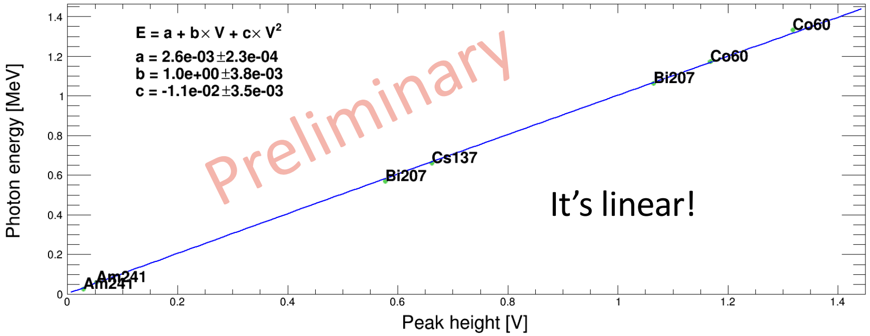
SiPM detection efficiency is matched well enough to CsI(Tl) emission

BurstCube 116-SiPM Array FEE Board

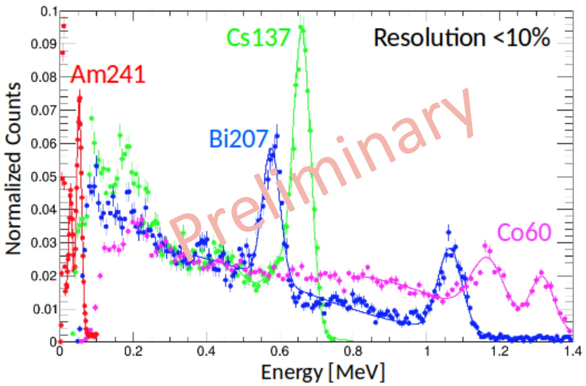
SiPM FEE board was tested with gamma-ray radiation sources 26 keV – 1.33 MeV

Temperatures tested span -10 °C to +50 °C
I2C sensor integrated on FEE

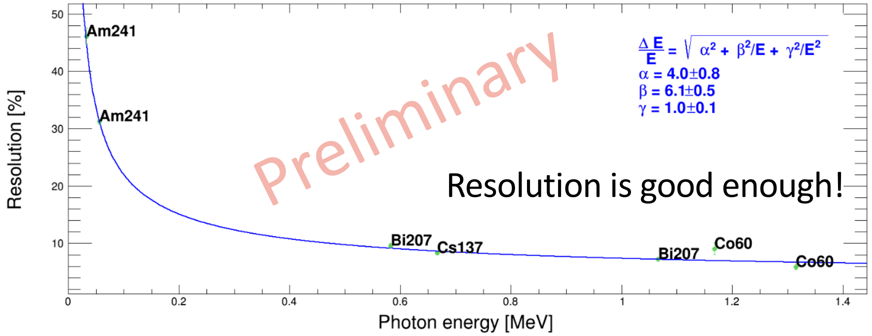




It's linear!

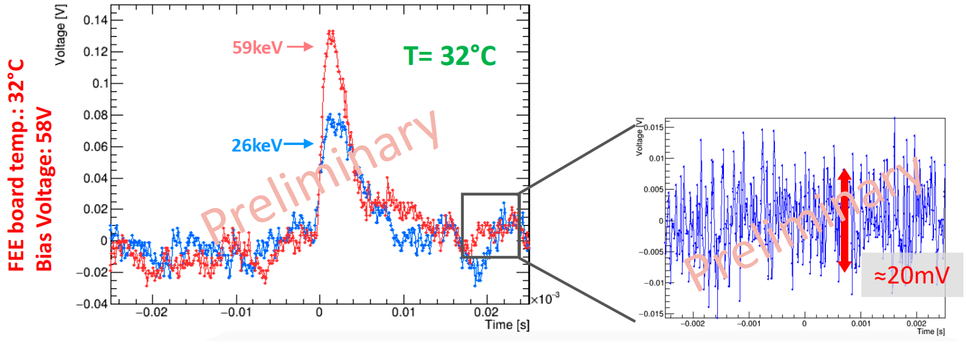


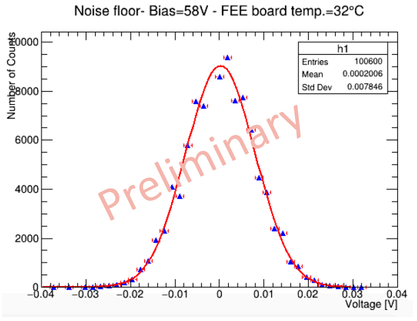
Resolution <10%



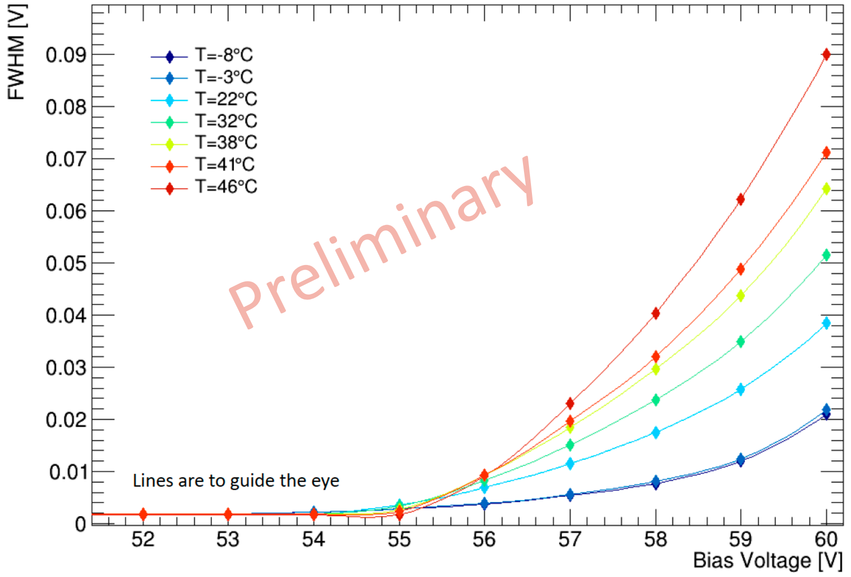
Resolution is good enough!

Noise Measurement with SiPM Array





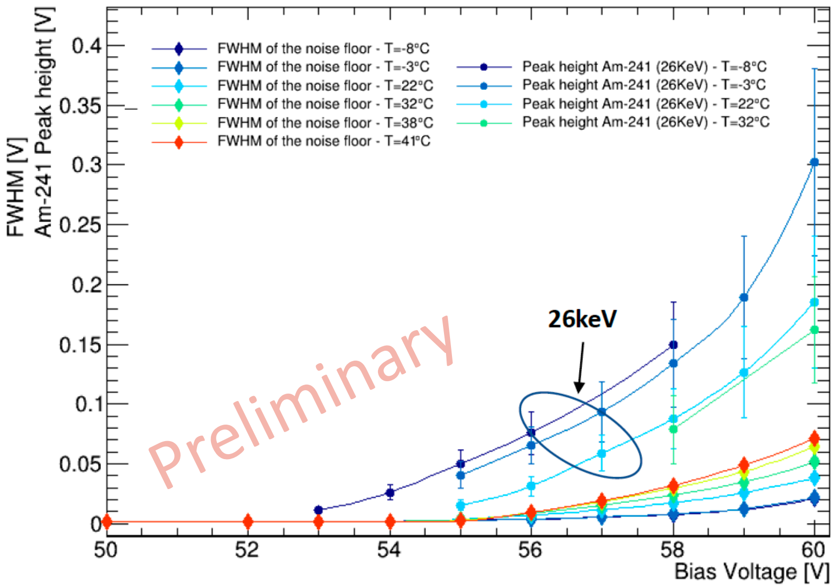
Repeat noise measurements over temperature range



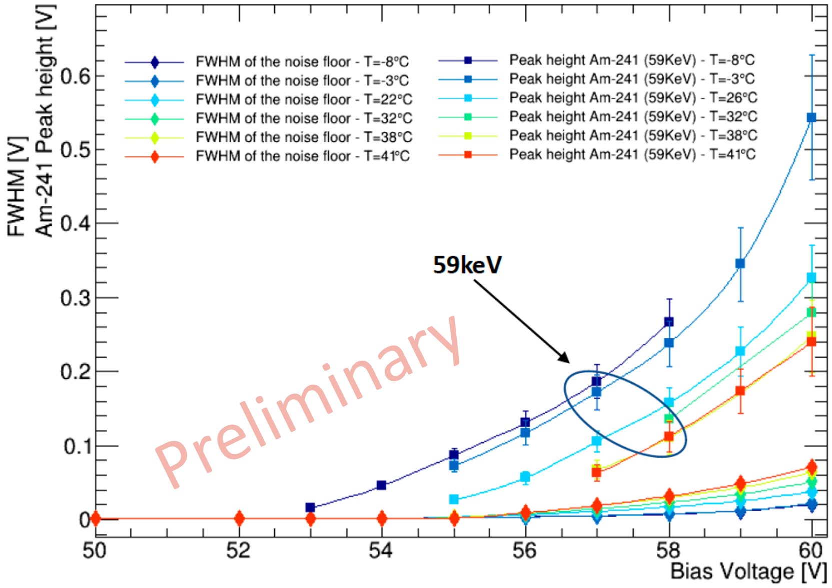
Noise increases with temperature

At what temperature range can we achieve our desired energy range?

SiPM FEE Noise with Am-241 Source



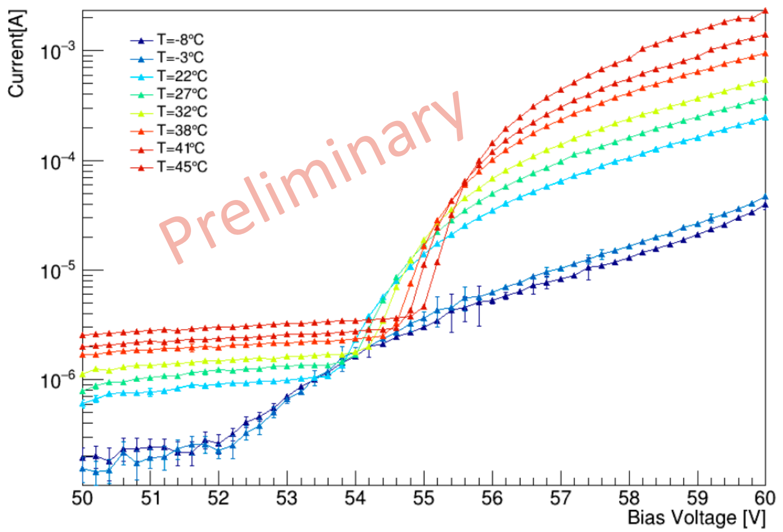
26 keV peak
Peak is indistinguishable at 38 °C

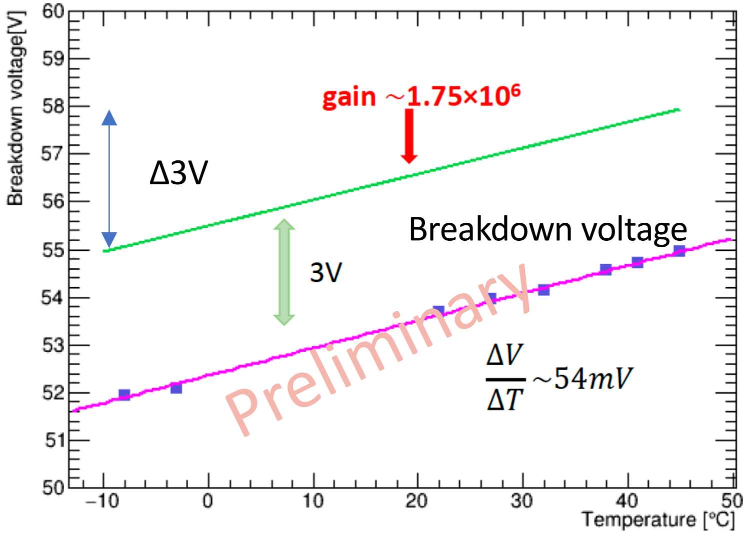


59 keV peak is seen up to 41 °C

- Gaussian fits to noise (FWHM) and peak (mean) are plotted vs. applied bias voltage from -8 °C to +41 °C
- Thermal analyses show expected temperature range during BurstCube flight is within +5 °C to +33 °C
- **BurstCube can operate beyond the required energy range for the mission**

Breakdown Voltage of SiPM FEE Measured



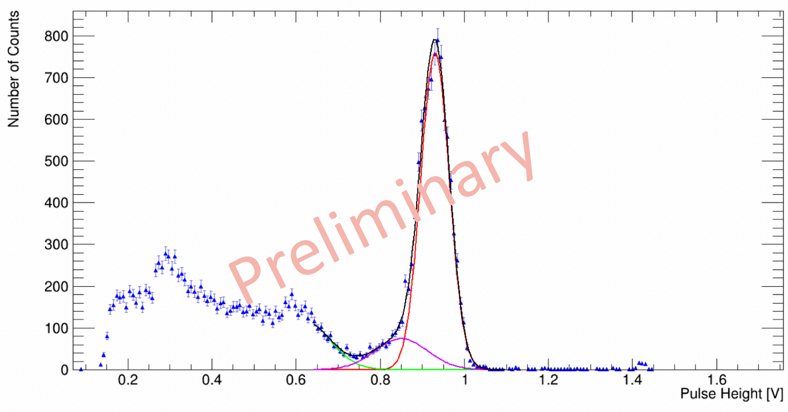


Sudden increase in current denotes breakdown voltage

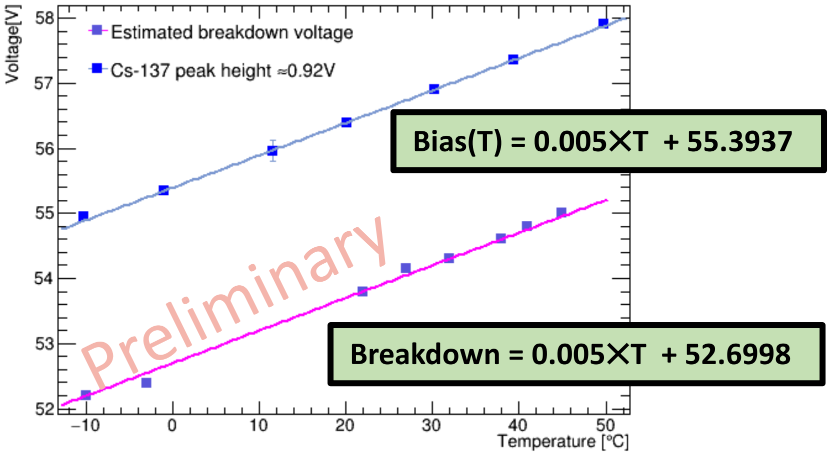
- SiPM breakdown voltage increases with increasing temperature and the gain must be compensated by adjusting the applied bias voltage
- **Measured breakdown voltage** sensitivity to temperature is linear for BurstCube SiPM array

Test of Compensation with Cs-137

Typical pulse height distribution with fit photo-peak



Cs-137 photo-peaks



Bias(T) = 0.005×T + 55.3937

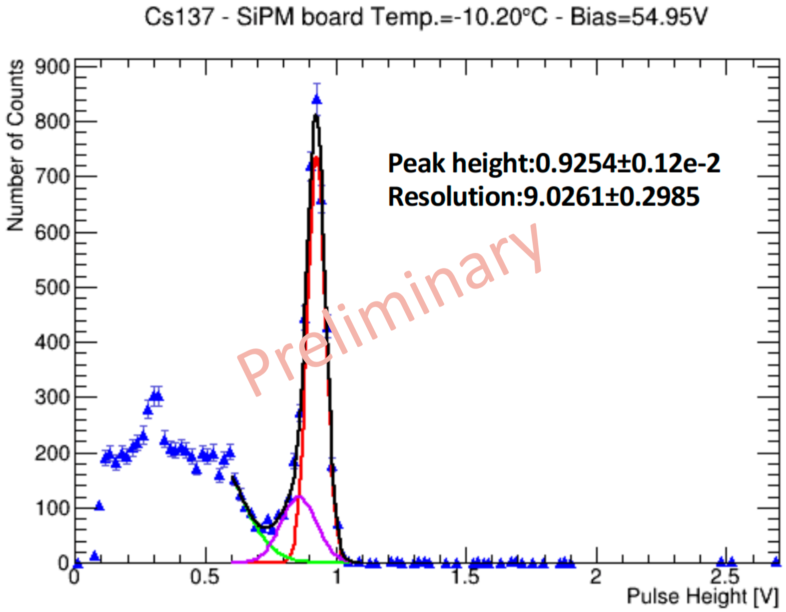
Breakdown = 0.005×T + 52.6998

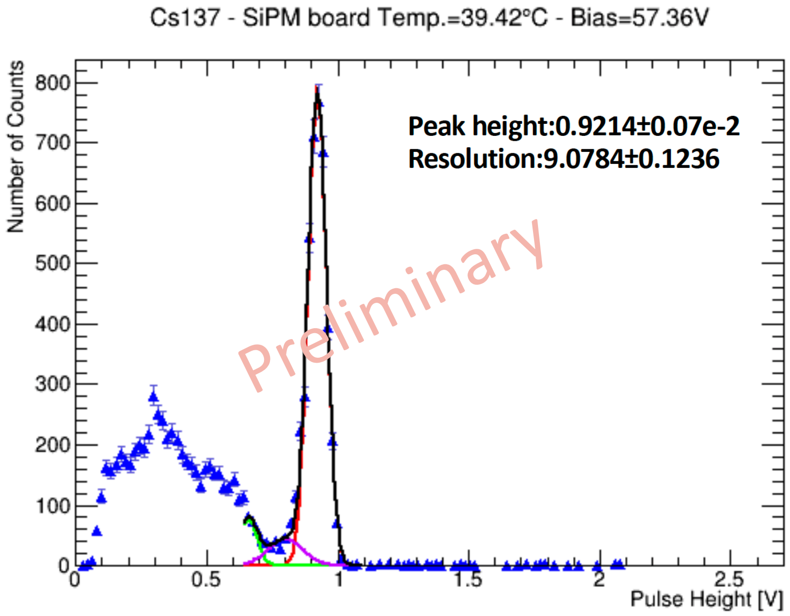
Peak height
~0.920 ± 0.005 V

Resolution (FWHM)
8.54 ± 0.08 %

- Bias voltage is adjusted for each temperature to match pulse heights with Cs-137
- Overvoltage of ~2.7 V results in constant gain
- Use the temperature compensation in thermal vacuum tests

Gain Control with Temp Compensation


Cs137 - SiPM board Temp.=-10.20°C - Bias=54.95V


Cs137 - SiPM board Temp.=39.42°C - Bias=57.36V

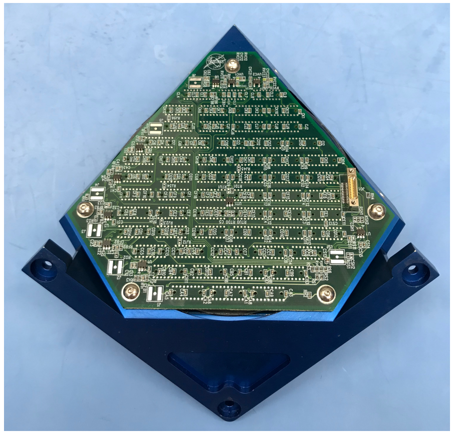
- **Bias voltage can compensate for temperature variations well within the temp range of the mission**
- Temperature compensation was successfully applied during the thermal vacuum tests

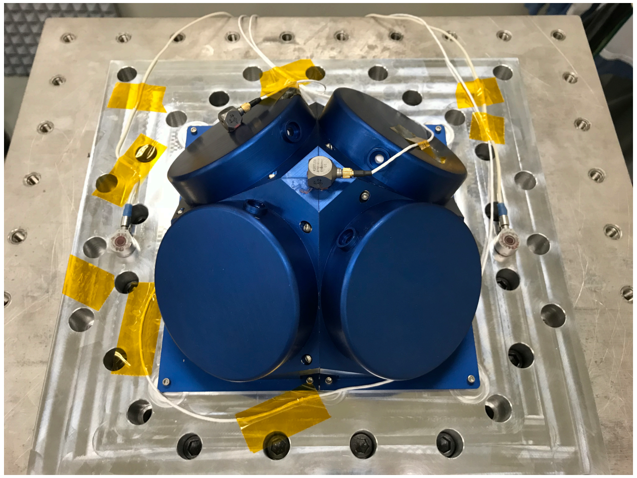
Pre-launch Environmental Tests*

- Vibration Tests (vibe)
  - Verifies if instruments can survive rocket launch and deployment
- Thermal-Vacuum Tests (TVAC)
  - Verifies instrument performance in space vacuum over temperature variations
  - Tests workmanship of parts
  - Includes non-powered survival temps (-10 °C, +50 °C), hot operational (+45 °C), and cold operational (-5 °C)
- All tests successfully follow GEVS and were completed July 2019
- Detector functionality tests and analysis verify success or failure (not an option).
  - Measure energy response with a gamma-ray radiation source
  - Tests ran during TVAC with temperature compensation applied
- **Following an independent review of the technology readiness level (TRL), BurstCube will be at TRL-6** (TRL-1: do unicorns exist?, TRL-9: this unicorn is from space)

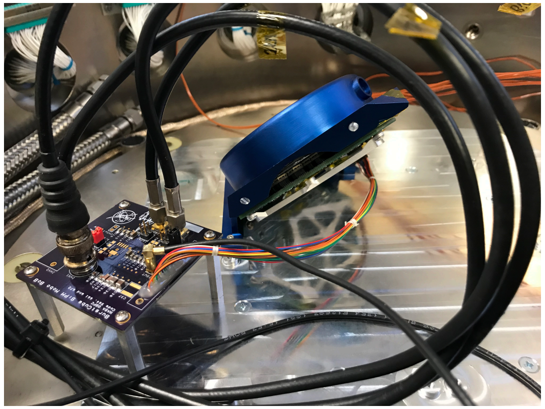
*per NASA Goddard's General Environmental Verification Standard (GEVS)

Proto-flight
Instrument Quarter



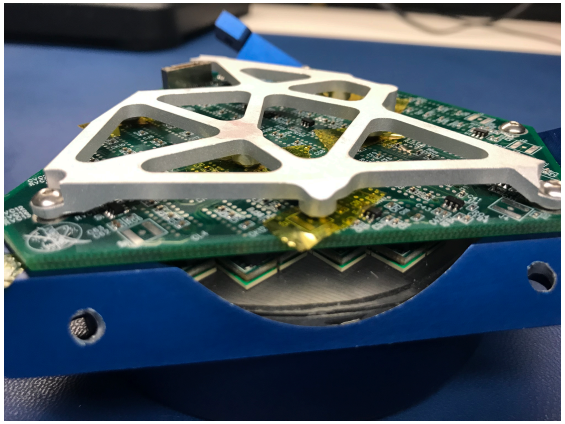


BurstCube on the vibe table

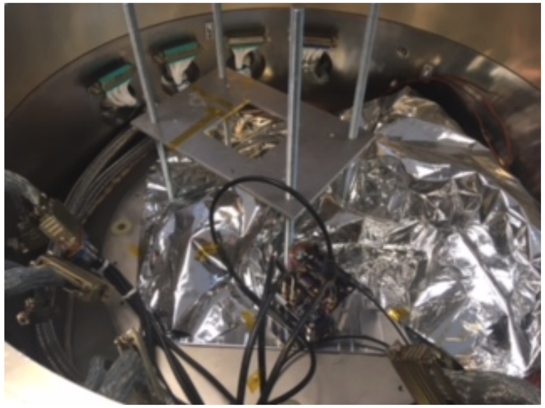


Proto-flight in the
TVAC chamber

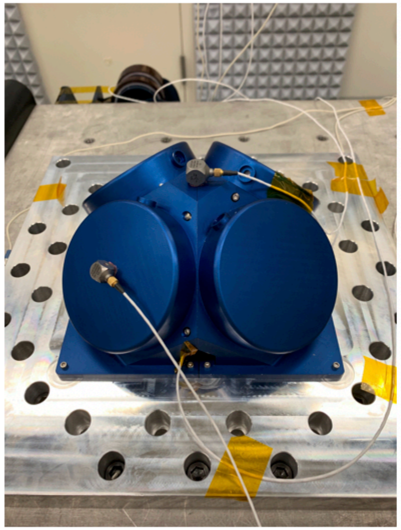
The real experts



Sideview of instrument quarter



BurstCube Current Status



- First BurstCube proto-flight detector has been constructed
- Design, integration and test of the 116-SiPM FEE board has been completed and **exceeds requirements**
- Proto-flight detector has **successfully completed environmental** vibration and thermal vacuum testing in July 2019
- Pending an independent TRL review, **BurstCube will be at TRL 6**
- Instrument digital (FPGA) electronics design and prototyping has begun
- Requirement documentations for interfaces to the spacecraft, Instrument flight software, ground pipelines and analysis, and calibration and simulations are in work
- **Flight hardware build** is expected to begin end of this year
- **Expected delivery of spacecraft to launch vehicle is planned for 2021**

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