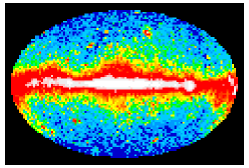
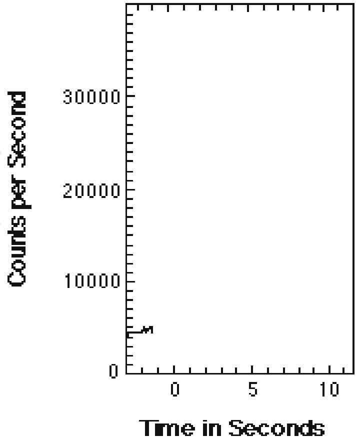
GALI: a gamma-ray burst localizing instrument

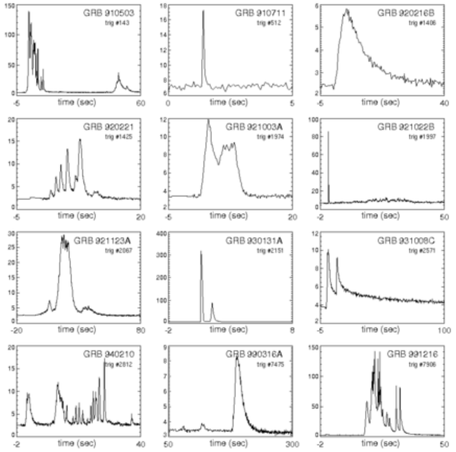
Shlomit Tarem, September 2021

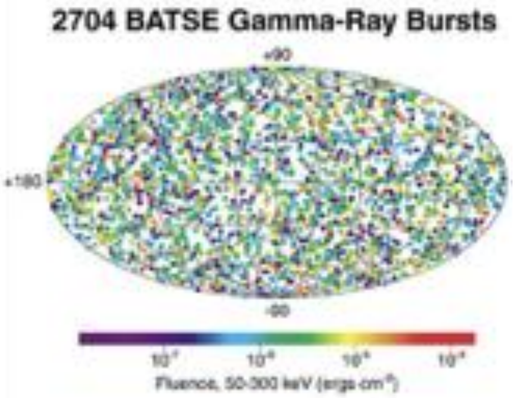
Introduction

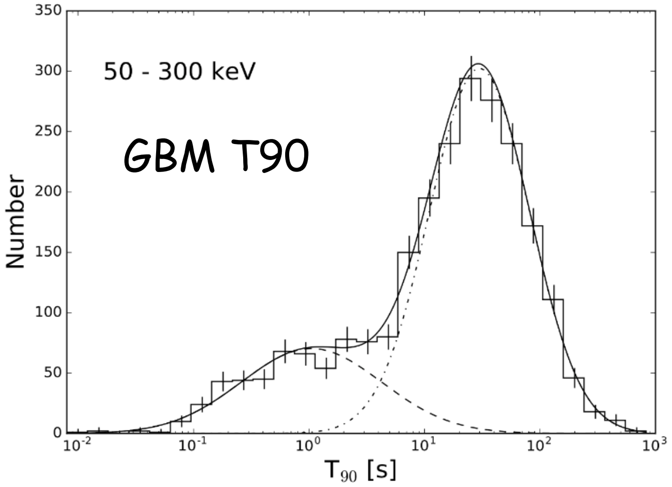
- γ-ray burst (GRB) are cosmic explosions detected as a short rise above the γ-ray background
- Most of the GRB flux is emitted between 1 keV – 1 MeV (photons)
- Flux decreasing with energy;
  GRB dominates background
  above 50 keV
- GRB temporal behavior is arbitrary, they last from 0.1 s – 100 s
  with two peaks around
  0.3 s and 30 s
- GRBs occur unexpectedly, anywhere in the sky, a few times a day





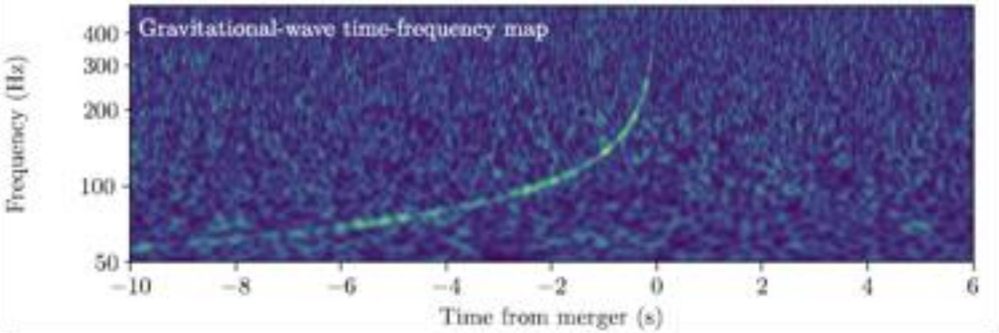




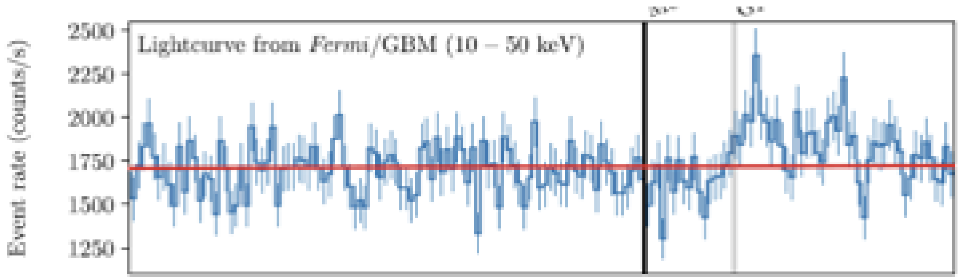


Top Level Science Mission Motivation and Goals

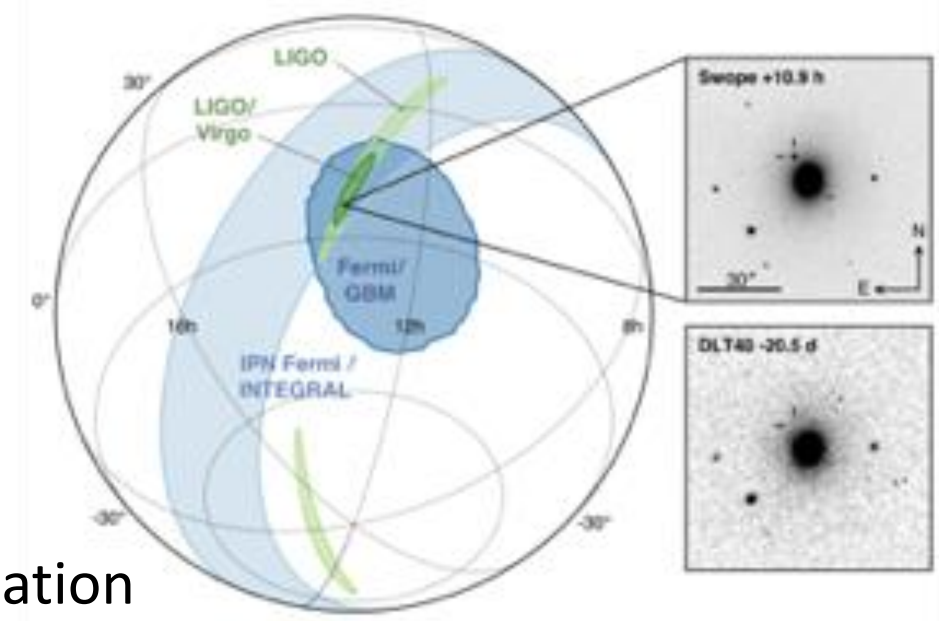
- Motivation to detect GRBs associated with gravitational wave (GW) events
- Neutron star mergers are allegedly the sources of short GRBs and also produce GWs
- One such event detected to date GW170817



LIGO/
VIRGO
t= 0



Fermi/
GBM
t= 2s



Visible
identification
t= 11hr

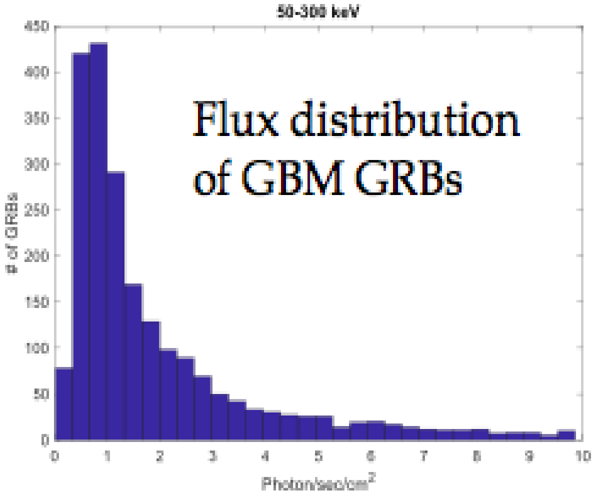
Top Level Science Mission Motivation and Goals

- Top Level goal – TO BE ON TARGET – FASTER and MORE ACCURATE
- GW170817 had favorable conditions
  - Three LIGO/VIRGO detectors were operating
  - It was in a VIRGO blind spot => 30 sq. deg. (and VIRGO was just commissioned)
  - It was only 40 Mpc away (LIGO/VIRGO design sensitivity is out to 200 Mpc)
- The GRB detection by Fermi/GBM had a 1000 sq. deg. uncertainty
- Host galaxy identified only ~11 hours later
- GRBs and their X-ray afterglows decay within seconds/minutes
- Two astronomical methods for seeking EM counterparts
  - Survey galaxies within LIGO/VIRGO uncertainty region (both angle and distance)
  - Use wide field imagers to capture that region
- Former becomes prohibitive as LIGO/VIRGO sensitivity increases for distant events
- Conclusion: Need sensitive, wide-field detector with good angular resolution

Overview of Science Requirements

- Detect as many GRBs as possible, at least 50/yr
  - Wide field instrument, at least half of the sky
  - Sensitivity to weak GRBs, reaching peak flux of 1 ph s^{-1} cm^{-2}
- Accurately detect direction of GRB
  - GALI’s Claim-to-fame
  - Goal is to allow standard, ground based telescopes to follow up
  - 3°x3° FoV of small robotic telescopes

- Reference:
  - Fermi/GBM detects 236 GRBs/yr, ~ 100 above 1 ph $s^{-1}cm^{-2}$
  - ISS/CALET(FoV ~ π str) detects ~43/yr (60% duty cycle because SAA)



Flux distribution of GBM GRBs

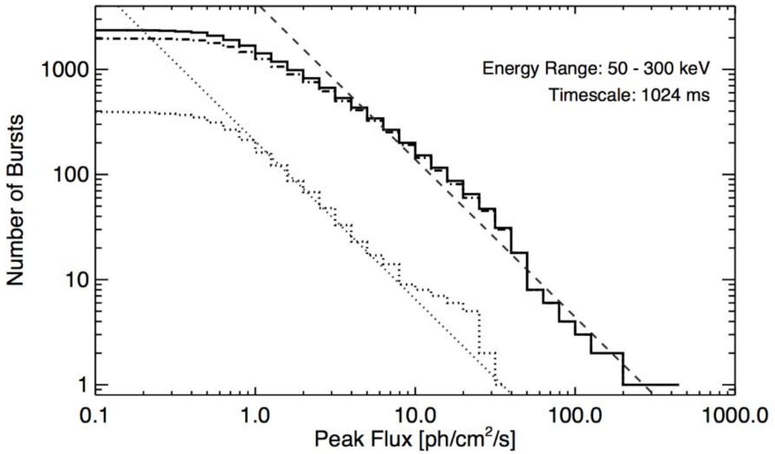
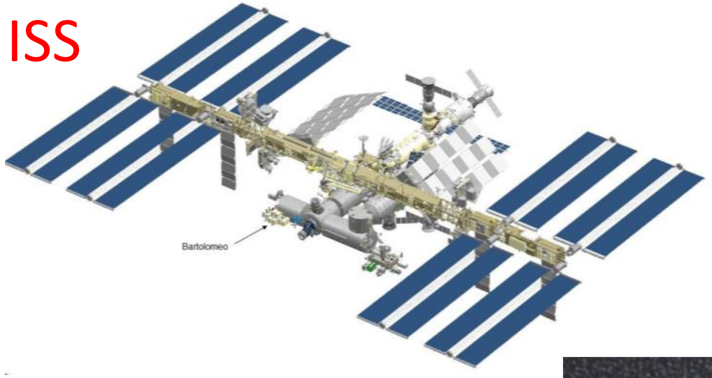
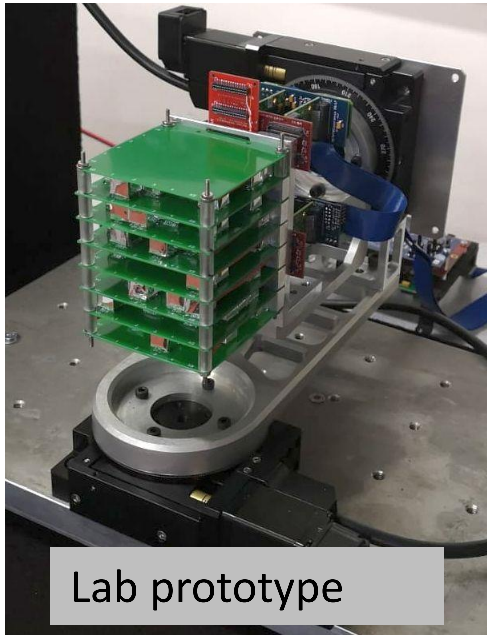


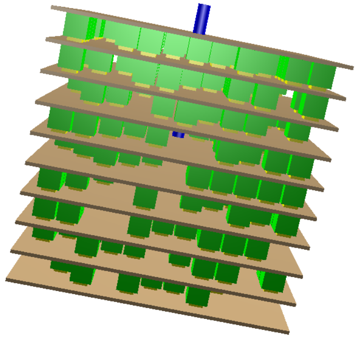
Figure 7. Integral distribution of GRB peak flux on the 1.024 s timescale. Energy ranges are 10–1000 keV (upper plot) and 50–300 keV (lower plot). Distributions are shown for the total sample (solid histogram), short GRBs (dots) and long GRBs (dash-dots), using $T_{90} = 2$ s as the distinguishing criterion. In each plot a power law with a slope of $-3/2$ (dashed line) is drawn to guide the eye.

Scientific Mission Overview

- GALI is a GRB detector to be mounted on the ISS
- Detection based on scintillators
  - Low level product is a list of photons with *t, E* (for each scintillator)
- GALI’s novelty is the use of an array of small scintillators, obtaining directionality through mutual occultation
- Onboard computer will take raw data and
  - Identify a GRB above background
  - Identify its direction in the sky
- Report GRB alert to the ground




Lab prototype

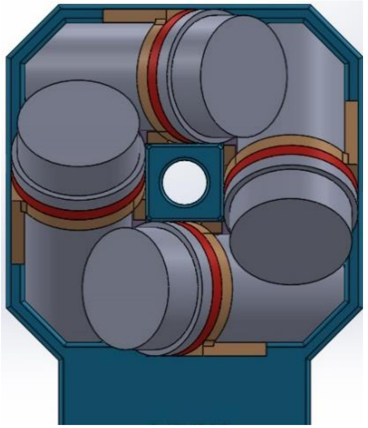

Design

Back Story of GALI

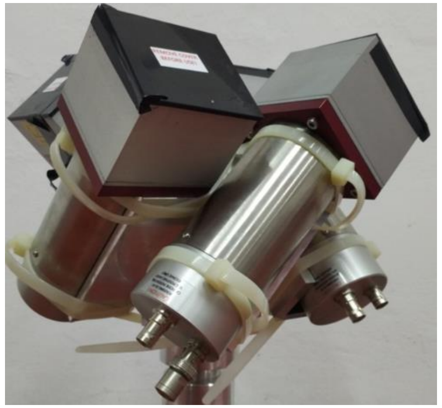
- In 2012 my colleague Ehud Behar was invited to join the ISS-TAO proposal by a team of Goddard scientists and build a small Gamma-ray trigger instrument to complement the lobster x-ray telescope.
- Prof. Behar has no background in instrumentation – hence suggested I join him
- The instrument was to be inspired by Fermi’s GRB but smaller and cheaper
- We started thinking about finding the GRBs direction and how to arrange scintillators to do it
- In the end – ISS-TAO was not funded by NASA and we continued a research project to optimize configurations for direction finding

The starting point

- Fermi has 12 NaI scintillators of 12.7 cm diameter 1.27 cm depth distributed in different directions over the large volume of the satellite. It has additional BGO scintillators for higher energies.
  - Fermi cost a total of $690M, no idea how much of it is the GBM but each scintillator cost 100s of $K
- Our design for GTM looked like this:
  - NaI scintillators have 3” diameter and are 1” thick



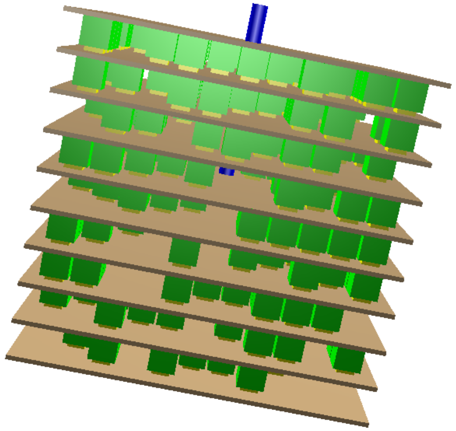
- The direction is found by comparing shares of photons between scintillators
- We had a lab model that looked like this:
  - I will compare it’s performance to GALI later



- NaI must be encased in vaccum - hygroscopic

Introducing GALI

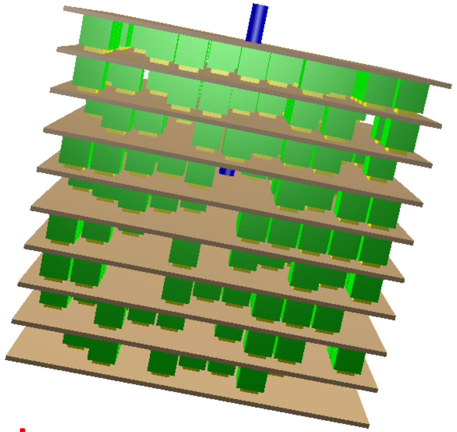
- Instead of a small number of large scintillators, GALI is a compact arrangement of many small scintillator cubes in a 3 dimensional array
- Each scintillator is a 9 mm cube of ScI(Tl)
- The cubes obstruct the photons from each other depending strongly on the photon direction
- Thus our ability to find the source direction by what combination of cubes was hit – share of photons between cubes
- We learned from simulation that ~30% is a good fill factor – the current design has 362 scintillator cubes in a 12 cm cube
- The current arrangement inside the 12 cm cube is more or less random, optimizing the arrangement needs further study



Goals and how we'll meet them

- GRB detection: 50 detections per year
- Readings summed over detectors and compared to the recent background
  - Simulated average sensitivity of ~0.9 ph cm^{-2} s^{-1} in the detection band (50-300 keV)
  - Open sky and isotropic GRB distribution yields ~110 GRB/year, based on the Fermi GBM.
  - Since the sky on the ISS is partially blocked we can expect ~70-80 GRB/year

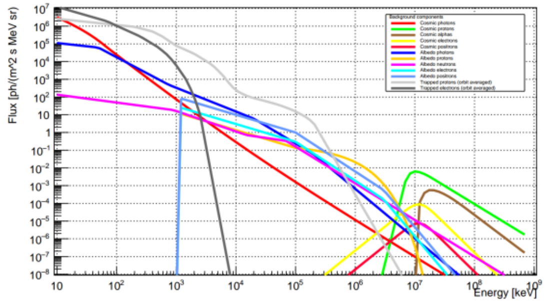
- GRB localization: 3° average error for 10 ph cm^{-2} s^{-1} total GRB flux
- **A compact configuration of many detectors causes angle dependent mutual obstruction between detectors**
  - Each scintillator is a 9 mm cube
  - Simulations show configuration with 362 detectors reach average accuracy of <5° for a flux of 5 ph cm-2 s-1 in the 10-1000 keV energy band
  - The configuration is made possible by using Silicon Photomultipliers (SiPM) coupled to scintillator crystals.



- Trigger warning - instant message / Spectrum and light-curve as products

Simulation

- Simulations performed using MEGAlib software (based on ROOT and Geant4).
- 5M gamma ray background events simulated – estimate expected number of per second on each scintillator
- Simulate bursts of 1000 ph cm^{-2} from different directions on the hemisphere, in 5 degree intervals – build sky map

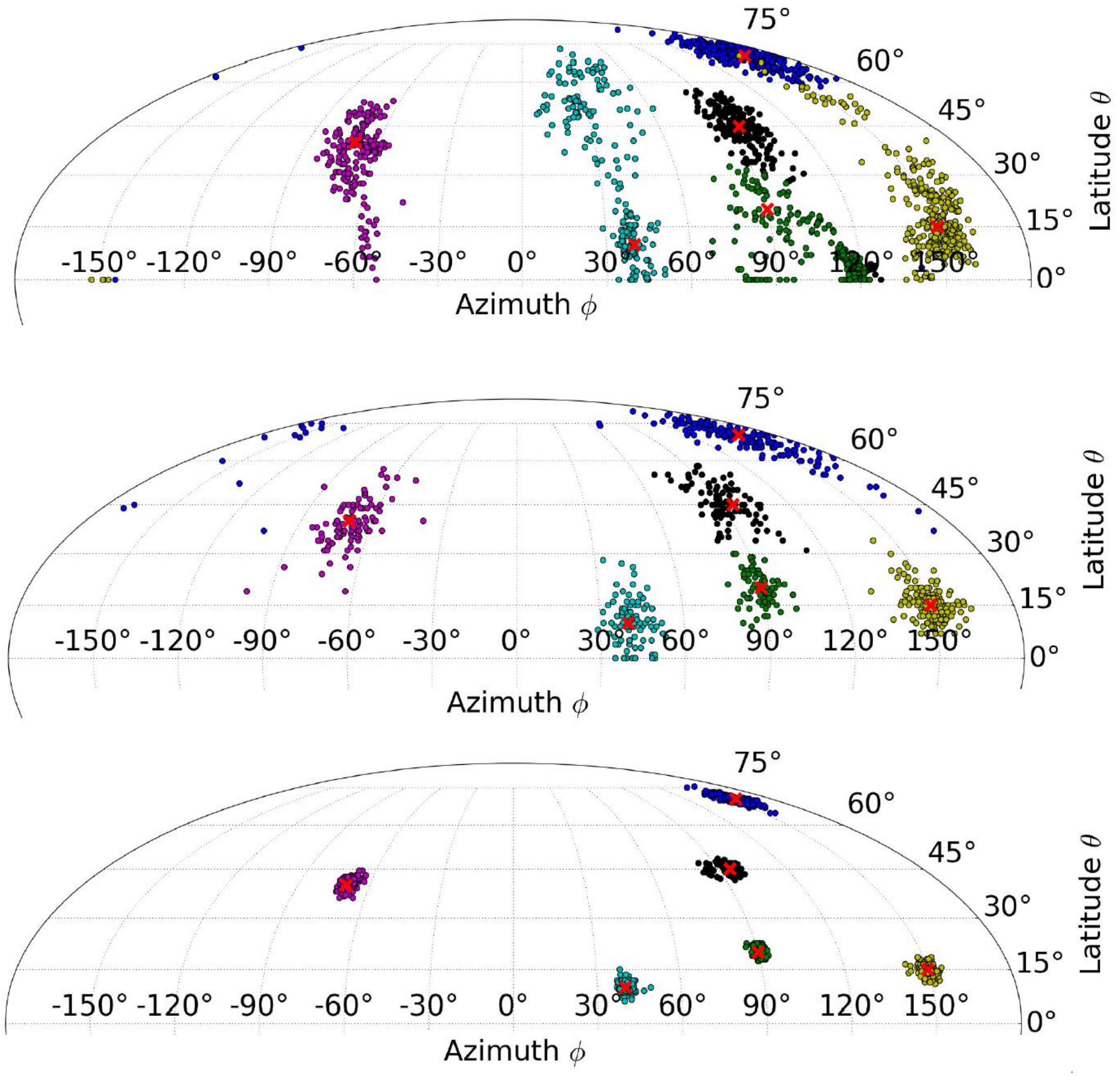


- The spectrum is that of a typical GRB (but large variations exist)
- Direction estimation is done by comparing the photon shares (between detectors) of a burst to the high statistics sky map – cstat statistic
- We simulated multiple detector configurations
- The average accuracy of each configuration is only slightly affected by the scintillator placement (~5%).

Comparison to GTM - simulation

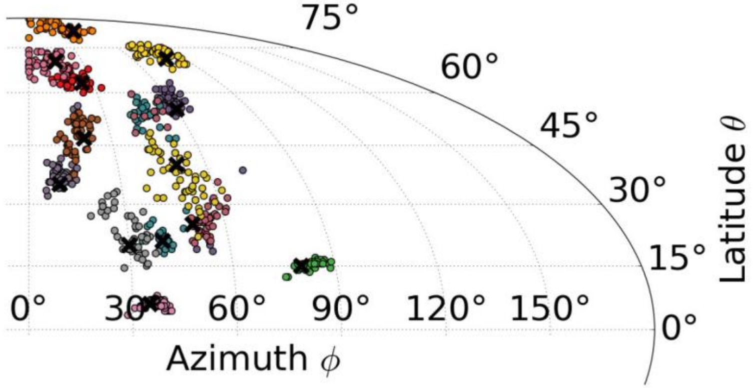
- A comparison between the simulation-generated GRB direction reconstructed by different detector configurations.
- Each dot represents a 1 second burst of 10 ph cm^{-2} s^{-1} at lower earth orbit.
- Dots are grouped by color according to the actual burst direction, which is represented by a mark.

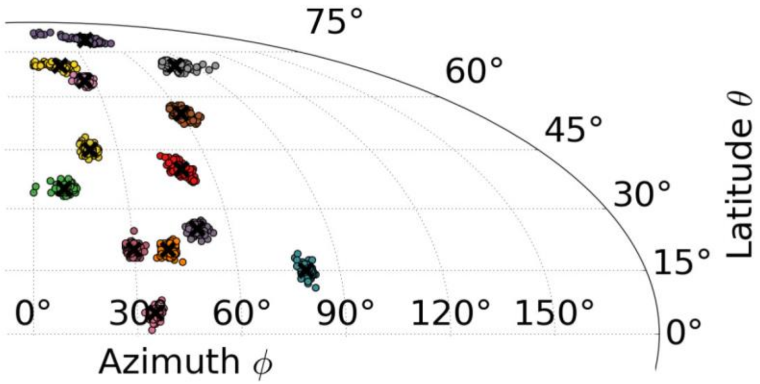
- Top: GTM
- Middle: 90 scintillators GALI
- Bottom: 350 scintillators GALI

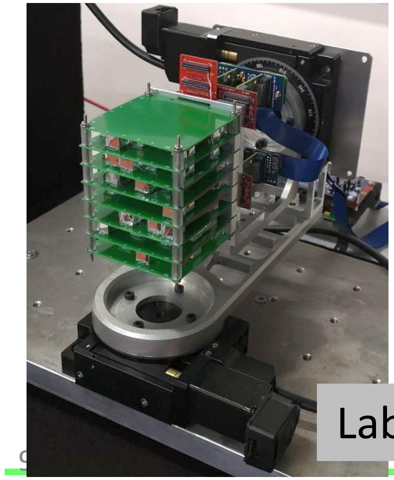


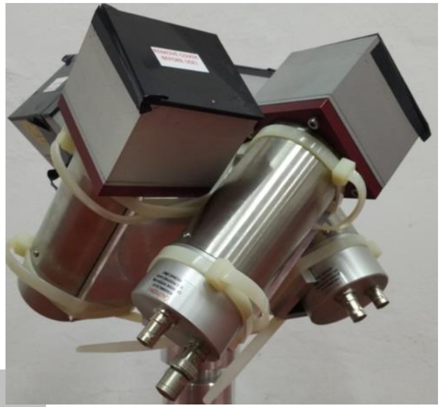
Comparison to GTM – measurements on prototypes

- A comparison between laboratory tests of the GTM (Top) and a 90-scintillator GALI (Bottom).
- The reconstructed direction of repeated 0.5 s bursts are plotted where each dot represents a burst.
- Dots are grouped by color according to the actual source direction, which is represented by a x mark.
- Confirming the simulations, the superior localization accuracy of GALI is clear.



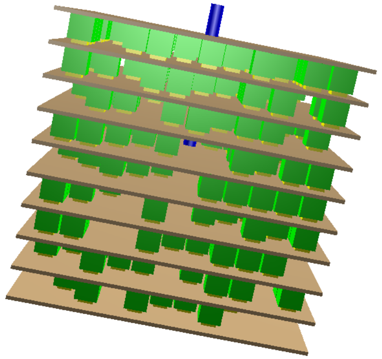




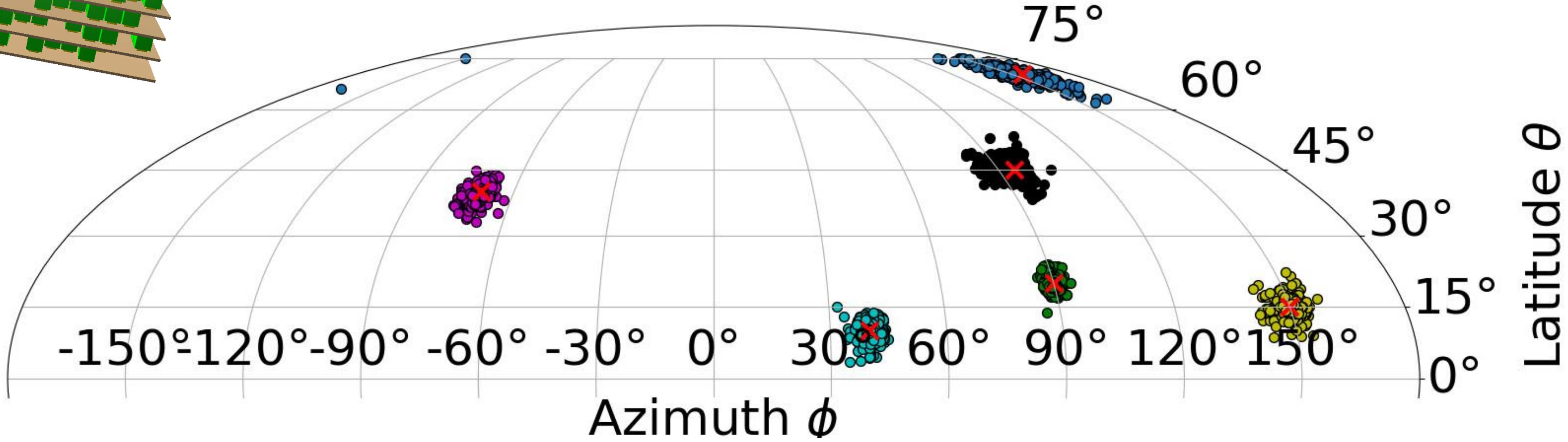


Lab prototypes

Simulation of Final Version



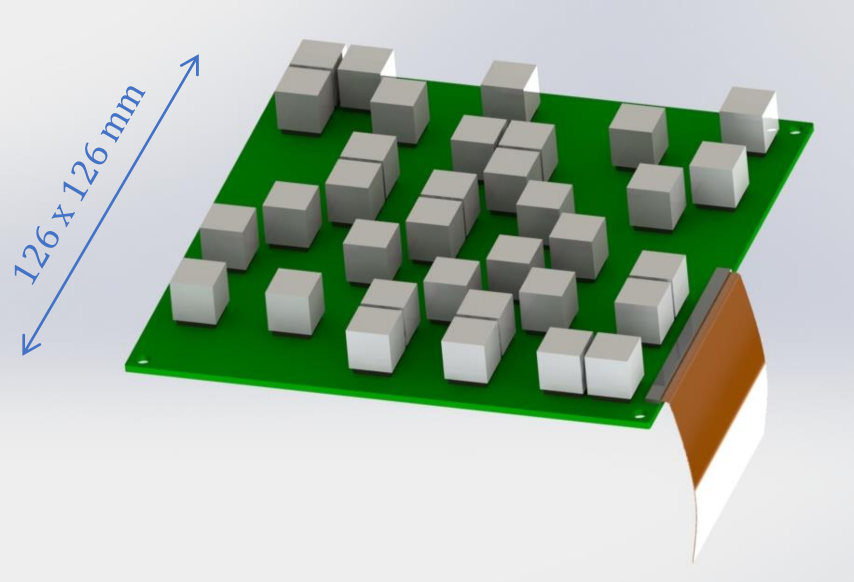
Flux of 10 ph cm^{-2} s^{-1} 10-1000 keV (1 second duration)



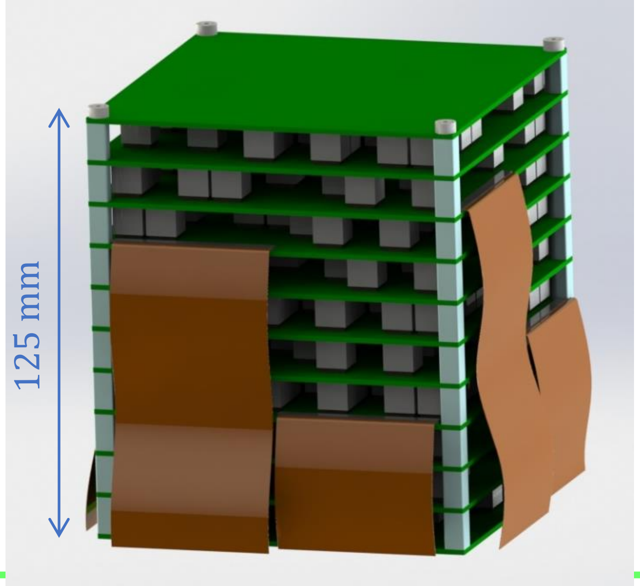
Expected average error 4.68° for 5 ph/cm^2. 50% of the bursts are expected to have an average error between 2.2° and 6.0°

GALI Instrument Design

- One PCB with 2D Array of up to 46 sensors
- Material: Arlon85NT: Polyimide reinforced with non-woven aramid substrate.
- Each PCB is a rigid-flex combination PCB: The flexible part is standard polyimide.
- Scintillators + silicon PM

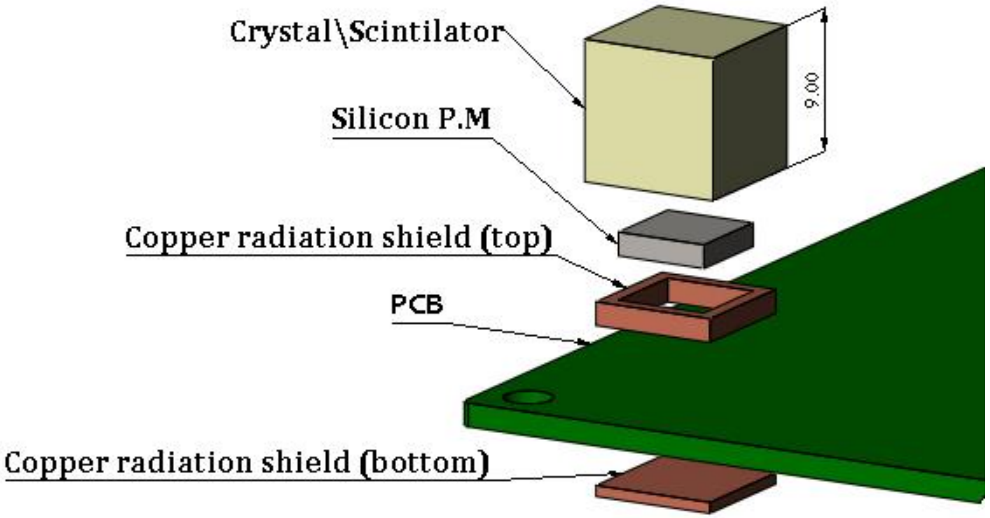


- Staggered 3D array of ~400 sensor
- 9 stacked PCB’s
- Each interfaced via a flat cable



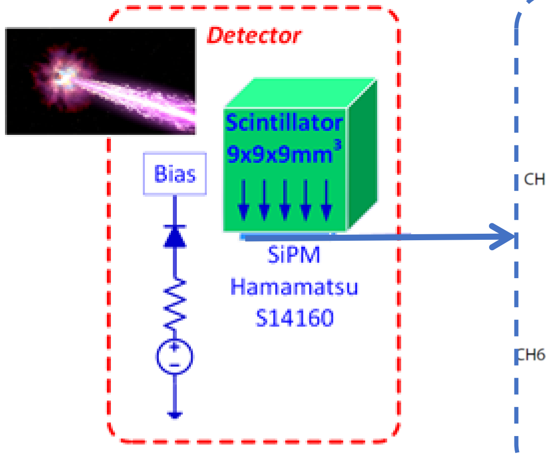
GALI Instrument Design - details

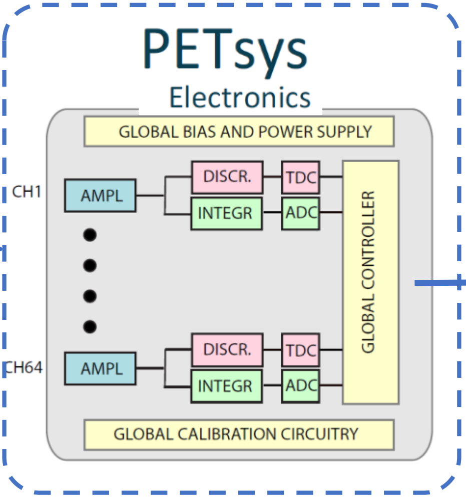
- Detection Sub-System
- Single sensor
  - Crystal scintillator covered with reflective material
  - Silicone photomultiplier
  - Copper radiation shield (top)
  - PCB- Arlon 85
  - Copper radiation shield (bottom)
- Open issues on Scintillators
  - Optical glue, top flex material holders and coating



Instrument Outline / Detection Sequence

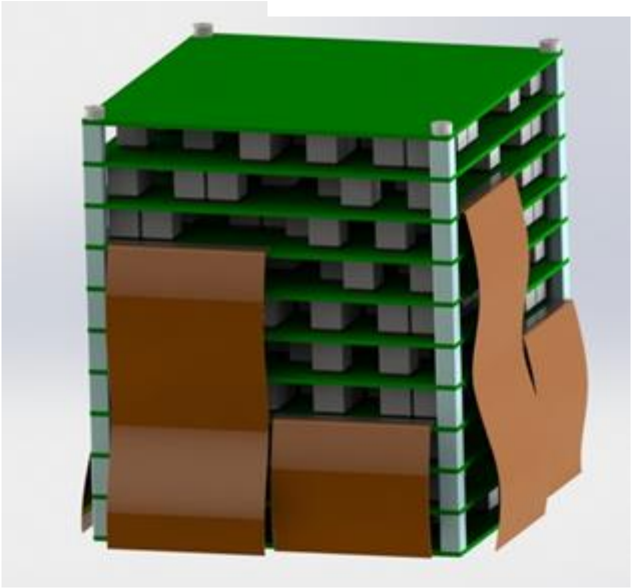
Scintillator => SiPM => Readout ASIC => FPGA => Computer

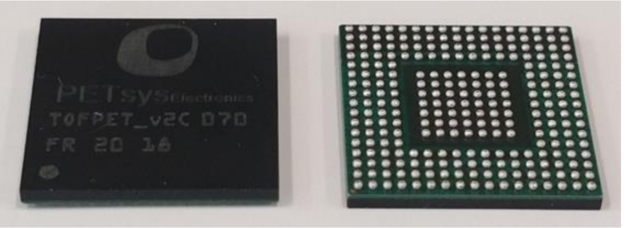




Xiphos Q8s

- SOC
- Space qualified
- Includes drivers/FPGA skeleton/coms
- Radiation protection features
- Support





Additional HW

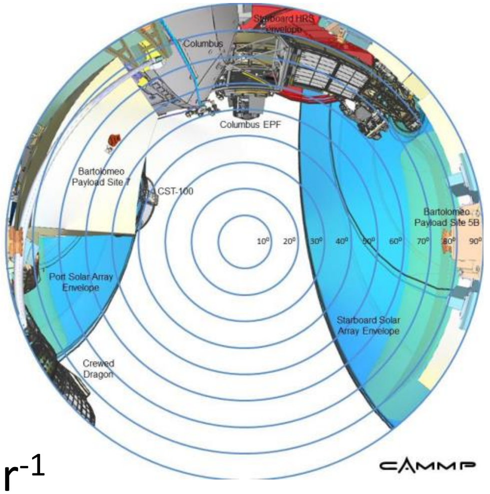
Power supply
LED calibrators
Thermal sensors
Star tracker
Sun sensors

Mission Implementation of Science Goals

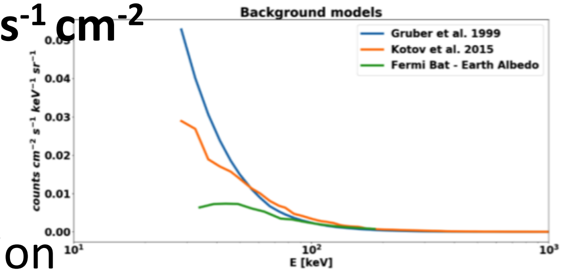
- Detect as many GRBs as possible, at least 50/yr
  - Wide field instrument, at least half of the sky π str
  - Sensitivity to weak GRBs, reaching peak flux of 1 ph s^{-1} cm^{-2}
  - Grasp = A_{eff}*FoV = 300 cm^2 str
- Accurately detect direction of GRB
  - GALI's Claim-to-fame
  - Goal is to allow standard, ground based telescopes to follow up
  - 3°x3° FoV of small robotic telescopes

- Reference:
  - Fermi/GBM detects 236 GRBs/yr, ~ 100 above 1 ph $s^{-1}cm^{-2}$
  - ISS/CALET(FoV ~ π str) detects ~43/yr (60% duty cycle because SAA)

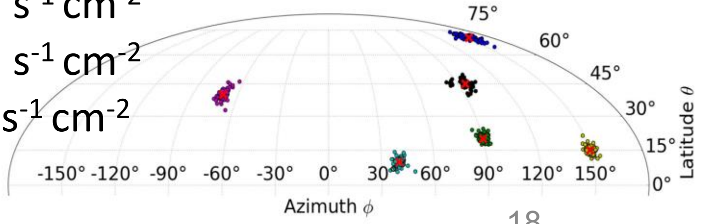
- Rough GALI features
  - FoV ~ 70% of sky, or **4.4 str**
  - A_{eff} ~ **100 cm^2**
  - Grasp **440 cm^2 str**



- Sensitivity (trigger band, 1s bursts)
  - Sky **background** is ~0.5 ph s^{-1} $cm^{-2}str^{-1}$
  - Over entire instrument 400 +/- 20 ph/s
  - Sensitivity (5σ) 100 ph/s or **1 ph s^{-1} cm^{-2}**



- Localization (full band)
  - GALI concept of mutual occultation
  - Localization depends on peak flux
  - Simulations show (1s bursts)
    - 1.7° uncertainty for 2.7 ph s^{-1} cm^{-2}
    - 4.5° uncertainty for 1.9 ph s^{-1} cm^{-2}
    - 10° uncertainty for 1.0 ph s^{-1} cm^{-2}

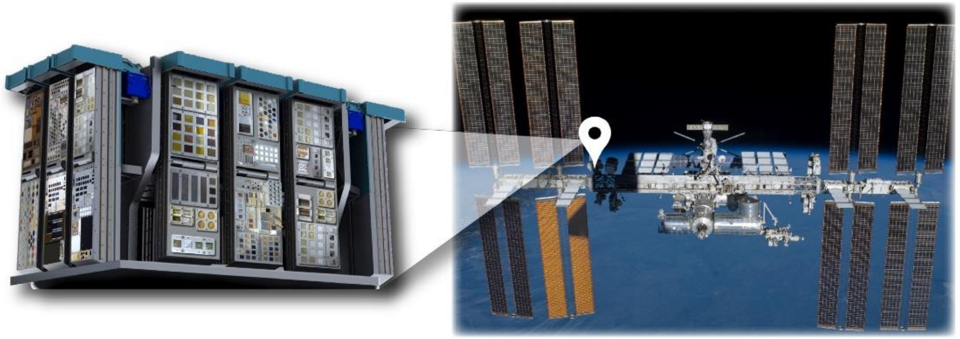


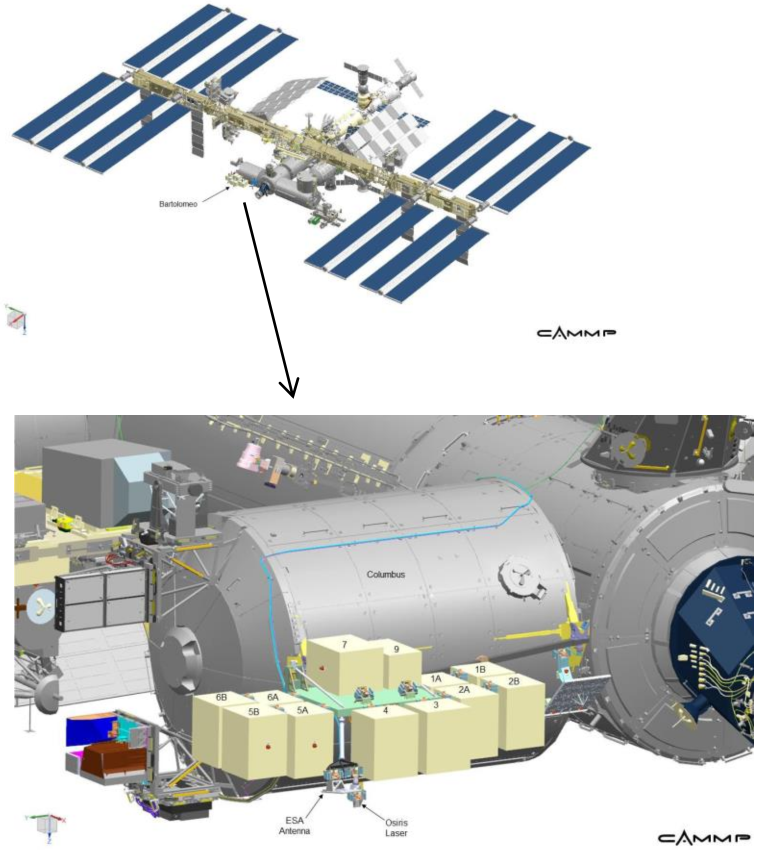
Status

- GALI is a Technion developed instrument with help from our collaborator NRCN
  - Joint programs funded by ISA and by Pazy
- Development boosted by NASA's decision to discontinue ISS-TAO and our GTM
- Proven laboratory prototype
- Schedule expedited by selection for the Rakia mission to the ISS
  - To launch in 2022 to an Airbus ISS platform

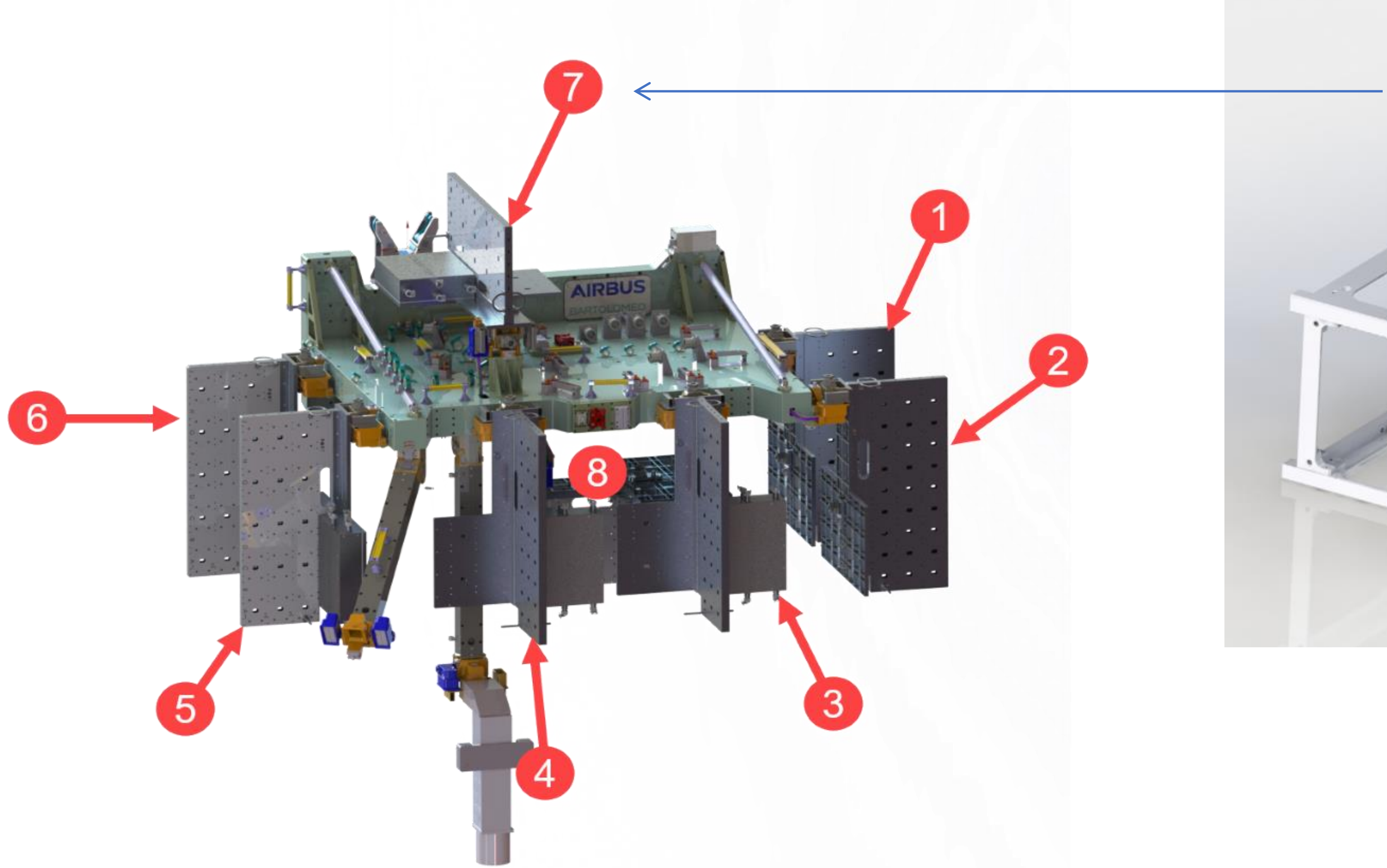
Status, ISS platform

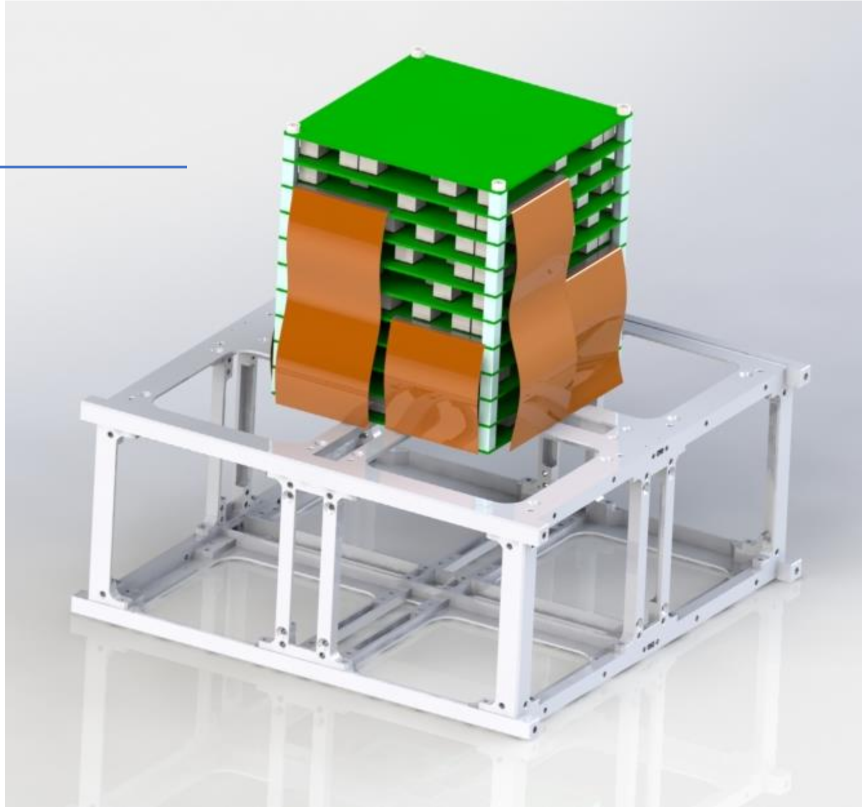
- Irrespective of Rakia, we need to find a vendor to place us outside the space station
- We have been negotiating with 3 companies
- *AIRBUS* on their Bartolomeo, **current leading platfor**
- *Alpha Space* on their MISSE location – limited platfor
- rnal platform (





Nice Pictures





Team

- Principle Investigators
  - Ehud Behar, Shlomit Tarem
- Detectors, simulations
  - Roi Rahin
- Electronics
  - Lucal Moleri, Alex Vdovin,, Julia Salh
- Software/firmware
  - Zvi Tarem, Ifat Mehalev, Yulia Kuniavsky, Roman Parpialo
- Mechanical design
  - Amir Figenboim
- Project students
  - Solomon Margolin,
    Ori Zaberchik

- Systems Engineering
  - Avner Kaidar
- Electronics Engineering
  - Hovik Agalarian
- Thermal analysis
  - Yoel Arcos

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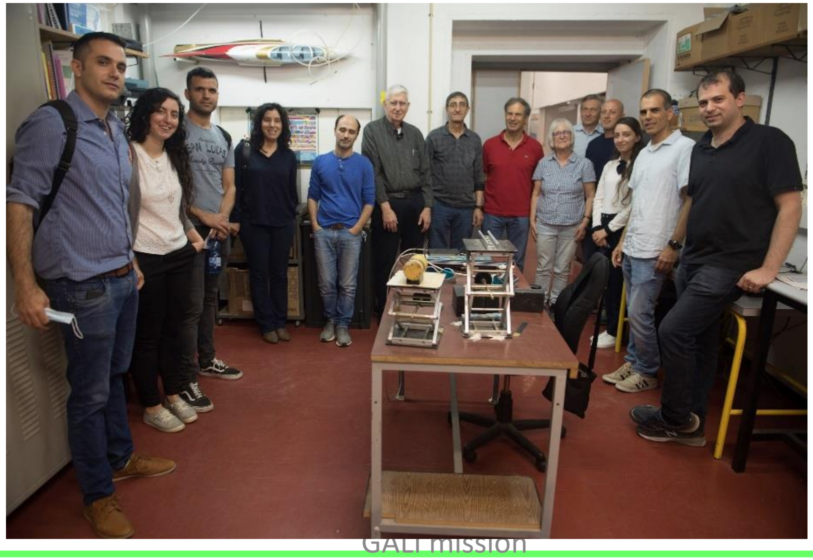

- Advisory team, NRCN
  - Alon Osovizky, Max Ghelman,
    Eran Vax