Future MeV and GeV Instruments: A Gamma-Ray Roadmap for the next decade

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CTAO Science Symposium
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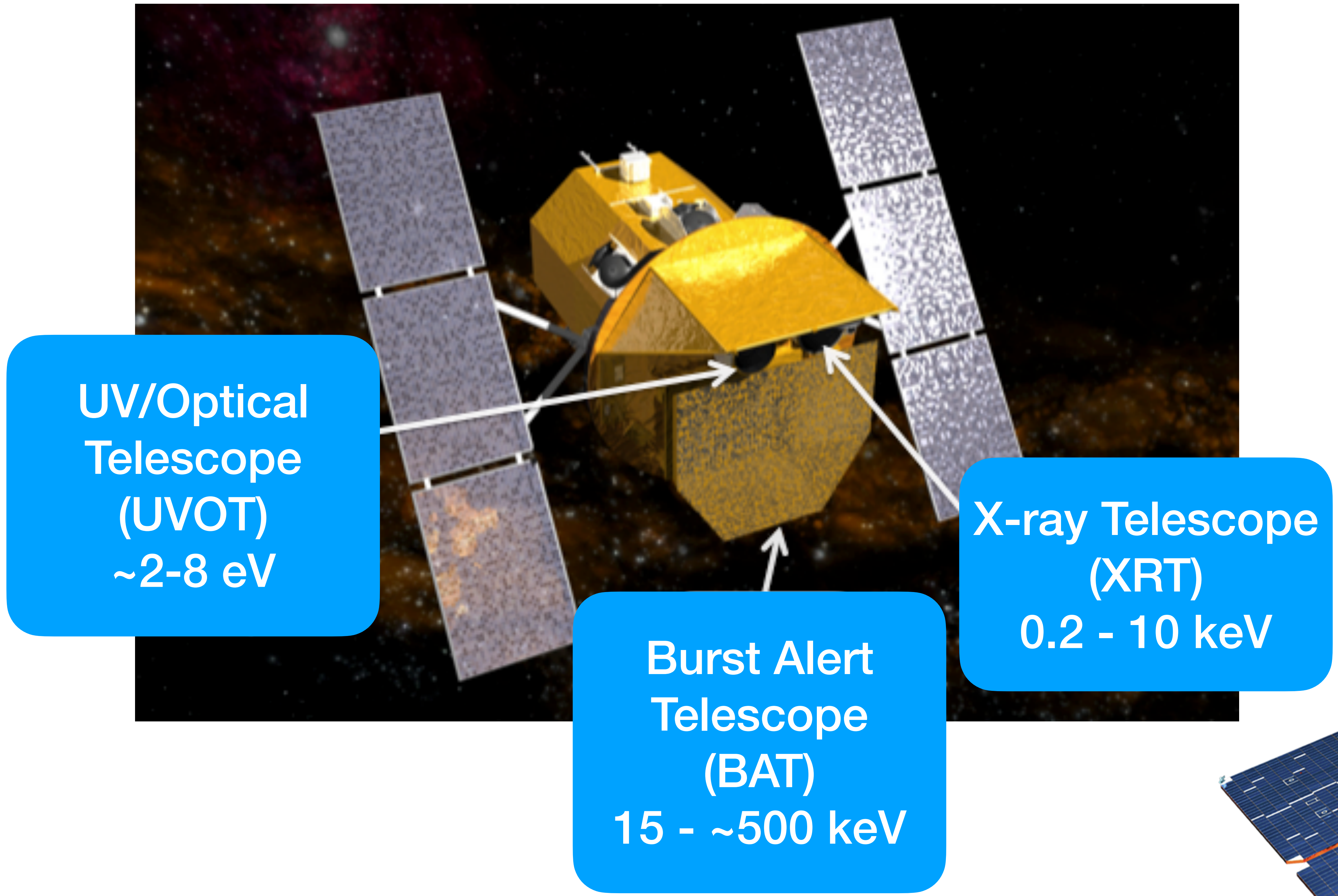
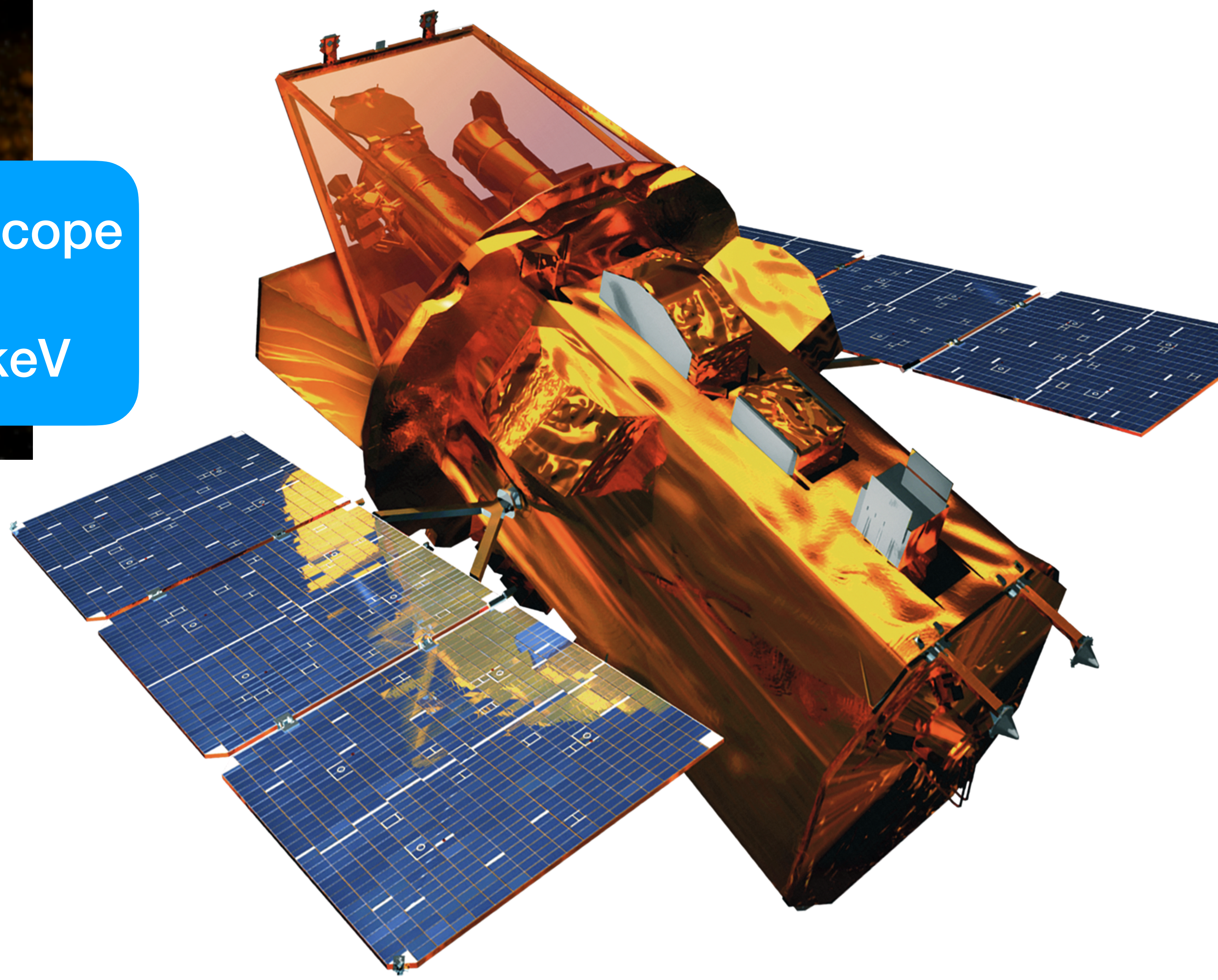
Where have we been?*

***Note: this is a NASA Centered perspective ie: US and Space**


National Aeronautics and Space Administration
NASA
ASTROPHYSICS FLEET
PRE-FORMULATION
PROBE ~2030
ATHENA EARLY 2030s
2020
2015
2010
2005
2000
1990
2025
TESS
NICER
NUSTAR
IXPE
CUTE
WEBB
HUBBLE
FERMI
CHANDRA
XMM-NEWTON
GEHRELS SWIFT
EUCLID
GLOWBUG
BURSTCUBE
SPRITE
XRISM
BLACKCAT
SPARCS
PANDORA
STARBURST
ASPERA
PUEO
TIGERISS
LANDOLT
MANTIS
GUSTO
VERY SMALL MISSIONS
SPHEREX
ROMAN
ULTRASAT
COSI
ARIEL
UVEX
LISA
TRADITIONAL MISSIONS
KEY
INTERNATIONAL PARTNER LED
ISS INSTRUMENT
SMALLSAT
CUBESAT
BALLOON
FORMULATION
IMPLEMENTATION
OPERATING
EXTENDED
Credit: NASA's Goddard Space Flight Center

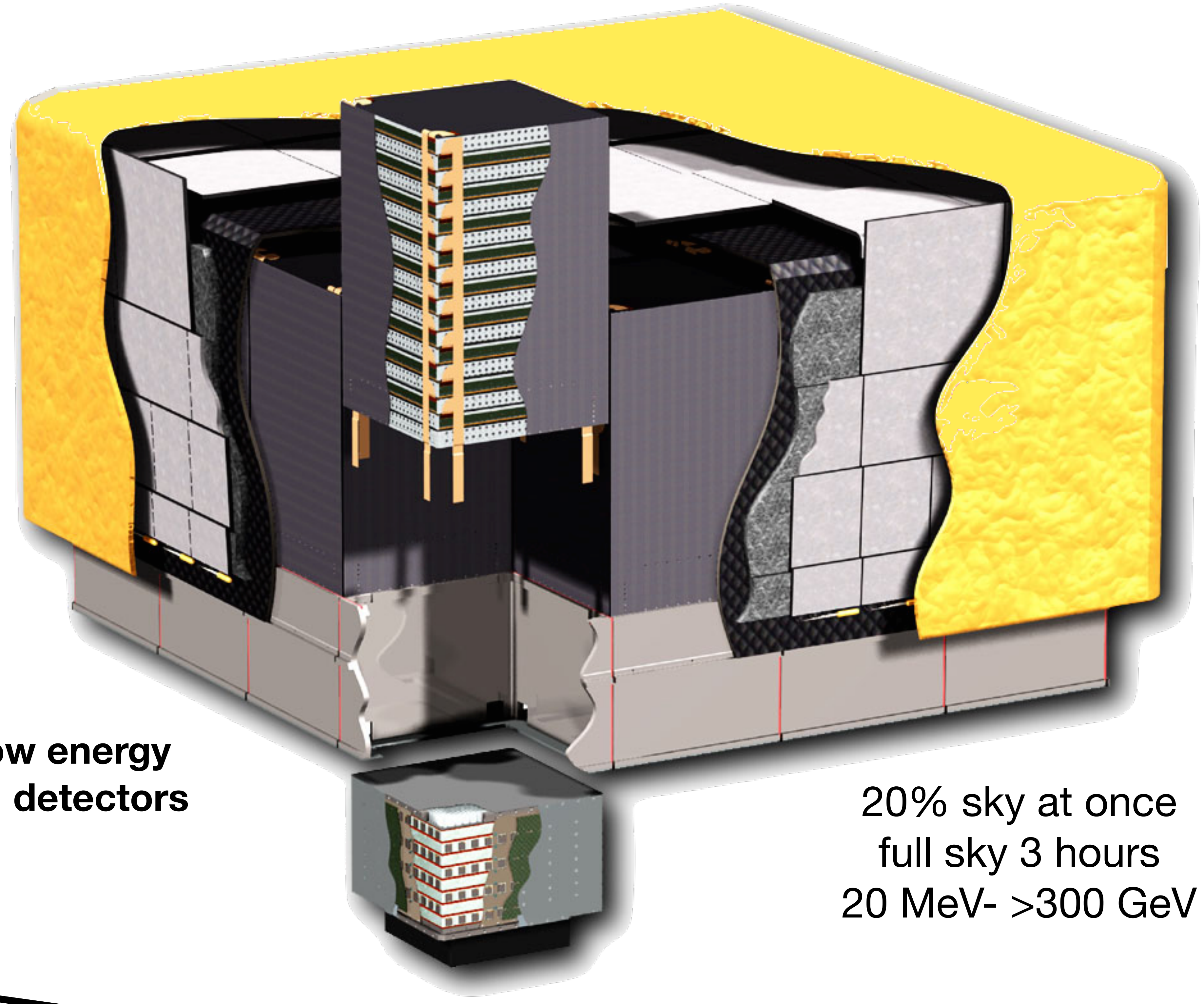
Neil Gehrels Swift Observatory



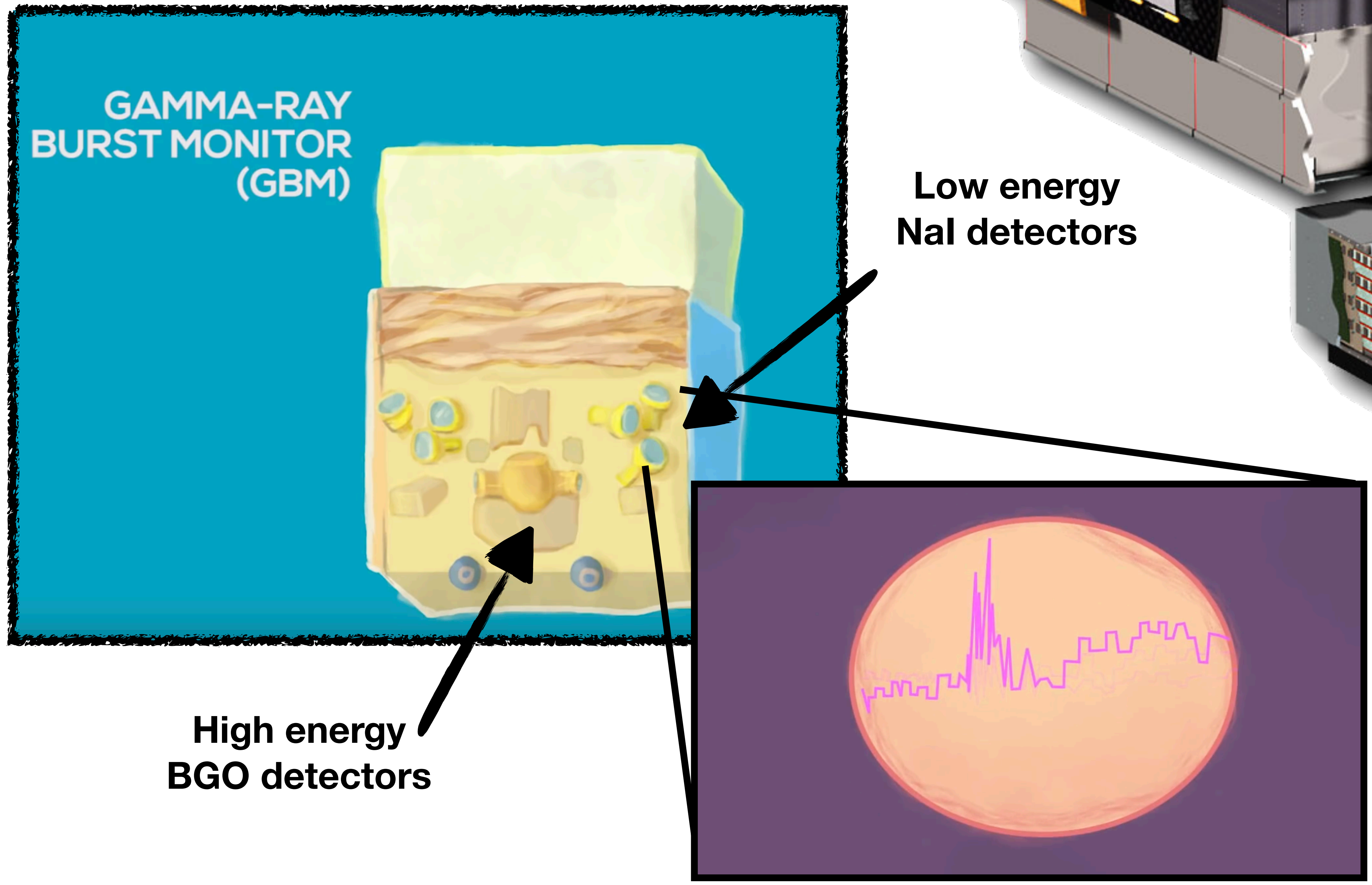


Fermi Gamma-ray Space Telescope

Large Area Telescope



20% sky at once
full sky 3 hours
20 MeV- >300 GeV



full unocculted sky continuous
8 keV - 40 MeV

Takeaways

- The Gamma-ray sky has been observed by large observatories since 1991 via CGRO and then followed with INTEGRAL, Swift, Fermi, and AGILE
- Gamma-ray observations have enabled huge discoveries over the past ~2 decades and most recently as we have entered the era of multi messenger astrophysics
- The next generation of discoveries in astrophysics need all-sky gamma-ray observatories complement CTA, and GW and neutrino observatories

Where are we going?

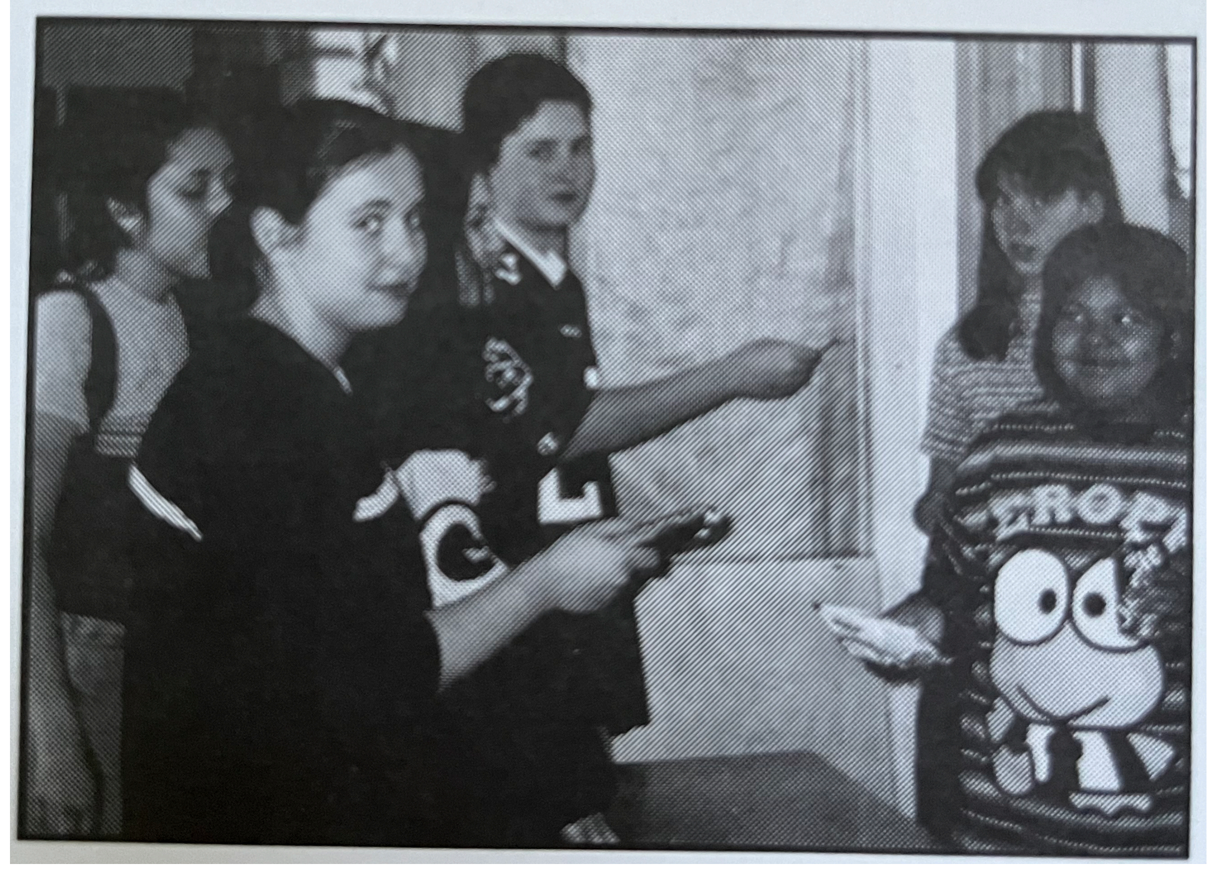
"The test of a first-rate intelligence is the ability to hold two opposed ideas in mind at the same time and still retain the ability to function." - F. Scott Fitzgerald

No MoO selected in 2024; both in Phase A were gamma-ray missions

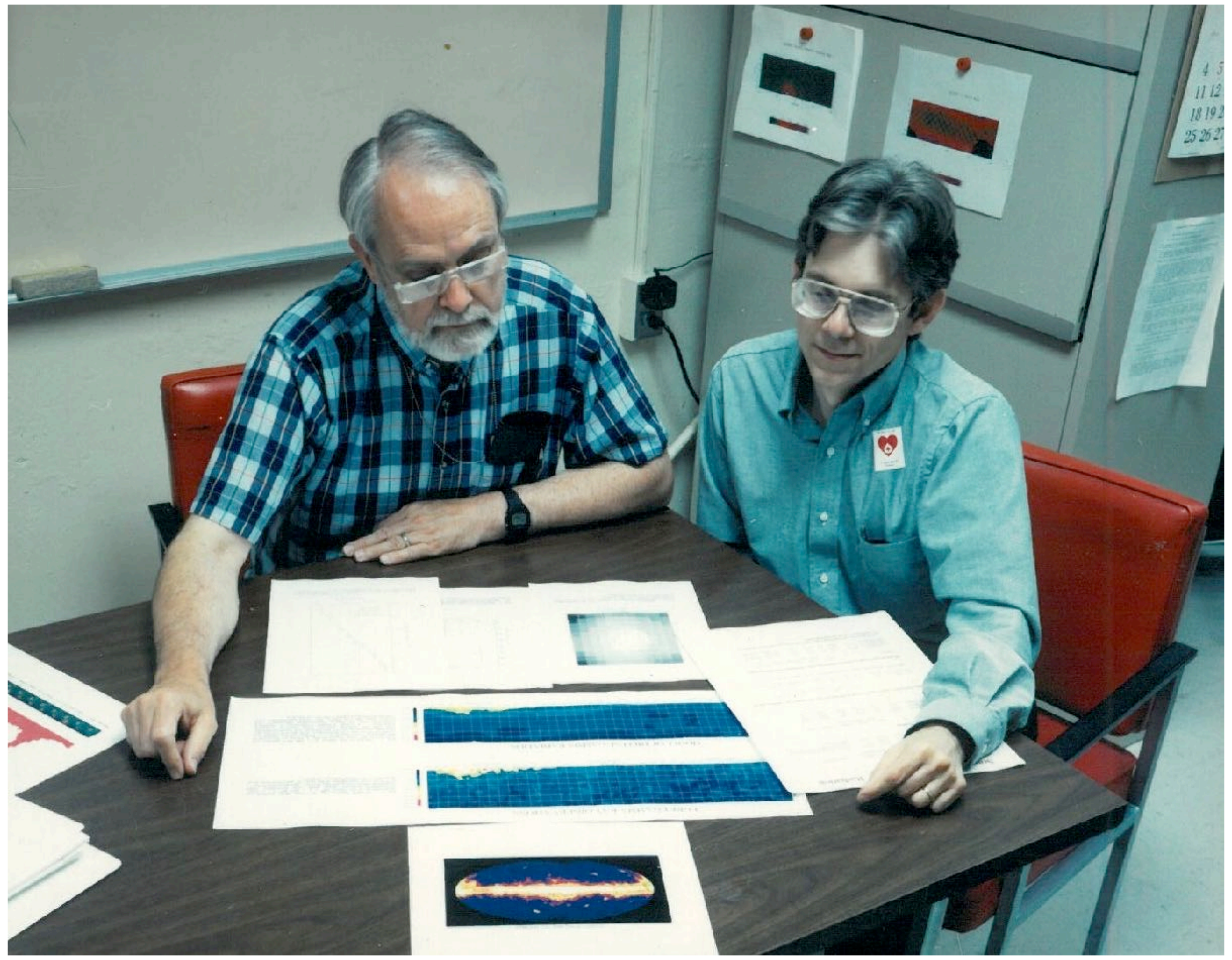
How did Fermi/Swift come to pass?

Back in the 90s…

- What was happening in ’97:
  - Second Hubble Servicing Mission
  - Deep Blue beat Kasparov in Chess (first time a computer beat a world champion).
  - The first episode of South Park aired.
  - The Spice Girls released their first single

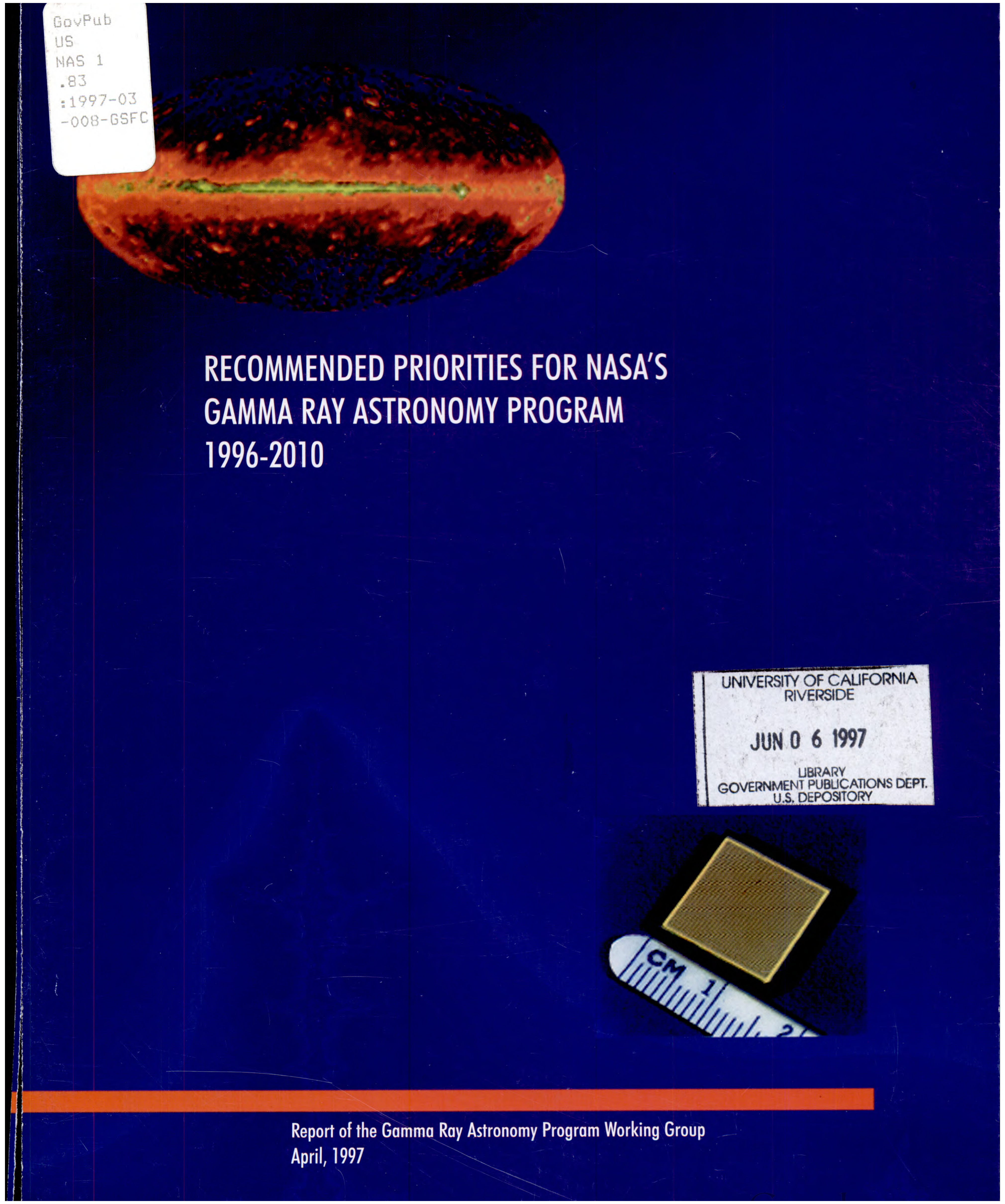
Jeremy Perkins in 1996, Me in 1997



Bob Hartman and Dave Thompson working on EGRET in 1993

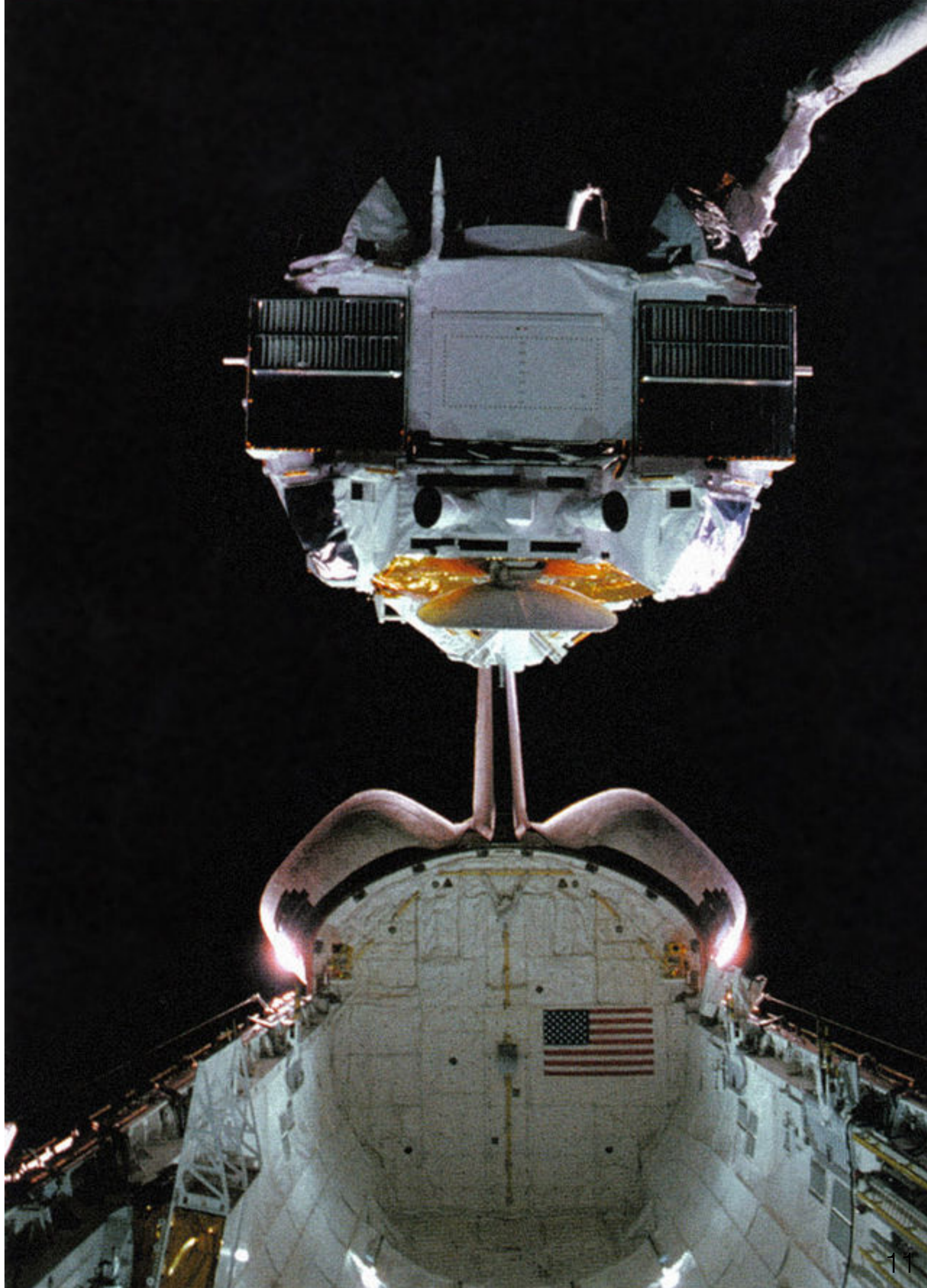
Also in ‘97

“The mandate of the working group is to recommend a road map to the future for use as an input to the next NASA strategic plan…”



Compton Gamma-ray Observatory

- One of the original **Four Great Observatories.** Launched 1991 and de-orbited in 2000 (three years after the report).
- Four Instruments:
  - The Burst Alert and Transient Source Experiment (BATSE) an all sky monitor 20 keV to 1 MeV
  - The Oriented Scintillation Spectrometer Experiment (OSSE) for the 0.05 to 10 MeV range
  - The Compton Telescope (CompTel) in the 0.8 to 30 MeV range capable of imaging 1 steradian.
  - The Energetic Gamma-Ray Experiment Telescope (EGRET) in the 30 MeV to 10 GeV range.



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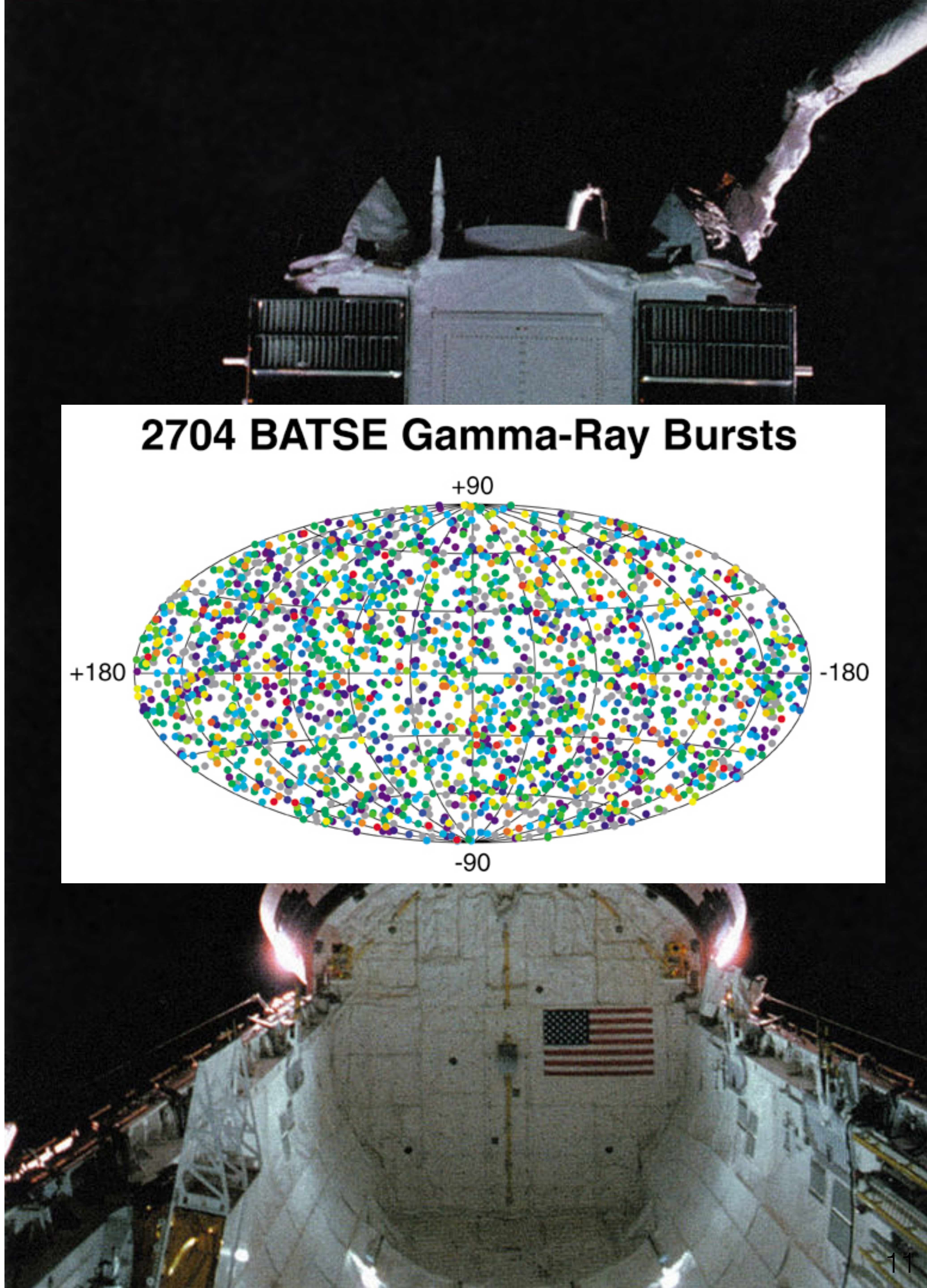

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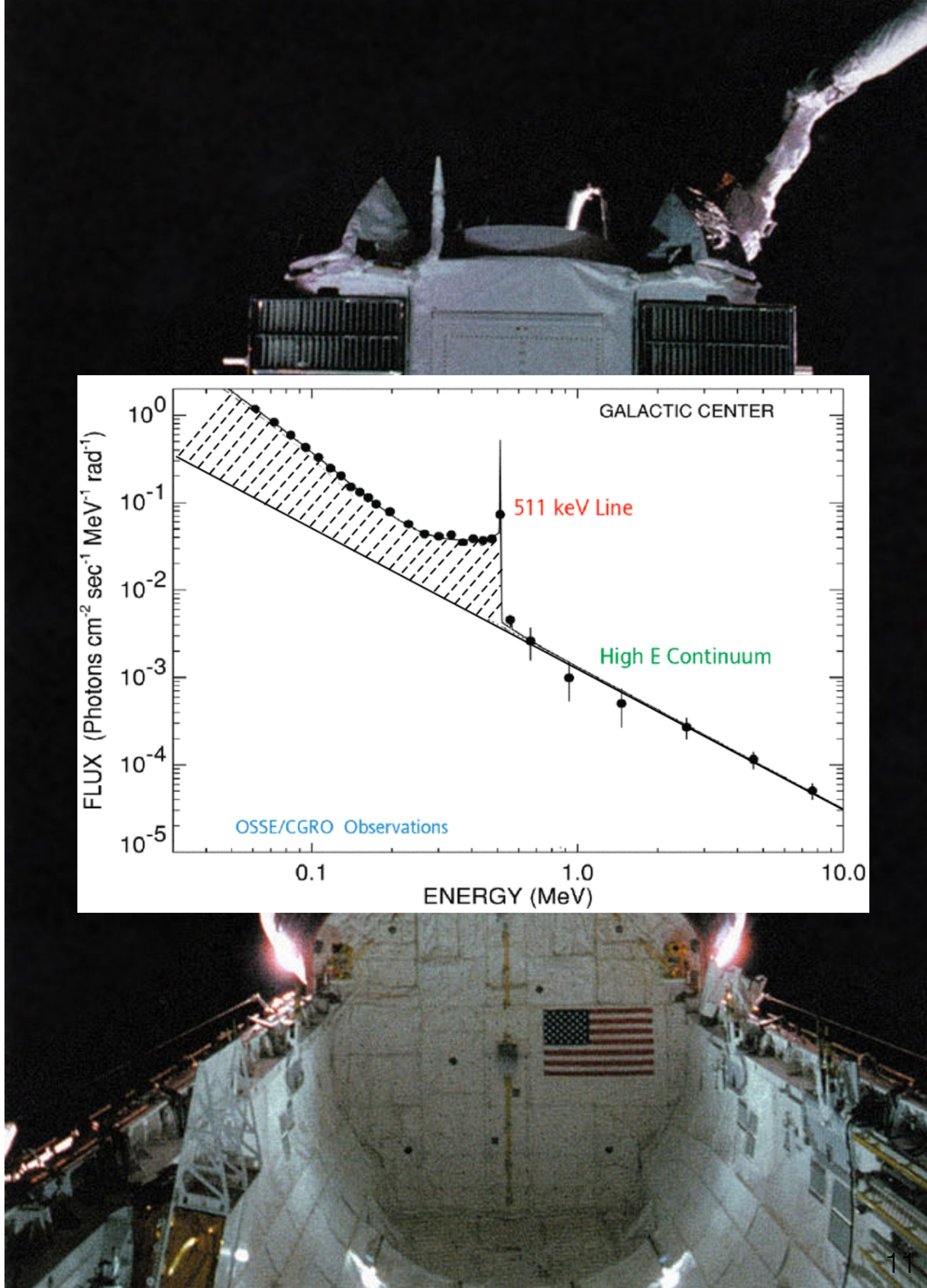

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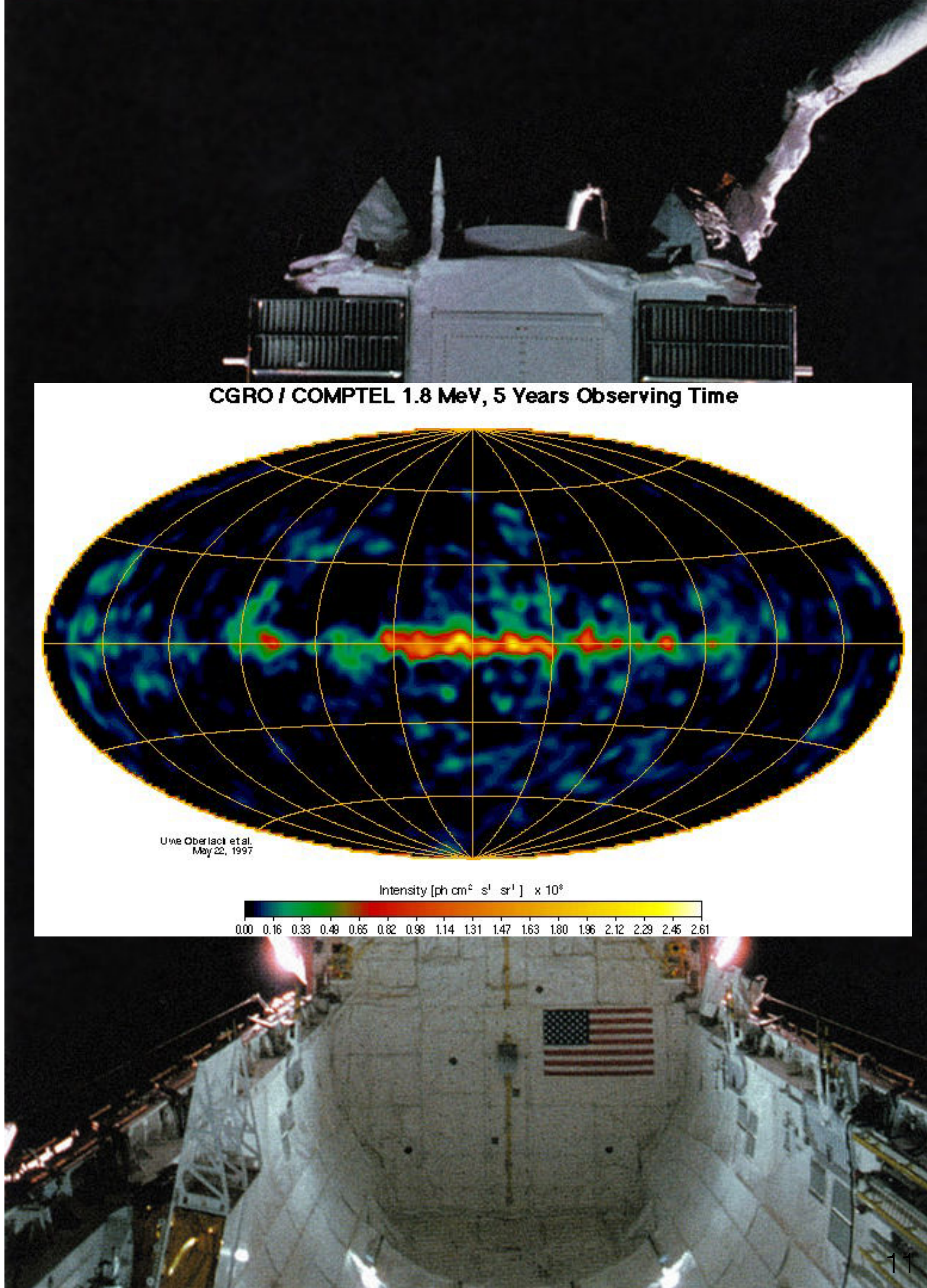

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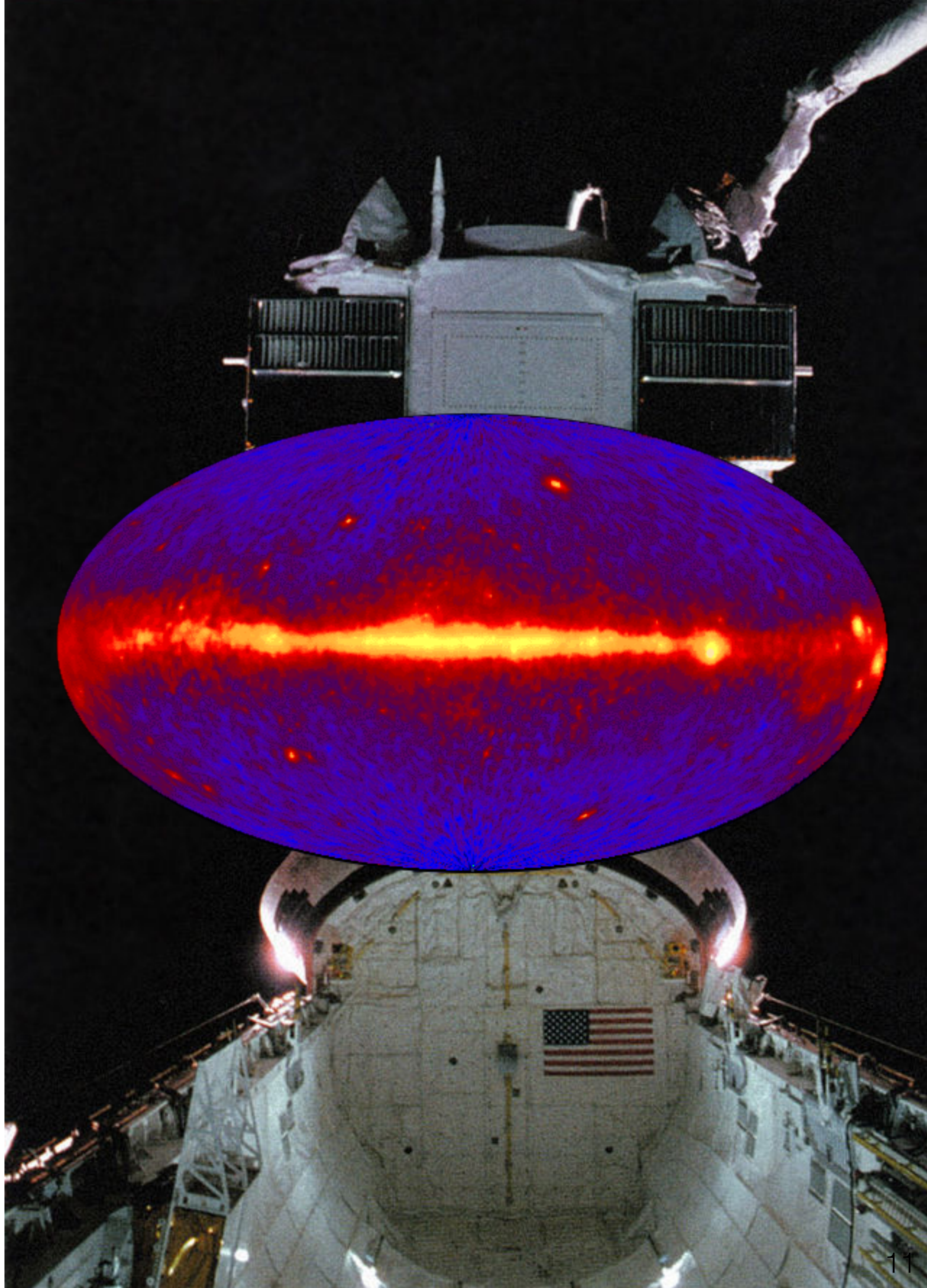

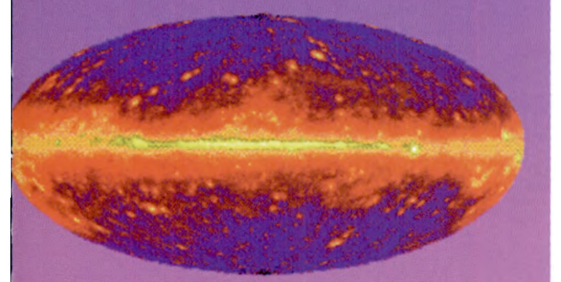

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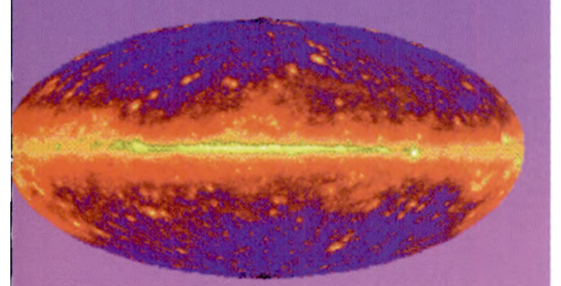

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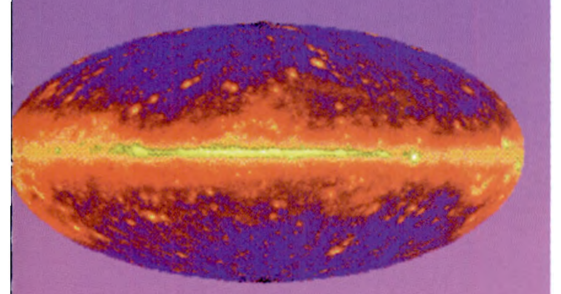

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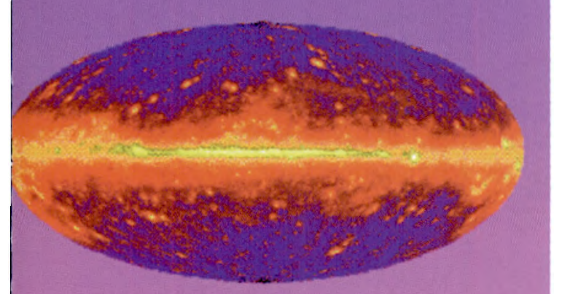

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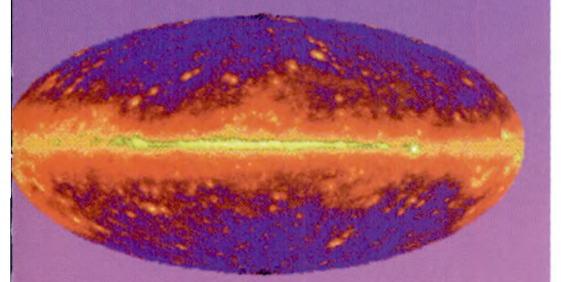

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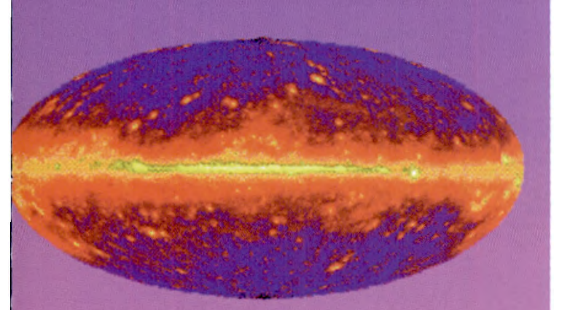

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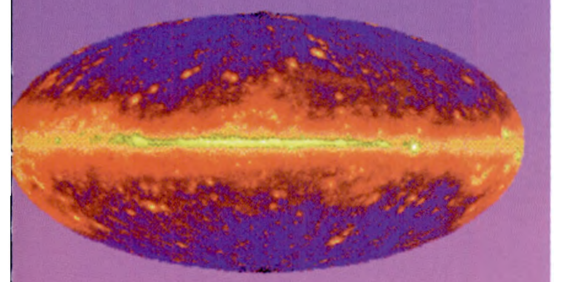

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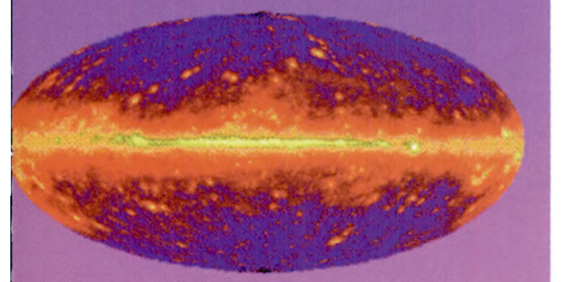

EXECUTIVE SUMMARY

With new results from the Compton Gamma Ray Observatory (CGRO), the Rossi X-ray Timing Explorer (RXTE), and GRANAT, hard X-ray and gamma-ray astronomy are in a period of discovery and vigor unparalleled in their history. The CGRO mission in particular has made fundamental contributions to understanding many classes of galactic and extragalactic objects. The CGRO discoveries of gamma-ray blazars, an isotropic distribution of gamma-ray bursts, bright black hole and neutron star transients, sites of galactic nucleosynthesis, and a large class of unidentified high energy sources have intrigued astronomers and the public alike. These discoveries have prompted a wide range of correlated observations by X-ray satellites and ground-based radio, IR, and optical observatories, adding to our rapidly expanding knowledge of the nature of high-energy emission. We now have the beginnings of a better understanding of the astrophysics of gamma-ray sources, and this in turn has raised fundamental new questions about the origin and evolution of high-energy objects and about the nonthermal astrophysical processes that occur in them.

Looking ahead to the next decade, further discoveries in hard X-ray and gamma-ray astronomy are anticipated with further CGRO and RXTE observations and with the ESA INTEGRAL mission (launch ~2001). However, there are currently no major missions being planned beyond INTEGRAL and none being planned at all by NASA. Of particular concern is the high-energy regime (100 MeV - 100 GeV), where observations will soon come to a virtual halt in the next 2 years as the EGRET instrument on CGRO runs out of spark-chamber gas. Also of concern is the present lack of plans for missions that would 1) significantly improve on the BATSE capabilities to study gamma-ray bursts as well as conduct a full-sky survey and monitor transient source 2) follow-on the first exploration of the MeV band by COMPTEL with much better sensitivity, and 3) continue the important studies of nucleosynthesis begun by balloon instruments, OSSE, and COMPTEL. From a scientific standpoint, there is an urgent need for new observational missions. From a technical standpoint, the timing is excellent since powerful new detector and imaging technologies are in hand that promise major steps in observational capabilities.

With this in mind, the GRAPWG recommends the following program in hard X-ray and gamma-ray astronomy.

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GAMMA-RAY ASTRONOMY PROGRAM WORKING GROUP MEMBERS:

Elena Aprile (Columbia)
Alan Bunner (NASA) [Ex-Officio (NASA Headquarters)]
Neil Gehrels (GSFC) [Co-Chair]
Jonathan Grindlay (Harvard)
Gerald Fishman (MSFC)
W. Neil Johnson (NRL)
Kevin Hurley (UCB/SSL)
Steve Kahn (Columbia)
Richard Lingenfelter (UCSD)
Peter Michelson (Stanford)
Thomas Prince (Caltech) [Co-Chair]
Roger Romani (Stanford)
James Ryan (UNH)
Bonnard Teegarden (GSFC)
David Thompson (GSFC)
Trevor Weekes (Harvard/Smithsonian)
Stanford Woosley (UCSC)

Intermediate Missions

The HIGHEST PRIORITY recommendation is:

A next generation 10 MeV to 100 GeV gamma-ray mission such as GLAST. 1 to 2 orders of mag improvement in sensitivity compared to EGRET.

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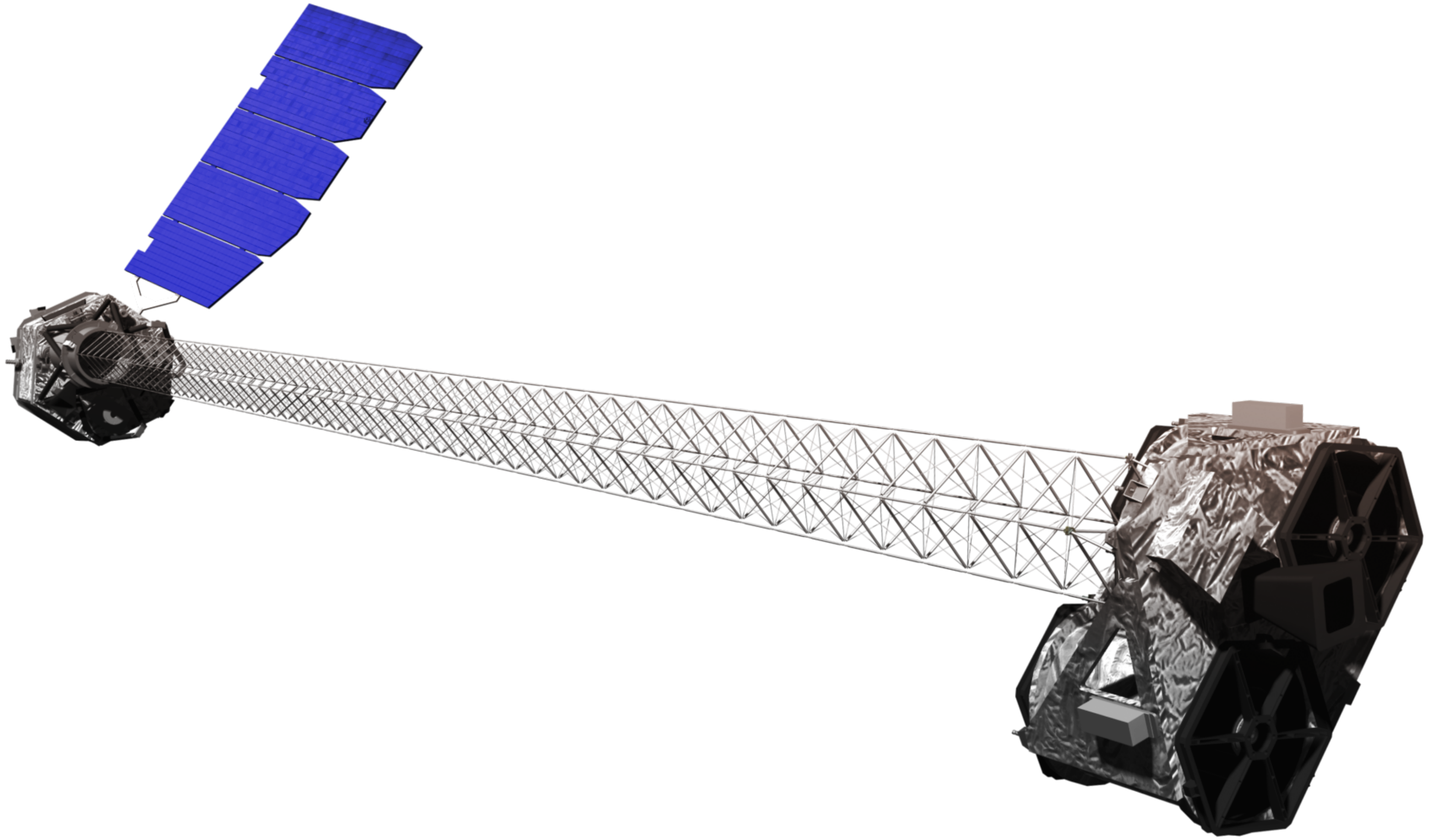
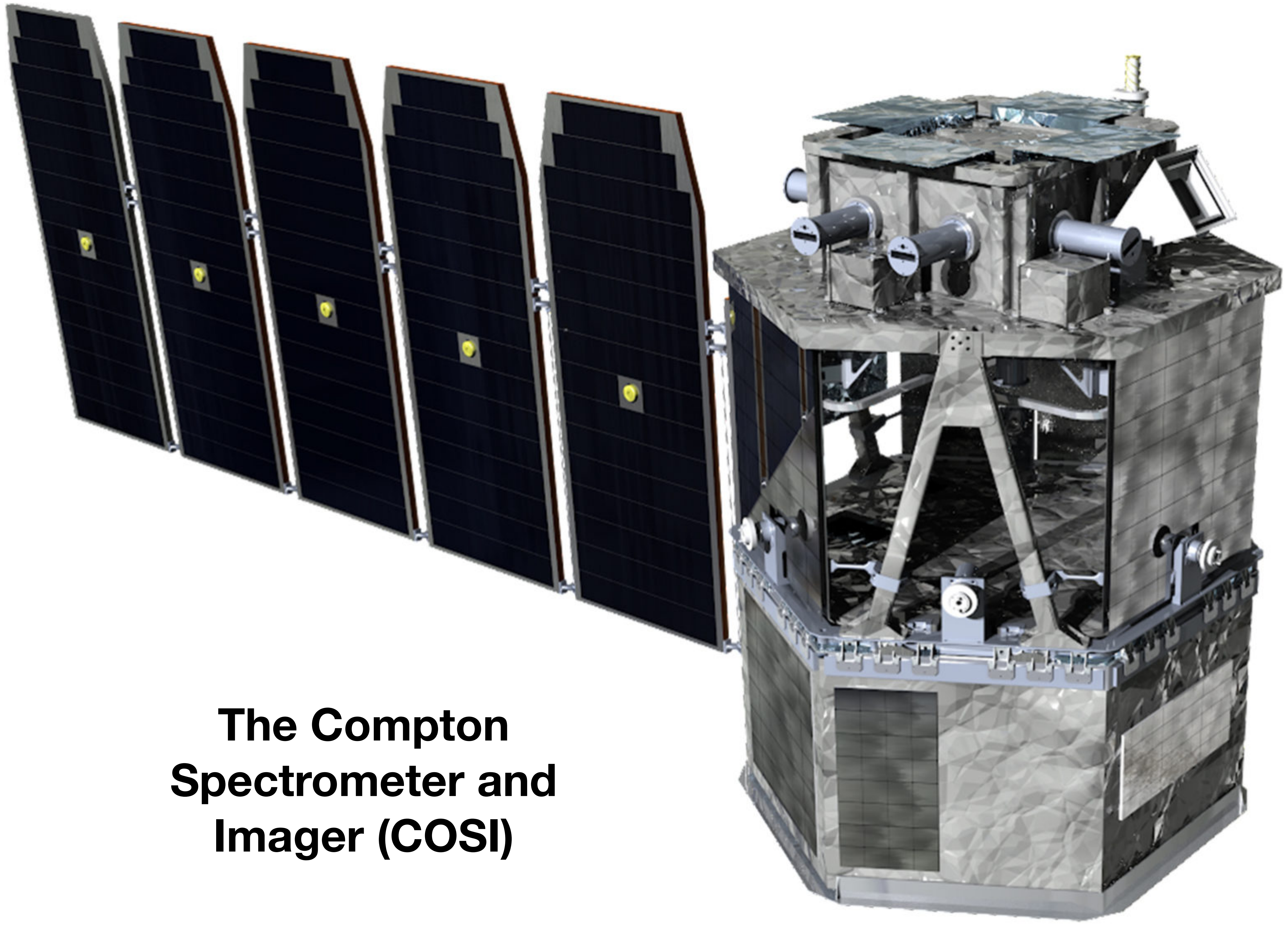
Intermediate Missions



Another very-high priority:

A Focusing Hard X-ray Telescope.

Intermediate Missions



The Compton Spectrometer and Imager (COSI)

The second very-high priority:

A next-generation nuclear line and MeV continuum mission. A major step forward compared to INTEGRAL in both sensitivity and energy range.

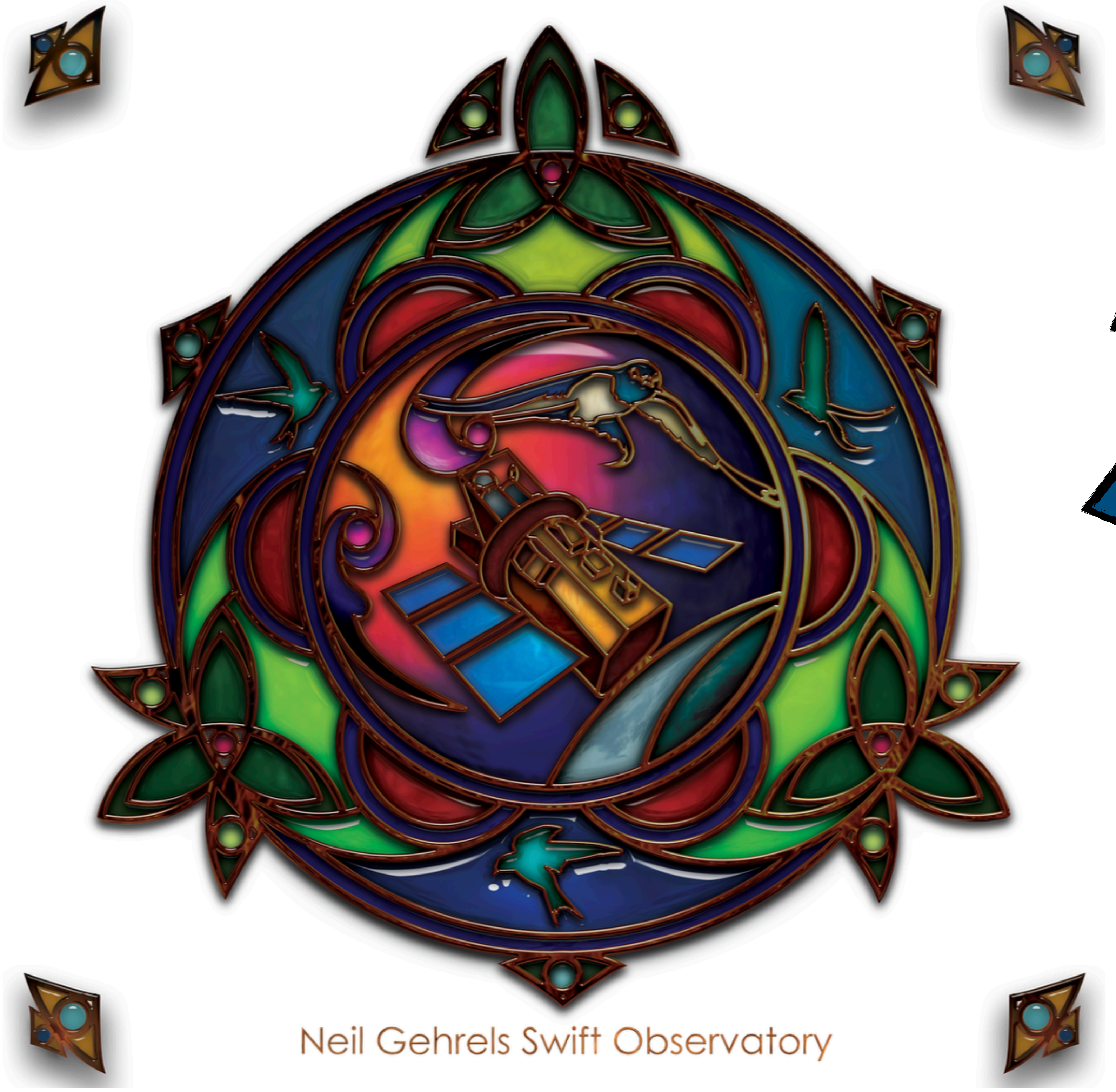
More info: https://science.nasa.gov/mission/cosi/

Participate in the COSI 2nd data challenge: https://github.com/cositools/cosi-data-challenge-2

MidEx and SMEX Missions

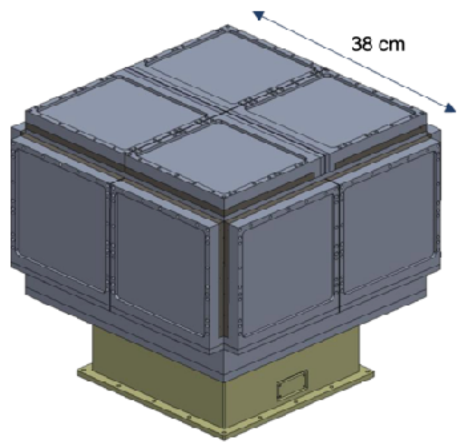
A gamma-ray burst localization mission. Such a mission would address the origin of gamma-ray bursts. Missions with coding apertures or an array of small telescopes would fill this need.

Probe and SMEX Missions



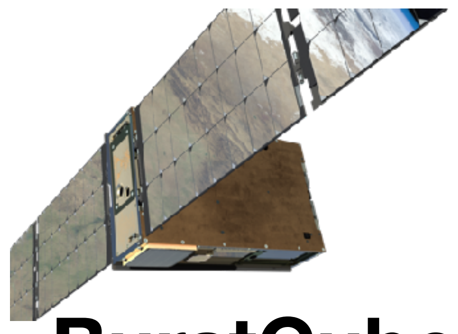
A gamma-ray burst localization mission. Such a mission would address the origin of gamma-ray bursts. Missions with coding apertures or an array of small telescopes would fill this need.

Coming Soon!



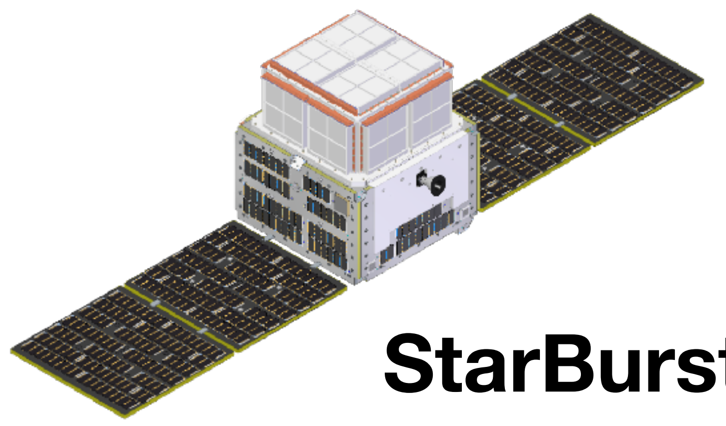
Glowbug

On the ISS



BurstCube

Deploying today



StarBurst

Launch 2025

KEY QUESTIONS IN GAMMA-RAY ASTRONOMY FROM 1997

- **What is the origin and nature of gamma-ray bursts?**
- **What are the physical conditions and processes near accreting black holes and neutron stars?**
- **How does matter behave in extreme conditions like those in neutron stars, supernova expulsions and active galactic nuclei?**
- **How do astrophysical accretion processes work and what are their instabilities, periodicities and modes?**
- **What is the nature of the jets emanating from galactic black holes and AGN and how are the particles accelerated?**
- **What is the origin of the diffuse gamma-ray background?**
- **What is the nature of the unidentified high energy gamma-ray sources?**
- **What are the sites of nucleosynthesis?**
- **How do supernovae work? What are the progenitors and explosion mechanisms? What has bene the rate in the last several hundred years?**
- **What and where are the sites of cosmic ray acceleration?**

Why did they recommend these missions?

- They developed a series of **Key Science Questions** that pointed to the need for this diverse set of missions.
    - Lesson: Lead with the Science
    - Lesson: Don't shy away from the big problems
    - Lesson: Make strong/bold recommendations
- Many of these questions are still open but we have made significant progress.

’97 Report Checklist

✓ Intermediate Missions: Fermi, NuSTAR and now COSI

✓ MIDEX and SMEX: Swift and NICER (EXIST in the report)

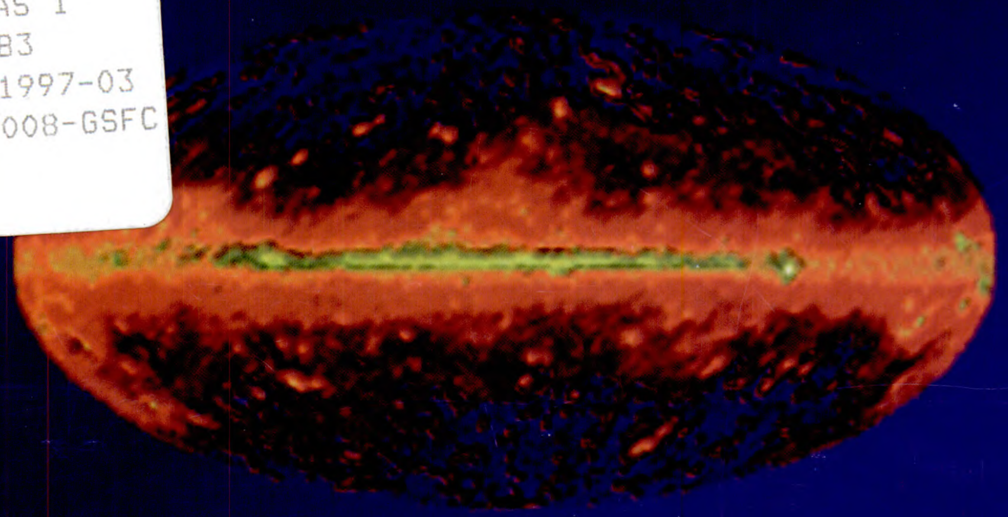
✓ Technology: a robust technology development program (SiPMs, new scintillators, upgraded silicon detectors, etc)

✓ Balloons (+ CubeSats!): long duration balloons enabled COSI, LEAP, etc.

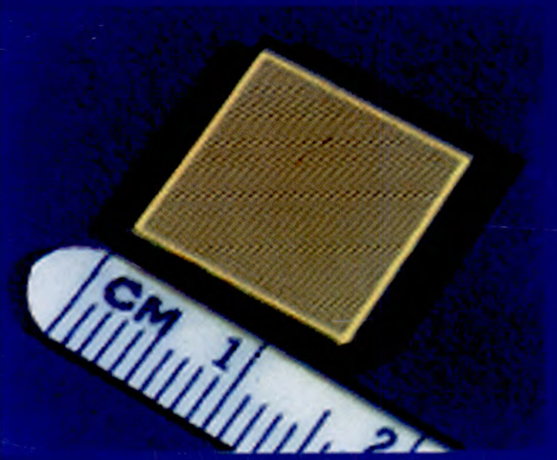
✓ Data Analysis & Theory: mainly supported through GI programs

✓ TeV Astronomy: VERITAS, HESS, HAWC, and MAGIC.

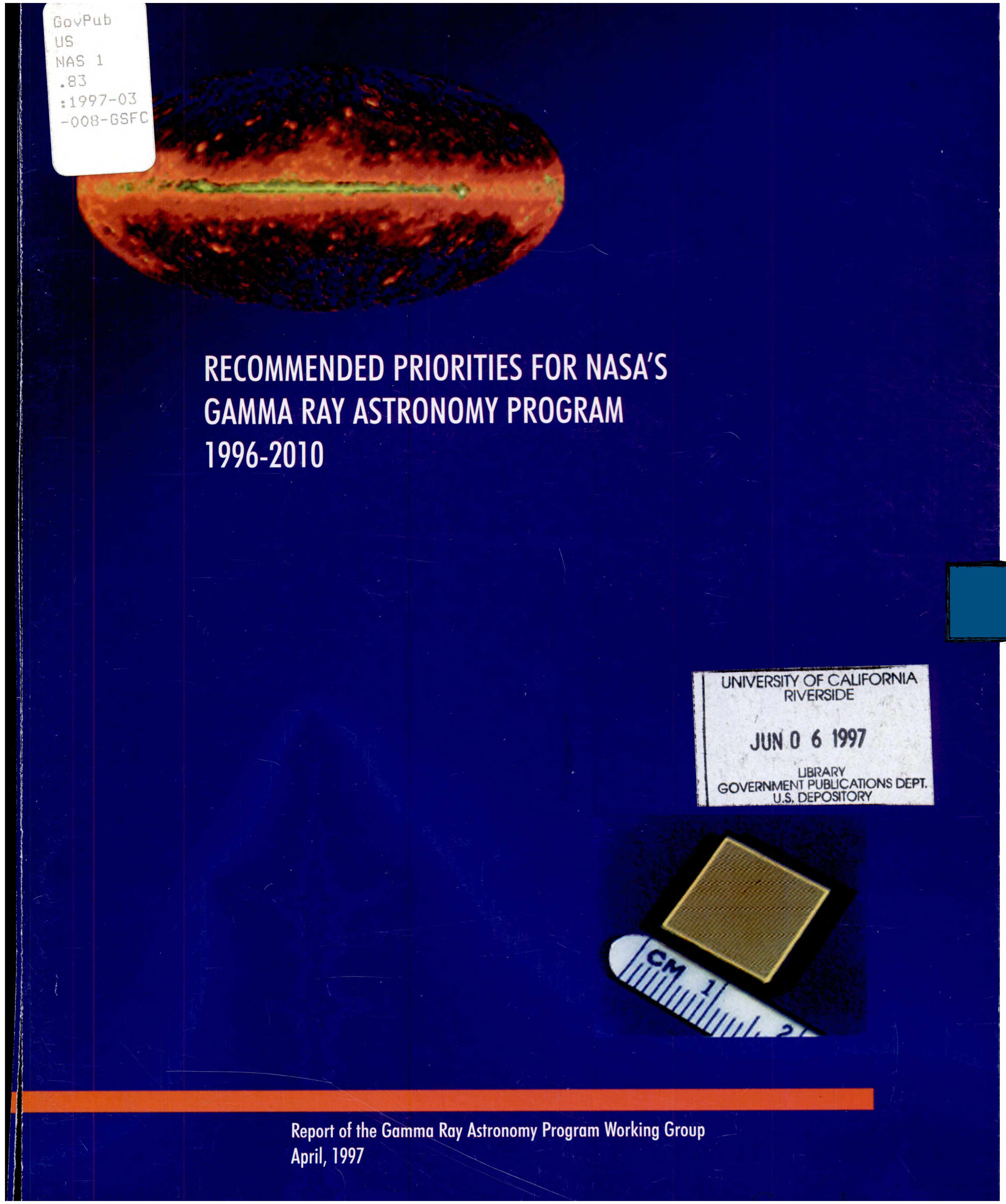
How can we replicate this success?



RECOMMENDED PRIORITIES FOR NASA'S GAMMA RAY ASTRONOMY PROGRAM 1996-2010



Report of the Gamma Ray Astronomy Program Working Group
April, 1997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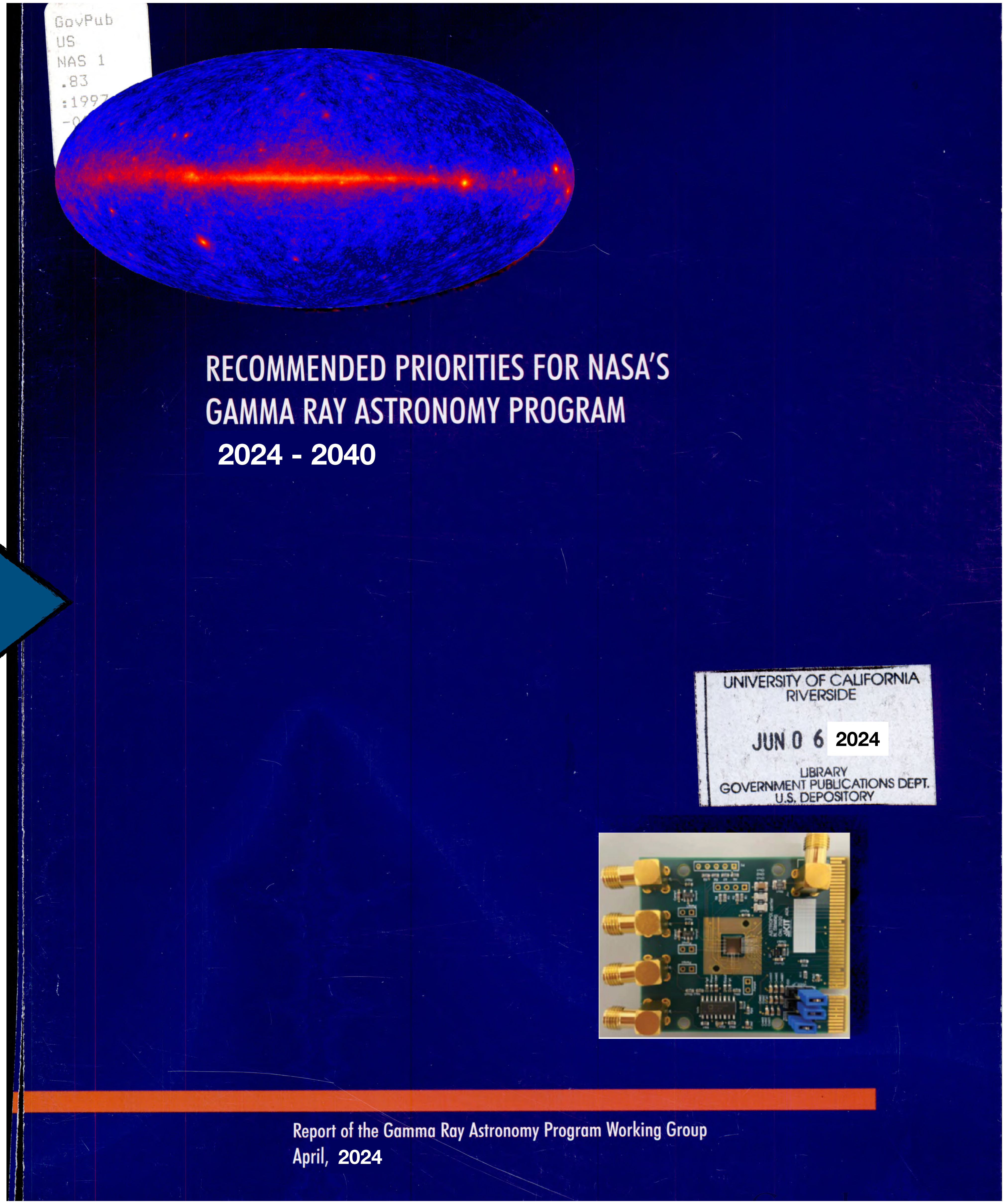
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Help develop the Roadmap

- Need the world wide gamma-ray, high-energy and multimessenger communities to contribute/provide input

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Future Innovations in Gamma-rays Science Analysis Group (FIG SAG) → 

→ NASA Astrophysics Advisory Committee (APAC) → NASA Astrophysics Division Director (Mark Clampin)

We are here

Future Innovations in Gamma-ray Science Analysis Group (FIG SAG)

Astrophysical gamma rays span ten orders of magnitude in energy and capture key physics from a broad range of astrophysical phenomena. This SAG will explore gamma-ray science priorities, necessary capabilities, new technologies, and theory/modeling needs drawing on the 2020 Decadal to inspire work toward 2040.
To get involved and stay informed, please enter your contact information here: https://forms.gle/VBijBgapMRwJm9dU6

Lead Chairs:
Chris Fryer & Michelle Hui

Co-chairs: Paolo Coppi, Milena Crnogorčević, Tiffany Lewis, Marcos Santander, and Zorawar Wadiasingh

Gamma-SIG: https://pcos.gsfc.nasa.gov/sigs/grsig.php
FIG SAG: https://pcos.gsfc.nasa.gov/sags/figsag.php

The FIG SAG report for 2024

- Of course, the ’97 roadmap led to new questions as well. Three key ones that should be included:
  - The report recommended an MeV all-sky mission but that did not materialize <— **we can emphasize that this is still missing from the portfolio**
  - Multimessenger Astronomy is (of course) not mentioned.
    - This report directly led to the advent of MMA (Fermi and Swift)
  - Inclusion, Diversity, and Equity are not mentioned.

Fermi/Swift capabilities are an Astro2020 Decadal priority

Sustaining Programs (Space)

Time-Domain Program (highest priority)

- A program of competed missions and missions of opportunity to realize and sustain the suite of capabilities required to study transient phenomena and follow-up multi-messenger events.
- Notional cost: $500 million–$800 million over the decade

Probe Line

- Competed line of cost-capped probe missions to bridge the gap between Explorers and strategic missions; focused on gaps in science and wavelength capabilities– this decade Far-IR and an X-ray complement to Athena
- $1.5 billion/mission, cadence of approx. one/decade

Programs that Sustain and Balance the Science

Turning to medium-scale missions and projects, the scientific richness of a broader set of themes—exploring *New Messengers and New Physics*, understanding *Cosmic Ecosystems*, and placing *Worlds and Suns in Context*—as well as the need to capitalize on major existing investments and those coming online in the next decades drive the essential sustaining projects (Tables S.5 and S.6). In space, the highest-priority sustaining activity is a **space-based time-domain and multi-messenger program** of small and medium-scale missions. In addition, the survey recommends a new line of probe missions to be competed in broad areas identified as important to accomplish the survey's scientific goals. For the coming decade, a far-IR mission, or an X-ray mission designed to complement the European Space Agency (ESA's) Athena mission, would provide powerful capabilities not possible at the Explorer scale. With science objectives that are more focused compared to a large strategic mission, and a cost cap of $1.5 billion, a cadence of one probe mission per decade is realistic. The selection of a probe mission in either area would not replace the need for a future large, strategic mission. For ground-based projects, the highest-priority sustaining activity is **a significant augmentation and expansion of mid-scale programs**, including the addition of strategic calls to support key survey priorities. The survey also strongly endorses investments in **technology development for advanced gravitational wave interferometers**, both to upgrade NSF's Laser Interferometer Gravitational-Wave Observatory (LIGO), and to prepare for the next large facility.[5]

Fermi/Swift capabilities are an Astro2020 Decadal priority

Sustaining Programs (Space)

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- A program of competed missions and ... of opportunity to realize ... of capabiliti... ph... eve...
- Not... the ...

Probe Li...

- Comp... to brid... strategi... on gaps in science and wav... capabilities– this decade Far-IR and an X-ray complement to Athena
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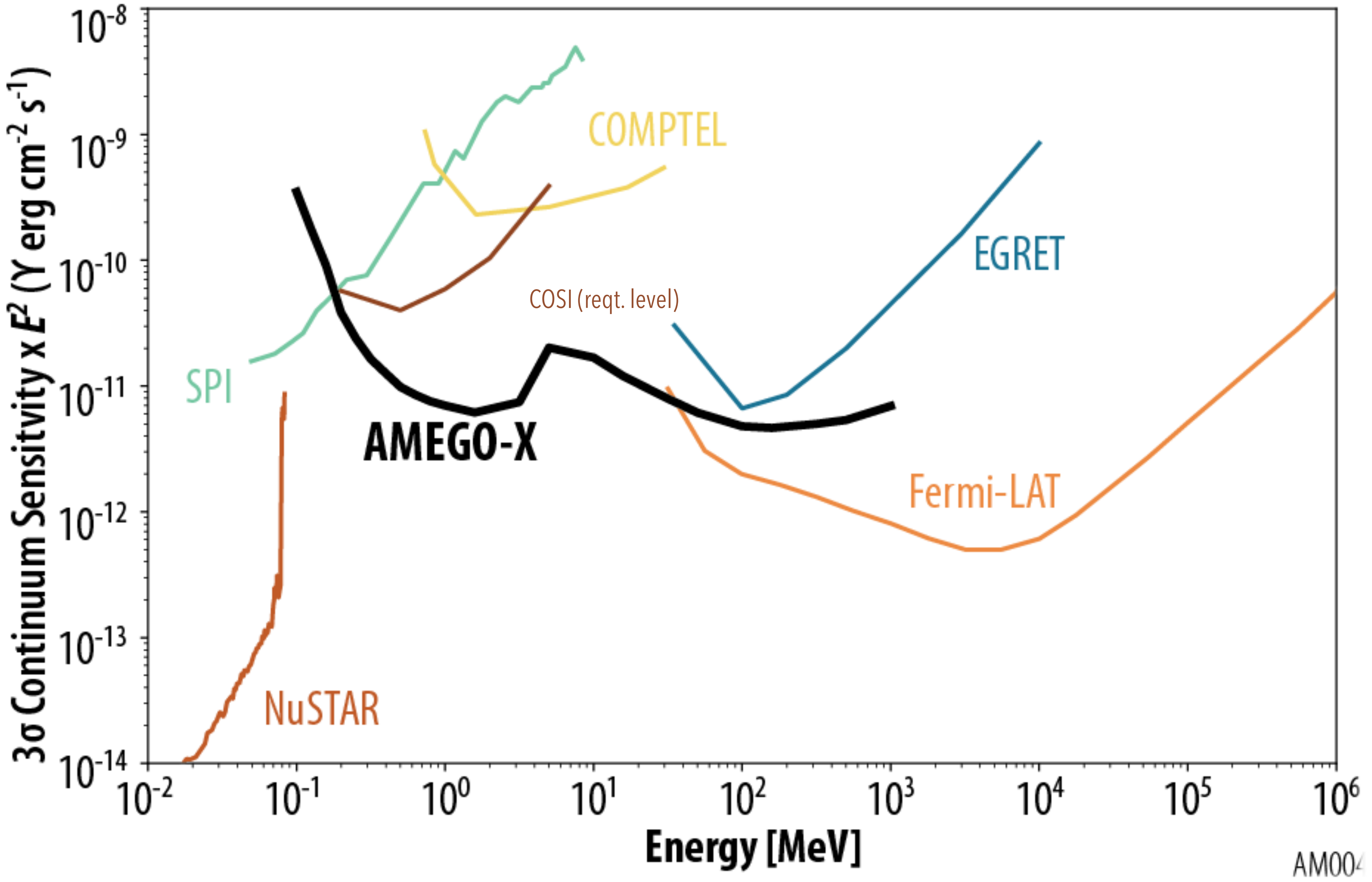
Astro2020: New Messengers, New Physics Decadal Priority!

A Telescope for the MeV Gamma-ray Regime

All-sky Medium Energy Gamma-ray Observatory eXplorer: AMEGO-X



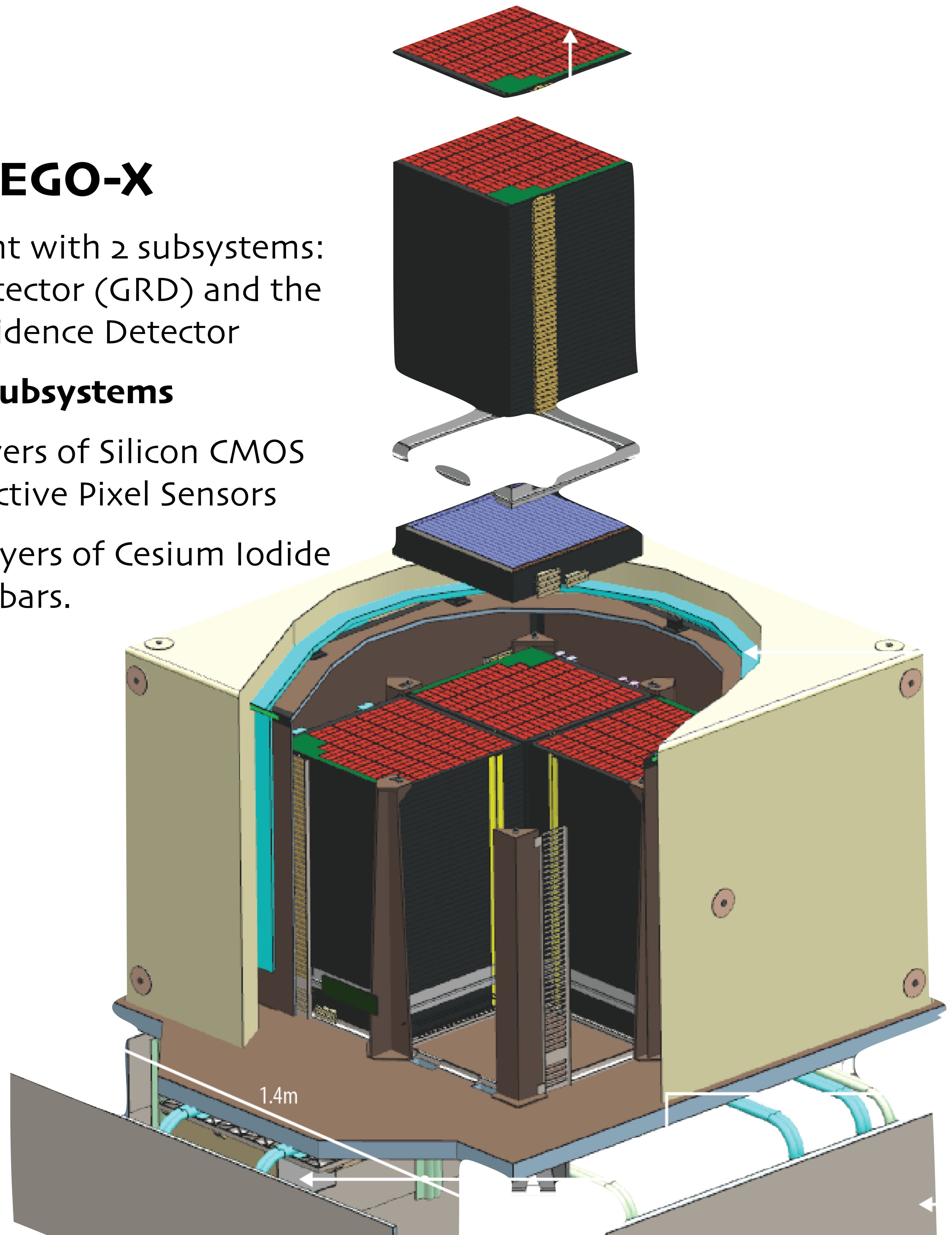
AMEGO-X

Single instrument with 2 subsystems: Gamma-Ray Detector (GRD) and the Anti-Coincidence Detector

GRD Subsystems

Tracker: 40 layers of Silicon CMOS monolithic Active Pixel Sensors

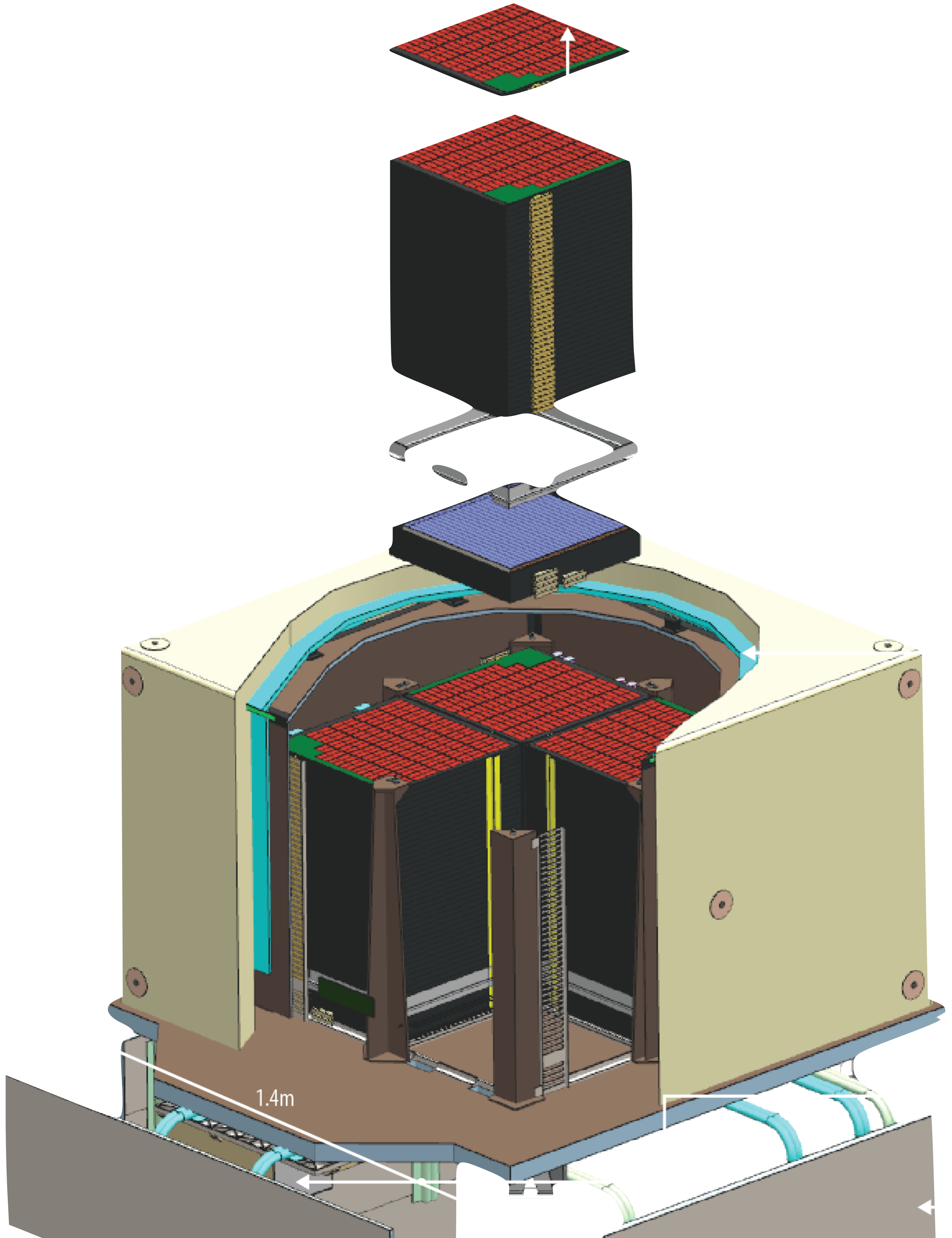
Calorimeter: 4 layers of Cesium Iodide bars.



AMEGO-X: arXiv:2208.04990
AstroPix: 2302.00101

AMEGO-X: Status and Plans

- Resubmit in the next MIDEX round (~2027)
  - New folks welcome! (Email me/Marco Ajello)
  - Important for the science team to keep publishing on the need for MeV instrumentation (we're happy to share sensitivity, effective area, energy/angular resolution etc…)
- Participate in gamma-ray roadmap activities

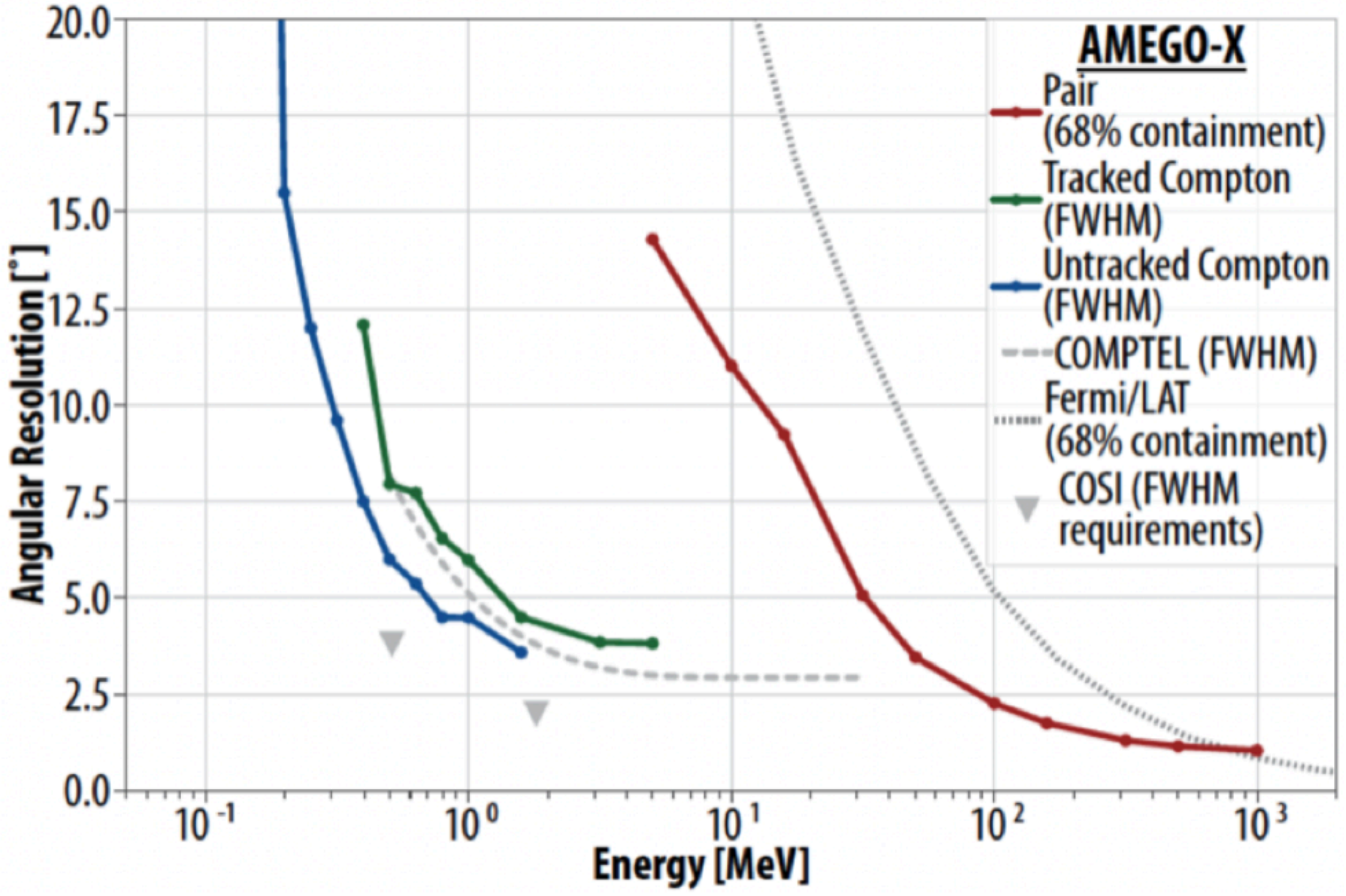


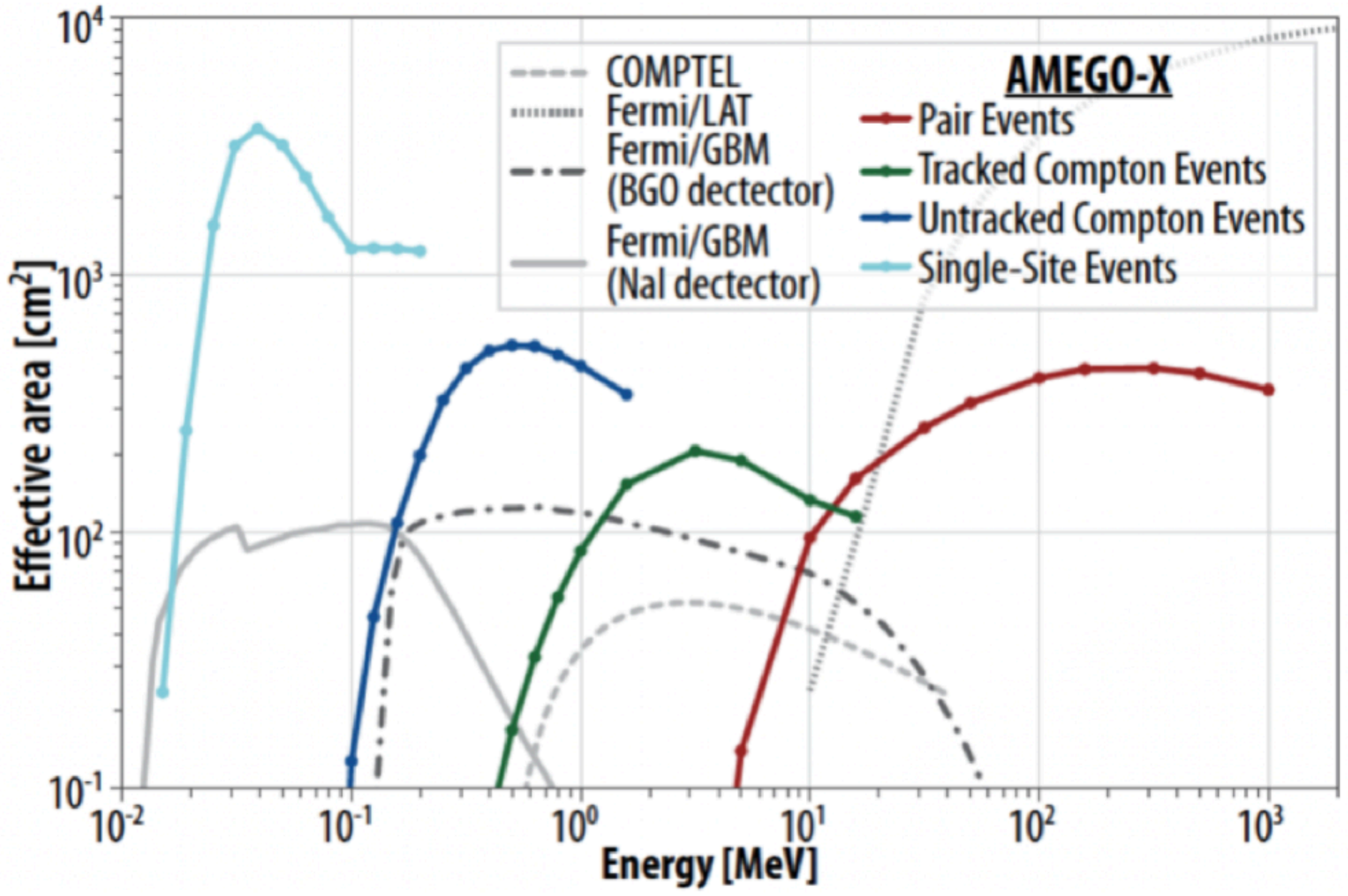
Friends observing space

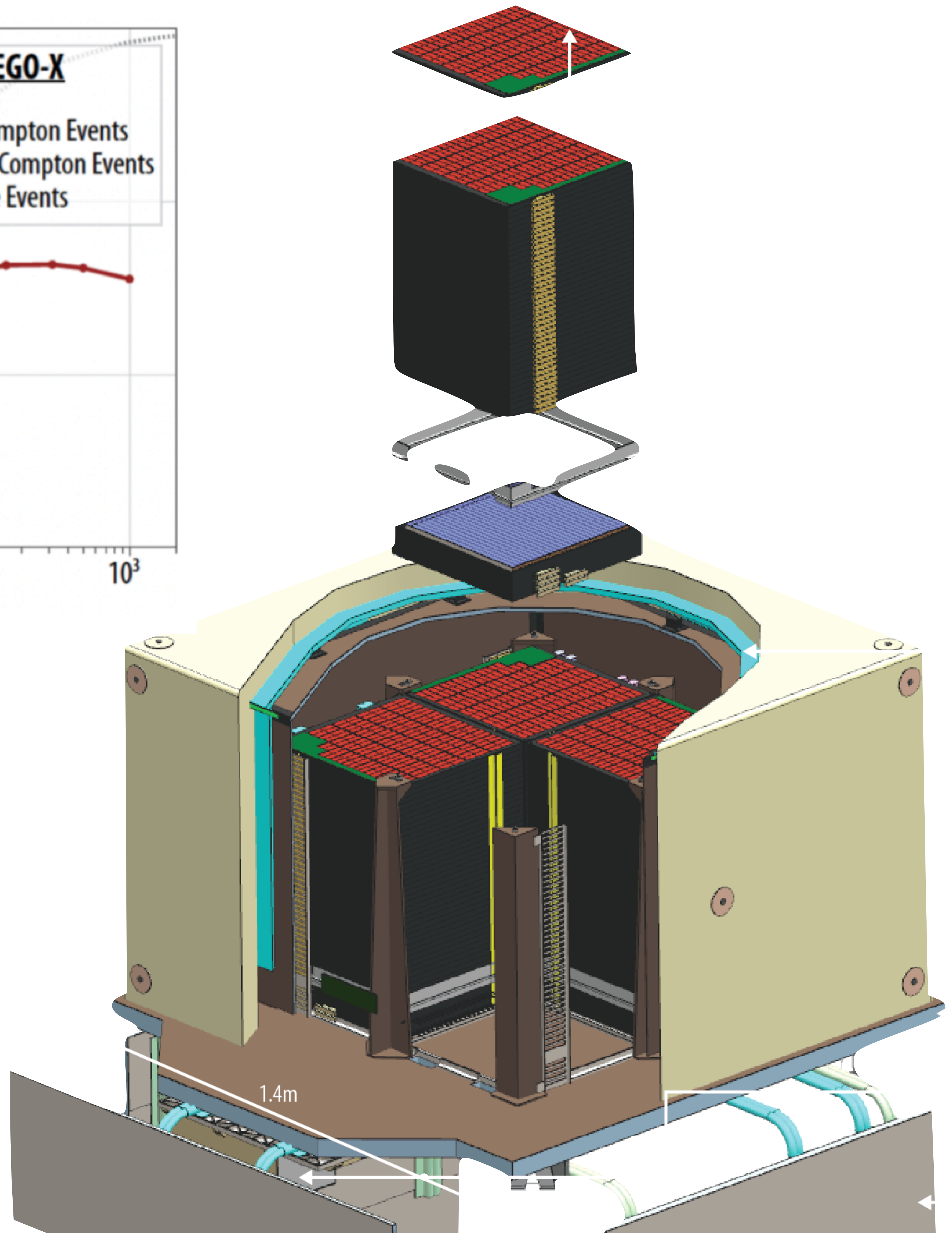
- Support Fermi/Swift! Senior review preparation
  - Fermi Symposium in DC area (September 9-13)
  - Swift20 in Rome Spring 2025
- BurstCube deployment TODAY at 13:26!
  Streaming Link: https://www.youtube.com/watch?v=D_qkY_KbK0E
- Join the Gamma-ray Science Interest Group (GammaSIG)
  - https://pcos.gsfc.nasa.gov/sigs/grsig.php
- Advocate with your own funding agency to support FIG SAG (Gamma-ray Roadmap) and a new Gamma-ray Observatory(s).
  - https://pcos.gsfc.nasa.gov/sags/figsag.php: Meeting in Michigan Tech: June 24-28
- Thanks to the CTAO Symposium organizers!

Backups

Instrument Capabilities



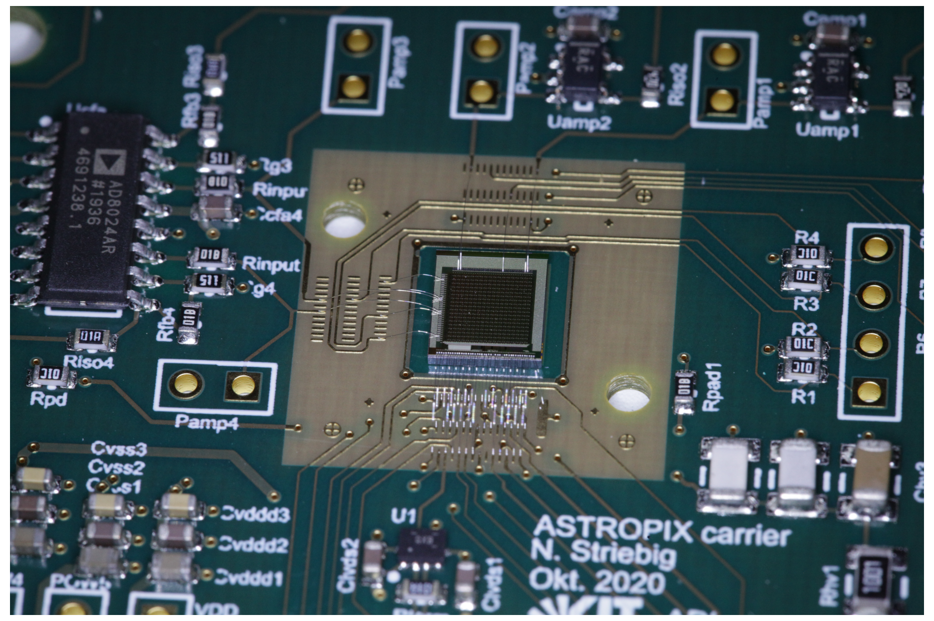




Parameter	
Energy Range	25 keV – 1 GeV
Energy Resolution	5% FWHM at 1 MeV, 17% (68% containment half width) at 100 MeV
Point Spread Function	4° FWHM at 1 MeV, 3° (68% containment) at 100 MeV
Localization Accuracy	transient: 1° (90% CL radius), persistent: 0.6° (90% CL radius)
Effective Area	1200 cm^2 at 100 keV, 500 cm^2 at 1 MeV, 400 cm^2 at 100 MeV
Field of View	2π sr (<10 MeV), 2.5 sr (>10 MeV)

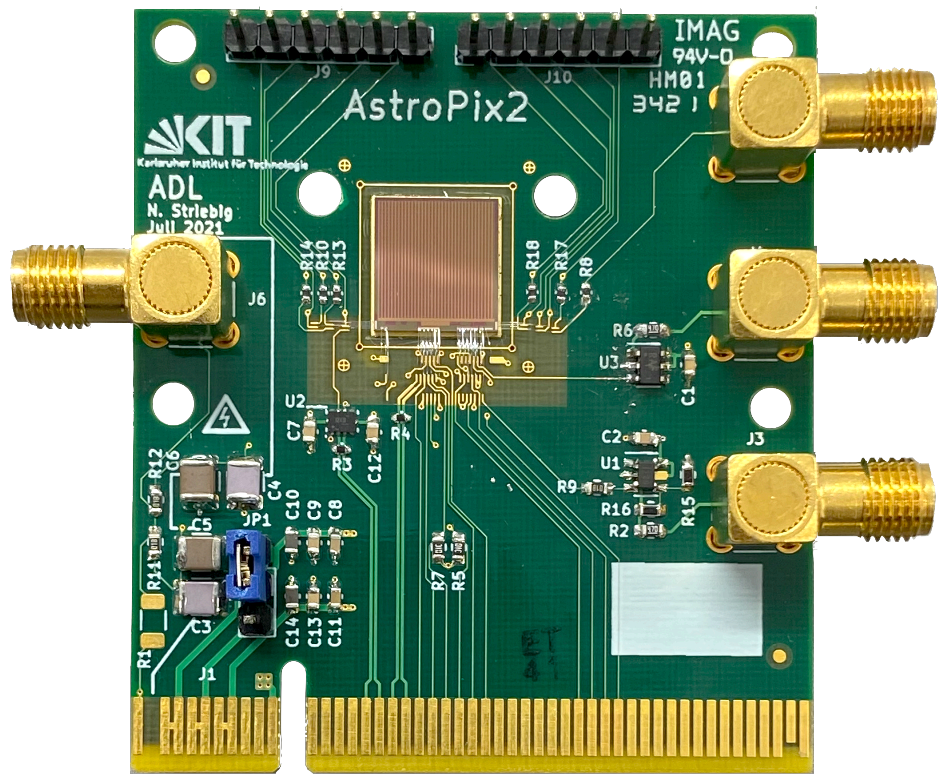
AMEGO-X: arXiv:2208.04990
AstroPix: 2302.00101

CMOS Monolithic Active Pixel Sensors



AstroPix_v1

On bench, tested in lab

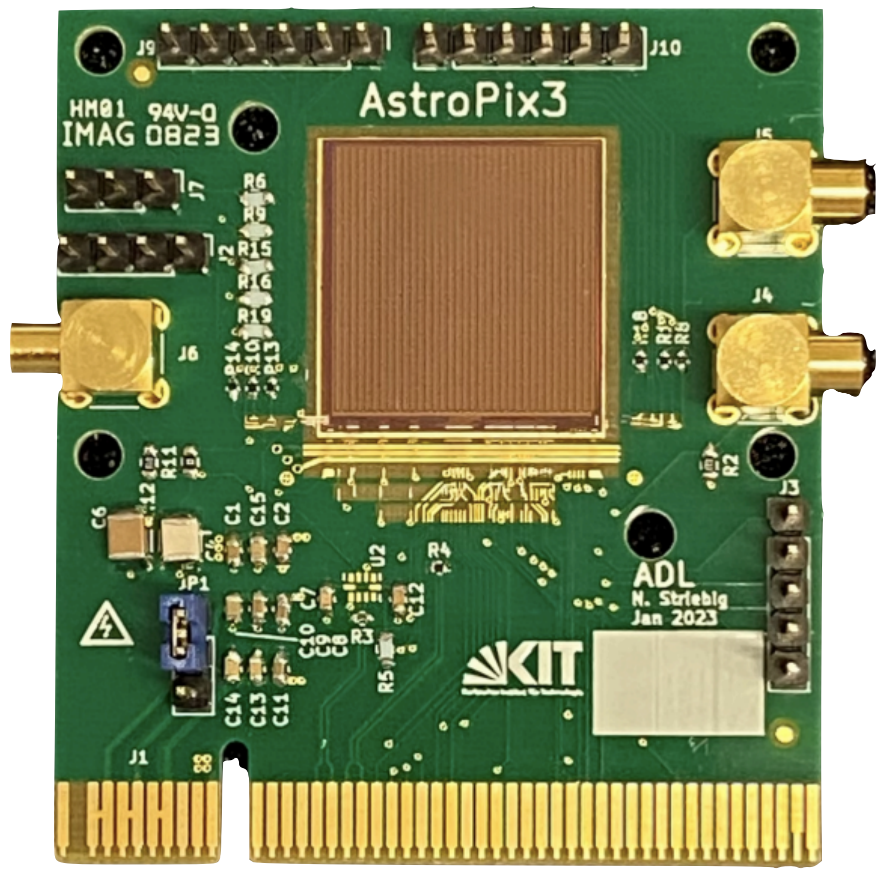


AstroPix_v2

On bench, tested at FNAL, LBNL. Space relevant radiation hardness confirmed

Flight prototype:

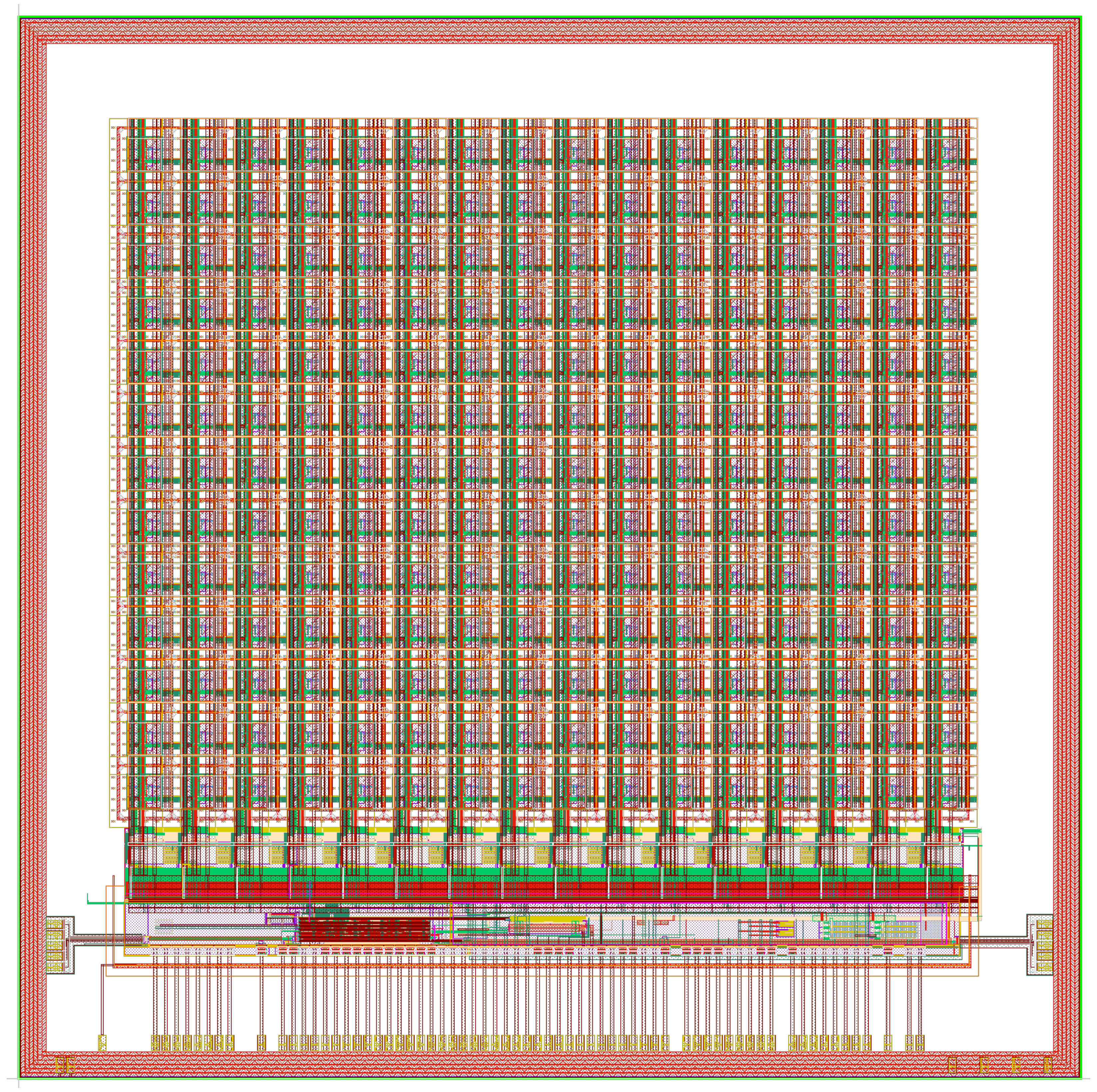
delivered in March 2023



AstroPix_v3: Testing underway

Flight design:

Delivered October 2023



AstroPix_v4

Summary Status of AstroPix

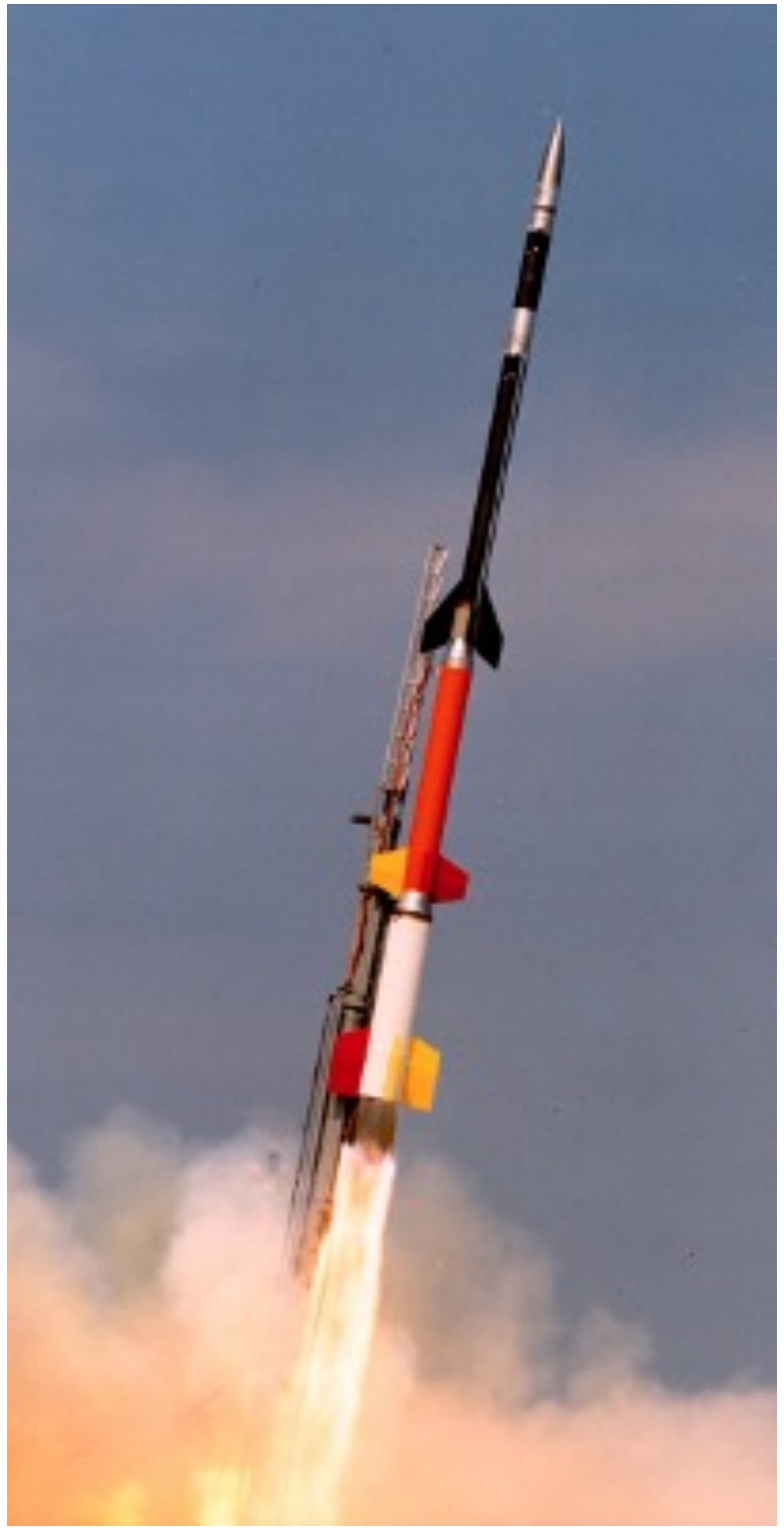
v3 testbed - First readout of Quad Chip

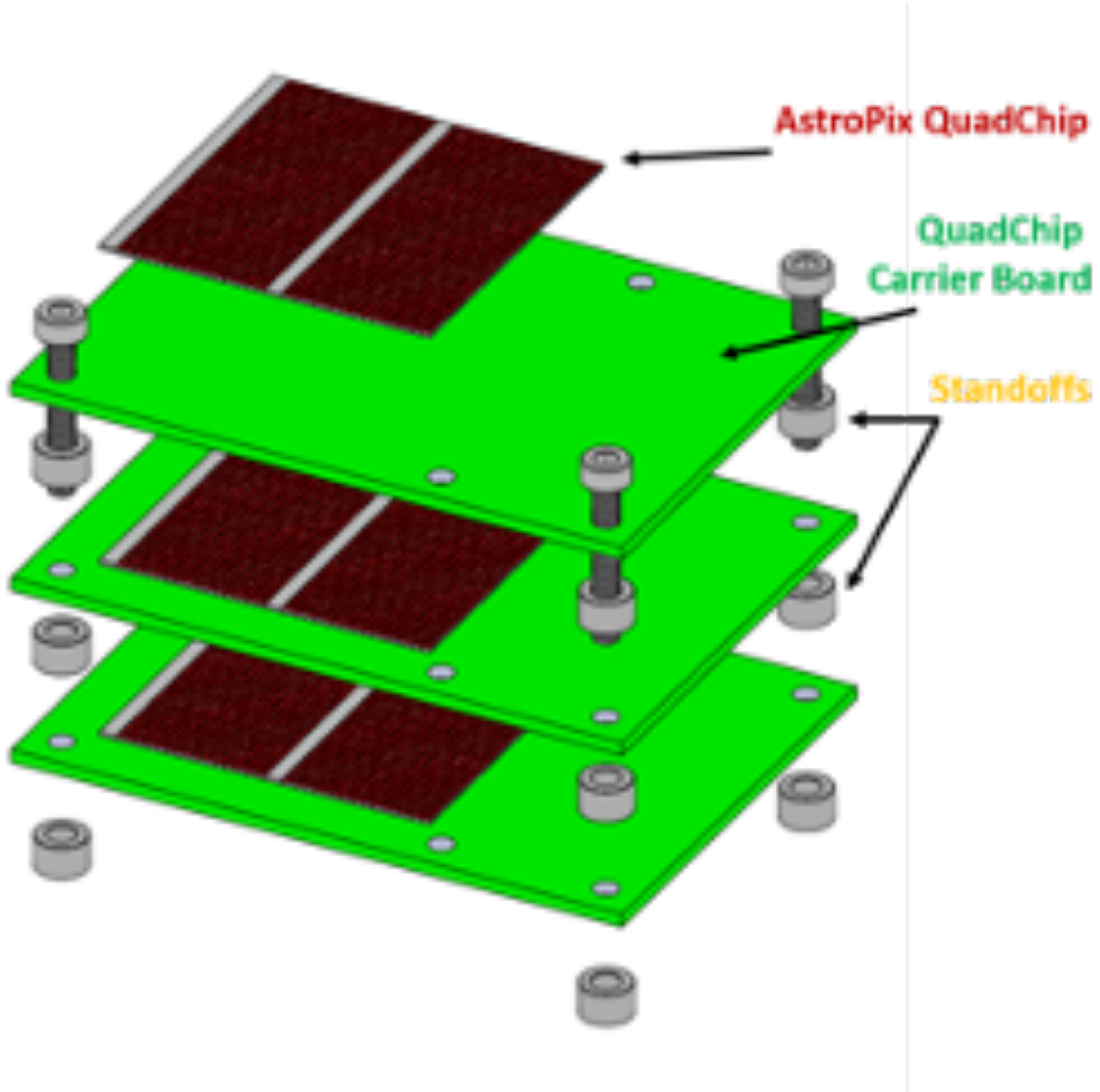
- 25 production wafers produced by TSI
    - Waiting to be shipped
- Estimation of yields (300 chips)
- Standardized testing procedures
- Integrate w/ initial mechanical
  + FEE at ANL to develop procedures

v4 delivery has occurred at KIT

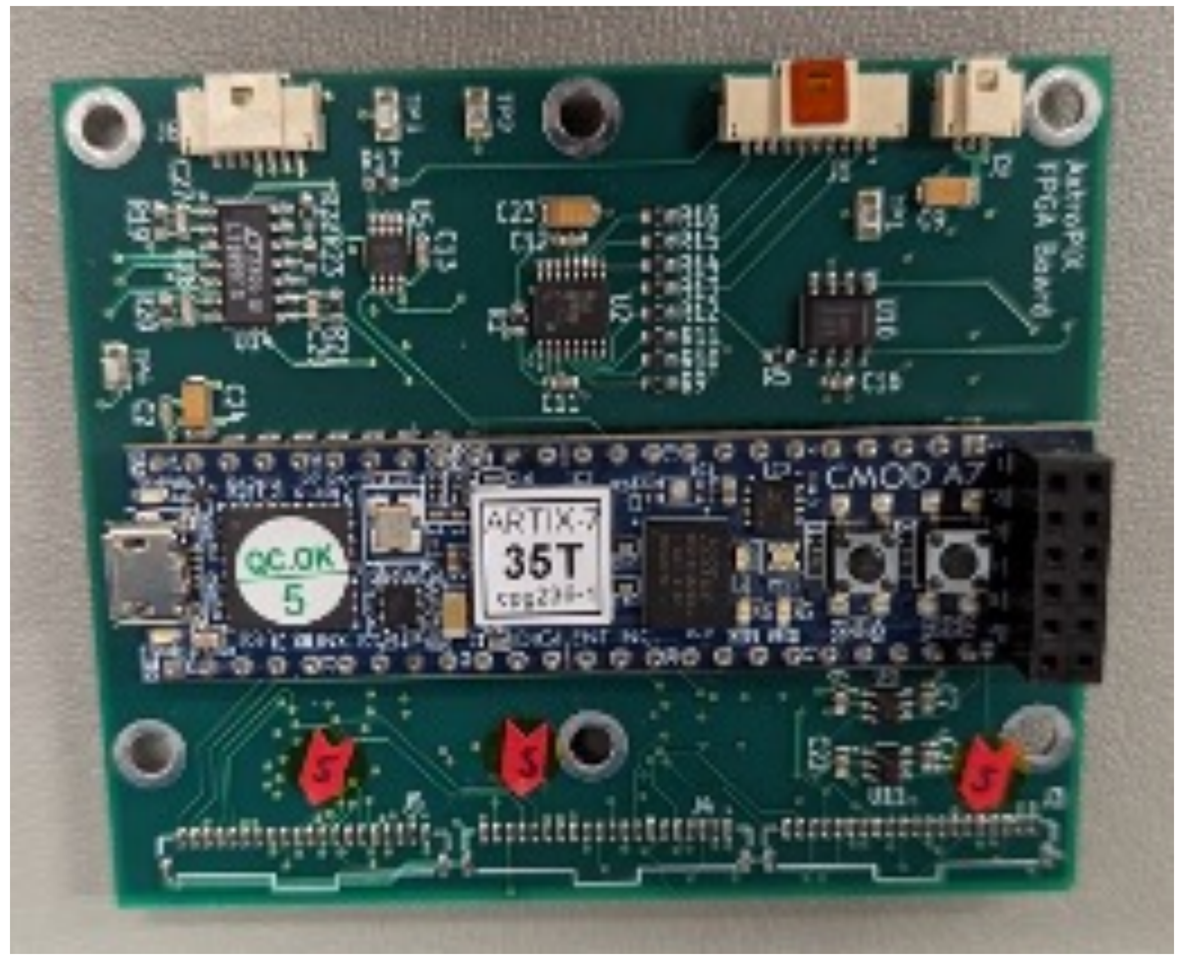
- Testing just begun; Confirmation of full depletion
- Carrier board for testing + firmware/software in mature stage
- Identify issues/mods needed for v5 submission
- Characterize performance (energy resolution, dynamic range, etc)

A-Sounding rocket Technology dEmonstration Payload (A-STEP)

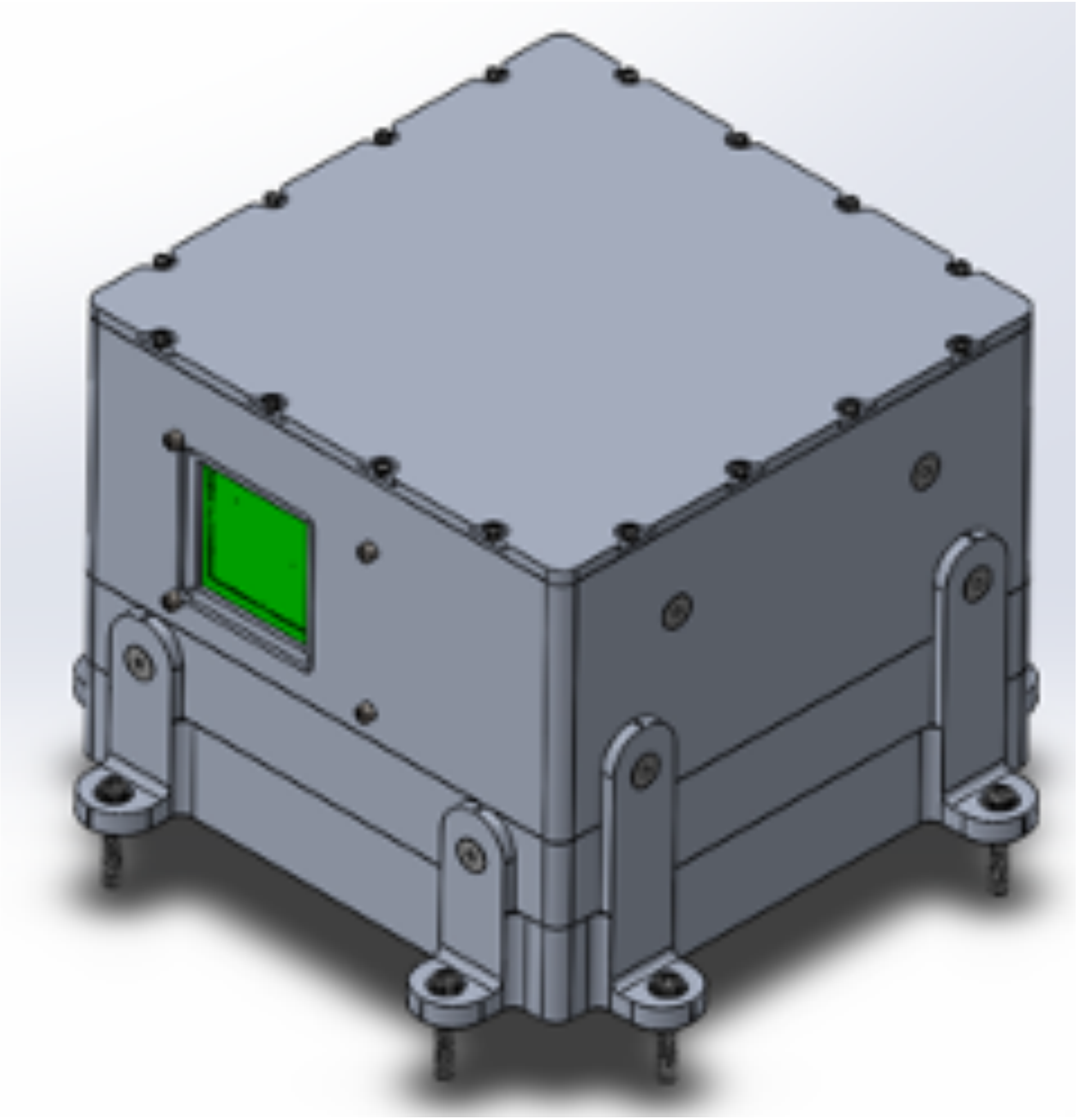




Instrument: 3 layers of AstroPix



COTS: Front-end electronics + flight computer



Payload: ~20 x 20 x 20 cm

Launch from WFF in ~summer 2025

AMEGO-X: Status and Plans

- Submitted Medium Size Explorer (MIDEX) proposal Dec 2021
  - Highly rated, not selected for Phase A
- Team launched ComPair Balloon (AMEGO prototype) in August 2023
- Development AstroPix detectors
  - Flight prototype in house tested at GSFC and ANL
  - Sounding rocket payload launch Summer 2025 (passed CDR in November)
  - AstroPix in ePIC: https://www.bnl.gov/eic/
- Build AMEGO-X Tower prototype (ComPair: APRA 2023)