GAMMA-RAY TRANSIENT NETWORK SCIENCE ANALYSIS GROUP REPORT

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https://pcos.gsfc.nasa.gov/sags/gtn-sag.php

https://arxiv.org/abs/2308.04485

Pathways to Discovery in Astronomy and Astrophysics for the 2020s

- Theme: New Messengers and New Physics
  - Priority Area: New Windows on the Dynamic Universe is aimed at combining time-resolved multi-wavelength electromagnetic observations from space and the ground with non-electromagnetic signals to probe the nature of black holes, neutron stars, the explosive events and mergers that give rise to them… S-2
  - NASA Time-Domain And MultiMessenger (TDAMM) Program: In space, the highest-priority sustaining activity is a space-based time-domain and multi-messenger program (S-3)
- ‘Support data archives and curation. Astronomy is evolving rapidly into a profession in which archiving of individual observations can produce scientific impacts that rival the original studies, and large-scale surveys are designed for science-ready archival manipulation from the beginning’ 1-16
- High-energy monitors
  - In addition, NASA’s workhorse hard X-ray and gamma ray transient facilities (Swift and Fermi, respectively) are aging and their longevity is uncertain. Higher sensitivity all-sky monitoring of the high-energy sky, complemented by capabilities in the optical such as from Kepler and TESS, is a critical part of our vision for the next decade in transient and multi-messenger astronomy. 2-33
  - ‘While ground-based measurements by observatories large and small are essential, several key capabilities that must be sustained to enable time-domain and multi-messenger astrophysics can only be realized in space. The most important of these are wide-field gamma-ray and X-ray monitoring, and rapid and flexible imaging and spectroscopic follow-up in the X-ray, ultraviolet (UV), and far-infrared (far-IR).’ 7-18

Pathways to Discovery in Astronomy and Astrophysics for the 2020s

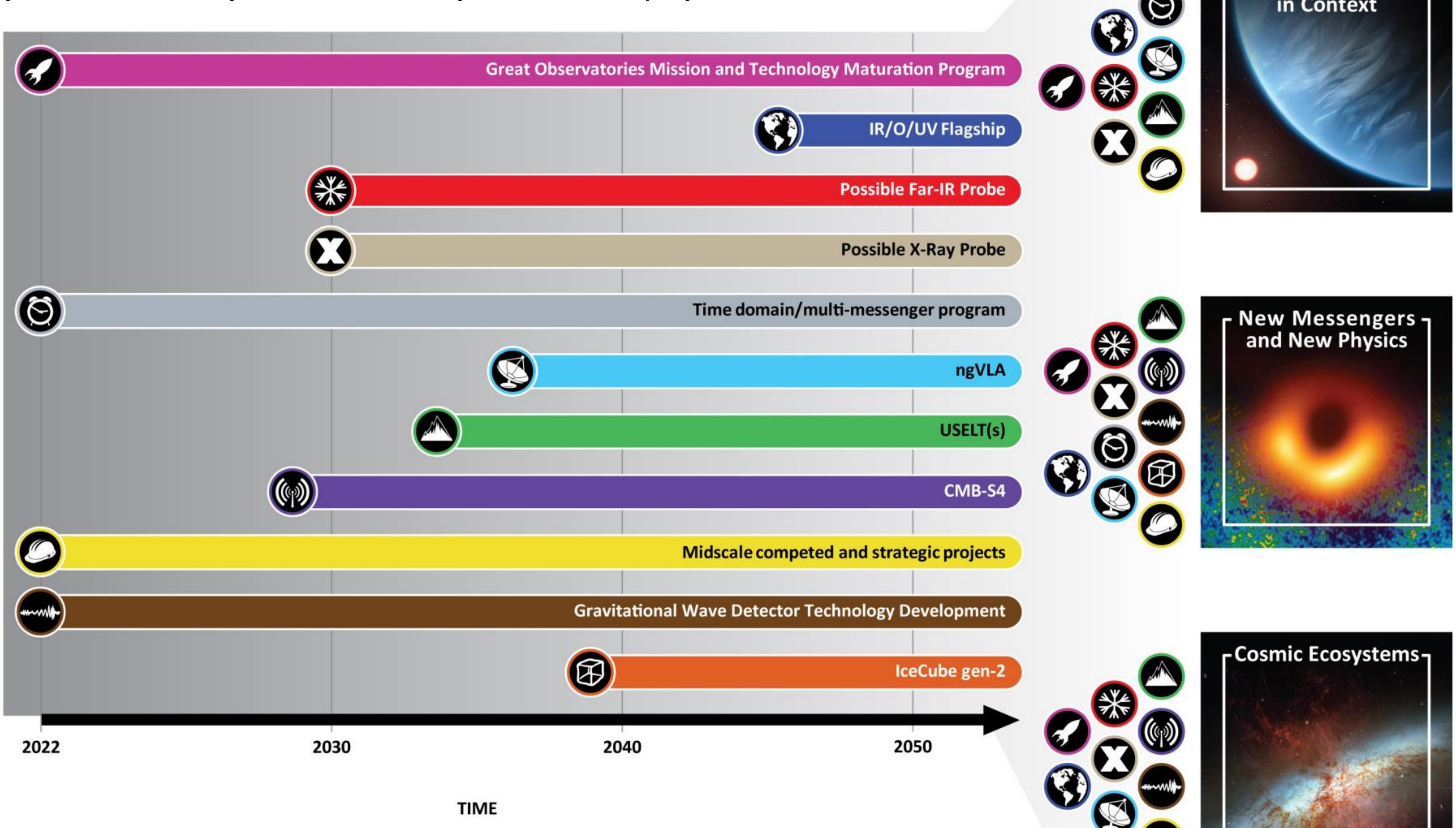
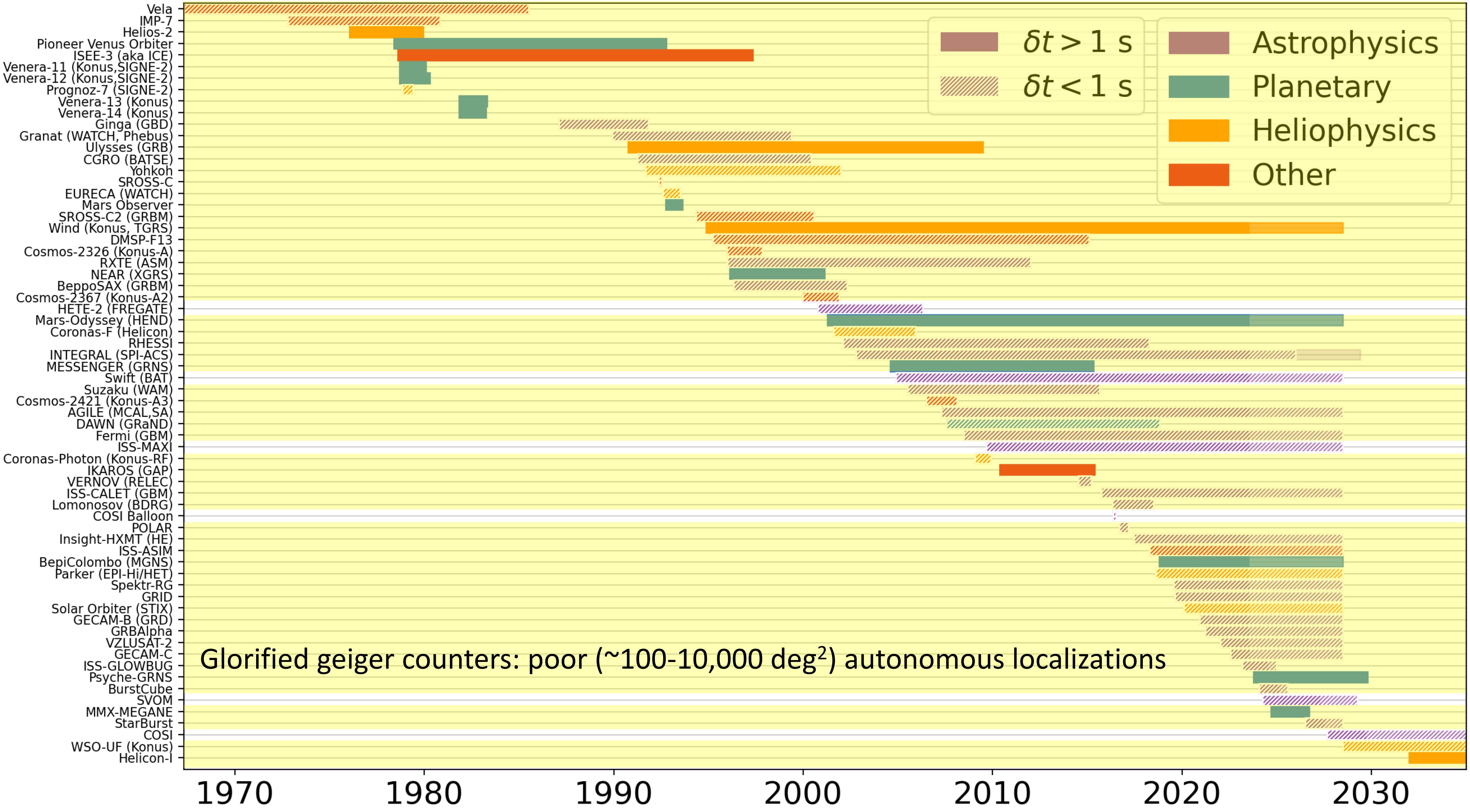


Figure S-1 – TDAMM program continues for decades

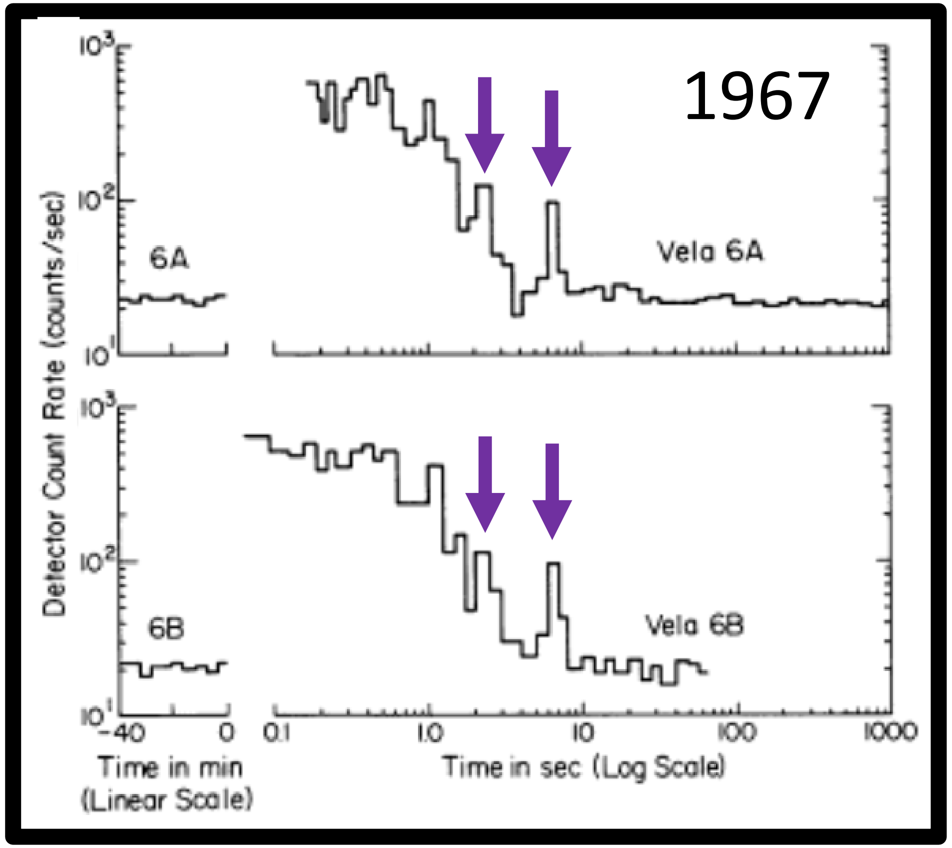


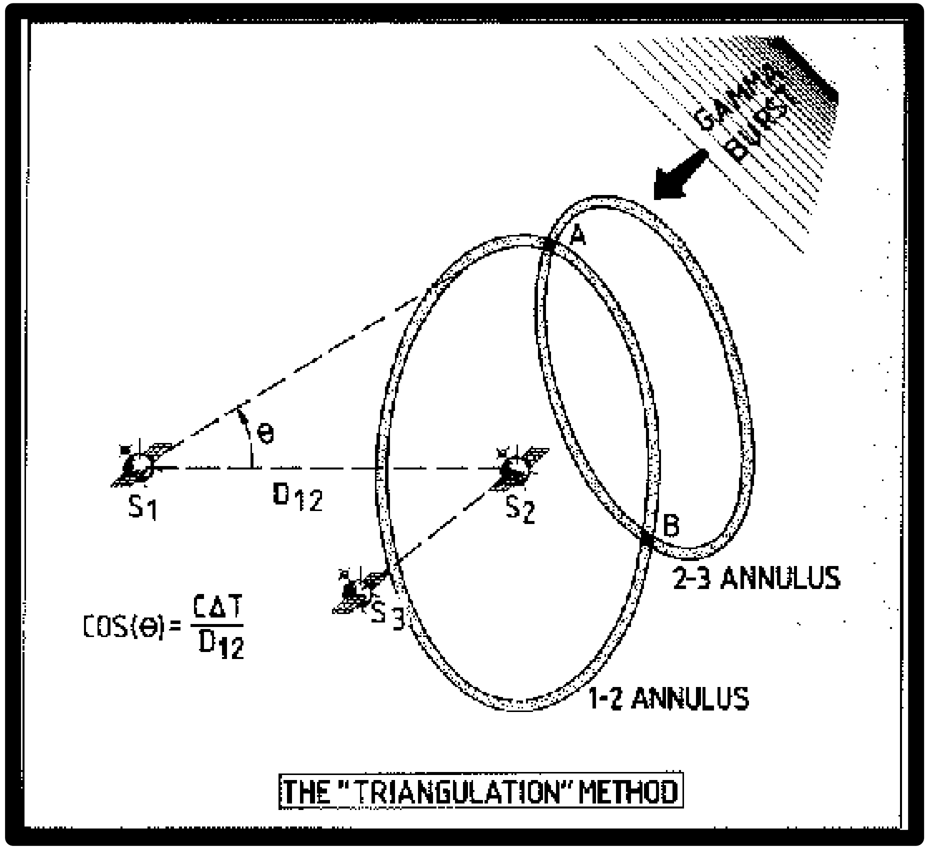
Glorified geiger counters: poor (~100-10,000 deg^2) autonomous localizations

Pseudo-Range Multilateration
(commonly known as triangulation)

$$\theta = \cos^{-1}\frac{c\delta T}{D},$$

$$d\theta = -\frac{c\,d(\delta T)}{D\sin\theta}$$

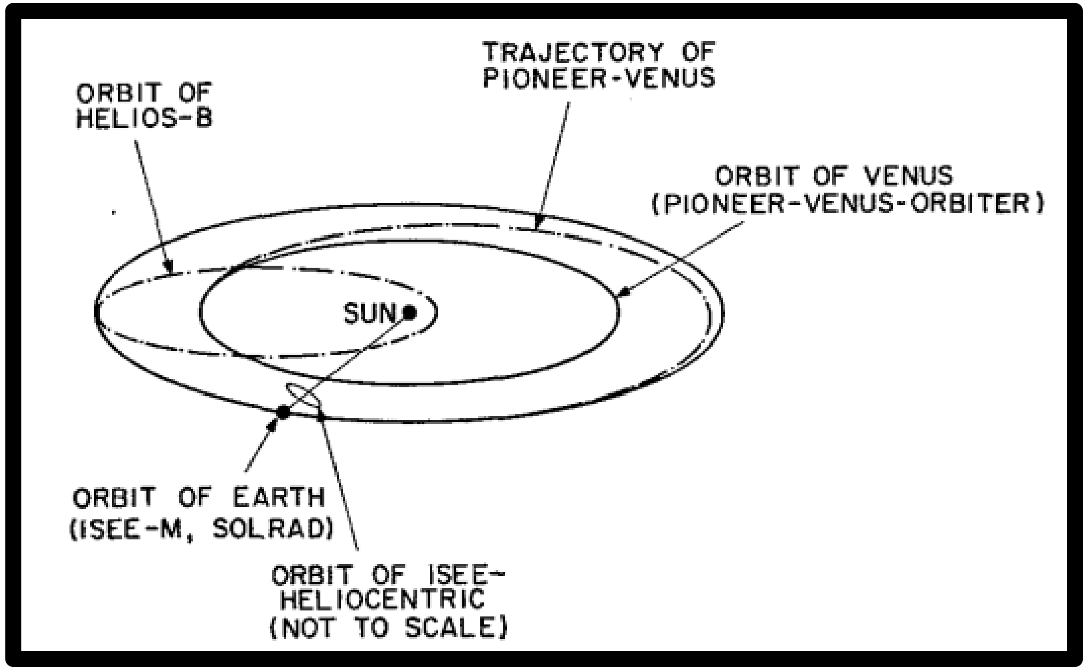




- θ – annulus radius
- **dθ – annulus width**
- c – speed of light
- δt – the arrival time difference (predominantly limited by data resolution, clock accuracy)
- D – distance between satellites (precision requires baselines beyond low Earth orbit)

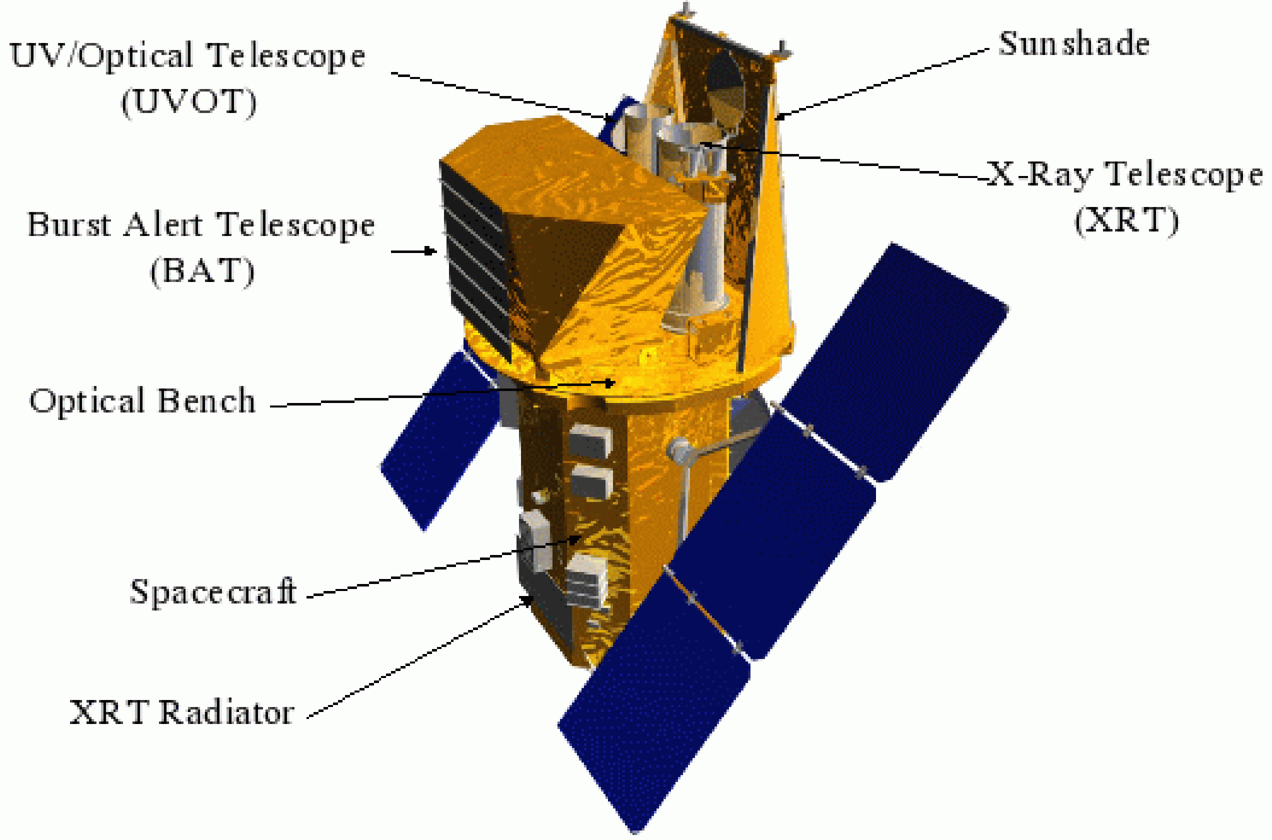
The InterPlanetary Network

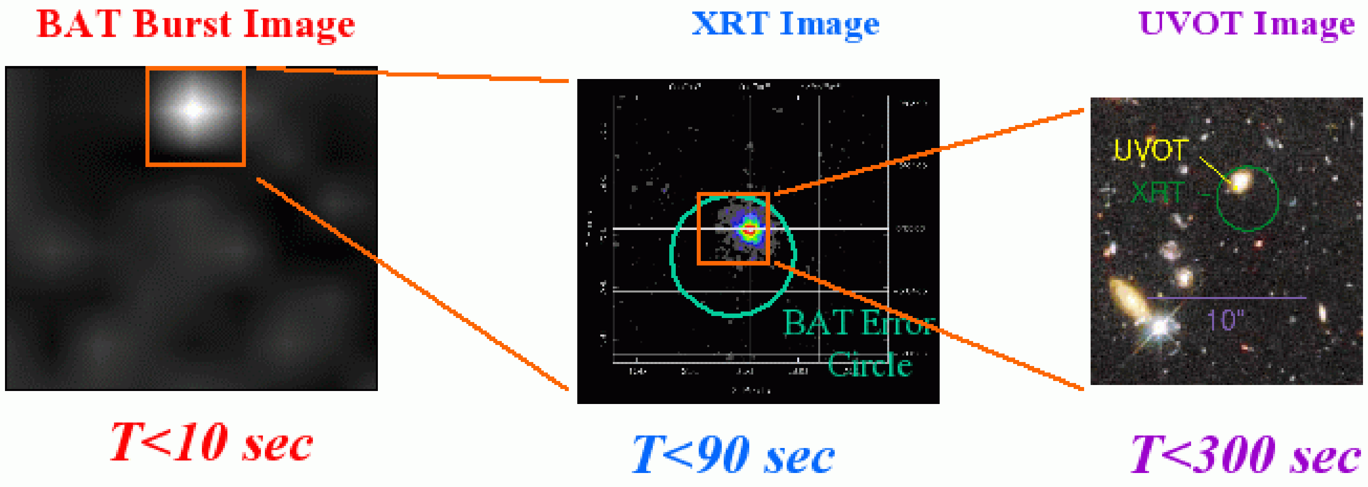
- Founded in 1974, collating data from US and Soviet scientists
  - International TDAMM partnerships
- Led by Kevin Hurley for 45 years
  - Operates over decades
- Several major discoveries
  - Including on the nature of black holes, neutron stars, the explosive events and mergers that give rise to them



The Neil Gehrels Swift Observatory

- Typical current operations
  - Detection by BAT, ~90/yr, ~3’
  - Repoint XRT, ~70/yr, ~3”
  - Repoint UVOT, ~25/yr, ~1”
  - Follow-up, ~45/yr, ~1”
  - Hope for broadband prompt coverage, ~25/yr
- **Weekly prompt+afterglow joint detections at ~1 arcsecond scale localizations, allowing robust host galaxy association**
- Large optical spectrometers give redshift, energetics





Gamma-ray Transient Network SAG - Terms of Reference

In full:

- What time-domain and multimessenger sources rely on the InterPlanetary Network (IPN)? What scientific discovery will the IPN enable? How does it fit into the new astrophysical landscape? What would be lost if the IPN ends? How does the science case for IPN depend on interplanetary probes and the long baseline they provide?
- Where can improvements be made to the existing IPN? What are the needs of the full astronomical community, especially the needs of those who study fast radio bursts, optically-identified relativistic transients, the gravitational wave community, and the neutrino community? How can we make use of advances to the Global Coordinates Network, and how do IPN alerts need to be improved? What are the needs of the international gamma-ray satellite community? Would engagement between these new satellites and the IPN benefit the astrophysical community? Would greater integration bring greater benefits?
- What benefits would extending the IPN beyond the current gamma-ray instruments bring? What future missions and instruments are needed to fully realize the Decadal-recommended science in partnership with the advancing capabilities in other wavelengths and other messengers?

In short:

- The IPN declined in importance with the launch of Swift. However, it has key capabilities (longevity, all-sky coverage, precise localizations) which may pair well with new facilities at other wavelengths and messengers, especially in the study of rare transients
- Could the IPN be part of the NASA solution to the strong Astro2020 Decadal TDAMM Recommendation?

GTN SAG Report

- 3 page executive summary
- 69 pages in the main report
- Sections
    - Intro (pages 1-4)
    - Sources and Science (pages 5-33)
    - Capability Requirements (pages 33-42)
    - **Actionable Items for Missions and Instruments (42-46)**
    - **Actionable Items for the IPN (48-60)**
    - Conclusions (60)

https://arxiv.org/abs/2308.04485

Letters of Support

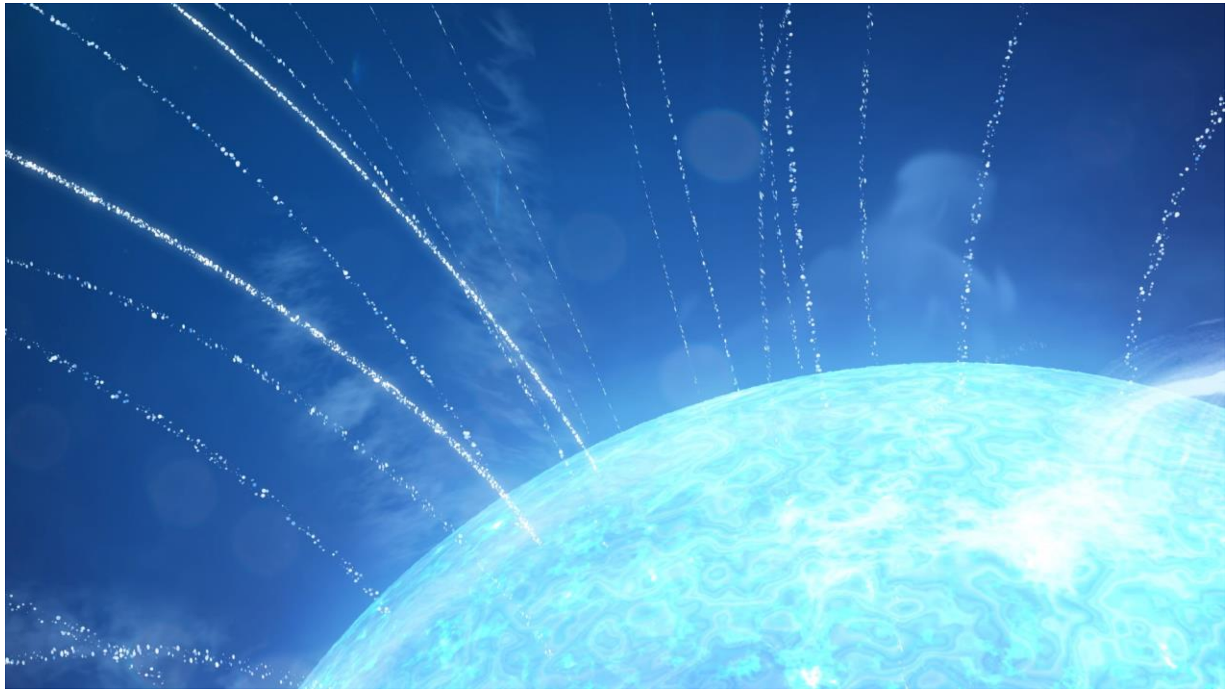
- CMB-S4 – Co-spokespeople Kevin M. Huffenberger, Jeffrey J. McMahon
- ngVLA – Director Anthony Beasley, ngVLA Project Scientist Eric Murphy, co-chairs of the ngVLA working group on exploring the dynamic universe Alessandra Corsi, Rachel Osten
- LSC – Spokesperson Patrick Brady
- LIGO Lab – Executive Director David Reitze
- Chime – PI Vicky Kaspi
- CTAC – Spokesperson Werner Hofmann
- HAWC – Spokespersons Alberta Carraminana, Ke Fang
- IceCube – Spokesperson Ignacio Taboada
- Fermi-GBM – PI Colleen Wilson-Hodge
- Veritas – Spokesperson Amy Furniss
- Rubin – TVS Chair Raffaella Margutti
- Swift – PI Brad Cenko
- COSI – PI John Tomsick
- WVU Fast Radio Burst group – Leads Duncan Lorimer, Maura McLaughlin

Sources and Science

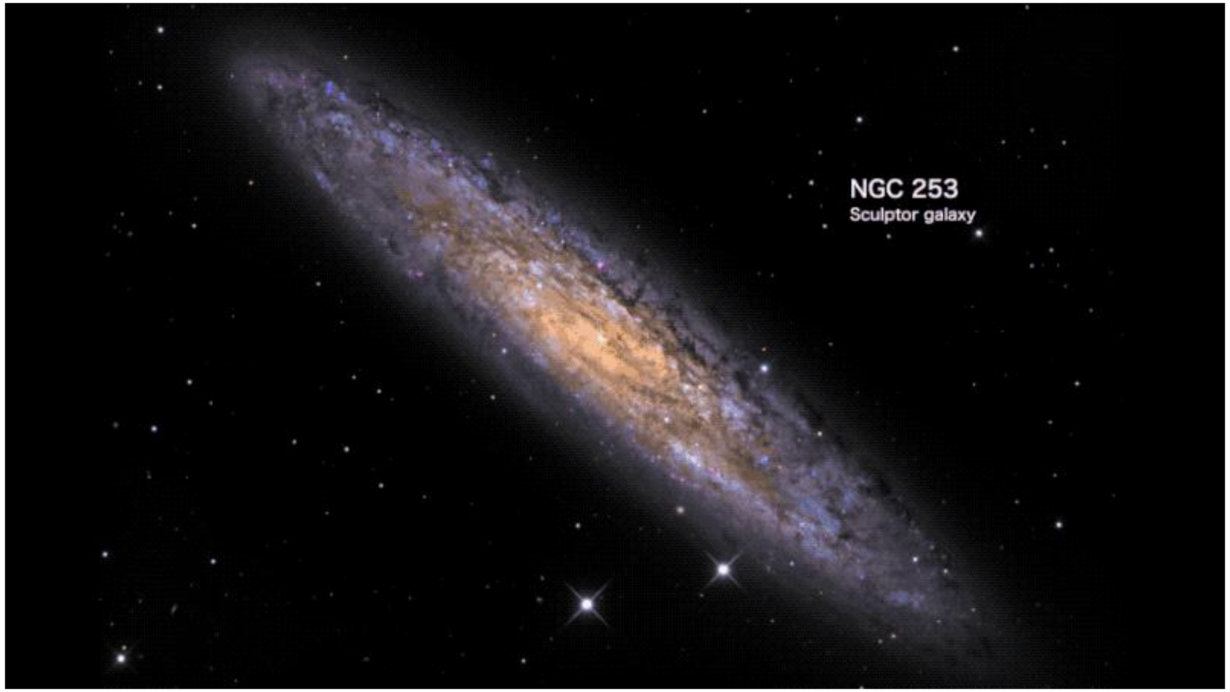
1. Magnetars
2. Compact Mergers
3. Collapsars
4. Other

Magnetars: Precise Timing

- Neutron stars with 10^{15} G magnetic fields
- Discovered by the IPN
- Release short-duration flashes of X-rays/gamma-rays
- An origin of fast radio bursts
- Likely gravitational wave sources



NASA Goddard/Chris Smith (USRA/GESTAR)



NASA Goddard , DSS, SDSS, and Adam Block/ Mount Lemmon SkyCenter/University of Arizona

Compact Mergers: Precise Localizations

- Neutron star merging with another neutron star, a black hole, or a white dwarf (?)
- Deep multimessenger searches with LIGO
- Immediate joint localizations aide the follow-up community
  - Prompt gamma-ray burst detections are critical for unlocking full science potential

NASA Goddard / CI Lab

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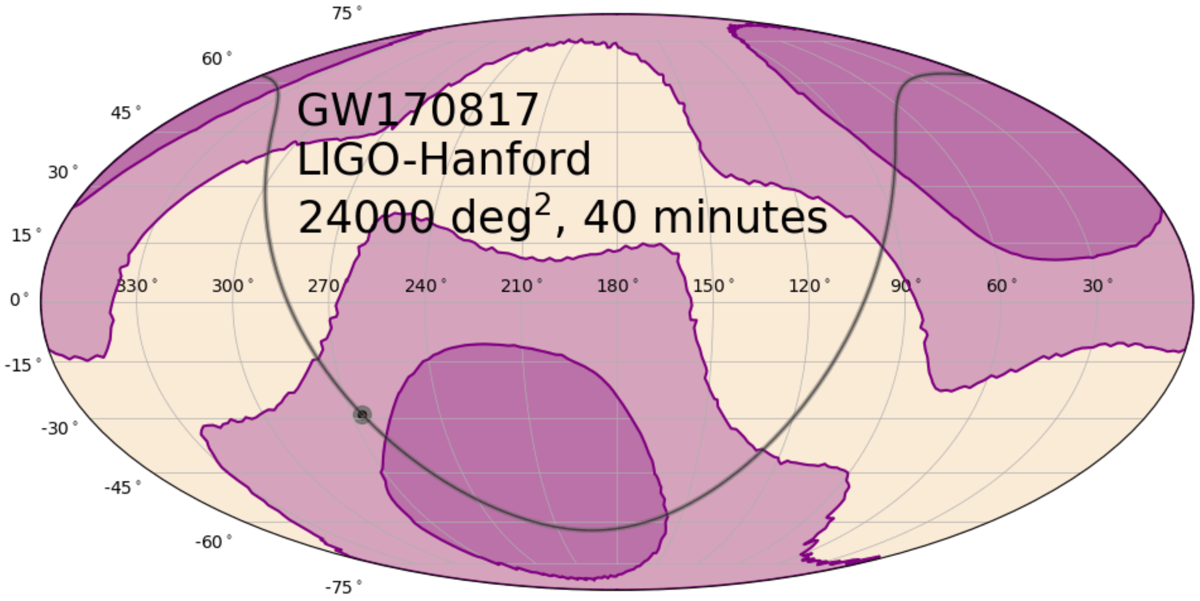
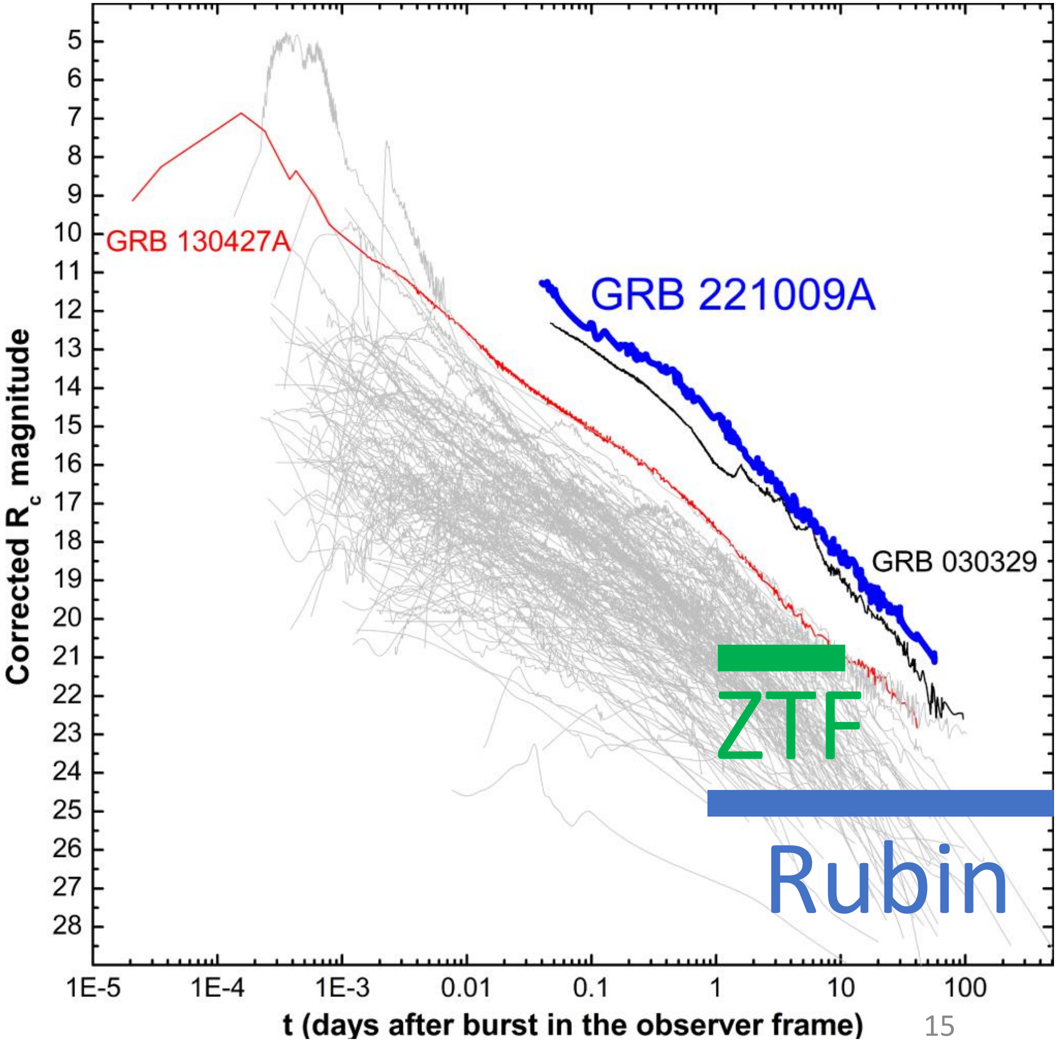
NASA Goddard / CI Lab



Collapsars: All-sky coverage

Credit: NASA Goddard's Conceptual Image Lab

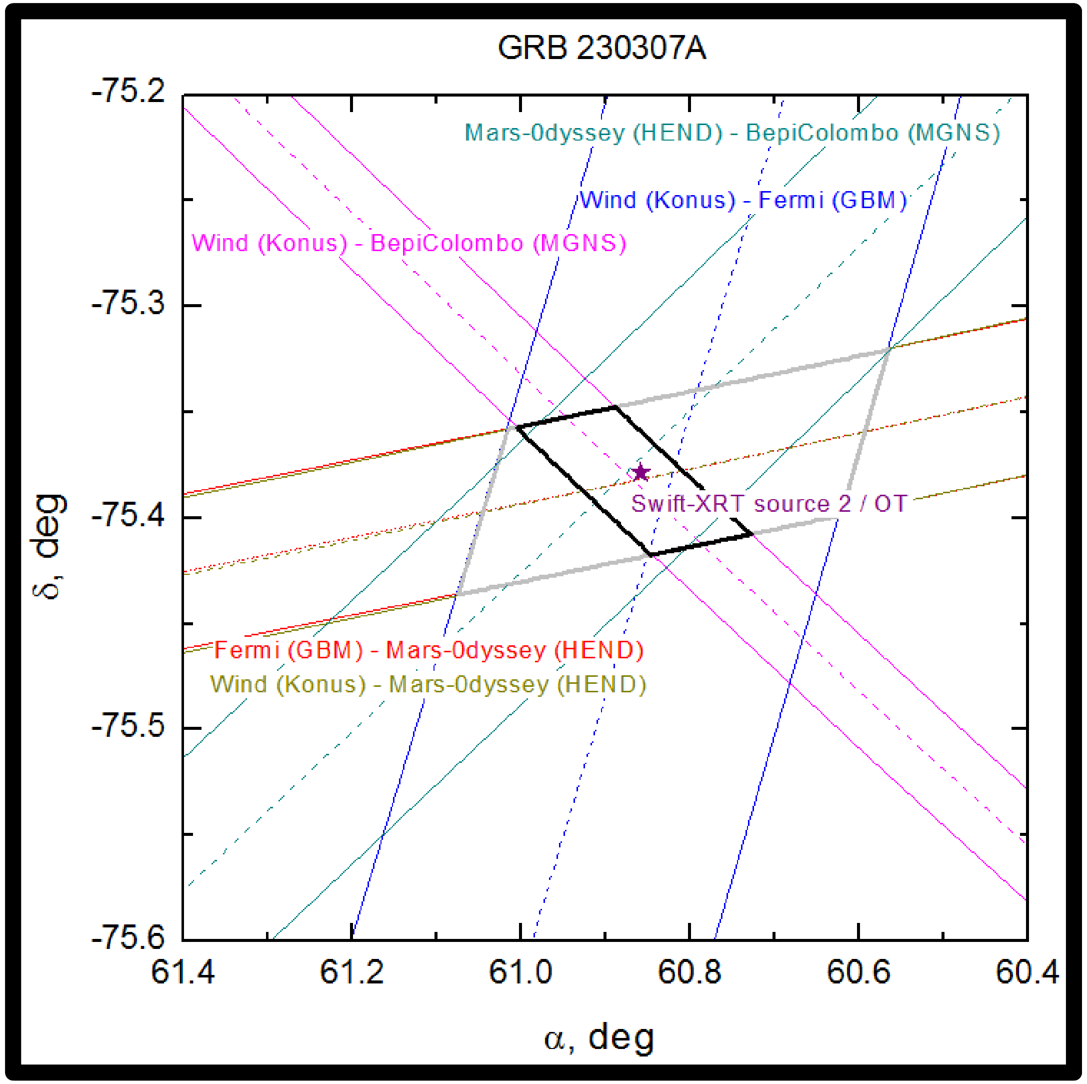
- Most luminous electromagnetic events
- Now routinely discovered in afterglow independently from prompt triggers
- The IPN and fixed-cadence observations of forthcoming UVOIR surveys, including Rubin and NEO Surveyor, will have weekly prompt+afterglow joint detections, comparable to Swift and targeted follow-up
- Non-detections in gamma-rays are important
- Failed ones are promising neutrino sources



Other - GRB 230307A

- Discovered by Fermi, flagged as second brightest ever
- IPN performed iterative localizations as data arrived
  - Serendipitous coverage by TESS, LEIA
- Swift and the 3.5m New Technology Telescope tiled the IPN localizations
- Recovery of afterglow led to identification of a very red transient
- JWST observations provide the most direct proof of r-process nucleosynthesis

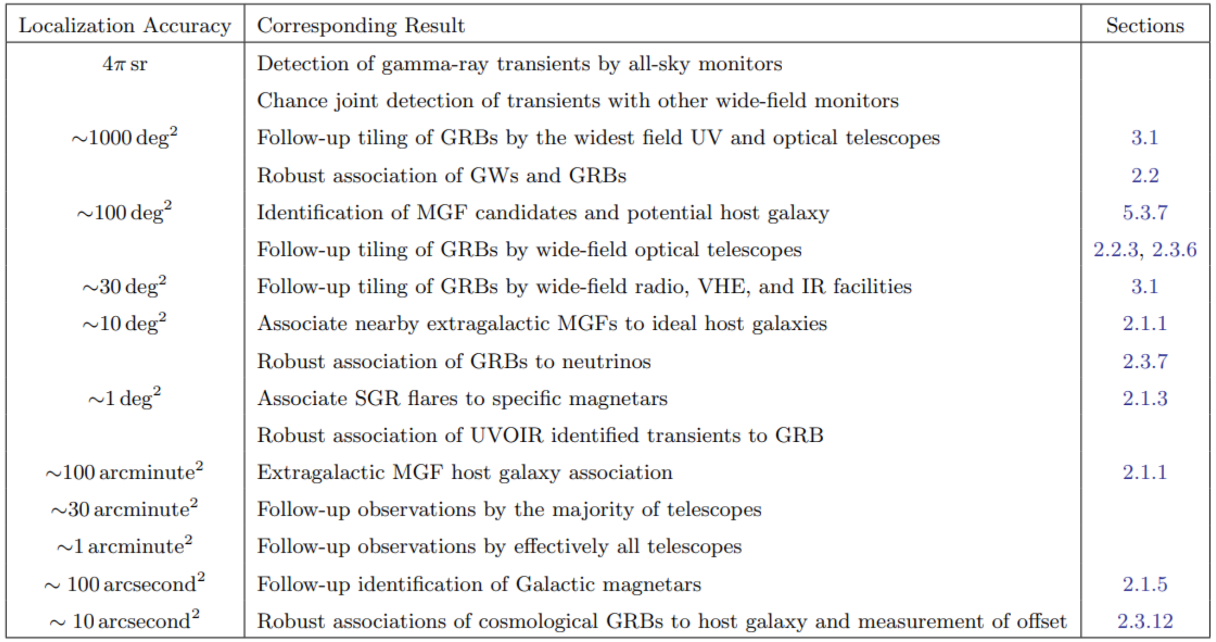
[2307.02098] JWST detection of heavy neutron capture elements in a compact object merger (arxiv.org)



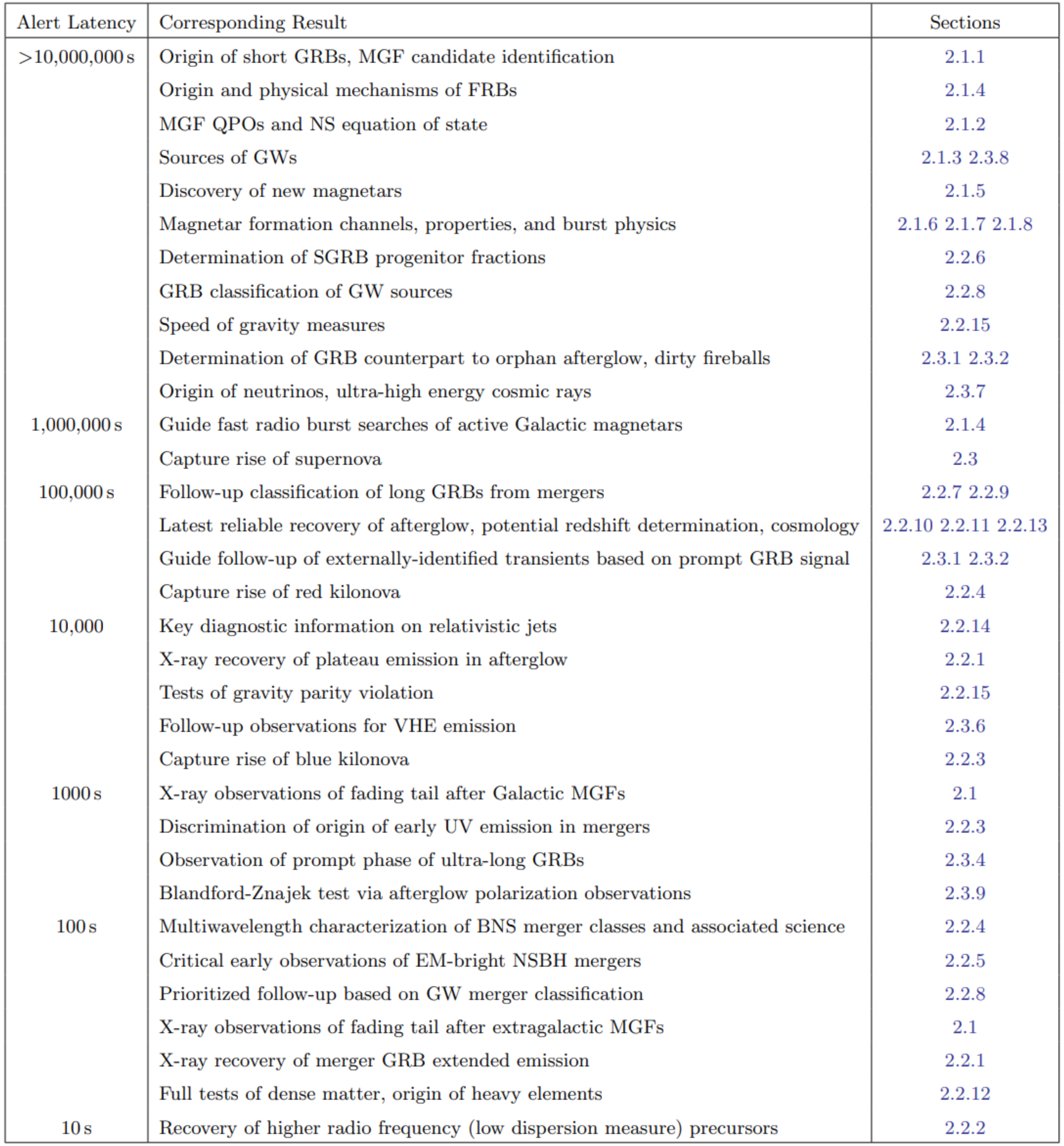
Key Science Questions

- What are the sources of gamma-ray bursts, fast radio bursts, gravitational waves, neutrinos, magnetars, relativistic supernovae, and exotic transients?
- What sub-classes exist within these sources, and what causes their differences?
- What produces a gamma-ray burst?
- What powers fast radio bursts?
- How were the heaviest elements produced?
- What governs the cosmological evolution of the universe? Is the universe flat? Is dark energy a cosmological constant?
- What processes underlie ultra-relativistic jets?
- What is the equation of state of dense matter?
- Is General Relativity the correct theory of gravity?
- What caused the matter excess over antimatter near the beginning of time?

Requirement Flowdown Examples (Chapter 3)



Localization Accuracy	Corresponding Result	Sections
4π sr	Detection of gamma-ray transients by all-sky monitors	
	Chance joint detection of transients with other wide-field monitors	
$\sim$1000 deg^2	Follow-up tiling of GRBs by the widest field UV and optical telescopes	3.1
	Robust association of GWs and GRBs	2.2
$\sim$100 deg^2	Identification of MGF candidates and potential host galaxy	5.3.7
	Follow-up tiling of GRBs by wide-field optical telescopes	2.2.3, 2.3.6
$\sim$30 deg^2	Follow-up tiling of GRBs by wide-field radio, VHE, and IR facilities	3.1
$\sim$10 deg^2	Associate nearby extragalactic MGFs to ideal host galaxies	2.1.1
	Robust association of GRBs to neutrinos	2.3.7
$\sim$1 deg^2	Associate SGR flares to specific magnetars	2.1.3
	Robust association of UVOIR identified transients to GRB	
$\sim$100 arcminute^2	Extragalactic MGF host galaxy association	2.1.1
$\sim$30 arcminute^2	Follow-up observations by the majority of telescopes	
$\sim$1 arcminute^2	Follow-up observations by effectively all telescopes	
$\sim$ 100 arcsecond^2	Follow-up identification of Galactic magnetars	2.1.5
$\sim$ 10 arcsecond^2	Robust associations of cosmological GRBs to host galaxy and measurement of offset	2.3.12



Alert Latency	Corresponding Result	Sections
>10,000,000 s	Origin of short GRBs, MGF candidate identification	2.1.1
	Origin and physical mechanisms of FRBs	2.1.4
	MGF QPOs and NS equation of state	2.1.2
	Sources of GWs	2.1.3 2.3.8
	Discovery of new magnetars	2.1.5
	Magnetar formation channels, properties, and burst physics	2.1.6 2.1.7 2.1.8
	Determination of SGRB progenitor fractions	2.2.6
	GRB classification of GW sources	2.2.8
	Speed of gravity measures	2.2.15
	Determination of GRB counterpart to orphan afterglow, dirty fireballs	2.3.1 2.3.2
	Origin of neutrinos, ultra-high energy cosmic rays	2.3.7
1,000,000 s	Guide fast radio burst searches of active Galactic magnetars	2.1.4
	Capture rise of supernova	2.3
100,000 s	Follow-up classification of long GRBs from mergers	2.2.7 2.2.9
	Latest reliable recovery of afterglow, potential redshift determination, cosmology	2.2.10 2.2.11 2.2.13
	Guide follow-up of externally-identified transients based on prompt GRB signal	2.3.1 2.3.2
	Capture rise of red kilonova	2.2.4
10,000	Key diagnostic information on relativistic jets	2.2.14
	X-ray recovery of plateau emission in afterglow	2.2.1
	Tests of gravity parity violation	2.2.15
	Follow-up observations for VHE emission	2.3.6
	Capture rise of blue kilonova	2.2.3
1000 s	X-ray observations of fading tail after Galactic MGFs	2.1
	Discrimination of origin of early UV emission in mergers	2.2.3
	Observation of prompt phase of ultra-long GRBs	2.3.4
	Blandford-Znajek test via afterglow polarization observations	2.3.9
100 s	Multiwavelength characterization of BNS merger classes and associated science	2.2.4
	Critical early observations of EM-bright NSBH mergers	2.2.5
	Prioritized follow-up based on GW merger classification	2.2.8
	X-ray observations of fading tail after extragalactic MGFs	2.1
	X-ray recovery of merger GRB extended emission	2.2.1
	Full tests of dense matter, origin of heavy elements	2.2.12
10 s	Recovery of higher radio frequency (low dispersion measure) precursors	2.2.2

Findings on Capability Requirements

- Precise localizations of gamma-ray transients – prompt gamma-ray bursts to $\sim$arcminute scale and final (prompt or otherwise) precision to at least $\sim$1 arcsecond
- Rapid alerts of triggers – ideally within 10 s of trigger time
- Total coverage of the transient sky – approaching instantaneous 4π sr with $\sim$week long (or greater) contiguous observing intervals
- Precise timing – absolute timing precision to $\sim$1 ms accuracy and relative timing precision to $\lesssim$100 μs
- Unbiased, complete, and sensitive observations of sources – kilosecond scale background stability, temporal coverage with no observing gaps, and fairly uniform sensitivity down to $\sim$1 photon s^{-1} cm^{-2}, though improved sensitivity would greatly enhance scientific return

Key Findings

- We find that the IPN has been, is, and will continue to be a workhorse for astrophysics. It will be critical to the NASA TDAMM program through the 2050s
- The IPN, with alterations, can meet nearly all requirements. The IPN cannot achieve the 10 s reporting latency and would likely struggle to achieve the ideal low energy threshold
- There are numerous operational and programmatic changes that would vastly enhance the scientific return from the full TDAMM community, for modest investment

Actionable Items for the IPN

- **The automatic collation of gamma-ray transient data and alert dissemination** – create a single alert access point for the broader TDAMM community to use
- **Signal-based gamma-ray transient catalogs** – create and maintain catalogs for the broader TDAMM community to use
- **A shared TDAMM database and archive** – house public and private data, create APIS for the broader TDAMM community to use; optimize real-time pipelines for active instrument teams
- **Development of multi-mission coherent analysis** – treat all gamma-ray burst monitors as a single effective telescope, recovering fainter transients or excluding prompt signatures to interesting limits
- **Preservation of historic data** – preserve datasets of old missions, e.g. Pioneer Venus Orbiter, and do so while knowledge exists in living memory
- **Additional improvements to the IPN** – detailed in the report

Actionable Items for NASA and Mission teams

1. **APD Enhancements of its own fleet**
   - Additional contacts for low Earth orbit gamma-ray burst monitors (Swift, COSI, etc)
   - Rideshare of StarBurst on the dedicated COSI, directly enhancing the science return from, and lifetime, of StarBurst
2. **APD enhancement to gamma-ray instruments on distant spacecraft of other divisions**
   - Planetary often launches gamma-ray spectrometers to study rocky objects; heliophysics often launches high energy monitors to study flares from the Sun
   - These missions often have inadequate clocks and infrequent contacts. The instruments often have limited temporal resolution and lack relevant responses. APD investment in additional contacts, on-board triggers, precision clocks, and calibration would have great scientific return.
   - The VERITAS Venus Probe will demonstrate an accurate clock, nominally 2028. The BPS Decadal push for inclusion of atomic optical clocks on distant spacecraft would (more than) meet the timing need
3. **A return to the intentional launch of distant, dedicated gamma-ray burst monitors**
   - Intentional design of IPN instruments for planetary / heliophysics would greatly increase the scientific return.
   - Allocating 2% of the mass of the Uranus Orbiter and Probe would allow the most prolific gamma-ray burst detector ever and sub-arcsecond annuli for decades. 2% includes substantial mass margin for structure and other additions (e.g. cabling)
   - Additional opportunities are available including Gateway, and perhaps more will be found following the Heliophysics Decadal

- **Greater support for the IPN, both across and within NASA science divisions**
  - **No funding mechanism exists within NASA to support the breadth and long-term planning necessary for the IPN to deliver the requested deliverables to the TDAMM community**
  - **The split in scientific divisions requires the IPN to rely on the goodwill of scientists in the planetary and heliophysics communities. Support from the individual scientists up to the HQ program office level and in reviews across divisions are necessary for the IPN to be a critical part of the NASA response to the Astro2020 Decadal recommended TDAMM Program**