Summary of the 2022 Annapolis NASA TDAMM Workshop

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On behalf of the SOC:

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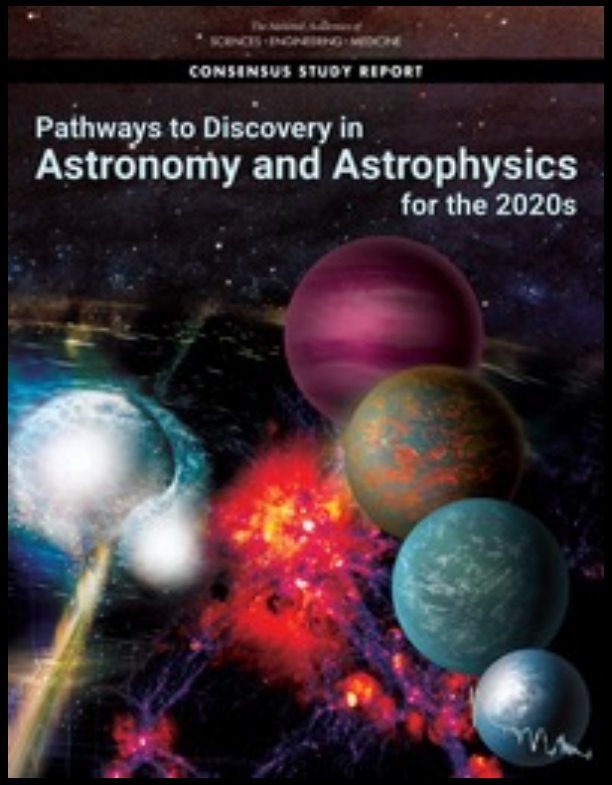
Mansi Kasliwal (Caltech)
Raf Margutti (Berkeley)
Brian Metzger (Columbia University)
Gijs Nelemans (Radboud University)
Samaya Nissanke (University of Amsterdam)
Andrew Romero-Wolf (NASA/JPL)
Rita Sambruna (NASA/Goddard)
Colleen Wilson-Hodge (NASA/Marshall)

The 2020 Decadal Report

The **New Messengers and New Physics** theme embodies the dual revolutions brought about by the marriage of observations of light with those from gravitational waves and elementary particles (multi-messenger astrophysics) along with the expansion of measurements of the sky over time (time-domain).



Recommendation:

NASA should establish a time-domain program to realize and sustain the necessary suite of space-based electromagnetic capabilities required to study transient and time-variable phenomena, and to follow-up multi-messenger events. This program should support the ***targeted development and launch*** *of competed Explorer-scale or somewhat larger missions and missions of opportunity.*

- As a first step in the response to the Decadal recommendation, NASA has organized, via the Physics of the Cosmos Program Office, a workshop to gather international community input on **TDAMM science priorities** to be addressed with future space missions.
- The workshop was held on August 22-24, 2022 in Annapolis, MD
- 350+ participants attended the hybrid presentations and discussions

Workshop Agenda – Day 1

Categories of Transients:
Jetted
Explosive
Merger-Driven
Non-Terminal

Legend:
SMBH
NS/BH
WD
Other

	Monday		
8:15 AM	Registration		
9:00 AM	Plenary Session Kickoff: Suvi Gezari Keynote Speaker Mark Clampin Program Scientist: Valerie Connaughton		
9:45 AM	Break		
	Jetted Transients-SMBH (blazars) Chairs: Gezari, Franckowiak Room B/C	Explosive Transients-WD (SNe Ia) Chairs: Cenko, Andrews Room A	Non-Terminal Transients-Other (supernova remnants, starburst galaxies, galaxy clusters) Chairs: Romero-Wolf, Burke-Spolaor Room F
10:00 AM	**Invited: Marcos Santander**	**Invited: Kate Maguire**	**Invited: Imre Bartos**
10:45 AM	**Contributed: Tiffany Lewis** ***Theoretical Modeling of TXS***	**Contributed: Benjamin Rose** ***A Forecast of Extragalactic Transient Light Curves for the Roman Time Domain Core Community Survey***	**Contributed: Henrike Fleischhack** ***PeVatrons – where are our Galaxy's most powerful accelerators hiding?***
11:00 AM	**Contributed: Haocheng Zhang** ***High-energy polarimetry as a probe for blazar hadronic signatures***	**Contributed: Abigail Polin** ***The Future of Type Ia SNe***	
	Explosive-Transients-NS/BH (core-collapse SNe) Chairs: Andrews, Franckowiak Room B/C	Non-Terminal Sources-WD (CVs, WD binaries) Chairs: Nelemans, Breivik Room A	Jetted Transients-Other (engine-powered SNe) Chairs: Margutti, Metzger Room F
1:30 PM	**Invited: Charlie Kilpatrick**	**Invited: Simone Scaringi**	**Invited: Anna Ho**
2:15 PM	**Contributed: Ori Fox** **Supernovae Interacting With Their Circumstellar Environments**	**Contributed: Kevin Burdge** **The future of "multi-messenger" time domain astronomy: Ultracomapct Galactic binaries**	**Contributed: Bei Zhou** **Choked-Jet Supernovae as Hidden Astrophysical Neutrino Sources**
2:30 PM	**Contributed: Chris Fryer** **Multi-Messenger/Multi-Phenomena Diagnostics of Core-Collapse**	**Contributed: RafaelMartínez-Galarza** **Towards the Seamless Discovery of High Energy Transients: New Data Representations**	
2:45 PM	**Contributed: Avishay Gal-Yam** **Early UV emission from exploding massive stars**		Merger-Driven Transients-Other II (classical and symbiotic novae) Room F Invited: Elias Aydi
3:30 PM		Break	
	Non-Terminal Sources-SMBH (SMBH binaries, AGN) Chairs:Burke-Spolaor, Gezari Room B/C	Jetted Transients-NS/BH (micro quasars, gamma-ray bursts) Chairs: Wilson-Hodge, Cenko Room A	Merger-Driven Transients-Other II (stellar mergers, common envelope systems) Chairs: Kasliwal, Metzger Room F
3:45 PM	**Invited: Tingting Liu**	**Invited: Amy Lien**	**Contributed: Navin Sridhar** **Applications of hyper-accreting X-ray sources to fast radio bursts and stellar merger transient events**
4:30 PM	**Contributed: Caitlin Witt Multi-Messenger Coordination on the Supermassive Scale**	**Contributed: Eric Burns** **How to Make Speed-of-Light Jets**	Merger-Driven Transients-WD (WD-WD, WD-NS, WD-BH) Chairs: Gijs Nelemans, Breivik
4:45 PM	**Contributed: Scott Noble Time and Wavelength Domain Predictions for Accreting Binary Black Holes**	**Contributed: Taya Govreen-Segal** **Prospects for Resolving the Hubble Tension with a Small Number of Binary Neutron Star Mergers with**	**Invited: Kyle Kremer**
5:00 PM	**Contributed: Daniel Stern Extreme Quasar Variability**	**Contributed: James Rhoads** **Looking for orphans (and their cousins) in wide fields.**	**Contributed: Yossef Zenati Transients from ONe white dwarf - neutron star/black hole mergers**

Workshop Agenda – Day 2

Categories of Transients:
Jetted
Explosive
Merger-Driven
Non-Terminal

Legend:
SMBH
NS/BH
WD
Other

	Tuesday		
	Small group meetings, self organized		
9:45 AM	Break		
	Jetted Transients-SMBH II (Tidal Disruption Events) Chairs: Gezari, Franckowiak Room A	Merger-Driven Transients-NS/BH (NS-NS, NS-BH, BH-BH) Chairs: Kasliwal, Nissanke Room B/C	Explosive Transients- Other (FRBs, FXTs) Chairs: Burke-Spolaor, Margutti Room F
10:45 AM	**Invited: Sjoert van Velzen**	**Invited: Alessandra Corsi**	**Invited: Shami Chatterjee**
11:00 AM	**Contributed: Yvette Cendes New Discoveries in Late-Time Emission from Tidal Disruption Events**	**Contributed: Samuele Ronchini Perspectives for multi-messenger astronomy with the next generation of gravitational-wave detectors and high-energy satellites**	**Contributed: W. Niel BrandtFuture Investigations of the New Extragalactic Population of Faint, Fast X-ray Transients**
11:15 AM	**Contributed: Robert Stein Identifying Transient Neutrino Sources with the Zwicky Transient Facility**	**Contributed: Eran Ofek Gravitational Waves in the UV**	**Contributed: Walid Majid Multi-wavelength characterization of FRBs**
12:00 PM	Discussion	Discussion	Discussion
12:00 PM	Lunch (On your own)		
	Merger-Driven Transients- SMBH (SMBH binaries, EMRIs) Chairs: Burke-Spolaor, Slutsky Room A	Merger-Driven Transients-Other I (common envelope systems) Chairs: Kasliwal, Metzger Room B/C	Non-Terminal Sources-NS/BH (XRBs, magnetars, pulars) Ramirez-Ruiz, Wilson-Hodge Room F
1:30 PM	**Invited: Elena Rossi**	**Invited: Kishalay De**	**Invited: Erin Kara**
2:15 PM	**Contributed: Jeremy Schnittman Supermassive Black Hole Mergers**	**Contributed: Yadira Gaibor Constraining occurrence rates of short-period post-common envelope binaries**	**Contributed: Maria Drout Stripped Star plus Compact Object Binaries: Identifying the Progenitors of Neutron Star Mergers**
2:30 PM	**Contributed: Krista Lynne Smith The Physics of Accretion Disks and Binary AGN with Very High-Cadence Band-filtered Optical/UV**	Discussion	**Contributed: Thomas Maccarone X-ray Binaries as Time Domain Sources**
3:45 PM	**End of Daily Sessions**		
4:30 PM		Editing of System Reports by Session Chairs	
	Wednesday		
9:00 AM	Infrastructure Panel		
	Short individual introductions GCN - Judy Racusin HEASARC - Alan Smale NOIRLab - Tom Matheson DSN - Joe Lazio Near Space Network (NSN) - Chris Roberts IPAC - George Helou		
	Discussion		
11:00 AM	Break		
11:15 AM	**Non-Terminal Sources Reports** **WD: Nelemans** **SMBH: Burke-Spolaor** **NSBH: Ramirez-Ruiz** **Other: Romero-Wolf**		
12:00 PM	Lunch		

Workshop Agenda – Summary Discussions

1:30 PM	**Merger-Driven Transients Reports** **SMBH: Slutsky** **NSBH: Kasliwal** **Other: Kasliwal** **WD: Breivik** **Jetted Transients Reports** **Other: Metzger** **SMBH: Franckowiak** **NSBH: Wilson-Hodge** **Explosive Transients Reports** **WD: Cenko** **NSBH: Andrews** **Other: Margutti**
3:30 PM	Next steps, report outline, writing assignments.
4:00 PM	Close Out

Each session had a scribe to take notes. The SOC presented summary reports for each source category:

Non-terminal sources (WD, NS/BH, SMBH, Other)

Merger-driven transients (WD, NS/BH, SMBH, Other)

Jetted-transients (NS/BH, SMBH, Other)

Explosive transients (WD, NS/BH, Other)

The SOC drafted the science findings in the TDAMM report based on the workshop **presentations**, scribe **notes**, and workshop summary **reports**.

Workshop Deliverable

The final deliverable is a written report available at:

https://pcos.gsfc.nasa.gov/TDAMM/docs/TDAMM_Report.pdf

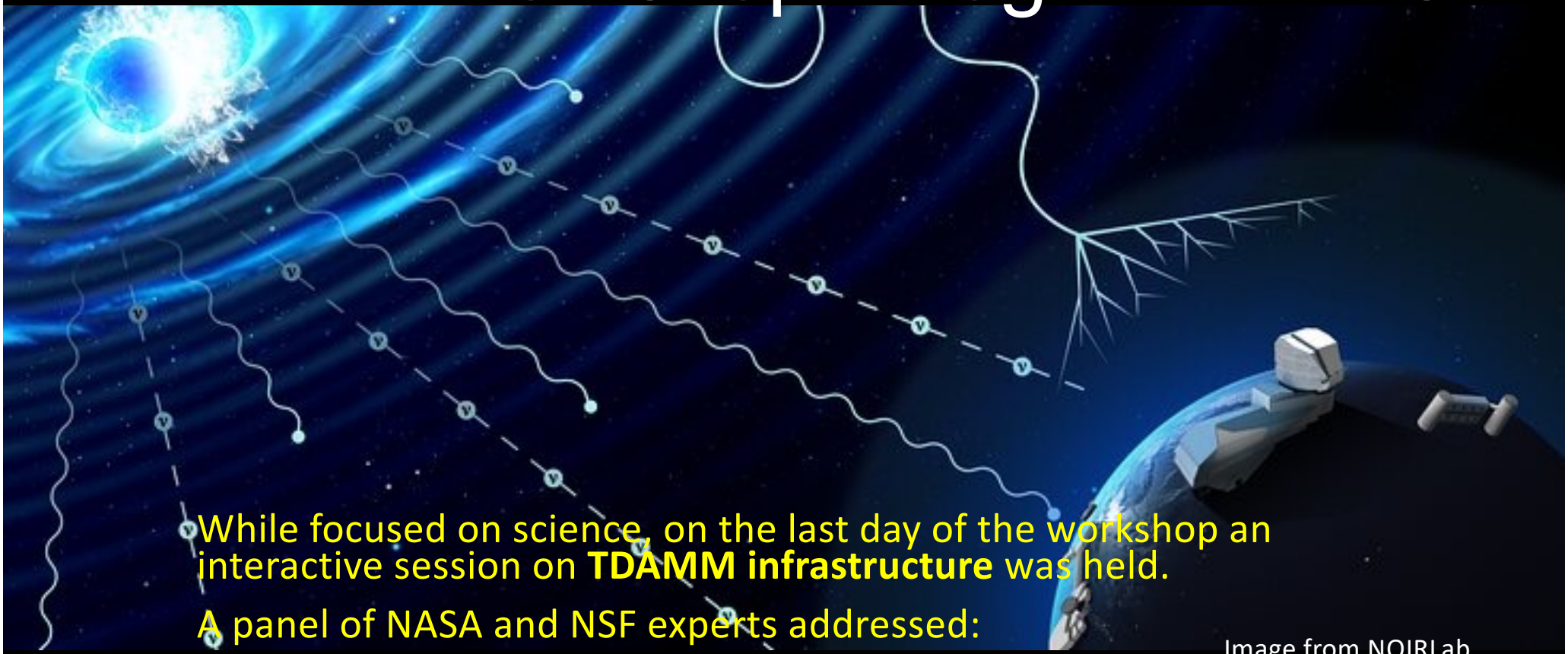
The Annapolis Workshop report has been revised and has been submitted as a review article in a special issue of Frontiers of Astronomy and Space Sciences:

"The Dynamic Universe: Realizing the Potential of Time Domain and Multimessenger Astrophysics"

TDAMM Workshop: Science

Source Class	EM	ν	Lo-f GW	Hi-f GW	CR	Phenomena
White Dwarfs	★		★			*Type Ia SNe, WD+WD mergers, detached WD binaries, novae, accreting WD LISA sources, accretion induced collapse, WD+NS/BH binaries*
NS / BH	★	★		★		*X-ray binaries, NS+NS mergers, NS+BH mergers, gamma-ray bursts, core-collapse SNe, common envelope events, stellar mergers, fast and blue optical transients*
SMBH	★	★	★		★	*blazars, tidal disruption events, extreme-mass ratio inspirals, binaries, coalescences, and recoiling systems, compact-object mergers in AGN disks*
Unknowns	★				★	*fast radio bursts, fast X-ray transients, pevatrons, "unknown unknowns"*
Interdisc.	★	★	★	★		*fundamental physics, cosmology, dense matter*

TDAMM Workshop: Programmatics



While focused on science, on the last day of the workshop an interactive session on **TDAMM infrastructure** was held.

A panel of NASA and NSF experts addressed:

* *GCN alerts*
* *Space Communications (DSN, NSN)*
* *Ground infrastructure (NOIRLab)*
* *Archives (HEASARC, IPAC)*

A vigorous discussion community ensued, identifying key issues.

Image from NOIRLab

Key Findings

Real-Time Cyberinfrastructure

- Real-time transient detections
- Software to do joint data analysis
- Archive coordination

Theory Funding

- Specific urgent topics
- Interdisciplinary aspects w/ physics, lab Astro, cosmology
- Precursor/preparatory science
- High Computing simulations

TDAMM General Observer Facility

- To streamline transient follow-up with NASA facilities
- Reduce coordination burden from observers
- Provide scheduling options
- Assist with proposals preparation and submission
- Manage funding

Key Findings

NASA-NSF-International Coordination

- Optimize observing schedules
- Archives and alerts standardization
- Joint proposals opportunities

Continuity of Capabilities Across EM Spectrum

- Wide-field, high-cadence imaging capabilities, especially in the **UV**, **X-rays** and **gamma-rays**
- Rapid follow-up wide-field imaging and spectroscopic capabilities
- In particular, wide-field, fast response and arcmin-scale localization X-ray and gamma-ray monitors are needed to replace the aging *Swift* and *Fermi* telescopes

Training a diverse workforce

- Capitalize on TDAMM science to inspire STEM
- Build on core value of Inclusion from the start
- Ensure diversity of PIs

Crediting hidden figures

- Data scientists, software/hardware developers, managers
- Ensure appropriate rewards and recognition

TDAMM Investments are Urgent

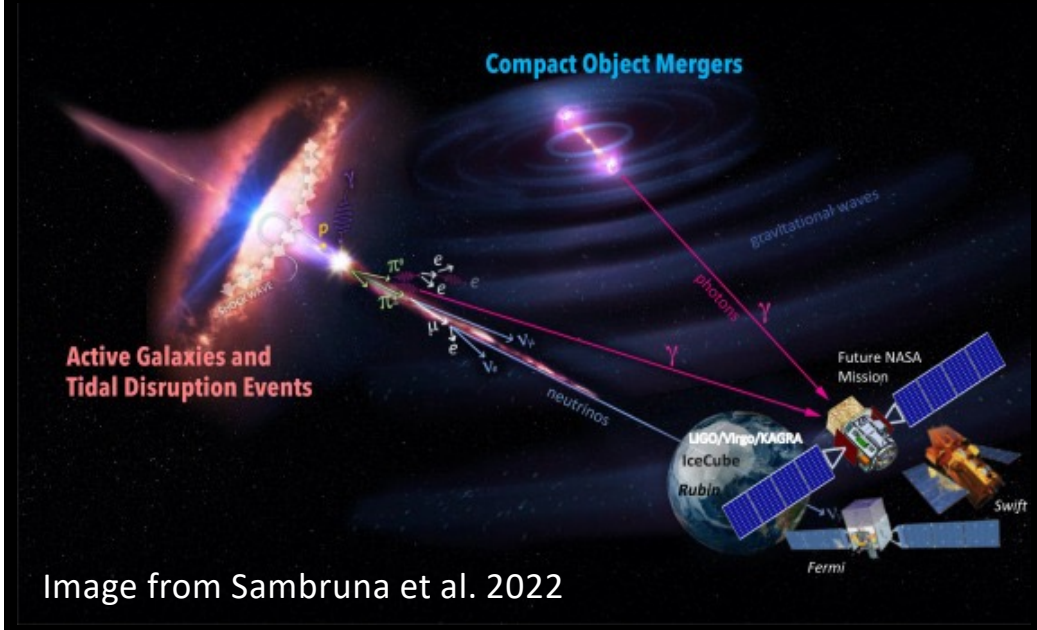


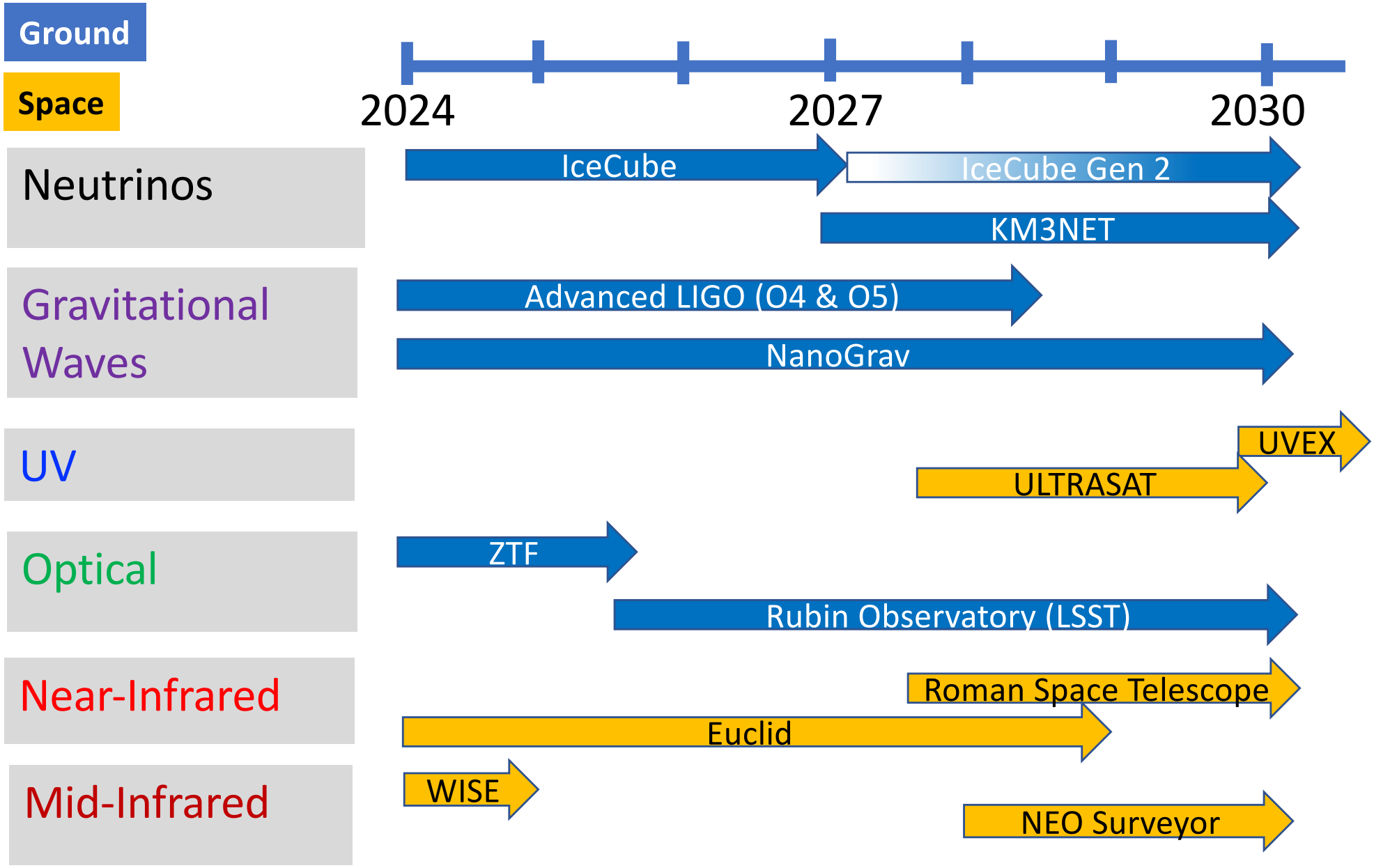
Image from Sambruna et al. 2022

The Decadal recommended TDAMM as the top priority of the Sustaining Program, with an investment of $800M over the decade, including an augmentation to the Explorers' line.

Starting investments in the next generation of wide-field, rapid response X-ray and gamma-ray missions with arcmin scale position is imperative if we want to meet the challenges of this rapidly expanding field and of the Decadal's objectives.

This effort should **start now**, *in order to launch these missions by the 2030s and overlap with the many observatories, in space and on the ground, becoming available then.*

Wide-Field Survey Facilities



Special *Frontiers* Research Issue

- Special Research issue in the peer reviewed Journal *Frontiers in Astronomy and Space Sciences*.
- Contributions drawn from the 1st TDAMM Workshop
- Topic editors: R. Sambruna (NASA GSFC), F. Civano (NASA GSFC)
- 13 papers accepted and published; 1 paper still under review
- 73 authors, 1500 downloads, 10k views of the papers in <1year

Time Domain and Multi-Messenger Astrophysics

Link to the journal:

Special *Frontiers* Research Issue

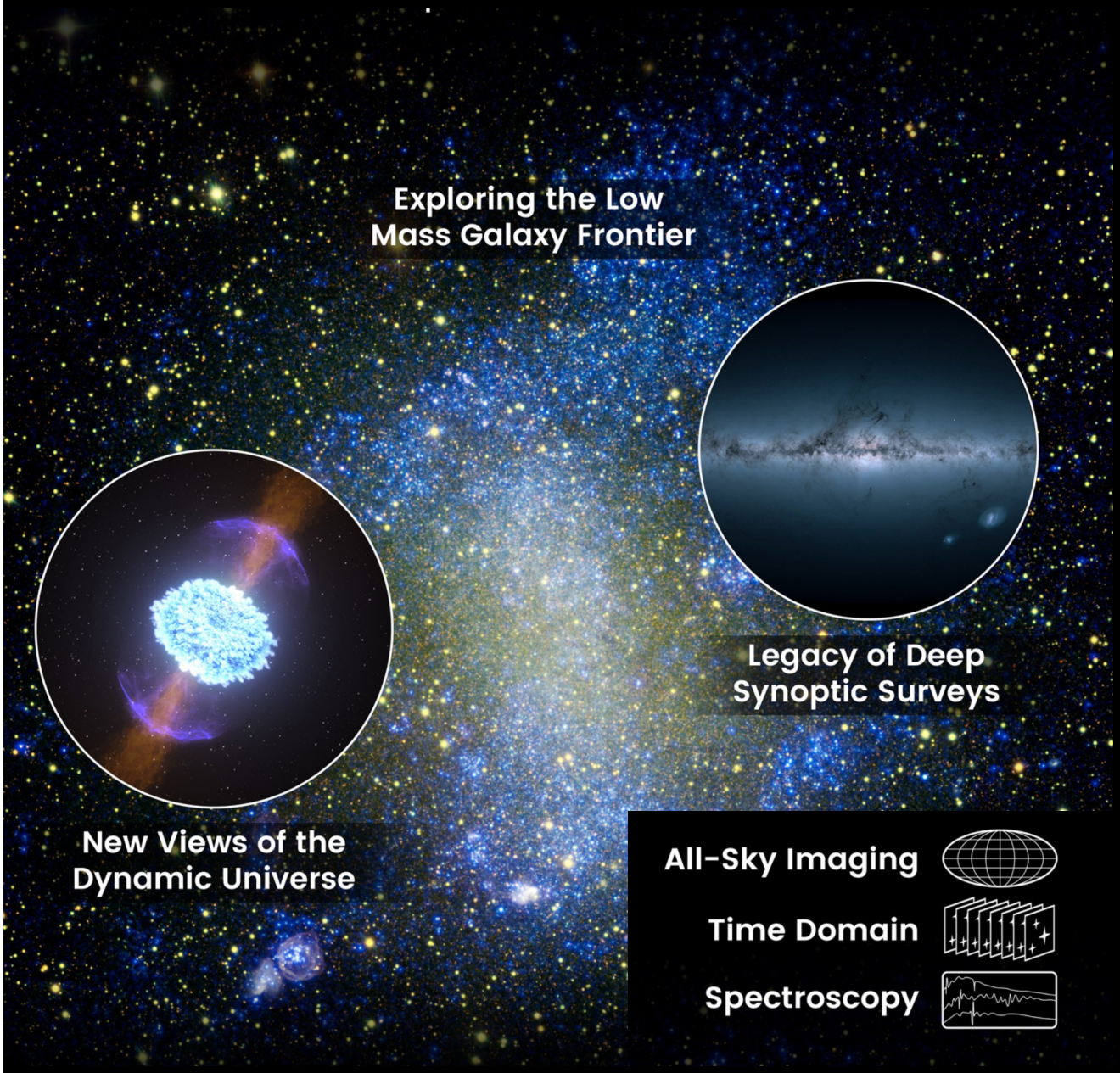
- **The Dynamic Universe: realizing the science potential of Time Domain and Multi-Messenger Astrophysics (TDAMM)**
- The dynamic universe: realizing the potential of classical time domain and multimessenger astrophysics
- Light travel time effects in blazar flares
- How do nuclear isomers influence the gamma-ray bursts in binary neutron star mergers?
- Fundamental physics studies in time domain and multi-messenger astronomy
- Frontiers in Astronomy Cosmic ray contributions from rapidly rotating stellar mass black holes: Cosmic Ray GeV to EeV proton and anti-proton sources
- Multi-messenger astrophysics of black holes and neutron stars as probed by ground-based gravitational wave detectors: from present to future
- The role of magnetar transient activity in time-domain and multimessenger astronomy
- A two-step strategy to identify episodic sources of gravitational waves and high-energy neutrinos in starburst galaxies
- NASA's Astrophysics Cross-Observatory Science Support (ACROSS) Initiative: Enabling Time-Domain and Multimessenger Astrophysics
- Rapid multi-band space-based optical timing: revolutionizing accretion physics
- Radio transients from compact objects across the mass spectrum in the era of multi-messenger astronomy
- Active galactic nuclei: global perspective and time-domain implications
- Multi-messenger emission characteristics of blazars

Progress Since Annapolis Workshop

Since the 2022 Annapolis TDAMM Workshop there have been several positive developments:

- *NASA Selection of UVEX as the MIDEX mission for launch in 2030*
- *NSF Call for Multi-messenger Coordination for Windows on the Universe in 2024*
- *NASA PhysCos TDAMM Initiative*
- *NASA Astrophysics Cross-Observatory Science Support (ACROSS) pilot project*
- *GCN Upgrades*
- *NOIRLab TDAMM Workshop on "Windows on the Universe: Infrastructure for a Collaborative Multi-Messenger Ecosystem", Tucson, AZ, October 16-18, 2023*
- *NASA TDAMM Workshop on "Multidisciplinary Science in the Multimessenger Era", Baton Rouge, LA, Sep 23-26, 2024*

UVEX : *The Ultraviolet Explorer*

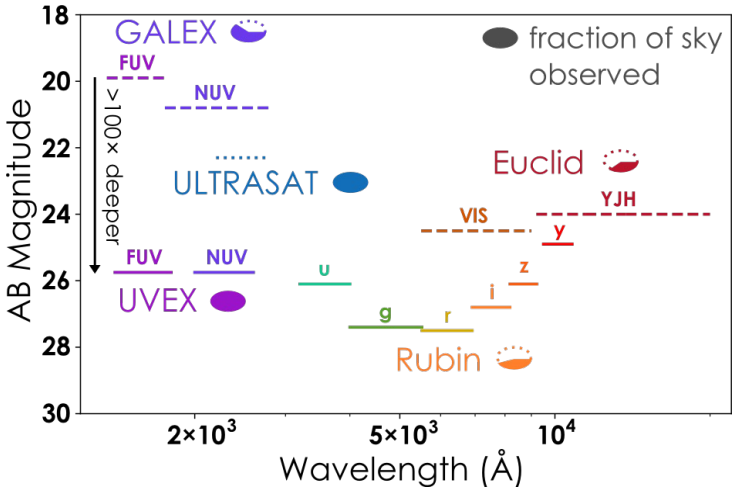


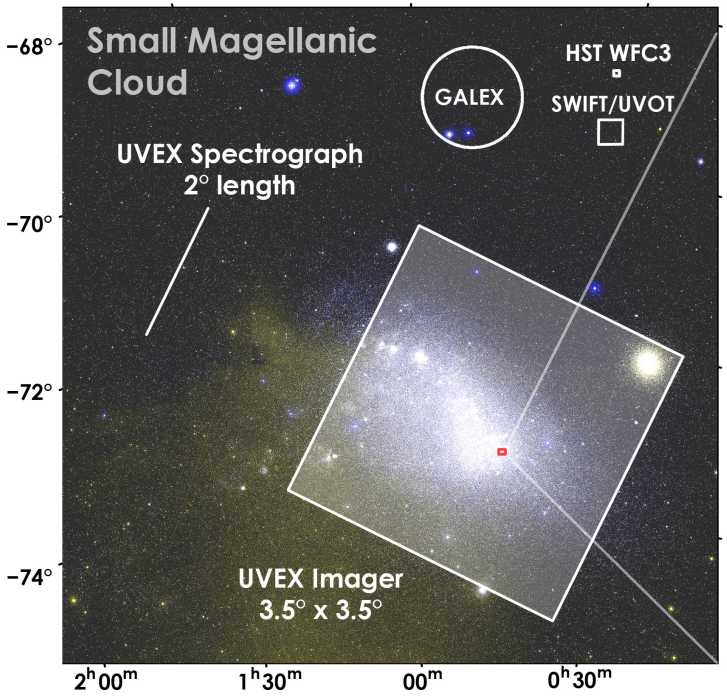
Selected by NASA as next MIDEX Mission for launch in 2030!

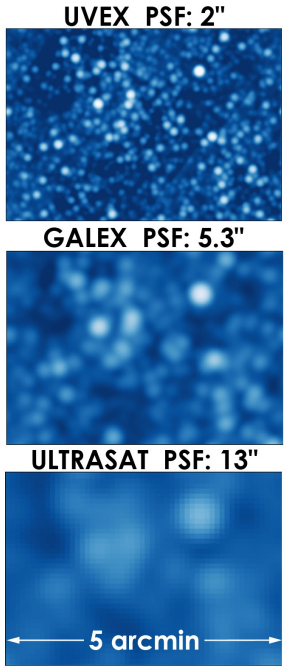
UVEX Capabilities

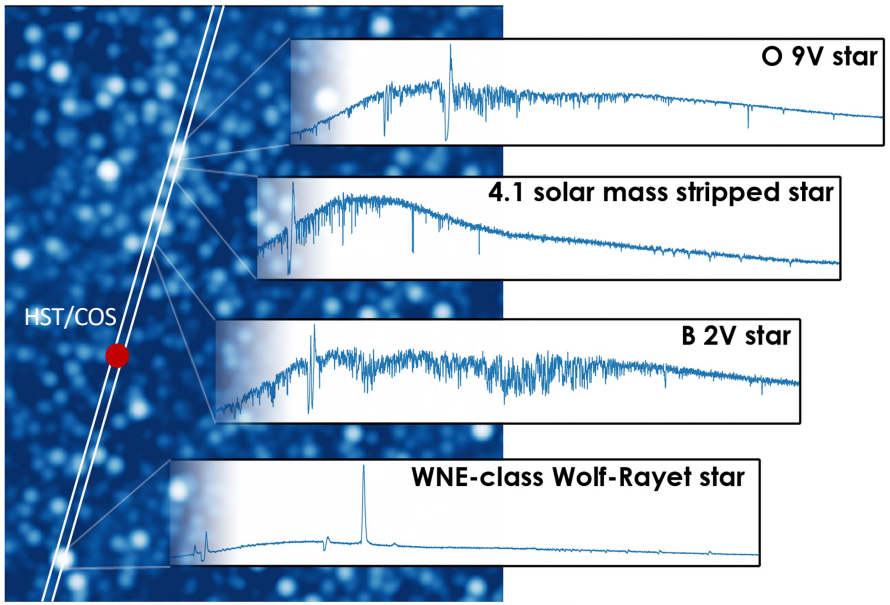
UVEX provides three crucial capabilities

- *Sensitive wide-field imaging in two ultraviolet bands (NUV & FUV)*
- *High angular resolution across large field of view (2.25 ''/10 deg^2)*
- *Broadband ultraviolet spectroscopy (1150 – 2650 Å)*



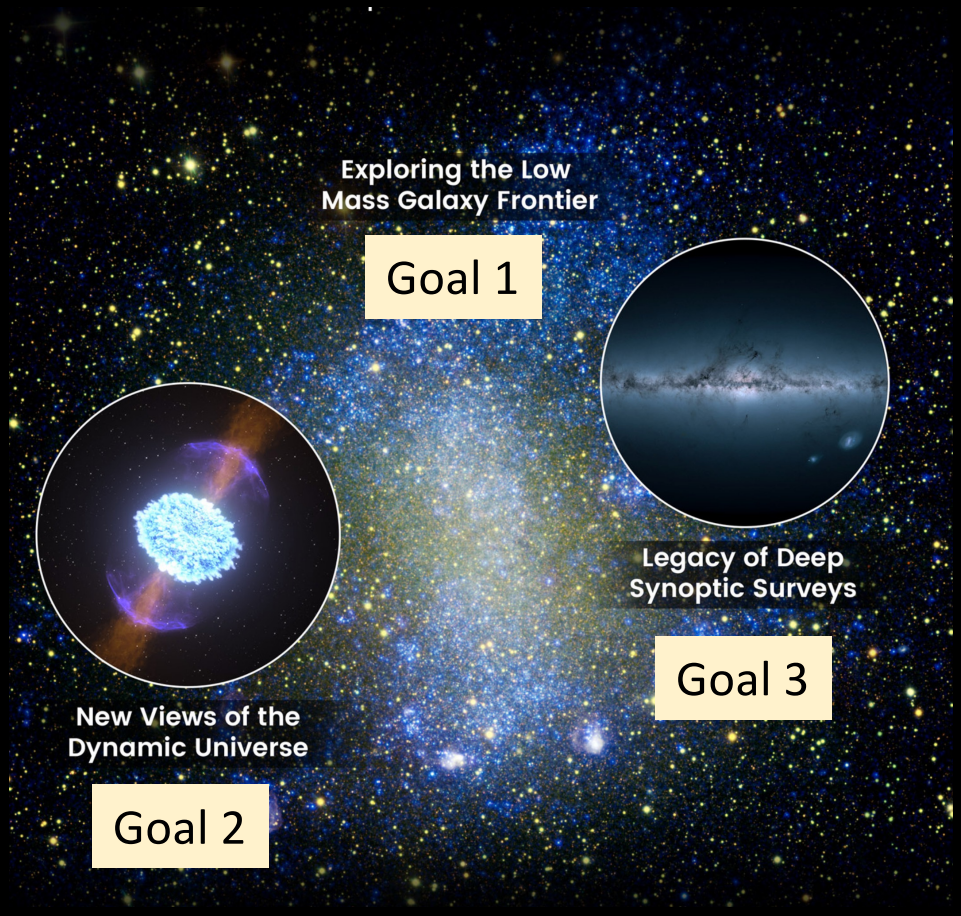






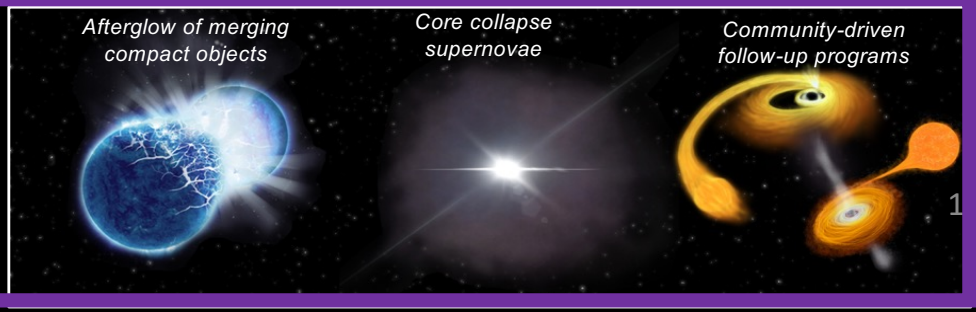
UV Spectroscopy from 1150 to 2650 Å

UVEX Goals



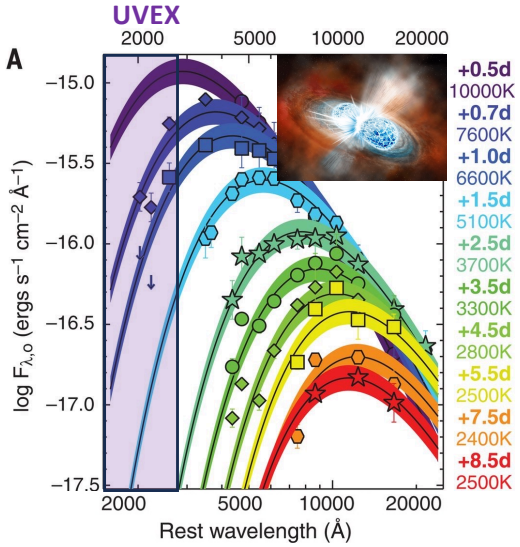
New Views of the Dynamic Universe

UVEX will follow-up multi-messenger and community triggers to probe the early UV emission of transients 2020 Decadal priority area: New Windows on the Dynamic Universe

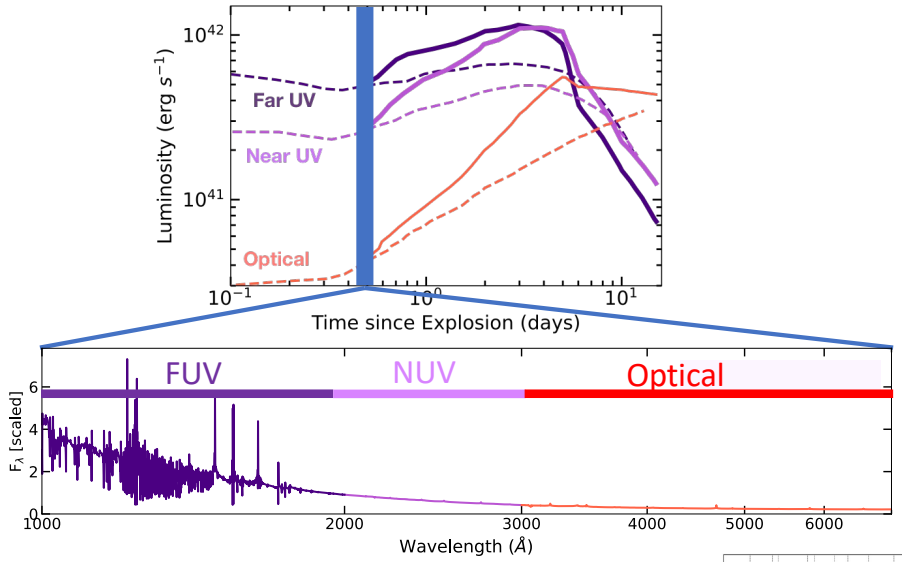


Why is UVEX is a powerful telescope for the Dynamic Universe?

GW-discovered neutron star mergers emit first in UV light.

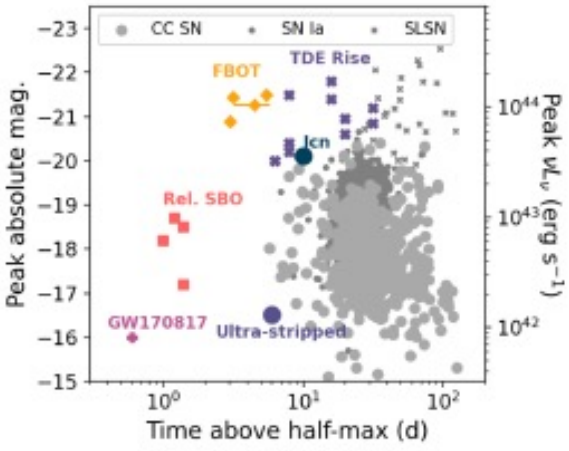


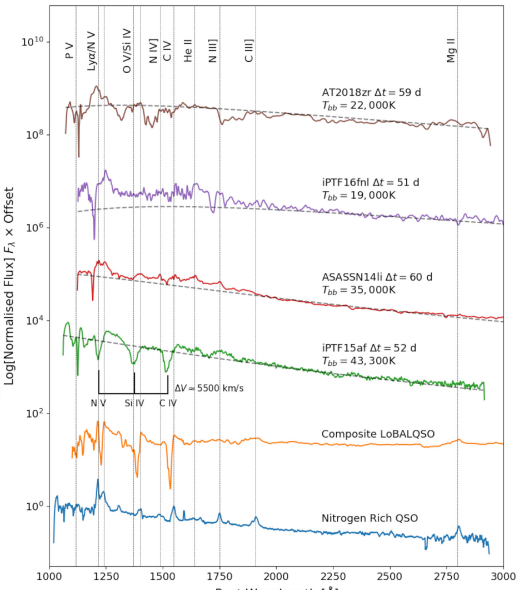
Key diagnostic lines lie in UV for understanding the progenitor stars of SNe and their mass-loss history.



New capability for the TDAMM community for rapid TOO UV spectroscopy of transient and variable objects.

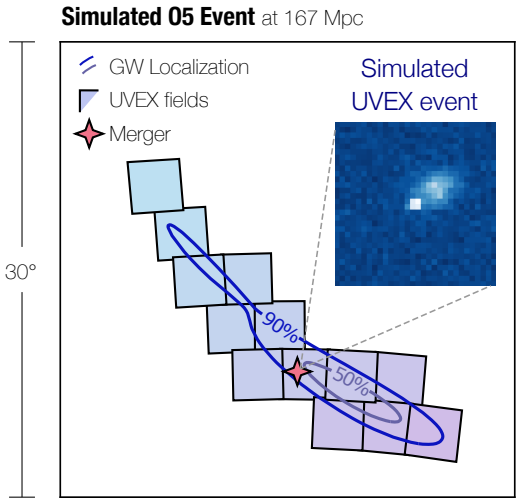
- 8% of time planned for community TOOs with a response time of < 6 hours.
- As a comparison, HST allocated approximately 2% of time (50 orbits) for TOO UV spectroscopy in Cycle 31, s and less than 1% of time (14 orbits) for disruptive TOOs (< 13 days turnaround time).
- In the era of Rubin, ULTRASAT, the demand for TOO UV spectroscopy from the community will only increase.





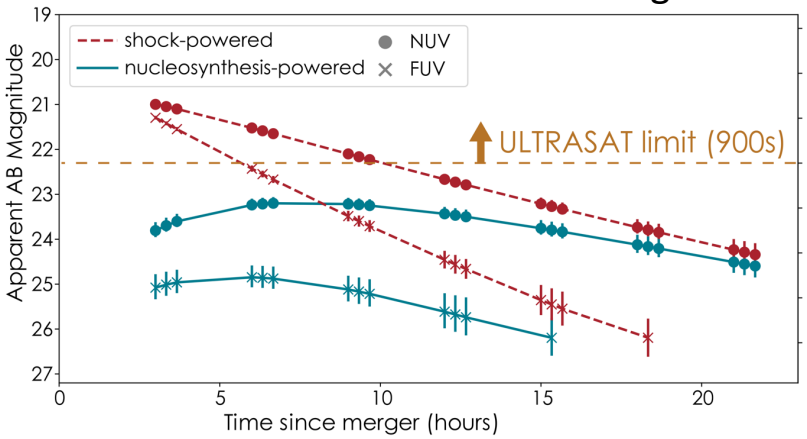
Gravitational Wave Counterparts

Perform rapid follow-up of gravitational wave events discovered by the LIGO/Virgo gravitational wave observatories from hours to days post-merger



The large UVEX FoV enables rapid searches for UV counterparts

Simulated UVEX neutron star merger

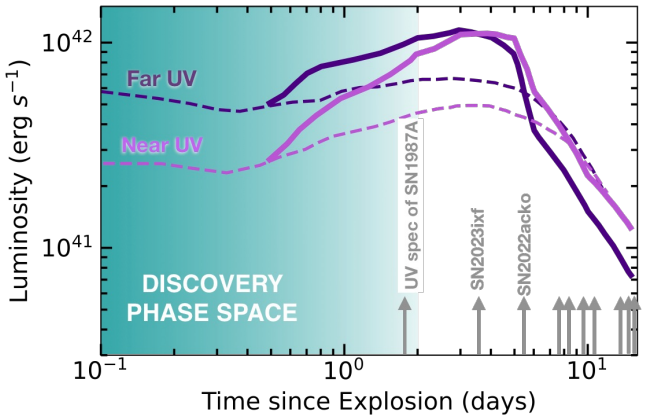


Sensitive UVEX imaging will probe the crucial times from hours to a day. Two UV bands distinguish among physical models

With a large field of view and two imaging bands UVEX is ideally suited for identifying counterparts to gravitational wave events and probing their fundamental physics

Spectroscopy of Young Core Collapse Supernovae

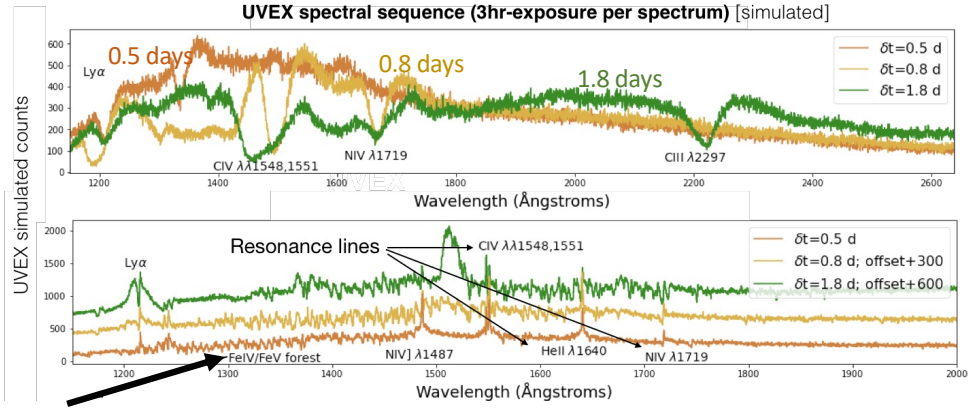
Measure pre-explosion mass loss and supernova properties through rapid spectroscopic observations of supernovae to understand their role in galactic enrichment



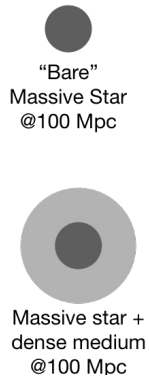
Emission from massive star explosions peaks in UV within days

Massive star mass loss and subsequent explosive demise are drivers of galactic chemical enrichment

Early UV spectra of supernovae are rich with information on mass-loss history, its chemical enrichment, and explosion properties



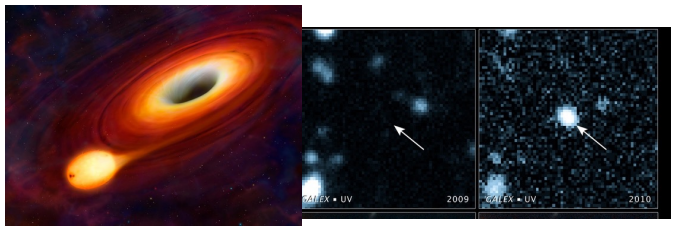
Constrains progenitor metallicity



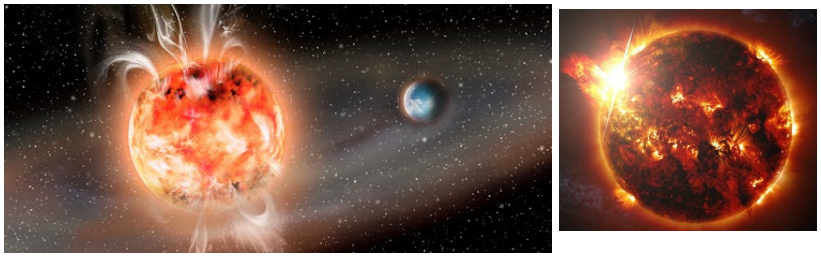
With unprecedented early UV spectroscopy UVEX provides a new window on supernova-driven galactic chemical enrichment

UVEX Community TOOs

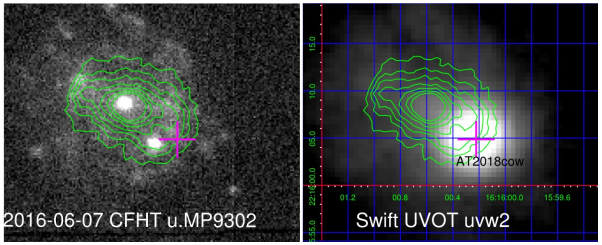
Provide a resource for the community to explore the dynamic sky through rapid UV spectroscopic follow-up



Broad absorption lines in stars being eaten by supermassive black holes



Energetic flares on active stars



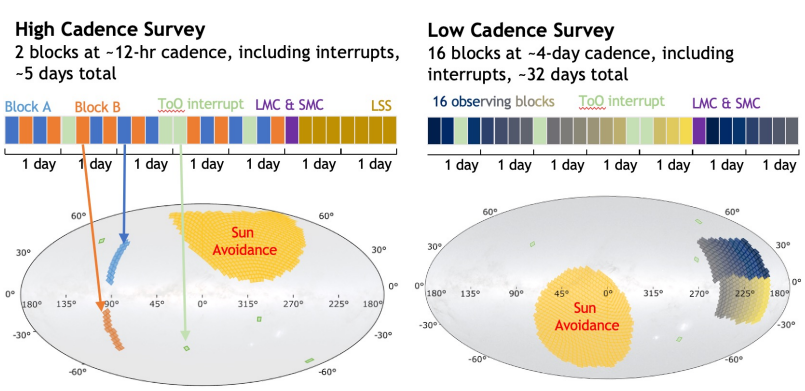
Relativistic supernovae - UV-bright fast blue optical transients

Accretion physics at the end of the stellar lifecycle – novae, low-mass X-ray binaries

By providing the first rapid spectroscopic UV follow-up capability UVEX enables a broad range of time-domain science and opens tremendous discovery space

Deep Synoptic Surveys

Explore the UV time domain sky by performing imaging surveys of the sky in two UV bands with cadences spanning hours to months



UVEX will discover variable and transient UV phenomena and alert the community for follow-up

A variety of cadences will probe fast transients, tidal disruption events and monitor variability

UVEX provides a modern UV time-domain survey

UV Time Domain Ecosystem in 2030

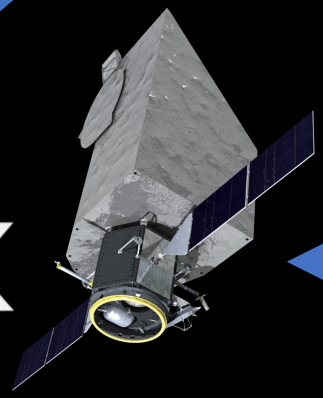
UVEX

UV Time Domain Ecosystem in 2030

All-sky NUV cadenced (4 days) imaging, and high cadence (5 min) imaging over 200 deg^2

Launch in 2030

UVEX



All-sky FUV & NUV cadenced (hours to months) imaging, and TOO UV spectroscopy

Southern sky optical cadenced (days) imaging, and deep static imaging

TDAMM Workshop: Science

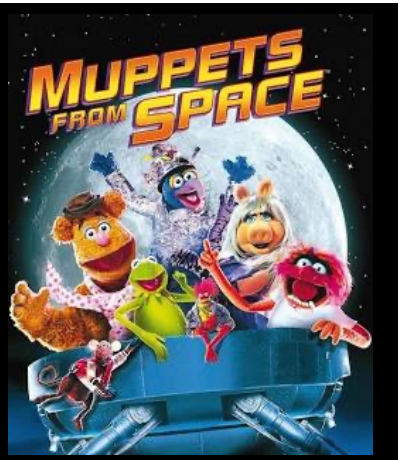
Source Class	EM	ν	Lo-f GW	Hi-f GW	CR	Phenomena
White Dwarfs	★		★			***Type Ia SNe, WD+WD mergers, detached WD binaries, novae, accreting WD LISA sources, accretion induced collapse, WD+NS/BH binaries***
NS / BH	★	★		★		*X-ray binaries,* ***NS+NS mergers, NS+BH mergers,*** *gamma-ray bursts,* ***core-collapse SNe,*** *common envelope events, stellar mergers,* ***fast and blue optical transients***
SMBH	★	★	★		★	***blazars, tidal disruption events****, extreme-mass ratio inspirals,* ***binaries****, coalescences, and* ***recoiling systems, compact-object mergers in AGN disks***
Unknowns	★				★	*fast radio bursts, fast X-ray transients, pevatrons,* ***"unknown unknowns"***
Interdisc.	★	★	★	★		***fundamental physics, cosmology, dense matter***

UVEX+ULTRASAT+Rubin address many of the priority science questions (**shown in bold**) highlighted in the Annapolis workshop.

TRANSIENTS FROM SPACE

Space Telescope Science Institute, Baltimore, MD – March 11 – 13 , 2025

Inspired by:



Rationale

Transient science is entering an exciting new era of discovery. The 2020 Decadal Survey named Time Domain Astronomy (TDA) as a top priority, Physics of the Cosmos (PhysCOS) Program is undertaking important steps in NASA's implementation of Astro 2020's recommendations in the area of Time Domain And Multi-Messenger (TDAMM) astrophysicsand. New discoveries will be greatly impacted by space-based telescopes, including, but not limited to, HST, JWST, Swift, Chandra, NICER, NuSTAR, Fermi, XMM, TESS, Euclid, UVEX, ULTRASAT, LISA, and Roman. These telescopes probe new phase space in time, wavelength, and redshift, thereby opening up new sub-fields. This STScI workshop will explore novel research made possible by these telescopes and discuss how the community can optimize scientific output in the future.

SOC

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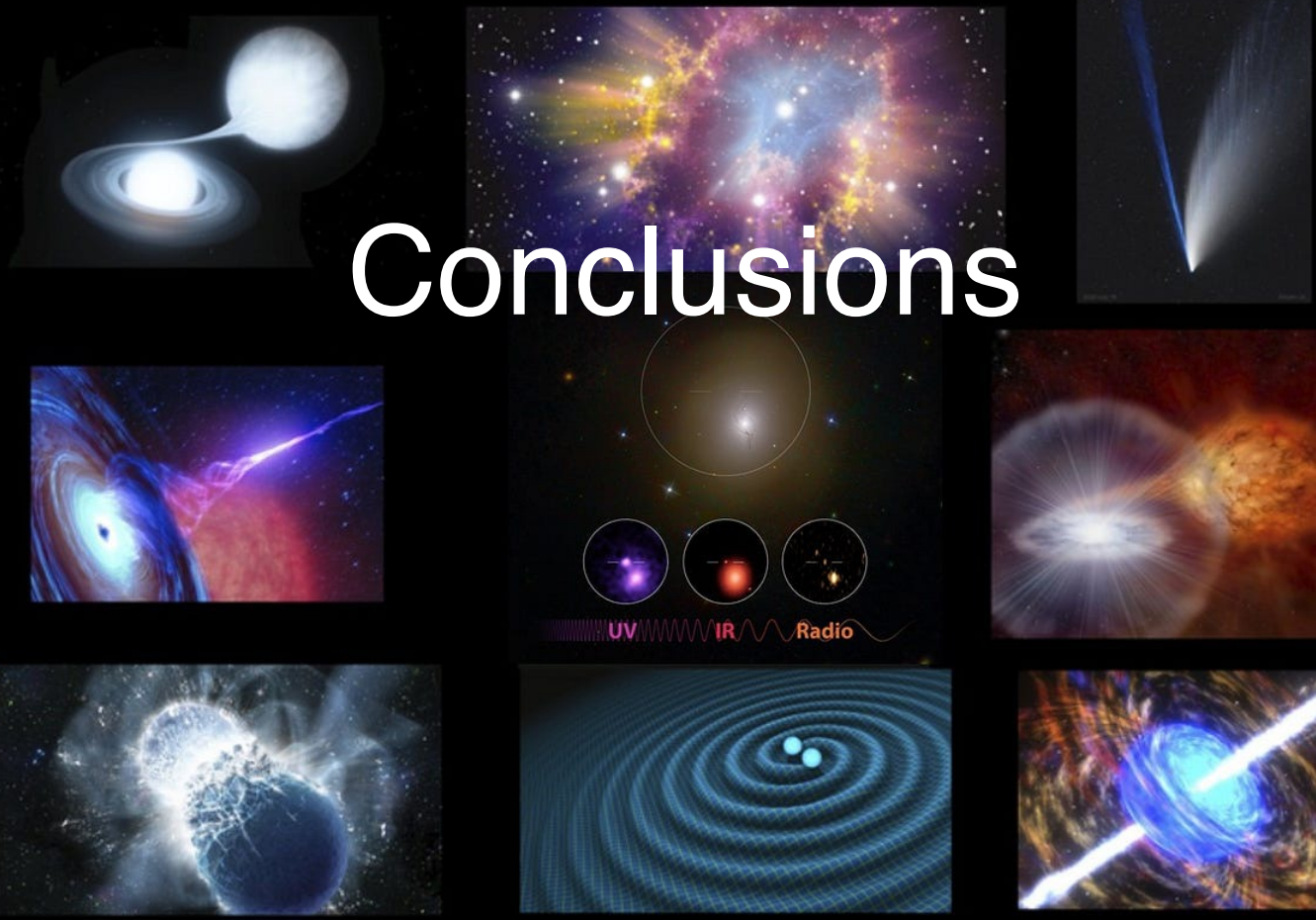

Conclusions

Realizing the promise of the “dual revolution” in multi-messenger astrophysics and time-domain astronomy requires significant and sustained investment in science, facilities, and infrastructure by NASA and the funding Agencies.

This investment must start NOW to leverage existing and planned capabilities of the 2030s both in space and on the ground.

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