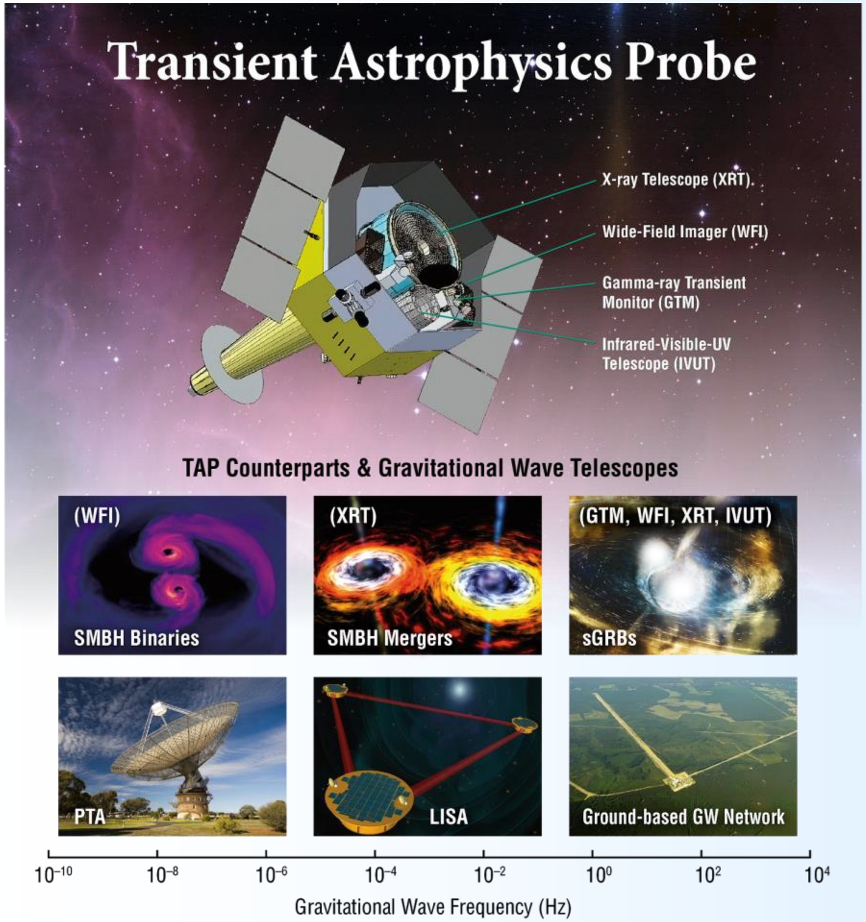
Transient Astrophysics Probe (TAP)



Brad Cenko: Mission Overview And Ground-Based GW Science

Jeremy Schnittman: LISA and Pulsar Timing Array Science

Scott Barthelmy: Instrument Overview, Risks, Schedule, and Cost

On behalf of Jordan Camp (TAP PI) and the TAP team

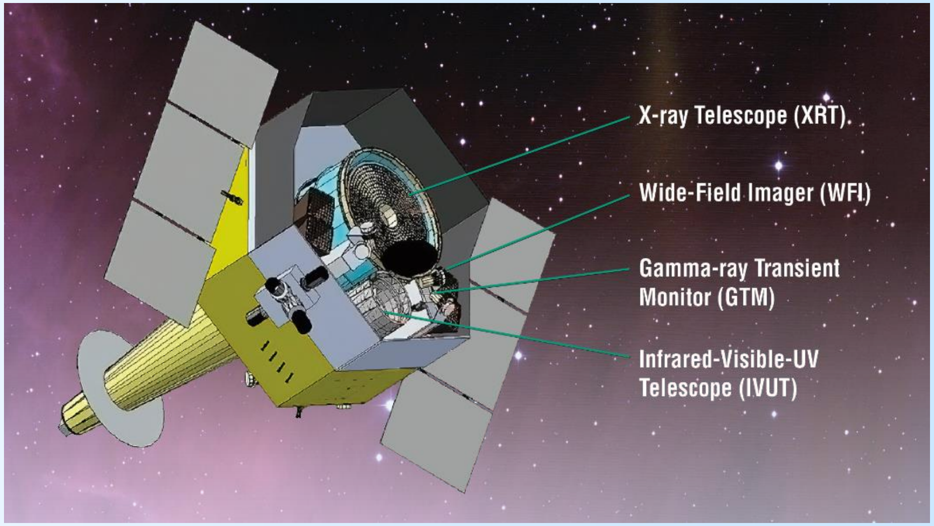
Mission Overview and Ground-Based Gravitational-Wave Science

Brad Cenko
NASA Goddard Space Flight Center

TAP in a Nutshell

Science Goals:
1) To fully realize the transformative scientific potential of the upcoming generation of gravitational-wave detectors

2) To understand the explosive and energetic universe via high-energy transient discovery and rapid-response, panchromatic follow-up.



A next-generation *Swift* for the multi-messenger and time-domain eras:

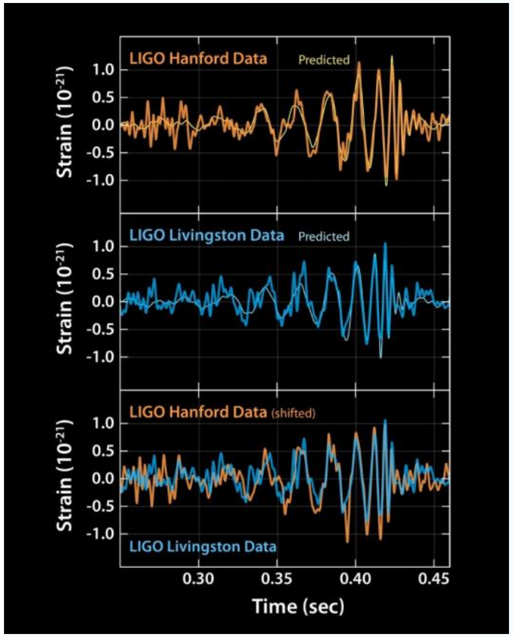
Like *Swift:*
- High-energy transient discovery
- Panchromatic, rapid response follow-up

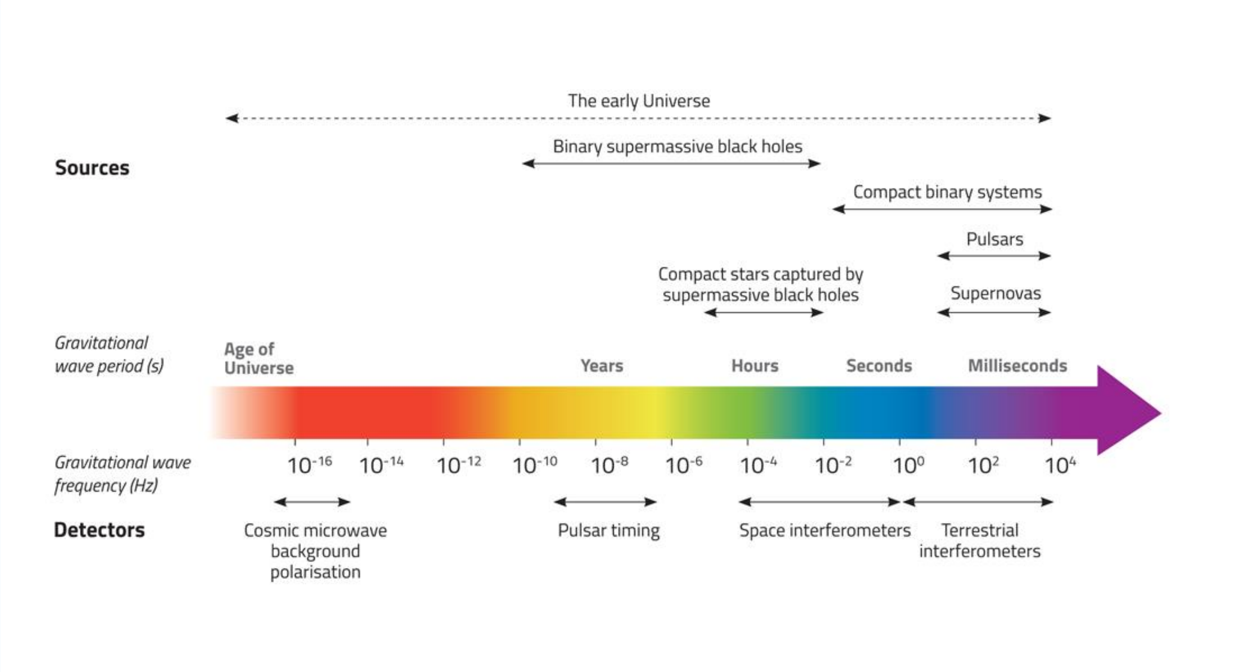
New Capabilities:
- IR imaging and spectroscopy
- Wide-field soft X-ray imaging
- 10x more sensitive X-ray telescope with 5x field-of-view

- Gamma-ray Transient Monitor (GTM): 4π sky coverage over 10-1000 keV
- Wide-Field Imager (WFI): 0.4 sr field-of-view over 0.3-5 keV
- X-ray Telescope (XRT): 0.8 deg^2 field-of-view with *Chandra*-like sensitivity and uniform (5″) PSF
- **Infrared-Visible-UV Telescope (IVUT): 70 cm telescope with 1 deg^2 field-of-view, 0.2-2.5 um bandpass, sensitivity to 23 mag (AB)**

NASA MIT TECHNION HARVARD WV MONTANA STATE UNIVERSITY Los Alamos NATIONAL LABORATORY UNIVERSITY OF MARYLAND CLEMSON UNIVERSITY NORTHWESTERN UNIVERSITY Ball UNIVERSITY OF LEICESTER U.S. NAVAL RESEARCH LABORATORY

Gravitational-wave Astronomy





GW150914: First direct detection of GWs from merging "stellar-mass" black holes (Abbott et al. 2016)

LIGO discoveries only the tip of the iceberg. Increased sensitivity from ground-based interferometers, plus new source classes from LISA and pulsar timing arrays.

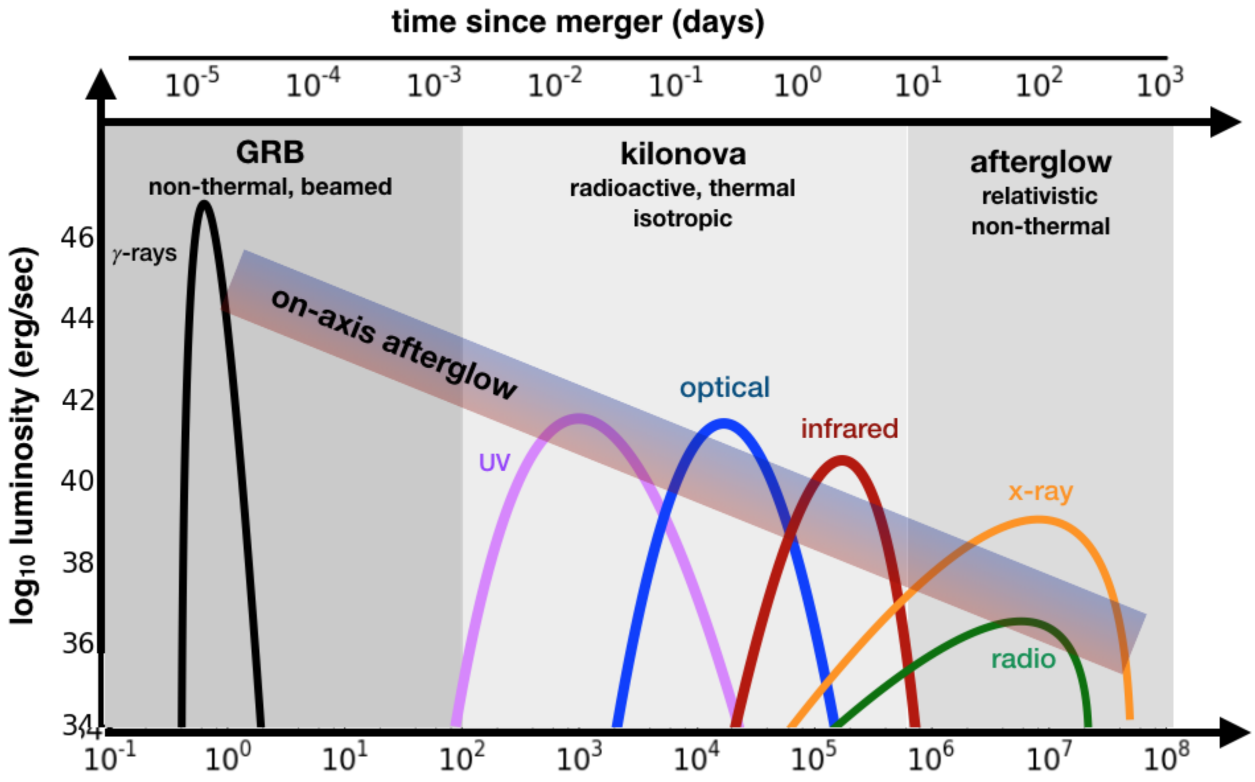
Ground-Based GW Detectors

- Increases in ground-based GW sensitivity will dramatically increases NS-NS detection rates
- Full harnessing of GW detections **requires** electromagnetic (EM) counterpart (e.g., GW150914 v. GW170817)
    - GW provides masses, spins, luminosity distance
    - EM provides astrophysical context (host galaxy, environment), ejecta mass, redshift, …
- **TAP was designed to detect and characterize GW counterparts in this era**

Observing Run	Timescale	NS-NS Rate (yr^{-1})	NS-NS Range (Mpc)
O1: LIGO	2015-2016	0.05-1.0	80
O2: LIGO/Virgo	2017-2018	0.2-4.5	100/30
O3: LIGO/Virgo	2019-2020	0.3-13	120/50
O4: LIGO/Virgo/ KAGRA	2021-2023	0.6-62	175/105/70
O5: LIGO/Virgo/ KAGRA	**2025+**	**10-200**	**330/200/130**
Voyager	~2030?	Daily	1,000
Cosmic Explorer	2035-2040	Hourly	>10,000

Not currently funded

NS-NS Counterpart Signatures



Kasen, NASA GW-EM Task Force

Short GRB ⇢ GTM

On-axis afterglow ⇢ WFI

Kilonova ⇢ IVUT

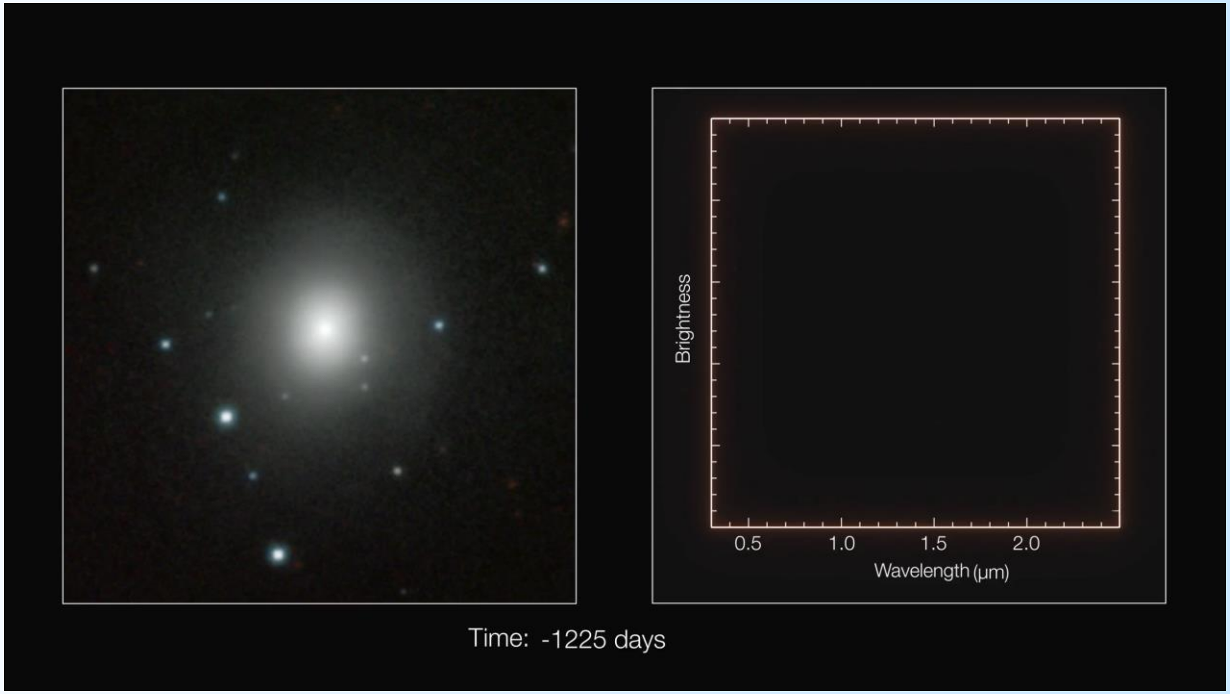
Off-axis afterglow ⇢ XRT

NS-NS counterparts are *panchromatic* and require a range of capabilities

Kilonova Counterpart

- Kilonova: transient powered by r-process nucleosynthesis in n-rich ejecta
- UV emission peaks on timescale of hours, NIR on timescale of days
- Fundamental physics
    - Ejecta mass -> NS equation of state
- Heavy element production
    - Total mass and abundance ratios

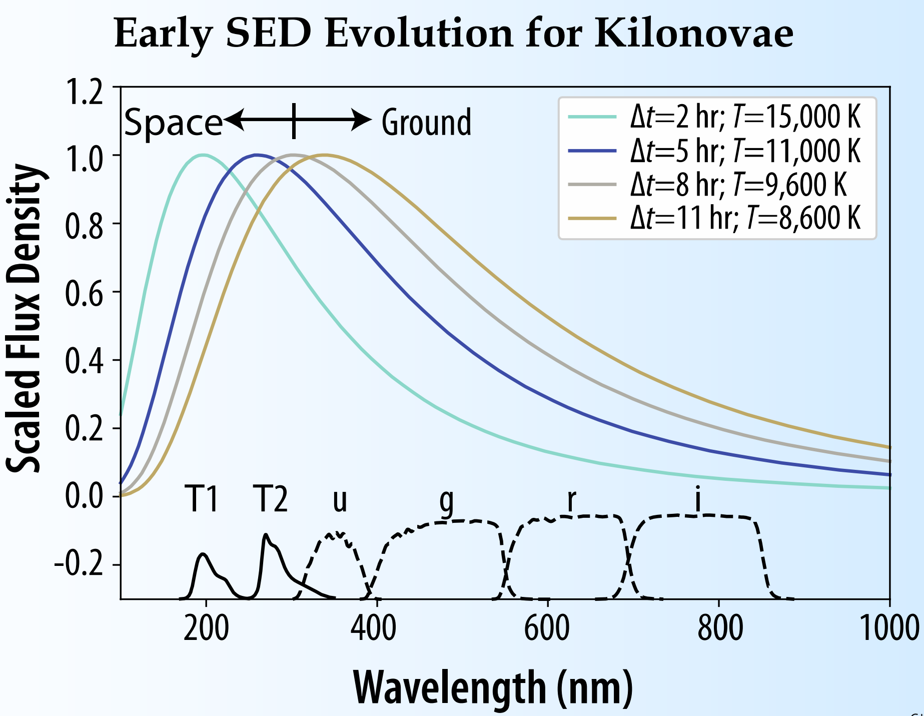
GW170817 in NGC4993



ESO

Kilonovae drive IVUT design: Response time and field-of-view, bandpass, sensitivity

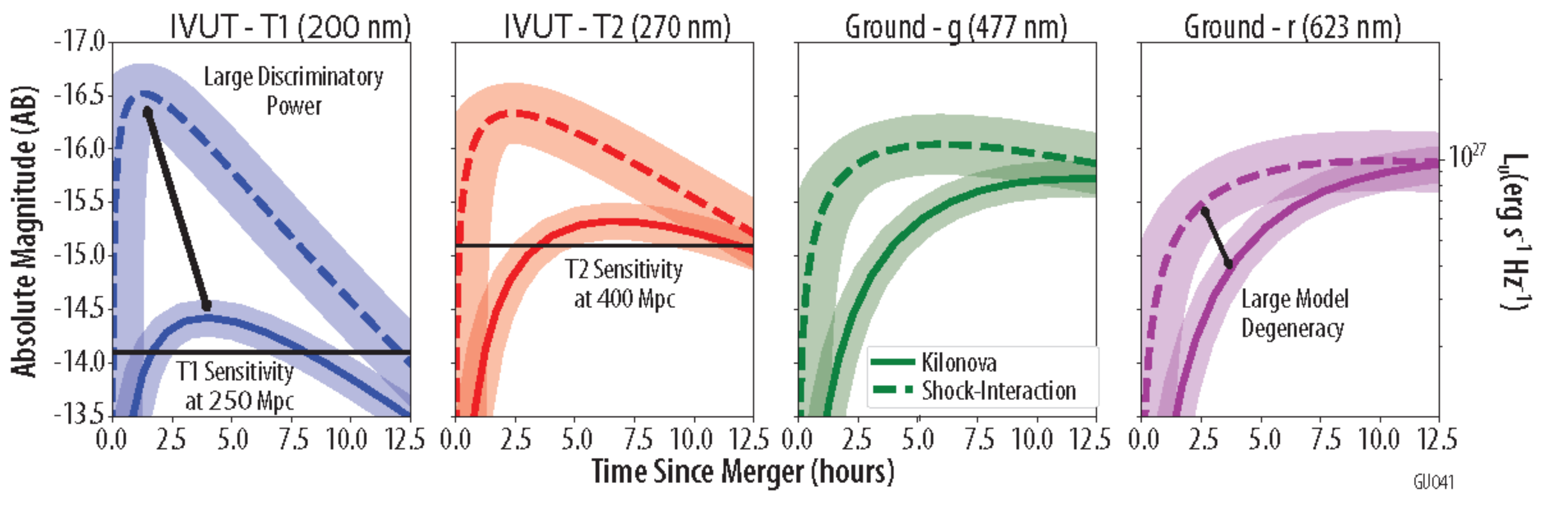
Kilonova – Why UV?



Peak of early emission expected to be at UV wavelengths (not observed for 170817!). TAP bandpass extends down to 0.2 um to uniquely capture this component.

Kilonova – Why UV?

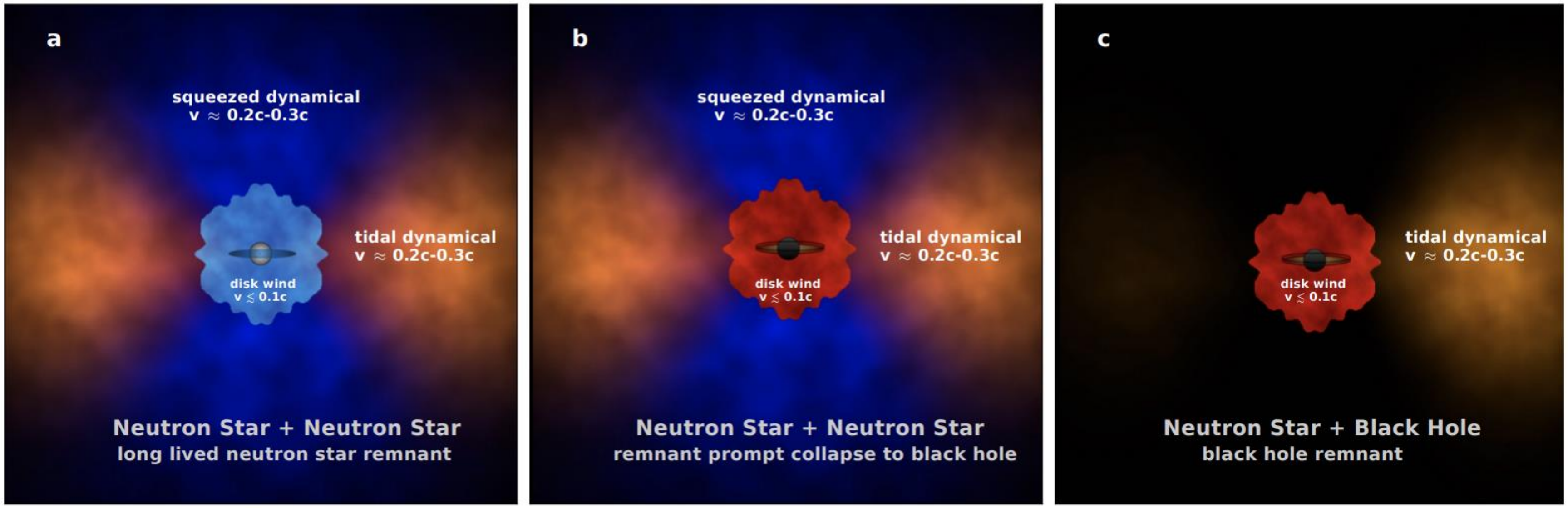
Shock Cooling vs. Radioactivity for Early UV/Optical Emission



Most powerful model discrimination at UV wavelengths (and *early* times).
IVUT can detect this emission *beyond* A+ NS-NS horizon distance.

Kilonova – Why IR?

Two Component (Red+Blue) Kilonova Models



Kasen+ 2017

Relative fraction of red vs. blue emission constrains remnant, and *IR component may be only kilonova emission from BH-NS mergers.* TAP provides *unique* wide-field NIR imaging for red counterparts missed by, e.g., LSST.

NS-NS Counterpart Yields

Joint GW+TAP Counterpart Discoveries

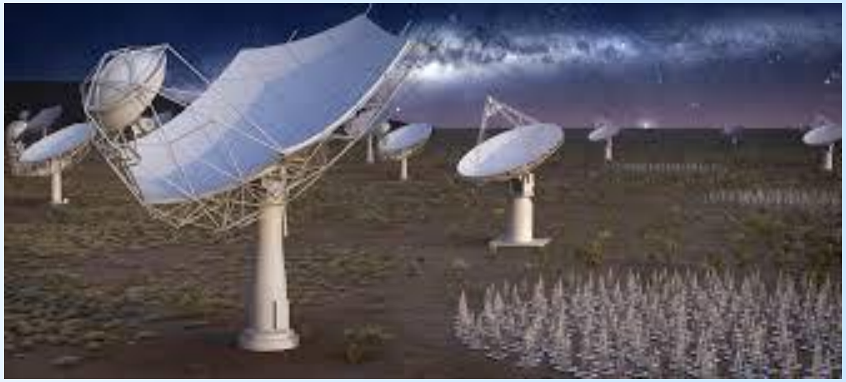
Counterpart Type	Instrument	Detections in 5 year mission
Short GRB	GTM	100
On-axis afterglow	WFI	100
Kilonova (UV)	IVUT	350
Kilonova (IR)	IVUT	280
Off-axis afterglow	XRT	35

Unlike current generation facilities, TAP is designed to construct *samples* of NS-NS counterparts

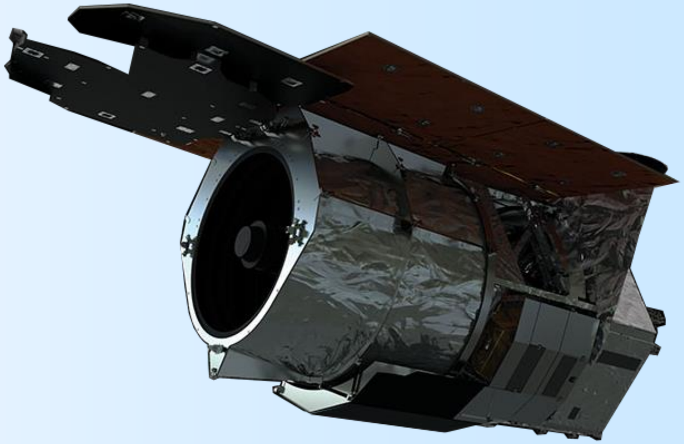
The New Time-Domain Era

VRO/LSST (Optical)

SKA (Radio)

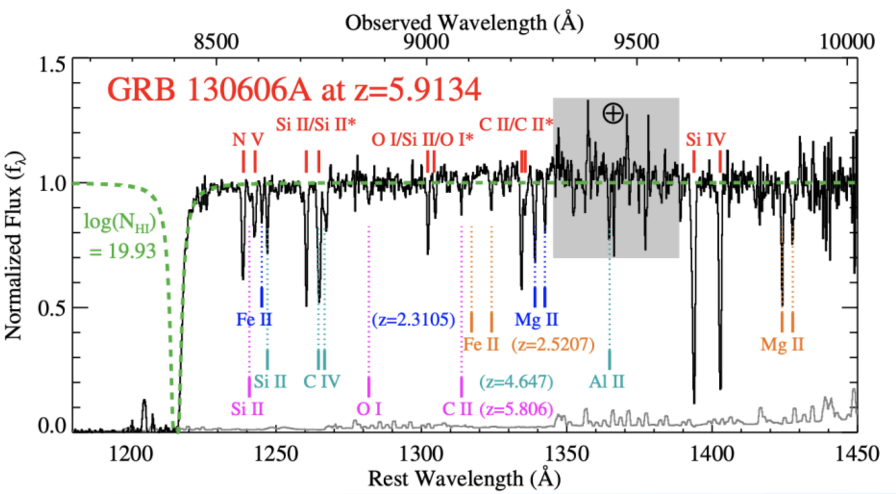


WFIRST (NIR)



In a period defined by powerful wide-field time-domain surveys, TAP will provide complementary high-energy surveys *and* rapid-response follow-up

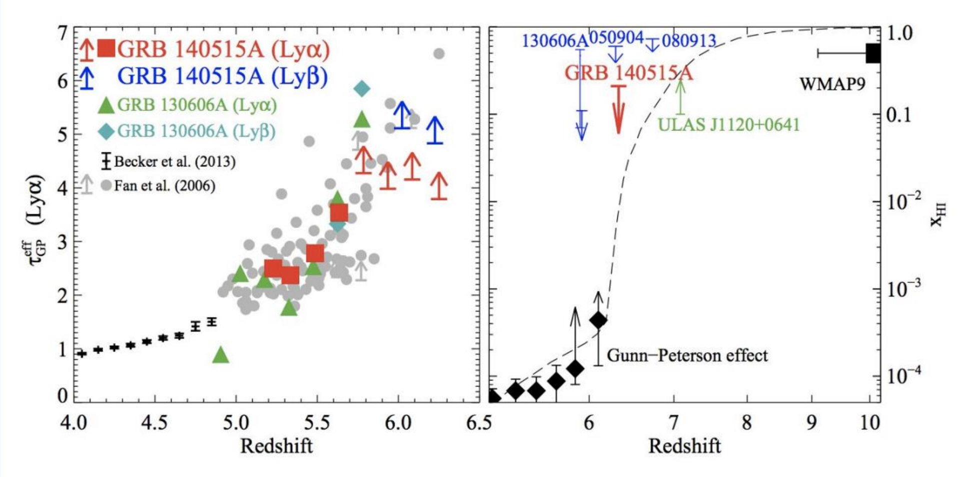
GRBs from the Epoch of Reionization



Chornock et al. 2014

Because of extreme luminosity and simple power-law spectra, GRBs serve as powerful probes of ISM and IGM in distant galaxies. **Lack of on-board NIR follow-up has limited yield of these high-z events.**

Chornock et al. 2015



TAP will detect a number of events from the epoch of reionization. **Rapid identification of these rare high-z events will enable robust constraints on the neutral H fraction from e.g., GSMTs.**

Additional TAP Transient Discoveries

Transient Type	Primary Instrument(s)	Detections in 5 year mission
High-Redshift ($z > 5$) GRBs	WFI/IVUT	125/110
SN Shock Breakout	XRT/IVUT	95/30
Jetted TDEs	WFI	530
Thermal TDEs	XRT	240
AGN (daily)	WFI/XRT	600/8000

Supernova Shock Breakouts ~20/yr

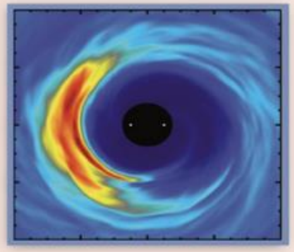
Elusive short bright X-ray flashes signaling SNe explosions.

Tidal Disruption Events ~150/yr

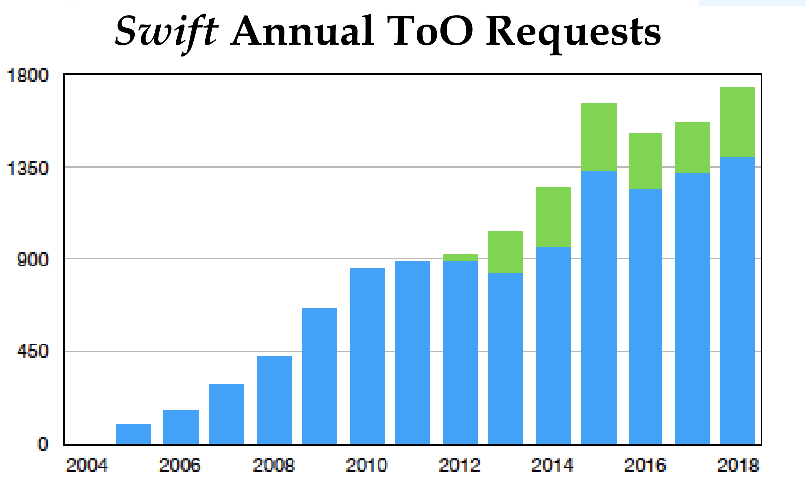
elucidating stellar dynamics, and providing super massive black hole demographics.

10^4 Galactic Nuclei

monitored weekly to search efficiently for modulated X-ray flux associated with the circumbinary disk of inspiraling supermassive black hole binaries.

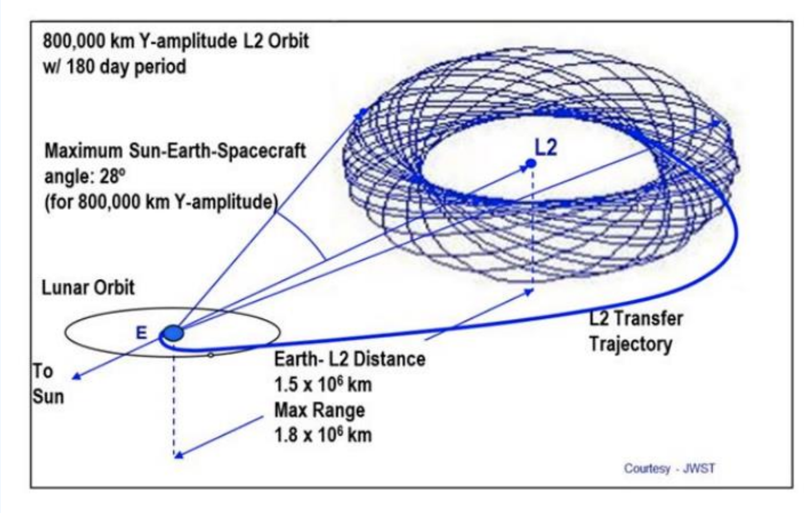


TAP Transient Follow-Up



Strong community need for rapid-response, multi-wavelength transient follow-up: >5 ToO requests received each day, before VRO/LSST and SKA! (green = joint *NuSTAR* ToOs)

TAP L2 Orbit



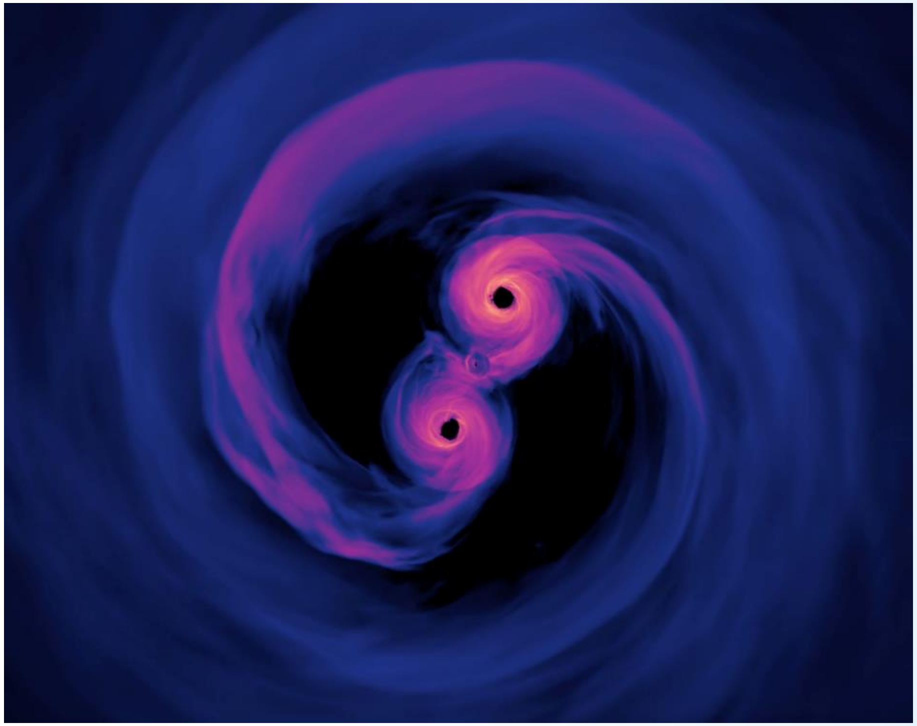
L2 orbit provides large field-of-regard, and dedicated ground stations provide continuous contact for ToO uploads

LISA and Pulsar Timing Array Science with TAP

Jeremy Schnittman
NASA Goddard Space Flight Center

LISA and PTA Science with TAP

Gravitational waves from merging Supermassive Black Hole Binaries (SMBHBs) are the most luminous and energetic events in the entire Universe



- Unlike LIGO sources, we expect many SMBHBs to be in gas-rich environments, conducive to bright EM counterparts

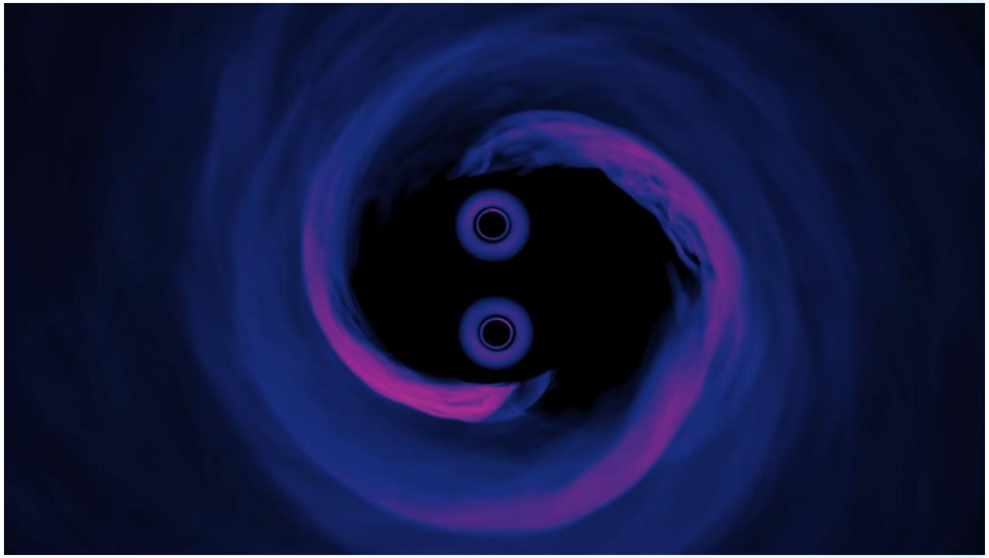
- Unique probes of fundamental physics and cosmology across the observable Universe

- GW signal can help identify the correct variable source in a crowded field, giving host galaxy and allowing for greatly enhanced science

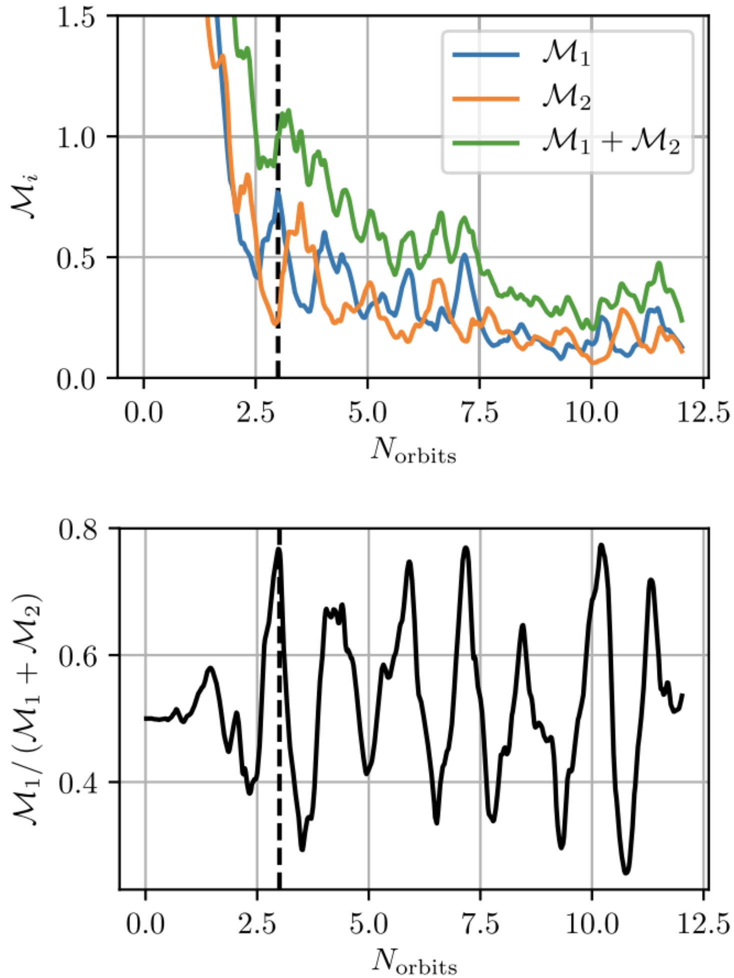
- EM variability will improve understanding of accretion physics, jet dynamics, and galactic environments

Circumbinary Accretion Disks

State-of-the-art MHD simulations show periodic variability in X-ray flux

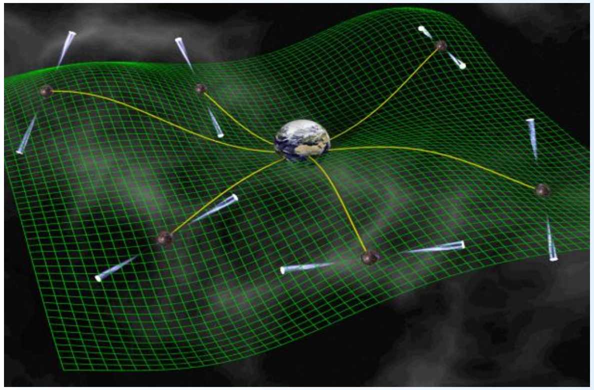


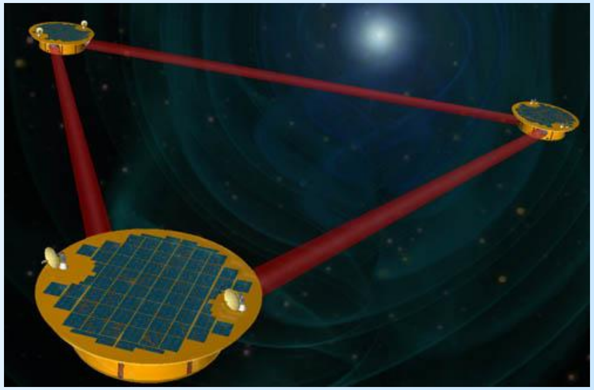
d'Ascoli+2018



Bowen+2019

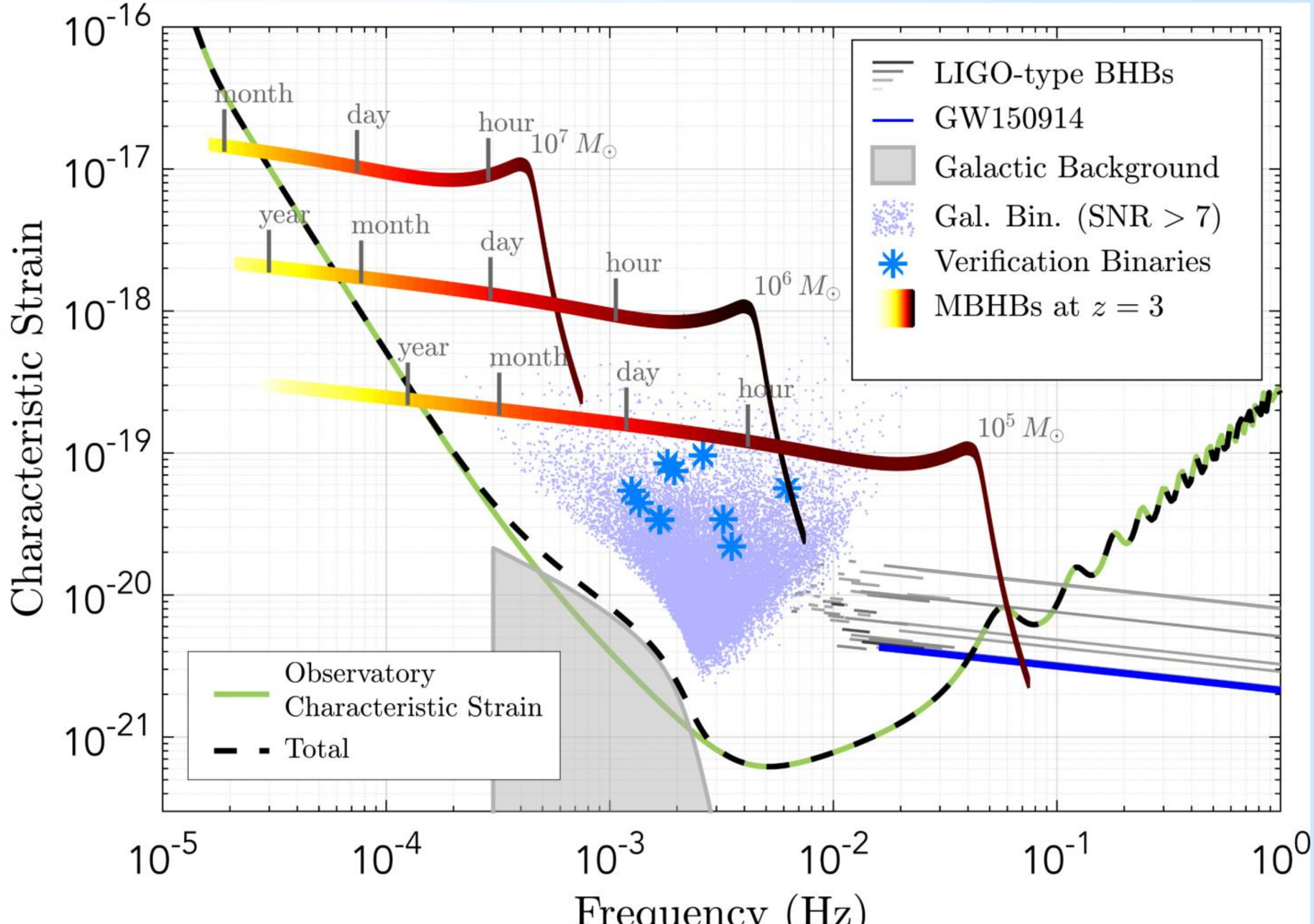
Pulsar Timing Arrays vs LISA





	PTA	LISA
M_{tot}	10^8-10^9 M_{sun}	10^6-10^7 M_{sun}
D (Gpc)	<0.2	>5
GW SNR	~10	>1000
X-ray flux	10^{-9} erg/s/cm^2	10^{-14} erg/s/cm^2
Period	months--years	hours--minutes
Lifetime	1000s of years	days

LISA localization



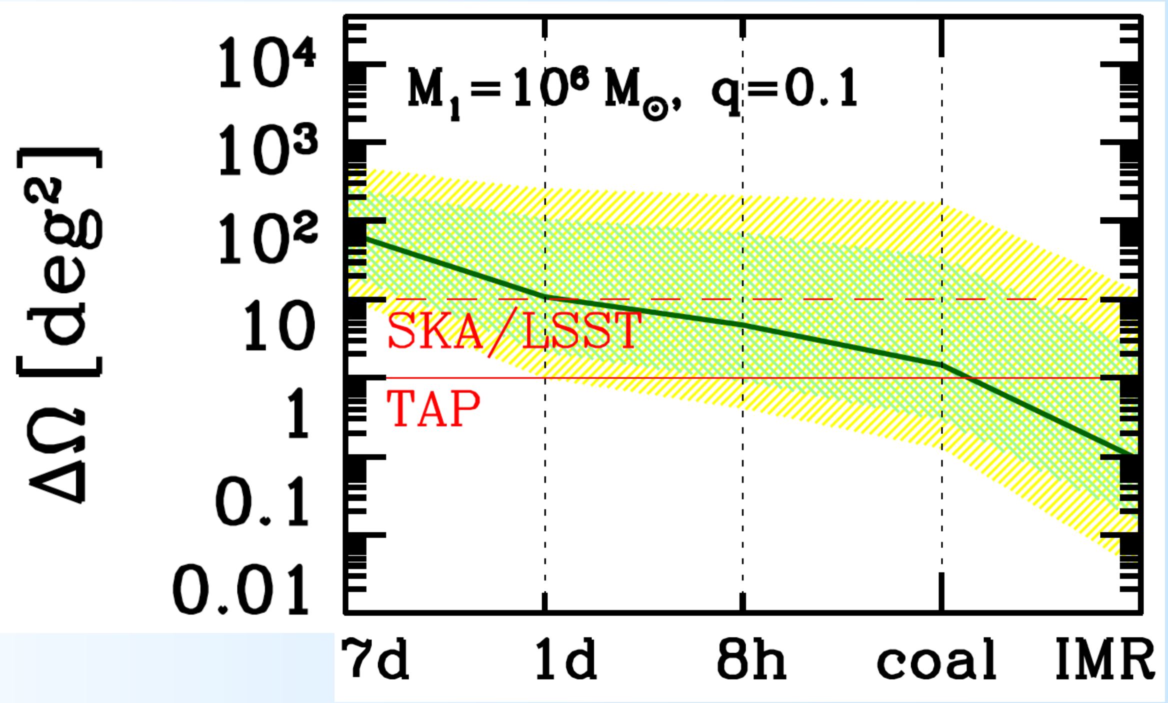
LISA localization

- For "Golden Binaries" with highest SNR in LISA, we expect to constrain the sky position to **~10 deg^2 a week before merger**

- **TAP is ideally suited to rapidly tiling the error region**, probing down to ~3x10^{-15} [cgs] in each 1-hr pointing

- By focusing on following up only the very best systems, TAP can be used efficiently to discover a **few SMBHB precursors per year**

- The precursor EM signal is currently better understood and more discriminating than the post-merger signature



Sesana+Klein 2018

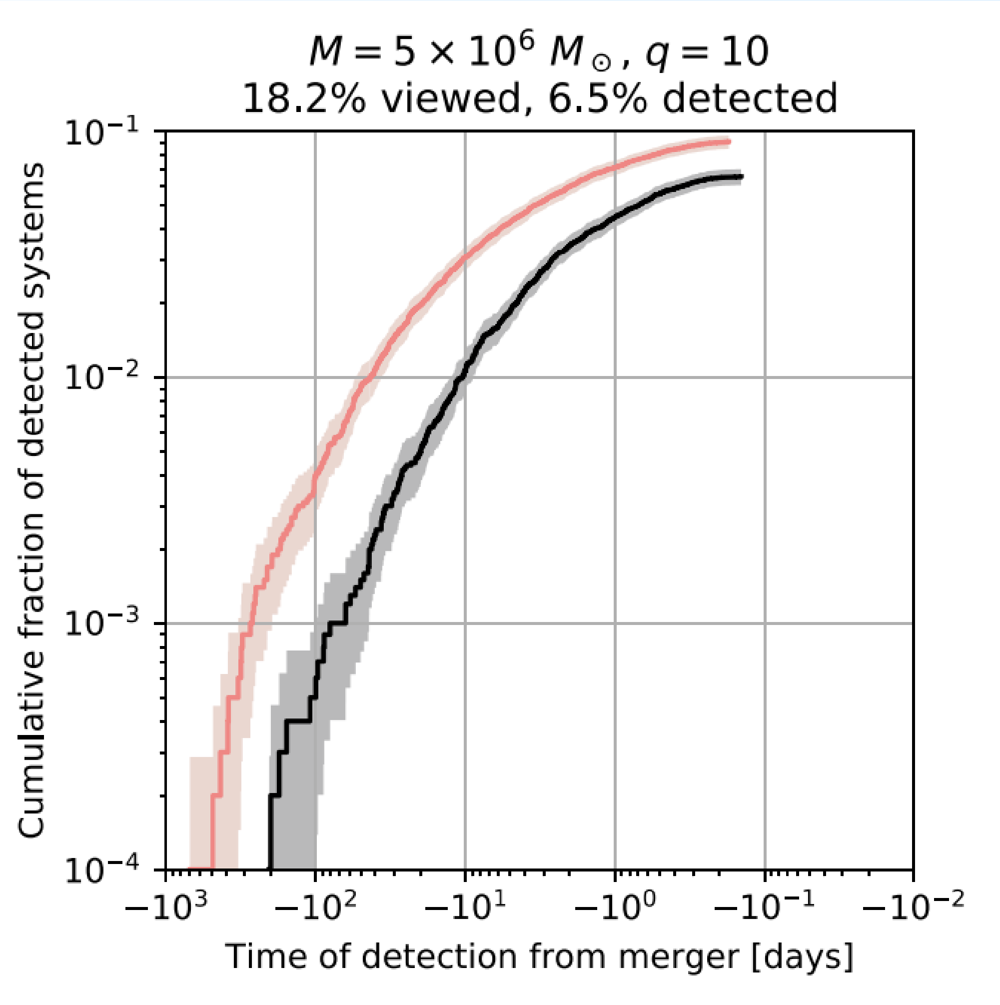
TAP follow-up of LISA triggers

A few % of all LISA SMBHB sources will be detectable with TAP days to weeks before merger: "Golden Binaries"

This corresponds to a **rate of ~few per year**

Lesson from LIGO is that **the vast majority of science comes from a minority of sources**

Dal Canton+ 2019



Mission, Instruments, Risk, Schedule, and Cost

Scott Barthelmy
NASA Goddard Space Flight Center

TAP Mission Overview

- TAP Instrument Suite
  - Needs to detect and follow-up its own transients (GW & many other transient types)
  - Needs to follow-up transients detected by other missions
  - We do this with 4 instruments: WFI, XRT, IVUT, and GTM

- Key Mission Parameters
  - A single observatory located at Sun-Earth L2
  - Large FoR: 45 deg Sun Avoidance (WFI, XRT, IVUT); No eclipses
  - Fast Comm: 24/7 Low Rate Uplink & Downlink (S-band)
    - Small subset of Science Data is real-time downlinked (and out to the world)
  - High Rate Comm for total Science Downlink (Ka-band)
  - Data Volume: 8 GB/day (MEV)
  - ToO visits commanded from TAP itself or the Ground
  - On-board detection of gamma-ray and soft X-ray transients
  - Autonomous follow-ups with high resolution X-ray, IR, Visible, & near-UV imaging.
  - Pre-planned observation schedule, uploaded every 1 or 2 days.
  - Start ~2023; Launch ~2029; Probe-class: $1B cost cap, Class B
  - 5 year mission, consumables for 10 years

TAP Mission-Driven Requirements

- Operations Requirements
  - Autonomous and continuous On-board repointing capability (just like *Swift*)
- Comm Requirement
  - 8 GB/day (MEV) downlink requirement
  - Near real-time 2-way comm requires new ground infrastructure, 3 or 4 dedicated antenna
- ACS Requirements
  - Ability to slew 50° in 70 sec (180° in 120 sec)
  - Pointing (absolute) 1 arcmin
  - Pointing knowledge 10 arcsec
  - Pointing stability 1 arcsec over 6 sec (3 sigma)
- Avionics Requirements
  - Command, Control, Data management of the 4 Instrument Electronics
- FSW
  - *Swift*-level level of autonomy

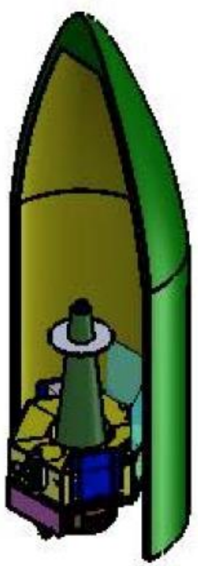
- Flight Requirements
  - JSWT-sized halo orbit
  - No eclipses
- Propulsion
  - Insertion into SE-L2
  - Station Keeping
  - Momentum Management
- Mechanical
  - XRT is long
  - Co-alignment of all instruments & S/C ACS info
  - SA and Antenna Mechanisms
- Operations
  - L&EO timeline
  - Mission timeline
  - 24/7/365 contact strategy

To do this, we have had 3 IDL runs, 2 MDL runs, plus Concept Study Report, CS Eng Report, CEMA cost estimate, & White Paper.

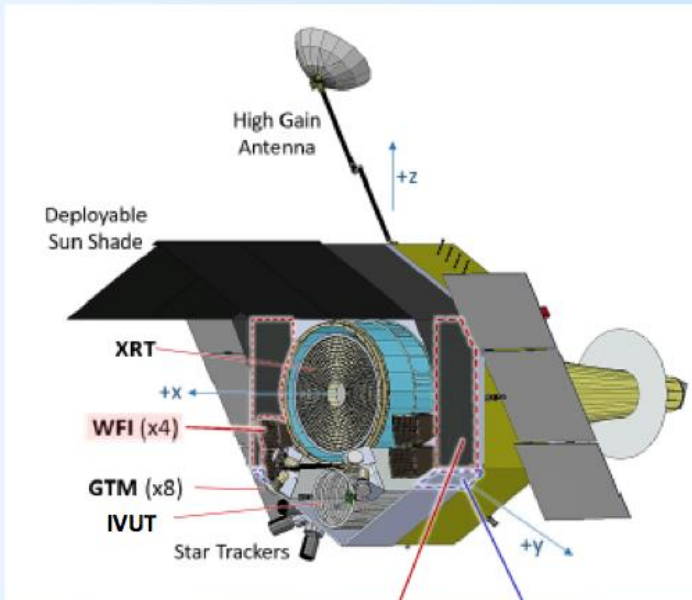
UNIVERSITY OF LEICESTER
U.S. NAVAL RESEARCH LABORATORY

TAP Spacecraft Views

Top view

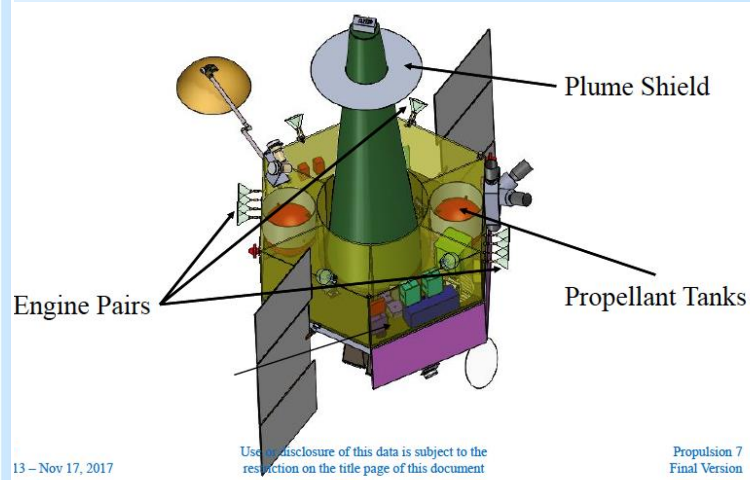


Stowed



Ample area exists for the FEE Radiator. IR backload from the solar array isn't an issue for this warm (~30C at ~200W) radiator.

The colder Detector Radiator (~-60C at ~10W) is located on the sun-shielded side with a nearly complete view of deep space

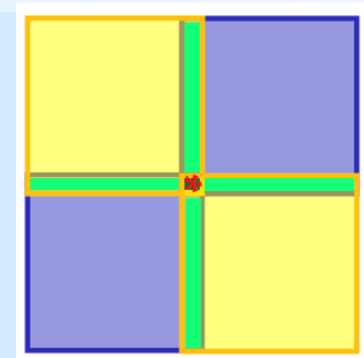


Bottom view

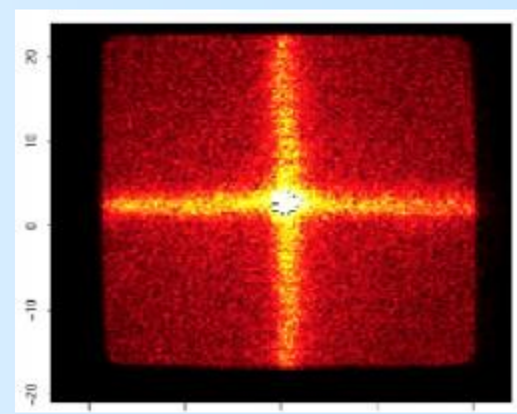
WFI – Wide-Field Imager Performance

- **Why WFI: Large FoV to find those Transients that have large location uncertainty (GW merger events, GRBs, PTA, …)**

- Sensitivity: 2×10^{-11} erg/s/cm^2 (at 2 ksec)
- Field of View: 37.2 x 37.2°
- Energy Range: 0.3 to 5 keV
- Energy Resolution: < 0.12 keV (FWHM)
- Point Spread Function: 9 arcmin (FWHM), Centroid to ~1 arcmin Uniform across entire FoV
- FoV: 18.6 x 18.6° (each module)
- A_{eff}: > 2.4 cm^2 (central core)
- Event Time Accuracy: 2 sec
- Data: < 5 GB / day (CBE)
- Normal Operations:
  - Stare Mode: Tiling the 4pi sky, monitoring the count rate curves for increases above ~6 SNR.
  - Transient Mode: When trigger found, calculate the direction (send to "FOM" processing, which sends RA,Dec to S/C request to slew).



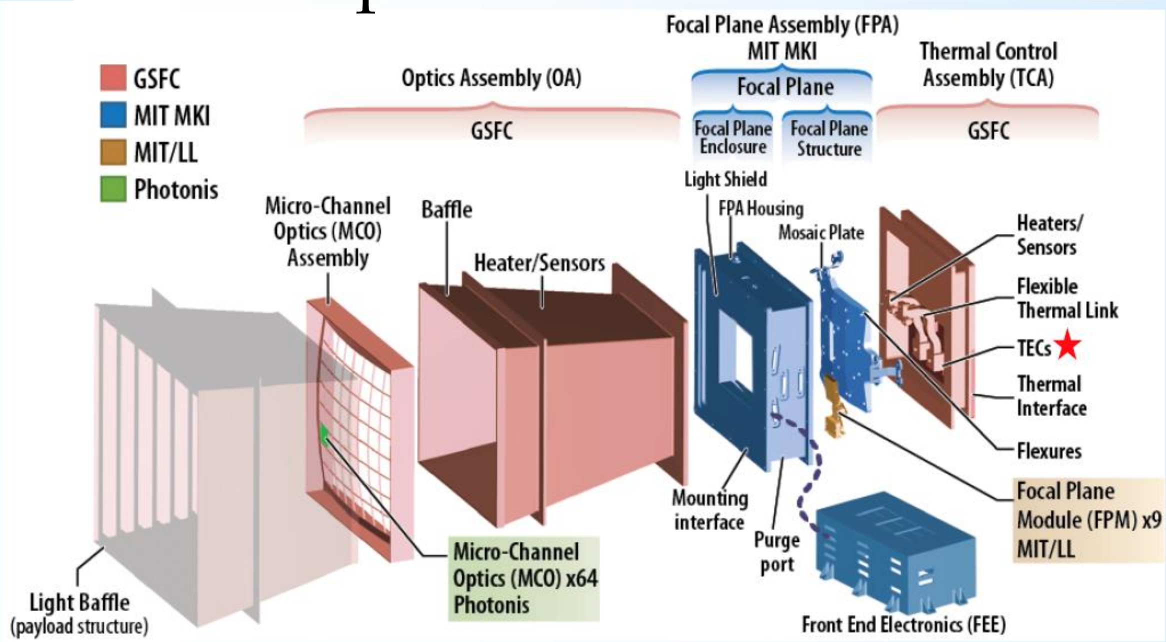
Overlap FoV
39.2x39.2°



MCO Focused Image
FWHM 9 arcmin

WFI Design Concept

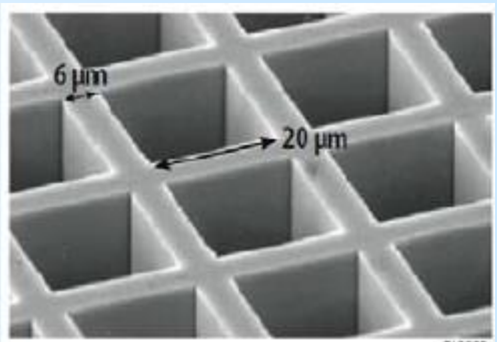
Exploded WFI Module



★ *Optional TEC cooling is available, however this is not needed for the TAP mission*

Same CCD as the XRT.
MIT / LL

WFI Modules



Micro-Channel Optic

Heritage: BepiColombo, STORM

XRT -- X-Ray Telescope Performance

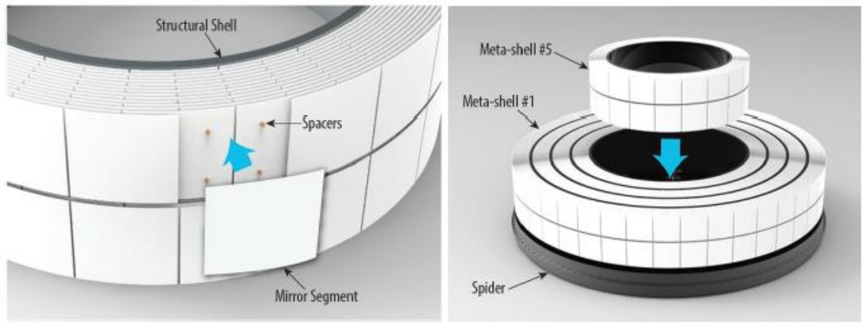
- **Why XRT: Improve localization of the the WFI-localized sources & other ToO targets. Be able to find LISA sources by deep tiling.**

- Sensitivity: $5\text{x}10^{-15}$ erg/s/cm^2 (at 2 ksec)
- FoV: 1^{o} diameter
- Energy Range: 0.3 to 6 keV
- Energy Resolution: < 0.12 keV (FWHM)
- PSF: 5 arcsec
- Localization 2 arcsec
- Data: < 0.4 MB / day (CBE)
- Normal Operations:
  - Stare Mode: Covering known and pre-planned sources (16 hr/day)
  - Transient Mode: Slew rapidly to the Flt-/Gnd-transients, obtain better localizations; measure the X-ray flux vs time and spectrum variations (2 4-hr ToO observations/day)

XRT Design Concept

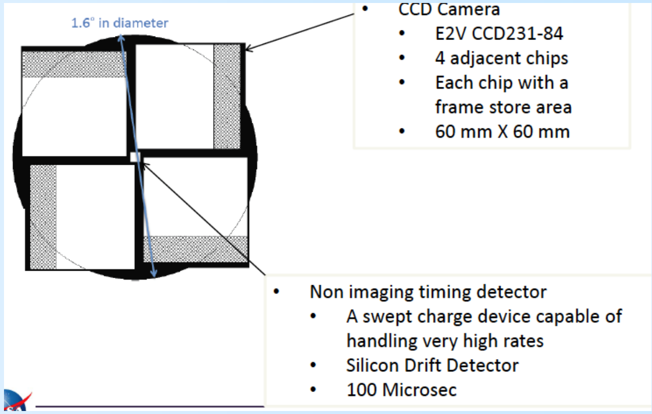
Exploded X-ray instrument

Mirror Assembly



Silicon panels provide improved surface smoothness and shape.

2x2 CCD Detector Array



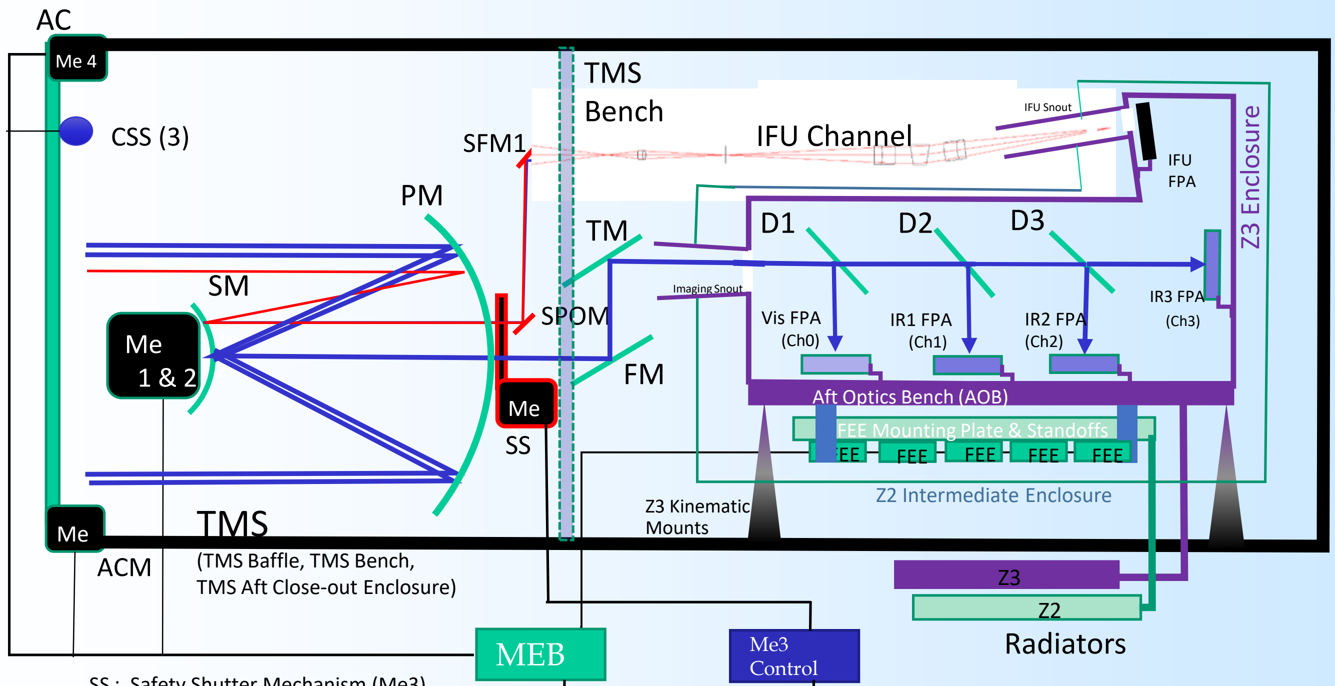
Same CCDs as the WFI. MIT / LL

IVUT -- Infrared, Visible, Ultraviolet Telescope

- **Why IVUT: Increase the EM band coverage of all source classes; further improvement on the WFI-/XRT-localizations; spectral measurements of the high-redshift GRBs and all the other source classes.**

- Sensitivity: 23 mag (300 sec)
- Range: 0.2 to 2.5 microns; simultaneous imaging in 4 bands
- FoV: 1.02°
- Primary Mirror dia. 70.0 cm
- F/#: 3.3
- Spectrum: 30 $\lambda/\Delta\lambda$
- FWHM: 2.7 arcsec
- Localization: 0.5 arcsec
- Stability: 0.2 arcsec (after the internal stabilizer, secondary mirror)
- Normal Modes of Operations:
  - Stare Mode: Covering known & pre-planned sources, 16 hr/day
  - Transient Mode: Slew rapidly to the Flt-/Gnd- transients, obtain better localizations; measure the X-ray flux vs time and spectral variations (8 hr/day, assumes 2 ToO's per day)

IVUT Design Concept



SS : Safety Shutter Mechanism (Me3)
SFM1: Spectrograph Fold Mirror #1
SMTT : Secondary Mirror Tip/Tilt Mechanism (Me1)
AC : Aperture Cover
CSS: Coarse Sun Sensor
FEE: Front End Electronics (ASIC)
Me1: Fast steering mirror mechanism

SPOM: Spectrograph Pickoff Mirror
FPA : Focal Plane Assembly
TMS : Telescope Metering Structure
MEB: Main Electronics Box
Me2: Focus mechanis

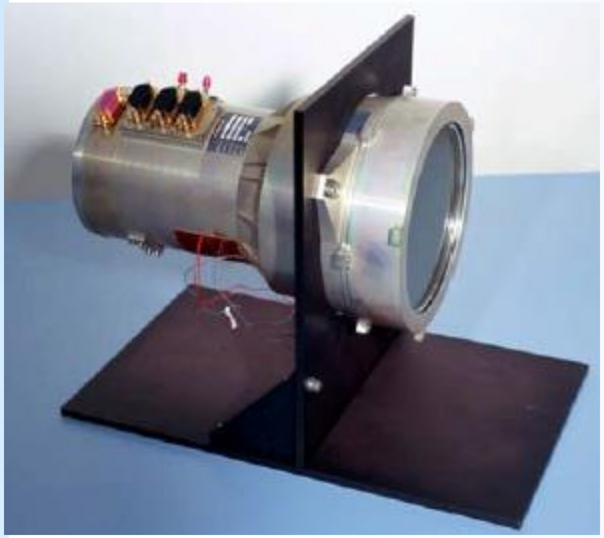
AOB: Aft Optics Bench
IFU: Integral Field Unit
PM: Primary Mirror
ACM : Aperture Cover Mechanism (Me4)

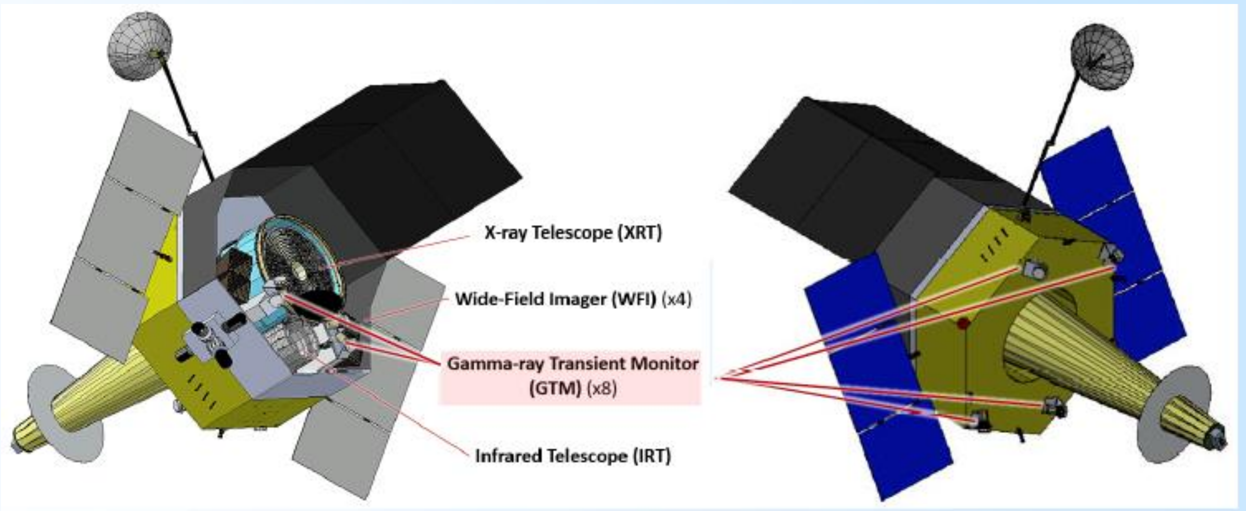
GTM -- Gamma-ray Transient Monitor Performance

- **Why GTM: Find GRBs, obtain rough localizations; provide temporal coincidence to other transients which proves they are astrophysical.**

- Trigger Threshold: < 1 photon/cm^2/s
- Field of View All 8 detectors yield 4pi, all sky
- Energy Resolution: < 20% at 100 keV (FWHM)
- Energy Range: 10 keV to 1 MeV
- Burst Location Error: < 20deg (radius)
- Deadtime per Event < 2.6 usec
- Event Time Accuracy < 100 usec
- Data: < 200 MB / day (MEV)
- Processing: Commandable thresholds (SNRs), binnings, RA,Dec location from s/c orientation
- Normal Modes of Operations:
  - Stare Mode: Covering the 4pi sky, monitoring the countrate curves for increases above N SNR.
  - Burst Mode: When trigger found, calculate the direction (send to "FOM" processing, which sends RA,Dec to S/C request to slew).

GTM Design Concept





Fermi-GBM (above): TAP-GTM will be of the same design, dimensions, and requirements.

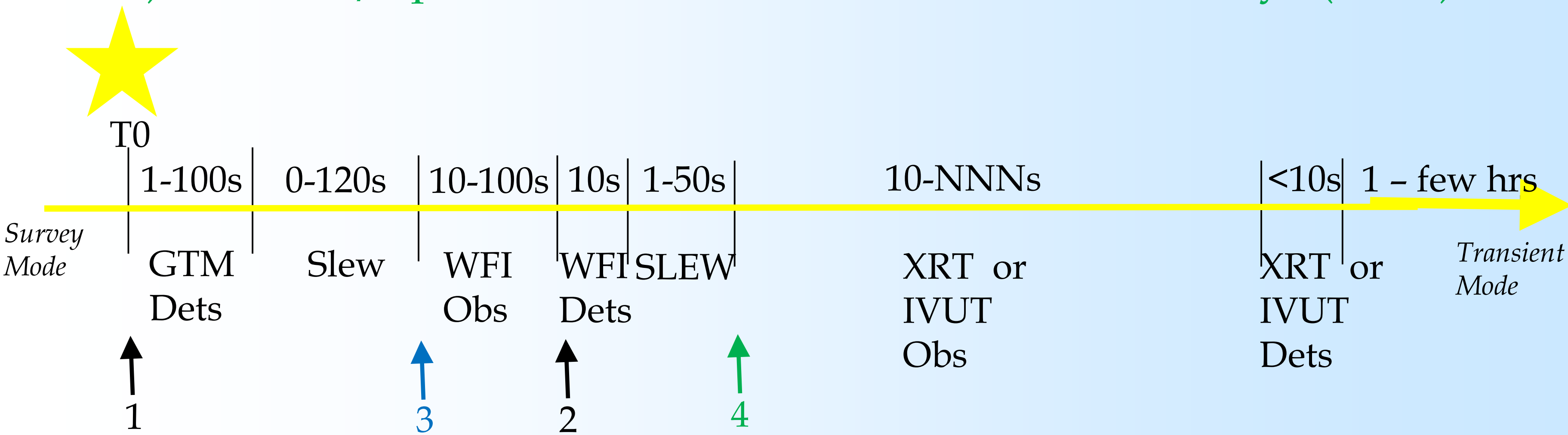
8 GTM detectors mounted on TAP in an octahedral direction arrangement.

TAP Modes of Operation

- Survey Mode
  - Spacecraft stares at preplanned targets (16 hr/day)
    - WFI: Tiling 4pi sky; monitoring known sources; looking for new sources
    - XRT: Covering known and pre-planned sources
    - IVUT: Covering known and pre-planned sources
    - GTM: Covering 4pi sky, monitoring count rate for increases ~7 SNR (24 hr/day)
- Transient Mode:
  - Spacecraft moves to get better information on the location (8 hr/day):
    - WFI: When new source found, calculate the direction (send to "FOM" processing, which sends RA,Dec to S/C request to slew)
    - XRT: Slew rapidly to the Flt-/Gnd- transients, obtain better localizations; measure the X-ray flux vs time and spectrum variations (2 4-hr ToO observations/day)
    - IVUT: Slew rapidly to the Flt-/Gnd- transients, obtain better localizations; measure the 4 fluxes vs time and spectral variations (8 hr/day, assumes 2 ToO's per day)
    - GTM: When trigger, calculate the direction (send to "FOM" processing, which sends RA,Dec to S/C request to slew, so WFI can observe)

TAP ToO Timeline

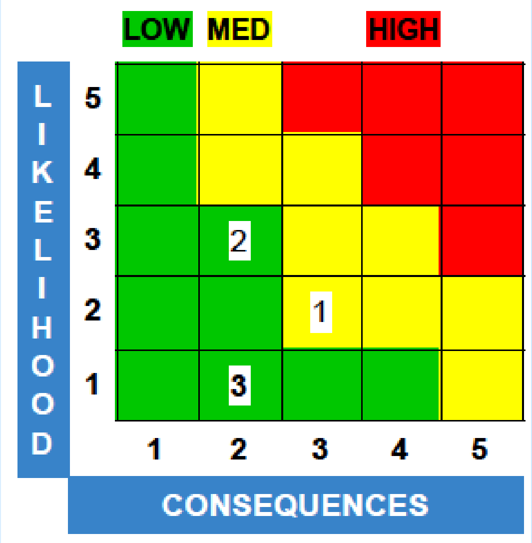
- 4 timelines depending on who made the initial detection:
  - 1) on-board GTM (<18°, or tiling if larger uncertainty)
  - 2) on-board WFI (0.017°)
  - 3) External/uploaded with large location uncertainty (0.5-18°)
  - 4) External/uploaded with medium location uncertainty (<0.5°)



"Dets" = Detects the source
"Obs" = Observes the target

TAP Risks

- The 3 top risks are:
  - 1) Getting a good overlap with other missions (LISA), instruments and projects for the GW portion of TAP.
    - Impact: The number of GW events that overlap with TAP decrease
    - Mitigation: We can adjust the launch date (by -6 mo, +6 - +12 mo)
  - 2) Cost
    - Impact: Detection losses depends on how many of the 4 descopes
    - Mitigation: 4 descopes to choose from (see CSR 4.5) for the 4 descopes)
  - 3) XRT Mirror TRL
    - Impact: The number of detections depends on the XRT PSF
    - Mitigation: Testing is currently in progress (a flight-like unit by Dec 2021)



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Instrument & Mission Studies & Reports

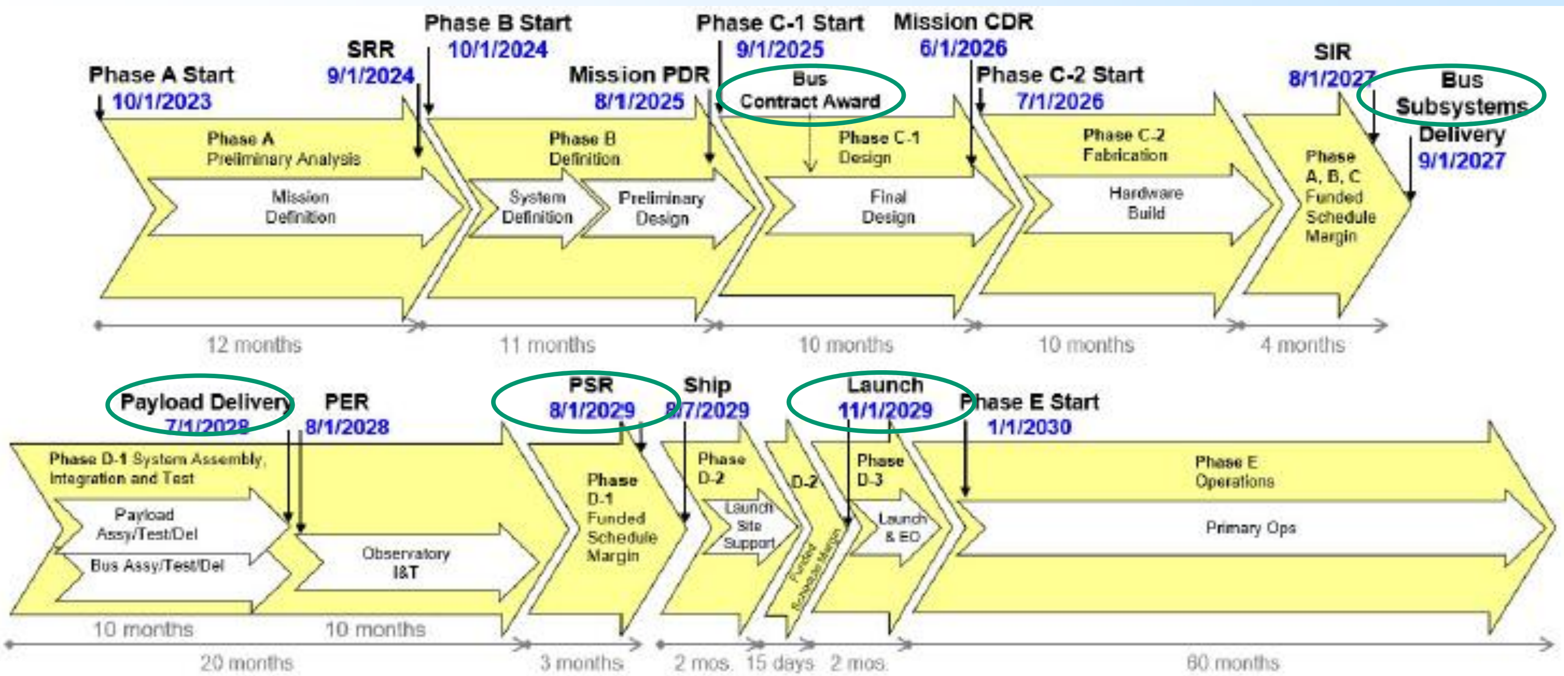
- We have conducted the following instrument-level and mission-level design studies and concept studies that are relevant to the proposed TAP design:

- 2013 Dec: IDL (at GSFC) for the XRT instrument (for the STAR-X mission proposal)
- 2014 Mar: MDL (at GSFC) for the STAR-X mission
- 2016 Mar: IDL (at GSFC) for the WFI instrument on the TAO (MoO on ISS).
- 2017 Aug: "The STAR-X X-ray Telescope Assembly (XTA)", [McClelland 2017]
- 2017 Aug: "Optical design of the STAR-X telescope", [Saha 2017].
- 2017 Nov: MDL (at GSFC) for the TAP mission
- 2017 Dec: Cost Estimating, Modeling, & Analysis Office (CEMA): cost estimate of TAP mission
- 2018 Mar: IDL (at GSFC) for the IVUT instrument (for the TAP mission)
- 2018 Dec: Engineering Concept Report (including TAP instrument and s/c MELs) sent to NASA
- 2019 Mar: Concept Study Report (CSR) for the TAP mission sent to NASA
- 2019 Jul: White Paper (WP) for the TAP mission sent to the Decadal Panel

TAP Schedule

Spacecraft Schedule:

11/2015 Bus contract awarded
09/2027 Bus Subsystems Delivery.
07/2028 Bus Assembly/Test/Delivery.
08/2029 End of mission-level I&T; Ship to launch facility.
11/2029 Launch plus 60 days of vendor support. During early orbit.



Reserves are included & funded.

TAP Cost Estimates

- Estimation done based on well-studied designs:
  - 5 IDL and MDL studies
  - CEMA cost estimate
- From the CSR work, cost estimate was 1.03 B$
- PCAT listed TAP as “possible” to fit within the cost cap.
- Descopes (CSR section 4.5):
  - 4 $\rightarrow$ 3 WFI Modules ($30M)
  - IVUT aperture diameter 70 $\rightarrow$ 60 cm ($19M)
  - XRT aperture remove 5th (the inner most) meta-shell ($24M)
  - GTM: remove redundant MEB ($2.8M)
  - Total cost reduction: $76 M (includes ancillary costs)

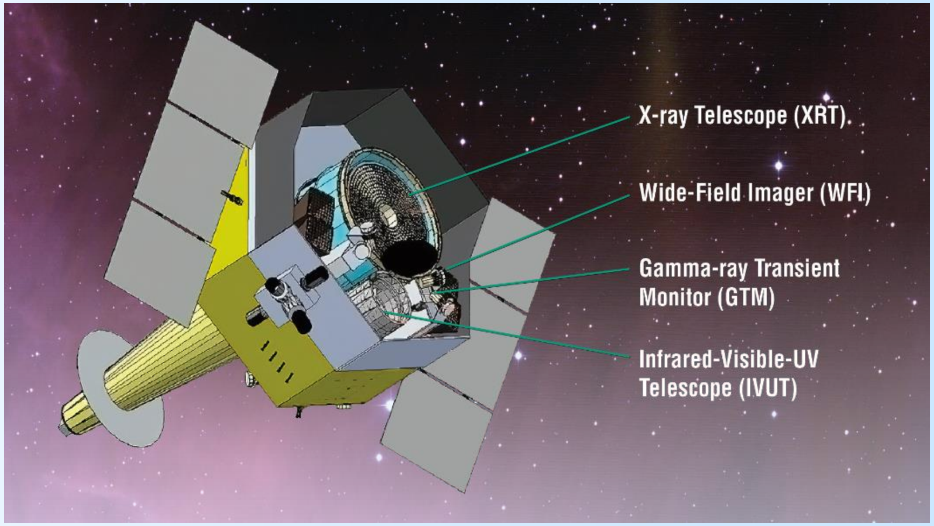
Mission and Instrument Summary

- Multiple instruments to:
  - Cover multiple band passes to cover a wide range of source categories
    - IR, Visible, UV, X-ray, gamma-ray
  - Series of improving positions, flux, and spectral
- Rapid response:
  - Via on-board autonomy for self-detected transients
  - Via 24/365 uplink for detections by other missions/projects
  - Via 24/365 downlink of TAP's detections/observations to other missions/projects
- High TRL
- Well studied by IDLs, MDLs, others
- Fits within the cost $1B cost cap for Probe class

TAP in a Nutshell

Science Goals:
1) To fully realize the transformative scientific potential of the upcoming generation of gravitational-wave detectors

2) To understand the explosive and energetic universe via high-energy transient discovery and rapid-response, panchromatic follow-up.



A next-generation *Swift* for the multi-messenger and time-domain eras:

Like *Swift:*
- High-energy transient discovery
- Panchromatic, rapid response follow-up

New Capabilities:
- IR imaging and spectroscopy
- Wide-field soft X-ray imaging
- 10x more sensitive X-ray telescope with 5x field-of-view

- Gamma-ray Transient Monitor (GTM): 4π sky coverage over 10-1000 keV
- Wide-Field Imager (WFI): 0.4 sr field-of-view over 0.3-5 keV
- X-ray Telescope (XRT): 0.8 deg^2 field-of-view with *Chandra*-like sensitivity and uniform (5”) PSF
- **Infrared-Visible-UV Telescope (IVUT): 70 cm telescope with 1 deg^2 field-of-view, 0.2-2.5 um bandpass, sensitivity to 23 mag (AB)**

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