STROBE-X: A Probe-Class TDAMM Mission

The STROBE-X Team

Mission Overview

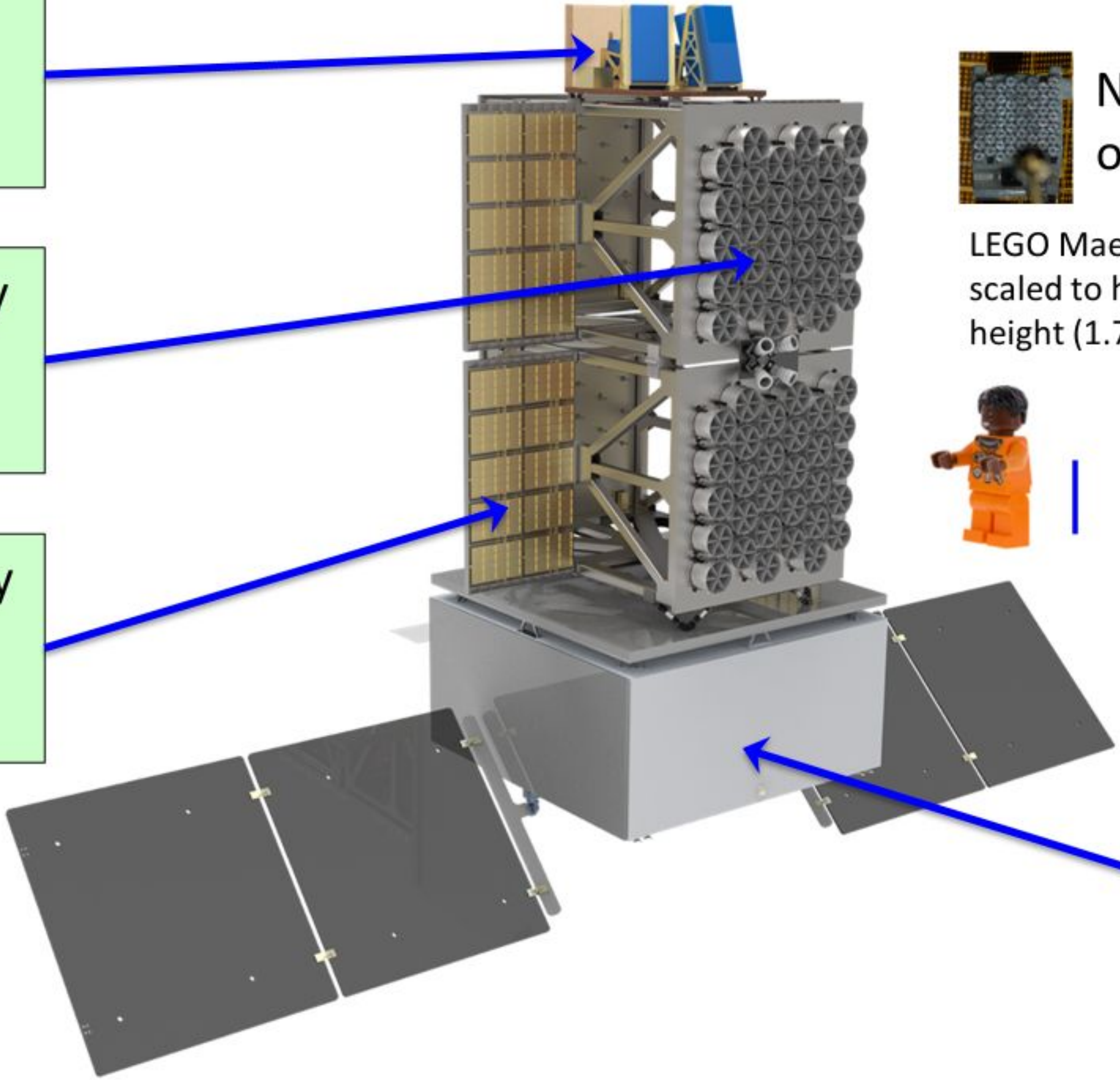
- STROBE-X is the game-changing, next-generation mission for high throughput X-ray spectroscopy and TDAMM
  - Unparalleled laboratory for probing objects with dense sampling on timescales from microseconds to years
- It directly addresses all three of NASA Astrophysics Science Objectives
  - Combines Astro2020 highest priority sustaining activities (TDAMM and an X-ray or FIR probe) into one powerful facility
- Probes real-time evolution of physical conditions at the heart of the most extreme astrophysical environments
- STROBE-X is a facility for the entire community:
  - Provides alerts from its onboard monitor
  - Responds to ground-based alerts in minutes
  - Delivers >10,000 pointed observations per year (with 70% GO time)

Transformational Capabilities

Wide-Field Monitor
(WFM)
2-50 keV

Low-Energy Modular Array
(LEMA)
0.2-12 keV

High-Energy Modular Array
(HEMA)
2-30 keV

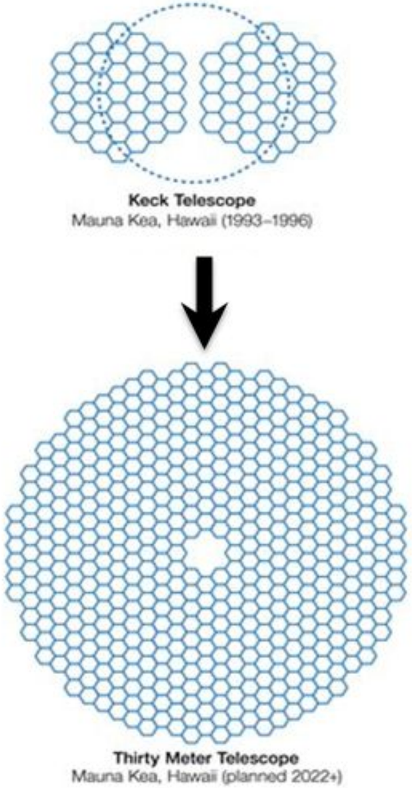


LM Rapidly Slewing S/C

NICER on ISS

LEGO Mae Jemison, scaled to her actual height (1.75 m)

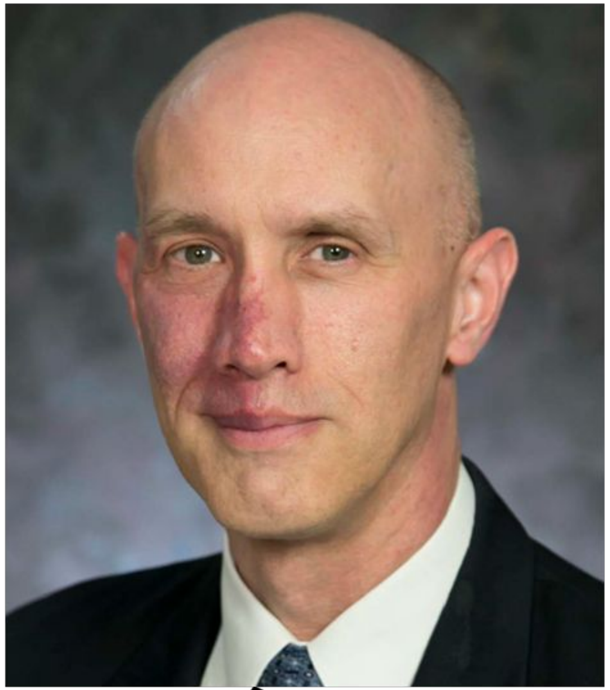
1 m



STROBE-X

SwRI Leads

- Pete Roming (STROBE-X PI)
  - Department Director
  - Division Chief Scientist
  - PI Swift UVOT



- Cynthia Froning (STROBE-X DPI)
  - Department Chief Scientist
  - Division Staff Scientist
  - Project Scientist HST-COS

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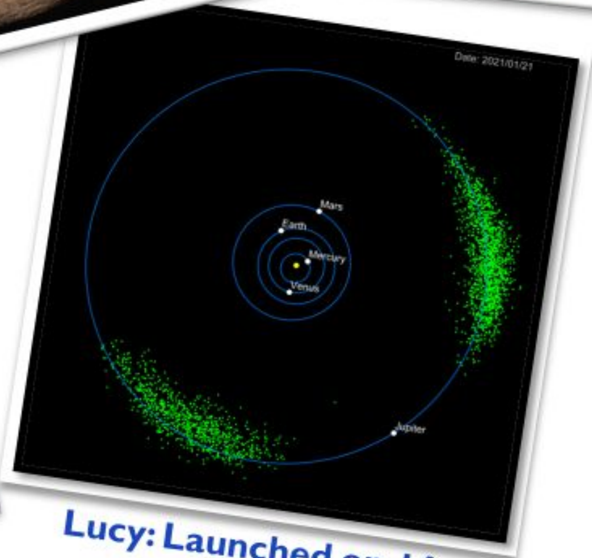
GRB 080913: 12.8 BLY

Alvin Pressure Hull



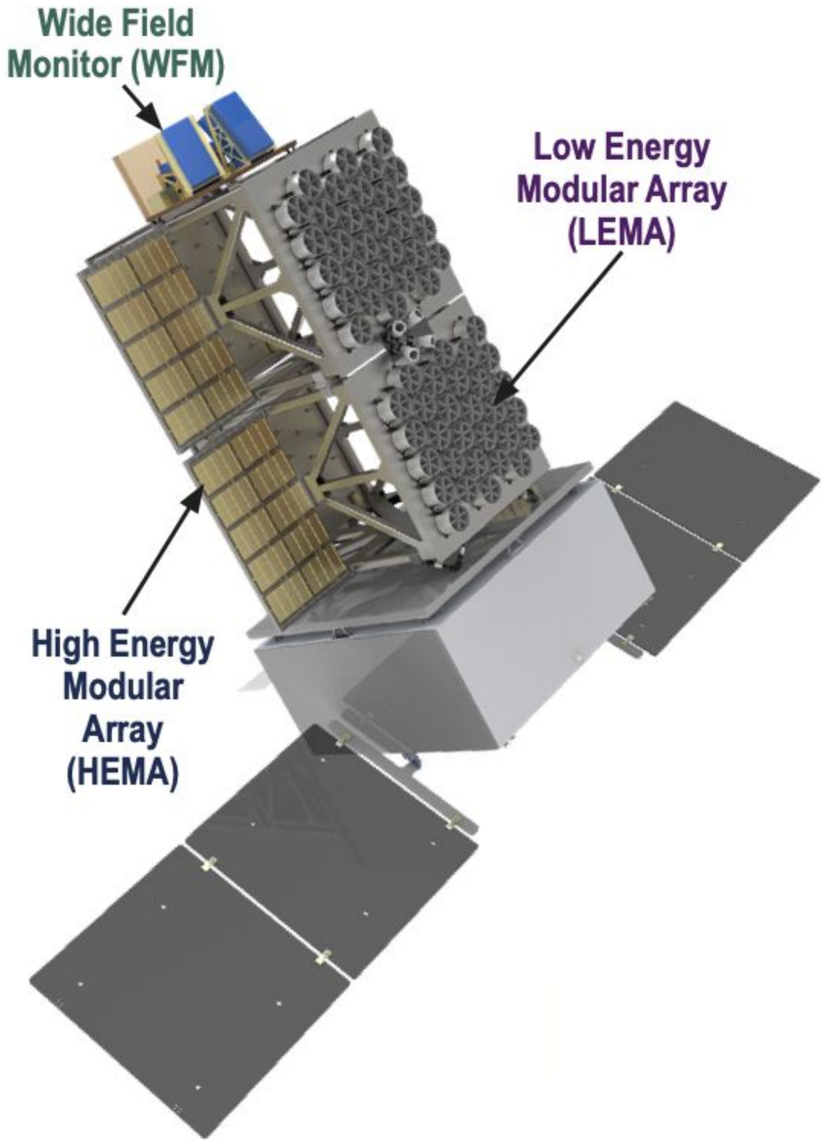
Lucy: Launched on 16 October 2021

SwRI Space
+55 Years of Scientific and Technical *Innovation*

- World Class Space Science Research and Instrument Development
- Industry Leader in Mission Design and Management, Instrumentation & Payloads, Spacecraft, Spaceflight Avionics, and Mission/Science Operations
- Participated in over 85 missions since the Space Science program started in 1977.
  - 6 as Mission Manager
  - 3 as Spacecraft Provider/Observatory Integrator
- SwRI Spacecraft have > 35 yrs on-orbit failure free

PI for 6 NASA major Science Missions

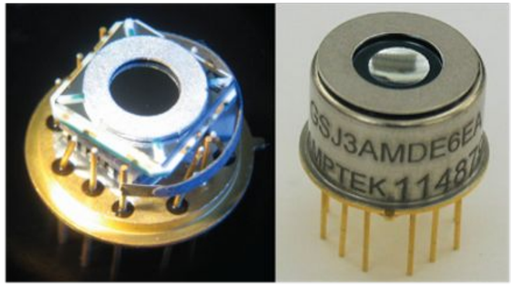
STROBE-X Mission Overview

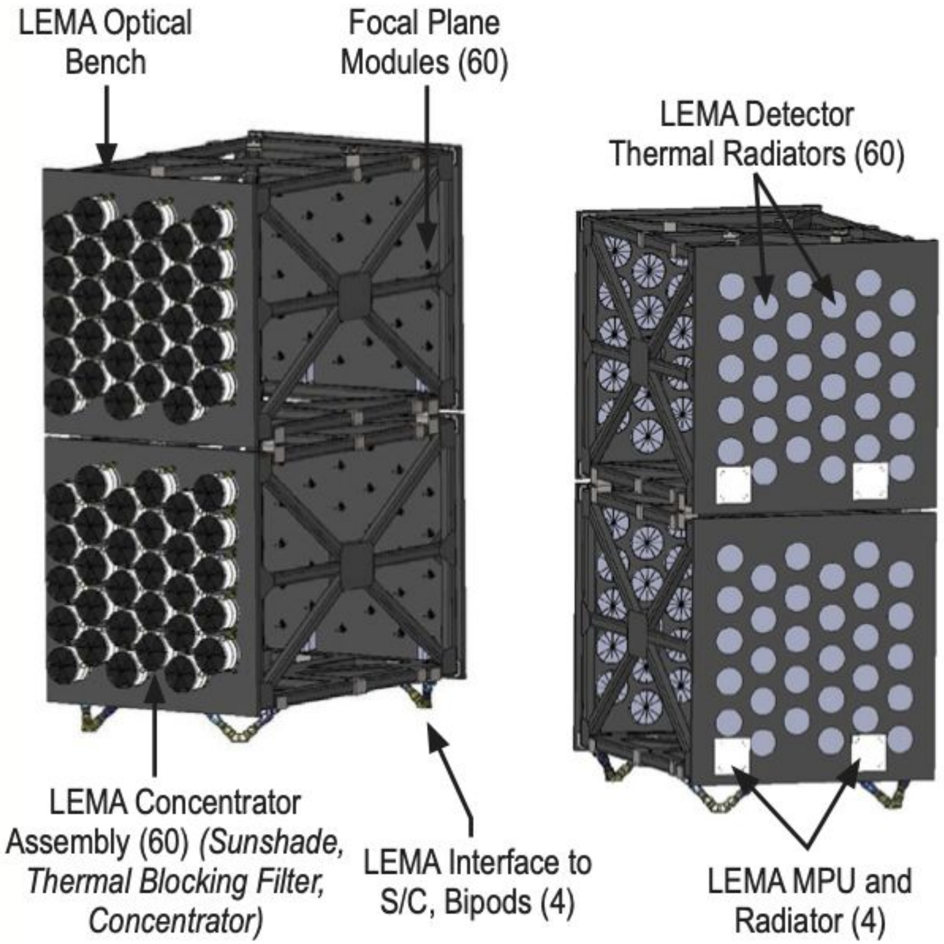


- Two pointed instruments (LEMA & HEMA) together covering 0.2–30 keV X-ray band
- Wide Field Monitor provides transient alerts and full sky source monitoring (2–50 keV)
- Highly modular design improves reliability at reduced cost and allows easy scaling, and integration schedule flexibility
- LEO orbit (<15° incl.) reduces background and radiation damage
- Rapid slewing agile spacecraft from Lockheed Martin:
  - Pointed instruments can observe >3 sources per orbit (avoiding Earth occultations)
  - Autonomously respond to onboard or ground transient alerts and begin observing in <9–14 min (depends on angle from boresight)
- Broad field of regard (entire sky outside 45° Sun exclusion zone)
- High rate downlinks (Ka band) to ground stations
- Low-latency alerts and TOO commanding via space-to-space link

STROBE-X

STROBE-X Low Energy Modular Array (LEMA)



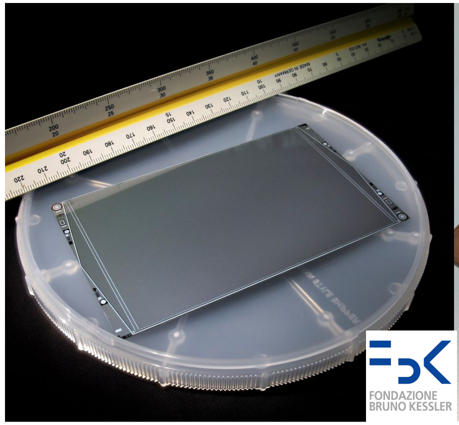


- Concentrator optics scaled up from NICER (diameter and focal length)
  - 4' FoV (non-imaging)
- SDDs and electronics inherited from NICER
  - ΔE = 85 eV @ 1keV
- Composite optical bench designed by BAE Inc.
- 2x30 concentrators, 1.6 m^2

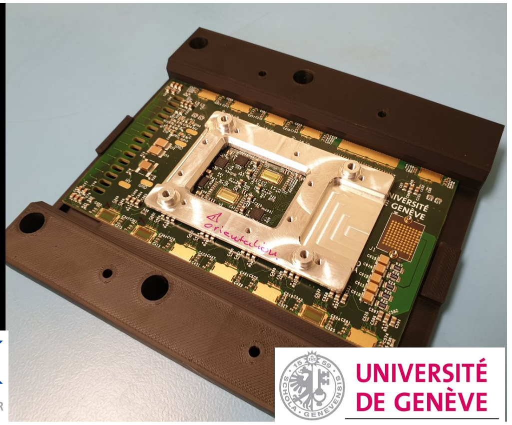
BAE SYSTEMS

STROBE-X

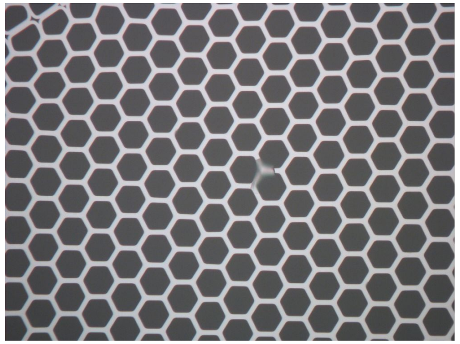
STROBE-X High Energy Modular Array (HEMA)



SDD

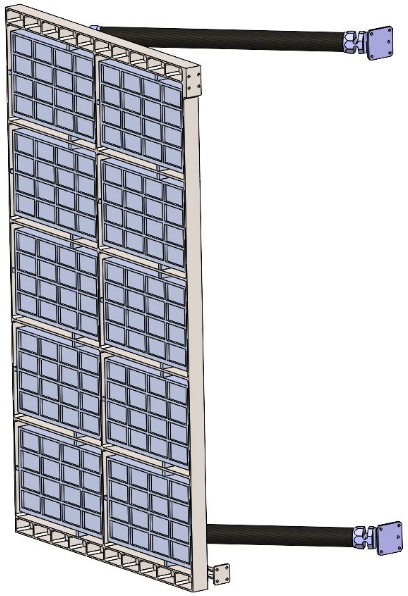


FEE



Collimator

Module



Panel (1 of 4)

Instrument Characteristic	Value
Energy Range	2–30 keV (Nominal) 2–80 keV (Extended)
Effective Area	3.4 m^2 at 8.5 keV
Field of View	1° FWHM
Field of Regard (FoR)	45° – 180° Sun Angle (BOL) 60° – 140° Sun Angle (EOL)
Extended Field of Regard (eFoR)	45° – 180° Sun Angle
Absolute Time Accuracy (to UTC)	7 μs
Energy Resolution	<500 eV at 6 keV
Maximum Source Flux	15 Crab
Maximum Expected Mass	743.1 kg
Maximum Expected Power	1128.6 W
Telemetry Rate	2450 kbps (1 Crab) 15 kbps (Background)

- Large area SDDs paired with lead-glass MC collimators in 16-detector "modules"
- Change from study:
  - 4x10 modules so 3.4 m^2
  - Fixed, not deployable panels

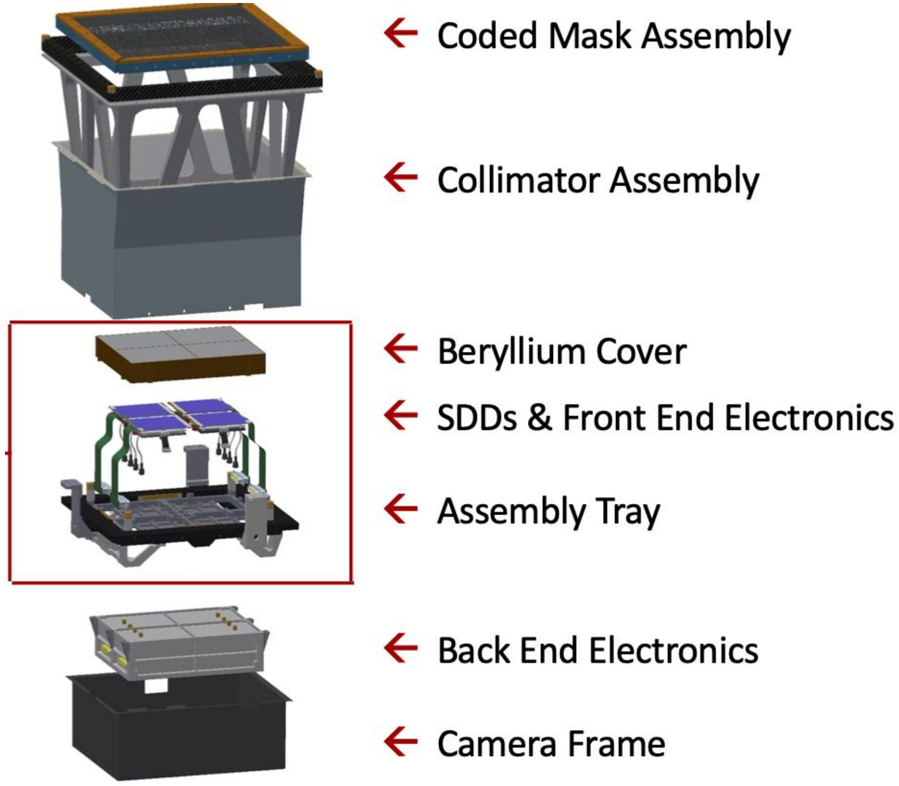
U.S. NAVAL RESEARCH LABORATORY

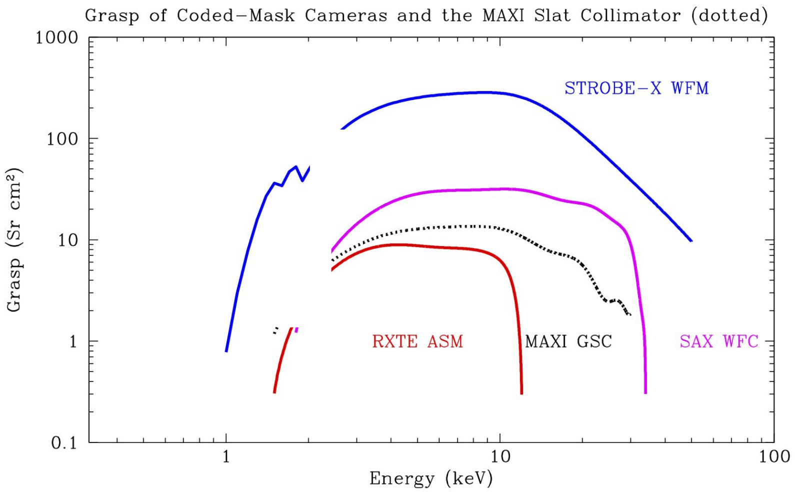
INAF ISTITUTO NAZIONALE DI ASTROFISICA

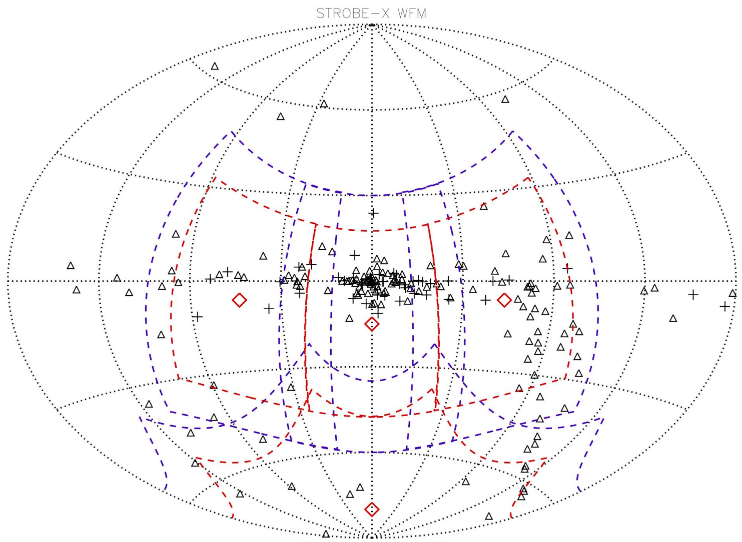
INFN

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

STROBE-X Wide Field Monitor (WFM)







- 1.5D coded mask camera with similar SDDs to HEMA
  - 2–50 keV, ΔE = 300 eV
- 4 camera pairs combine to view ⅓ of the sky at a time
- All data come down in event mode
- Onboard processing can produce alerts

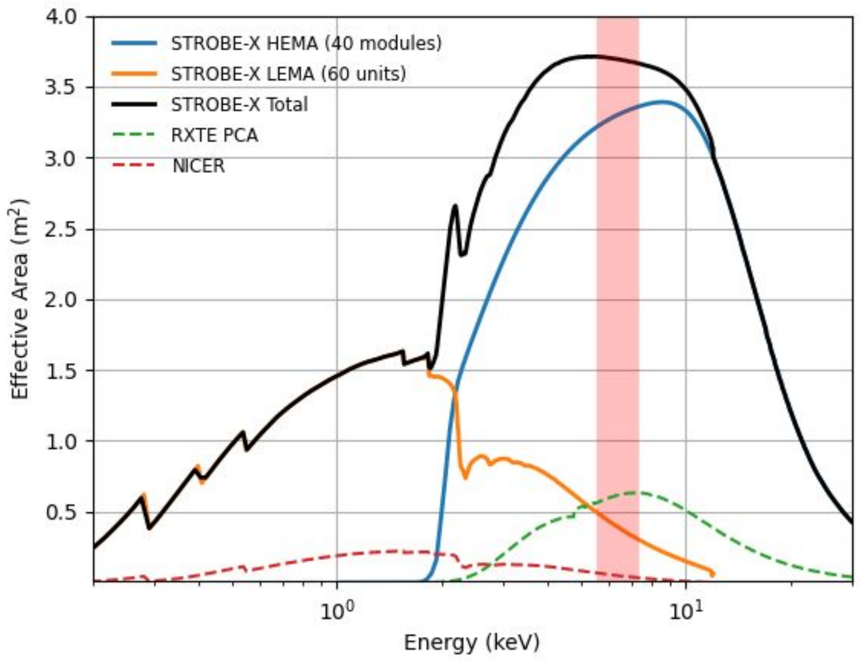
SRON Netherlands Institute for Space Research

ICE INSTITUT DE CIÈNCIES DE L'ESPAI

CSIC

IEEC

STROBE-X Key Capabilities

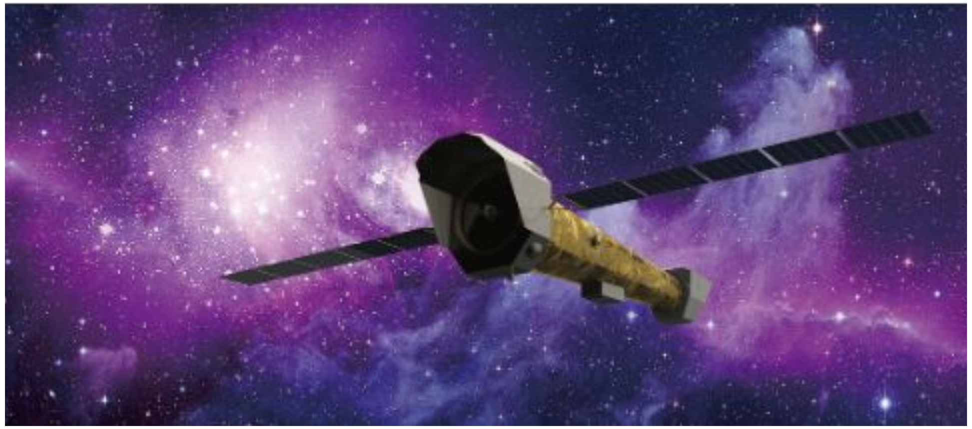


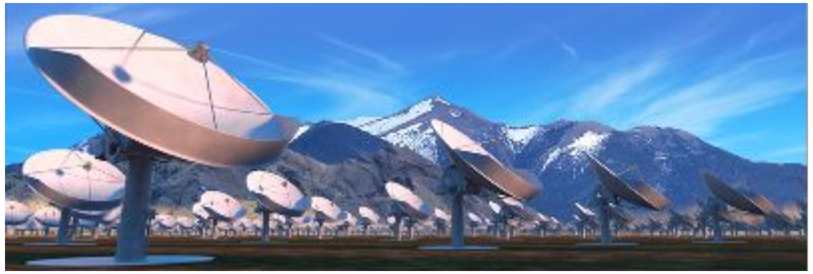
Enormous collecting area, with similar count rates from LEMA and HEMA for typical spectra

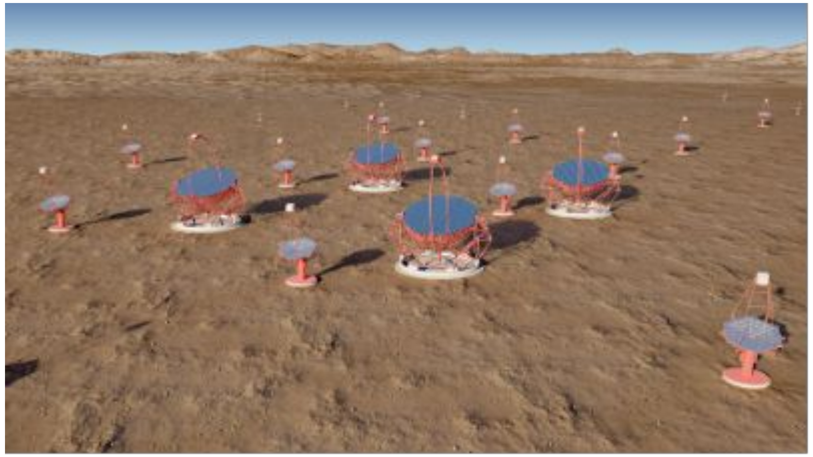
- Serves the broad TDAMM and X-ray astrophysics community with rapid alerts (arcmin localizations), and rapid response to TOOs on a range of timescales
- Pointed instruments provide unprecedented sensitivity to probe flux and spectral variability on short timescales to reveal fundamental physics and astrophysics
- High throughput instruments allow measurements over a huge dynamic range in source brightness
- Simultaneous broadband coverage provides measurements that constrain absorption, thermal emission, comptonization and reflection spectra and their temporal relationships

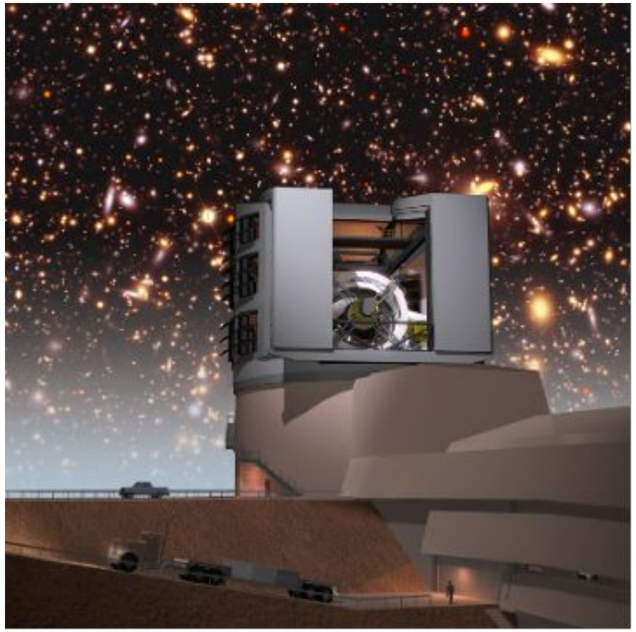
STROBE-X

Powerful Synergies with Upcoming Facilities

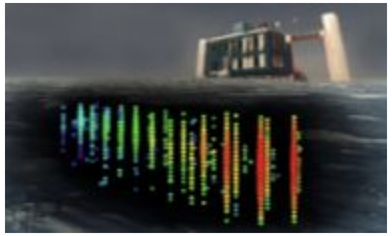








Bright source capability and high throughput will ***validate black hole spin measurement techniques****, enabling Athena to apply lower-count-rate methods with confidence.*



STROBE-X

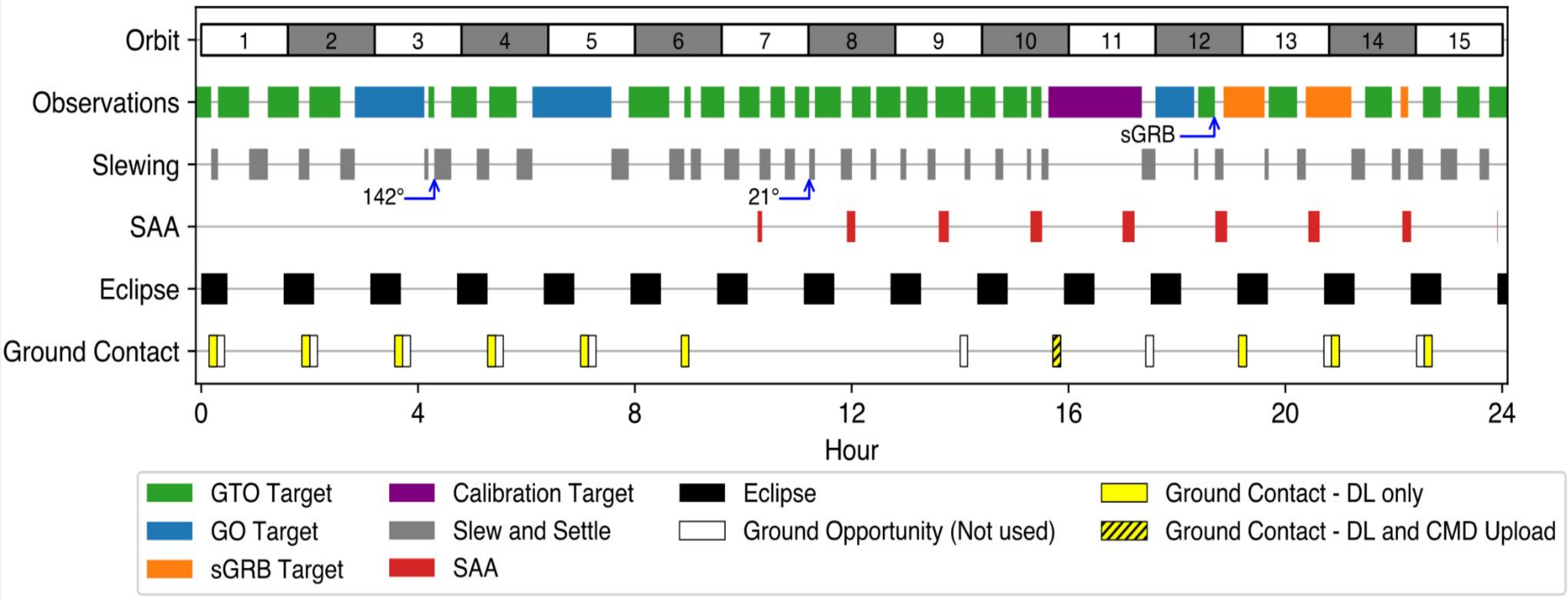
Instantaneous wide field sensitivity, along with deeper monitoring capability from pointed instruments, make STROBE-X the ***ideal partner for wide field transient surveys*** *from radio, through optical, gamma-rays to neutrinos and gravitational waves.*

STROBE-X Operations Model

- STROBE-X concept of operations aims towards high efficiency and rapid response to events from a wide range of astronomical messengers.
  - STROBE-X is expected to observe many 10s of targets per day, ensuring a broad range of science.
  - Observing plans will be built by the Science Operations Team (SOT) on every working day, and uplinked to the spacecraft the following day, meaning that the latency getting a target in the observing plan is typically no more than 48 hours.
- If faster response is needed, target-of-opportunities (TOOs) can be uplinked to the spacecraft for immediate observation.
  - TOO requests can be put in the old fashioned way (web form), but also utilizing an API interface, for automated submission, e.g. from a transient broker.
  - WFM will detect new transients and automatically repoint
- The STROBE-X SOT will be on-call 24/7 to respond to WFM triggers and target-of-opportunity requests.

STROBE-X

STROBE-X: Typical Day in the Life



STROBE-X

STROBE-X: Novel TDAMM Operations

- Enabling TDAMM Science requires a **novel** concept of operation.
- With the next generation of GW detectors, we will know about NS-NS mergers 10-15 minutes before they happen, and have localizations that easily fit inside the WFM field of view.
  - Therefore, if we can respond in real-time, we could repoint STROBE-X to catch the NS-NS merger as it happens.
- In order to enable this kind of capability, this will require STROBE-X to have the following capabilities:
  - Automated repointing to external triggers.
  - Low latency communications to allow for rapid TOO uplink.
  - The ability to uplink TOOs with **no-human-in-the-loop.**
- STROBE-X plans to do the above and more, enabling true rapid response TDAMM science!

STROBE-X

STROBE-X: A True Swift-like TDAMM mission

- Lots of proposed missions talk about having "Swift like" response.
  - Typically this means TOO response in the 4-8 hour range. This is what Swift could do 20 years ago, but not today.
  - Currently Swift's highest urgency TOO response time (from receipt of request to execution of command) is **ten seconds.**
- STROBE-X a **true Swift-like TDAMM mission.** This is achieved by:
  - Designing a spacecraft capable of true autonomous response to triggers.
  - Using a continuous communications solution to allow near-zero latency commanding of the spacecraft.
  - By leveraging the heritage and expertise of the Swift Science Operations team at Penn State to design a next generation operations for STROBE-X, that builds upon and improves what Swift does **today**.

STROBE-X Science Overview

Key science goals:

Time domain and multi-messenger astronomy (Nicole Lloyd-Ronning to present)

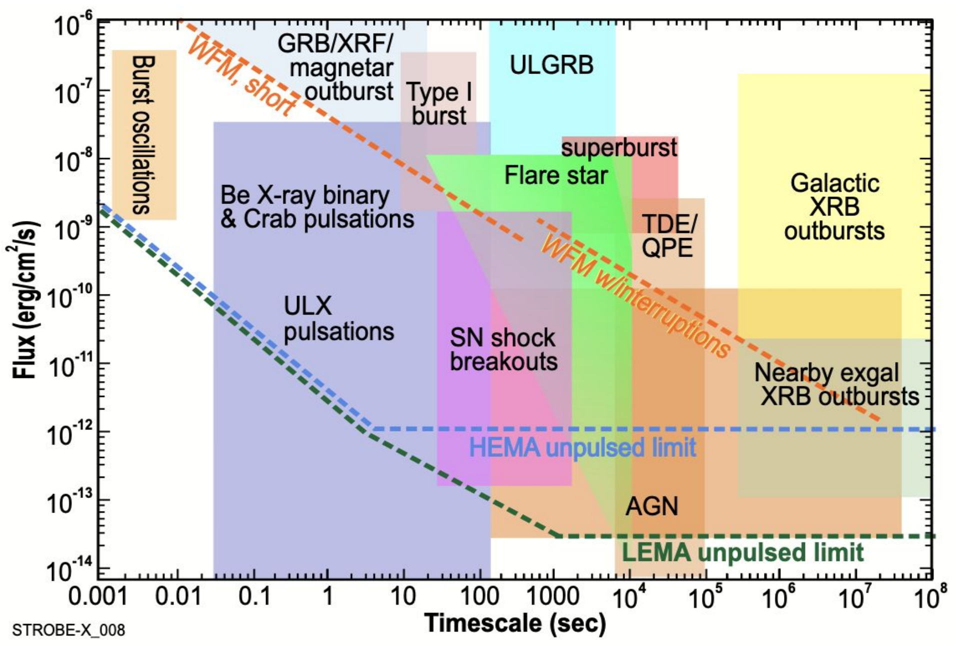
Neutron star equation of state (Anna Watts to present)

Black hole spins (Jack Steiner to present)

Dynamic Universe and General Observer programs (I will present)

STROBE-X

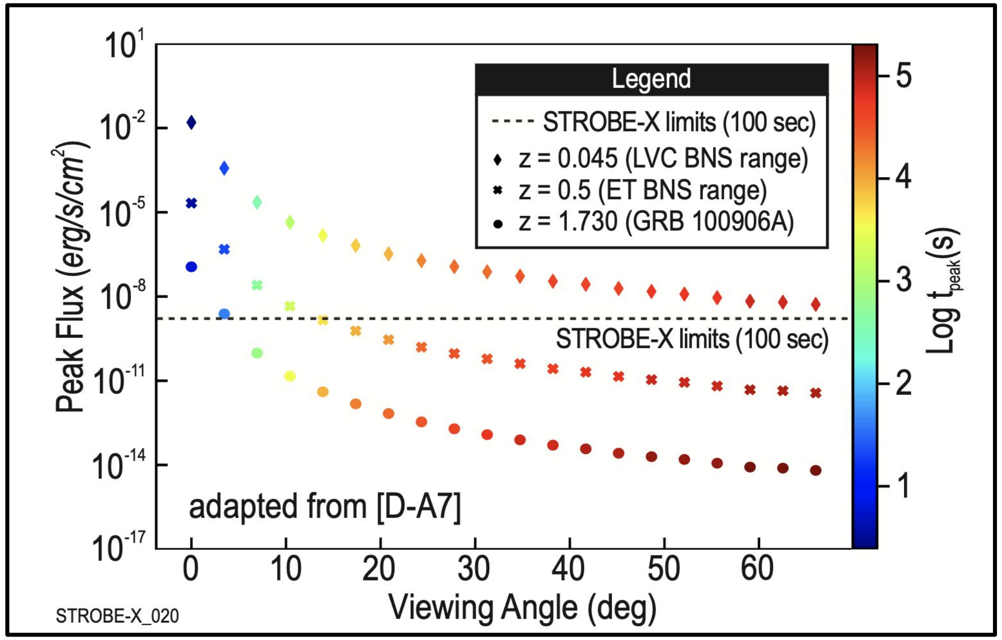
STROBE-X TDAMM



Neutron Star Mergers, GW sources

- Detect and localize > 5 NSM/yr
  - Timing, position to ground < 5 mins after trigger (positions of ~1' on the sky)
  - Up to ~20 joint GW/NSM per year with ET +.

- **X-ray Plateaus in sGRB light curves**
  - Remnant constraints: NS vs. BH, potentially out to z=2
  - Redshifts from absorption edge → constrain NSM delay time distributions



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STROBE-X TDAMM

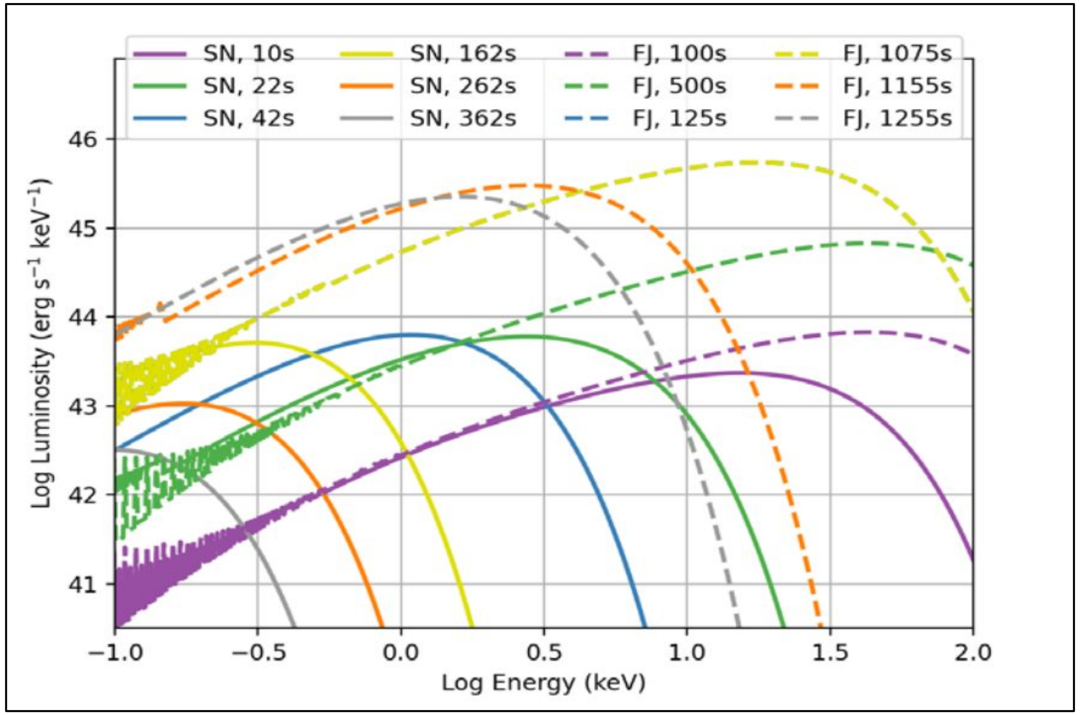
Neutrino Sources, Coincident with Blazar Flares:

- Constraining models of cosmic ray and neutrino production in blazar jets.
- WFM allows monitoring of ~100 bright AGN
- High cadence follow-up for flares of fainter AGN
- Expect > 5 over the mission

ICE CUBE/NASA

SN Shock Breakout + Early Emission:

- Constraining jet vs convection driven SNe
- Out to 200 Mpc



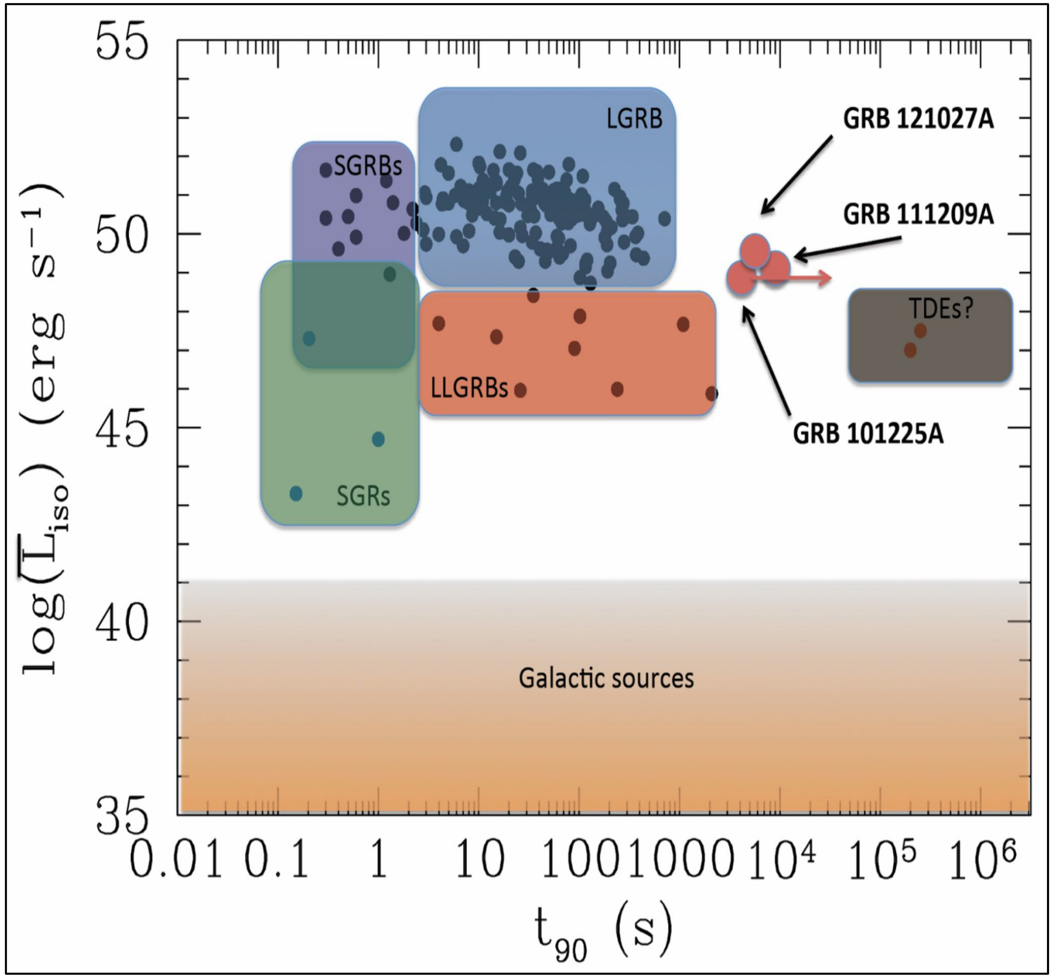
STROBE-X

STROBE-X TDAMM

Long GRBs

- **X-ray Flashes**: A significant subset of GRBs have a peak energy in the X-rays < 50 keV. Open question whether they are the "tail end" of a standard long GRB progenitor or are the result of a unique progenitor/central engine. > 10 XRFs/yr with STROBE-X.

- **Ultra Long GRBs**: GRBs with prompt emission > 1000s. Still unknown progenitor/physics. We expect > 4/yr with STROBE-X.



Levan, 2015

STROBE-X

STROBE-X and equation of state (Anna)

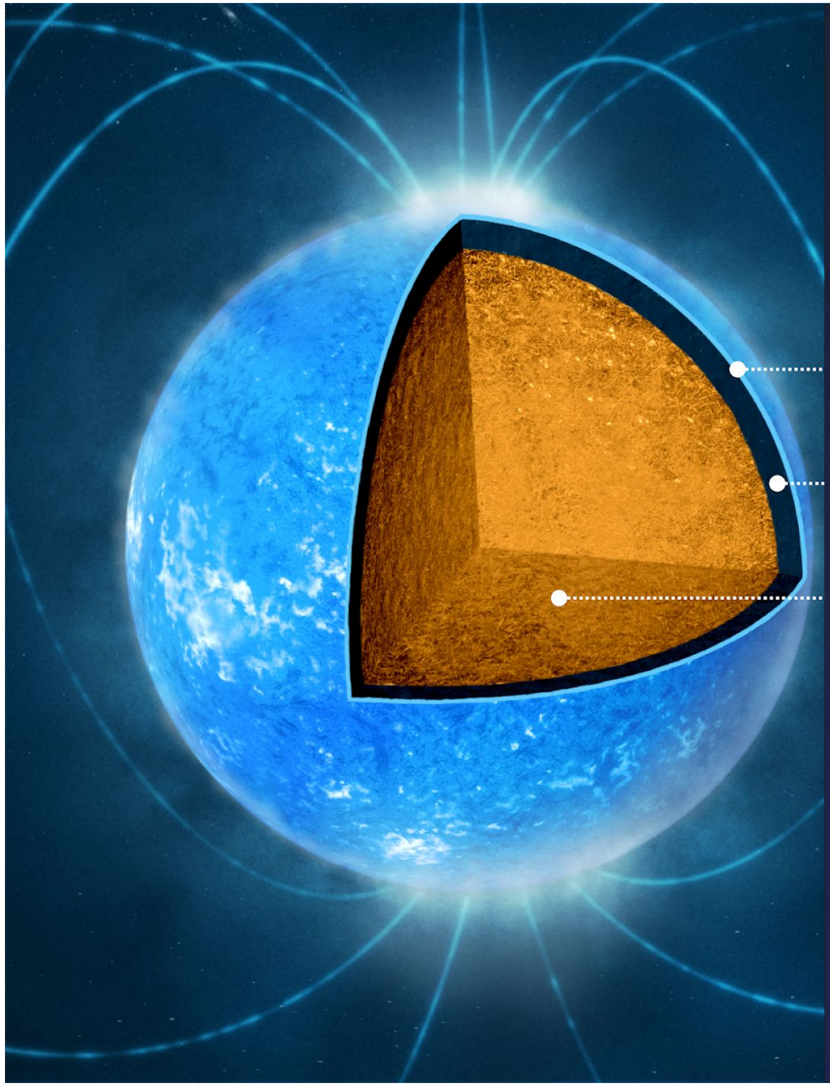
Dense matter EoS

Core reaches several times nuclear saturation density

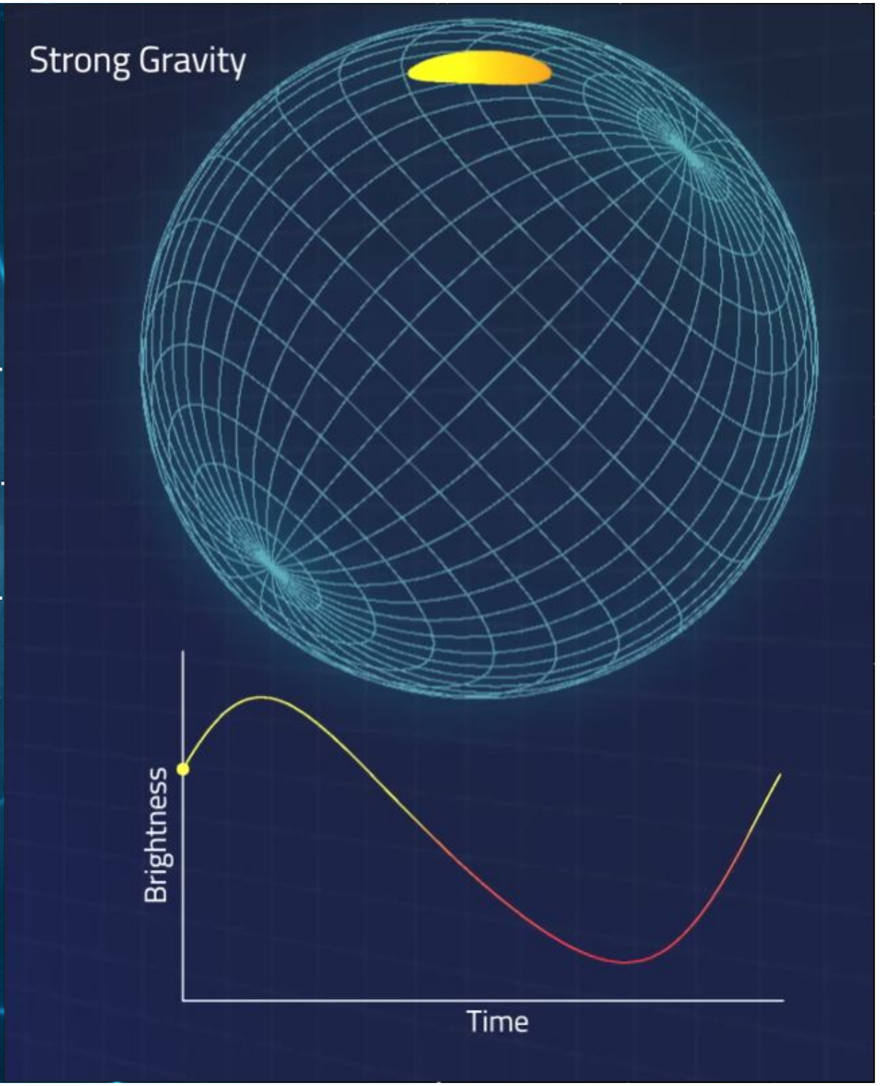
Neutron-rich nucleonic? Hyperons? Deconfined quarks?

Technique

Pulse profile modeling (PPM)



Watts et al. 2016



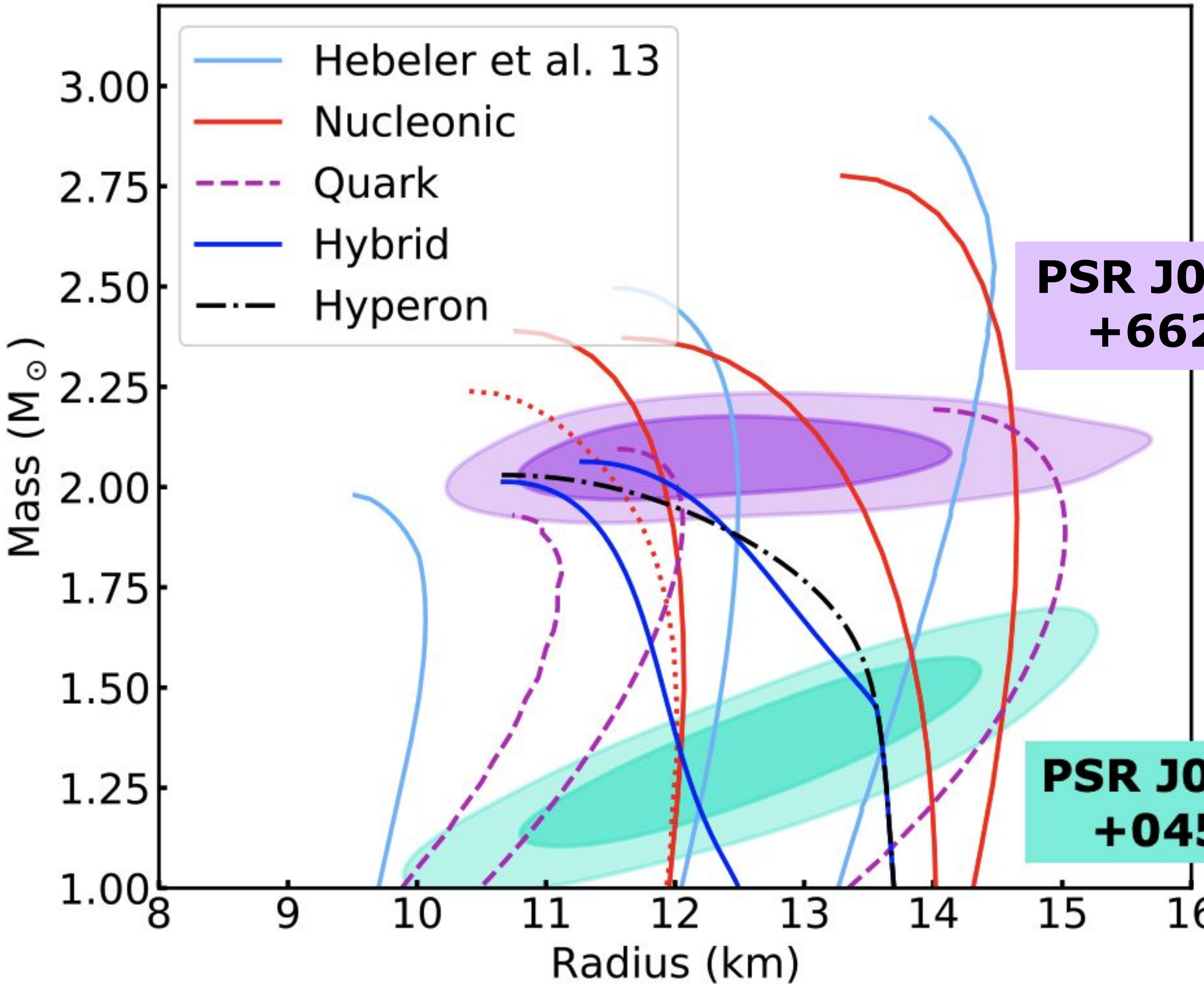
Morsink/Moir/Arzoumanian/NASA

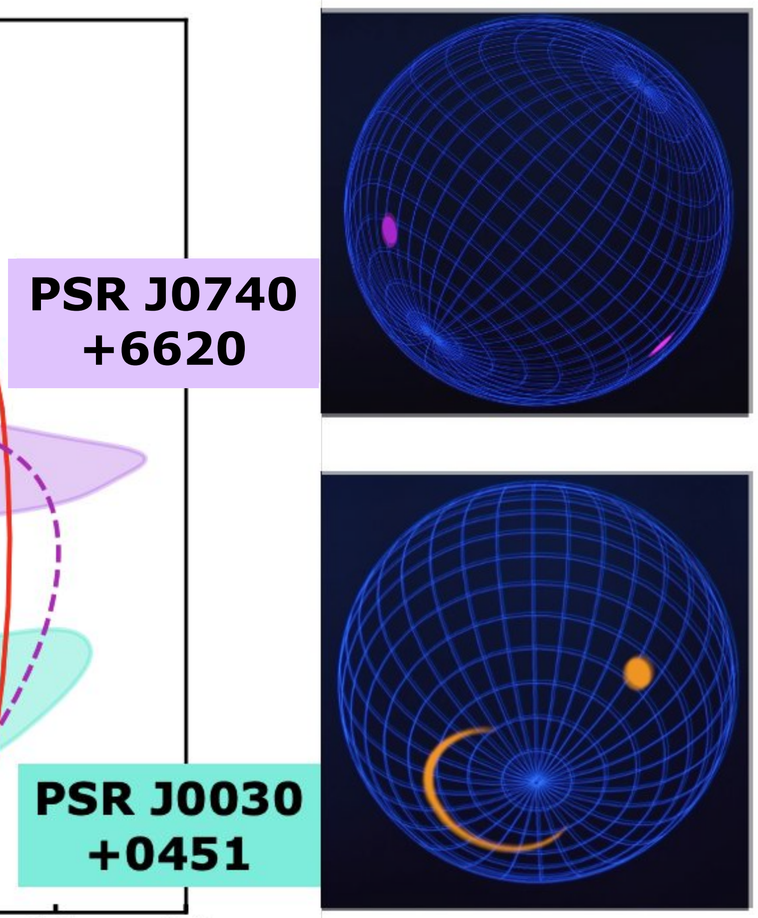
STROBE-X

STROBE-X and equation of state (Anna)

NICER: PPM of rotation-powered MSPs

To date: 2 sources with M, R at ±10% (68% credible interval)





Riley et al. 19, 21, Miller et al. 19, 21, Salmi et al. 22, 23, Vinciguerra et al. 24

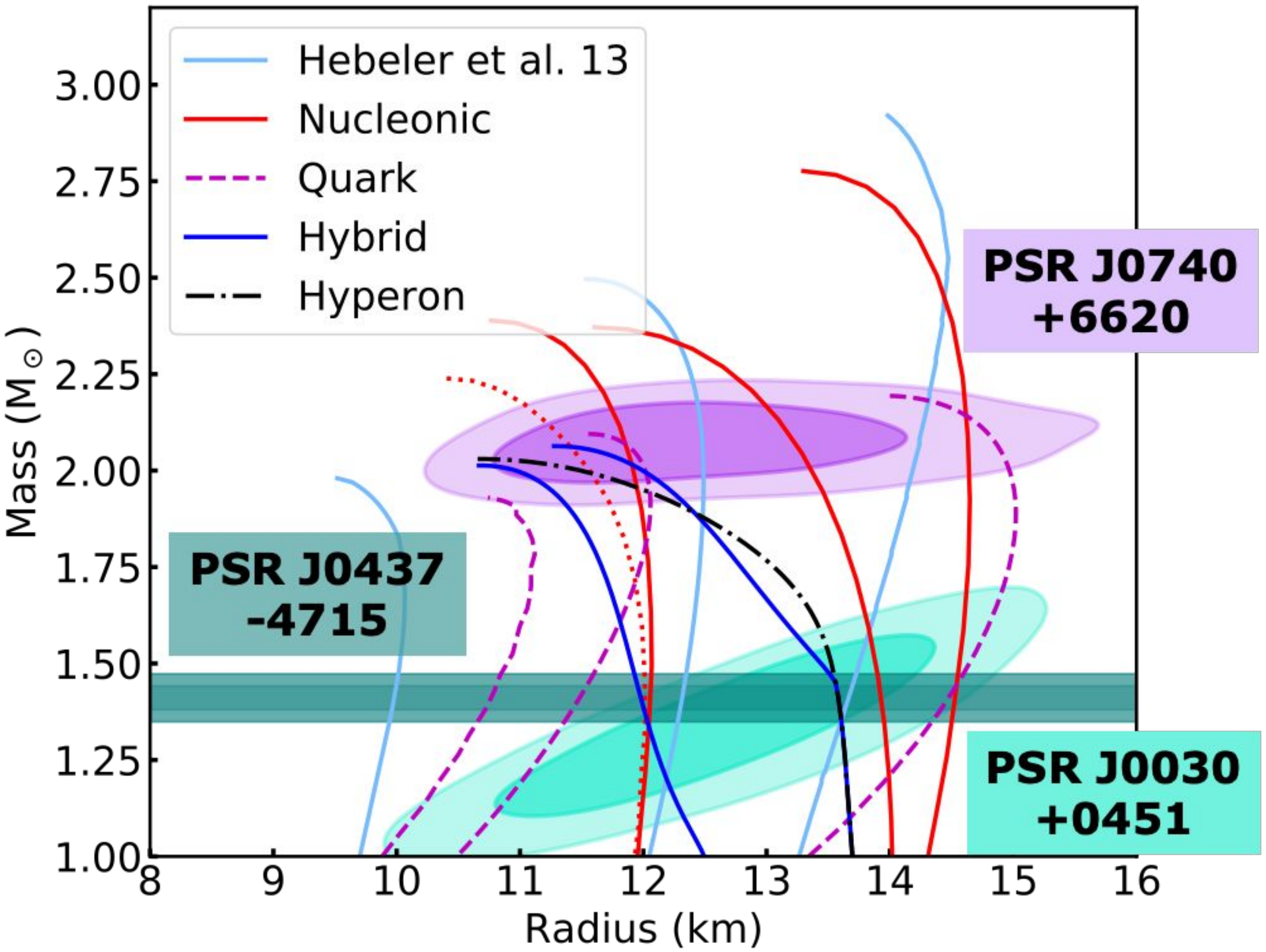
STROBE-X

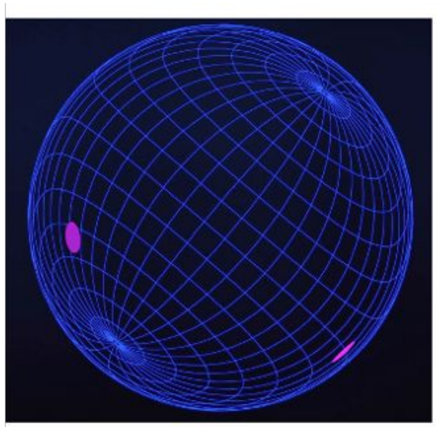
STROBE-X and equation of state (Anna)

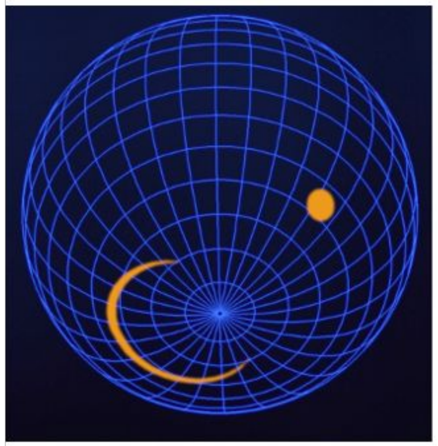
NICER: PPM of rotation-powered MSPs

To date: 2 sources with M, R at ±10% (68% credible interval)

New results this week (at APS April) for PSR J0740+6620 and PSR J0437-4715







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Salmi et al., Dittmann et al., Choudhury et al. submitted

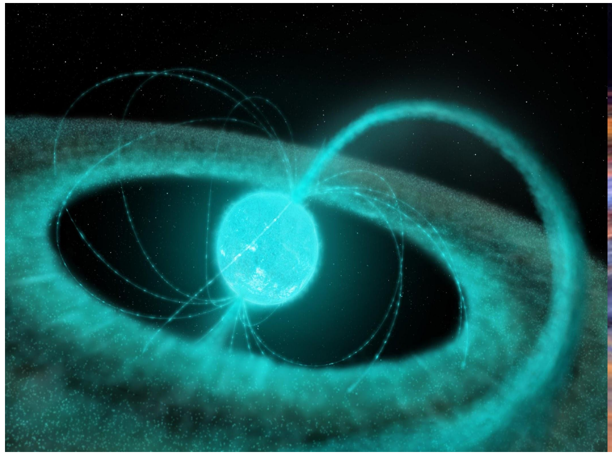
STROBE-X

STROBE-X and equation of state (Anna)

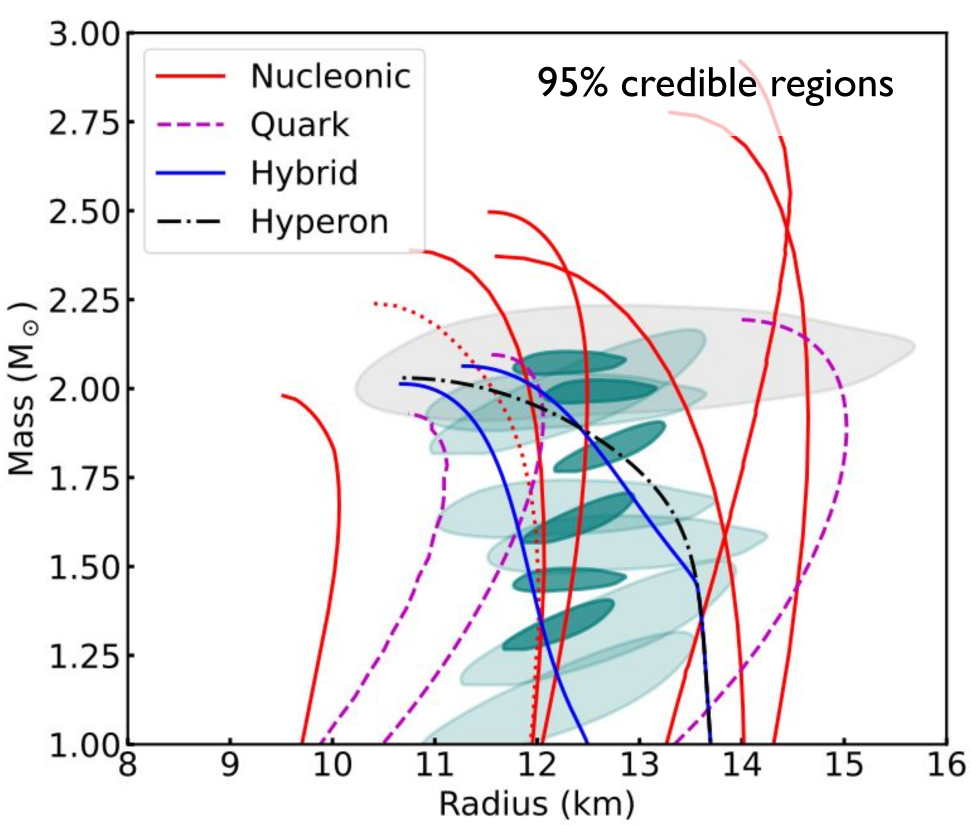
PPM with STROBE-X

Faint RMSPs (with mass priors).

Accreting NS (accretion-powered pulsations and burst oscillations).



Variability, atmosphere models, challenging but tractable (e.g. Salmi et al. 18, Kini et al. 23, 24)



Initial survey to ± 5%, cross-checks to address systematics. Deep observations to hit ± 2-3% for most promising sources.

STROBE-X

Images:

EOS studies: Rutherford et al. 2023, Huang et al. 2024

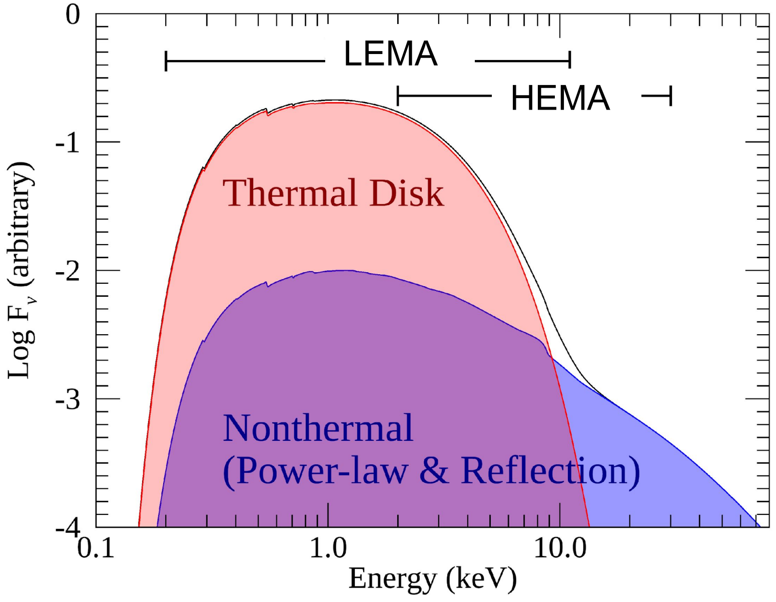
Gravity and Extreme Physics: Black Holes

Goal: Determine black hole spin across the mass scale from stellar-mass to supermassive

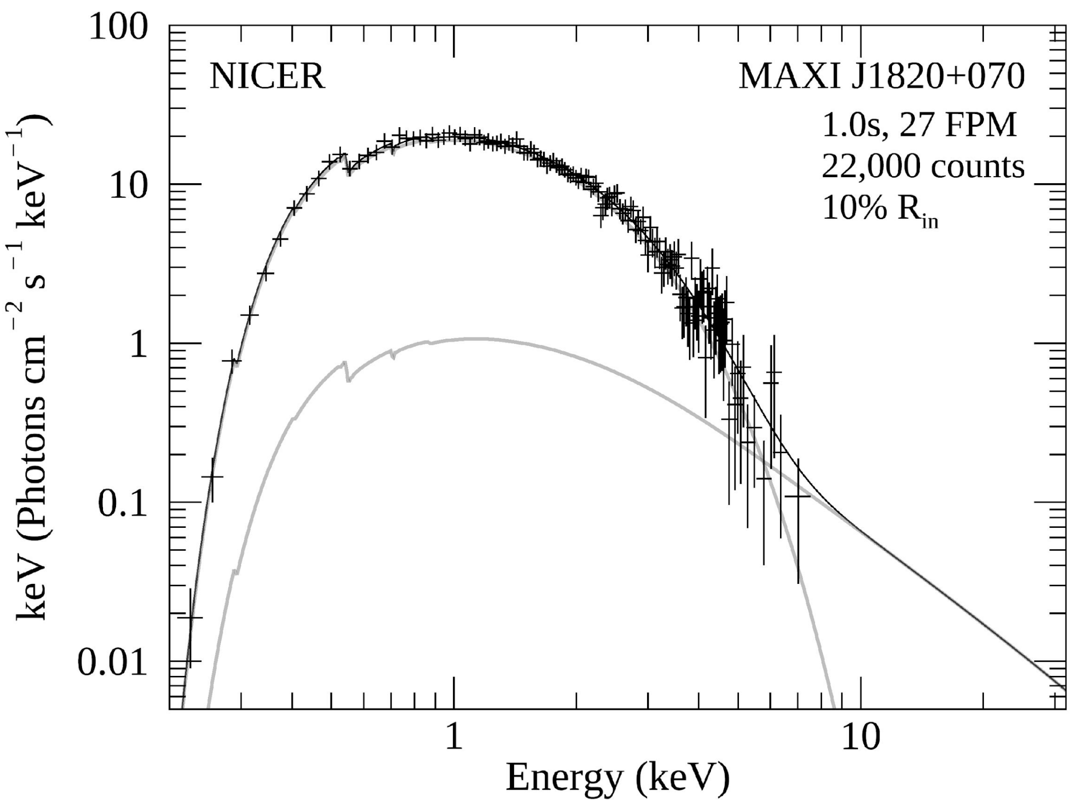
- Continuum Spectroscopy
- Reflection Spectroscopy
- Reverberation and QPO timing

Key corollary: calibrate and validate spin-measurement methods

Continuum Spectroscopy of Stellar-Mass BHs



- Current state-of-the-art reaches viscous timescale



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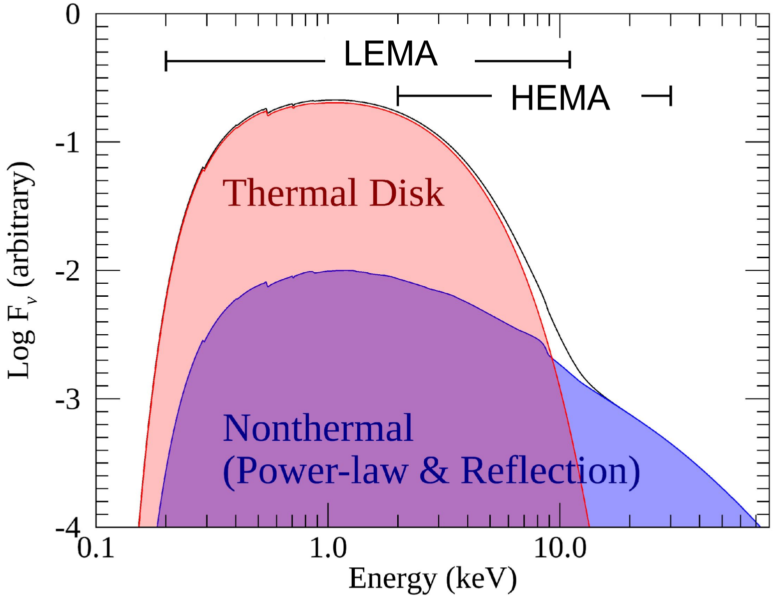
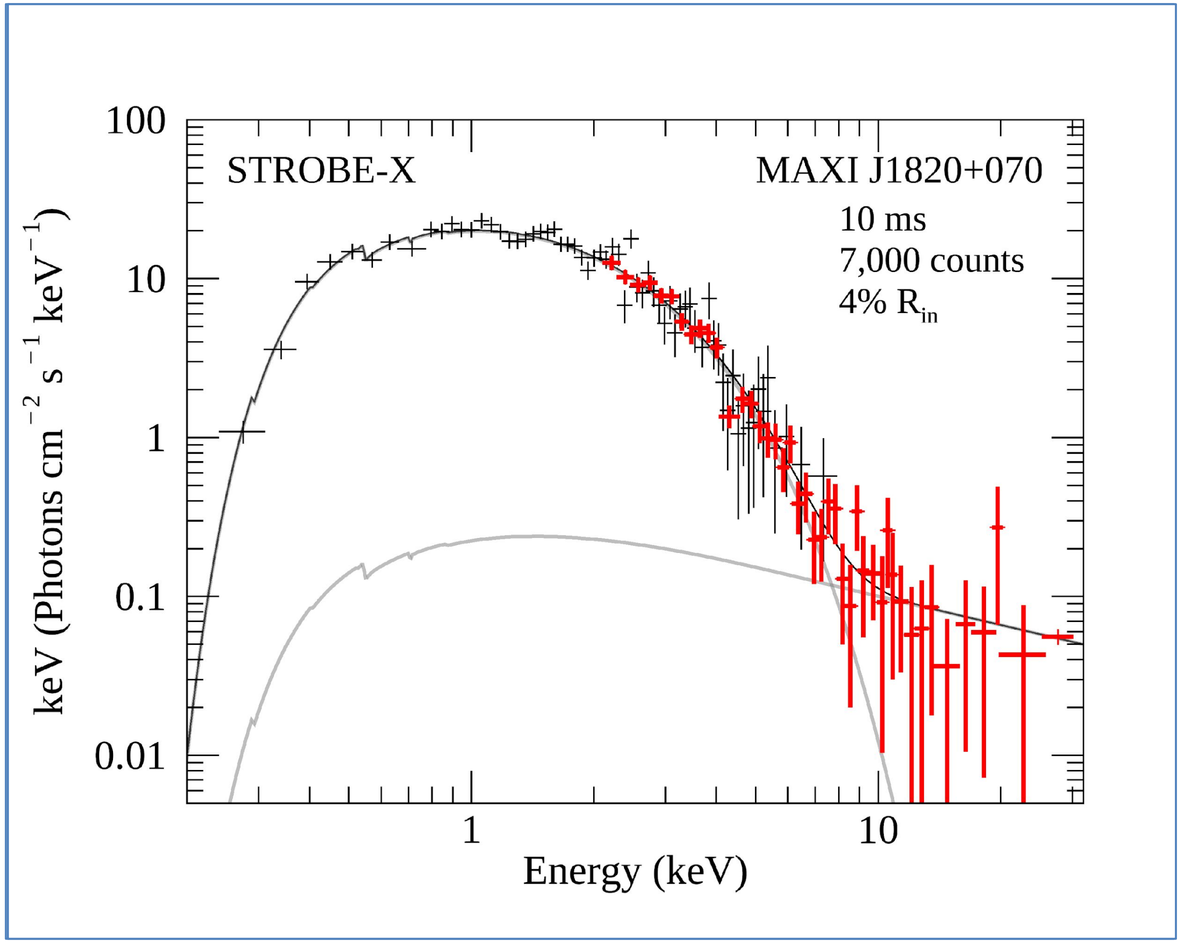
Continuum Spectroscopy of Stellar-Mass BHs



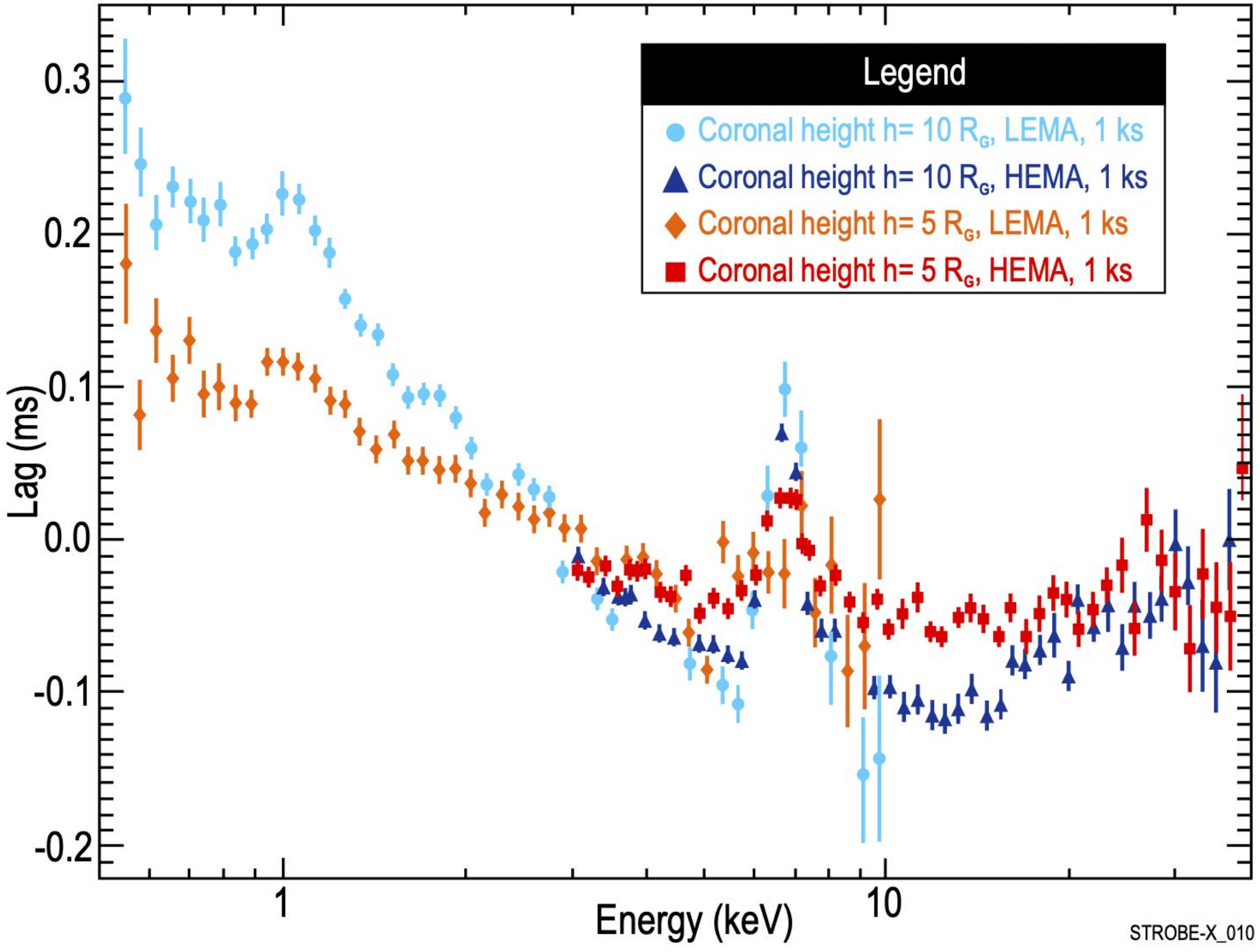


- STROBE-X will probe *dynamical* timescales!
  - with higher precision

STROBE-X

Reflection & Reverberation in Stellar-Mass BHs

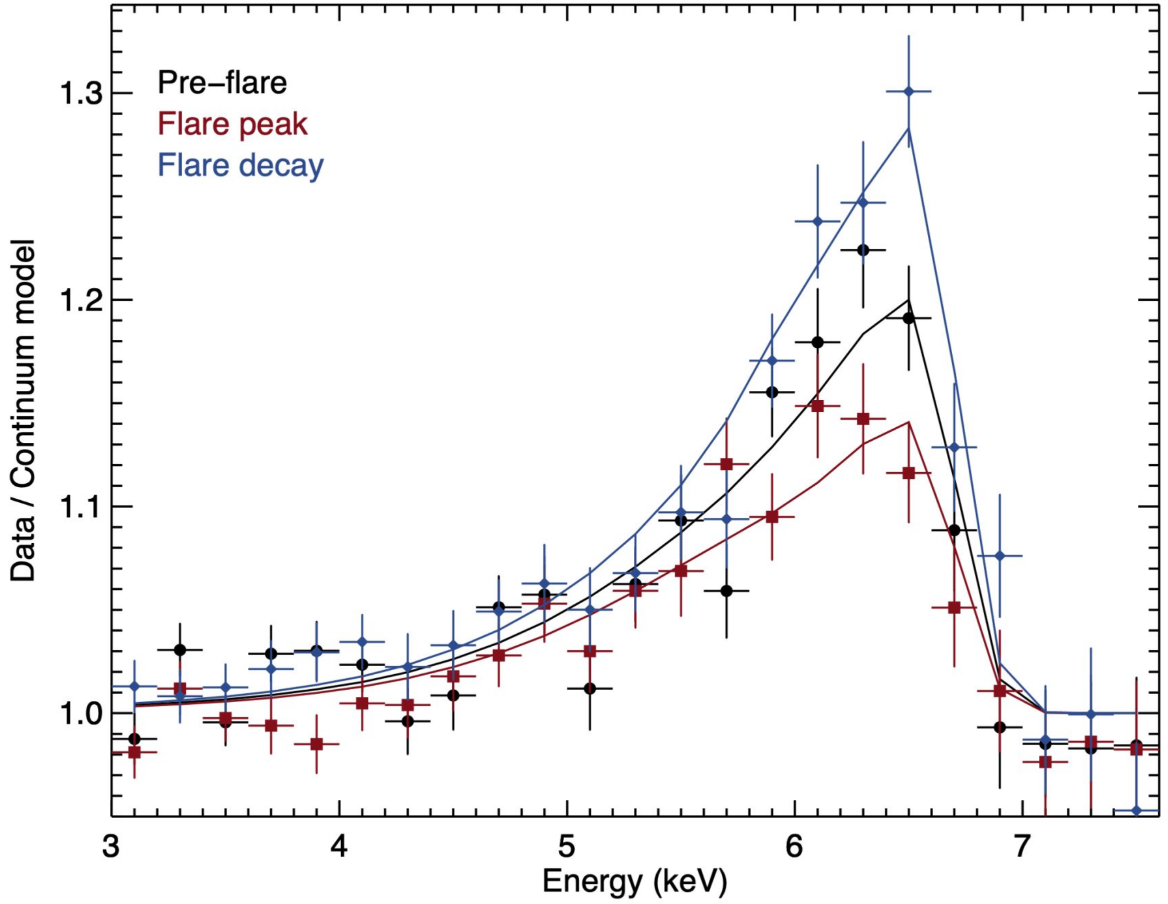
- Simulated typical BH transient, based on GX 339-4
- Lags measured with high precision over short timescales
- Precisely constrains disk-coronal geometry and spin



STROBE-X

Reflection & Reverberation in AGN

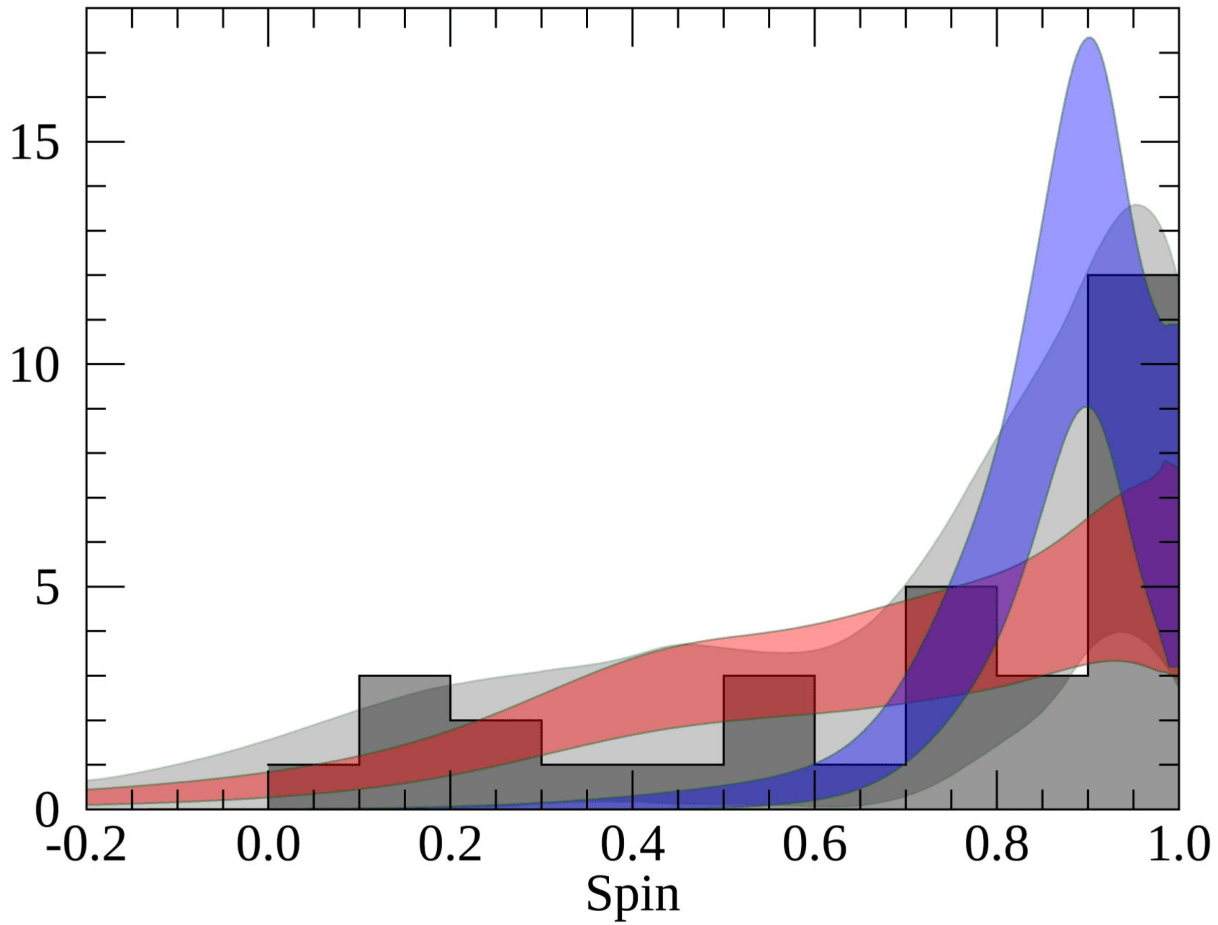
- Simulation with STROBE-X of MCG-6-30-15, based on Wilkins et al. (2021).
- The corona flares, increasing 2.5x in 5ks. 1.5ks bins of LEMA+HEMA spectra capture the effect of the flare on the relativistically-broadened Fe-K line.
- The Fe-K response is delayed with respect to the coronal continuum emission, so that the line initially appears weaker, and then appears appreciably stronger as the fluorescence peaks while the continuum has diminished.
- The line profile evolves with as the flare propagates to different regions of the disk.



STROBE-X

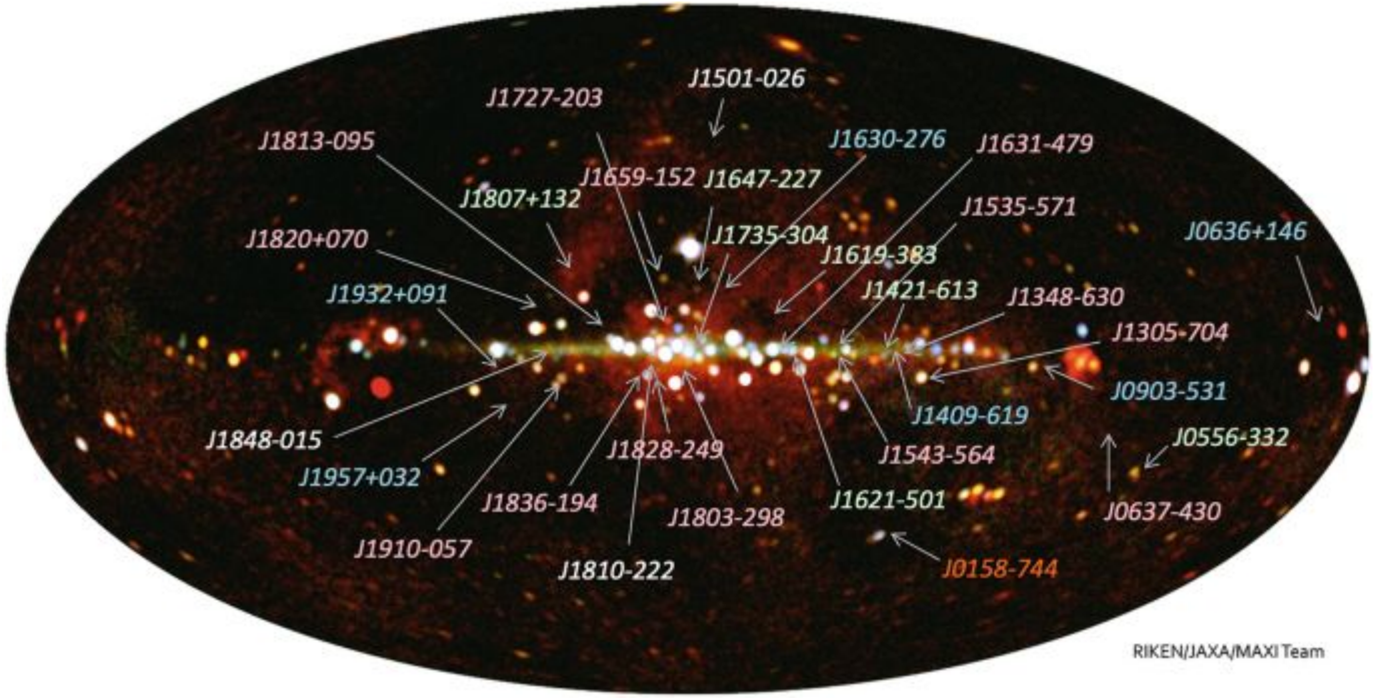
What we can learn: Stellar-Mass BH example

- Histogram of BH spins from current thermal and reflection fit results (gray)
- Colored bands show simulated 95% distributions after 5 years of STROBE-X operation for distinct but presently viable models (i): continuous in spin (red) or (ii) unimodal (blue)
- These scenarios are readily distinguished from one another via STROBE-X



STROBE-X

The dynamic Universe (Tom)



Daily maps with ~5 mCrab sensitivity

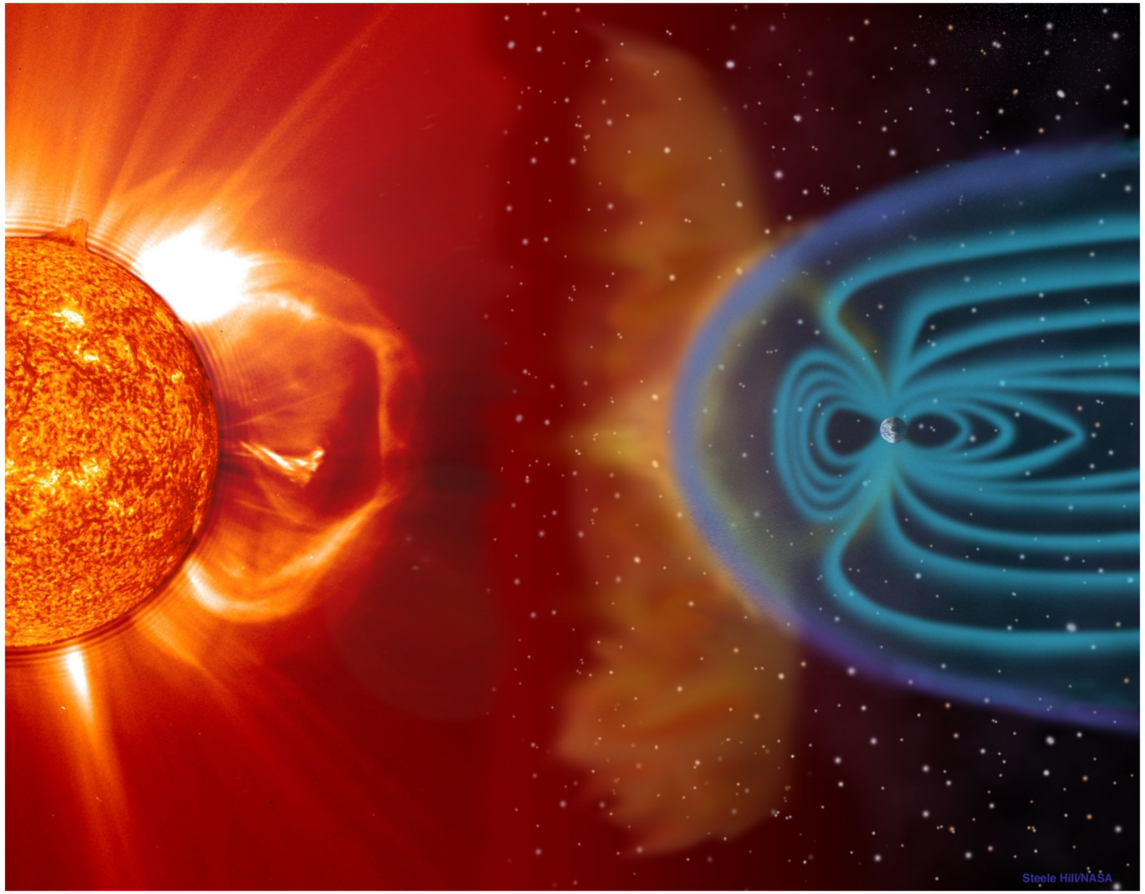
5' resolution, avoiding the confusion near the Galactic Center that plagues many wide-field instruments

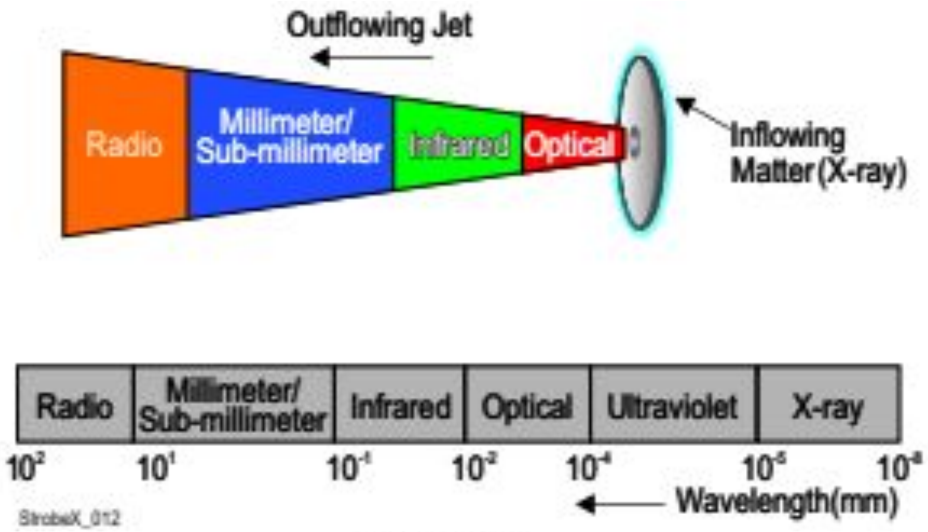
Swift-like flexibility in follow-up, but with ability to make spectra and power spectra for discovered sources

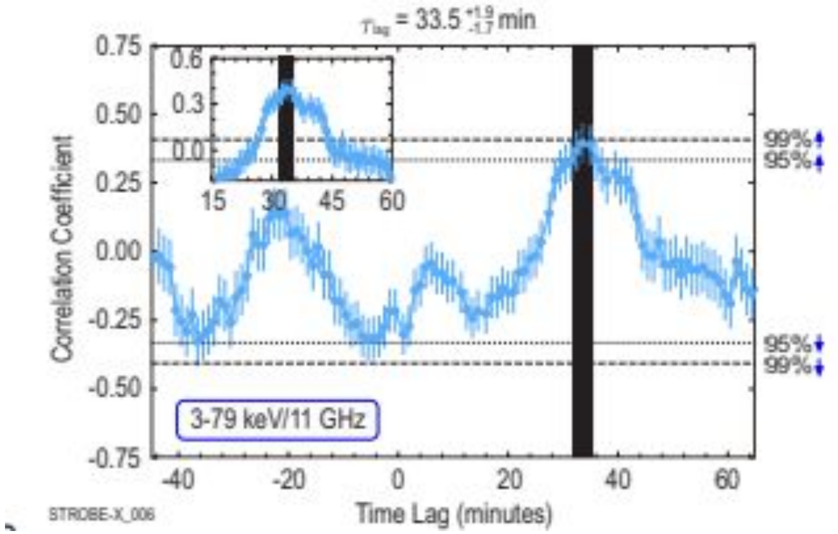
Over years, will stack up to be the best medium-energy X-ray survey ever made

STROBE-X

STROBE-X GO science



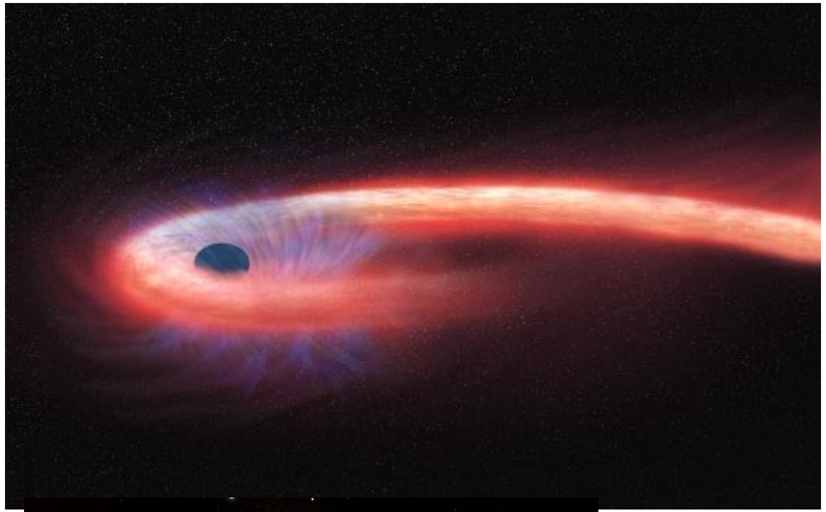




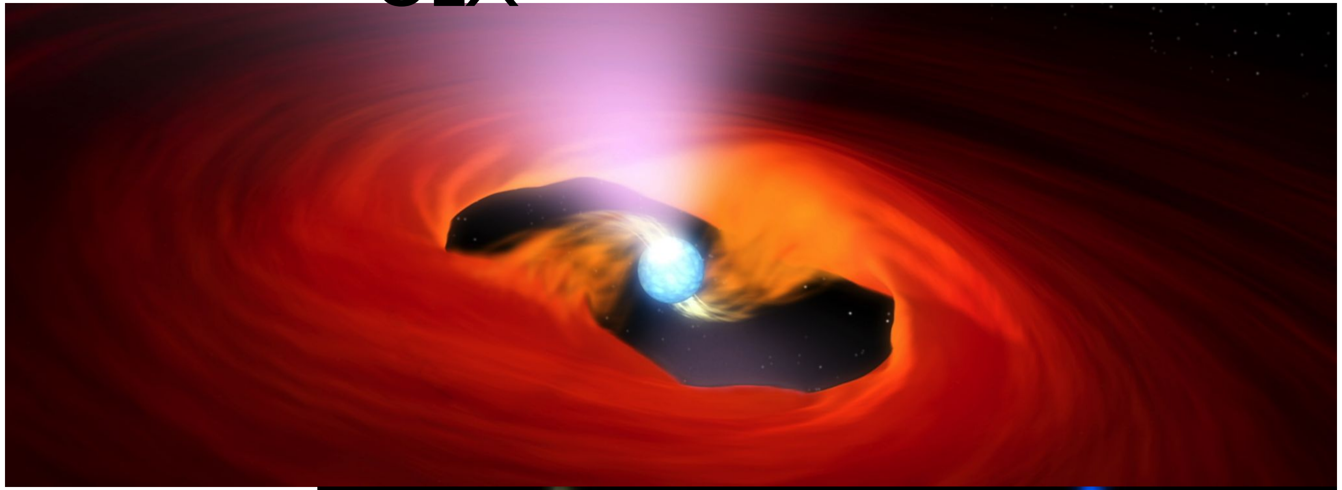
STROBE-X

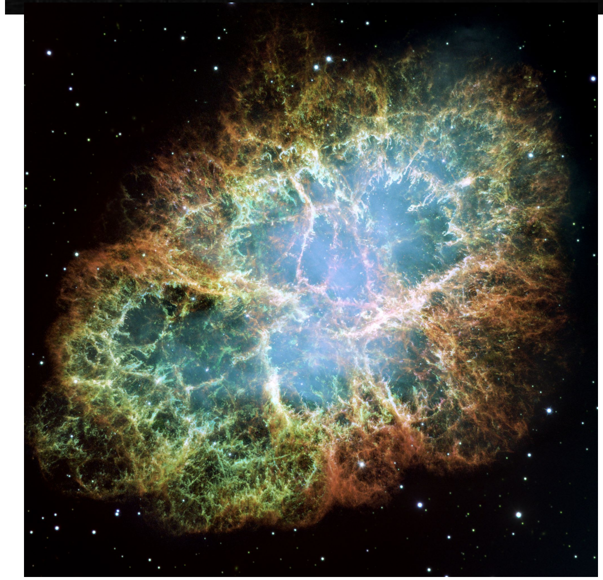
STROBE-X GO science

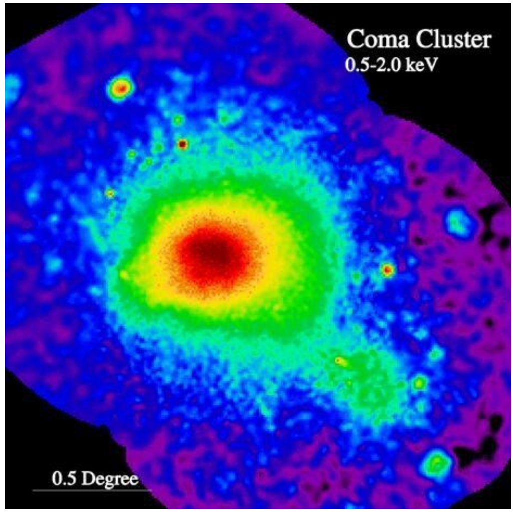
TDE

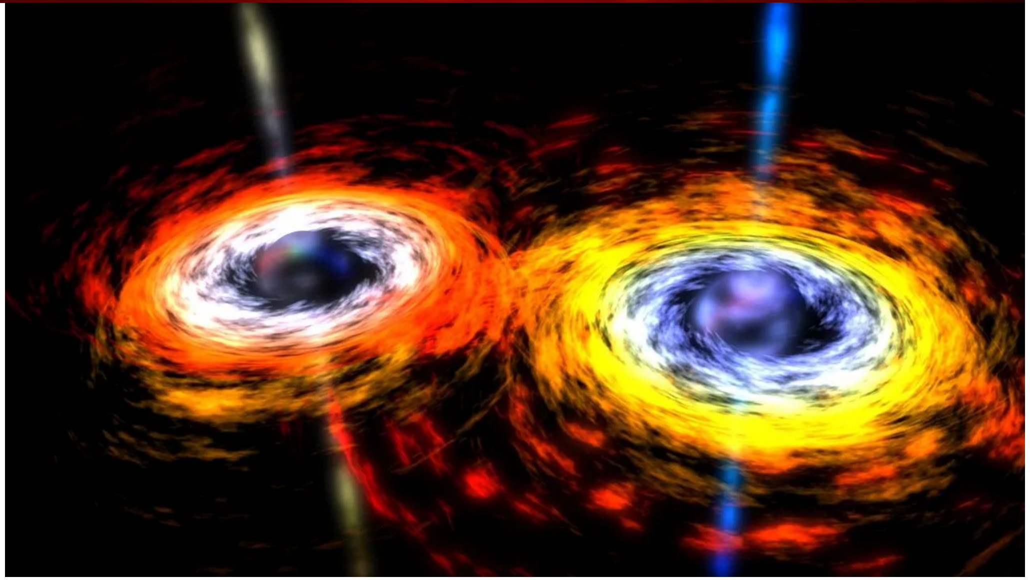


ULX









high-Z elements

Merging supermassive BHs

STROBE-X

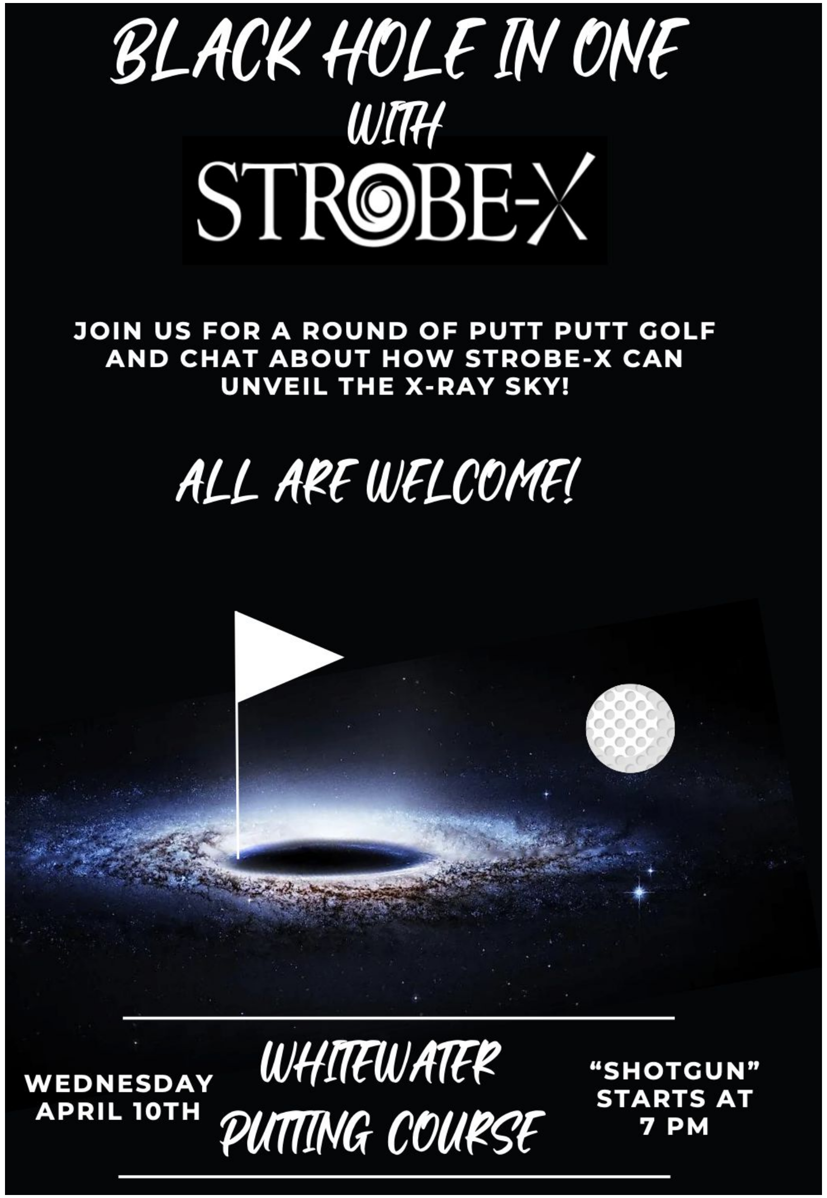
Summary

STROBE-X will capture the Universe in motion, allowing spectroscopic monitoring instead of just flux monitoring

Capabilities span all key NASA goals

This will be *your* observatory, with about 7000 guest observations per year

Questions directed to Paul Ray in the chat



https://strobe-x.org
@STROBEXastro

STROBE-X

Mission and instrument papers will appear soon in JATIS (and arXiv)