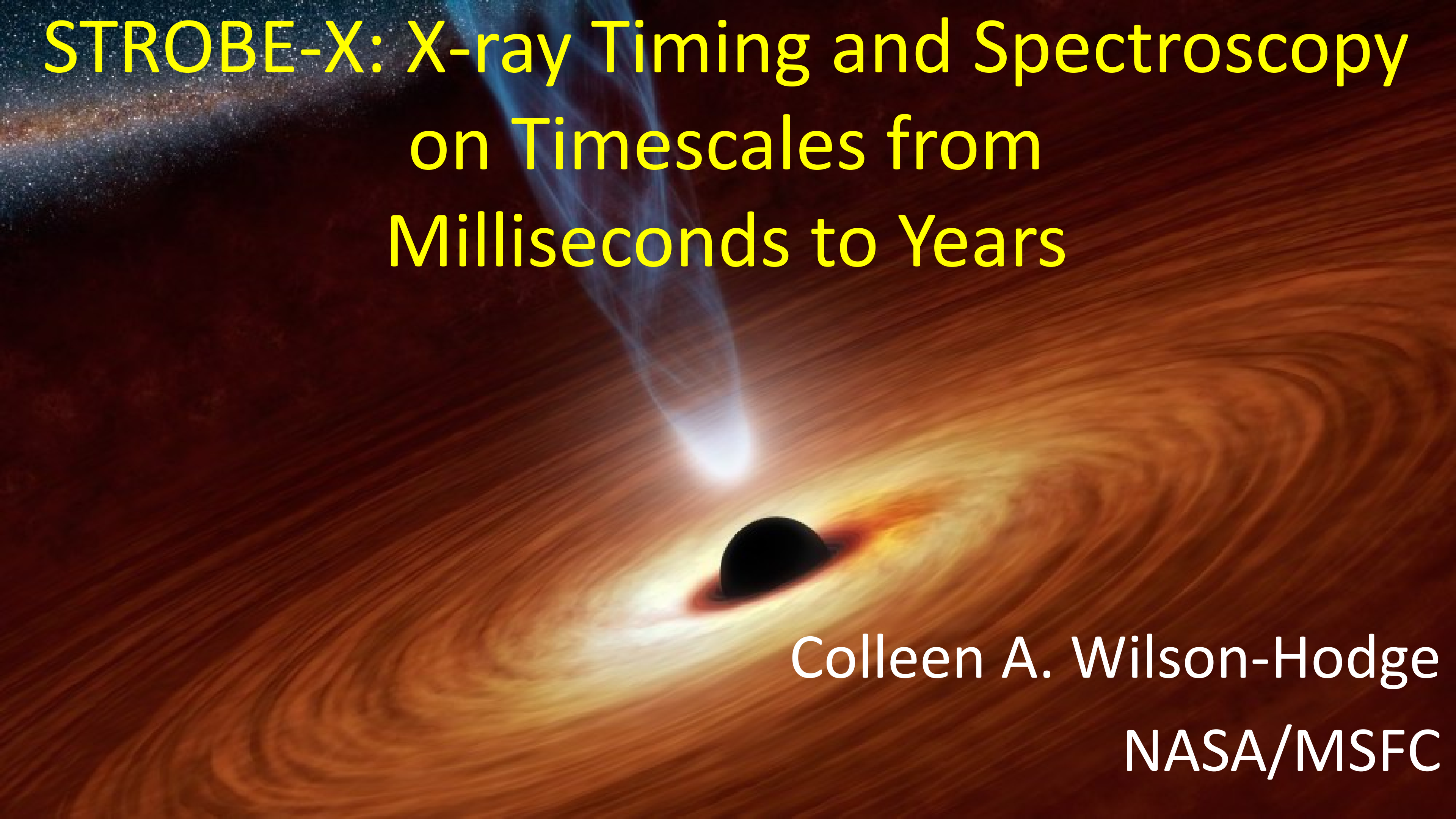


STROBE-X: X-ray Timing and Spectroscopy on Timescales from Milliseconds to Years

Colleen A. Wilson-Hodge
NASA/MSFC

Outline

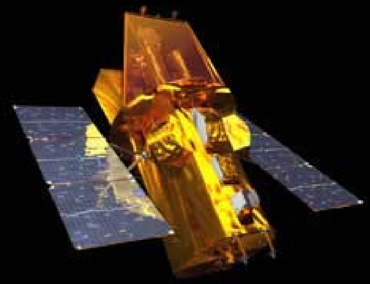
- Introduction
- STROBE-X science
  - Stellar mass black holes
  - Active galactic nuclei
  - Neutron star equation of state
  - Time domain astrophysics
- STROBE-X Mission
  - STROBE-X Instruments
    - X-ray Concentrator Array
    - Large Area Detector
    - Wide field Monitor

Why a Flexible, High-Throughput Observatory?

- The high-energy sky is highly dynamic –requires catching the right source at the right time
  - Necessitates both wide field monitoring and the ability to repoint quickly (as RXTE and Swift have demonstrated)
  - Critical capability in the era of time domain astronomy
- Large areas with low dead time access the shortest timescales
- Both soft and hard X-ray bands are needed to accurately measure the continuum spectral shape, constrain absorption, and understand the relationship between thermal and non-thermal components

STROBE-X and NASA Missions

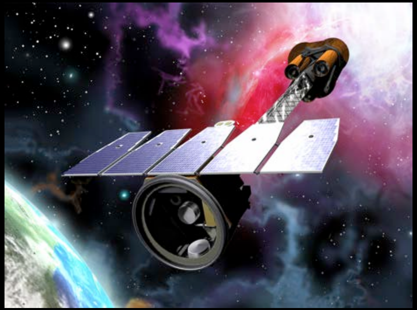
RXTE 1995-2012



Swift 2004-

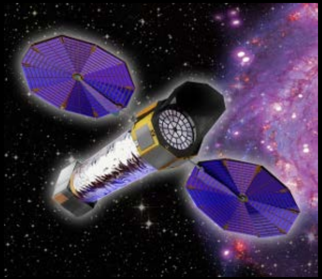
Fermi 2008-

NICER 2017-



IXPE 2020-

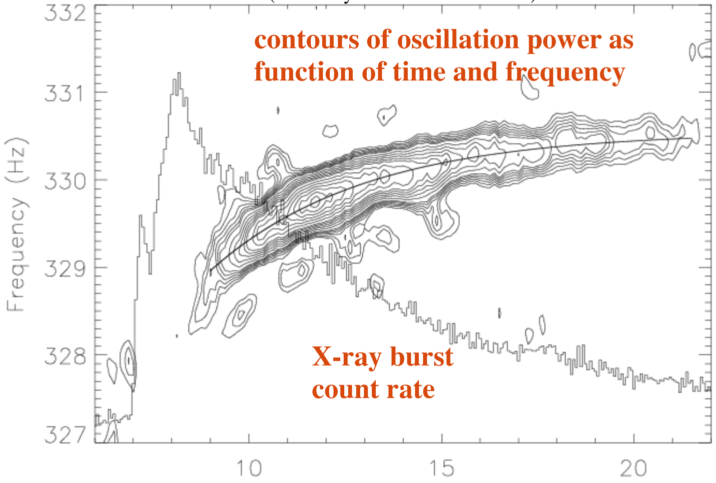
Chandra 1999-

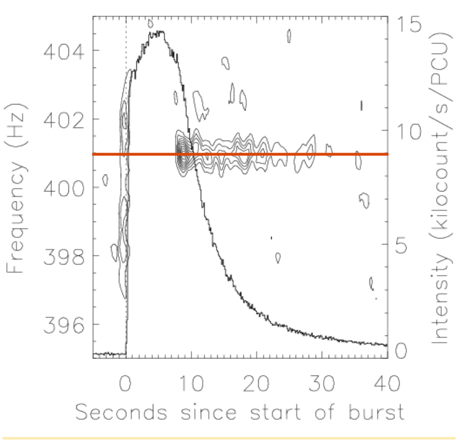


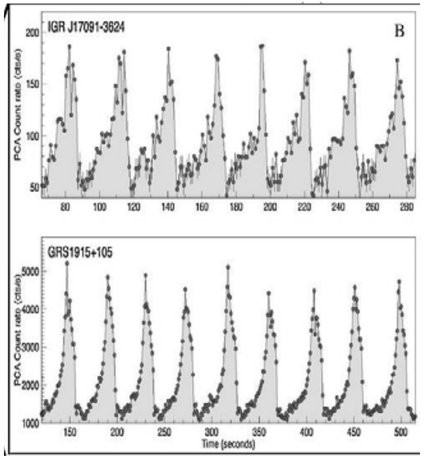
Lynx 2030?

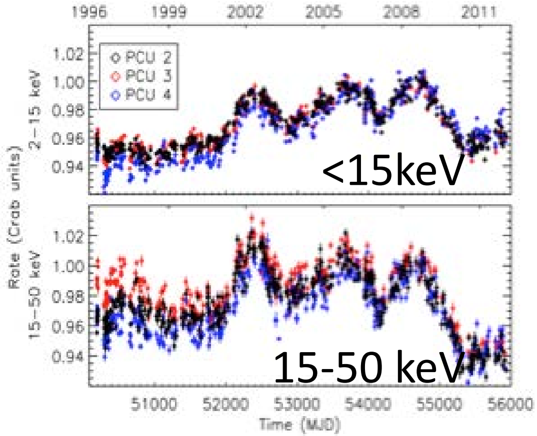
Rossi X-ray Timing Explorer Highlights

4U 1702-43 (Strohmayer & Markwardt 1999)

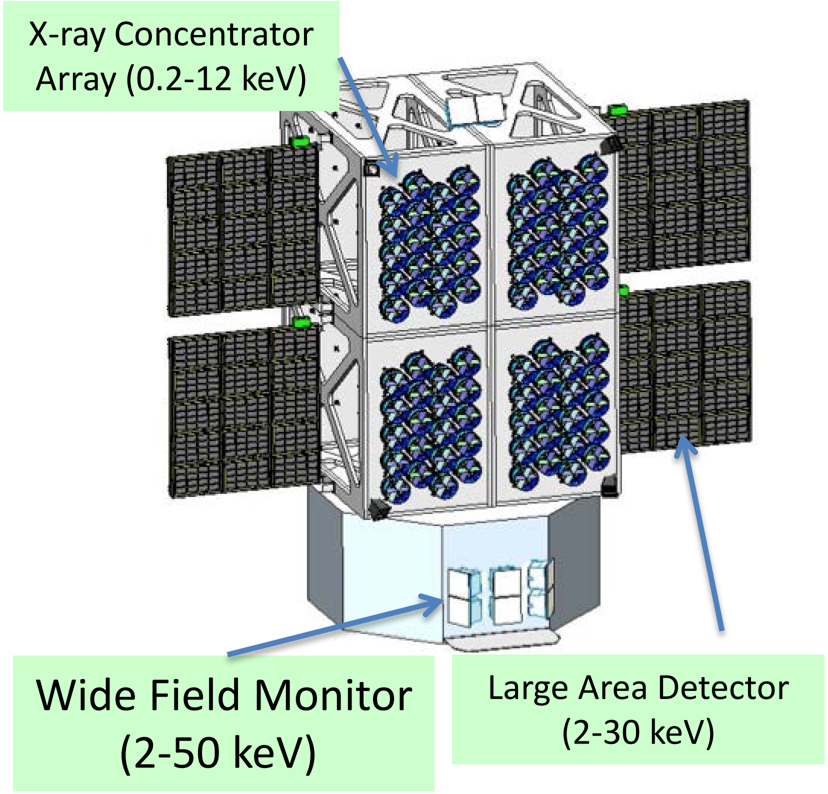




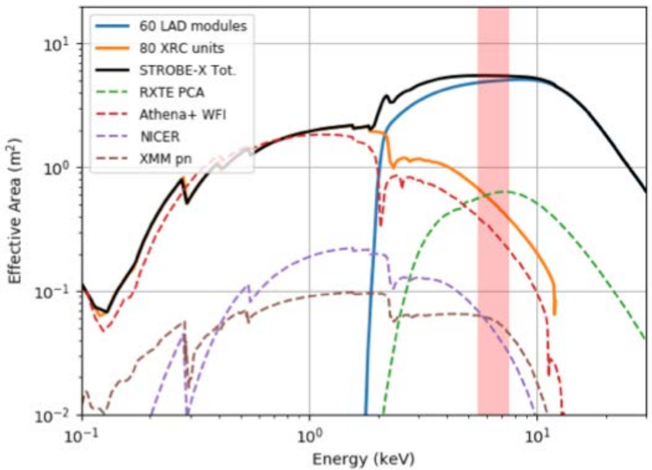




STROBE-X Instrument Concept



Large effective area >5 m^2 @ 6 keV



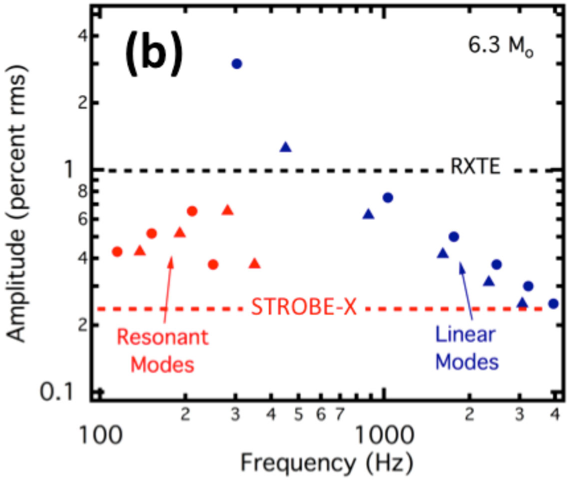
- STROBE-X combines the strengths of NICER and LOFT: High throughput X-ray timing with good spectroscopy
- All components are already high TRL
- Highly modular design improves reliability at reduced cost and allows easy scaling.

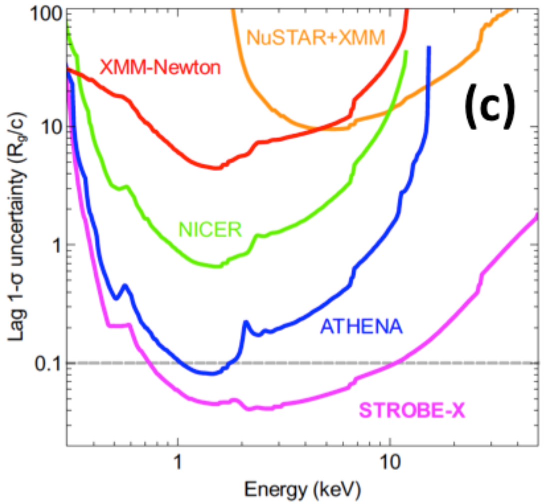
STROBE-X Science Goals

STROBE-X is designed for both timing and spectroscopy in the 0.2-30 keV X-ray band, with huge collecting area and good spectral resolution.

It is optimized for the study of matter in the most extreme conditions found in the Universe and addresses several key science areas, including:

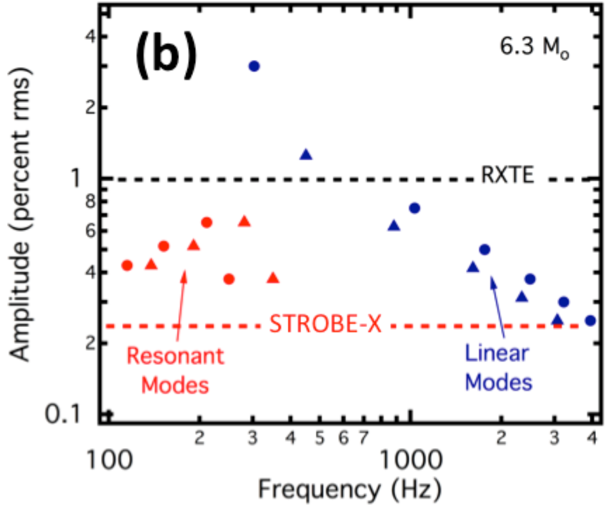
- Probing stationary spacetimes near black holes (BHs) to explore the effects of strong-field gravity and measure masses and spins of BHs.
- X-ray reverberation mapping of BH accretion flows across all mass scales, from stellar BHs in our Galaxy to supermassive BHs in active galactic nuclei
- Fully determining the equation of state of ultradense matter by measuring the neutron star mass-radius relation using ~20 pulsars over an extended mass range
- Continuously surveying the dynamic X-ray sky with large duty cycle and high spectral and timing resolution. Cross-correlation with high-cadence surveys at other wavelengths and in gravitational waves and neutrinos.

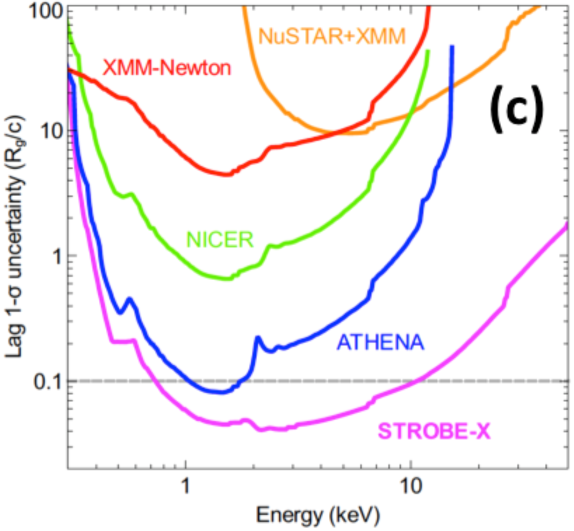




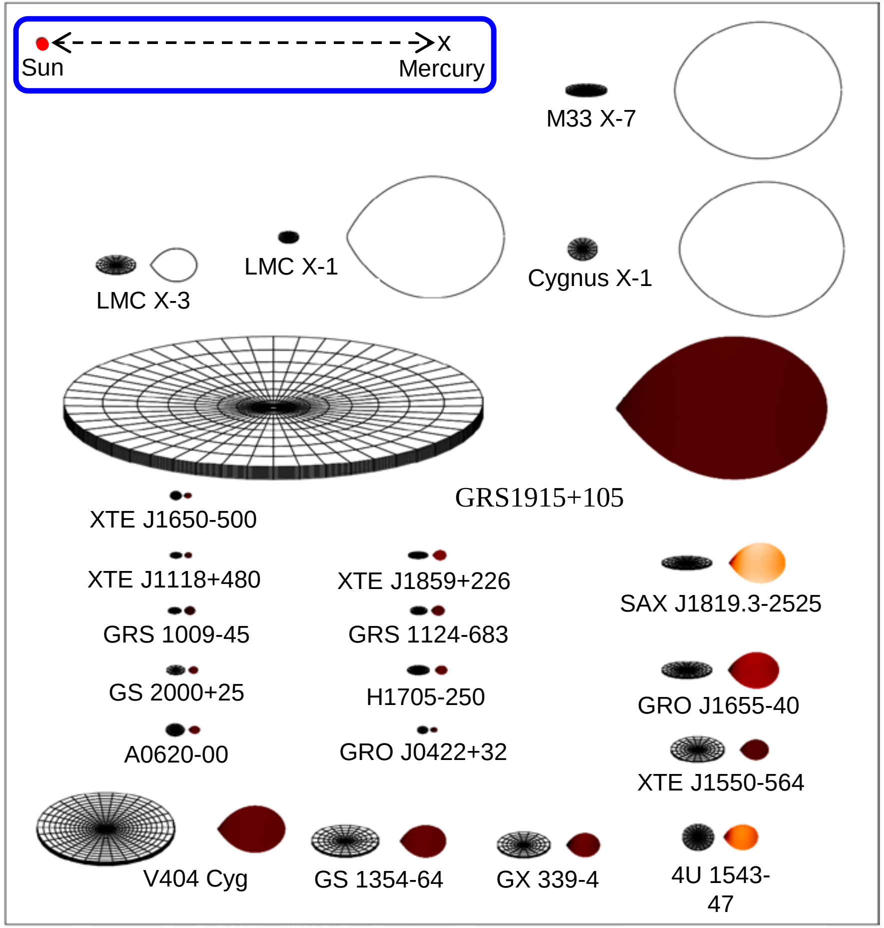
Black Holes on All Mass Scales

- Three complementary approaches to measuring black hole spin: HFQPOs, continuum fitting and reflection fitting all accessible with STROBE-X
  - Critical for understanding systematics of each technique
- X-ray reverberation probes geometry for both stellar mass BH and AGN
  - Limiting factor usually photon count, so STROBE-X will probe changes in accretion geometry on timescales shorter than the dynamical timescale of AGN
  - Stellar mass BH will be mapped through all spectral states and LAD will measure lags associated with Compton hump
- Also, disk winds, QPOs, state changes, disk-jet connection and more!



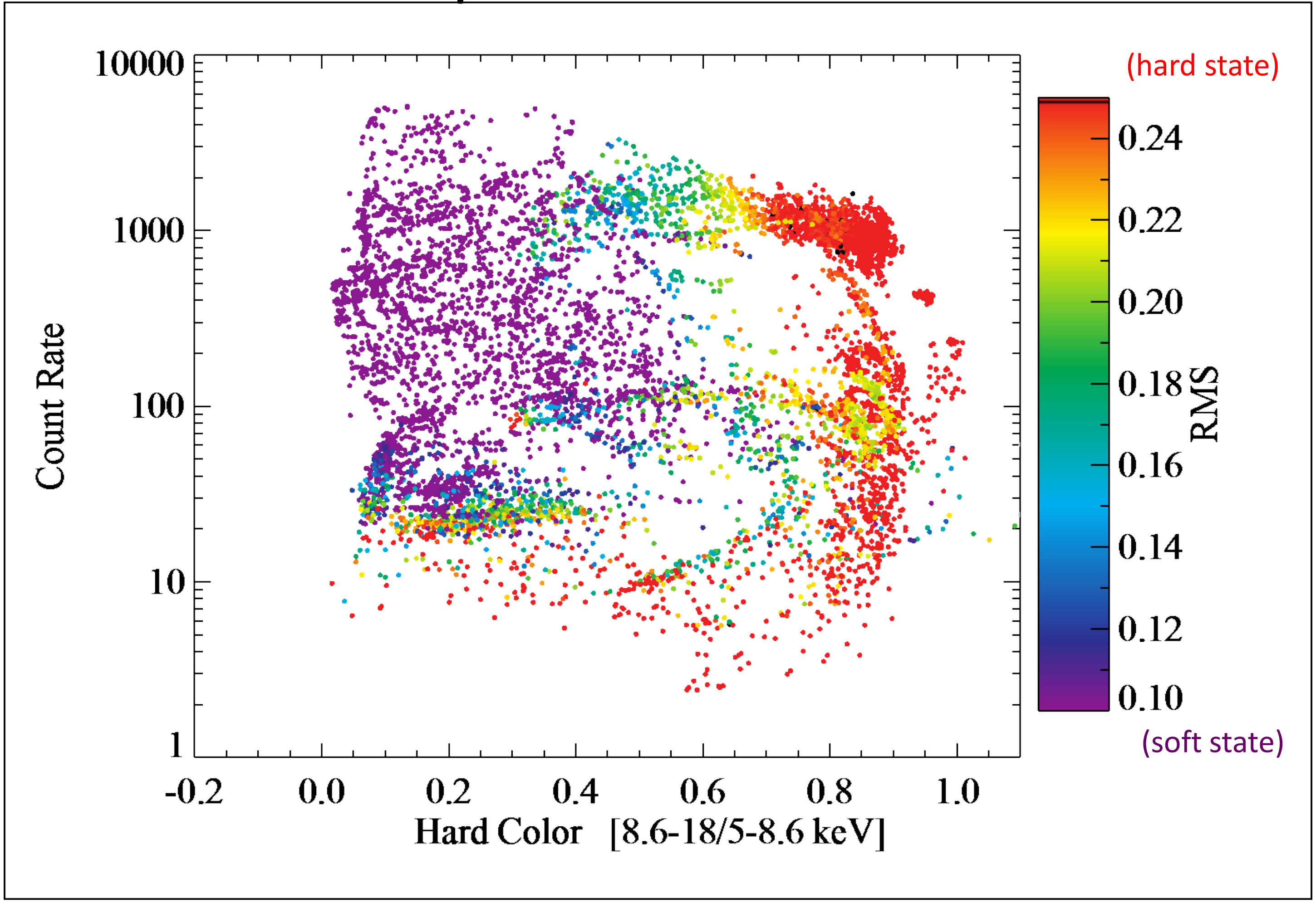


The Current Black Hole Binary Zoo



Courtesy: J. Orosz

RXTE's Map of Black Hole Behavior



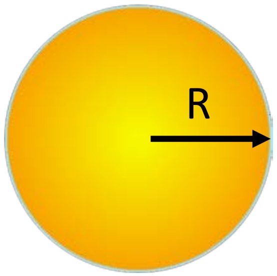
Measuring R_{in} via Thermal Continuum Fitting

Radius R of a Star

$L = 4\pi D^2 F = 4\pi R^2 \sigma T^4$

Solid angle: $(R/D)^2 = F/\sigma T^4$

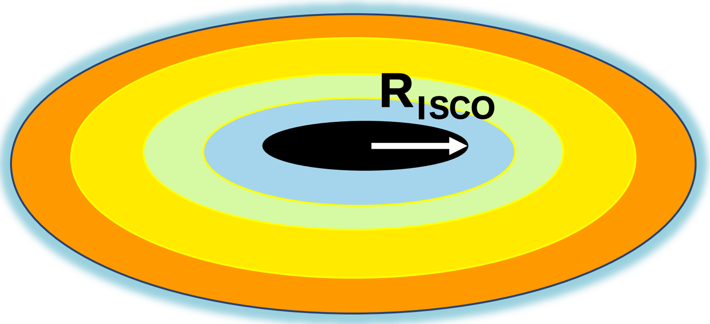
$D \rightarrow$ R



Radius $R_{\rm ISCO}$ of Disk Hole

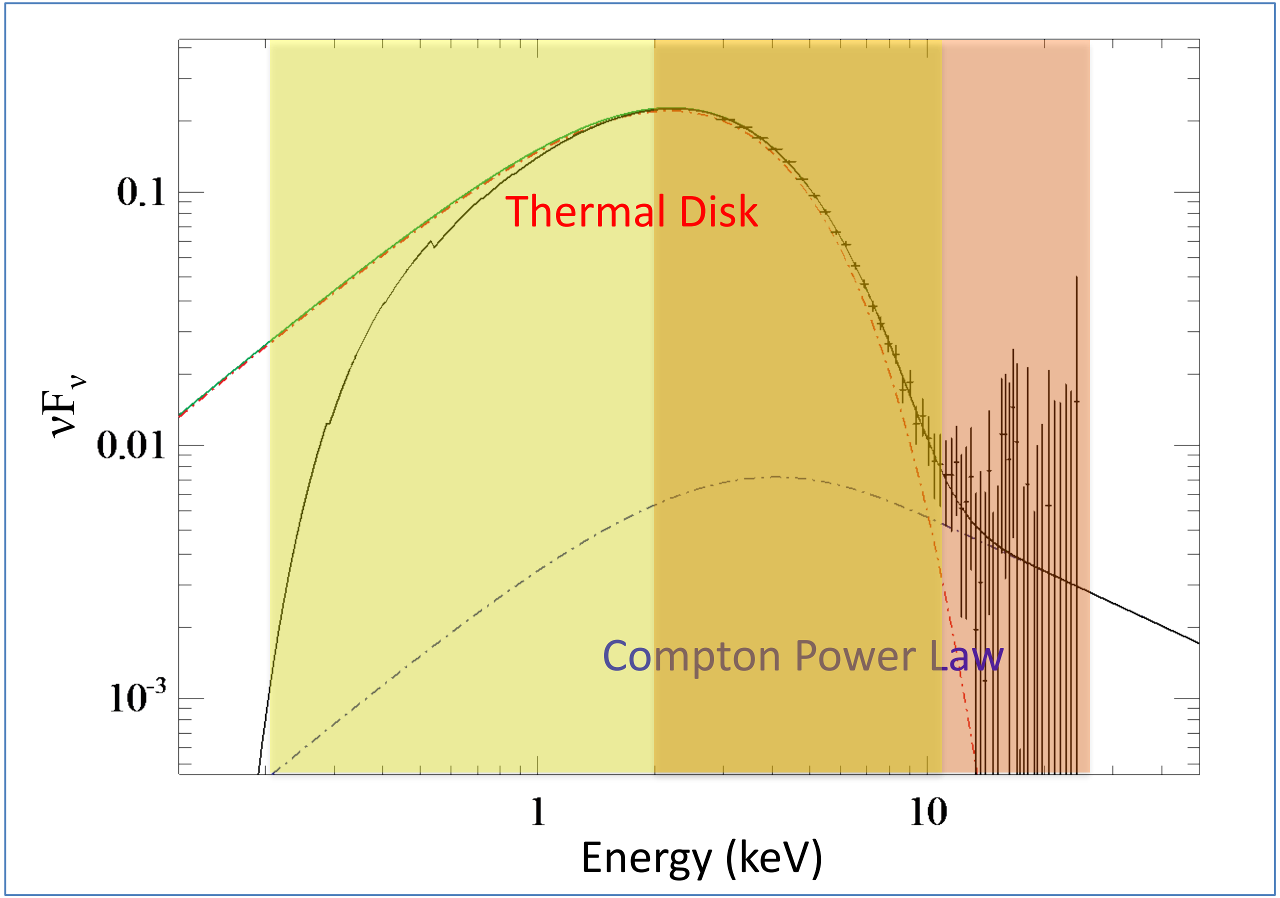
F and $T \rightarrow$ solid angle

D and $i \rightarrow$ $R_{\rm ISCO}$

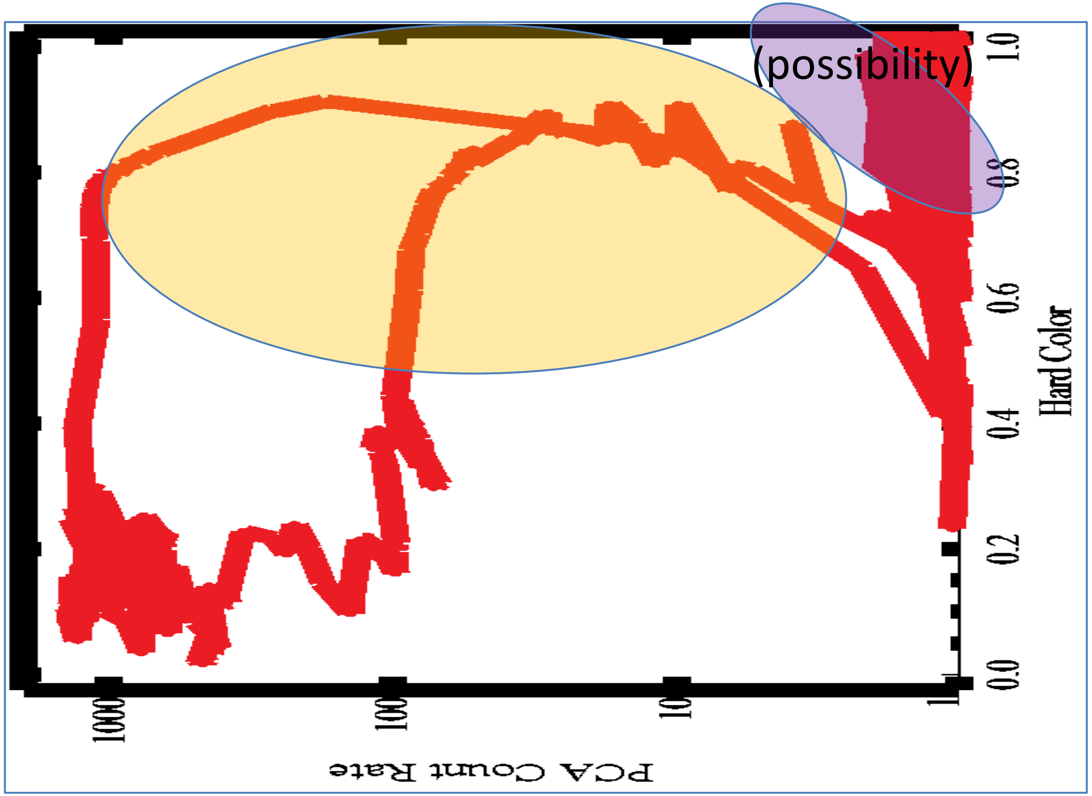


$R_{\rm ISCO}$ and **M** $\longrightarrow$ a_*

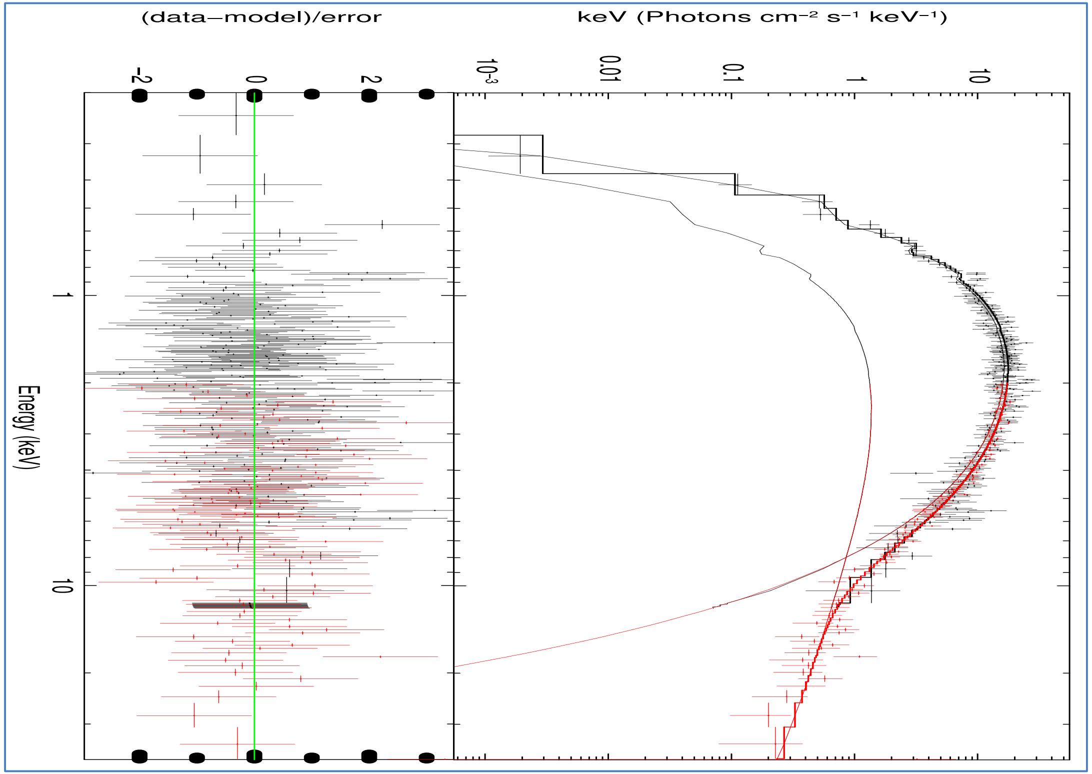
STROBE-X's view of the thermal state



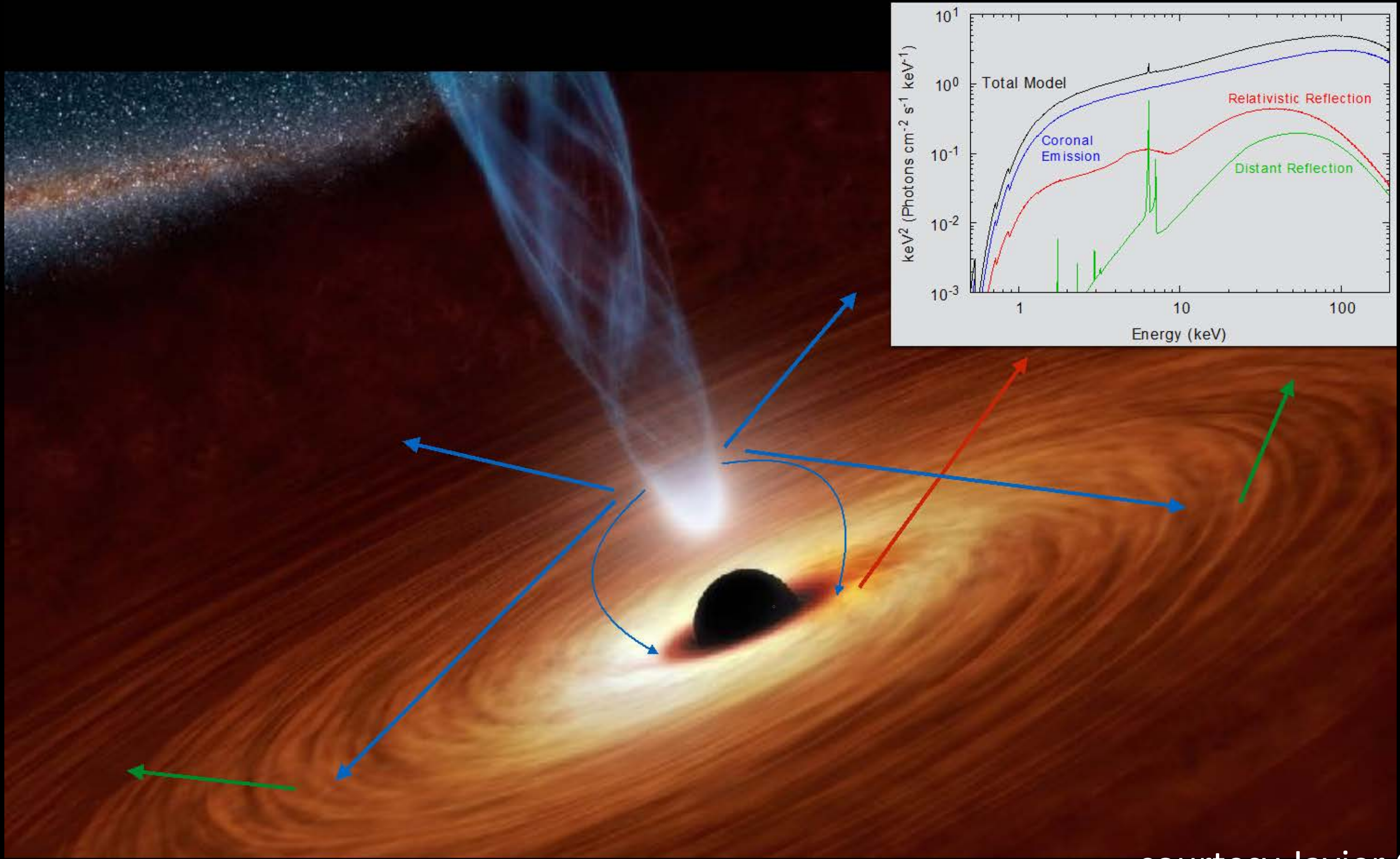
Continuum Fitting 2.0 with STROBE-X



STROBE-X: Continuum spectra on a dynamical timescale!



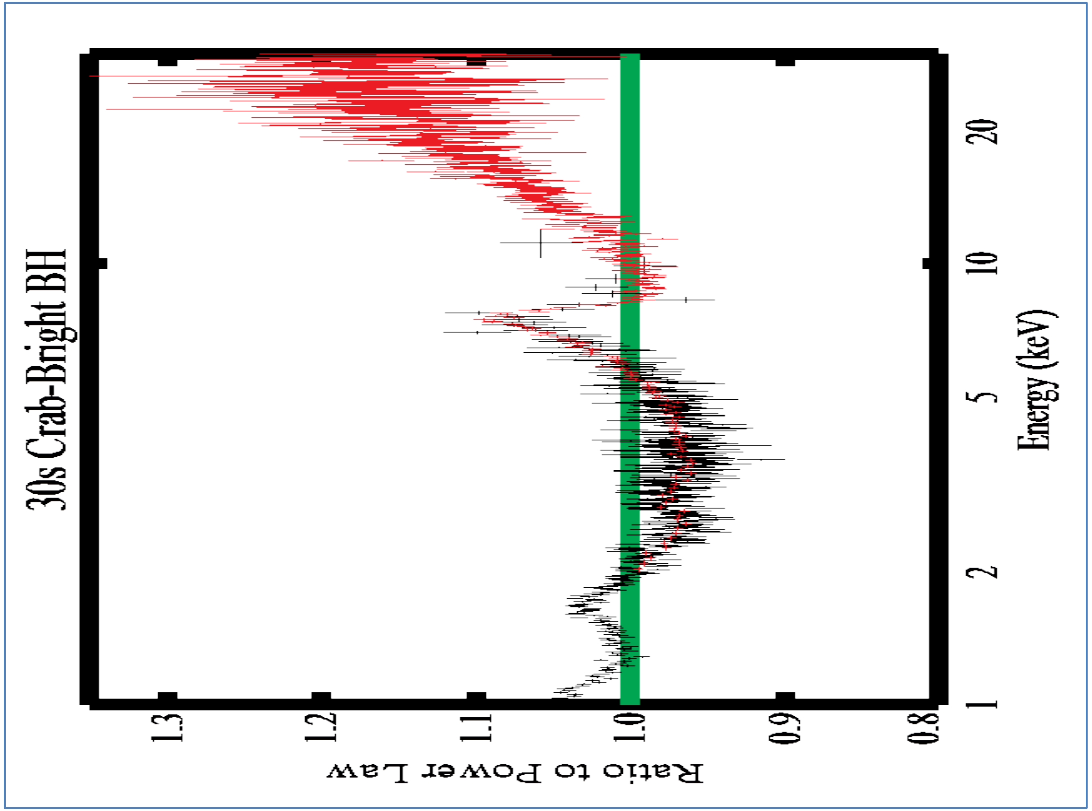
3 Crab
15kCnt
0.01s



courtesy Javier Garcia

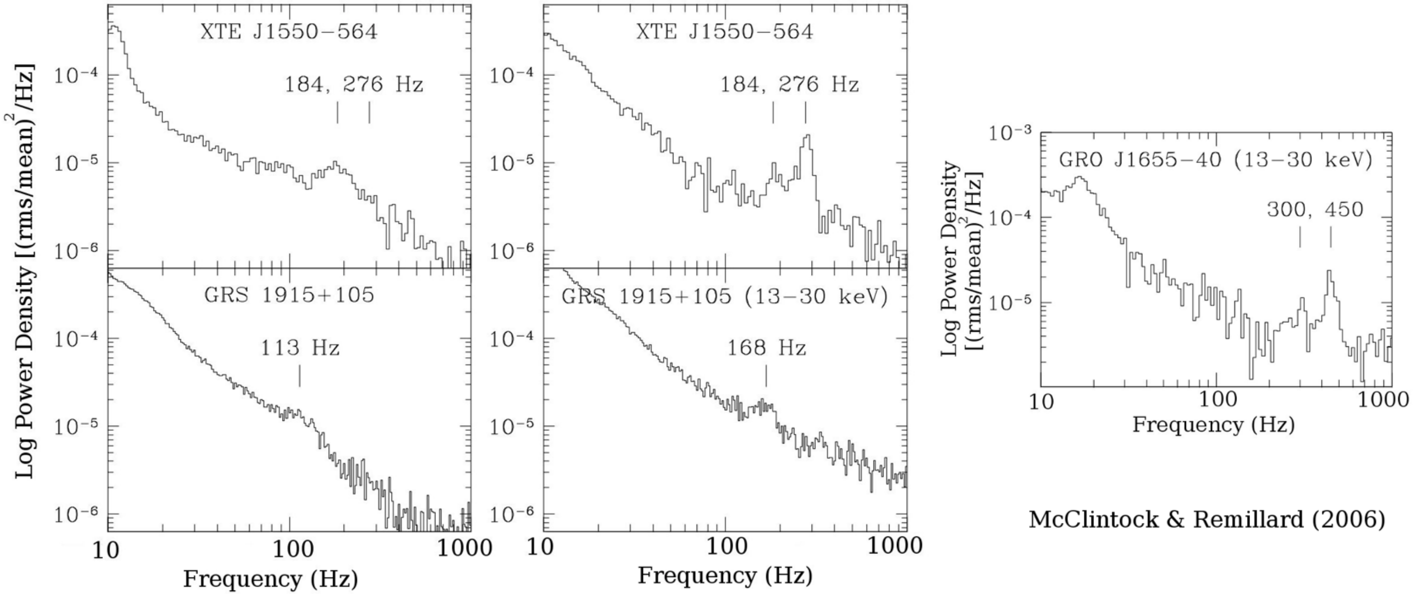
X-ray Reflection from Accretion Disks

Reflection is Dynamic with STROBE-X



- -Measure spins
- -Measure disk truncation
- -Reach viscous timescale

Spin from High-Frequency QPOs



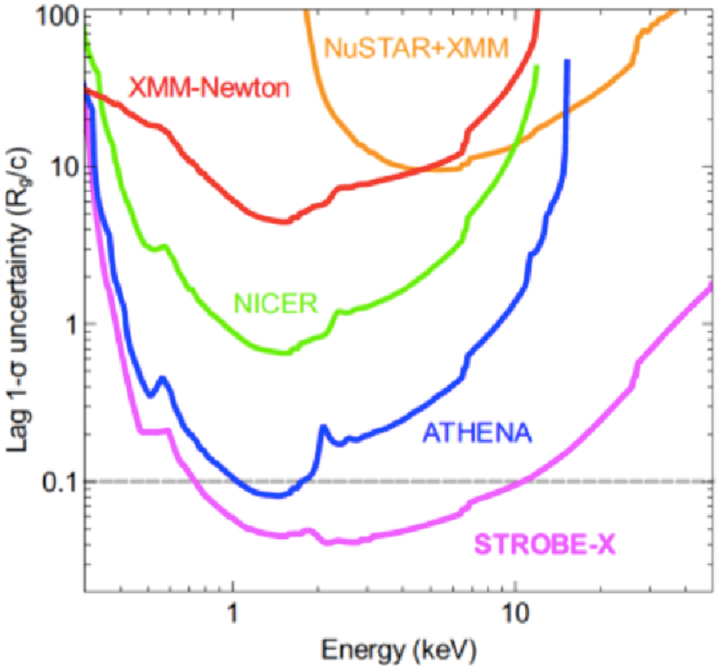
McClintock & Remillard (2006)

-Handful of measurements

-Uncertain model

We need more and better data

X-ray Reverberation Sensitivity



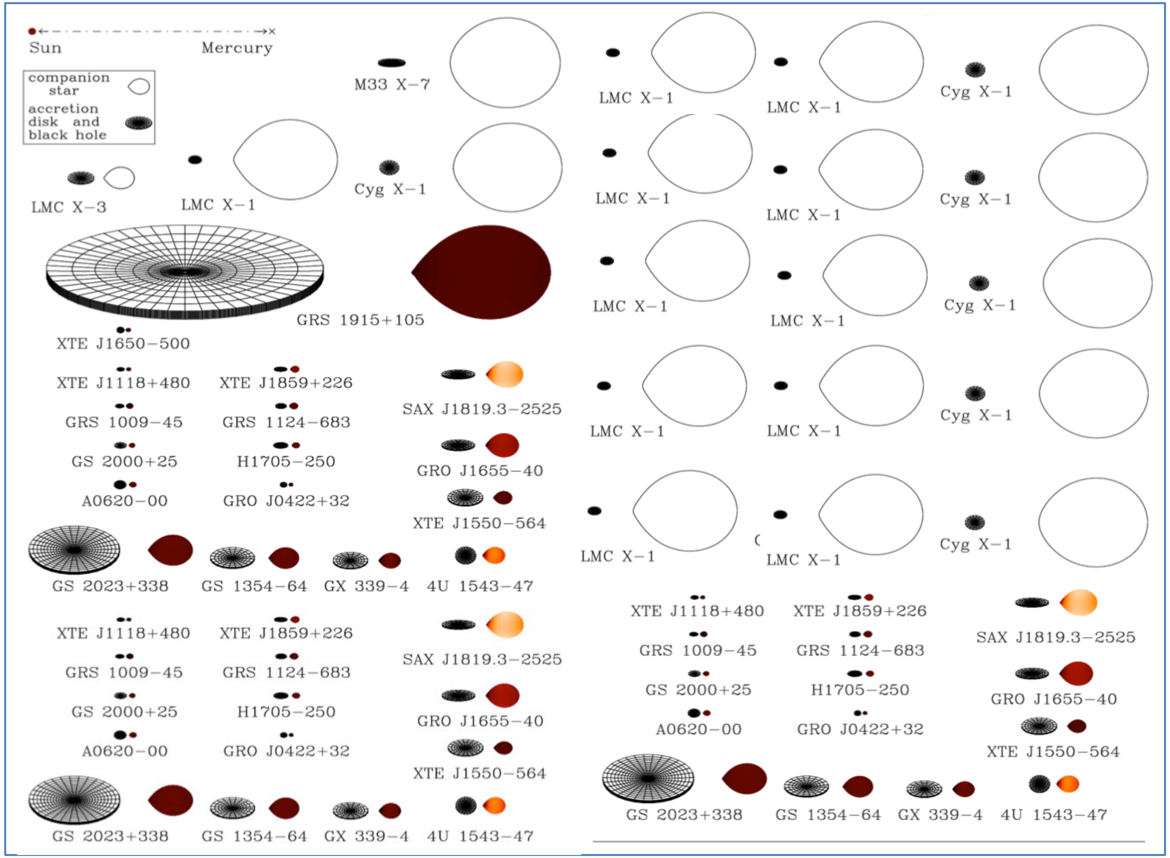
Two orders of magnitude better than XMM!

Ability to handle high count rates is key

- STROBE-X *better than Athena everywhere*, especially Fe K, will uniquely cover Compton hump

slide credit: Ed Cackett

A Local Group Menagerie with STROBE-X

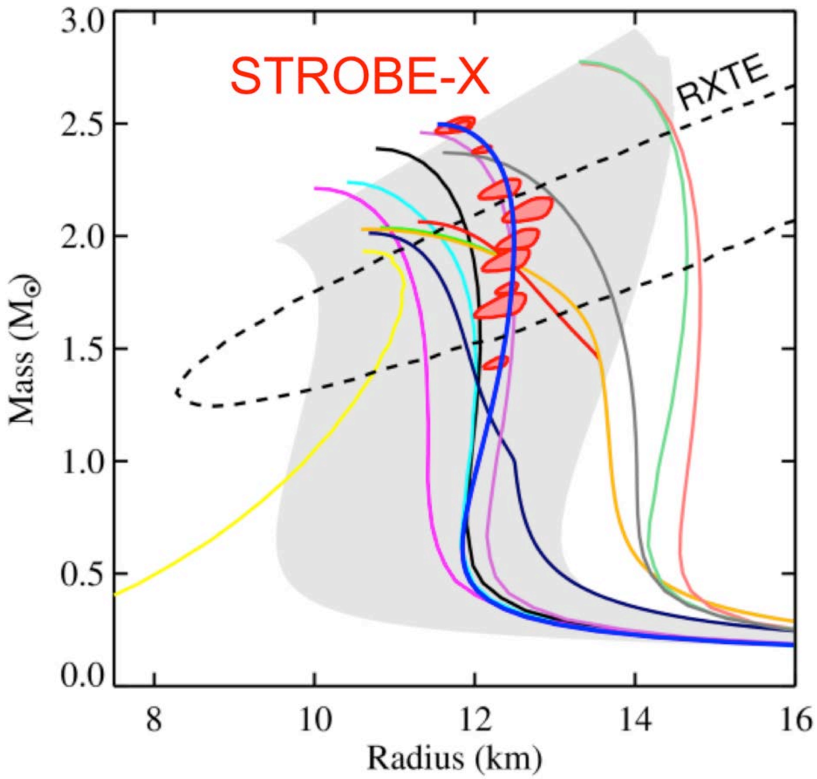


Cause for Excitement

- Have access to the outskirts of all Local Group members
  - Low N_H, less crowded
  - Many low-mass LG members
  - Can sweep up radius estimates for a dozen proximate sources in 10 ks. (~100s-1ks apiece for ~5000 ct benchmark)
  - Distance known precisely
- Establish a critical-mass population of 50-100 stellar BH spins (and masses)
- Age of big glass on the ground: can get masses for stellar BHs in the Local Group (R~26+) with AO.

Neutron Stars

- Fully determine the ultradense matter equation of state by measuring the neutron star mass-radius relation using >20 pulsars
  - Measurements spanning low to high masses are critical to nail down the precise EOS
- Both burst oscillations and thermal surface emission will be accessible
- Also could contribute to PTA detection of gravitational waves, etc…



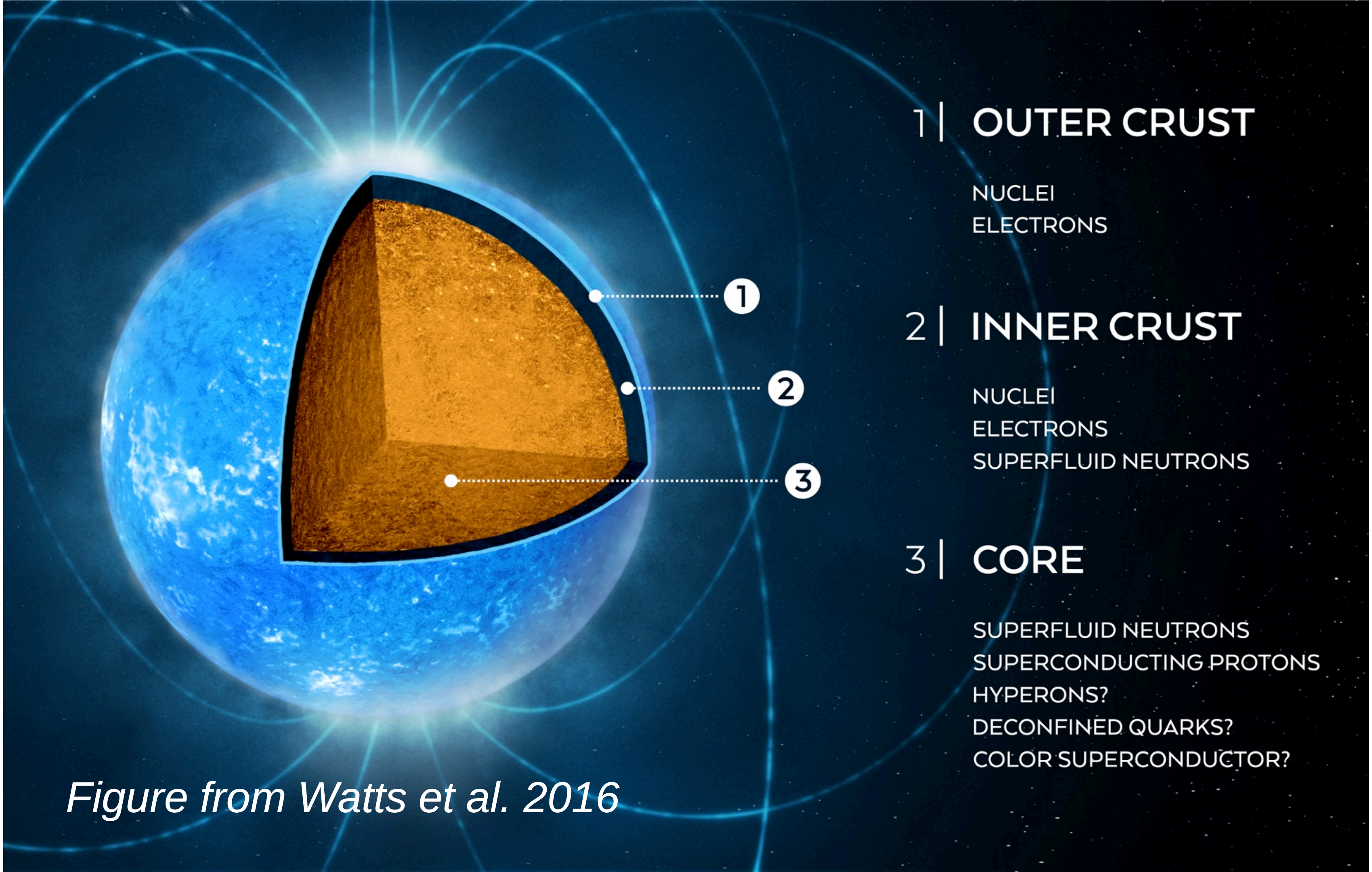


Figure from Watts et al. 2016

Understanding the Strong Force

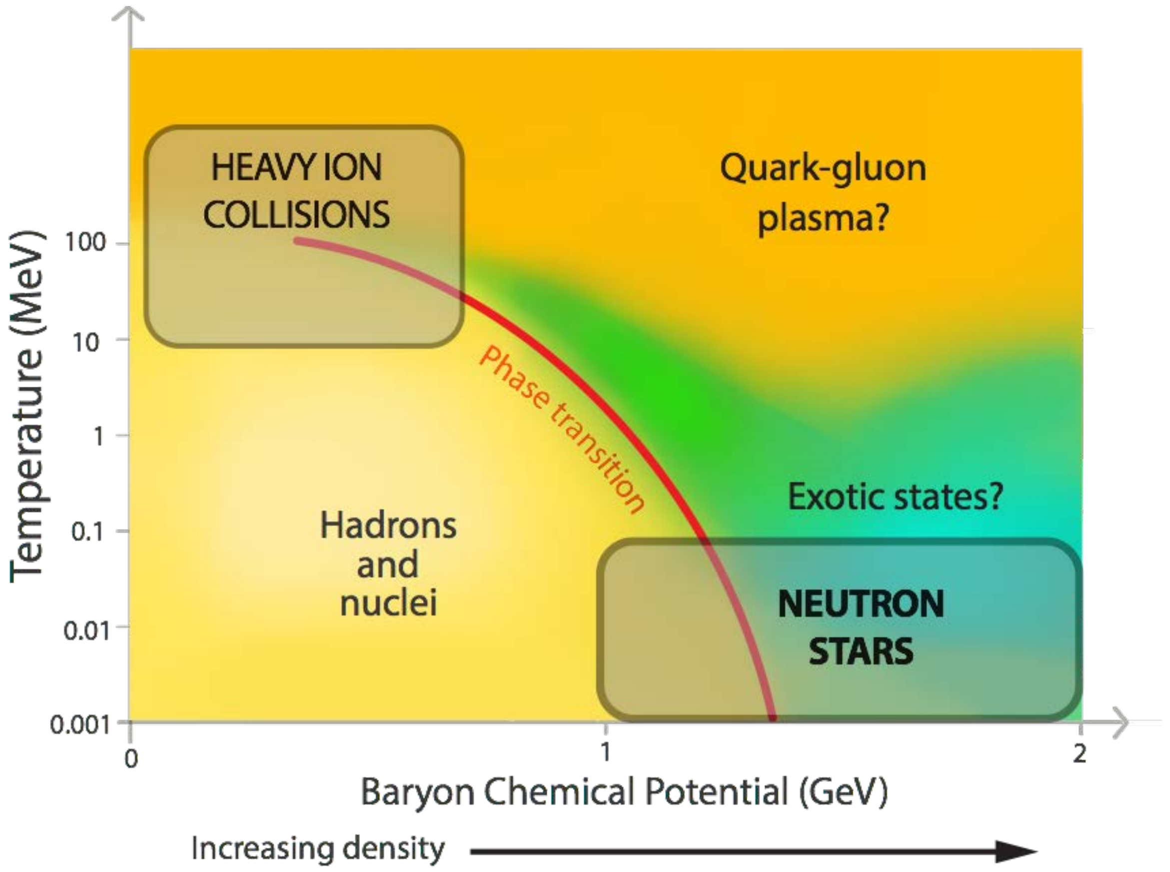
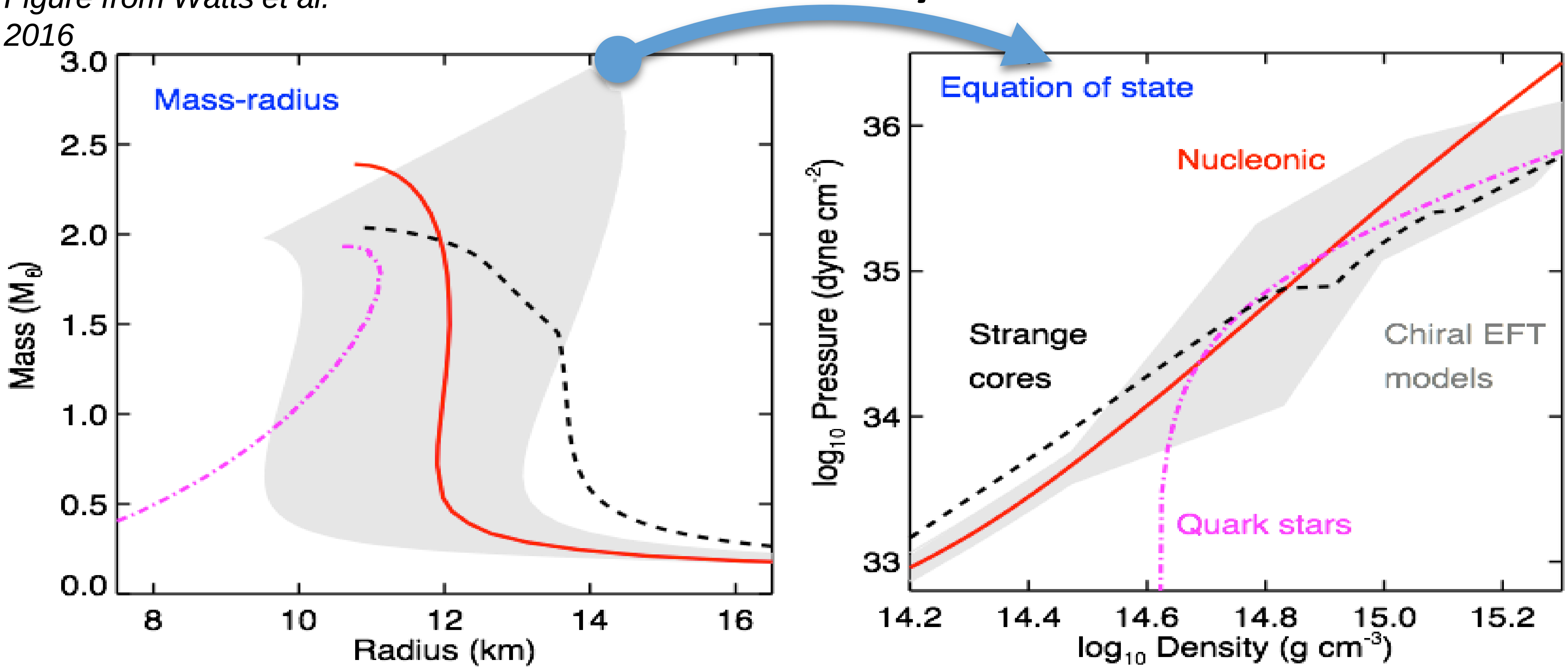


Figure from Watts et al. 2016

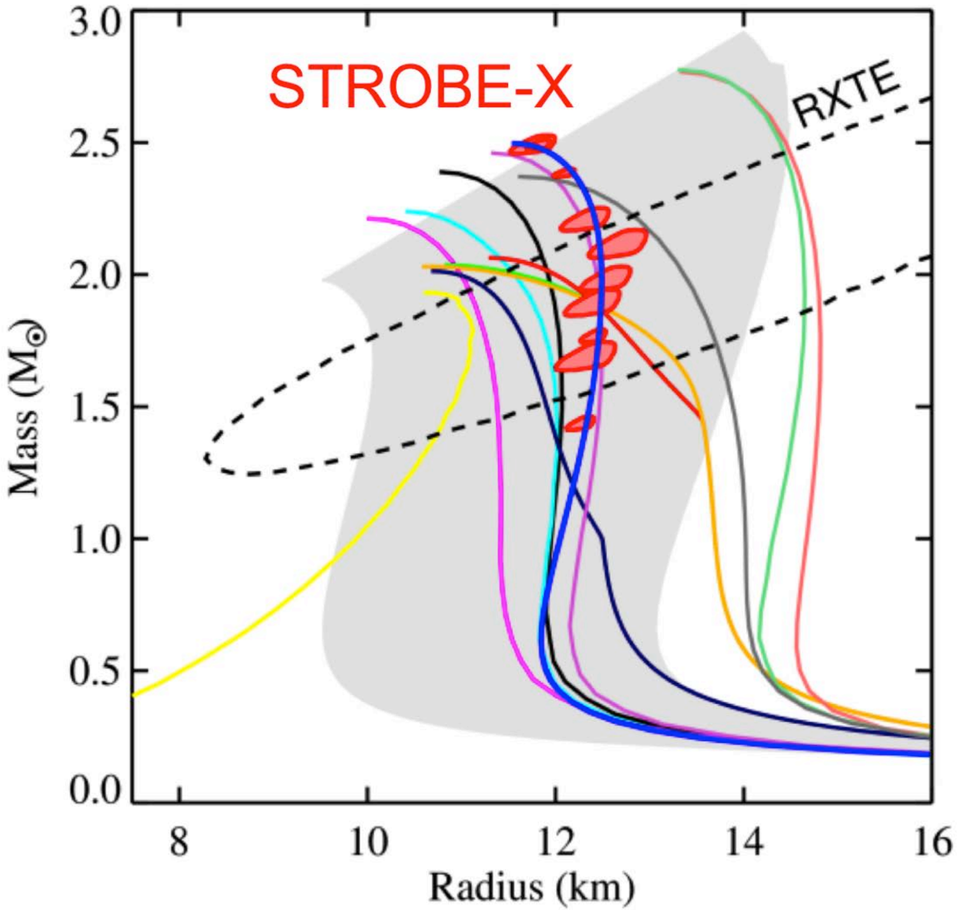
From Astronomy to QCD

Figure from Watts et al. 2016



WE NEED SIMULTANEOUS MEASUREMENTS OF MASS & RADIUS, TO ACCURACIES OF A FEW %, FOR A RANGE OF MASSES

How do we intend to accomplish this?



Approaches to Masses & Radii

- Modeling of X-ray modulation light curves
  - Rotation powered (millisecond) pulsars [NICER pioneering]
  - Accretion powered (millisecond pulsars)
  - Burst oscilations*
- X-ray Bursts
  - Cooling tails*
  - Lines/absorption edges?*
- Thermal evolution
  - Cooling curves of young neutron stars
  - Post-accretion cooling
- Global oscillation modes*

* Short duration phenomena – need collecting area!

INTERPRETATION AND SYSTEMATICS CAN BE LIMITING:
ADOPT MULTIPLE APPROACHES & INDEPENDENT CONSTRAINTS

Lightcurve modeling

LIGHTCURVE MODELLING

NICER's top rotation-powered MSP targets

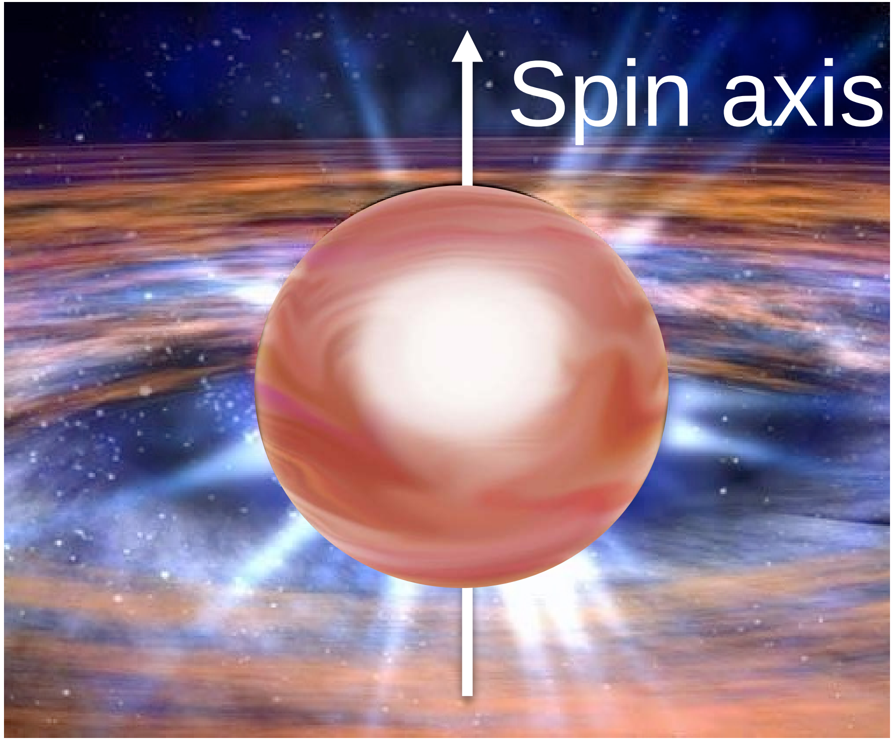
Pulsar	Spin period (ms)	Distance (pc)	Mass ($M_\odot$)	NICER rate (ksec^{-1})	Comments
J0437-4715	5.76	156.79 ±0.25	1.44±0.07	1430	[illegible] known
J0030+0451	4.87	300_{-10}^{+20}		314	
J1231-1411	3.68	440		210	
J2124-3358	4.93	410_{-70}^{+90}		100	
J1614-2230	3.15	700	1.928±0.017	18	High mass

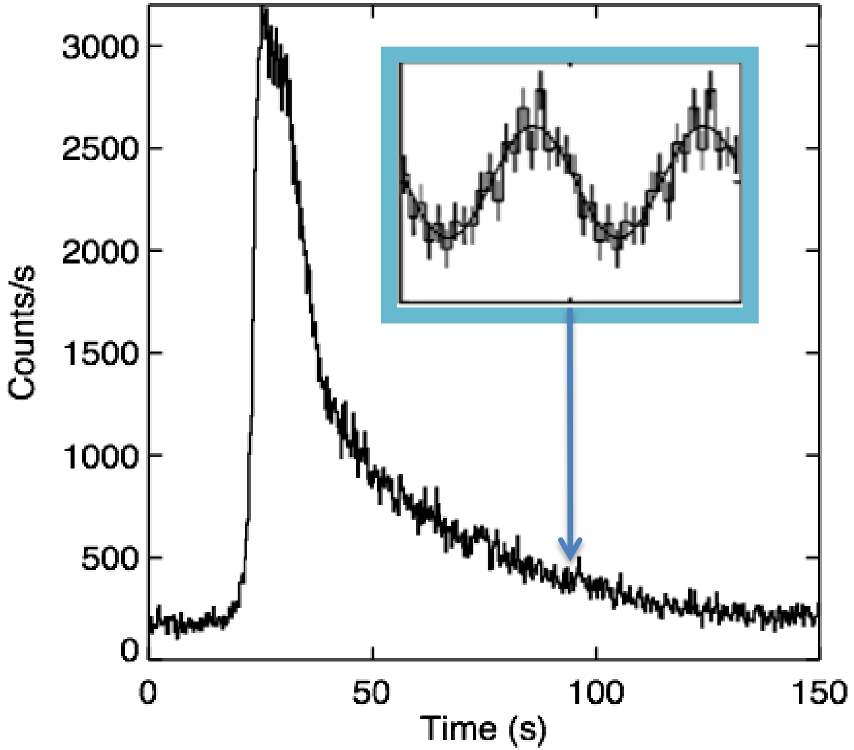
STROBE-X brings this population within *easy* reach

Need 10^{5-6} photons, depending on geometry

NICER expects 5% measurements of R for J0437 and J0030, and better than 10% measurement of M for J0030

Burst Oscillations

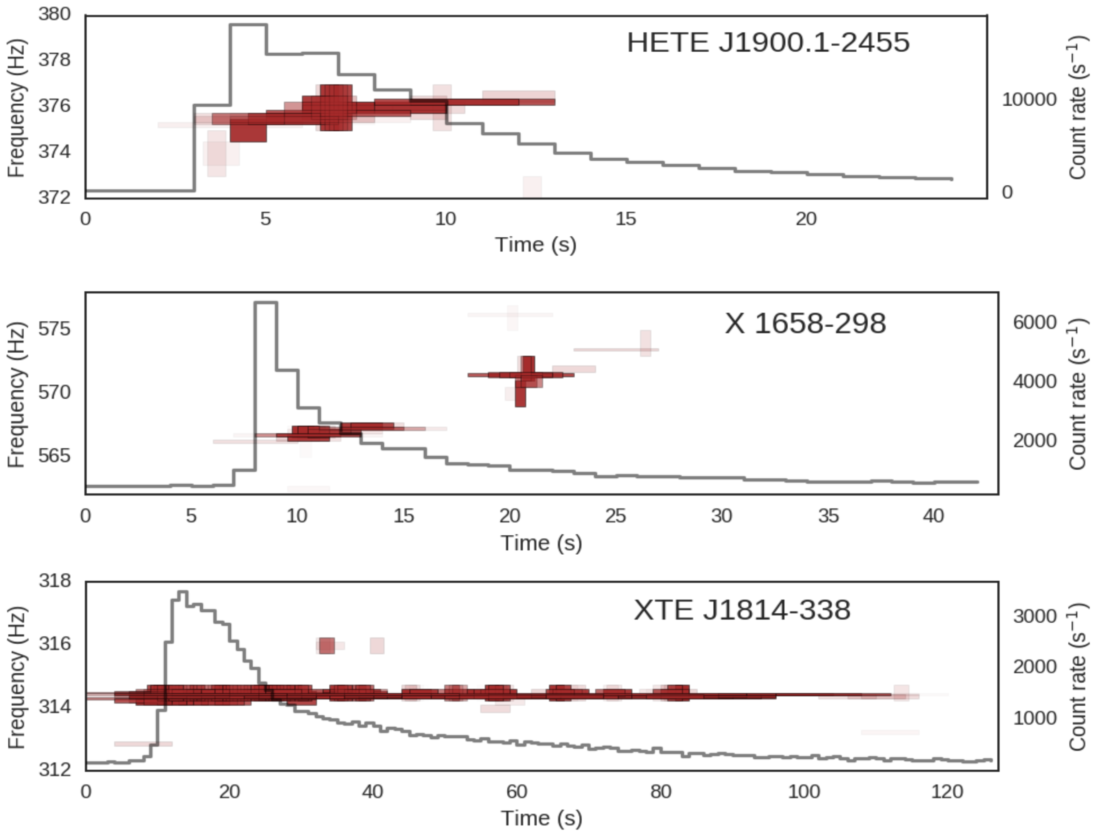




IN SOME BURSTS ANOMALOUSLY BRIGHT PATCHES FORM. THESE ARE KNOWN AS BURST OSCILLATIONS

Discovered in 1996 by Strohmayer et al., for review see Watts, ARAA, 2012

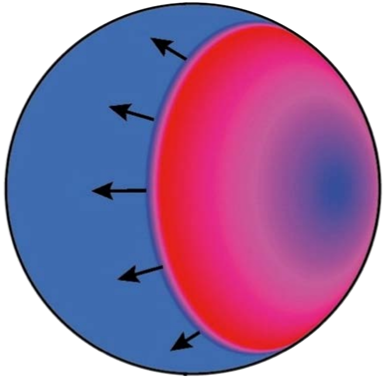
Burst Oscillations



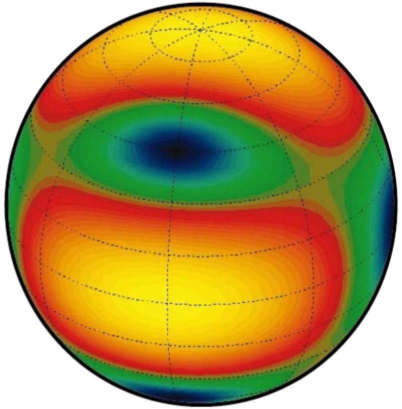
Bilous et al. in prep

Burst Oscillations: Oscillation Mechanism

- Burst is thought to ignite at a point, from which flame spreads across ocean
- How do observable patterns form and persist?



IGNITION AND FLAME SPREAD

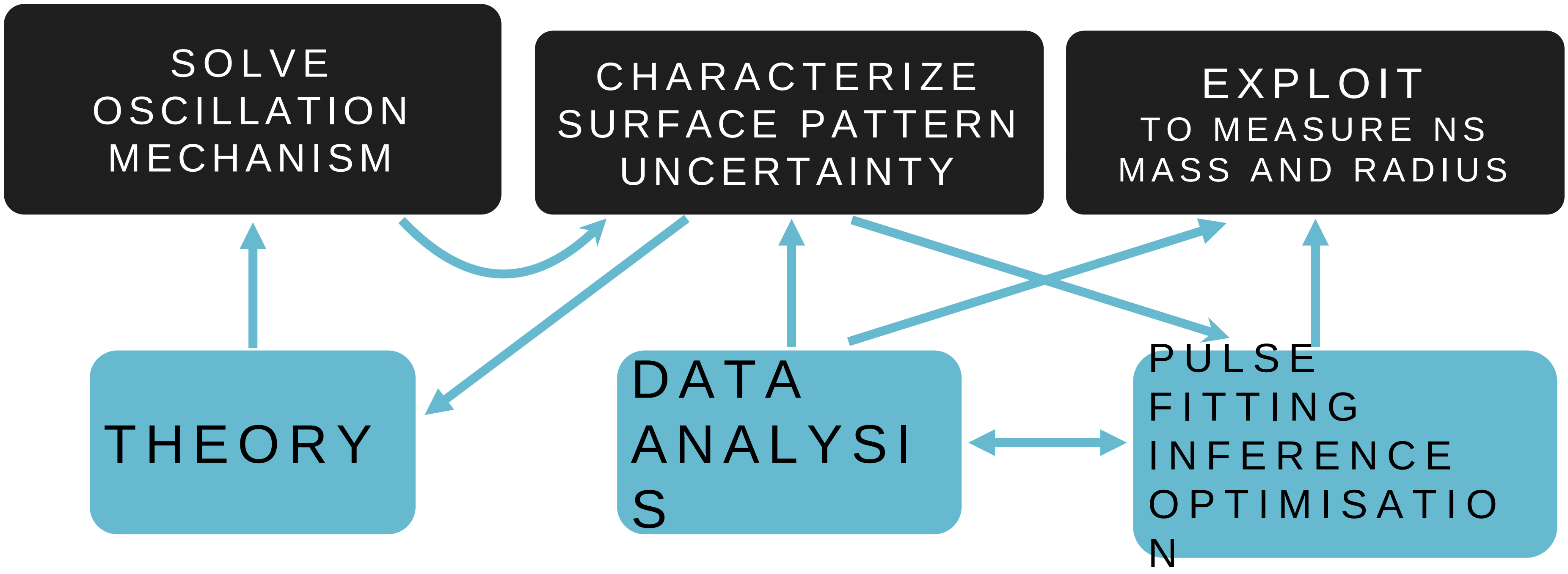


LARGE-SCALE OCEAN MODES

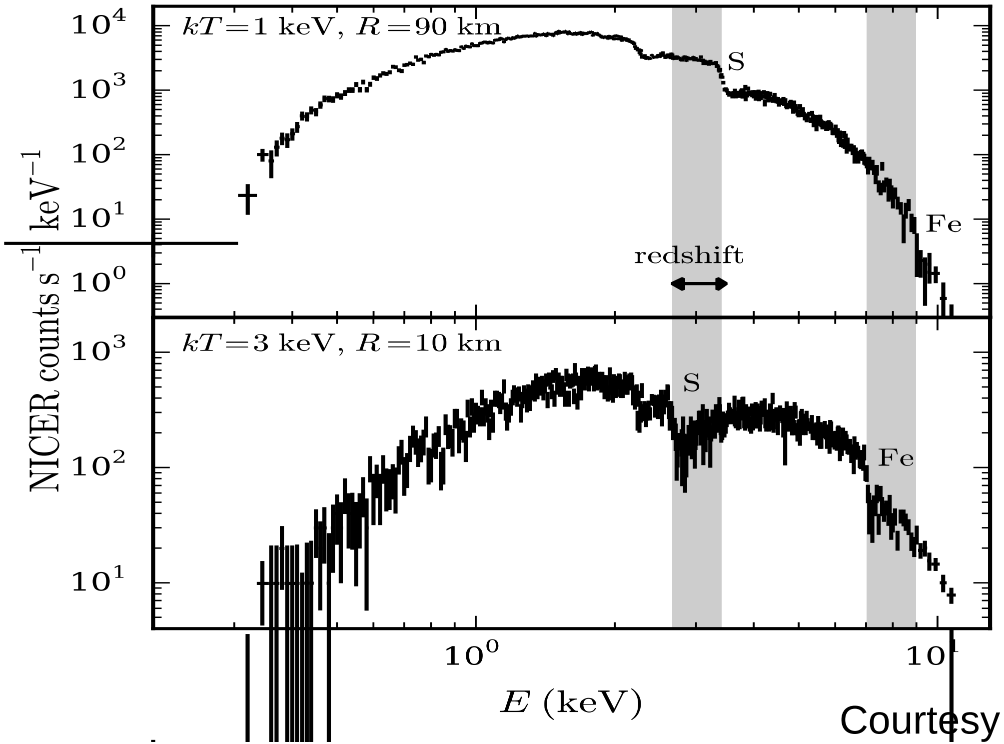
ROLE OF CONVECTION

BURST OSCILLATION APPROACH

Unique challenges, including uncertain and evolving surface pattern — need to combine bursts



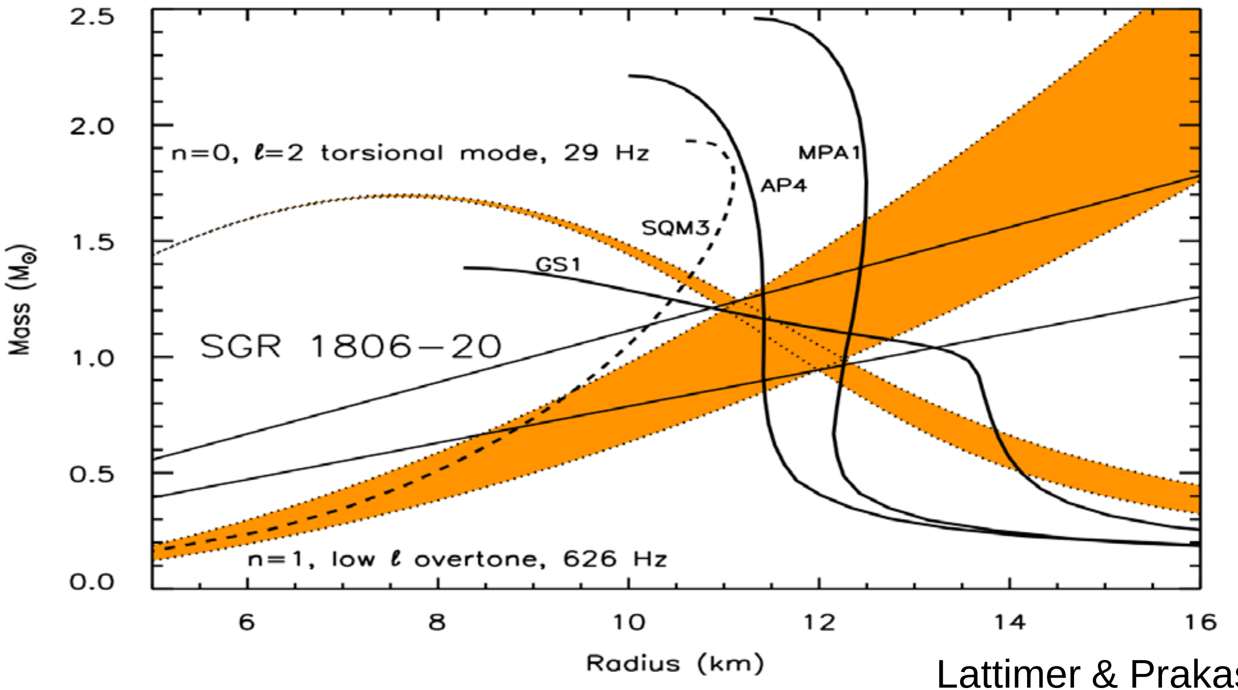
BURST SPECTROSCOPY — EDGES



Courtesy of L. Keek

SUPER-EXPANSION BURST PROVIDES OPPORTUNITY TO CONSTRAIN M/R

NS OSCILLATION MODES



Lattimer & Prakash 2007

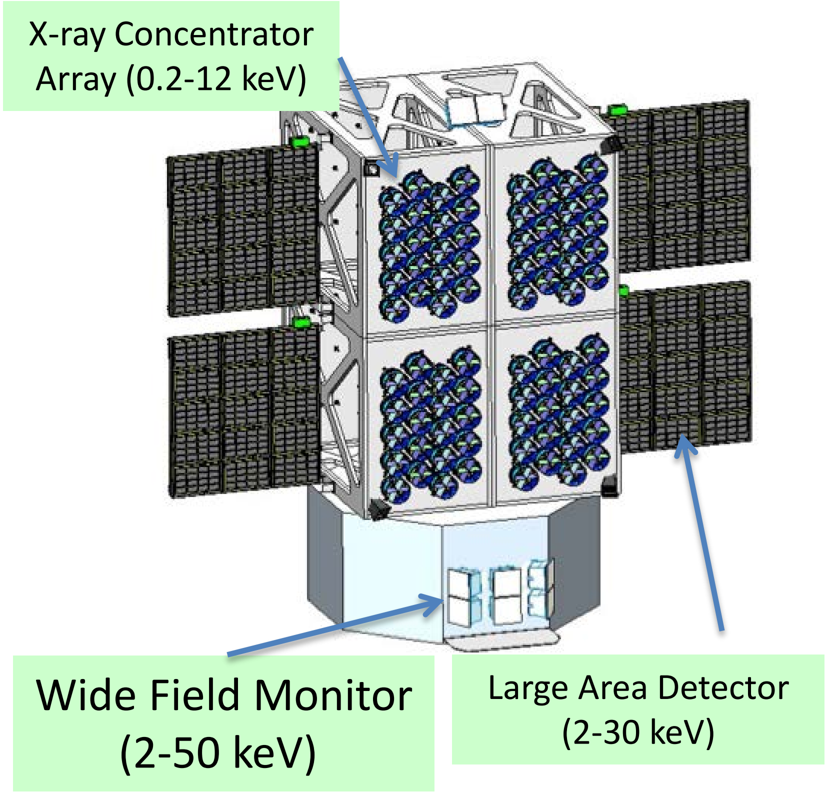
STROBE-X OFFERS THE POSSIBILITY TO DETECT SUCH MODULATIONS DURING, E.G., SUPERBURSTS — BUT INTERPRETATION REMAINS CHALLENGING

Rapid and Extreme Explosions

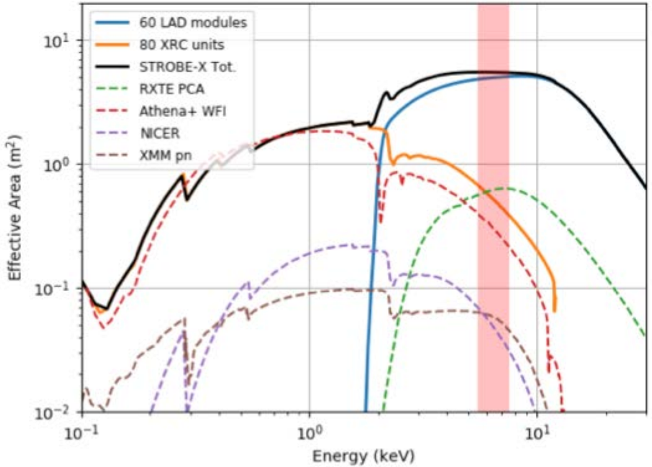
- Gamma-ray bursts and X-ray flashes
- LIGO EM counterparts
- TDEs
- Supernova shock breakouts
- Stellar flares
- Much more…

- Arcmin localization allows optical follow up with single pointing
- Large instantaneous FOV probes rare events
- 300 eV spectral resolution sensitive to lines

STROBE-X Instrument Concept



Large effective area >5 m^2 @ 6 keV

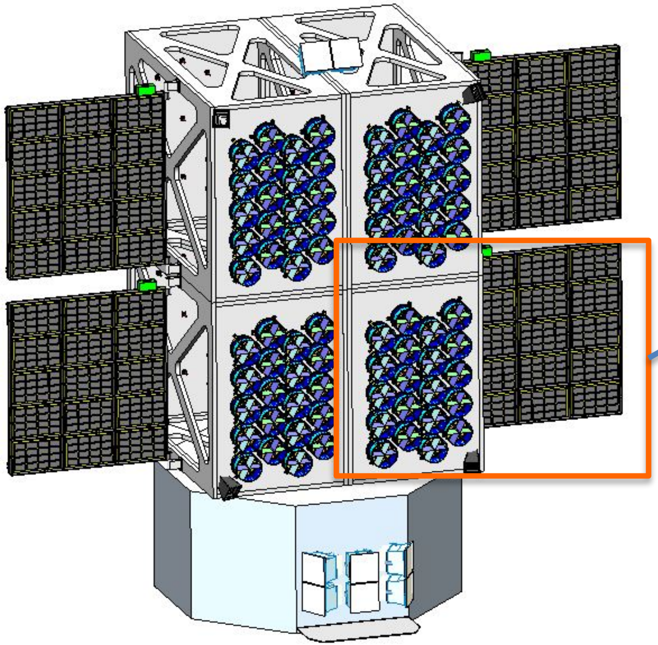


- STROBE-X combines the strengths of NICER and LOFT: High throughput X-ray timing with good spectroscopy
- All components are already high TRL
- Highly modular design improves reliability at reduced cost and allows easy scaling.

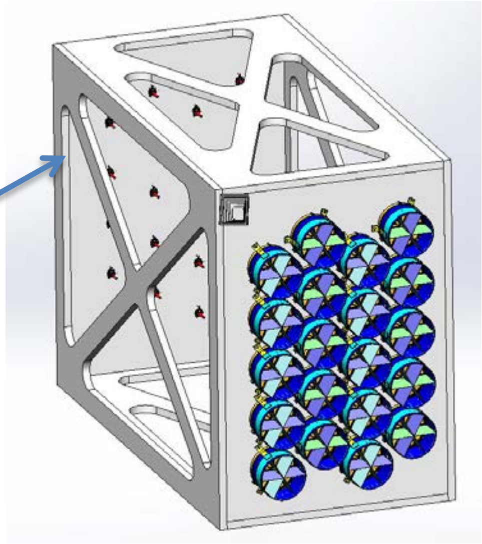
STROBE-X Mission

- 5 year mission
- Low Earth Orbit, 550 km, ~14 deg inclination
- Flexible repointing, quick ~minutes to hours
- Average data rate 9.5 Gbit/orbit – event-by-event data in all 3 instruments
- On-board data storage for 5 orbits

STROBE-X Optical Bench



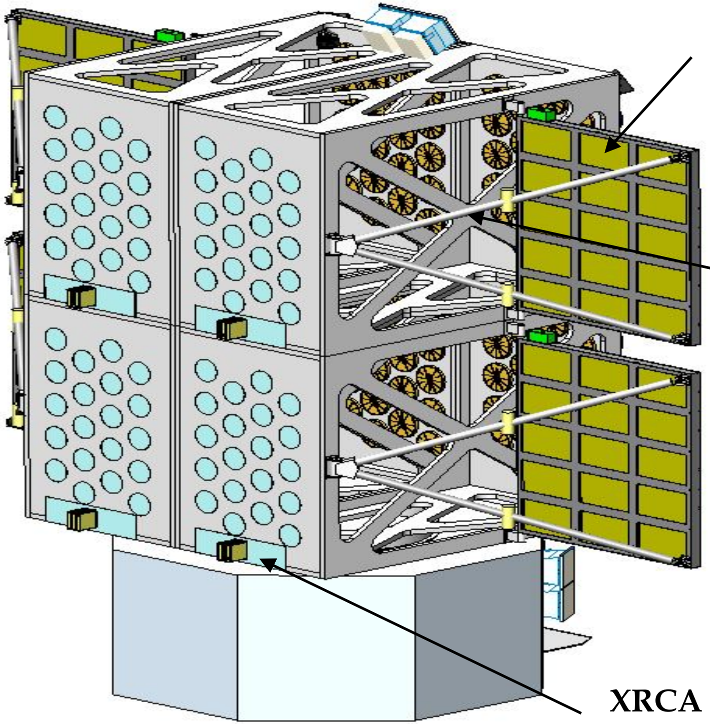
- Composite honeycomb structure
  - Reduces mass from NICER aluminum bench
  - Provides low coefficient of thermal expansion



- Designed as identical quadrants containing:
  - Optical bench
  - 20 XRCA units
  - Back-end electronics
  - LAD panel & deployment
  - 15 LAD modules
  - Back-end electronics
  - Star camera

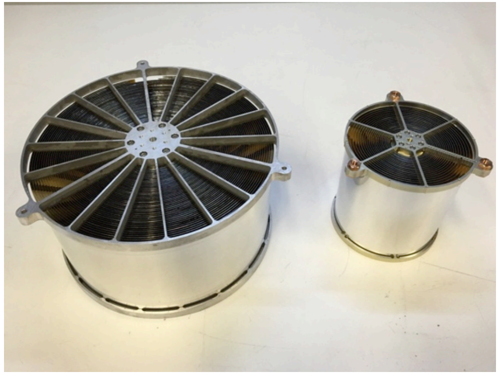
STROBE-X LAD Panel Deployment

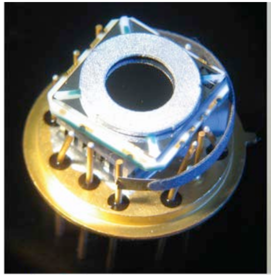
- Deployment system:
  - Launch locks
  - Kickoff spring
  - 4 bar linkage
- Deployed accuracy
  - ±1 arcmin
- Repeatable within 4%
- High reliability
- Strong heritage



X-ray Concentrator Array

- Low background, high throughput
- Enables high time resolution observations of the faintest sources, both extragalactic and galactic
- Sensitive timing and spectroscopy to thermal emission and iron lines
- Scaled up version of NICER concentrators with NICER SDDs
  - Focal length of 3 m and 2’ focal spots for enhanced throughput >2.5 keV
  - Inexpensive Foil optics: large areas w/ low background
  - Energy resolution: 85-175 eV FWHM
  - Effective area @ 1.5 keV: >2.0 m^2

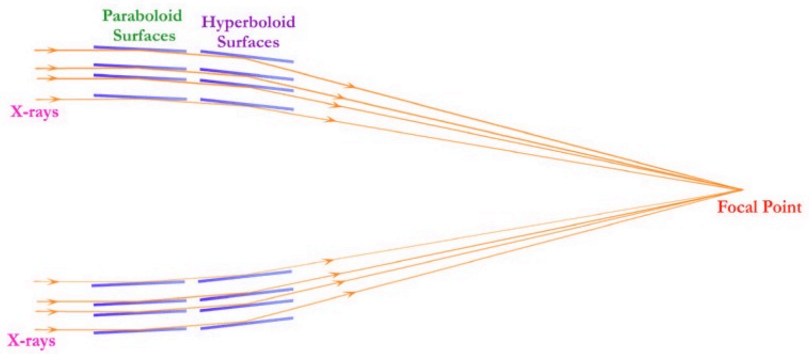




Baseline is 80 XRCA units

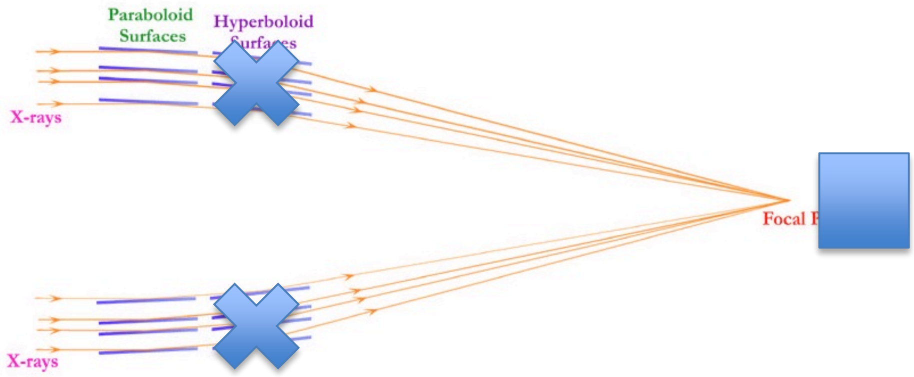
How does an X-ray concentrator work?

Typical X-ray Optics



- Two bounces to focus X-rays to an image
- Low background
- Requires high precision manufacturing
- Expensive to manufacture
- High precision mounting and alignment

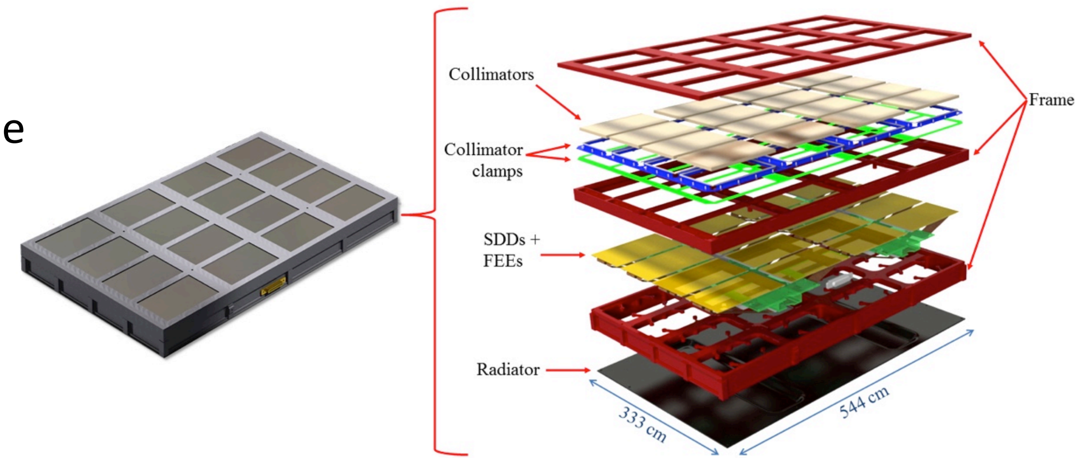
X-ray Concentrator



- Simple single bounce design
- Concentrates X-rays to a single pixel
- Greatly reduces background
- Inexpensive to manufacture
- Alignment is easy to do

Large Area Detector

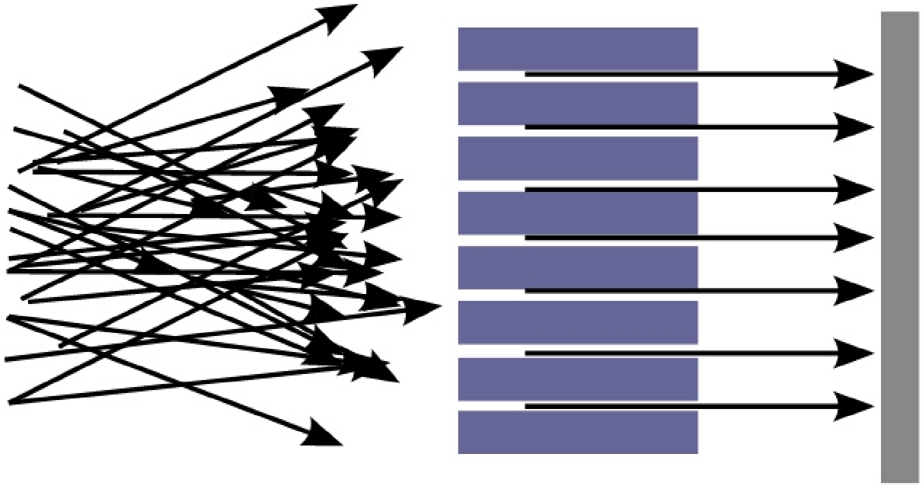
1 LAD Module

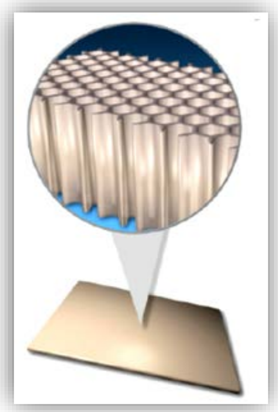


- High time resolution and good energy resolution over the 2-30 keV range
  - Best sensitivity to QPOs; most prominent in harder X-rays
  - Sensitive to non-thermal emission and Compton hump
- SDDs and lightweight microcapillary plate collimators developed for ESA's LOFT M3 & M4.
  - Energy resolution: 200–500 eV FWHM
  - Effective Area @ 10 keV >5 m^2

Baseline is 60 LAD modules

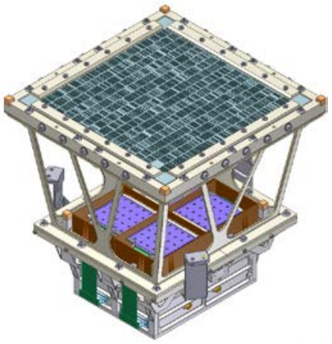
How does an X-ray collimator work?

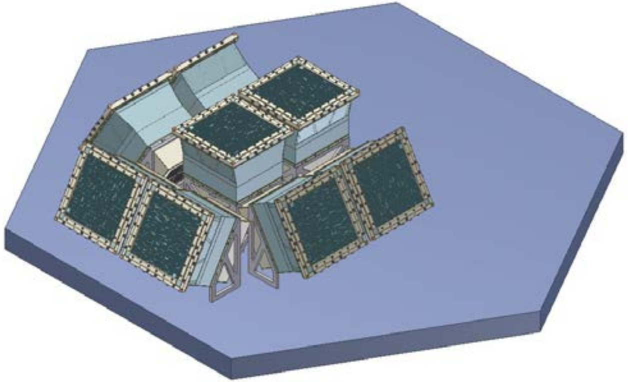




Microchannel Plate Collimators
(widely used in space)

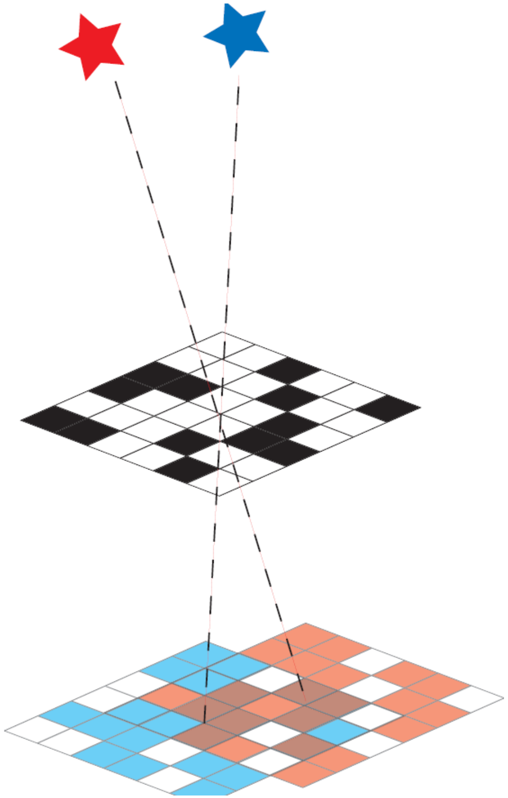
Wide Field Monitor

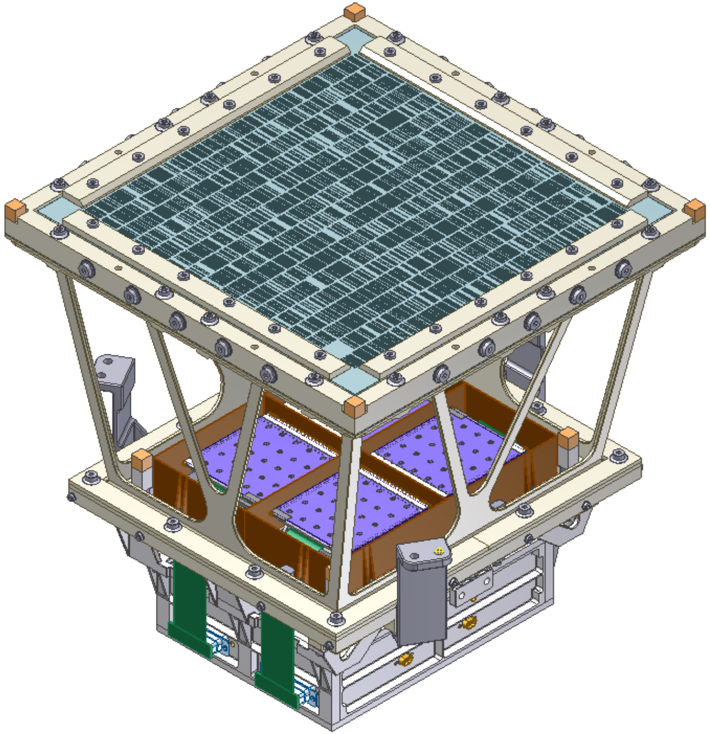




- Wide-field coded-mask imager
- Instantaneous FoV: >1/3 of sky; 50% of sky accessible to LAD
- Sensitive to transients from milliseconds to years
- LOFT SDDs and mask
- Energy resolution: 300 eV FWHM
- Identifies new transients and source states for main instruments, while monitoring long-term source behavior for a large fraction of the sky.

How does a coded aperature imager work?





STROBE-X Summary

- STROBE-X will provide groundbreaking measurements for stellar mass and supermassive black holes
- STROBE-X will map out the equation of state for a large number of neutron stars
- STROBE-X's sensitive instruments will provide far reaching new observations in time-domain astrophysics.

What is next for STROBE-X?

- Mission Design Lab study in April
  - Fully define spacecraft, orbit, ground operations, communications, etc.
- Science team report due to NASA in December
  - Detailed science case
  - Point design under $1B
- Overall Goal – demonstrate to the Astrophysics Decadal Survey that compelling science can be done with STROBE-X for under $1B.
- Most likely outcome – Probe class (<$1B) mission call in early 2020s.