The Future of X-ray Timing: A Probe-class Mission Concept

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LOFT UNITES SPECTROSCOPY & TIMING, AT ENORMOUS AREA

RXTE
1100 eV, 0.65 m^2

XMM
130 eV, 0.085 m^2

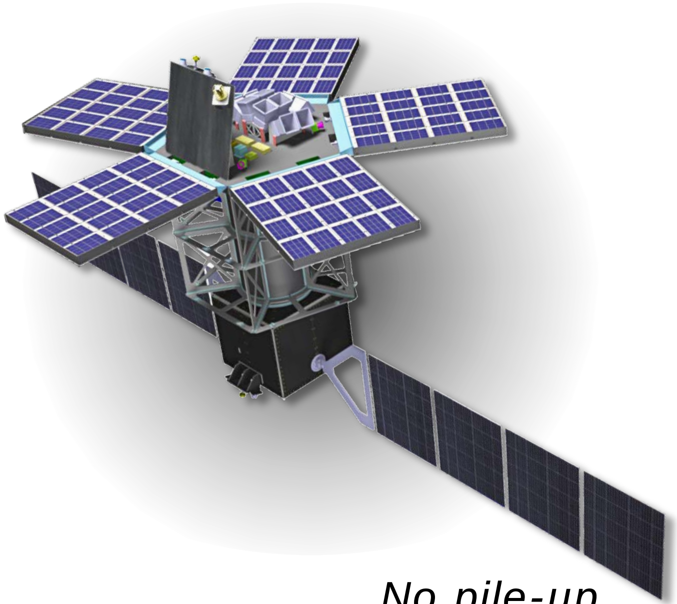
pile-up-limited

[*Athena/WFI: 130 eV, 0.2 m^2*]
spectroscopy x 40

TIMING x 13

SPECTROSCOPY x 100

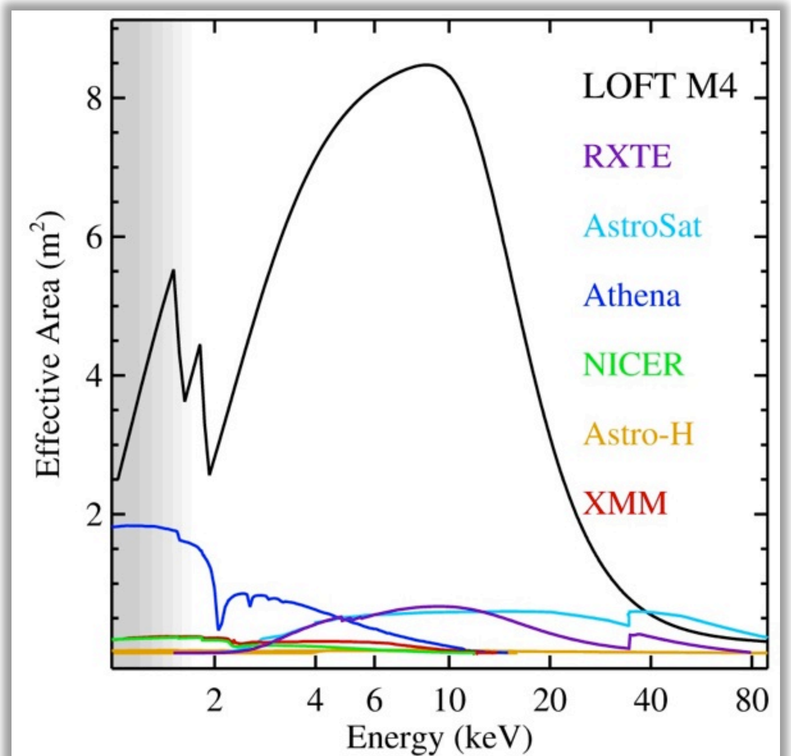
LOFT
200 eV, 8.5 m^2

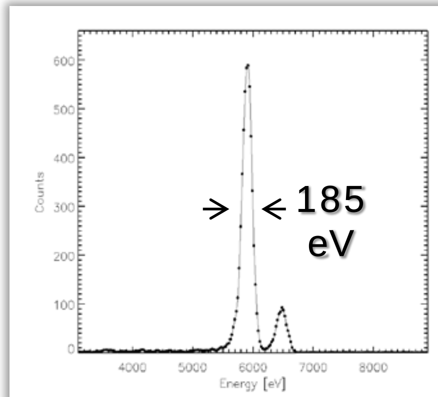


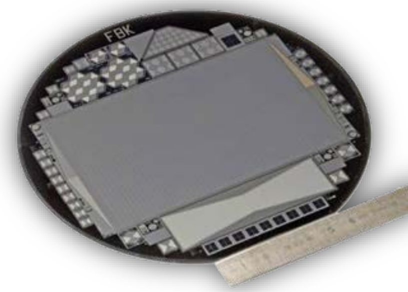
No pile-up

LOFT was proposed for ESA's M4 call.

Very Large Collecting Area AND Good Energy Resolution
(based on mature technologies)

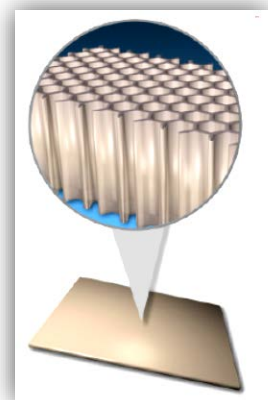






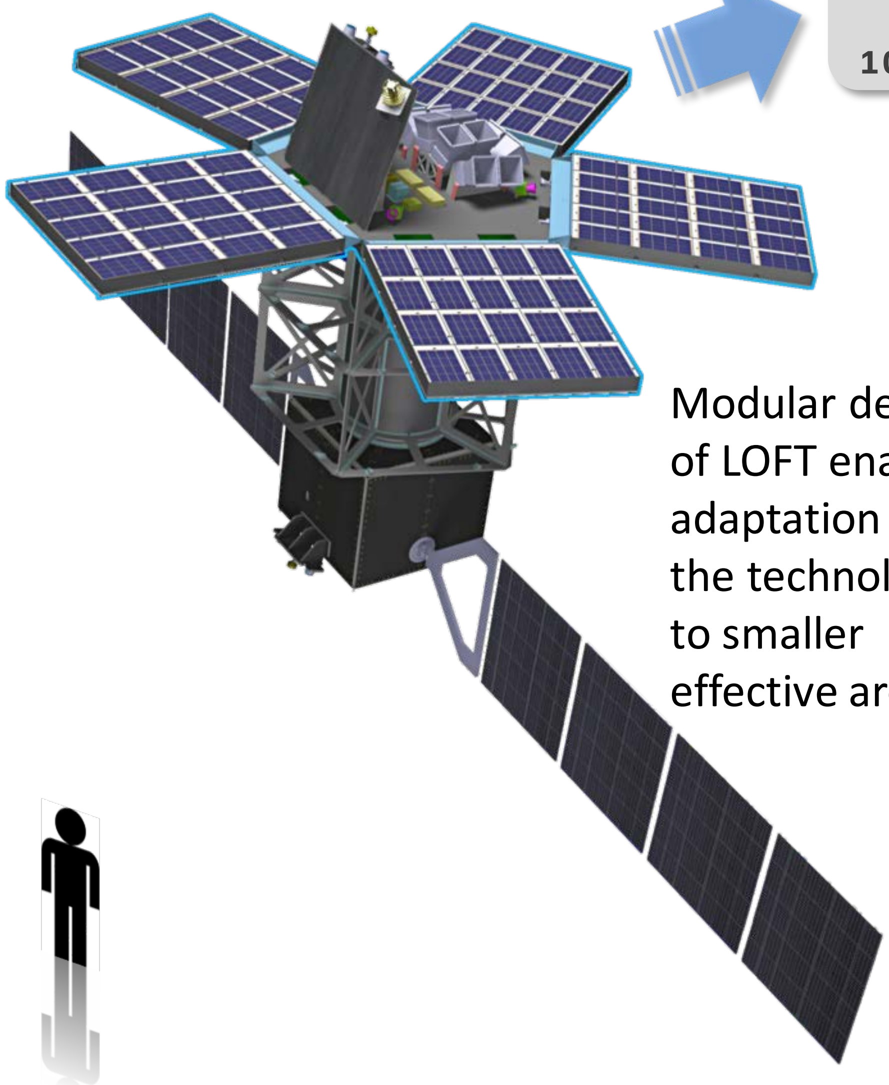
Silicon Drift Detectors
LHC/ALICE Heritage

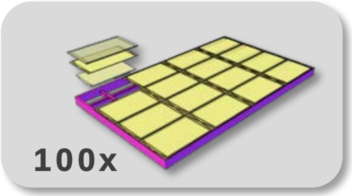
Probe-class X-ray Timing mission
- Large effective area
- Good spectral resolution

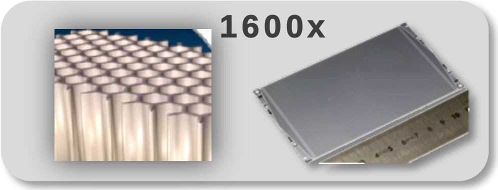


Microchannel Plate Collimators
(widely used in space)

LOFT - Large Area Detector





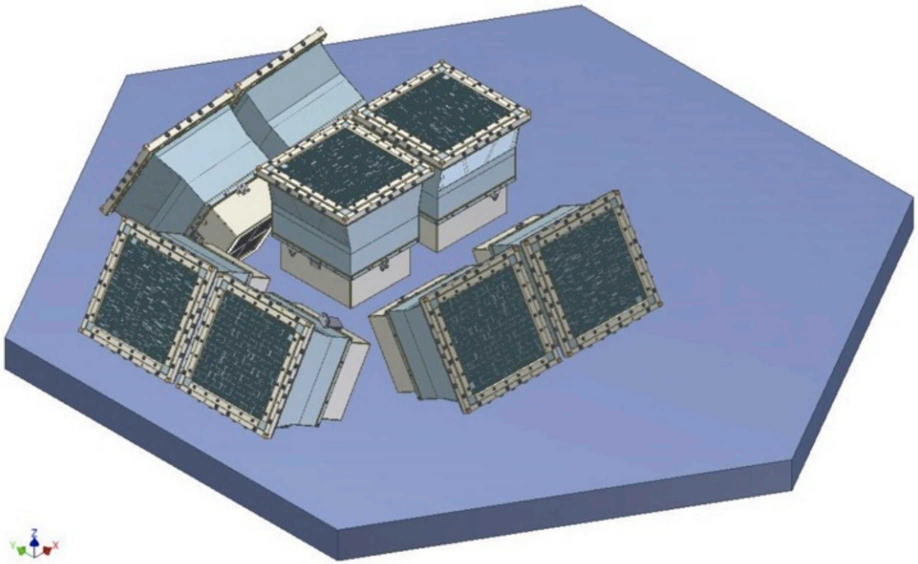


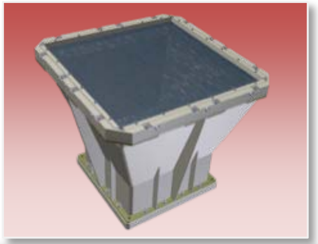
Modular design of LOFT enables adaptation of the technology to smaller effective areas

Effective Area	3.2 m^2 @ 2 keV 8.5 m^2 @ 8 keV 1.1 m^2 @ 30 keV
Energy Range	2-30 keV (30-80 keV ext.)
Energy Resolution FWHM @ 6 keV	<240 eV (45% of the sky) <350 eV (75% of the sky)
Collimated FoV	1 deg FWHM
Dead Time	<0.1% @ 1Crab
Absolute Time Accuracy	1 μs

LOFT-M4 - Wide Field Monitor

A powerful all-sky or wide field monitor is a crucial component of a future X-ray timing mission for transient detection,
along with rapid repointing capability for transient follow-up.





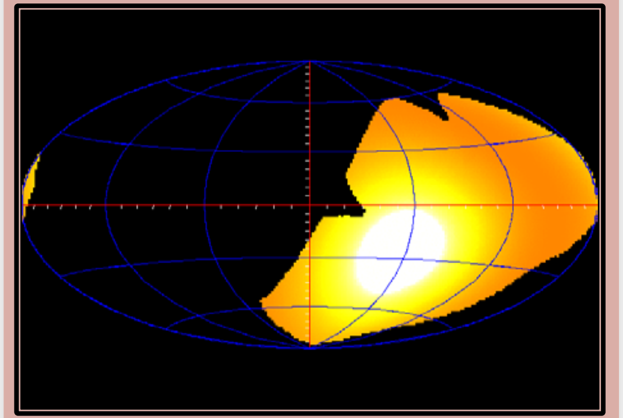
4 Units

8 Cameras

Field of View	5.5 steradian
Position Accuracy (10σ)	1 arcmin
Energy range	2-50 keV
Energy Resolution	300 eV @ 6 keV
Collecting Area	1460 cm^2
Time Resolution	10 μs (trigger) ~minutes (images)
Sensitivity (5σ, Galactic Center)	330 mCrab (3s) 2.1 mCrab (1day)
Ground Transmission of GRB Coordinates	< 30s

Wide Field Monitor

45% of the Sky Monitored at Any Time



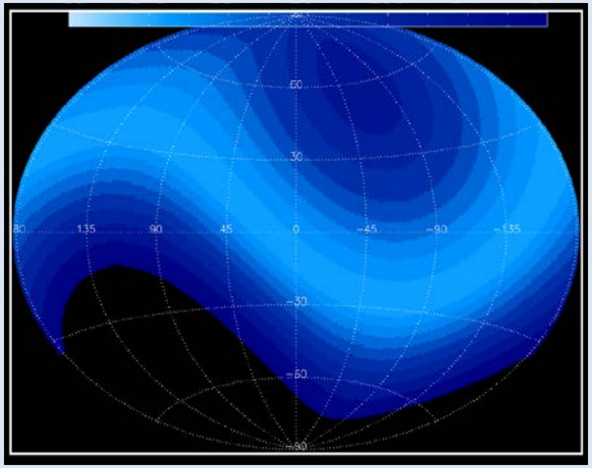
WFM Sky Coverage Keeps Track of the Sky All the time

Anti-Sun region:

key to simultaneous observations with ground-based facilities (e.g., TeV).

Large Area Detector

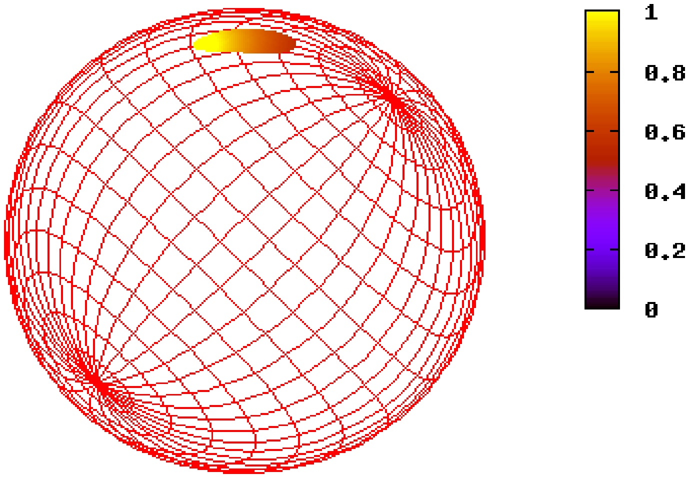
75% Instantaneous Sky Visibility

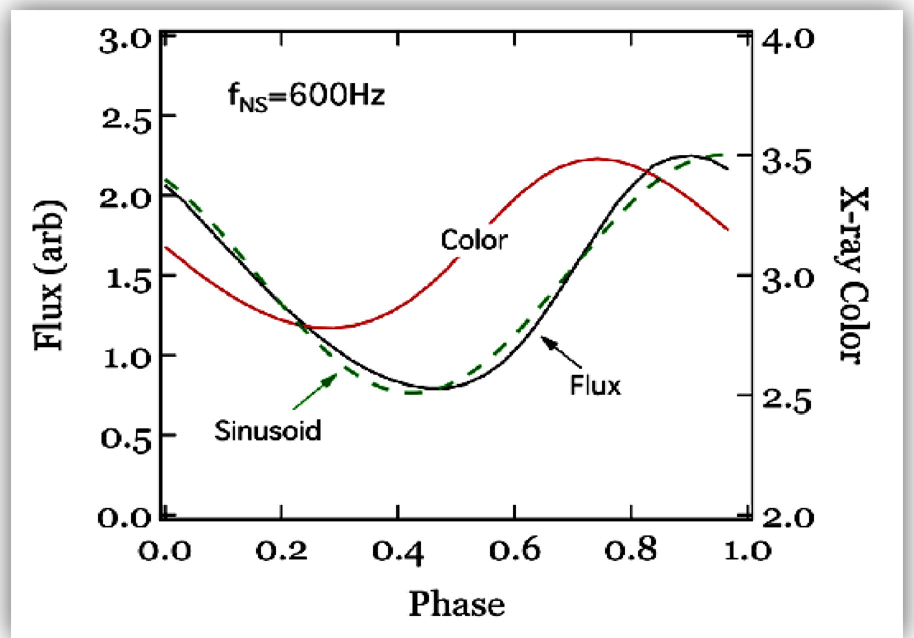


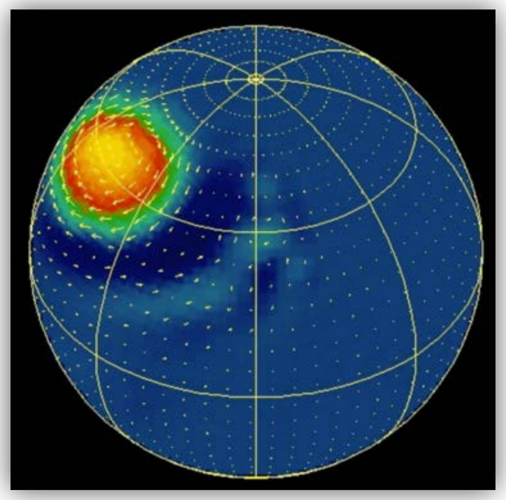
Excellent coverage of transients

Key Science Objectives

- Determining Mass and Radius for neutron stars to constrain the equation of state of ultradense matter.
- Testing General relativity in the strong gravity regime
- Time domain science enabled by a wide-field monitor and quick follow-up





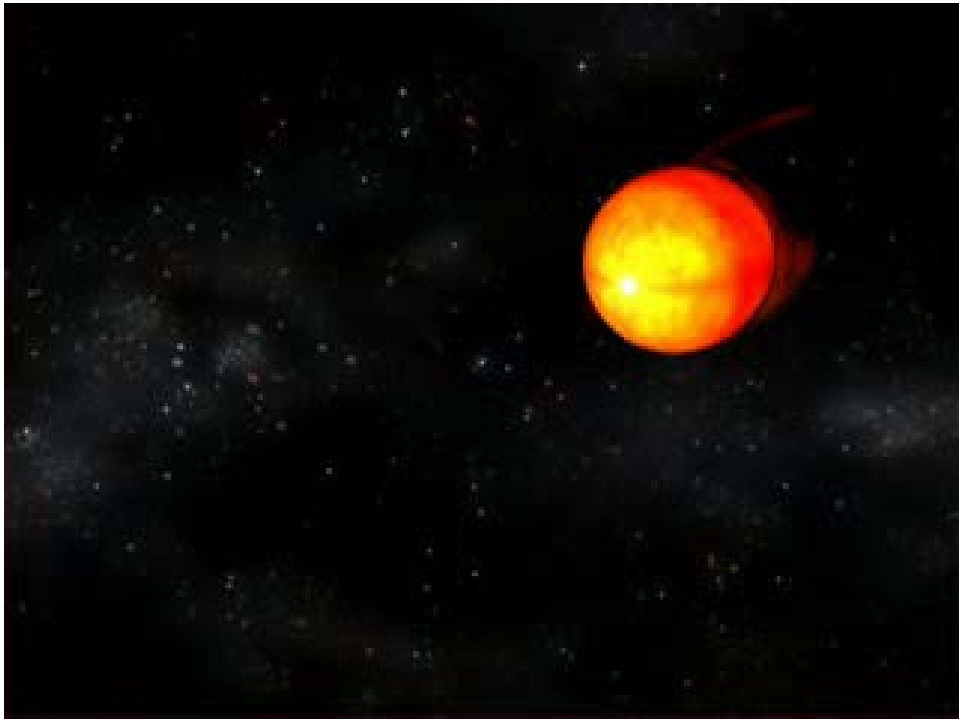


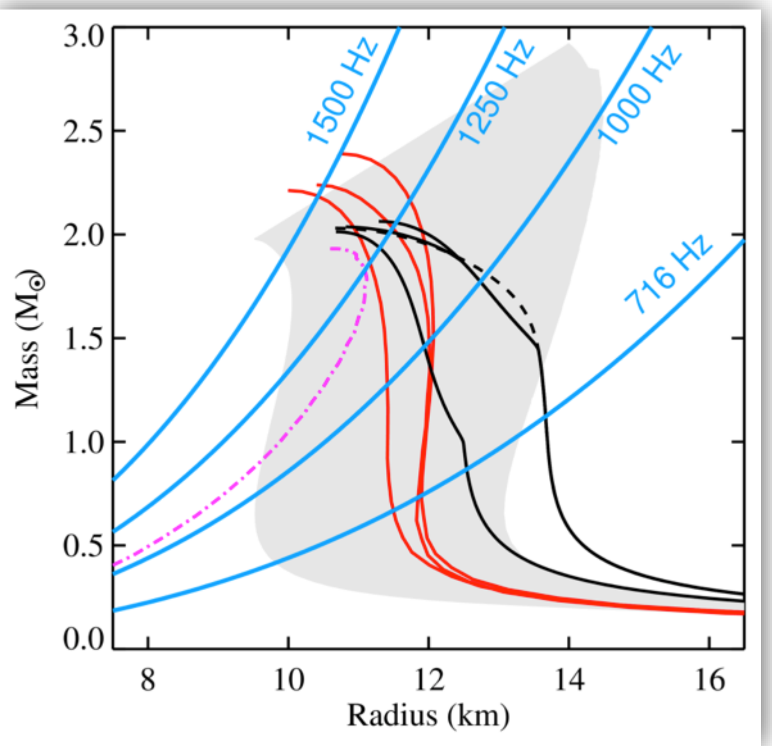
Hotspot in thermonuclear burst (Spitkovsky et al. 2002)

Hotspots on accreting neutron stars generate pulsations.

Relativistic effects (light-bending, redshifts, aberration) encode information about M and R.

PROBE-CLASS MISSION CAN USE ACCRETING PULSARS WITH THERMONUCLEAR BURSTS

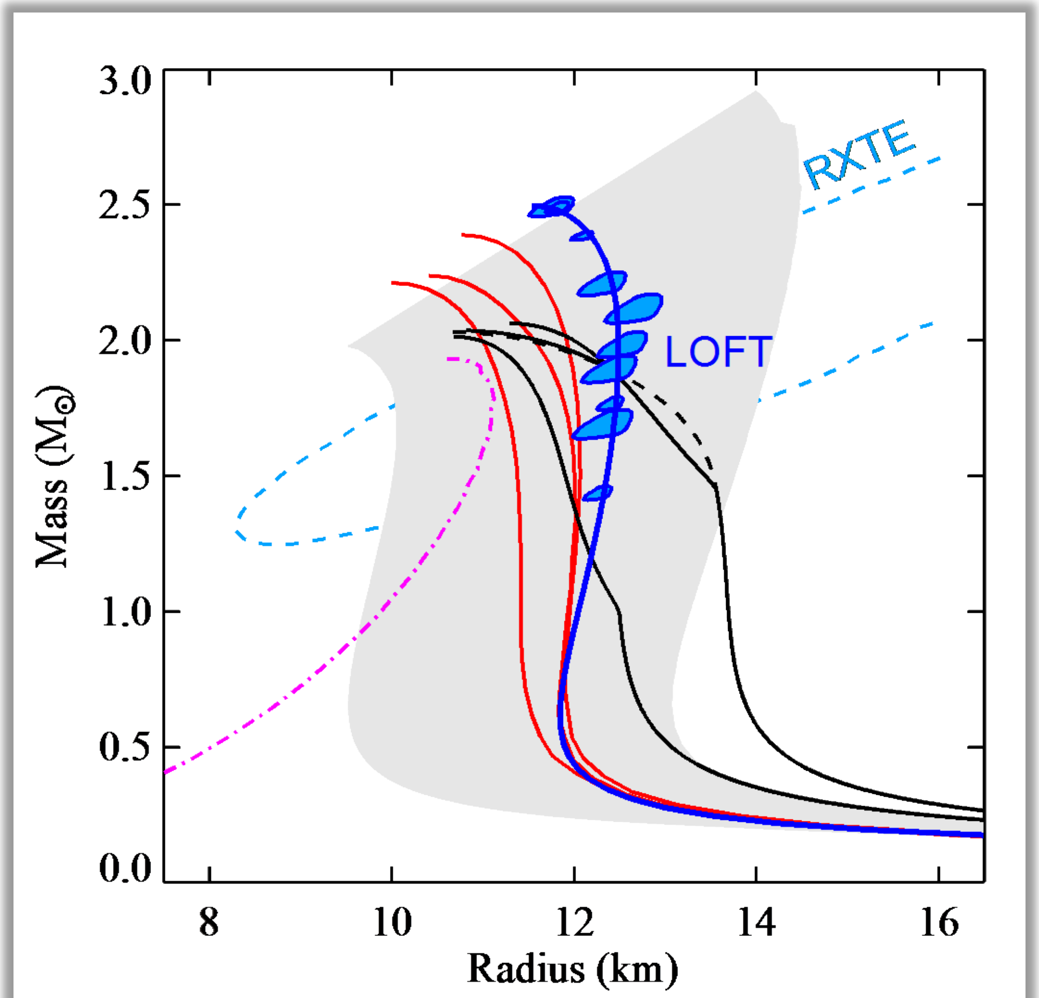




For most accreting NS spin is not yet known. Pulsations (especially for high accretion rate sources) are weak or intermittent.

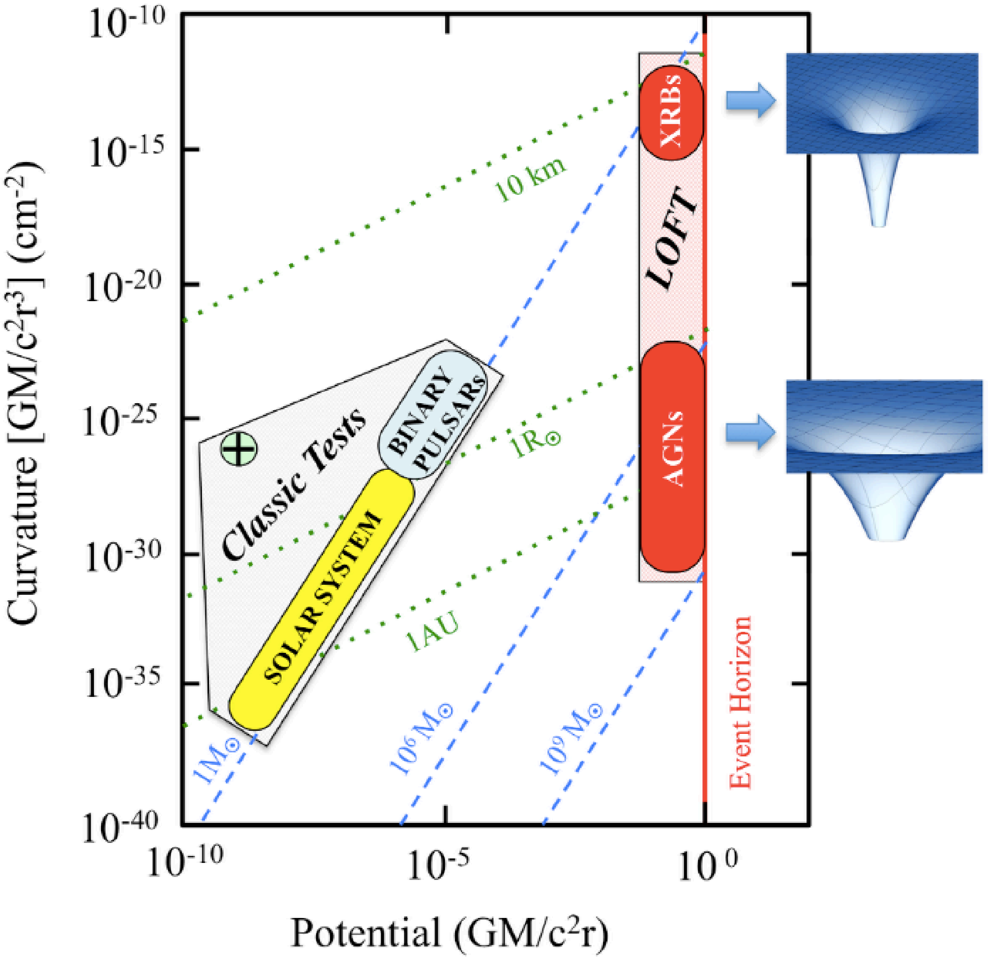
Spin rates constrain EOS via mass-shedding limit.

A PROBE-CLASS MISSION WOULD EXTEND THE KNOWN SPIN DISTRIBUTION OF ACCRETING NEUTRON STARS.



- Detailed simulations carried out to evaluate fitting procedure and accuracies (Lo et al. 2013, ApJ).
- Few % accuracy needs ~10^6 photons: ~ 8-10m^2 area crucial.
- Multiple same-source cross-checks.
- Smaller areas require a trade between longer observing times for fewer sources or weaker constraints

USING ONLY KNOWN SOURCES, LOFT'S PULSE PROFILE MODELLING MEASUREMENTS WILL MAP THE M-R RELATION AND HENCE THE EOS.

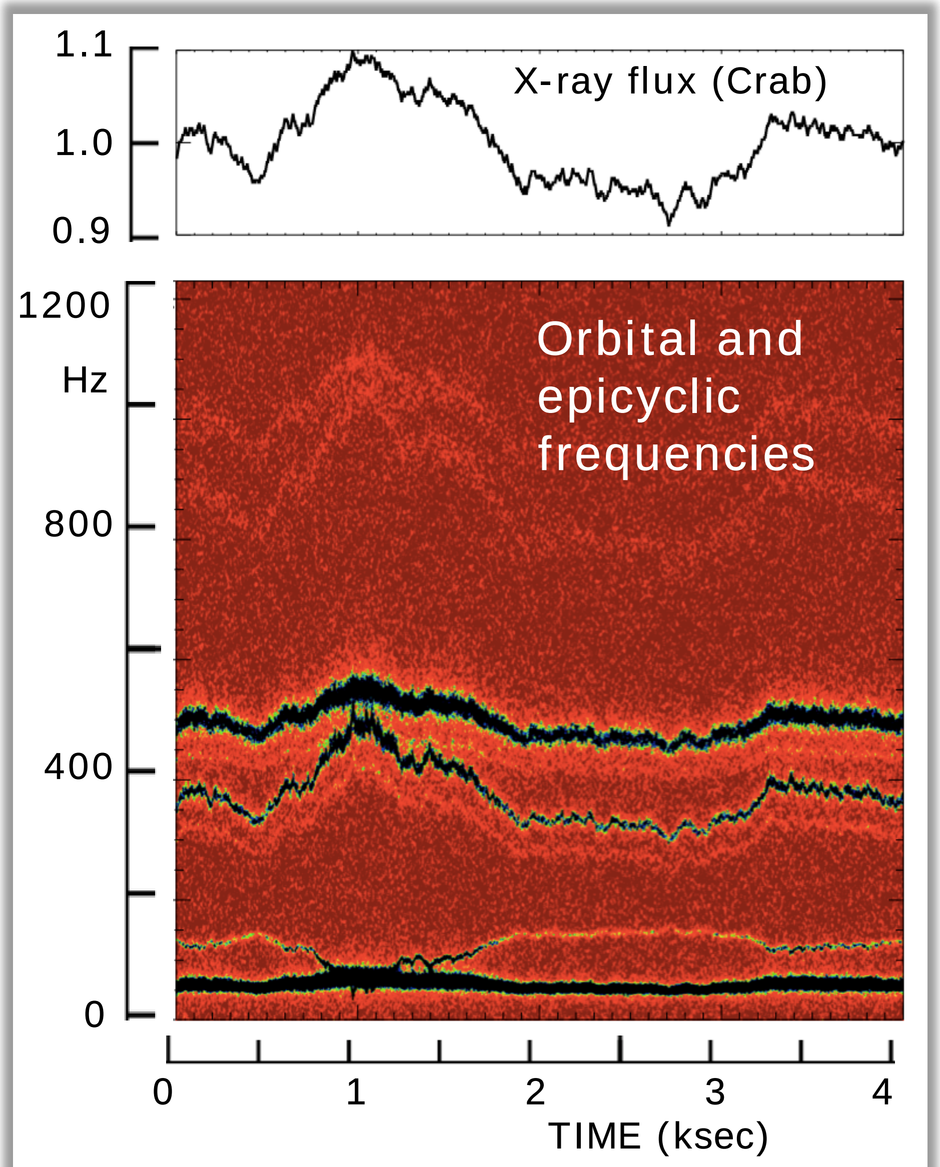


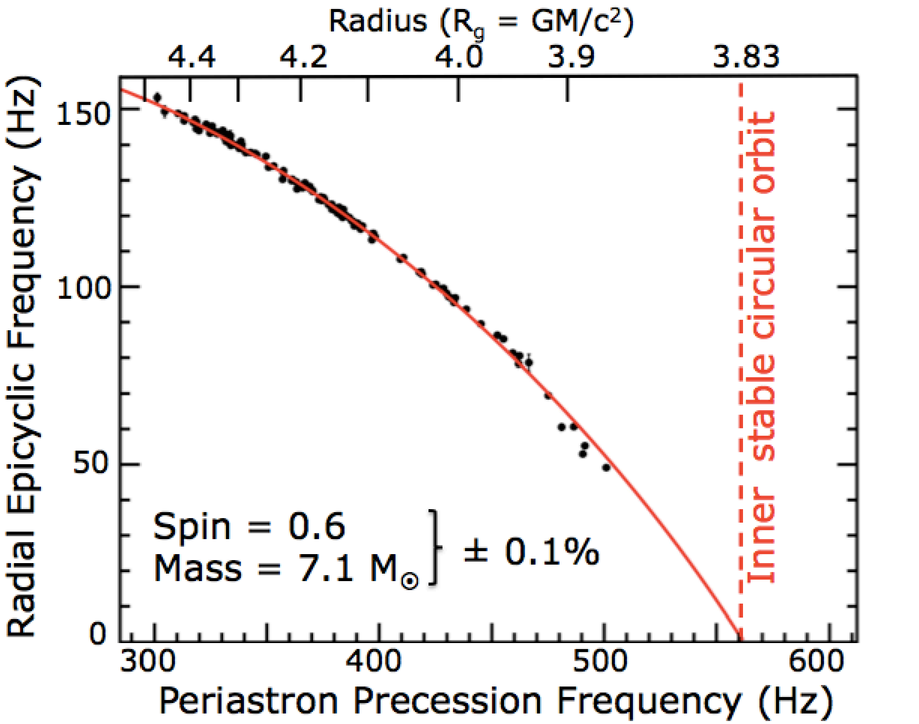
factor 10^{16} in curvature

factor 10^5 in field strength

Complementary to gravitational wave experiments, X-ray timing probes *static* spacetimes

Relativistic epicyclic motion

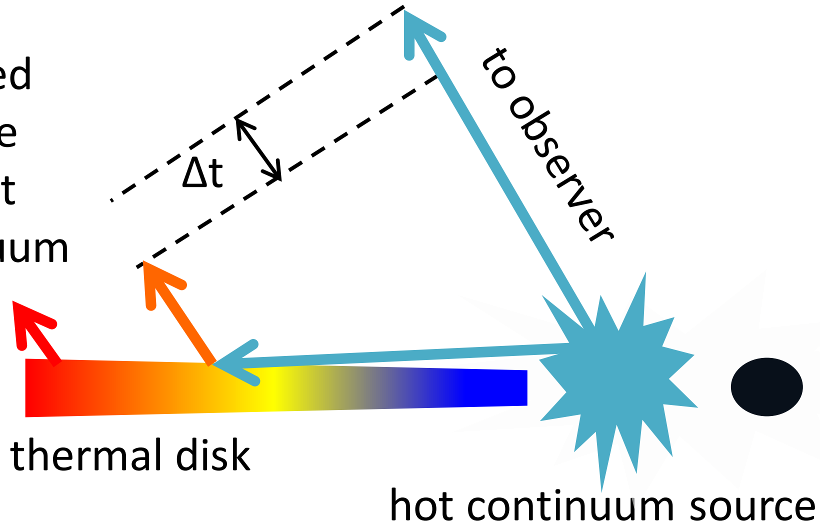


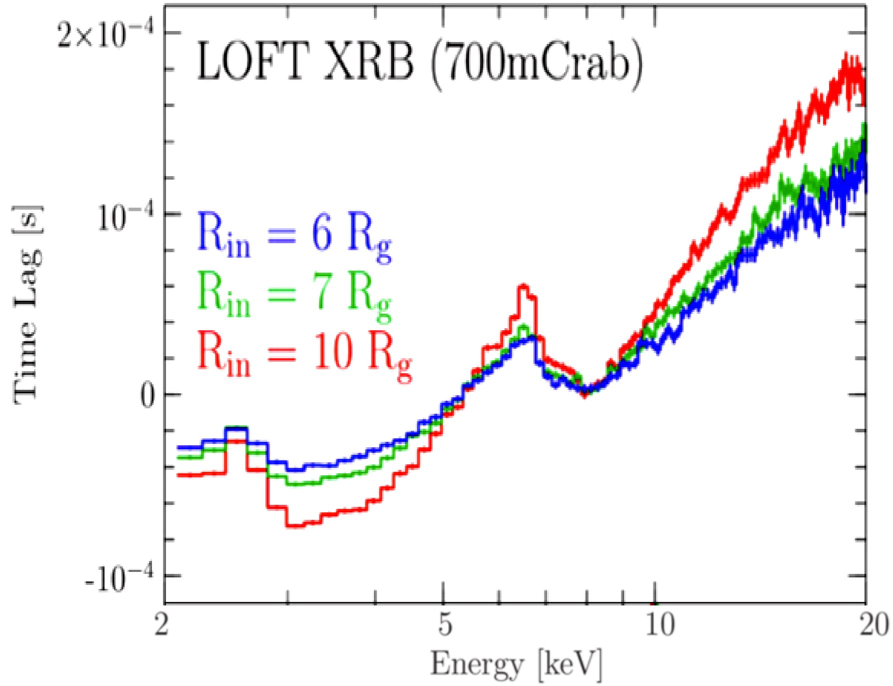


- Precisely measure orbital and epicyclic frequencies at each radius
- Compare curve to GR predictions
- Measure black hole mass and spin to 0.1% precision with LOFT
- Ratio of QPO power to noise scales with area

Reverberation

reflected iron line *lags* hot continuum





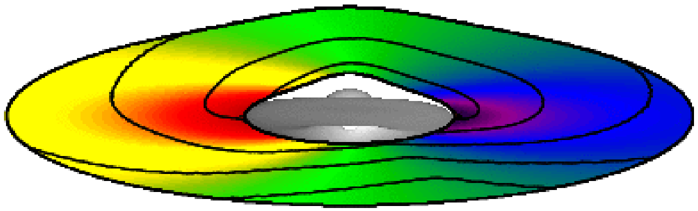
- Variable hot inner flow irradiates disk
- Probe disk velocity/redshift map as radiation fronts propagate over the disk
- Obtain strong field velocities and relativistic effects as a function of absolute radius
- For XRB, lag scales linearly with area

Reverberation (barely) detected in XMM data

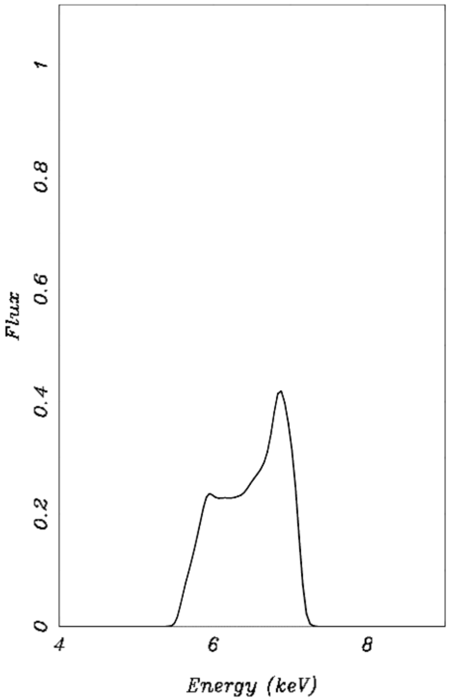
LOFT improves S/N by
- factor ~6 in AGN
- factor >200 in X-ray binaries!

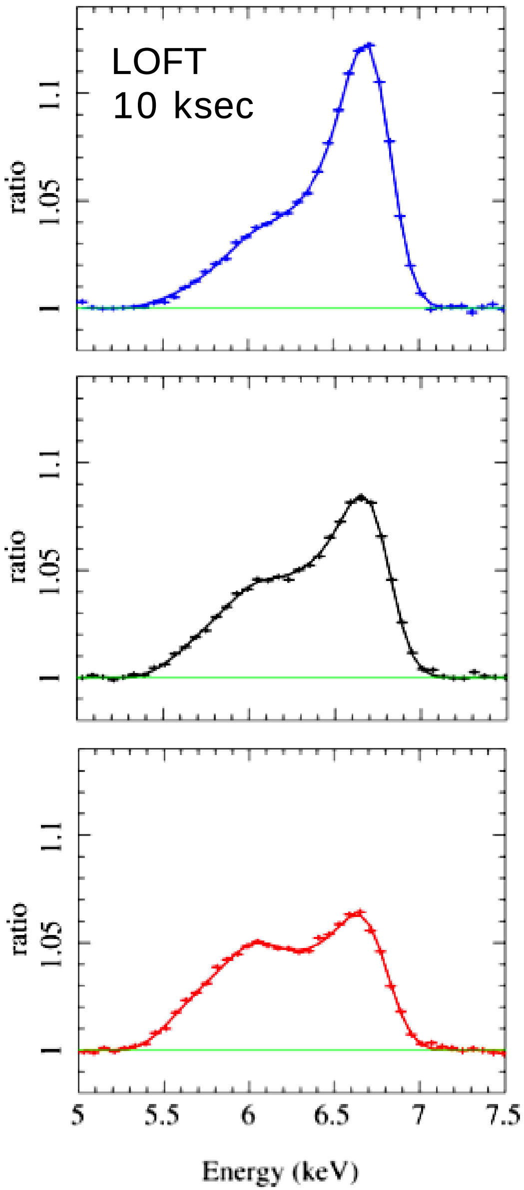
➔ Breakthrough capability 🡐

Precessing hot torus



Ingram, Done, Fragile
2009, 2012





- Frame dragging: central hot torus <u>precesses</u>
- Hard radiation sweeps around over disk
- Reflection line profile varies periodically

LOFT observations:

- Confirm black hole frame dragging
- Track the line profile, probing the disk velocity and redshift map

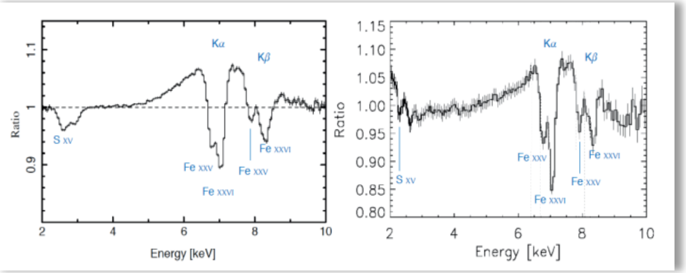
- EXTREME-THROUGHPUT SPECTROSCOPY WITH LAD
- VERY WIDE ANGLE MONITORING WITH WFM

12 White Papers by >300 authors from the community:

- Accretion/ejection in XRBs
- PSR Magnetospheric physics
- Thermonuclear bursts
- HMXRB and ULX
- Gamma ray bursts
- Tidal disruptions
- Blazars
- Cataclysmic variables
- Binary evolution
- Terrestrial γ-ray flashes
- Flare stars
- Radio-quiet AGN

LAD Pointed observations

LAD – 1 ks XMM – 78 ks



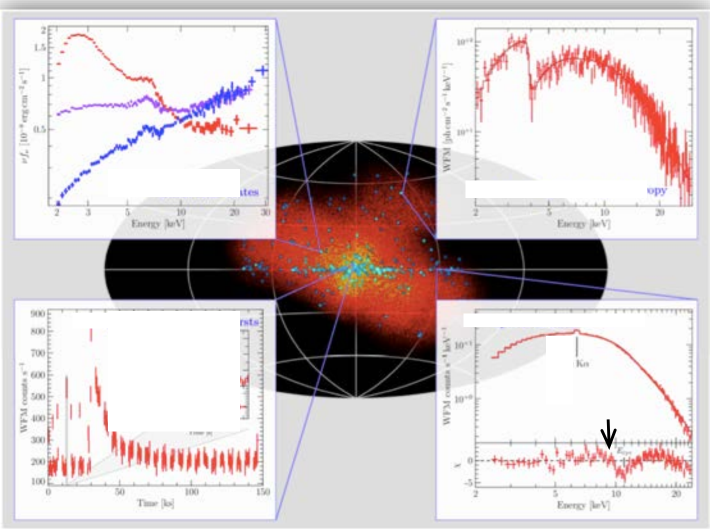
Winds in XRBs (4U 1630-47)

Simultaneous WFM observations

2-50 keV bandwidth

Galactic BH states

~5000 thermo-nuclear bursts
10 super bursts /yr



30 s triggers

>100 GRBs/yr

Cyclotron lines

5.5 steradian field of view

300 eV resolution

X-ray Timing Science Highlights

- Accreting pulsars (Her X-1, Cen X-3) and accretion torques and torque noise; also modeled spectra for such polar caps
- Accreting black holes (Cyg X-1); QPO modes in persistent frequency ratios; long history of X-ray transients of the BH variety
- X-ray bursts, as nuclear explosions of accreted material
- SAX J1808 and accreting millisecond pulsars
- GRS 1915+105 (heartbeat mode and other astonishing, repeatable fluid dynamics)
- Rapid Burster and others as equally surprising phenomenology in NS as well as BH
- NS surface emissions modified by gravitational lensing
- rotation powered X-ray pulsars of various types, and in relation to gamma-rays, radio, etc
- Long-term variations in the Crab Nebula

Summary

- A Probe-class X-ray timing mission is feasible with technology developed for the proposed ESA medium class LOFT mission
- Significant advances are possible with a probe-class or even a MidEX class timing mission
- Science Impact
  - RXTE (1995-2012)
    - 2838 refereed articles with 80,604 citations
    - 2434 non-refereed articles with 9696 citations
    - About 100 Ph.D. Theses!
  - LOFT (proposed for ESA M4)
    - 800+ supporters
    - 270 papers