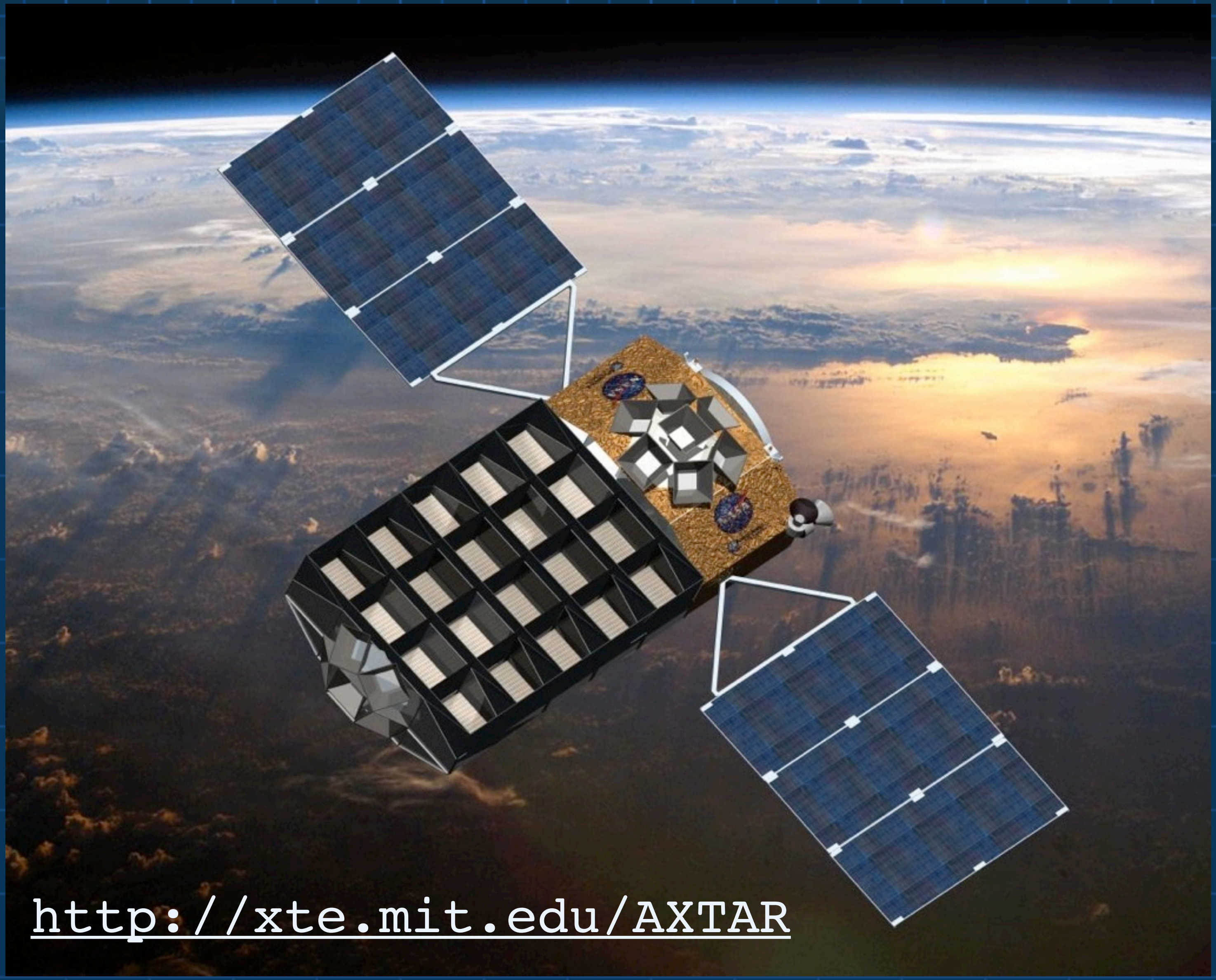
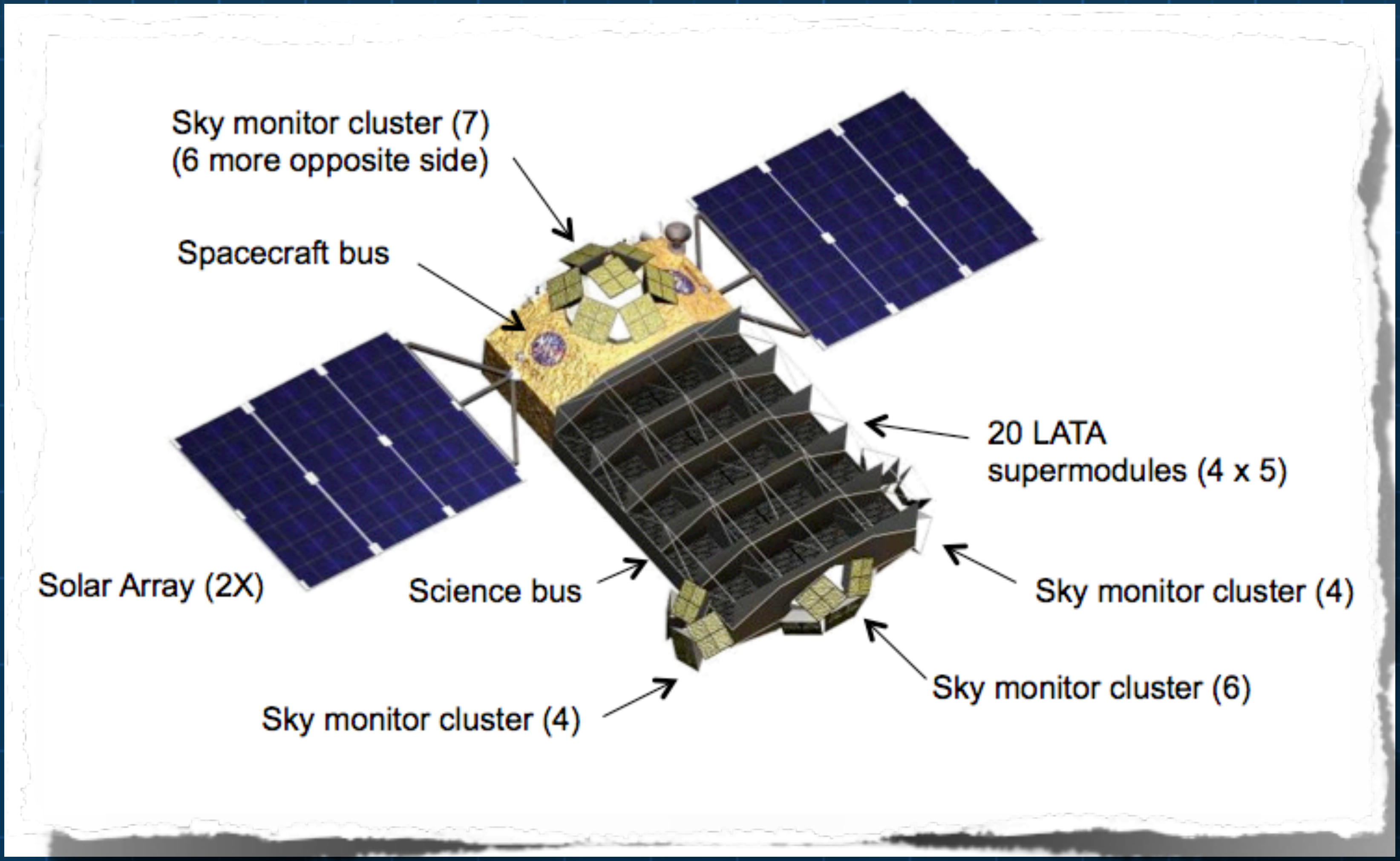
The Advanced X-ray Timing Array (AXTAR)



Paul Ray (NRL), Deepto Chakrabarty (MIT), Marc Christophersen (NRL),
Bernard Phlips (NRL), Dimitrios Psaltis (Arizona), Ron Remillard (MIT),
Colleen Wilson-Hodge (NASA/MSFC), Michael Wolff (NRL), Kent Wood (NRL),
for the AXTAR Collaboration

AXTAR Basics

Collimated 1.8–80 keV X-ray timing and spectral mission with much larger area than RXTE

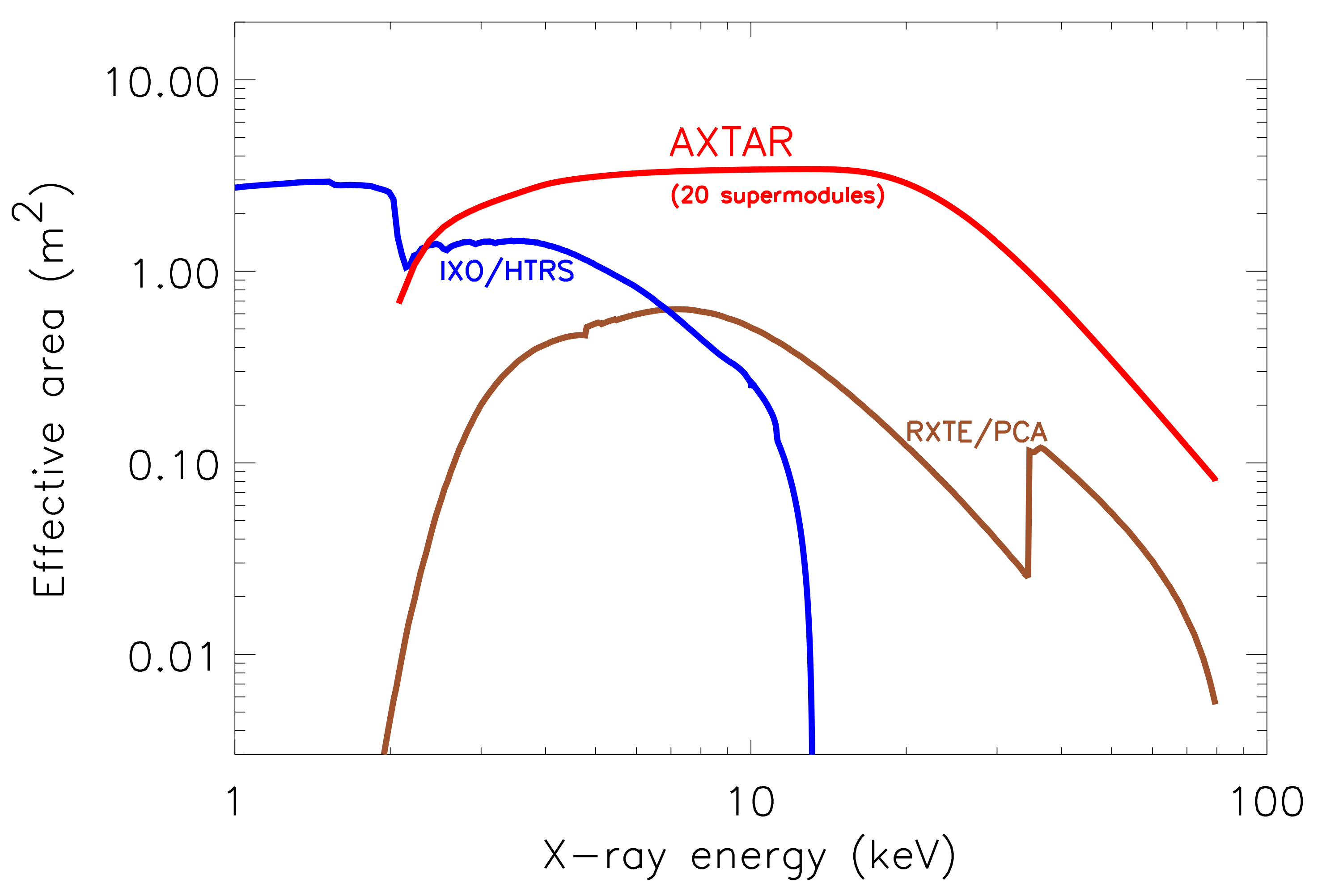


- **Large Area Timing Array (LATA)**
  - 3.2 m^2 effective area
  - <600 eV energy resolution
  - Low inclination LEO orbit
- **Sky Monitor (SM)**
  - Multiple coded-aperture cameras (40°x40° FOV each)
  - High duty cycle monitoring of sky
  - < 5 mCrab in 1 day
- **Flexible scheduling and rapid response**
  - Targets from GI program

Cost Category:
Small (<$400M, excluding launch)

AXTAR Basics

Collimated 1.8–80 keV X-ray timing and spectral mission with much larger area than RXTE



- **Large Area Timing Array (LATA)**
  - 3.2 m^2 effective area
  - <600 eV energy resolution
  - Low inclination LEO orbit
- **Sky Monitor (SM)**
  - Multiple coded-aperture cameras (40°x40° FOV each)
  - High duty cycle monitoring of sky
  - < 5 mCrab in 1 day
- **Flexible scheduling and rapid response**
  - Targets from GI program

Cost Category:
Small (<$400M, excluding launch)

AXTAR Science

Fast timing probes short timescales such as the spin of a neutron star or the last stable orbit around a stellar-mass black hole

A key metric is S/N per unit time
(e.g. coherence time of an oscillation or rise time of a burst)
Example: In 1 ms, AXTAR gets S/N >10, while RXTE had S/N <3

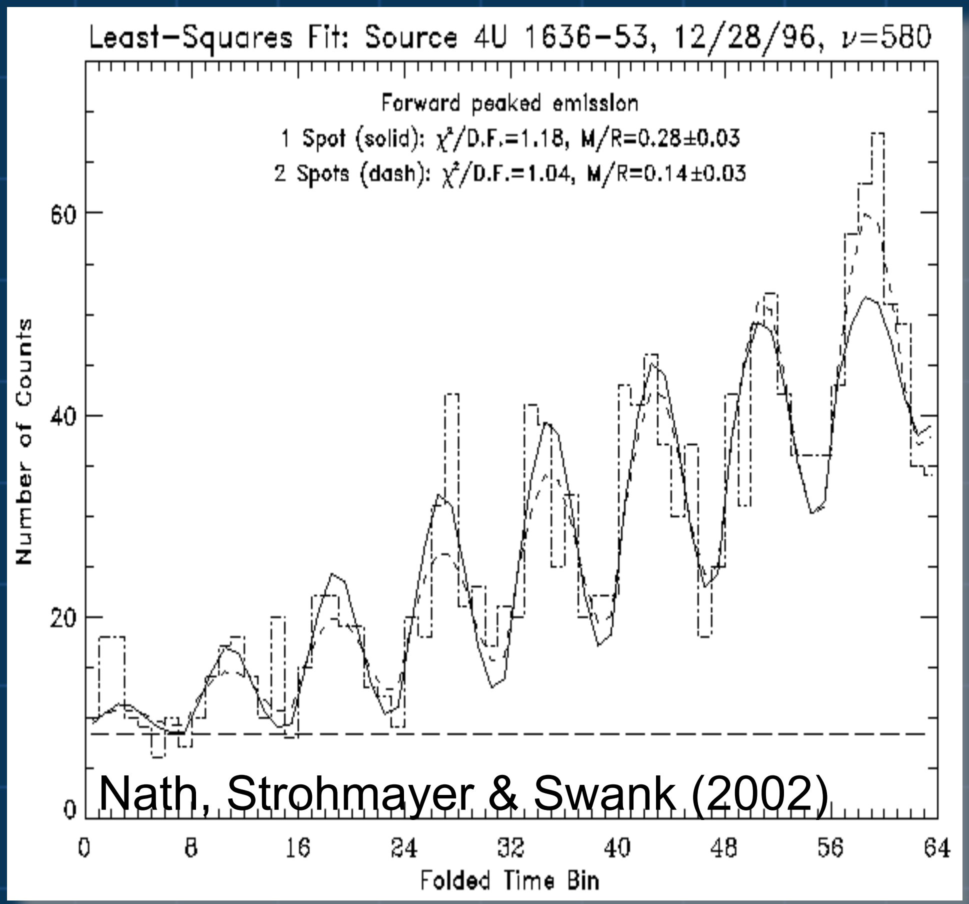
Two IXO science questions were key design drivers for AXTAR

How does matter behave at very high density?
- Detailed studies of bursts in X-ray binaries

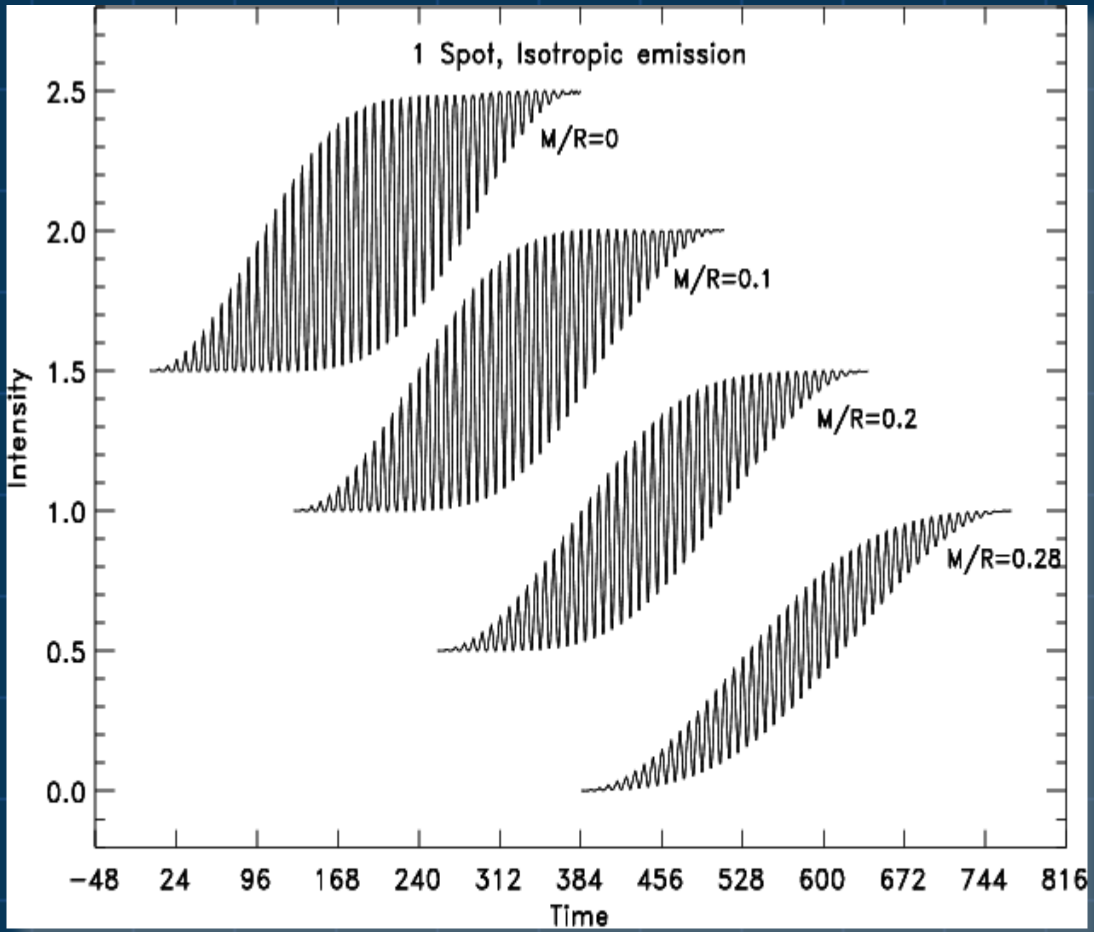
What happens close to a black hole?
- Multiple techniques, including high frequency QPO studies

Burst Oscillations Probe the Structure of Neutron Stars

- Pulse strength and shape depends on M/R or 'compactness' because of light bending (a General Relativistic effect).
  - ✦ More compact stars have weaker modulations.
  - ✦ Pulse shapes (harmonic content) also depend on relativistic effects (e.g. Doppler shifts due to rotation, which depends on *R*, since the spin frequency is known).
- For sources where phase-resolved spectroscopy is possible, rotational Doppler shift of hot spot emission also sensitive to radius (for known spin rate). This measurement is NOT possible with RXTE due to insufficient sensitivity
- Model dependence is minimized by small size of spot at burst onset.

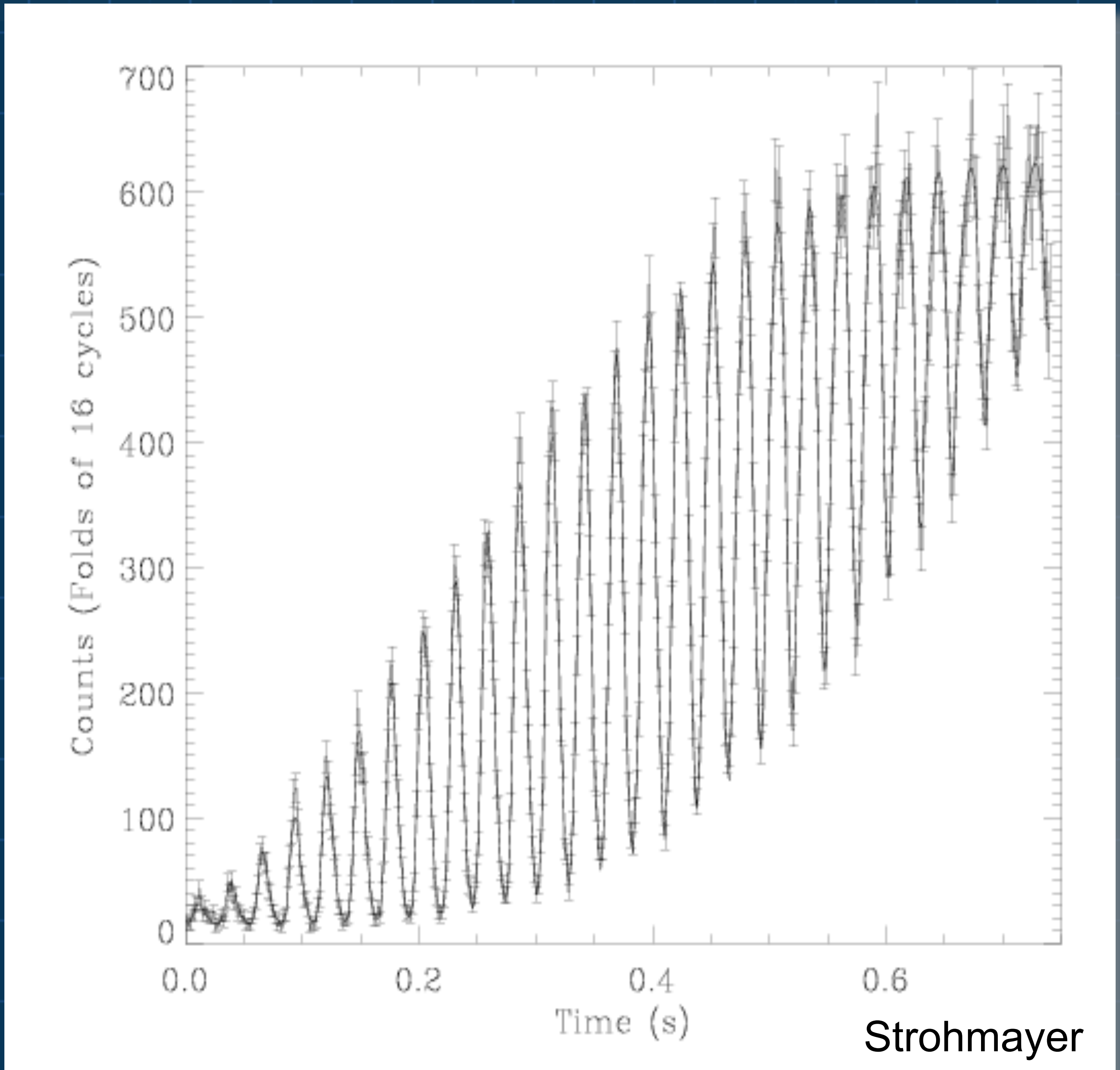


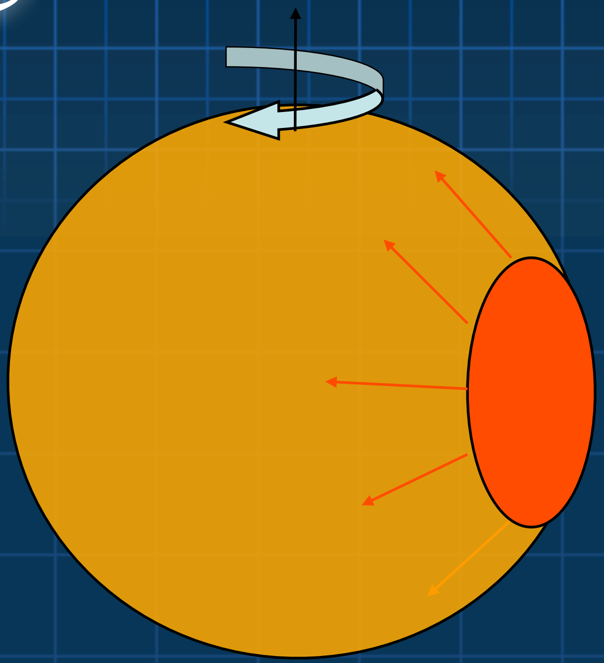
Nath, Strohmayer & Swank (2002)



Approved for public release, distribution unlimited

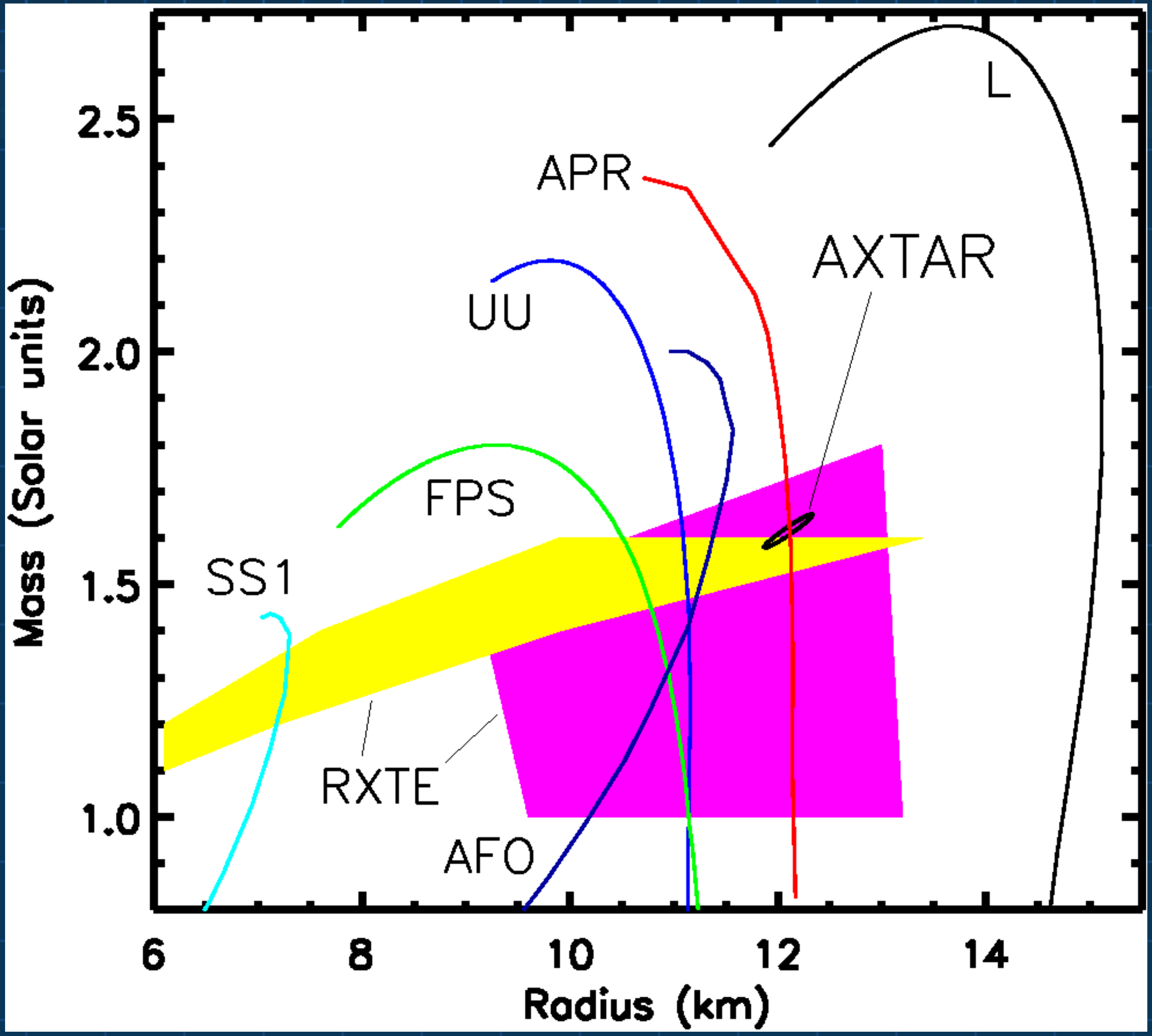
Simulated AXTAR Lightcurve





- Use blackbody emission from neutron star surface.
- Circular hot region which grows linearly with time.
- Flux and spin rate for bursts from 4U 1636-53.

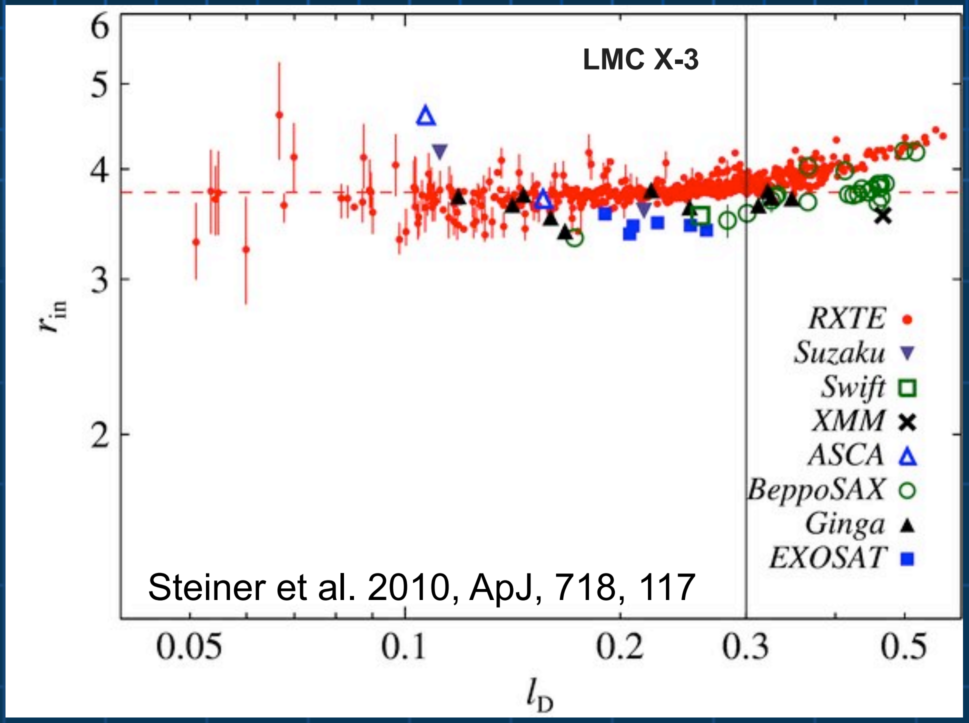
Neutron star mass-radius constraints with AXTAR: Simulation of an X-ray burst oscillation



AXTAR will routinely make 5–10% measurements of neutron star radii in X-ray bursters, thus conclusively discriminating between candidate equations of state for dense matter.

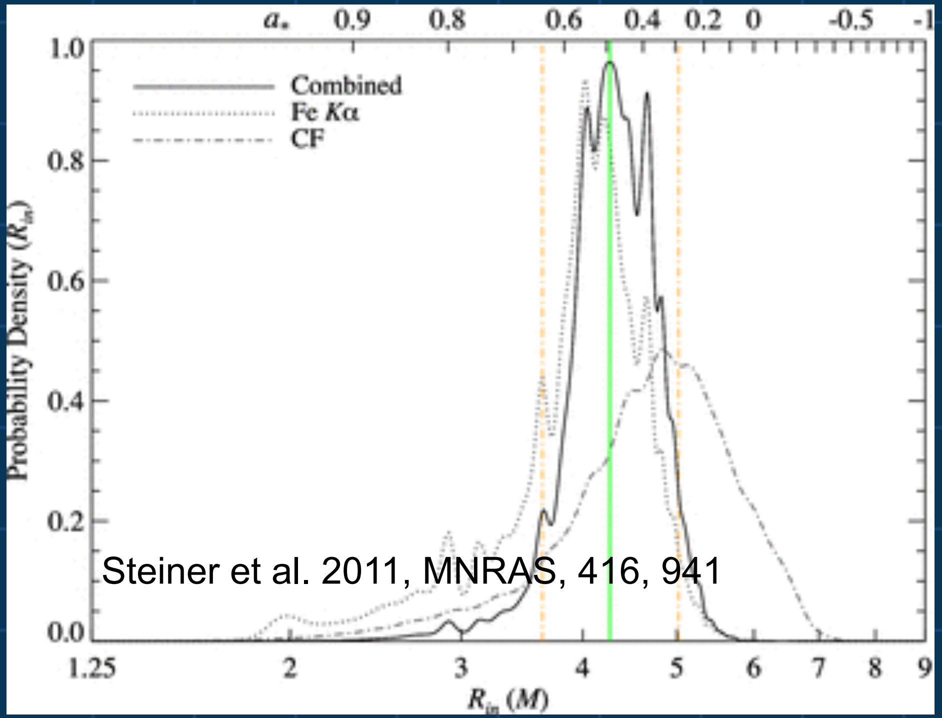
What Happens Close to a Black Hole?

- Multifaceted attack on BH spin
  - ✦ Continuum fitting
    - Large area and broad energy coverage are critical
  - ✦ Fe lines
    - Needs modest resolution and good coverage of continuum
  - ✦ HFQPOs
    - Unsolved problem that AXTAR can solve and integrate into 3-method solution
    - New QPO features distinguishes correct model



Continuum fitting produces robust, repeatable measurements

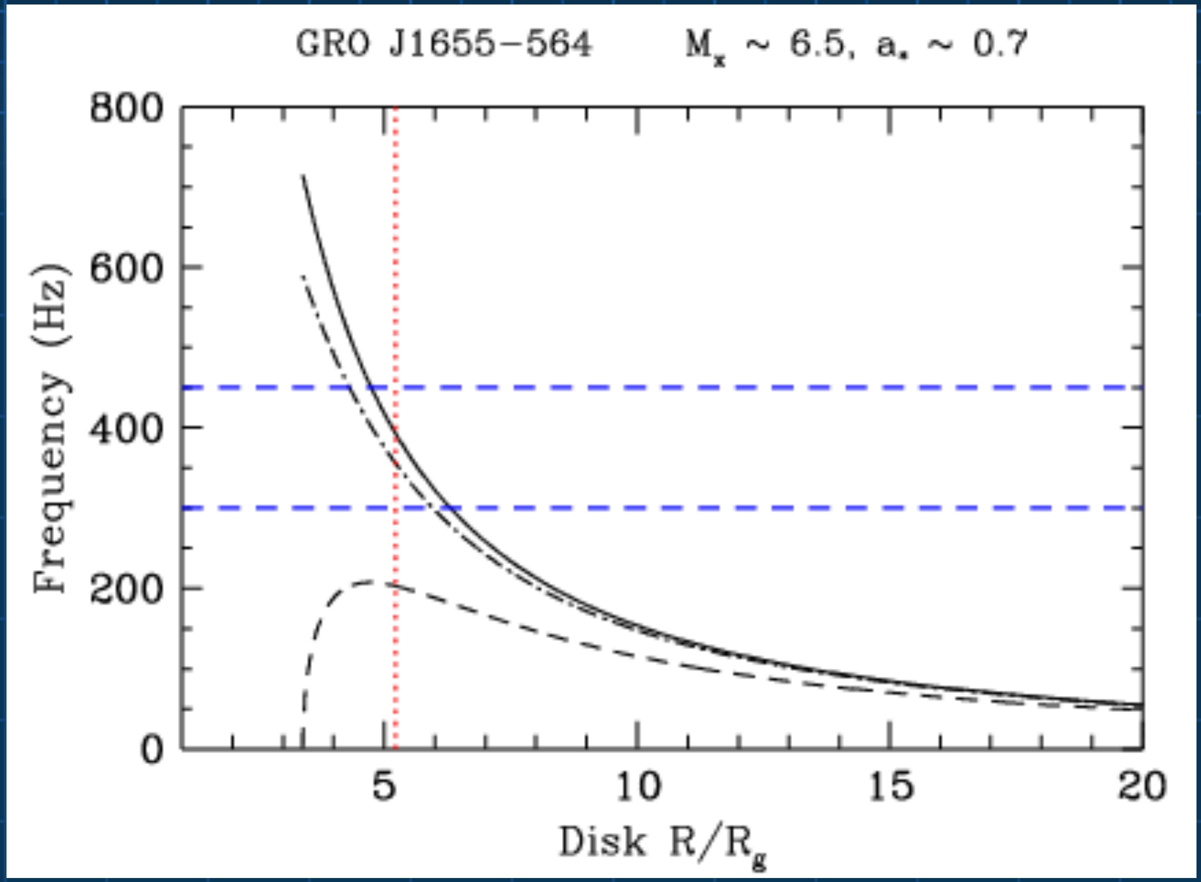
- Testing GR
  - ✦ Above assumes GR and using Kerr metric to measure BH spin
  - ✦ For any one observable (e.g. Fe line profile or single mode frequency) BH spin and deviation from Kerr are highly degenerate
  - ✦ Multiple modes or observables can break this and test GR



Two methods have different systematics, different model dependencies

Why are HFQPOs Compelling?

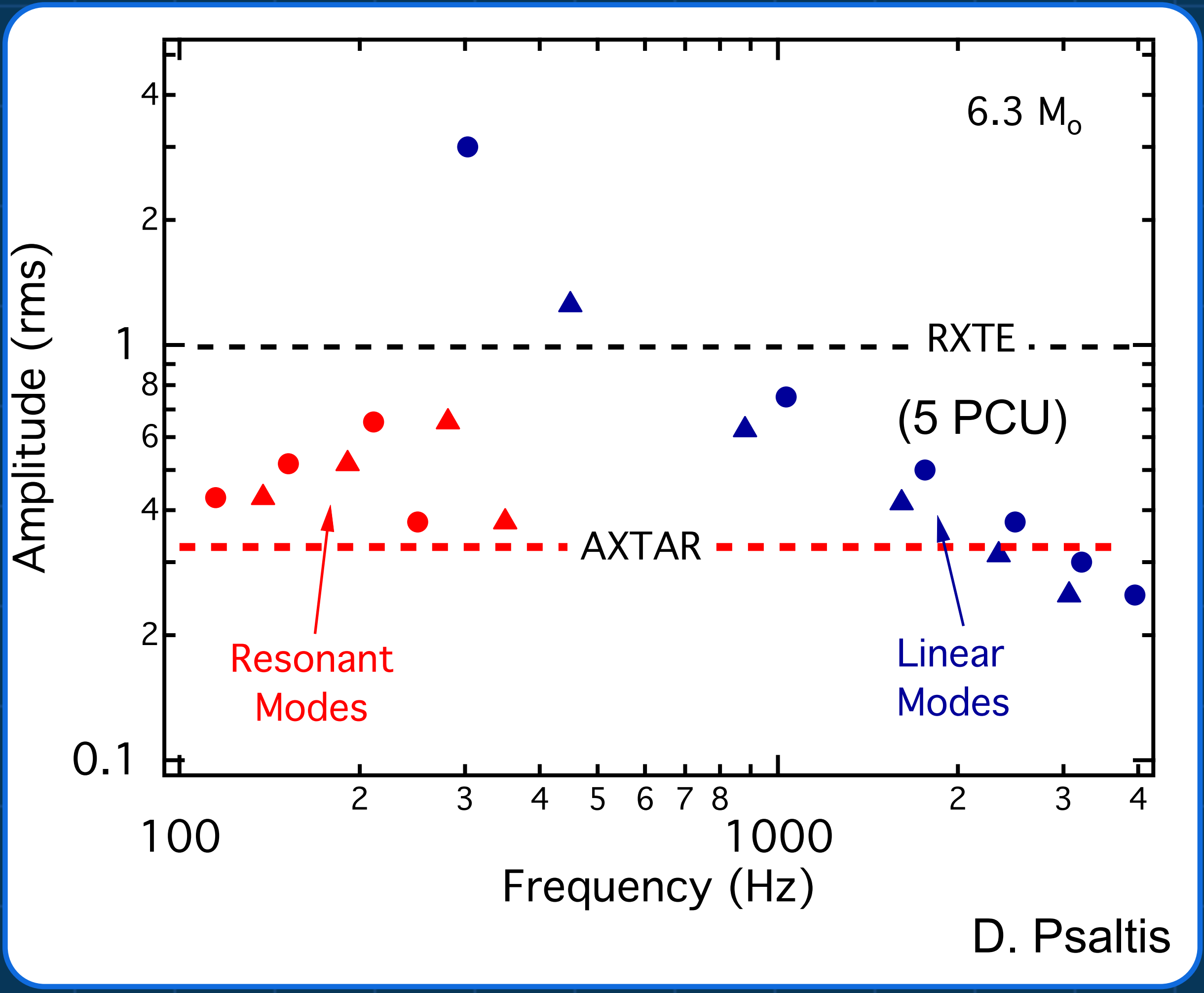
- **HFQPOs and Strong Gravity**
  - QPO ν ~ dynamical frequencies of accretion disk for R < 10 R_g
  - Stable ν (1st order) for each BH, despite large changes in L_X
  - 3:2 frequency ratio HFQPO pairs → common mechanism
  - Roughly ν ~ 1/*M* for cases of HFQPOs plus known BH mass
  - Study matter in strong gravity with immunity to (*D*, A_V , *i*)



- **Next slide describes how AXTAR can exploit this**

AXTAR Strategy for HFQPOs

- Large area yields high count rates to see weaker features in power spectrum
  - Detect HFQPOs and weaker PDS features to rms ~ 0.3% at 5 σ in 10ks for ~20 BHBs
  - Analyzing new modes will distinguish models
- Focus on spin (BHs with known mass) and combine HFQPO analyses with spin determinations from continuum fitting and Fe-line analyses.
- Observe BHs (most are transients) many times to cover all states (thermal, steep power law, hard/jet) , to witness state transitions, and to sample different luminosities for further inputs for constructing HFQPO theory



Approved for public release, distribution unlimited

Technical Requirements

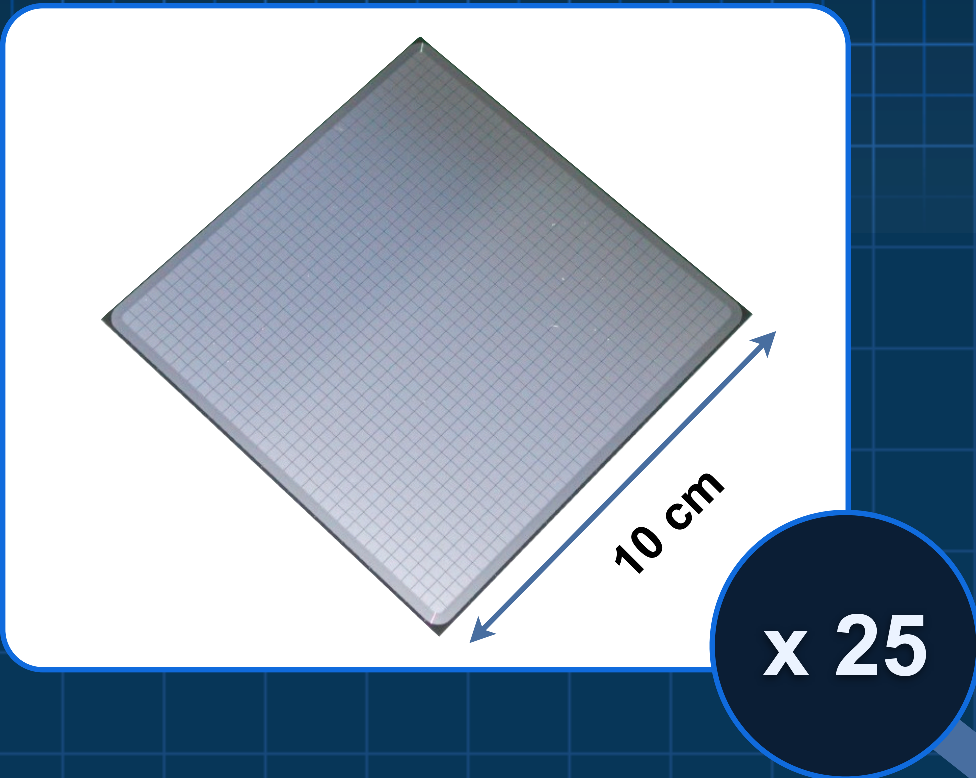
- Effective Area: >3 m^2 (Recall RXTE was 0.6 m^2 initially, mostly <0.4 m^2)
  - Largest area mission yet flown
- Energy Range: below 2 keV to at least 30 keV
- Achieve high count rates with minimal dead time
- Fast response to transients and state changes; flexible scheduling
- Sky monitor to provide triggers and context information, plus stand-alone science

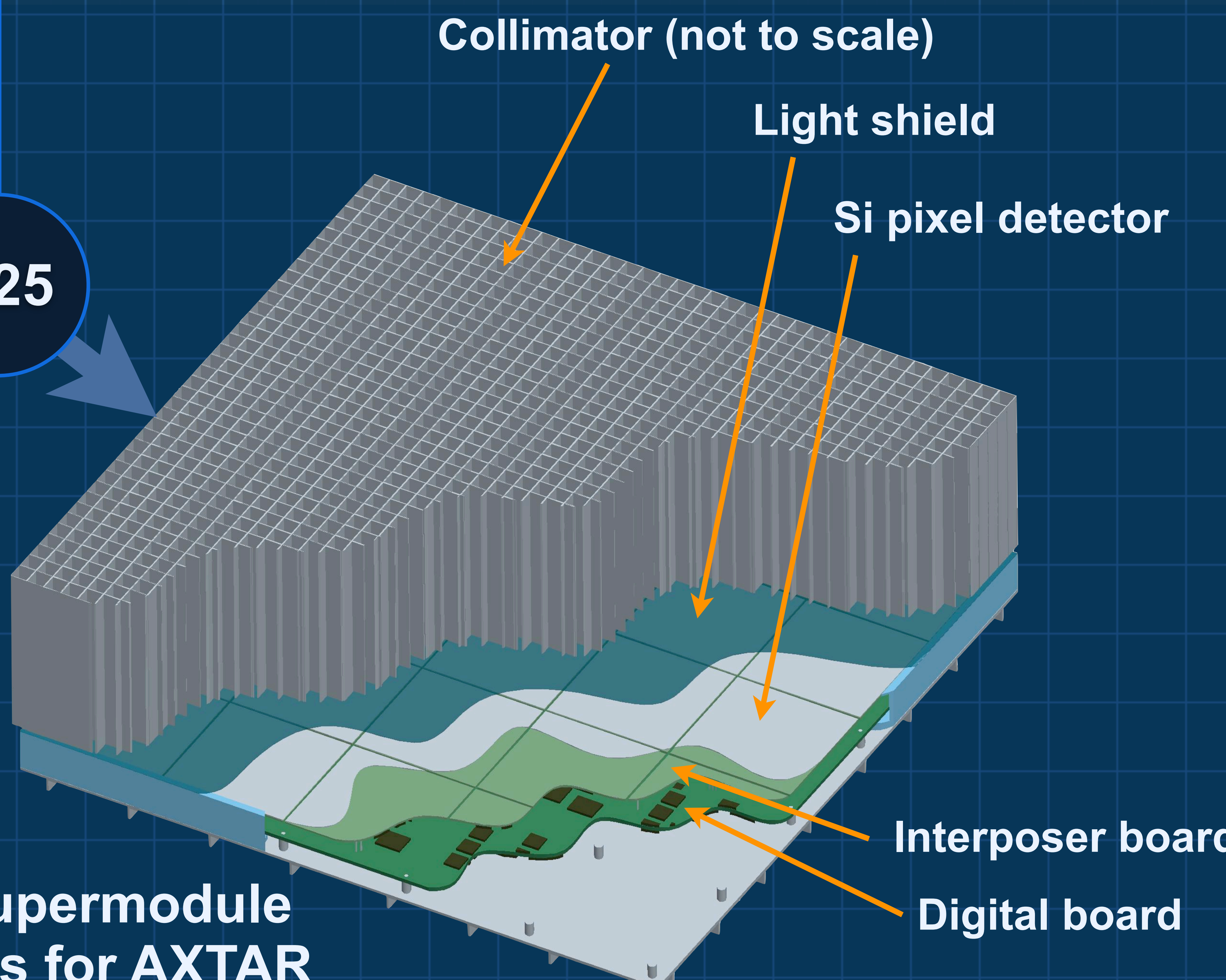
Table 1. Mission Requirements

Parameter	Baseline	Drivers	Technology Factors
		Large Area Timing Array (LATA)	
Effective Area	3.2 m^2	NS radius, BH QPOs	Mass, cost, power
Minimum Energy	1.8 keV	Source states, absorption meas., soft srcs	Detector electronics noise
Maximum Energy	>30 keV	BH QPOs, NS kHz QPOs, Cycl. lines	Silicon thickness
Deadtime	10%@10 Crab*	Bright sources, X-ray bursts	Digital elec. design, pixel size
Time Resolution	1 μs	Resolve ms oscillations	Shaping time, GPS, Digital elec.
		Sky Monitor (SM)	
Sensitivity (1 d)	$<$ 5 mCrab*	Faint transients, multi-source monitoring	Camera size/weight/power
Sky Coverage	$>$ 2 sr	TOO triggering, multi-source monitoring	# cameras vs. gimbaled designs
Source Location	1 arcmin	Transient followup	Pixel size, camera dimensions
		AXTAR Mission	
Solar Avoidance Ang.	30°	Access to transients	Thermal/Power design
Telemetry Rate	1 Mbps	Bright sources	Ground stations/TDRSS costs
Slew Rate	$> 6^\circ$ min^{-1}	Flexible scheduling, fast TOO response	Reaction wheels

*1 Crab = 3.2×10^{-8} erg cm^{-2} s^{-1} (2–30 keV)

Large Area Timing Array (LATA) Supermodule

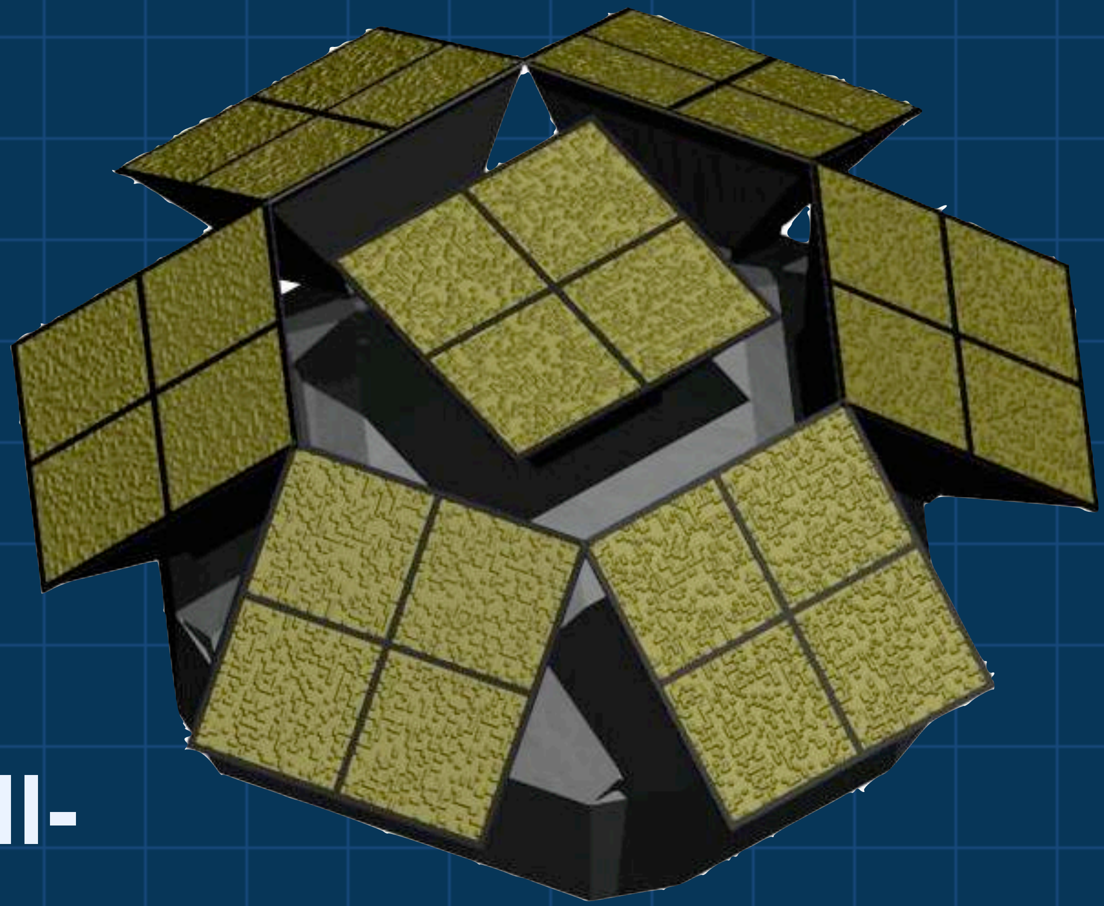




2025 cm^2 per supermodule
20 supermodules for AXTAR

Sky Monitor (SM)

- Same Si pixel detectors provide 2-d imaging when paired with a coded mask
  - Arcminute source localizations
  - ~300 cm^2 area per camera
  - <5 mcrab sensitivity (1 day), 20x better than RXTE/ASM



- 32 cameras could provide all-sky *continuous* coverage
  - Timescales from ms to years
  - Reduced configurations still provide high duty-cycle monitoring

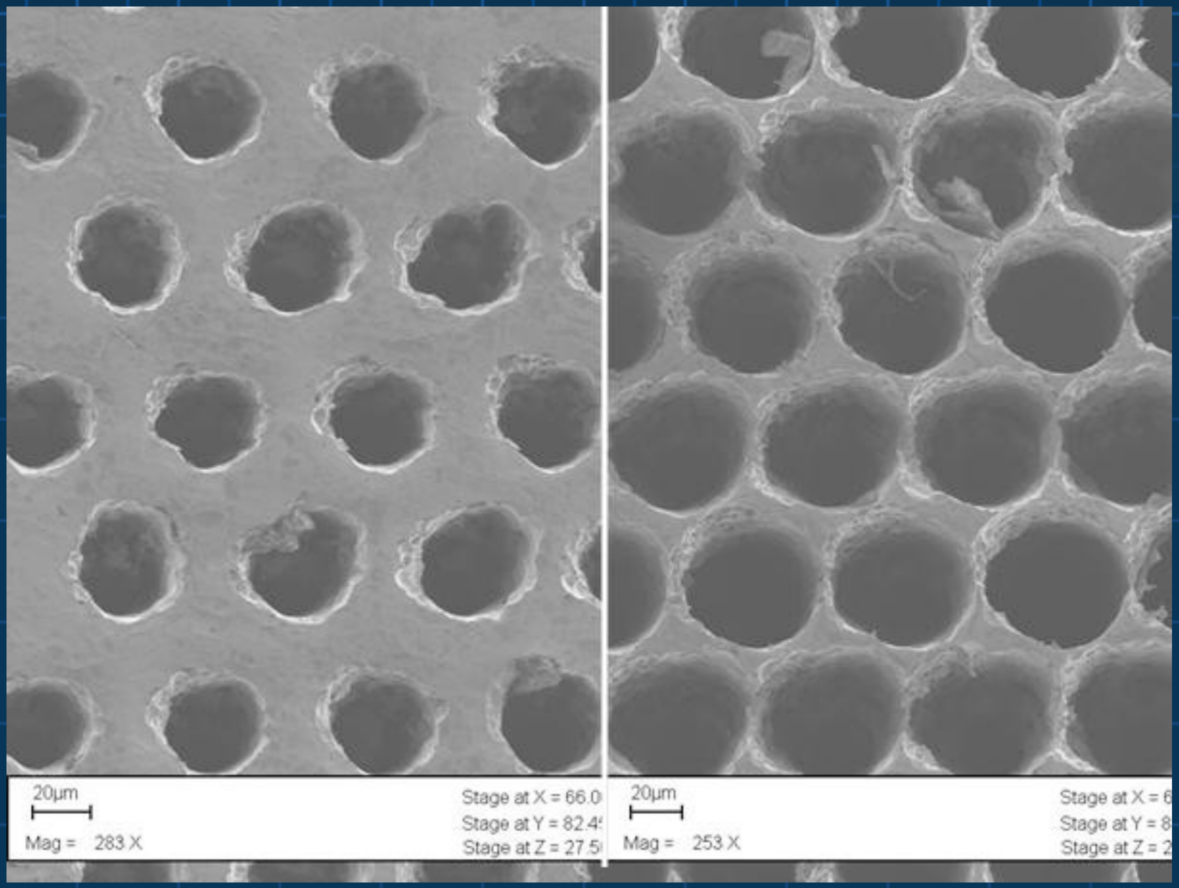
Critical for BH science!

Capabilities

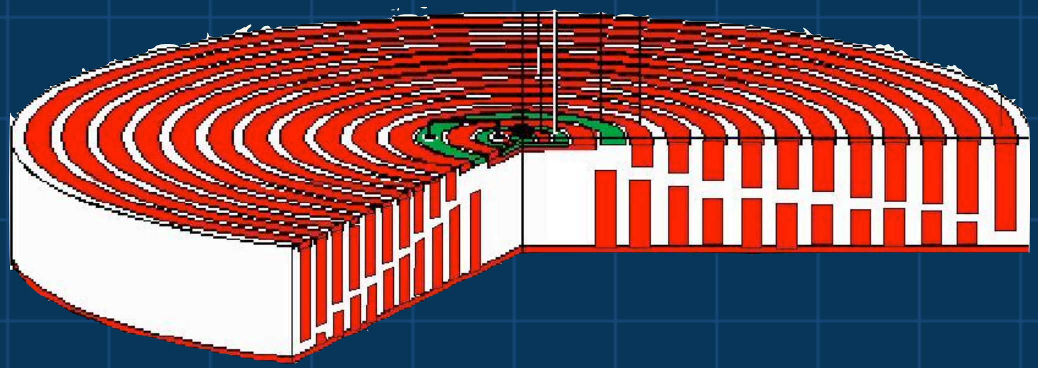
- 1.8–50 keV coverage with $\Delta E < 600$ eV
- Count rate of 120,000 cts/s on 1 Crab
  - S/N > 10 in 1 ms on 1 Crab source!
- Ms exposures on range of X-ray binaries over large luminosity range and transitions through all spectral states
- SM live-sky coverage ~50%
  - Transient source and spectral state monitoring
  - Eyes for GW detectors, tidal disruption events, GRB survey and much more science as well

Technology Development Options

- **Micromachined Tantalum Collimators**
  - Reduce instrument mass by a factor of five
  - Have demonstrated laser machining + chemical etching in NRL's Nanoscience Institute
  - Need to develop large scale production techniques
- **Silicon Pixel Detectors and Readouts**
  - Optimize for LATA and SM designs
- **Silicon Drift Detectors (SDDs)**
  - Improve energy resolution by a factor of two to <300 eV
    - Improves Fe-line science
  - Reduce power requirements
  - Need to research techniques for making thick (>0.5 mm) SDDs and customize design for X-ray timing



Christophersen, M., Phlips, B. F., Woolf R. S., and Jackson L. A., "Micromachined Tantalum Collimators for Space Applications" in 2011 IEEE Nuclear Science Symposium Proceedings (in press)



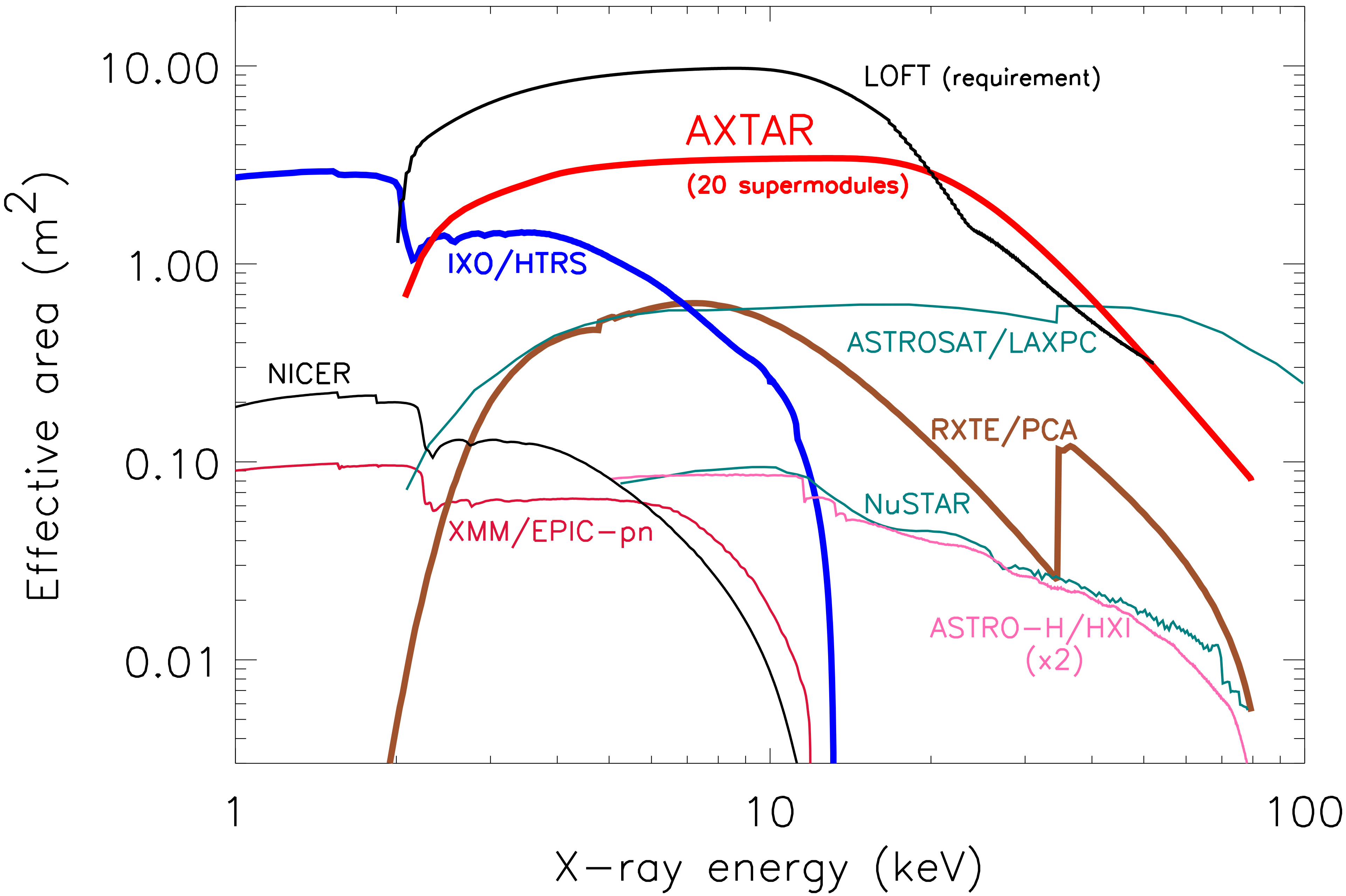
Benefit of an MDL Run

- **Initial version of AXTAR concept studied by MSFC Advanced Concepts Office**
  - **Target was Taurus II launch**
  - **Collimator was clone of RXTE collimator (20 cm thick BeCu hexagonal cells)**

    Study details presented in SPIE paper (arXiv:1007.0988), and NASA/TM-2011-216476

- **New study needed for several reasons**
  - **Large mass reduction from Ta collimator drives redesign of S/V components and structure**
    - Without S/V redesign, AXTAR is 2000 kg (RXTE was 3200 kg)
  - **Independent cost estimate**
- **MDL run will improve system fidelity and cost confidence in a mission with better performance**

Effective Area Comparison



Enormous improvement in effective area over RXTE:
7x @ 4keV, 14x @15 keV, 24x @20keV, 36x @30 keV

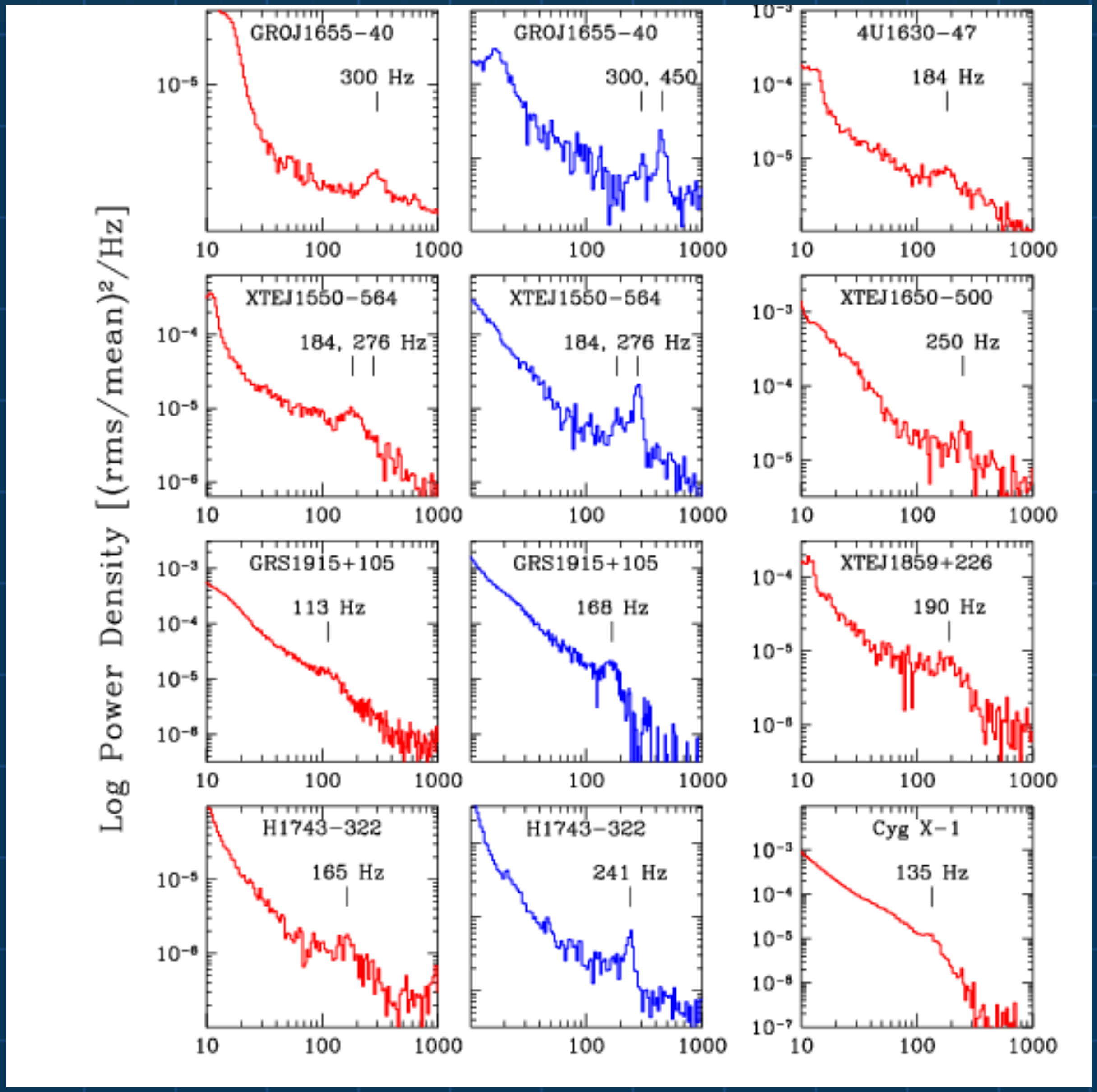
Recall that QPO S/N scales linearly with area *A*, not $A^{1/2}$

BACKUPS

BH High Frequency QPOs (100-450 Hz)

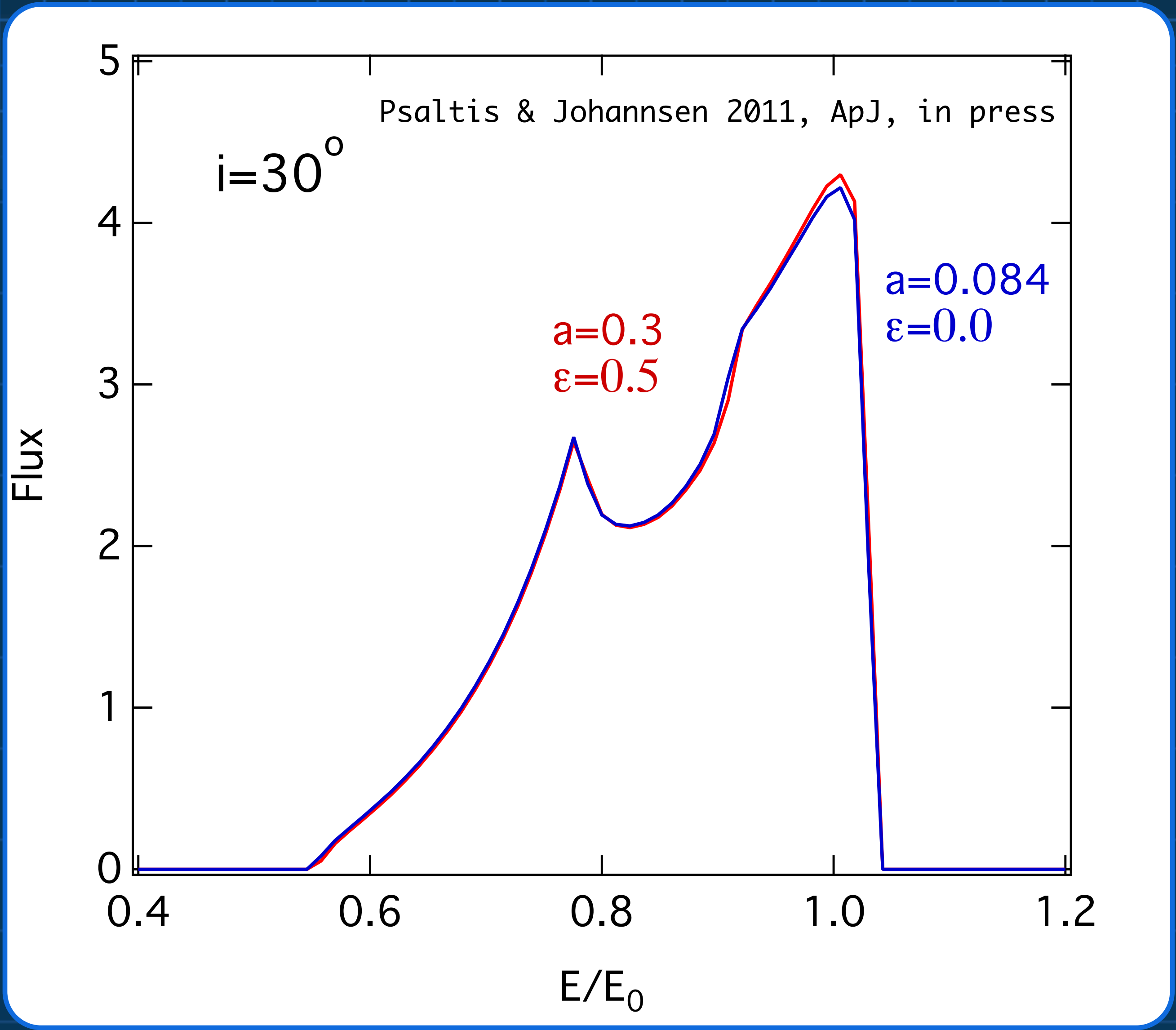
- Seen in 8 BH sources
- 4 have pairs of QPOs
    - All consistent with 3:2 ratio
- Frequencies are stable to ~5%
- Always seen in “Steep Power Law” state
- Immune to luminosity changes

6–40 keV 13–40 keV 6–40 keV

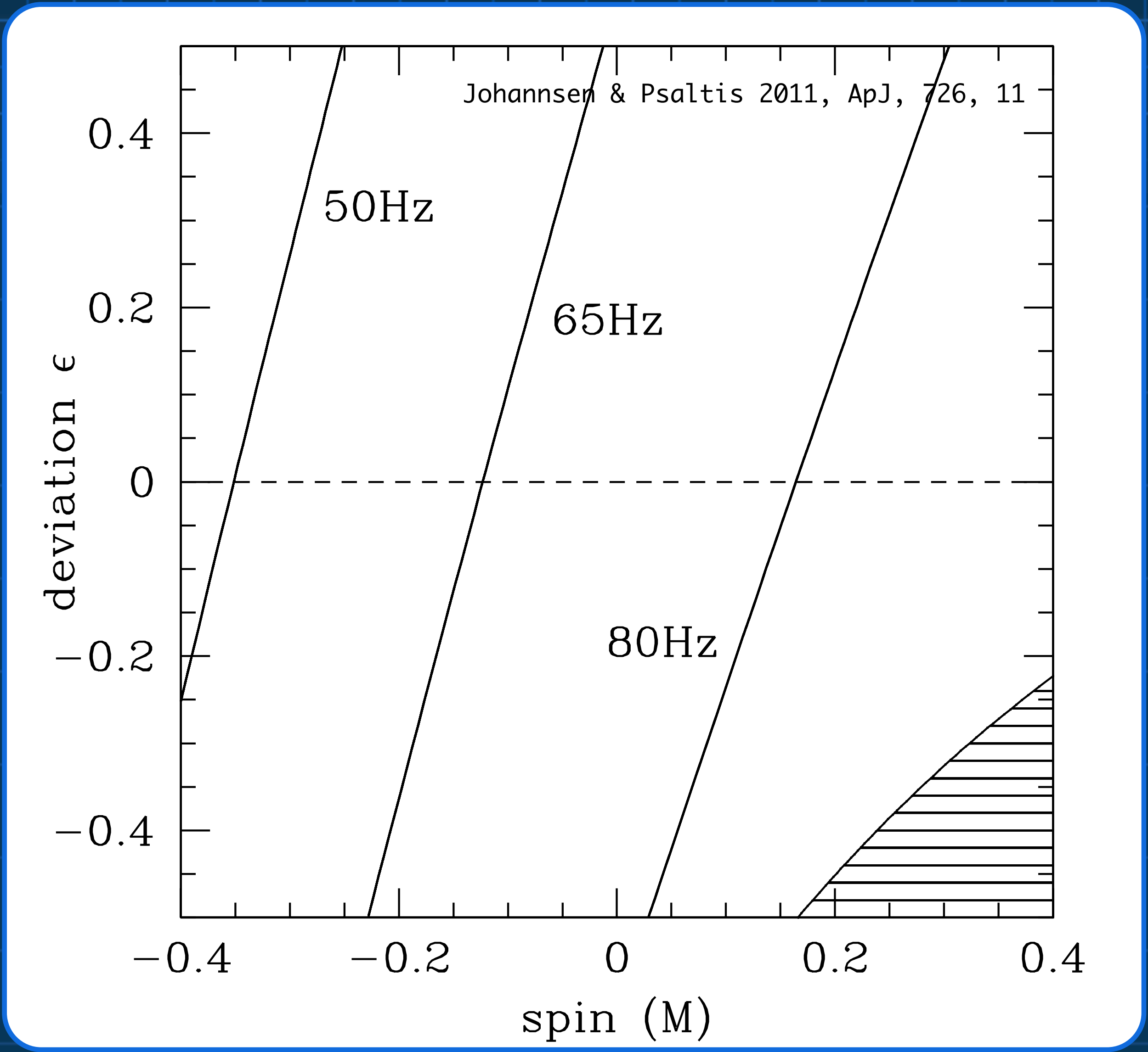


QPO rms: 0.8–1.5% 2–5% 0.8–2.4%

Testing General Relativity



Nearly identical Fe-line profiles



For single mode frequency, spin and deviation from Kerr are degenerate

Solution: Measure two fundamental frequencies (e.g. c-mode and g-mode, or Fe line and one mode)

Benefits of More Counts

- Key equation for QPO sensitivity:

$$S/N = \frac{1}{2} I r^2 \left(\frac{T}{\Delta\nu} \right)^{1/2}$$

van der Klis (1989)

- Implications for 10x increase in area (with similar energy response):
  - 1σ detection of a QPO becomes 10σ in same T ⇒ study of fainter QPOs, revealing harmonics, etc.
  - 3σ detection in T becomes 3σ detection in 0.01T ⇒ weak detection 200 ks now can be detected and tracked every 2 ks, revealing evolution, true frequency width, correlation with spectral states, etc.