X-ray Burst Oscillations: From Flame Spreading to the Cooling Wake

Simin Mahmoodifar

NASA/GSFC-NPP

July 20, 2016

with Tod Strohmayer (NASA/GSFC)

Mahmoodifar, S., & Strohmayer, T. 2016, ApJ, 818, 93.

NASA POSTDOCTORAL PROGRAM

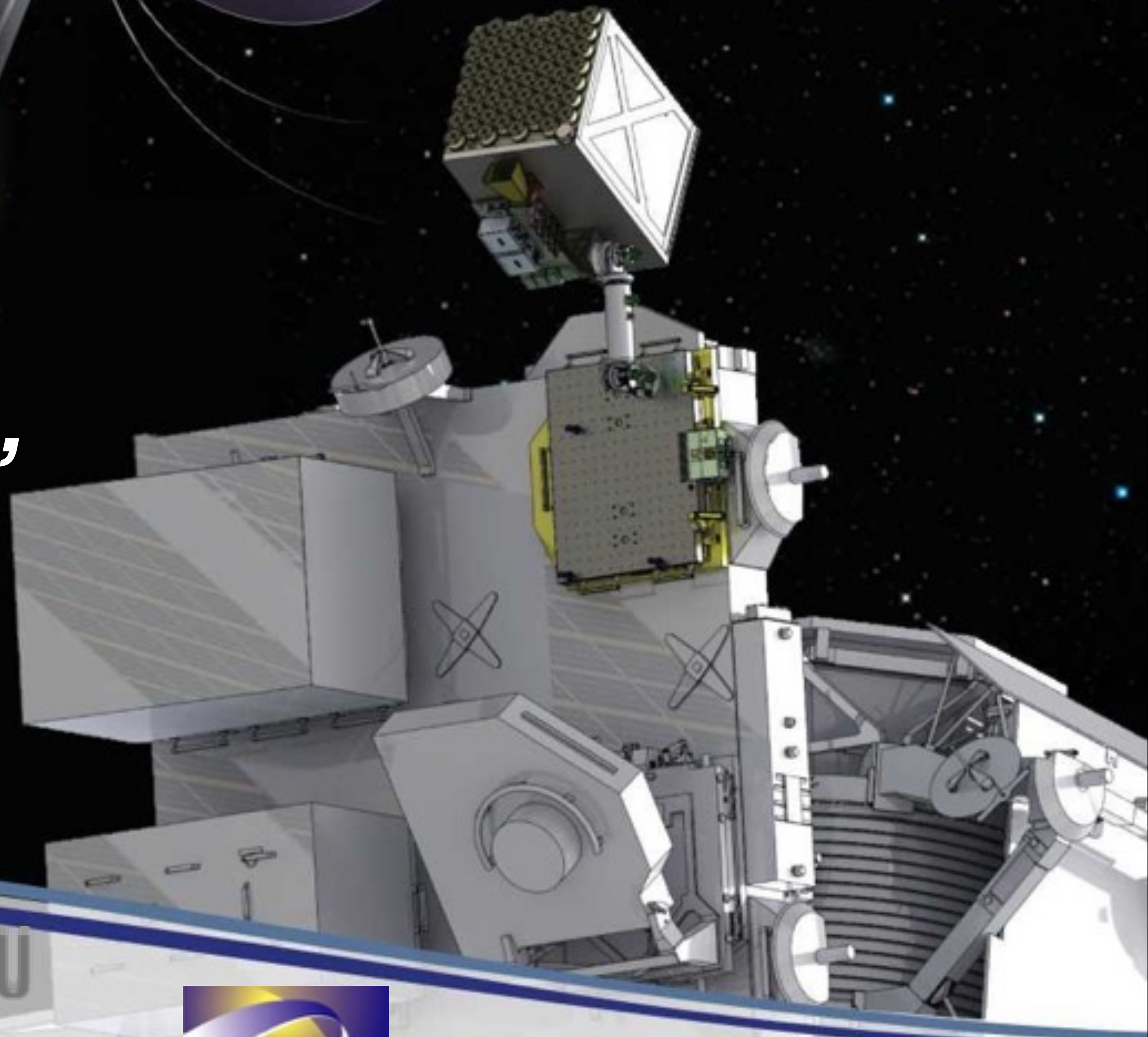
Administered by Oak Ridge Associated Universities

NICER

Neutron star Interior Composition ExploreR

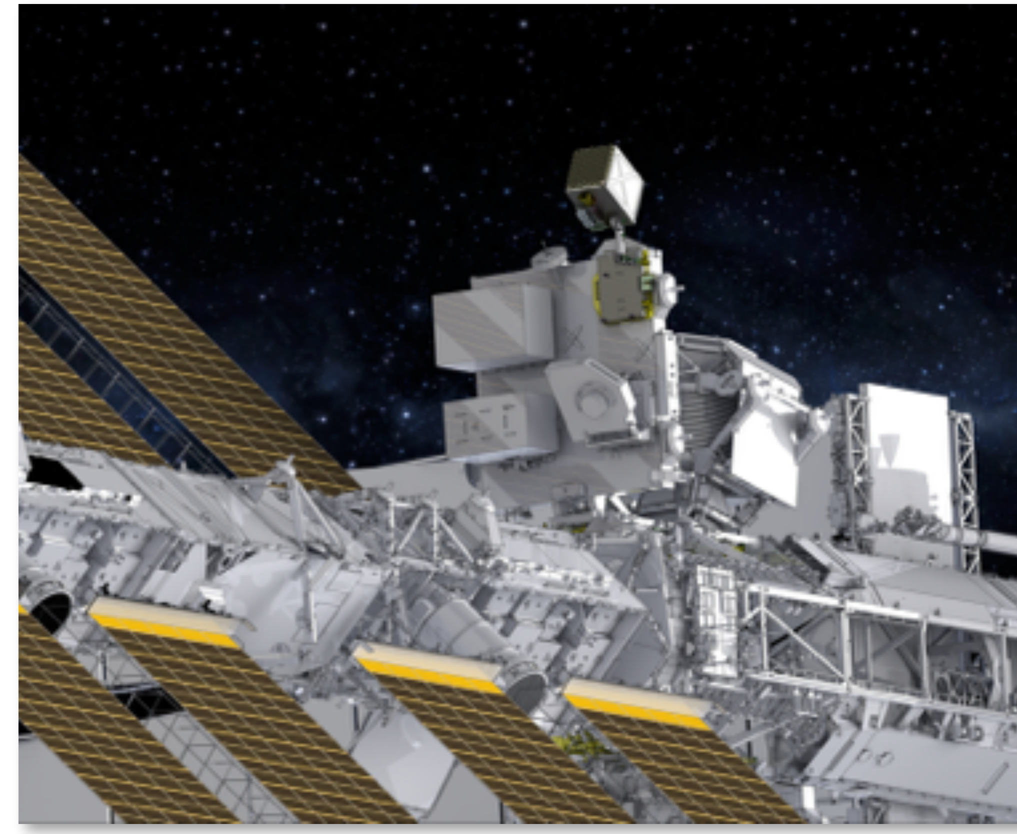
Overview & Status, June 2016

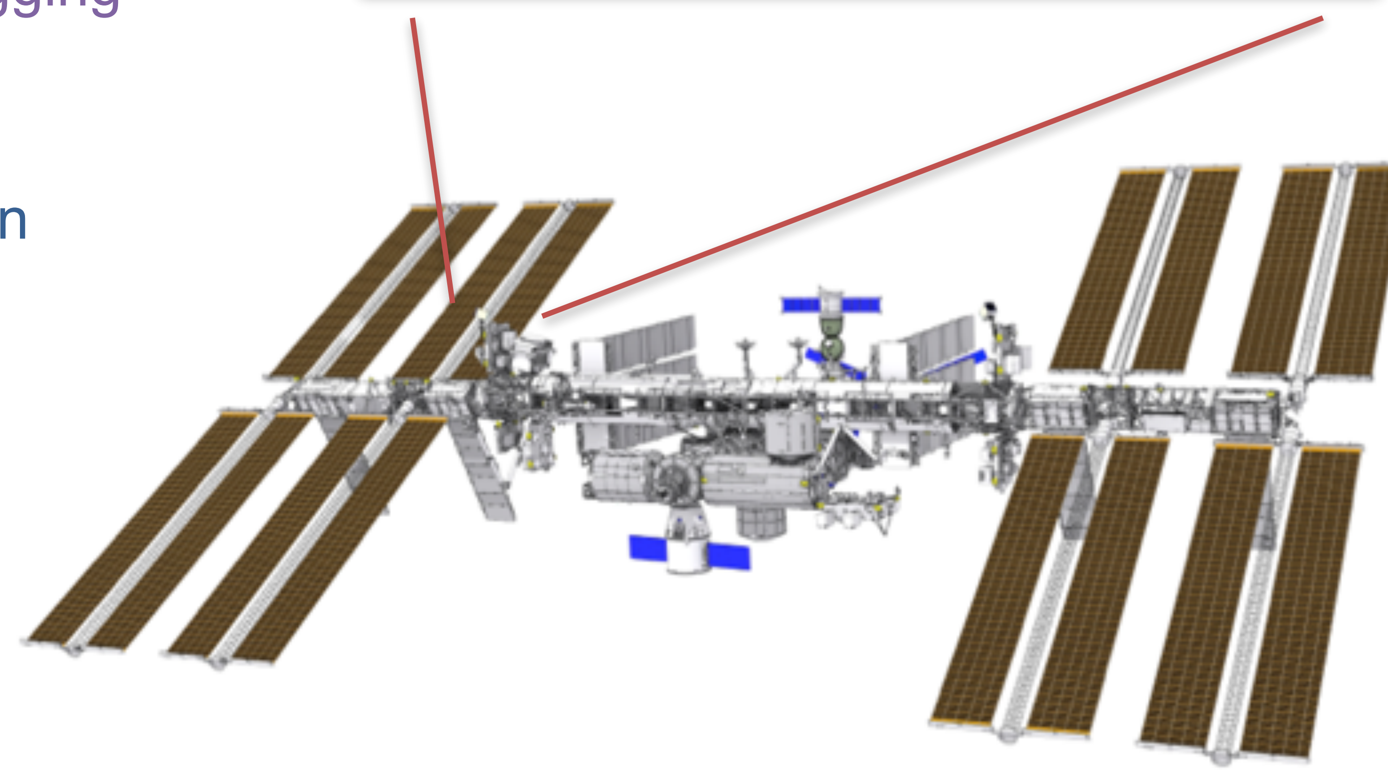
Zaven Arzoumanian



Neutron star astrophysics from the International Space Station

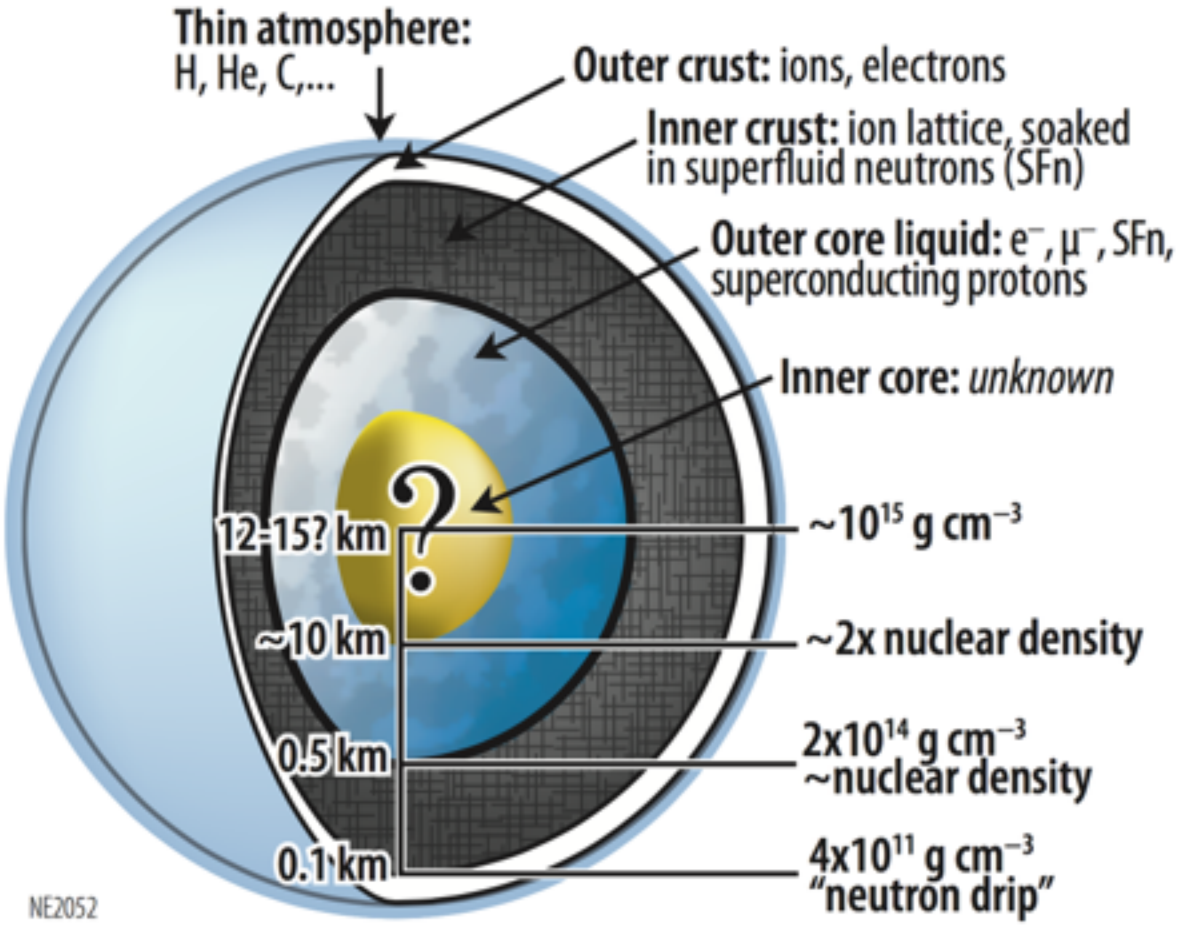
- ***PI:*** Keith Gendreau, NASA GSFC
- ***Science:*** Neutron star structure, dynamics, & energetics through soft X-ray timing spectroscopy
- ***Launch***: February 2017, SpaceX-11 resupply
- ***Platform:*** ISS external attached payload, with active pointing
- ***Lifetime:*** 18 months baseline, possibility of extension
- ***Instrument:*** 0.2–12 keV "concentrator" optics, silicon-drift detectors, GPS absolute time tagging and position
- ***Enhancements:***
  - Demonstration of pulsar-based navigation
  - PI discretionary and ToO time
- ***Status:***
  - Completed environmental testing, ISS safety, & Pre-Ship reviews
  - Delivered to KSC

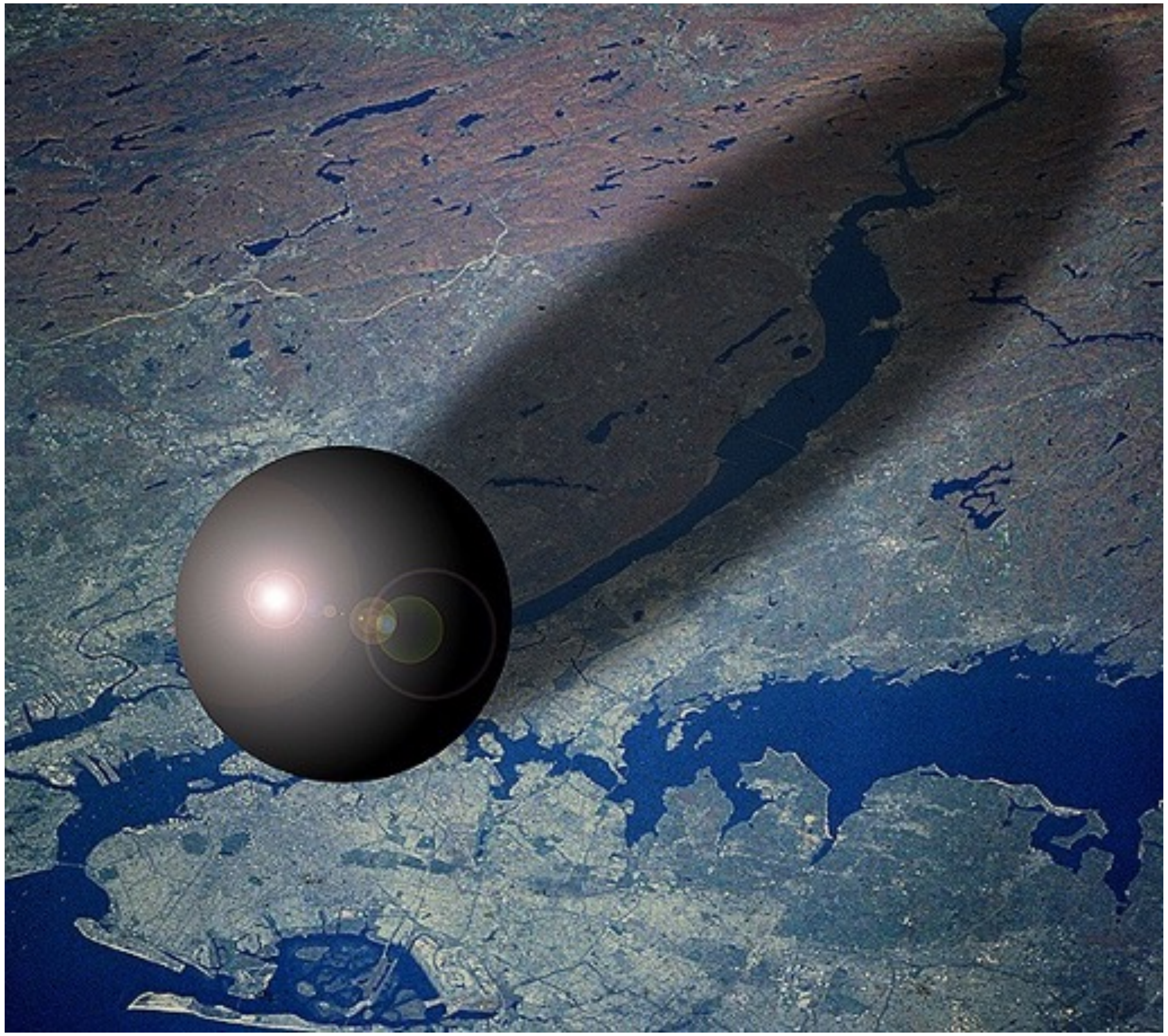




NICER's key science objective

Constrain the equation of state of bulk nuclear matter through precise mass and radius measurements.

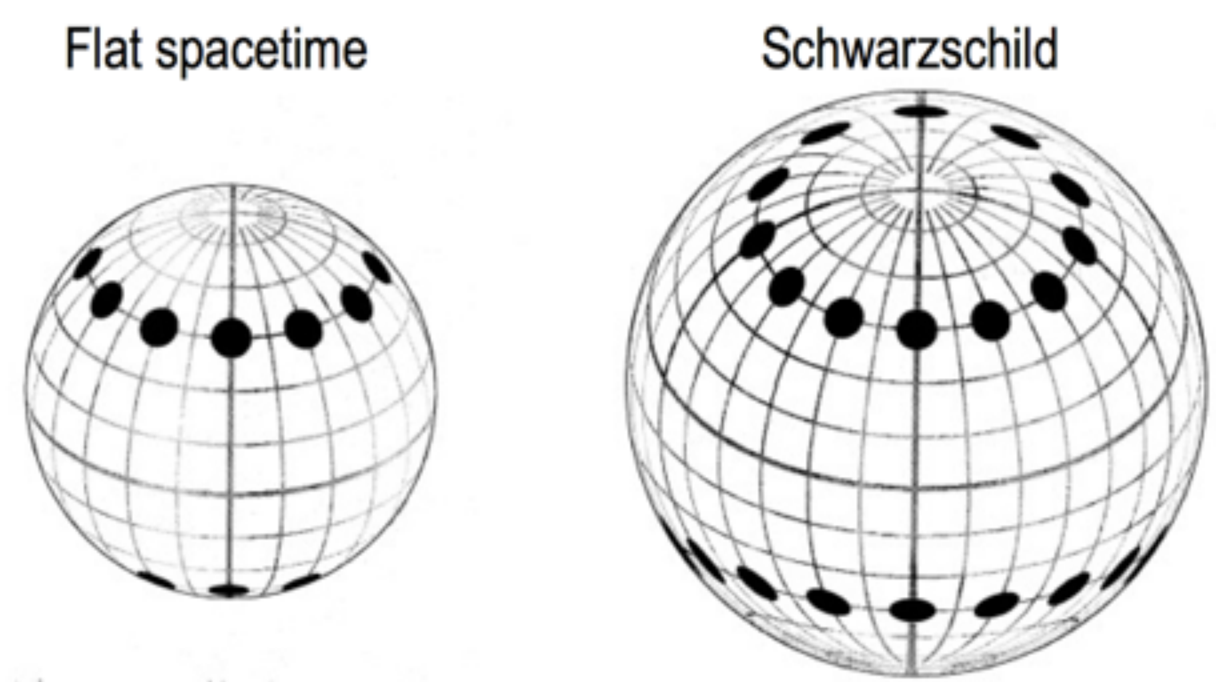




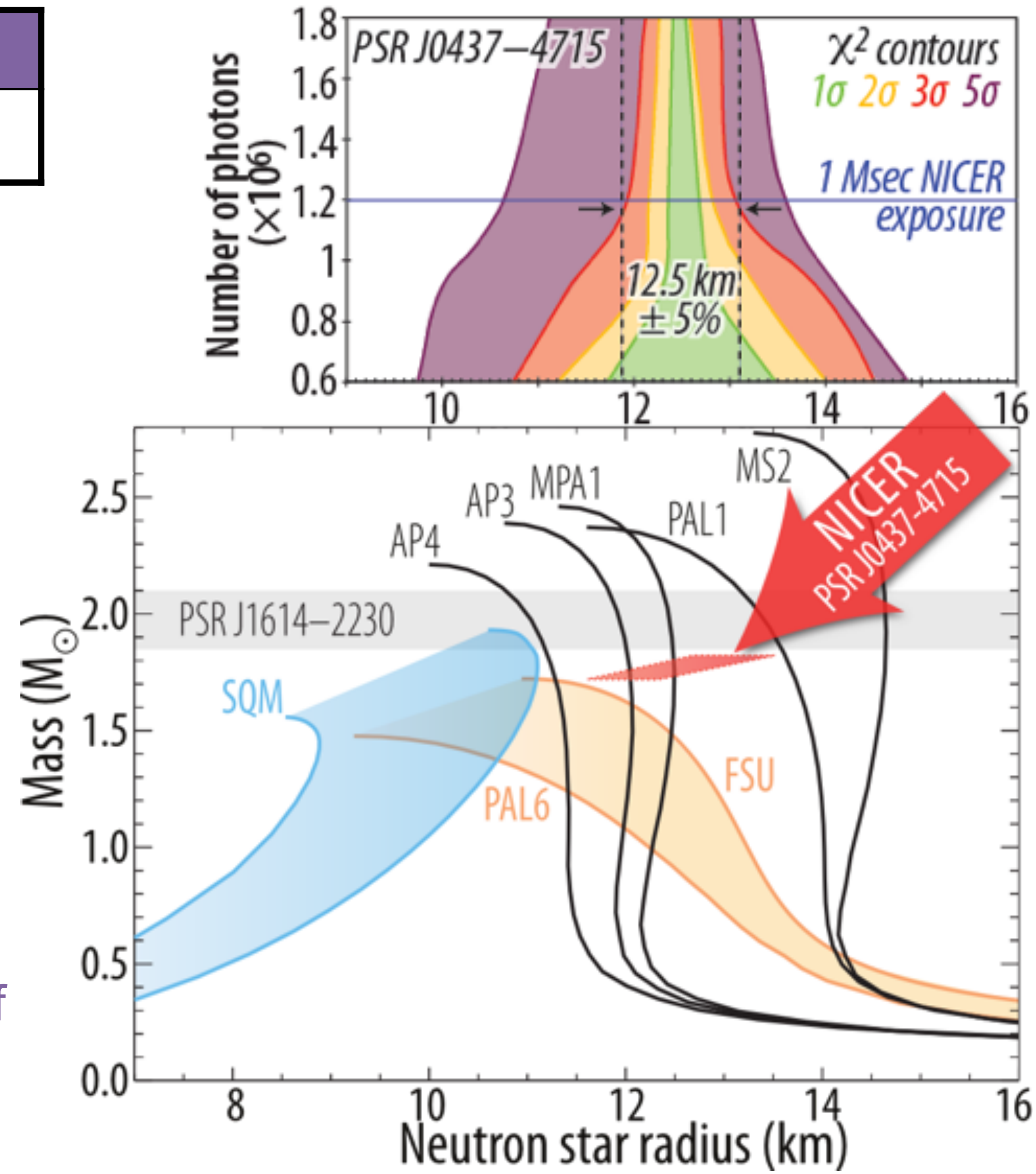
Science objectives
I — Neutron star structure

Surface radiation exposes interior properties

Objective	Measurements
Structure — Uncover nature of matter within neutron stars	Neutron star radii, masses, & cooling timescales



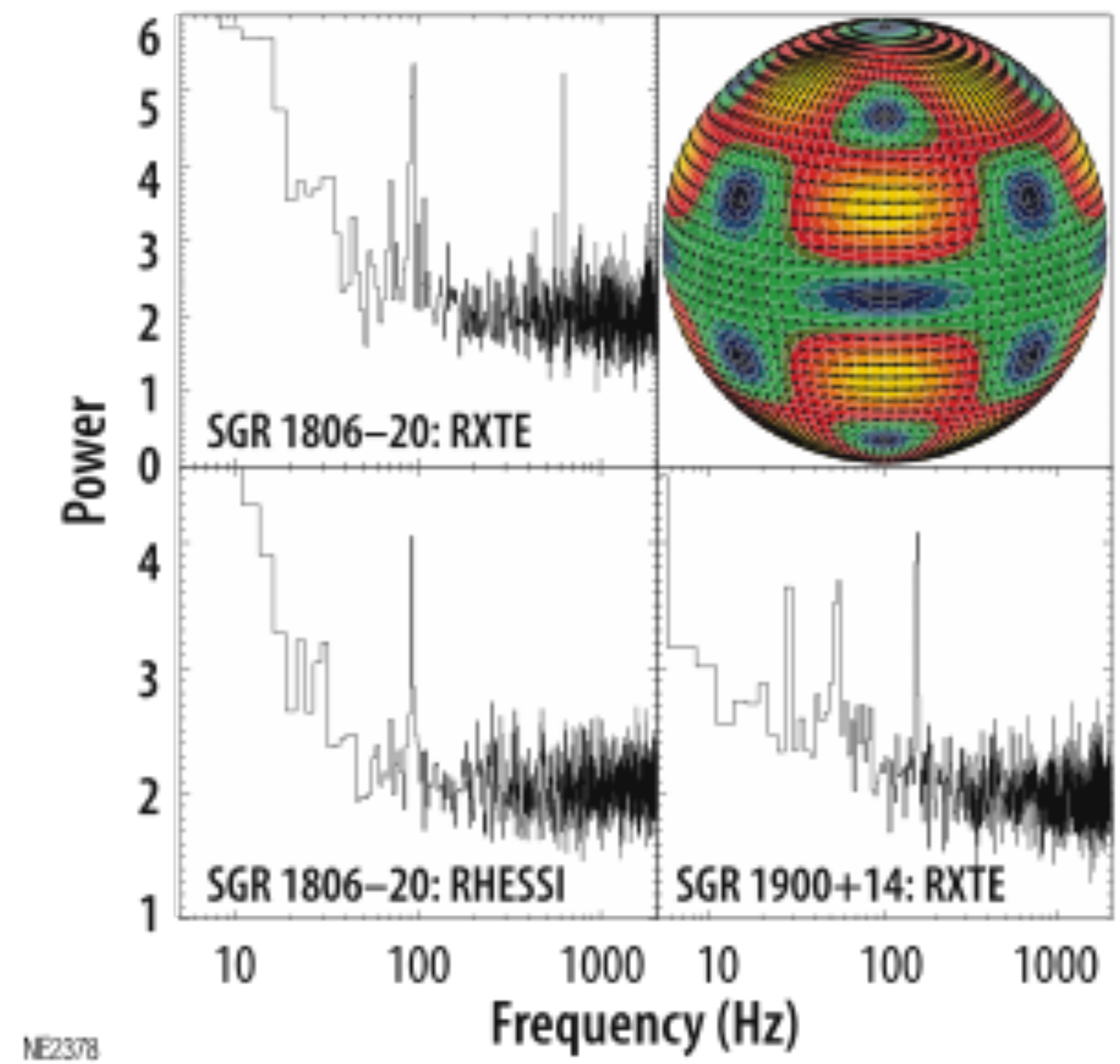
Simulations show *M/R* can be recovered to ±5% with 10^{5-6} photons through modeling of gravitationally altered lightcurves



Science objectives
II — Neutron star dynamics

Spin, accretion, and "starquake" phenomena probe crustal physics and external interactions

Objective	Measurements
Dynamics — Reveal physics of variability on many timescales	Rotational stability, outbursts, oscillations, and precession



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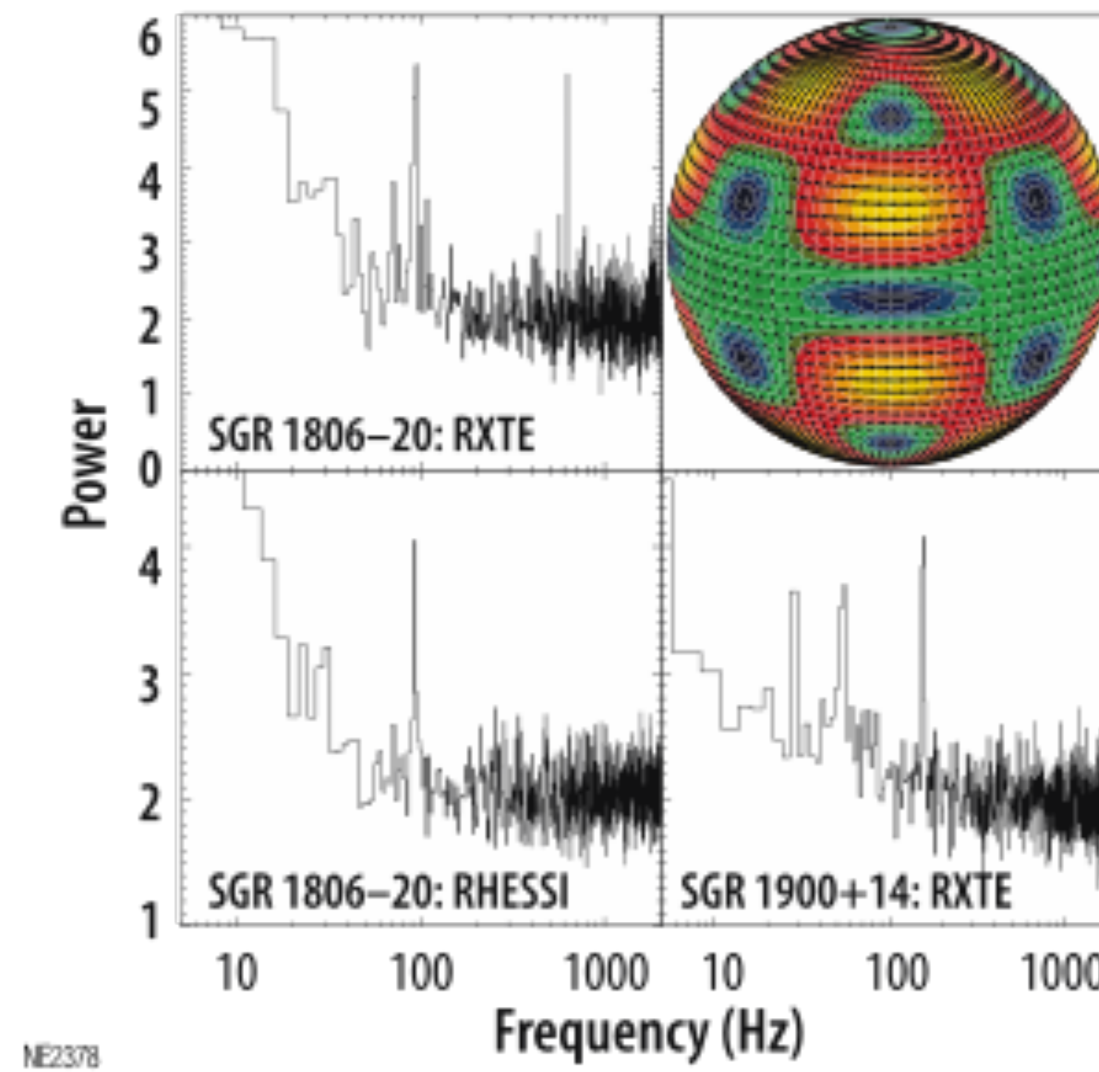

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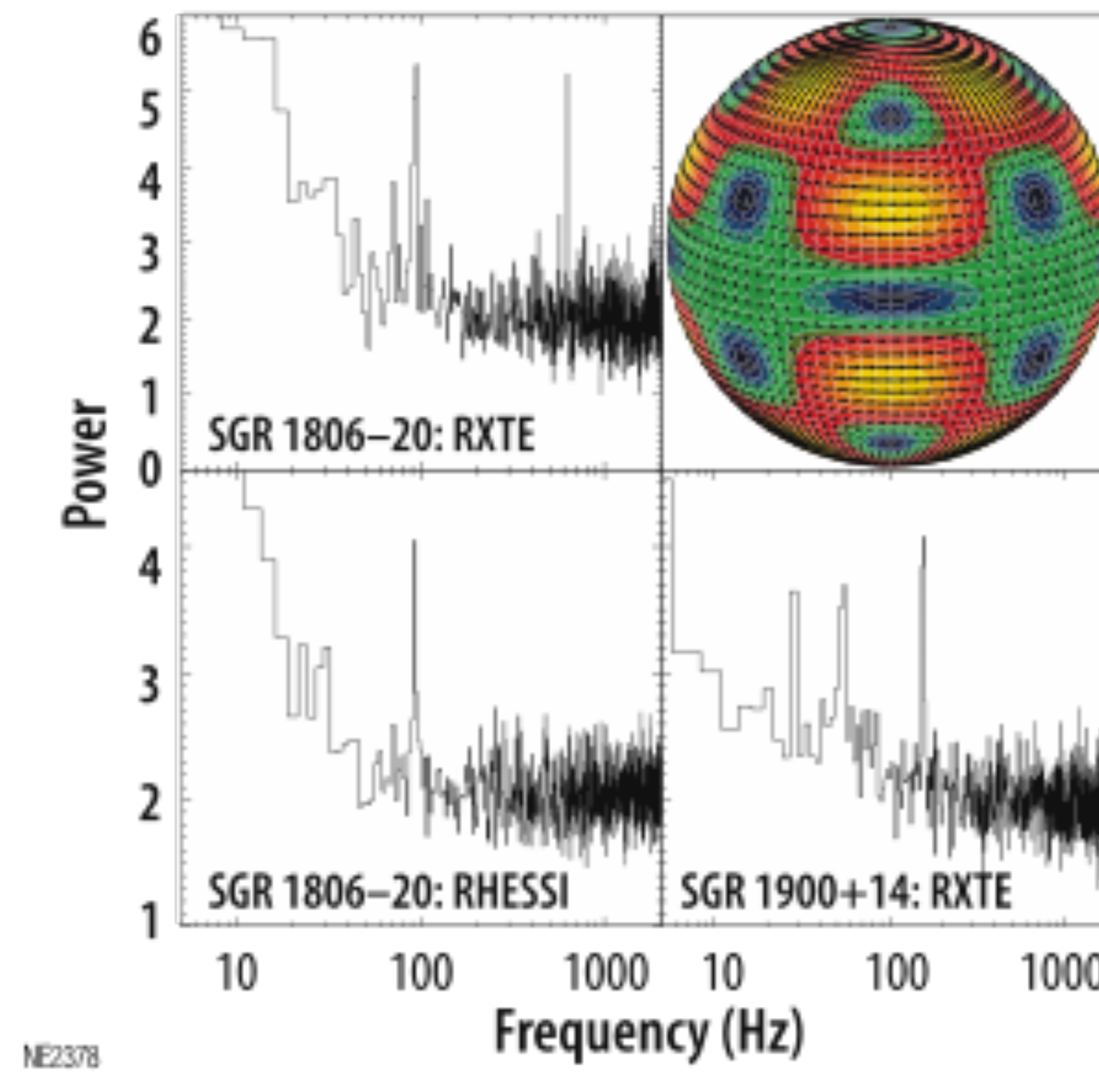
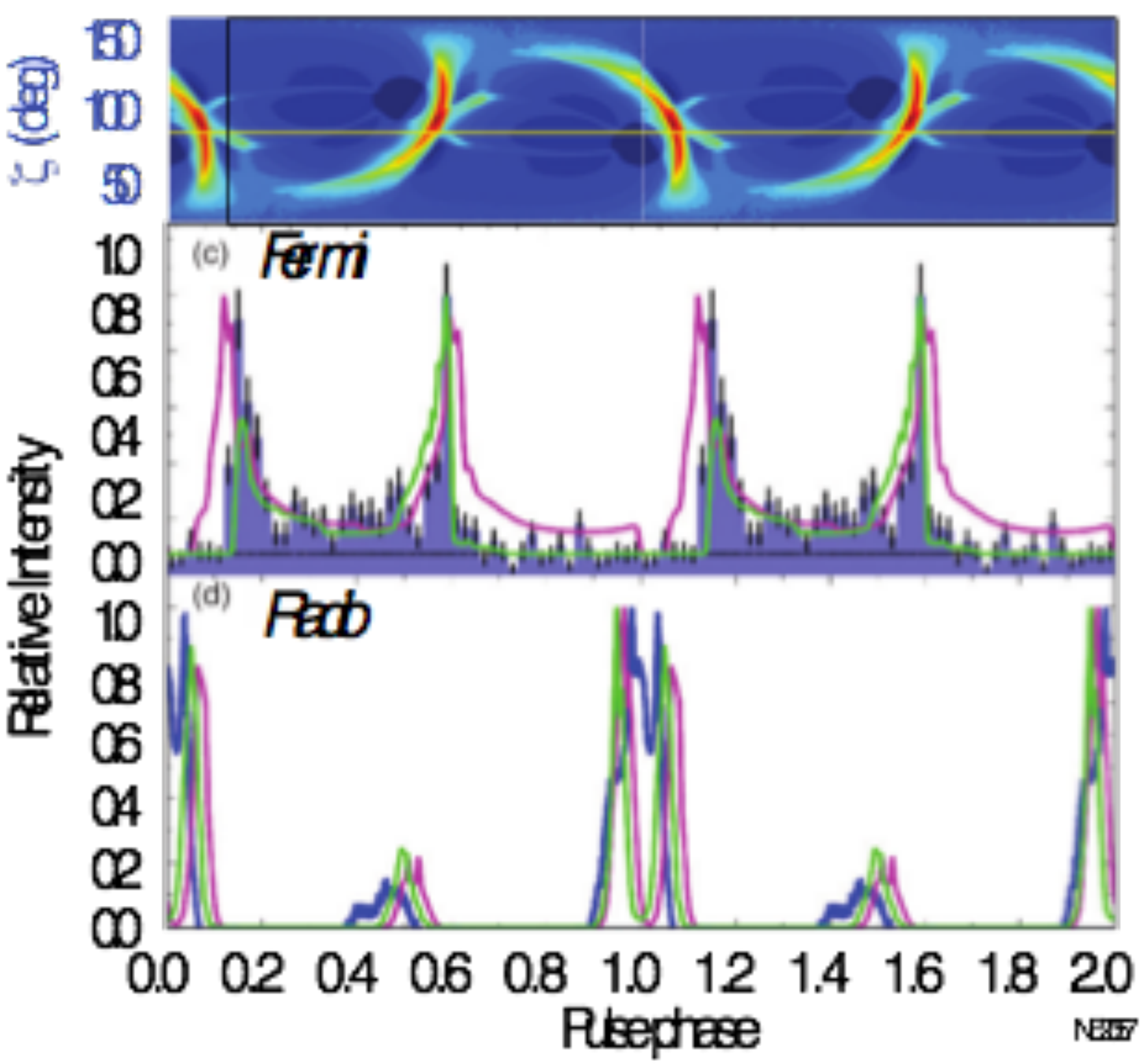
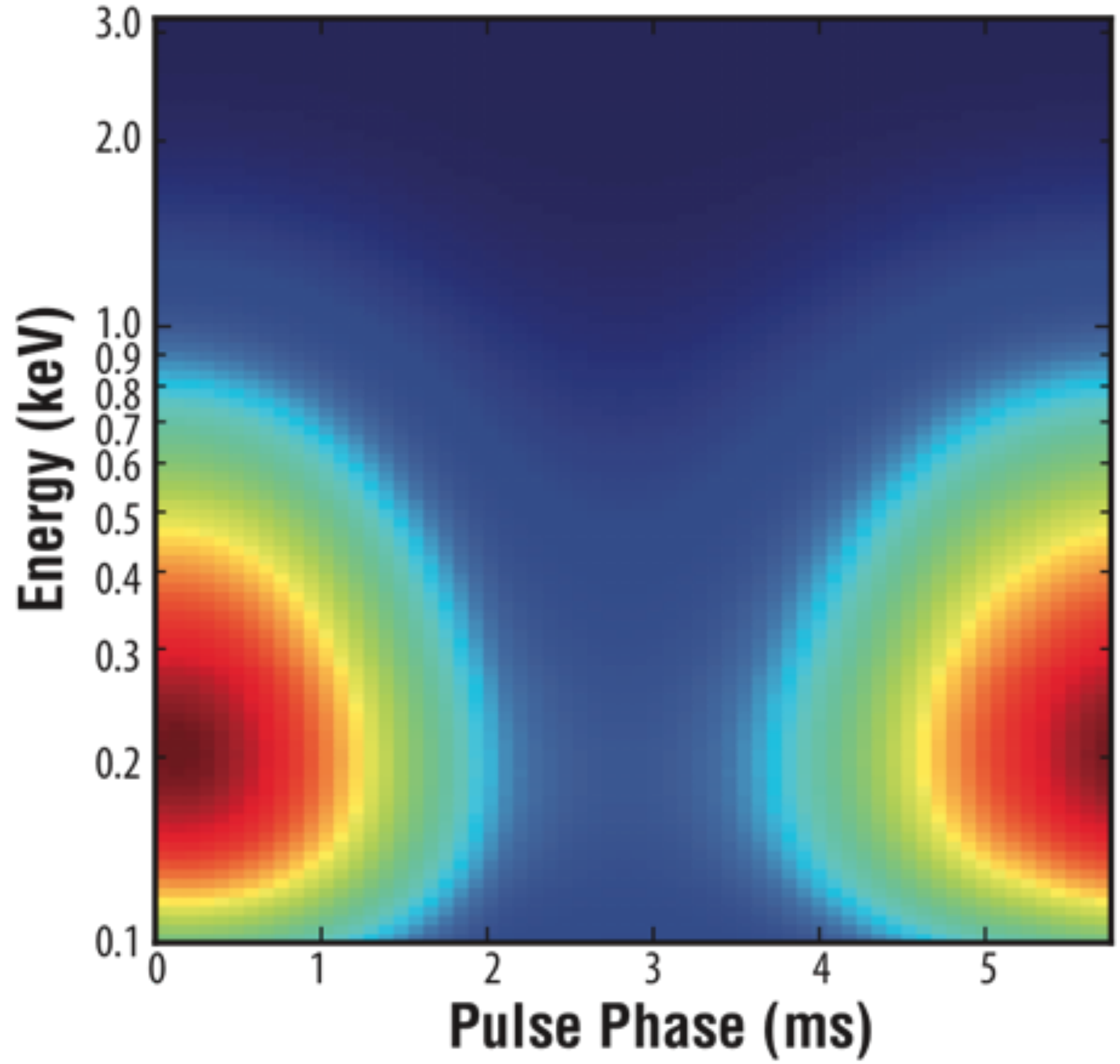


Science objectives
III — Neutron star energetics

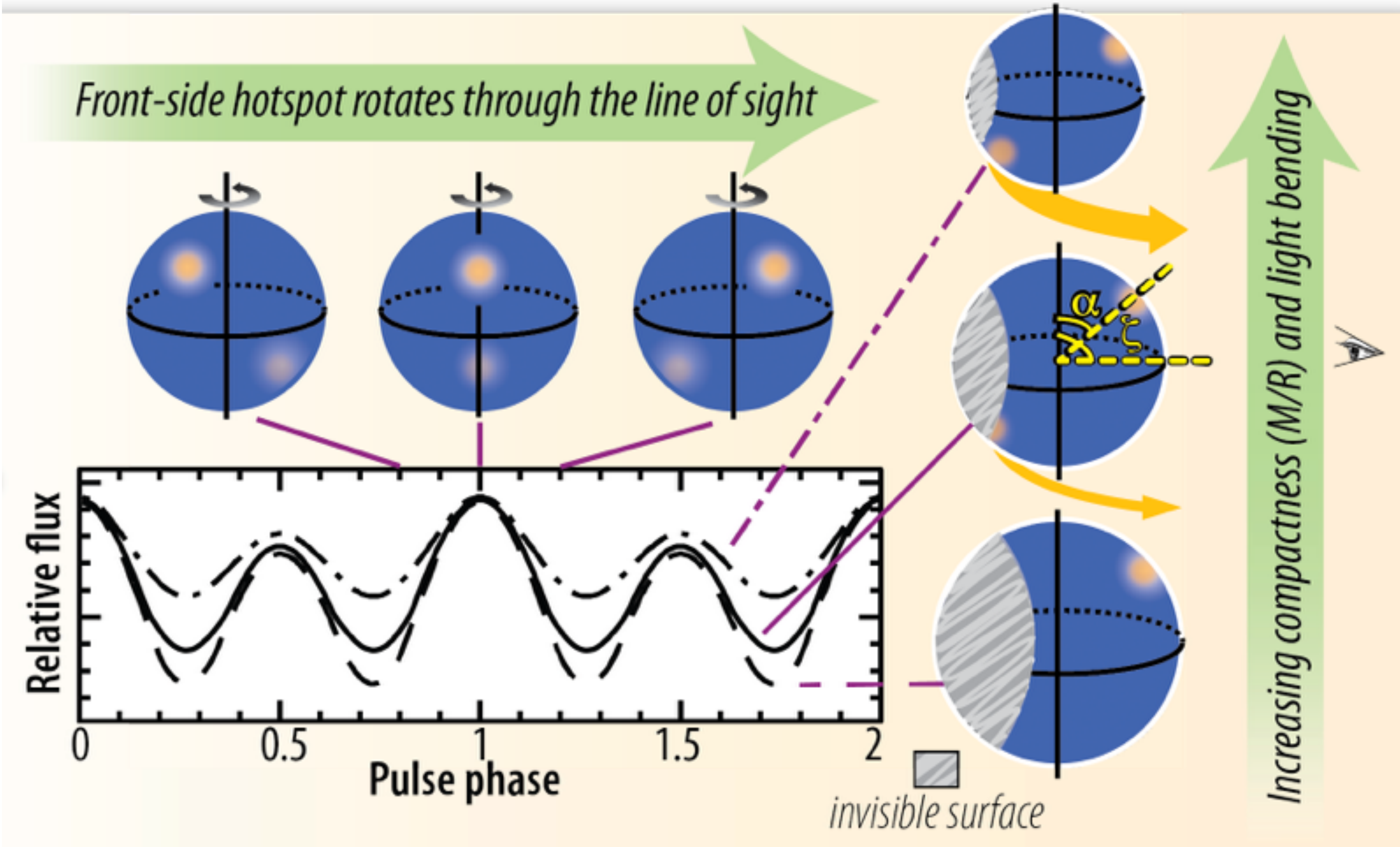
Sites & mechanisms of radiation reveal thermal, magnetic, nuclear, etc., energy stores

Objective	Measurements
Energetics — Determine where energy is stored and extracted	Intrinsic radiation patterns, spectra, and luminosities





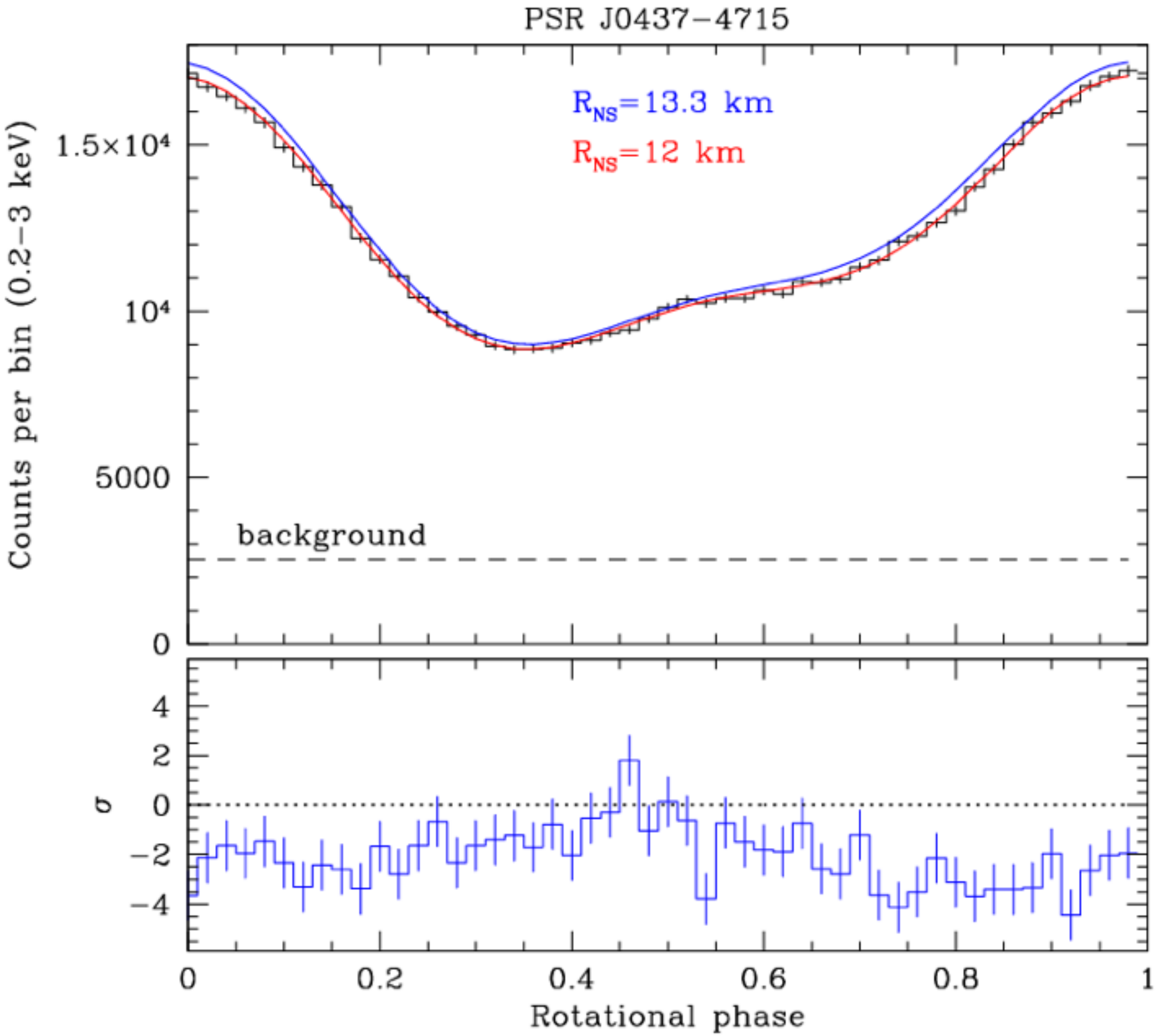
Inferring neutron star radii through lightcurve modeling



Constrain the compactness (*M/R*) and viewing geometry of a pulsar through the depth of modulation and harmonic content of emission from rotating hot-spots.

Inferring neutron star radii through lightcurve modeling (cont.)

With a 1 Msec NICER exposure, a 10% radius difference produces 2–4σ differences in *broadband* lightcurve shape at multiple pulse phases.



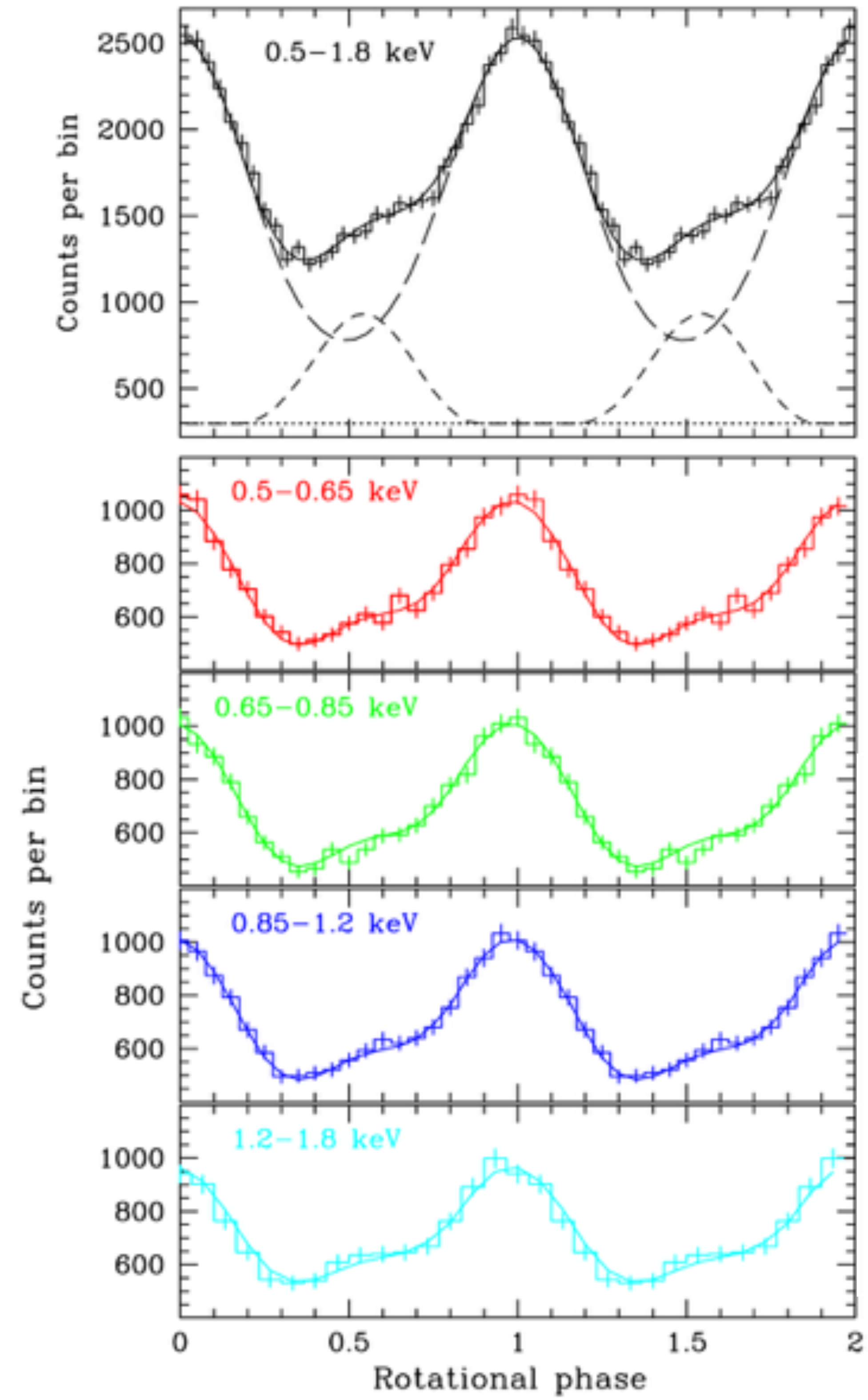
Inferring neutron star radii through lightcurve modeling (cont.)

Targeting (mainly) thermal emission from rotation-powered MSPs

- $\dot{E} \approx 10^{33\text{–}34}$ erg/s, $L_X \approx 10^{30\text{–}31}$ erg/s
- Soft, thermal X-rays from $R_{\rm eff} \leq 2$ km
- Broad pulses ⇒ surface PC emission
- Non-magnetic ($B < 10^{10}$ G, effectively 0 G) hydrogen atmosphere
  - ➢ harder than blackbody for same $T_{\rm eff}$
  - ➢ anisotropic emission pattern (limb-darkening)
  - ➢ available models agree to within 1% around peak of spectrum

Likely targets:

- PSR J0437–4715 (1 cps with NICER)
  - ➢ m = 1.44 ± 0.07 $M_\odot$, d = 156.79 ± 0.25 pc
- PSR J0030+0451
- PSR J2124–3358
- PSR J1231–1411

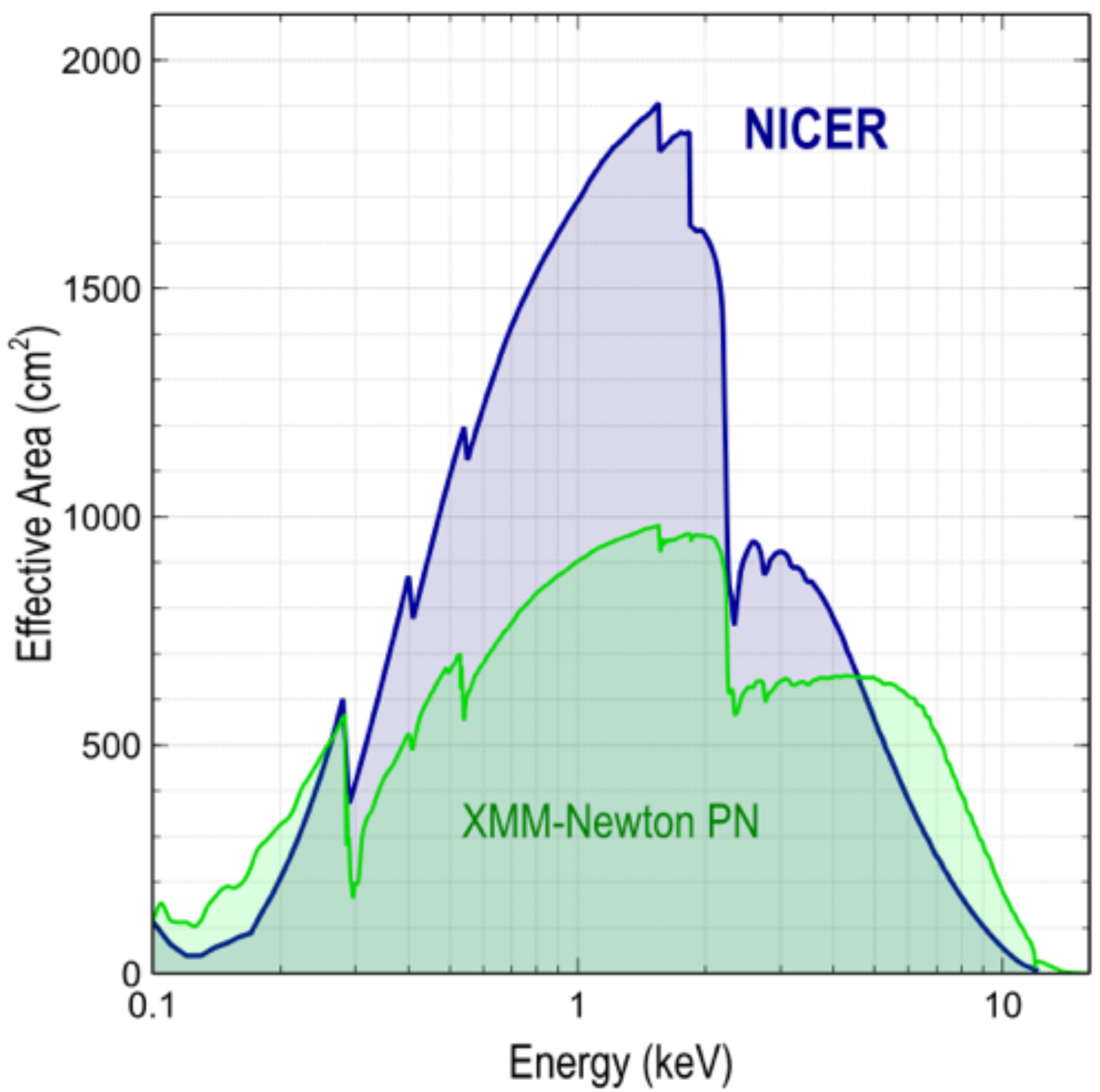


Bogdanov ApJ, 762, 96 (2013)

Unique capabilities for new discovery space

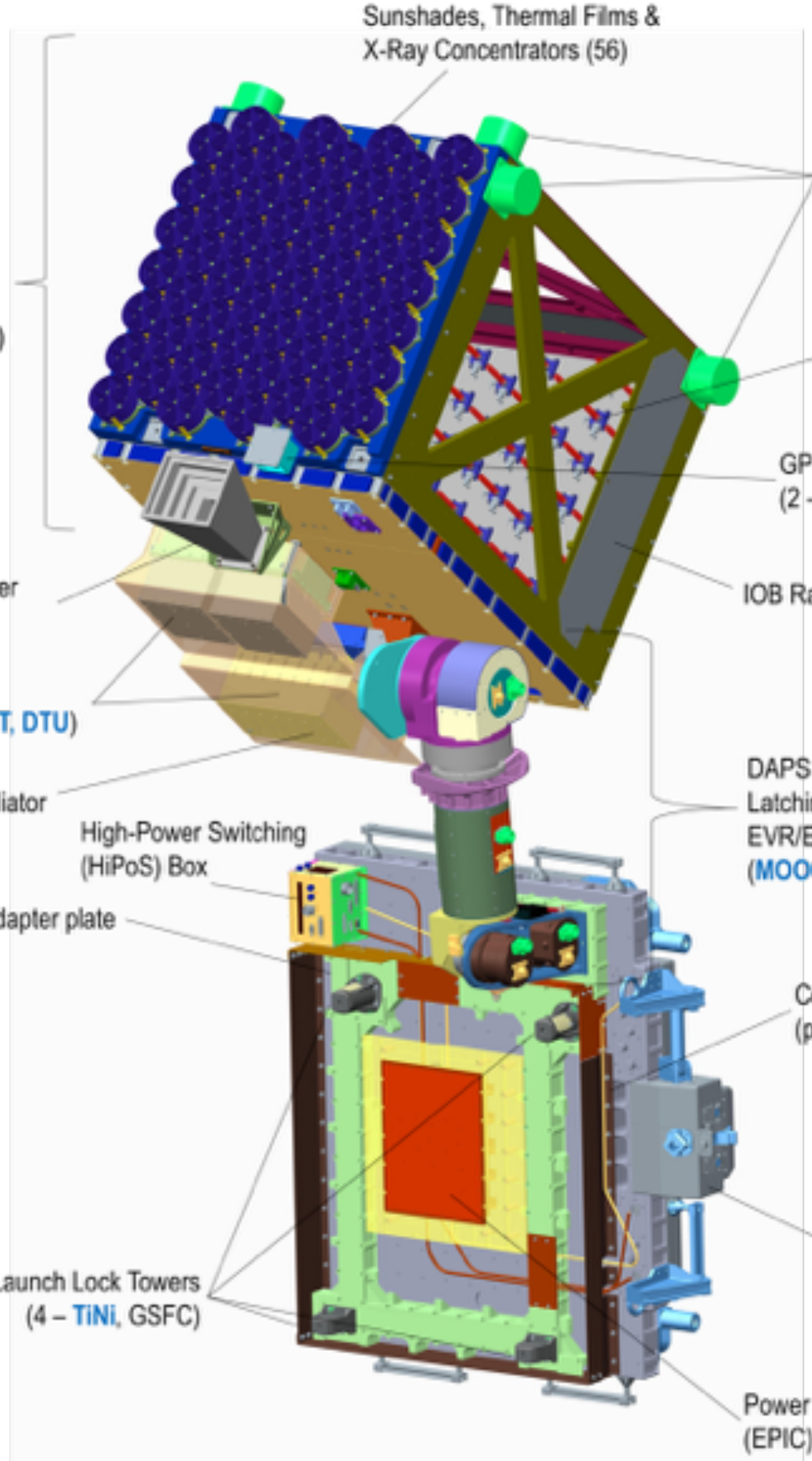
A novel combination of sensitivity, timing, and energy resolution

- Spectral band: 0.2–12 keV
- Timing resolution: < 100 nsec RMS absolute
- Energy resolution: < 150 eV @ 6 keV
- Non-imaging FOV: 6 arcmin diameter
- Background: ~ 0.3 cps
- Sensitivity, 5σ: 5.3 x 10^{-14} erg/s/cm^2
  - 0.5–10 keV, 10 ksec (Crab-like spectrum)
  - ~3x better than XMM-*Newton*'s timing capability (PN clocked)
- Max countrate: ~38,000 cps (3.3 Crab)
  - Deadtime accounted for in telemetry



The NICER Payload

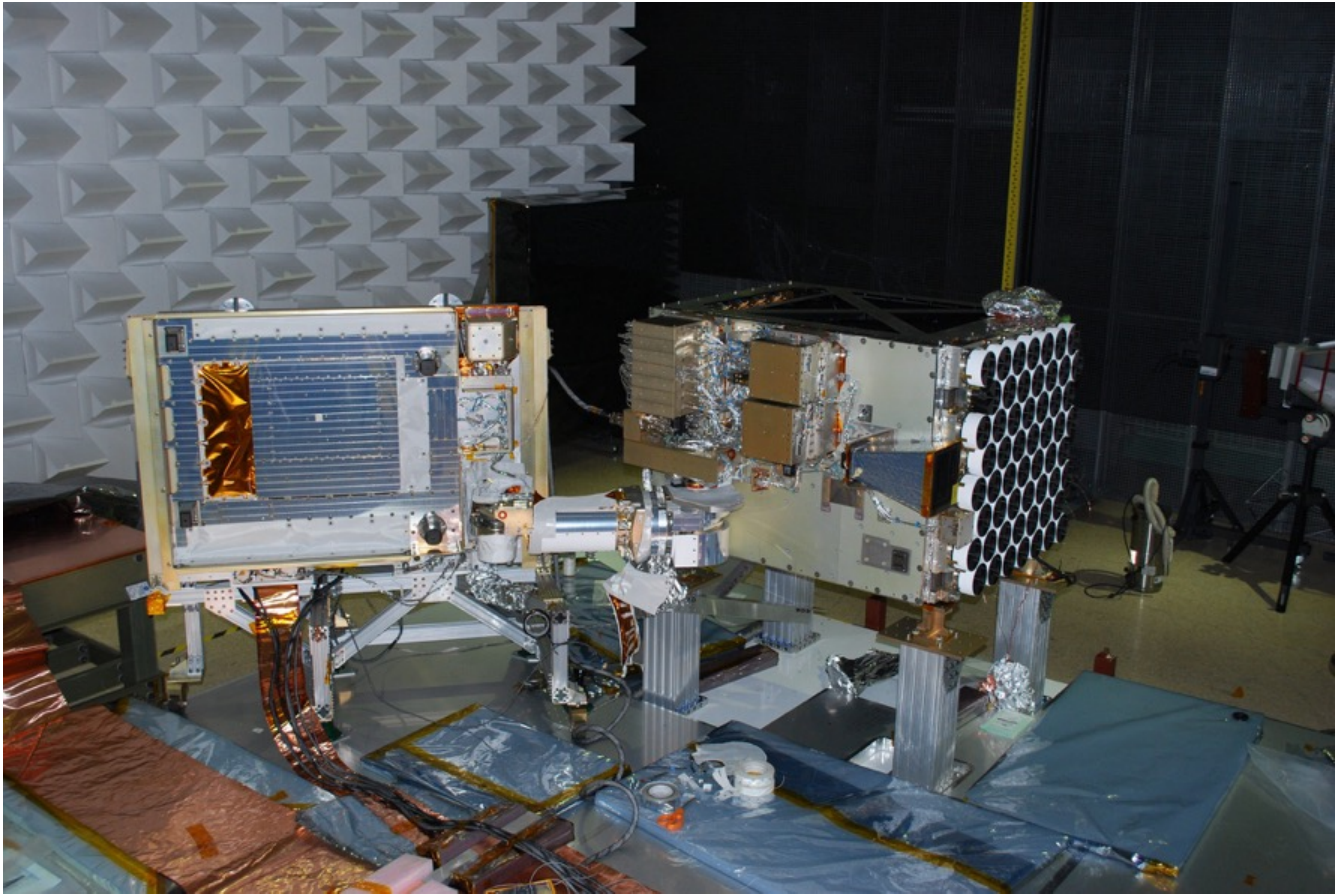
An innovative configuration of high-heritage components



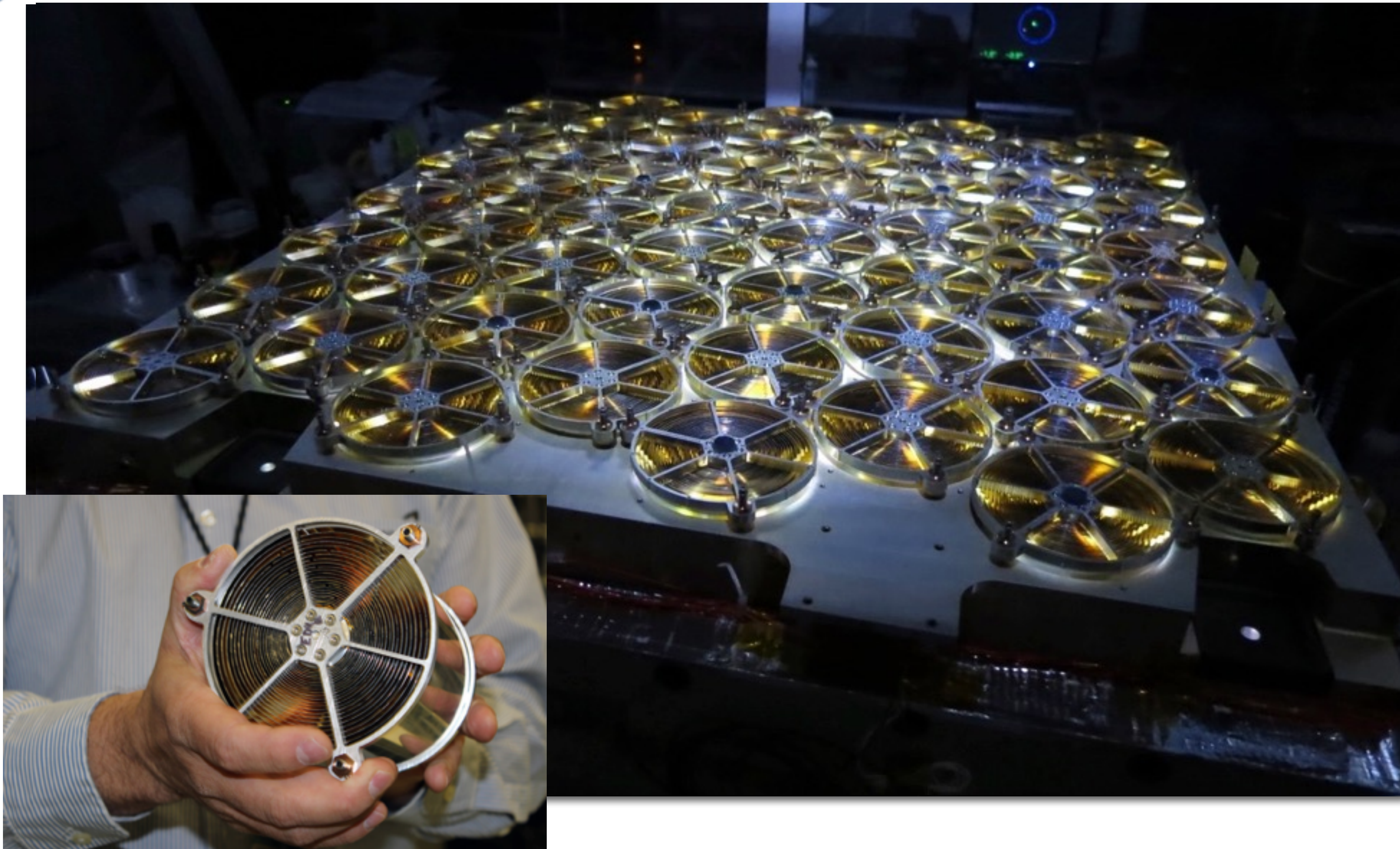
- **X-ray Timing Instrument (XTI)**
  - 56 optics, detectors, & radiation shielding held in an optical bench
- **Thermal Control System**
  - Radiators, heaters to maintain alignment, phase-change material for survival heat storage
- **Deployment and Pointing System**
  - Deployment lifts XTI for view of sky, Az-El gimbal offers 2π sr regard
  - Star tracker pointing reference
- **Electrical and C&DH System**
  - Power and digital interface to ISS
- **Flt Releasable Attachment Mechanism**
  - Electrical, mechanical interface to ISS & vehicle, provided by ISS program

NICER in Stowed Configuration

Deployed during EMI/EMC testing



X-ray Concentrator optics

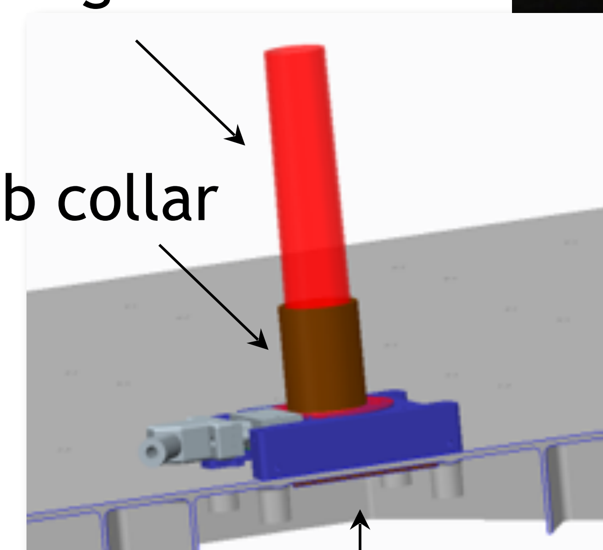


Detector (focal plane) plate

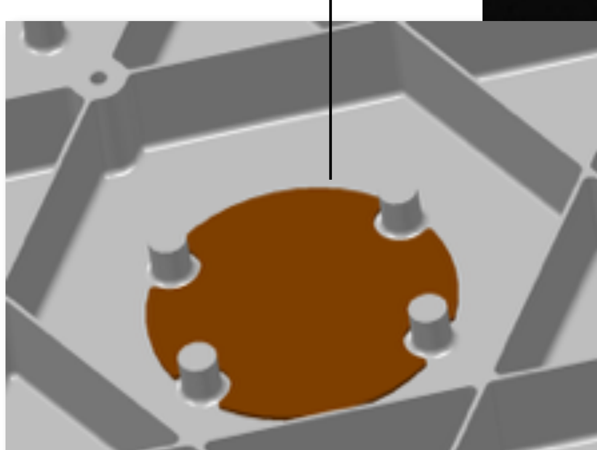
Radiation shielding

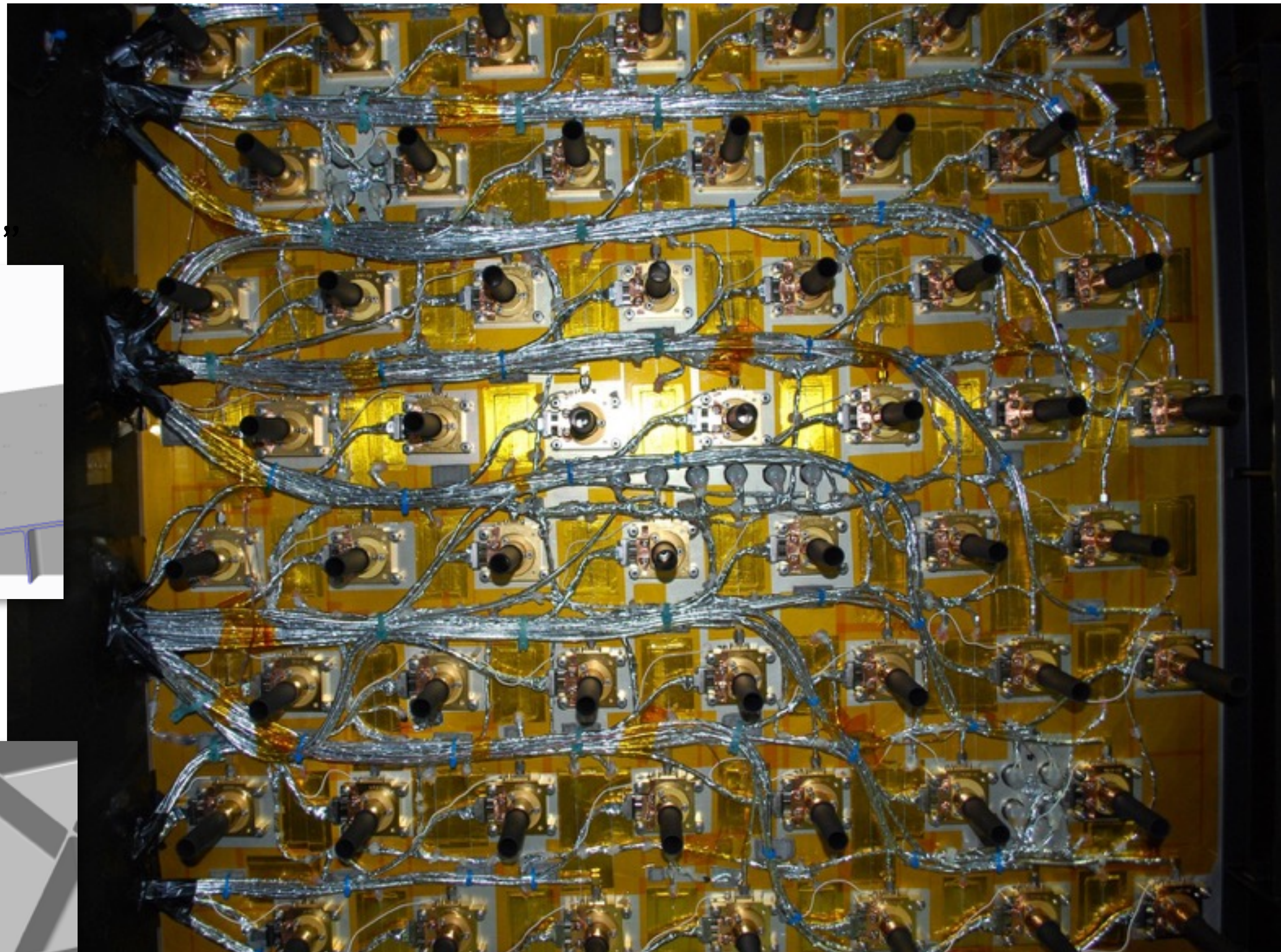
Au/Ag “traffic cone”

Pb collar



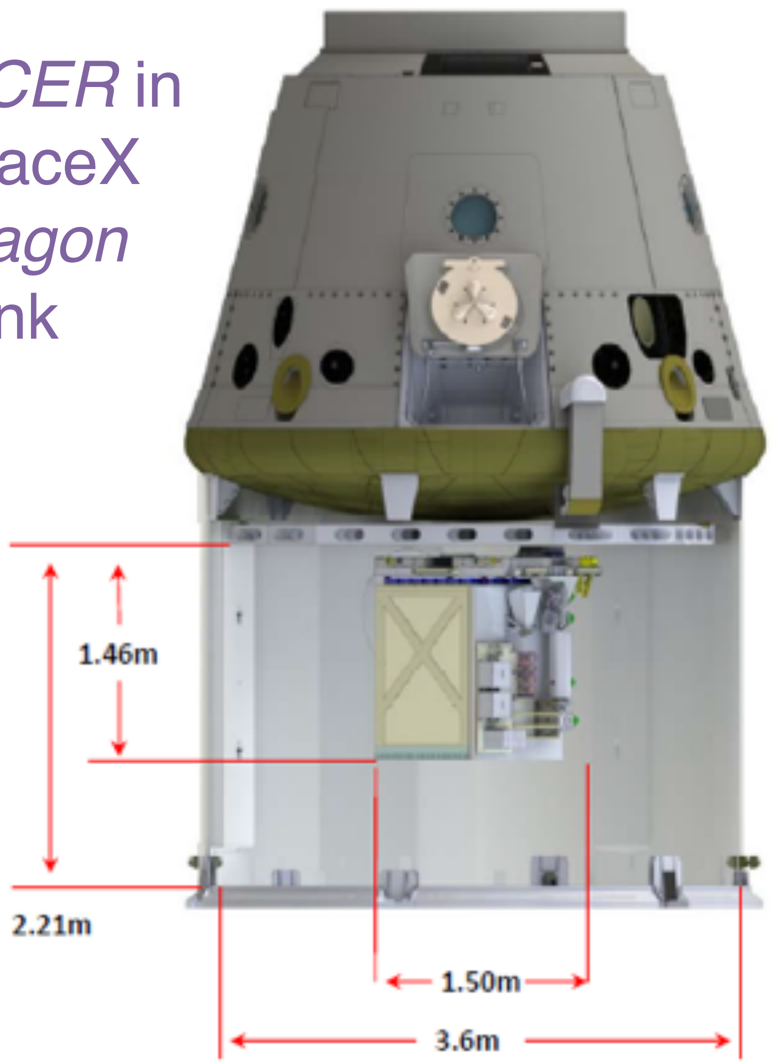
Pb disk

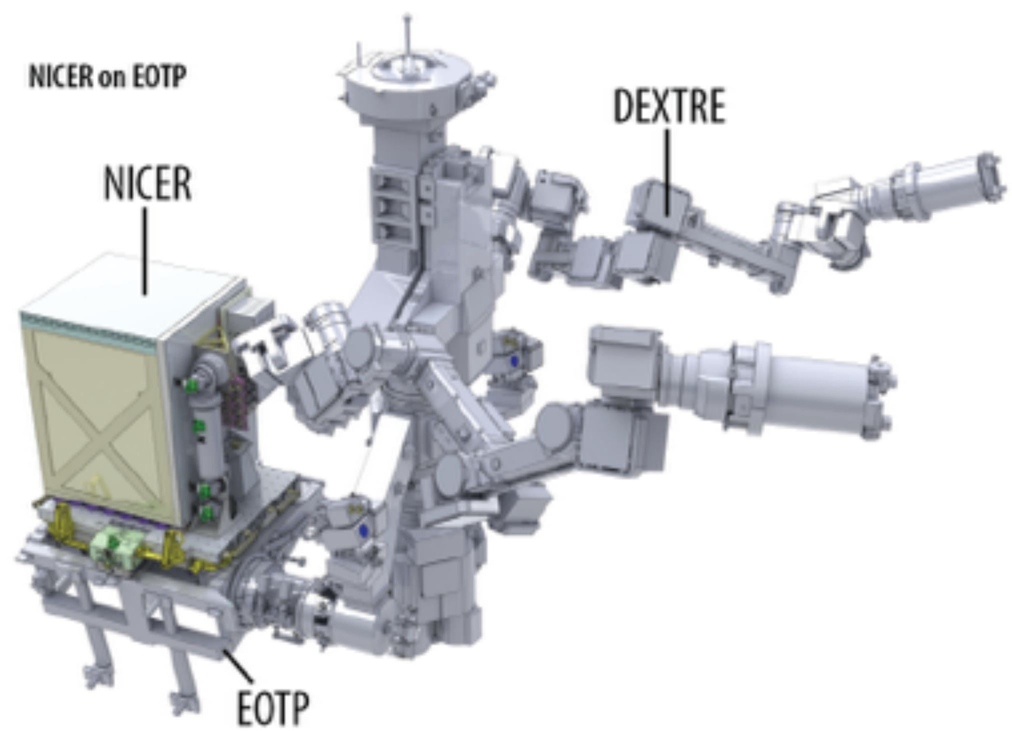




Transport and ISS installation

NICER in SpaceX *Dragon* trunk

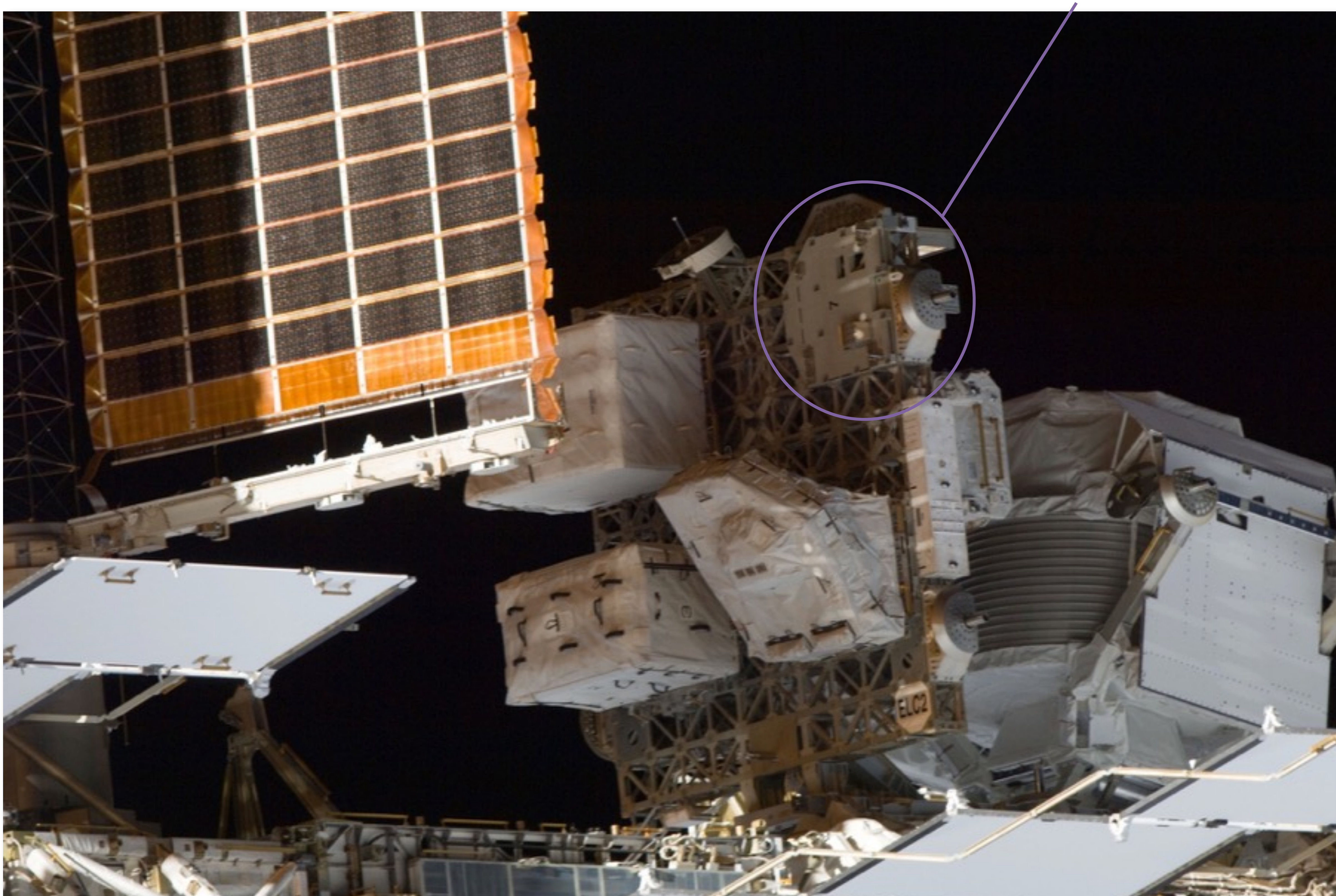




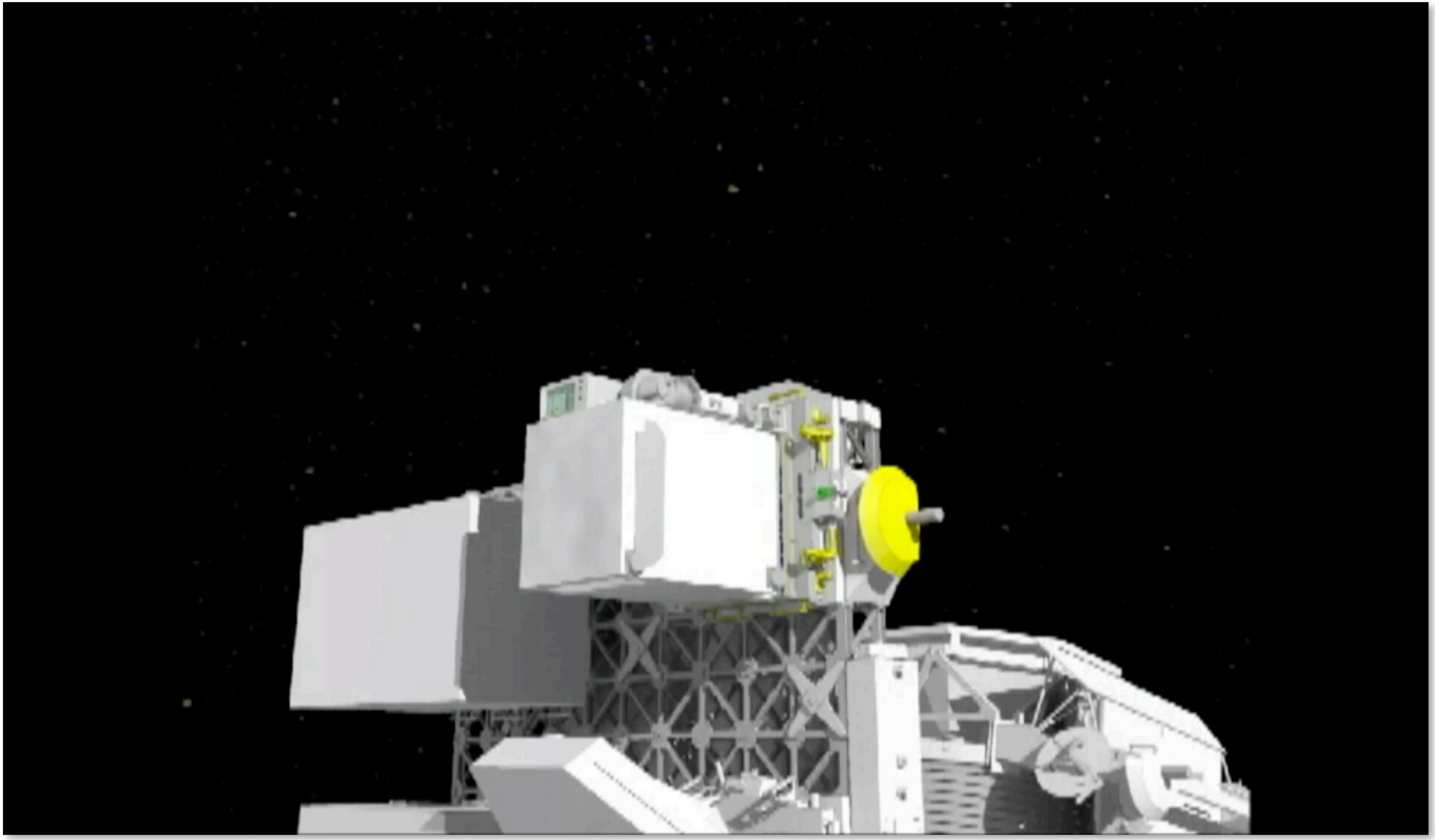
Robotic installation…

Transport and ISS installation (cont.)

… to NICER's future home



Deployment and tracking



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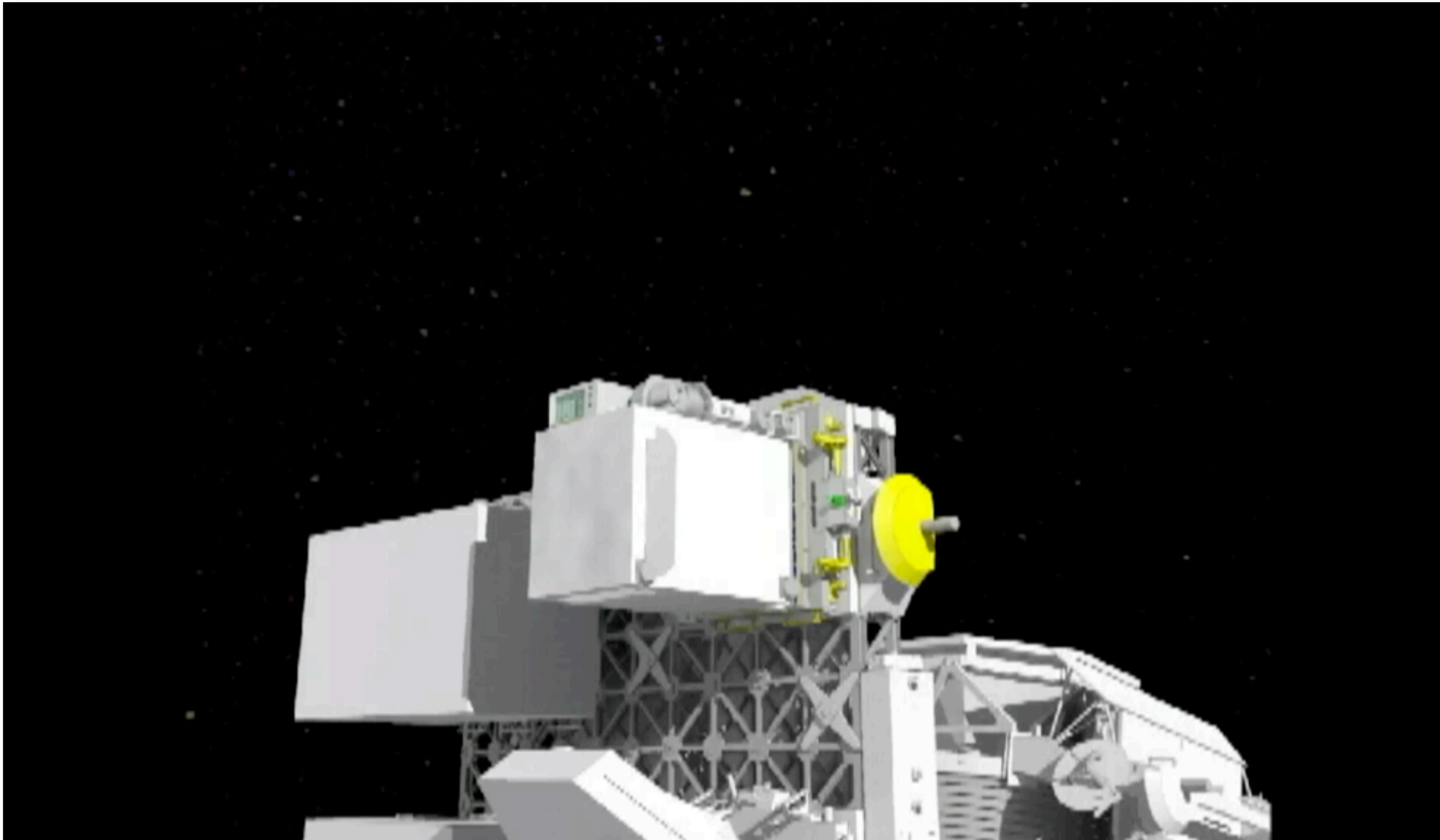

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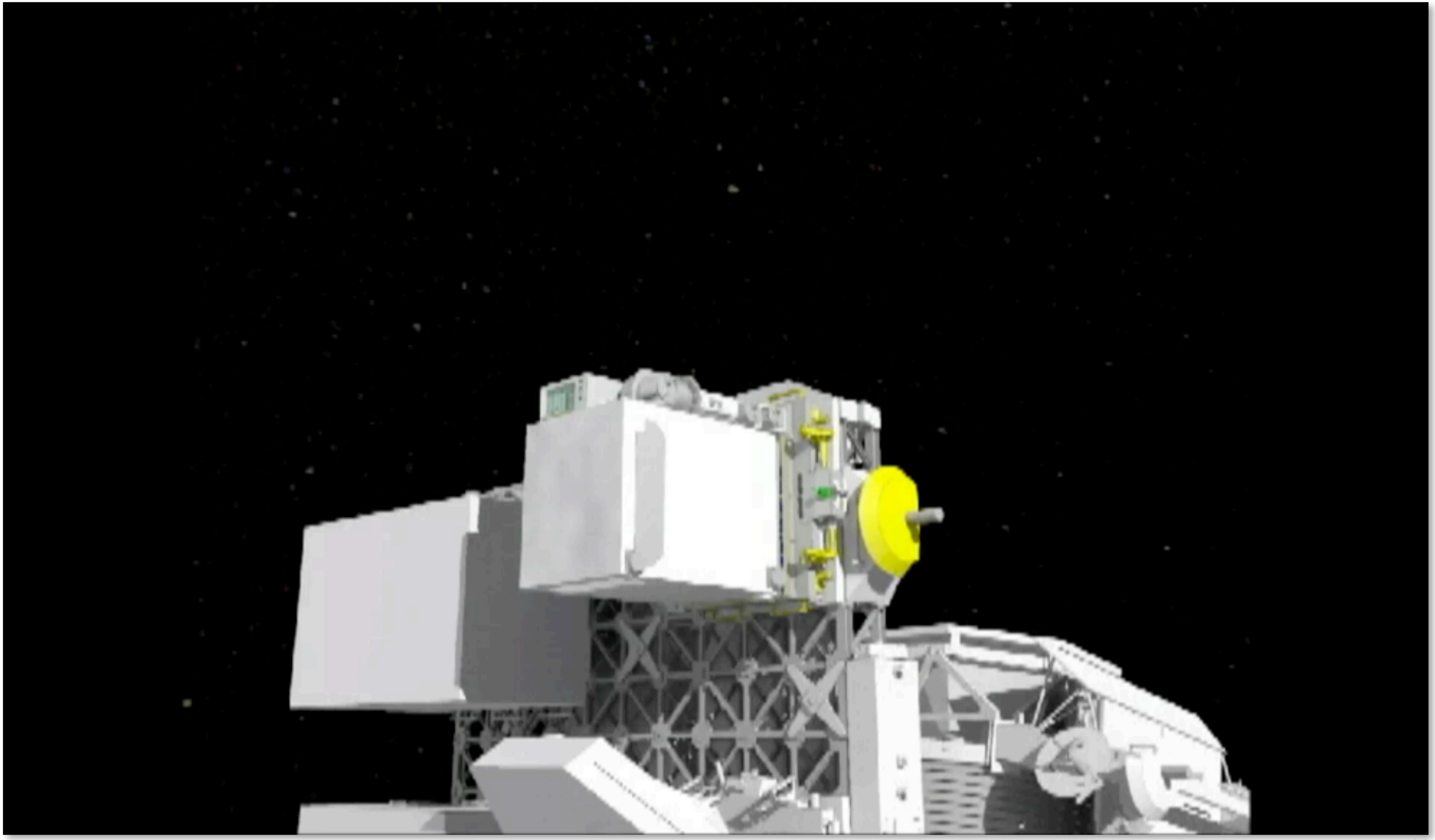
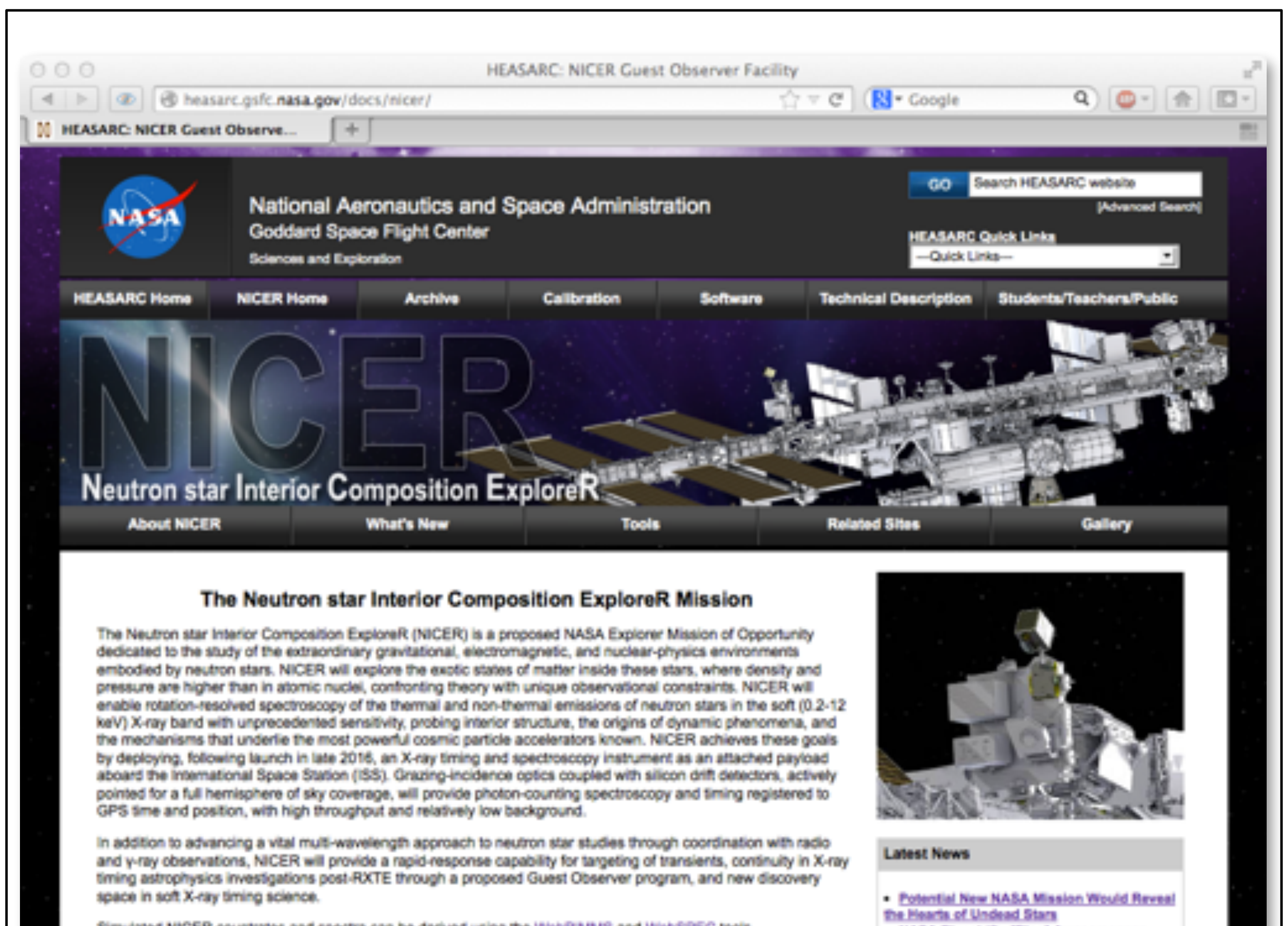
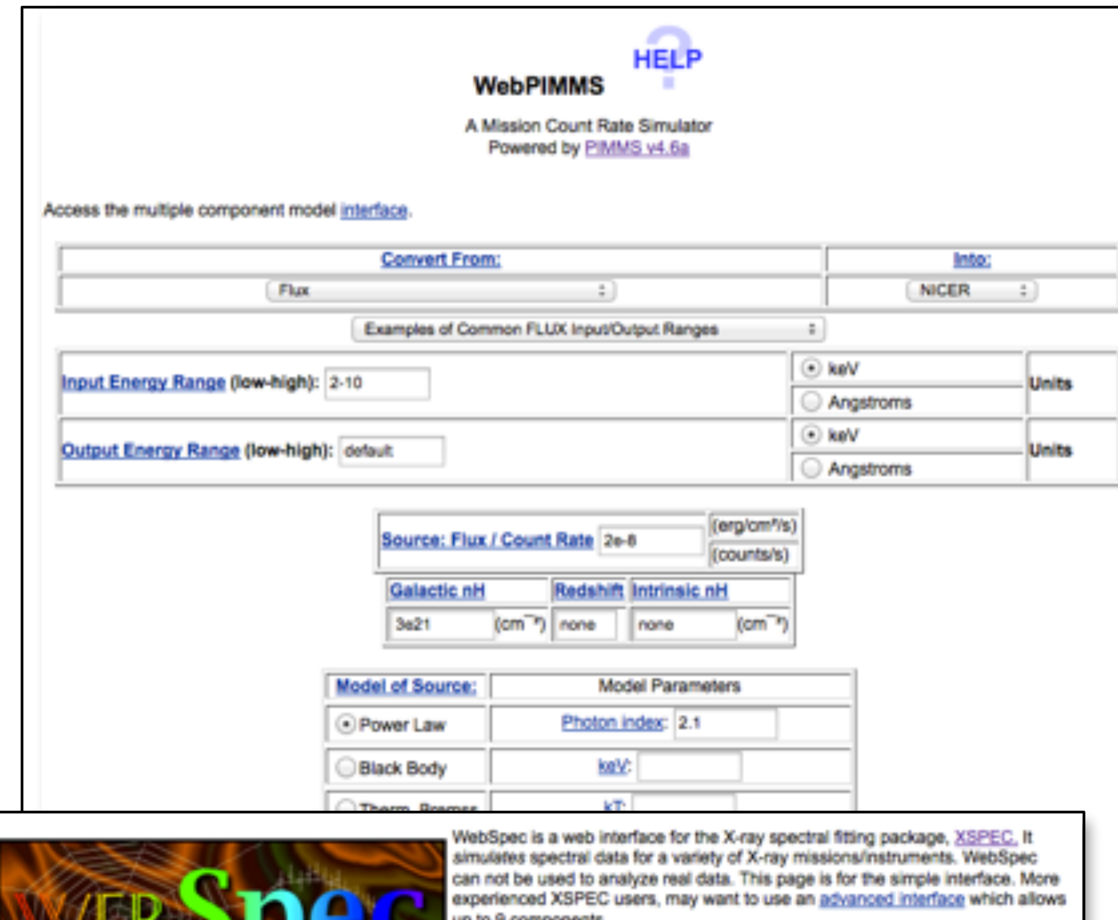


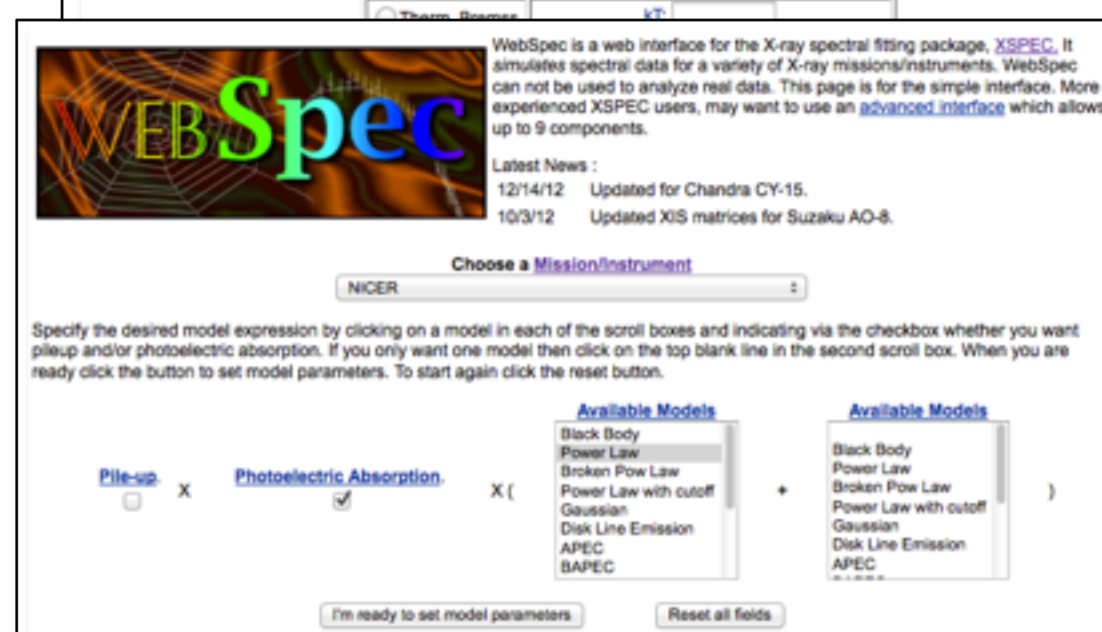
Guest Observer Program

NICER tools at HEASARC available to anticipate observations of your favorite targets

- Timing-spectral studies of AGN and black-hole binaries
- Highly redshifted iron lines
- Coronal emission from stars, other soft transients
- … and more!







Baseline Science and GO timeline

- **Early Feb 2017** — Launch
- **Feb 2017** — On-orbit checkout
- **Mar 2017** — Beginning of Baseline Science ops
- **Summer 2017** — Establishment of NICER GOF; Discretionary time requests considered
- **Sep 2017** — First public data release to HEASARC
- **Feb 2018** — Release of NICER GO Cycle 1 call for proposals, *observations contingent on mission extension*
- **Spring 2018** — Consideration of NICER mission extension by Astrophysics Senior Review
- **Aug 2018** — Cycle 1 targets announced
- **Sep 2018** — End of Baseline Science mission; Beginning of Cycle 1 GO observations *if mission extension is approved.*

X-ray Burst Oscillations: From Flame Spreading to the Cooling Wake

with Tod Strohmayer (NASA/GSFC)

Mahmoodifar, S., & Strohmayer, T. 2016, ApJ, 818, 93.

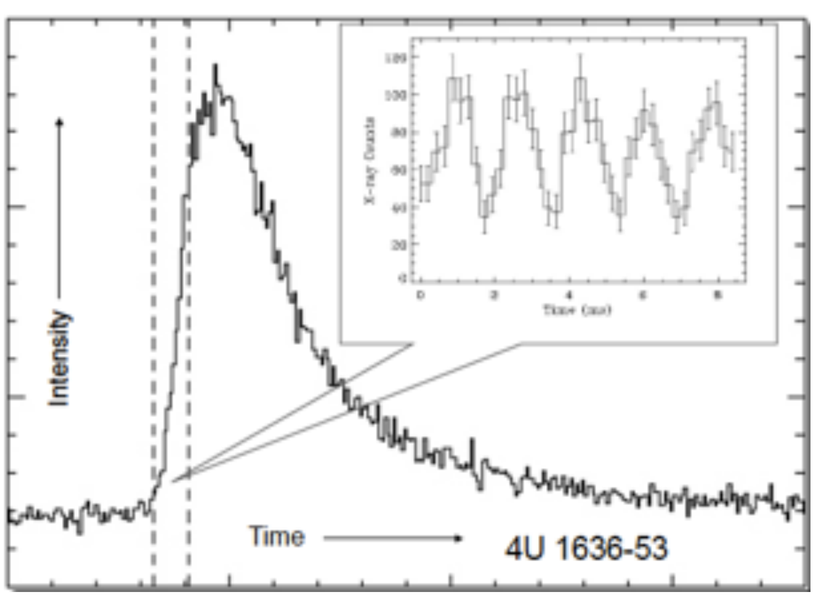
Type I X-ray Burst Characteristics

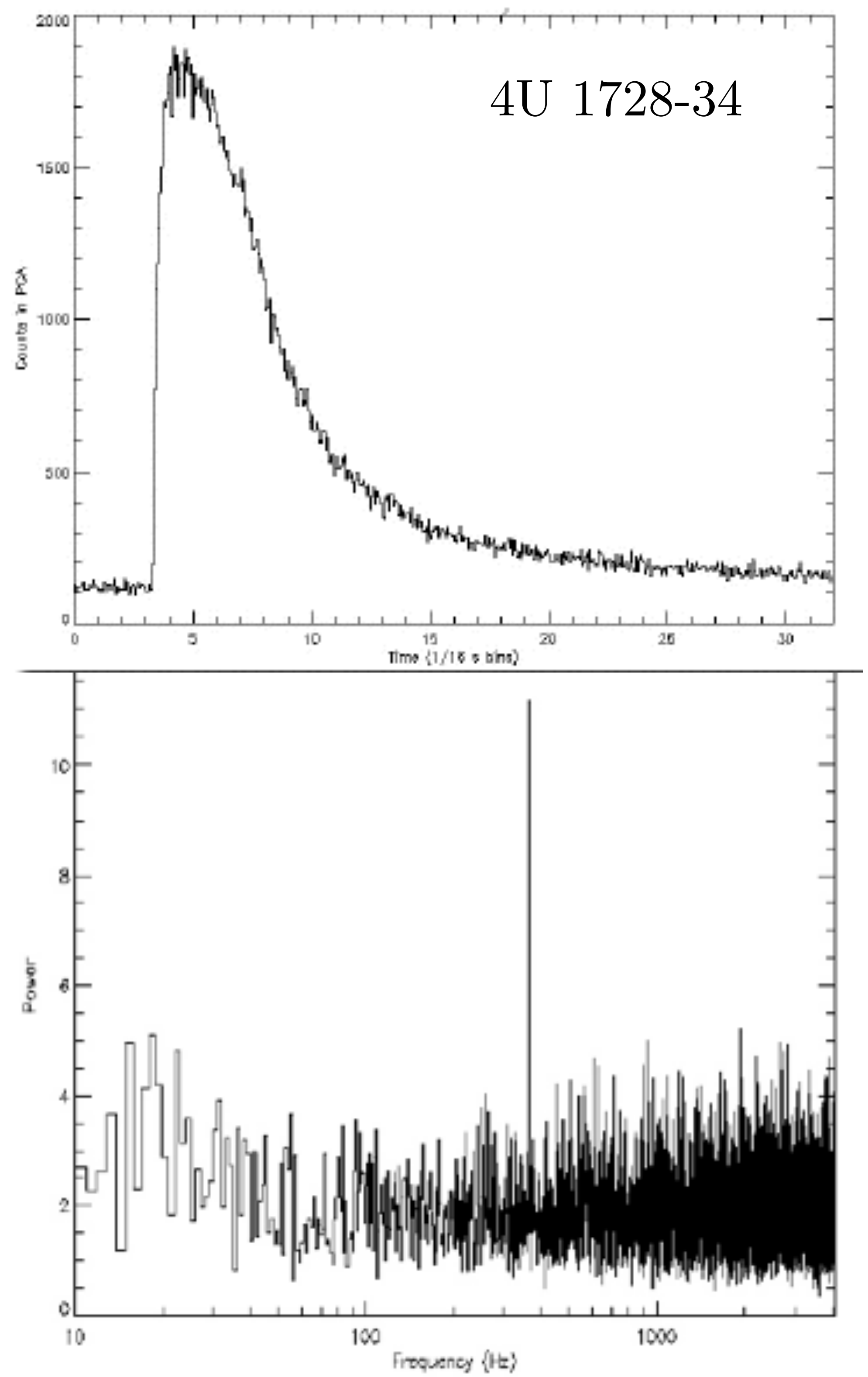
- Rise time ~ 1-10 sec.
- Decay time ~ tens to hundreds of seconds.

- X-ray spectrum consistent with a black-body of temperature T_{bb}=2-3 keV.

- Burst oscillations, in about 10% of the bursts observed with high time resolution detectors.

- Oscillations observed both during the rise and/or decay of the burst.





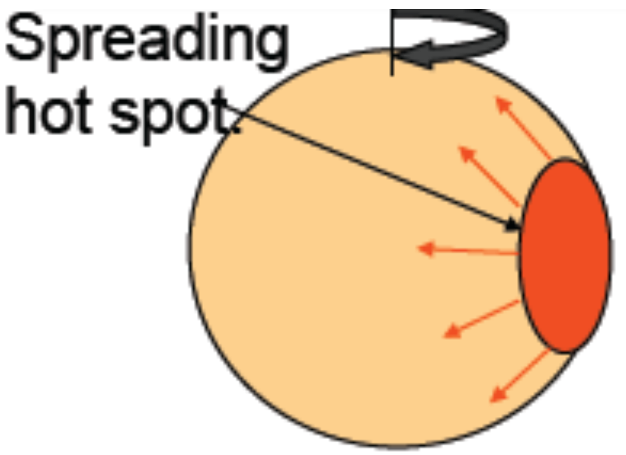
Strohmayer et al. 1996; Strohmayer & Bildsten 2006
Reviews: Galloway et al. 2008; Watts 2012

Current models for burst oscillations

- Hot-spot model

Spreading hot spot on a rotating star

(Strohmayer et al. 1996; Nath, Strohmaye & Swank 2002; Bhattacharyya et al. 2005)



Coriolis force effects $v_{flame} \propto 1/\cos\theta$

(Spitkovsky, Levin & Ushomirsky 2002; Maurer & Watts 2008; Cavecchi et al. 2012, 2014; Chakraborty & Bhattacharyya 2014)

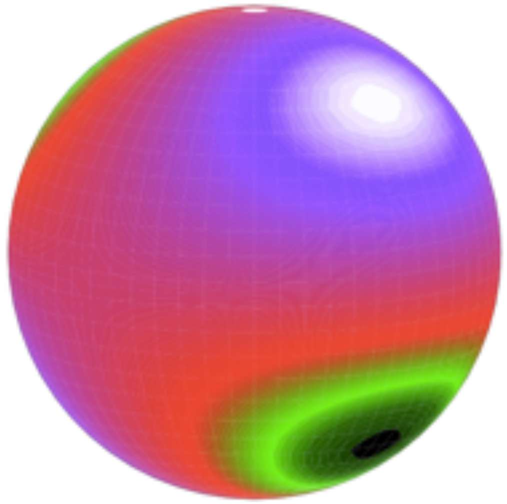
- Surface modes

(Bildsten et al. 1996; Heyl 2004; Piro & Bildsten 2005; Cumming 2005; Lee & Strohmayer 2005)

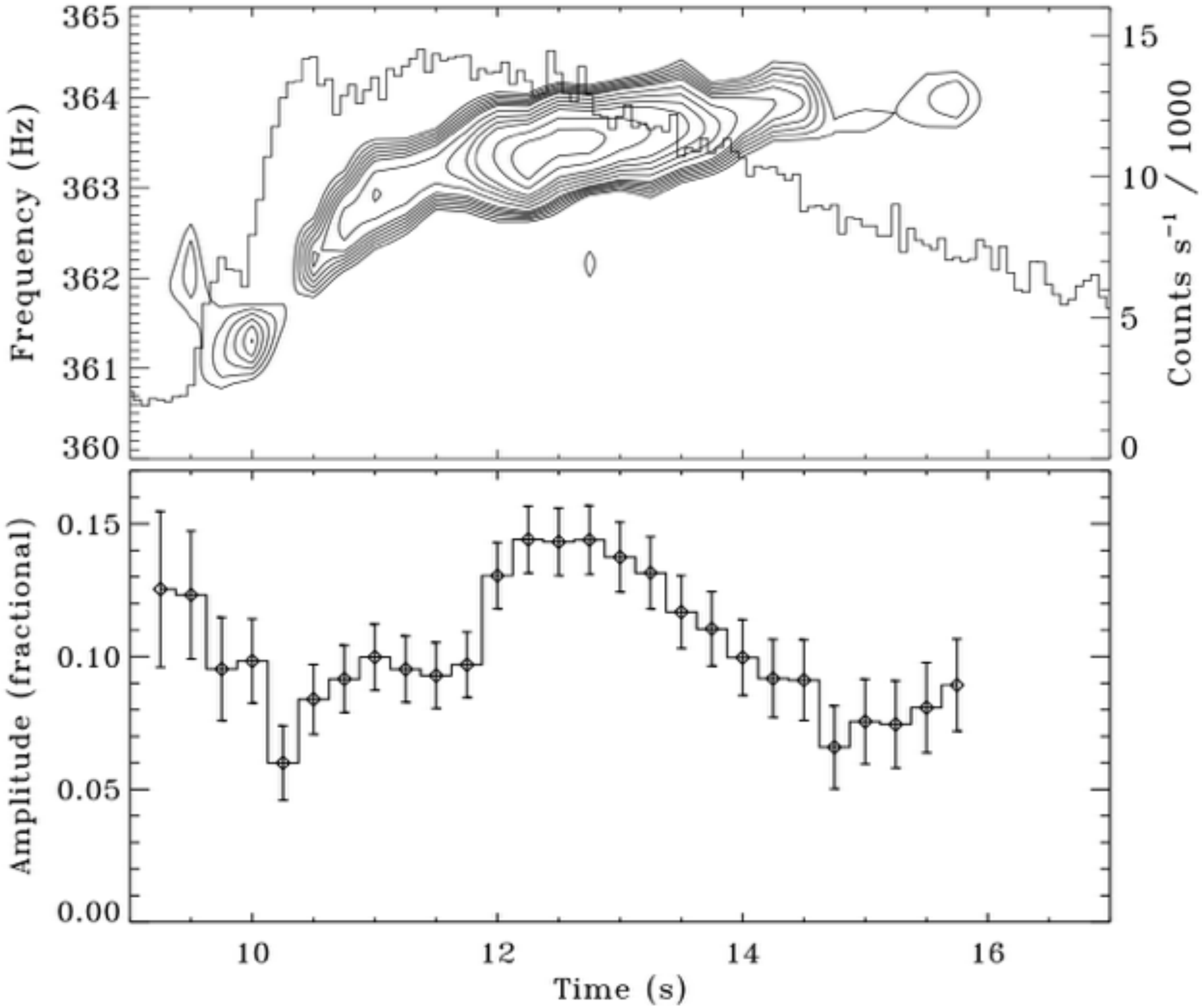
g-modes

buoyant r-modes

l=2, m=1 buoyant r-mode (Heyl 2004)



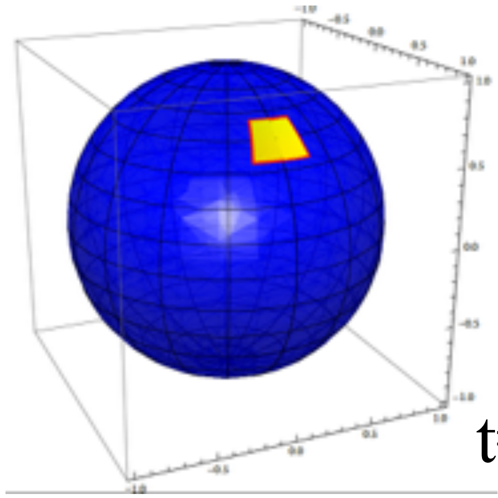
Burst from 4U 1728-34 observed by RXTE in 1997



Dynamic power spectrum overplotted on the PCA light curve (top) for the 1997 Sept. 20 burst from 4U 1728- 34, and the fractional amplitude (half-amplitude) of oscillations during the burst (bottom).

- Oscillations have been observed during the rise and/or decay of some X-ray bursts.
- Those seen during the rise can be well explained by a spreading hot spot model.
- large amplitude oscillations in the decay phase remain mysterious because of the absence of a clear-cut source of asymmetry.
- To date there have not been any quantitative studies that consistently track the oscillation amplitude both during the rise and decay (cooling tail) of bursts.
- Our computations of the light curves and amplitudes of oscillations in X-ray burst models realistically account for both flame spreading and subsequent cooling.

Evolution of a spreading hot spot (affected by Coriolis forces)



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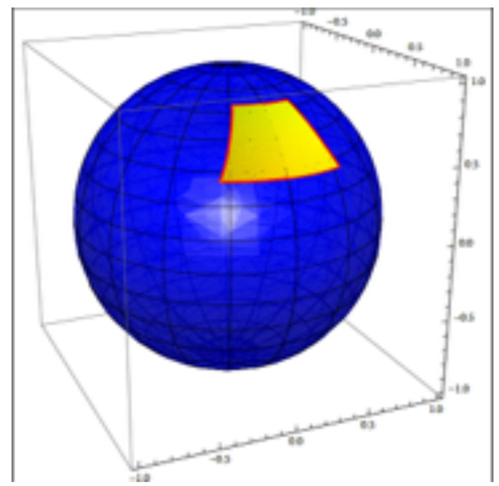
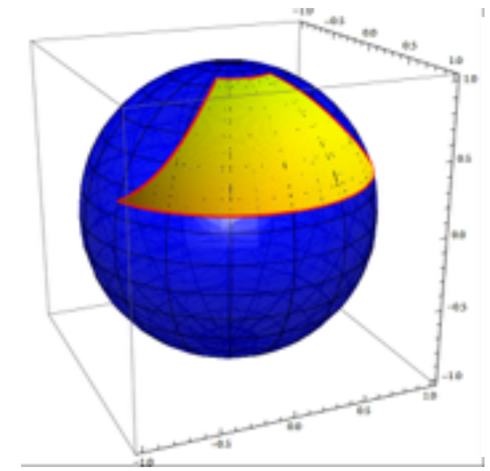
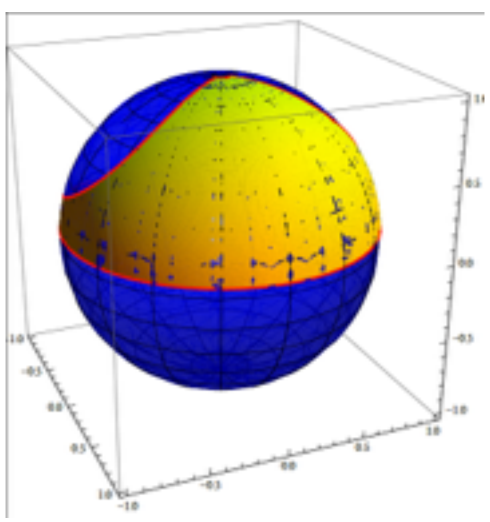


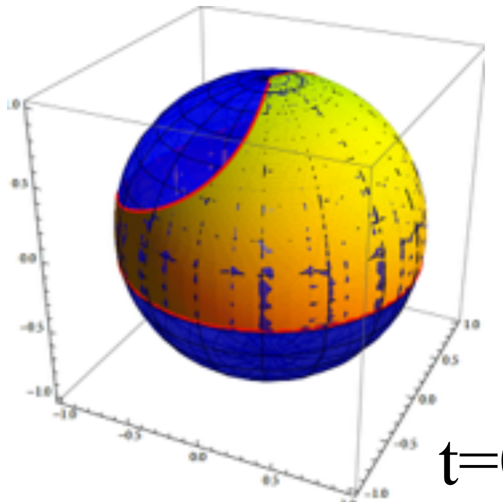
t=0.1s



t=0.2s



t=0.3s



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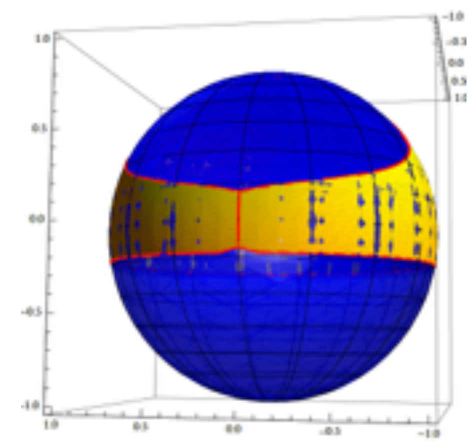
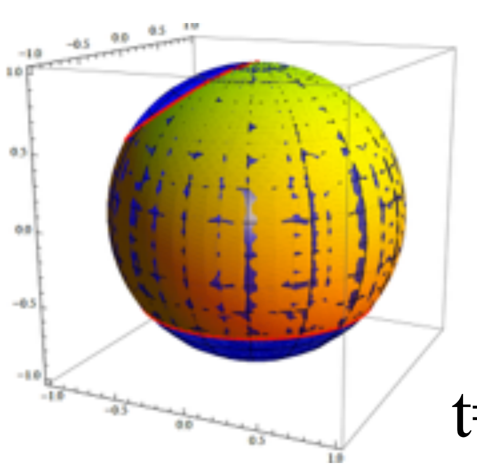
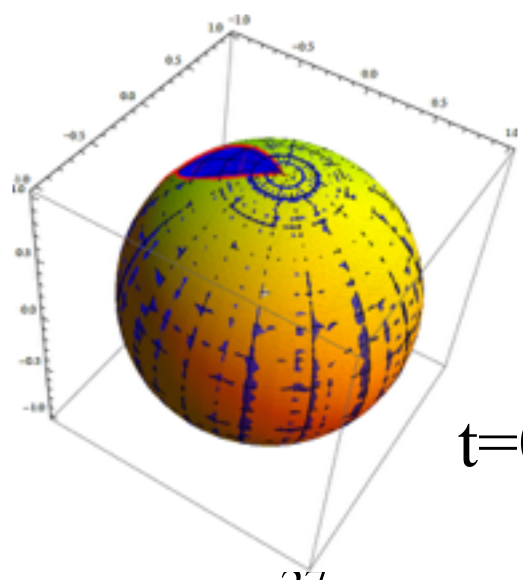


t=0.4s



t=0.6s



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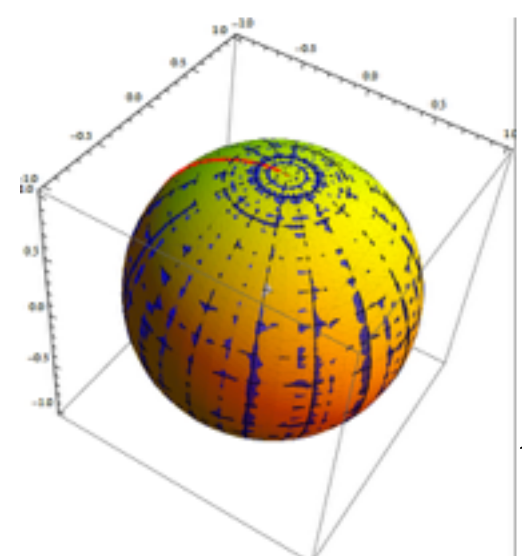
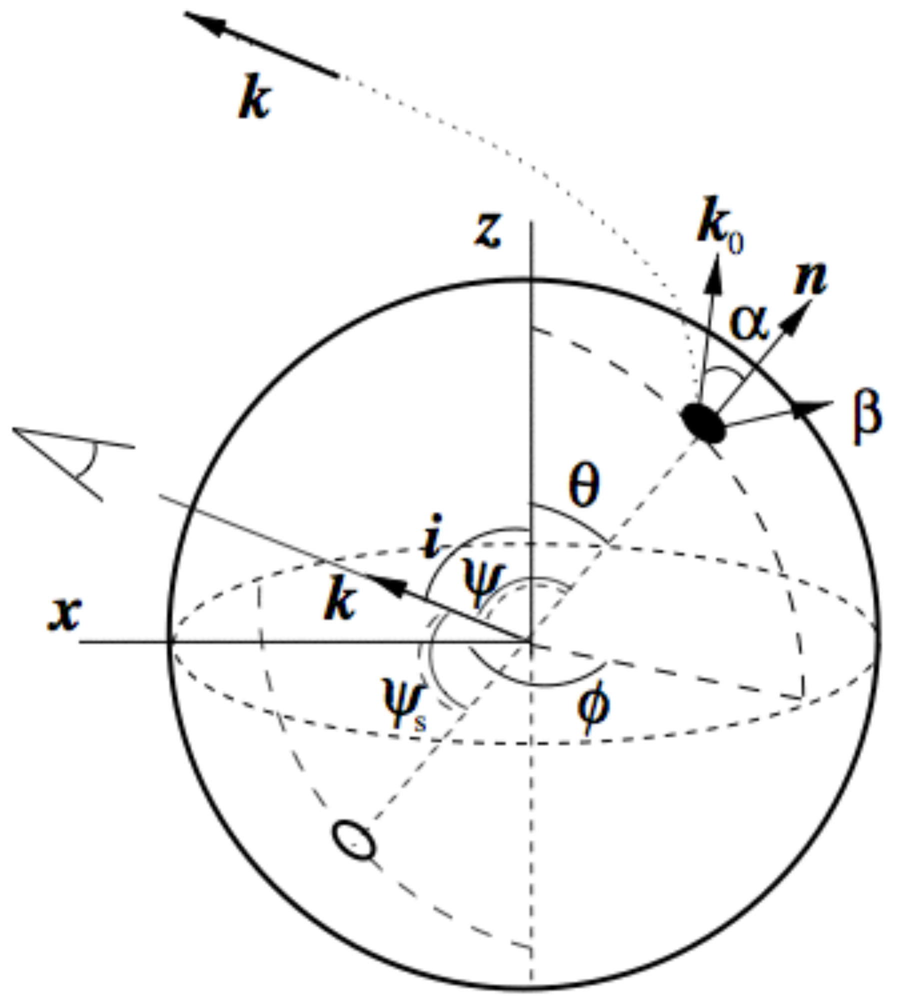


t=1s

Modeling X-ray emission from a spreading hot spot

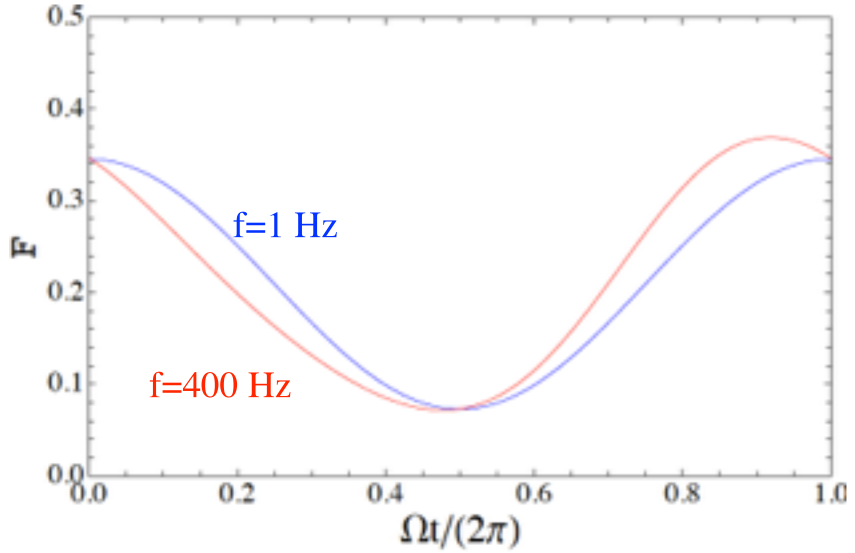


Viironen &Poutanen (A&A 2004)

- Rotating star
- X-ray emitting hot-spot
- Relativistic effects:

  Light bending in a Schwarzschild geometry
  Gravitational redshift
  Doppler shifts
  Relativistic aberration

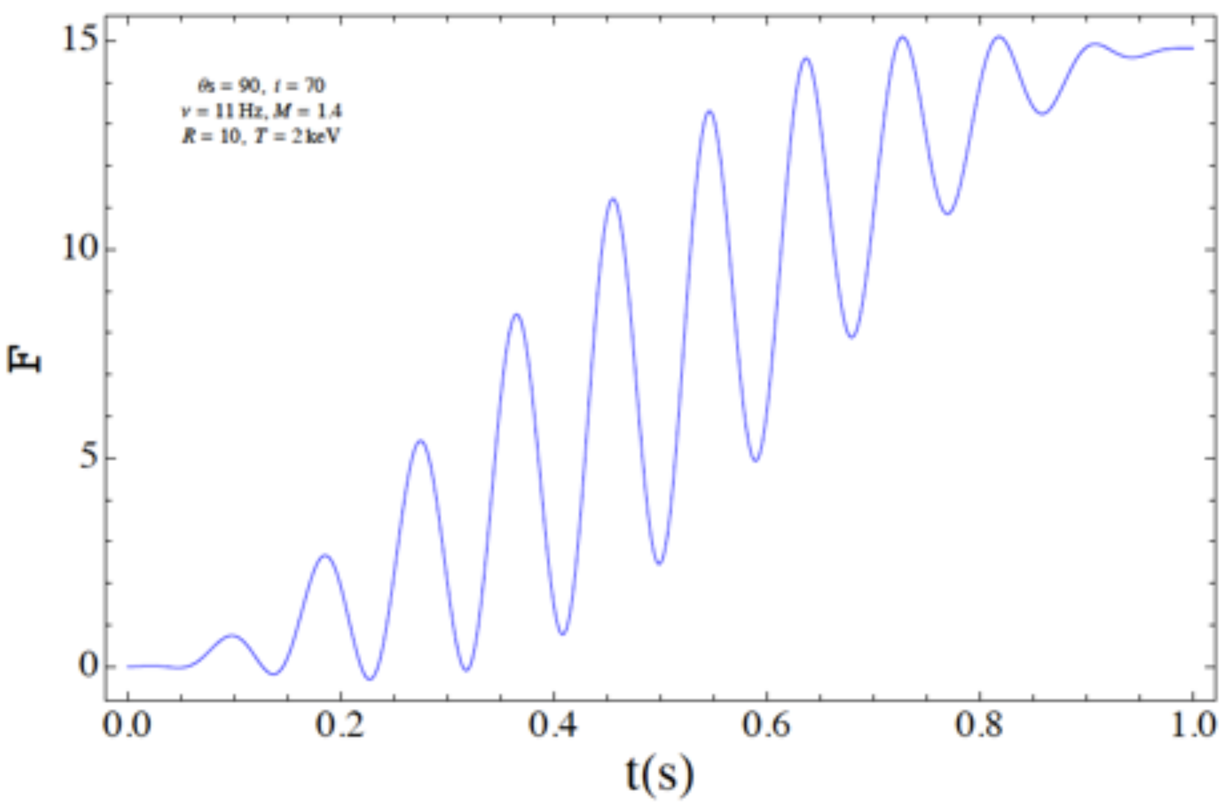
(Beloborodov 2002; Poutanen & Gierlinski 2003; Poutanen & Beloborodov 2006; Morsink et al. 2007; Lo et al. 2013)



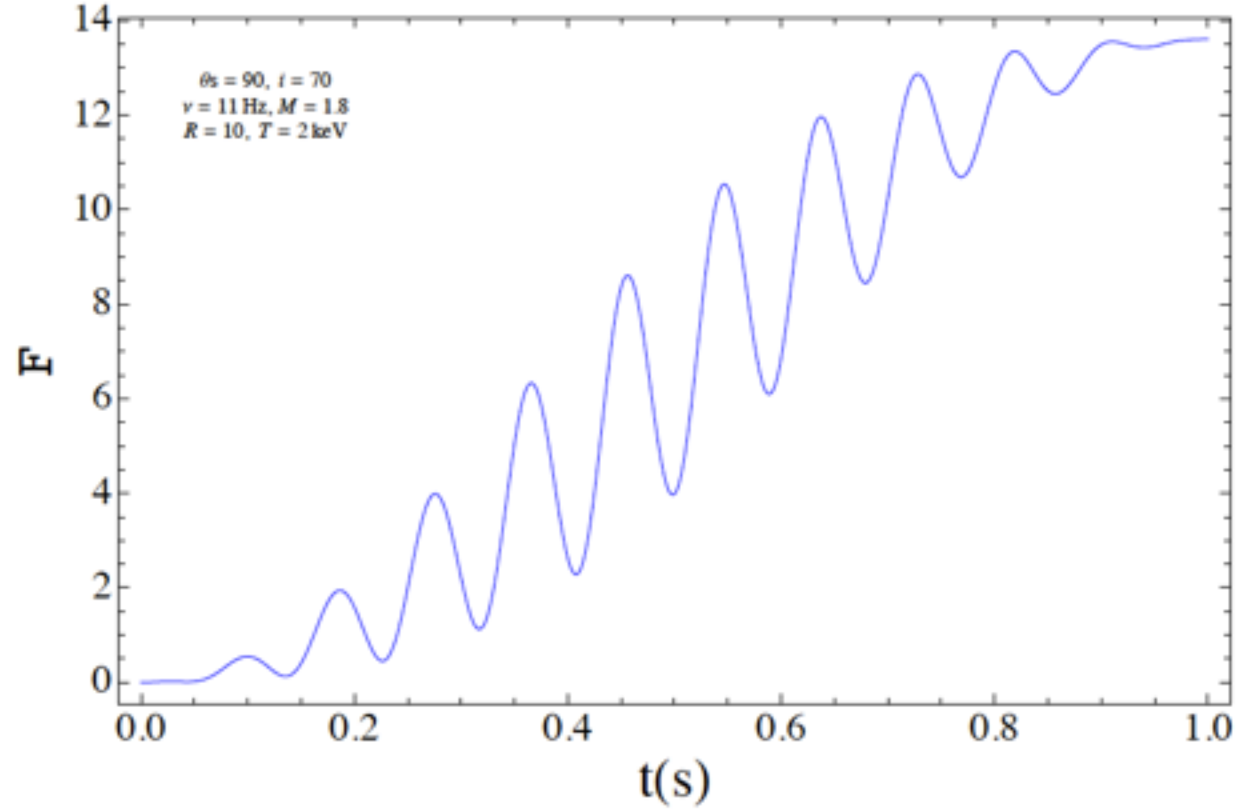
Pulse profiles consistent with the waveform comparison results of the LOFT Science Working Group on Dense Matter.
(Poutanen, Lamb, Miller, Morsink et al.)

Light curves during the rise

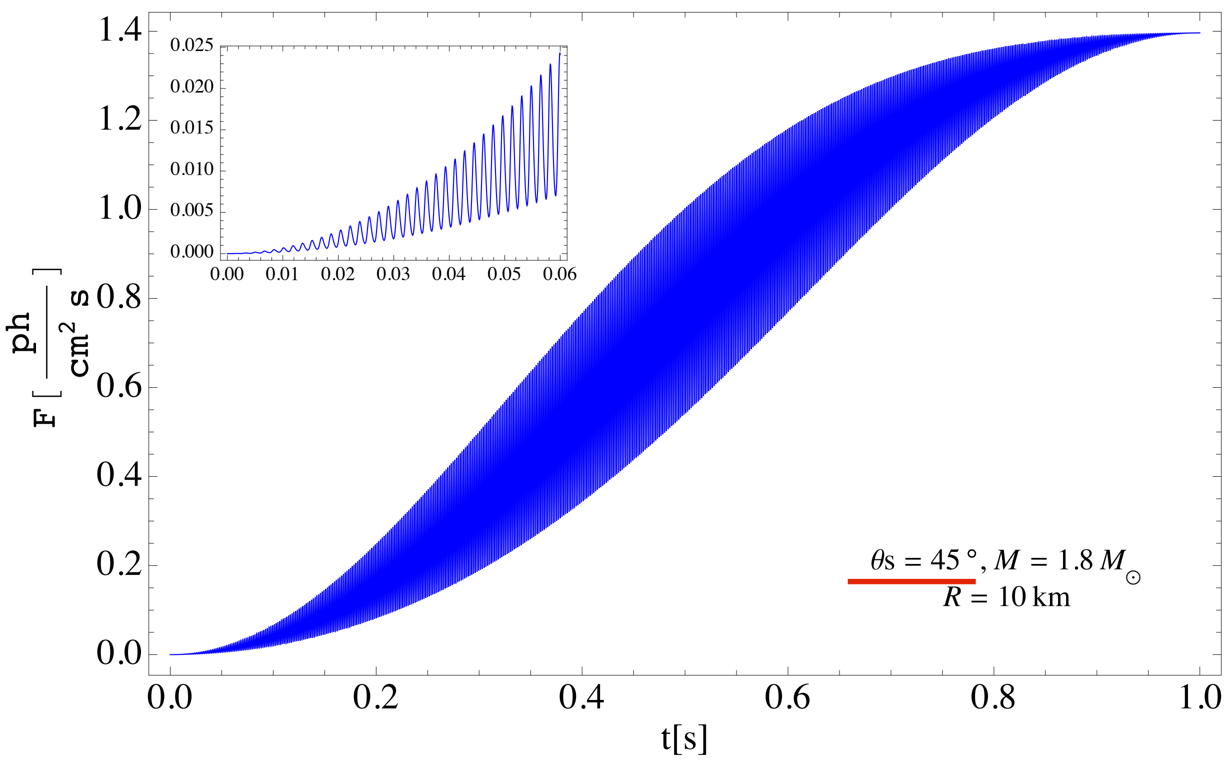
$\mathrm{M}= 1.4\mathrm{M}_{\odot}$

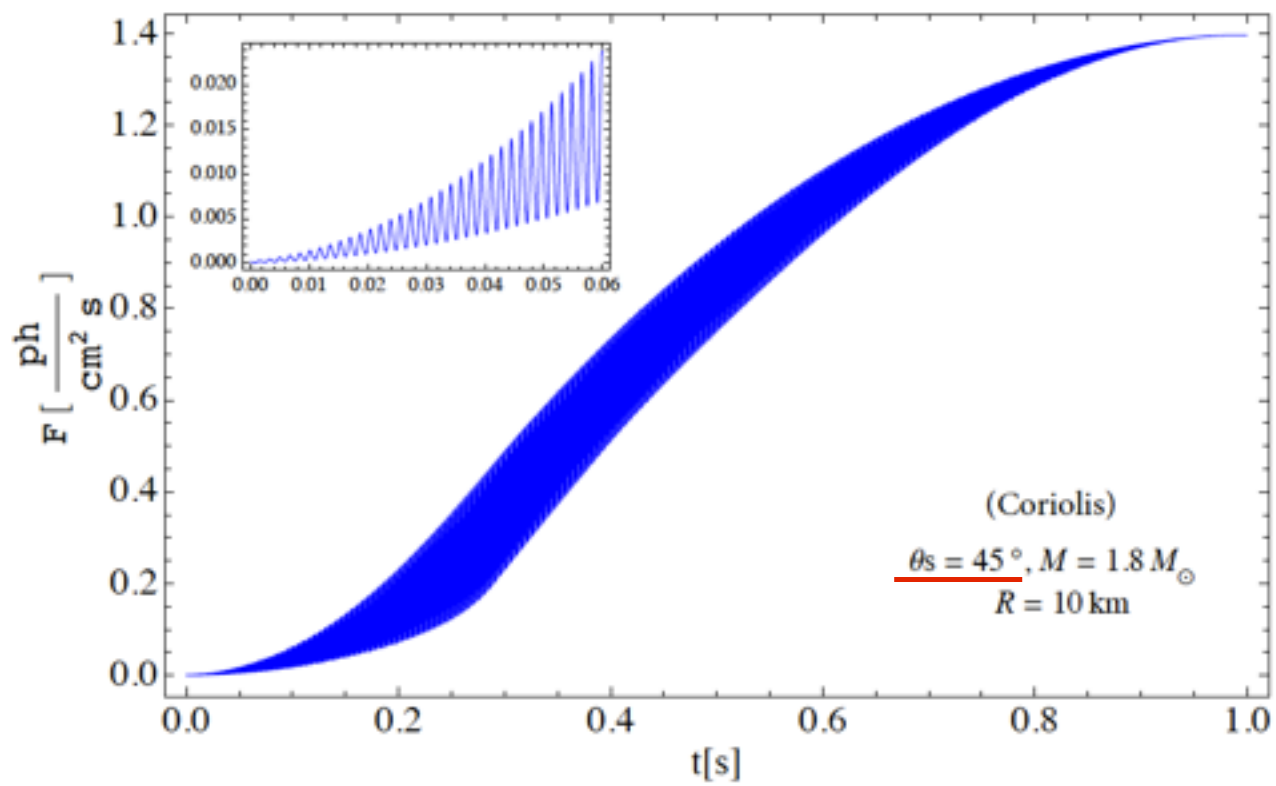


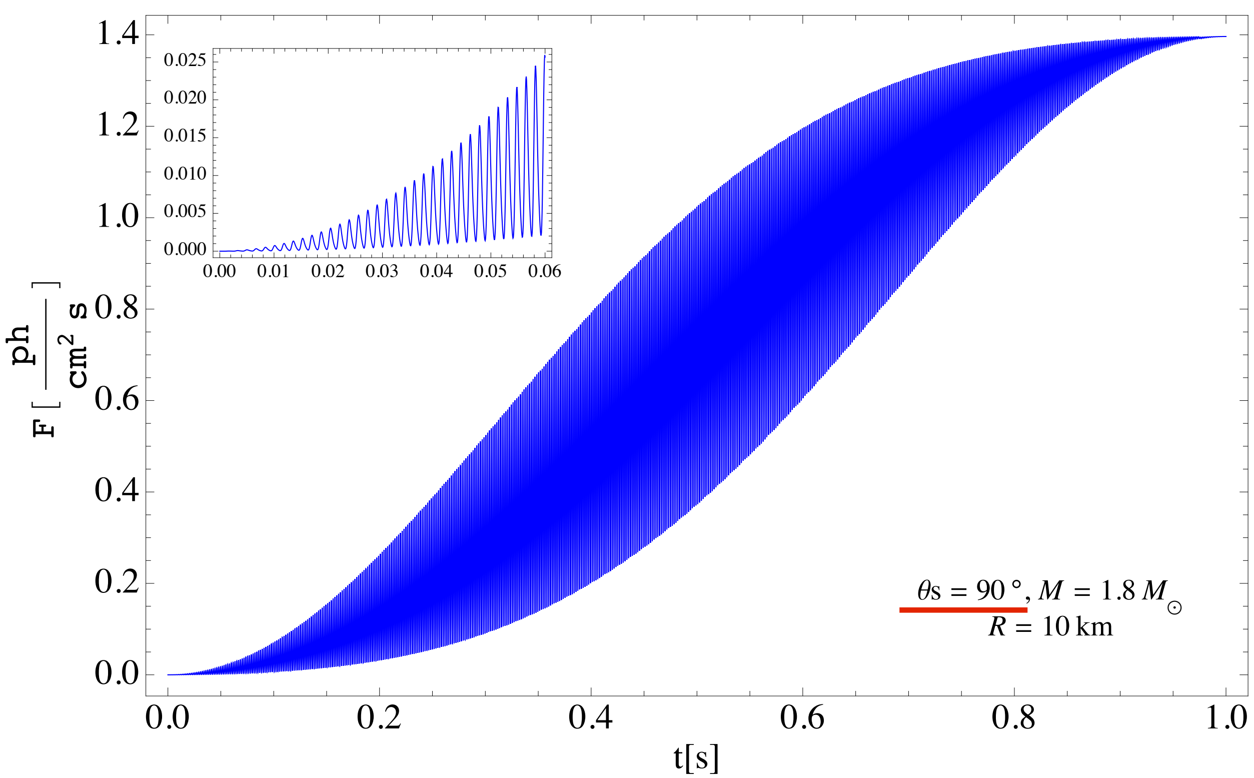
$\mathrm{M}= 1.8\mathrm{M}_{\odot}$

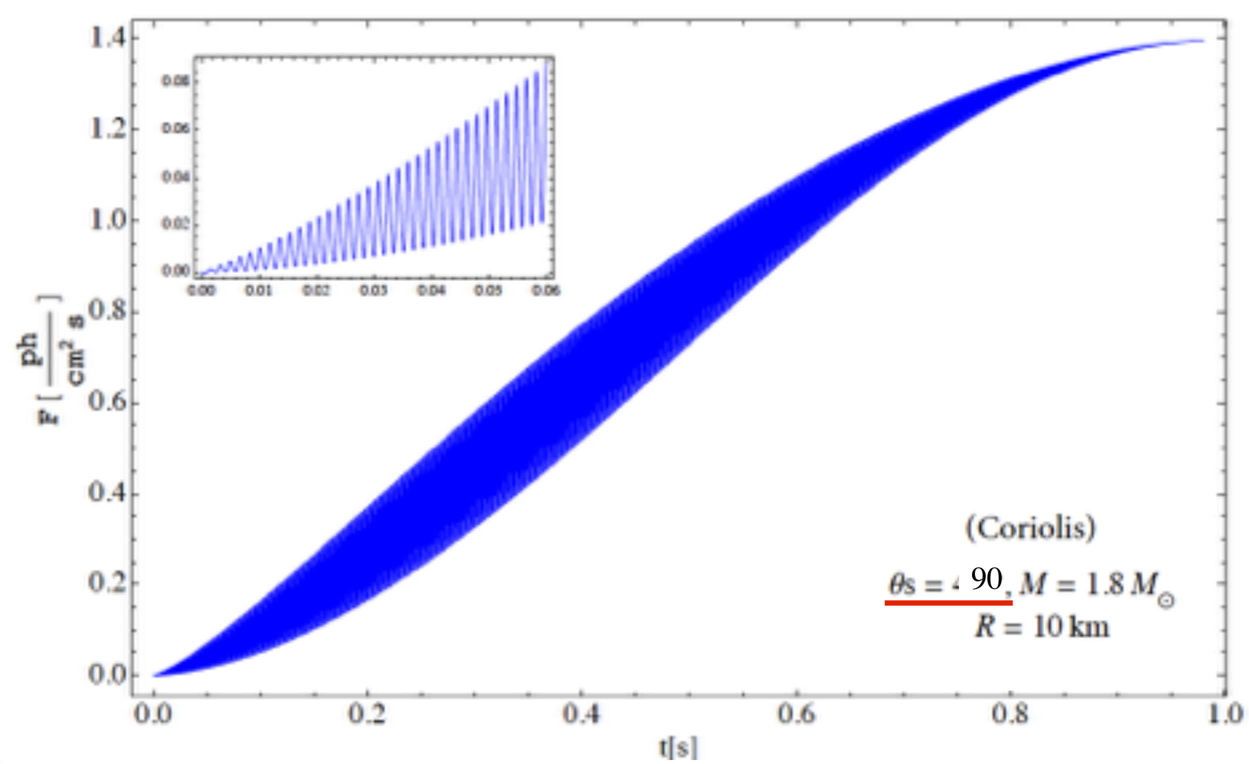


Light curves during the rise (Coriolis force effects)









Cooling models:

- **Canonical Cooling**

"Symmetric" model in which each patch on the NS heats and cools in the same manner

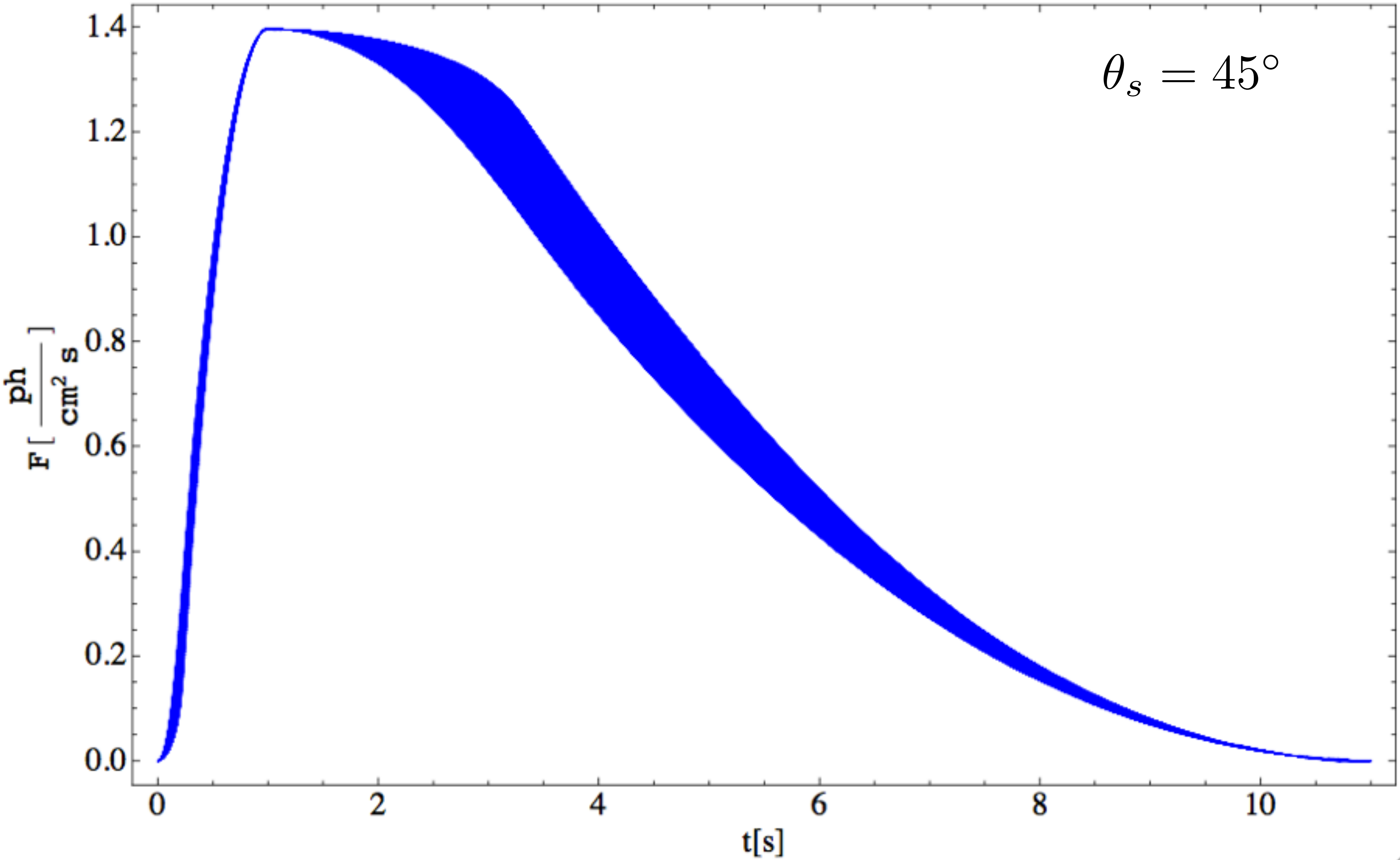
$$\begin{aligned} T &= T_0 + (T_1 - T_0)[1 - \exp(-t/t_{\rm lr})], \quad t \leqslant t_m \\ &= T_m \exp(-t/t_{\rm ld}), \quad t \geqslant t_m \end{aligned}$$

Latitude dependent cooling model which allows for variations in the cooling timescale with latitude, as could result from rotationally induced changes in the effective gravity.

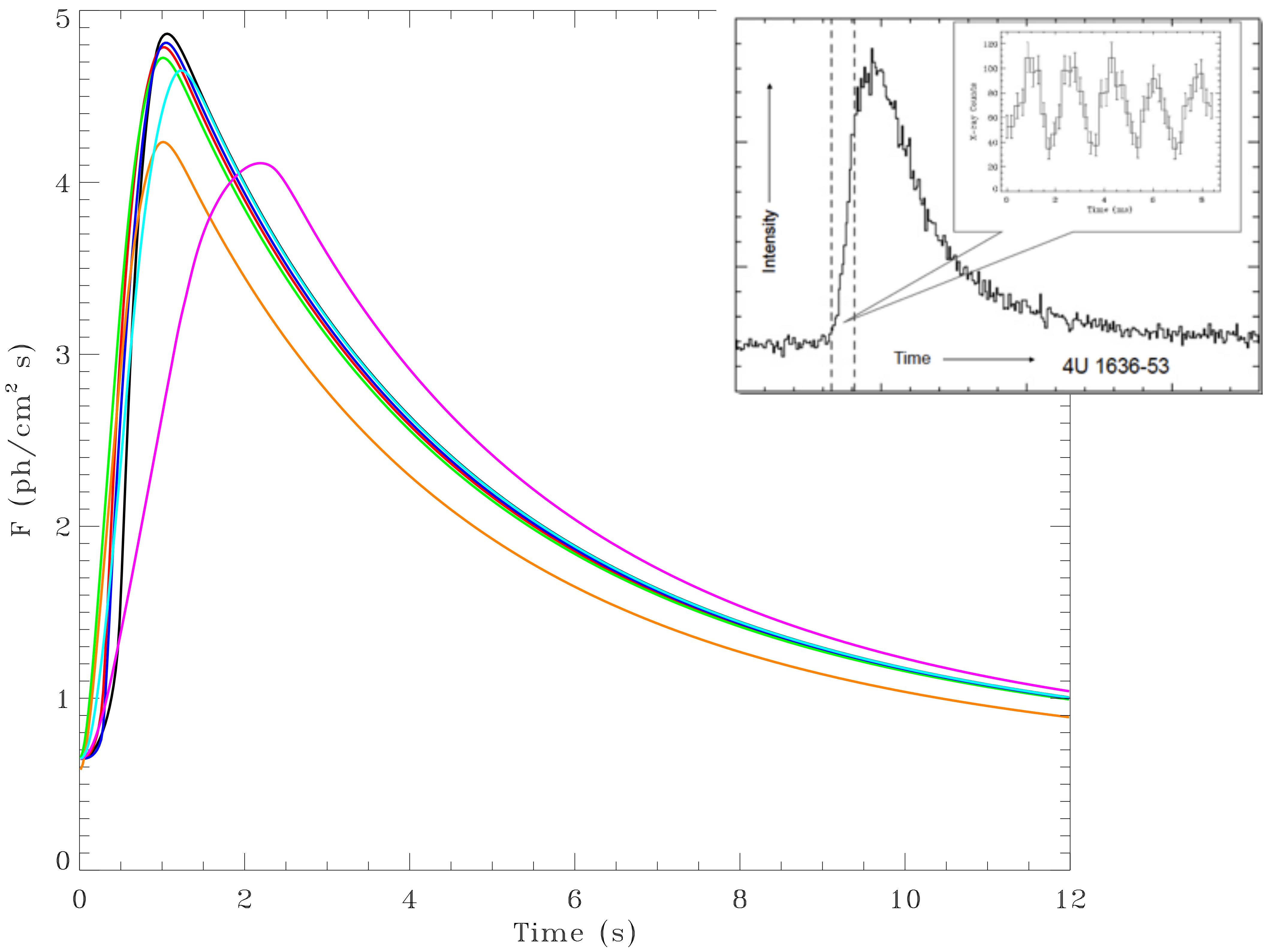
- **Spreading Cooling Wake**

"Asymmetric" model where parts of the star that ignite first cool faster than those that burn last.
This may happen, for example, if there is significant transverse heat exchange between hot and cold regions, or if the local cooling time is shorter near the ignition site than elsewhere on the star.

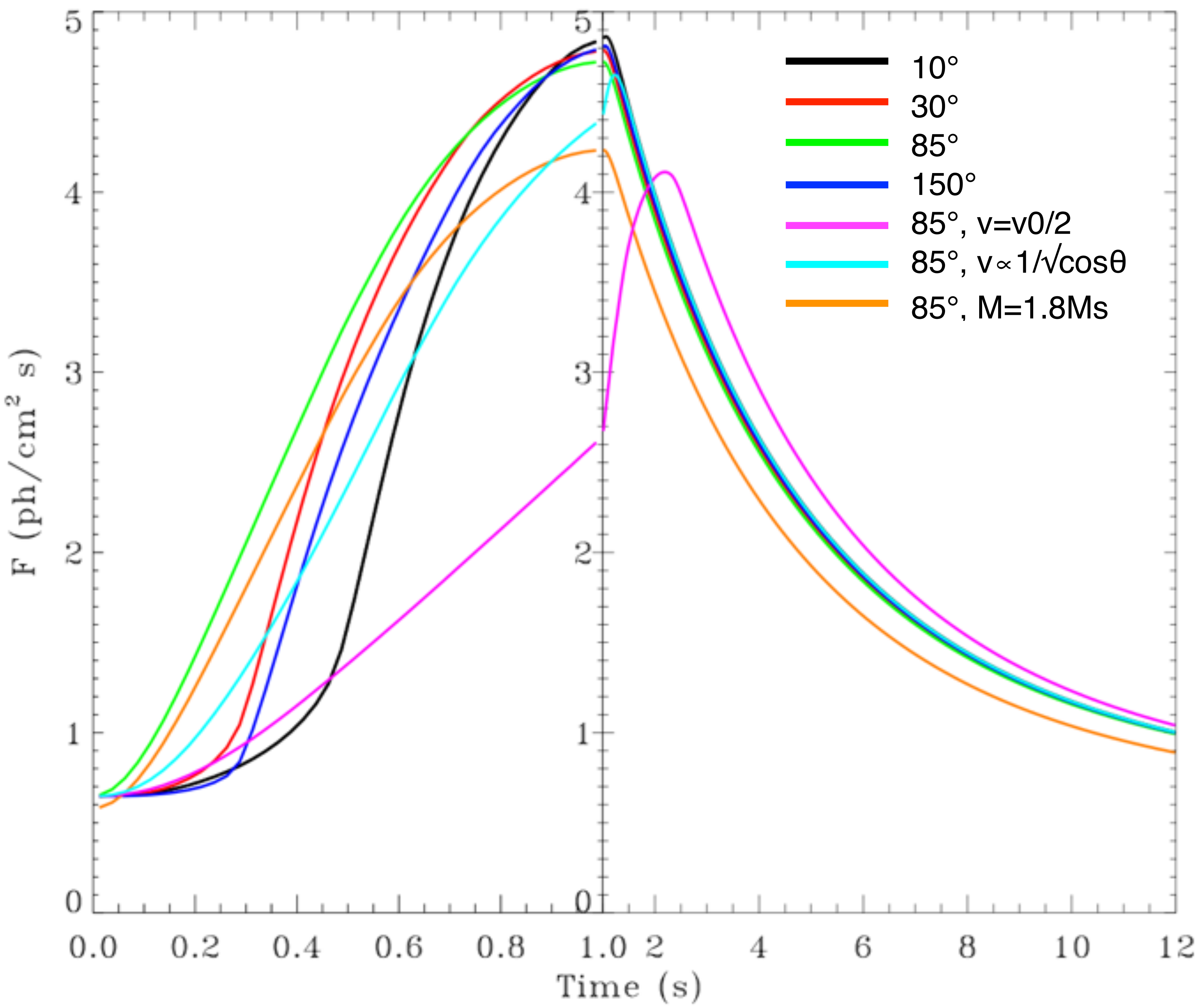
Model light curve for the rise and decay (cooling wake)



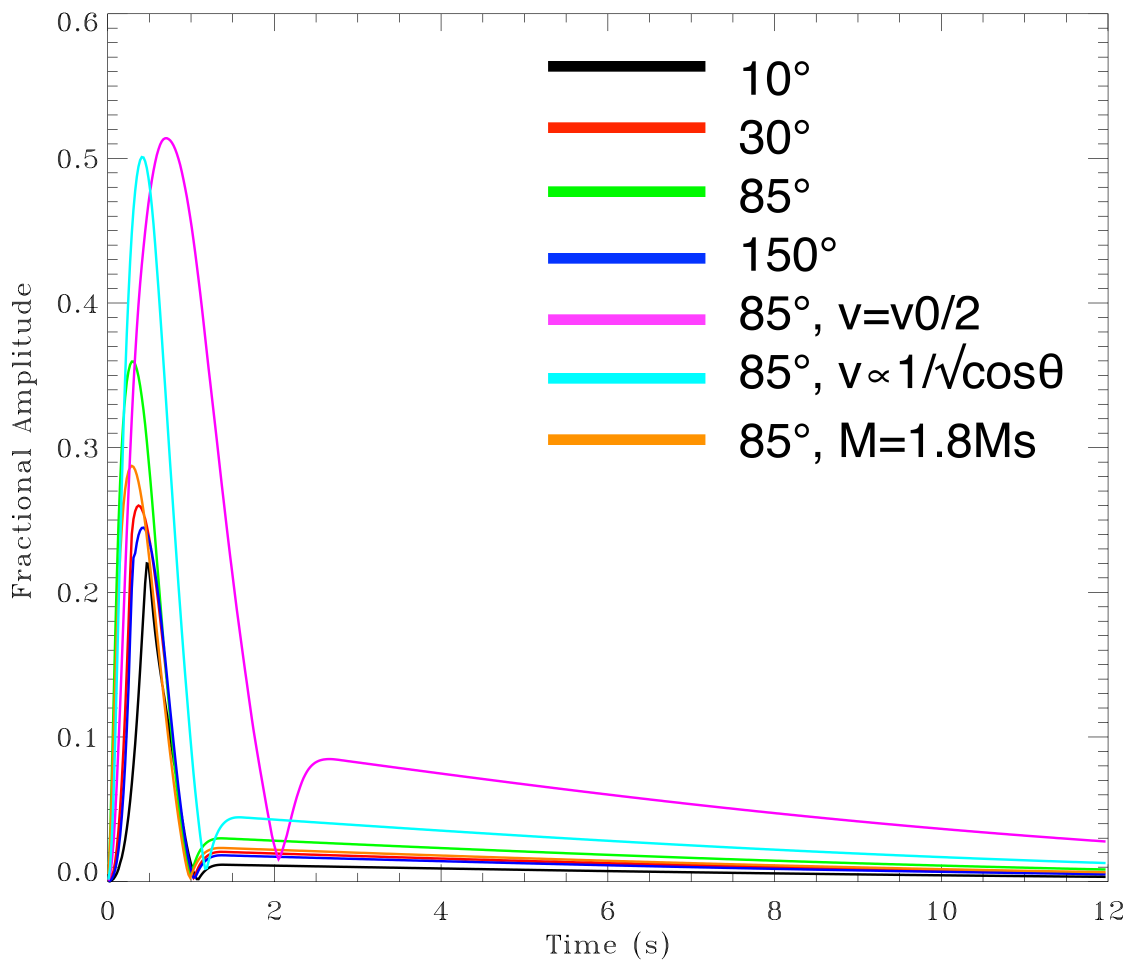
Smoothed bolometric light curves for different ignition latitudes (canonical cooling model)

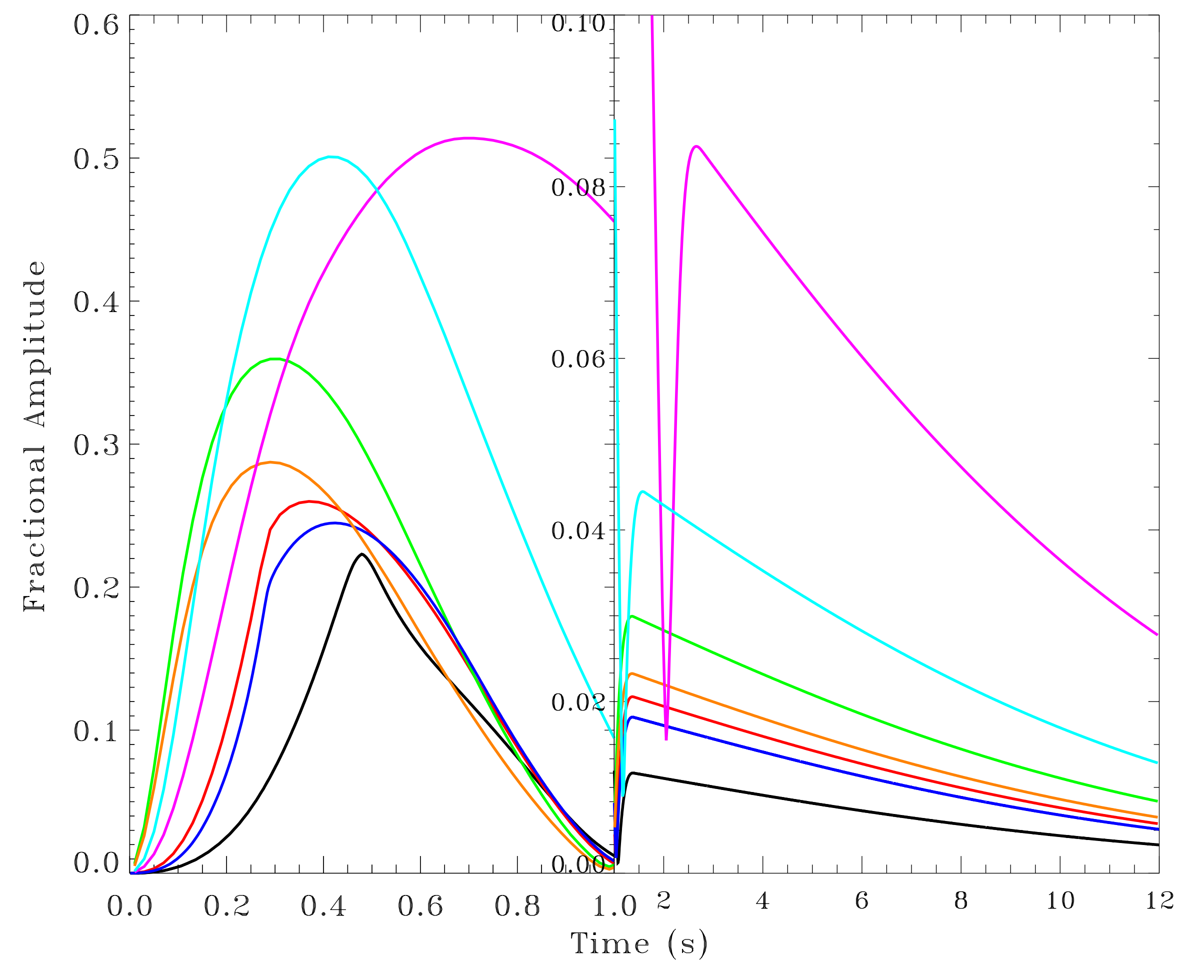


Burst Rise and Decay (Canonical cooling model)



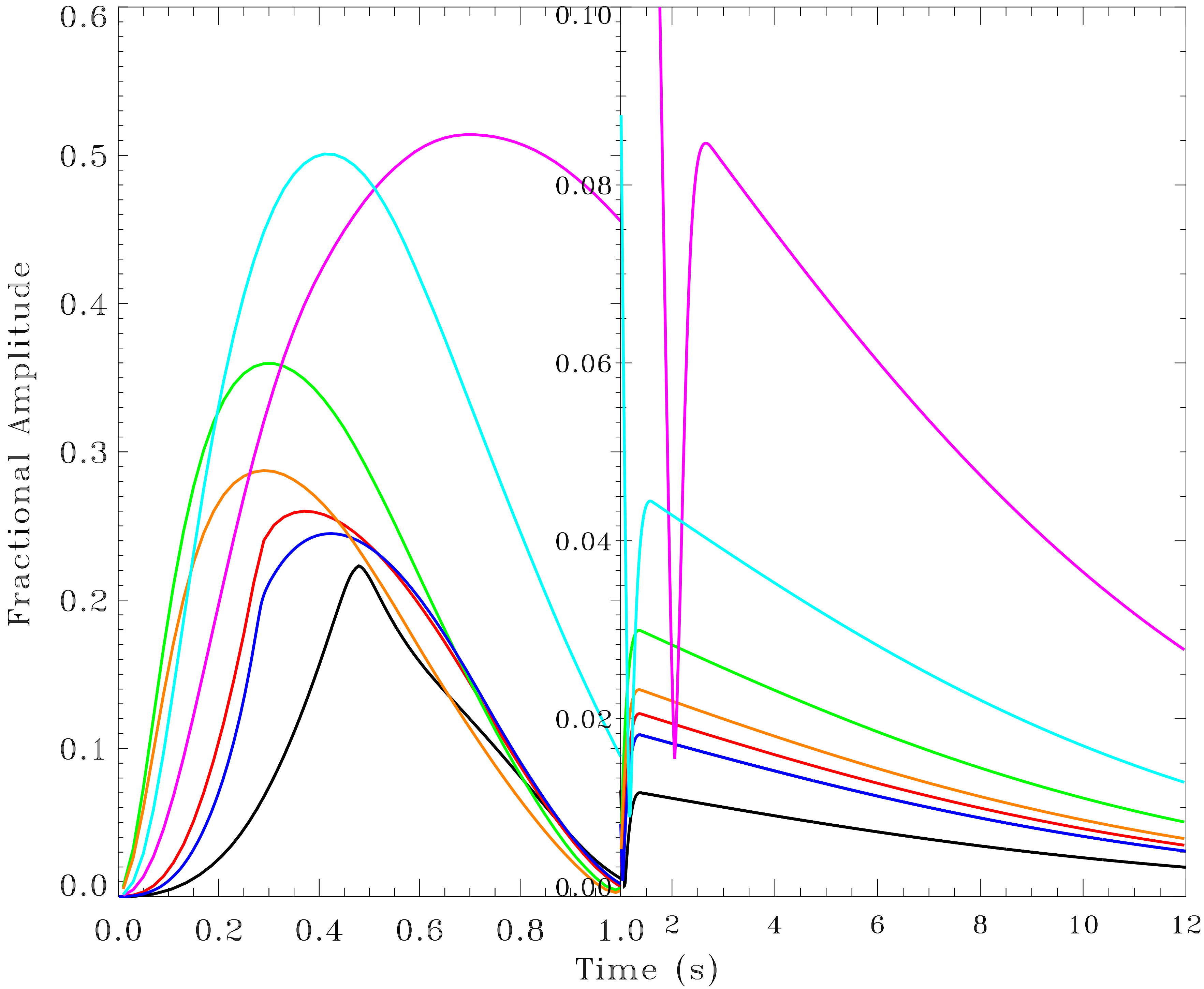
Fractional Oscillation Amplitude ("Symmetric" cooling model)



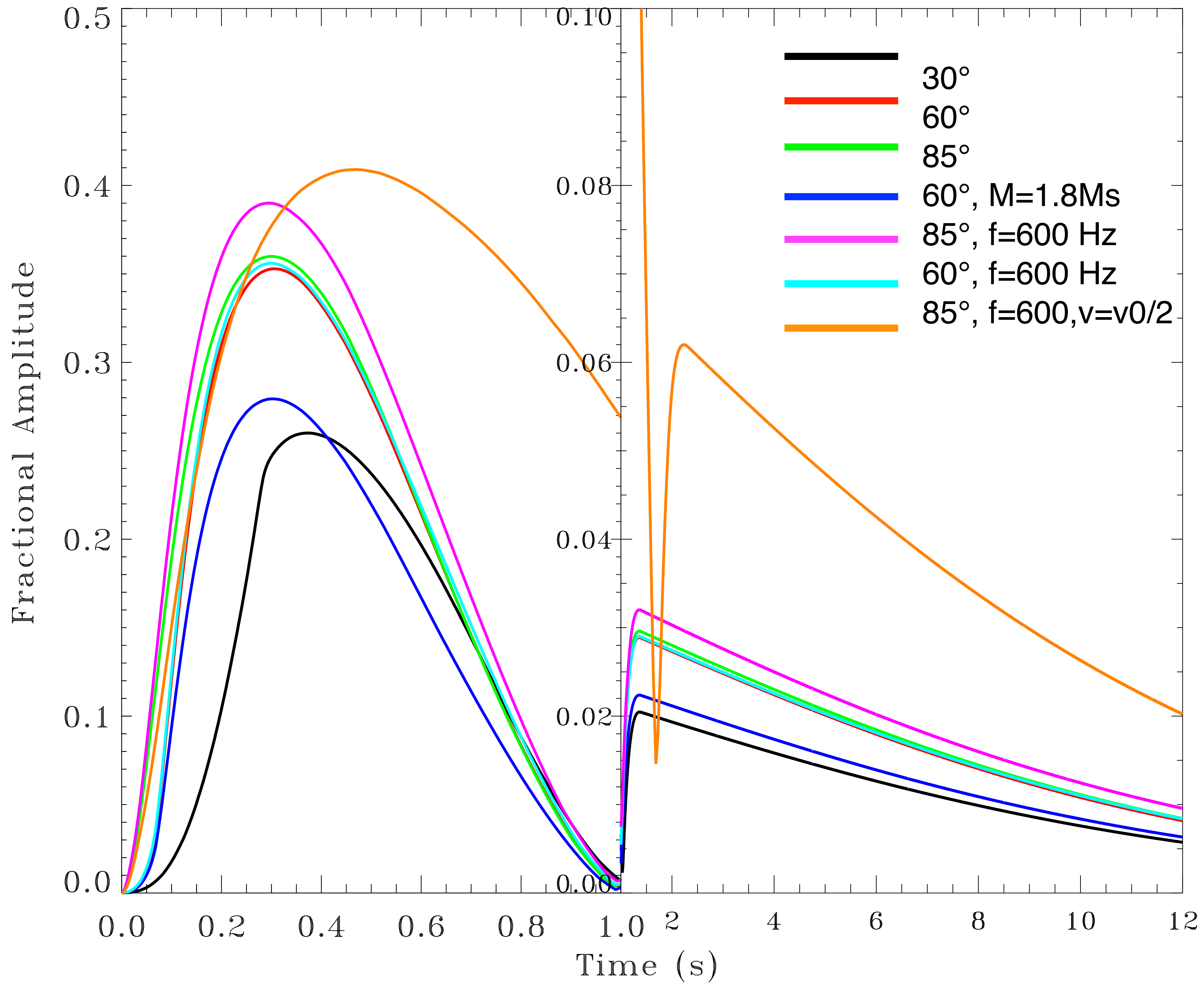


Light curve varies as $A+B\sin(2\pi\nu t)$, the fractional amplitude is defined as B/A.

Fractional Oscillation Amplitude ("Symmetric" cooling model)



“Canonical” cooling model with latitude-dependent cooling timescales.



Histograms of the largest fractional rms amplitudes of detected burst oscillations

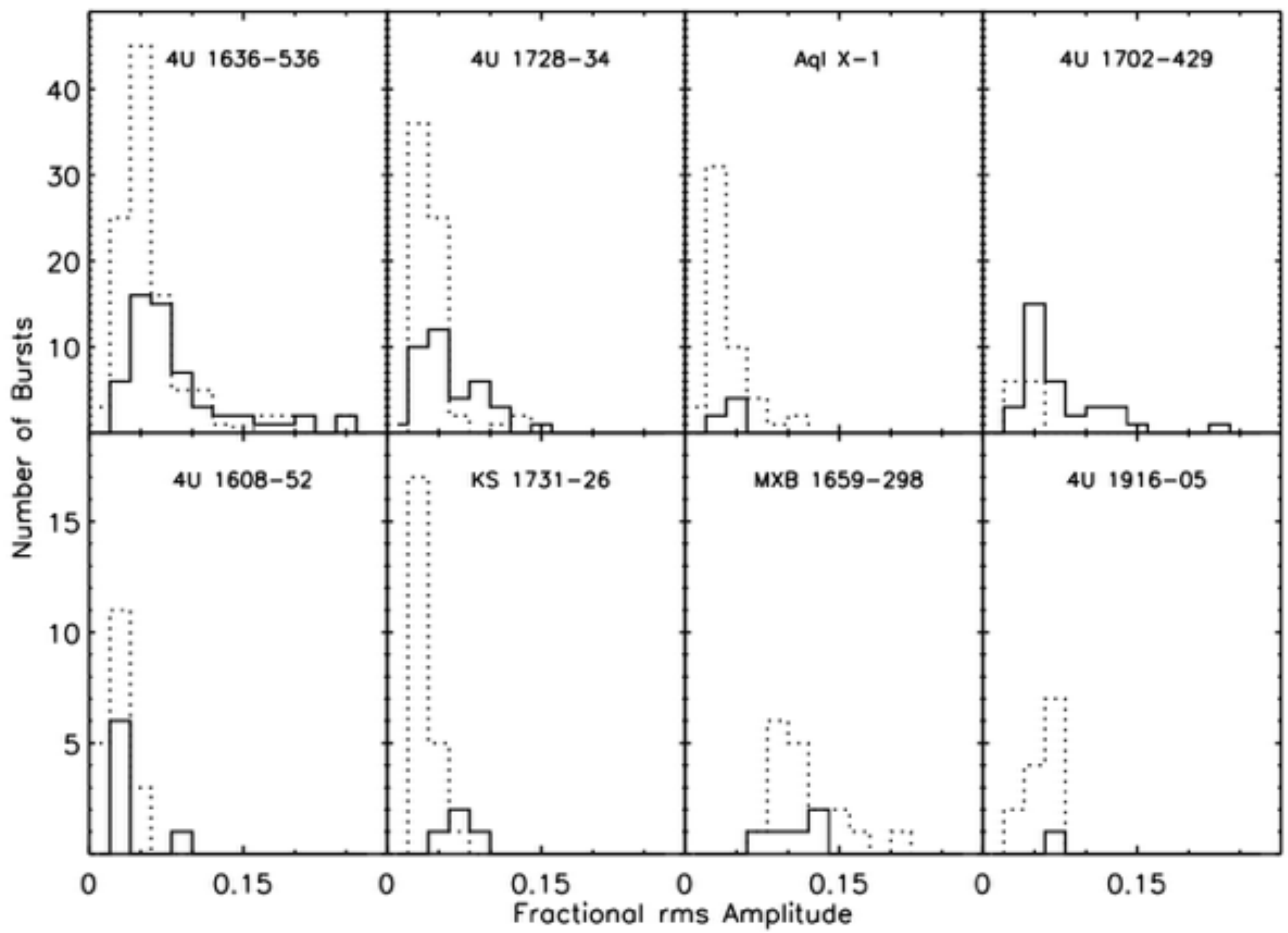
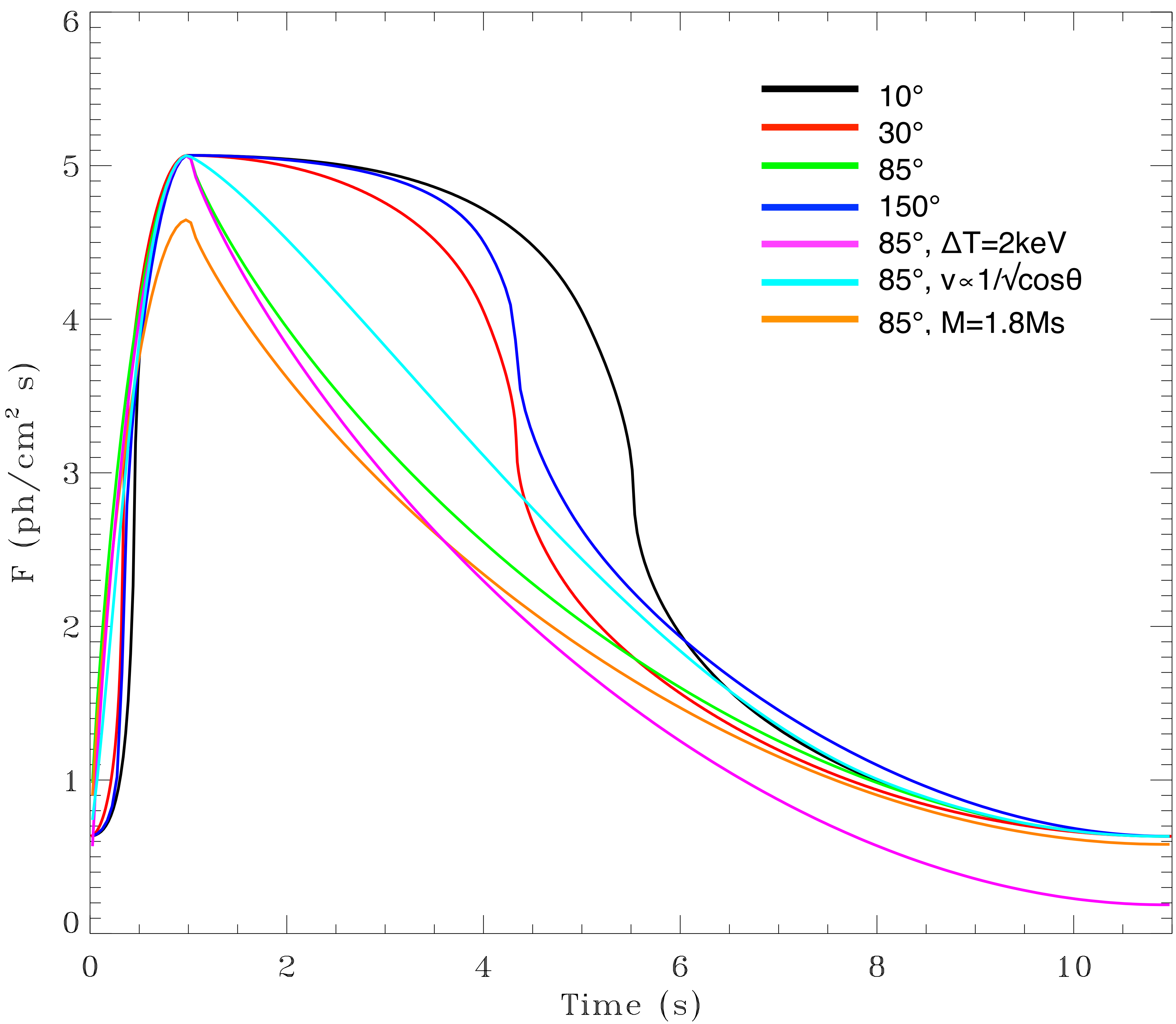


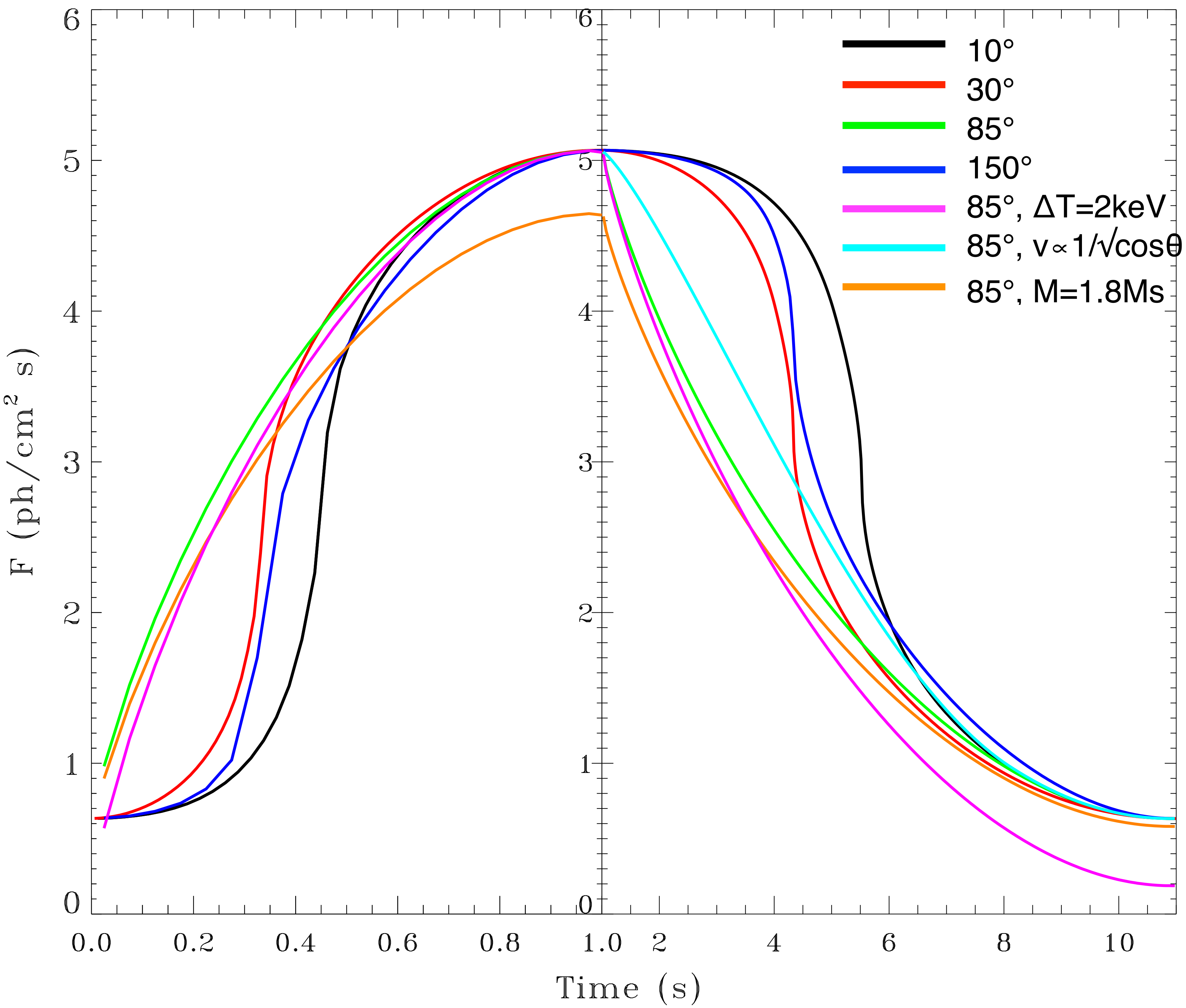
Fig. 18.—Histograms of the largest fractional rms amplitudes of detected oscillations (*solid lines*), and of the upper limits on the rms amplitude in the burst decay when oscillations are not detected (*dotted line*).

Galloway et al. 2008, ApJ 179, 360

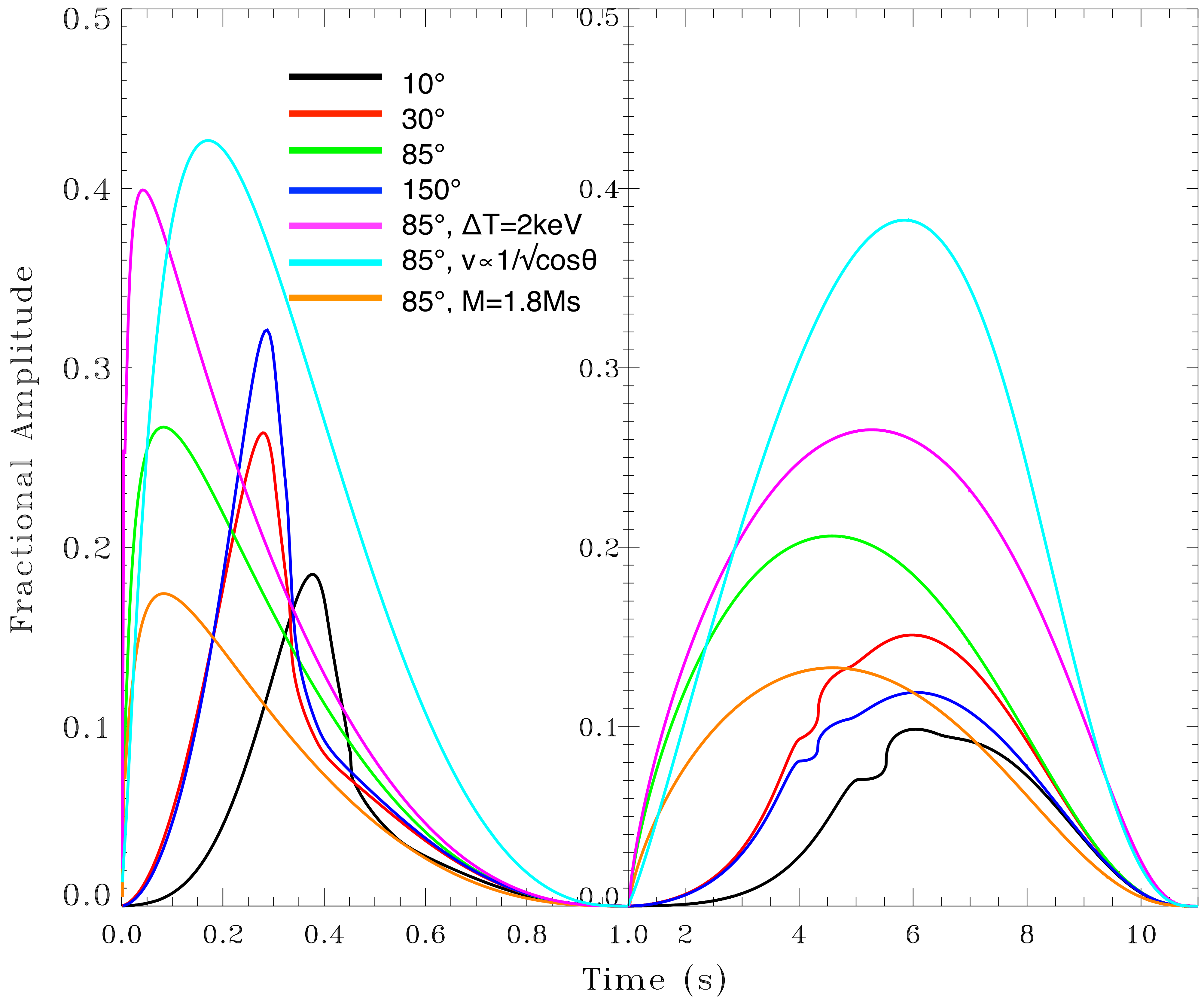
Bolometric light curves for the asymmetric cooling model



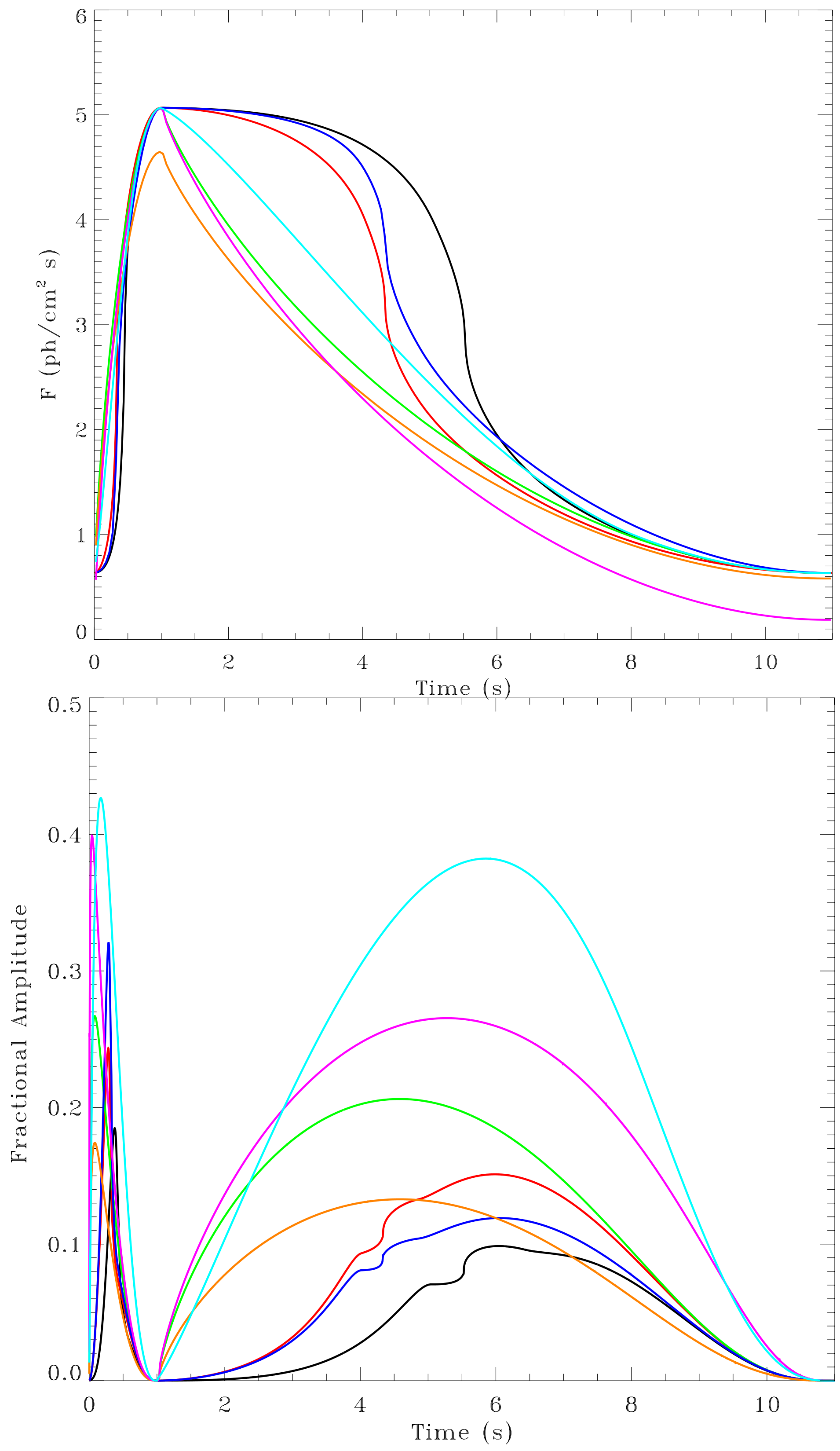
Bolometric light curves for the asymmetric cooling model

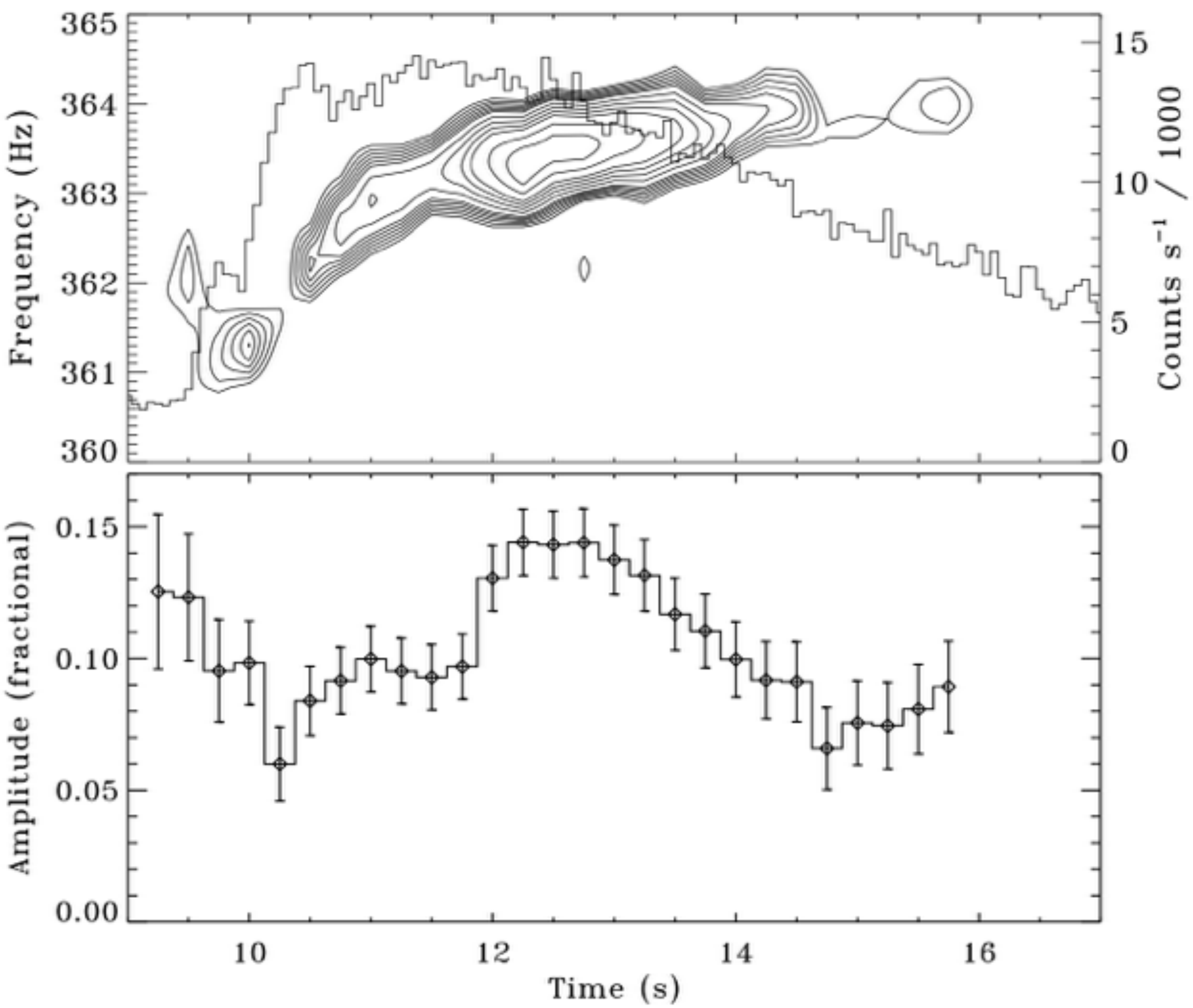


Fractional Oscillation Amplitude (Asymmetric cooling model)



Asymmetric cooling model and burst from 4U 1728-34



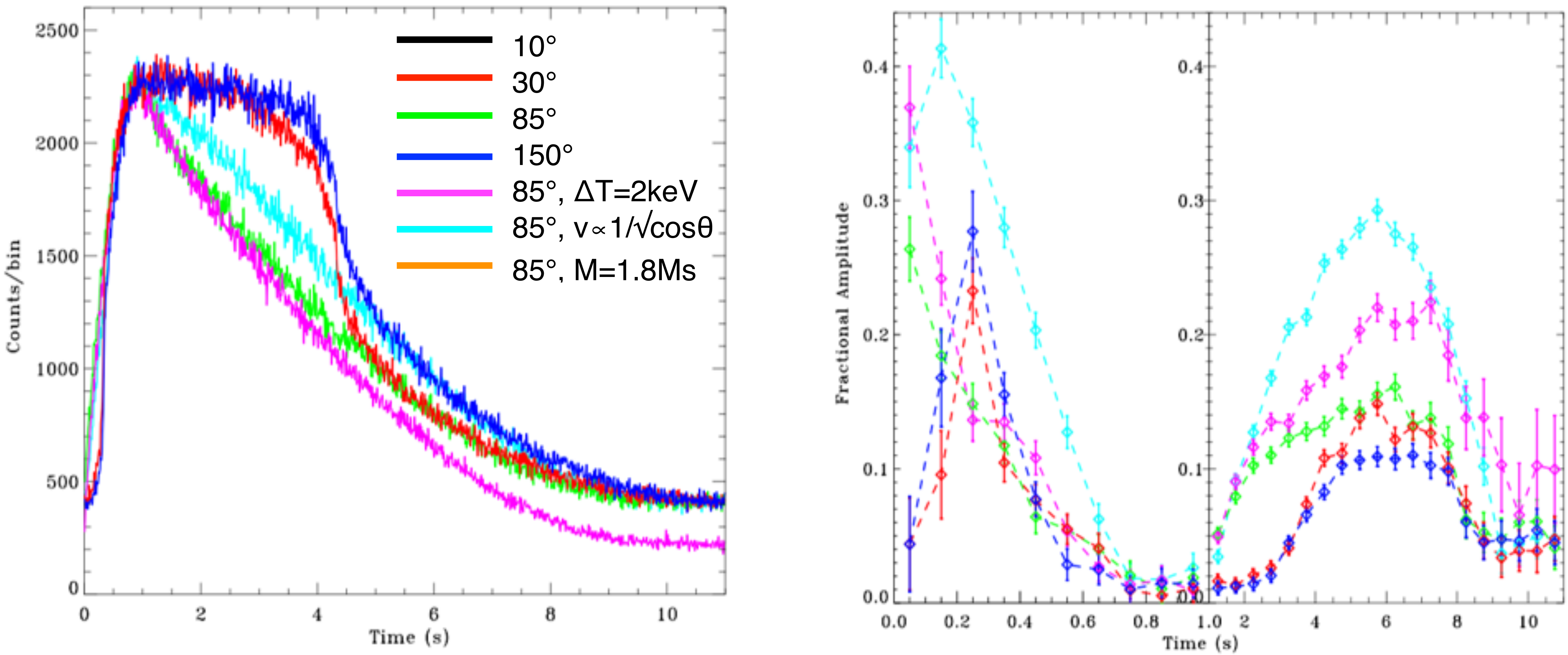


Dynamic power spectrum overplotted on the PCA light curve (top) for the 1997 Sept. 20 burst from 4U 1728- 34, and the fractional amplitude (half-amplitude) of oscillations during the burst (bottom).

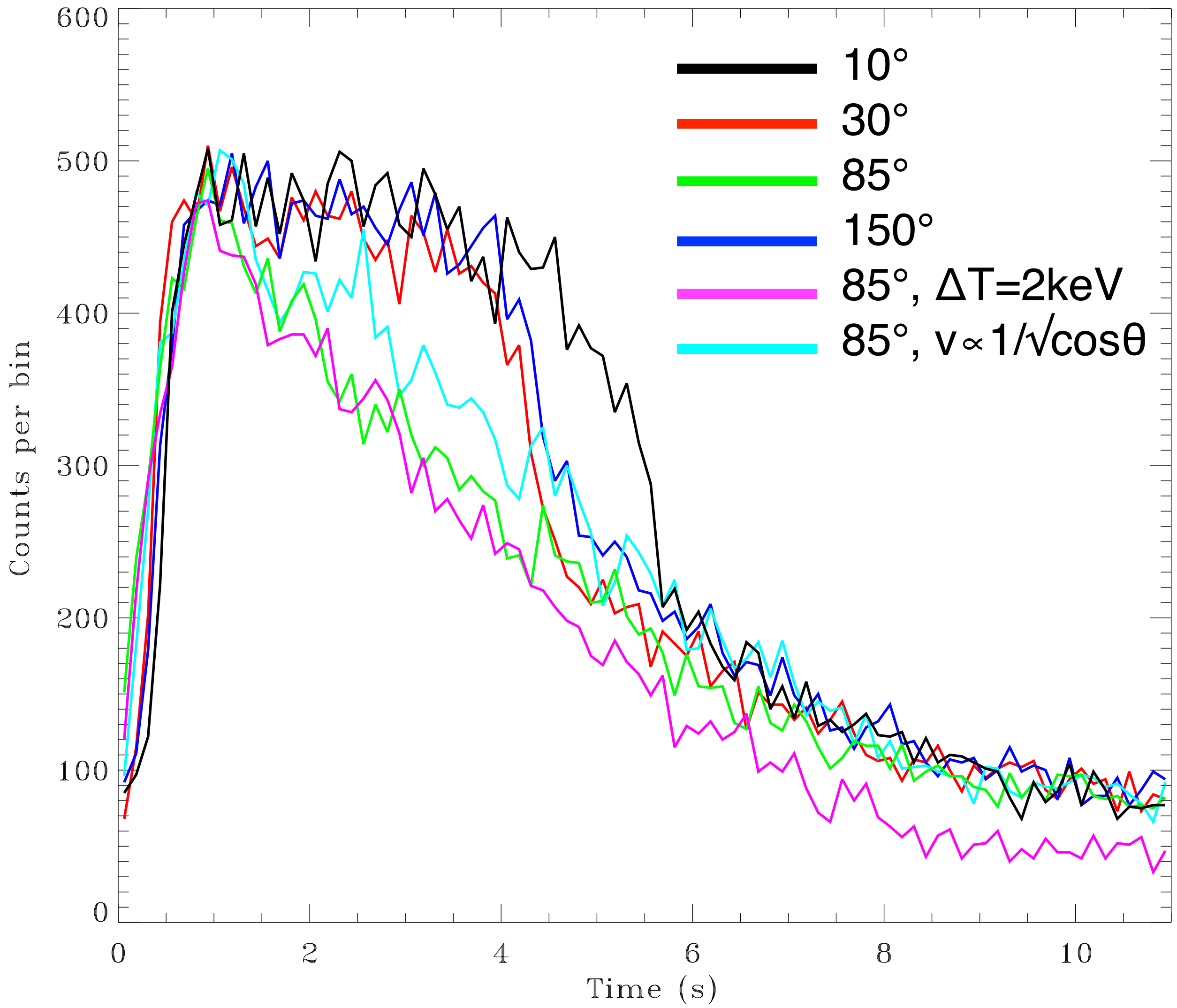
Summary of Cooling Models

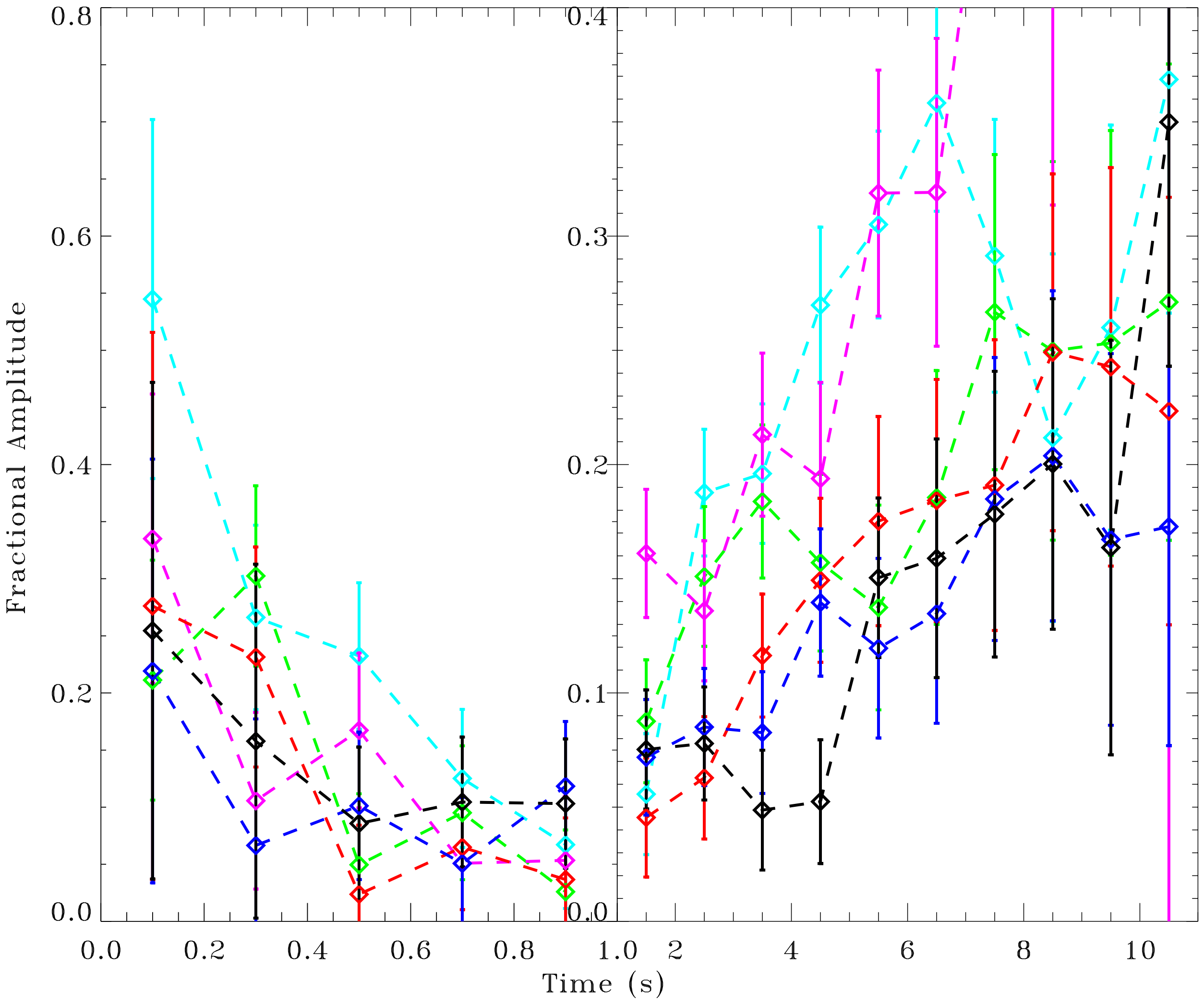
The "canonical" cooling models can generate oscillations in the tails of bursts, but they cannot easily produce the highest observed modulation amplitudes. On the other hand, a relatively simple phenomenological model with asymmetric cooling, where the speed of the cooling wake is different in different regions on the star, and is not symmetric about the rotation axis, can achieve higher amplitudes consistent with the highest observed.

Simulated eXTP measurements of X-ray burst oscillations for a bright burster similar to 4U 1636-536



Simulated NICER measurements of X-ray burst oscillations for a bright burster similar to 4U 1636-536

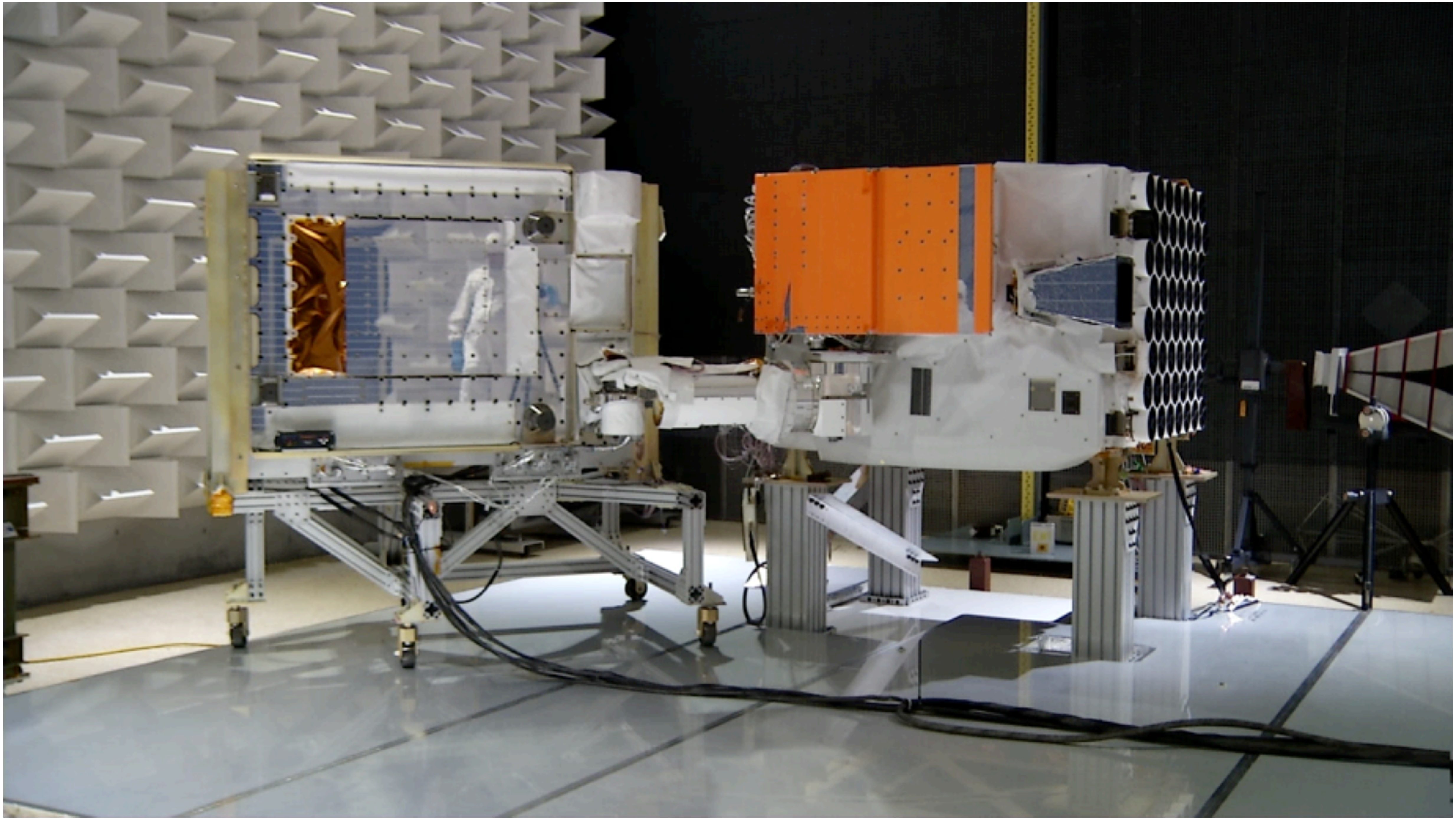




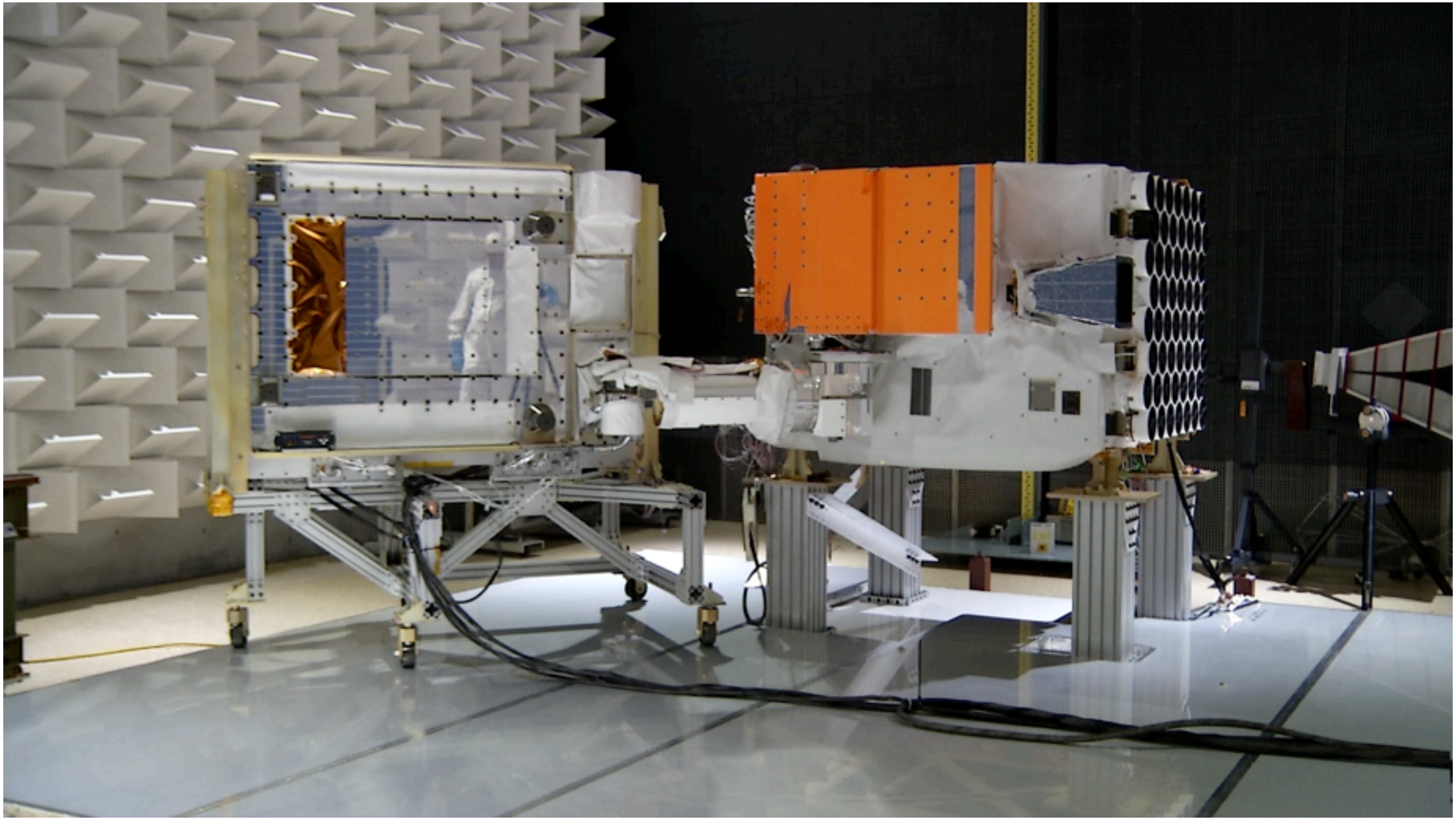
Conclusion

- Burst oscillations can be used as probes of NS properties.
  - M & R (Pulse profile modeling)
  - NS spin frequency
  - Ignition latitude and flame spreading geometry
- Theoretical explanation of why and how burst oscillations develop is still an open question.
- The "canonical" cooling models cannot easily produce the highest observed modulation amplitudes.
- A simple phenomenological model with asymmetric cooling can achieve higher amplitudes consistent with the highest observed.
- Future capabilities: NICER, Astrosat eXTP, and LOFT-P(?)

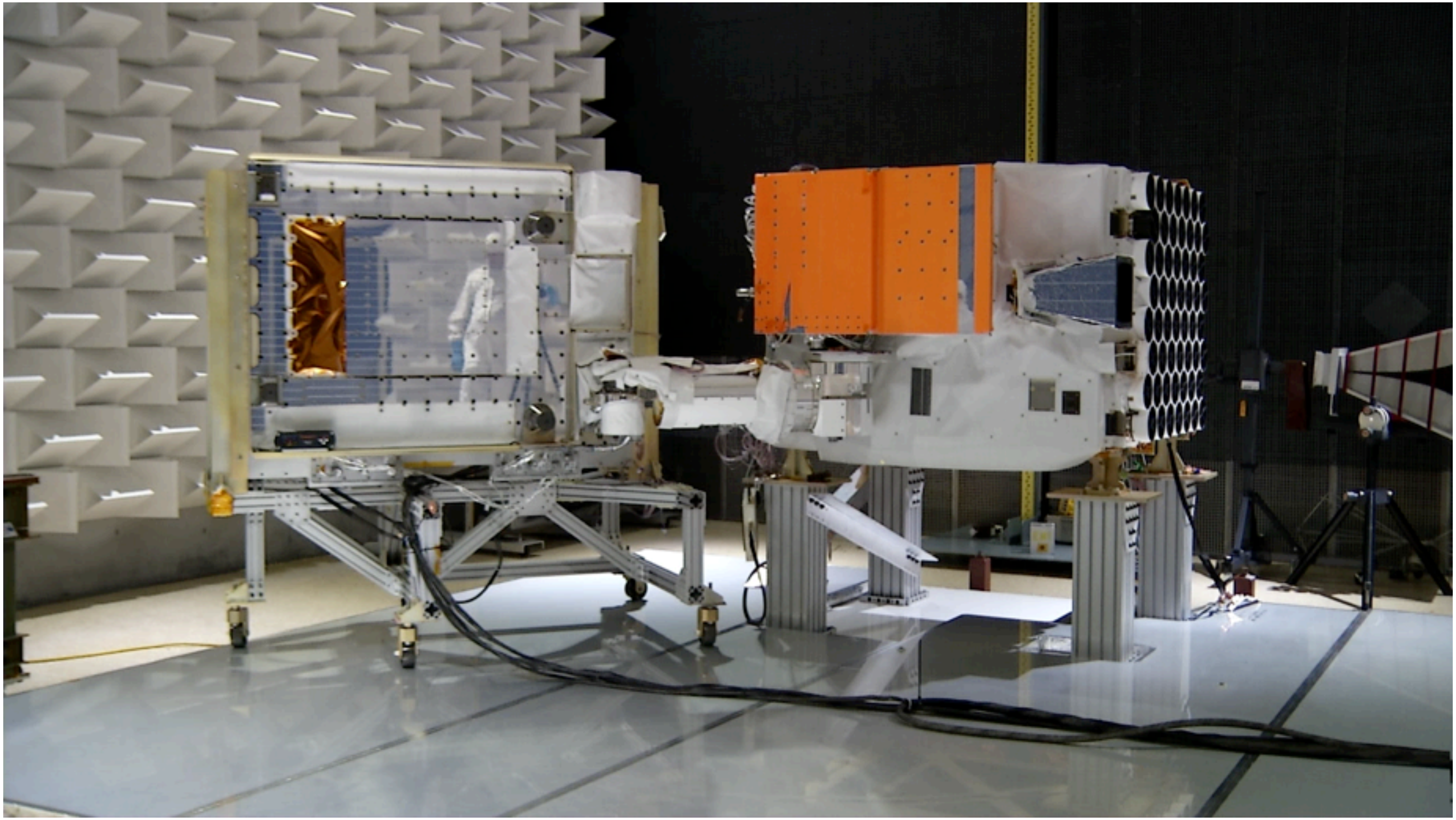
NICER stow time-lapse



NICER stow time-lapse

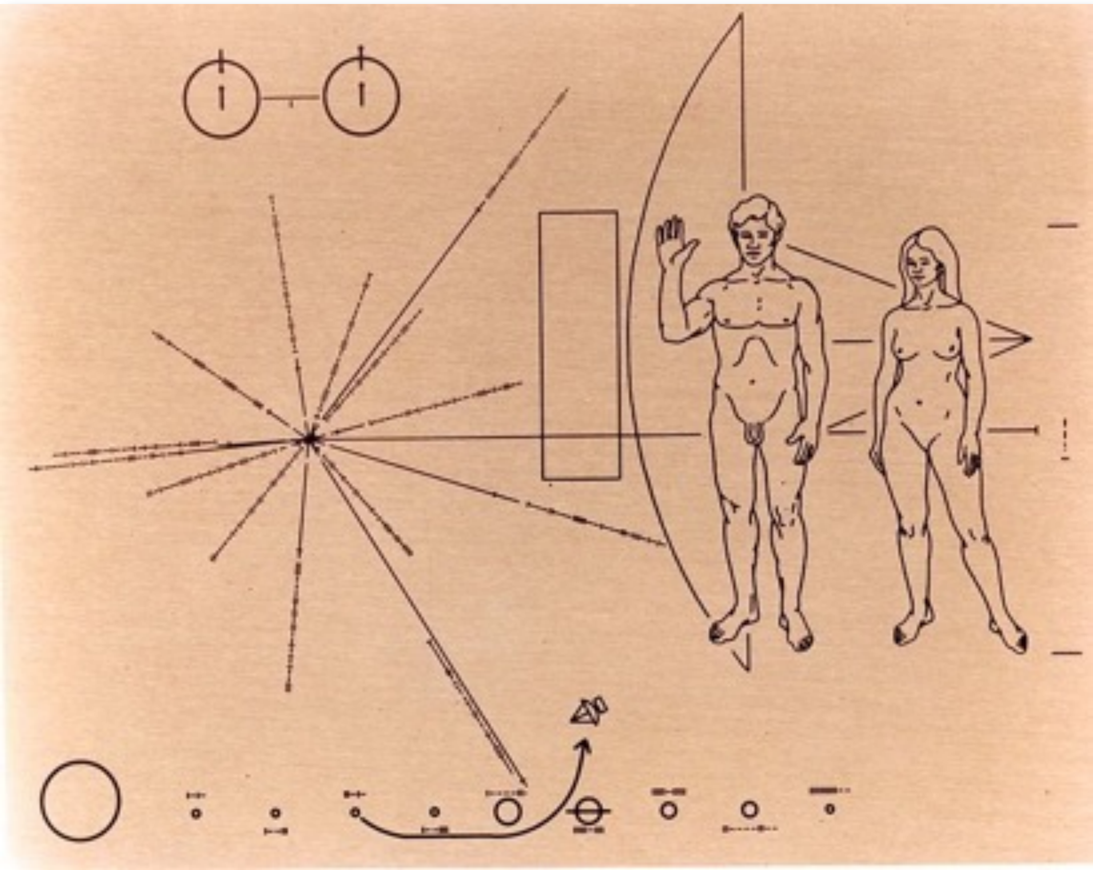


NICER stow time-lapse

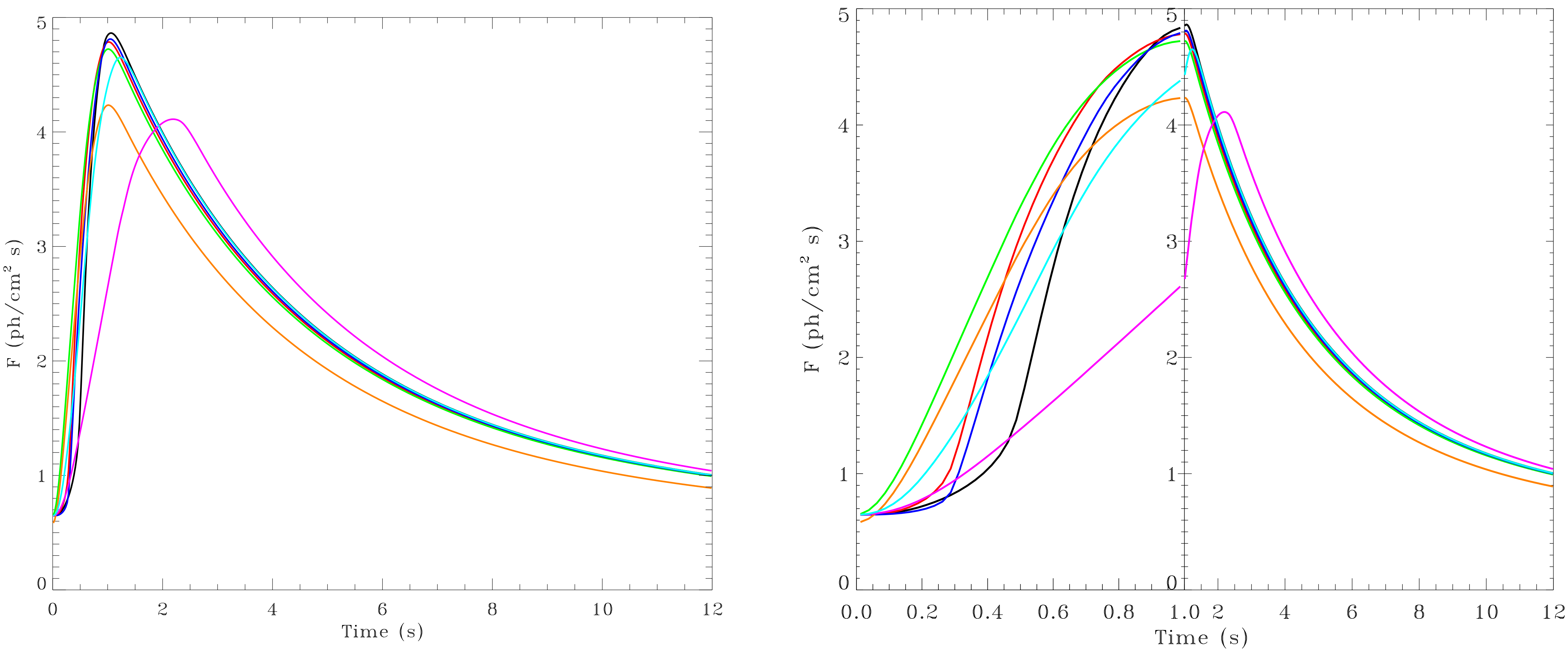


What is SEXTANT?

- Station Explorer for X-ray Timing and Navigation Technology
  – STMD/GCD funded tech enhancement: SEXTANT development and NICER cost share
  – Excellent opportunity for combined Science and Technology return
- Primary goals
  – Demo GPS-like navigation anywhere in the Solar System using X-ray observations of millisecond pulsars (MSPs)
  – Provide *first real-time, on-orbit demo* of X-ray pulsar-based navigation (XNAV)
  – Determine practical limitations of XNAV
- Additional goals include cataloging/ characterizing additional “beacon” MSPs and assessing feasibility of pulsar-based time transfer

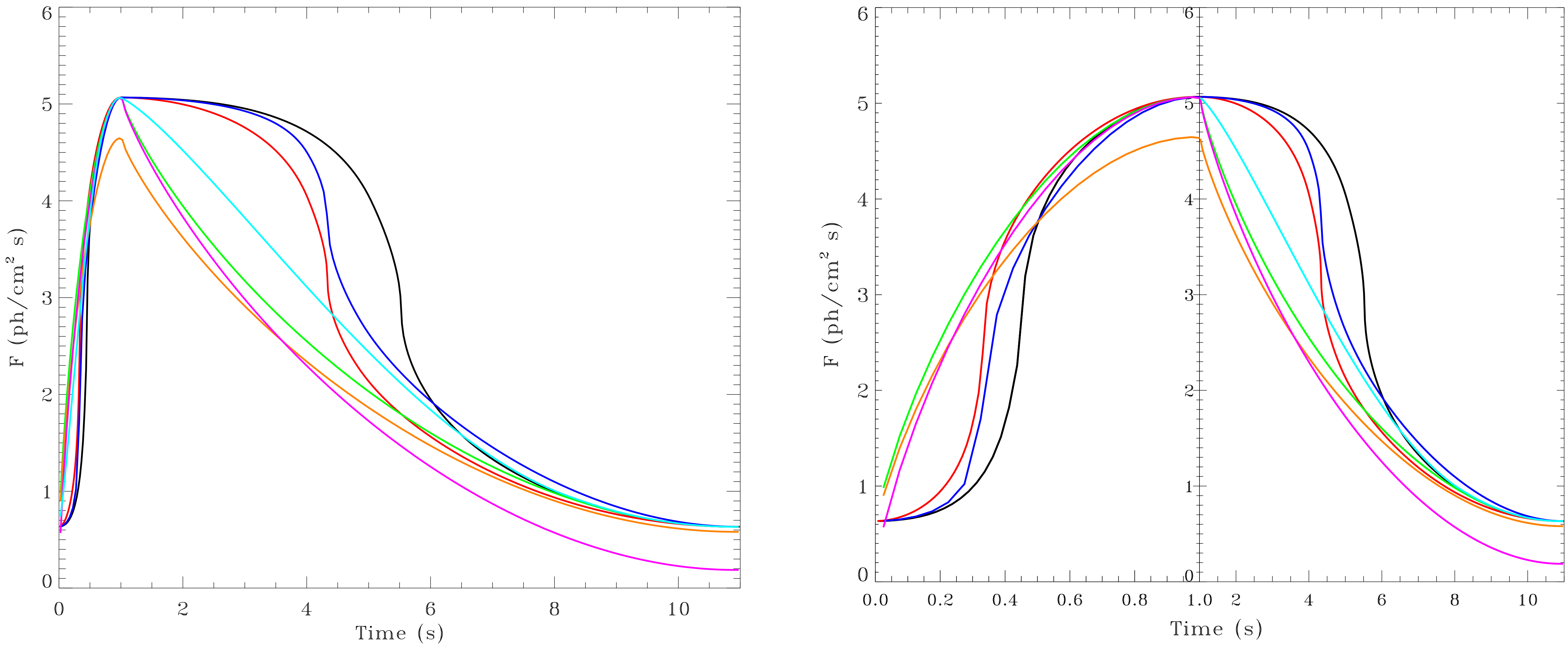


Smoothed bolometric light curves (canonical cooling model)



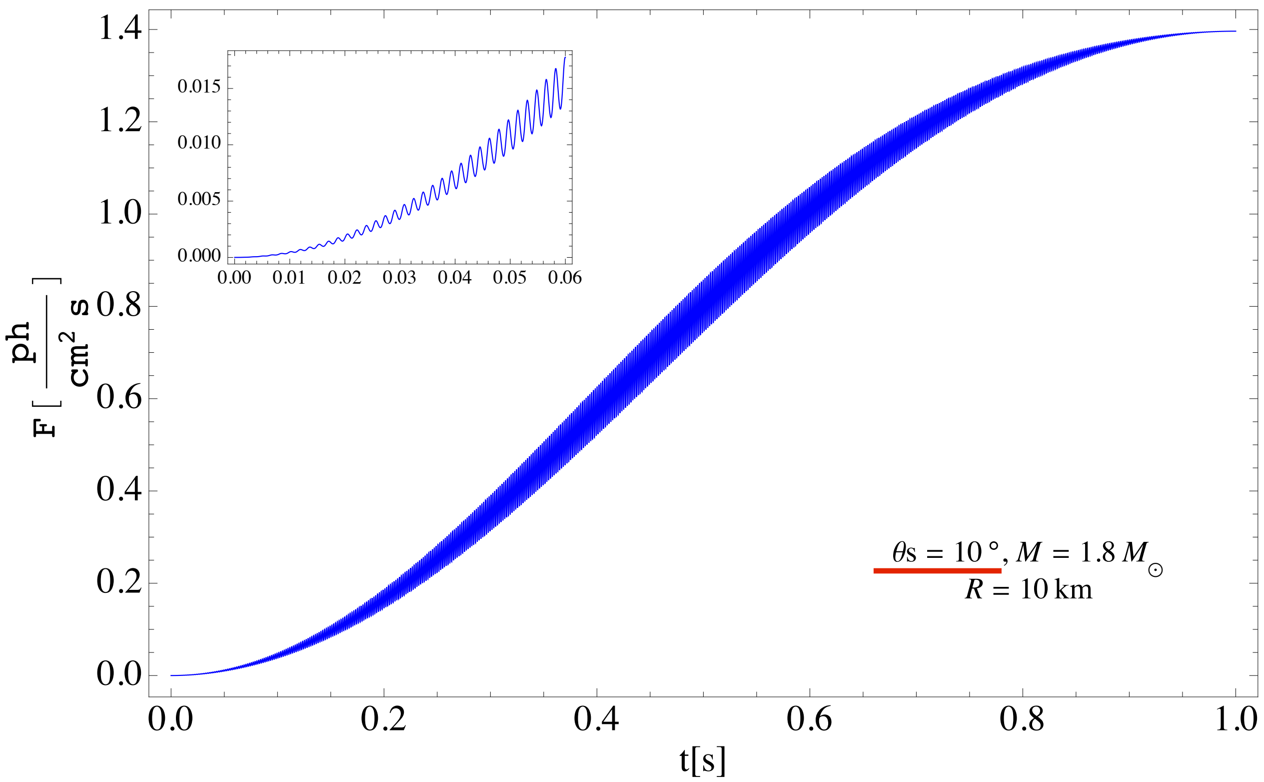
Smoothed bolometric light curves during the rise and decay of the burst (averaged over five rotation cycles). The black, red, green and blue curves correspond to models with M= 1.4M⊙, R=10 km, ν=400 Hz, D =10 kpc, observer inclination angle i = 70°, and flame spreading velocity $v_{flame} \propto 1/\cos\theta$, with ignition latitude θ_s = 10, 30, 85 and 150° respectively. The orange and cyan curves have similar parameters as the green curve (θ_s = 85°) but with M = 1.8M⊙ and $v_{flame} \propto \sqrt{(1/\cos\theta)}$ respectively. The magenta model is the same as the cyan one but with a spreading speed that is half of that model.

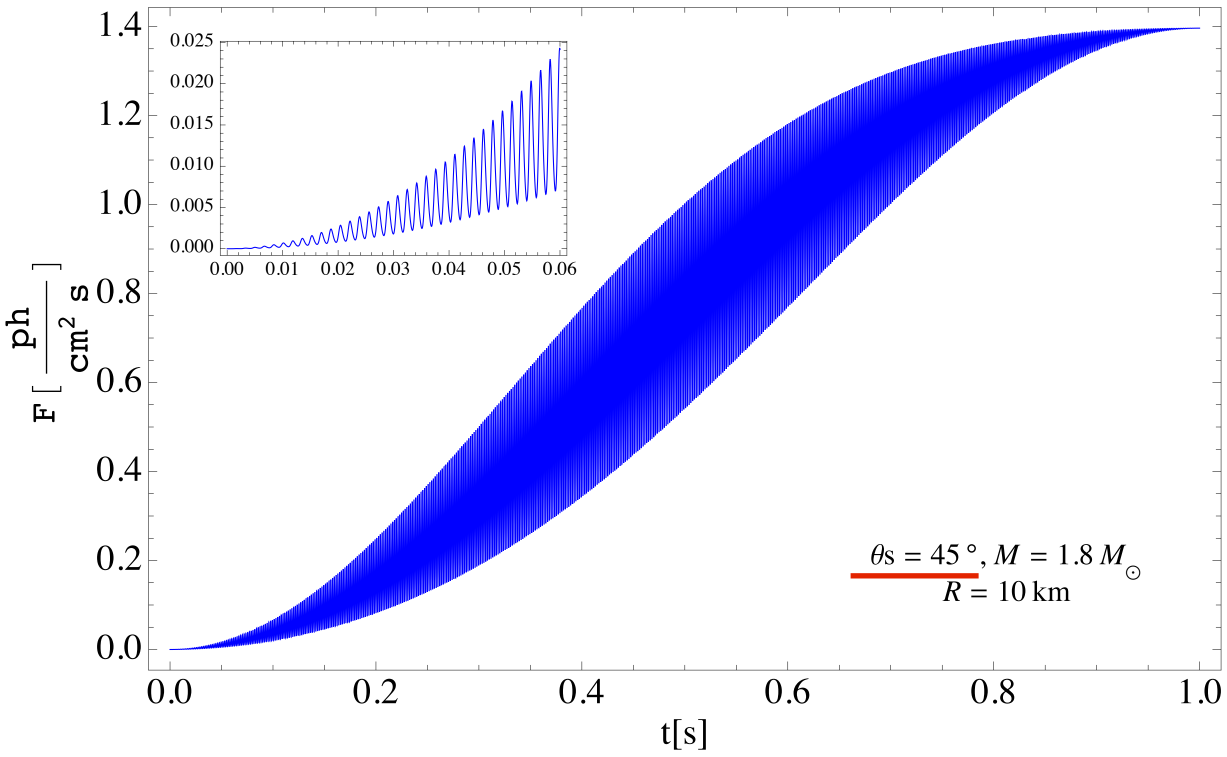
Asymmetric cooling model (spreading cooling wake)

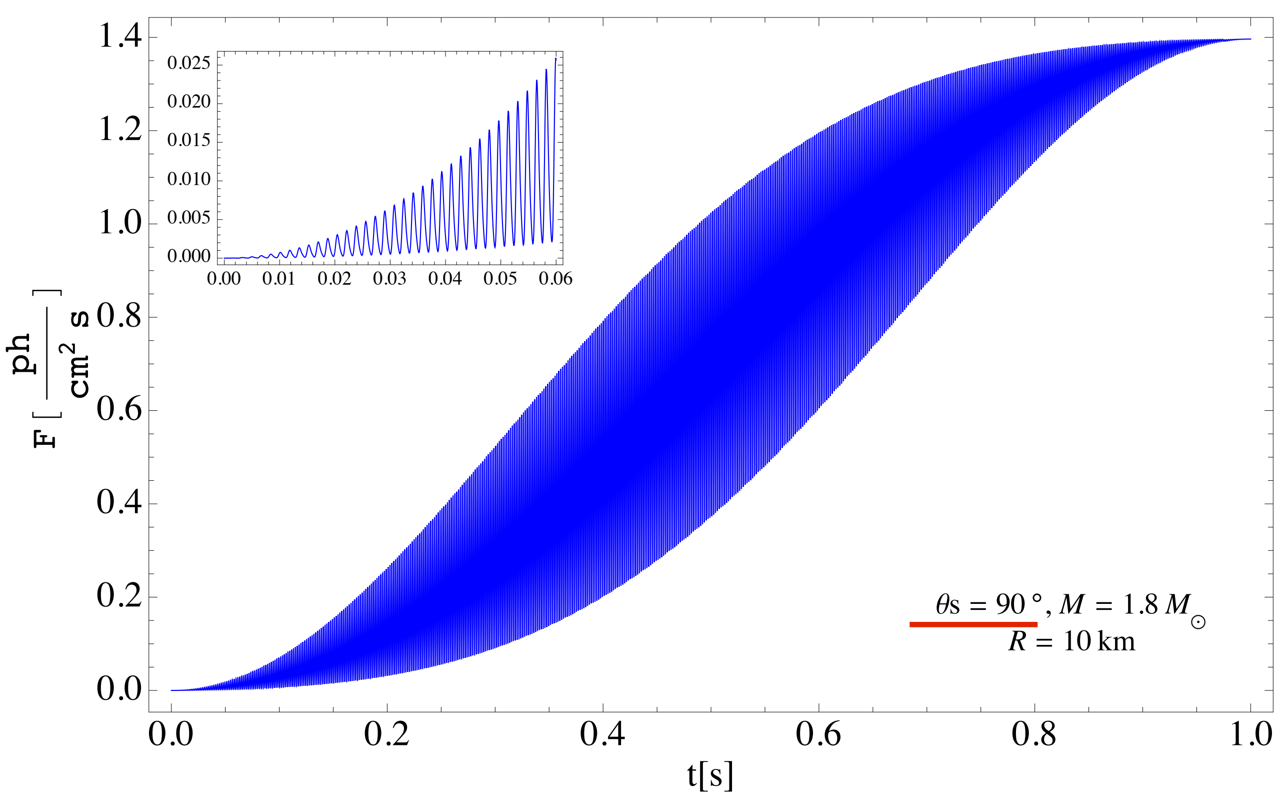


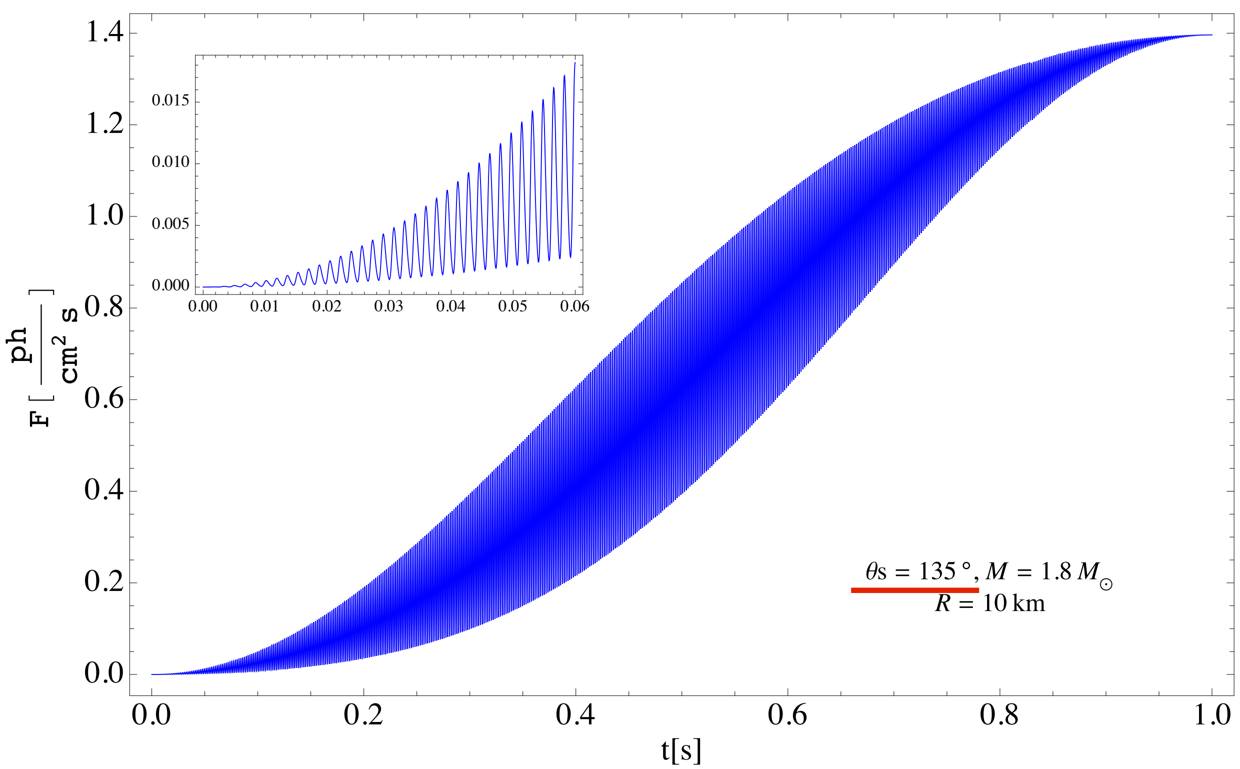
The black, red, green and blue curves correspond to models with $M = 1.4M_\odot$, R=10 km, ν=400 Hz, D=10 kpc, observer inclination angle i = 70°, hotspot temperature T_h = 3 keV, $\Delta T = T_h - T_c$ = 1.5 keV and flame spreading velocity $v_{flame} \propto 1/\cos\theta$ with ignition latitude θs = 10, 30, 85 and 150° respectively. The orange, magenta and cyan curves are similar to the green curve (θs = 85°) but with $M = 1.8M_\odot$, ΔT=2 keV and $v_{flame} \propto \sqrt{(1/\cos\theta)}$ respectively. Right panel shows the light curves on an expanded scale up to t = 1 s (burst rise).

Different ignition latitudes





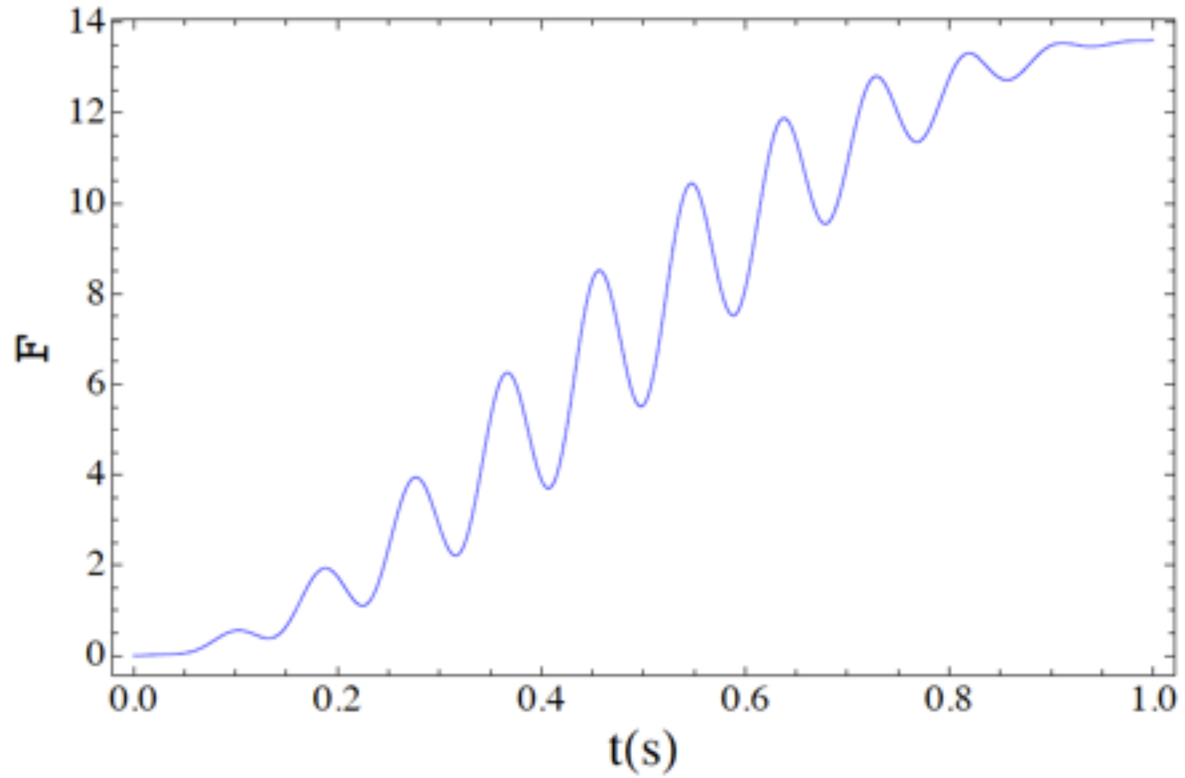


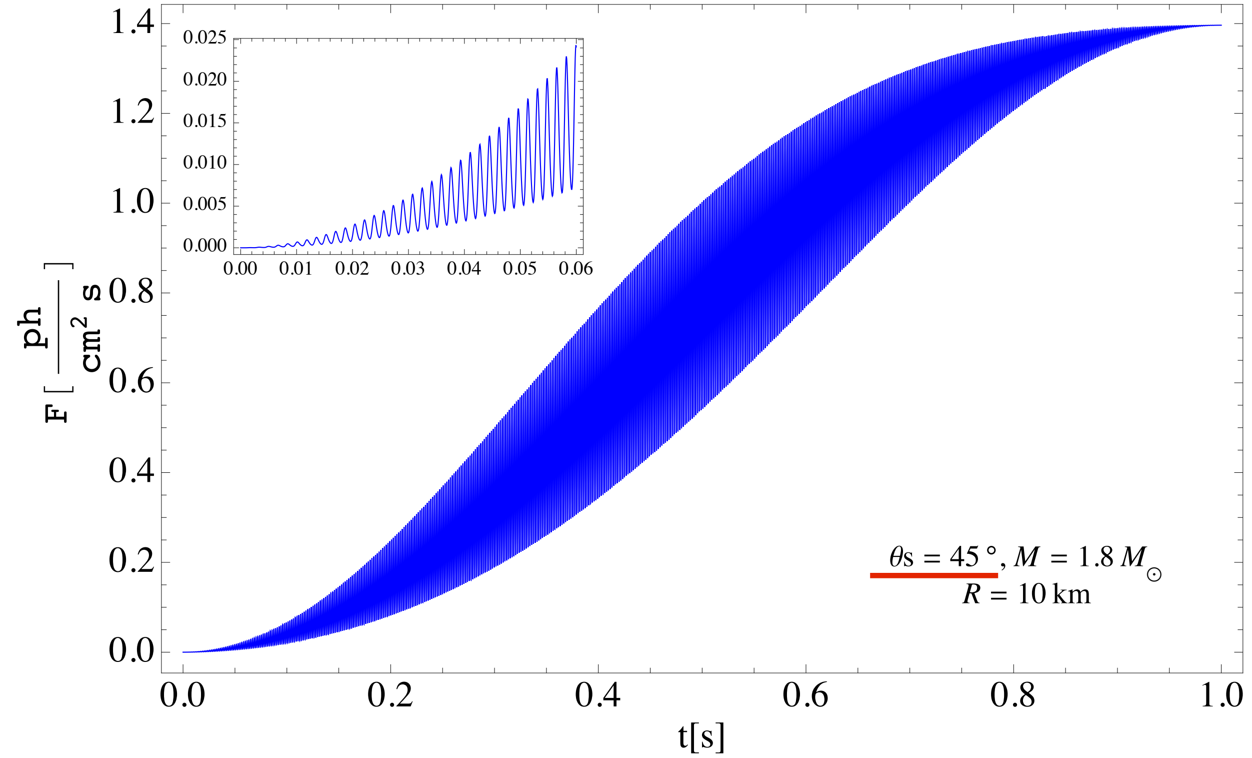


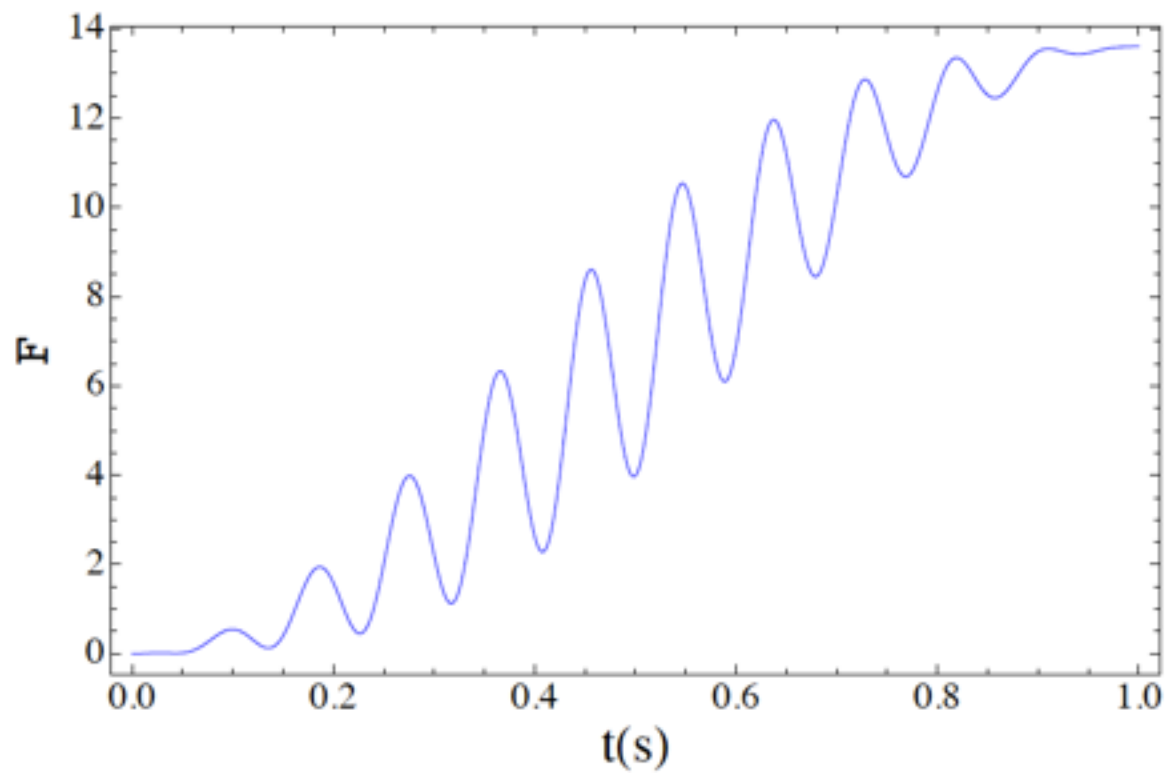
Different spin frequencies
(with $M=1.8M_{\odot}$, R=10 km, T=2 keV, i=70°)

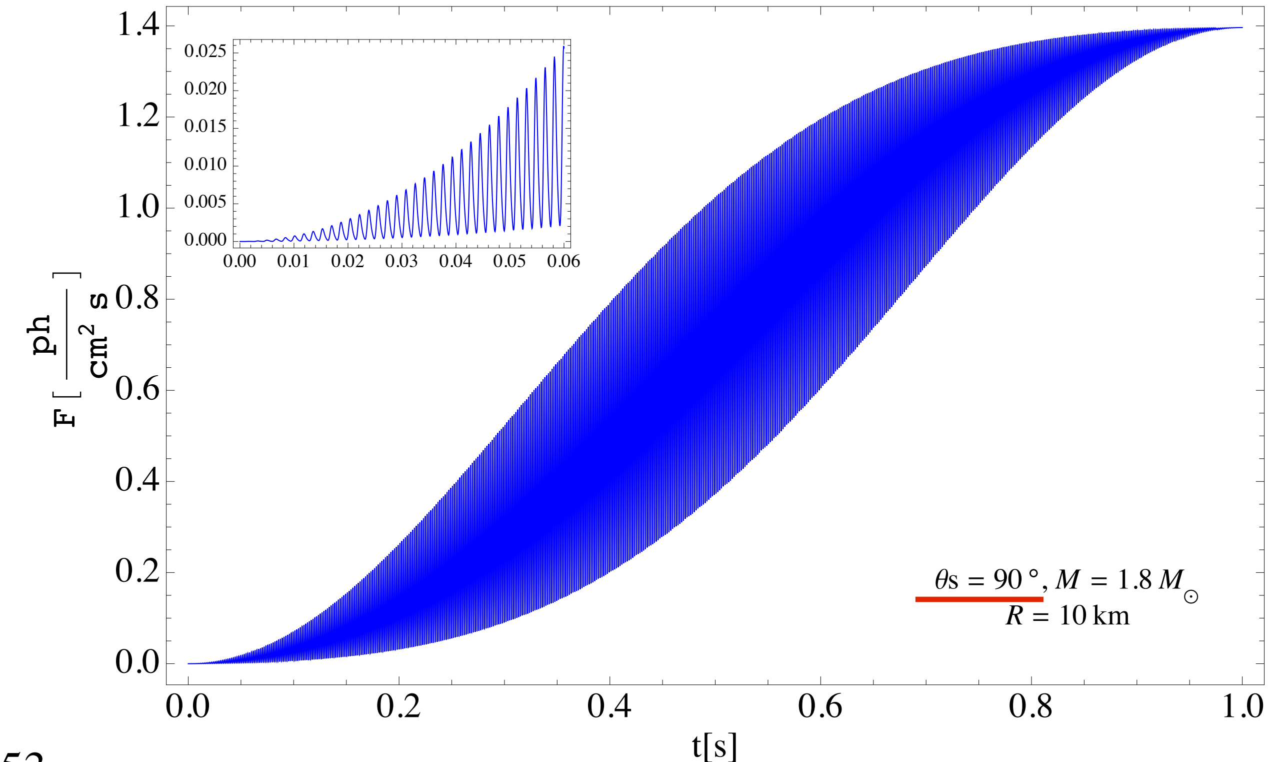
f=11 Hz

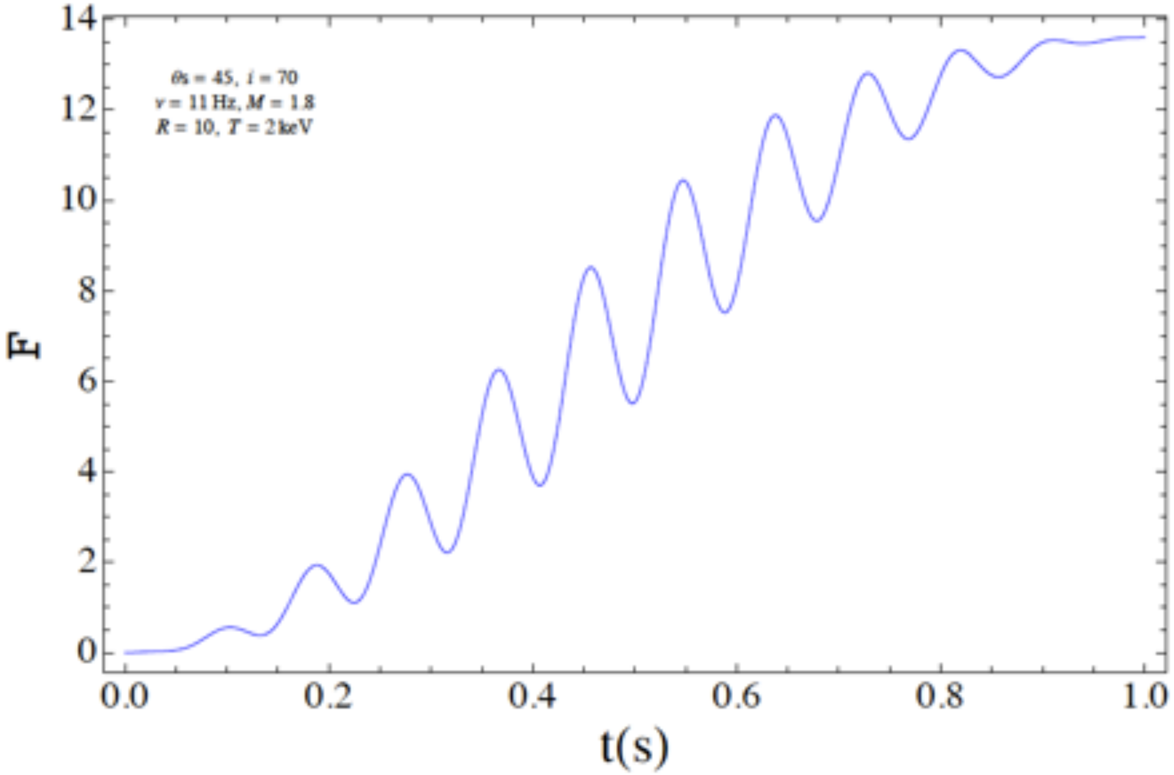
f=582 Hz

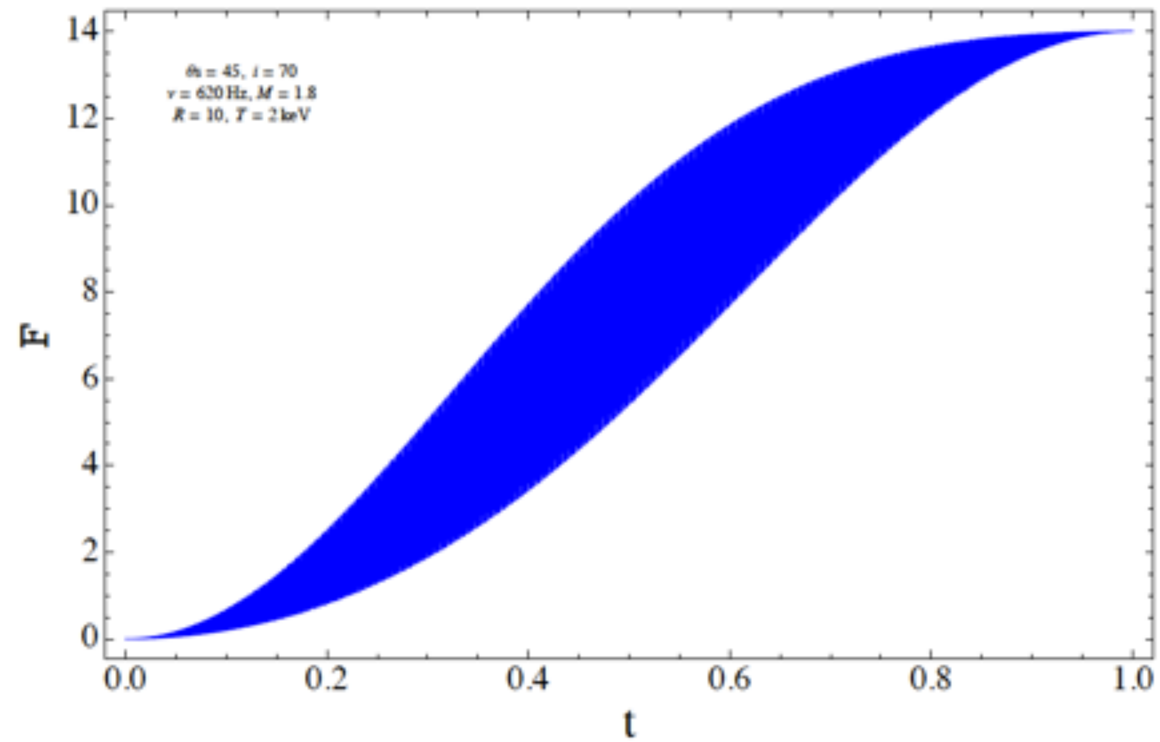


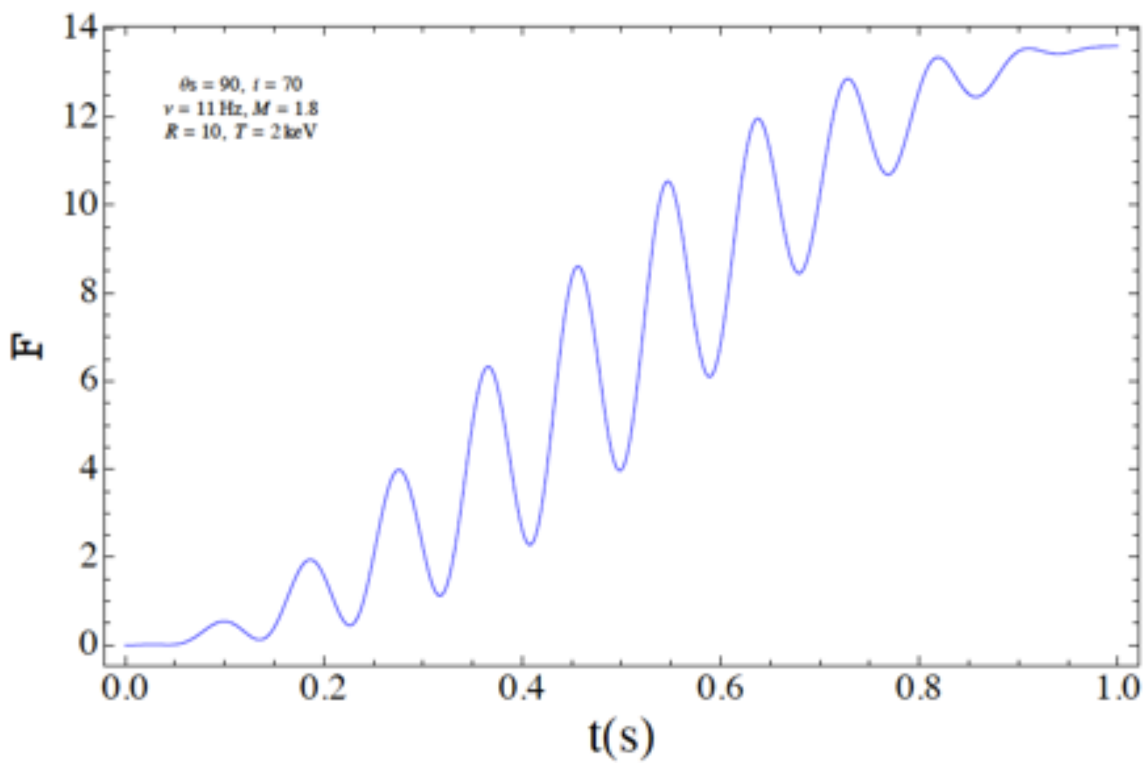


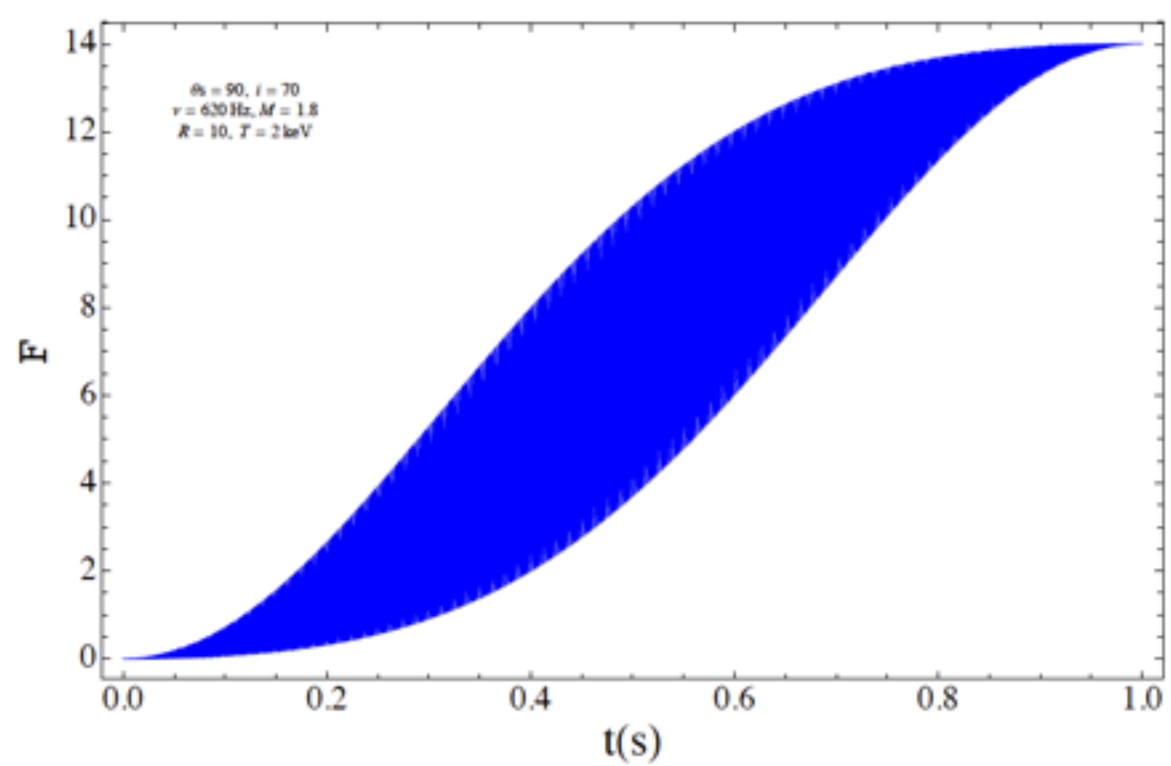




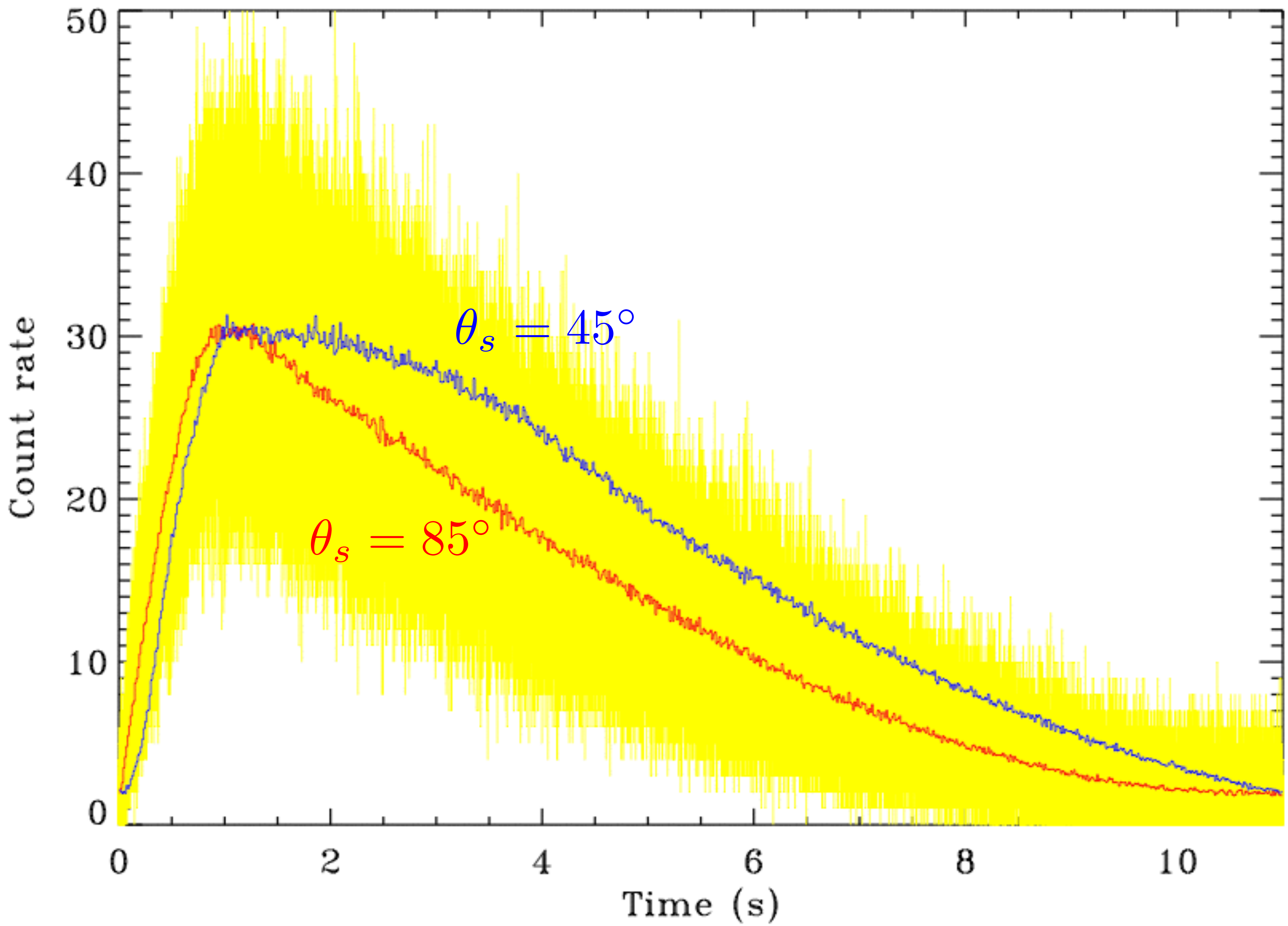

θs = 45, i = 70
ν = 11 Hz, M = 1.8
R = 10, T = 2 keV
F
t(s)


θs = 45, i = 70
ν = 620 Hz, M = 1.8
R = 10, T = 2 keV
F
t

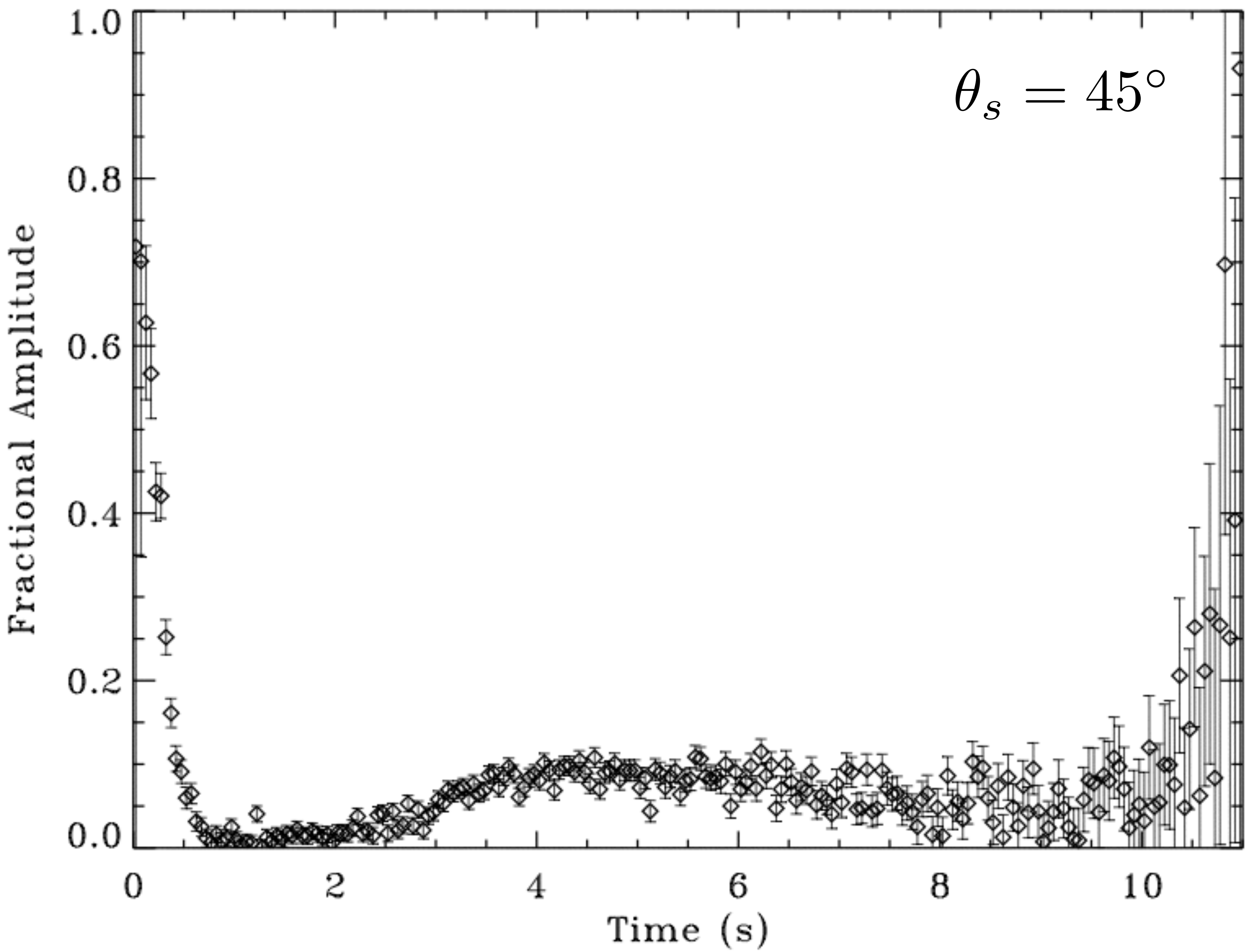

θs = 90, i = 70
ν = 11 Hz, M = 1.8
R = 10, T = 2 keV
F
t(s)


θs = 90, i = 70
ν = 620 Hz, M = 1.8
R = 10, T = 2 keV
F
t(s)

Light curves for $\theta_s = 45^\circ$ vs 85° (LOFT Simulation)



Fractional amplitude (LOFT Simulation)

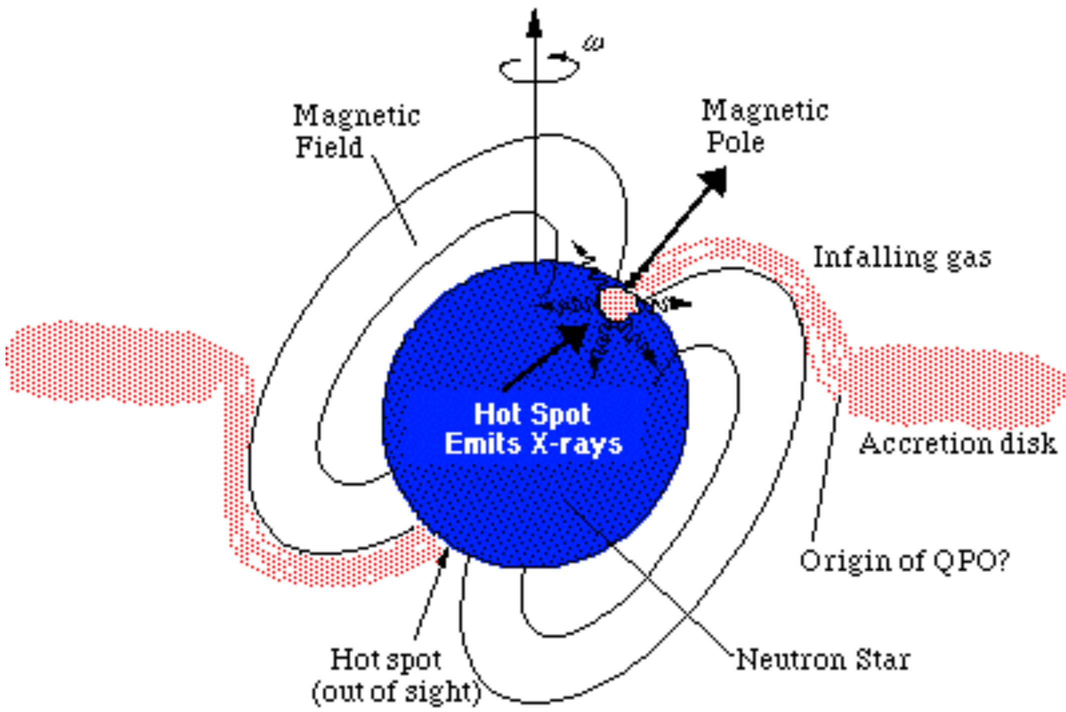


Current models for burst oscillations

- Hot-spot model

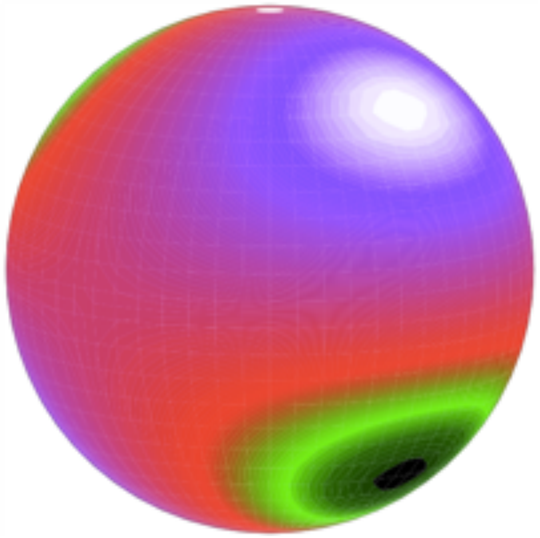
Spreading hot spot
(Strohmayer et al. 1996; Nath, strohmaye & Swank 2002; Bhattacharyya et a. 2005)

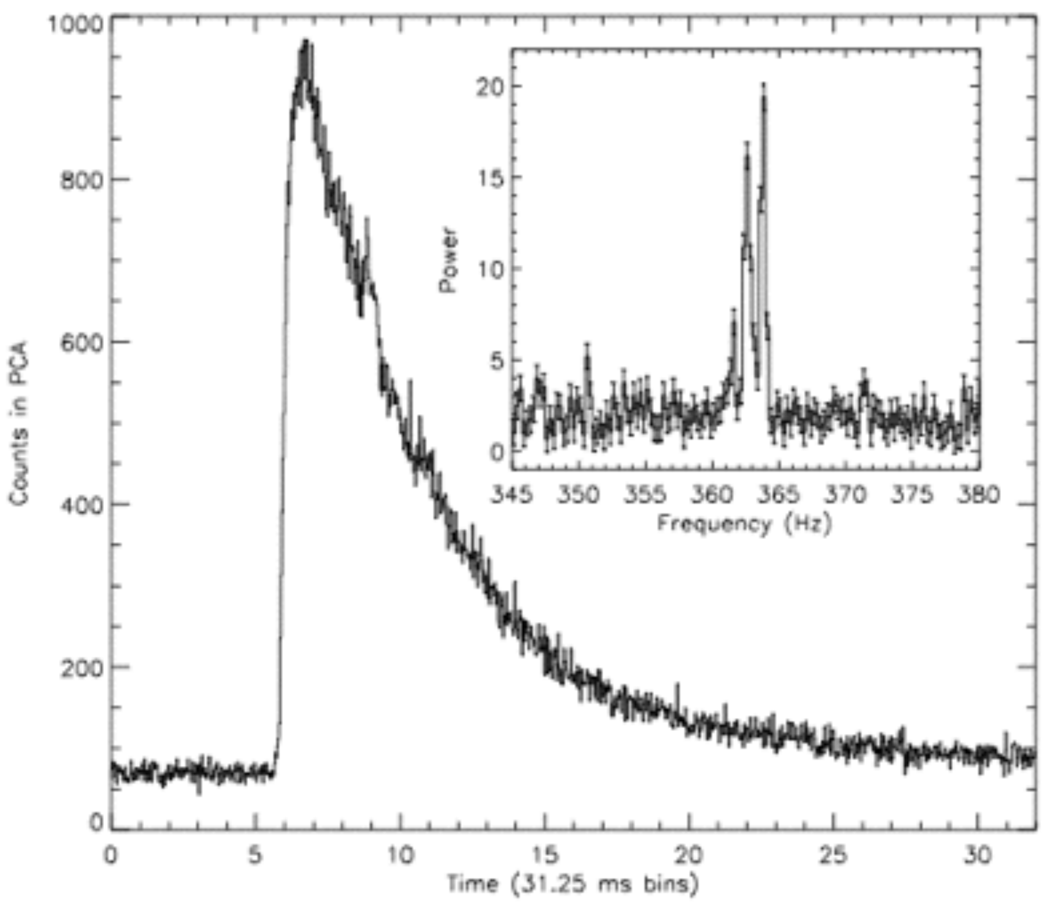
Coriolis force effects
(Spitkovsky, Levin & Ushomirsky 2002; Maurer & Watts 2008)



- Surface modes (Bildsten et al. 1996; Heyl 2004; Piro & Bildsten 2005; Lee & Strohmayer 2005)

g-modes
buoyant r-modes
Kelvin modes
l=2, m=1 buoyant r-mode (Heyl 2004)




1000
800
600
400
200
0
Counts in PCA
0
5
10
15
20
25
30
Time (31.25 ms bins)
20
15
10
5
0
Power
345
350
355
360
365
370
375
380
Frequency (Hz)