X-rays from Compact Stars: Probing Fundamental Physics

Tod Strohmayer, NASA's Goddard Space Flight Center

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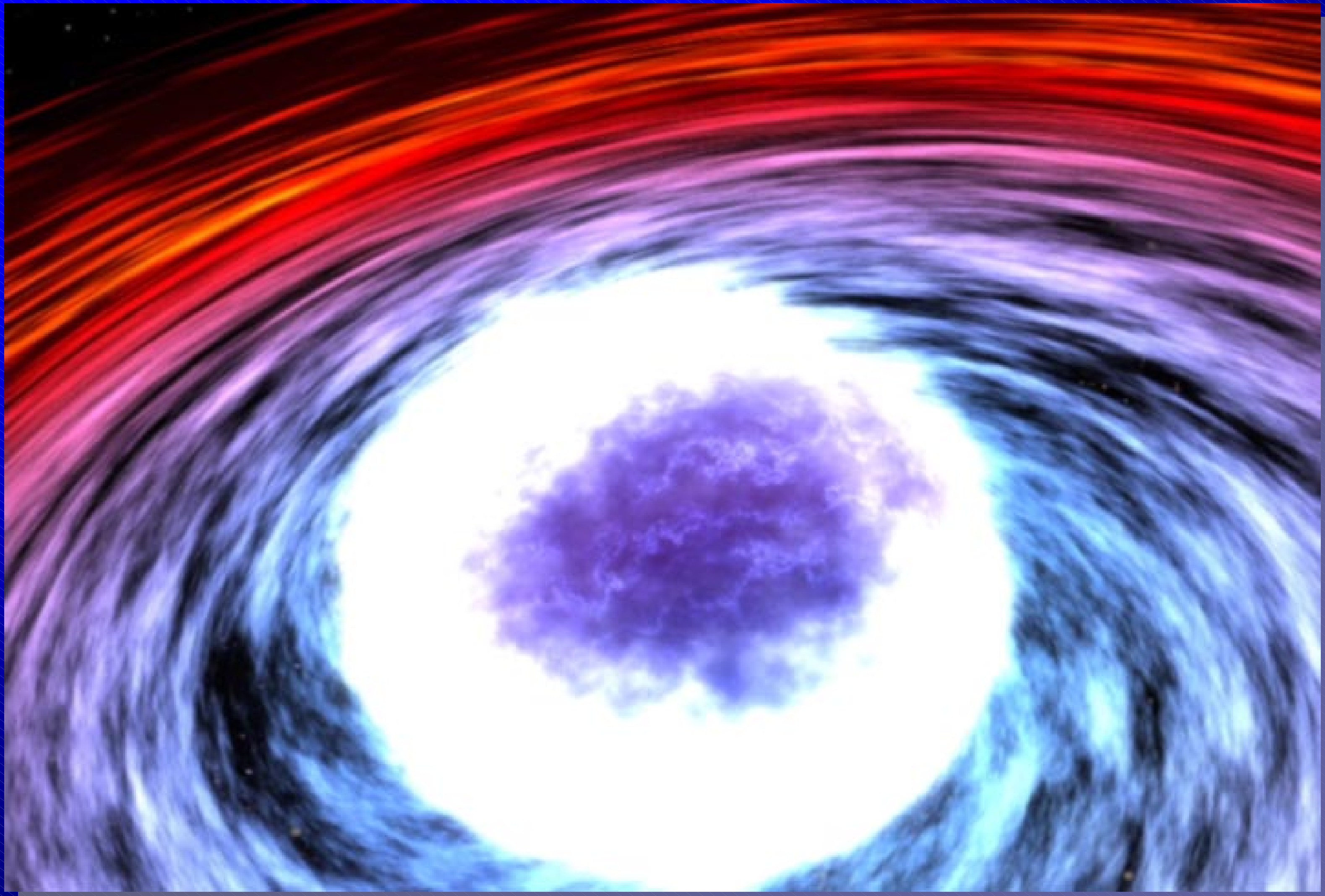

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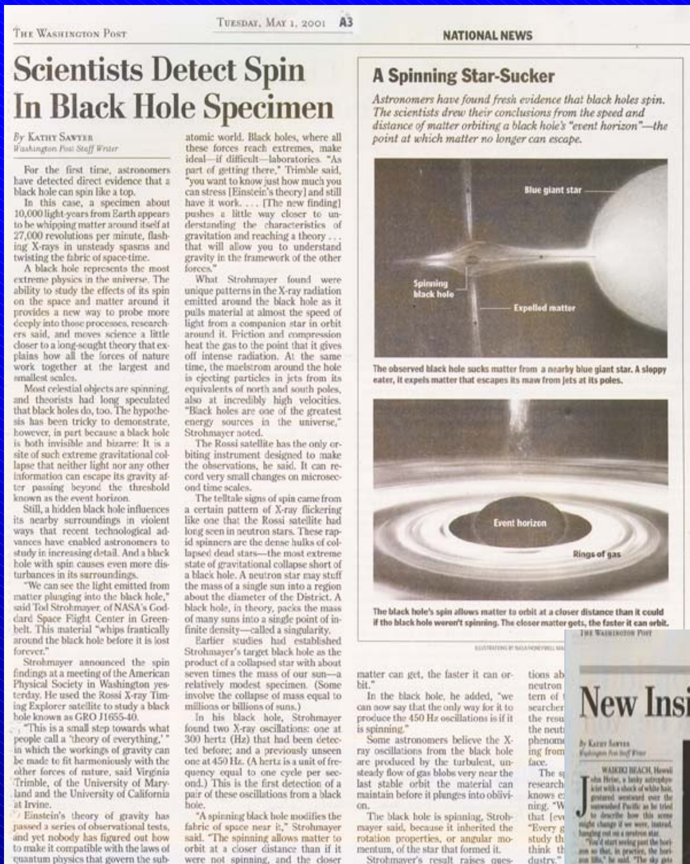
Compact Stars: Nature's Extreme Physics Labs



- Neutron stars, ~1.5 Solar masses compressed inside a sphere ~20 km in diameter.
- Highest density matter observable in universe.
- Highest magnetic field strengths observable in the universe.
- Black holes have the strongest gravitational fields accessible to study.
- General Relativity (GR) *required* to describe structure. Complex Physics!!

Did Einstein have the last word on Gravity?

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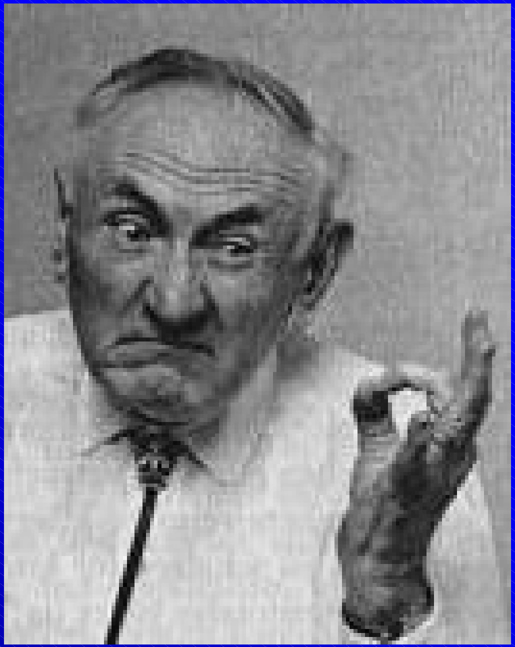
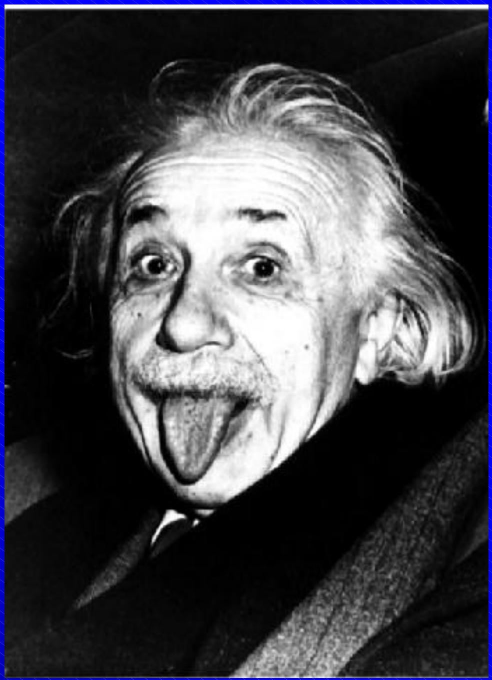


Fritz Zwicky

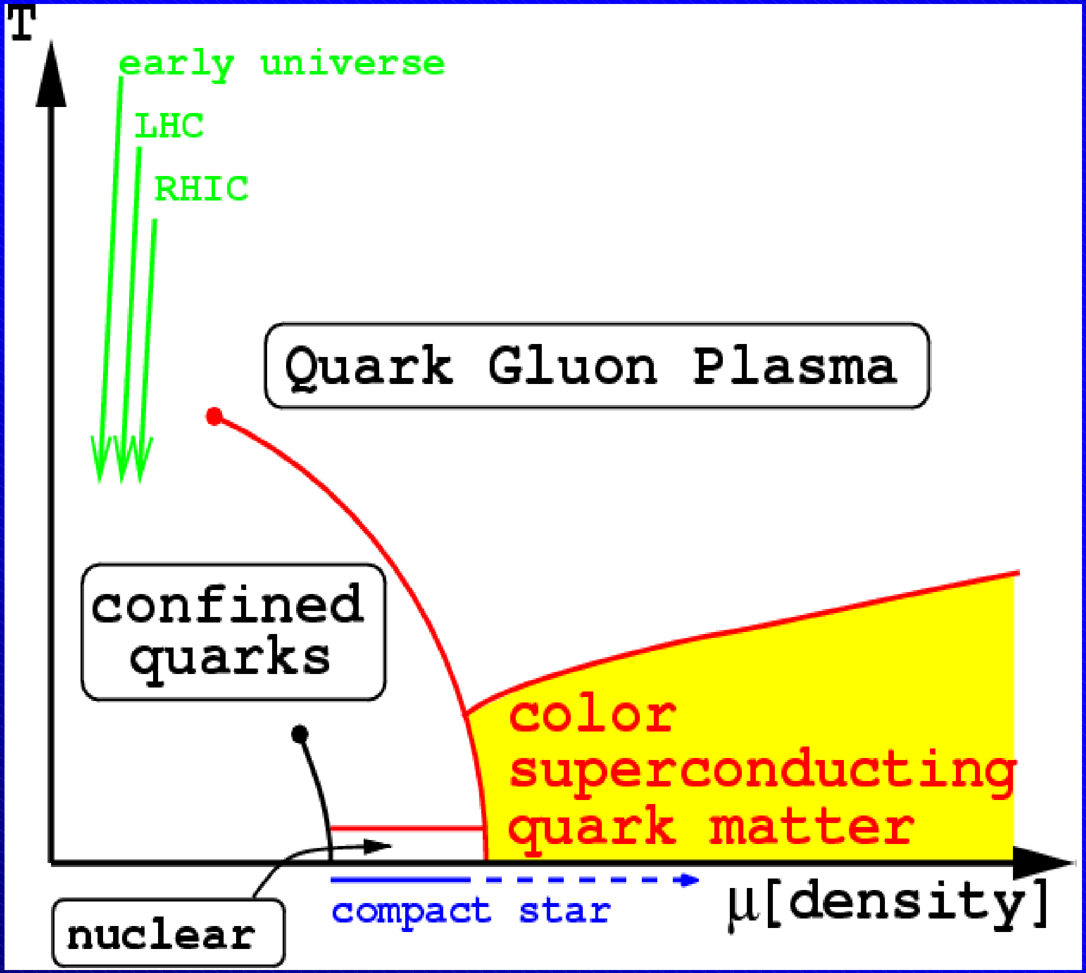


Albert Einstein

- Speculations about the existence of "Dark Stars" preceded Einstein.
- Einstein's Theory of General Relativity predicted existence of black holes (event horizons).
- Strong field gravity effects still untested.
- Existence of event horizons
- Existence of unstable circular orbits
- Dragging of inertial frames.
- Need black holes, NSs to test.

QCD phase diagram: New states of matter

Rho 2000, thanks to David Kaplan



- Theory of QCD still largely unconstrained.
- Recent theoretical work has explored QCD phase diagram (Alford, Wilczek, Reddy, Rajagopal, et al.)
- Exotic states of Quark matter postulated, CFL, color superconducting states.
- Neutron star interiors could contain such states. Can we infer its presence??

Fundamental Physics: The Equation of State (EOS) of ultra-dense matter

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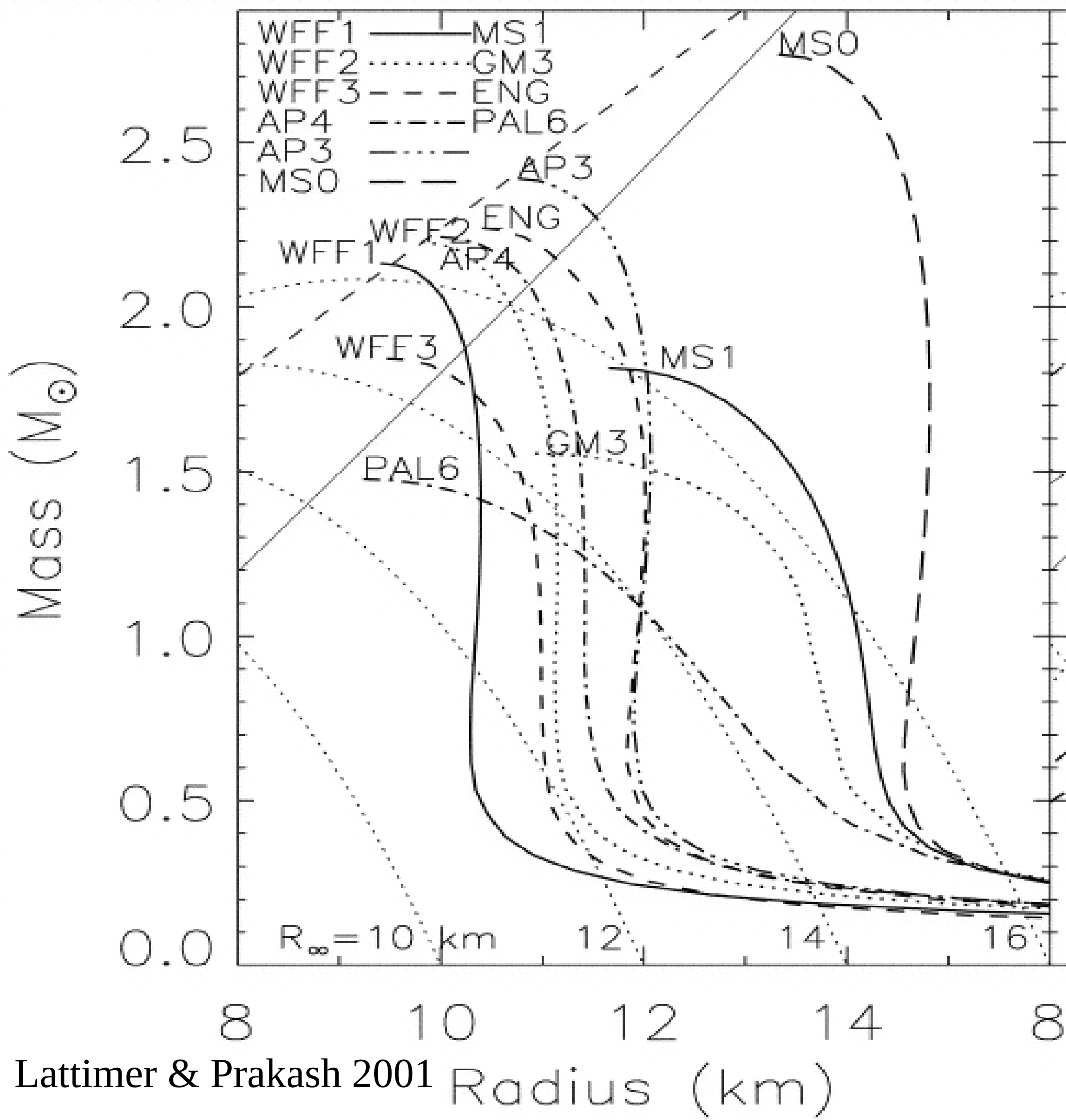

Lattimer & Prakash 2001

$$dP/dr = -\rho \, G \, M(r) / r^2$$

- Mass measurements, limits softening of EOS from hyperons, quarks, other exotic stuff.
- Radius provides direct information on nuclear interactions (nuclear symmetry energy).
- Other observables, such as global oscillations might also be crucial.

Black Holes and Neutron Stars: Fun Facts

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- E_{grav} = GMm/R = $(GM/c^2R)\, mc^2 \sim 0.2\, mc^2$!!
- Orbital Period (near "surface"): $2\pi\, (R^3/GM)^{1/2}$ ~1 ms
- Stellar Pulsation periods: 0.01 ms < P_{puls} < 100 ms
- Spin Periods: P_{spin} > 0.5 ms
- Dynamical timescale: $T_{dyn} = 1 / (G\, \rho_{avg})^{1/2}$ < 1 ms
- Escape Velocity: ~ $(GM/R)^{1/2}$ = 0.3 c ==> c
- Rotational Velocity (1 ms spin) : ΩR = 0.2 c
- Surface red-shift: $(1+z) = 1/ (1 - 2GM/c^2R)^{1/2} \sim 1.4$

Things happen FAST on and near stellar mass compact objects. You need sub-millisecond timing to see it happen!!

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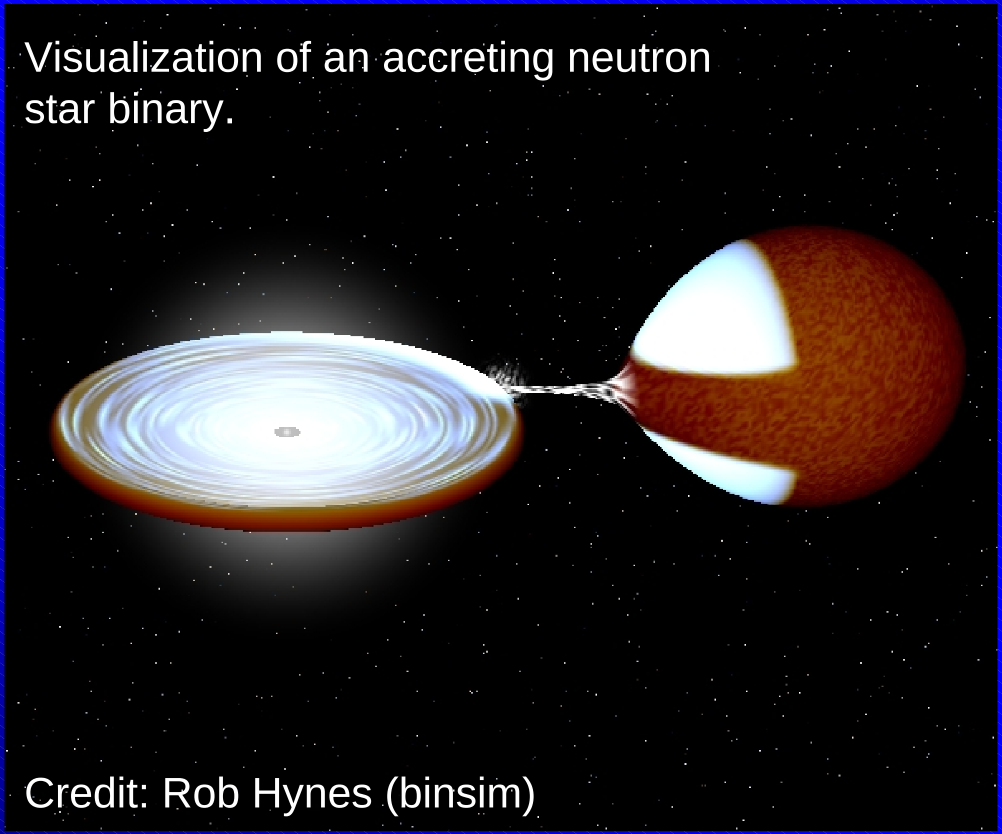
Accreting X-ray Binaries



- Accretion Powered: X-ray binaries
  - High Mass X-ray Binaries (HMXB): X-ray pulsars (young, high B-field). Disk population.
  - Low Mass X-ray Binaries (LMXB): Old (~10^9 yr), low B-field (10^9 G) pulsars???.
    - Nuclear Powered: X-ray burst sources

$$L_{edd} = 4\pi G M m_p c / \sigma_T = 4\pi R^2 \sigma T^4$$

$$===> \quad T \sim 10^7 \text{ K} \sim \text{keV photons, X-rays!}$$

Black Hole X-ray Novae

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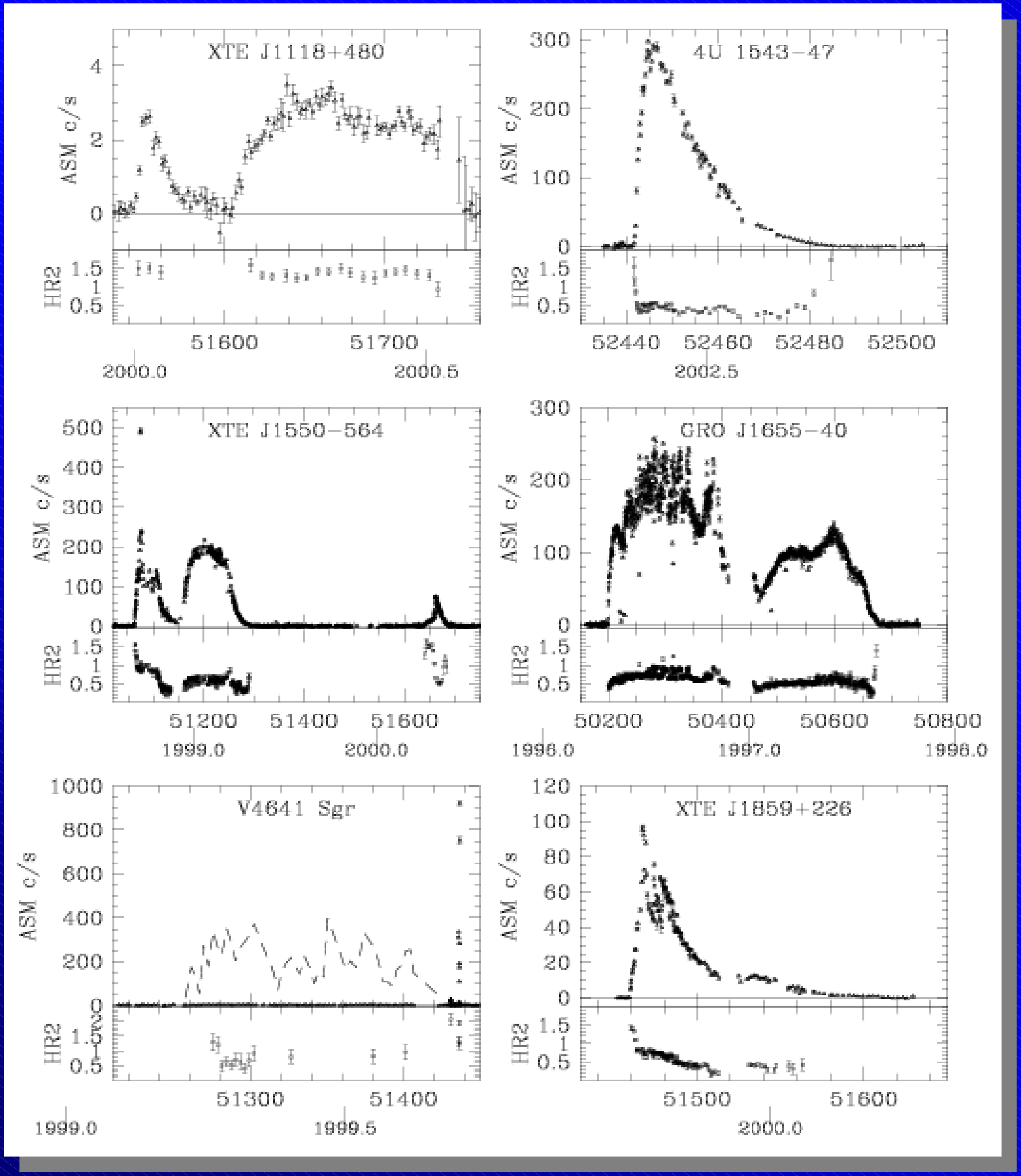
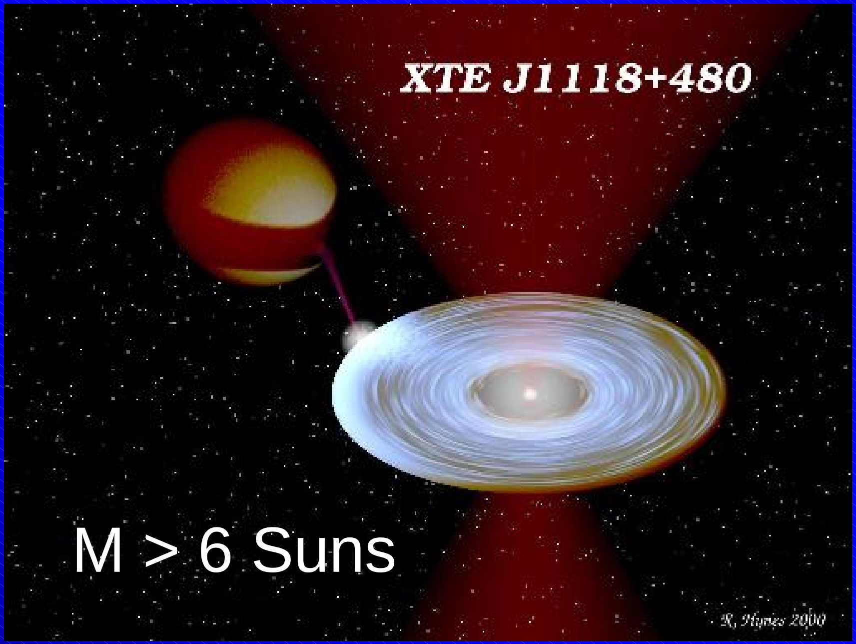
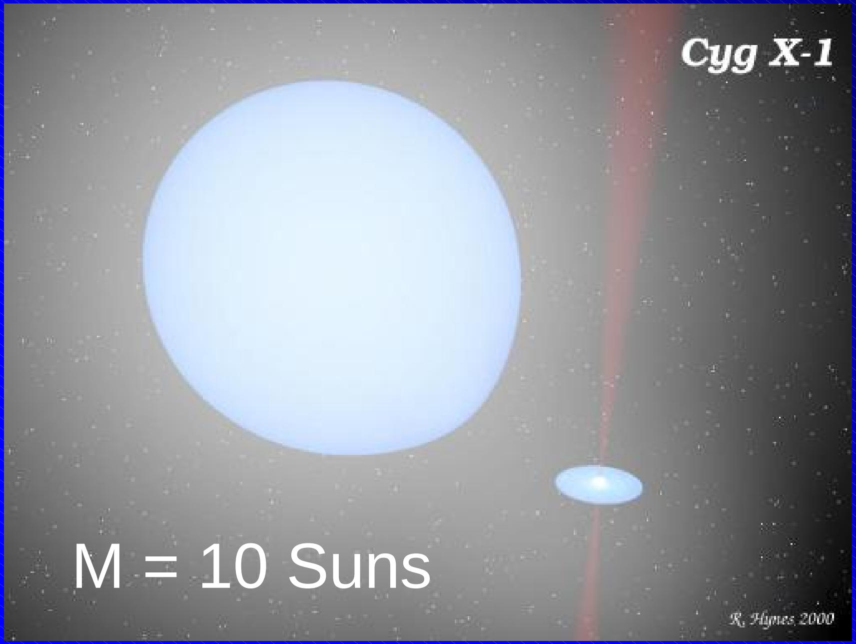


- Longterm (outburst) behavior can give clues to the nature of the binary system (and indirectly the mass of the compact object.
- Outbursts qualitatively understood in terms of accretion disk instability mechanism.
- Complications due to irradiation, warping.
- Outburst durations tied to physical size of accretion disk (orbital period).

How Do You "Weigh" a Black Hole





- Measure the orbital period and velocity of the companion star.
- Can usually be done with optical telescopes, if and when the X-ray emission has stopped (quiescence).
- Use of Kepler's laws gives the mass of the compact star.

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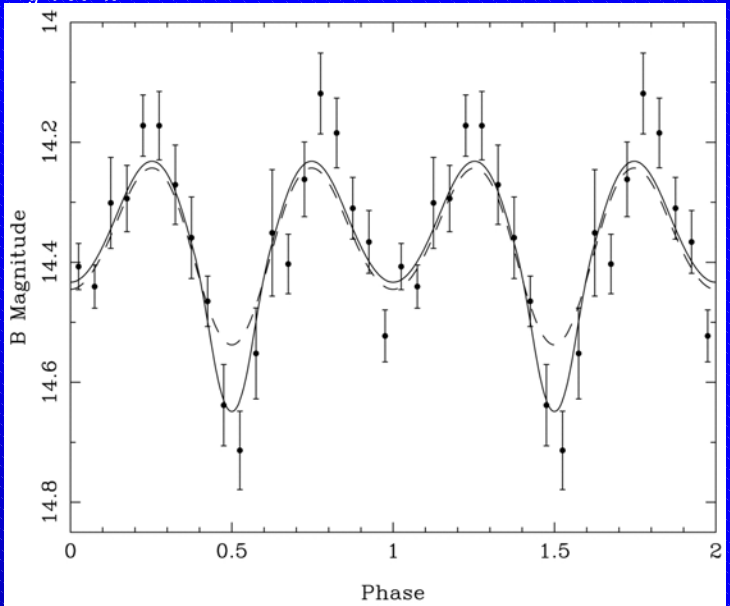
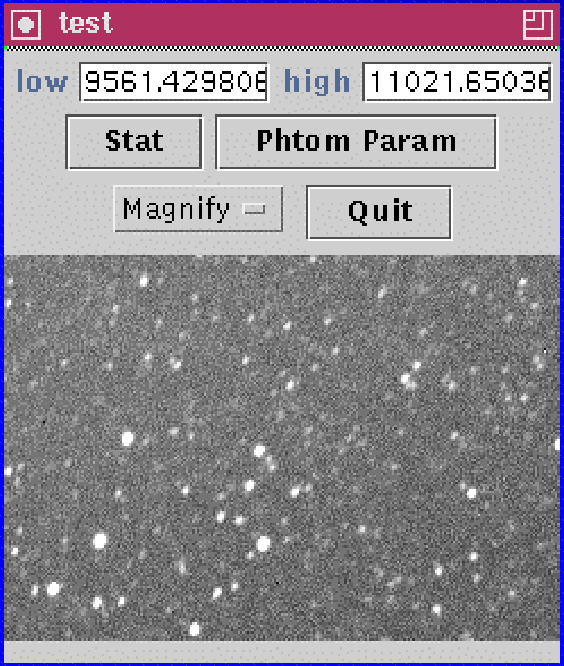
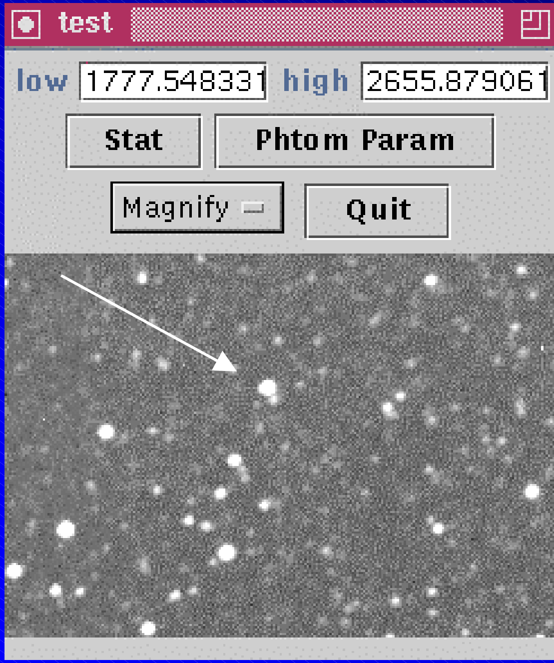
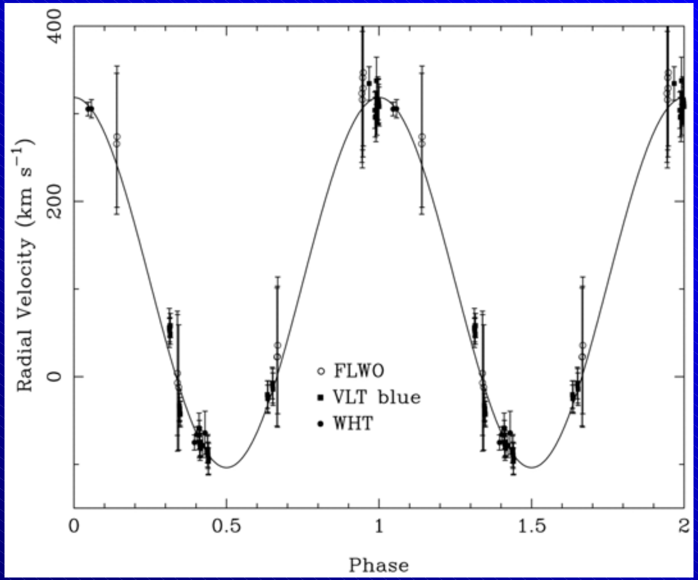
V4641 Sgr; a "naked eye" Black Hole









- Black hole has mass of 8 Suns.
- Has been VERY variable in optical light recently, and can be seen with the unaided eye at times.

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Galactic Black Hole Binaries

Table 4.2. *Confirmed black-hole binaries: X-ray and optical data*

Source	f(M)[a] ($M_\odot$)	M_1^a ($M_\odot$)	f(HFQPO) (Hz)	f(LFQPO) (Hz)	Radio[b]	E^c_{max} (MeV)	References
0422+32	1.19±0.02	3.2–13.2	–	0.035–32	P	0.8,1–2:	1,2,3,4,5
0538–641	2.3±0.3	5.9–9.2	–	0.46	–	0.05	6,7
0540–697	0.14±0.05	4.0–10.0:	–	0.075	–	0.02	8,7
0620–003	2.72±0.06	8.7–12.9	–	–	P,J?	0.03:	9,10,11
1009–45	3.17±0.12	6.3–8.0	–	0.04–0.3	–[d]	0.40, 1:	12,4,13
1118+480	6.1±0.3	6.5–7.2	–	0.07–0.15	P	0.15	14,15,16,17
1124–684	3.01±0.15	6.5–8.2	–	3.0–8.4	P	0.50	18,19,20,21
1543–475	0.25±0.01	7.4–11.4[e]	–	7	–[f]	0.20	22,4
1550–564	6.86±0.71	8.4–10.8	92,184,276	0.1–10	P,J	0.20	23,24,25,26,27
1655–40	2.73±0.09	6.0–6.6	300,450	0.1–28	P,J	0.80	28,29,30,31,54
1659–487	> 2.0[g]	–	–	0.09–7.4	P	0.45, 1:	32,33,4,13
1705–250	4.86±0.13	5.6–8.3	–	–	–[d]	0.1	34,35
1819.3–2525	3.13±0.13	6.8–7.4	–	–	P,J	0.02	36,37
1859+226	7.4±1.1	7.6–12:	150,187	0.5–10	P,J?	0.2	38,39,40,41
1915+105	9.5±3.0	10.0–18.0:	40,67,113,165	0.001–10	P,J	0.5, 1:	42,43,44,4,13
1956+350	0.244±0.005	6.9–13.2	–	0.035–12	P,J	1.5, 3–5:	45,46,47,48,49
2000+251	5.01±0.12	7.1–7.8	–	2.4–2.6	P	0.3	18,50,51
2023+338	6.08±0.06	10.1–13.4	–	–	P	0.4	52,53

McClintock & Remillard (2006)

- 18 confirmed (dynamical) black hole binaries.
- 22 candidate black hole systems based on X-ray and radio observations, and comparisons with confirmed systems.

Black Hole Accretion "States"

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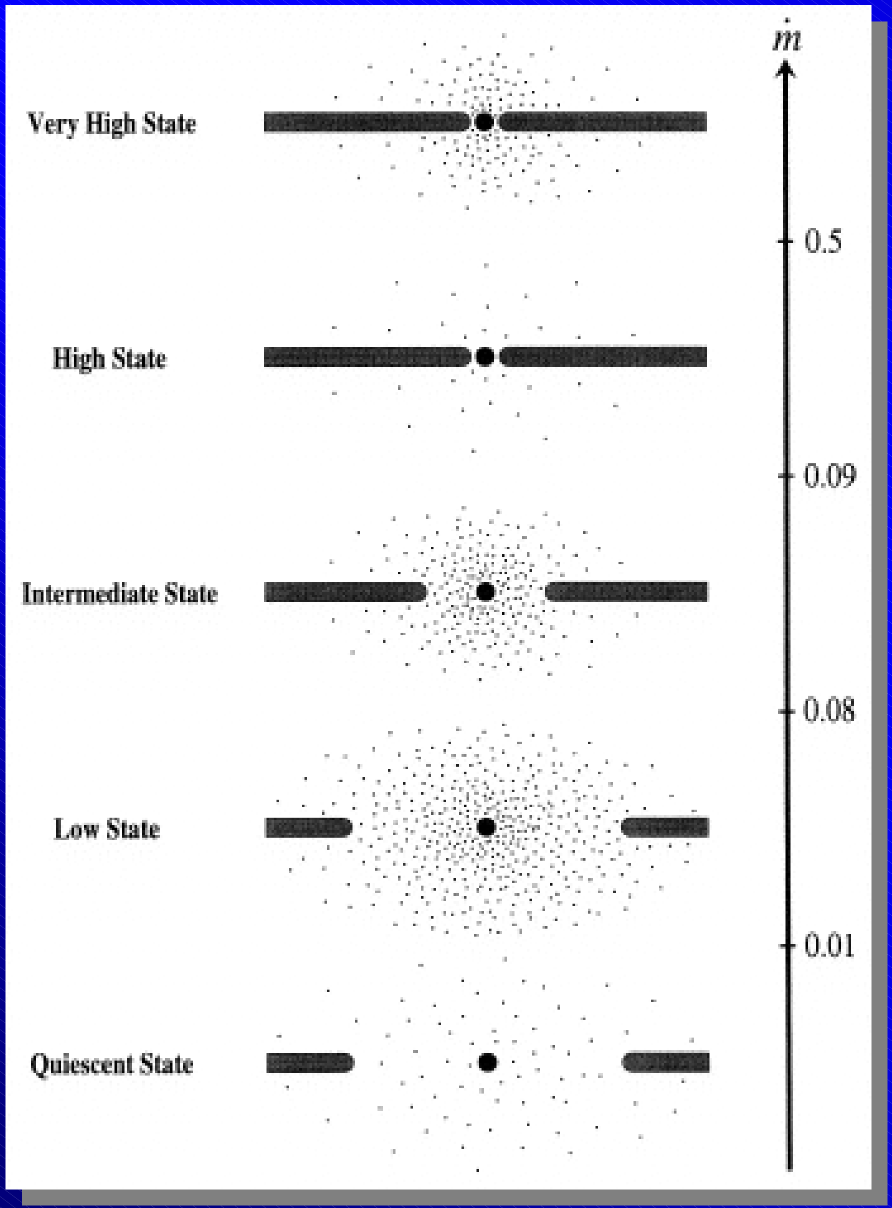
Esin et al. 1997



- Good evidence for geometrically thin, optically thick disk during some stages of accretion (thermal spectrum).
- Advective flows (ADAF, ADIOS, CDAF), may describe some accretion states (quiescent).
- Non-thermal spectra require hot, optically thin Comptonizing "corona".
- Geometry of the corona is a matter of strong debate.
- How "state" correlates with $\dot{m}$ is not really understood. Other parameters?

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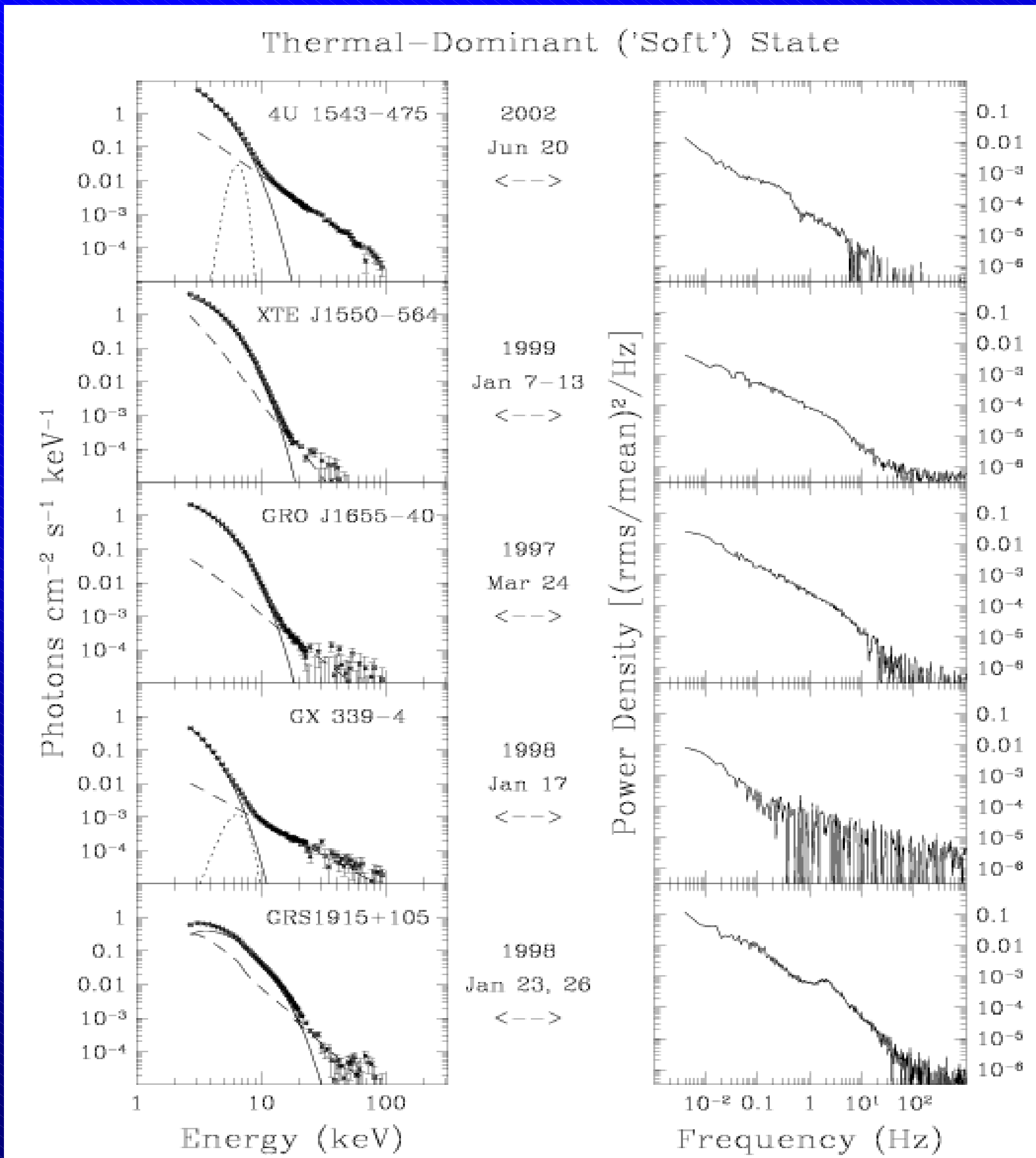
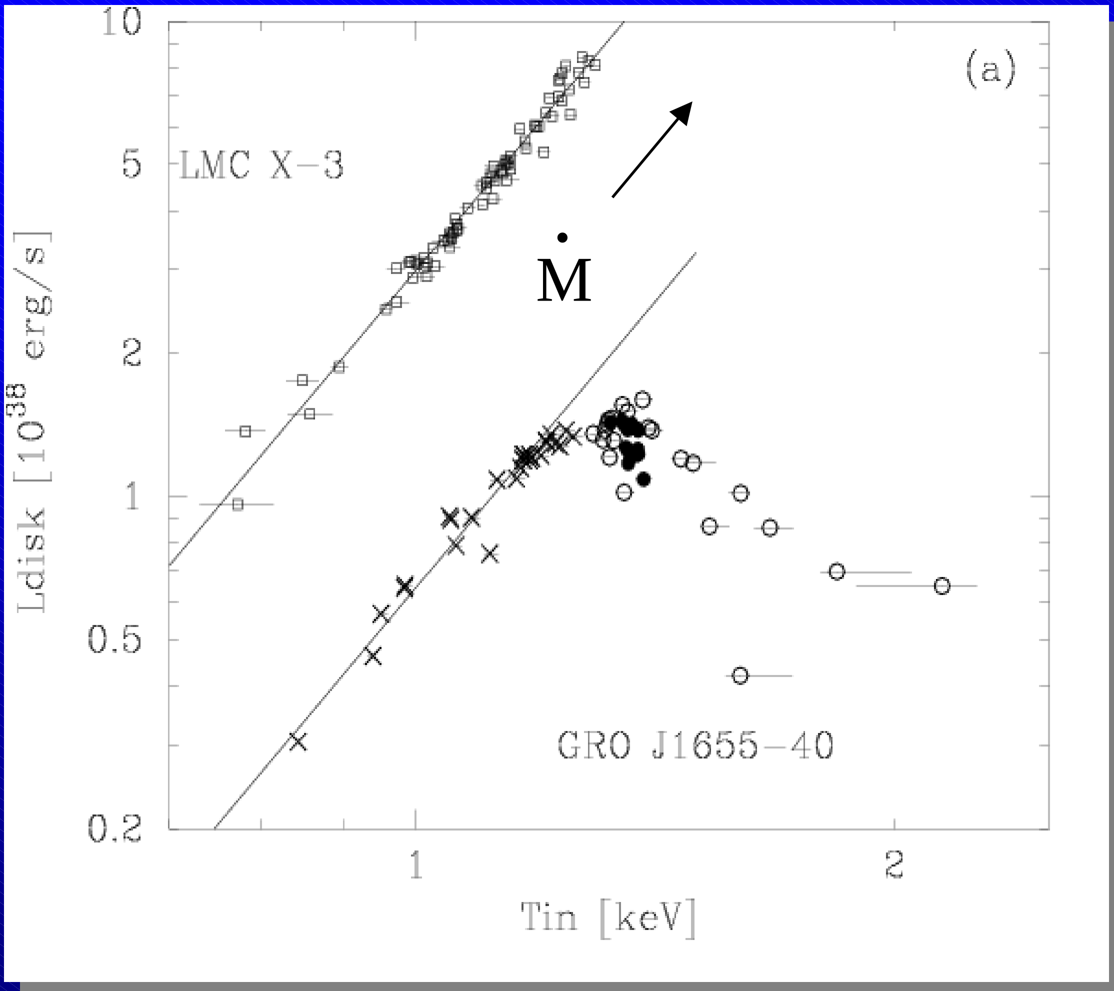
Accretion States: High/Soft (Thermal Dominant)



- Spectrum dominated (> 80%) by a ~1 keV MCD blackbody spectrum.
- Often associated with highest luminosities.
- R_{in} often consistent with R_{sch} for black hole of the implied mass.
- Weak, aperiodic variability with ~1/f dependence (< 10% rms).
- Not associated with radio emission.

Thermal State: Evidence for Inner Accretion Disk Radius



Kubota et al. 2001

- $L \propto T_{in}^4$ for thermal disk spectrum.
- Variations in L seem to fit this relation assuming a constant inner radius which is qualitatively consistent with R_{sch}
- detailed comparisons with theory require relativistic and spectral hardening corrections.
- $T_{in} \propto M^{-1/4}$ (possible mass constraint)

Accretion States: Very High or steep power law (SPL) state

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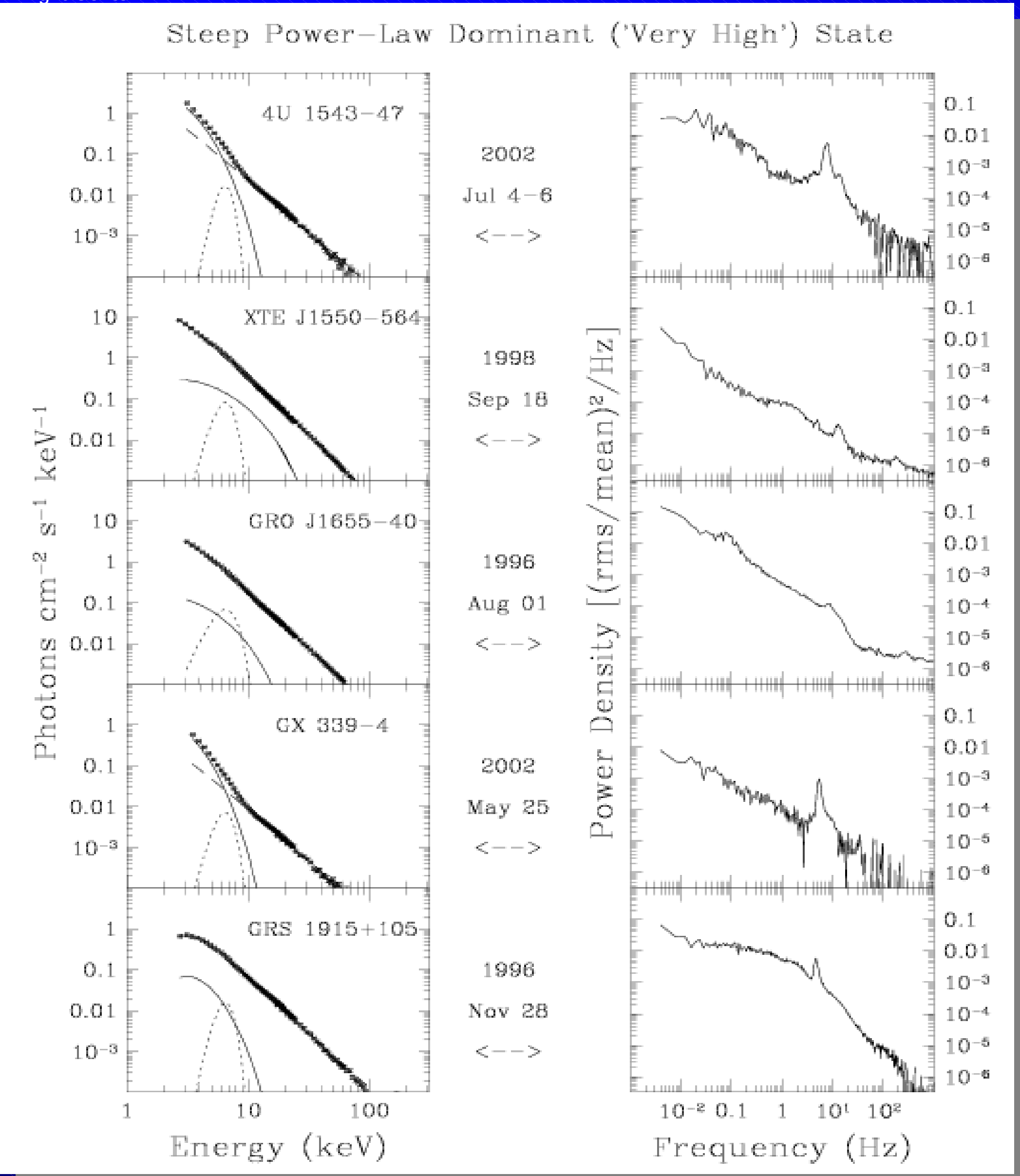
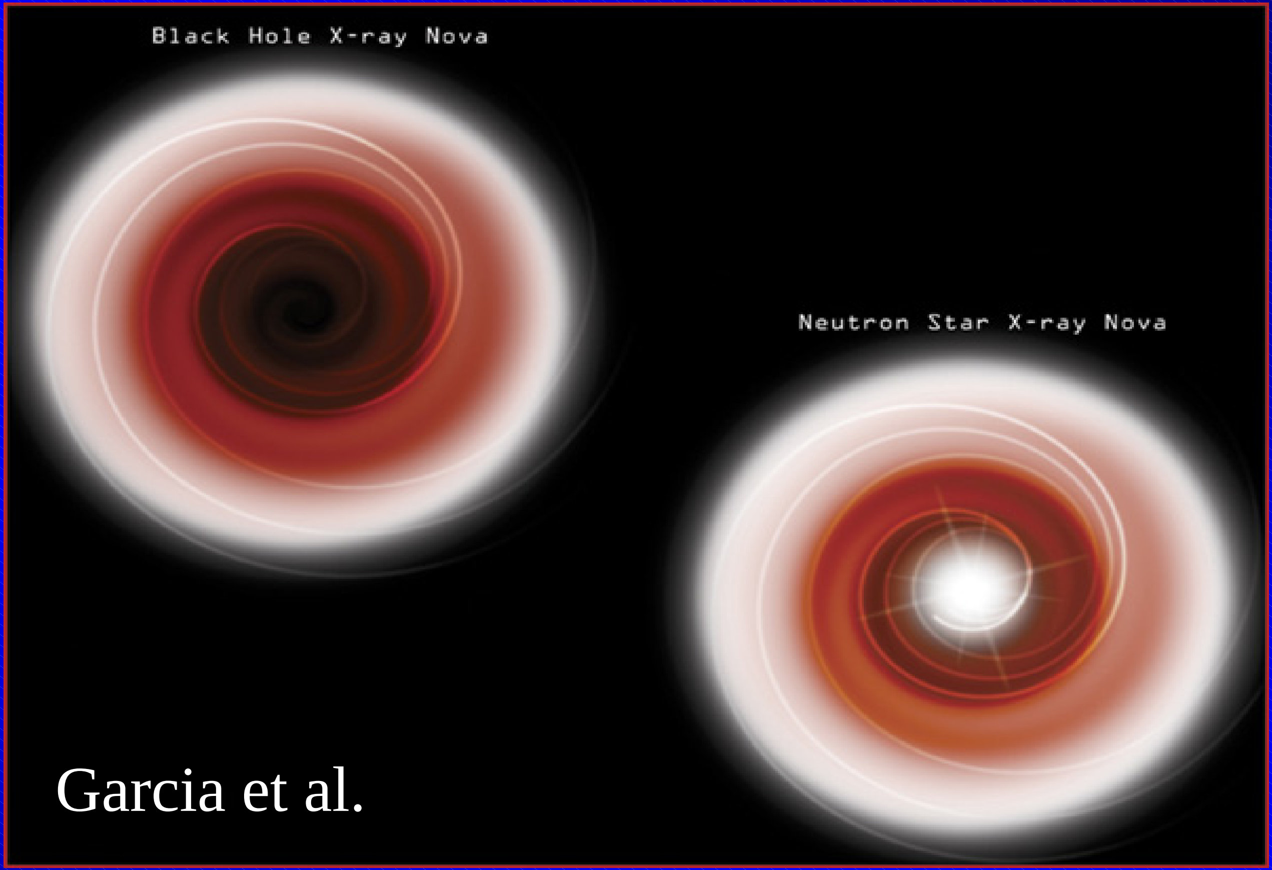


- Spectrum dominated by a steep (index > 2.4) power law.
- May contribute > 50% of the X-ray flux.
- Low frequency (0.05 - 30 Hz) X-ray QPOs are usually present, High frequency QPOs (> 100 Hz) may be present.
- Power law can continue up to an Mev.

Black Hole Event Horizons?



- Hypothesis: Accreting black holes in "quiescence" should be fainter than accreting neutron stars.
- Disk accretion processes the same (only cares about mass).
- Energy gets advected down the black hole (crosses the event horizon). Neutron star surface thermalizes and radiates extra energy.

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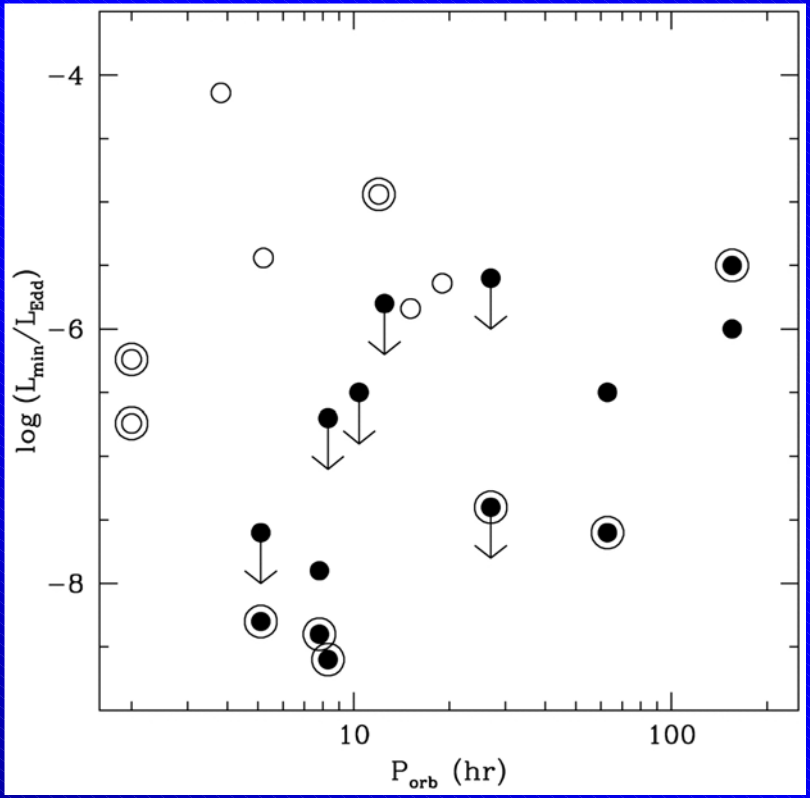
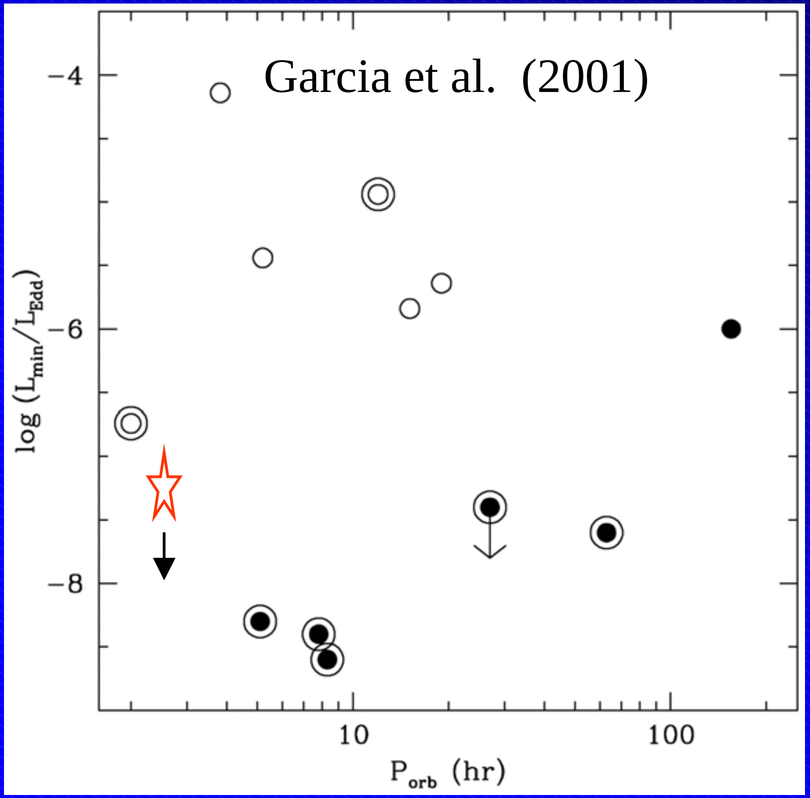
Black Hole Event Horizons?





- Quiescent states dominated by Advection Dominant Accretion Flow (ADAF, Narayan & Yi 1994; ADIOS Blandford & Begelman 199).
- Data appears suggestive of a difference, but it is proof of event horizon??
- Concerns in comparing systems in the same state; selection effects, etc. (new result on 1H 1905+00, Jonker et al. 2007).

X-ray Timing: “Black Hole Microscopy”

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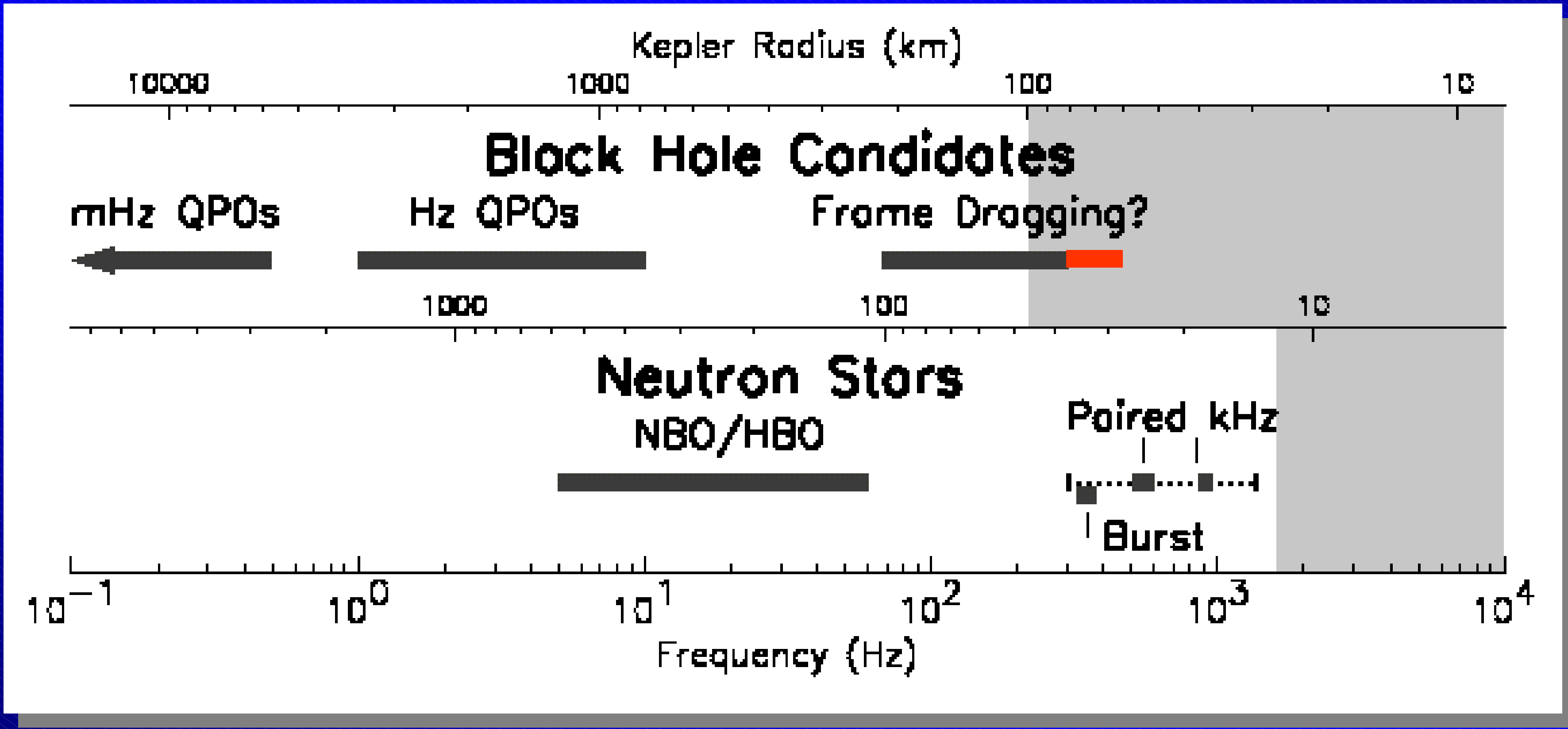
- X-ray Timing (QPOs) probes down to the inner-most stable circular orbit (ISCO) of NSs and stellar mass BHs.
- Dynamic range of ~ 3 - 4 decades in radius.



- 450 Hz QPO ==> “spatial resolution” ~ 1 nano arcsec at GC

RXTE Revolutionized Black Hole Studies

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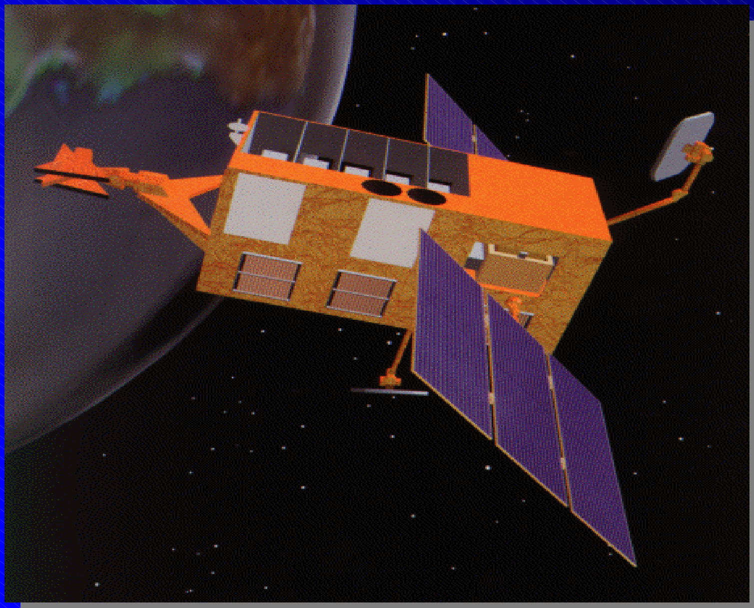
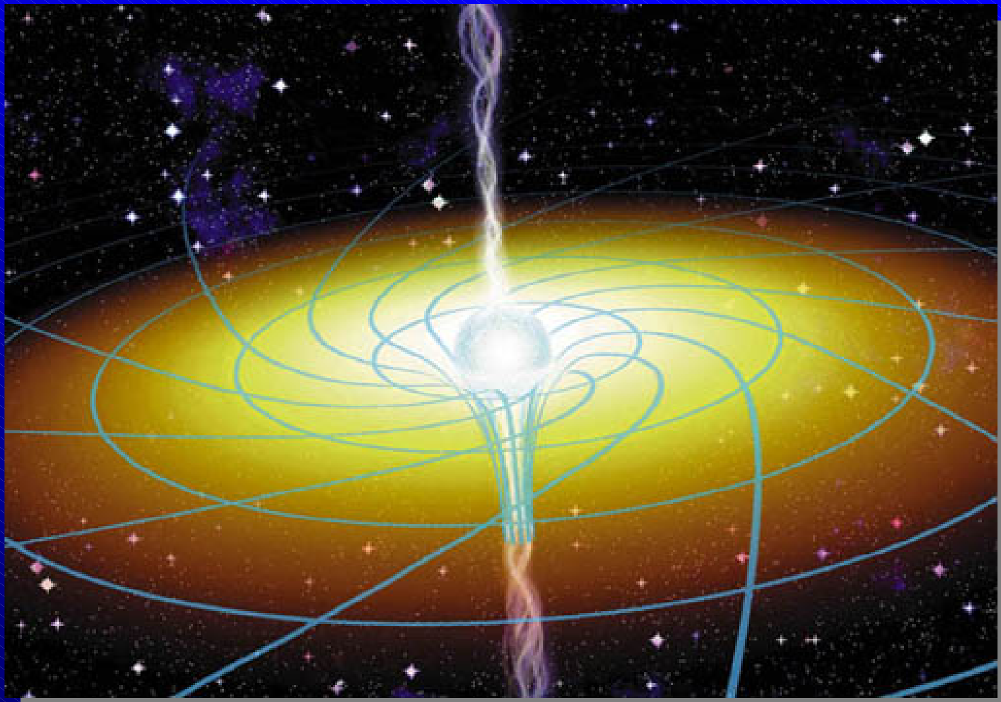
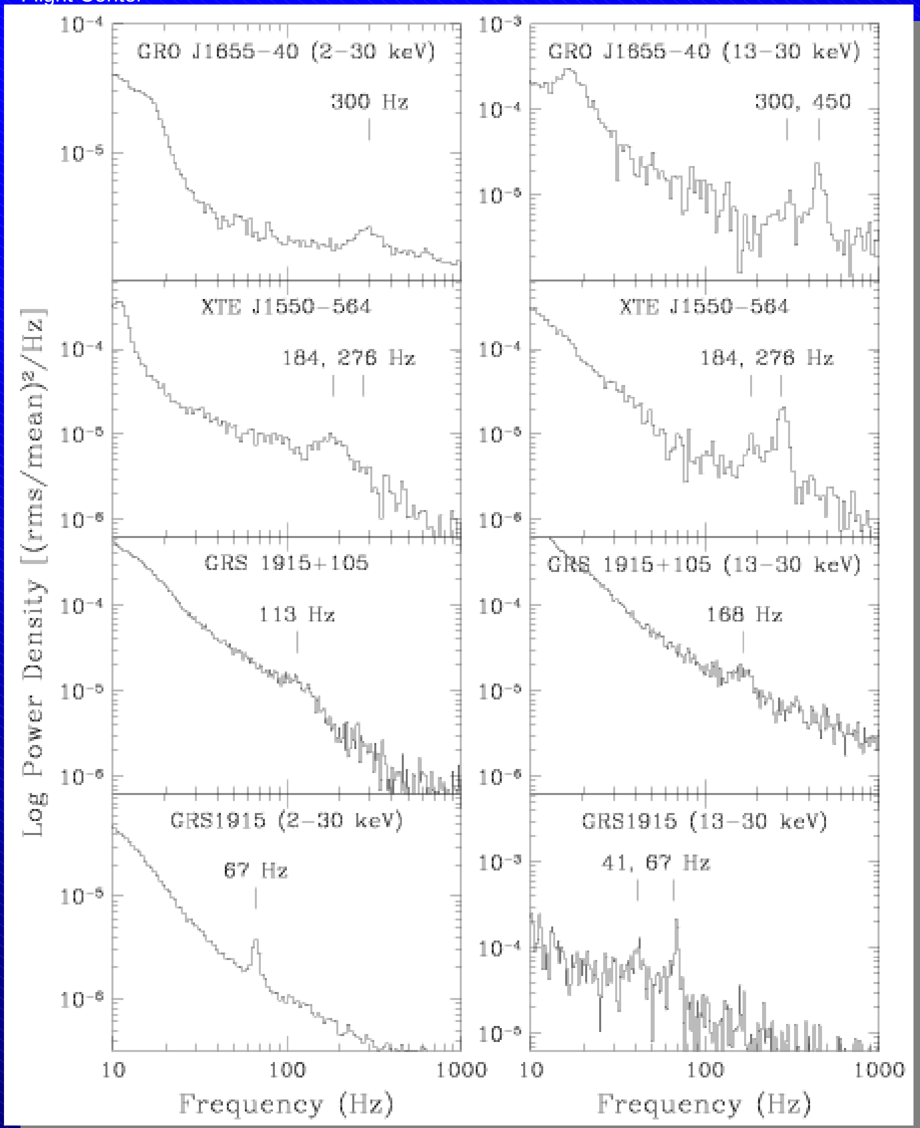
- RXTE has extended the frontiers of research on compact stars and general relativity using
  - Large collecting area
  - State-of-the-art data system
  - High telemetry rate
  - Low background



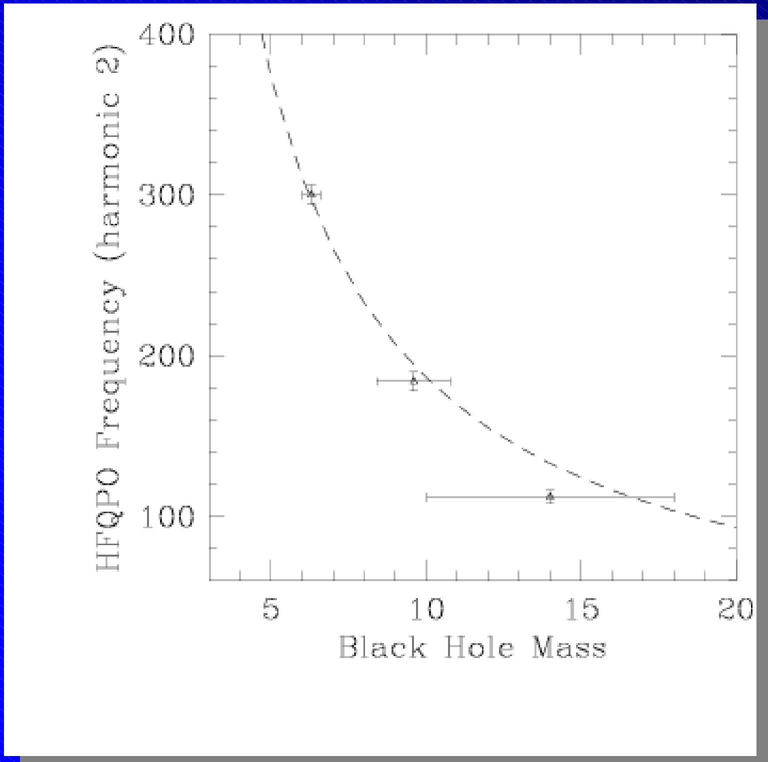


- Discovered millisecond spin periods of accreting neutron stars
- Millisecond oscillations in BH and NS binaries
- New ways to investigate EOS and physics of super-dense matter
- New probes of strong gravity (GR)
- Stimulating new theoretical work

Black Hole High Frequency QPOs



McClintock & Remillard (2006)



- ν_{kep} = 220 Hz (M / 10 Msun)$^{-1}$
- Frequencies in 3:2 ratio in 3 sources.
- Consistent with 1/M scaling.

High Frequency QPOs in XTE J1550-564

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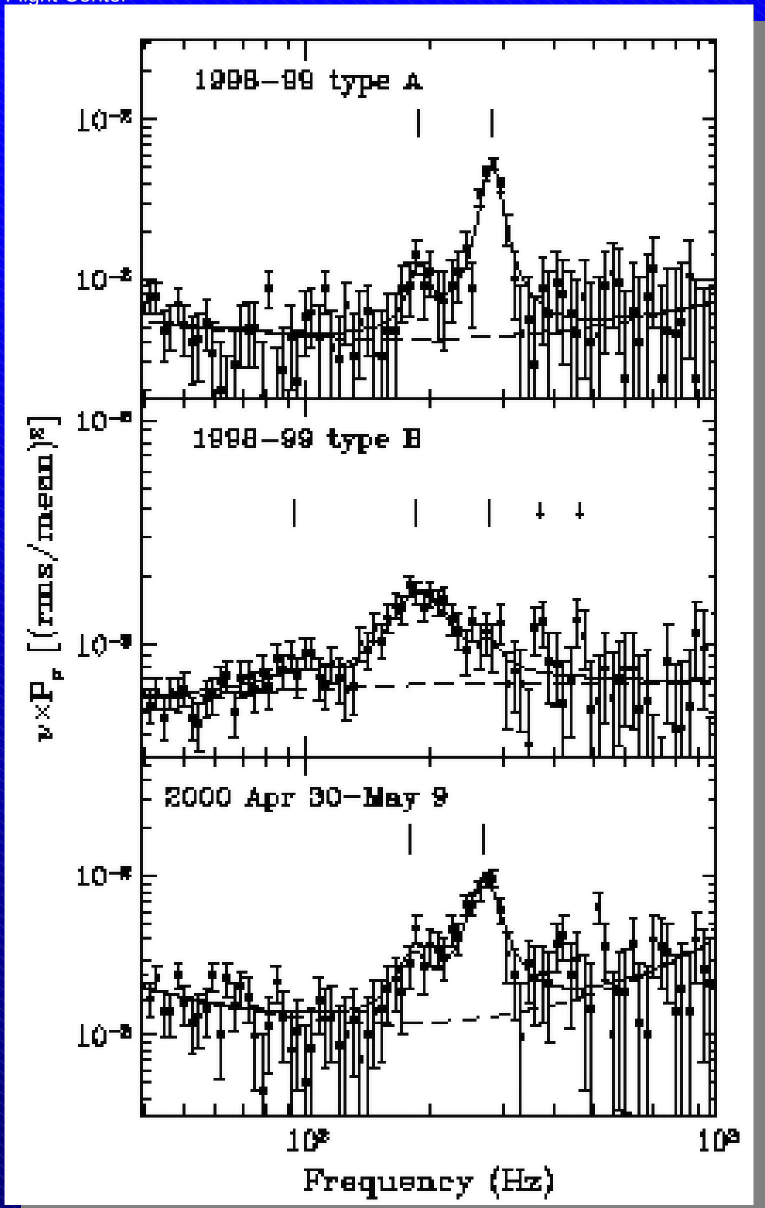

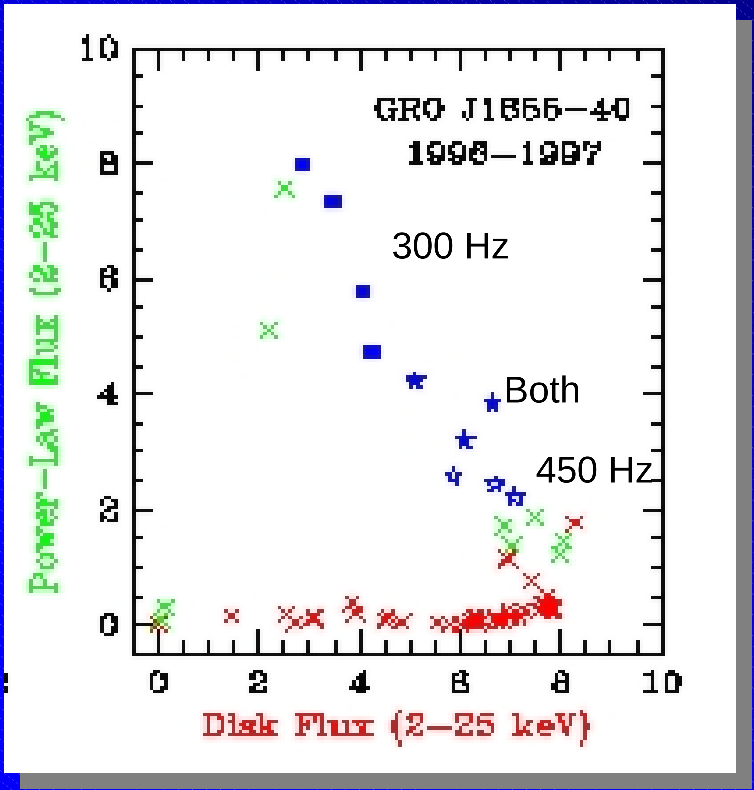

- Miller et al. (2001), Remillard et al. (2002) find harmonically related QPOs.
- QPOs correlated with spectral state.
- Power law component important.

Black Hole space-time: Black Holes have no "hair"

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Rotating black holes described by Kerr metric

$ds^2 = (1 - 2GMr/\rho c^2)\, dt^2 - (1/c^2)\, [\, (4GMra\sin^2\theta/\rho c)\, dt\, d\phi + (\rho/\Delta)\, dr^2 + \rho\, d\theta^2 + (r^2 + a^2 + (2GMra^2\sin^2\theta)/\rho c^2)\, \sin^2\theta\, d\phi^2\,]$

With; $a=J/Mc$ (angular momentum)

$\Delta = r^2 - (2GMr/c^2) + a^2$

$\rho = r^2 + a^2\cos^2\theta$

With $J = 0$ (non-spinning hole) reduces to the Schwarzschild space-time .

Dynamics described by only two parameters, M, and J (a).

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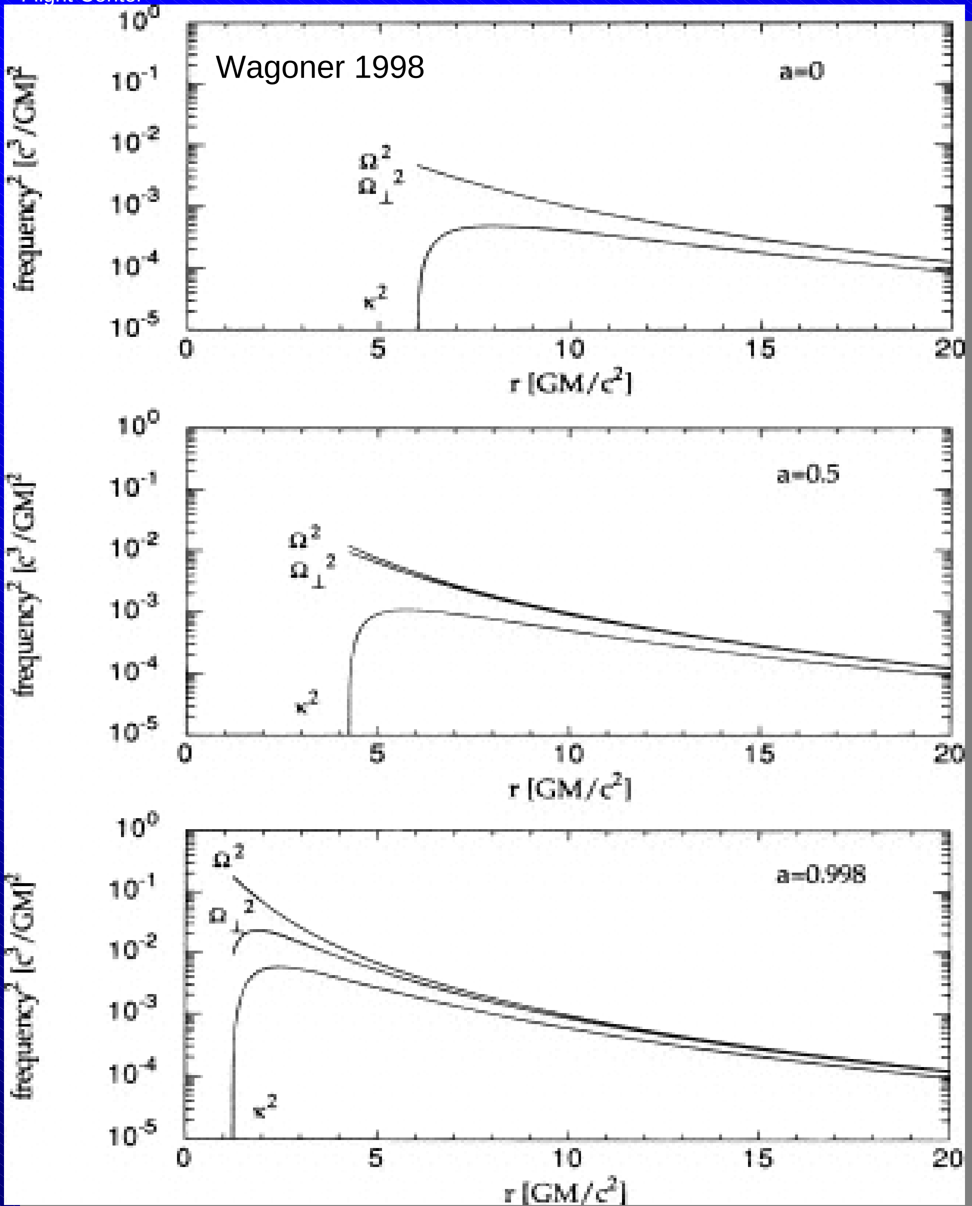
General Relativistic Frequencies in Black Hole Accretion Disks



- GR fundamentally changes orbit dynamics.
- Inner-most stable circular orbit (ISCO).
- 3 characteristic particle frequencies at a given radius.
- Leads to apsidal and gravito-magnetic precession.
- Mode trapping.

Evidence for Black Hole Spin in a Microquasar (GRO J1655-40)

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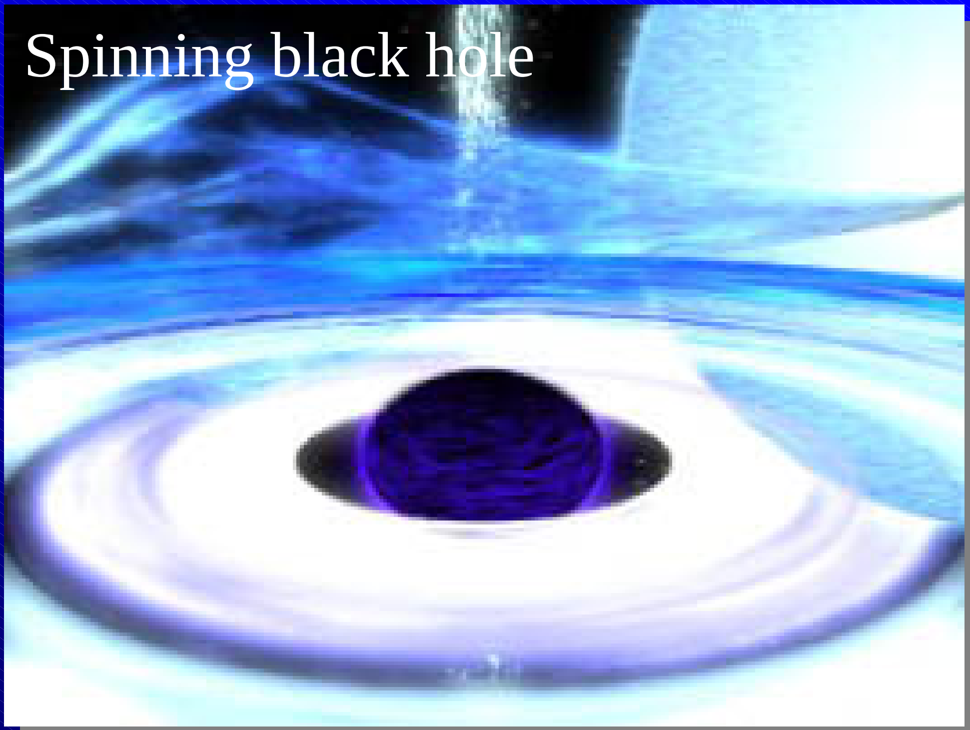
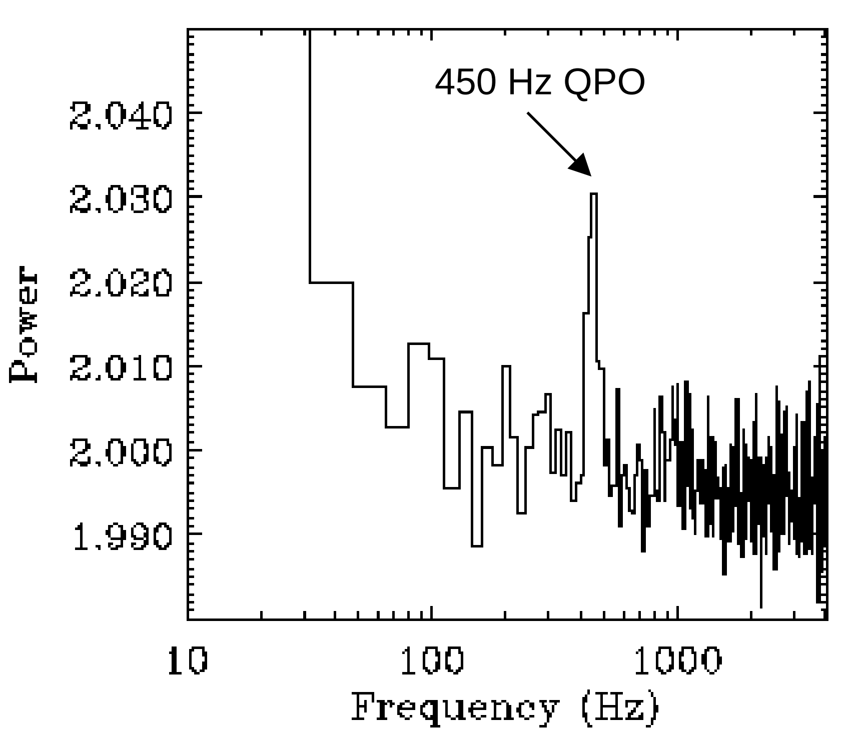
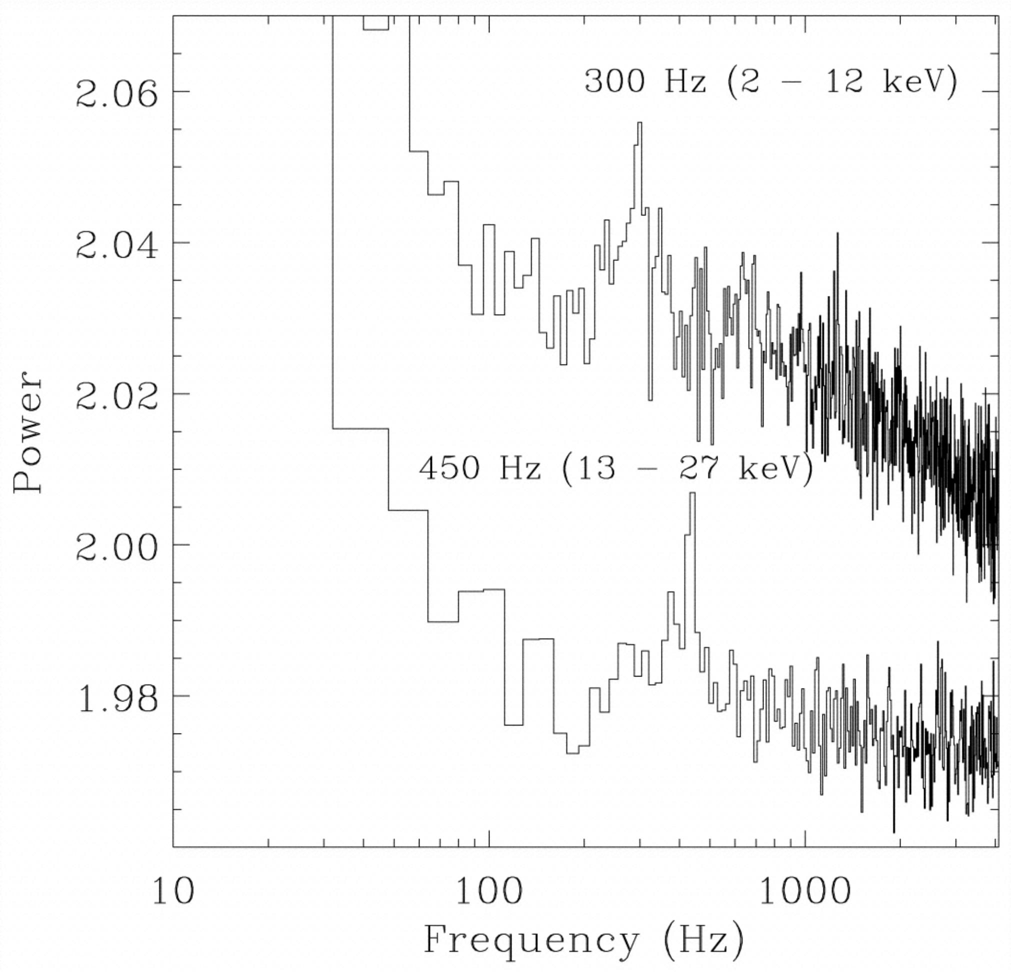
- Newly discovered 450 Hz QPO is fastest known in a black hole.
- First detection of simultaneous high frequency QPOs in a black hole binary (300 and 450 Hz).
- Because the mass of GRO J1655-40 is known (~ 7 M_{sun}), the 450 Hz QPO implies that the black hole is spinning.

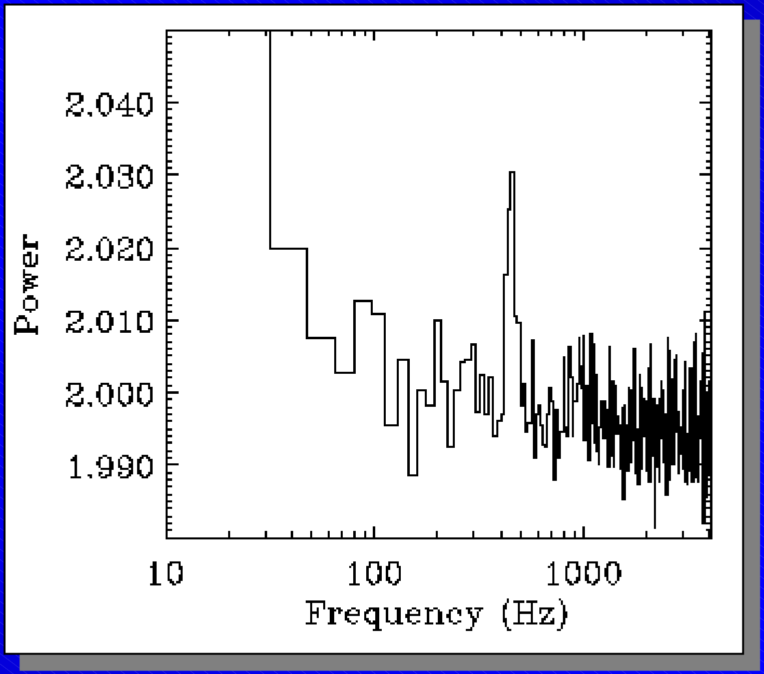




450 Hz QPO in GRO J1655-40



- Discovered in hard X-ray band, 13-30 keV.
- 5% amplitude (rms). Q ~ 20. Strong energy dependence.
- Fastest known BH modulation.



Constraining Black Hole Spin

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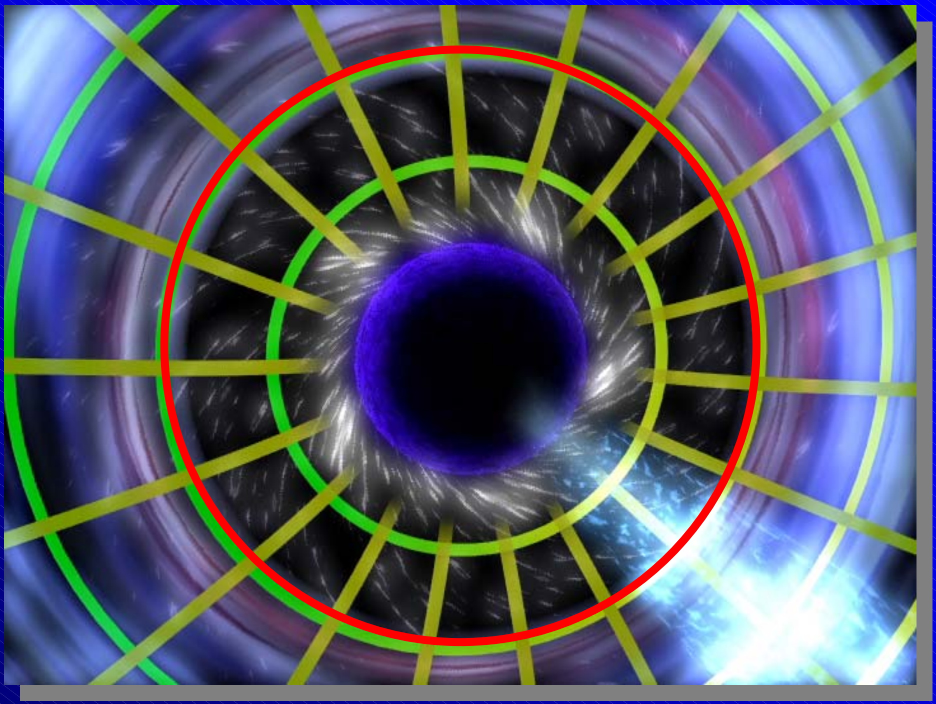
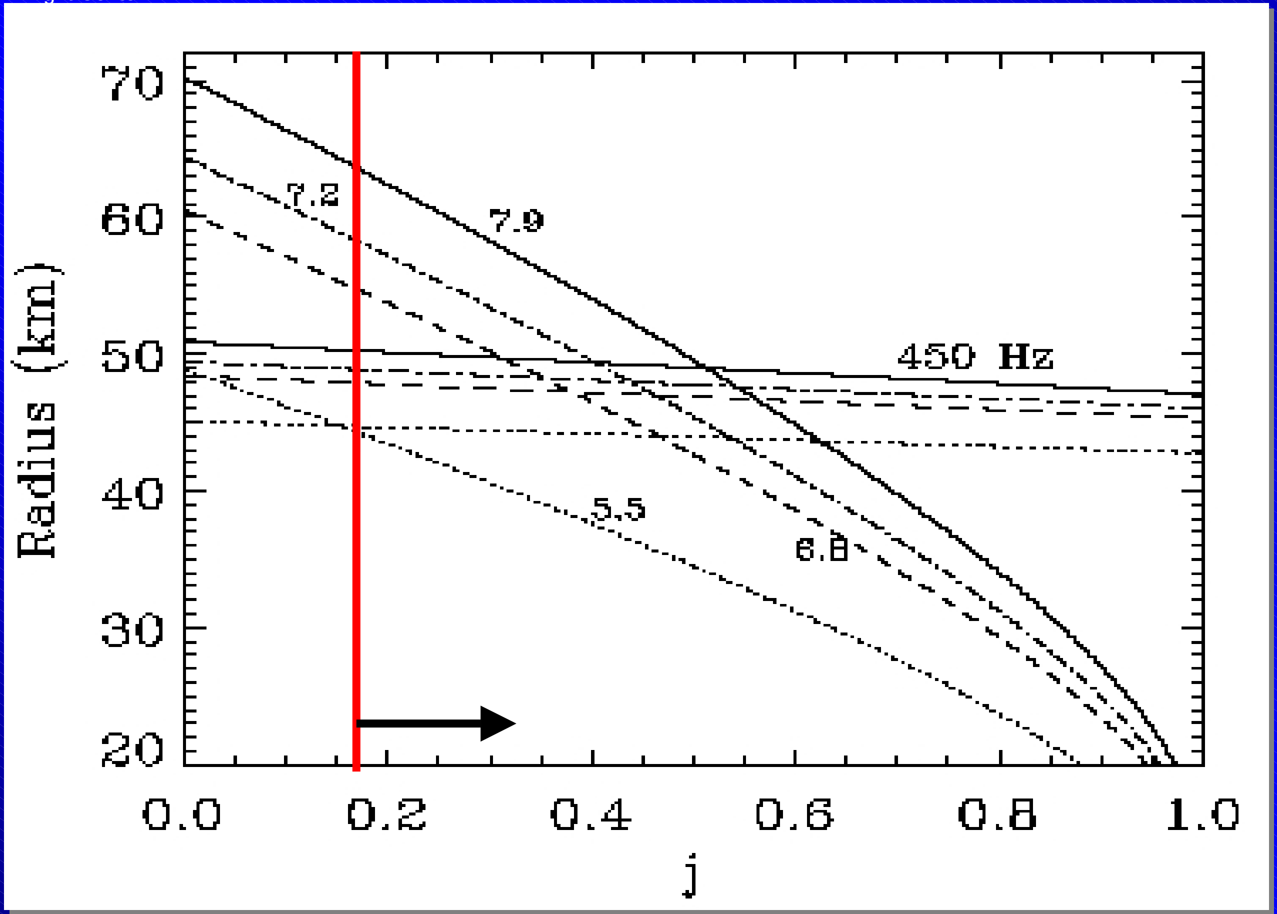
- Highest characteristic frequency at a given radius is the Keplerian (orbital) frequency.
- Stable circular orbits extend closer to spinning black hole.
- Closer orbits have higher orbital frequencies.

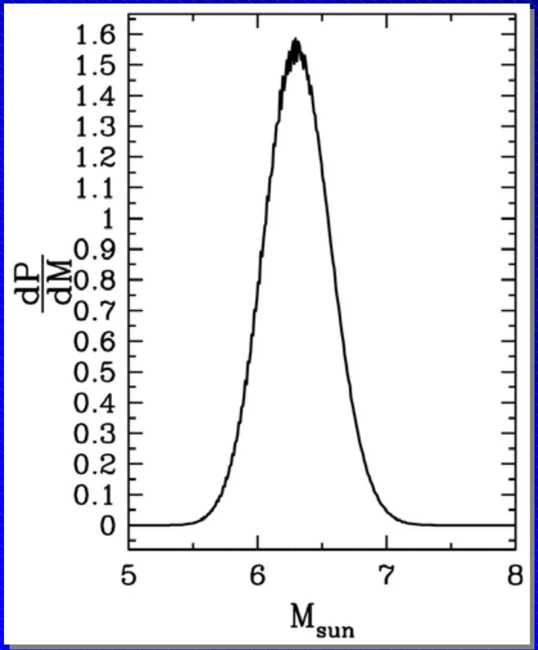


Schwarzschild (non-rotating)

Kerr (rotating)

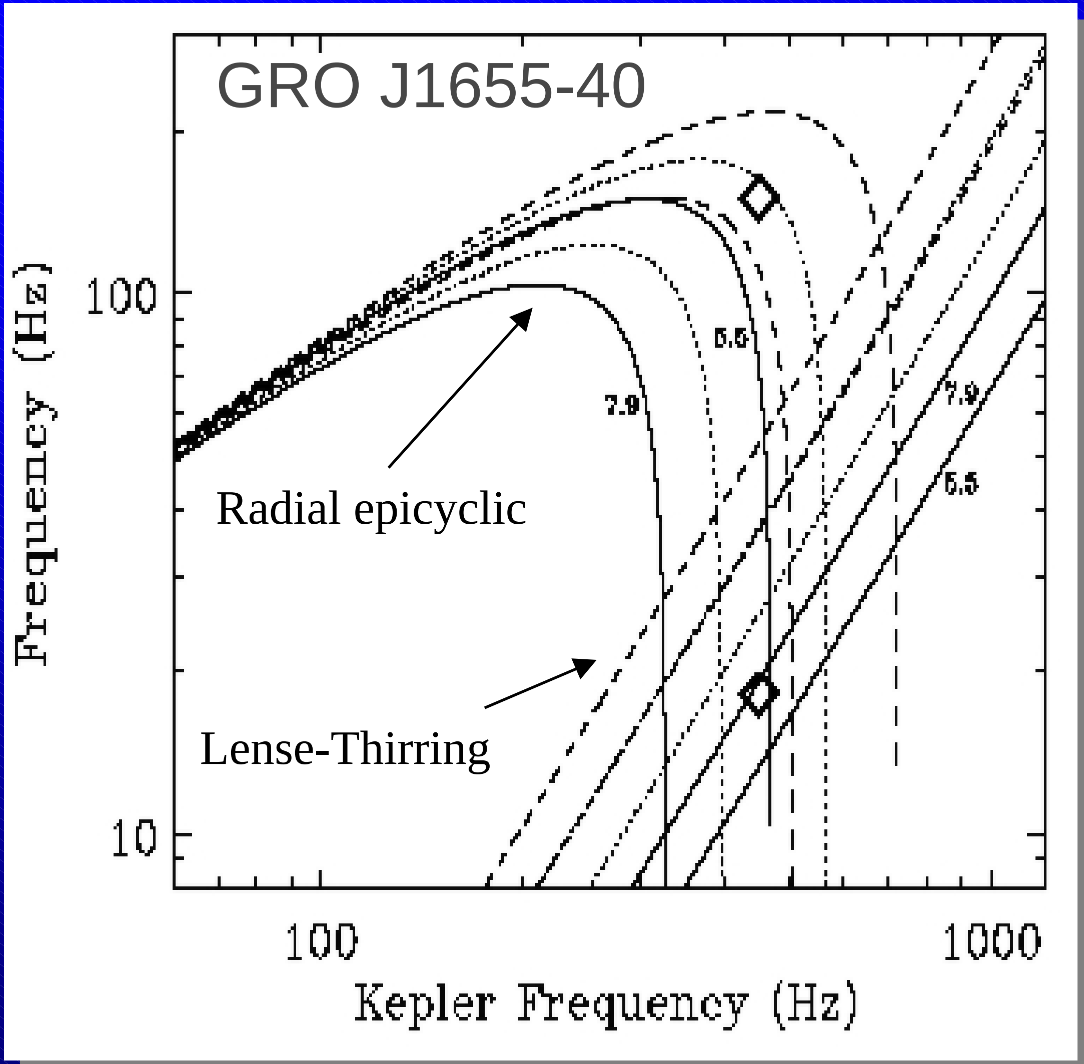
Evidence for Black Hole Spin in GRO J1655-40





- Mass of GRO J1655-40 tightly constrained $M = 6.3 \pm 0.5\ M_\odot$ (Greene, Bailyn & Orosz 2001).
- 450 Hz QPO in GRO J1655-40 is too high for non-rotating hole.

Models of X-ray Variability: Relativistic Precession



Solid: j=0.2, dotted: j=0.4, dashed: j=0.6

- QPOs reflect fundamental GR test particle frequencies.
- Higher QPO frequency is orbital.
- Frequency separation is associated with radial epicyclic frequency.
- Lower frequency QPOs may be due to Lense -Thirring precession (frame dragging).
- Stella, Vietri, Morsink (1999); Psaltis & Norman (2000).
- However, see Markovic & Lamb (2000).

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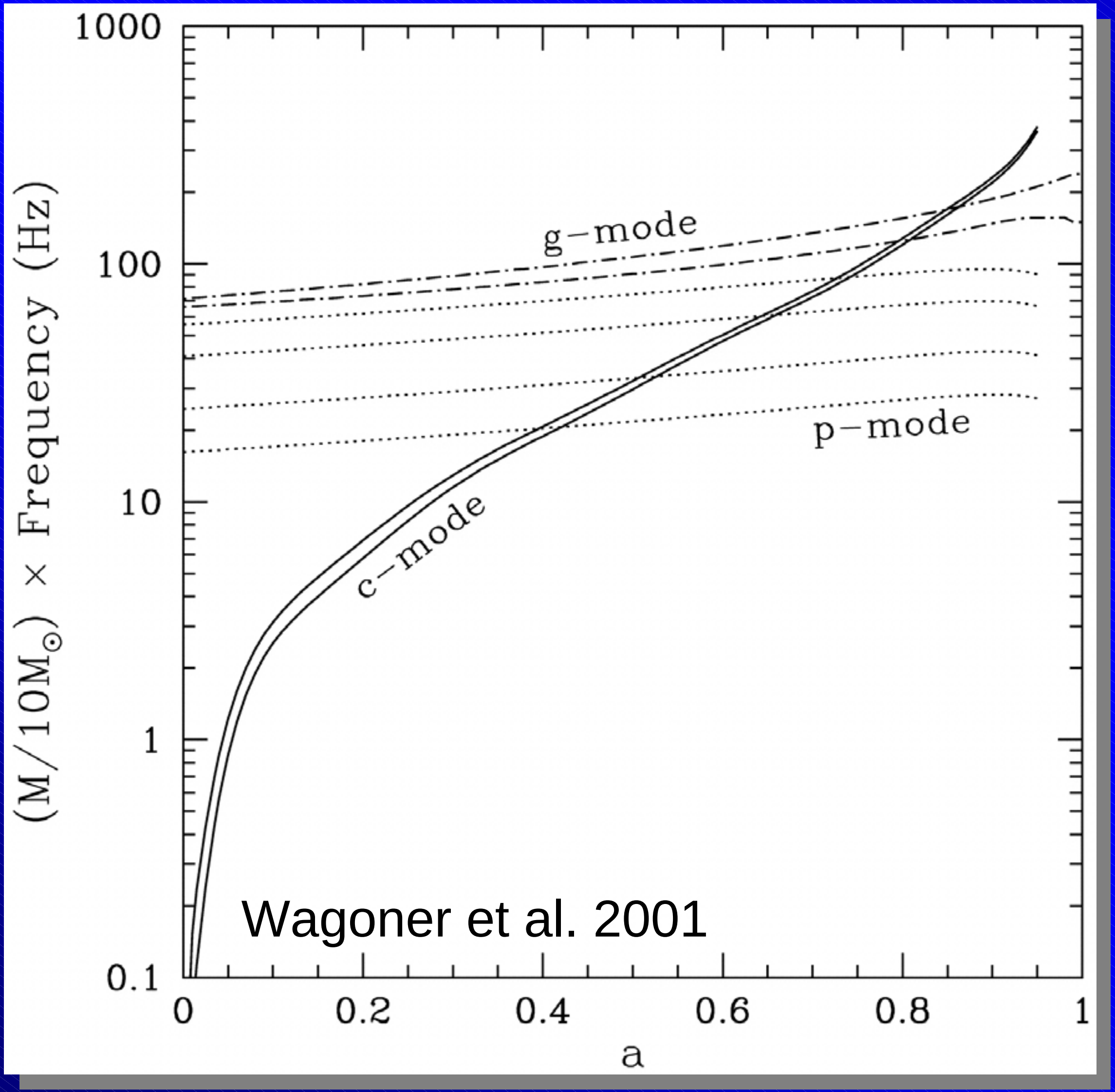
Models of X-ray Variability: "Diskoseismology"



- Fundamental oscillation modes of accretion disks.
- Pair of modes could be fundamental g- and c-modes.
- Requires rapidly spinning holes to match observed frequencies.
- Relatively insensitive to luminosity (stable).
- Excitation, amplitudes? Can constrain a if correct.
- Wagoner, Nowak, Perez, Silbergleit, Kato, Fukue, Thorne.

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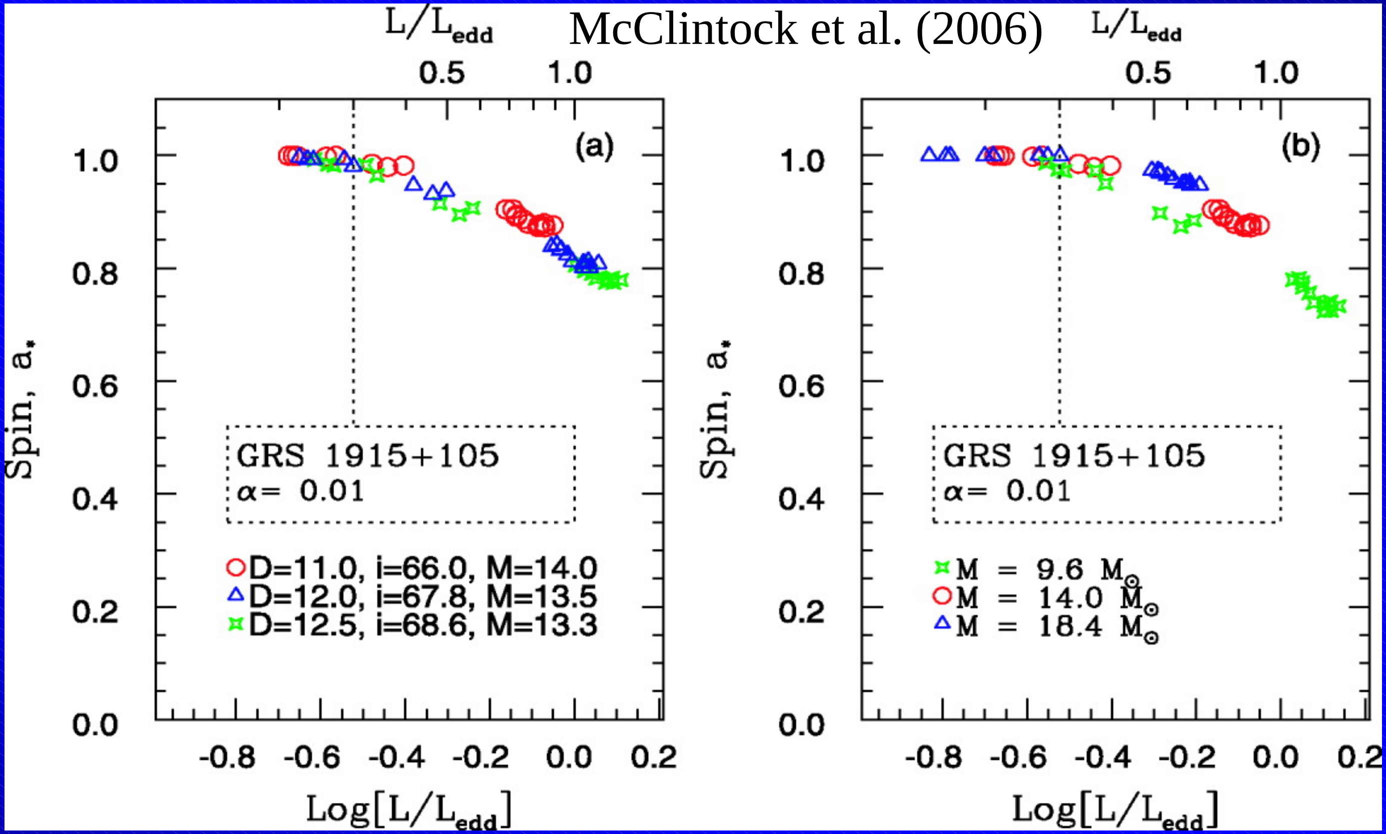
Constraining Black Hole Spin: X-ray Spectra



- For thermal emission from thin disk: $T_{in} \alpha M^{-1/4} R_{in}^{-3/4}$
- Innermost stable radius is determined by angular momentum, a.
- Spectral modeling, if M and distance constrained, can be used to estimate a.

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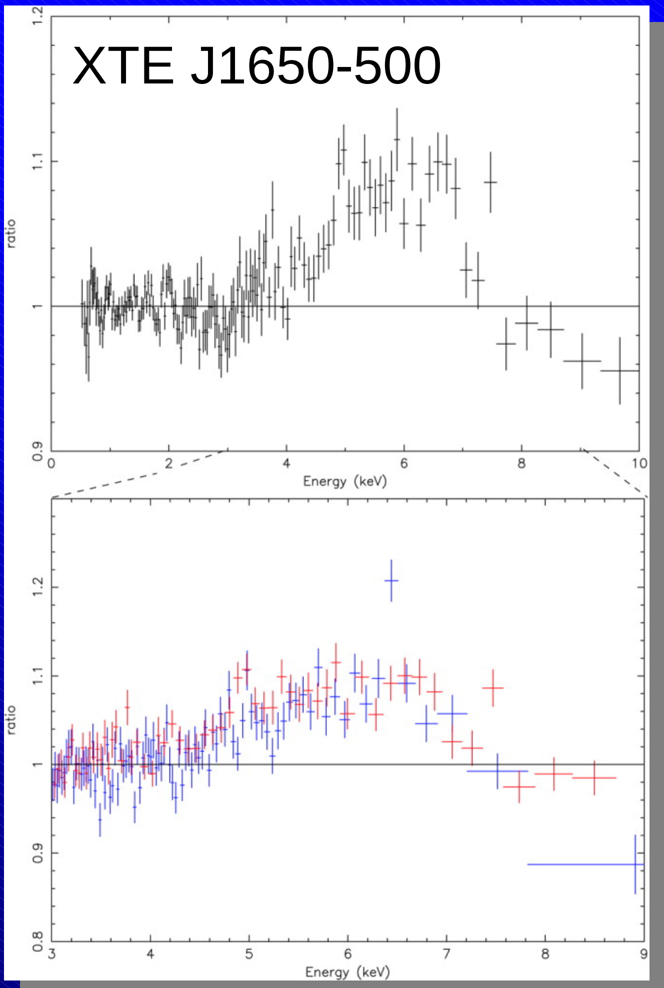
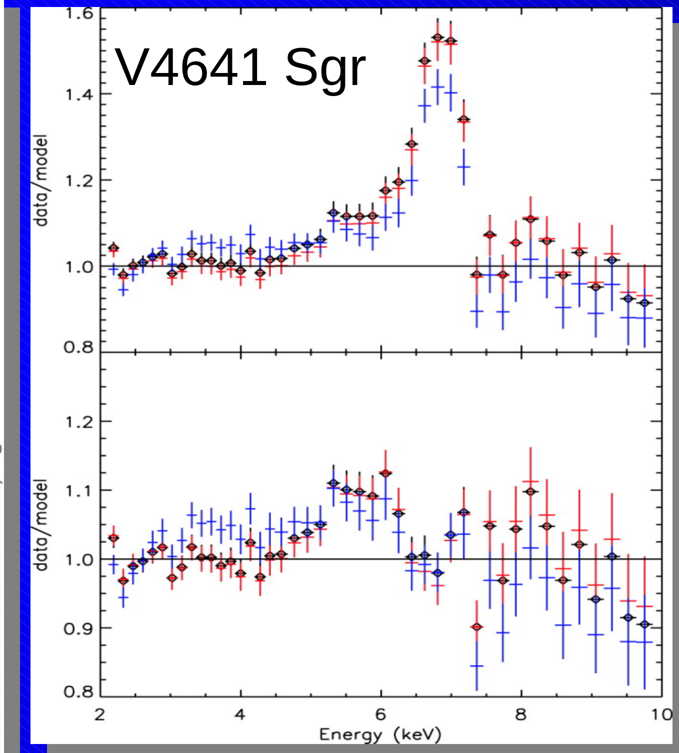
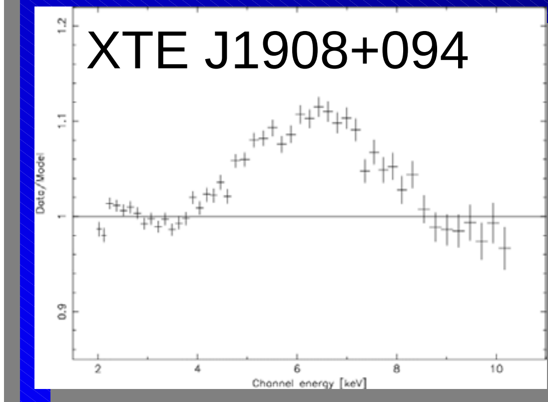
Relativistic Fe Kα Lines from Galactic Black Hole Binaries

Miller et al. 2002







In 't Zand et al. 2002

Miller et al, 2002

- Broad, asymmetric lines, thought to be reflection features from inner disk, probes curved space-time near black hole event horizon. Gravitational redshift and relativistic beaming important.

Sources of Thermonuclear X-ray Bursts: LMXBs Containing Neutron Stars

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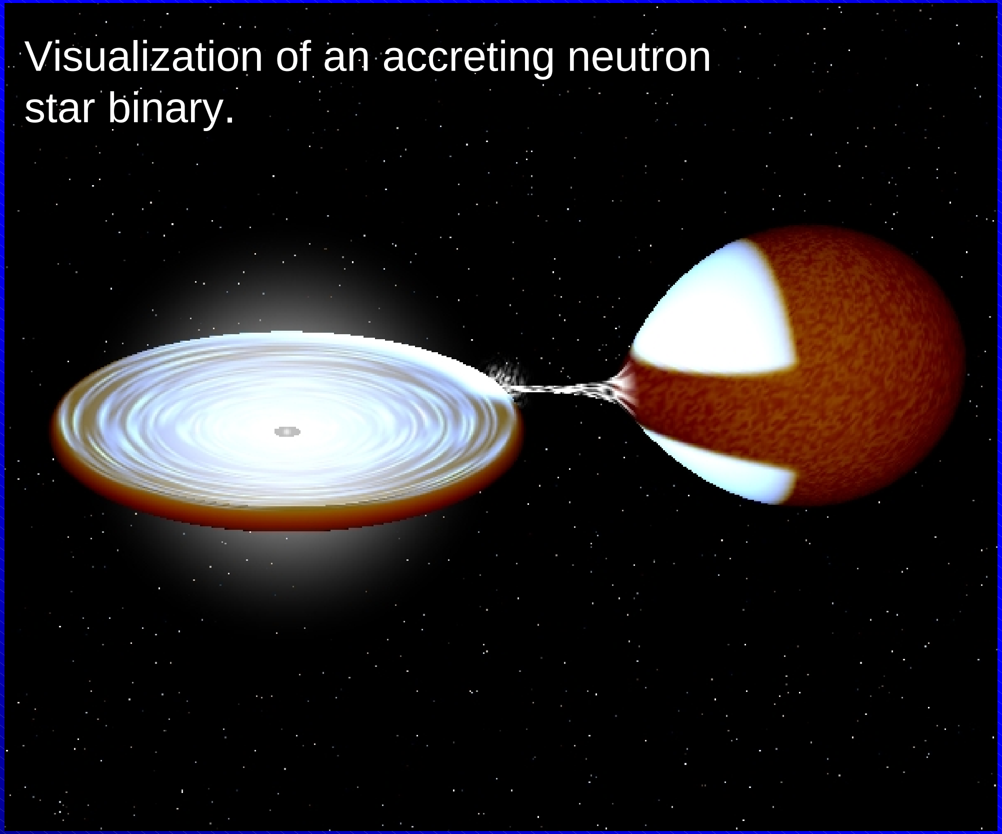

Credit: Rob Hynes (binsim)

Fun fact: a typical burst is equivalent to 100, 15 M-ton 'bombs' over each cm^2 !!

Accretion should spin-up the neutron star!

- Accreting neutron stars in low mass X-ray binaries (LMXBs).
- Approximately 80 burst sources are known.
- Concentrated in the Galactic bulge, old stars.
- Bursts triggered by thermally unstable He burning at column of few x 10^8 gm cm^{-2}
- Liberates ~ 10^{39} – 10^{43} ergs.
- Recurrence times of hours to a few days (or years).

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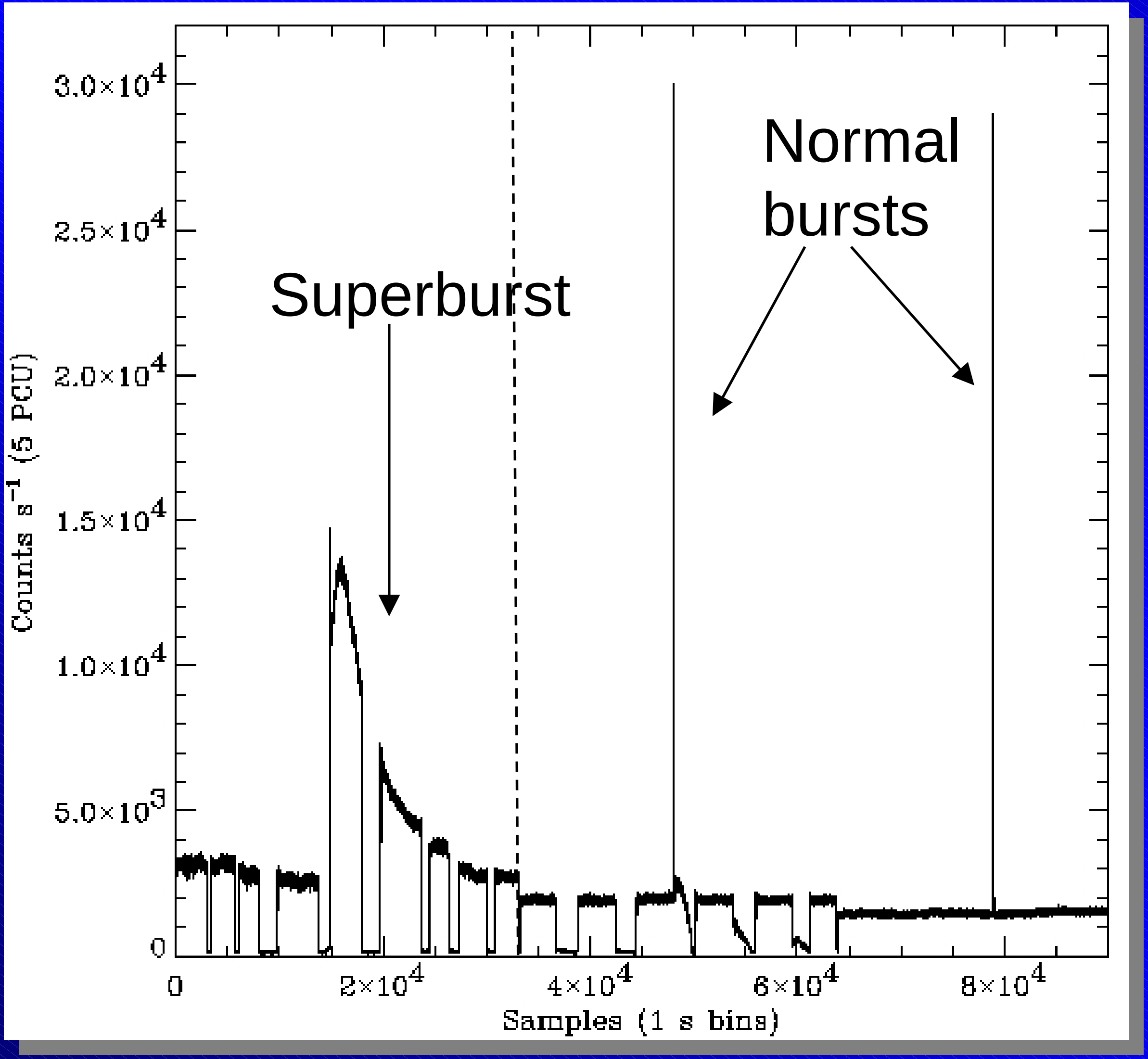
X-ray Bursting Neutron Stars and Black hole event horizons?

- Accreted matter piles onto the neutron star, doesn’t vanish across an event horizon. We see the results, X-ray bursts.
- If binary parameters are the same, mass donors similar, then if black holes had a “surface,” should they also produce X-ray bursts?
- Stability calculations by Cooper, Narayan, Heyl, suggest you would have bursts.
- Observationally, no confirmed black hole binary has ever shown a *bona fide,* thermonuclear X-ray burst (Remillard et al. 2006).
- Seems consistent with an event horizon, but may be consistent with other scenarios without an event horizon.
- Observation of 1 burst would falsify the argument.

Accreting Neutron Star binaries: What do we see?



- Accretion of matter converts gravitational potential energy to radiation (X-rays, persistent flux)
- At various accretion rates, thermonuclear instabilities occur in the accreted material. X-ray bursts.
- Can produce normal bursts (hours to days) and superbursts (years).
- Normal bursts powered by H – He, superbursts powered by C, heavier elements!

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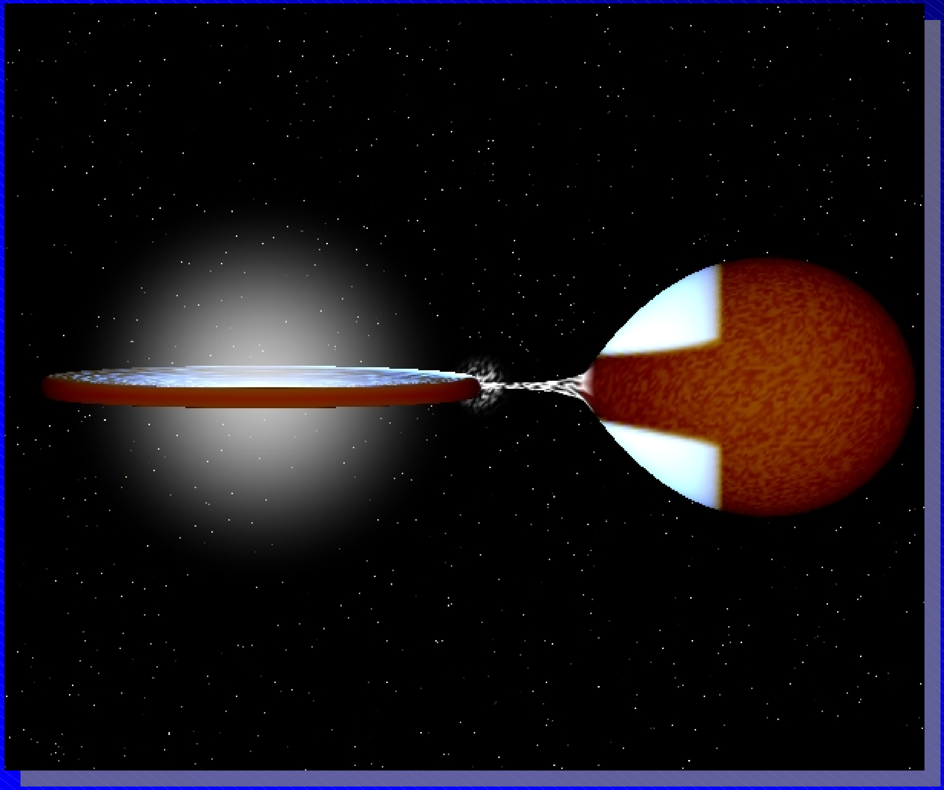
EXO 0748-676 Summary

- Eclipsing – dipping LMXB, discovered by EXOSAT.
- Orbital period of 3.82 hours.
- Eclipses and orbit period indicate high inclination: 75 < *i* < 82 degrees.
- X-ray bursts indicate neutron star accretor.
- ~1 Hz QPOs and so far only 1 observed kHz QPO.



- Evidence for gravitationally redshifted absorption lines (Cottam et al. 2002), z = 0.35.

Why Study Bursting Neutron Stars?

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- $E_{emit} / E_{obs} = (1+z) = 1/ (1 - 2GM/c^2R)^{1/2}$ **=>** m/R
- Continuum spectroscopy; $L_{obs} = 4\pi R^2 \sigma T_{eff}^4 = 4\pi d^2 f_{obs}$
- Eddington limited bursts; $L_{Edd} = 4\pi R^2 \sigma {T^{Edd}}_{eff}^4 = g(M, R)$
- For most likely rotation rates, line widths are rotationally dominated, measure line widths and can constrain R (if Ω known).
- If detect several absorption lines in a series (Hα, and Hβ, for example), can constrain m/R^2 .
- Timing (burst oscillations) also give M – R constraints.
- In principle, there are several independent methods which can be used to obtain M and R (Constellation-X can do all).

Hi-res X-ray Spectroscopy of Neutron Stars: Recent Results

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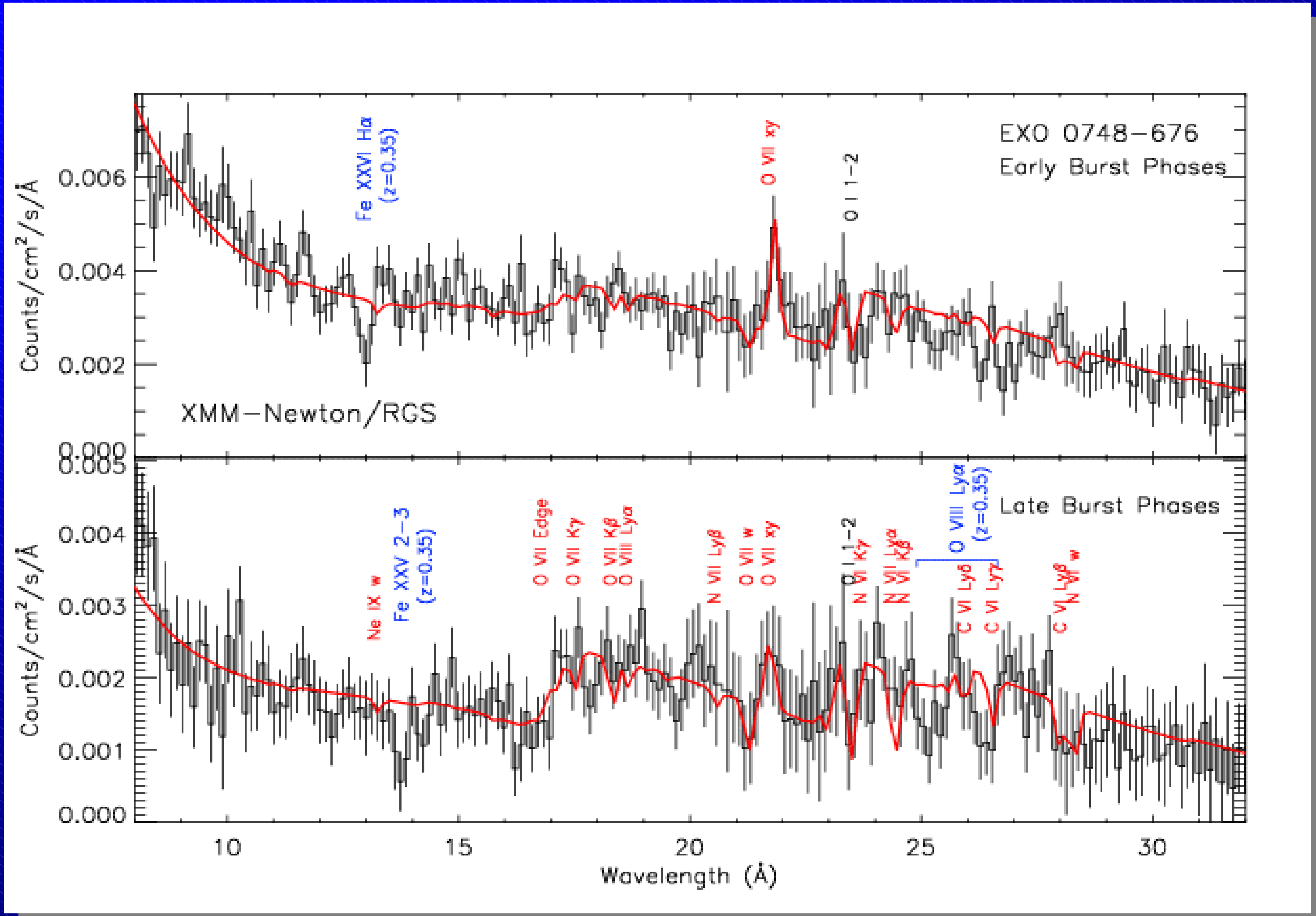
XMM/Newton grating observations of X-ray bursts from an accreting neutron star (EXO 0748-676); Cottam, Paerels, & Mendez (2002).



EXO 0748-676: Search for Burst Oscillations

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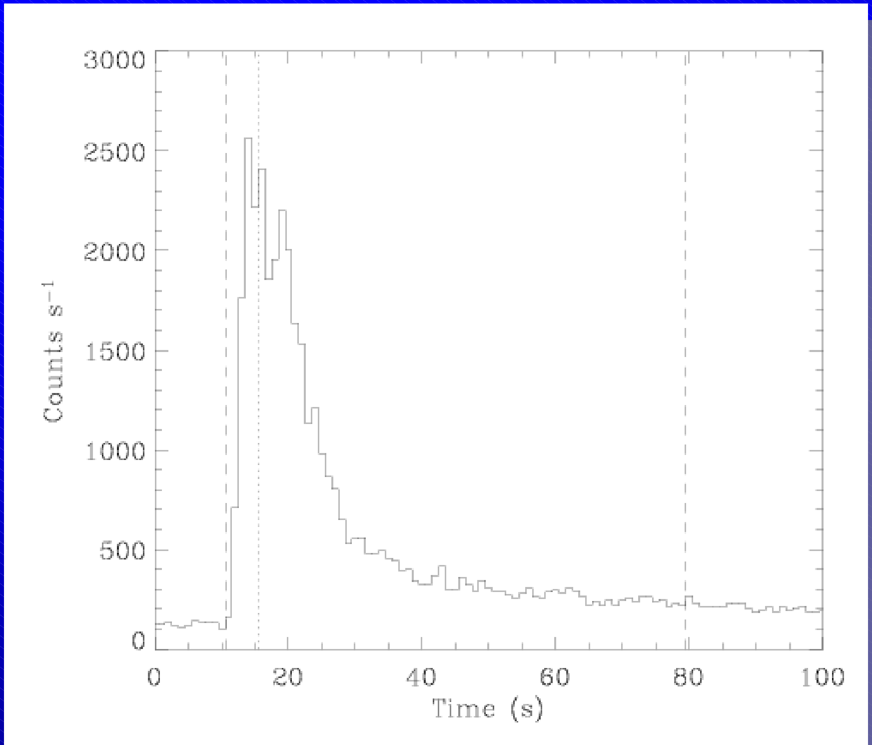
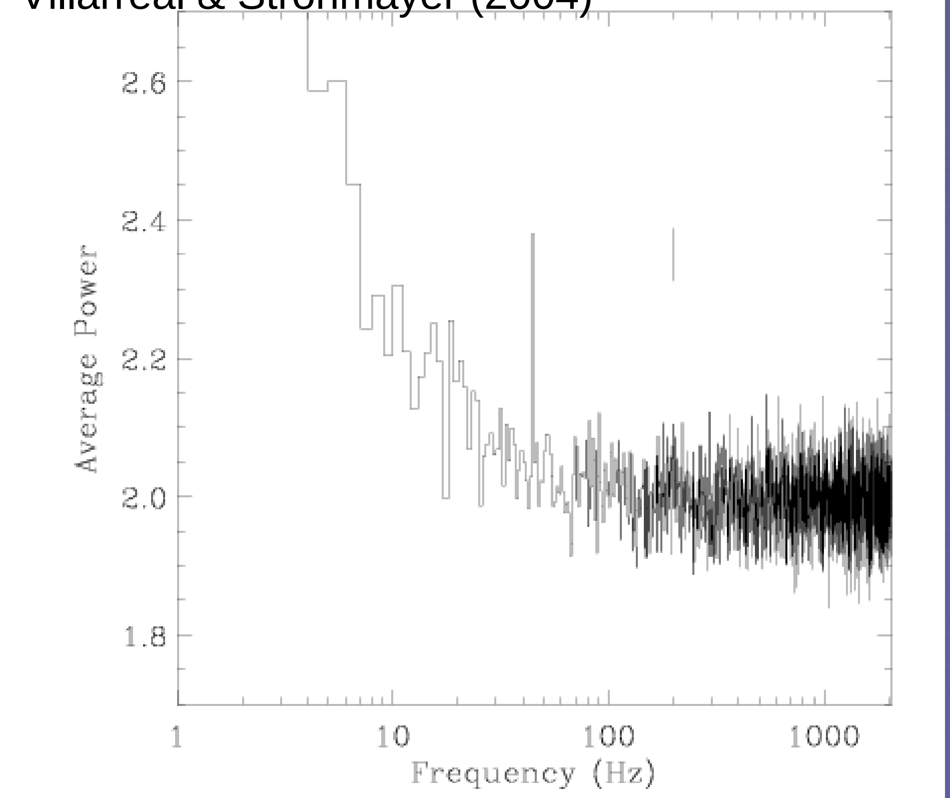


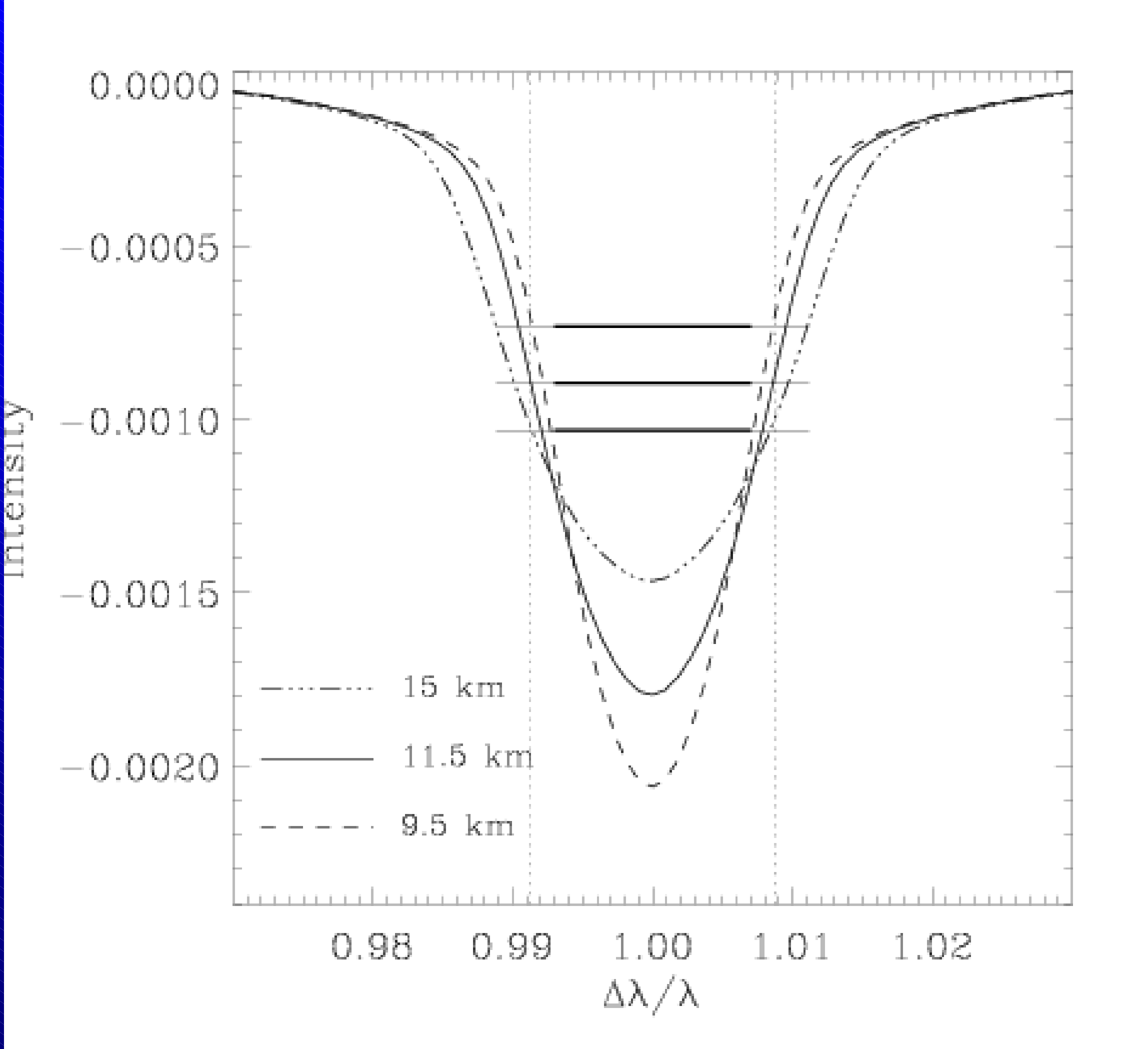
- 38 RXTE X-ray bursts.
- Calculated Power spectra for rise and decay intervals

Villarreal & Strohmayer (2004)



- Averaged (stacked) all 38 burst power spectra.
- 45 Hz signal detected in decay intervals.

Rotational Doppler Broadening of Lines



- Surface rotational velocity gives Doppler shift.
- Dominates over thermal Doppler and pressure (Stark) broadening.
- Line widths from Cottam et al. (2002) consistent with 45 Hz spin, and constrain the neutron star radius (9.5 < R < 15) km.

Spectral Line Profiles: Probing Frame Dragging Around a Neutron Star

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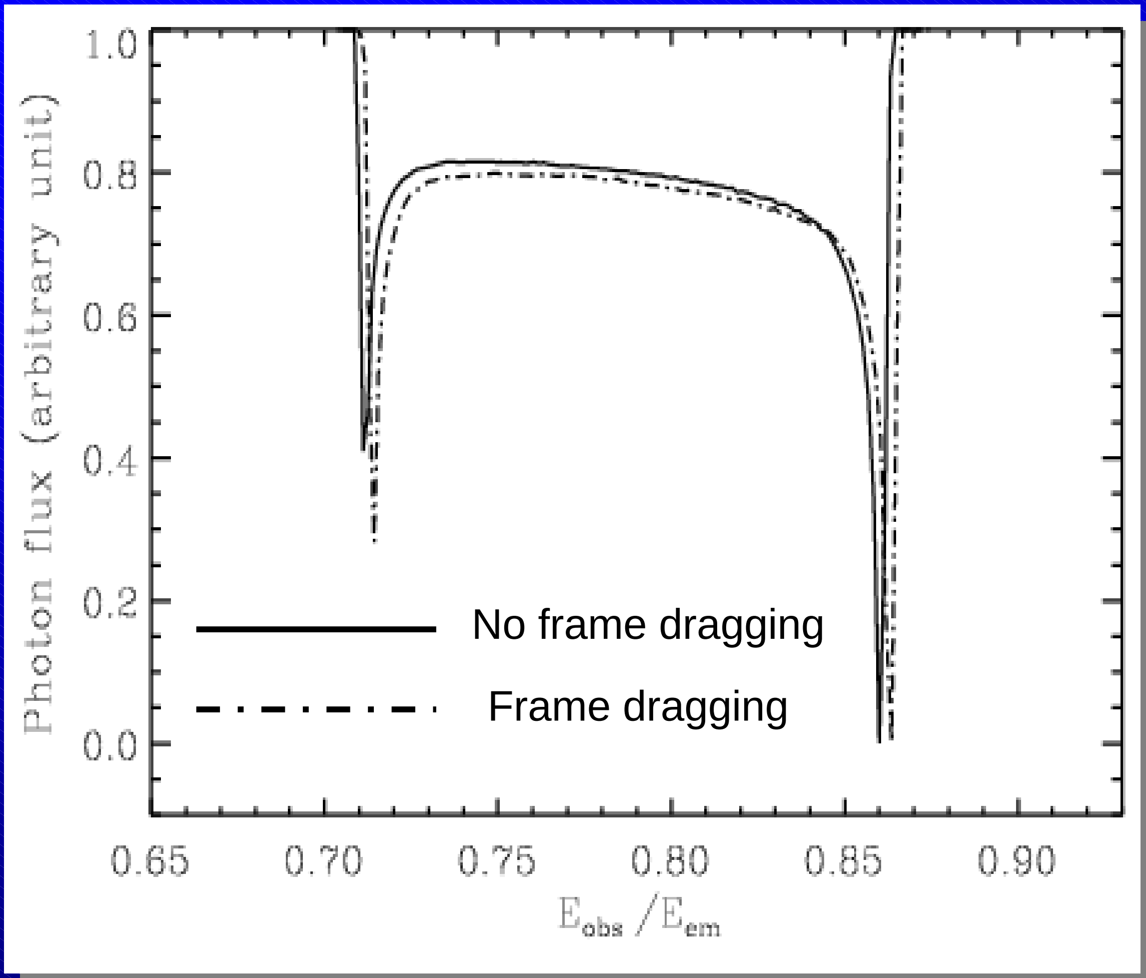

Credit: Bhattacharyya, Miller & Lamb (2003)

- Accreting neutron stars in binaries spinning at ~300 - 600 Hz.
- v_{rot} ~ 0.1c at surface!
- Linewidth dominated by rotation. Measurement of width can constrain R.
- Double peaked profile when fraction of NS surface emitting (as during burst oscillations).
- Relative depth of two peaks is sensitive to frame dragging term (Bhattacharyya, Miller & Lamb 2003).

EOS of Neutron Stars: Future with Constellation-X

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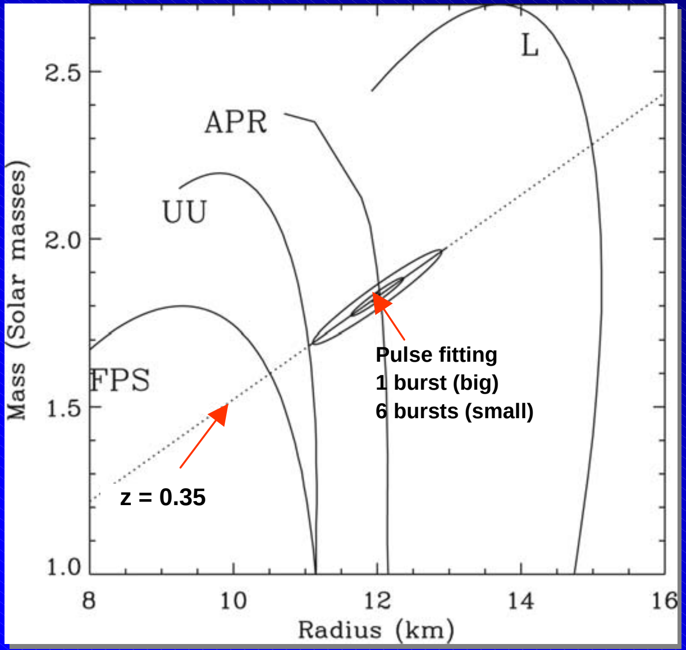
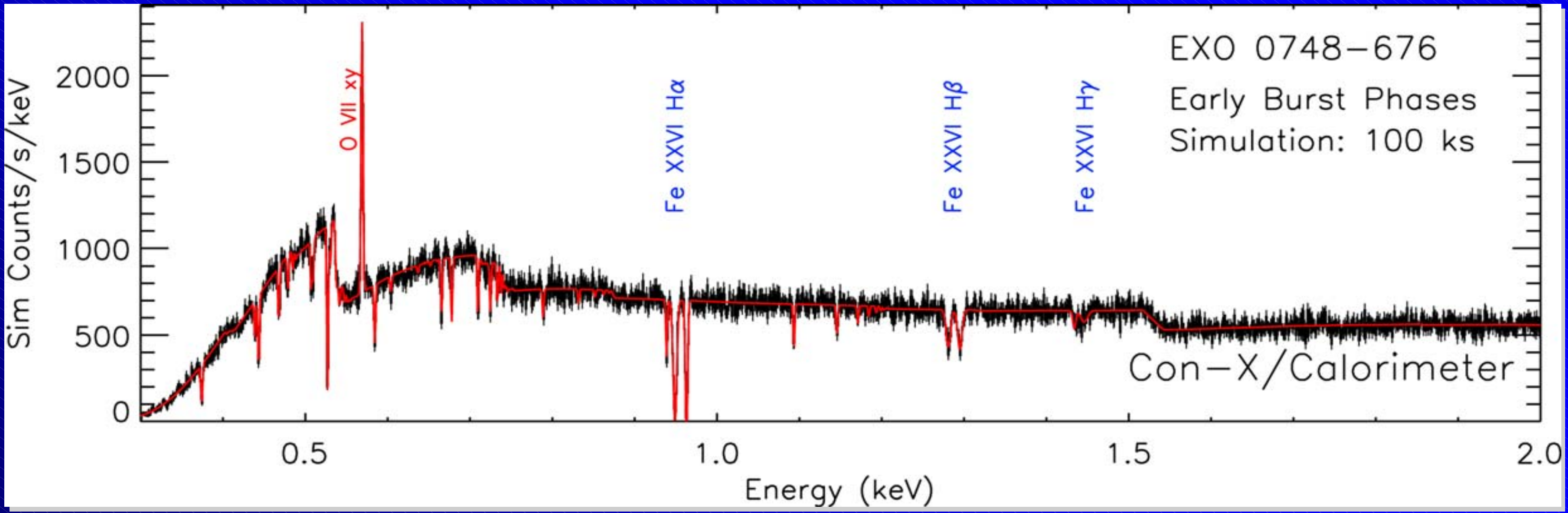
- Con-X will provide many high S/N measurements of X-ray burst absorption spectra:
- The relative strength of higher-order transitions provides a measure of density ⇒ unique M, R.
- Absorption line widths can constrain R to 5 – 10%.
- Pulse shapes of burst oscillations can provide independent measure of mass and radius to a few percent.
- Measure of gravitational red-shift at the surface of the star for multiple sources, constrains M/R.





Oscillations during X-ray Bursts

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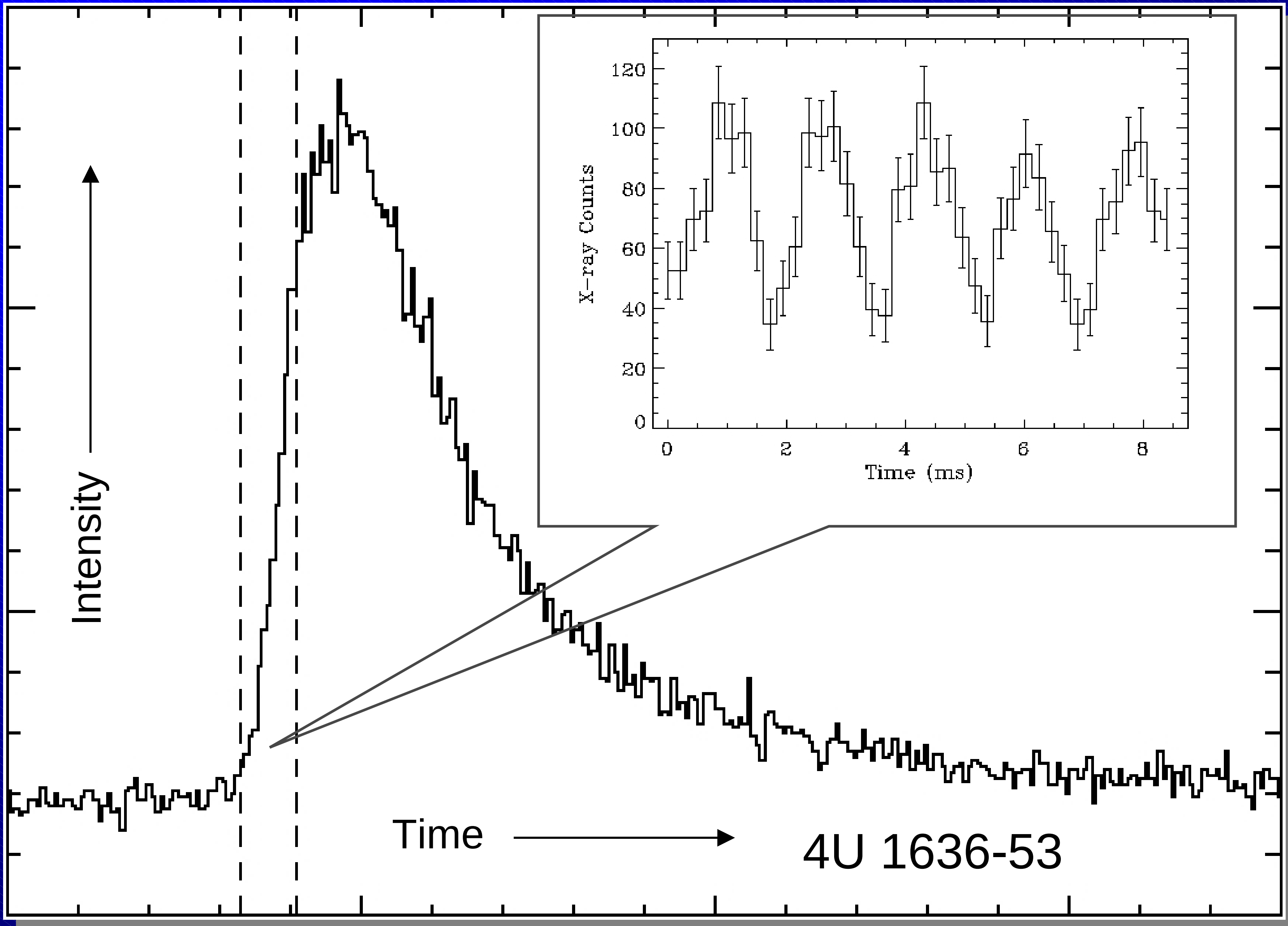

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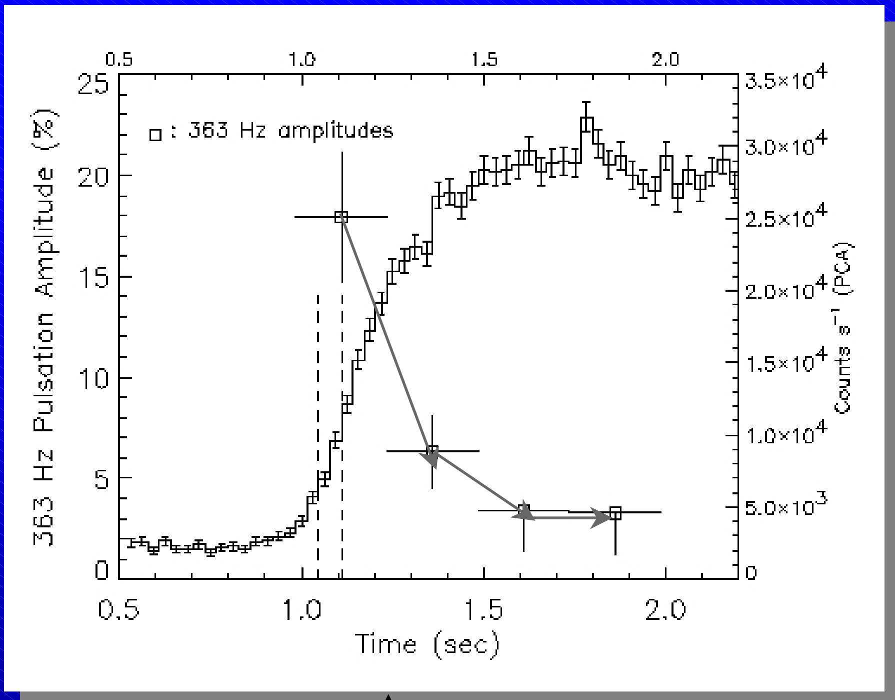
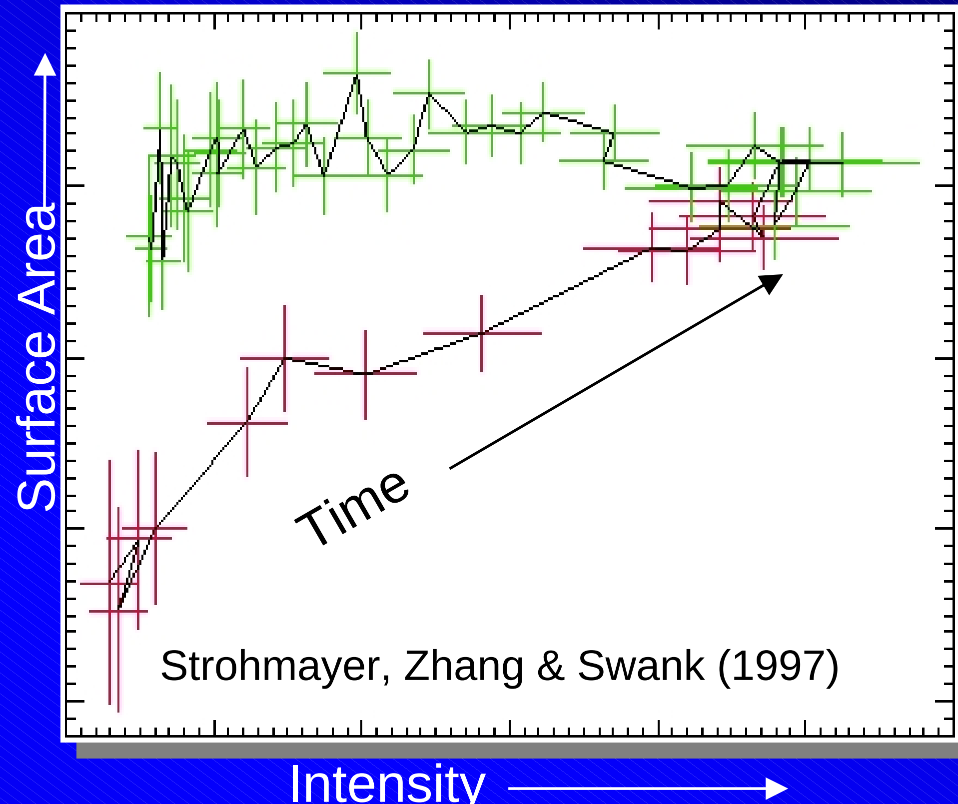
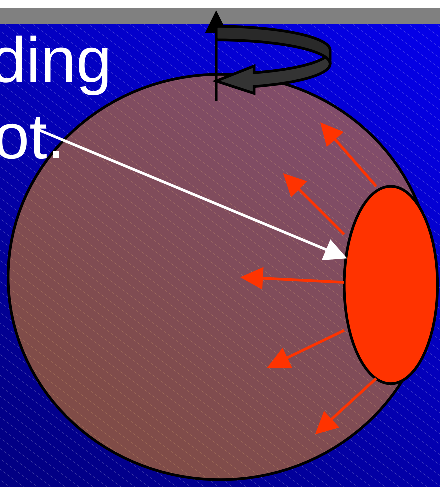
Timing and Spectral Evidence for Rotational Modulation





Spreading hot spot



- Oscillations caused by hot spot on rotating neutron star
- Modulation amplitude drops as spot grows.
- Spectra track increasing size of X-ray emitting area on star.

Discovery of Neutron Star Spin Rates in Bursting LMXBs

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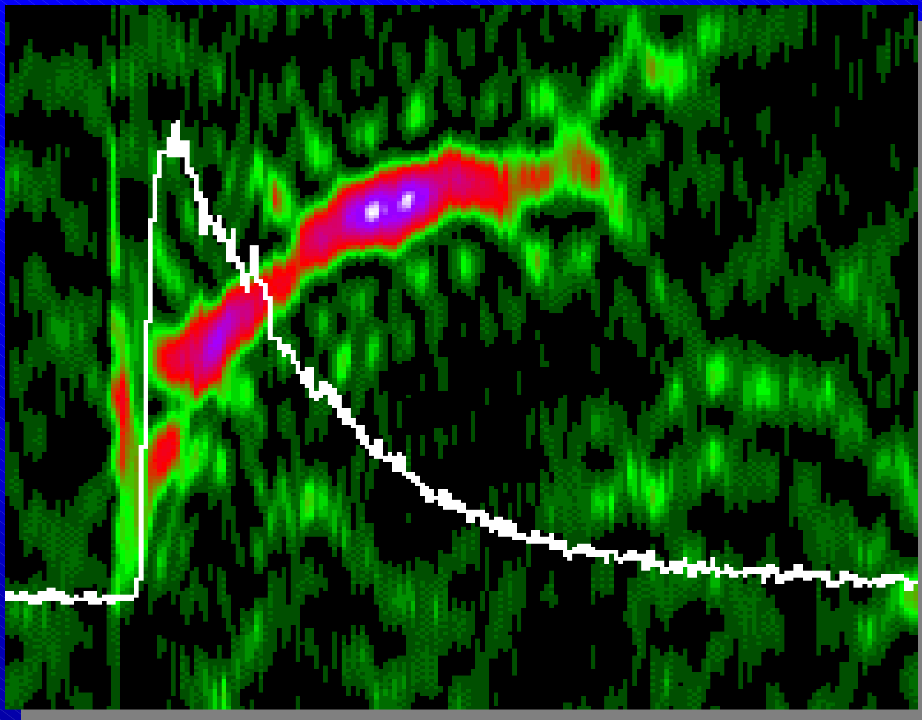
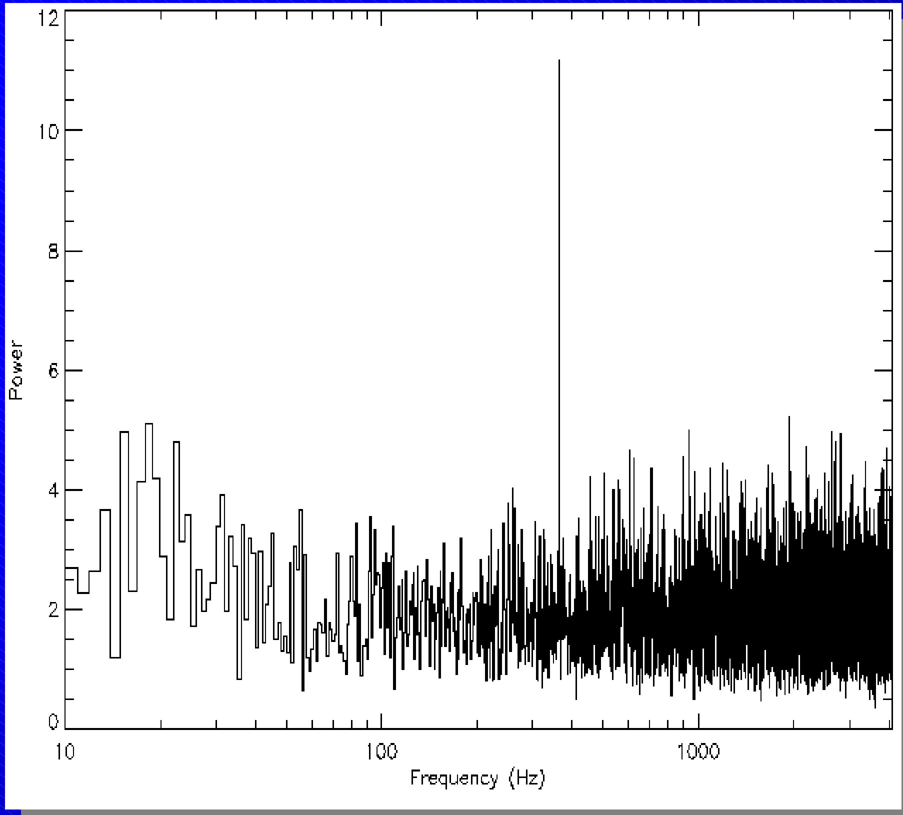


- Discovered in Feb. 1996, shortly after RXTE's launch (Strohmayer et al, 1996)
- First indication of ms spins in accreting LMXBs.



- 4U 1728-34, well known X-ray burst source.
- Power spectra of burst time series show significant peak at 363 Hz.

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Source Summary

Sources	Frequency (Hz)	Separation (Hz)
KS 1731-26	524	260
4U 1728-34	363	363 – 280
Galactic Center	589	Unknown
4U 1636-53	581	276 – 251
Aql X-1	549	Unknown
4U 1702-429	330	330
X1658-298	567	Unknown
4U 1916-053	270	290-348
4U 1608-52	619	312
SAX J1808-365	401*	200
SAX J1750-290	601	Unknown
XTE J1814-338	314*	Unknown
A1744-361	530	Unknown
SAX J1748.9-2021	410	Unknown

EXO 0748-676 45 Hz

*millisecond pulsar

How Fast Can Neutron Stars Spin?

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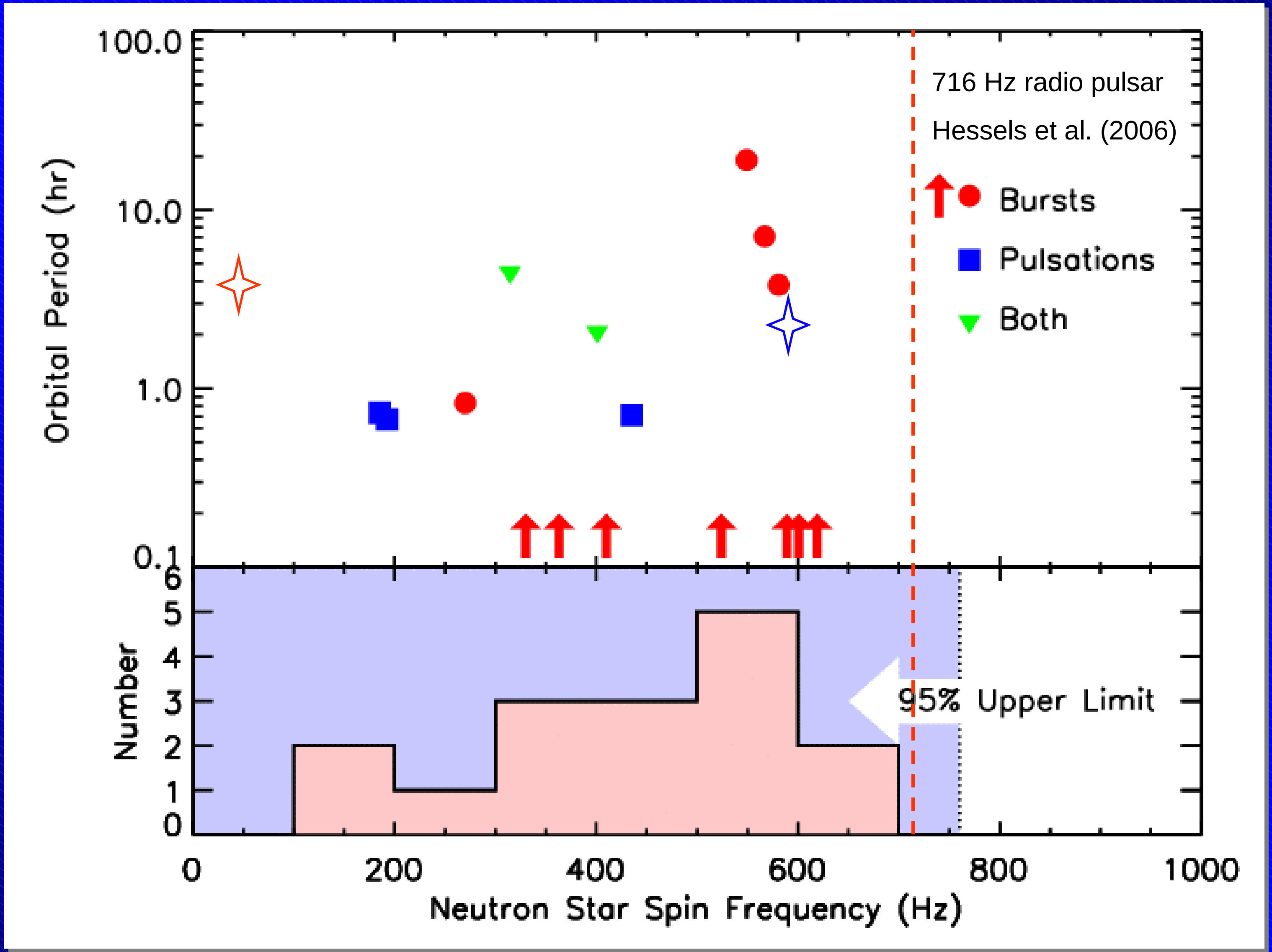

Chakrabarty et al. (2003) suggest upper limit to neutron star spin frequencies.

Burst Oscillations Probe the Structure of Neutron Stars

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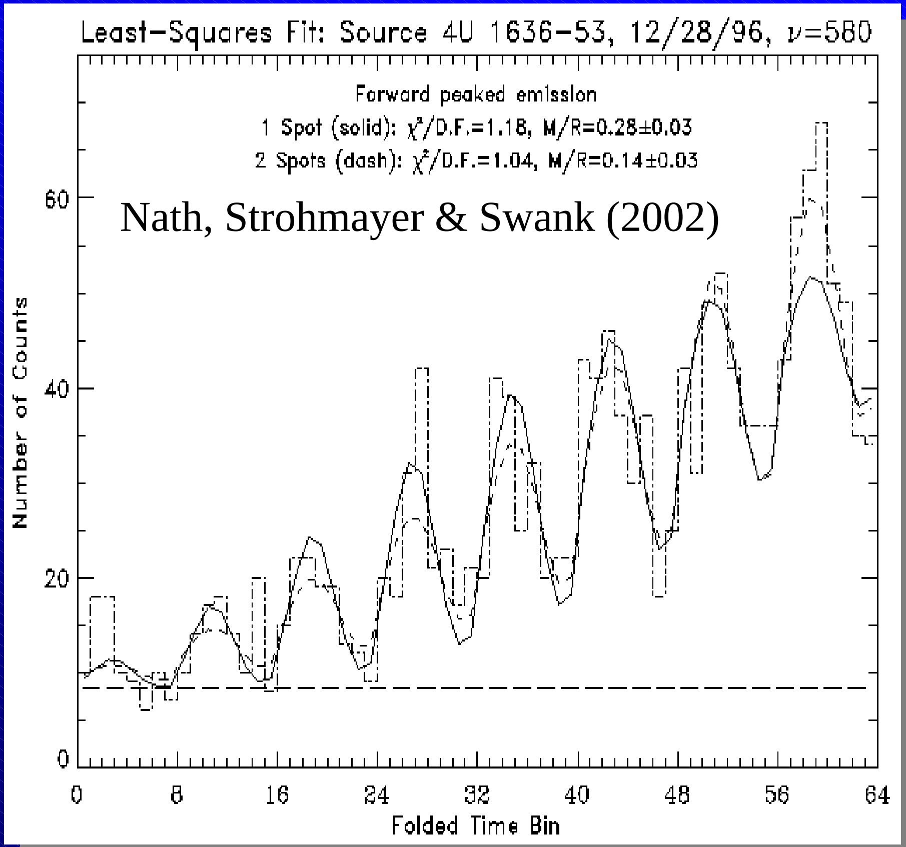
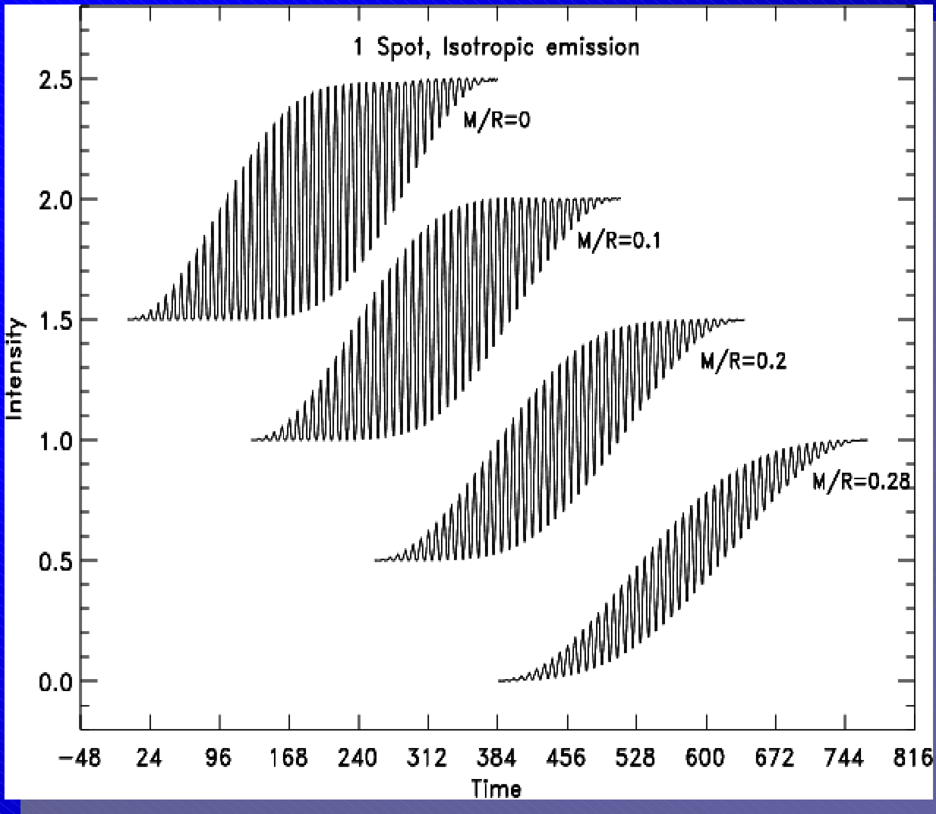
- Pulse strength and shape depends on M/R or 'compactness' because of light bending (a General Relativistic effect).
- More compact stars have weaker modulations.
- Pulse shapes (harmonic content) also depend on relativistic effects (Doppler shifts due to rotation, which depends on R (ie. spin frequency known).





Rotational Modulation of Neutron Star Emission: The Model

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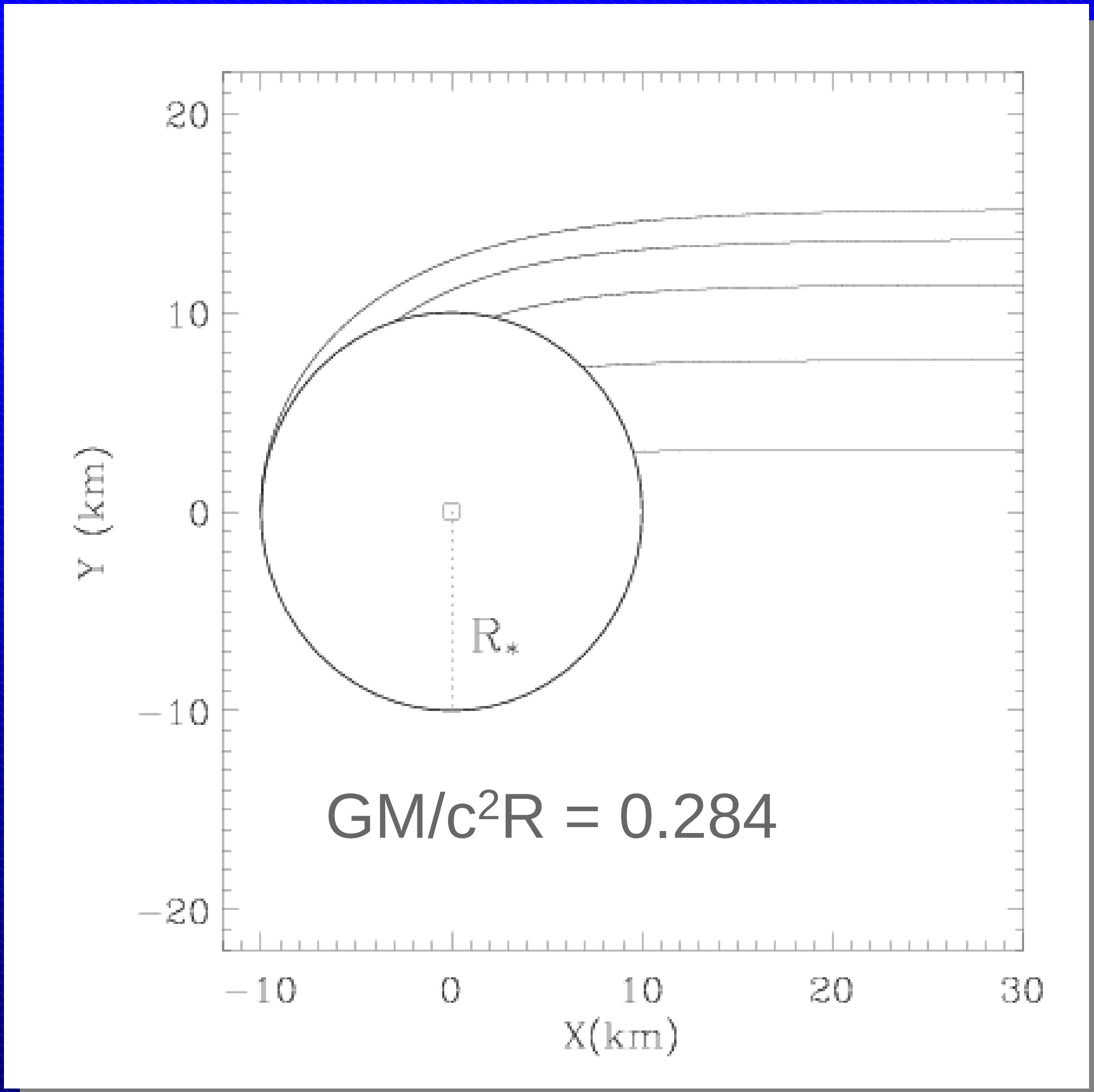
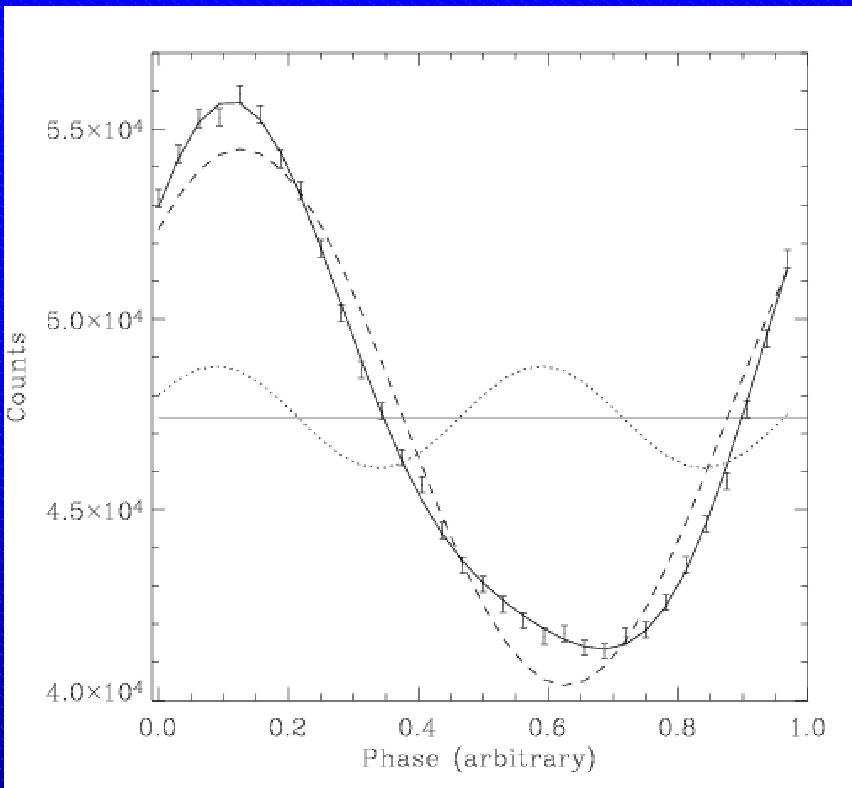
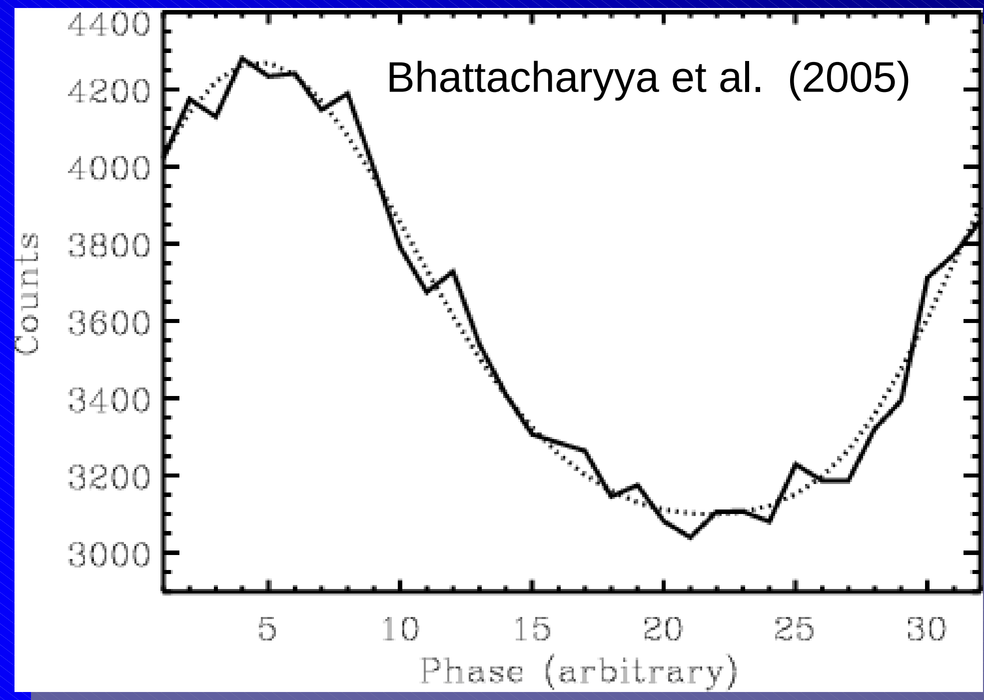


- Gravitational Light Deflection: Kerr metric with appropriate angular momentum.
- Gravitational redshift
- Rotational doppler shifts and aberration of the intensity.
- “Beaming” of intensity in NS rest frame.
- Arbitrary geometry of emission regions.
- Self-consistent neutron star structure (several EOSs).

Bhattacharyya, Strohmayer, Miller & Markwardt (2005).

Mass – Radius Constraints: Recent Results: XTE J1814-338





- 27 X-ray bursts from XTE J1814-338 (accreting ms pulsar).
- High signal to noise burst oscillation profiles, with first ever harmonics.
- Phase resolved profiles in 5 energy bands.

- Use Bayesian method, determine likelihoods for each combination of parameters (uniform priors).
- Parameters: R/M, spot location and size (2), beaming exponent, observers inclination angle. Fix surface temperature (BB).

Compactness limits from pulse fitting in XTE J1814-338

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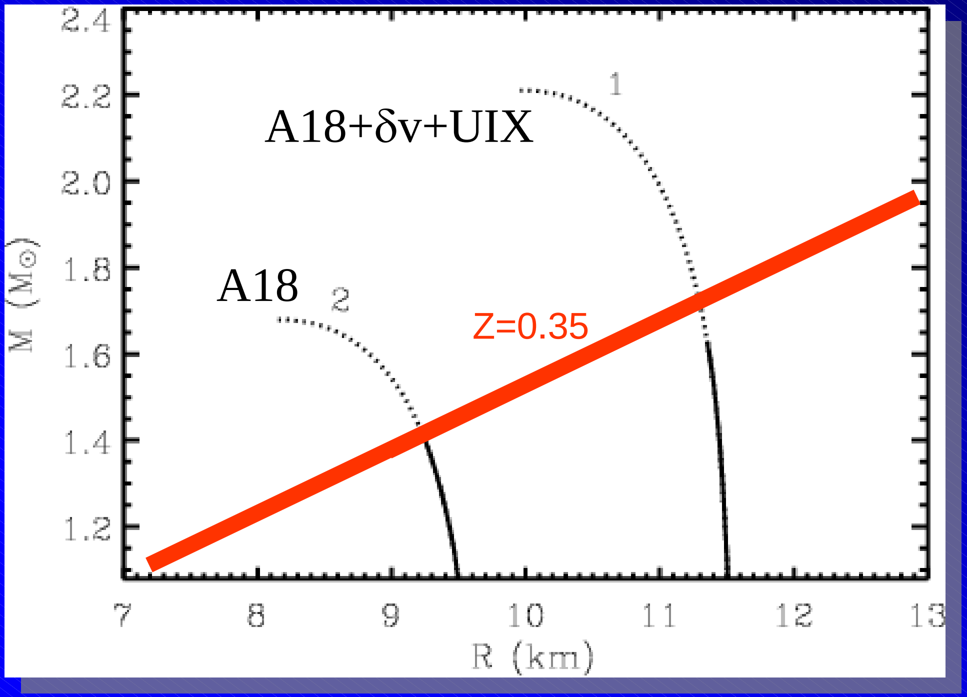
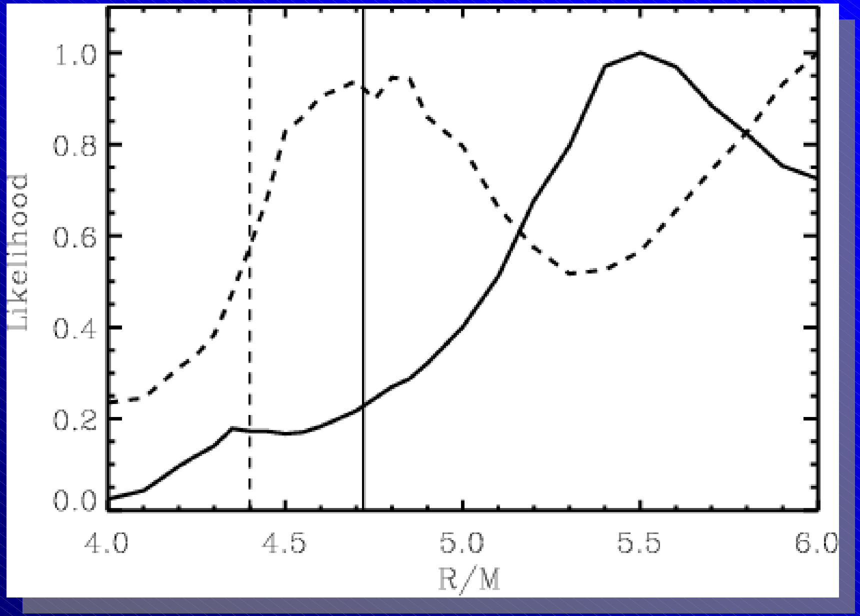
- Results for two representative EOSs (soft and stiff).
- Model provides an acceptable fit in the χ^2 sense.
- R/M distributions peak in "reasonable" range. R/M > 4.2.
- Likelihoods do not yet favor a particular EOS.





- Lattitude of hot spot near rotational equator (+ - 30 degrees).
- Moderately low inclination (30 – 50 degrees)
- Some evidence for spot size evolution during outburst.

Sources of Thermonuclear X-ray Bursts: LMXBs Containing Neutron Stars

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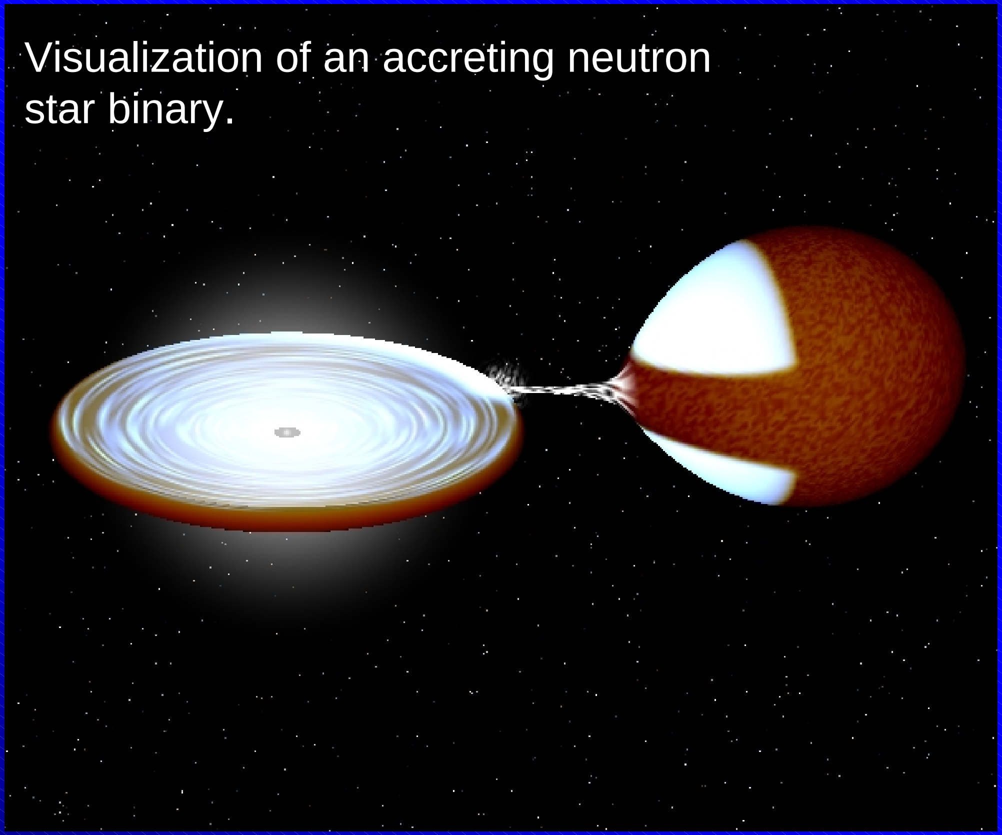

Credit: Rob Hynes (binsim)

Fun fact: a typical burst is equivalent to 100, 15 M-ton 'bombs' over each cm^2 !!

Accretion should spin-up the neutron star!

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NASA's Rossi X-ray Timing Explorer (RXTE)

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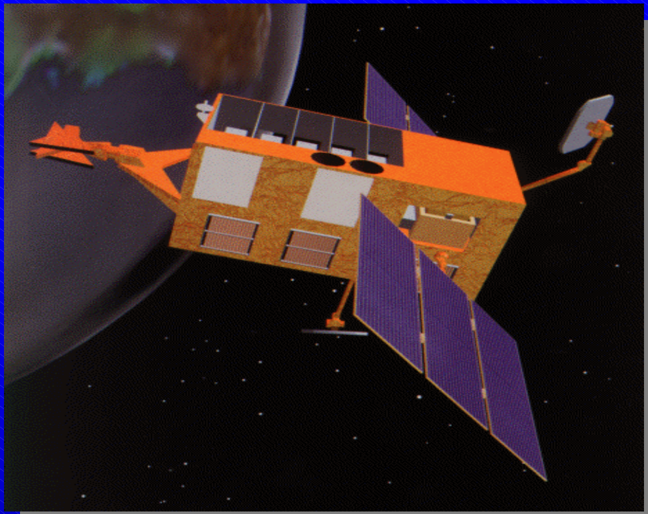
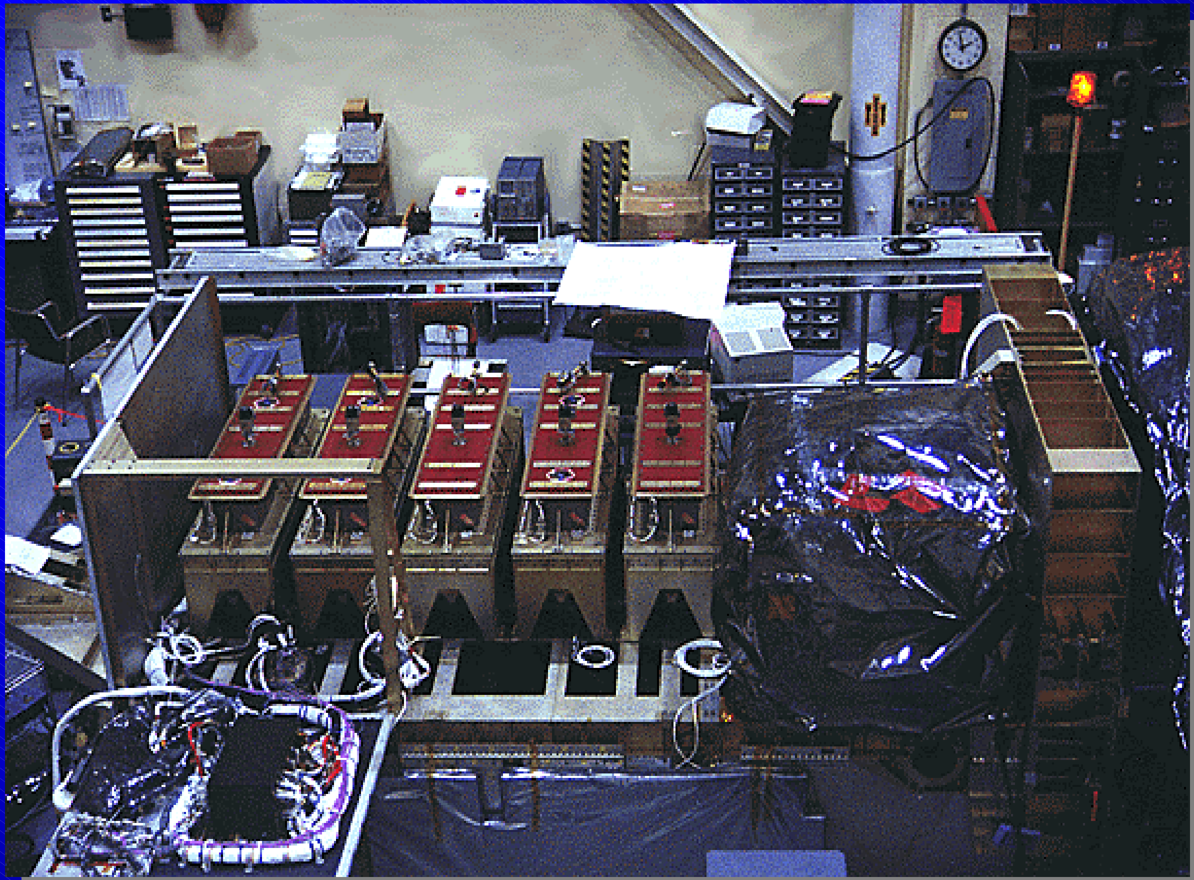


Launched in December, 1995, 10th anniversary party and symposium held at Goddard in January '06 !

http://heasarc.gsfc.nasa.gov/docs/xte/xte_1st.html



RXTE's Unique Strengths

- Large collecting area
- High time resolution
- High telemetry capacity
- Flexible observing

X-ray Bursts from Accreting ms Pulsars: SAX J1808 and XTE J1814

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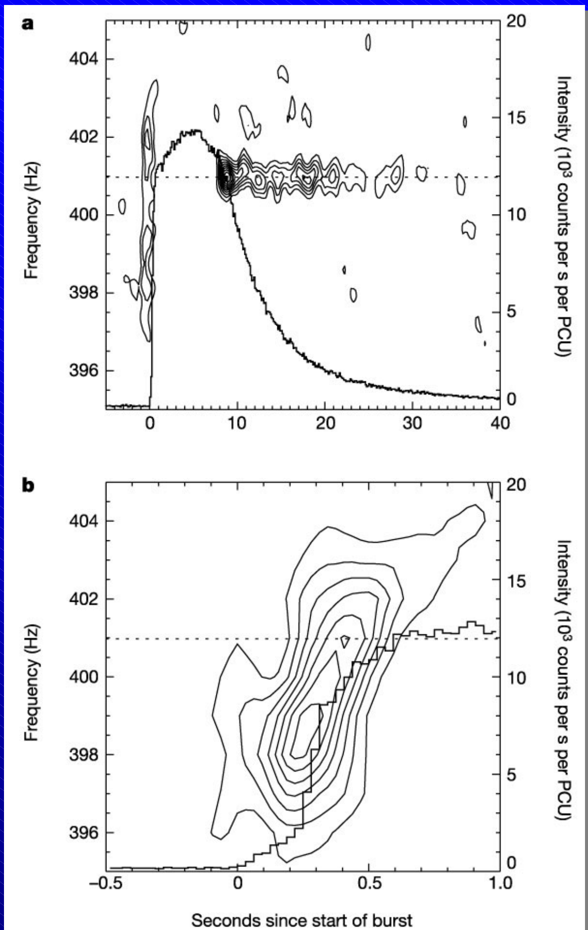
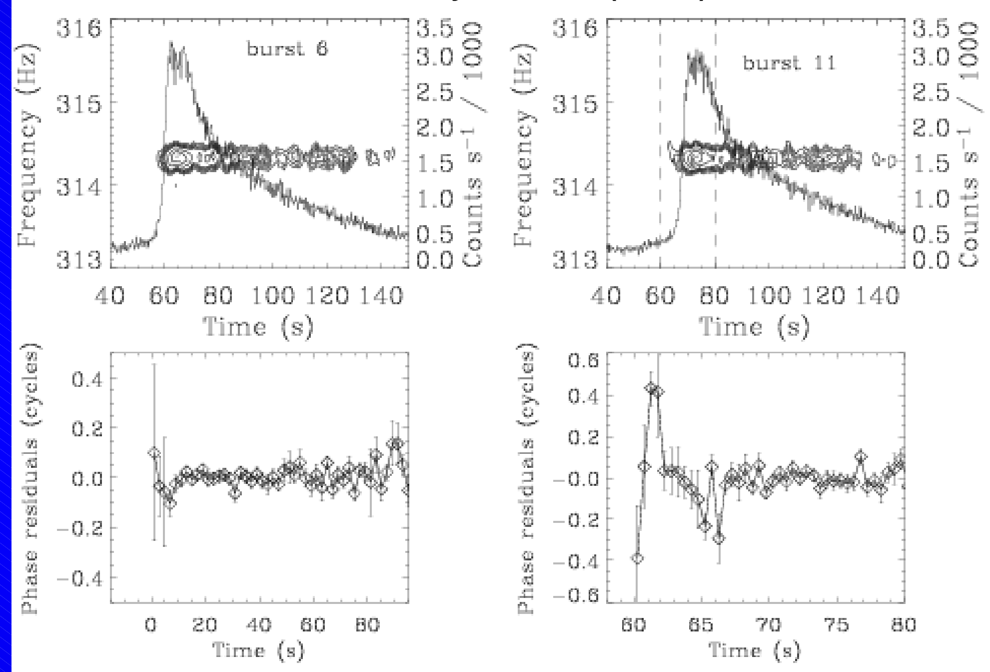
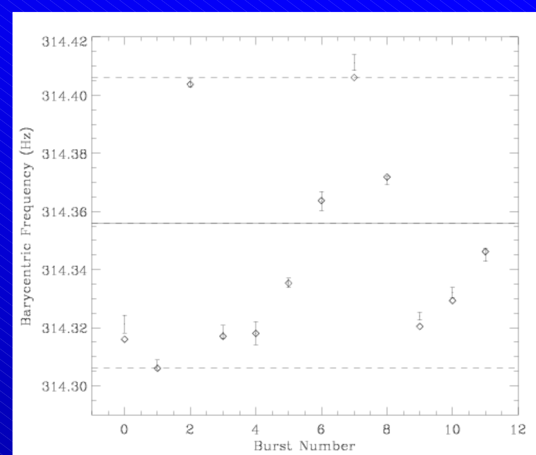
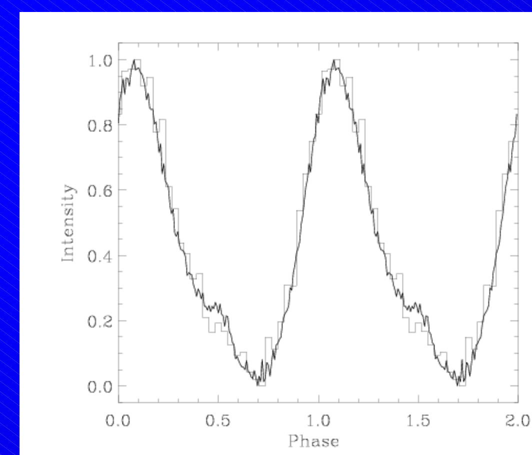


SAX J1808: Chakrabarty et al. (2003)

XTE J1814-338: Strohmayer et al. (2003)







Puzzle # 1: Frequency Evolution of Burst Oscillations

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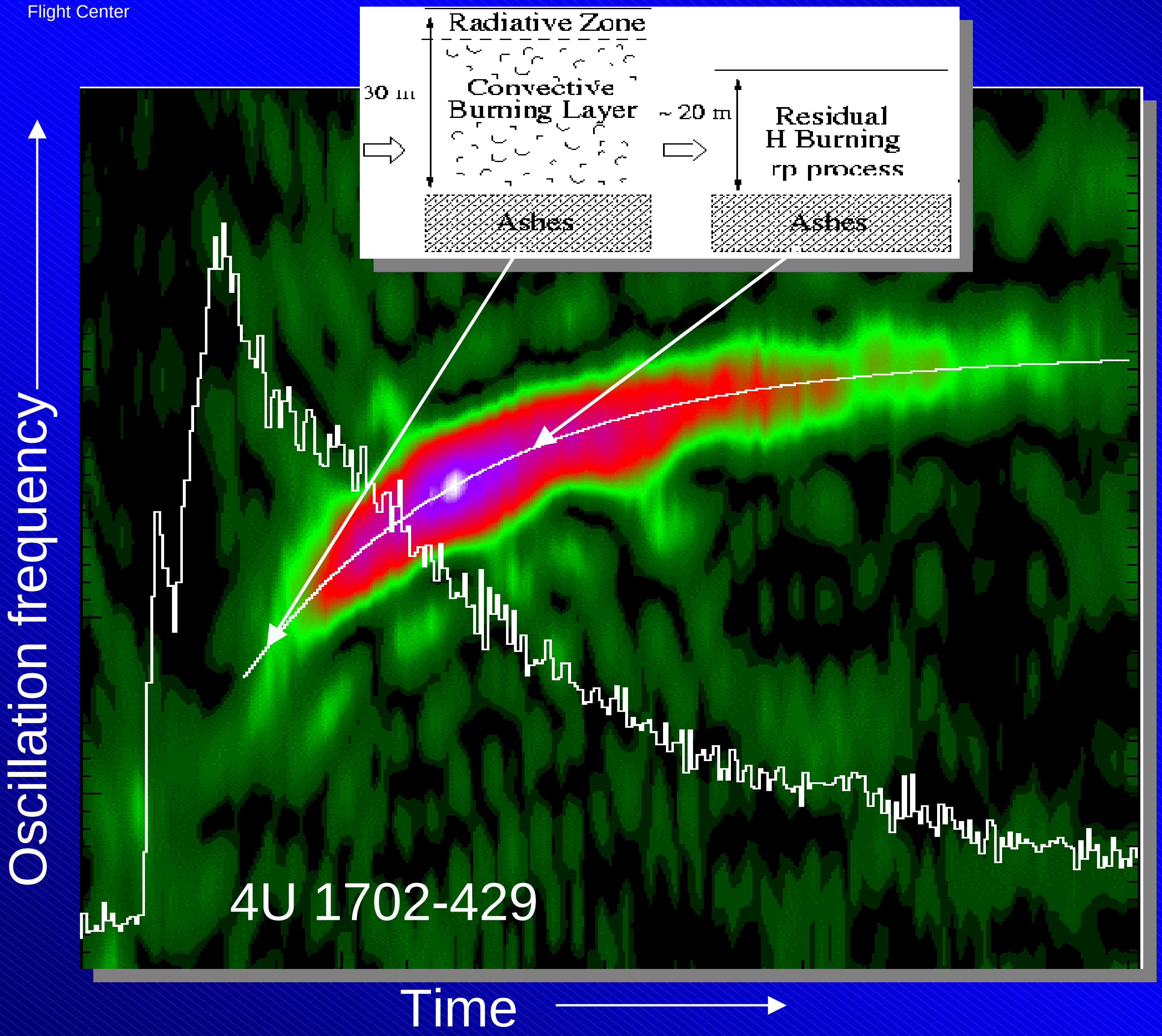
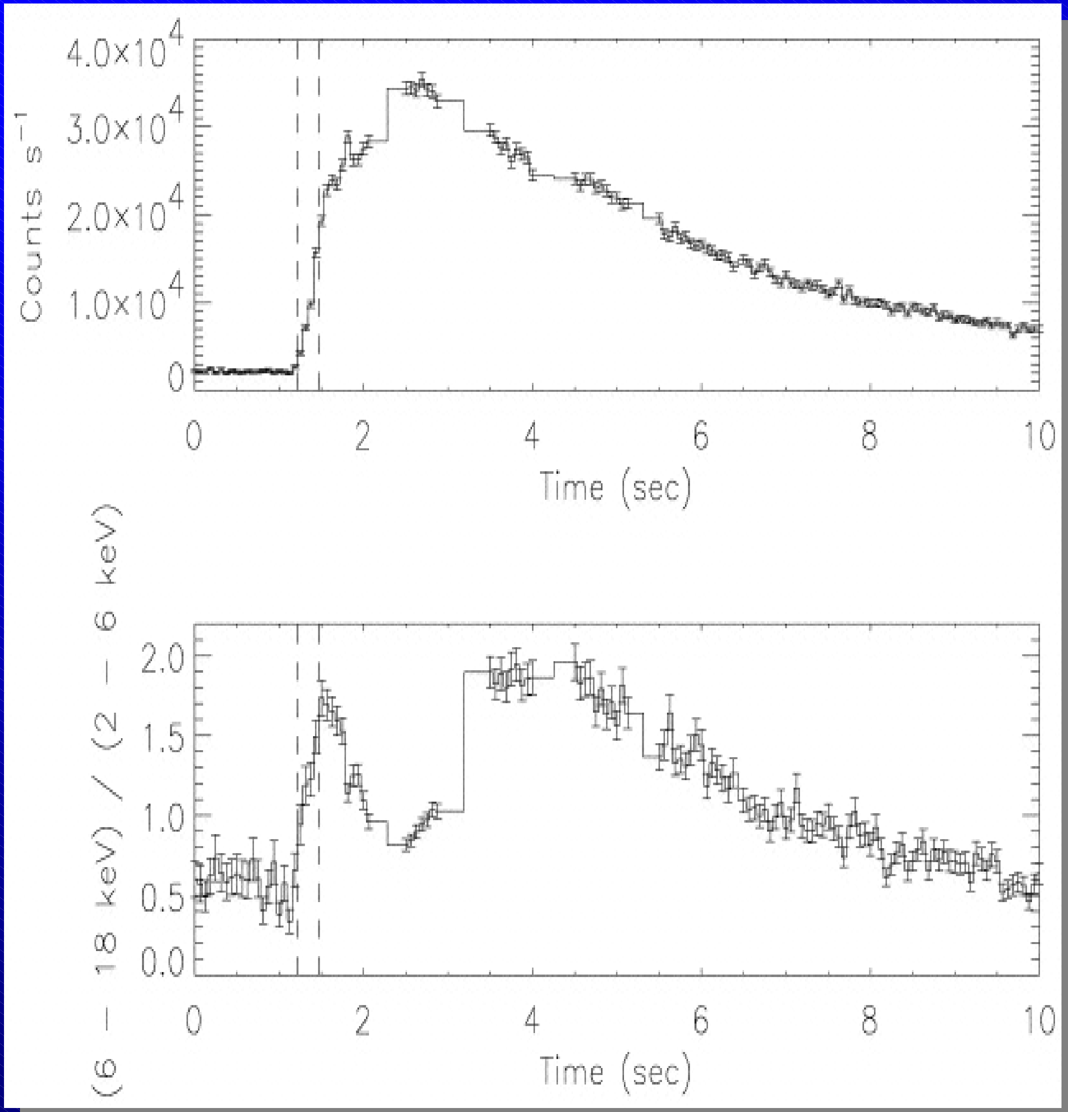
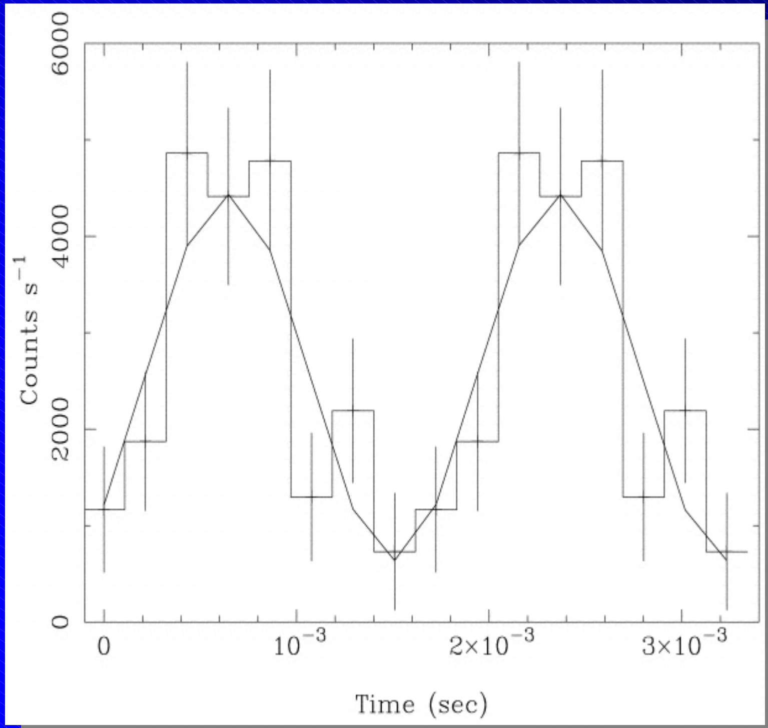


- Expanding layer slows down relative to bulk of the star.
- Change in spin frequency crudely consistent with expected height increase, but perhaps not for most extreme variations.
- X-ray burst expands surface layers by ~ 30 meters.

Oscillation Amplitudes at Burst Onset: 4U 1636-53 (581 Hz)





- Oscillations at rising edge approach 100% modulation of the burst flux (persistent flux level subtracted).

4U 1636-53: Strohmayer et al. (1998)

Coherence of Burst Oscillations

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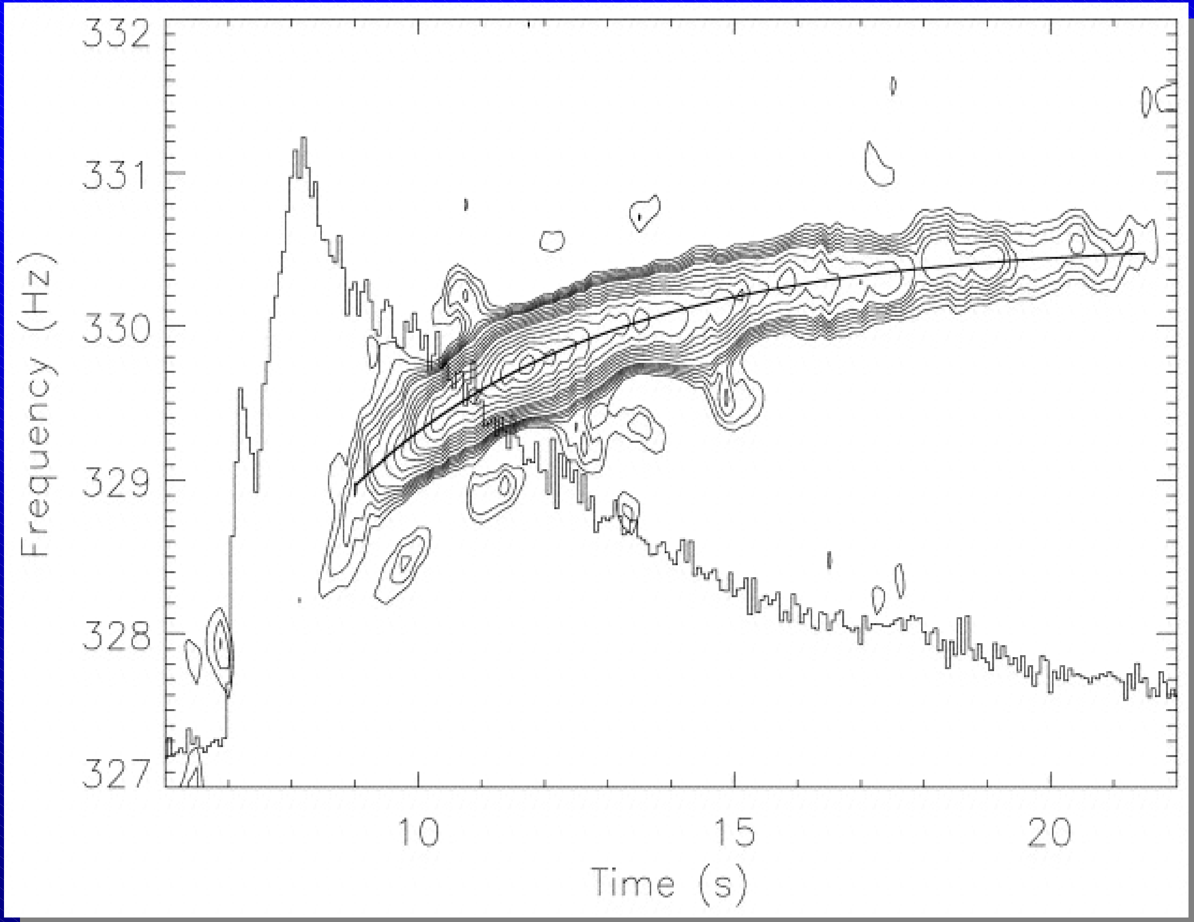
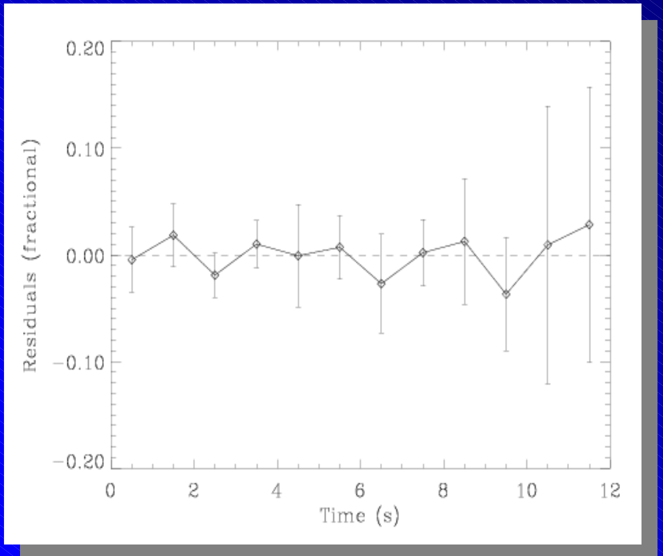
4U 1702-429: Strohmayer & Markwardt (1999)

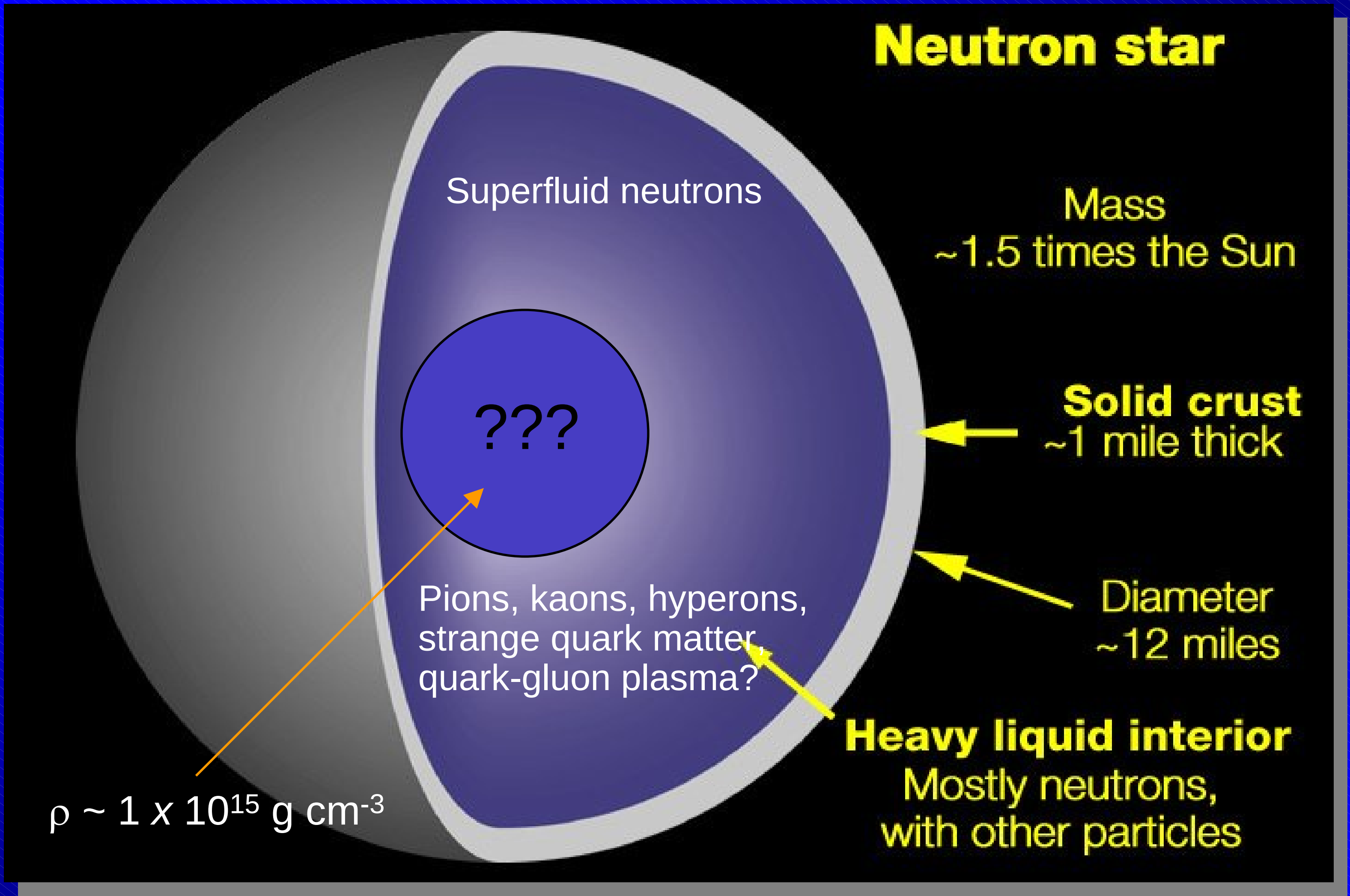




- Burst oscillations generally have high coherence (Q > 4,000)
- exponential recovery in some bursts.

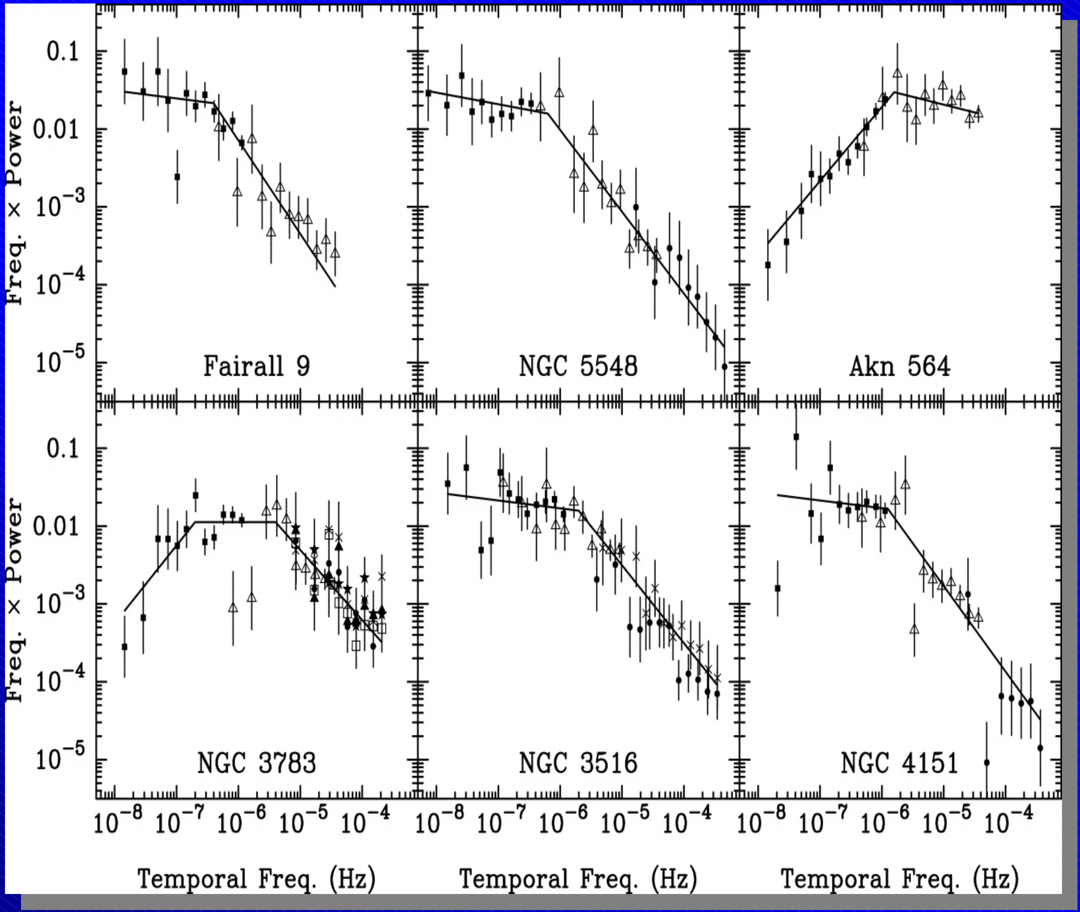
Model: $f(t) = f_0 (1 - \delta e^{(-t/\tau)})$

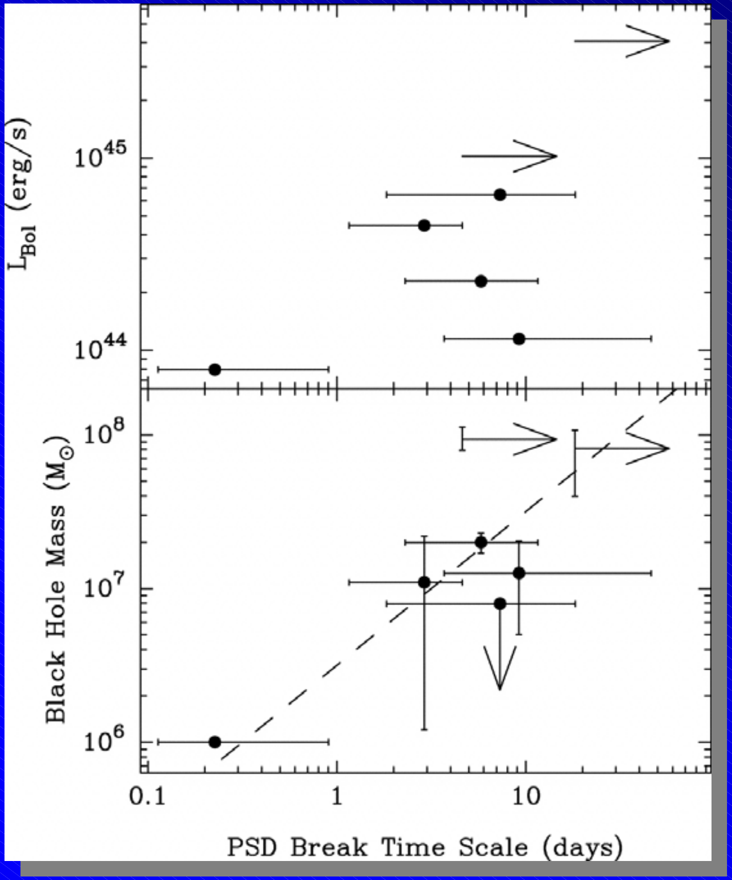
Inside Neutron Stars



- The physical constituents of neutron star interiors still largely remain a mystery after 35 years.

Mass Estimates From Power Spectral Measurements





- From RXTE monitoring, indications of breaks in PDS of AGN.
- Comparisons with GBH suggest 1/M scaling of break frequency.

Extreme Weather on Neutron Stars

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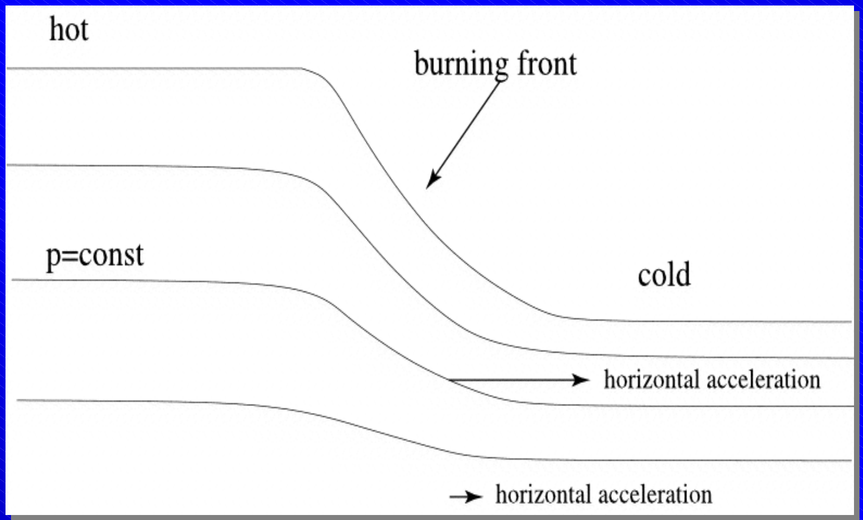
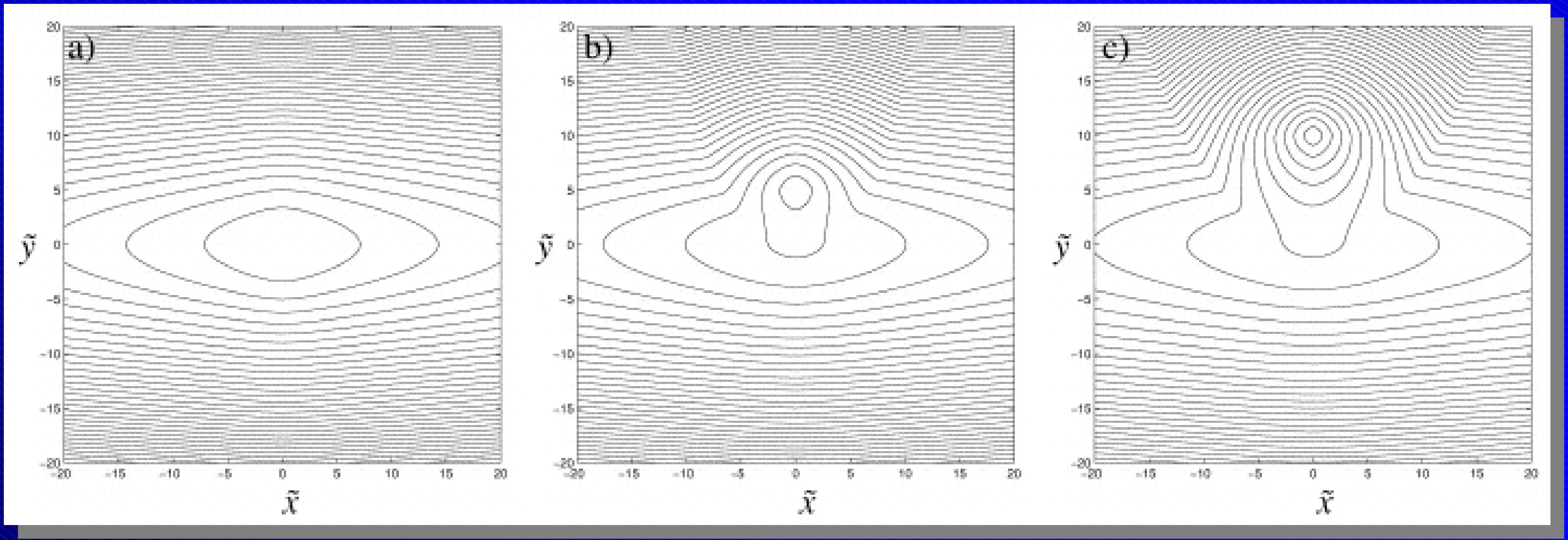


- Spitkovsky, Levin & Ushomirsky (2002) explored burning front propagation on rotating neutron stars.
- Burst heating and Coriolis force drive zonal flows; vortices and retrograde flows may account for late time asymmetry and frequency drifts.

From Spitkovsky, Levin & Ushomirsky (2002)



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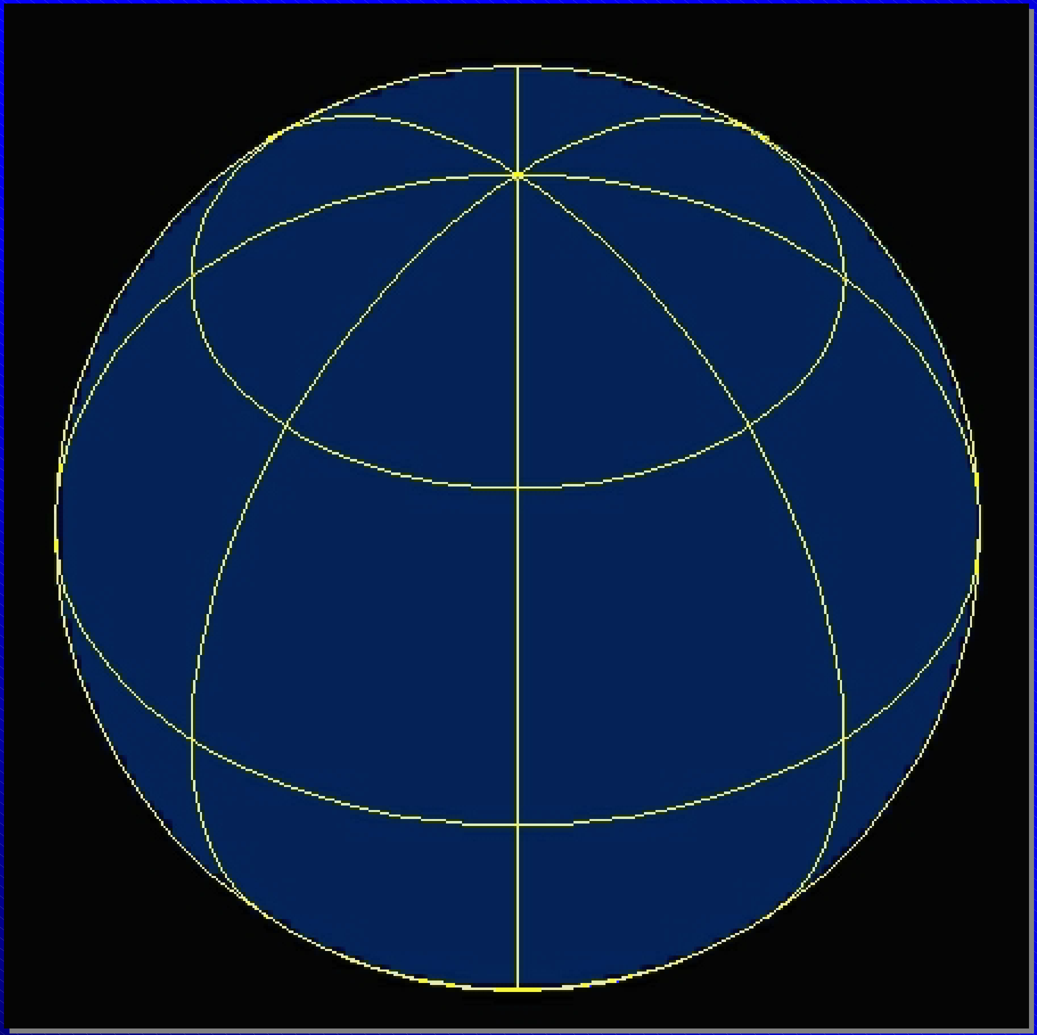
Burst Oscillations: Ignition and Spreading.



Thanks to Anatoly Spitkovsky!

- Combining spreading theory (Spitkovsky, Levin & Ushomirsky 2002), with burning calculations (Schatz, Bildsten, Cumming, Heger, Woosley…), can give detailed predictions for hot spot geometry and lightcurves.
- Comparison with precision measurements can probe various burning physics as well as the neutron star properties.

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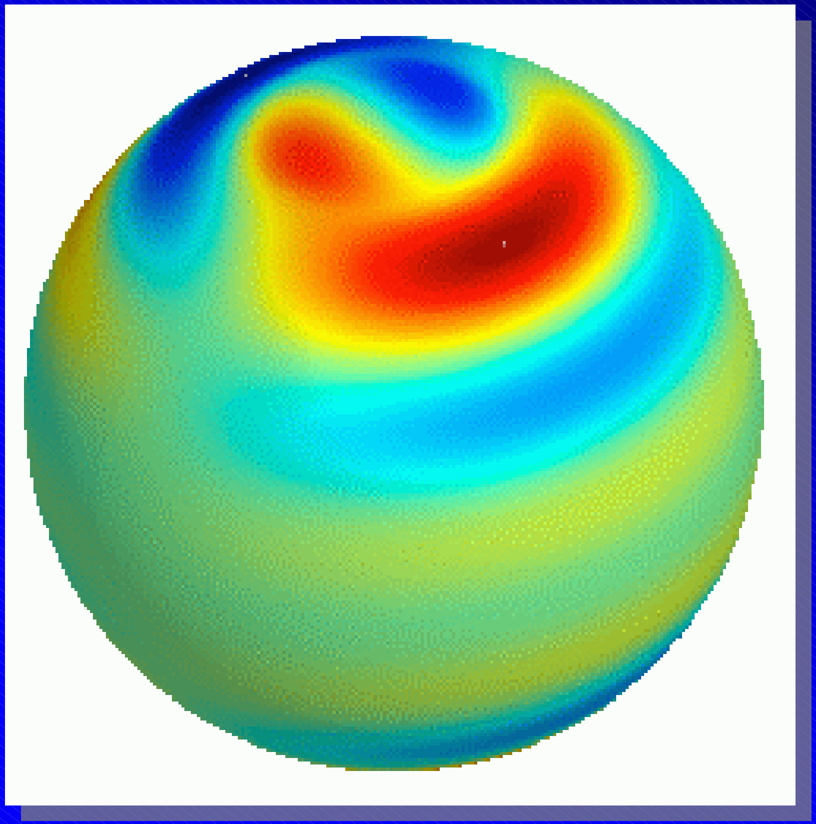
What Breaks the Symmetry?

- Why do pulsations persist as the burst decays away??
- Global Oscillation modes could provide late time asymmetry.
- Heyl suggested r-modes. Recent work by Lee & Strohmayer (2005), Heyl (2005). Are the modes unstable?
- Piro & Bildsten (2005), suggest connection with crustal interface mode, to account for frequency stability.
- Cumming (2005) finds dynamically unstable shear modes, associated with differential rotation, perhaps "self-excited" by bursts.



Cumming (2005)

Rotational Modulation of Neutron Star Emission: The Model

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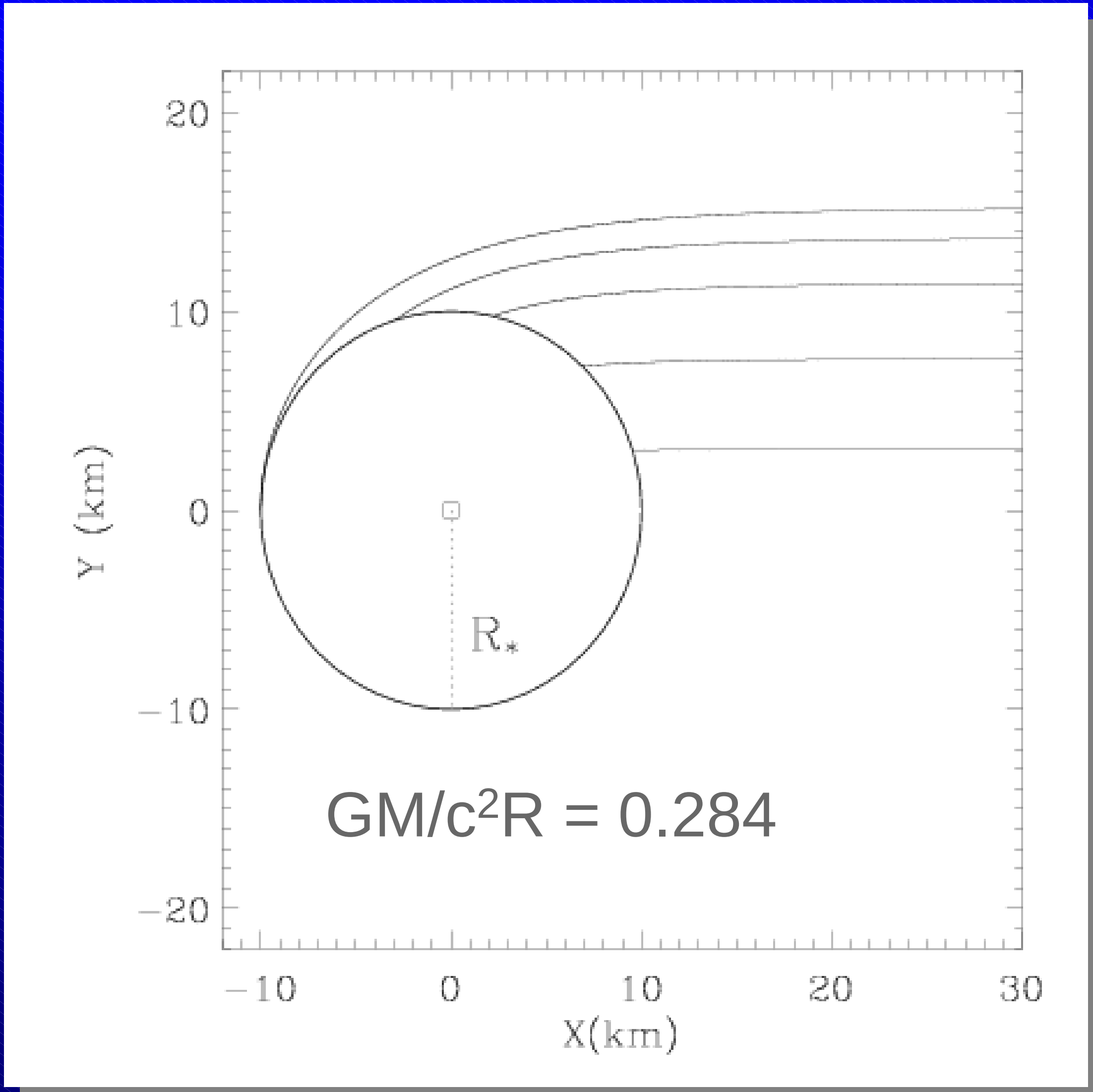

- Gravitational Light Deflection: Schwarzschild metric.
- Gravitational redshift
- Rotational doppler shifts and aberration of the intensity.
- "Beaming" of intensity in NS rest frame.
- Arbitrary geometry of emission regions.
- Observed response using various detector response matrices.

Miller, Bhattacharyya, Muno, Ozel, Psaltis, Braje, Romani, Nath, etc.

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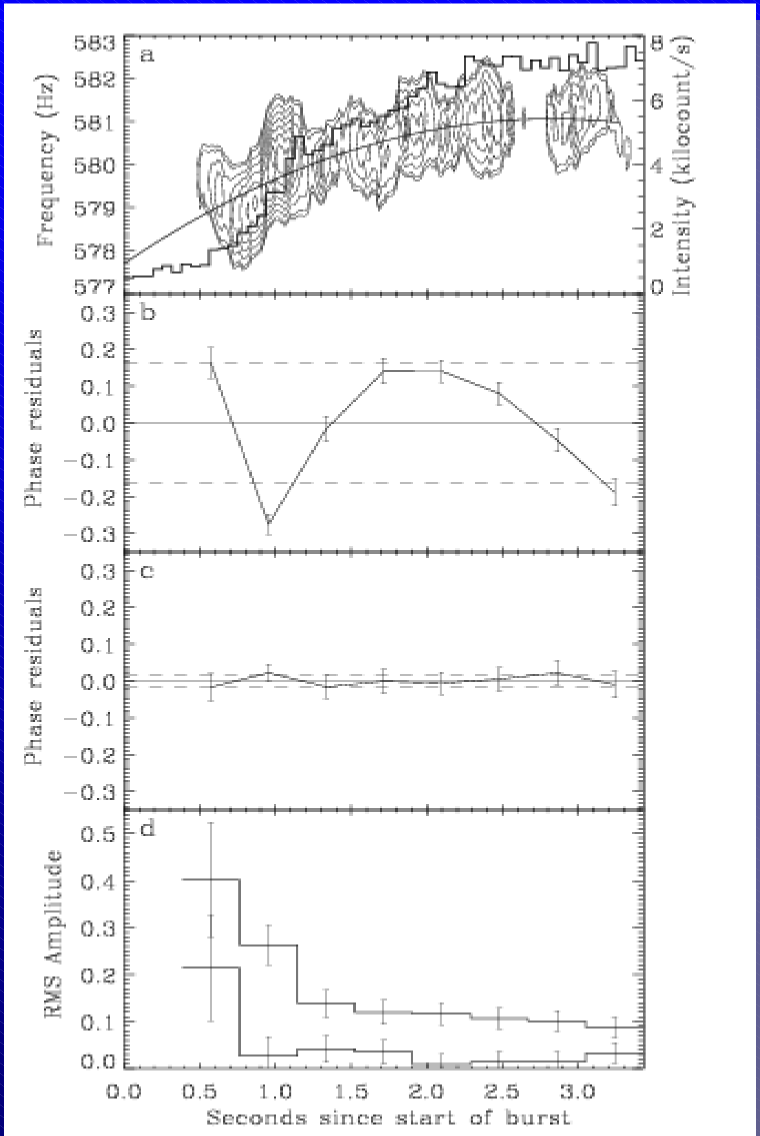
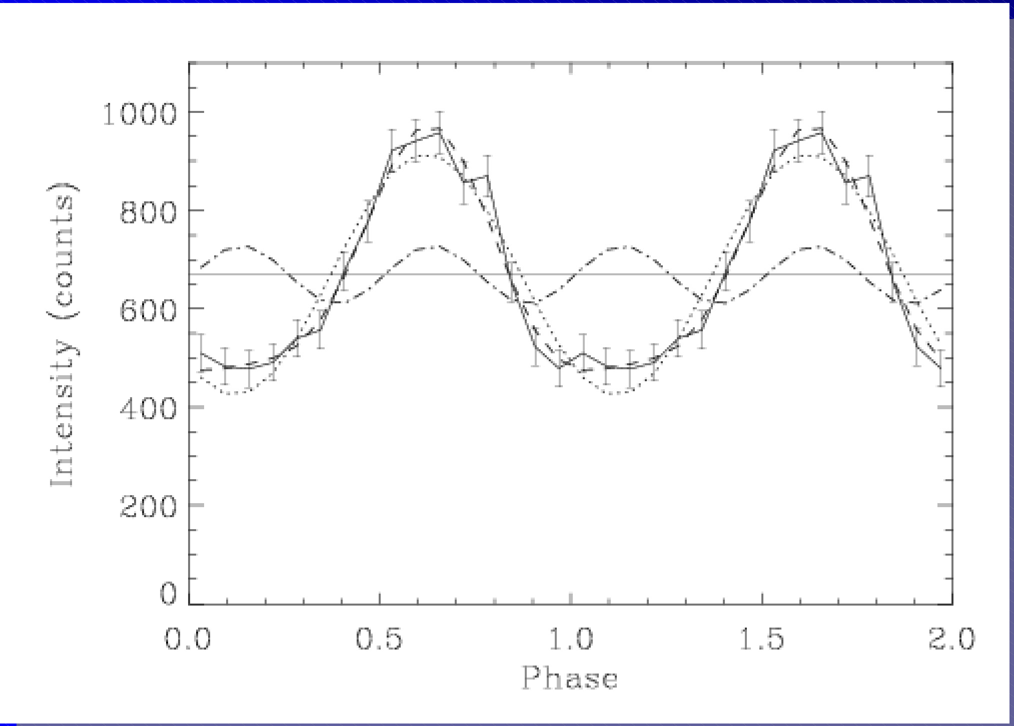
Oscillations at Burst Onset (4U 1636-53)





Bhattacharyya & Strohmayer (2005)

- Frequency drifts during the rise.
- Evidence for harmonic structure in first few tenths of a second of burst.
- Insights into nature of flame spreading.

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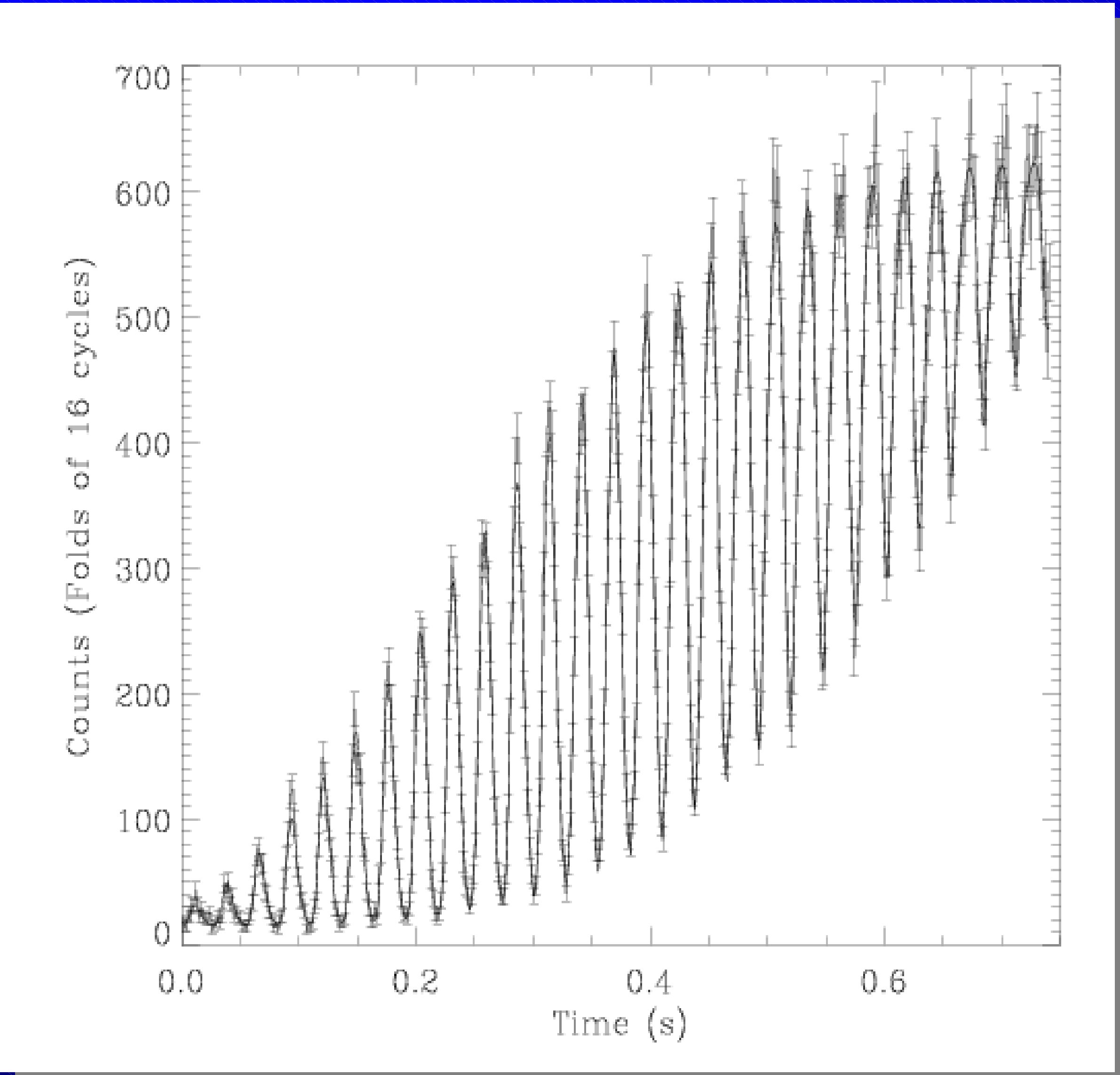
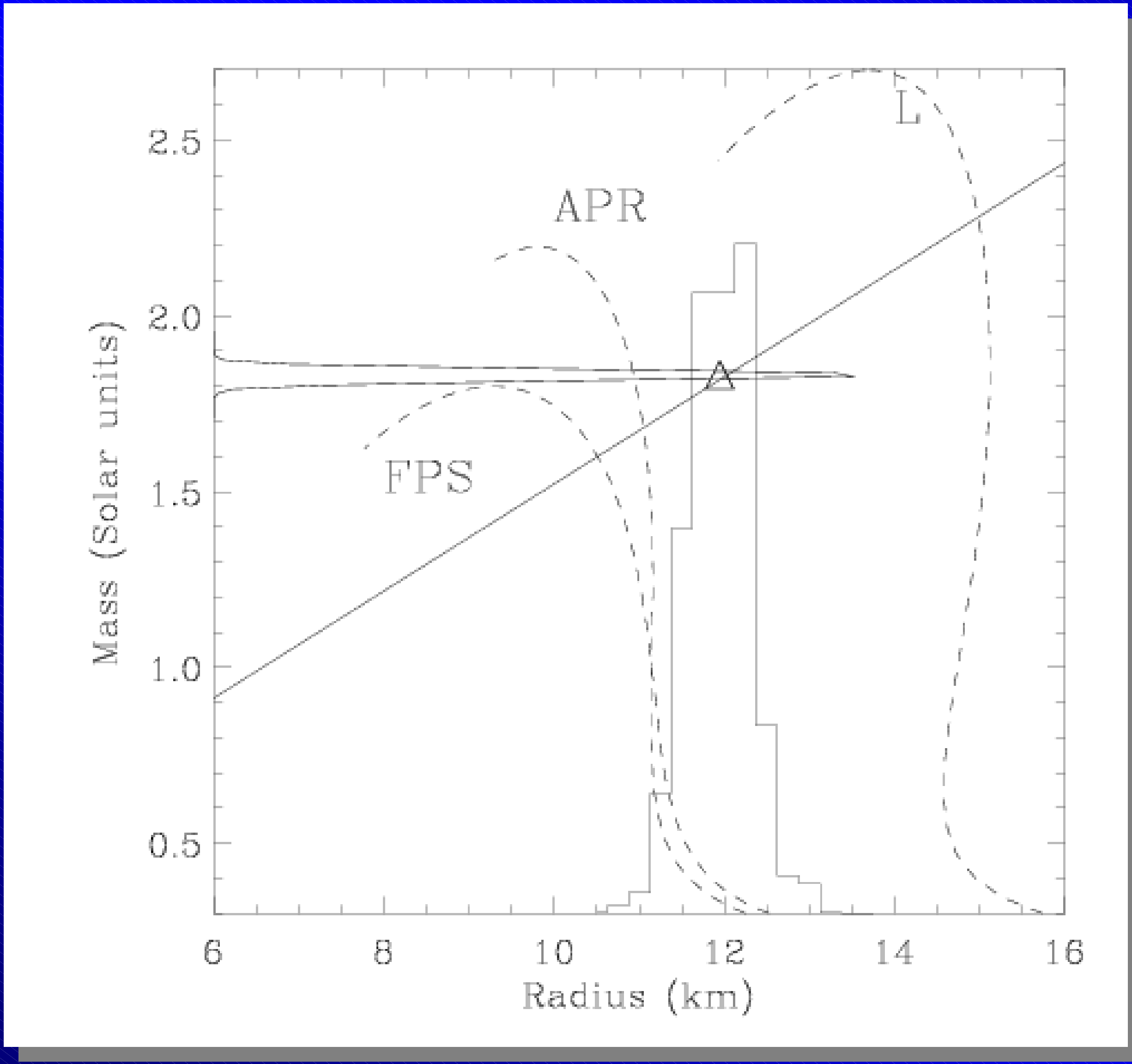
Simulated Lightcurve: 10x PCA



- 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.

Fitting of Pulsations During Burst Rise: Simulations



- Simulations for typical bursts from 4U 1636-53.
- Assume spot geometry is known.
- Fits for a single burst, bolometric profiles.

SGR 1806-20: RHESSI Confirmation of the Oscillations

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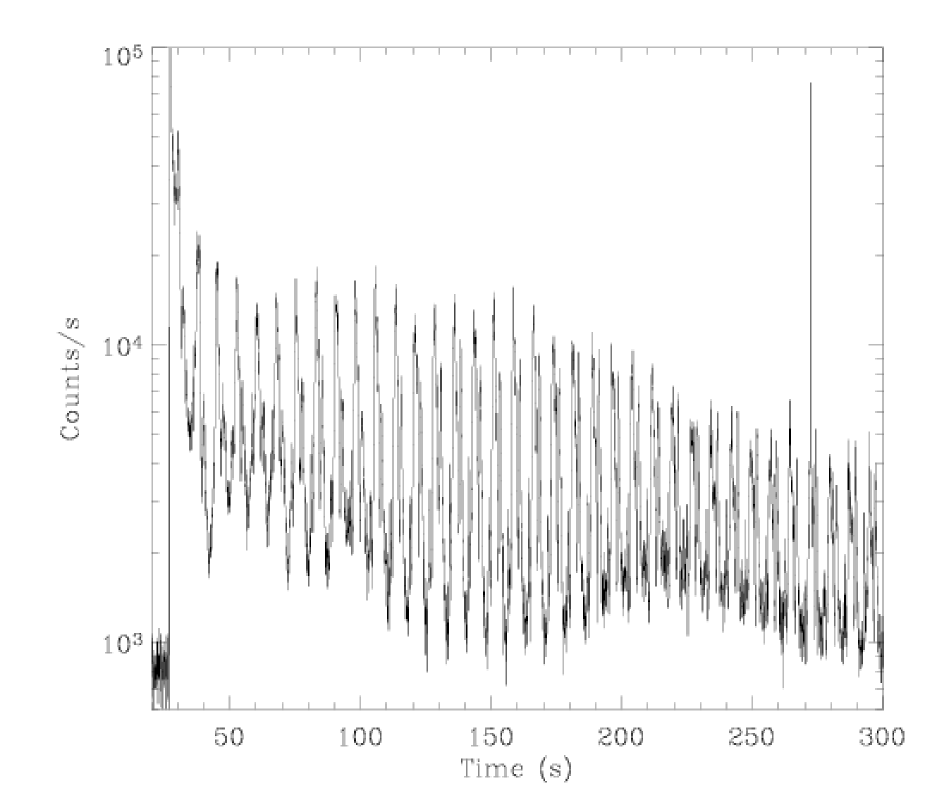
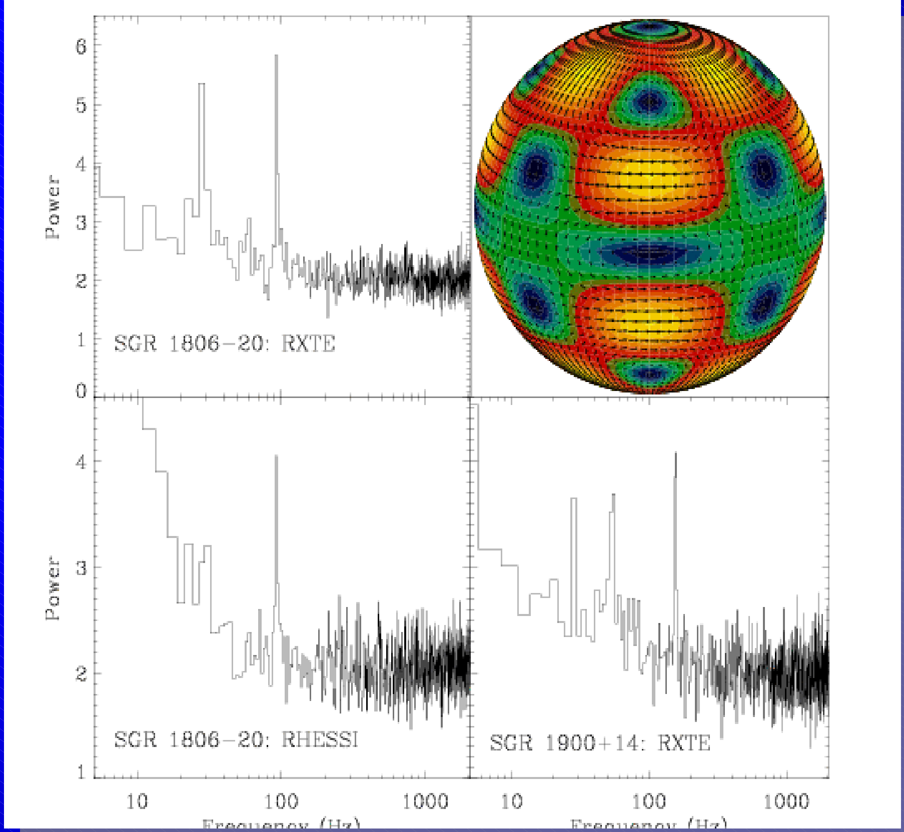


- *Ramaty High Energy Solar Spectroscopic Imager* (RHESSI) also detected the December, 2004 flare from SGR 1806-20 (Hurley et al. 2005).



- Timing study by Watts & Strohmayer (2006, astro-ph/0512630) confirms 92 Hz oscillation, and evidence for higher frequency (626 Hz) modulation.

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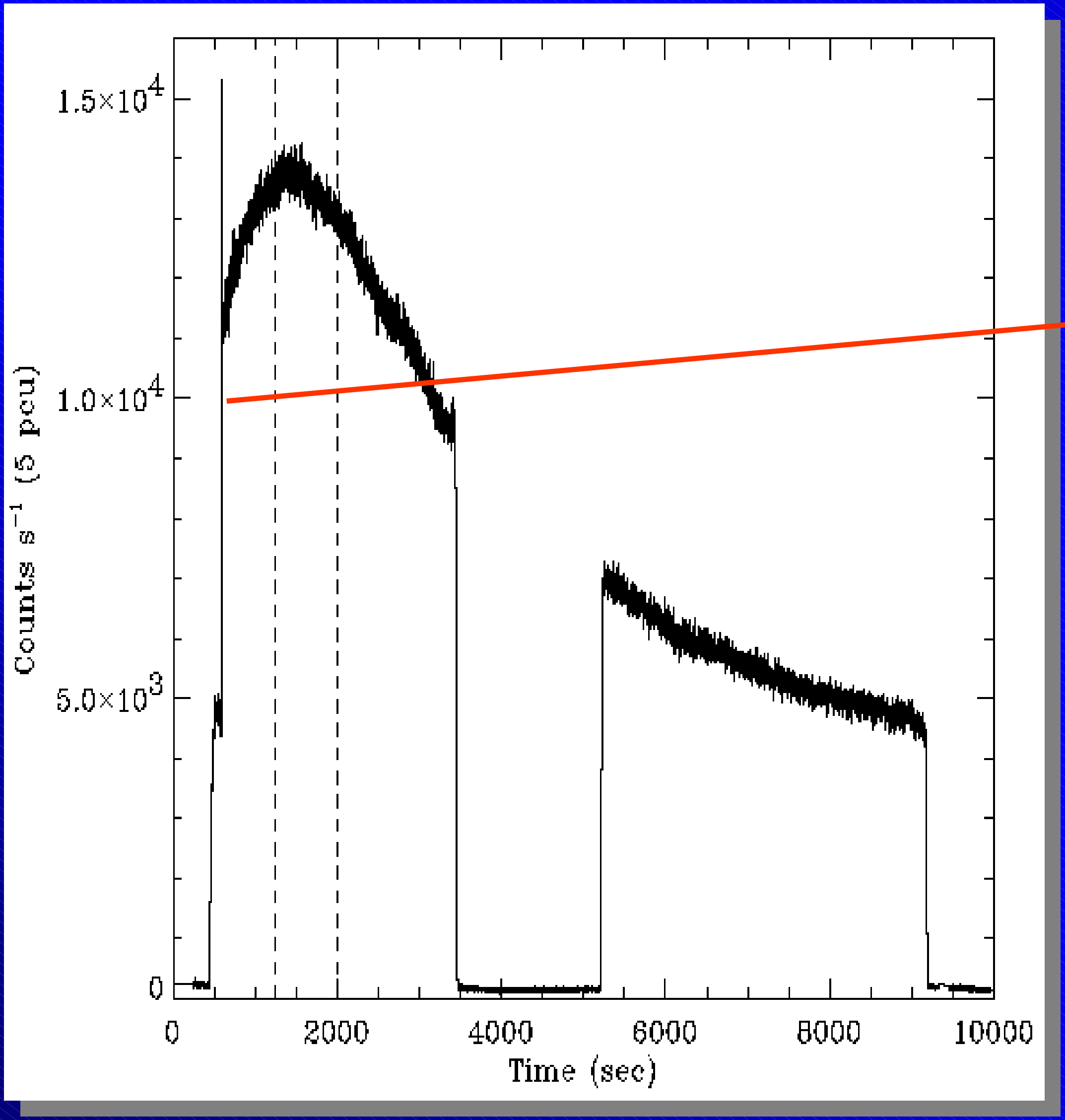
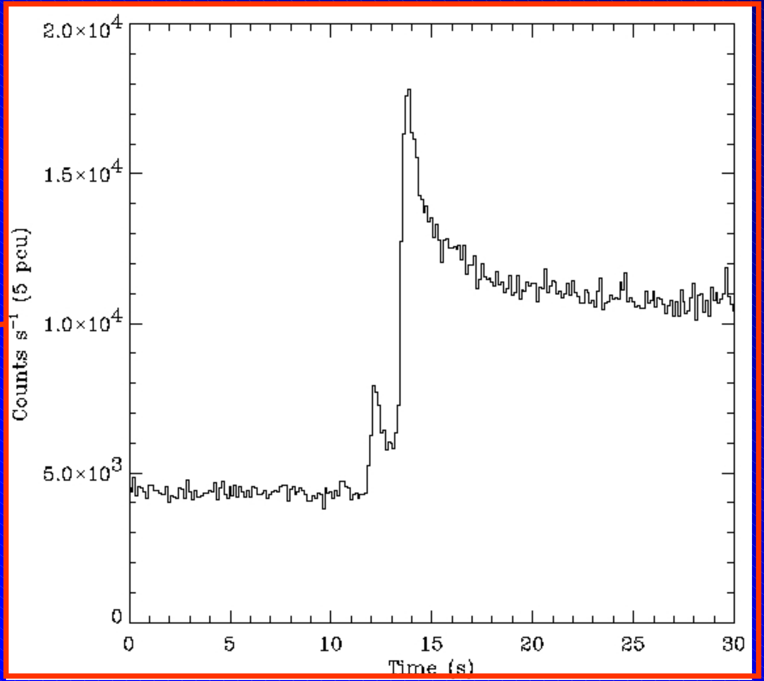
Burst Modeling: A Theoretical Opportunity

- To capitalize on current and future observations, we need a detailed, multi-dimensional model of the X-ray flux from bursting neutron stars:
- Input physics: nuclear energy release; reaction networks, etc.
- Atmospheric physics, transfer of nuclear energy to photon flux.
- Flame spreading; time dependence of flame propagation.
- Propagation of flux at surface to the observer, including all relativistic physics.
- Fitting of models to the data to derive neutron star properties (M, R, sin i, etc.), and perhaps constrain nuclear physics.
- This is a substantial collaborative effort. Something JINA could support?
- Synergistic with astrophysics community; could support future observing efforts.

RXTE/PCA Observes Superburst from 4U 1636-53





- Unique double precursor near rise of the burst.
- Heat flow from below may trigger H/He layer.

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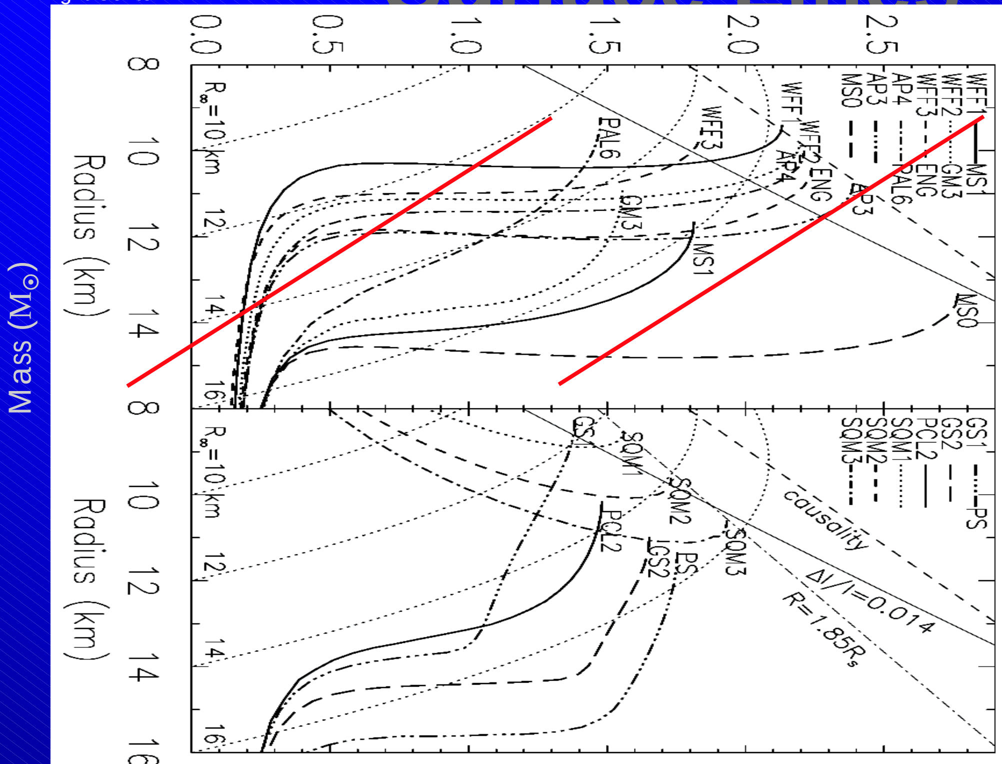
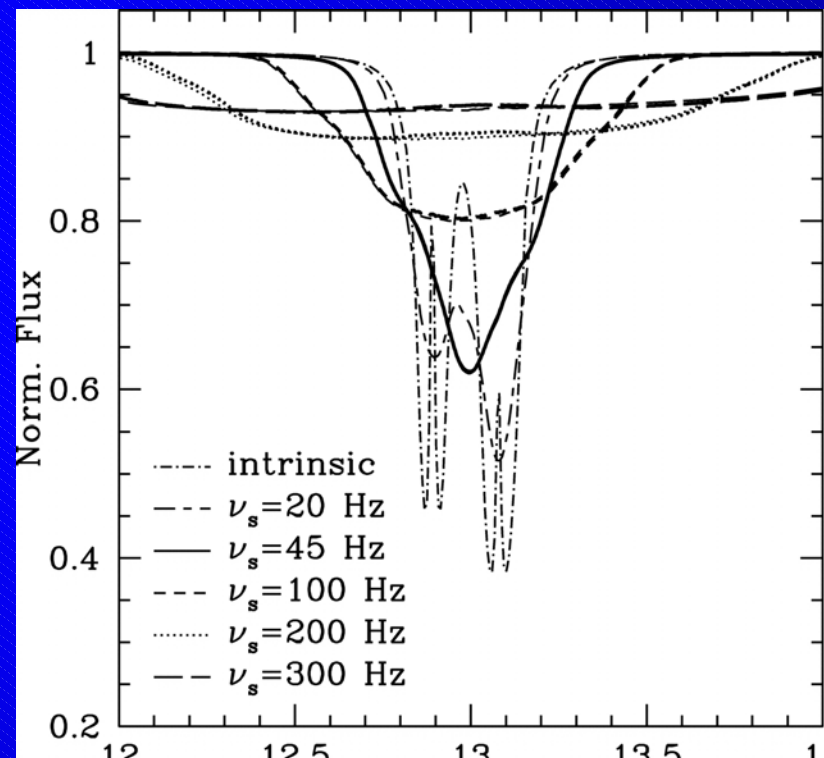
EXO Absorption Lines: Caveats

- Line Identifications not completely secure.
- Any single line feature is not detected with extremely high statistical significance.
- Indications of several (weak) features at consistent redshift, perhaps mitigates these concerns somewhat.
- Such narrow lines were not expected. Presumption that the NS is spinning at hundreds of Hz, like other LMXB bursters.
- Equivalent widths; are they compatible with reasonable Fe abundances; maybe (see Chang, Bildsten & Wasserman 2005).

Rotational Broadening of Surface Lines



- Rotation broadens lines, if Spin frequency known, can constrain R (with caveats).



Chang et al. (2006)

- For Fe XXVI Hα, and 45 Hz, fine structure splitting of line is comparable to rotational effect. Need good intrinsic profile (Chang et al 2006).

RXTE Observes Three Hour Thermonuclear Burst from a Neutron Star (4U 1820-30)

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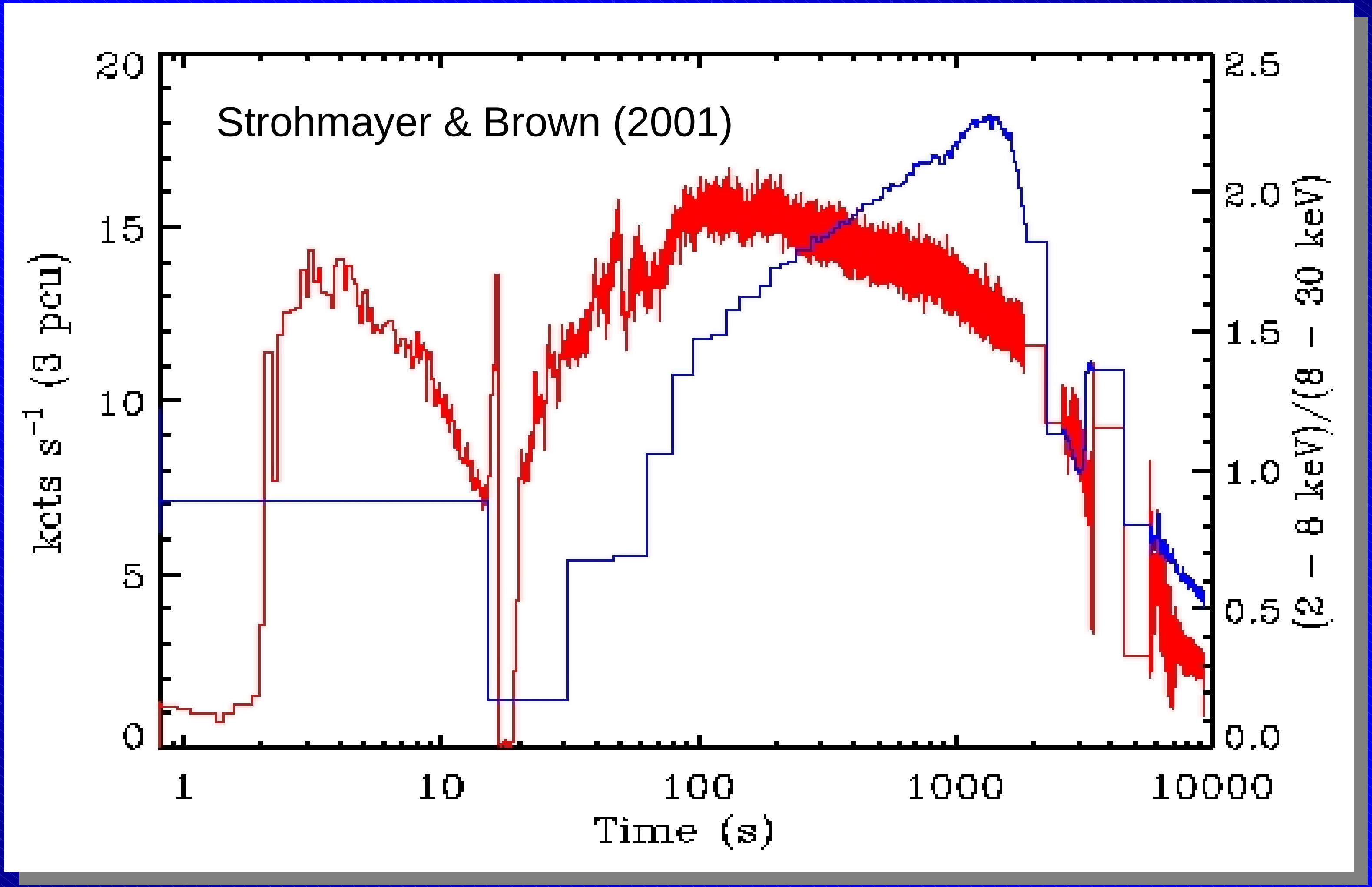
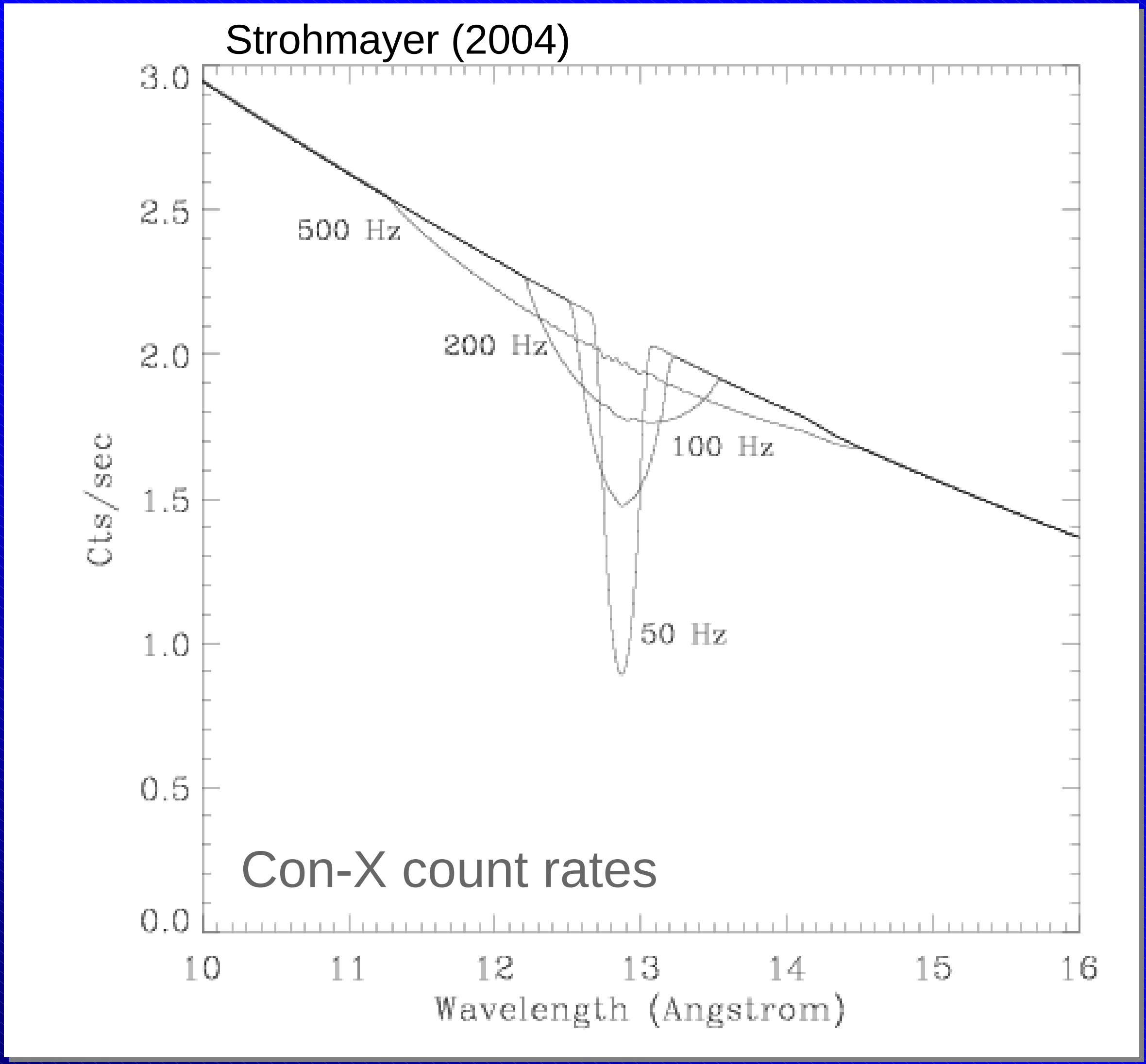


- Burst produced ~ 2 *x* 10^{42} ergs in X-rays, perhaps 10x more energy not seen (neutrinos; heat flowing into the crust).
- Energy source likely carbon burning at great depth (~10^{13} g cm^{-2}).

Line Spectroscopy and M - R Constraints for Neutron Stars



- Lines features from NS surface will be broadened by rotational velocities.
- For many sources, the rotational broadening will dominate (for example, Stark broadening).
- For known spins, velocity gives radius information.
- Asymmetric and double-peaked shapes possible, can constrain emitting surface.

Ozel, Psaltis, Datta, Kapoor, Bildsten, Chang, Paerels.

Phase Resolved Spectroscopy

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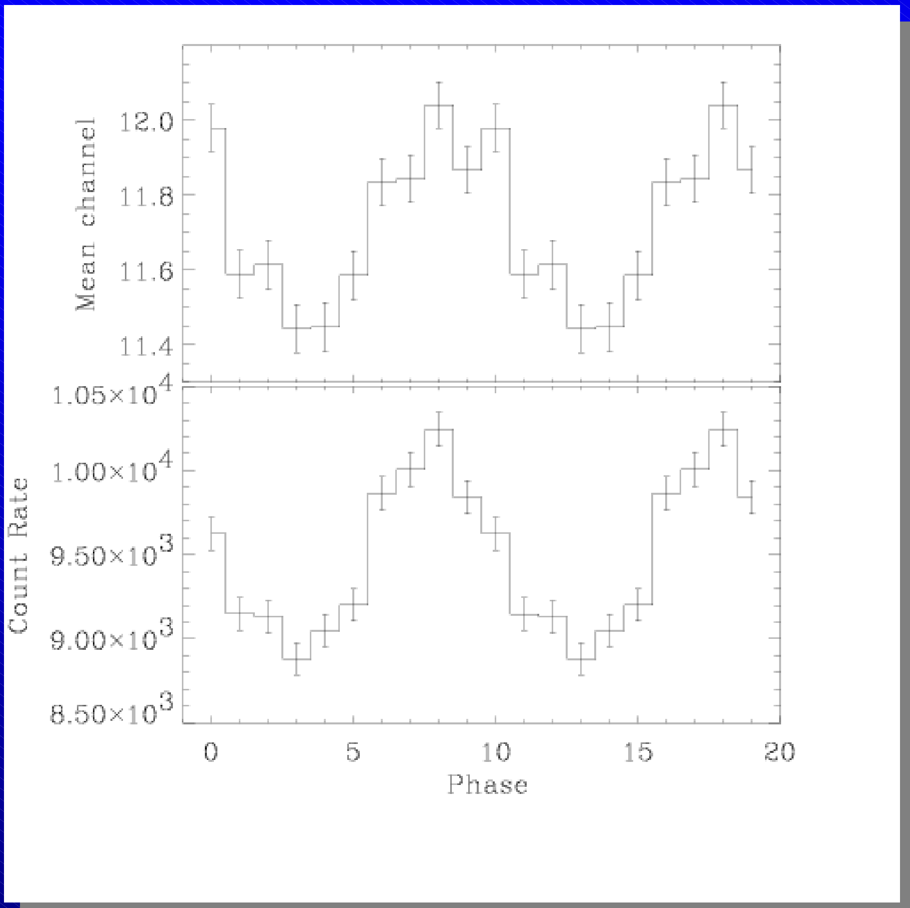
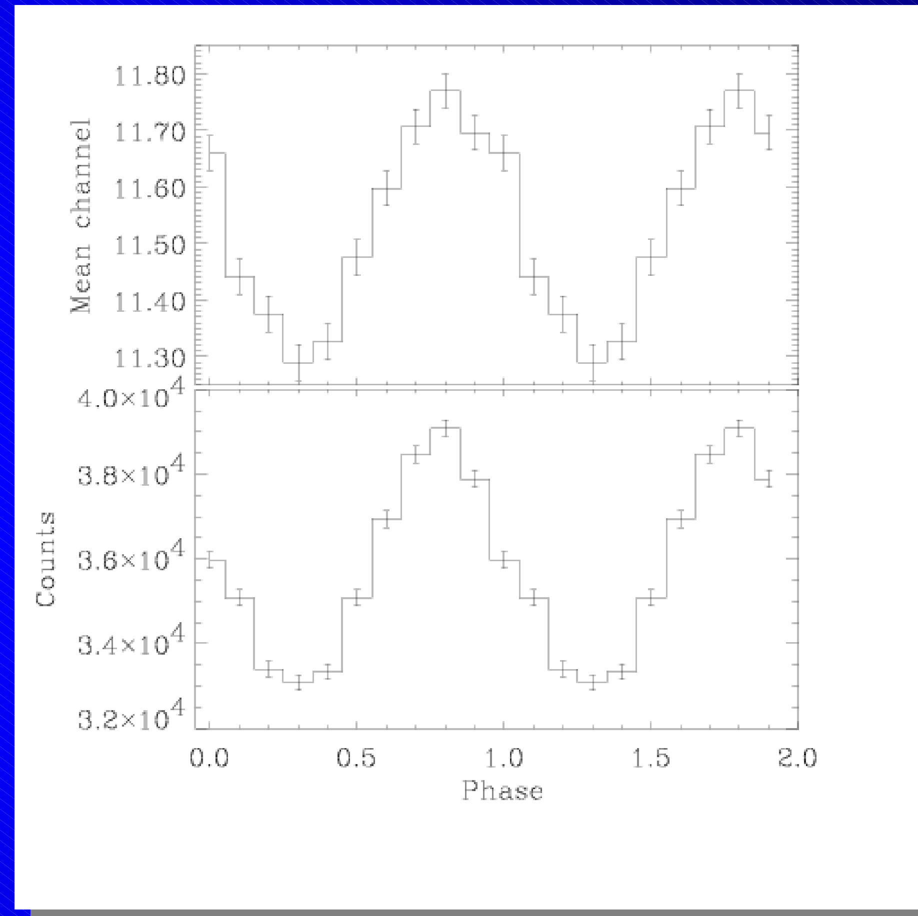
4U 1702-429

Rises: 4 bursts



Tails: 4 bursts



- Spectra (or average hardness) with pulse phase show modulations consistent with temperature asymmetry.

Stability of Burst Oscillations

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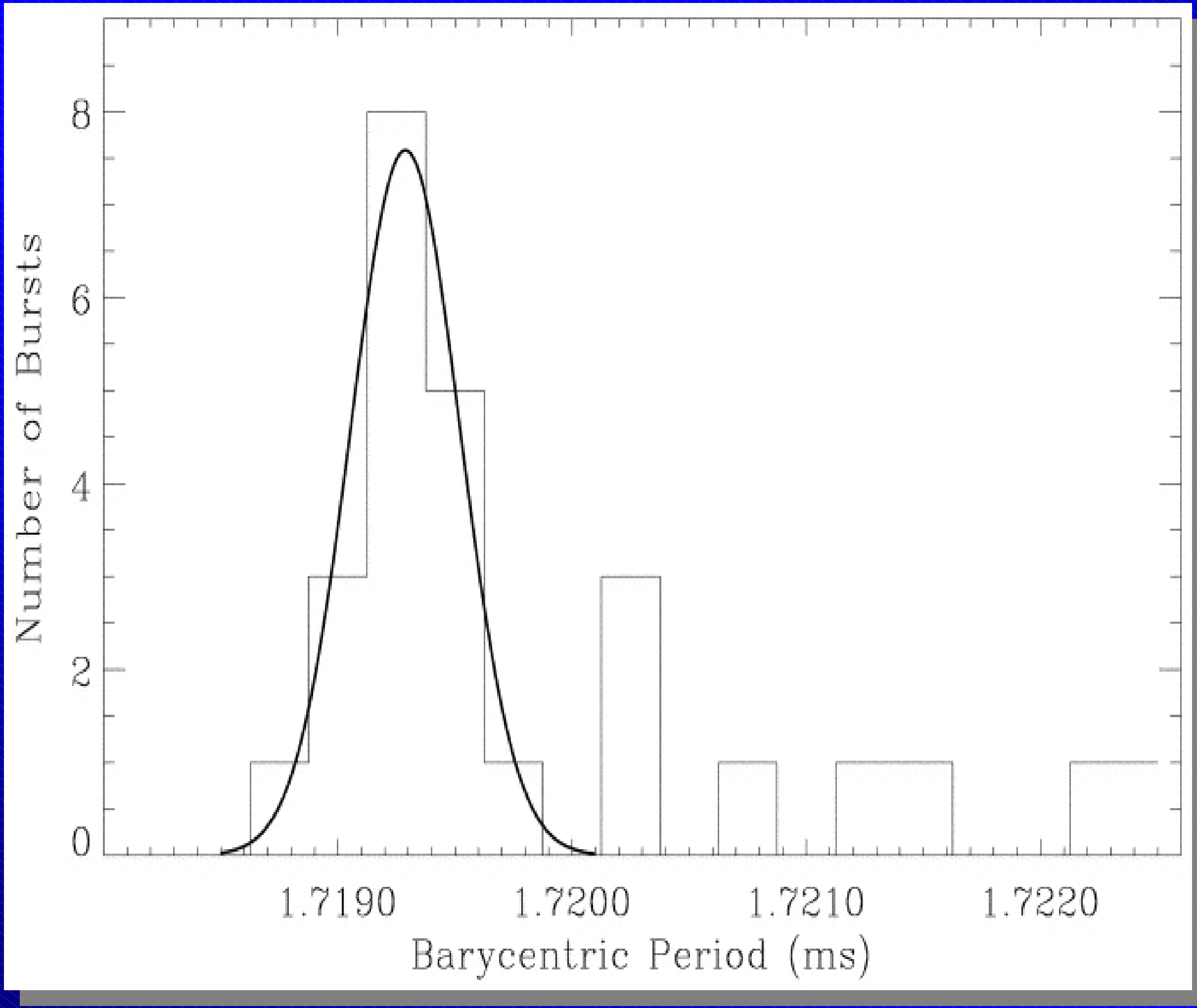

- Burst oscillation frequencies in 4U 1636-53 have $\delta f/f \sim 0.003$
- No apparent correlation with orbital phase.
- Difficult to infer orbital parameters from sample of bursts, for example, neutron star velocity.

4U 1636-53: Giles et al. (2002)

The SGR 1806-20 Flare Re-visited

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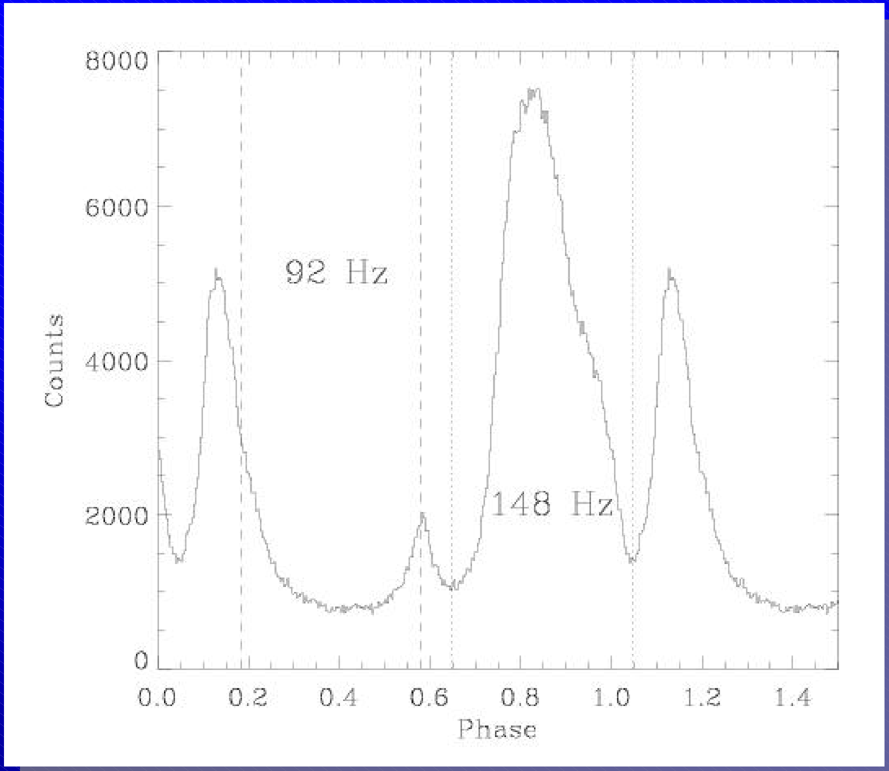
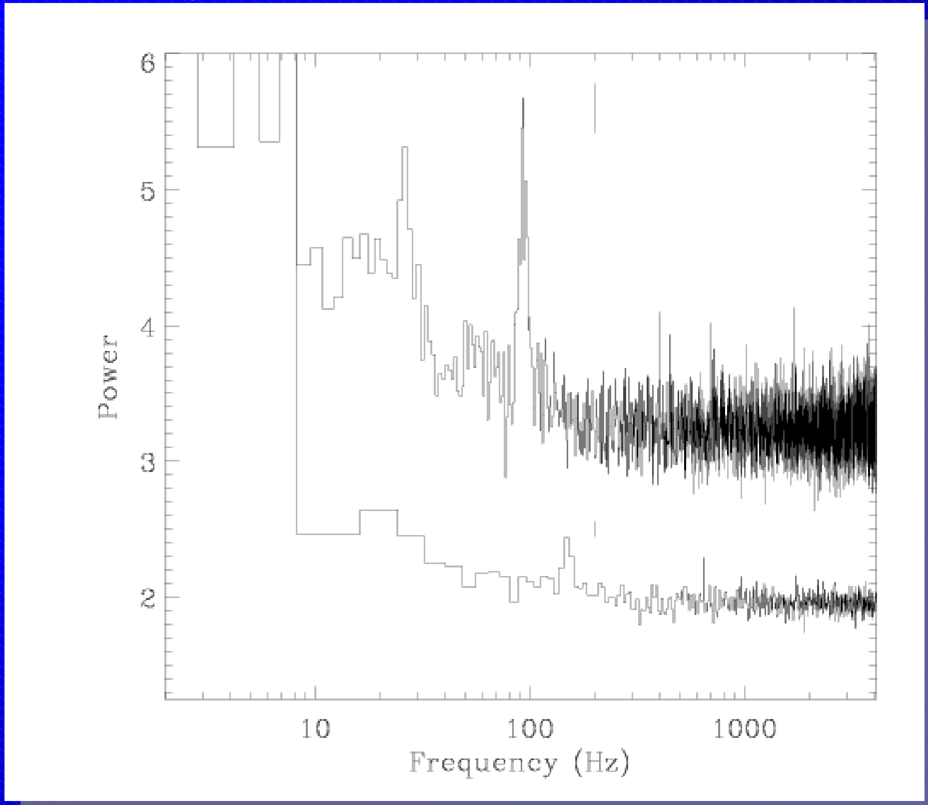
- SGR 1806 flare data now public.
- Phase averaging of power spectra confirms strong 92 Hz QPO.





Phase averaging also shows 148 Hz feature with high significance, but lower amplitude. Stay tuned.

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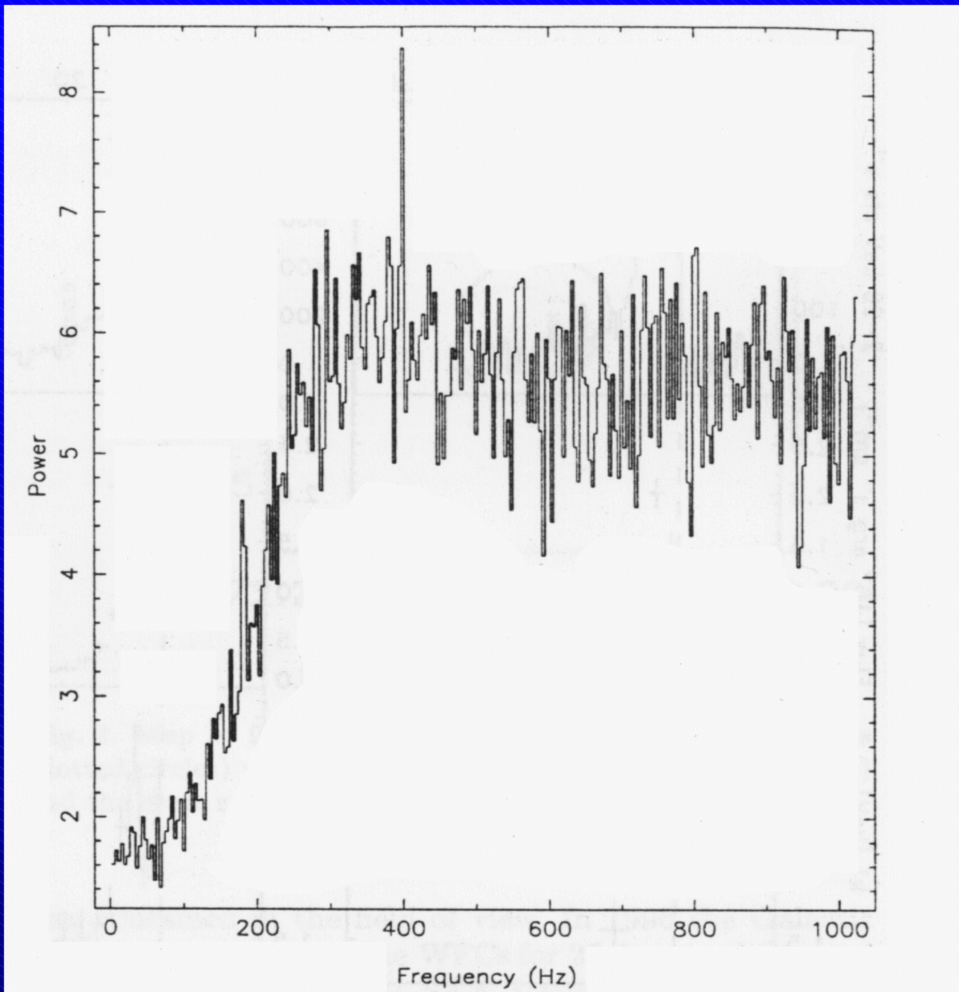
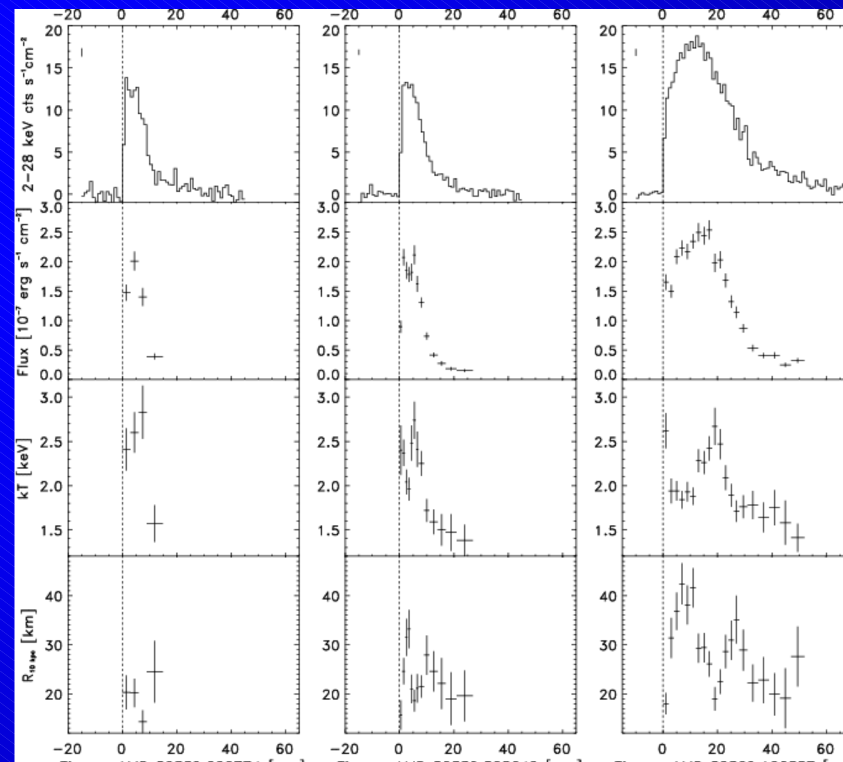
*SAX J1808.4-3658 (401 Hz Pulsar)

- In ‘t Zand et al. (2001) using BeppoSAX/WFC, find evidence for 401 pulsations in bright burst from SAX J1808





From in ‘t Zand et al. (2001)

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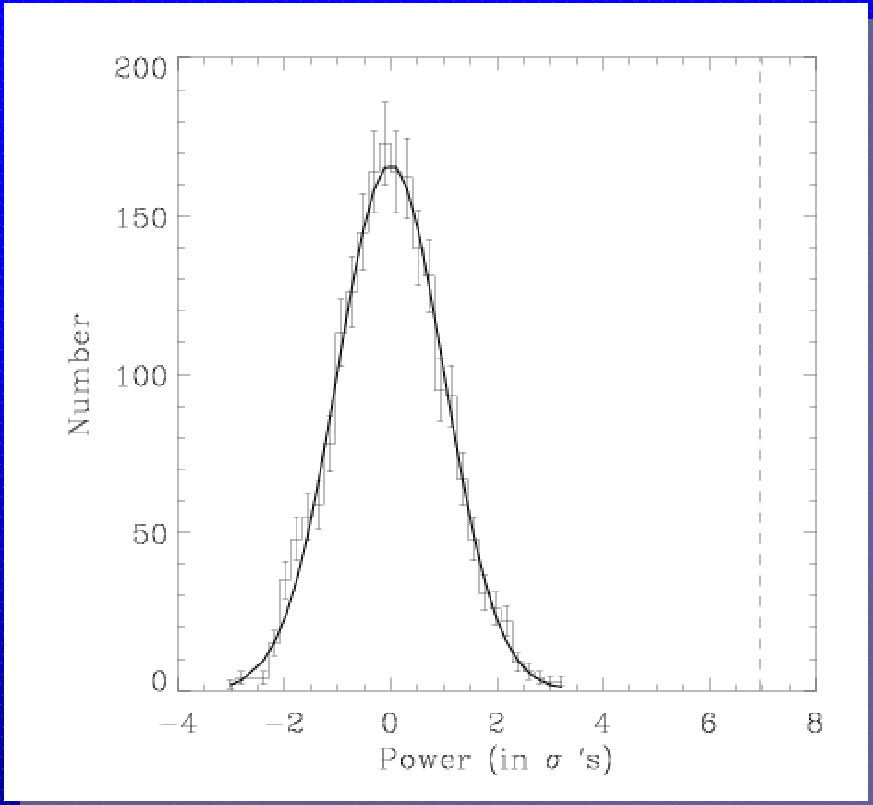
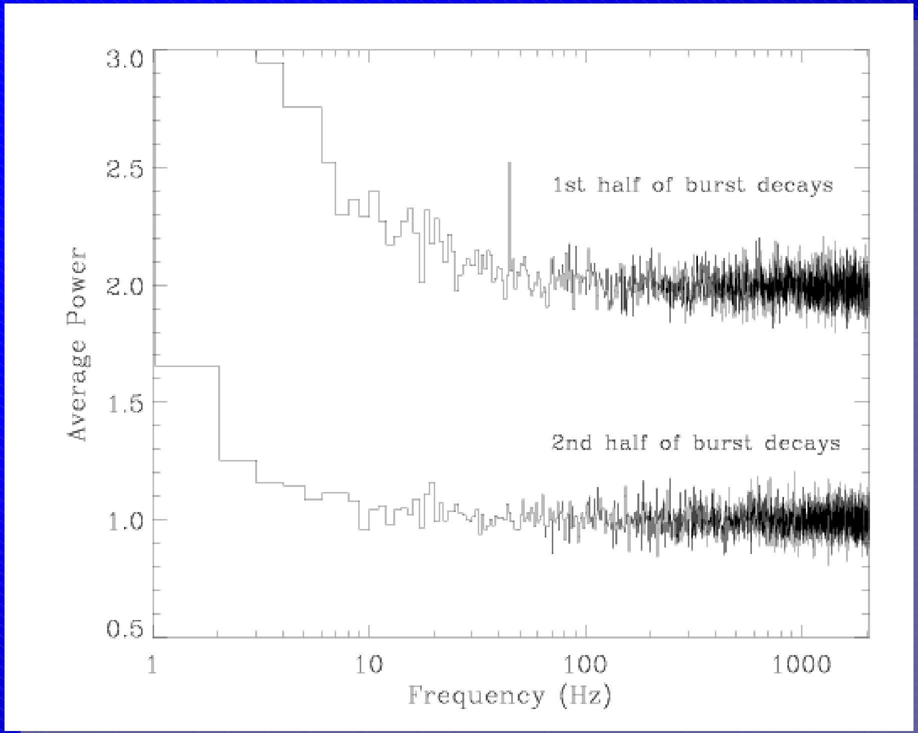
45 Hz Signal: Summary



- Signal significant at 4 x 10^{-8} level.
- Average amplitude of 3% (rms).



Signal definitely associated with brightest parts of the X-ray bursts.

Coherence of Burst Oscillations con't

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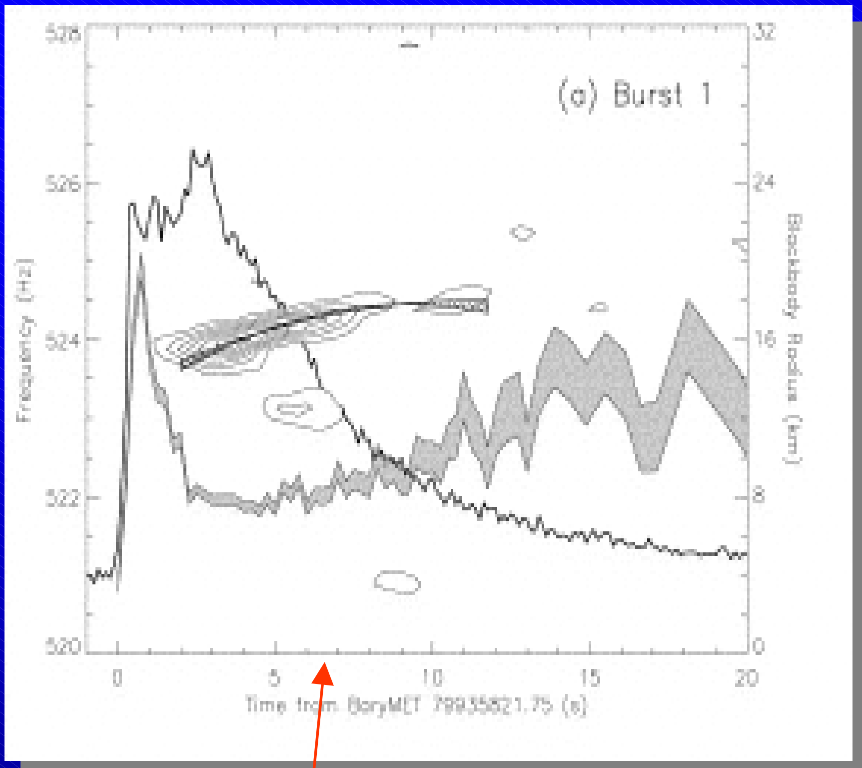
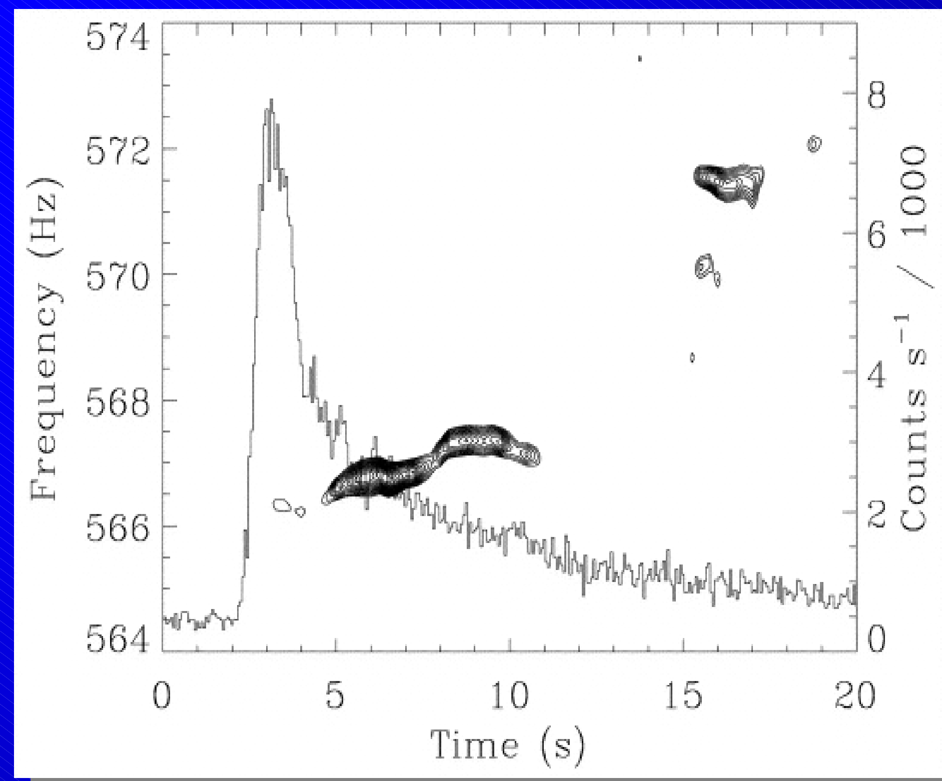


KS 1731-260: Muno et al. (2000)

X1658-298: Wijnands, Strohmayer & Franco (2001)

- Some bursts require higher order polynomials to fit evolution.
- Some phase jitter (Muno et al. 2000).



Burst Oscillations and Source State

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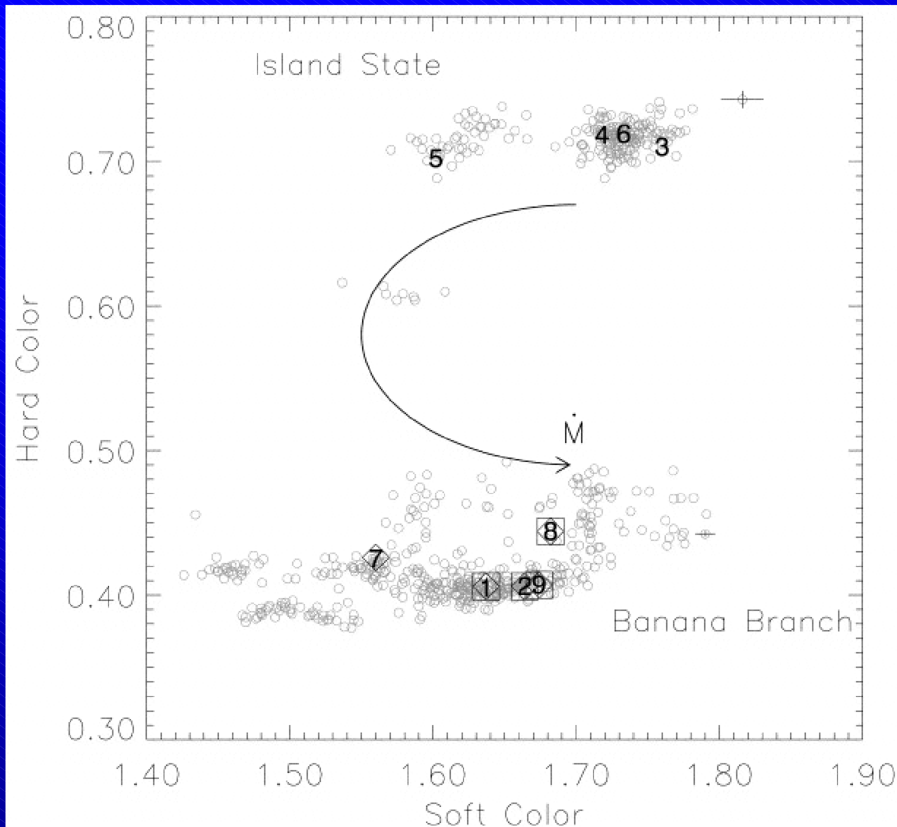
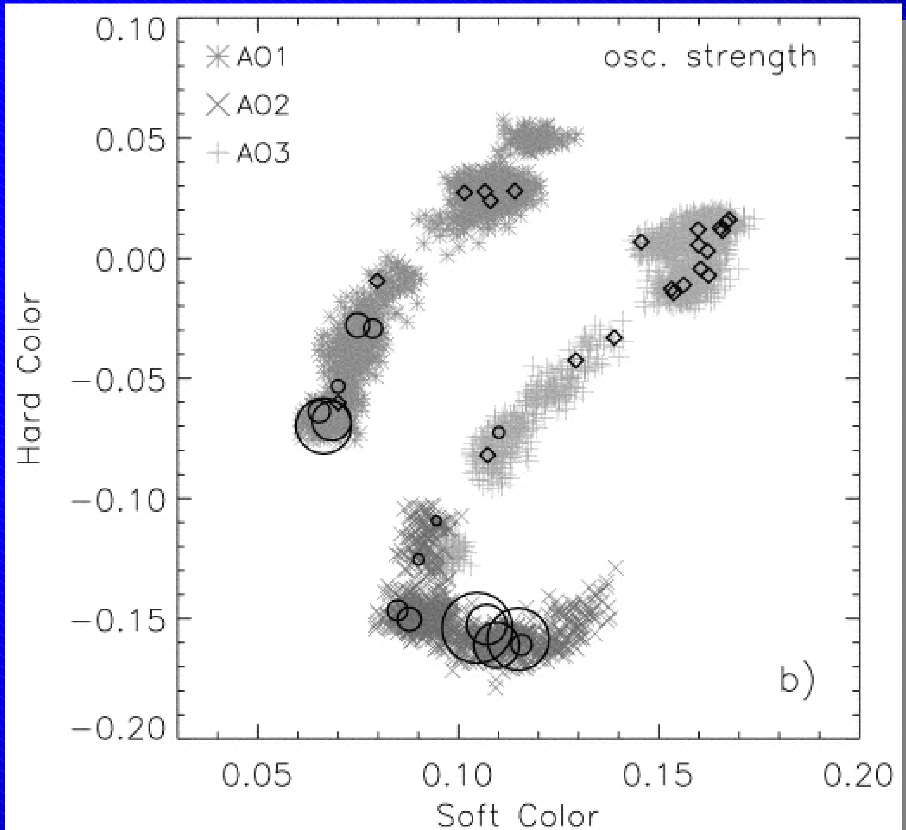


KS 1731-260: Muno et al (2000)

- Connection with mass accretion rate dependence of nuclear burning

- Bursts with oscillations correlated with position in the X-ray CC diagram

4U 1728-34: Franco (2001)



Pulse Profile and Phase Residuals

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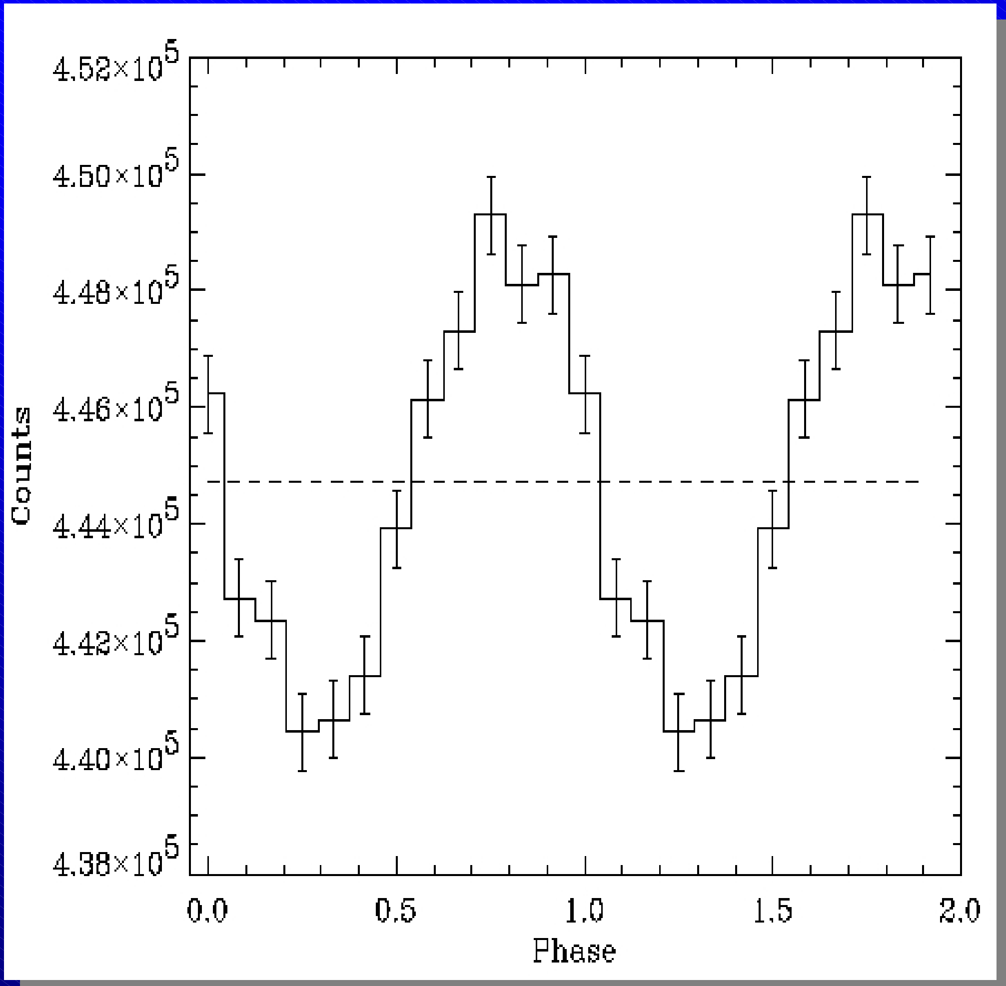

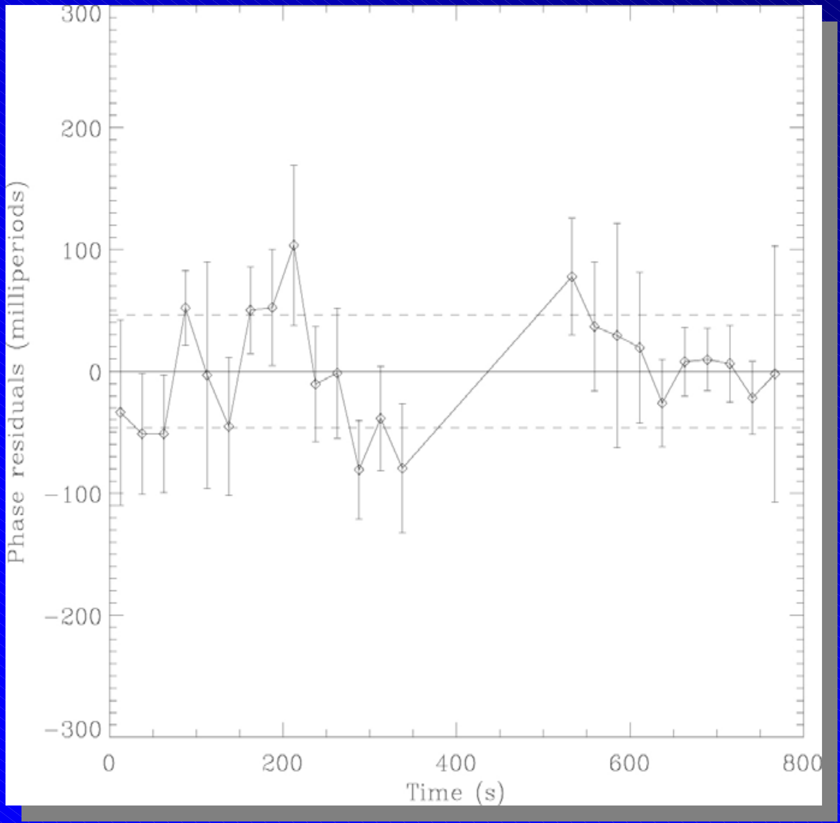

- 1% pulse amplitude (mean)
- ~30 μsec (rms)

Discovery of XTE J1814-338

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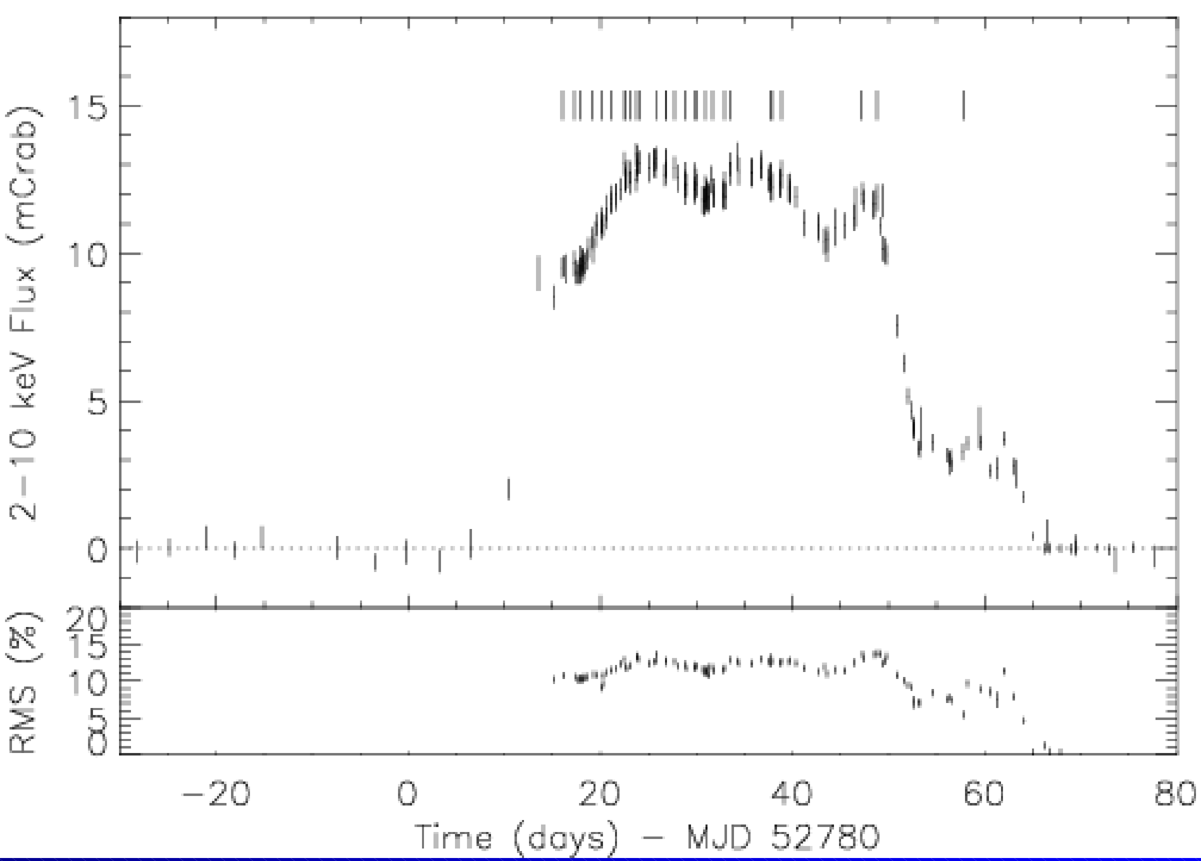
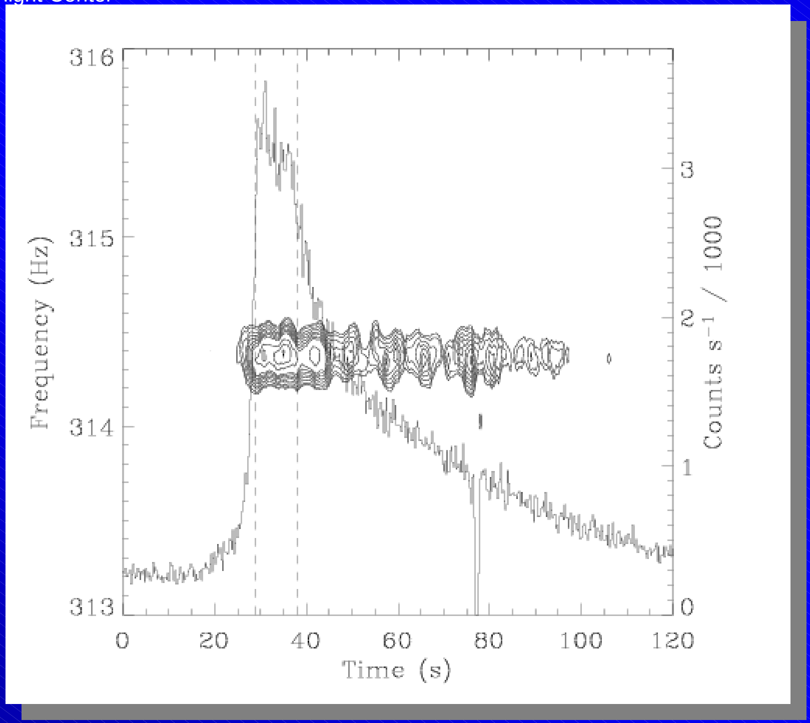
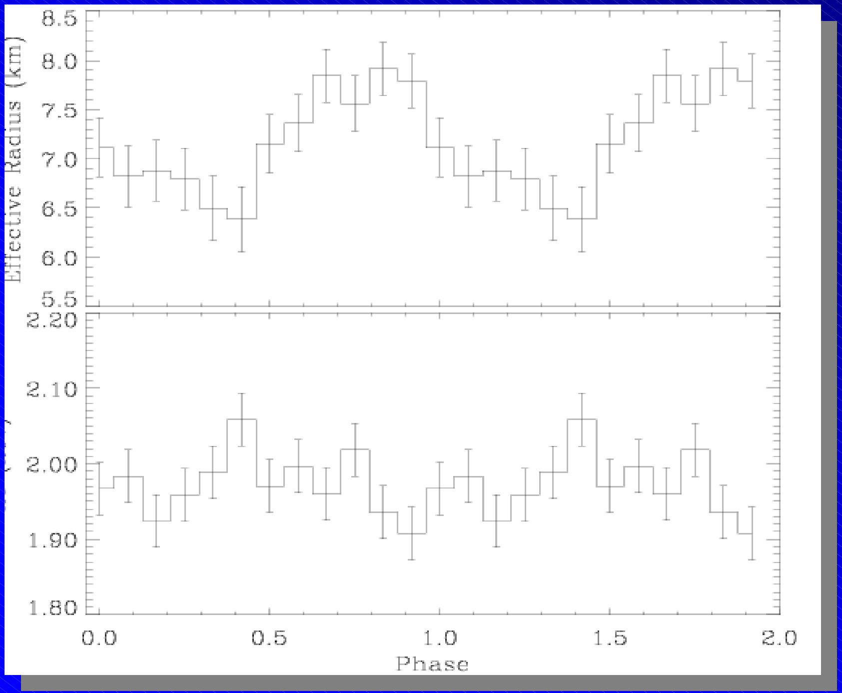
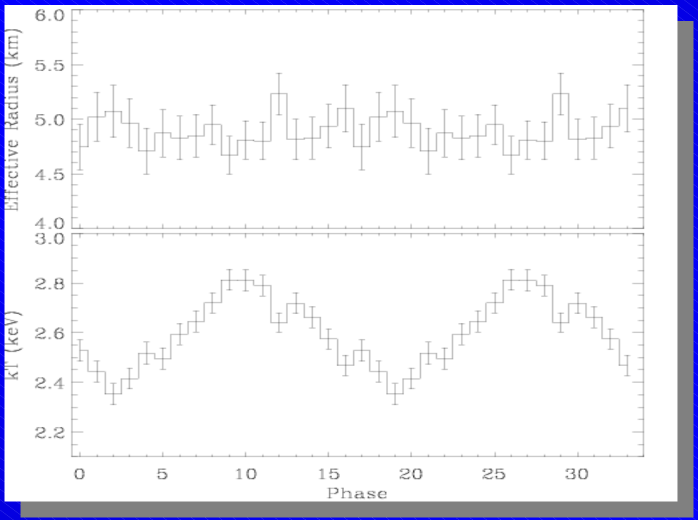


- 1% pulse amplitude (mean)
- ~30 μsec (rms)

Pulse Phase Spectroscopy: XTE J1814-338

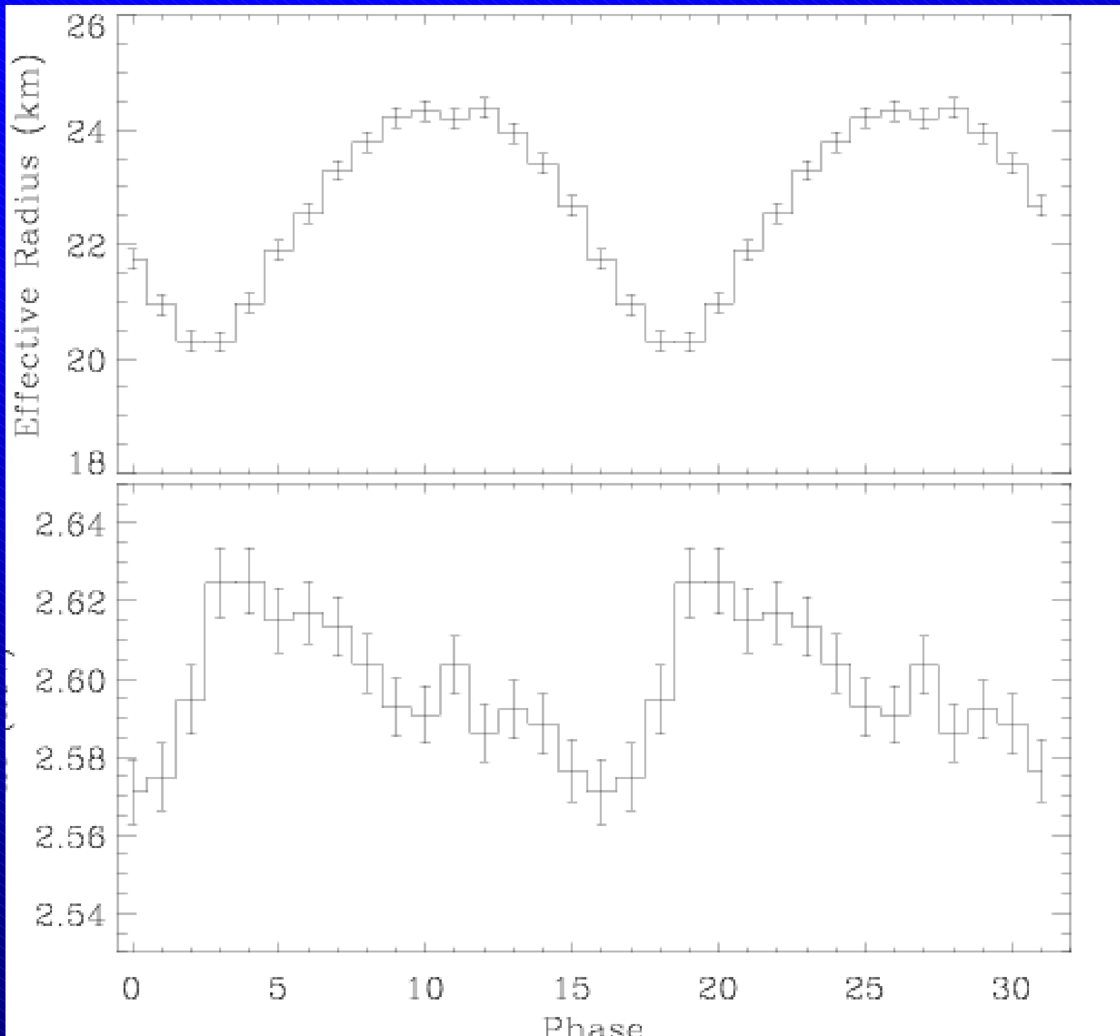






- Modulation consistent with varying projected area, at ~constant temperature
- This is not what would be seen from a “mode” where kT varied with some angular dependence

Pulse Phase Spectroscopy: Seeing the Surface Velocity.



- Simulation for J1814-like burst, with 10x RXTE/PCA.
- The rotational doppler shift can be seen in the phase dependence of the fitted kT.
- Could provide a measurement of radius.

Amplitudes at Onset: Rotational Model

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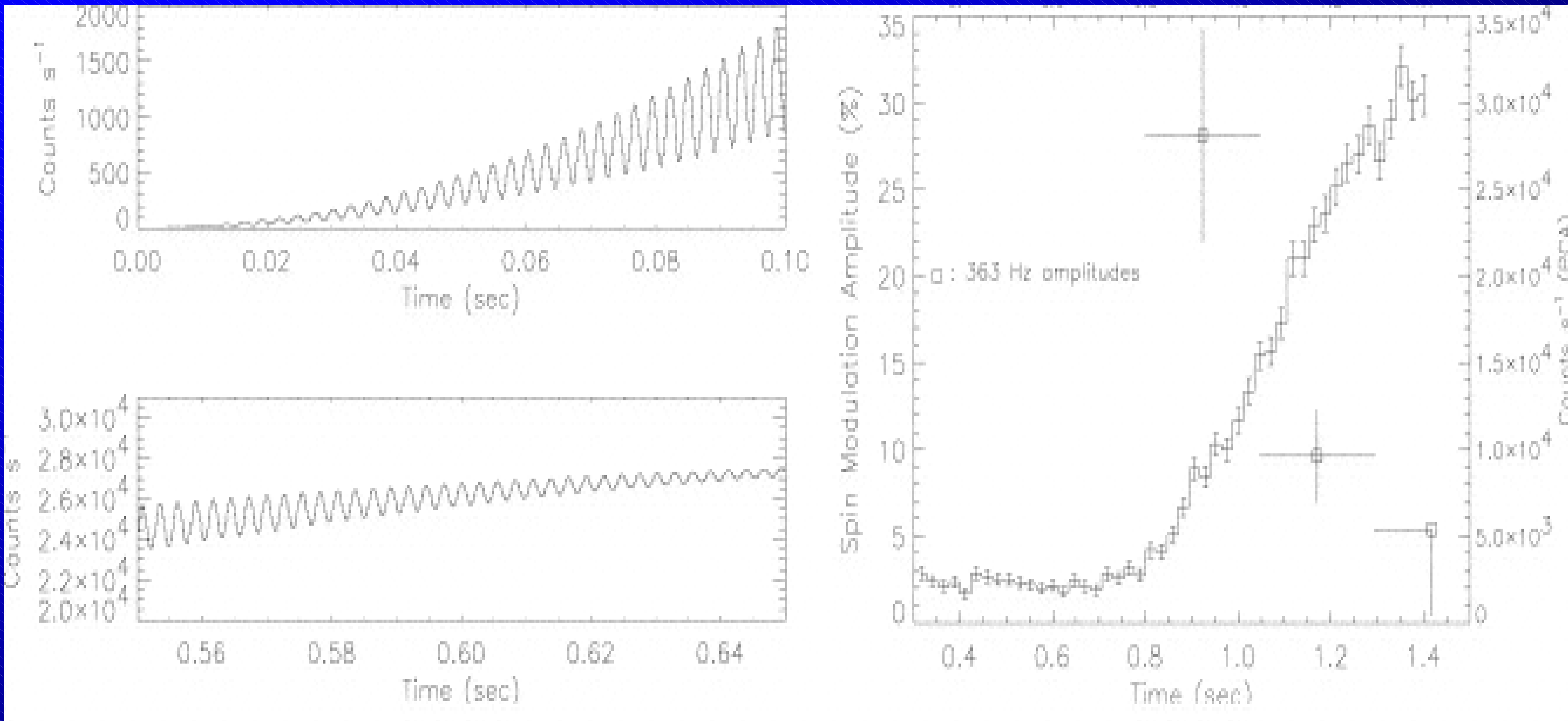

FIG. 4*a* FIG. 4*b*

- Simple expanding hot spot on rotating neutron star, including GR light deflection, can account for amplitudes and trend.

Strohmayer, Zhang & Swank (1997)

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Outline

- Motivation: Precise Mass and Radius measurements, constraining EOS.
- Accreting Neutron stars: X-ray burst sources (X-ray emission from surface). Why study accreting sources?
- Fast timing of X-ray bursts (with RXTE): “burst oscillations”
- Burst oscillations. Bursts from accreting ms pulsars. => Spin modulation
- Using burst oscillations to constrain neutron star parameters
- Pulsation amplitudes, Pulse shapes (profile fitting). Recent results on XTE J1814-338 (Bhattacharyya et al 2004). Pulsars too (SAX J1808; Poutanen & Gierlinski 2002);
- Using high-res spectroscopy and timing (to get spin). Recent results on EXO 0748-676 (Cottam et al. 2002; Villarreal & Strohmayer 2004).
- Is there an upper limit to neutron star spin rates? If so, what is it telling us?

“Normal” Thermonuclear Bursts

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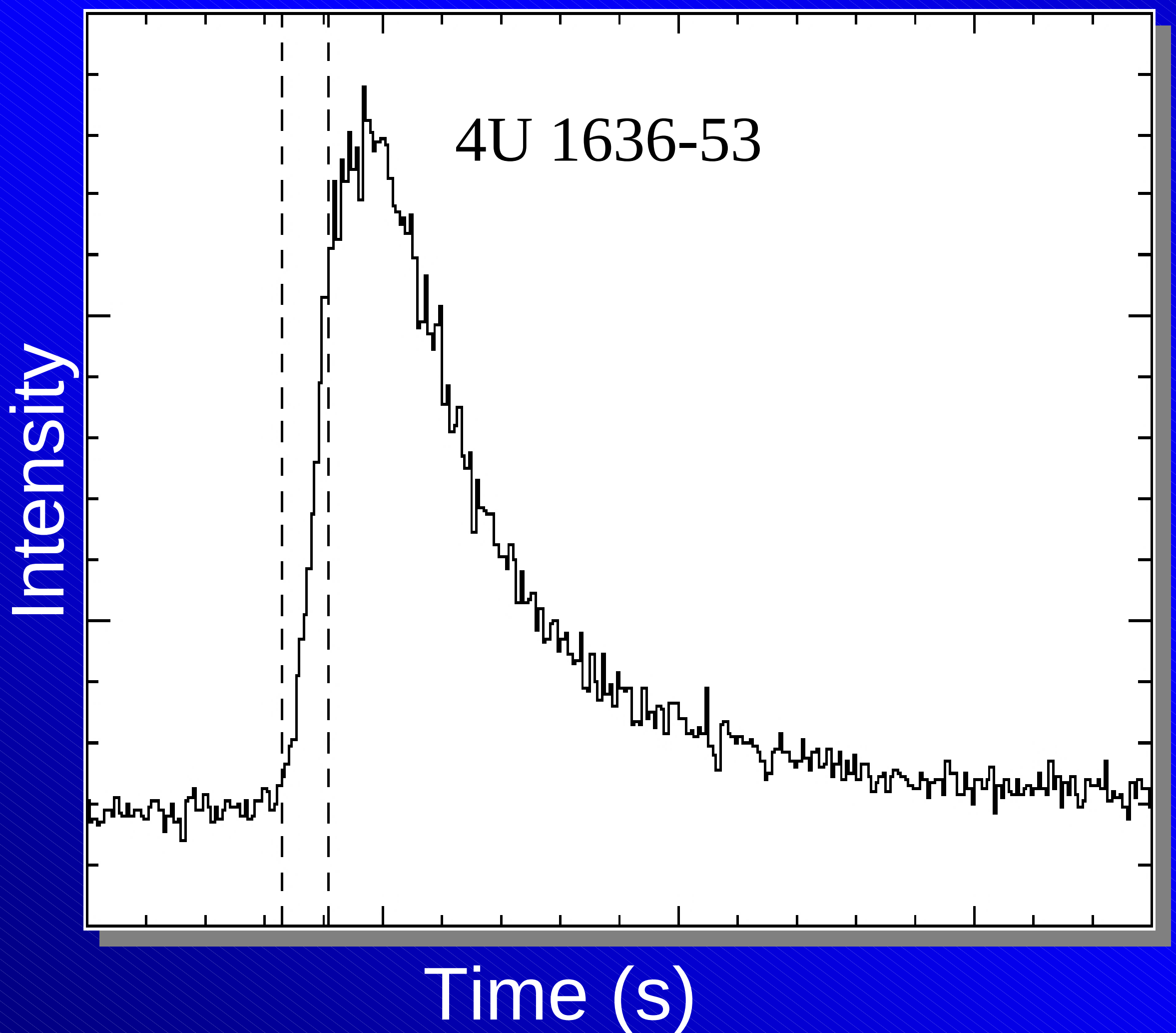

He Ignition at a column depth of 2×10^6 kg cm^{-2}

- 10 - 200 s flares.
- Thermal spectra which soften with time.
- 3 - 12 hr recurrence times, sometimes quasi-periodic.
- ~ 10^{39} ergs
- H and He primary fuels

Properties of Burst Oscillations

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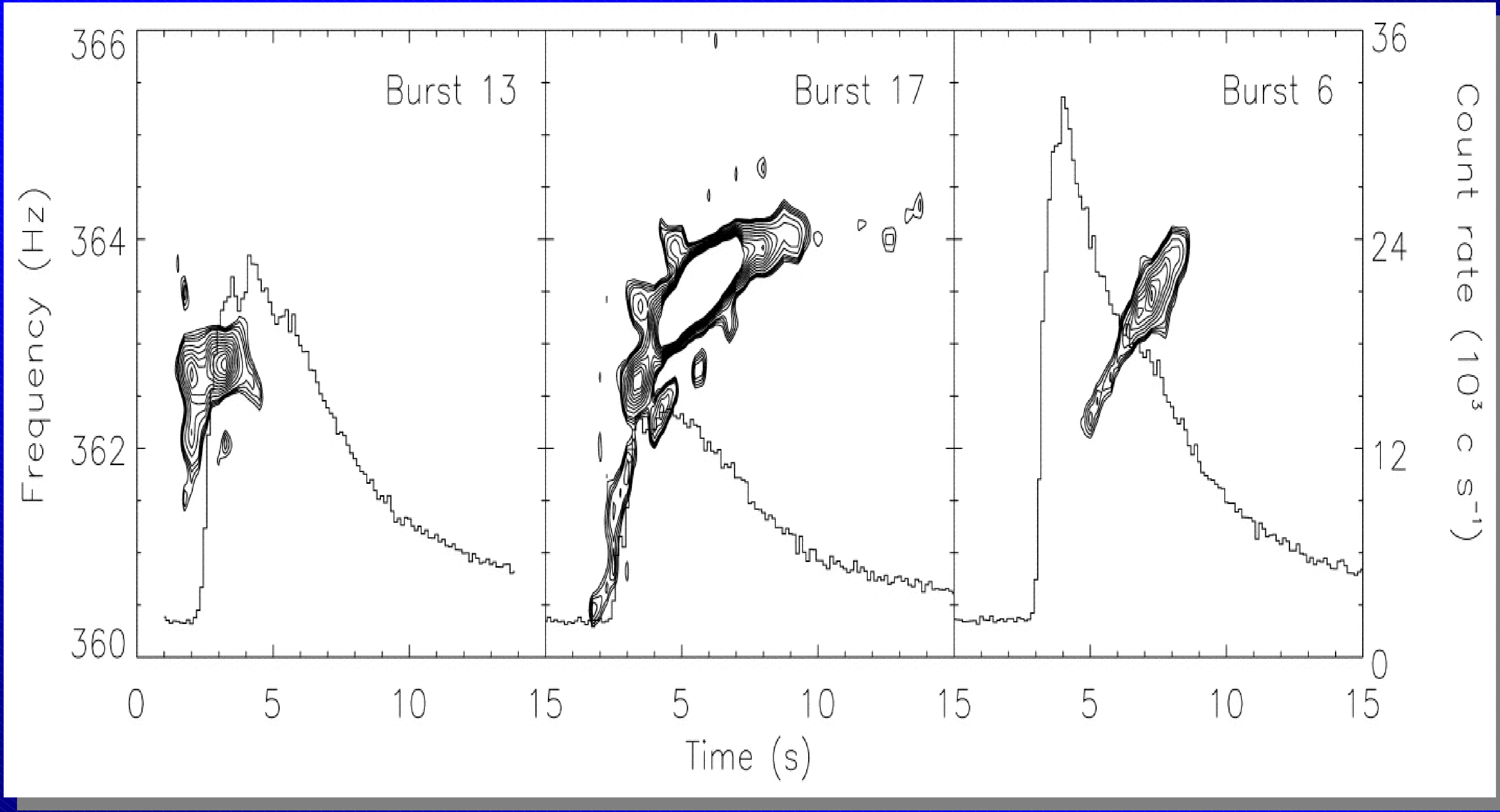
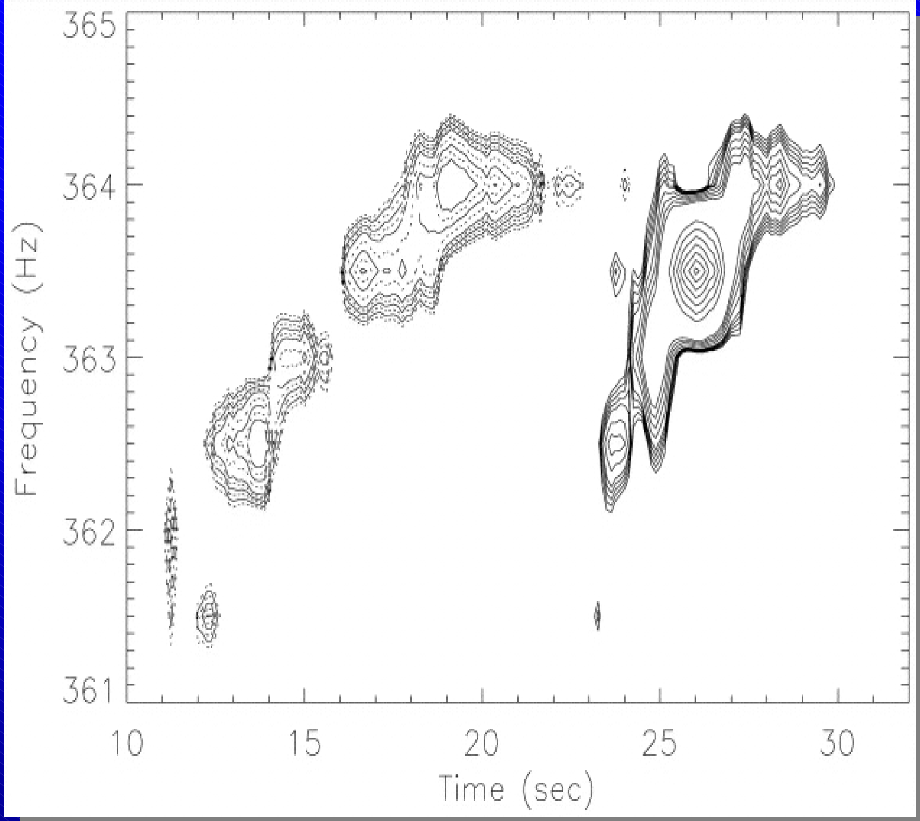
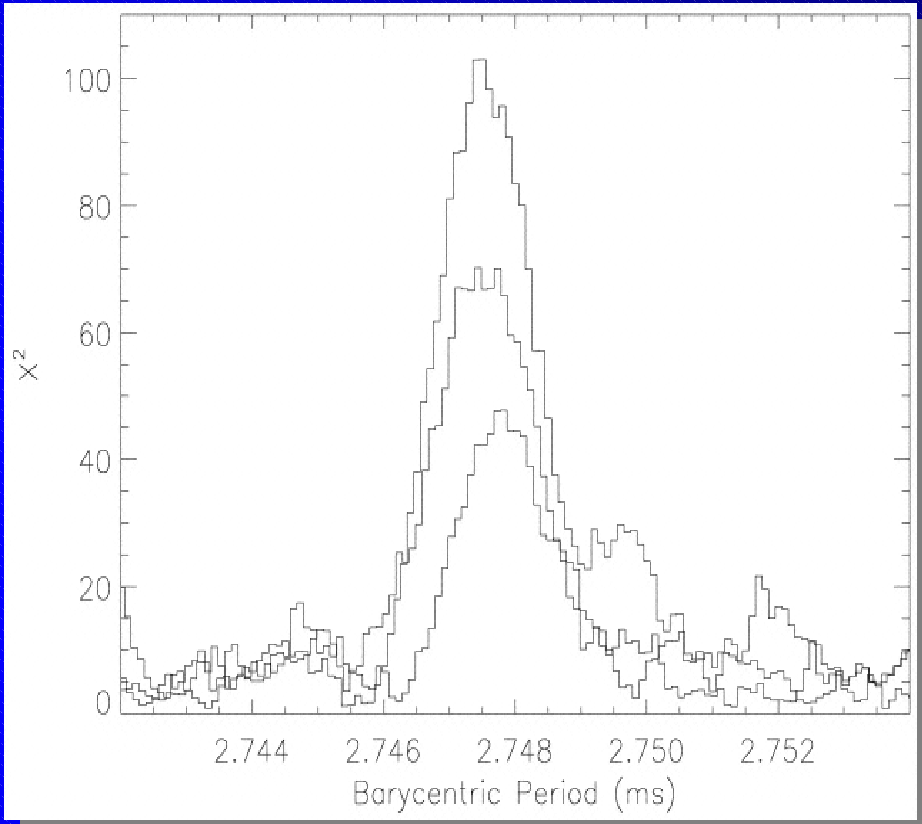


A Sample of Bursts from 4U 1728-34

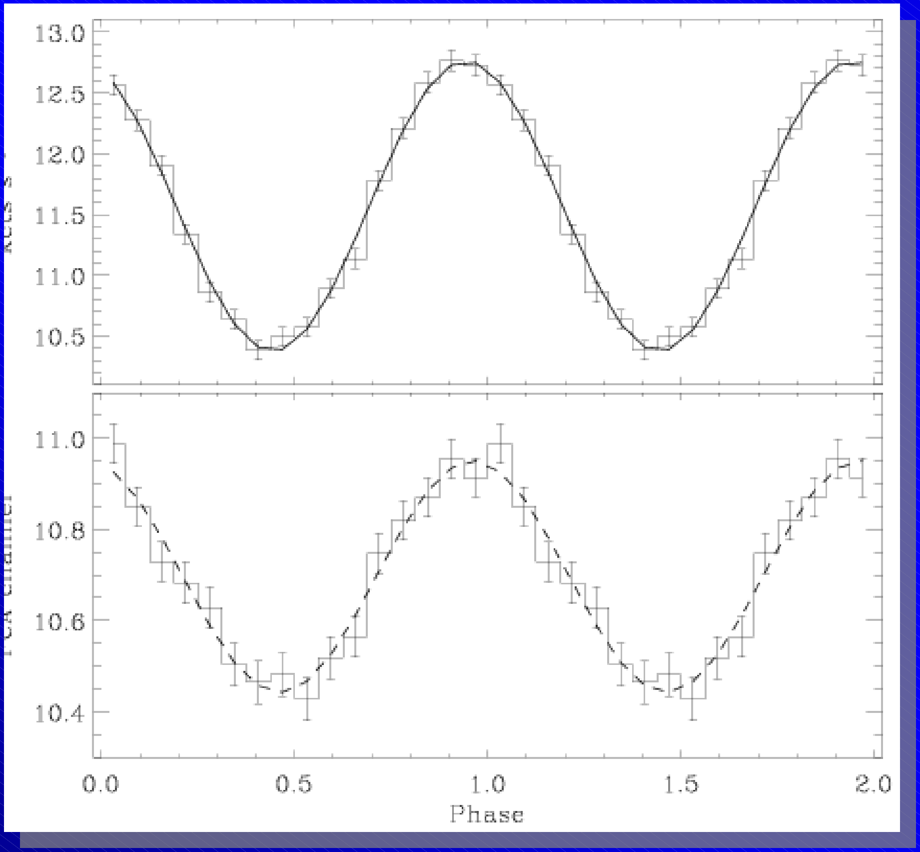
Long term Stability of the Oscillation Frequency

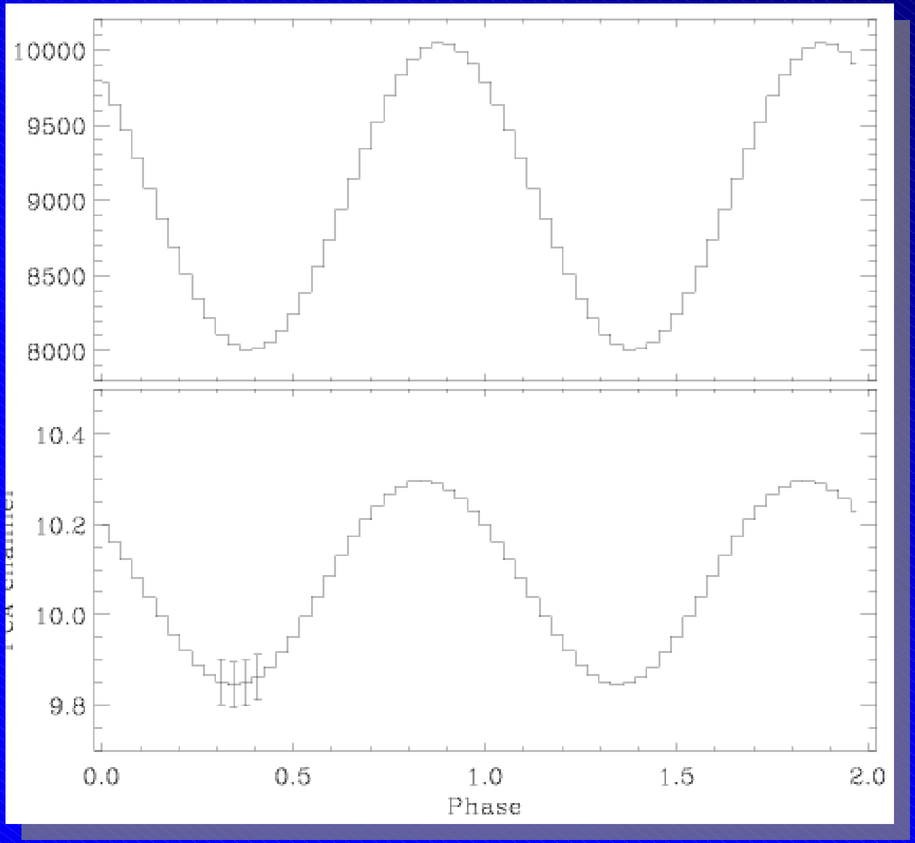




- Bursts from 4U 1728-34 separated by years have the same oscillation frequency
- for 4U 1728-34 timescale to change period ~ 2.3 x 10^4 yr

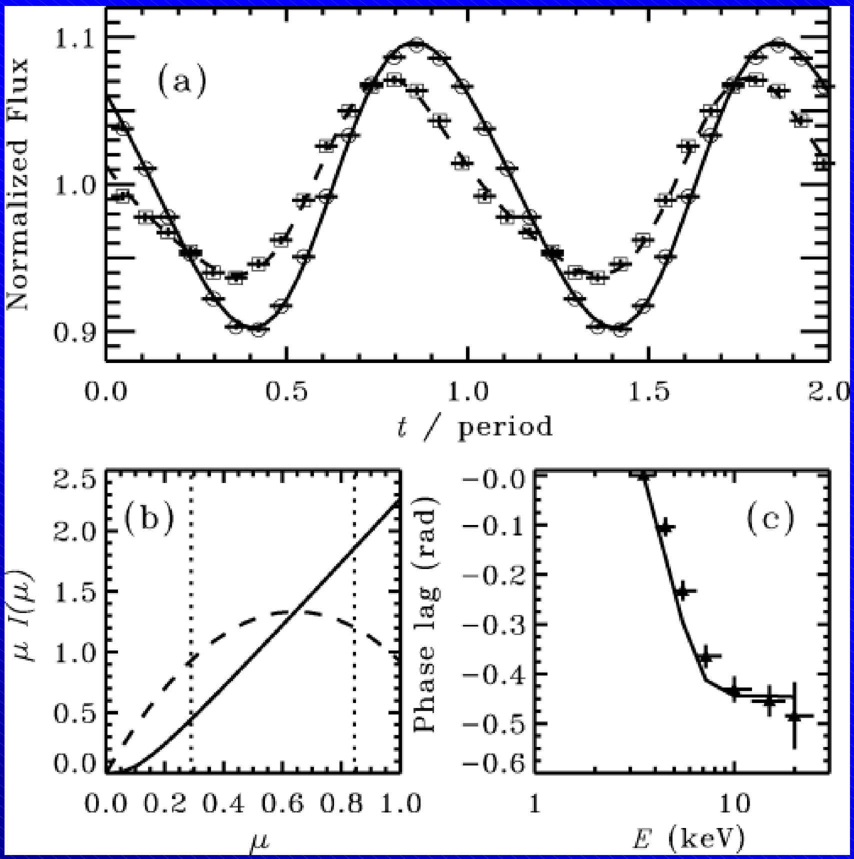
Phase Resolved Spectroscopy: Rotational Doppler shifts, 4U 1636-53



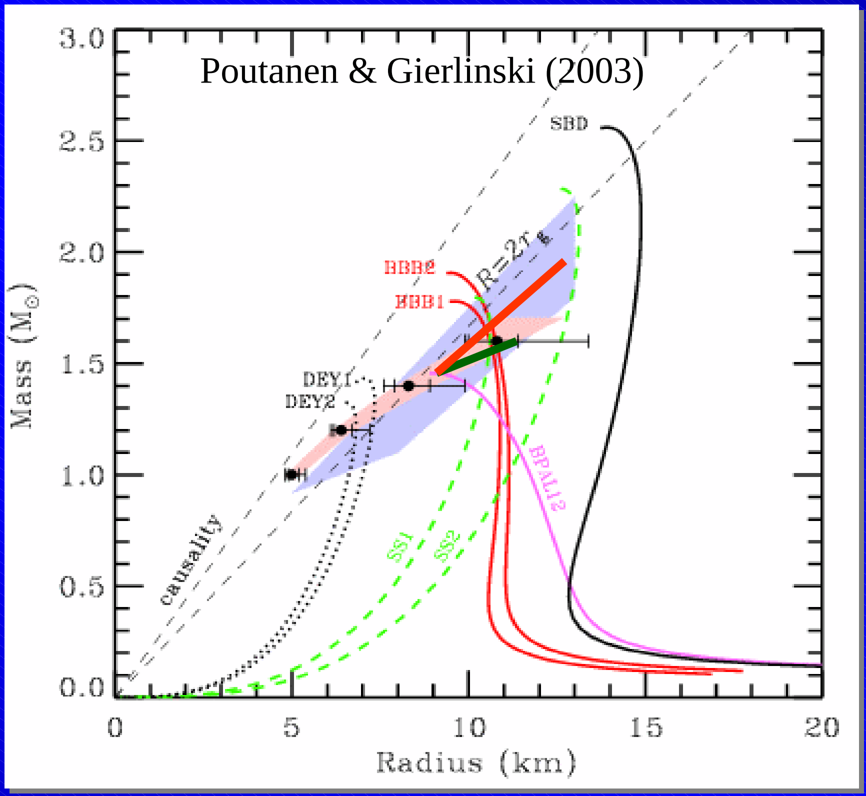


- Spectra (or average hardness) with pulse phase show modulations consistent with temperature asymmetry.
- Attempt to constrain emission geometry (is an angular mode present).
- Model fitting in progress: stay tuned…

Mass – Radius Constraints: Persistent Pulse Profiles



- Comparison of constraints from SAX J1808.4-3658 (Poutanen & Gierlinski 2003, red), and XTE J1814-338 (Bhattacharyya et al. 2005, green line).



- Two component model: Thermal spot (soft); comptonized (hard).
- Very high signal to noise pulse profile.

Nuclear flows during X-ray Bursts: With Hydrogen

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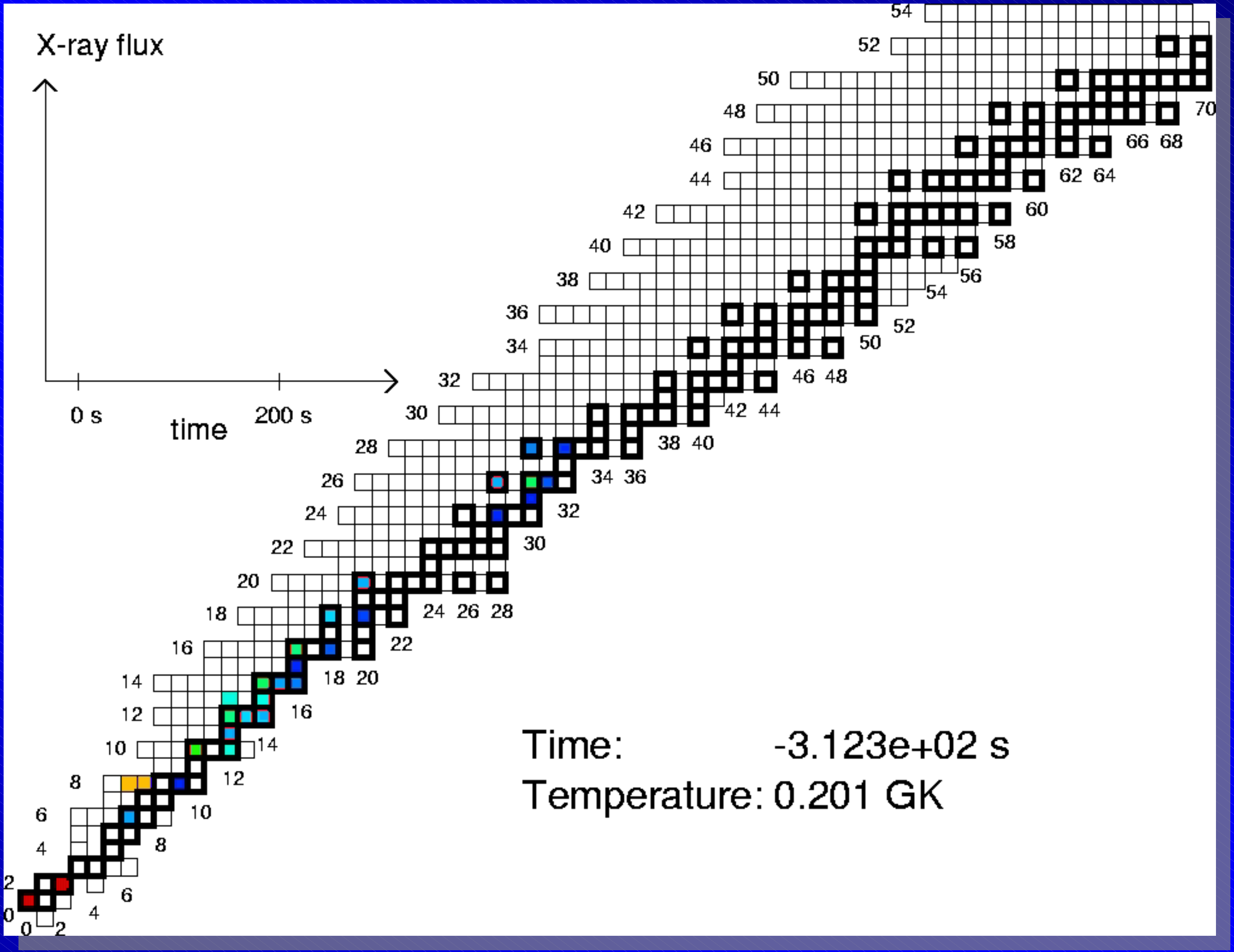
- Composition is important for superbursts.
- With hydrogen around, carbon tends to be destroyed by rp process burning.
- Is enough carbon left over to account for superbursts?



Thanks to Hendrik Schatz (MSU) for the movie

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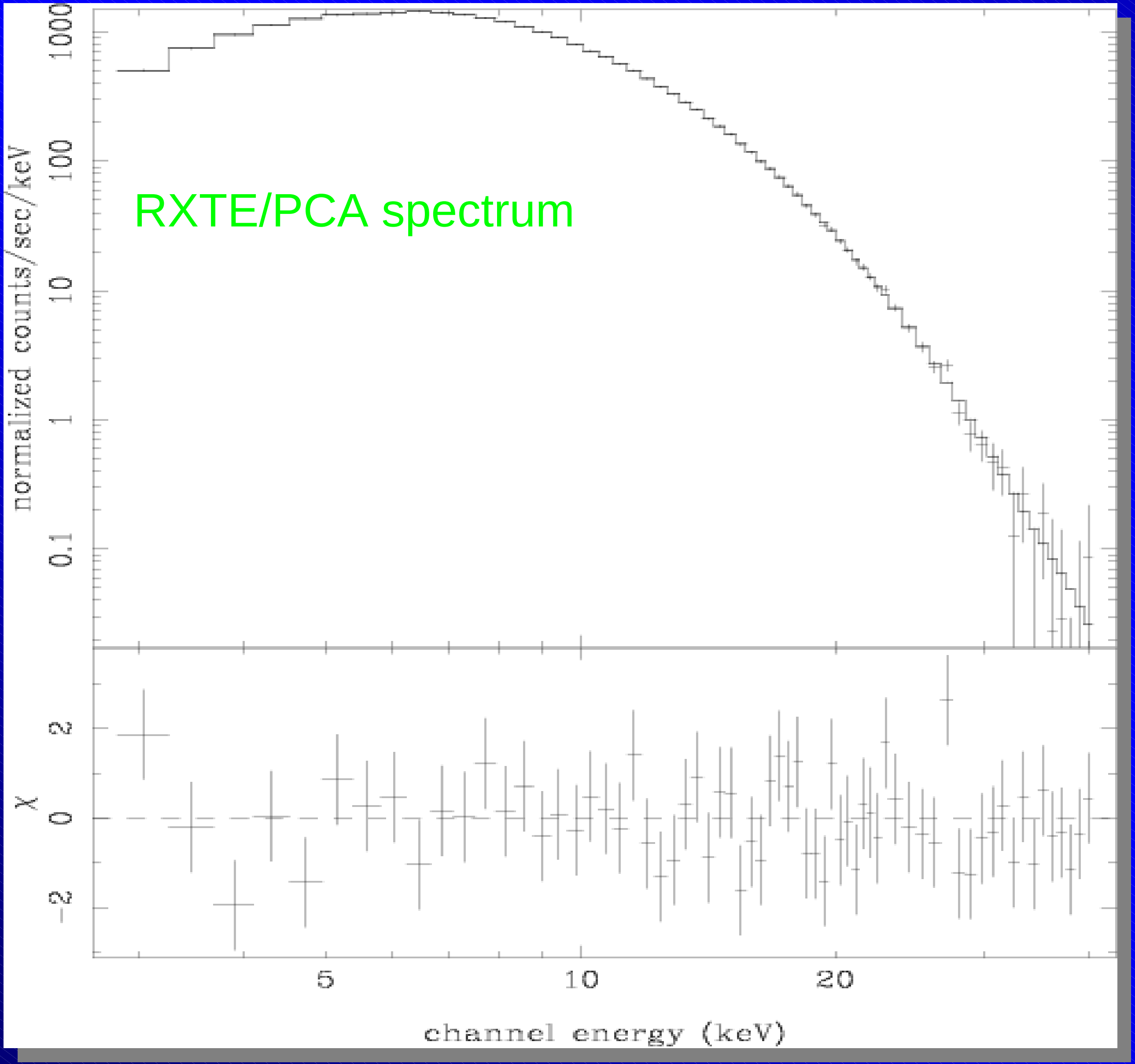
Superburst from 4U 1820-30: Spectral Modelling



- Long decay timescale gives high signal to noise spectra.
- Thermal (black body) spectrum strongly preferred for continuum.
- Discrete components, ~ 6 keV broad line, and 9 keV edge required.

Fundamental Physics: Existence of New States of Matter?

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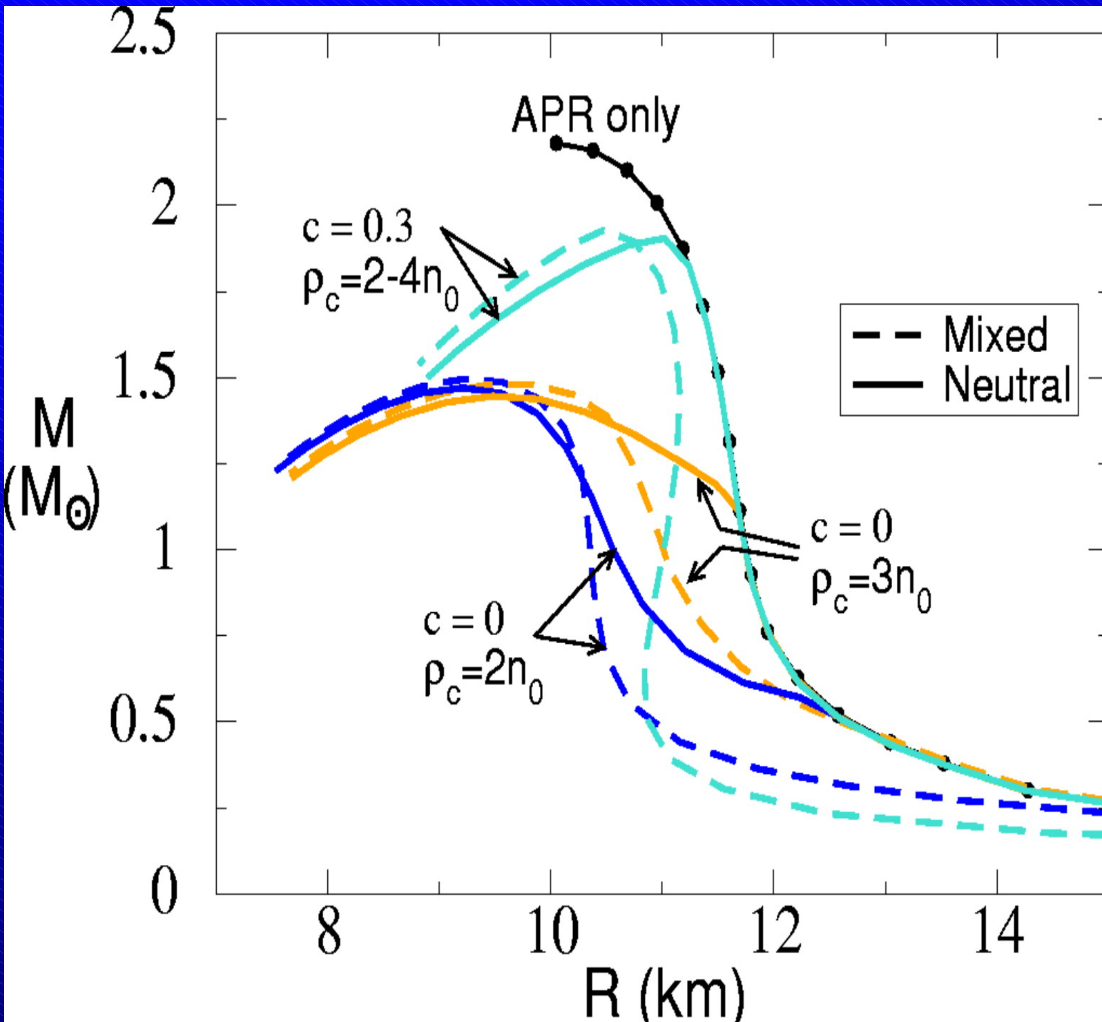

Alford et al. (2005)

- Theoretical work suggests quark matter could exist in neutron stars, possibly co-existing with a nuclear component.
- Mass – Radius measurements alone may not be enough to discriminate the presence of quark matter.
- Other observables, such as global oscillations might be crucial.

Puzzle # 2: Oscillations in the Cooling Phase

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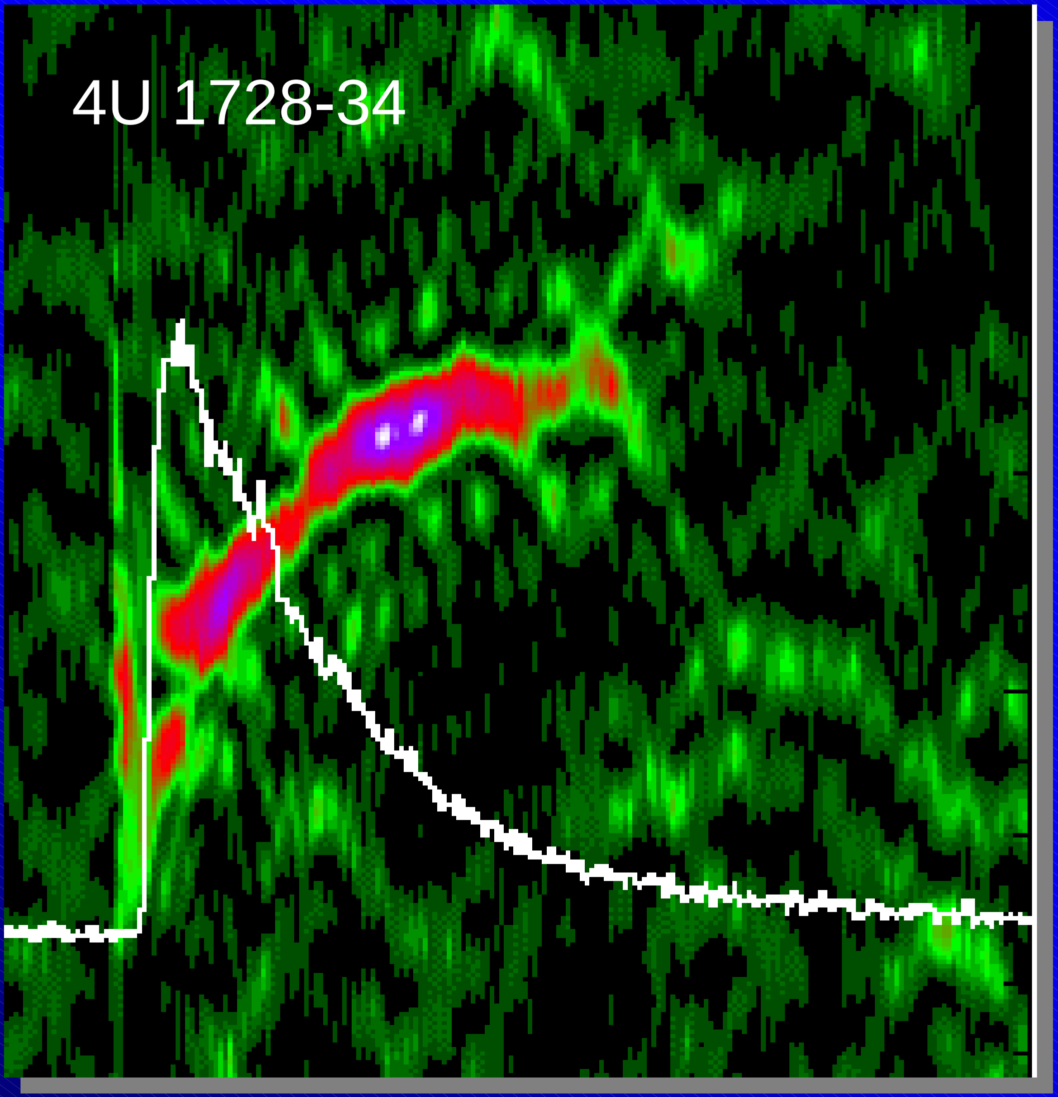

- Pulsations in the cooling tails can be as large as 15% (rms)
- If the whole surface is burned, what causes the flux asymmetry?
- Cooling time asymmetry is probably not large enough
- Oscillation modes (Heyl 2002 suggests *r*-modes; Piro & Bildsten 2005, Lee & Strohmayer 2005, Heyl 2005) ?

Double-peaked bursts: A Spreading Phenomenon?

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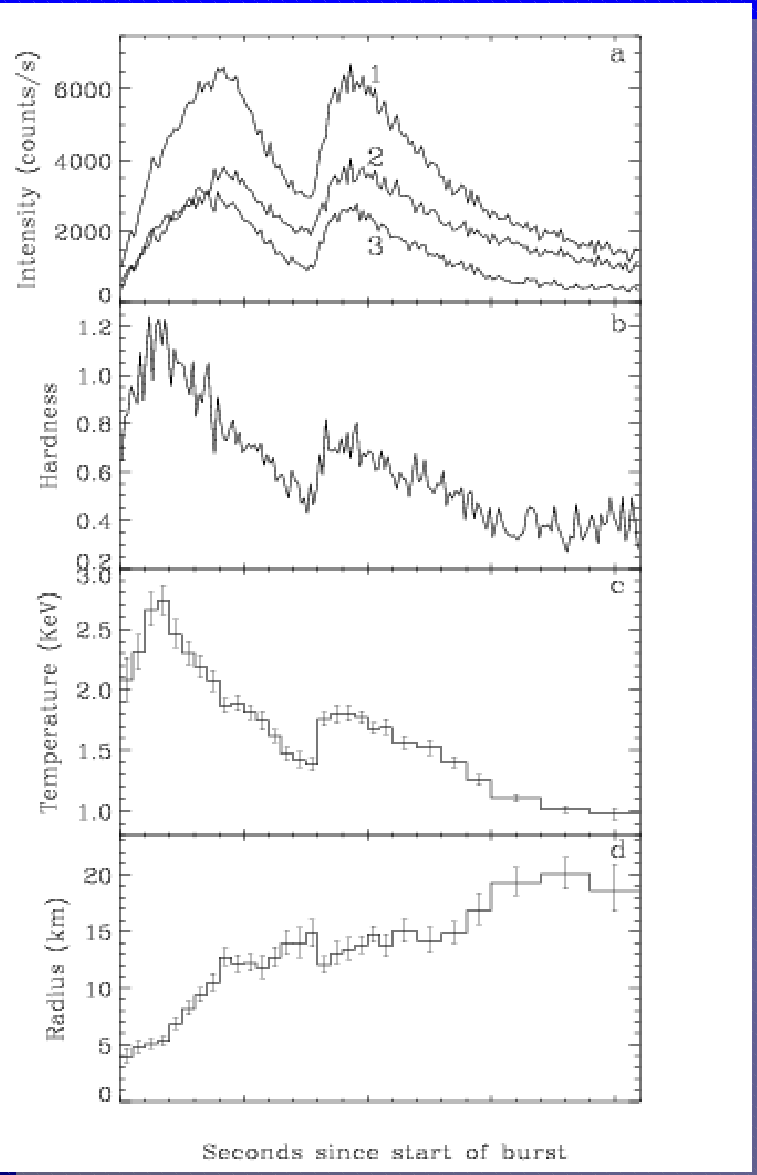

- A small fraction of bursts show multiple peaks NOT associated with photospheric radius expansion (4U 1636-53, a famous example).
- These are sub-Eddington in peak flux.
- Several models proposed: 1) shear instability (Fujimoto): 2) “Delayed” nuclear energy release (Fisker et al.).
- All of these “one dimensional” in some sense

Bhattacharyya & Strohmayer (2005)

Double-peaked bursts: A Spreading Phenomenon?

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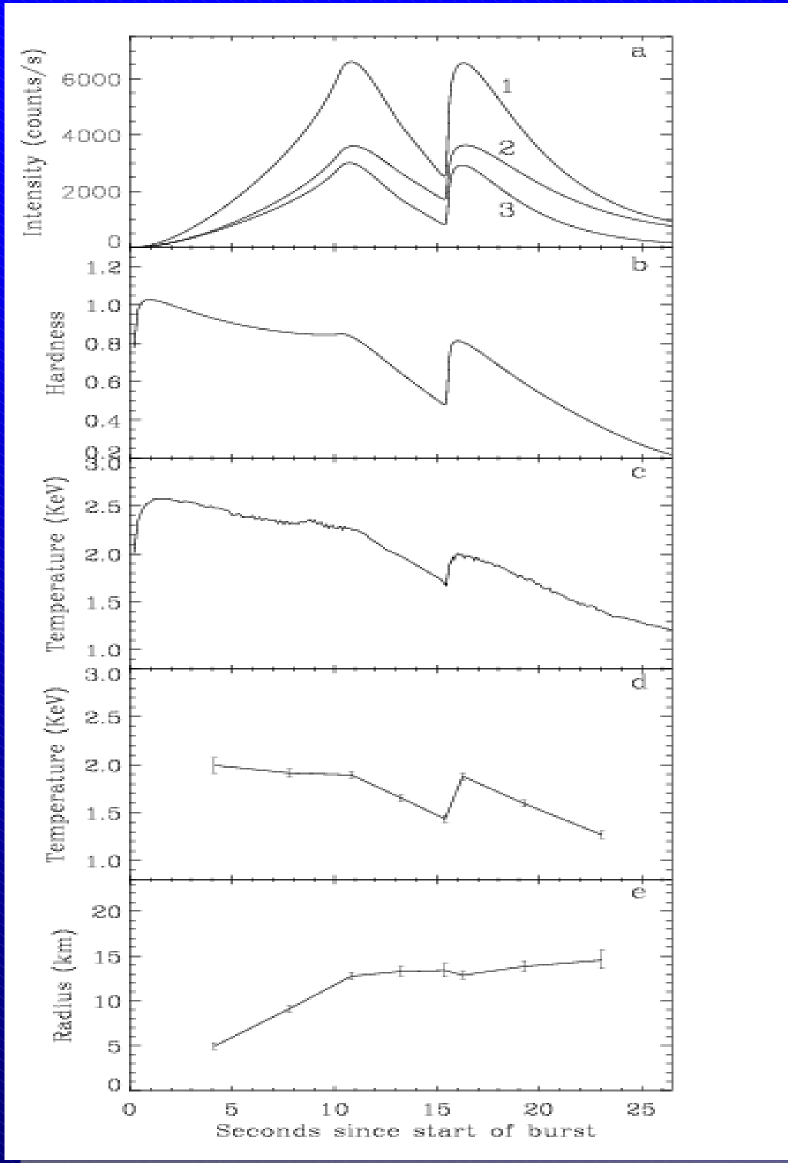

- We explore spreading in a manner analogous to Spitkovsky et al (2002).
- Using fully relativistic model of photon propagation from NS surface (Bhattacharyya et al. 2005).
- Spreading from equator appears implausible.
- Spreading from a pole with front "stalling" near equator can qualitatively explain observed properties.

Bhattacharyya & Strohmayer (2005)

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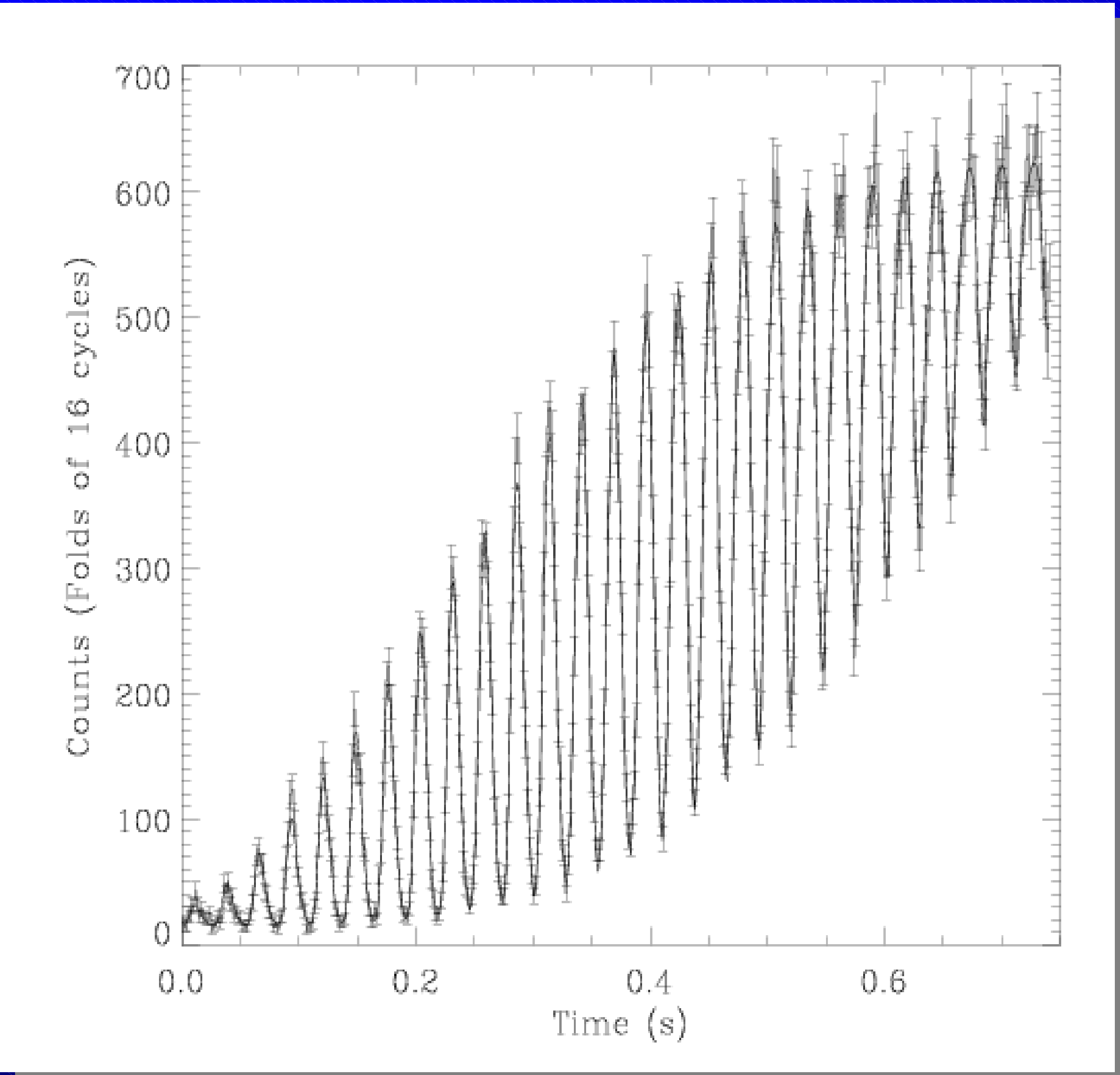
Future: Simulated Lightcurve: 10x RXTE/PCA



- 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.

First Superburst from 4U 1735-44 (BeppoSAX/WFC)

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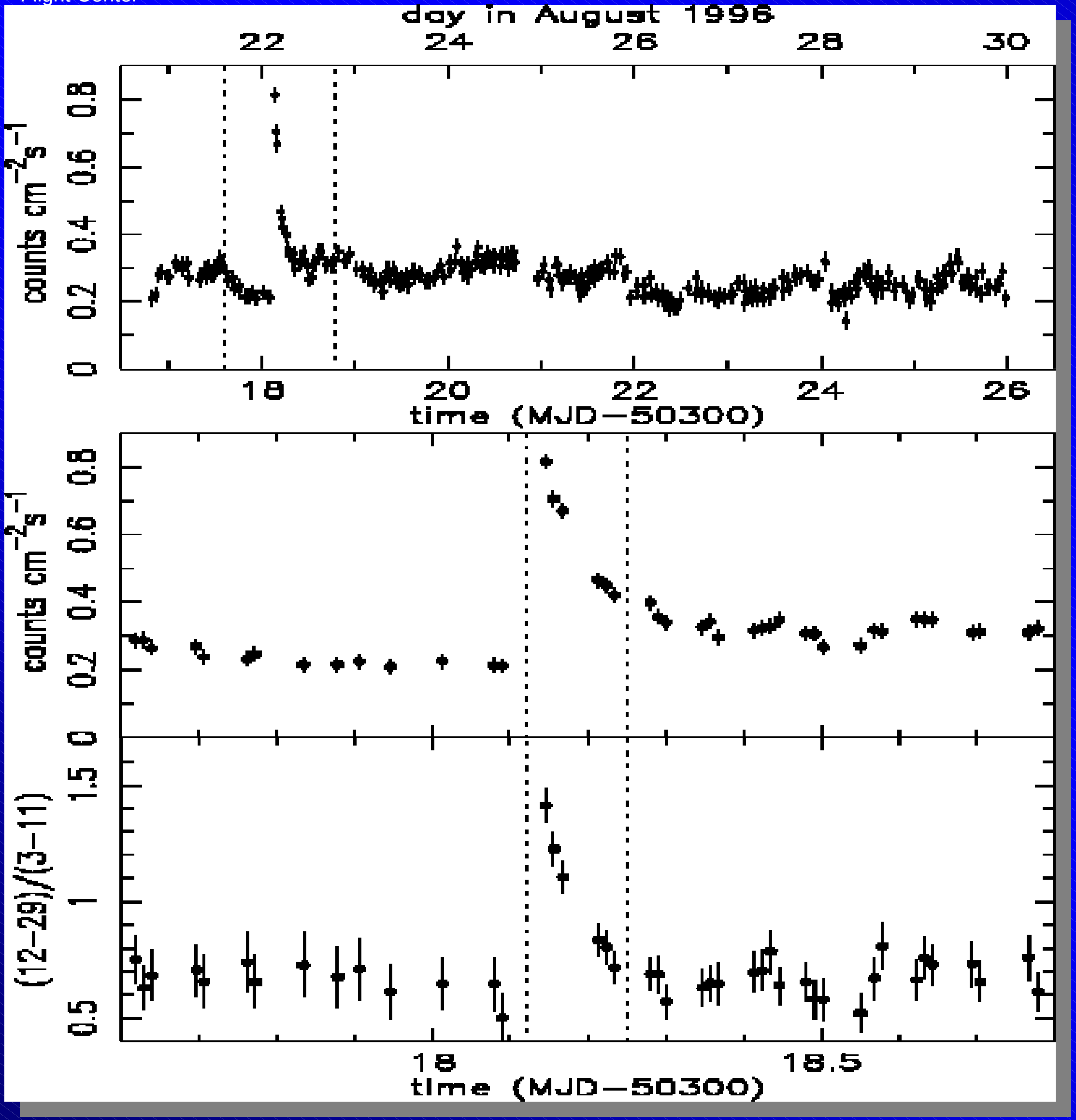

Cornelisse et al. (2000)

- Long, 3 - 5 hr flares seen to date from 9 low mass X-ray binaries (LMXB).
- Spectra consistent with thermal, show softening with time.
- Two superbursts from 4U 1636-53, 4.7 yr apart.
- 1,000 x more energy than standard Type I bursts!

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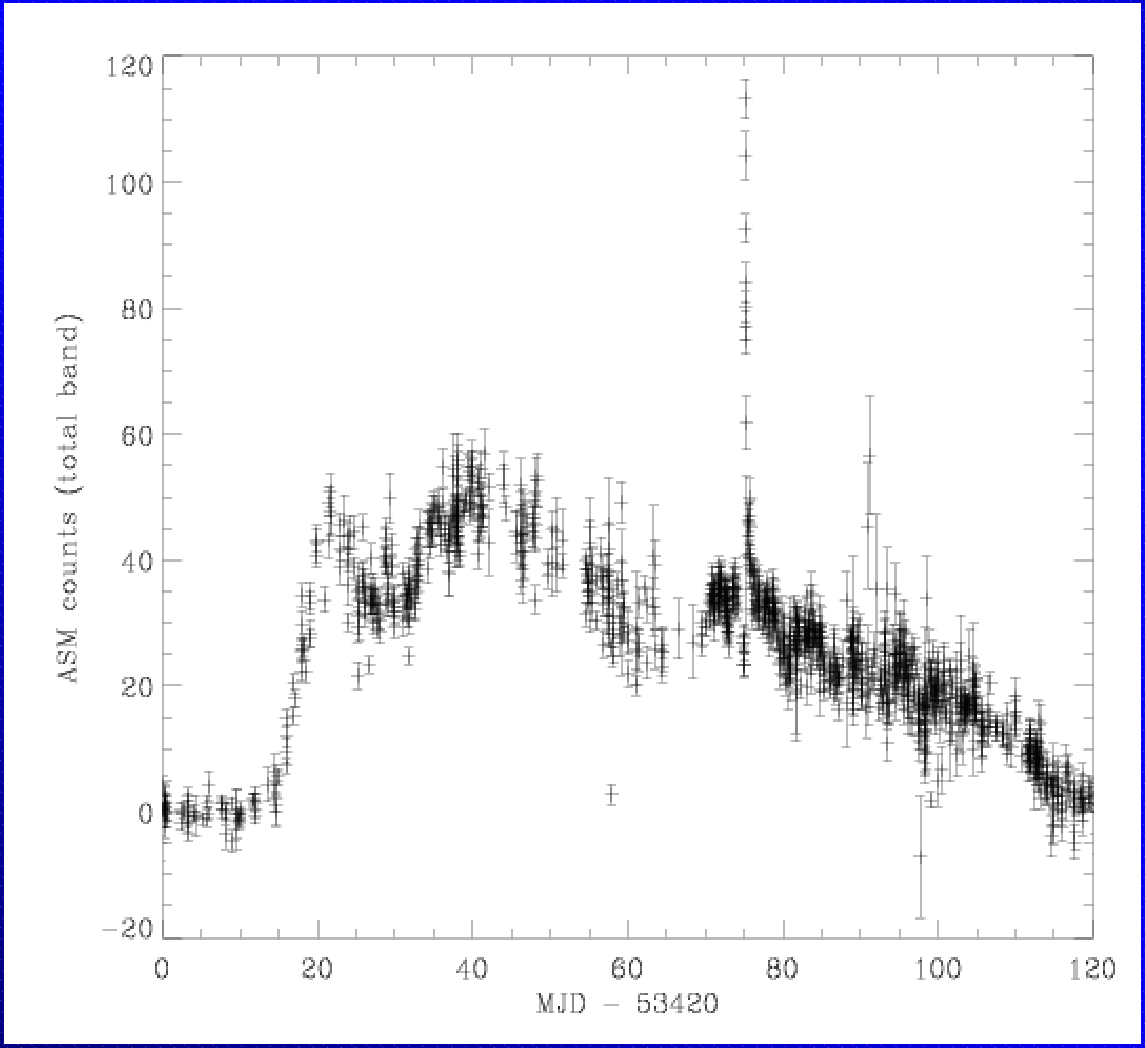
New Superburst from 4U 1608-522 (RXTE/ASM)



Levine et al. (2005)

- Seen in the transient source 4U 1608-522.
- Spectrum consistent with thermal, shows softening with time.
- Observed during the most recent outburst.
- RXTE and XMM programs to observe superbursts. ASM notice was not disseminated, missed this one!

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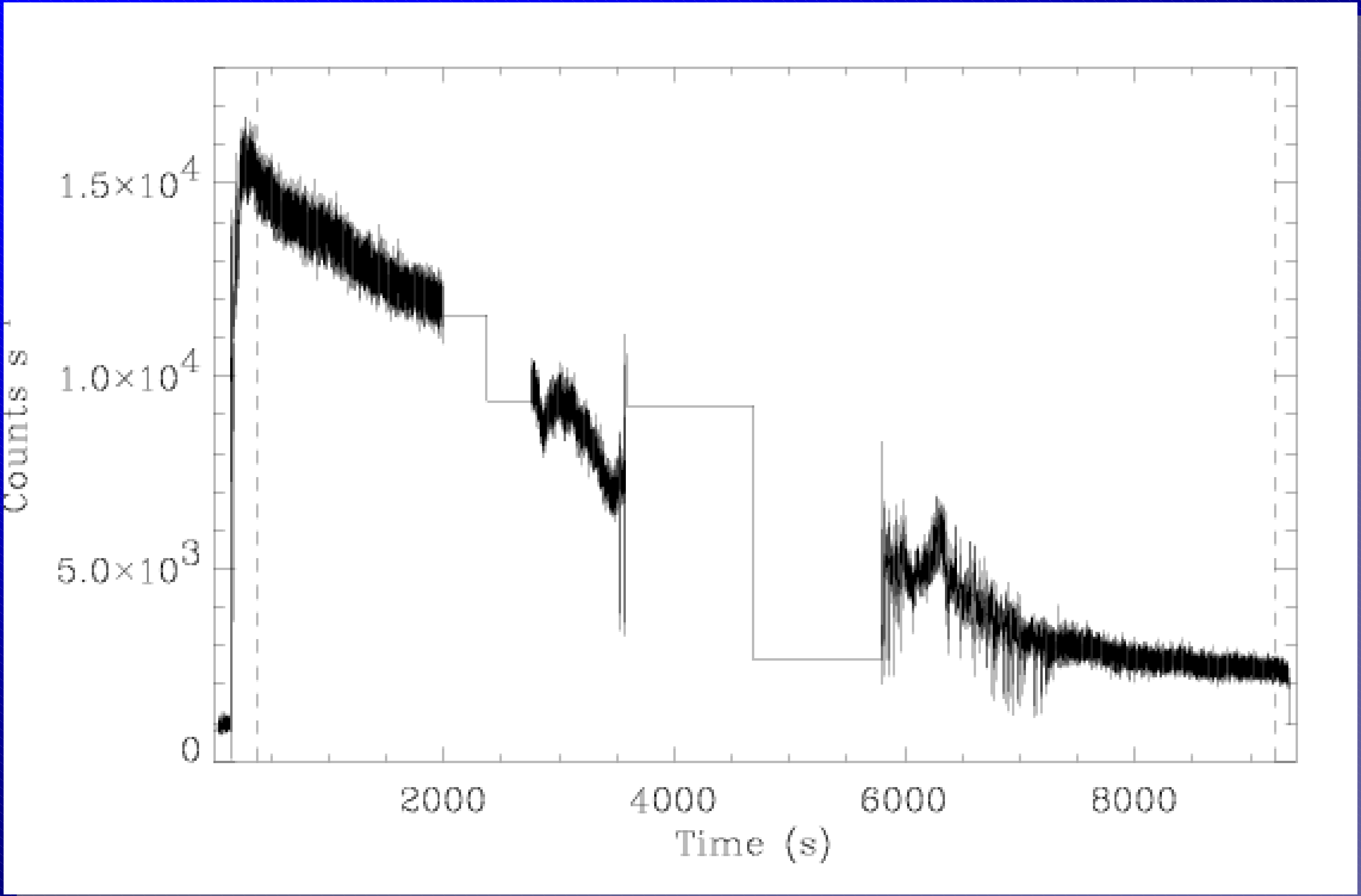
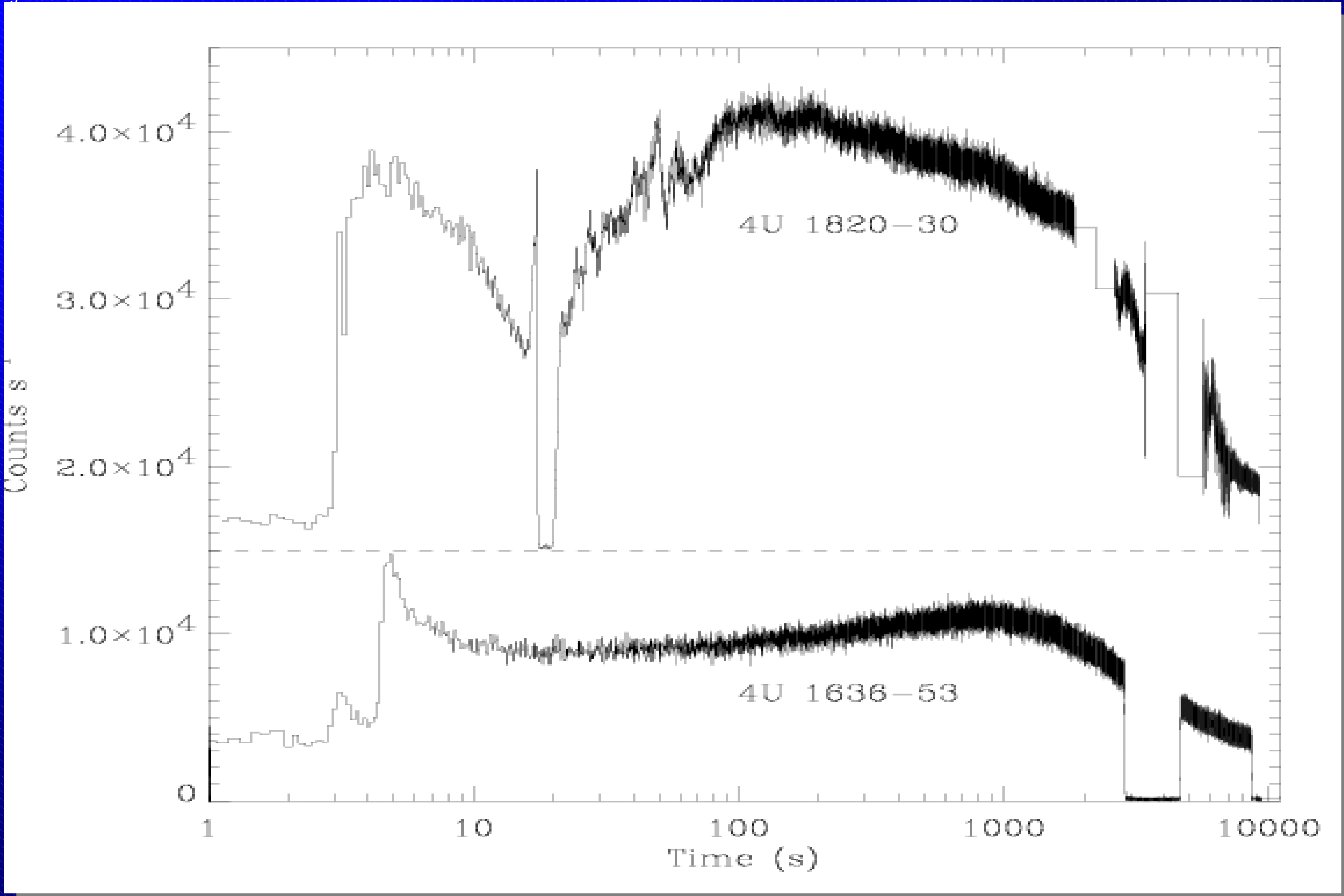
Probing the Accretion disk in 4U 1820-30: Reflection Spectra



Superbursts observed with RXTE/PCA



Superburst Sources

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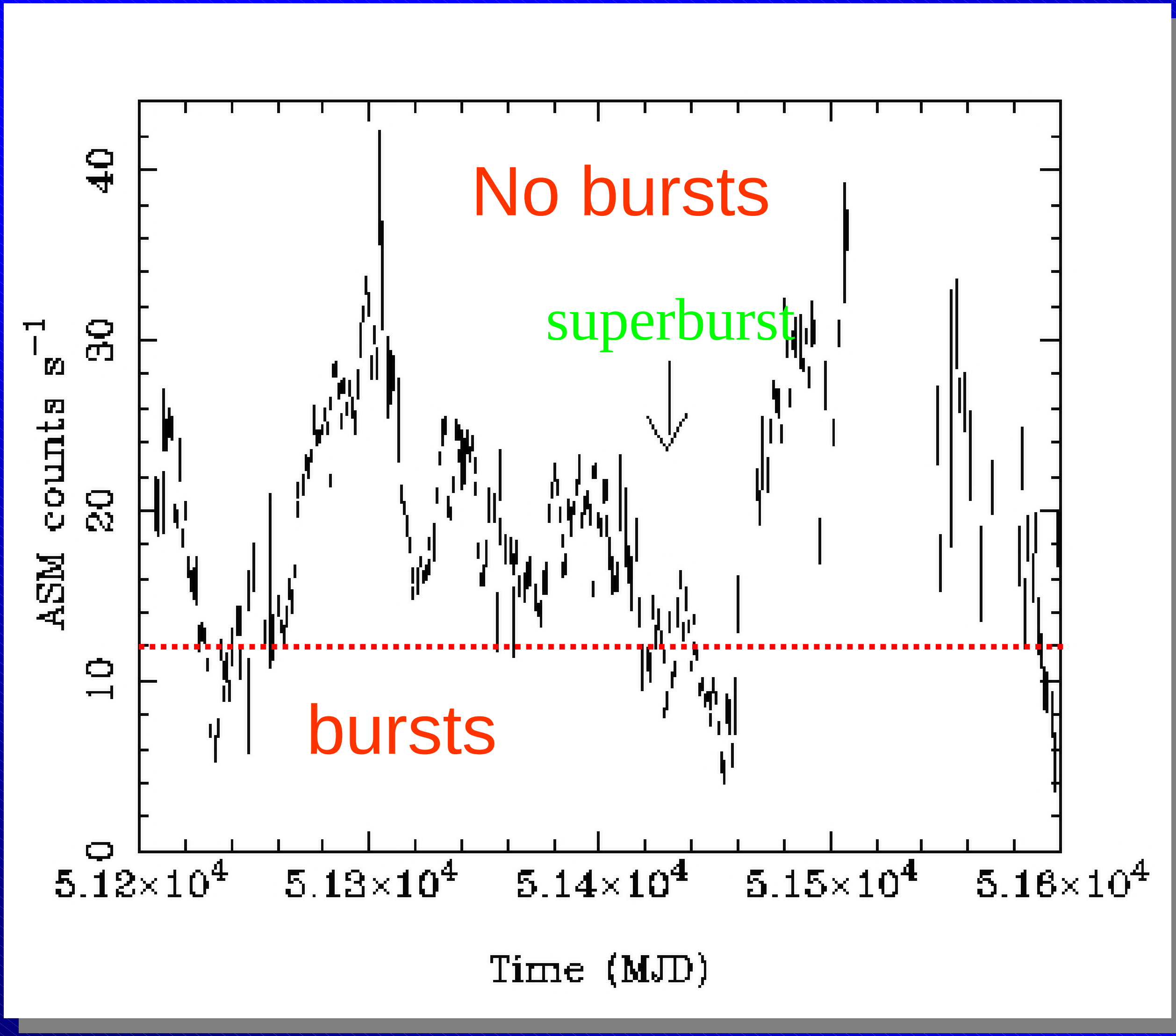
Sources	Observations	Number (recurrence)
4U 1735-44	SAX - WFC	1
4U 1820-30	RXTE - PCA	1
4U 1636-53	RXTE - ASM, PCA	2 (4.7 yr)
KS 1731-260	SAX - WFC	1
Serpens X-1	SAX - WFC	1
GX 3+1	RXTE – ASM	1
4U 1254-69	SAX-WFC	1
4U 0614+091	RXTE-ASM	1
4U 1608-522	RXTE-ASM	1

4U 1728-34	GX 9+9	Aql X-1
4U 1702-429	GX 9+1	
Cyg X-2	GX 13+1	
GS 1826-238	4U 1705-440	

Superburst from 4U 1820-30: Carbon Production



- Thermonuclear (helium) burning is stabilized at high accretion rates (ie. no normal bursts).
- Lower peak burning temperatures will likely synthesize lots of Carbon.
- Higher temperature during unstable burning yields little Carbon

Strohmayer & Brown (2002)

A Carbon “bomb” on a Neutron Star

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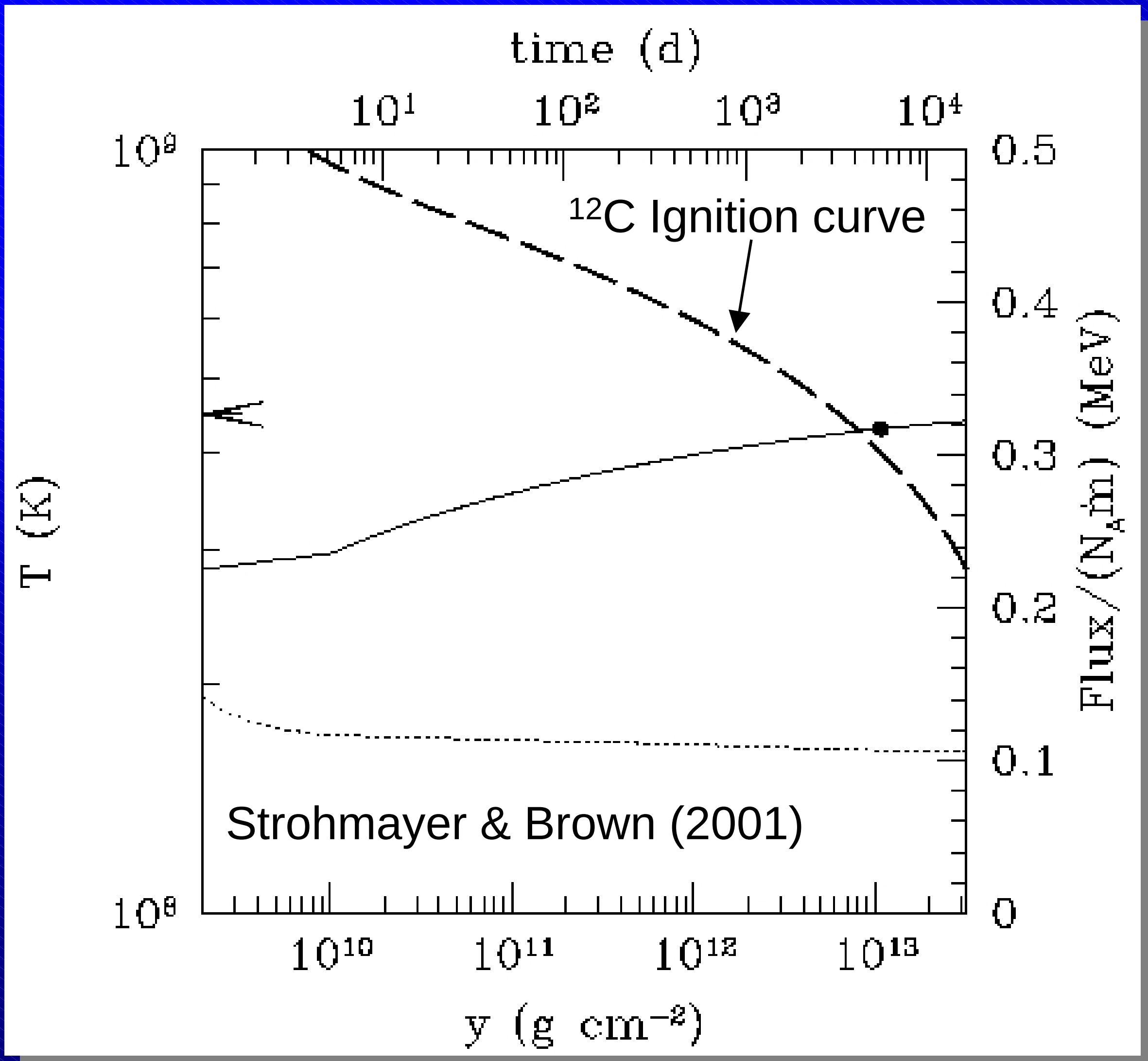
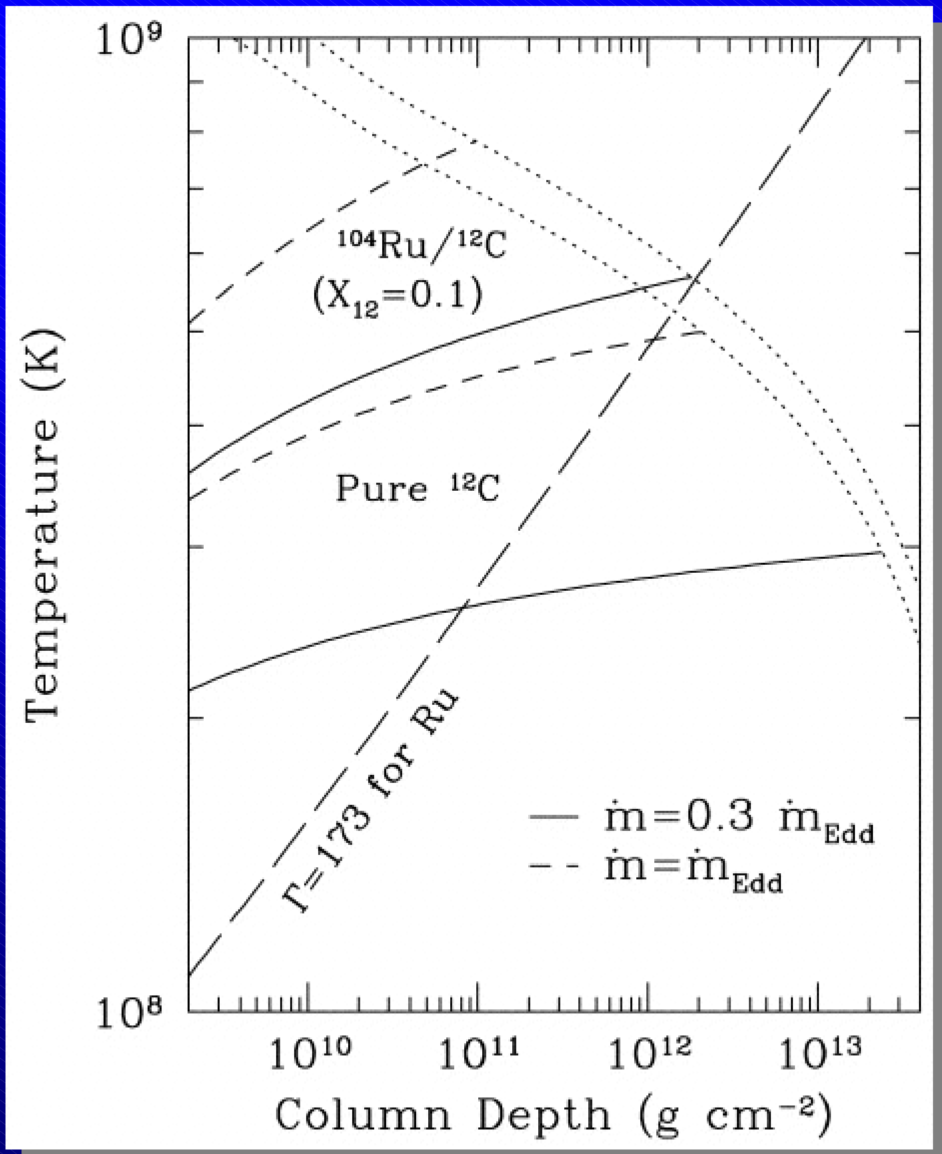
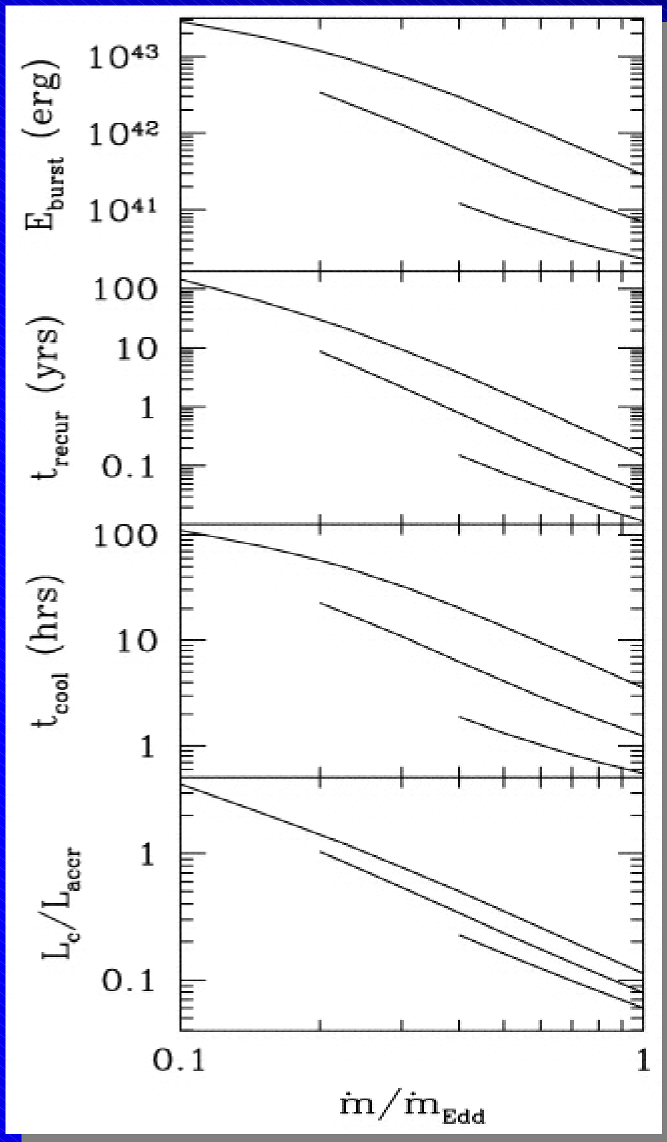


- Too much energy for unstable helium burning
- Carbon burning can supply total energy, recurrence time ~ 10 years.
- Carbon produced during stable burning of accreted helium.
- Carbon ignites at 10^{13} g cm^{-2}. Total energy is ~10-20 times greater than X-ray fluence.
- Significant energy loss to neutrinos, energy will flow inward to be released on longer timescale.

Carbon Flashes on Neutron Stars: Mixed Accretors





Cumming & Bildsten 2001

RXTE Observes Three Hour Burst from a Neutron Star (4U 1820-30)

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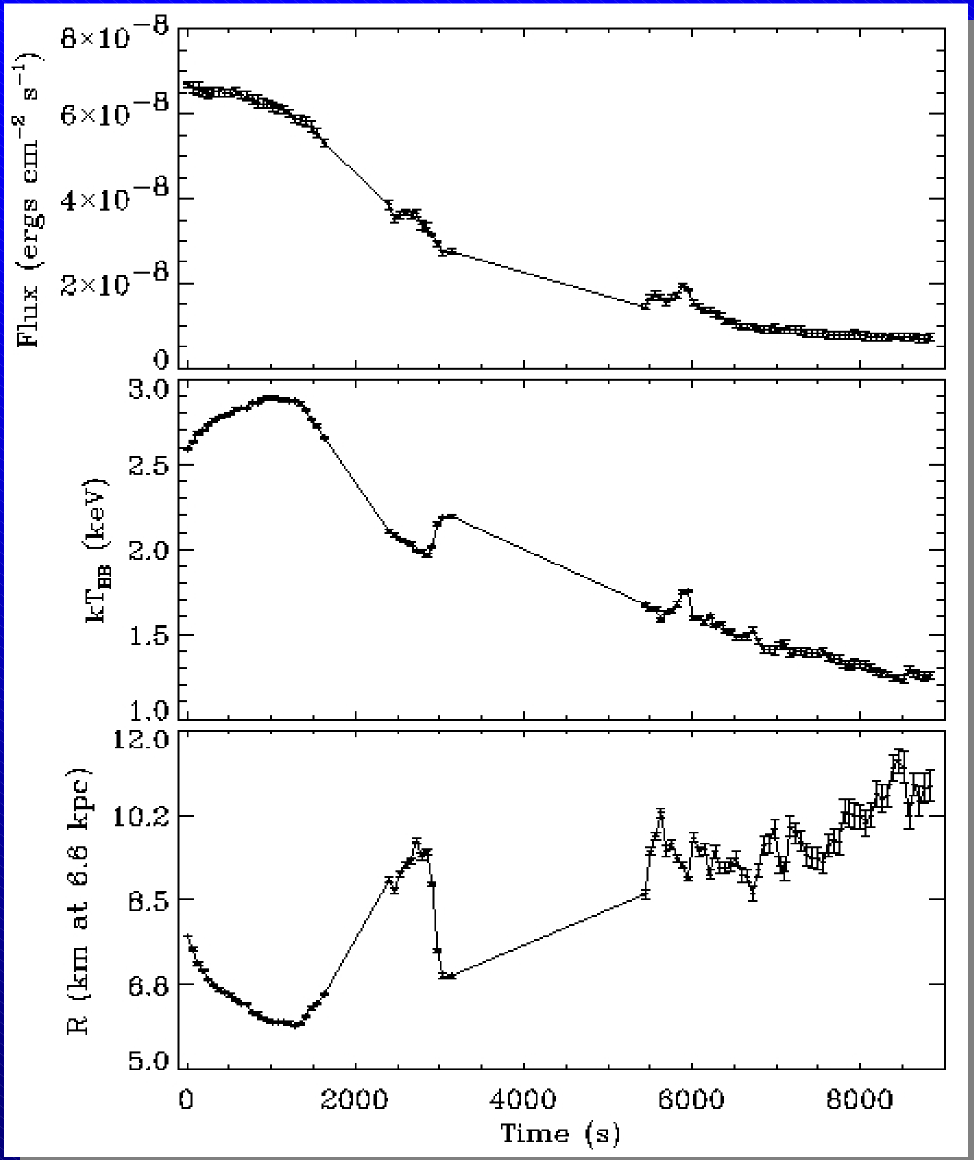

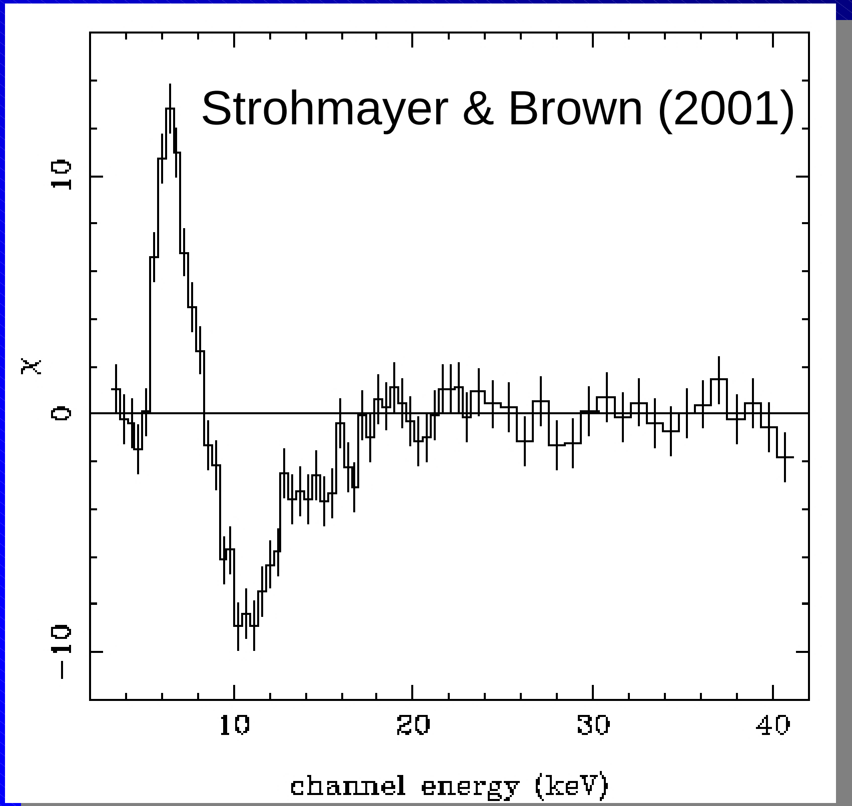

- Peak flux consistent with Eddington limit from neutron star.
- Broad ~6 keV line and ~9 keV edge from reflection off inner disk.
- New probes of disks and neutron star.

Superburst from 4U 1820-30: Disk Reflection

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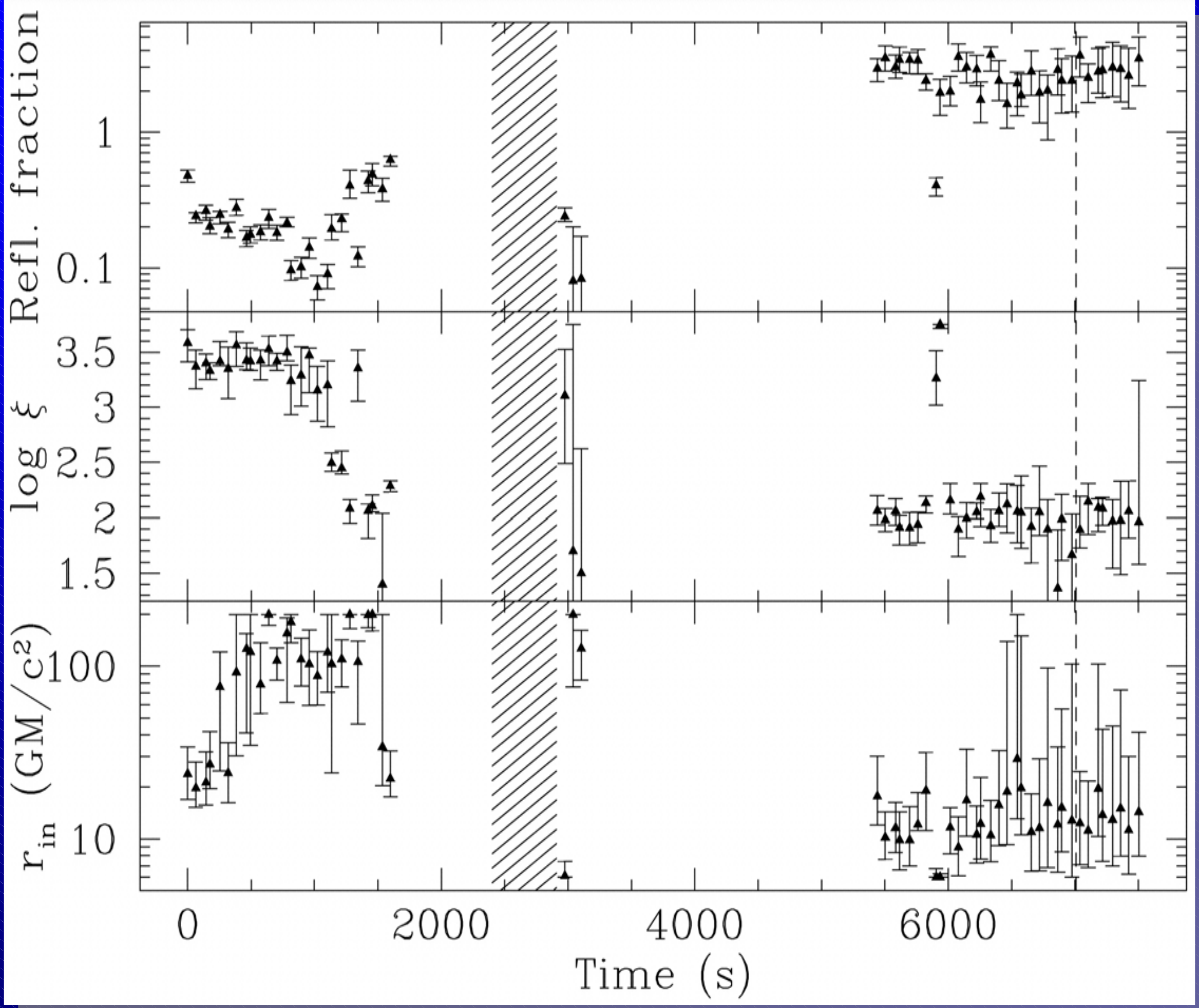

Ballantyne & Strohmayer (2004)

- Discrete spectral components likely due to reflection of burst flux from disk.
- Broad Fe Kα line and smeared edge.
- Line and edge parameters vary significantly through burst.
- Broad Fe line gives evidence for relativistic disk.

Superburst from 4U 1820-30: Evolution of the Disk

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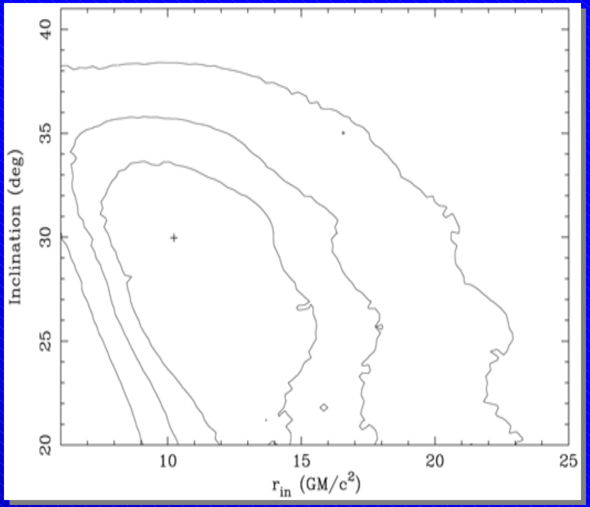
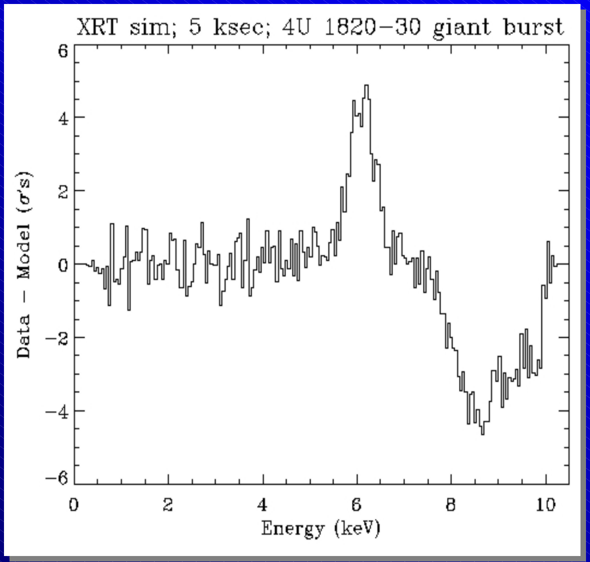
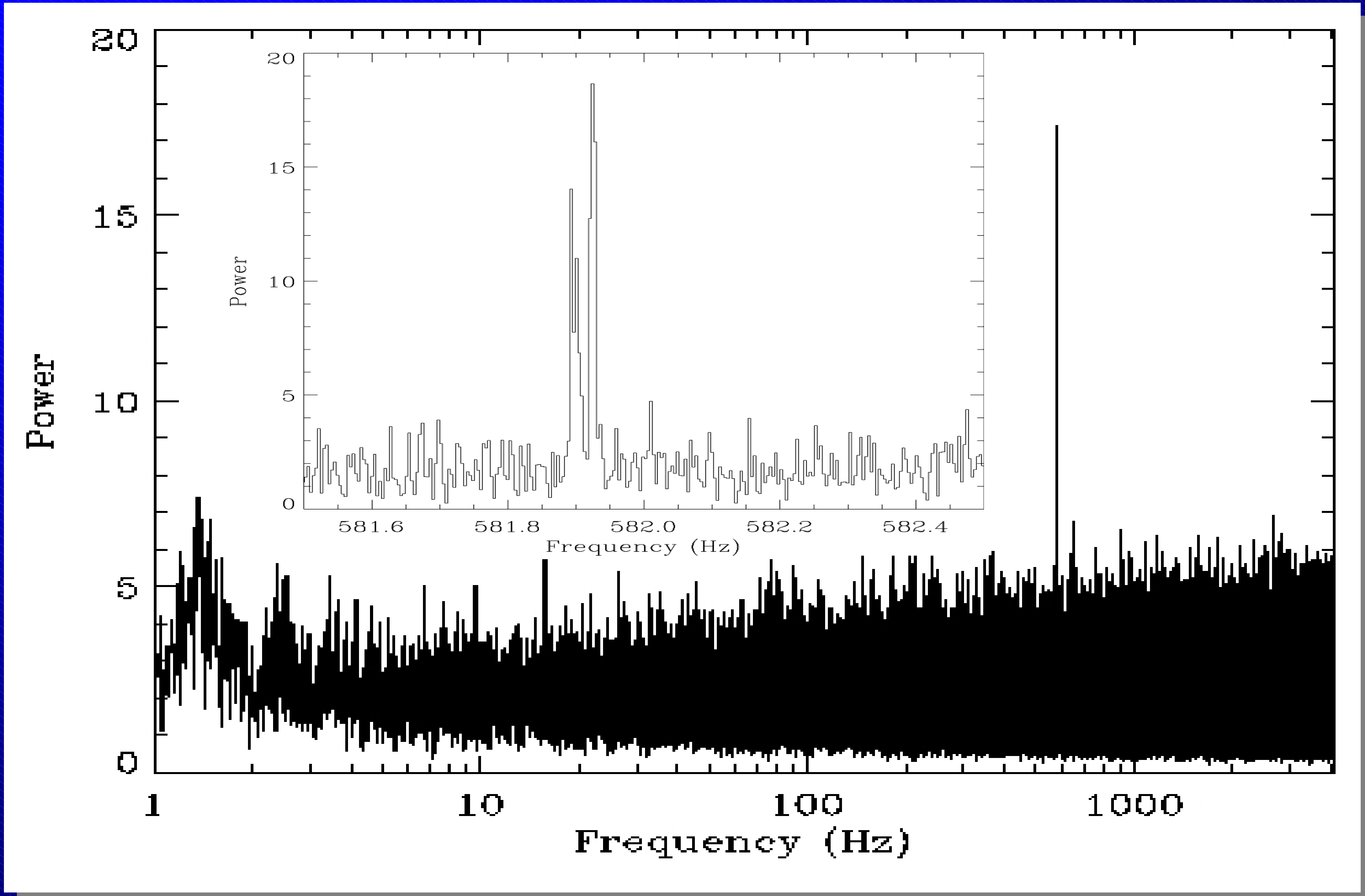
Reflection model fits constrain the system inclination. Important for dynamical mass studies.



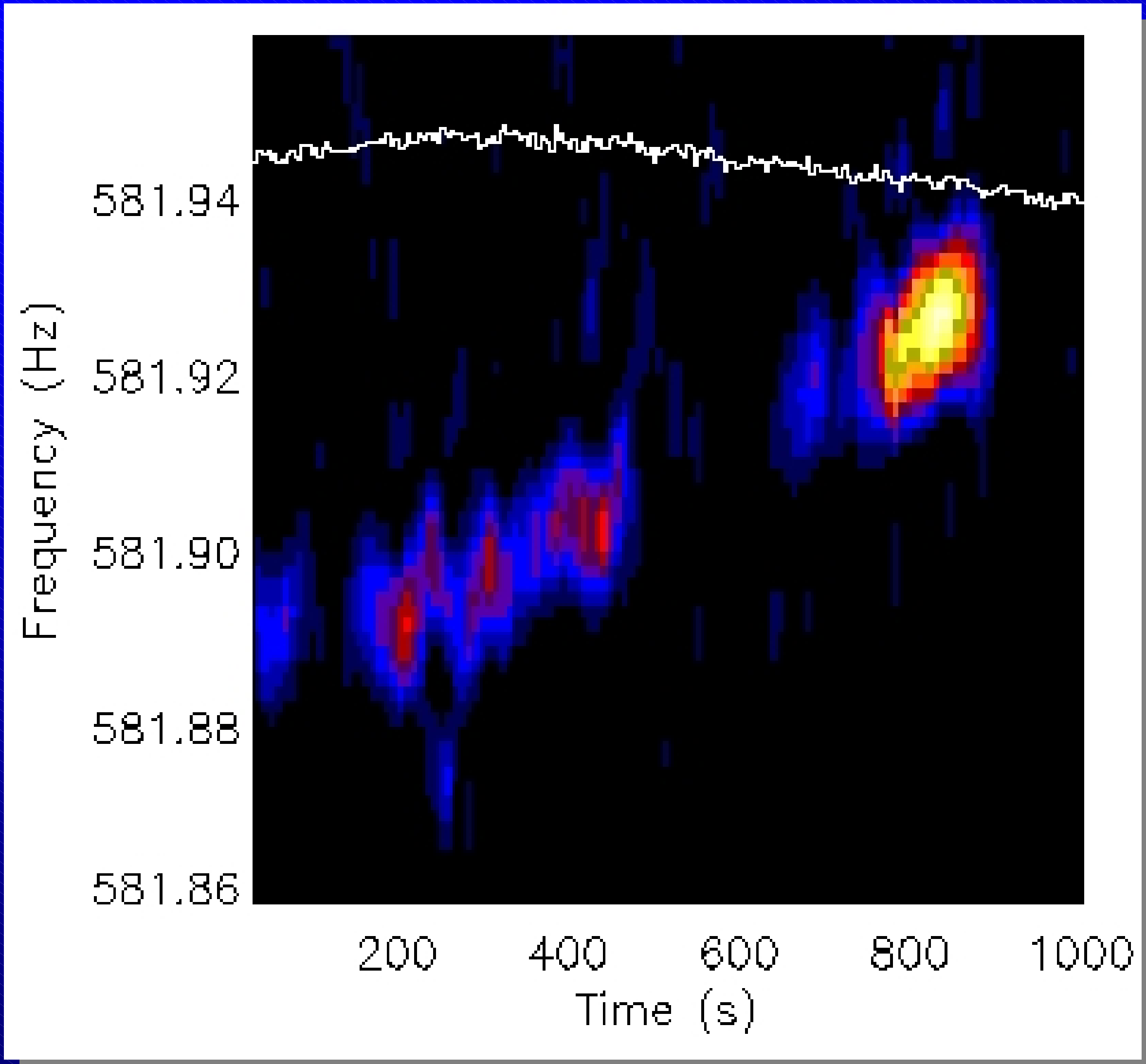


SWIFT studies

Pulsations During the Superburst from 4U 1636-53



Time Dependence of the Pulsation Frequency



- Pulse train lasts ~1000 seconds. Much longer than in normal bursts.
- Frequency drifts by about 0.03 Hz in 800 s. Much smaller than drift in normal bursts.
- Orbital modulation of neutron star spin frequency.

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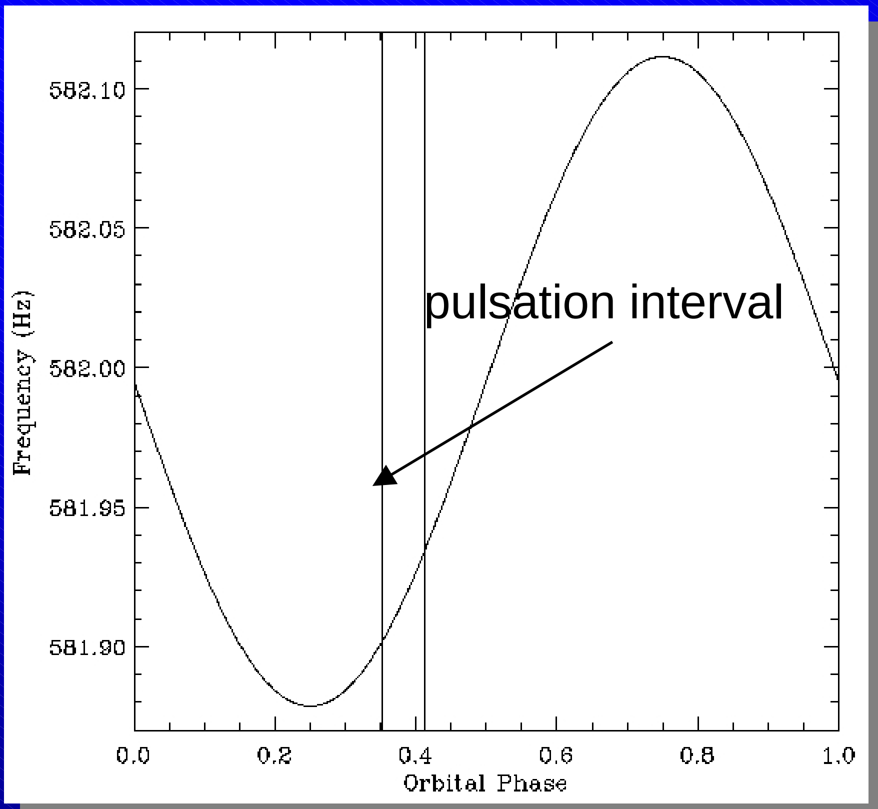
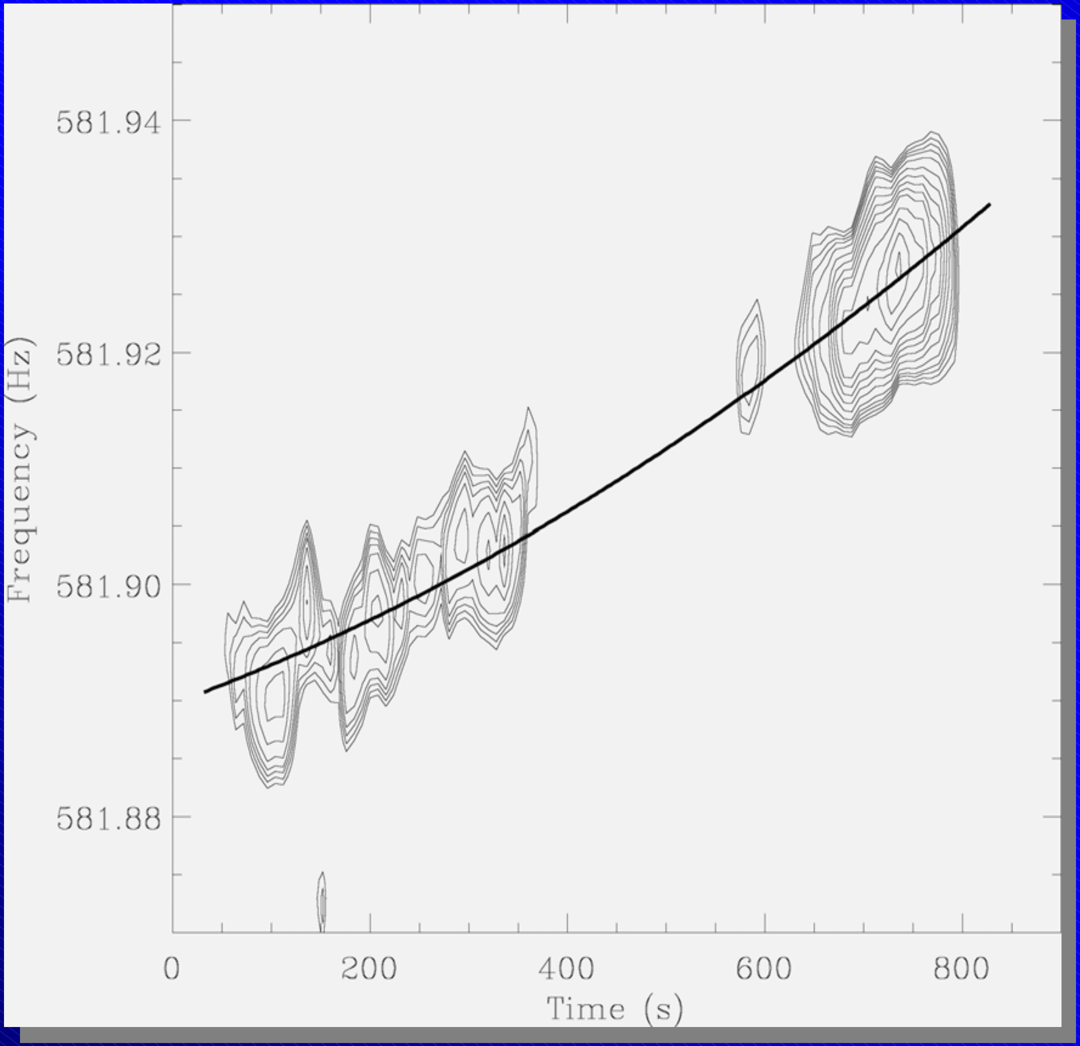
Predicted Orbital Modulation from Optical Ephemeris for 4U 1636-53

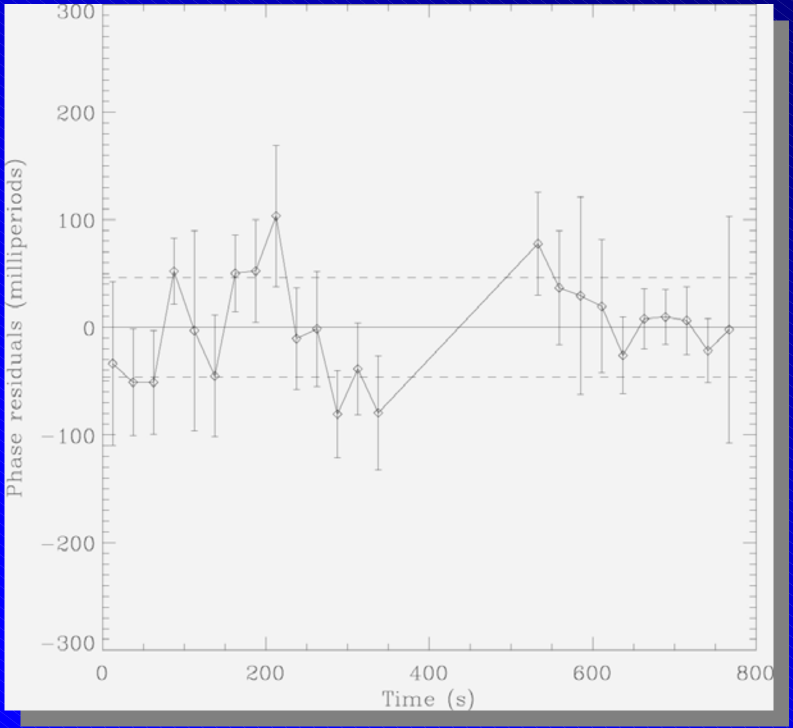


QuickTime™ and a
Video decompressor
are needed to see this picture.

- 3.8 hr orbital period. Ephemeris from Augusteijn et al. (1998) and Giles et al. (2002).
- Only assumption, optical maximum corresponds to superior conjunction of the optical secondary.

Phase Coherent Timing with Circular Orbit Model





- Circular orbit describes the frequency and phase evolution very well.
- Range of parameters allowed due to short data segment.

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EXO 0748-676 Burst Oscillations: The Movie

QuickTime™ and a
Video decompressor
are needed to see this picture.

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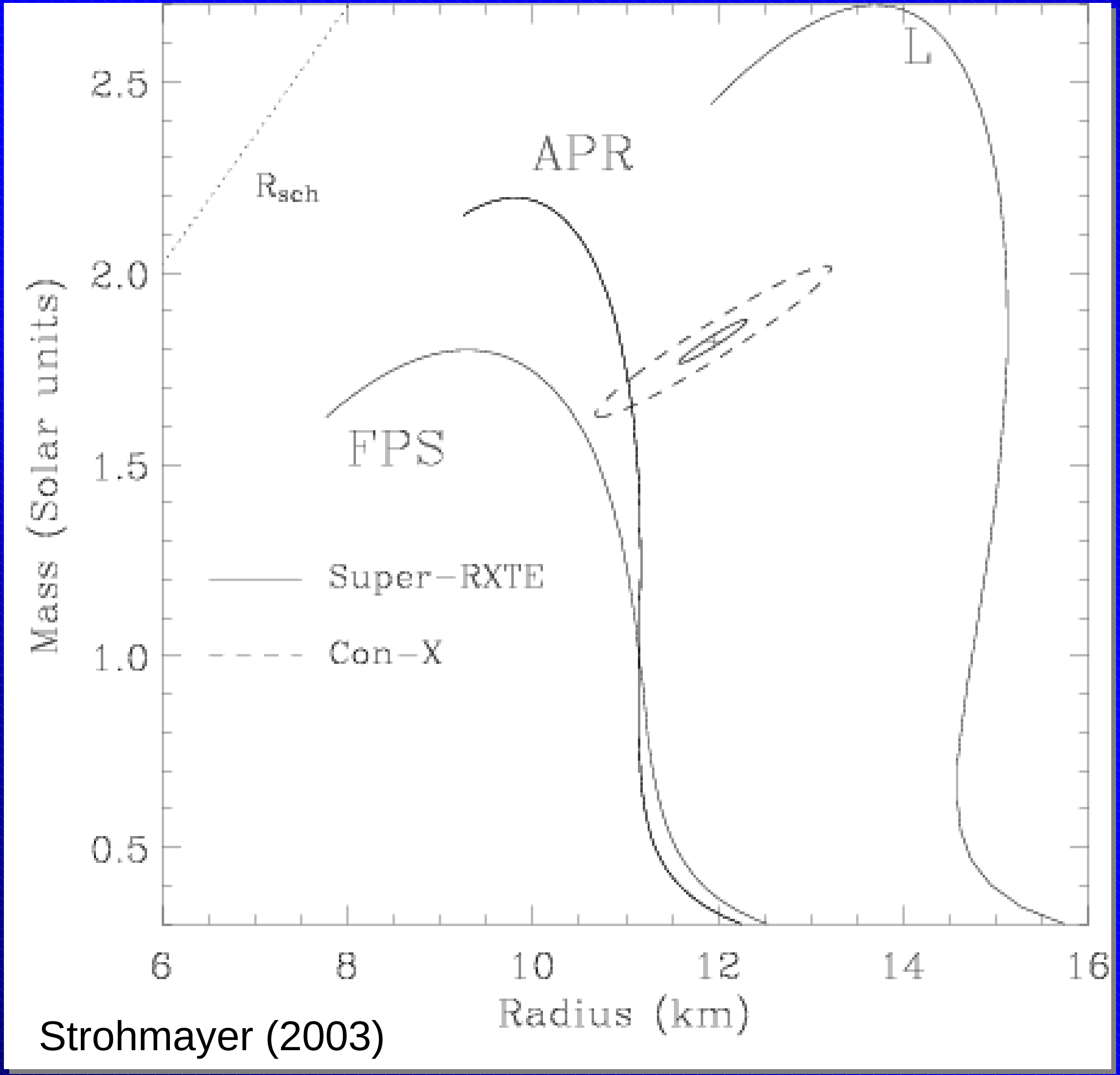
M - R Constraints for Neutron Stars: The Future



Strohmayer (2003)

- Pulse shapes of burst oscillations encode information on the neutron star mass and radius.
- Modulation amplitude sensitive to compactness, M/R.
- Pulse sharpness (harmonic content) sensitive to surface velocity, and hence radius for known spin frequency.
- Geometry and evolution of the hot region can be a complicating factor.
- Statistical limits for future missions look promising.

Fundamental Physics: The Neutron Star Equation of State (EOS)

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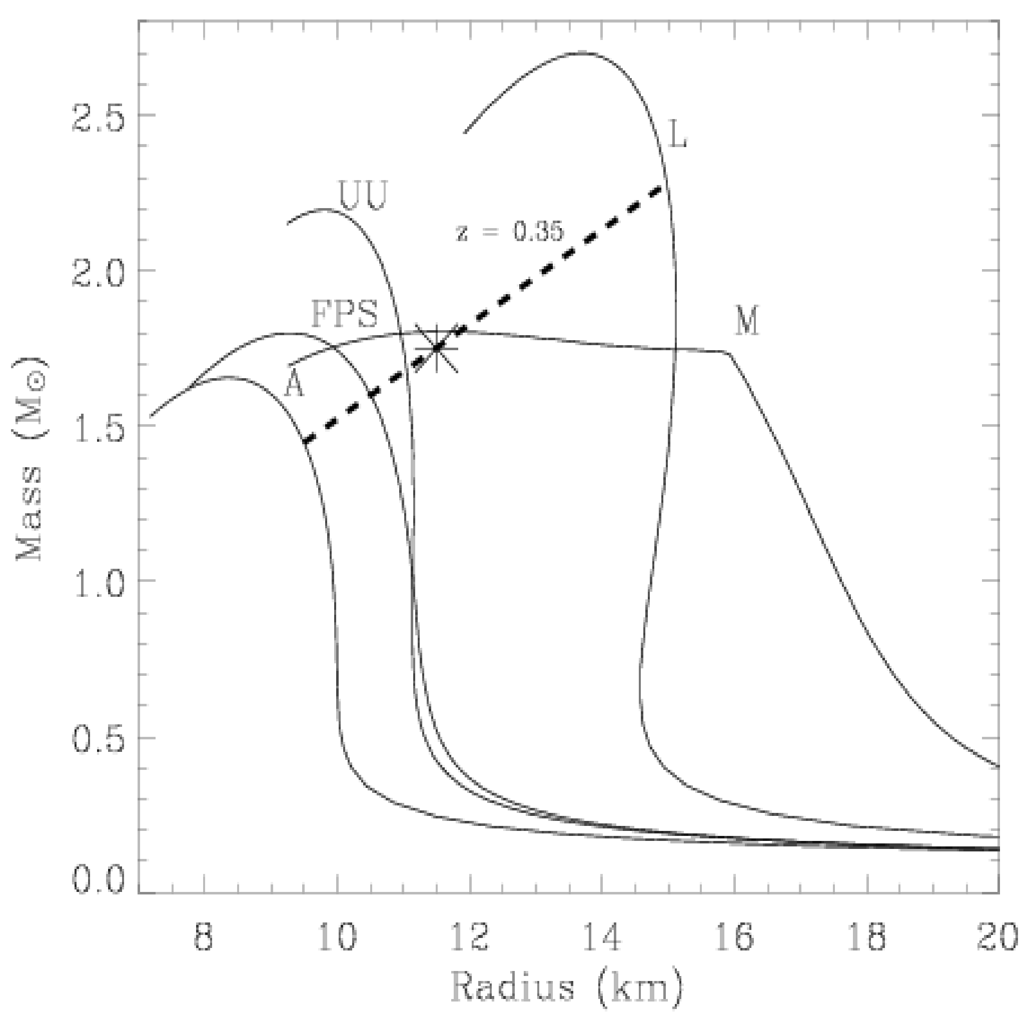

- EXO 0748-676 now an excellent candidate for precise neutron star Mass and Radius measurements.
- Can constrain the dense matter EOS.
- Need better line profile measurements; and models (including fine structure splitting, Chang et al.) to narrow radius range.