Burst Oscillations: Problems and Prospects

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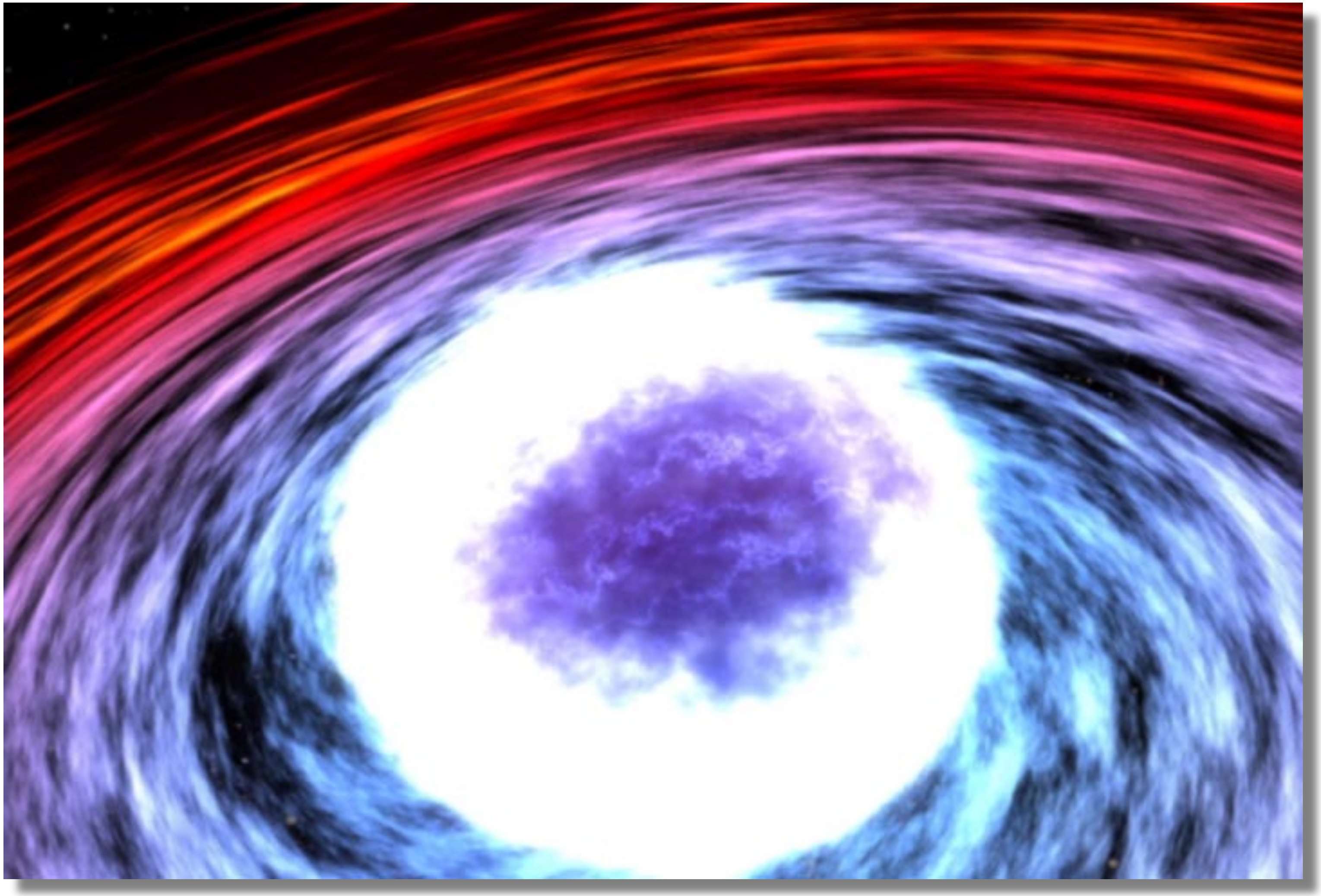
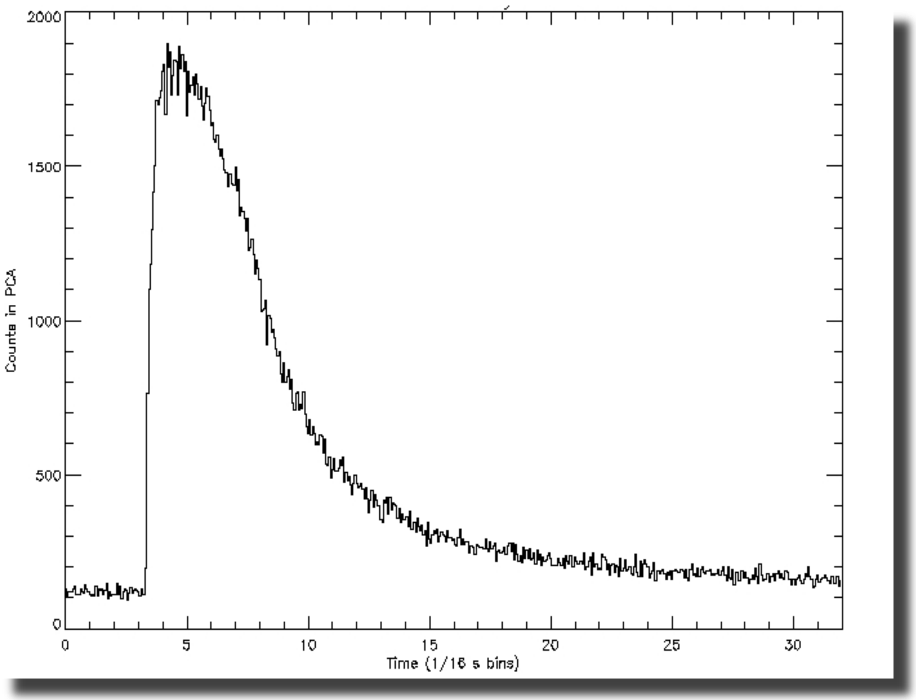
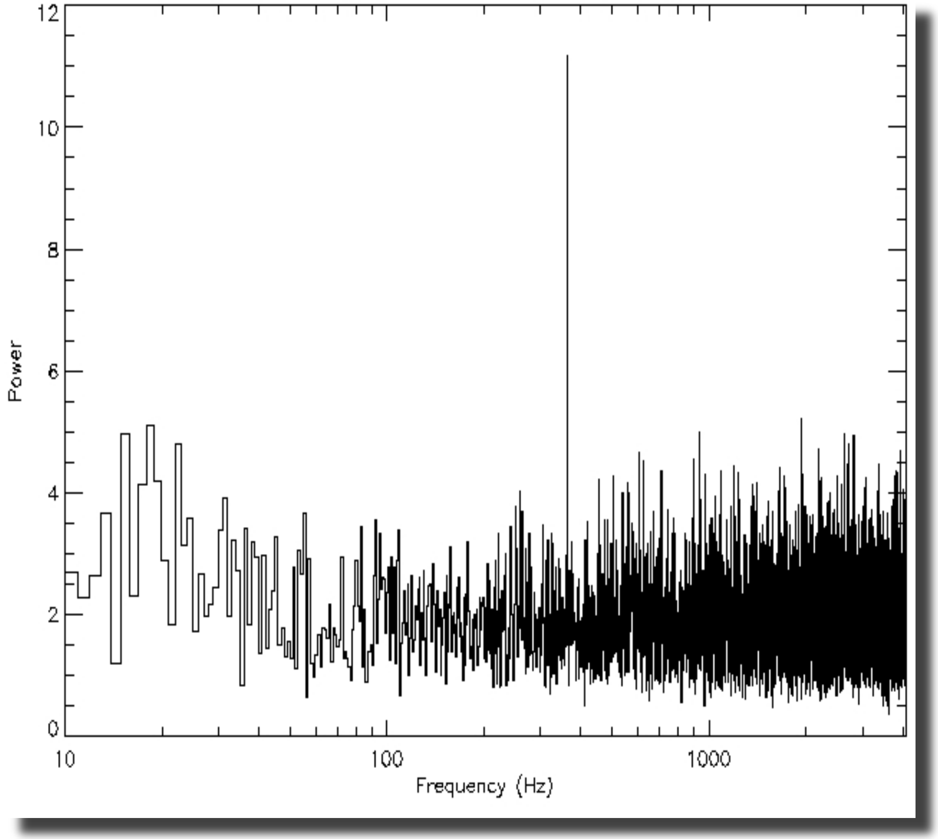


Burst Oscillations: Neutron Star Spins



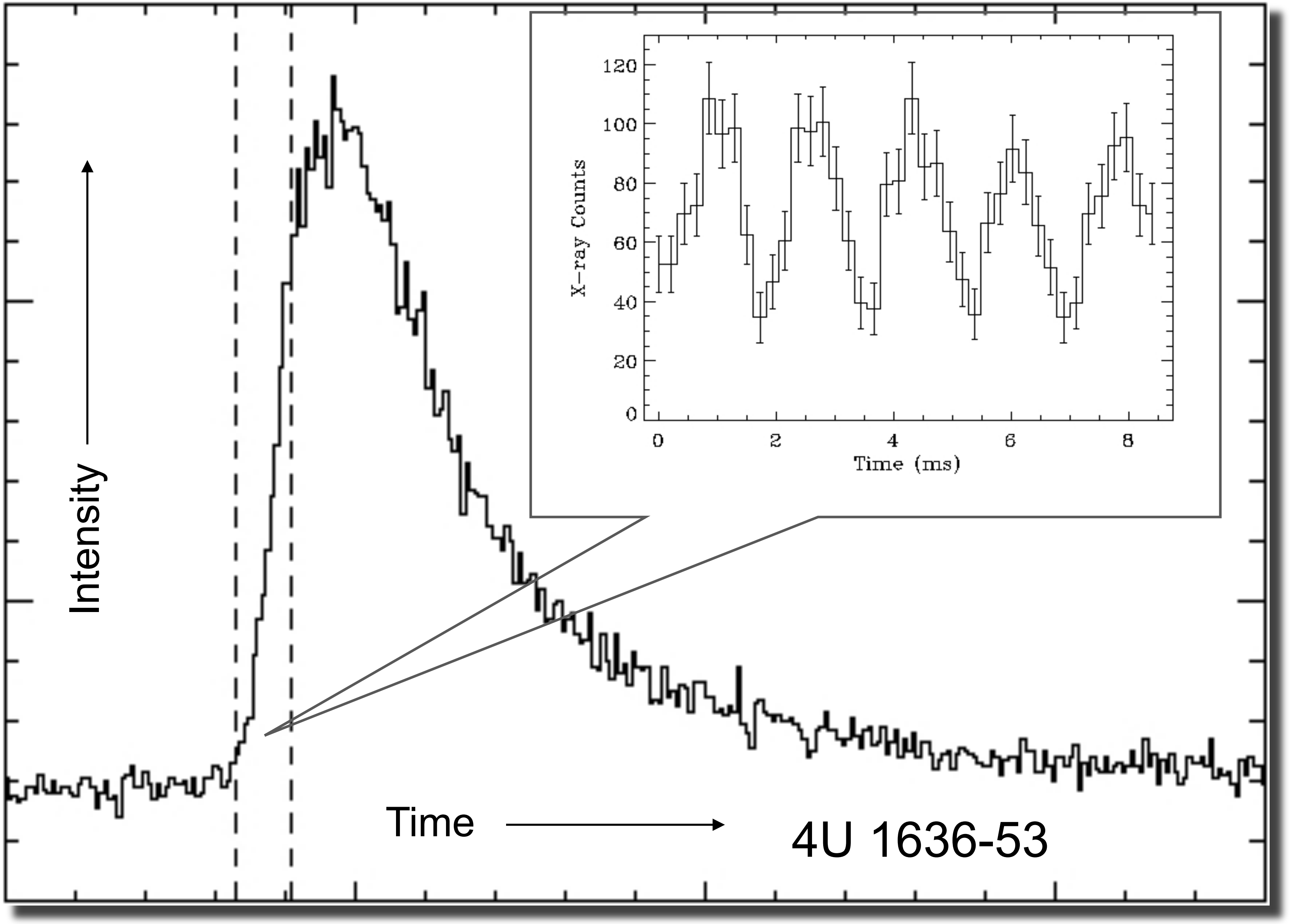
- Discovered in Feb. 1996, shortly after RXTE’s launch (Strohmayer et al, 1996)
- First indication of ms spins in accreting LMXBs.
- 4U 1728-34, well known, frequent burster.
- Power spectra of burst time series shows significant peak at 363 Hz.



Outline, Assumptions

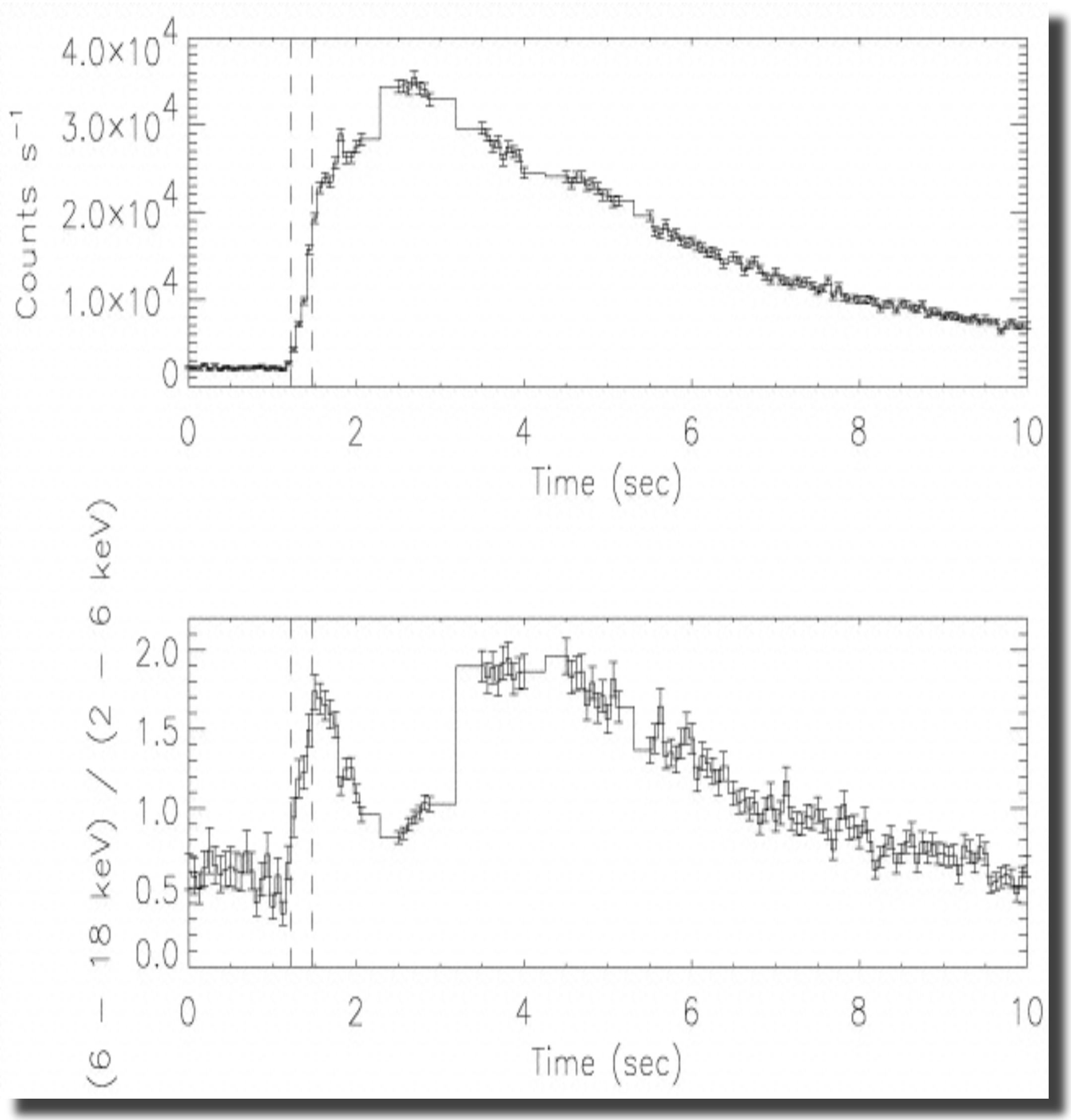
- Burst oscillations are due to spin modulation of “brightness asymmetries” on the neutron star surface.
- What do observations say about how such asymmetries form, evolve, and radiate?
- Incomplete observational overview.
- What are some of the remaining puzzles?
- How might we resolve them?
- Recent, and ongoing work on phase-resolved spectra of burst oscillations, searches for oscillation modes, 4U 1636-536 superburst.

Oscillations at Burst Onset and Rise

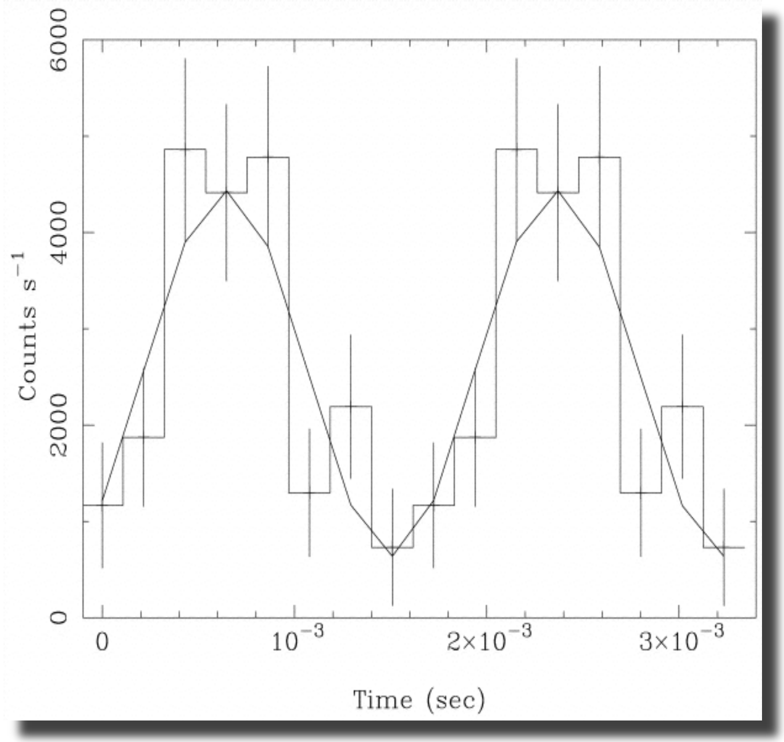


4U 1636-53

Burst Oscillation Amplitudes at Onset

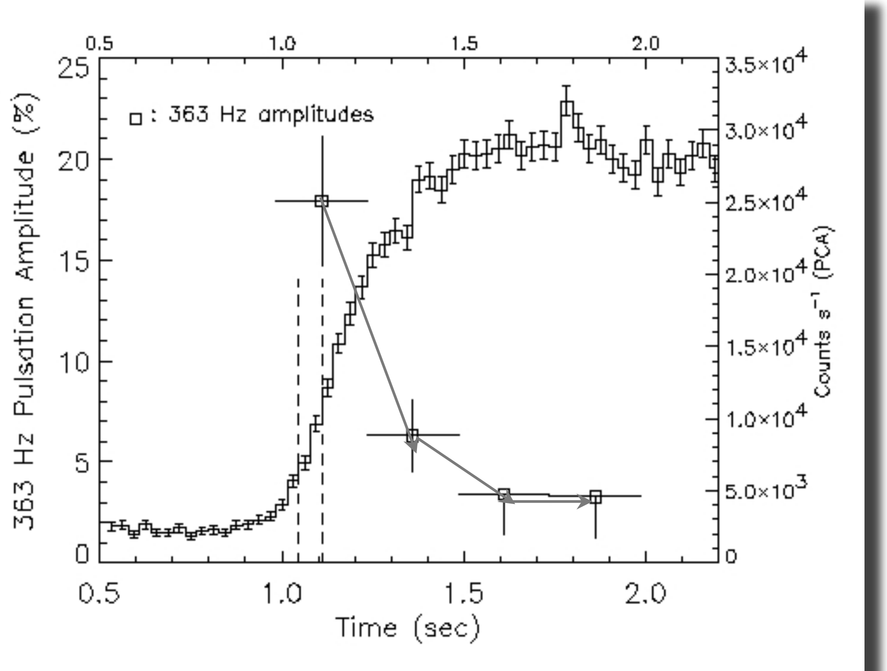


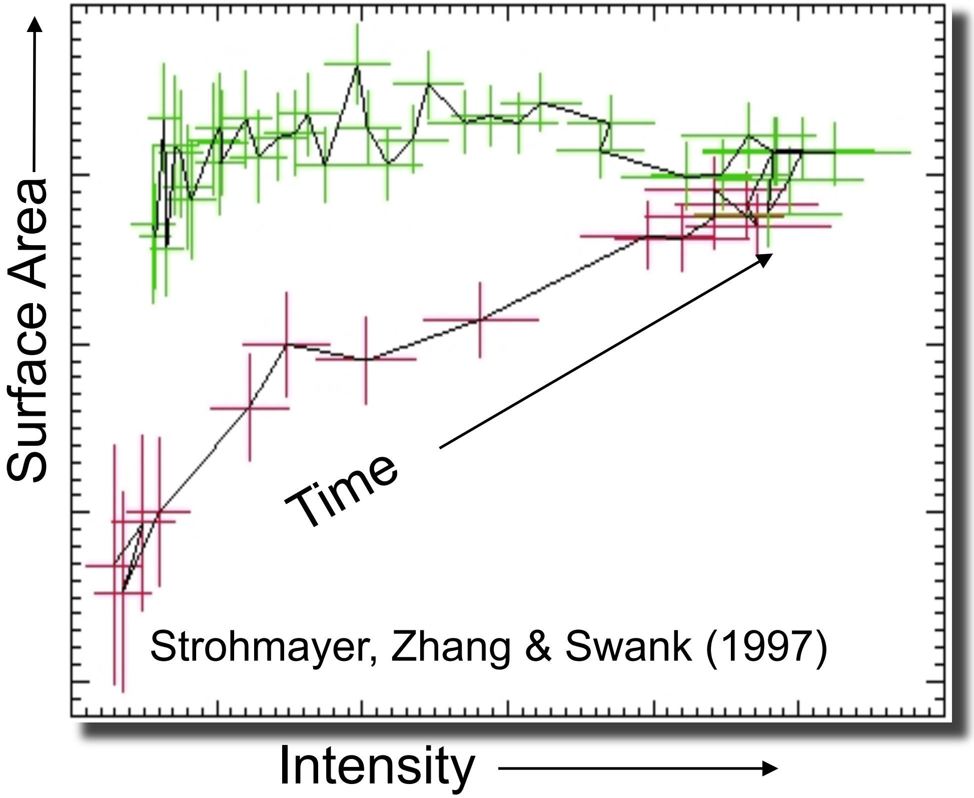
4U 1636-53: Strohmayer et al. (1998)



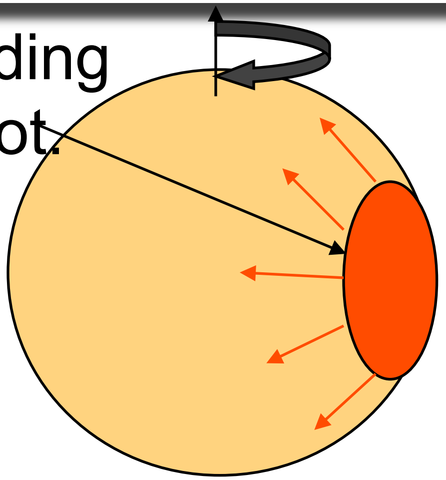
- Oscillations at rising edge approach 100% modulation of the burst flux (persistent flux level subtracted).

Timing and Spectral Evidence for Rotational Modulation





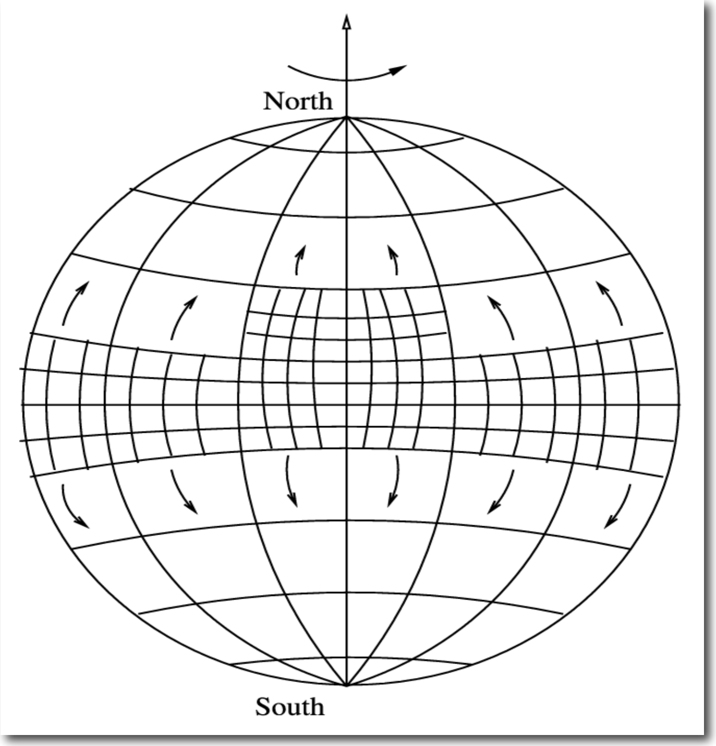
Strohmayer, Zhang & Swank (1997)



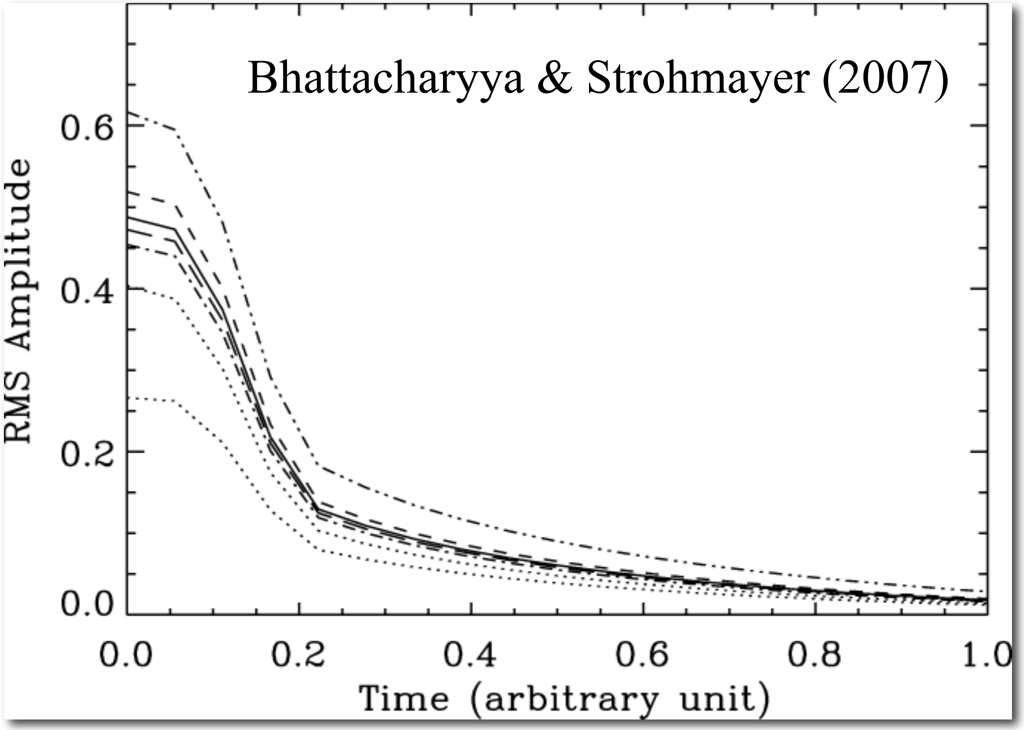
Spreading hot spot

- Oscillations at onset 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.

Coriolis Force influences spreading speed

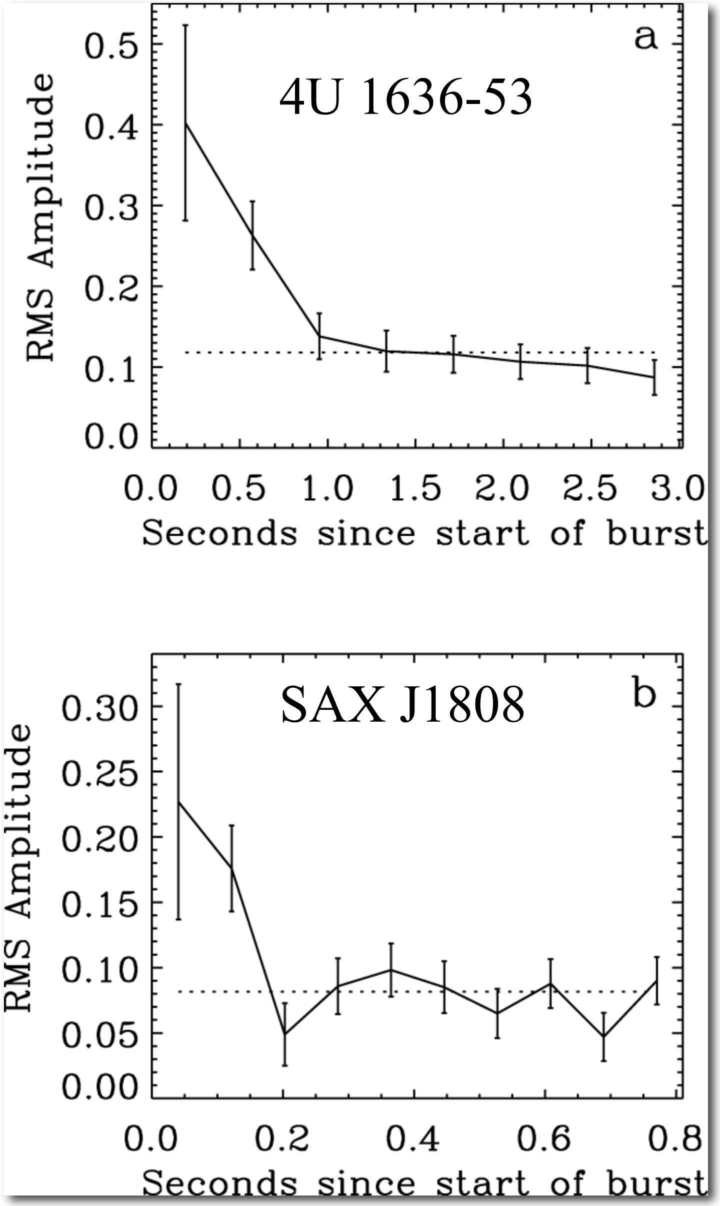


- Spitkovsky, Levin & Ushomirsky (2002) showed Coriolis force relevant to ignition and spreading.
- Flame speed faster at equator, slows with increasing lattitude.

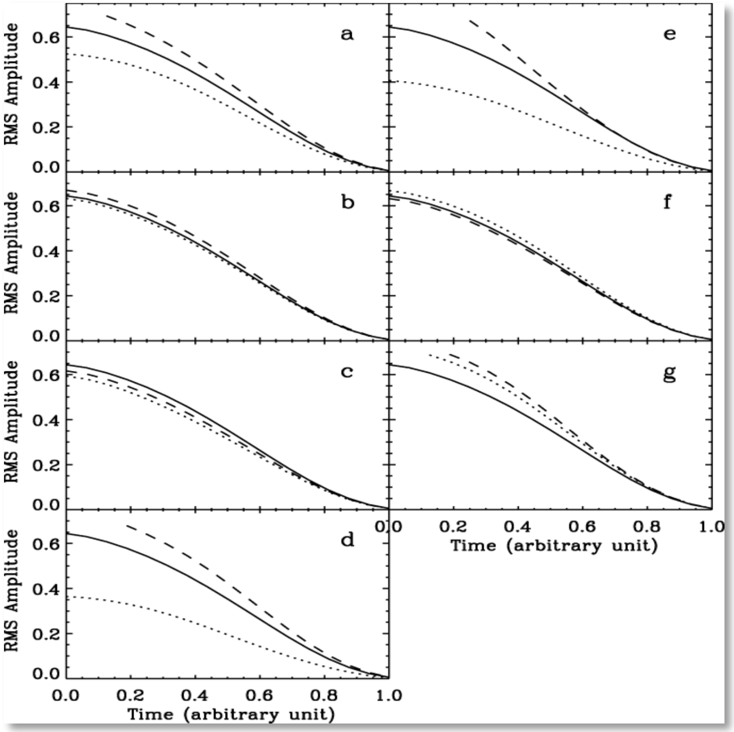


Modelling of near-equatorial ignition, and Coriolis dependent spreading, can better explain amplitude evolution of some bursts.

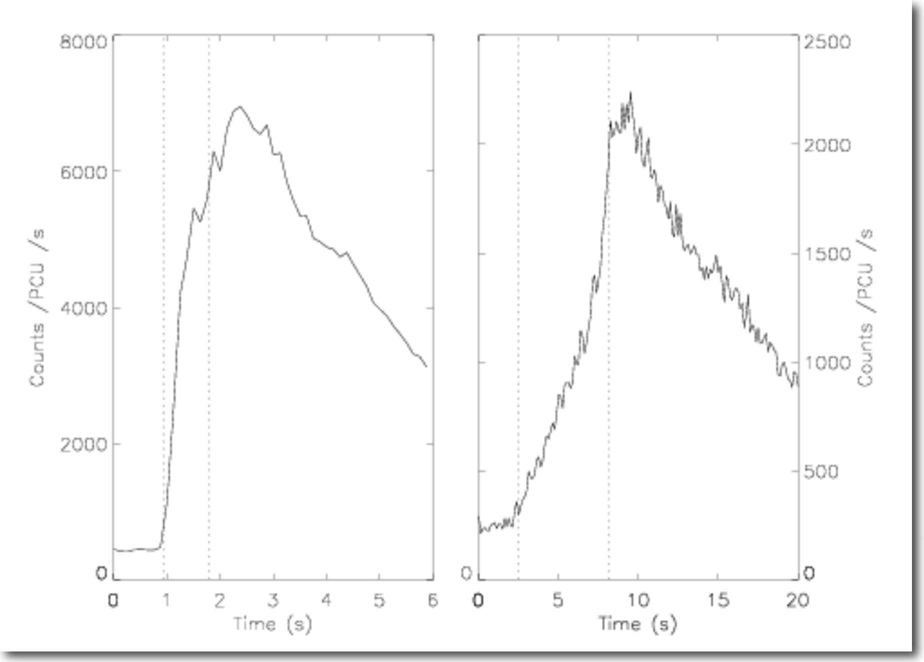
Burst Rise: Amplitude Evolution



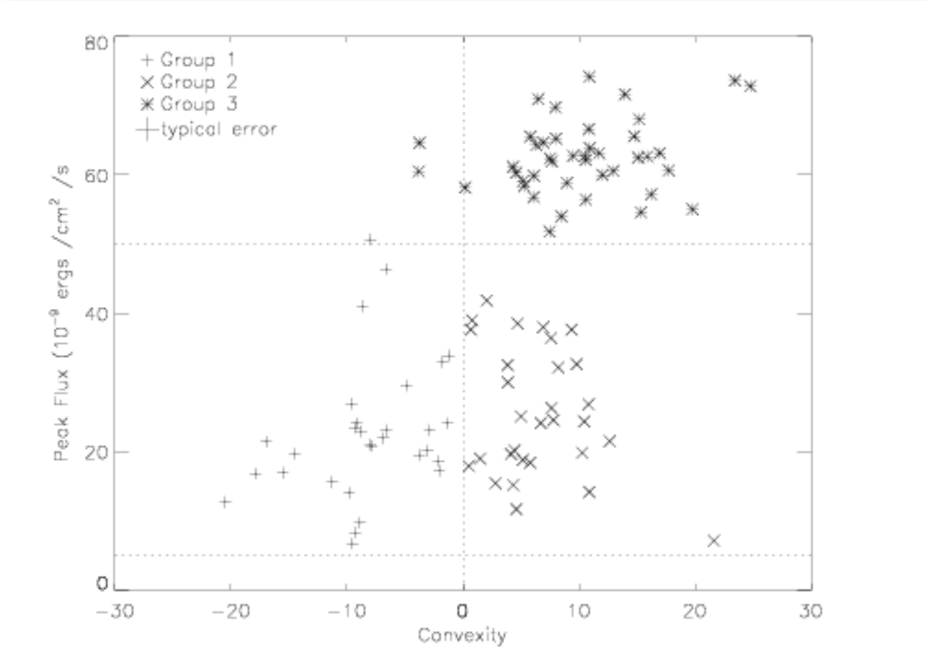
- Amplitude evolution during burst rise, encodes information on nature of flame spreading.
- Some bursts show high initial amplitude, rapid decrease, and then persist at lower amplitude.



Ignition, spreading, and the shape of the rising part of the light curve

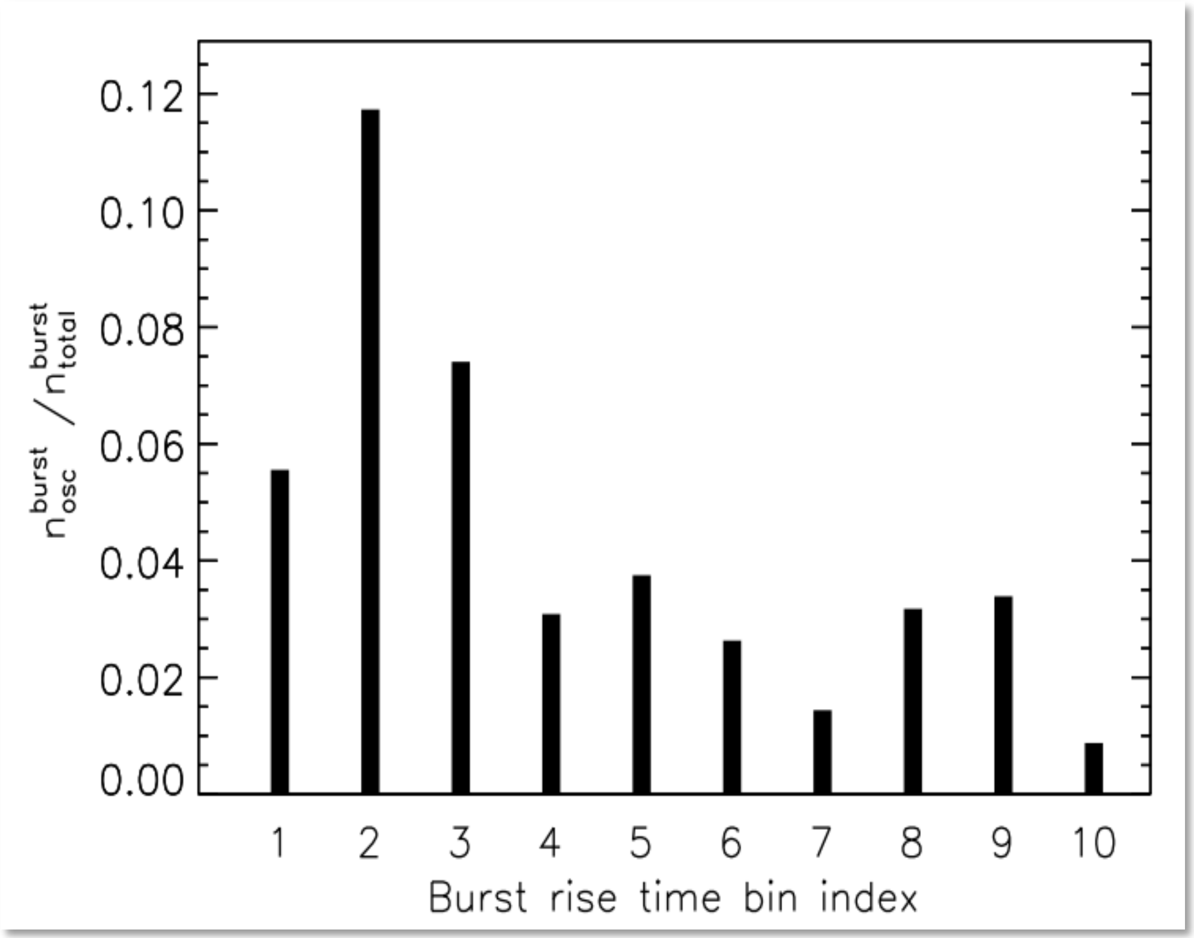


- Watts & Maurer (2007) explore shapes of burst rising phases.
- Find that bursts group according to peak flux and “convexity,” and suggest that ignition latitude varies with accretion rate.



- Negative convexity bursts ignited at high latitude (near the pole).
- High flux, positive convexity bursts are He ignited near the equator

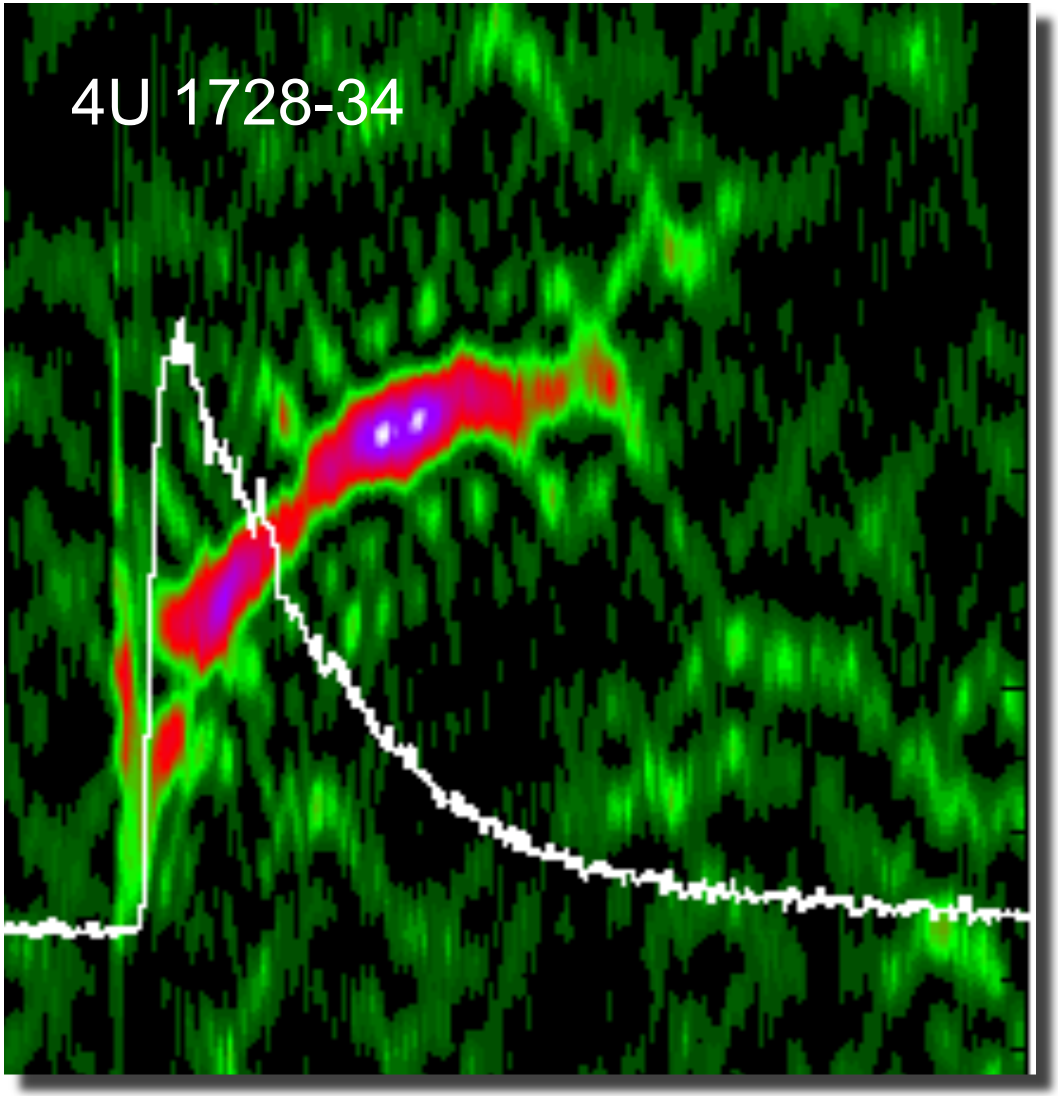
Burst Rise Oscillations: 4U 1636-536



Chakraborty & Bhattacharyya (2014)

- Systematic study of “all” 4U 1636-536 bursts with rise oscillations.
- Amplitude decreases with time during rise.
- Amplitude evolution consistent with “concave up” shape.
- Nuclear flames spread! And evidence supports a latitude dependent spreading (perhaps like Coriolis).
- General consistency with Maurer & Watts.

Oscillations in the Cooling Phase

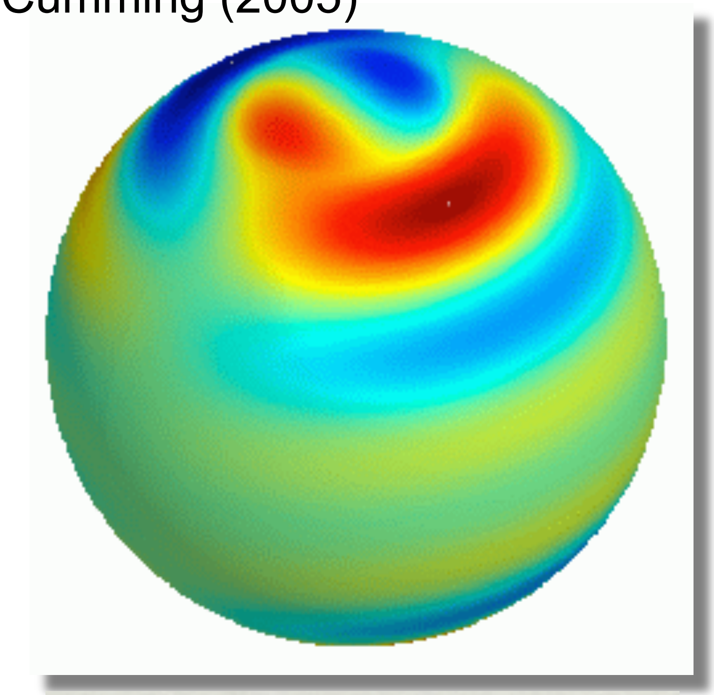


- Pulsations in the cooling tails can be as large as 15 - 20% $(f_{max}-f_{min})/(f_{max}+f_{min})$
- If the whole surface is burned, what causes the flux asymmetry?
- Oscillation modes (Heyl 2002 suggests *r*-modes; Piro & Bildsten 2005, Lee & Strohmayer 2005, Heyl 2005; Cumming 2005) ?
- Frequency and phase can evolution be modeled.

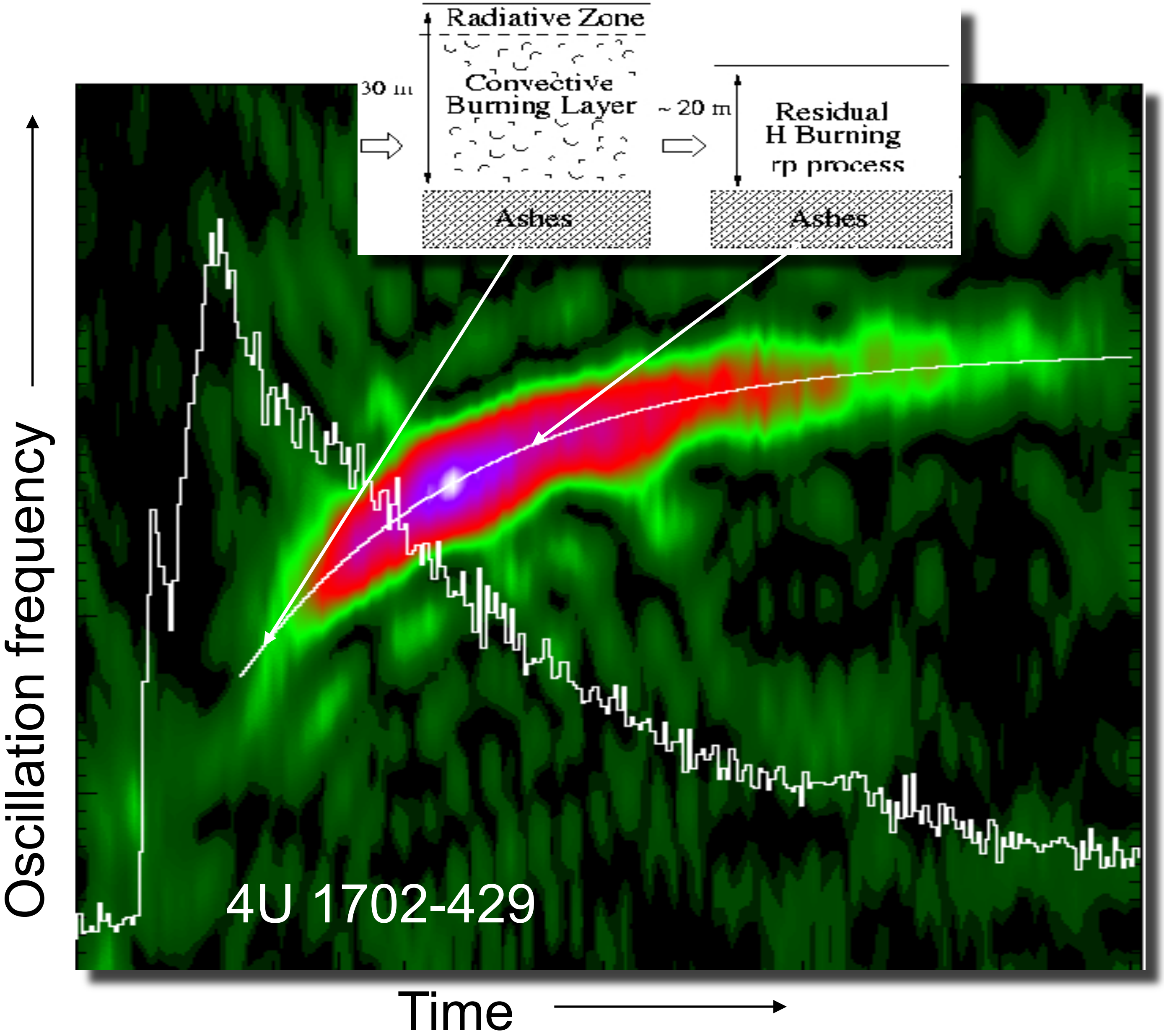
What Breaks the Symmetry?

- Global Oscillation modes could provide late time asymmetry.
- r-modes suggested by Heyl (2005), Lee & Strohmayer (2005). Are the modes unstable?
- Spitkovsky et al. suggest vortices “trapped” in zonal wind set up by differential cooling. Equatorial waveguide, modes.
- Cumming (2005) finds dynamically unstable shear modes, associated with differential rotation, perhaps “self-excited” by bursts.
- Cooling wake, what does cooling over the whole surface produce?

Cumming (2005)



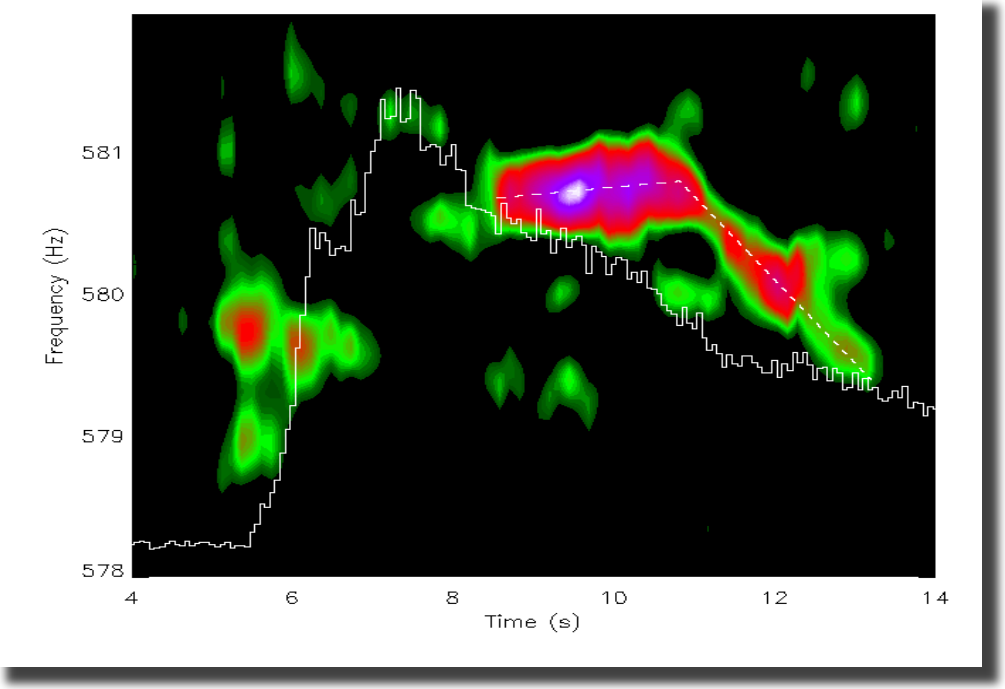
Puzzle: Frequency Evolution of Burst Oscillations

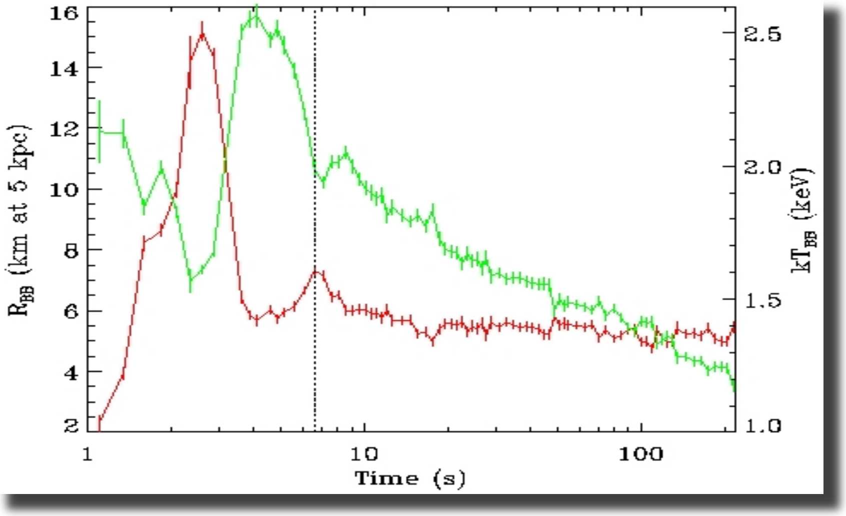


slows down relative to bulk of the star.

- 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.

Spin Down of Burst Oscillations in 4U1636-53

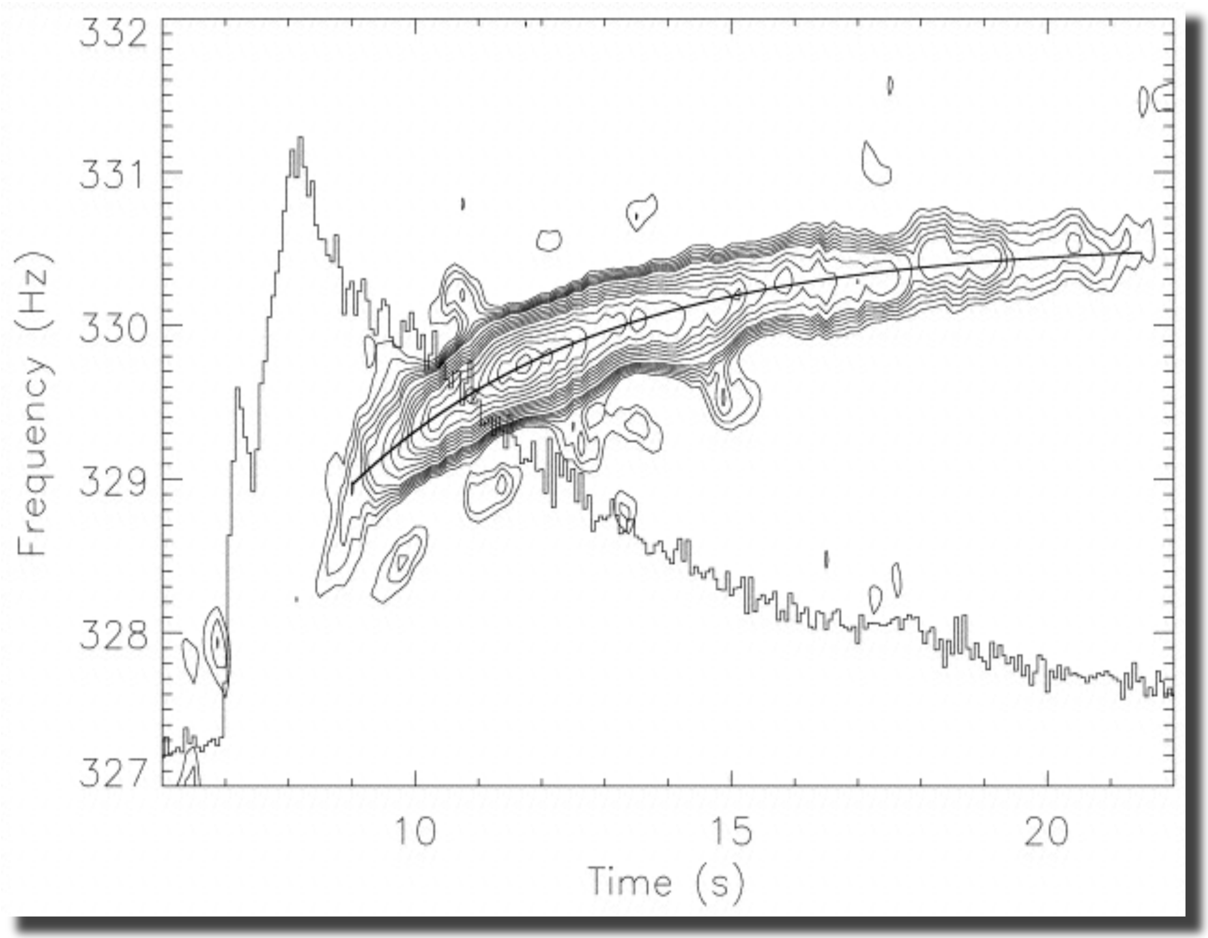


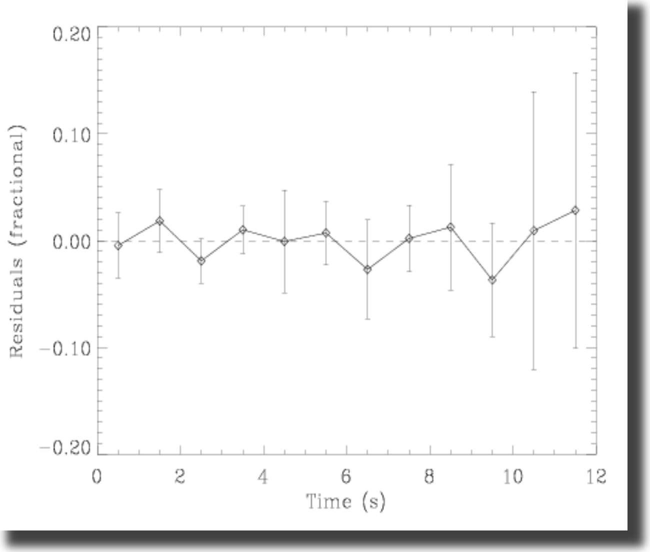


- Small fraction of bursts show episodes of spin down (Miller 1999; Strohmayer 1999; Muno 2001).
- Spin down in 4U 1636-53 is associated with extended thermal tail and transition evident in spectral evolution.
- Magnitude of spin down may reflect an expansion of the surface layers by only 10 - 30 meters!

Coherence of Burst Oscillations

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

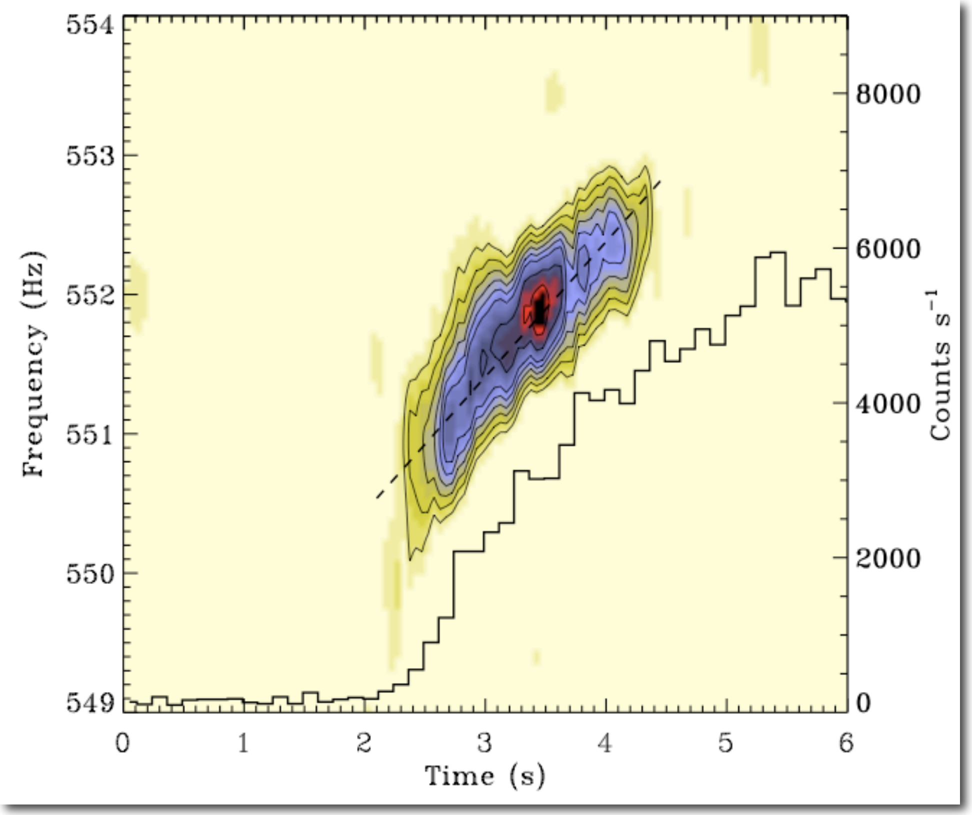




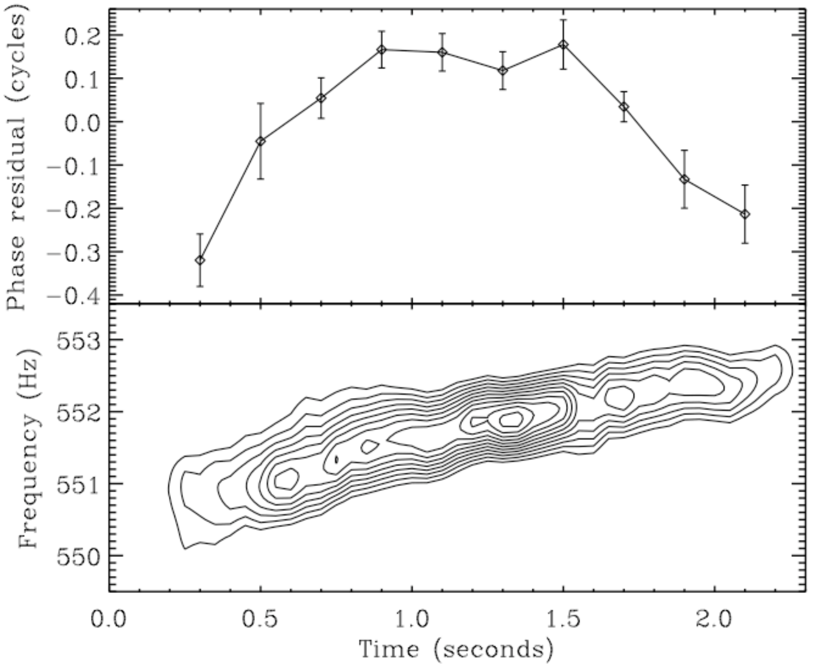
- Burst oscillations generally have high coherence (Q > 4,000)
- exponential recovery in some bursts.

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

EXO 0748-676: The Burst Oscillation Frequency



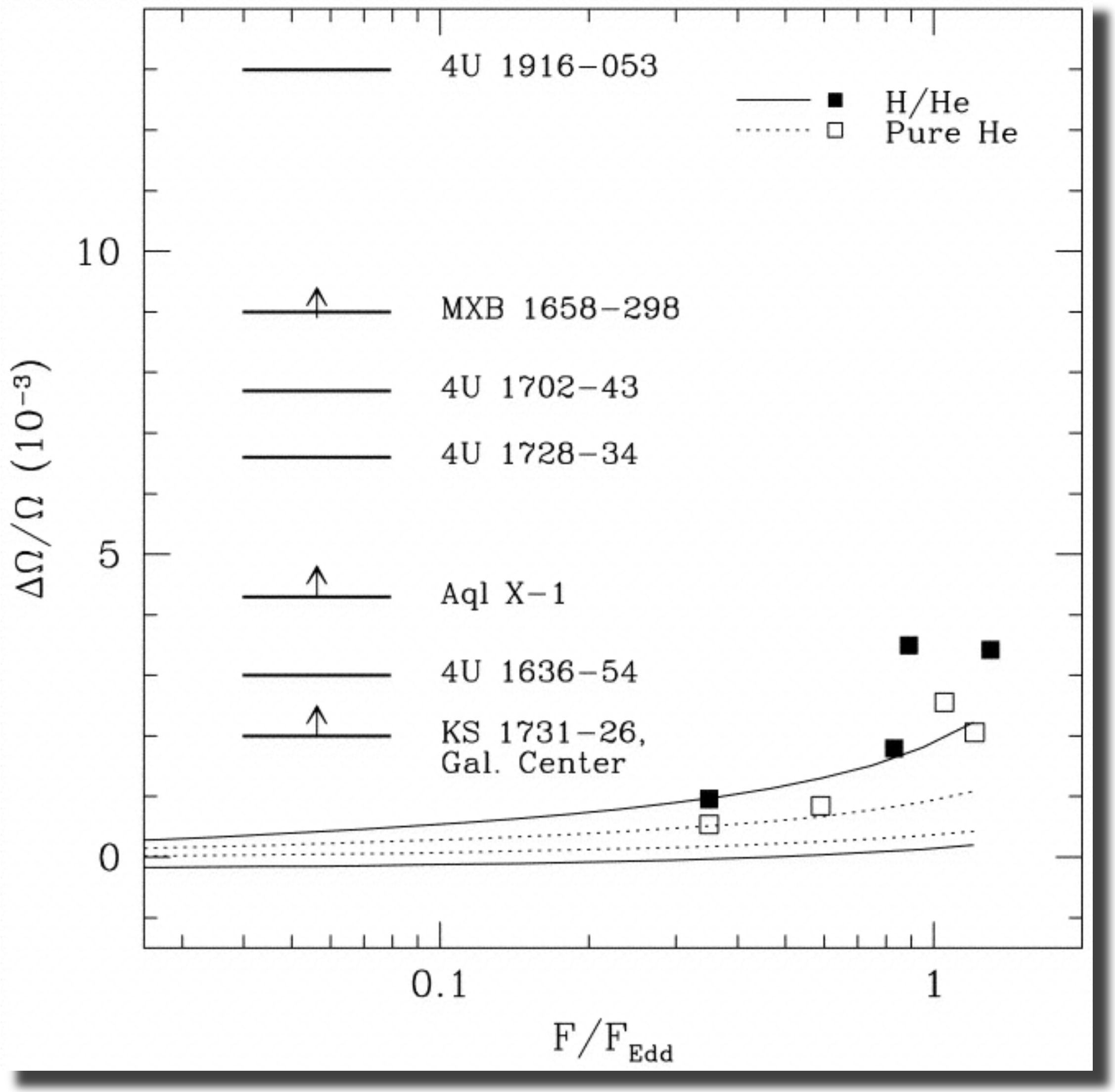
- Pulsations seen on rising edge, two bursts (552 Hz; Galloway et al. 2010).
- Frequency drifts by ~1 Hz during rise.



- Low fraction of bursts with detectable oscillations?
- And only on rise?

Frequency Drifts due to Hydrostatic Expansion

From Cumming et al. (2002)

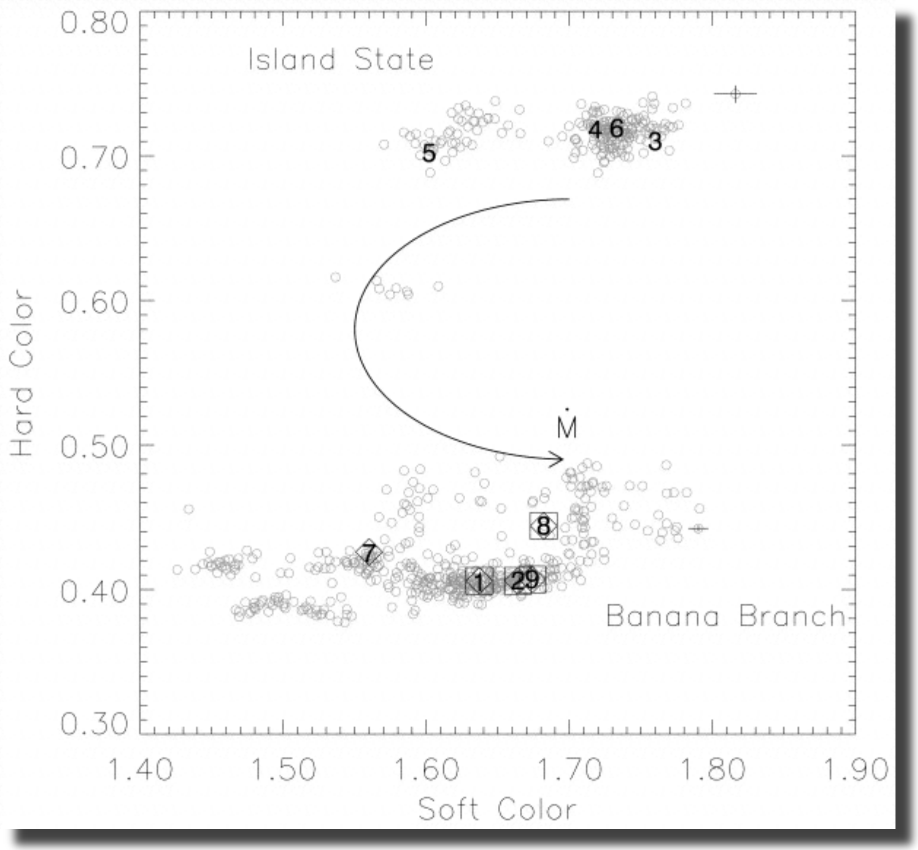


- Fractional frequency shifts appear to be a bit too large in some sources for hydrostatic expansion alone
- If differential rotation persists, then top layers can spin down enough, but seems unlikely.
- Hydrodynamics important?

Presence of Shearing Layer, and Vertical Heat Transport

- Coherent frequency drifts indicate shearing layers during bursts. ~ 10s of "phase wraps" in some cases.
- If timescale to transport heat across the layer is long compared to "shearing" time, then modulations will be smeared out (Cumming and Bildsten, H vs He layers).
- Could account for variations in amplitudes (non-detections for some bursts).
- Probably needs to be better modeled for future.

Burst Oscillations and Source State

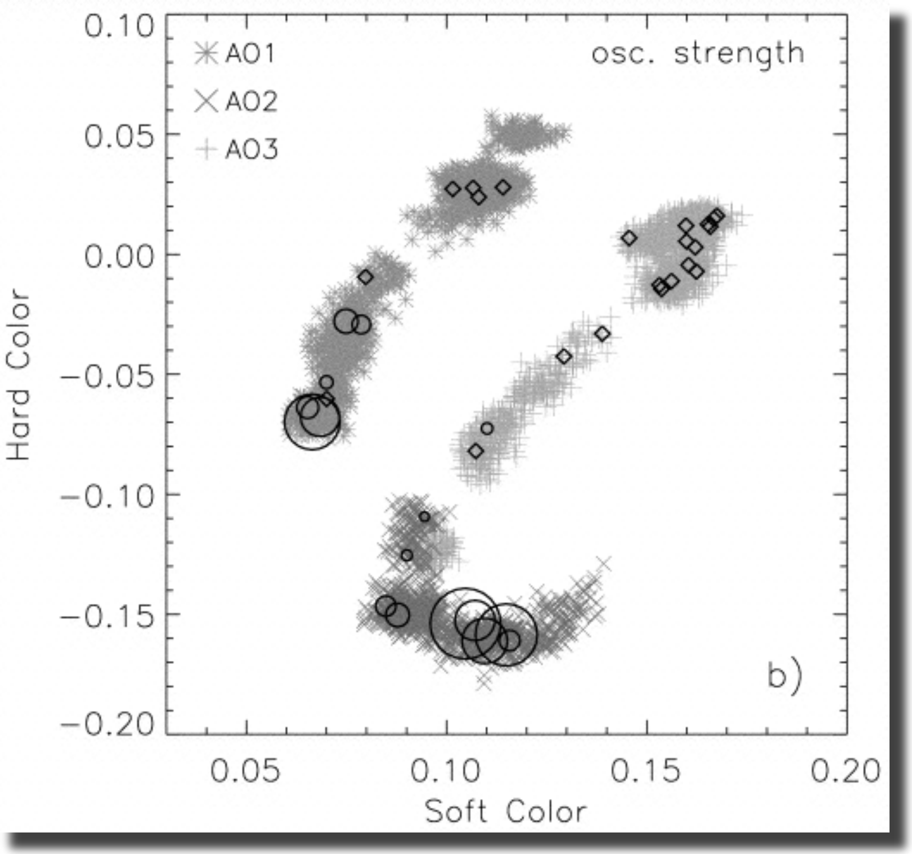


KS 1731-260: Muno et al (2000)

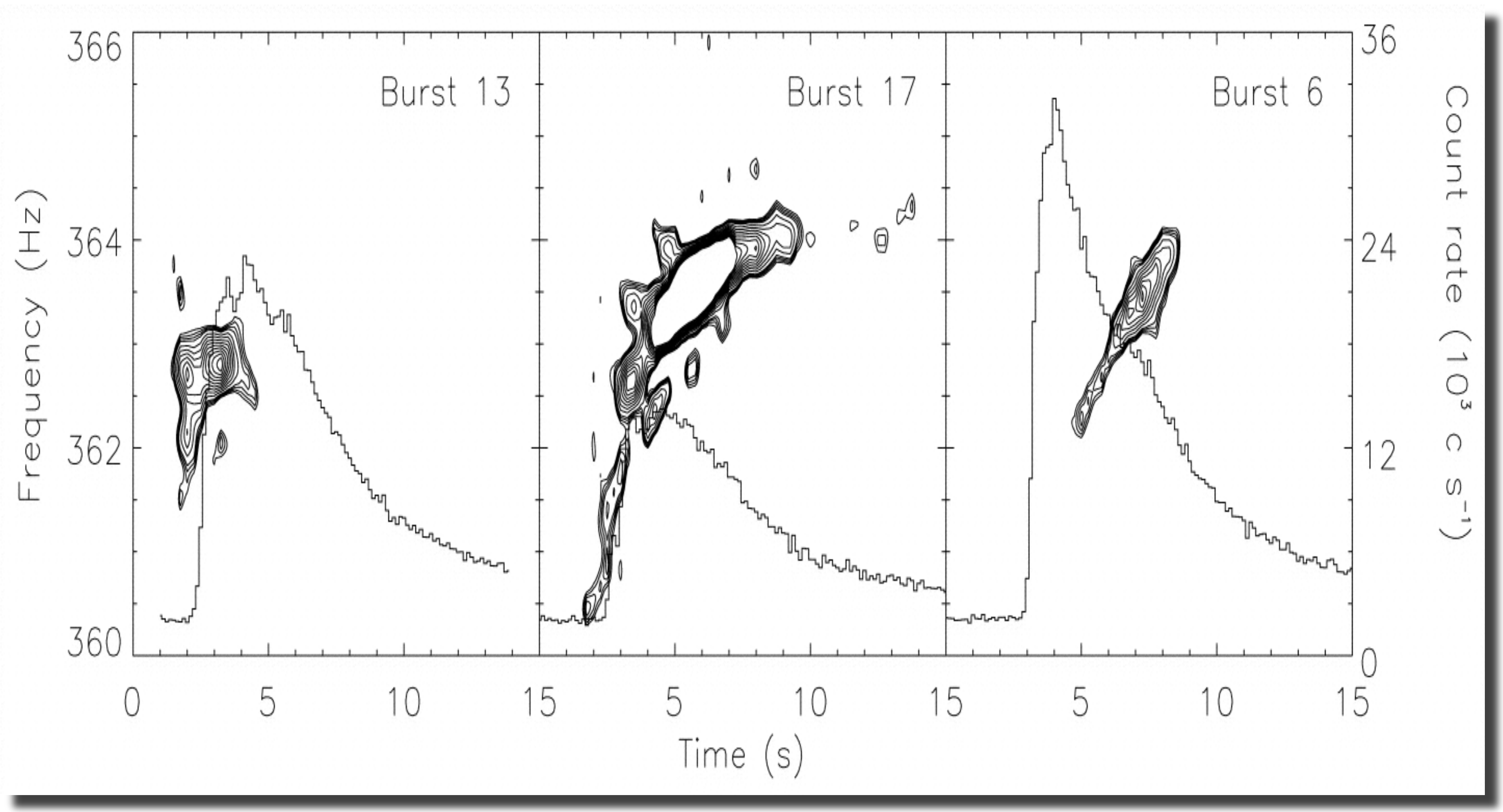
- Connection with mass accretion rate dependence of nuclear burning

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

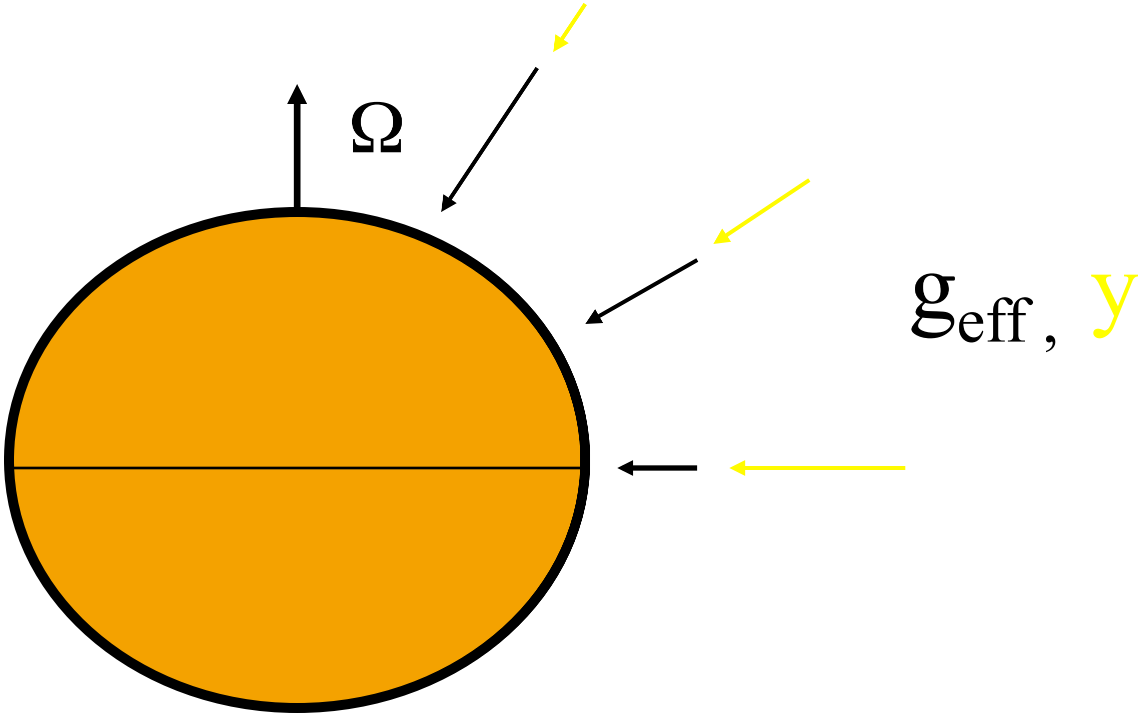
4U 1728-34: Franco (2001)



Properties of Burst Oscillations



Ignition: Where Does it Happen?

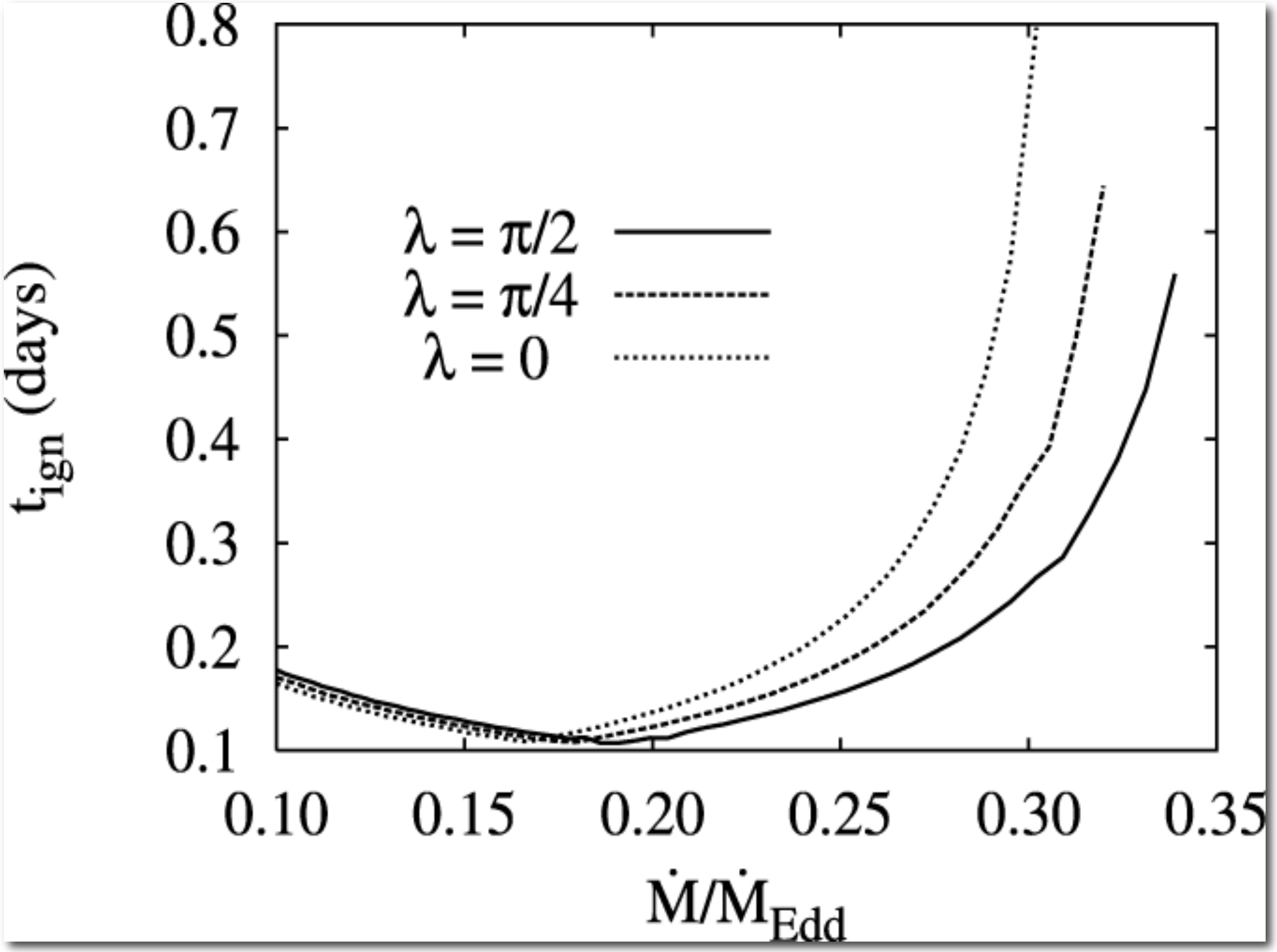


$P = y g_{eff} = \text{const}$

Independent of latitude.

- Local accretion rate is higher at the equator. Preference for ignition near equator.
- Ignition stabilizes above a critical local accretion rate.
- At higher accretion rates, ignition could move of equator to higher latitudes (Cooper & Narayan 2007).
- Can we see this?

Rapid Spin and Ignition Latitude



Cooper & Narayan (2007)

- Variation in effective gravity with latitude, give changes in ignition timescale with latitude.
- Higher accretion rates yield shorter ignition times away from equator.
- Need fast rotation.

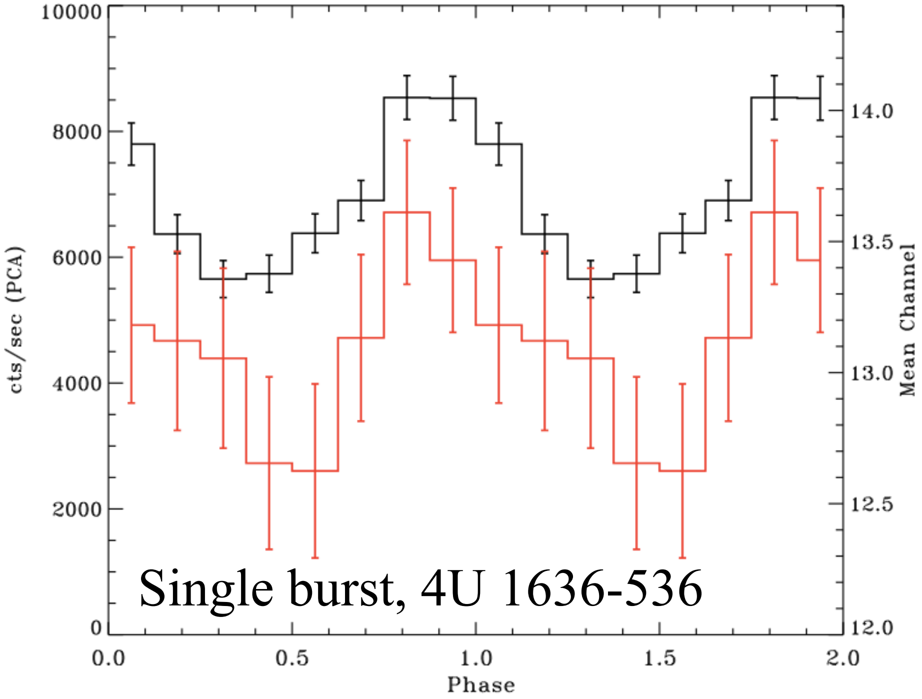
Accretion State Dependence of Oscillations

- Mass accretion rate
- Composition? → Mode visibility
- Latitude of ignition?
- Ignition depth, spreading speed, PRE?

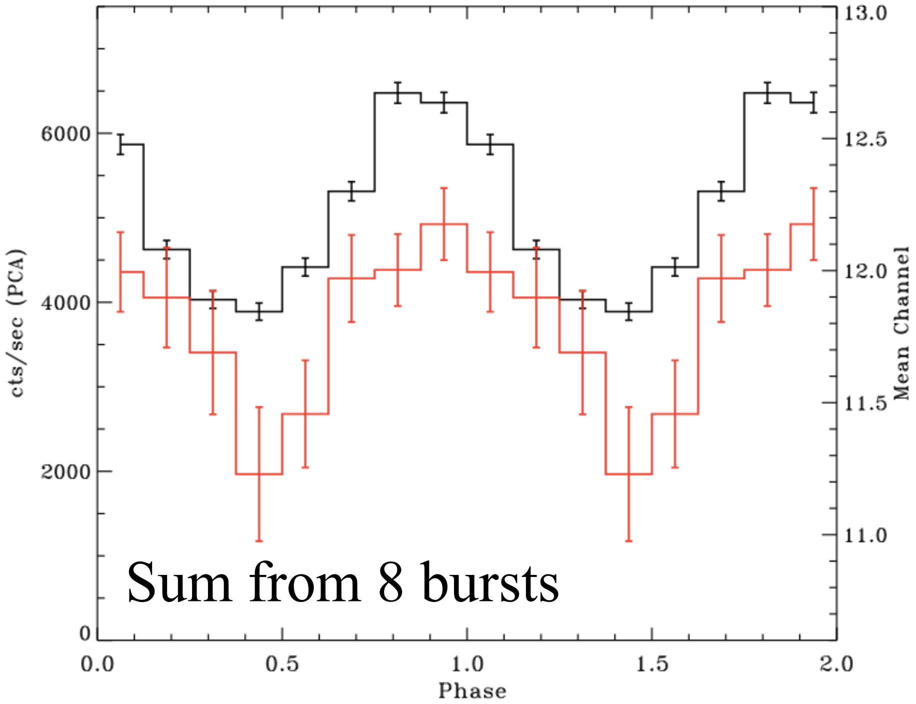
Given the above, perhaps a dependence on accretion state is then not unexpected, but disentangling the various effects appears to be difficult!

Properties of Oscillations: Phase-resolved Spectra (rises)

- Extracted phase-resolved spectra (RXTE/PCA) for bursts from 4U 1636-536. typical interval ~0.5 s.
- Compute the full band count rate, and the mean PCA energy channel versus pulse phase.



Single burst, 4U 1636-536



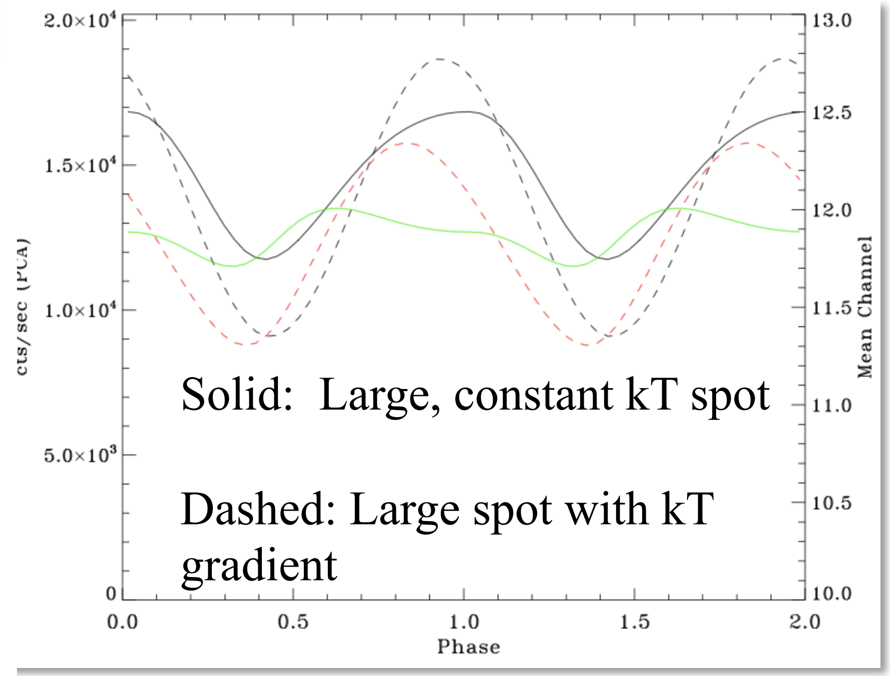
Sum from 8 bursts

- Mean channel is a measure of spectral hardness (temperature).
- Extract single burst data (left) as well as coherently adding spectra from several bursts (coherent sum from 8 burst rises (right).

Modeling Emission from a Rotating Neutron Star

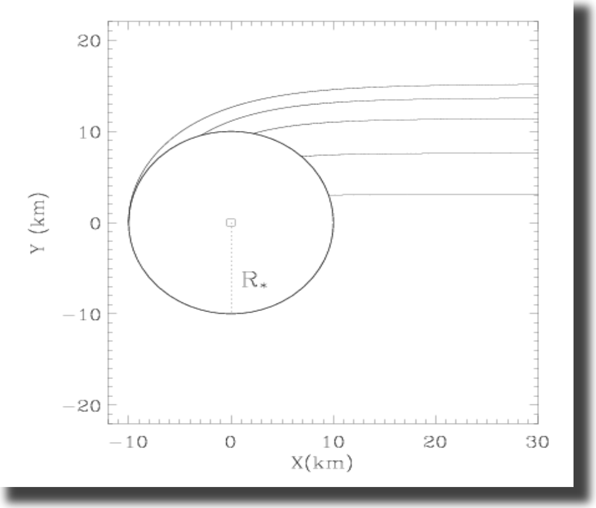
- Rotating star
- X-ray emitting hot-spot
- Relativistic effects:
  - Light bending in a Schwarzschild geometry
  - Gravitational redshift
  - Doppler shifts
  - Relativistic aberration

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



Solid: Large, constant kT spot

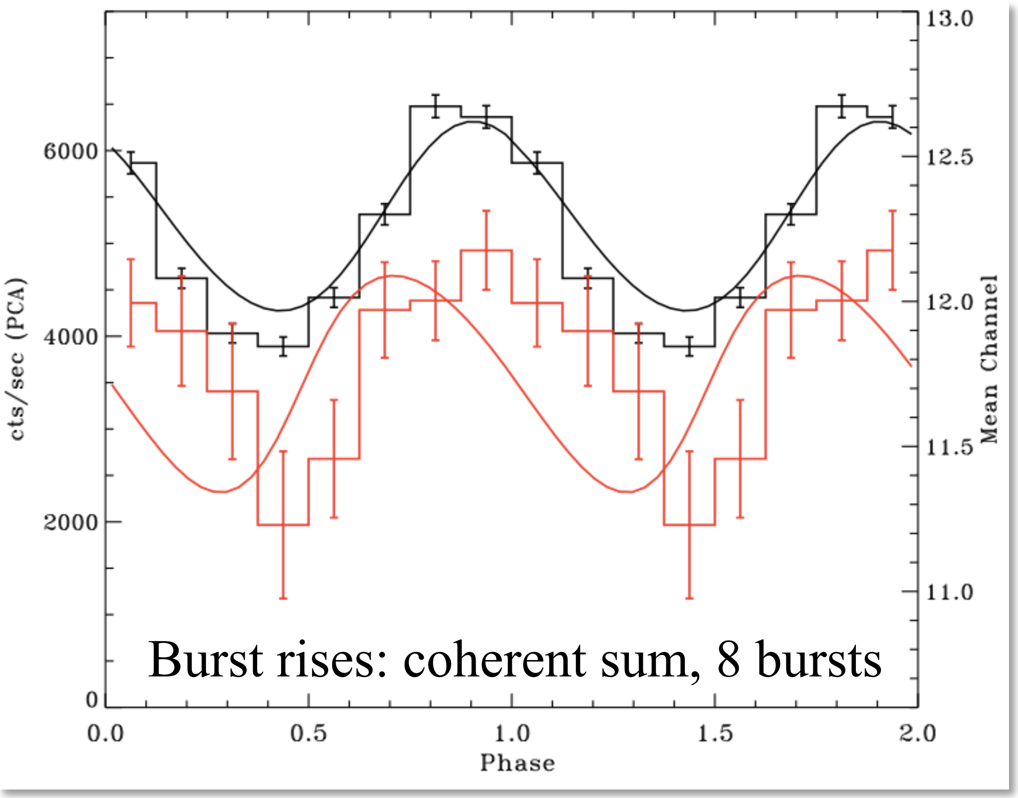
Dashed: Large spot with kT gradient

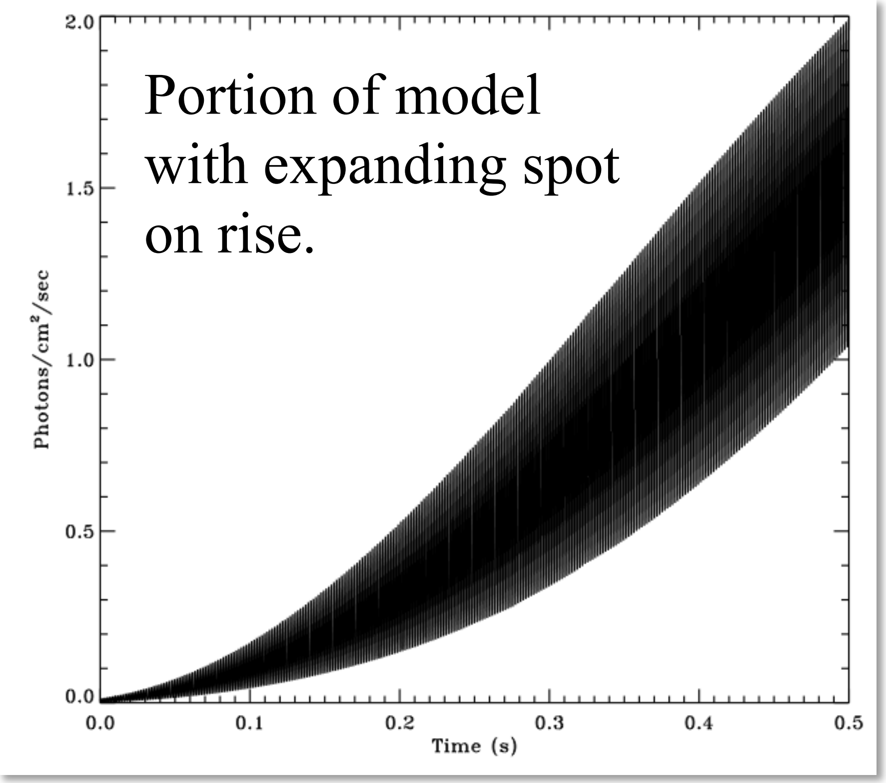


Pulse profiles consistent with the results of the LOFT Science Working Group on Dense Matter. (Poutanen, Lamb, Morsink, Psaltis et al.)

Phase-resolved Spectra: Modeling

- Use fully relativistic model (Schwarzchild+Doppler) to compute same observables from the model.
- Fold physical model spectrum through PCA response matrix.

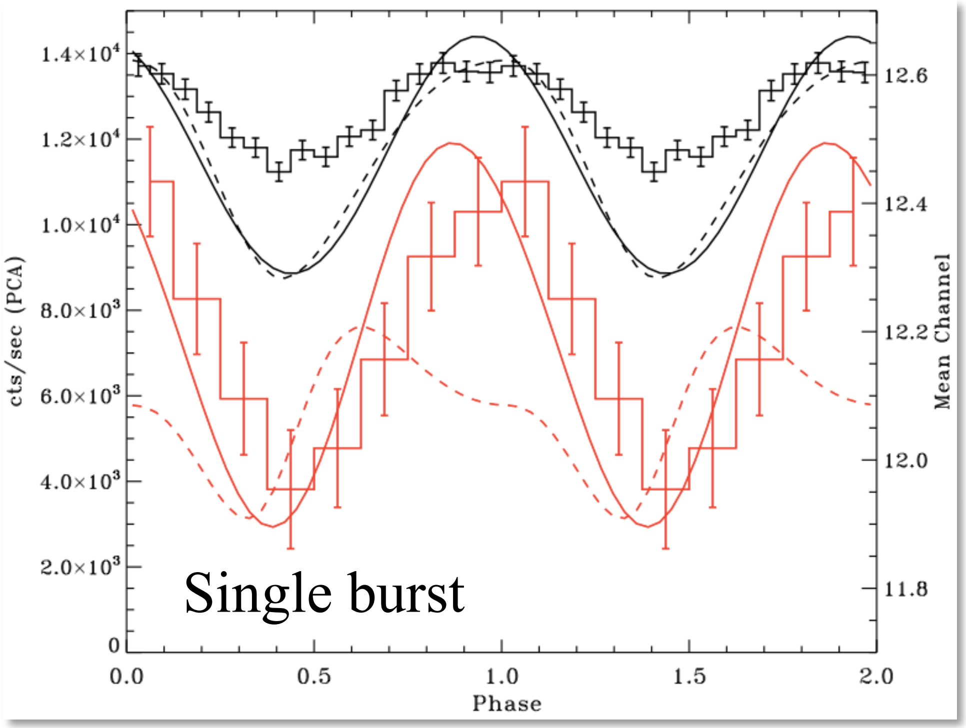




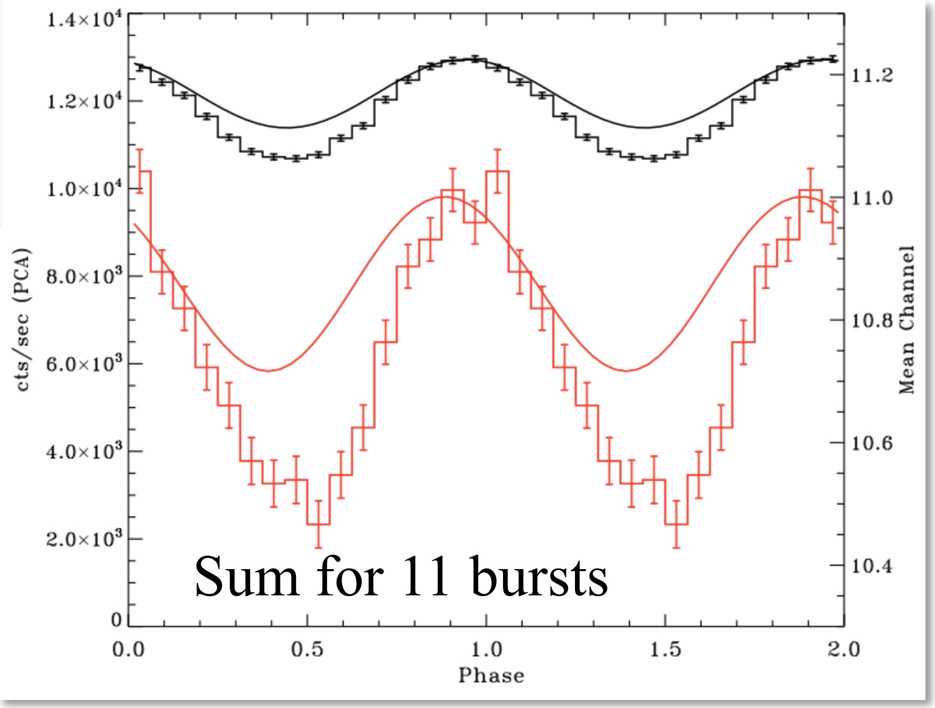
Portion of model with expanding spot on rise.

- For 4U 1636-536, use f_{spin} = 582 Hz, M=1.6 M_{sun}, R= 10 km.
- Use isotropic emission from single temperature hot-spot (right).
- Modeling still in progress, but model-predicted “leads” do not seem to be evident in the data.

Properties of Oscillations: Phase-resolved Spectra (tails)

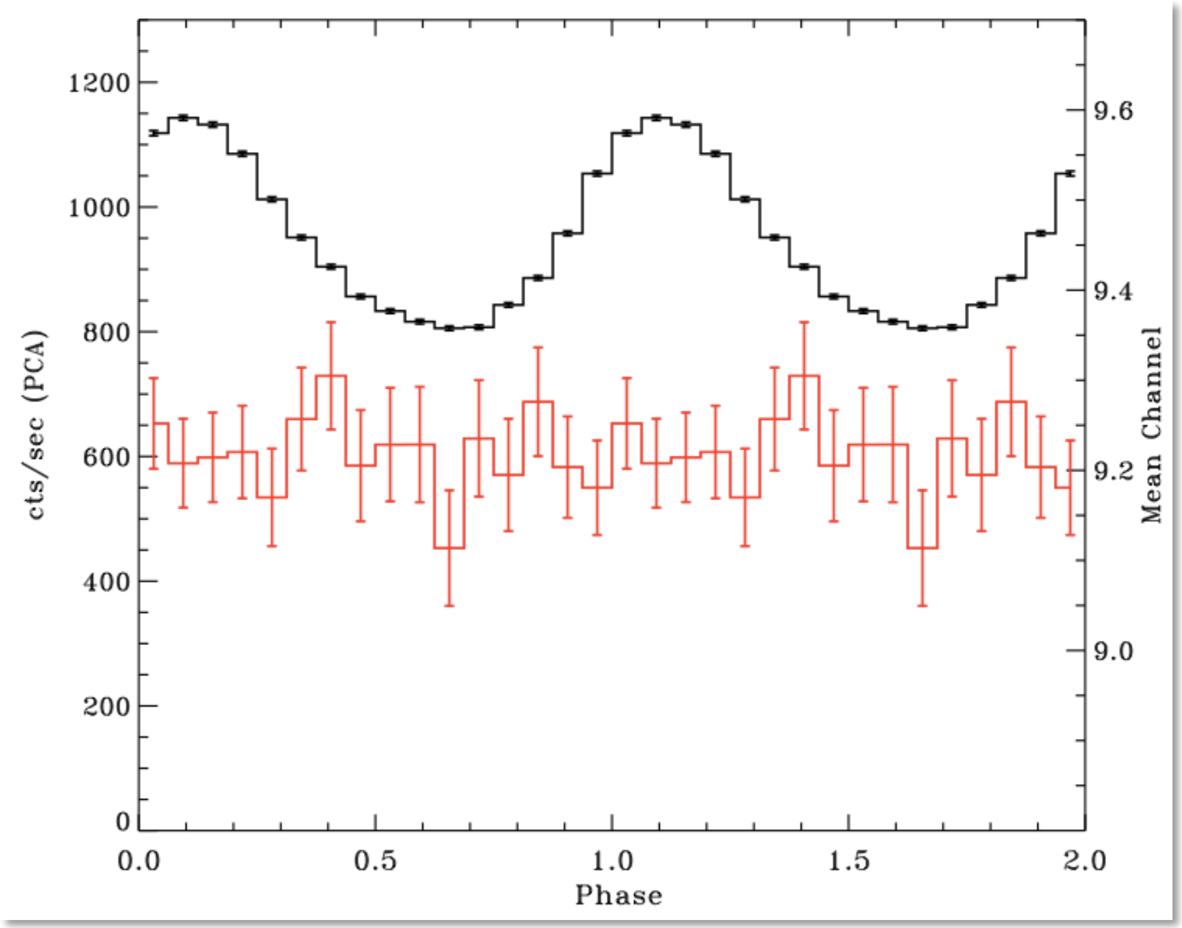


- Compute several models and PCA observables, for comparison with data.
- Modulation in mean PCA channel is IN PHASE with pulsed light curve. Single temperature spot models predict a lead.



- Extracted phase-resolved spectra from bursts from 4U 1636-536, oscillations in the cooling tail, typical pulse interval, 5 s.
- Compute count rate (full band) and mean PCA channel vs pulse phase

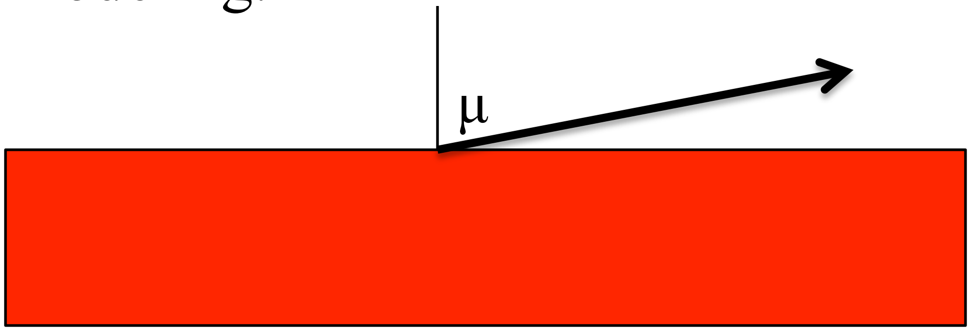
Phase-resolved Spectra: XTE J1814-338



- Whereas burst oscillations from 4U 1636-536 show a strong "color" modulation, curiously there is no significant variation in mean PCA channel with phase in J1814.
- J1814 has a slower spin rate, 314 Hz, and is a persistent pulsar (when in outburst).
- What accounts for the differences with 4U 1636?

Phase-resolved spectroscopy: Implications

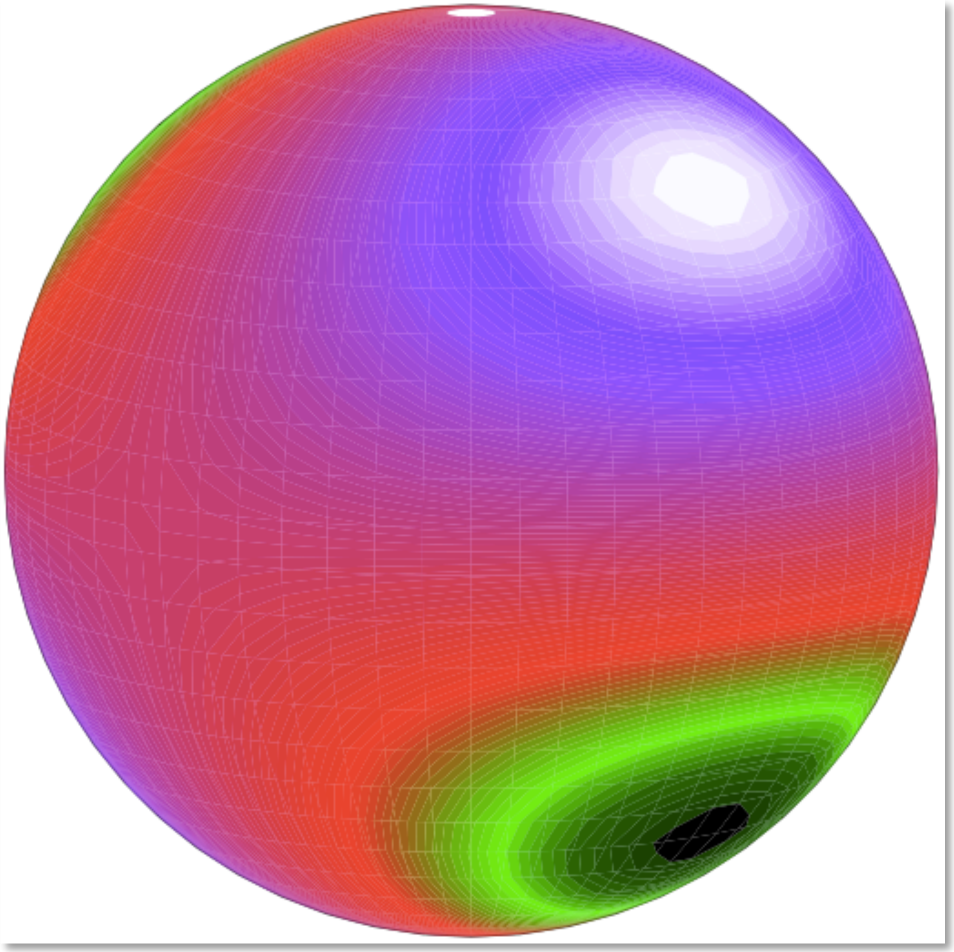
- Significant and substantial modulation of mean PCA channel, a "color" oscillation, but apparently "in phase" with the flux modulation in 4U 1636-536 (rises and tails, but seems most solid for tail oscillations).
- Doppler shifts associated with fast rotation of a constant kT spot should "lead" the flux modulation (see Artigue et al. 2014, for example).
- Models with kT gradients are less out of phase, but still lead.
- Are there other effects (physics) needed in the modeling? Angular dependence of the emissivity and spectrum, eg., full atmosphere modeling.



$I(\mu)$, $T(\mu)$

Work in progress!

Neutron Star Seismology

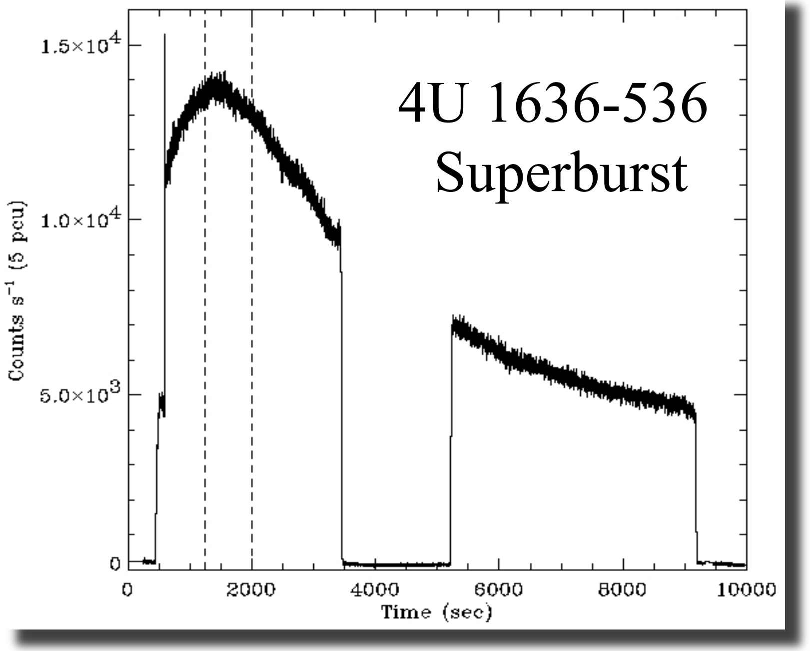


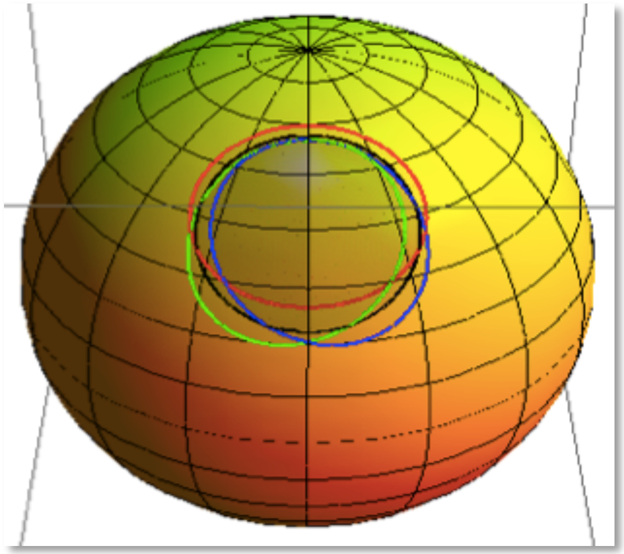
Brightness pattern for an *l*=2, *m*=1 g-mode (slow rotation limit).

- Stellar oscillations are a powerful probe of internal structure (e.g. helioseismology).
- For example, p-modes sense the sound speed. Mode frequencies scale as $< \rho >^{1/2}$ (thus M and R).
- Solid crust supports torsional shear modes, ${}_{l}t_{n}$ for n = 0 modes, effective wavelength is R, for n > 0 it is ΔR, if V_s = constant, then $f_{n=0} / f_{n>0} \sim \Delta R/R$, constrain crust thickness (magnetar QPOs).
- g-modes supported by buoyancy (thermal and density gradients), can probe R, and envelope structure.

How Might Non-radial Oscillations be Observed?

- Pulsation modes can modulate the temperature (flux) across the neutron star's surface – coupled with spin can produce flux modulation at mode's **inertial frame frequency** (Lee & Strohmayer, Heyl 2005).
- Surface displacements generated by pulsation modes can periodically distort the X-ray emitting hot-spot (Numata & Lee 2010). Works for transverse (quasi-toroidal) displacements. Such modes include surface g-modes, and r-modes.
- Since hot-spot rotates with the star, the modulation frequency seen by a distant observer is the **co-rotating frame frequency** (Strohmayer & Mahmoodifar 2014, ApJ, 784, 72) .





Coherent Searches for Pulsation Modes

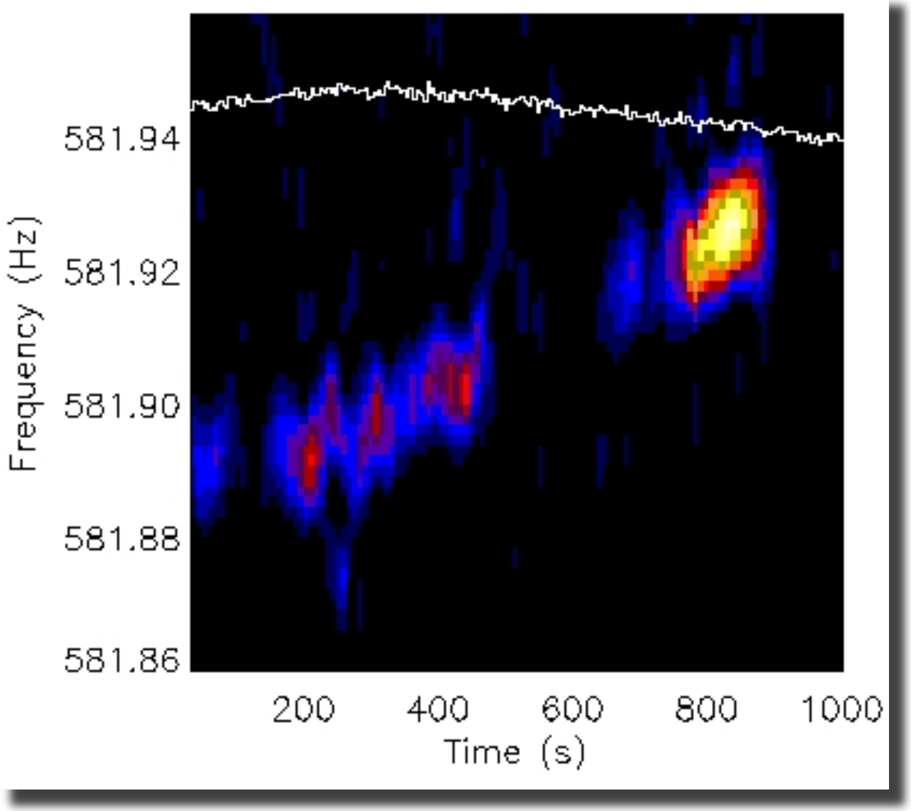
- Use orbit model to remove time delays associated with neutron star's orbital motion. Observer is effectively at the binary's center of mass.
- "Coherence Recovery," improves sensitive to weak, coherent signals. Narrow band signal is not "smeared" into many Fourier bins.
- "Targeted" search for r-modes and surface g-modes. Spin frequency is known, so search mode frequency range (relative to spin) that is expected theoretically. Keeps N_{trial} low and thus improves overall sensitivity.

$$0.417 \leq \sigma / \Omega \leq 0.757 \text{ (rotating frame)}$$

$$1.243 \leq \sigma / \Omega \leq 1.583 \text{ (inertial frame)}$$

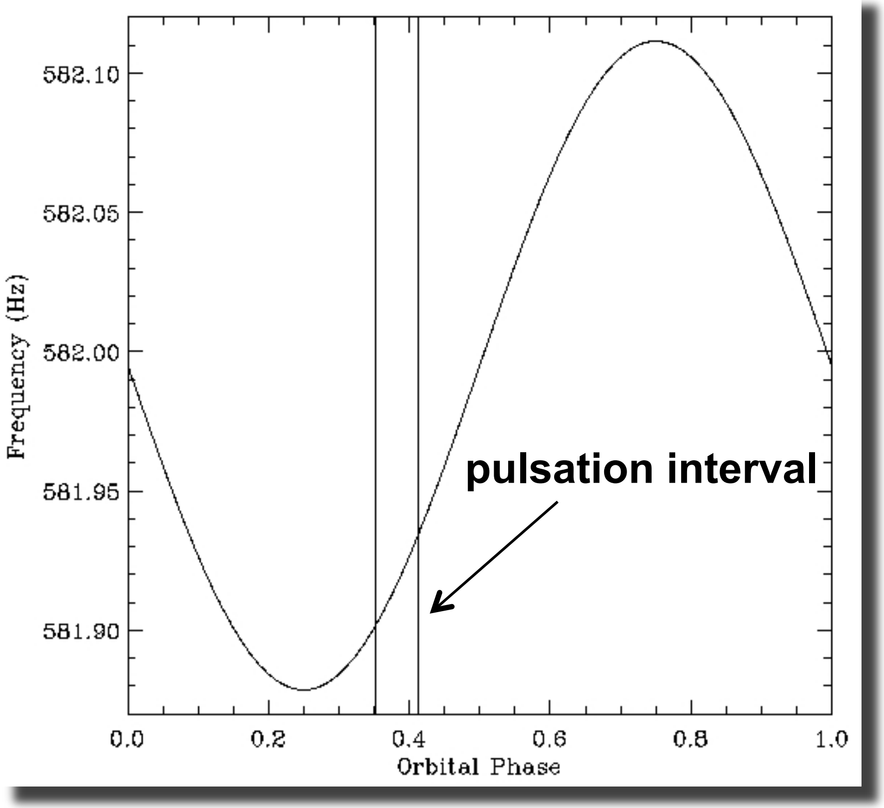
- Bin light curve using corrected times (4096 Hz sampling).
- Create power spectra using 4 energy ranges (focusing on superburst thermal component).

4U 1636-535: February 2001 Superburst

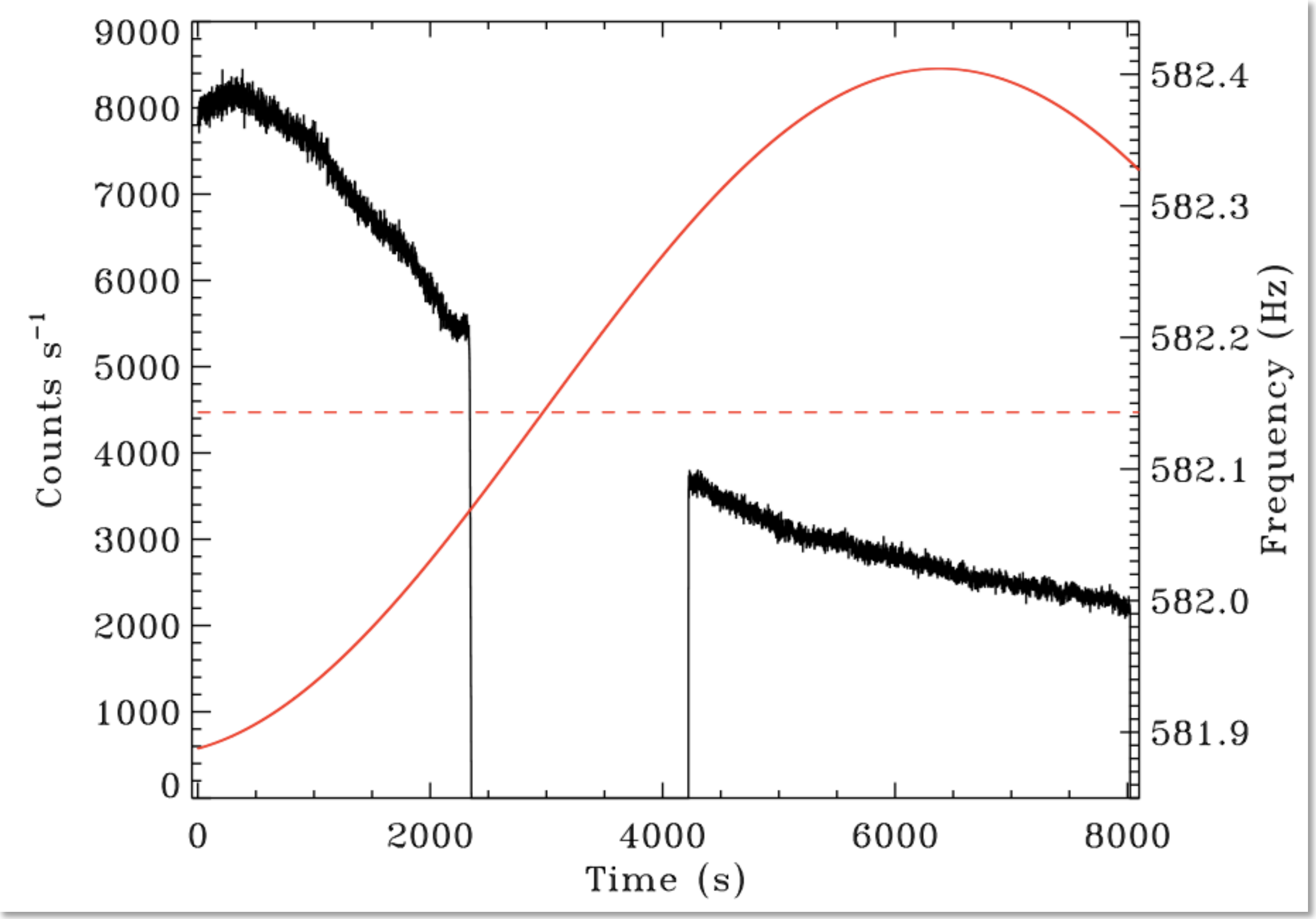


- 582 Hz spin pulsations detected for ~800 s near burst peak.
- Frequency drift consistent with orbital motion of the neutron star.

- Orbital period known (3.79 hr), fit for other parameters; ν_{spin}, v_{ns} and epoch of T_{90} (Strohmayer & Markwardt 2002).
- Barycenter, then remove orbital time delays.

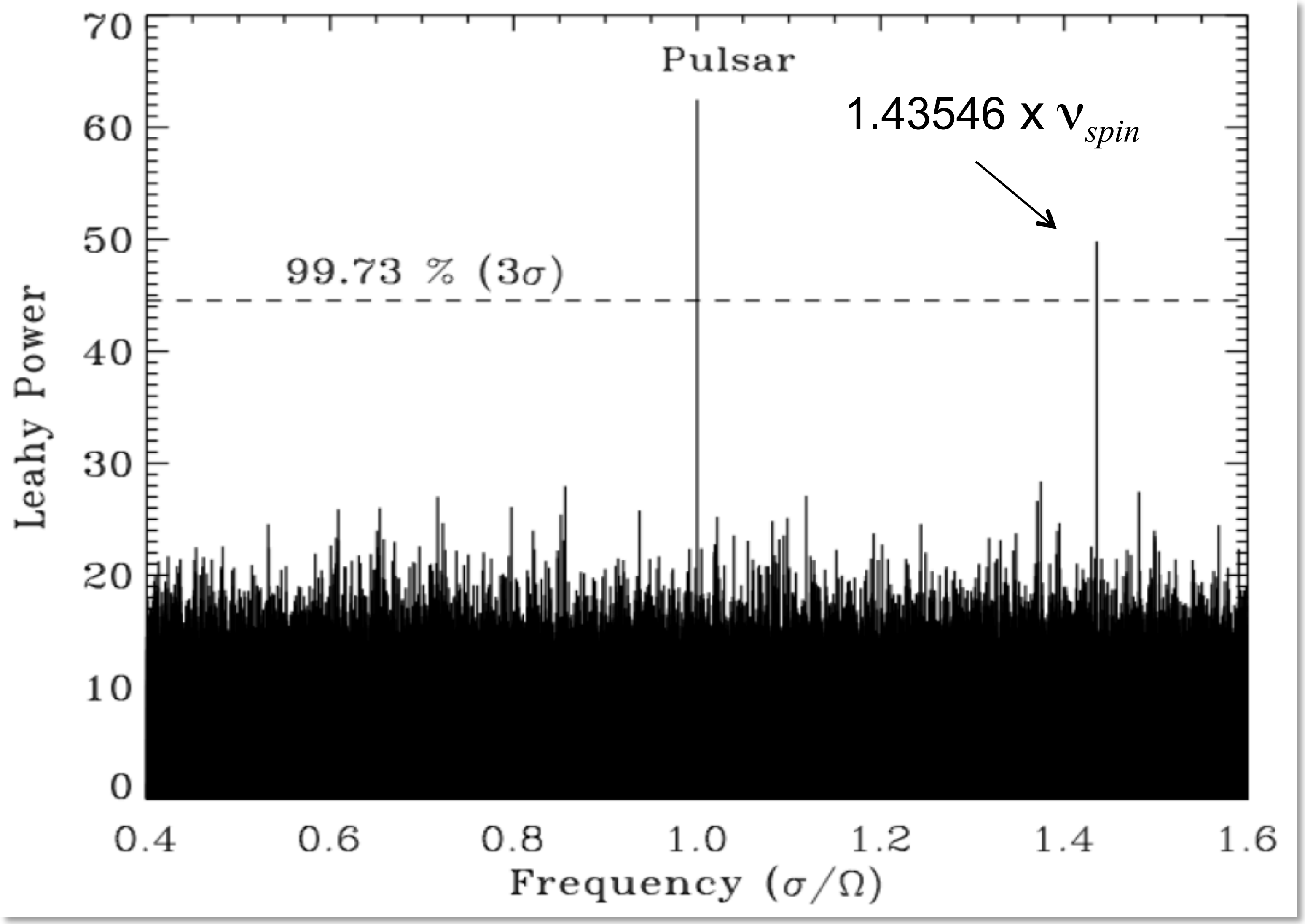


4U 1636-535 Superburst Light Curve



$N_{bins} \approx (\Delta\nu/\nu) = (v_{ns}/c) = (0.5/582)*835/(1/8000) = 5700!$

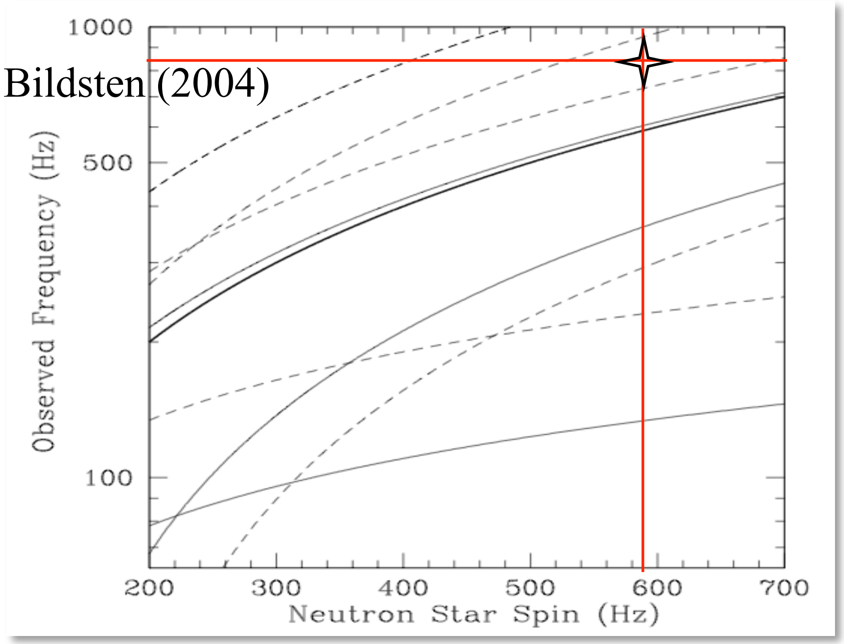
Coherent Search in the Superburst



Estimated significance: 2.5×10^{-4} $\exp(-49.3/2) \times N_{trials} = \exp(-49.3/2) \times (4 \times 3.17 \times 10^6)$

Possible Mode Identifications

- g-modes in envelope above the solid crust. Piro & Bildsten (2004) and Strohmayer & Lee (1996) computed modes in accreting, nuclear burning envelopes (ε-mechanism). Mode frequencies 20 – 30 Hz, but modes modified by fast rotation (Bildsten et al. 1996; Piro & Bildsten 2004).
- latitudinal dependence of Coriolis force “squeezes” modes closer to equator.
- Observed frequency (835 Hz) is larger than spin, so, if |m|=1, need prograde (m=-1) mode (this is a Kelvin mode), but frequency is not high enough to reach observed (likely rules out l=1). So, |m|=2. Then l=2, m=2 or l=2, m=-1 appear plausible.



Piro & Bildsten (2004)