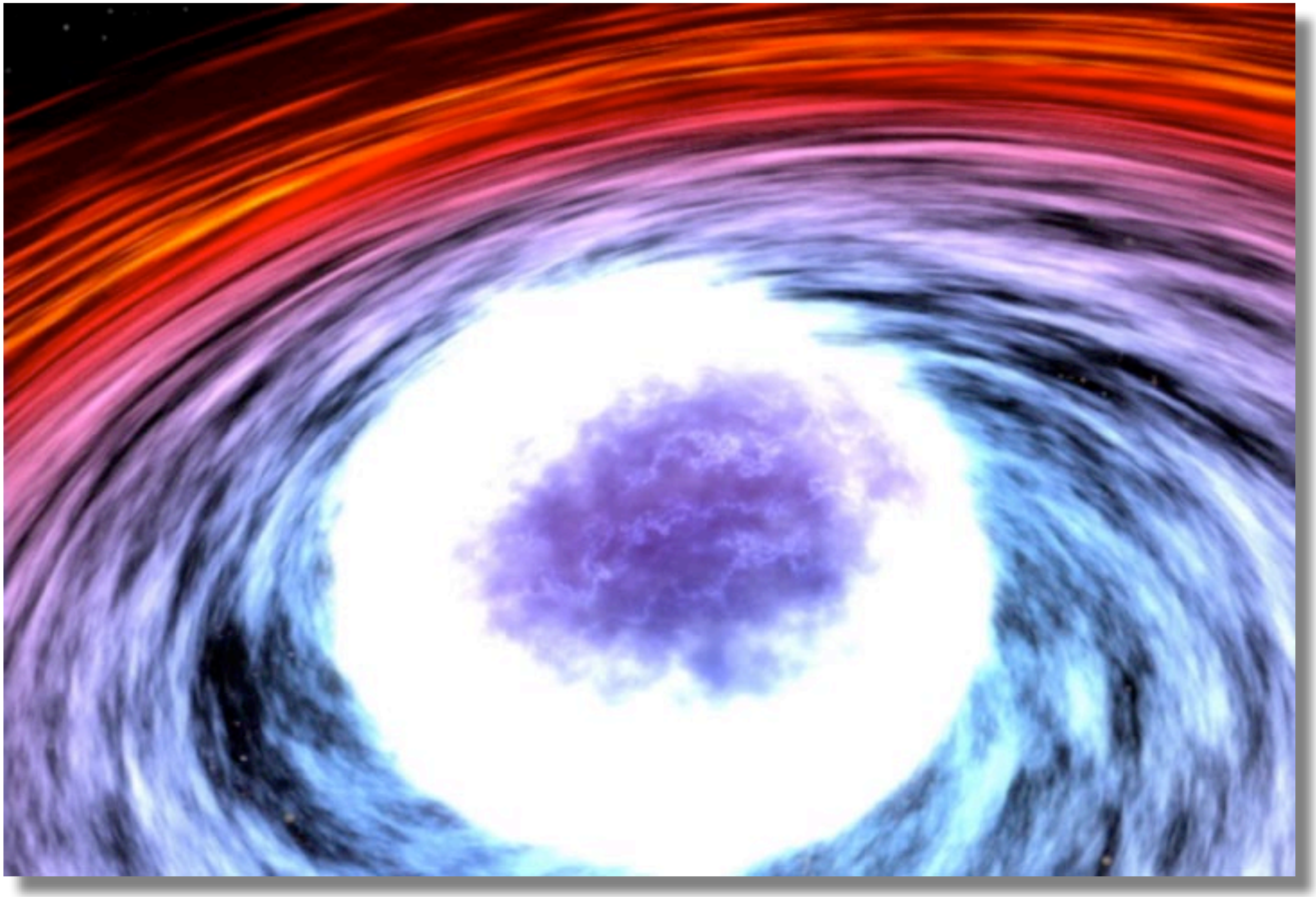
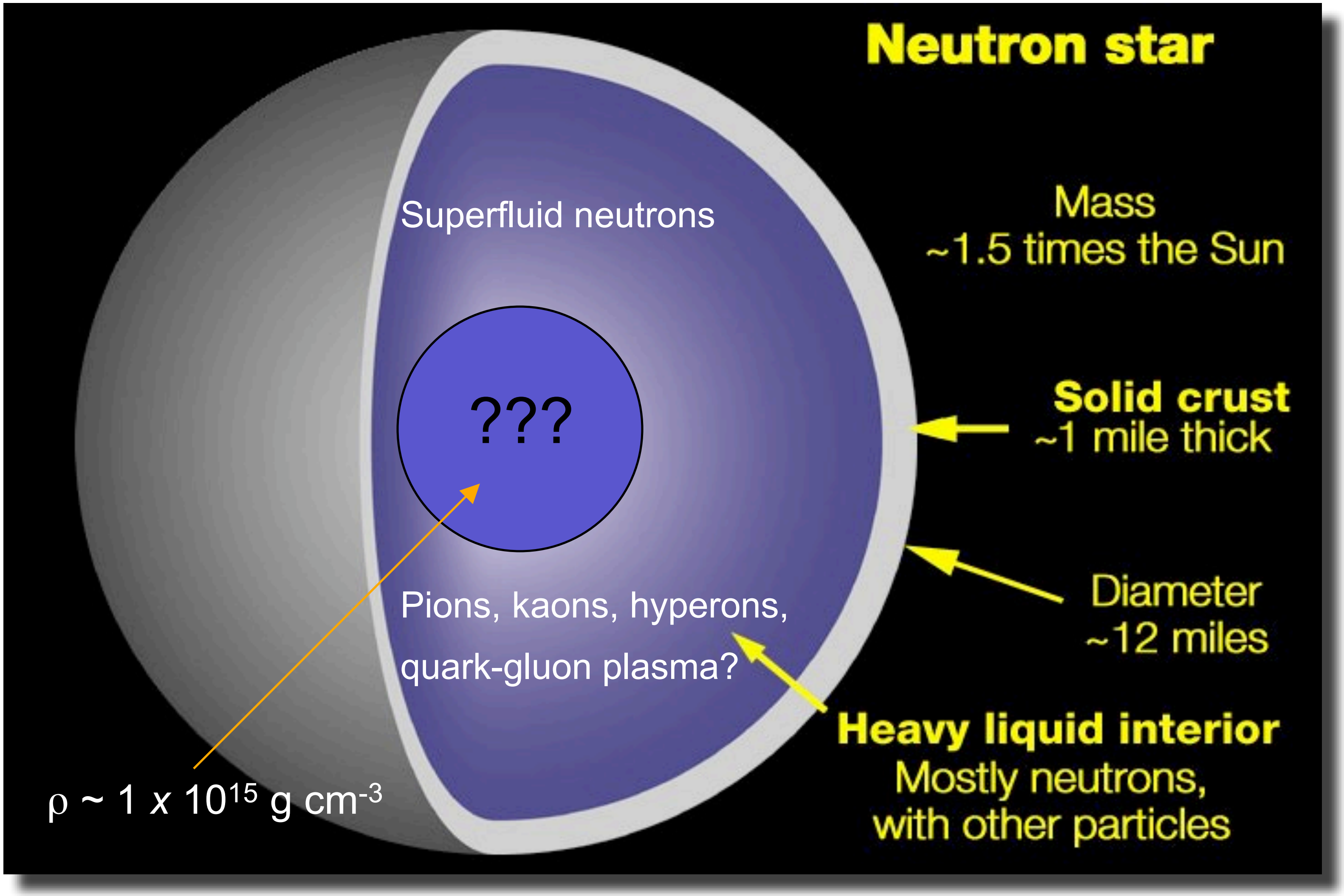
X-ray Bursts: Nuclear Physics on Neutron Stars

Tod Strohmayer, NASA's Goddard Space Flight Center



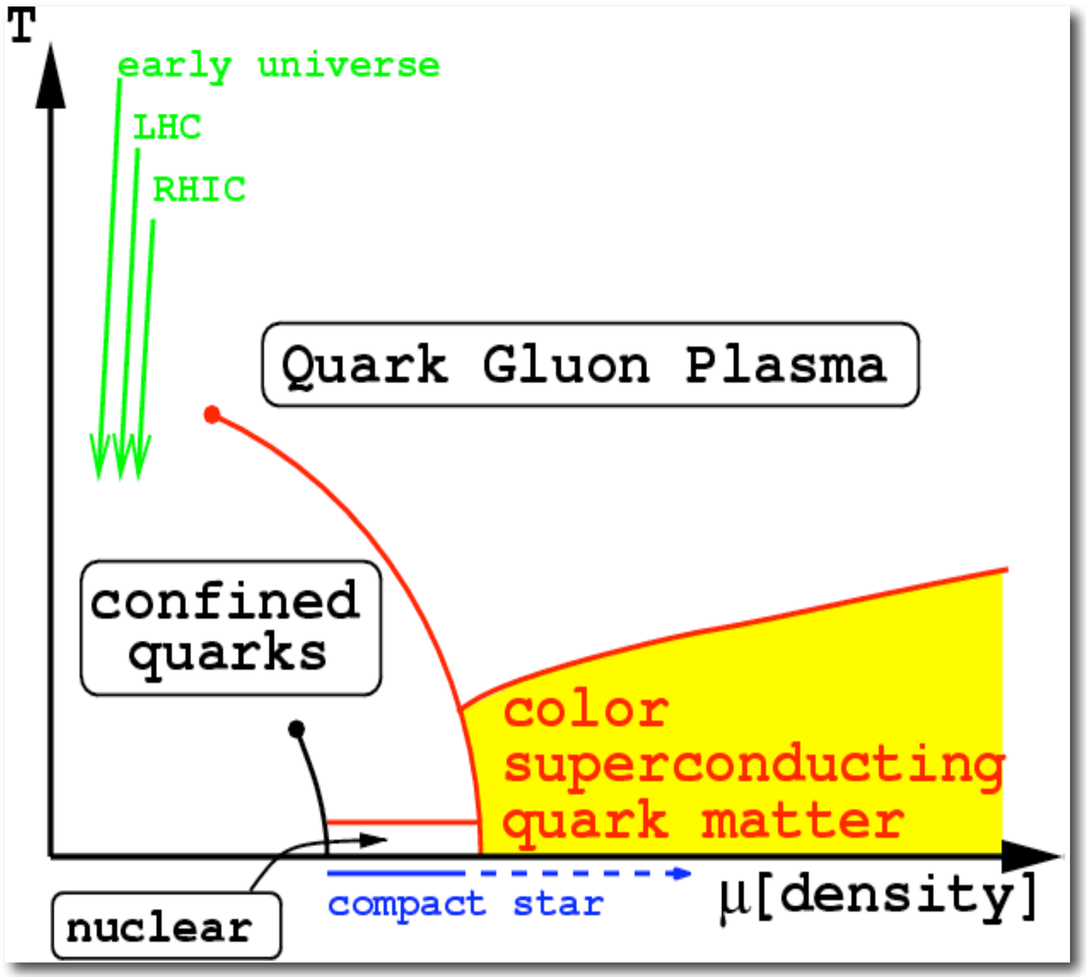
Inside 'Extreme' Neutron Stars



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

QCD phase diagram: New states of matter

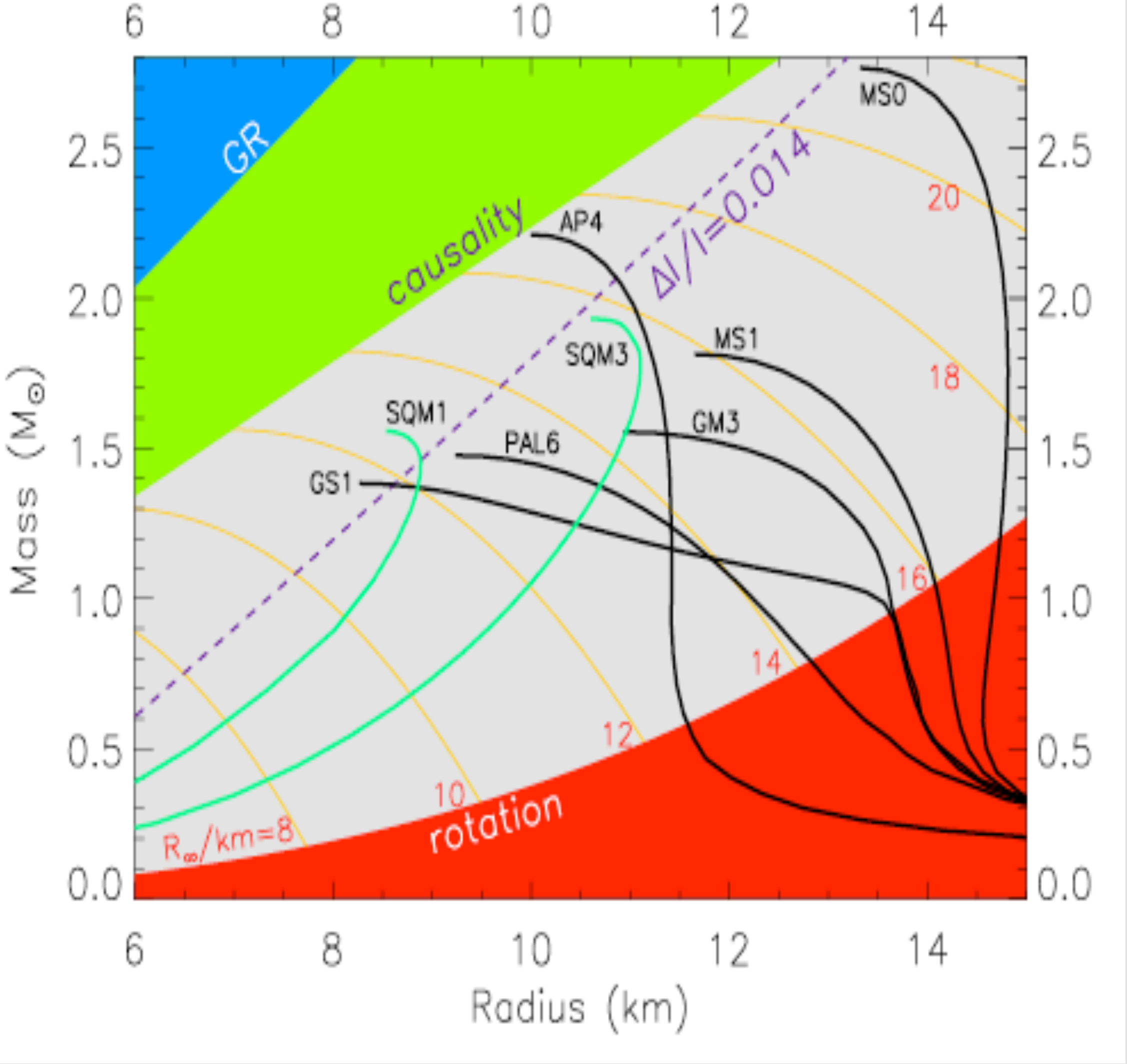
Rho 2000, thanks to David Kaplan



- 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??

The Neutron Star Equation of State

Lattimer & Prakash 2004



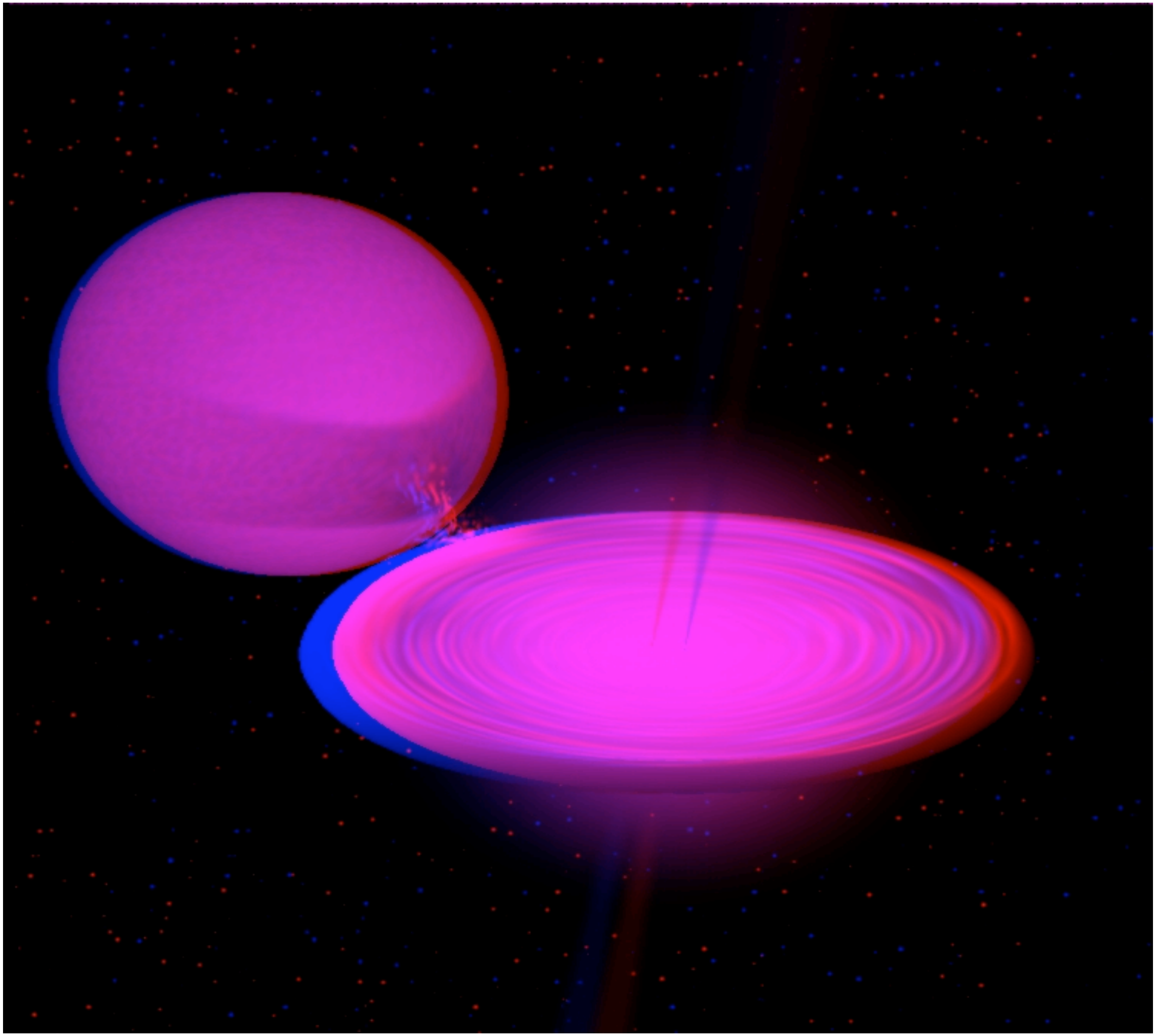
$$dP/dr = -\rho\ G\ M(r) / r^2$$

- 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.

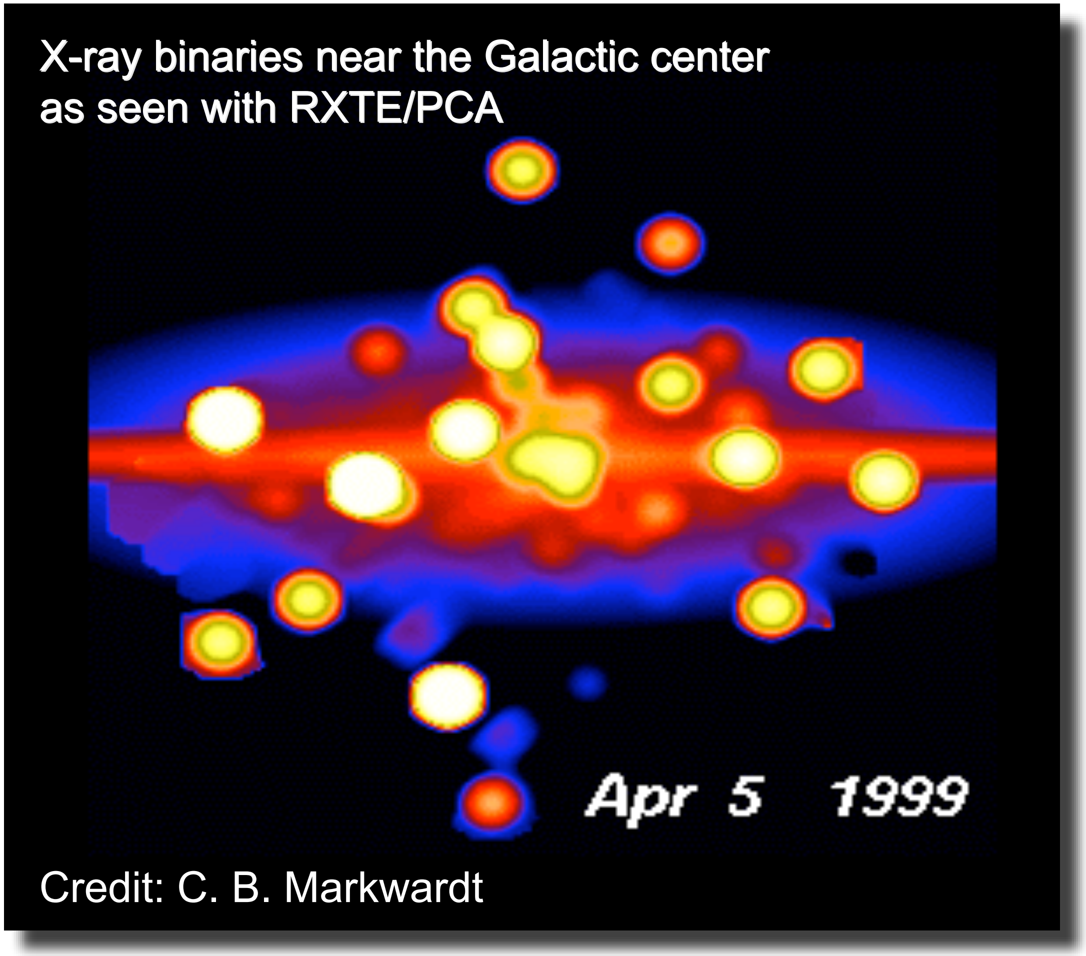
Neutron Star Fun Facts

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

Things happen FAST on and near neutron stars.
You need sub-millisecond timing to see it happen!!



Sources of Thermonuclear Bursts: LMXBs Containing Neutron Stars

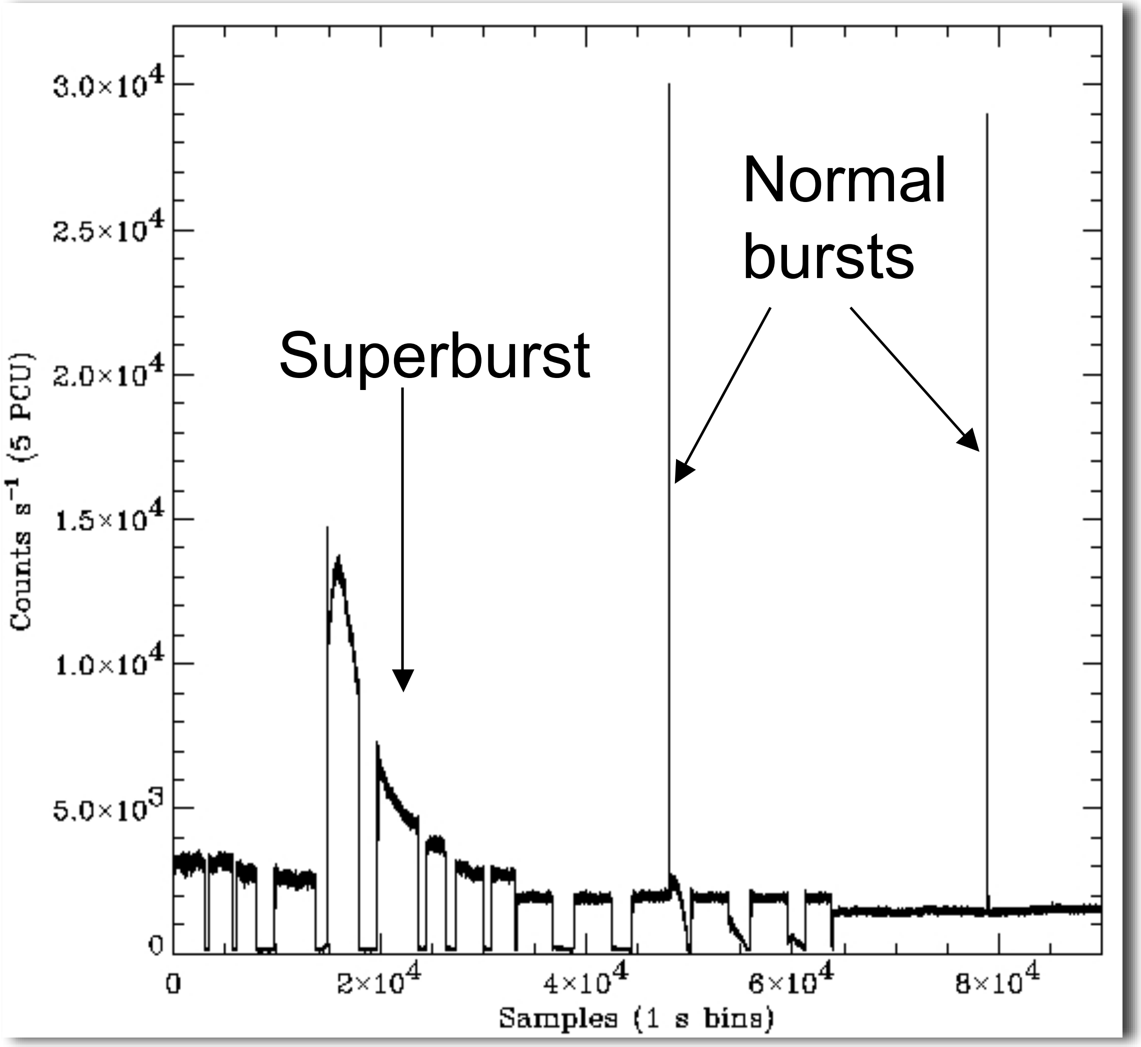


Credit: C. B. Markwardt

- Accreting neutron stars in low mass X-ray binaries (LMXBs).
- Approximately 70 burst sources are known.
- Concentrated in the Galactic bulge.
- Bursts triggered by thermally unstable H or He burning at column of few x 10^8 gm cm^{-2}
- Liberates ~ $10^{39} - 10^{43}$ ergs. First discovered 1976 (Grindlay et al., Belian et al. 1976
- Recurrence times of hours to a few days (or years).

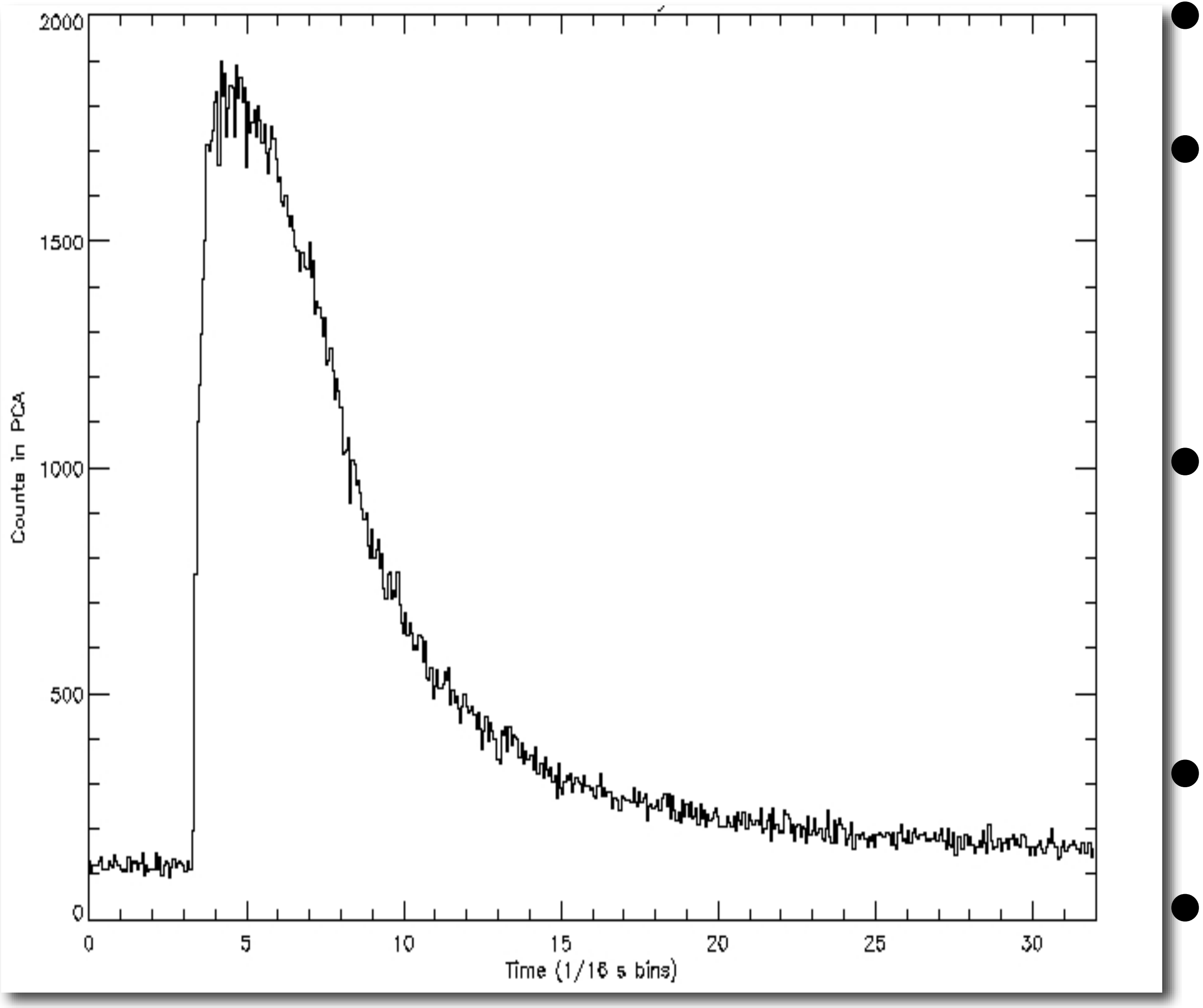
Fun fact: a typical burst is equivalent to 100, 15 M-ton 'bombs' over each cm^2 !!

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).

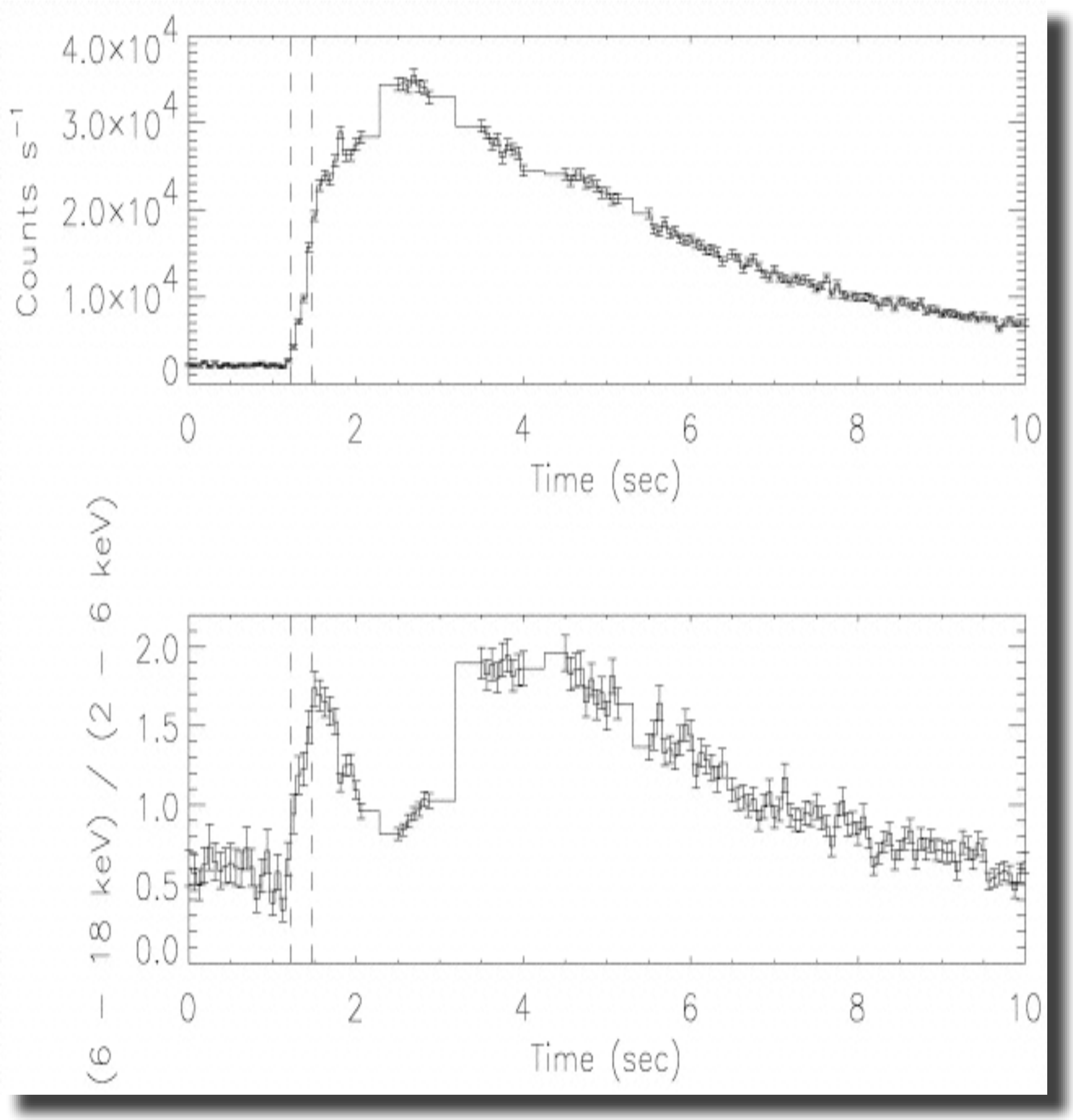
“Normal” Thermonuclear Bursts



- 10 - 200 s flares.
- Thermal spectra which soften with time.
- 3 - 18 hr recurrence times, sometimes quasi-periodic.
- ~ 10^{39} ergs
- H and He primary fuels.

He Ignition at a column depth of 2 x 10^{8} g cm^{-2}

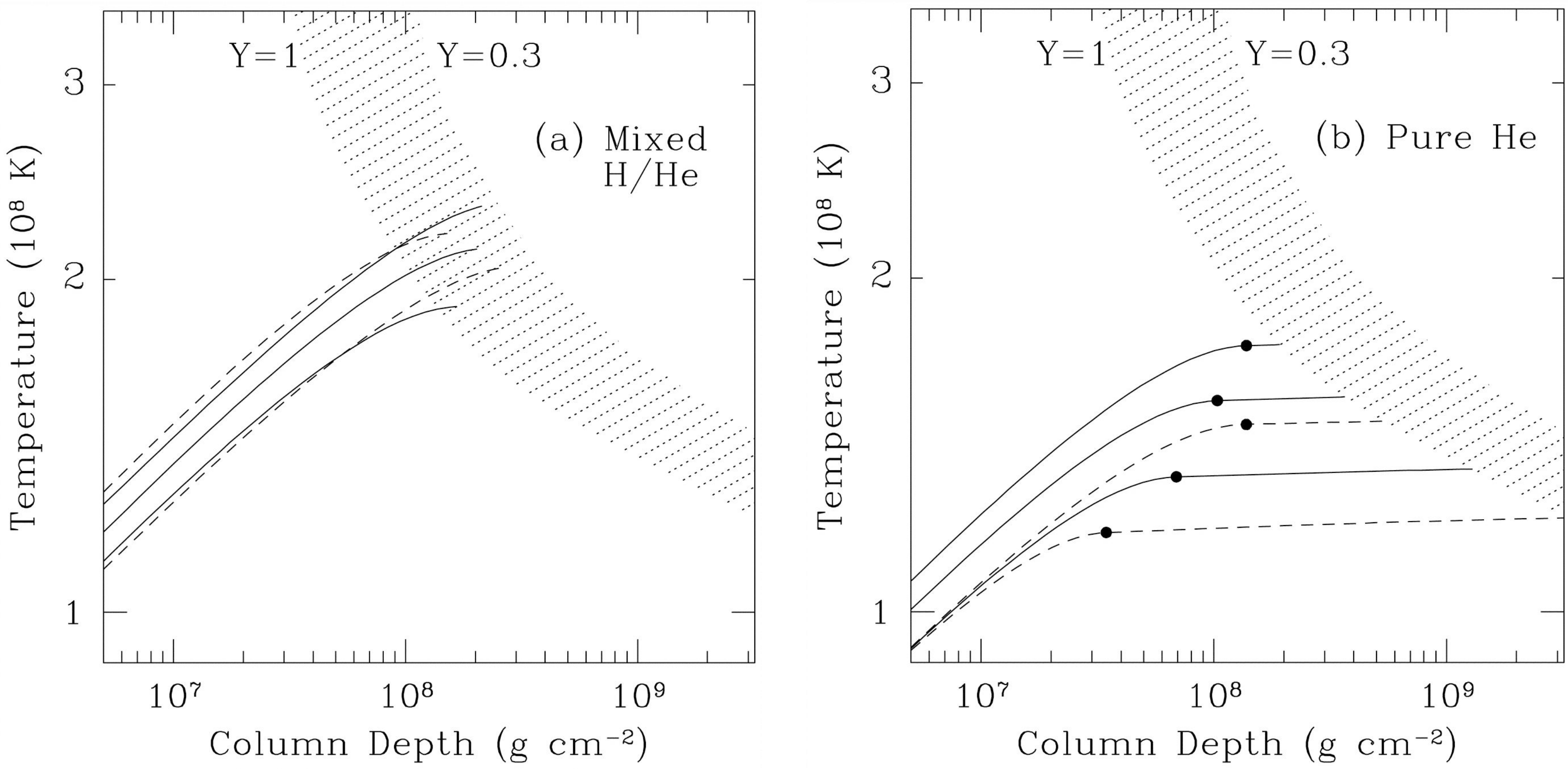
Photospheric Radius Expansion



- Local atmospheric flux can reach Eddington limit.
- Radiation pressure drives wind, expands photosphere.
- Models indicate L stays constant. R increases, Teff drops, spectrum softens.

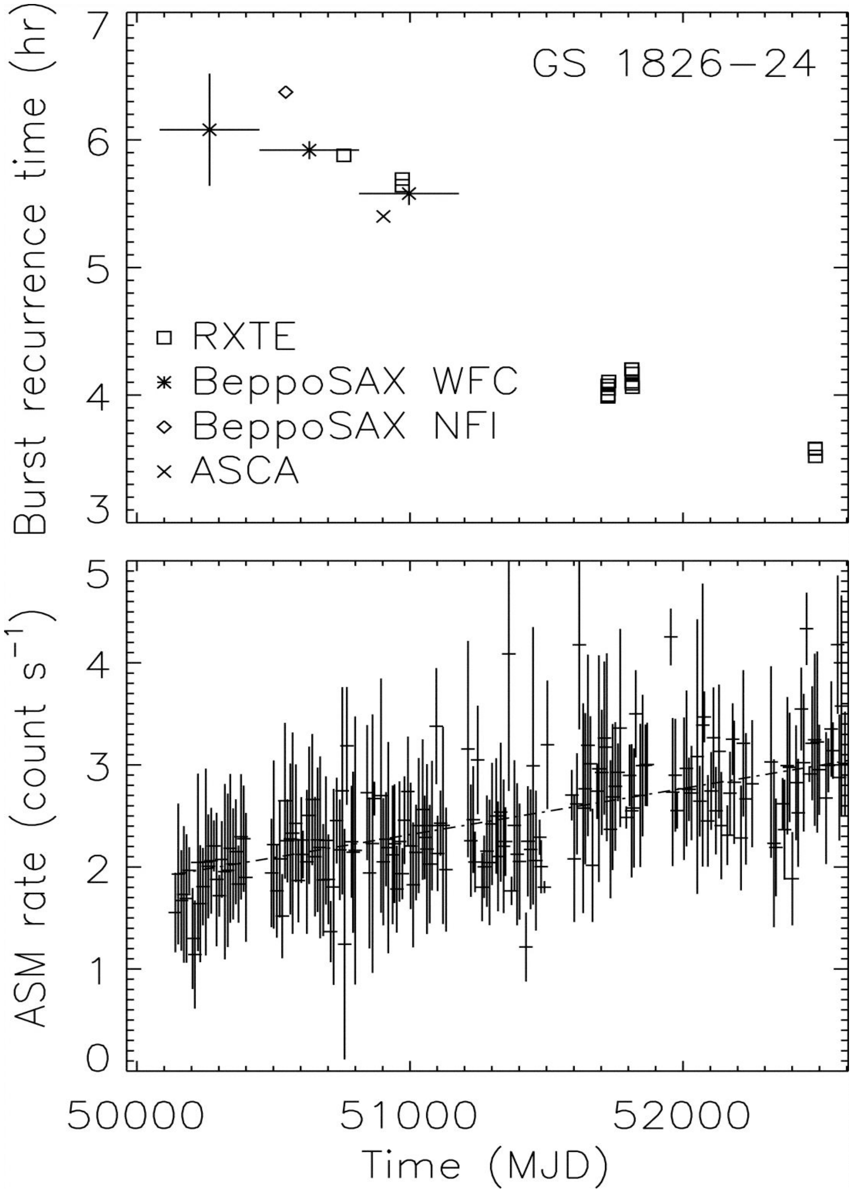
Thin Shell, Thermal Instability

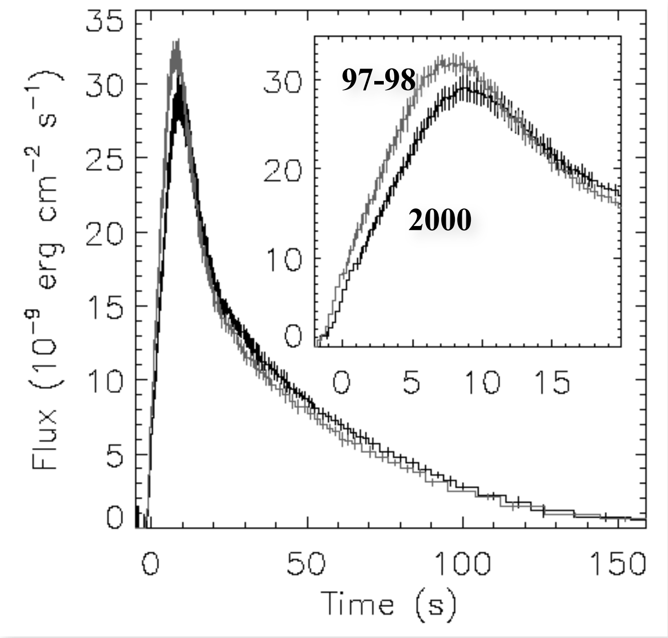
Cumming & Bildsten (2000)



- Thermal stability set by competition between radiative cooling (α T^4) and nuclear energy generation rate. Strong T dependence of 3α wins over cooling at ~1-2x10^8 K and r ~ 1x10^6 g cm^{-3}.

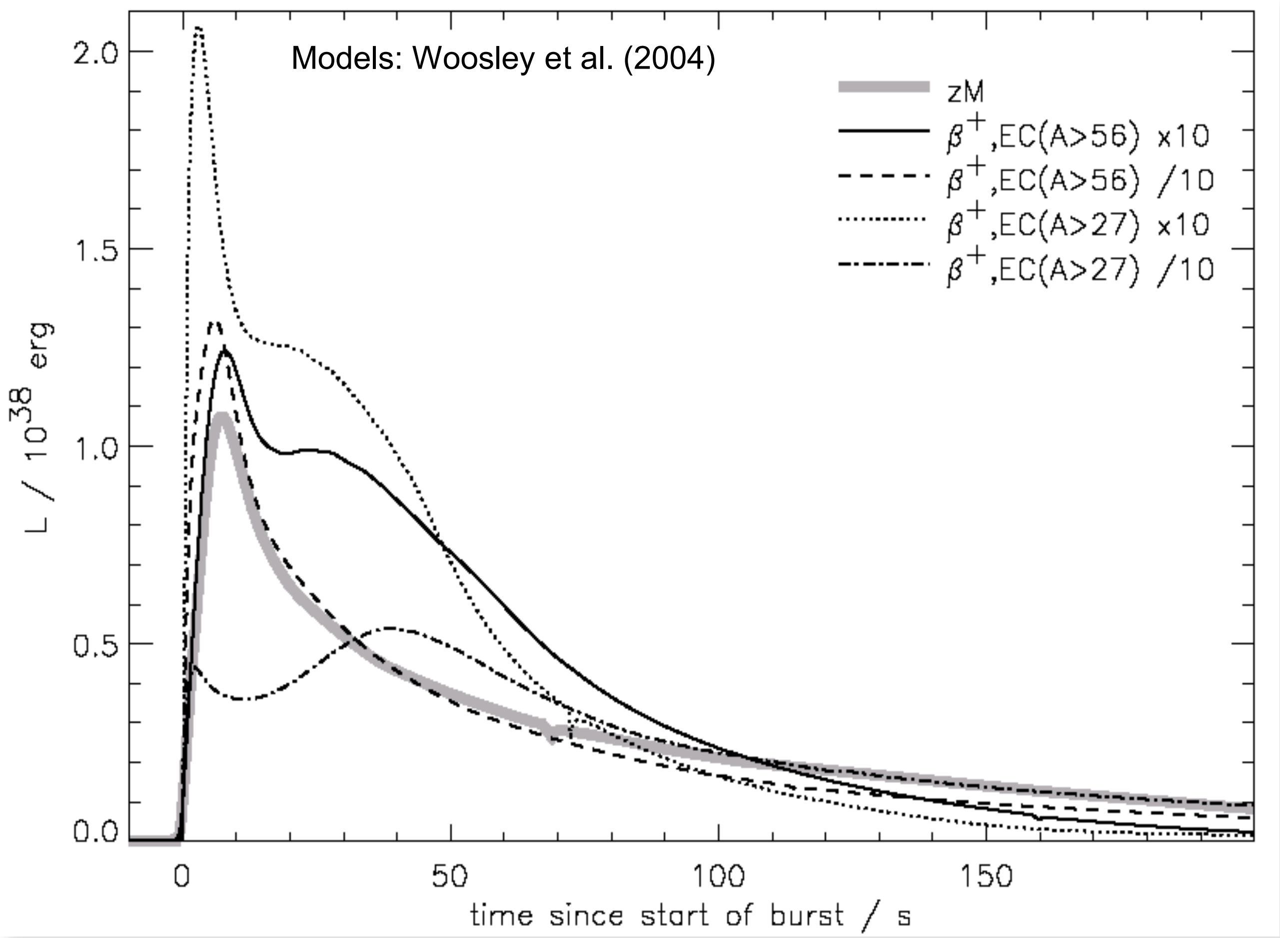
GS 1826-24: The “Textbook” Burster





- Very steady X-ray flux, and thus mass accretion rate.
- Regular “clocked” bursts.
- Long duration and $\alpha \approx 40$ => mixed H-He burning.
- Mdot comfortably in the mixed ignition regime

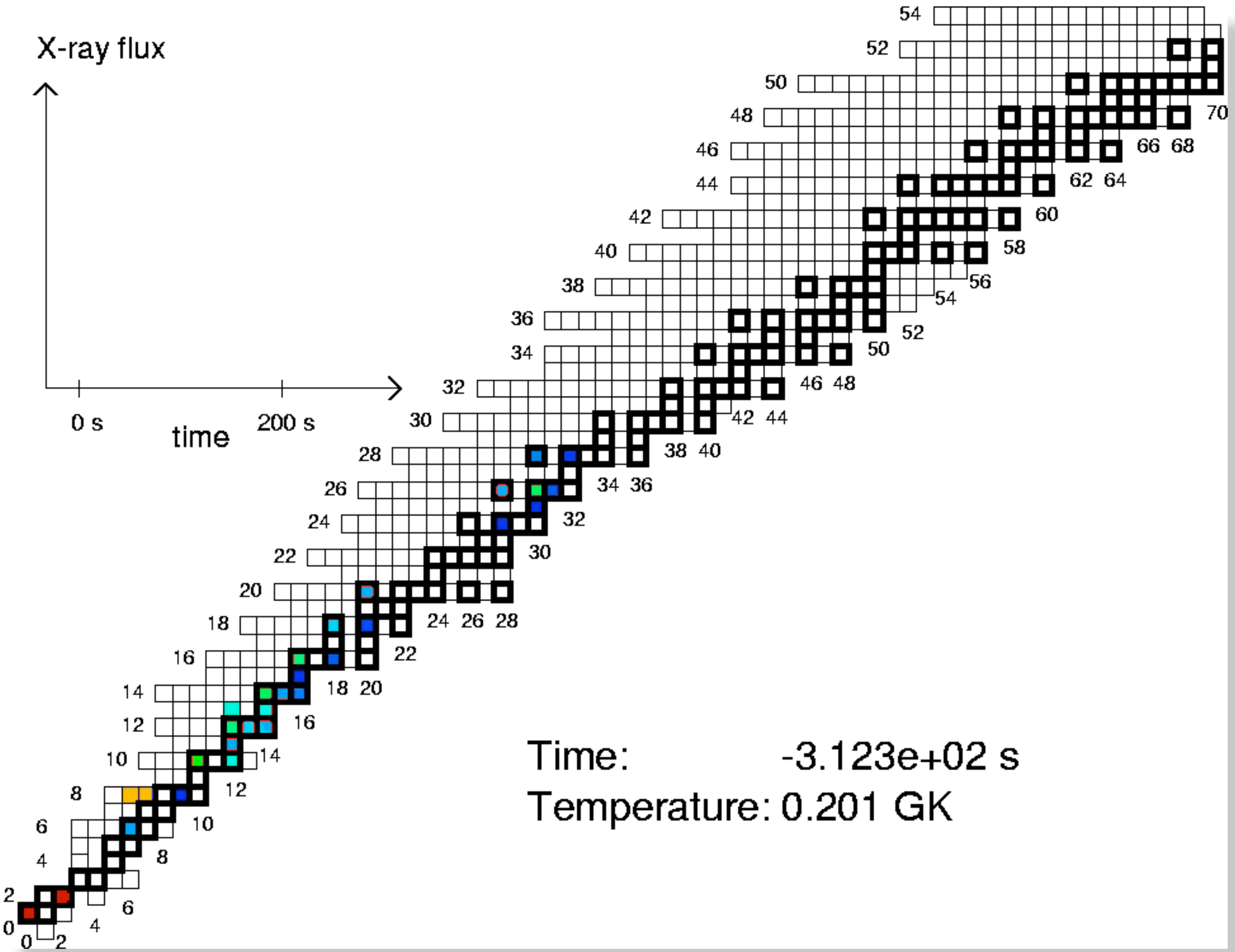
X-ray Bursts: Nuclear Physics and Burst Profiles



- rp-process important when significant hydrogen present. Various reaction rates can dramatically effect light curves.

Nuclear flows during X-ray Bursts: With Hydrogen

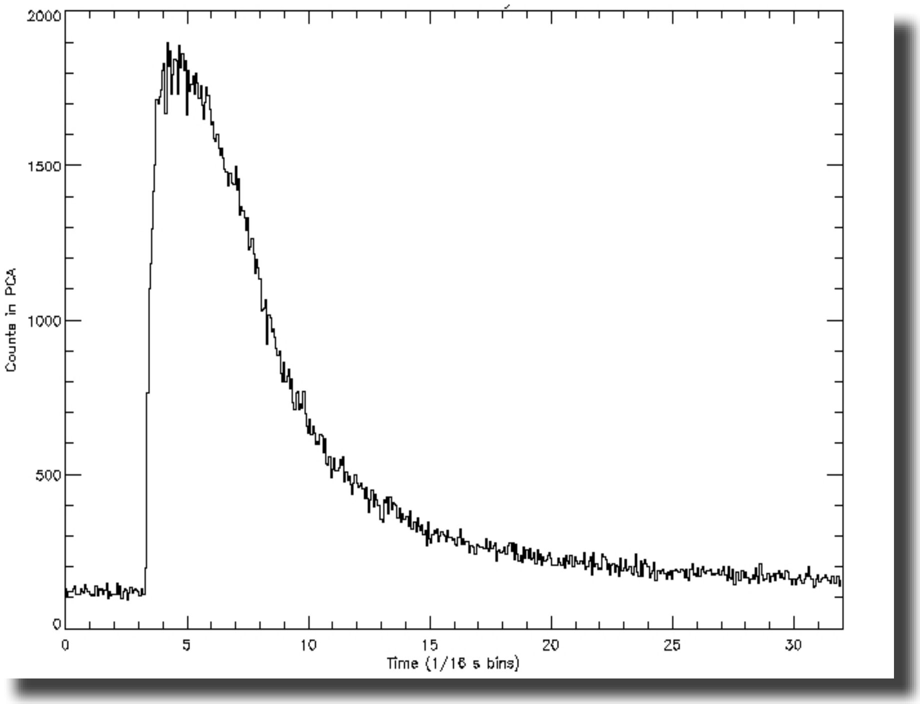
- Composition is important for superbursts.
- With hydrogen around, carbon tends to be destroyed by rp process burning.
- Is enough carbon left over to account for superbursts? Still not clear



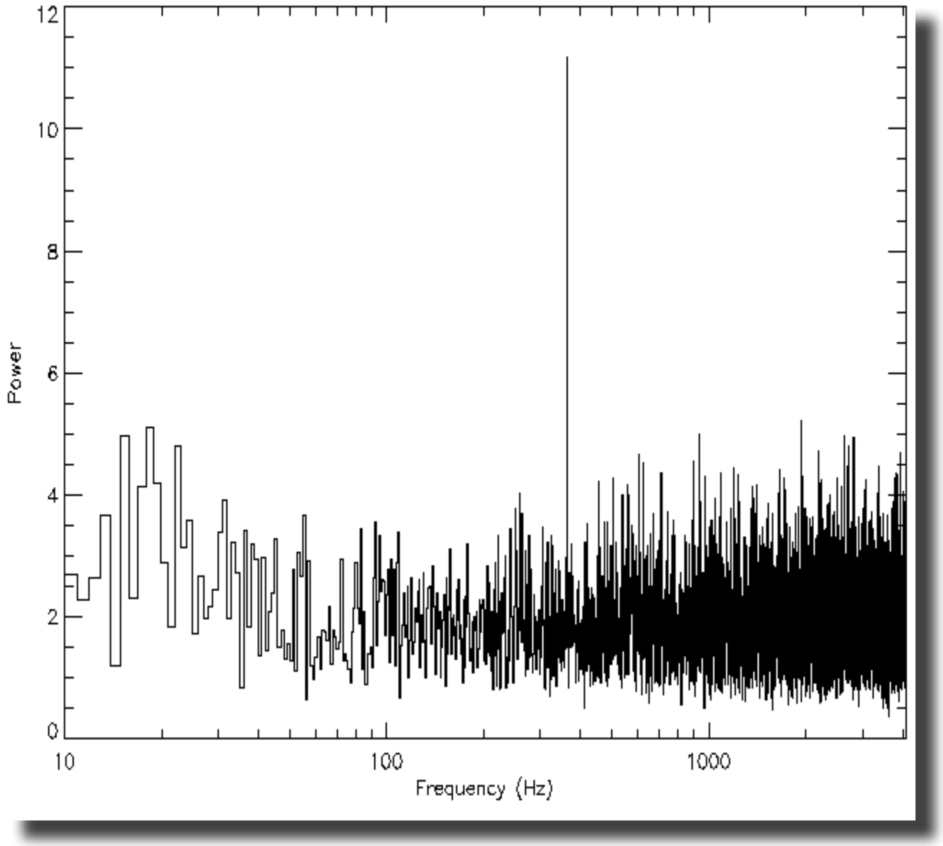
Thanks to Hendrik Schatz (MSU) for the movie

Discovery of 363 Hz Burst Oscillations from 4U 1728-34

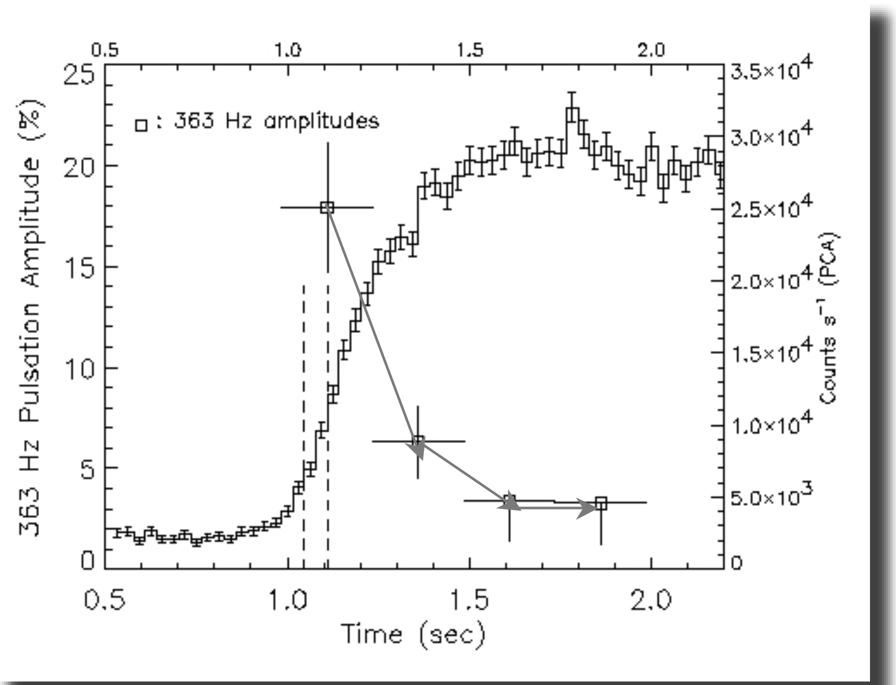
- Discovered in Feb. 1996, shortly after RXTE's launch (Strohmayer et al, 1996)
- First indication of ms spins in accreting LMXBs.

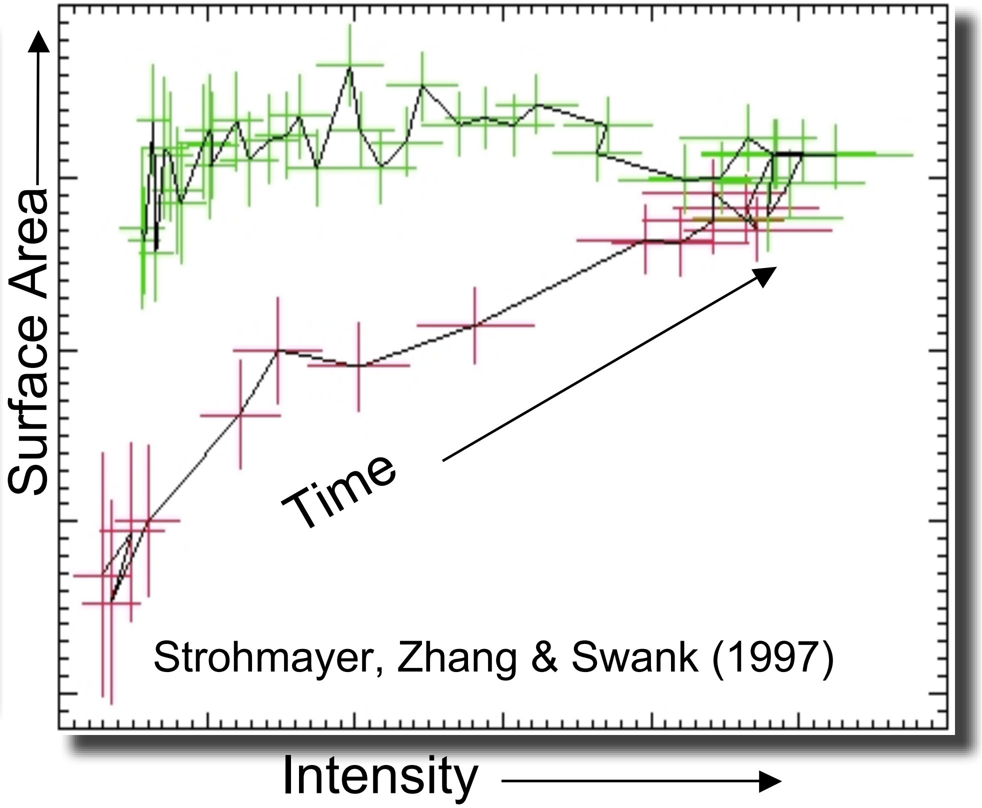


- 4U 1728-34, well known, reliable burster.
- Power spectra of burst time series show significant peak at 363 Hz.

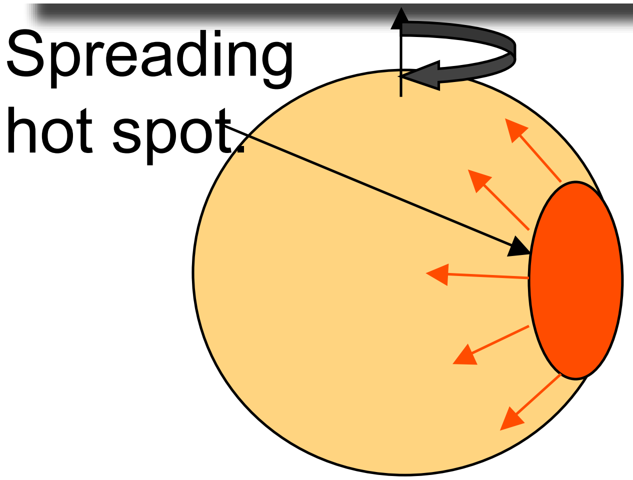


Timing and Spectral Evidence for Rotational Modulation



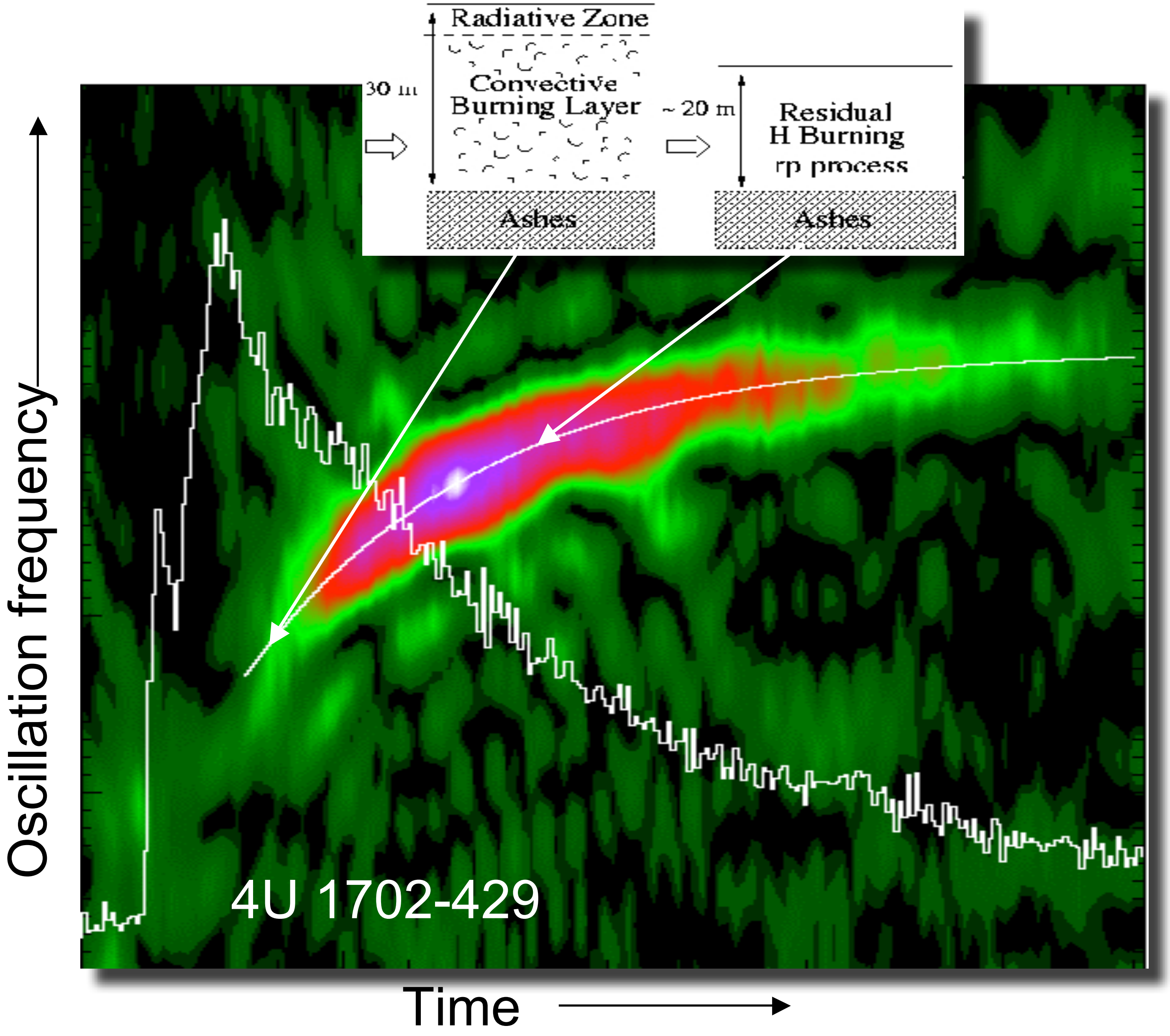


Strohmayer, Zhang & Swank (1997)



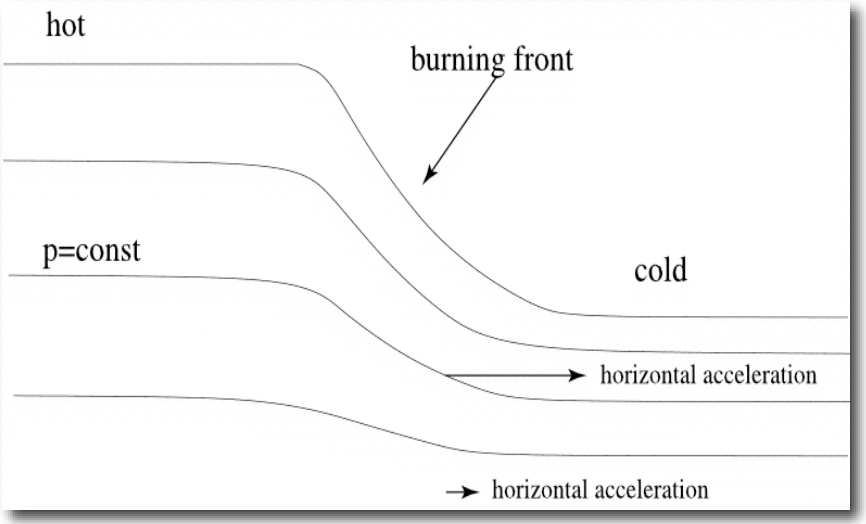
- Oscillations caused by hot spot on rotating neutron star
- Modulation amplitude drops as spot grows.
- Spectra track increasing size of X-ray emitting area on star.

Puzzle # 1: Frequency Evolution of Burst Oscillations



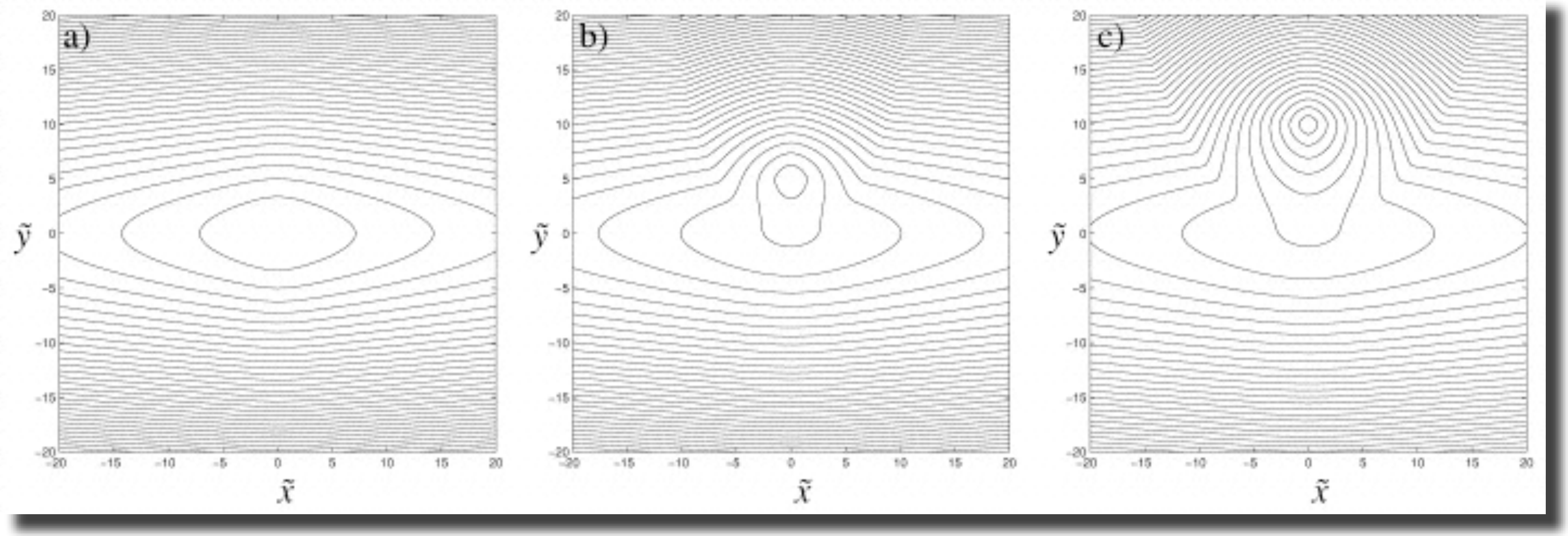
- Expanding layer slows down relative to bulk of the star.
- Change in spin frequency crudely consistent with expected height increase, but perhaps not for most extreme variations.
- X-ray burst expands surface layers by ~ 30 meters.

Extreme Weather on Neutron Stars

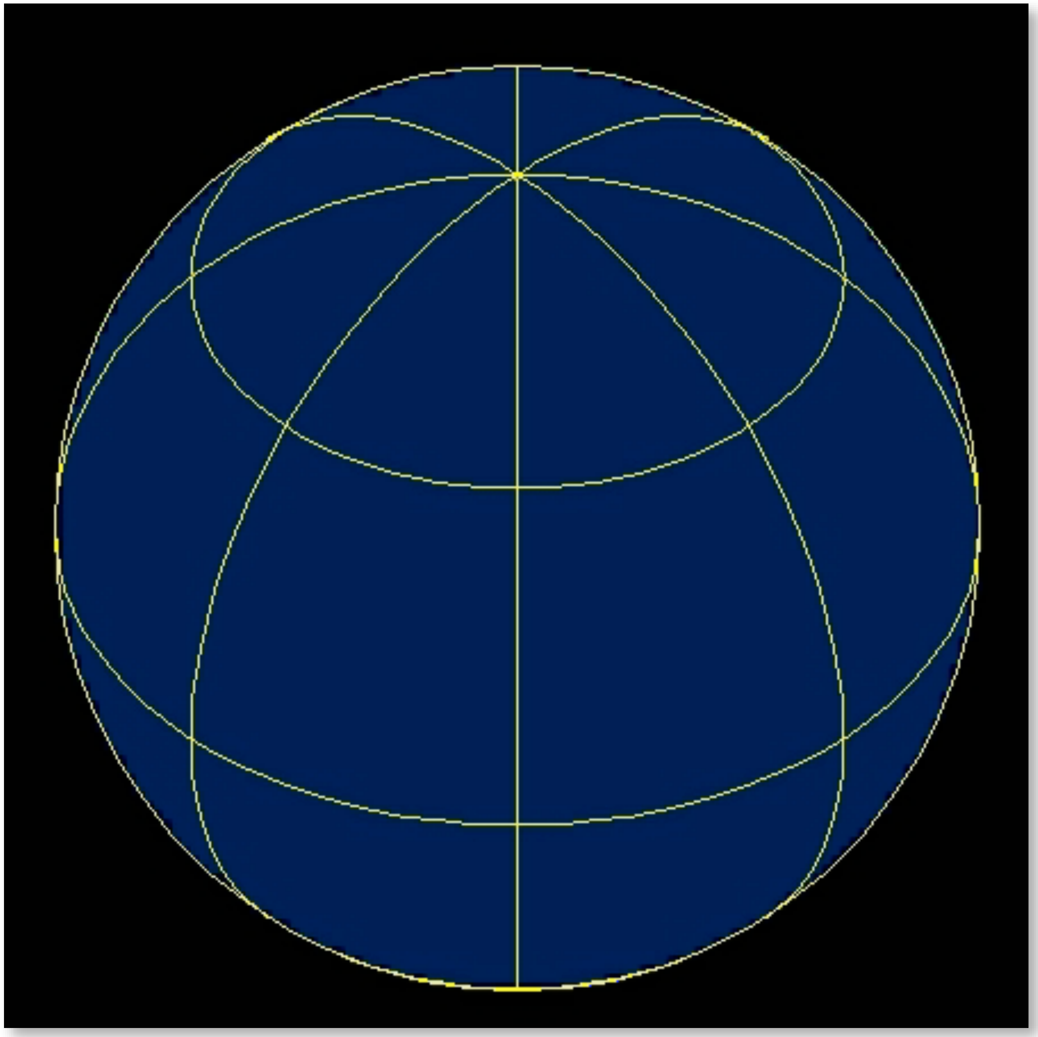


From Spitkovsky, Levin & Ushomirsky (2002)

- 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.



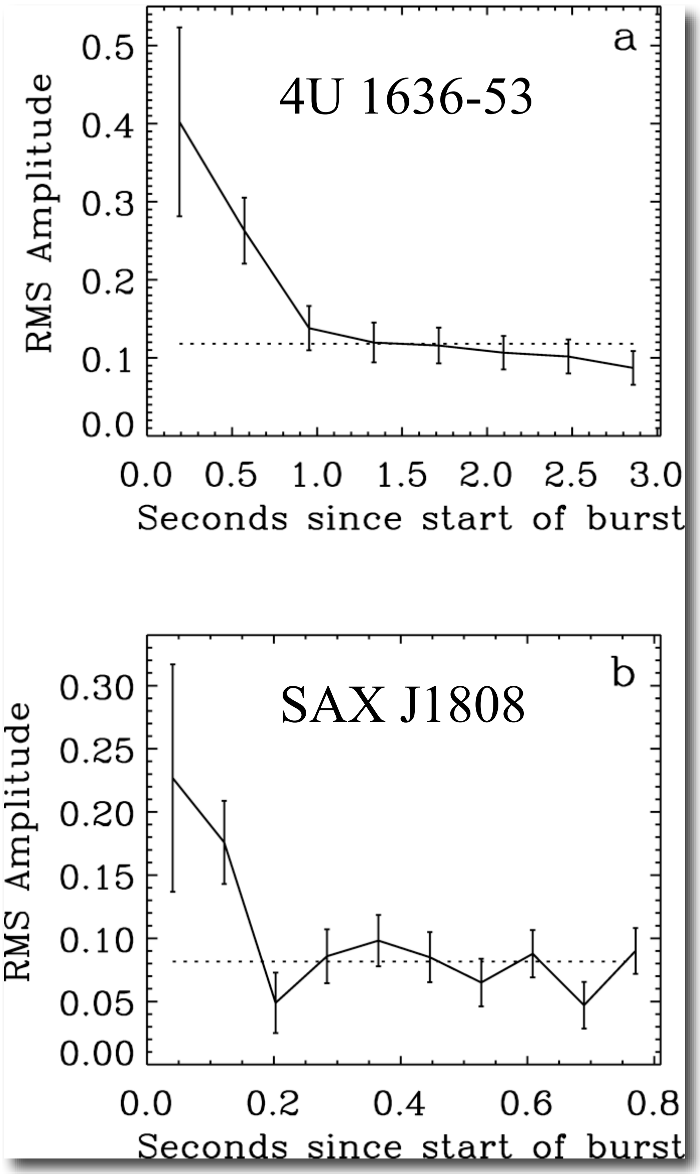
Burst Oscillations: Ignition and Spreading



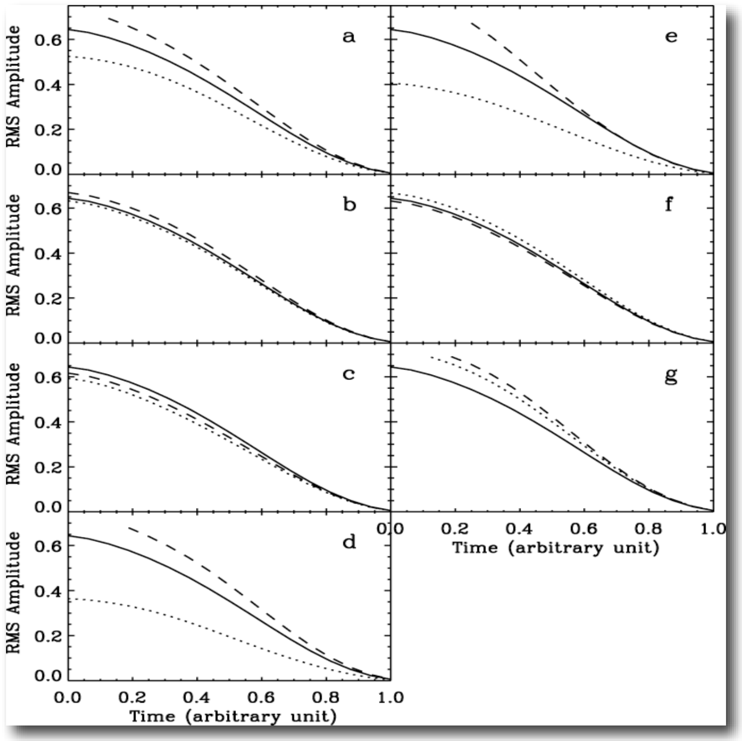
Thanks to Anatoly Spitkovsky!

- 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.

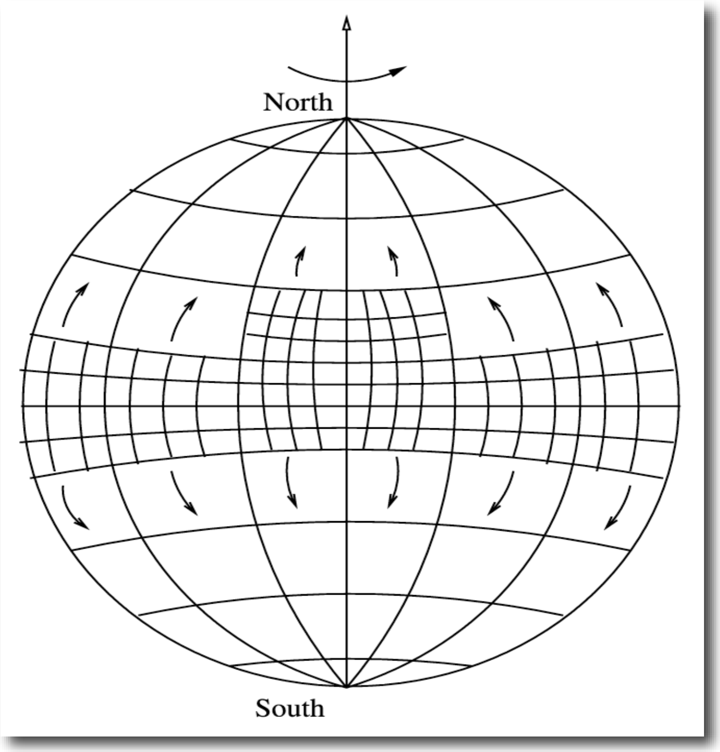
Burst Rise: Amplitude Evolution



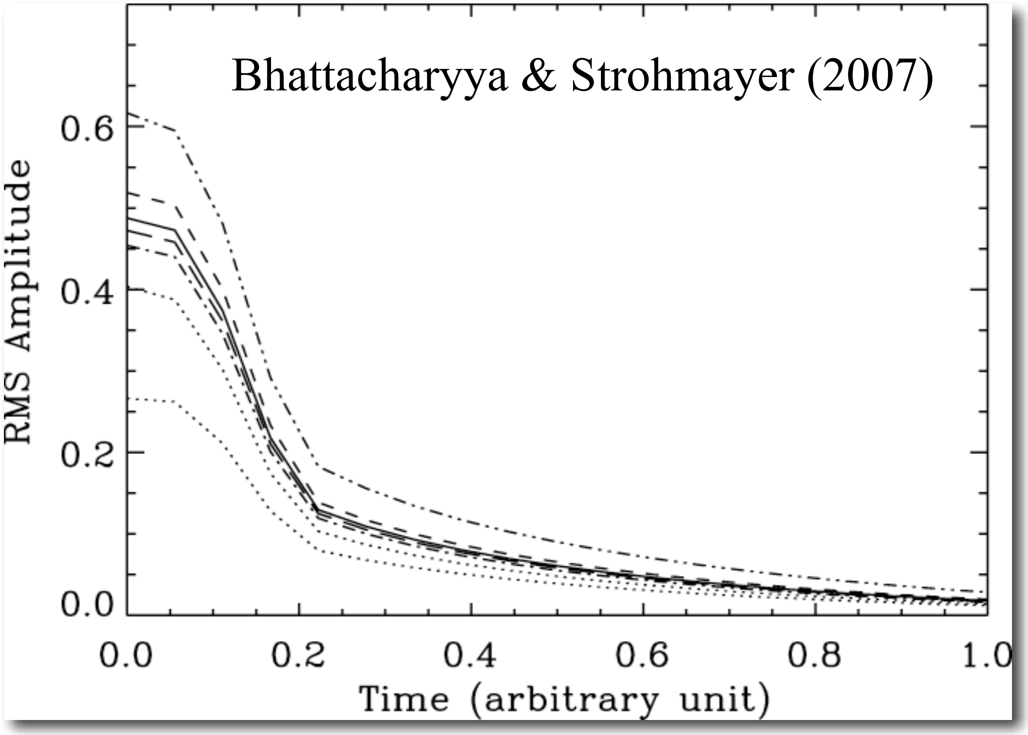
- Amplitude evolution during burst rise, encodes information on nature of flame spreading.
- Some bursts show high initial amplitude, rapid decrease, and then persist at lower amplitude.



Coriolis Force influences spreading speed

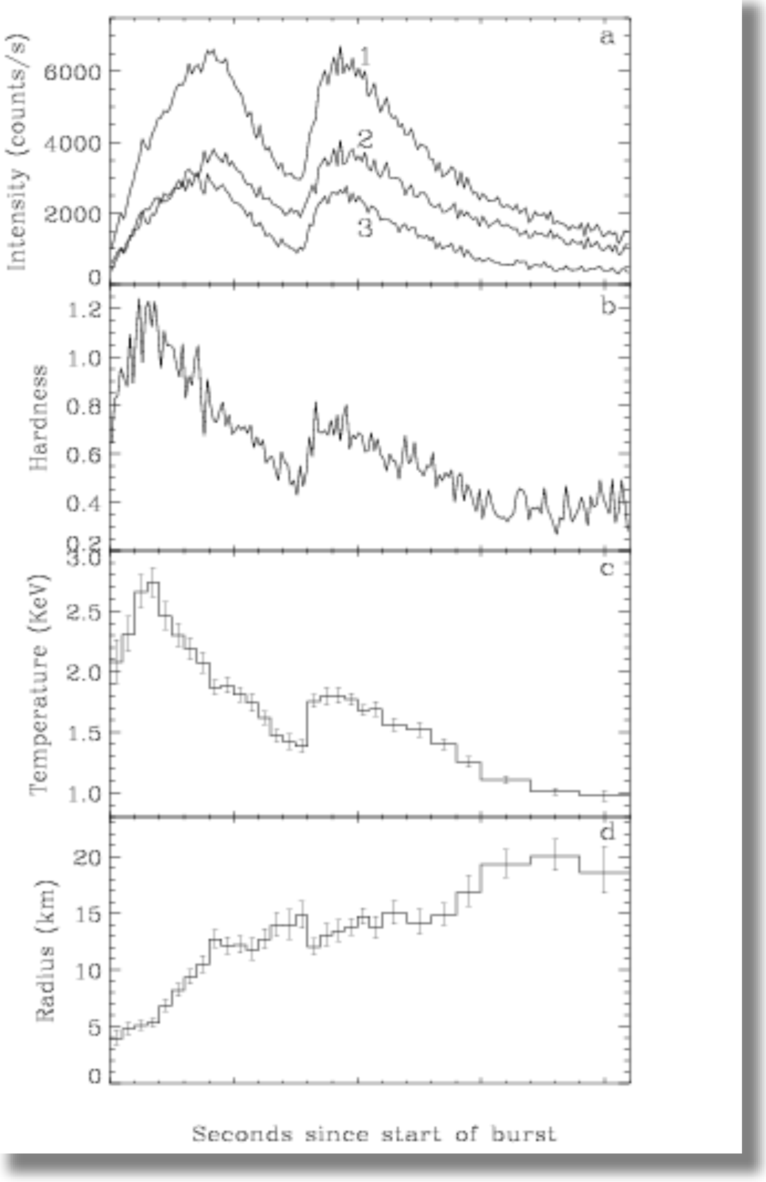


- Spitkovsky, Levin & Ushomirsky (2002) showed Coriolis force relevant to ignition and spreading.
- Flame speed faster at equator, slows with increasing lattitude.



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

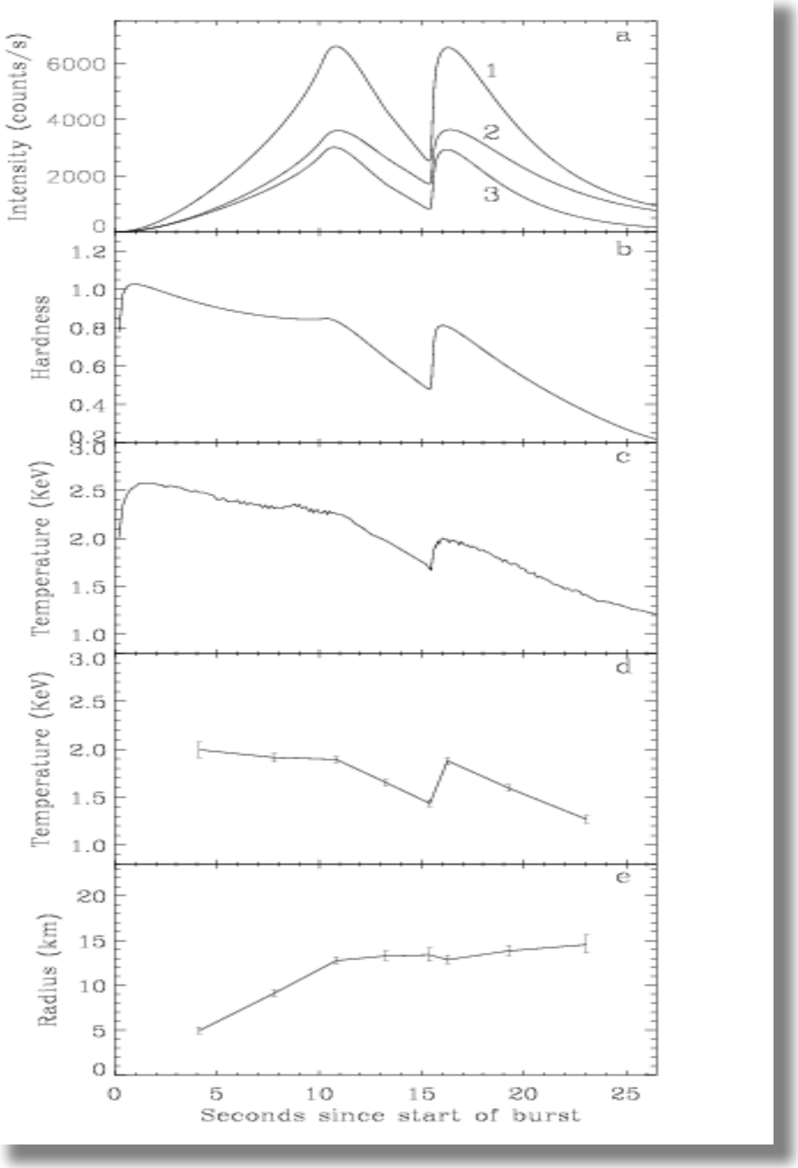
Double-peaked bursts: A Spreading Phenomenon?



- 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)

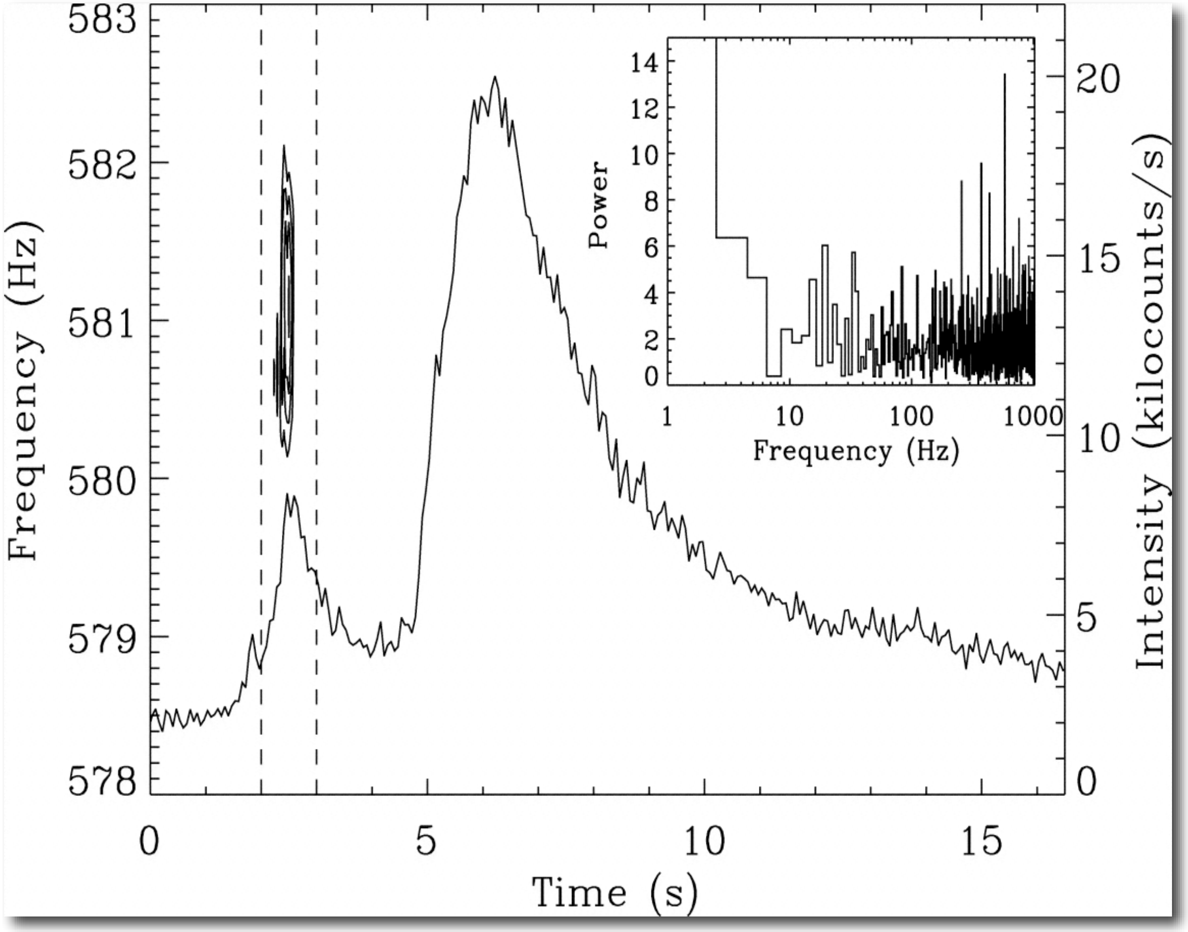
Double-peaked bursts: A Spreading Phenomenon?



- 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)

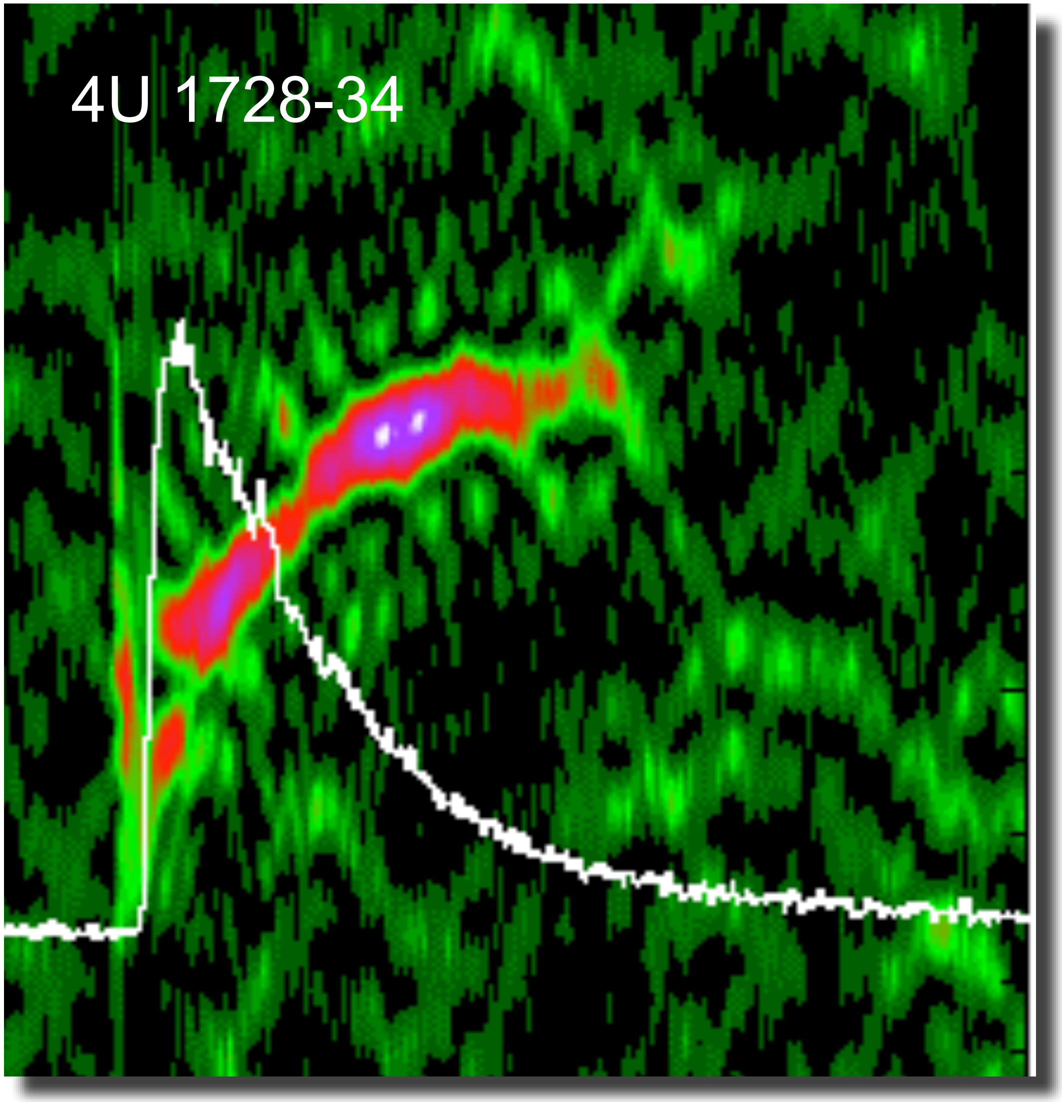
A Double-peaked Burst with Oscillations: Evidence of Stalling?



Bhattacharyya & Strohmayer (2006)

- An unusual double-peaked burst from 4U 1636-53 shows 582 oscillations during the first (weaker) peak.
- A spreading model can account for double peaks, and oscillations, but ignition must be at high latitude (but not the pole).
- Stalling of the front required again. Some indications for this in the behavior of R.

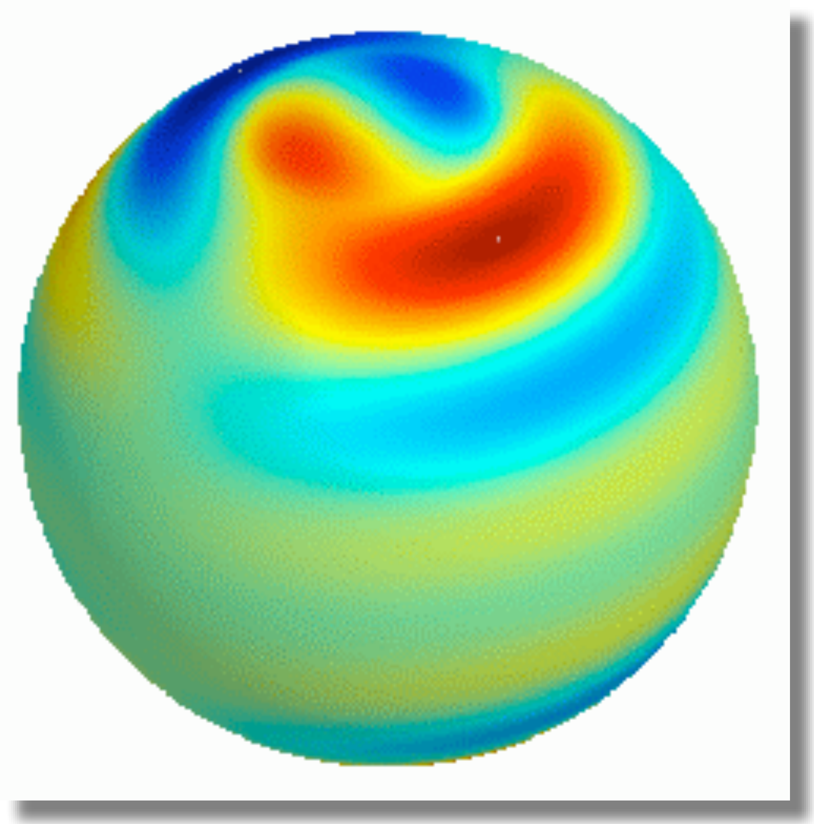
Puzzle: Oscillations in the Cooling Phase



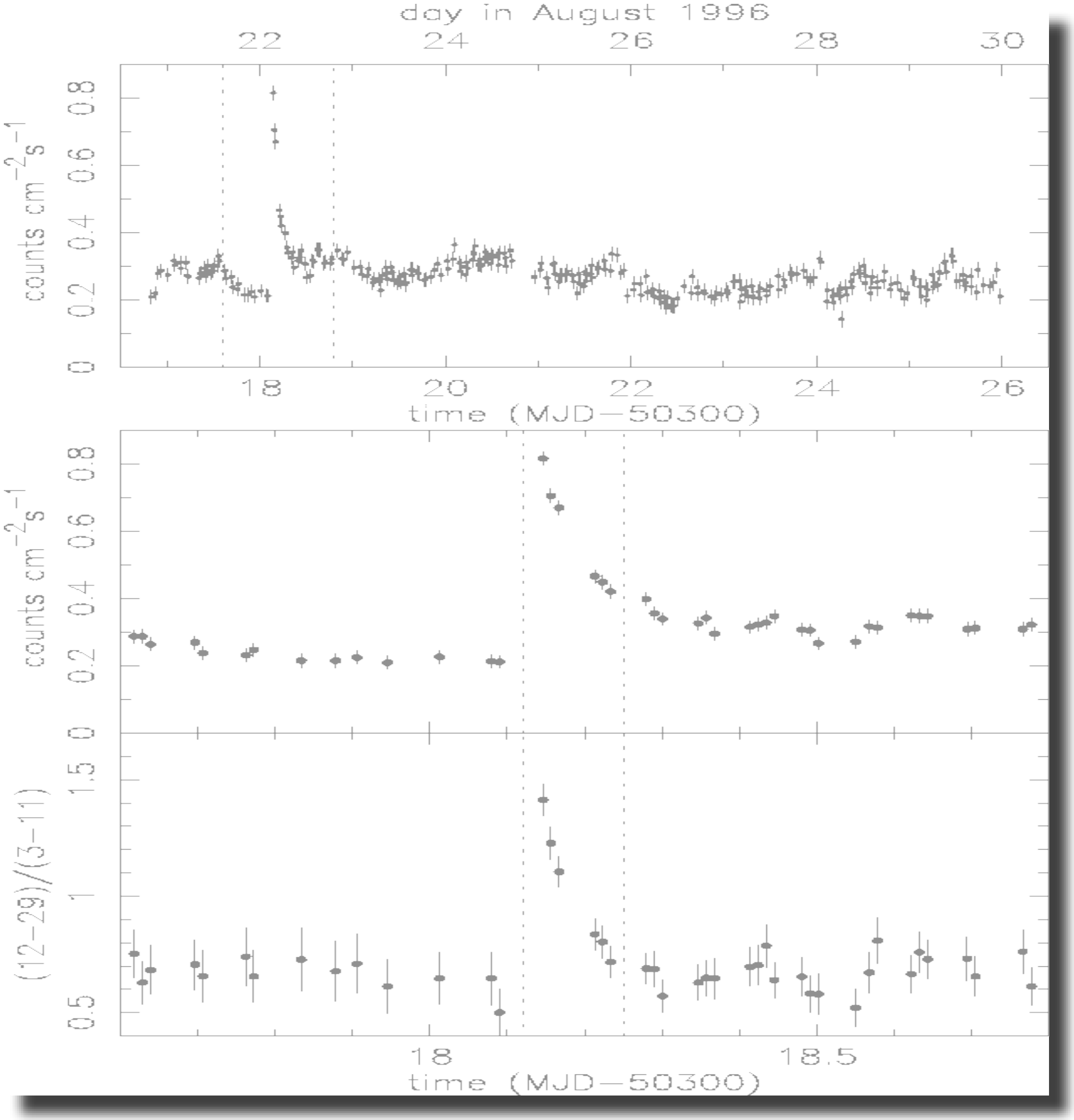
- Pulsations in the cooling tails can be as large as 15% (rms)
- If the whole surface is burned, what causes the flux asymmetry?
- Cooling time asymmetry is probably not large enough
- Oscillation modes (Heyl 2002 suggests *r*-modes; Piro & Bildsten 2005, Lee & Strohmayer 2005, Heyl 2005) ?

What Breaks the Symmetry?

- 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.



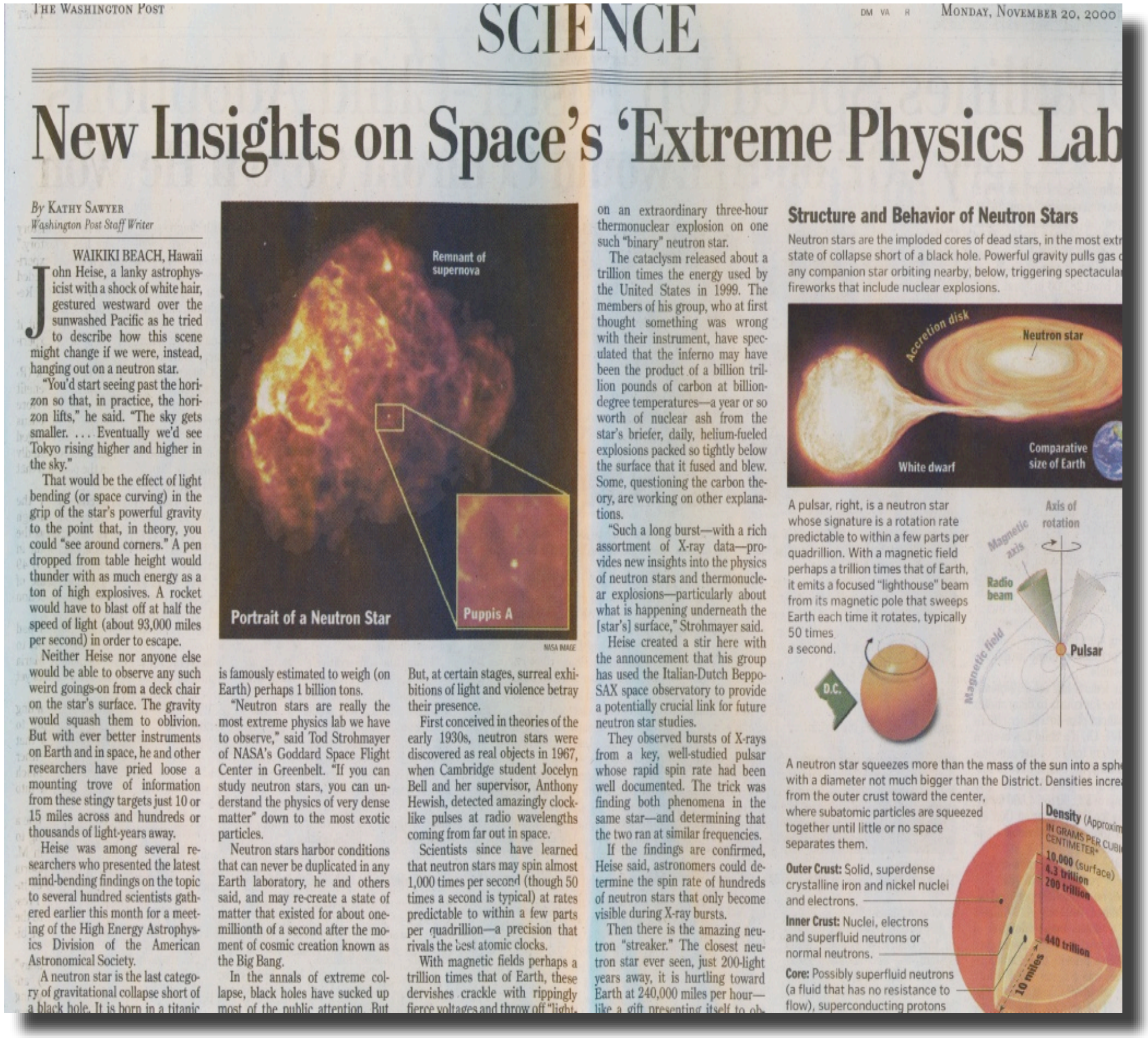
First Superburst from 4U 1735-44 (BeppoSAX/WFC)



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.

RXTE and BeppoSAX Observe “Superbursts” from Accreting Neutron Stars



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DM VA R
MONDAY, NOVEMBER 20, 2000

New Insights on Space’s ‘Extreme Physics Lab

By KATHY SAWYER
Washington Post Staff Writer

WAIKIKI BEACH, Hawaii

John Heise, a lanky astrophysicist with a shock of white hair, gestured westward over the sunwashed Pacific as he tried to describe how this scene might change if we were, instead, hanging out on a neutron star.

“You’d start seeing past the horizon so that, in practice, the horizon lifts,” he said. “The sky gets smaller. . . . Eventually we’d see Tokyo rising higher and higher in the sky.”

That would be the effect of light bending (or space curving) in the grip of the star’s powerful gravity to the point that, in theory, you could “see around corners.” A pen dropped from table height would thunder with as much energy as a ton of high explosives. A rocket would have to blast off at half the speed of light (about 93,000 miles per second) in order to escape.

Neither Heise nor anyone else would be able to observe any such weird goings-on from a deck chair on the star’s surface. The gravity would squash them to oblivion. But with ever better instruments on Earth and in space, he and other researchers have pried loose a mounting trove of information from these stingy targets just 10 or 15 miles across and hundreds or thousands of light-years away.

Heise was among several researchers who presented the latest mind-bending findings on the topic to several hundred scientists gathered earlier this month for a meeting of the High Energy Astrophysics Division of the American Astronomical Society.

A neutron star is the last category of gravitational collapse short of a black hole. It is born in a titanic

NASA IMAGE

is famously estimated to weigh (on Earth) perhaps 1 billion tons.

“Neutron stars are really the most extreme physics lab we have to observe,” said Tod Strohmayer of NASA’s Goddard Space Flight Center in Greenbelt. “If you can study neutron stars, you can understand the physics of very dense matter” down to the most exotic particles.

Neutron stars harbor conditions that can never be duplicated in any Earth laboratory, he and others said, and may re-create a state of matter that existed for about one-millionth of a second after the moment of cosmic creation known as the Big Bang.

In the annals of extreme collapse, black holes have sucked up most of the public attention. But

But, at certain stages, surreal exhibitions of light and violence betray their presence.

First conceived in theories of the early 1930s, neutron stars were discovered as real objects in 1967, when Cambridge student Jocelyn Bell and her supervisor, Anthony Hewish, detected amazingly clock-like pulses at radio wavelengths coming from far out in space.

Scientists since have learned that neutron stars may spin almost 1,000 times per second (though 50 times a second is typical) at rates predictable to within a few parts per quadrillion—a precision that rivals the best atomic clocks.

With magnetic fields perhaps a trillion times that of Earth, these dervishes crackle with rippingly fierce voltages and throw off “light-

on an extraordinary three-hour thermonuclear explosion on one such “binary” neutron star.

The cataclysm released about a trillion times the energy used by the United States in 1999. The members of his group, who at first thought something was wrong with their instrument, have speculated that the inferno may have been the product of a billion trillion pounds of carbon at billion-degree temperatures—a year or so worth of nuclear ash from the star’s briefer, daily, helium-fueled explosions packed so tightly below the surface that it fused and blew. Some, questioning the carbon theory, are working on other explanations.

“Such a long burst—with a rich assortment of X-ray data—provides new insights into the physics of neutron stars and thermonuclear explosions—particularly about what is happening underneath the [star’s] surface,” Strohmayer said.

Heise created a stir here with the announcement that his group has used the Italian-Dutch BeppoSAX space observatory to provide a potentially crucial link for future neutron star studies.

They observed bursts of X-rays from a key, well-studied pulsar whose rapid spin rate had been well documented. The trick was finding both phenomena in the same star—and determining that the two ran at similar frequencies.

If the findings are confirmed, Heise said, astronomers could determine the spin rate of hundreds of neutron stars that only become visible during X-ray bursts.

Then there is the amazing neutron “streaker.” The closest neutron star ever seen, just 200-light years away, it is hurtling toward Earth at 240,000 miles per hour—like a gift presenting itself to ob-

Structure and Behavior of Neutron Stars

Neutron stars are the imploded cores of dead stars, in the most extr
state of collapse short of a black hole. Powerful gravity pulls gas o
any companion star orbiting nearby, below, triggering spectacular
fireworks that include nuclear explosions.

A pulsar, right, is a neutron star whose signature is a rotation rate predictable to within a few parts per quadrillion. With a magnetic field perhaps a trillion times that of Earth, it emits a focused “lighthouse” beam from its magnetic pole that sweeps Earth each time it rotates, typically 50 times a second.

A neutron star squeezes more than the mass of the sun into a sph
with a diameter not much bigger than the District. Densities incre
from the outer crust toward the center,
where subatomic particles are squeezed
together until little or no space
separates them.

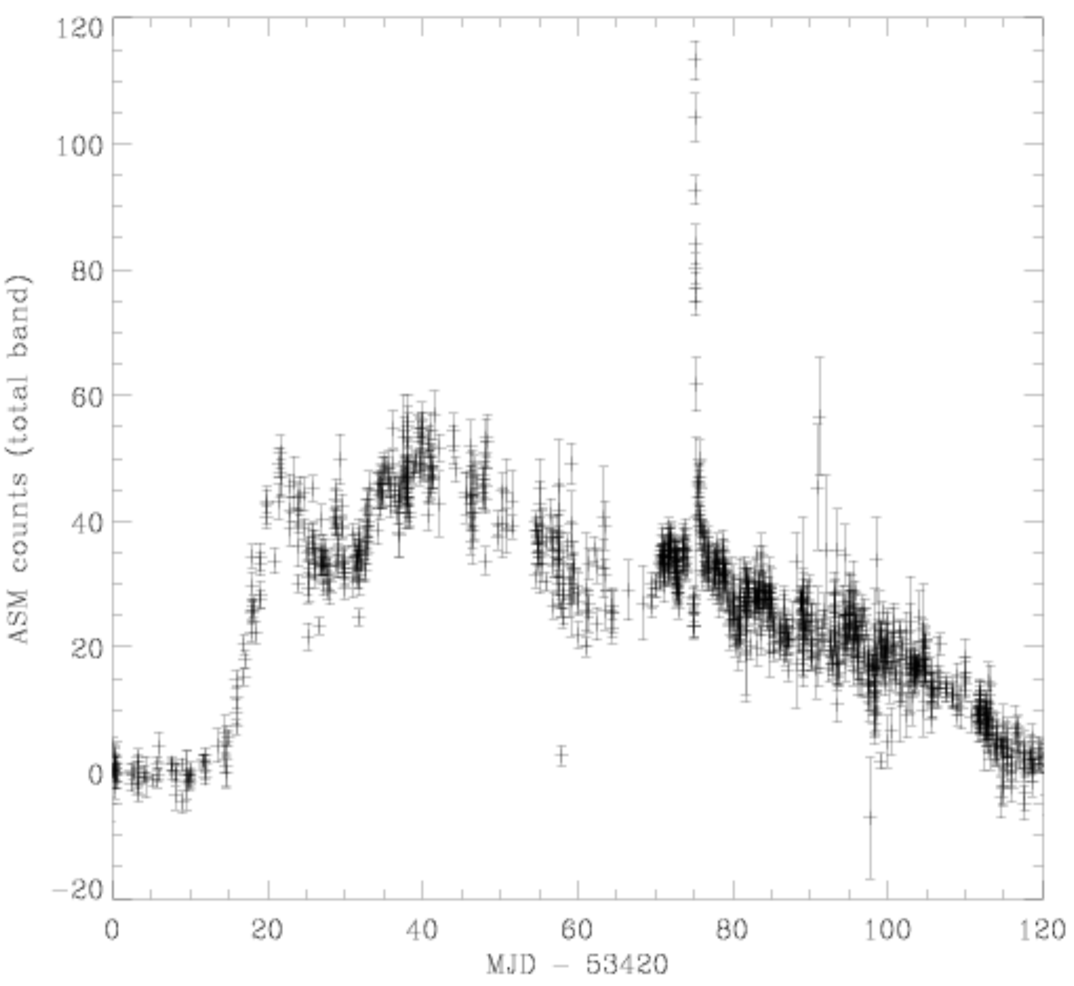
Outer Crust: Solid, superdense crystalline iron and nickel nuclei and electrons.

Inner Crust: Nuclei, electrons and superfluid neutrons or normal neutrons.

Core: Possibly superfluid neutrons (a fluid that has no resistance to flow), superconducting protons

- Long, 3-5 hr. X-ray bursts observed from 5 accreting neutron star binaries (Heise et al. 2000; Strohmayer 2000; Wijnands 2001).
- Bursts reveal new regime of nuclear burning. 1,000 times more energy release than normal bursts.
- Stories made headlines in national papers, Washington Post, NY Times.

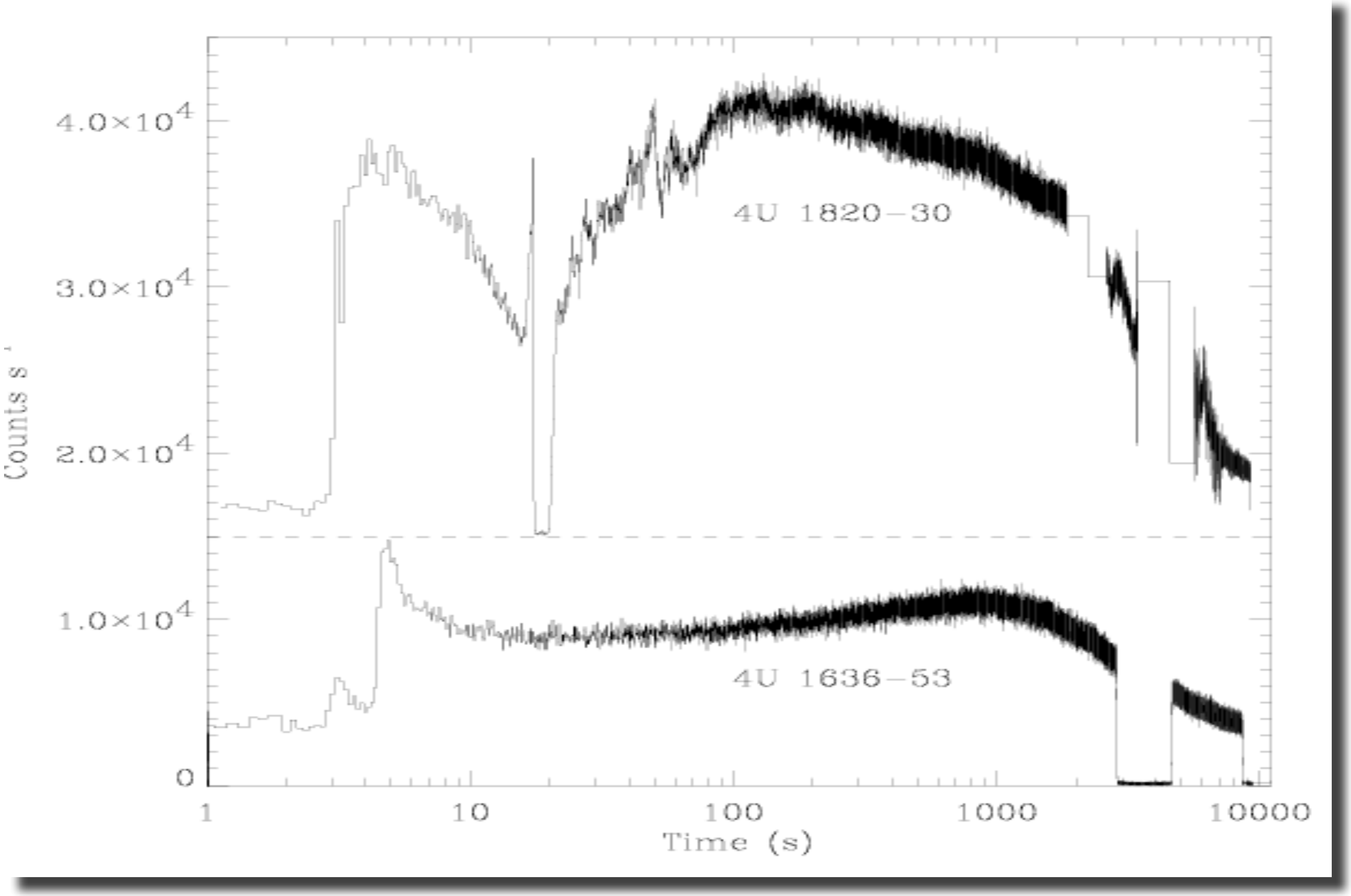
New Superburst from 4U 1608-522 (RXTE/ASM)



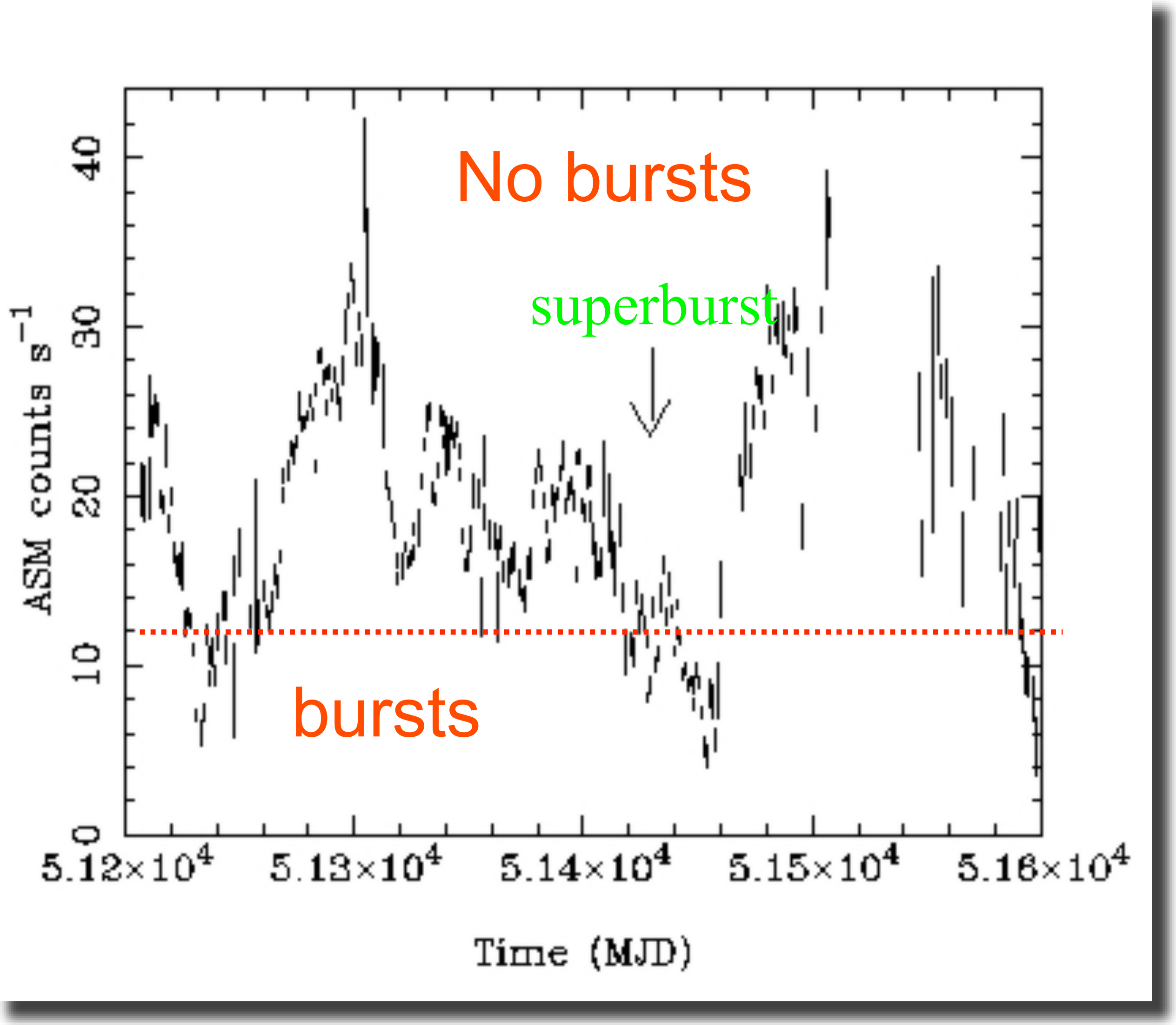
Levine et al. (2005)

- 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!

Superbursts observed with RXTE/PCA



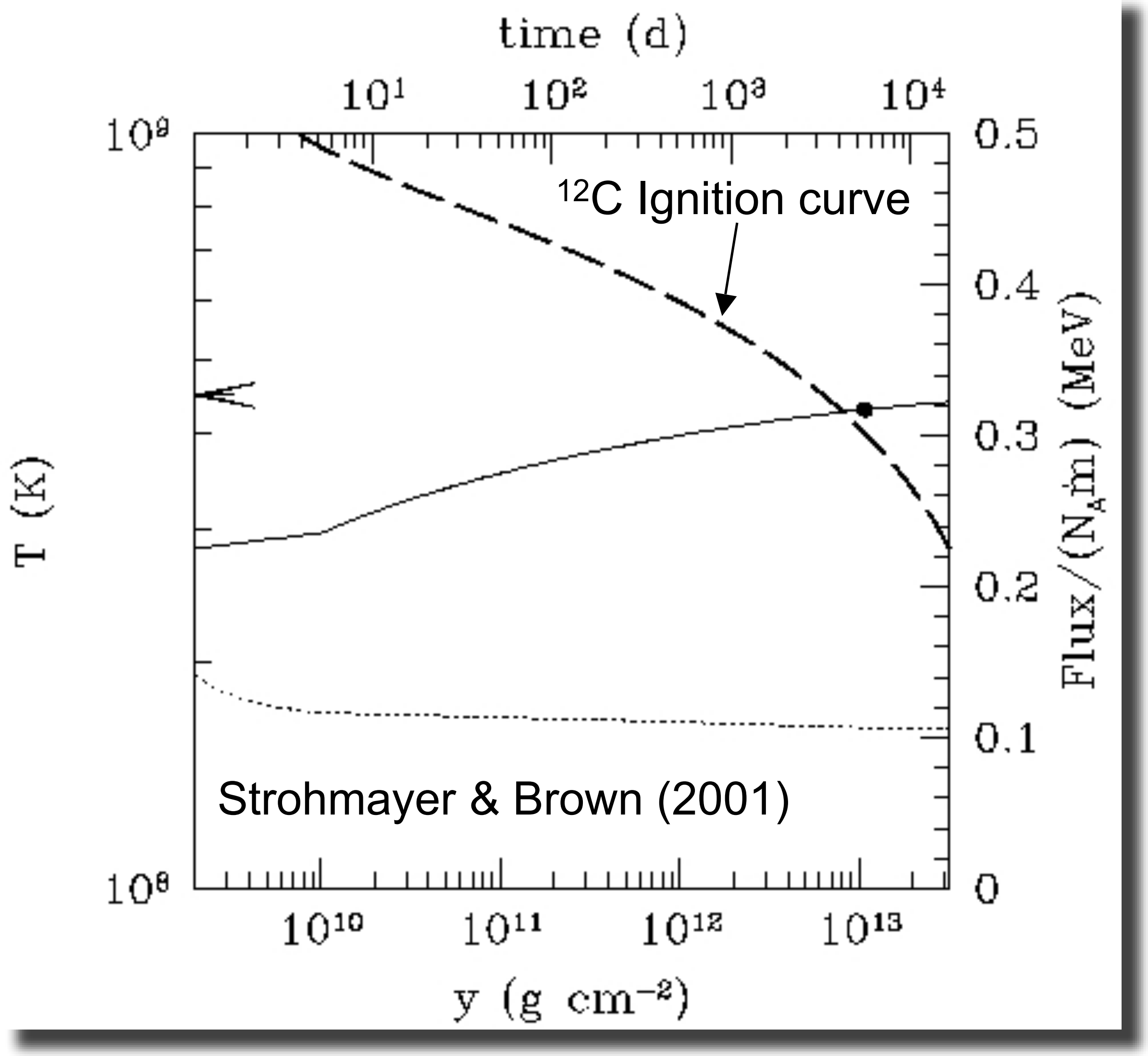
Superburst from 4U 1820-30: Carbon Production



Strohmayer & Brown (2002)

- 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

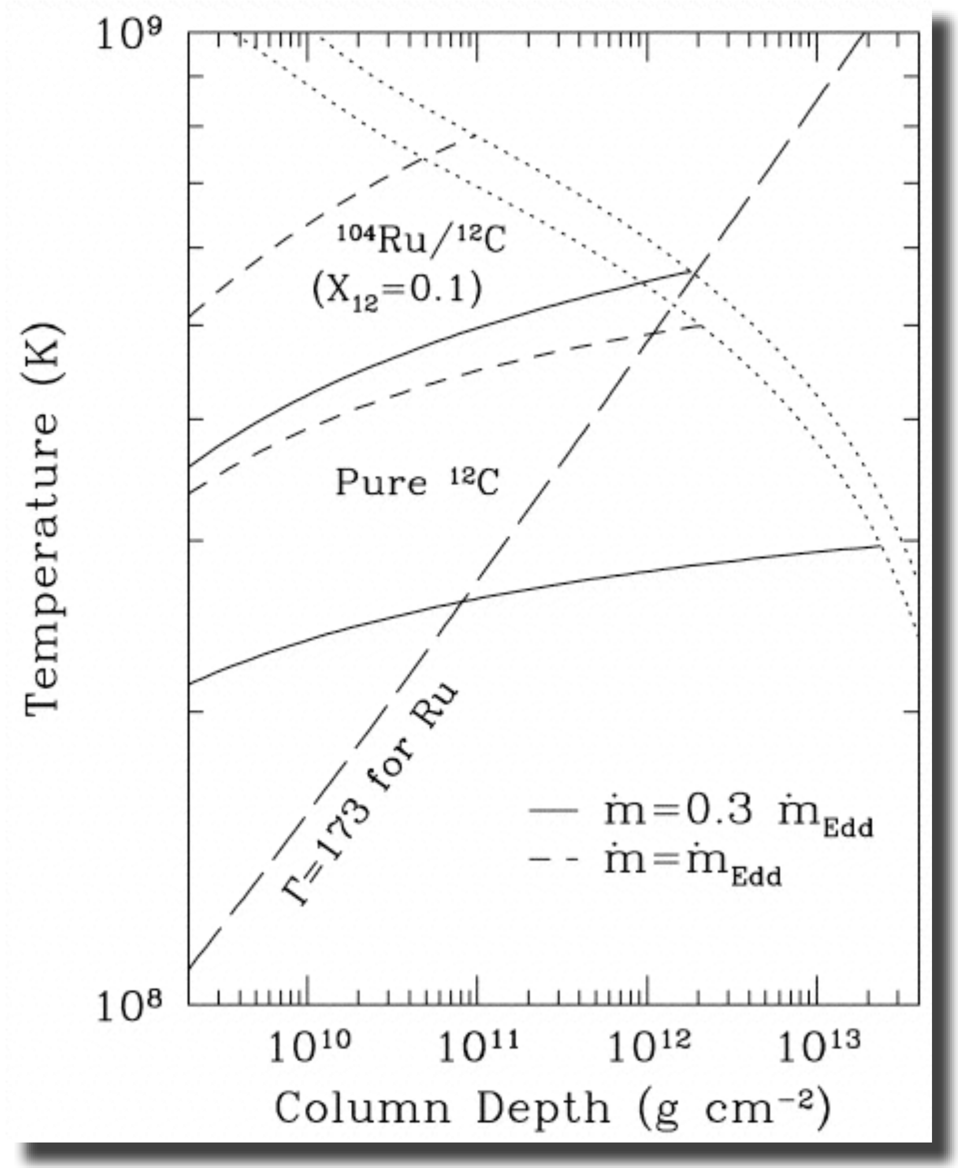
A Carbon "bomb" on a Neutron Star

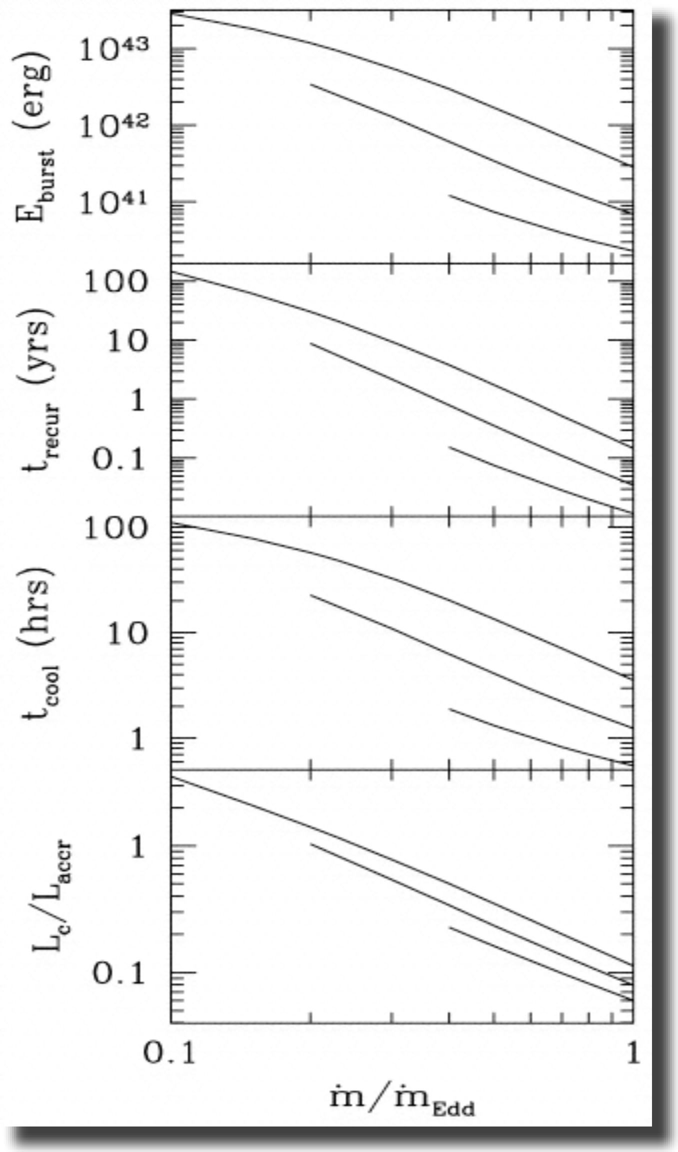


Strohmayer & Brown (2001)

- 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.

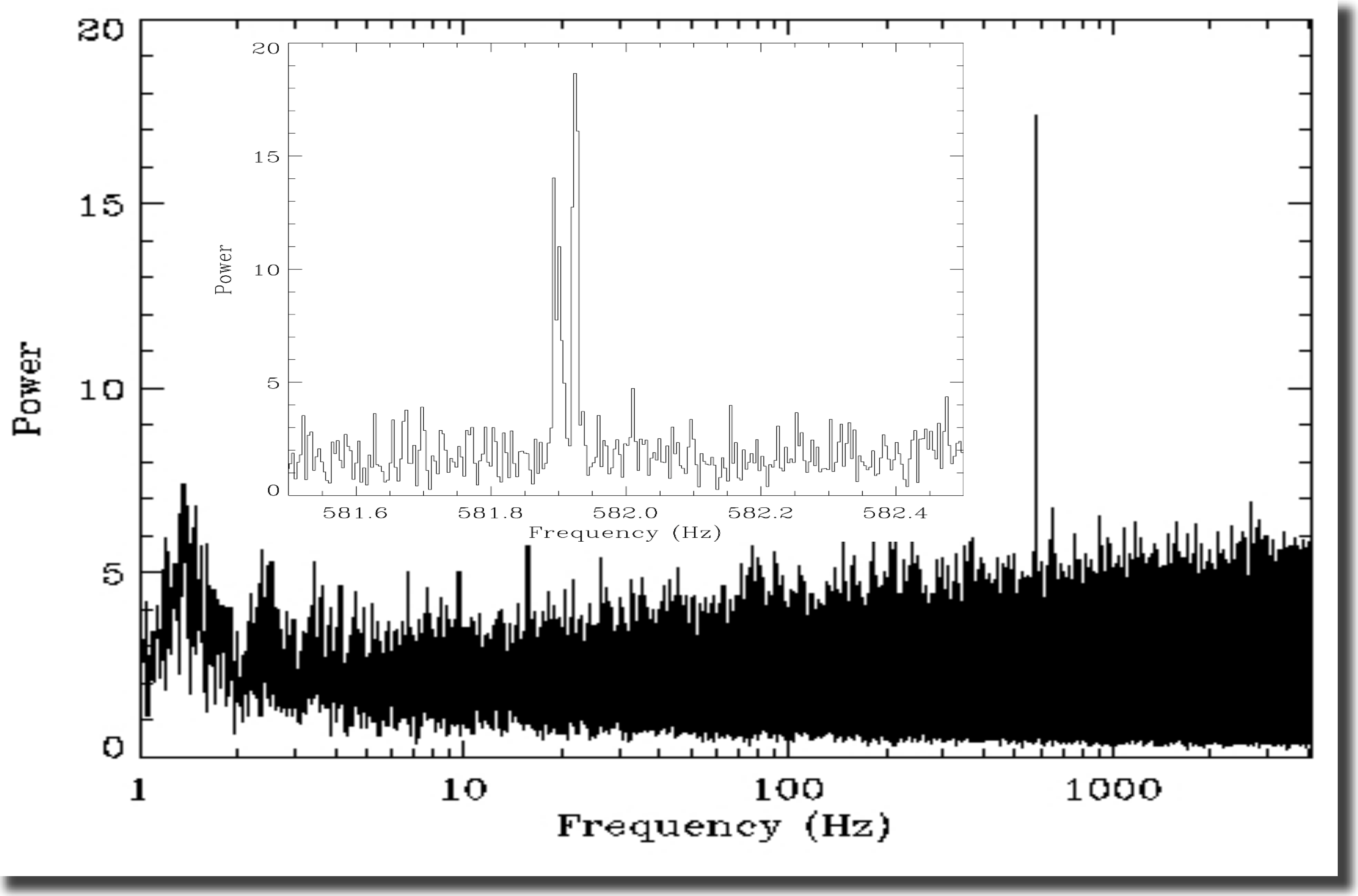
Carbon Flashes on Neutron Stars: Mixed H-He Accretors



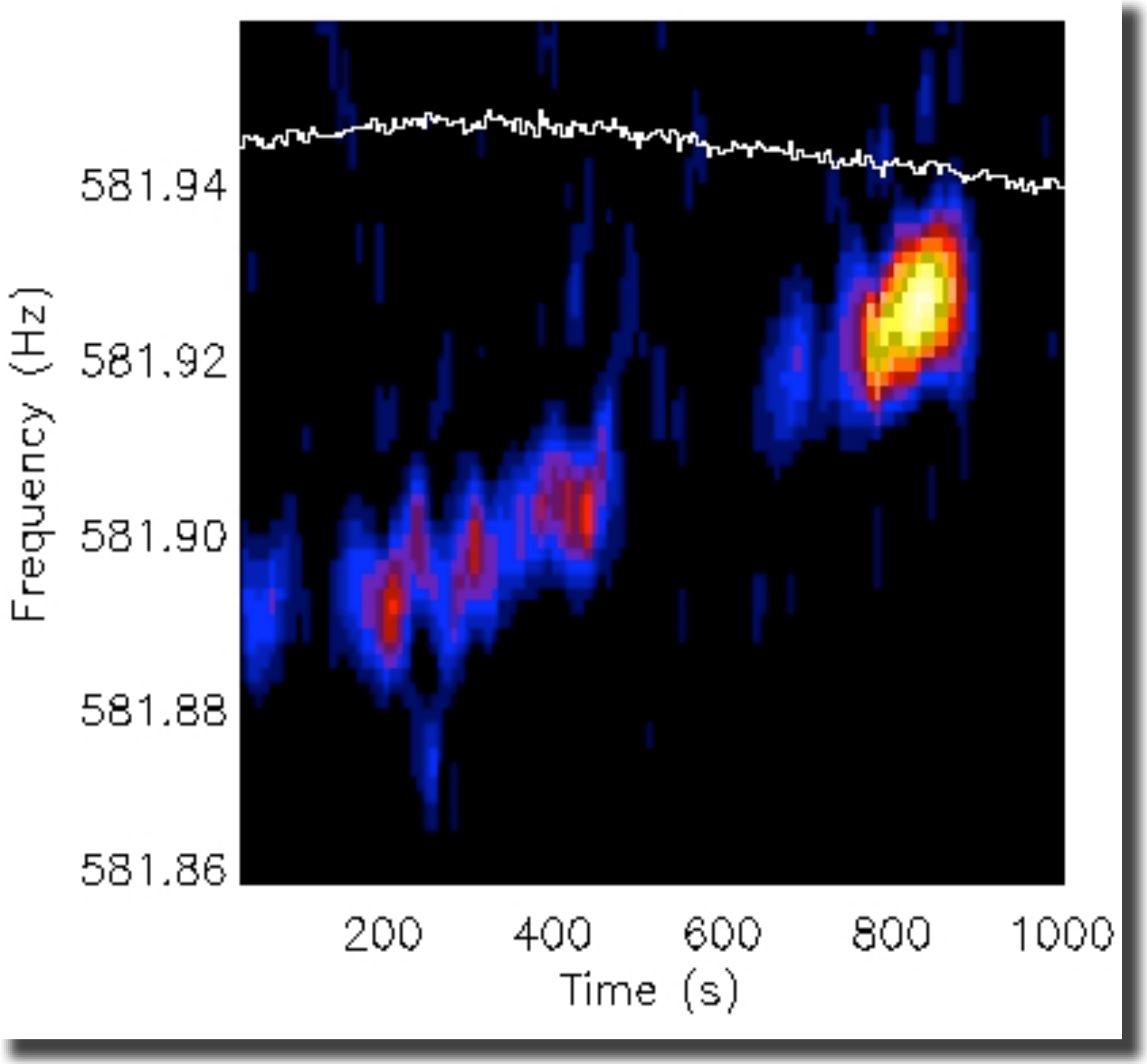


Cumming & Bildsten 2001

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.