X-ray Bursts and Neutron Star Crusts

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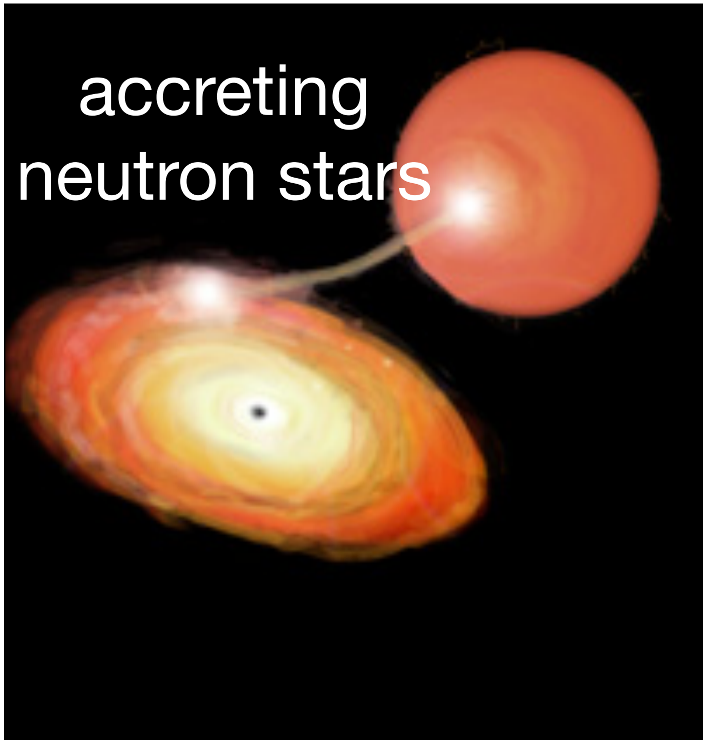
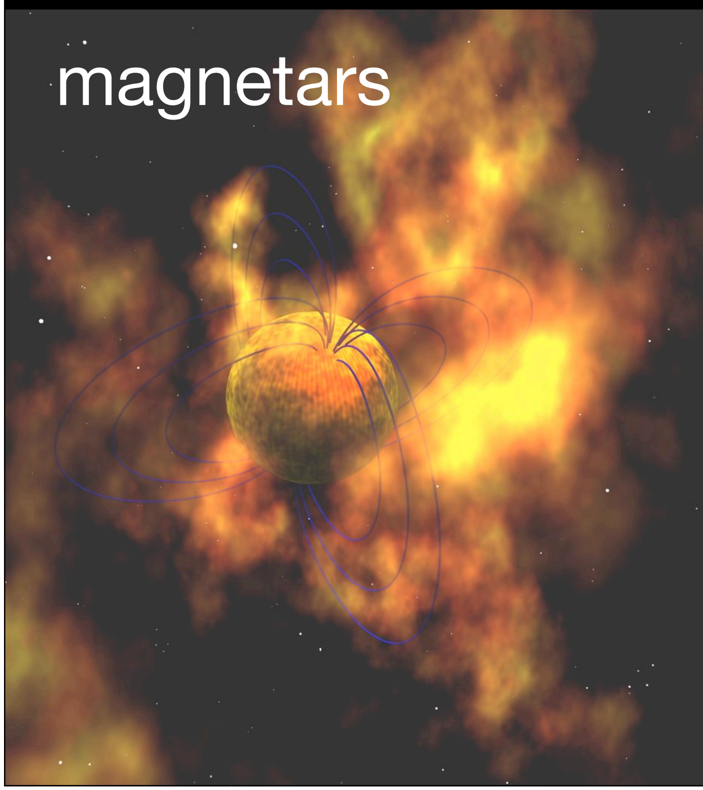
Nuclear Astrophysics Town Hall Meeting
Detroit 9-10 October 2012





Three reasons to be interested from a nuclear astrophysics perspective

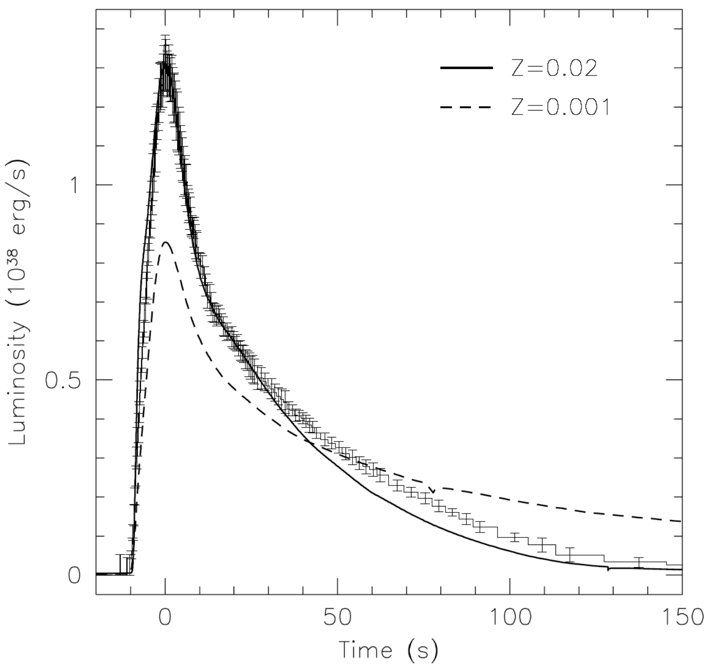
1. from the surface to the inner crust, matter explores the full range of proton-rich to neutron-rich nuclei

2. bright transient events: opportunity to study the neutron star and probe dense matter, e.g. radius measurement

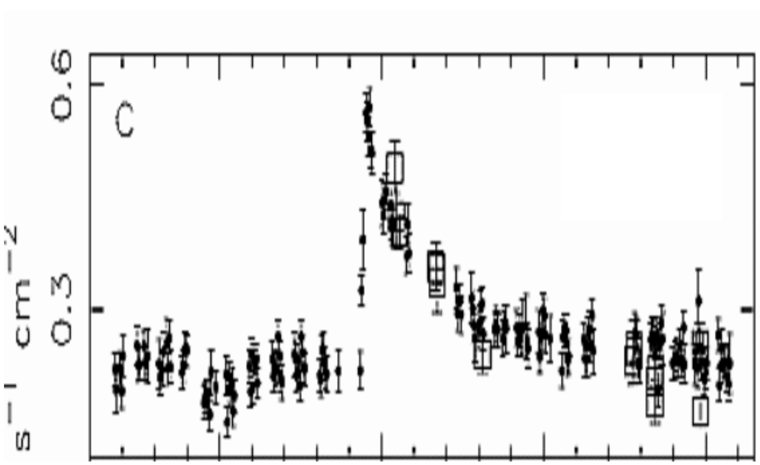
3. fast evolution times: study time evolution of thin shell flashes and other stellar processes on observable timescales

Observational signatures of nuclear burning (10 yrs ago)

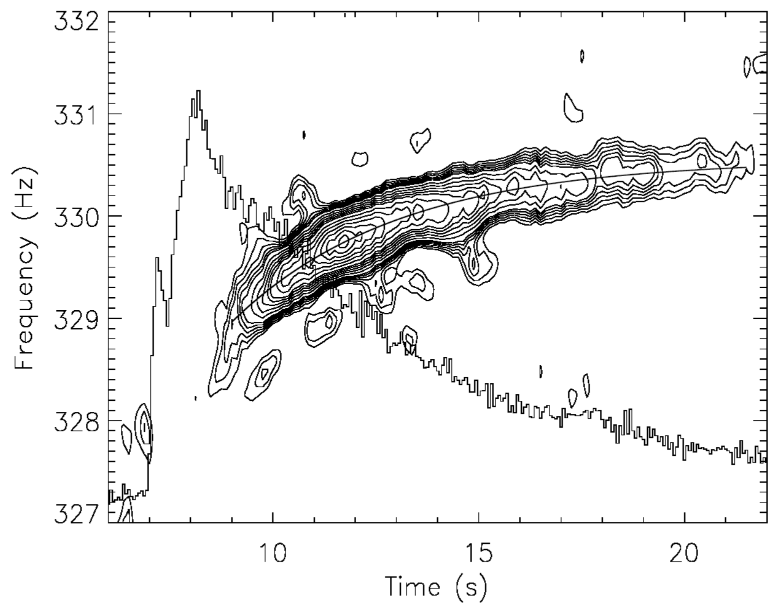
- Type I X-ray bursts
- Superbursts
- Burst oscillations



Heger et al. (2007)



Kuulkers et al. (2002)



Strohmayer & Markwardt (1999)

Recent advances (last ~5 years)

New observational windows

p-rich side

- Type I X-ray bursts
- Superbursts
- Burst oscillations
- mHz QPOs (oscillatory burning mode)
- long helium flashes
- rare events and objects
- large observational catalog of bursts
- evidence for ejected shell in PRE bursts

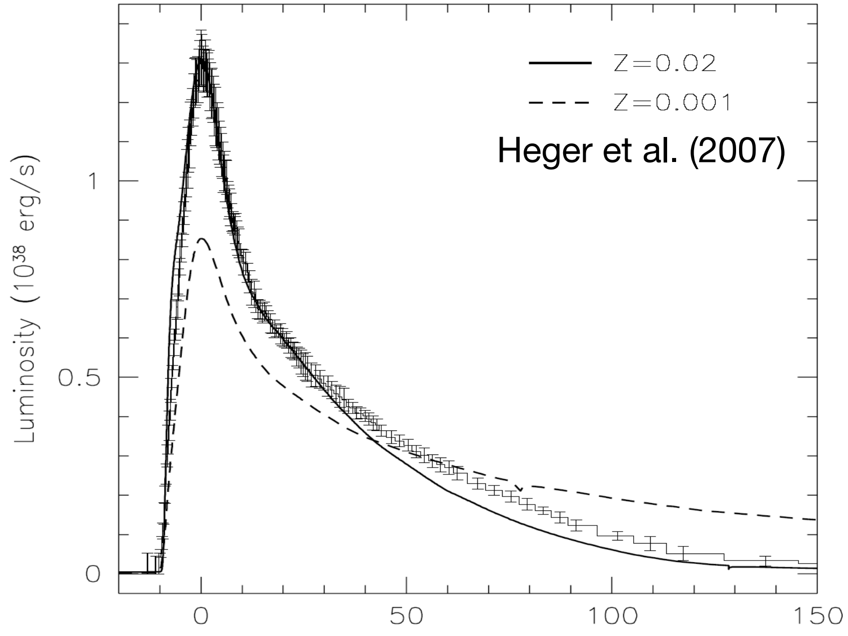
n-rich side

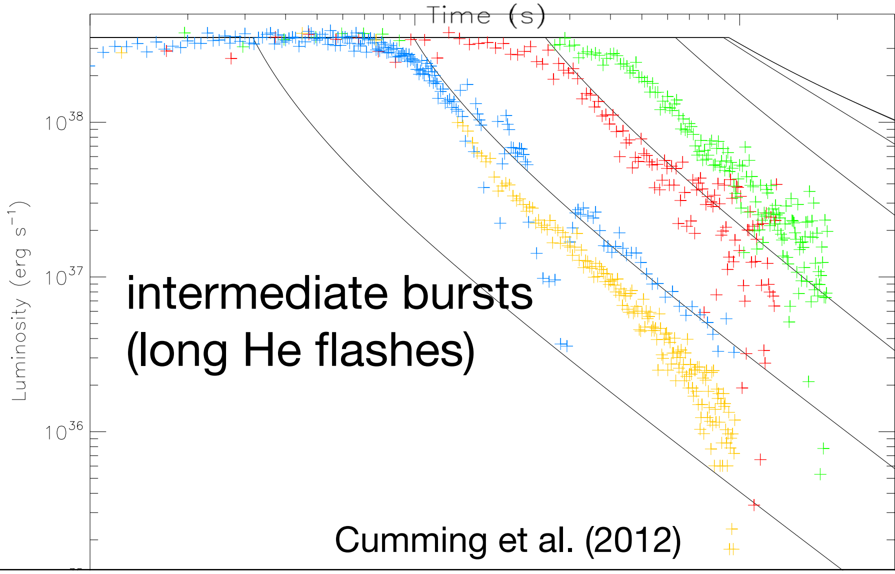
- thermal tomography of neutron star crusts (crust relaxation in accreting transients and magnetars)
- mechanical properties of crust from magnetar crust oscillations (QPOs in SGR giant flares)

resurgence of work on measuring M,R from X-ray burst spectra

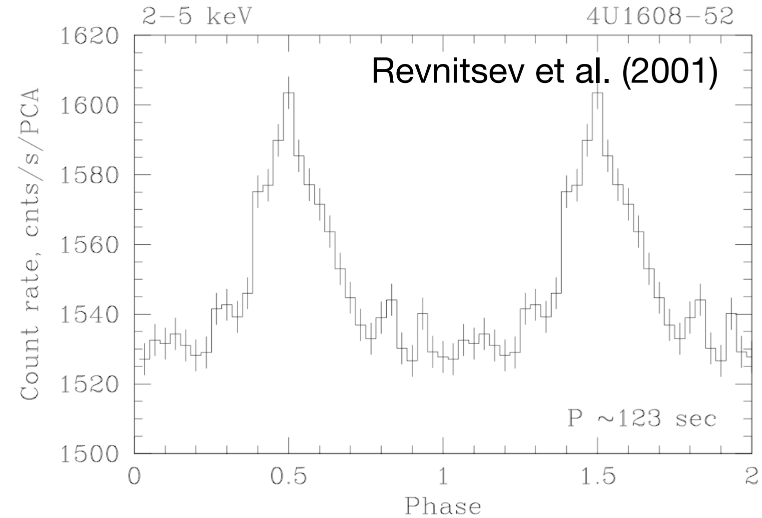
Identification of burning regimes

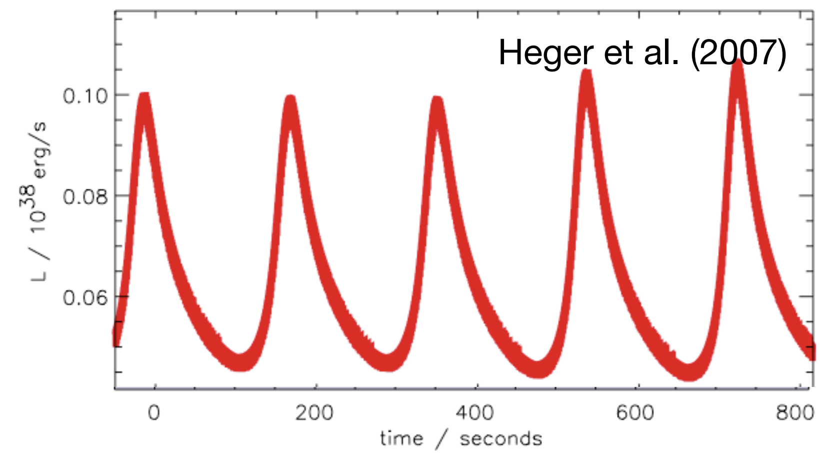
rp-process powered bursts from GS1826-24





mHz QPOs: marginally stable burning



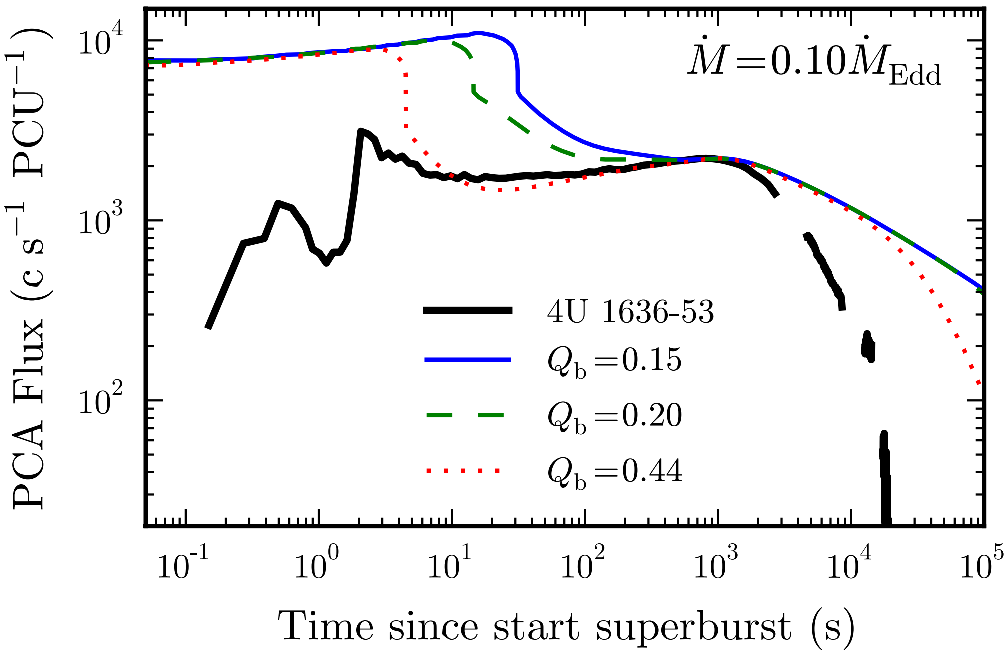


an rp-process powered clock!

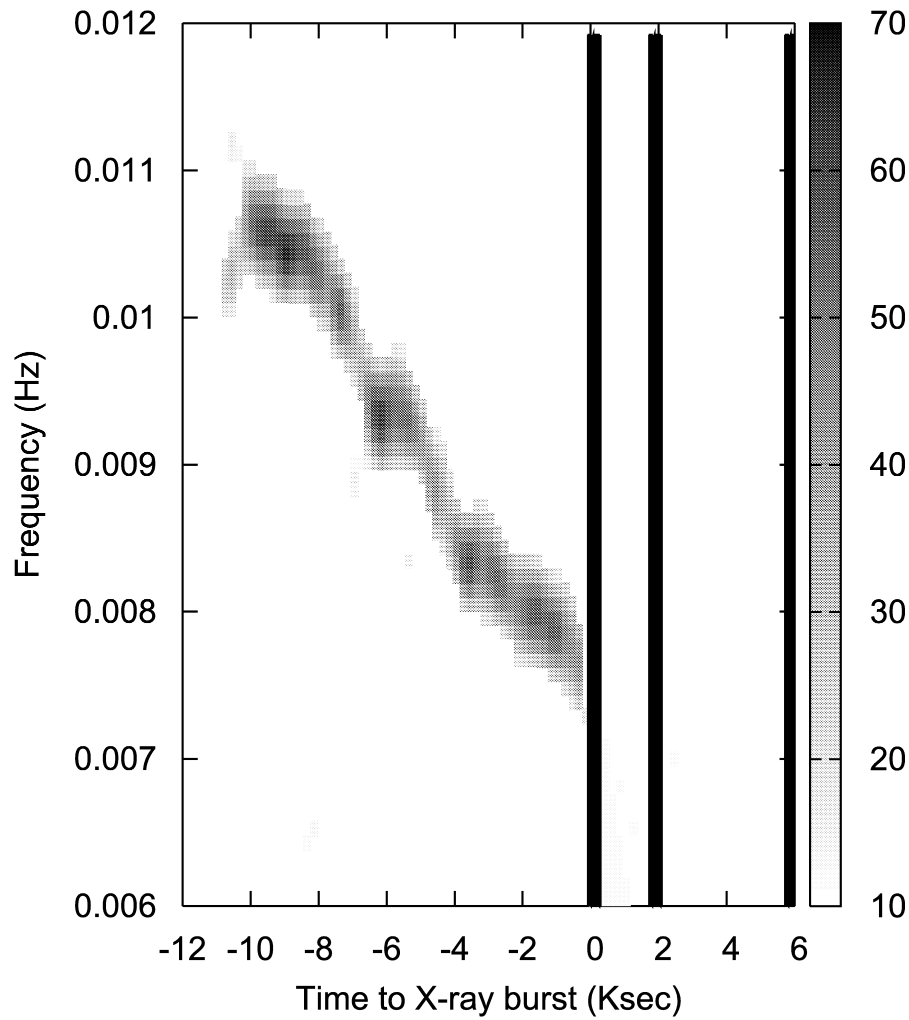
Coupling between burning shells

Altamirano et al. (2008): mHz QPO frequency drift predicts the onset of the flash!

Superburst precursors



Keek et al. (2011)

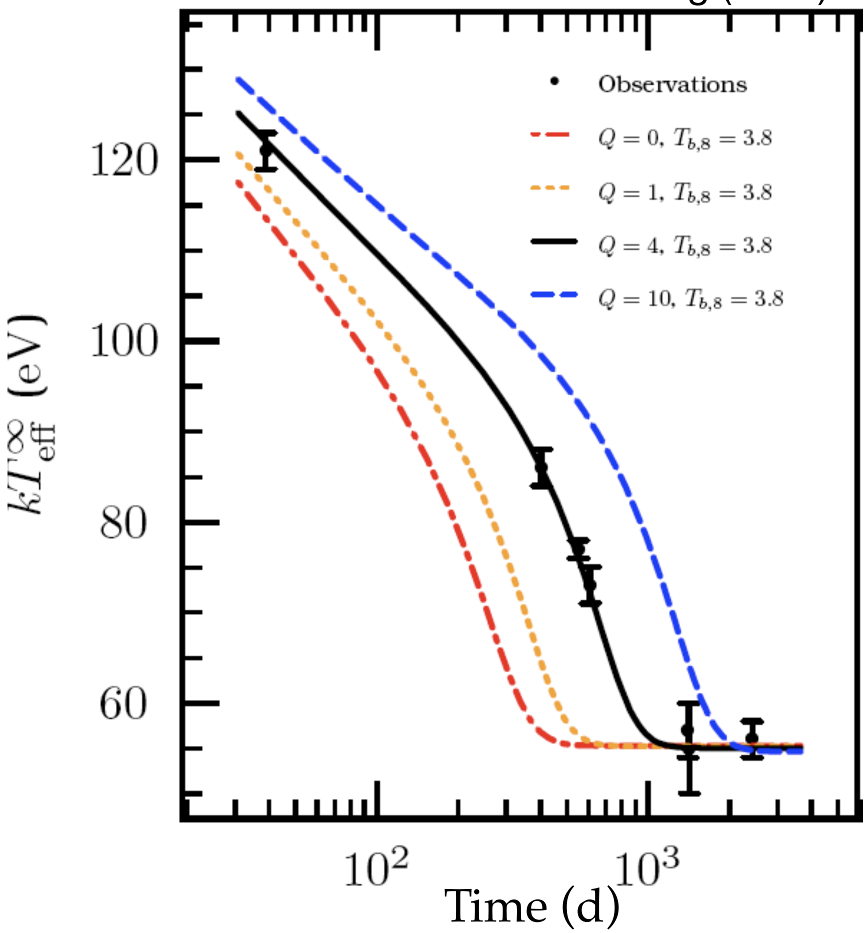


A probe of unstable carbon burning in a different and more directly observable environment

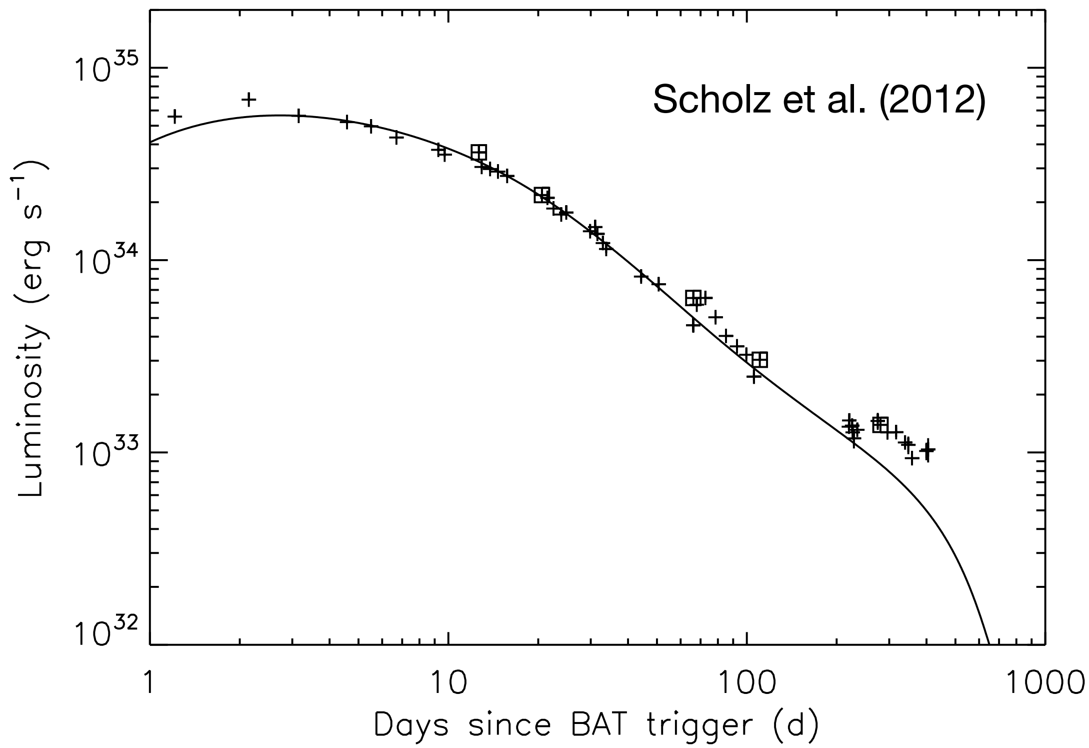
Thermal tomography of neutron star crusts

Accreting neutron star MXB 1659-29

Brown & Cumming (2009)



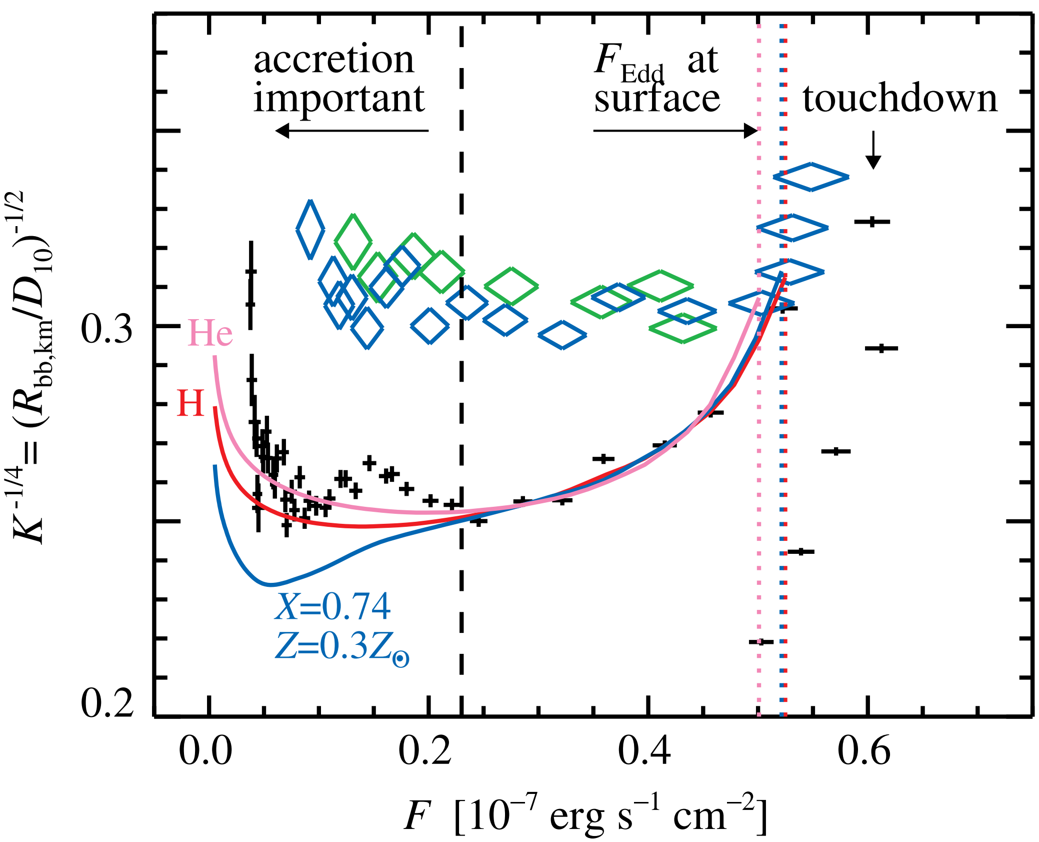
Magnetar Swift J1822.3-1606

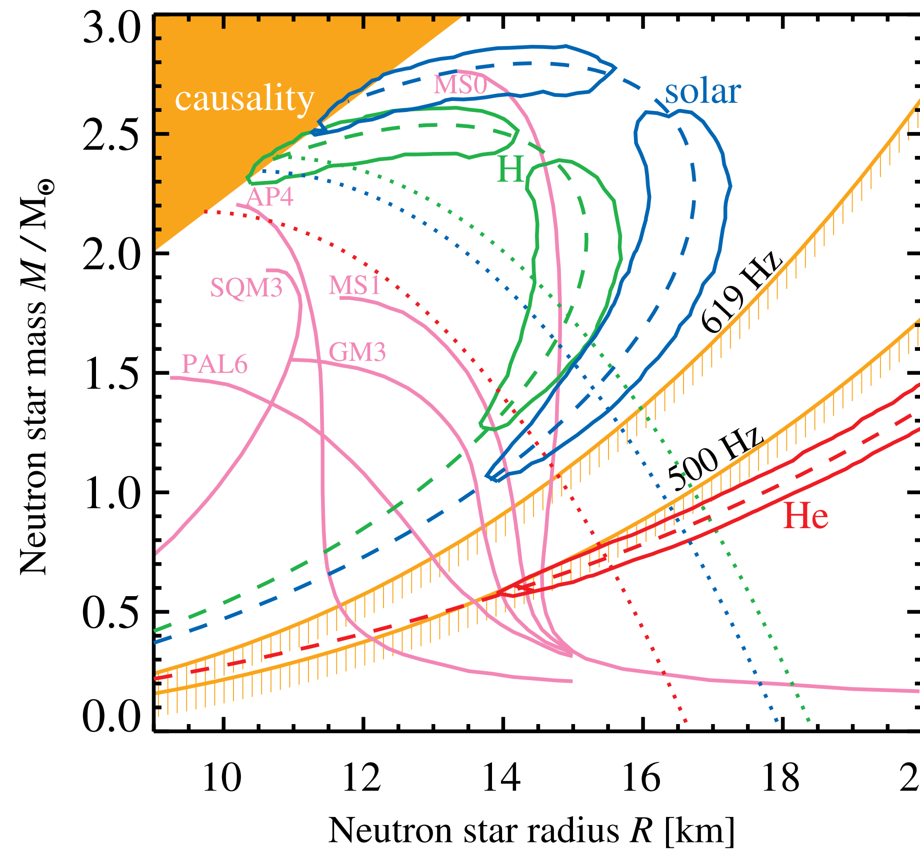


Nuclear evolution in the crust determines the heating AND the conductivity/thermal time

For magnetars, need to understand the crust composition etc. to infer the magnetic heating profile

Spectral evolution during bursts: constrain neutron star mass and radius





4U 1724-307; Suleimanov et al. (2011)
see also papers by Ozel et al., Steiner et al.

Highlighted the systematic effects in radius determination that we need to understand

Recent advances (last ~5 years)
Observations

X-ray missions: XMM, Chandra, RXTE, Swift, INTEGRAL

1. Long term monitoring of X-ray bursters and magnetars. Regular monitoring + ability to follow up when source "does something". Joint timing, flux and spectral variations.

2. Archival data analysis. Large databases of X-ray bursts (thousands), e.g. RXTE burst catalog (Galloway et al.) or ongoing MINBAR multi-mission catalog

Recent advances (last ~5 years)
Theory

1. Improved calculations of X-ray burst spectra (thermal emission)

2. Sensitivity studies: how burst observables depend on rp-process nuclear physics (masses + rates)

3. Multizone (spherical) models with full reaction networks. Survey of parameter space. Successes: GS 1826, 10 minute recurrence times, mHz QPOs

4. Improved understanding of how carbon burning proceeds and gives rise to precursors etc.

5. Evolution of multicomponent mixtures of nuclei to high density in the ocean and crust

6. >1D simulations of the burning front on a rotating neutron star. Low mach number/ hydrostatic codes in development.

Outstanding Problems(Opportunities)
(major issues we don’t understand)

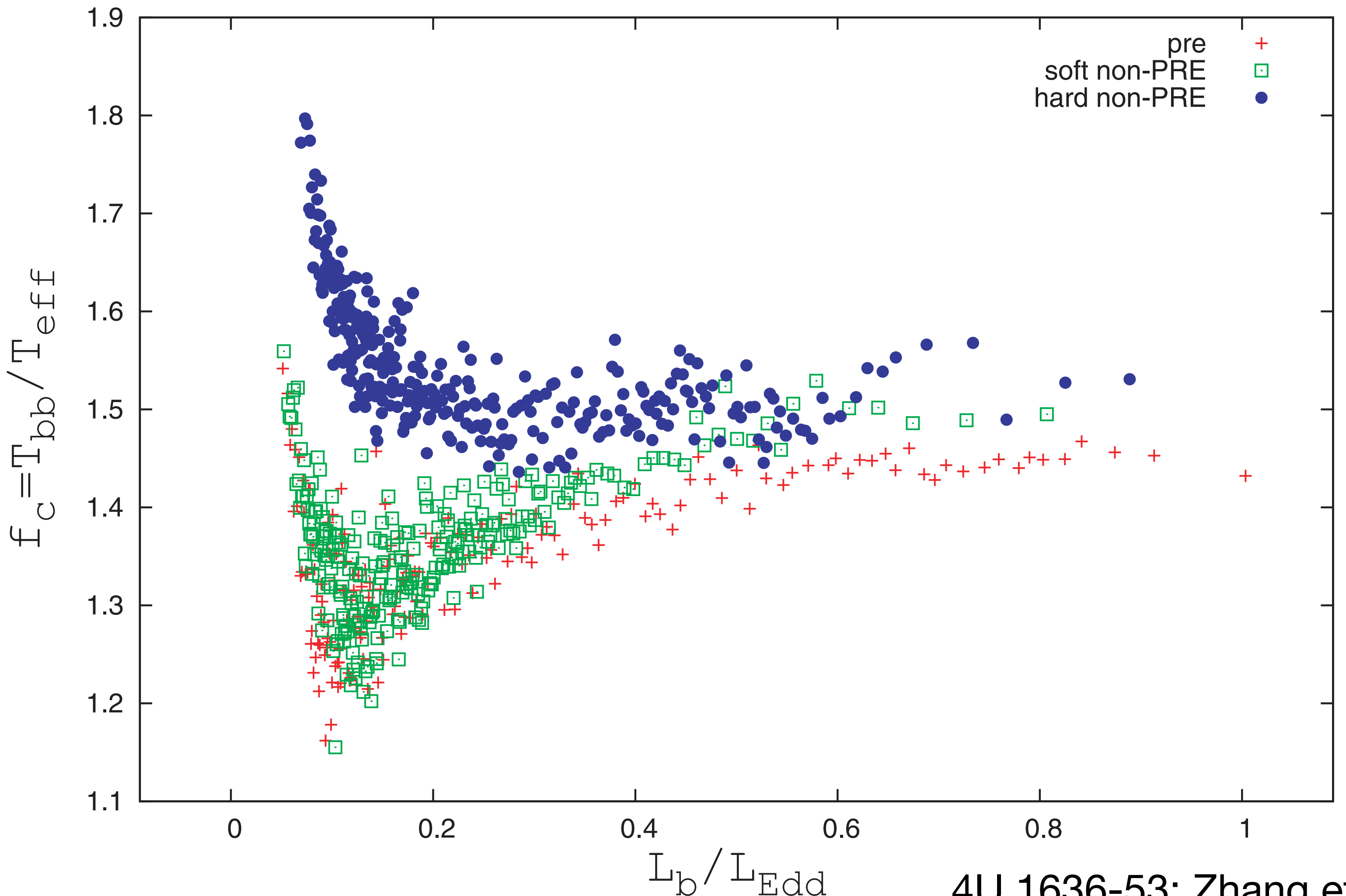
1. Changes in the spectral behavior of bursts with accretion rate. Make it difficult (impossible?) to determine R.

2. Superburst ignition. How to make the fuel? How to make it hot enough to ignite? Is there a low energy heat source?

3. Origin of burst oscillations. Major problems with surface wave picture.

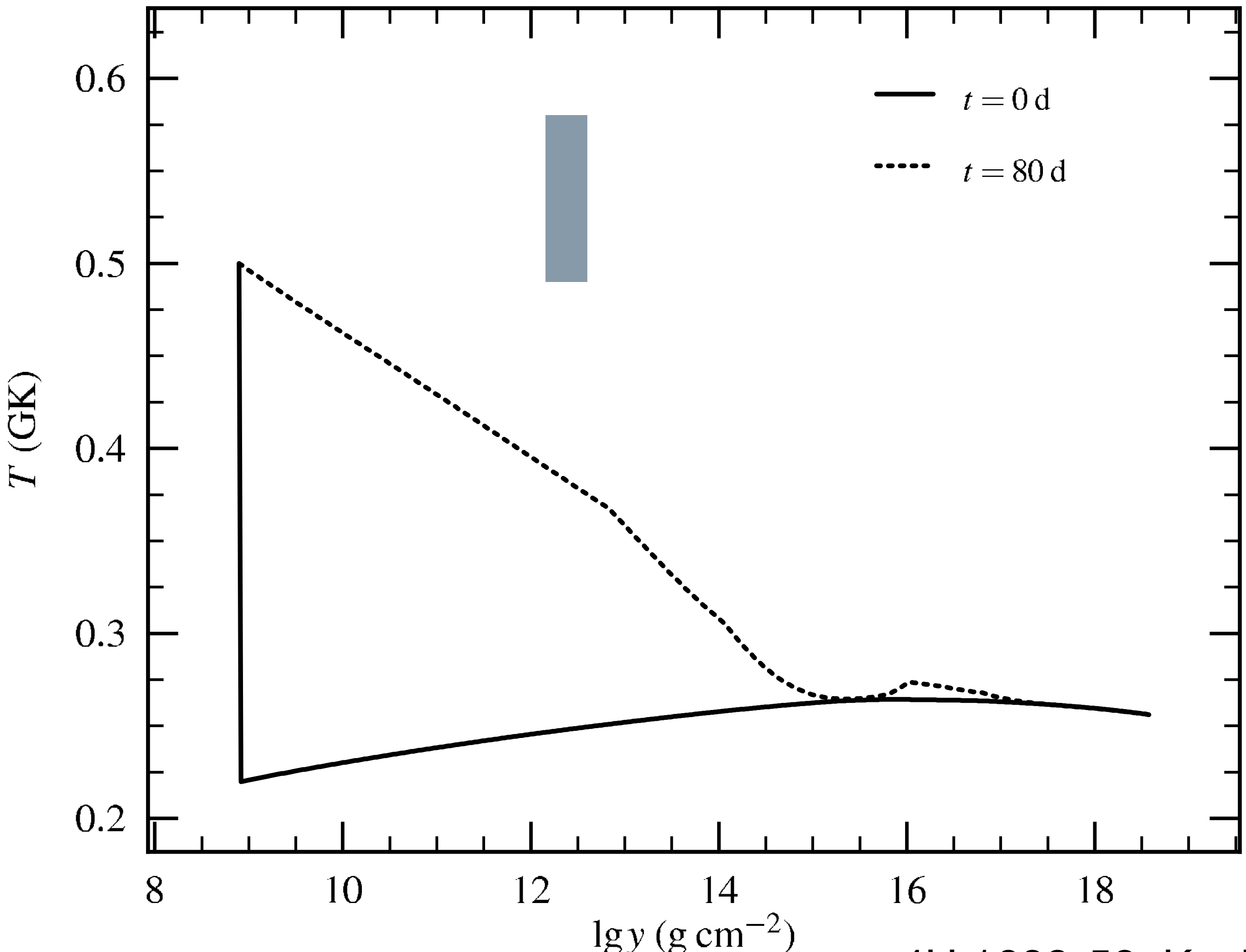
4. Change in burst behavior with accretion rate: onset of stable burning at accretion rates several times smaller than predicted; interaction between mHz QPOs and bursts

1. Changes in the **spectral behavior of bursts** with accretion rate. A major source of systematic uncertainty when measuring radius.



4U 1636-53; Zhang et al. (2011)

2. **Superburst ignition and crust heating.** How to make the fuel? How to make it hot enough to ignite? Is there a heat source at low density? Feedback between burst ashes and crust heating: what is the evolution of rp-ashes through the crust?

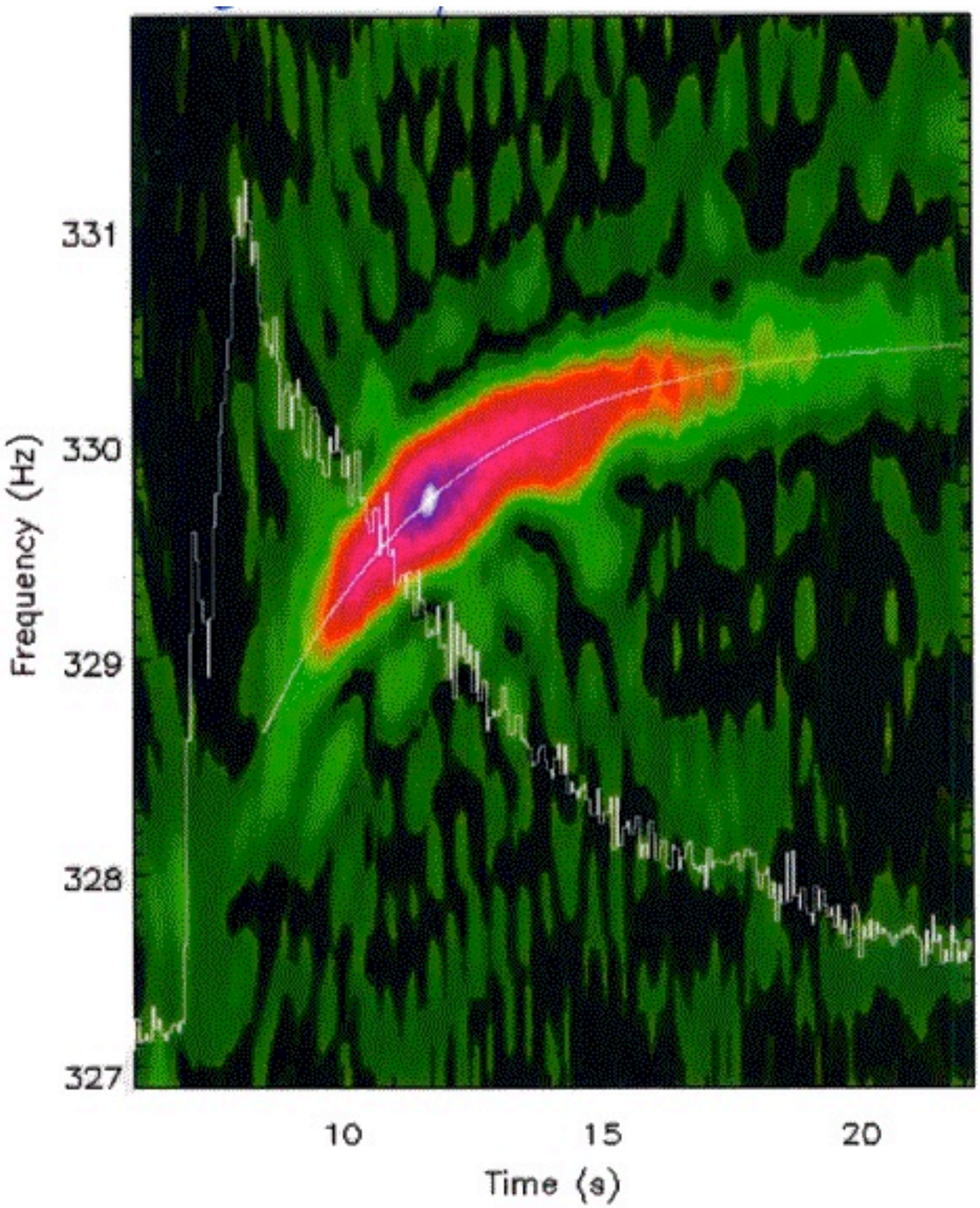


Can't heat the neutron star ocean to ignition temperature in the ~60 days of accretion before the superburst went off

This is one of a few examples of superbursts that are hard to explain with carbon ignition

4U 1608-52 Keek et al. (2008)

3. **Origin of burst oscillations**. Especially in the burst tails.

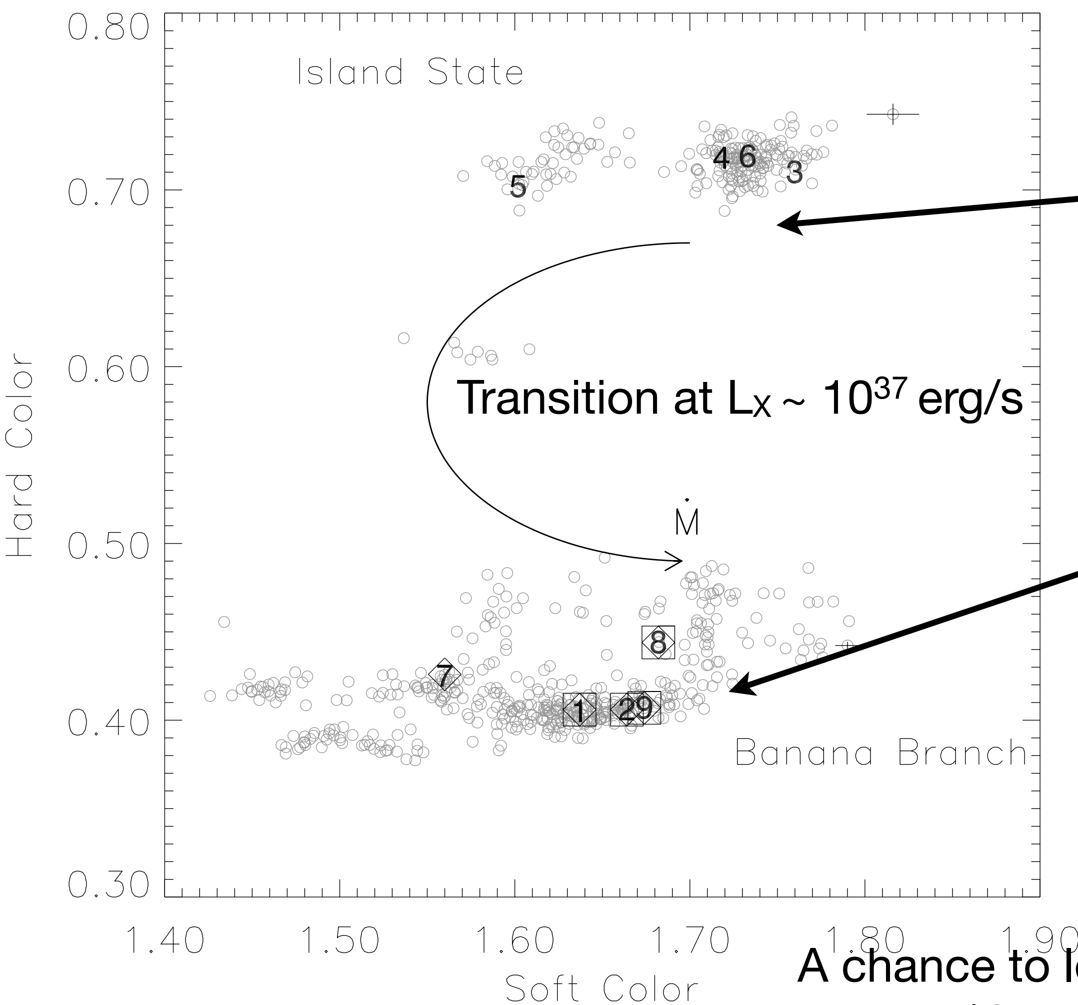


Even if burst oscillations in the rise are due to a spreading hot spot, why are oscillations seen in the tail when the whole star is burning?

Connection to nuclear astro:
- New regime of burning propagation
- Doppler shifted pulse profiles => radius measurement

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

4. **Change in burst behavior with accretion rate:** onset of stable burning at accretion rates several times smaller than predicted; interaction between mHz QPOs and bursts



Island state (low accretion rate)
Regular Type I bursts
Long duration, energetics consistent with all fuel burning in bursts

Banana state (high accretion rate)
Short, irregular bursts
Some stable burning
Burst oscillations
Superbursts
mHz QPOs

A chance to learn something about accretion/ mixing (if we understand the nuclear physics part)

What next? Theory

"Beyond 1D"

1. Models of burning front propagation across the surface of rotating neutron stars

2. Photospheric radius expansion bursts. Radiation hydro to go beyond 1D quasi-static models. Help to understand systematics in R determination.

3. Global models of burning behavior: either new physics in 1D models or include spreading/circulation of matter over the neutron star surface.

4. We need a closer tie between observations and theory.
E.g. GS1826 <---> sensitivity studies

KEPLER <---> MINBAR

5. Open source 1D models (MESA?)

6. The evolution of a nuclear mixture through the crust: mass models, rates, which reactions? --> heat sources, thermal and mechanical properties

What next?   Observations

1. Near term: continued monitoring of bursters + magnetars with XMM/Chandra, Swift, INTEGRAL
2. Archival: e.g. MINBAR catalog
3. Future: Indian ASTROSAT launch 2013?, Large timing mission such as LOFT, [improved distances from GAIA]

1. Large area timing mission (10x XTE) would enable following individual pulse trains in burst oscillations. Test "spreading hot spot" paradigm. Doppler shifts => constrain R.
2. Long term continuous monitoring of LMXBs. E.g. measure quenching timescale for superbursts
3. Sensitive spectral capability to look for line features

Crucial input from nuclear physics

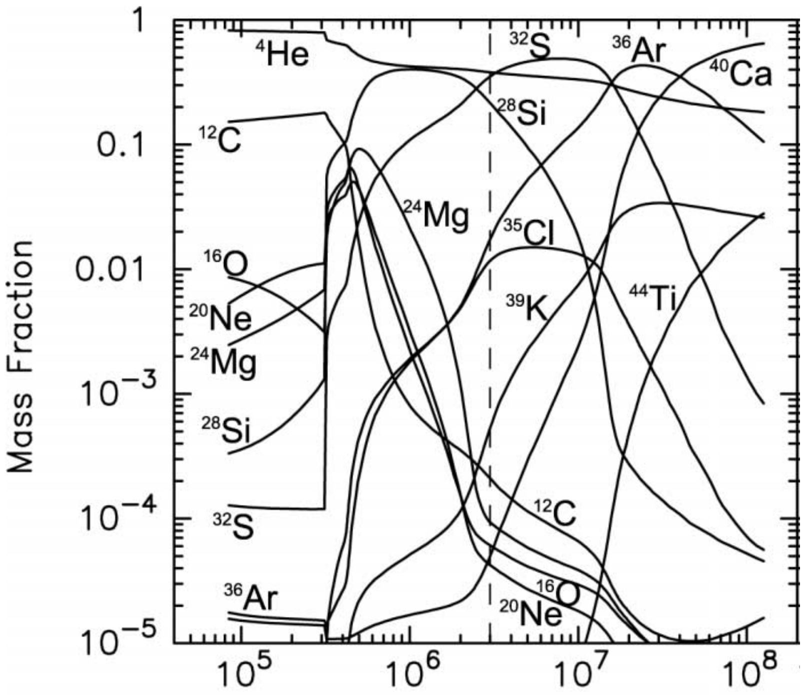
If we can

1. Nail down rp-process pathways and outcomes
2. Properties of neutron-rich nuclei at and beyond neutron drip

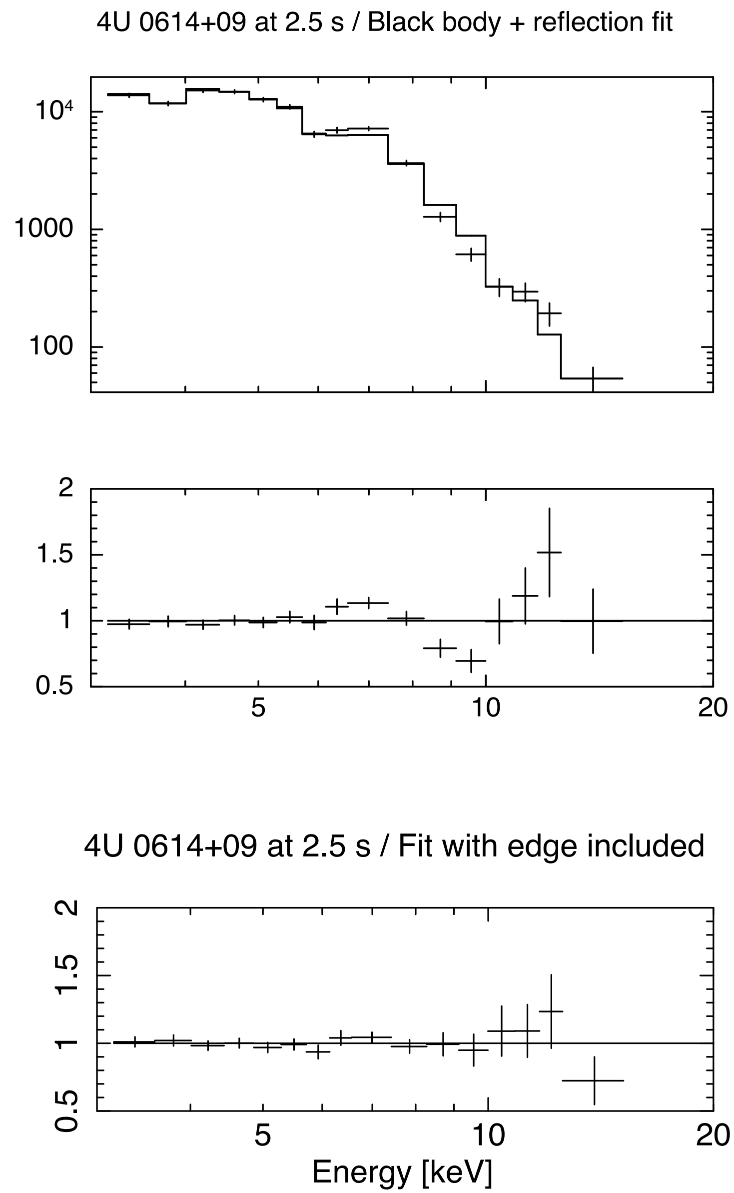
opportunity to probe
- dense matter properties of crust and core
- stellar processes in thermonuclear flashes
- accretion physics

Message to nuclear experimentalists and theorists:
- we need masses, rates at the proton drip line and at and beyond the neutron drip line
- thermal and transport properties of dense matter

Evidence for absorption edges in photospheric radius expansion bursts



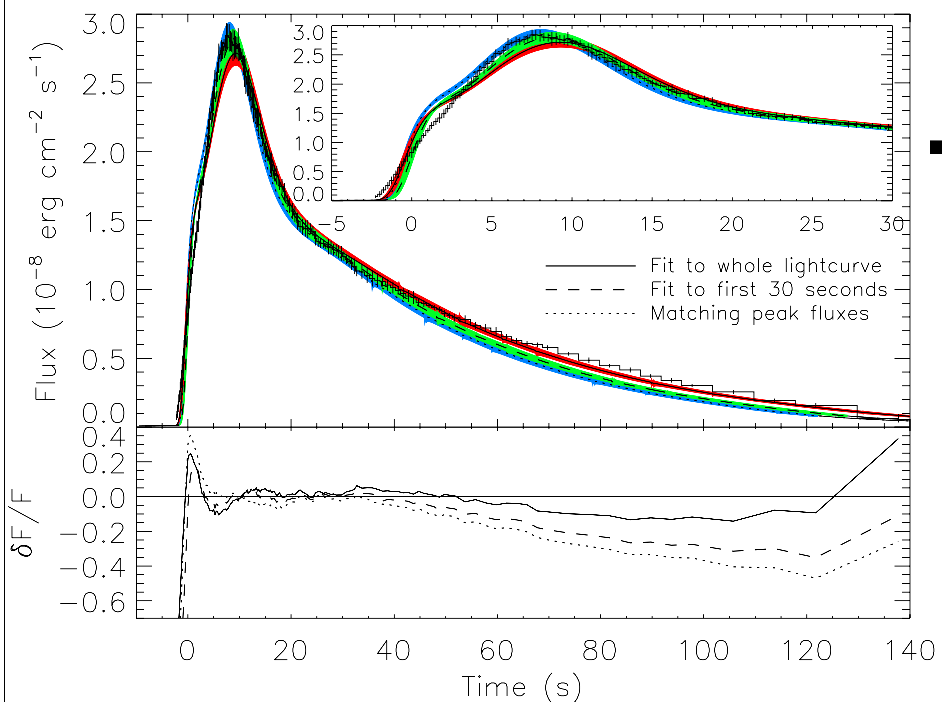
Weinberg, Bildsten,Schatz (2006)

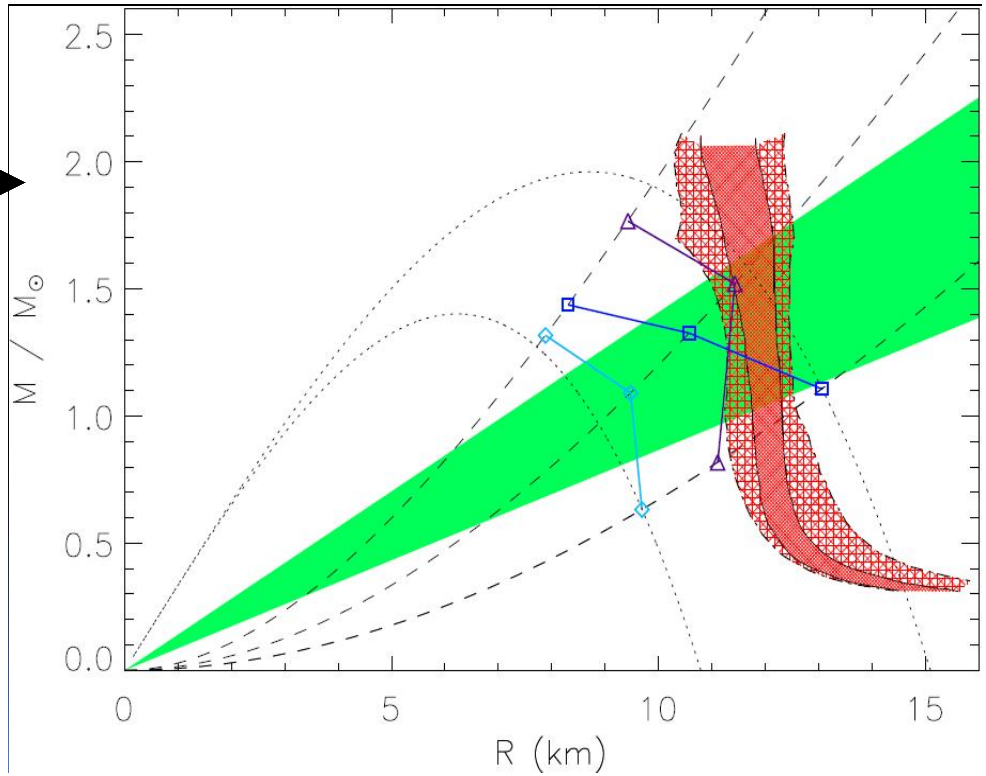


in ’t Zand and Weinberg (2010)

One last example

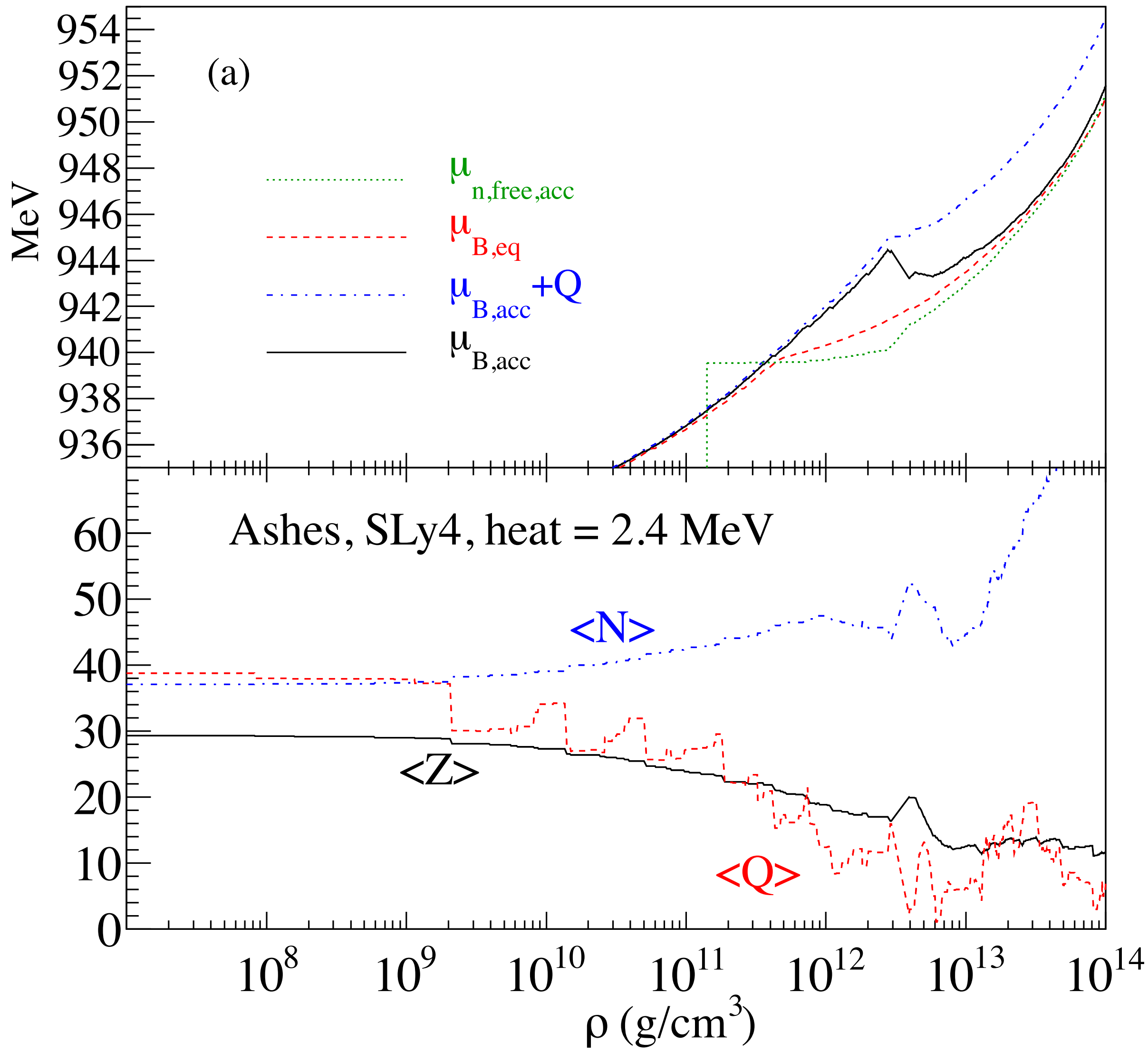
If we get the lightcurve of GS 1826 right (rp-process) then we can use it as a "standard candle" instead of PRE bursts => a second independent way to constrain radii





Zamfir et al. (2012)

Evolution of a mixture of nuclei through the crust



Steiner (2012)