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Probing Neutron Star Physics with Thermonuclear X-ray Bursts

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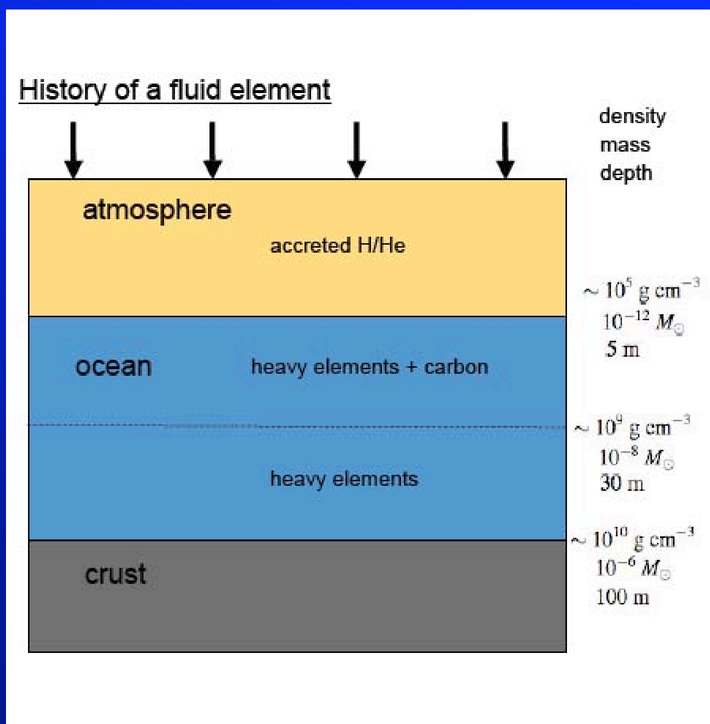
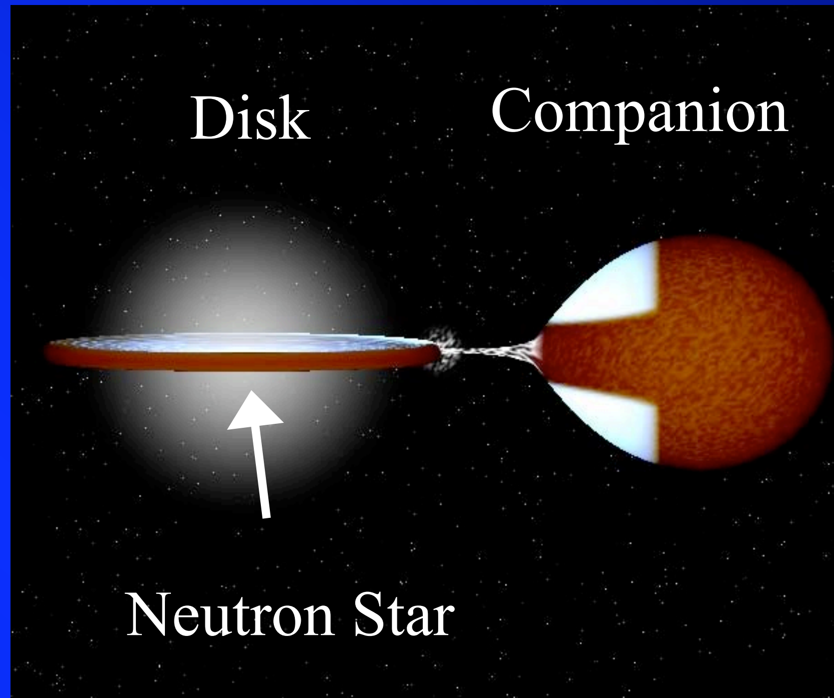
Key Points

- Particular types of bursts are rare (days ~ year)
  ==> Very difficult to observe them in dedicated observations
- The bursts are short-lived (tens of minutes - hours)
  ==> Very difficult to execute a TOO
- Provide a back-drop against which neutron star and accretion processes can be done
  ==> Fundamental physics
- Swift/XRT has spectral resolution to search for accretion disk features and surface redshifts

X-ray Burst Introduction

- X-ray bursts are thermonuclear burning flashes on neutron star surface
- Fed by binary mass transfer





- Accreted hydrogen builds up on NS surface
- Eventually reaches critical density/temp and flashes

Inside ‘Extreme’ Neutron Stars

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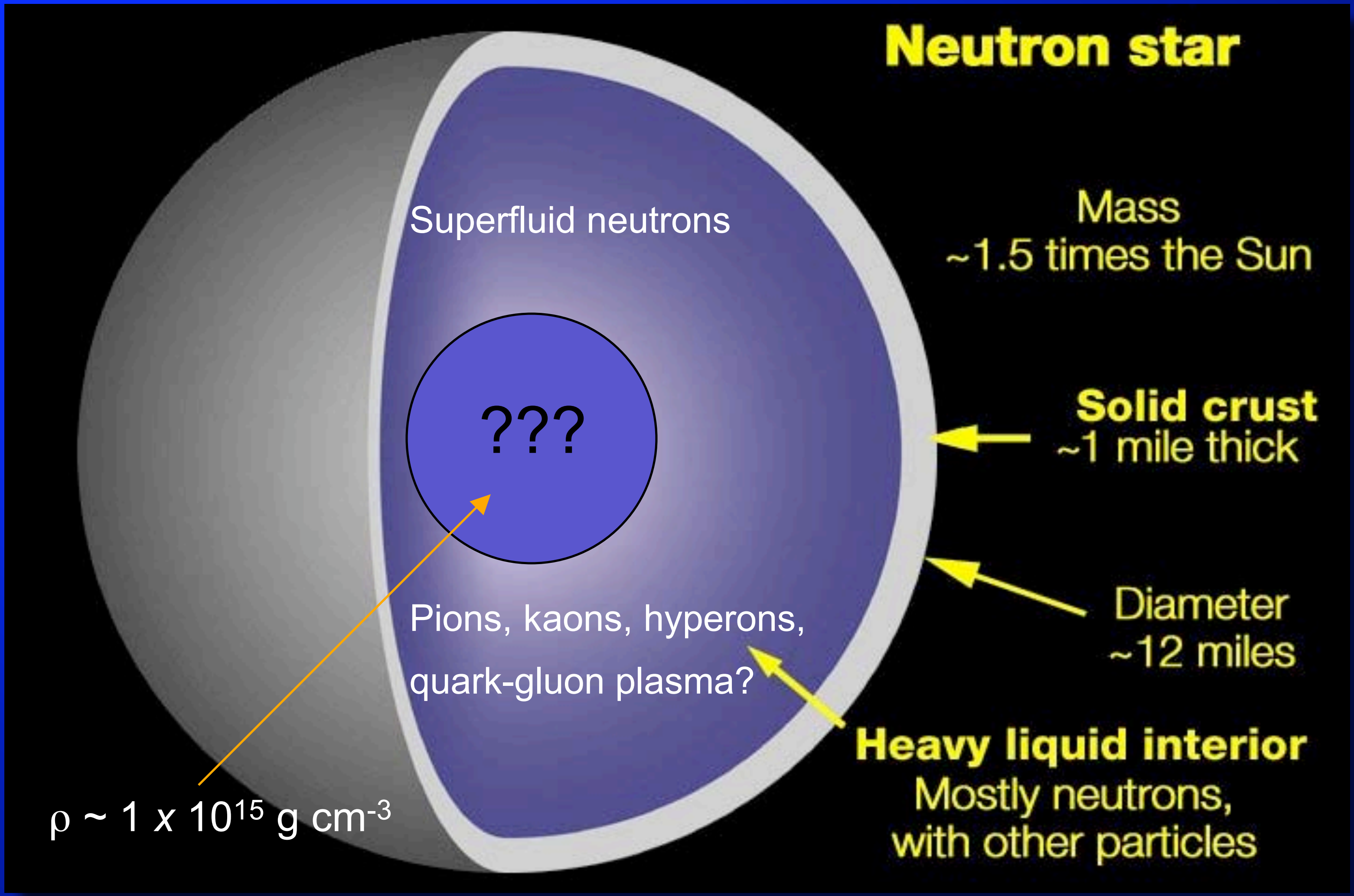

- The physical constituents of neutron star interiors still largely remain a mystery after 35 years.

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

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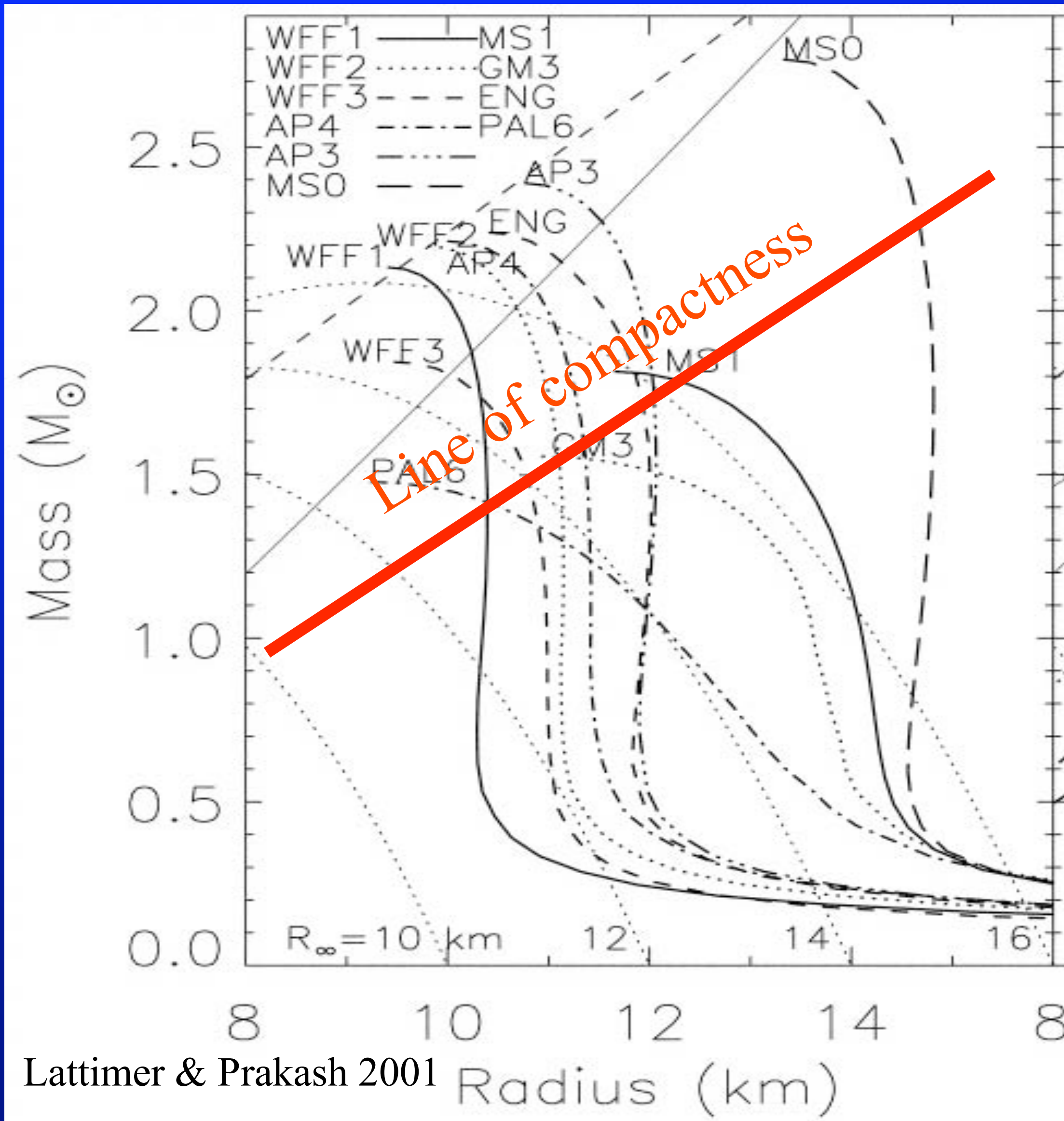


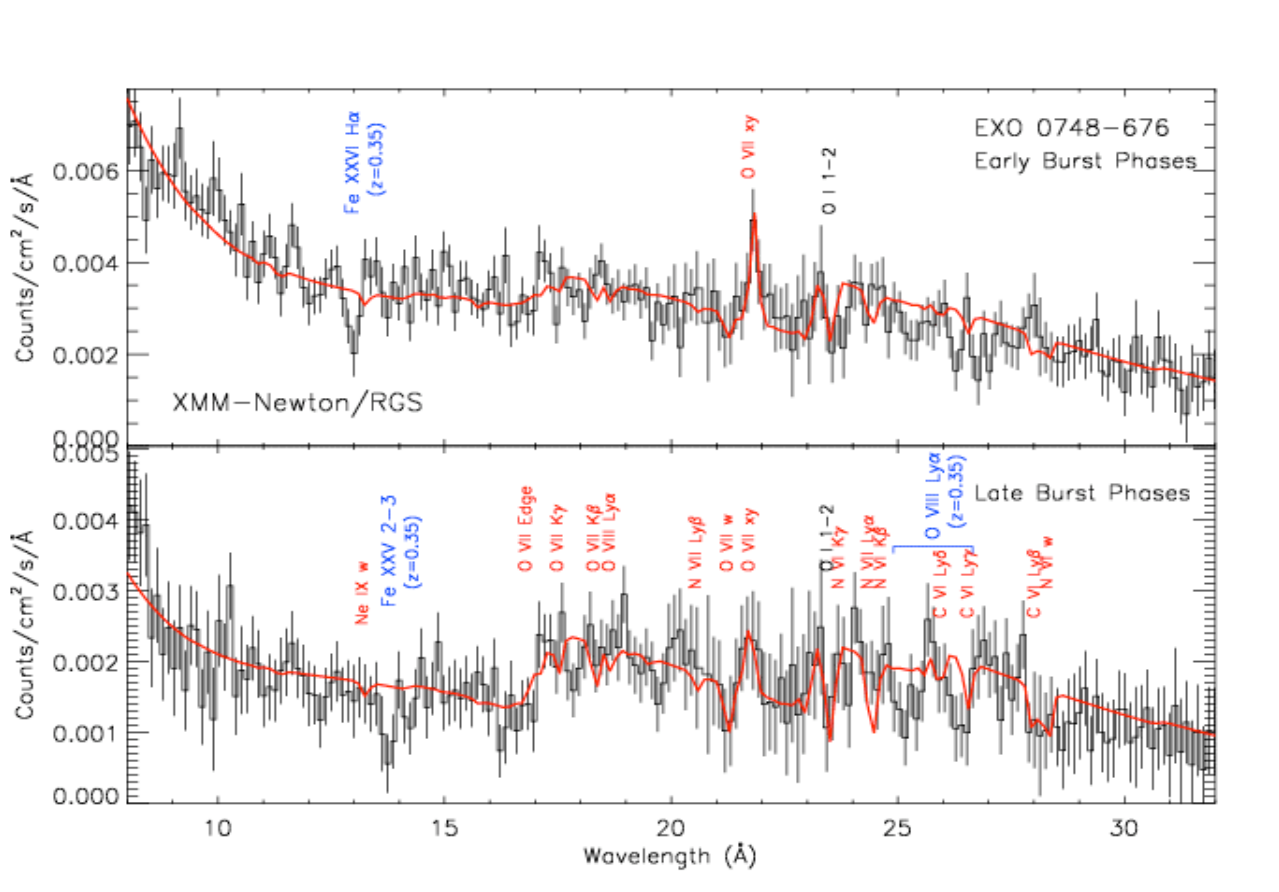
Lattimer & Prakash 2001

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

- Mass measurements, limits softening of EOS from hyperons, quarks, other "exotica".
- Surface redshift yields "compactness" M/R

X-ray Spectroscopy of Neutron Stars

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



Unfortunately this result has not been confirmed with more data, nor with different bursters.

“Normal” Thermonuclear Bursts

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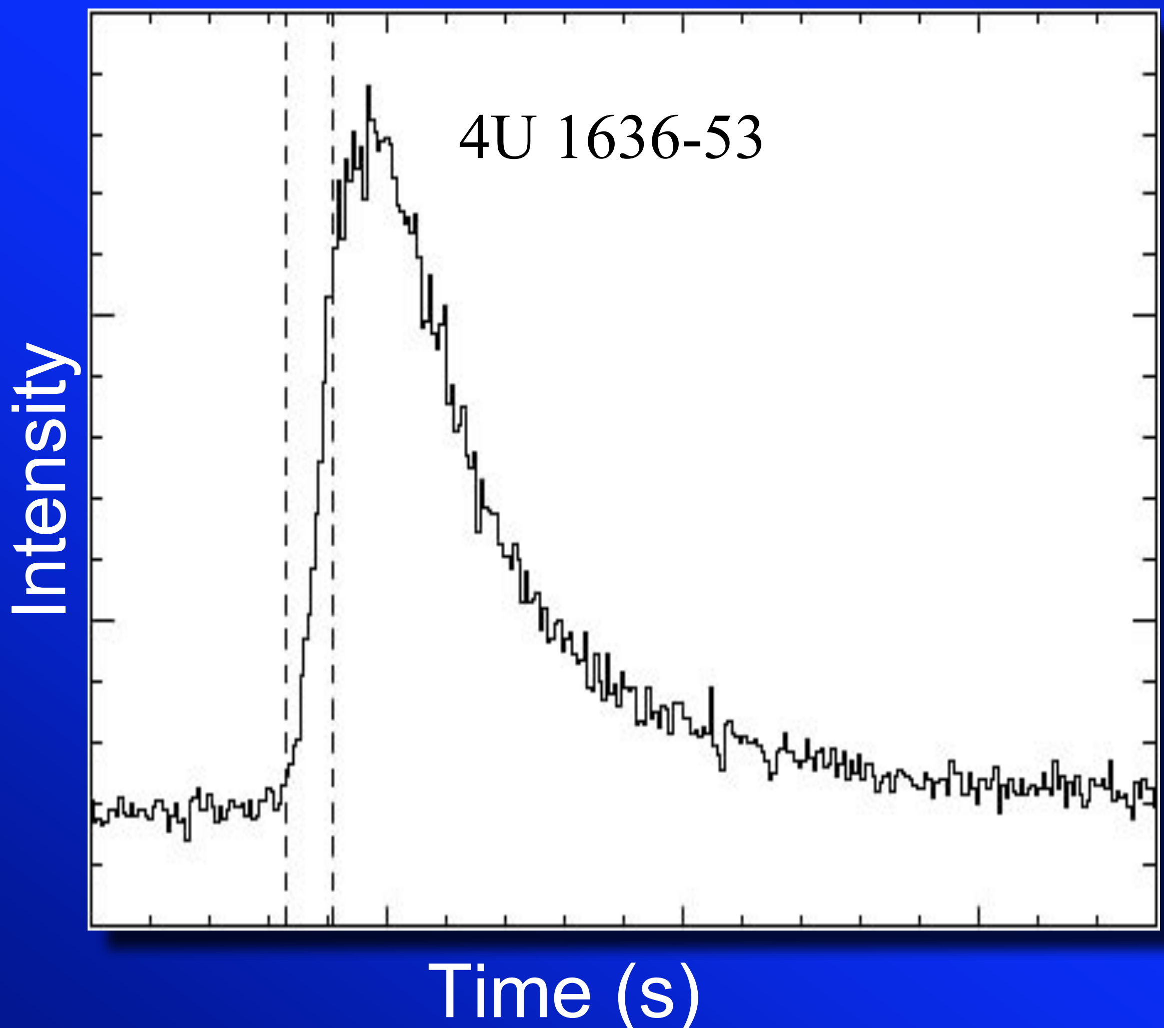
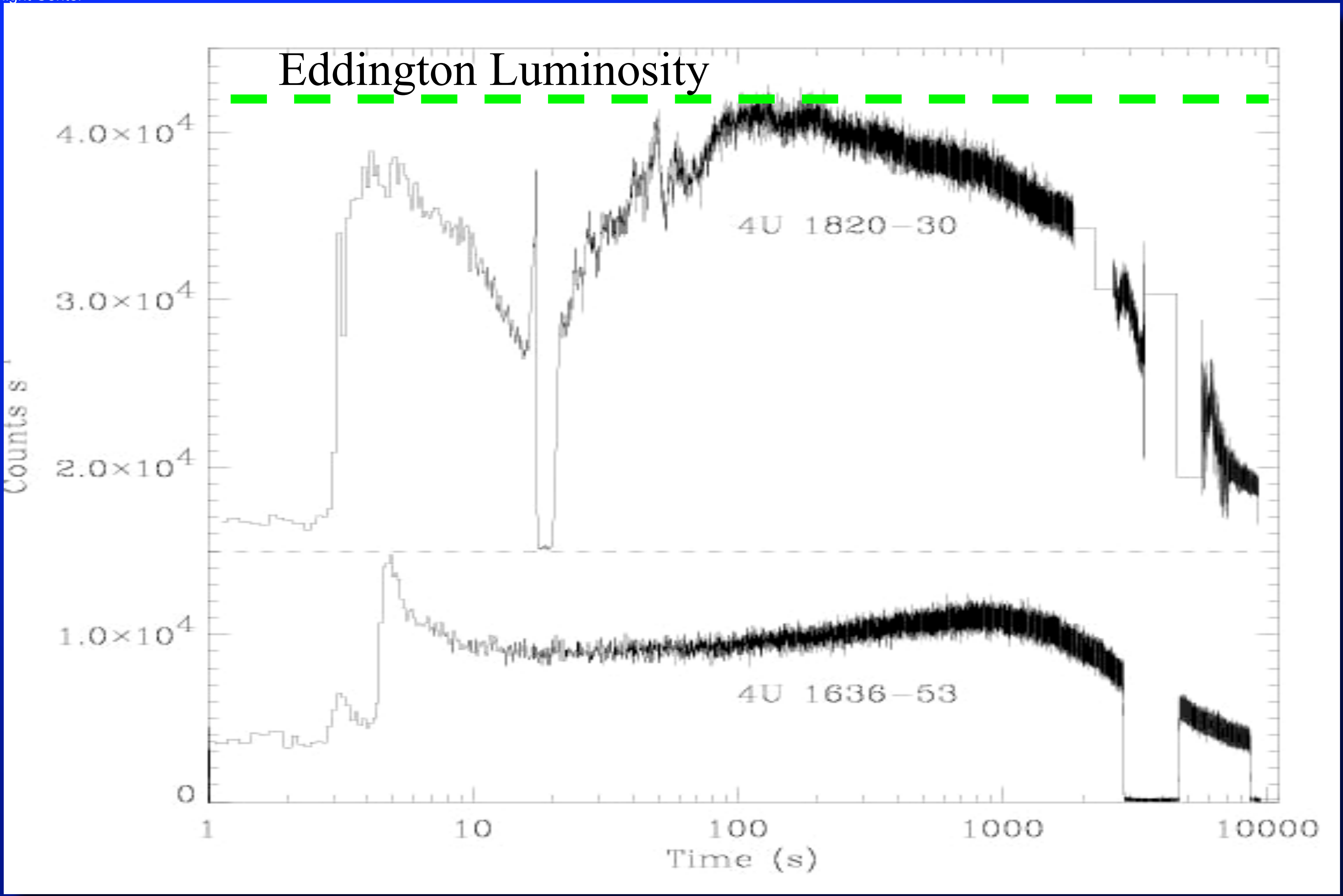


- Vast majority
- 10 - 200 s flares.
- 3 - 12 hr recurrence times, sometimes quasi-periodic.
- ~ 10^{39} ergs
- H and He primary fuels

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

Superbursts observed with RXTE/PCA



Super-bursts Compared to Normal Bursts

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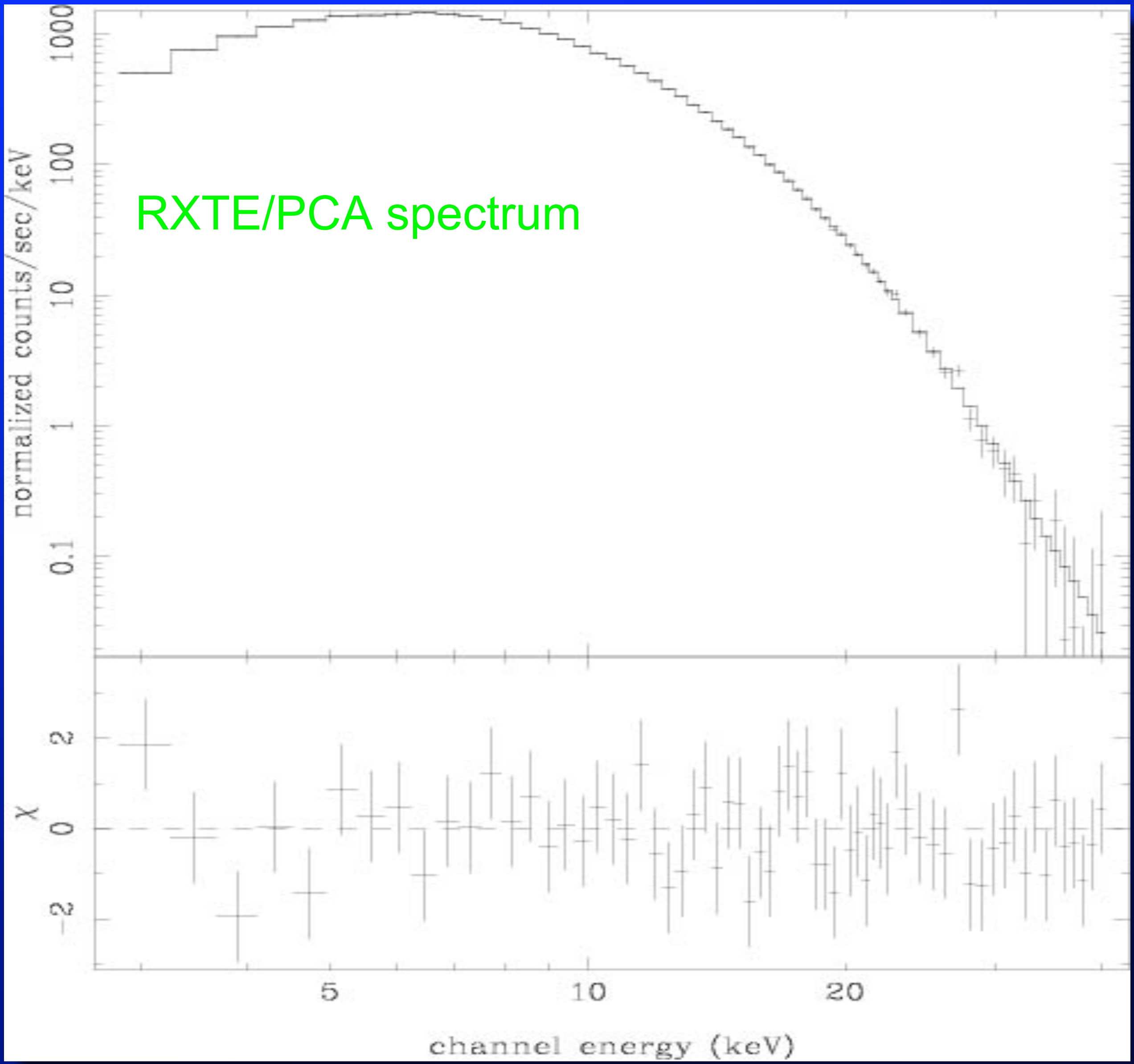
- Superbursts can last several hours (up to ~6)
- Burning of substantial carbon layer deep below surface; longer diffusion timescale ==> higher fluence
- Recurrence time of ~years (to build carbon layer)

Superburst from 4U 1820-30: Spectral Modeling



- 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.

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

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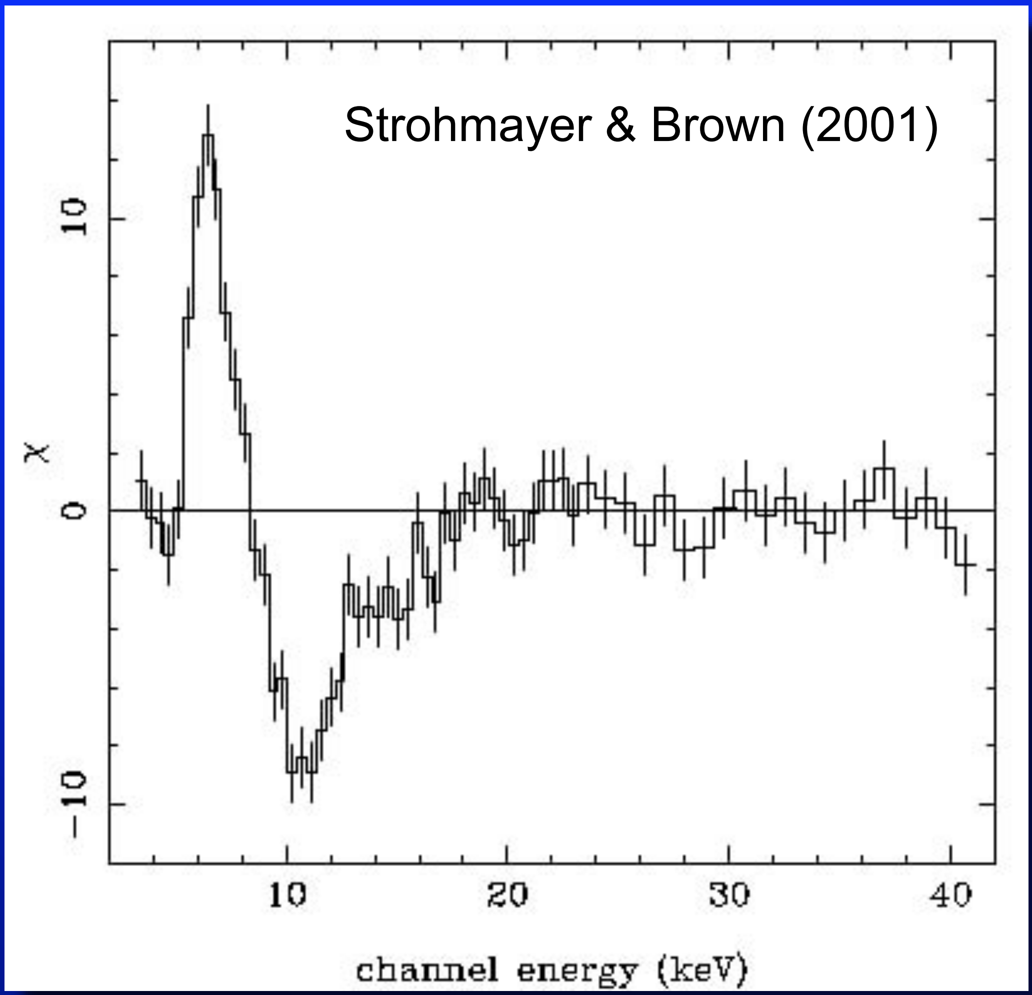
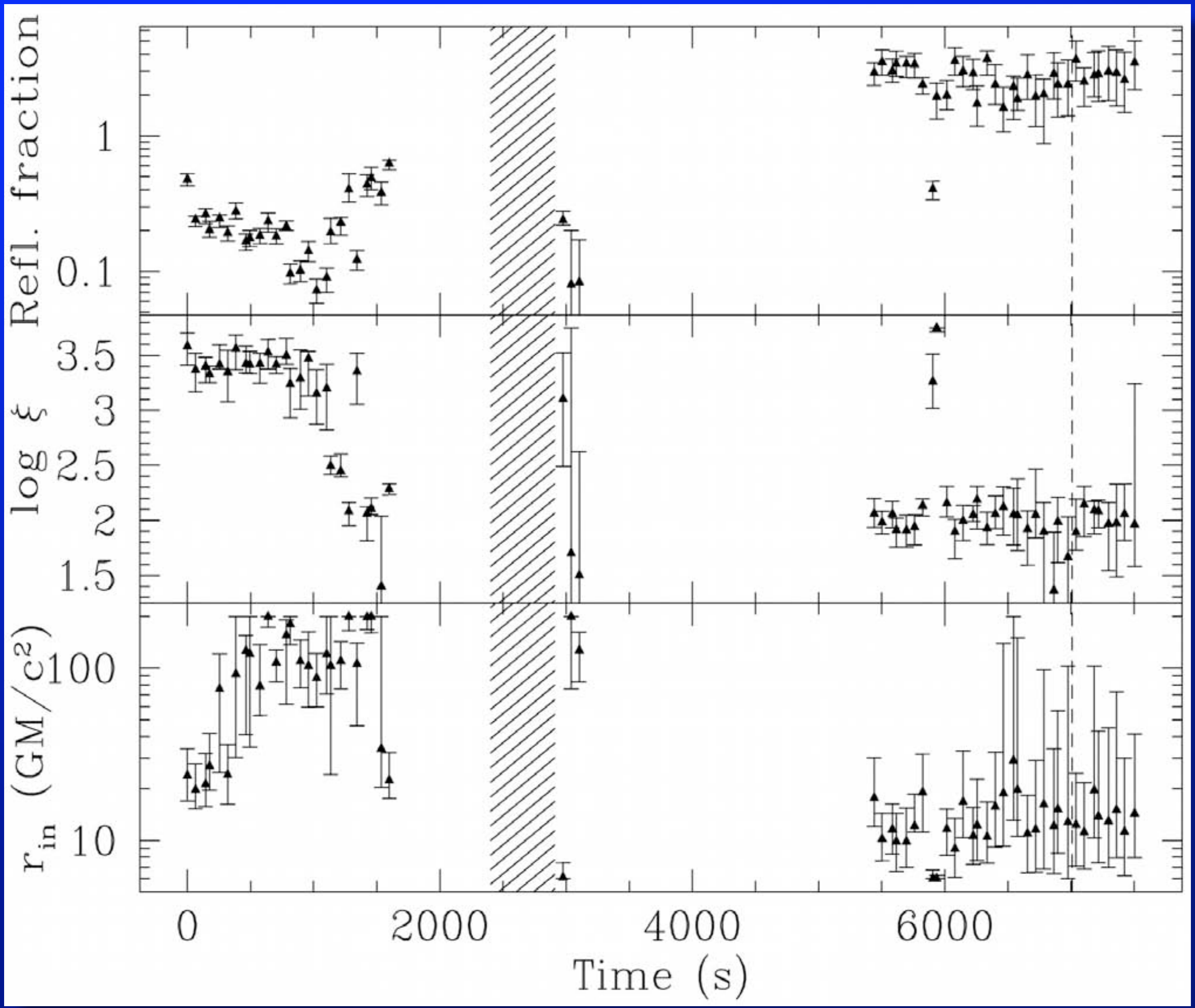


- Broad ~6 keV line and ~9 keV edge from reflection off inner disk.

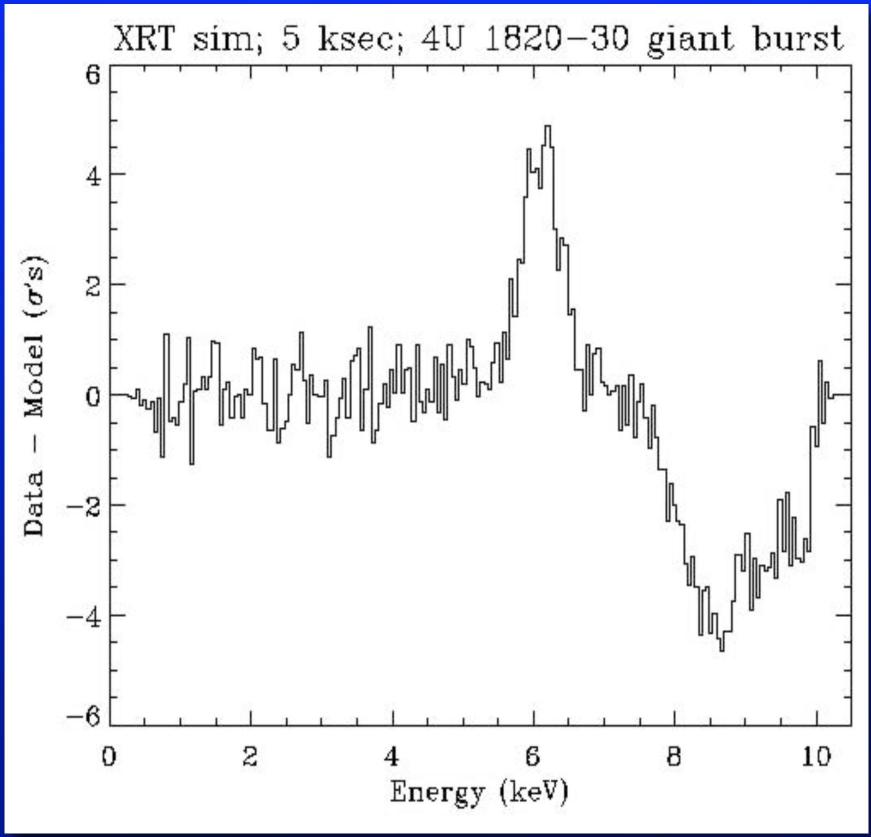
Superburst from 4U 1820-30: Disk Reflection

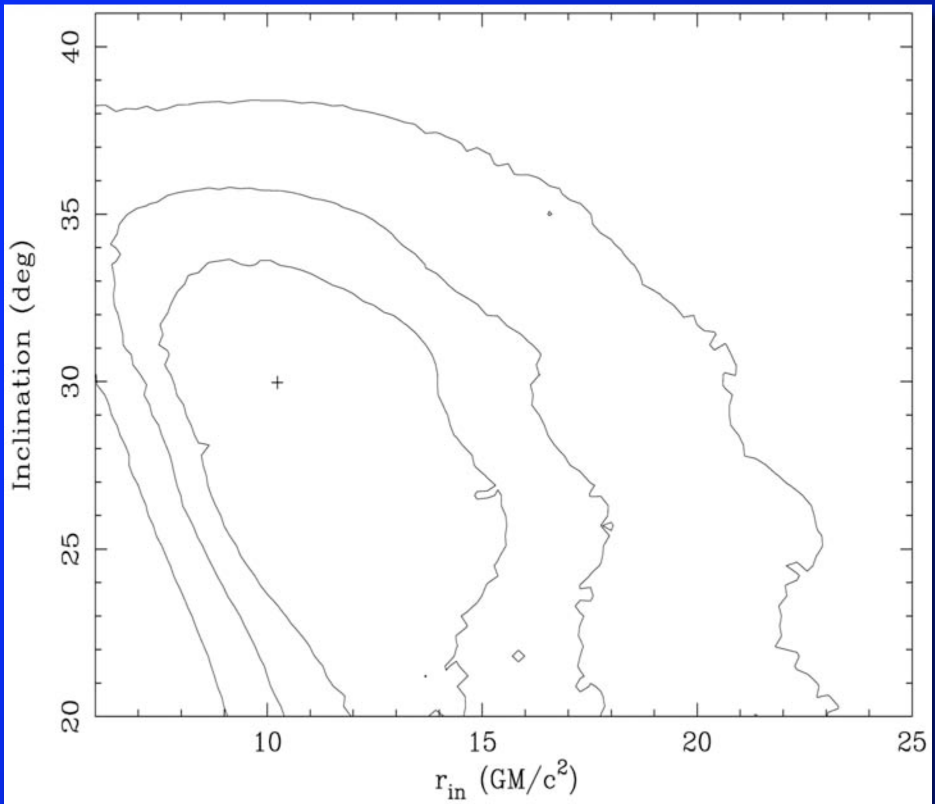


Ballantyne & Strohmayer (2004)

- 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: Follow-up by Swift XRT





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Ultra-Compact Binaries

- **Ultra-compact binaries are neutron star binaries with periods < ~1 hr**
- **Systems are very old**
  - companion is typically a helium dwarf
  - Mass transfer rates are very low
- **Significant helium "fuel ocean" can build on the neutron star surface, leading to long (20-40 min) X-ray bursts**

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Radius Expansion Bursts

- Bursts that exceed the Eddington luminosity will drive a wind ("photospheric radius expansion")
- This dredges up the thermonuclear ashes (a few 10s of meters)
- The ashes will be seen in absorption against the hot photosphere, permitting a redshift measurement

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Observe the Ashes in Absorption

Photoionization edges of sulfur and silicon will be the strongest

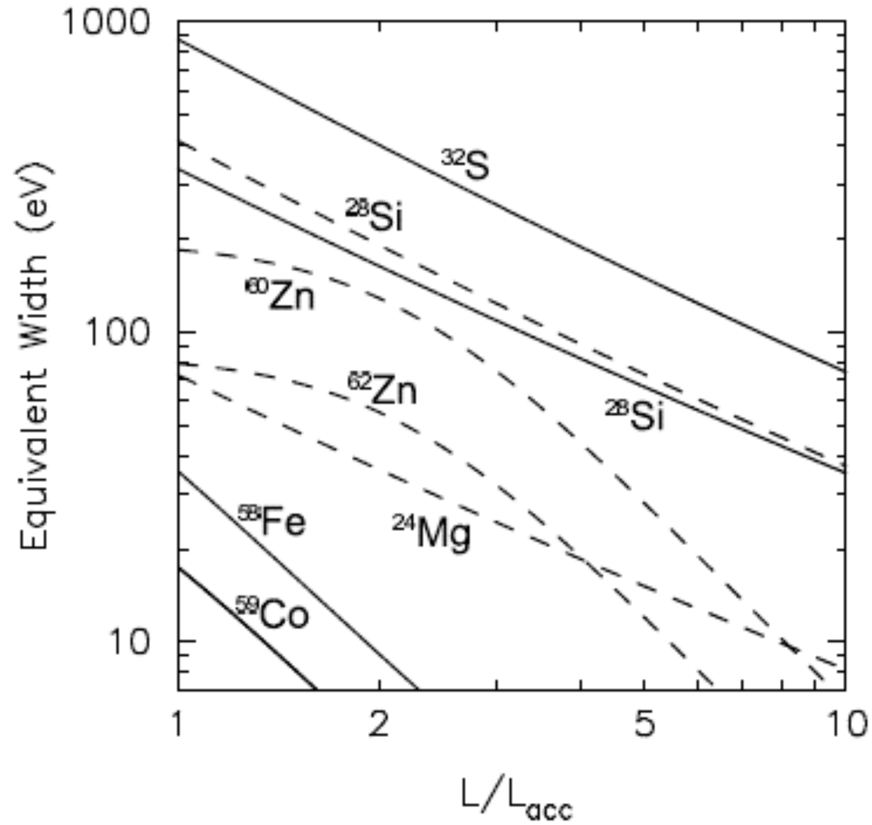

FIG. 15.—Equivalent width of the photoionization edge due to ashes residing in the photosphere at the NS surface for models He0.1 (*solid lines*) and HHe0.1 (*dashed lines*). The EW is plotted as a function of the ratio of surface luminosity to accretion luminosity for a cooling NS atmosphere following the RE phase. Detecting such edges might allow for a measurement of the NS gravitational redshift.

Weinberg et al. 2006

Simulation: case of UCXB burst

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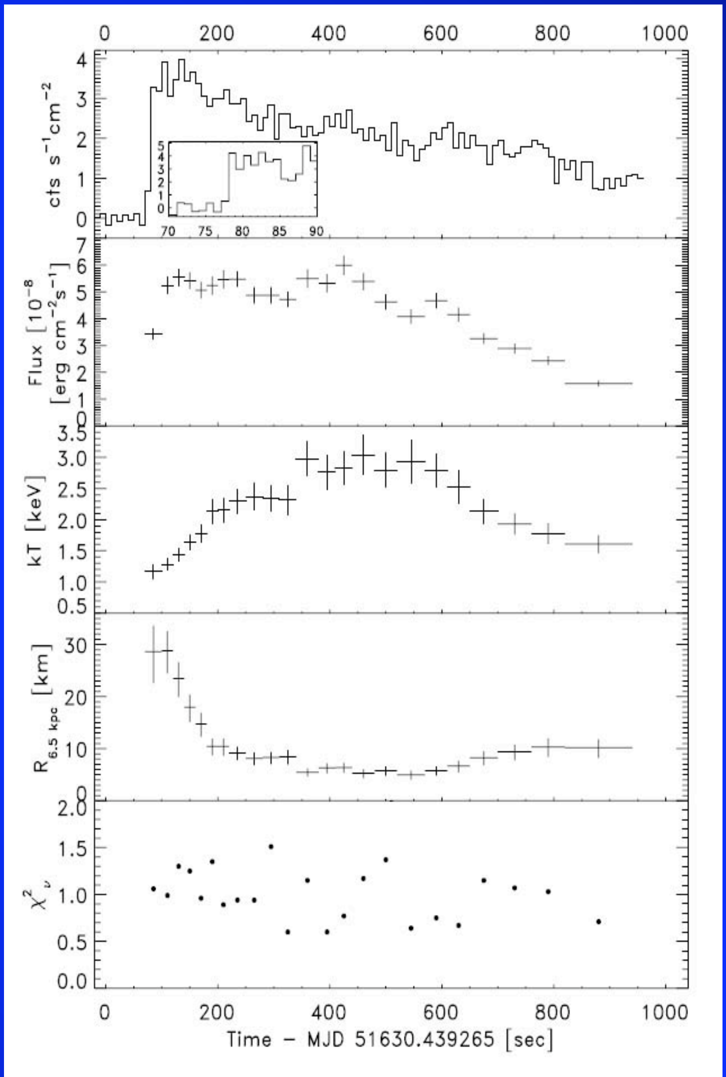
Burst from SLX 1737-282

- Burst with peak flux of 2 Crab
- E-folding decay time 682 s (longest of all non-superbursts)
- N_H=2 x 10^{22} cm^{-2}
- Redshifted Si edge at 2.03 keV (EW 150 eV)
- Redshifted S edge at 2.65 keV (EW 400 eV)
- Slew response time 60 s, kT ~ 2.5 keV
- Fluence caught: 90%



1 and 0.25 times predicted EW

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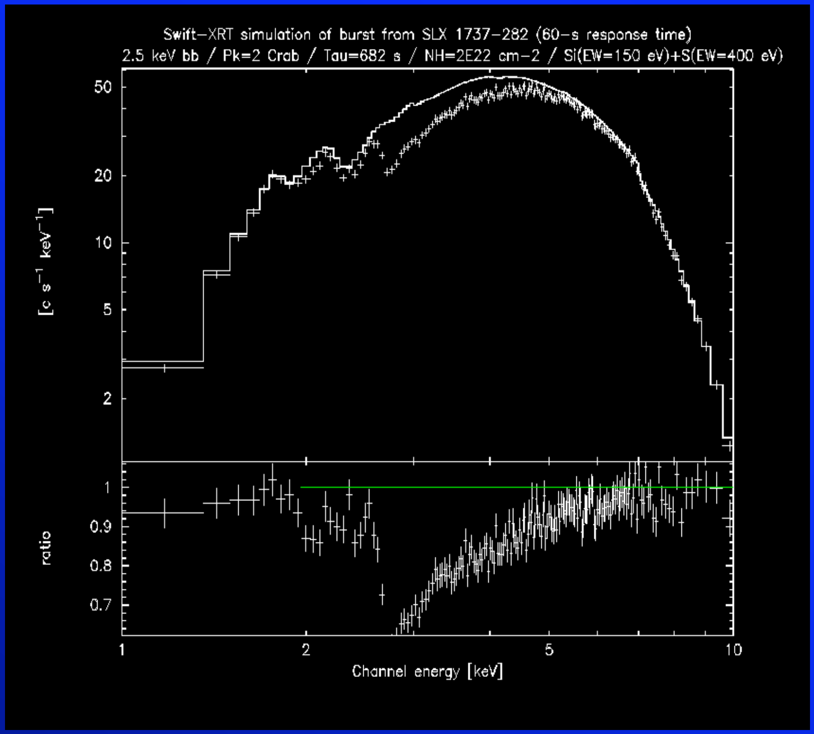

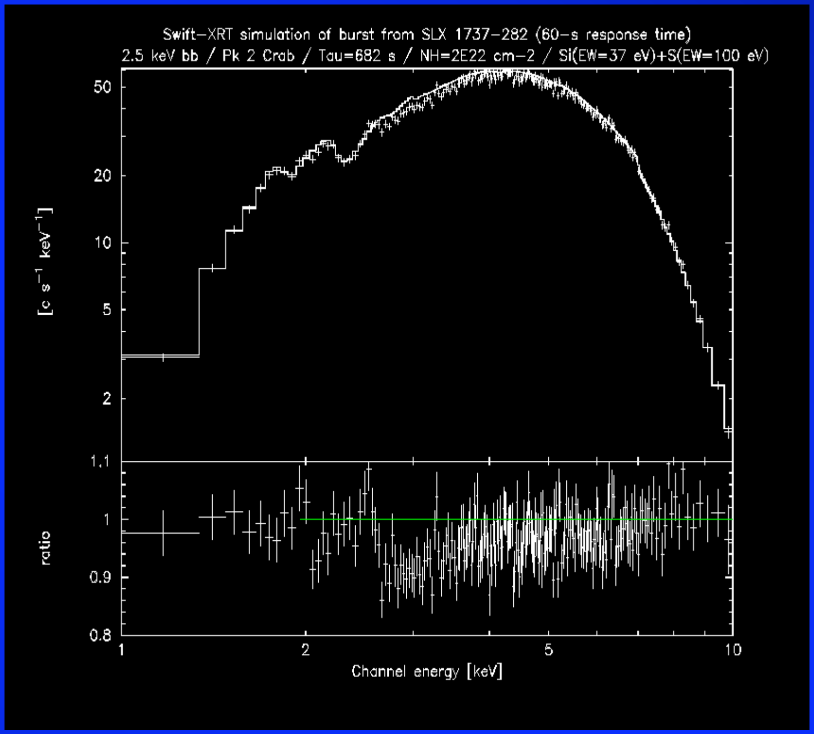

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Triggering Strategy

- **There are a few sources which only exhibit long bursts (tau>100 s) with long recurrence times (order 20 d) and PRE: 1RXS J171824.2-402934, SLX 1737-282, 1A 1246-588, M15 X-2, 1RXS J170854.4-321857**
- **Desire to have a GRB-like follow-up for bursts from any of these sources**
  - Since they may be detected in an on-board image rather than as a rate trigger, they should be in the catalog with a large merit
  - Follow-up past 5000 seconds not necessary
  - Expect about 9 per year
- **Superbursts are much more difficult to trigger. Need to filter out:**
  - Background of normal X-ray bursts
  - Persistent emission
  - Superbursts can have the same peak flux as normal bursts, so the filter must be fluence based
  - Possibly could require flight software changes
  - Expect about 2 per year

Superburst Sources

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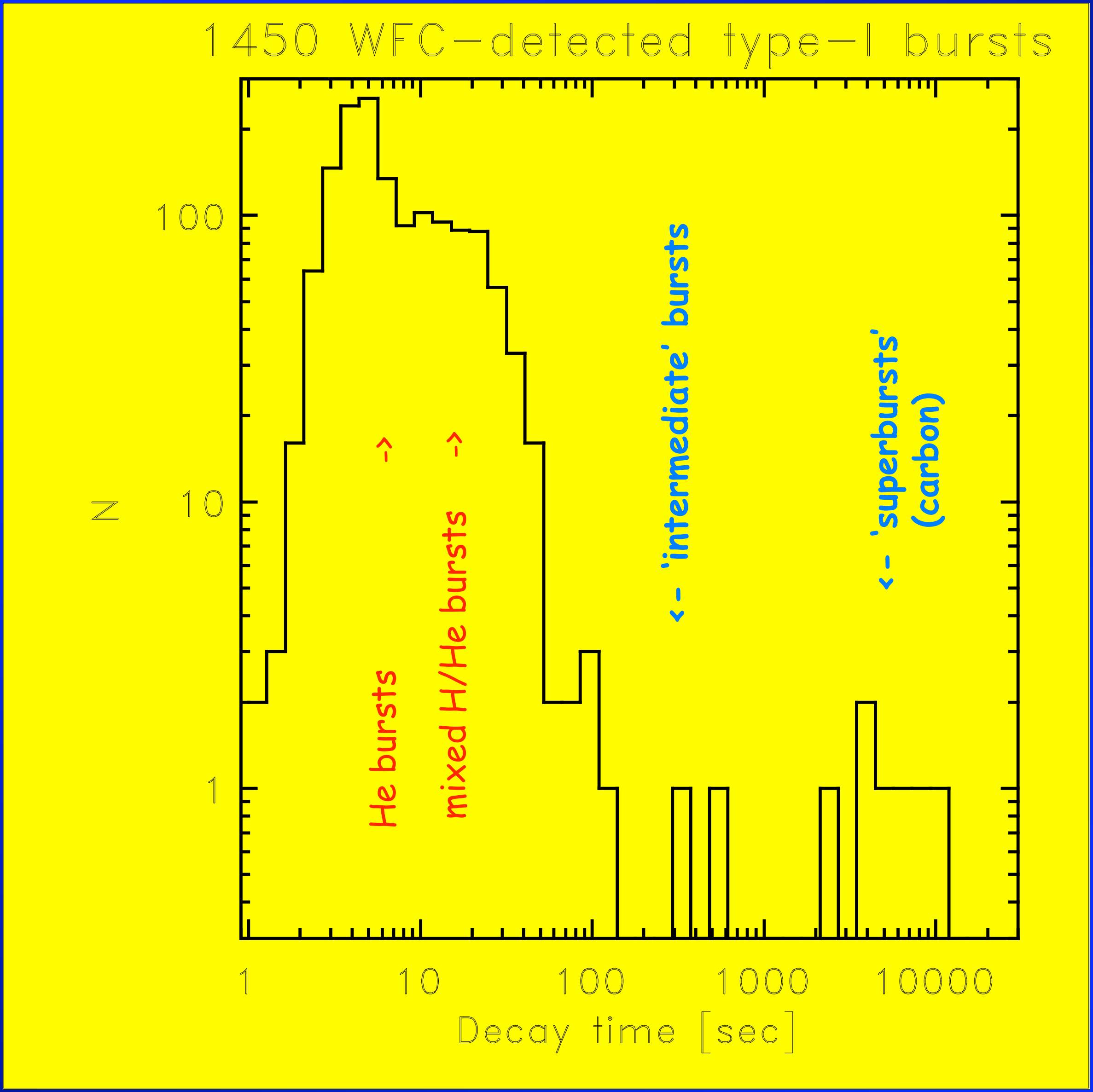
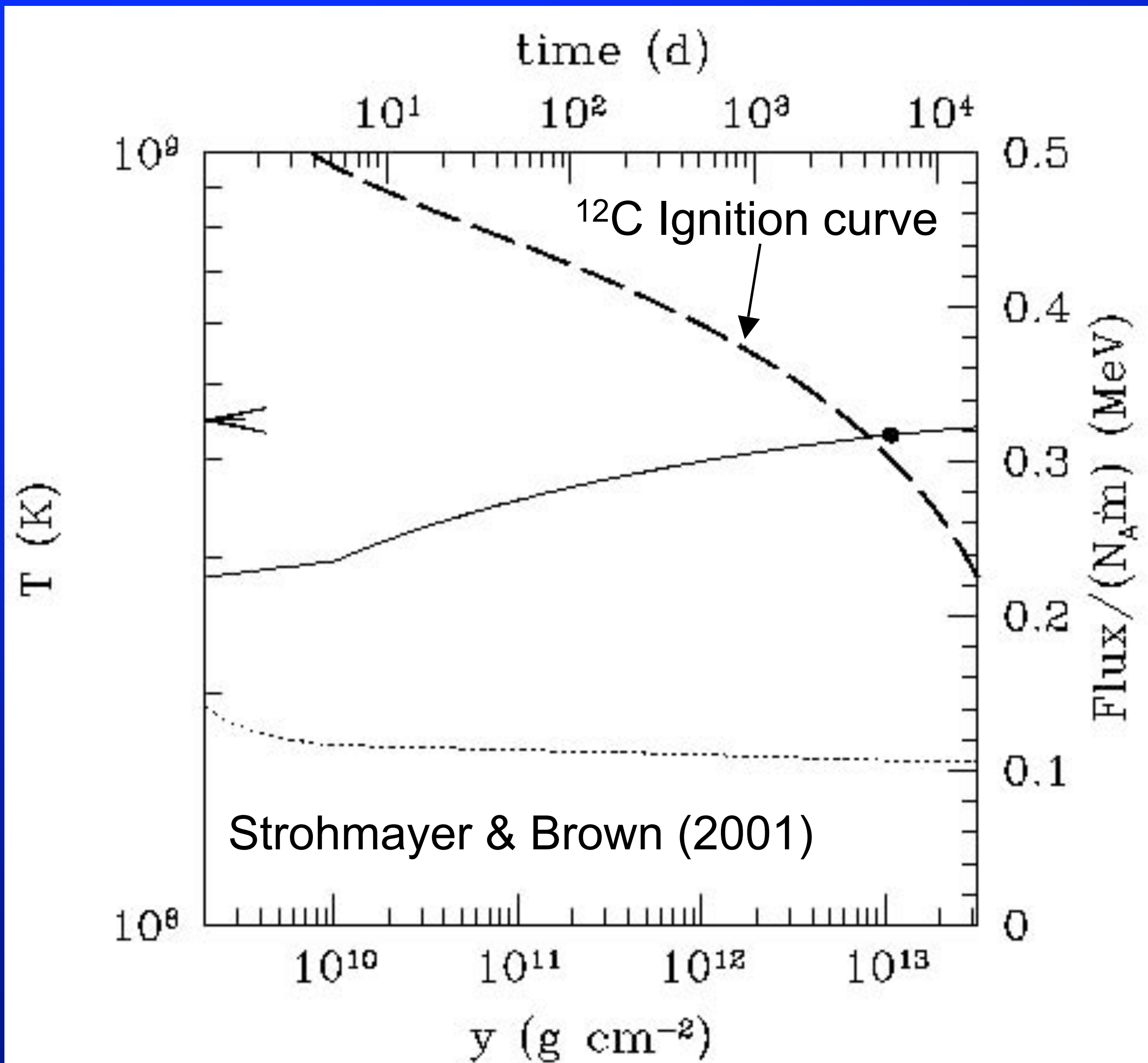
Sources	Observations	Number (recurrence)
4U 1735-44	SAX - WFC	1
4U 1820-30	RXTE - PCA	1
4U 1636-53	RXTE - ASM, PCA	2 (4.7 yr)
KS 1731-260	SAX - WFC	1
Serpens X-1	SAX - WFC	1
GX 3+1	RXTE – ASM	1
4U 1254-69	SAX-WFC	1
4U 0614+091	RXTE-ASM	1
4U 1608-522	RXTE-ASM	1

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	

Distribution of Burst Types

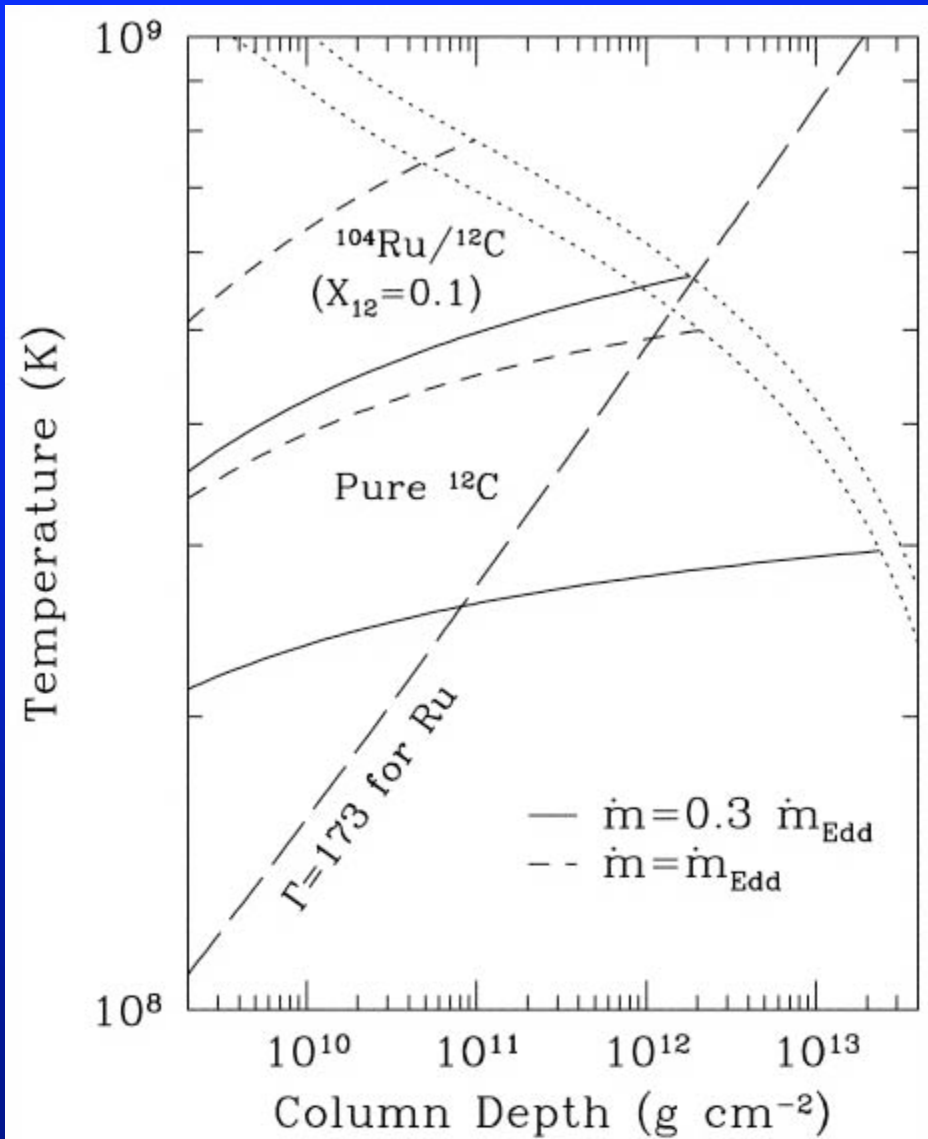


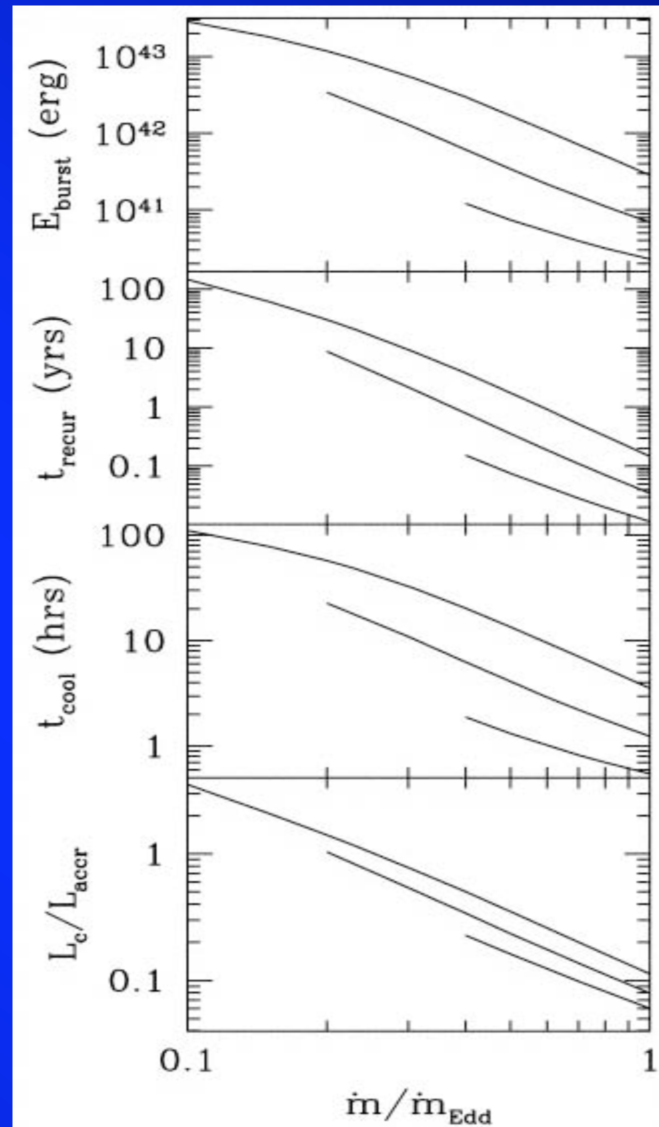
A Carbon "bomb" on a Neutron Star



- 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

Superburst from 4U 1820-30: Carbon Production

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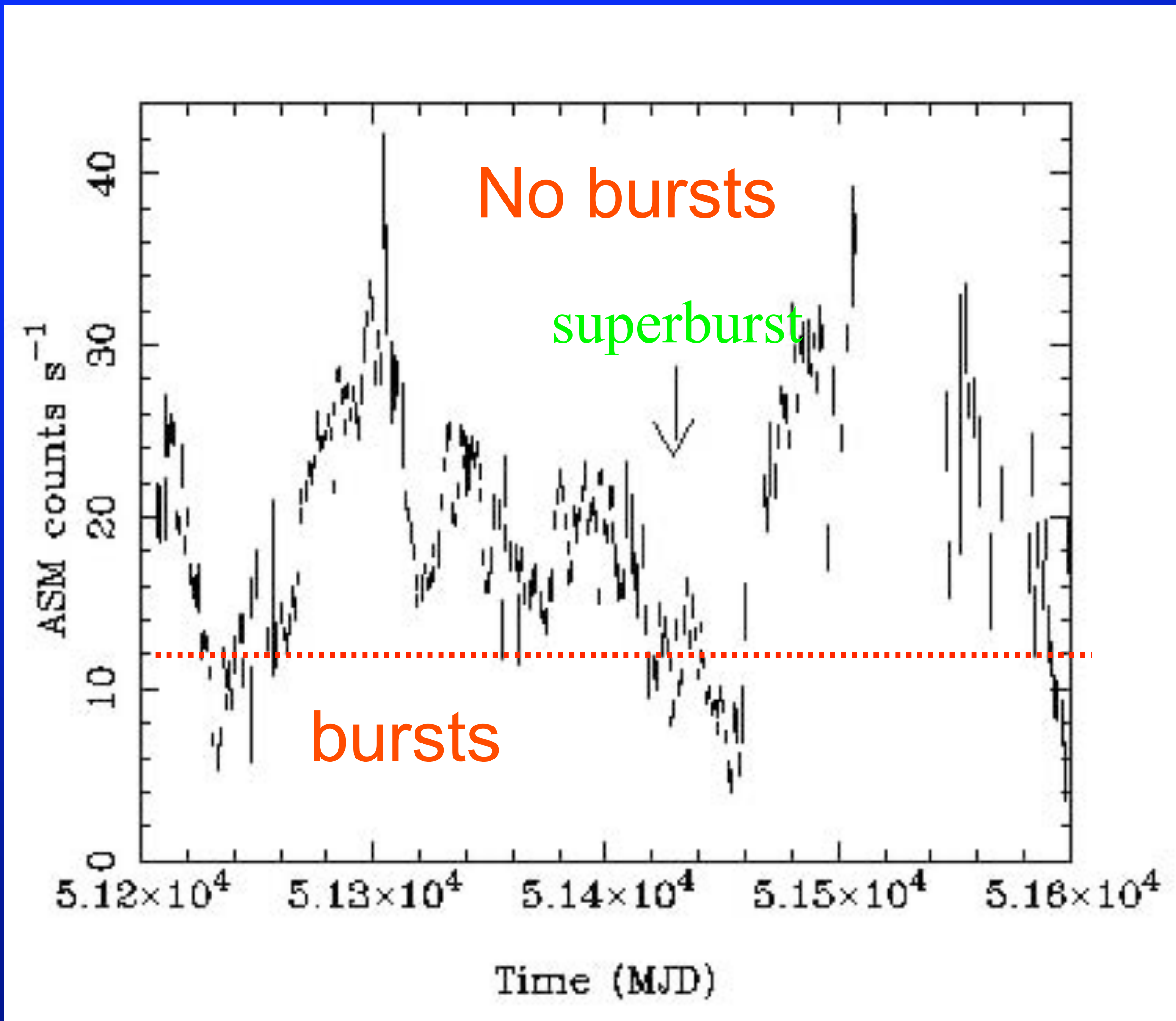

- Thermonuclear (helium) burning is stabilized at high accretion rates (ie. no normal bursts).
- Lower peak burning temperatures will likely synthesize lots of Carbon.
- Higher temperature during unstable burning yields little Carbon

Strohmayer & Brown (2002)

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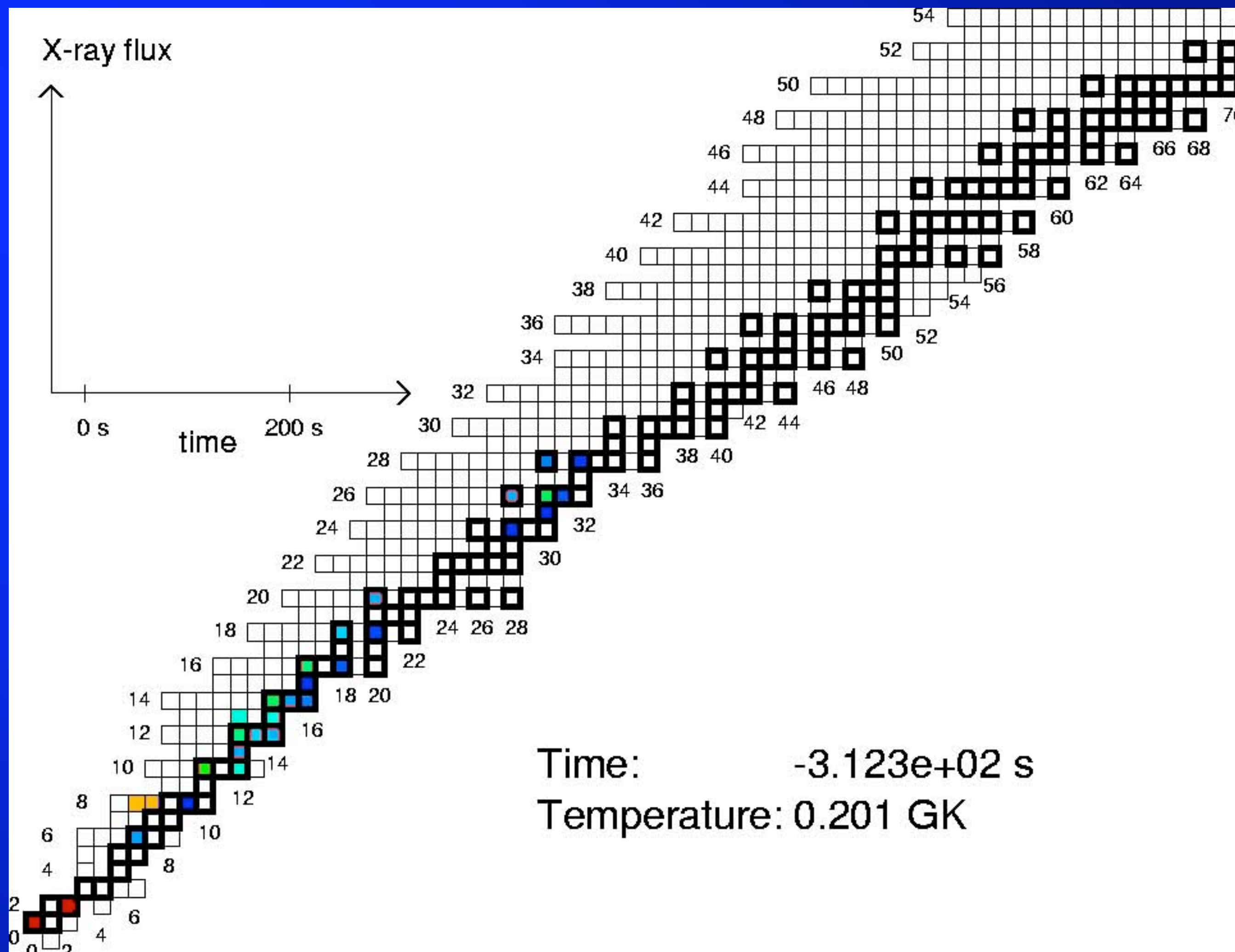
Nuclear flows during X-ray Bursts: With Hydrogen

- 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?



Thanks to Hendrik Schatz (MSU) for the movie

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Superburst Summary

- The accretion disk is ionized by the intense X-ray irradiation from the neutron star, and then becomes neutral again
- A chance to study the structure and ionization properties of accretion disks