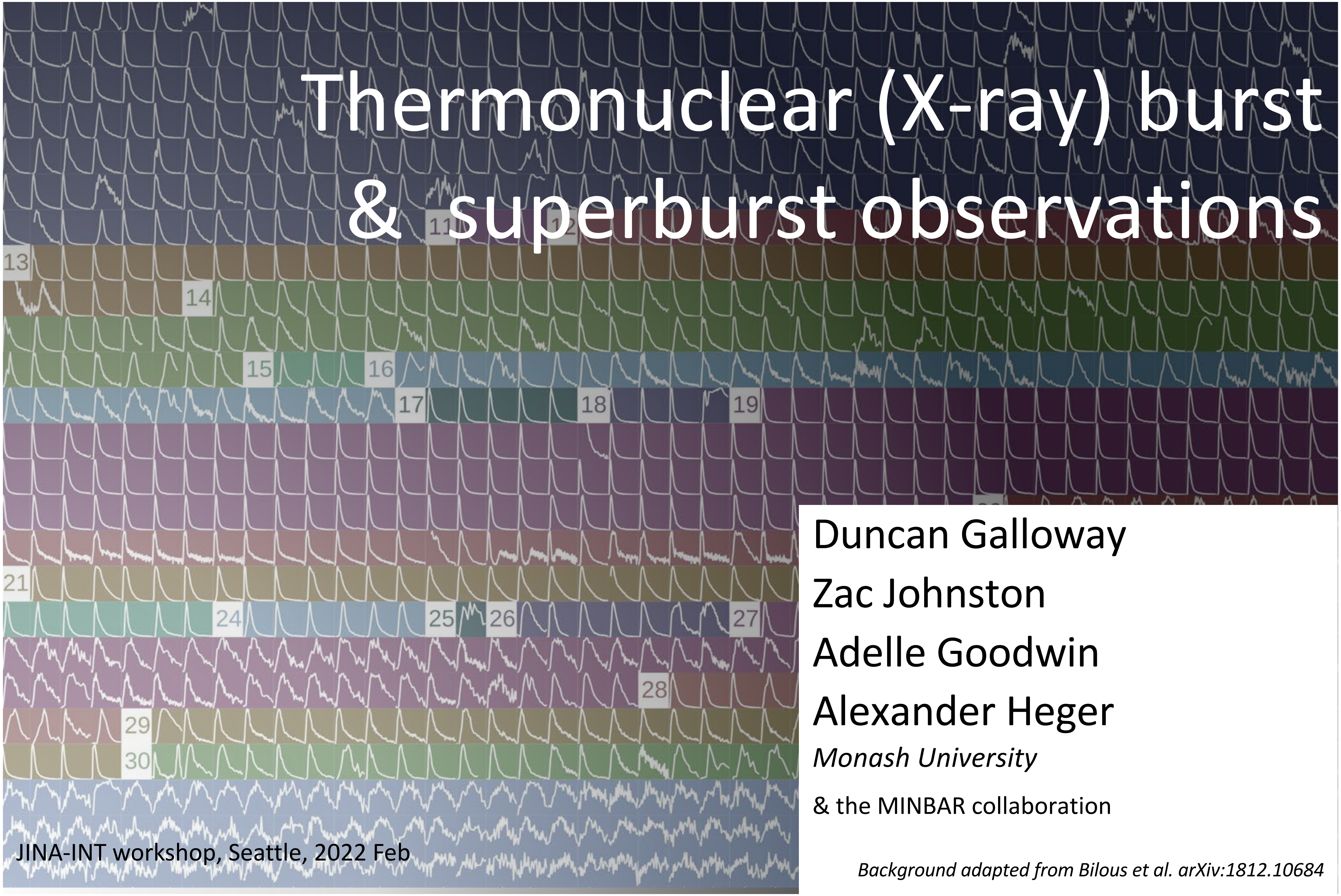
Thermonuclear (X-ray) burst & superburst observations



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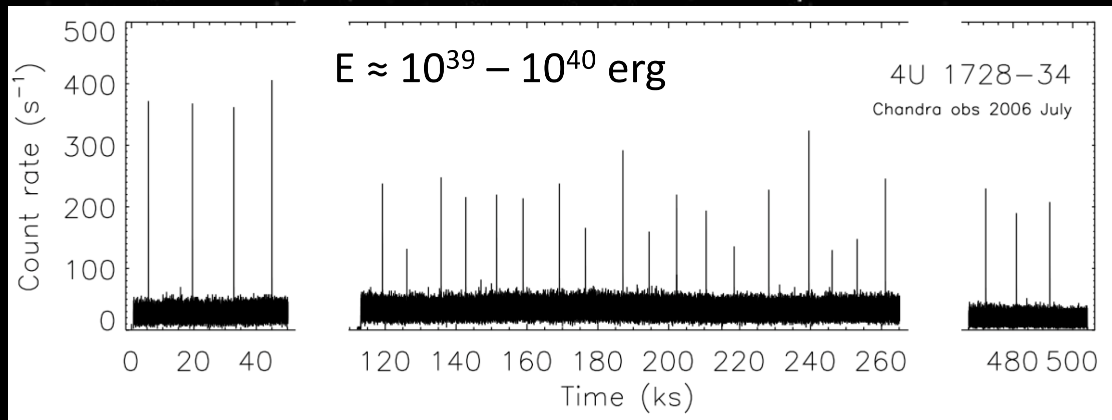
JINA-INT workshop, Seattle, 2022 Feb

Background adapted from Bilous et al. arXiv:1812.10684

Thermonuclear X-ray bursts

- Low-mass X-ray binary systems are thought to accrete through gigayear timescales, spinning up the neutron star (and ultimately producing millisecond radio pulsars)
- Total mass transfer likely results in massive neutron stars (up to twice solar; cf. with Demorest et al. 2010)
- About half of known sources are characterized as transients, with episodes of higher accretion
- Thermonuclear bursts occur when accreted fuel ignites, producing bright X-ray flashes
- ~10^4 events seen (ever – in 't Zand estimate)



Chandra X-ray observation of the prolific burst source 4U 1728-34, showing quasi-regular bursting activity

Burst ignition

- “Normal” (frequent) bursts ignite via the triple-alpha reaction, unstable at these temperatures & densities

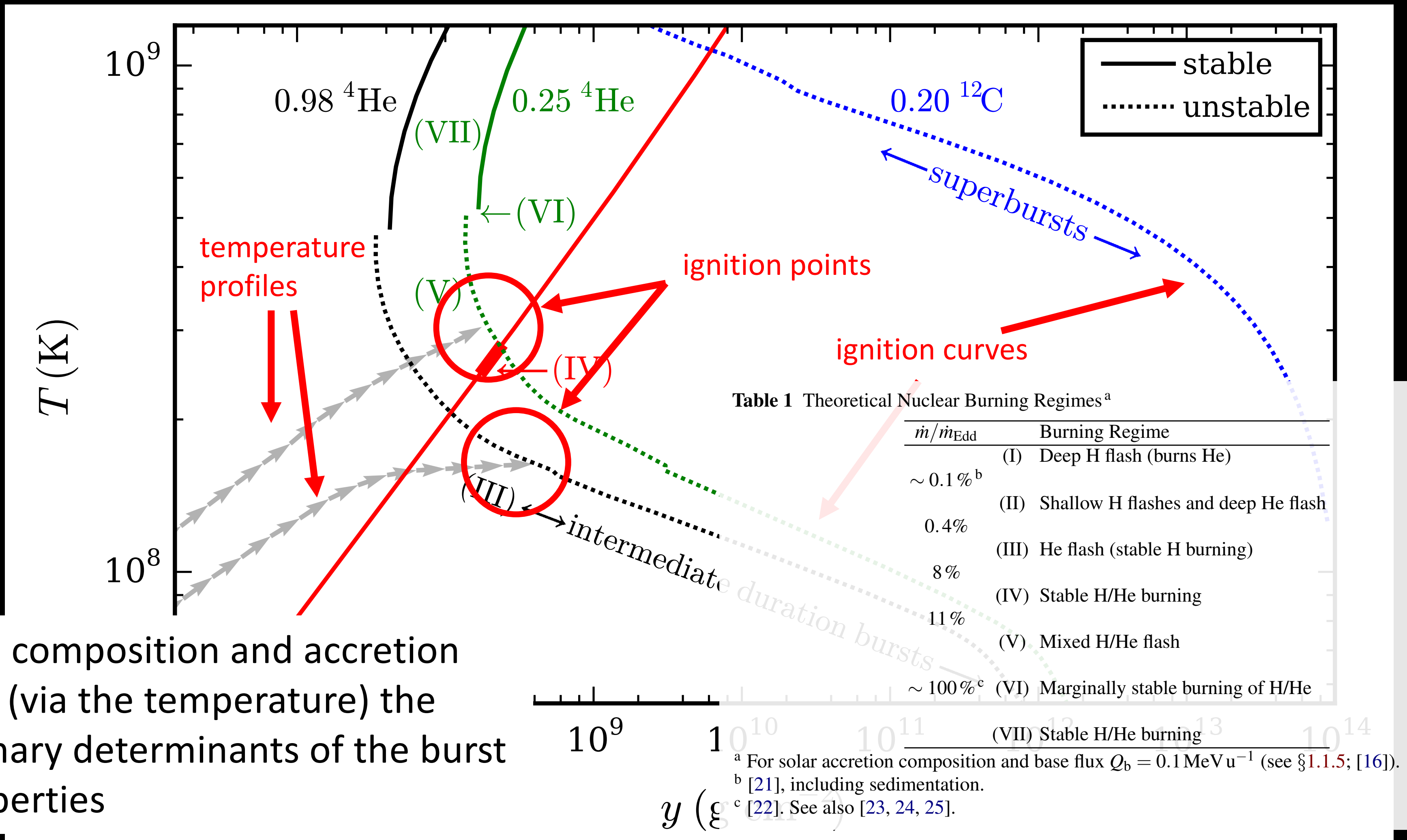


Table 1 Theoretical Nuclear Burning Regimes[a]

$\dot{m}/\dot{m}_{\rm Edd}$		Burning Regime
	(I)	Deep H flash (burns He)
$\sim 0.1\,\%$[b]		
	(II)	Shallow H flashes and deep He flash
0.4%		
	(III)	He flash (stable H burning)
8 %		
	(IV)	Stable H/He burning
11 %		
	(V)	Mixed H/He flash
$\sim 100\,\%$[c]	(VI)	Marginally stable burning of H/He
	(VII)	Stable H/He burning

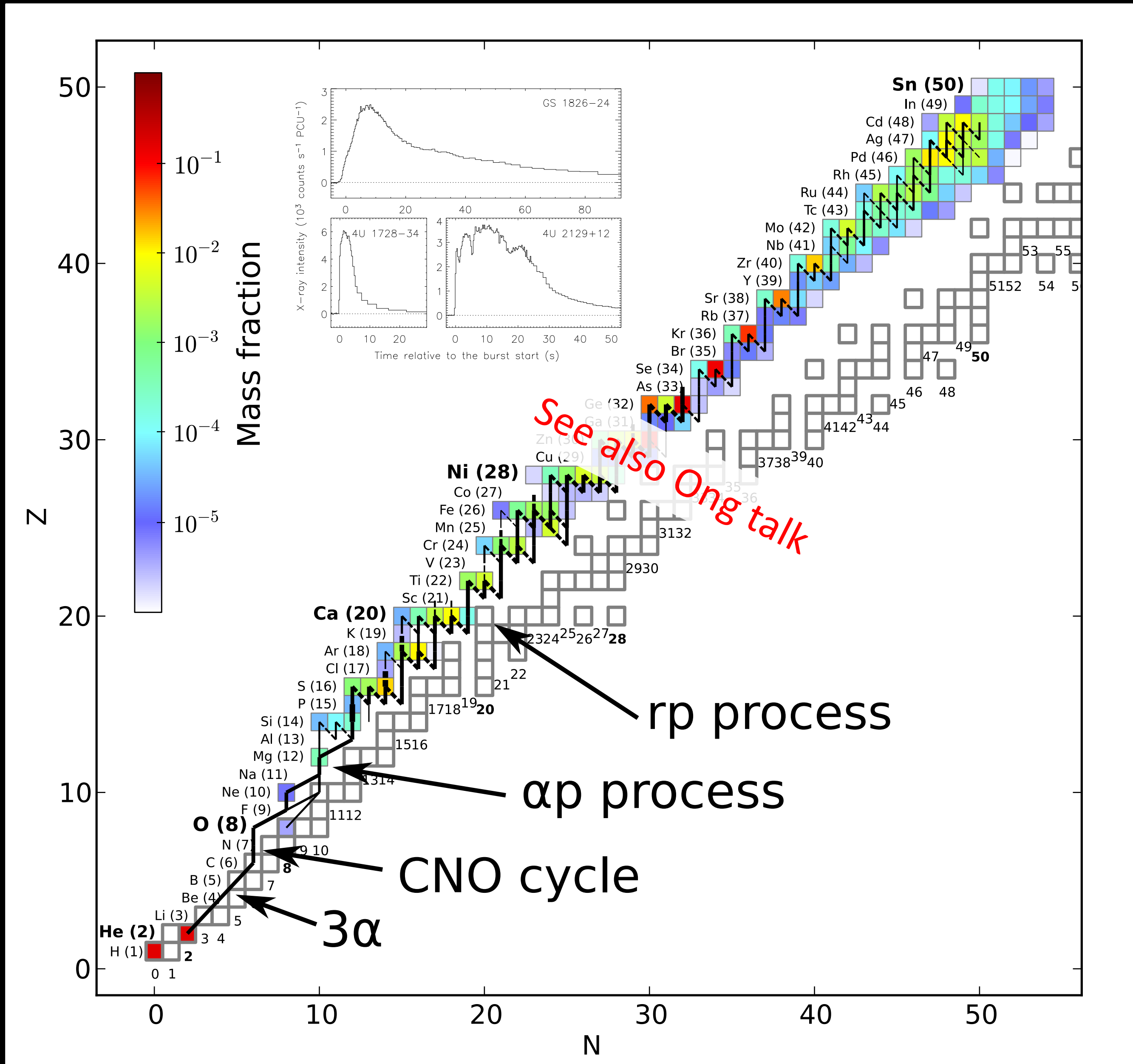
[a] For solar accretion composition and base flux $Q_b = 0.1\,{\rm MeV\,u^{-1}}$ (see §1.1.5; [16]).
[b] [21], including sedimentation.
[c] [22]. See also [23, 24, 25].

Galloway & Keek 2021, arXiv:1712.06227

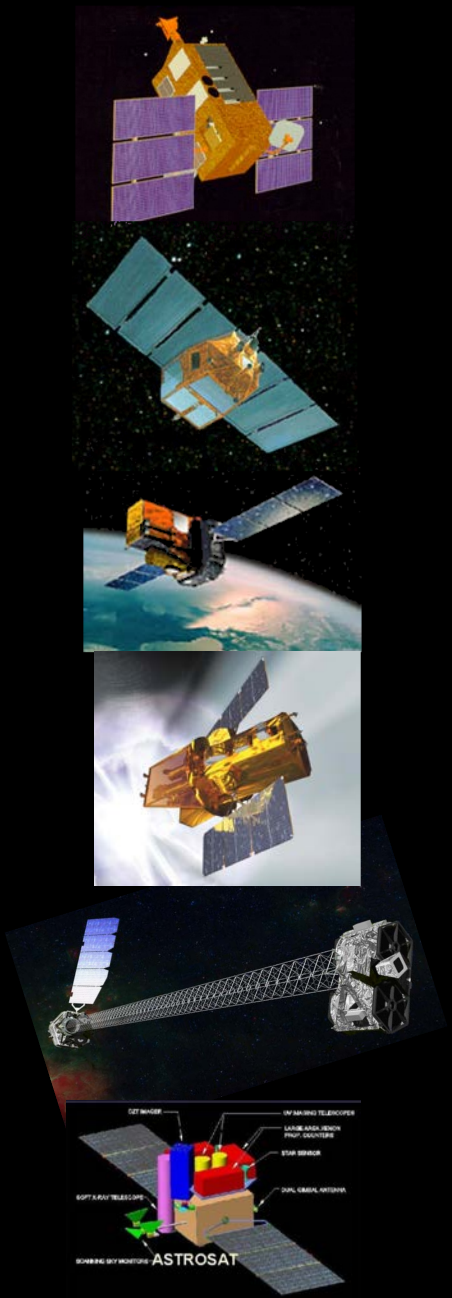
Fuel composition and accretion rate (via the temperature) the primary determinants of the burst properties

Key thermonuclear reactions

- Bursts ignite via the He 3α reaction
- If hydrogen is also present, burning will also take place via the (α,p) and rp processes
  - Leads to a wide range of nuclear "ashes" well beyond Fe
  - Implications for crust, cooling



A long history of observations



First bursts observed in the '70s by *SAS* and many new sources discovered through to the '80s, most notably with *EXOSAT* observations

- *Rossi X-ray Timing Explorer* (*RXTE*) with the Proportional Counter Array (PCA) instrument, featuring high sensitivity & fast (μs) timing, 1995 Dec–2012 Jan +MINBAR

[source for an earlier burst catalogue Galloway et al. 2008, ApJS 179, 360]

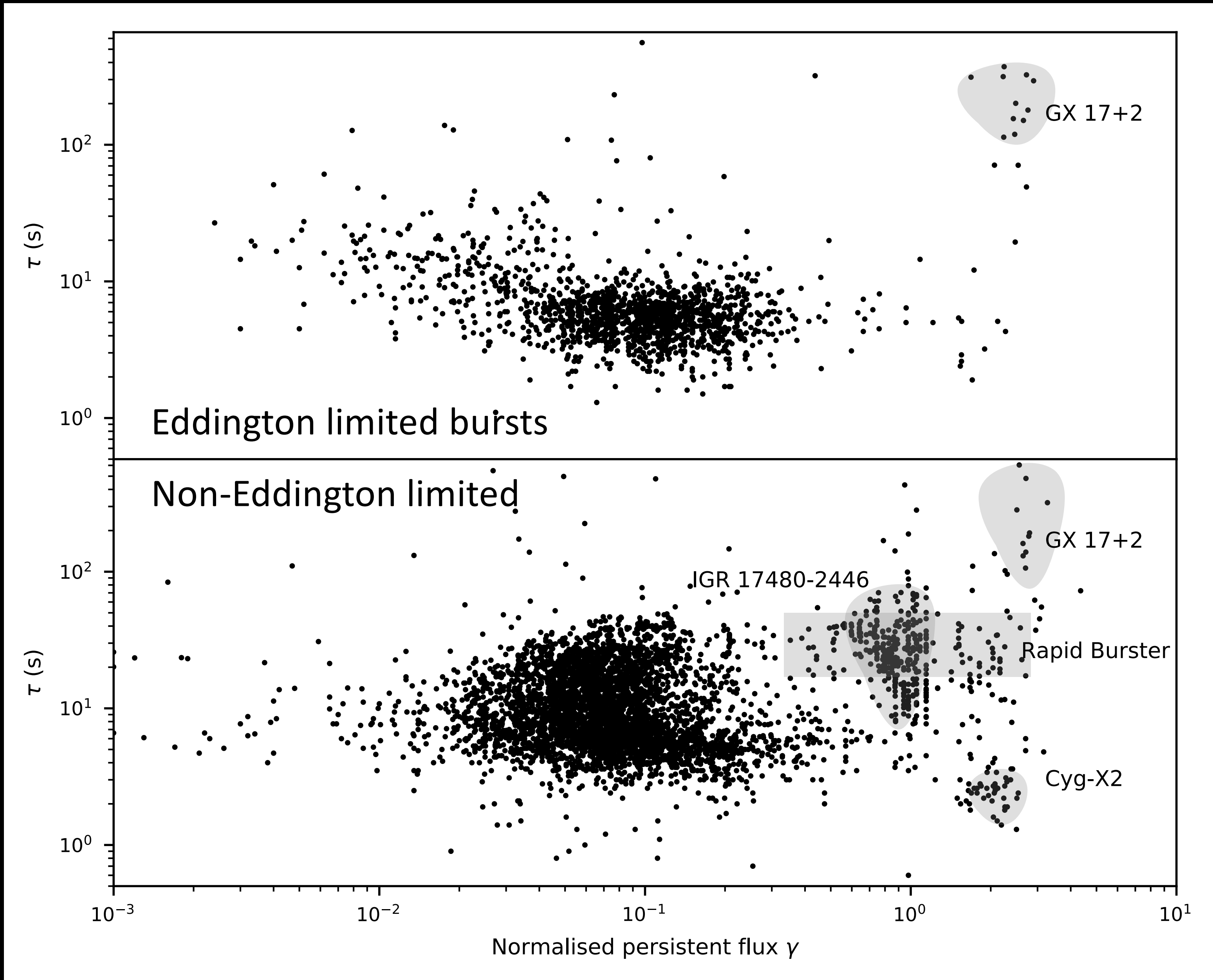
- *BeppoSAX*, Dutch-Italian mission with the Wide Field Camera (WFC) observing many burst sources simultaneously with moderate sensitivity, through '90s +MINBAR
- *INTEGRAL* mission by ESA, with the Joint European Monitor of X-rays (JEM-X); wide-field, moderate sensitivity, 2002 onwards +MINBAR
- *Swift* & MAXI; wide-field, detecting new transients, long bursts etc.
- *NUSTAR*, hard X-ray sensitivity, launched 2012 June
- *ASTROSAT*, launched Sep 2015, LAXPC large-area detector
- NICER, deployed to the ISS in 2017 June, focus on X-ray pulsations and bursts

The Multi-INstrument Burst ARchive

- The Multi-INstrument Burst ARchive seeks to gather all the bursts observed by long-duration missions *BeppoSAX*/WFC, *RXTE*/PCA, and *INTEGRAL*/JEM-X; data release 1 now available
  http://burst.sci.monash.edu/minbar
- Complementary strengths of (high sensititivity) PCA instrument with wide fields of WFC and JEM-X, to provide an improved global view of burst behaviour and rare events
- >7000 events from 85 (of 112) sources, drawn from more than 100,000 observations
- Includes analyses of the observations; and burst oscillations in events observed by *RXTE*/PCA

Straczynski, J.M. (1994)

MINBAR overview



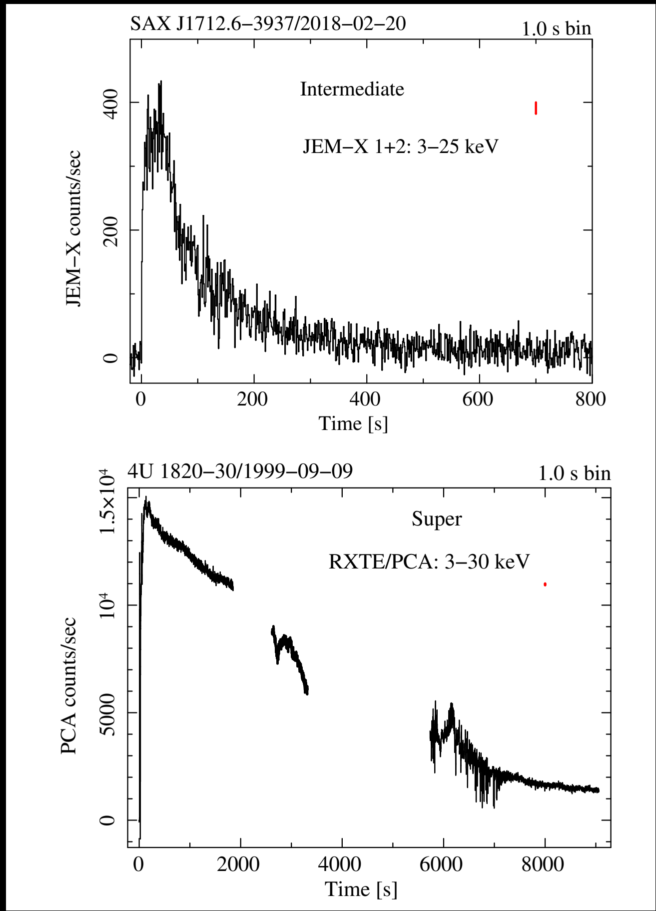
Shows the *burst timescale* τ (depends upon the burst fuel) as a function of accretion rate

Broad groups comprising the bulk of burst sources, but also outliers for atypical sources

Some of this behavior is understood, some not

Intermediate-duration and “super” bursts

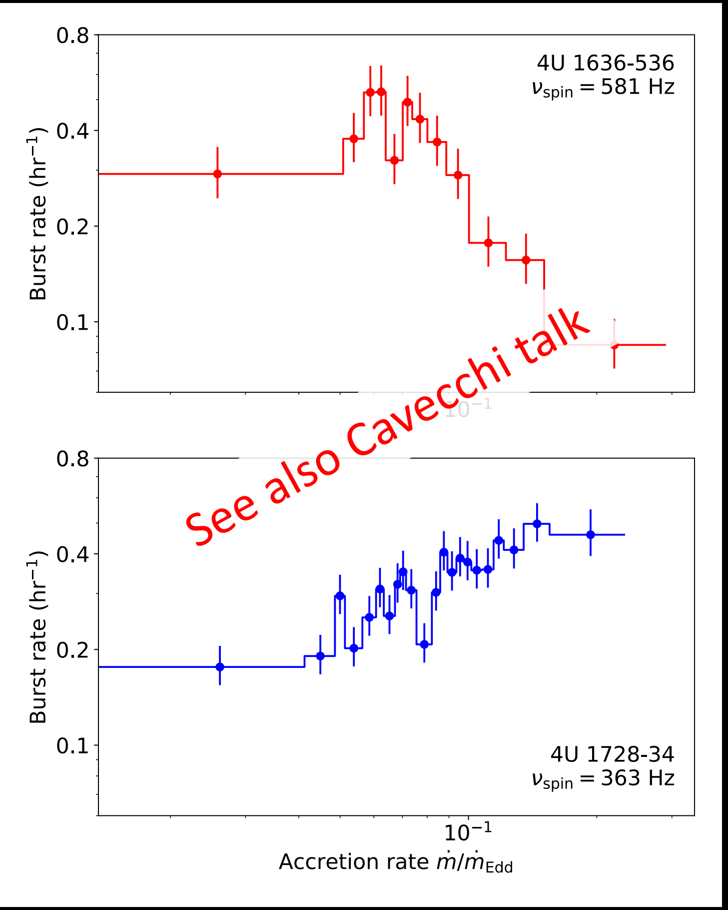
- Extreme tail of the “frequent” (H/He) burst population go to durations of minutes
- Associated typically with low accretion rates, ultracompact (H-deficient) donors and long burst intervals, allowing accumulation of a deep He layer
- Separate class of bursts with durations of *hours*, the so-called “super” bursts; first example identified in 1996 Cornelisse et al. (2000, ApJL 357, L21)
- And now ”hyperbursts”! Page et al. (2022, arXiv:2202.03962)
- All extremely challenging to observe, due to unpredictability and long recurrence times (vs. typical duty cycles of a few % for X-ray observatories)



Alizai et al. (2022, in prep)

Still some fundamental questions

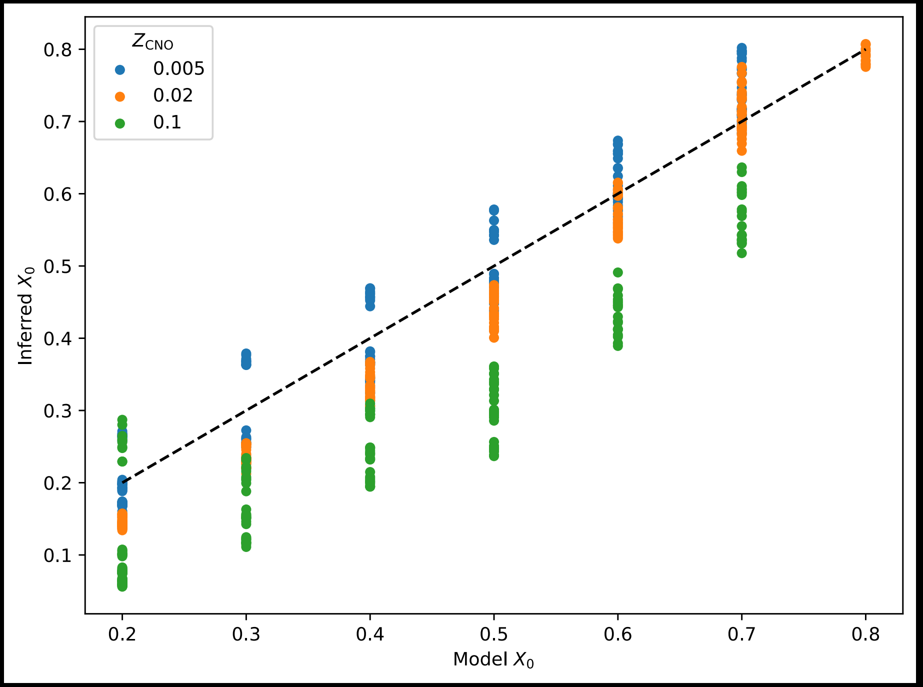
- It has long been puzzling that for some sources the burst rate *decreases* as the accretion rate increases, the opposite of the predictions of numerical models
- Burst properties are also weird, with long (irregular) recurrence times & short timescales (He rich fuel)
- Also issues with the fuel production for superbursts, thought to burn C instead of H/He; maybe a role for stable burning in both these puzzles
  e.g. Keek & Heger (2016, MNRAS 456, L11)
- Ignition depth (inferred from fluence) is too low for superbursts – additional sources of heat that contribute to earlier ignition Cumming et al. (2006, ApJ 646, 429)



Galloway et al. (2018, ApJL 857, L24)

What can observations tell us?

- On their own, measurements of burst *lightcurve, fluence, recurrence time* & hence (with the *persistent flux*) the *"alpha"-value*, give us only very coarse constraints on the burst source
- Can give a rough indicator of distance from *photospheric radius-expansion* (PRE) bursts e.g. Kuulkers et al. (2003, A&A 399, 663)
- MINBAR motivates development of tools that allow us to deduce fuel composition (H-fraction) from burst properties – *concord*
- Example shown comparing results from simulated observations with unknown CNO-mass fraction, inclination etc.



http://github.com/outs1der/concord

What *can't* observations (alone) tell us?

- Can't tell us much about thermal conditions in the deep crust (which affects cooling) particularly because for the most common mixed H/He bursts, the fuel layer is heated by steady H-burning prior to ignition e.g. Heger et al. (2004, ApJ 671, L141)
- Exception is very energetic bursts which ignite in "deep" layers, so called "intermediate-duration" bursts e.g. Falanga et al. (2008, A&A 484, 43) & superbursts e.g. in 't Zand (2017, arXiv:1702.04899)
- Even for these events we need to compare to cooling models
- More detailed comparisons of H-rich bursts can in principle constrain (some) individual reactions e.g. Meisel et al. (2019, ApJ 872, #84)

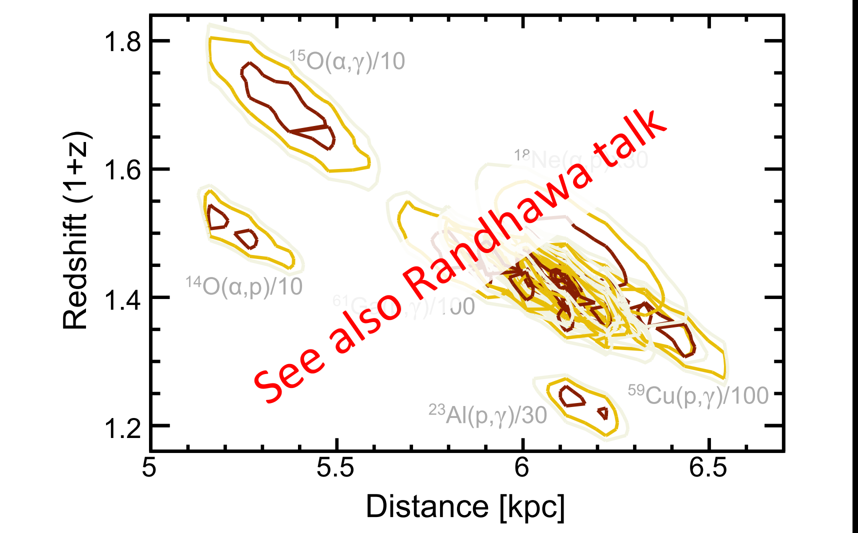
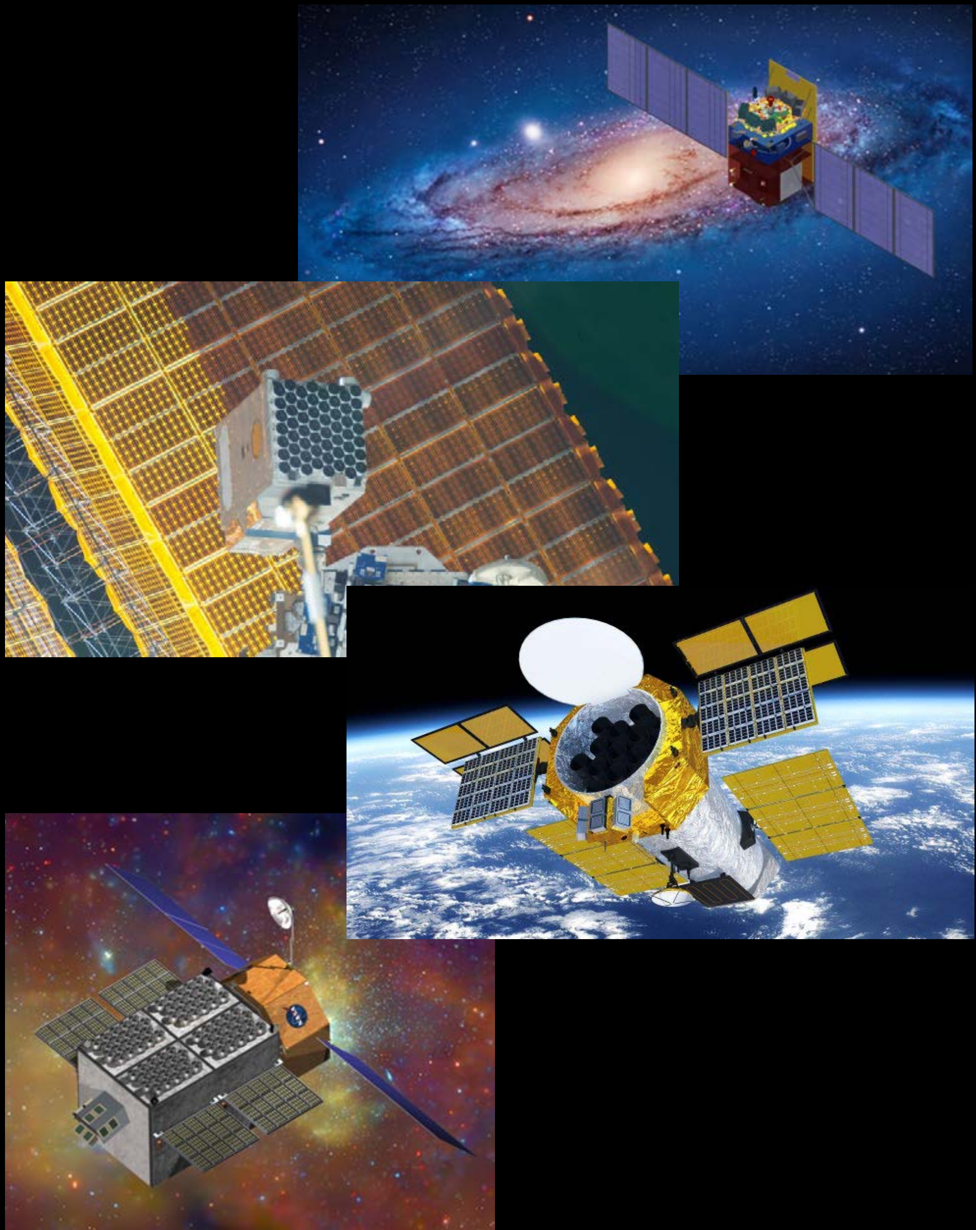


Figure 7. The 68% (red lines), 95% (yellow lines), and 99% (gray lines) confidence intervals for the distance-redshift determination performed comparing light curves shown in Figure 1 to the GS 1826-24 2007 bursting epoch. Cases significantly deviating from the result for the baseline calculation are labeled.

The future: new observations



- Current and future instruments offer excellent capabilities for burst studies
- But…
- Difficult to improve on the current sample substantially purely in numerical terms
- Strategic observations are the answer
- E.g. *NICER* specifically offers good low-energy response to probe spectral evolution during PRE bursts Keek et al. 2018 ApJ 856, L37

Summary and future prospects

- We (think we) understand many aspects of burst phenomenology, but much work is yet to be done
- Large burst samples like MINBAR provide a key resource, & allow us to prioritise sources to target for more intensive observation, and with new instruments offering new capabilities
- Soon-to-be-released intermediate-duration & superburst sample will offer additional opportunities for modellers
- Model-observation comparisons are key IMO to
  - Validate numerical models
  - Improve our understanding of how the burst ignition conditions arise
  - Constrain source properties including fuel composition, accretion rate, and possibly also neutron star mass and radius
  - Constrain the rates of individual nuclear reactions & motivate nuclear experiments