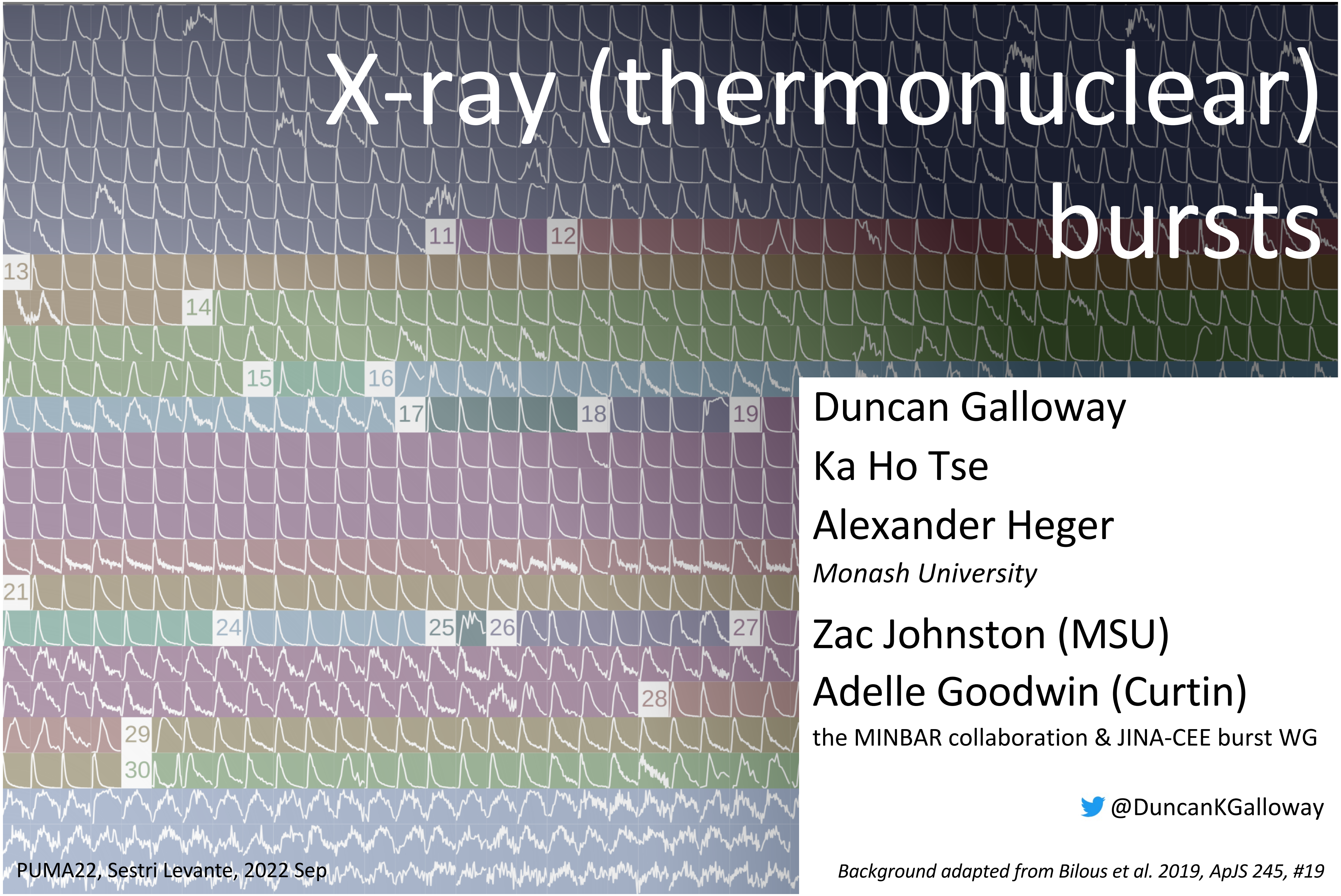
X-ray (thermonuclear) bursts



Duncan Galloway
Ka Ho Tse
Alexander Heger
Monash University
Zac Johnston (MSU)
Adelle Goodwin (Curtin)
the MINBAR collaboration & JINA-CEE burst WG

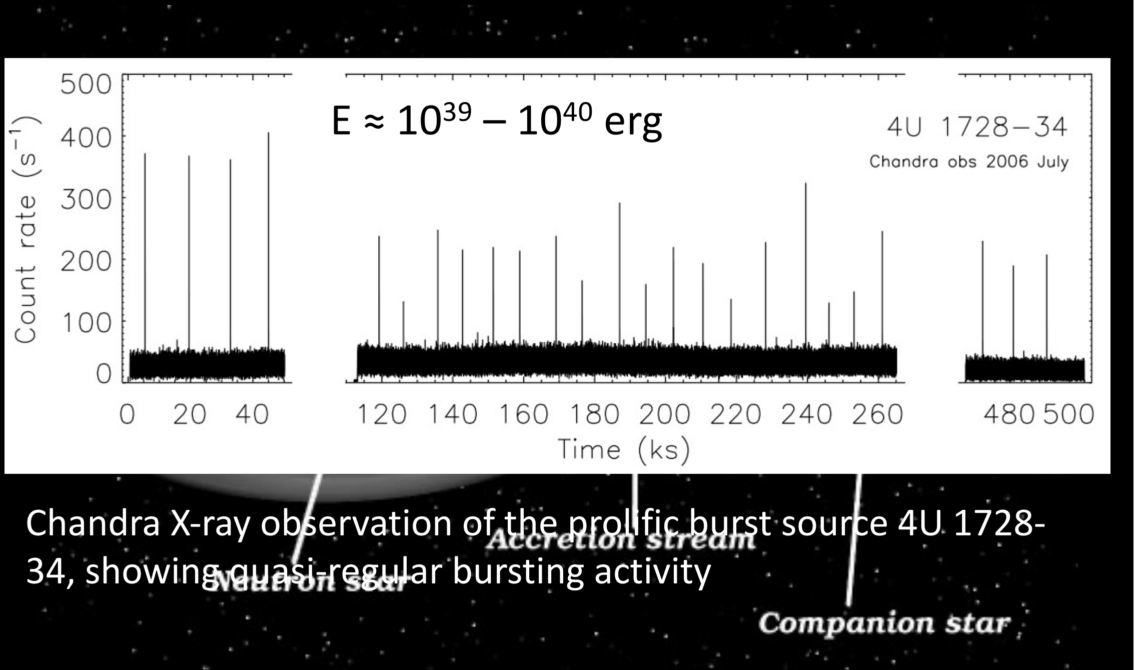
@DuncanKGalloway

PUMA22, Sestri Levante, 2022 Sep

Background adapted from Bilous et al. 2019, ApJS 245, #19

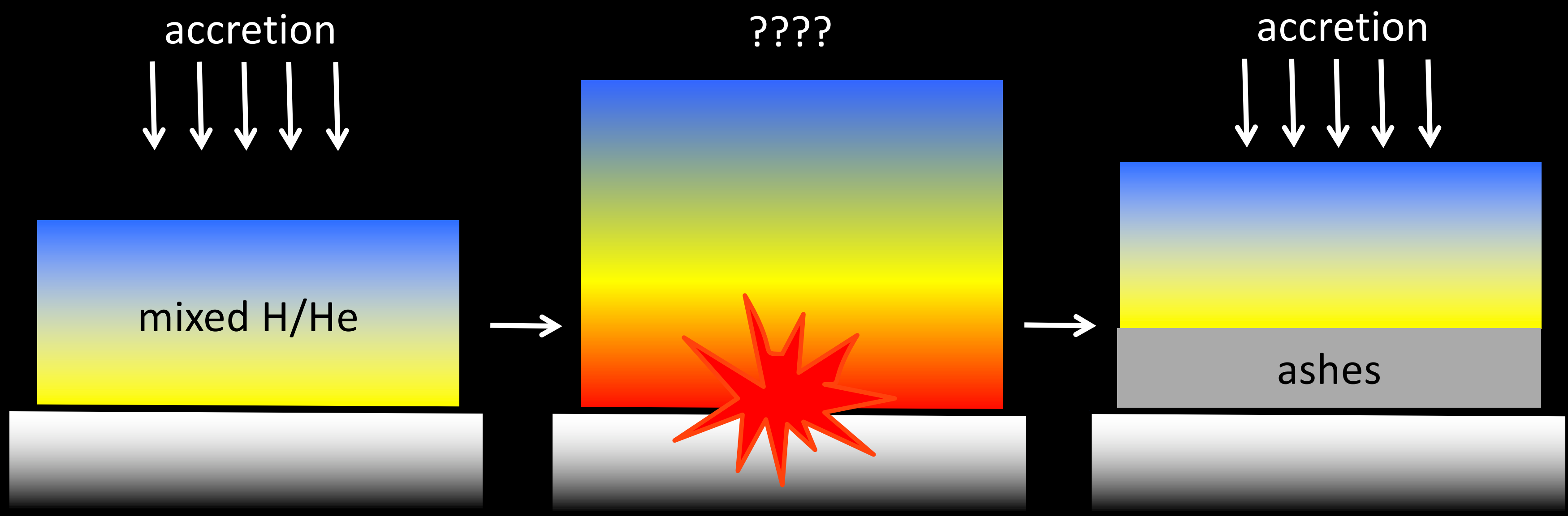
Neutron star ”explosions” – X-ray bursts

- *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 (with all instruments to date)

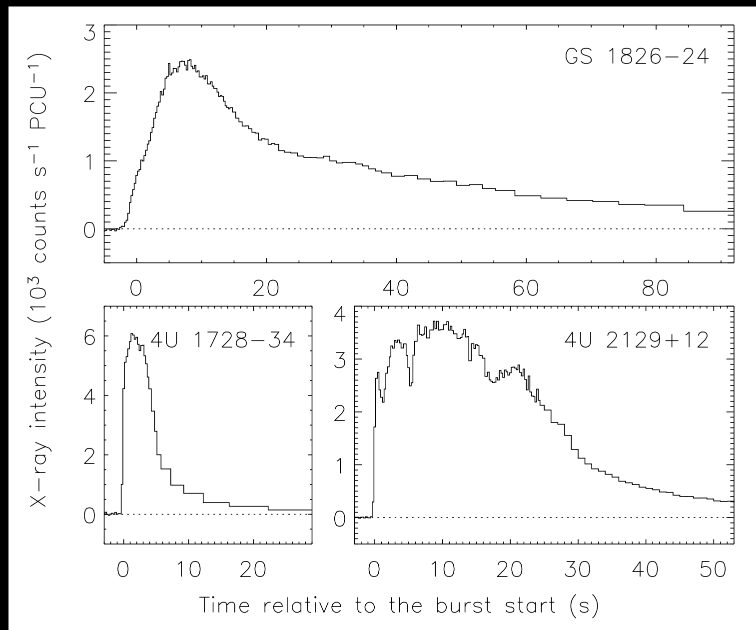


Chandra X-ray observation of the prolific burst source 4U 1728-34, showing quasi-regular bursting activity

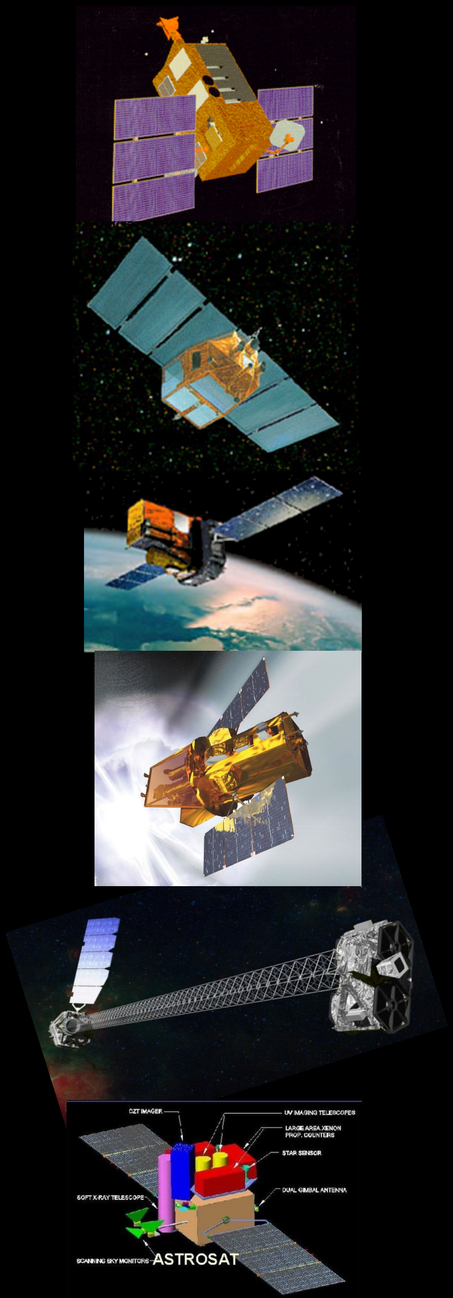
Thermonuclear burst physics



- This process repeats on timescales of hours-days, depending upon the accretion rate & fuel composition
- About 110 known sources
  http://burst.sci.monash.edu/sources
- Most accrete a mix of H/He, but some “ultracompacts” accrete (almost) pure He



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

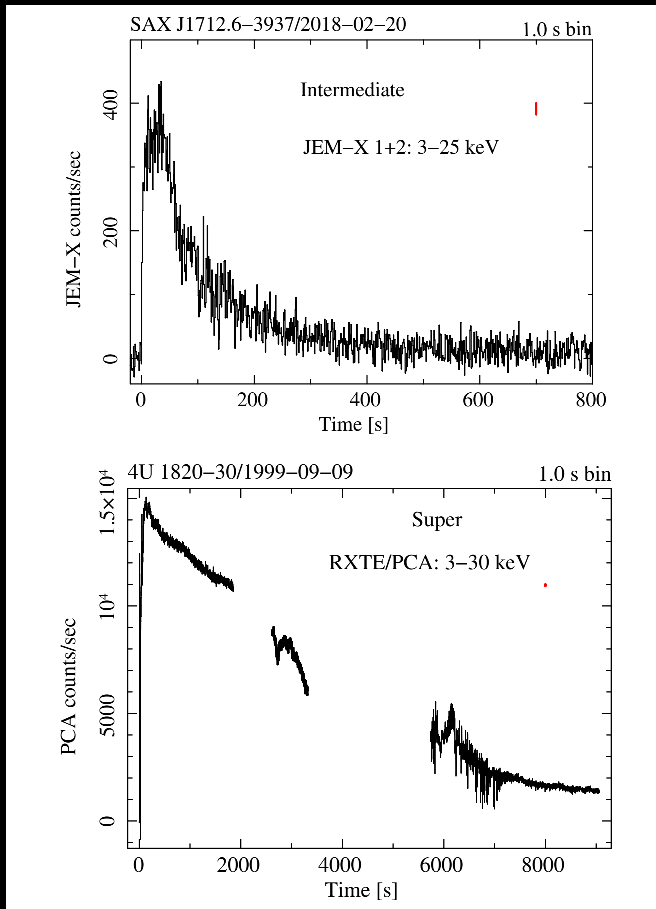
- *Rossi X-ray Timing Explorer* (*RXTE*) with the Proportional Counter Array (PCA) instrument, featuring high sensitivity & fast (μs) timing, 1995 Dec–2012 Jan +MINBAR

[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

Intermediate-duration and “super” bursts

- Normal “frequent” (H/He) bursts typically last 10 s through to ~1 min, but can reach durations of tens of minutes
- Long bursts associated 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)
- Rare bursts are 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)

A key diagnostic for neutron star binaries

- Presence of bursts indicates a NS accretor, as opposed to a BH which otherwise have similar obs. properties
- *Photospheric radius-expansion* bursts reach the Eddington luminosity, indicate the distance Kuulkers et al. 2003, A&A 399, 633
- *Burst oscillations* identify the neutron star spin e.g. Ootes et al. 2017, ApJ 834, #21
- Time-resolved spectroscopy used to infer NS mass & radius e.g. Özel et al. 2016, ARAA 54, 401

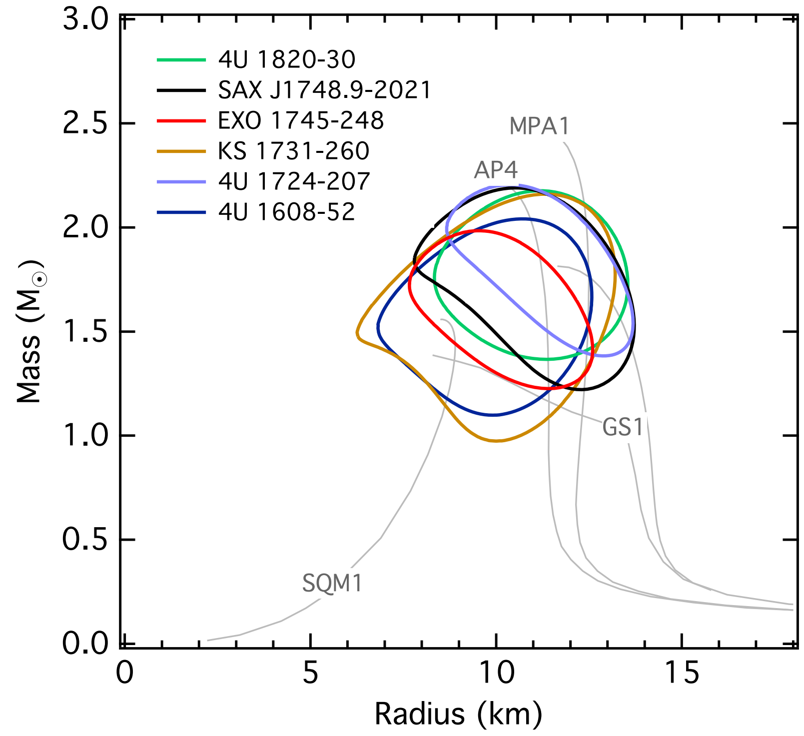


Figure 11. The combined constraints at the 68% confidence level over the neutron s (right) all neutron stars in low-mass X-ray binaries during quiescence.

The correct data selection criteria and approaches to systematic errors remain uncertainty and there is no single consensus in the community! See e.g. Poutanen et al. 2014, MNRAS 442, 3777

Burst ignition

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

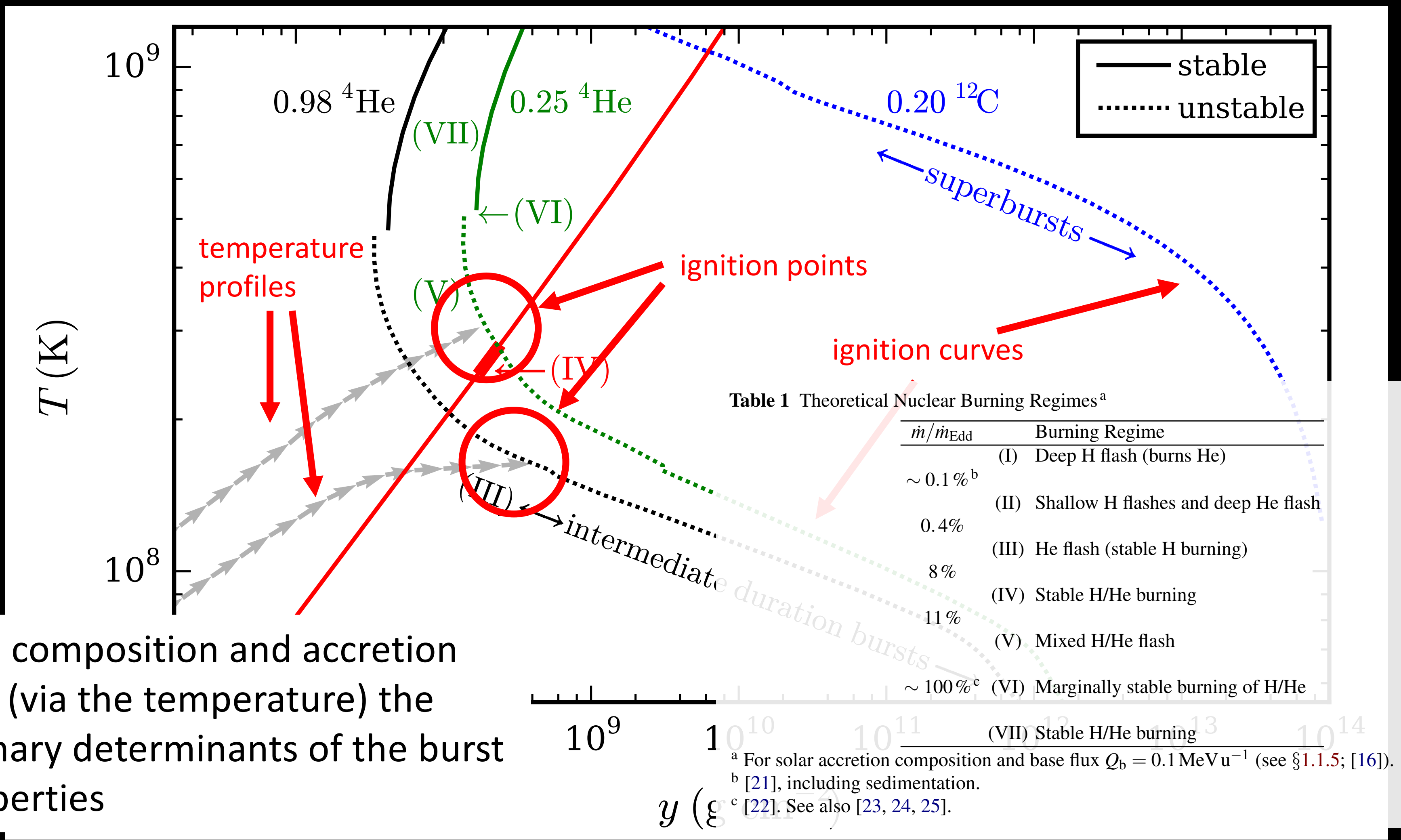


Table 1 Theoretical Nuclear Burning Regimes[a]

$\dot{m}/\dot{m}_{\rm Edd}$	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

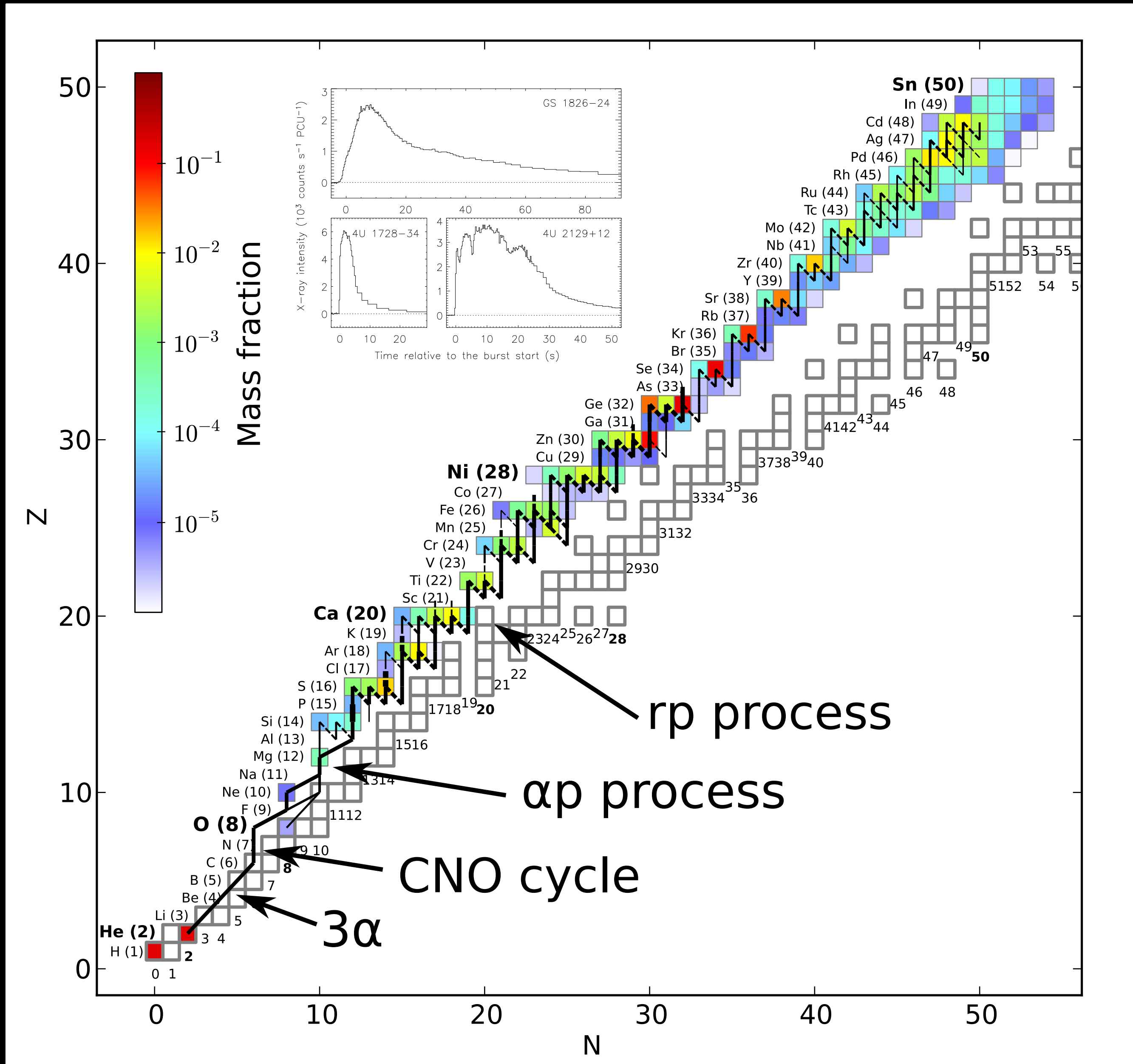
[a] For solar accretion composition and base flux $Q_{\rm b} = 0.1\,{\rm MeV\,u^{-1}}$ (see §1.1.5; [16]).
[b] [21], including sedimentation.
[c] [22]. See also [23, 24, 25].

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

Galloway & Keek 2021, arXiv:1712.06227

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



Seeing bursts through a 1D lens

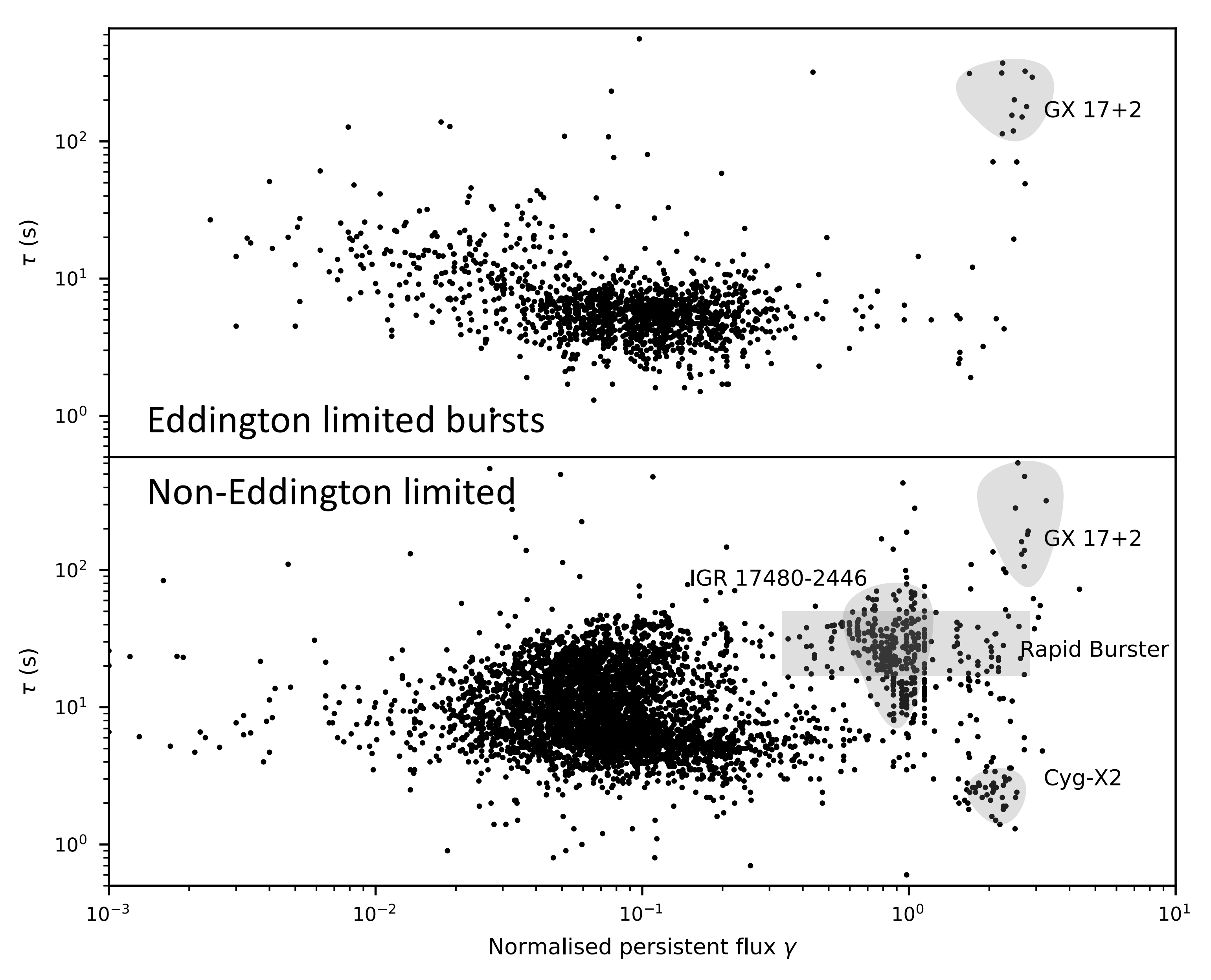
- We can't directly identify what fuel is burning & what nuclear reactions are taking place, so we have to compare our observations (burst rate, energy, lightcurve shape) with *numerical simulations* to infer system properties
- These simulations are generally limited to 1D due to the requirement for extensive nuclear networks (and hence computational expense) as well as uncertainty about 3D effects
- It's a necessary assumption that the burst fuel spreads (evenly?) over the neutron-star surface, and ignites completely, producing uniform emission; although demonstrably false in many cases
- Other astrophysical uncertainties (distance, emission anisotropy, fuel composition etc.) may be resolvable by doing more detailed comparisons; at different accretion rates; and/or incorporating different types of measurements

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



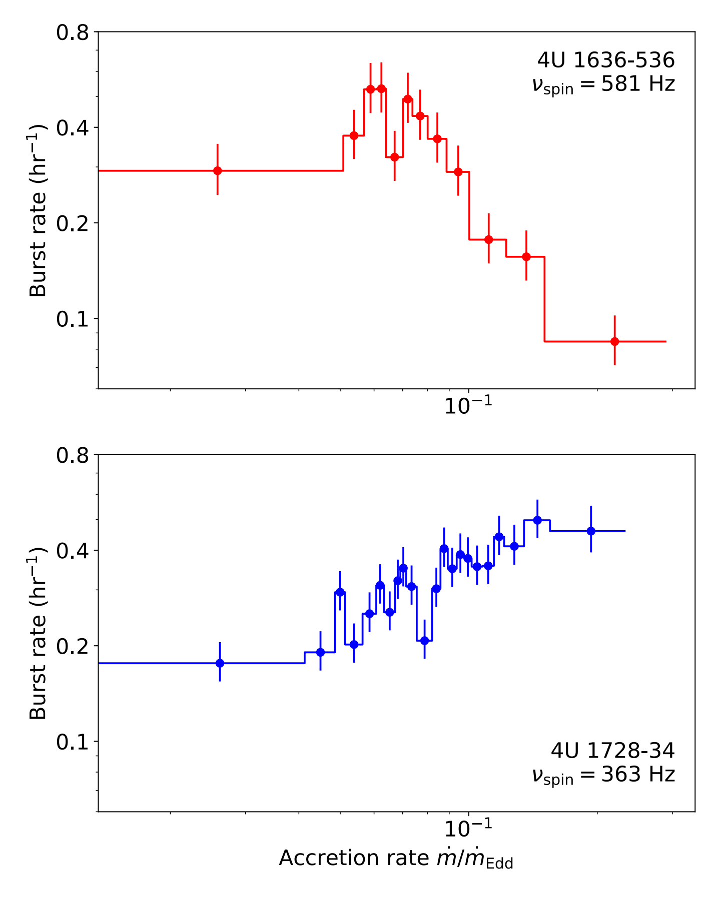
Shows the *burst timescale* τ (depends upon the burst fuel) as a function of accretion rate

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

Some of this behavior is understood, some not

Still some profound puzzles

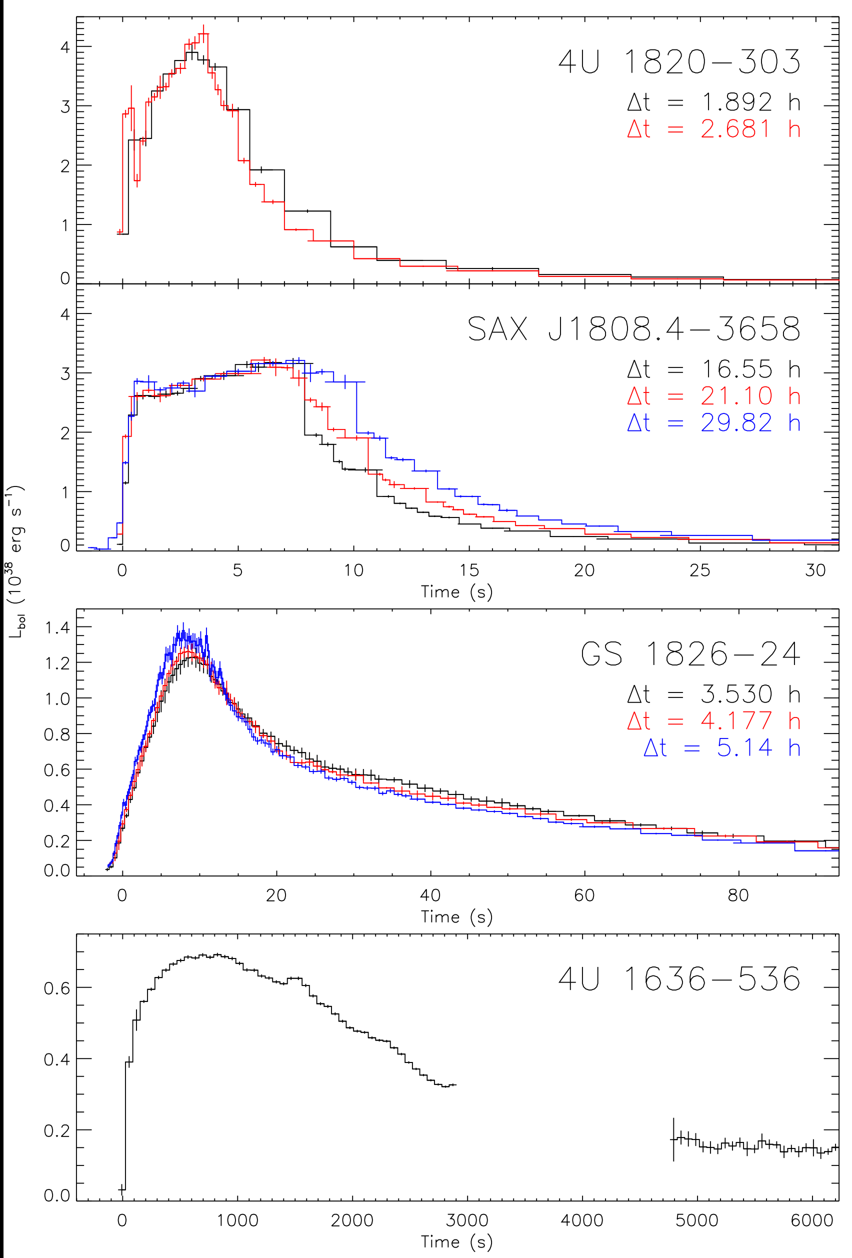
- It has long been known that for some sources the burst rate *decreases* as the accretion rate increases, the opposite of the predictions of numerical models
- Burst properties are also weird, with long (irregular) recurrence times & short timescales (He rich fuel)
- Remarkably, rotation seems to play a role in this turnover, with the *maximum burst rate* occurring at *lower accretion rates* for *faster-spinning* neutron stars
- Perhaps explained by an increasing role for equatorial steady burning as accretion rate rises, plus additional rotationally-induced mixing Cavecchi et al. 2020, MNRAS 499, 2148



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

Verifying burst models against observations

- We assembled a set of observed bursts with well-constrained recurrence times Galloway et al. (2017, PASA #34); see also http://burst.sci.monash.edu/reference
- Serve as test cases for multiple codes (KEPLER, MESA etc.) to understand variations between models
- Enable multi-epoch comparisons to resolve astrophysical uncertainties
- GS 1826–24 the "Clocked burster" Meisel (2018, 2019); Johnston et al. (2020, MNRAS 494, 4576)
- SAX J1808.4–3658 401 Hz AMSP Johnston &c (2018); Goodwin &c (2019)
- Can we also improve accessibility to the simulation results?



Simulating entire transient outbursts

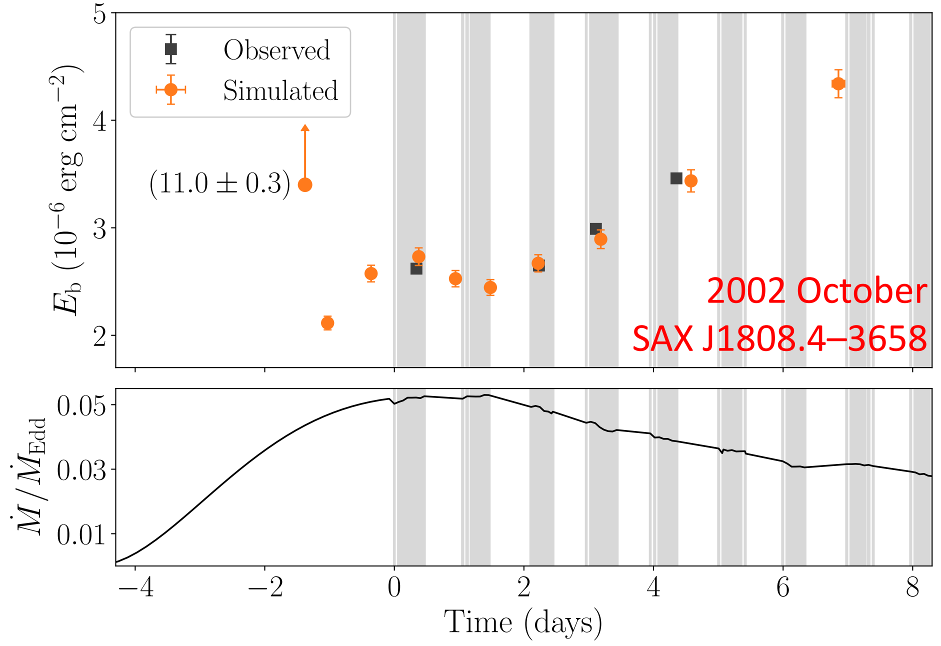
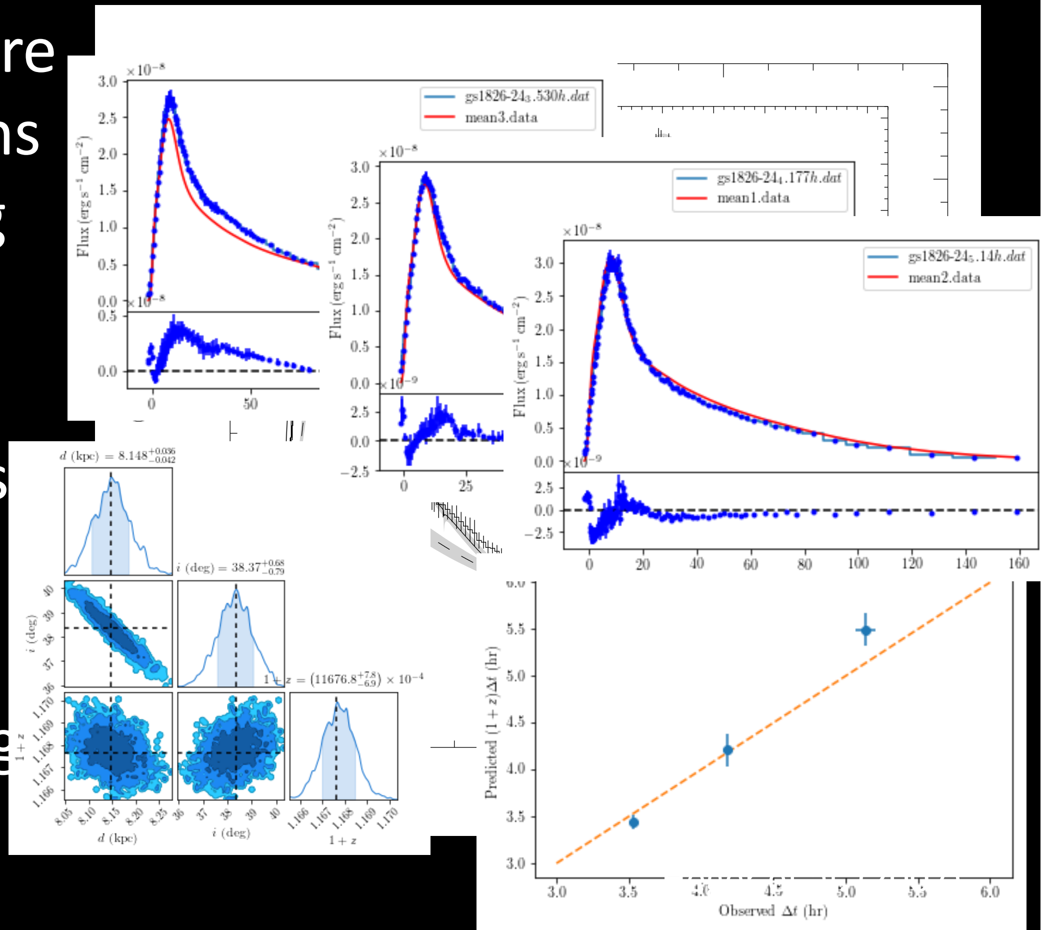


Figure 3. Upper panel: Fluence, E_b, of the modelled burst sequence against the four observed bursts. Lower panel: the time-varying accretion rate over the event, as a fraction of the Eddington-limited accretion rate. The vertical grey bands indicate when the telescope was collecting data. Note that extra bursts predicted by the model fall outside these observing windows. As is typical for KEPLER models, the first burst was anomalously energetic, and its off-axis E_b is indicated next to the arrow. The fluences have been calculated from the burst energy with the scaling factor $c_2 = 4\pi d^2 \xi_b \approx 1.05 \times 10^{45}$ cm^2, chosen such that the RMS error with observations is minimised (§ 3.2).

- Work at Monash has focused on extending the model-observation comparisons to provide more stringent tests
- Time-varying accretion rate input to KEPLER to simulate a ~week-long outburst of bursts
  Johnston &c MNRAS 477, p2112 (2018)
- Parameter space exploration limited due to computational cost of KEPLER model runs, but promising in principle
- Parallel efforts with cheaper "settle" code

The future: improved model-observation comparisons

- Multiple-epoch comparisons are likely *necessary* to resolve degeneracies (e.g. in GS 1826-24, the "Clocked burster")
- Despite being the best studied burst source, there remain uncertainties about the fuel composition
- We lack suitable tools to compare multiple sets of burst simulations against models (& incorporating other observables)
- Also difficulties balancing (e.g.) recurrence time comparisons vs lightcurves
- "concord" software to do this is now in development and testing
https://github.com/outs1der/concord



Improved inference tools

- Burst model-observation comparisons can be combined with other data and fed into your favourite MCMC sampler
- Bilby is both a cute Australian marsupial and a versatile MCMC inference library adopted for use by the LIGO Scientific Collaboration Ashton &c 2019, ApJS 241(2) #27
- Potentially a good choice for MCMC newbies, user friendly, choice of samplers, good documentation

Figure 11. All letters from the BILBY logo, generated using the BILBY package; see Section 7.

Summary and the future

- Ongoing difficulties in fully incorporating all sources of information (multi-”messengers”) related to bursts
- Development of improved software tools for thermonuclear burst observation-model comparison ongoing, can take advantage of lots of modelling expertise & accumulated observations
- Incorporate efforts to resolve astrophysical uncertainties and understand the burst physics in more detail
- Among current objectives are “baseline” burst model-observation comparison cases that can be easily accessed by anyone
- These cases can be adapted to incorporate additional constraints from different types of data including observational, theoretical, nuclear experimental
- Can also be used to further extend the scope of burst modelling, apply to additional sources, etc.