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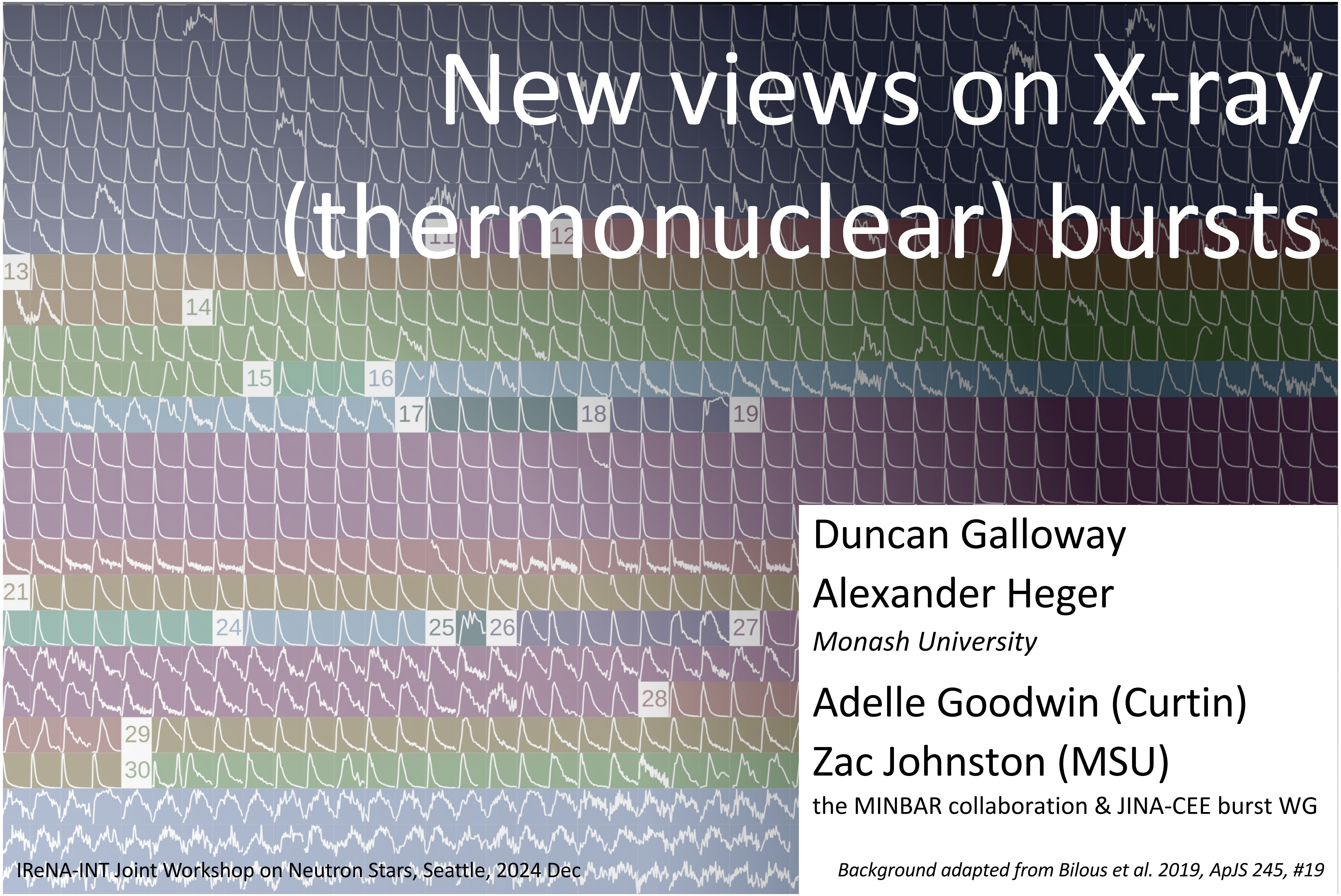

New views on X-ray (thermonuclear) bursts

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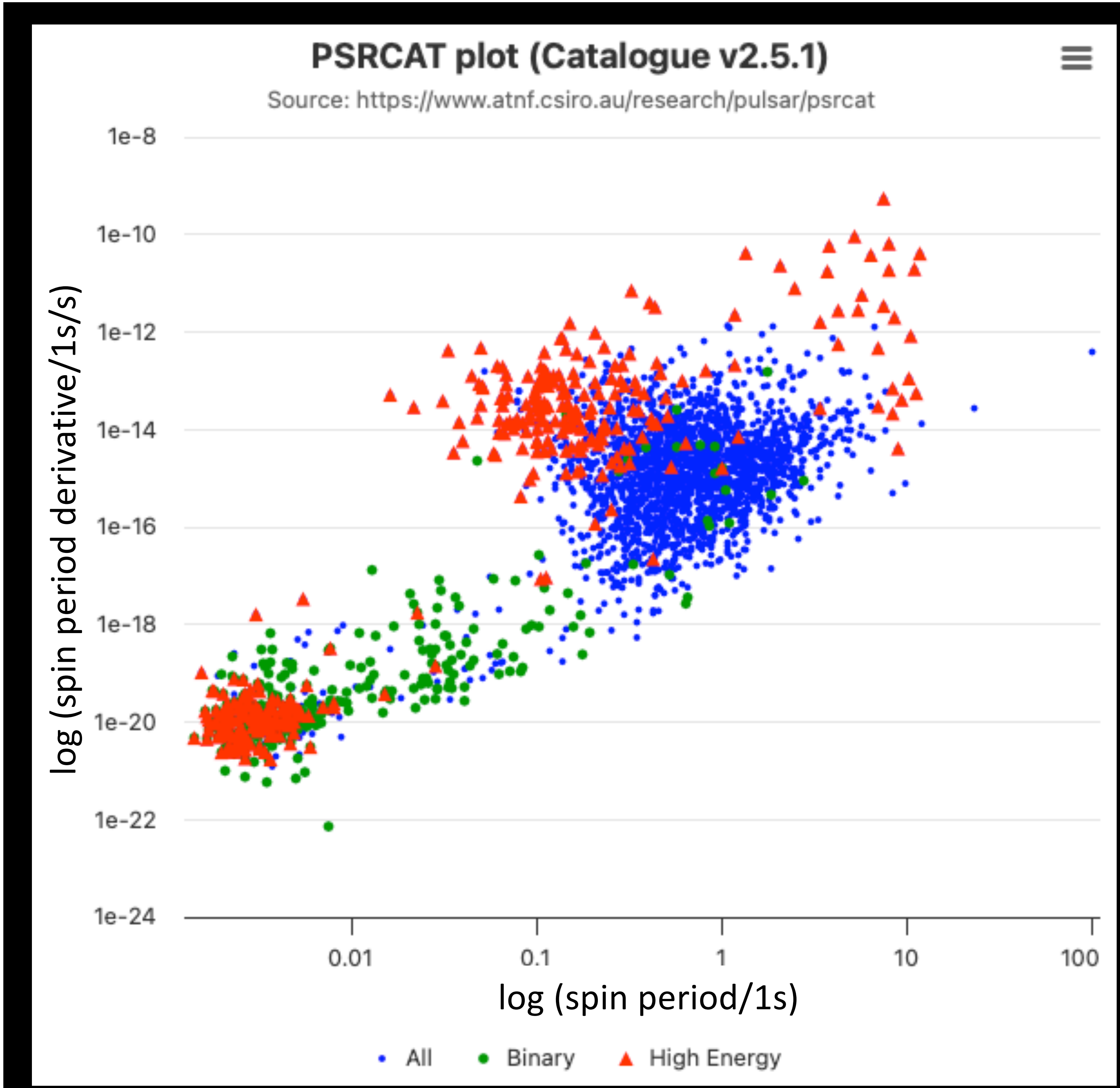
IReNA-INT Joint Workshop on Neutron Stars, Seattle, 2024 Dec

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

Neutron stars – stellar “zombies”

- Understood to form from supernova explosions of ˜8–20 $M_\odot$ stars
- Typical masses 1.4–2$M_\odot$, radius ≈10 km (likely exceeding *nuclear density* in the core!)
- Largest known population is from *radio pulsars*, a few thousand examples
- Most interesting* types in *binaries* with either stellar companions, or other neutron stars
- First case raises the possibility of *accretion*, second of *collisions*

* totally objective unbiased view



3748 pulsars on a "P-Pdot diagram" (Manchester et al. 2005, AJ 129)

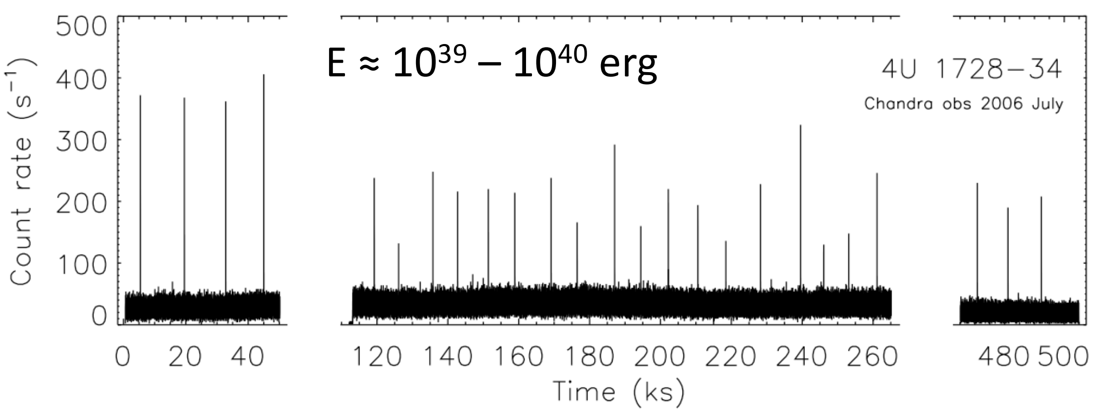
Pulsars born spinning slowly (but spinning down fast)

"Recycling" by a binary companion brings them to ms spin periods

Now have even a few examples of NS switching from radio pulsar to accretion mode

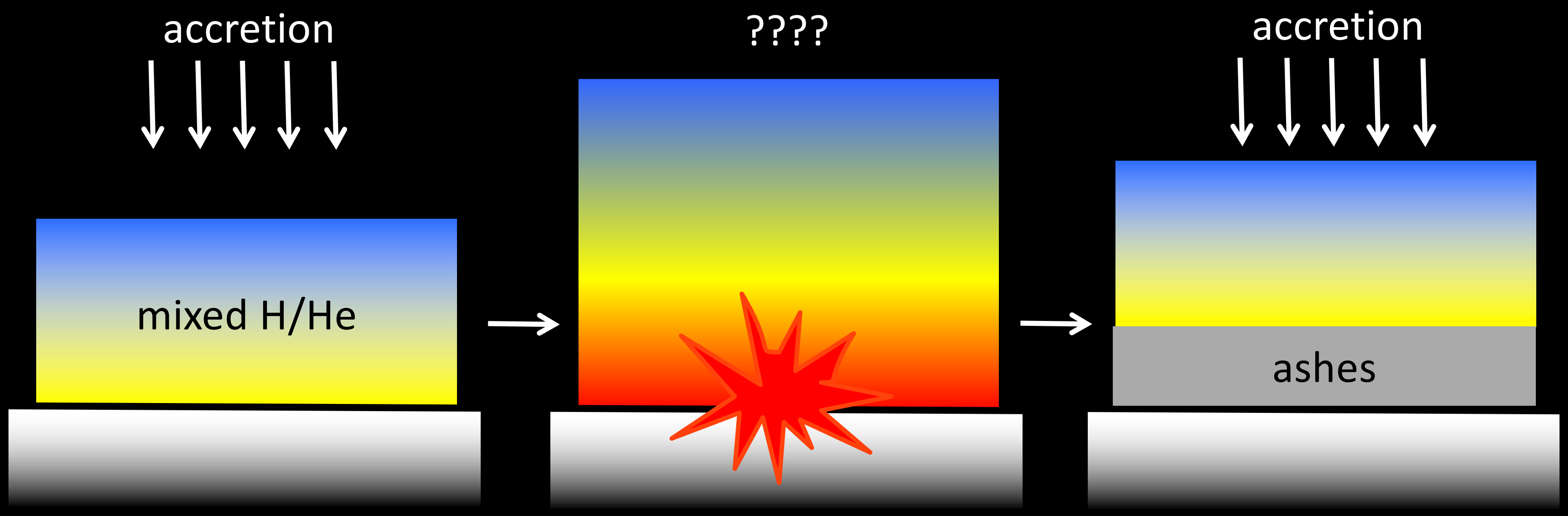
Neutron star ”explosions” – X-ray bursts

- *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)

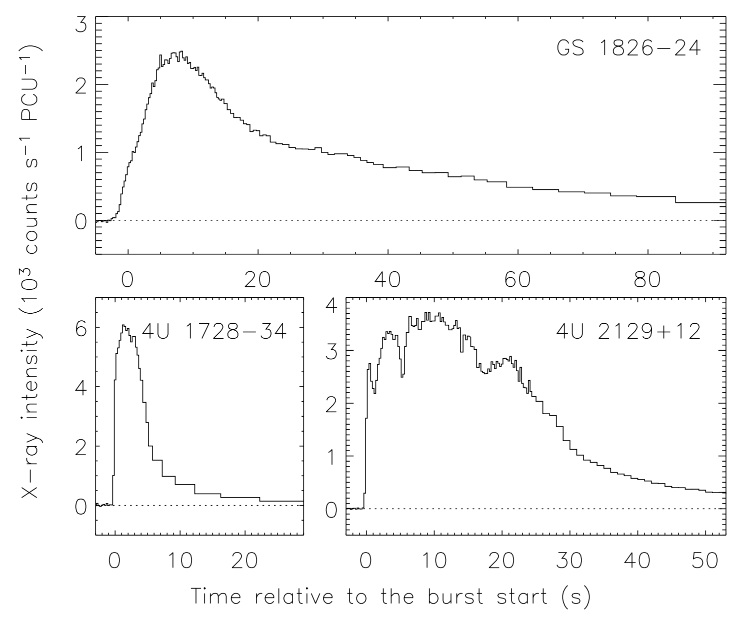


Chandra X-ray observation of the prolific burst source 4U 1728-34, showing quasi-regular bursting activity

Thermonuclear burst physics

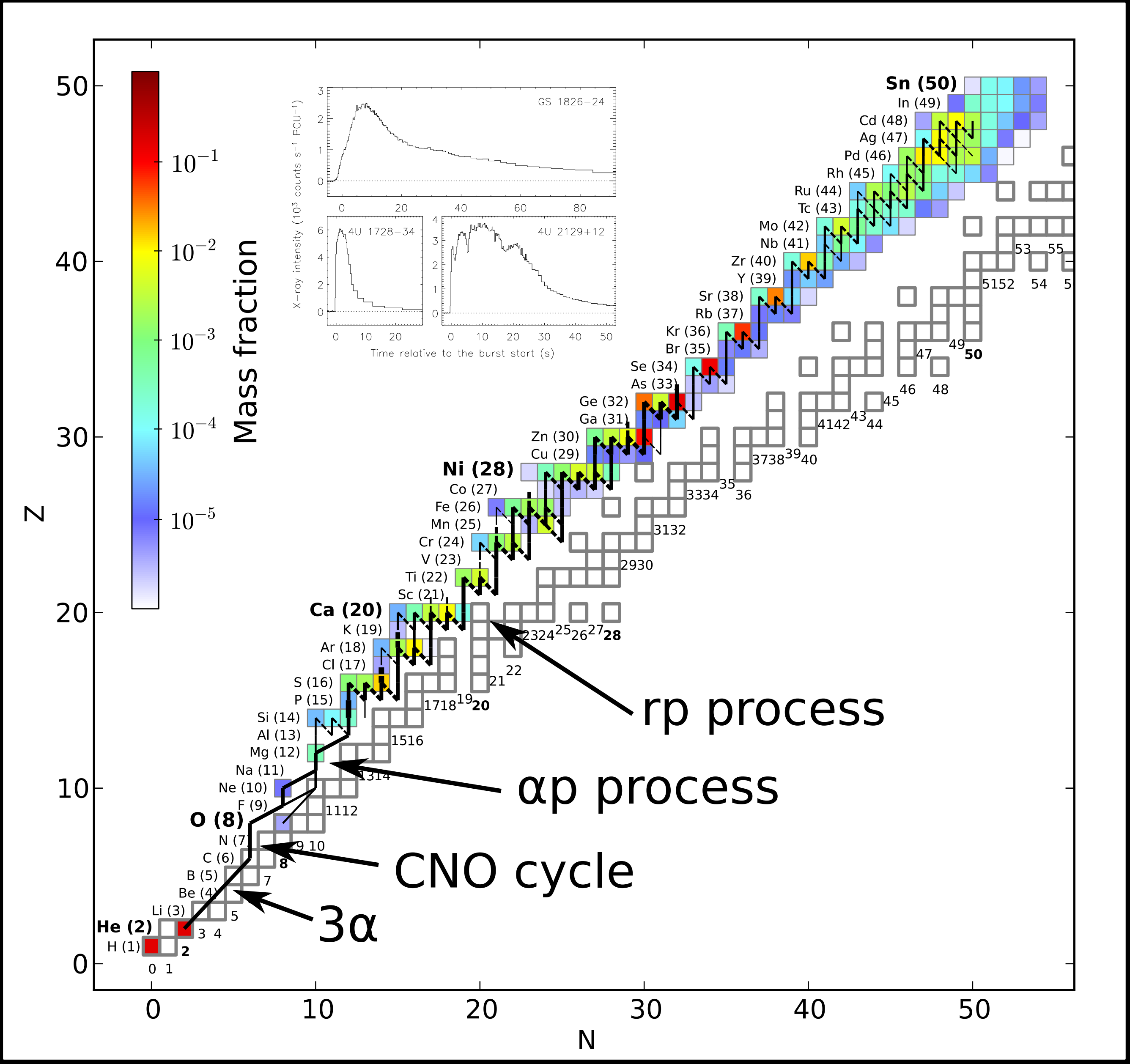


- This process repe
  hours-days, depe
  accretion rate &
- About 110 know
  http://burst.sci.monash.edu
- Most accrete a n
  “ultracompacts”
  He



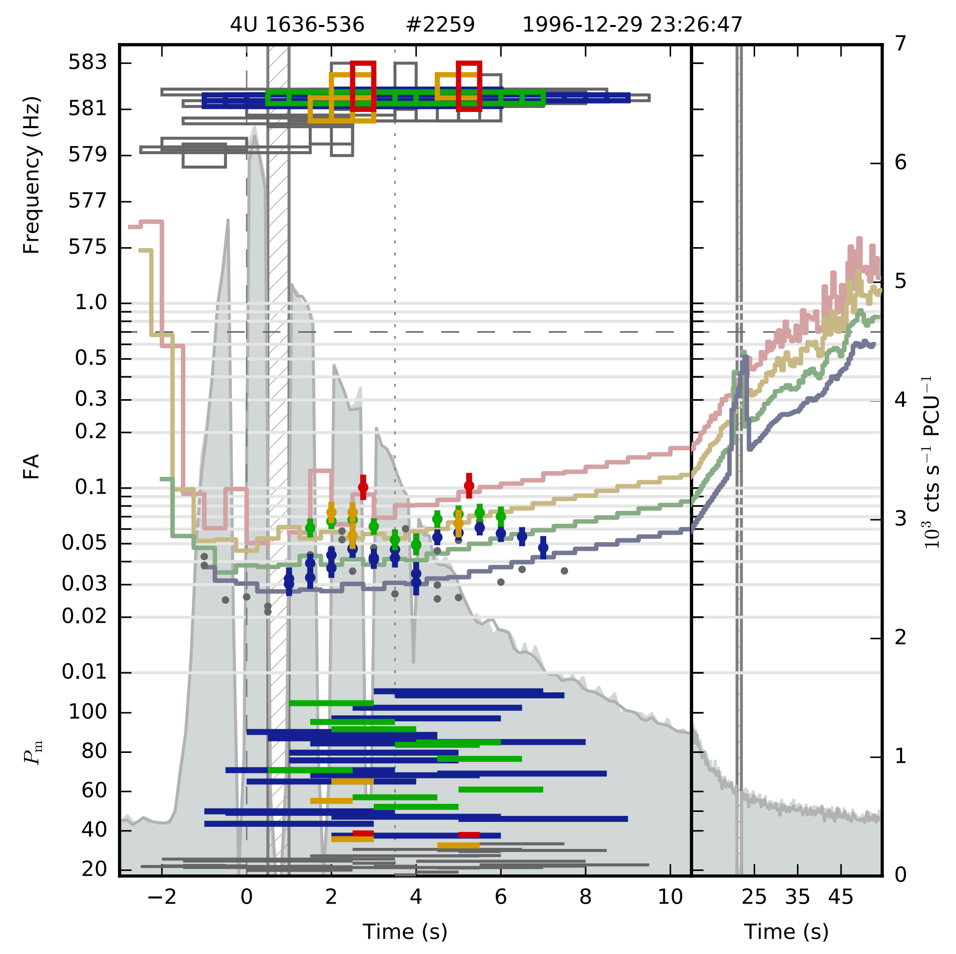
Key thermonuclear reactions

- 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 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



gure 8. An example of diagnostic plots for a cluster of TBO candidates belonging to the same frequency group. Th nel corresponds to RP (Rise+Peak) regions, the right to T (Tail). On both panels, the background shows LC, binn 125-s time bins, for the real (shaded) and mean of the simulated (line) data sets. Vertical lines mark T_{peak} and dT_{halftime}. gions excluded from the analysis (outside GTI, with large frequency covariance in the power spectra, or bad LC modeling

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- *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

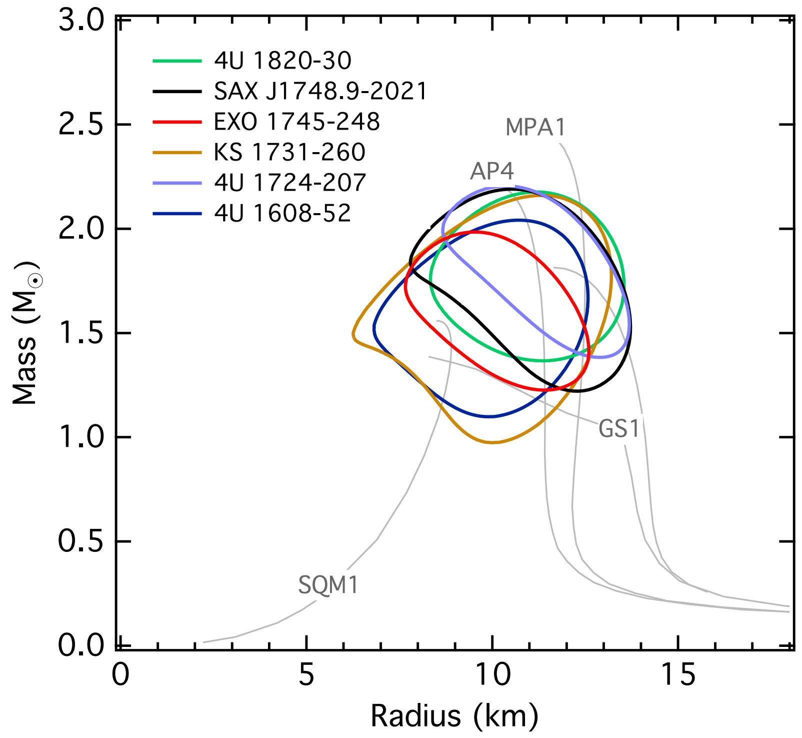
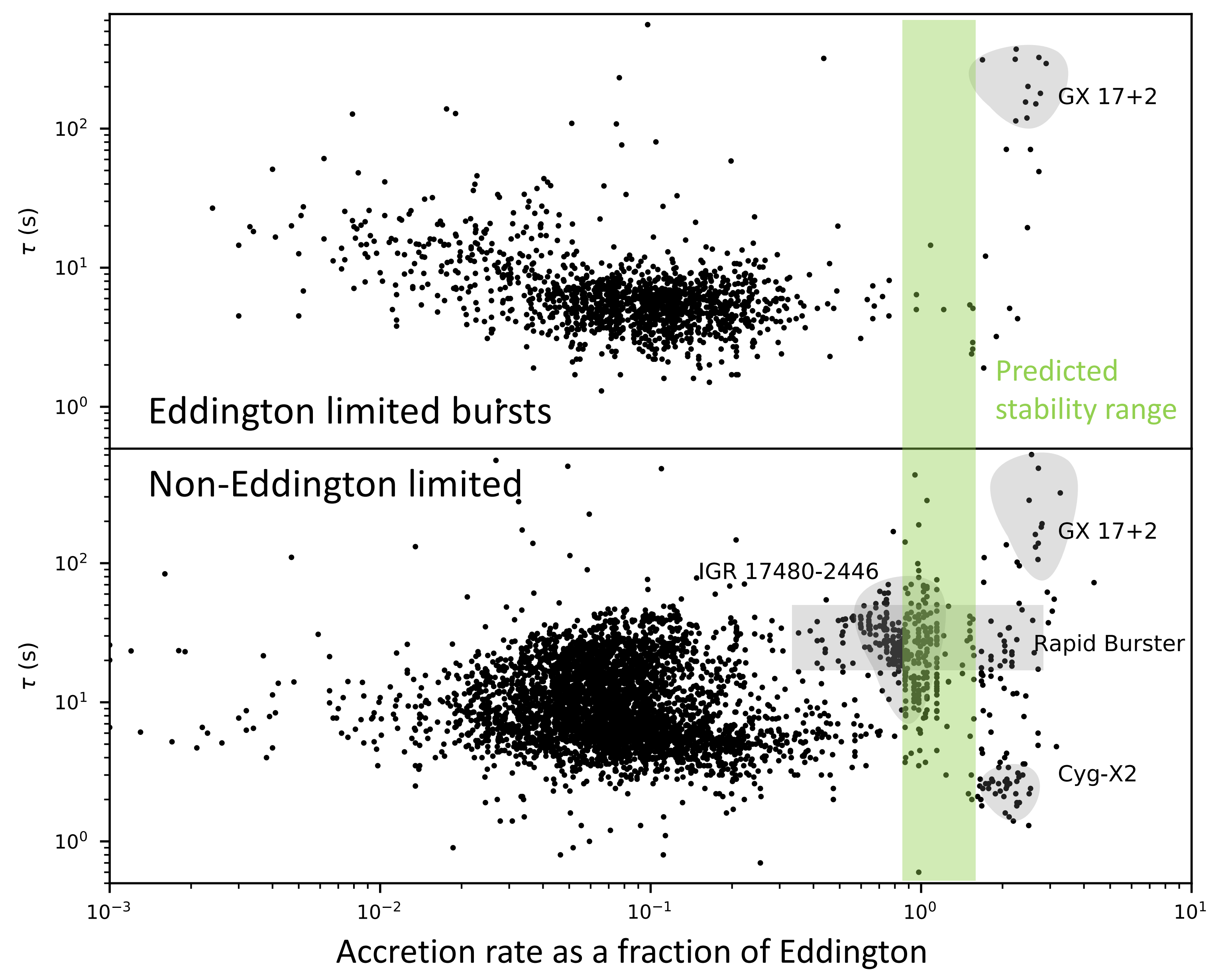


Figure 11. The combined constraints at the 68% confidence level over the neutron s
(right) all neutron stars in low-mass X-ray binaries during quiescence.

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

Diversity of behaviour in the MINBAR sample



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

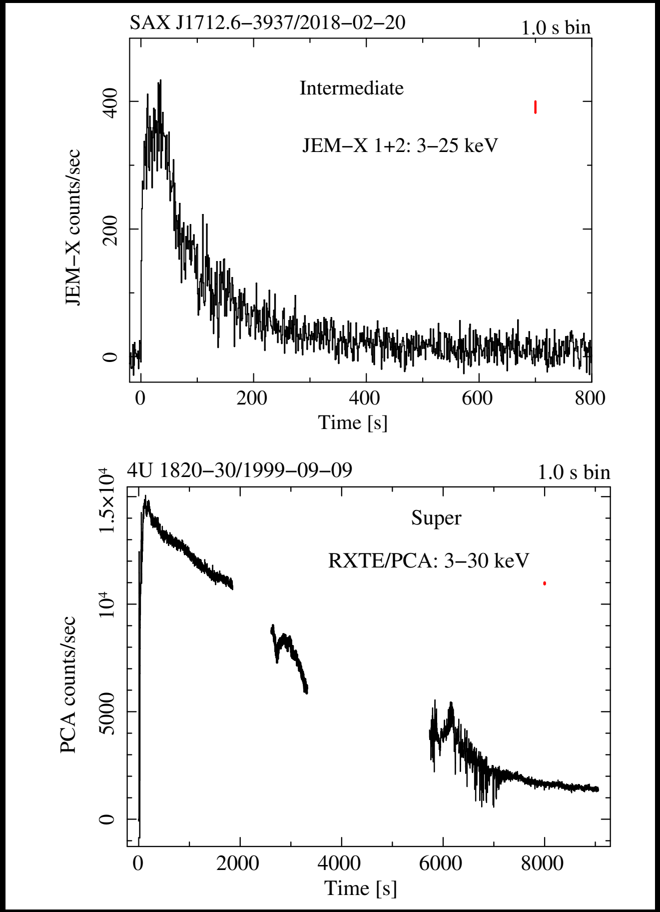
Broad groups comprising the bulk of burst sources, but also outliers for atypical sources

Some of this behavior is understood, some not

Galloway et al. 2020, ApJS 249, 32

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 perhaps ”hyperbursts”! Page et al. (2022, ApJ 933, 216)
- 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. (2023, MNRAS 521, 3608)

Burst ignition

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

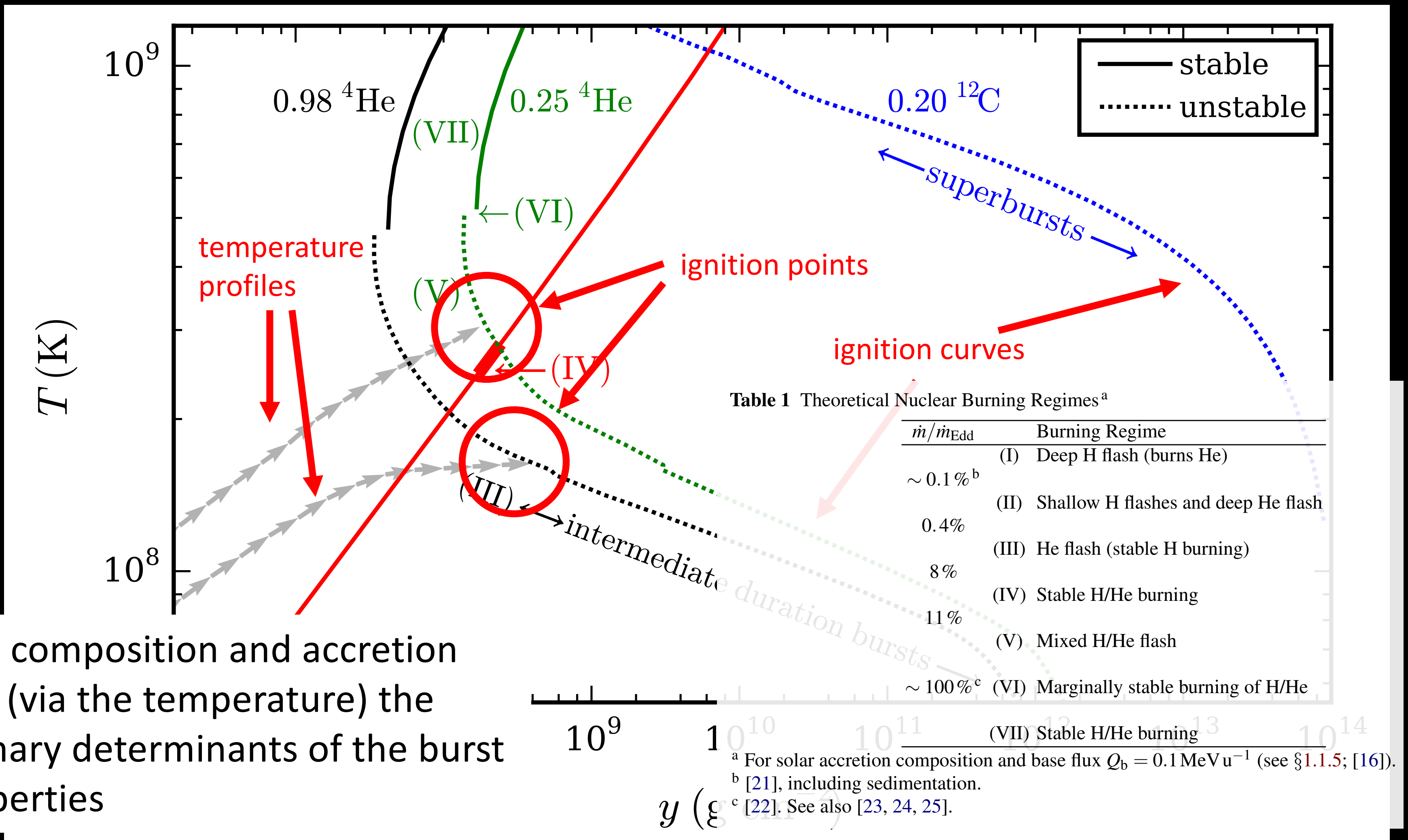


Table 1 Theoretical Nuclear Burning Regimes[a]

$\dot{m}/\dot{m}_{\mathrm{Edd}}$	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 $Q_{\mathrm{b}} = 0.1\,\mathrm{MeV\,u^{-1}}$ (see §1.1.5; [16]).

[b] [21], including sedimentation.

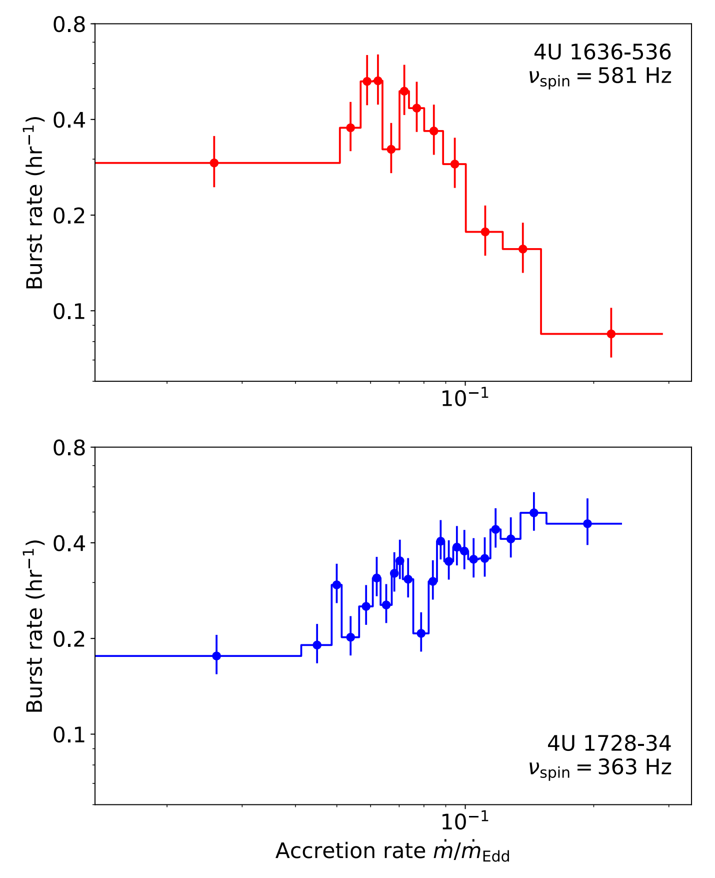
[c] [22]. See also [23, 24, 25].

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

Galloway & Keek 2021, arXiv:1712.06227

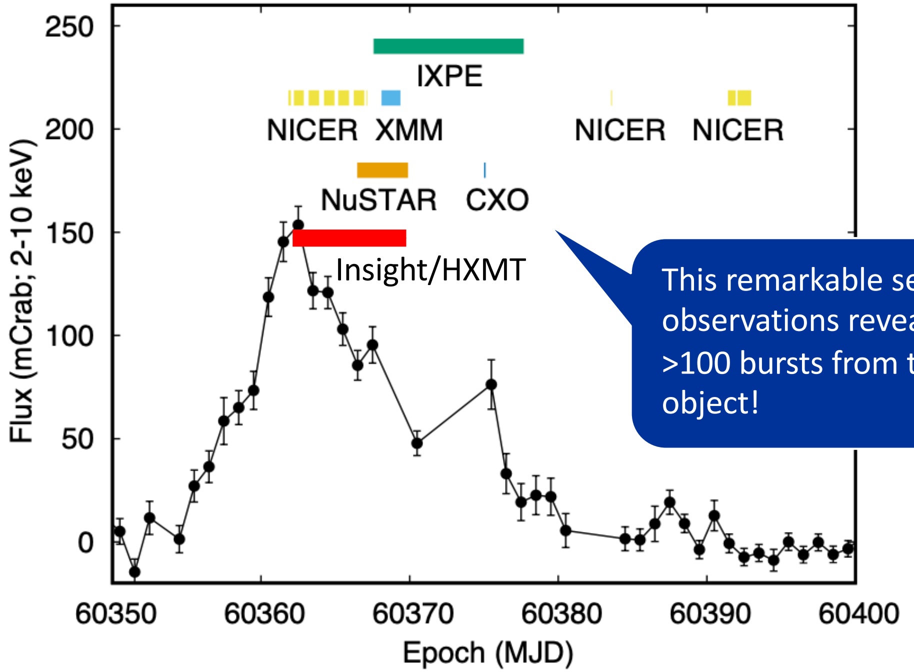
Still some profound puzzles

- Many bursts (perhaps the majority) do *not* behave as predicted by numerical models; dimensionality probably a factor
- E.g. 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
- 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)

New view 1: new instruments



This remarkable set of observations revealed >100 bursts from this object!

Figure 1. Light curve of the 2024 outburst of SRGA J1444 observed by MAXI (Matsuoka et al. 2009). We converted 2–20 keV observed count rates into 2–10 keV flux values assuming that the spectrum is described by a power law with a photon index $\Gamma = 1.9$ absorbed by an equivalent hydrogen column of $N_{\rm H} = 2.9\times10^{22}$ $\rm cm^{-2}$ (Ng et al. 2024). Horizontal bars indicate the time intervals covered by observations of the instruments discussed in this paper.

- New satellite-based instruments offer somewhat different quality data than what's been gathered to date, but generally can't compete with the accumulated *quantity*
- Coverage of high priority targets, e.g. AMSP outbursts is much, much better
- One exception is *polarization*, which has now been detected from an AMSP with *IXPE* (but not during bursts) Papitto et al. 2024, arXiv:2408.00608

New view 2: new burst regimes

- There has long been difficulty conclusively identifying the ignition source (H/He)
- Observations unusually early in the outburst of SAX J1808.4–3658 show weak bursts very different from the normal strong H-poor PRE bursts later in the outburst
  (Casten et al. 2023, ApJ 948, 117)
- Also very different from model predictions… could these bursts be H-triggered?

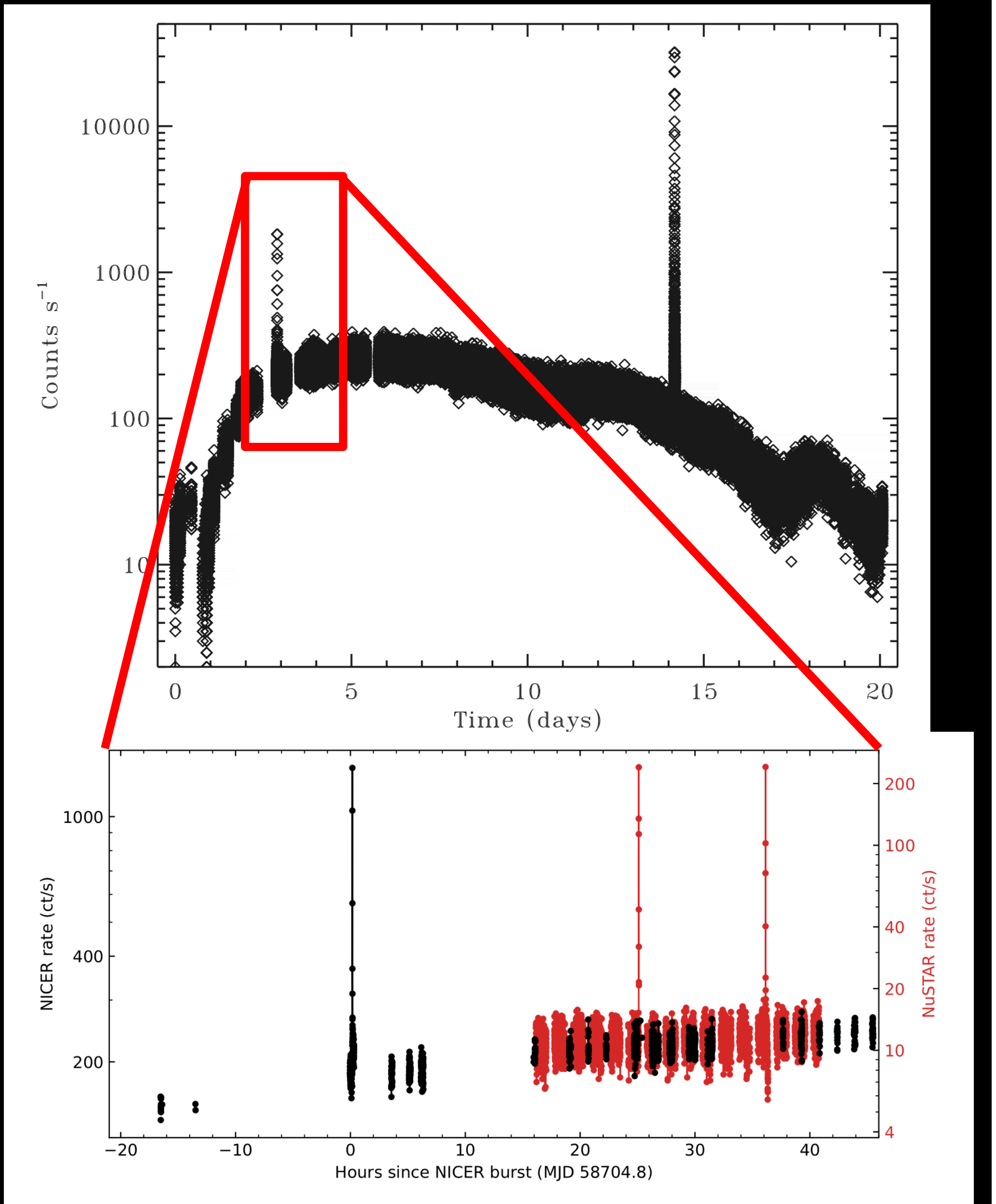


Figure 6. Light curves from NICER (black, left axis) and NuSTAR (red, right

New view 3: new wavebands

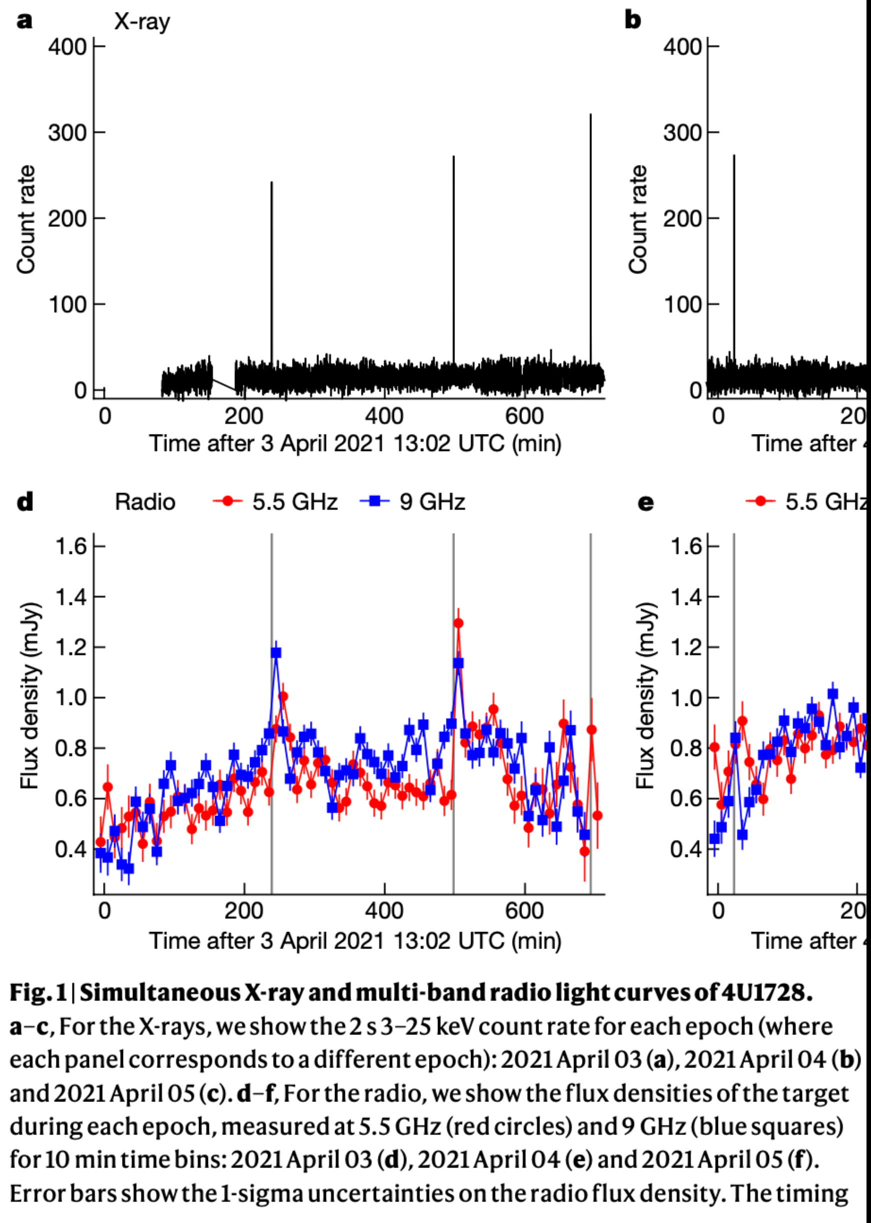


Fig. 1 | Simultaneous X-ray and multi-band radio light curves of 4U1728. **a**–**c**, For the X-rays, we show the 2 s 3–25 keV count rate for each epoch (where each panel corresponds to a different epoch): 2021 April 03 (**a**), 2021 April 04 (**b**) and 2021 April 05 (**c**). **d**–**f**, For the radio, we show the flux densities of the target during each epoch, measured at 5.5 GHz (red circles) and 9 GHz (blue squares) for 10 min time bins: 2021 April 03 (**d**), 2021 April 04 (**e**) and 2021 April 05 (**f**). Error bars show the 1-sigma uncertainties on the radio flux density. The timing

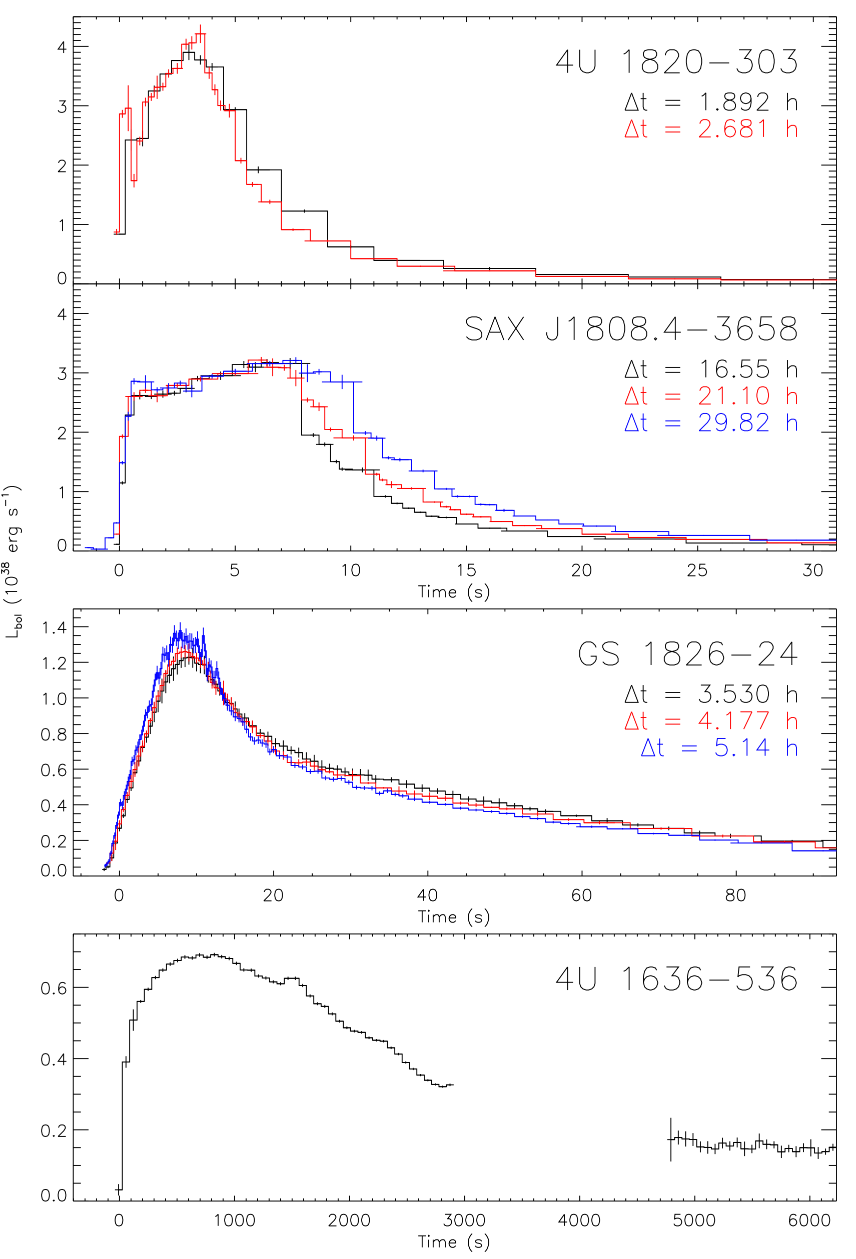
- Neutron-star binaries also drive relativistic jets, which can be detected in radio
- Observations with the Australia Telescope Compact Array reveal radio “flares” following thermonuclear bursts detected with *INTEGRAL* Russell et al. 2024, Nature 627, 8005
- Delay between X-ray and radio allows the speed of the jet to be measured; exciting implications for future work

New(-ish) view 4: bursts through a 1D lens

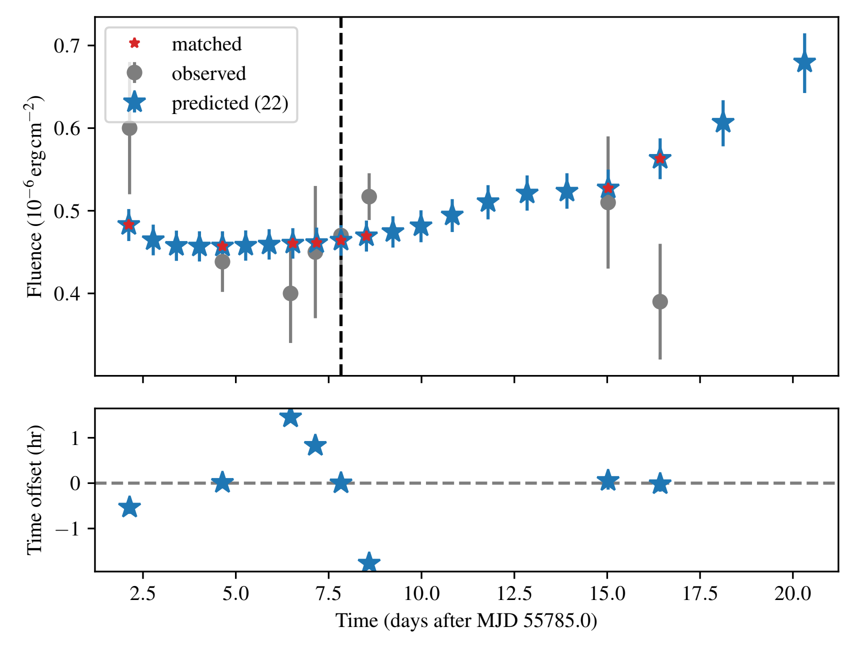
- We can’t directly identify what fuel is burning & what nuclear reactions are taking place, so we have to compare our observations (burst rate, energy, lightcurve shape) with *numerical simulations* to infer system properties
- These simulations are generally limited to 1D due to the requirement for 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

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)
- Work continues on the tools required to perform these comparisons

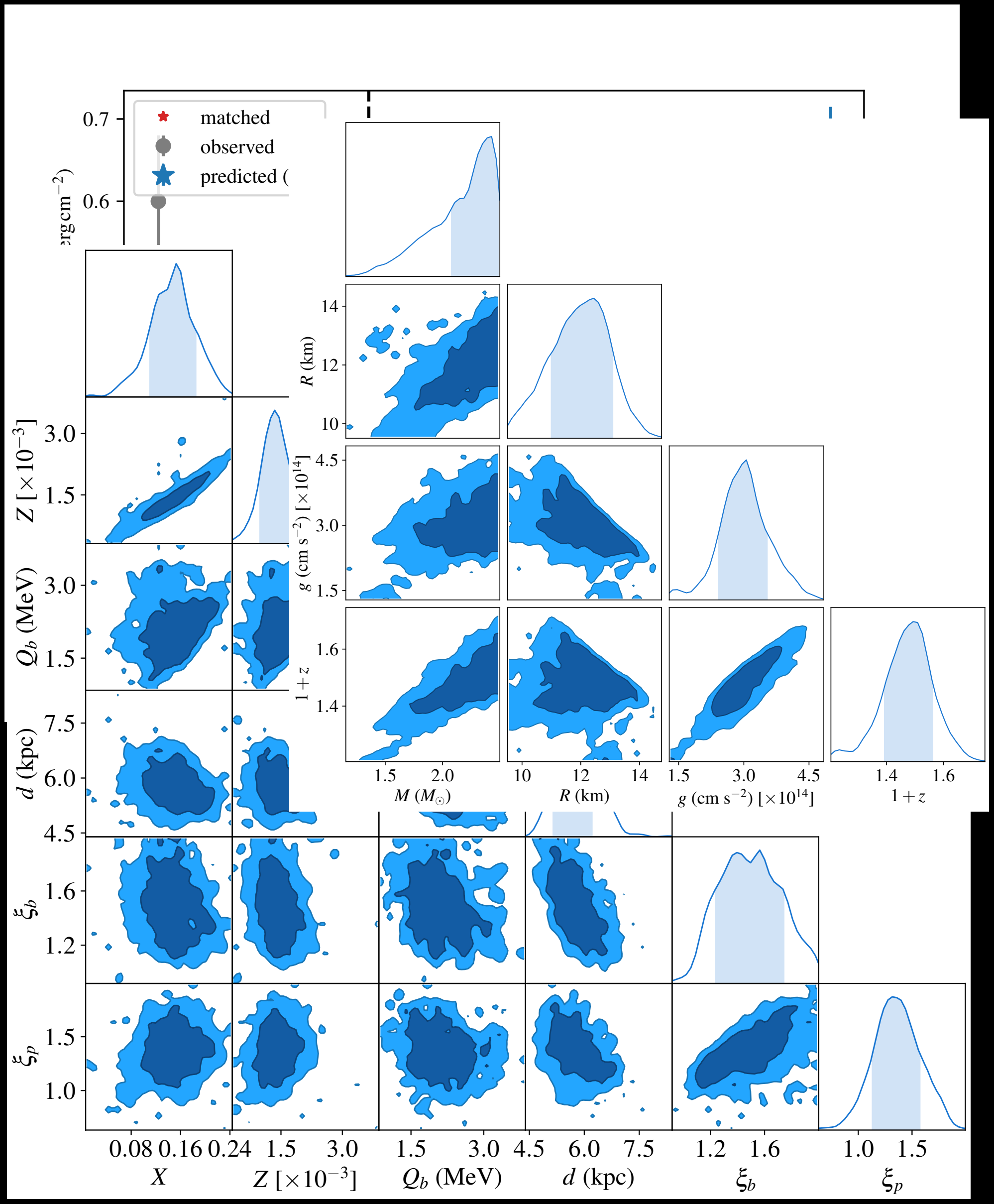


Giving it the beans(p)



- Code originally used for SAX J1808.4–3658, now has been applied to two other sources https://github.com/adellej/beans
- Primarily uses an ignition code which doesn't fully track burning, limited applications (H-poor bursts only)
- Extensive development and testing over the last few years
- Latest result: system parameter constraints in IGR J17498–2921 Galloway et al. 2024, MNRAS 535, 647

Giving it the beans(p)



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Summary and the future

- Surprisingly exciting developments in burst observations over the last few years, likely impact not yet known
- New instruments/observables/wavebands are the most exciting but there's also the demonstrated benefit of targeting poorly studied burst states, very early in transient outbursts (perhaps also at high accretion rates?)
- Numerical models remain critical – we need (more) large samples of model results to apply to burst sources, with full nuclear reaction networks, quantify model uncertainties etc.
- Development of improved software tools for thermonuclear burst observation-model comparison ongoing, can take advantage of existing model grids & accumulated observations
- These tools can be adapted to incorporate additional constraints from different types of data including observational, theoretical, nuclear experimental