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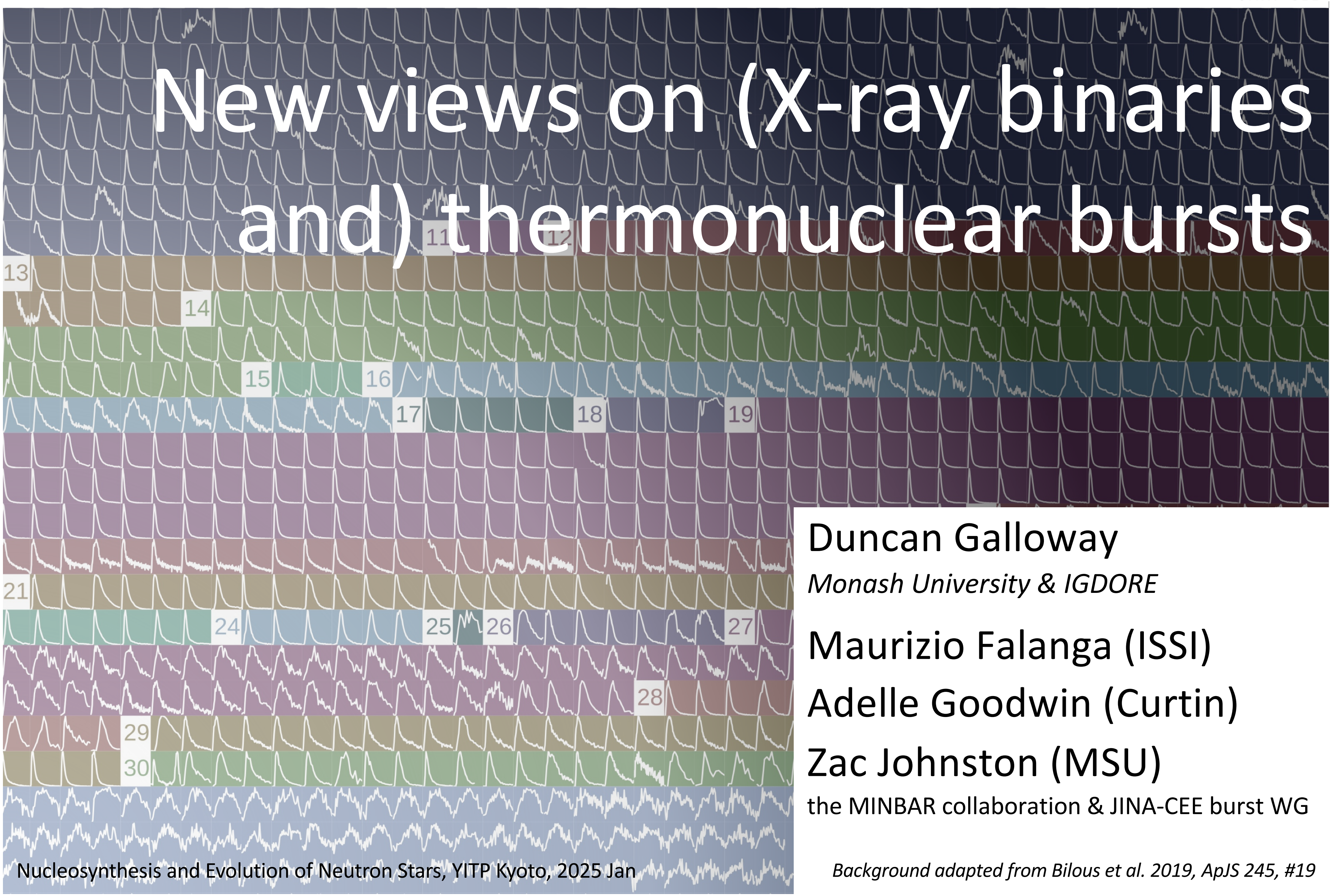

New views on (X-ray binaries and) thermonuclear bursts

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the MINBAR collaboration & JINA-CEE burst WG

Nucleosynthesis and Evolution of Neutron Stars, YITP Kyoto, 2025 Jan

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

X-ray binaries

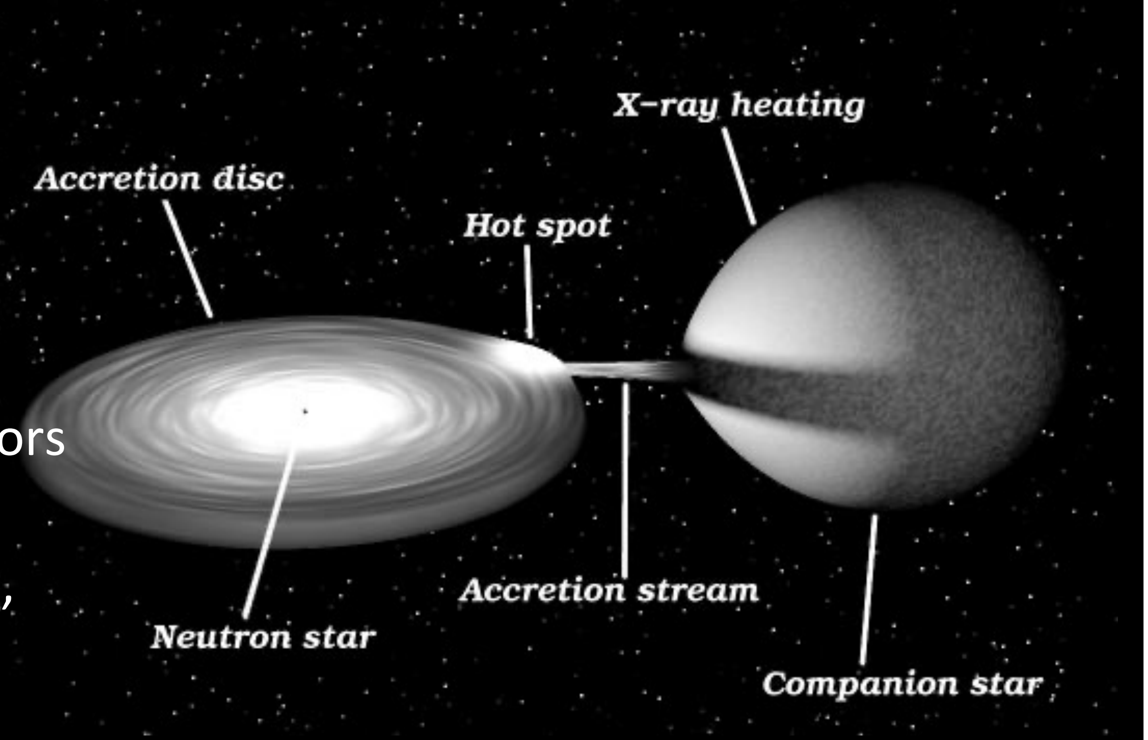
- A compact object (neutron star or black hole) with a stellar companion, which donates matter via *accretion*
- Typical rates of mass transfer (via Roche lobe overflow/stellar winds) coupled with compactness of the target results in ~thermal emission in the X-ray band
- Accretion disk and companion are also detectable in UV, optical; systems also drive *jets* detectable in radio
- Two main flavours:

High-mass X-ray binaries

- *Young* objects, high B-fields, precursors of binary NS

Low-mass X-ray binaries

- *Old* objects, low B-fields, precursors of millisecond pulsars
- Characterised by ms spin periods, thermonuclear bursts

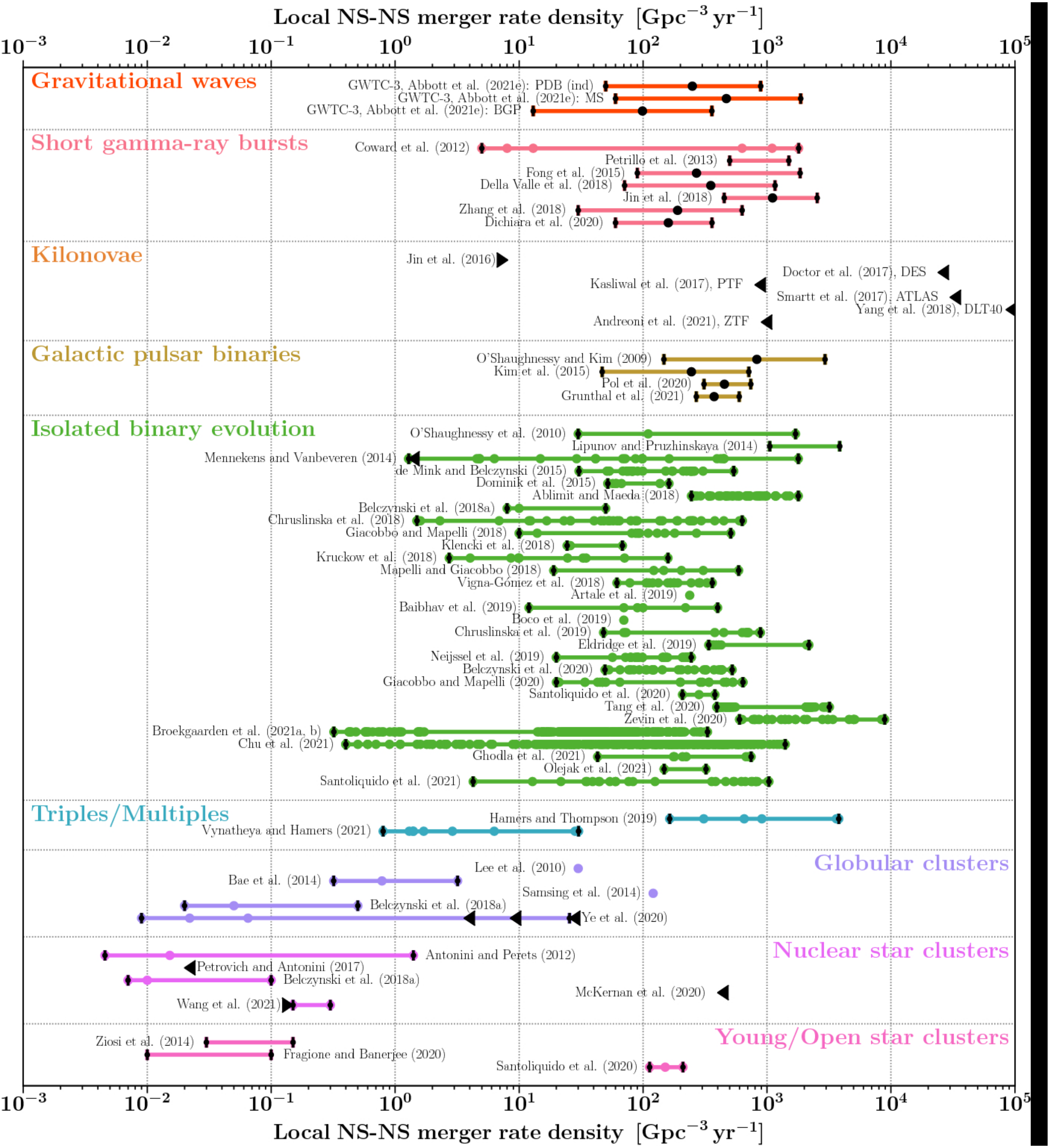


High-mass X-ray binaries

- Earliest X-ray sources ever detected; characterized by X-ray pulses @ the NS spin period (seconds and longer)
- Supergiant companions in close orbits, for many sources with few-days orbital periods correlated with spin (Corbet diagram)
- Observational work focused on measuring B-field from X-ray cyclotron lines, X-ray pulse shape analysis, pulse timing, etc. (see e.g. Takagi poster on A 0535+262 for a nice example)
- From 2015 onwards the detection of GW with LIGO led to renewed interest in these objects as the progenitors of BNS, vigorous efforts in population modelling (e.g. Mandel & Broekgaarden 2022)

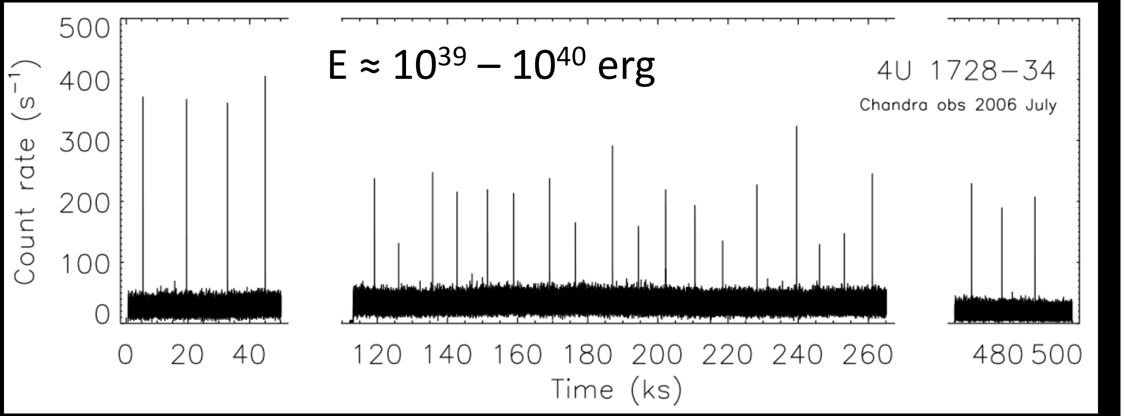
- Lots of effort going on here to keep track of!
- Lack of additional BNS mergers to date a damper on enthusiasm

Mandel & Broekgaarden (2022)



Low-mass X-ray binaries & X-ray bursts

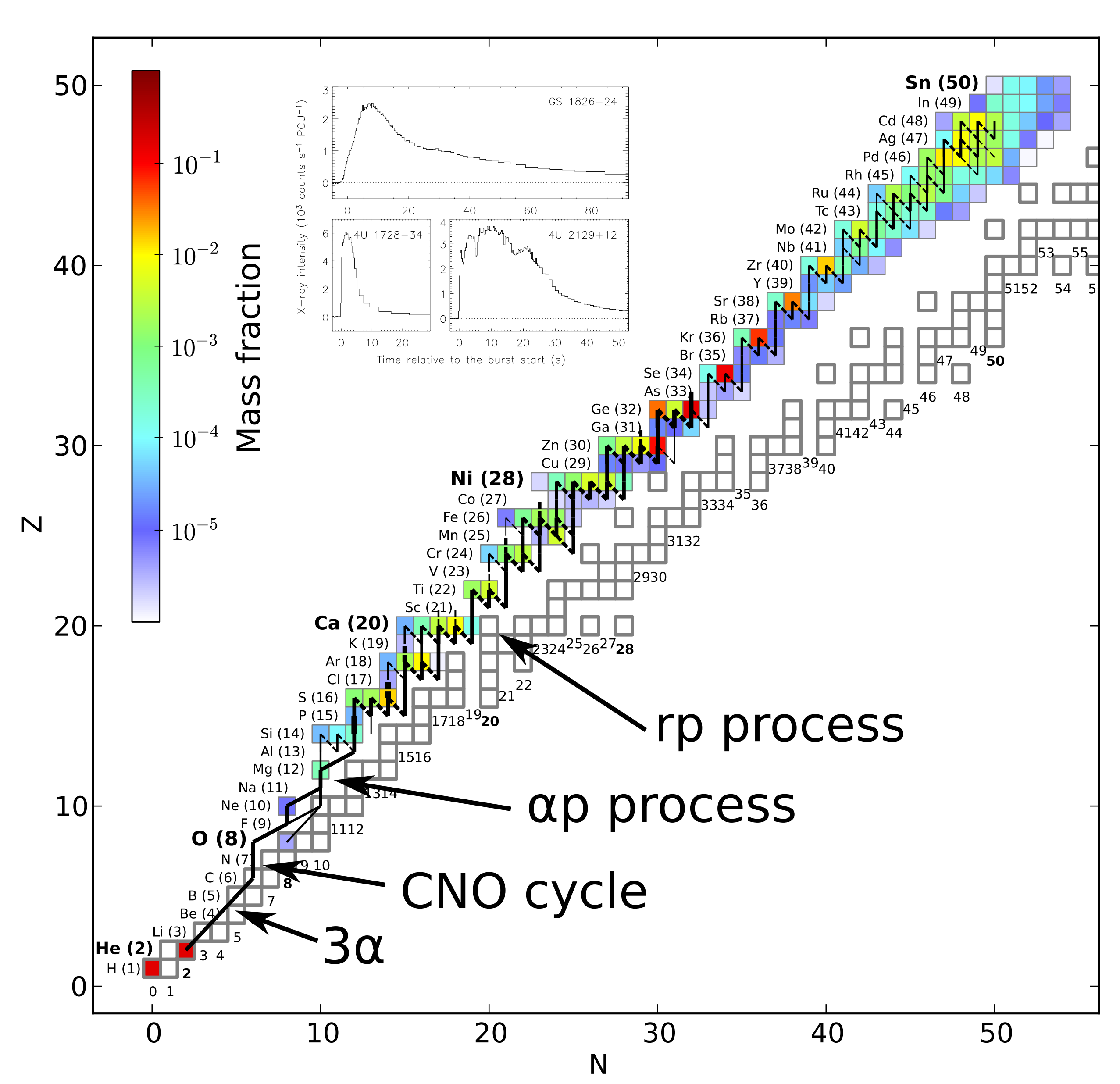
- *Low-mass X-ray binary* systems are thought to accrete through gigayear timescales, spinning up the neutron star (and ultimately producing millisecond radio pulsars)
- Total mass transfer likely results in massive neutron stars (up to twice solar; cf. with Romani et al. 2022)
- About half of the ~120 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

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



Burst ignition

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

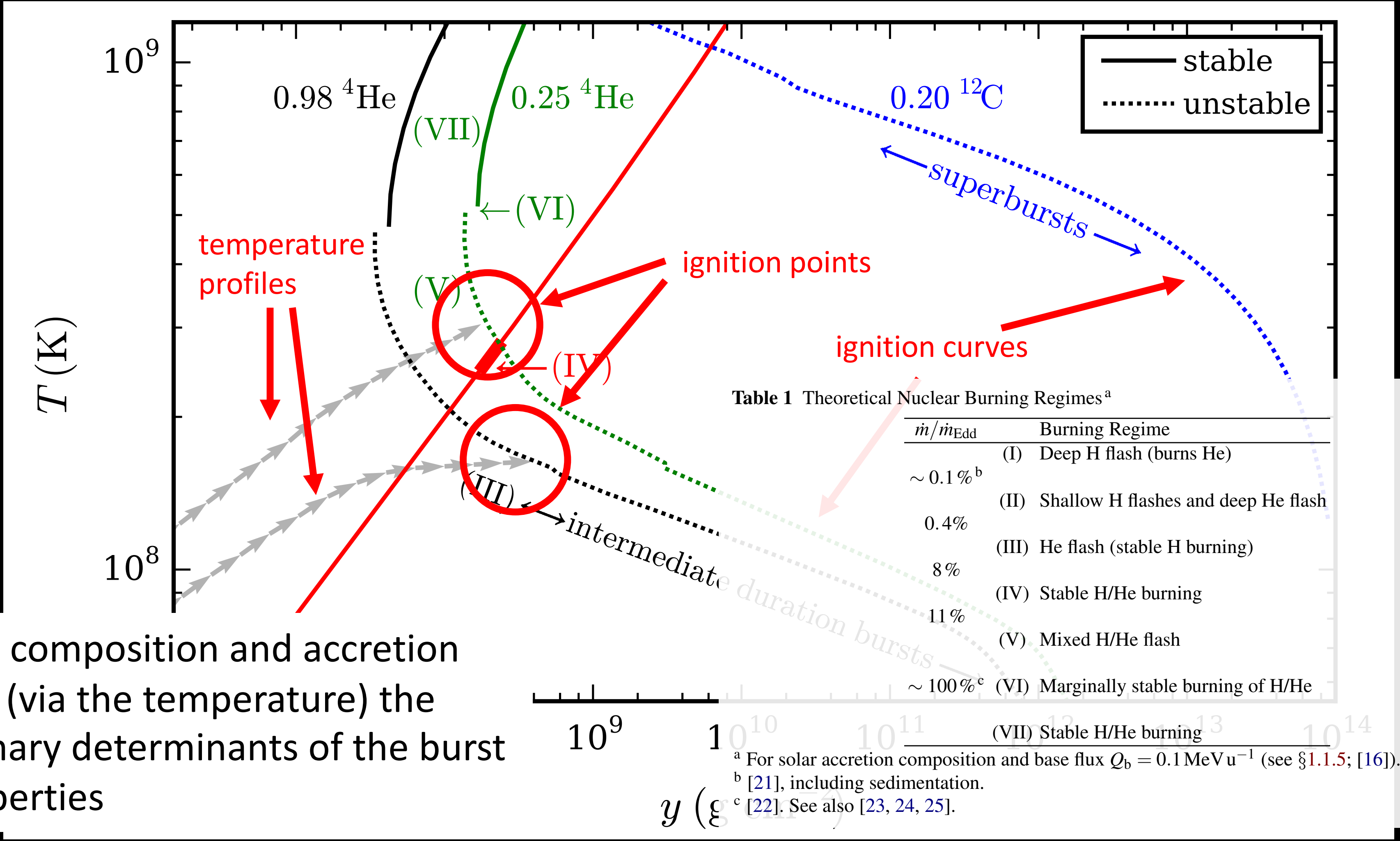


Table 1 Theoretical Nuclear Burning Regimes[a]

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

[b] [21], including sedimentation.

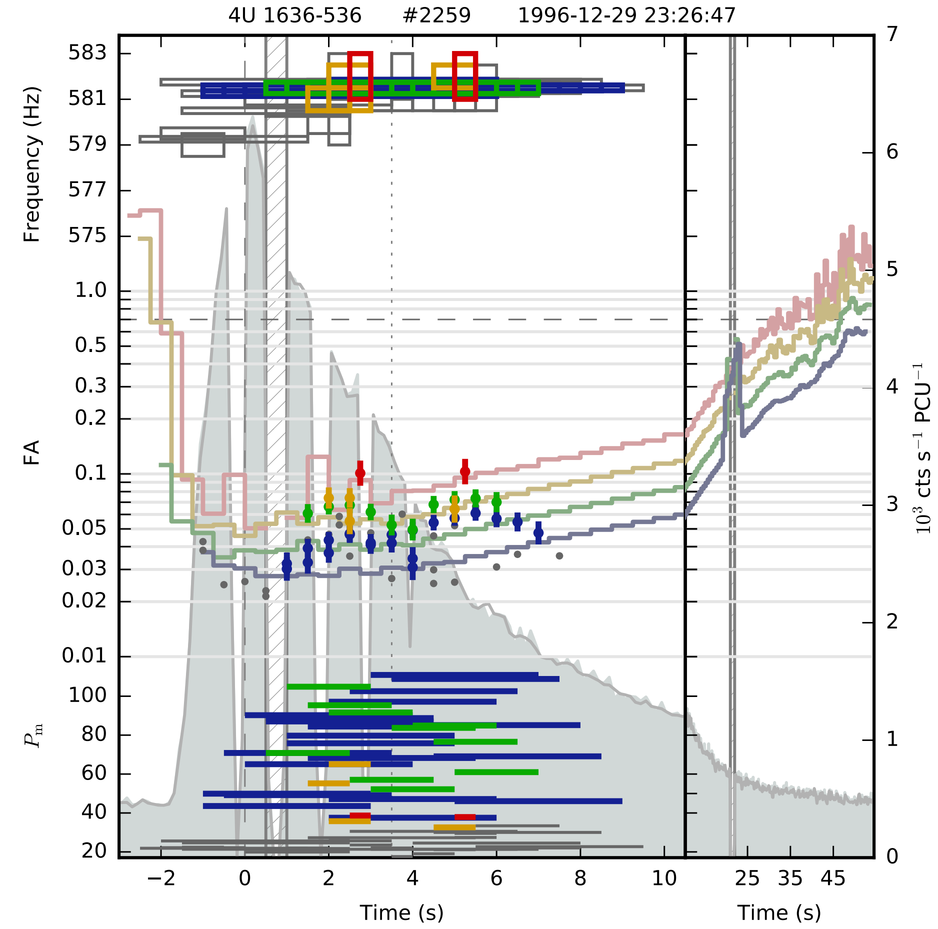
[c] [22]. See also [23, 24, 25].

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

Galloway & Keek 2021, arXiv:1712.06227

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. The nel corresponds to RP (Rise+Peak) regions, the right to T (Tail). On both panels, the background shows LC, binne 125-s time bins, for the real (shaded) and mean of the simulated (line) data sets. Vertical lines mark $T_{\rm peak}$ and $dT_{\rm halftime}$. gions excluded from the analysis (outside GTI, with large frequency covariance in the power spectra, or bad LC modeling own as dashed. Only candidates from time windows completely in the dashed regions were discarded. In the foreground

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- Time-resolved spectroscopy used to infer NS mass & radius e.g. Özel et al. 2016, ARAA 54, 401

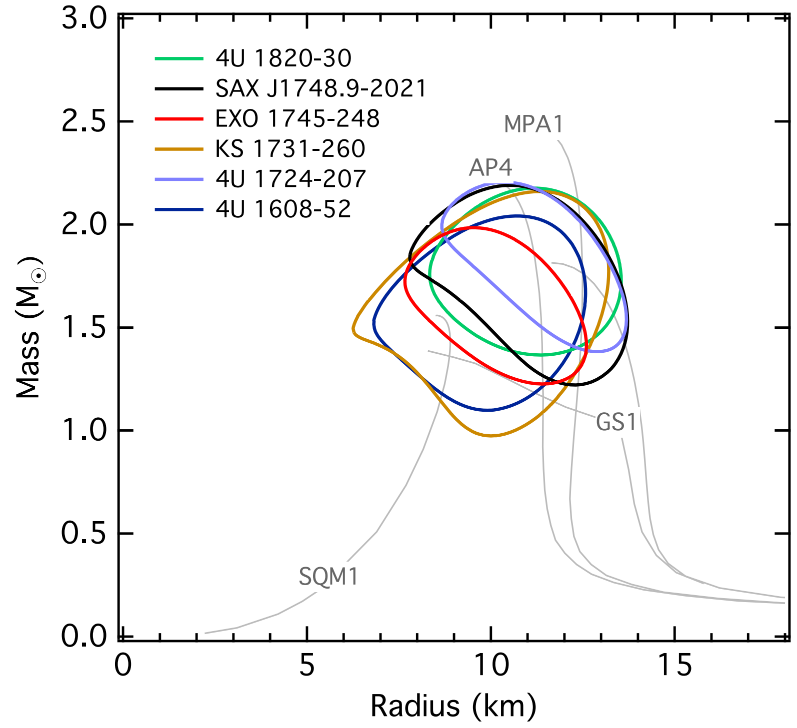
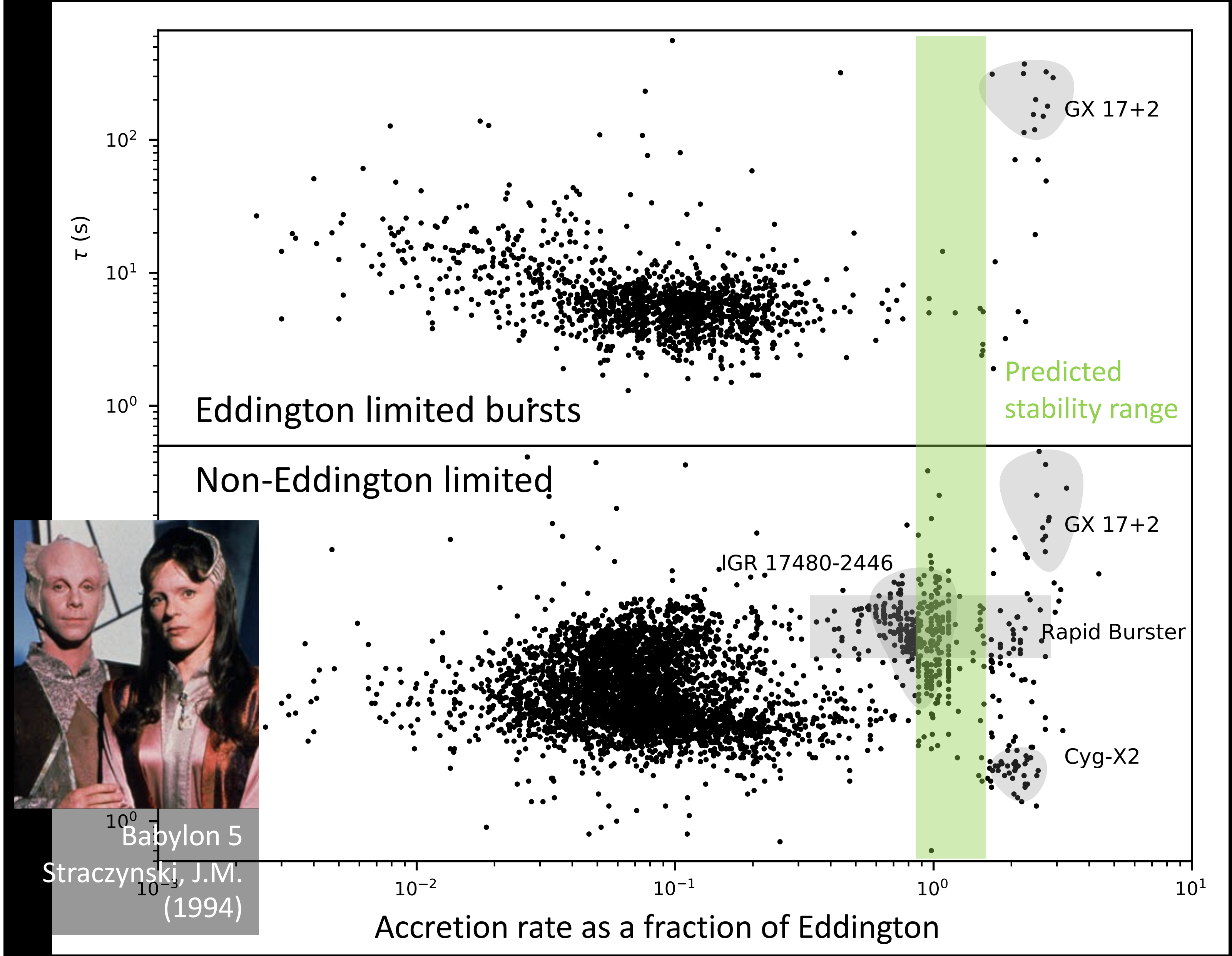


Figure 11. The combined constraints at the 68% confidence level over the neutron s
(right) all neutron stars in low-mass X-ray binaries during quiescence.

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 large burst samples



Babylon 5
Straczynski, J.M.
(1994)

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

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

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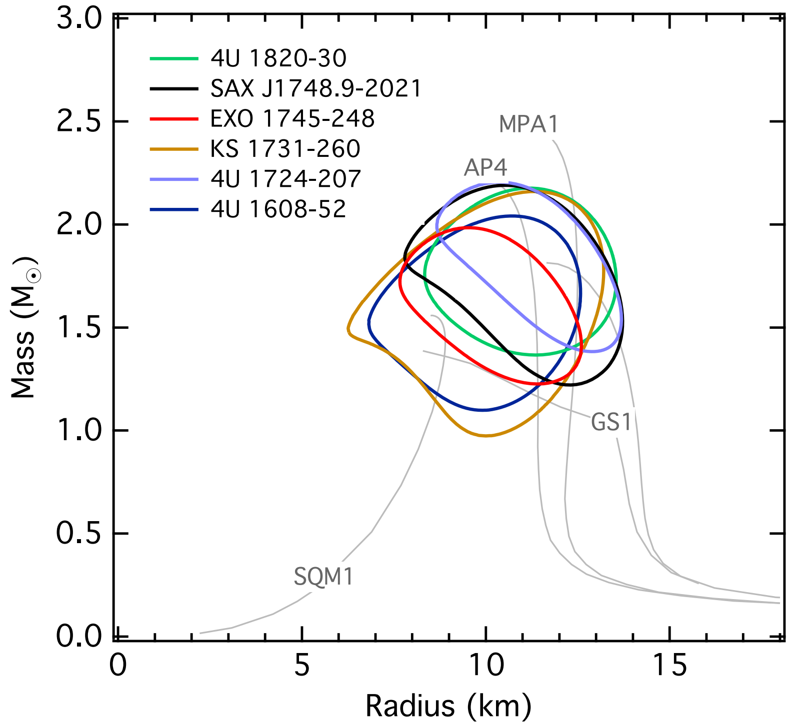

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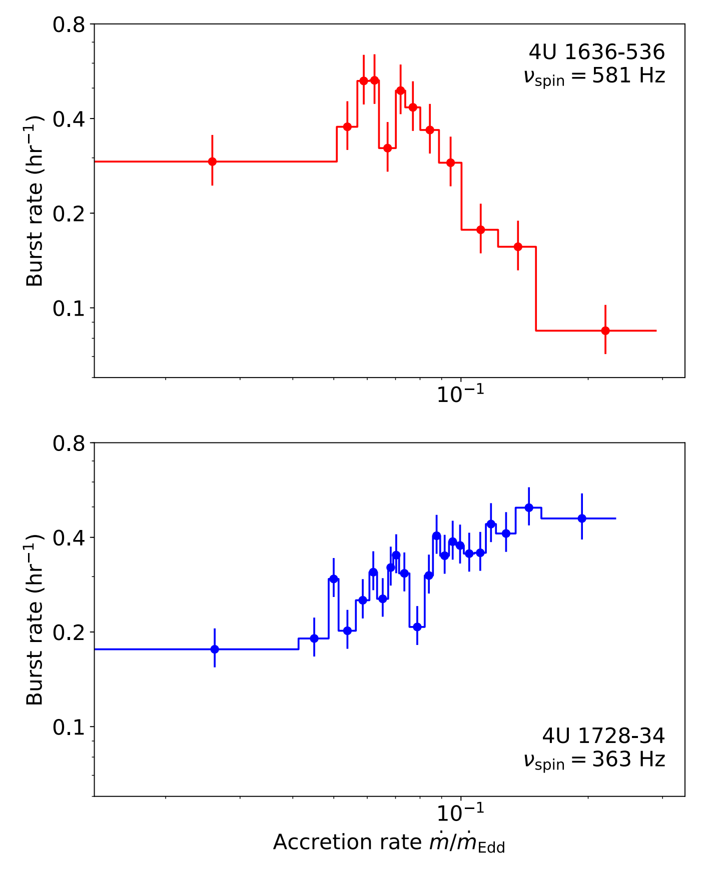
Still some profound puzzles

- Many bursts (perhaps the majority) do *not* behave as predicted by numerical models; 3-D effects 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

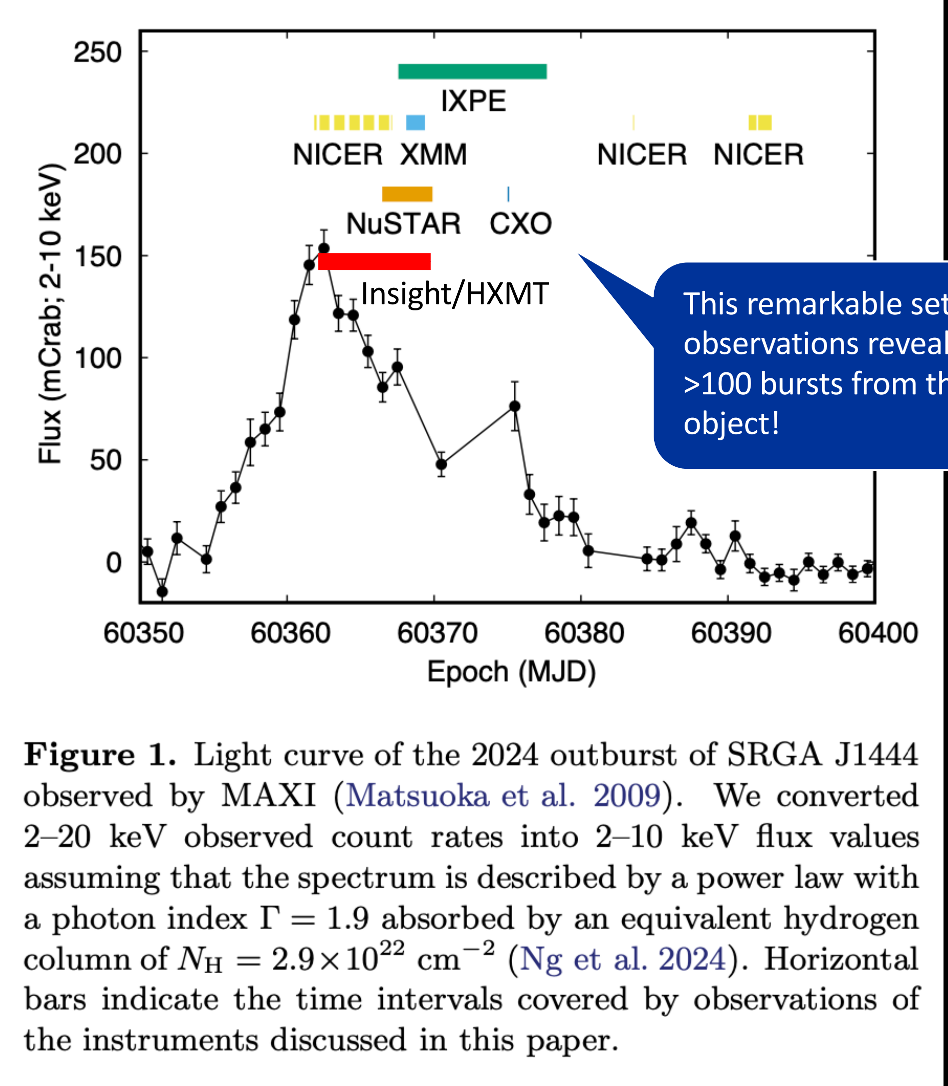


Figure 1. Light curve of the 2024 outburst of SRGA J1444 observed by MAXI (Matsuoka et al. 2009). We converted 2–20 keV observed count rates into 2–10 keV flux values assuming that the spectrum is described by a power law with a photon index $\Gamma = 1.9$ absorbed by an equivalent hydrogen column of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

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

See also Dohi poster on this “clocked” burster

- 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
- E.g. Aoyama poster describing followup of a new transient object with *NinjaSat*
- Additionally can test for *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?

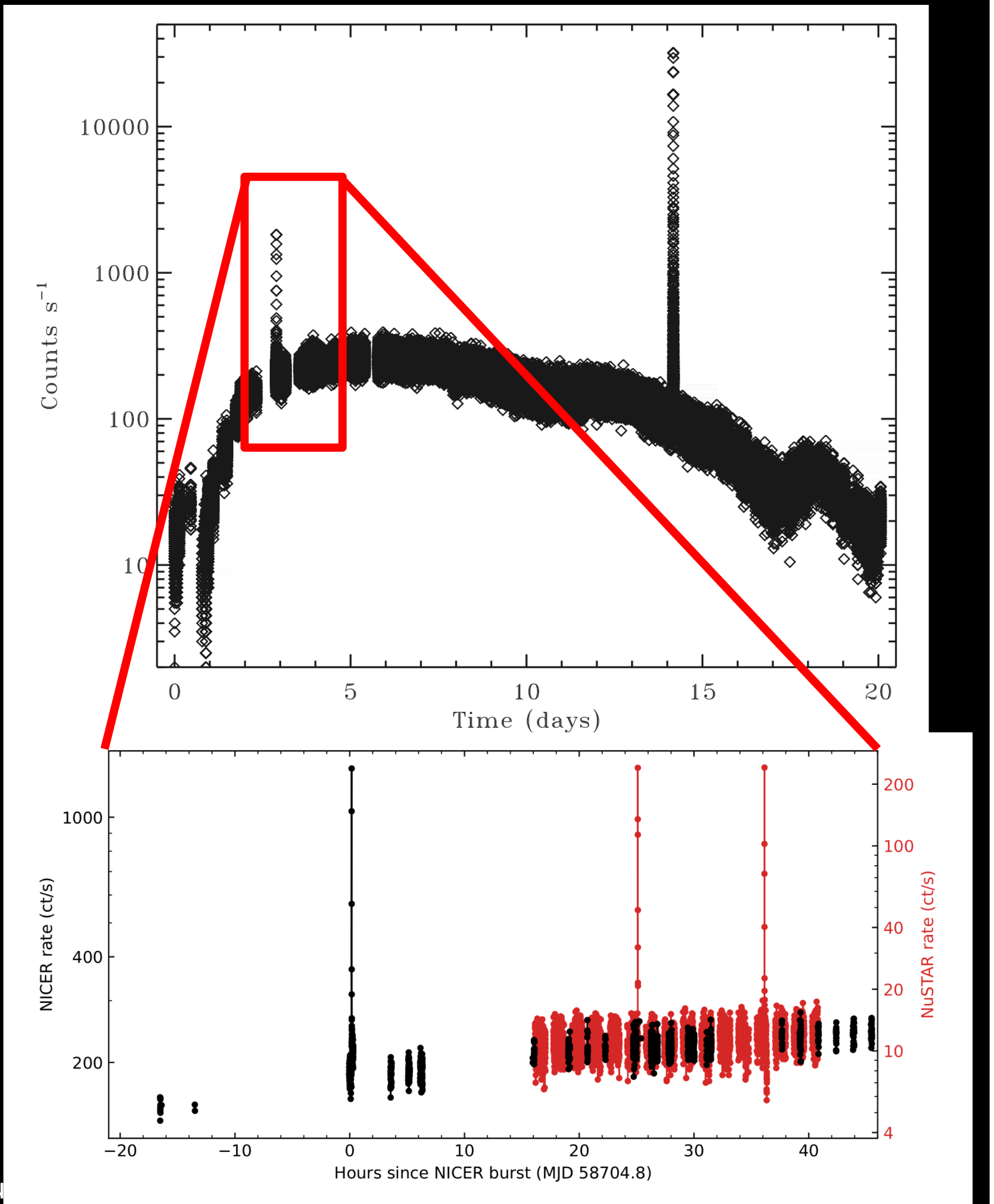


Figure 6. Light curves from NICER (black, left axis) and NuSTAR (red, right

New view 3: new wavebands

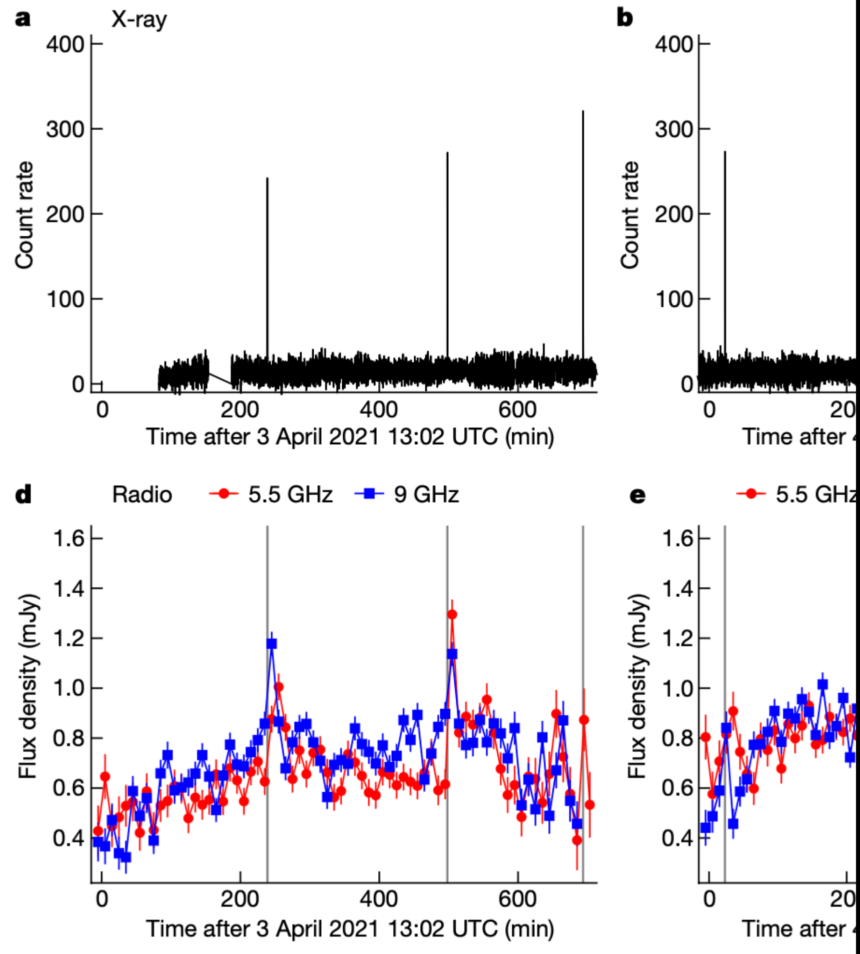


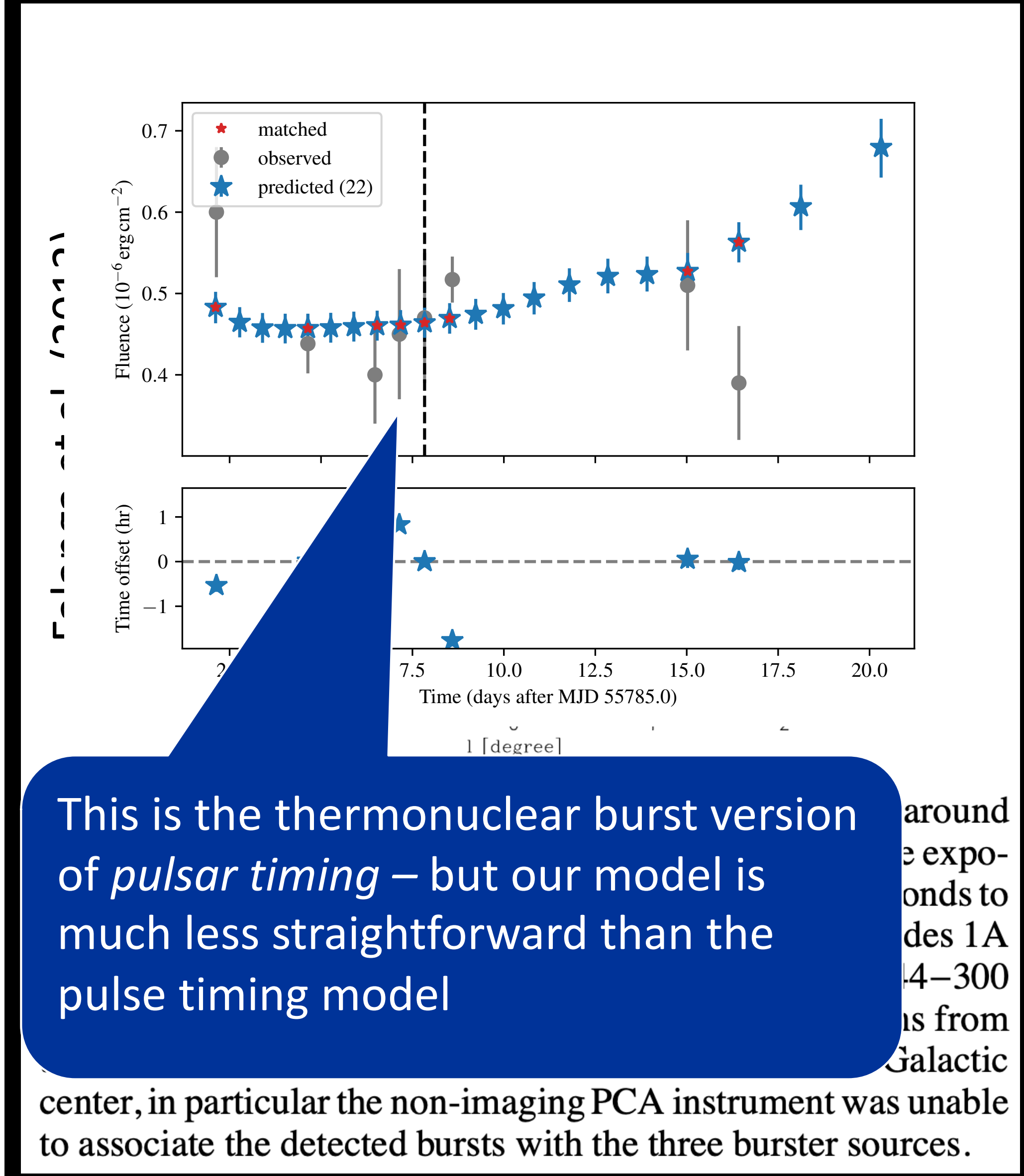
Fig. 1 | Simultaneous X-ray and multi-band radio light curves of 4U1728. **a**–**c**, For the X-rays, we show the 2 s 3–25 keV count rate for each epoch (where each panel corresponds to a different epoch): 2021 April 03 (**a**), 2021 April 04 (**b**) and 2021 April 05 (**c**). **d**–**f**, For the radio, 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

Seeing bursts through a 1D lens

- We can't *directly* identify what fuel is burning (& hence exactly 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
- *We want to know these properties so we can correctly interpret the burst behaviour AND learn about the host neutron stars, bursting systems and their evolutionary history*
- The most detailed 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
- There are other astrophysical uncertainties (distance, emission anisotropy, fuel composition etc.) that confound our analysis

Bursts from millisecond pulsars



around
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4–300
ns from
Galactic
center, in particular the non-imaging PCA instrument was unable to associate the detected bursts with the three burster sources.

This is the thermonuclear burst version of *pulsar timing* – but our model is much less straightforward than the pulse timing model

- These neutron-star binaries also show *X-ray* pulsations which indicate the neutron star spin (hundreds of times per second!)
- Only about 25 known; long-duration observational program with *INTEGRAL* led by Falanga, Li (ISSI)
- Several are bursters, including SAX J1808.4–3658 (the first such example discovered)
- This and several other sources are the focus of comparison with a simple (fast) ignition code via an MCMC approach, developed by Adelle Goodwin and myself, with the help of the Astronomy Data and Computing Services (ADACS) https://github.com/adellej/beans

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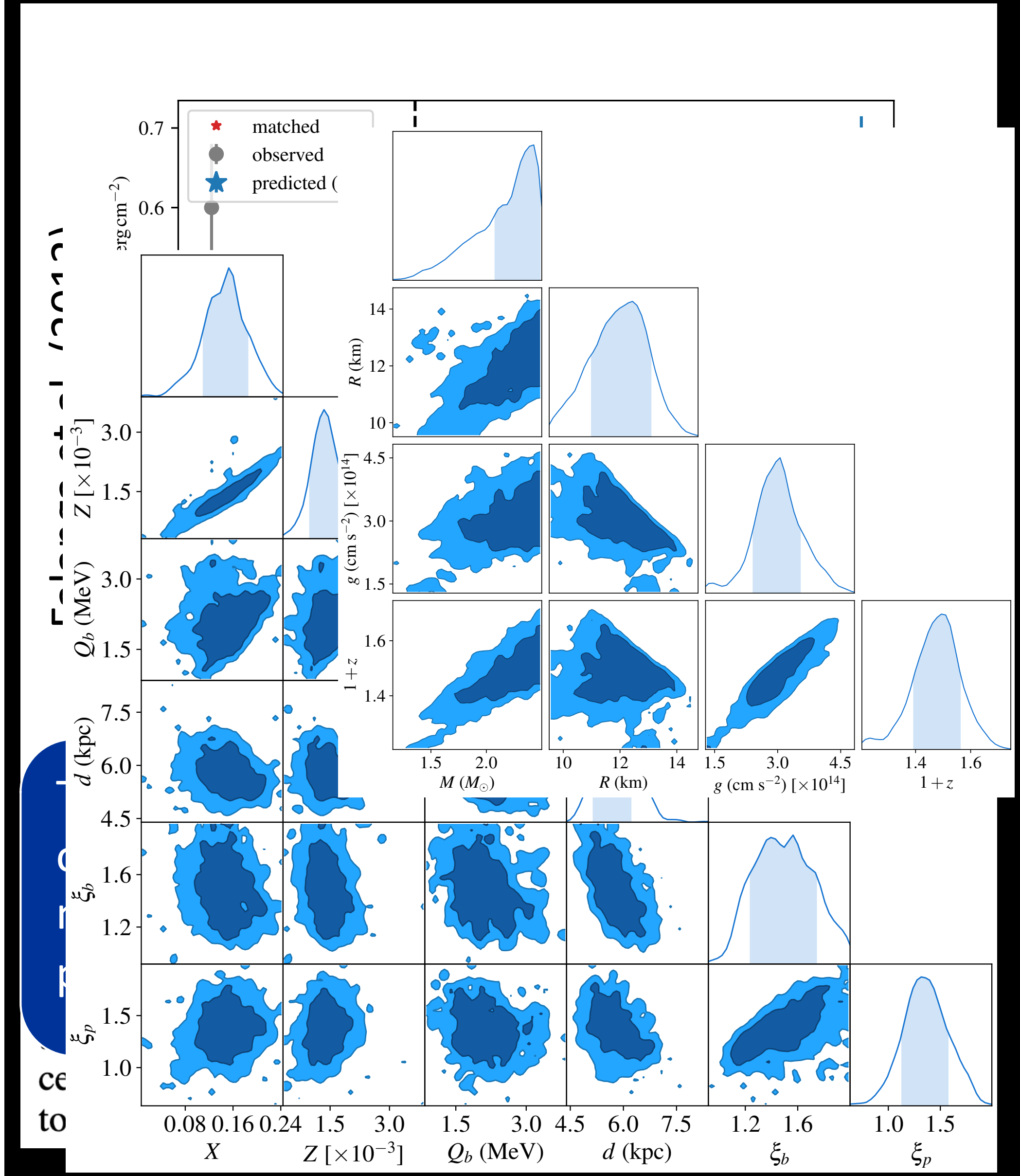

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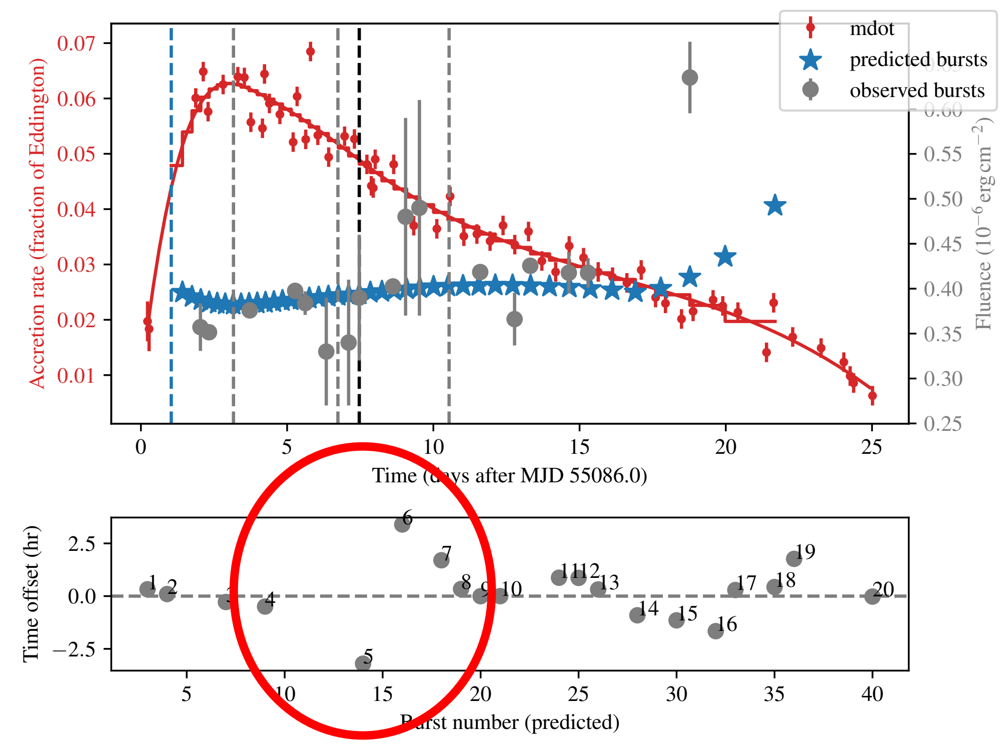
- Latest result: system parameter constraints in IGR J17498–2921

Galloway et al. 2024, MNRAS 535, 647

Going to larger numbers of bursts is a problem

- Convergence of the chains is incomplete; it's not clear if our solution is the best globally (or even locally!)
- There is not much literature on how to "fix" badly-behaved MCMC chains
- One issue we *know* affects our results arises from the goal of simulating an *entire* burst history *coherently*, which means that errors accumulate



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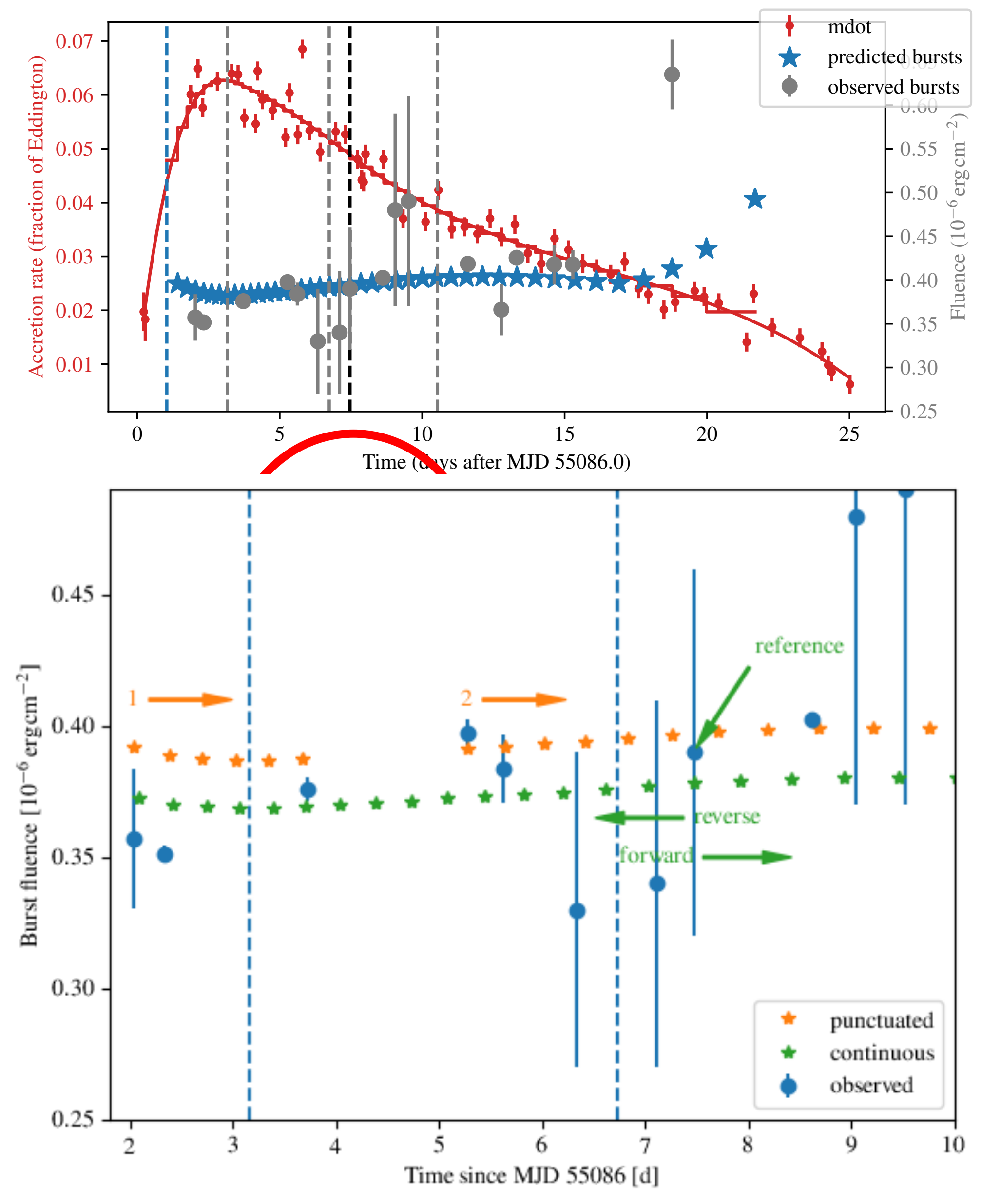
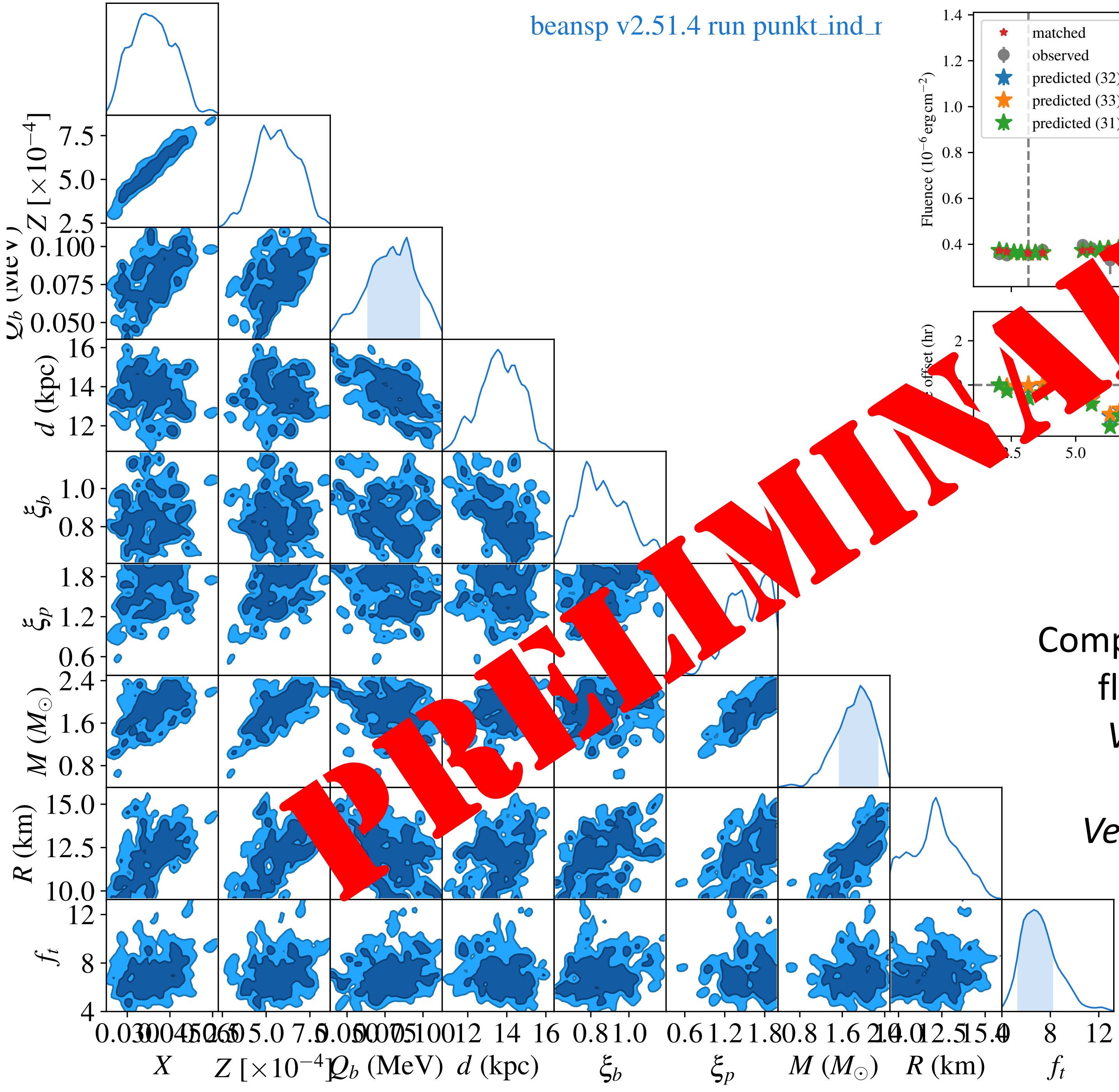
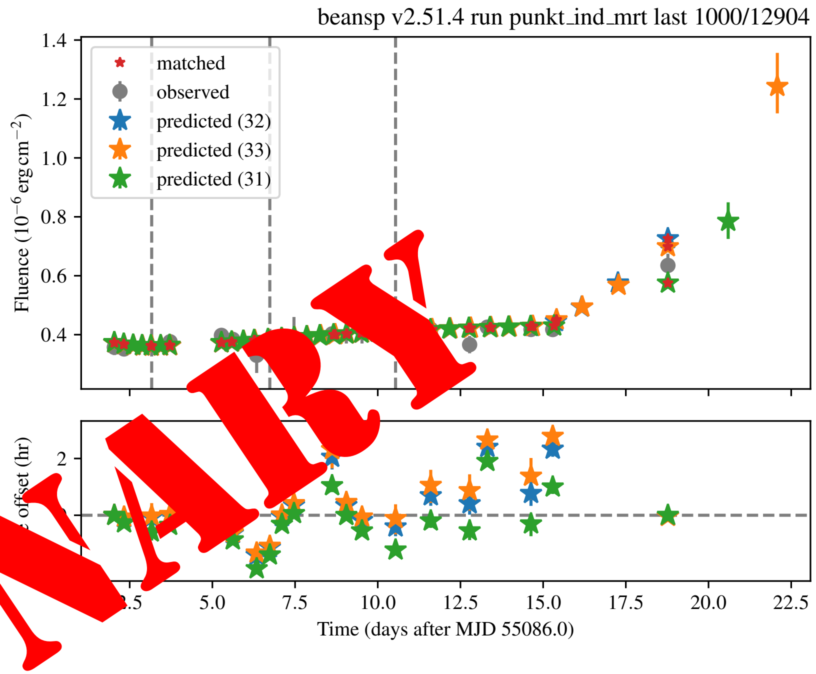
- Given that we can only know the accretion rate approximately, accurately simulating the entire "train" accurately is likely unachievable in practice
- Extensive work over the last few months during a visit to ISSI (Bern), first to allow "gaps" in the burst trains
- … and next to simulate each burst pair independently, starting from each observed burst







12904 steps in, still not converging

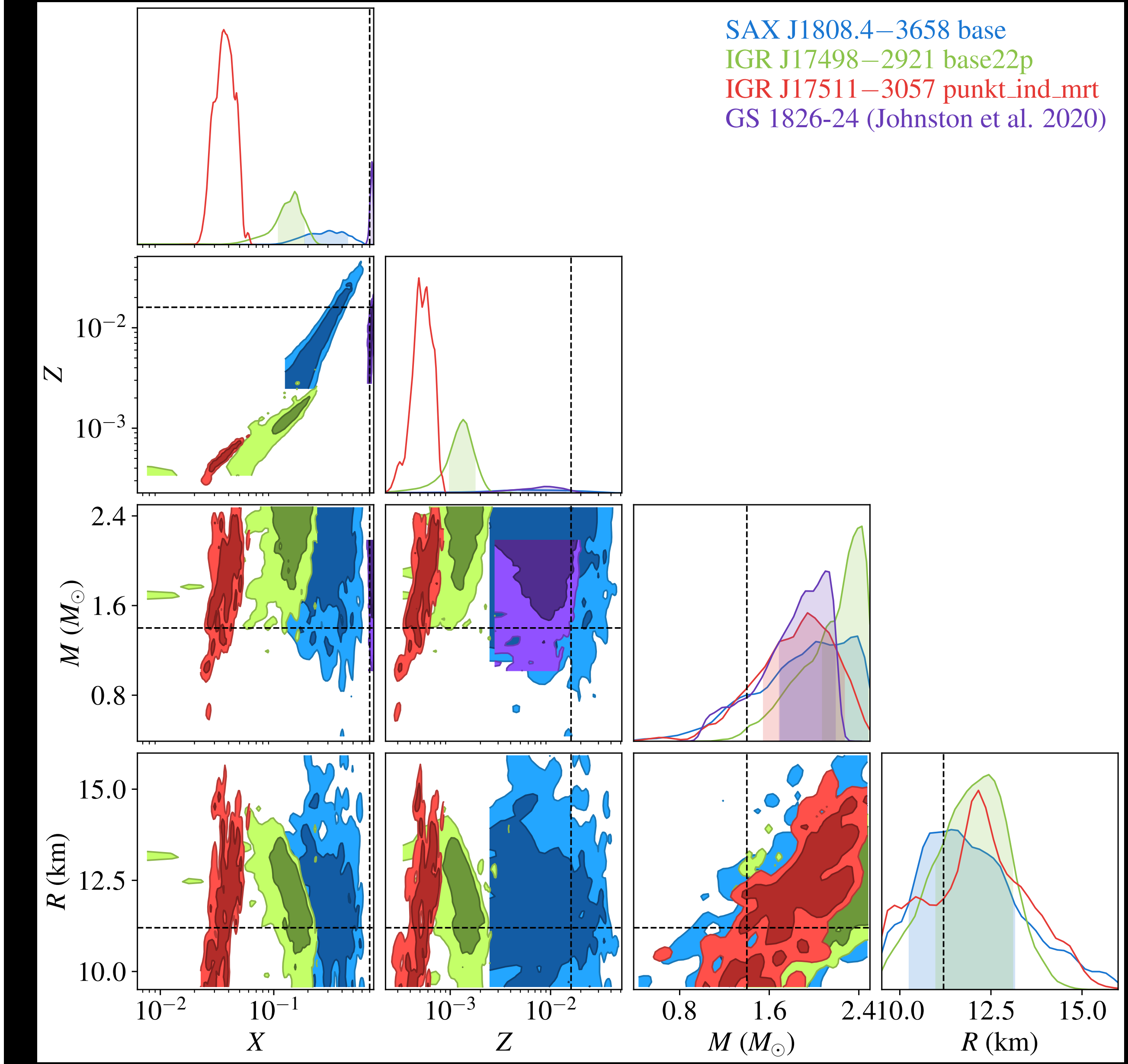
Comparison of burst times and fluences is good; RMS≈1 hr

Very low H-fraction & CNO metallicity

Very (unbelievably?) narrow posterior distributions

Also includes systematic variation of burst times

Broader population context



- What is the distribution of fuel composition for the entire population of bursters?
- This information is *critical* to guide reaction rate sensitivity studies (for example) – see Sultana poster
- These studies in turn have historically influenced experimental work; setting priorities for most important reactions to investigate
- To date only really done for one case (GS 1826-24; Cyburt et al. 2010, 2016) but other ignition cases exist

Summary and lessons learned

- Thermonuclear bursts are a key phenomenon to probe X-ray binaries and measure neutron star properties
- Utility is improving with time thanks to new sources, new observational capabilities and new analysis tools
- Numerical models remain critical to understanding thermonuclear bursts – we need (more) large samples of model results to apply, WITH full nuclear reaction networks, quantify model uncertainties etc.
- Development of software tools for burst observation-model comparison remains promising, can take advantage of existing model codes (and grids) & extensive accumulated observations
- Code development remains a challenge! Learn and adopt software development best practice, or work with someone who knows how to do this, like ADACS (do your unit tests!)
- Understanding complex tools like MCMC is also a challenge; applying the code to additional sources will promote increased robustness, additional tests like applying different samplers (e.g. via bilby) may be helpful
- These tools can be combined with additional constraints from different types of data including observational, theoretical, nuclear experimental