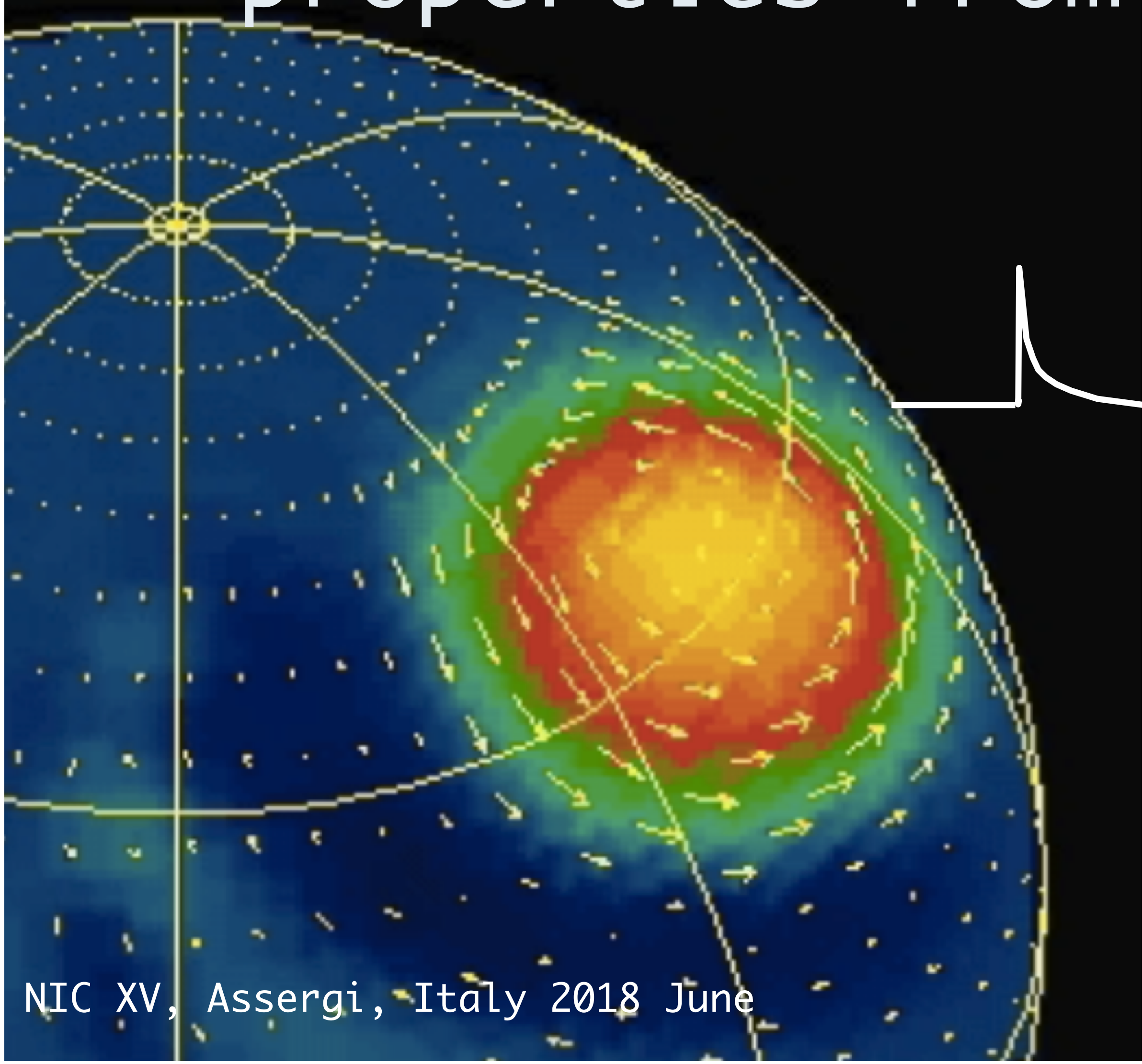
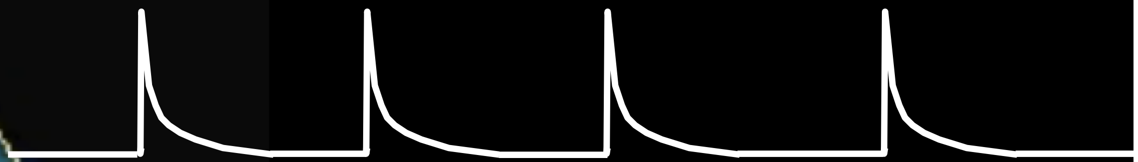
Measuring neutron star properties from thermonuclear bursts





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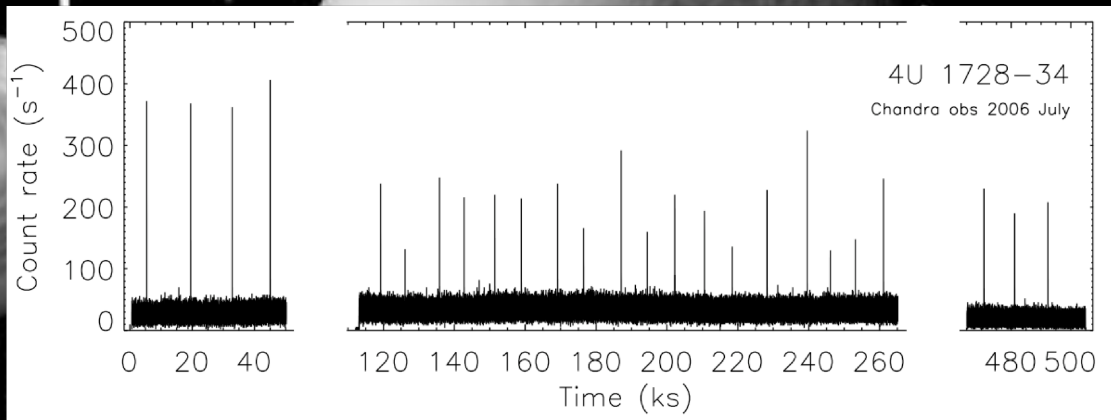
Thermonuclear X-ray bursts

- Neutron-star low-mass binaries exhibit a unique type of variability on timescales of seconds to minutes – X-ray bursts
- These systems are thought to accrete through gigayear timescales, sufficient to reduce the magnetic field to a point where it is dynamically unimportant
- Thermonuclear bursts occur when accreted fuel undergoes unstable ignition, producing bright X-ray flashes

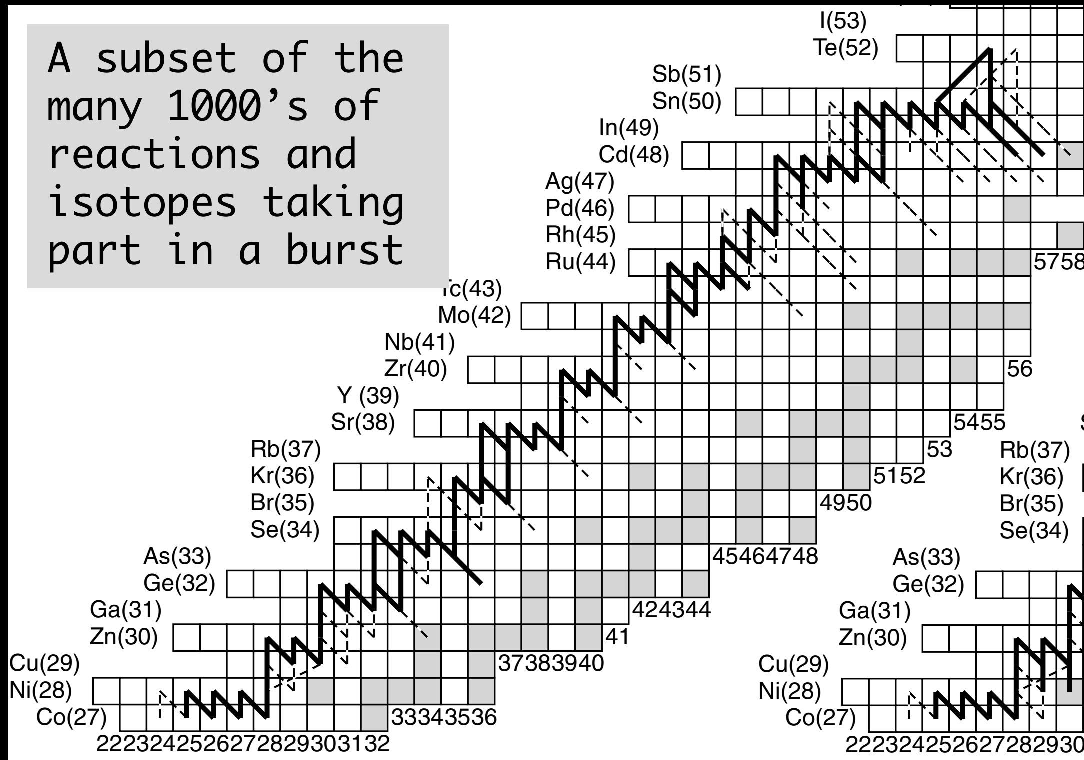


Chandra X-ray observation of the prolific burst source 4U 1728-34, showing quasi-regular bursting activity

Key thermonuclear reactions

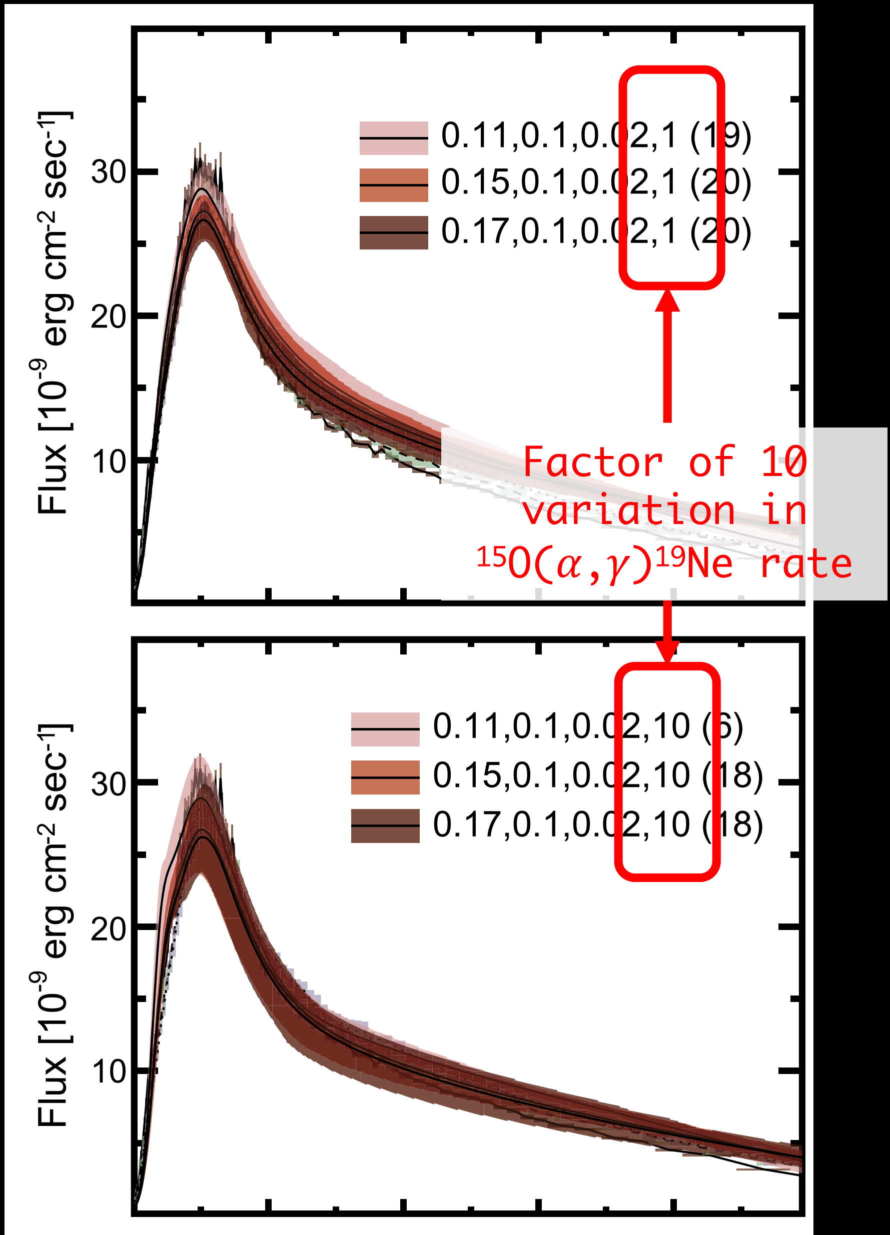
- Bursts typically ignite via the triple-alpha reaction, and if hydrogen is present, burn also via the (α,p) and rp processes
- Fuel composition and accretion rate the primary determinants of the burst properties
- Much work has focussed on the rp-process, which can produce heavy proton-rich nuclei in the burst ashes
- Many reactions with poorly measured rates

A subset of the many 1000's of reactions and isotopes taking part in a burst



Schatz et al. 2001

Constraining nuclear reactions



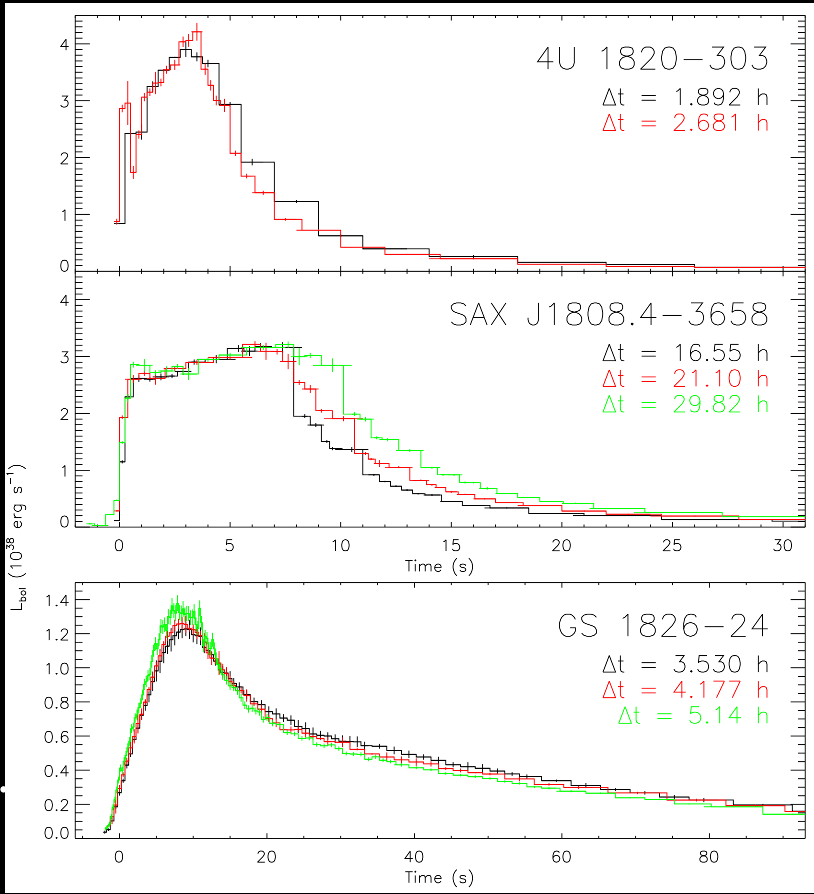
- Burst lightcurves are sensitive to certain nuclear reactions, from 1-zone and Kepler simulations e.g. Cyburt et al. 2016, ApJ 830, #55
- Holds promise for constraining reaction rates/masses via model-observation comparisons e.g. Meisel et al. 2018, ApJ 860 #147
- This study instead used MESA Paxton et al. 2015, ApJS 220, #15

This seems straightforward – why haven't we done this already?

- Even for the best-understood burst sources, we don't know the basic system parameters (surface gravity, fuel composition etc.)
- There are four reasons for this shortcoming:
    1. We lack *suitable observations* to compare against our models
    2. We can't efficiently *explore the parameter space* to find the best combination of parameters to match observations
    3. We lack a comprehensive way to *compare models to observations*
    4. There are *astrophysical uncertainties* (distance, system inclination) that confound our measurements
- As a result, we can't (yet) robustly reproduce the burst behavior for any source, which means we can't (yet) robustly test for the effects of different reaction rates or masses

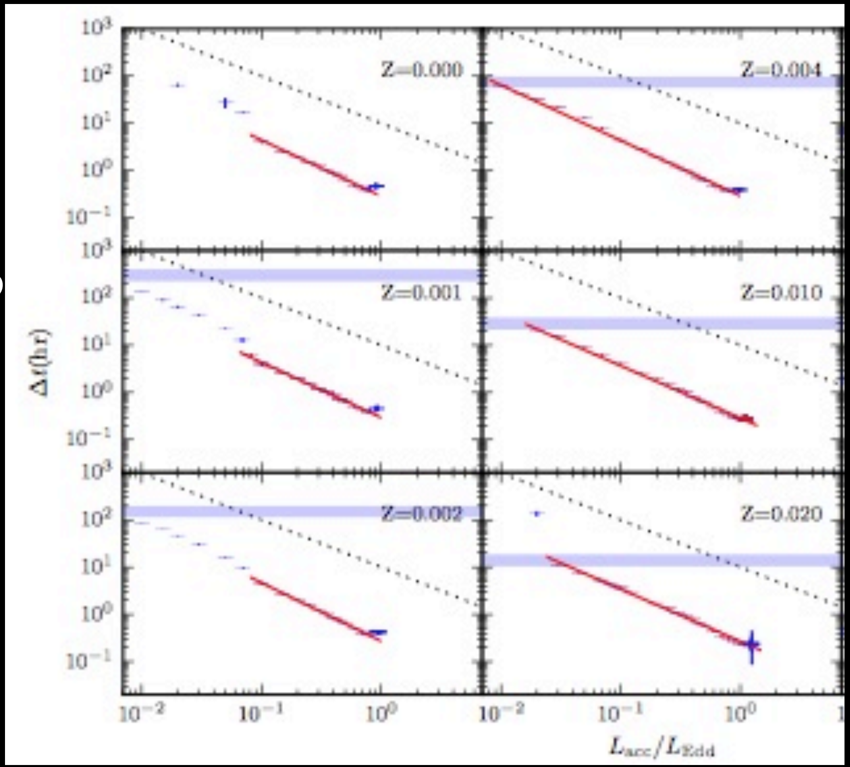
1. Gathering suitable observations

- 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 imminent! http://burst.sci.monash.edu/minbar
- Improved global view of burst behaviour and rare events; now >7000 events from 85 (of 112) sources
- Analysis of burst rates as a function of accretion rate Galloway et al. 2018, ApJ 857, L24
- "Reference" bursts for model comparisons Galloway et al. 2017, PASA 34, e019



2. Exploring parameter space

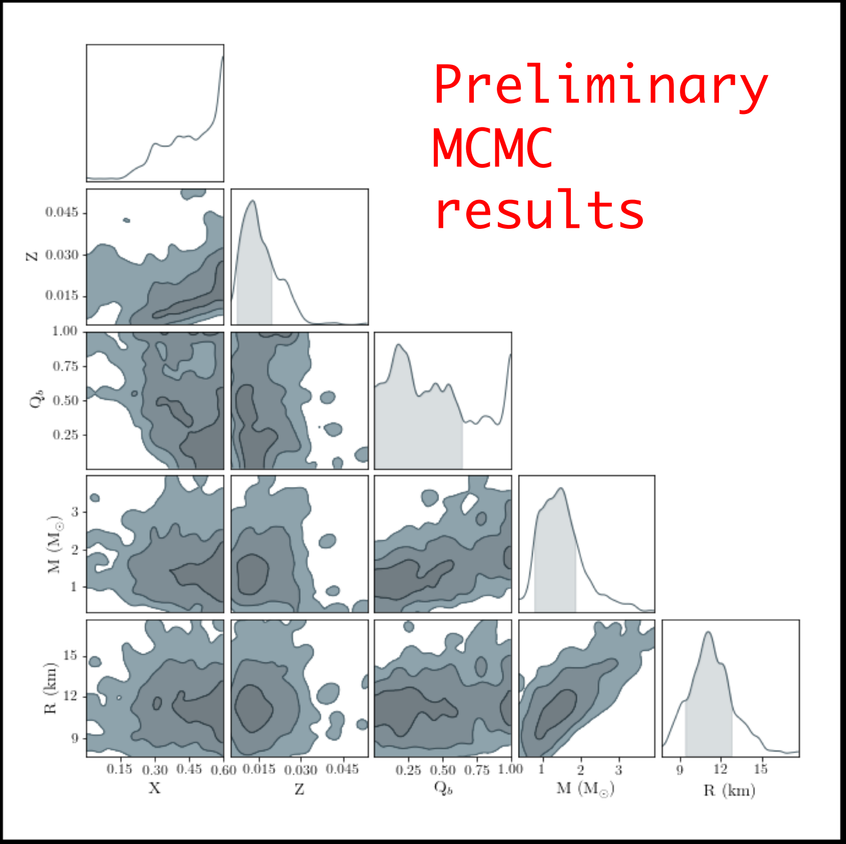
- State-of-the-art codes are 1-D with adaptive nuclear reaction grids like KEPLER and MESA, which take ~week for each run
- Not feasible for e.g. MCMC parameter space exploration
- We can run & release large samples of model results e.g. Lampe et al. 2016
- New grids are being used via interpolation schemes to do fast (x10^8 speedup!) parameter exploration see Johnston poster #49, inside the library



Lampe et al. 2016, ApJ 819, 46

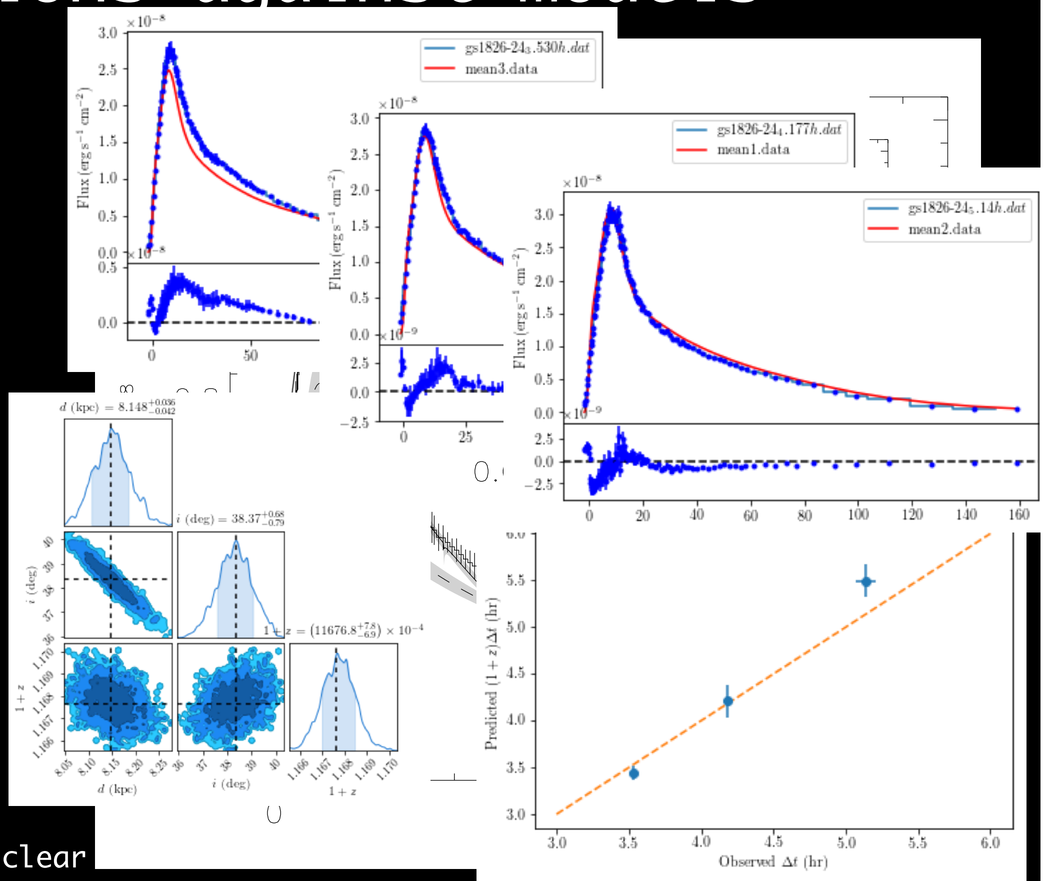
2. Exploring parameter space #2

- We can also use simpler (faster) ignition codes, provided we have confidence that we understand how the predictions differ between models e.g. Cumming & Bildsten 2000, ApJ 544, 453
- This work has revealed surprising new results about the neutrino flux from bursts
- Previously assumed to lose ≈35% of energy, KEPLER measurements suggest max. 14% and typically much lower see Goodwin poster #249, in the hall



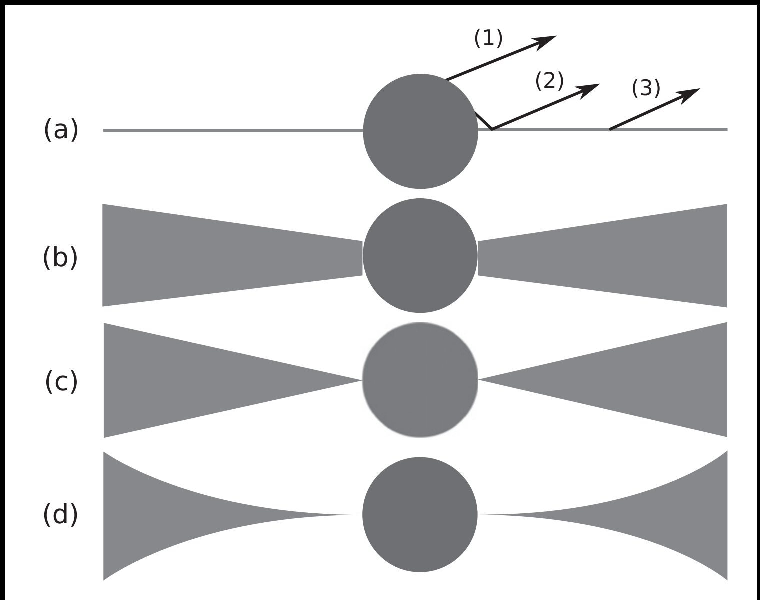
3. Model-observation comparisons

- Multiple-epoch comparisons are likely necessary to resolve degeneracies (e.g. in GS 1826-24, the “Clocked burster”)
- We lack suitable tools to compare multiple sets of burst simulations against models
- Also difficulties balancing (e.g.) recurrence time comparisons vs. lightcurves
- “concord” software to do this is now in development and testing



4. Astrophysical uncertainties

- Distance to bursters are typically poorly known, introducing uncertainties to the burst energetics e.g. Galloway et al. (ApJS 179, 360, 2008)
- Burst emission is enhanced/attenuated due to the anisotropy of the environment (the accretion disk) e.g. He & Keek (ApJ 819, #47 2016)



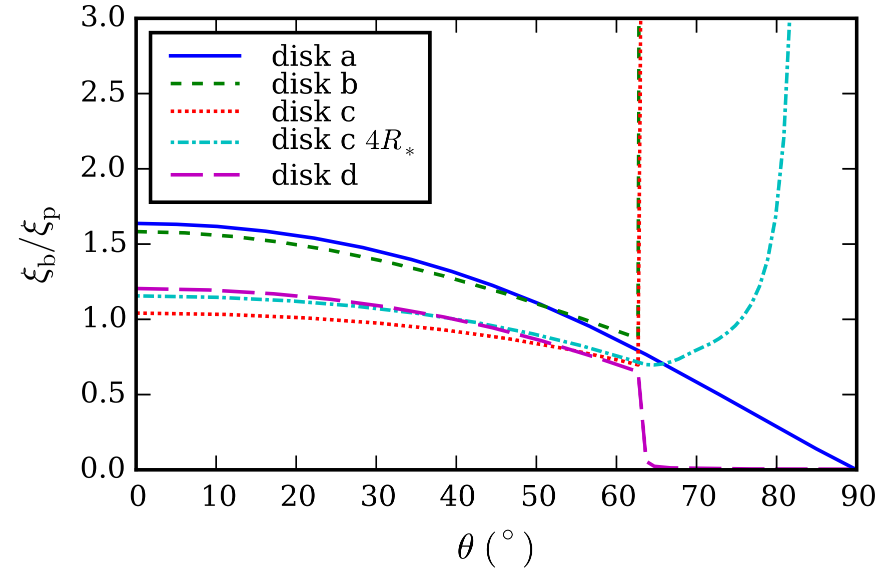


Figure 12. ξ_b/ξ_p for different disk shapes, as presented in Figures 8 and 11. The observed α-parameter differs from the intrinsic value by this factor.

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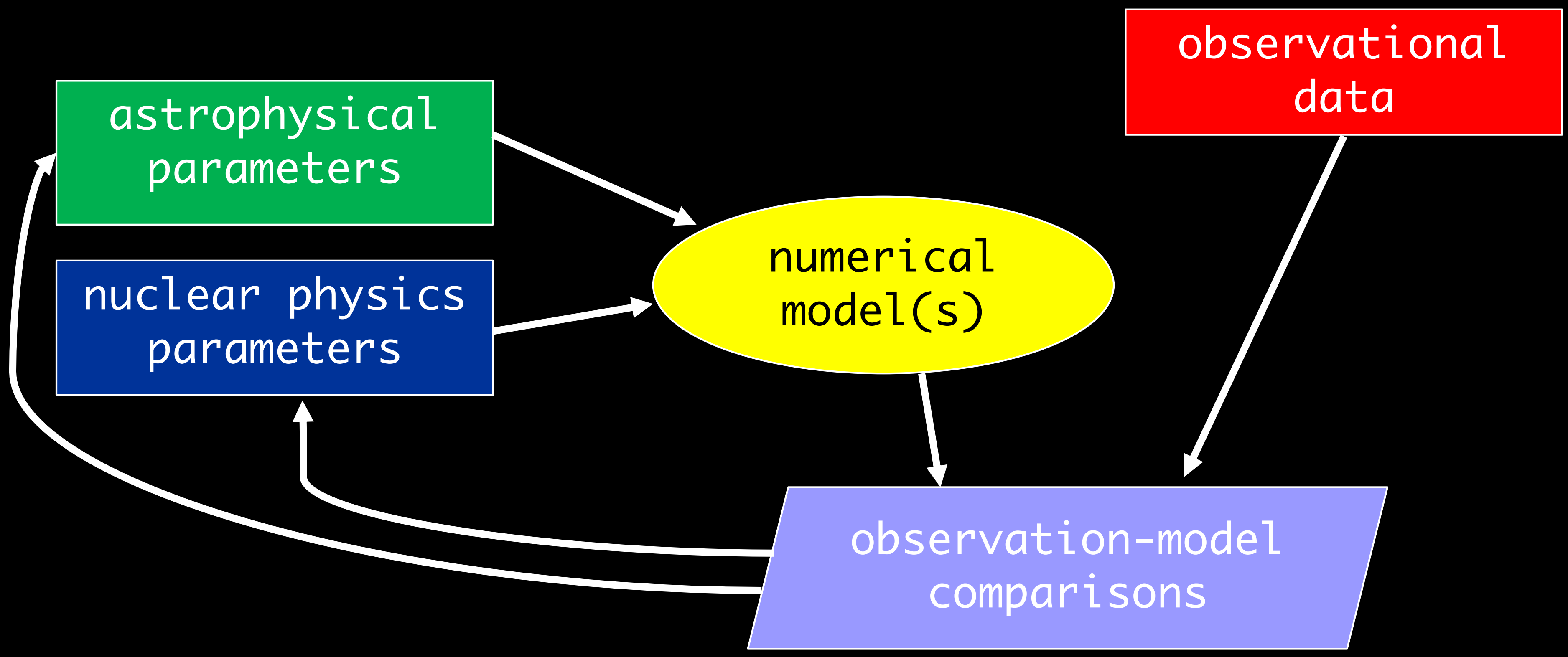
- Burst emission is enhanced/attenuated due to the anisotropy of the environment (the accretion disk) e.g. He & Keek (ApJ 819, #47 2016)
- Estimates of the accretion rate are made via the persistent emission, which suffers the same problem (but a different factor)
- Burst emission is affected by gravitational redshift, depends on (unknown) mass & radius
- With new tools and data, we can *model* these effects and then marginalize out to get constraints on the parameters of interest

Ultimate goal

- A synergy of observation, simulation, and nuclear experiment



Cf. with talk by B. Côté

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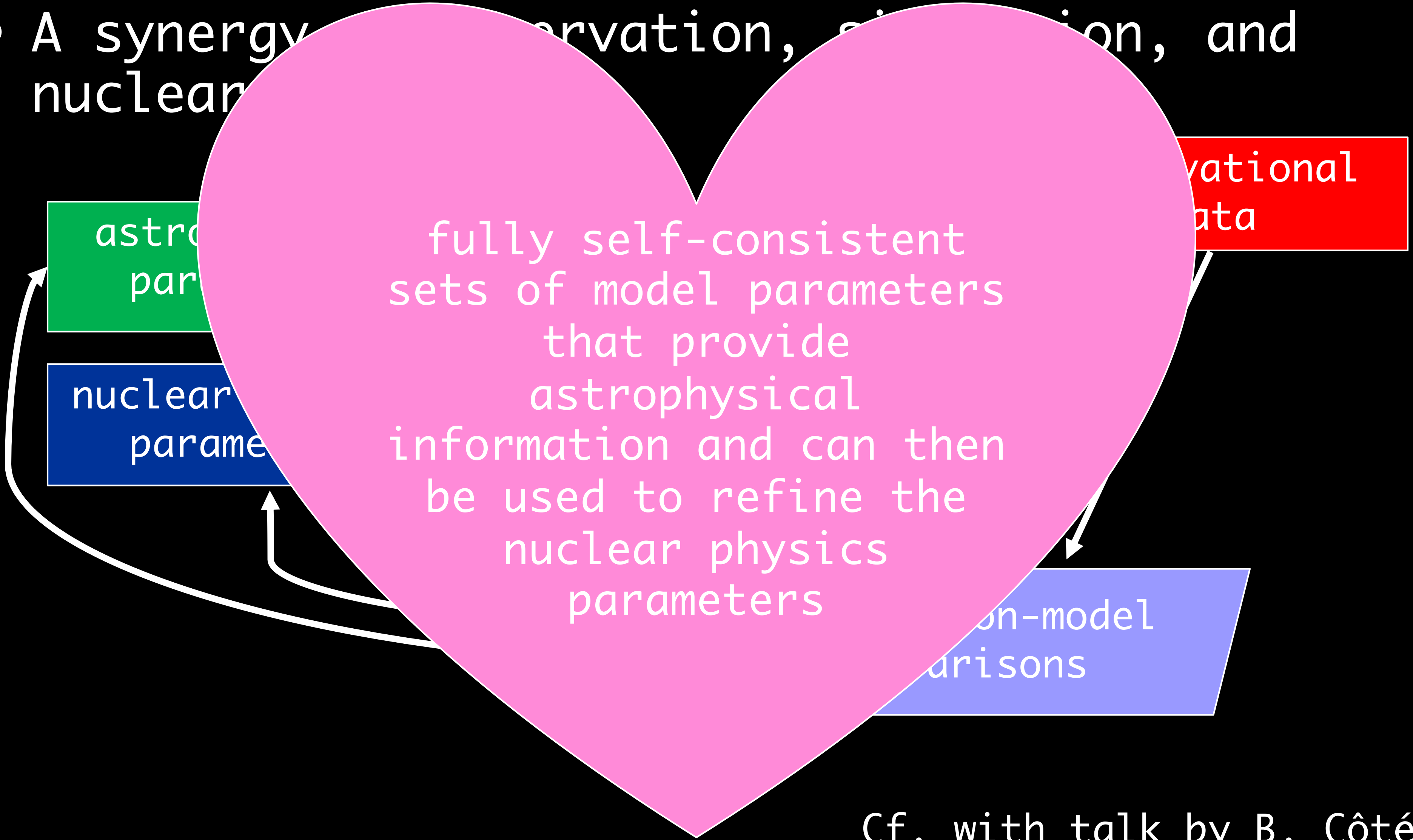

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Summary and future prospects

- We now have access to a substantial accumulated observational dataset to analyse, as well as detailed models
- We are making good progress on the tools required to combine these elements to provide models consistent with observations
- Anticipate within 12 months we have a complete solution of astrophysical parameters for the best-studied source, GS 1824-26 (or we'll show it can't be done!)
- Prospects for application to other sources are good, and incorporating nuclear physics may allow us to constrain reaction rates etc.