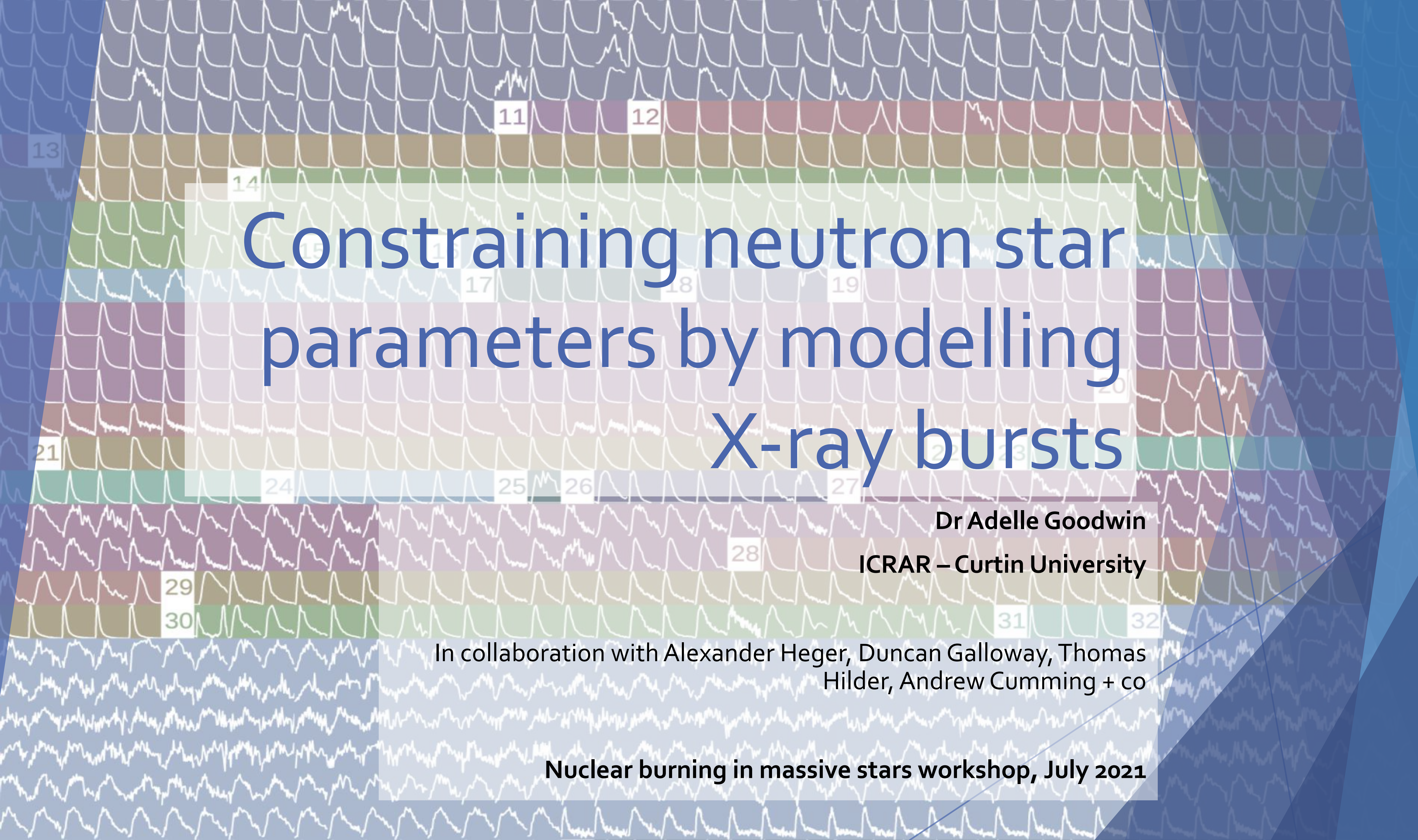


Constraining neutron star parameters by modelling X-ray bursts

Dr Adelle Goodwin

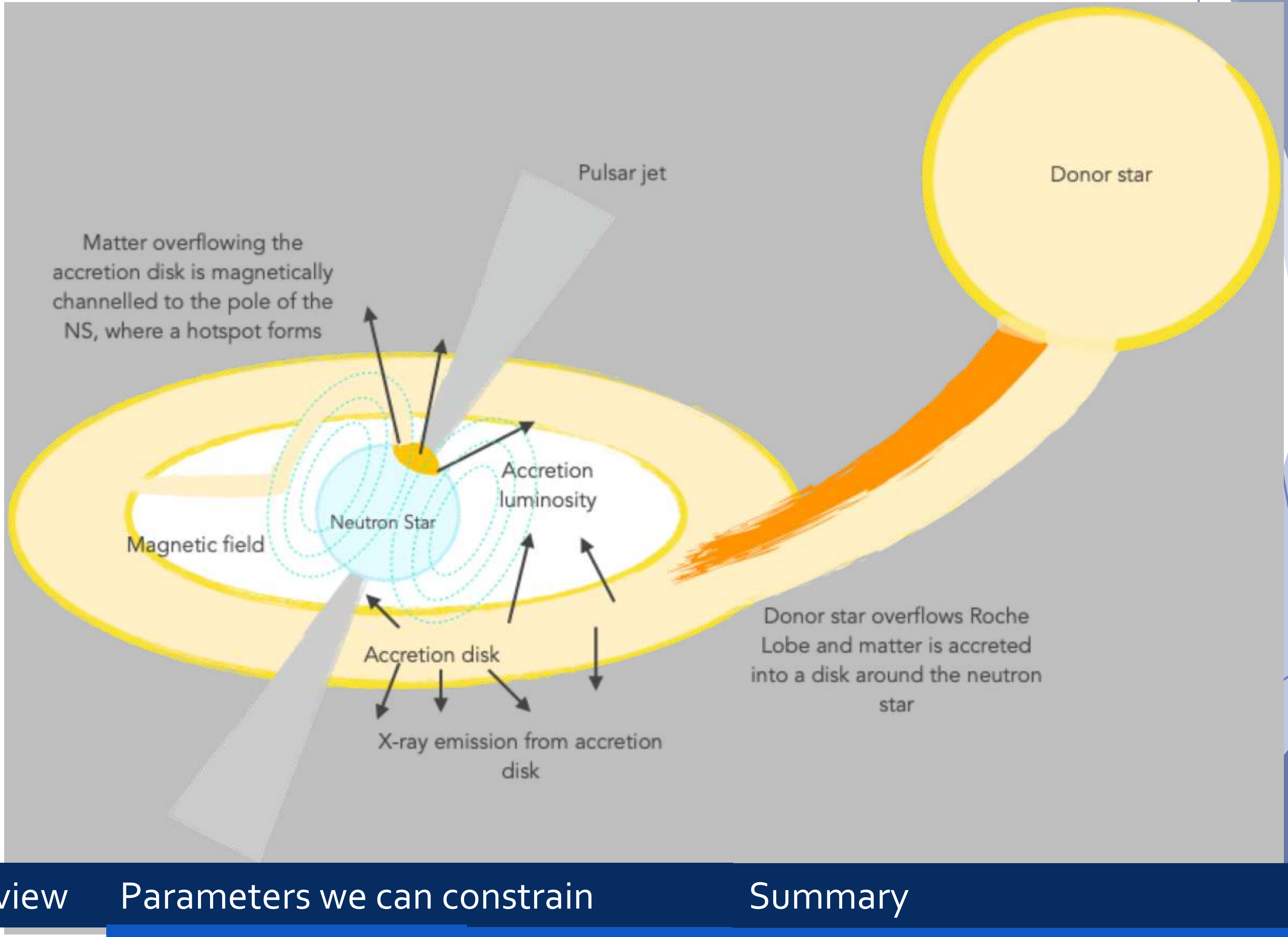
ICRAR – Curtin University

In collaboration with Alexander Heger, Duncan Galloway, Thomas Hilder, Andrew Cumming + co

Nuclear burning in massive stars workshop, July 2021

X-ray bursts: what systems produce them?

Accreting
neutron stars

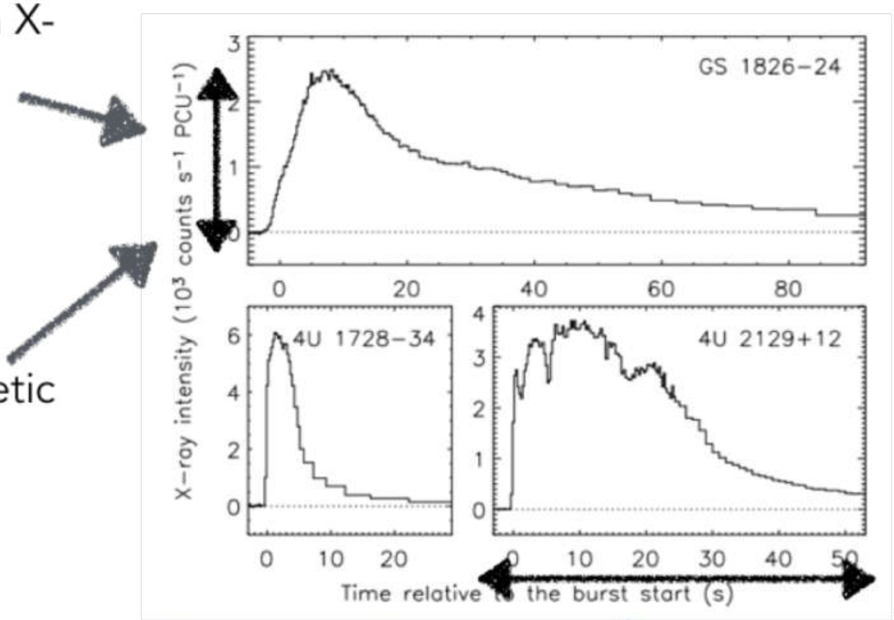


X-ray burst properties

Thermonuclear runaway on the surface of an accreting neutron star

Bright (in X-Ray)

Energetic (~10^{39} erg)



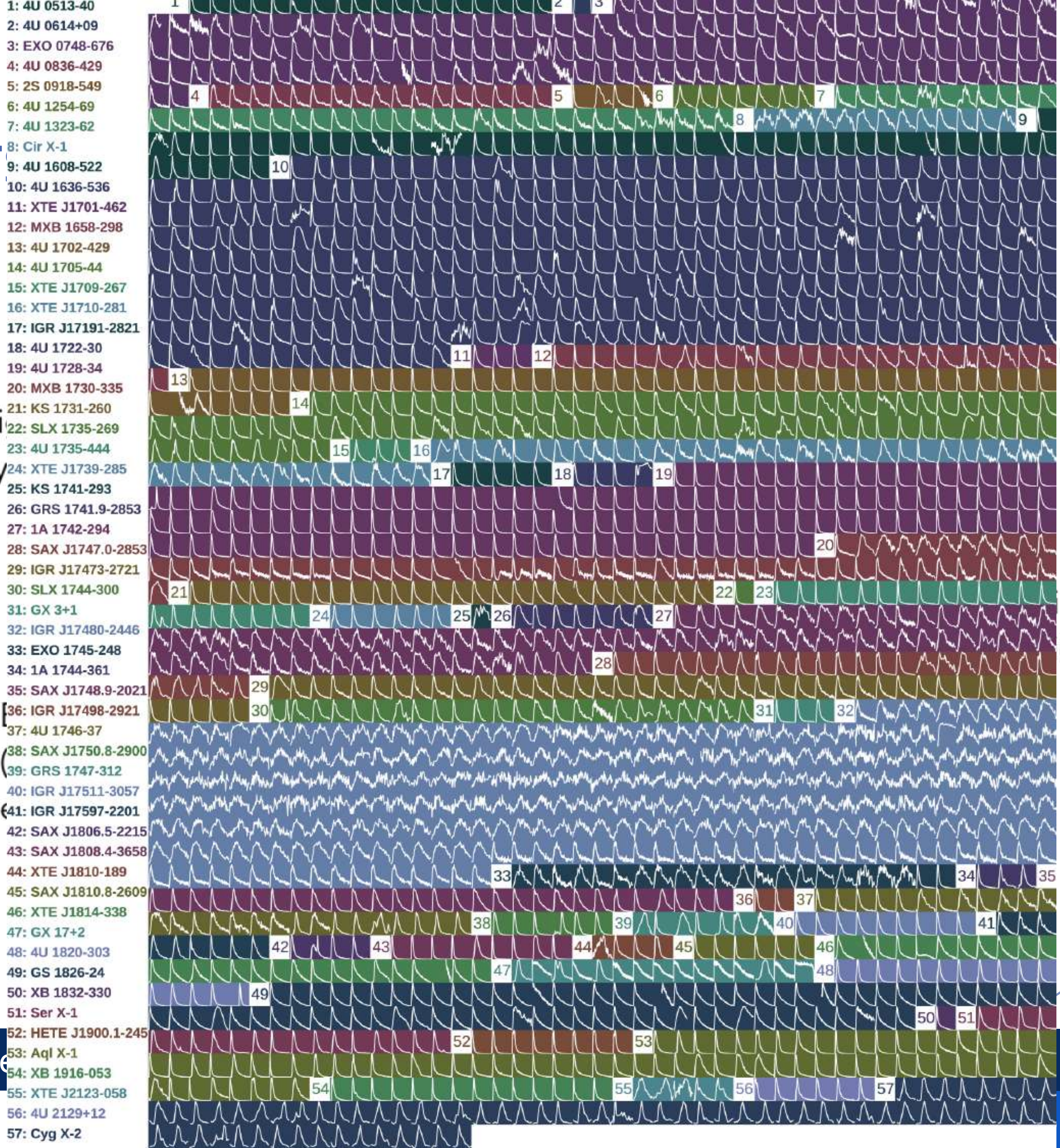
Galloway et al (2008)

Powered by unstable ignition of hydrogen/helium on the surface of a neutron star

Short (~10s of seconds)

X-ray bur

Bilous+ 2019



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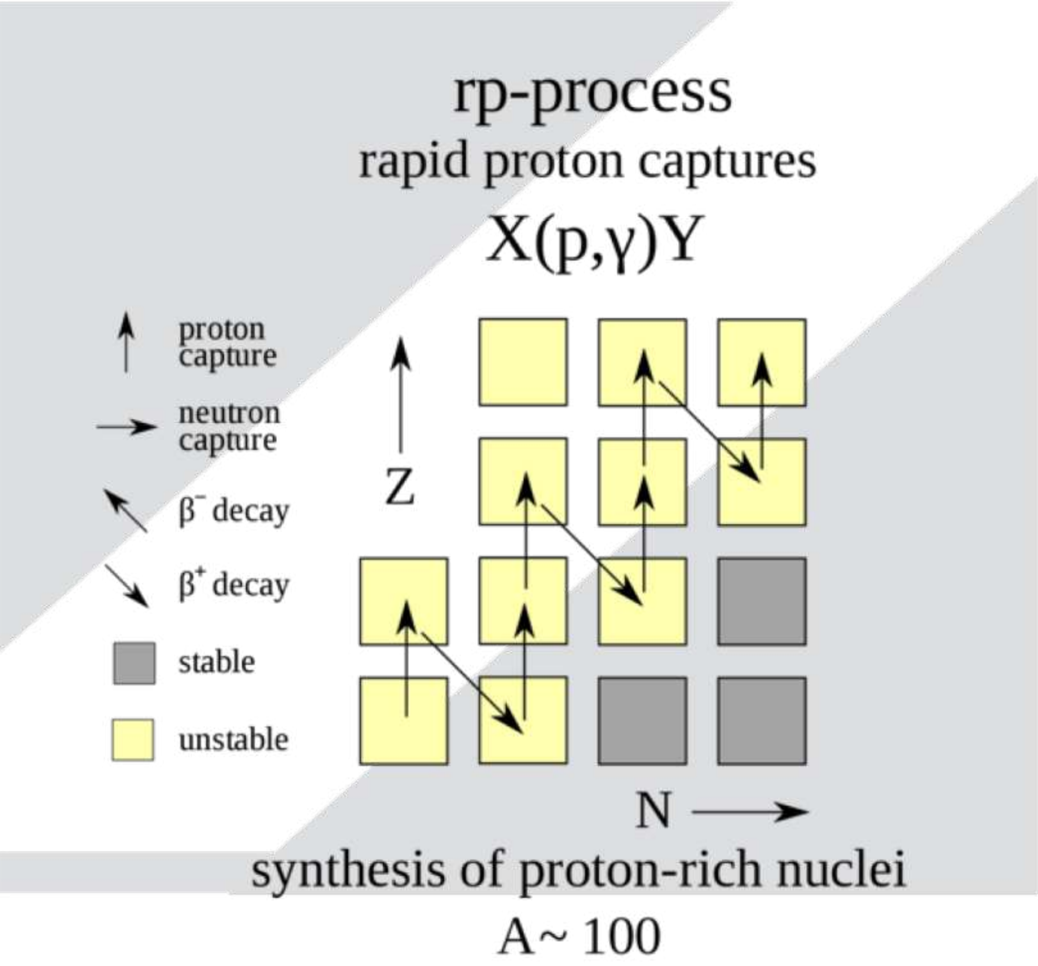
Nuclear Burning in Type I X-ray bursts



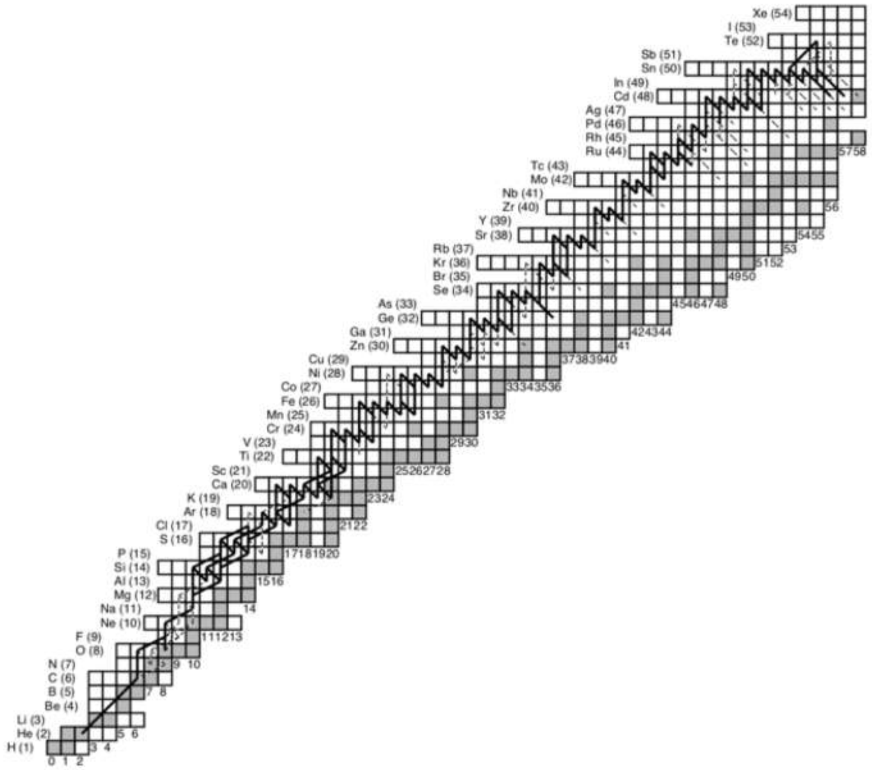


Fig. 3.1. Schematic showing the dominant pathways of the nuclear reaction flows during the rp process. Elements far beyond ^{56}Fe can easily be reached. Filled squares denote stable nuclides (after Schatz et al. 2001).

Strohmayer & Bildsten (2001)

Modelling X-ray bursts

Two types of models:

1. Simple (semi) analytic models - integrate an ignition column and make simple assumptions about energy output (e.g. settle)
2. Complex models - include a nuclear reaction network to determine energy output (e.g. KEPLER)

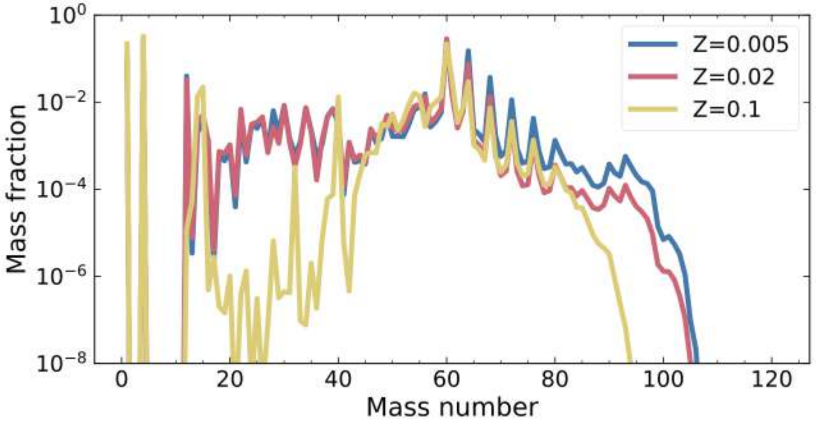
Predict observed burst:

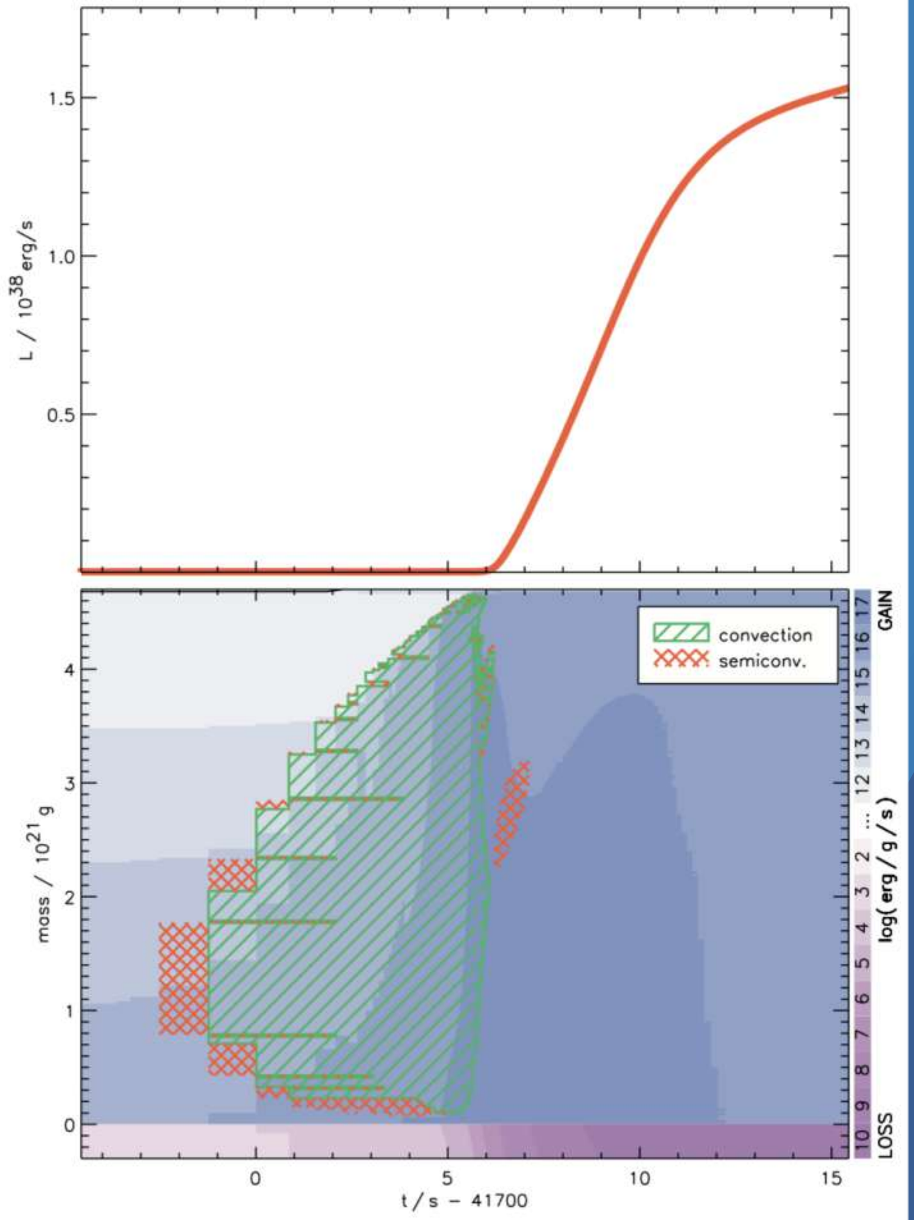
Inputs	Outputs
Fuel composition	Rise times
Neutron star mass	Durations
Neutron star radius	Energies
	Recurrence times

Kepler

Woosley et al (2004)

- 1D implicit hydrodynamics code
- Adaptive nuclear reaction network
- Multi-zone
- Has been used for 20 years to simulate X-ray bursts on neutron stars
- Takes ~4 days to run





Settle

Cumming & Bildsten (2000)

- "0D" semi-analytic code
- Integrates neutron star atmosphere by making simple assumptions about thermal profile to find ignition conditions
- One-zone ignition criterion
- Makes simple assumptions about burst energy output -
- Runs in a few seconds

Ignition criterion

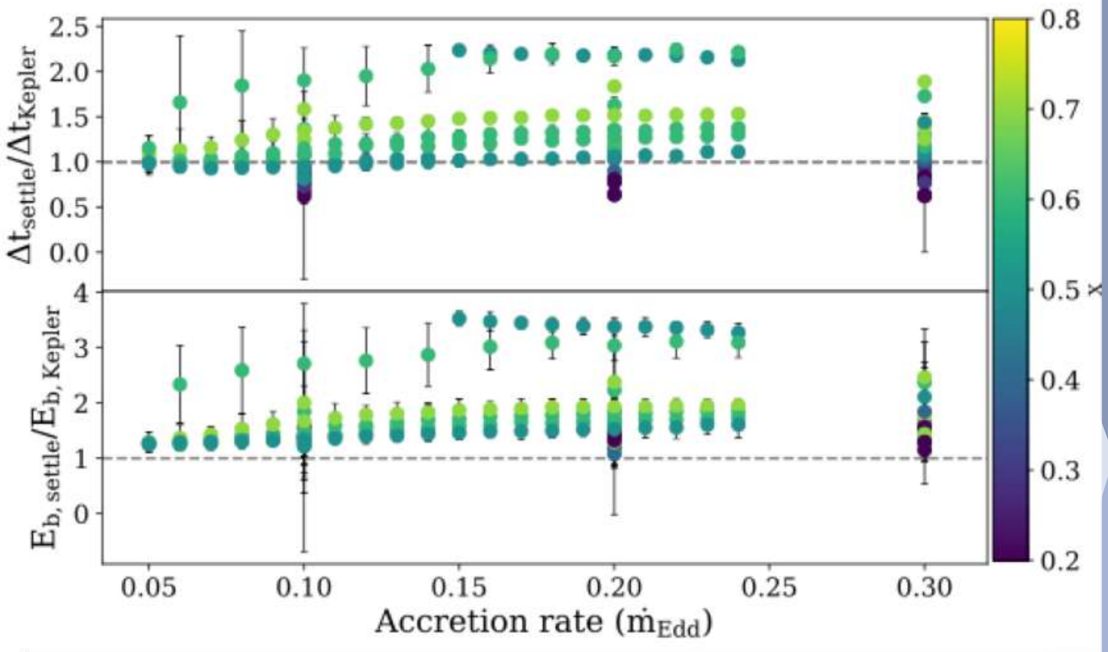
$$\epsilon_{3\alpha} = 5.3 \times 10^{21}\,\mathrm{erg\,g^{-1}\,s^{-1}}\; f\frac{\rho_5^2 Y^3}{T_8^3}\exp\left(\frac{-44}{T_8}\right)$$

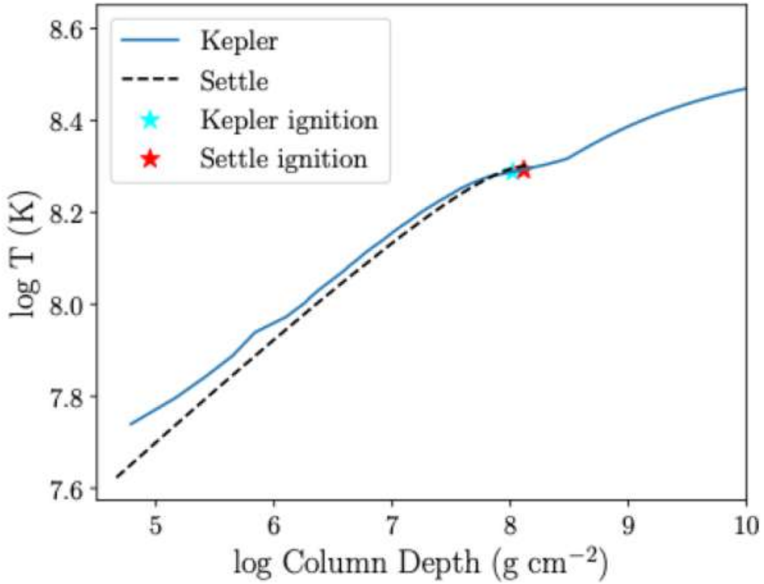
$$\epsilon_{\mathrm{cool}} \approx \frac{acT^4}{3\kappa y^2}.$$

Ignition depth, y, is chosen such that:

$$d\epsilon_{3\alpha}/dT = d\epsilon_{\mathrm{cool}}/dT$$

Settle vs Kepler





- ➢ Simple code systematically over-estimates energy and recurrence times of bursts
- ➢ Due to thermal/compositional inertia?

What parameters can we constrain with X-ray bursts?

- Nuclear reaction rates via sensitivity studies
- Neutron star parameters that effect observed burst properties:
  - M, R, g, X, Z, Qb, d, inclination, accretion rate
- Binary properties, binary evolution

What parameters can we constrain with X-ray bursts?

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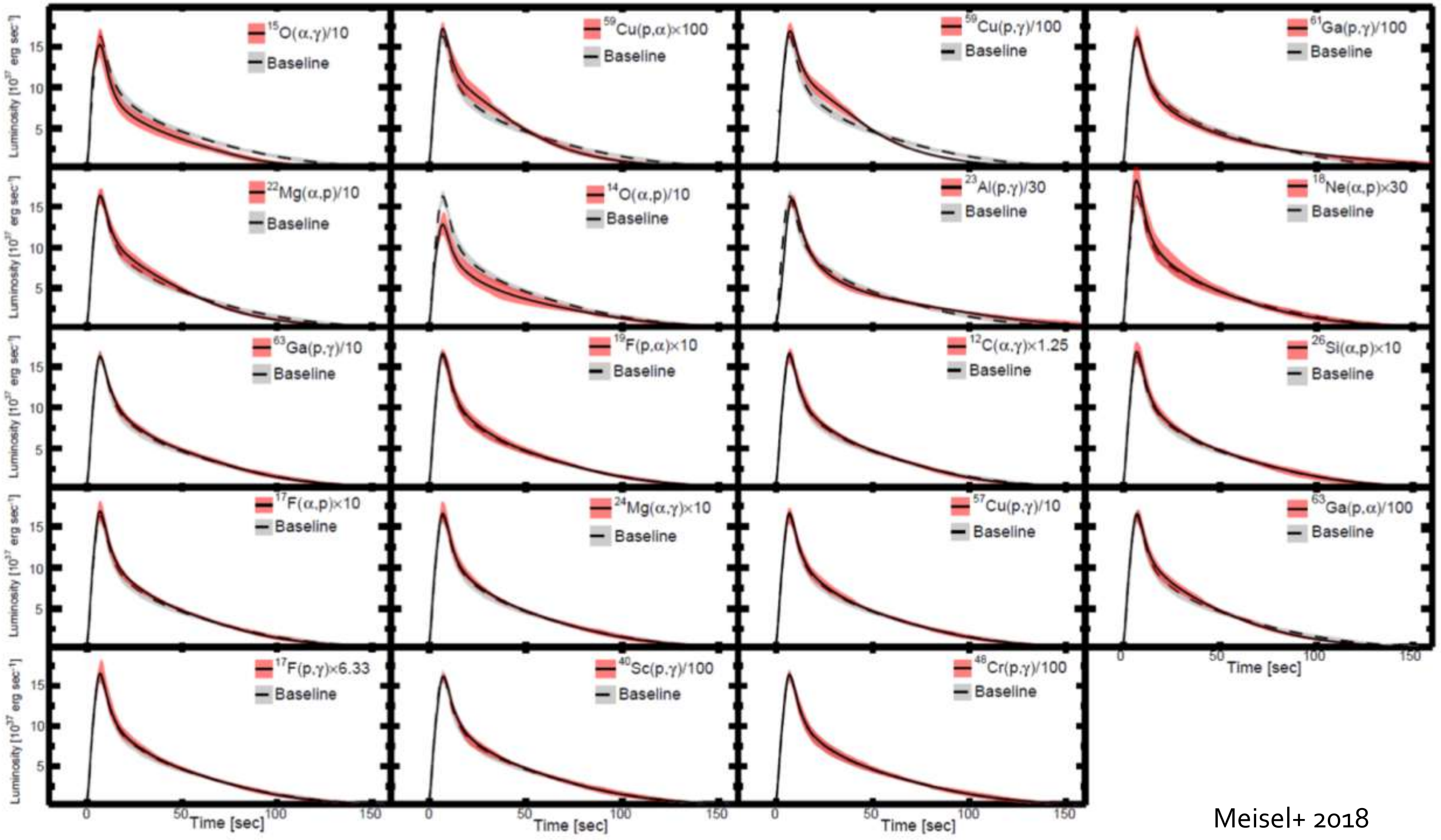
X-ray burst reaction rate sensitivity studies

- Sensitivity studies: vary the nuclear reaction rates and determine the effect on X-ray burst lightcurves

Using MESA or Kepler to generate lightcurves



Meisel+ 2018

What parameters can we constrain with X-ray bursts?

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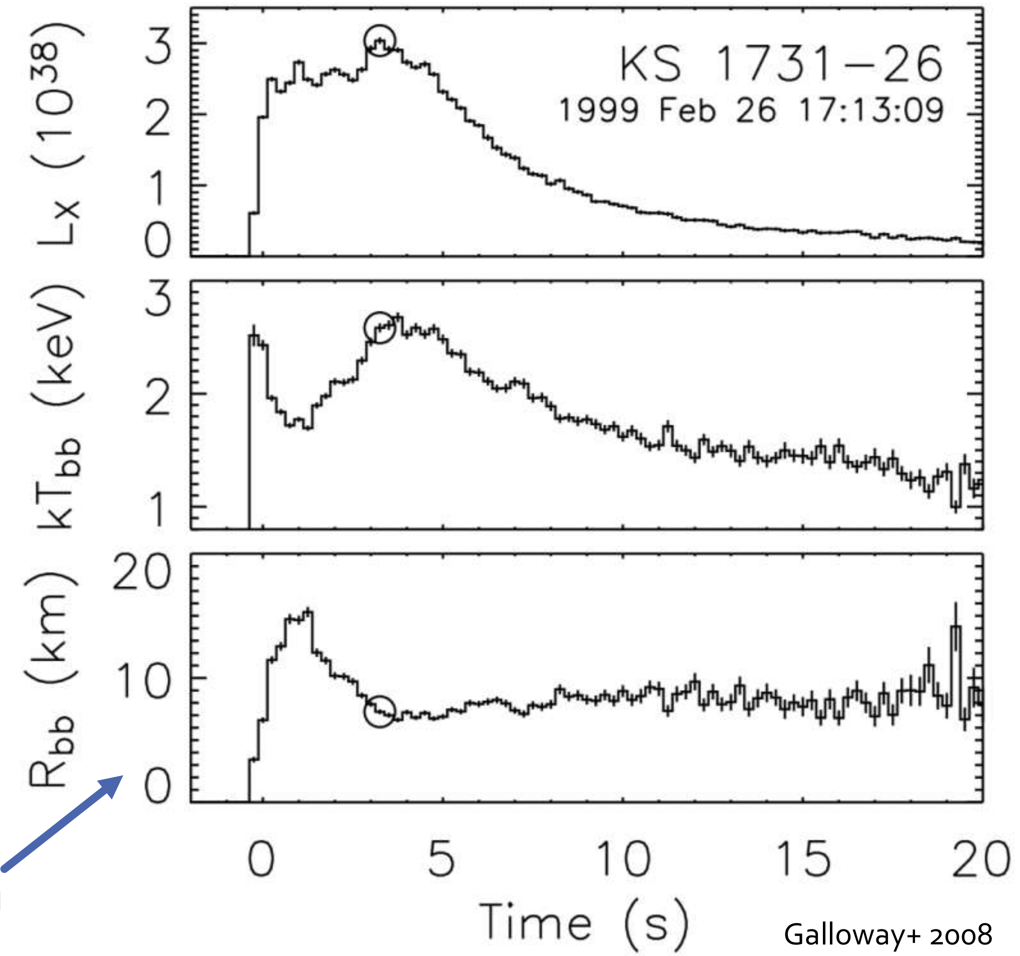
X-ray bursts as standard candles for distance estimates

- Photospheric radius expansion: the outwards radiation pressure equals the gravitational force binding the outer layers of accreted material to the star.
- Luminosity reaches Eddington luminosity and photosphere expands

- Enables distance estimates



Galloway+ 2008

Anti-correlation between kT and R in the first few seconds with constant flux -> expanding photosphere

What parameters can we constrain with X-ray bursts?

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  - M, R, g, **X**, Z, Qb, d, inclination, accretion rate

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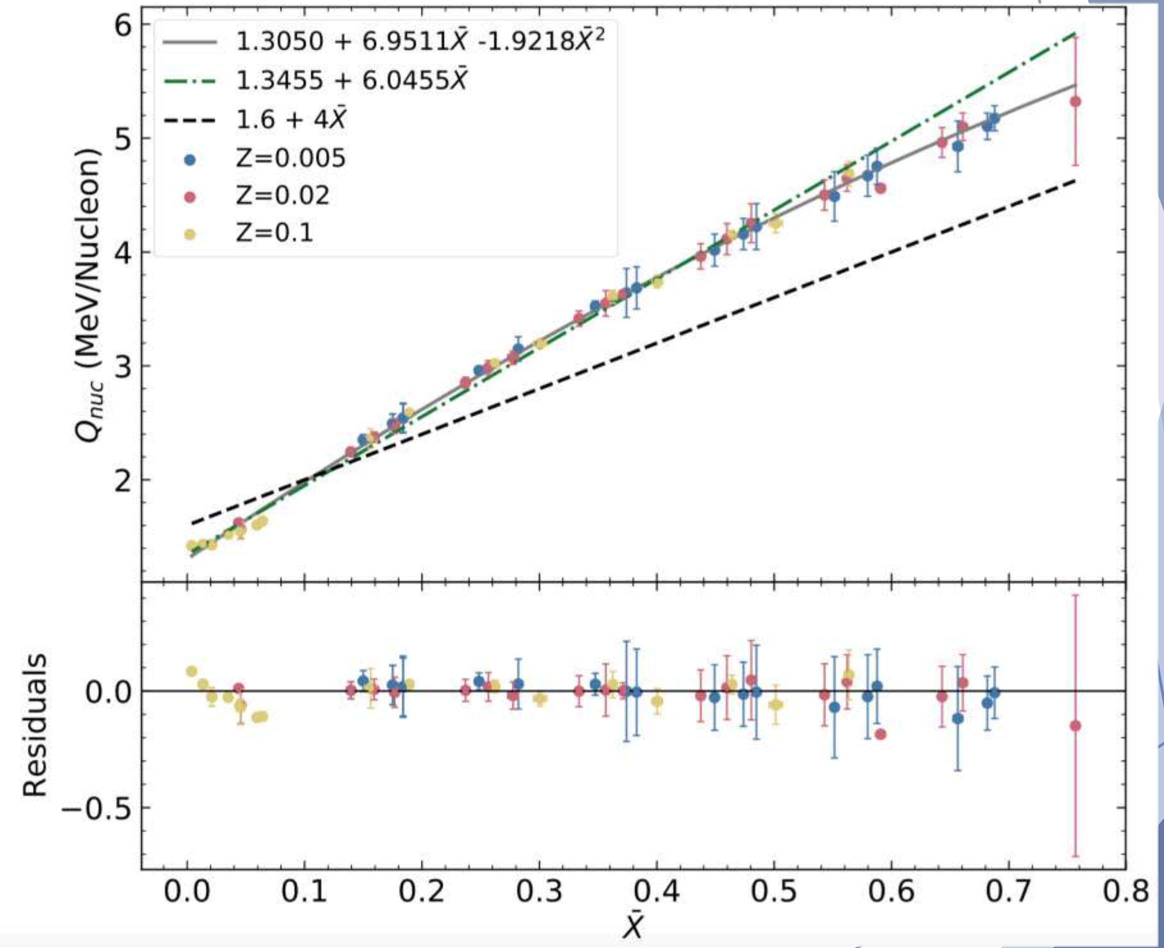
Goodwin+ 2019

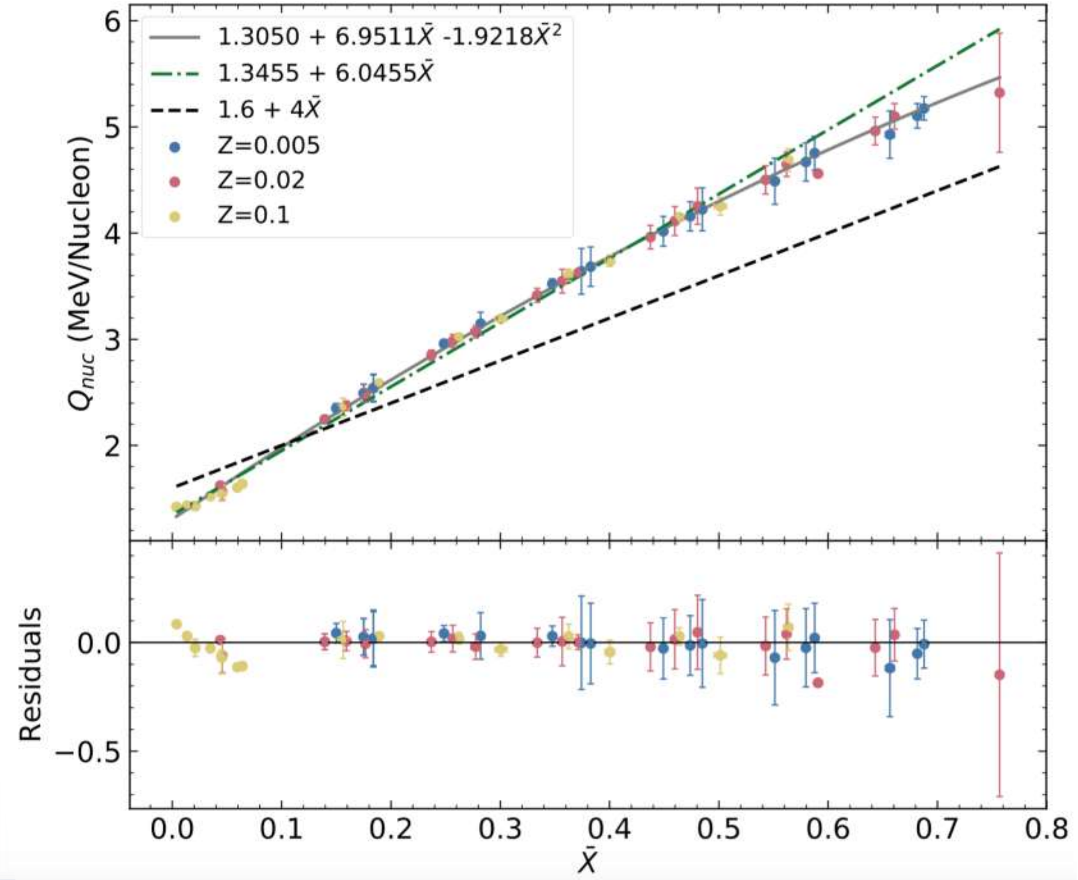
Kepler burst energy/composition predictions

- Ran grid of Kepler models
- Extract Energy (Qnuc) and average H fraction of burst ignition column
- Determine relationship

Qnuc = 1.35+6.05X



Kepler burst energy/composition predictions - useful for observers



Qnuc = 1.35+ 6.05X

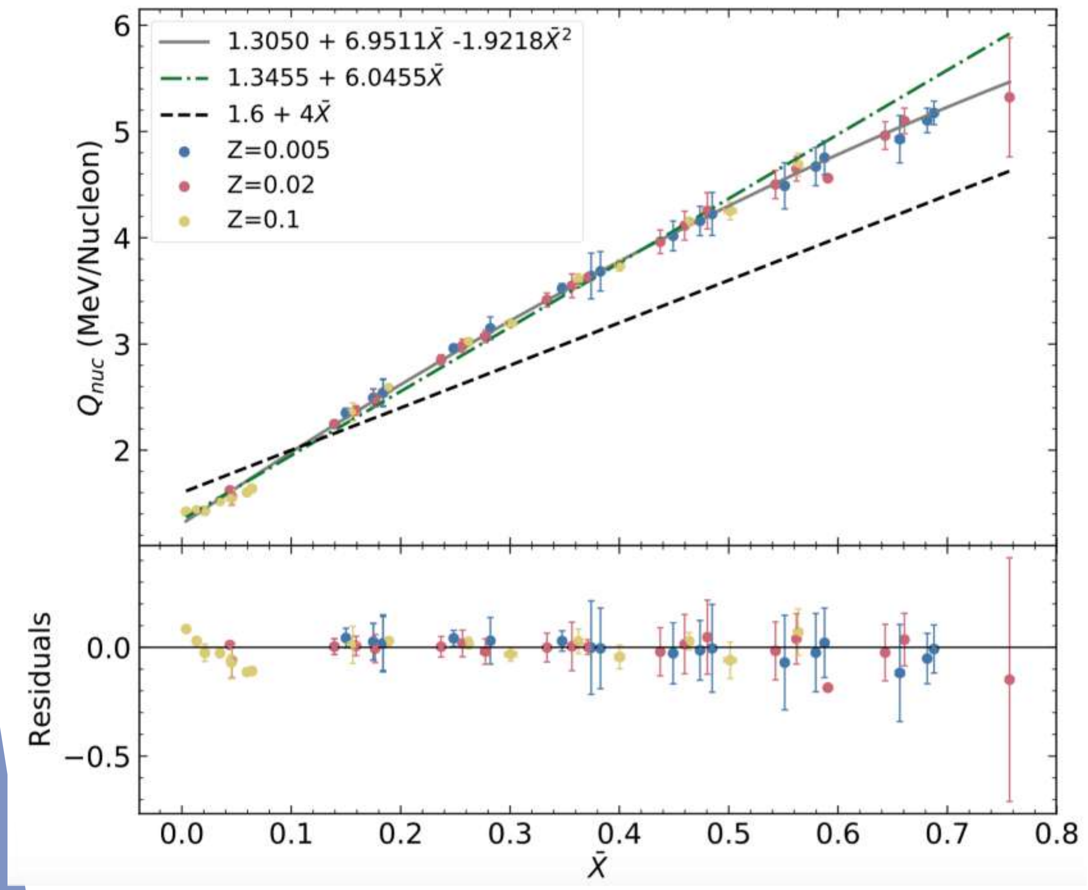
Q_{grav} =~ GM/R

$$Q_{\rm nuc} = \frac{Q_{\rm grav}(1+z)}{\alpha} = \frac{218}{\alpha} \quad {\rm MeV/nucleon}$$

$$\alpha = \frac{F_{\rm pers} c_{\rm bol} \Delta t}{E_{\rm b}}$$

→ observed

Kepler burst energy/composition predictions - useful for observers



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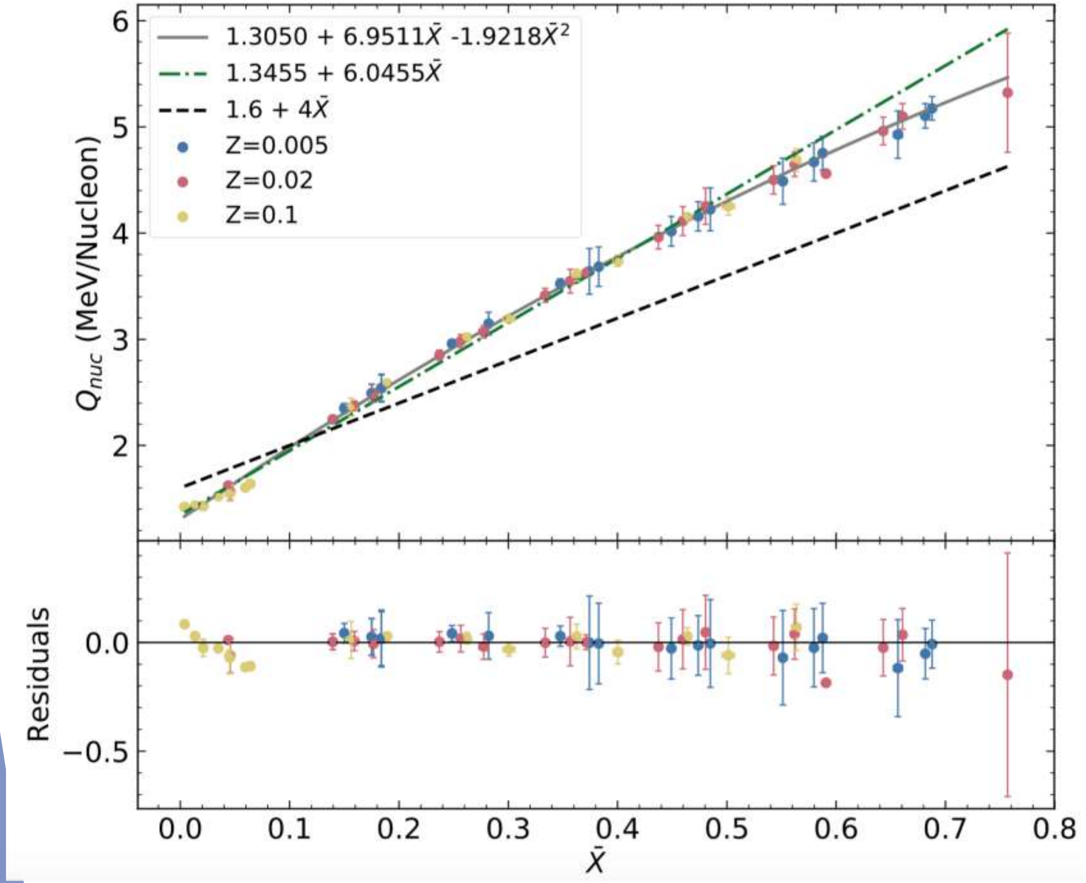
Can estimate X of burst fuel!

Kepler burst energy/composition predictions - useful for observers



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Can estimate X of burst fuel!

$$t_{\rm cno} = 9.8\,{\rm h} \frac{X_0}{0.7} \frac{0.02}{Z}.$$

One step further: can estimate X of accreted fuel (X_o)!

What parameters can we constrain with X-ray bursts?

- Nuclear reaction rates via sensitivity studies
- **Neutron star parameters that effect observed burst properties:**
  - **M, R, g, X, Z, Qb, d, inclination, accretion rate**
- Binary properties, binary evolution

Matching observations with models

Bayesian Estimation of Accreting Neutron Star parameters (BEANS)

- Match observed burst parameters (energy, alpha, recurrence time) with predicted to infer system properties
- Can use MCMC for simple (fast) models (Goodwin+2019) or educated guesses for slower models (Johnston+ 2018)

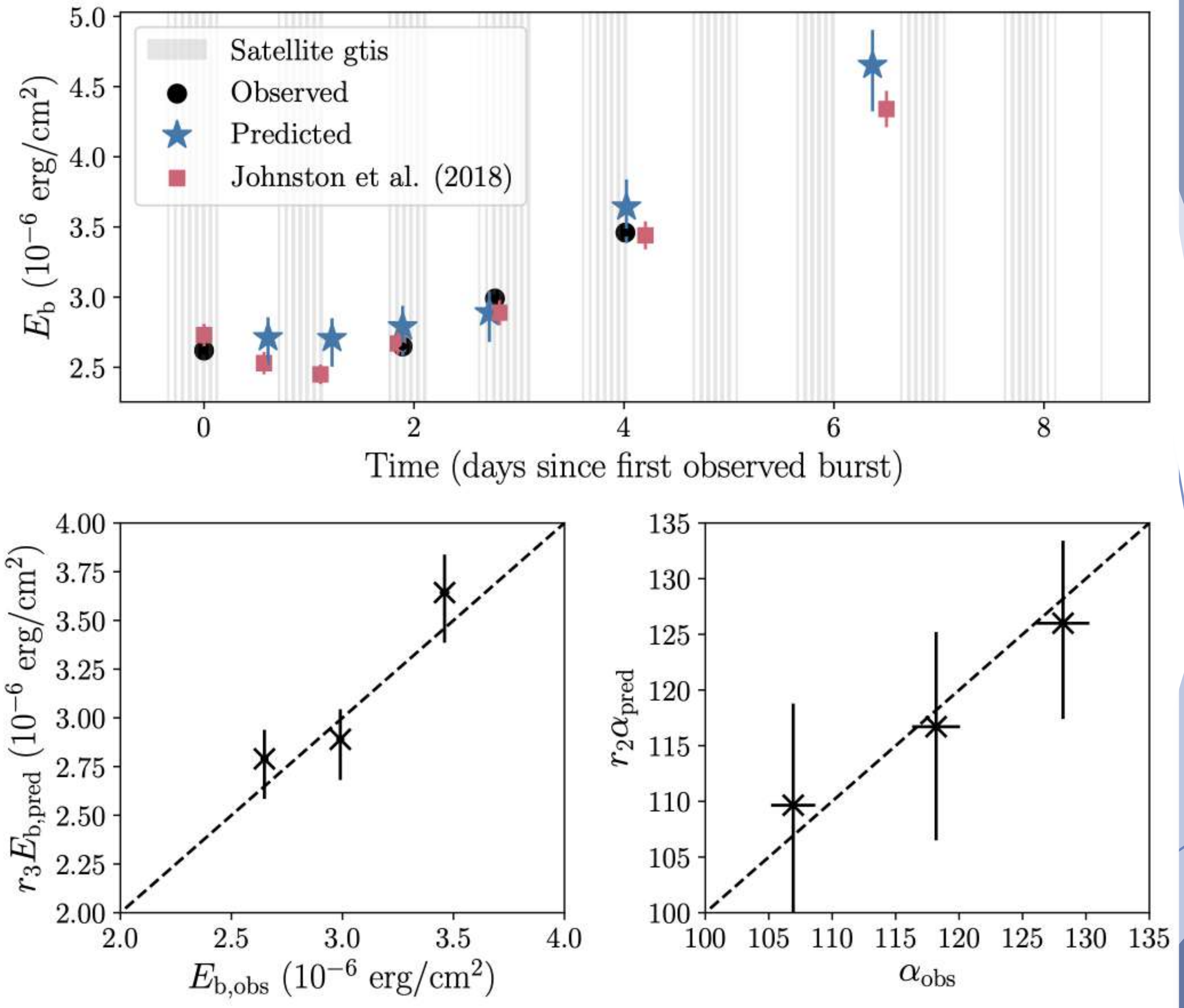
Observed parameters: accretion rate, burst energy, alpha, recurrence time

Predicted parameters: distance/inclination, neutron star mass and radius, fuel composition

Case study: SAX J1808.4-3658

Goodwin+ 2019

- AMXP at 3.5 kpc
- Goes into outburst every 3-4 years
- Burst train from 2002 outburst



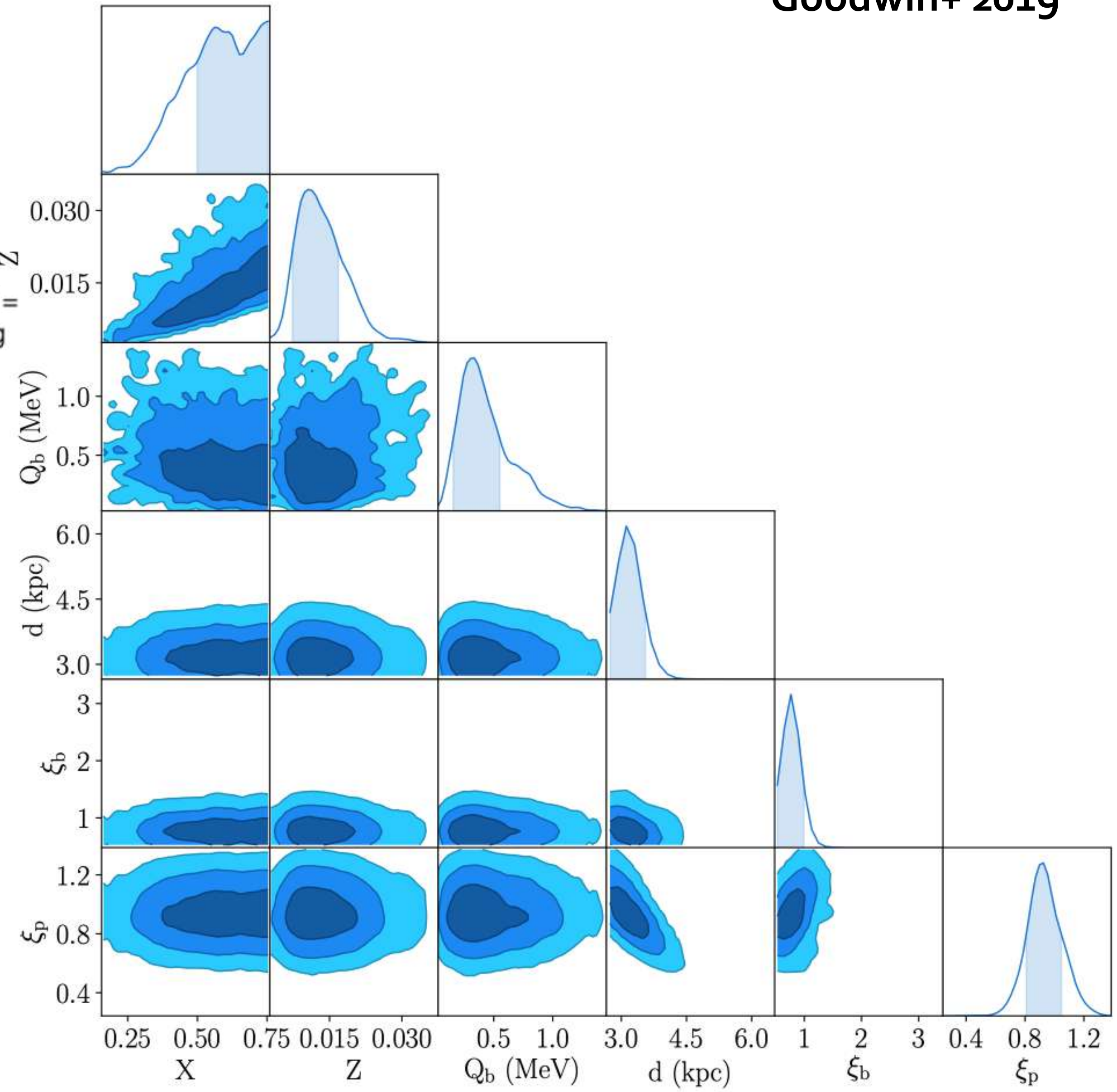
Results

Goodwin+ 2019

Table 2. SAX J1808.4–3658 derived neutron star parameters

Parameter	Value
X	$0.58^{+0.13}_{-0.14}$
Z	$0.013^{+0.006}_{-0.004}$
Q_b (MeV/nucleon)	$0.4^{+0.3}_{-0.15}$
M ($M_\odot$)	$1.5^{+0.6}_{-0.3}$
R (km)	$11.8^{+1.3}_{-1.0}$
$\dot{m}_\mathrm{max}$	$0.037^{+0.002}_{-0.002}$
g (10^{14} cm s^{-2})	$1.88^{+0.7}_{-0.4}$
$1 + z$	$1.27^{+0.13}_{-0.05}$
d (kpc)	$3.3^{+0.3}_{-0.2}$
ξ_b	$0.74^{+0.10}_{-0.10}$
ξ_p	$0.87^{+0.12}_{-0.10}$
cos i	$0.36^{+0.07}_{-0.04}$

Johnston et al (2018) find X = 0.44, Galloway & Cumming (2006) found X = 0.5



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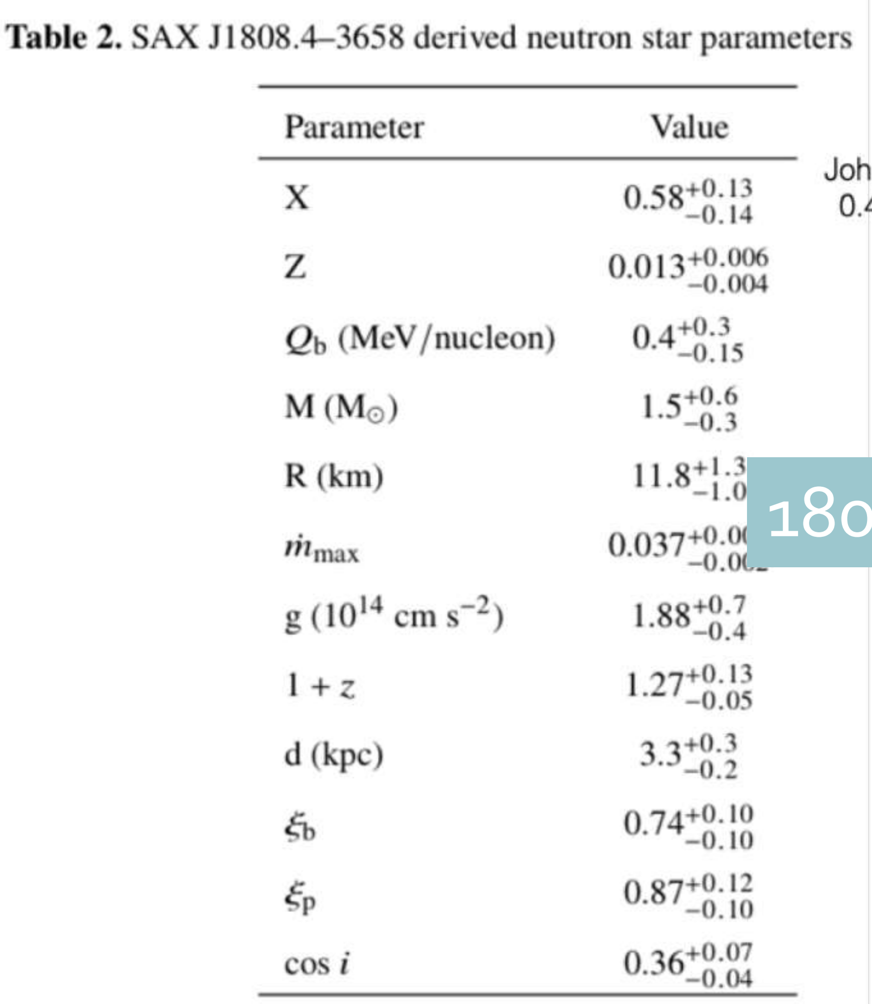

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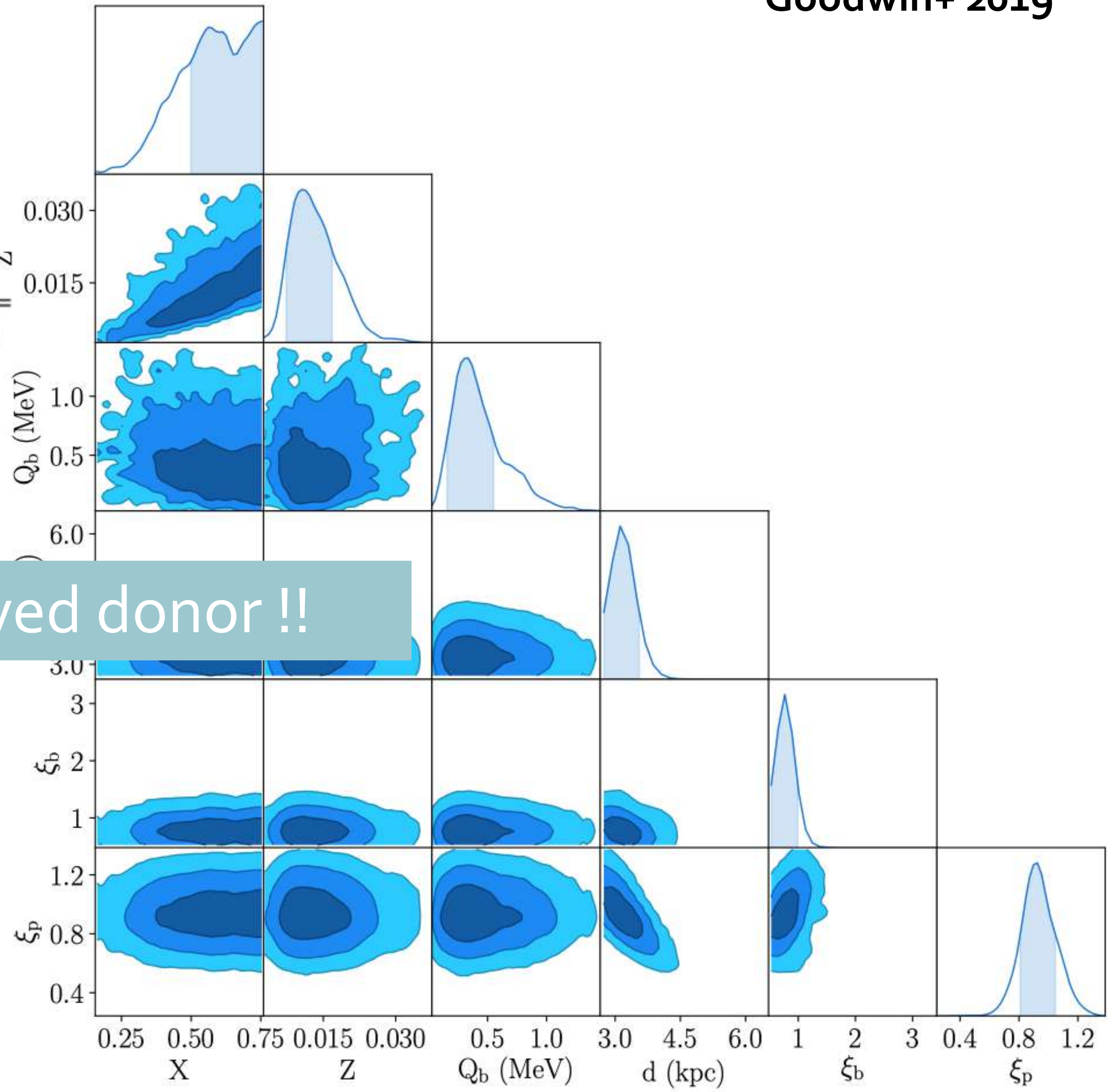


1808 has evolved donor !!

Neutron star mass and radius?

Goodwin+ 2019

We imposed a neutron star mass and radius equation of state constraints

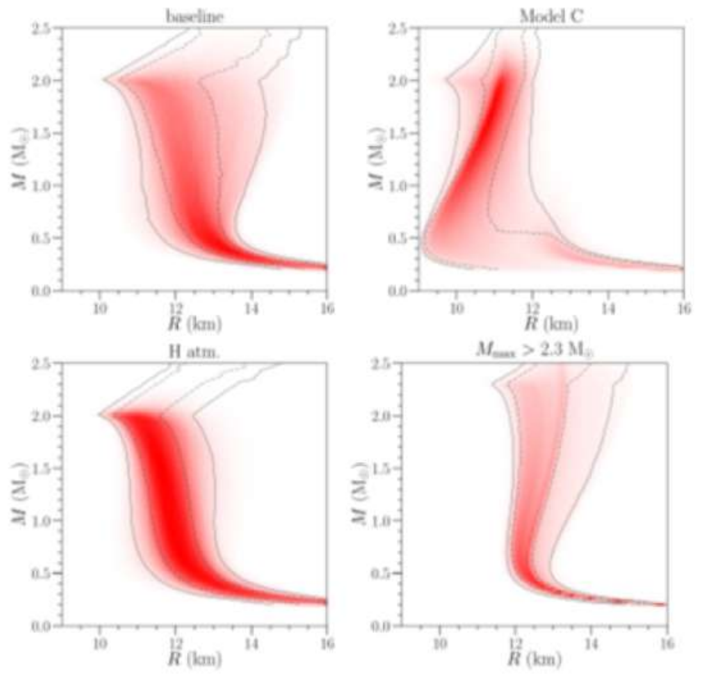
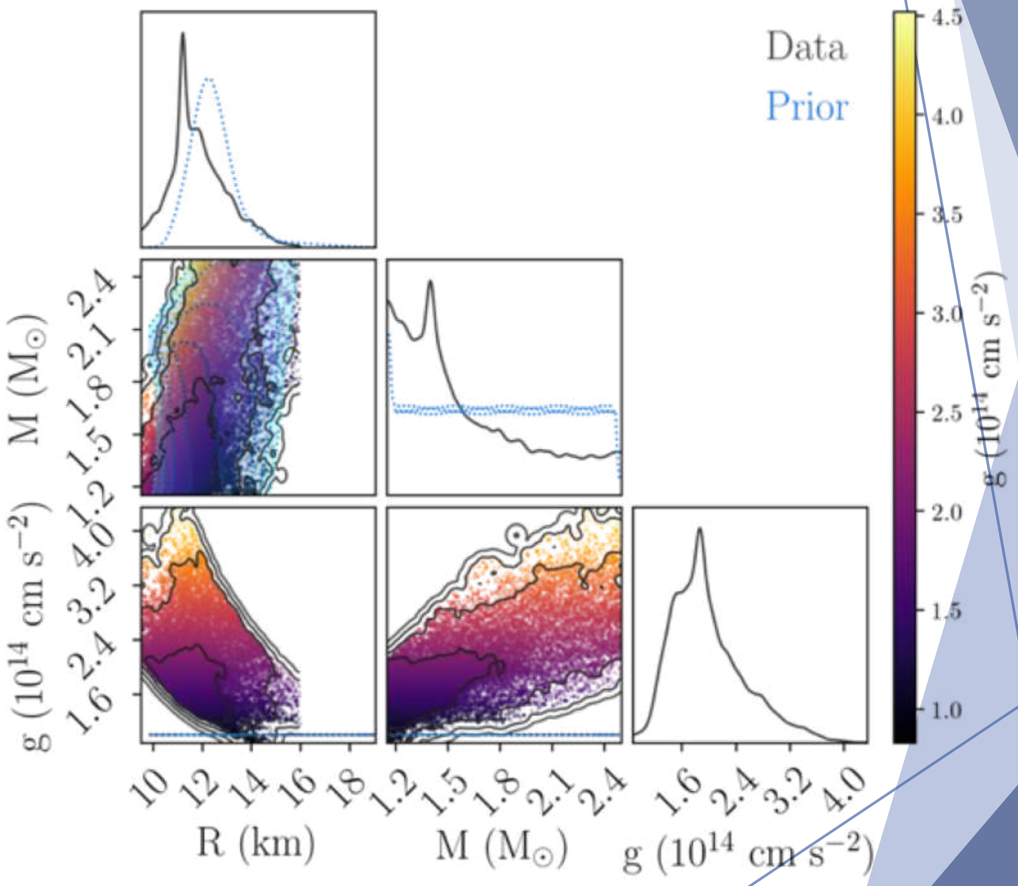


Figure 9. Probability distributions for radii as a function of mass for the baseline data set and baseline model (upper left-hand panel), for the baseline data set with Model C (upper right-hand panel), the baseline model and assuming H atmospheres (lower left-hand panel), and the baseline model and baseline data set requiring $M_{\max} > 2.3\ M_\odot$ (lower right-hand panel).

Steiner et al (2018)



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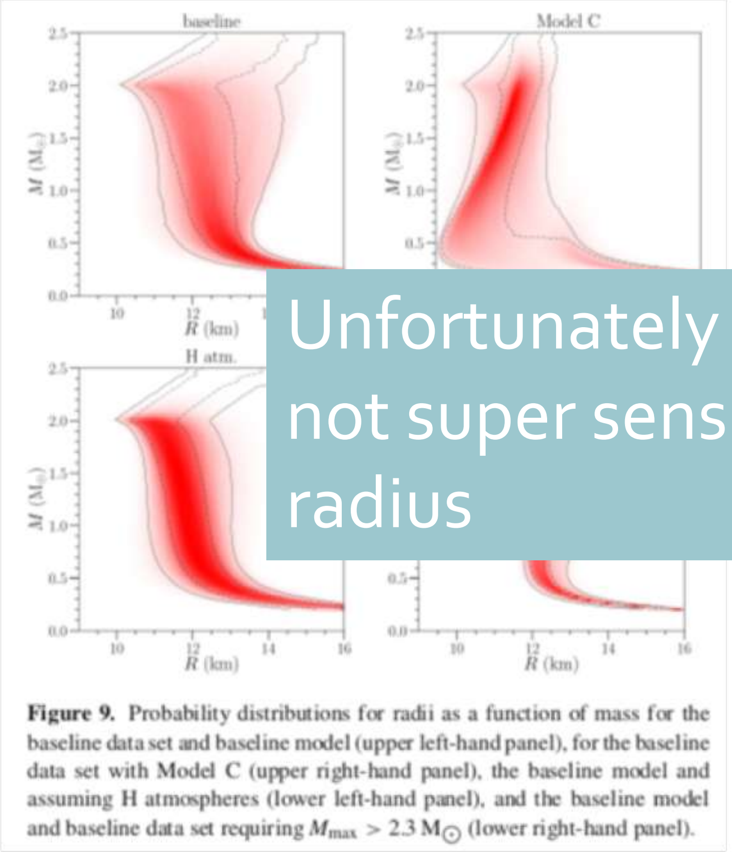

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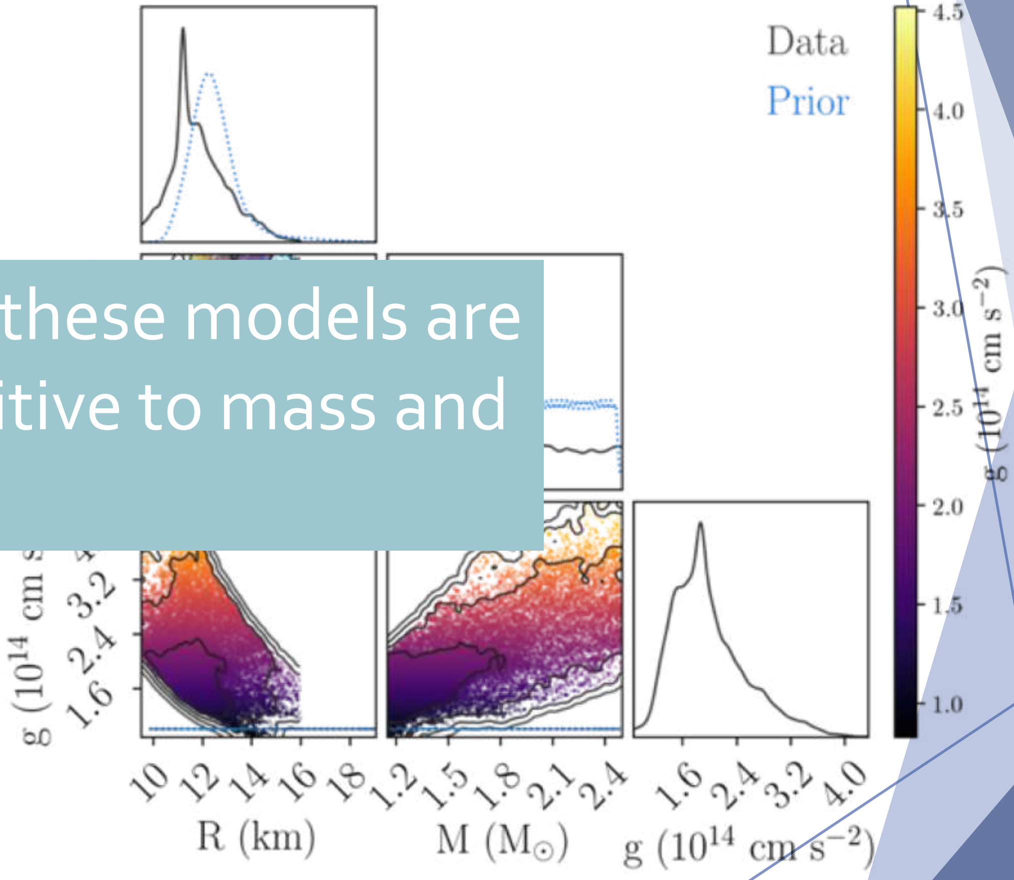
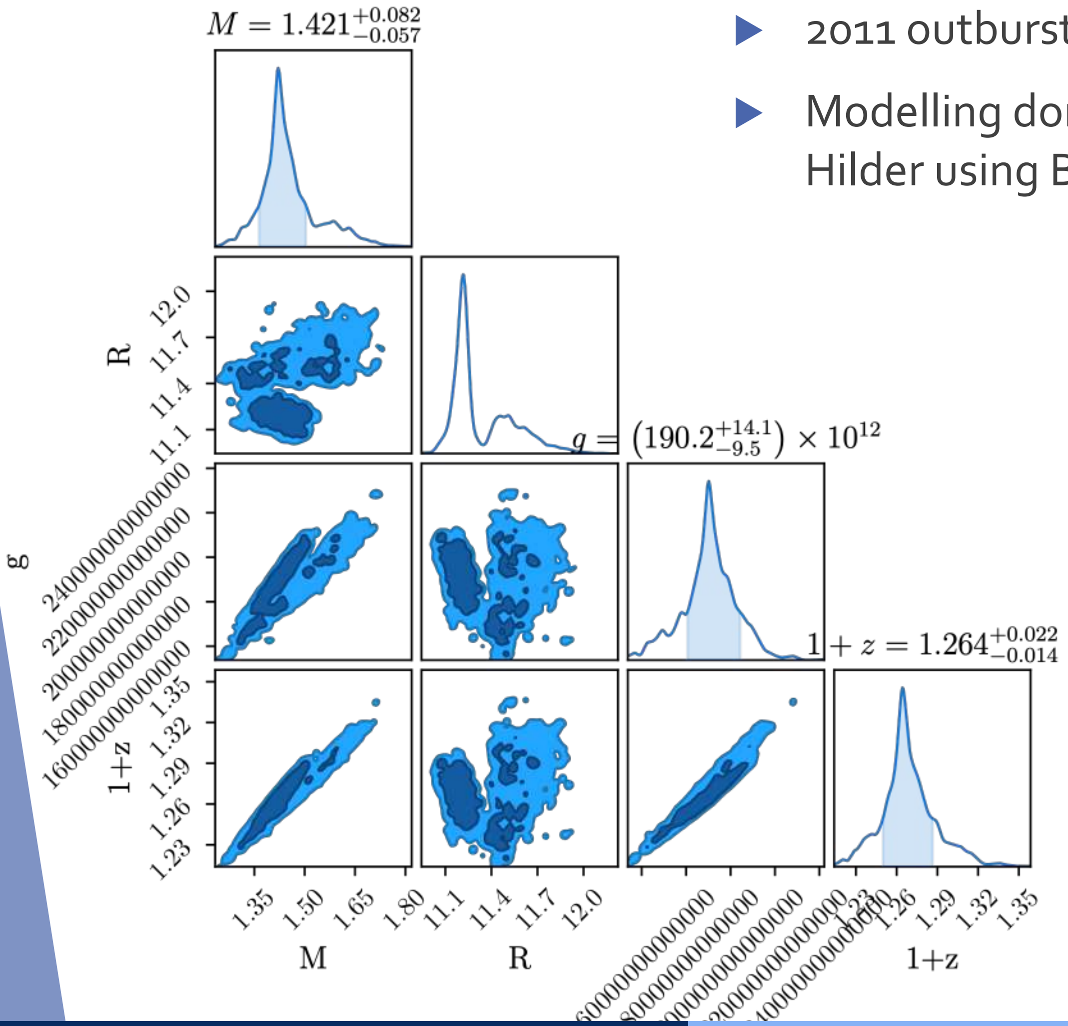
Unfortunately these models are not super sensitive to mass and radius

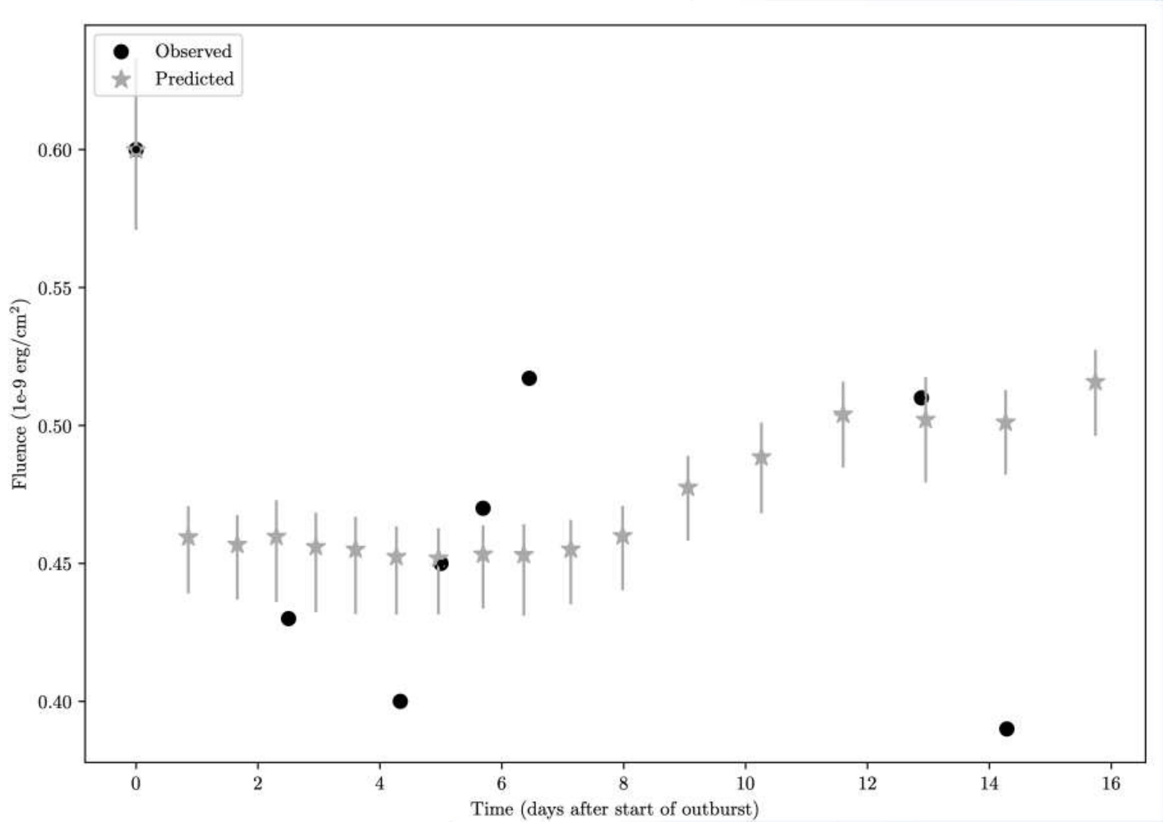


Preliminary

Case study: IGR J17498-2921

- 2011 outburst: train of 8 bursts observed
- Modelling done by an undergraduate student Thomas Hilder using BEANS





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- **Binary properties, binary evolution**

1808 has evolved donor !!

Goodwin+ 2020

Towards the evolution and progenitors of individual accreting neutron stars

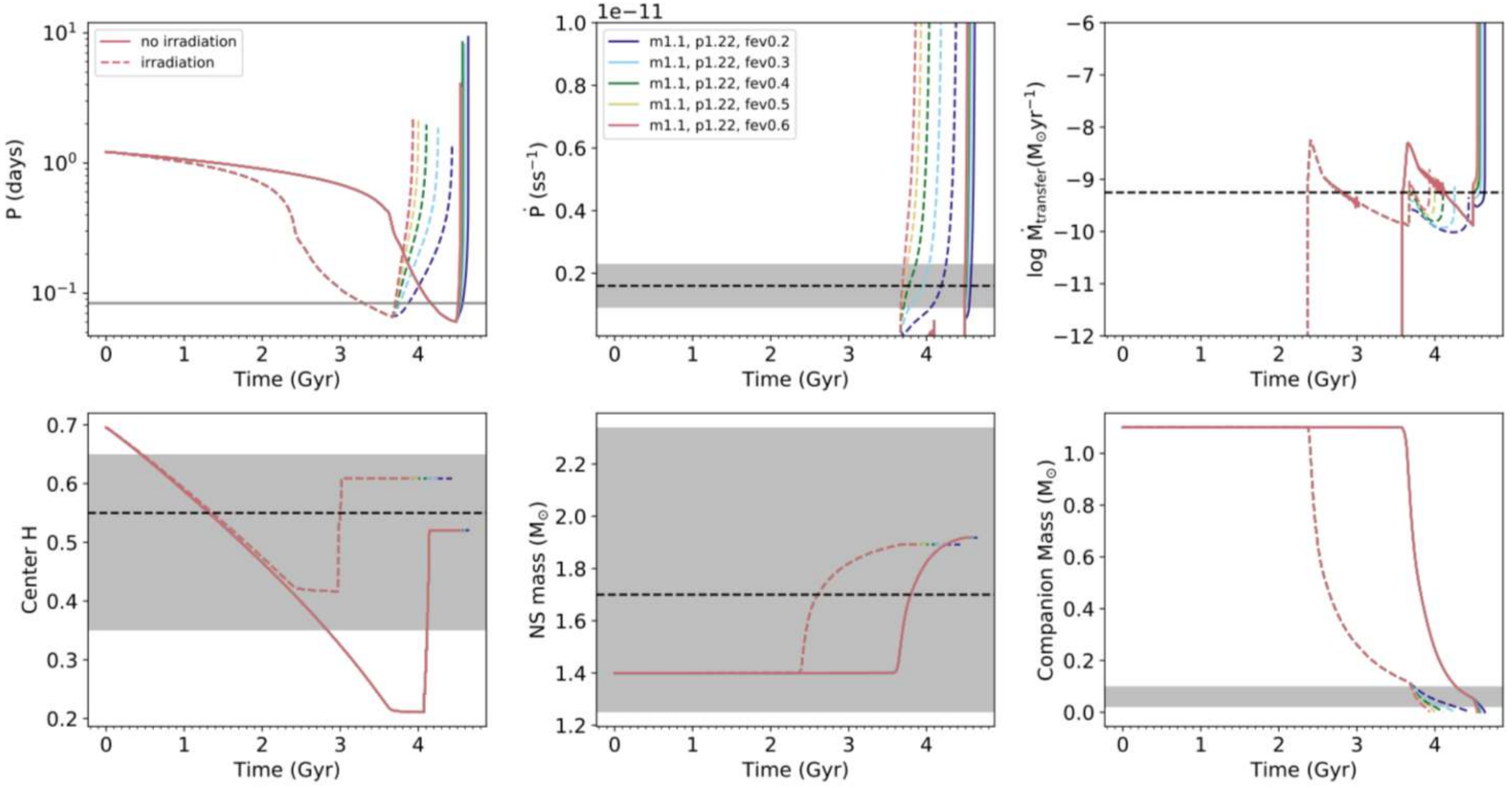
Run MESA binary evolution models to determine the progenitor of systems that have been well-constrained through X-ray burst modelling

E.g.
SAX J1808.4-3658

- Assumptions:
  - ☐ Evolution begins after the NS has formed
  - ☐ Companion star is now fully convective (since it's ~0.05M_sun)
  - ☐ Accreted fuel composition is same as central composition of companion star
  - ☐ Min initial Mc is set by minimum mass of star that can reach central H fraction of 0.58 in the Hubble time
  - ☐ Eddington limited accretion
  - ☐ Mass transfer scheme follows Ritter (1988)
  - ☐ Initially assume 50% mass transfer efficiency (this is highly unconstrained)

Goodwin+ 2020

Results



Goodwin+ 2020

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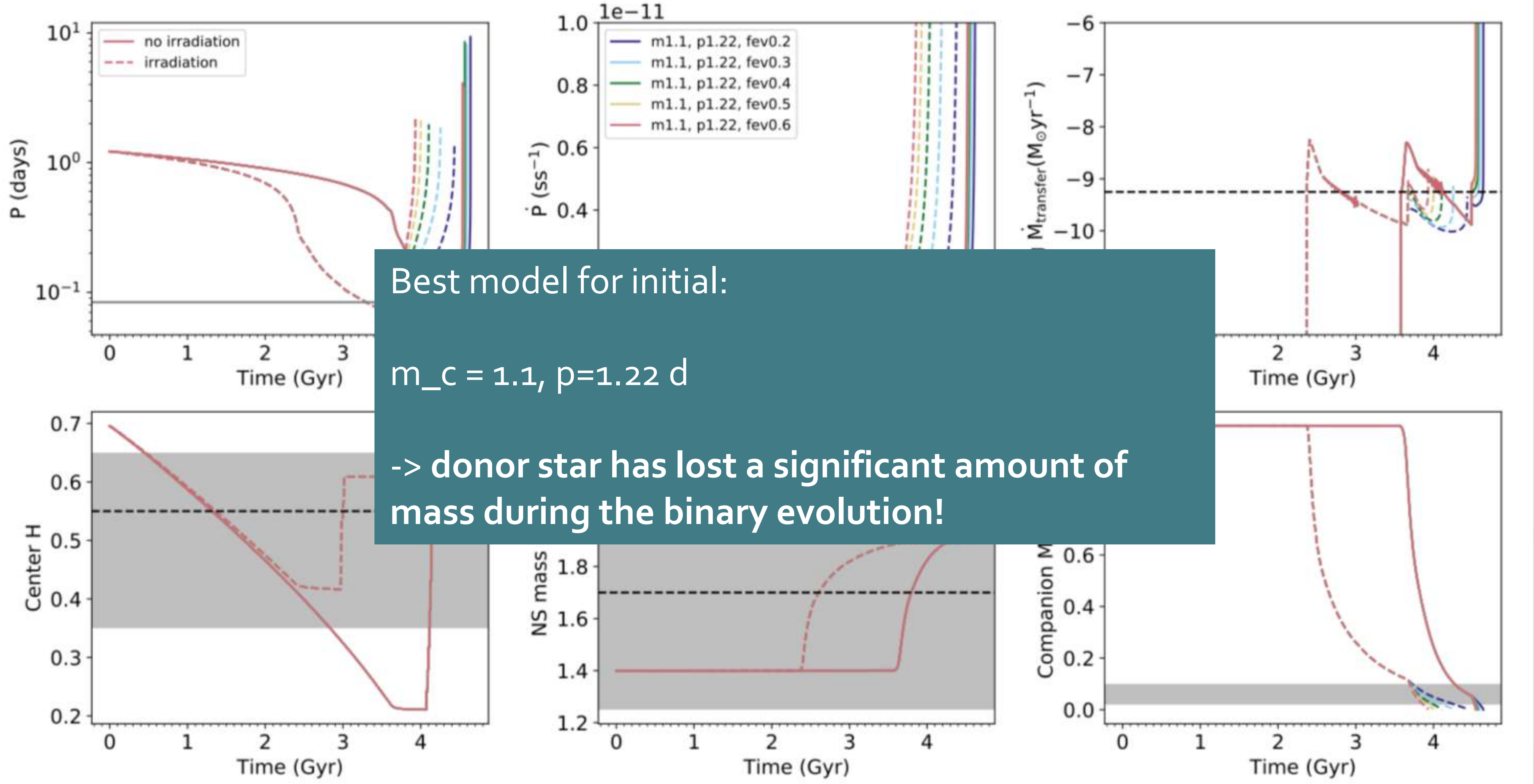

Best model for initial:

m_c = 1.1, p=1.22 d

-> donor star has lost a significant amount of mass during the binary evolution!

Summary

- X-ray bursts are energetic explosions on the surface of accreting neutron stars

- Detailed modelling and observations of X-ray bursts (and combining the two) can constrain:
  1. Nuclear reaction rate sensitivities
  2. Distance
  3. Neutron star mass, radius, surface gravity
  4. Binary inclination, accreted fuel (donor star) composition
  5. Binary evolutionary pathways