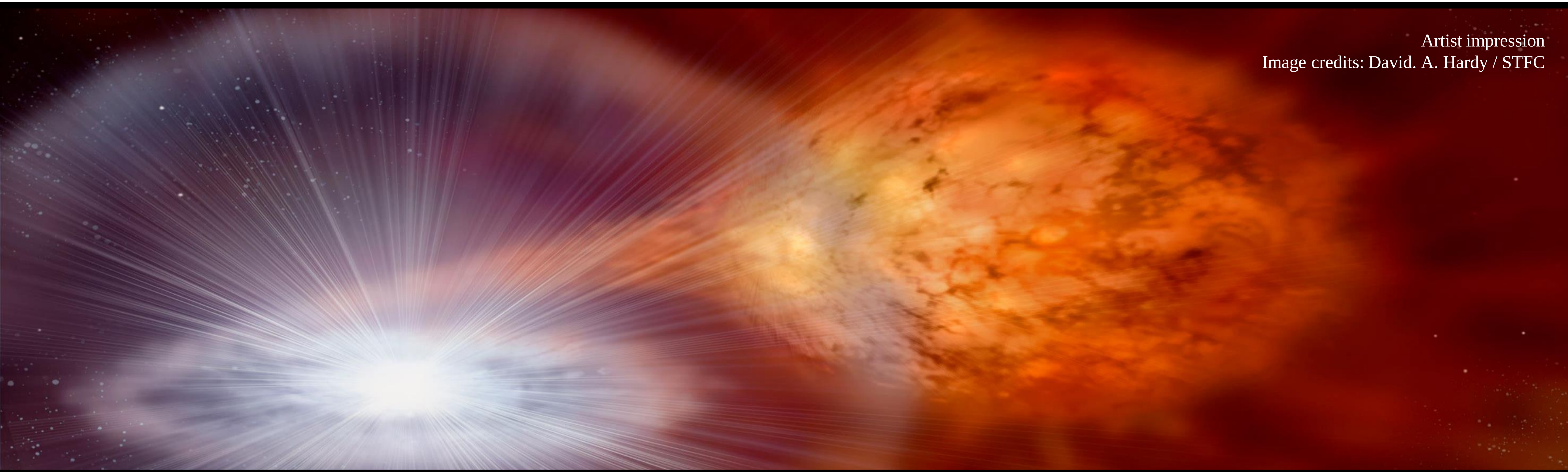
Pulse Profile Modelling of Thermonuclear Burst Oscillations


Artist impression
Image credits: David. A. Hardy / STFC

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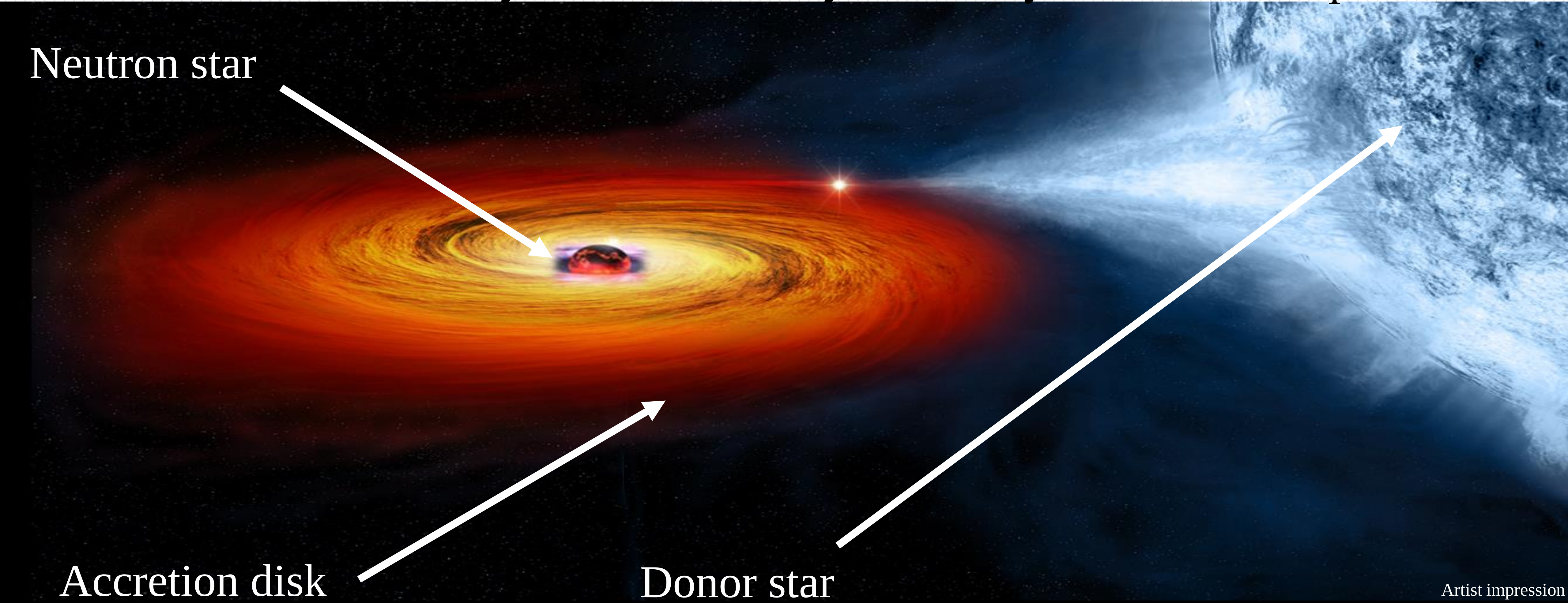
Outline:

1. **Context**
   Thermonuclear burst & burst oscillation
2. **Motivations**
   Modelling burst oscillations: advantages and challenges
3. **Modelling**
   Case study, phenomenological models, etc.
4. **Results**
   Biased & unbiased estimates of mass & radius
5. **Conclusion**
   Take away

Intro Accretion leads to thermonuclear bursts

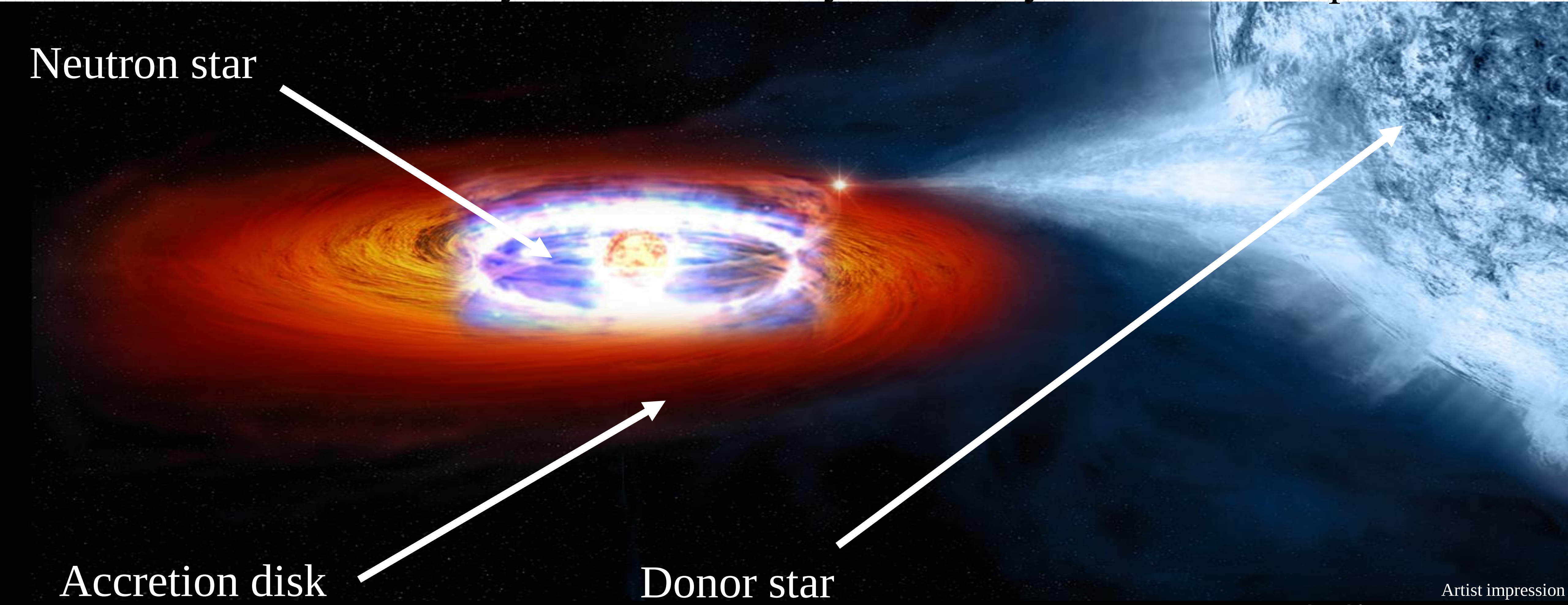
Thermonuclear burst : sudden and intense release of X-rays that happens in a neutron star's outer layers and caused by a runaway nuclear fusion process



Artist impression
Adapted from: NASA/CXC/M.Weiss.

Intro Accretion leads to thermonuclear bursts

Thermonuclear burst : sudden and intense release of X-rays that happens in a neutron star’s outer layers and caused by a runaway nuclear fusion process

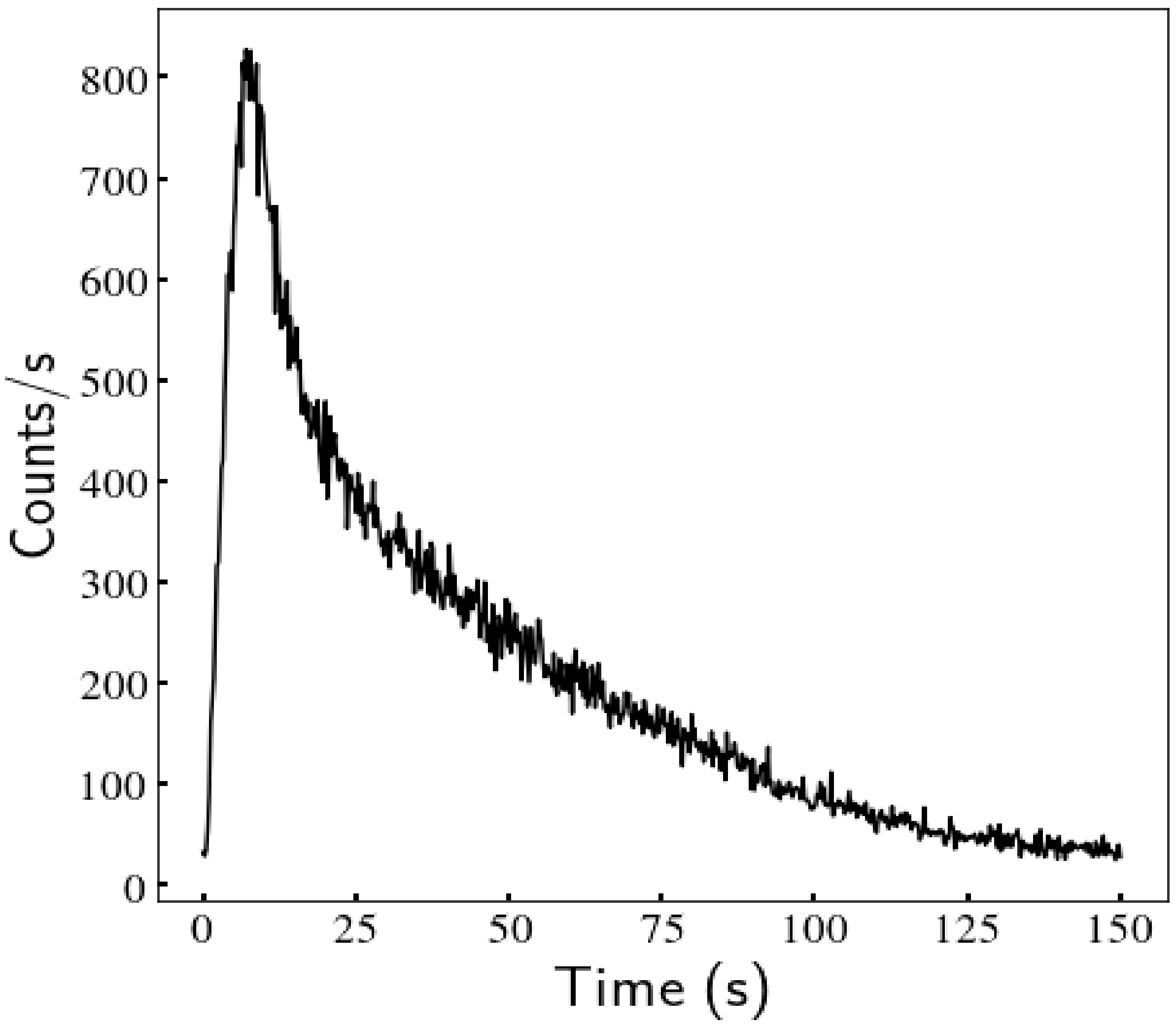


Artist impression
Adapted from: NASA/CXC/M.Weiss.

Intro

What is thermonuclear burst?

Burst light curve



Properties

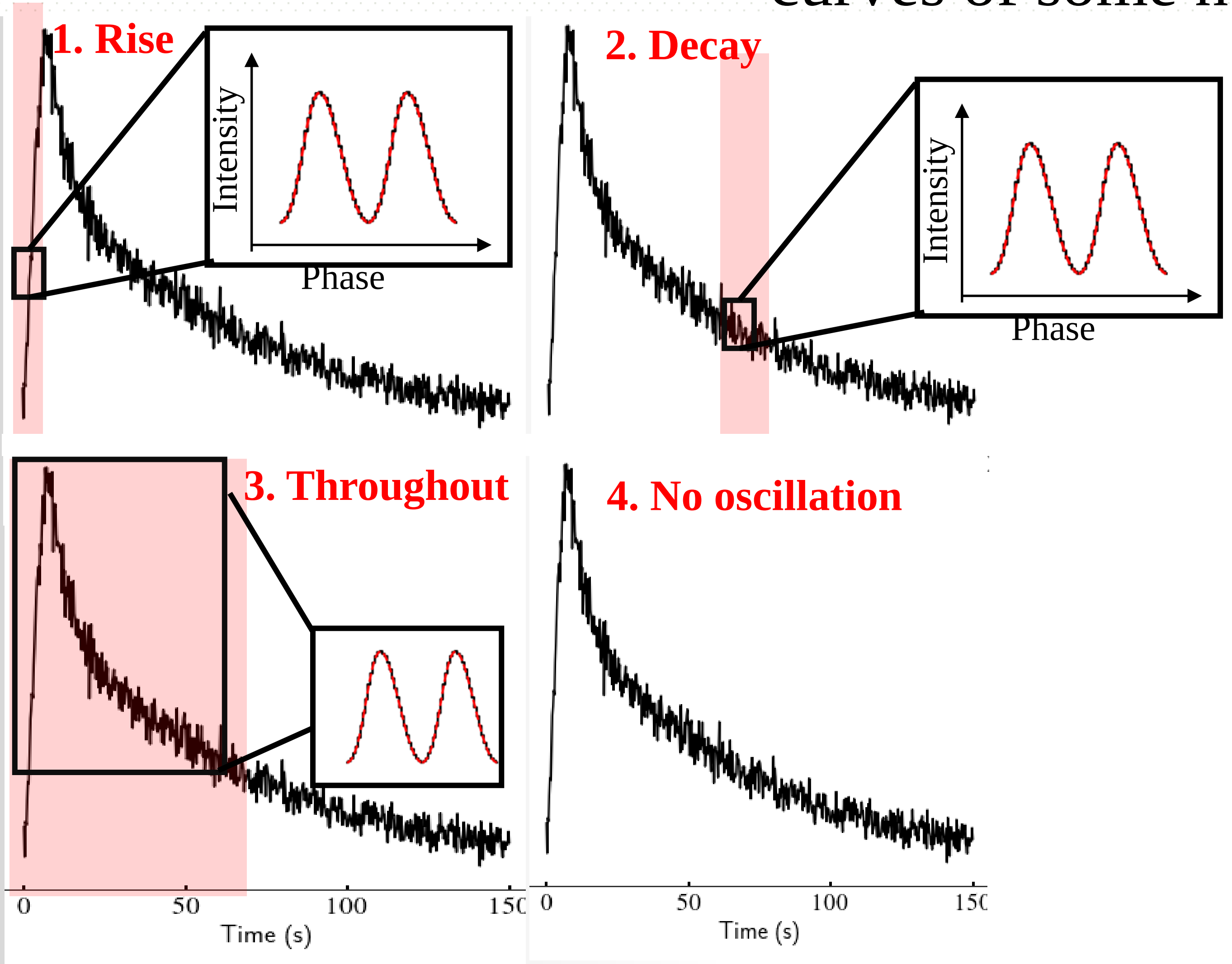
(normal burst)

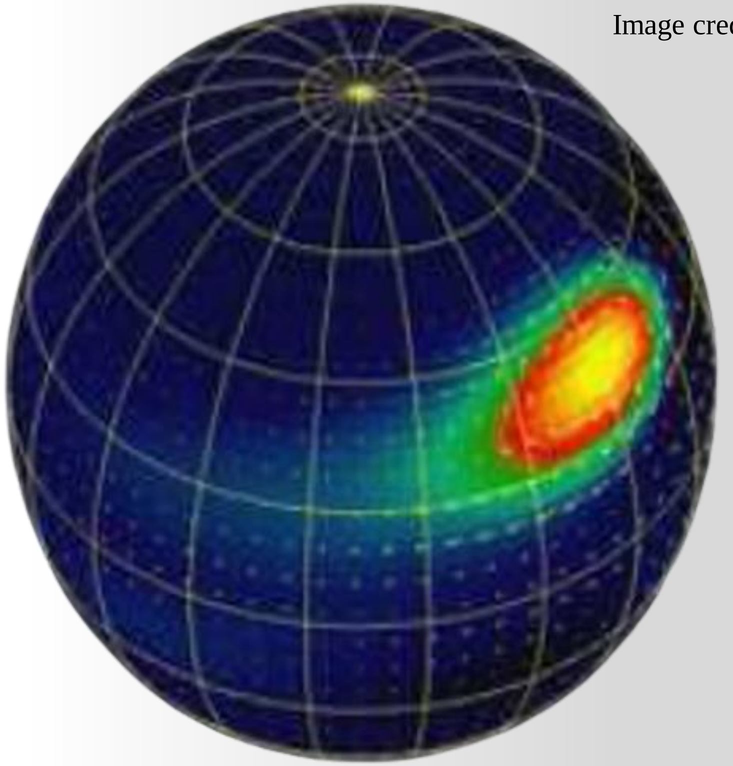
Fuel :	H/He
Duration :	10-100 s
Energy released :	10^{39} ergs
Recurrence time:	hours – days

Intro

What are burst oscillations?

Burst oscillations (BOs) : coherent pulsations found in some of the burst light curves of some neutron stars





Cause: Uneven heat distribution on the NS surface or in their atmosphere

Motiv. What makes BOs sources interesting for PPM?

1. The pulsations → Used to constrain the stellar properties: Mass, radius, etc.
   See Bas' talk

2. Spin very fast → Helps constrain the mass & radius separately
   $f \sim 250 - 620$ Hz

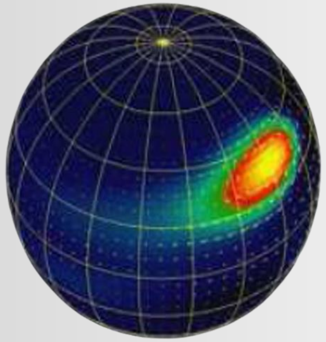
3. Different population → Allows for independent cross-checks

4. Very bright events → Accumulation of more photons
   Energy released $\sim 10^{39}$ ergs
   Hence tighter constraints on parameters

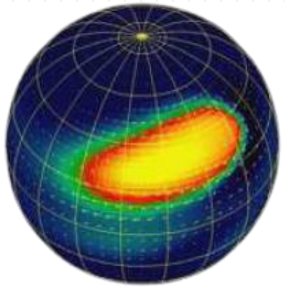
Motiv. Modelling BOs is challenging

What is the origin of uneven heat distribution ?

Image credit: Spitkovsky

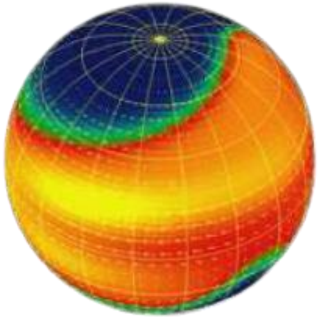


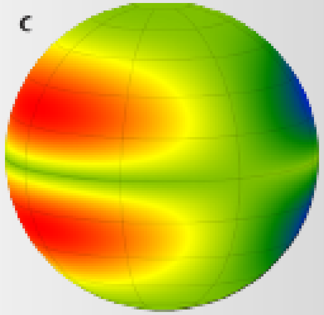
Burst ignites
Flame spreading
e.g. Stromahyer et al. 1997, Spitovsky et al. 2002, Cavecchi et .al 2013



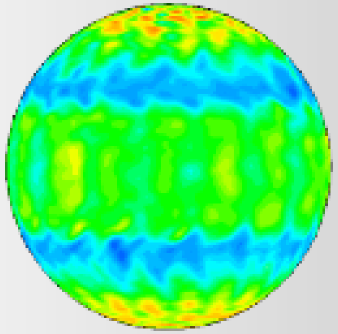
Flame stall: magnetic/ Coriolis confinement ?
e.g. Spitovsky et al. 2002, Cavecchi et .al 2013

Flames engulf the surface?





R-modes
e.g. Heyl 2004, Lee 2004, Piro et al 2005, Cavecchi et .al 2015, Chambers et al. 2019

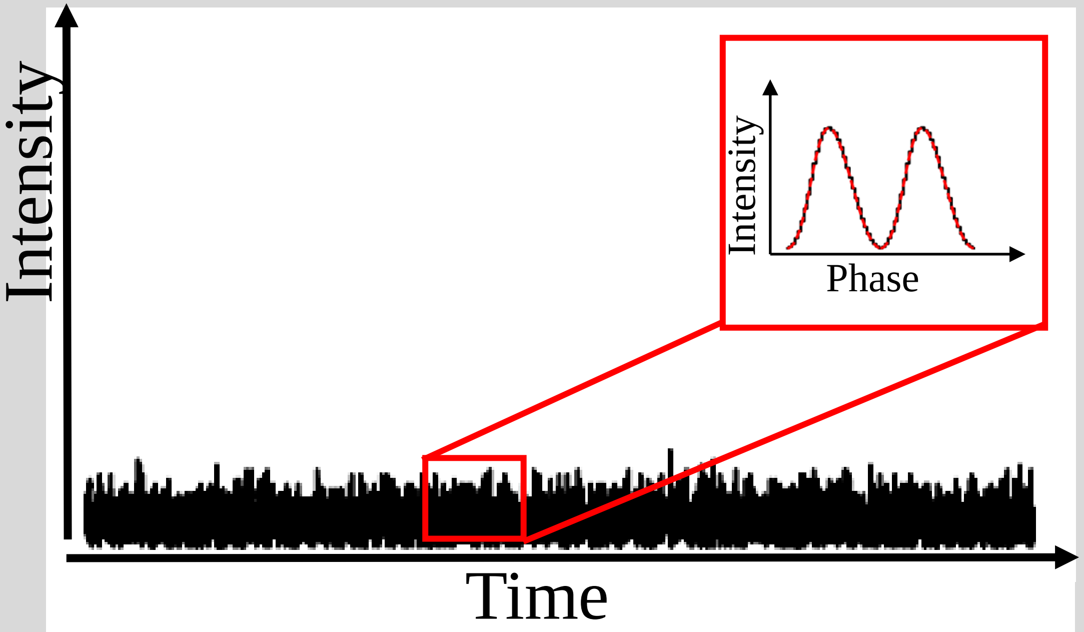


Convective patterns

e.g. Garcia et al. 2019

Motiv. Modelling BOs is challenging

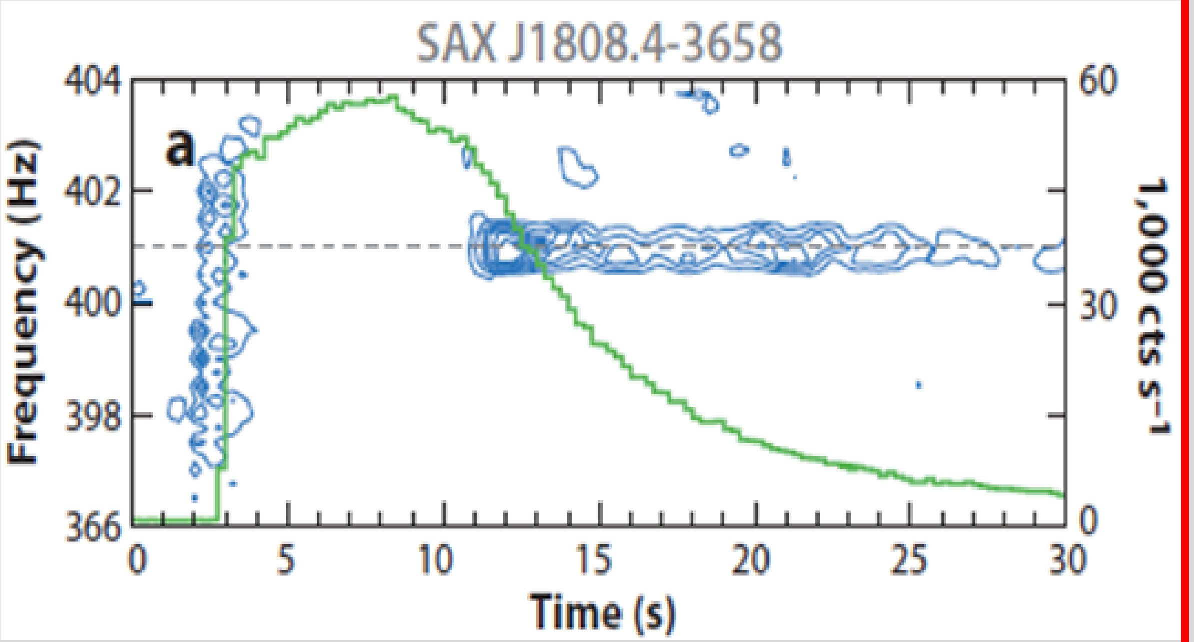
RMP



VS

Burst

Watts 2012



RMPs have very stable light-curves & pulsations, still modelling is computationally expensive. See Bas' & Devarshi talk.

Burst light-curves are highly variable; modelling even more computationally expensive

Motiv. Modelling BOs is challenging?

Recap

Origin Of pulsation uncertain

Variable light-curves

Pulse fraction variable

Frequency drift

Model. Properties of XTE J1814-338

What makes J1814 Interesting ?

1. Very stable pulsations
2. High pulse fraction: ~ 10%
3. Harmonic content

Model. XTE J1814-338

Recap

- Origin Of pulsation uncertain
- Variable light-curves
- Pulse fraction variable
- ~~Frequency drift~~

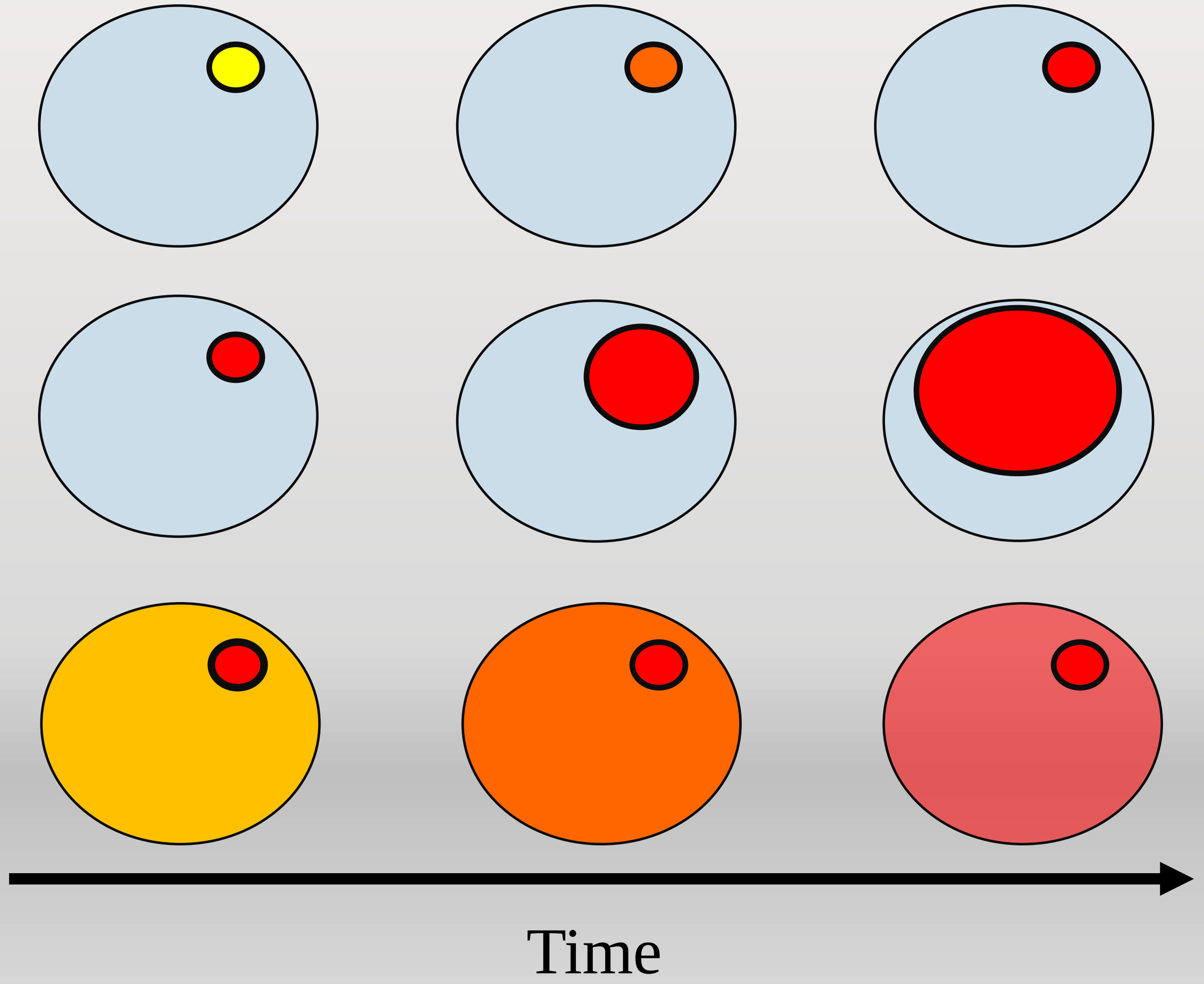
Model. Phenomenological models

Models that mimic J1814 bursts light-curves & oscillation properties

T_{spot} **varies** →

ζ_{spot} **varies** →

T_{star} **varies** →



Model. Study case: XTE J1814-338

Synthetic bursts

24 bursts of 10^5 counts each
RXTE data like

24 bursts of 10^6 counts each
e-XTP & STROBE-X data like

24 bursts of 10^7 counts each
Combining bursts of e-XTP &STROBE-X

Results

XTE J1814-338

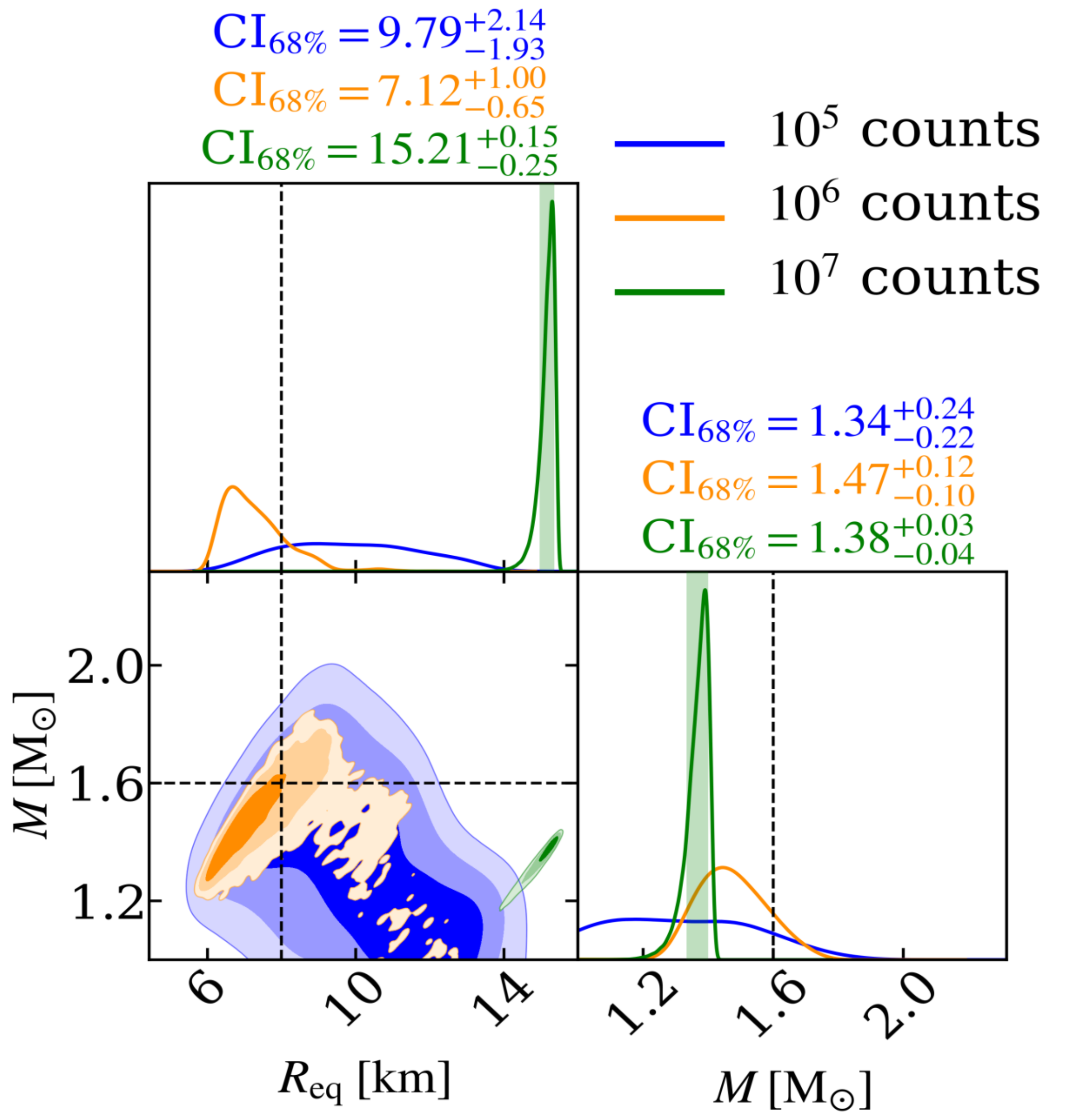
1st Approach: neglecting variability

Synthetic data produced with models that has variability

Inference runs performed with a model that has no time dependance

Results

XTE J1814-338

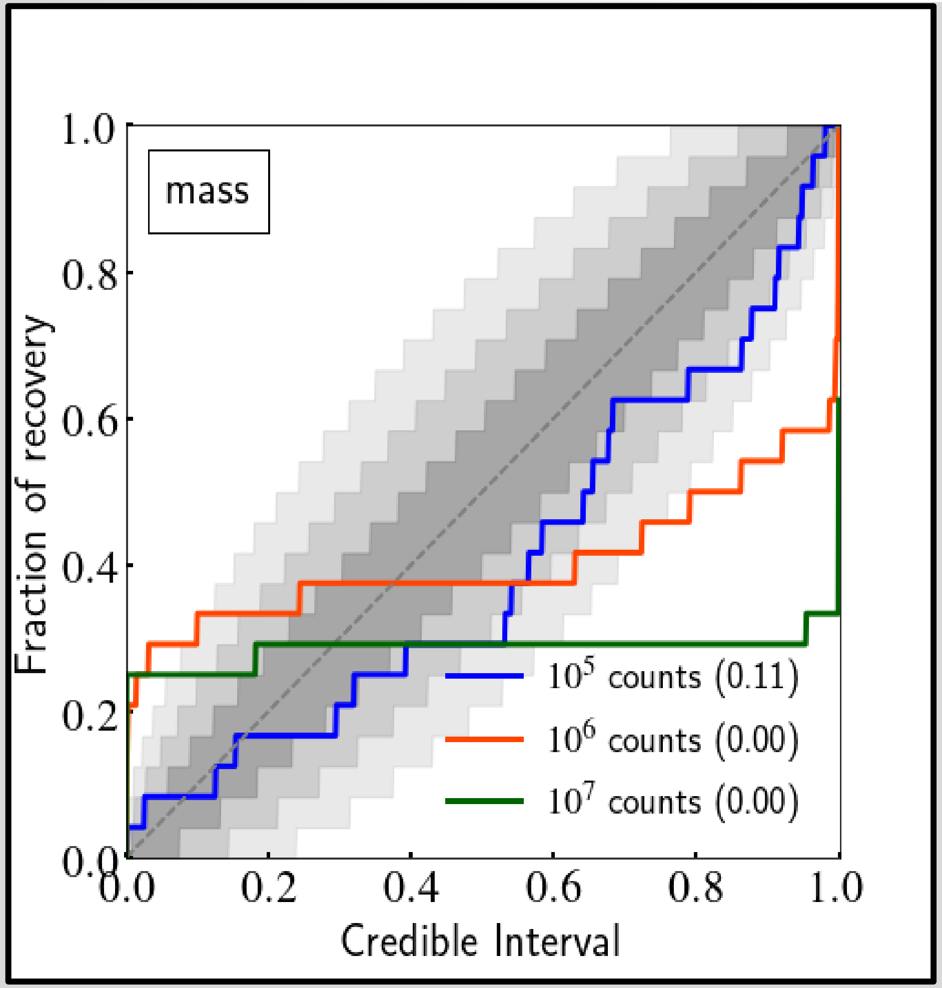


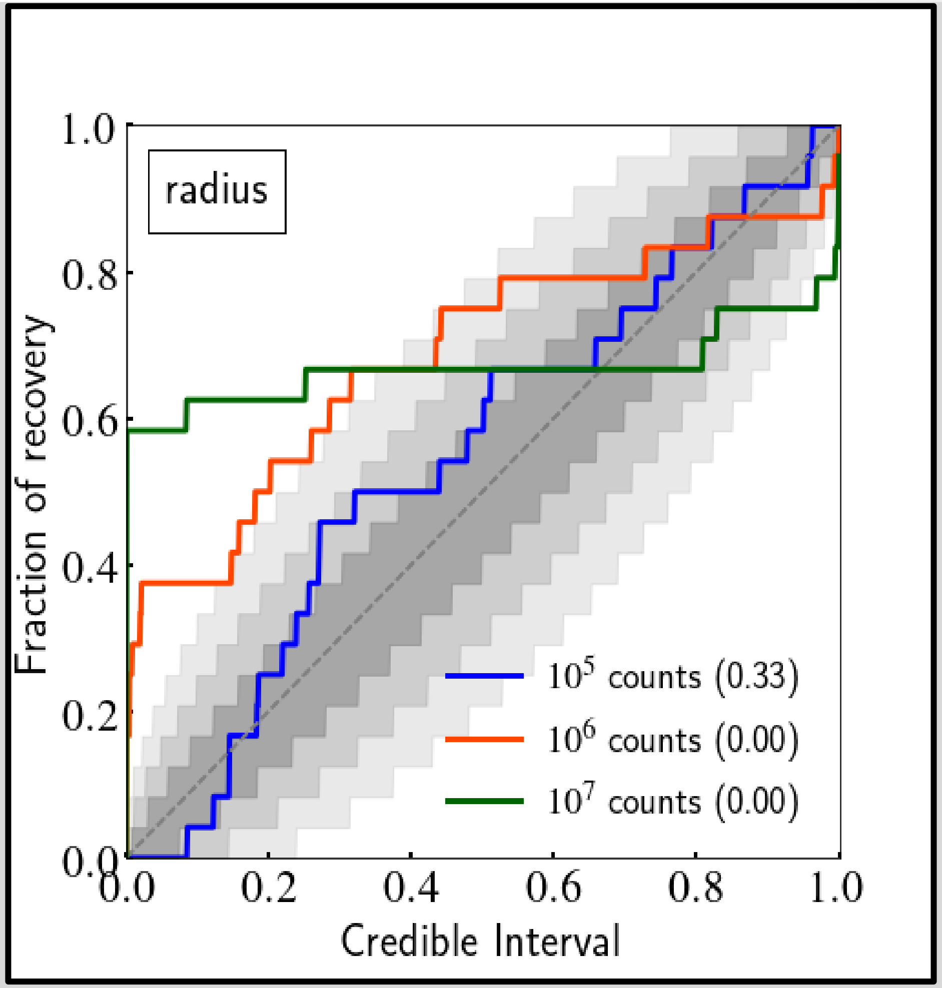
10^5 counts: **Broad posteriors**

10^7 counts: **median of the distribution is very far from the injected value.**

Results XTE J1814-338

1st Approach: neglecting variability





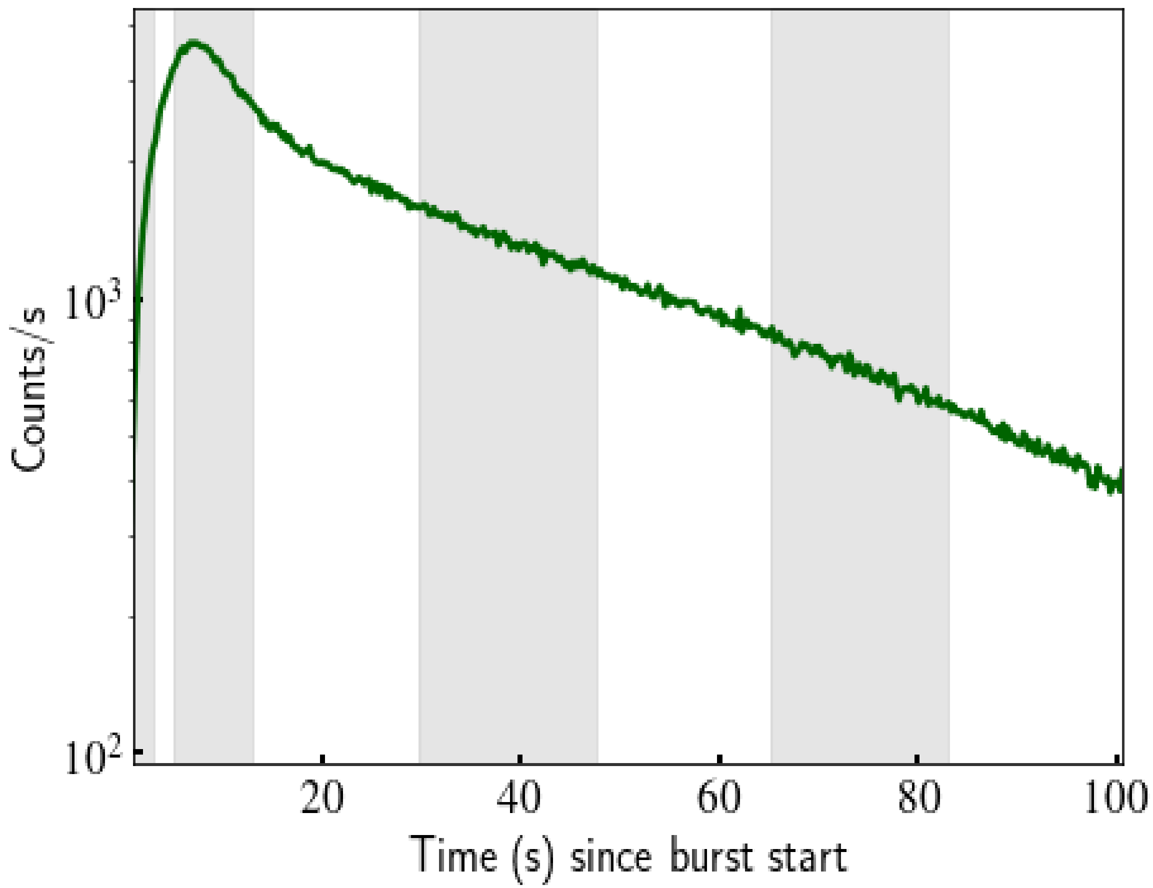
When variability is neglected: Mass and radius are incorrectly recovered.

PP-Plots

Results Study case: XTE J1814-338

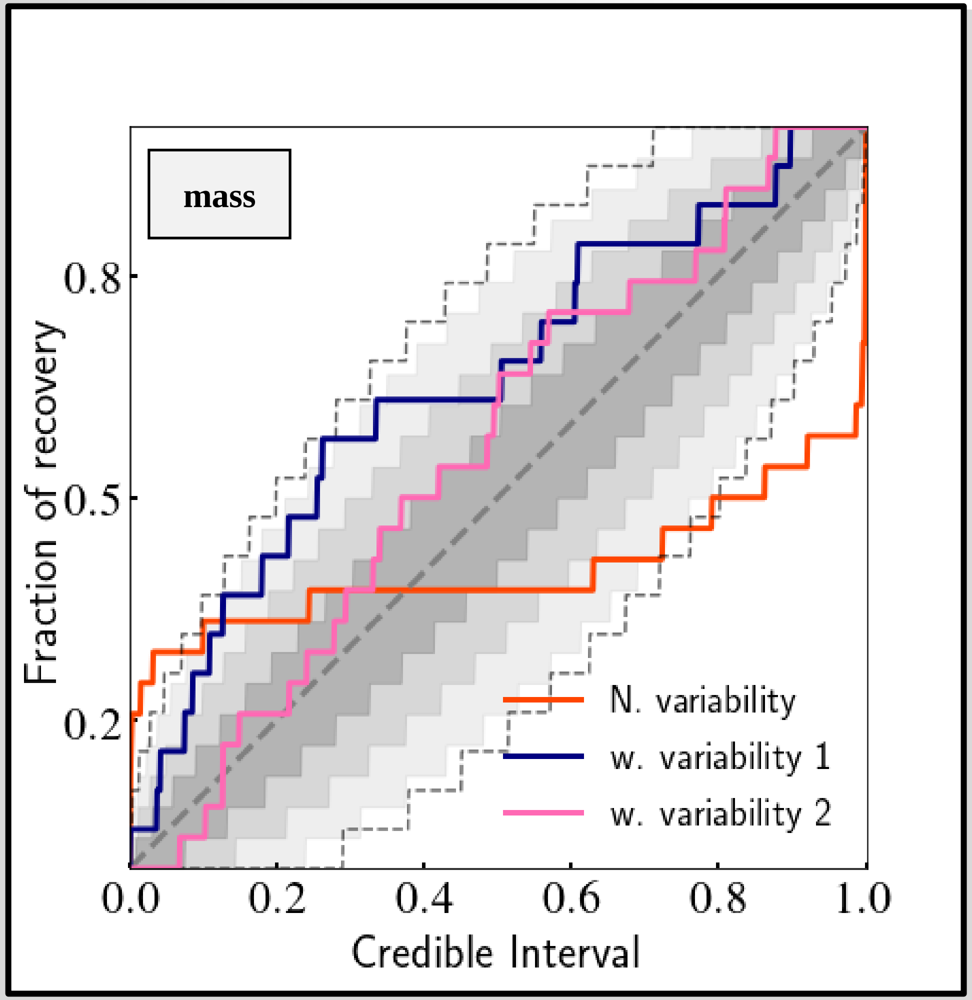
2st Approach: keeping track of varying parameters using only 10^6 counts data set

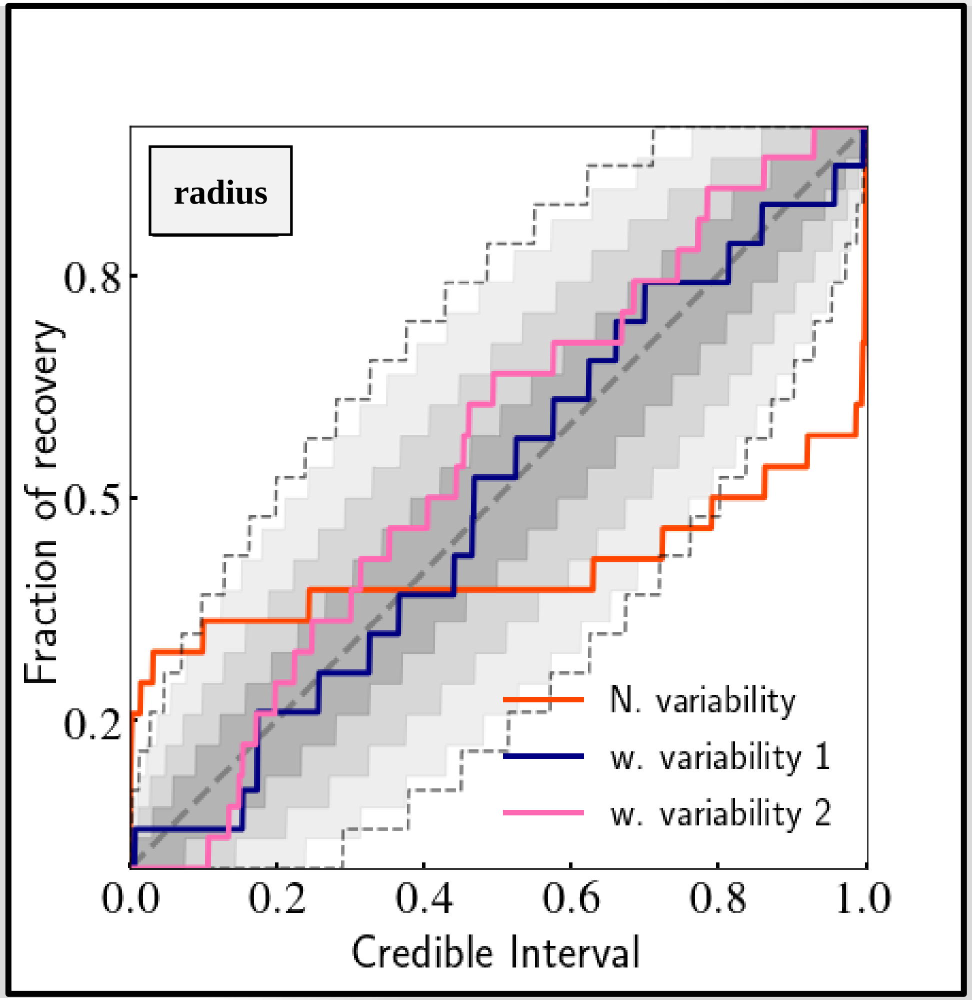
Inference runs performed with a model that has now time dependence



Results XTE J1814-338

2st Approach: accounting for variability



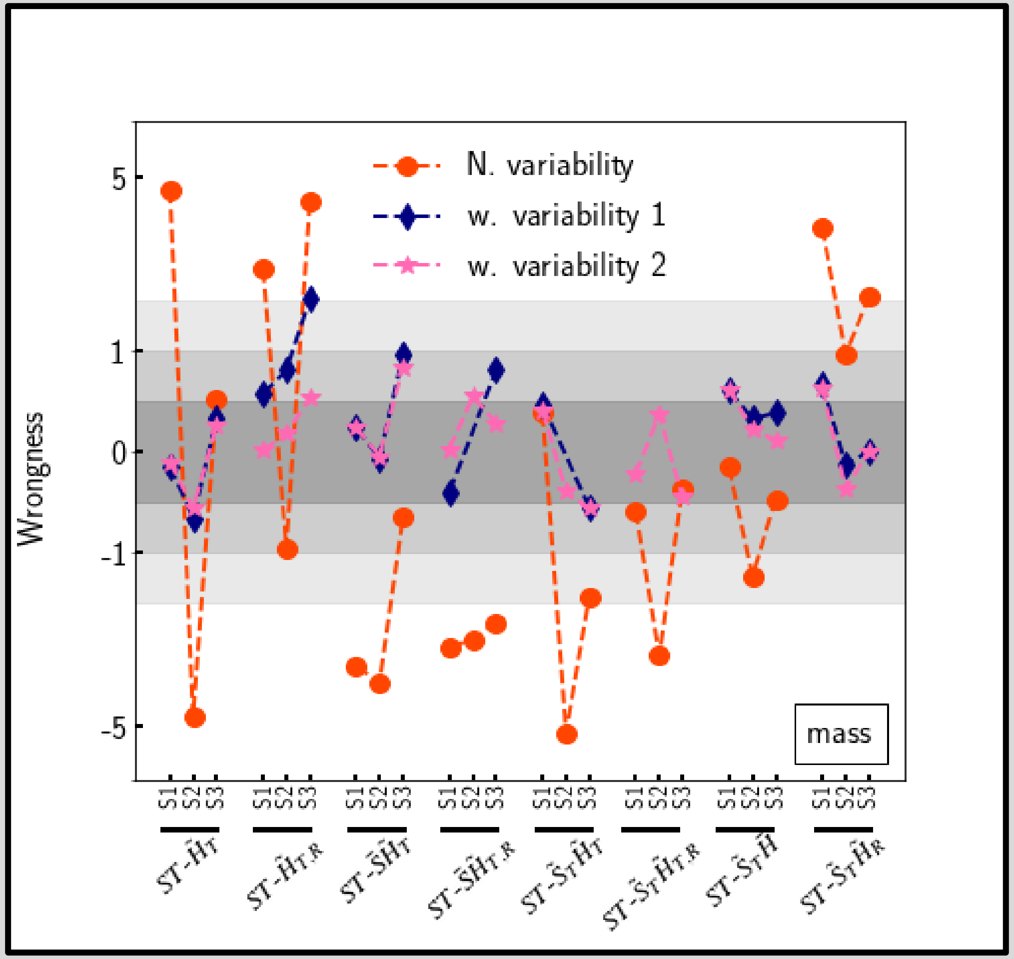


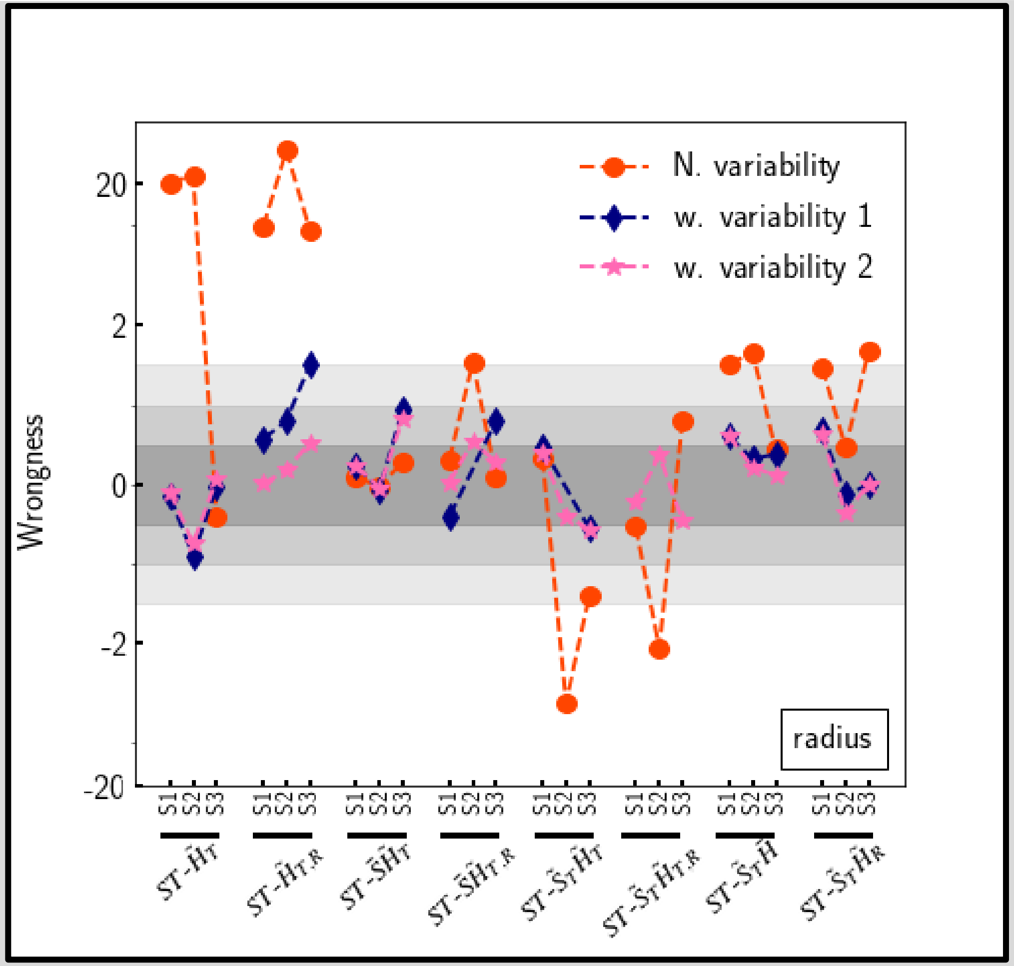
When variability is accounted for: Mass and radius are correctly recovered.

PP-Plots

Results Study case: XTE J1814-338

2st Approach: accounting for variability





Conclusion

- Modelling burst oscillations to constrain NS mases and radii is possible.
- Modelling is challenging .
- Variability needs to be addressed to get useful constraints.
- We need theoretical models to reduce some of the uncertainties.