MONASH University

OzGrav

ARC Centre of Excellence for Gravitational Wave Discovery

PROPERTIES OF LONG-LIVED BINARY NEUTRON STAR MERGER REMNANTS

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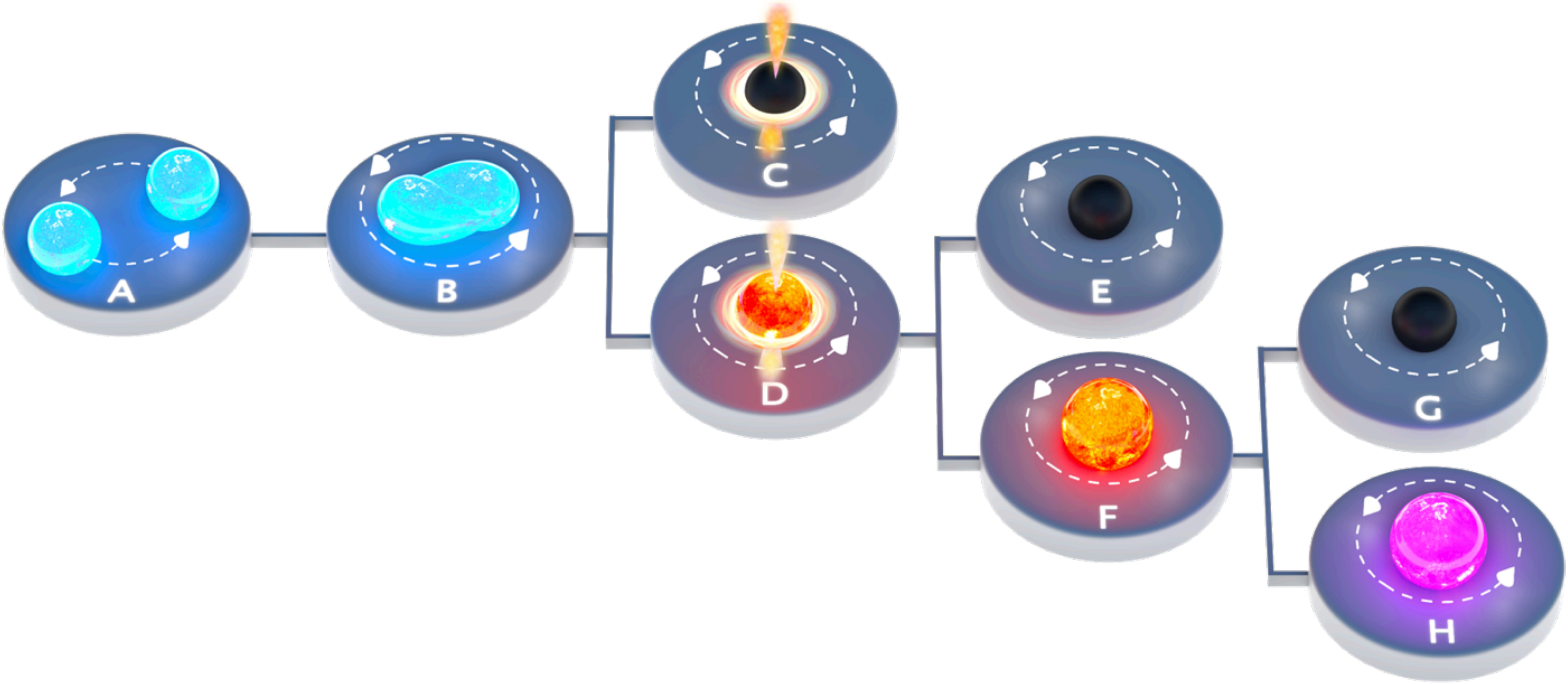
NEUTRON STAR MERGERS

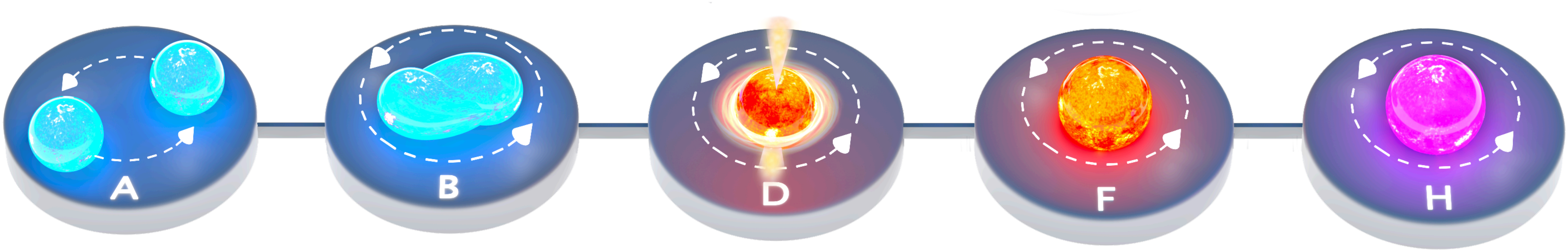


Credit: Carl Knox

Post-merger remnant scenarios and evolution

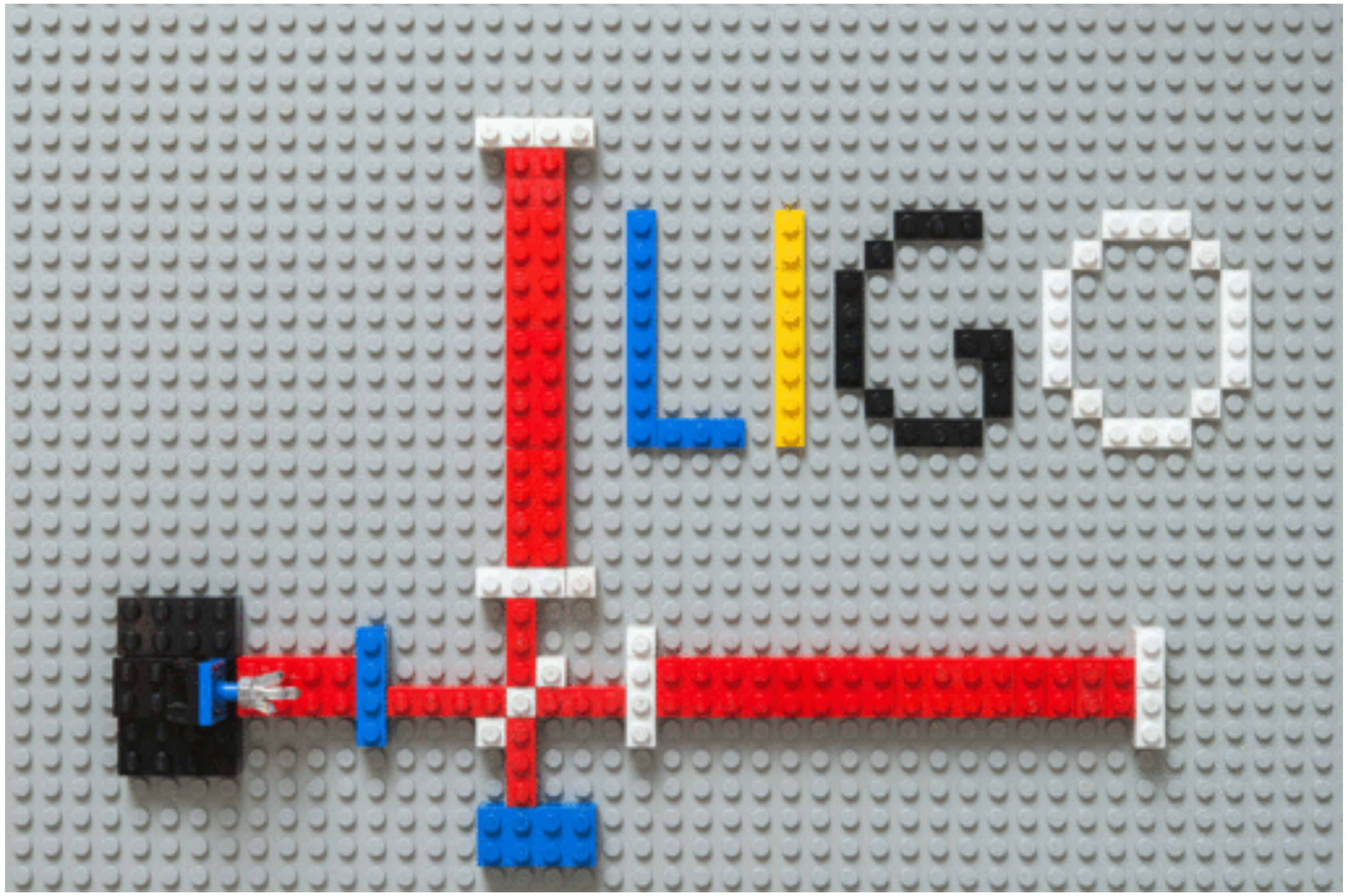
LONG-LIVED NEUTRON STARS

- How do you make a long-lived neutron star?
  - Neutron star post-merger remnant born with mass less than the M_{TOV} - will produce an ***infinitely stable*** remnant (H).
  - Post-merger remnant born with mass between $1 - 1.2M_{\text{TOV}}$ will ***collapse*** into a black hole at some time t_{col} (F).



A LONG-LIVED NEUTRON STAR IS BORN…

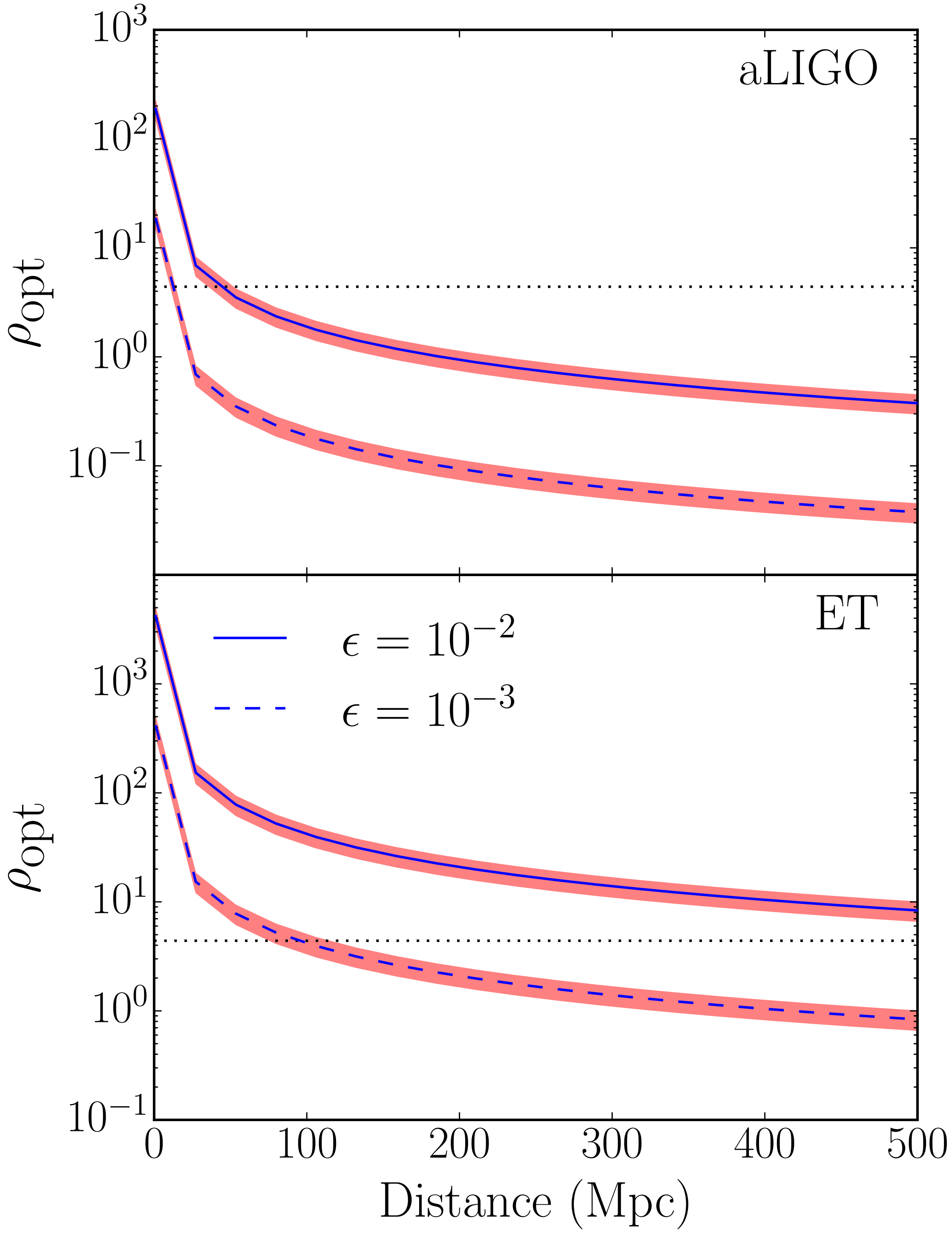
- It will emit gravitational waves!
- Can we detect them? How?



Credit: Paul Lasky

WORTH LOOKING?… NOT REALLY…

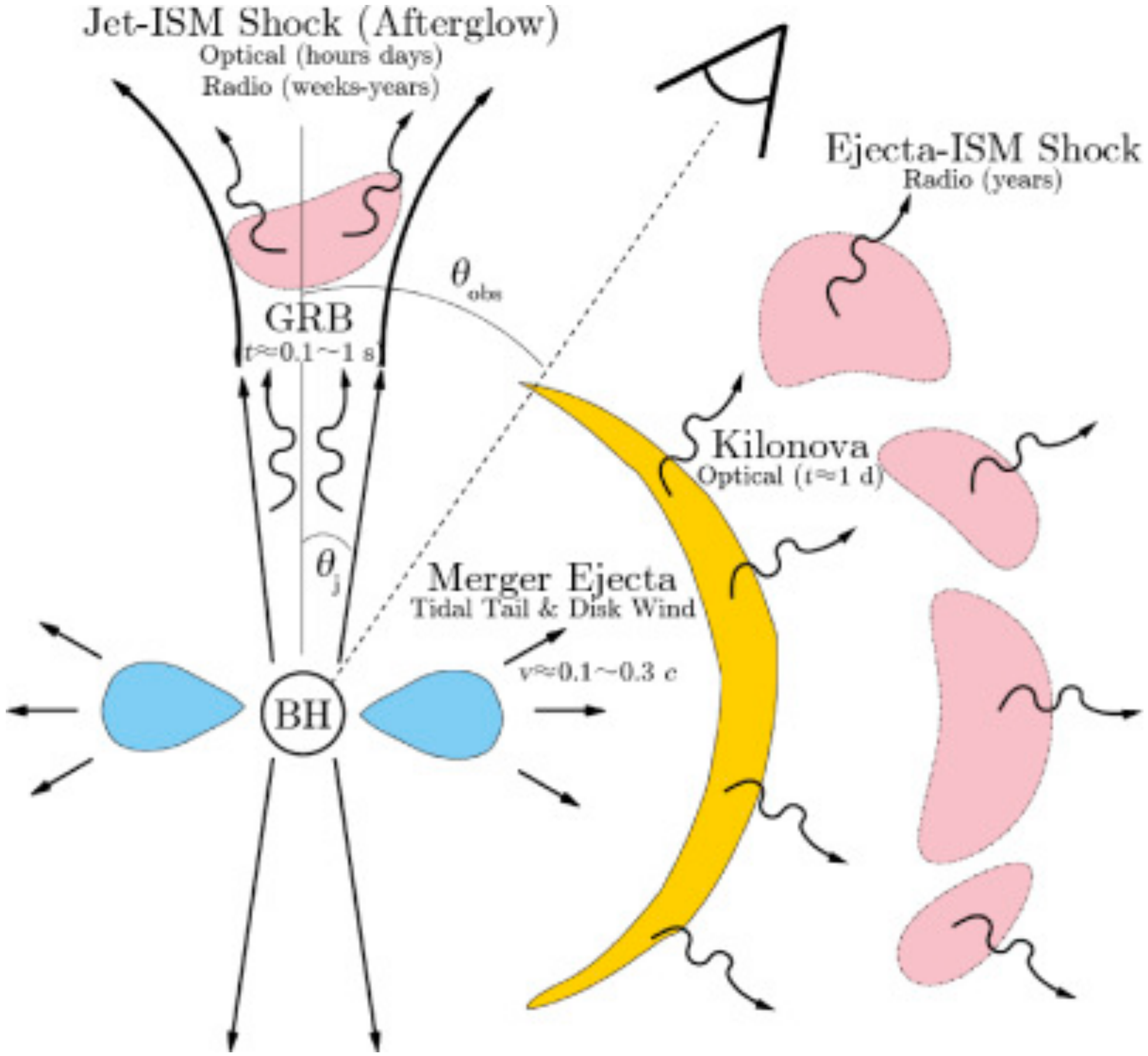
- Detecting gravitational waves from a long-lived post-merger remnant
- Constraining parameters from the X-ray afterglow leads to much more sensitive search… but still not really worth looking.



Sarin et al. (2018)

GAMMA-RAY BURST AFTERGLOWS

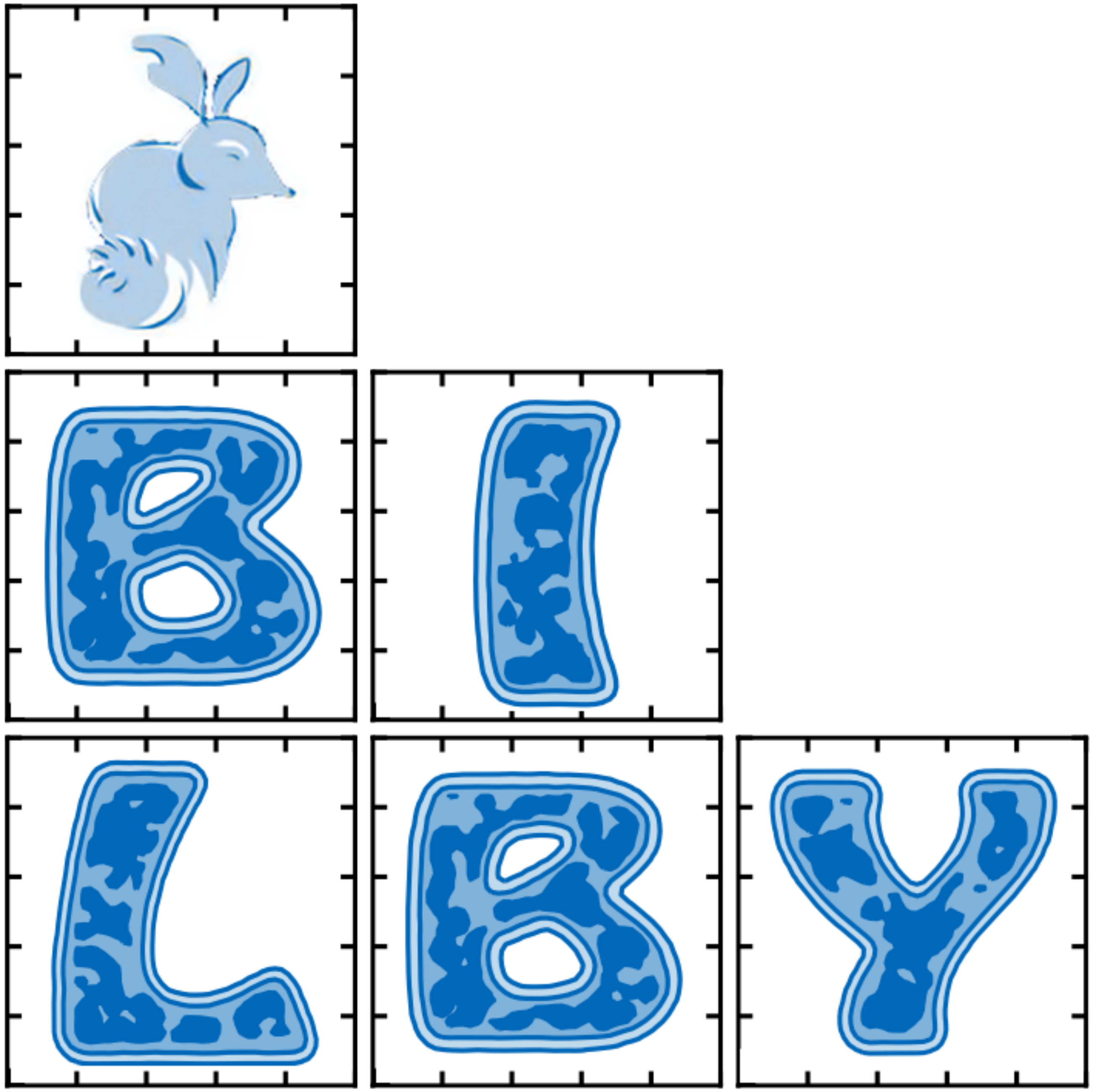
- Gamma-ray bursts often have an extended x-ray, optical, radio emission referred as an afterglow.
- Origin of the X-ray afterglow is unclear
  - External shock from a relativistic fireball.
  - Long-lived neutron star?
  - Both?



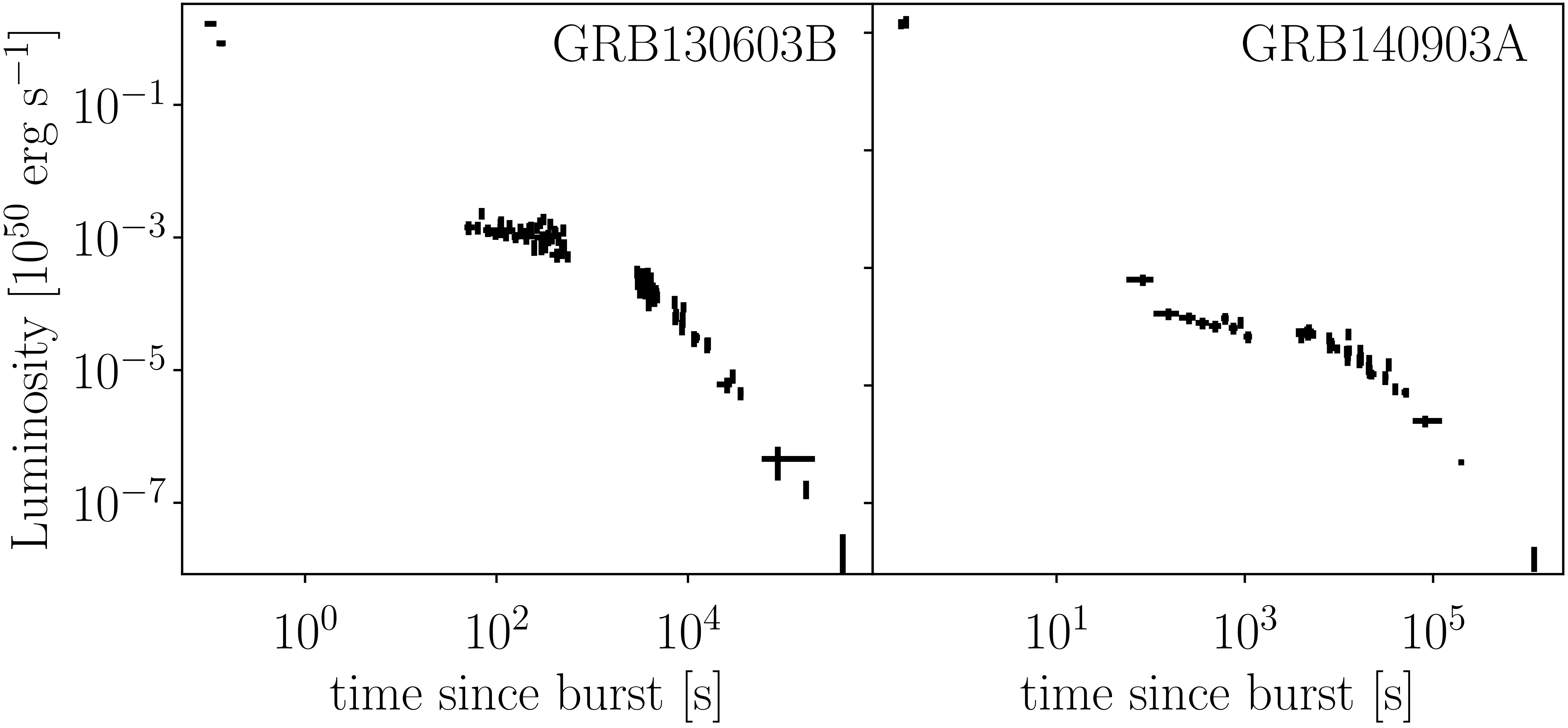
Schematic from Metzger and Berger (2012)

HOW DO YOU COMPARE TWO MODELS?

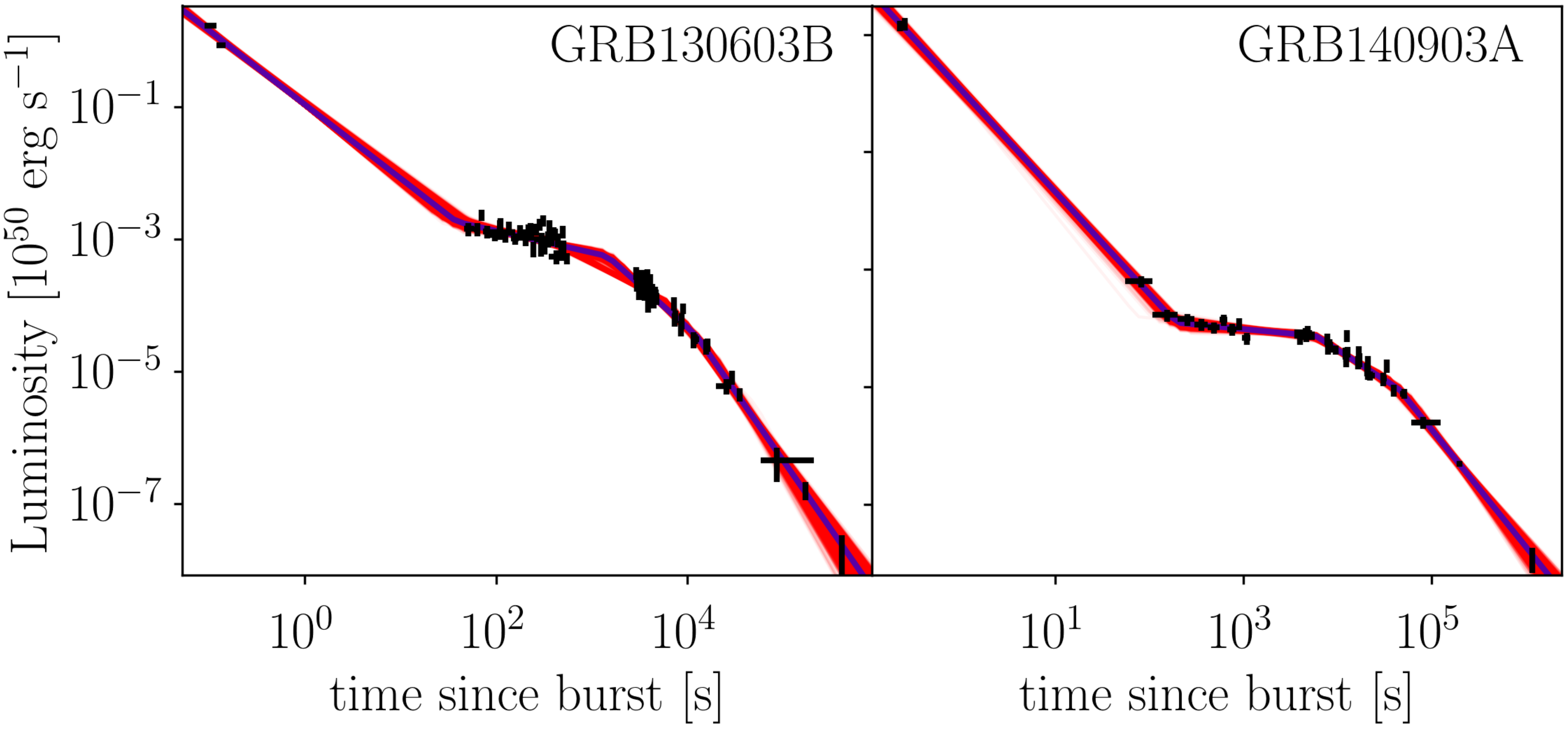
- Models of both external shock and a long-lived neutron stars have been fit to X-ray afterglows.
- Bayesian Inference is a great framework for comparing two models.
- To do this and so much more.. check out Bilby!



Ashton… Sarin… et al. (2019)

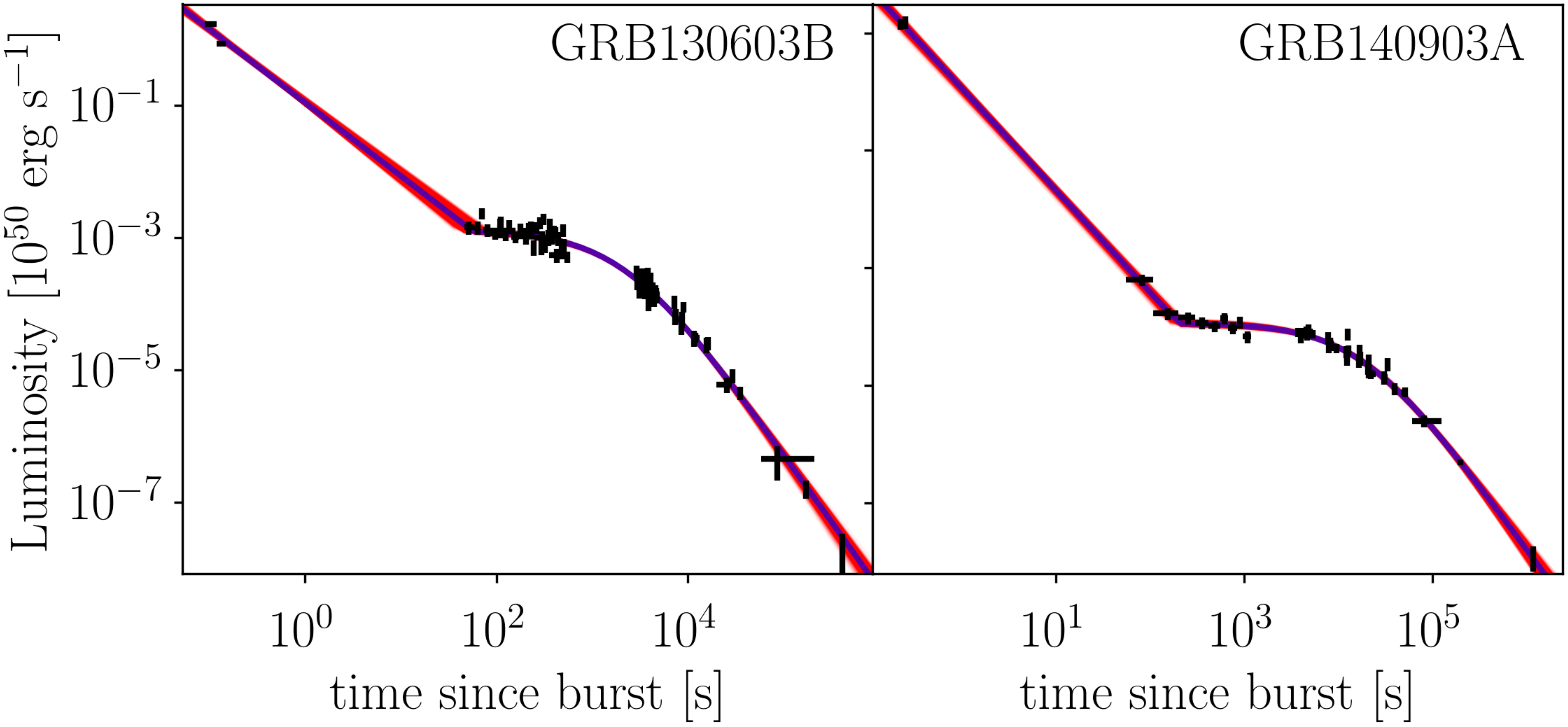

GRB130603B
GRB140903A
Luminosity [10^{50} erg s^{-1}]
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{0}
10^{2}
10^{4}
time since burst [s]
10^{1}
10^{3}
10^{5}
time since burst [s]

Fireball



$$L = A_1 t^{\alpha_1} + A_2 t^{\alpha_2} + ... + A_n t^{\alpha_n}$$

Long-lived neutron star



$$L = A_1 t^{\alpha_1} + A_2 \left(1 + \frac{t}{\tau}\right)^{\frac{1+n}{1-n}}$$

	Bayes Factor
GRB130603B	~ 30
GRB140903A	~ 1700

- GRB140903A: magnetar model is ~1700 times more likely than the most likely fireball, assuming both hypotheses are equally likely…

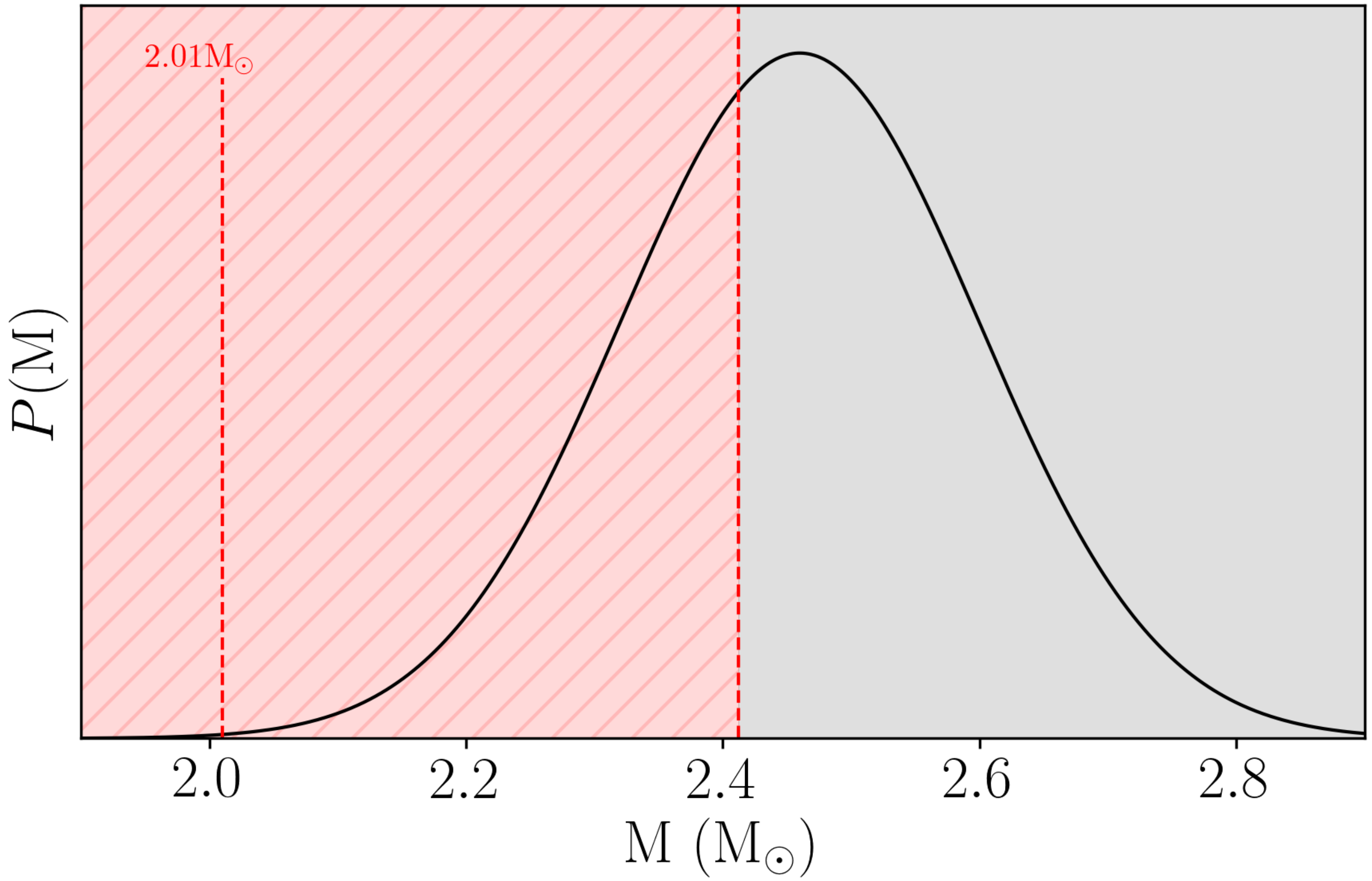
MODEL SELECTION

- The correct metric for model selection is the Odds.
- Prior odds describe our prior belief of the likelihood of one hypothesis over another

$$\mathcal{O}_B^A = \frac{\mathcal{Z}_\mathcal{A}}{\mathcal{Z}_\mathcal{B}} \times \frac{\Pi_A}{\Pi_B}$$

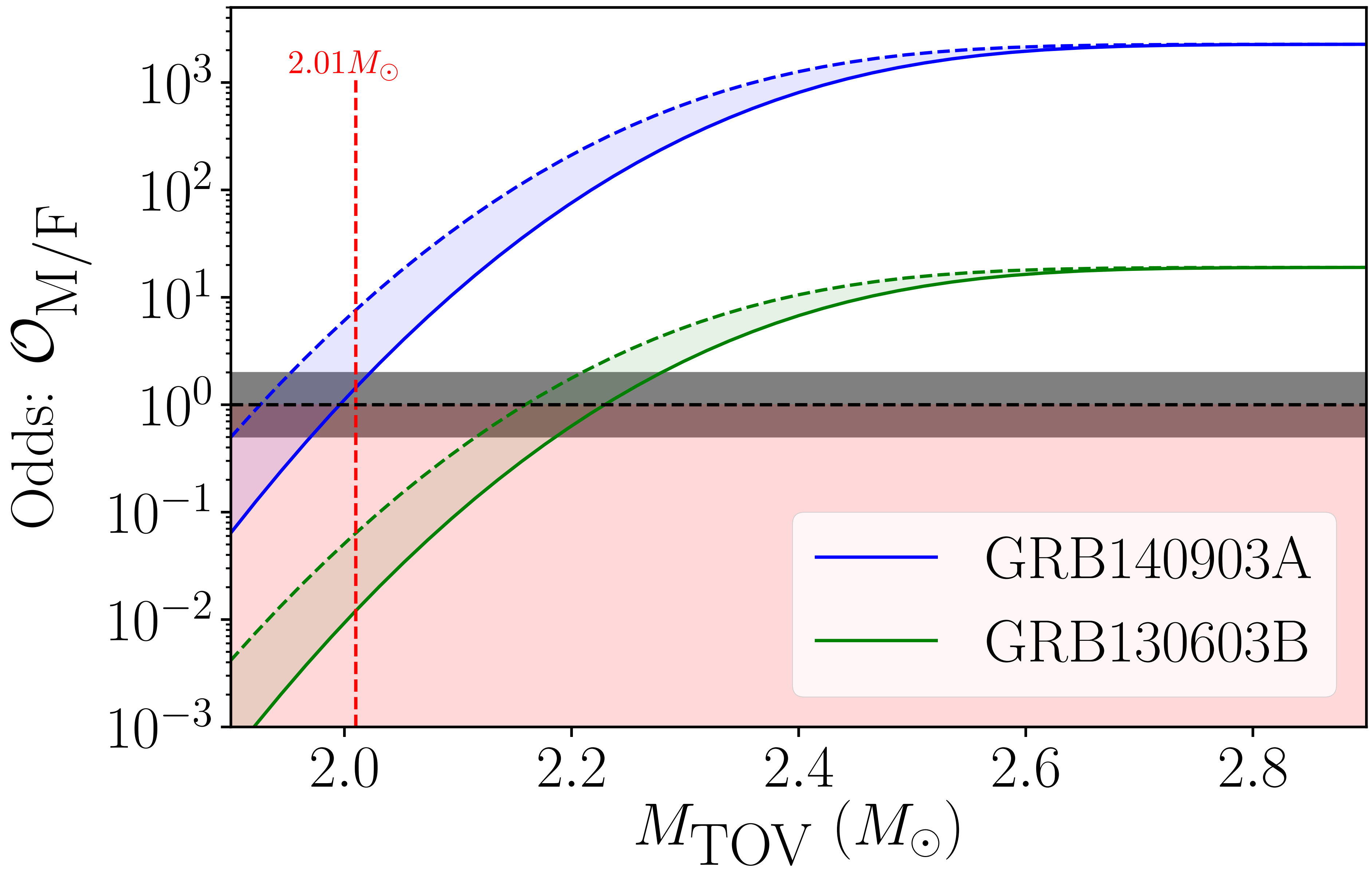
PRIOR ODDS

- A long-lived neutron star model requires one to actually form.
- Inform prior odds with knowledge of the local neutron star mass distribution (Kiziltan et al. 2013, Lasky et al. 2014)



$$\frac{\Pi_M}{\Pi_F} = \int_0^{\mathrm{M}_{\mathrm{TOV}}} P(\mathrm{M})\ d\mathrm{M}$$

ODDS



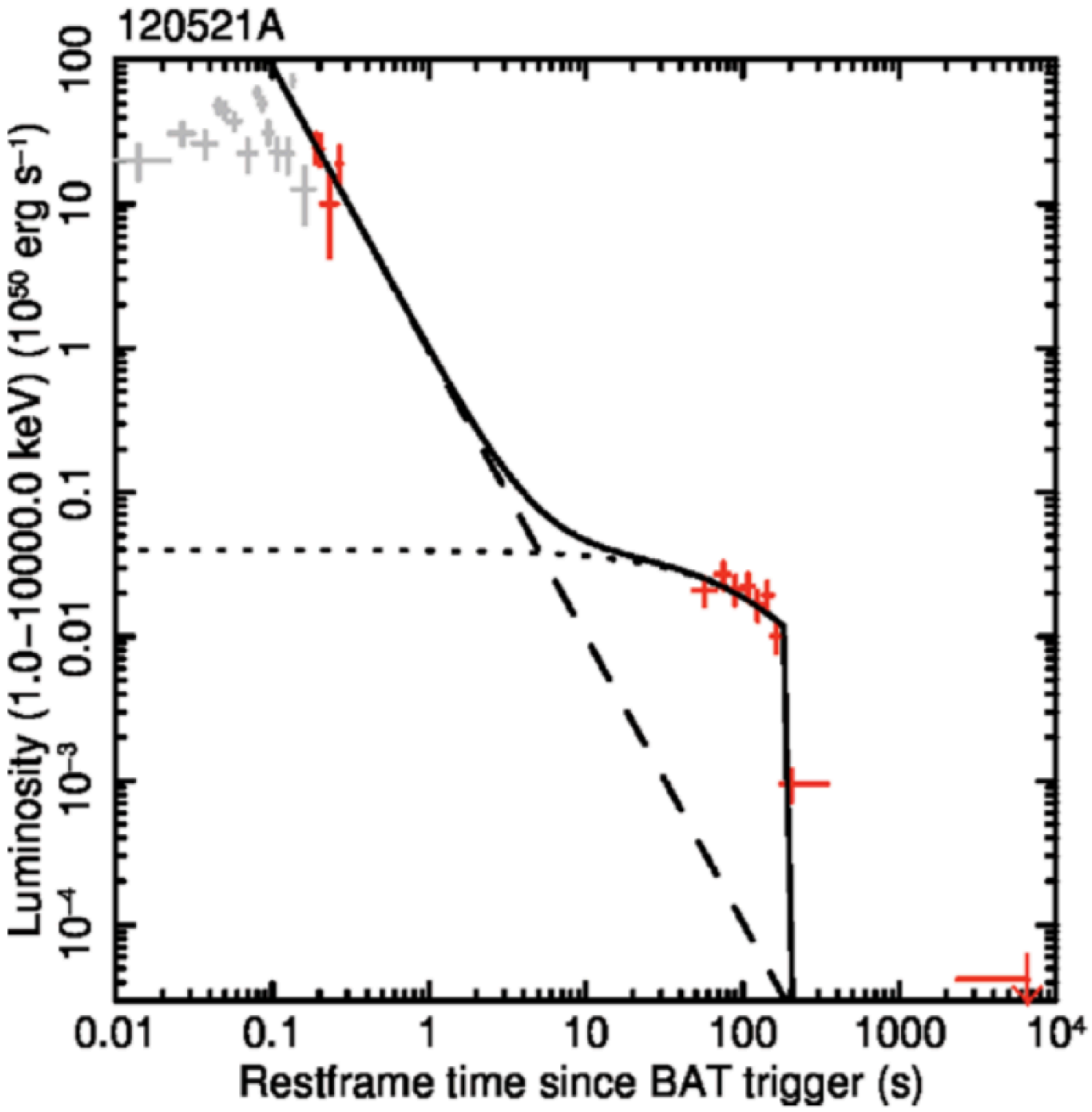
- Model selection becomes dependent on the equation of state.
- GRB140903A favours the magnetar model for all possible equation of states.

MODEL SELECTION

- Model selection is not conclusive without a known equation of state.
- Magnetar model is preferred over the fireball model for all equation of states for GRB140903A.
- For more details see Sarin et al. (2019)

AFTERGLOWS

- GRB130603B and GRB140903A X-ray observations require systematic model selection.
- A smaller subset of GRBs have more telltale observations.



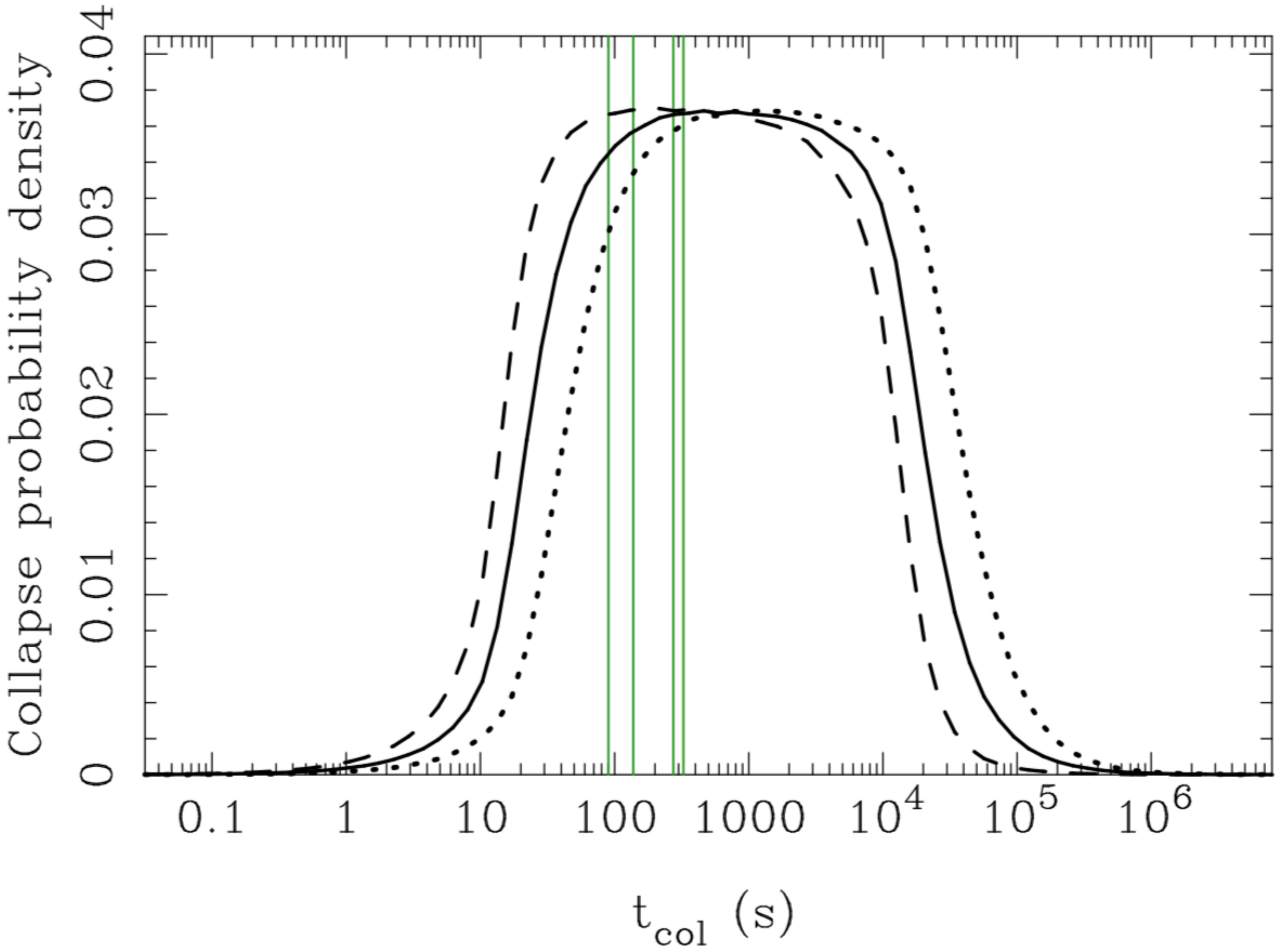
Rowlinson et al. (2013)

WHY DO THEY COLLAPSE?

- $M_{\rm tot} \gtrsim 1 - 1.2 \times M_{\rm TOV}$
- Initially supported against collapse due to rigid-body rotation.
- Spin-down and collapse.

COLLAPSE TIME

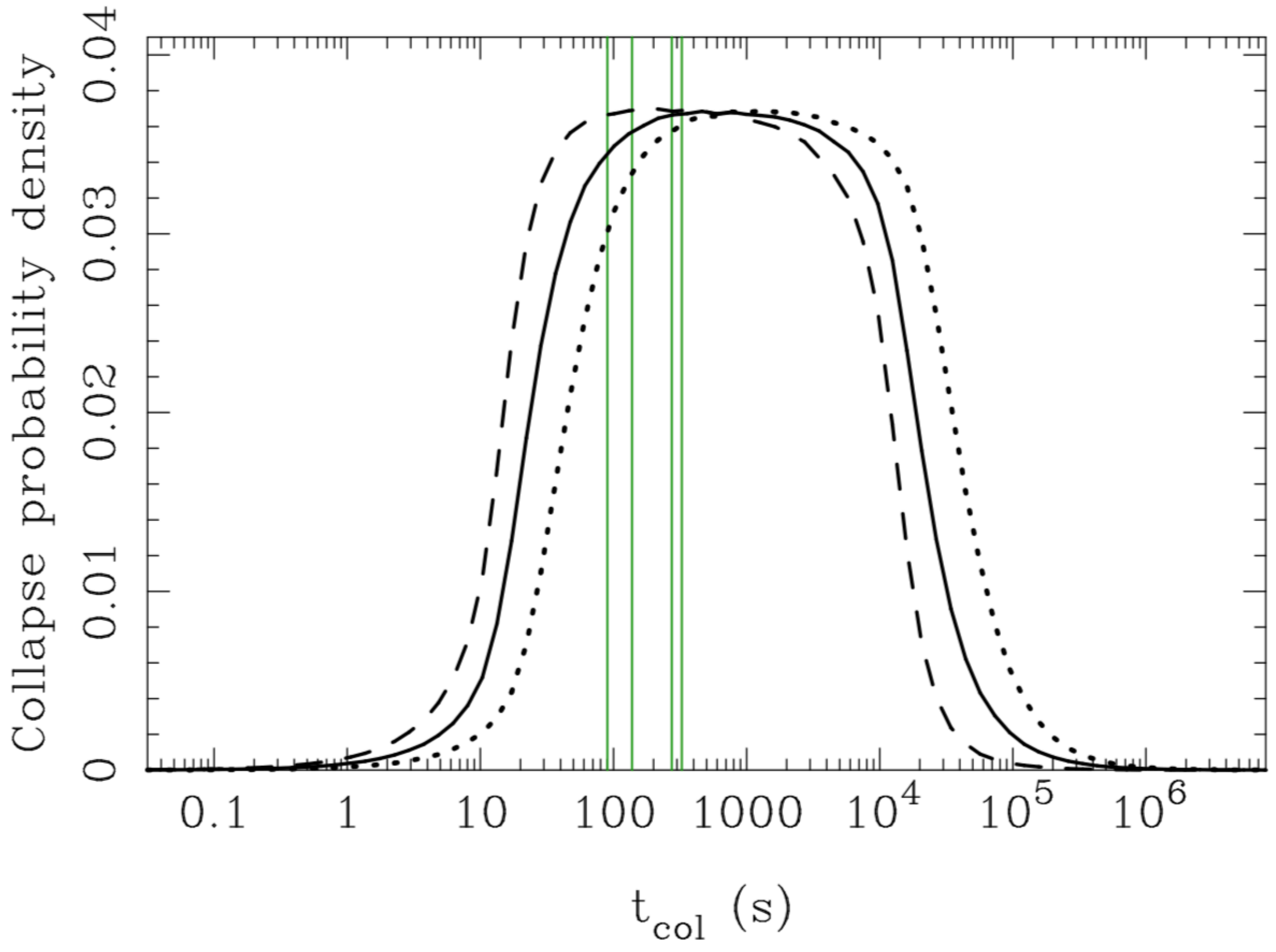
- The collapse time of a neutron star is strongly related to the equation of state, the mass, spin-down mechanism, magnetic field etc.



Theoretical collapse time distribution for different EOS from Ravi & Lasky (2014).

INCONSISTENCIES

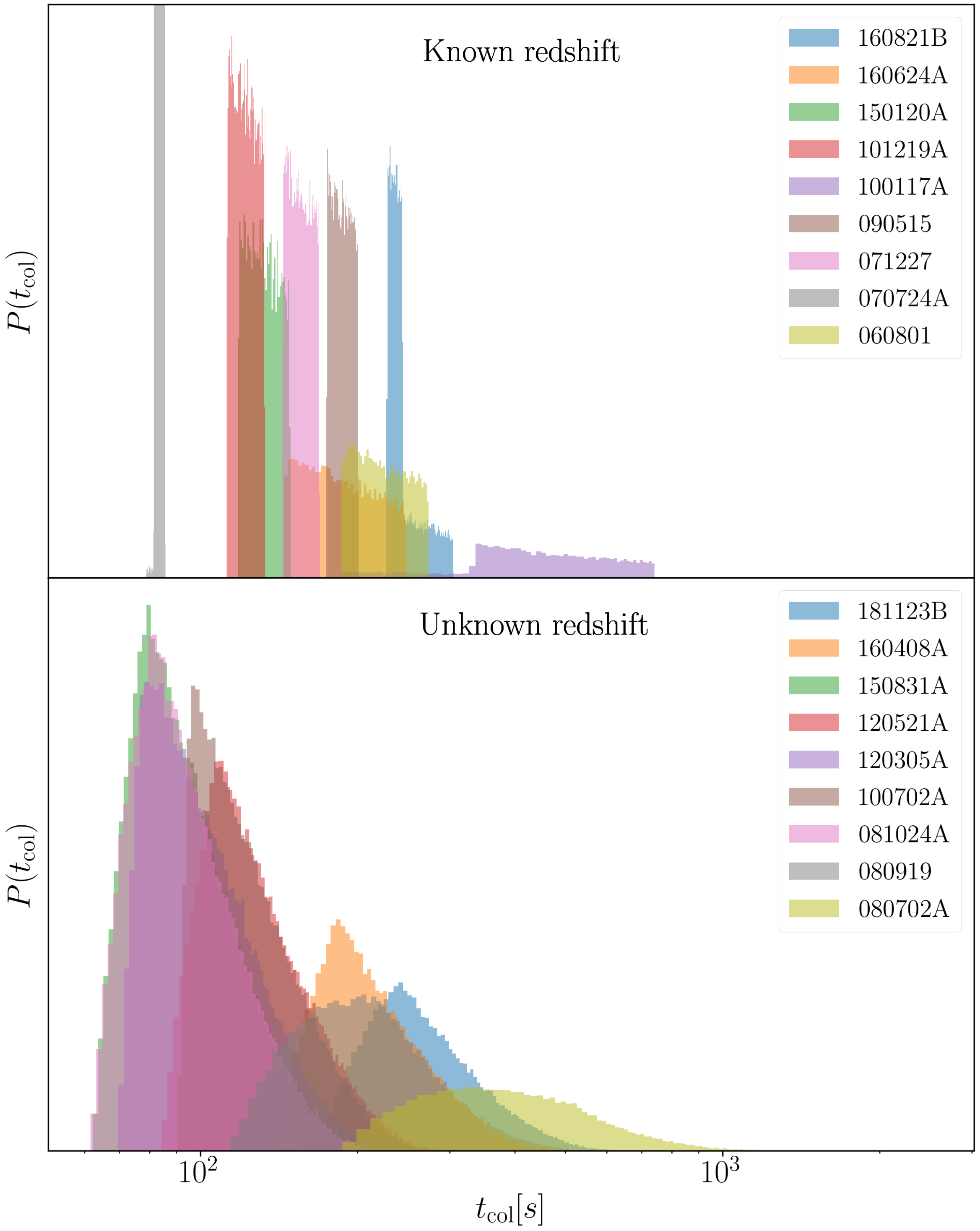
- The distribution seems at odds with the 4 reliable measurements
- Two hypotheses
    - Initial rapid spin-down through the emission of gravitational waves (Gao et al. 2016)
    - These stars are actually quark stars (Ang Li et al. 2016)

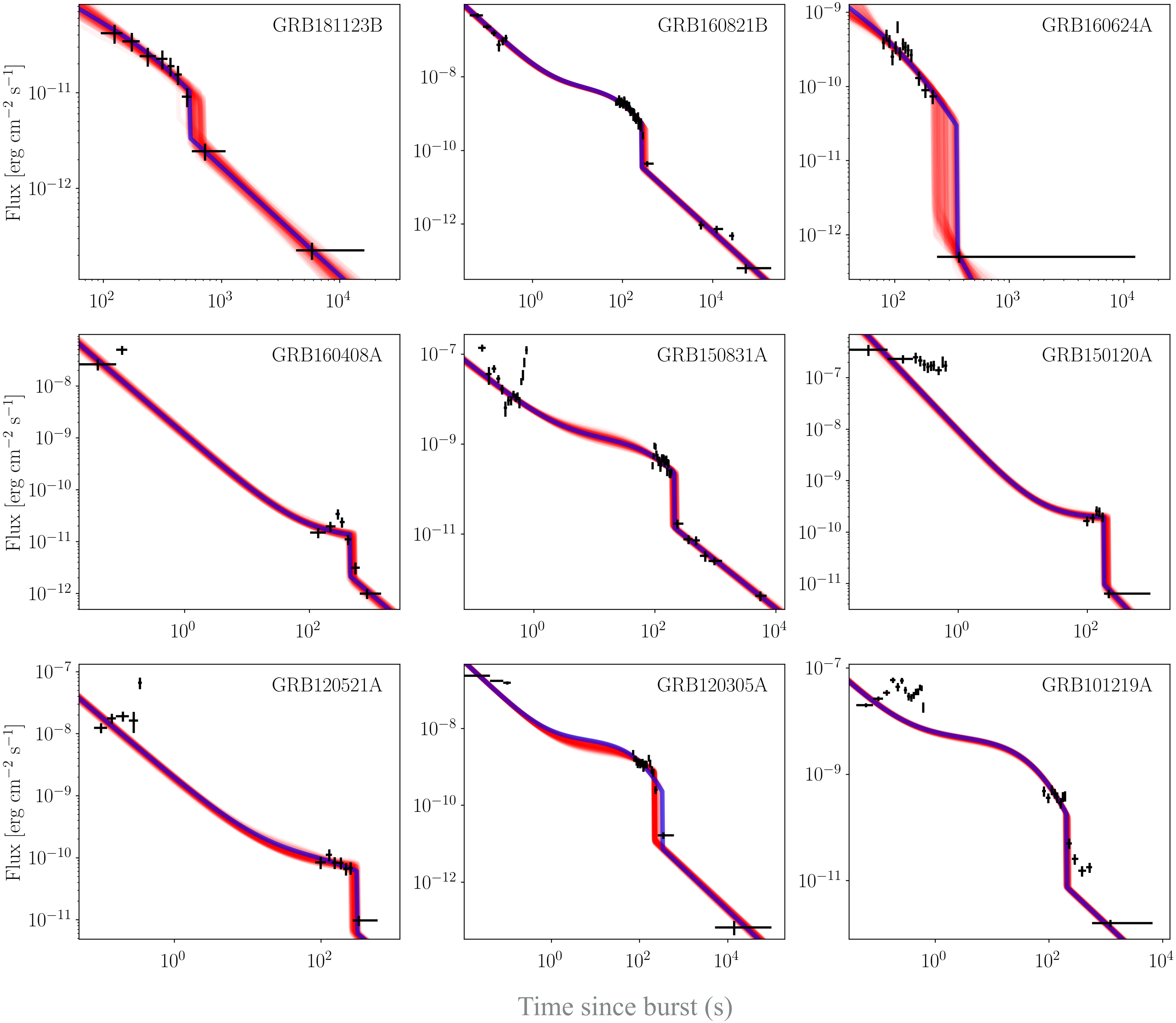


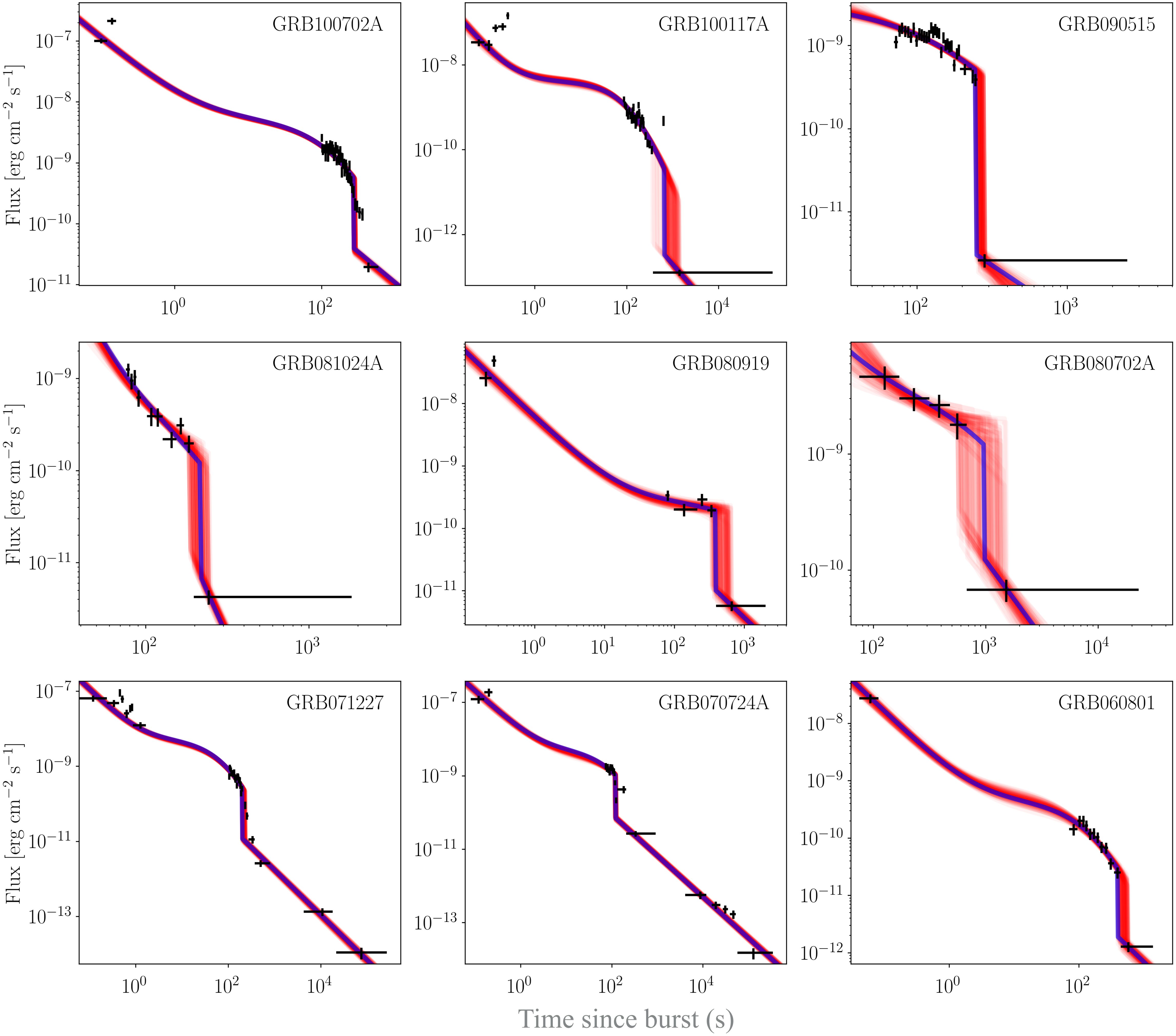
Ravi and Lasky (2014)

INFERRING COLLAPSE TIME

- We measure the collapse-time of 18 putative long-lived neutron stars from the X-ray afterglow of 72 short gamma-ray bursts.




GRB181123B
GRB160821B
GRB160624A
GRB160408A
GRB150831A
GRB150120A
GRB120521A
GRB120305A
GRB101219A
Flux [erg cm^{-2} s^{-1}]
Time since burst (s)


GRB100702A
GRB100117A
GRB090515
GRB081024A
GRB080919
GRB080702A
GRB071227
GRB070724A
GRB060801
Flux [erg cm^{-2} s^{-1}]
Time since burst (s)
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

POPULATION PROPERTIES

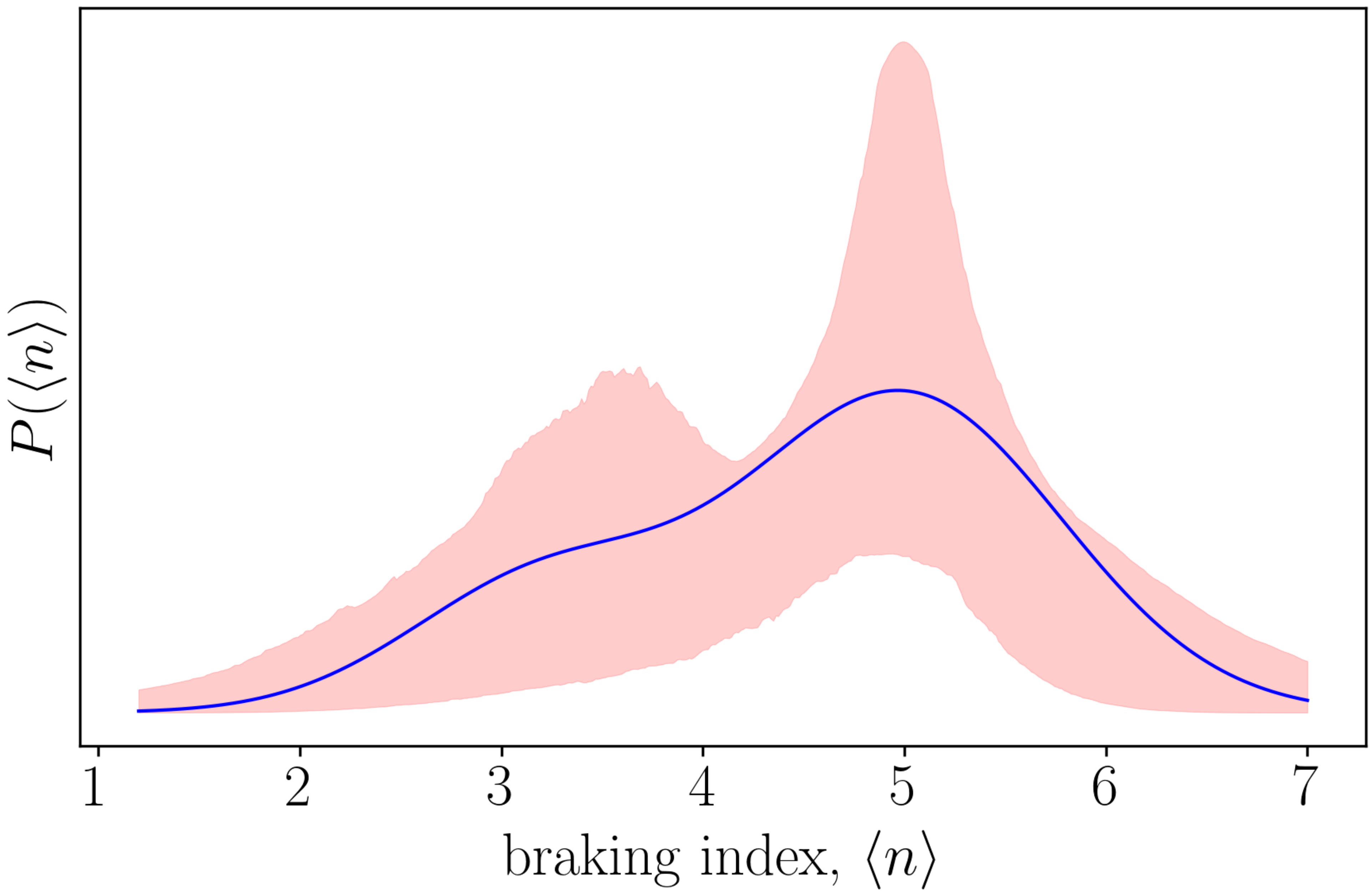
- Individual events are interesting…
- But exciting secrets are hidden in the population.

$$\mathrm{tcol} = \frac{\tau_i}{p_{0,i}^{\gamma_i}} \left[\left(\frac{M_{p,i} - M_{\mathrm{TOV}}}{\alpha M_{\mathrm{TOV}}} \right)^{\frac{\gamma_i}{\beta}} - p_{0,i}^{\gamma_i} \right] .$$

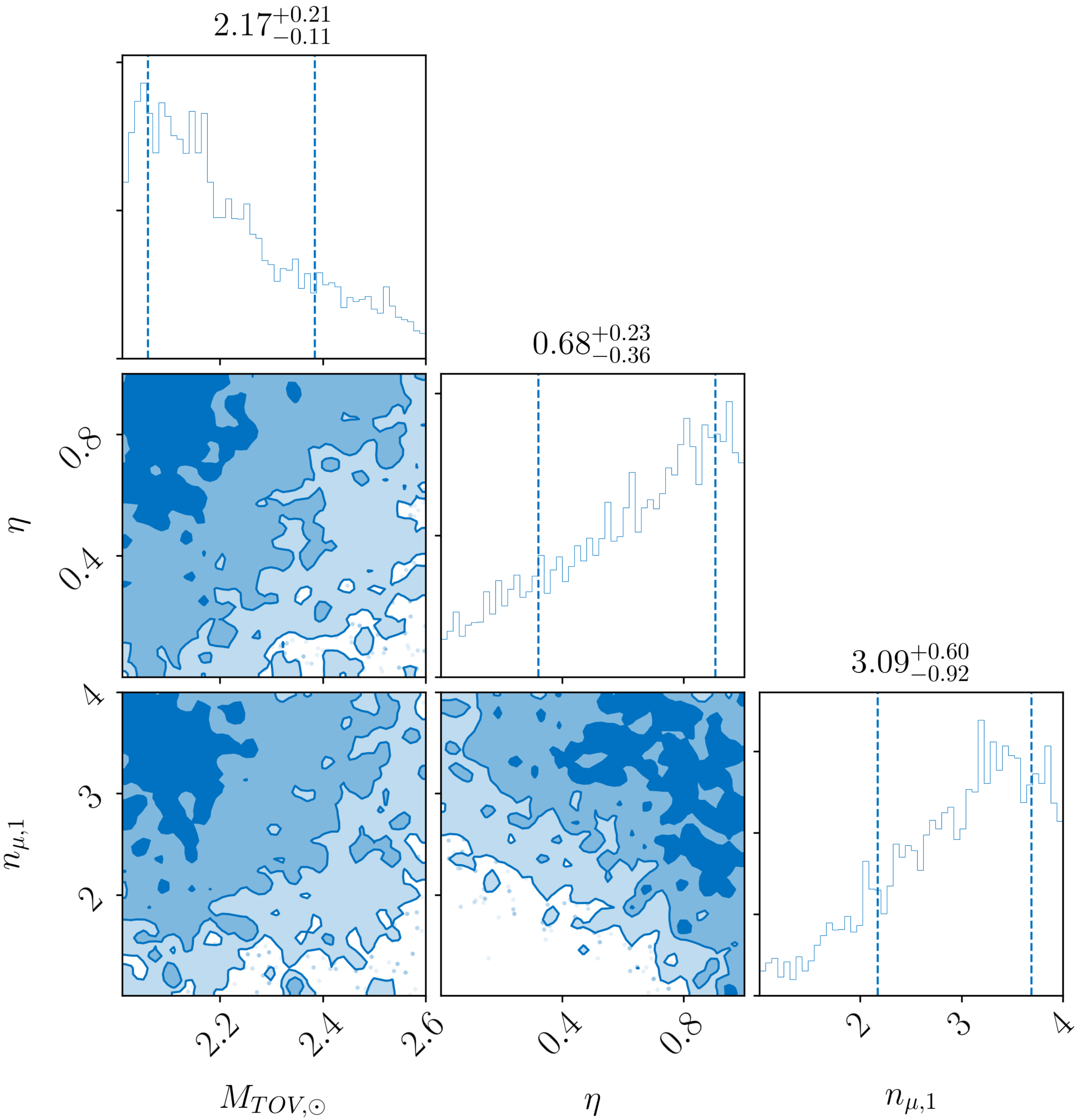
$$\gamma_i = \frac{\langle n \rangle_i + 1}{\langle n \rangle_i - 1},$$

$$M_{\max} = M_{\mathrm{TOV}} \left(1 + \alpha p^{\beta} \right)$$

RESULTS

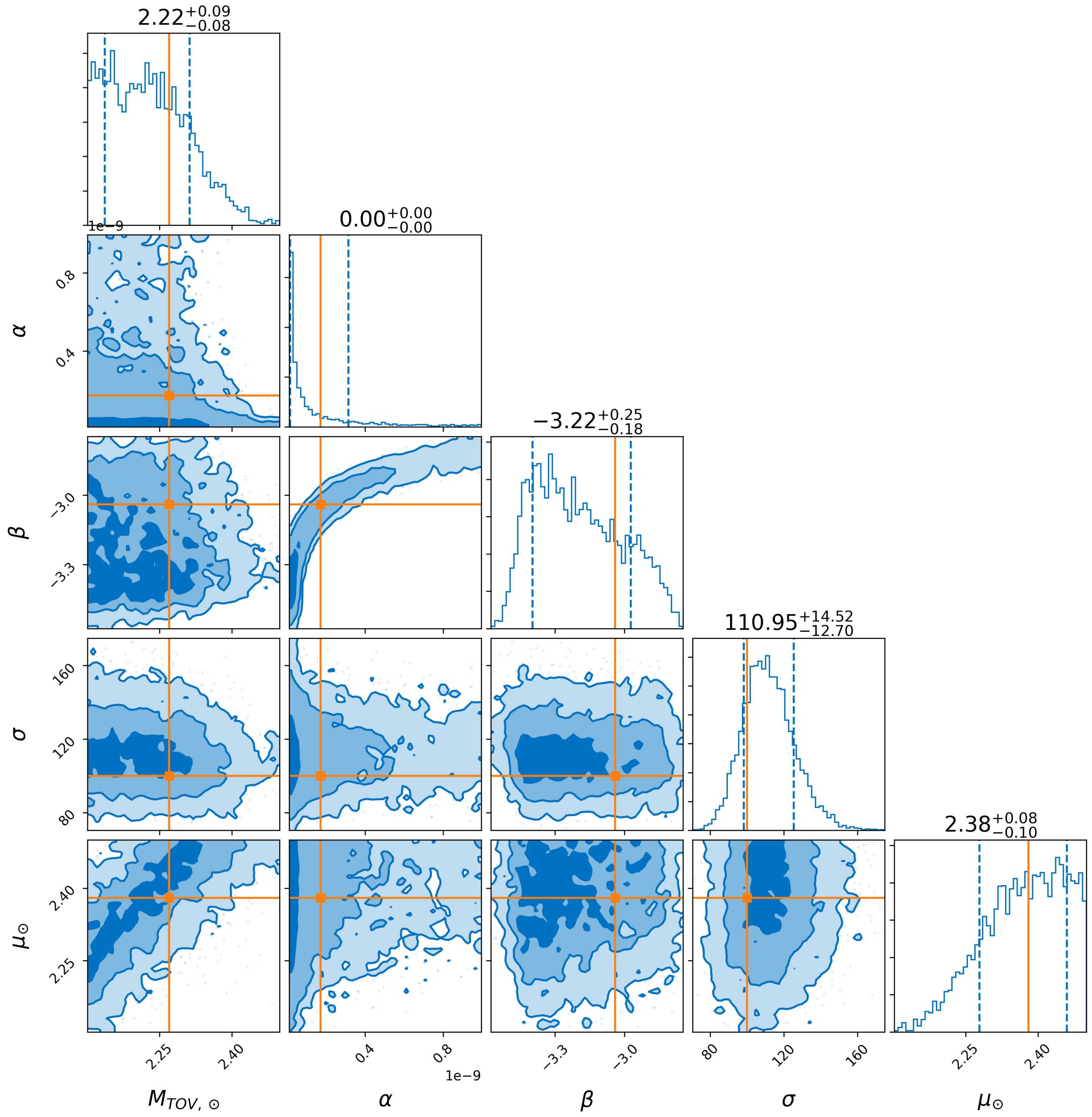


RESULTS


$2.17^{+0.21}_{-0.11}$
$0.68^{+0.23}_{-0.36}$
$3.09^{+0.60}_{-0.92}$
η
0.8
0.4
$n_{\mu,1}$
4
3
2
2.2
2.4
2.6
0.4
0.8
2
3
4
$M_{TOV,\odot}$
η
$n_{\mu,1}$

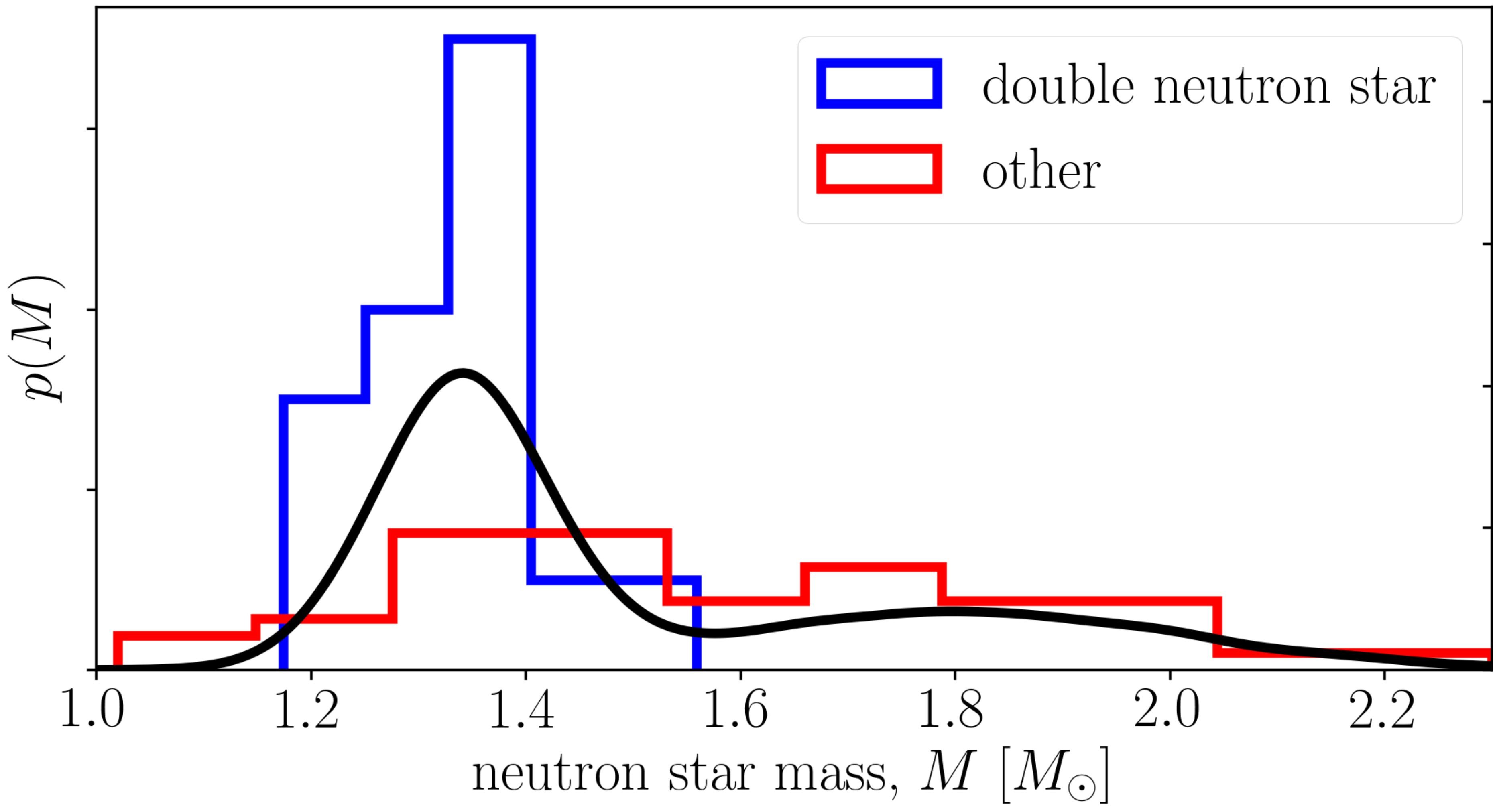
INJECTION STUDY

- These results are incredibly sensitive to the assumed neutron star mass distribution.



BNS MASS DISTRIBUTION

- Is the local binary neutron star mass distribution observed in radio a good representation of merging binary neutron stars?
- Selection effects? Eccentricity/Mass
- Dynamical mergers?

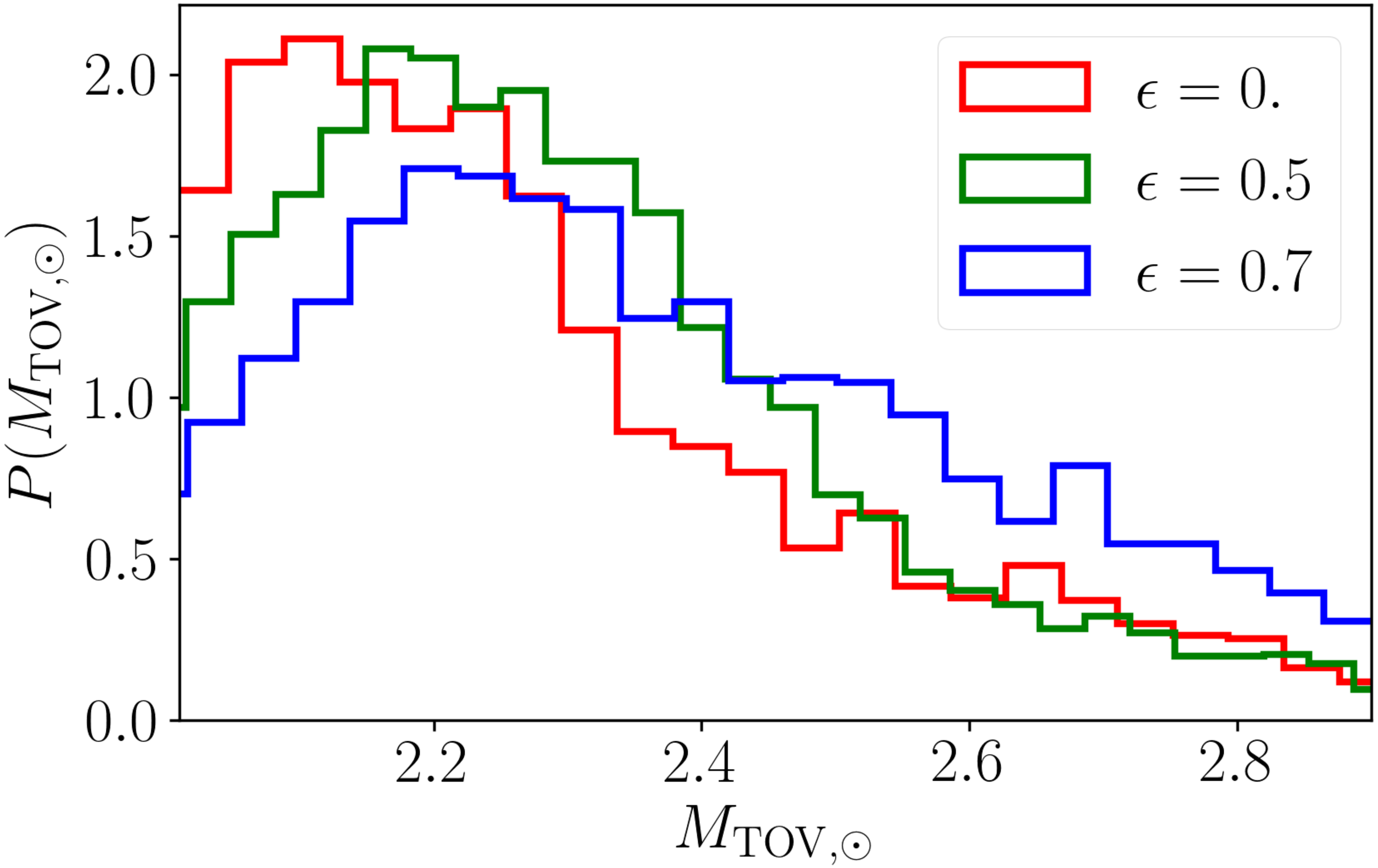


- Assume instead, the mass distribution of binary neutron stars is a mixture model of neutron stars in binaries and single neutron star.
- In our galaxy, this is well approximated as a double-peaked Gaussian (Alsing et al. 2018).

$$p(M) = (1-\epsilon)\,\mathcal{N}\left(\mu_1,\, \sigma_1\right) + \epsilon\mathcal{N}\left(\mu_2,\, \sigma_2\right)$$

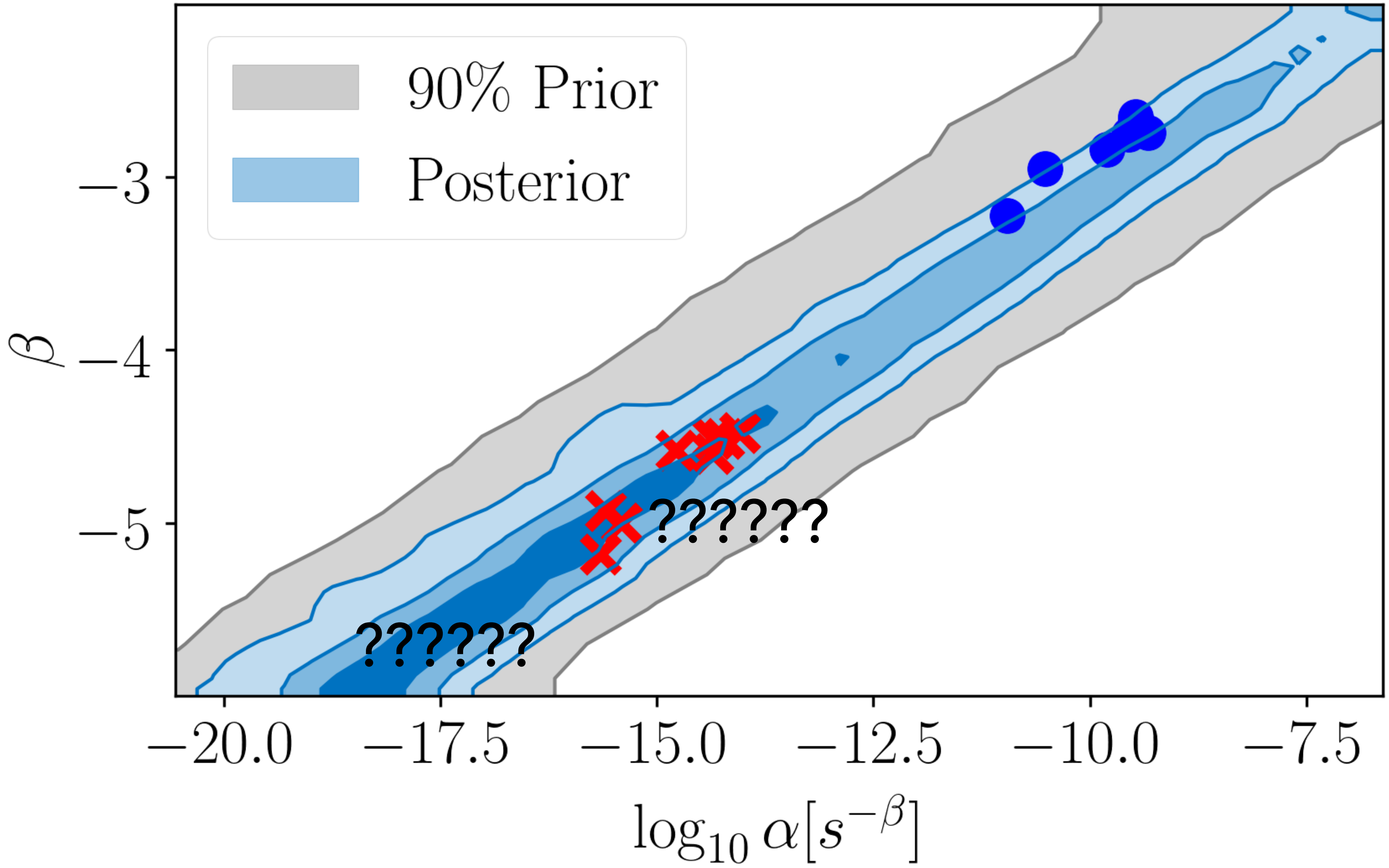
$$\mu_1 = 1.32M_\odot, \sigma_1 = 0.11M_\odot, \mu_2 = 1.8M_\odot, \sigma_2 = 0.21M_\odot$$

RESULTS



- Measurement of M_{TOV} depends on knowing ϵ.
- We measure $M_{\mathrm{TOV}} = = 2.3^{+0.35}_{-0.19} M_{\odot}$ marginalised over all values of ϵ.

RESULTS - WORK IN PROGRESS



- This seems to suggest that quark stars are favoured over hadronic, and possibly favours even more extreme equation of states..
- Currently investigating the cause, possible bias or systematics. We have almost fixed it so stay tuned for this soon!

CONCLUSIONS

- Inferring the post-merger remnant of binary neutron stars is incredibly informative for the nuclear equation of state.
- Gravitational-wave detection from long-lived remnant is unlikely (see Sarin et al. 2018).
- X-ray afterglows of short gamma-ray bursts can be used to indirectly infer the presence of a long-lived remnant (see Sarin et al. 2019).
- Assuming the locally observed binary neutron star population is good representation of binaries that merge, we measure $M_{\rm TOV} = = 2.17^{+0.21}_{-0.11} M_{\odot}$.
- I have Bilby stickers to give away.