MONASH University

OzGrav

ARC Centre of Excellence for Gravitational Wave Discovery

OBSERVATIONAL IMPLICATIONS OF BINARY NEUTRON STAR MERGERS

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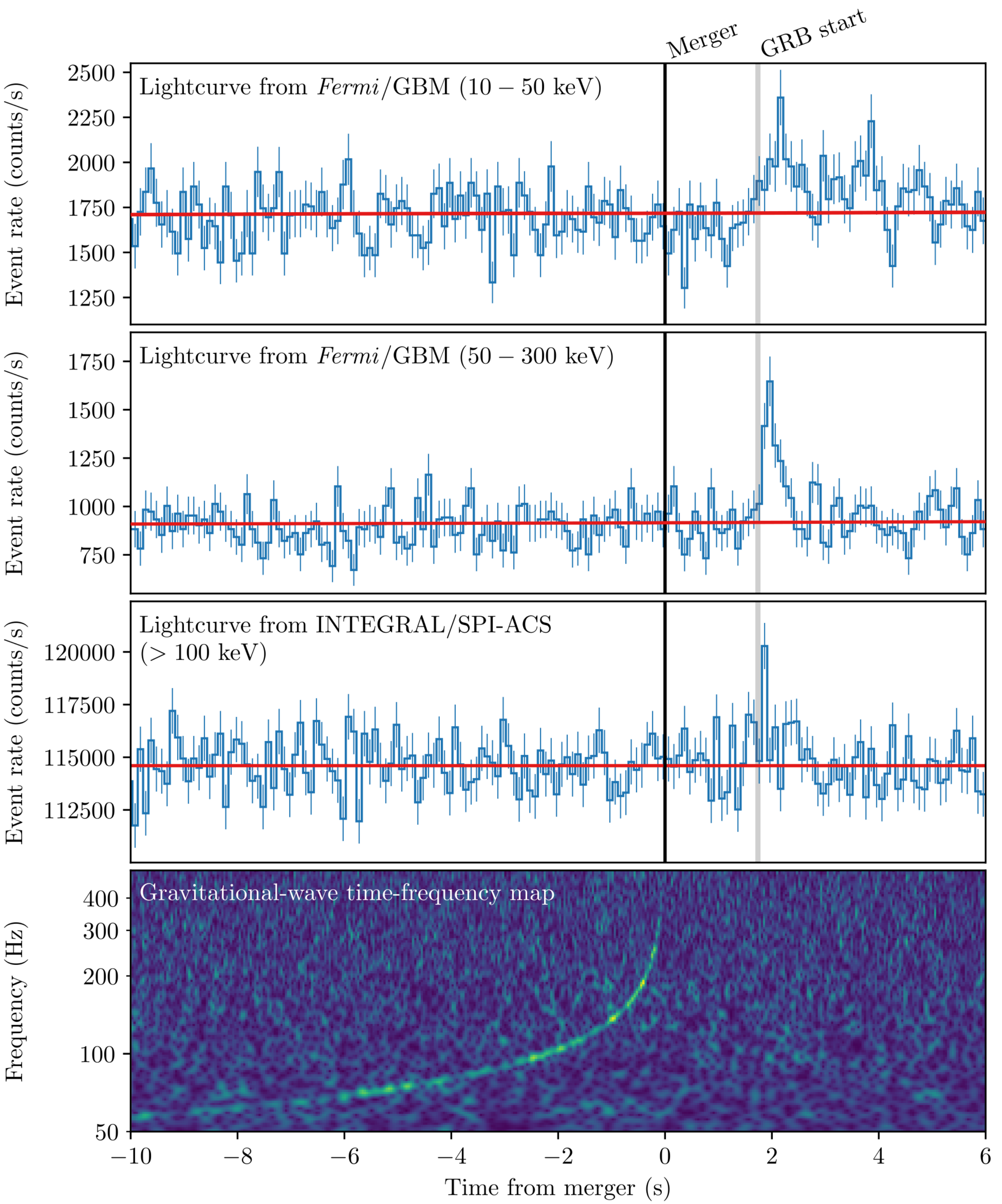
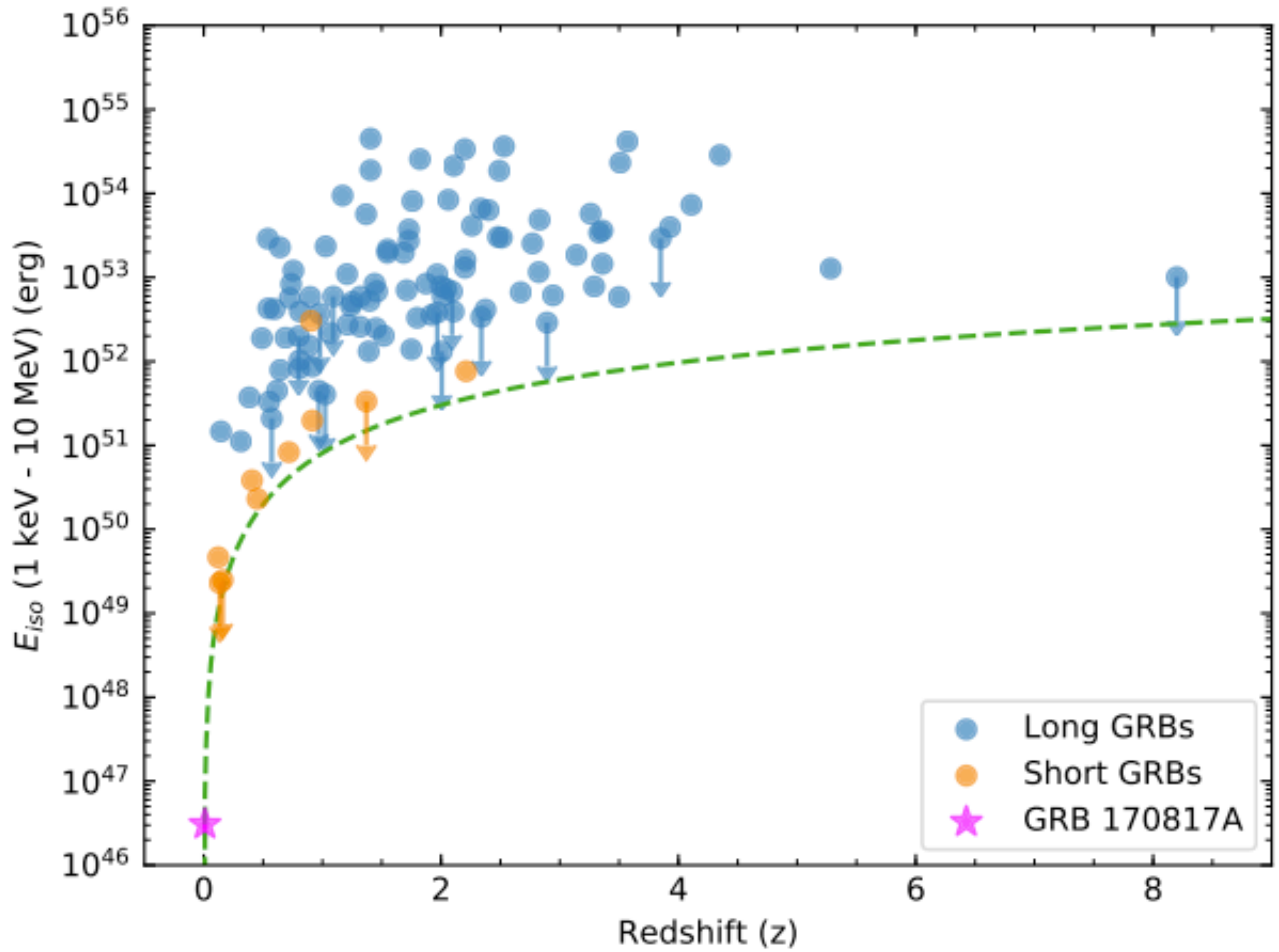
PAUL LASKY GREG ASHTON

- The first binary neutron star merger observed in gravitational waves and in electromagnetic radiation!

- Lets first look at the gamma-ray burst itself.



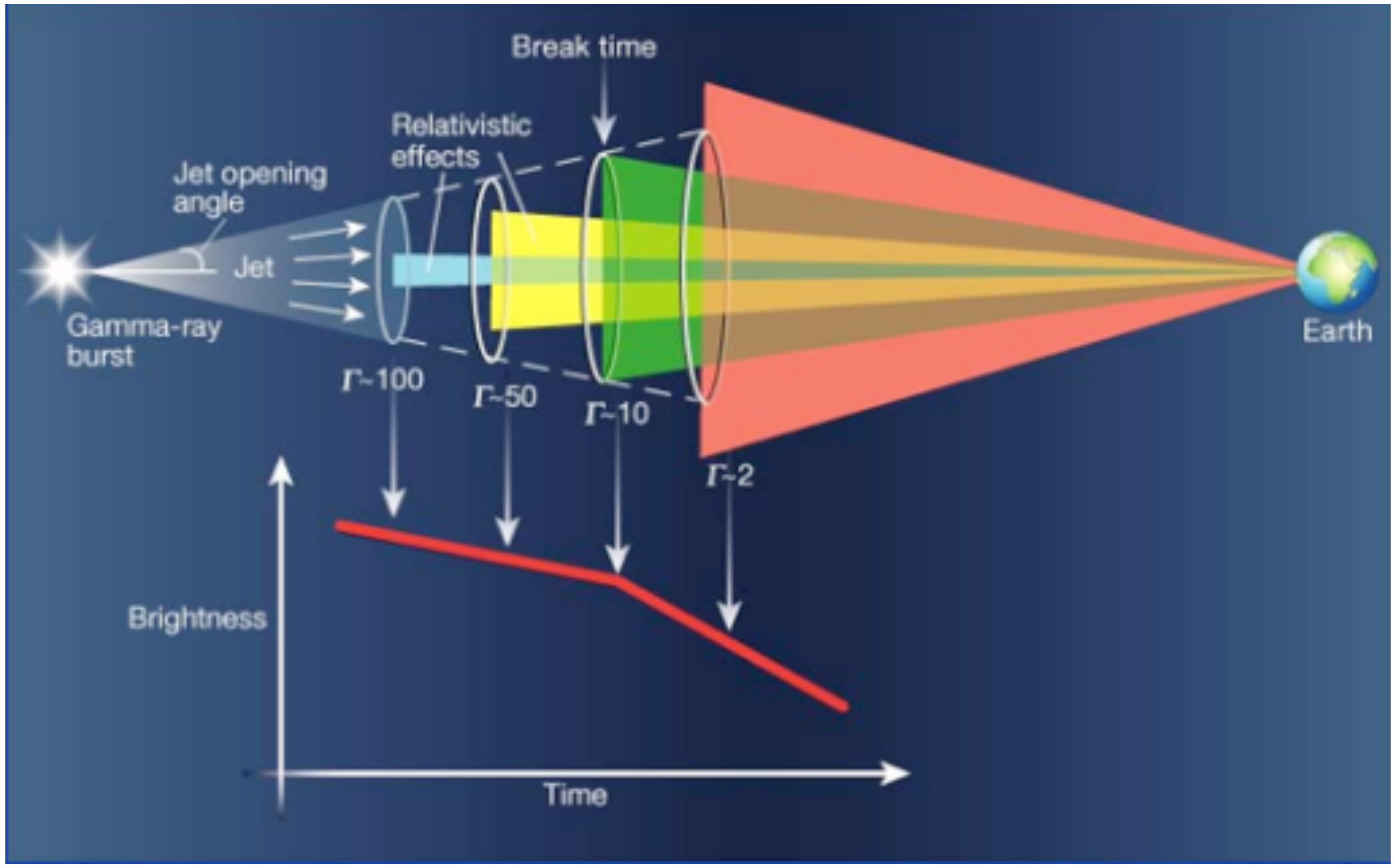
- GRB170817A was peculiar…



Abbott et al. 2017 (GRB+GW paper)

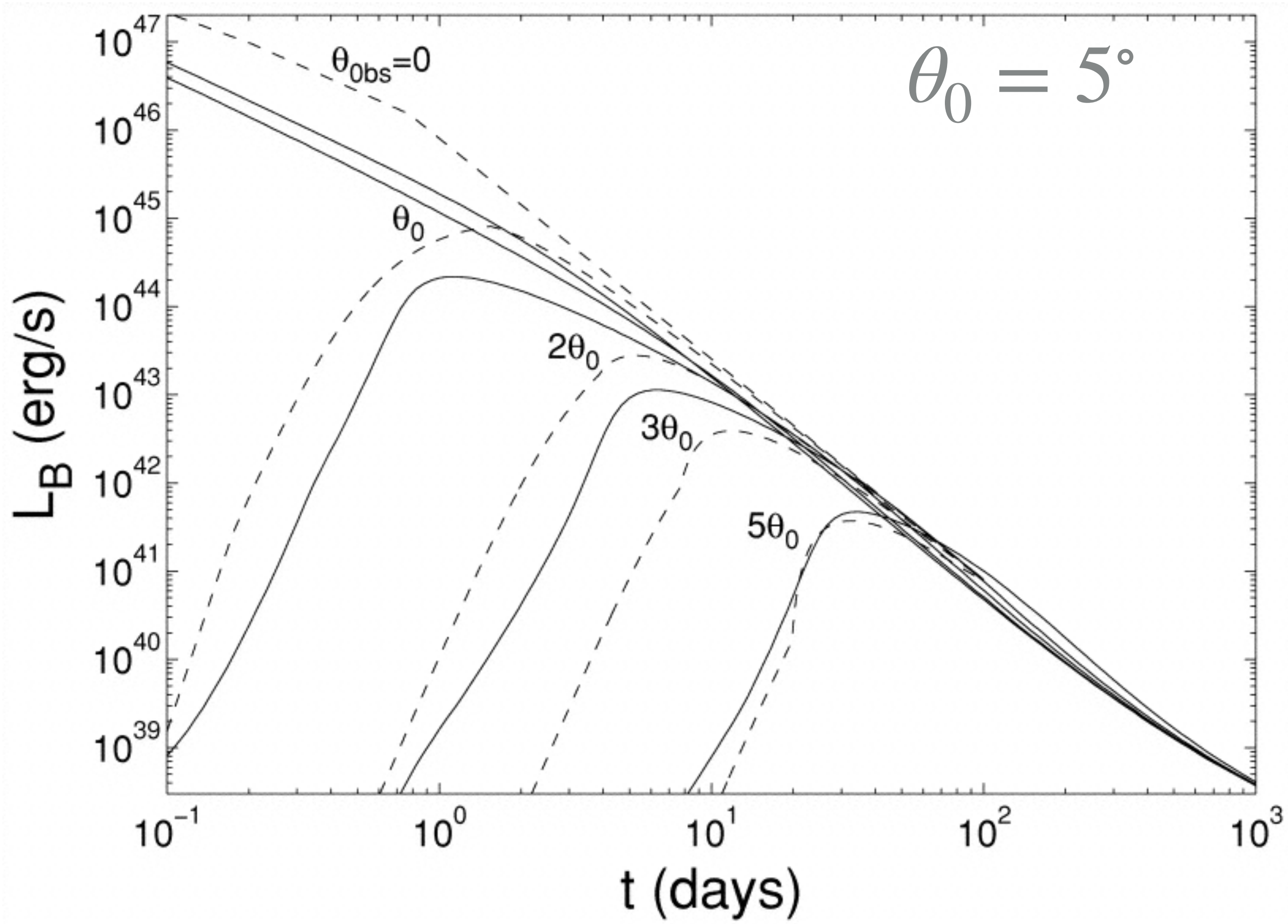
- Close and **dim**… why!?

- General theory for afterglows.
- Assume observer is located at angle within the jet opening angle θ_j.
- Relativistic beaming effects mean the observer only sees emission from $1/\Gamma$ cone.
- As the jet slows down and $1/\Gamma$ becomes comparable to θ_j you ``notice" the missing energy, change in slope; this is the ``jet break" in a simple picture.



Woosley 2001

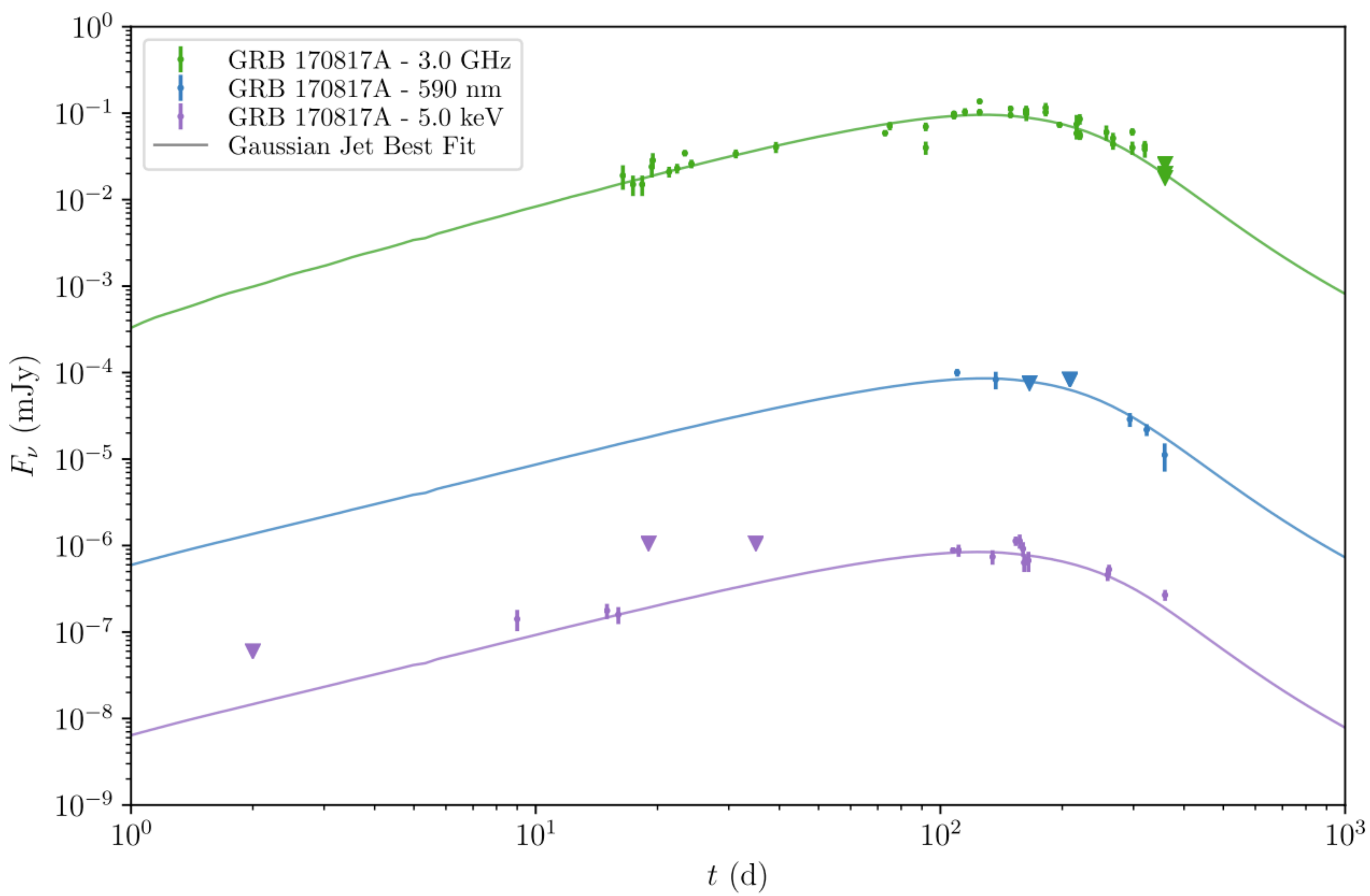
- What if you were off-axis to begin with?



Granot 2002

- Now relativistic beaming is working in your favour, the light curve rises and peaks when $1/\Gamma$ cone covers the observers line of sight.

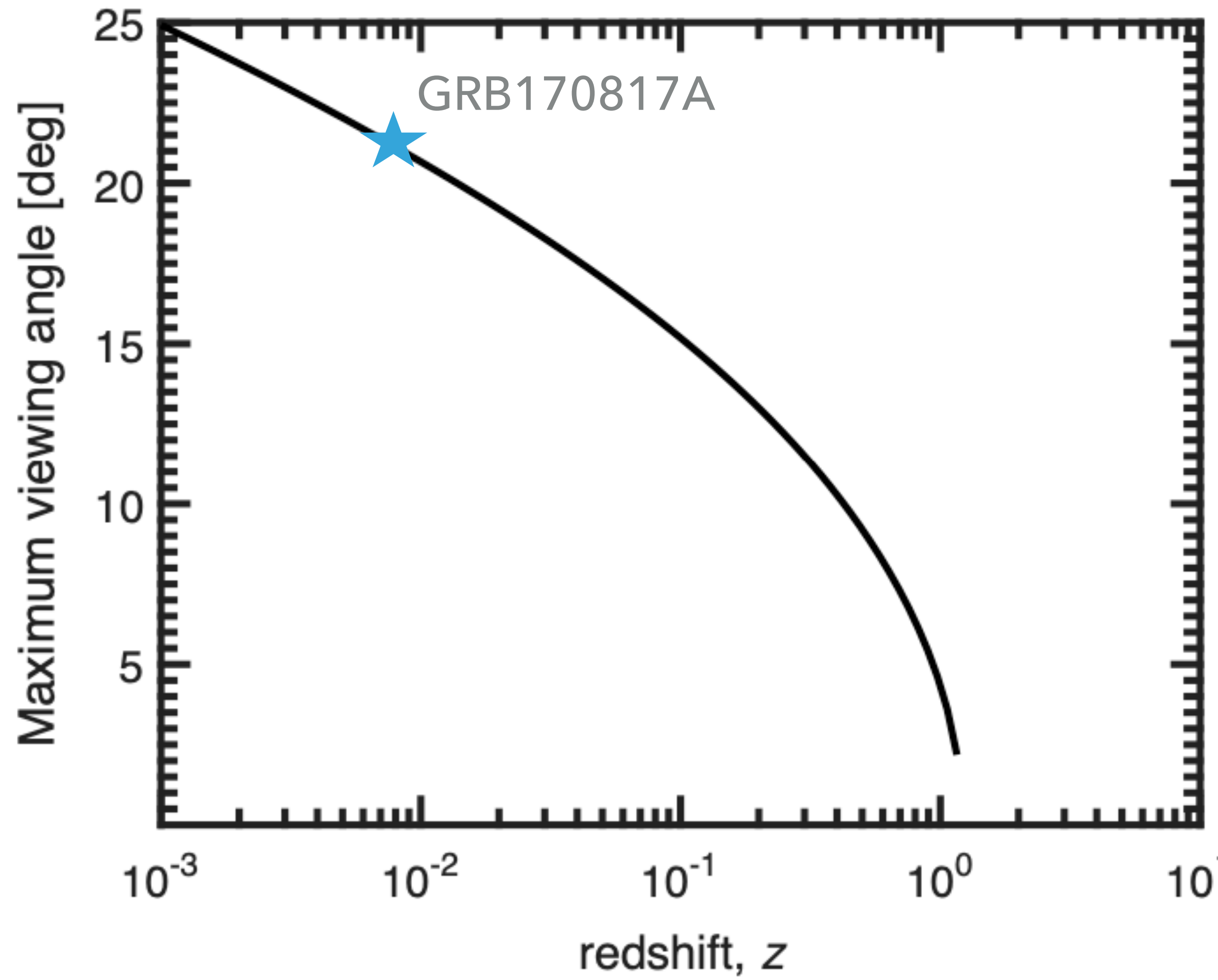
- The afterglow of GRB170817A
- We now believe through various arguments that GRB170817 resulted in a structured jet, and $\theta_{obs} \sim 23^{\circ}$. The light curve peaked around a 100 days post merger.



Ryan et al. 2019

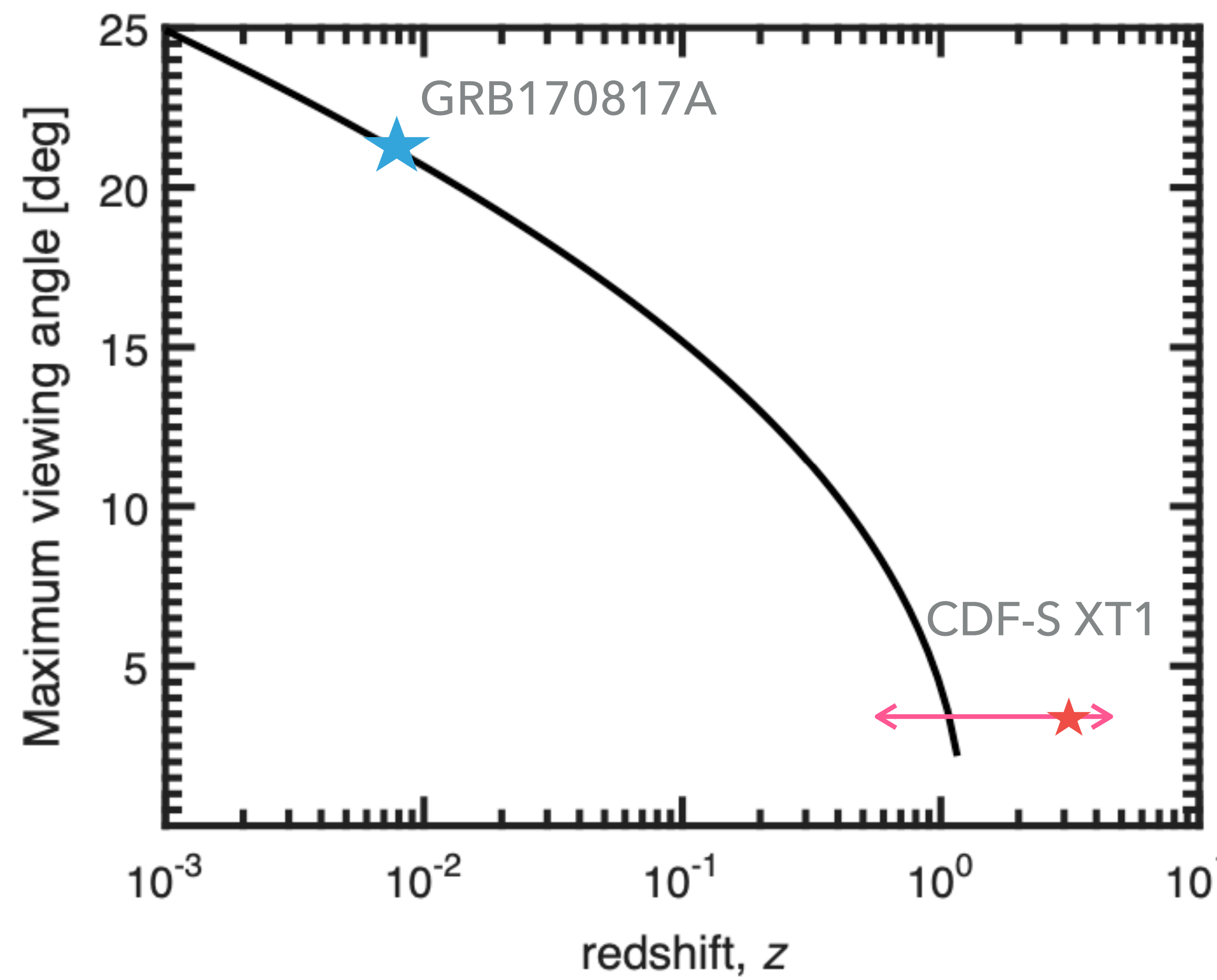
Looks a lot like the off-axis afterglows shown previously…

- GRB170817A was on the cusp of being undetectable as a GRB.
- GRB170817A was only detectable because it was so close! There must be systems where we were too far away or too far off-axis…



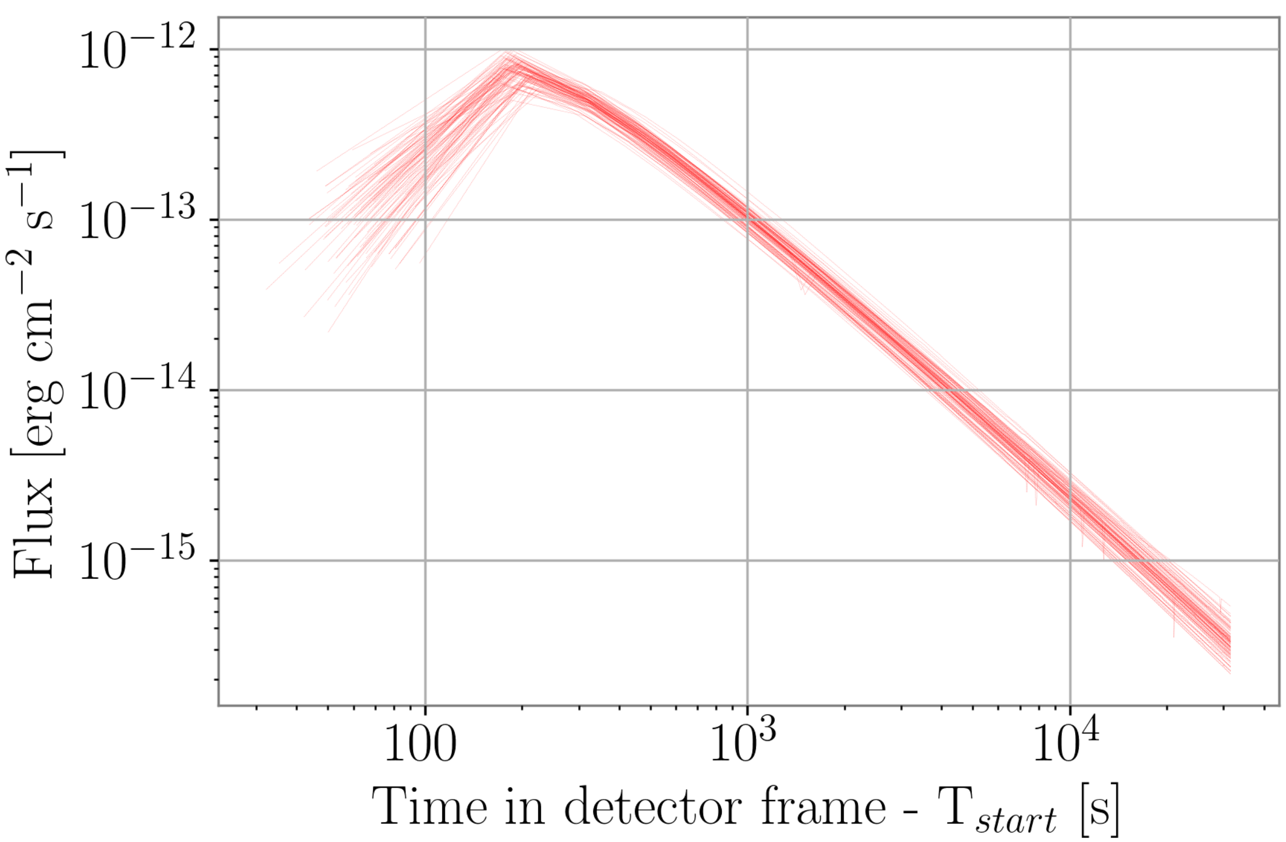
Modified from Howell et al. 2019

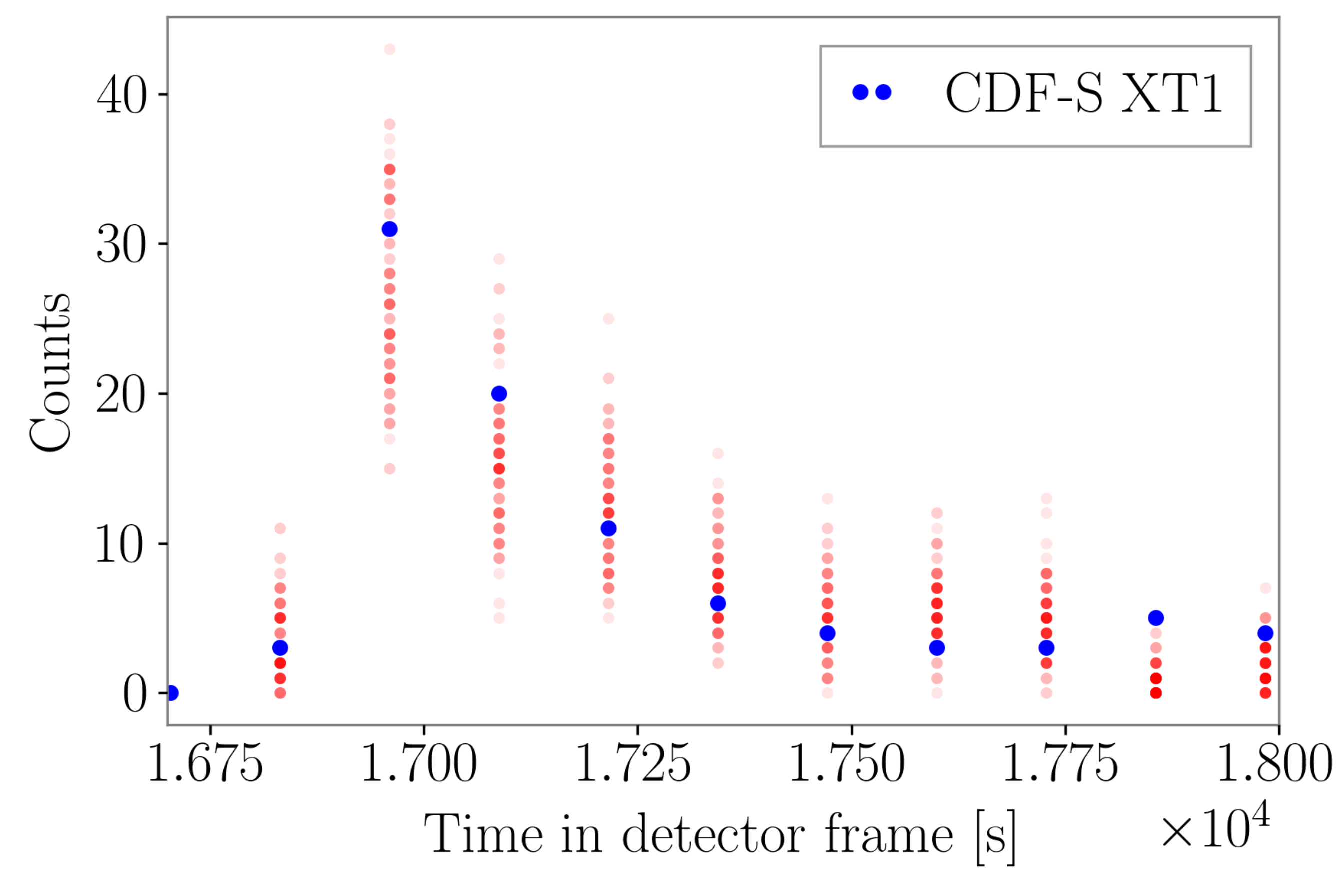
- GRB170817A was on the cusp of being undetectable as a GRB.
- GRB170817A was only detectable because it was so close! There must be systems where we were too far away or too far off-axis…
- We think we found a candidate…



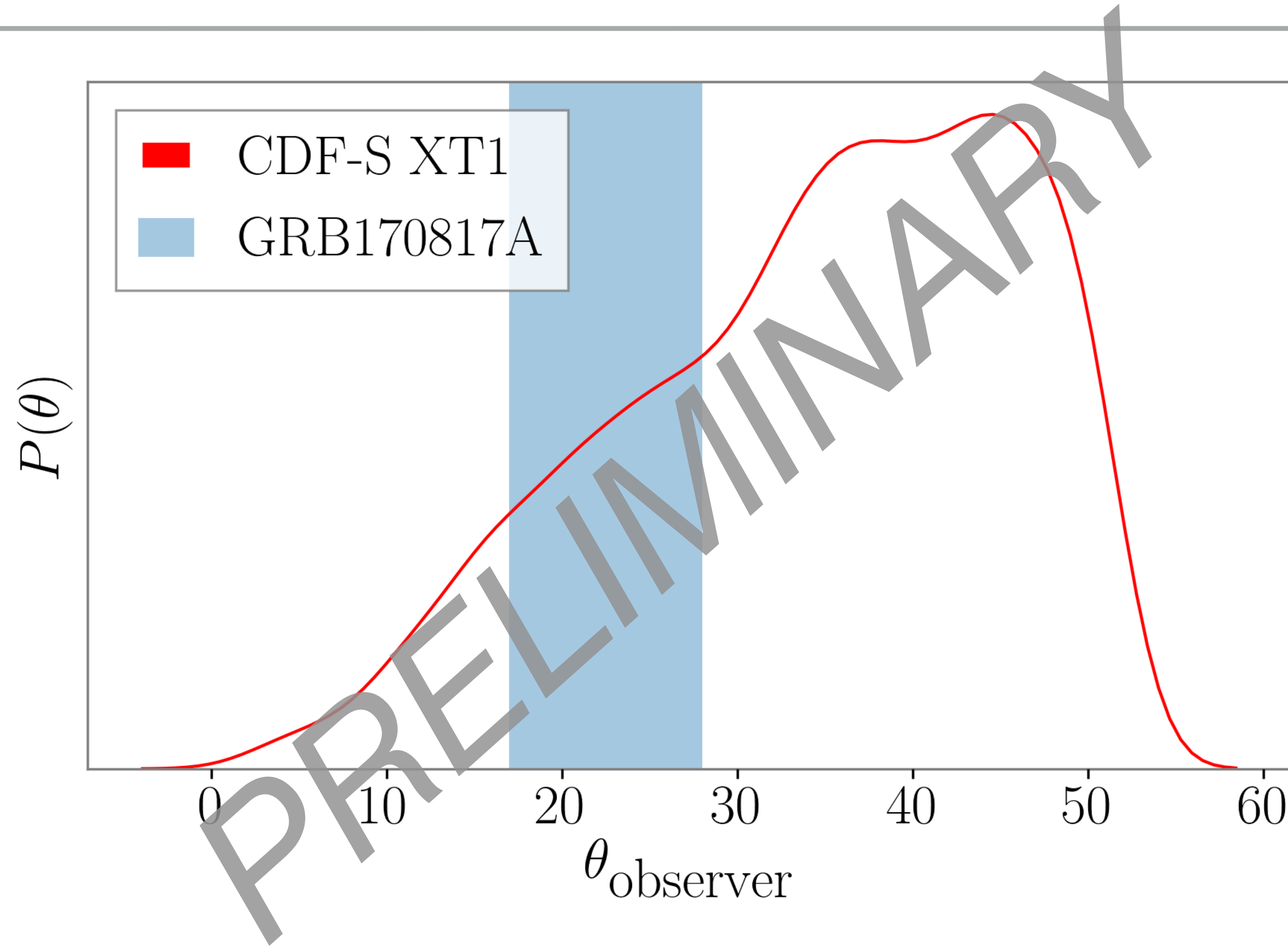
Modified from Howell et al. 2019

- We analyse CDF-S XT1with off-axis afterglow models.
- Structured jet model similar in profile to GRB170817A fits the data!





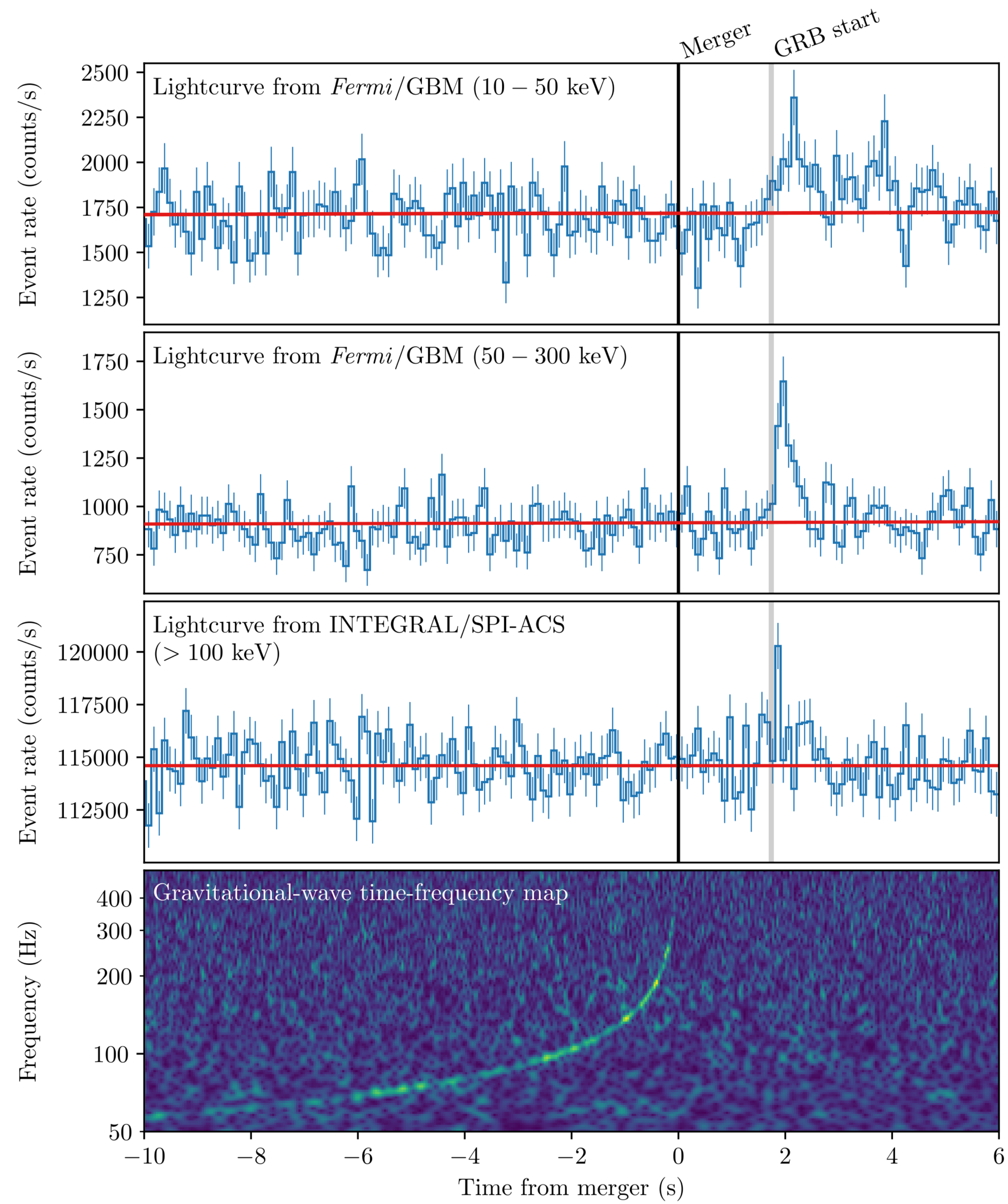
Sarin et al. in prep. Data from Bauer et al. 17

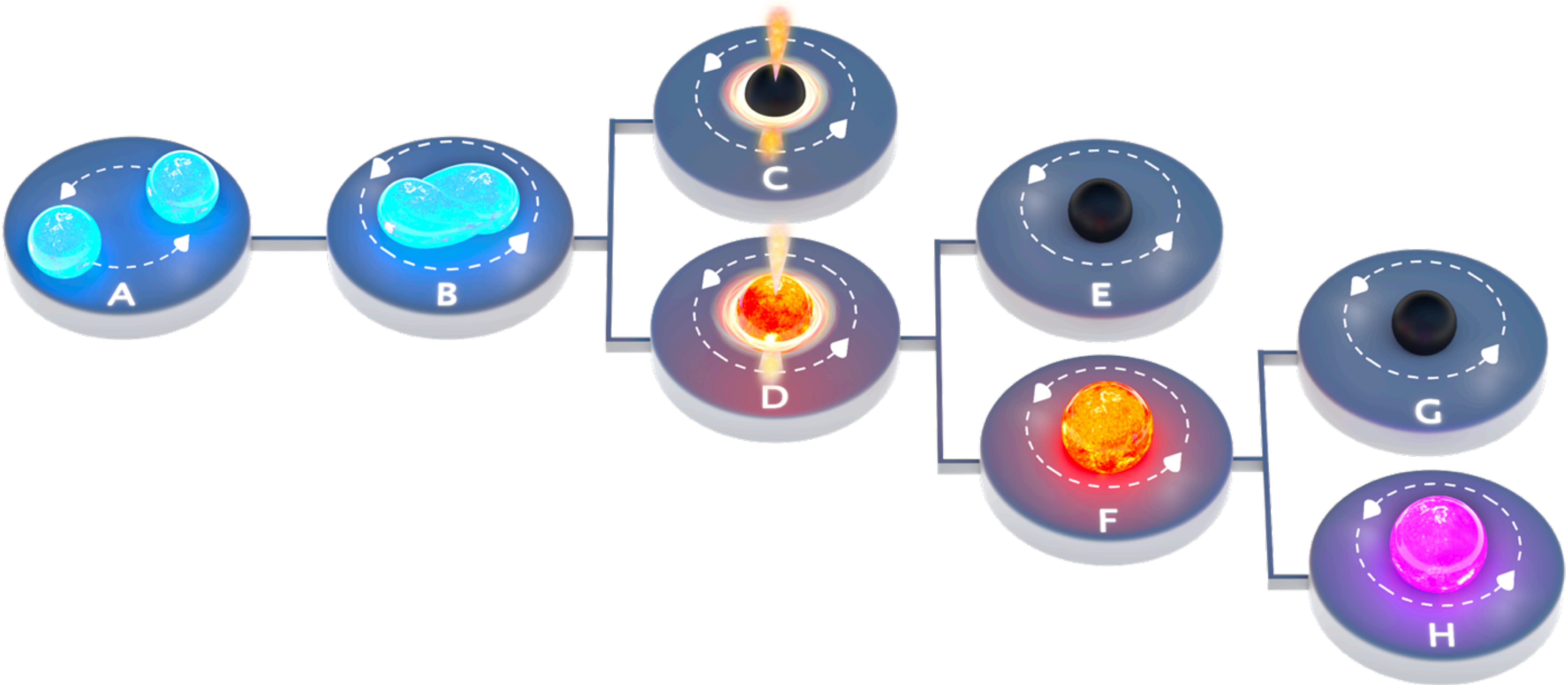


Sarin et al. in prep.

- We infer CDF-S XT1 to be the X-ray afterglow of a structured jet with $\theta_{obs} \sim 36°$.
- This is the first orphan afterglow ever detected in X-rays!
- We think this may be the afterglow of a short gamma-ray burst so perhaps CDF-XT1 is a neutron star merger at a redshift $z \sim 2.23$!

- The first binary neutron star merger observed in gravitational waves and in electromagnetic radiation!
- But what remained behind after the merger?
- Despite the wealth of observations, the fate of the remnant is still uncertain.. See e.g. Ai et al. 2019

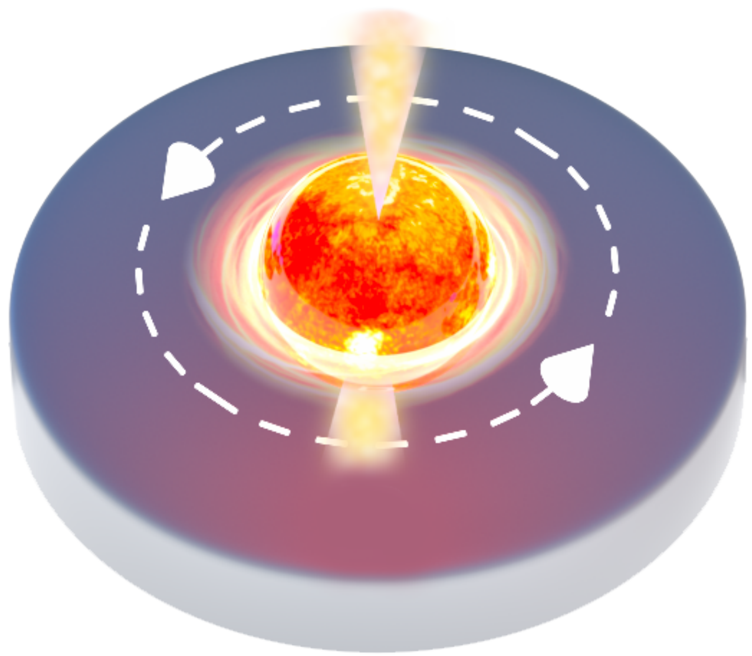


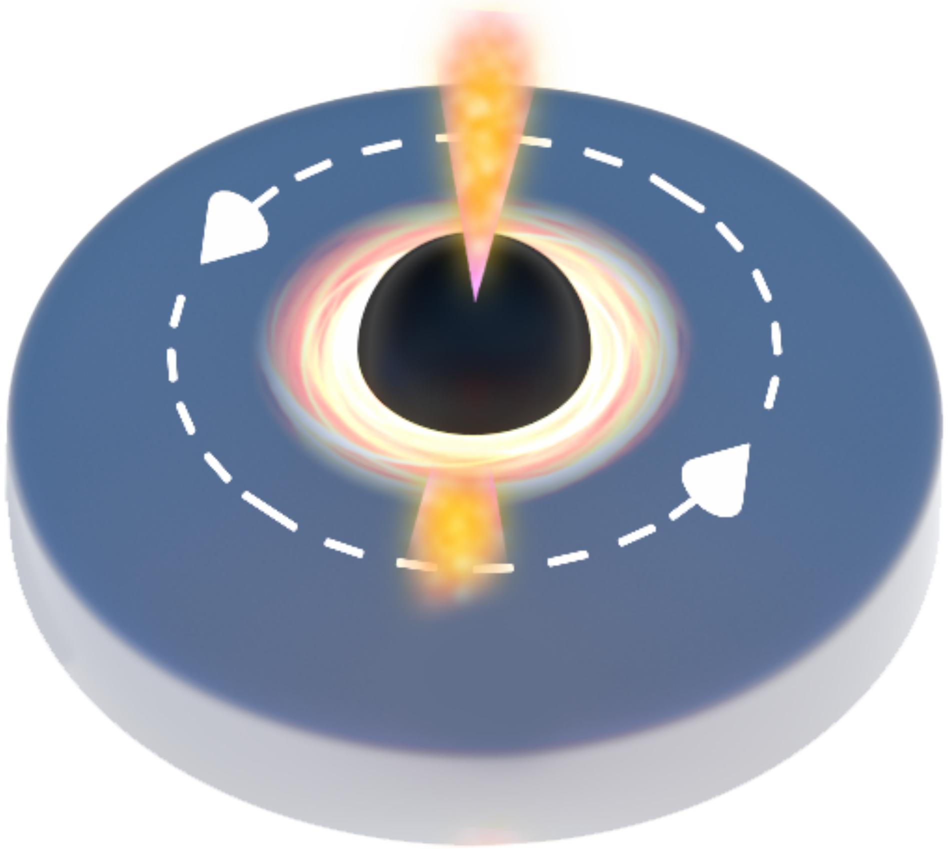


Credit: Carl Knox

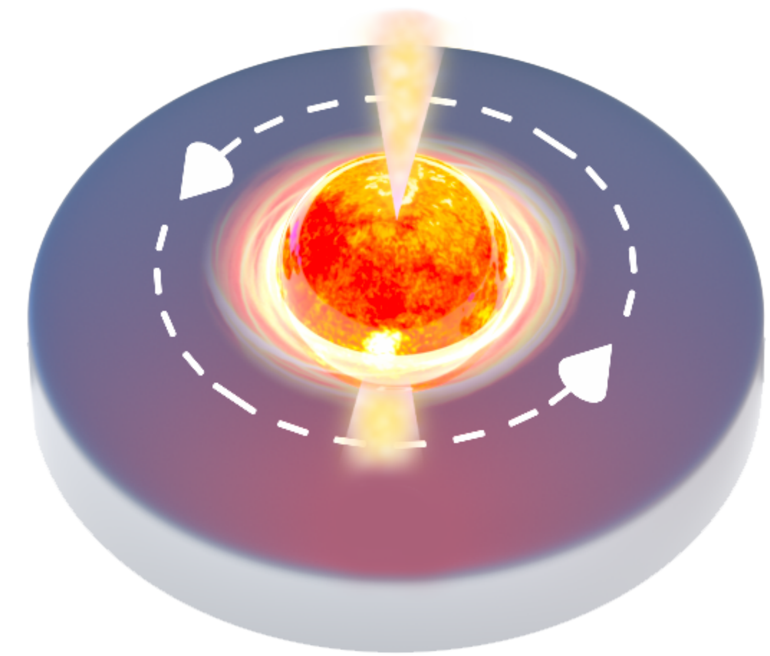
Sarin and Lasky (in prep.)

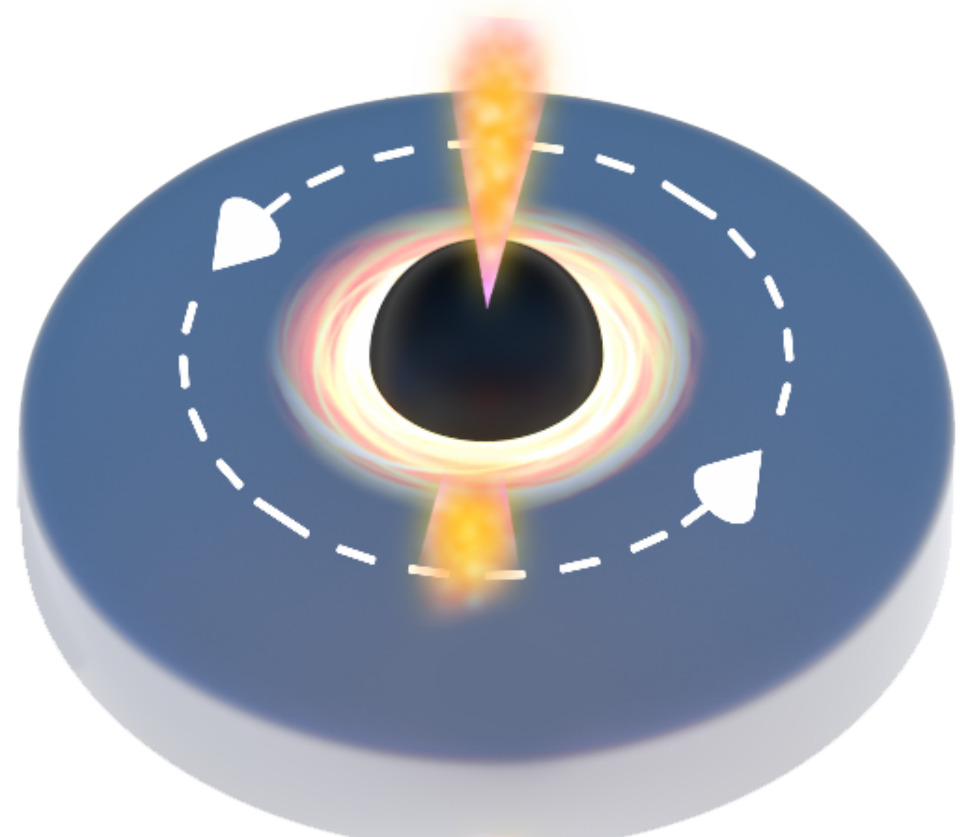
- One of the very first consequences of a neutron star merger is a gamma-ray burst!
- What does this tell you about the remnant?
- Prevailing wisdom - You need a black hole to launch a jet…



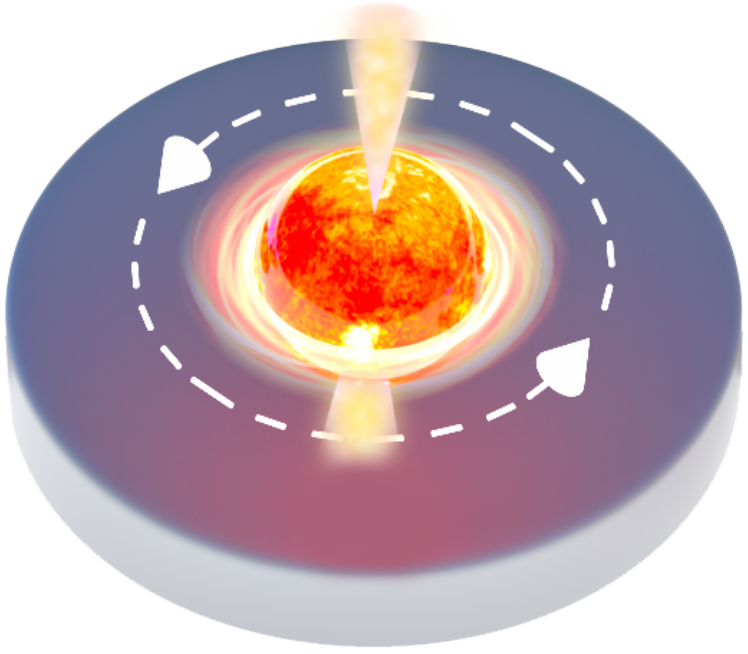


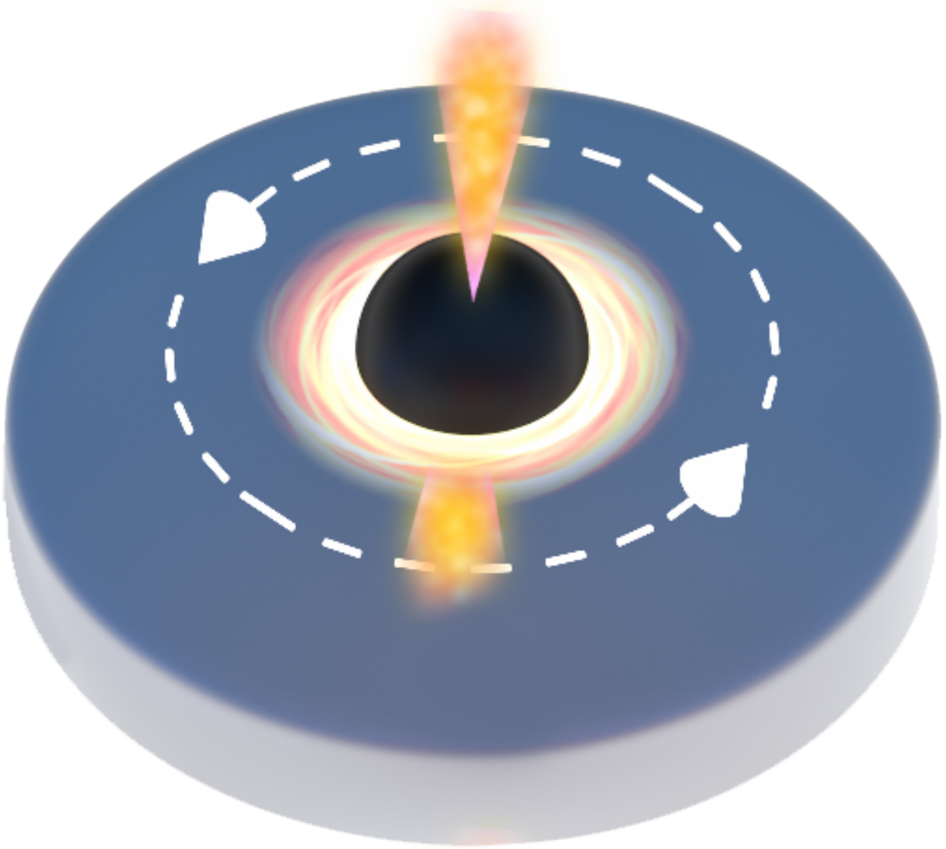
- If a jet requires a black hole central engine then the existence of gamma-ray burst immediately informs the nature of the remnant.
- Either the remnant was a short lived neutron star or it promptly collapsed into a black hole.
- But do you really need a black hole to launch a jet?



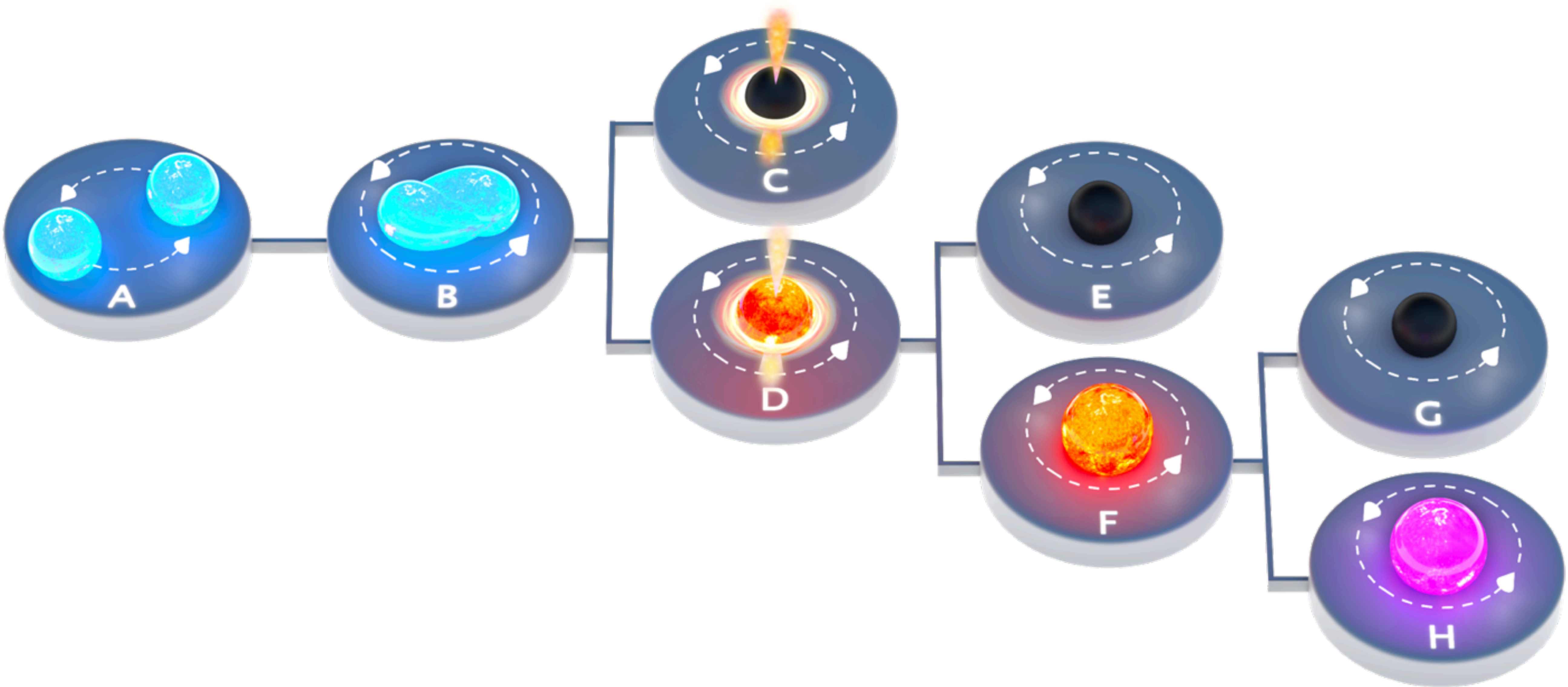


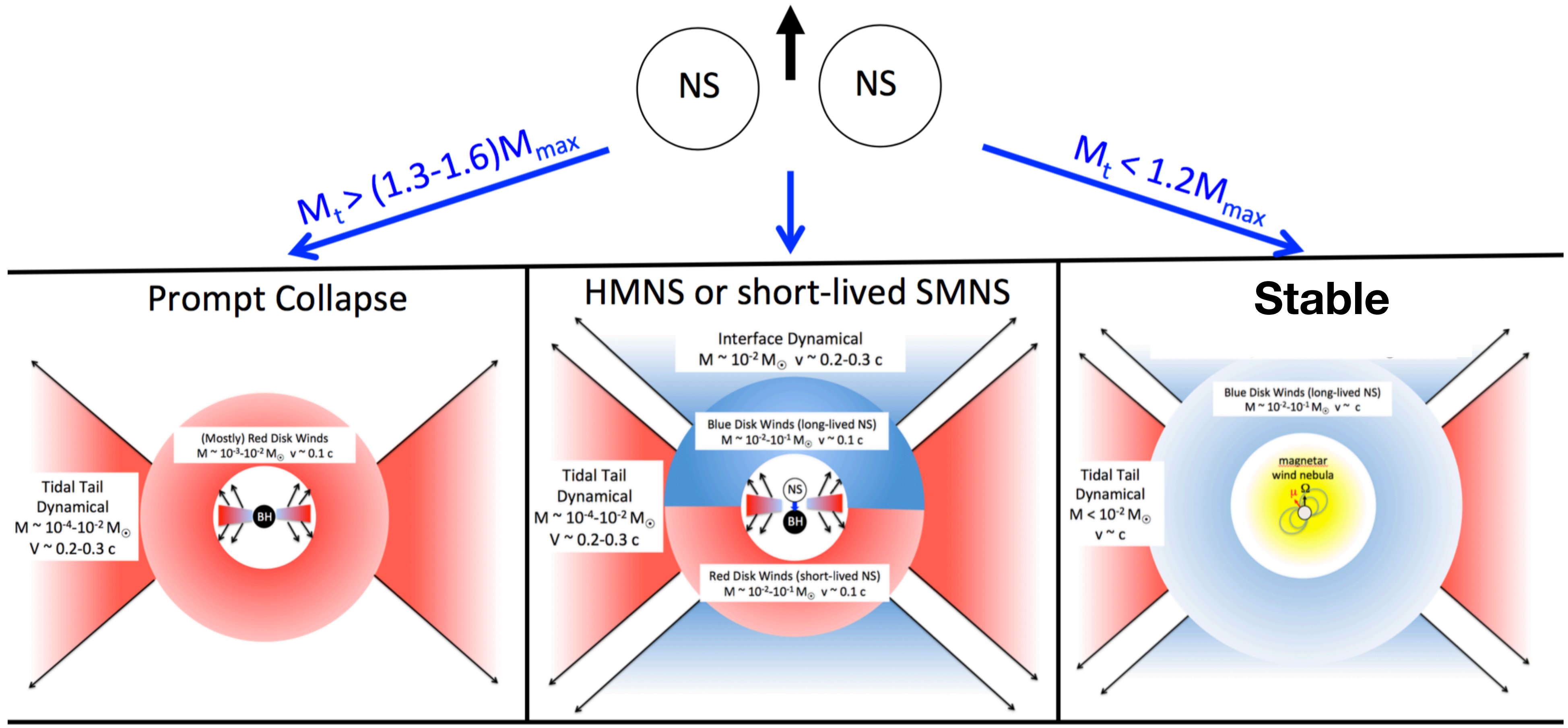
- Alternative viewpoints in e.g. Mösta et al. 2020 and Beniamini et al. 2020 for whether a neutron star can launch a jet.
- The limitations of current numerical simulations? See for e.g., Kiuchi et al. 2015. Ciolfi 2020.
- Effect of neutrinos? Magneto-rotational instabilities?





- Mösta et al. 2020 show that a neutron star central engine can indeed produce a successful short gamma-ray burst!

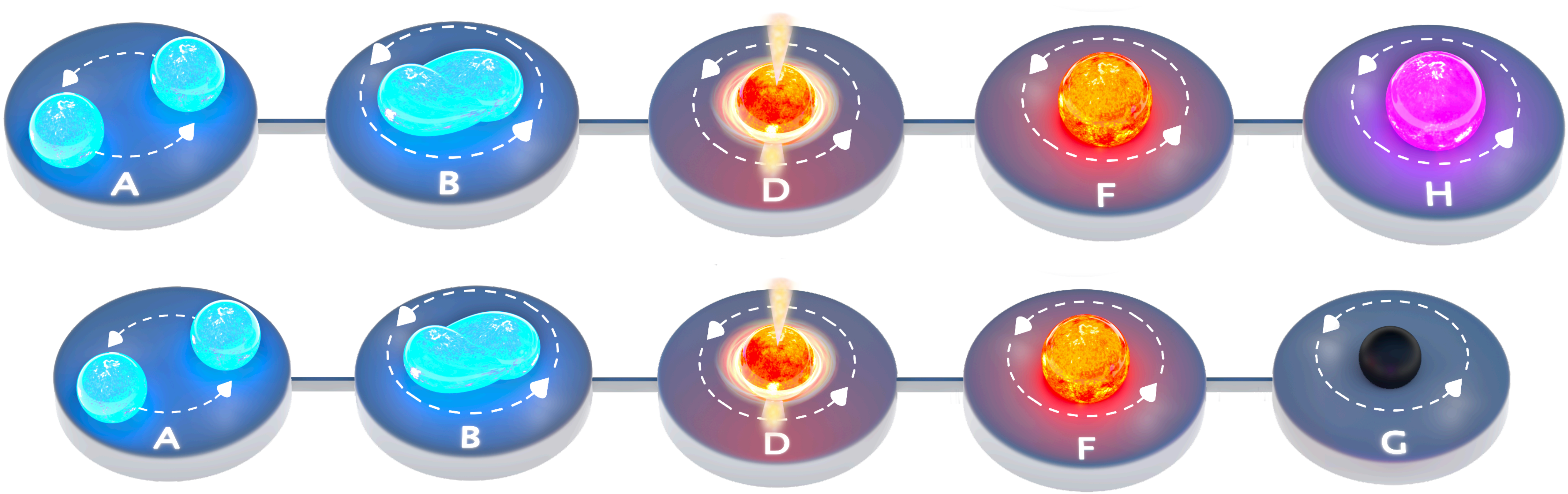




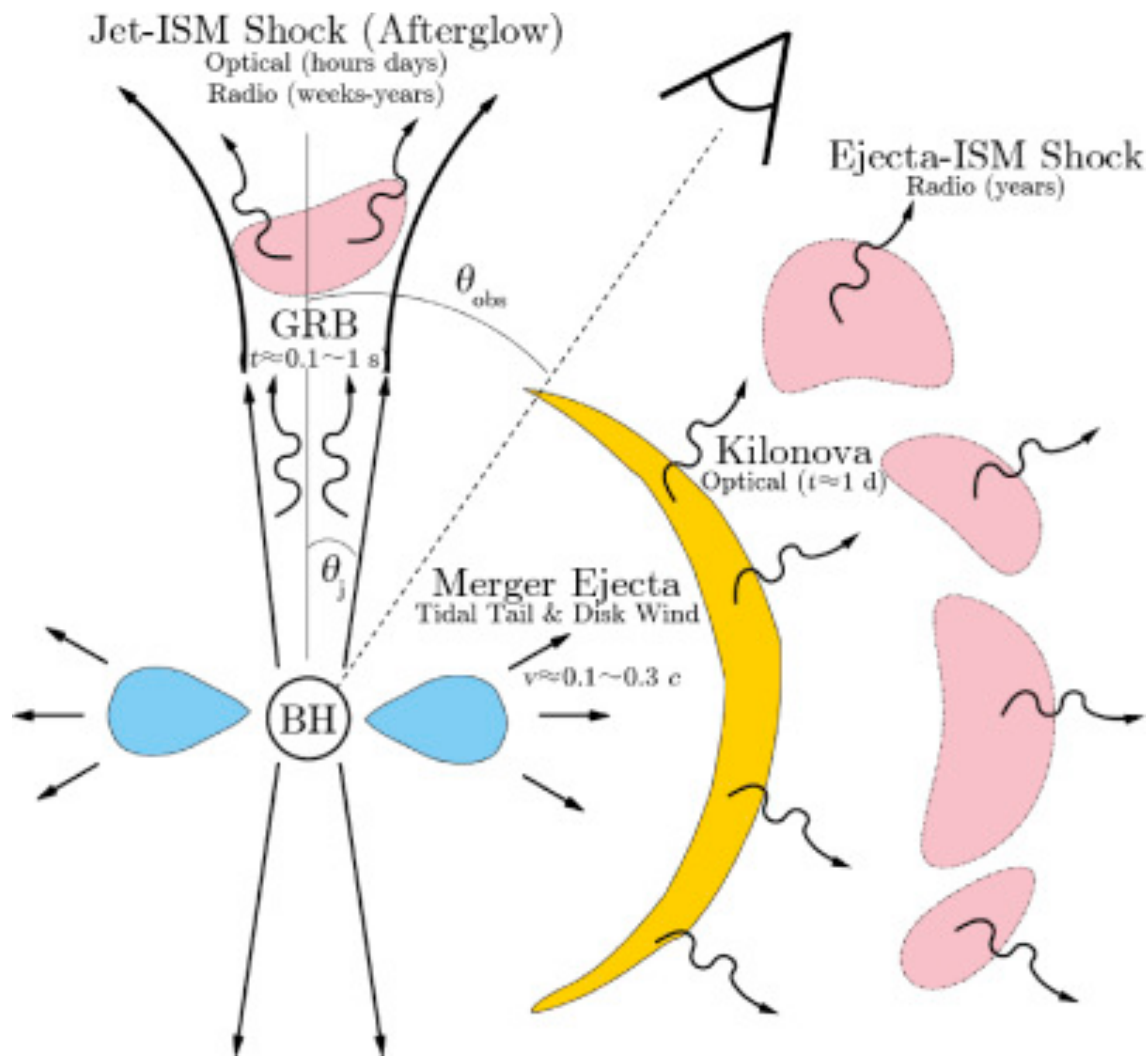
Schematic from Margalit and Metzger (2017)

- In general, the presence of a neutron star will make the kilonova more `blue'. This is a consequence of the neutrinos emitted from the neutron star.
- Currently, kilonova models are not robust enough to determine the nature of the remnant see e.g., contrary views in Yu et al. 2018 and Metzger et al. 2018 for GW170817.
- This is an active area of development and may soon become a viable way of inferring the nature of the remnant!

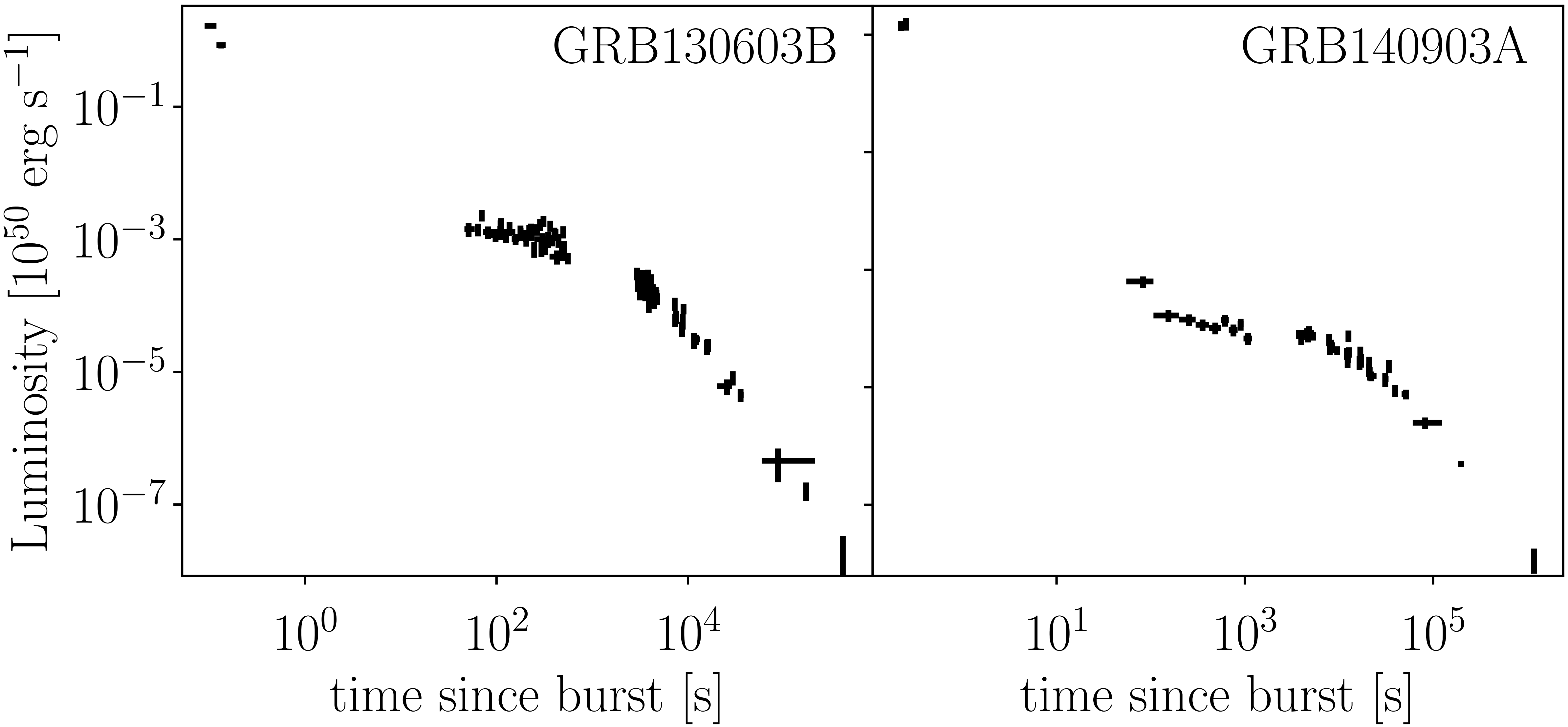
- For the rest of the talk, I will focus on long-lived neutron stars.
- How do you make a long-lived neutron star?
  - Neutron star post-merger remnant born with mass less than the $M_{\rm TOV}$ - will produce an ***infinitely stable*** remnant (H).
  - Post-merger remnant born with mass between $1 -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



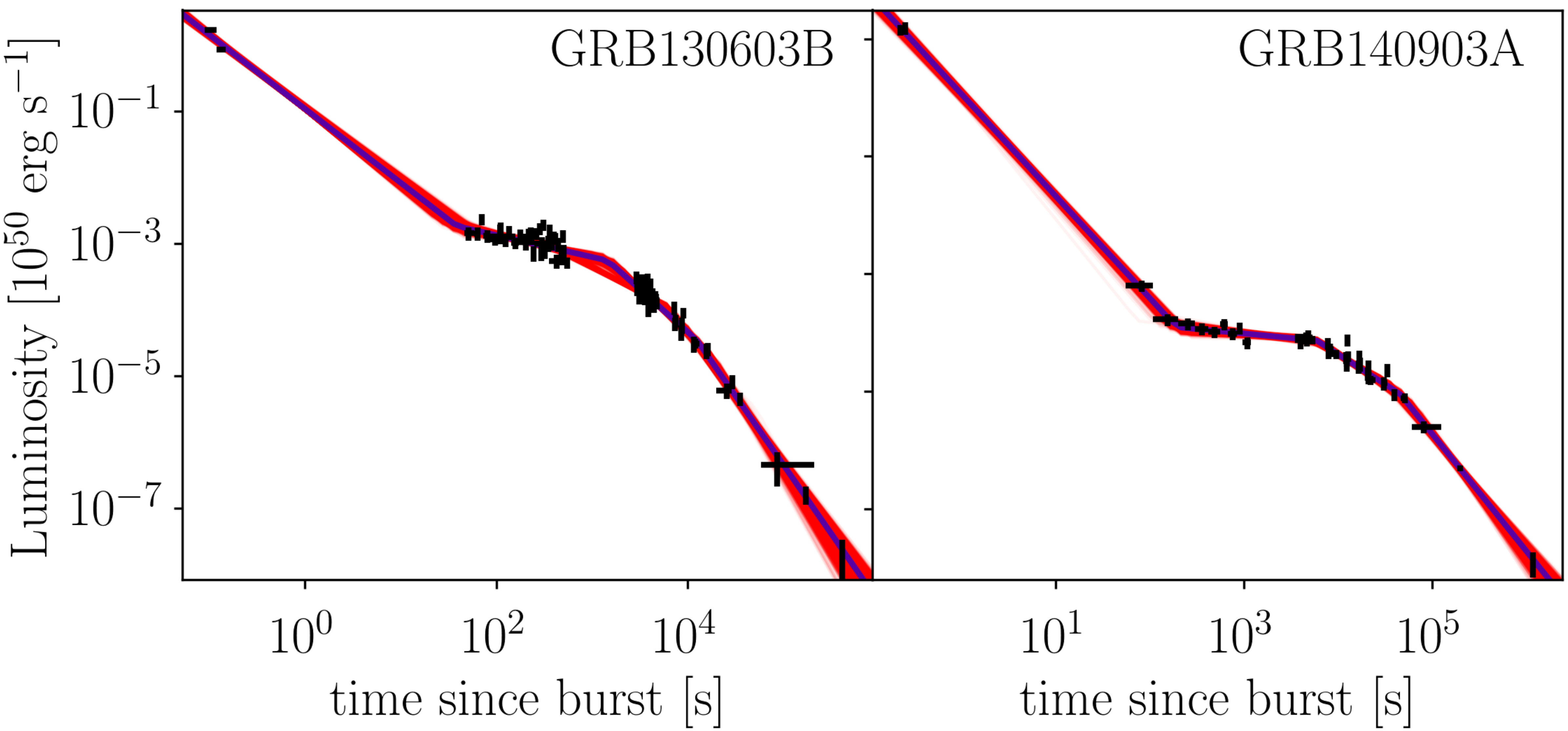
- Gamma-ray bursts often have an extended x-ray, optical, radio emission referred as an afterglow.
- Origin of the X-ray afterglow is unclear
  - External shock from a relativistic fireball.
  - Long-lived neutron star?
  - Both?



Schematic from Metzger and Berger (2012)

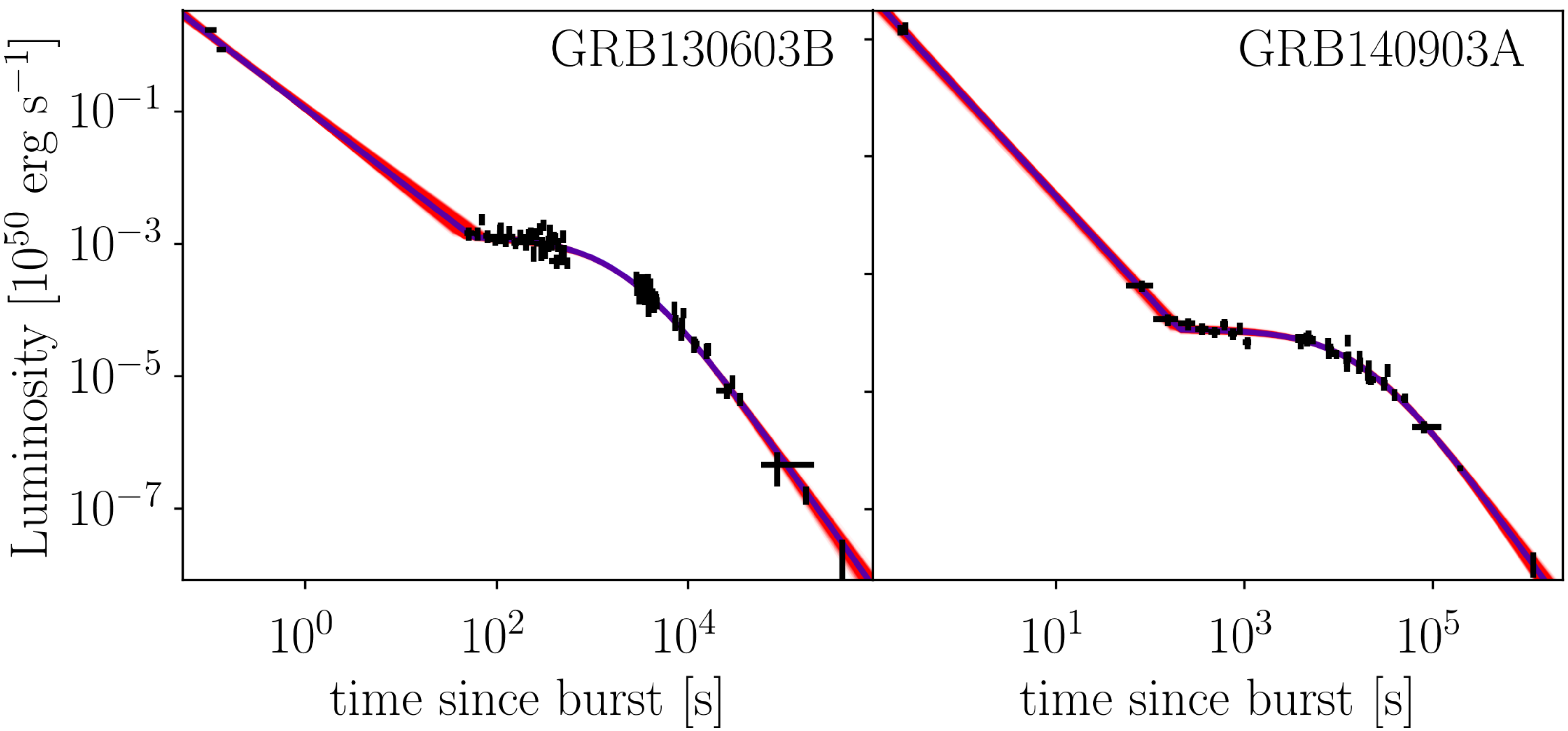

GRB130603B
GRB140903A
Luminosity [10^{50} erg s^{-1}]
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{0}
10^{2}
10^{4}
10^{1}
10^{3}
10^{5}
time since burst [s]
time since burst [s]

Fireball

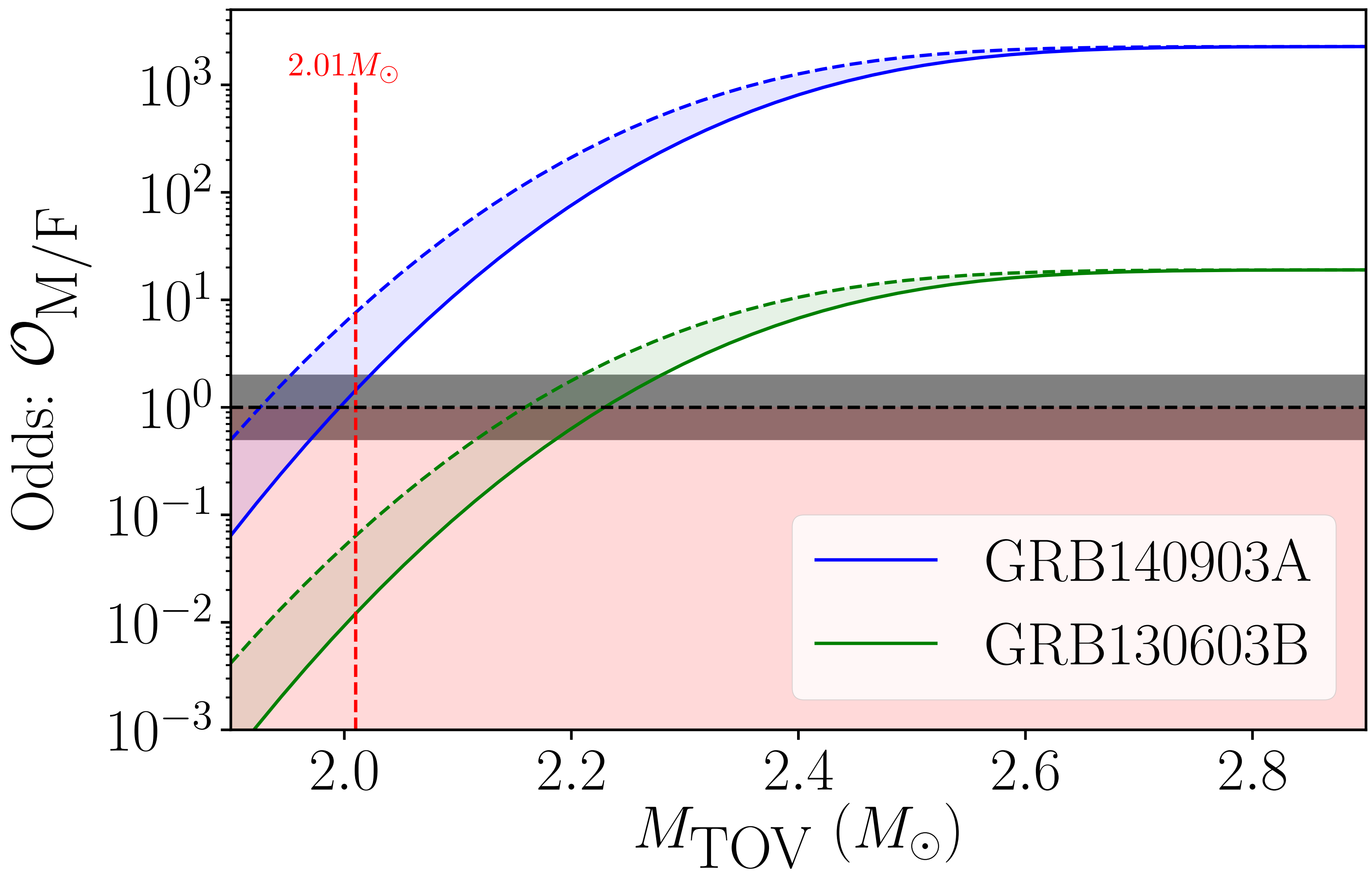


$$L = A_1 t^{\alpha_1} + A_2 t^{\alpha_2} + ... + A_n t^{\alpha_n}$$

Long-lived neutron star



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



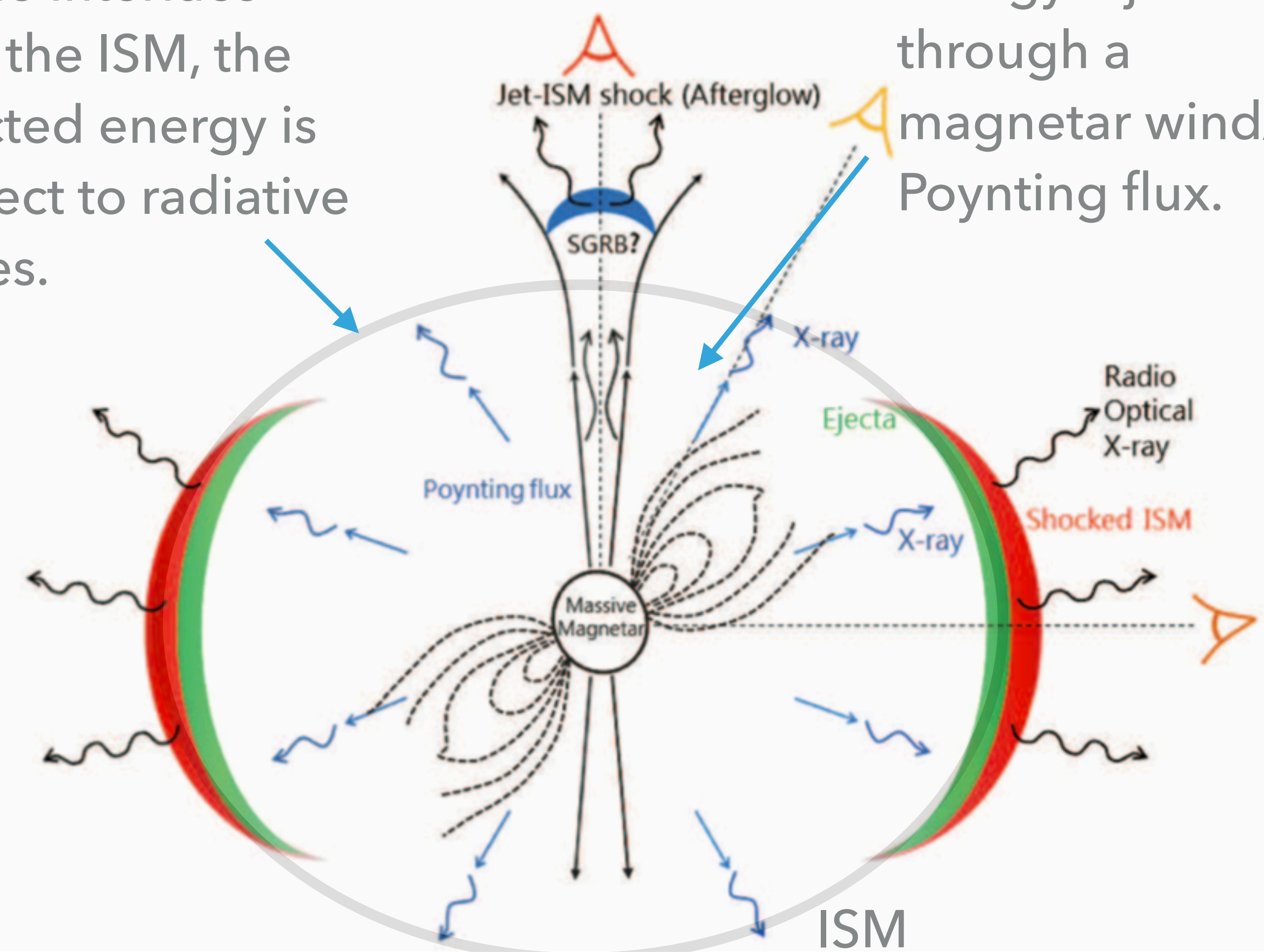
Sarin et al. (2019)

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

- The magnetar model commonly used in the literature is missing critical physics..
- More physical models out there, such as the Plerion model (Strang and Melatos 2019)
- In Sarin et al. (in prep.) we extend the magnetar model to include the effect of radiative losses at the jet-ISM shock interface.

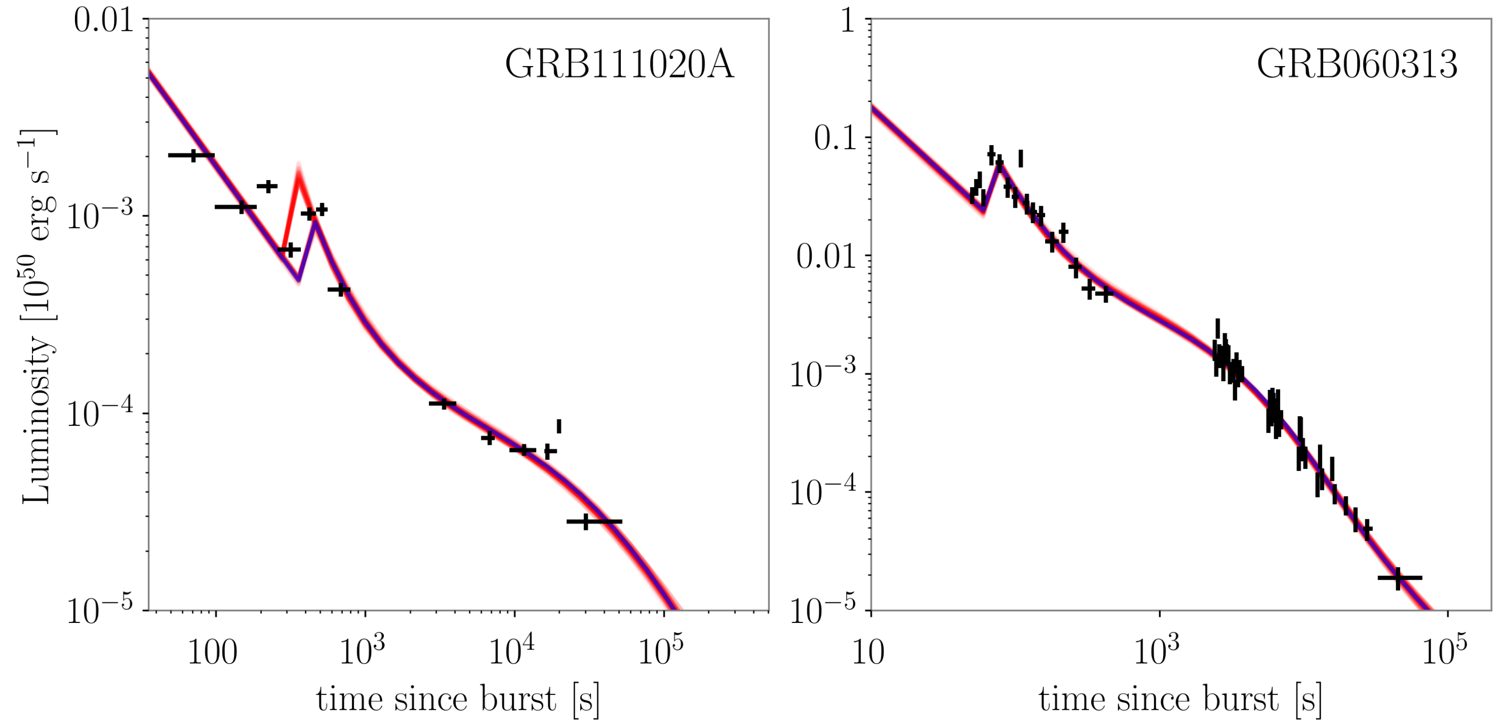
At the interface with the ISM, the injected energy is subject to radiative losses.

Energy injection through a magnetar wind/ Poynting flux.



Modified from Gao et al. (2013)

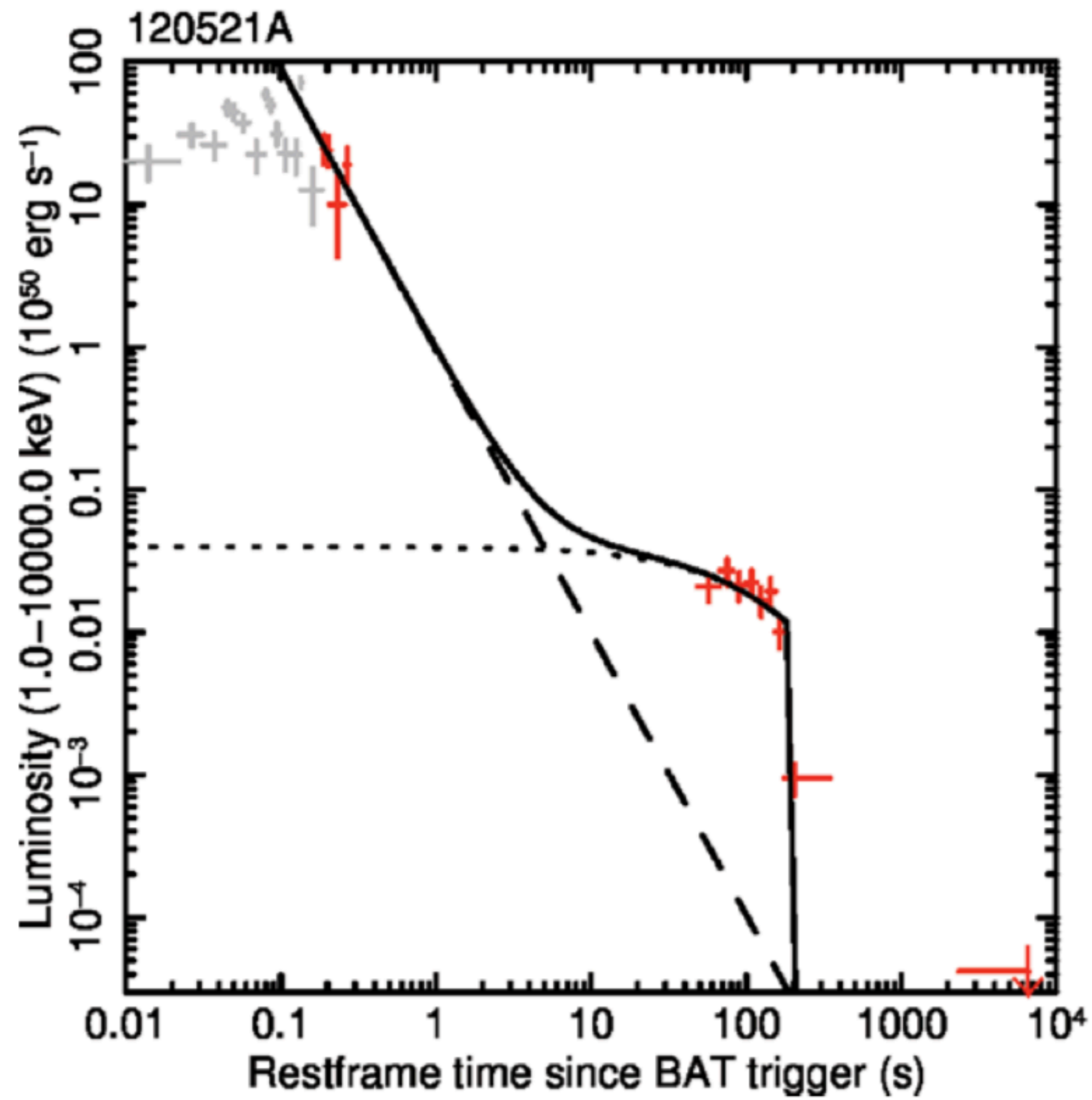
- This new model can naturally explain a subset of X-ray flares seen in gamma-ray burst afterglows
- Furthermore, the new model is a better fit to the data than fireball shock and the magnetar model introduced previously!



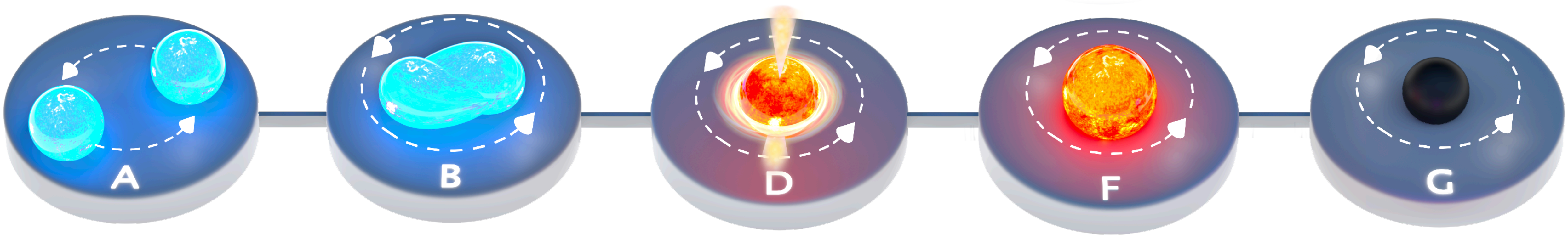
GRB	$\ln BF_{\mathcal{M}_{\text{rad-loss}}/\mathcal{M}_{\text{mag}}}$
GRB050319	3.1
GRB051221A	160.2
GRB060313	183.7
GRB060729	141.2
GRB061121	241.2
GRB070809	0.3
GRB080430	51.4
GRB111020A	93.9

Sarin et al. (in prep.)

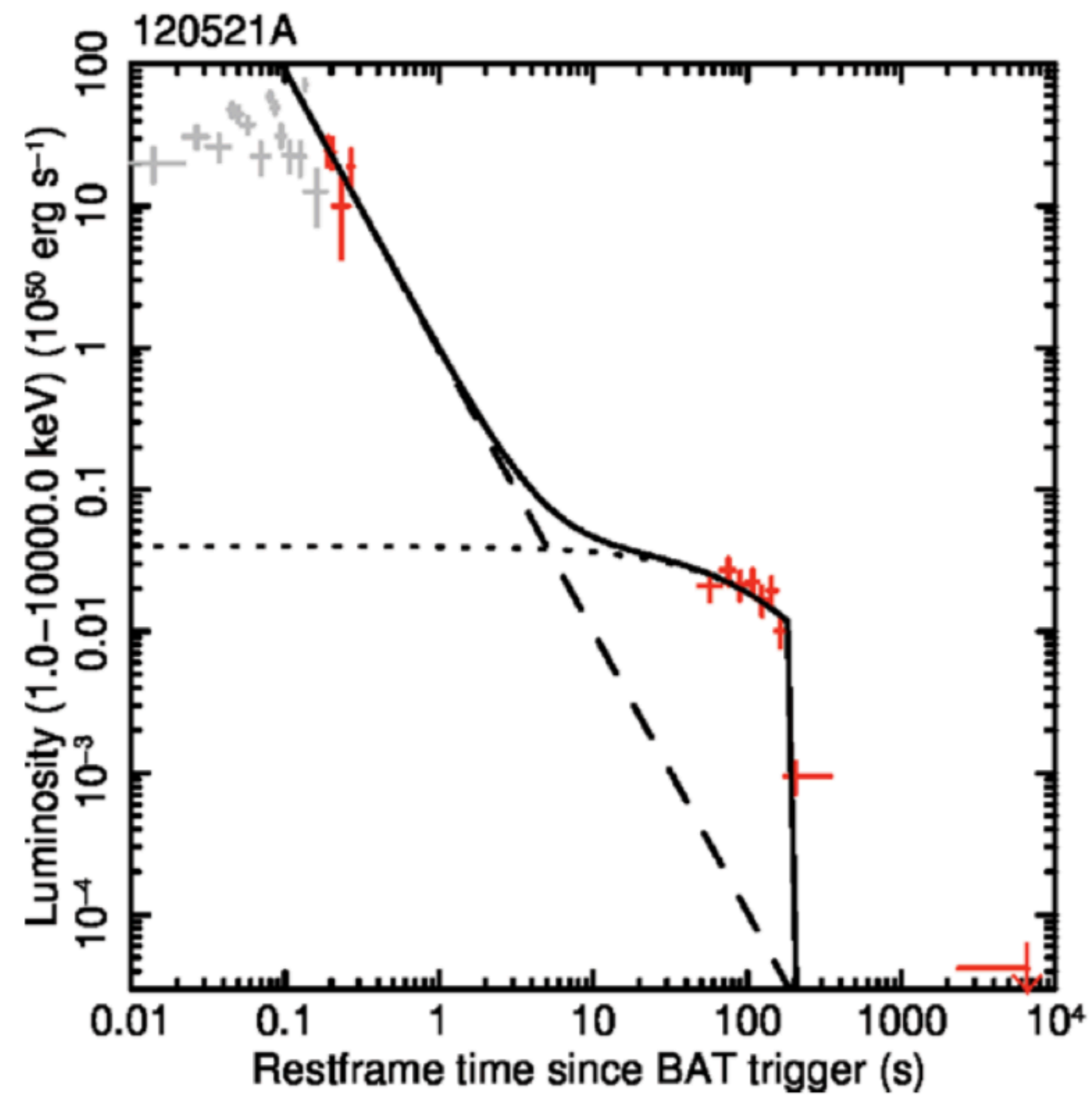
- GRB130603B and GRB140903A X-ray observations require systematic model selection.
- A smaller subset of GRBs have more telltale observations.



Rowlinson et al. (2013)

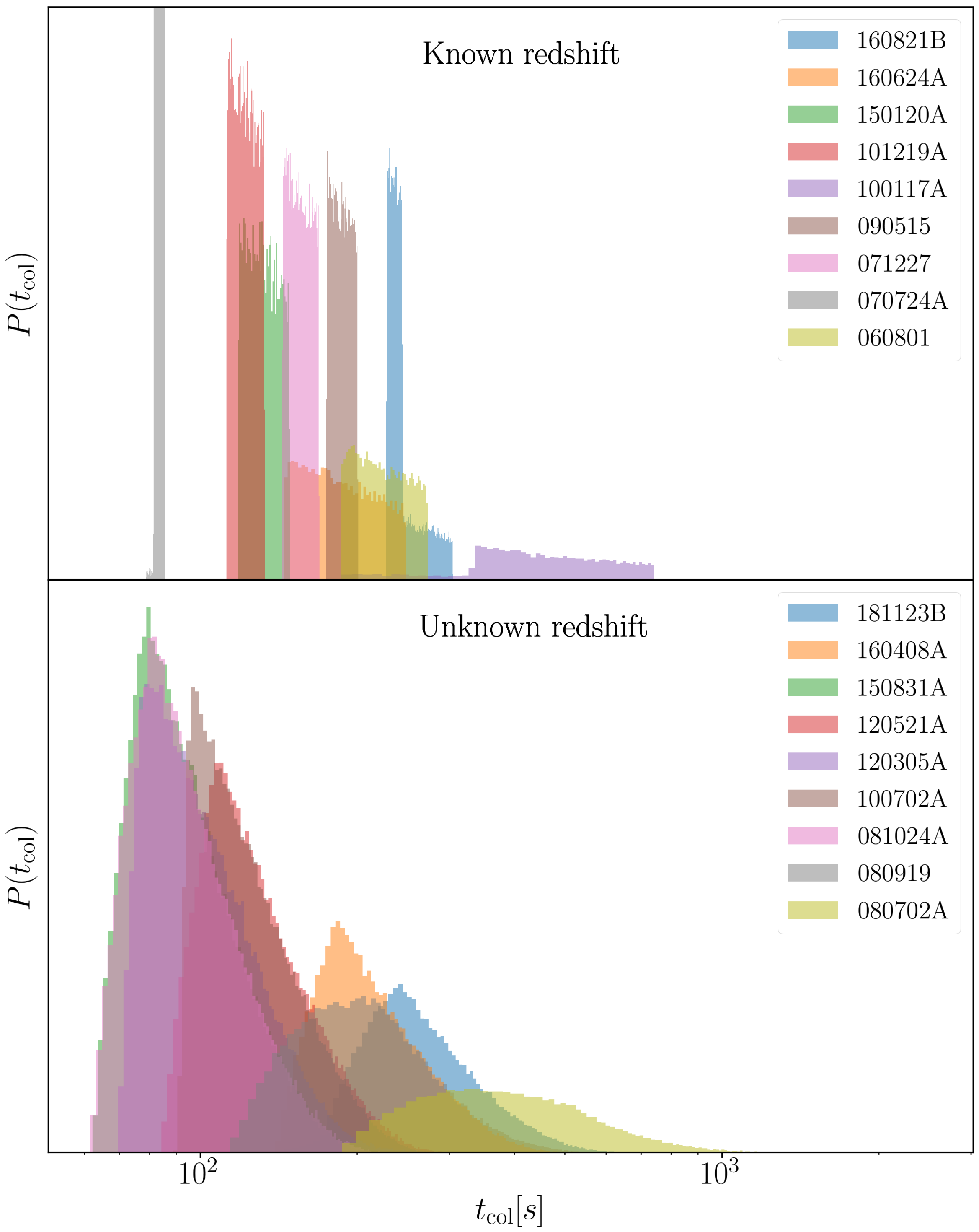


- Collapse of long-lived neutron star
- $M_{\rm tot} \gtrsim 1 - 1.2 \times M_{\rm TOV}$
- Initially supported against collapse due to rigid-body rotation.
- Spin-down and collapse.



Rowlinson et al. (2013)

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



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

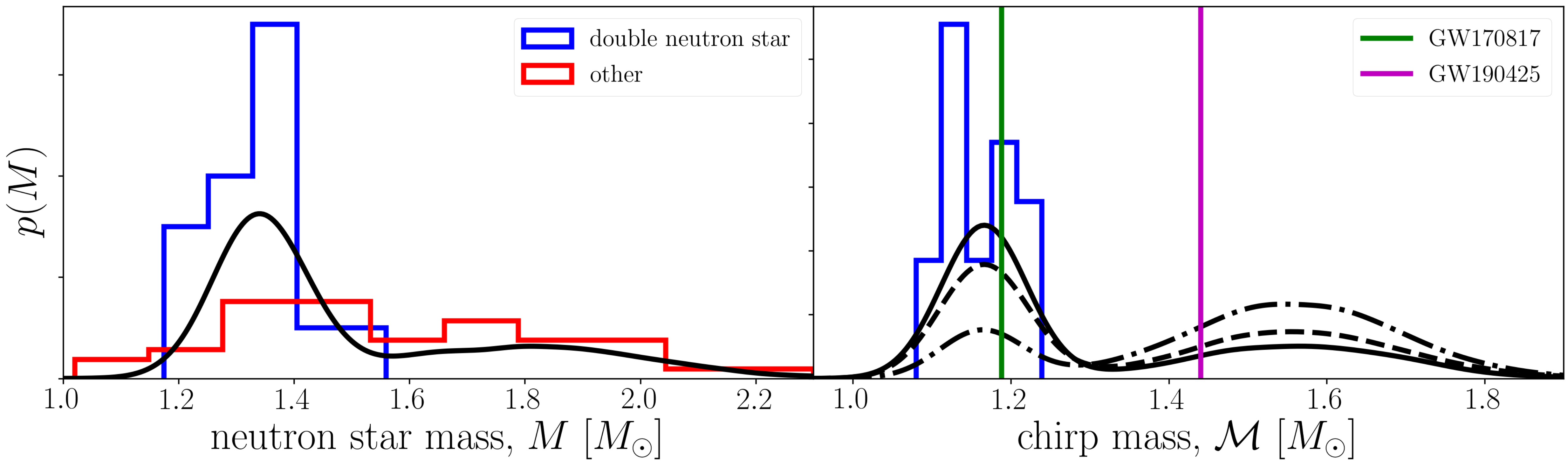
$$t_{\mathrm{col,i}} = \frac{\tau_i}{p_{0,i}^{\gamma_i}} \left[\left(\frac{M_{p,i} - M_{\mathrm{TOV}}}{\alpha M_{\mathrm{TOV}}} \right)^{\frac{\gamma_i}{\beta}} - p_{0,i}^{\gamma_i} \right].$$

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

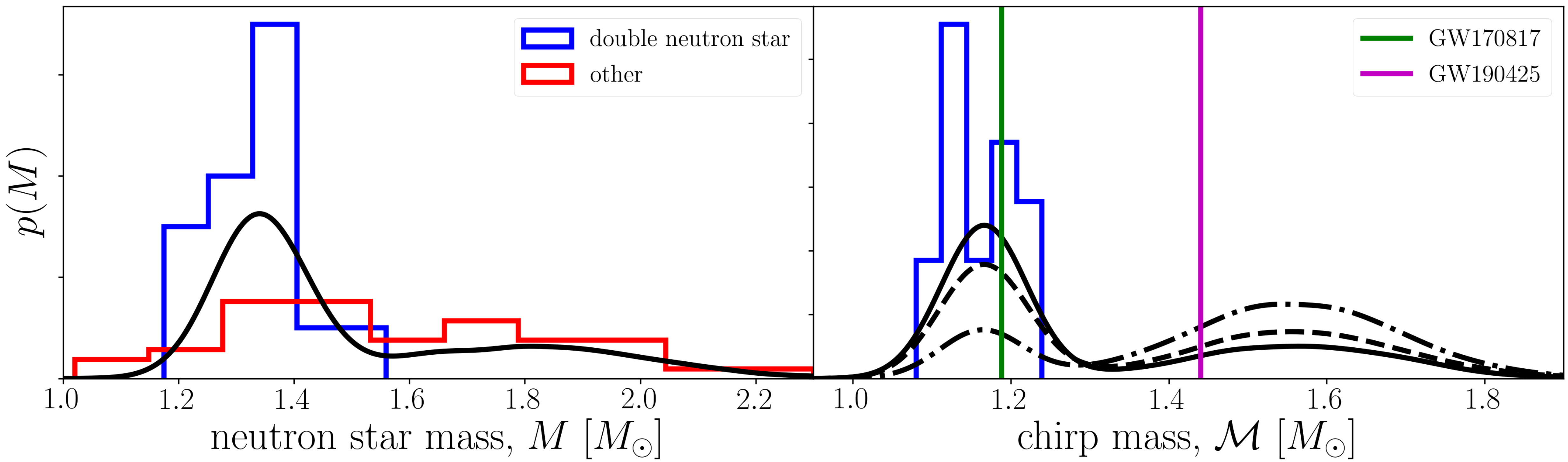
$$M_{\mathrm{max}} = M_{\mathrm{TOV}} \left(1 + \alpha p^{\beta}\right)$$

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

- We do not measure the mass and initial spin of the neutron star born in these short gamma-ray bursts.
- For the initial spin, we can use angular momentum conservation and the breakup frequency to set a reasonable prior. i.e uniform between 0.5-1ms.
- For the mass…



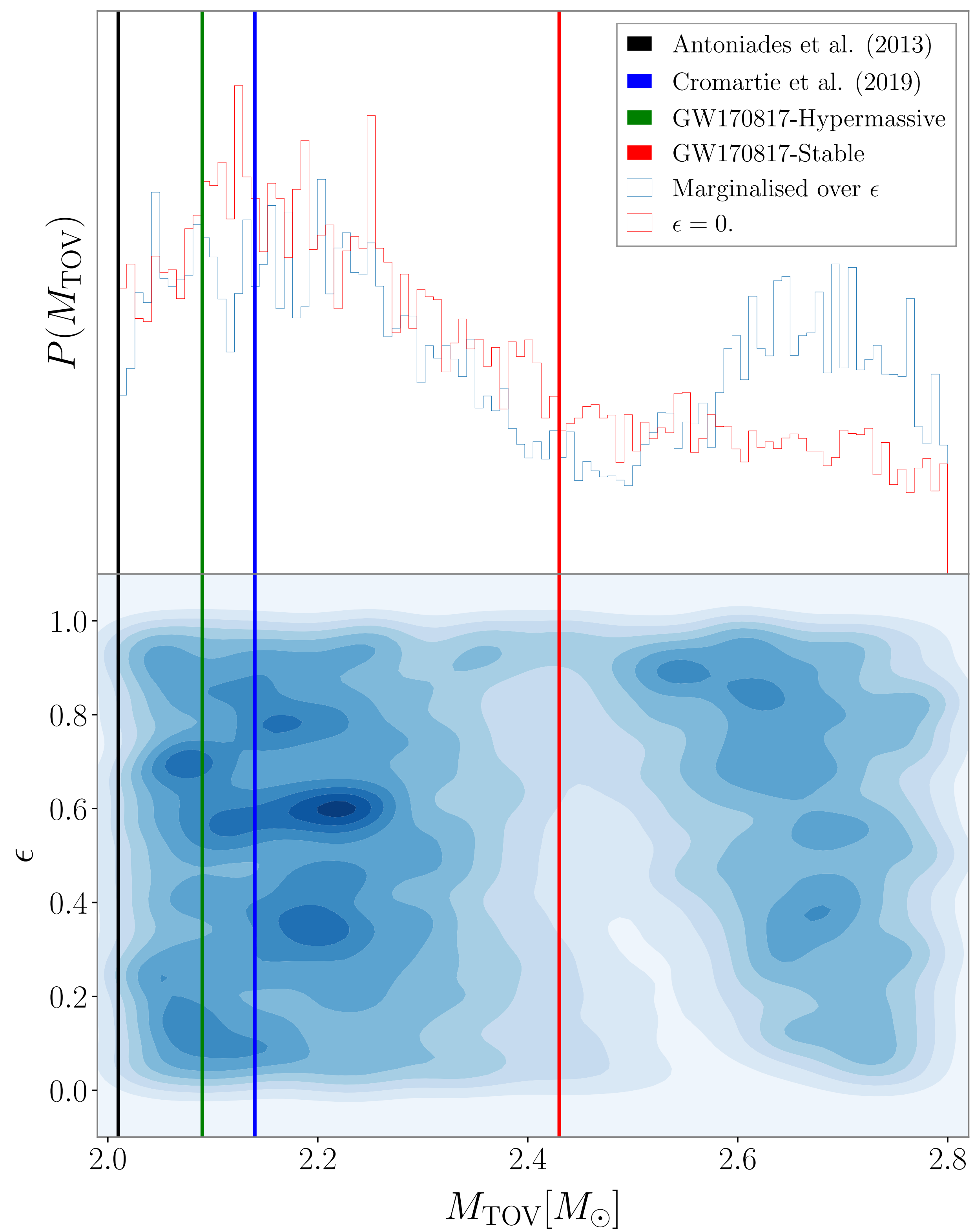
- Observations of GW190425 suggests the local distribution of binary neutron stars observed in radio is a poor representation of the binary neutron star mergers (Abbott et al. 2020)
- Or… GW190425 has progenitors including the lowest mass black hole ever observed (see Han et al. 2020)
- So what is a reasonable prior for the masses?

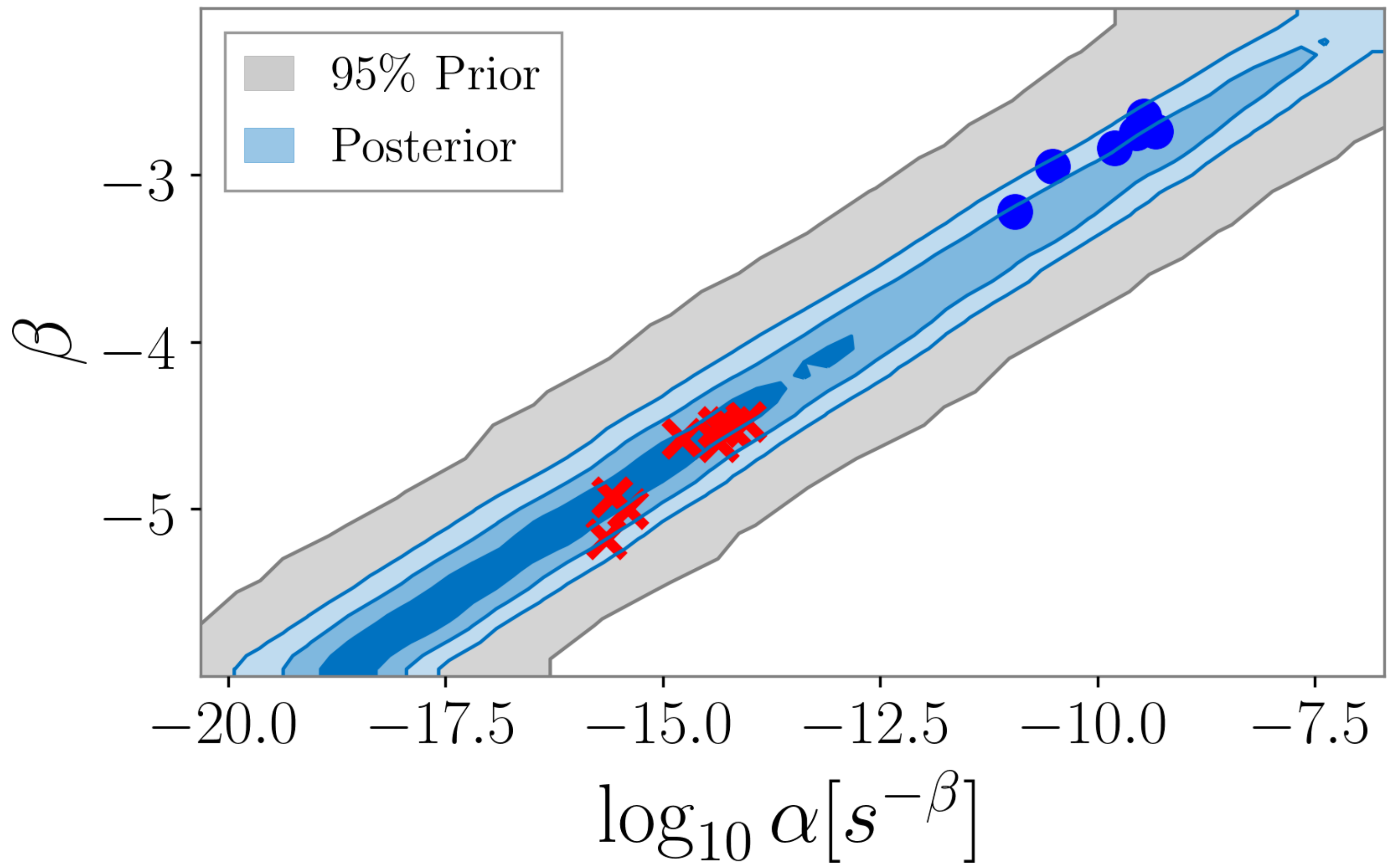


$$p(M) = (1-\epsilon)\,\mathcal{N}\left(\mu_1,\, \sigma_1\right) + \epsilon\mathcal{N}\left(\mu_2,\, \sigma_2\right)$$

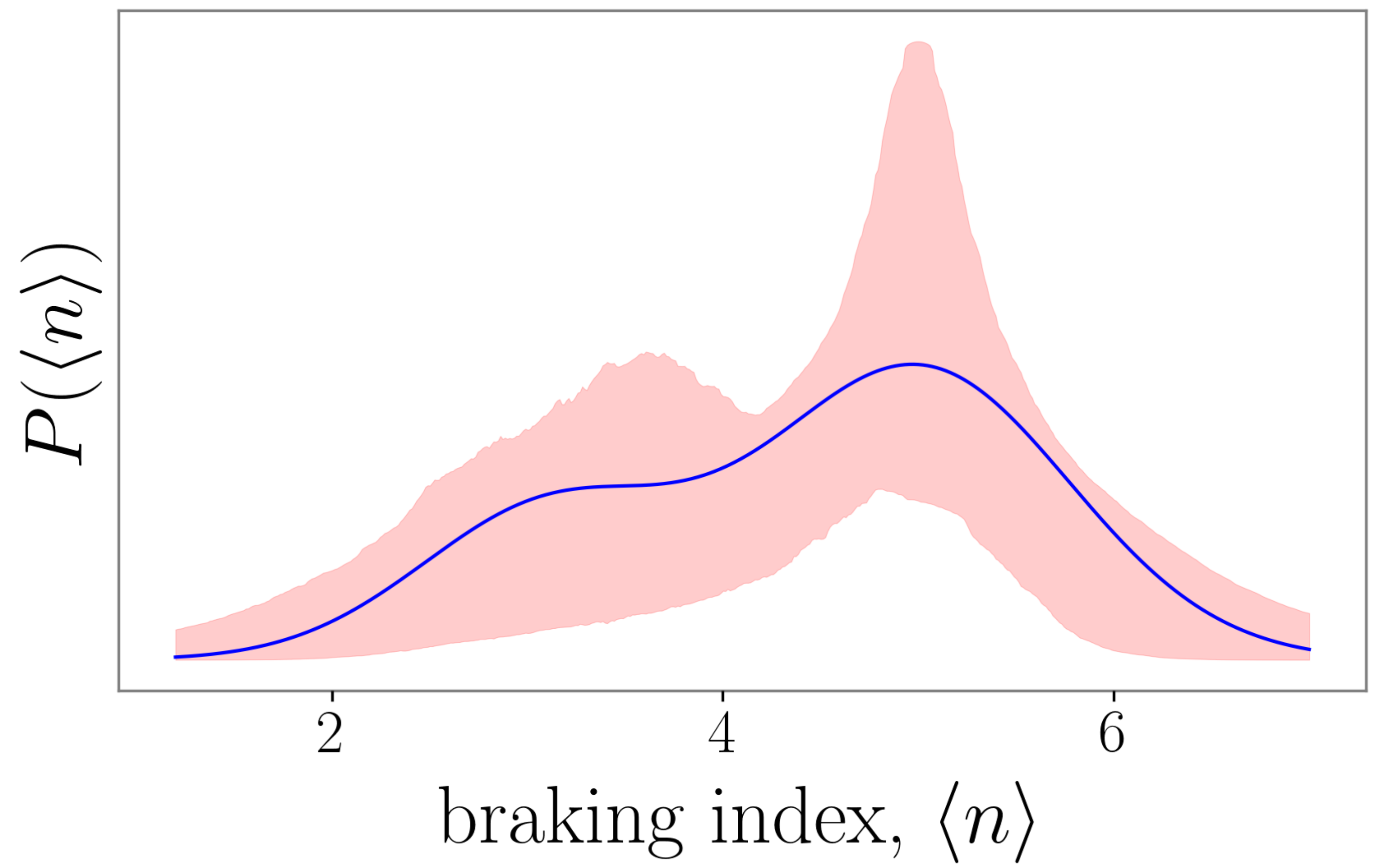
$$\mu_1 = 1.32 M_\odot, \sigma_1 = 0.11 M_\odot, \mu_2 = 1.8 M_\odot, \sigma_2 = 0.21 M_\odot$$

- We measure $M_{\mathrm{TOV}} = 2.31^{+0.36}_{-0.21} M_{\odot}$ marginalised over all values of ϵ.
- If instead, GW190425 is not a binary neutron star merger. Then we measure $M_{\mathrm{TOV}} = 2.26^{+0.31}_{-0.17} M_{\odot}$
- With future gravitational-wave observations we will be able to measure ϵ and get a tighter constraint on M_{TOV}.
- This implies that a significant fraction of future neutron star mergers will also produce long-lived neutron stars!





- In theory, this method can be used to determine the equation of state.
- In practice, the population is not yet informative…
- Some indications that these post-merger remnants are quark stars, at the one-sigma level.
- This may point towards a temperature dependent phase transition from hadronic to deconfined quarks!



- A significant fraction of these objects spin-down predominantly through gravitational-wave emission. While the rest also indicate potentially some spin-down early in their lifetime through gravitational-wave emission.
- This will produce a stochastic gravitational wave background that will be detectable by third generation telescopes (Cheng et al. 2017).

- We have developed a method to search for orphan afterglows and find CDF-S XT1 to be an orphan afterglow at a redshift of 2.23.
- Gamma-ray burst afterglow observations point towards a neutron star central engine for a significant fraction of short gamma-ray bursts.
- Such central engines emit a copious amount of gravitational-waves which will become detectable with third-generation telescopes (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, Sarin et al. 2020).
- The population properties of neutron star remnants that collapse indirectly through the X-ray afterglow can constrain the equation of state and spin-down mechanism (see Sarin et al. 2020).