THE MULTI-MESSENGER SIGNATURES OF NEUTRON STAR BINARY MERGERS

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Sarin and Lasky (2021)
Invited review in General
Relativity and Gravitation.

Image credit: Carl Knox

- A central engine potentially launches an ultra-relativistic jet.
- Ejecta from the merger and the accretion disc around the remnant central engine powers a kilonova.
- The jet may through some mechanism produces prompt gamma-ray emission.
- The jet later interacts with the surrounding ISM producing a synchrotron radiation.

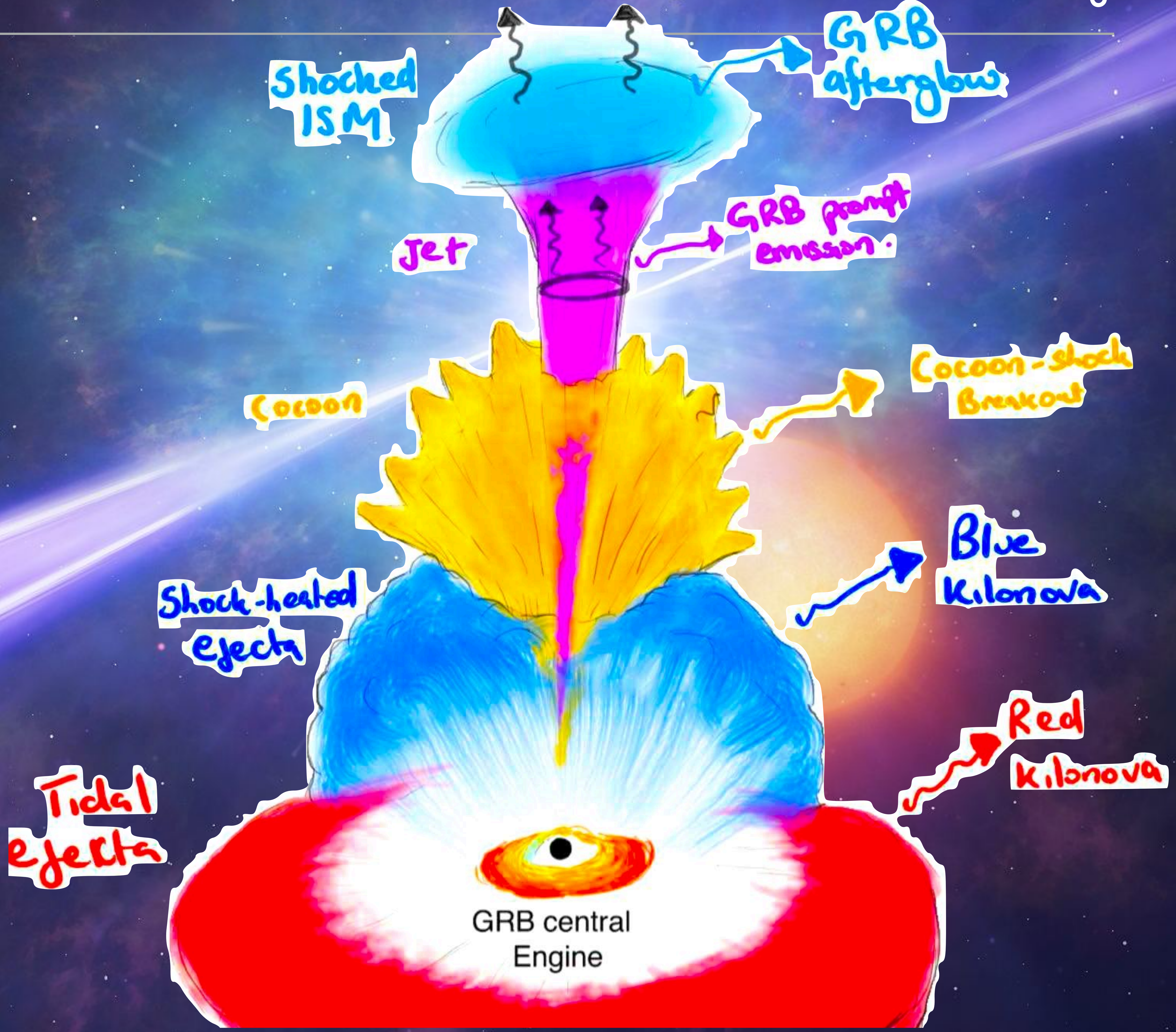
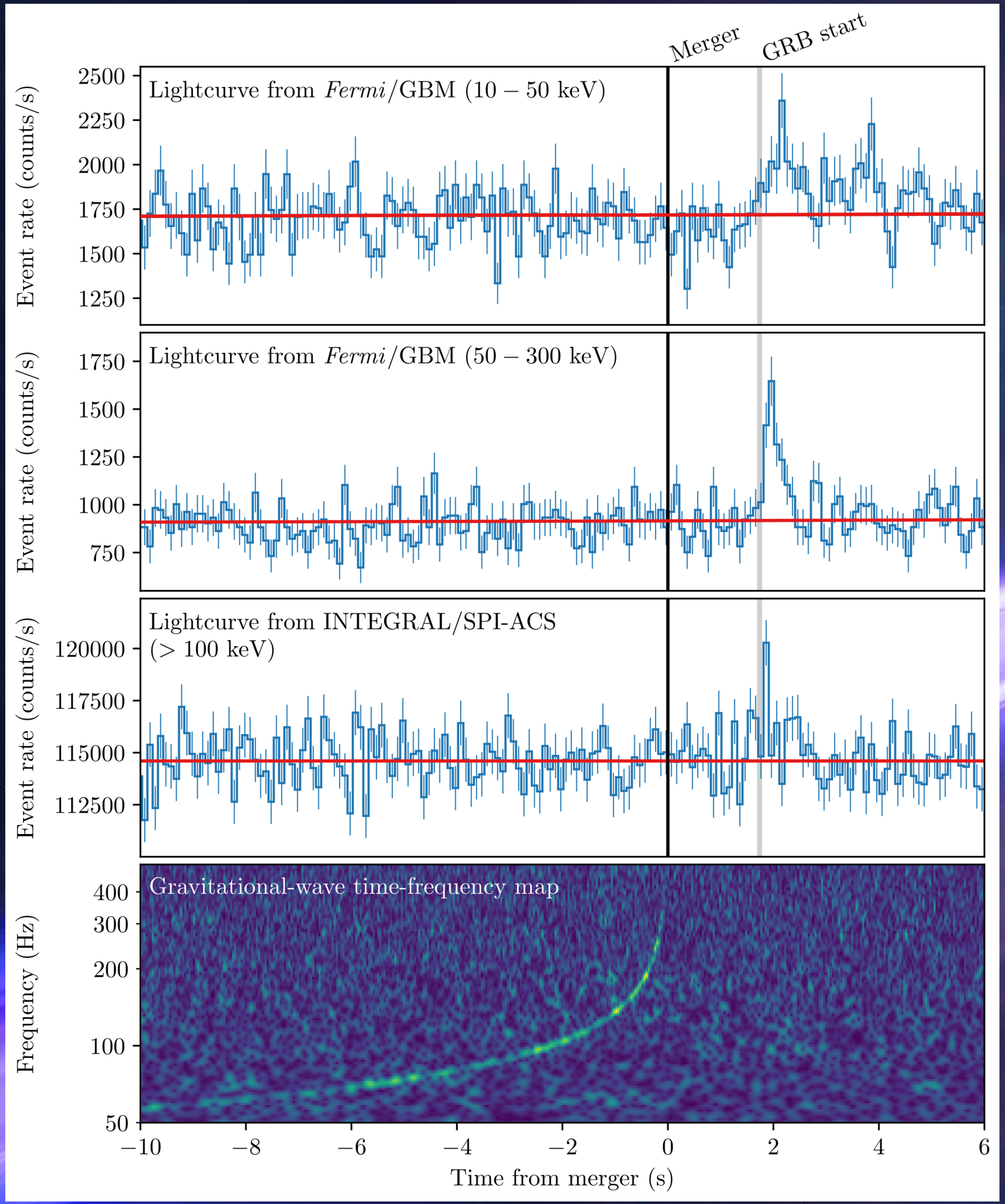
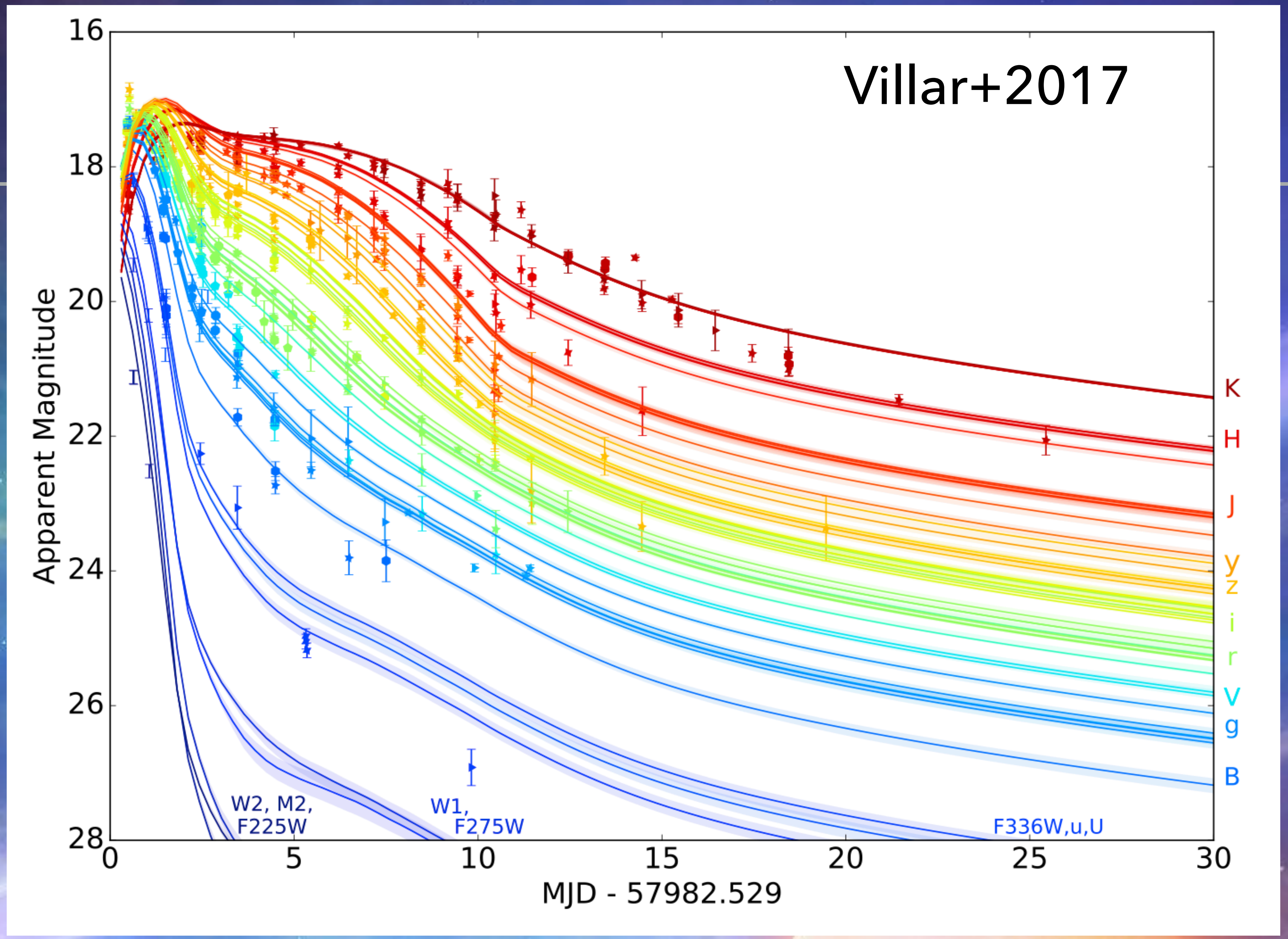


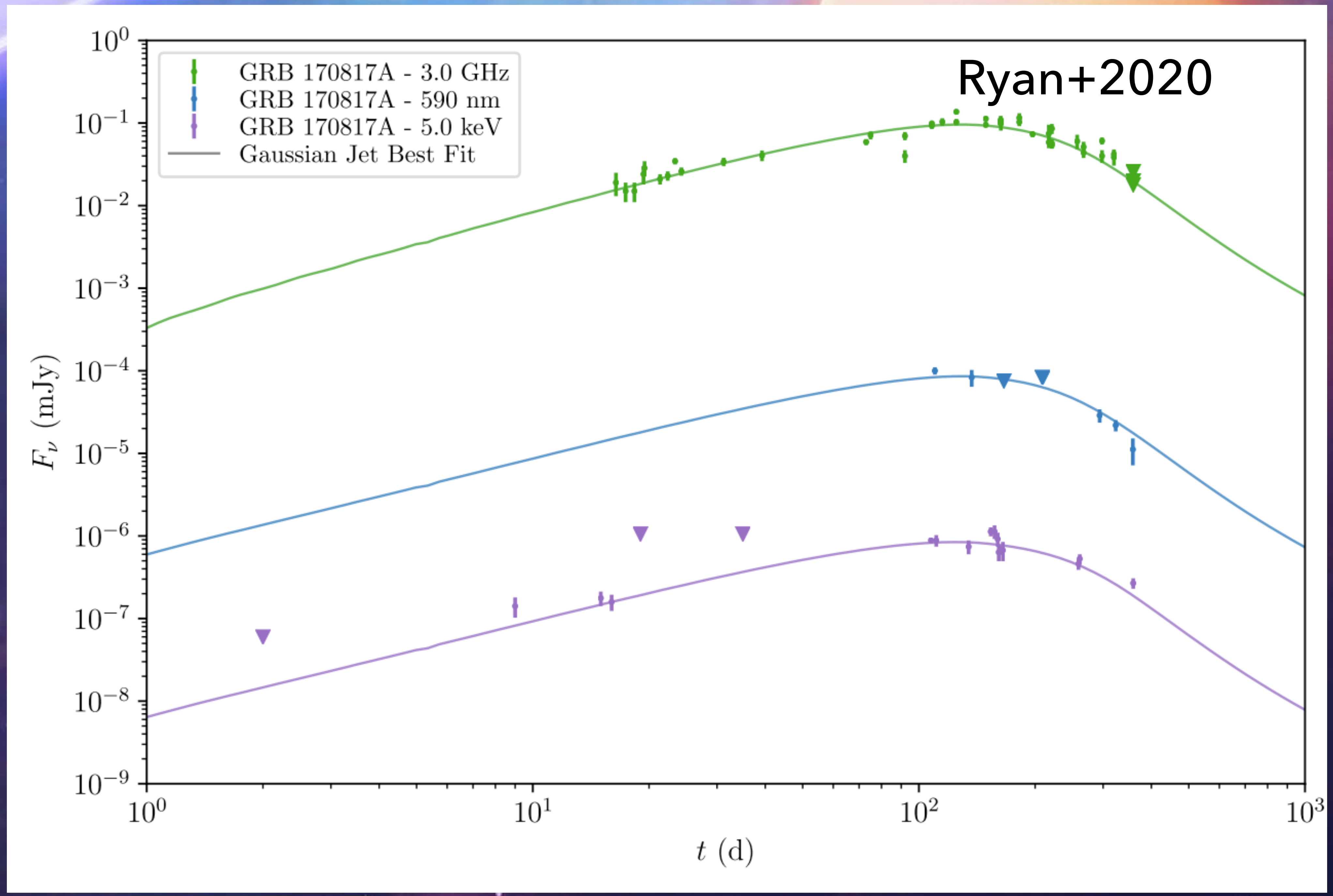
Figure from Ascenzi+2020

WHAT DID WE SEE WITH GW170817?



Abbott+2017





- Short gamma-ray bursts are not only produced in BNS mergers but potentially also in NSBH mergers.
- Tentative hints already in the population e.g. Troja+2008, Siellez+2016, Gompertz+2020

$$\mathcal{R}_{\rm SGRB} = f_{\rm s,BNS}\eta_{\rm BNS}\mathcal{R}_{\rm BNS} + f_{\rm s,NSBH}\eta_{\rm NSBH}\mathcal{R}_{\rm NSBH}$$

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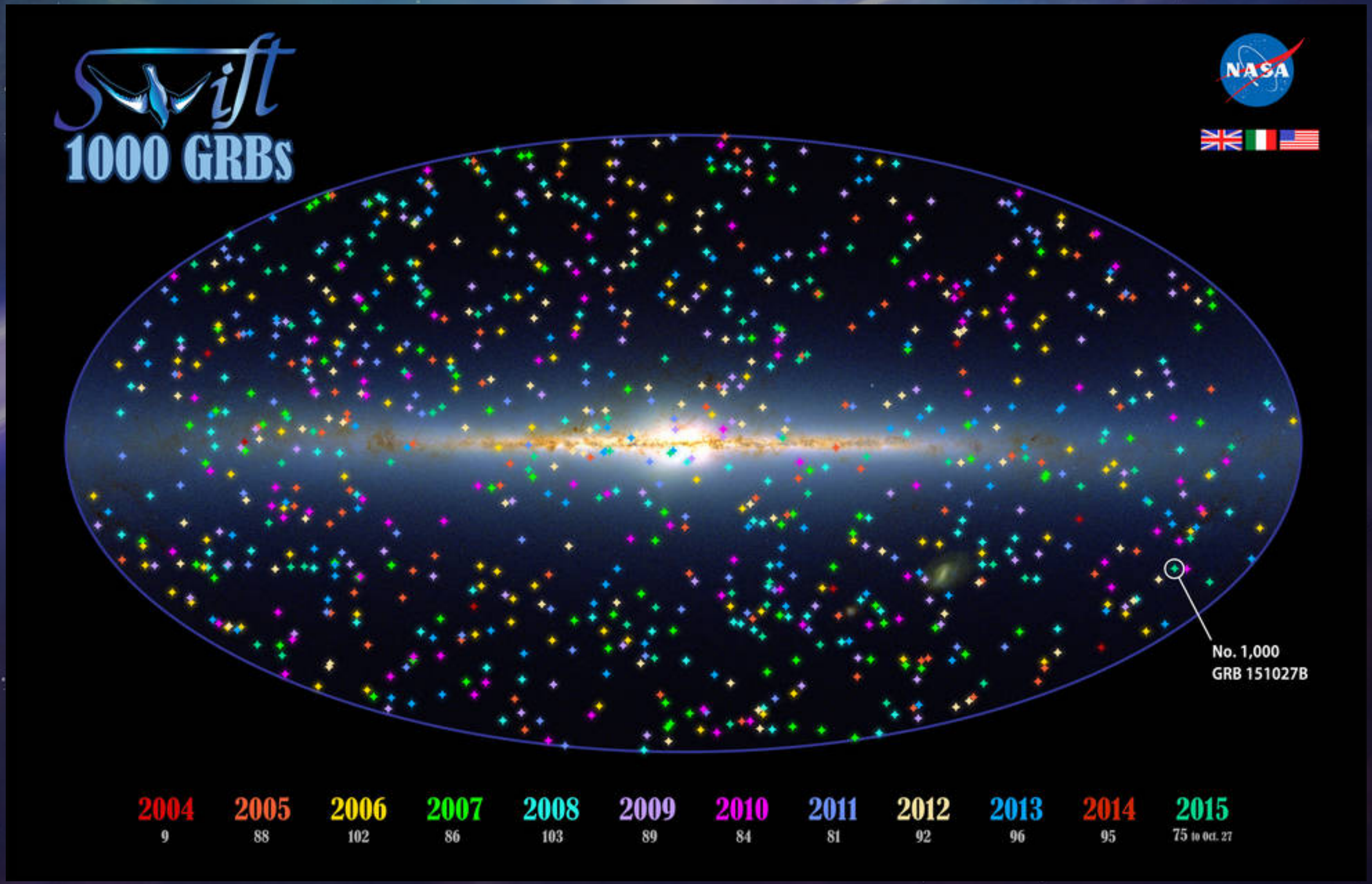
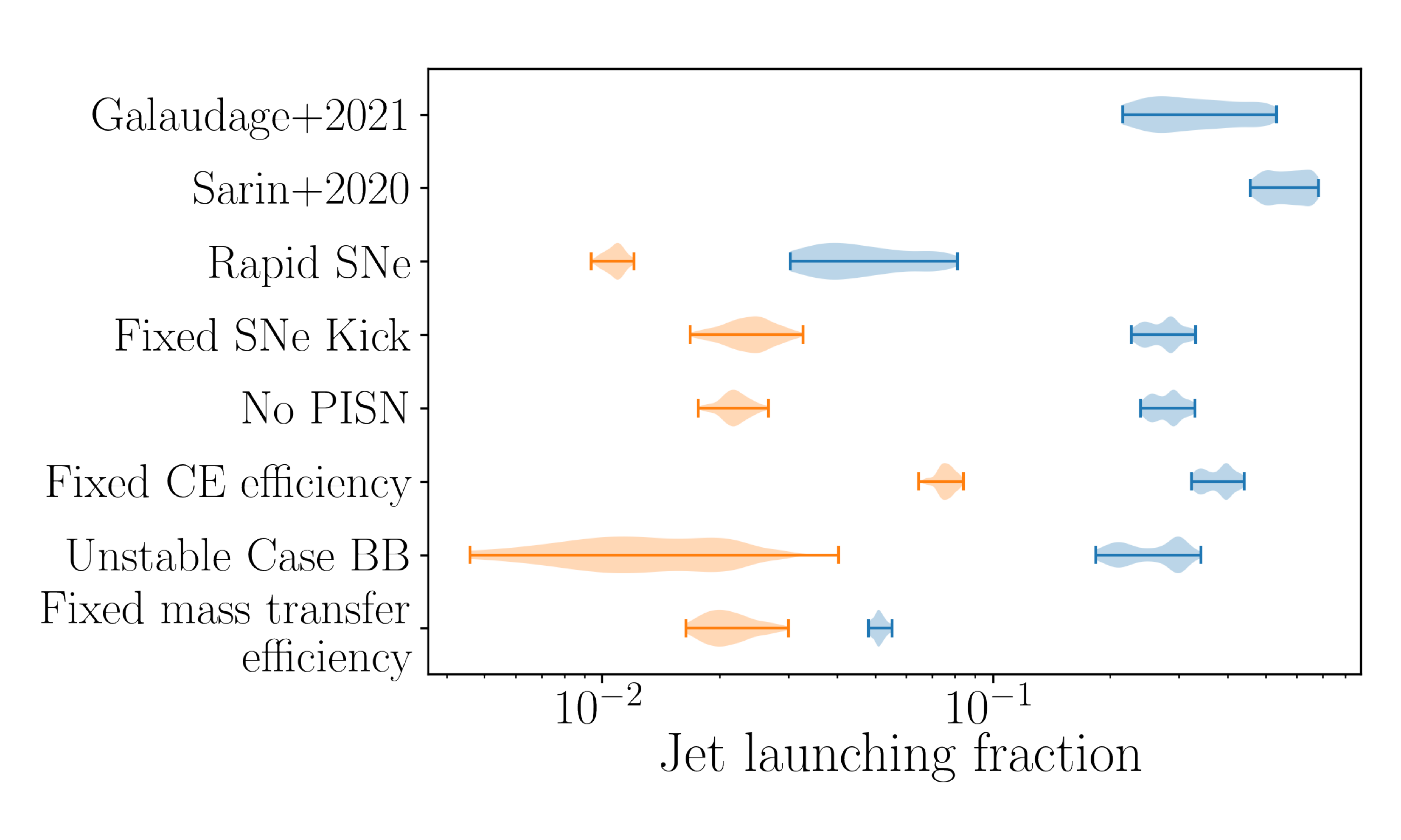
- We have already observed plenty of short gamma-ray bursts and several neutron star binary candidates in gravitational waves.
- What can we learn by linking the observations of short gamma-ray bursts with the binaries that produce them?



Credit: NASA GSFC

$$\mathcal{R}_{\mathrm{SGRB}} = f_{\mathrm{s,BNS}}\eta_{\mathrm{BNS}}\mathcal{R}_{\mathrm{BNS}} + f_{\mathrm{s,NSBH}}\eta_{\mathrm{NSBH}}\mathcal{R}_{\mathrm{NSBH}}$$

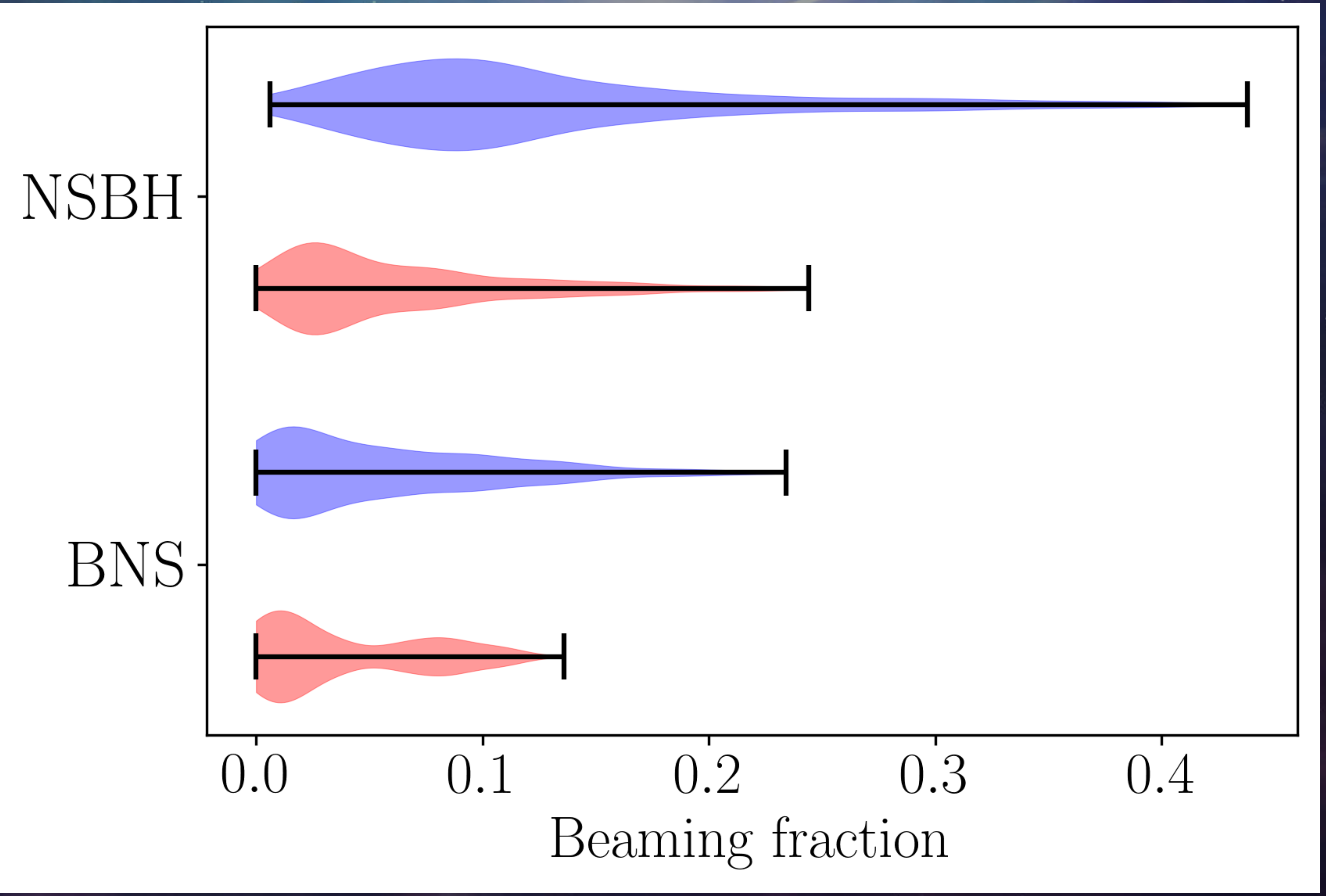
- $f_{s,\mathrm{BNS}}$ and $f_{s,\mathrm{NSBH}}$ are the fraction of BNS and NSBH mergers that launch jets.
- Dictated by the properties of the binaries that merge –> tell us about binary evolution!
  - Most assumptions about binary evolution predict ~1-2% and ~30% of NSBH and BNS launch jets.



Sarin+2022b

$$\mathcal{R}_{\rm SGRB} = f_{\rm s,BNS}\eta_{\rm BNS}\mathcal{R}_{\rm BNS} + f_{\rm s,NSBH}\eta_{\rm NSBH}\mathcal{R}_{\rm NSBH}$$

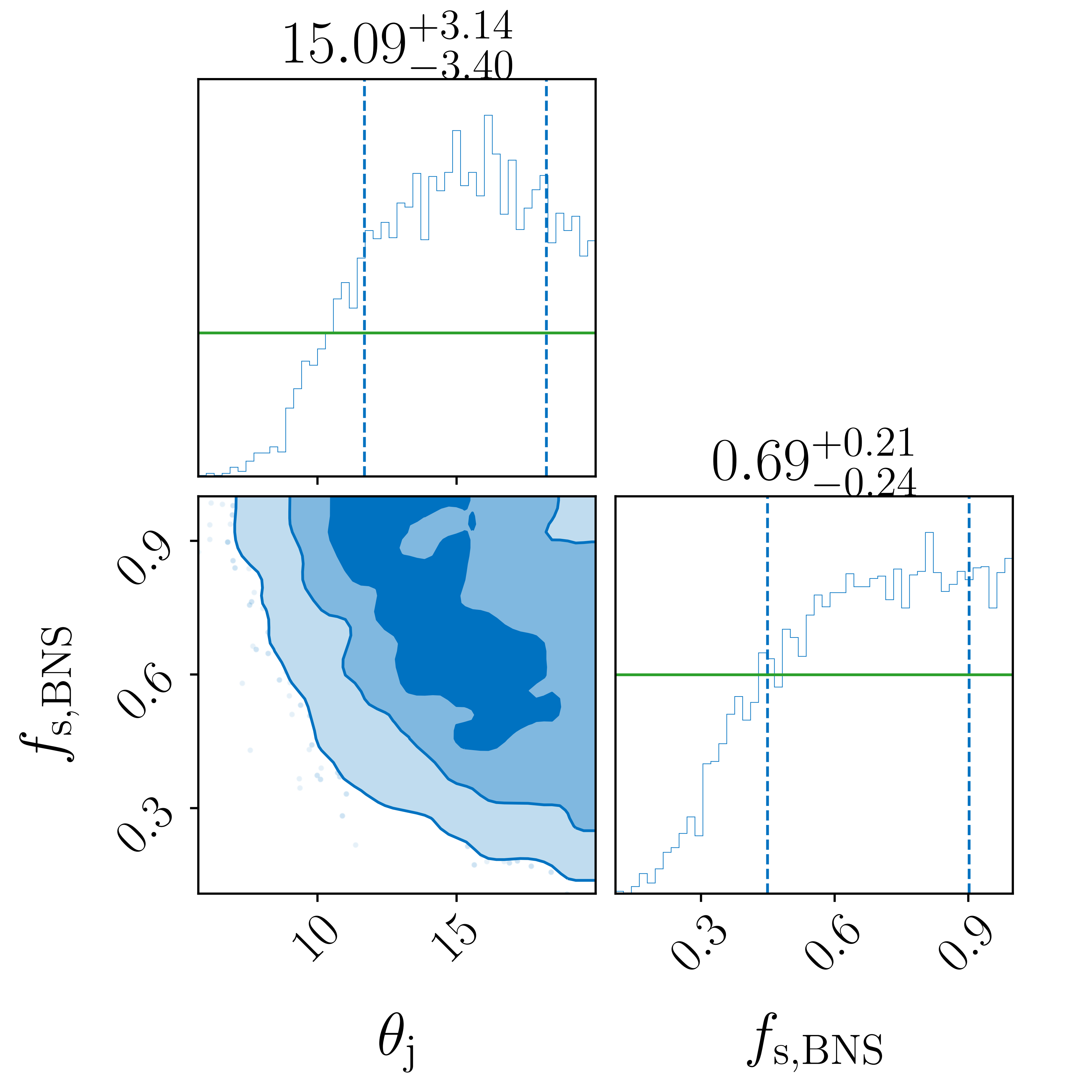
- $\eta_{\rm BNS}$ and $\eta_{\rm NSBH}$ are the 'beaming fraction' of BNS and NSBH mergers.
- Dictated by the gamma-ray burst physics–> tell us about jet launching and propagation!
  - BNS jets are more collimated.
  - Power-law jets are visible for larger range of observer viewing angle compared to a Gaussian structure.



Sarin+2022b

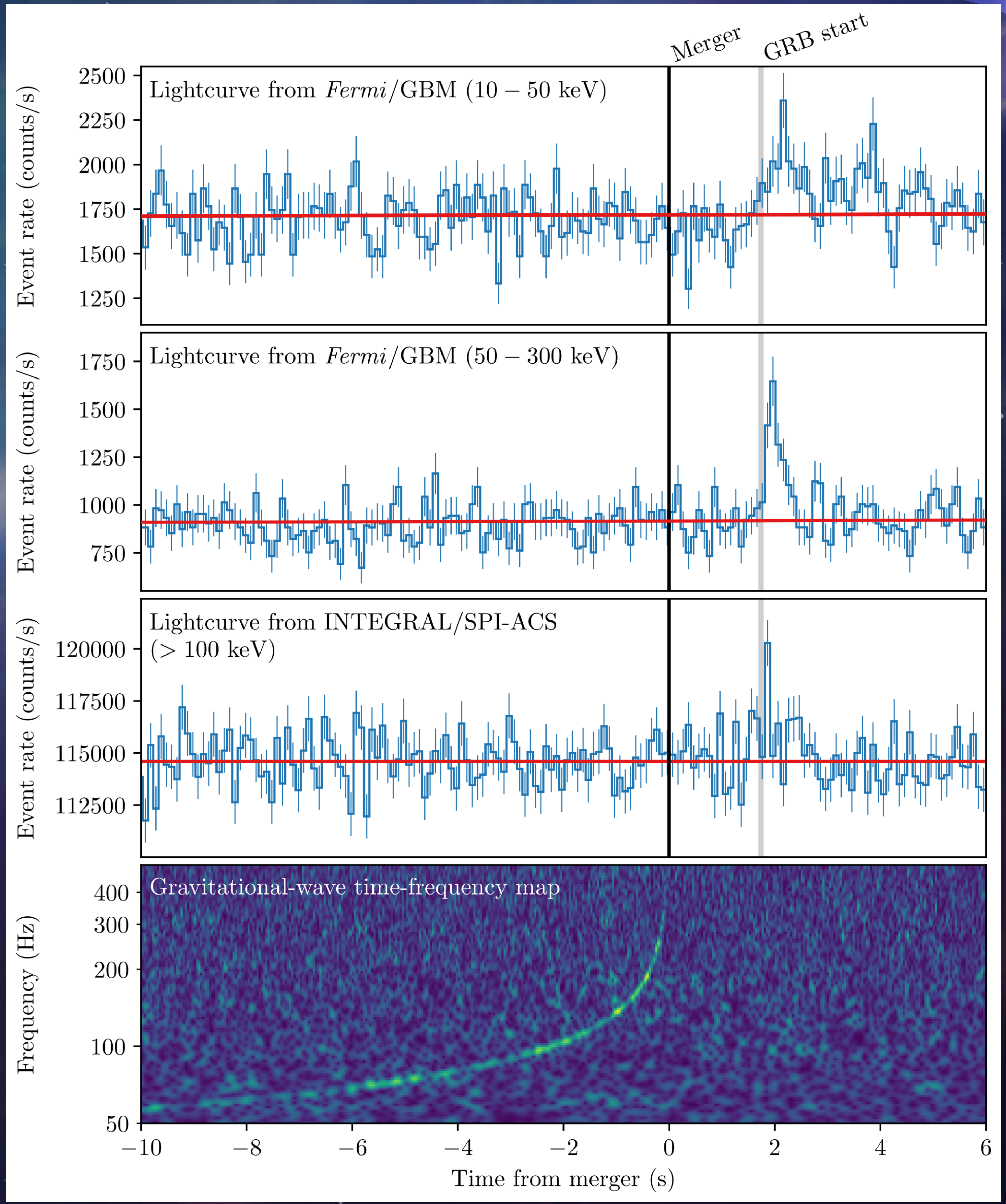
$$\mathcal{R}_{\rm SGRB} = f_{\rm s,BNS}\eta_{\rm BNS}\mathcal{R}_{\rm BNS} + f_{\rm s,NSBH}\eta_{\rm NSBH}\mathcal{R}_{\rm NSBH}$$

- The average opening angle of short gamma-ray bursts is $\theta_j \sim 15^\circ$
- $f_{s,\rm BNS} \gtrsim 0.4$ (90% confidence)
  - Rules out models where there is a mass gap between neutron stars and black holes.
  - Extragalactic binary neutron star mass distribution is broad and not like binary neutron stars in our Galaxy.
- Get a 15% improvement on the BNS merger rate from GWTC-2.



Sarin+2022b

- The first binary neutron star merger observed in gravitational waves and in electromagnetic radiation.
- But what remained behind after the merger?
  - When did the remnant collapse into a black hole?



- The merger outcome dictates what the potential observables are and what timescales we need to observe them.
  - Kilonova
  - Jets
  - Gravitational waves
  - FRBs

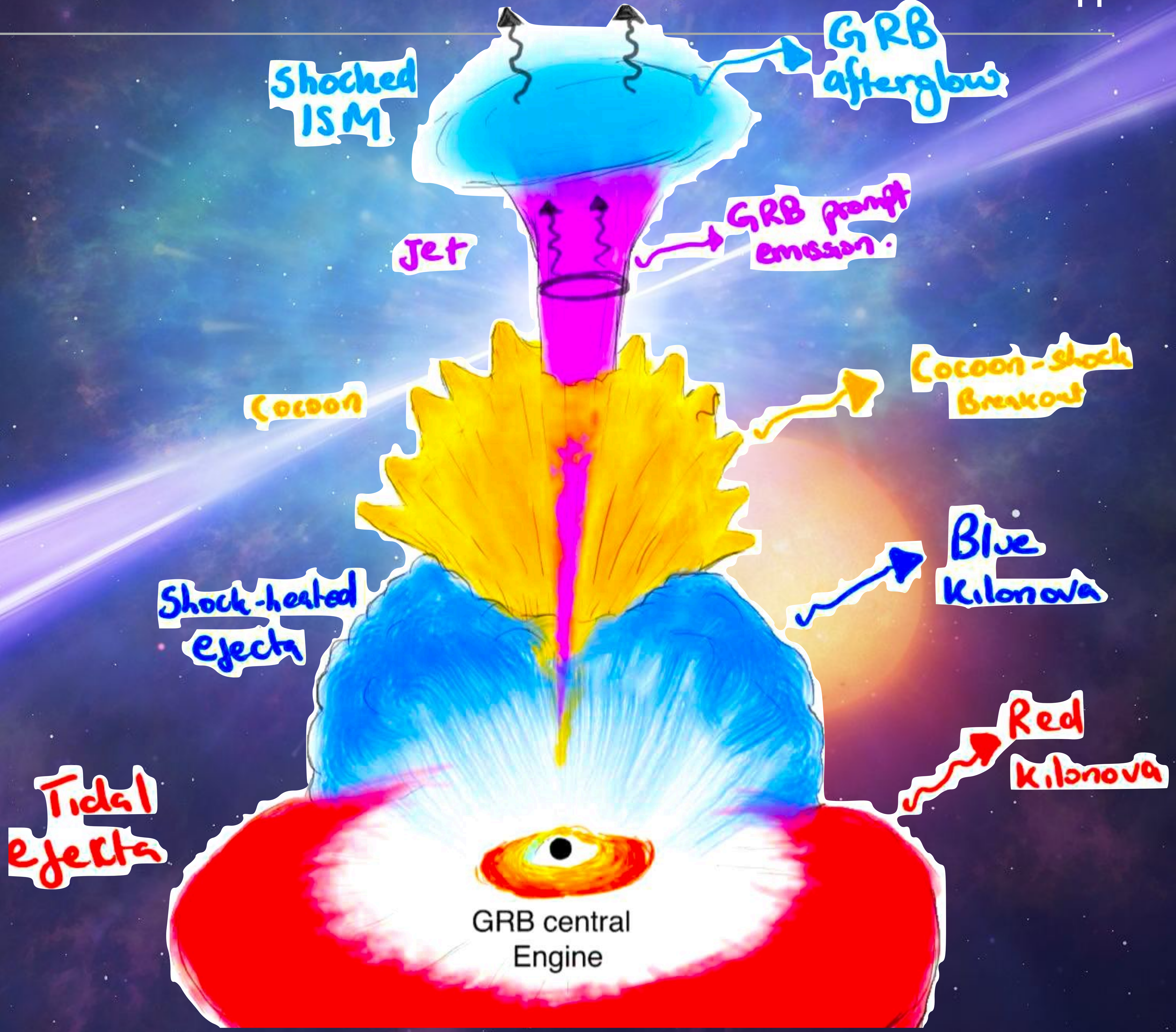
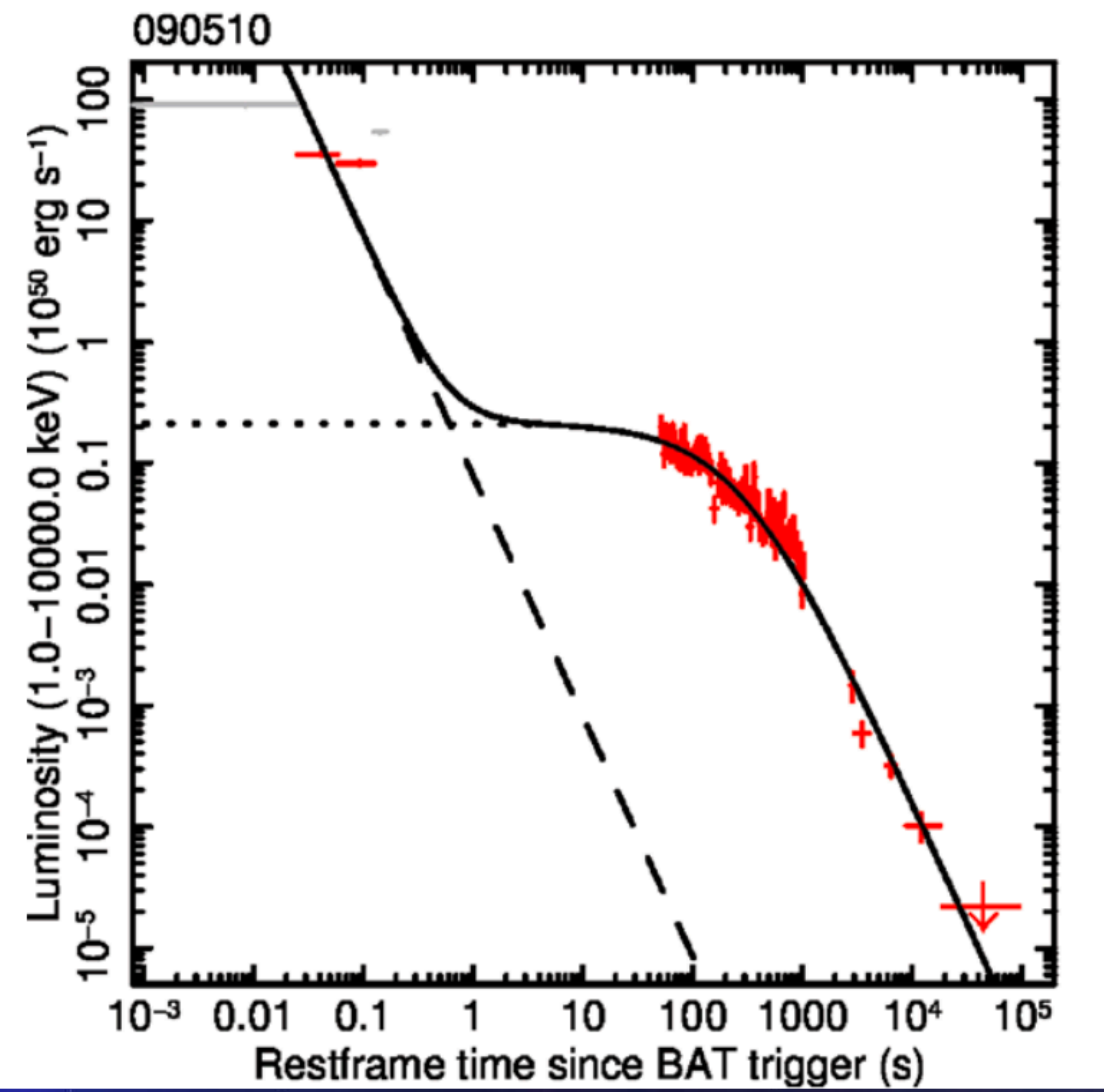
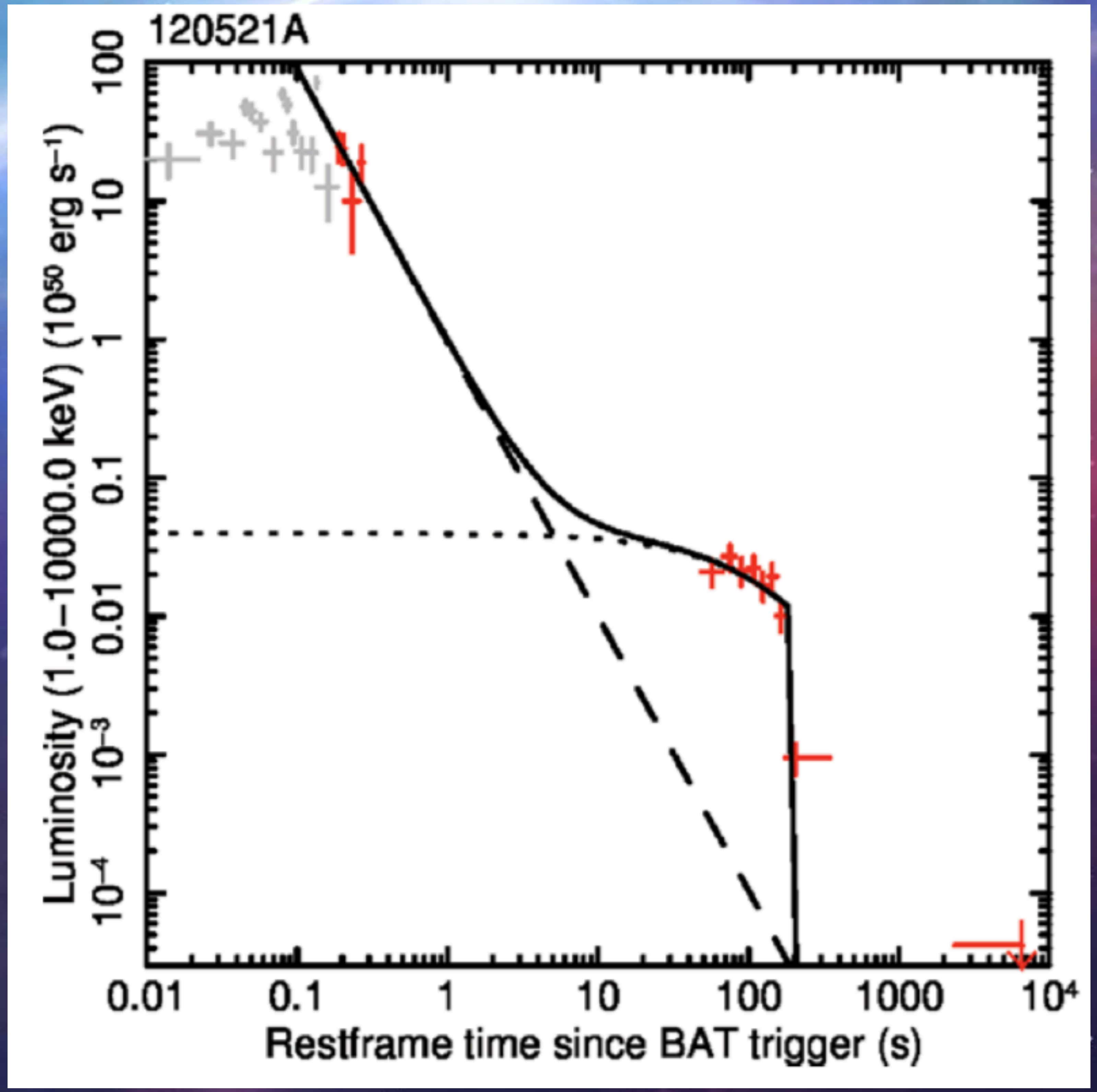


Figure from Ascenzi+2020

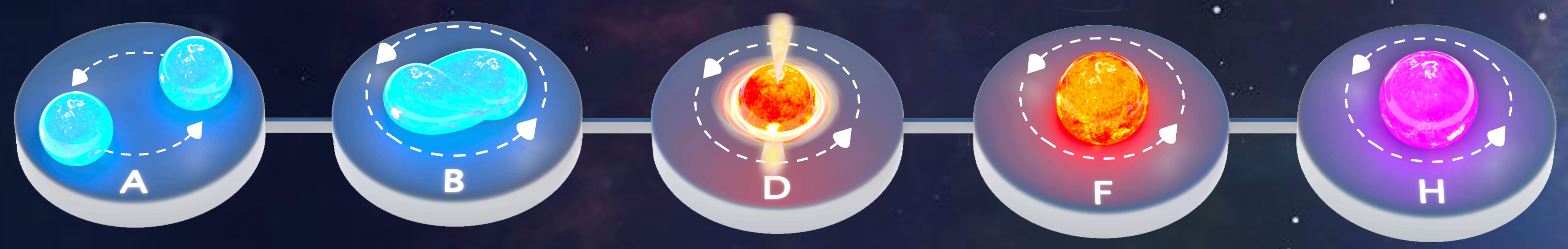
- The X-ray afterglows of a good fraction of GRBs have features that are incredibly difficult to explain with the interaction of a jet with the surrounding interstellar medium.

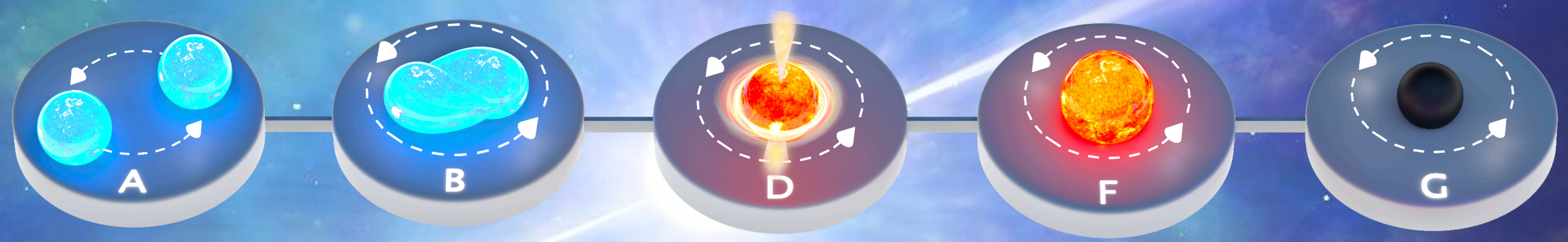


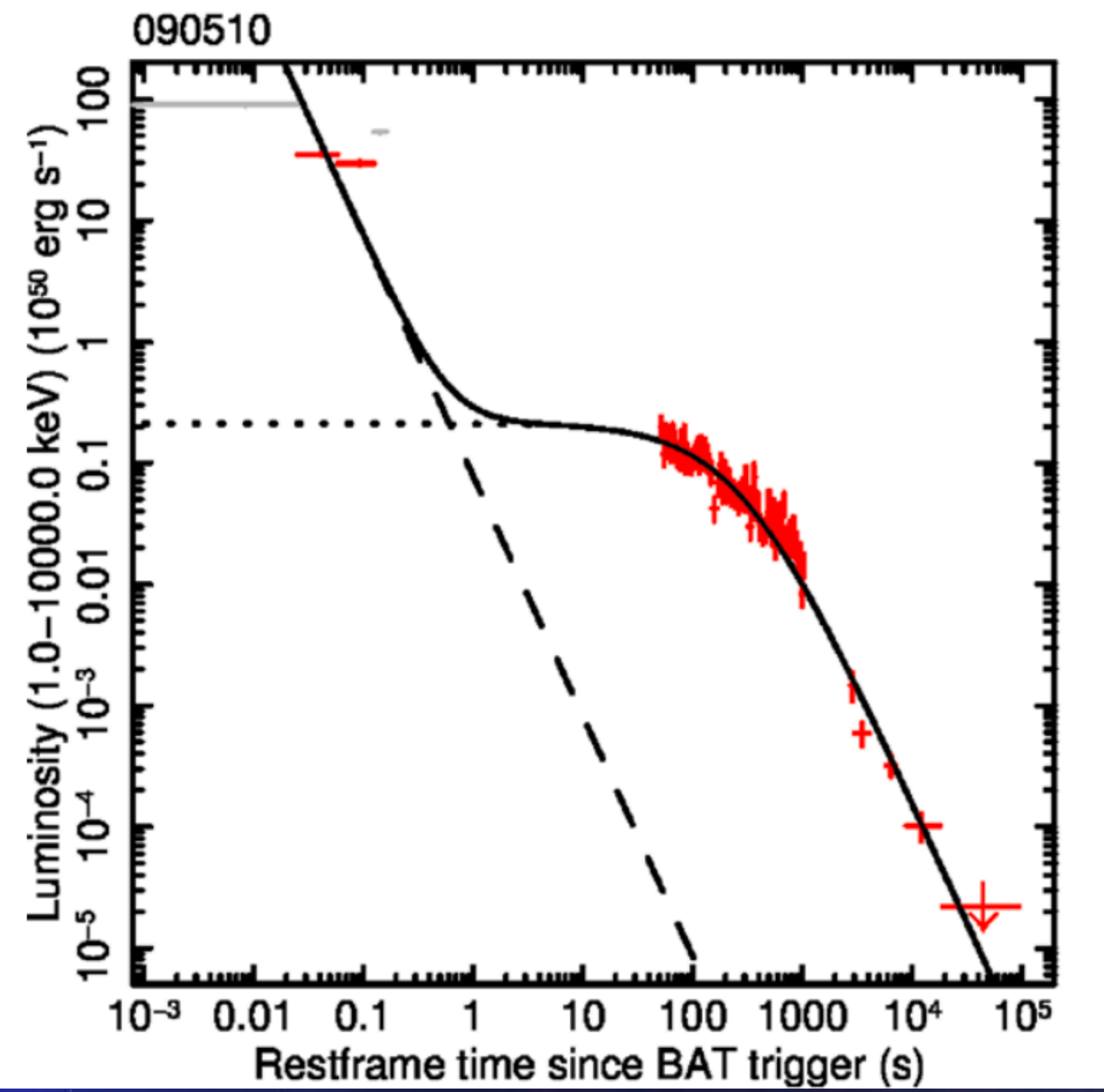


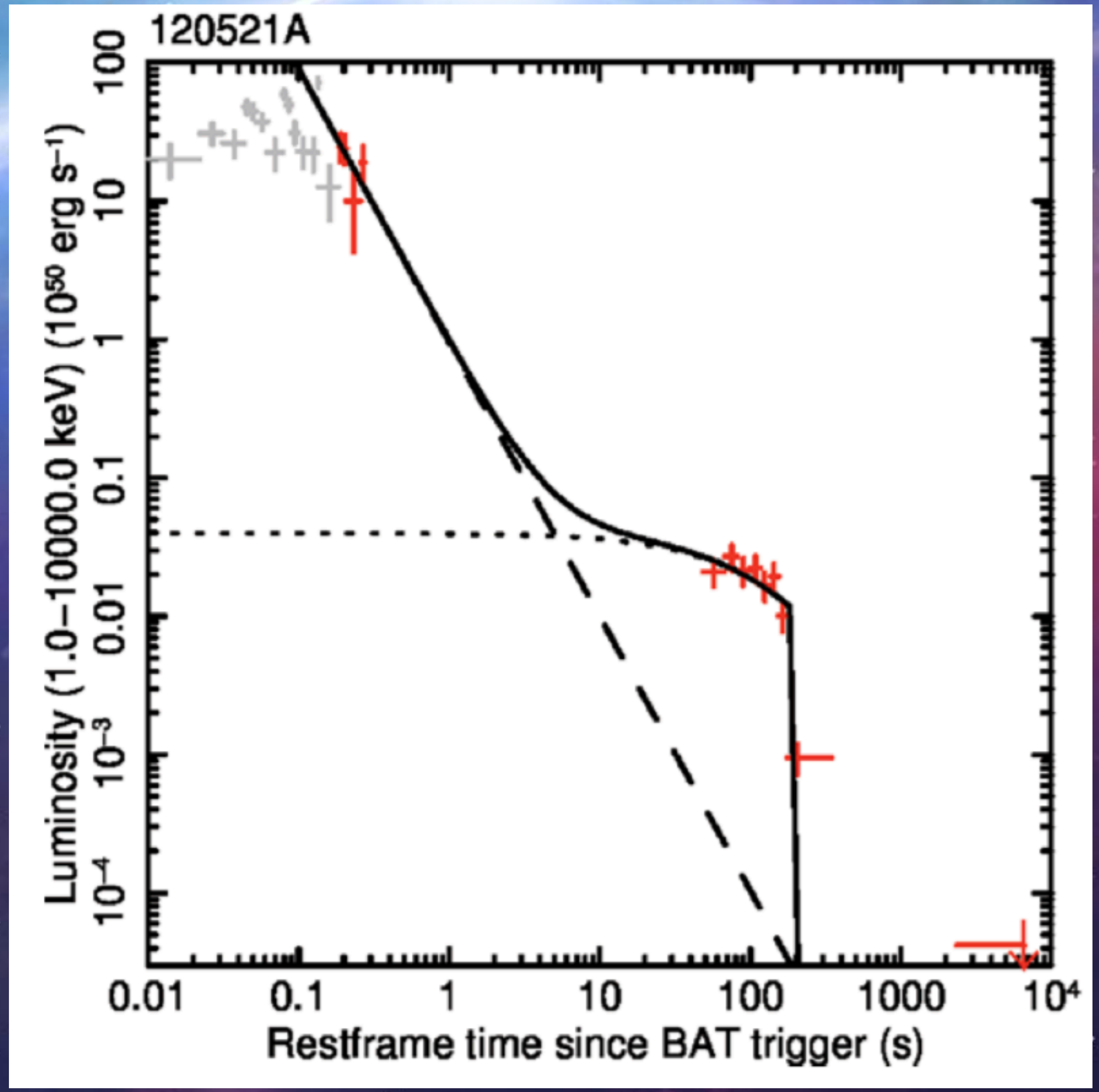
Rowlinson+2013

- These features are easily interpreted by adding an additional energy source. The spin-down energy of a highly magnetic, rapidly rotating neutron star!

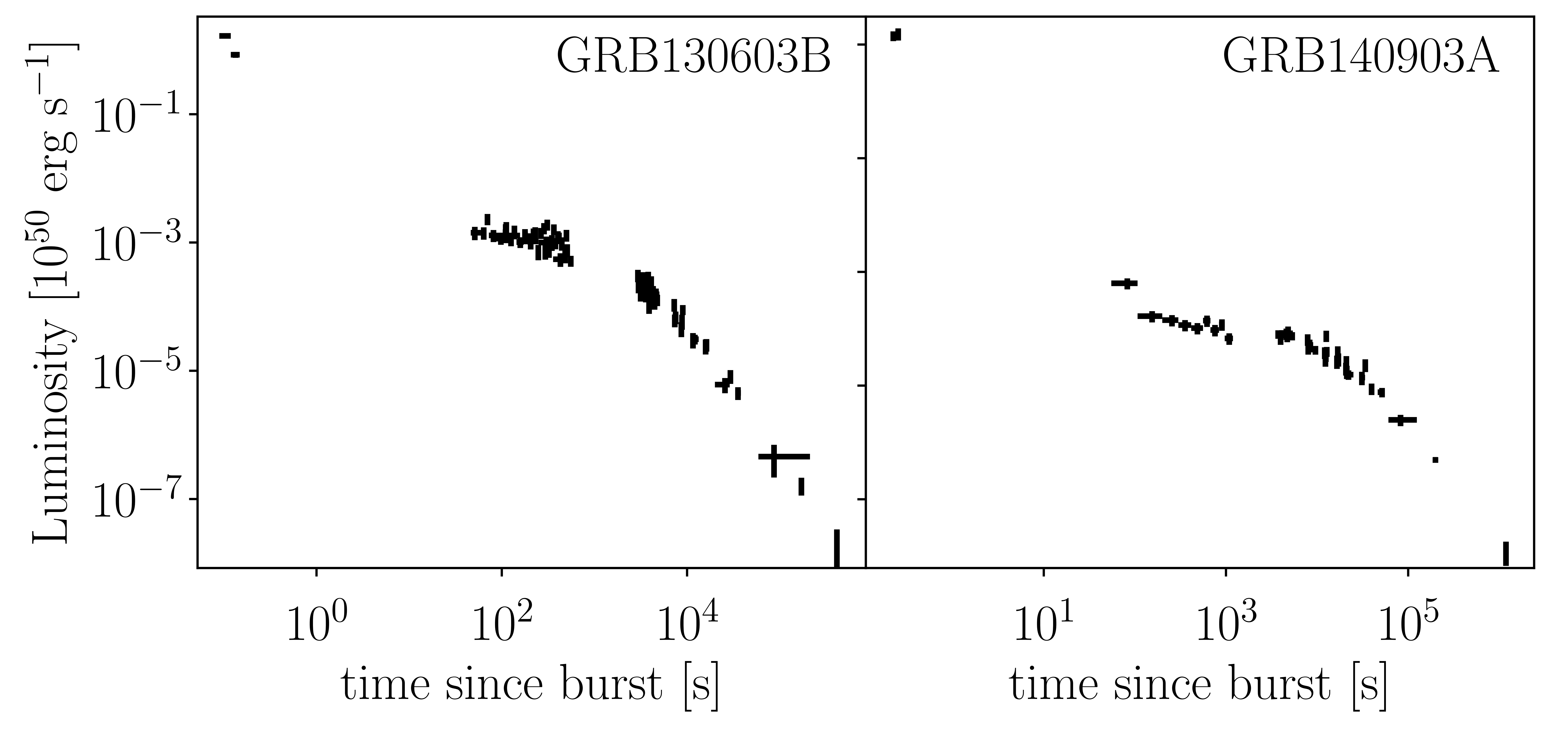








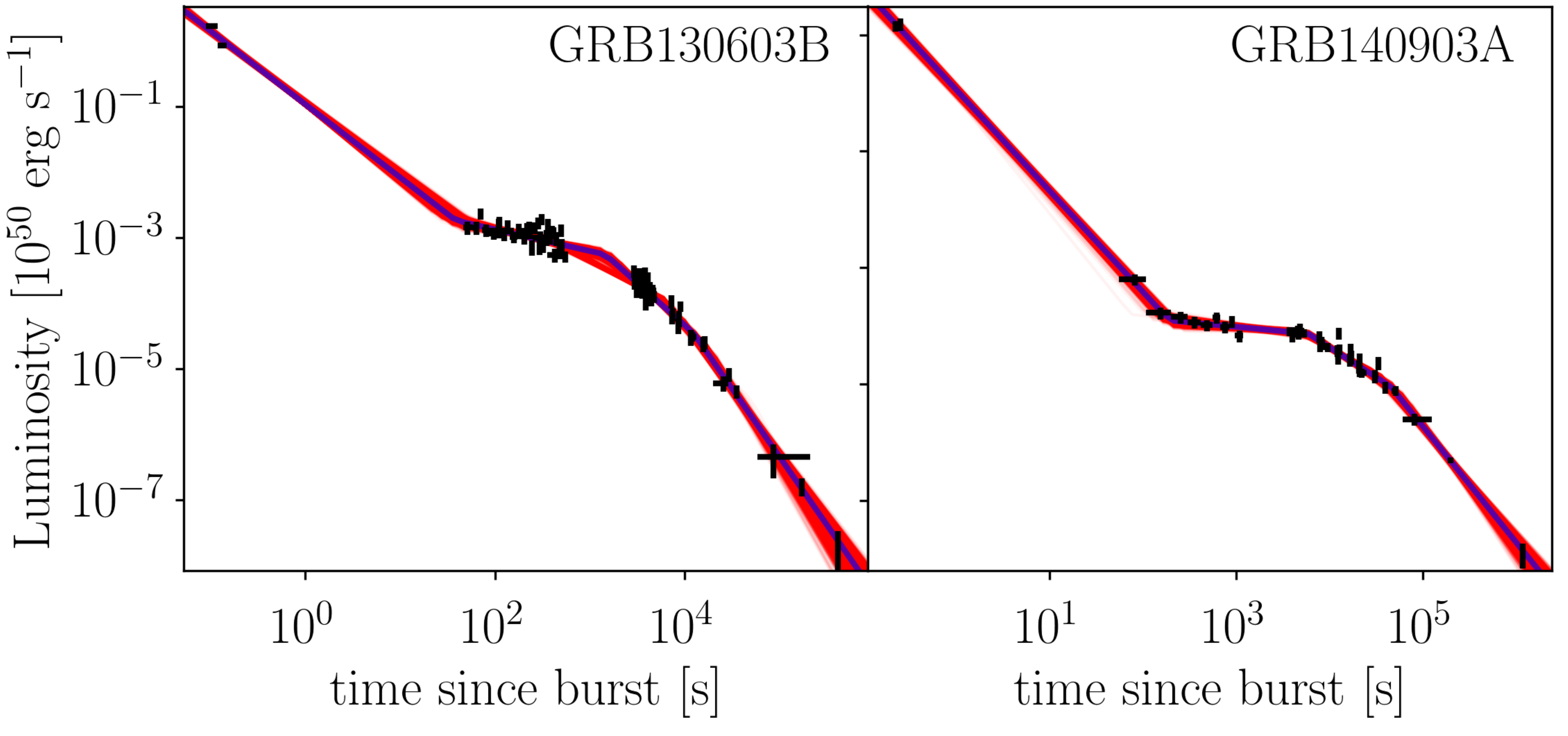
Rowlinson+2013



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]

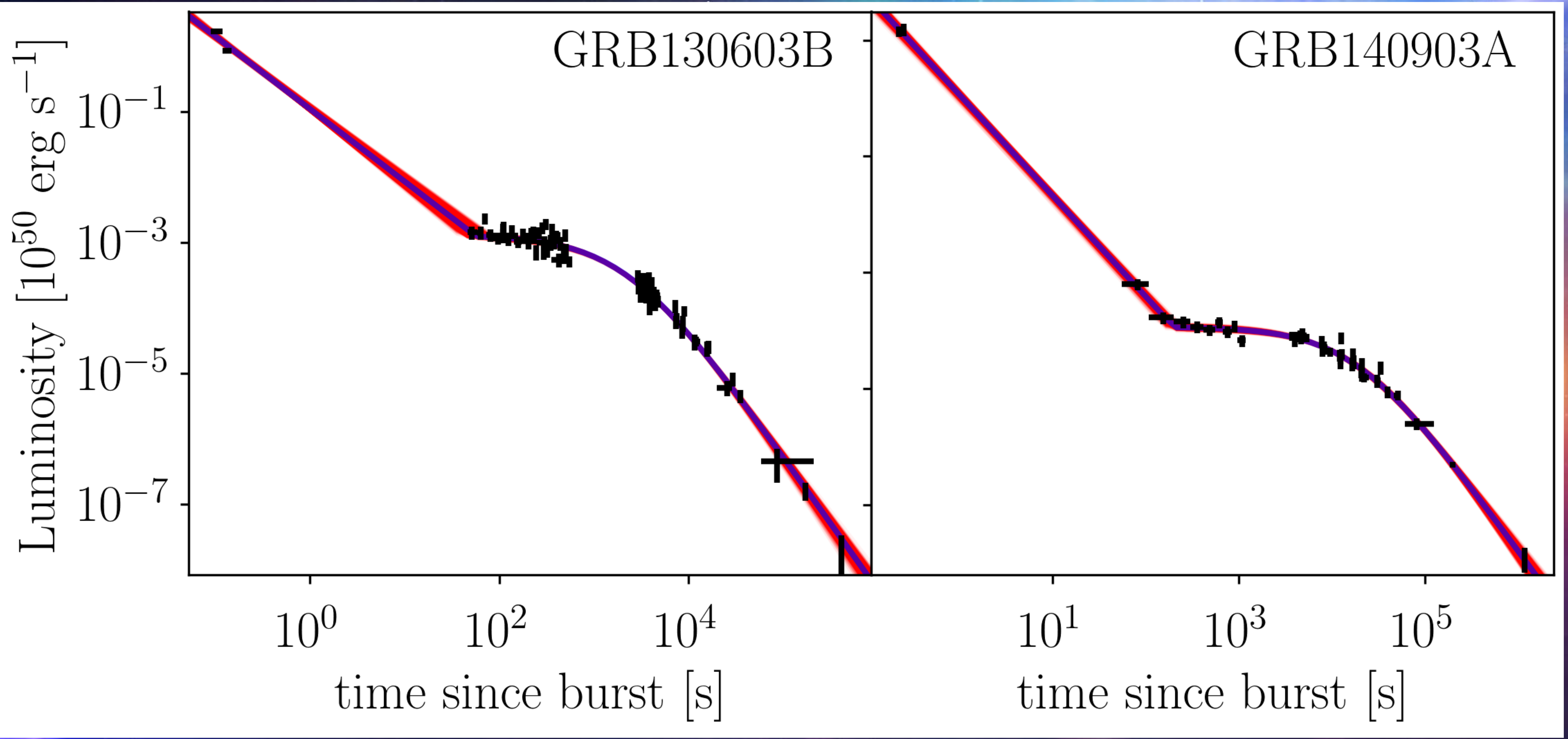
Sarin+2019

Interaction of jet

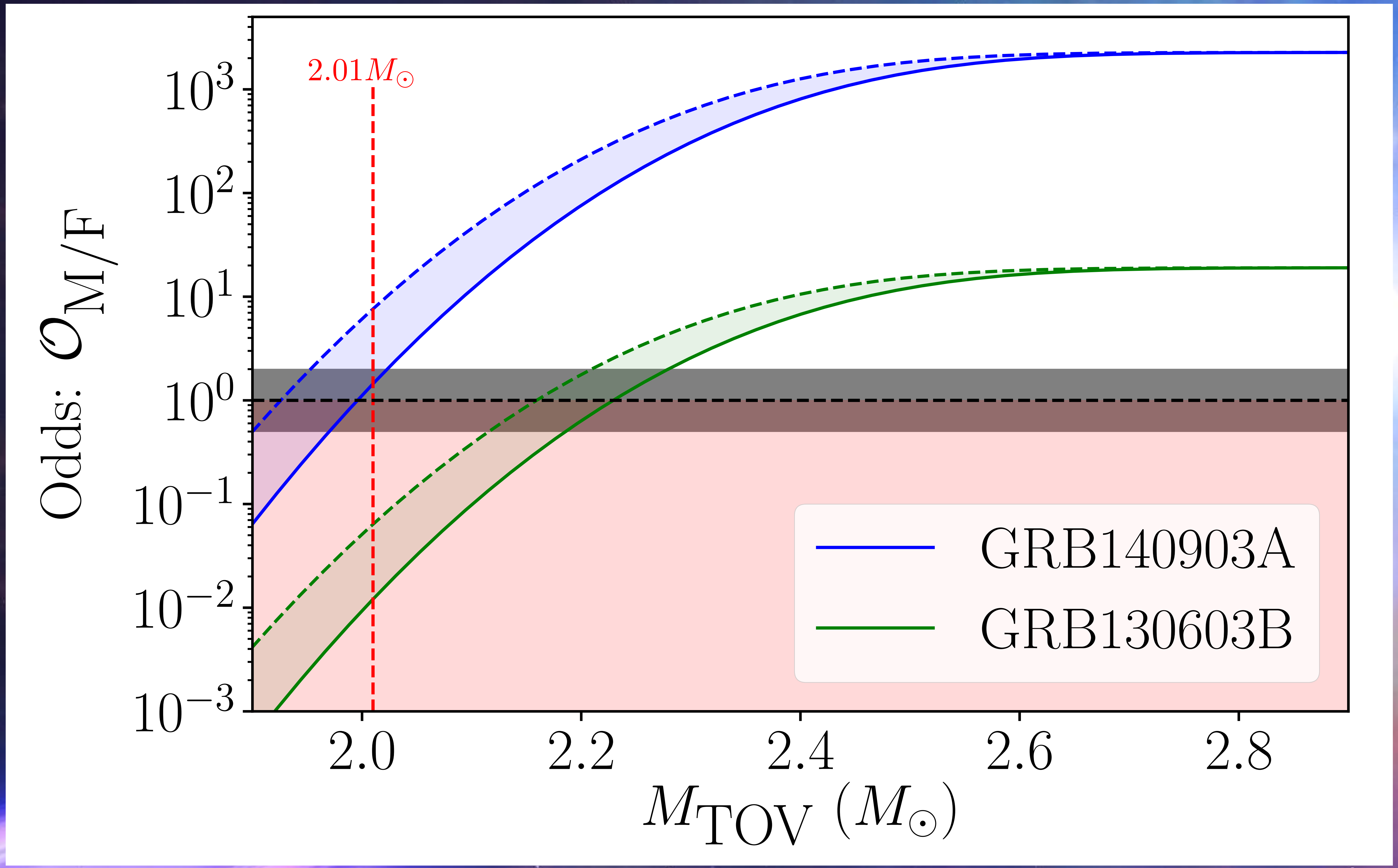


Sarin+2019

Long-lived neutron star remnant



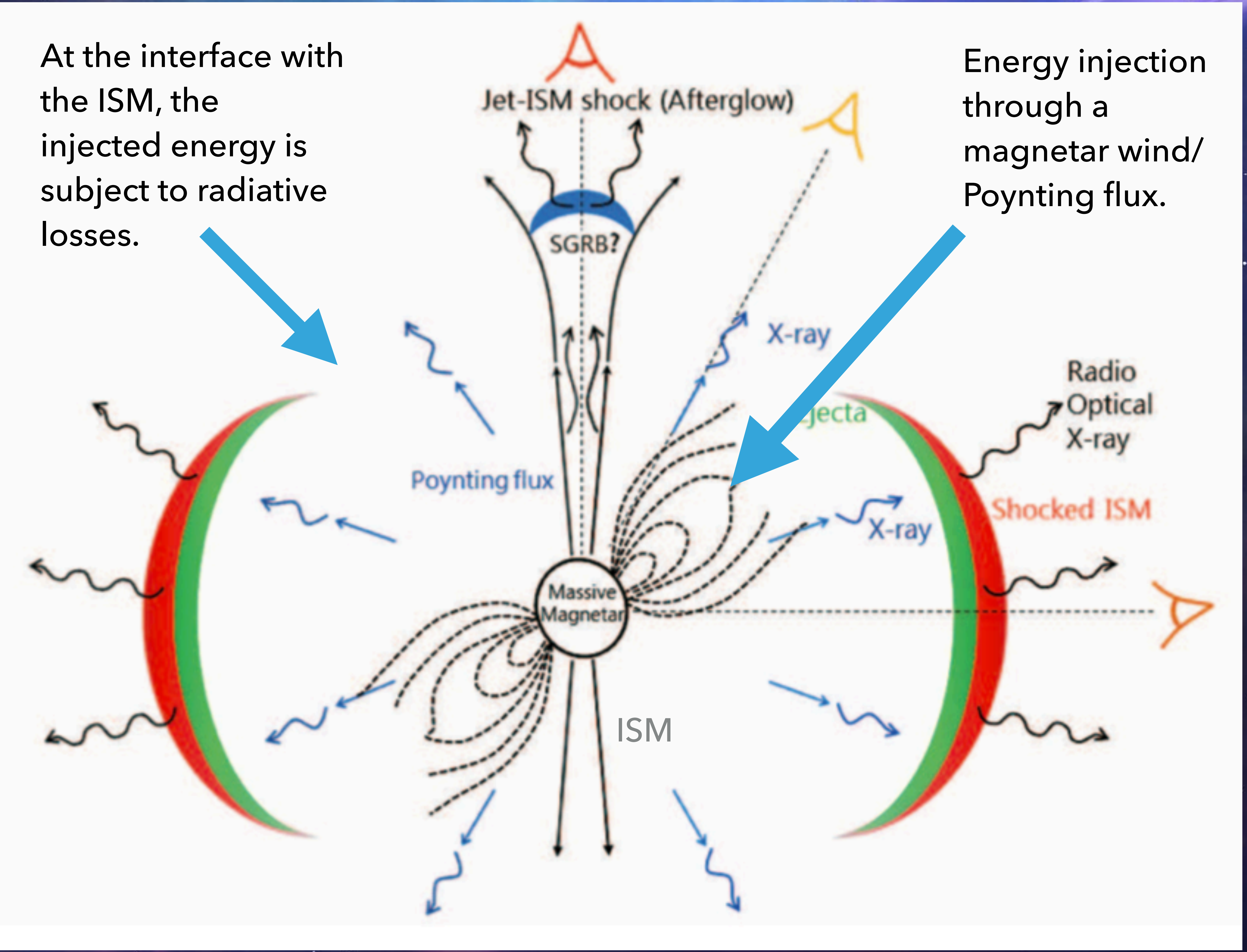
Sarin+2019



Sarin+2019

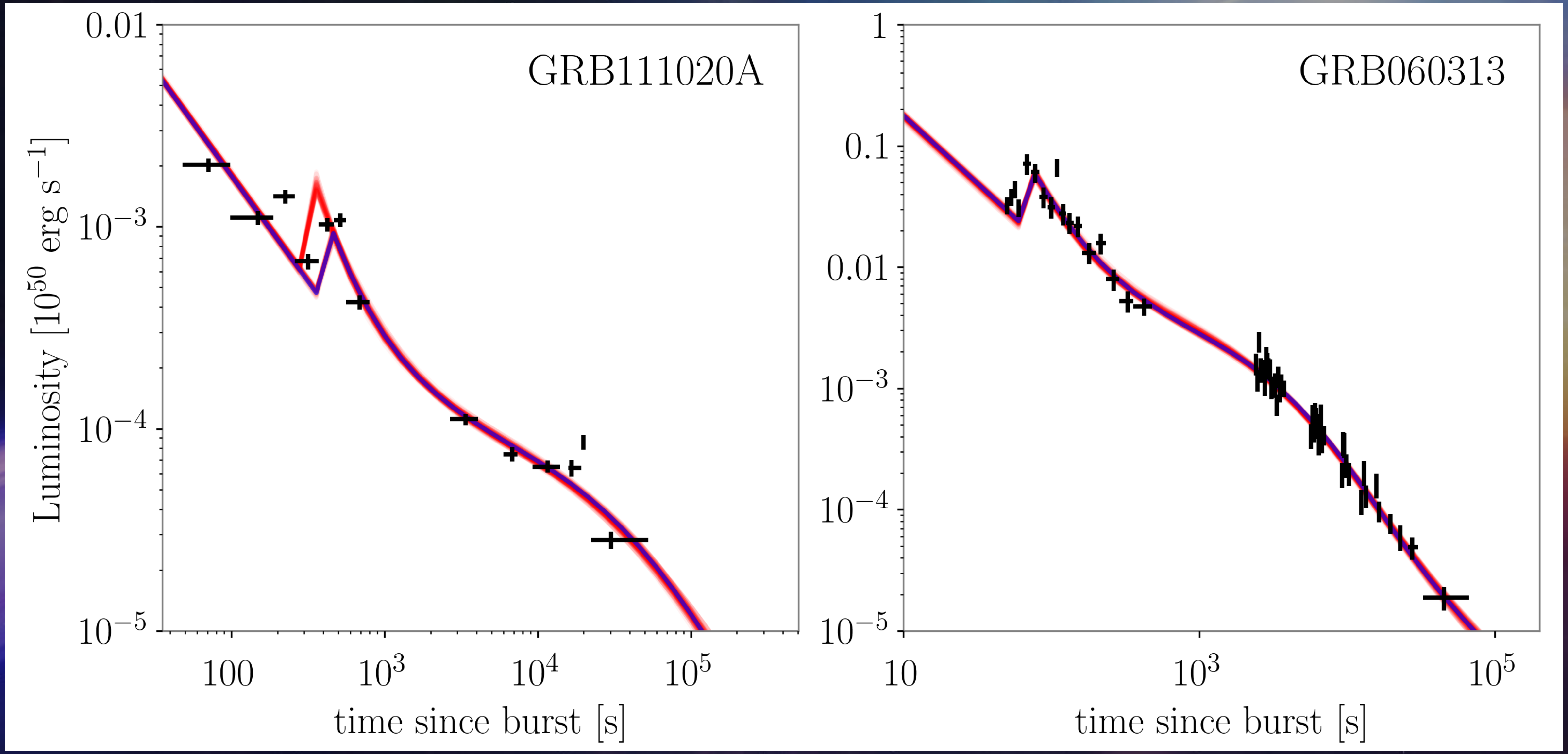
- Selecting between a jet or neutron star interpretation for an afterglow is dependent on the equation of state.
- GRB140903A data favours the existence of a nascent neutron star for all possible equation of states.

- The magnetar model commonly used in the literature is missing critical physics..
- In Sarin+2020b we extend the magnetar model to include the effect of radiative losses at the jet-ISM shock interface.



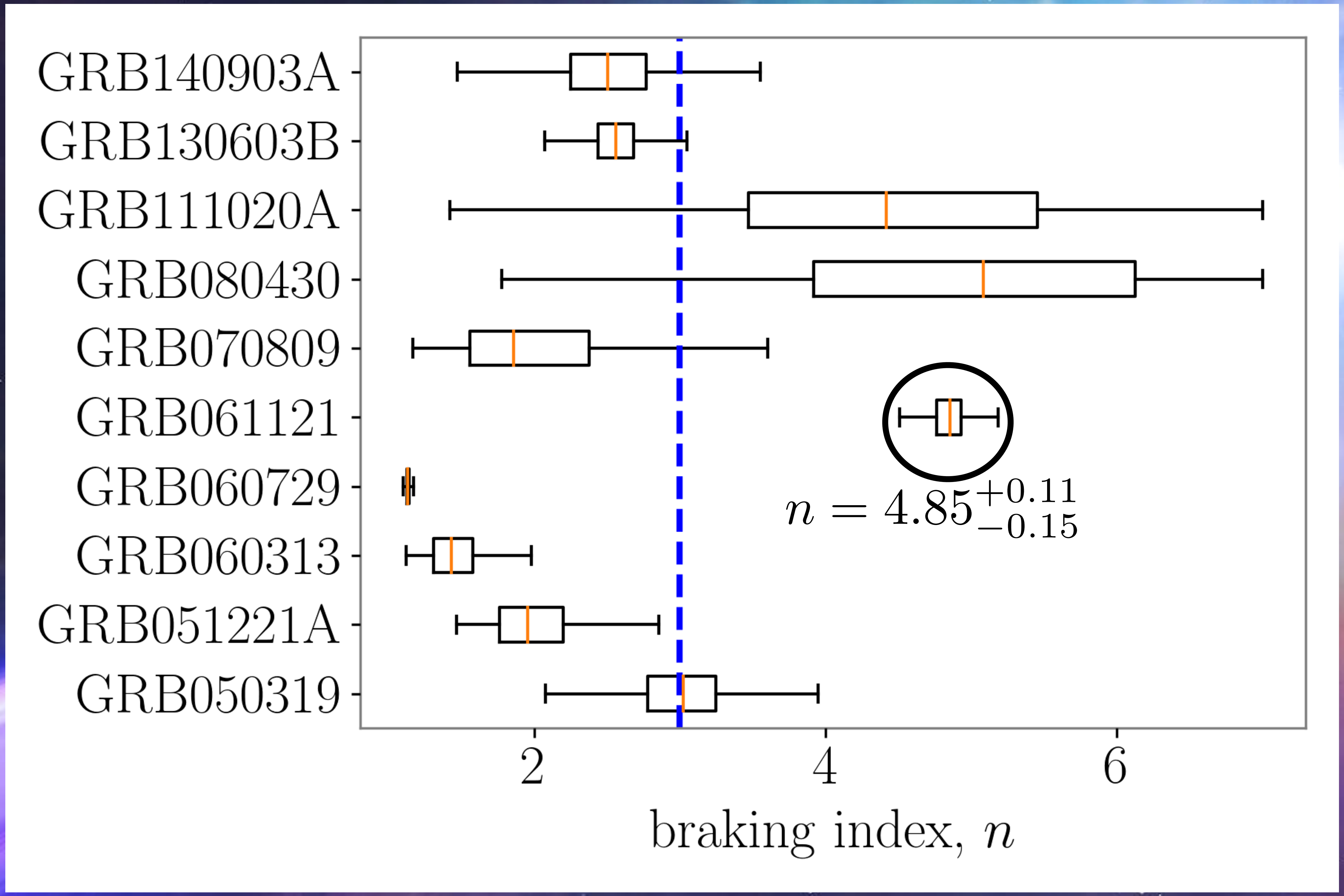
Modified from Gao+(2013)

- New model can naturally explain flares!
  - Breakout of excess energy from central engine at shock interface



Sarin+2020b

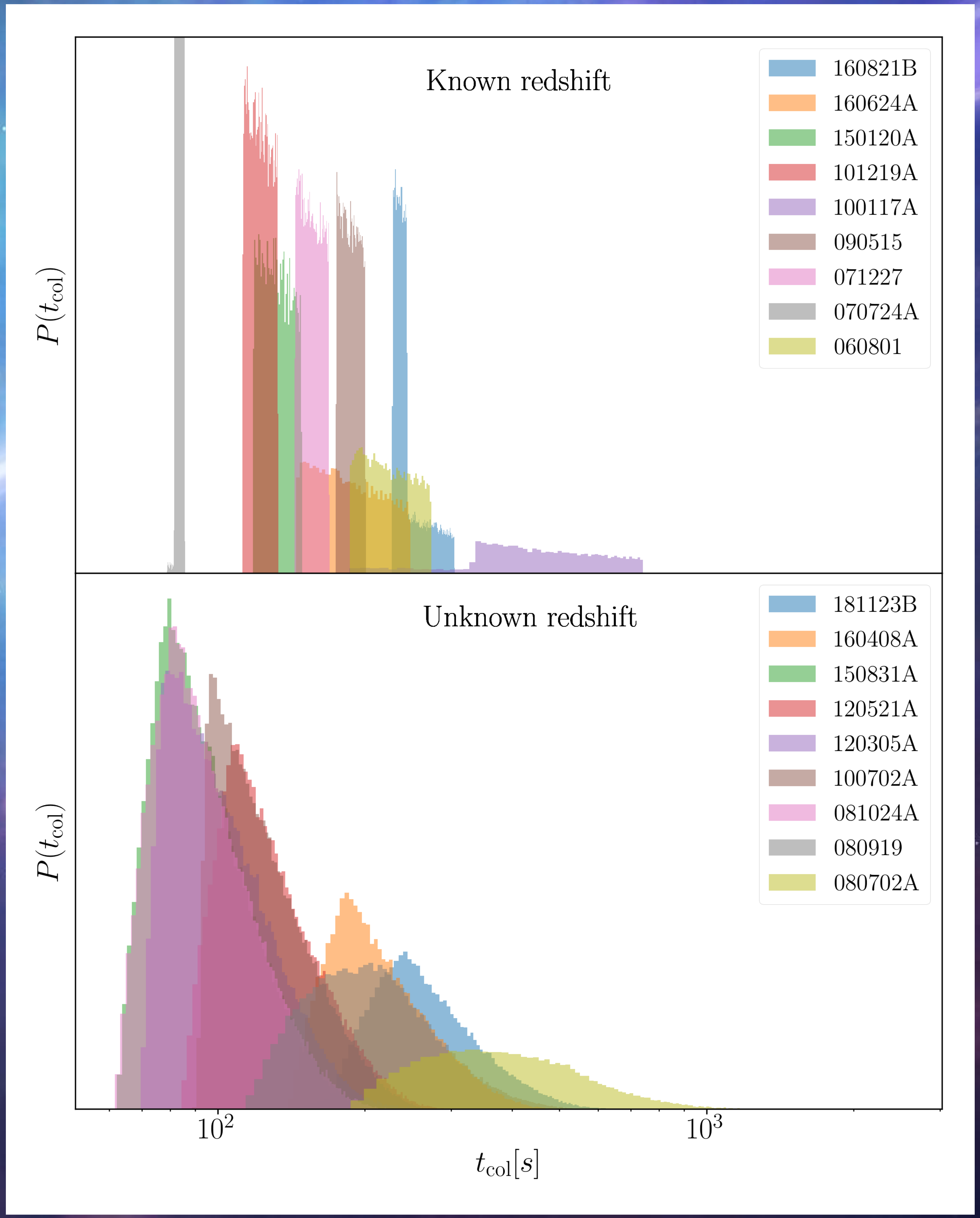
- Can measure the braking index of putative nascent neutron stars.



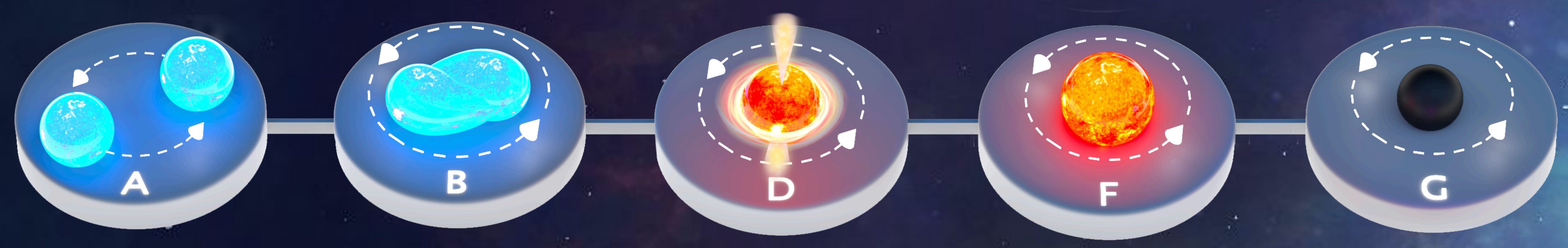
Sarin+2020b

- GRB061121 potentially spins down predominantly through gravitational-wave emission.
- Do we expect to detect these gravitational waves in aLIGO? No. See e.g., Sarin+2018.

- We can look at the population as a whole.
- We measured the collapse-time of 18 putative long-lived neutron stars from the X-ray afterglow of 72 short gamma-ray bursts.



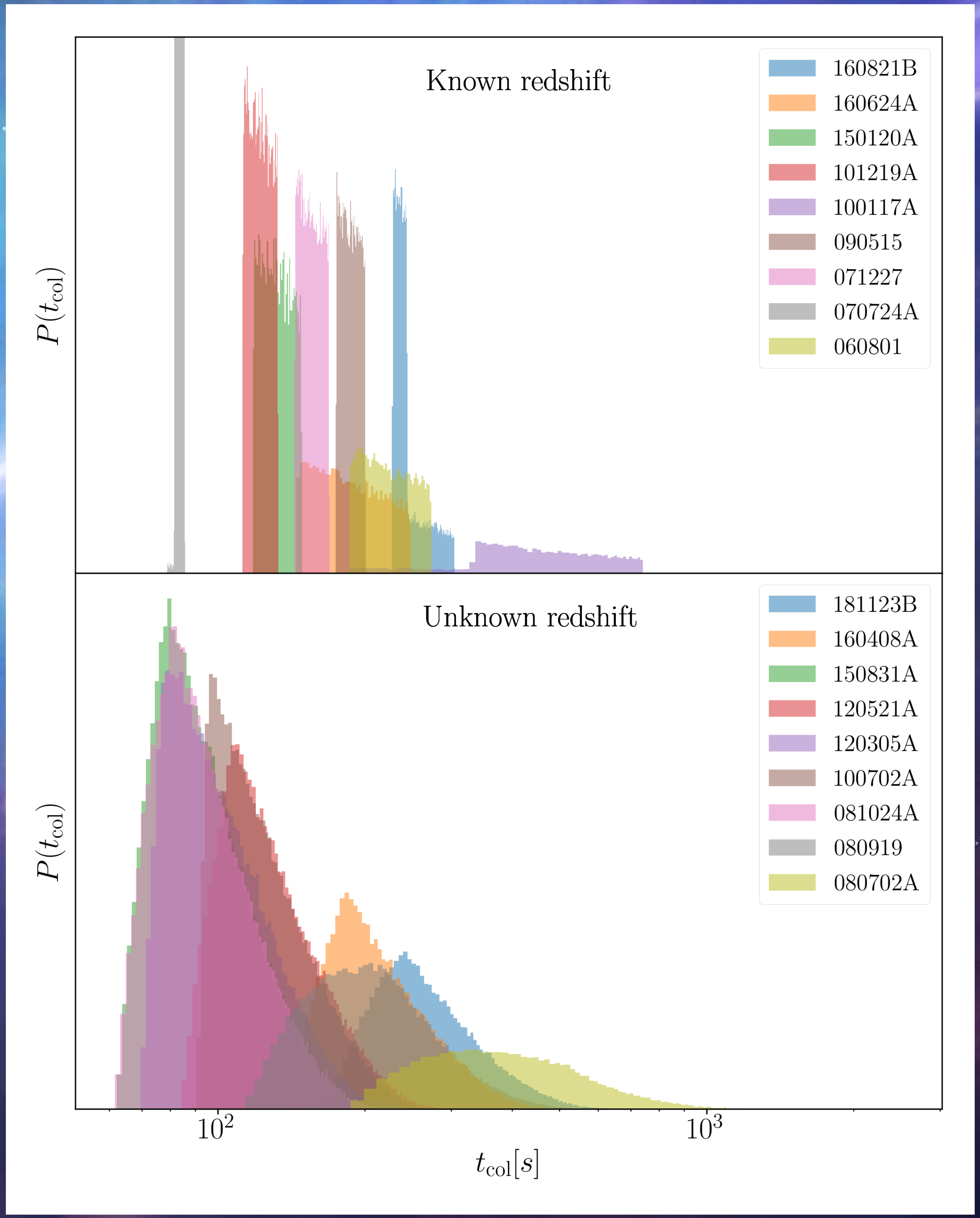
Sarin+2020a



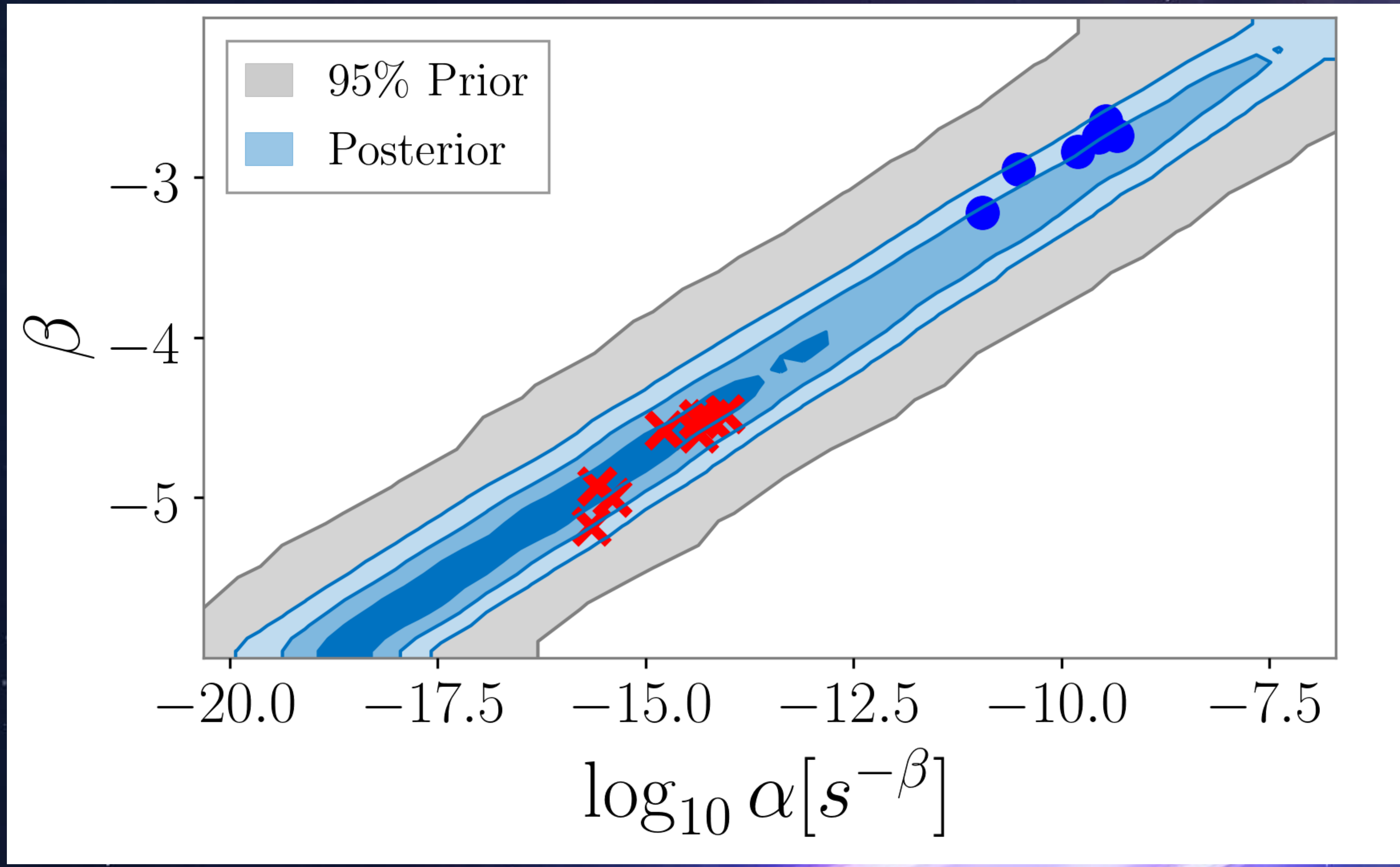
$$t_{col,i} \propto \tau_i, p_{0,i}, M_{p,i}, \gamma_i, \alpha, \beta, M_{\mathrm{TOV}}$$

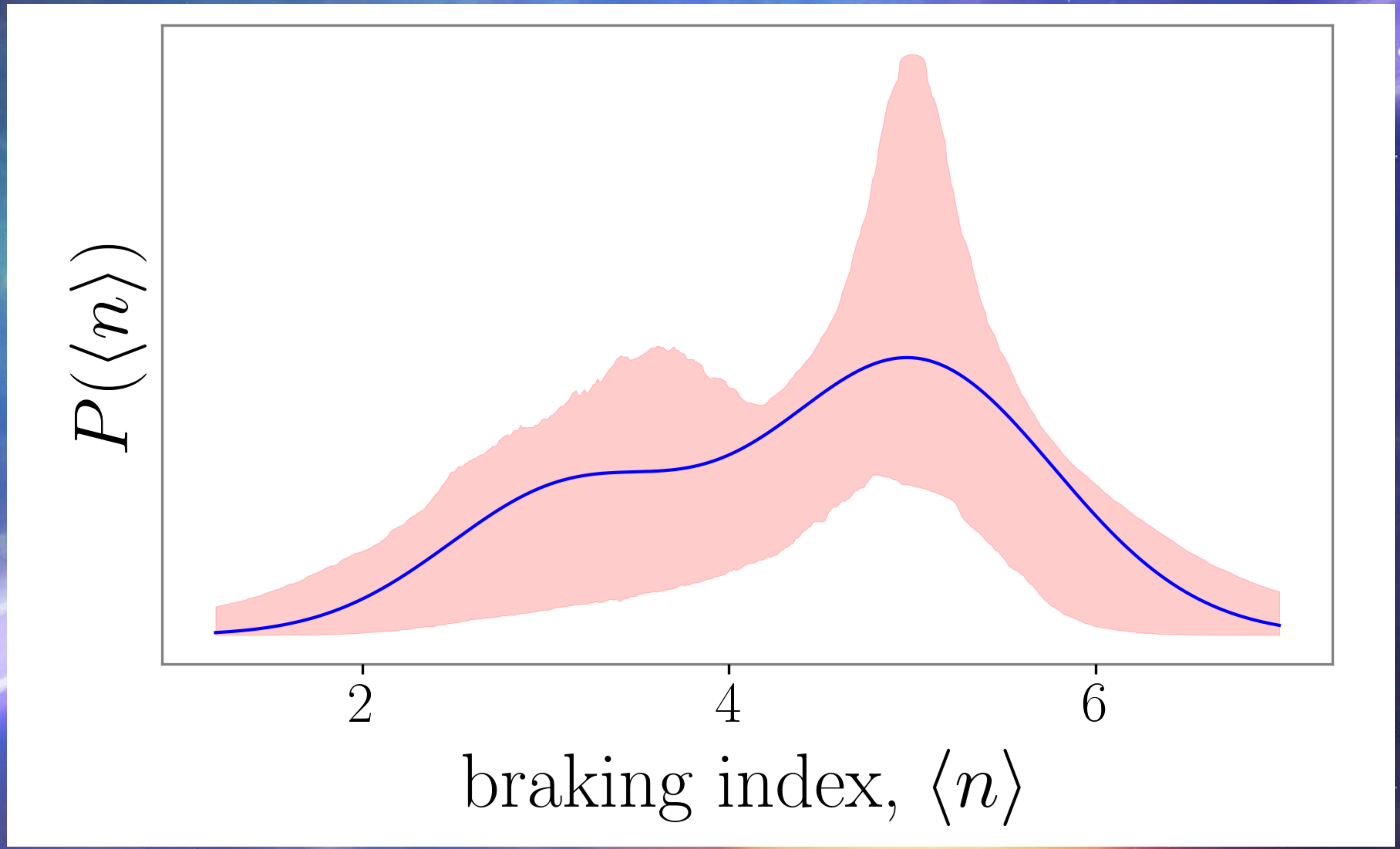
$$\gamma_i = \frac{\langle n \rangle_i + 1}{\langle n \rangle_i - 1},$$

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



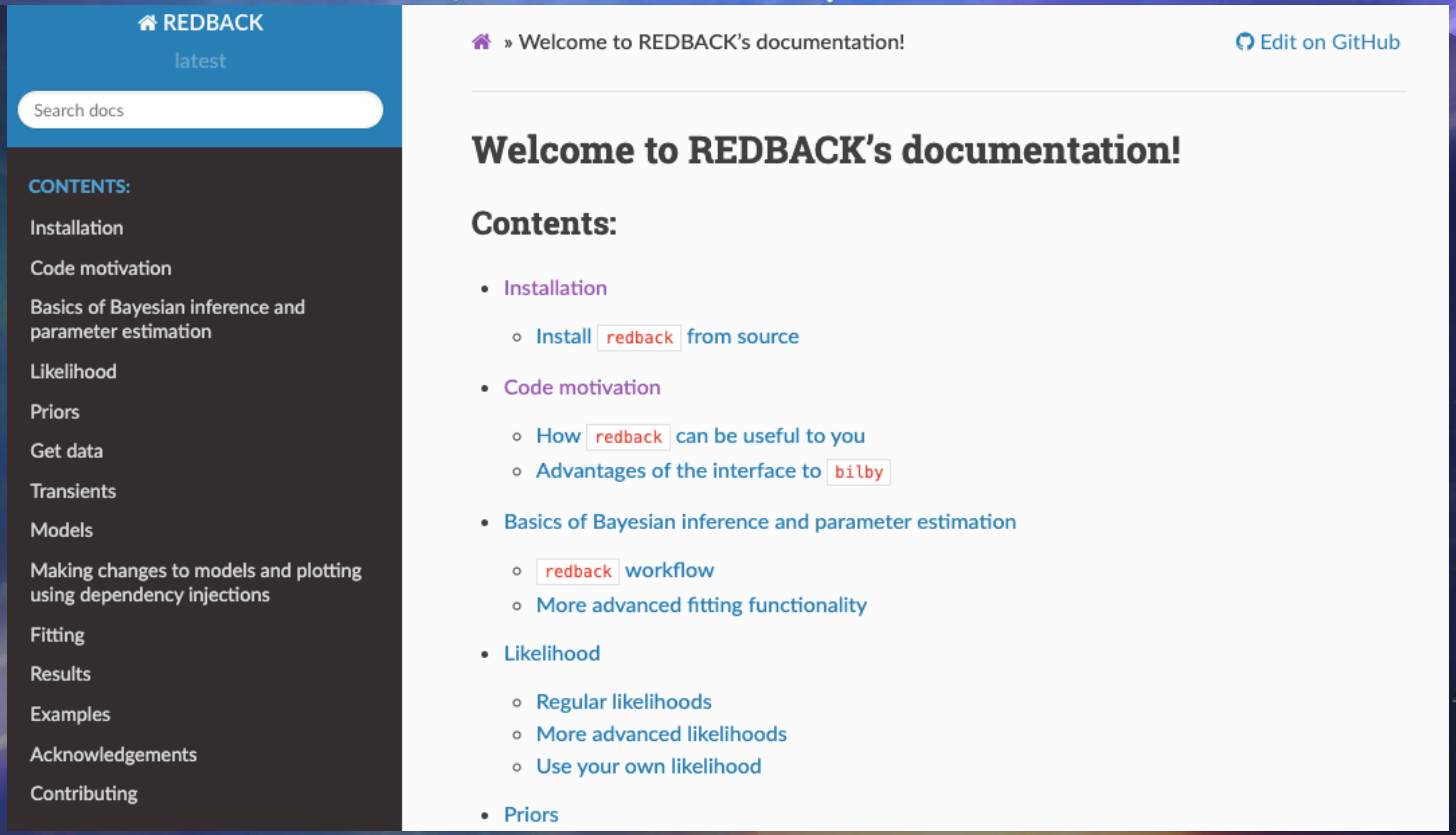
Sarin+2020a

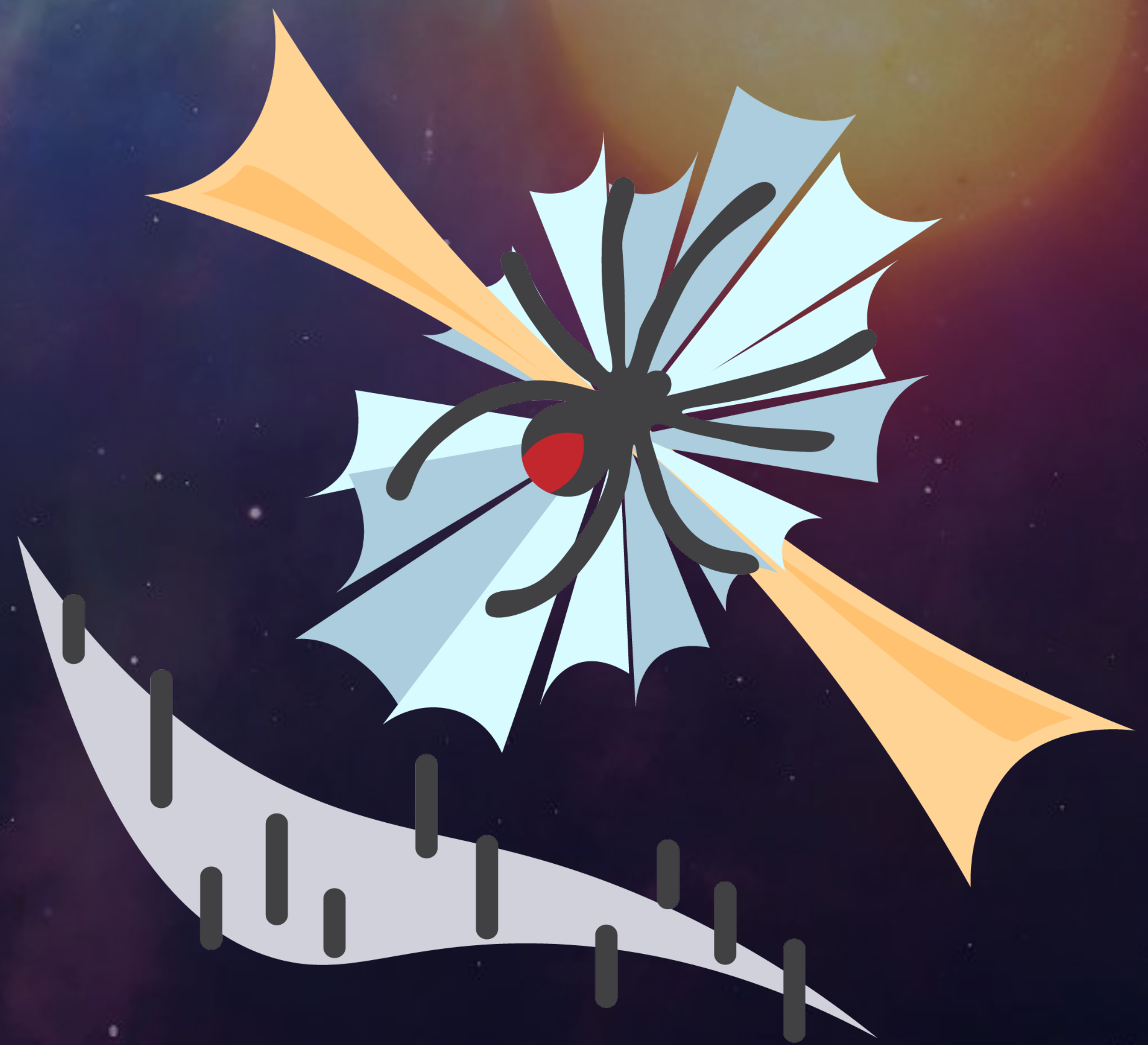


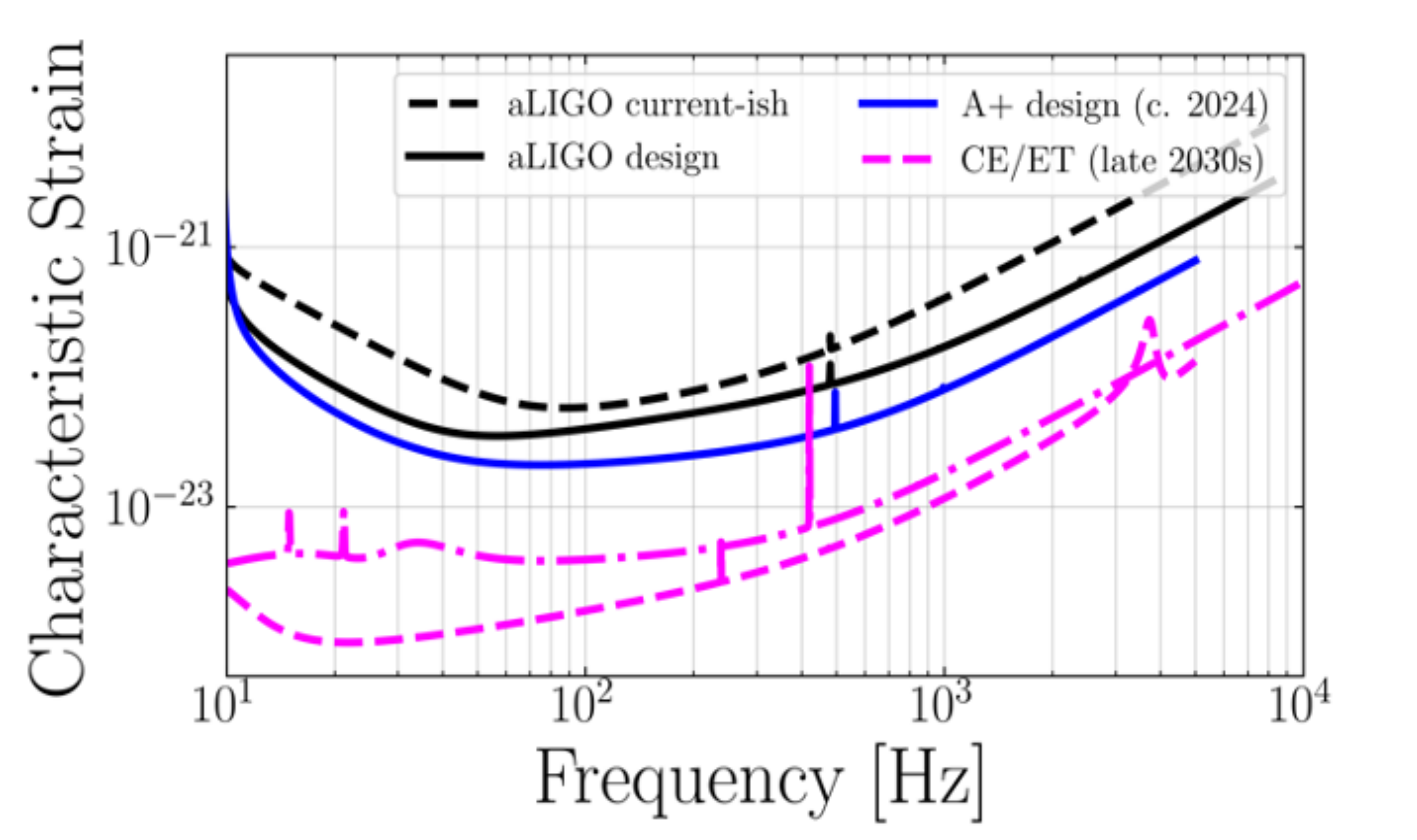


- Some indications that these post-merger remnants are quark stars, at the one-sigma level.
- A significant fraction of these objects spin-down predominantly through gravitational-wave emission.
  - Impact on kilonova and radio remnant!

- An open source bayesian inference package for fitting and simulating electromagnetic transients.
  - GRB afterglows, kilonovae, supernovae, TDE's, FBOTs, millisecond magnetar's, engine-driven explosions, and other exotica.
- Interface to download data for different transients from Swift/ZTF/BATSE/Lasair.
- ~15 different samplers, over ~100 models for different electromagnetic transients. Users can also fit their own model.
- Hosted on Github with several of examples, documentation, unit tests. Installable with pip.
  - Currently in alpha with a paper in preparation.
- All contributors in alpha will be invited to be authors!

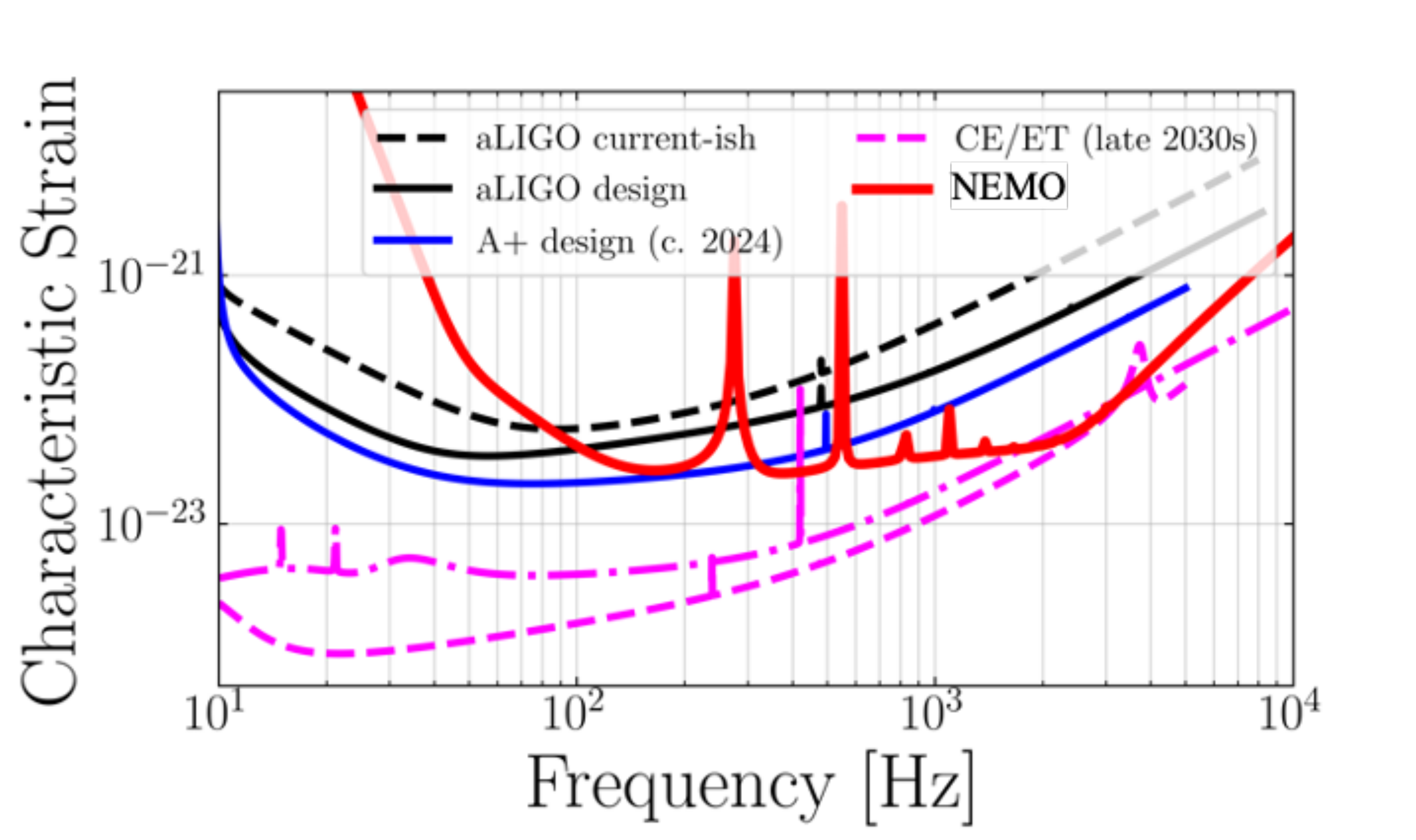






Mostly funded,
minimal technology risk

Not funded,
Unchartered territory in terms of technology



Ackley (incl. NS)+2020

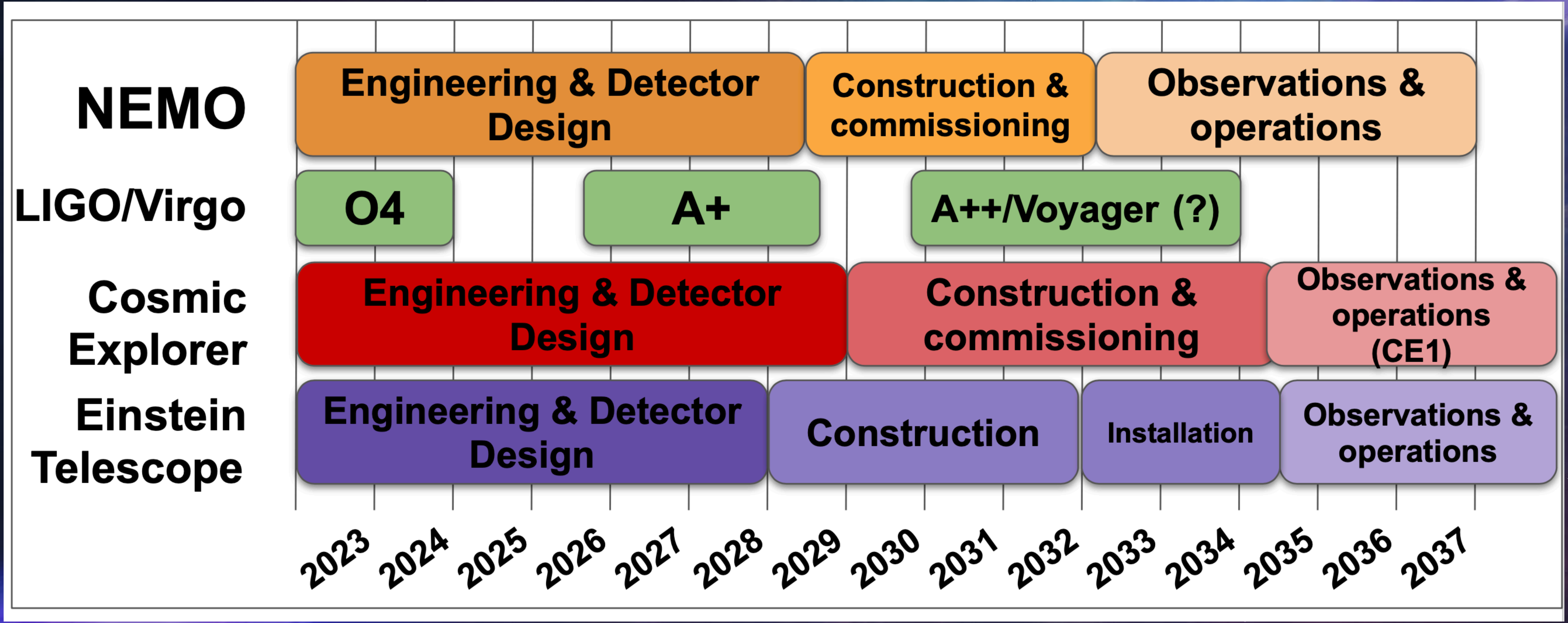
Mostly funded, minimal technology risk

Not funded, Unchartered territory in terms of technology

Scale: ~$100 M (cf ~$2B for CE)

Dedicated science goals: neutron stars

Technology development for full 3G detector

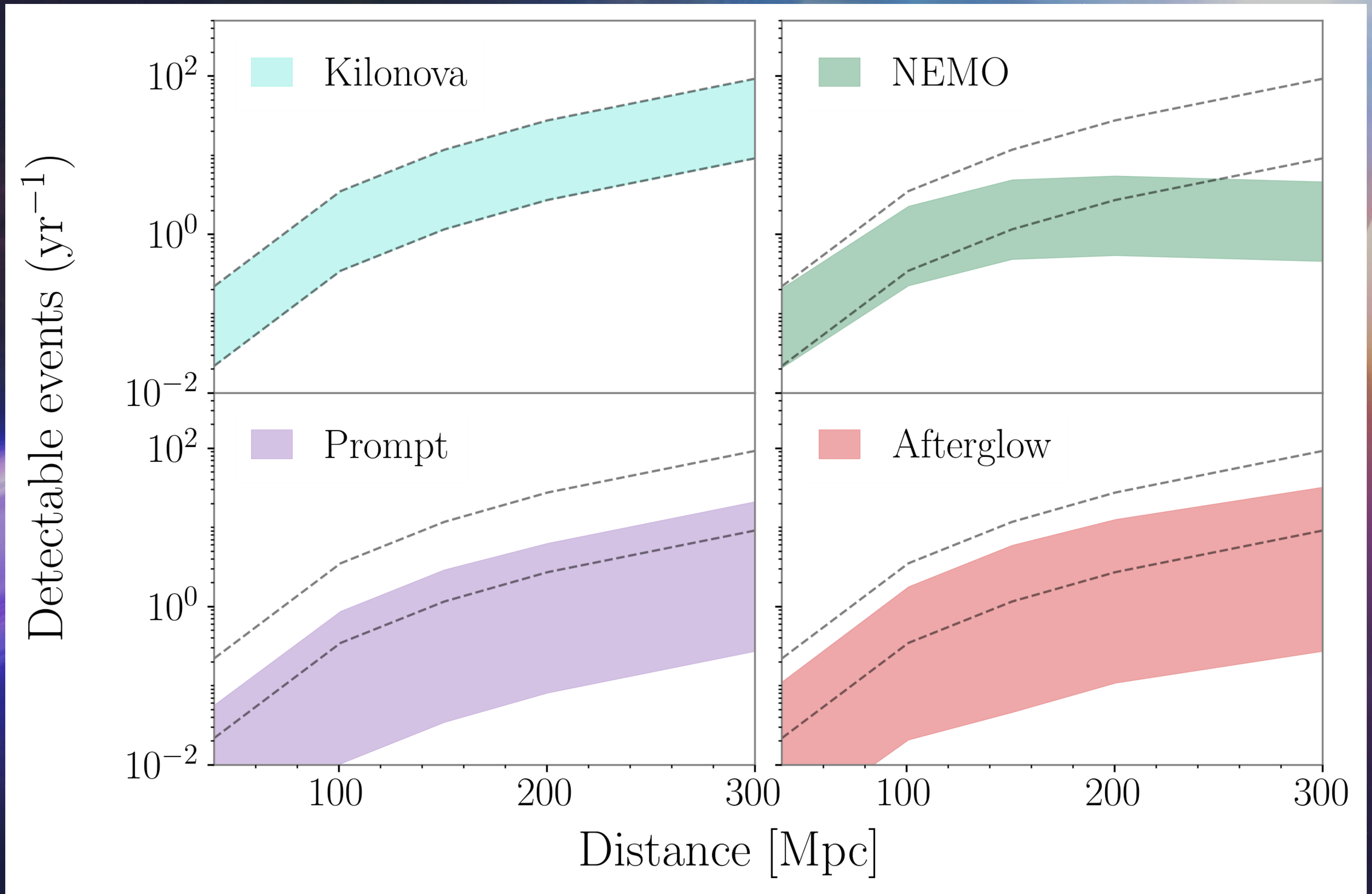


- NEMO may begin operation in an era where it is the only gravitational-wave detector.

- Plenty of survey/all sky telescopes in the late 2020s-2030s.
- Many electromagnetic counterparts will be discovered independently of the GW trigger.
- Question really is: *How confidently can we associate an EM counterpart with a GW signal?*

Adapted from a talk by Marica Branchesi

- Simulate a realistic distribution of BNS and their EM counterpart.
  - Is it detectable? Can the EM counterpart be confidently associated with the GW signal?
- Use the sensitivity limits of Vera Rubin (r > 24.7), Theseus ($\gtrsim 3 \times 10^8 \mathrm{erg\ cm^{-2}\ s^{-1}}$) and NEMO (SNR > 8) to calculate detectability with a population of BNS's at various distances and inclinations.

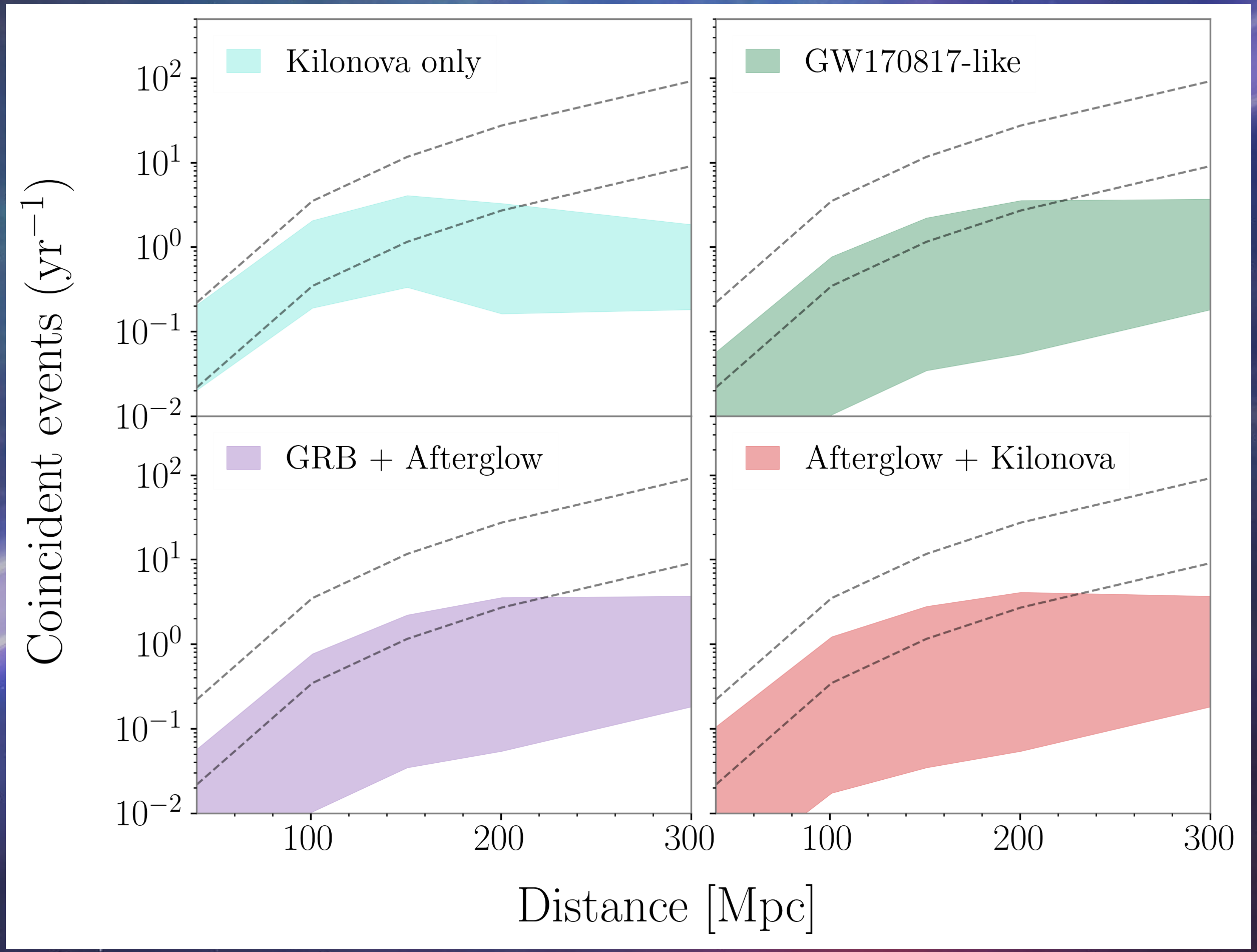


Sarin and Lasky (2022a)

- 3^{+11}_{-2} (90% CI) events per year could have a detectable prompt, afterglow, kilonova, and GW signal and be confidently associated with each other.

- 13^{+23}_{-10} (90% CI) KN + GW events per year.

- 14^{+25}_{-11} (90% CI) MM events per year observed in gravitational waves with NEMO alone.



	prompt afterglow kilonova	prompt afterglow	afterglow kilonova	kilonova
$\mathcal{F}$ (< 300 Mpc)	$0.096^{+0.072}_{-0.068}$	$0.096^{+0.072}_{-0.068}$	$0.13^{+0.13}_{-0.09}$	$0.38^{+0.3}_{-0.01}$
$\mathcal{R}$ (yr^{-1})	3^{+11}_{-2} yr^{-1}	3^{+11}_{-2} yr^{-1}	4^{+18}_{-3} yr^{-1}	13^{+23}_{-10} yr^{-1}

Sarin and Lasky (2022a)

- Current constraints suggest that >40% of BNS mergers launch jets.
  - Disfavours the existence of a mass gap between neutron stars and black holes.
- The merger outcome has significant implications for what we might see from a binary neutron star merger. Early X-ray afterglow observations are invaluable in determining the fate of binary neutron star mergers.
- If you want to fit a model to an electromagnetic transient consider using Redback!
- NEMO will enable direct constraints on the neutron star central engine preceding full 3G gravitational-wave detectors at a fraction of the cost.
- Survey telescopes provide localisation so NEMO alone can do multi-messenger astronomy!
  - ~40% of BNS mergers out to 300 Mpc detected with NEMO alone could be confidently associated with their electromagnetic counterpart.