NORDITA
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THE DIVERSE EM COUNTERPARTS OF NEUTRON STAR BINARY MERGERS

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OzGrav

Sarin and Lasky (2021)
Review in General
Relativity and Gravitation.

Image credit: Carl Knox

- The properties of the merger dictate what the potential observables are and what timescales we need to observe them.
  - Kilonova
  - Jets/GRB
  - Gravitational waves
  - Radio remnant
  - FRBs

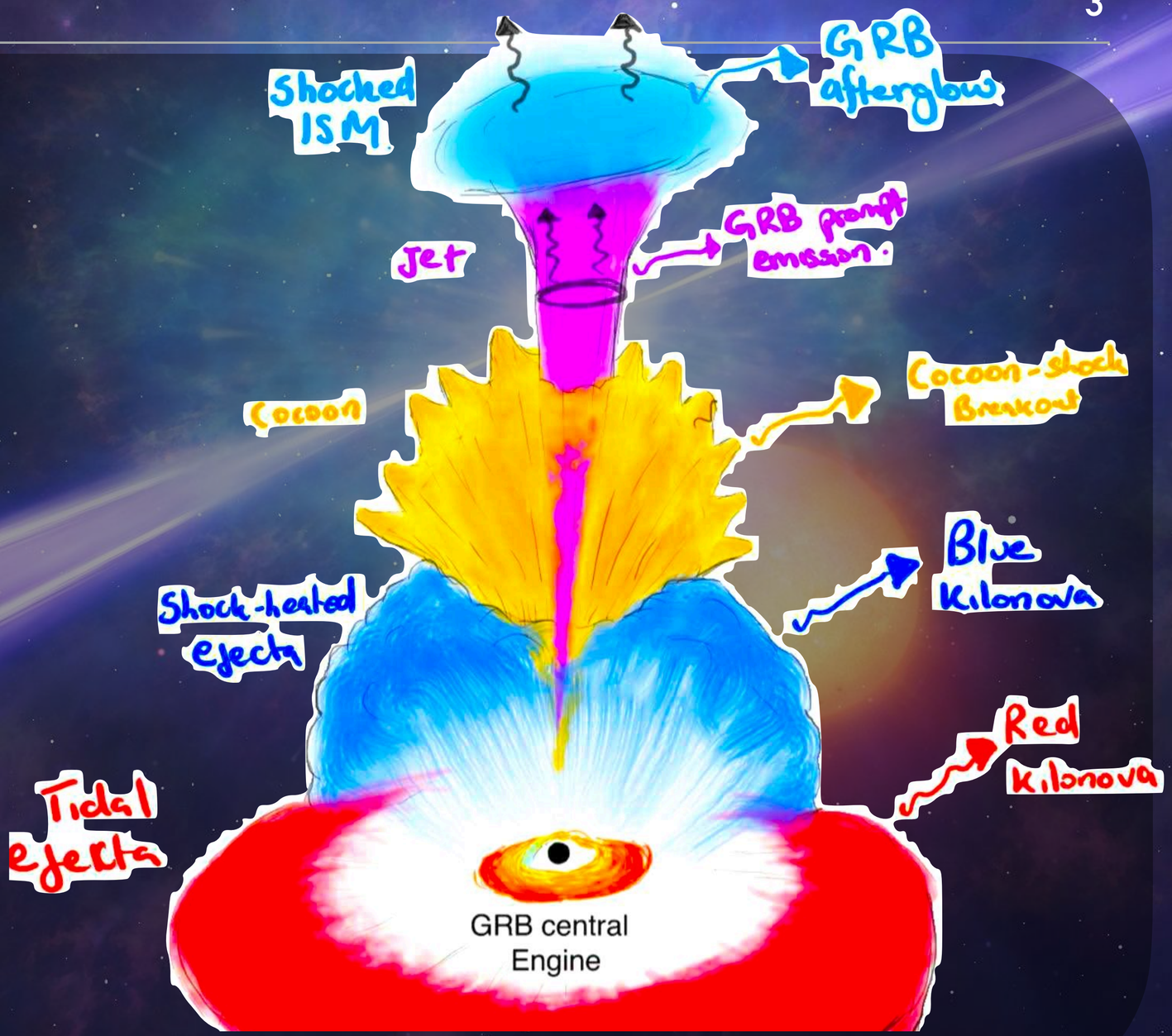

Figure from Ascenzi+2020

- What can we do with the data we already have!?
- 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
- Single extraordinary events e.g., GRB211211A

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

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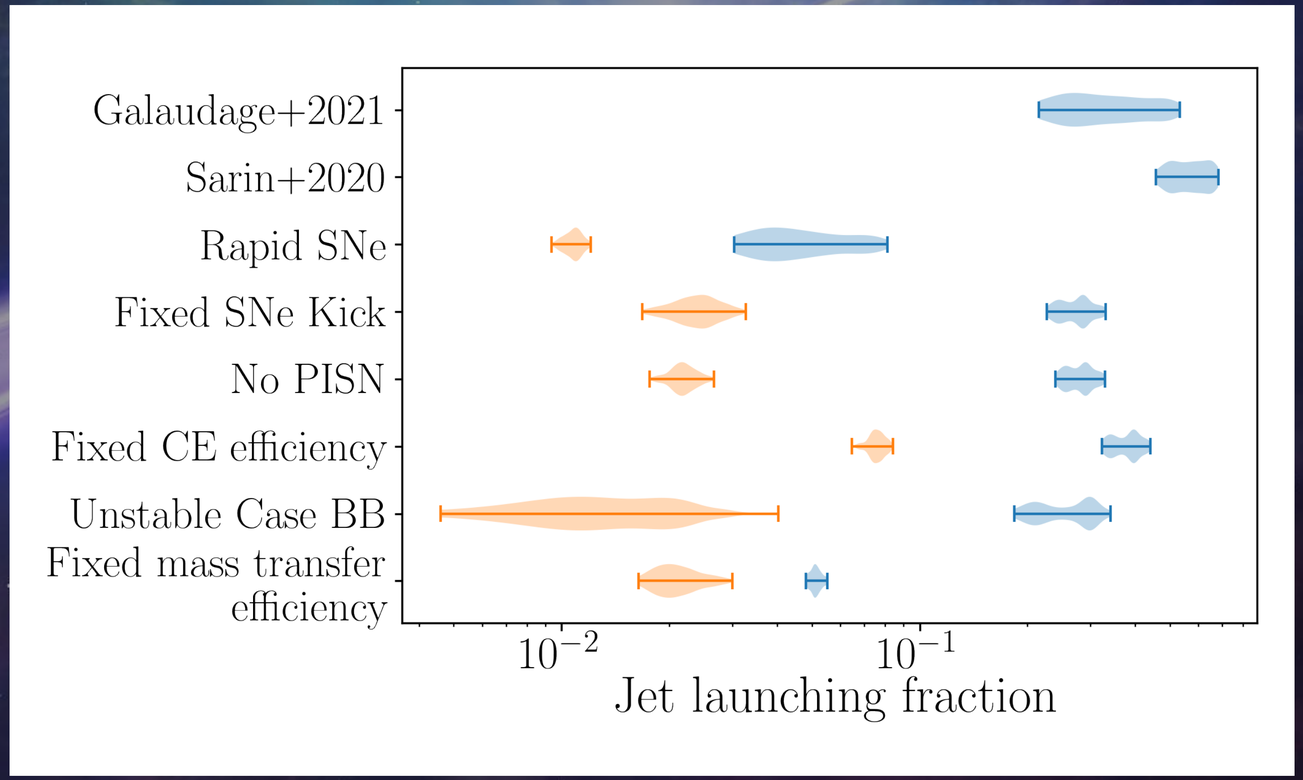
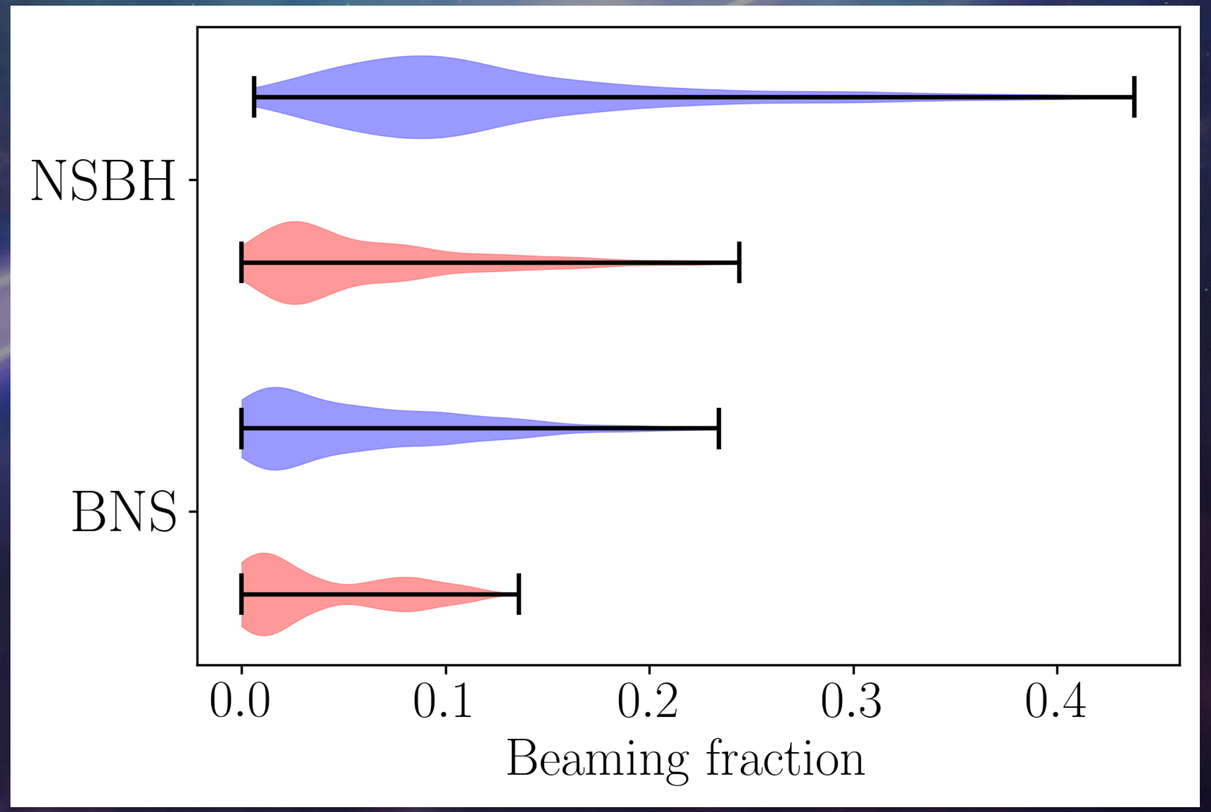
- $f_{s,\rm BNS}$ and $f_{s,\rm NSBH}$ are the fraction of BNS and NSBH mergers that launch jets.
- Dictated by the properties of the binaries that merge –> tell us about binary evolution!
  - Most assumptions about binary evolution predict ~1-2% and ~30% of NSBH and BNS launch jets.



Sarin+2022b

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

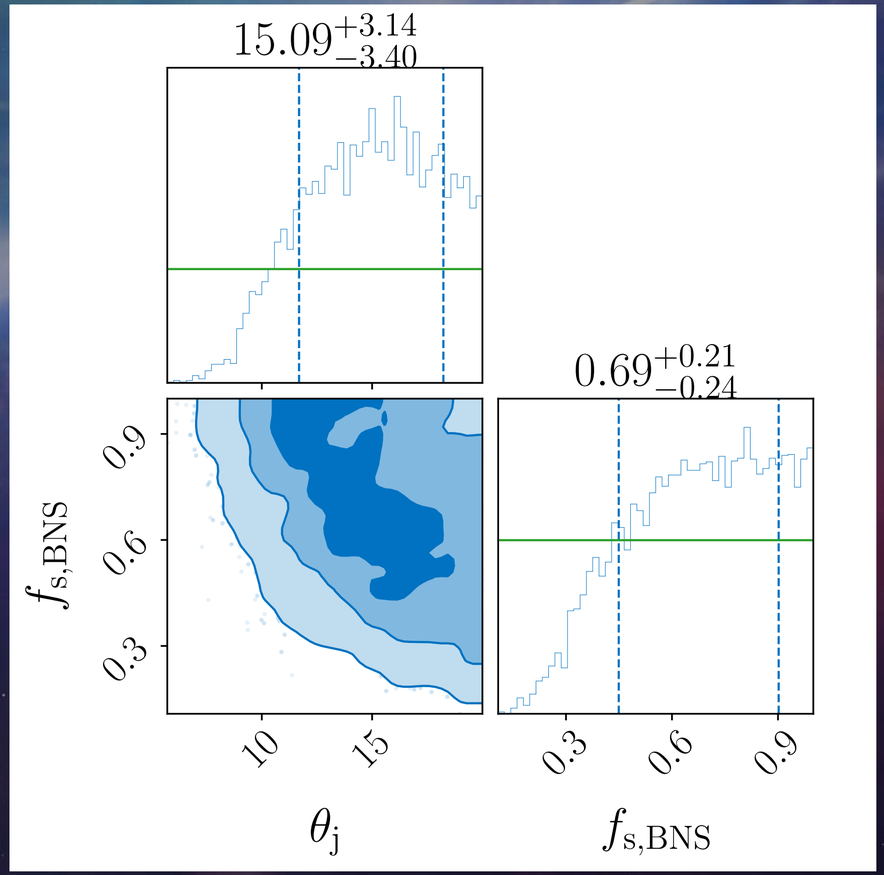
- $\eta_{\rm BNS}$ and $\eta_{\rm NSBH}$ are the 'beaming fraction' of BNS and NSBH mergers.
- Dictated by the gamma-ray burst physics–> tell us about jet launching and propagation!
  - BNS jets are more collimated.
  - Power-law jets are visible for larger range of observer viewing angle compared to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

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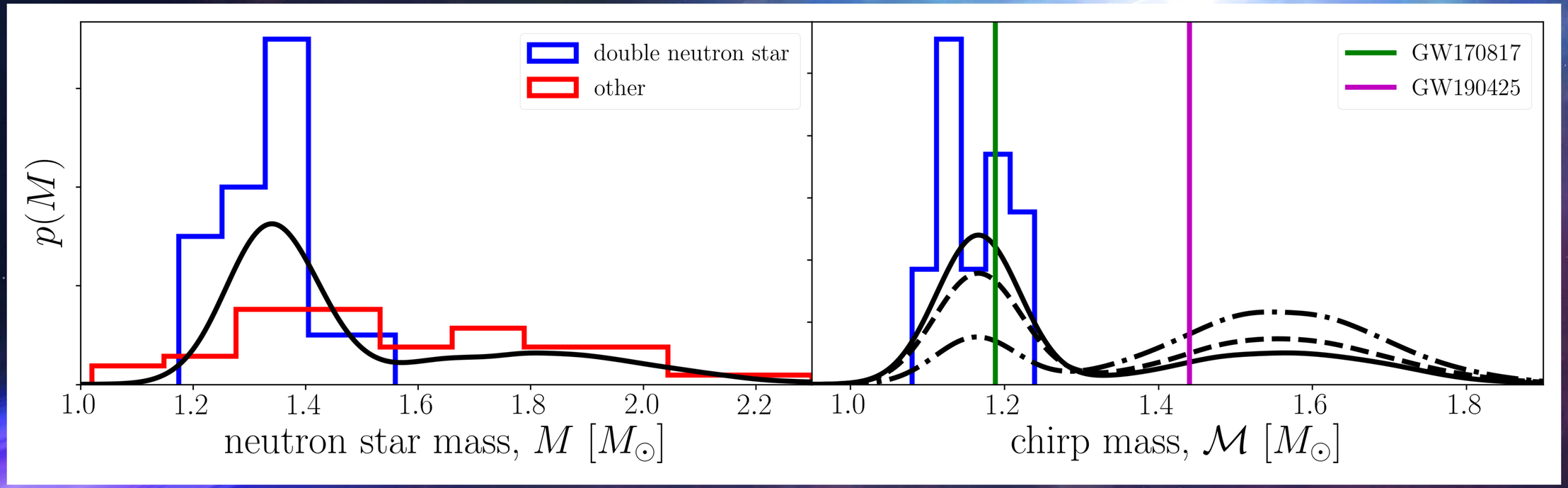
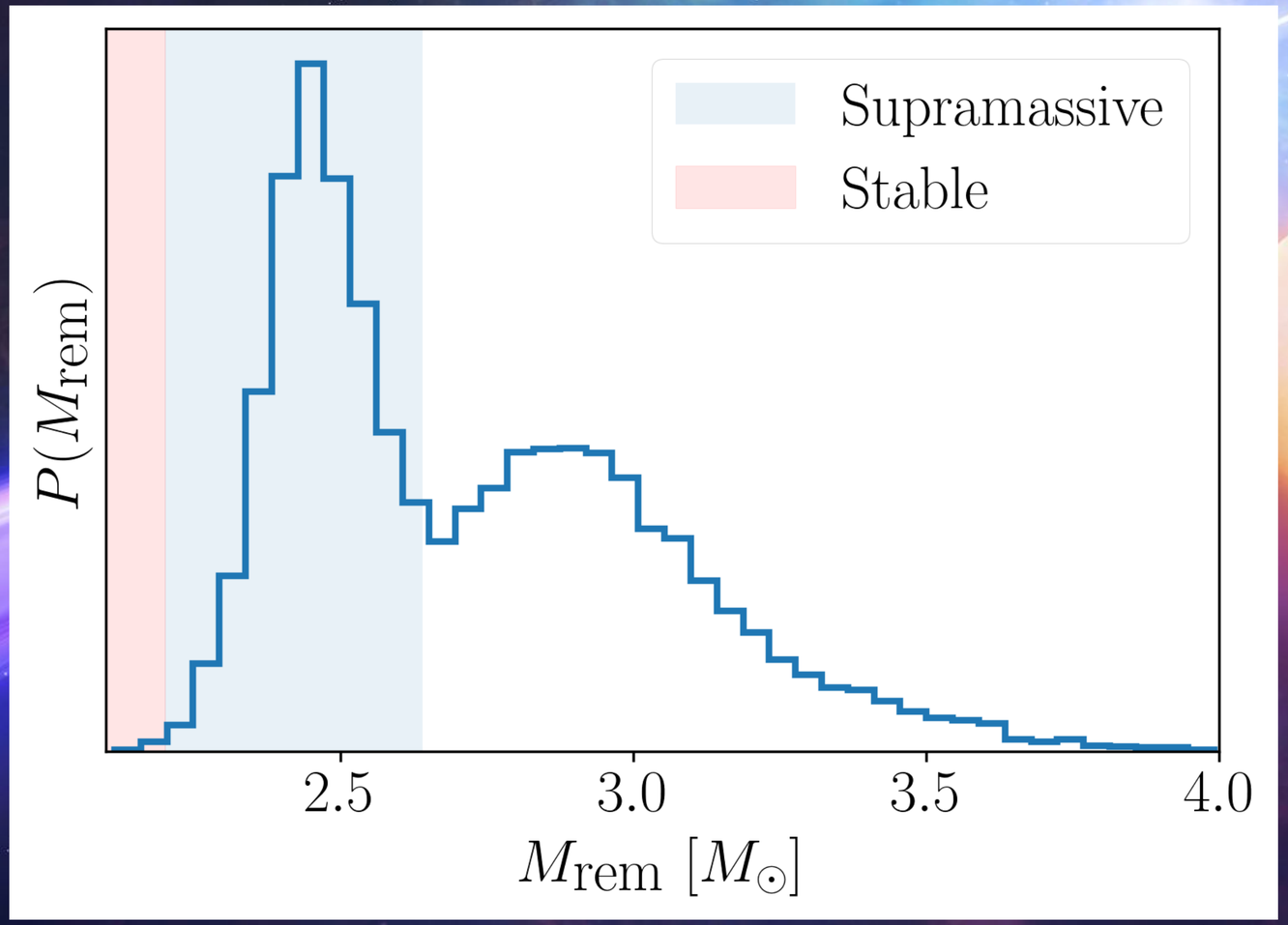
- We don't know the binary neutron star mass distribution...
  - We don't know the equation of state either...



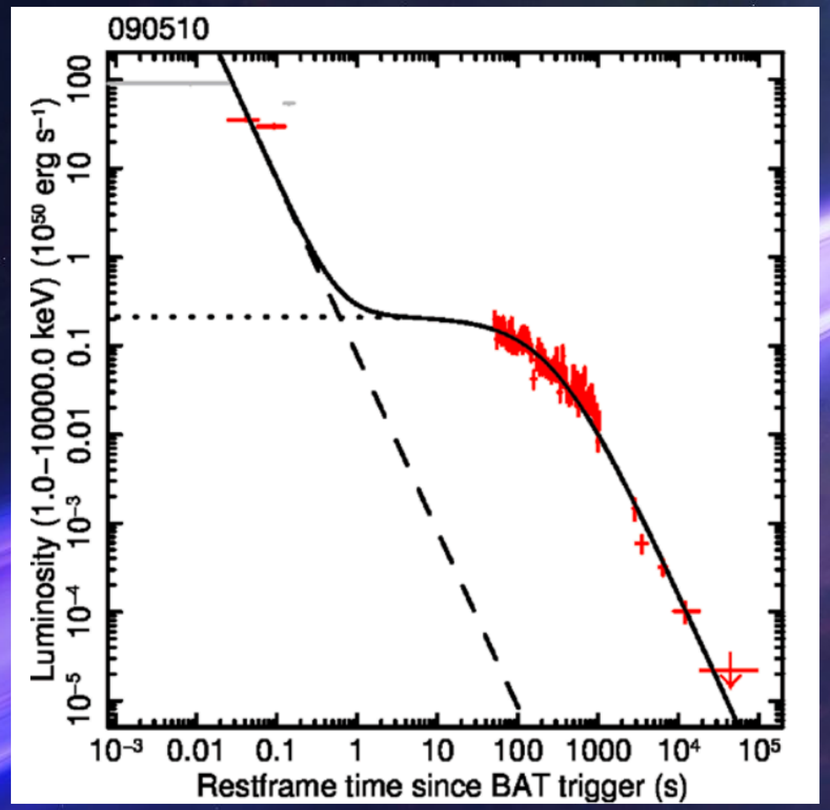
Sarin+2020a

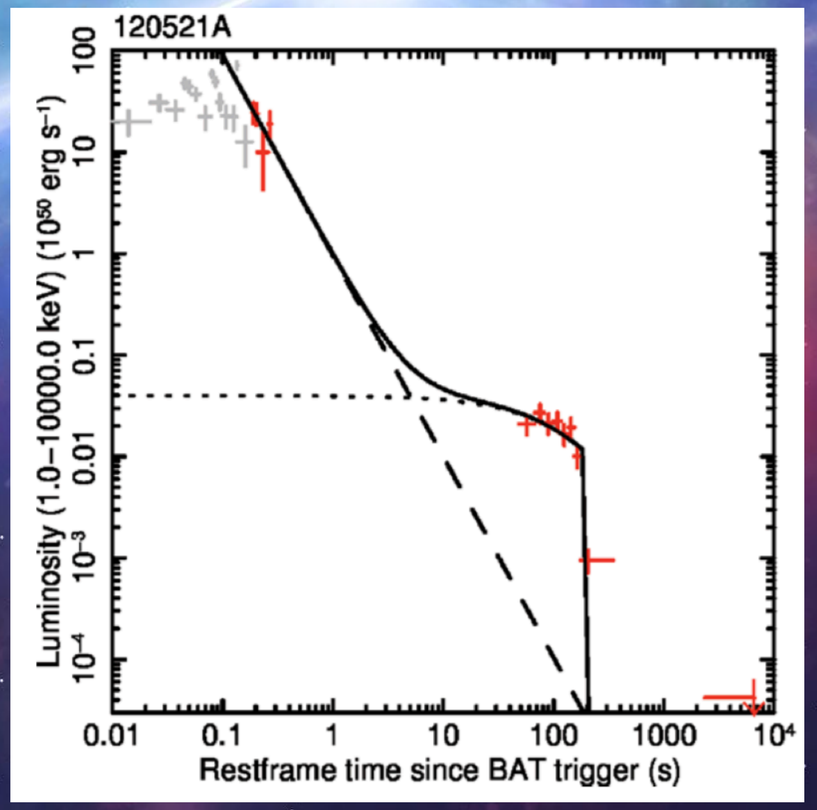
SO HOW MANY MERGERS DO WE EXPECT TO PRODUCE A LONG-LIVED NS?

- ~50% of neutron star mergers should form a long-lived remnant.
- An engine which can dramatically alter the multi-messenger signals from a BNS merger



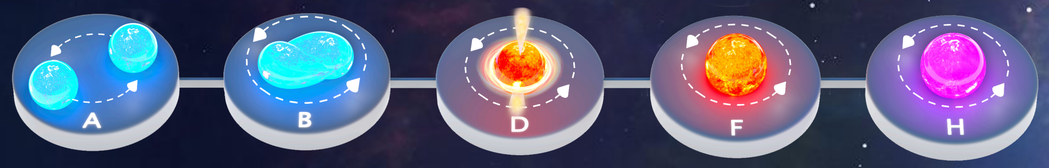
- The X-ray afterglows of a good fraction of GRBs have features that are incredibly difficult to explain with the interaction of a jet with the surrounding interstellar medium.

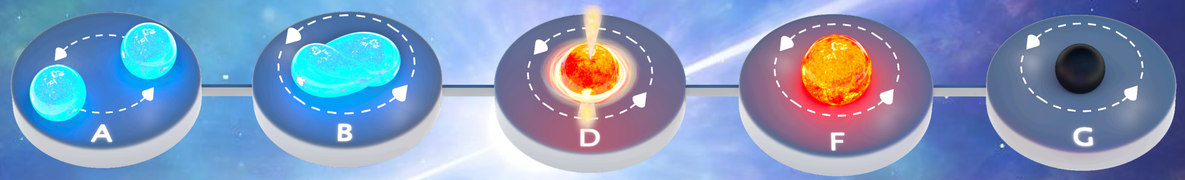


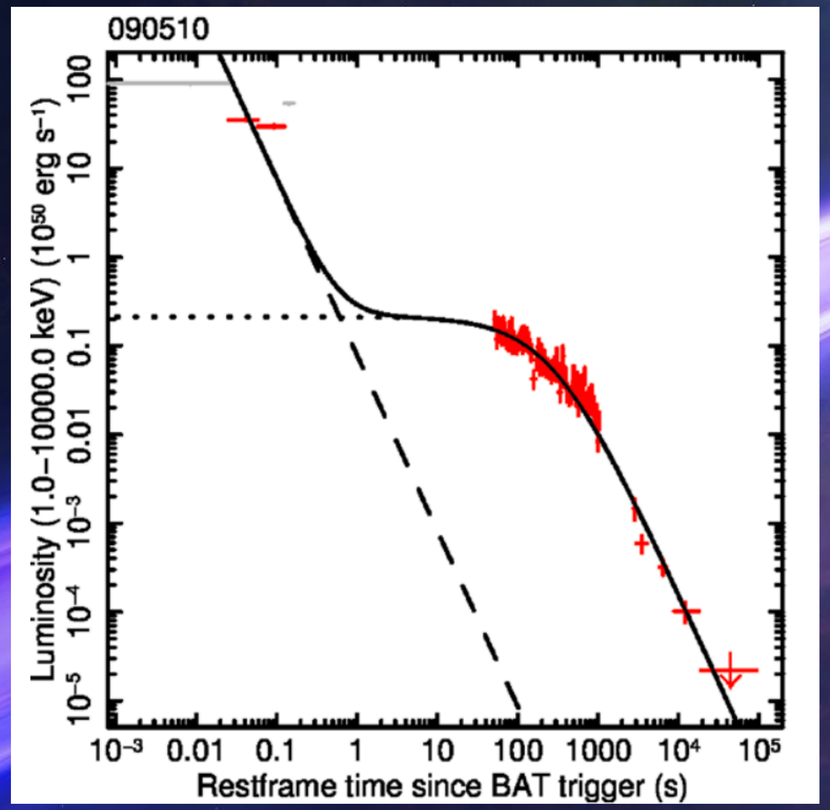


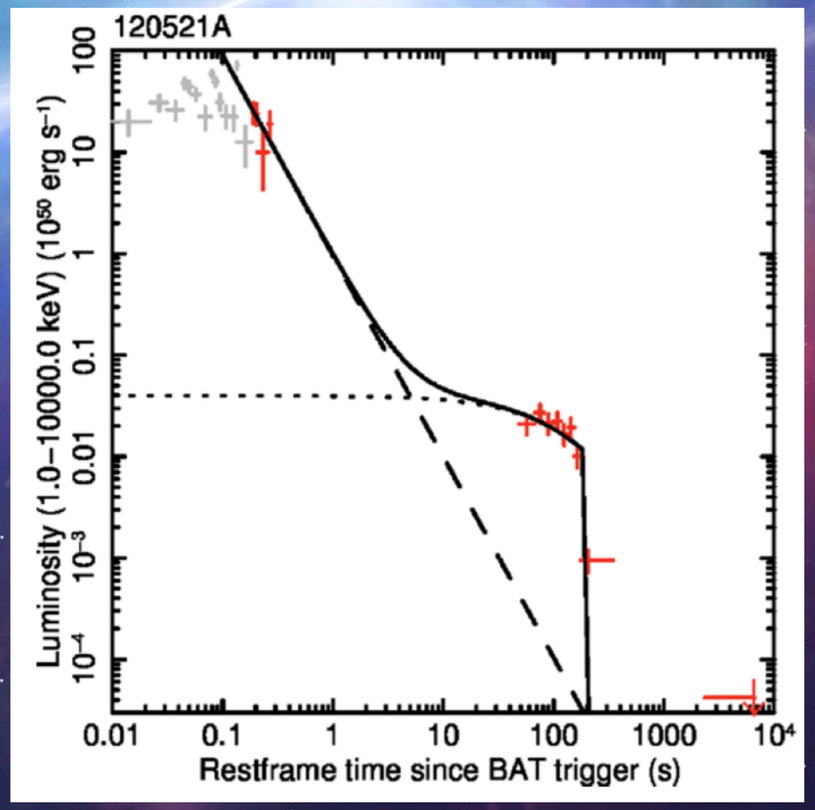
Rowlinson+2013

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



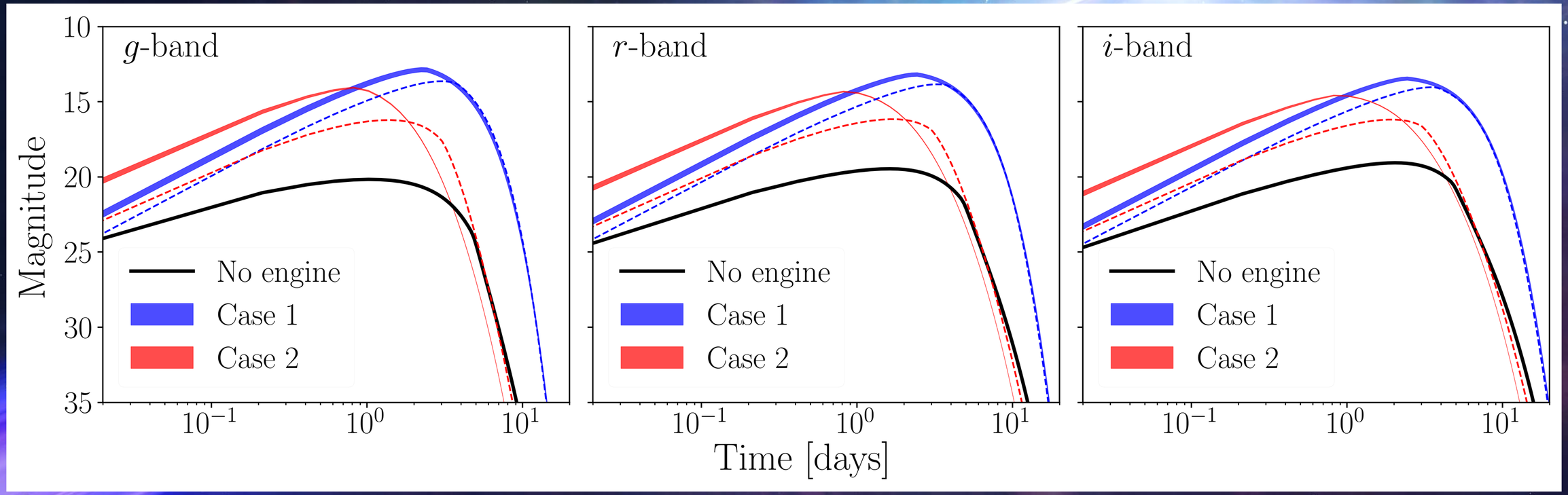






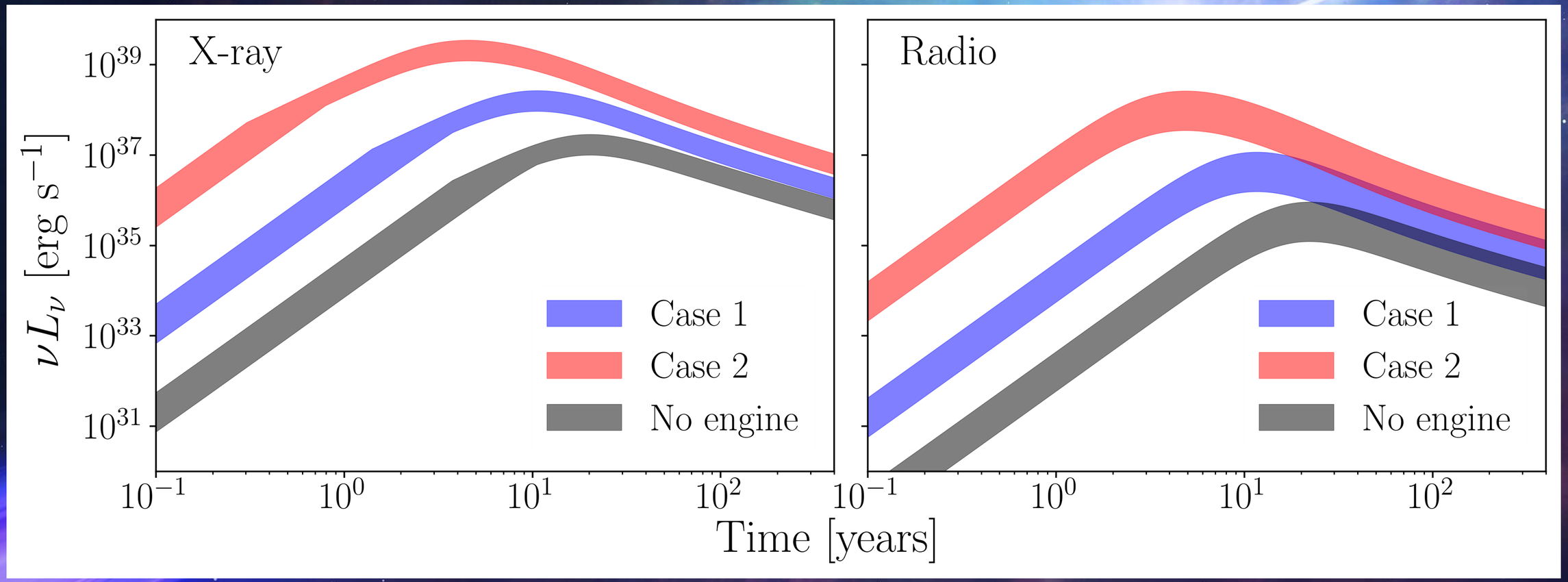
Rowlinson+2013

- The large rotational energy reservoir (1e53 c.f. 1e51) can dramatically alter the kilonova and kilonova afterglow signature.



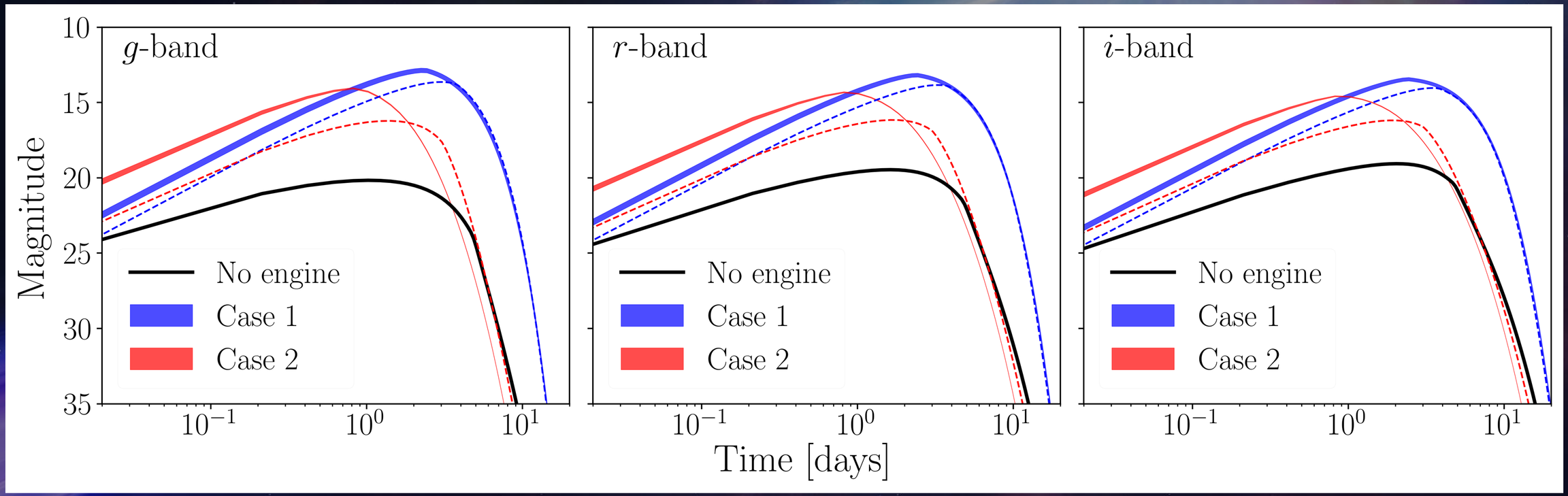
Sarin+2022c

- Kilonova afterglows/Radio remnants



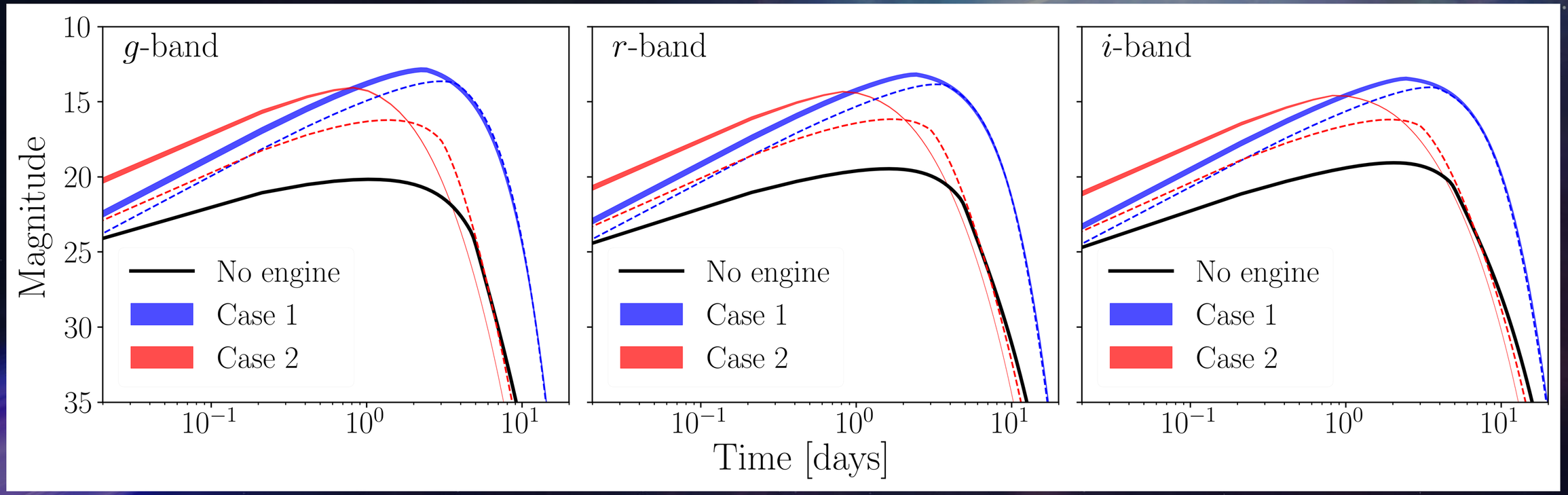
Sarin+2022c

- Nuclear heating e.g., Zhu+21, Barnes+21
- Interaction with jet e.g., Klion+21, Nativi+21
- Ejecta distribution… one/two components? Stratified shells expanding homologously?



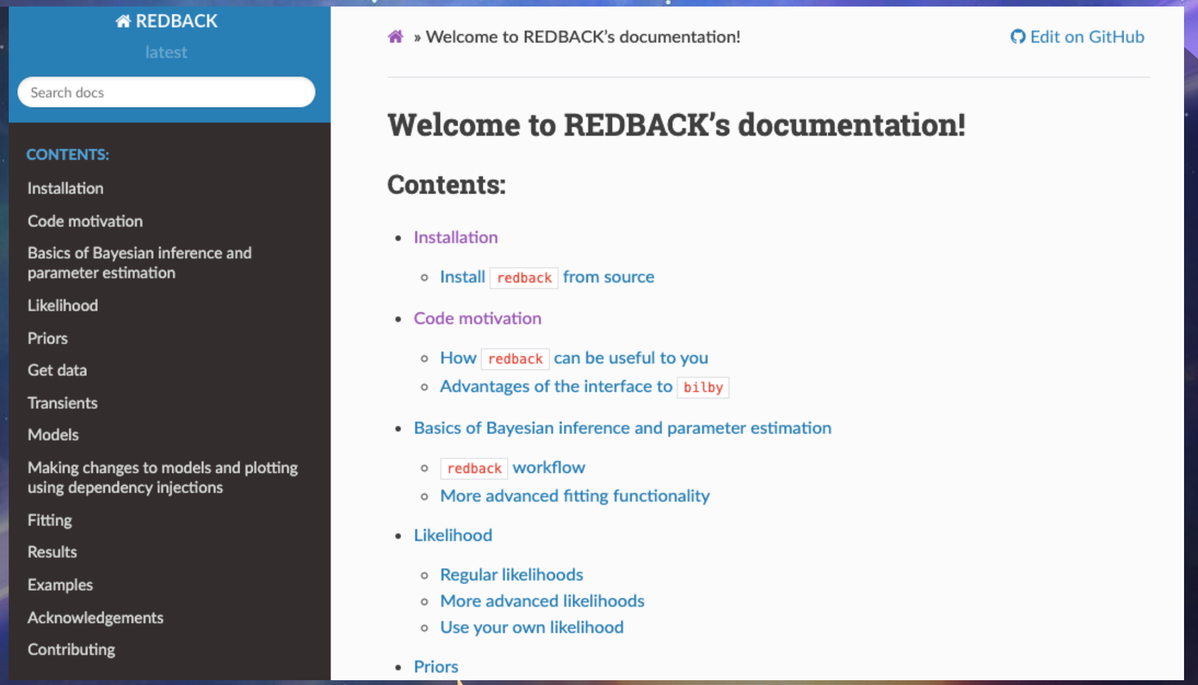
Sarin+2022c

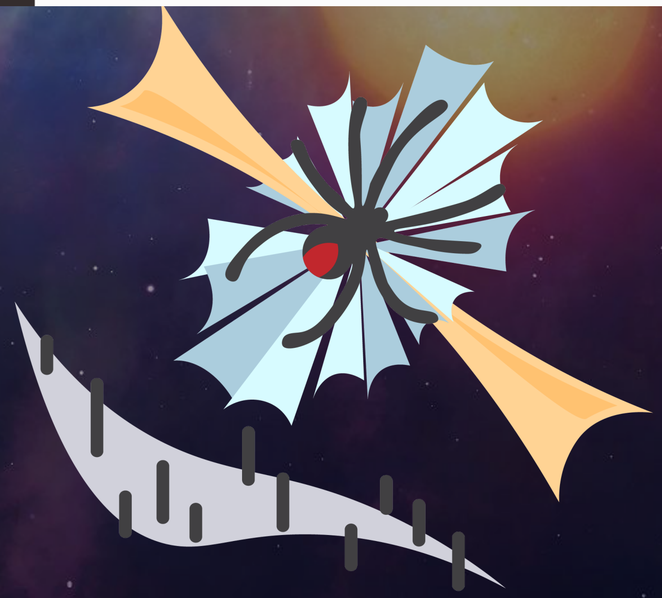
- Given the systematics; conclusions should be drawn through principled inference.
  - Or at the very least through more than just photometry!



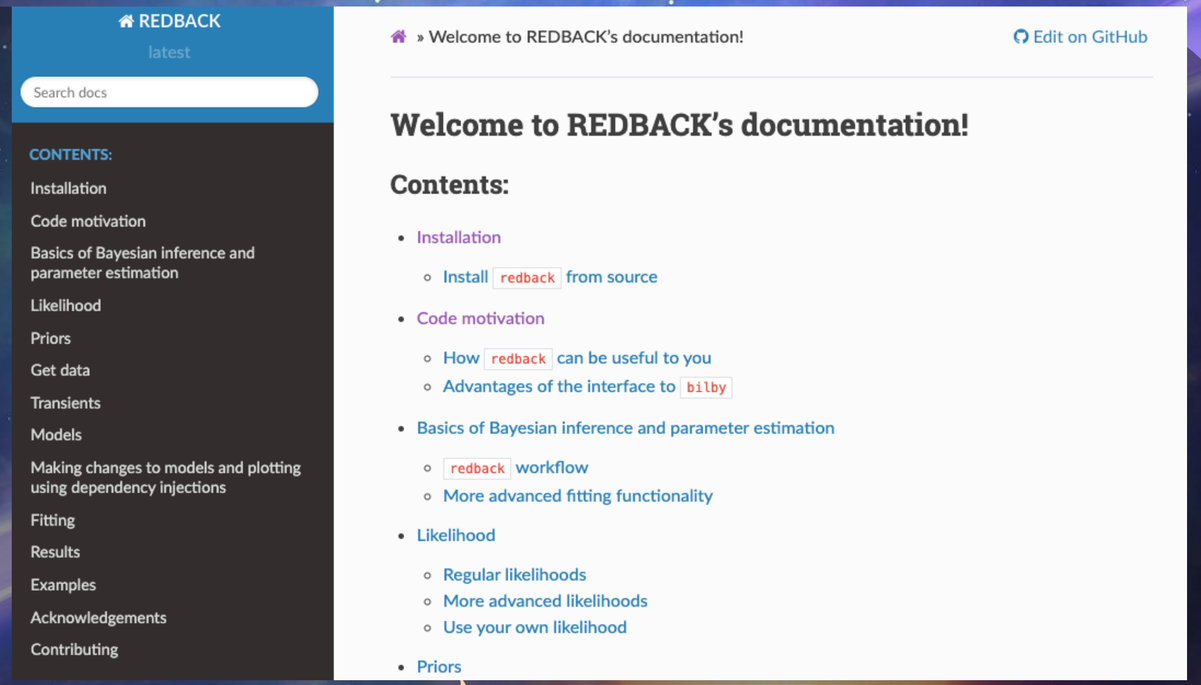
Sarin+2022c

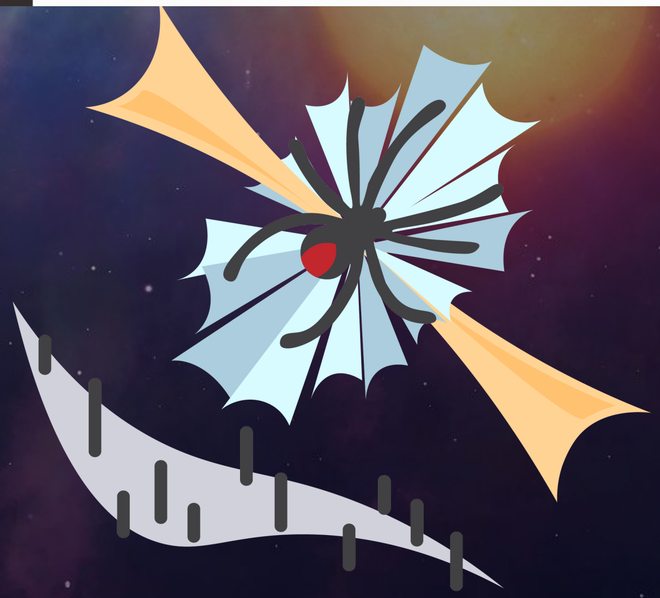
- Open-source Bayesian inference package for fitting and simulating electromagnetic transients.
  - GRB afterglows, kilonovae, supernovae, TDE's, FBOTs and other exotica.
- Interface to download and process data for different transients from public catalogs.
- ~15 different samplers, over ~150 models for different electromagnetic transients. Users can also fit their own model.
- Fit magnitudes, flux, flux density or luminosity.





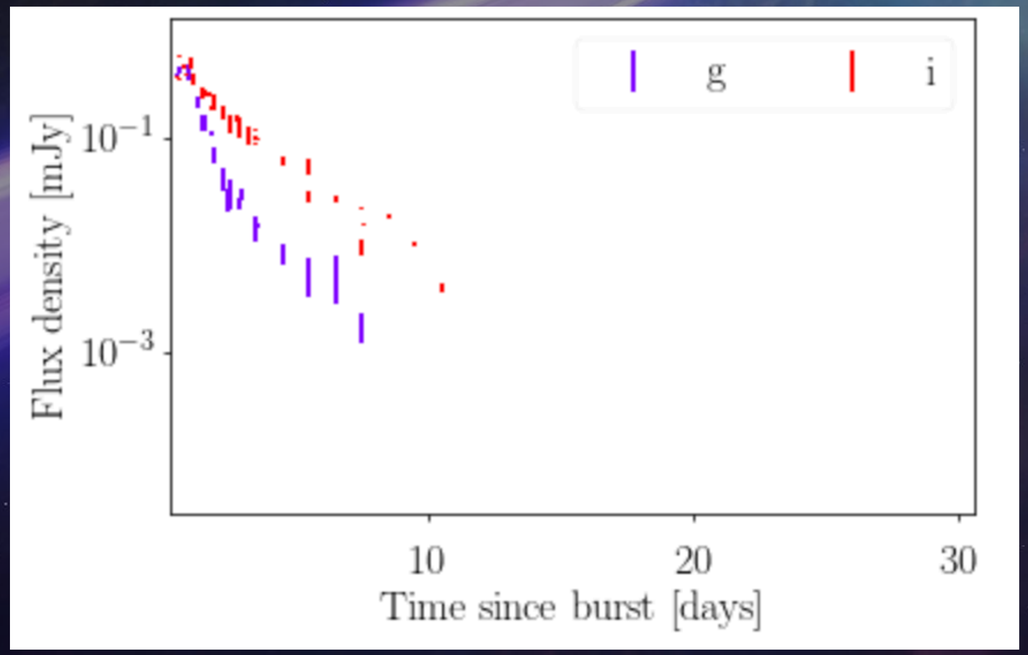
- Simulate realistic populations for current or next-generation instruments.
- Infer population properties. Joint inference with GWs for multi-messenger analyses.
- Hosted on Github with several examples, documentation, and unit tests. Installable with pip.
  - Currently in alpha with a paper in preparation.





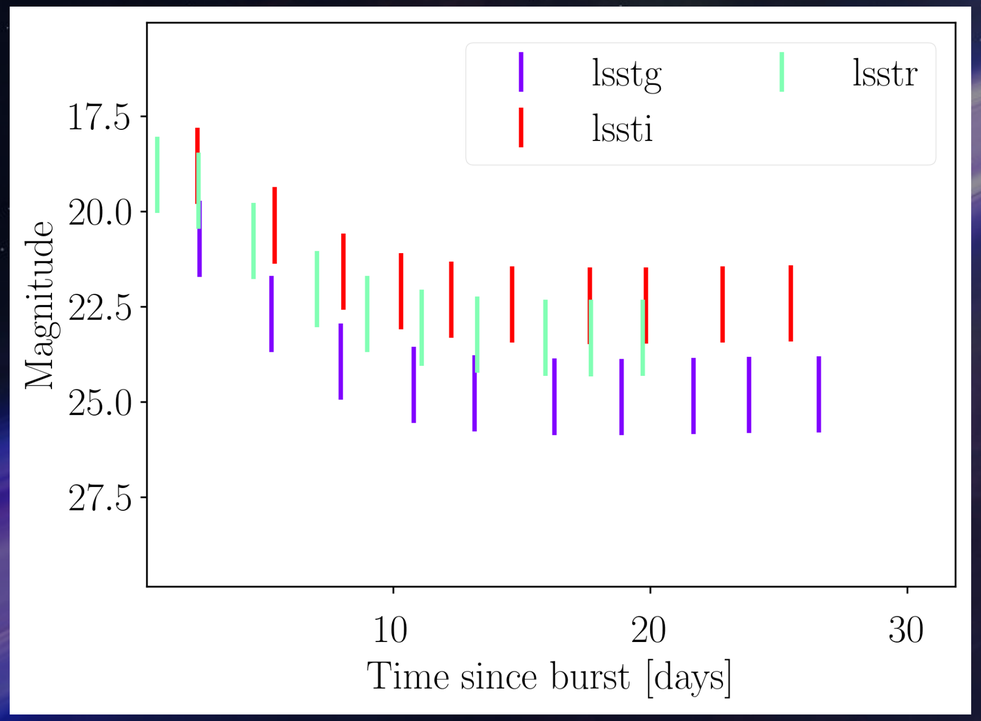
- Download and process data from public catalogues
  - Laser, Open access catalogs, Swift, BATSE, FINK.

```
kne = 'at2017gfo'
kilonova = redback.kilonova.Kilonova.from_open_access_catalogue(
    name=kne, data_mode="flux_density", active_bands=np.array(["g", "i"]))
kilonova.plot_data(save=False, plot_others=False)
```

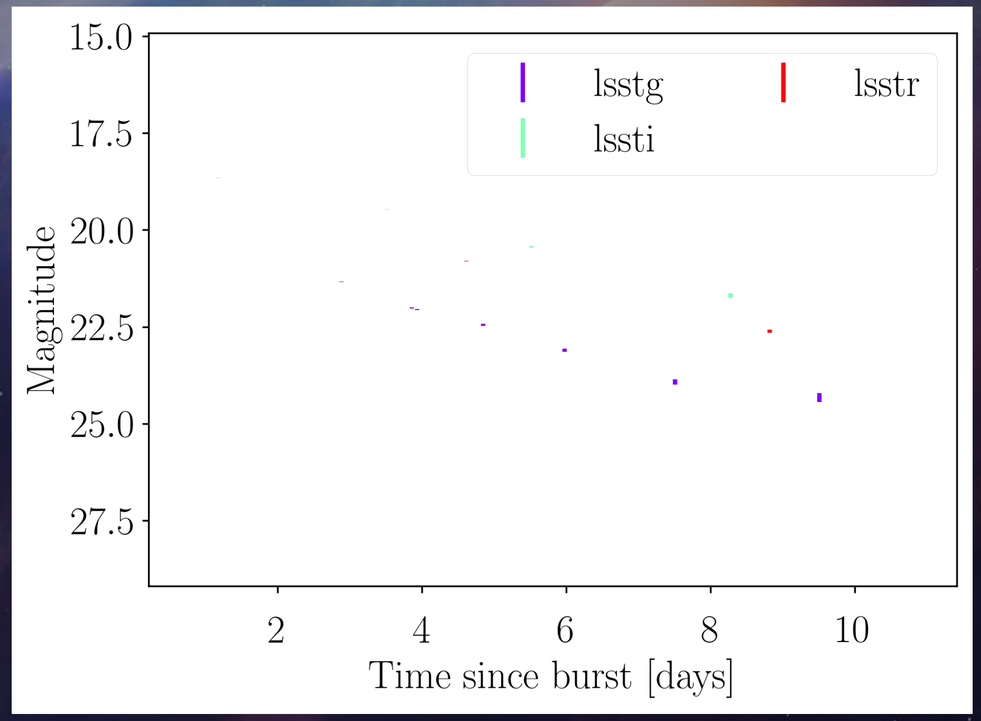


- Simulate transient data for realistic surveys e.g., ZTF, Rubin, Roman
  - Place complicated constraints on population/survey.

Simulated Kilonova in LSST with ToO observations

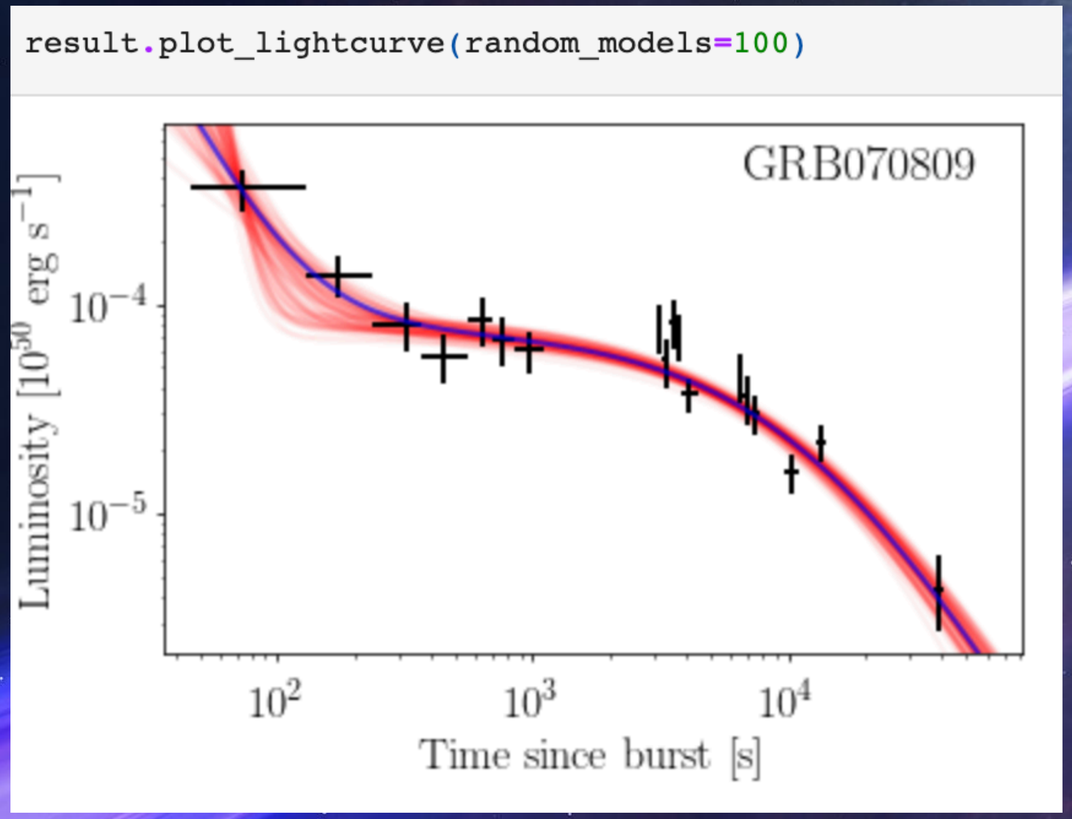


Simulated Kilonova in LSST with Rubin baseline v3.0 survey.

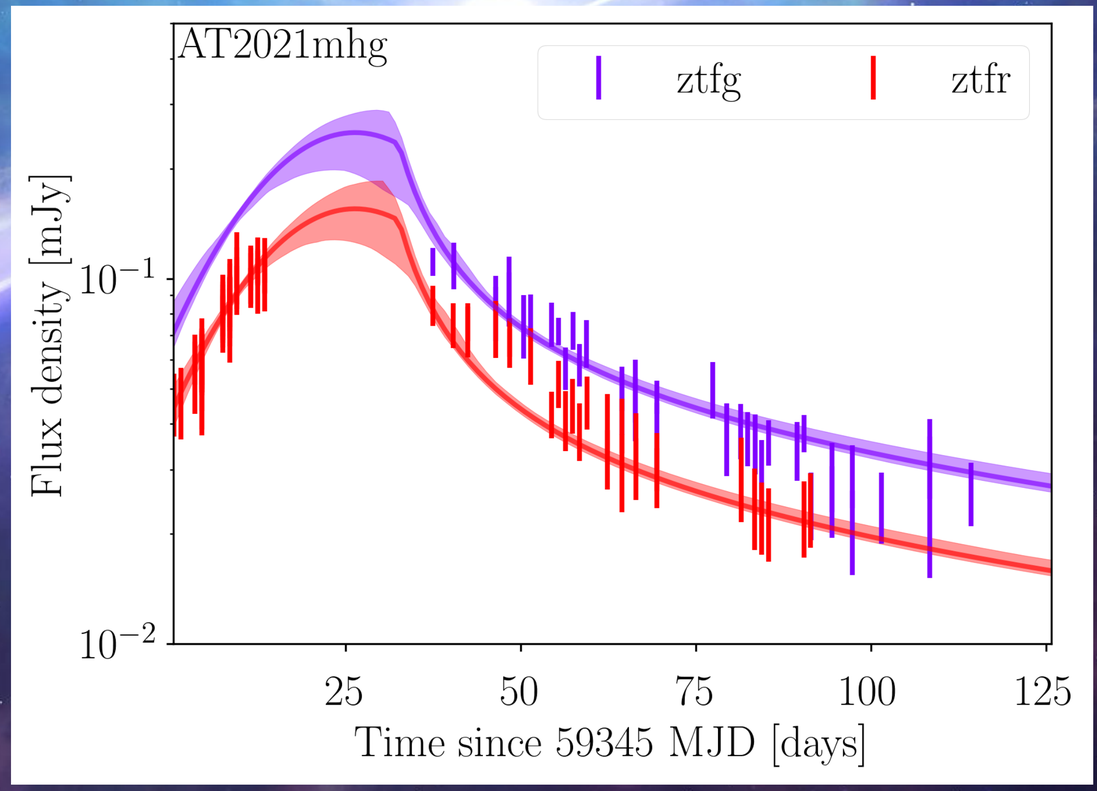


- Result object; plot lightcurve, multiband lightcurve, corner, data frame of posterior values.

```
result.plot_lightcurve(random_models=100)
```



Sarin+ in prep.



Sarin and Metzger in prep.

- The merger outcome has significant implications for what we might see from a binary neutron star merger.
  - Mergers lighter than GW170817 may not have a GRB but could have an afterglow with a bright or fast kilonova.
- Current constraints suggest that >40% of BNS mergers launch GRB jets.
- Early X-ray afterglow observations are invaluable in determining the fate of binary neutron star mergers. They will be rare.
  - In their absence, the combination of optical + radio may be most useful.
- Want to fit a model to an electromagnetic transient?
  - Consider using Redback!
  - Bonus: Easy multi-messenger inference!

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