Can we constrain the aftermath of binary neutron star mergers with short gamma-ray bursts?

Barbara Patricelli[1,2,3]

[1] European Gravitational Observatory
[2] INFN - Sezione di Pisa
[3] INAF - Osservatorio Astronomico di Roma

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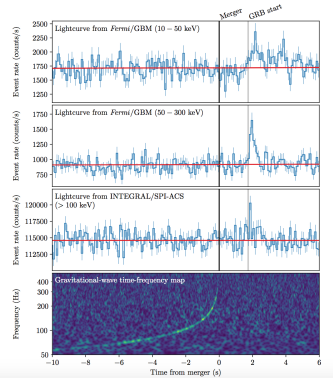
Patricelli B. & Bernardini M.G., MNRAS Letters, 499, 96 (2020)

GW170817 and GRB170817A



Abbott et al. 2017, ApJL, 848, 13

- short GRB 170817A observed in coincidence with GW170817
- First direct proof that BNS mergers are progenitors of short GRBs

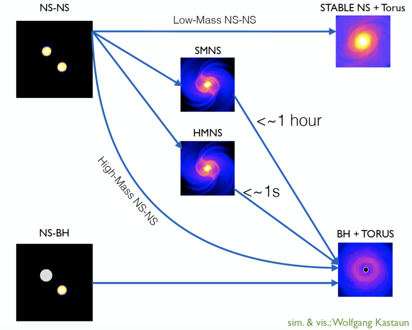
Which is the central engine of GRBs? Is it a BH or a NS?

$\Updownarrow$

Which is the remnant of a BNS merger?

The compact remnant

The outcome of a BNS coalescence depends primarily on the masses of the inspiraling objects and on the equation of state (EOS) of nuclear matter.



sim. & vis.: Wolfgang Kastaun

- Stable NS (continuous-wave GW signal)
- Supramassive NS (SMNS) collapsing to a BH in 10 - 10^4 s (long-transient GW signal)
- Hypermassive NS (HMNS) collapsing to a BH in < 1 s (burst-like GW signal)
- BH prompt formation (high frequency quasi normal mode ringdown GW signal)

Searches for post-merger GW signals associated with GW170817 have not found any significant signal candidate (Abbott et al. 2017, 2019)

Magnetars as GRB central engine

Observations of GRB emission, in particular of their X-ray emission, **point towards magnetars as plausible candidates as short GRB central engines:** (Dai & Lu 1998, Zhang & Meszaros 2001, Metzger et al. 2011)

- **late X-ray emission** (plateau, observed in $\sim 50\%$ of cases) powered by the spin-down of the magnetar

  (see, e.g., Corsi & Meszaros 2006)

- **extended emission** (observed in $\sim 15\%$ of cases) powered by either spin-down or by "propeller" mechanism

  (see, e.g., Metzger et al. 2008, Siegel & Ciolfi 2016a,b)

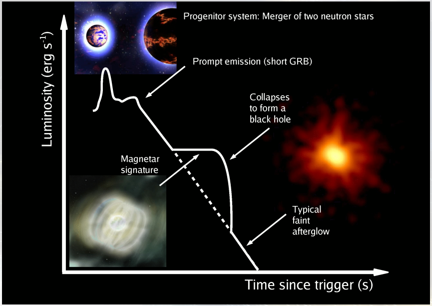


Image credit: Antonia Rowlinson/University of Leicester/NASA/Swift

But the analysis of EM emission from GRB 170817A seems to support the rapid formation of a BH (see, e.g., Radice et al. 2018)

The Idea

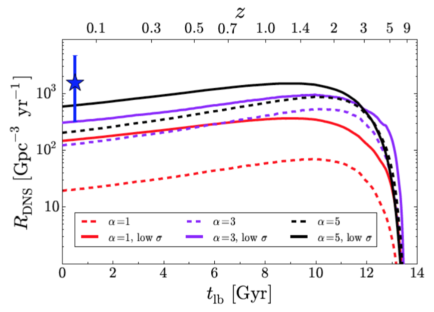
Is there another approach to constrain the GRB central engine?

We can investigate if the rate of magnetars produced in BNS mergers is sufficient to power short GRBs

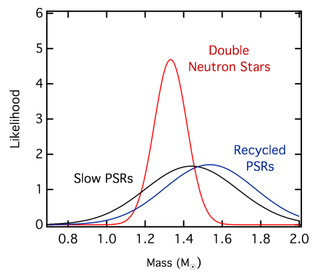
- We produced a catalog of BNS merging systems up to z=1, combining cosmic BNS merger rate with NS mass distribution
- We used this catalog to predict the number of BNS systems ending as a stable NS or a SMNS (magnetars) for different EOSs
- We compared the rate of magnetars with the rate of short GRBs in the same volume

The BNS catalog

1) The BNS merger rate density:
theoretical model by Mapelli
& Giacobbo 2018



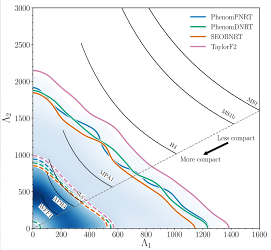
2) The NS masses:
mass distribution of galactic systems
(Özel & Freire 2016)



Gaussian with: μ=1.33 M$_\odot$, σ=0.09 M$_\odot$

The BNS merger remnant

Three EOSs: APR4, H4 and MS1

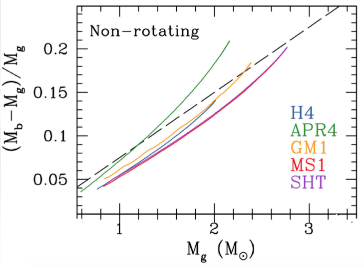


- they cover a relatively wide range of maximum NS masses...
- ... but all with a maximum gravitational mass $\gtrsim 2\ M_\odot$, consistent with EM limits (see Cromartie et al. 2020)

3) Mass of the remnant (Piro et al. 2017):

$$\boxed{M_{b,tot} = m_{b,1} + m_{b,2} - M_{lost}}$$

- M_{lost}=0.01 $M_\odot$
- $m_g \Rightarrow m_b$:



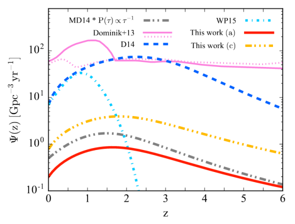
$\boxed{M_{b,tot}\text{ is then compared with the maximum NS mass}}$

The short GRB rate

- Rates derived by Ghirlanda et al. 2016 using all the available observer-frame constraints (i.e. peak flux, fluence, peak energy and duration distributions) of Fermi/GBM short GRBs and the rest-frame properties of short GRBs detected by Swift.

Two assumptions:

- the intrinsic Ep - Liso and Ep - Eiso correlations hold (**case “a”**)
- the distributions of intrinsic peak energy, luminosity, and duration are independent (**case “c”**)



- we assign to each BNS system a random inclination of the orbital plane with respect to the line of sight (θ_i)
- we draw from our sample the BNS systems having $\theta_i < \theta_j$, with θ_j[1] in the range 3° - 8°, with a fiducial value $\theta_j = 5^\circ$ (Fong et al. 2014, Ghirlanda et al. 2019)

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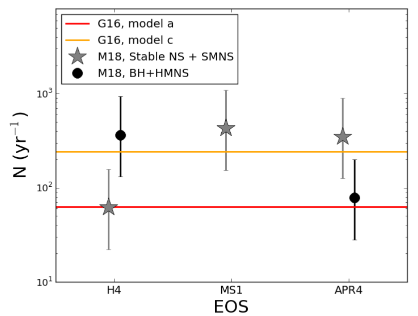
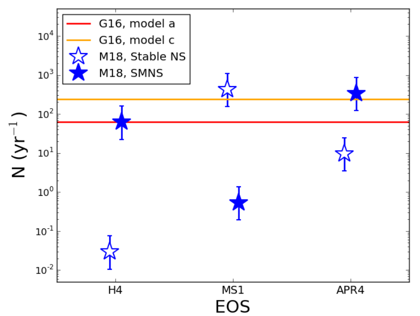
[1] θ_j is the jet opening angle

Results: Rate of magnetars/BHs vs short GRB rate



- The percentage of BNS mergers ending as a magnetar is: ~ 14 % (H4), ~ 82 % (APR4), ~ 100 % (MS1)
- **The rates of magnetars obtained with APR4 and MS1 are consistent with the short GRB rate**
- At least for the EOSs APR4 and MS1, the BH central engine is disfavoured

Results: Rate of stable NS/SMNS vs short GRB rate



- The rate of magnetars is dominated by SMNSs for the APR4 and H4 EOSs
- if we believe that features as X-ray plateaus are produced by magnetars, **we have to require that the SMNS survives long enough (minutes-hours)** at least in those cases

Conclusions

- For most EOSs the rate of magnetars produced in BNS mergers is high enough to power all the short GRBs
- More observations are needed to better probe the magnetar-short GRB connection

Future perspectives

- Future EM missions such as **Theseus and Athena** will be key instruments to monitor the GRB afterglow evolution and put constraints on the GRB jet structure
- Higher sensitivity 2nd generation GW detectors and 3rd generation GW detectors (e.g., **the Einstein Telescope**) will be key instruments to put more stringent constraints on the BNS merger rates and to detect post-merger GW signals

$\Downarrow$

This will allow us to unambiguously identify the central engine of short GRBs.