Multi-messenger Astrophysics: Gravitational waves of quark matter EOSs and ejecta parameter estimation with kilonova modelling

DR. ATUL KEDIA

CCRG @ RIT

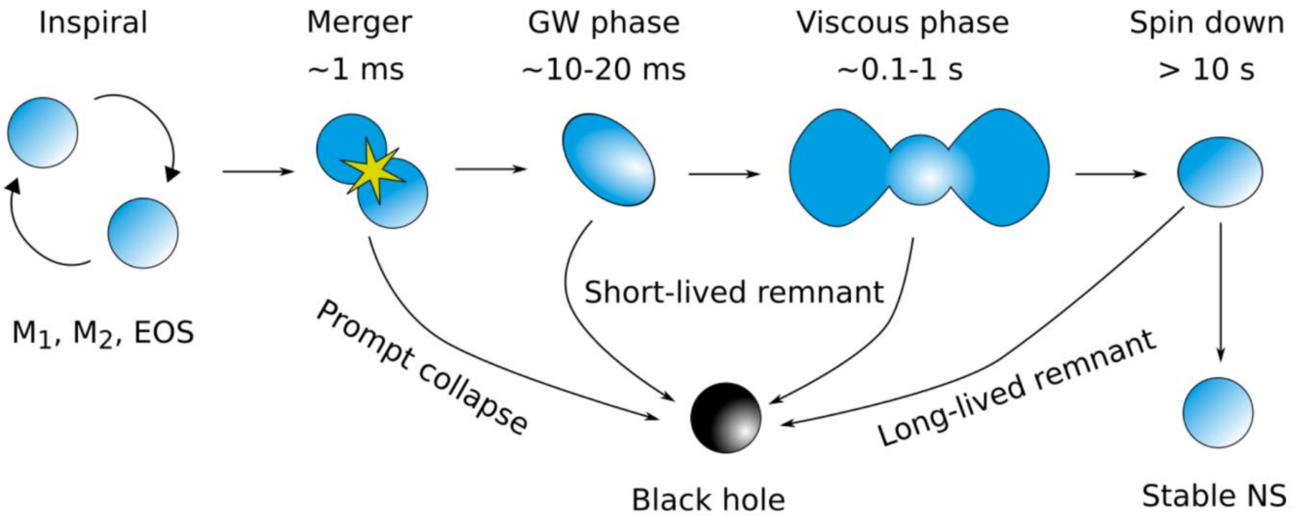
ATULKEDIA93@GMAIL.COM,
ASKSMA@RIT.EDU

CCRG Lunch talk | 3/3/2023

Collaborators: Marko Ristic, Richard O'Shaughnessy, Anjali Yelikar (RIT), Ryan Wollaeger, Chris Fontes, Eve Chase, Chris Fryer, Oleg Korobkin (LANL)

Runtime ~ 40mins

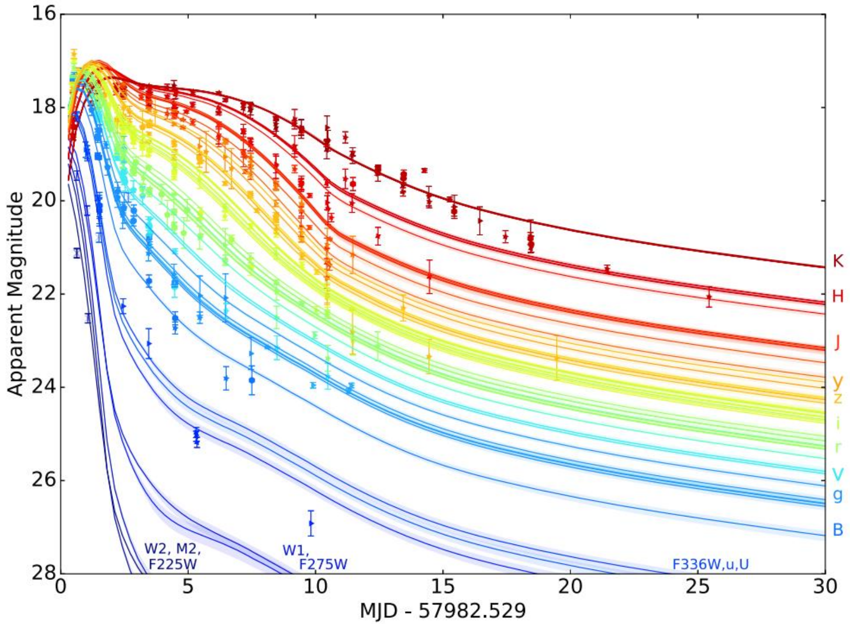
Stages of a Binary Neutron Star merger



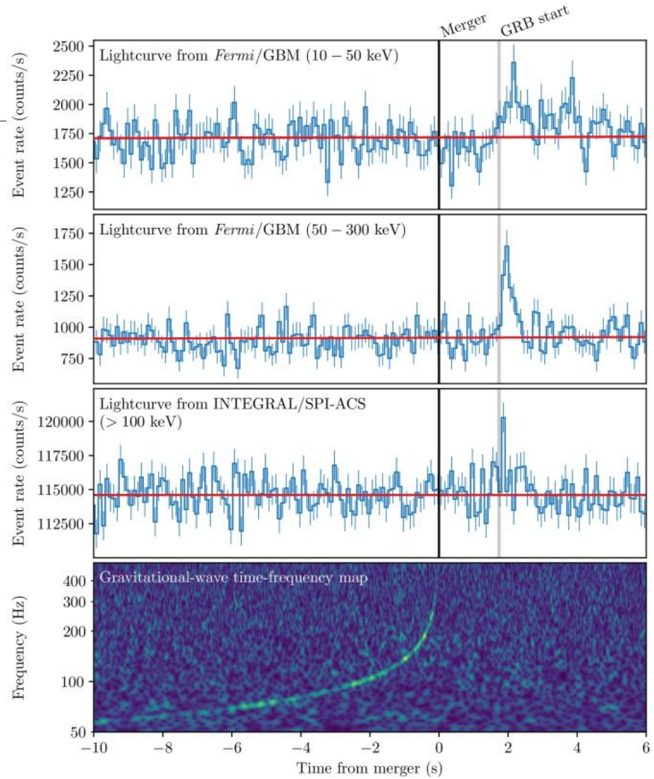
Credits: Radice, Bernuzzi, Perego (2020)

AT2017gfo / GW170817

sGRB ~ 2s



Villar et al ApJL 2017



Abbott et al PRL 2017

Index

1. Quark-Hadron Crossover equation of state
    1. EOS
    2. GW for QHC and Hadronic EoSs
2. Kilonova
    1. Ejecta models
    2. Surrogates
    3. Parameter Estimation

Equation of State (EoS)

Equation of state (EoS) $P(\rho, Y_e, T)$ in the form of Pressure v. density $P(\rho)$

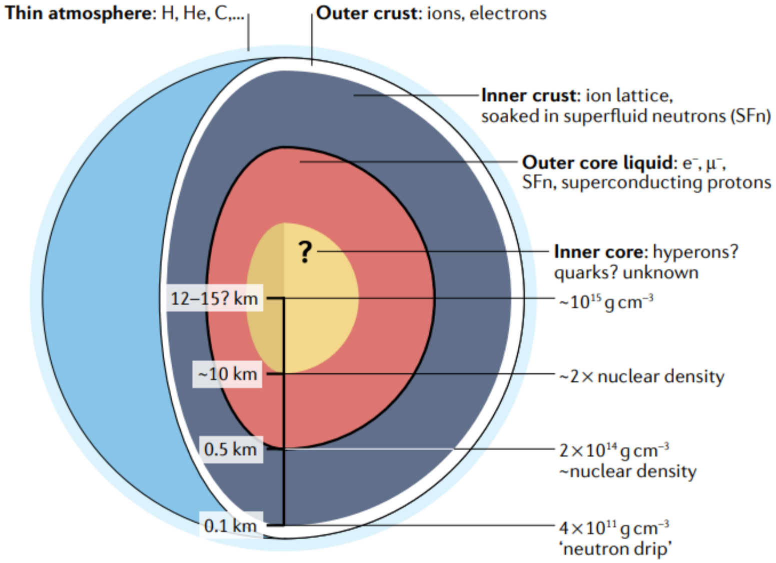


Fig. 1 | **Schematic of the structure of a neutron star and its internal structure.** The figure illustrates the thin atmosphere, the outer and inner crust, and the outer and inner core, with the respective densities at different depths. Adapted with permission from NASA, NICER Team.

Yunes, Miller and Yagi, Nature Rev. Phys. (2022)

Equation of State (EoS)

Equation of state (EoS) $P(\rho, Y_e, T)$ in the form of Pressure v. density $P(\rho)$

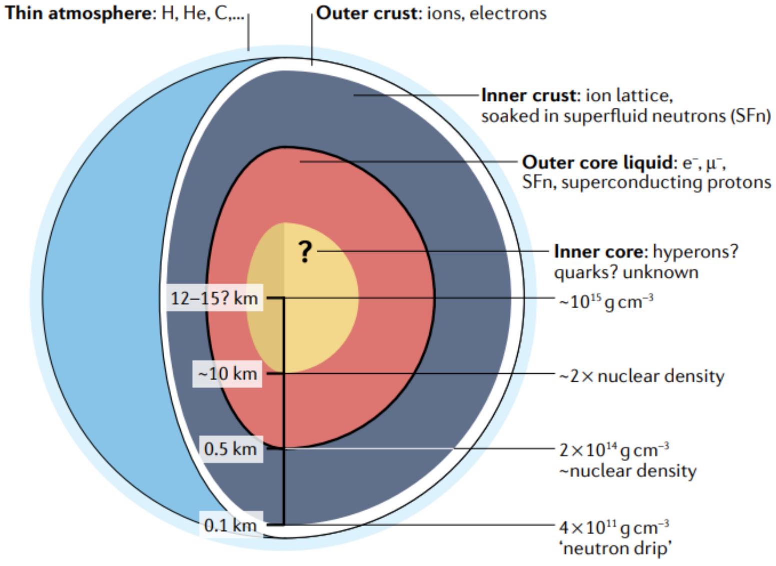
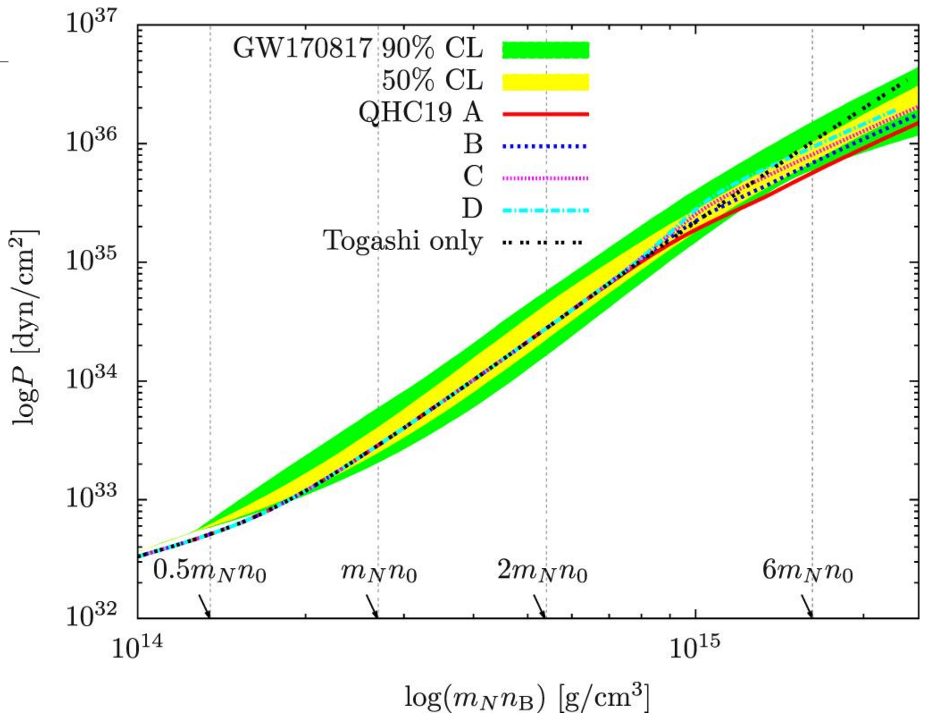


Fig. 1 | **Schematic of the structure of a neutron star and its internal structure.** The figure illustrates the thin atmosphere, the outer and inner crust, and the outer and inner core, with the respective densities at different depths. Adapted with permission from NASA, NICER Team.



Baym, Furusawa, Hatsuda et al. *ApJ* (2019) 885:42

Yunes, Miller and Yagi, Nature Rev. Phys. (2022)

Equation of state (EoS) $P(\rho, Y_e, T)$ in the form of Pressure v. density $P(\rho)$

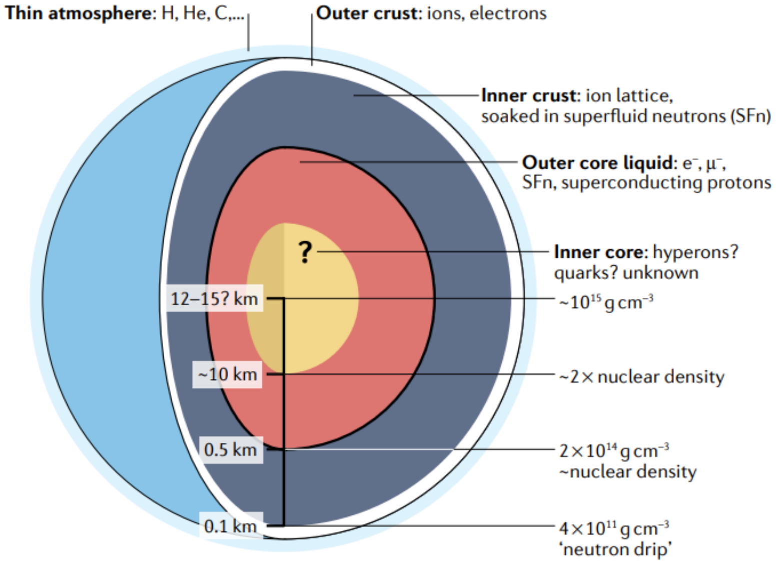
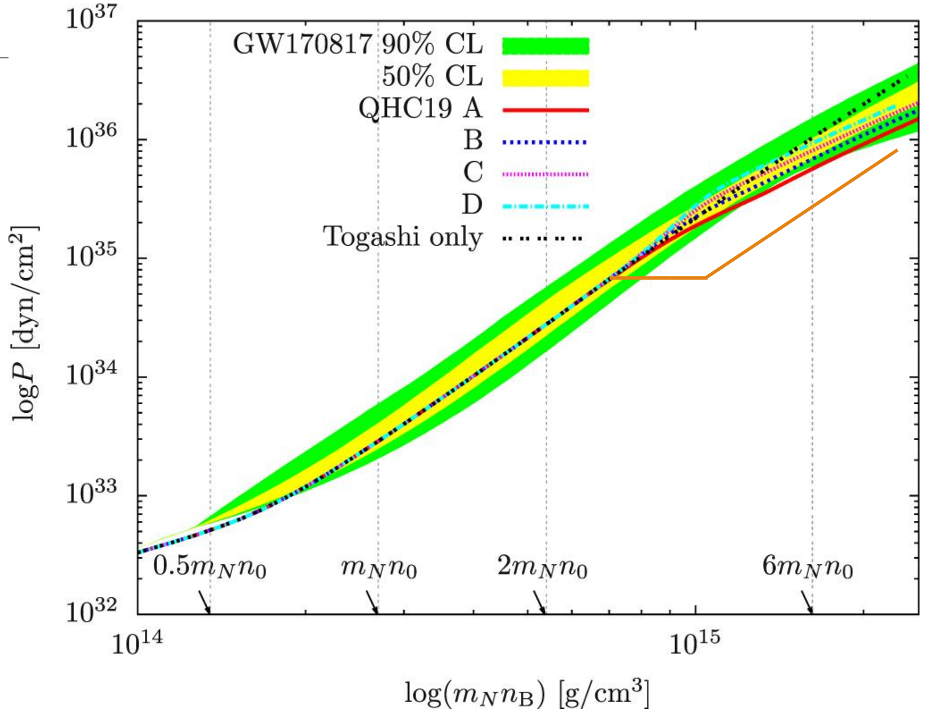


Fig. 1 | **Schematic of the structure of a neutron star and its internal structure.** The figure illustrates the thin atmosphere, the outer and inner crust, and the outer and inner core, with the respective densities at different depths. Adapted with permission from NASA, NICER Team.



Baym, Furusawa, Hatsuda et al. *ApJ* (2019) 885:42

Yunes, Miller and Yagi, Nature Rev. Phys. (2022)

Quark-Hadron Equation of State

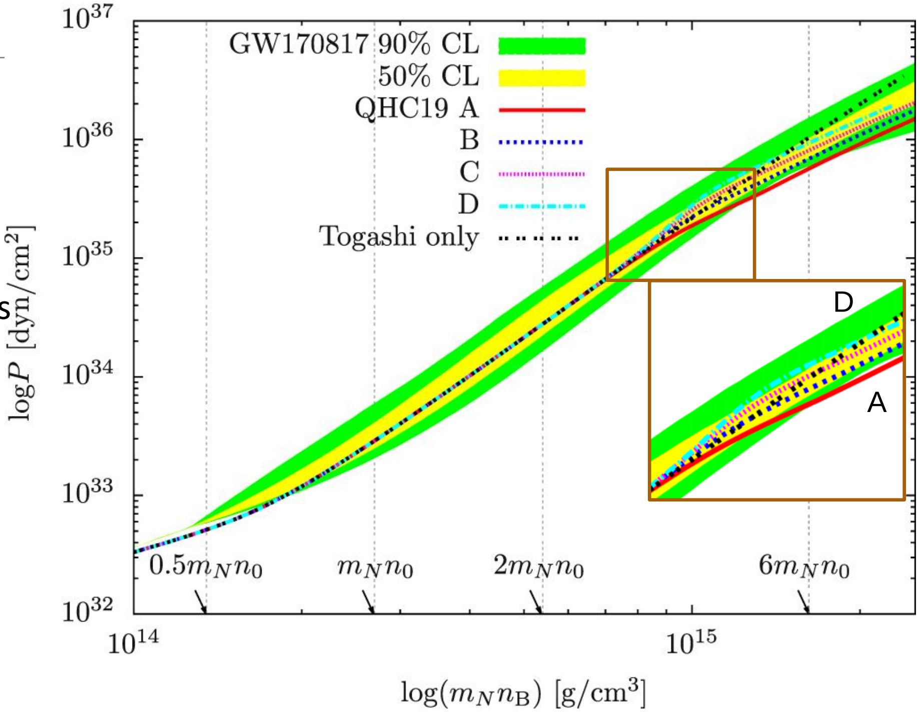
Quark-Hadron Crossover (QHC19A-D) EoS
Baym et al. 2019, 2018

Cold EoS ($T = 0$)

Hadronic EoS: Togashi EoS (extension of APR) for densities
$< 2n_0 \approx 5.4 \times 10^{14}\ gm/cm^3$

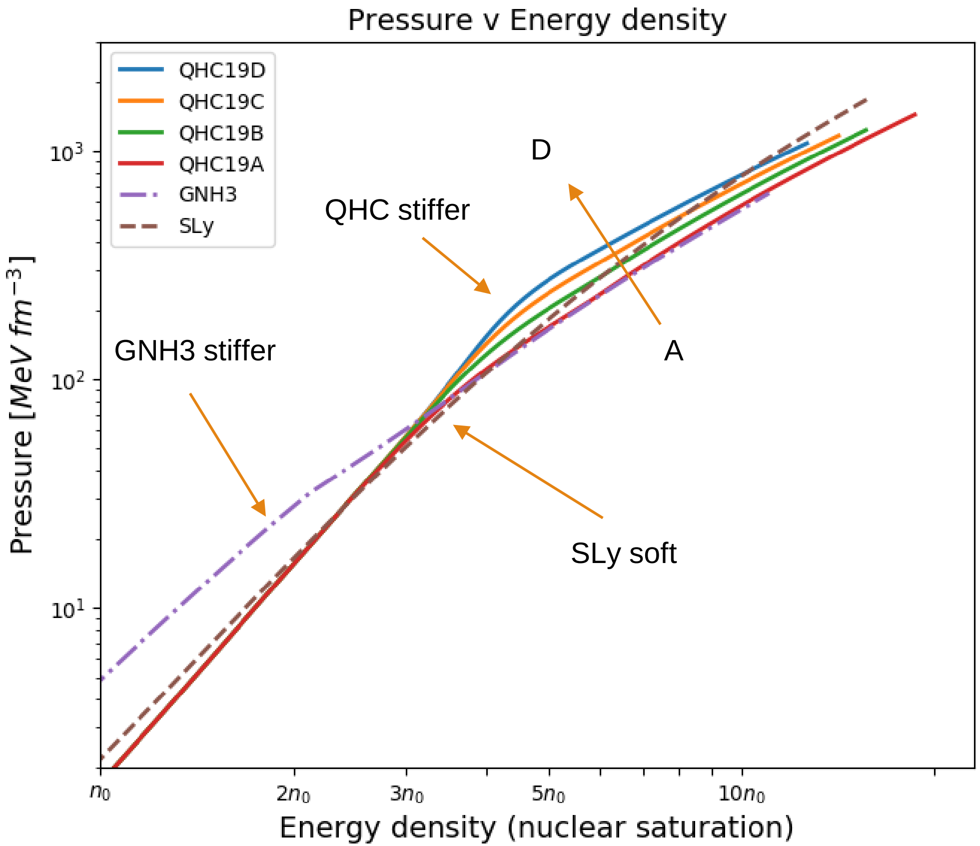
Quark EoS: Nambu-Jona-Lasinio model
$> 5n_0 \approx 1.3 \times 10^{15}\ gm/cm^3$

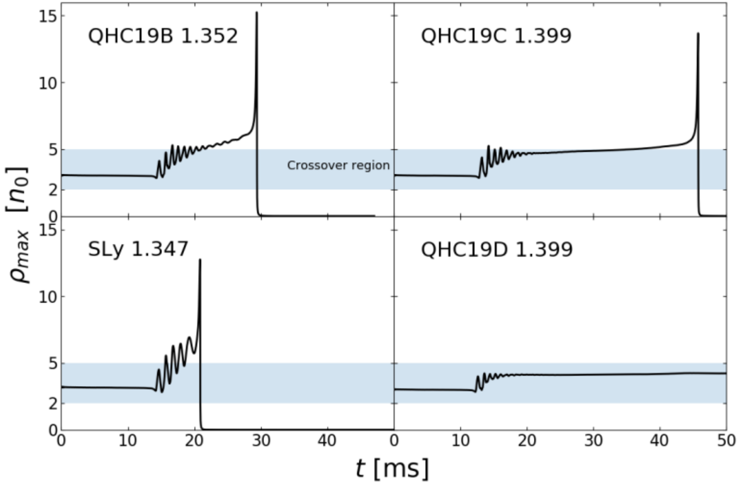
Smooth fitting in the intermediate Crossover region: $2n_0 - 5n_0$



Baym, Furusawa, Hatsuda et al. *ApJ* (2019) 885:42

QHC and hadronic EoS comparison





AK et al., PRD (2022)

GW Spectrum and Future detections

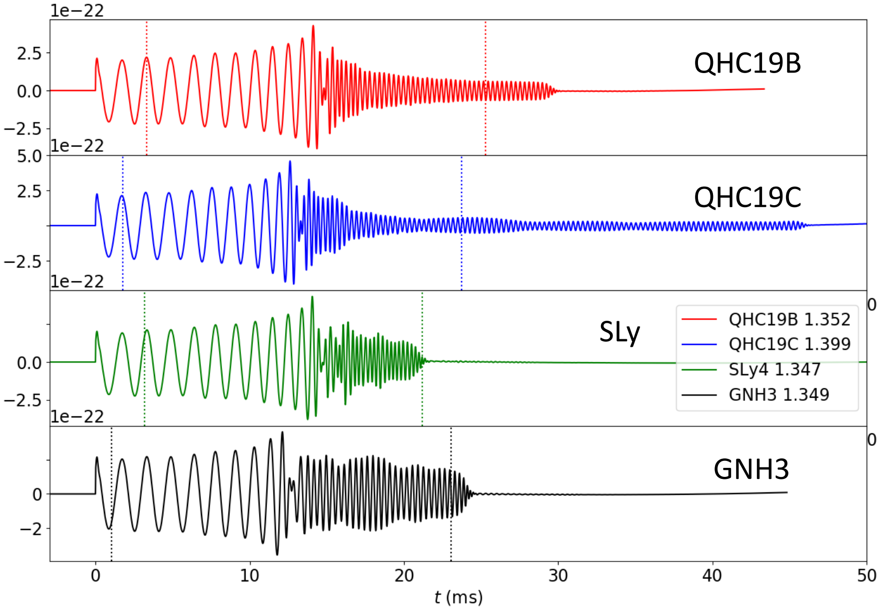


Fig: h_+(at 50 Mpc) v time (ms).

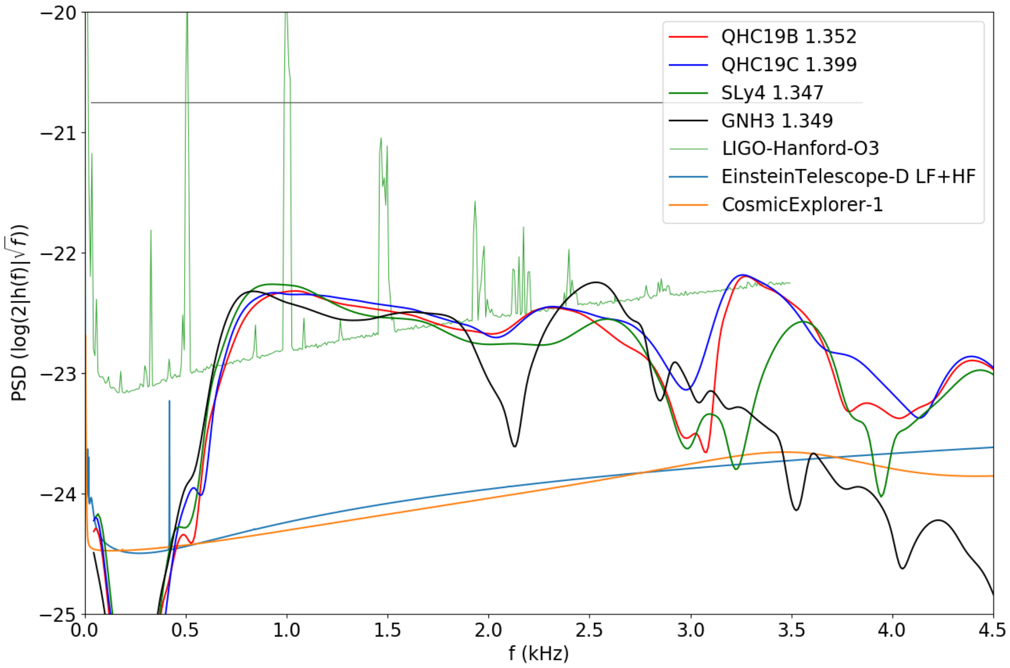
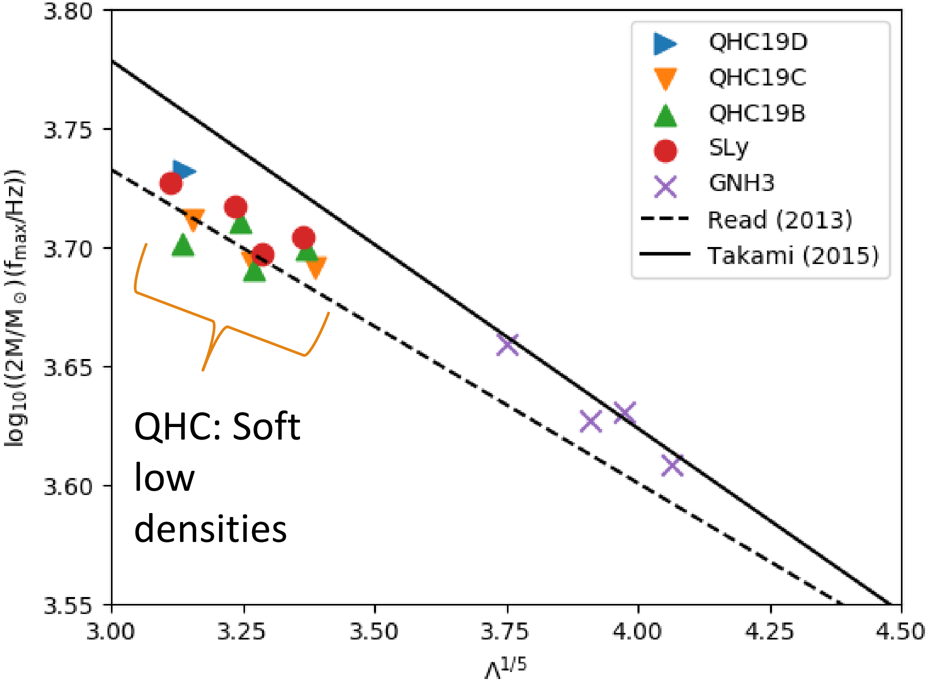
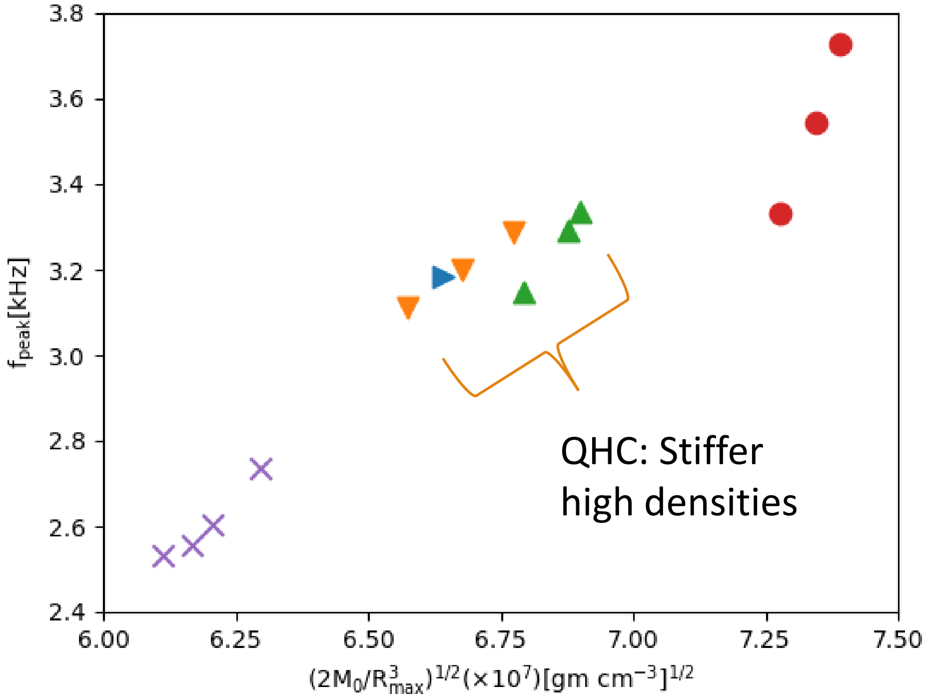


Fig: Power spectral density ($\log(2|h(f)|\sqrt{f})$) in frequency domain.
v Einstein Telescope, and Cosmic Explorer strain limits

GW frequencies f_{max} and f_{peak}





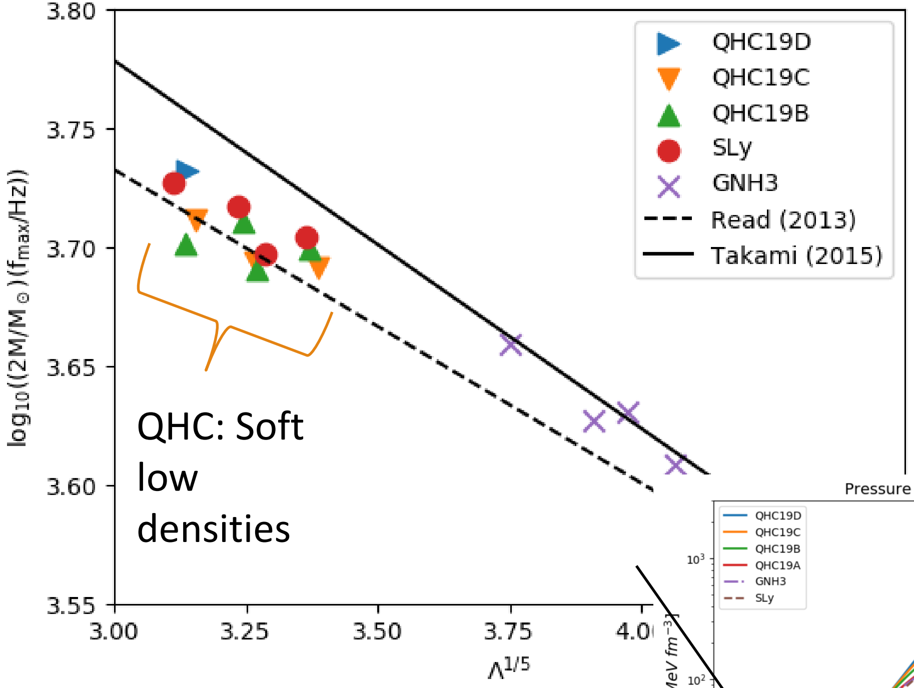
Left Fig – $\log(f_{max})$ v tidal deformability ($\Lambda^{1/5}$)

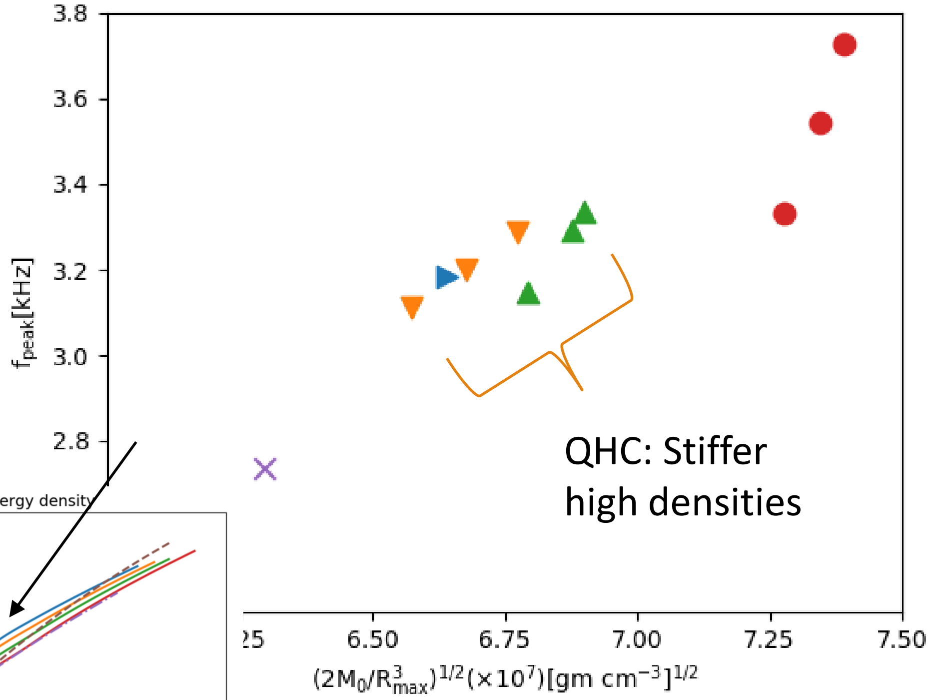
Right Fig – f_{peak} v "Density"

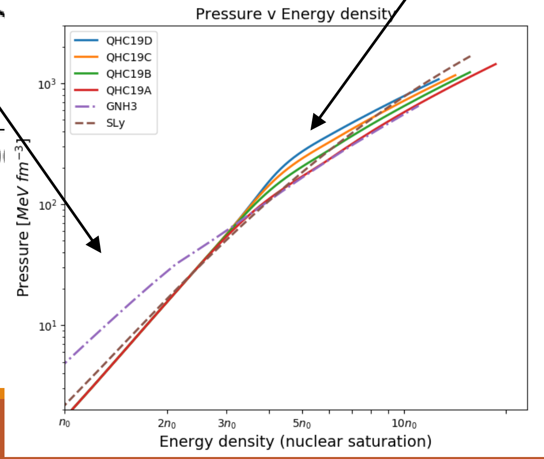
Q-universality relations : Takami et al. (2015), Read et al. (2013)

AK, Kim, Suh, Mathews, PRD (2022)

GW frequencies f_{max} and f_{peak}







Left Fig – $\log(f_{max})$ v tidal deformability ($\Lambda^{1/5}$)

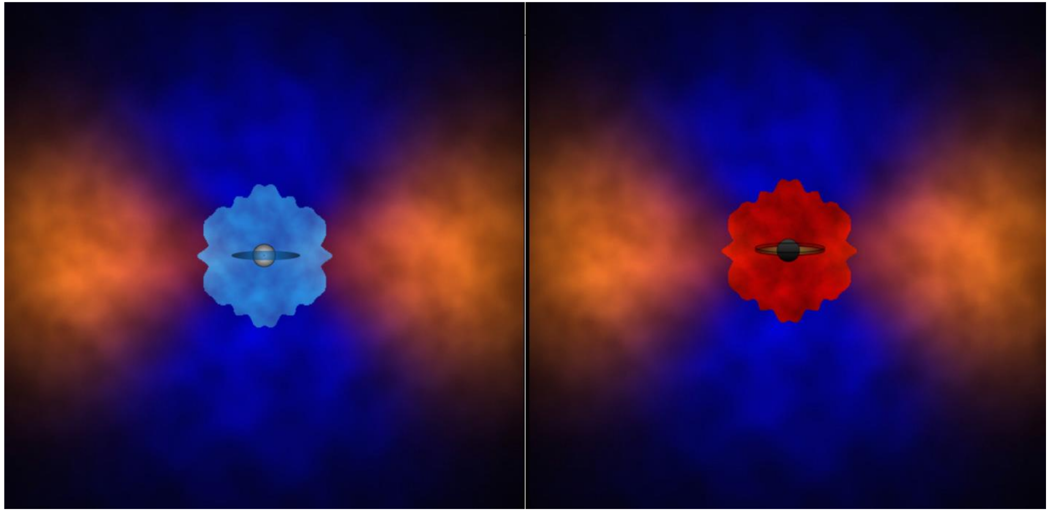
Right Fig – f_{peak} v “Density”

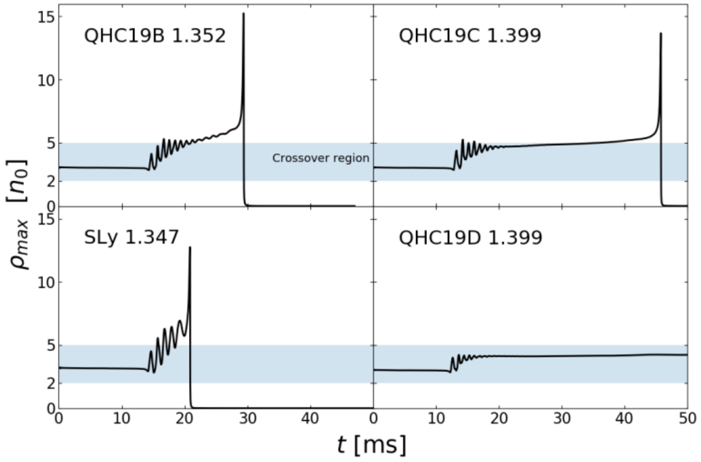
AK, Kim, Suh, Mathews, PRD (2022)

Related works

- Back and forth phase transition Reverse phase transition(as density increases/decreases) and its GW.) (Ujevic et al https://arxiv.org/abs/2211.04662)
- Reverse phase transition - Hadron core-Quark crust (Ren & Zhang https://arxiv.org/abs/2211.12043) QHC but with Inverted phase transition: Holds possibilities of coexisting layers of quark matter and hadronic matter.
- Cooper triplet phase transition (Tajima et al https://arxiv.org/abs/2211.14194)
- GW signal from phase transition in BNSM Mallick et al (https://arxiv.org/abs/2212.00462 , https://arxiv.org/abs/2207.14485)
- GW for realistic PT (Fujimoto et al https://arxiv.org/abs/2205.03882)
- Weih, Hanauske, and Rezzolla (PRL 2020) ; Most, … Rezzolla (PRL 2019) GW differences in premerger and postmerger with and without PT.

EoS effect on the NS merger remnant and ejecta



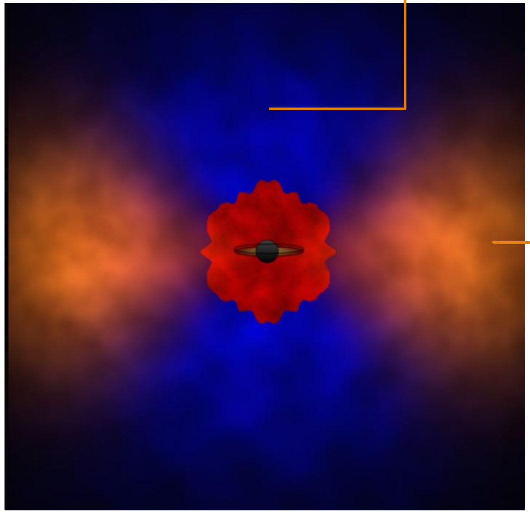


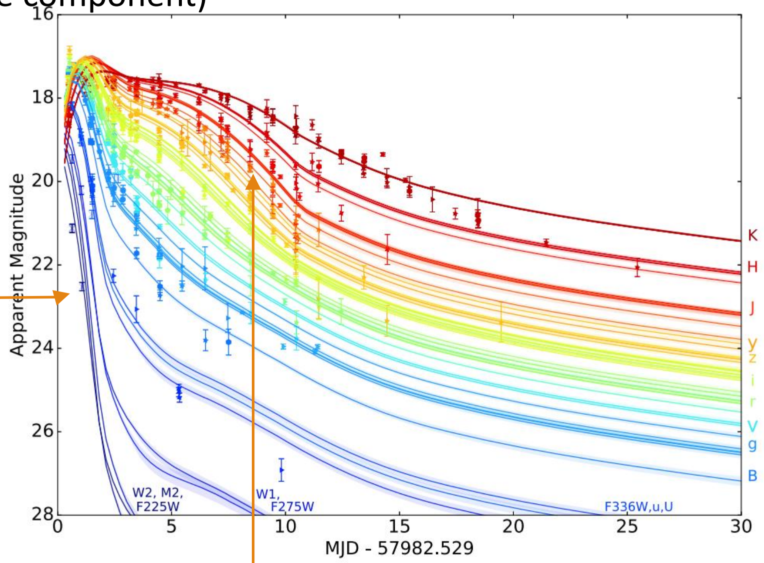
AK et al PRD 2022

Kasen et al Nature 2017

Ejecta components corresponding to kilonova spectrum

Wind ejecta (blue component)

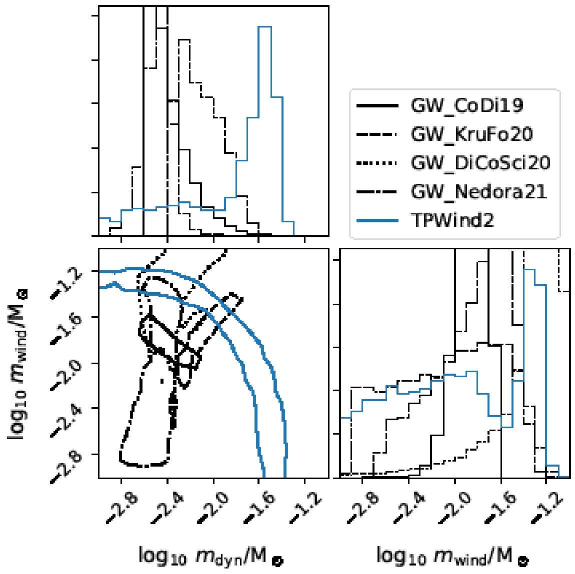


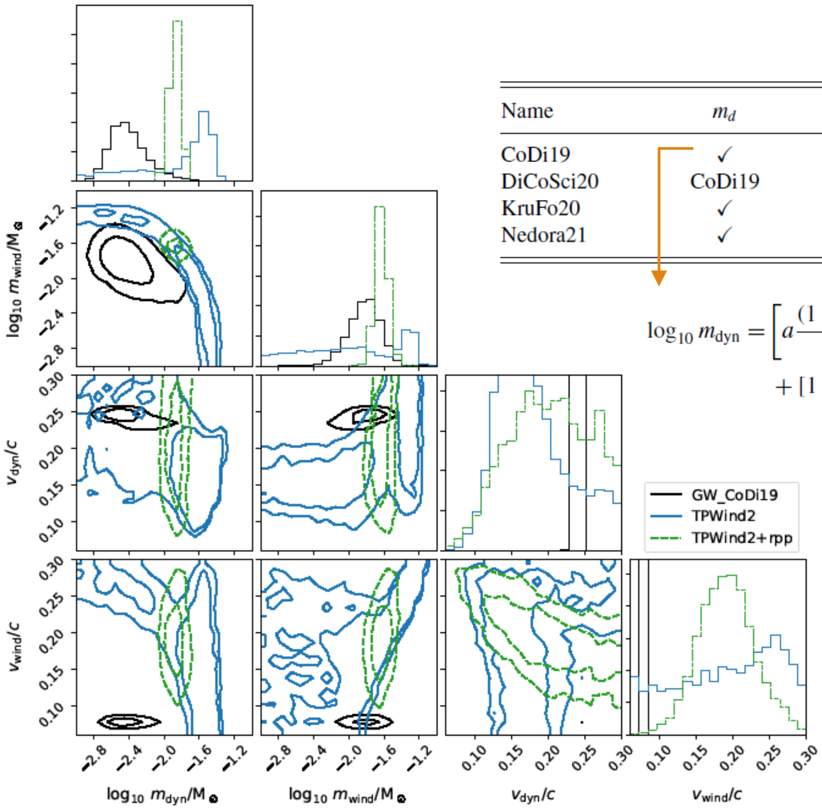


Dynamical ejecta
(red component)

Kasen et al Nature 2017

EM v GW ejecta parameter tension

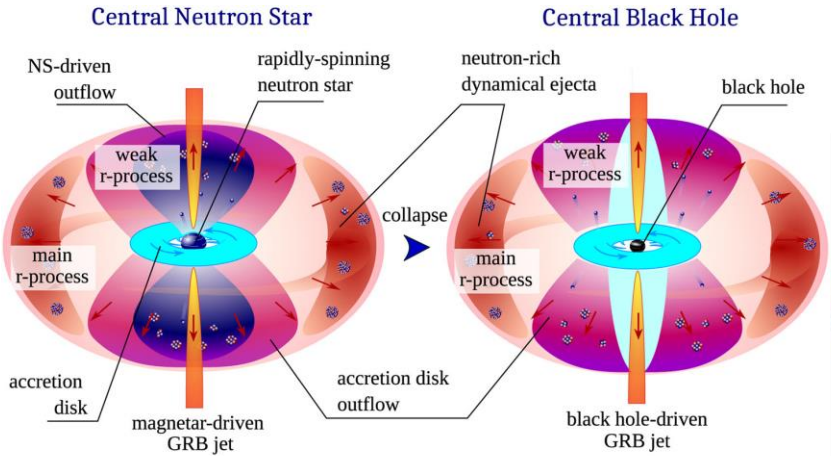


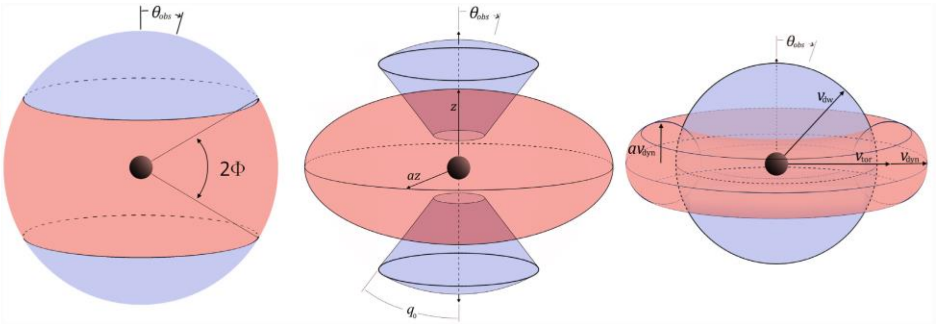


Name	m_d	m_w
CoDi19	✓	✓
DiCoSci20	CoDi19	✓
KruFo20	✓	✓
Nedora21	✓	CoDi19

$$\log_{10} m_{\rm dyn} = \left[a \frac{(1-2C_1)m_1}{C_1} + b\, m_2 \left(\frac{m_1}{m_2}\right)^n + \frac{d}{2} \right] + [1 \leftrightarrow 2],$$

Kilonova ejecta morphologies





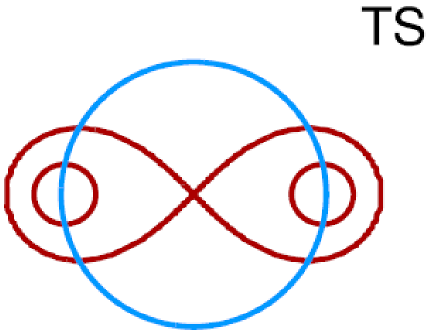
Rosswog, Korobkin, 2022

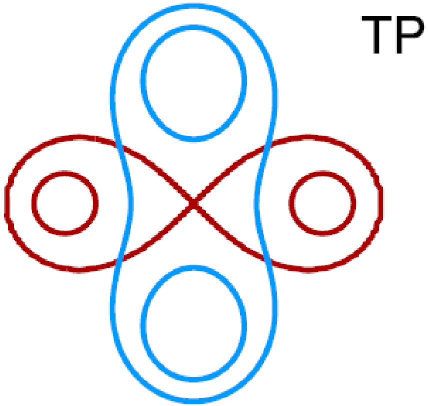
Heinzel et al, 2021

Simulation setup

- Radiative transfer software using tabulated binned opacities on **SuperNu**. (Wollaeger et al 2013, 2014)
- Composition and radioactive heating from r-process elements, nucleosynthetic results from **WinNet.** (Winteler et al. 2012)
- Nuclear model
  - Heating rates (Korobkin et al.)
  - Thermalization model of (Barnes et al. (2016))
  - Atomic opacities (Fontes et at. 2020)
- Reprocessing of light from one component to another.
- Active learning to choose next set of models to reduce Chi^2 error.

(Wollaeger et al 2013, 2014, 2018, 2021; Ristic et al, PhysRevResearch (2022))





Ejecta profiles

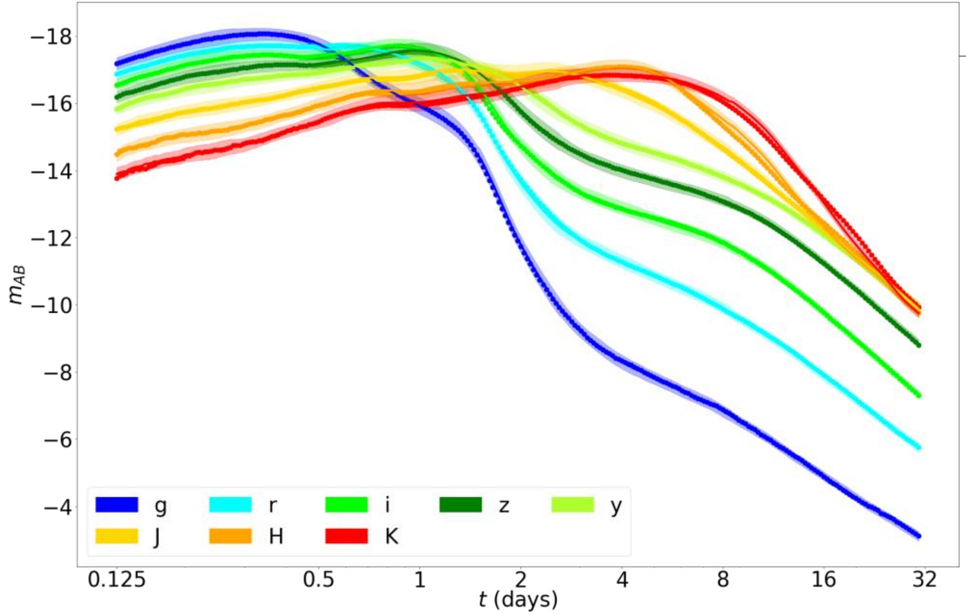
TABLE I. Ejecta morphologies and compositions studied in this paper. The composition of the dynamical component is fixed at $Y_e = 0.04$. In terms of this notation, the previous investigation studied a TPwind2 outflow [32].

	Wind		
Name	Morphology	Y_e	Dynamical
TPwind1	Peanut	0.37	Torus
TSwind1	Spherical	0.37	Torus
TSwind2	Spherical	0.27	Torus

Mass [Mo]	Velocity [c]
0.001, 0.003, 0.01, 0.03, 0.1	0.05, 0.15, 0.3

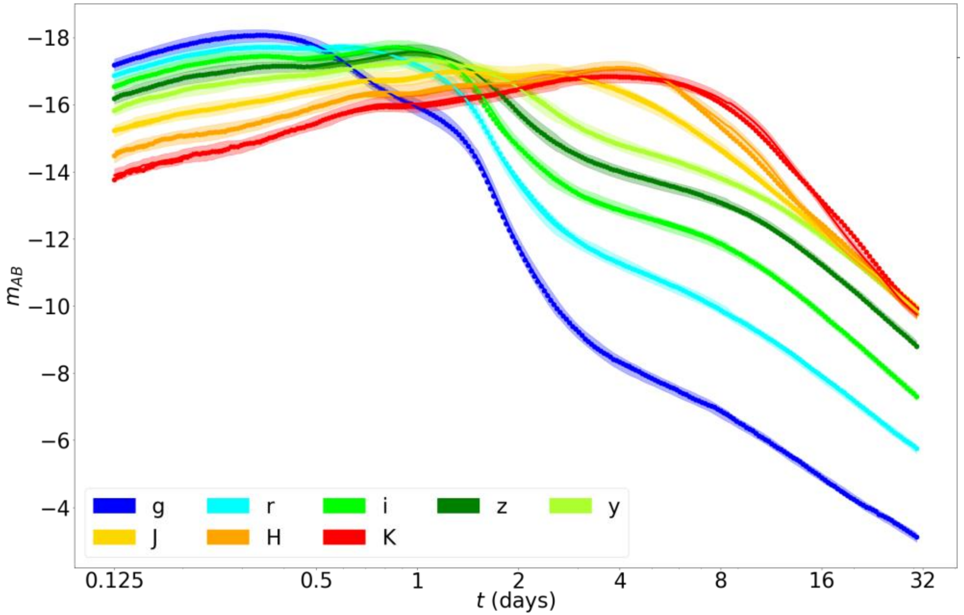
225 + 225 (active learning sims) = 450 /Name

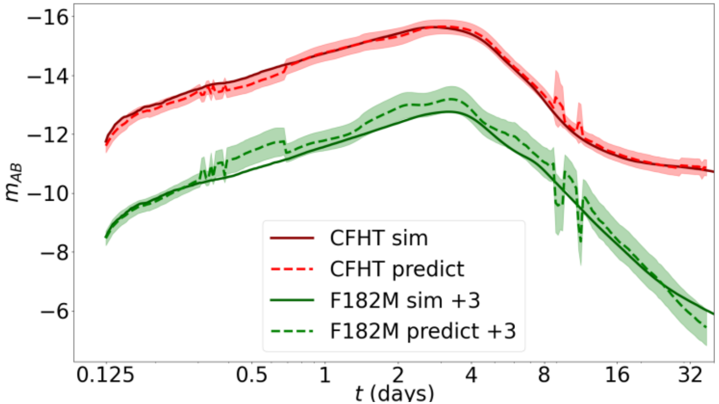
Gaussian Process regression Surrogate models

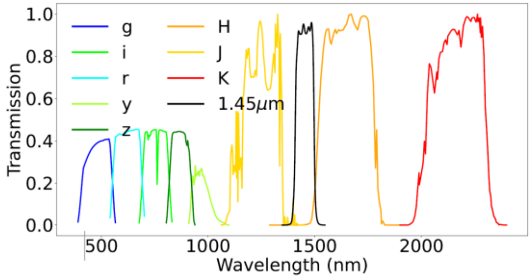


(*mdyn*, *vdyn*, *mwind*, *vwind*) = (0.097, 0.198, 0.084, 0.298)
TSwind2

Gaussian Process regression Surrogate models







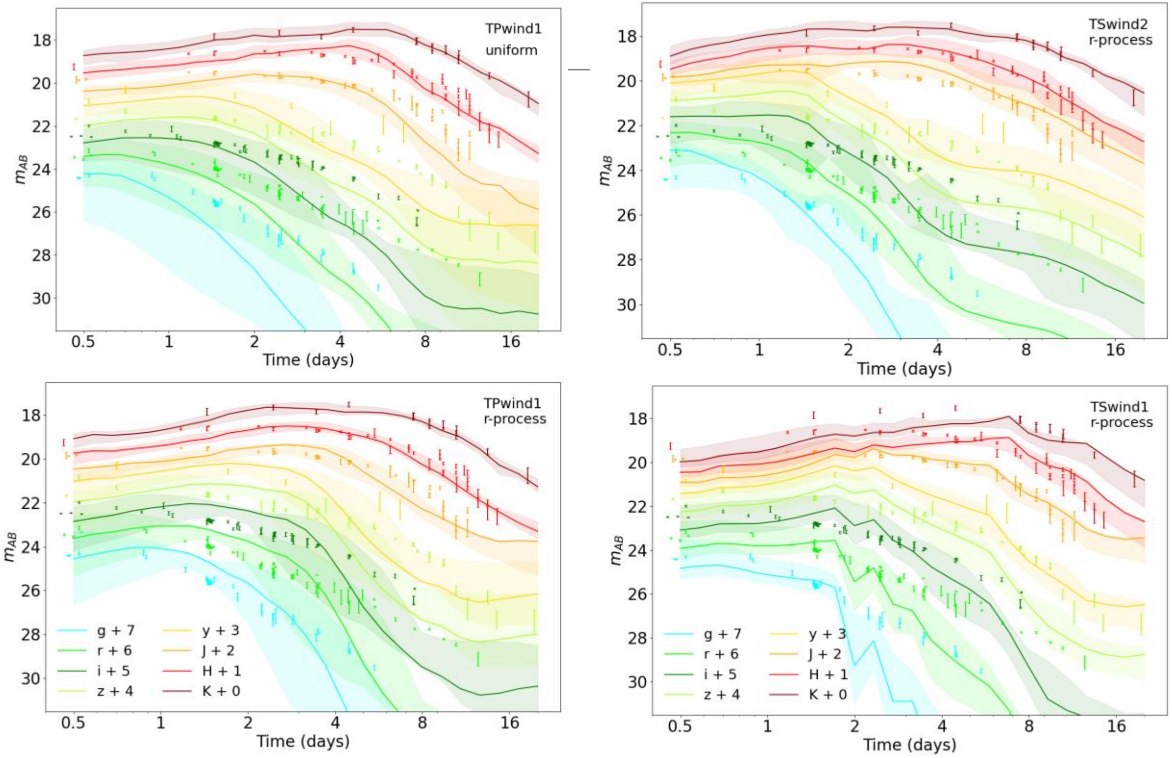
(*mdyn*, *vdyn*, *mwind*, *vwind*) = (0.097, 0.198, 0.084, 0.298)

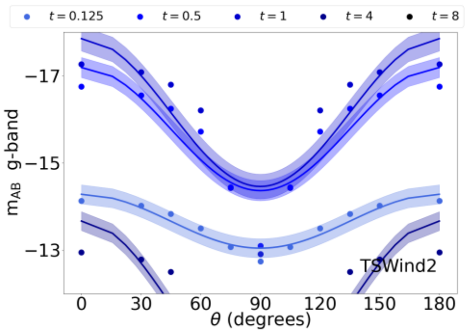
TSwind2

Simulation data : https://zenodo.org/record/7335961#.ZAE4iXbMKsIvı

GP Surrogate models : https://github.com/markoris/surrogate_kne

Fit Light curves (to AT2017gfo)

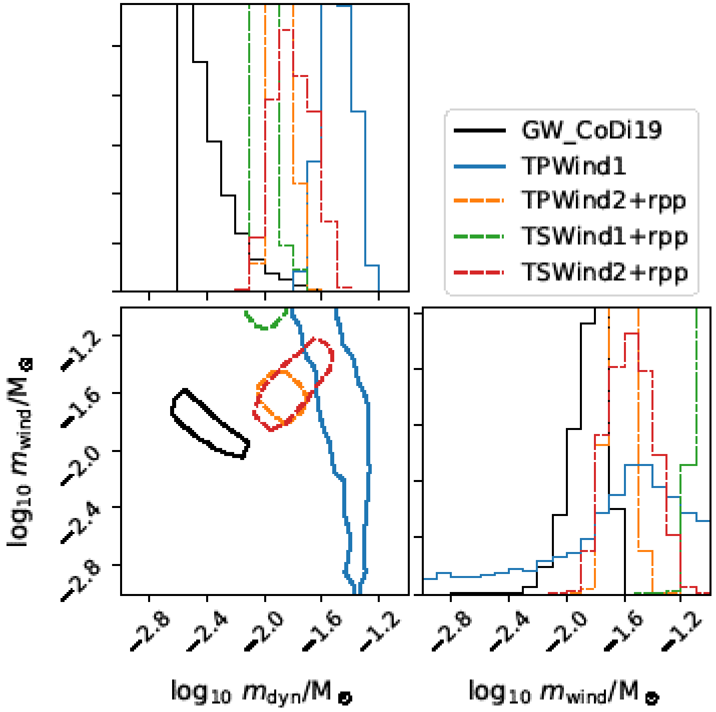


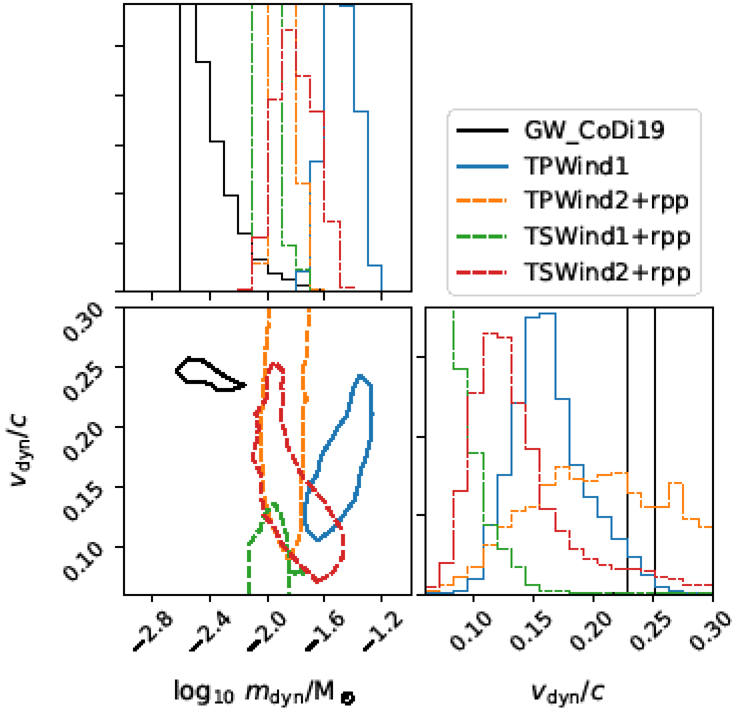


Lanthanide curtaining

AK et al [arXiv:2211.04363 [astro-ph.HE]](https://arxiv.org/abs/2211.04363)
(Accepted at Phys. Rev. Research)

GW v EM ejecta parameter estimate tension





[arXiv:2211.04363 [astro-ph.HE]](https://arxiv.org/abs/2211.04363)

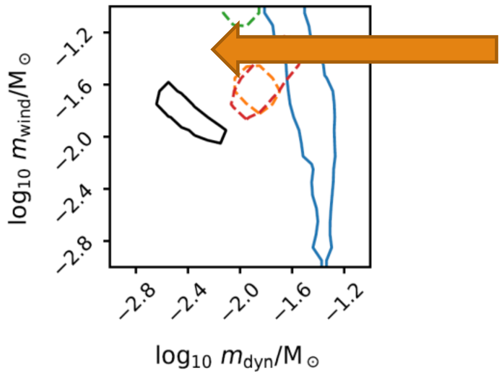
(Accepted at Phys. Rev. Research)

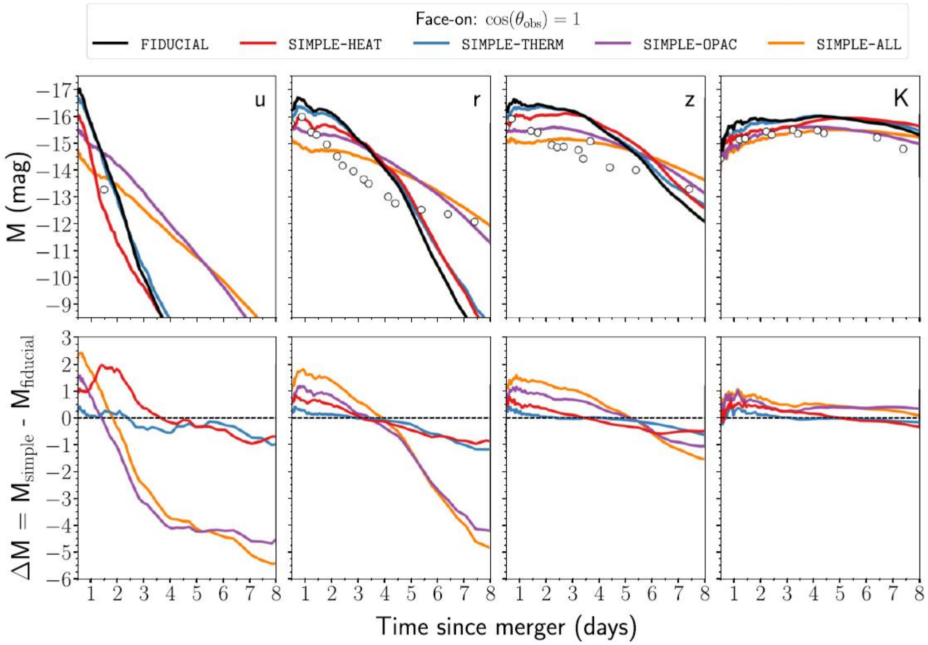
Potential relief

Fiducial: All updated

Simple-Heat: heating rate formula non-local

(*mdyn*, *vdyn*, *mwind*, *vwind*) = (0.005, 0.2, 0.05, 0.05)

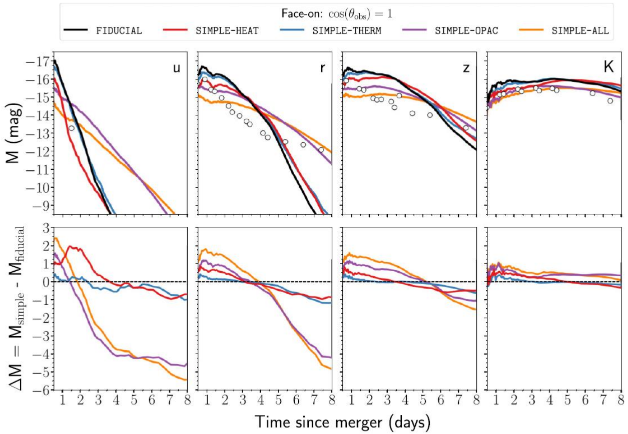




Bulla, MNRAS (2023) – POSSIS update

Ongoing work

- Upgrades to the binned Opacity (Fontes et al 2022)
- Heating rates new formulation (Rosswog and Korobkin 2022)
- Variable Ye along ejecta profiles
- Third component to power the missing Blue peak cocoon shock cooling, or magnetar-like central engine activity. (motivated by the recent GRB211211A)
- Disk Wind simulations with vbhlight (Miller et al.)



Simulation data : https://zenodo.org/record/7335961#.ZAE4iXbMKsM
GP Surrogate models : https://github.com/markoris/surrogate_kne