Neutron star merger ejecta estimation from kilonova light curve (surrogates)

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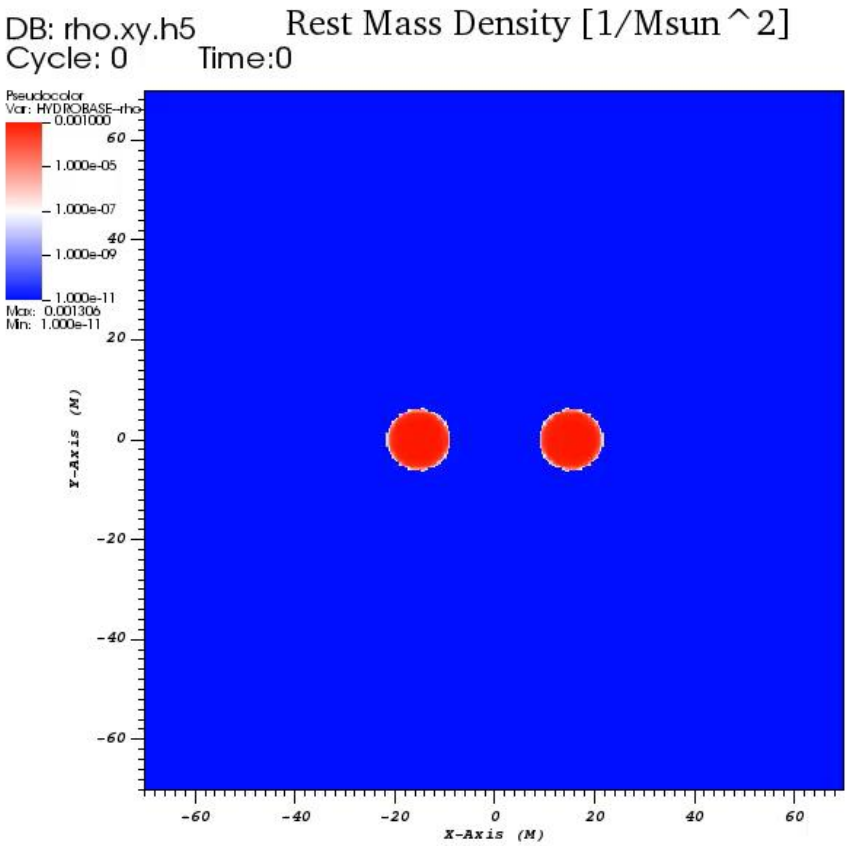
illustration: UC Berkeley news

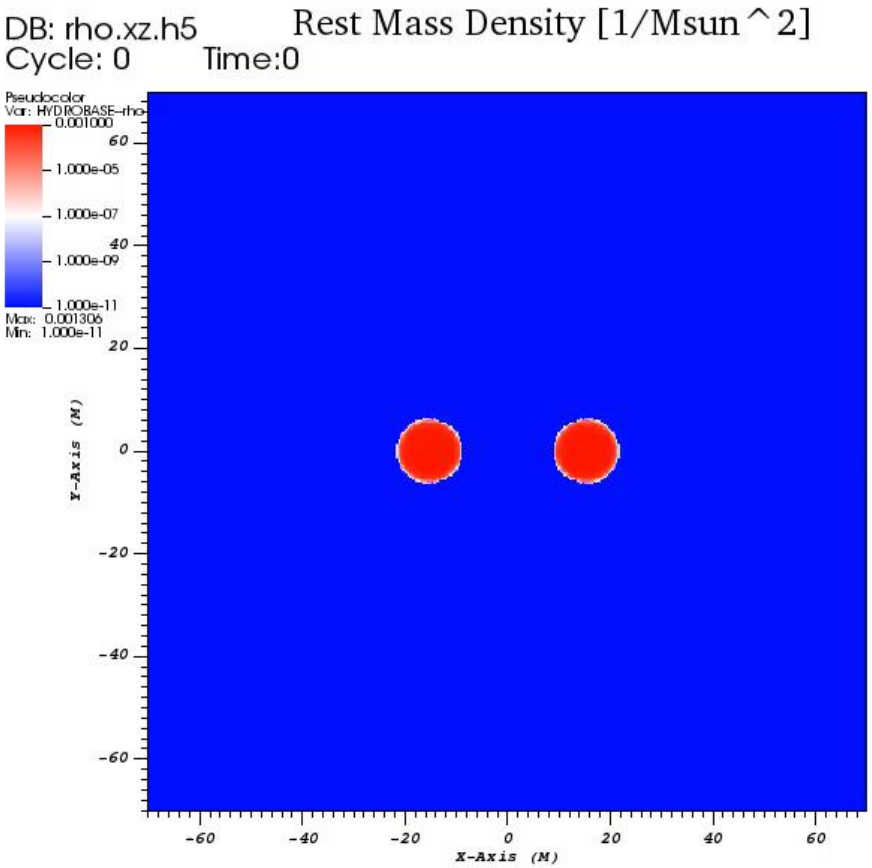
Phys. Rev. Res. 5, 013168 (2023) ; Phys. Rev. D 106, 103027 (2022)

Neutron Star merger



Top-Down view

AK et al., PRD (2022); movies available on atulkedia93.github.io



Cross-section Edge-on view

Equation of State (EoS)

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

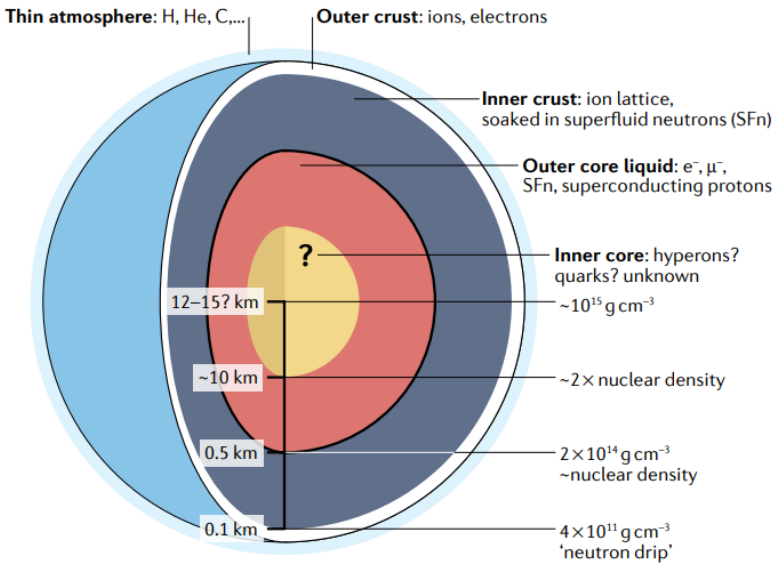
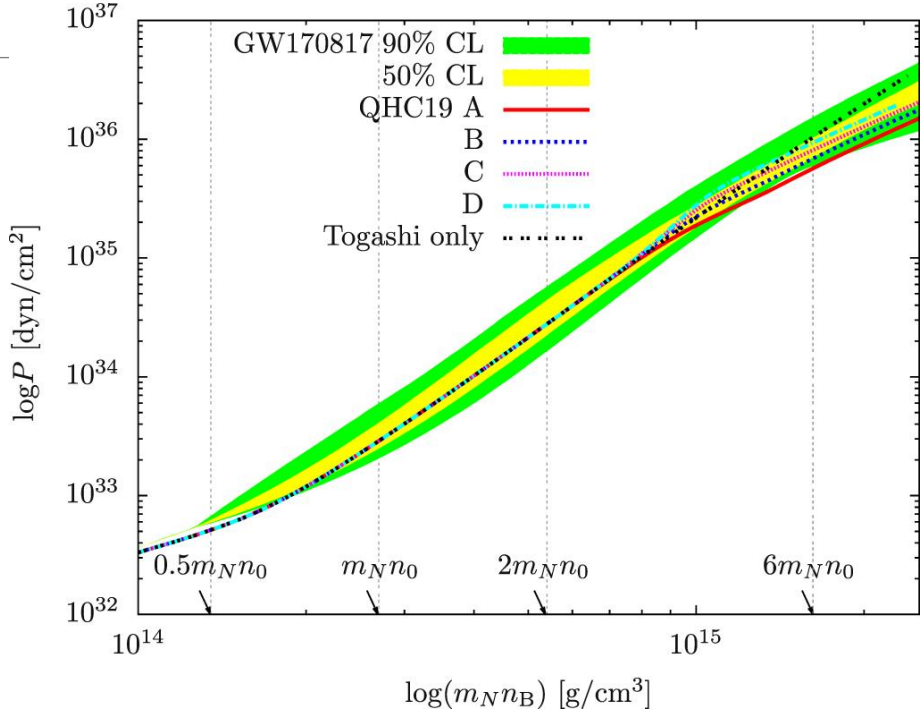


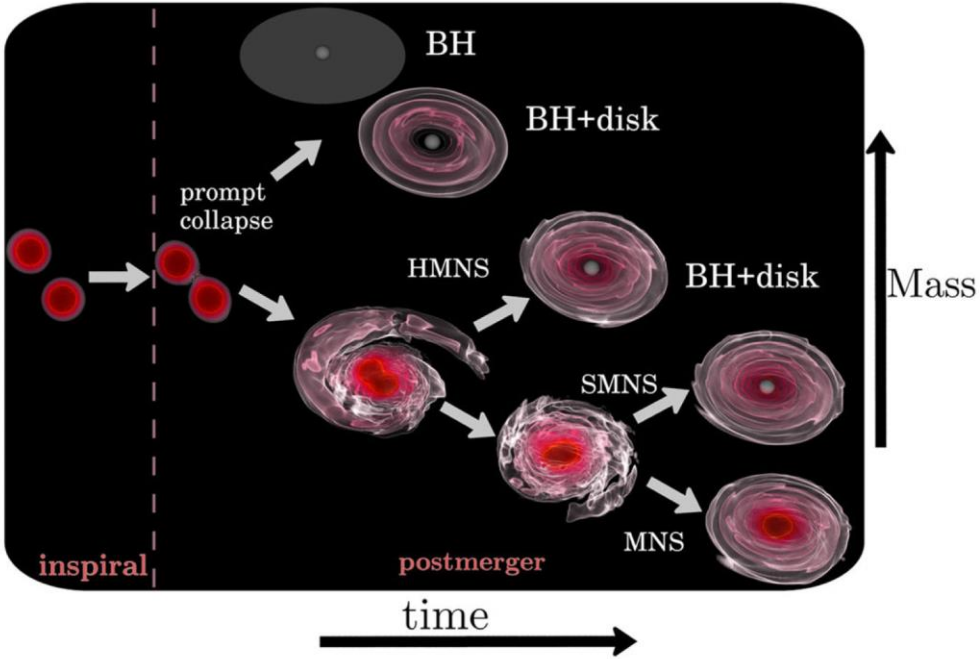
Fig. 1 | **Schematic of the structure of a neutron star and its internal structure.** The figure illustrates the thin atmosphere, the outer and inner crust, and the outer and inner core, with the respective densities at different depths. Adapted with permission from NASA, NICER Team.



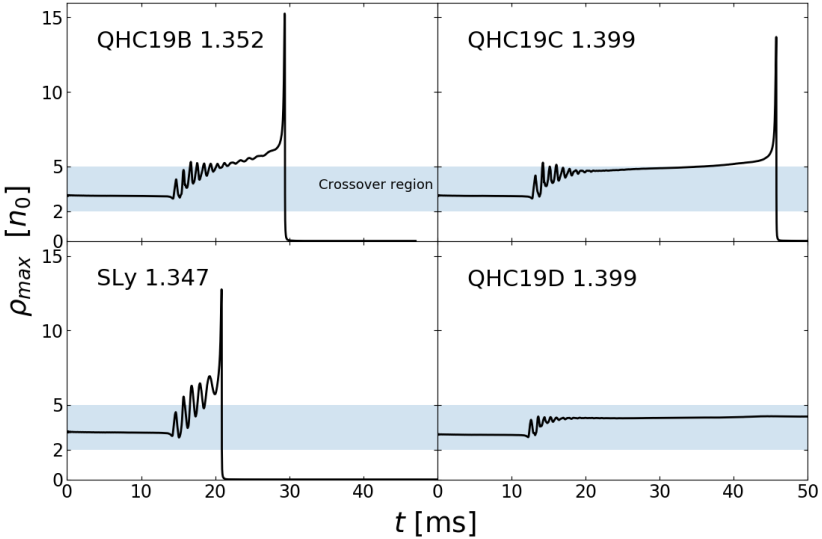
Baym, Furusawa, Hatsuda et al. *ApJ* (2019) 885:42

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

Impact of the EoS on the remnant



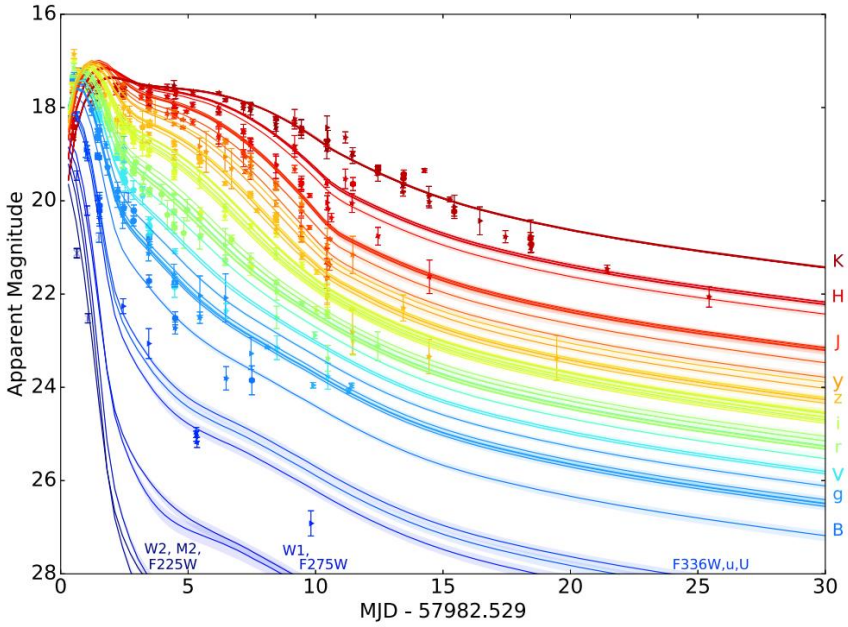
Dietrich et al. GRG (2020)



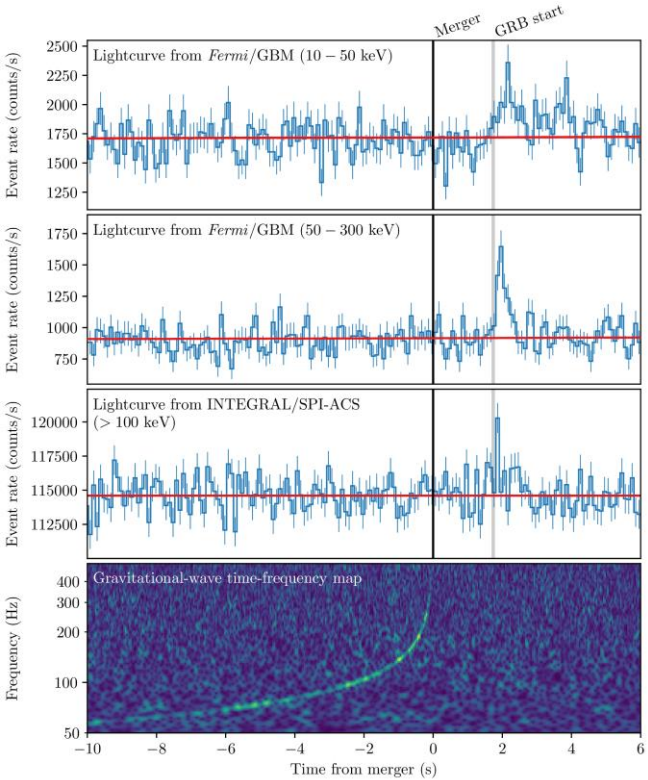
AK et al., PRD (2022)

AT2017gfo / GW170817

sGRB ~ 2s



Villar et al ApJL 2017



Abbott et al PRL 2017 , LIGO+Virgo

Multi-Messenger Astrophysics

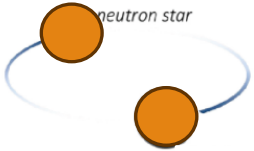
Binary properties

$\vec{x} = \{M_{BII}, M_{NS}, \chi_{BII}, \Lambda_{NS}, \dots\}$

Outflow properties

$\vec{y} = \{M_{dyn}, M_{wind}, v_{dyn}, v_{wind}, \dots\}$

Light curves



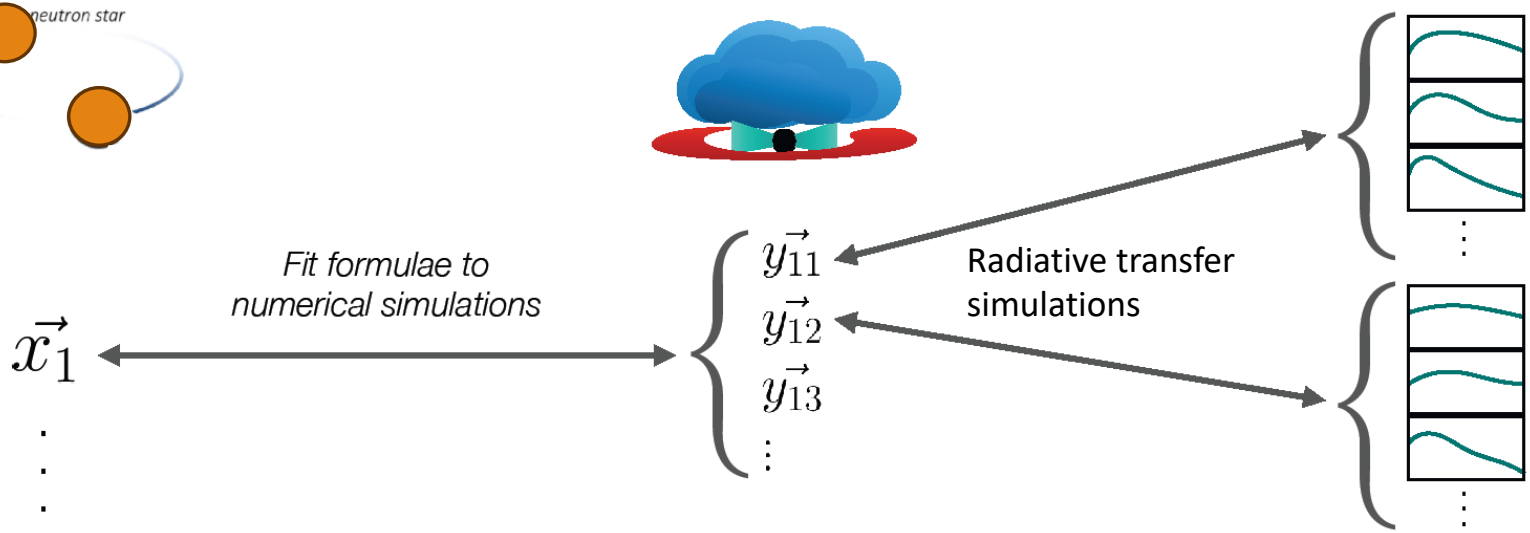
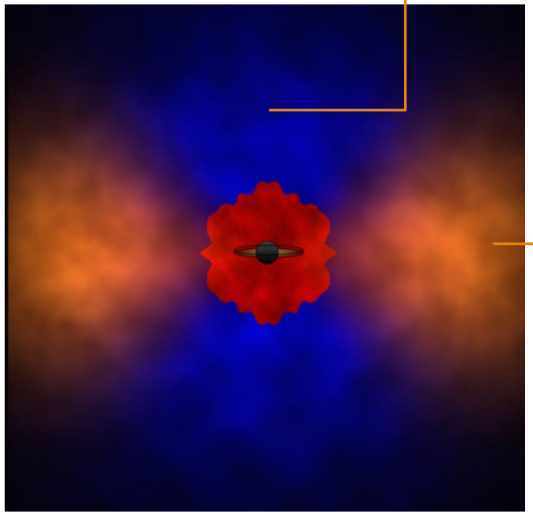
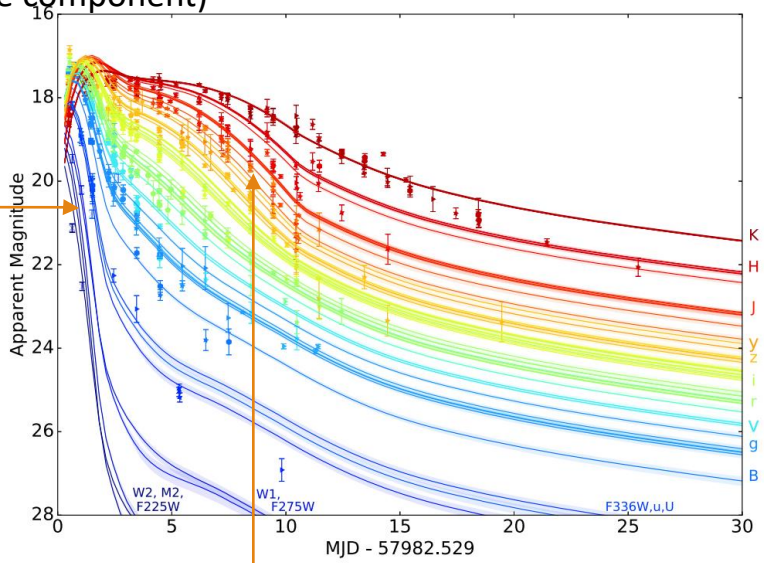


Fig. Credit: Raaijmakers et al, ApJ (2021) ; modified here

Ejecta components corresponding to the kilonova spectrum

Wind ejecta (blue component)

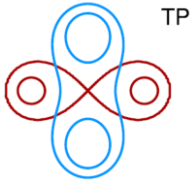




Dynamical ejecta
(red component)

Kasen et al Nature 2017

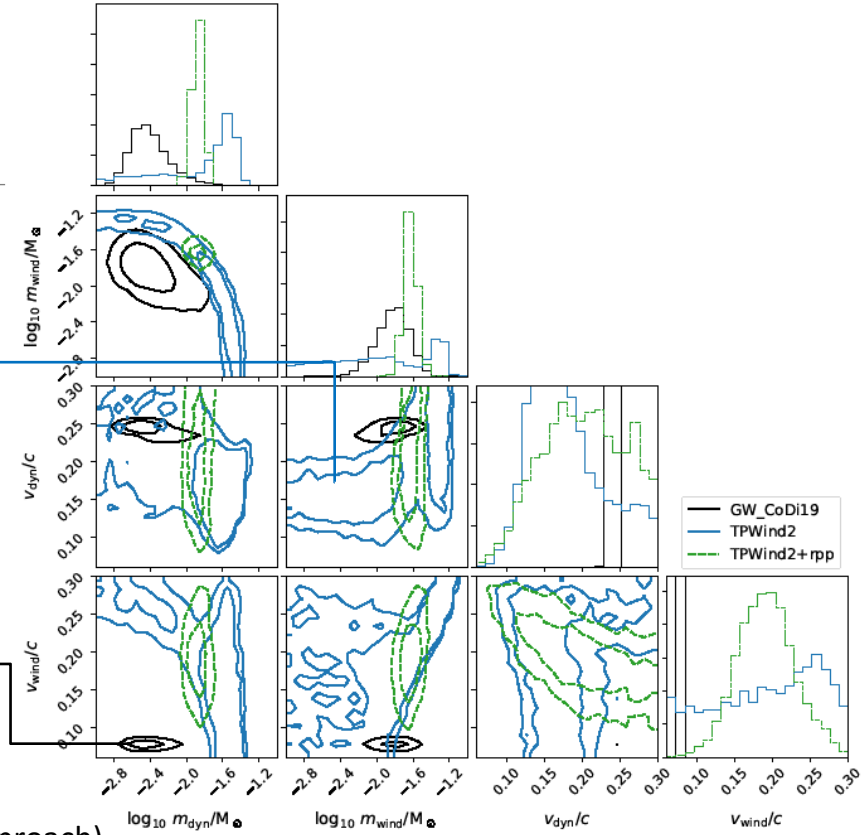
EM v GW ejecta parameter tension



Kilonova approach

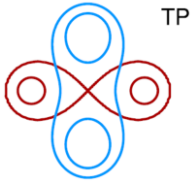
← Assuming(Torus, Peanut morphology)

GW approach



Ejecta masses (Kilonova approach) > Ejecta masses (GW approach)

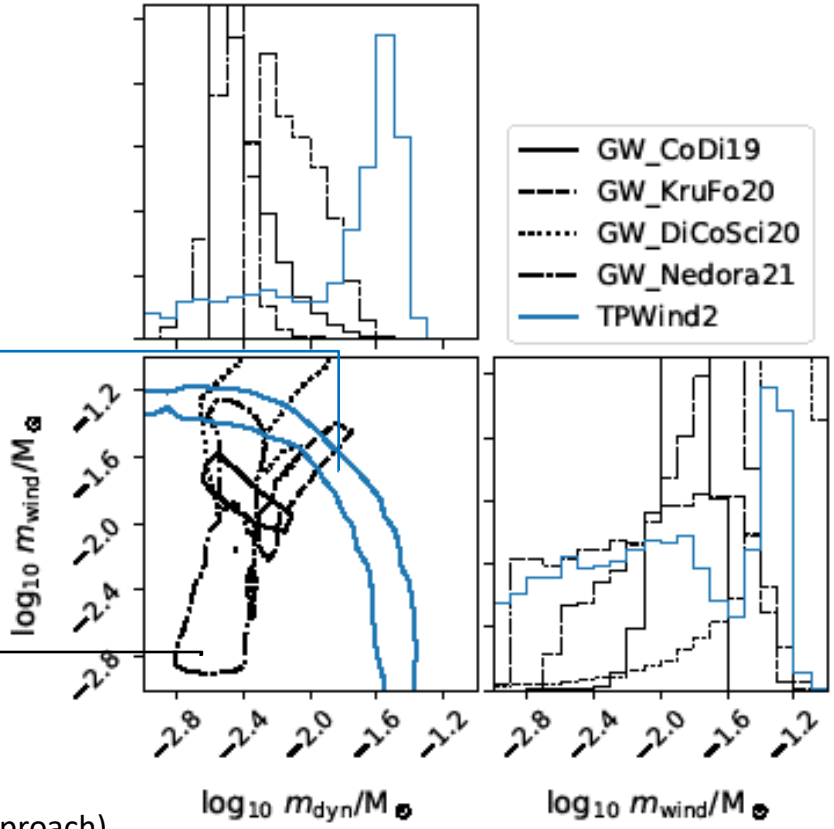
EM v GW ejecta parameter tension



Kilonova approach

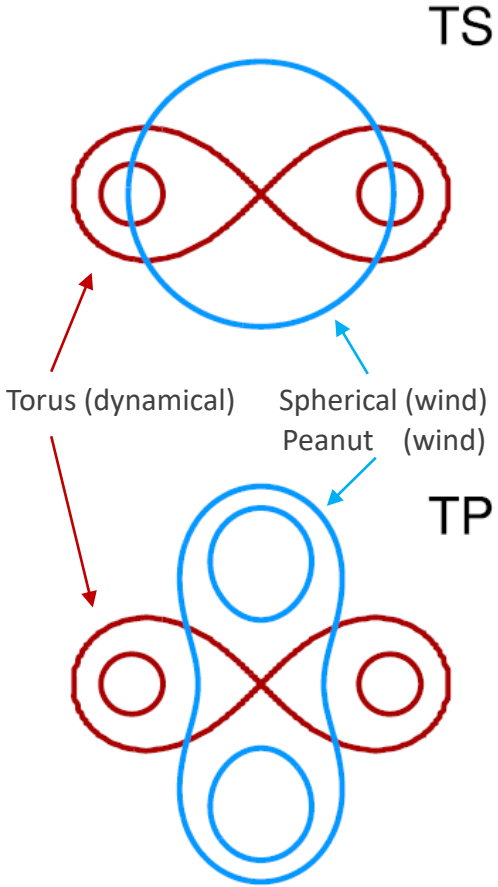
← Assuming(Torus, Peanut morphology)

GW approach



Ejecta masses (Kilonova approach) > Ejecta masses (GW approach)

Ejecta profiles



Korobkin et al 2021 ; Wollaeger et al 2021

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].

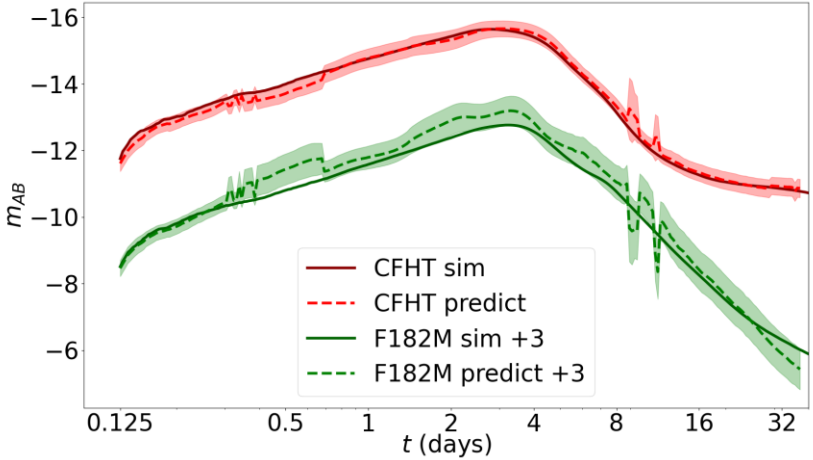
	Wind		
Name	Morphology	Y_e	Dynamical
TPwind1	Peanut	0.37	Torus
TSwind1	Spherical	0.37	Torus
TSwind2	Spherical	0.27	Torus

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

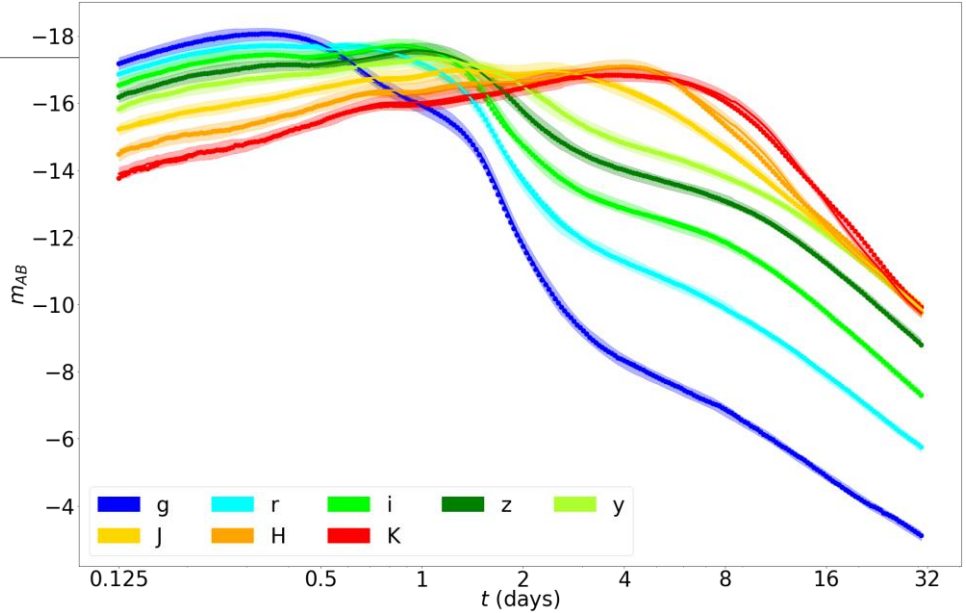
225 + 225 (active learning sims) = 450 /${Name}

Gaussian Process regression Surrogate models

Example interpolation for un-simulated parameters



TPwind1 wavelength interpolation



TSwind2 light curve interpolation
(*mdyn*, *vdyn*, *mwind*, *vwind*, *Θ*) = (0.097, 0.198, 0.084, 0.298, pole)

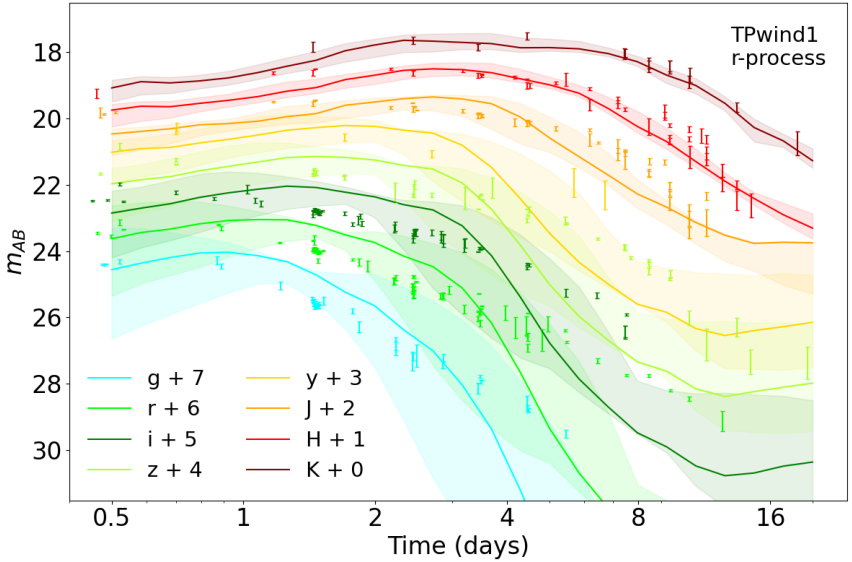
Simulation data : https://zenodo.org/record/7335961#.ZAE4iXbMKsM
GP Surrogate models : https://github.com/markoris/surrogate_kne

Simulation setup

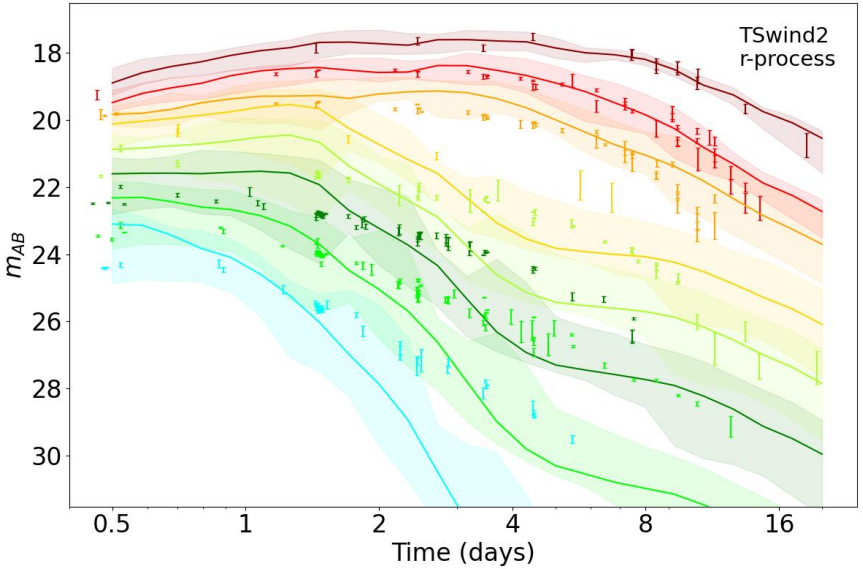
- Radiative transfer software using tabulated binned opacities on **SuperNu**. (Wollaeger et al 2013, 2014)
- Composition and radioactive heating from r-process elements, nucleosynthetic results from **WinNet.** (Winteler et al. 2012)
- Nuclear model
  - Heating rates (Korobkin et al. 2012)
  - Thermalization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

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

Fit Light curves (to AT2017gfo)



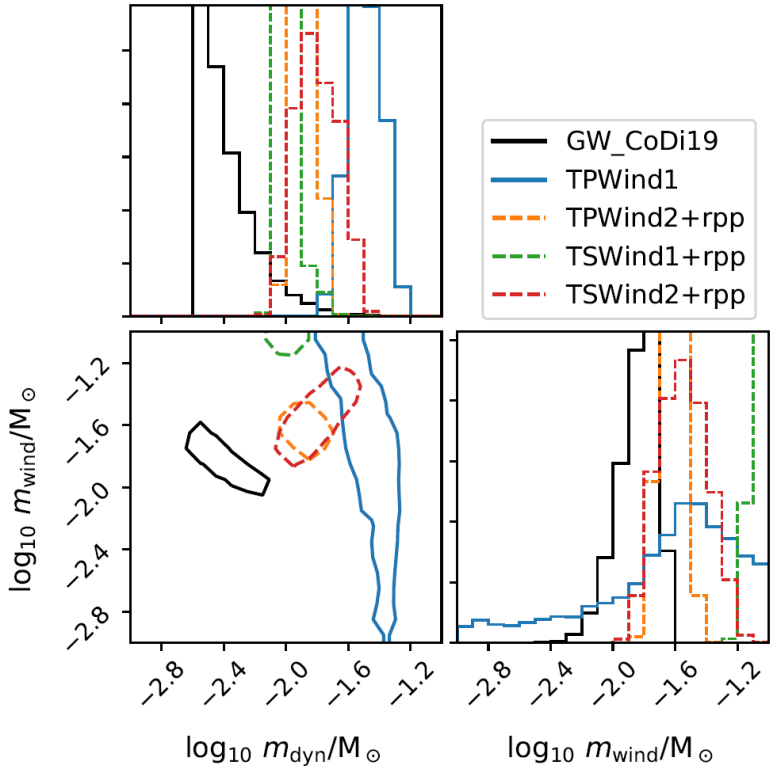
TorusPeanut (high wind Ye)



TorusSpherical (low wind Ye)

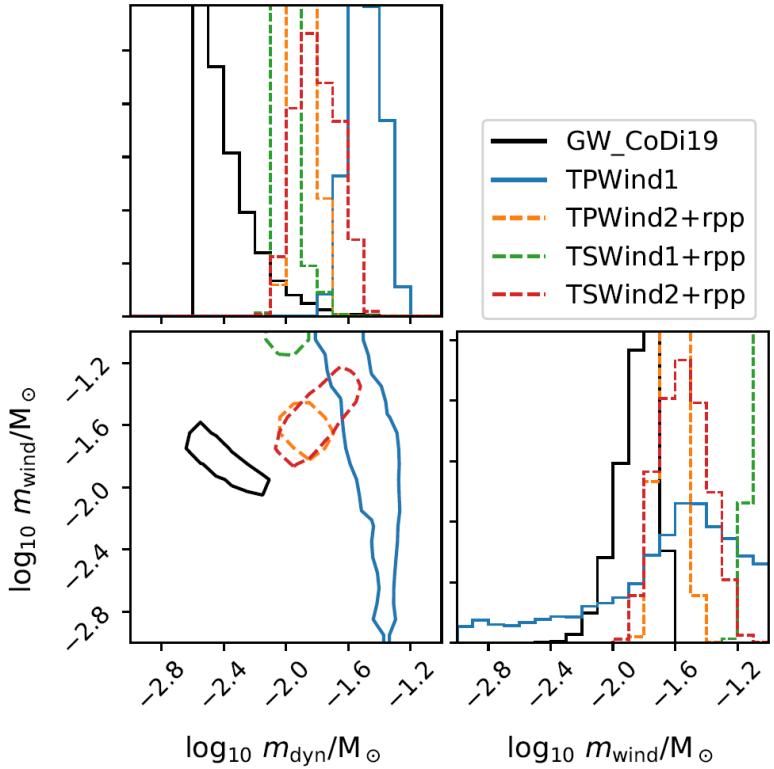
AK et al
Phys. Rev. Research 5, 013168 (2023)

EM v GW ejecta parameter estimation



AK et al, Phys. Rev. Research 5, 013168 (2023)

EM v GW ejecta parameter estimation



AK et al, Phys. Rev. Research 5, 013168 (2023)

Ejecta parameters with the broader ejecta model:

- Different morphologies predict different ranges in the parameter space
- TSwind2 and TPwind2 are significantly closer to GW estimate!
- Some differences still remains!

Collaborators: Marko Ristic (also in this N3AS school), R. O'Shaughnessy (RIT),
R. Wollaeger, C. Fontes, E. Chase, C. Fryer, O. Korobkin (LANL)

Summary

- Multi-messenger ejecta inference
- GW and EM disagree in about ejecta properties
- New radiative transfer simulations with broader ejecta morphologies
- GW and EM still disagree, but less so.
  - Blue luminosity slightly underluminous
- More nuclear and atomic physics improvements are needed in the model

Ongoing work

- Upgrades to nuclear and atomic physics
  - Upgrades to the binned opacity straight from MNRAS (Fontes et al (2022))
  - Thermalization efficiencies (relativistic using AK et al PRE 2021)
  - Heating rates new formulation (Rosswog and Korobkin 2022);

Update example at Bulla, MNRAS (2023)

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