Inferring r-process yields from Neutron Star Mergers: Uncertainties in Kilonova Modeling and the role of UV

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Introduction

- GW170817 demonstrated the potential of GW+EM observations of NS mergers: most direct observation of r-process production to date. But what can we really learn from the observations.

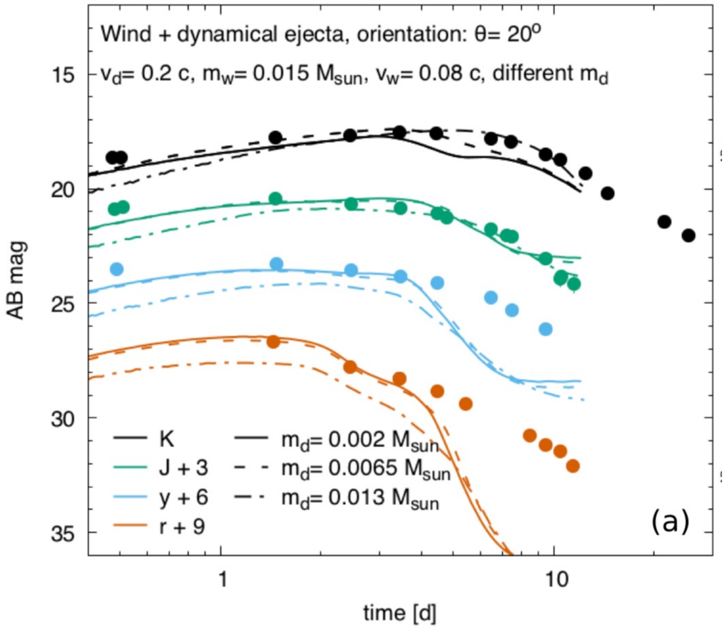


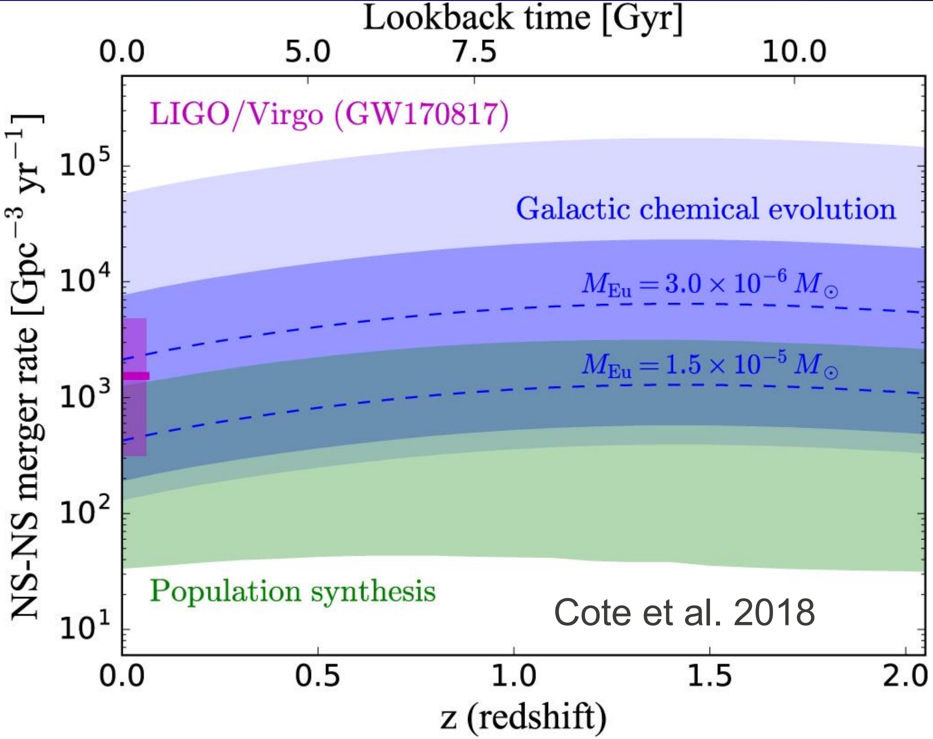
Table 1
Estimates of Ejected Masses for High-opacity Lanthanide-rich Material (m_{dyn}) and Medium-opacity "Winds" (m_w), Sourced from the Recent Literature for GW170817

Reference	m_{dyn} [$M_\odot$]	m_w [$M_\odot$]
Abbott et al. (2017a)	0.001–0.01	…
Arcavi et al. (2017)	…	0.02–0.025
Cowperthwaite et al. (2017)	0.04	0.01
Chornock et al. (2017)	0.035	0.02
Evans et al. (2017)	0.002–0.03	0.03–0.1
Kasen et al. (2017)	0.04	0.025
Kasliwal et al. (2017b)	>0.02	>0.03
Nicholl et al. (2017)	0.03	…
Perego et al. (2017)	0.005–0.01	10^{-5} – 0.024
Rosswog et al. (2017)	0.01	0.03
Smartt et al. (2017)	0.03–0.05	0.018
Tanaka et al. (2017)	0.01	0.03
Tanvir et al. (2017)	0.002–0.01	0.015
Troja et al. (2017)	0.001–0.01	0.015–0.03

- Getting from the observations to constraining properties of the merger ejecta requires multiple aspects of simulation (merger, disk calculations, and radiation flow) and physics (atomic, nuclear cross-section, dense nuclear matter, neutrino, …)
- Can we maximize what we can do with observations?

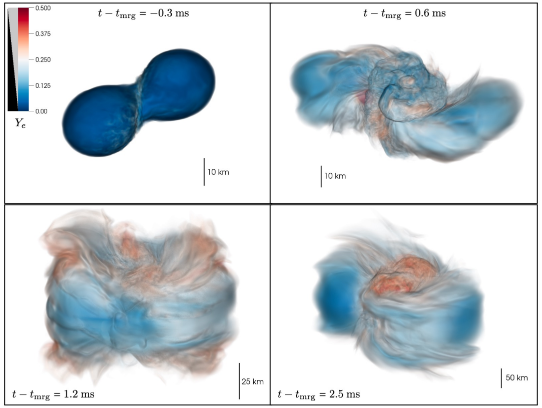
Getting exact yields is critical for detectability and r-process production

- With the high rate predicted by GW170817, a yield somewhere between the minimum and maximum values was consistent to explain the r-process production in the universe (e.g. Cote et al. 2018). Even so, there is evidence that they can't produce all the r-process elements (Cote et al. 2019).
- We now know that we were "lucky" with GW170817 (on par with our luck with SN 1987a). The rate is now ~3 times lower, requiring the average yield to be equal to the highest values predicted by GW170817 (if GCE calculations are correct).
- These high yields are also important in determining the detectability of these events.

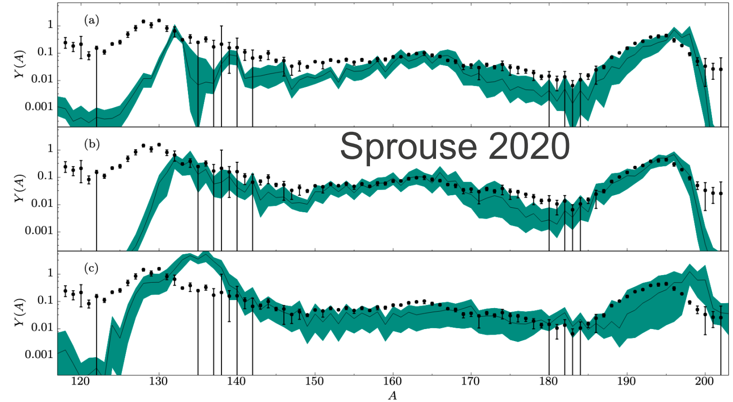


Merger rate now believed to be 80-800 Gpc^{-3} y^{-1} (Abbott et al. 2021more consistent with population synthesis). To explain the majority of r-process, mergers must be at the high end of r-process production.

Pathway to Production (Understanding the Uncertainties)



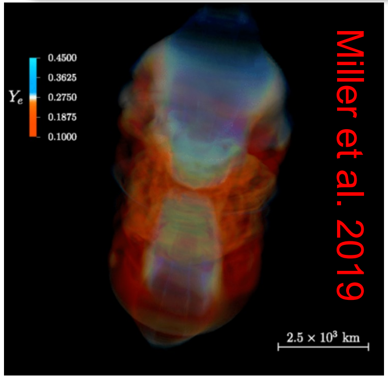
Radice et al. 2019



Light-curves are sensitive to ejecta properties (morphology, velocity distribution), composition (both for opacities and energy deposition), and atomic physics.

Detailed merger and disk calculations

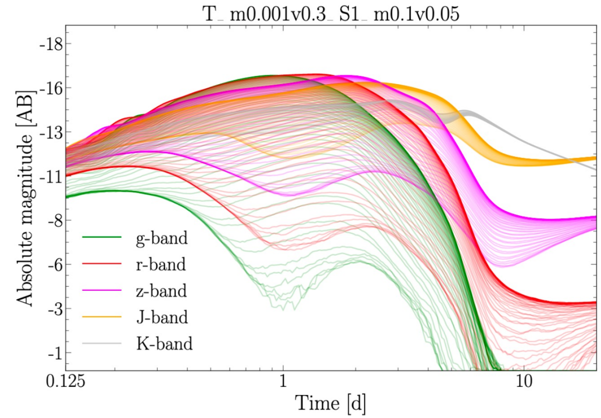
Nucleosynthetic Yields



Miller et al. 2019

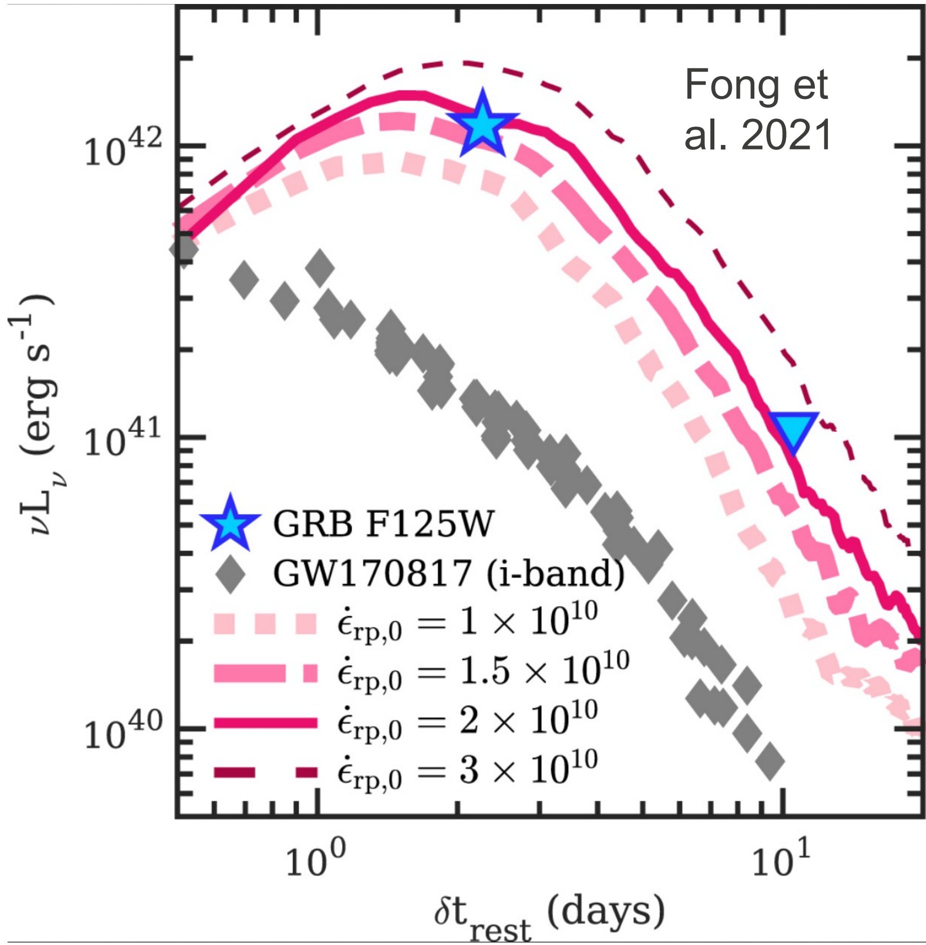
Physics and numerical uncertainties include angular momentum conservation, neutrino physics, equation of state, final escape fractions and trajectories.

r-process nucleosynthesis relies both on these trajectories but also on a broad range of nuclear uncertainties.



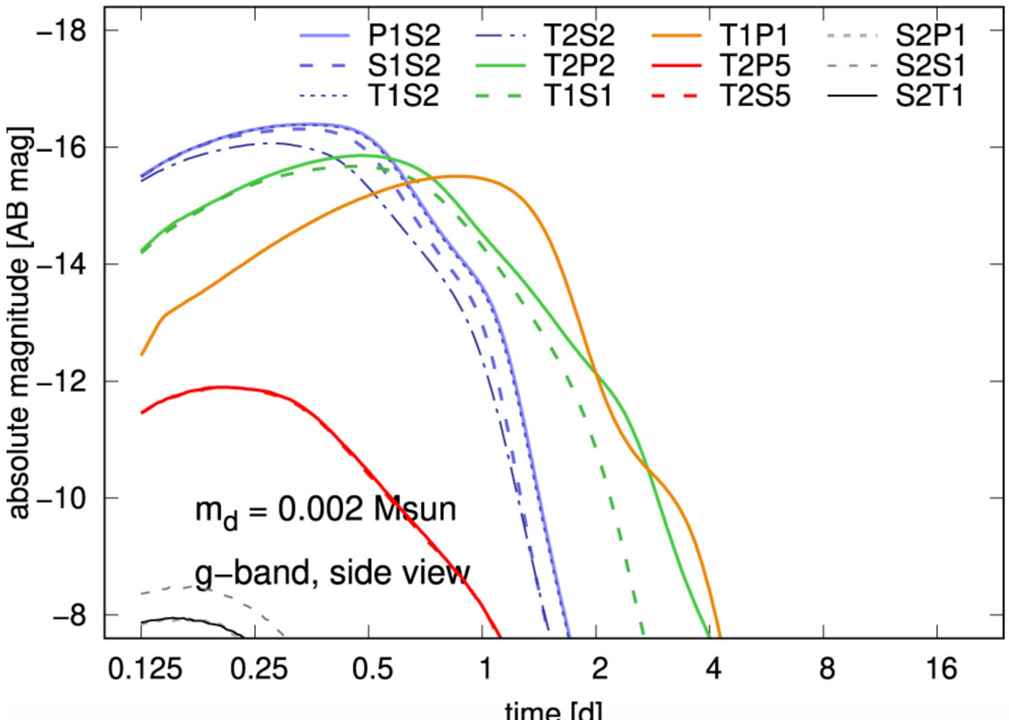
Energy Deposition

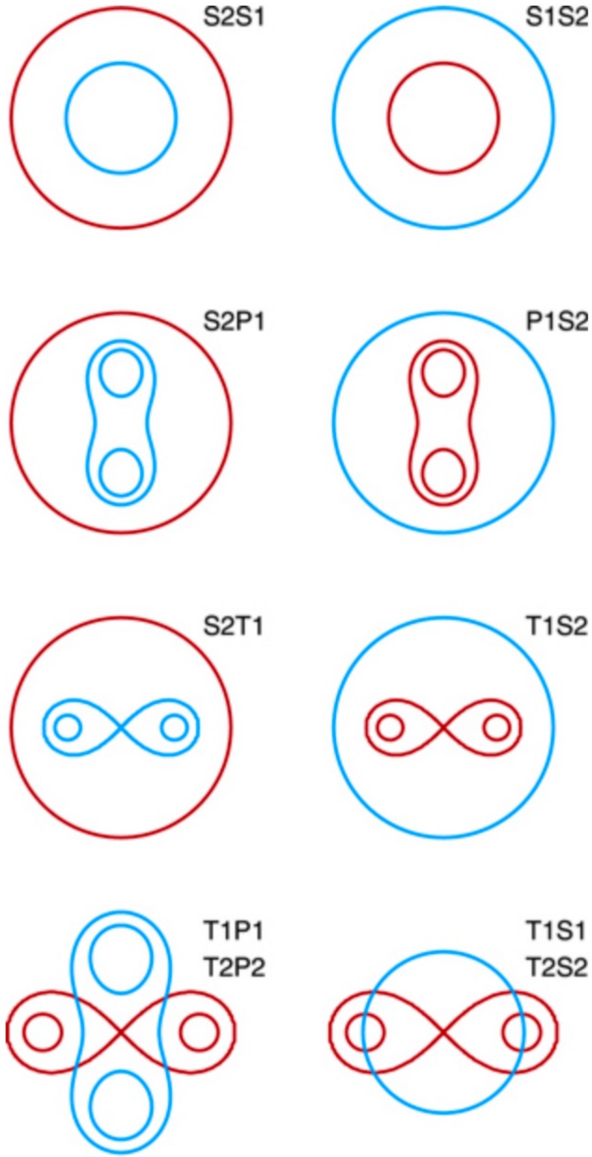
- Energy deposition comes from γ-rays, e^- and α-particles.
- Preliminary studies have been done assuming angle-averaged interactions (stopping power) and spherically symmetric ejecta profiles (Barnes et al. 2016 and subsequent papers). Many light-curve calculations use the formulae derived from these studies.
- Magnetic field effects, breaks from angle-averaged properties, detailed ejecta morphologies can all alter this heating.



Geometry Effects on the Light-Curves

Even with a 2-component model, the geometry can alter the light-curves dramatically (Korobkin et al. 2020)



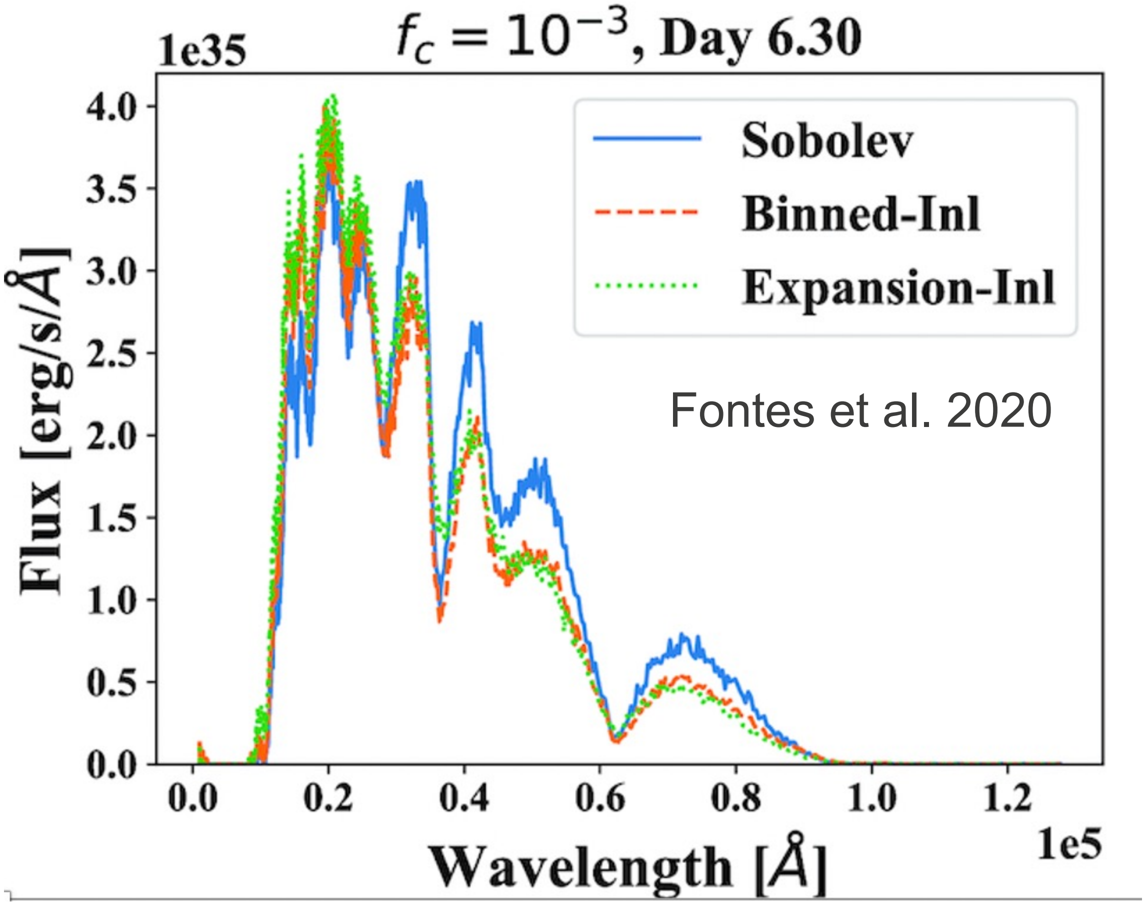


Uncertainties in Opacities

There are a number of uncertainties in calculating opacities:

- Current atomic models do not match
- NLTE effects (radiation/electron distributions) will alter the opacities
- The implementation of the opacities also leads to uncertainties:

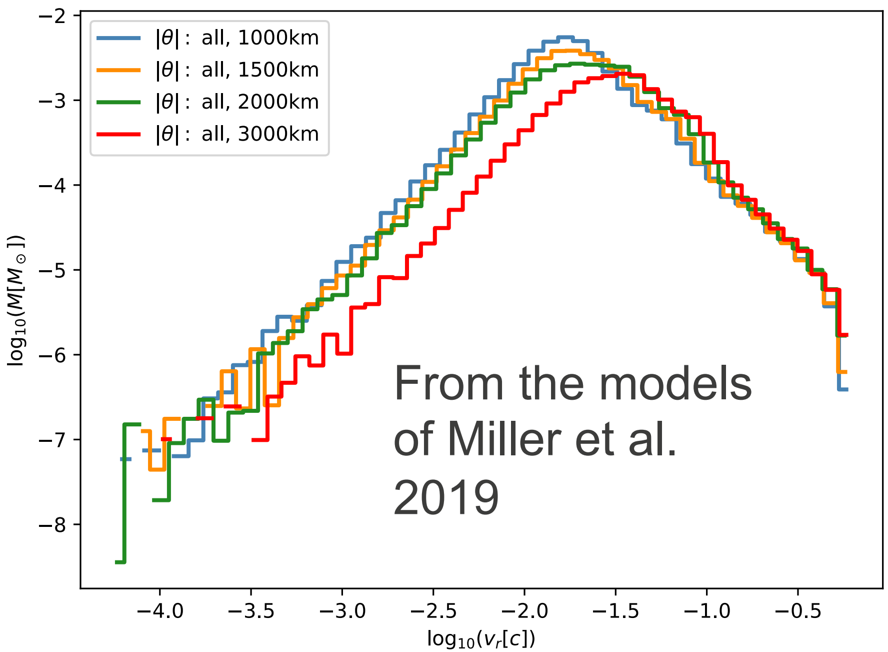
➢ Continuous Sobolev
➢ Expansion approximation
➢ Binned approximation



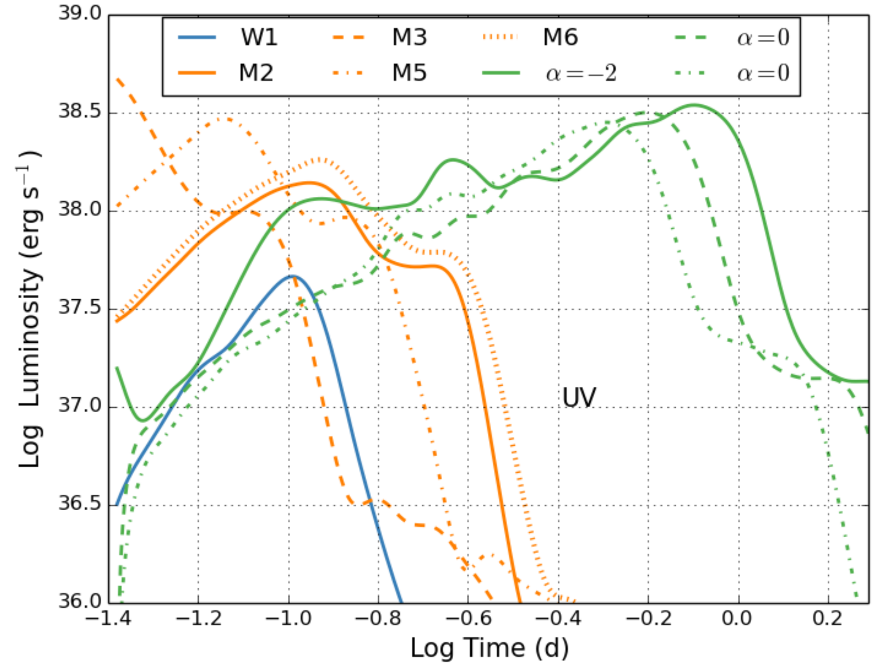
Fontes et al. 2020

Velocity Distribution

Although models of mergers are improving, getting accurate velocity profiles of the ejecta is difficult.



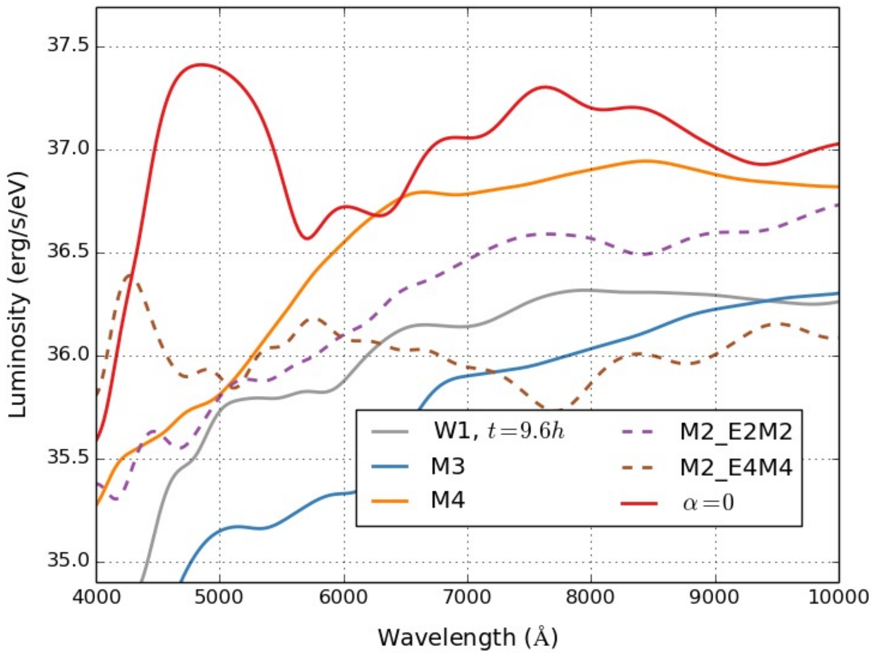
From the models of Miller et al. 2019



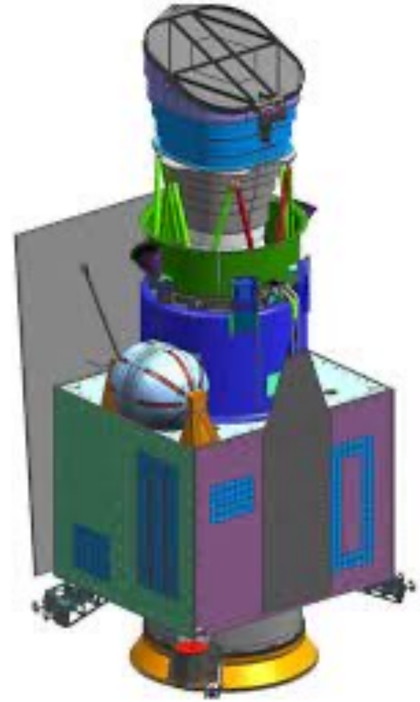
Although these distributions do not affect the late-time IR much (equivalent to a factor of few in the total mass). Other bands that are more sensitive may be used to constrain the velocity distribution.

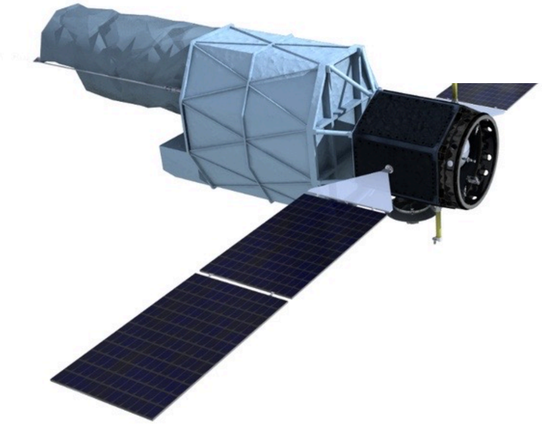
UV is sensitive to many ejecta uncertainties

UltraSat is a wide-field UV imager (will detect GW counterparts)
UVEX can quickly slew to GW counterparts to get UV spectra.



UV will constrain velocity distributions

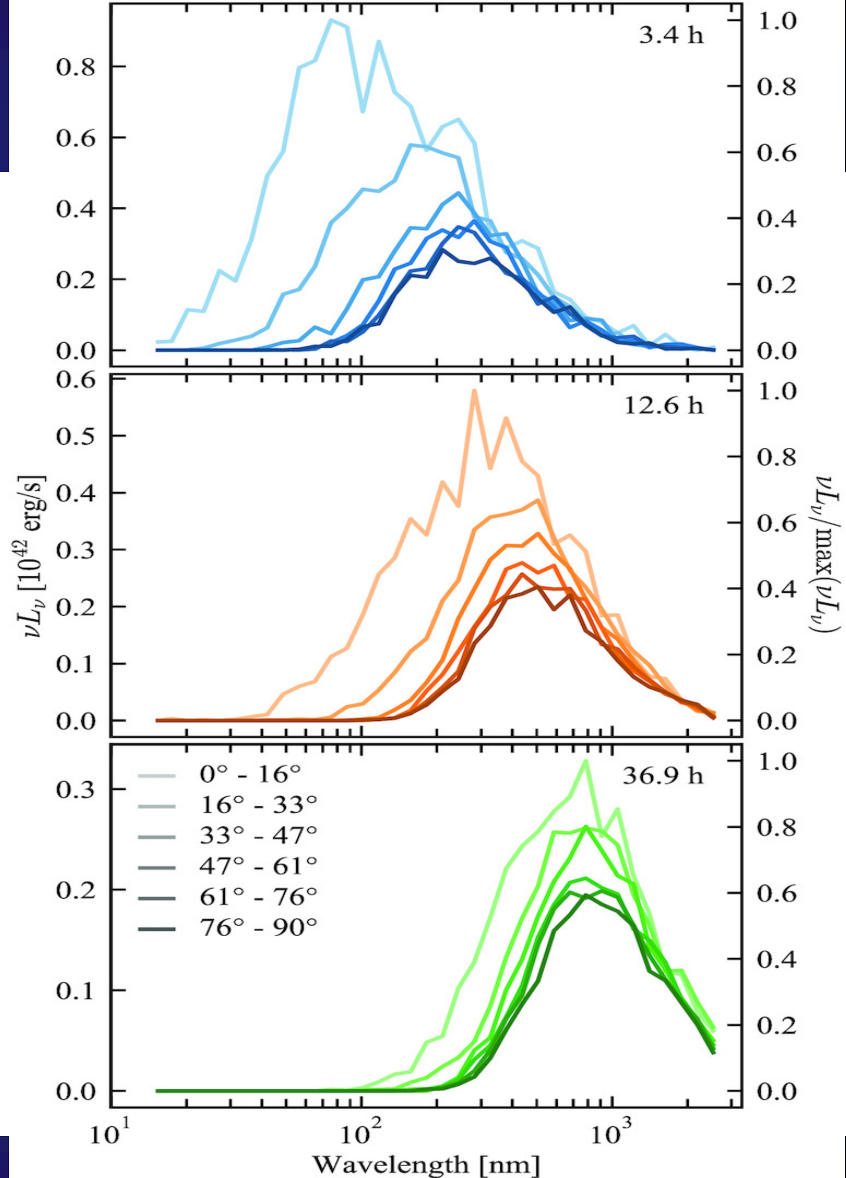




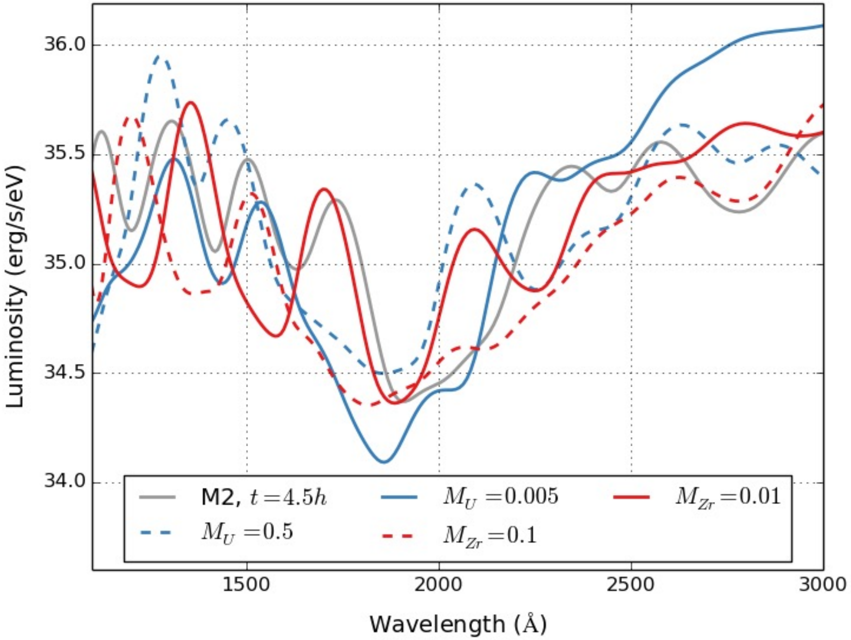
UltraSat will observe KN lightcurves. UVEX will observe UV spectra

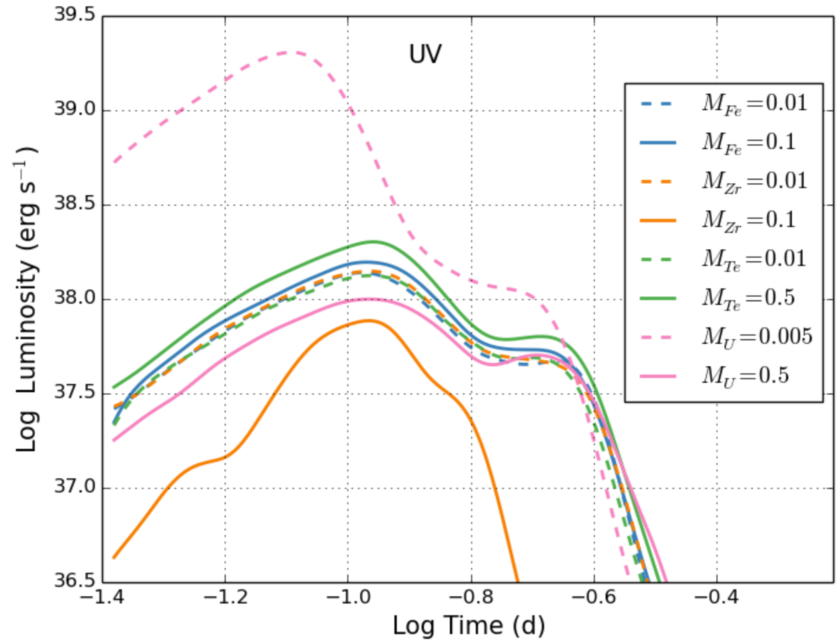
Ultraviolet probes shock interactions

- Ultraviolet probes the outermost ejecta: for discussions see Arcavi (2018), Banerjee et al. (2020). But we must get the observations as soon as possible.
- emergence of the magnetar outflow can reheat the ejecta: e.g. Li and Yu (2016), Wu et al. (2021), Jordona-Mitjans et al. (2022)
- Shock interactions of the jet with the outflow may also reheat the ejecta to produce UV: Klion et al. (2021) (right).



UV Light Curves and Spectra can Probe Abundances as well





Fryer et al. 2023

Understanding Kilonovae is hard!

- Observations: We need as much broadband data as possible. UV is particularly sensitive to many ejecta properties.
- Theory: Quantitative Solutions require broad physics input as well as detailed numerical calculations. This will require a broad set of groups to work together – a number of centers are being developed to facilitate this collaboration (e.g. N3AS, NP3M, CeNAM, ...)