Difficulties in Modeling Kilonova Transients

adding complexity/reality? to our simple stories

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Inferring the r-Process Yield

Cote et al. 2018

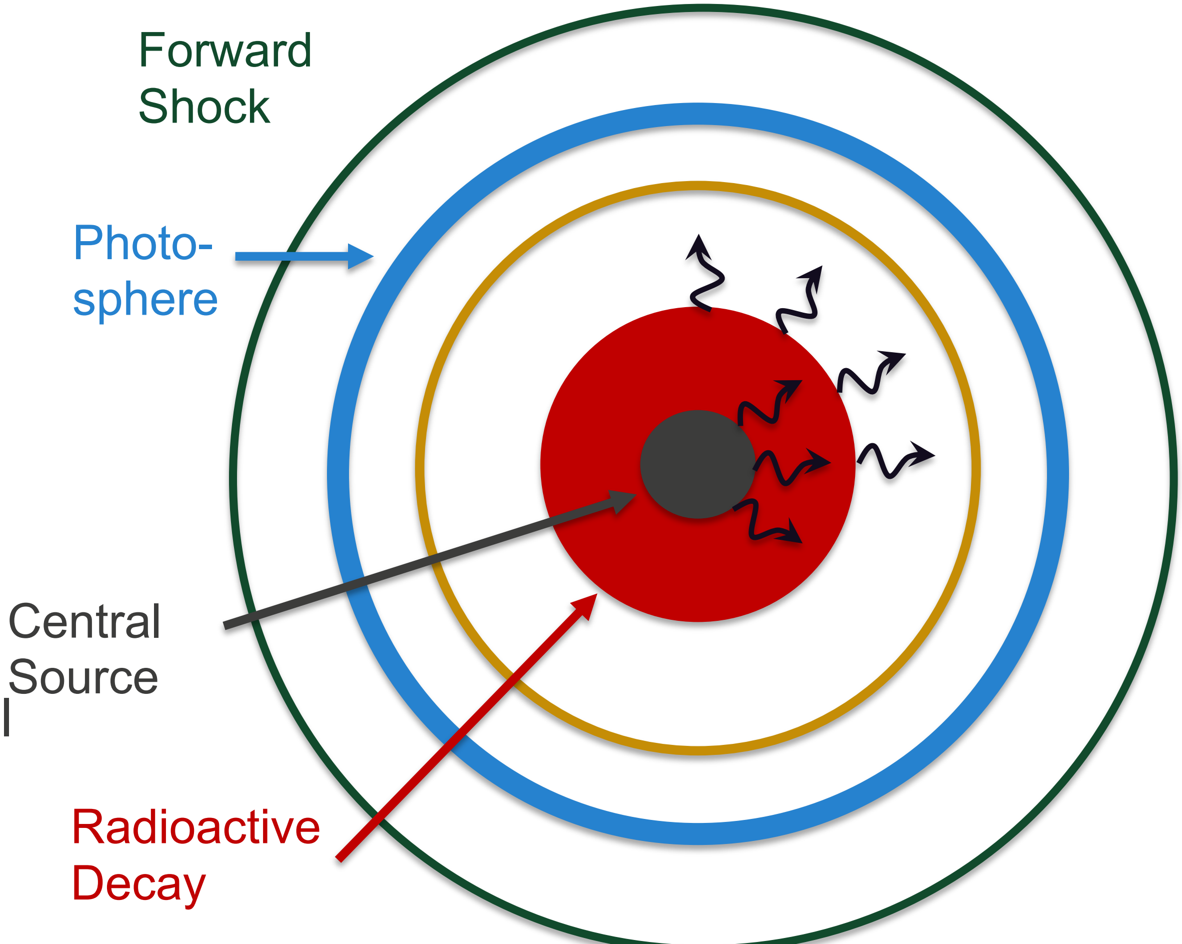
- In the flurry of results studying GW170817, a range of ejecta masses were predicted.
- Some of the differences are due to using only a fraction of the data, but modeling uncertainties are a prominent aspect of the uncertainties.

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

Reference	$m_{\rm dyn}$ $[M_\odot]$	$m_{\rm w}$ $[M_\odot]$
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

Light Curve Basics

- Forward shock moves through circumstellar medium (for massive star progenitors, this is a clumpy stellar wind).
- Photosphere moves inward in mass (typically still outward in radius): r_{phot} evolves with m_{ejecta} $(vt)^{-2}$
- Energy from radioactive decay or an on-going central engine (e.g. magnetar, fallback) is transported out of the center.



Arnett Law

- Arnett (1982) derived the luminosity of a transient powered by a central ^{56}Ni source. This led to a shape function that depended on the diffusion time, the expansion time (inward motion of the photosphere), and the nickel decay timescale:

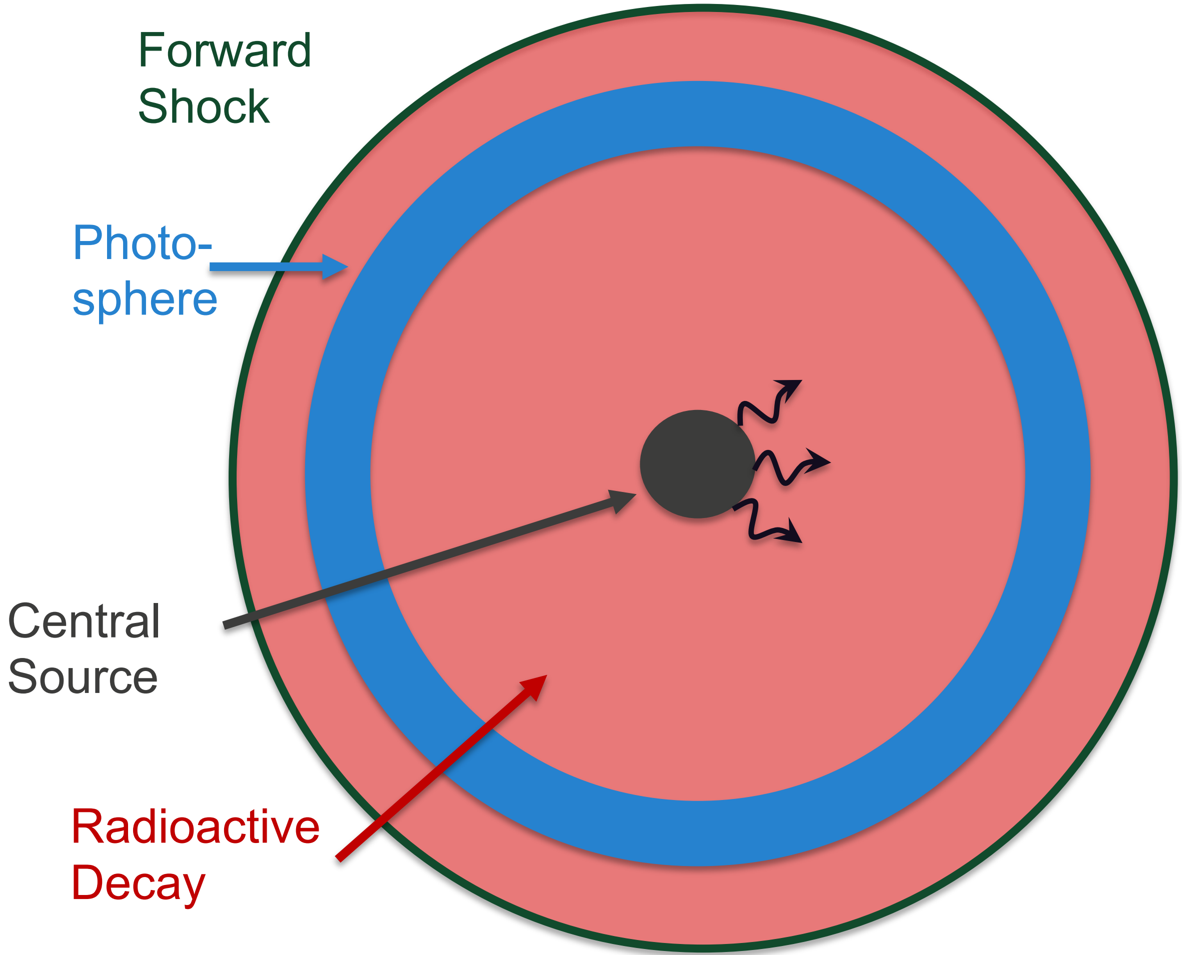
$$y = (2\tau_d \tau_h)^{\frac{1}{2}} / 2\tau_{\mathrm{Ni}} \sim (\kappa_t M_{\mathrm{ej}} / V_{\mathrm{sc}})^{\frac{1}{2}}$$

$$\begin{aligned} L &= \epsilon_{\mathrm{Ni}} M_{\mathrm{Ni}} M_{\odot} \Lambda(x, y) \\ &= 2.055 \times 10^{10} L_{\odot} M_{\mathrm{Ni}} \Lambda(x, y) \end{aligned}$$

- This derivation is remarkably good at matching Ia and many Ib/c light-curves.
- It also explains many of the trends/degeneracies (opacity, ejecta mass and expansion velocity).
- But just because it fits the light curve doesn’t mean you can trust the masses inferred from simple approaches like this (e.g. see M. Hamuy thesis)

Different picture from Kilonovae

- Shock heating: jet interacting with wind (e.g. Shrestha et al. 2023) but reverse shock likely to be weak
- Radioactive isotopes much more distributed.
- Mass is low, velocity is high – fast LC evolution.
- Long-term central engine: magnetar, fallback accretion



Uncertainties in Modeling Kilonova Light-Curves

- Initial Conditions: velocity distribution: $m(v,\theta,t)$, $v(m,\theta,t)$; composition, entropy, additional power sources (magnetar, fallback), surrounding medium
- Transport:

➢ Energy Deposition: nuclear decay properties, γ, e, α transport.

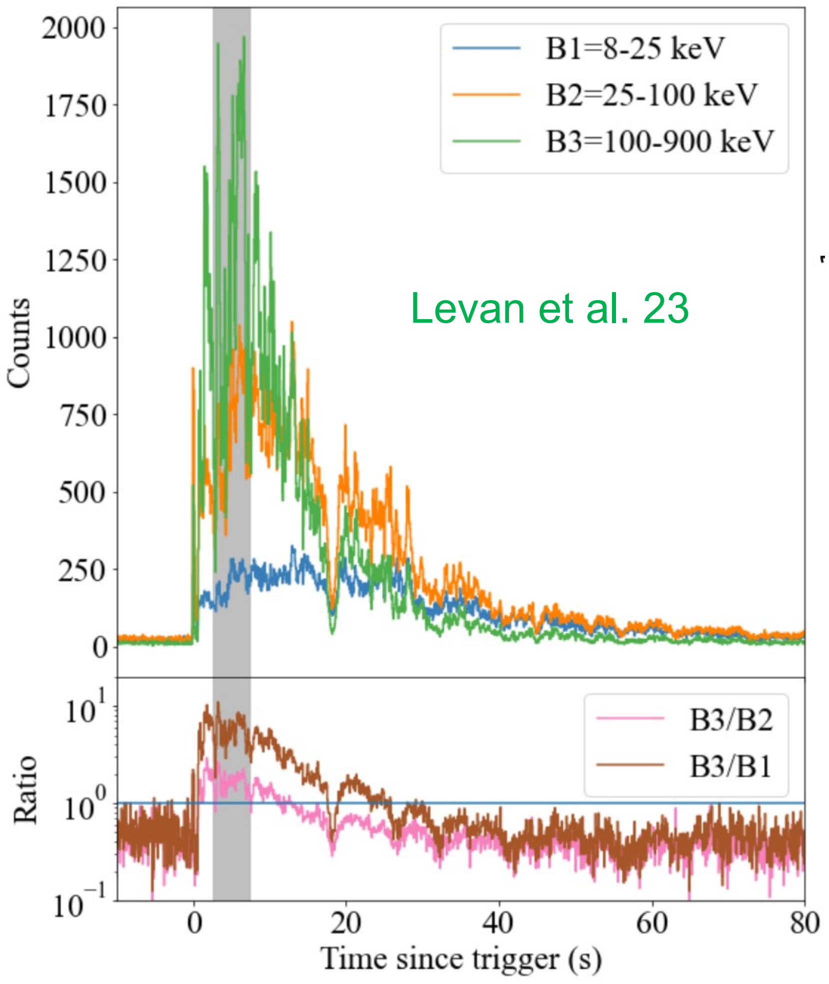
➢ transport methods: flux limited diffusion, other closure methods that include angular effects, methods that include full angular information: e.g. discrete ordinate (e.g. S_n), Implicit Monte Carlo+discrete diffusion Monte Carlo (e.g. SuperNu), …

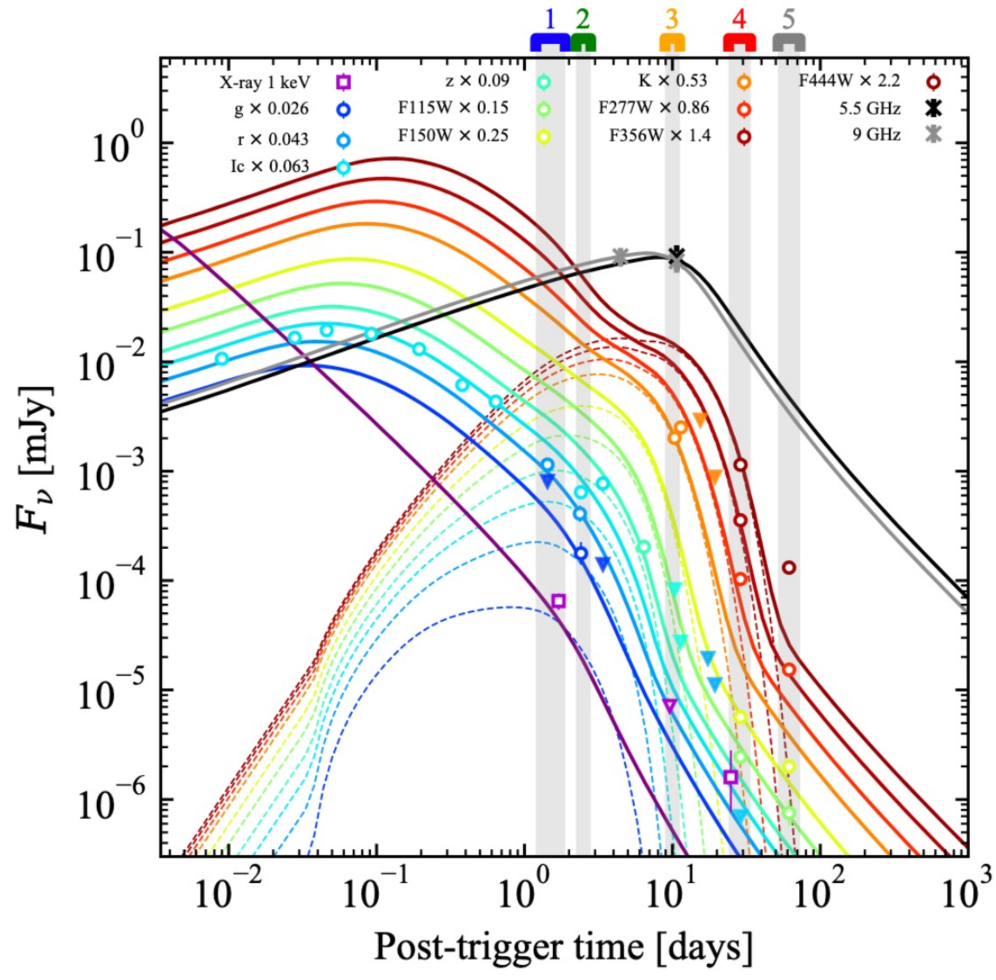
➢ atomic physics: in LTE, NLTE

➢ Implementation of the atomic physics: Sobolev, binning (expansion, …)

➢ Interaction with matter: shocks, …

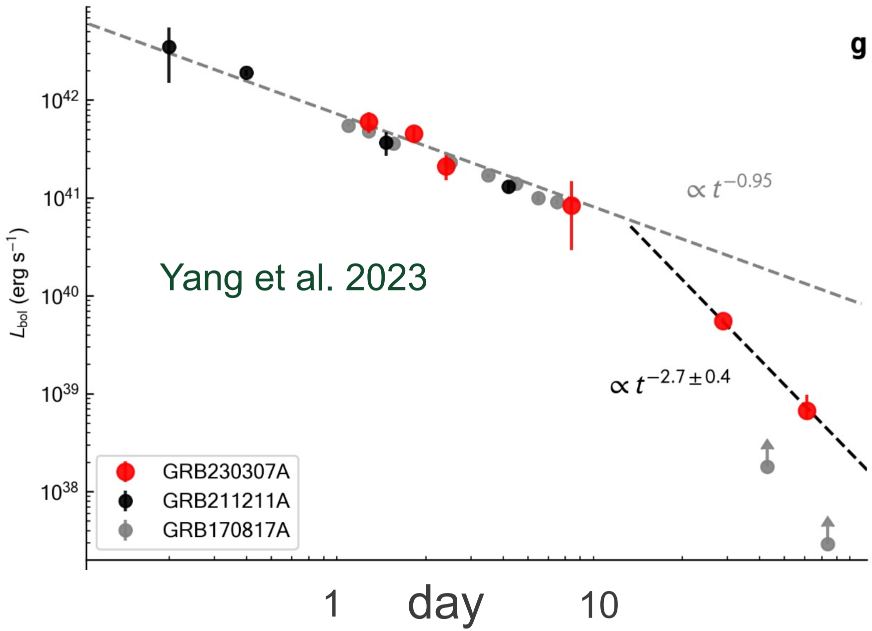
For example, 230307A, a long duration GRB with a kilonova?

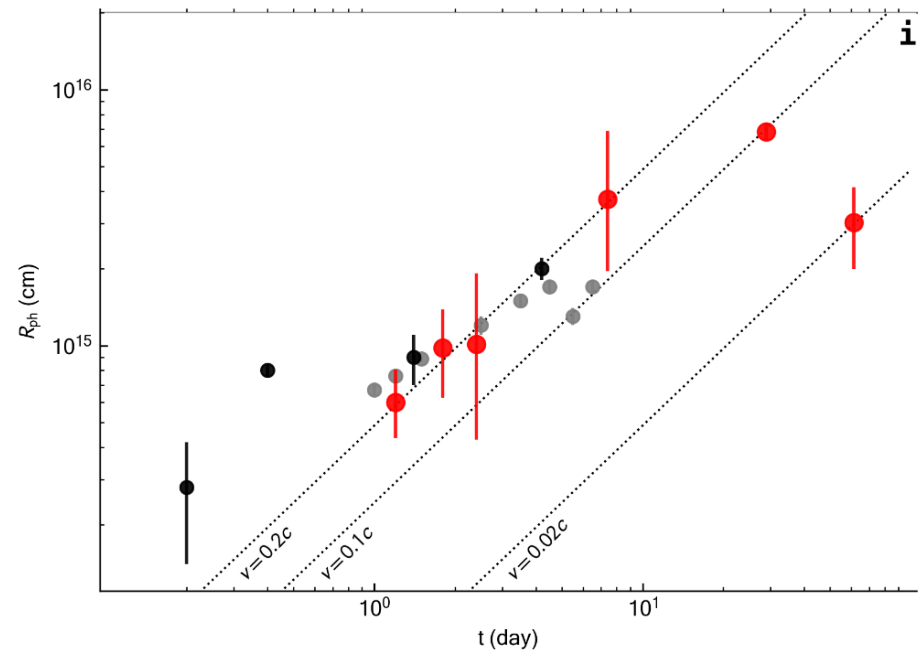




GRB230307A – many similarities to other kilonova

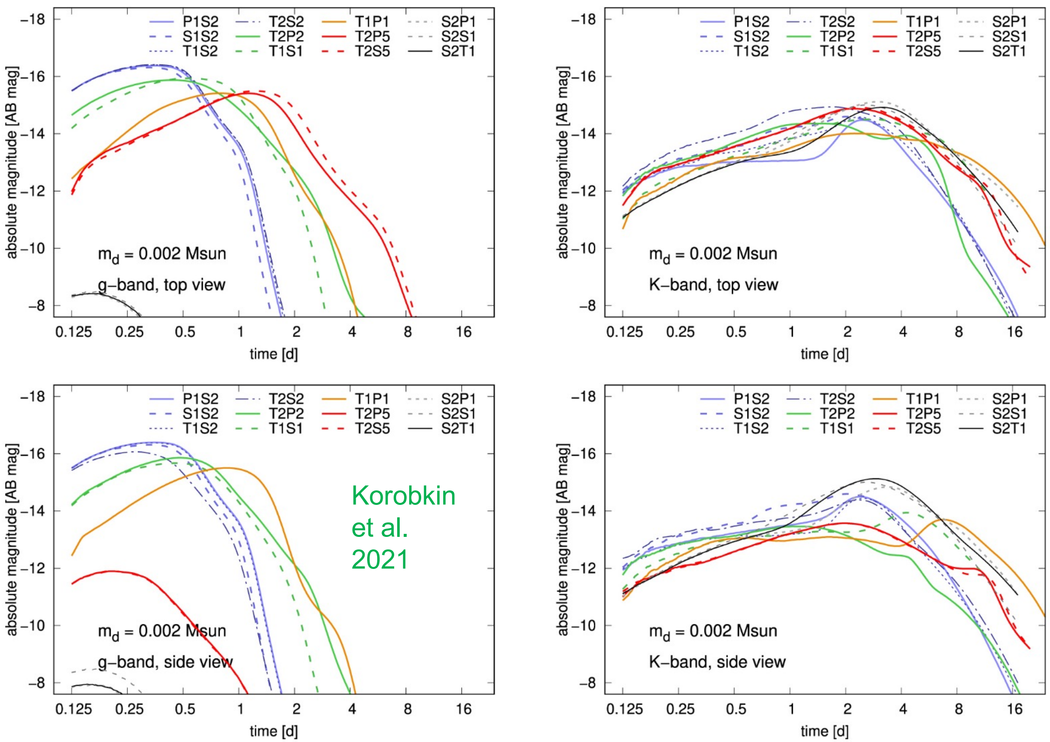
The light curve is very quickly evolving. After 30d, the photosphere begins to move in dramatically (evidence of drop in opacity as discussed by Kasen?).

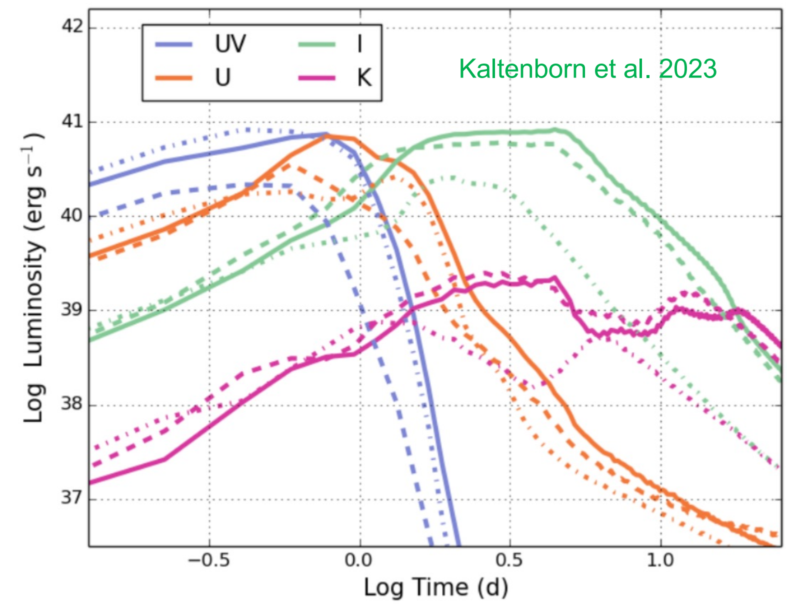


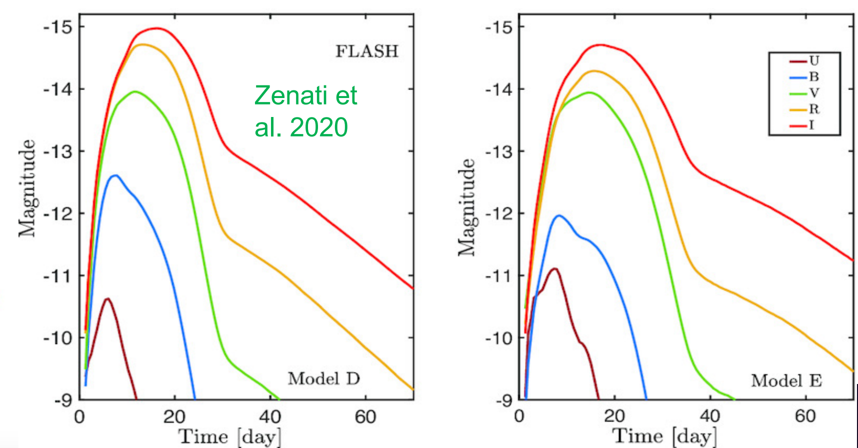


If it looks like a duck, is it?

- How do we tell the difference between different ejecta. Is it in the IR because the photons are downgraded or because it is cool



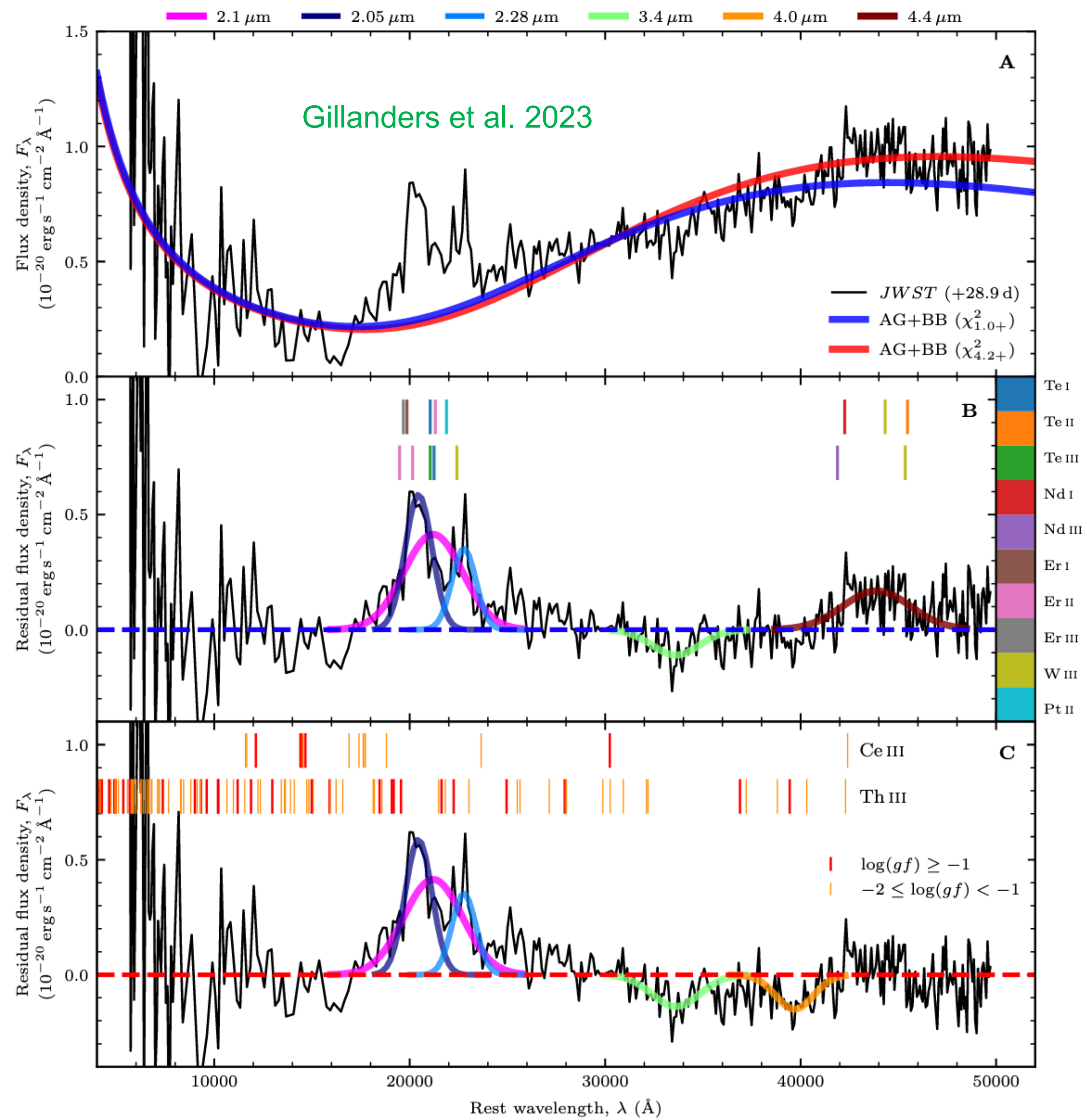




Matching to a Kilonova

Two important features at ~30d.

- Photosphere still exists at 30d (lots of mass or high opacity out to 5μm). We certainly can't do this with opacities without Lanthanides, but can we even do this with Lanthanides?
- Strong emission feature at 2-2.2μm. TeIII (NLTE required - Hotokezaka…)

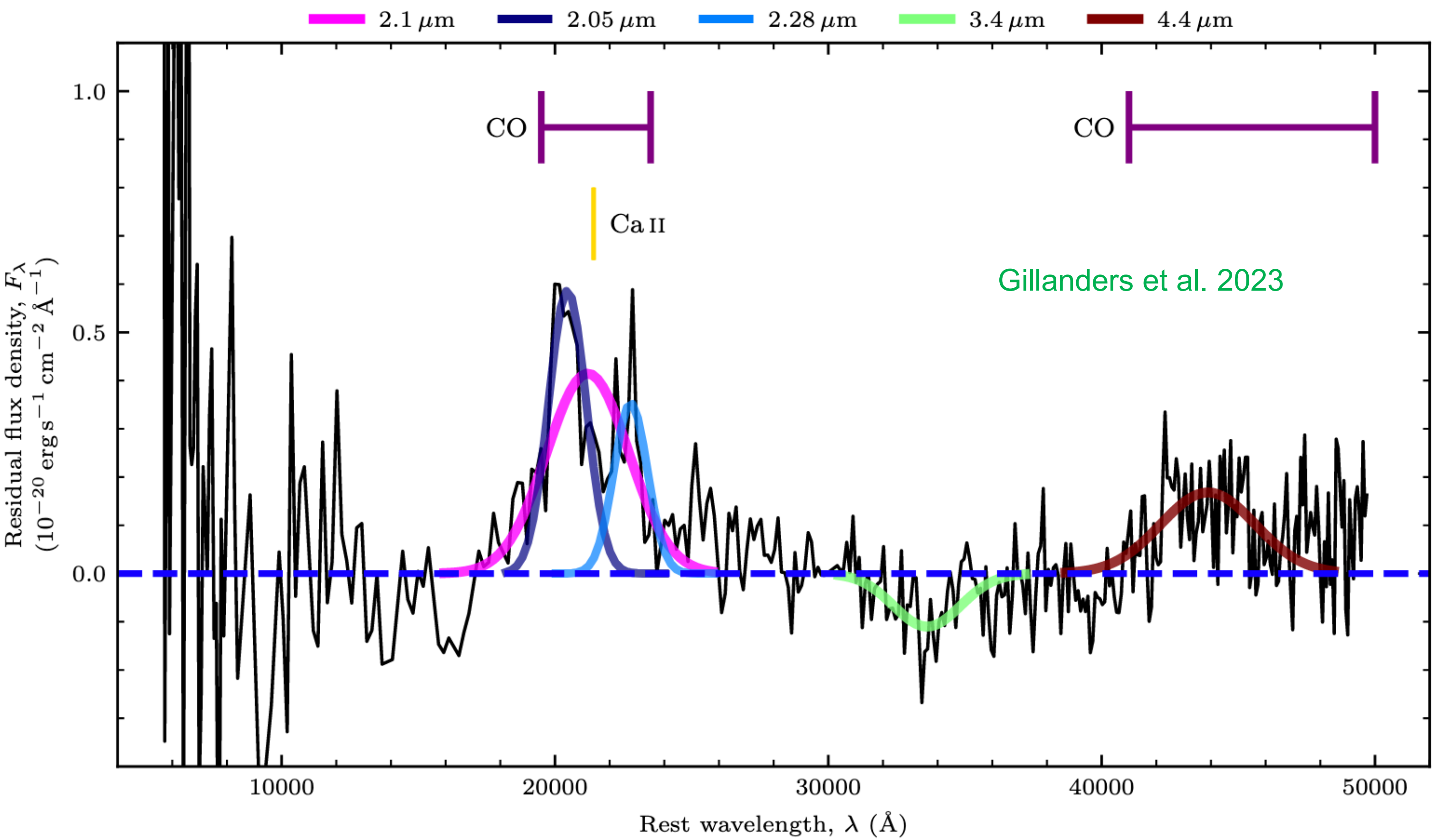


But can we explain these with Ca+CO features from a WD/NS merger?

The features and high opacities might be a combination of CaII, CO molecular lines and dust.

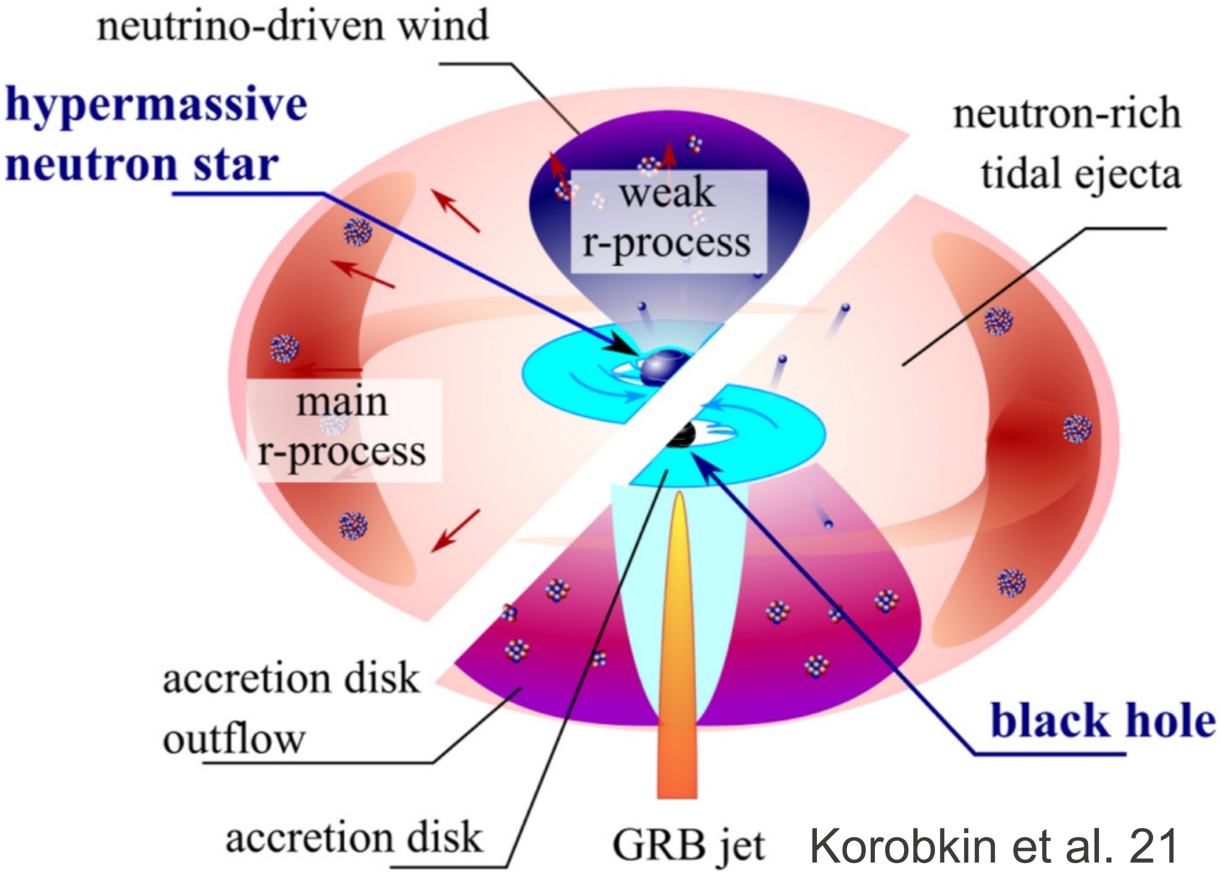
Can explain offsets: Toonen et al. 2018

Also see: Yang et al. 2023, Zhong et al. 2023



Blue versus Red Components Too Simplistic

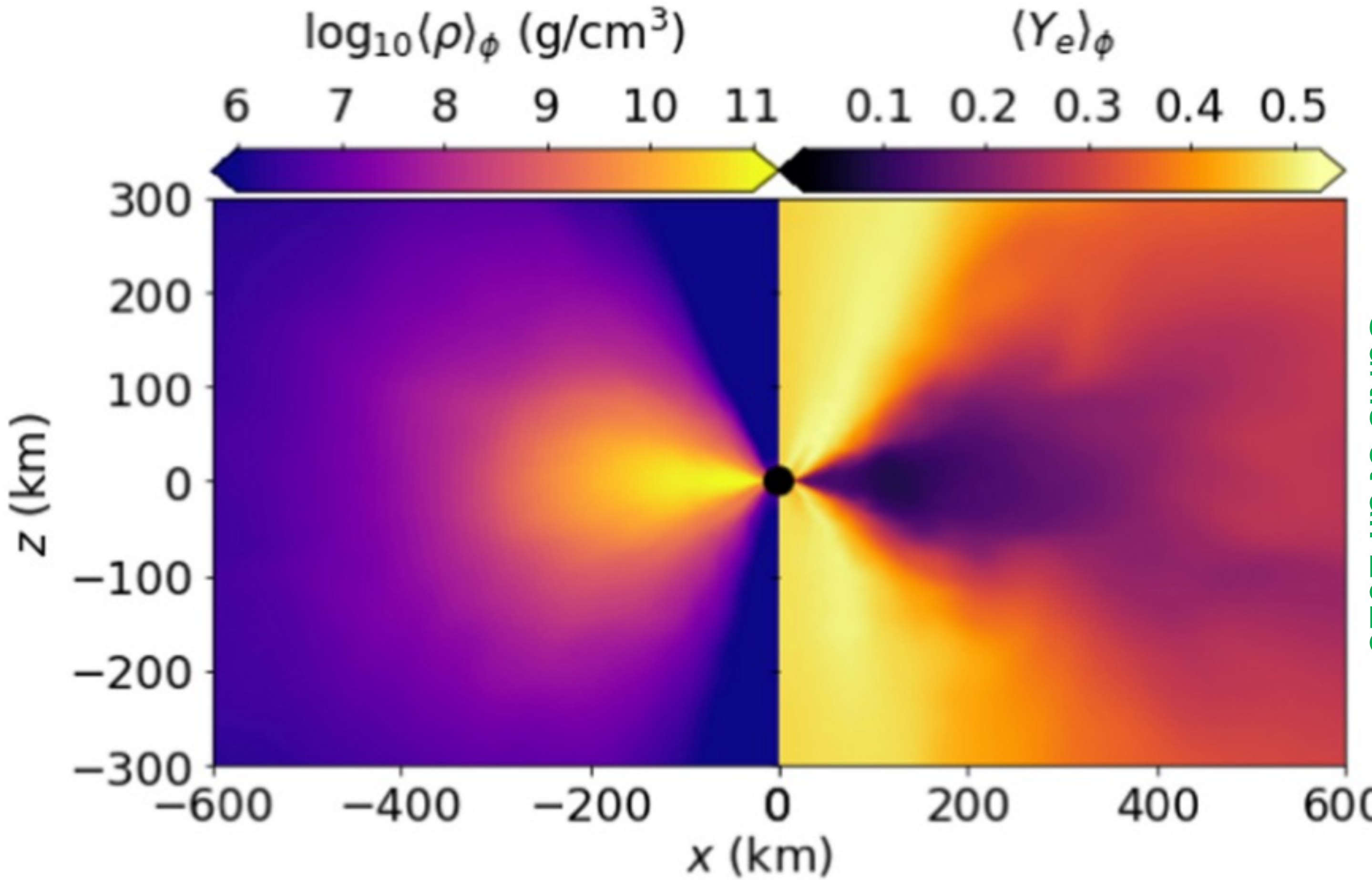
- While true that the dynamical ejecta has a lower electron fraction from the disk wind, it may be too simple to say that one is a “red” vs. “blue” component.
  - ➢ Some of the disk ejecta can have low electron fractions and produce large amounts of Lanthanides (e.g. Ricigliano talk)
  - ➢ Low electron fractions do not preclude blue emission.



Korobkin et al. 21

Disk Ejecta Composition

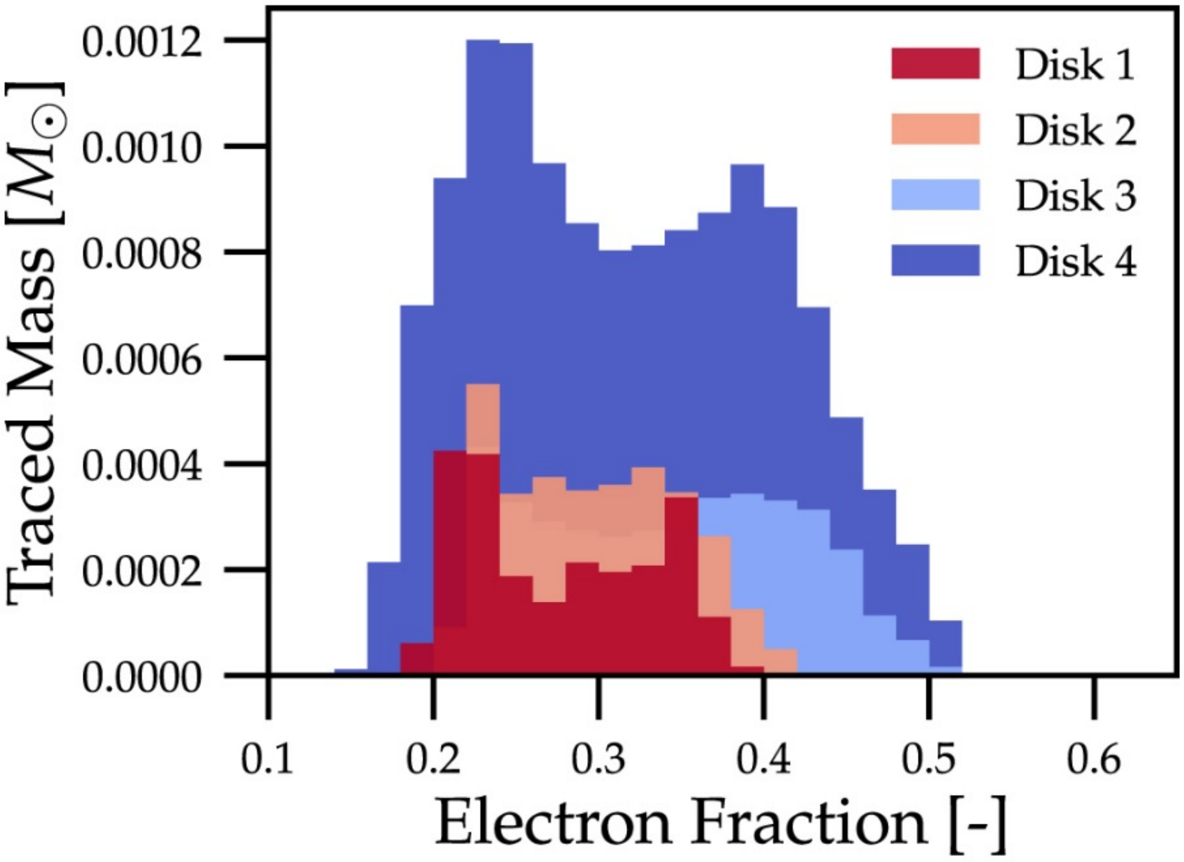
Disk winds produce a range of electron fractions that depend on angle.



Curtis et al. 2023

Different disks produce different electron fraction distributions

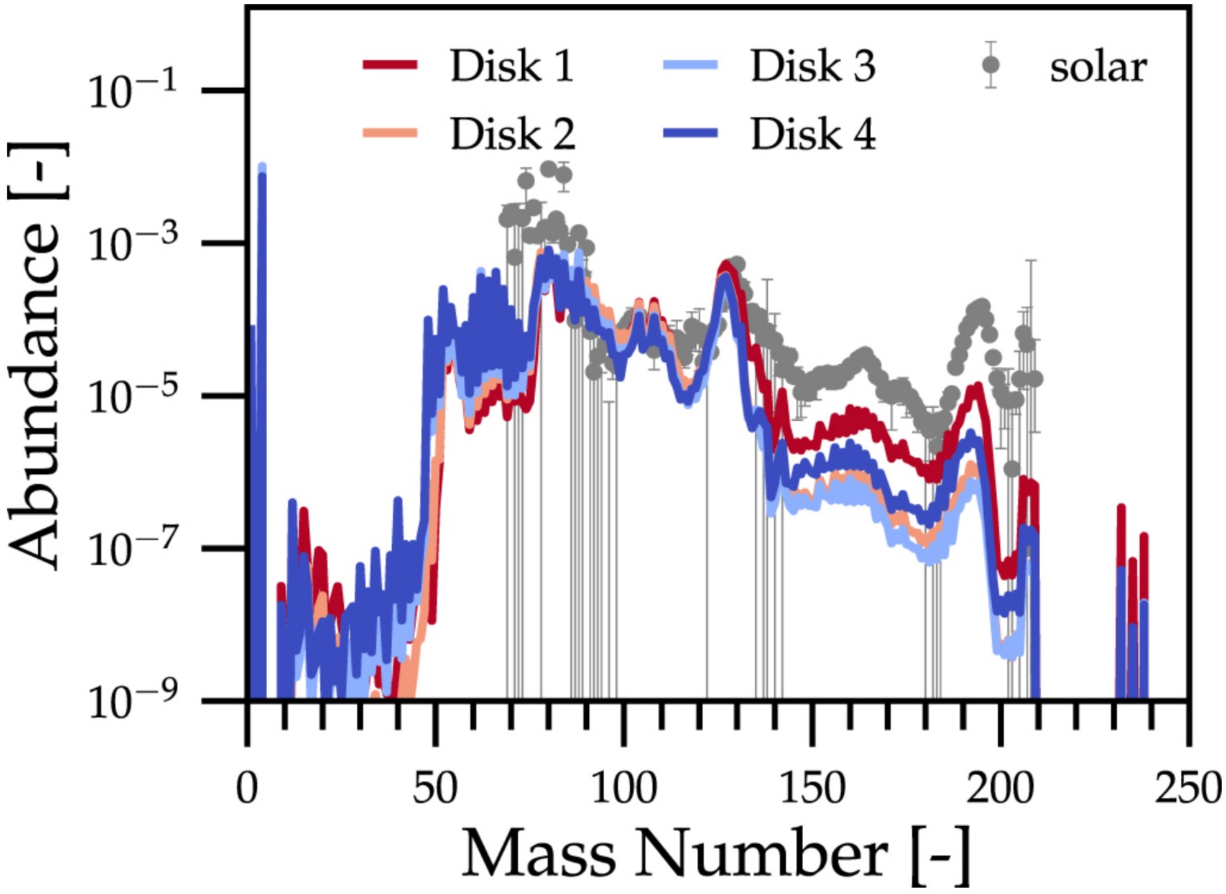
The more massive the disk, the broader the range of electron fractions. The exact merger r-process signature depends on the details of the merger.



Curtis et al. 2023

The disk alone can produce 3rd peak r-process

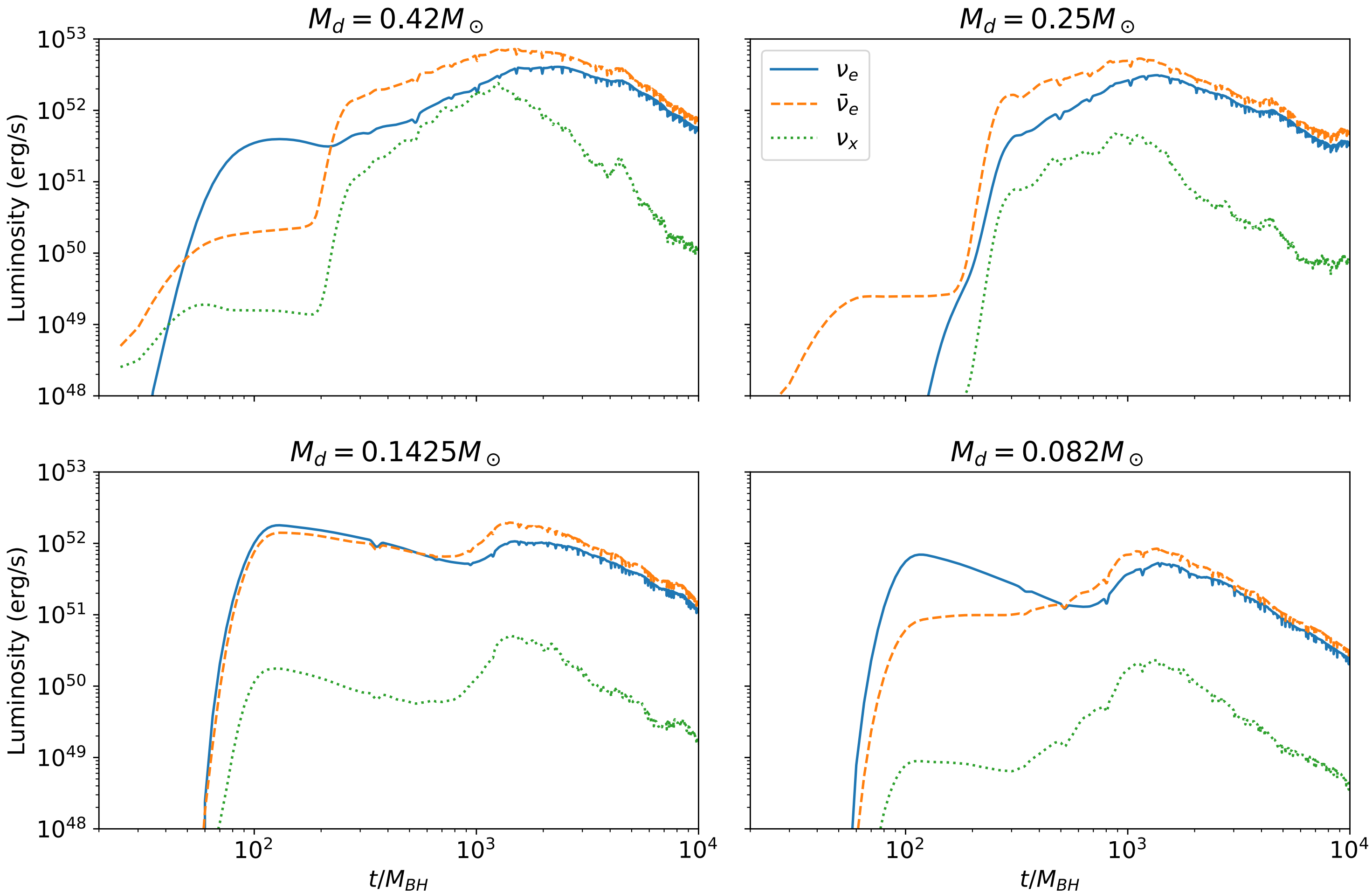
The ratio of the 2nd and 3rd peak elements should not be robust. (recall also talks by Martinez-Pinedo, Rosswog) What variations are allowed by the data?



Curtis et al. 2023

It is harder to distinguish BH vs. NS from the composition than we thought.

The disk neutrino luminosity dominates the neutrino flux. NS neutrinos will alter the yields, but will this change be detectable?



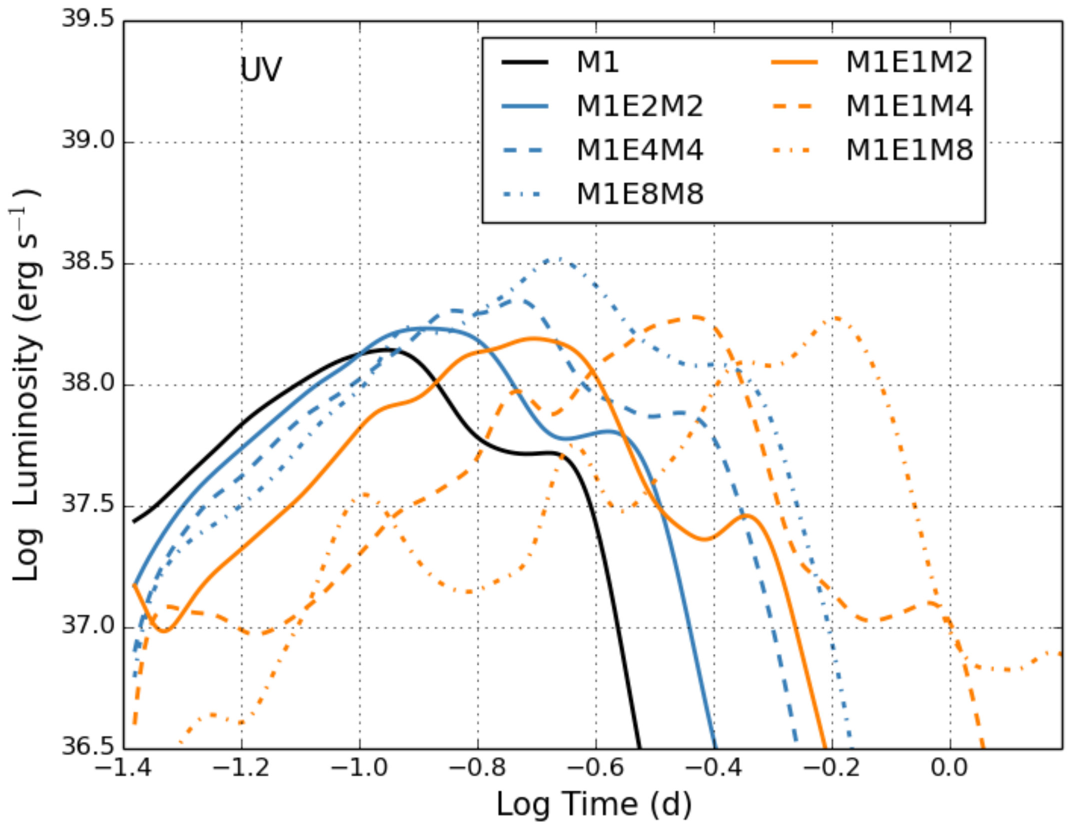
Low Y_e doesn't mean the emission has to all be red

Series of UV light curves from spherical ejecta models.

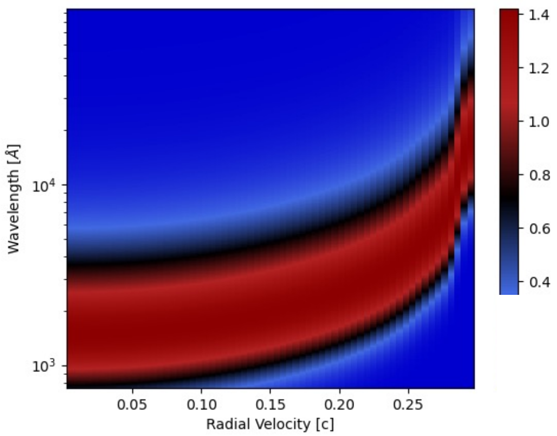
UV can be bright almost out to a day depending upon the ejecta mass.

The composition of this material is from the electron fraction of Y_e=0.19 ejecta.

Low Y_e still produces some blue!

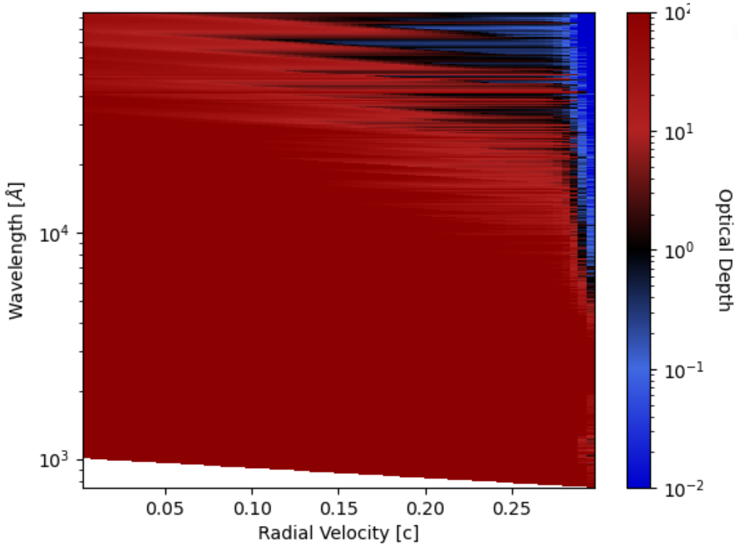


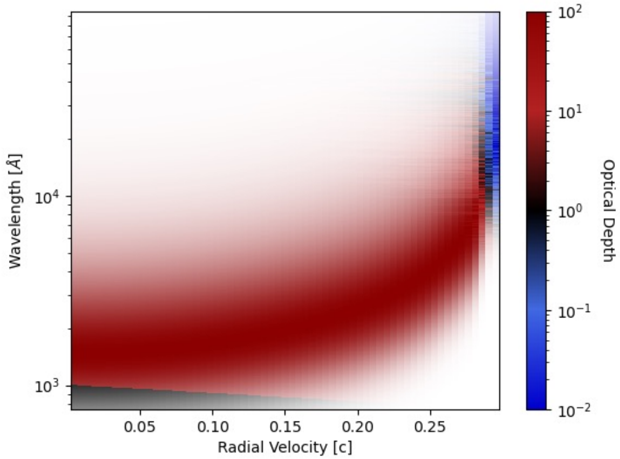
Observations are driven by Emission and Optical Depth



Emission (wavelength) as a function of the velocity coordinate of the ejecta for neutron-rich ejecta (Ye=0.19) at 0.49d.
This is a 1-dimensional mode using the standard wind-eject velocity for a lot of LANL studies.

Corresponding wavelength-dependent optical depth as a function of velocity coordinate.

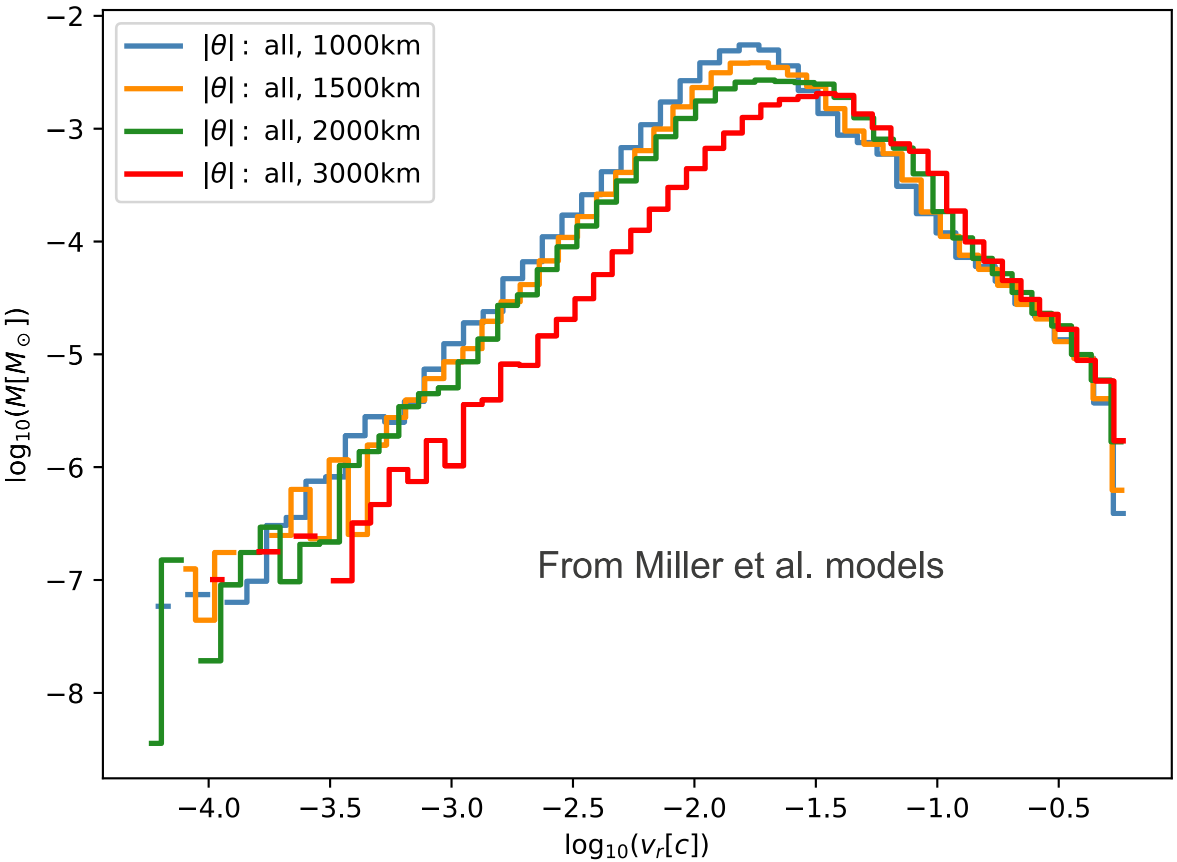




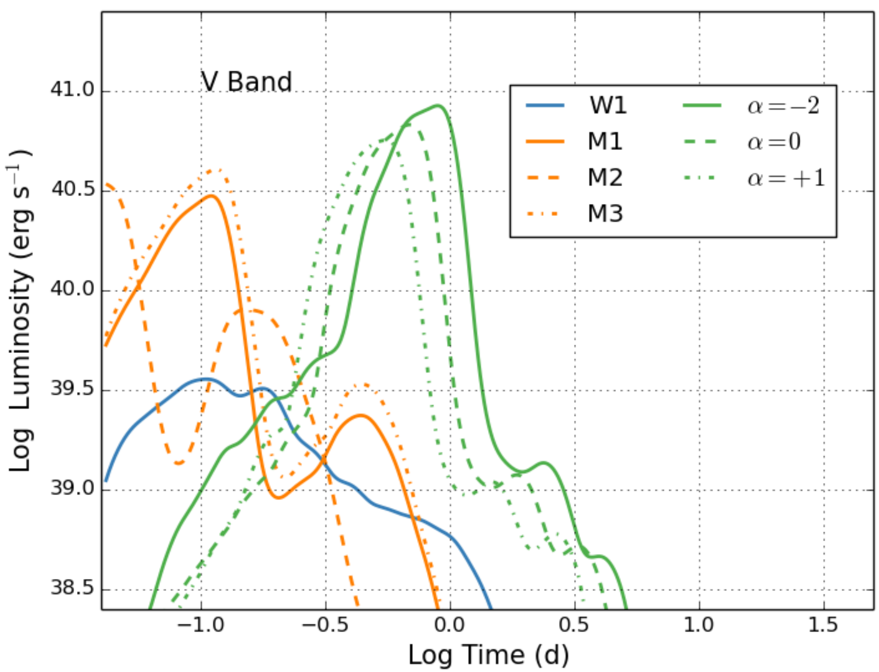
Combining these two gives an idea of what we observe.

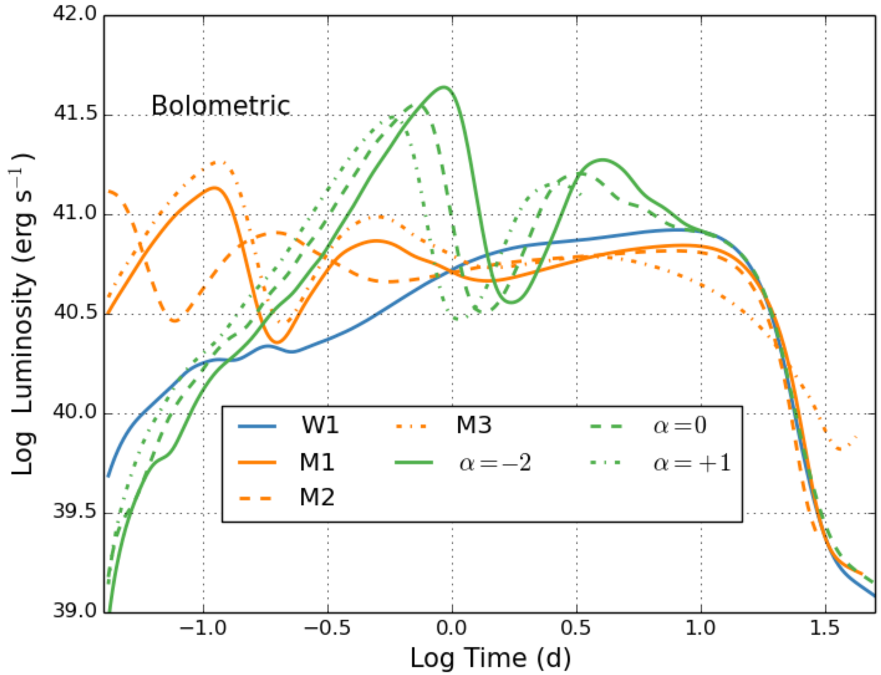
Distribution matters

- Many models assume power-law or simple models for the distribution of matter versus velocity.
- Disk models show that the velocity distribution can be very different than a simple power-law.



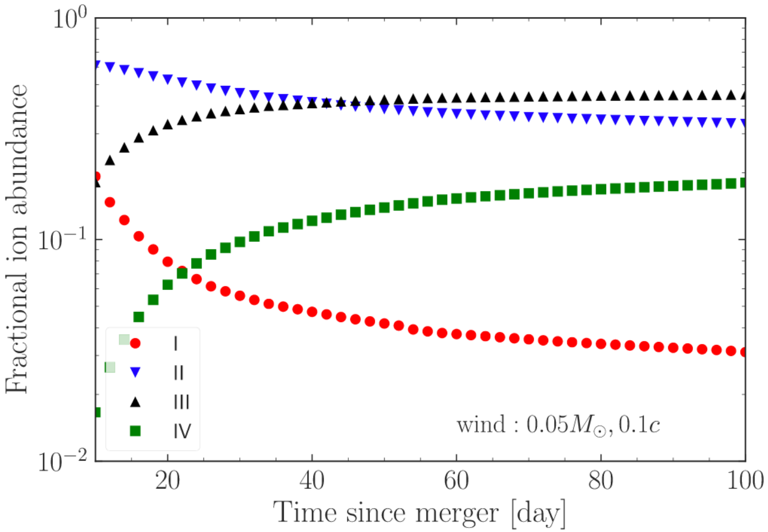
Different Morphologies produce Different Light Curves

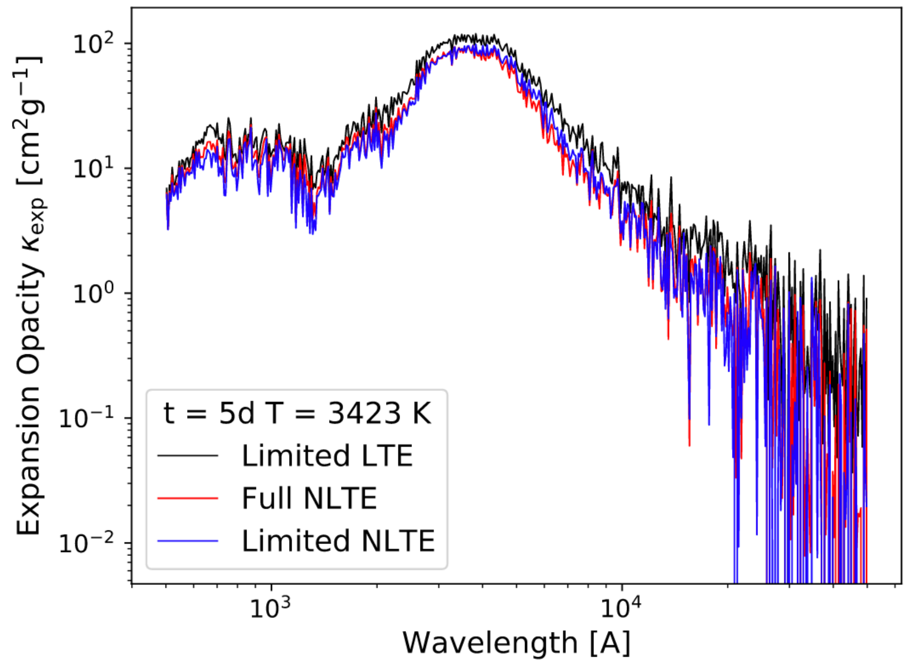




NLTE – High ionization fractions to late times

In a 1-zone model, steady-state model, Hotokezaka et al. 2021 found that decay electrons ionize the material (a larger fraction would be doubly ionized.





Pognan et al. 2022 also studied different NLTE solutions to compare different relative opacities.

Conclusions

- The interpretation of kilonova observations requires understanding a broad range of physics from the details of the ejecta properties to the detailed atomic and plasma physics.
- Given the rarity of these events, understanding of this physics will rely heavily on theoretical modeling of the ejecta properties, nuclear physics, atomic physics, radiation transport and numerical methods.
- We need to compare to other transients and determine what observations can distinguish between the different phenomena and, ultimately, constrain the ejecta properties to determine the r-process production.
- The work presented at this meeting is critical to making these advances.