Difficulties in Modeling Kilonova Transients

adding complexity/reality to our simple stories drives closer connection to the physics frontier

C. Fryer (LANL)

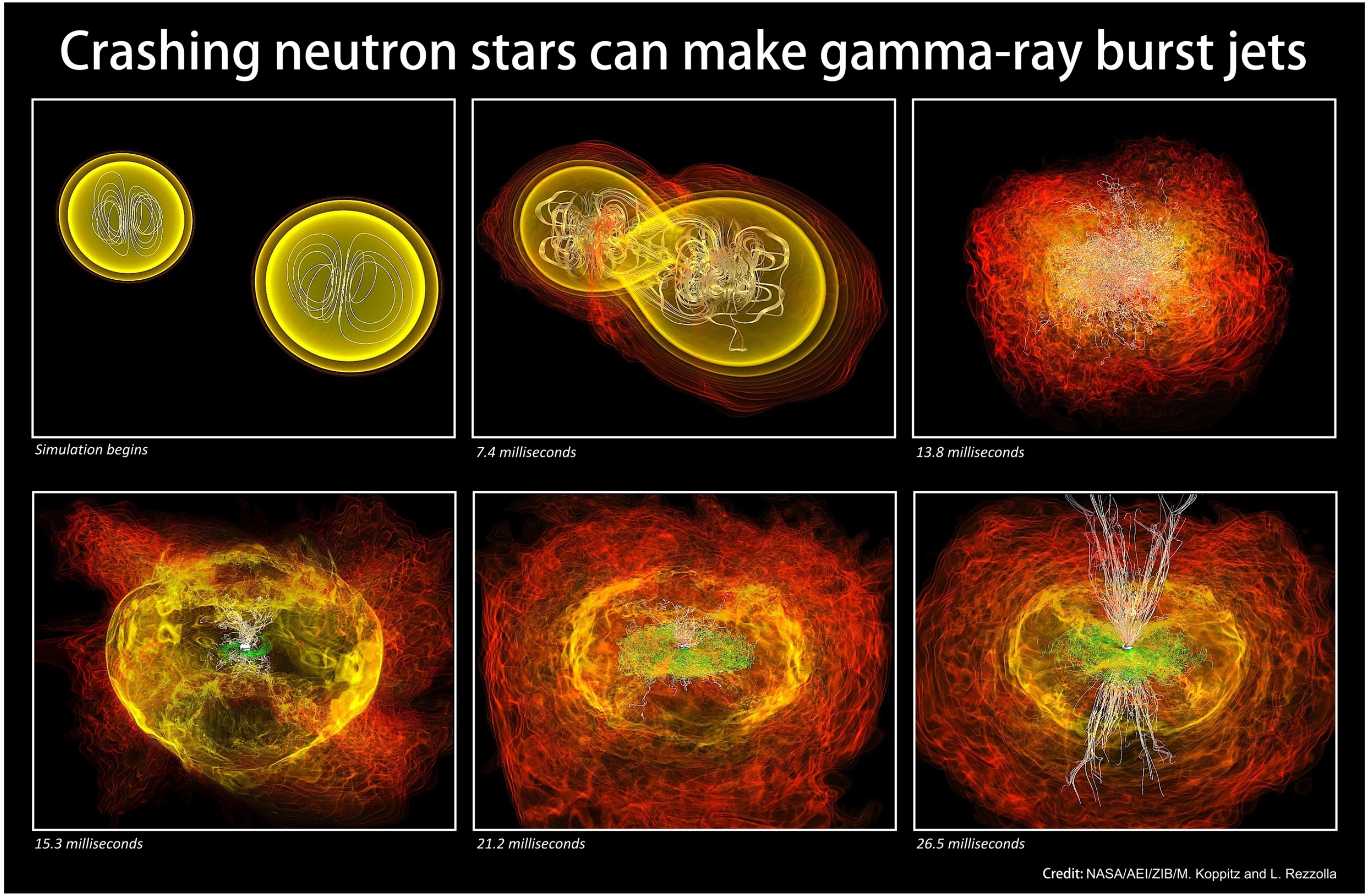
Los Alamos NATIONAL LABORATORY EST. 1943

NNSA National Nuclear Security Administration

The Connection Between Neutron Star Mergers, Kilonovae and the Origin of the r-Process

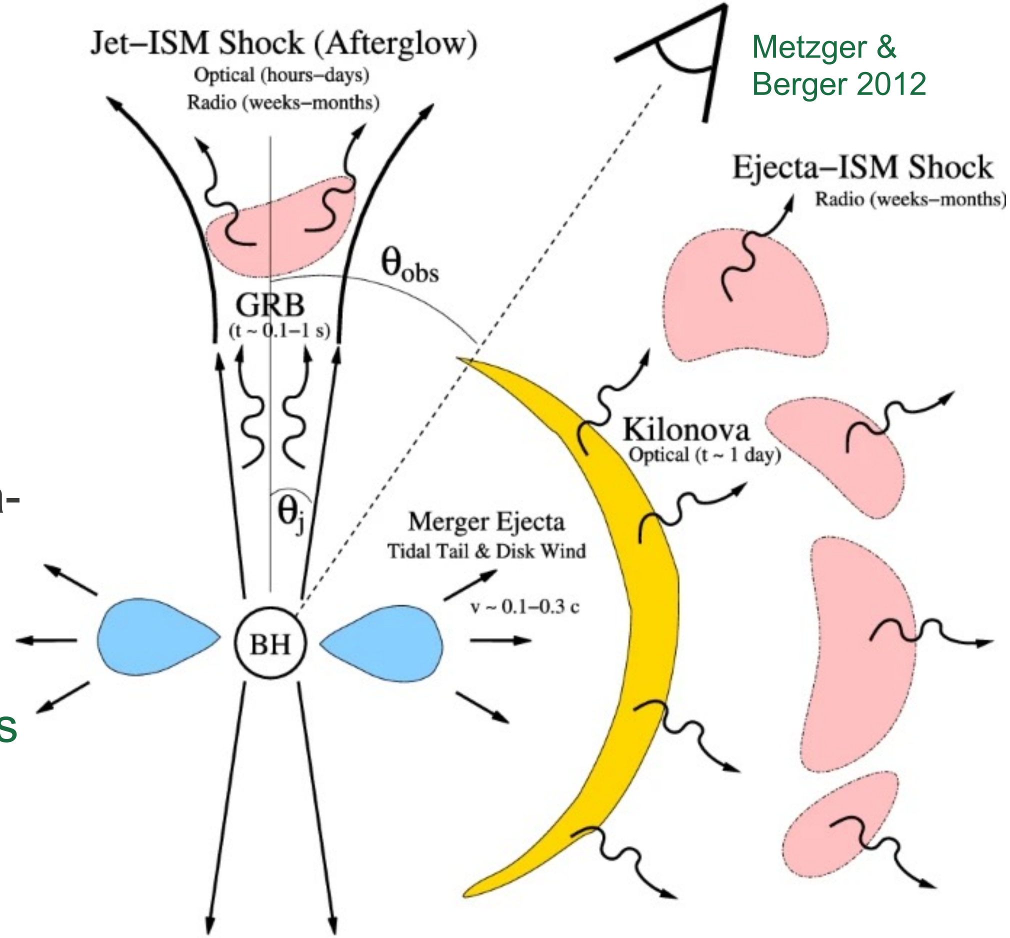
NS mergers have long been proposed as the origin of GRBs (Paczynski 1991) and potential sources of the r-process (Lattimer & Schramm 1974).

With GW170817, we were able to definitively test these theories.



The ejecta produces radioactively powered transient

- Material is ejected during the initial merger (e.g. tidal ejecta) and in a wind from the disk formed during the merger. This disk can also drive a jet (van Eerten talk).
- The merger and disk wind ejecta are composed of radioactive isotopes whose decay can power a supernova-like transient, a.k.a. kilonova.
- This talk will focus on the modeling (and difficulties therein) of these kilonova transients. The LANL results presented here were funded by an internal LANL grant which I defended at the 2018 Vulcano meeting)



Metzger & Berger 2012

Inferring the r-Process Yield:

- 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.

Cote et al. 2018

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

Uncertainties in Modeling Kilonova Light-Curves: Pushing the Physics Frontier

- Initial Conditions: velocity distribution: m(v,θ,t), v(m,θ,t); composition, entropy, additional power sources (magnetar, fallback), surrounding medium (MHD, nuclear EOS, neutrinos, …):
- Transport:

➢ Energy Deposition: nuclear decay properties (low energy nuclear physics), γ, e, α transport (plasma physics).

➢ 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), …

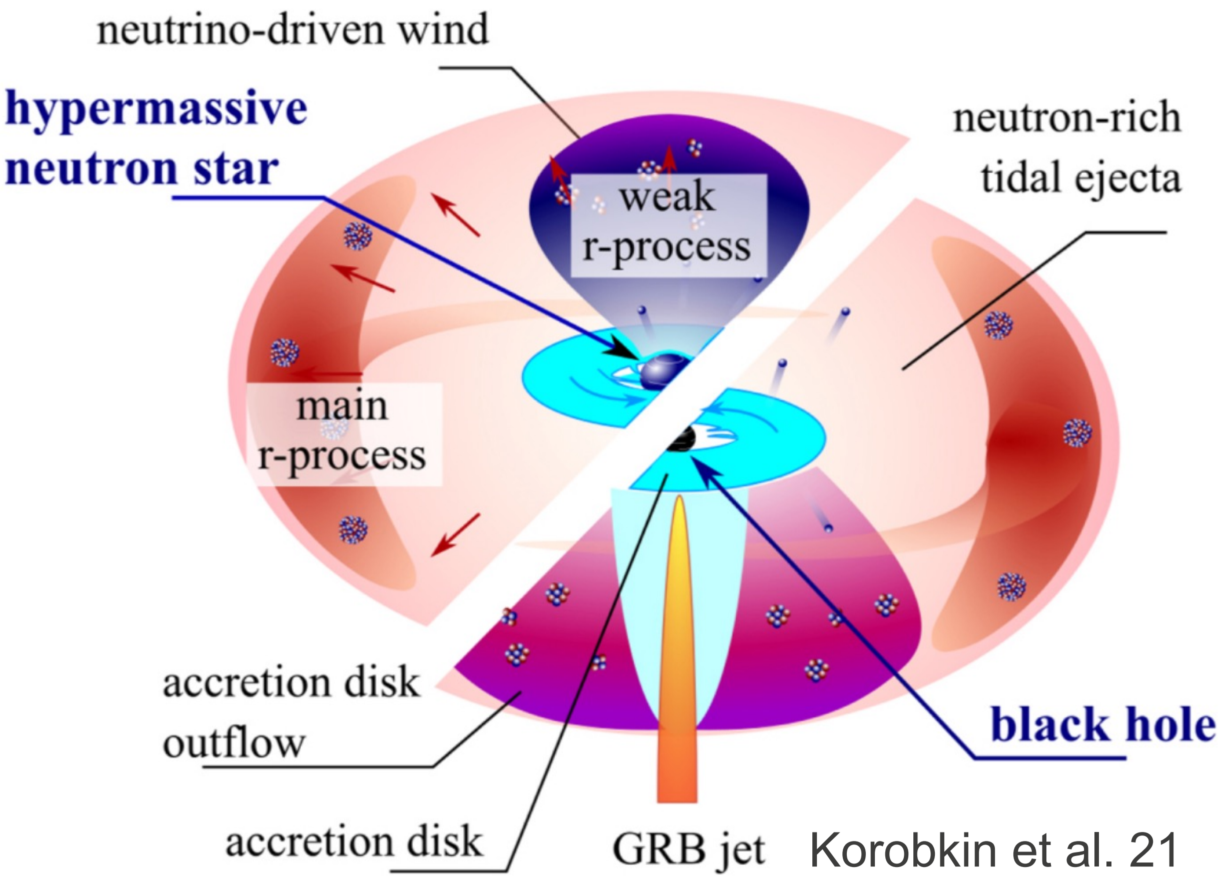
➢ atomic physics: in LTE, NLTE

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

➢ Interaction with matter: shocks (hydrodynamics), …

Blue versus Red Components Too Simplistic

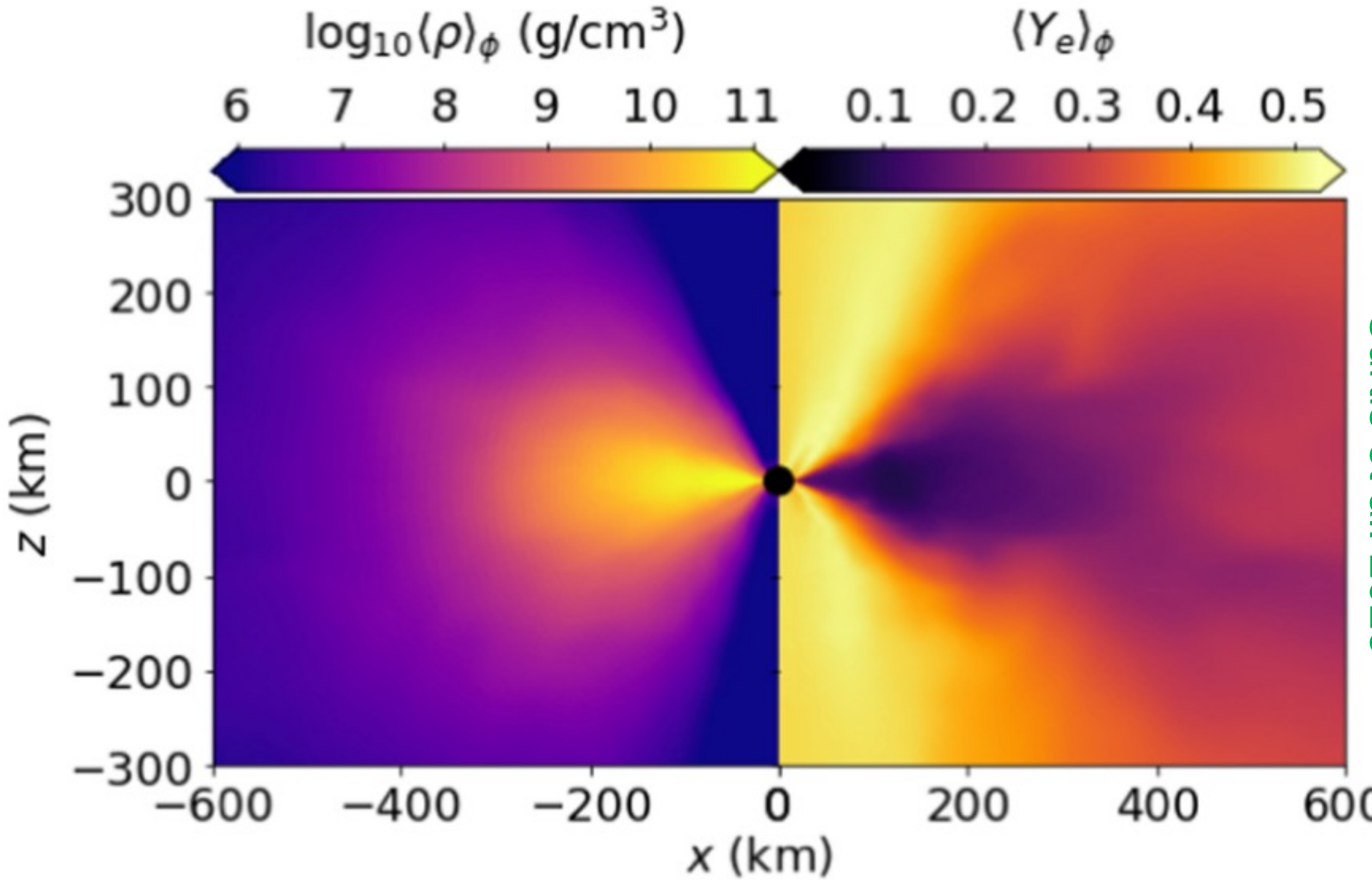
- While true that the dynamical ejecta has a lower electron fraction from the disk wind, it may be too simple to say that one is a “red” vs. “blue” component.
  - ➢ Some of the disk ejecta can have low electron fractions and produce large amounts of Lanthanides (e.g. Ricigliano talk)
  - ➢ Low electron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



Korobkin et al. 21

Disk Ejecta Composition

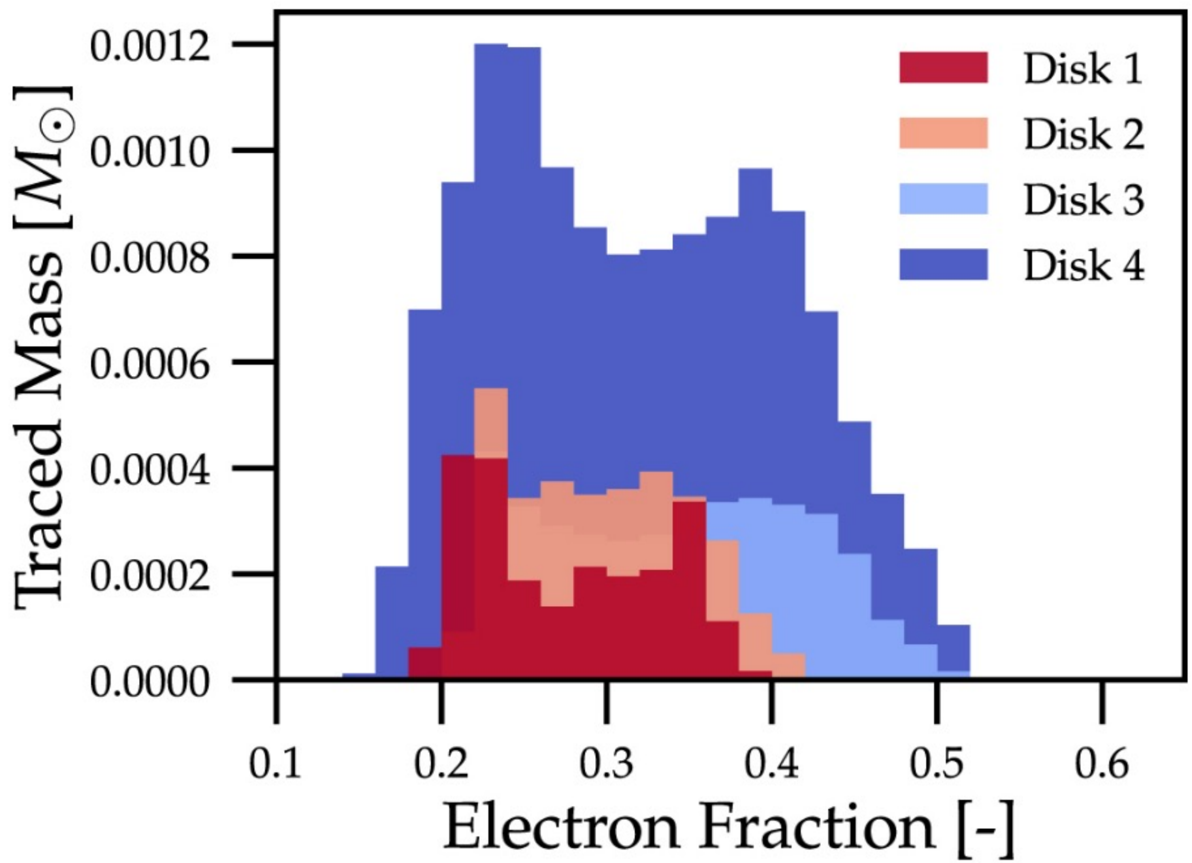
Disk winds produce a range of electron fractions that depend on angle.



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

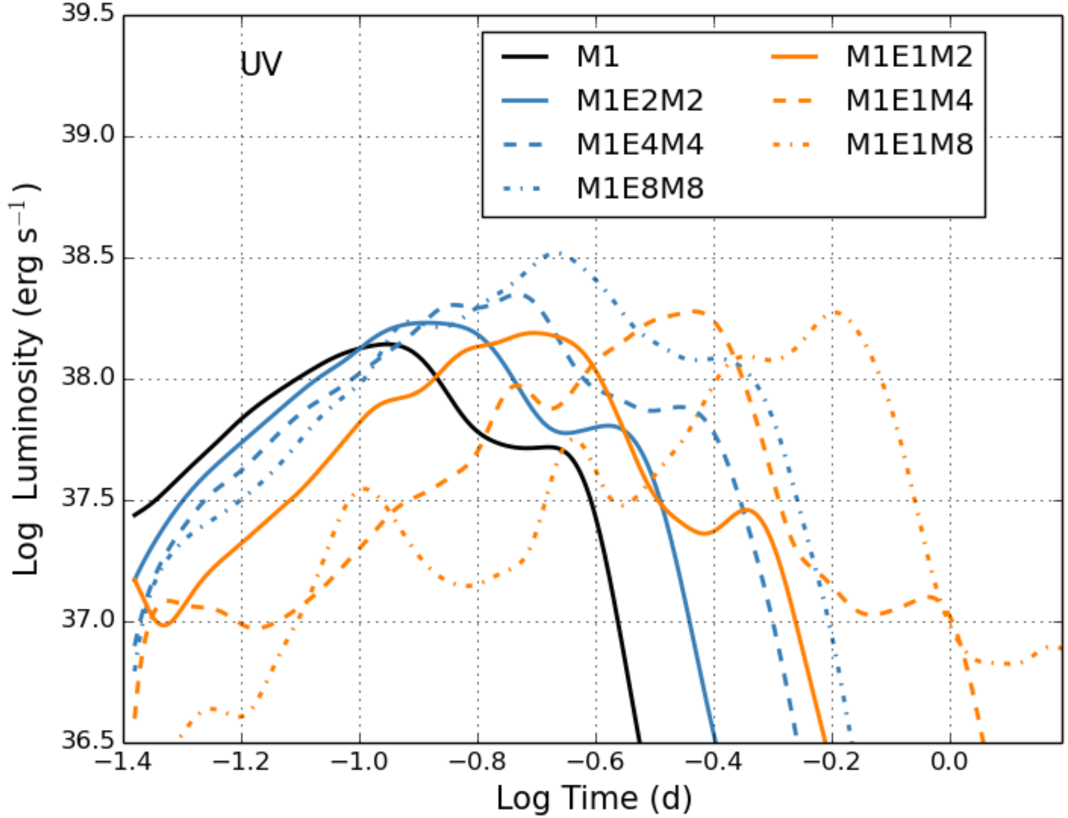
Low Y_e doesn't mean the emission has to all be red

Series of UV light curves from spherical ejecta models.

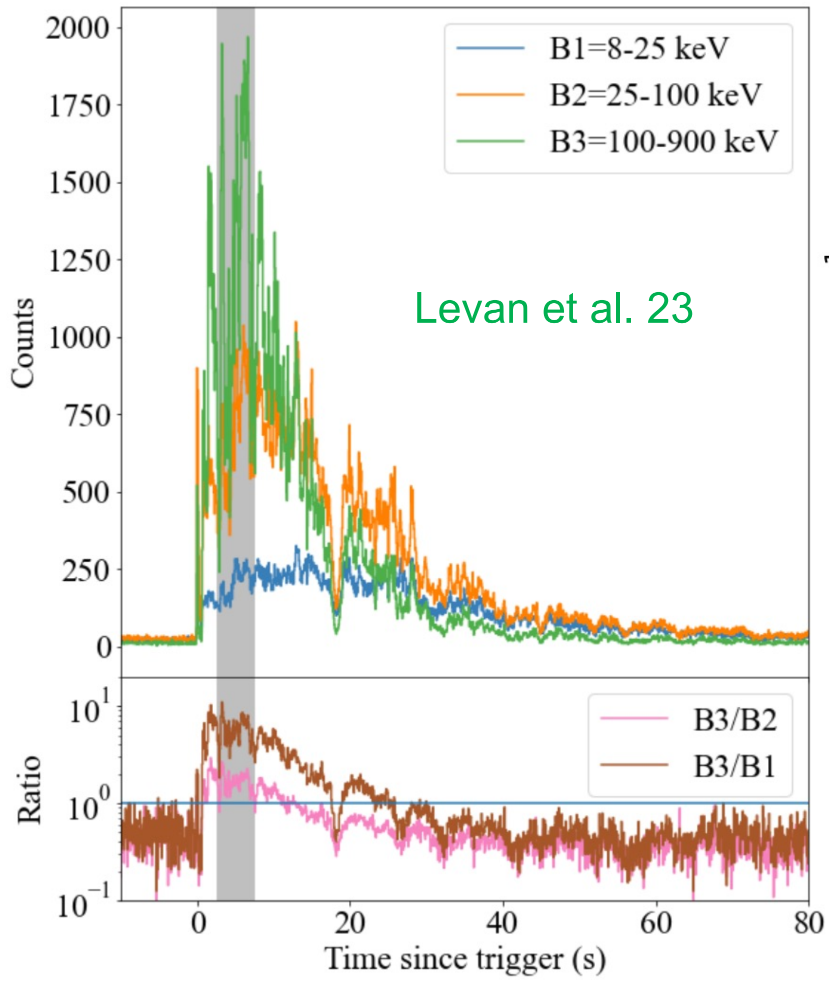
UV can be bright almost out to a day depending upon the ejecta mass.

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

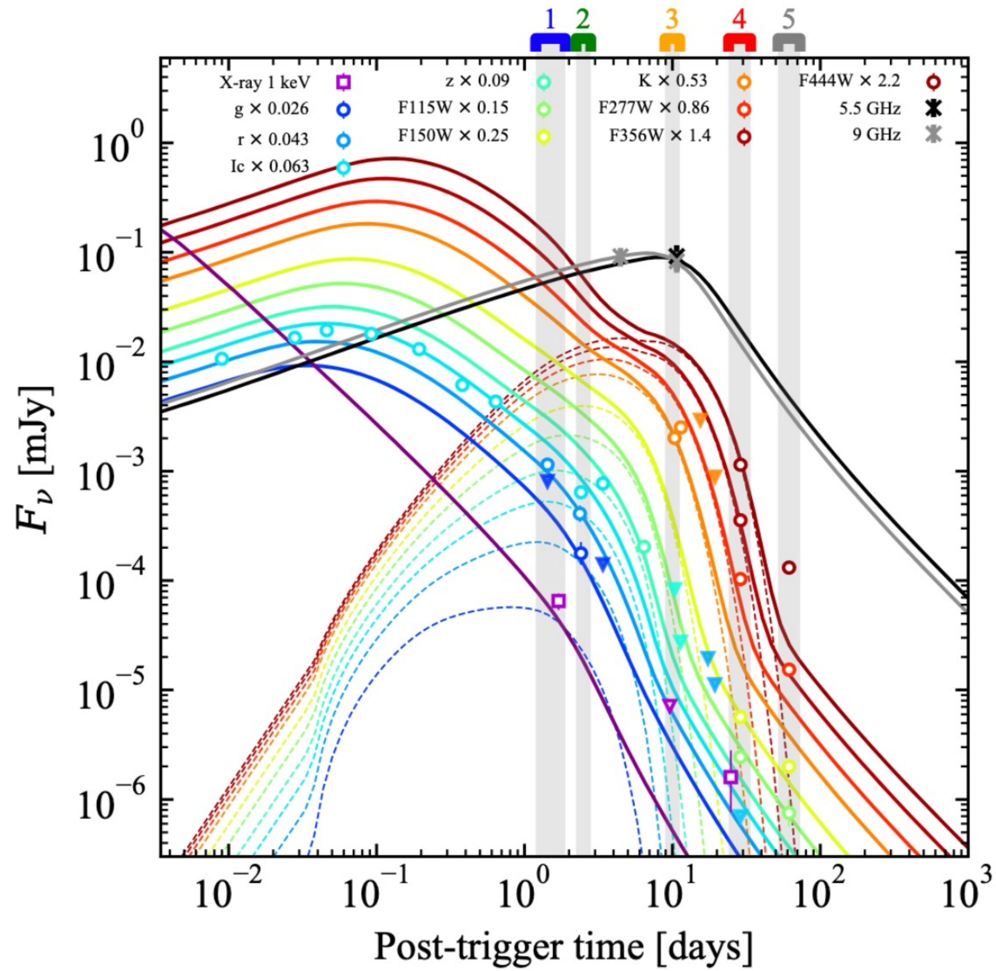
Low Y_e still produces some blue!



For example, 230307A, a long duration GRB with a kilonova or something else entirely?

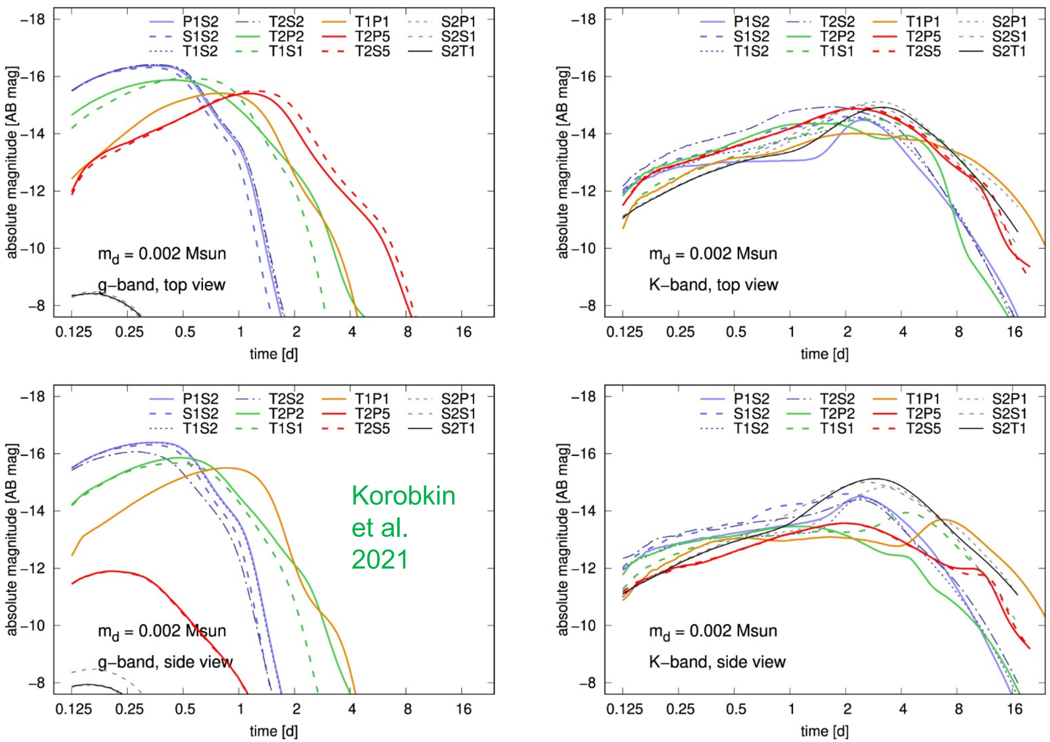


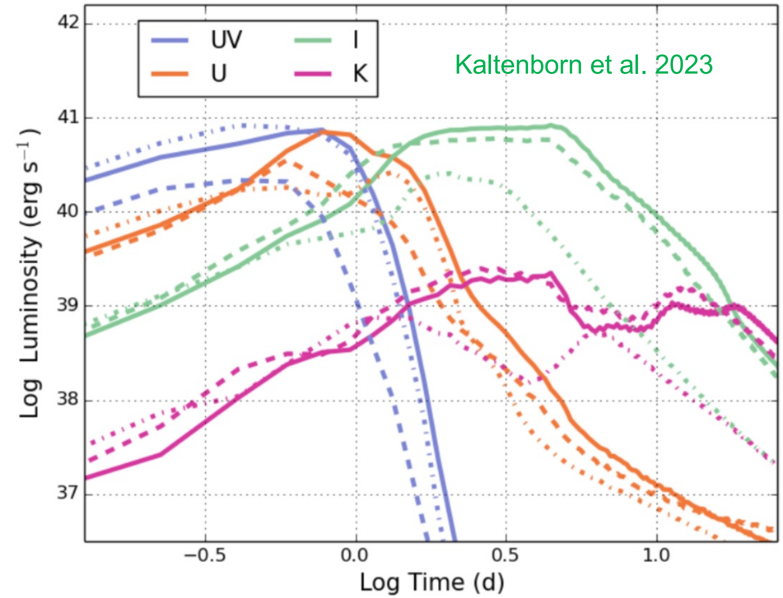
Levan et al. 23

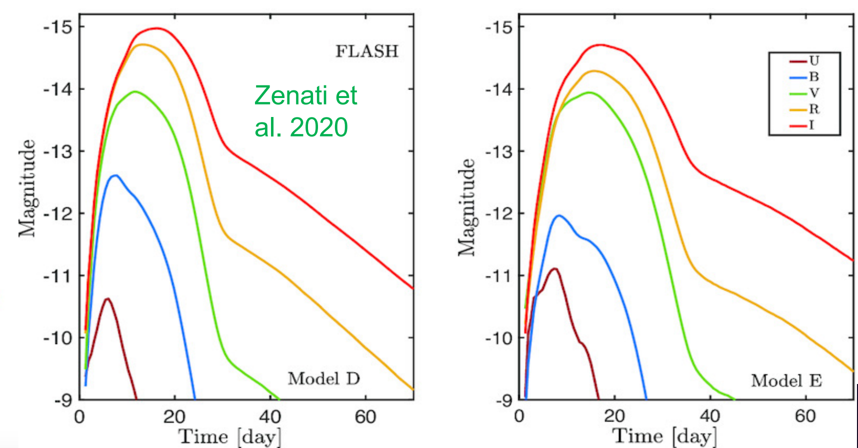


If it looks like a duck, is it?

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



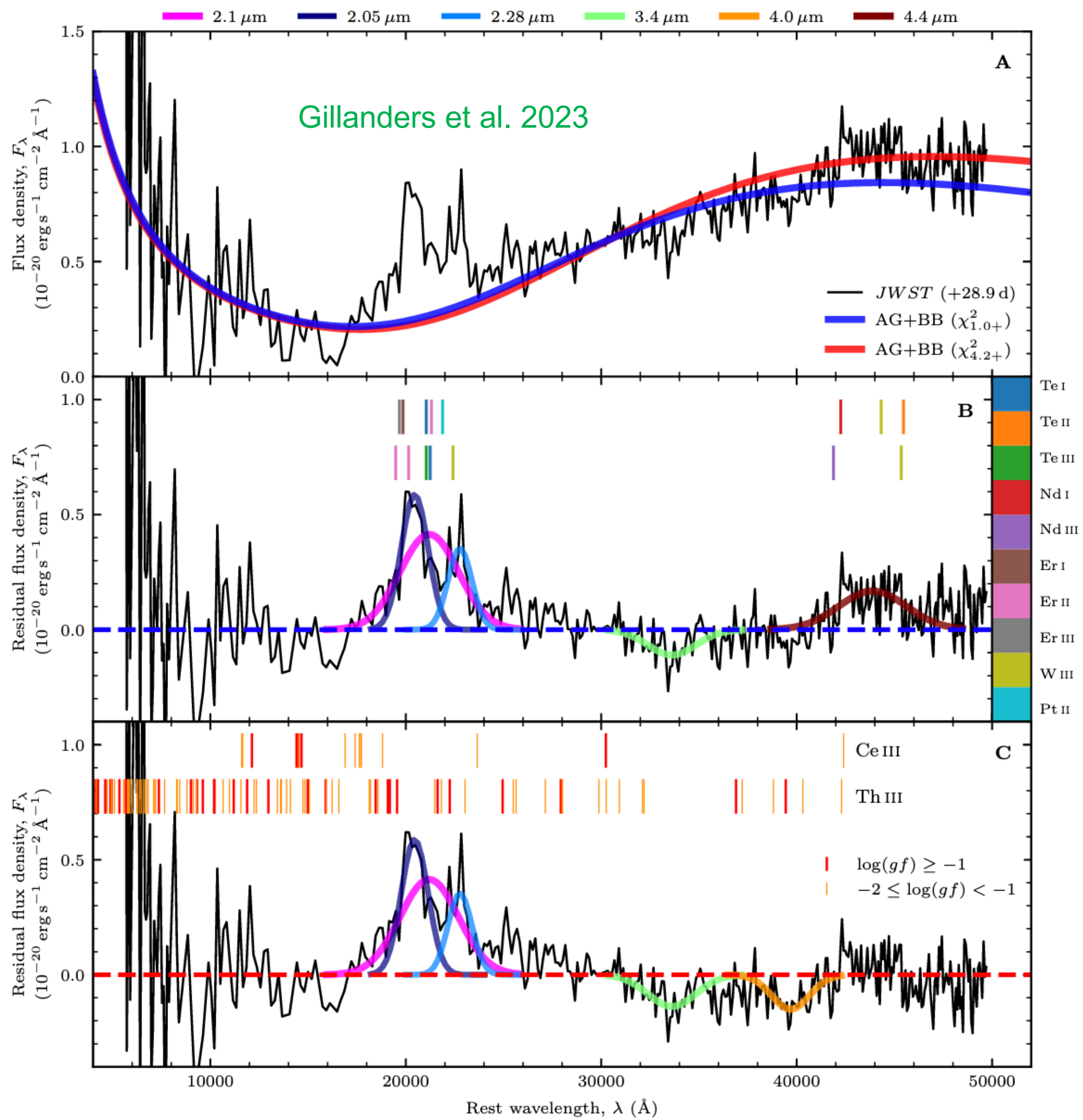




Matching to a Kilonova

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…)

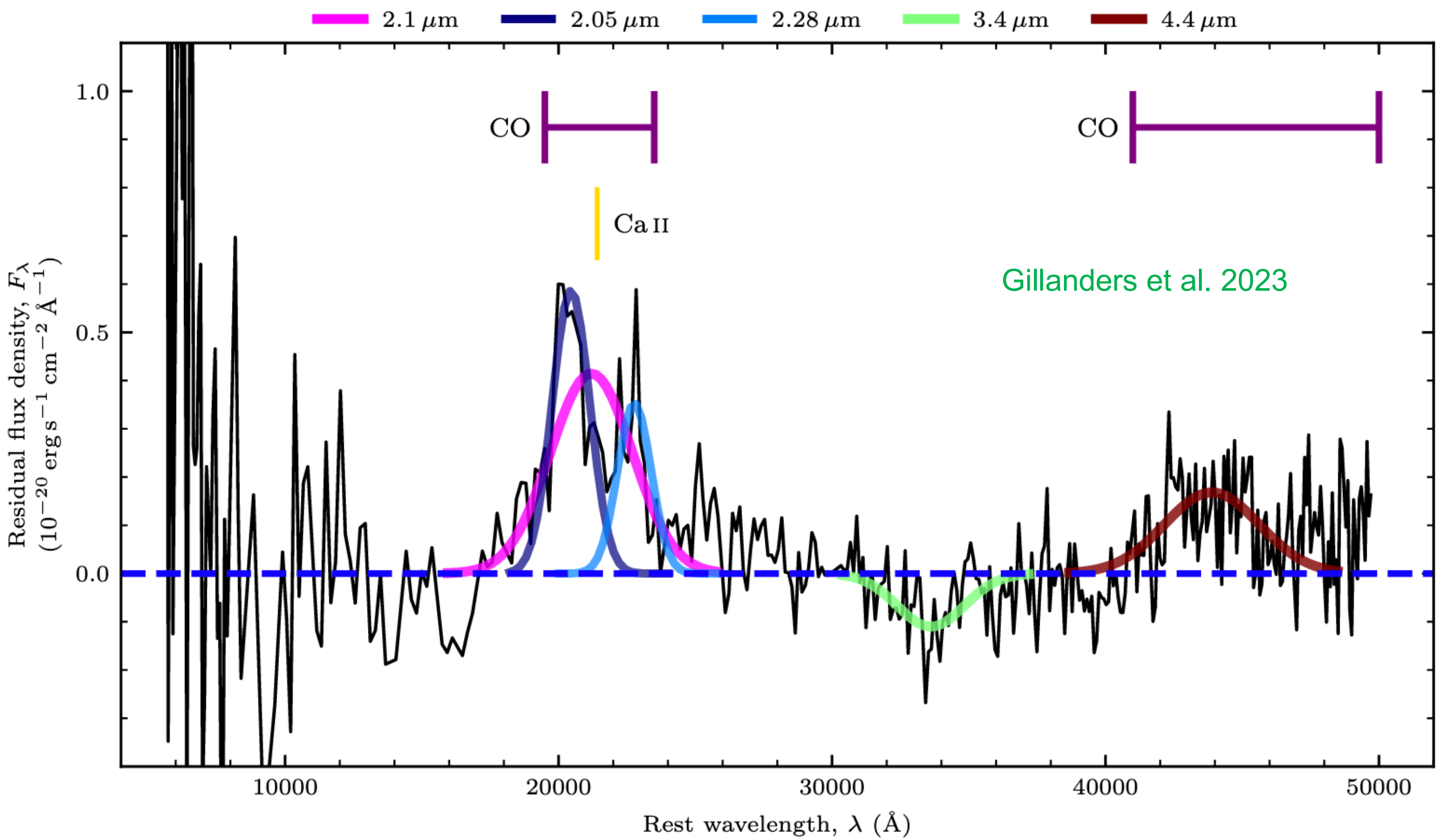


But can we explain these with Ca+CO features from a WD/NS merger?

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



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.
- Time Domain and Multi-Messenger astronomy is driving strong connections between astronomy and physics and that is a good thing! (see 3rd TDAMM meeting in Baton Rouge, Sep. 23-26)
- Gamma-rays will be important. NASA is working to determine its long-term gamma-ray plan (FIGSAG). Lots of ways to contribute: MG17 meeting (session), virtual telecons, in-person meeting at MTU (June 24-28)