# Radiative Transfer Modeling of Explosive Transients

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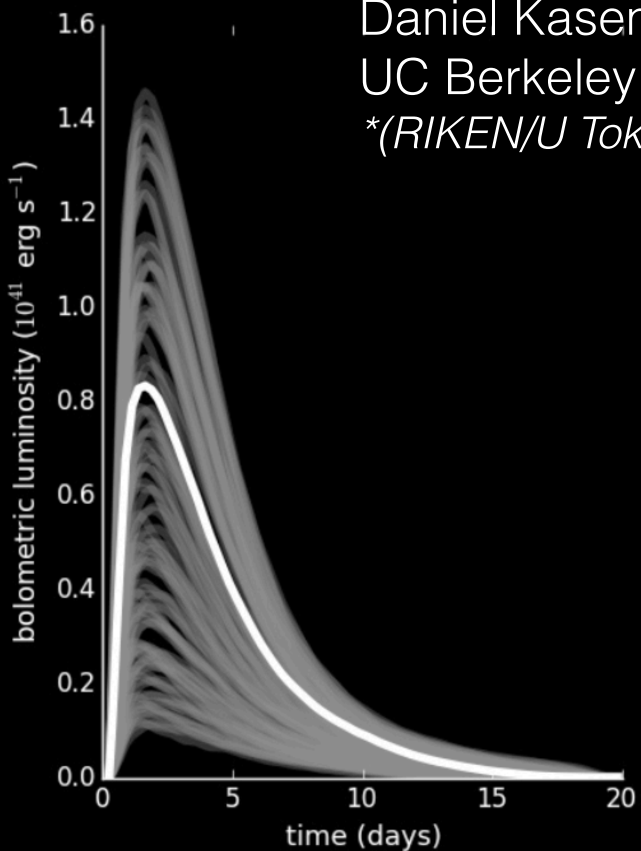
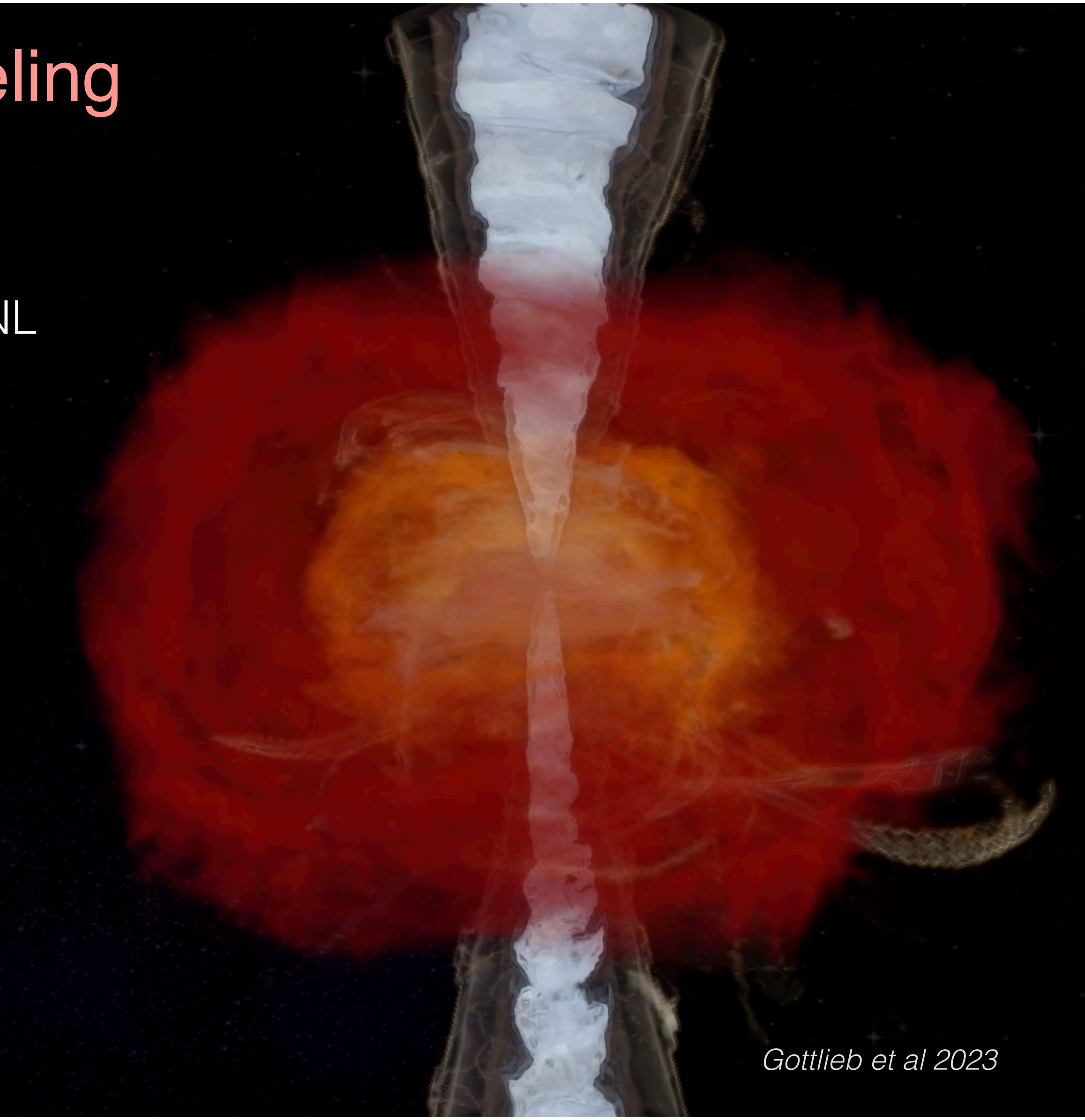
*(RIKEN/U Tokyo)*



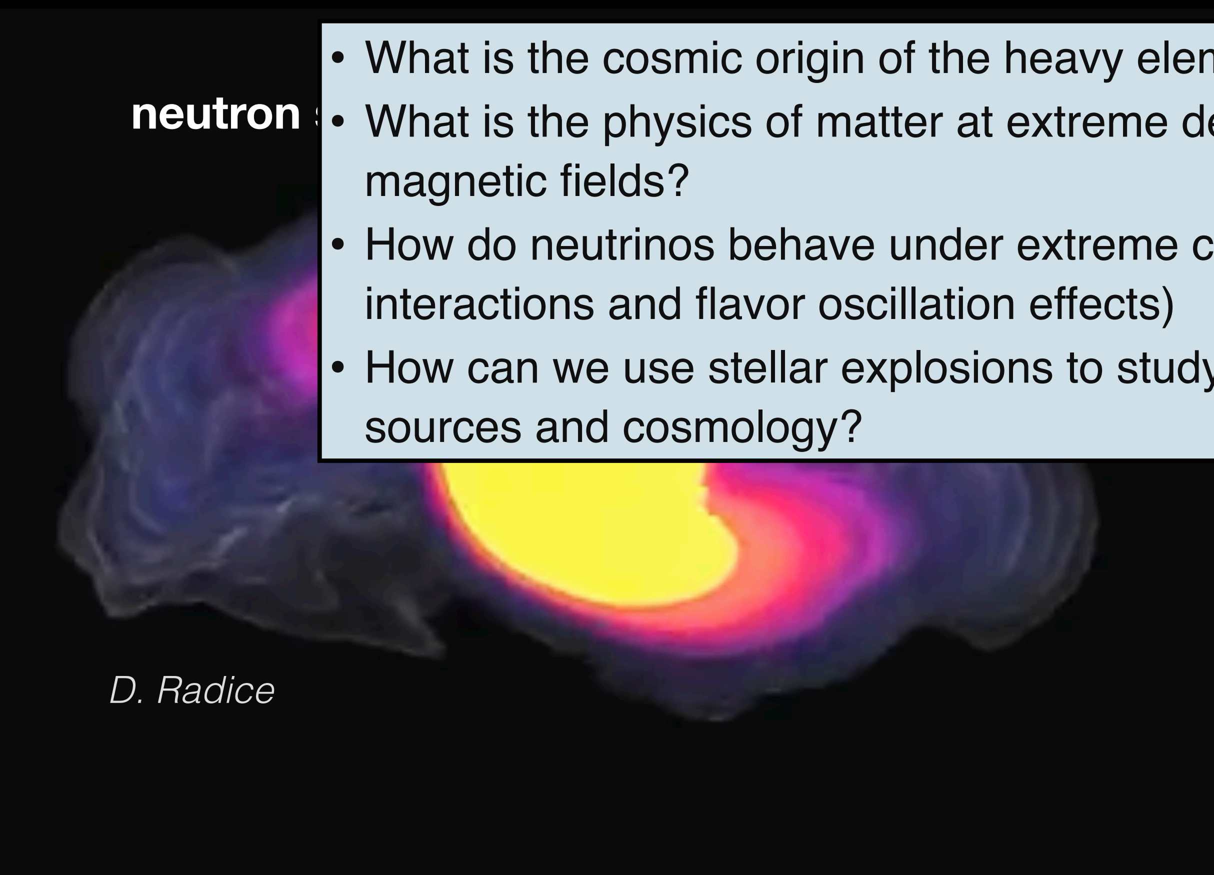

*Dharba & Kasen 2021*



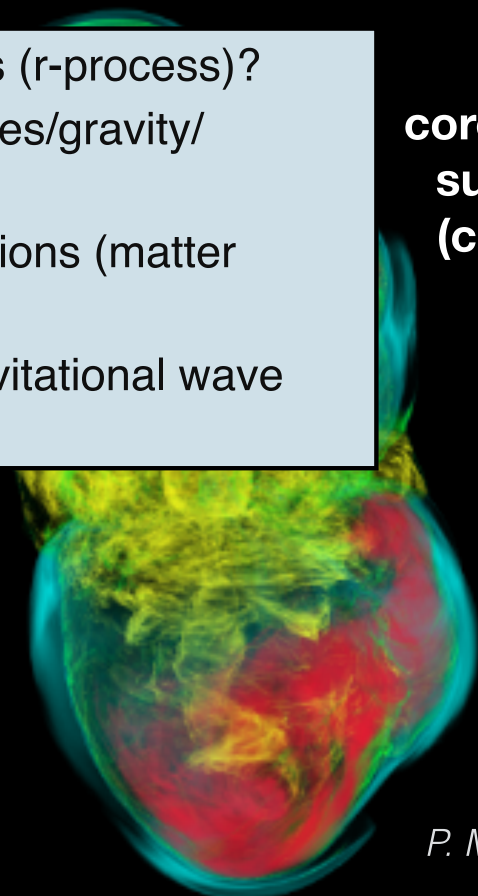
*Gottlieb et al 2023*

# Stellar explosions as cosmic laboratories of physics

- What is the cosmic origin of the heavy elements (r-process)?
- What is the physics of matter at extreme densities/gravity/magnetic fields?
- How do neutrinos behave under extreme conditions (matter interactions and flavor oscillation effects)
- How can we use stellar explosions to study gravitational wave sources and cosmology?

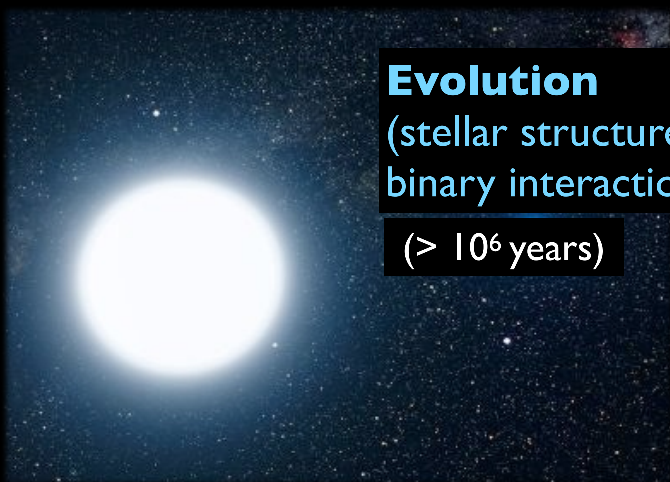



**core collapse supernova (collapsar)**



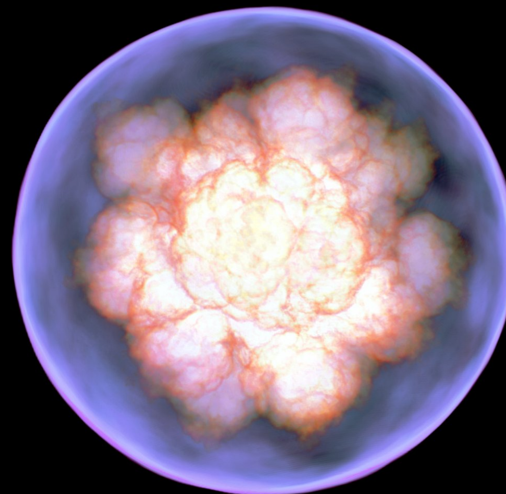
*P. Moesta*

# End-to-end simulation of astrophysical explosions



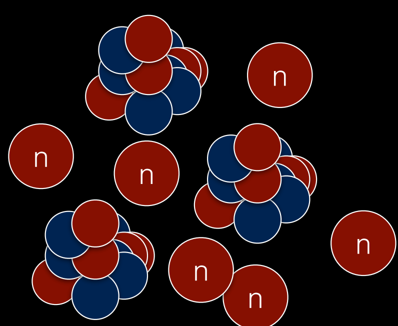
**Evolution**
(stellar structure,
binary interactions)

(> $10^6$ years)



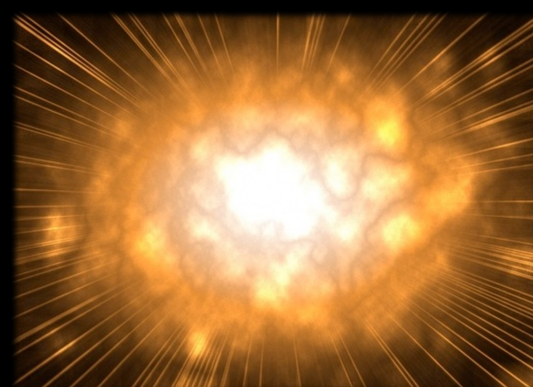
**Explosion**
gravity
neutrino physics
equation of state

(seconds-hours)




**Nucleosynthesis**
nuclear reactions
weak interactions

(seconds)

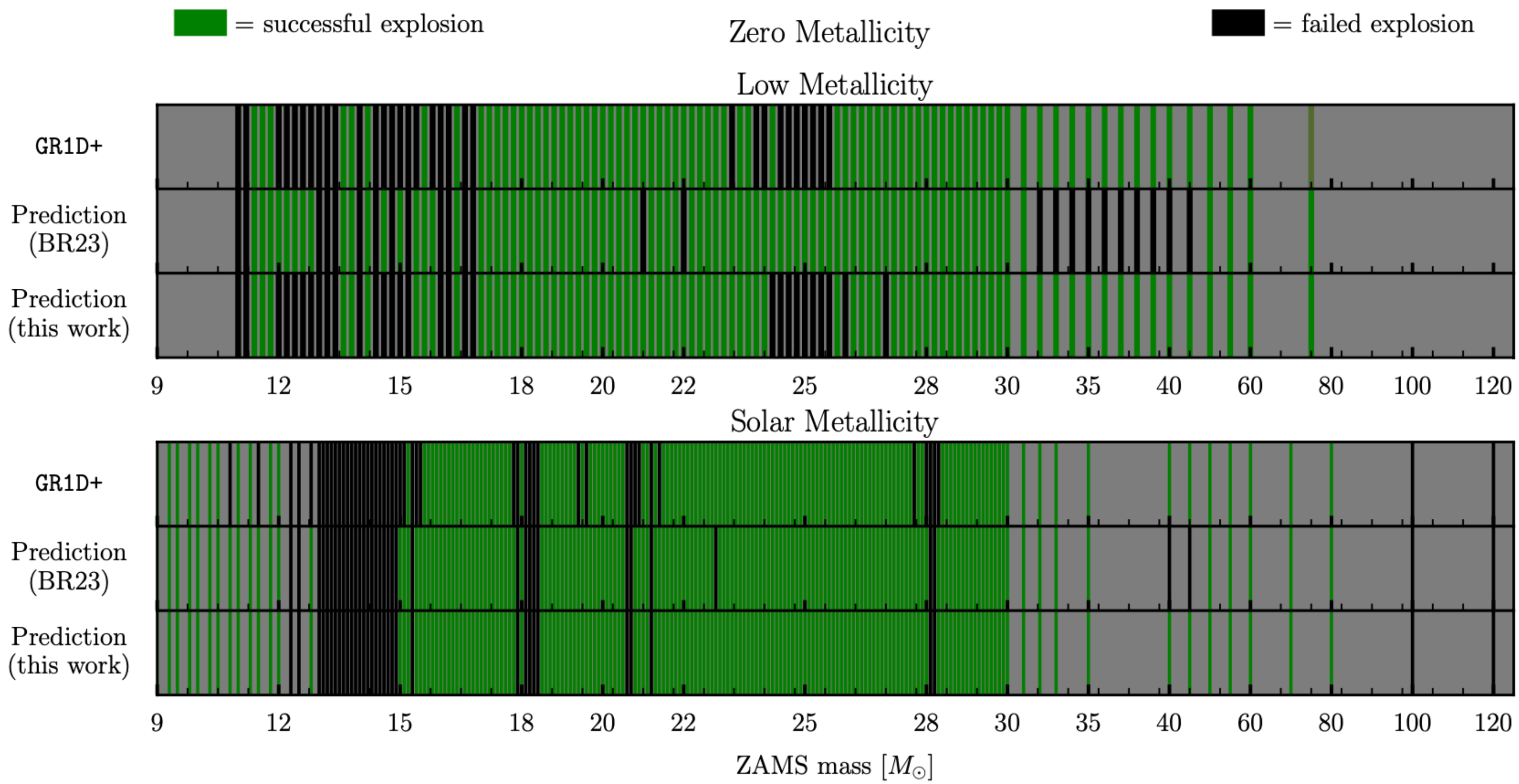


**Observables**
radiation transport

(days/years)

# Predicted Outcome of Massive Star Death

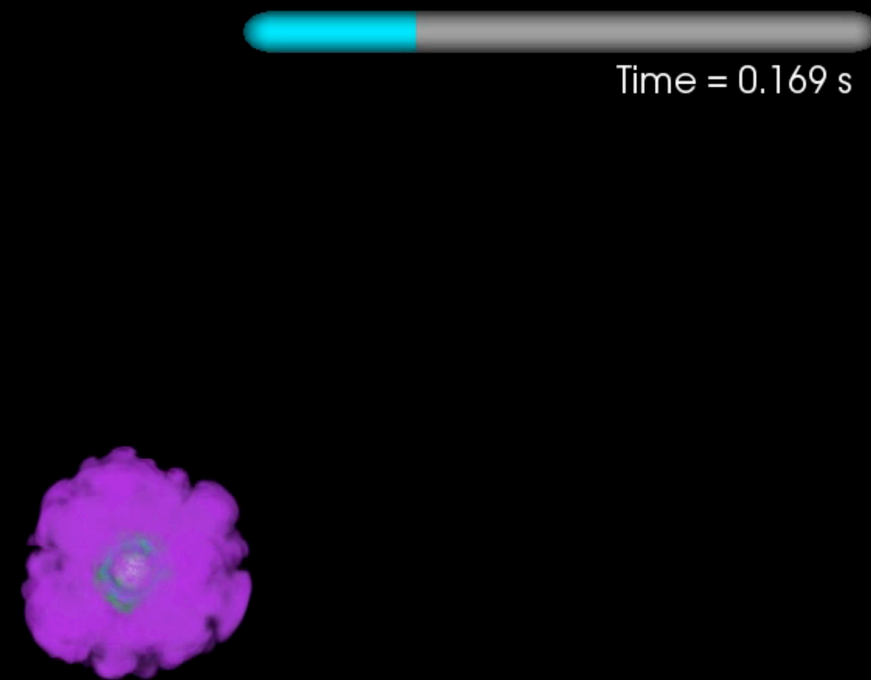
## 1D parameterized explosion models




Boccioli+ 2025

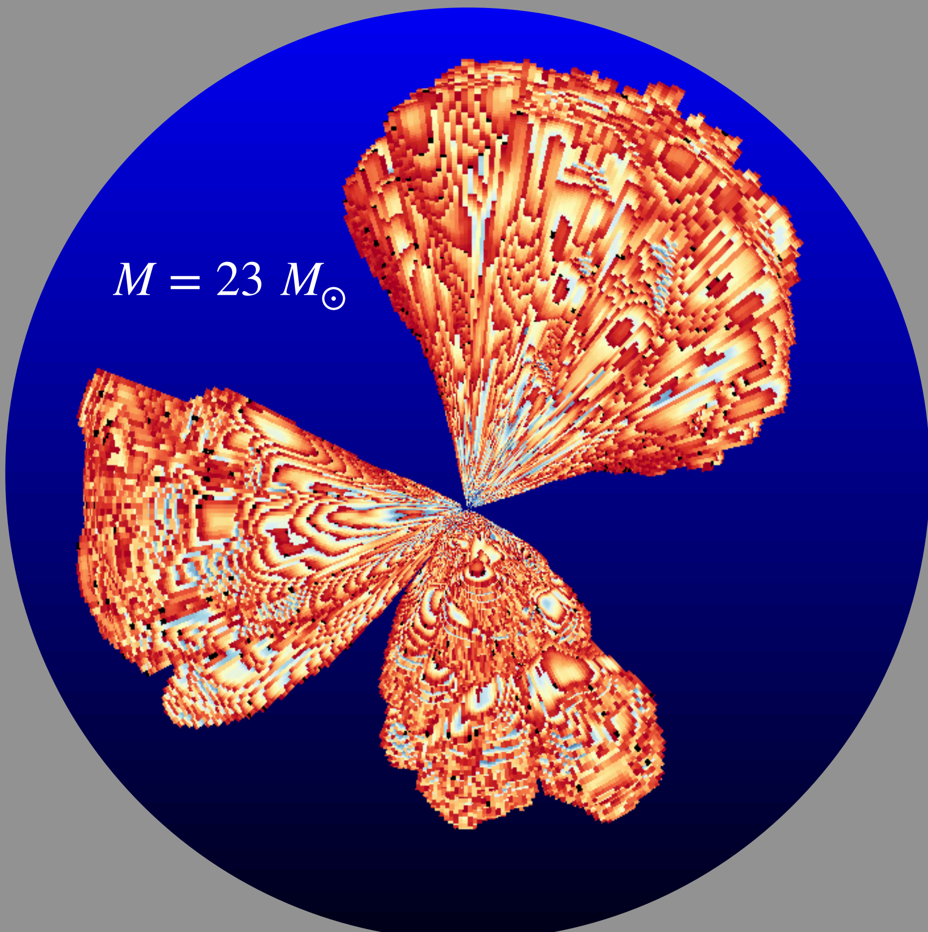
# Core Collapse Supernovae Simulation

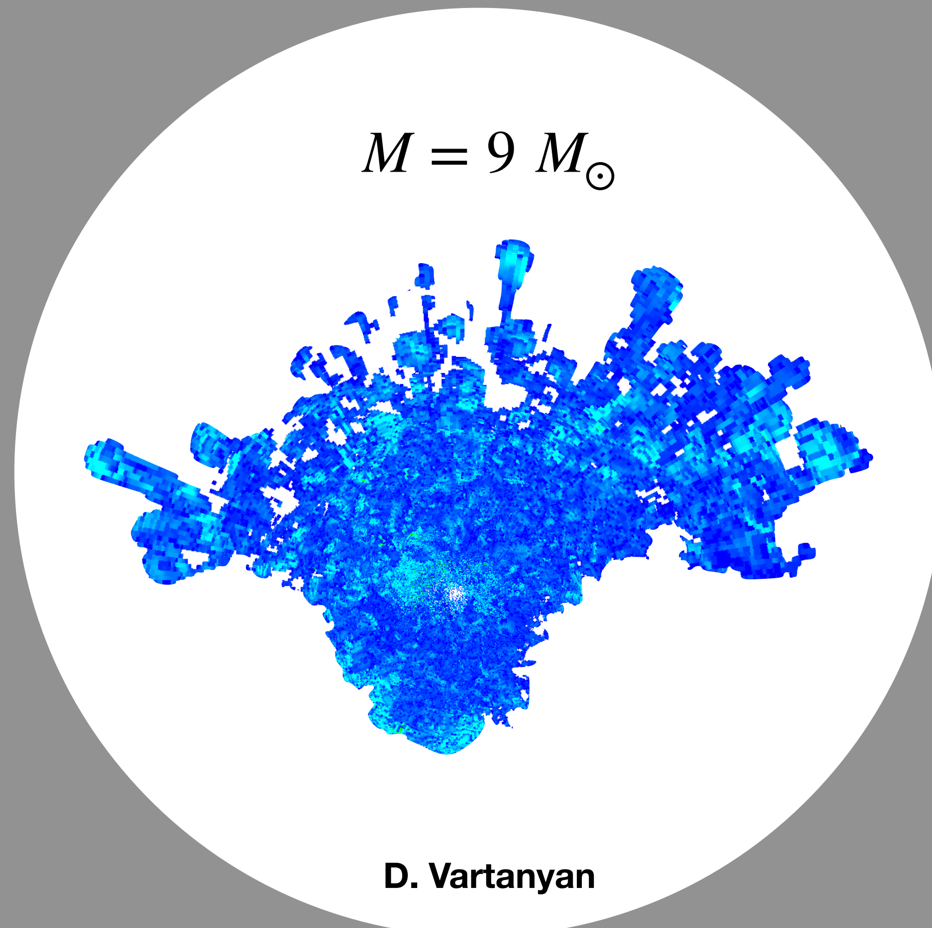
*D. Vartanyan (Fornax code)*

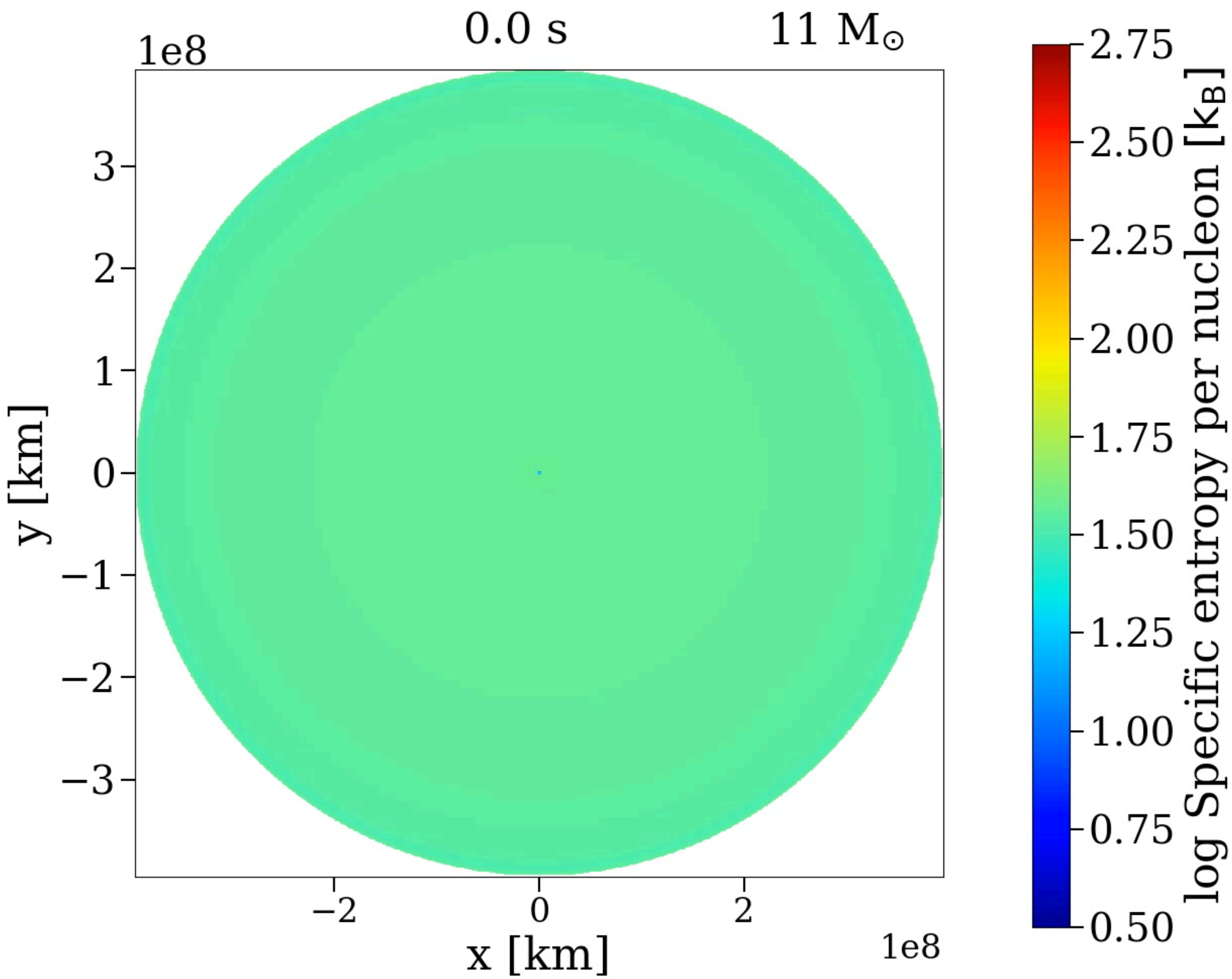


# 3D Fornax Core-Collapse Models

$^{56}$Ni distribution in inner regions



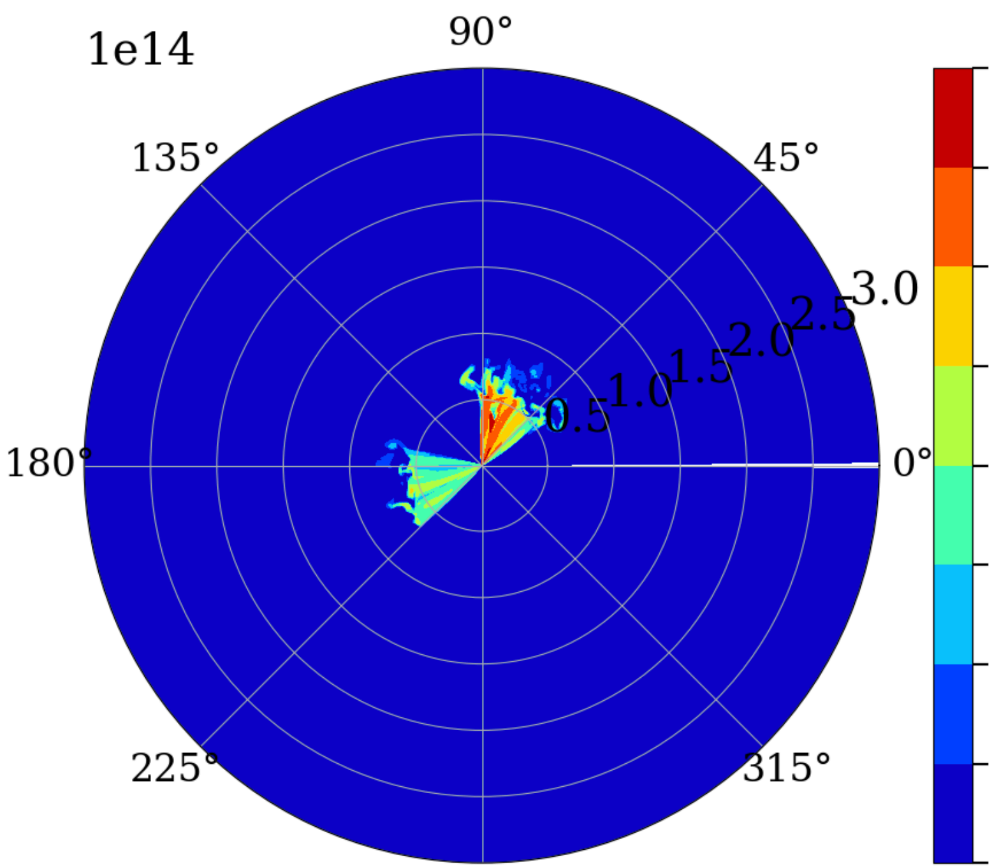



3D core collapse supernova model run to breakout

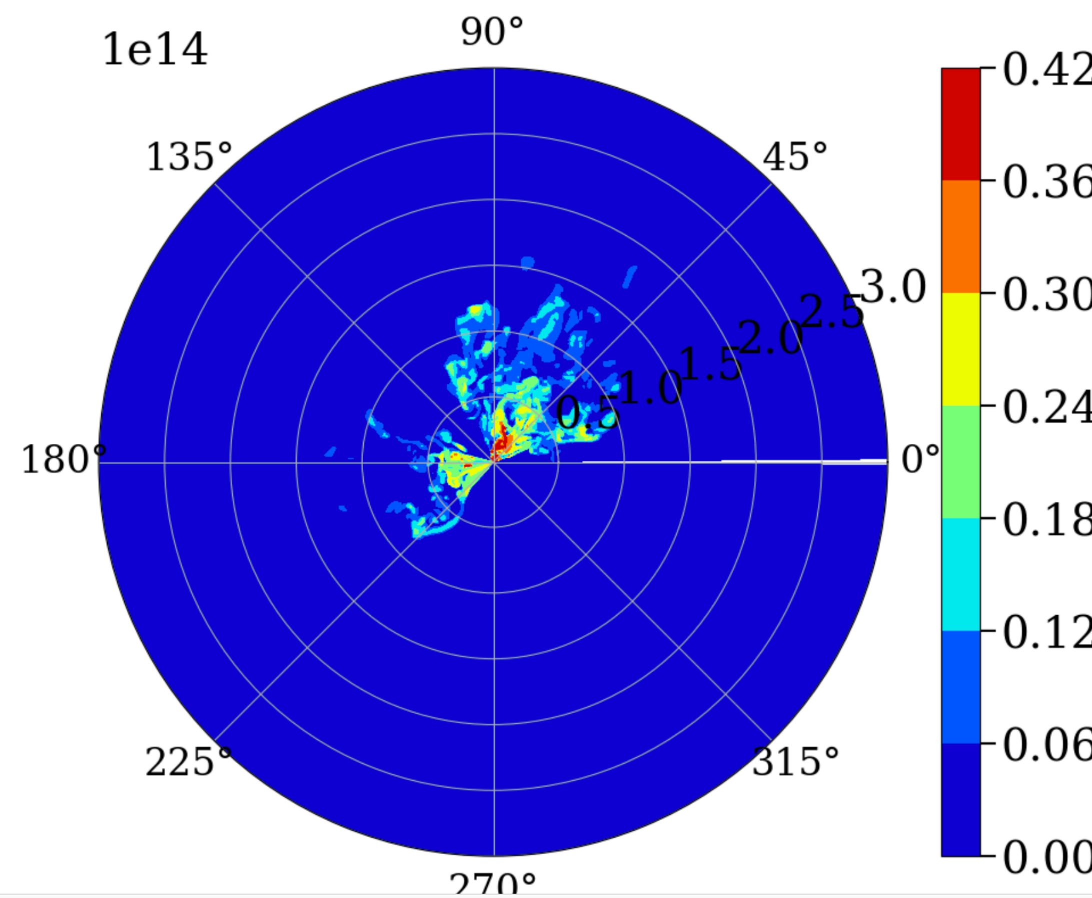
**Vartanyan et al (2025)**

# 56Ni structure of 3D core collapse simulation

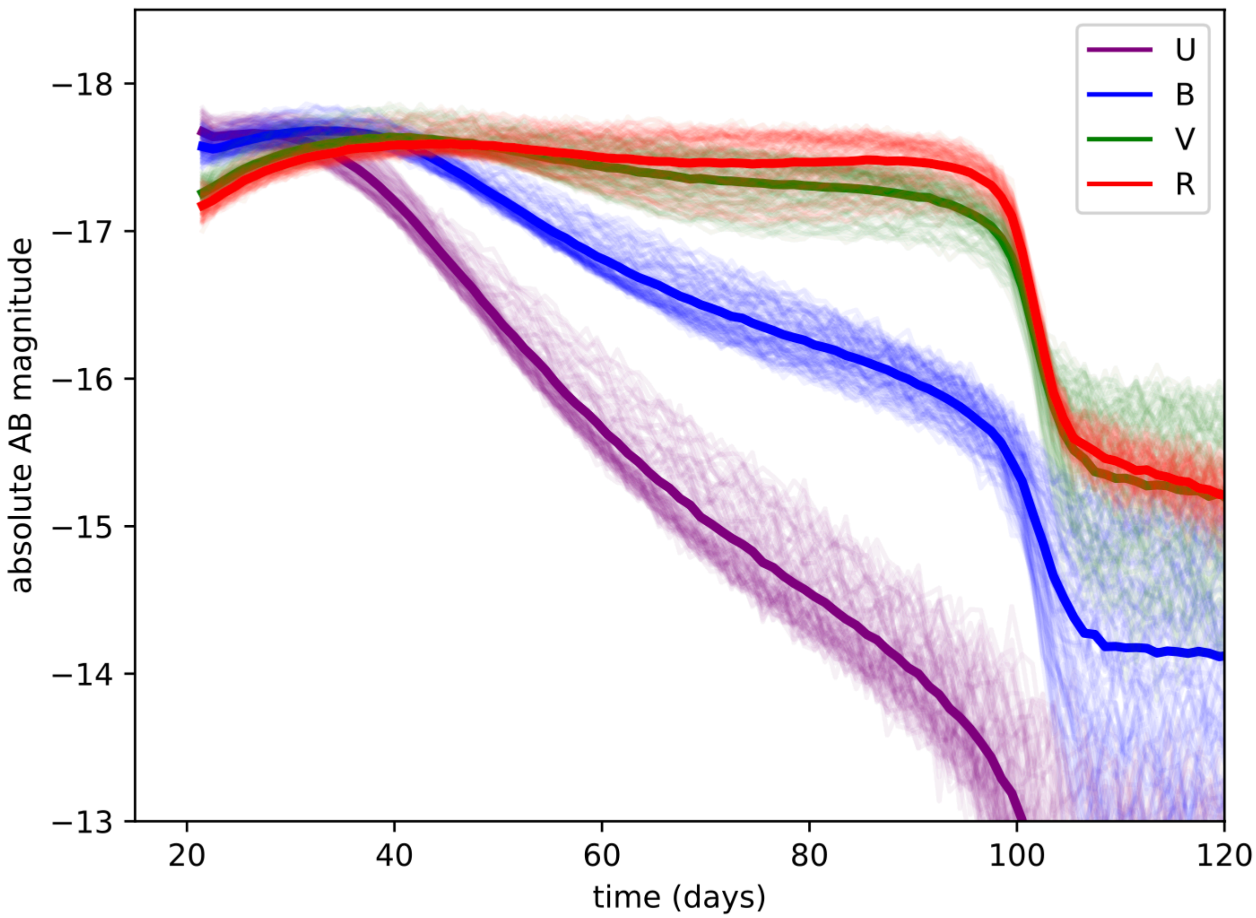
t = 2 days (just following shock breakout)




t = 11.5 days (after reverse shock)



# Broadband light curves of 3D Supernova Simulation
## (17 Msun Red Supergiant progenitor)




Vartanyan et al (2025)

# Broadband light curves of 3D Supernova Simulation
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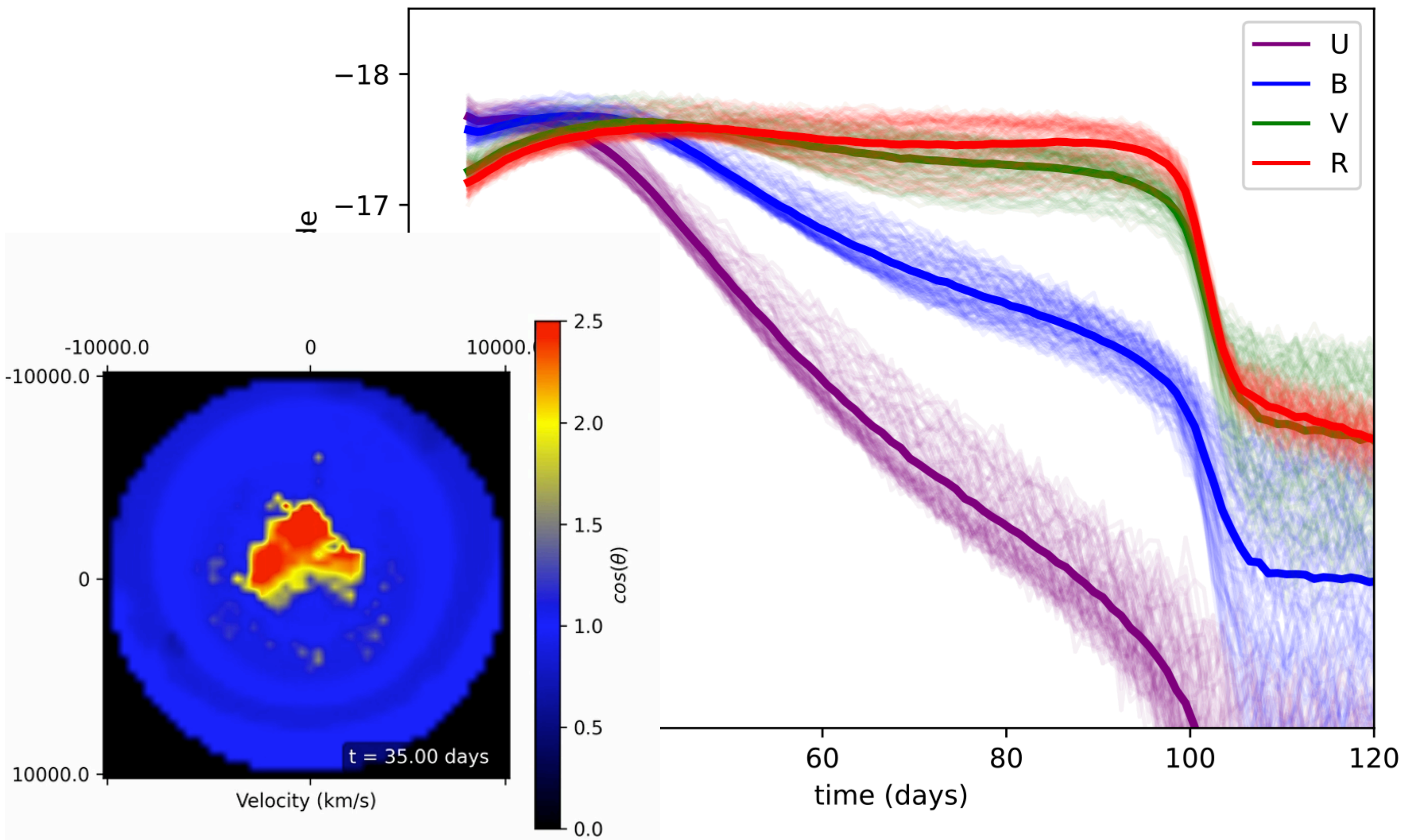
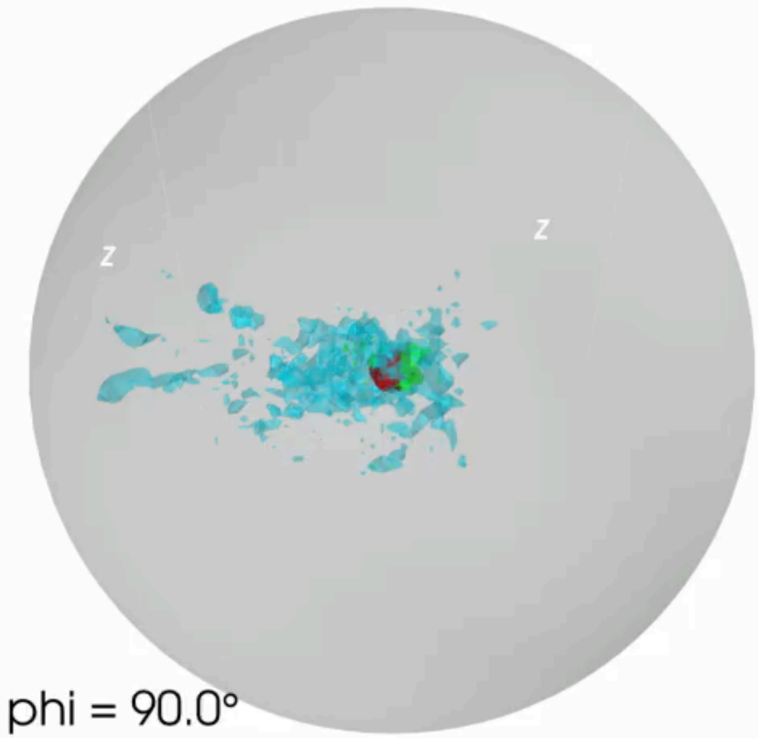
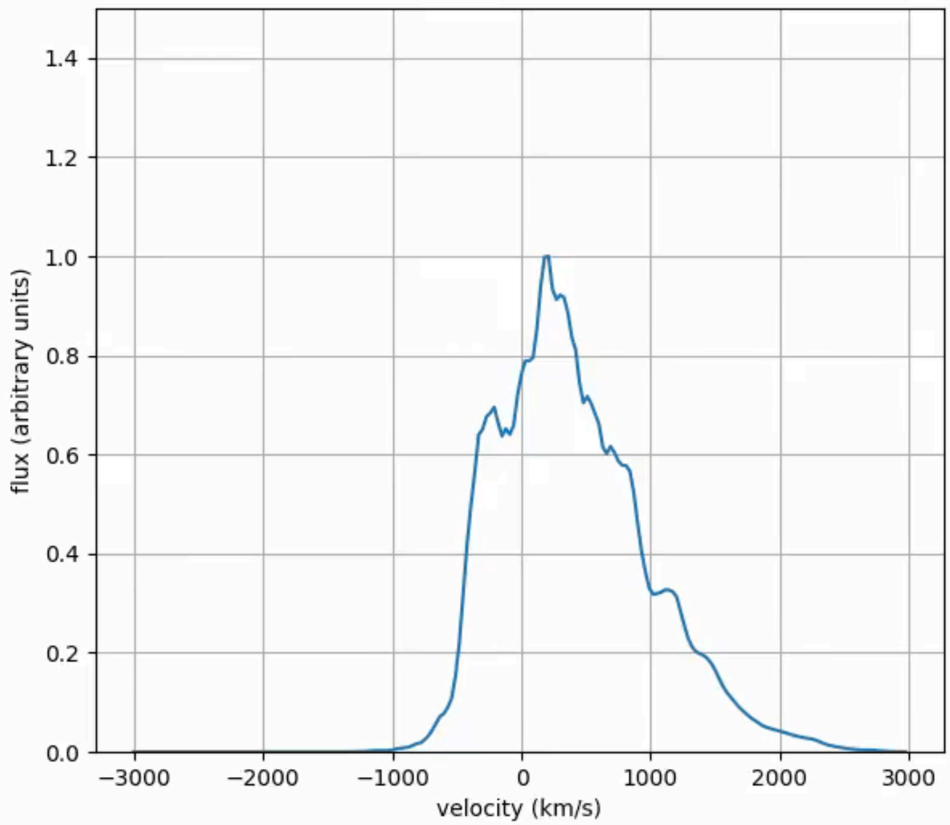



Vartanyan et al (2025)

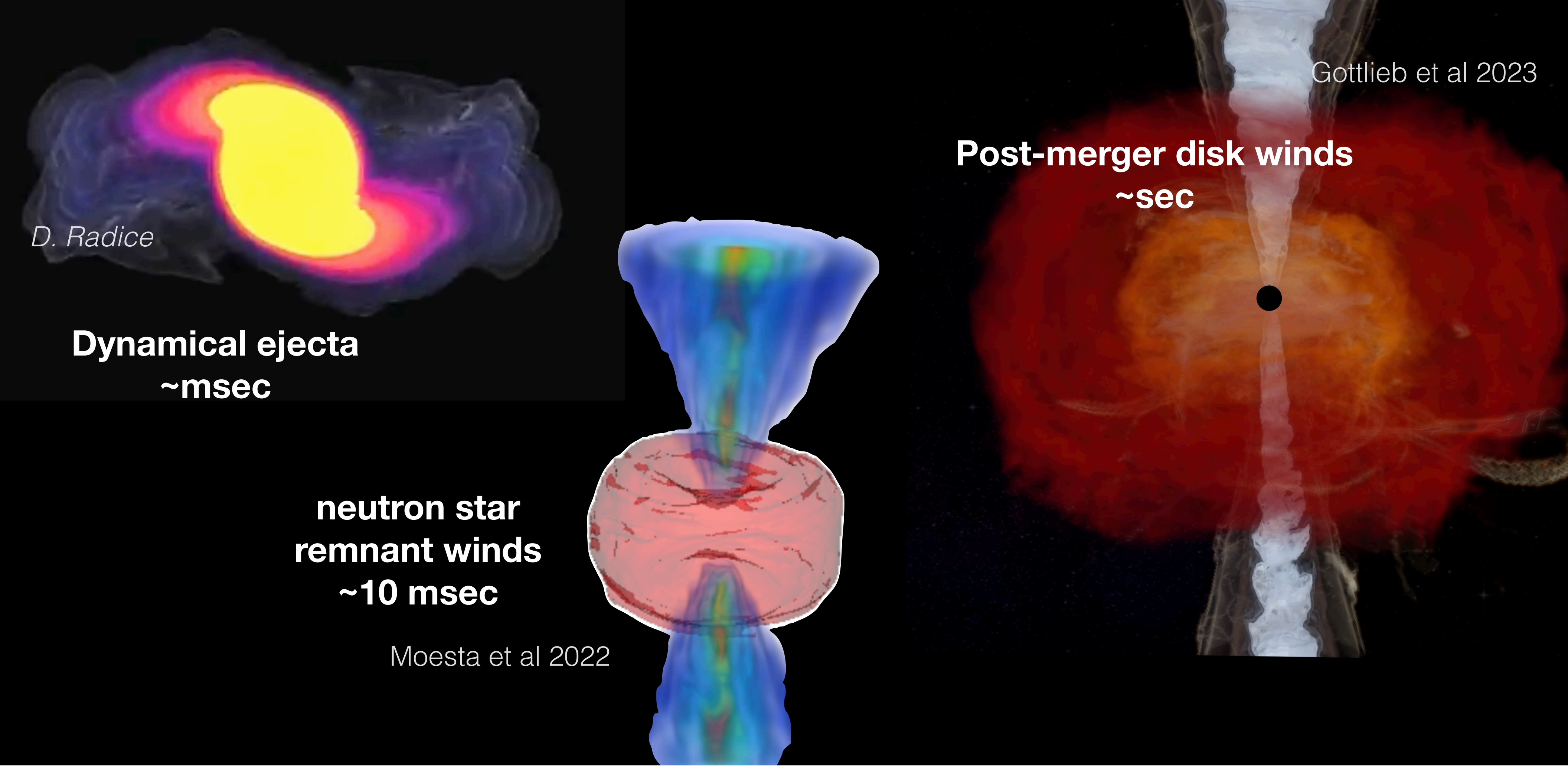
# Asymmetry and Late Time (> 300 day) Spectra Line Profiles




illustrative Doppler shift of single Fe line

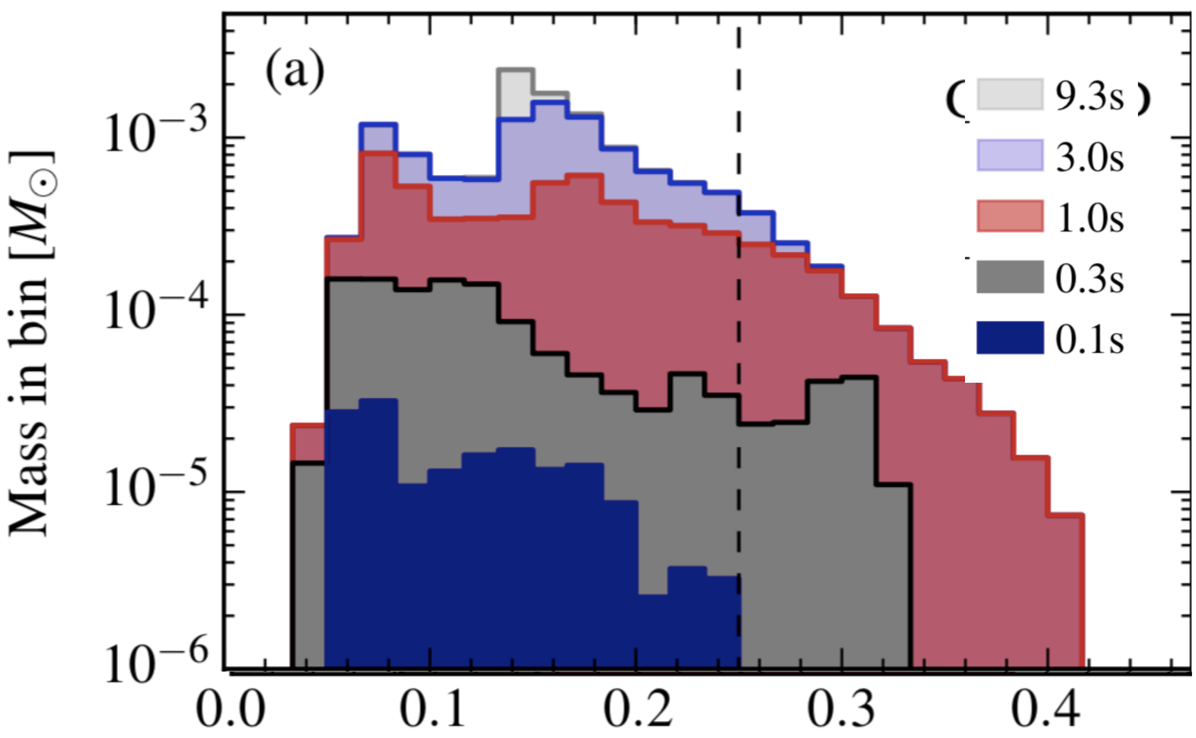


# Neutron Star Mergers - Ejecta

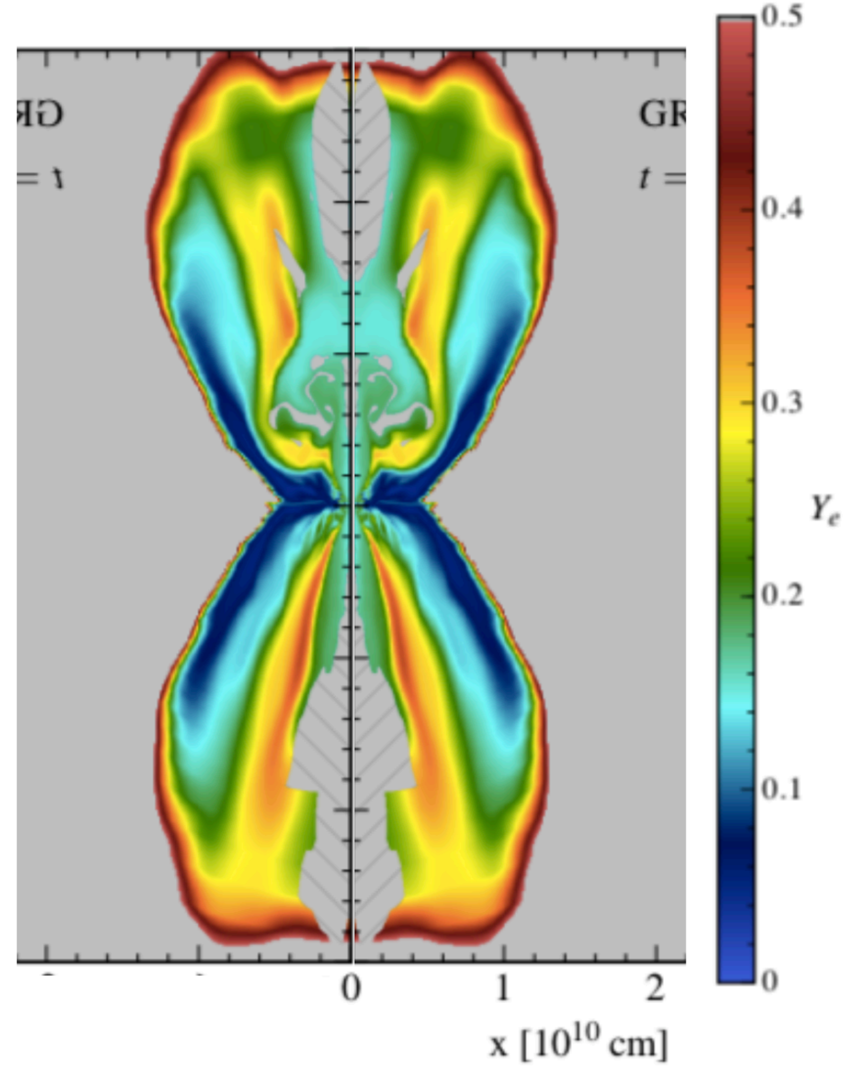


# Outflows from accretion disk winds

*Fernandez et al 2019, Christie et al 2020, Klion, Tchekhovskoy, DK+ 2022*

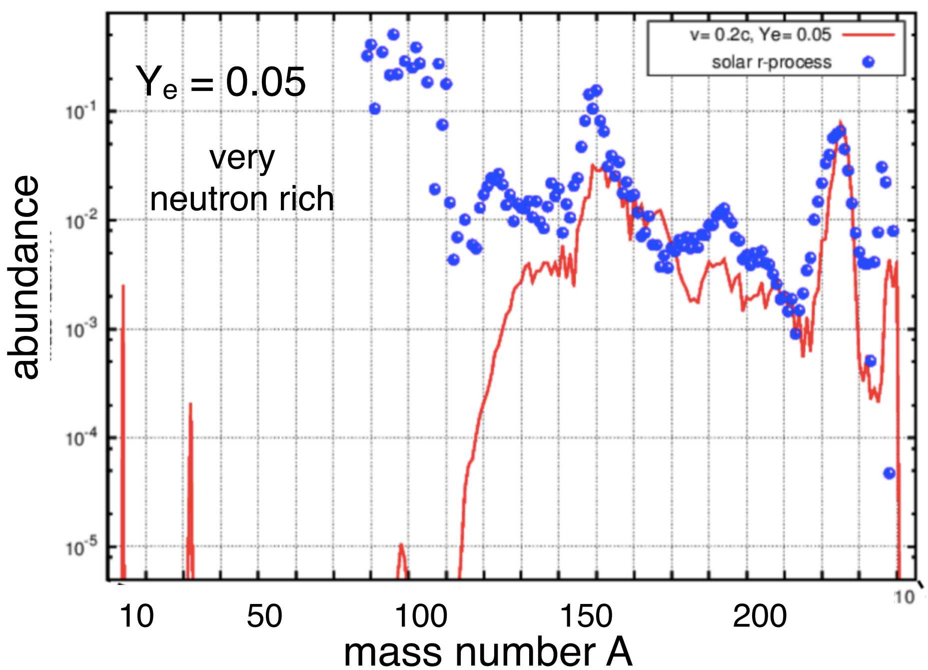



**Electron Fraction (Ye)**

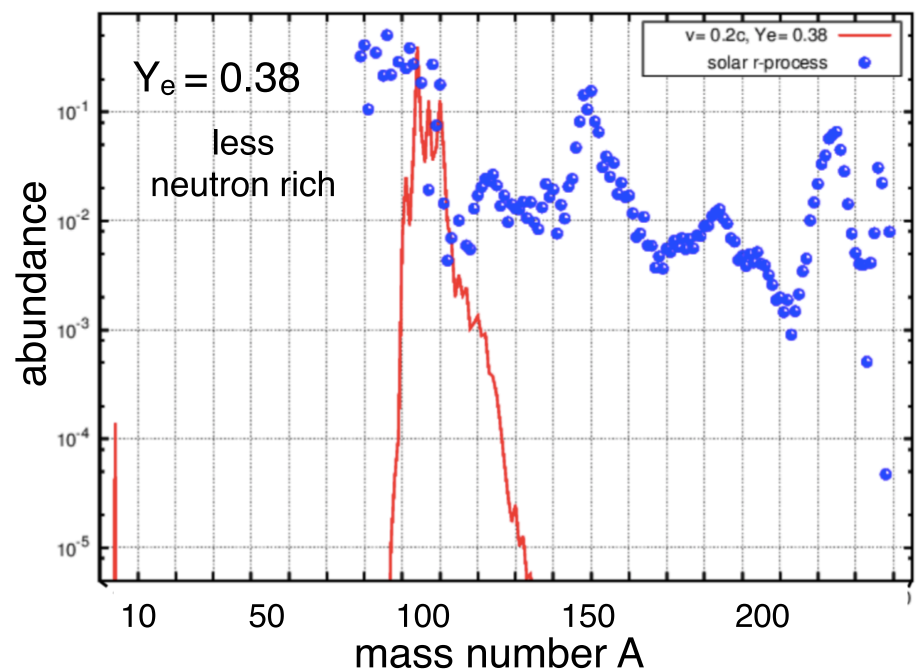


# Simulated r-process abundances, compared to solar *Rosswog+2017, Kasliwal, DK +2022*

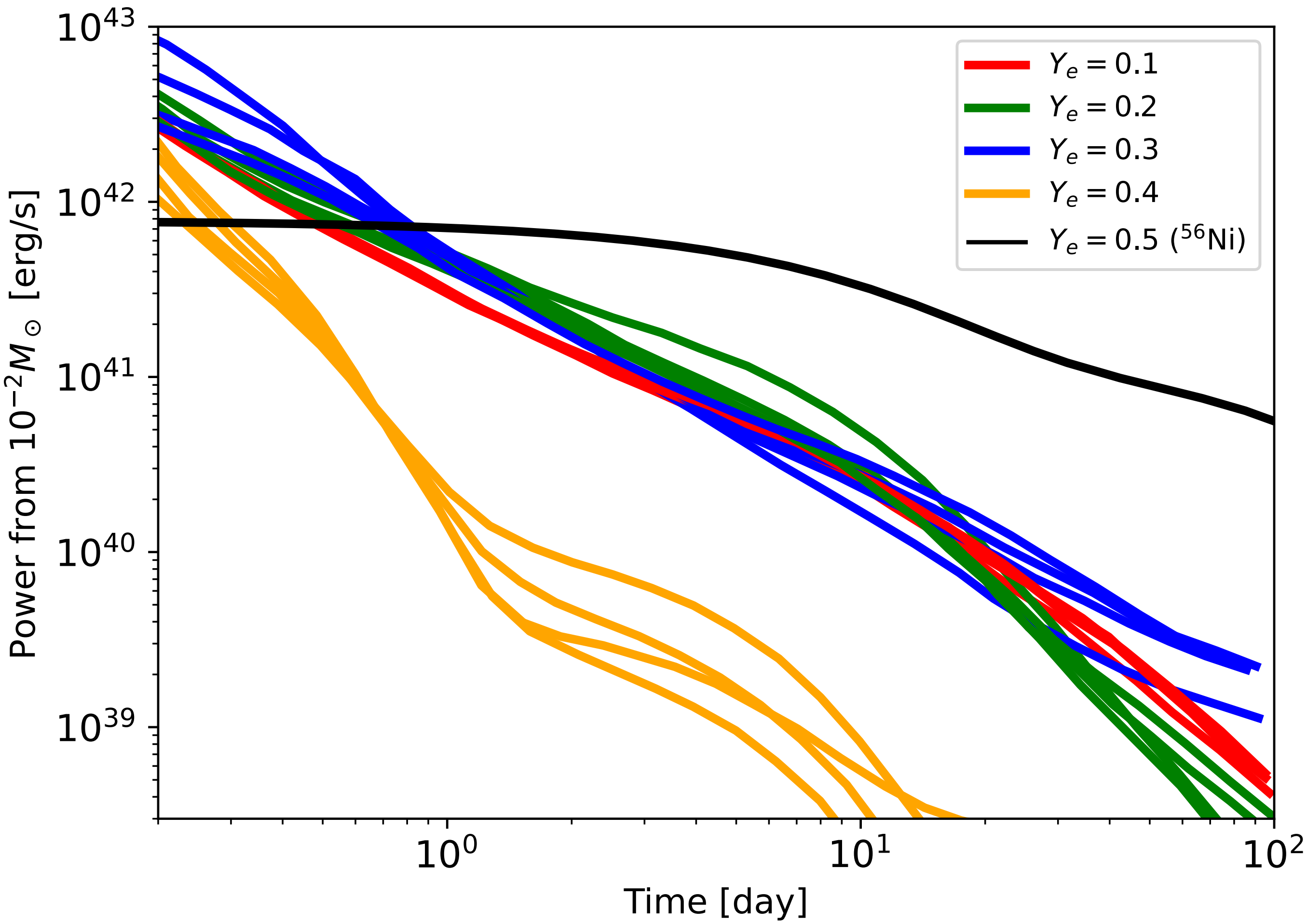
$Y_e \lesssim 0.25 \rightarrow \text{heavy r} - \text{process}$



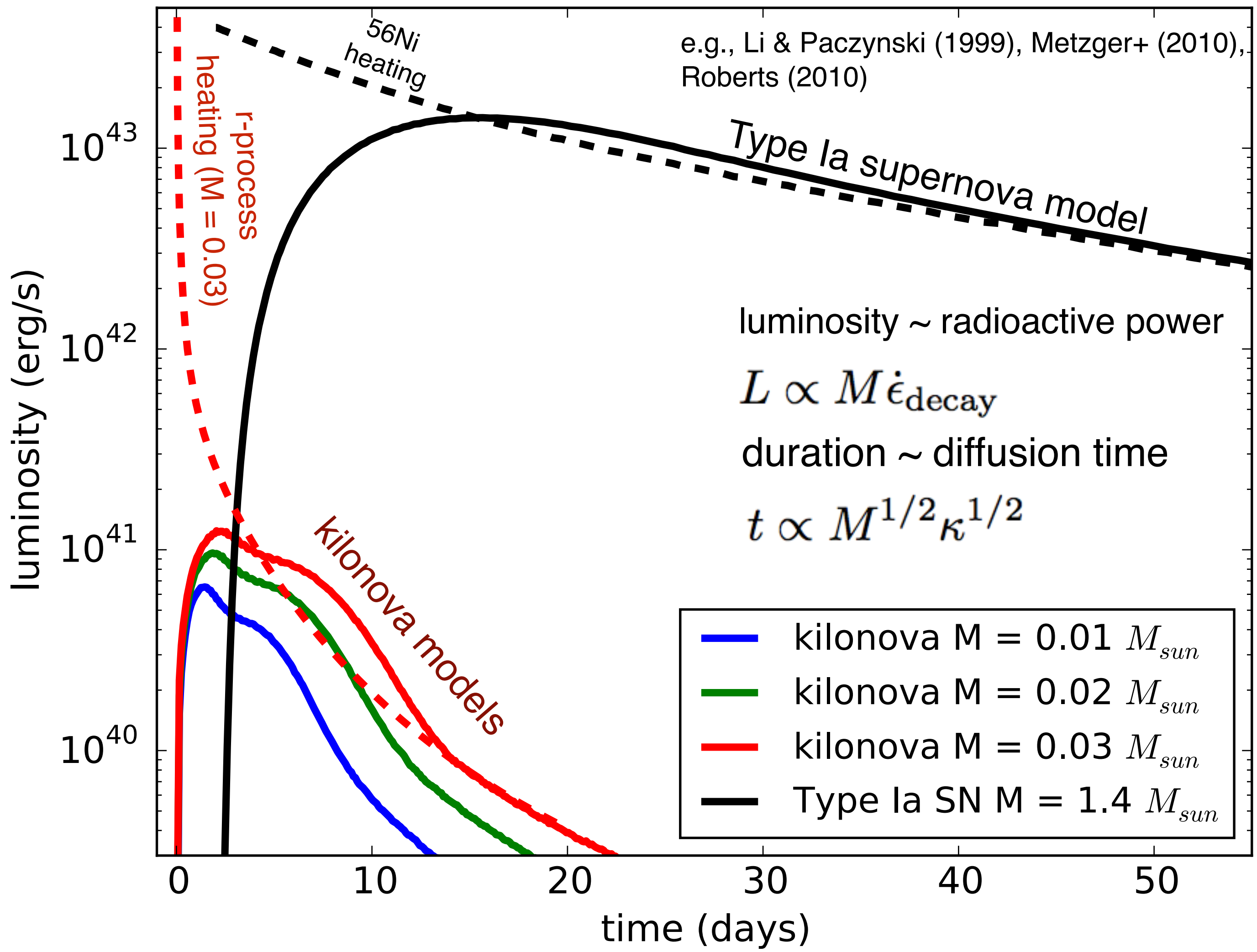

$Y_e \gtrsim 0.25 \rightarrow \text{light r} - \text{process}$



# radioactive power rates



# Model kilonova light curves



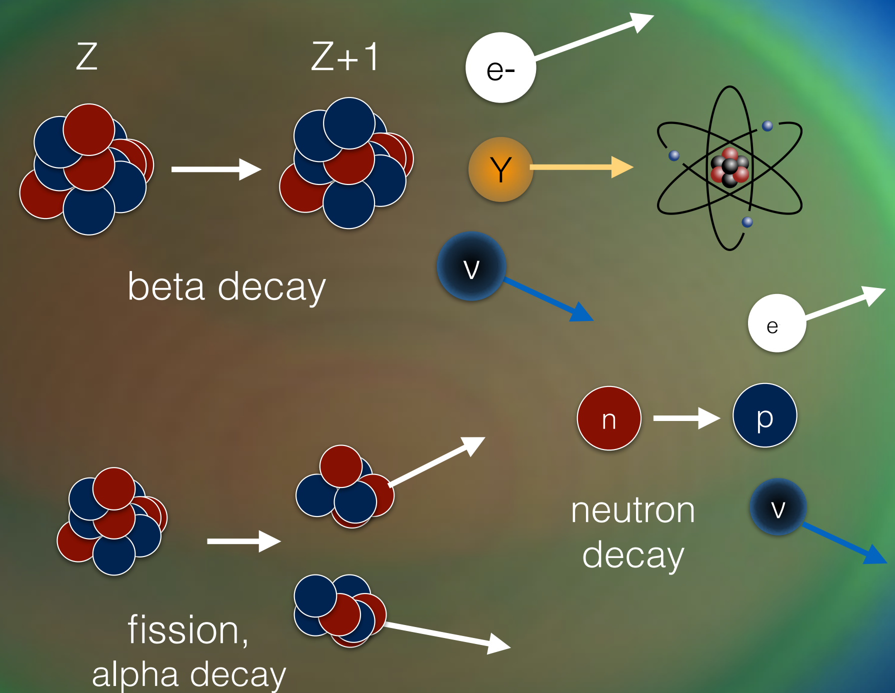
# Kilonova: visible glow of expanding, radioactive debris cloud

$M \sim 10^{-2} - 10^{-1} M_\odot$

$v \sim 0.1c - 0.3c$

$r \sim 10^{15}$ cm $\sim 100$ AU

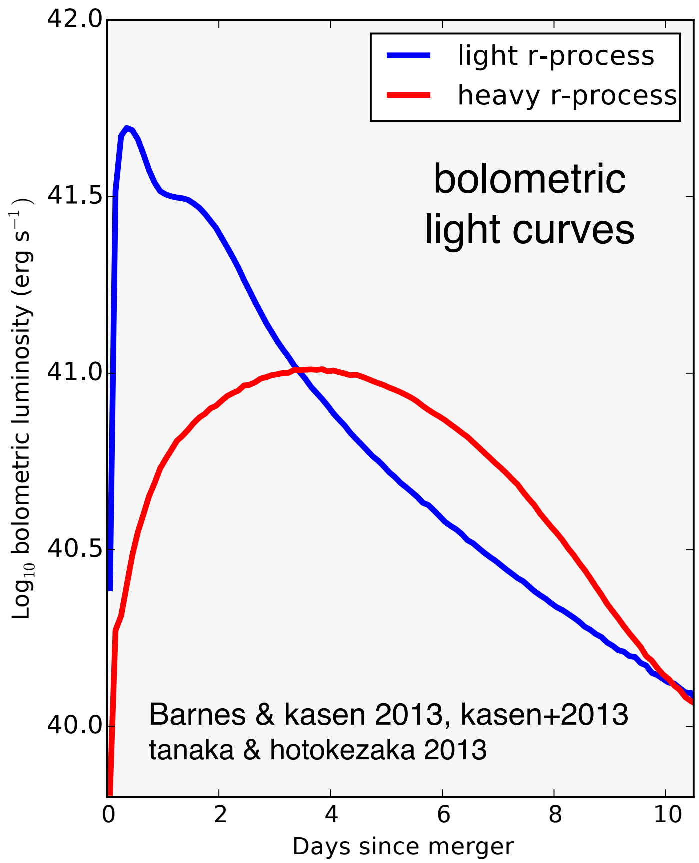
$T \sim 1{,}000 - 10{,}000$ K

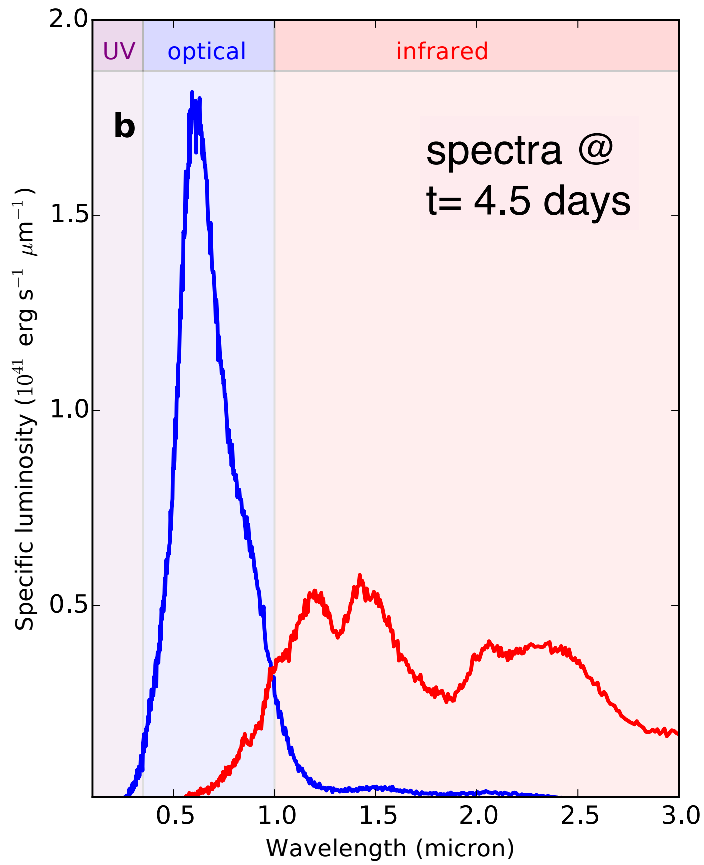


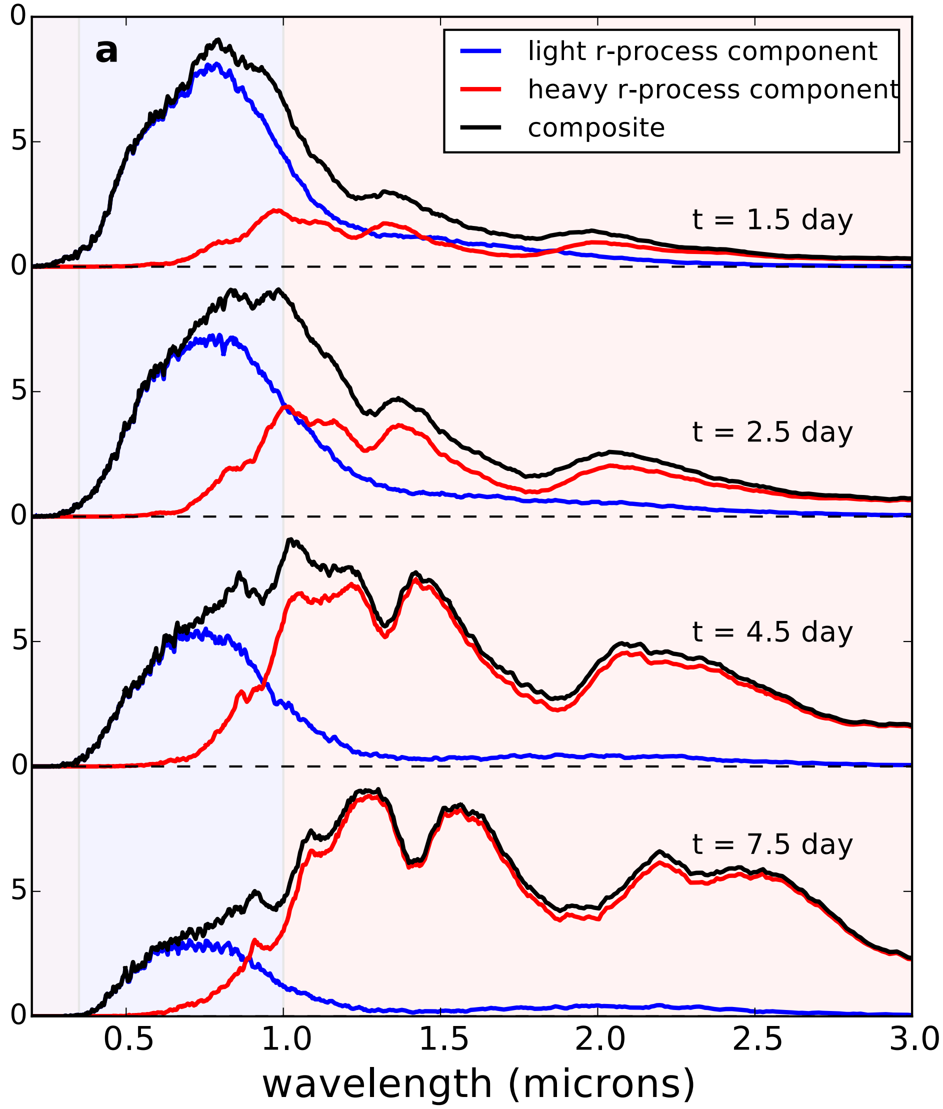

$$\dot{\epsilon}_{\rm nuc} \approx 10^{42} \left(\frac{t}{1 \ \rm day}\right)^{-1.3} \left(\frac{M}{0.05 \ M_\odot}\right) \ \rm erg \ s^{-1} \approx 2 \times 10^{8} \ L_\odot$$

# Kilonova Model Light Curves and Spectra

lanthanide "rich" —> high opacity —> longer, red emission
lanthanide "free" —> low opacity —> briefer, blue emission





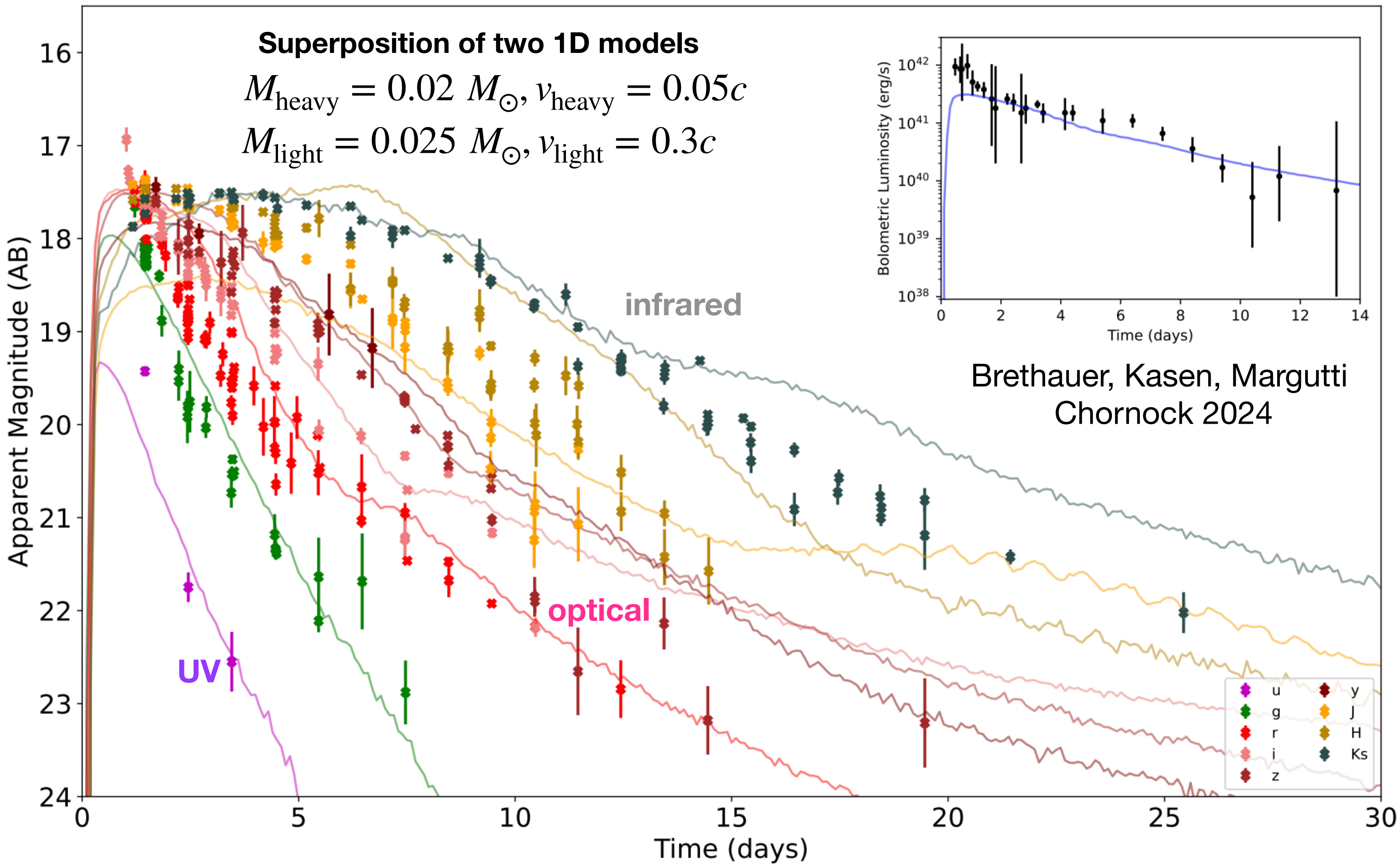

# Two component ejecta models and the kilonova associated with GW170817

*0.025 $M_{sun}$ of v ~ 0.2c lanthanide free, "blue" ejecta*

*0.040 $M_{sun}$ of v ~ 0.1c lanthanide rich, "red" ejecta*

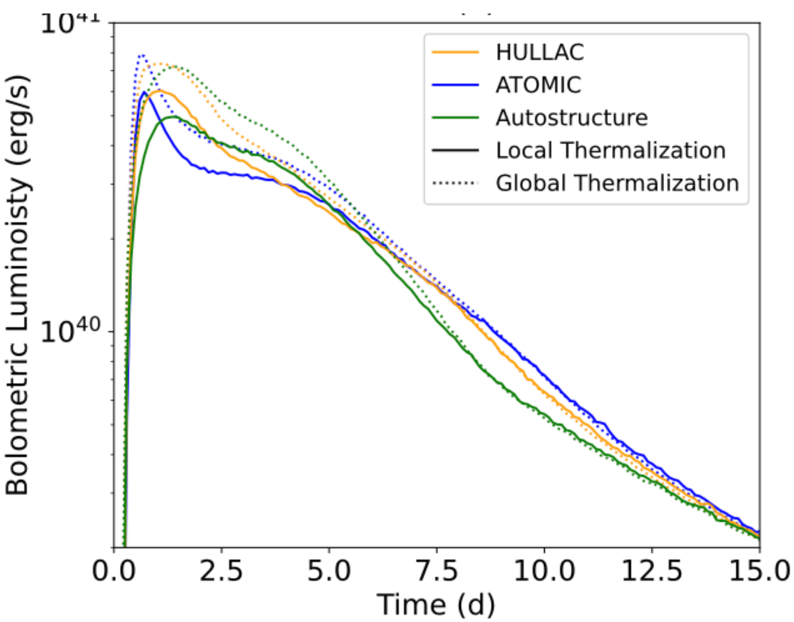
**Kasen et al 2017**

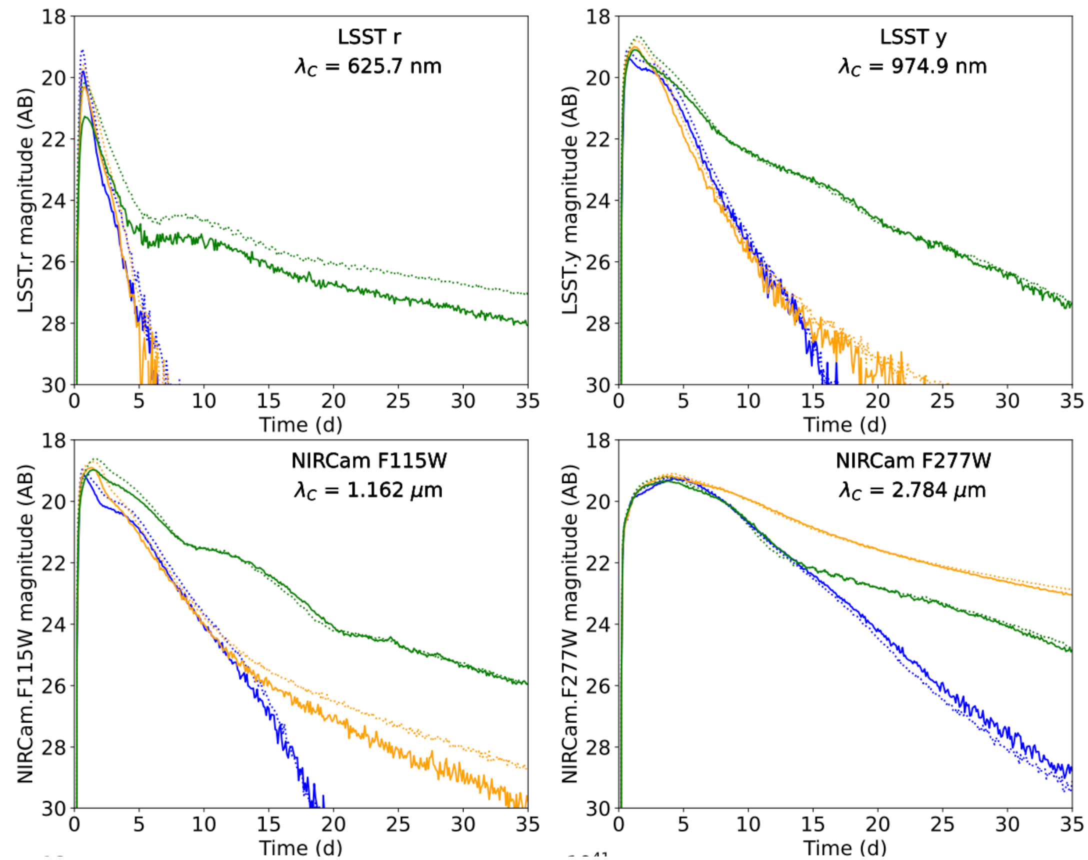
# Modeling the Emission from the GW170817 Kilonova



# Effect of atomic data on kilonova light curve predictions

Brethauer, Kasen, Margutti
Chornock 2024

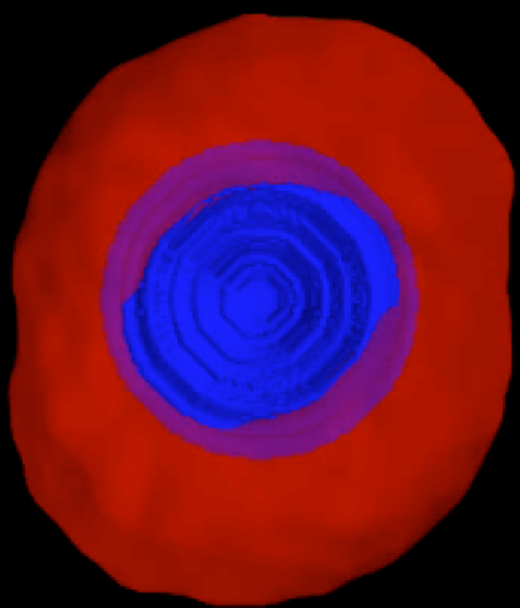


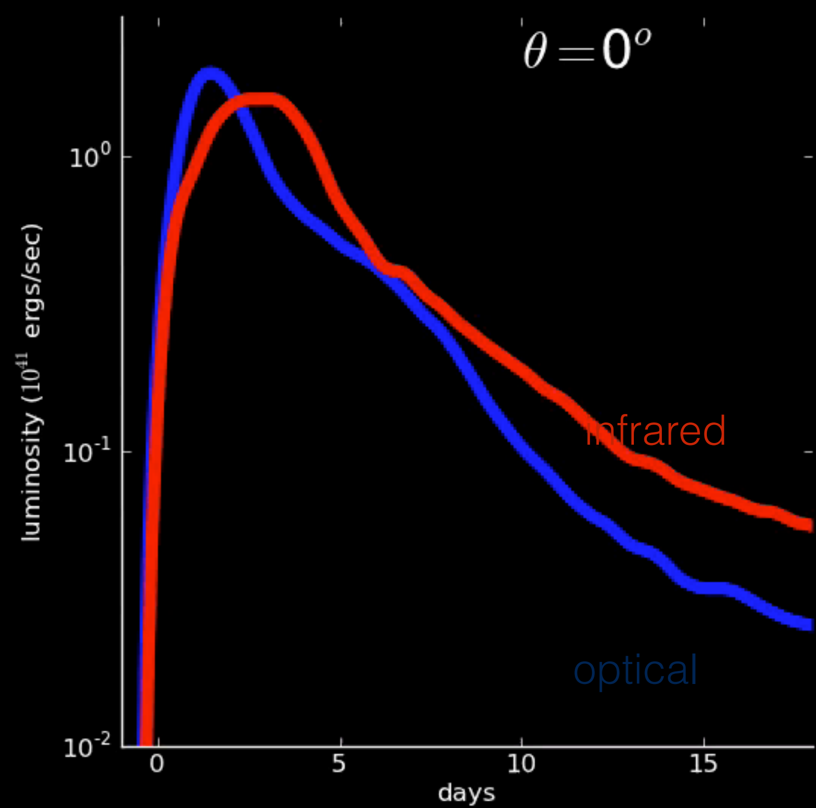




Tanaka et 2020
Fontes et al 2020
Kasen et al 2017

# Effects of Asymmetry and the “Lanthanide Curtain”

kasen+2015

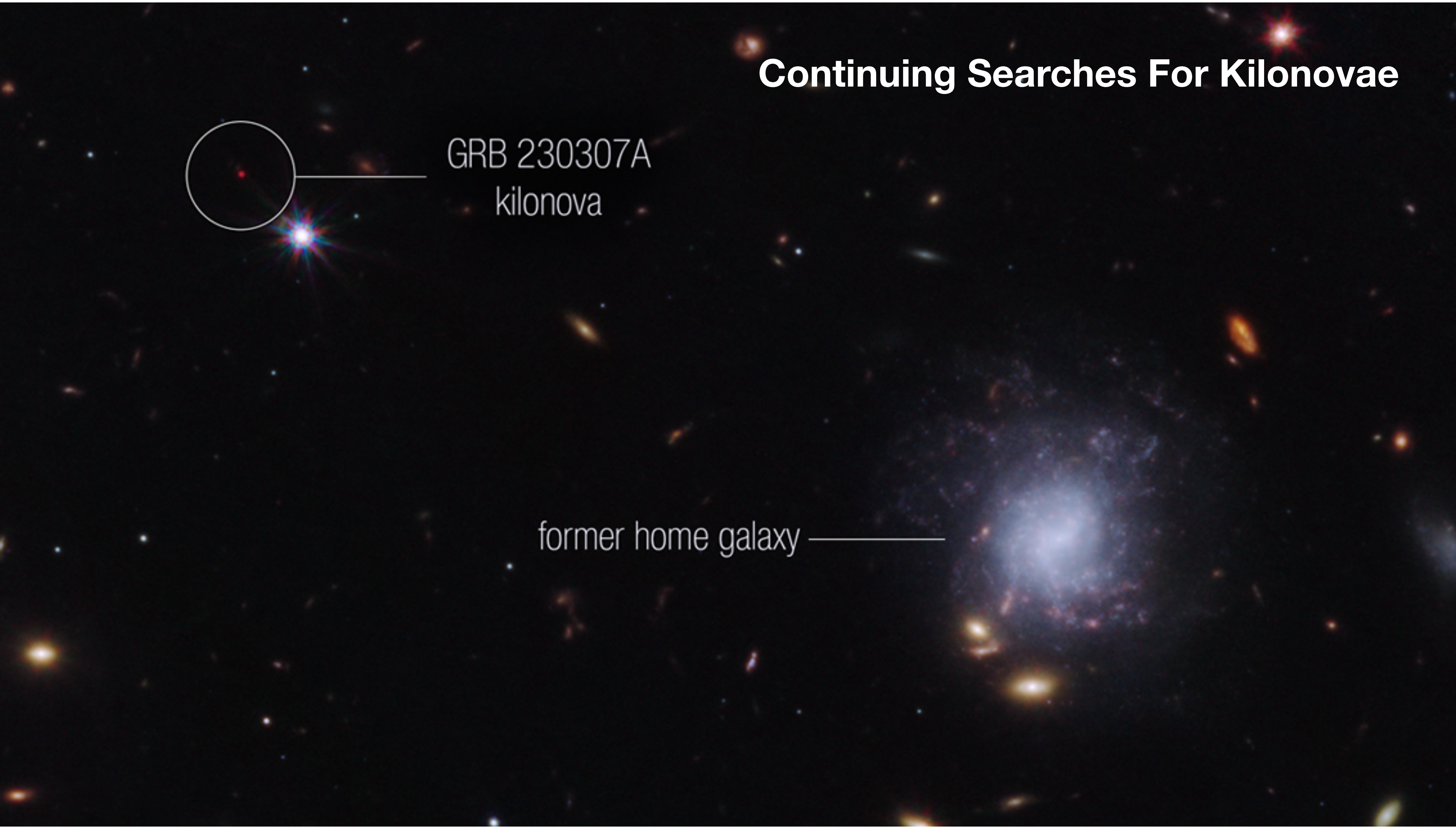




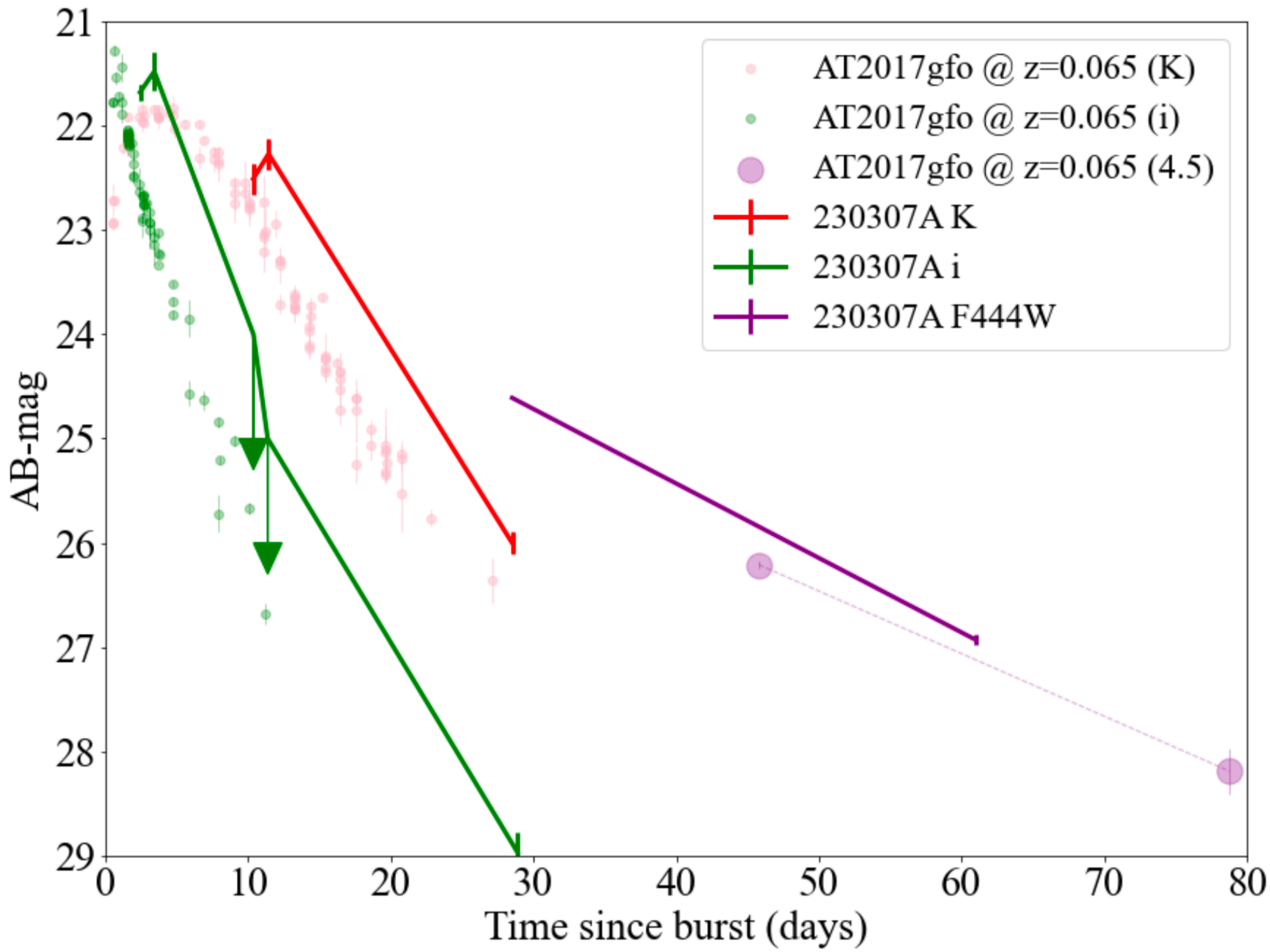

Kawaguchi+ 2018, 2024, Bulla+ 2018,
Korokbin+ 2020, Darbha + DK 2020

C.f. Sneppen+ 2023

# Continuing Searches For Kilonovae



# GRB 230307A — infrared bright excess afterglow emission

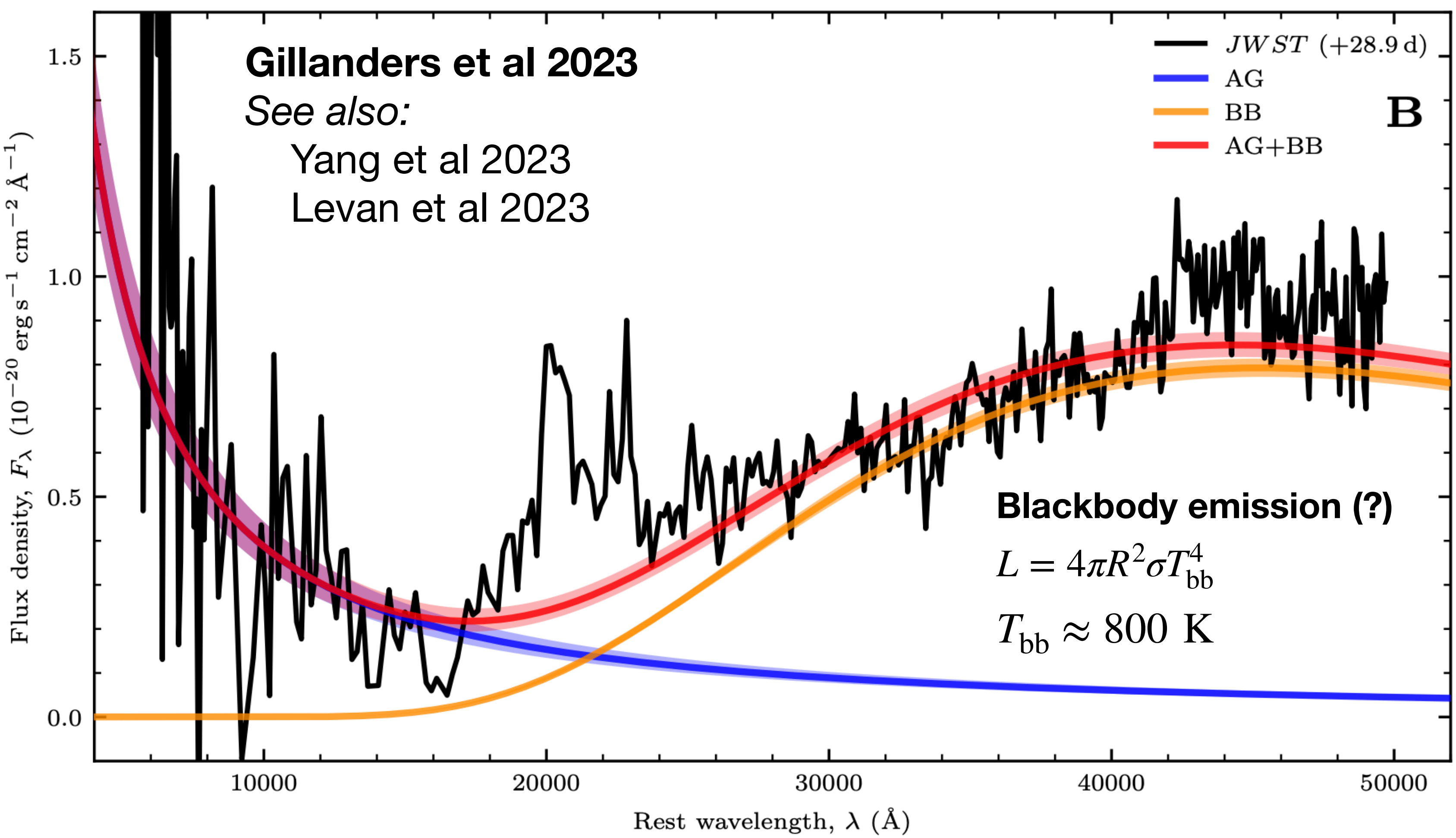



**Levan et al 2023**
see also:
Yang et al 2023
Gillanders et al 2023

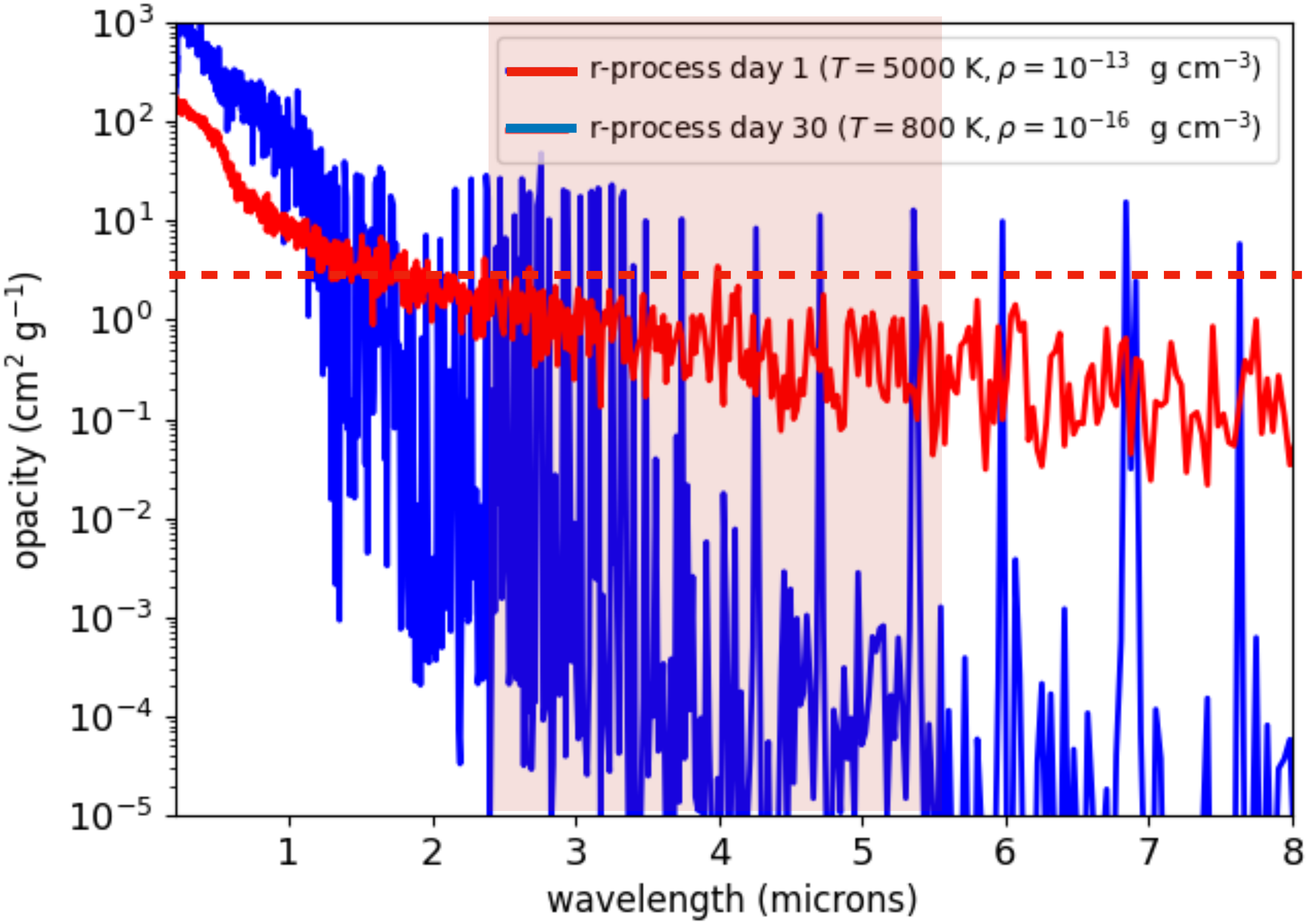
**Also GRB 211211A**
Troja et al 2022

**And others from long + short GRBs**
e.g., Rastinejad 2025

# JWST observations of GRB230307A excess at day +29



# opacity of heavy r-process mixture



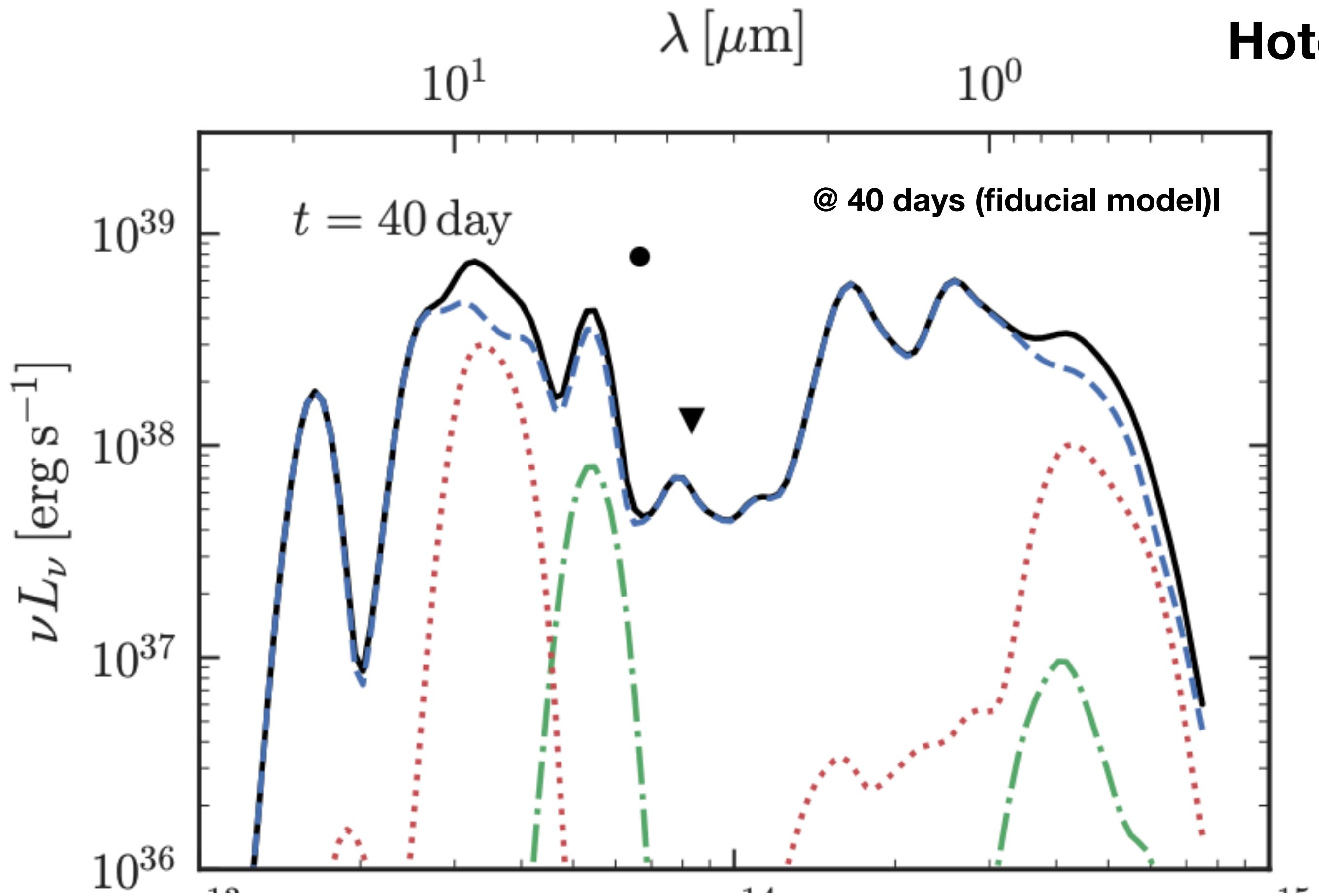

**To have a optically thick blackbody photosphere:**

$$\tau \sim R\rho\kappa \sim 1$$

$$\kappa \sim 5\ M_{0.05}^{-1} v_{0.1}^{2} t_{30}^{2}\ \mathrm{g\ cm^{-2}}$$

# Expectations for late time spectra

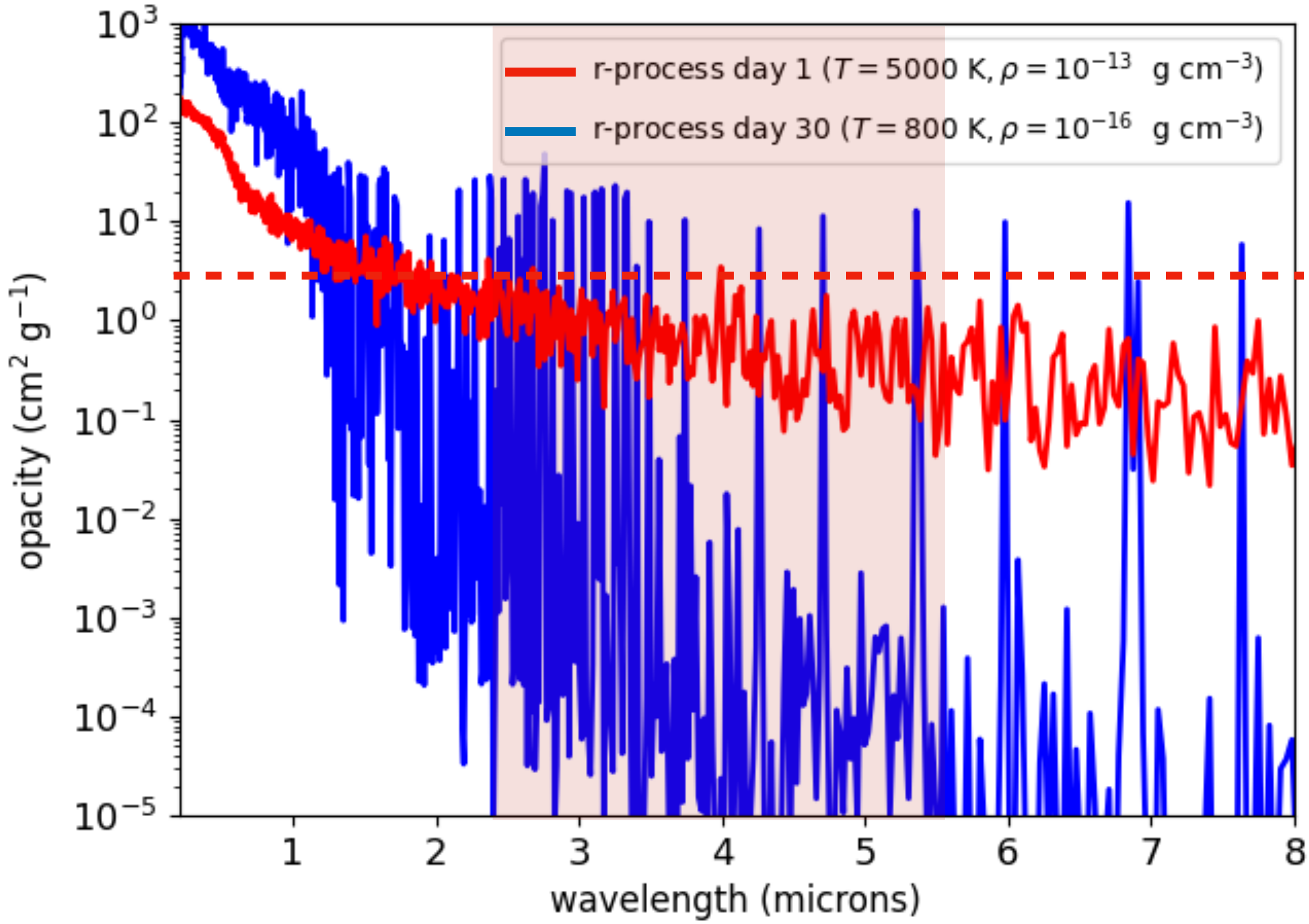
**Hotokezaka et al 2021**




(optically thin nebular line emission)

(optically thin nebular line emission)

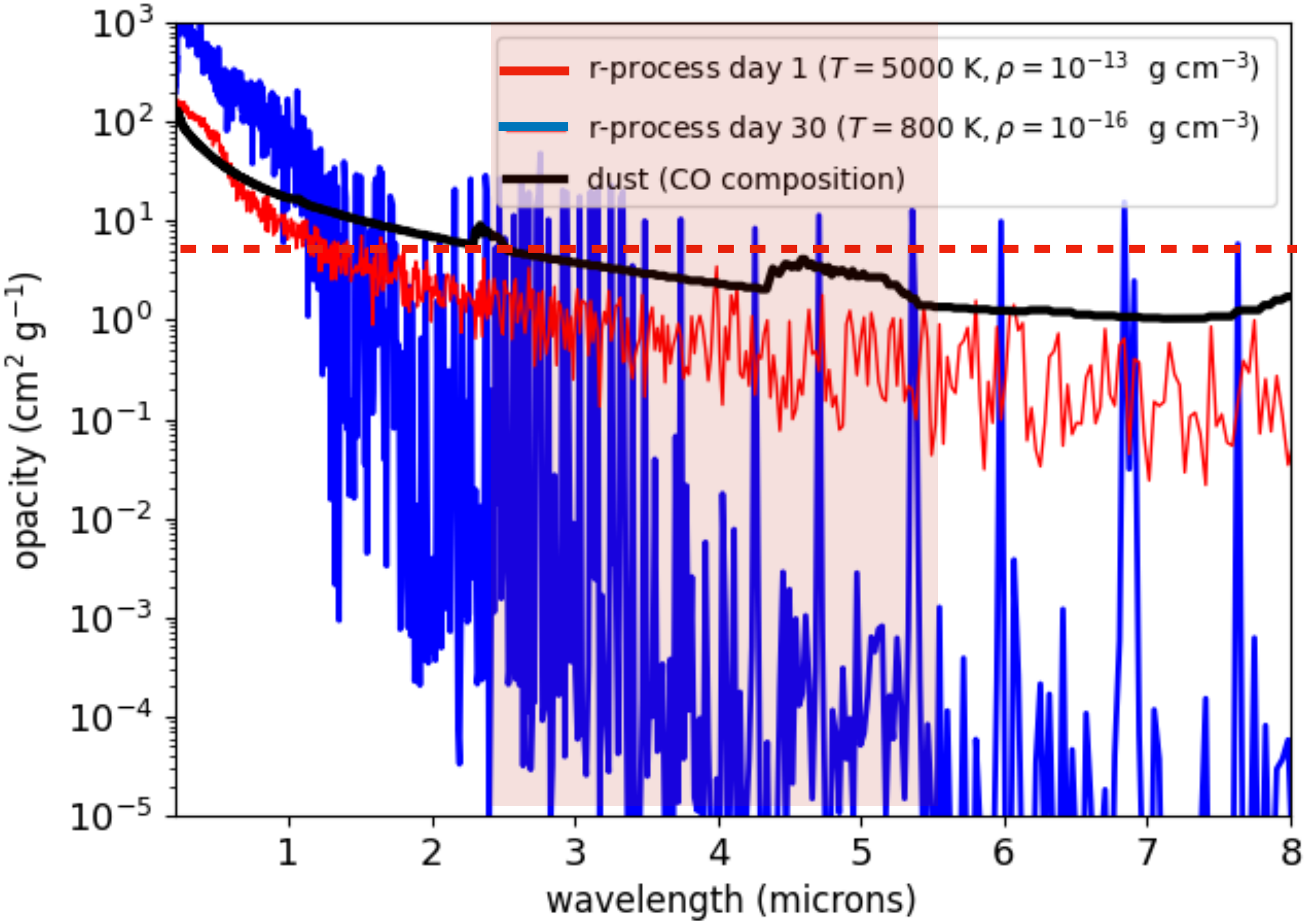
# opacity of heavy r-process mixture




**Missing Opacity at infrared wavelengths?**

- Incomplete atomic data?
- NLTE effects ?
- Anions? (e.g., $Nd^-$)?
- Molecules?
- Dust?

# Contributions of dust grains to opacity?




Carbon/silicate dust
*Li & Drain 2001*

1% dust to gas mass fraction

C.f.
*Gall et al 2017*

# White Dwarf + NS/BH Post-merger Disks

$t_{\text{visc}} \sim 100 - 1000 \text{ s}$

$M_{\text{disk}} \sim 0.6\ M_{\odot}$

$R_{\text{disk}} \sim 10^4 \text{ km}$

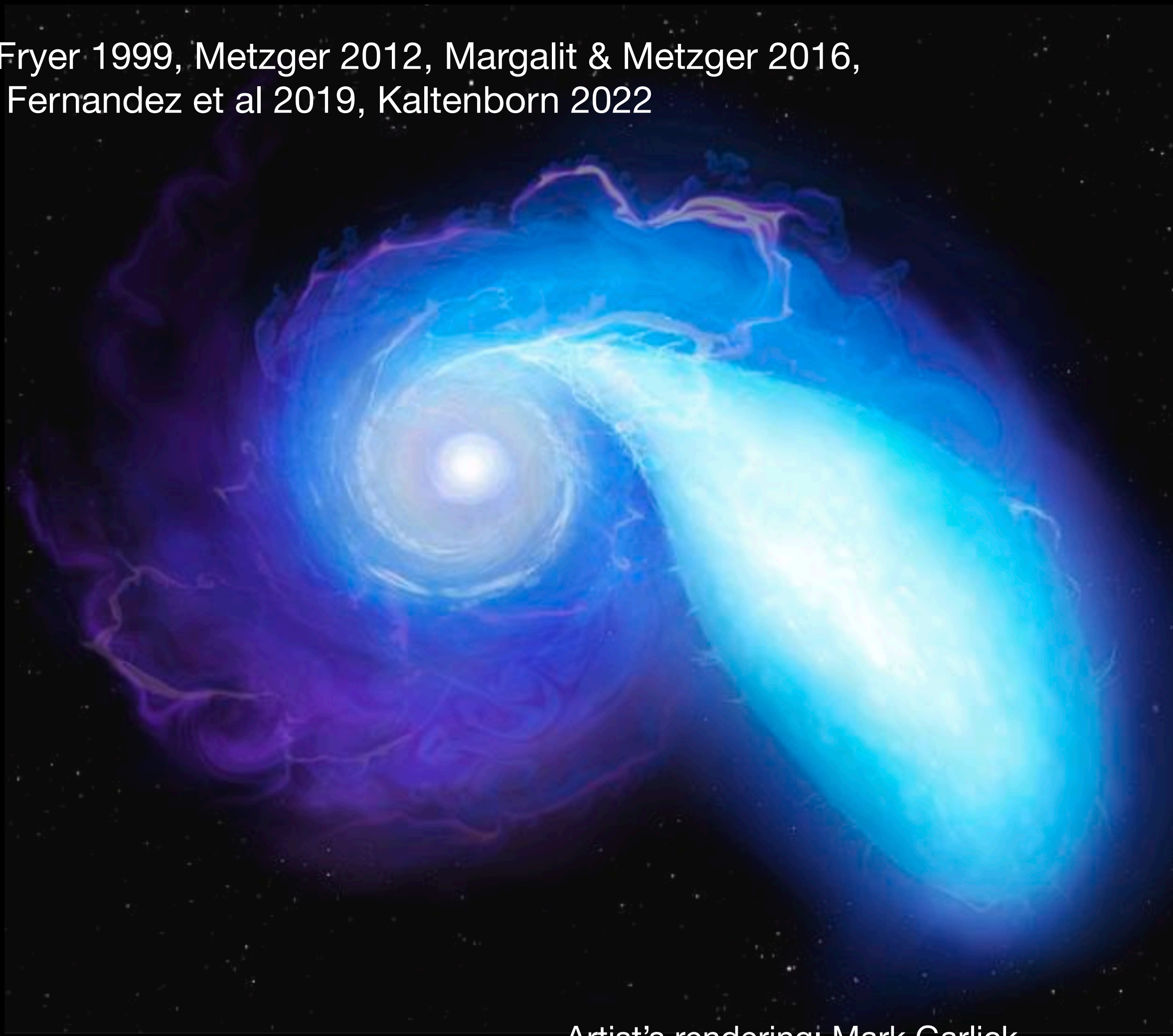
$\rho_{\text{disk}} \sim 10^4 \text{ g cm}^3$

$T_{\text{disk}} \sim 10^9 \text{ K}$

Composition

C/O , O/Ne, He ($Y_e = 0.5$)

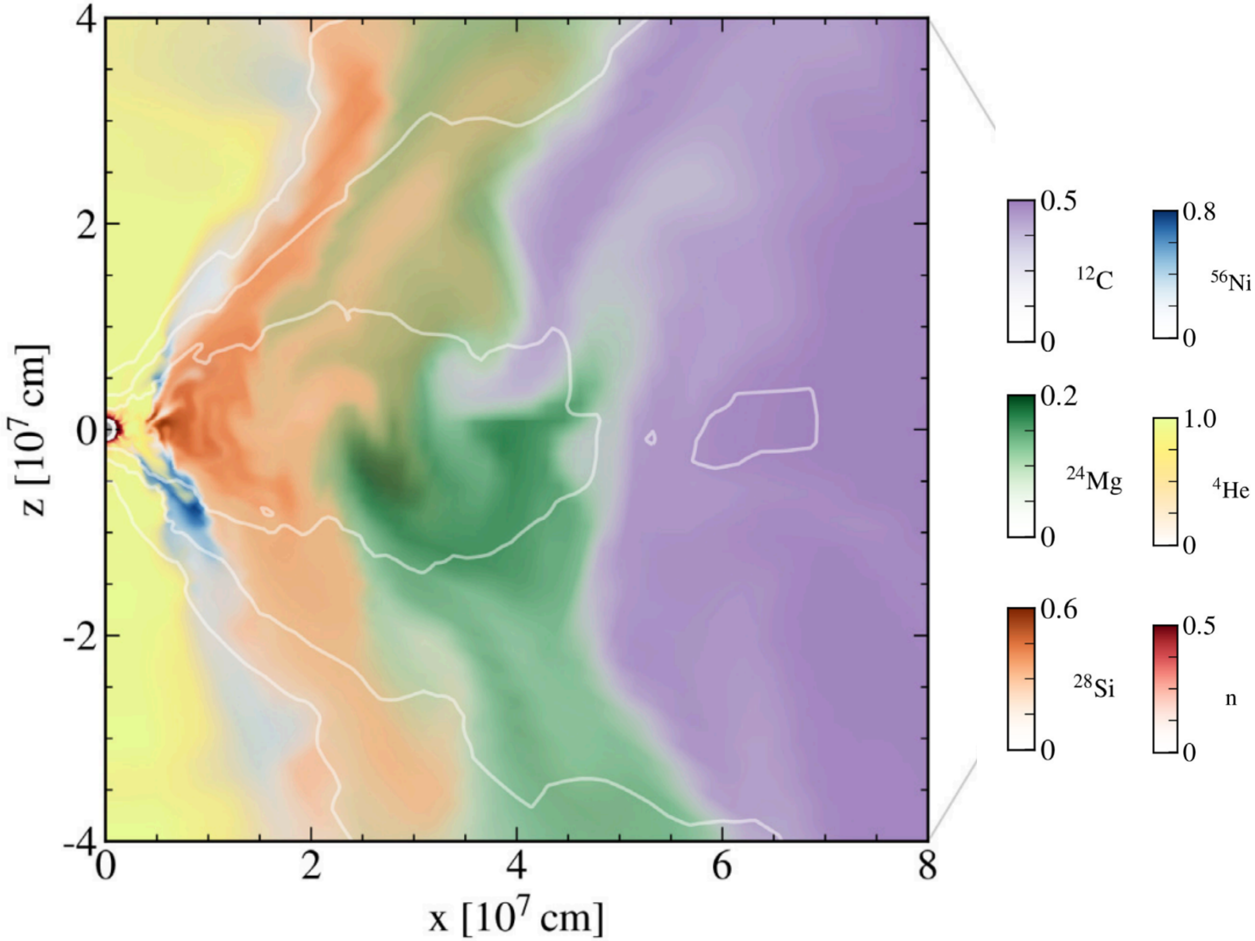
Fryer 1999, Metzger 2012, Margalit & Metzger 2016, Fernandez et al 2019, Kaltenborn 2022



Artist’s rendering: Mark Garlick

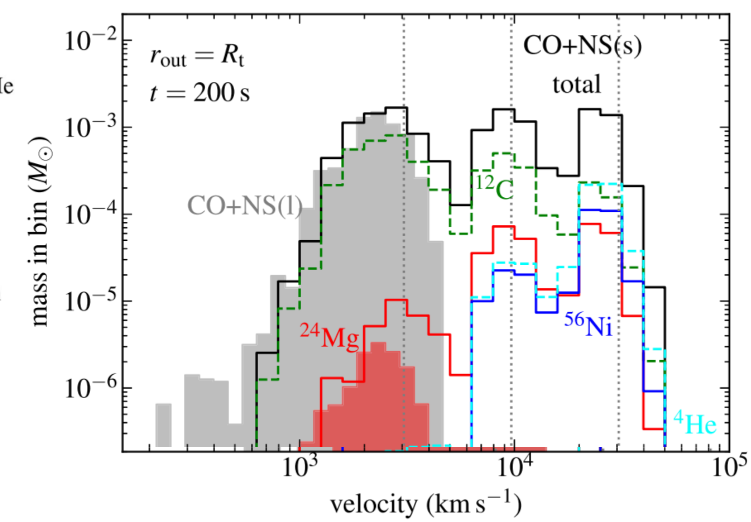
# Simulated Accretion Disk from White Dwarf + NS merger

Fernandez et al 2019

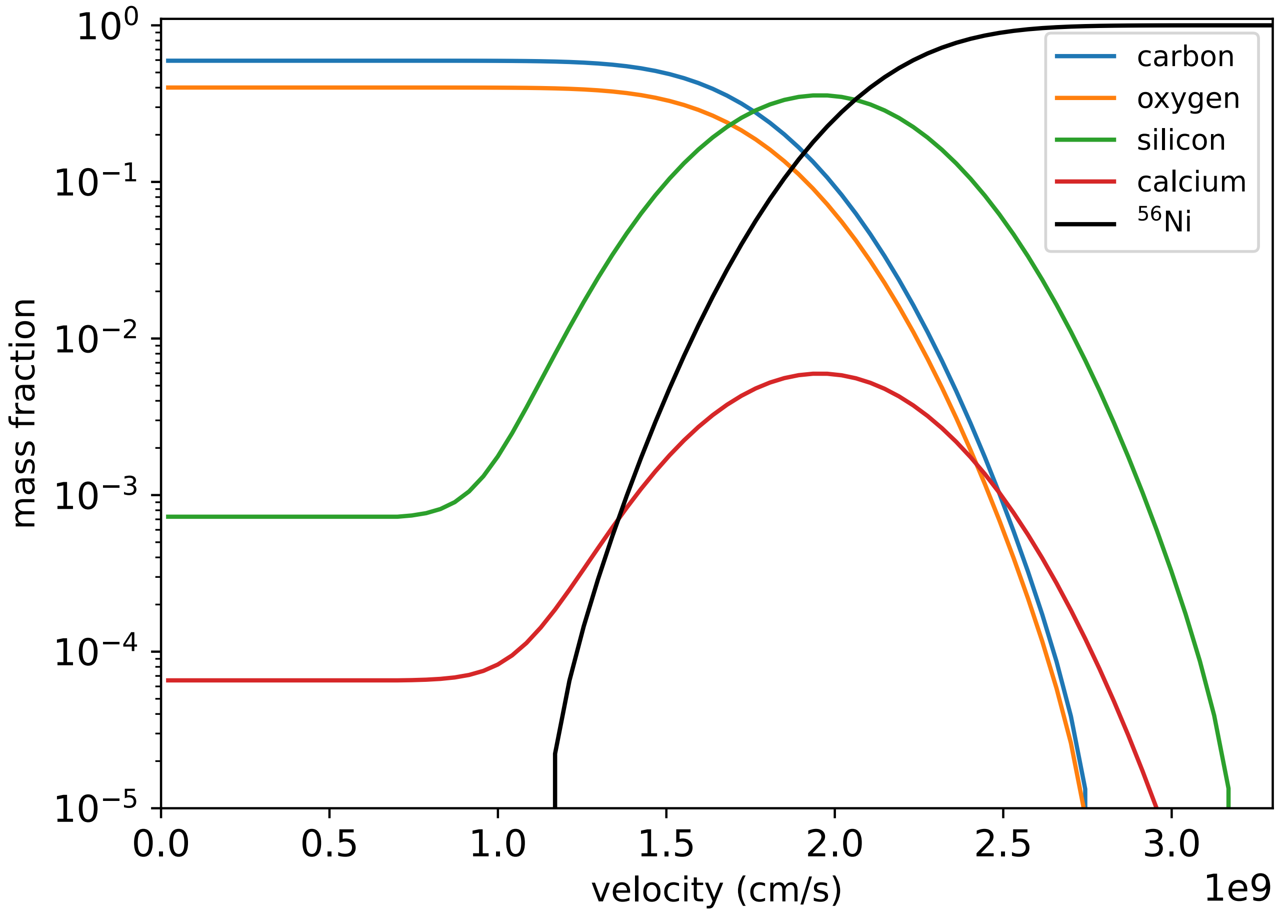



$$M_{\rm ej} \approx 0.2\ M_\odot \quad v \approx 0.03c$$

$$Y_e \approx 0.5 \quad M_{56Ni} \approx 0.01\ M_\odot$$



# Toy 1D "WD merger" ejecta model



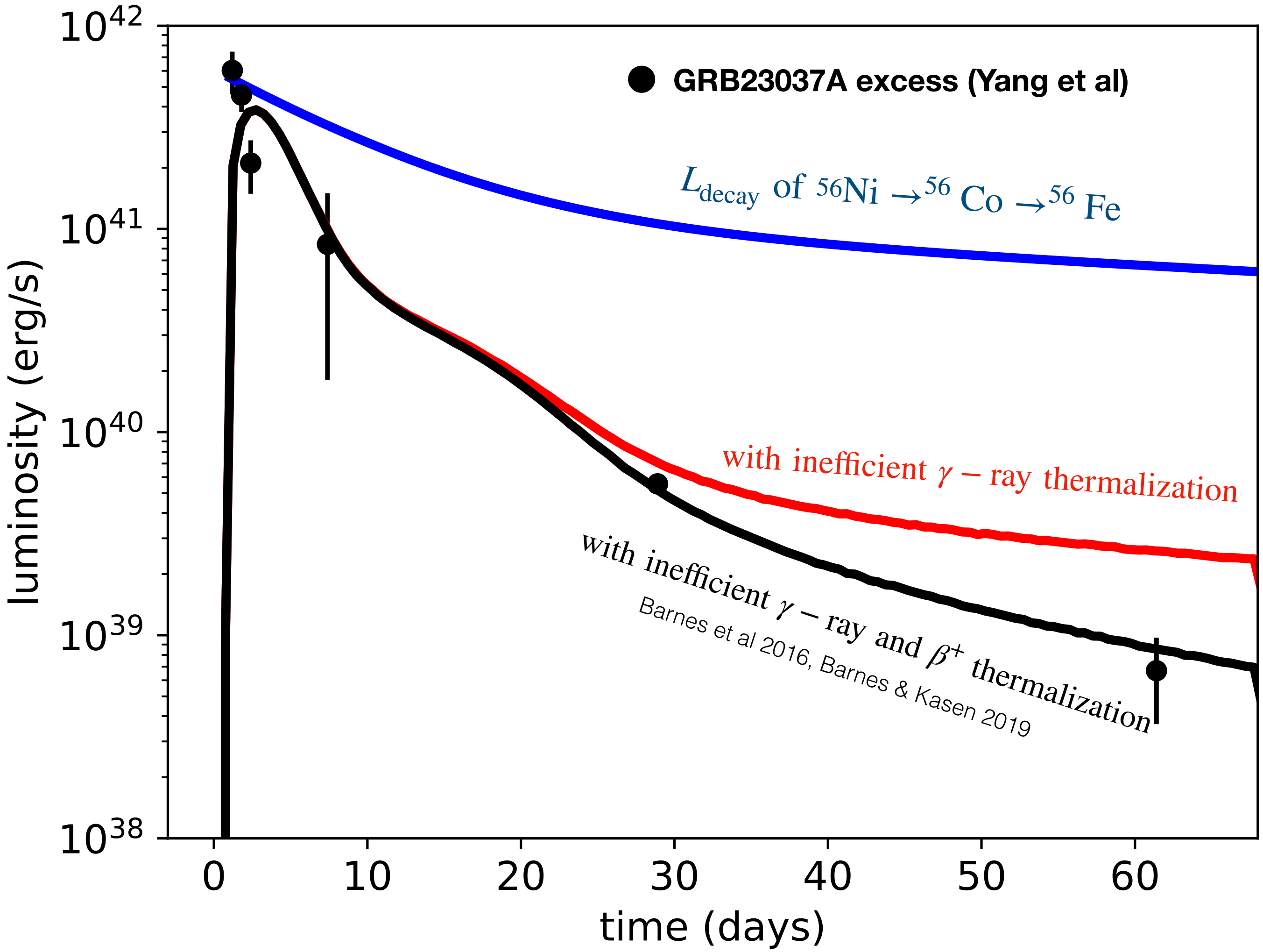

$M_{ej} = 0.2\ M_\odot$

$M_{56Ni} = 8 \times 10^{-3}\ M_\odot$

$KE = 2 \times 10^{50}$ erg

Light curve powered by radioactive 56Ni in the ***outer*** layers

# WD + NS(BH) rad transport model for GRB230307A excess




$M_{ej} = 0.2\ M_\odot$

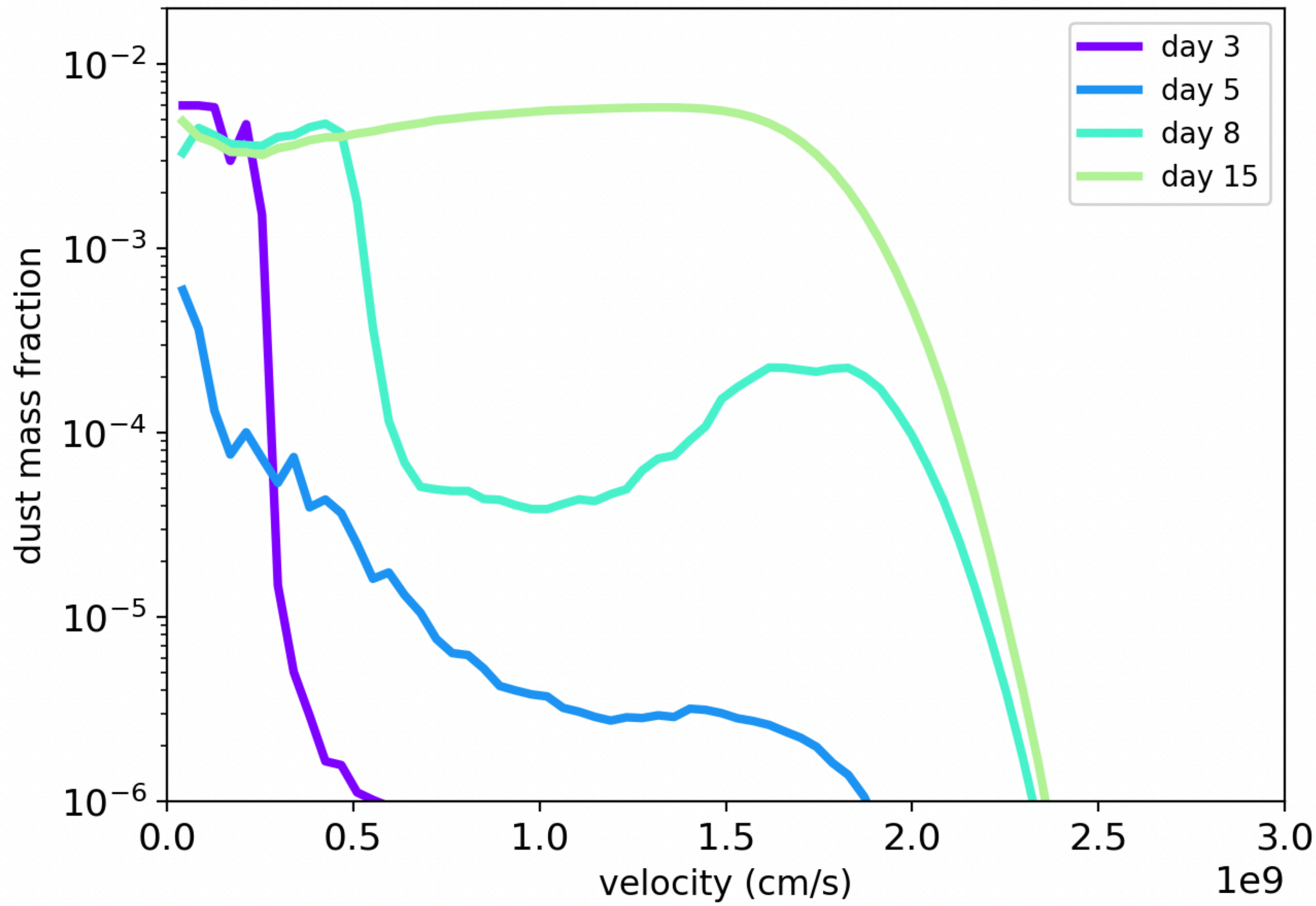
$M_{56Ni} = 8 \times 10^{-3}\ M_\odot$

Dust formation (5% of C)

$T \lesssim 2000$ K

(Draine et al 2003)

# Dust Formation in Ejecta



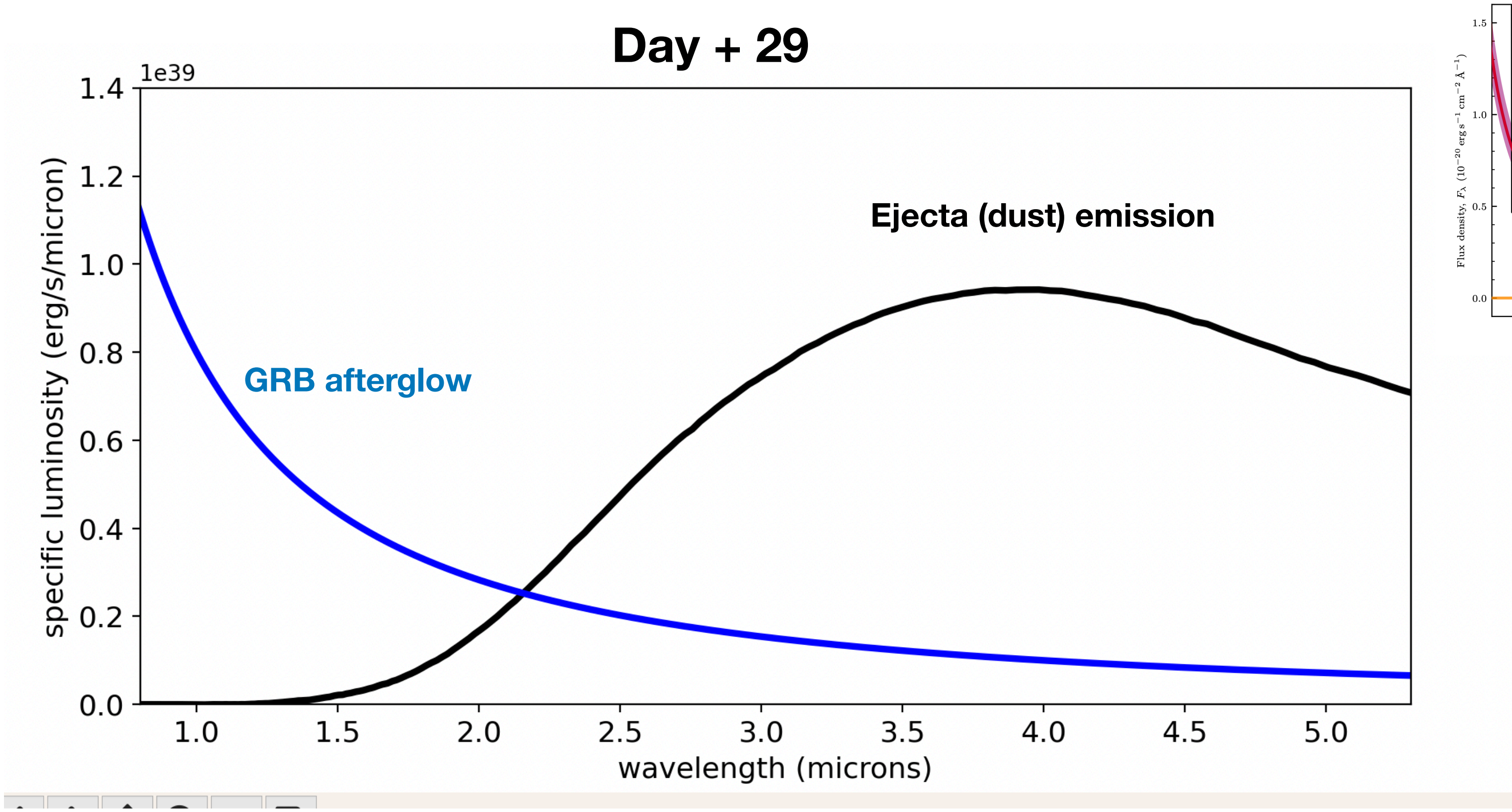

Proportional to C / O abundance

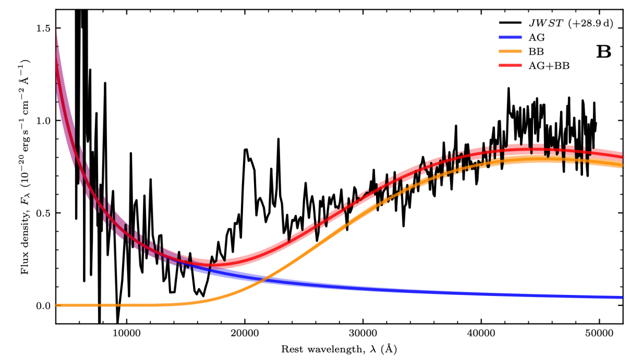
Maximum. value 1%

$T_{\mathrm{dest}} = 2000\ K$

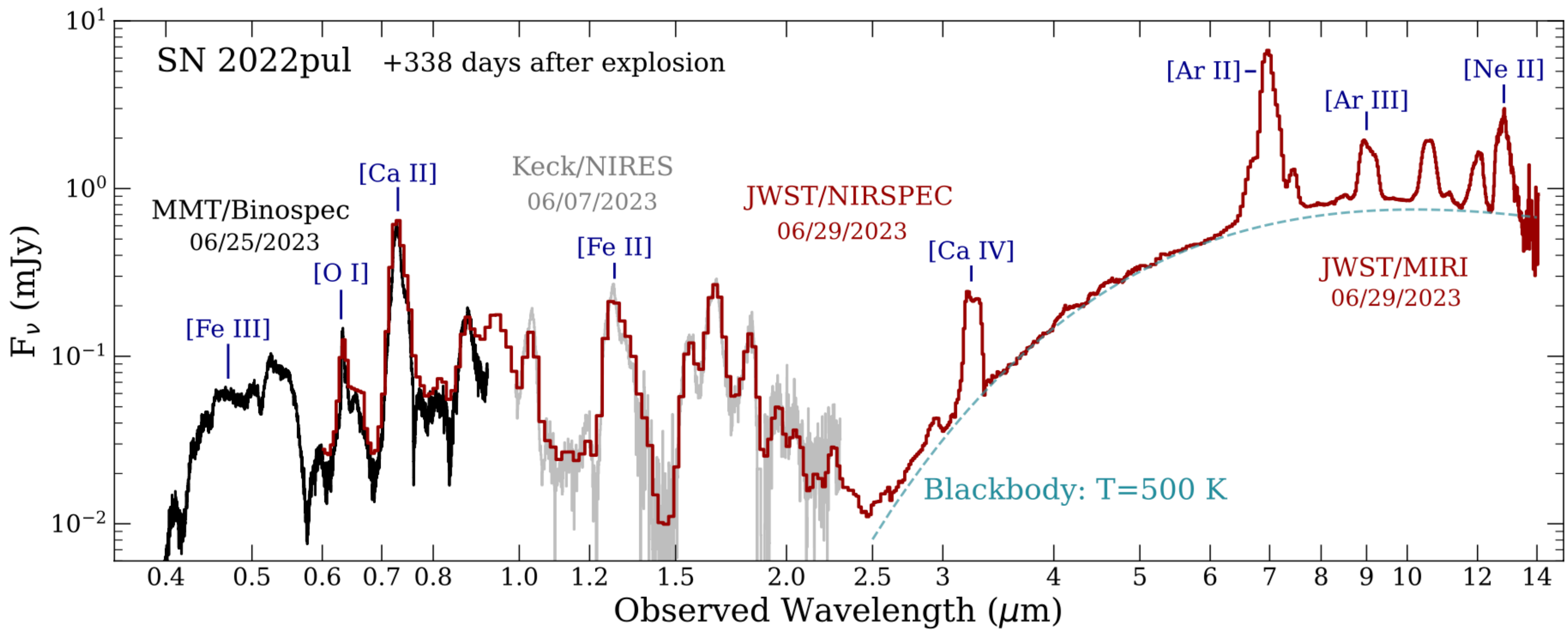
# Synthetic spectrum from toy WD + NS ejecta

## Infrared blackbody emission from dust



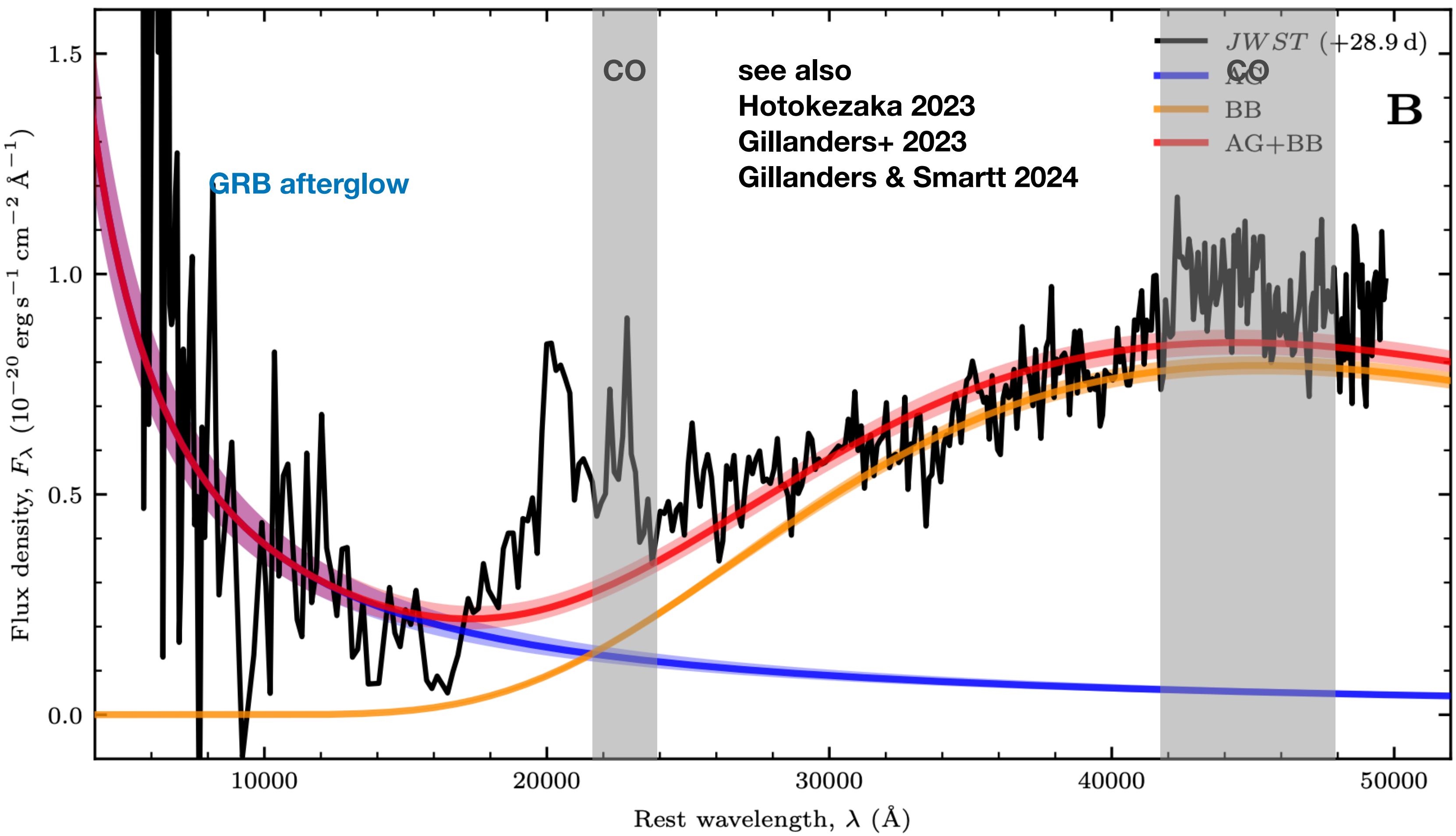



# JWST observations of Type Ia SN2022pul

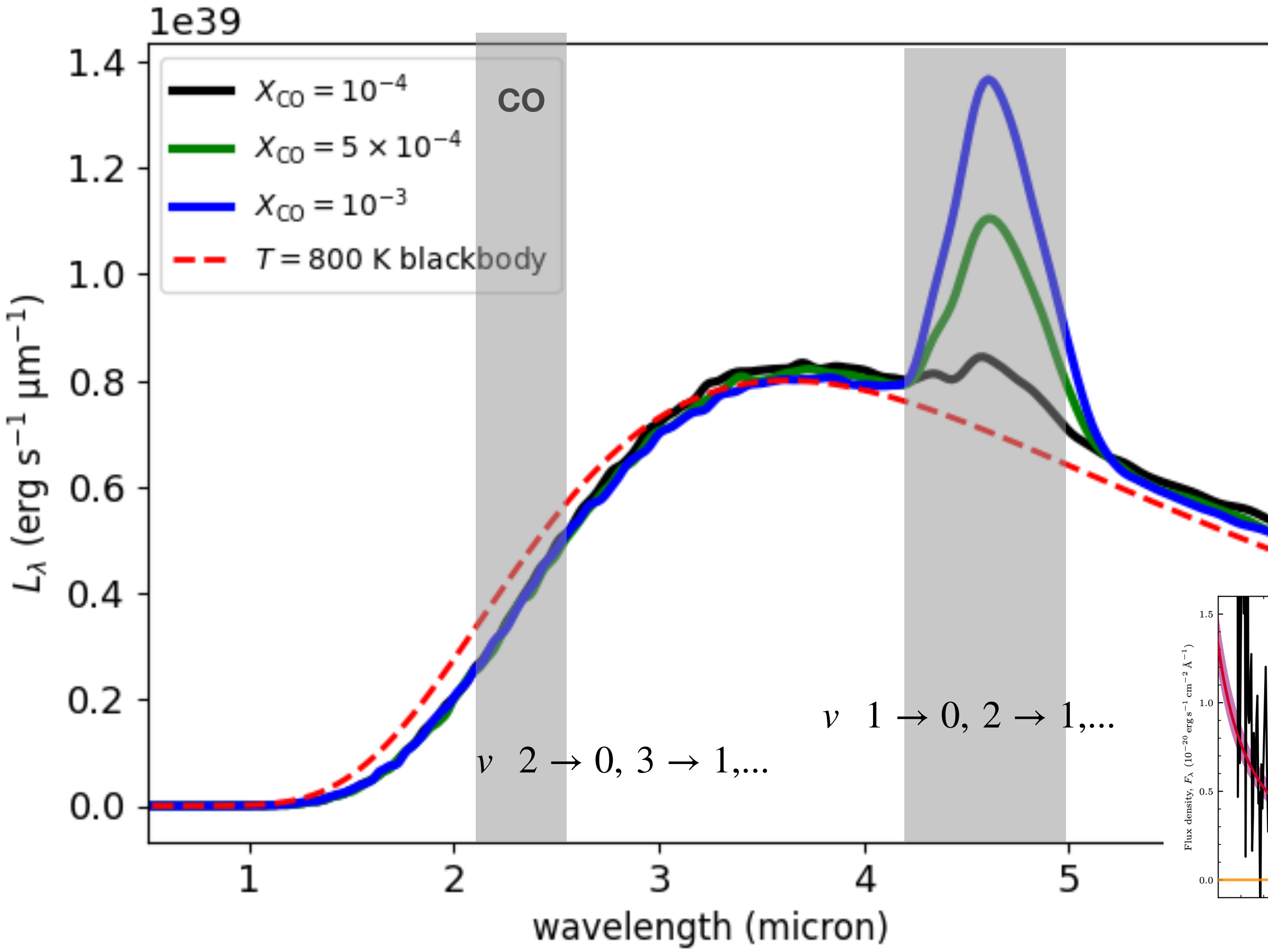



**Siebert et al 2023**

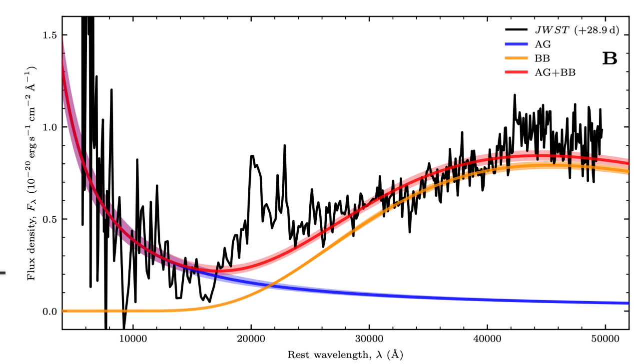
# Spectral features of GRB230307A excess at day +29



# Model CO molecular emission lines




**LTE level populations**



# Looking Forward

- Are there kilonova Imposters — fast infrared transients from dusty ejecta (implications for GRB and blind searches)?
- Could dust affect the colors of legitimate kilonovae (implications for r-process inferences)?
- Are we missing fundamental aspects of the radiation transport (sources of opacity, detailed atomic physics, NLTE effects)
- Can we infer the yields from complex 3D geometries?