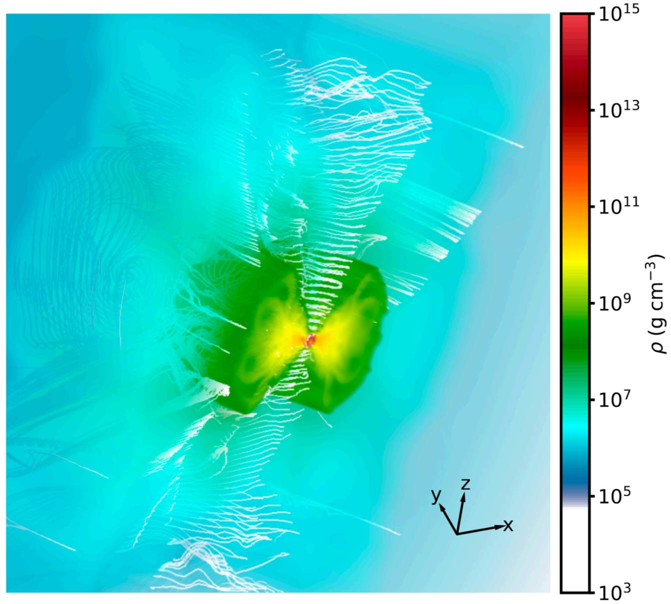
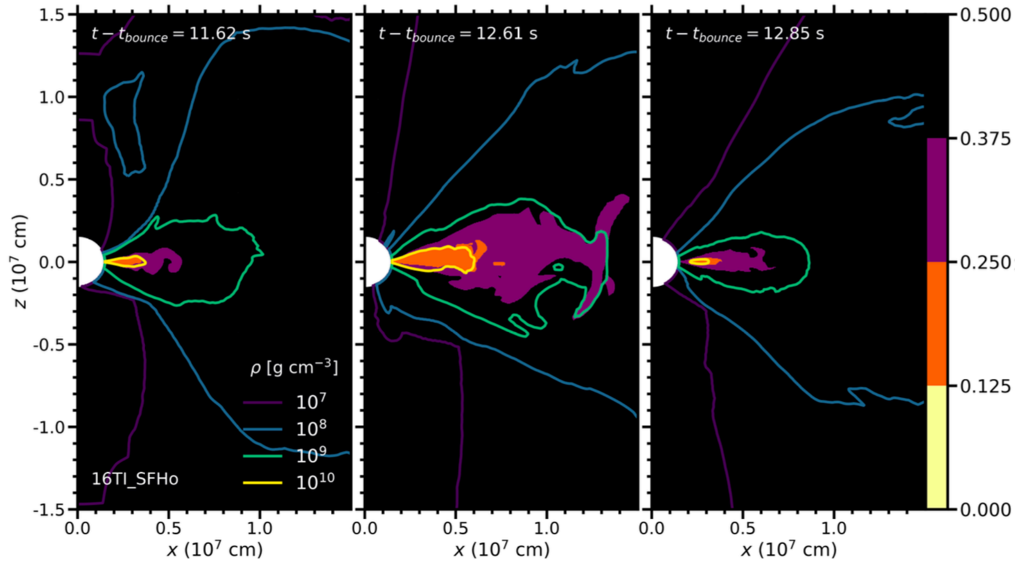
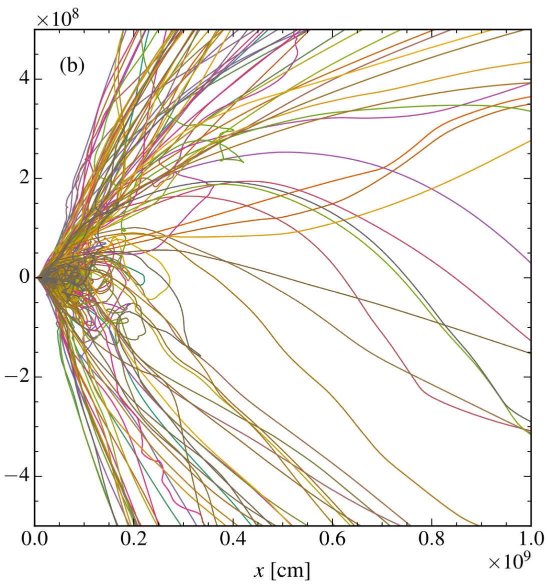


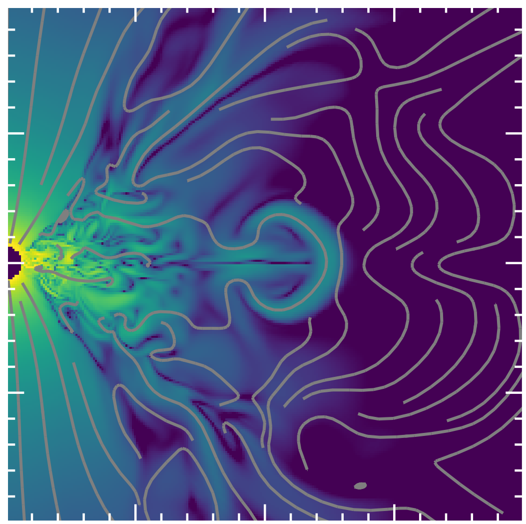
Fahlman, RF, & Morsink (2023)



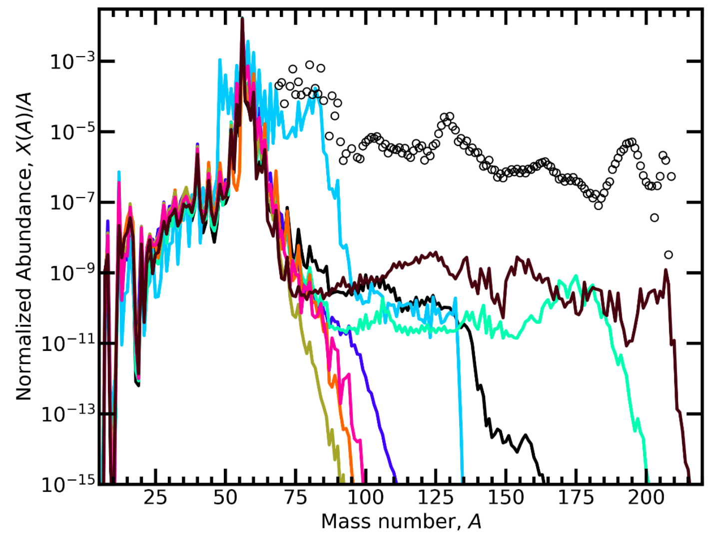
Dean & RF (2024a)



Wu, RF, et al. (2016)



RF, Tchekhovskoy et al. (2019)



Dean & RF (2024b)

Disk Outflows in NS Mergers & Collapsars

Rodrigo Fernández (University of Alberta)

with Coleman Dean & Steven Fahlman

Overview

1) Disk Outflows in NS Mergers: r-process production

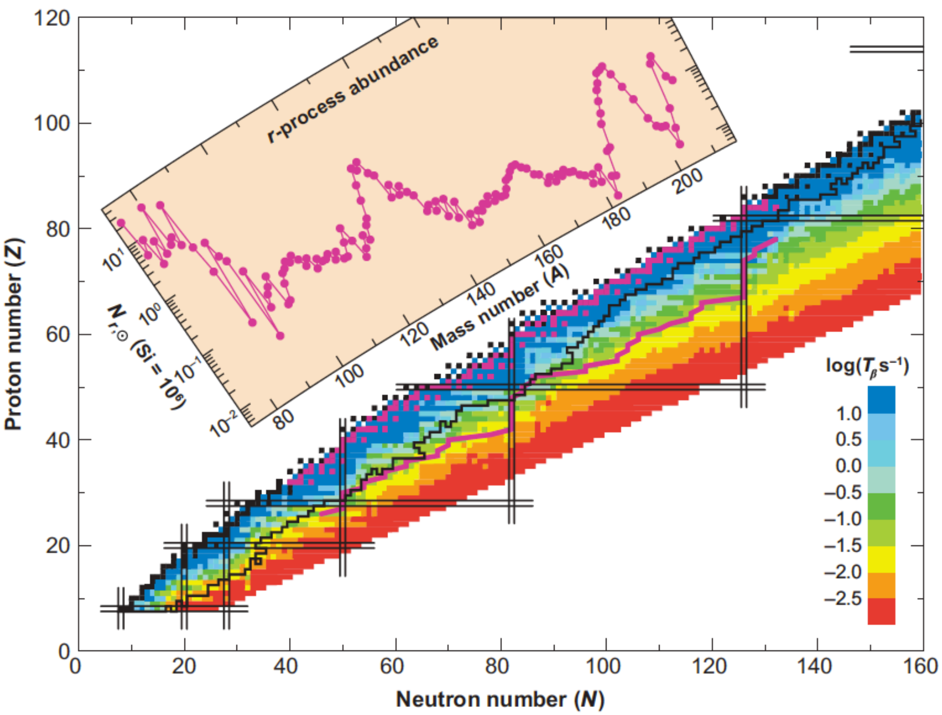
2) Disk Outflows in Collapsars: dynamics

3) Disk Outflows in Collapsars: nucleosynthesis

r-Process Nucleosynthesis

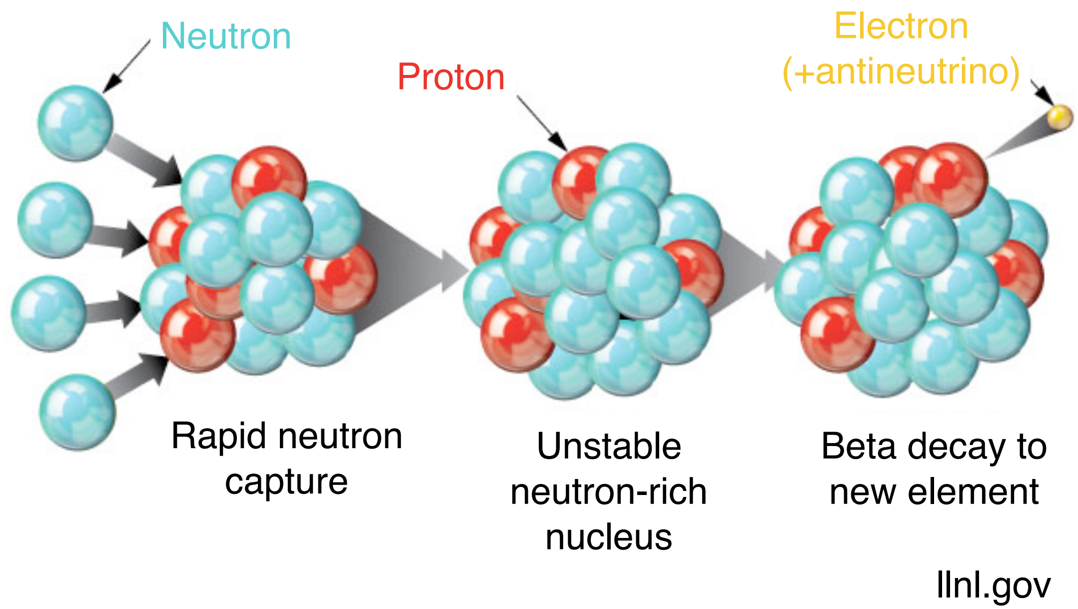
~50% of elements
heavier than Zinc (Z=30)

Nuclear Chart & Solar System abundances:



Möller, Nix, & Kratz (1997)

$$t_{\mathrm{n-capture}} \ll t_{\beta-\mathrm{decay}}$$

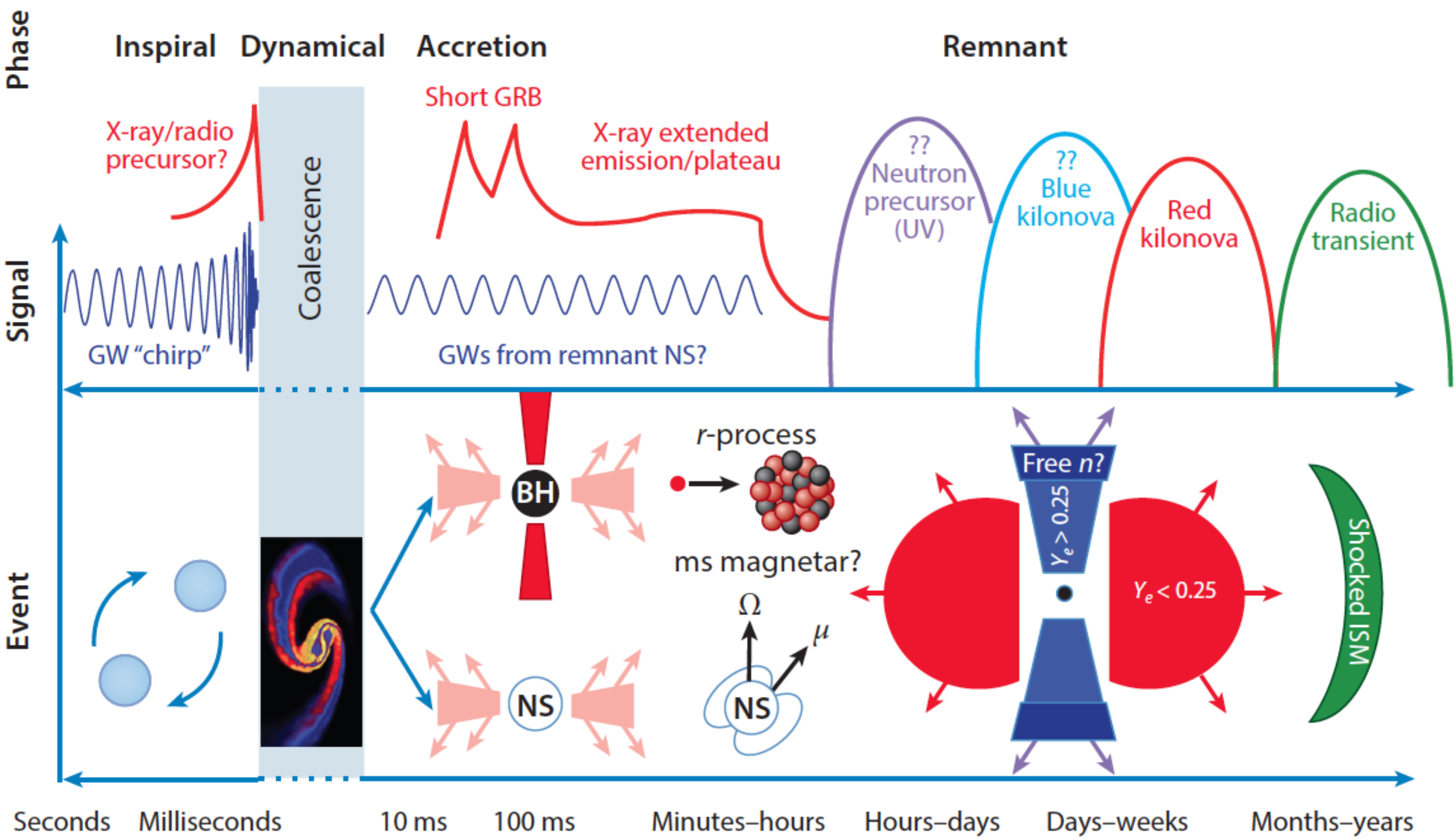


Astrophysical sites:

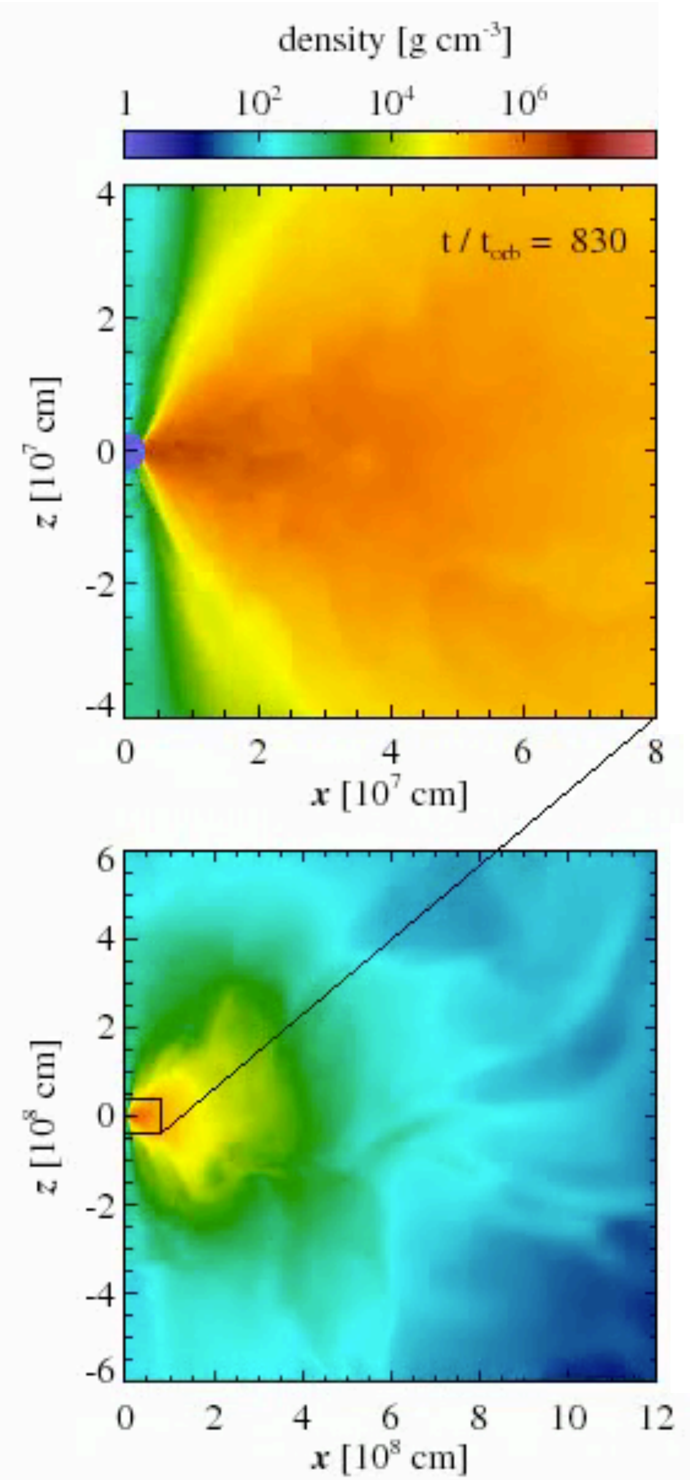
1) Neutron Star Mergers

2) Massive Star Explosions

Neutron Star Mergers: Overview



RF & Metzger (2016)



Accretion Disk Outflow

Slow evolution: neutrino reprocessing.

For GW170817 parameters,
dominates the ejecta (0.05 - 0.10M_{sun})

Disk is embedded in a low-density medium:
easy to eject mass.

Need 3D MHD for:
- MRI turbulence
- outflow speeds consistent with observations

RF & Metzger (2013)

Just et al. (2015)

Fujibayashi et al. (2017)

Haddadi et al. (2021)

Setiawan et al. (2005)

Lee, Ramirez-Ruiz, & Lopez-Camara (2009)

Metzger (2009)

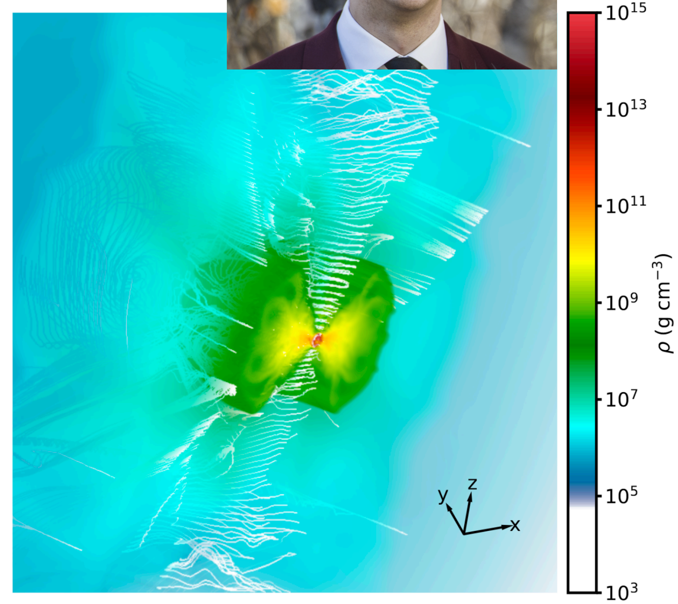
Disk Outflow in 3D MHD

Adapted the FLASH4.5 public code to do:

1) 3D MHD in non-uniform spherical coordinates

2) Include a neutrino-leakage scheme

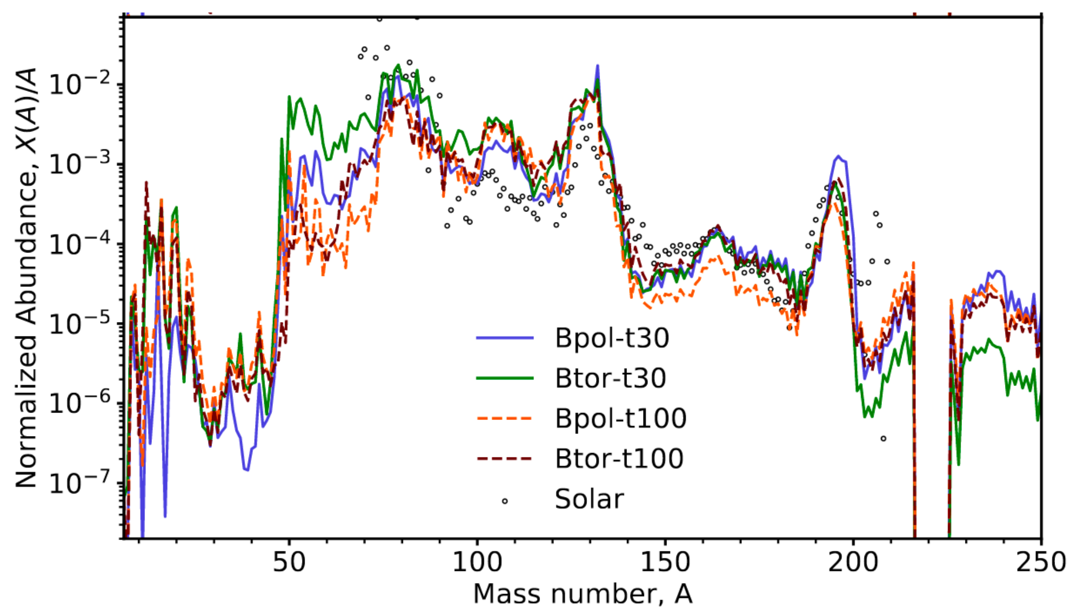
3) EOS with wide range of density



Evolved disk around hypermassive NS for ~1-2 s:

- variable HMNS lifetime
- different initial B field geometry

Obtained production of all r-process elements and speeds compatible with GW170817



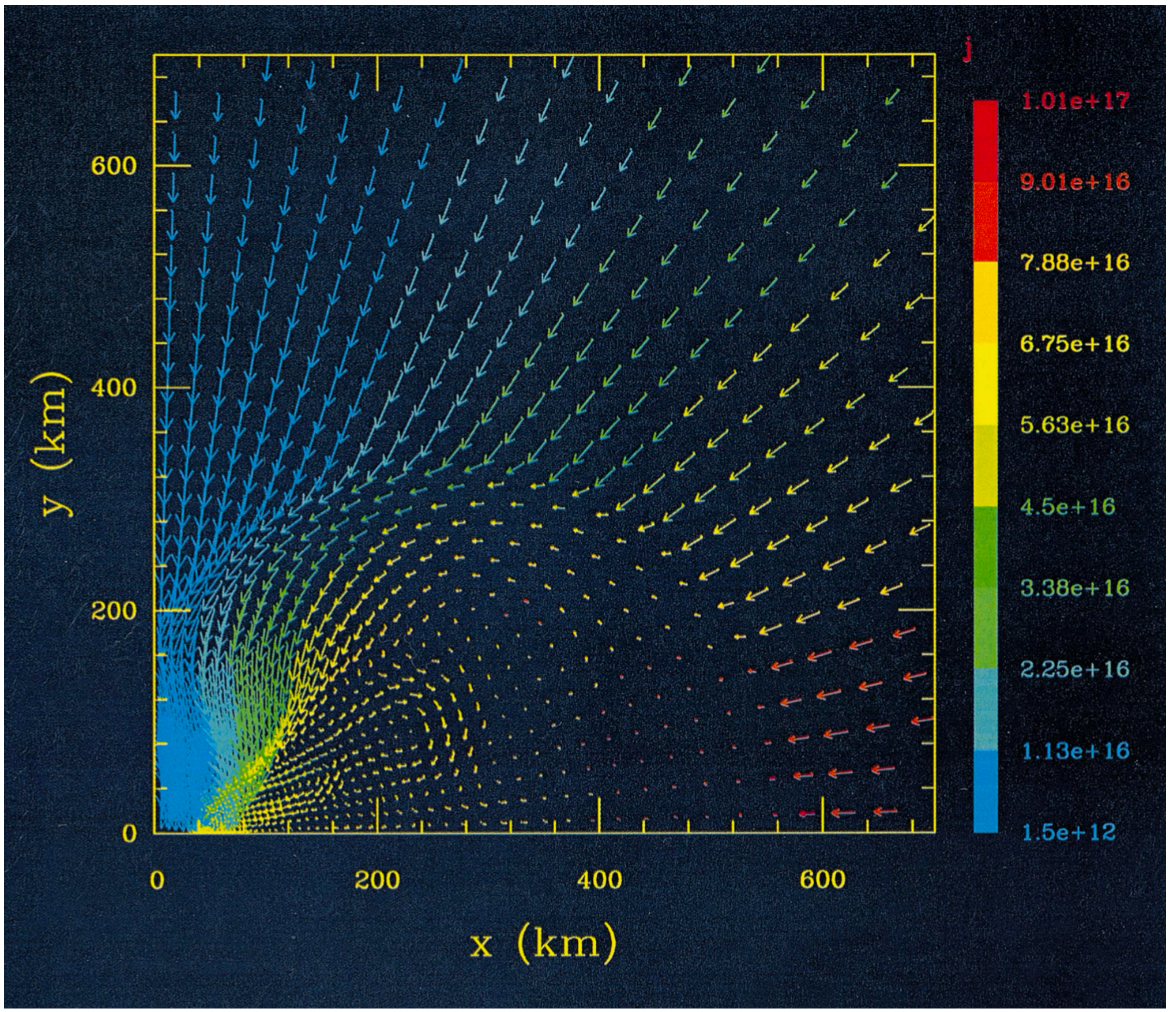
Fahlman, RF, & Morsink (2023)

Combi & Siegel (2023), Kiuchi et al. (2023), Curtis+ (2024)

Siegel & Metzger (2017), RF, Tchekhovskoy+ (2019), Miller+ (2019), Hayashi+ (2022), Just+ (2022), Janiuk & James (2022)

Progenitor rotation: BH accretion disk

Accretion flow circularizes at $r \sim r_{circ}$



MacFadyen & Woosley (1999)

$$r_{\rm circ} \simeq \frac{j^2}{GM}$$

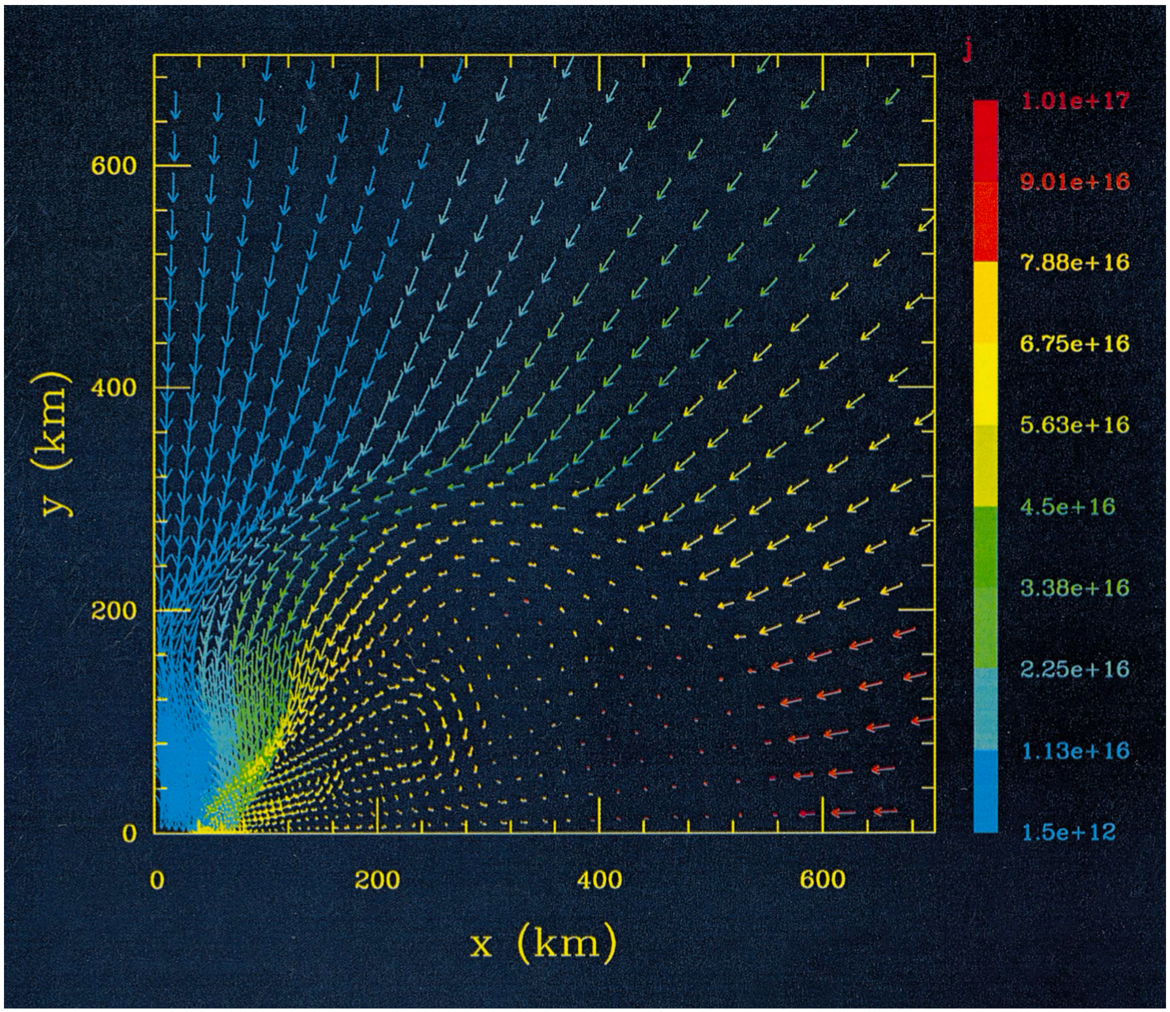
If neutrino cooling is important: **collapsar**

Candidate r-process site due to neutronization, short delay time. Also engine for Ic-BL SNe associated with long GRBs (need large ^{56}Ni).

(Long history of work in the GRB/SN context)

Progenitor rotation: BH accretion disk

Accretion flow circularizes at $r \sim r_{circ}$



MacFadyen & Woosley (1999)

Differences with NS merger disks:

1) Accretion time

2) Confining ram pressure

3) BH mass change

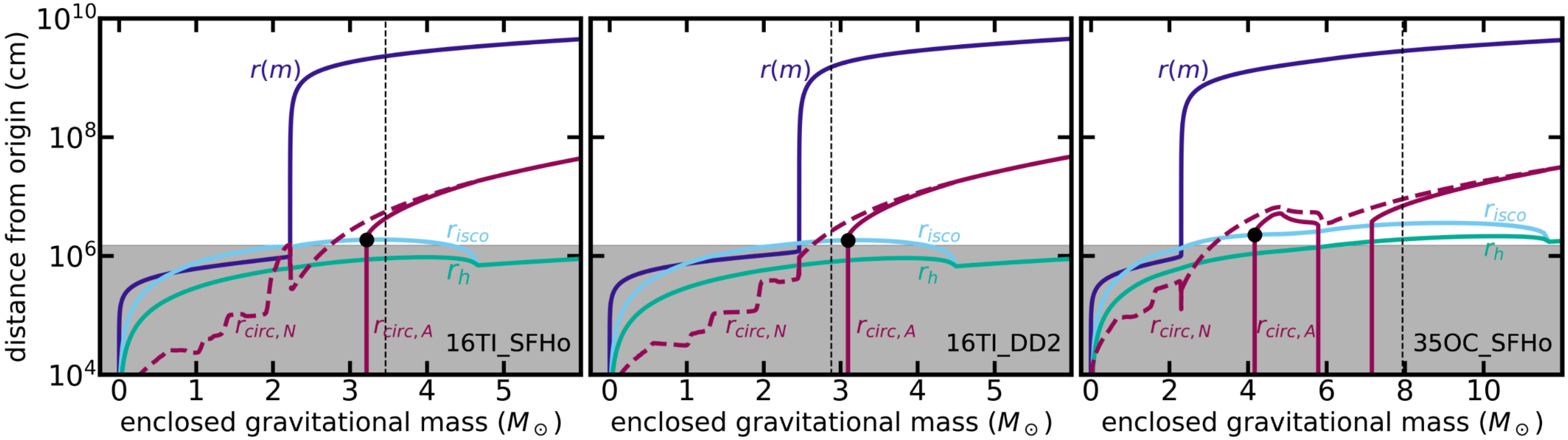
4) Self-gravity

Collapsar Disk Evolution

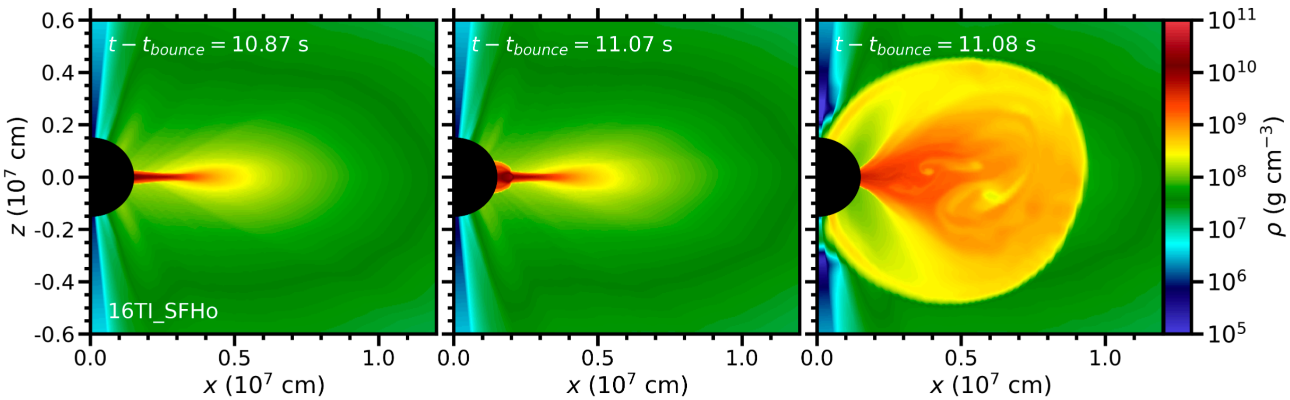
Global viscous hydrodynamic simulations (no jet):

- entire star from core-collapse to shock breakout
  GR1D from pre-supernova to BH formation
  FLASH 2D for disk formation until shock breakout
- neutrino emission/absorption & nuclear network.
- self-gravity with pseudo-Newtonian BH

Coleman Dean & RF (2024a)



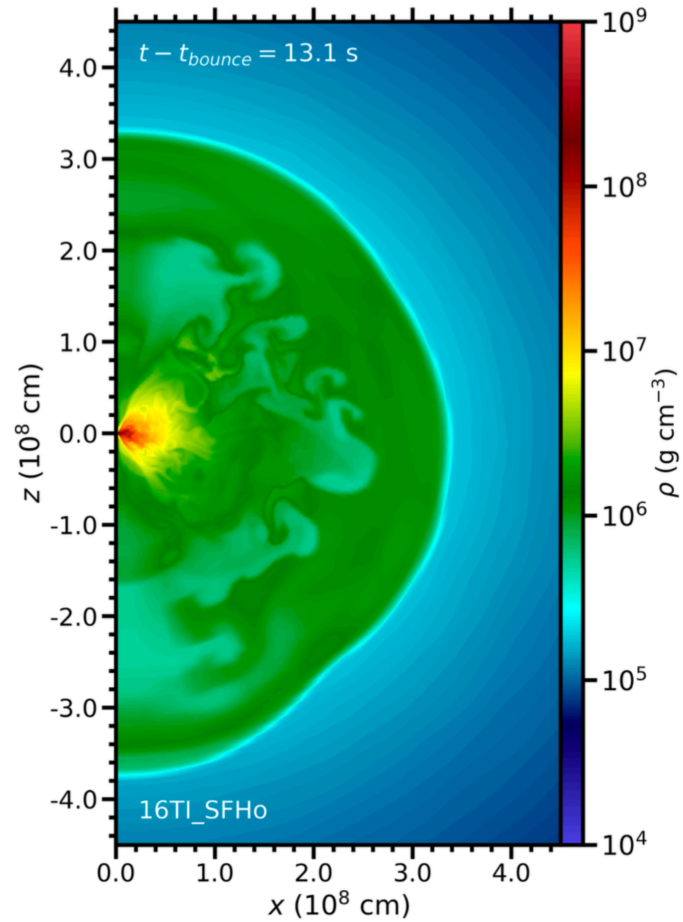
Collapsar Disk Evolution



- Self-consistent disk formation
- Confined by supersonic flow: shock wave
- Neutrino cooling phases lasts 2-5 s
- Evolve ADAF phase past shock breakout ~100 s

also Just et al. (2022), Fujibayashi et al. (2022,2023)

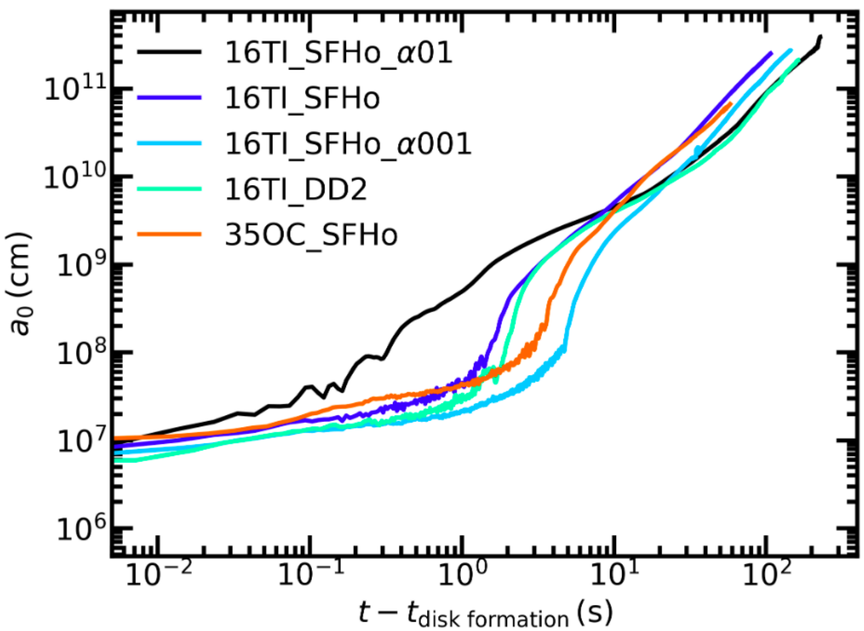
previous work by Harikae et al., Lee et al., Lopez-Camara et al.,
Aloy & Obergaulinger, Sekiguchi & Shibata, and more



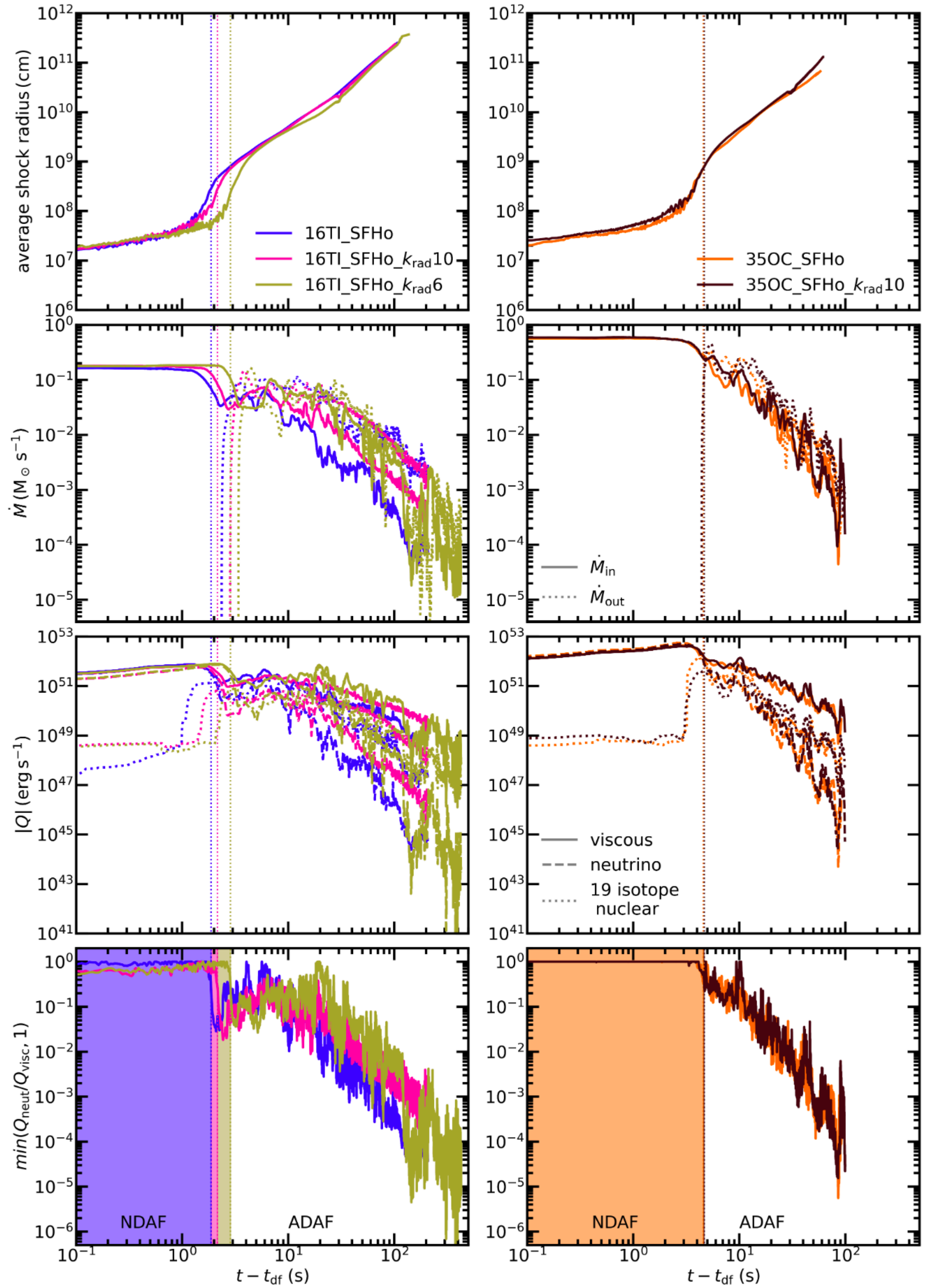
Dean & RF (2024a)

Disk Explosion

The disk undergoes neutrino cooled phase for ~2s, the transitions into advective (ADAF), resulting in rapid expansion.

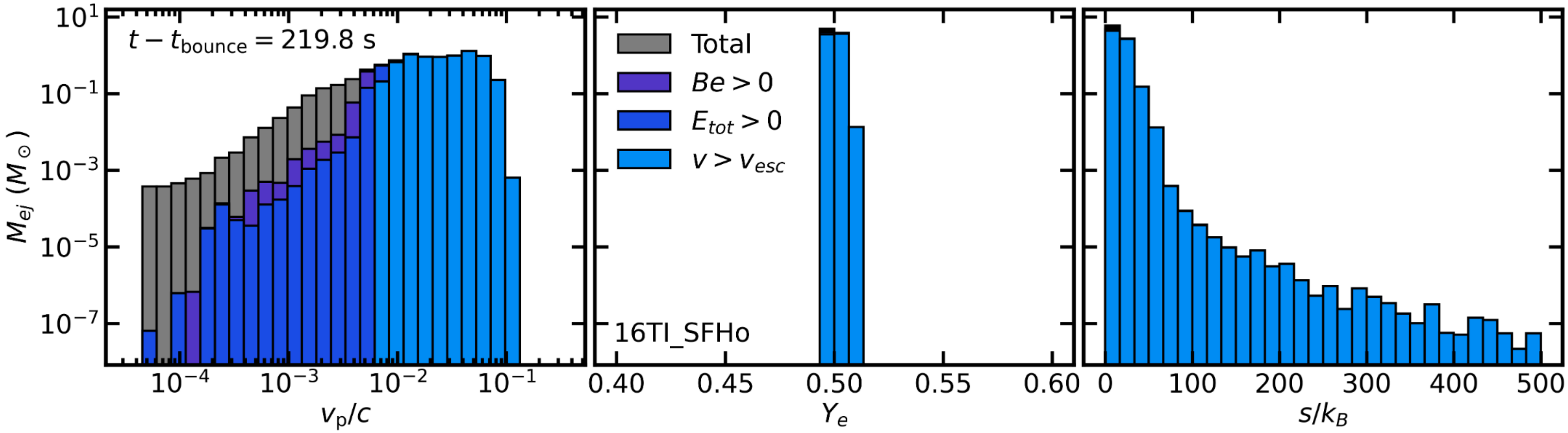


Dean & RF (2024a)



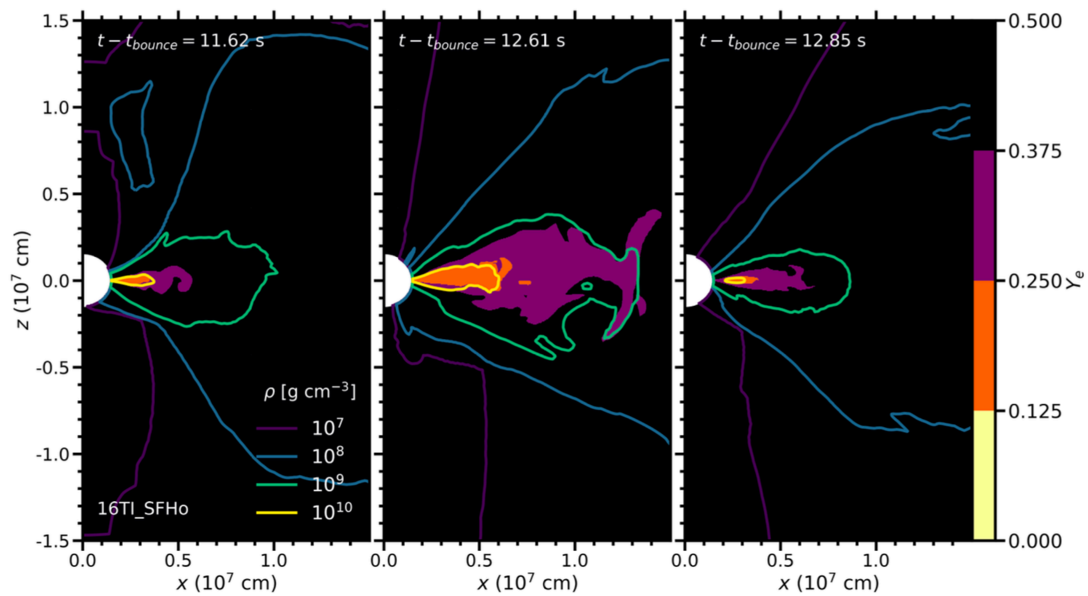
Dean & RF (2024b)

Outflow Properties



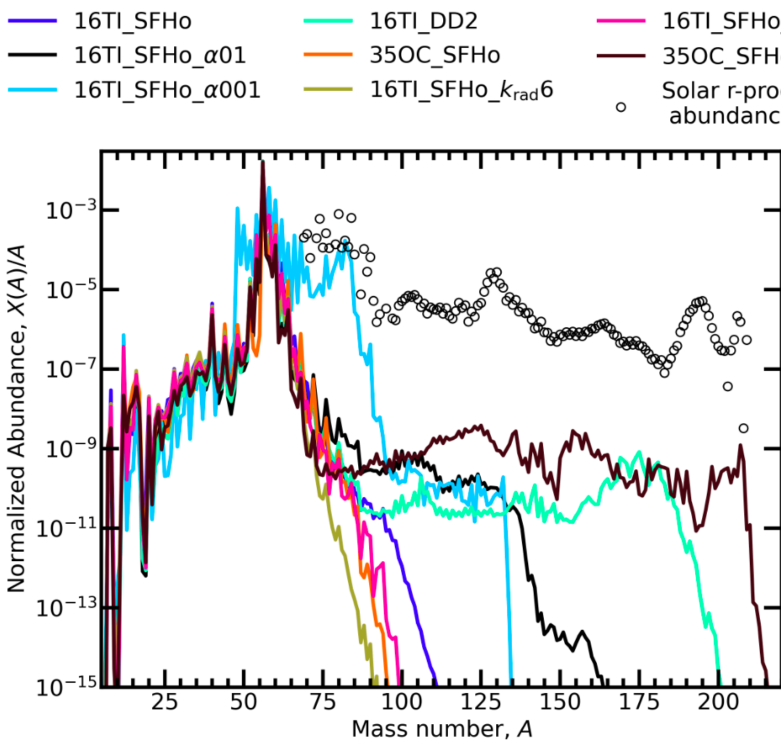
Neutron rich matter is quickly accreted by the BH and none of it ejected.

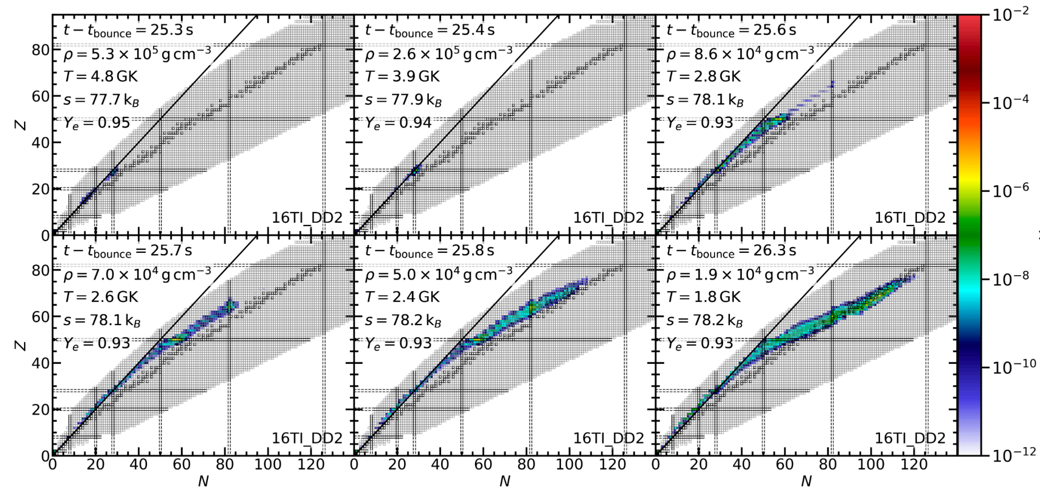
Need large-scale B-field for the Lorentz force to eject matter during neutrino-cooled phase.



Dean & RF (2024a)

R-process Yield





Dean & RF (2024b)

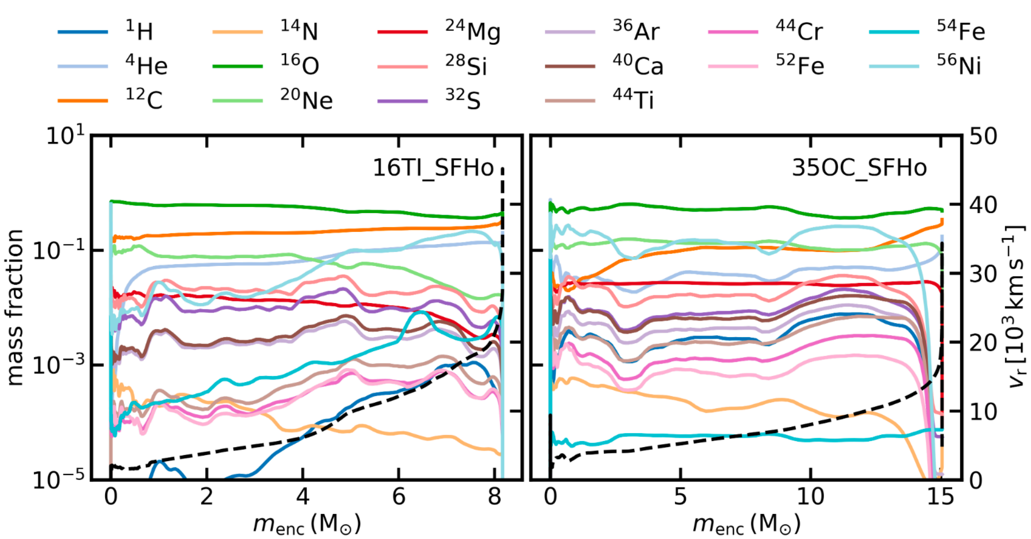
Only the model with lowest viscosity yielded first r-process peak elements.

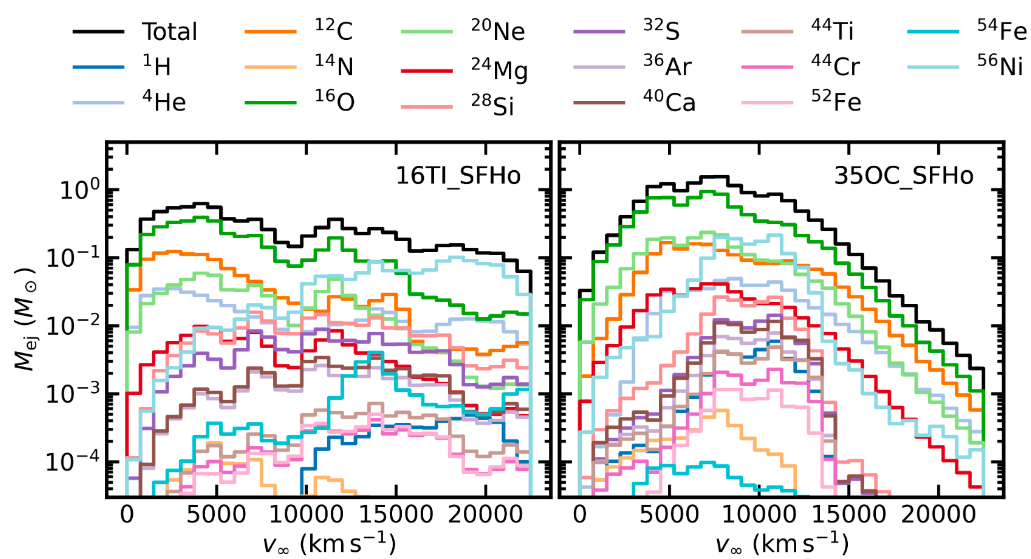
Models that reached A~200 did so along a proton-rich path: the rp-process (in small amounts).

Bulk Ejecta Properties & Alpha Element Yield

Model	M_{ej} ($M_\odot$)	K_{ej} (10^{51} ergs)	K_∞ (10^{51} ergs)	$\langle v_\infty \rangle$ (10^3 km/s)	$Y_{e,min}(t_{max})$	$M_{^{56}Ni}$ ($M_\odot$)	t_{peak} (days)
16TI_SFHo	8.19	9.07	9.20	8.7	0.498	1.28	44.7
16TI_SFHo_α01	8.97	2.39	2.41	4.8	0.499	0.29	63.1
16TI_SFHo_α001	7.93	4.34	4.37	6.0	0.481	0.81	52.9
16TI_DD2	9.17	3.67	3.70	5.6	0.500	0.63	59.2
35OC_SFHo	15.1	9.45	10.6	7.7	0.497	1.39	64.3

Dean & RF (2024a)





Dean & RF (2024b)

Summary

1) While both NS merger and Collapsar disks produce neutron-rich material, they differ fundamentally in their ability to eject it

2) Collapsar Disk Outflows alone can explode the star robustly with $E \sim 10^{52}$ erg

3) Collapsars eject little neutron-rich mass in viscous hydrodynamics. Only 1st r-process peak material with $\alpha = 0.01$, nothing for higher α. Need large-scale **B** for outflows during the neutrino-cooled phase.

4) Collapsar disks easily eject ~1 M_{sun} of ^{56}Ni, well-mixed. Very promising as Ic-BL engines.

Thanks to: