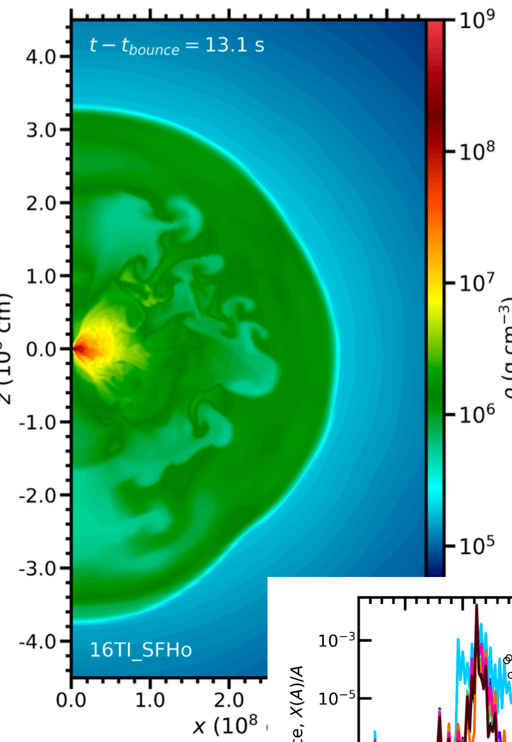
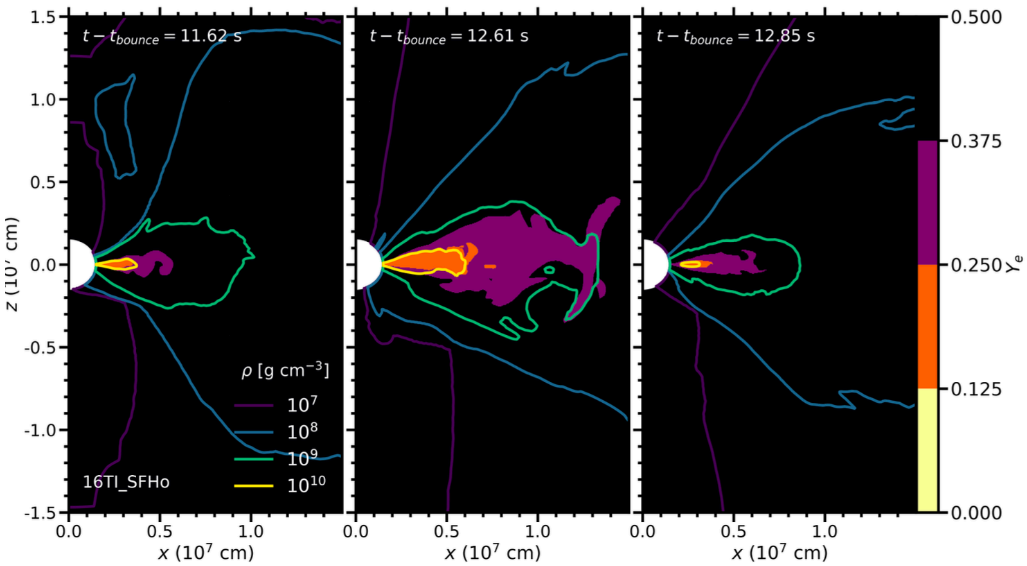
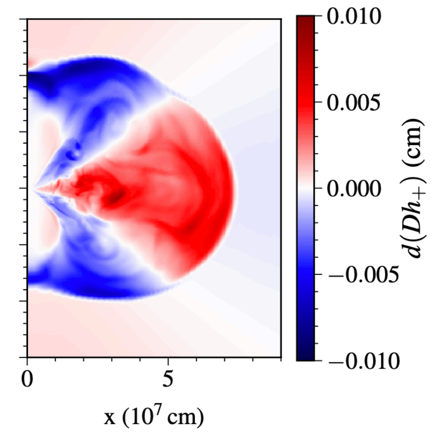
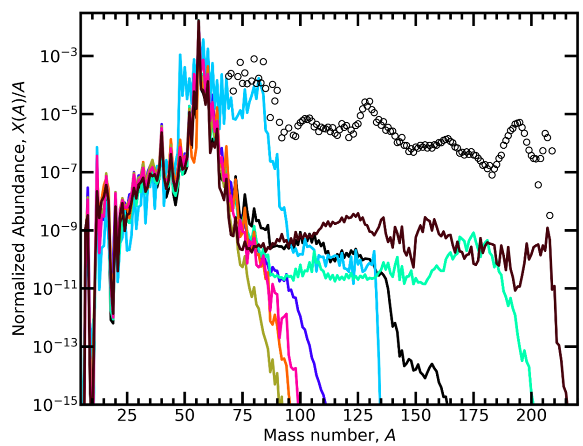


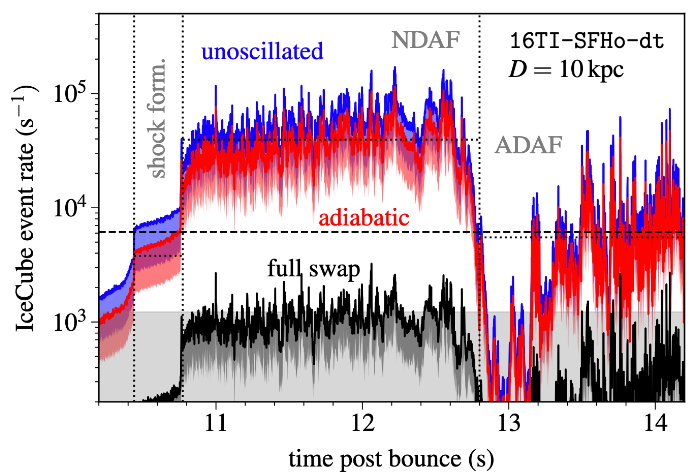


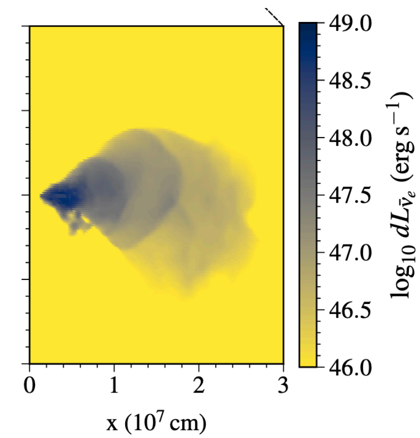
Dean & RF (2024a)





Dean & RF (2024b)





RF et al. (2025)

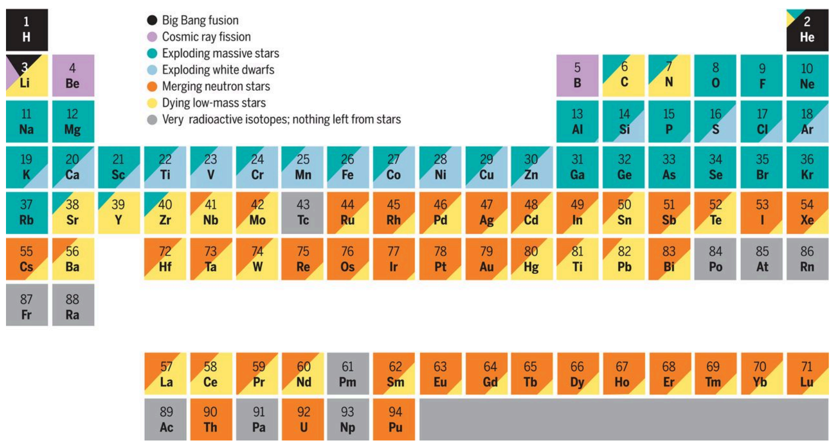
Collapsar Disk Outflows: Nucleosynthesis and Multi-Messenger Signatures

Rodrigo Fernández (University of Alberta)

with **Coleman Dean**, Silas Janke (Heidelberg), and Irene Tamborra (NBI)

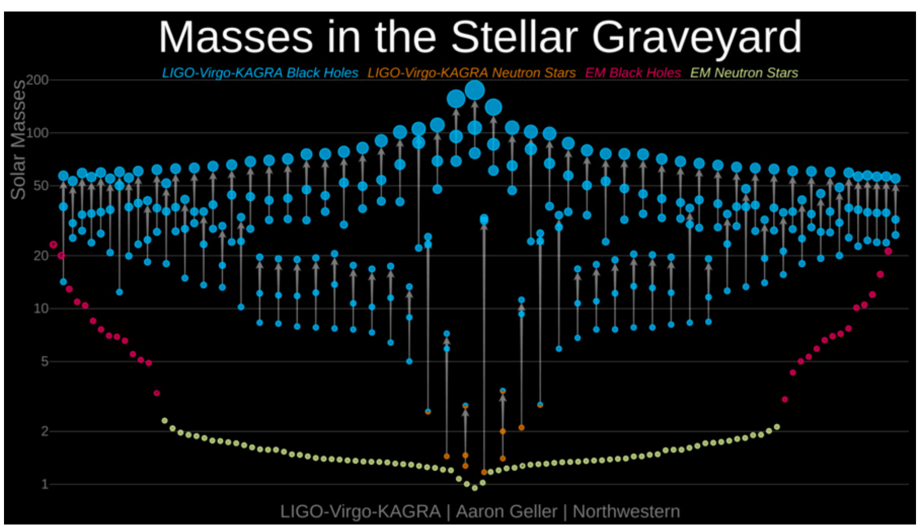
Studying Collapsar Disk Outflows

Nucleosynthesis



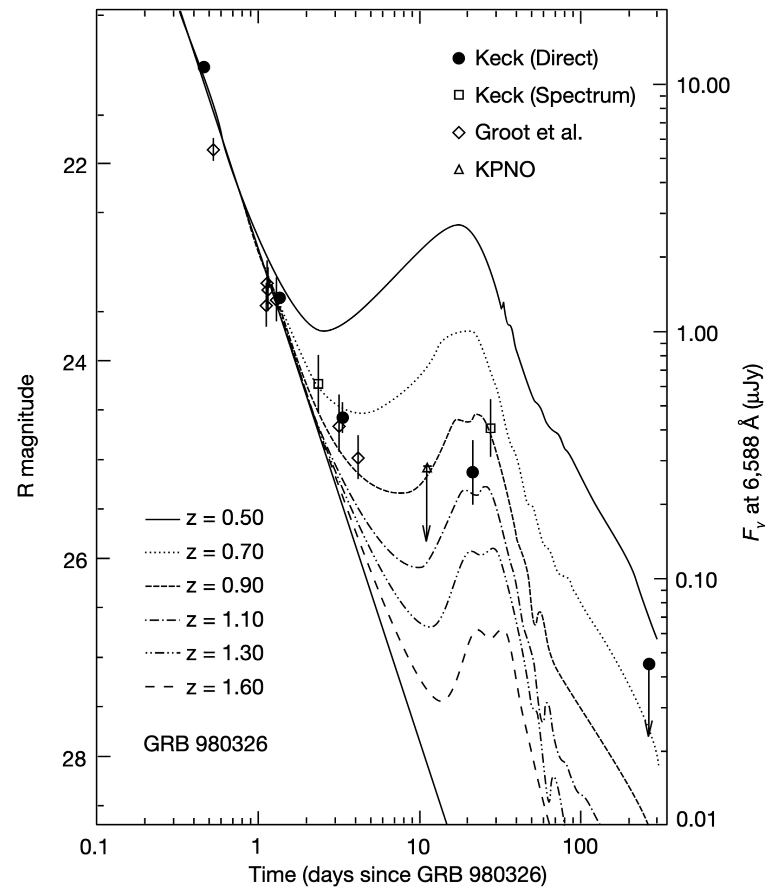
Johnson (2019)

Signatures of BH Formation



Aaron Geller / Northwestern / LIGO-Virgo-KAGRA (GWTC-3)

Ic-BL SNe engines

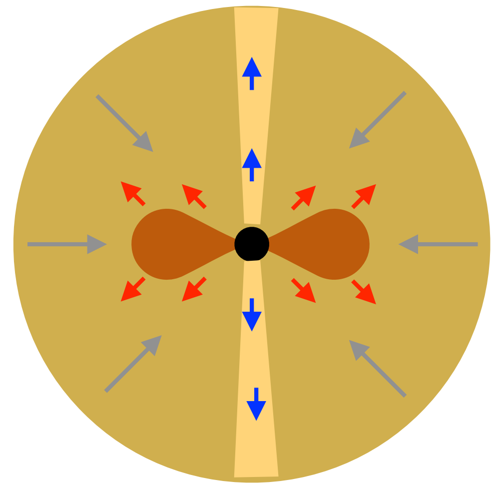


Bloom et al. (1999)

Global Collapsar Disk Simulations

Long history of global simulations

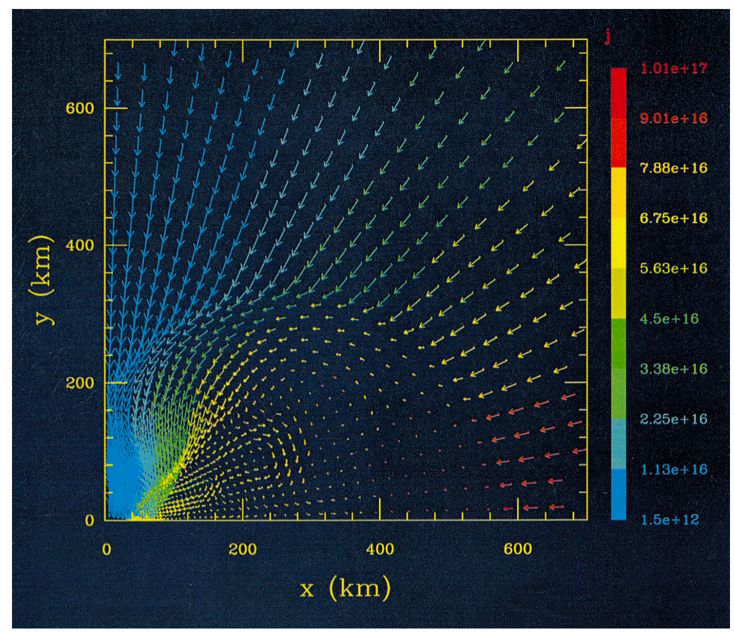
(e.g., MacFadyen & Woosley, Harikae+, Lee+, Lopez-Camara+, Aloy & Obergaulinger, Sekiguchi & Shibata, and many others)



Technically challenging problem with large parameter space.

To address key science questions, we need:

- Full star simulations (initial & boundary cnd.)
- Angular momentum transport (disk evolution)
- Neutrino transport (Ye evolution, r-process)
- Nuclear evolution (Ni56 mass)
- Long-term evolution (ejecta properties)
- Self-Gravity (accretion, unbound ejecta)



MacFadyen & Woosley (1999)

Tradeoffs are inevitable

Global Collapsar Disk Simulations

Long history of global simulations

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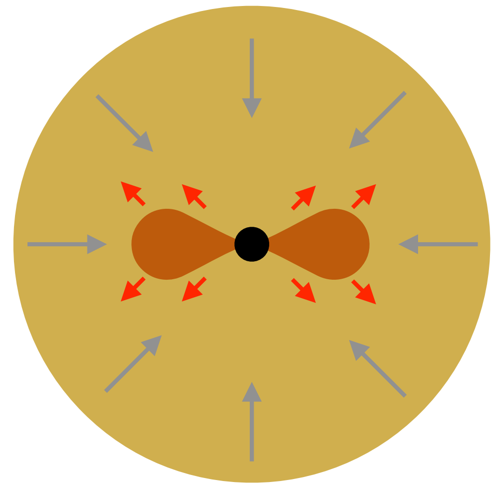

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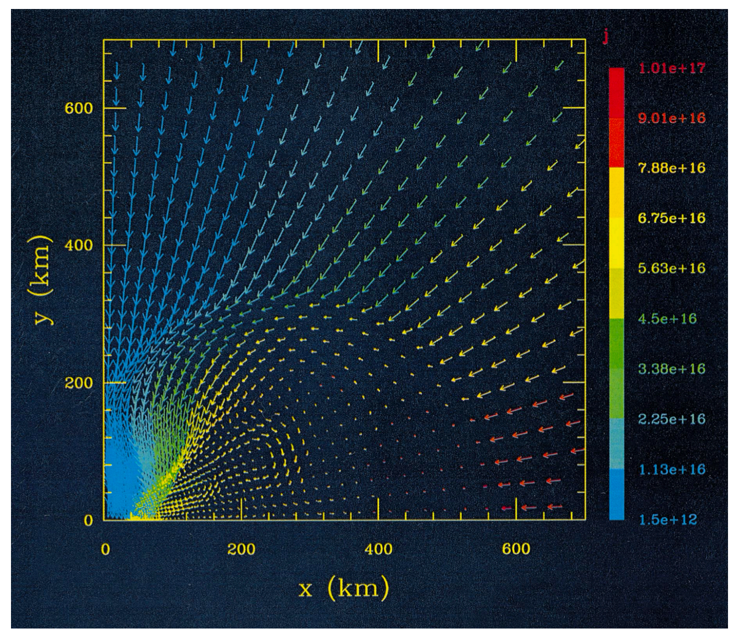


MacFadyen & Woosley (1999)

Tradeoffs are inevitable

Global Collapsar Disk Simulations

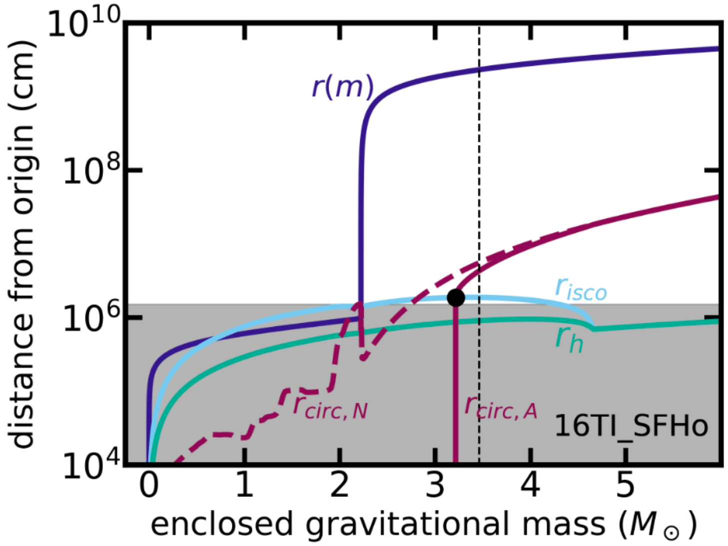
Step 1: GR1D evolution from core-collapse
to BH formation: 16TI & 35OC (Woosley & Heger 2006)

Step 2: FLASH for 2D Newtonian hydrodynamics:

* self-gravity with pseudo-Newtonian BH excision (updating mass & spin)
* map from 1D, evolve to shock breakout
* viscous stress: alpha prescription
* neutrino emission (leakage) & absorption (annular light bulb) for Ye
* coupled 19-isotope nuclear network (Ni56) + tracer particles (r-process)

Coleman Dean & RF (2024a)

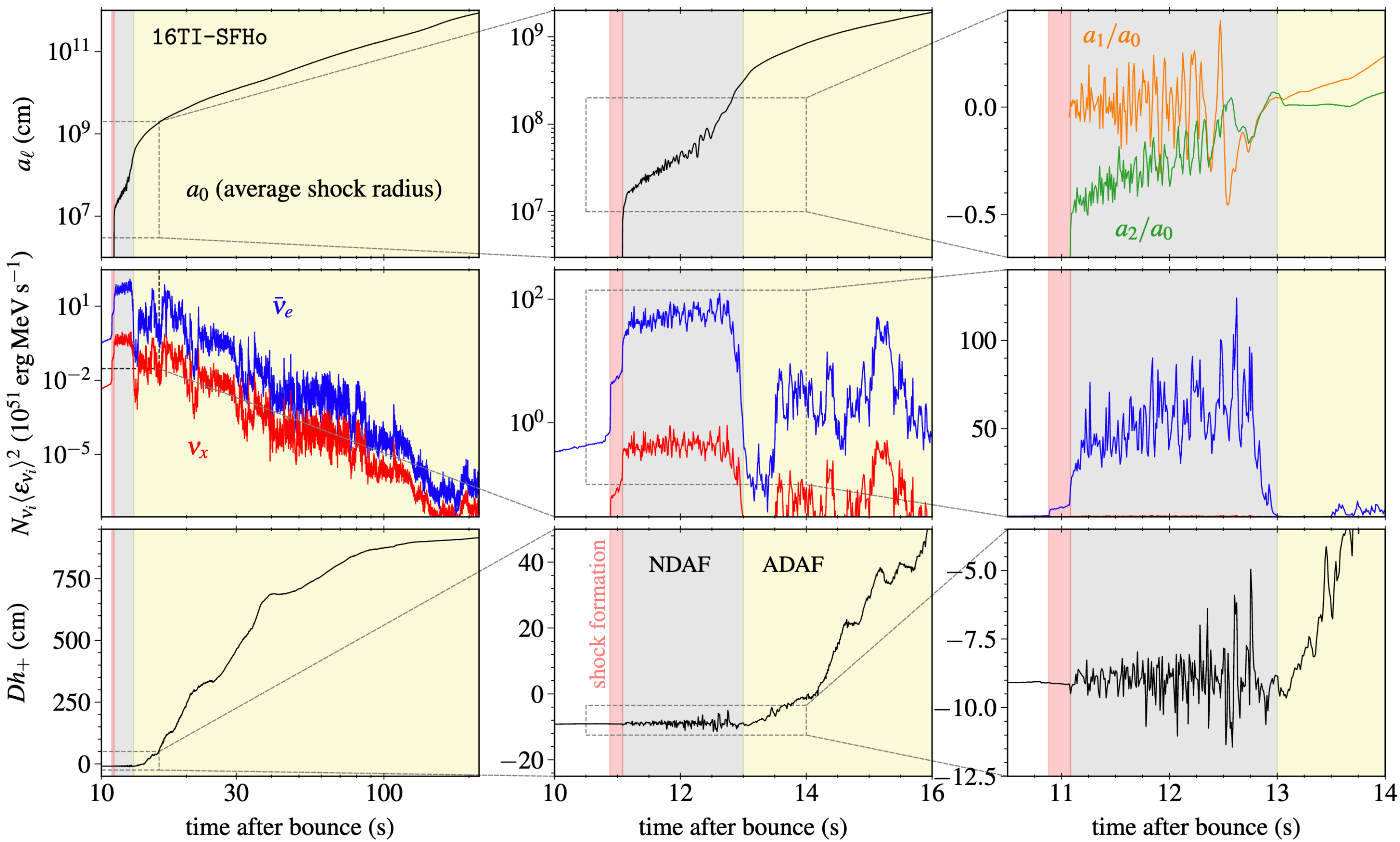
$$r_{\rm circ} \simeq \frac{j^2}{GM}$$



see also Just+ (2022), Fujibayashi+(2022)

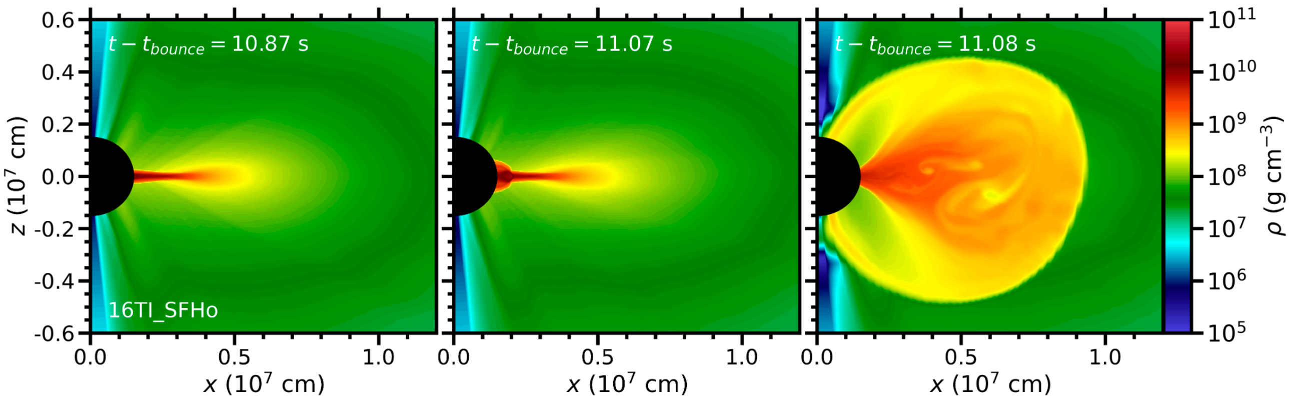
Dean & RF (2024a)

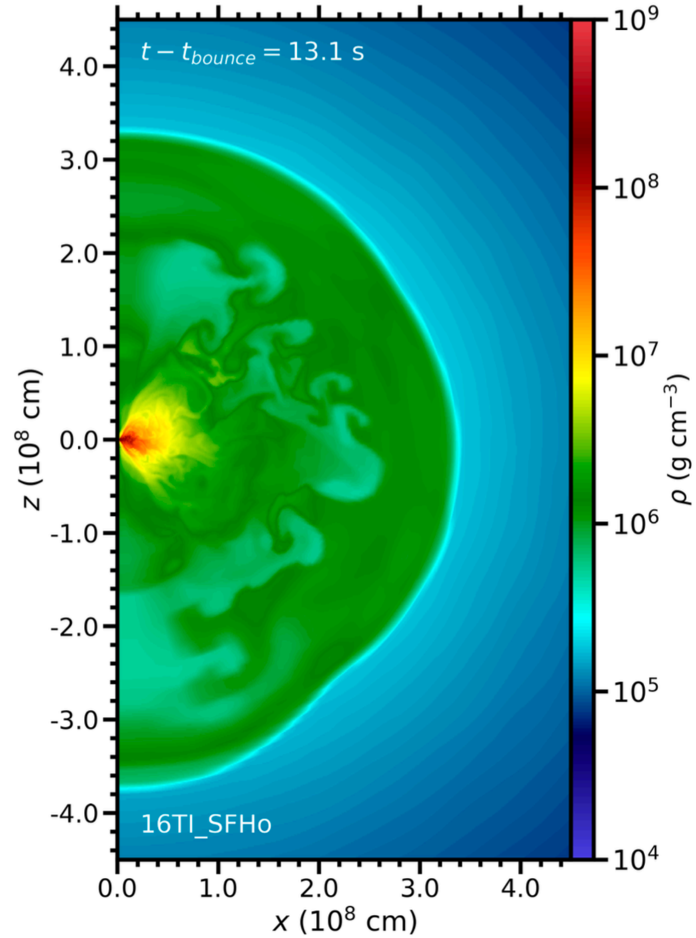
Collapsar Disk Evolution



RF, Janke, Dean, & Tamborra (2025)

Collapsar Disk Evolution





- Initially a Dwarf Disk (equatorial shock)
- Shocked Bubble
- Neutrino cooled (NDAF) phase: 2 - 6 s

  Oscillations & Gradual Expansion
- Transition to ADAF: runaway expansion

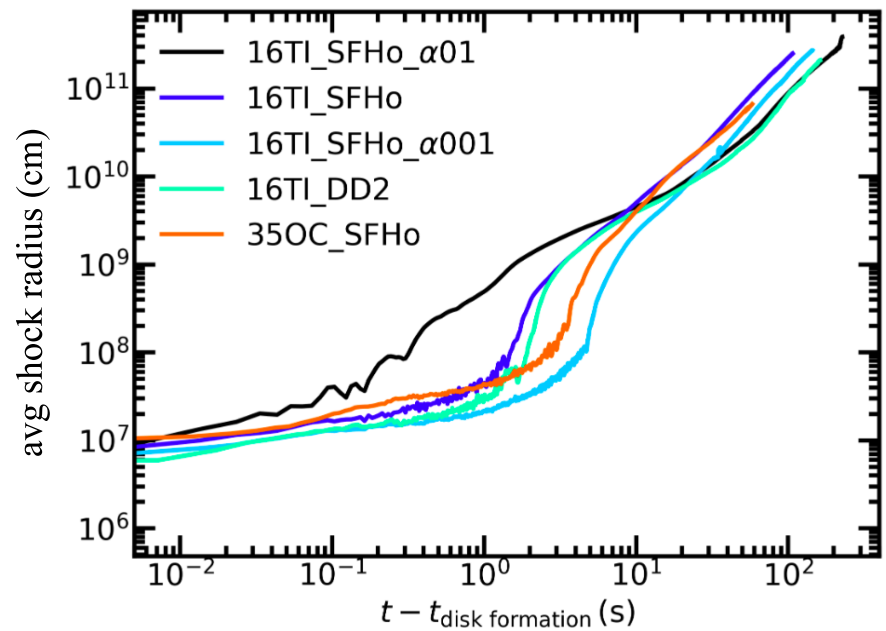
Dean & RF (2024a)

Disk Outflow Explodes the Star

Shock reaches the surface in all cases.

Explosion energies compatible with Type Ic-BL SNe.

Ejecta masses a bit large and velocities a bit small, by factor ~2.

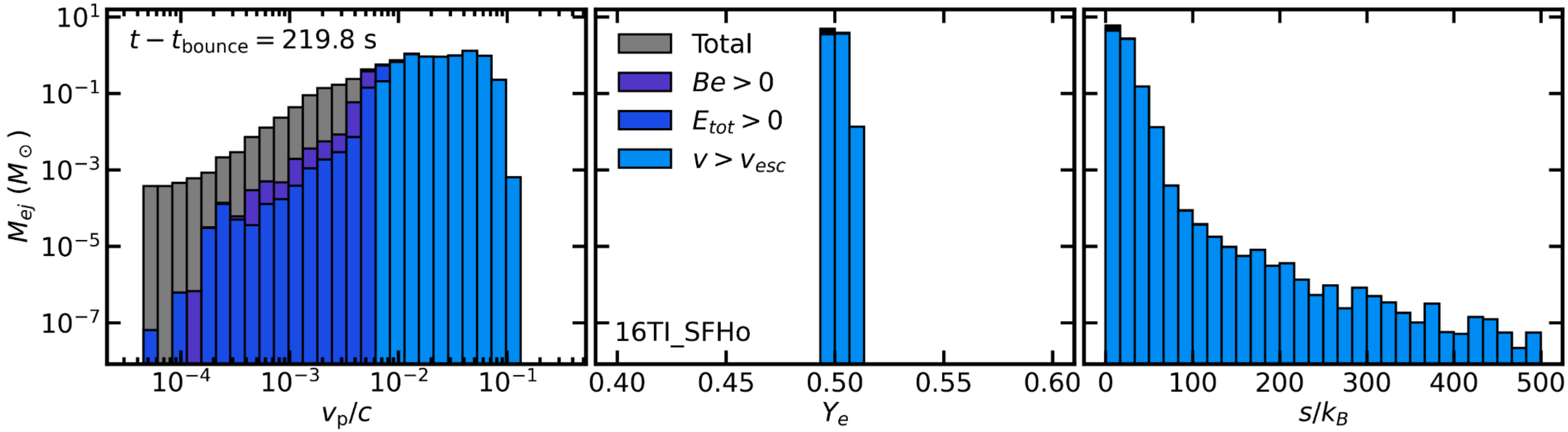


Dean & RF (2024a)

(pre-collapse)	Model	$M_{\rm ej}$ ($\rm M_\odot$)	$K_{\rm ej}$ (10^{51} ergs)	K_∞ (10^{51} ergs)	$\langle v_\infty \rangle$ (10^3 km/s)
16TI: 14 $M_{\rm sun}$	16TI_SFHo	8.19	9.07	9.20	8.7
	16TI_SFHo_α01	8.97	2.39	2.41	4.8
	16TI_SFHo_α001	7.93	4.34	4.37	6.0
	16TI_DD2	9.17	3.67	3.70	5.6
35OC: 28 $M_{\rm sun}$	35OC_SFHo	15.1	9.45	10.6	7.7

Dean & RF (2024a)

Ejecta Properties

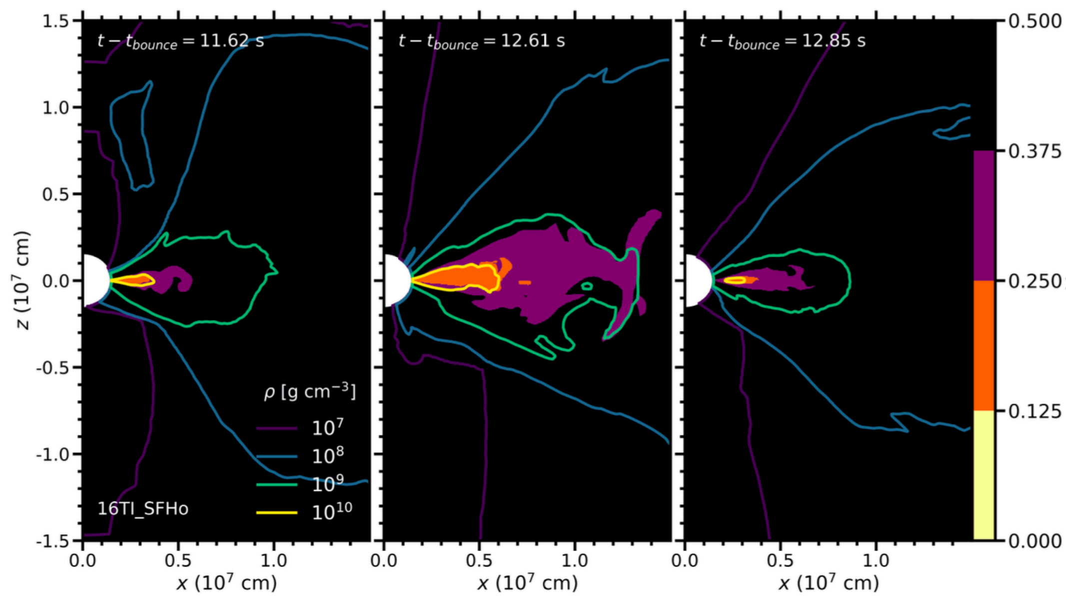


consistent with Just et al. (2022) & Fujibayashi et al. (2024)

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

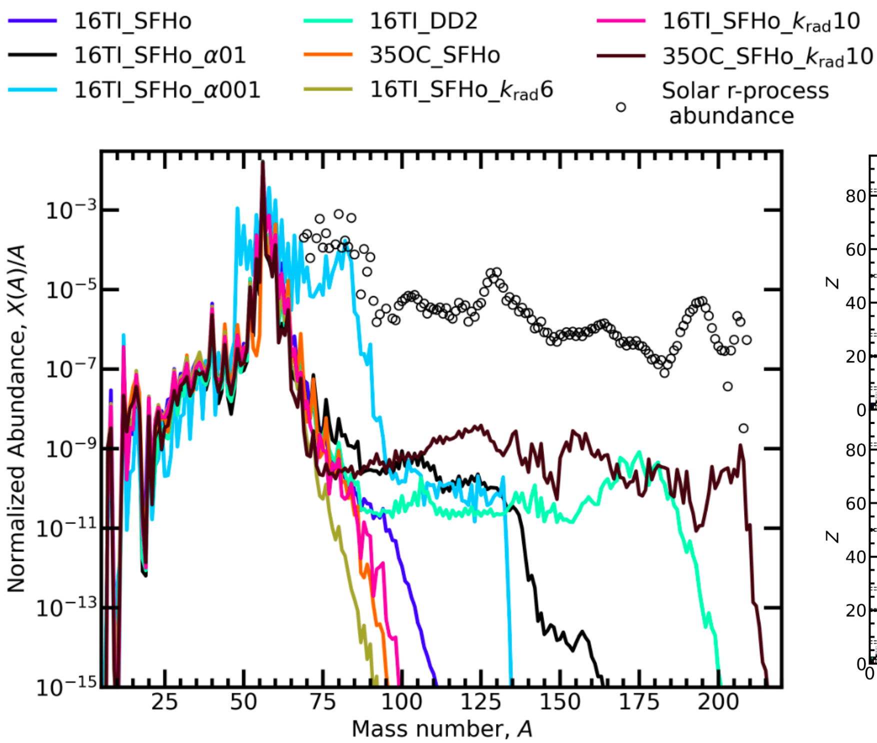
Need large-scale B-field for the Lorentz force to eject matter during neutrino-cooled phase.

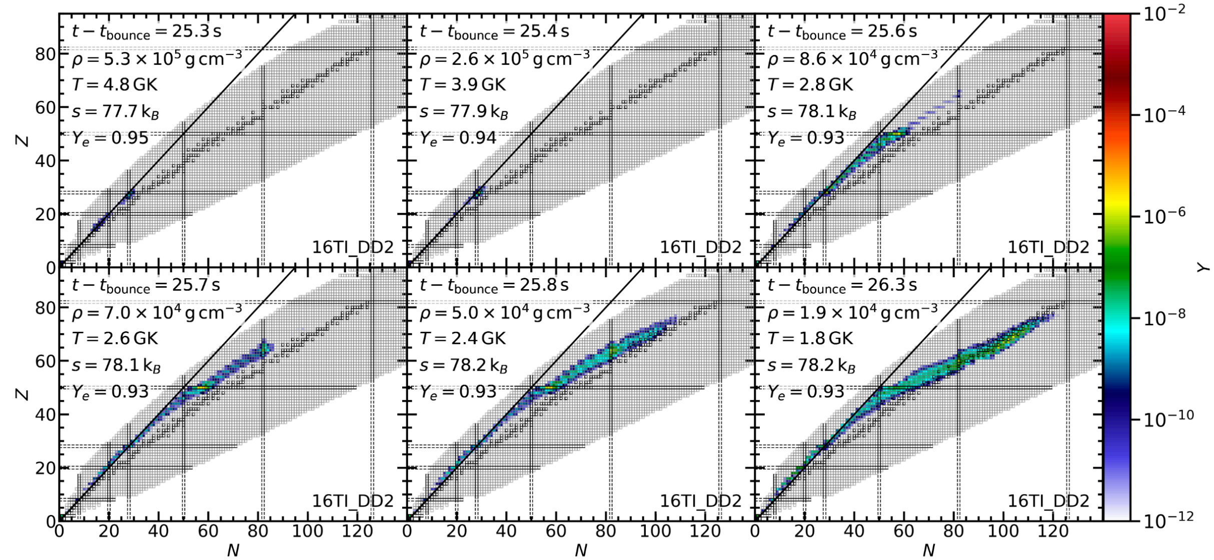
see Issa+ 2024 & Shibata+ 2025



Dean & RF (2024a)

R-process Yield: Very Low





Dean & RF (2024b)

Only low-viscosity yielded first r-process peak (longer NDAF phase).

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

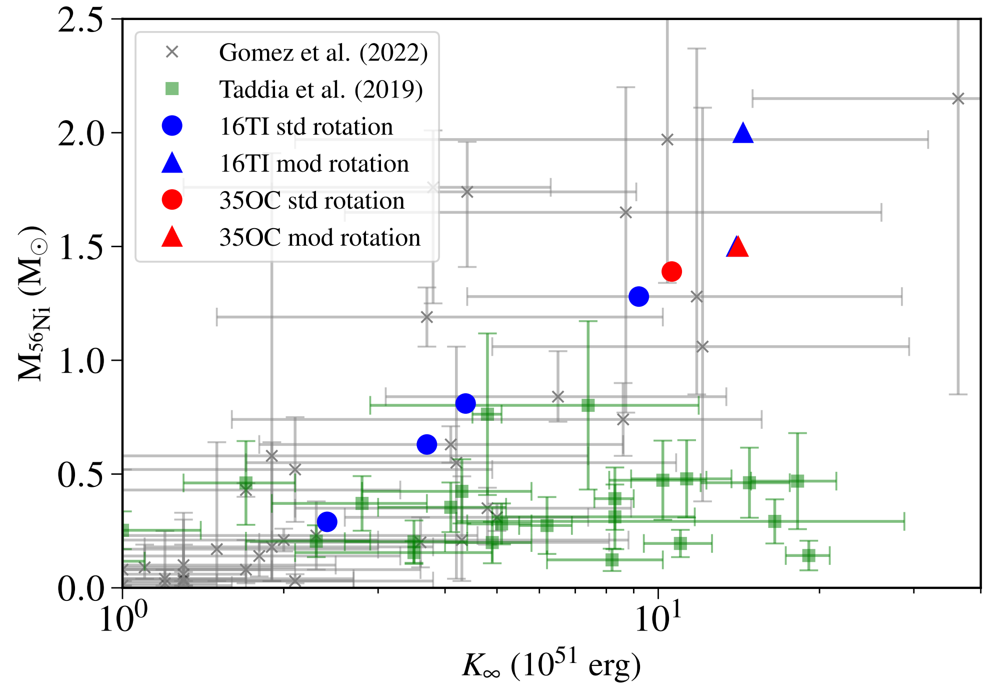
Modifying stellar rotation profile (deeper circularization) did not improve r-process yield.

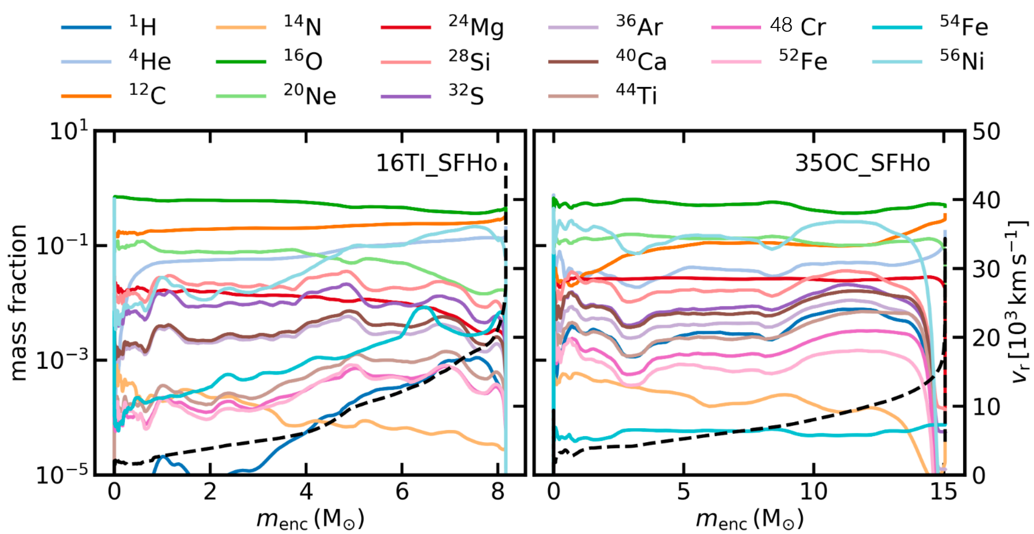
19-Isotope Yield

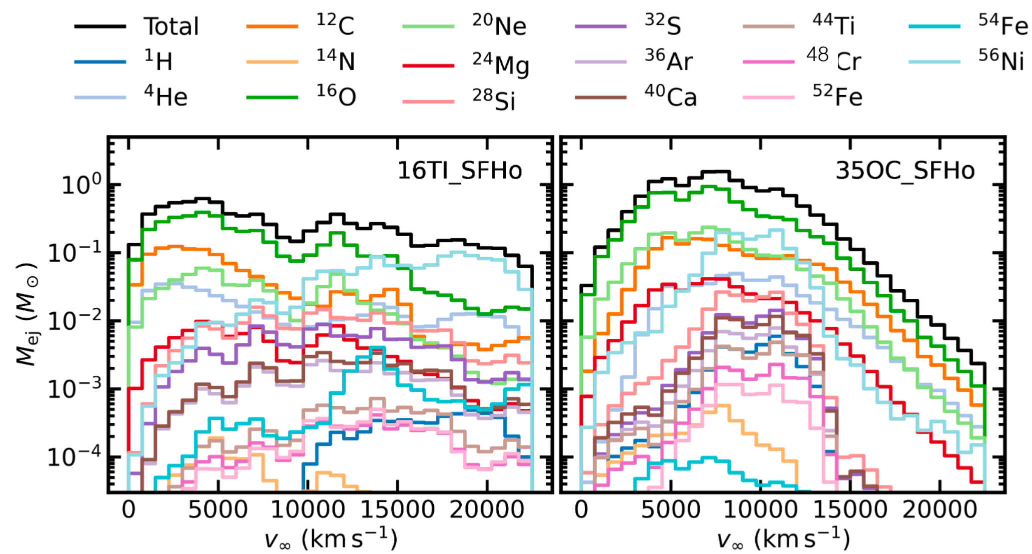
^{56}Ni masses: 0.3 - 2 M_{sun}.

(see also Fujibayashi+2024, Menegazzi+2025, Shibata+2025)

~1/2 of the ejecta from the disk
~1/2 unprocessed
mostly oxygen

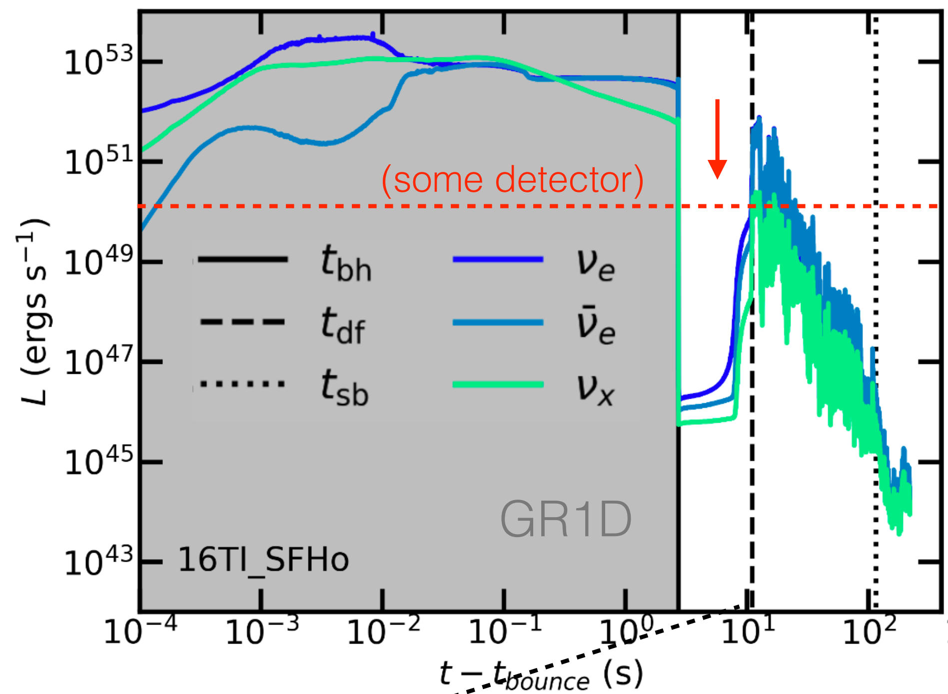






Dean & RF (2024b)

Dean & RF (2024a)

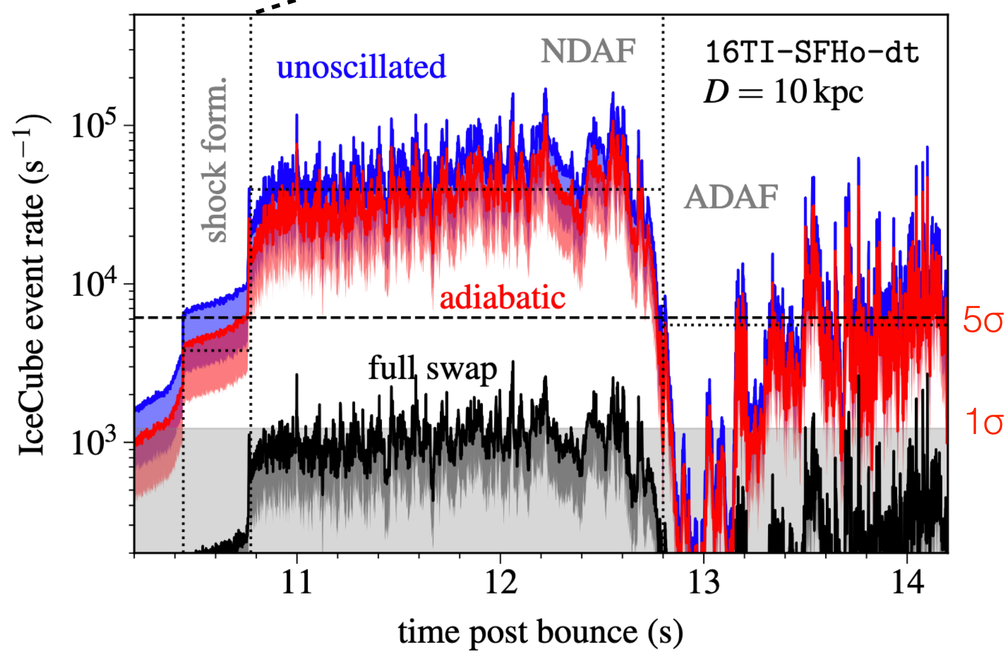


Neutrino Emission

Gap in emission (few s) between
- BH formation
- disk formation

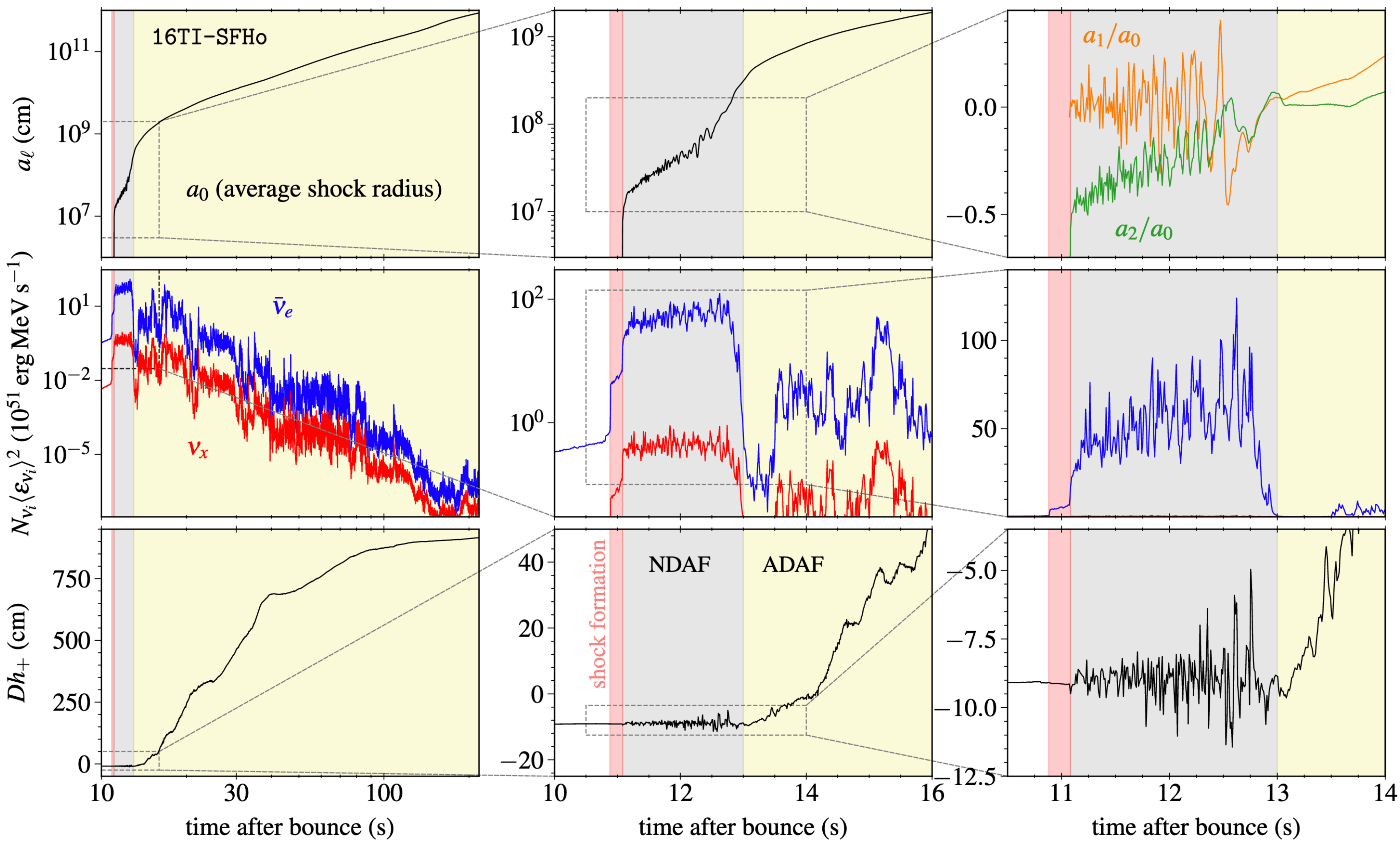
Sensitive to flavor transformation:
very low ν_x emission

Galactic collapsar easily detectable by IceCube, emission dominated by neutrino-cooled (NDAF) phase.



RF, Janke, Dean, & Tamborra (2025)

Neutrino and GW Emission



RF, Janke, Dean, & Tamborra (2025)

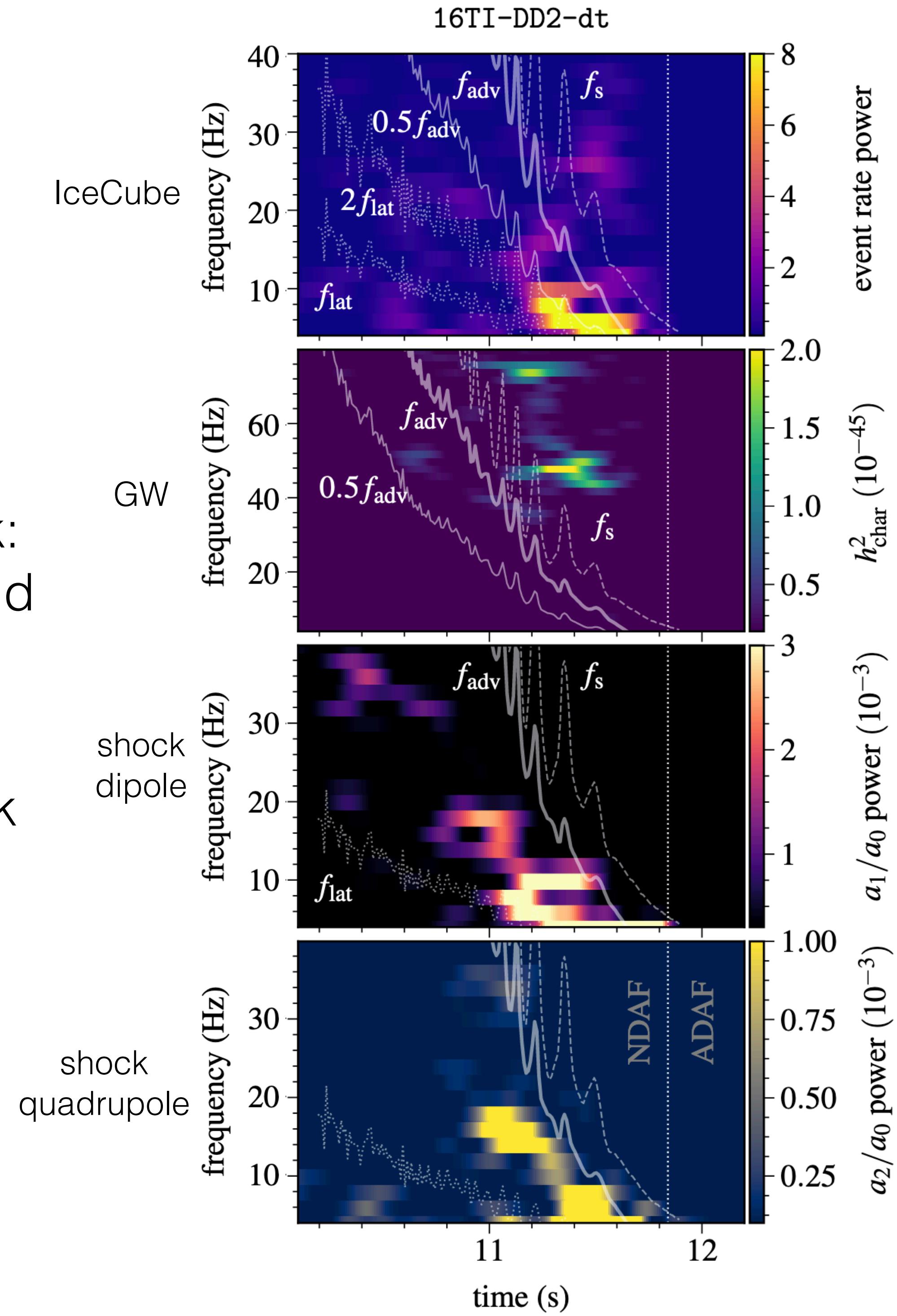
Time Variations

Correlated emission in the
frequency range 10 - 50 Hz.

Characteristic frequencies of the disk: radial advection, lateral & radial sound crossing

Neutrinos: densest regions of the disk
GW: global shock oscillations.

Not considering higher-frequency components (mass quadrupole limitations)



RF, Janke, Dean, & Tamborra (2025)

Summary

1) Collapsar Disk Outflows alone can explode its progenitor star with $E \sim 10^{52}$ erg

2) 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.

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

4) The neutrino and GW signal from a galactic collapsar are easily detectable. Correlated time-variations are key diagnostics.

(I) arXiv:2403.08877 **(II) arXiv:2408.15338** **(III) arXiv:2507.17836**

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