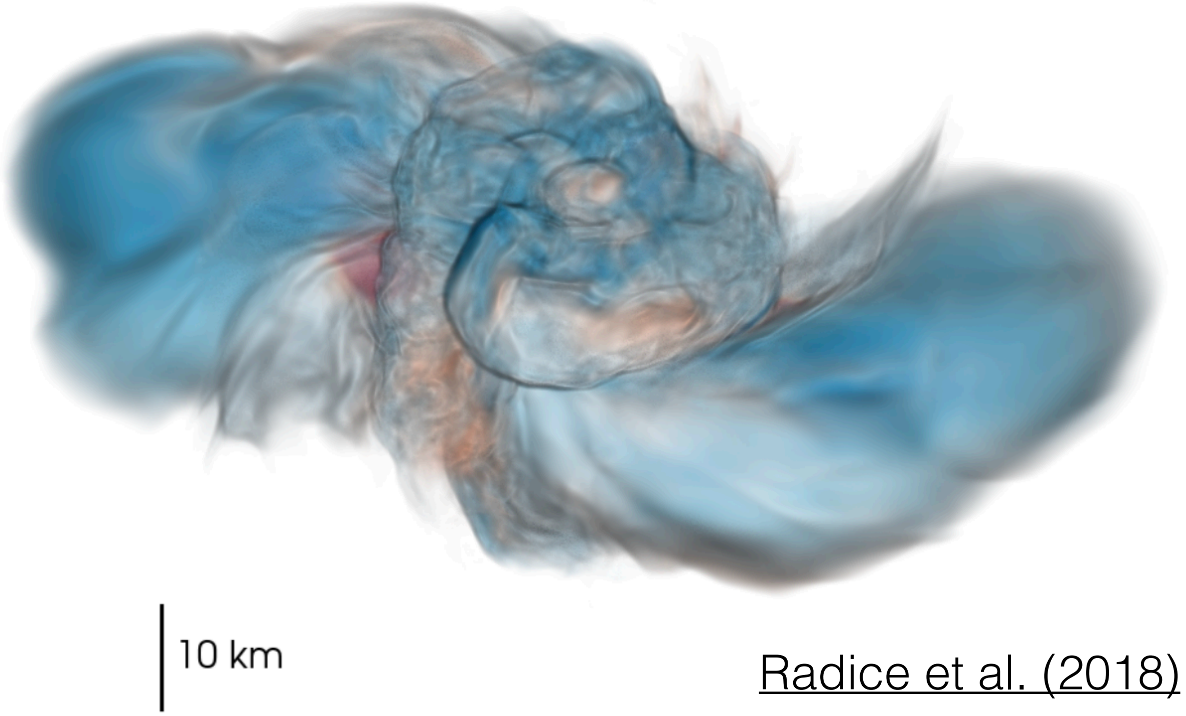
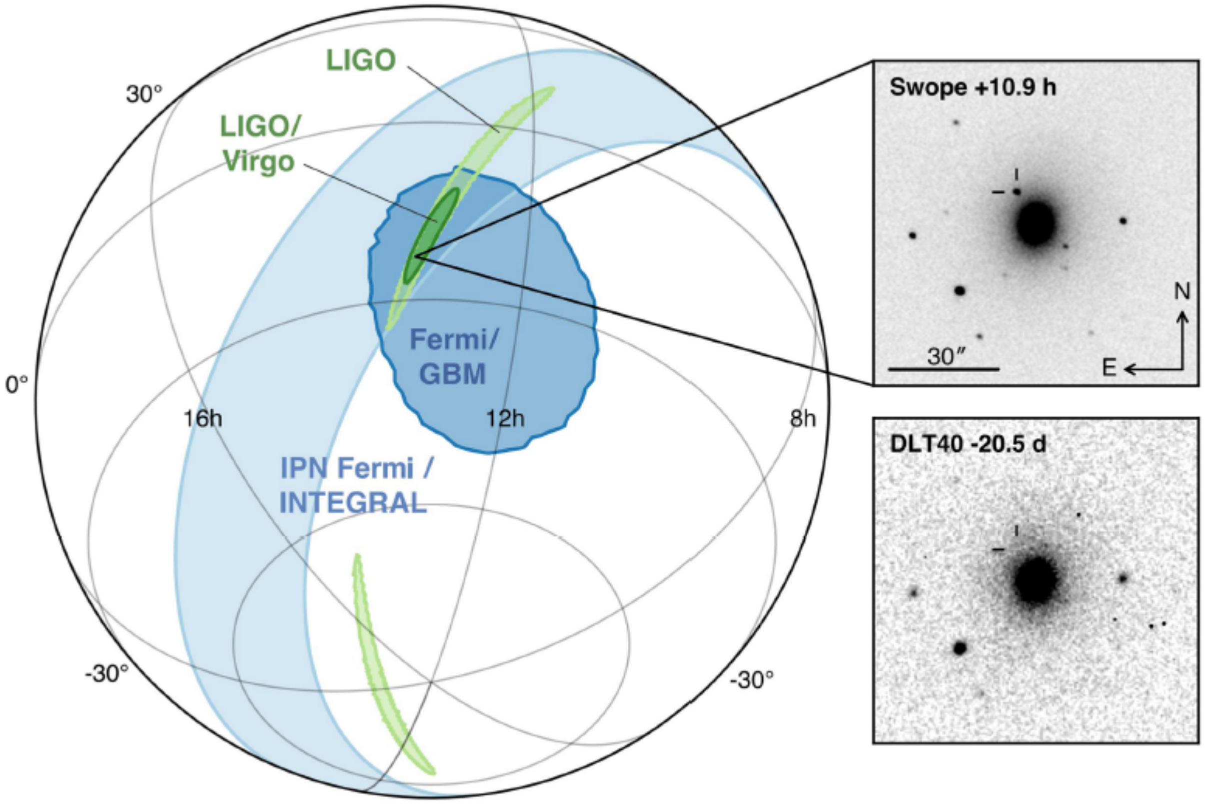
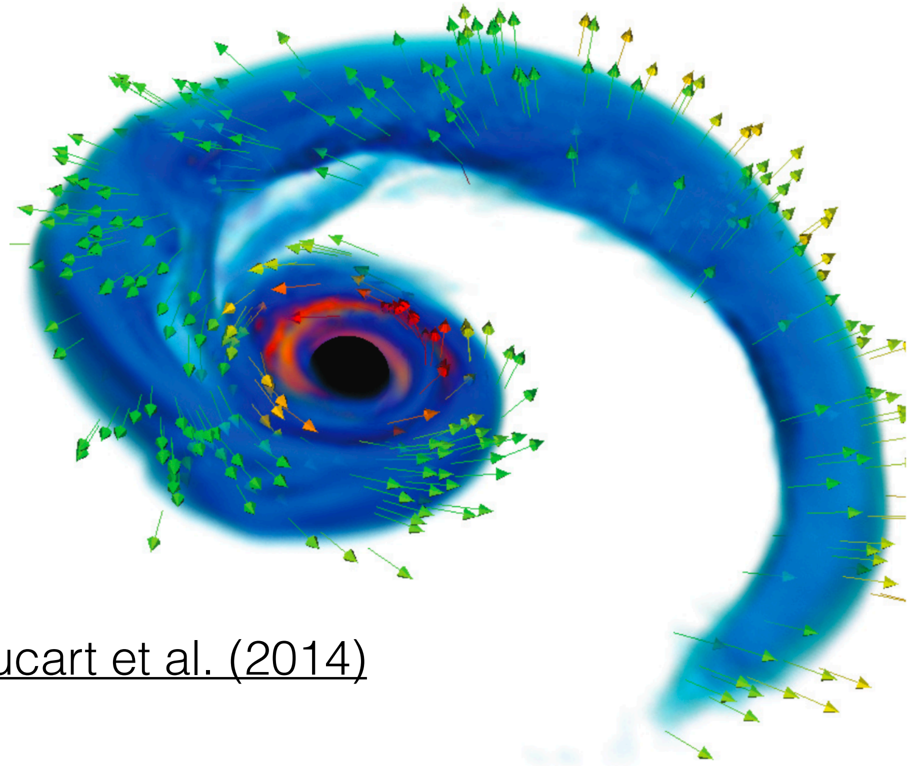


Radice et al. (2018)



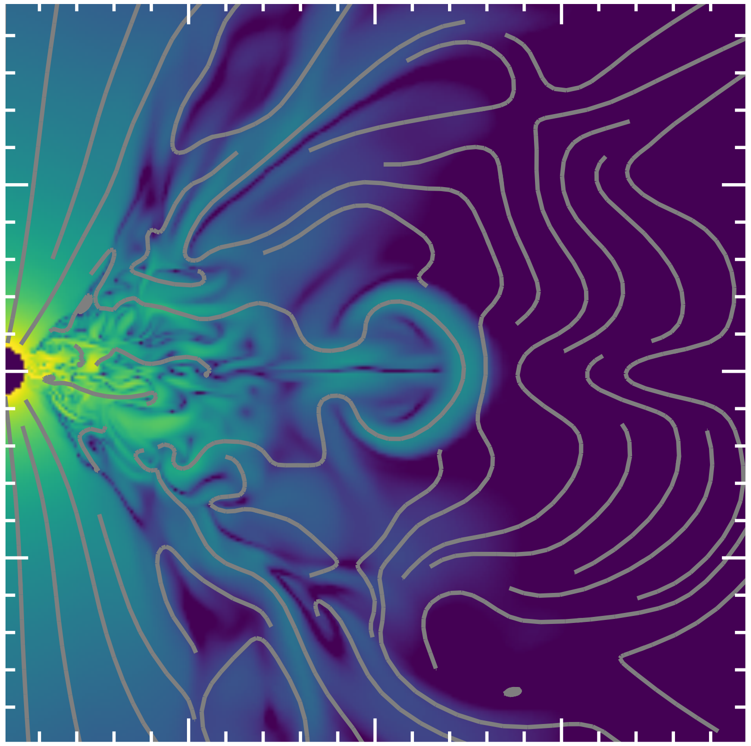
Abbott et al. (2017) [LVC]: GW170817



Foucart et al. (2014)

Neutron Star Mergers III

Rodrigo Fernández (University of Alberta)



RF et al. (2019)

Outline

~~1) Neutron stars~~

~~2) Overview of Merger Phases~~

~~3) Inspiral Phase: GW & EM precursors~~

~~4) Dynamical Phase: Mass Ejection, NSNS vs NSBH~~

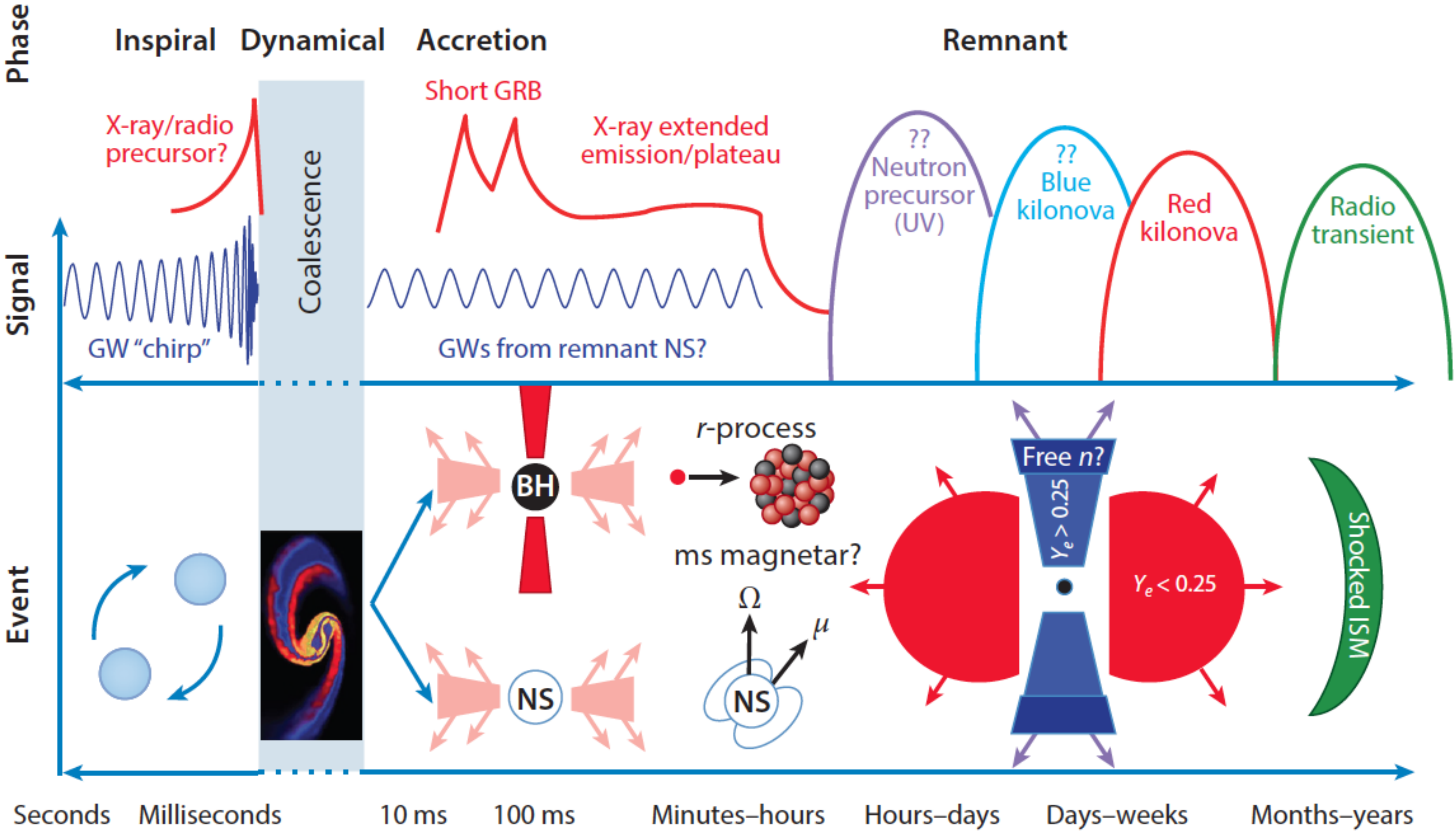
~~5) Merger Remnant: Post-merger GWs, EOS~~

~~6) r-process in a nutshell~~

~~7) Accretion Disk: evolution & mass ejection~~

8) EM Counterparts: Kilonovae, GRBs, and more

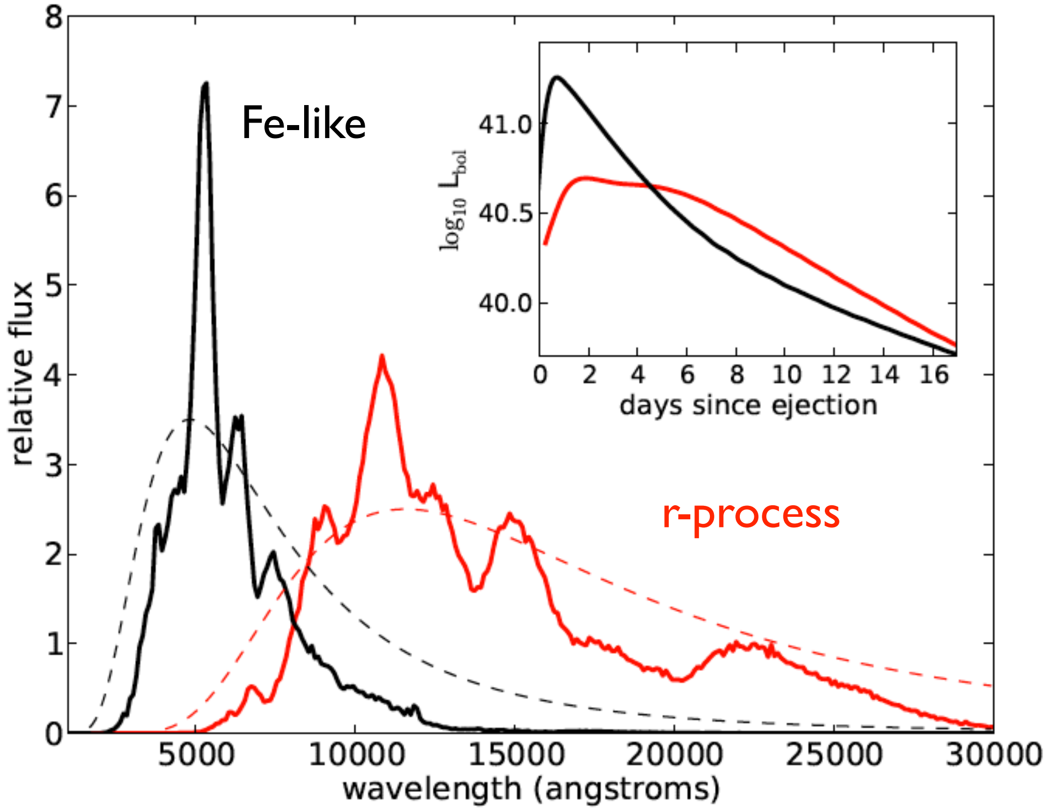
Neutron Star Mergers: Overview



RF & Metzger (2016)

r-process opacities: kilonova color

Theoretical kilonova spectra & light curves:



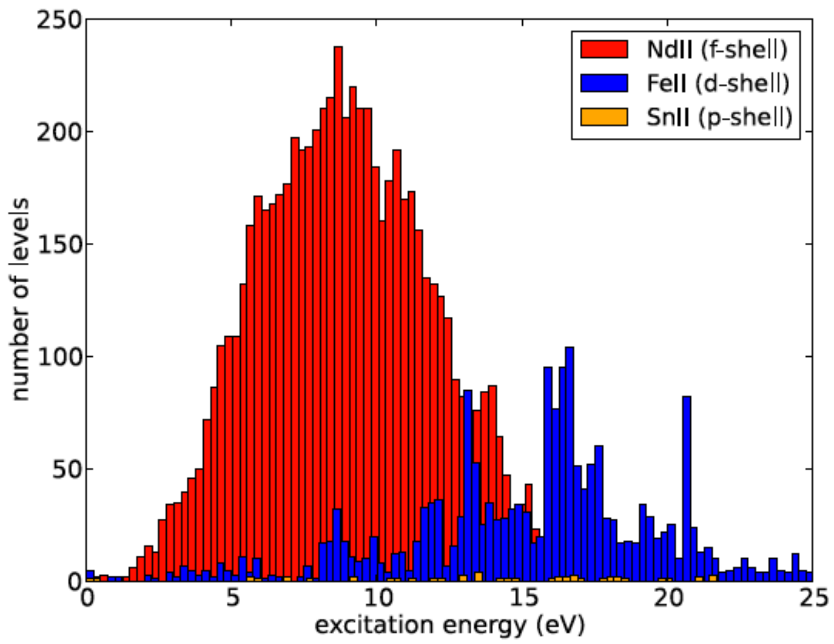
r-process-dominated material generates IR transient

(large number of lines in optical)

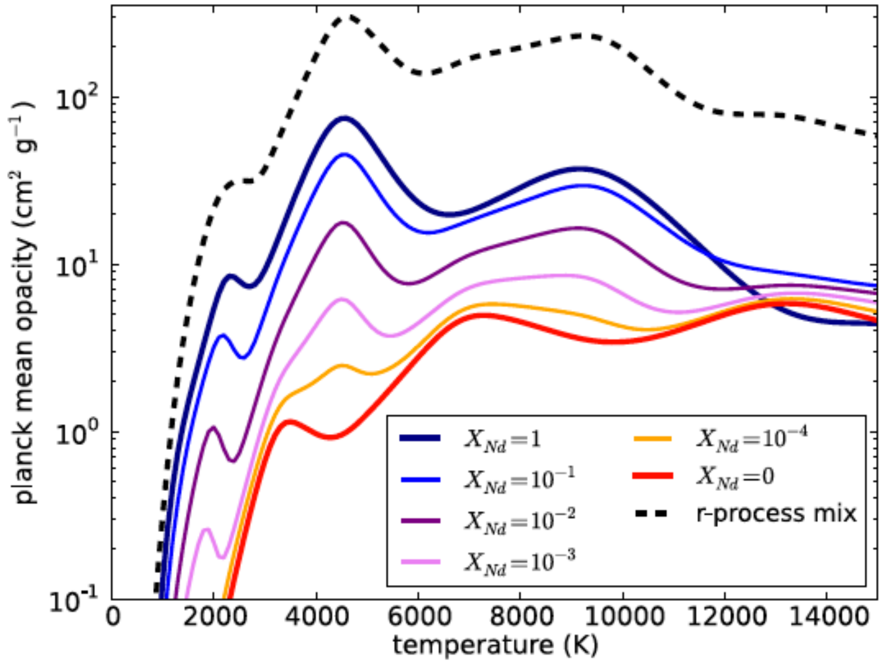
Kasen et al. (2013)

also Tanaka & Hotokezaka (2013), Fontes+ (2015), Tanaka et al. (2020)

Lanthanides have more atomic transitions



Much higher opacity than iron-group elements

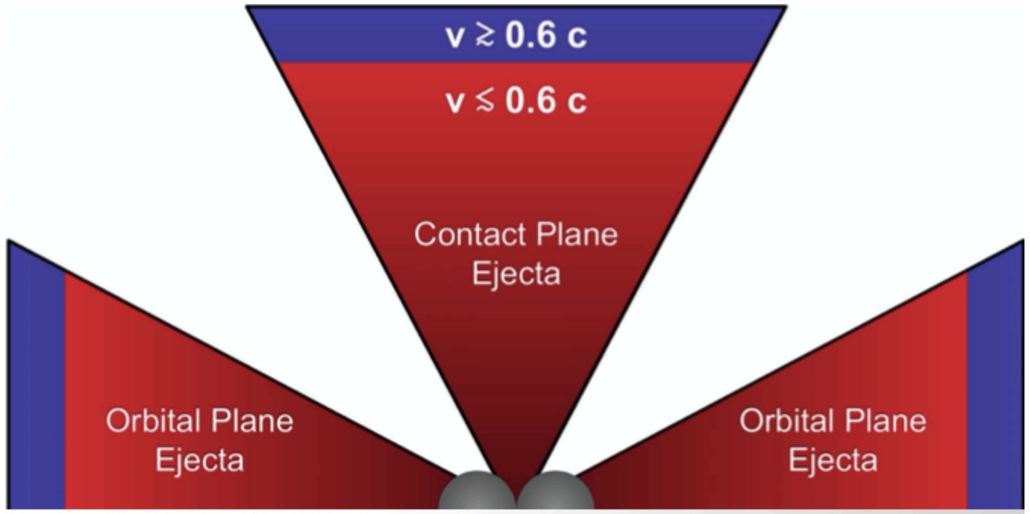


Non-LTE modeling: e.g., Pognan et al. (2023)

Neutron-powered Kilonova Precursors

Fastest portion of the ejecta is such that neutron-capture freezes out: free neutrons left over which decay and produce heating.

Metzger et al. (2015)



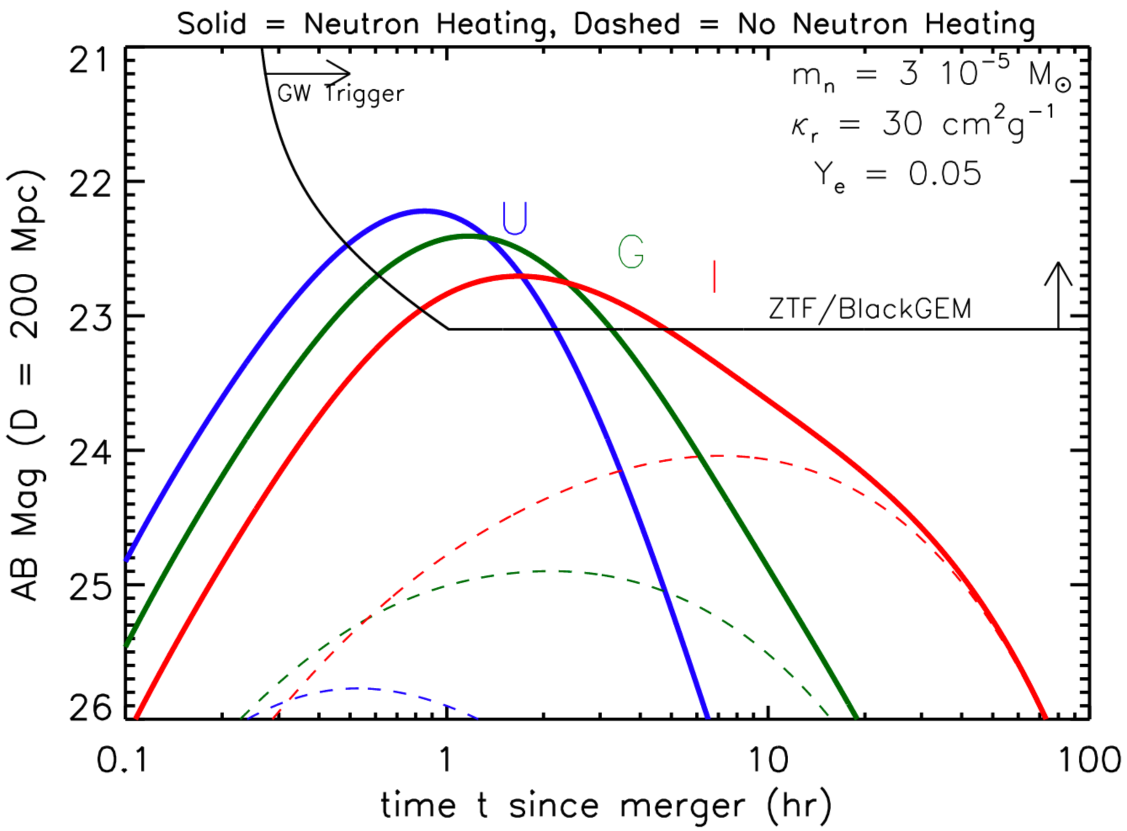
Dean et al. (2021)

Leading portion of the ejecta, low optical depth: thermal transient peaking on ~hr timescales, powered by neutron decay heating.

Amount of fast ejecta is low (10^{-6} to 10^{-4} M_{sun}), numerical simulations have not converged. First few hours important to constraint KN models.

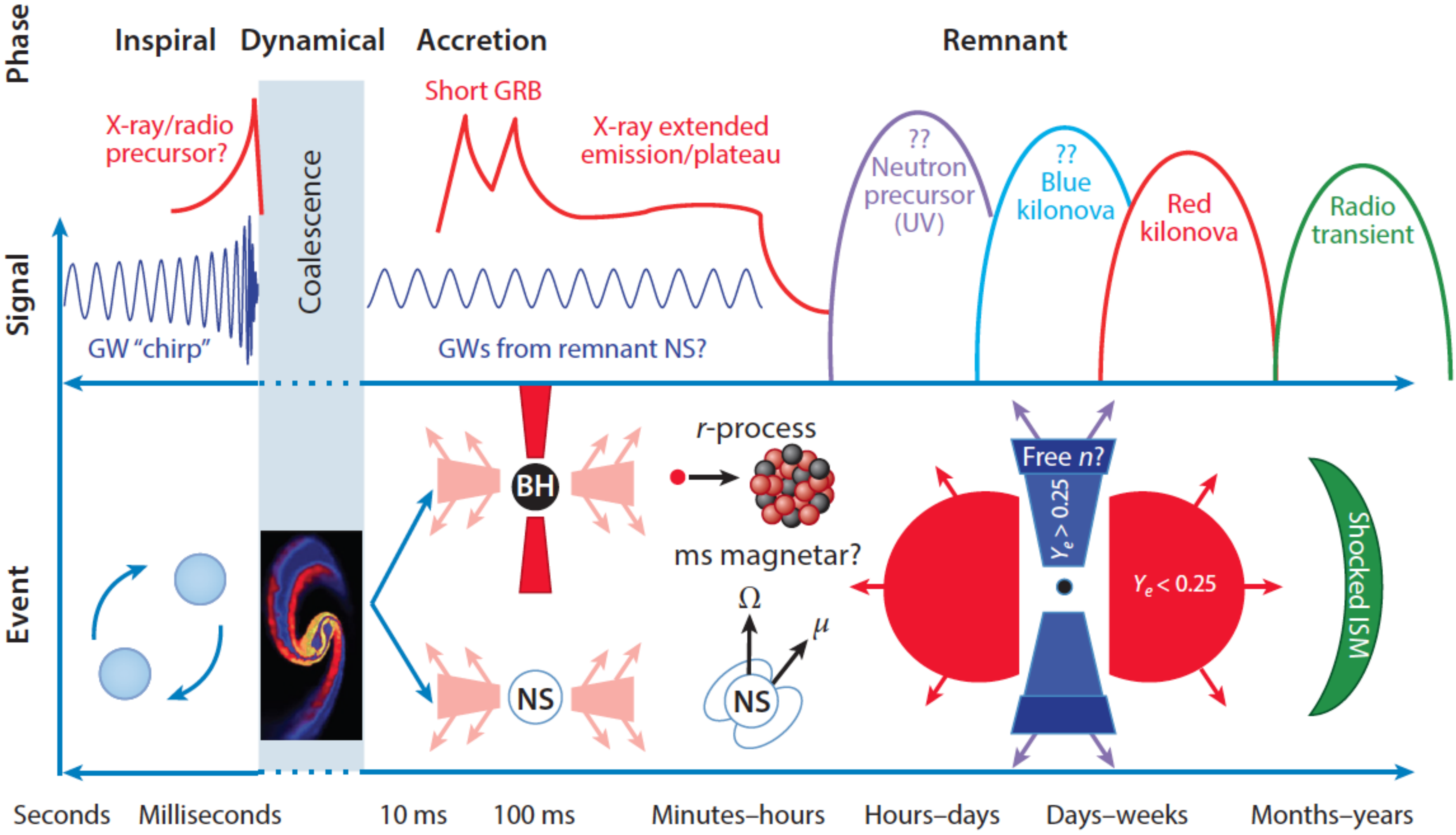
Bauswein et al. (2013), Radice et al. (2018), Dean et al. (2021)

Arcavi (2018)



Metzger et al. (2015)

Neutron Star Mergers: Overview

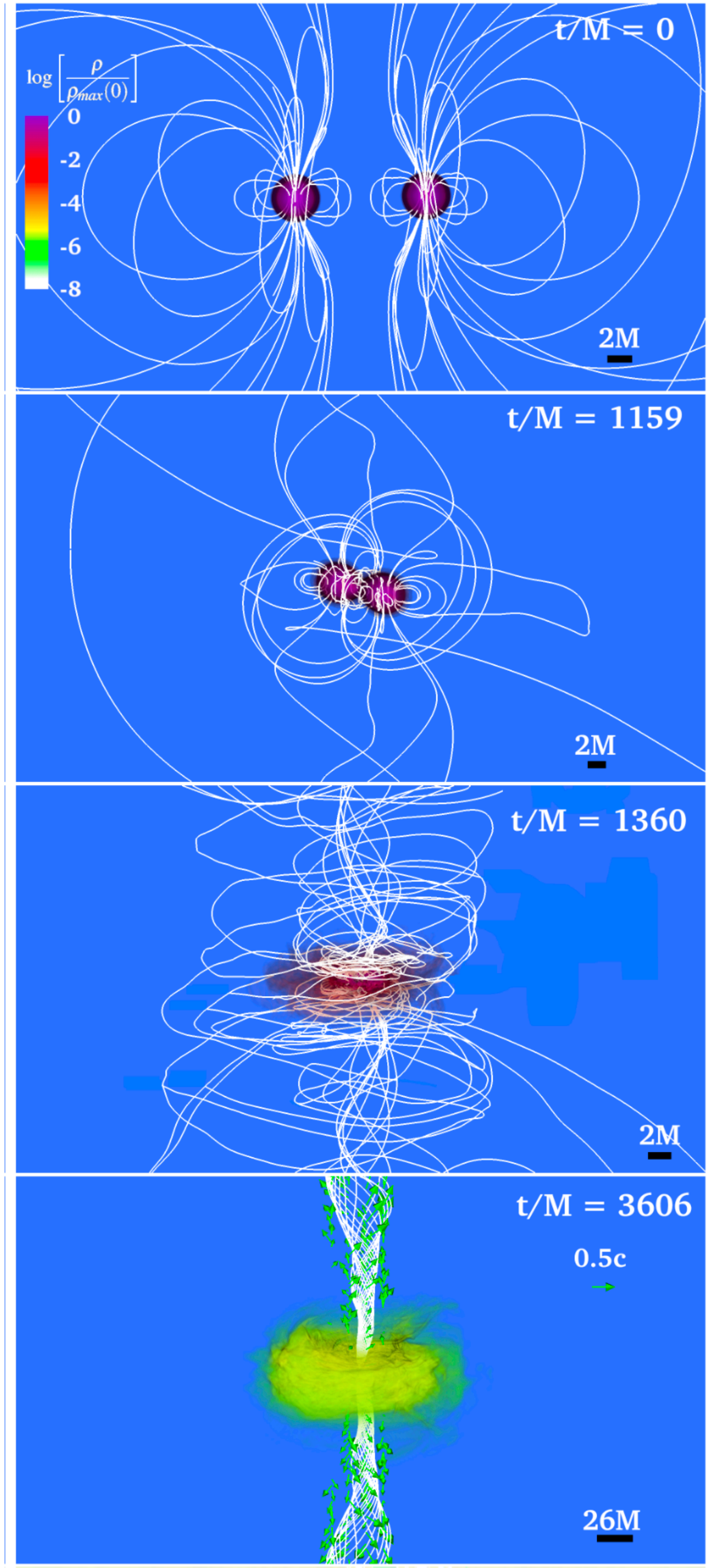


RF & Metzger (2016)

GRB Emission: Jets

NSs have magnetic fields, merger tangles magnetic fields and can launch magnetically-powered jets. Jet onset can now be obtained self-consistently in GRMHD simulations that form BHs.

Current challenges include obtaining proper field amplification given resolution limitations, and understanding whether successful relativistic jets can be produced with longer-lived HMNS.



Sun et al. (2022)

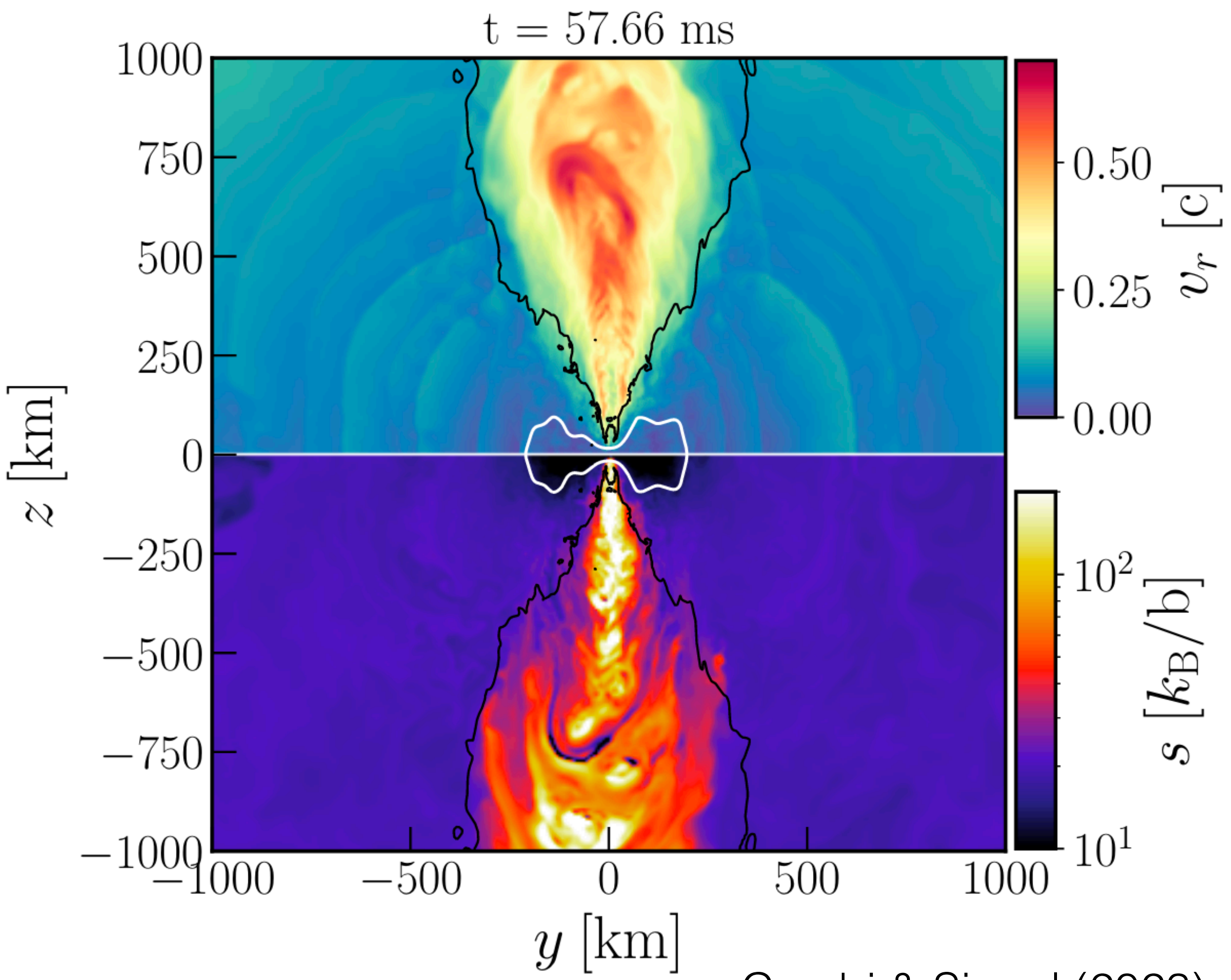
GRB Emission: Jets

Recent GRMHD simulations of NSNS mergers with full physics have produced successful jets that can break out of the slower ejecta.

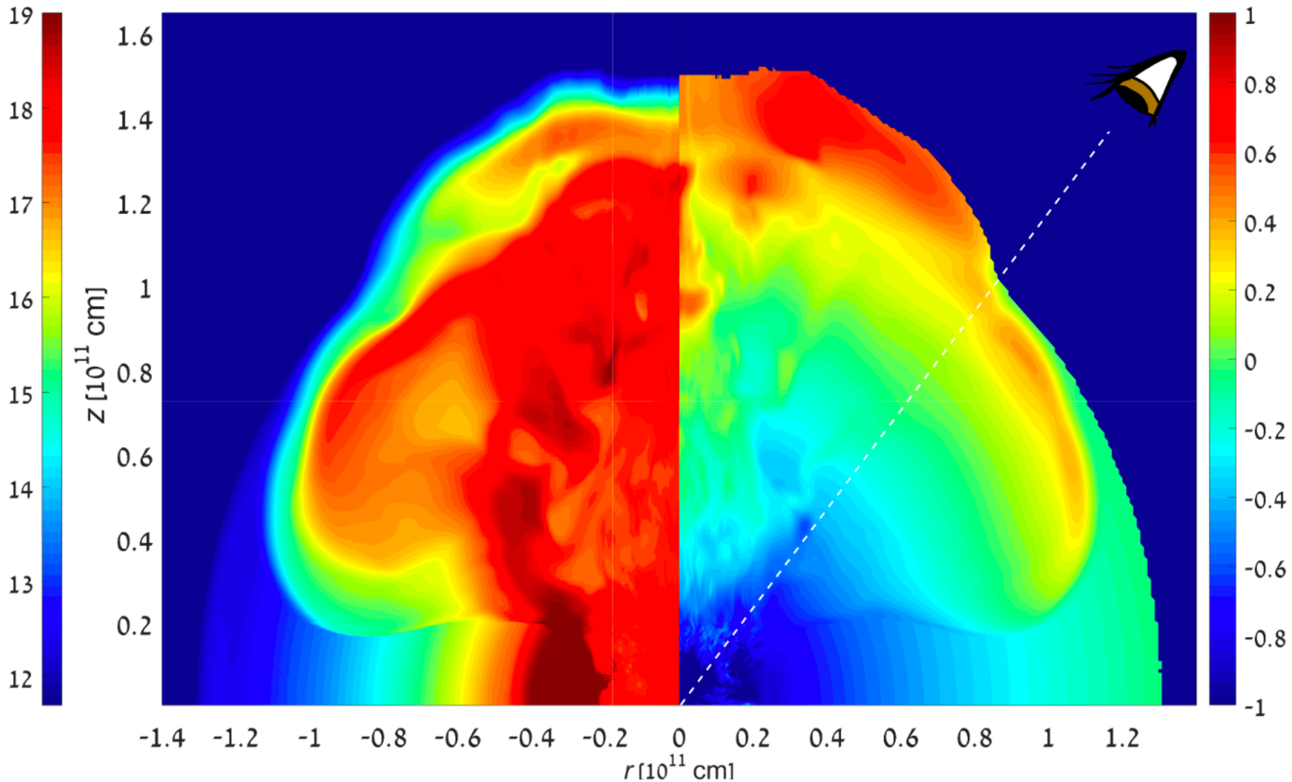
Whether the jet can break out depends on the jet power, ejecta mass, and opening angle. Nature of jet in GW170817 was subject of debate. Superluminal apparent motion of radio afterglow centroid favours successful jet.

Duffell et al. (2018)

Mooley et al. (2018)



Combi & Siegel (2023)

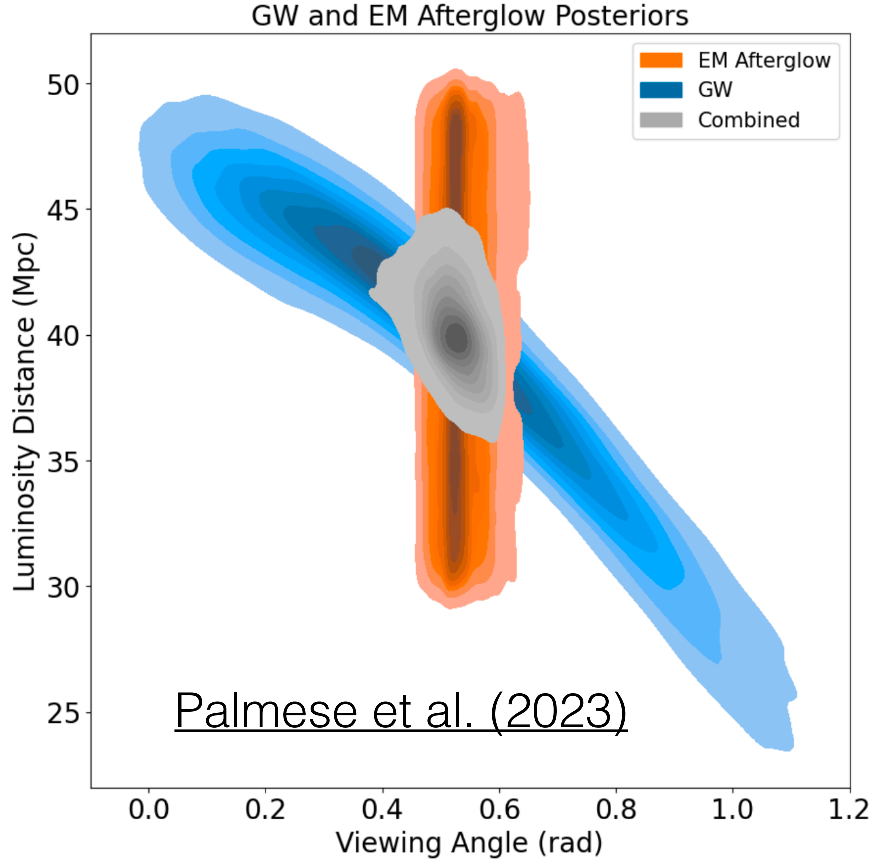


Gottlieb et al. (2018)

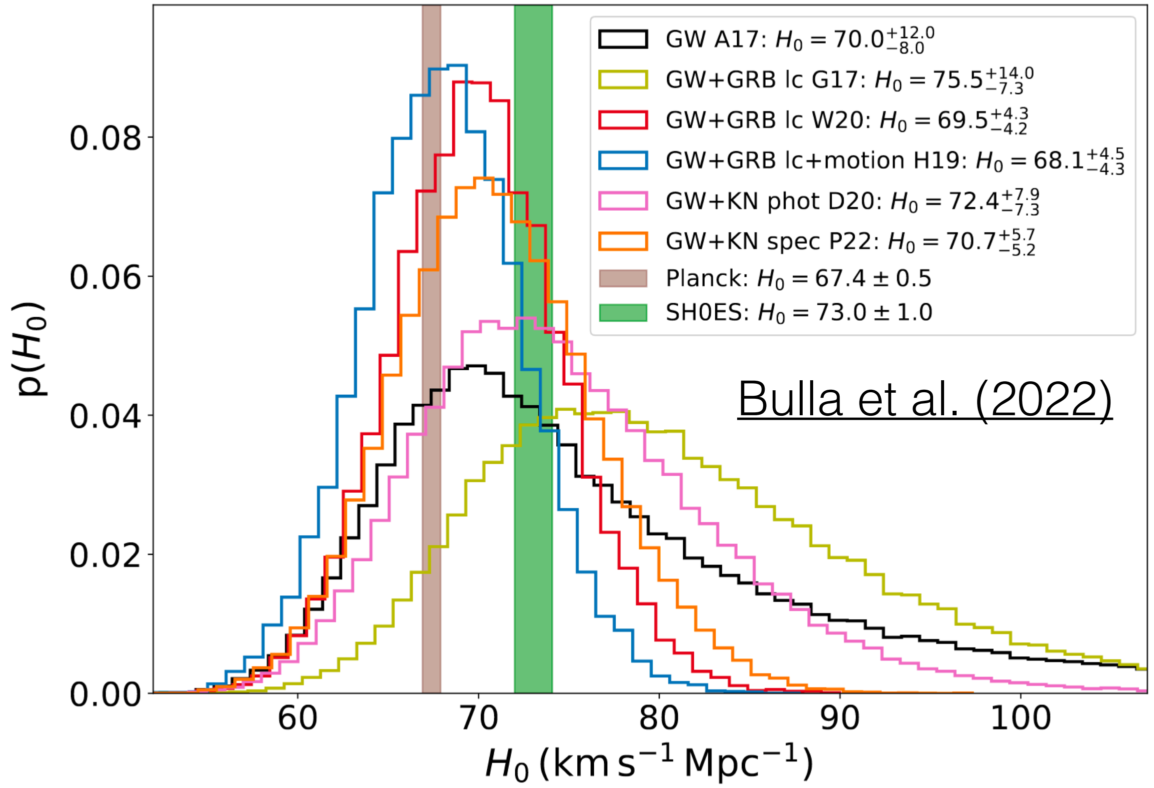
GRB Emission: application to Cosmology

There is a degeneracy in gravitational wave luminosity and inclination angle of a source. This degeneracy can be broken by using information from the EM counterpart.

Constraints on the Hubble constant (redshift from host galaxy, luminosity from GWs and inclination angle) have been placed using GW170817. Best constraints use inclination angle information such as that from super-luminal apparent motion of radio afterglow centroid.



Palmese et al. (2023)

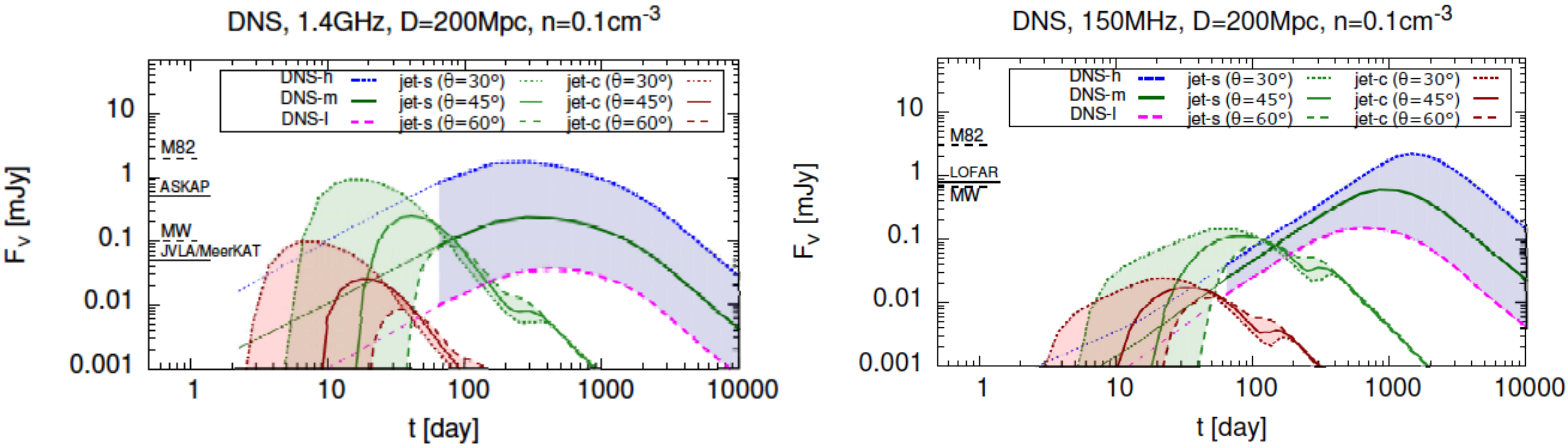


Bulla et al. (2022)

Late-time Radio Transient

Sub-relativistic ejecta interacts with ISM and accelerates particles: synchrotron emission. Distinct from GRB afterglow.

Nakar & Piran (2011)



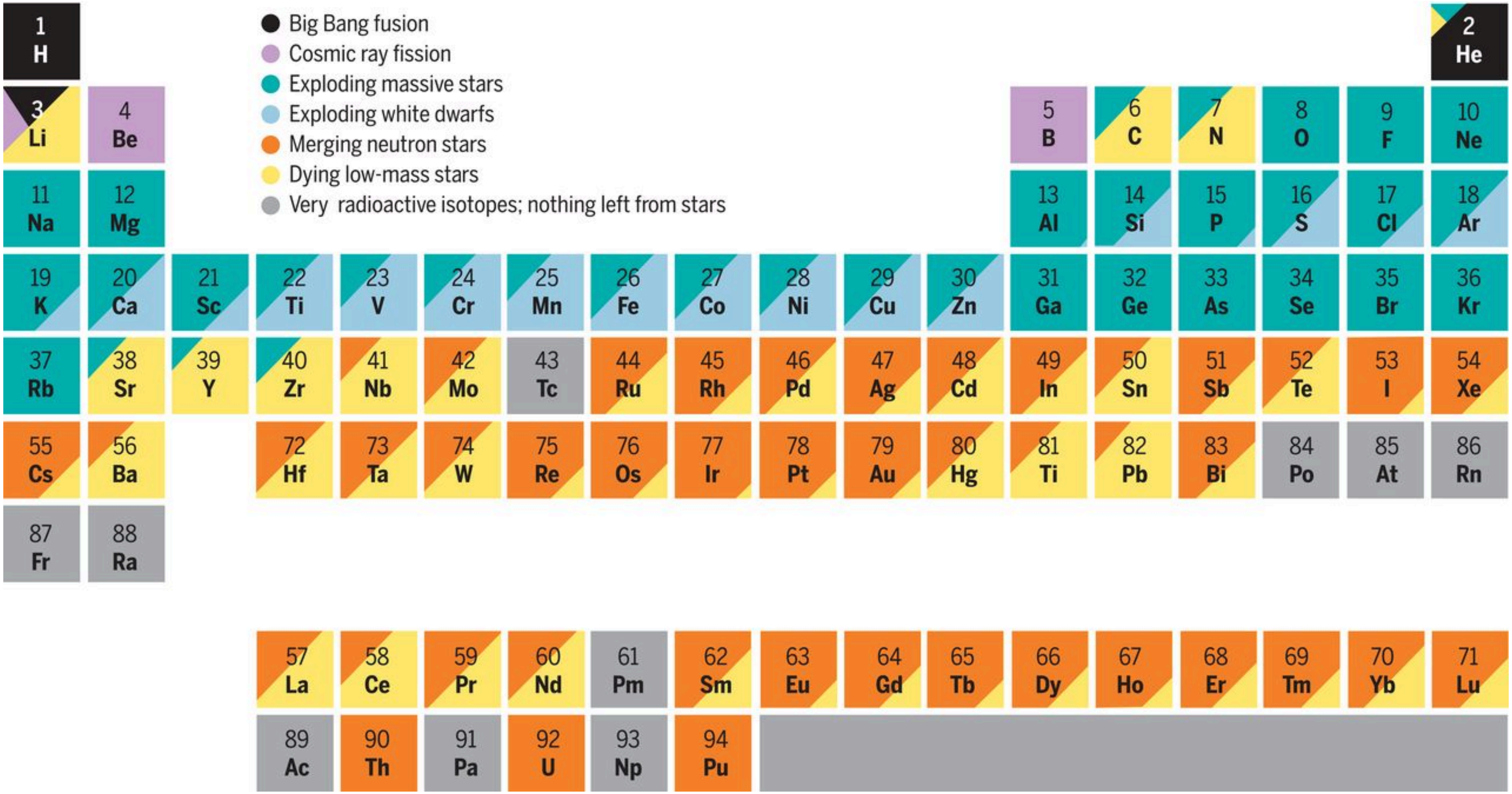
Hotokezaka et al. (2016)

Radio transient on ~yr to ~decades timescale (predicted).

Dependent on kinetic energy of ejecta and circum-burst densities.

Radio upper limit at 4.5yr: Balasubramanian et al. (2022)

Nucleosynthesis



- ● Big Bang fusion
- ● Cosmic ray fission
- ● Exploding massive stars
- ● Exploding white dwarfs
- ● Merging neutron stars
- ● Dying low-mass stars
- ● Very radioactive isotopes; nothing left from stars

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Ti	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
			89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu									

Johnson (2019)

Outline

1) Overview of nucleosynthesis channels

2) NSE and Reaction Networks

3) NS mergers

4) CCSNe

Cosmic Origin of Elements

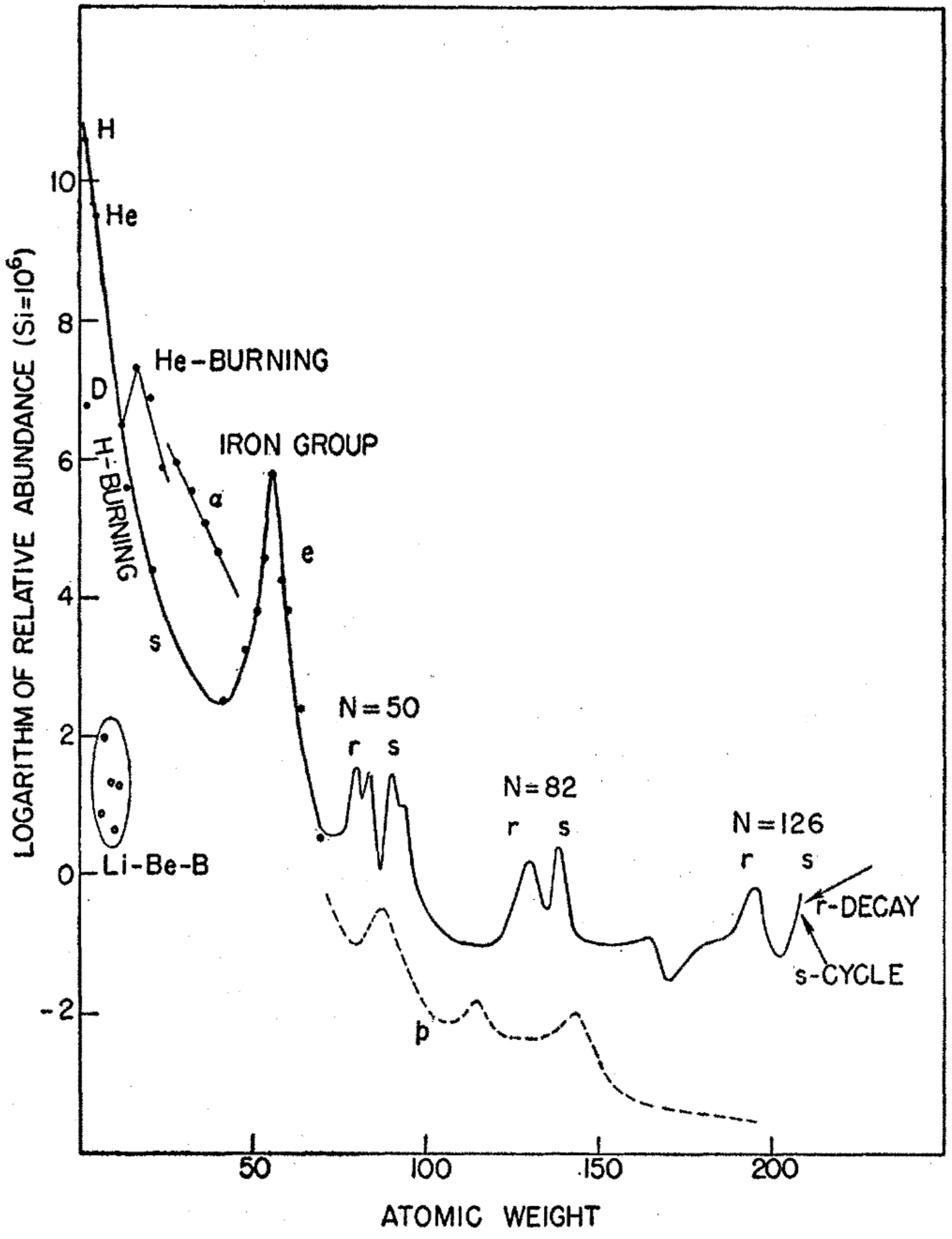
Theory of cosmic nucleosynthesis first formulated by Burbidge, Burbidge, Fowler, & Hoyle (1957). Much work thereafter.

1) Big Bang nucleosynthesis

2) Low-mass stars (carbon, s-process)

3) High-mass stars (alpha elements)

4) Explosive nucleosynthesis
(iron peak, r-process)



Burbidge et al. (1957)

Nuclear Statistical Equilibrium (NSE)

For $T > 5 \times 10^9$ K in a collisional plasma, forward and reverse nuclear reactions are much faster than any other timescale in the system, hence nuclear abundances are at their equilibrium values.

The equilibrium abundances can be obtained by equating chemical potentials. If nuclei follow a Maxwell-Boltzmann distribution, we obtain a Saha-like equation:

$$^4\,\mathrm{He} \Leftrightarrow 2\mathrm{n} + 2\mathrm{p}$$

$$\mu_{\mathrm{He}} = 2\mu_{\mathrm{n}} + 2\mu_{\mathrm{p}}$$

nuclear binding energy

$$X_i = \frac{m_i}{\rho}\omega_i \left(\frac{m_i kT}{2\pi\hbar^2}\right)^{3/2} \exp\left(\frac{\mu_i + \chi_i}{kT}\right)$$

All abundances are completely determined by (ρ, T, Y_e).

$$Y_e = \frac{n_p}{n_p + n_n}$$

Out of NSE: Reaction Networks

When $T < 5 \times 10^9$ K (approximately), reaction rates are no longer balanced and the time-dependent evolution of abundances must be solved. These are systems of coupled ODEs for the abundances Y_i of the isotopes that make up the network.

Typical form:

$$\frac{dY_i}{dt} = R_i Y_i + \sum_j R_{ij} Y_i Y_j + ...$$

The RHS contains all the reactions the create or destroy isotope i. This then results in a Jacobian matrix relating all isotopes. Given the vastly different timescales of reaction rates, these are stiff sets of ODEs requiring inversion of the Jacobian matrix (band diagonal). Calculations of the r-process typically use 7000+ isotopes.

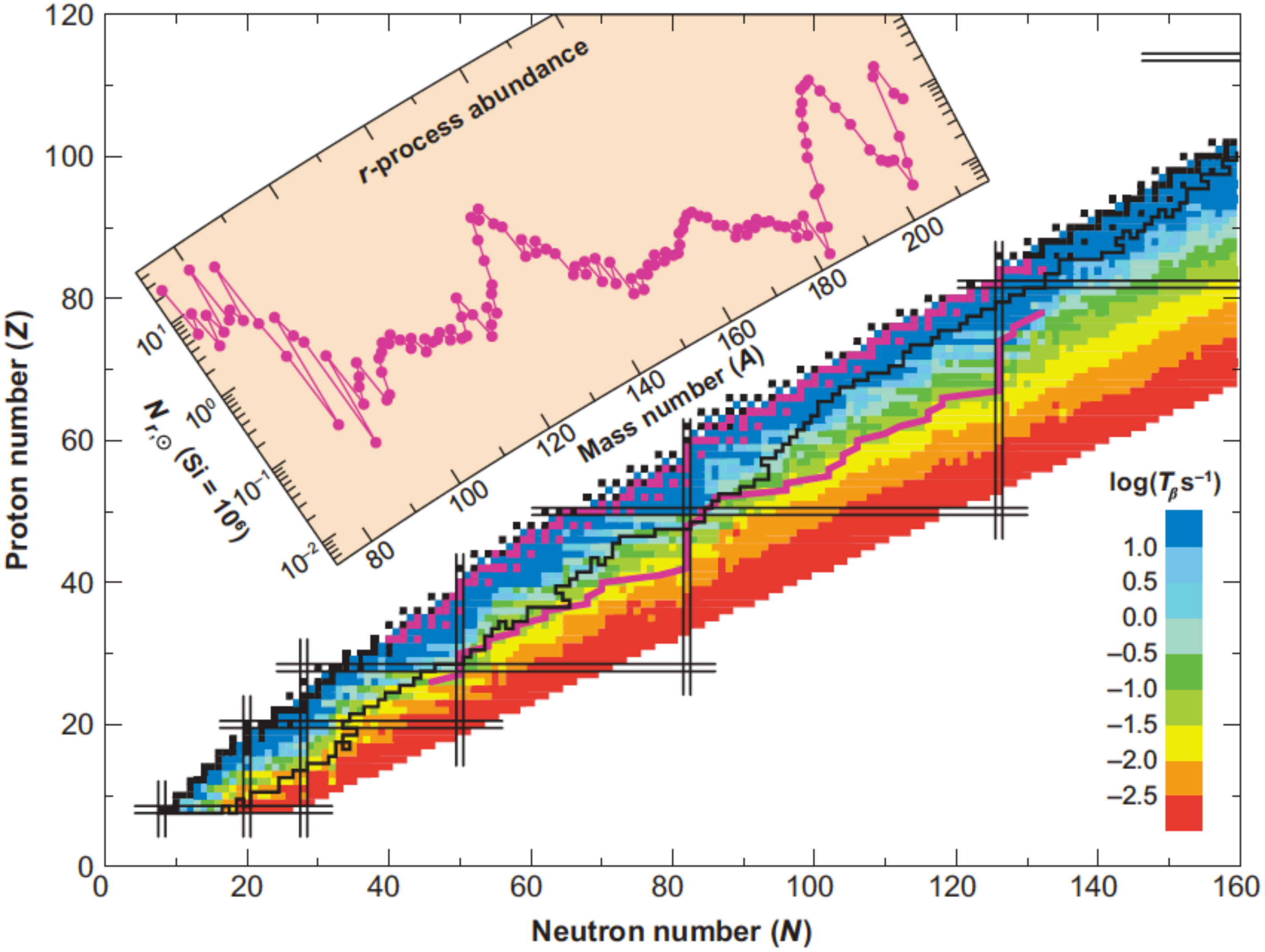
Public network code: Skynet

For more on this, see the lecture notes by Frank Timmes

Nuclear Data: Uncertainties

The nuclei involved in the r-process are unstable to beta decay (by definition). The more neutron rich, the shorter the beta decay lifetime.

The properties of many these nuclei (e.g., binding energy / nuclear masses) are not known experimentally: theoretical extrapolation calibrated with known data.



Möller, Nix, & Kratz (1997)

The nuclear physicists are constantly studying these properties in rare isotope beam facilities like TRIUMF (Canada) and FRIB (US) or the upcoming GSI-FAIR (Germany). The large number of nuclei and short lifetimes require a targeted approach: informed by astrophysics!

e.g., Mumpower et al. (2016)

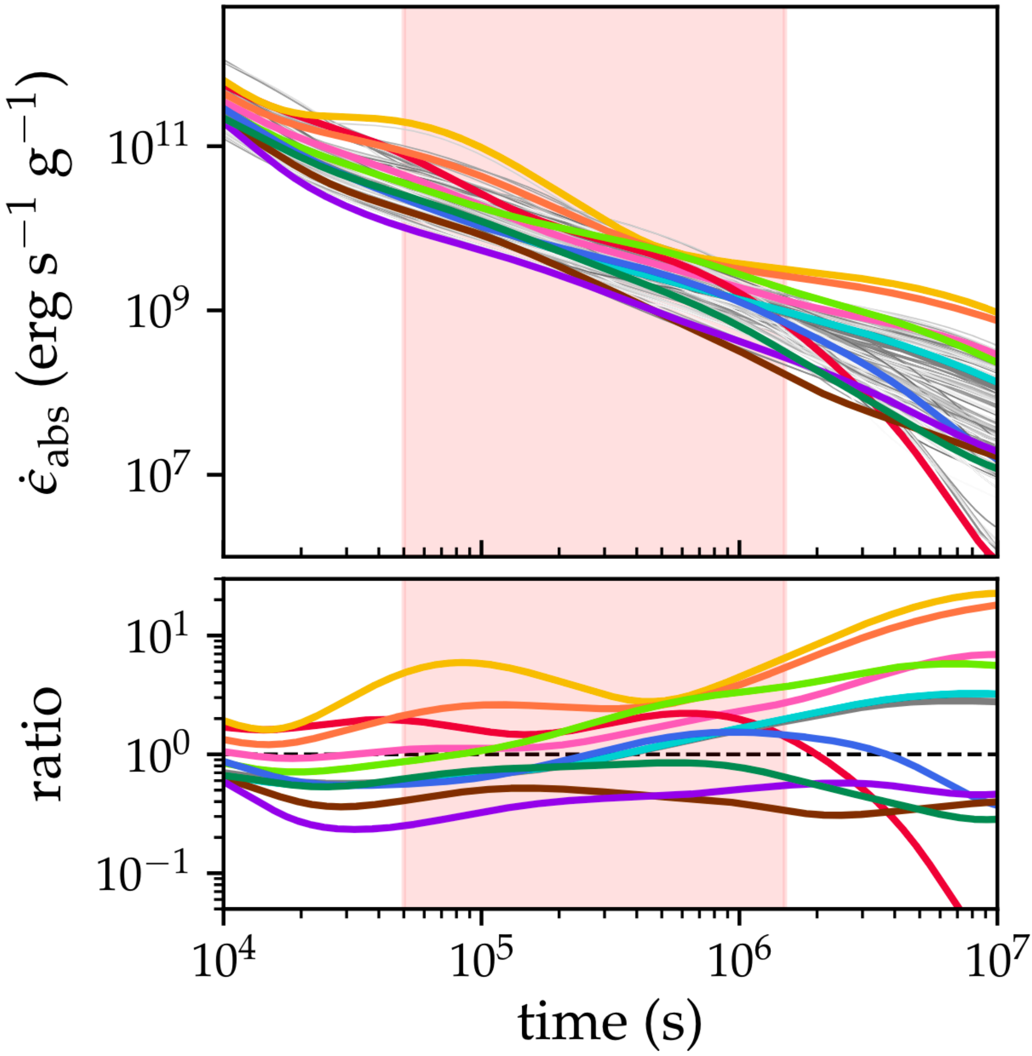
R-process Heating: Nuclear Uncertainties

Nuclear uncertainties have a direct impact on kilonova predictions in two ways:

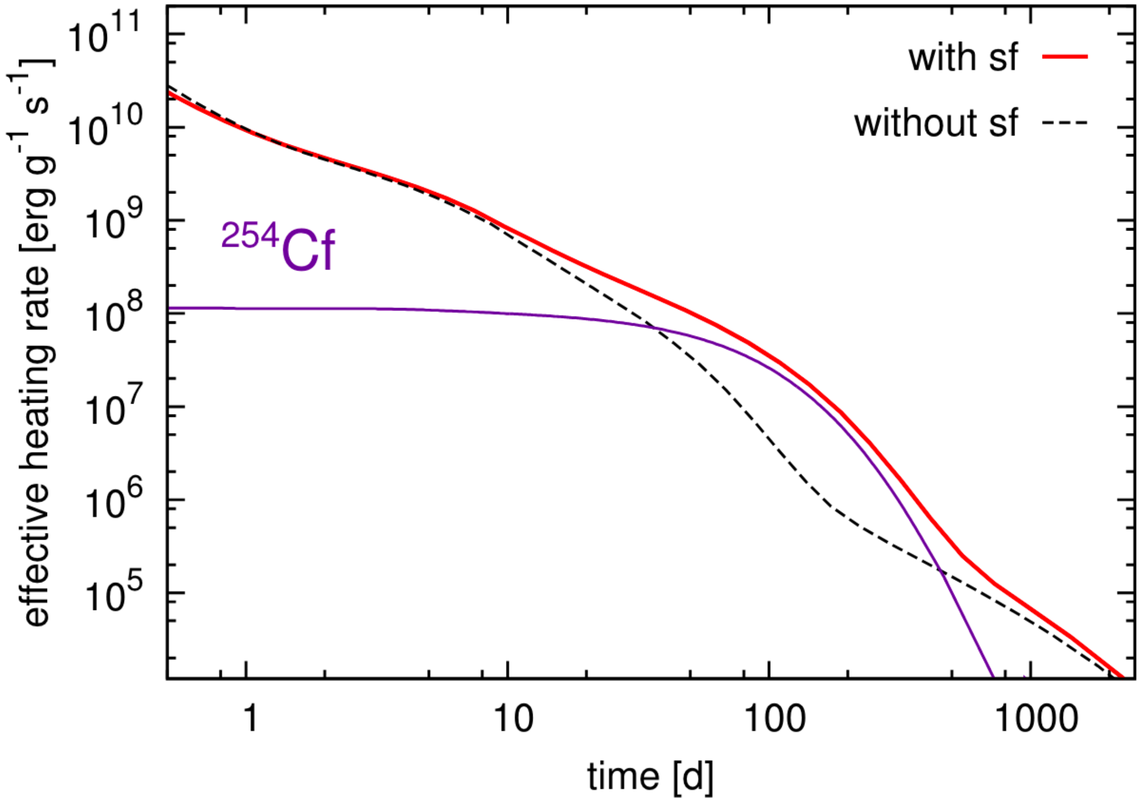
1) Uncertainties in the abundances, which affect opacities and heating rates

2) For fixed abundances, uncertainties in nuclear properties (beta decay, fission, etc) that affect the heating rate.

At late time, individual nuclei can have an outsize importance in setting the heating rate, modifying the time-dependence of kilonova light curves.



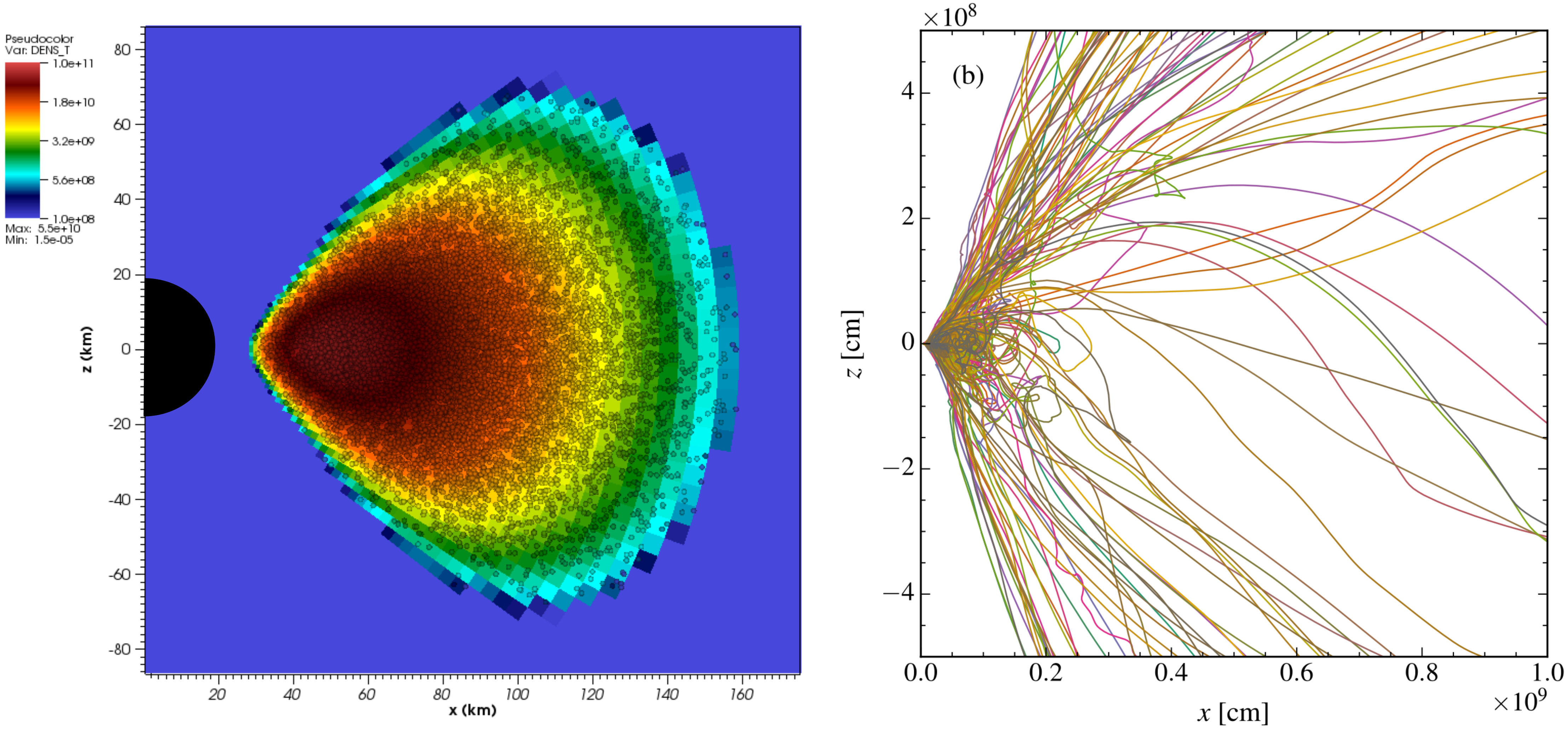
Barnes et al. (2021)



Zhu et al. (2018)

Tracer Particles & Trajectories

To compute nucleosynthesis from simulation ejecta, the traditional approach is to use passive tracer particles that sample the ejecta in mass. Each particle generates a thermodynamic trajectory in time, which is then used as input to the nuclear reaction network.



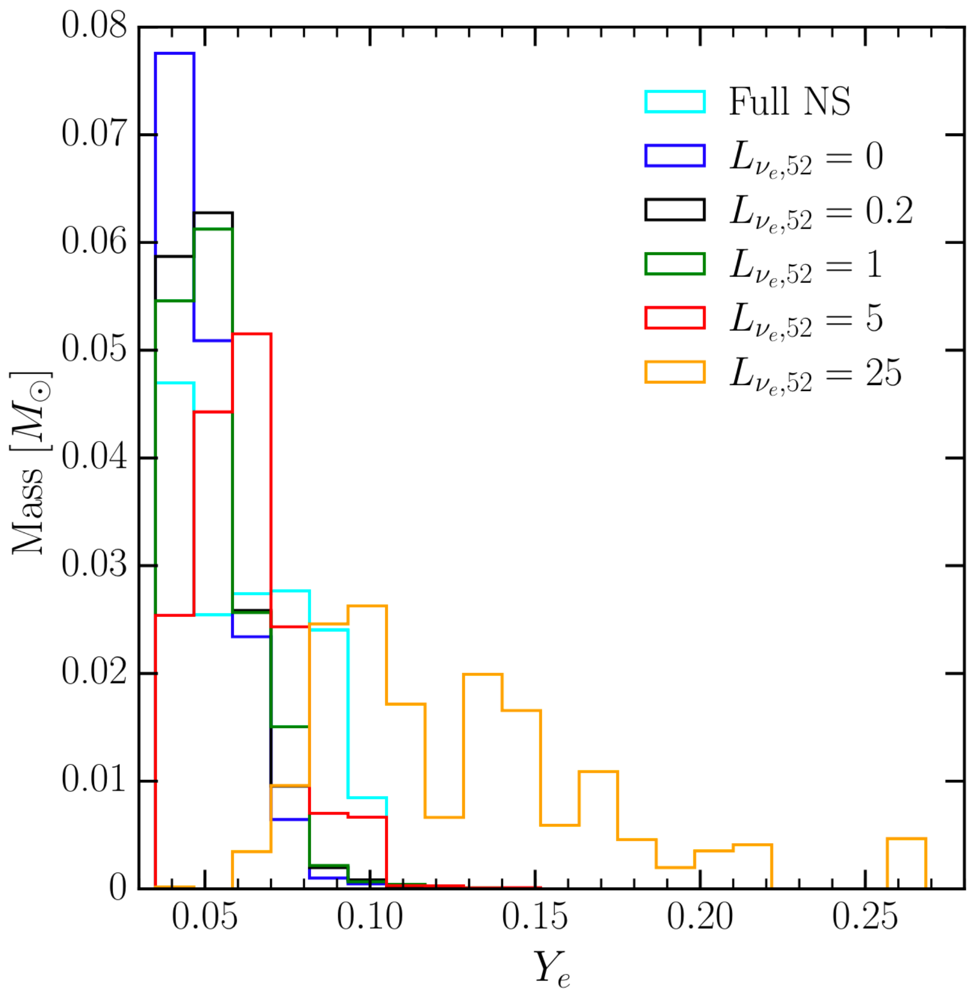
Wu et al. (2016)

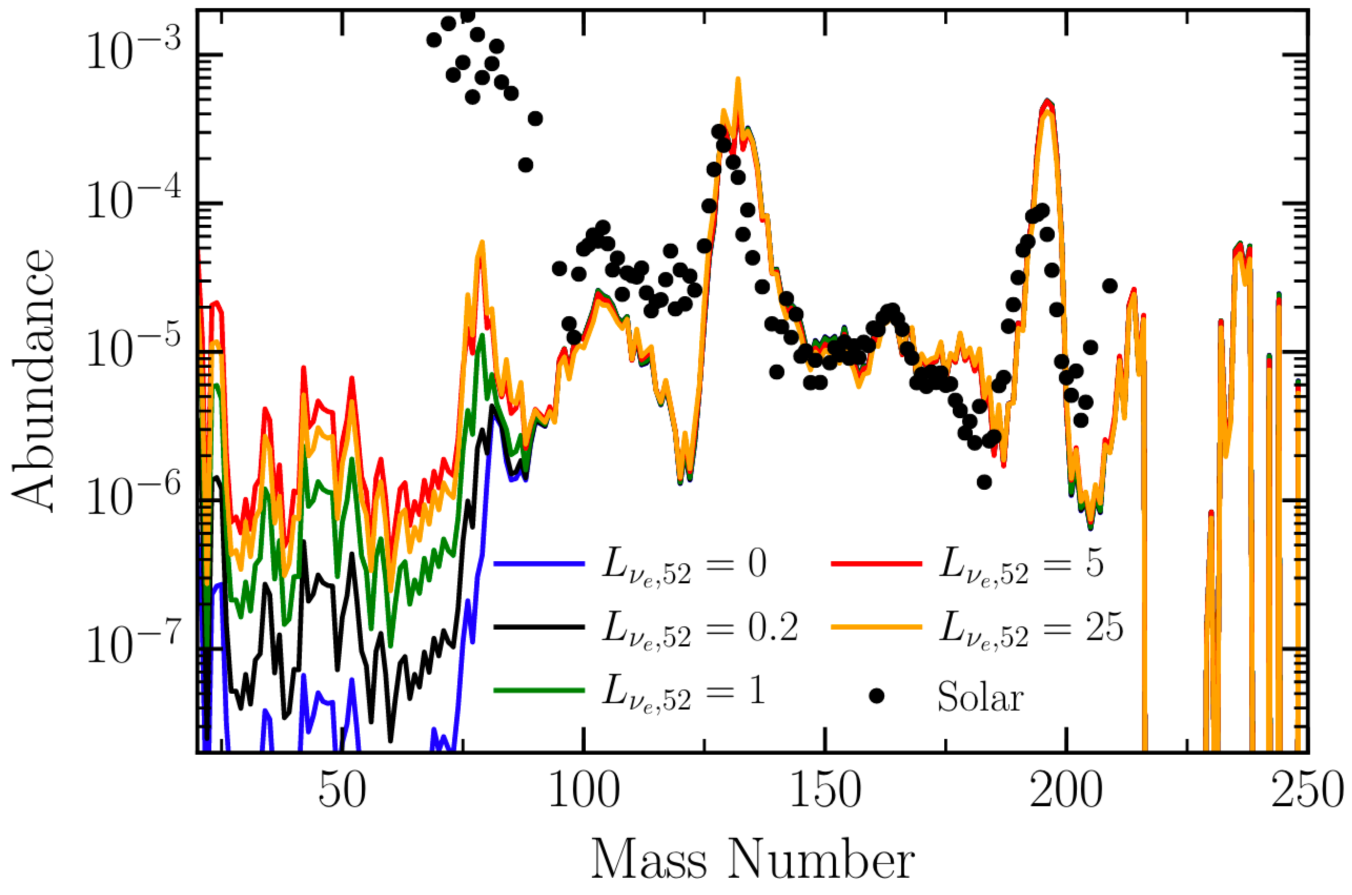
NS Mergers: Ejecta Components

Matter is initially very neutron-rich (Y_e ~ 0.05 from cold NS matter):

1) Tidal dynamical ejecta (BHSN) preserves initial Ye and expands quickly: ideal for producing heavy r-process elements, including fission cycles that generate universal abundance curve above 2nd peak.

Freiburghaus et al. (1999)



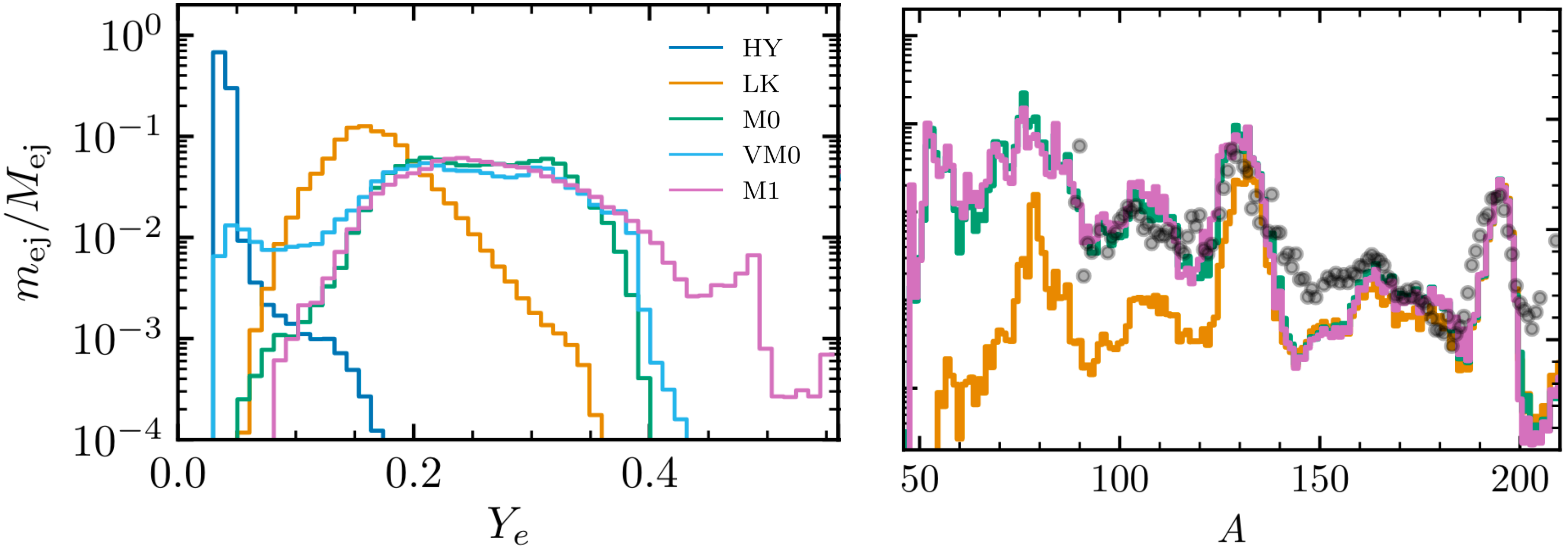


Roberts et al. (2017)

NS Mergers: Ejecta Components

Matter is initially very neutron-rich (Y_e ~ 0.05-0.1 from cold NS matter):

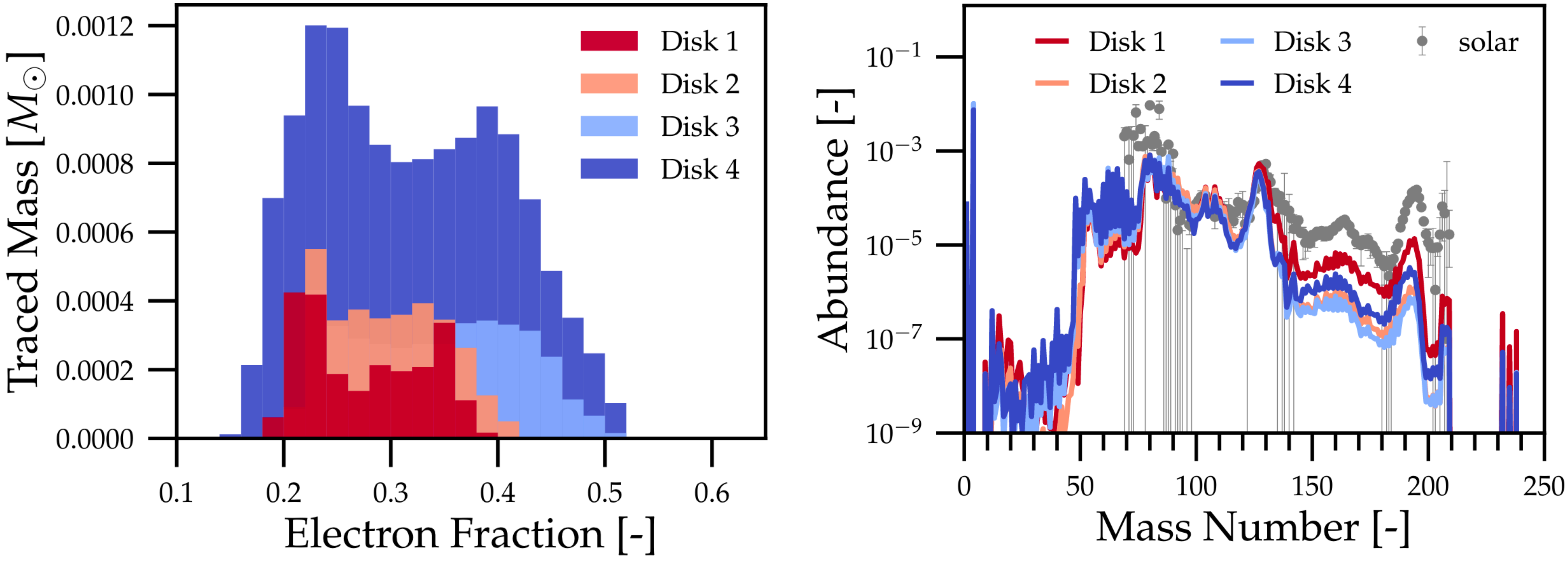
2) Shocked dynamical ejecta (NSNS) undergoes some reprocessing by neutrinos, so the electron fraction can increase



Zappa et al. (2023)

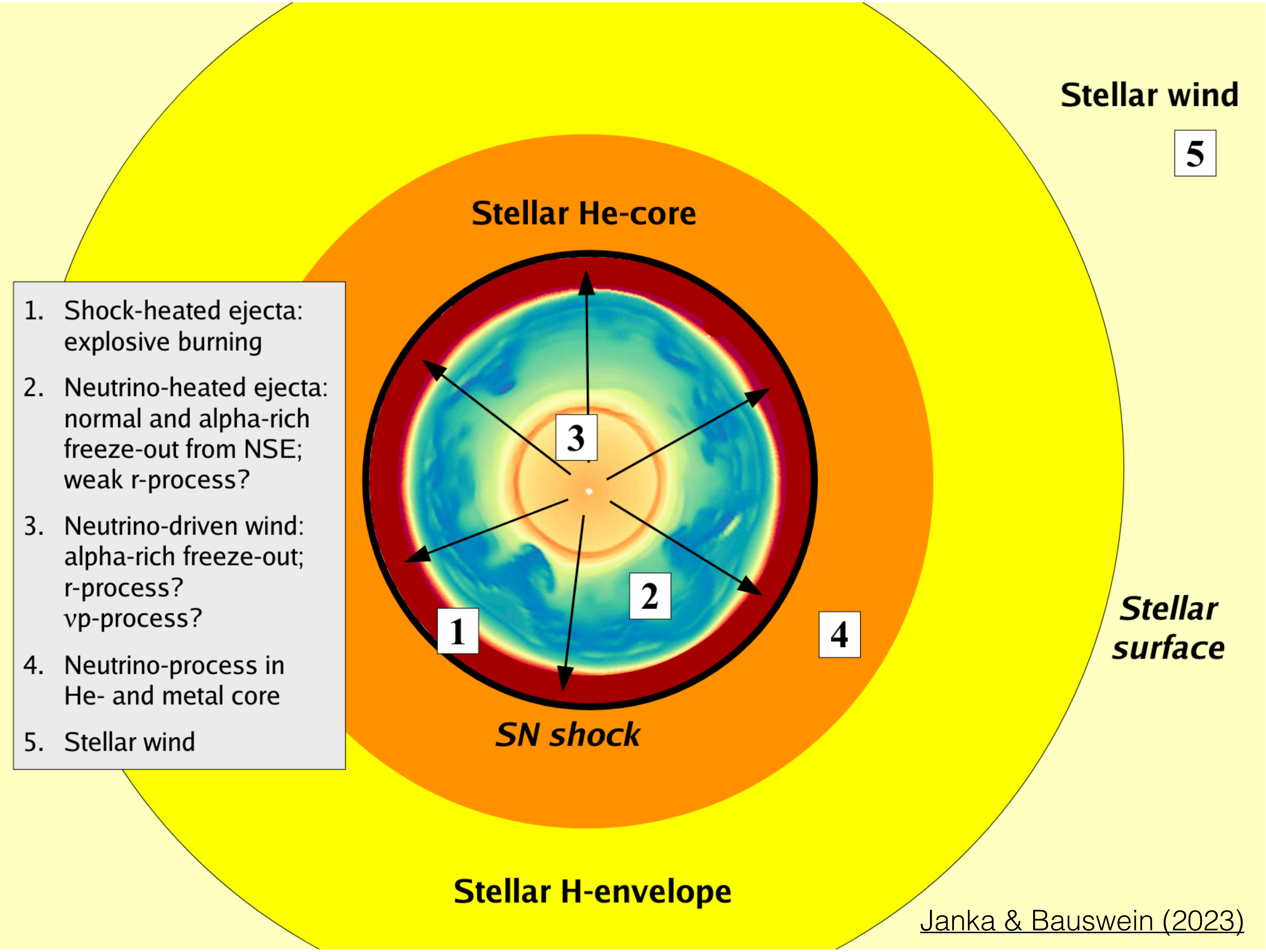
NS Mergers: Ejecta Components

3) Disk outflow undergoes significant neutrino reprocessing, broad distribution of Ye



Curtis et al. (2023)

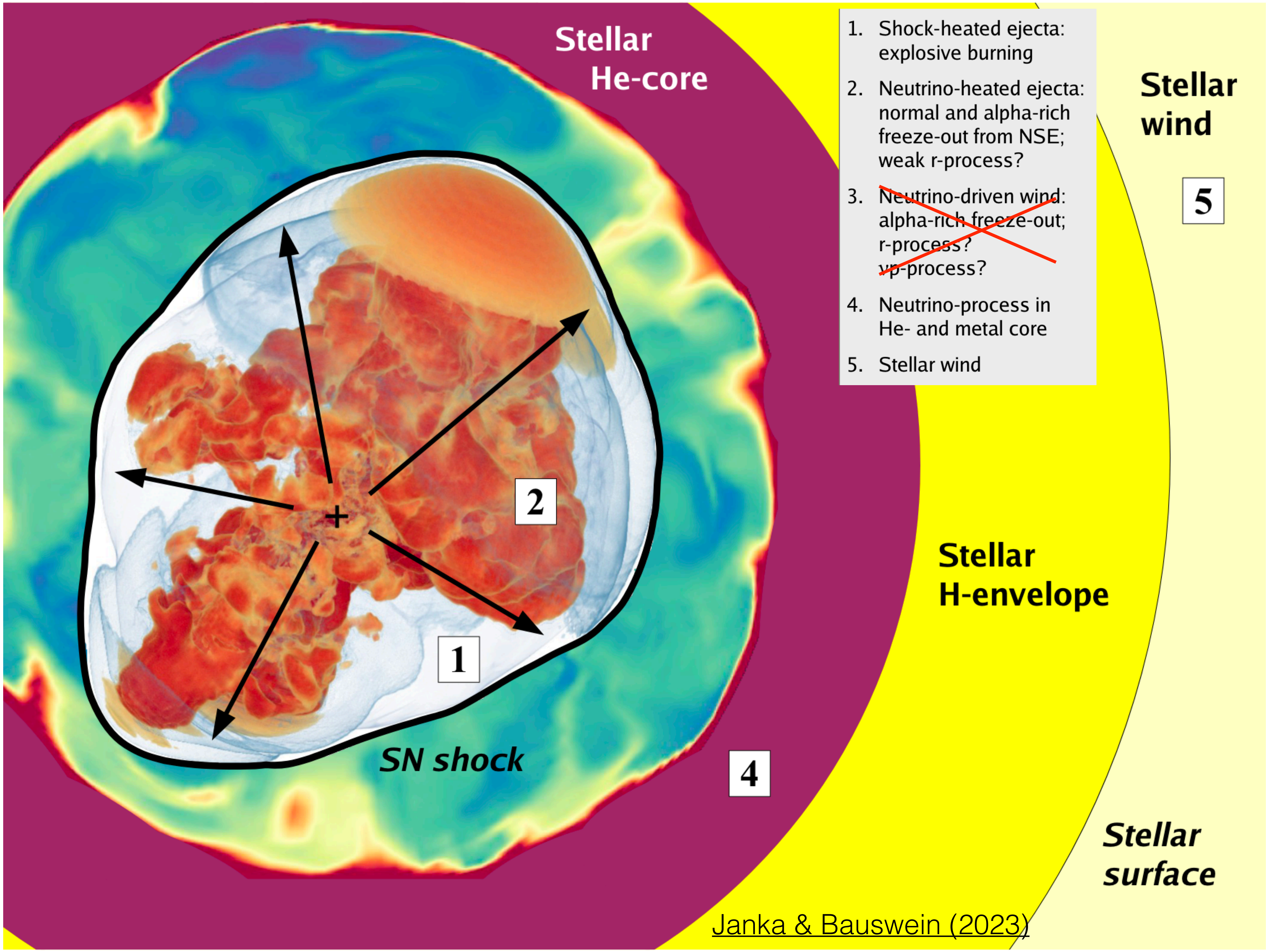
ECSNe (ONeMg): Ejecta Components



1. Shock-heated ejecta: explosive burning
2. Neutrino-heated ejecta: normal and alpha-rich freeze-out from NSE; weak r-process?
3. Neutrino-driven wind: alpha-rich freeze-out; r-process? νp-process?
4. Neutrino-process in He- and metal core
5. Stellar wind

Janka & Bauswein (2023)

Iron Cores: Ejecta Components



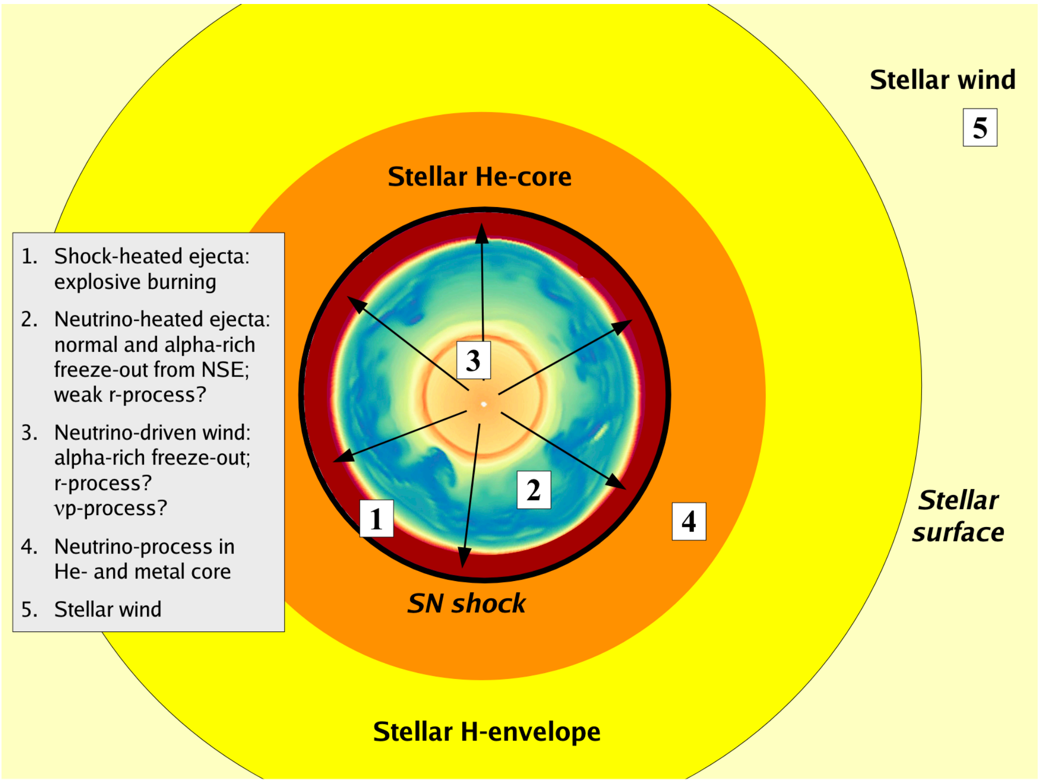
1. Shock-heated ejecta: explosive burning
2. Neutrino-heated ejecta: normal and alpha-rich freeze-out from NSE; weak r-process?
3. ~~Neutrino-driven wind: alpha-rich freeze-out; r-process? νp-process?~~
4. Neutrino-process in He- and metal core
5. Stellar wind

Janka & Bauswein (2023)

CCSN Ejecta Composition

Stellar Wind: ejects material in the star as well as that produced by shell burning, brought to the surface by transport processes like convection or rotationally-induced flows.

Shock heated ejecta: material outside r = 10,000 - 15,000km is cold enough that no significant nuclear processes occur, this happens primarily for material lighter than oxygen.



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3. Neutrino-driven wind: alpha-rich freeze-out; r-process? νp-process?
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Janka & Bauswein (2023)

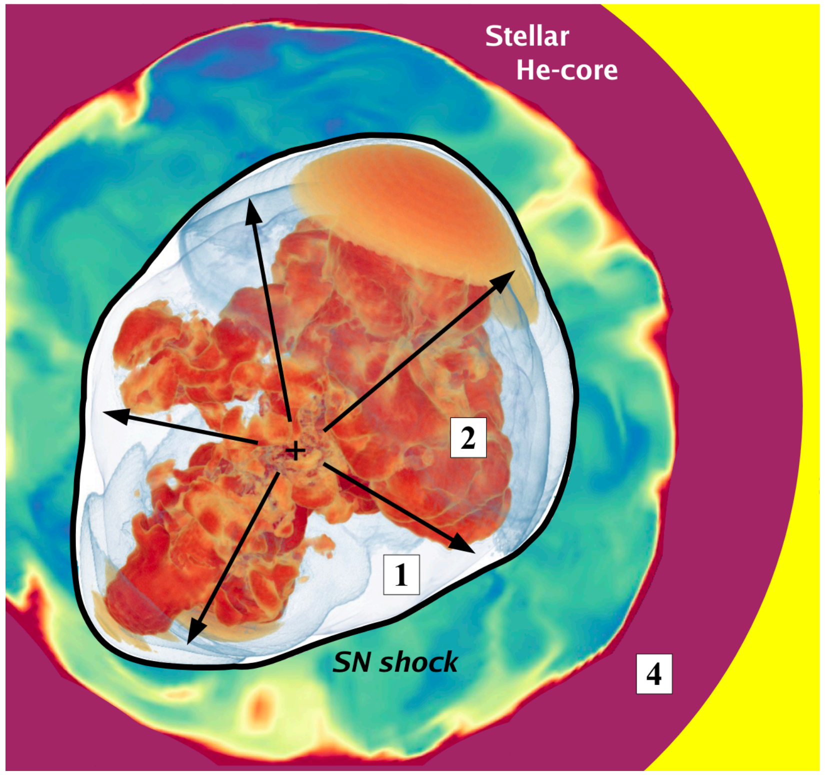
Deeper inside, shock heated ejecta contains the products of explosive burning of Si, O, Ne, and C. This material reaches NSE and produces mostly iron group elements. Retains its original Ye because the shock expansion is too fast for weak interactions to change the composition.

CCSN Ejecta Composition

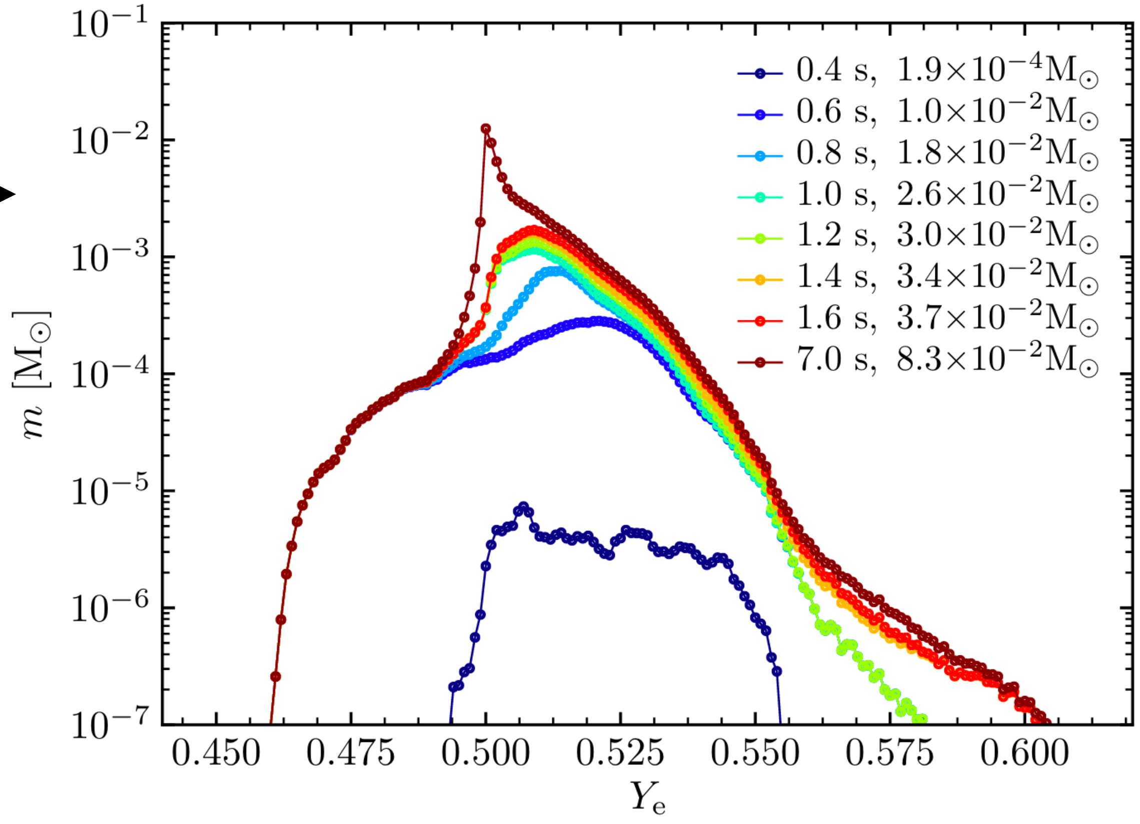
Neutrino Heated Ejecta: this material resides in the gain region and has its Ye modified by neutrino absorption. All matter reaches NSE.

In iron cores, Ye ~ 0.5 or larger due to the longer residency time of matter in the gain region, so this component makes ^{56}Ni as well as proton-rich nuclei in the iron group and up to ^{92}Mo.

ECSNe undergo more rapid shock expansion, to material in this component is exposed to neutrinos for a shorter time, with a correspondingly lower Ye. Can make neutron-rich trans iron elements (Zn) and even 1st peak r-process elements.



Janka & Bauswein (2023)

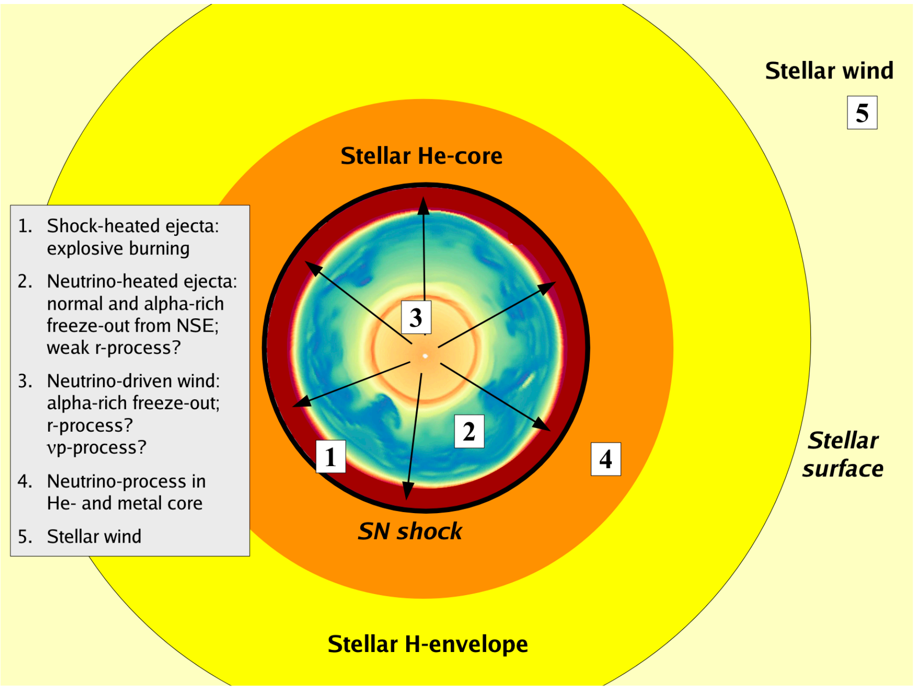


Bollig et al. (2021)

CCSN Ejecta Composition

Neutrino driven wind: during the late-time contraction and cooling of the PNS, the atmosphere is subject to neutrino heating and does not allow for a hydrostatic solution: secular and mostly spherical wind.

Duncan et al. (1986) Qiang & Woosley (1996)



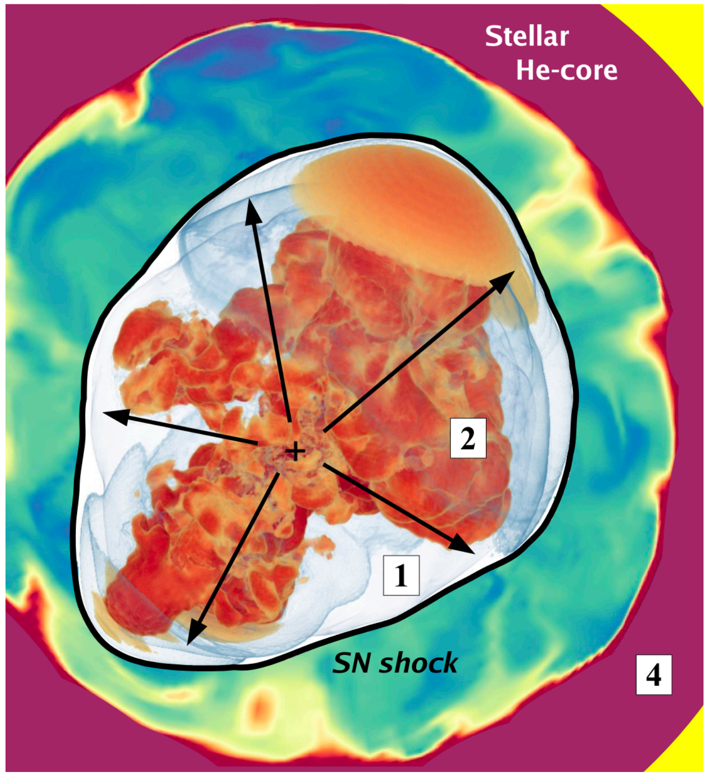
Janka & Bauswein (2023)

Prevalent in ECSN ejecta, while in iron core ejecta a spherical cavity does not develop because of continued accretion from downward plumes.

Neutrino absorption dominates over emission, Ye ~ 0.5 because luminosities of electron neutrinos and antineutrinos are similar. This was originally considered an r-process site, but modern simulations find that the conditions allow at most light r-process production.

Wanajo et al. (2018), Witt et al. (2021), Wang & Burrows (2023)

CCSN Ejecta Composition

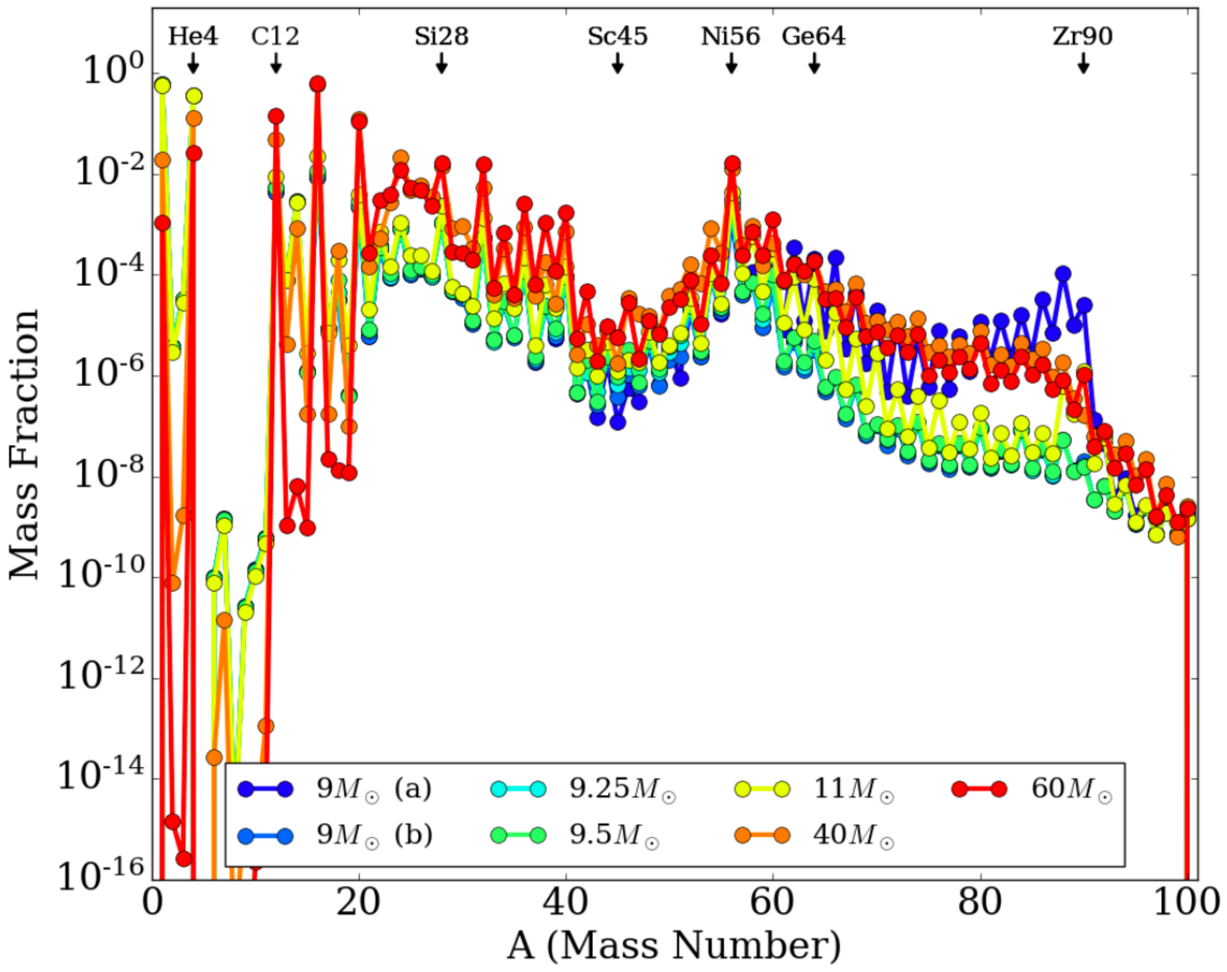


Janka & Bauswein (2023)

He Shell and metal core: before shock passage, the external layers of the star are subject to the intense neutrino flux from the PNS, which can induce non-trivial nuclear processes that produce rare isotopes.

e.g., Sieverding et al. (2019)

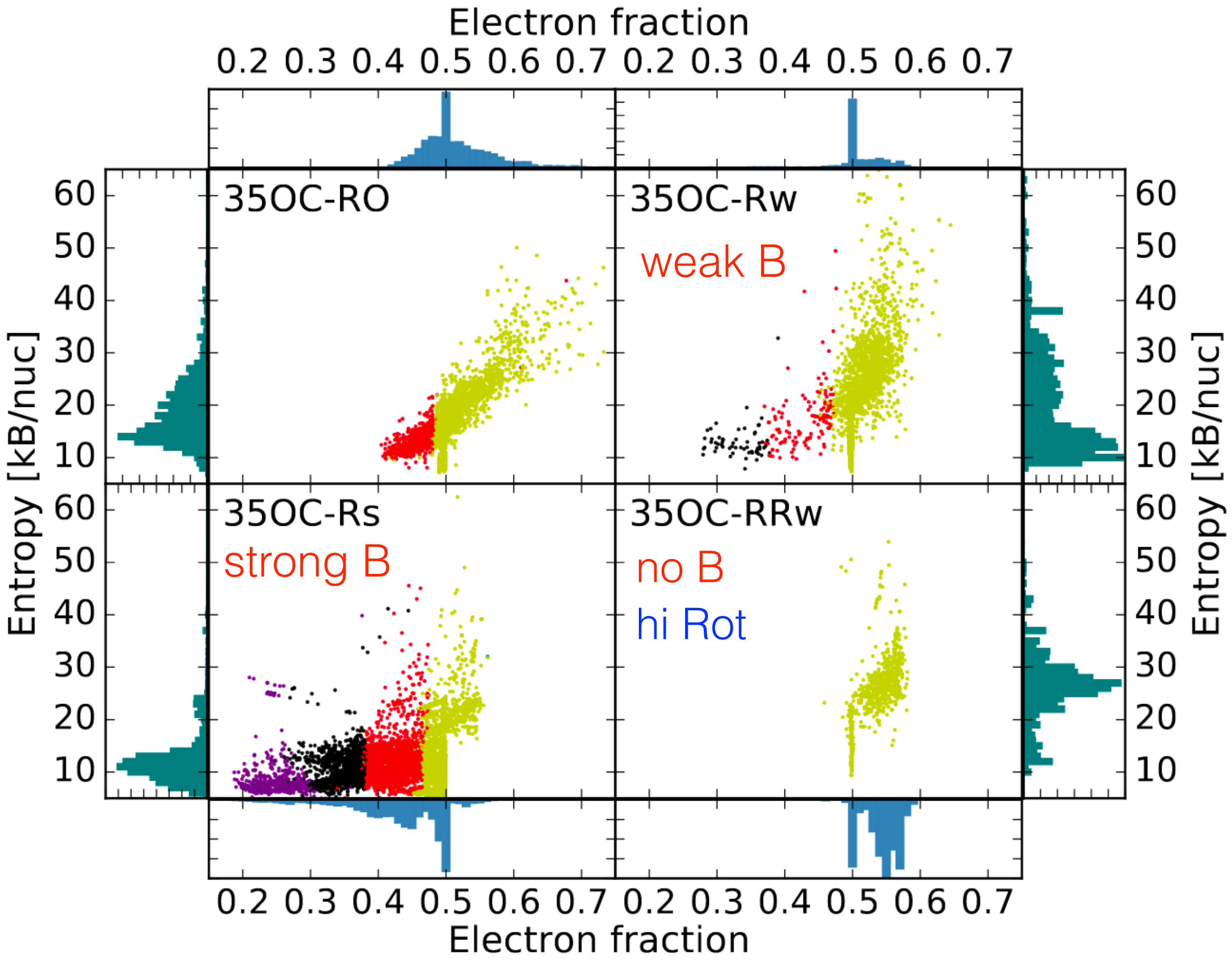
Overall, the ejecta from CCSNe is mostly alpha elements plus iron and trans-iron group elements. Yields appear to be somewhat sensitive to progenitor.

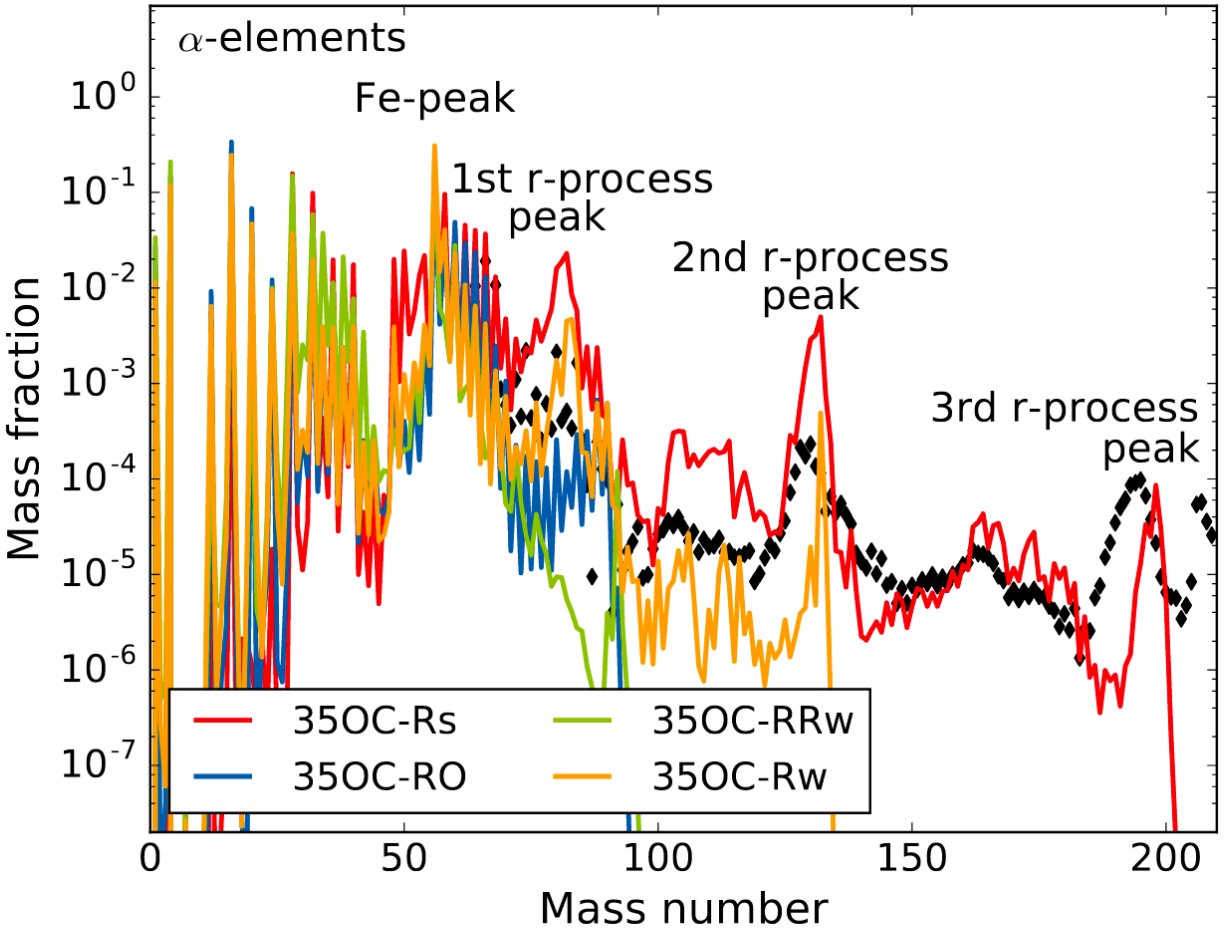


Wang & Burrows (2023)

Magnetorotational CCSNe

Production of heavy r-process elements is obtained, but for cases of strong initial magnetic field, which produces a magnetically-dominated explosion. This appears to be a requirement for this mechanism to remain an r-process candidate.





Reichert et al. (2021)