Supernova nucleosynthesis (and how to model it)

Russbach School on Nuclear Astrophysics 2025

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Prepared by LLNL under Contract DE-AC52-07NA27344.

Andre Sieverding

Nucleosynthesis with multi-dimensional supernova simulations
Thanks to my collaborators!

- Thanks to my collaborators
- H.T. Janka, D. Kresse, R. Glas (Max-Planck Insitute for Astrophysics)
- W.R.Hix, J.A. Harris, E.J. Lentz (Oak Ridge National Laboratory)
- S. Bruenn (Florida Atlantic University)
- J. Randhawa, R.J. DeBoer, T. Ahn (University of Notre Dame)
- D. Zetterberg (University of Tennessee)
- Y.-Z. Qian (University of Minnesota)
- B. Müller, A. Heger (Monash University)
- G. Martinez-Pinedo,
- M. Lugaro (Konkoly Observatory)
- ...

MARIE CURIE ACTIONS

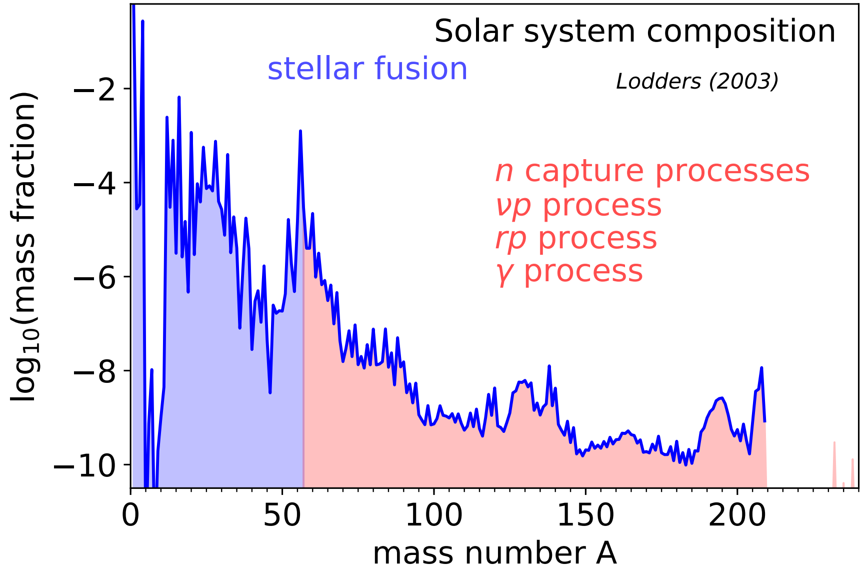
MAX PLANCK INSTITUTE
FOR ASTROPHYSICS

Outline

1. Core-collapse supernova mechanism
2. 1D models
3. Multi-D models
4. Insights from 3D models and the role of neutrinos

Nucleosynthesis and chemical evolution

- Stars and stellar explosions provide the conditions necessary for nuclear reactions
- Life cycles of stars enrich the interstellar gas with nucleosynthesis products
- Massive stars and core-collapse supernova are crucial:
- **Stellar and explosive nucleosynthesis**



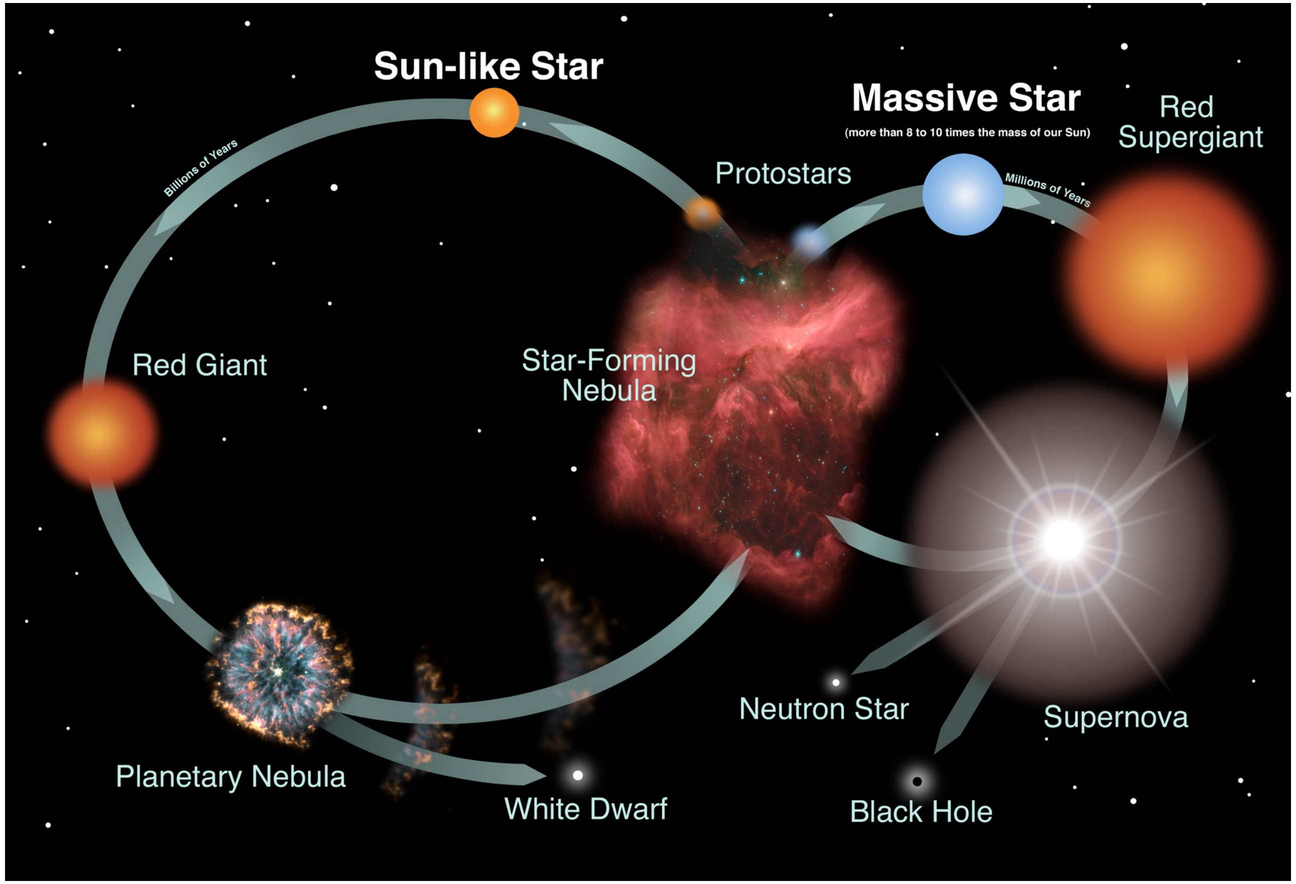
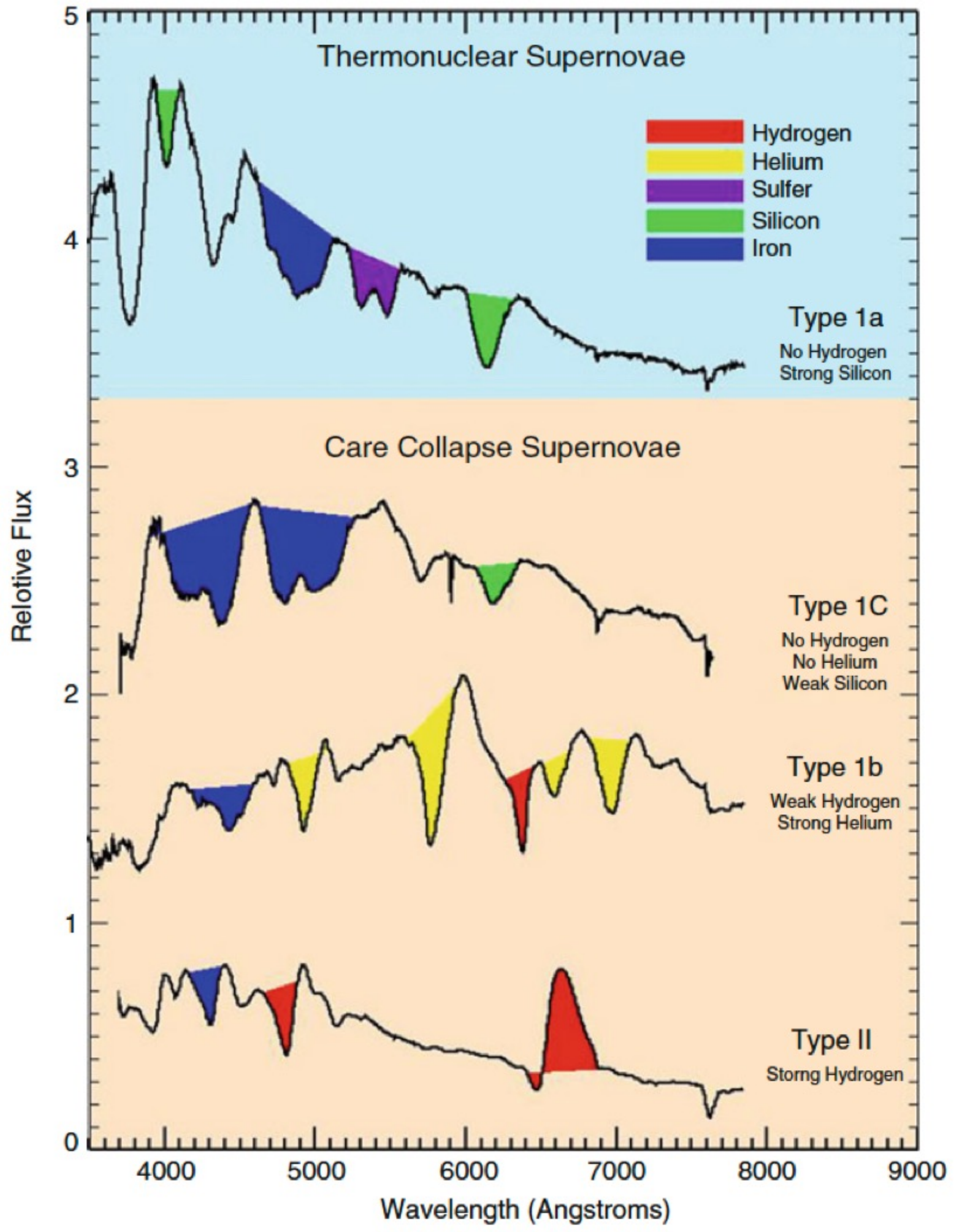


Image credit: NASA and the Night Sky Network

Supernova classification

- Most SN observations are extra-galactic
- **Astronomy classification:** based on spectra (Type I a,b,c, Type II)
- **Astrophysics classification:** progenitor system, explosion mechanism
- Thermonuclear SNe → Type Ia
- **Core-collapse** of massive stars that have retained their H envelope → Type II
- Core-collapse of stripped, binary stars (that have lost most or all of their H envelope) → Type Ib,c

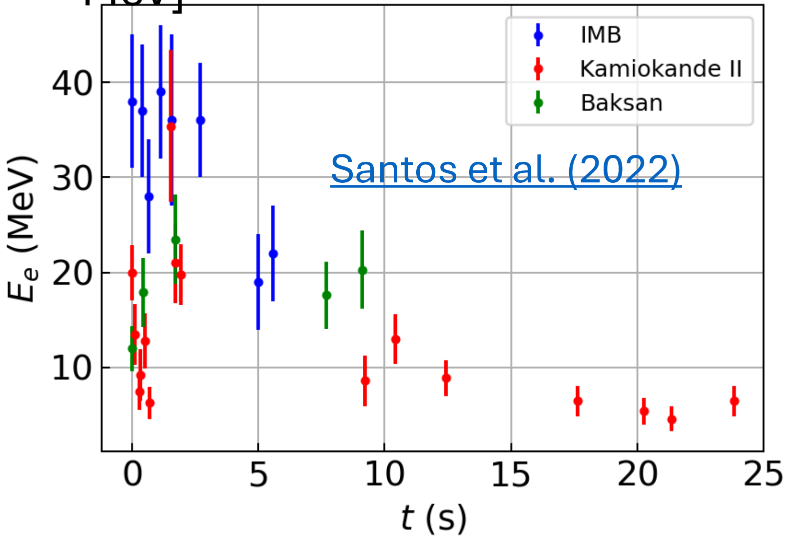


Observational signatures

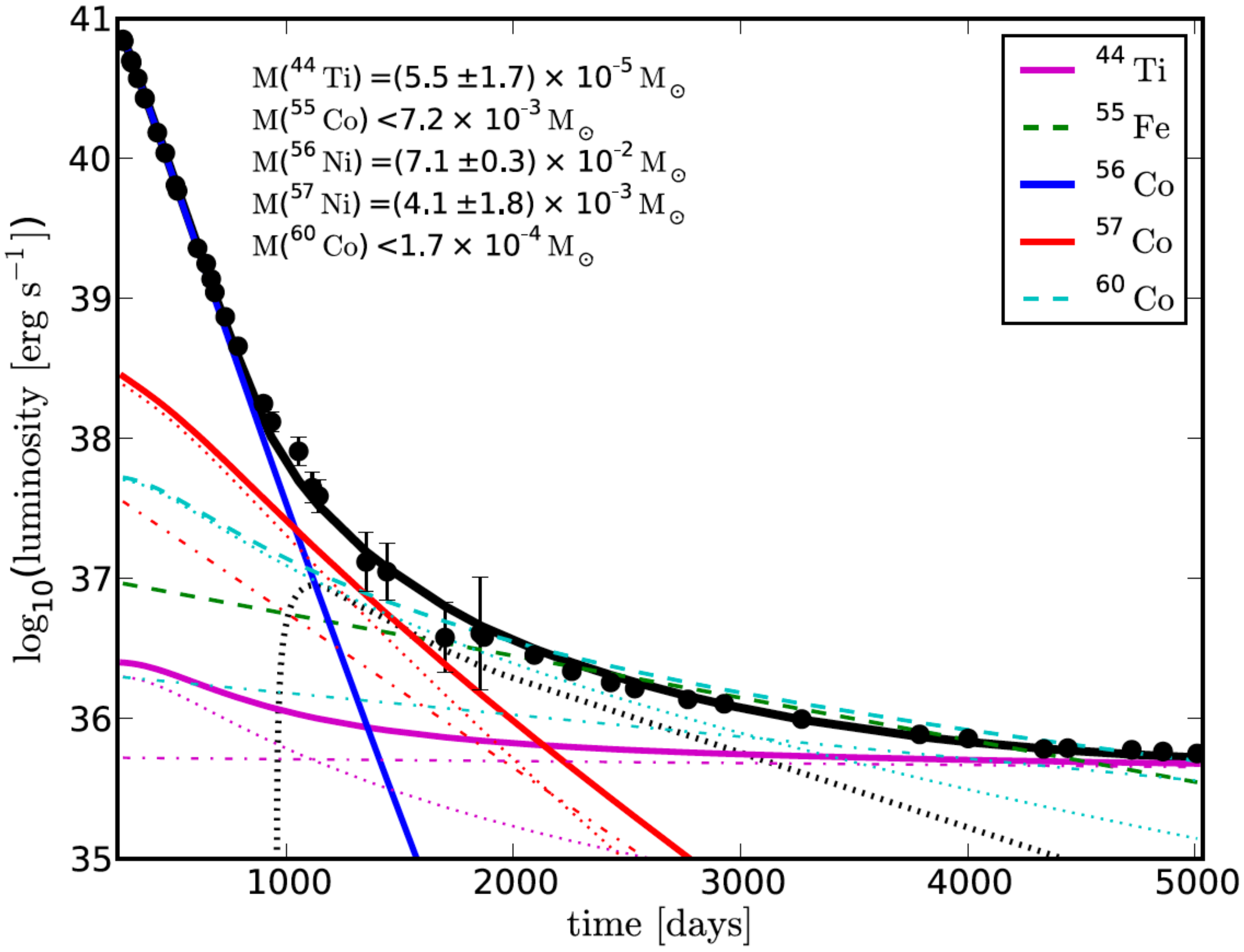
[1 erg = g cm / s^2 = 6.24 x 10^5 MeV]

- Fades on timescales of years
- Associated with massive stars (> 10)
- Typical kinetic energies of 10^{51} erg* = 1 FOE = 1B
- EM emission powered by radioactive decay, mostly $^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$
- Neutrino emission observed in SN1987A

[1 erg = g cm^2 / s^2 = 6.24 x 10^5 MeV]



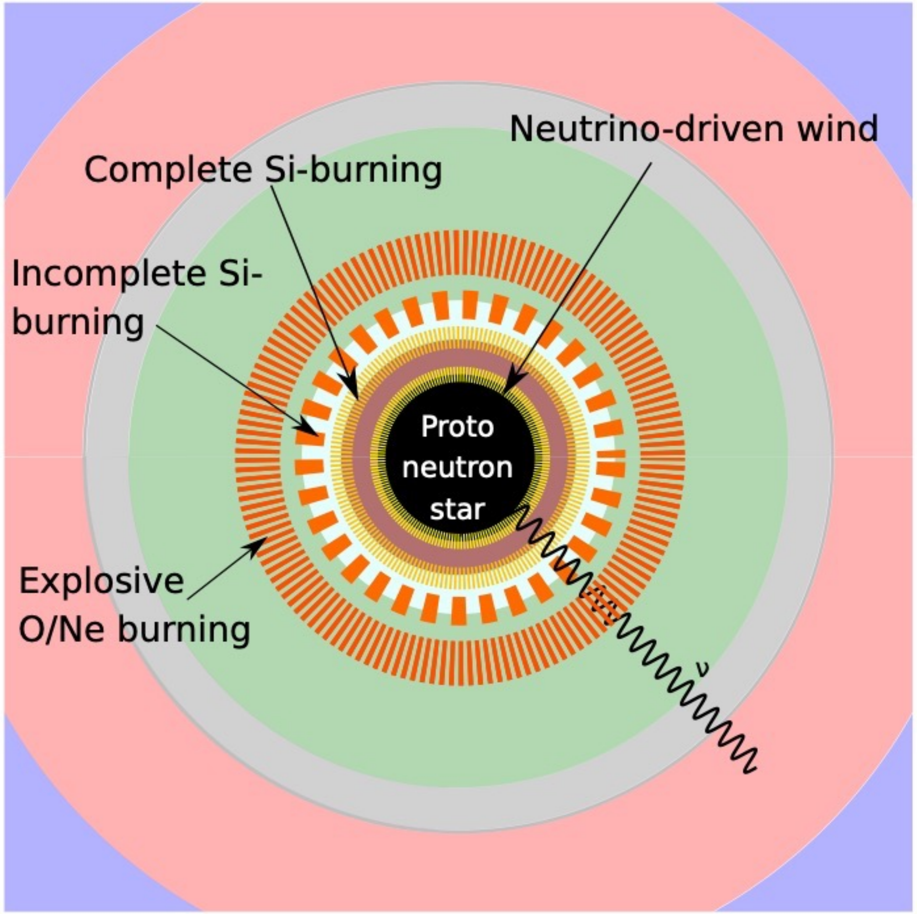
Santos et al. (2022)



Seitenzahl et al. 2014

Core-collapse supernova nucleosynthesis

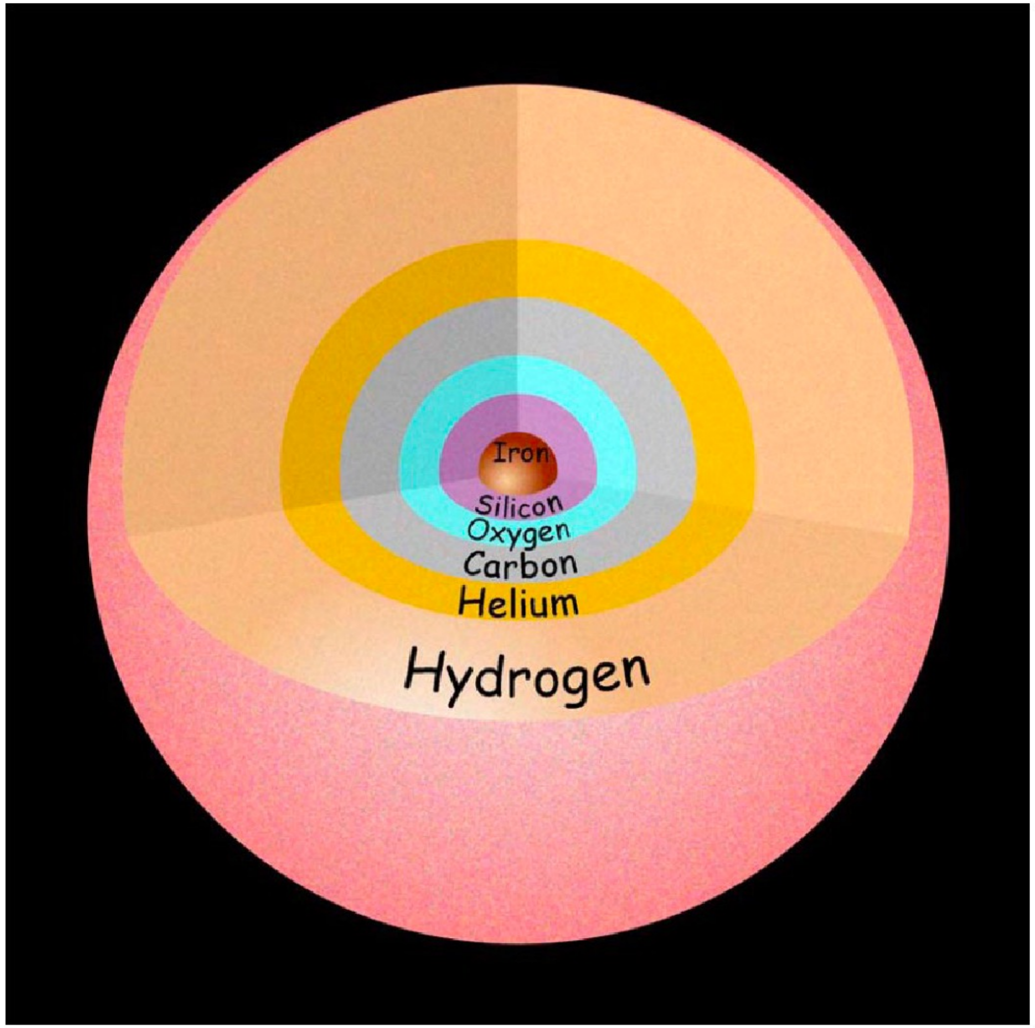
- Rich nucleosynthesis
- *(early) Neutrino heated ejecta*
  - Neutrinos determine conditions
  - $n + \nu_e \leftrightarrow p + e^-$
  - $p + \bar{\nu}_e \leftrightarrow n + e^+$
- *(late) neutrino driven winds*
- *Explosive nuclear burning*
  - Production of   and Fe-group elements
- *Outer layers*
  - Weak s-process
  - n-process
  - γ process
  - ν *process*



Core-Collapse Supernova mechanism

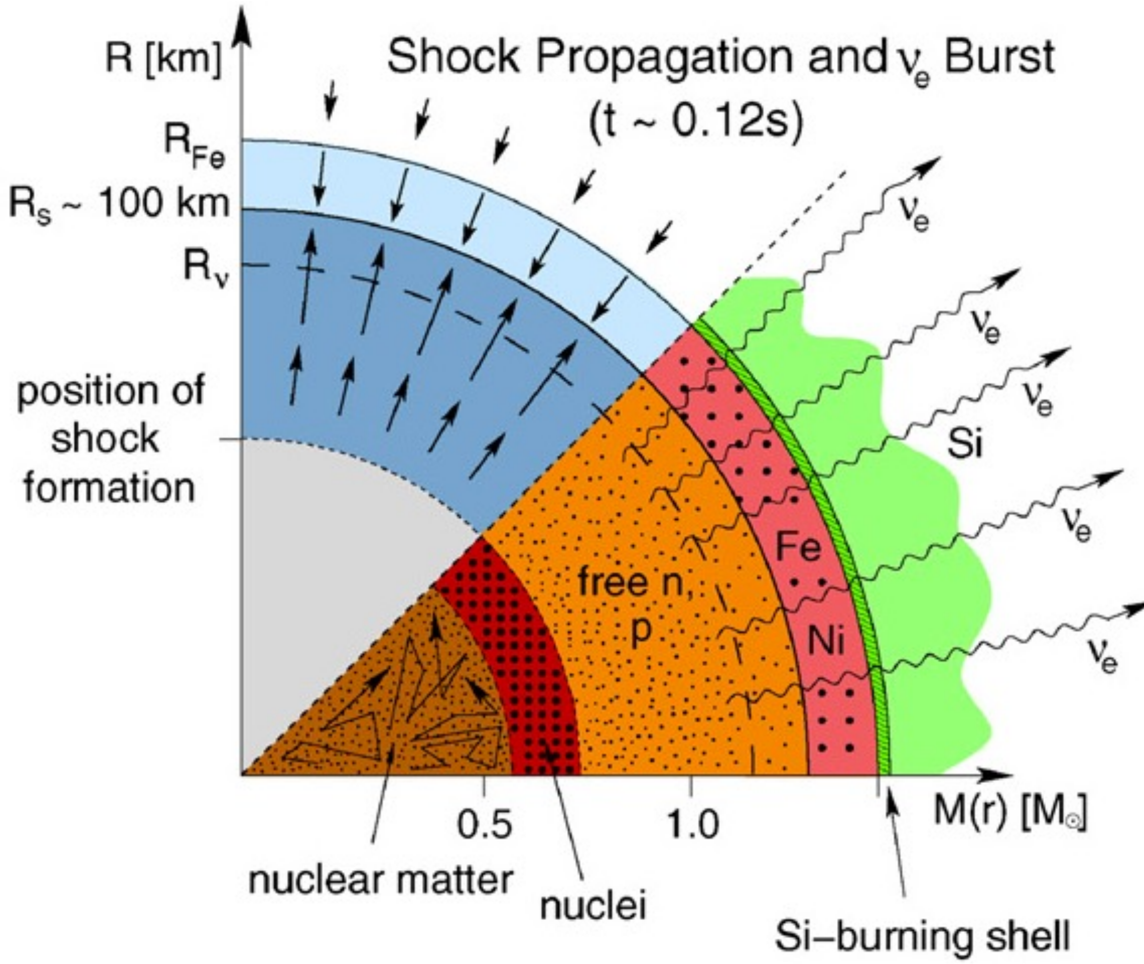
Massive star progenitors and core-collapse

- Massive stars provide the conditions for nuclear burning up to Fe (see lecture by Marco Limongi)
- Fe core eventually collapses

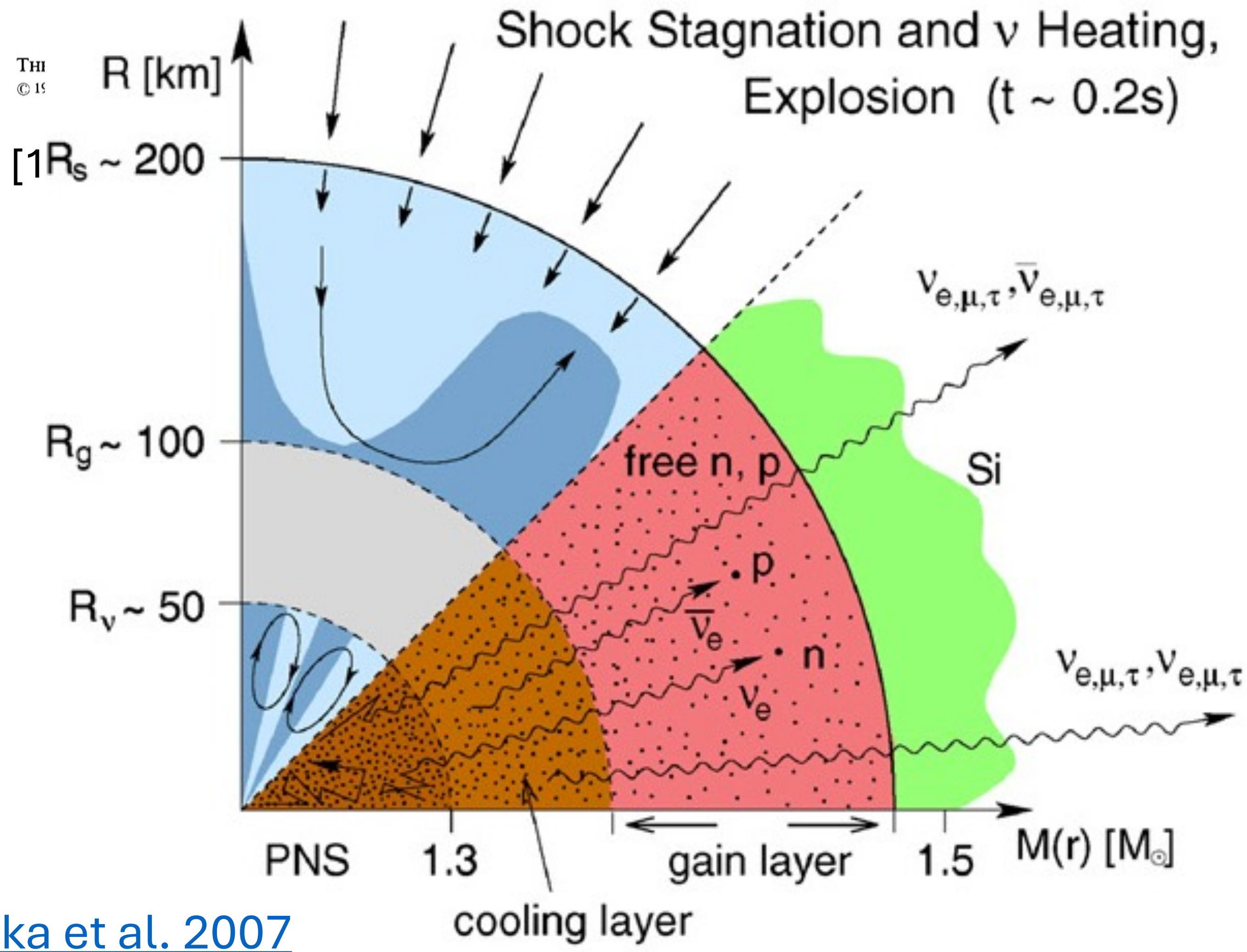


Massive star progenitors and core-collapse

- Massive stars provide the conditions for nuclear burning up to Fe (see lecture by Marco Limongi)
- Fe core eventually collapses
- Electron captures make the matter neutron rich and produce neutrinos
- $(A, Z) + e^- \rightarrow (A, Z-1) + \nu_e$
- Nuclei are dissociated into neutrons and protons
- “Bounce” as nuclear density is reached
- Initial shock stalls

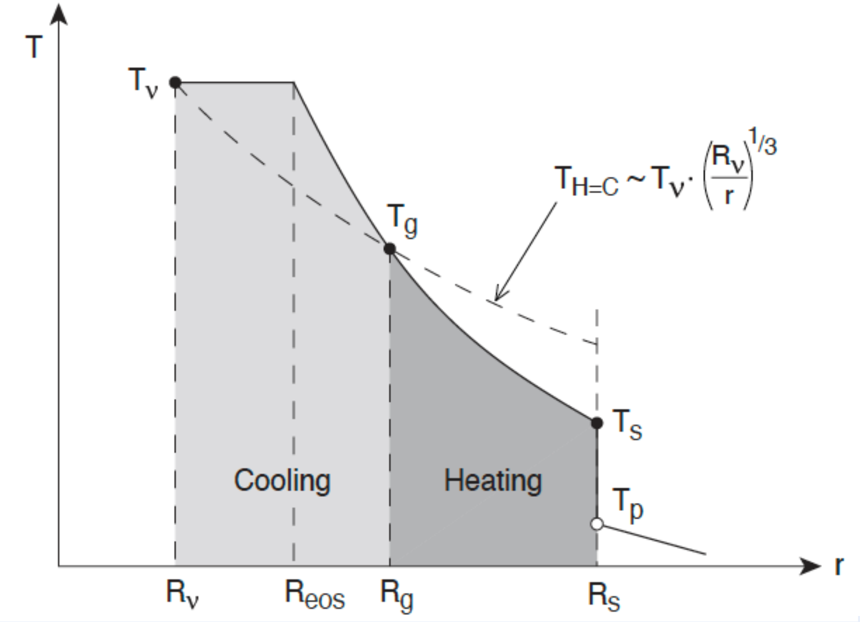


Neutrino driven mechanism



[Janka et al. 2007](#)

- Binding energy of a neutron star = neutrino energy ~10^{53} erg
- Typical SN ejecta kinetic energy ~10^{51} erg
- Heating: $\propto L_{\nu}\, T_{\nu}^{2}/R^{2}$
- Cooling: $\propto T_{m}^{6} \approx \frac{1}{R^{6}}$



Neutrino driven mechanism

THE ASTROPHYSICAL JOURNAL, **295**: 14–23, 1985 August 1

REVIVAL OF A STALLED SUPERNOVA SHOCK BY NEUTRINO HEATING

HANS A. BETHE
Laboratory of Nuclear Studies, Cornell University

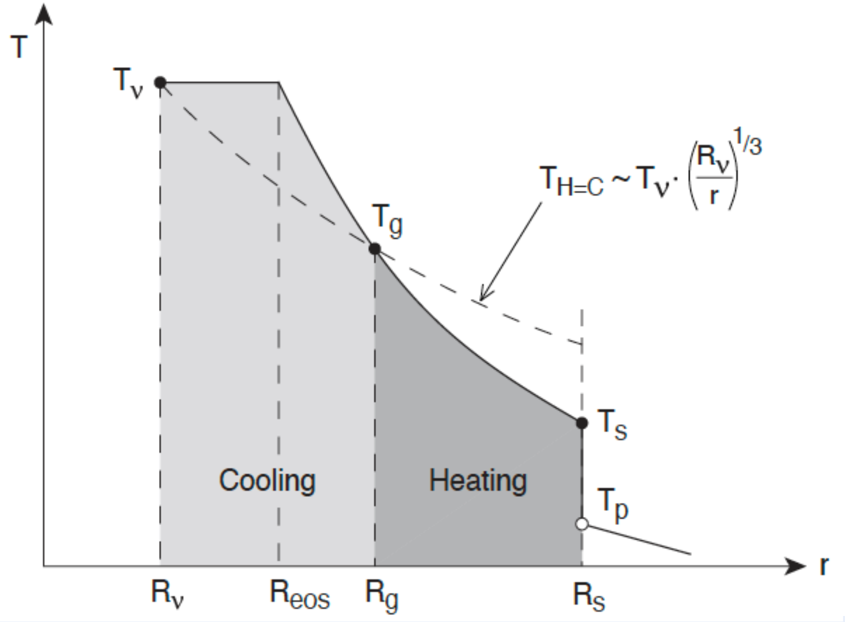
AND

JAMES R. WILSON
Lawrence Livermore National Laboratory
Received 1984 March 23; accepted 1985 February 5

ABSTRACT

We analyze the mechanism for revival of a stalled supernova shock found by one of us (J. R. W.) in a computation. Neutrinos from the hot, inner core of the supernova are absorbed in the outer layers, and although only about 0.1% of their energy is so absorbed, this is enough to eject the outer part of the star and leave only enough mass to form a neutron star. The neutrino absorption is independent of the density of material. After the shock recedes to some extent, neutrino heating establishes a sufficient pressure gradient to push the material beyond about 150 km outward, while the material further in falls rapidly toward the core. This makes the density near 150 km decrease spectacularly, creating a quasi-vacuum in which the pressure is mainly carried by radiation. This is a perfect condition to make the internal energy of the matter sufficient to escape from the gravitational attraction of the star. The net energy of the outgoing shock is about 4×10^{50} ergs.

- Binding energy of a neutron star = neutrino energy ~10^{53} erg
- Typical SN ejecta kinetic energy ~10^{51} erg
- Heating: $\propto L_\nu\, T_\nu^2/R^2$
- Cooling: $\propto T_m^6 \approx \frac{1}{R^6}$



Neutrino driven mechanism

THE ASTROPHYSICAL JOURNAL, 295: 14–23, 1985 August 1

REVIVAL OF A STALLED SUPERNOVA SHOCK BY NEUTRINO HEATING

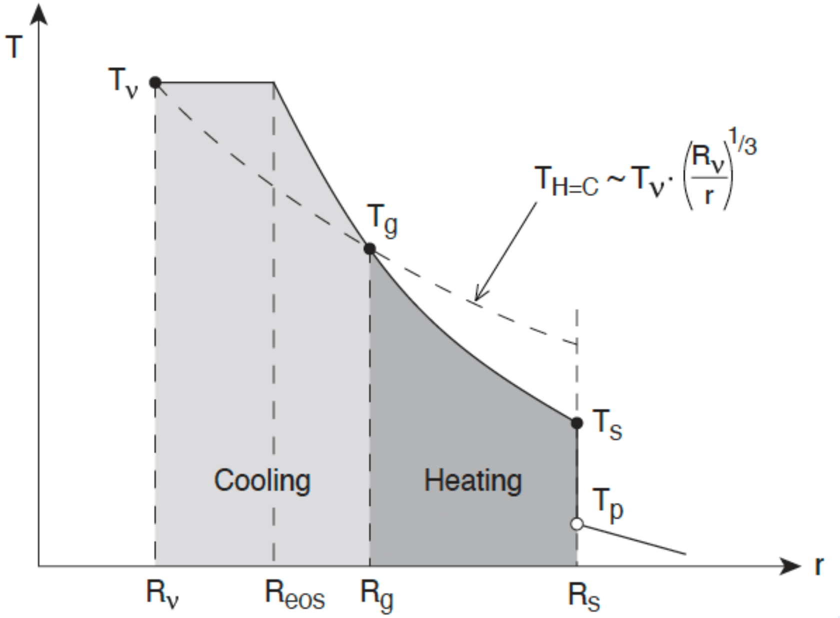
HANS A. BETHE
Laboratory of Nuclear Studies, Cornell University
AND
JAMES R. WILSON
Lawrence Livermore National Laboratory
Received 1984 March 23; accepted 1985 February 5

ABSTRACT

We analyze the mechanism for revival of a stalled supernova shock found by one of us (J. R. W.) in a computation. Neutrinos from the hot, inner core of the supernova are absorbed in the outer layers, and although only about 0.1% of their energy is so absorbed, this is enough to eject the outer part of the star and leave only enough mass to form a neutron star. The neutrino absorption is independent of the density of material. After the shock recedes to some extent, neutrino heating establishes a sufficient pressure gradient to push the material beyond about 150 km outward, while the material further in falls rapidly toward the core. This makes the density near 150 km decrease spectacularly, creating a quasi-vacuum in which the pressure is mainly carried by radiation. This is a perfect condition to make the internal energy of the matter sufficient to escape from the gravitational attraction of the star. The net energy of the outgoing shock is about 4×10^{50} ergs.

There are **other possible mechanisms**, e.g. driven by magnetic fields, that are expected to be rare

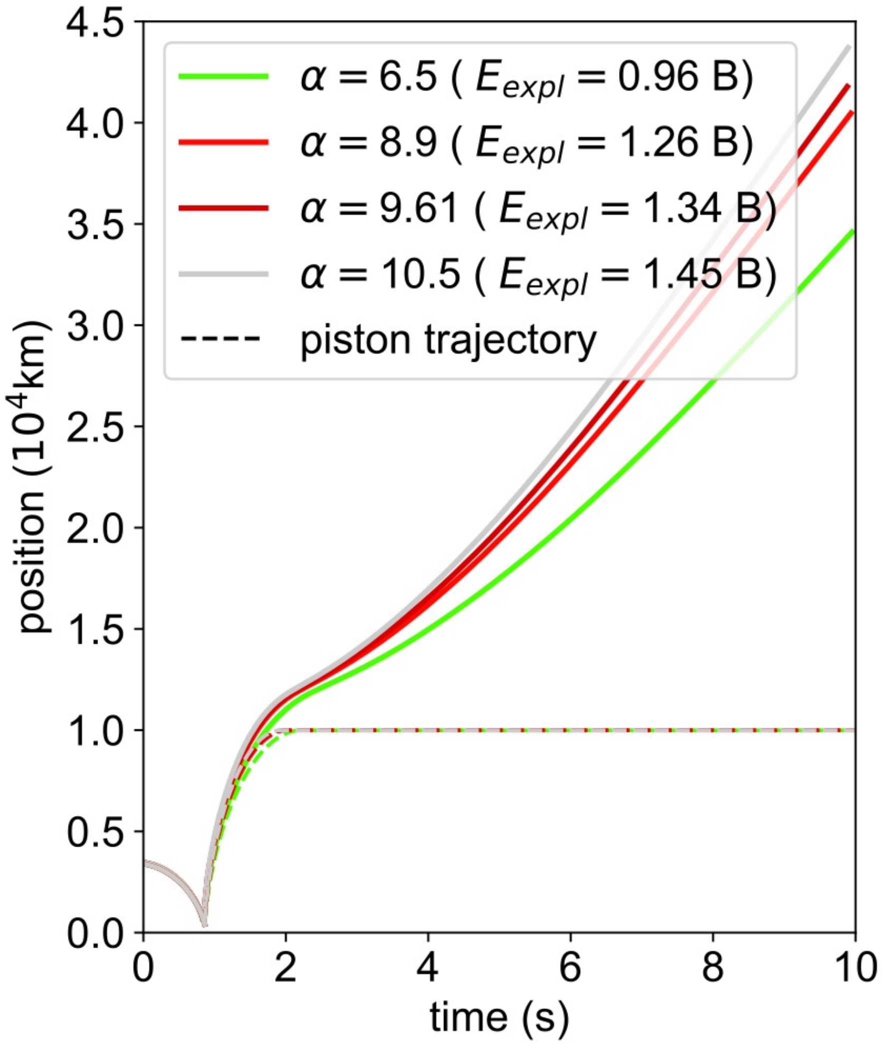
- Binding energy of a neutron star = neutrino energy ~10^{53} erg
- Typical SN ejecta kinetic energy ~10^{51} erg
- Heating: $\propto L_\nu\, T_\nu^2/R^2$
- Cooling: $\propto T_m^6 \approx \frac{1}{R^6}$



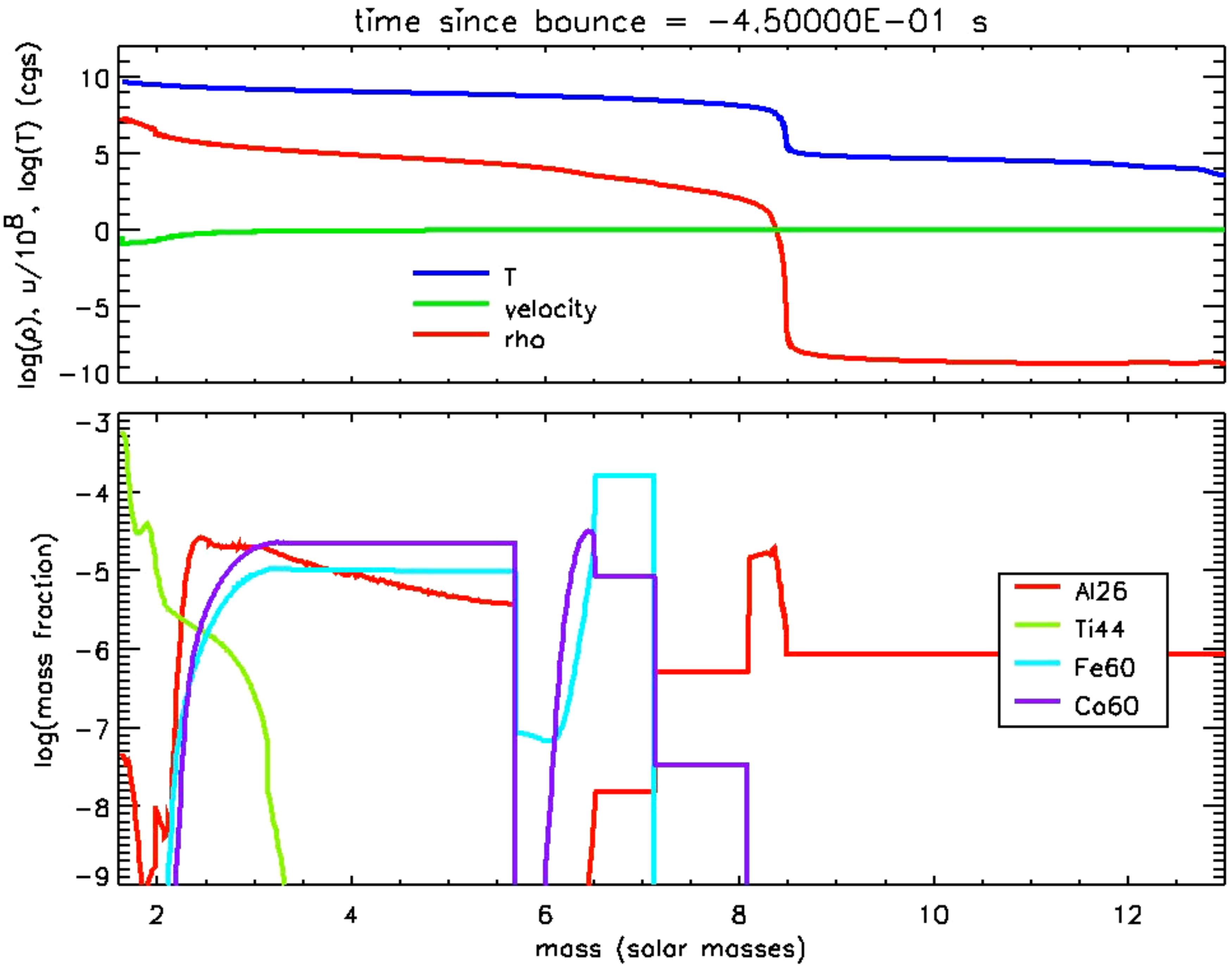
1D models

Fully parameterized 1D models

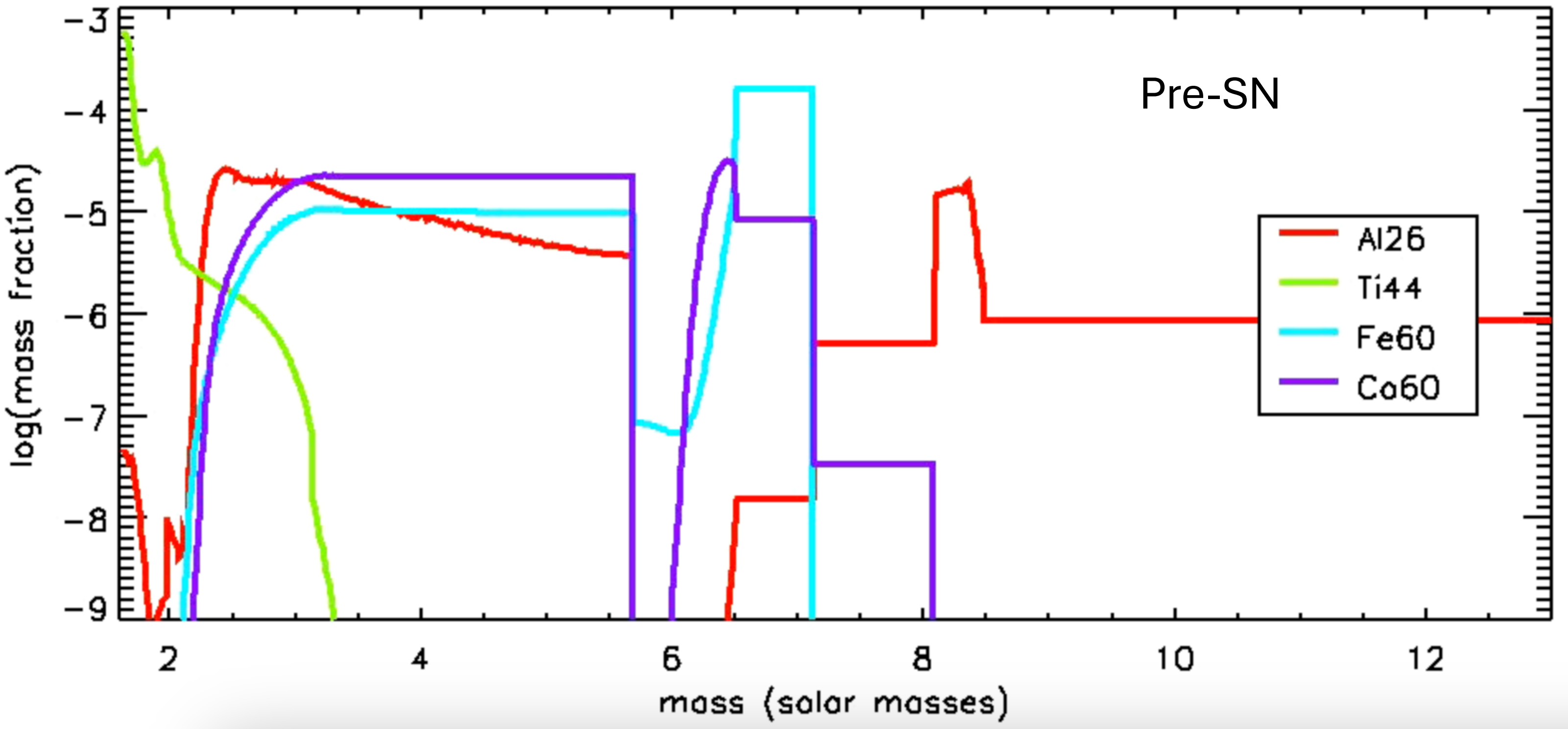
- Neutrino transport is very expensive: 6 flavors x 6 spatial dimensions x evolution in time
- Hot neutron star physics is complicated
- **Solution:** Remove the core and assume an explosion
  - Tune to observable quantities (e.g. explosion energy, ^{56}Ni mass)
  - Computationally very cheap
  - Can be modelled to long times
  - Neglect effects of neutrinos

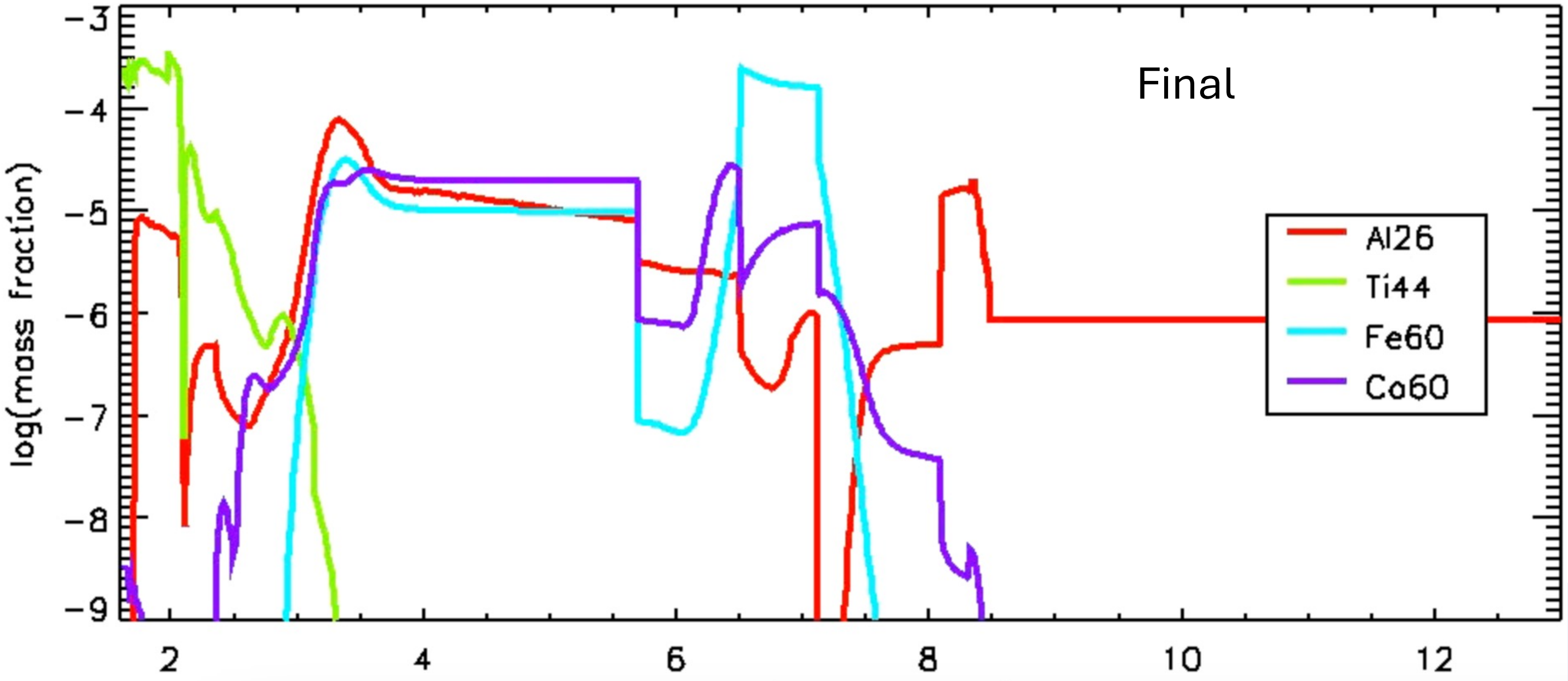


For a detailed comparison of different methods see Imasheva et al. 2025 (arXiv:2501.13172)



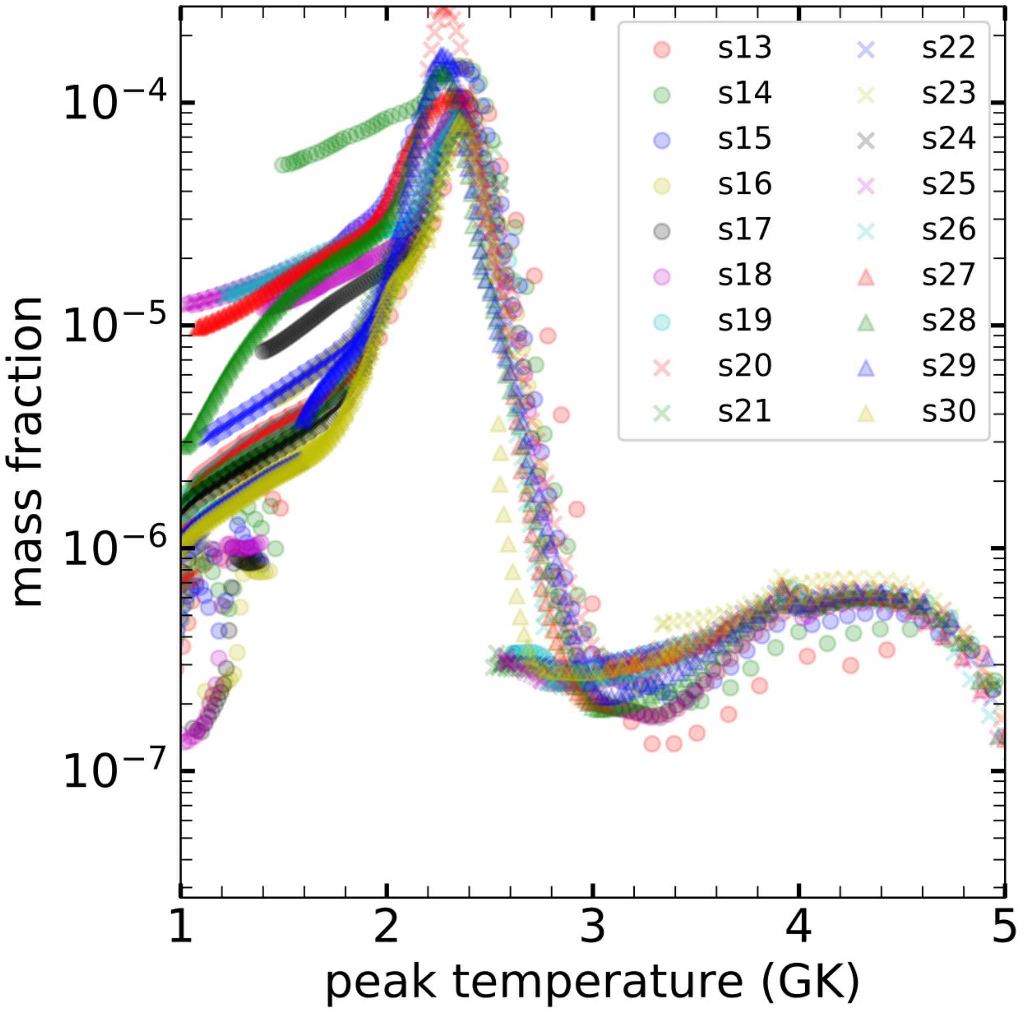
25 $M_{\odot}$ star
Heger et al. 2002
https://2sn.org/nucleosynthesis/RHHW02.shtml


Pre-SN
log(mass fraction)
mass (solar masses)
Al26
Ti44
Fe60
Co60
−3
−4
−5
−6
−7
−8
−9
2
4
6
8
10
12


Final
log(mass fraction)
Al26
Ti44
Fe60
Co60
−3
−4
−5
−6
−7
−8
−9
2
4
6
8
10
12

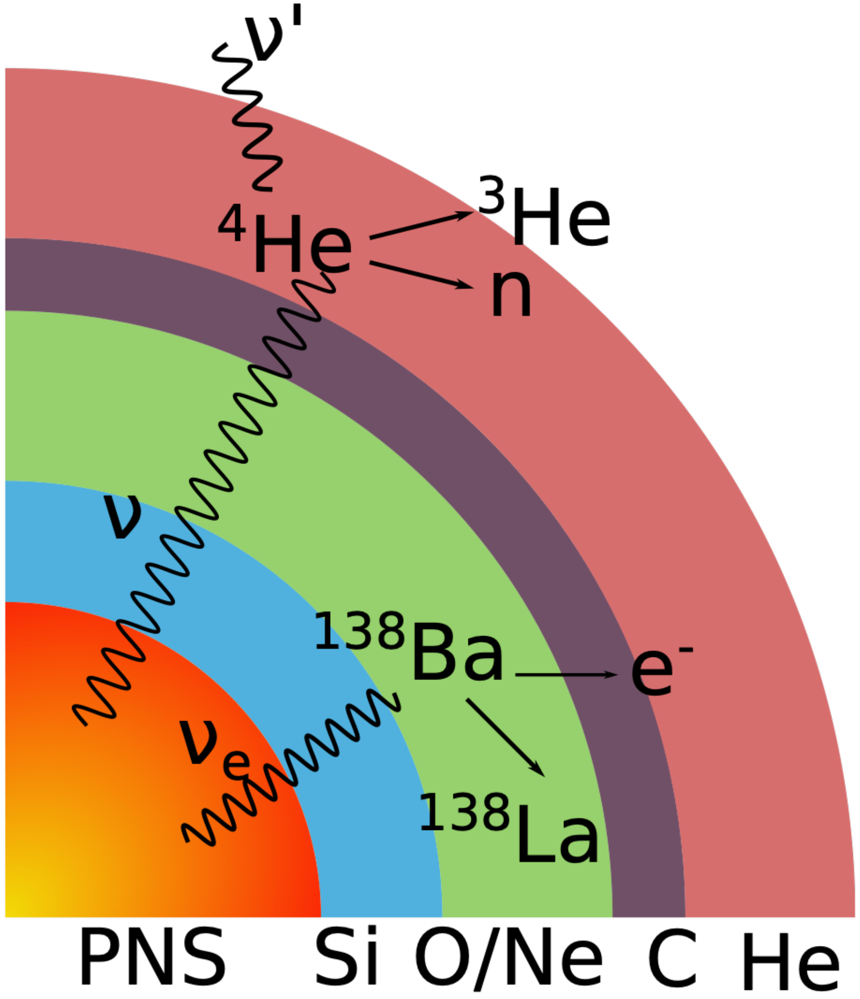
Explosive burning

- Starting from the initial "onion shell" composition
- Explosive variants of the hydrostatic burning stages
- Feedback from nuclear energy generation on dynamic evolution is small
- Initial composition and peak temperature are determined what is produced
  - $T_{Peak} \propto E_{exp}^{\frac{1}{4}} R^{-3/4}$
- Relevant energy range for nuclear reactions is accessible: 100s keV to a few MeV

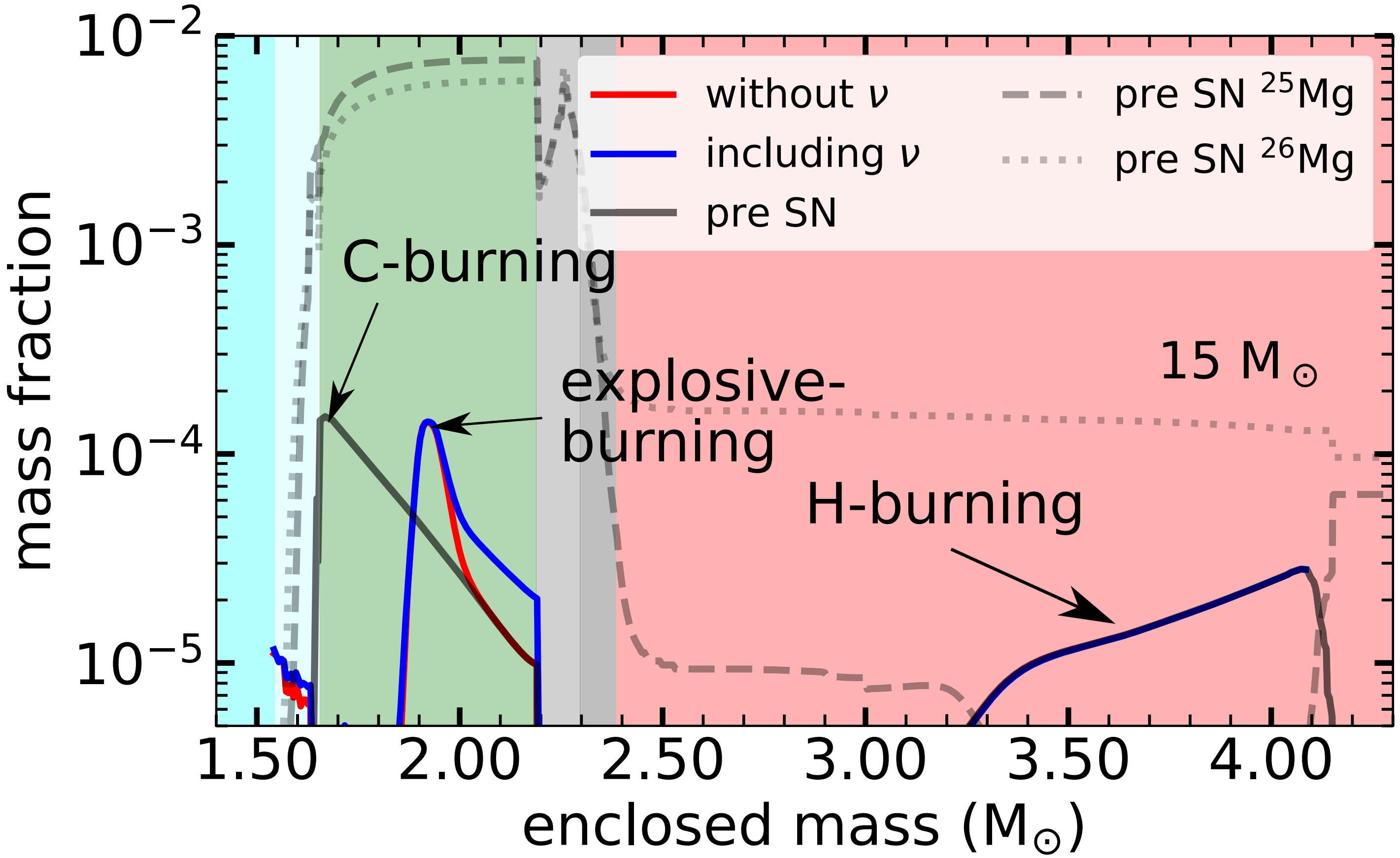


^{26}Al made by $^{25}Mg(p,\gamma)$

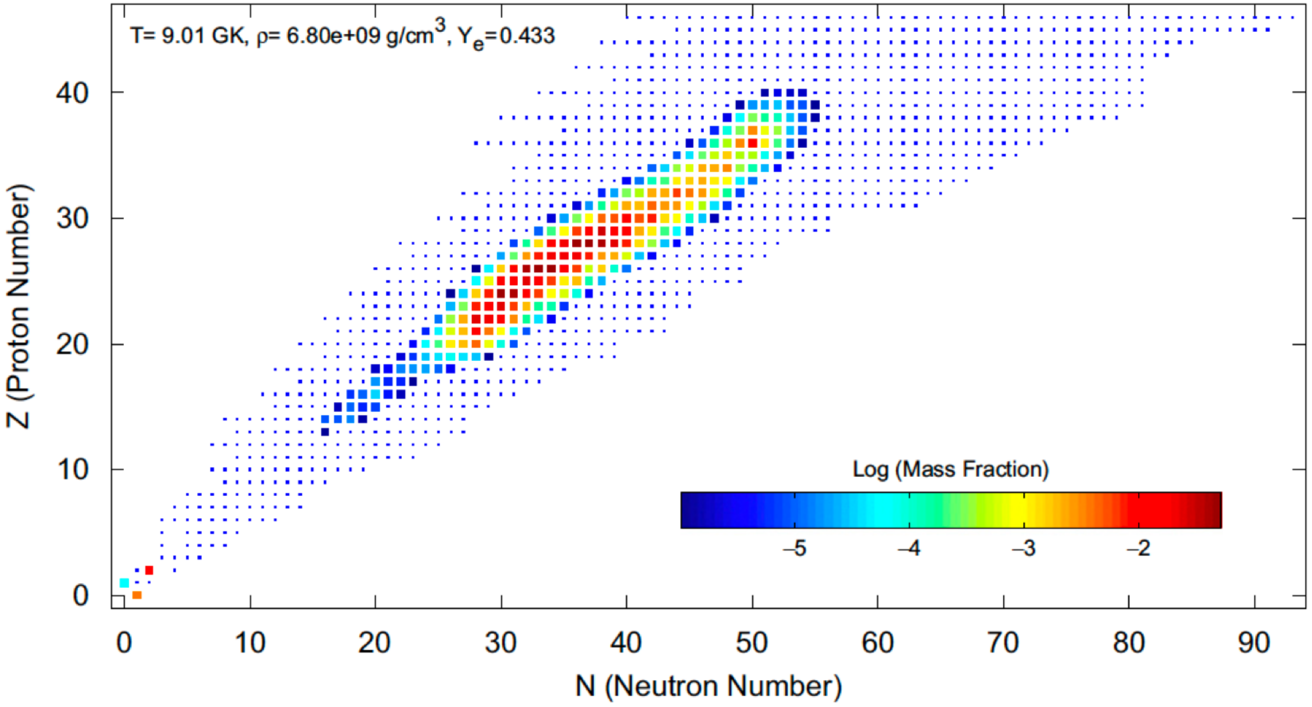
The ν process



- High energy neutrinos (~10 MeV) induce reaction on abundant nuclei *[Woosely et al. 1990 ...]*

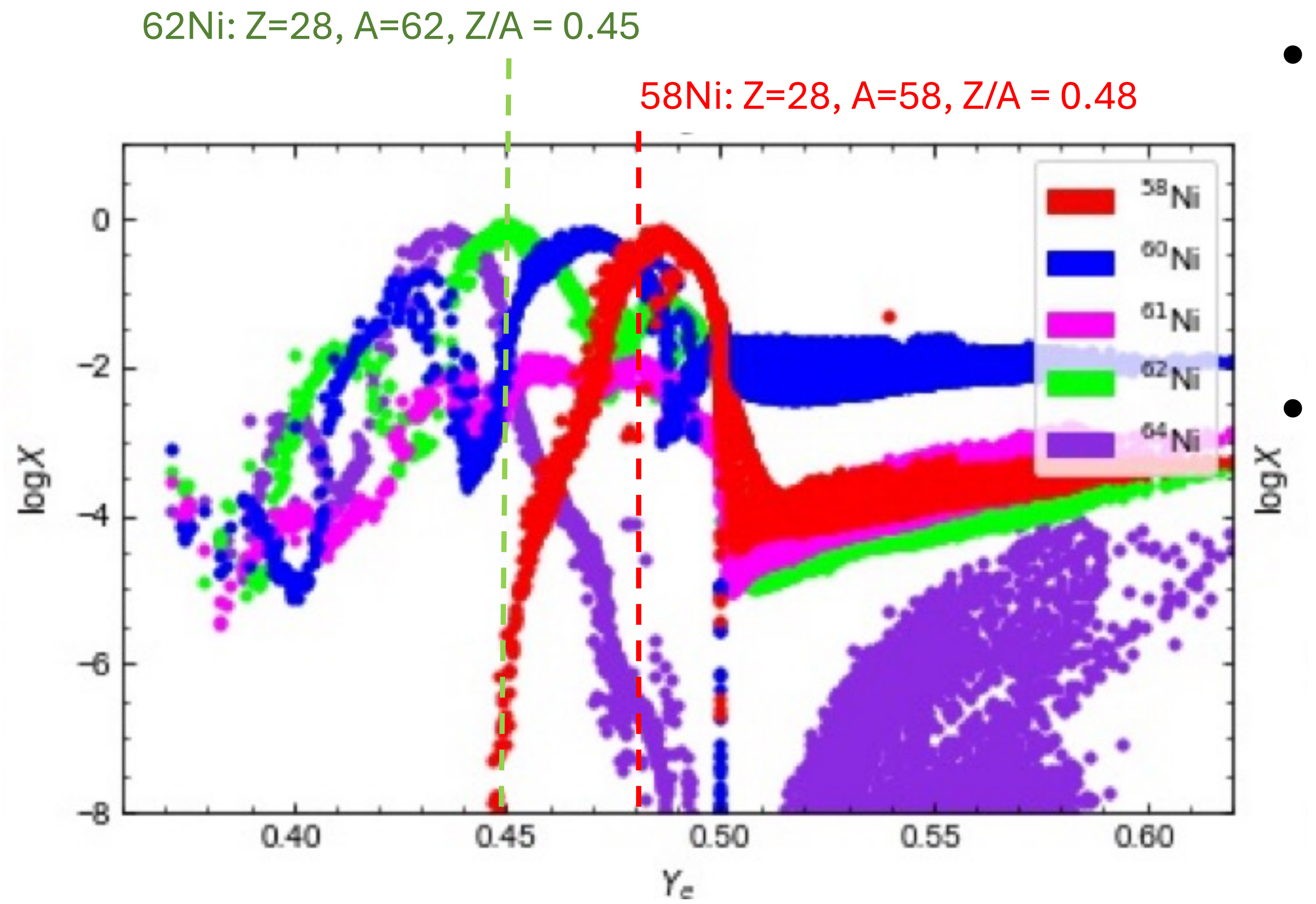


NSE - the product of Si-burning



- At high temperature or on long timescale an equilibrium is reached
- $(A, Z) \leftrightarrow Z\,p + (A - Z)\,n$
- $Y_{(A,Z)} \propto Y_p Y_n e^{E_B/k_B T}$
- While satisfying mass conservation and the Y_e
- In equilibrium, abundances are **independent** of reaction cross sections
- Starting (or end) point for reaction network calculations
- **"Freeze-out":** When dynamic timescale becomes shorter than the reaction timescale
- 3-alpha is typically the first reaction to break:
  - X_n, X_p, X_α + heavy nuclei
- In explosive Si burning, ^{56}Ni is the main product

Freeze-out patterns



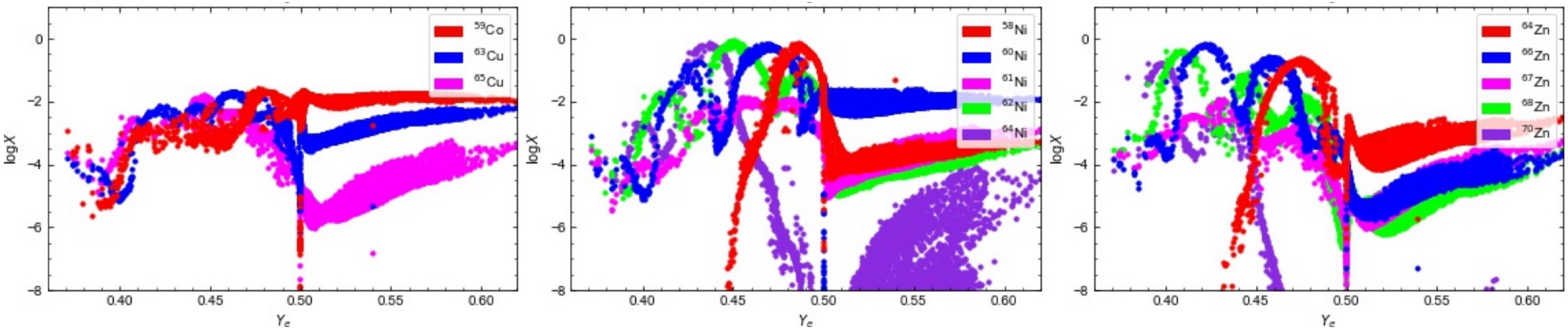
- As first guess for the most abundant isotope in NSE:

  $Z/A = Y_e$
- For increasing Y_e, free protons and ^{4}He are favored

Impact of the electron fraction (Y_e) on the nucleosynthesis

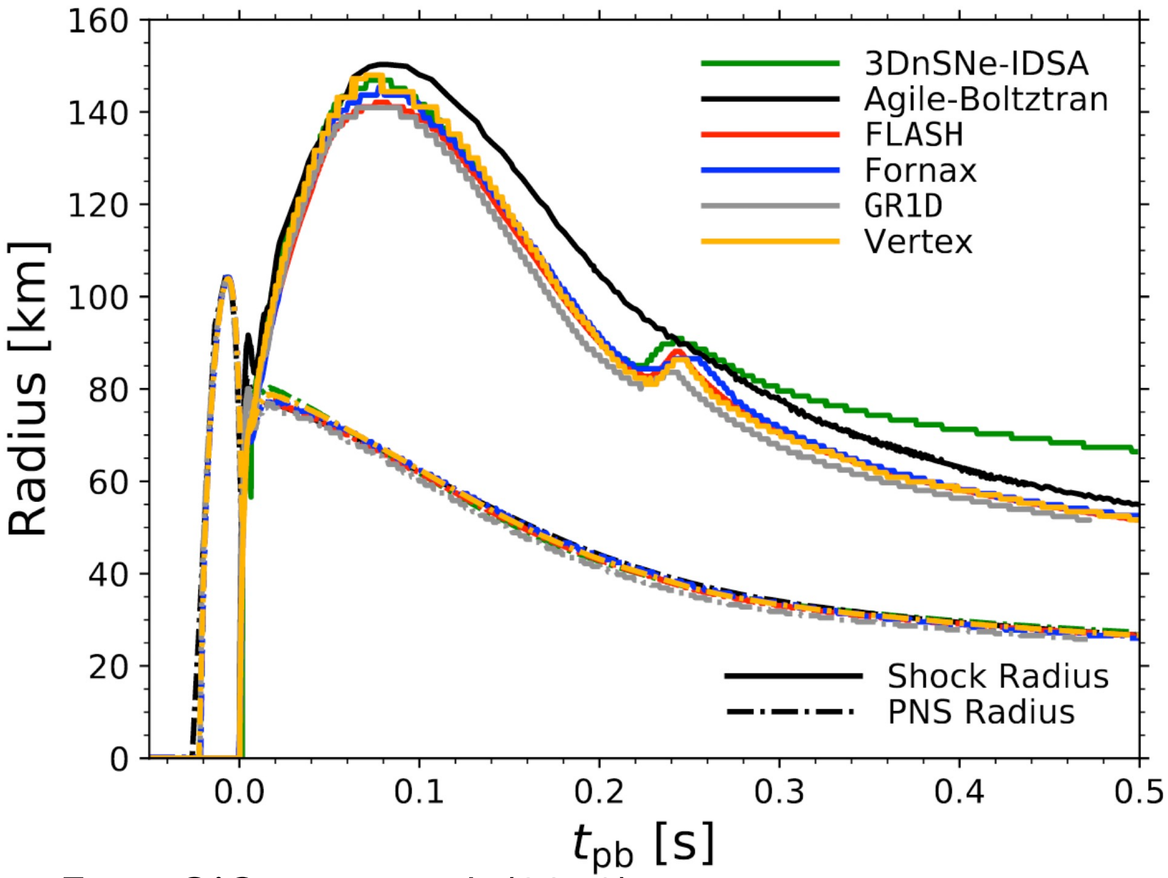
- As material expands, non-equilibrium nuclear reactions shape the composition (freeze-out)
- The "seeds" at freeze out have a large impact on the final outcome
- <u>**Neutrinos are crucial describe Y_e!**</u>

- $n + \nu_e \leftrightarrow p + e^-$
- $p + \bar{\nu}_e \leftrightarrow n + e^+$



Results from model D9.6 (2D), Figure by D. Zetterberg (ORNL summer intern)

Spherically symmetric simulations (1D)



From O'Connor et al. (2018)

- Even with the best neutrino transport and equation of state: In 1D**, all codes agree:**
  - CCSN do no explode ….

1D simulations with modifications

- Include neutrinos (with adjustments)
- Include the neutron star
- Several approaches:
  - Increased neutrino heating
    [Perego et al. 2015] "PUSH"
  - Parameterized neutrino emission
    [Ertl et al. 2016] "PHOT-B"
  - Additional "turbulent" energy transport and pressure
    [Couch et al. 2019] "STIR"
  - .....

<u>**Can predict explosion/non-explosion**</u>

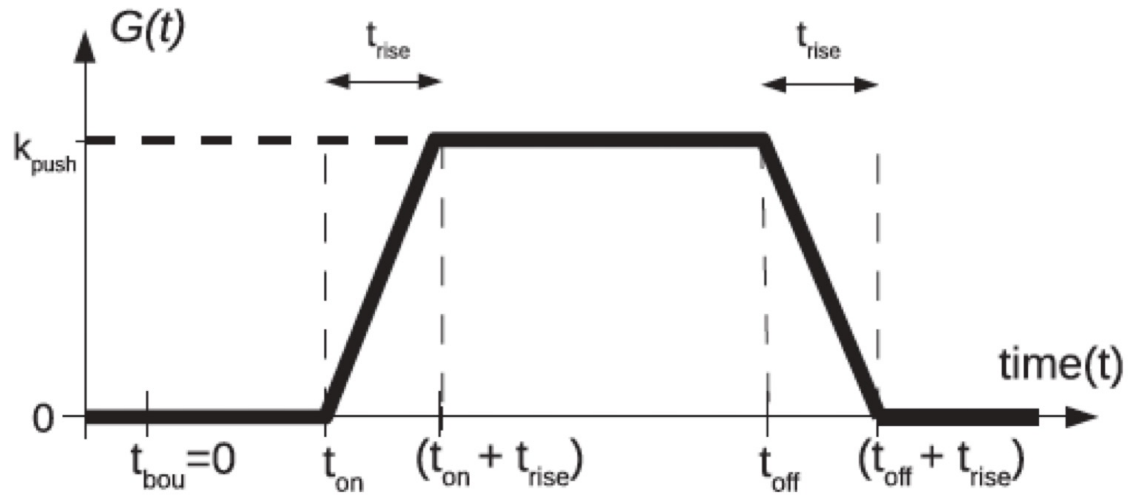
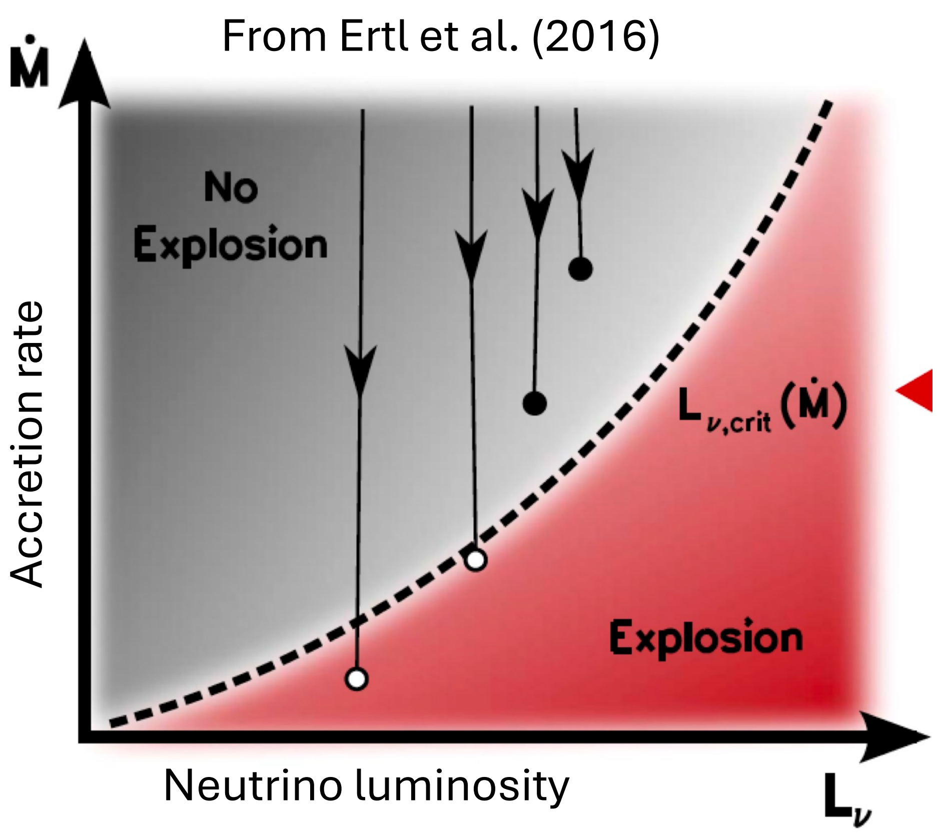


Figure 3. Function $\mathcal{G}(t)$ determines the temporal behavior of the heating due to PUSH. The quantity t_{on} is robustly set by multi-dimensional models. We

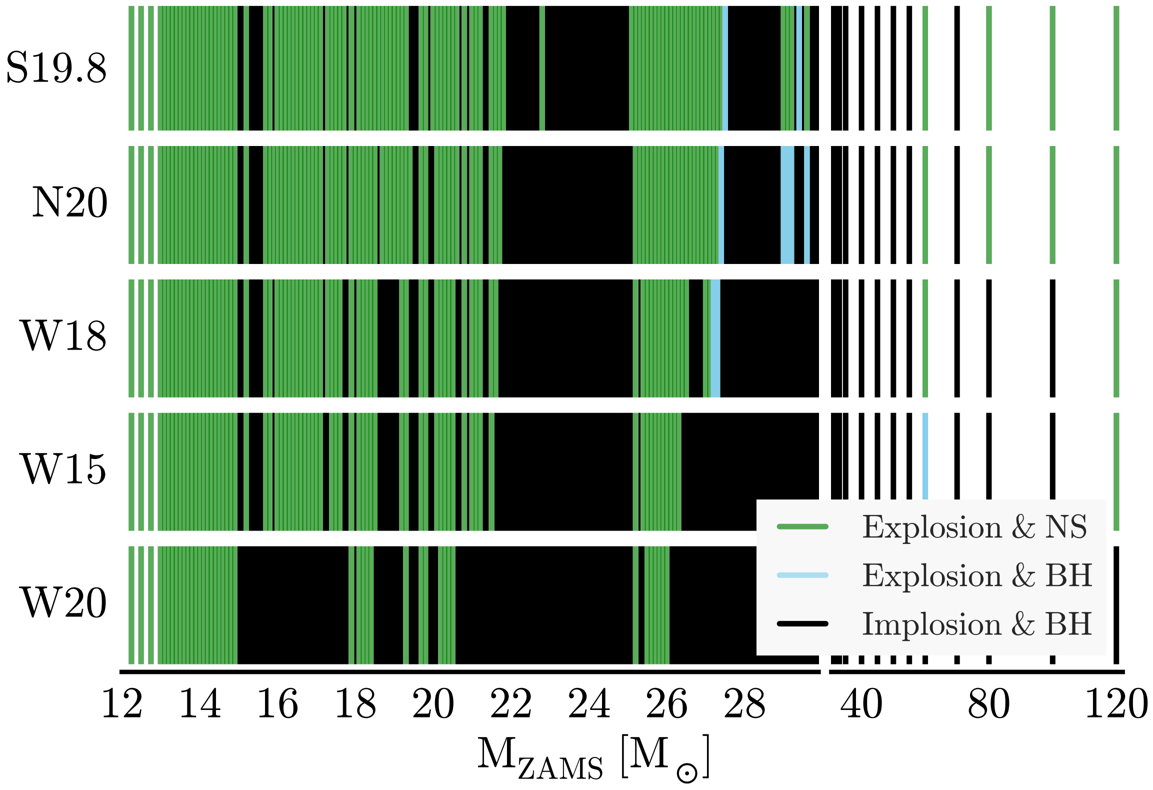
[Perego et al. 2015]

Explodability



- **Competition between neutrino-heating and ongoing collapse**
- **Some supernovae may not be successful**

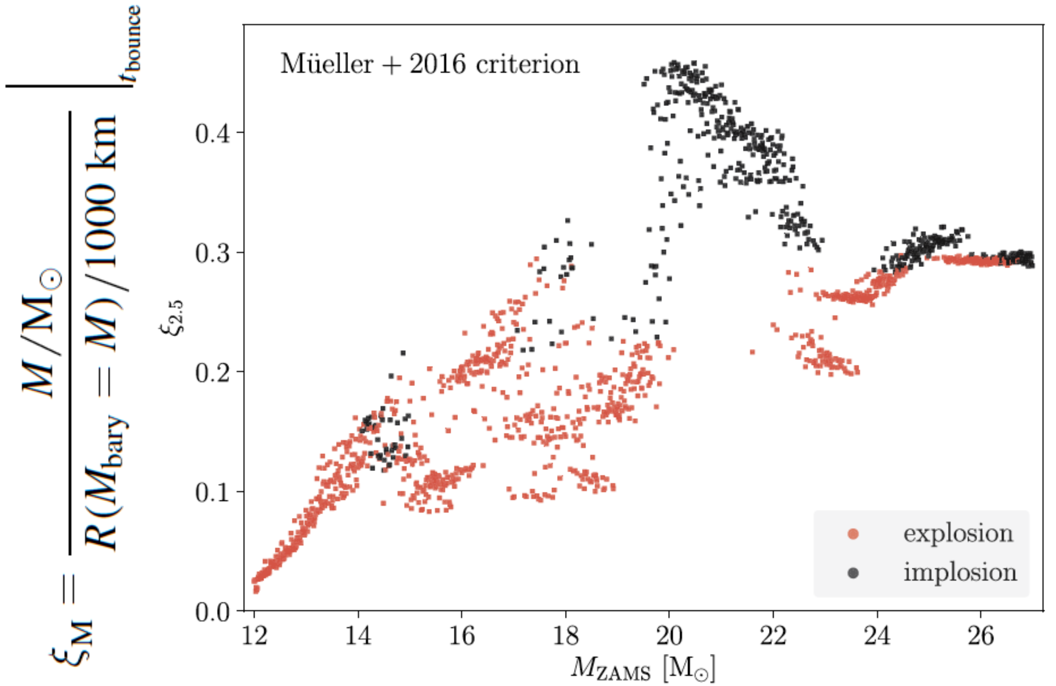
The Supernova "landscape"



[Sukhbold et al. 2016]

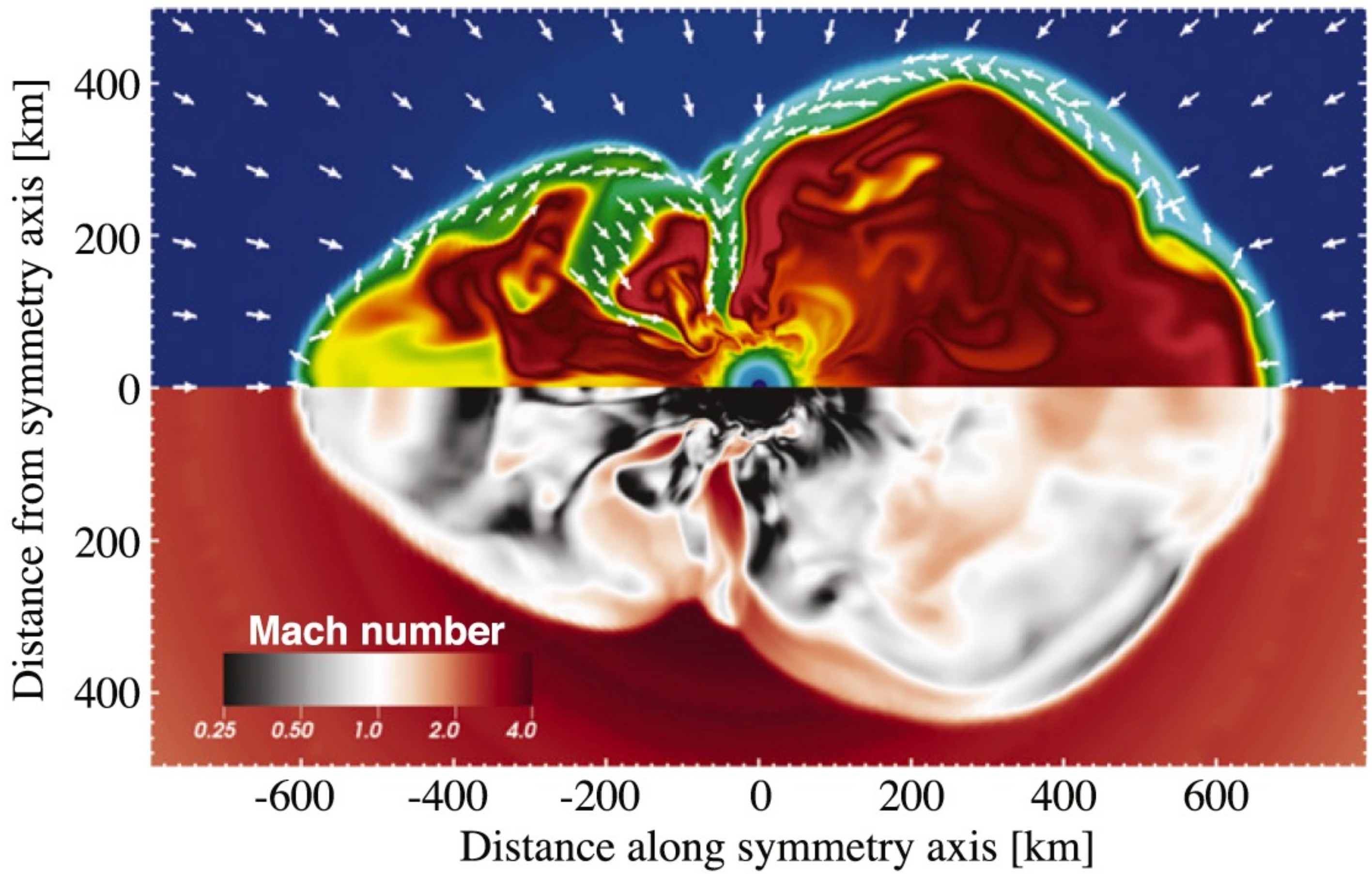
Need predictive models

- 1D models are crucial to study populations of stars
- Calibration and model dependent



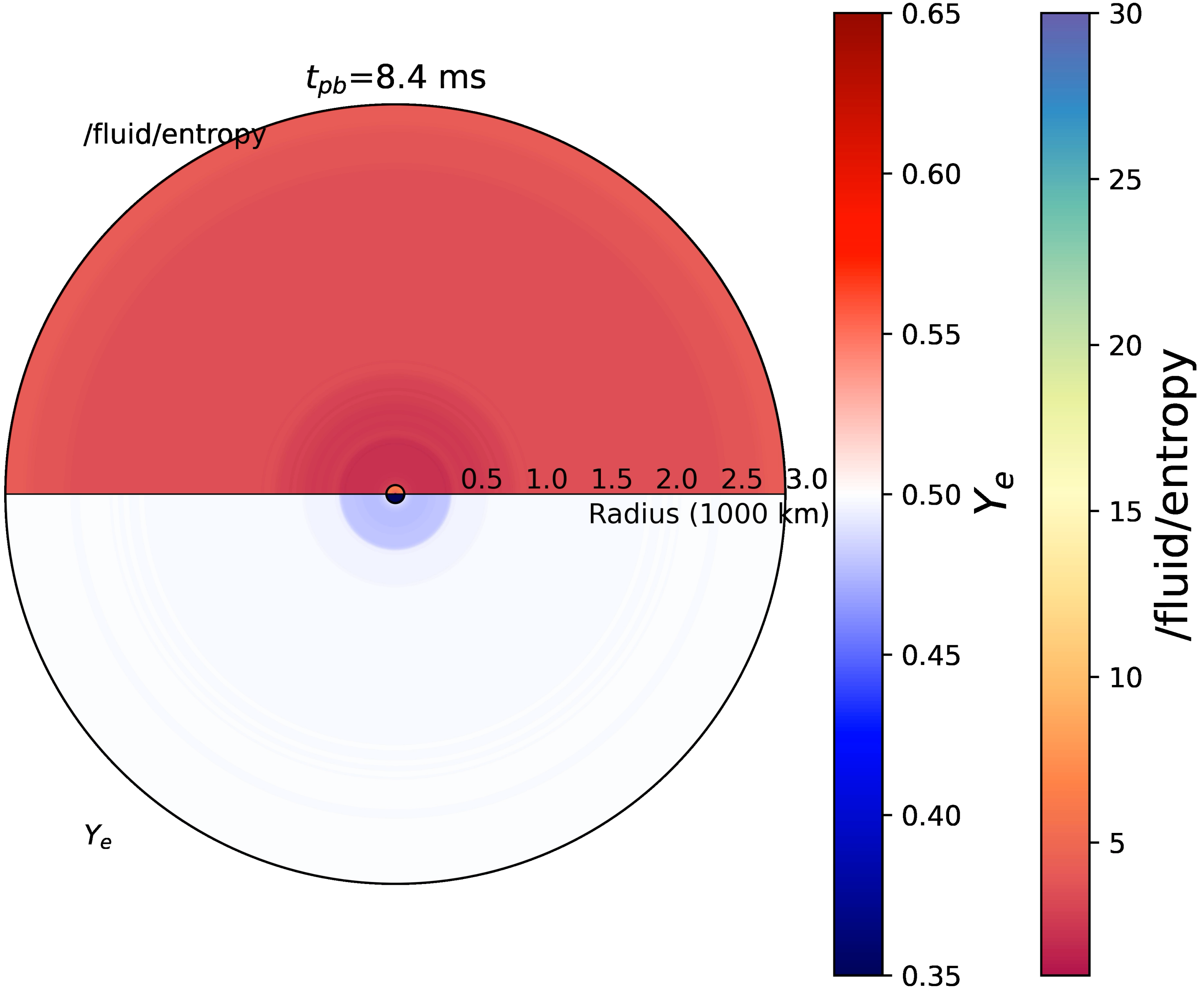
Multi-D models

Multi-D effects



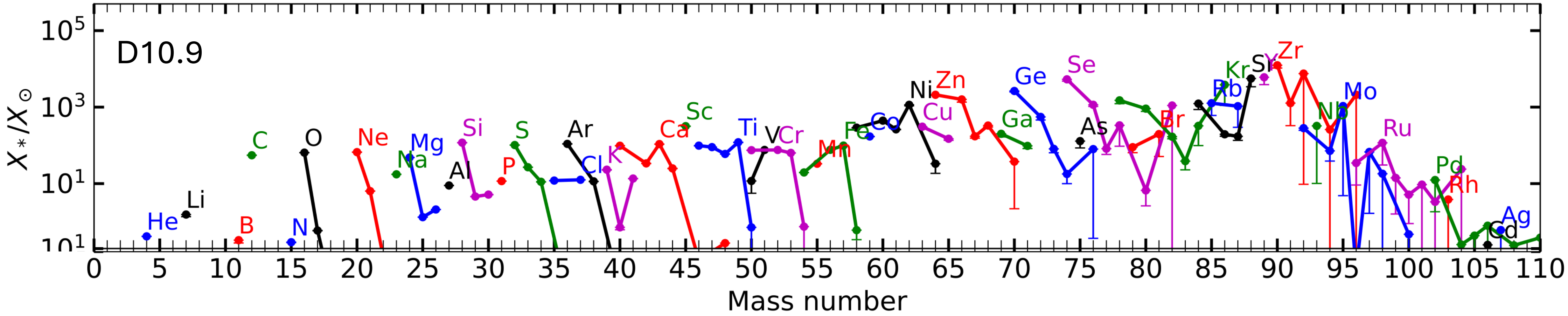
[Bruenn et al. 2016]

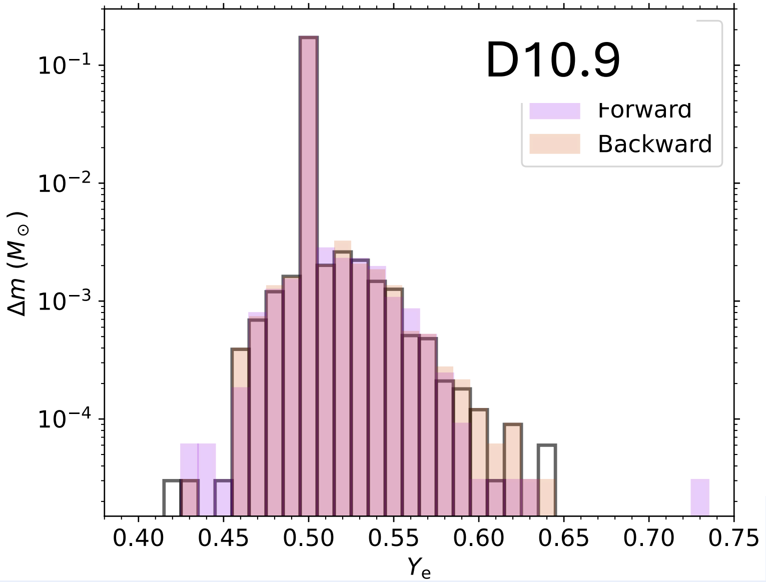
- Convective overturns bring cold matter into the heating region
- Simultaneous down-flows and explosion
- Large-scale instabilities (SASI)

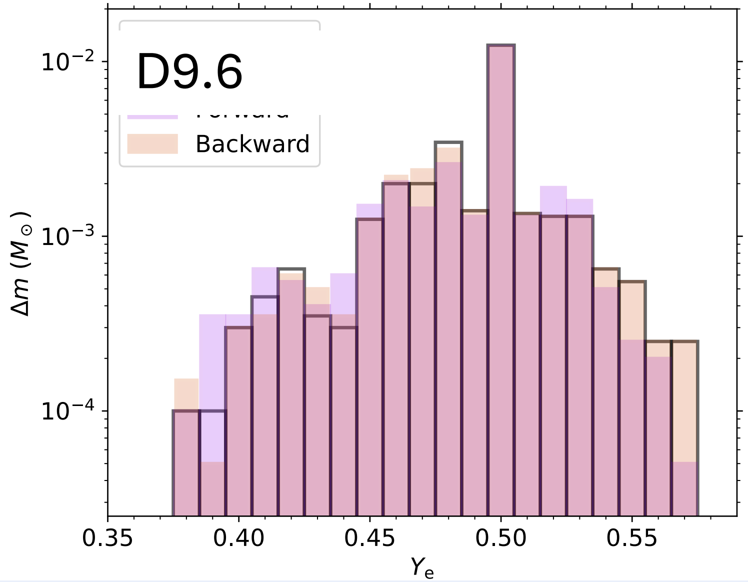


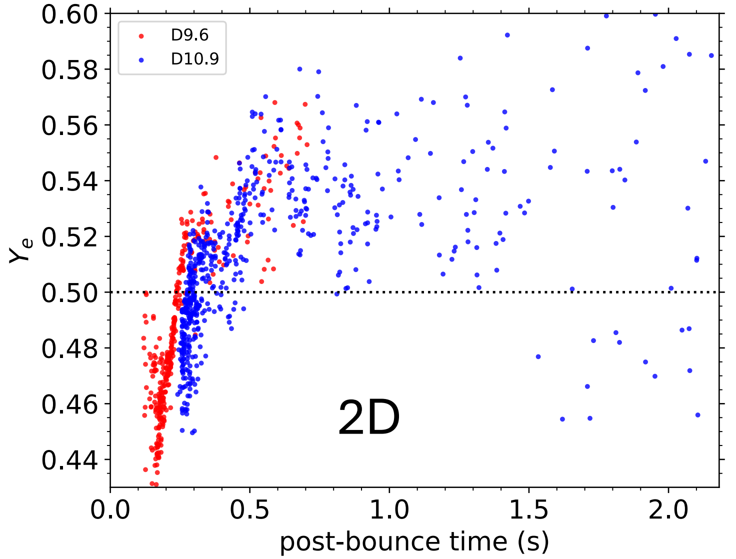
t_{pb}=8.4 ms
/fluid/entropy
0.5 1.0 1.5 2.0 2.5 3.0
Radius (1000 km)
Y_e
0.65
0.60
0.55
0.50
0.45
0.40
0.35
Y_e
30
25
20
15
10
5
/fluid/entropy

Variability of conditions from multi-D simulations

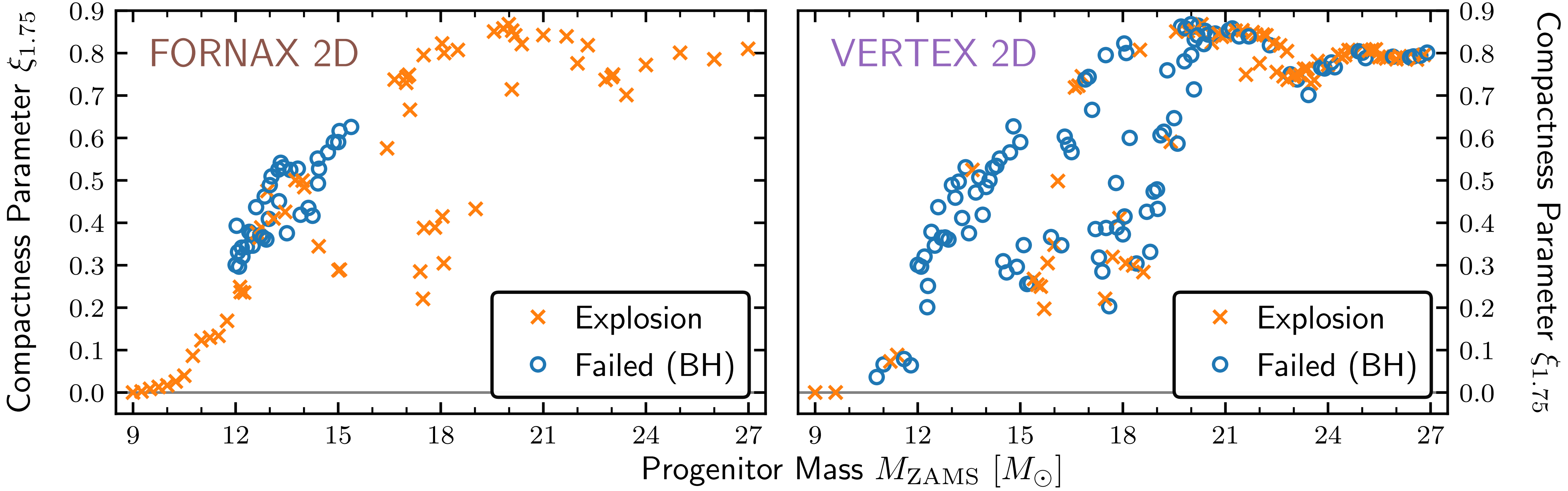








Explodability in multi-D is still code dependent

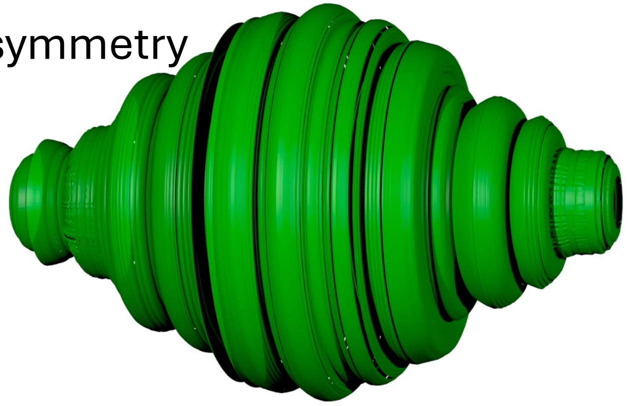


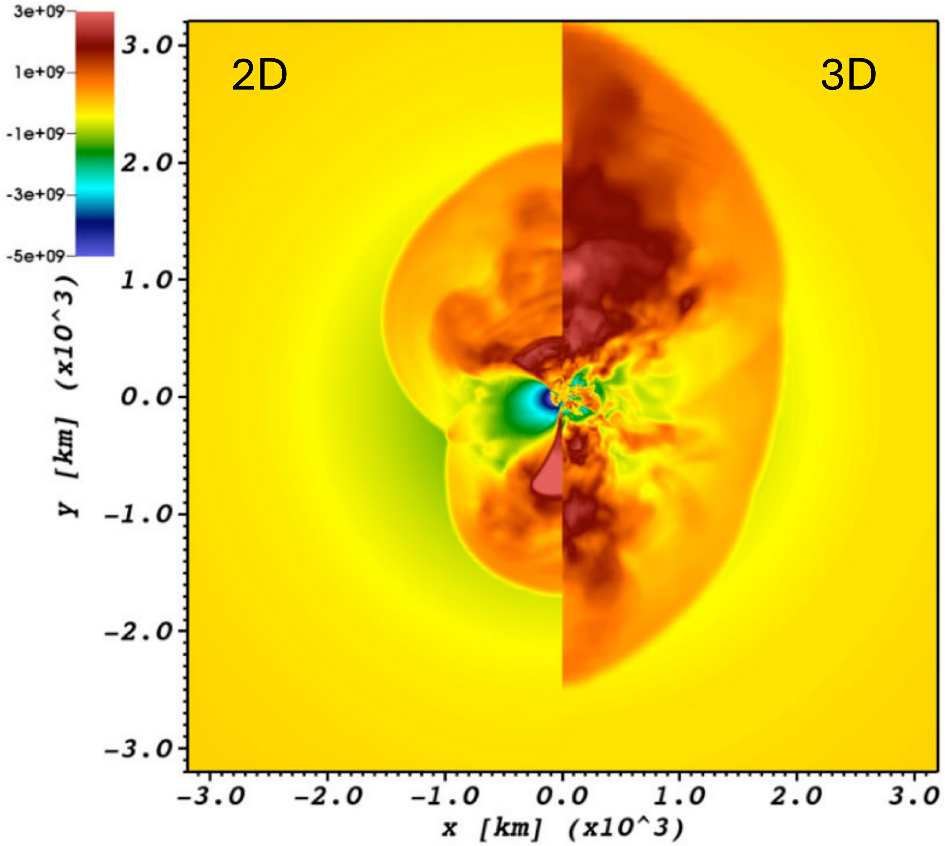
[Janka et al. 2025, Glas et al., in prep.]

2D vs. 3D

Image from Sandoval et al. (2021)

2D axisymmetry



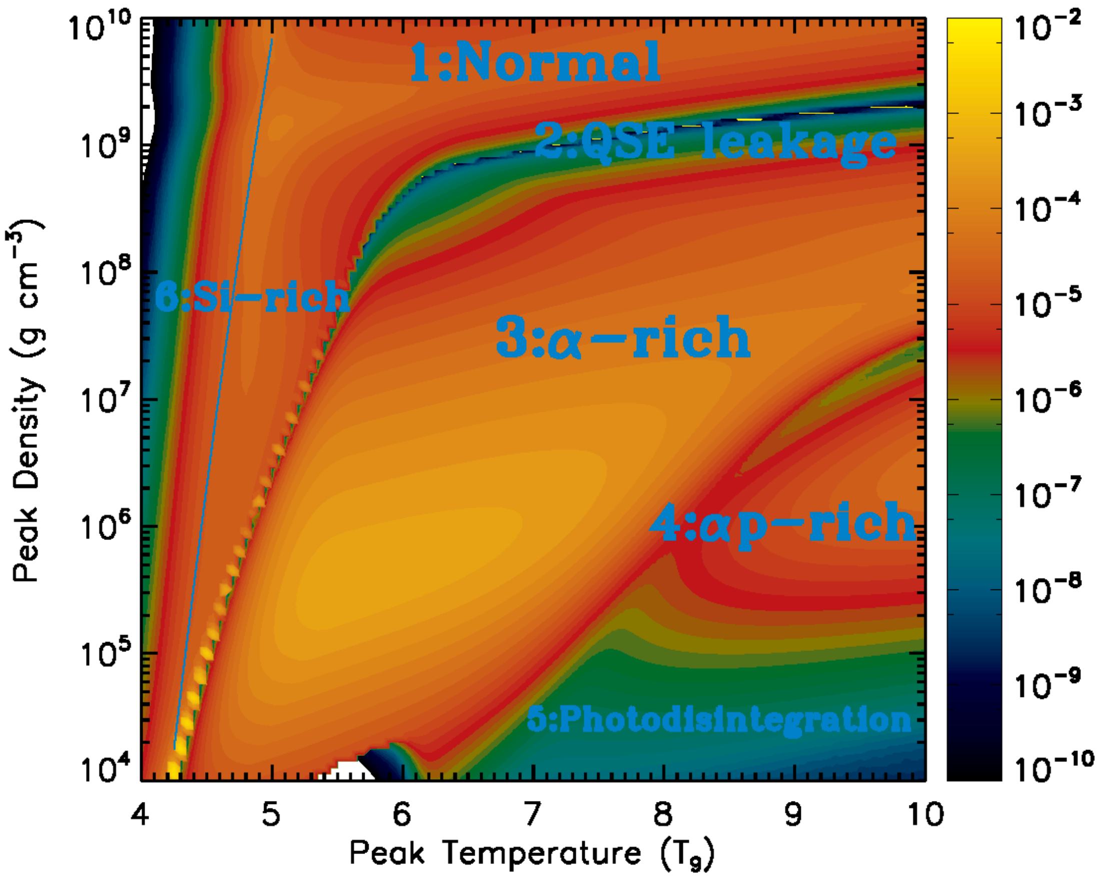


From Müller et al. 2015

- Fragmentation in 3D leads to more efficient mixing and energy transfer
- Large scale downflows are broken up into smaller streams
- Less asymmetry, less episodic behavior

Insights from 3D models

Aside: Synthesis of ^{44}Ti



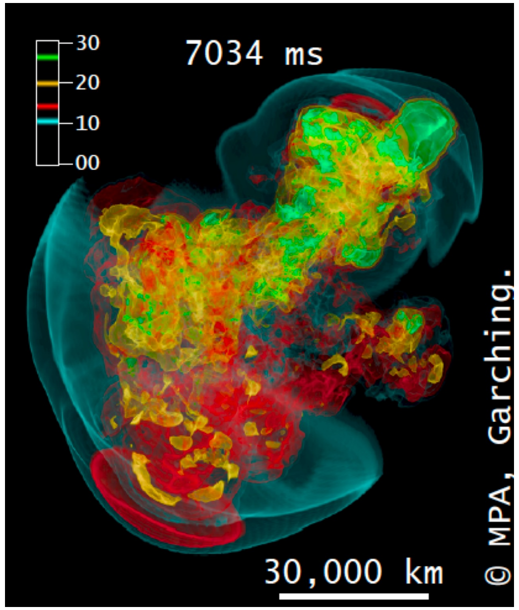
From Magkotsios et al. 2010

- ^{44}Ti is produced from an α-rich freeze-out
- Nuclear flow between ^{12}C and ^{56}Ni is interrupted
- Non-equilibrium reactions and timing determines final ^{44}Ti abundance
- **^{44}Ti is a very sensitive tracer of the conditions**
- Parameterized, monotonic trajectories typically don't produce mass fractions > 10^{-2}
- Largest sensitivity to $^{44}Ti(\alpha,p)^{47}V$ [Hermansen et al. 2020]

Confronting simulations with observational constraints

Are ^{44}Ti-producing supernovae exceptional?⋆

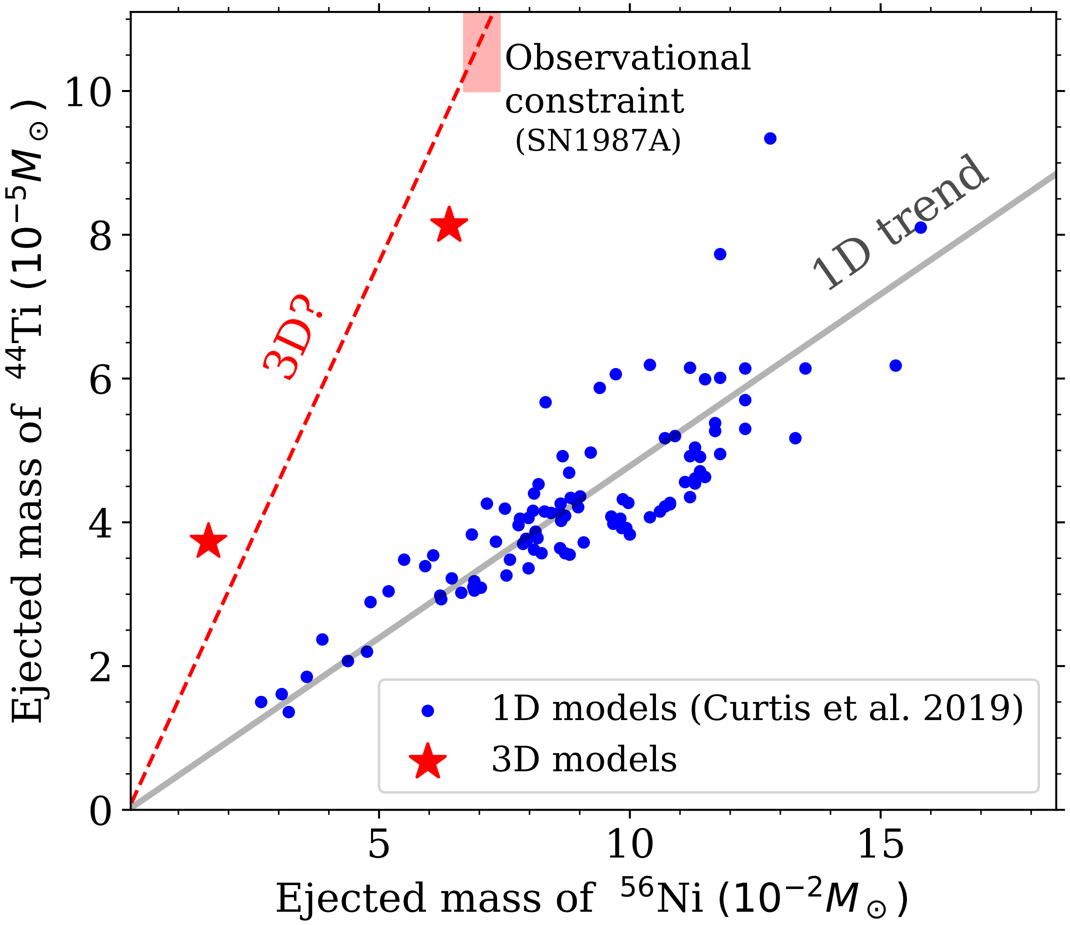
L.-S. The[1], D. D. Clayton[1], R. Diehl[2], D. H. Hartmann[1], A. F. Iyudin[2,3], M. D. Leising[1], B. S. Meyer[1], Y. Motizuki[4], and V. Schönfelder[2]



^{44}Ti yields from 1D supernova models cannot explain observations!

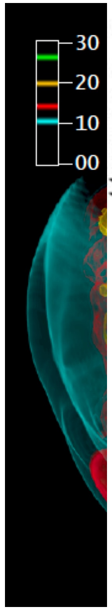
Multi-D simulations may be the answer

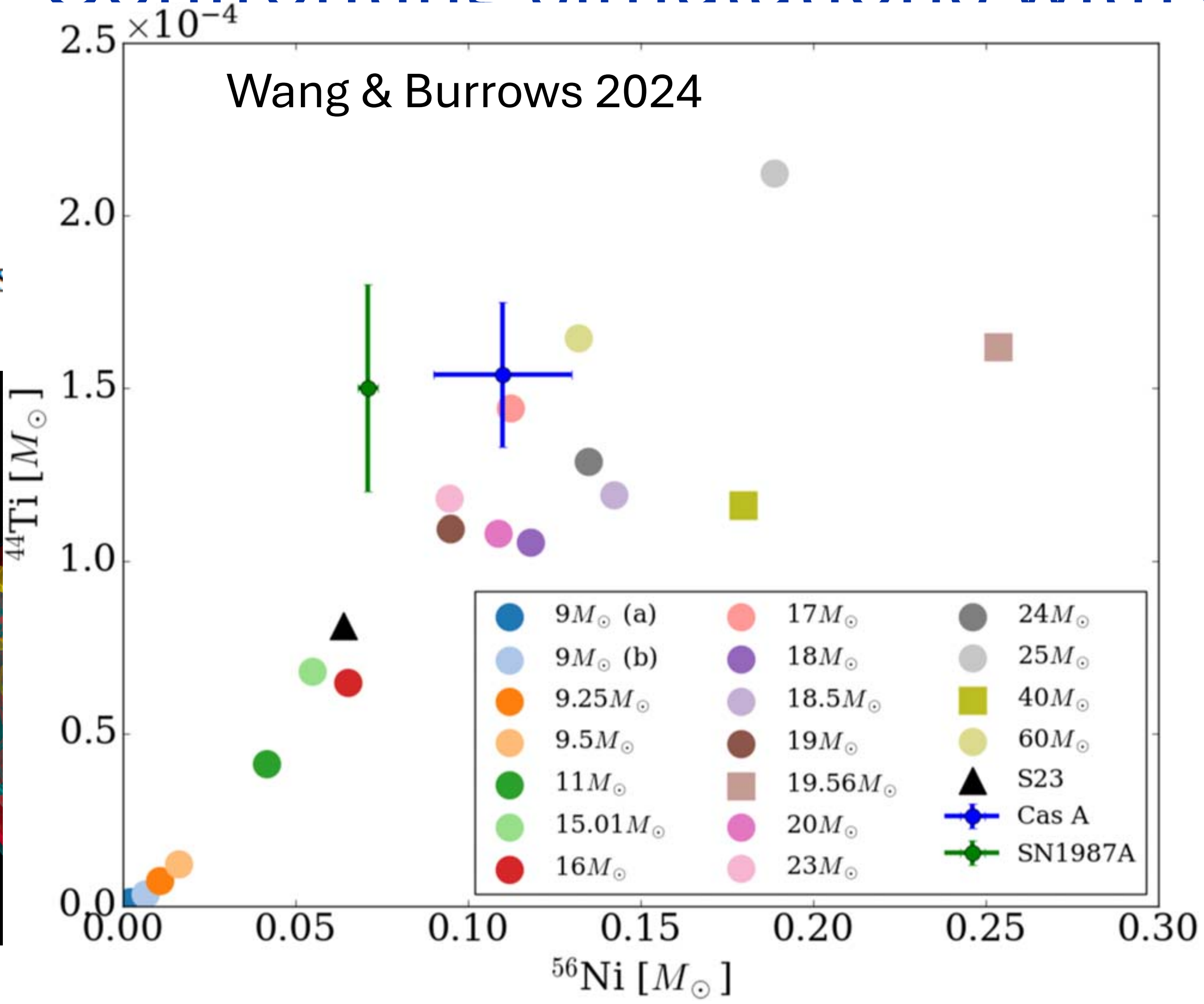
Without fine-tuning

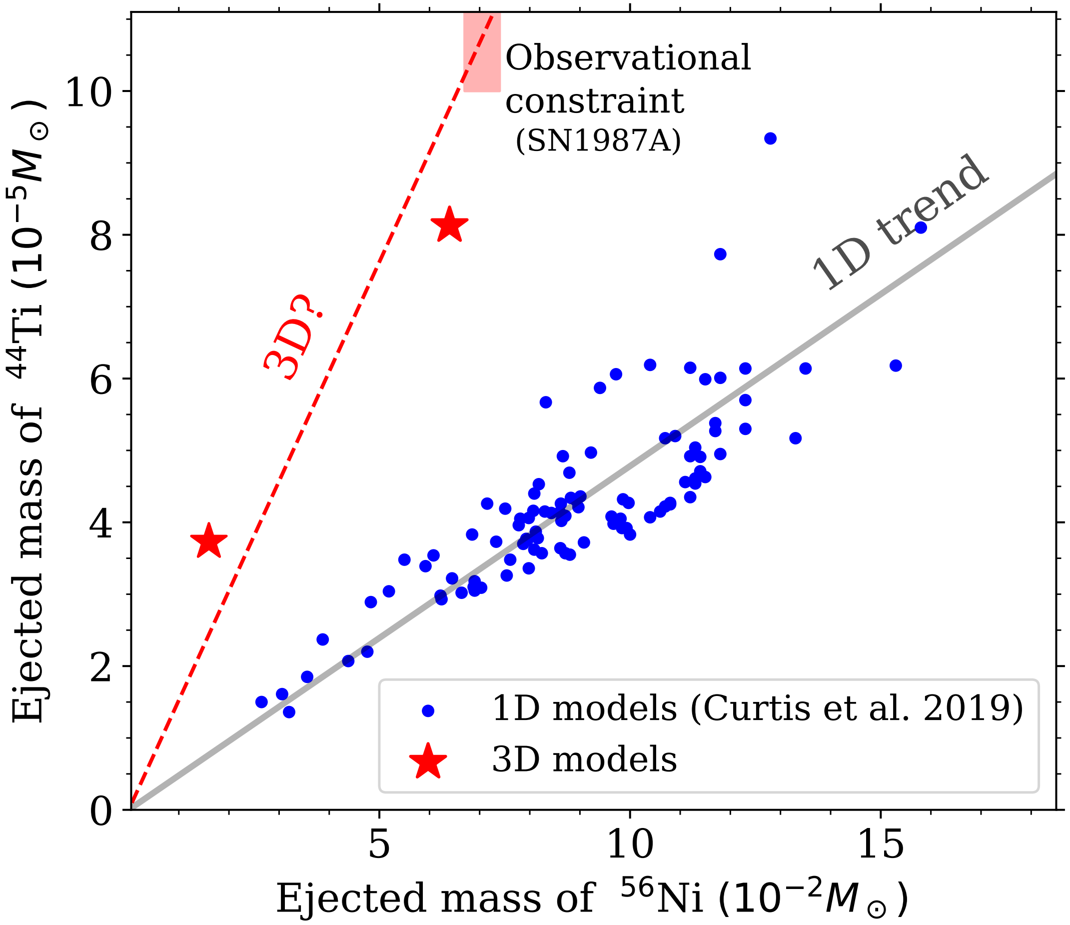


Confronting simulations with observational

L.-S

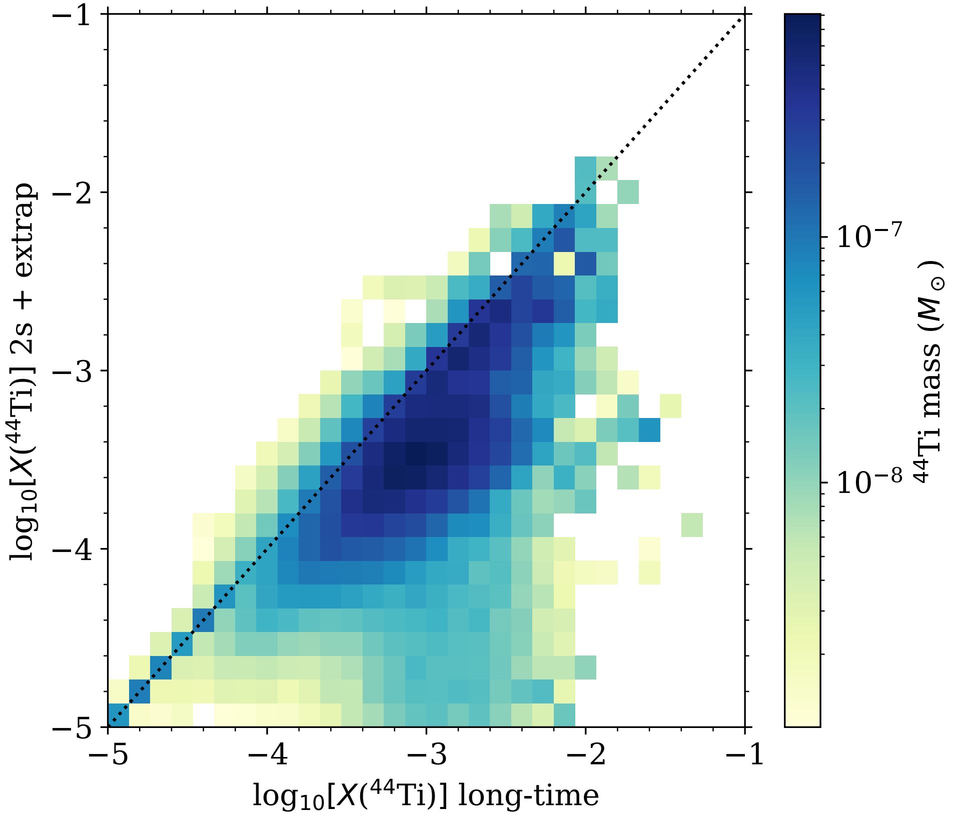


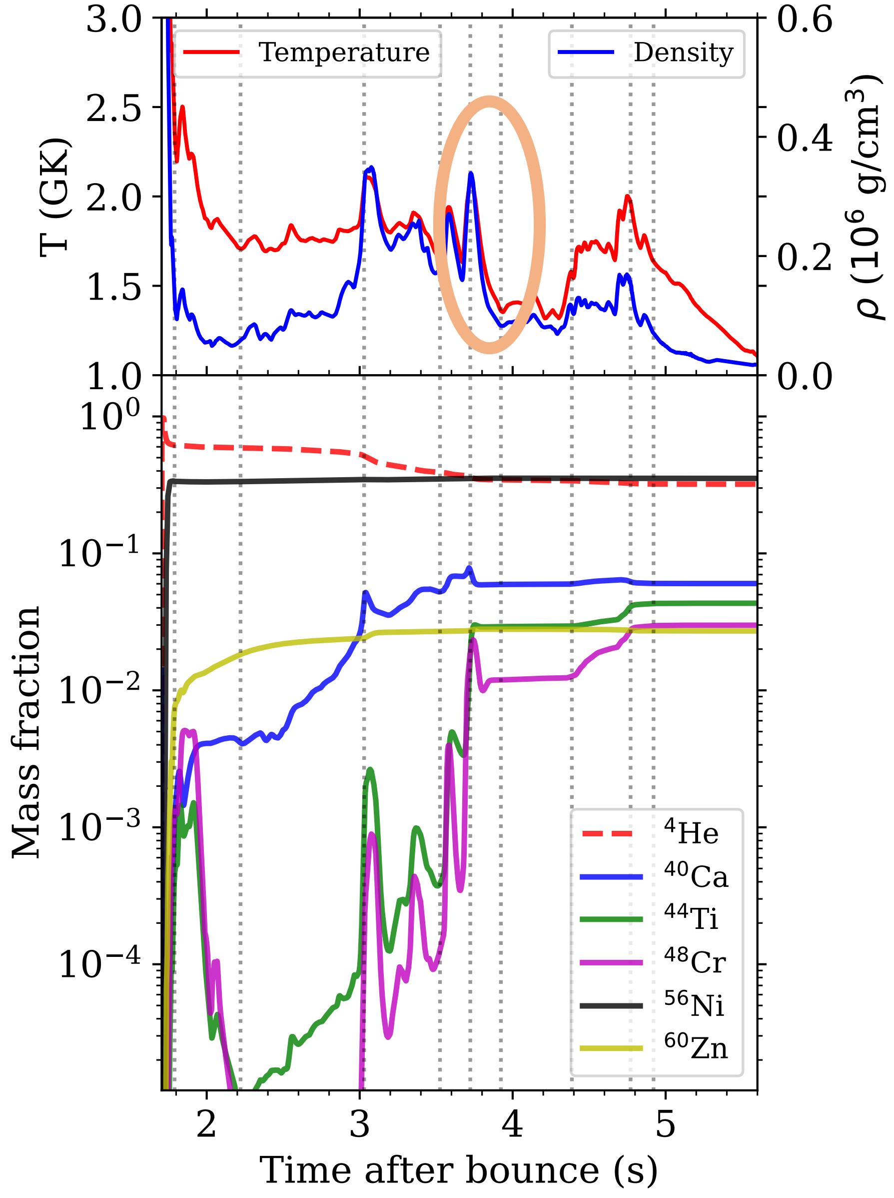




Non-monotonic late-time evolution

- Late time re-heating reactivate charged-particle reactions





Stable isotopes

The Astrophysical Journal, 900:179 (33pp), 2020 September 10 Kobayashi, Karakas, & Lugaro

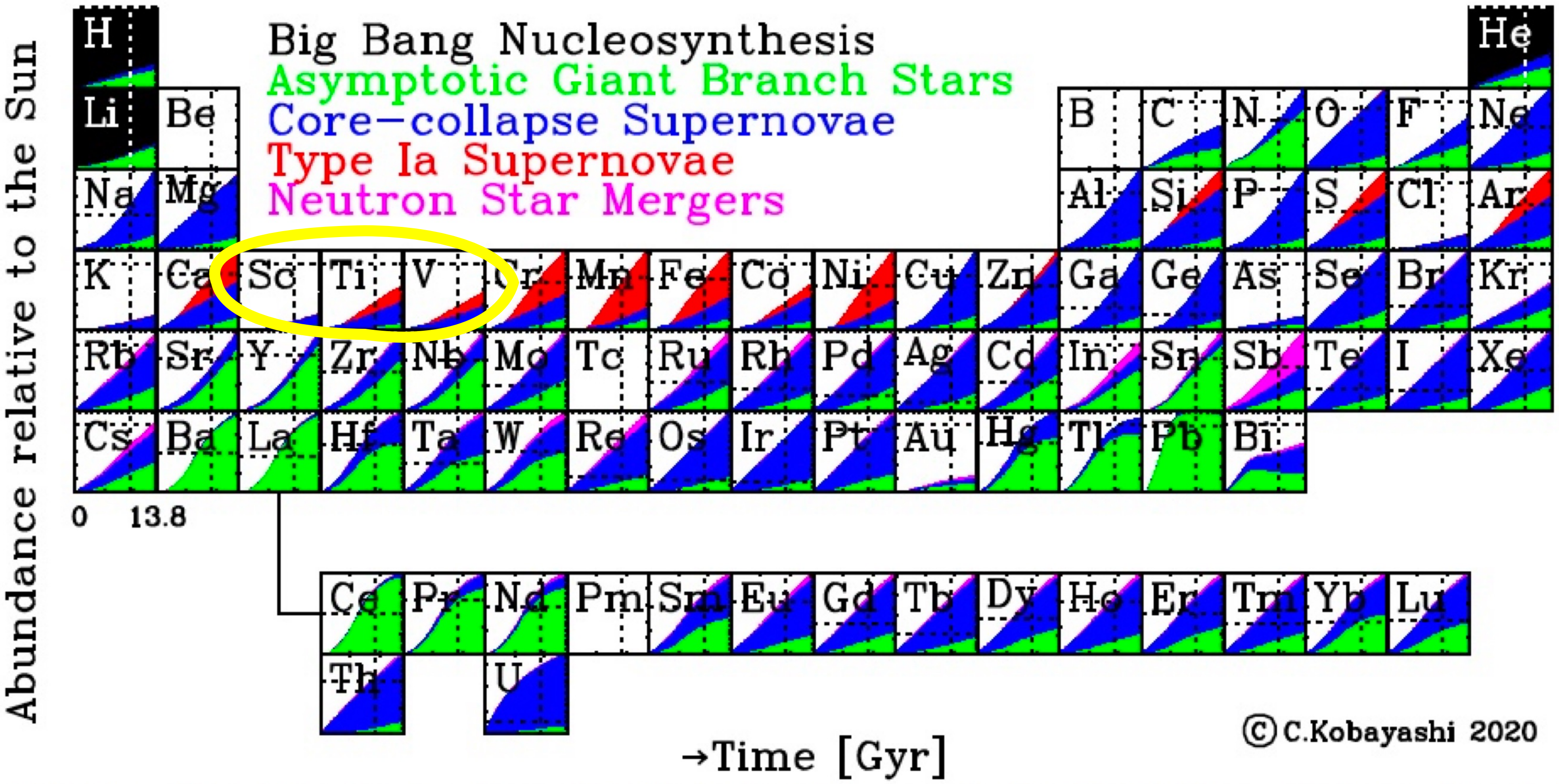
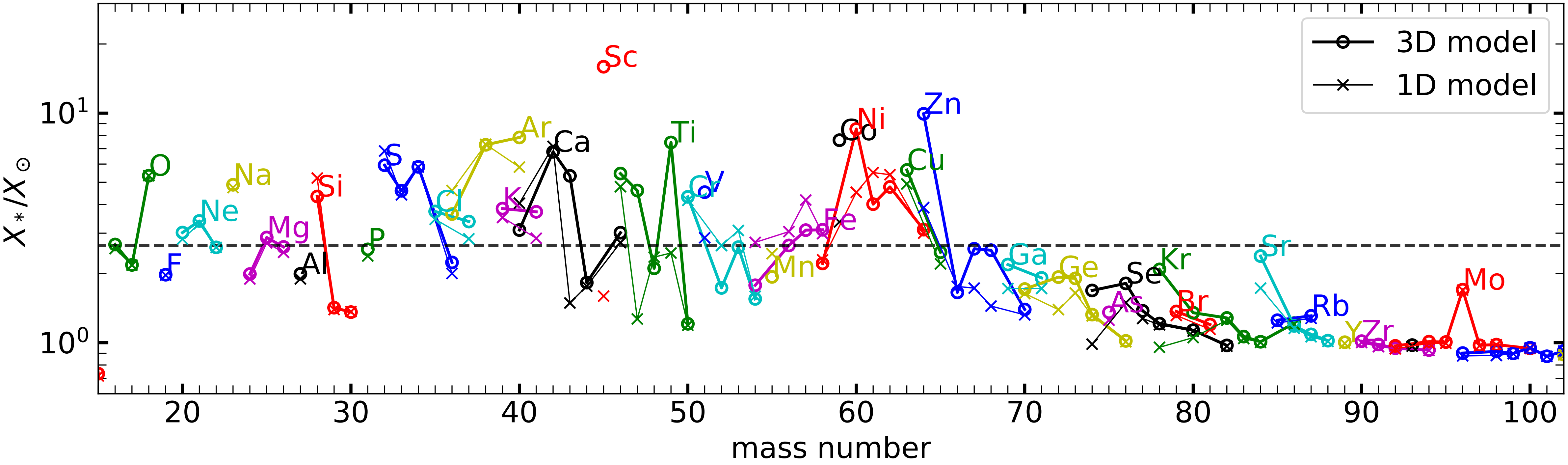


Figure 39. The time evolution (in Gyr) of the origin of elements in the periodic table: Big Bang nucleosynthesis (black), AGB stars (green), core-collapse supernovae including SNe II, HNe, ECSNe, and MRSNe (blue), SNe Ia (red), and NSMs (magenta). The amounts returned via stellar mass loss are also included for AGB stars and core-collapse supernovae depending on the progenitor mass. The dotted lines indicate the observed solar values.

Stable isotopes

s11.8 (3D)

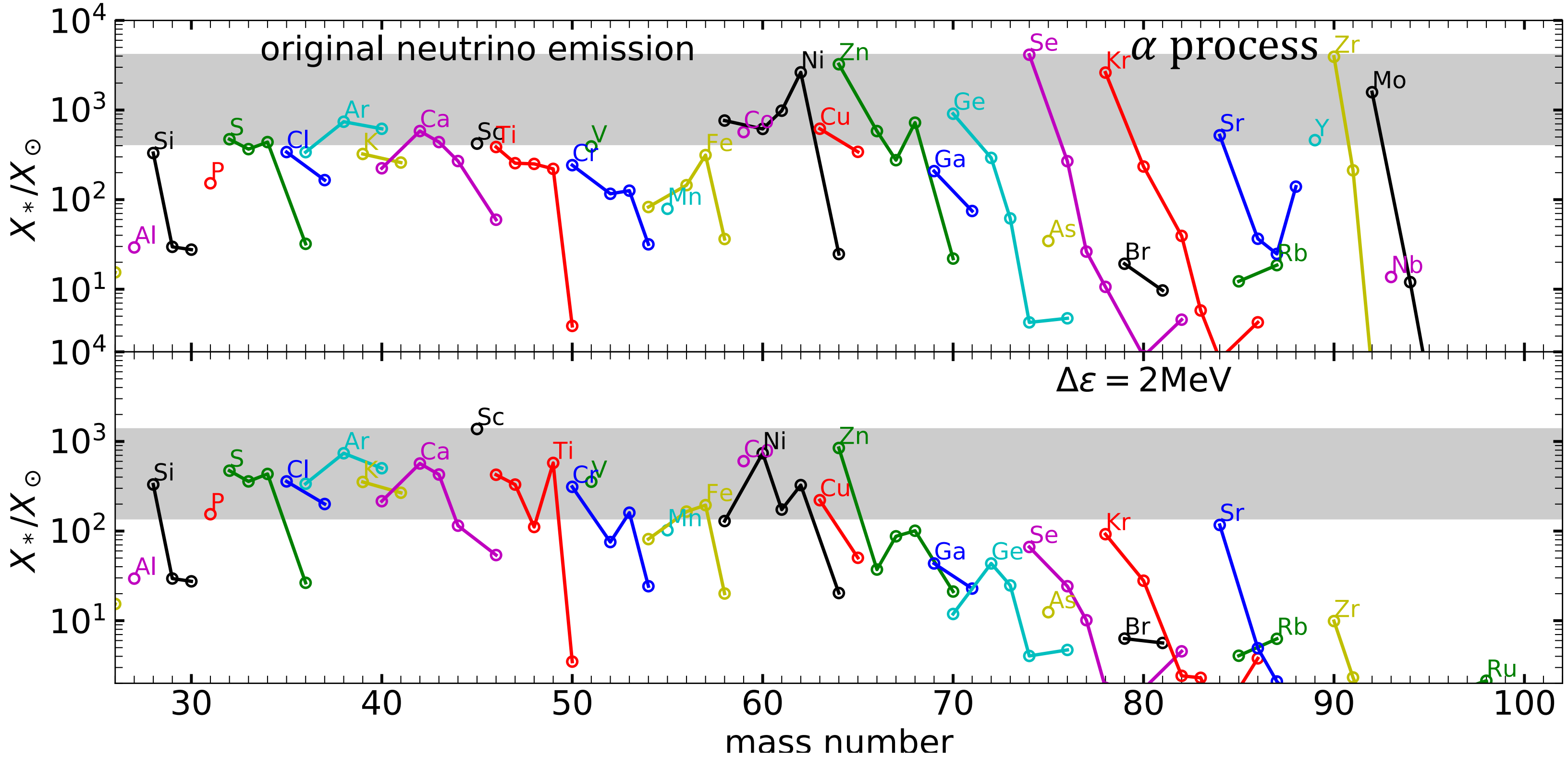


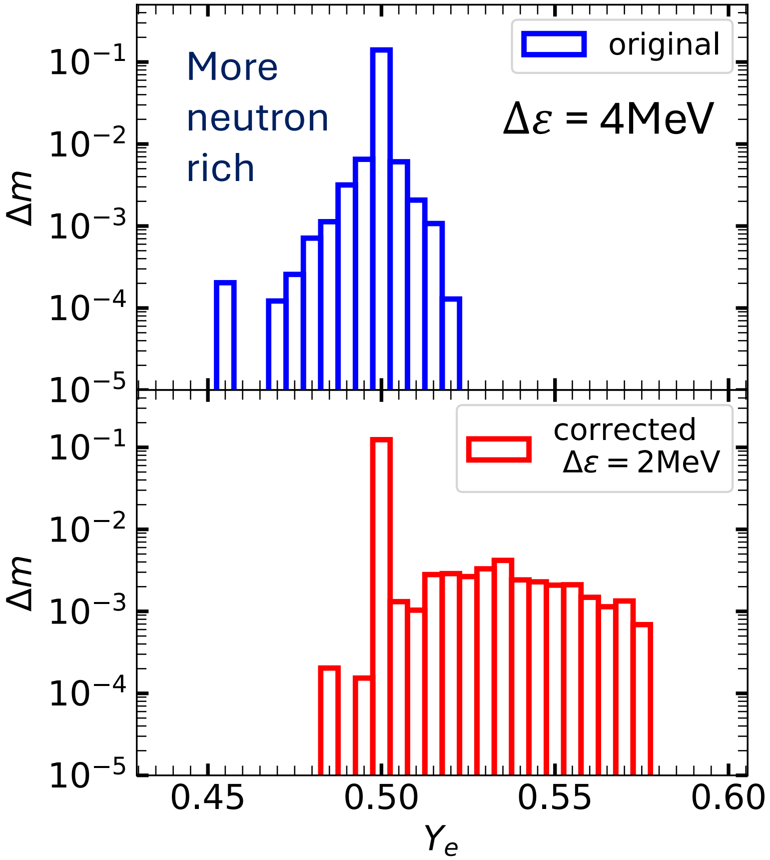
- ^{45}Sc is a signature of proton-rich nucleosynthesis

Impact of the neutrino spectra

s11.8 (3D)

$\Delta\varepsilon = \langle \varepsilon_{\bar{\nu}_e} \rangle - \langle \varepsilon_{\nu_e} \rangle$



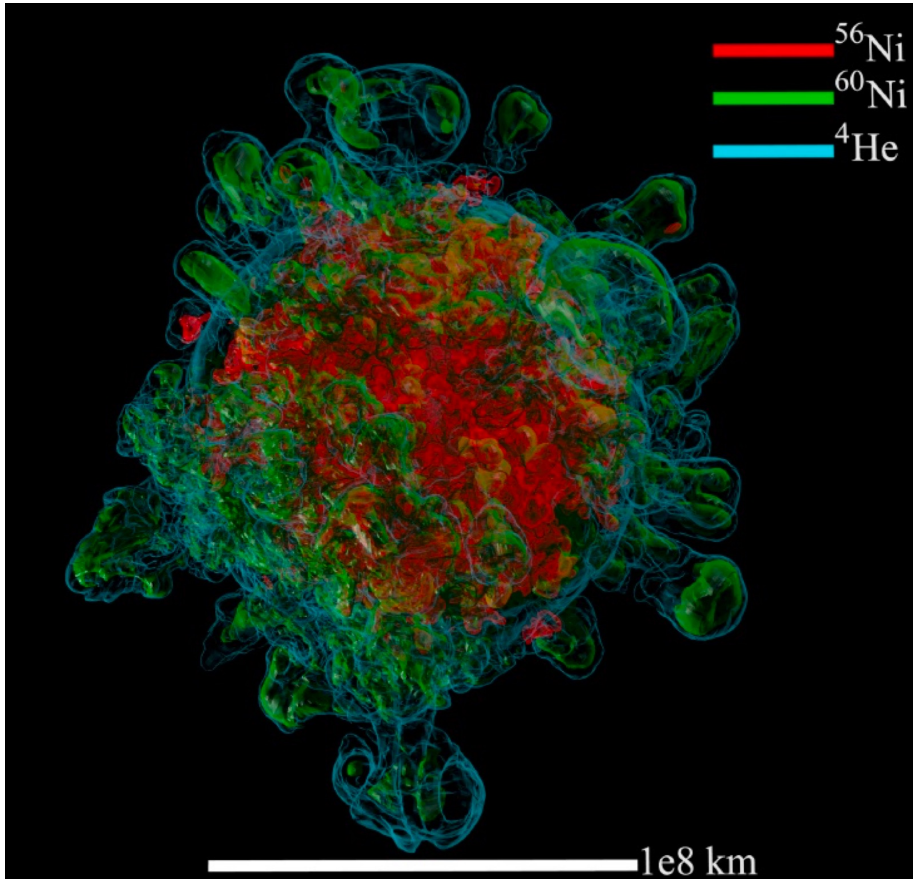


Integration of neutrino flavor evolution with simulation is crucial (e.g. [Xiong et al. 2024] [Abbar et al. 2024])

Parameter-free multi-D simulations

- Successful explosions in 2D and 3D
- Models are increasingly compatible with observations

- **Challenges for nucleosynthesis with multi-D**:
  - Quantitative differences between codes
  - Progenitor-explosion connection
  - Long-term evolution (~ several seconds)
  - In-situ vs. postprocessing nucleosynthesis
    - Sandoval et al. (2021) 160 species
    - García-Senz et al. (2024) 90 species with effective reactions
  - Neutrino flavor evolution



From Sandoval et al 2021

Summary

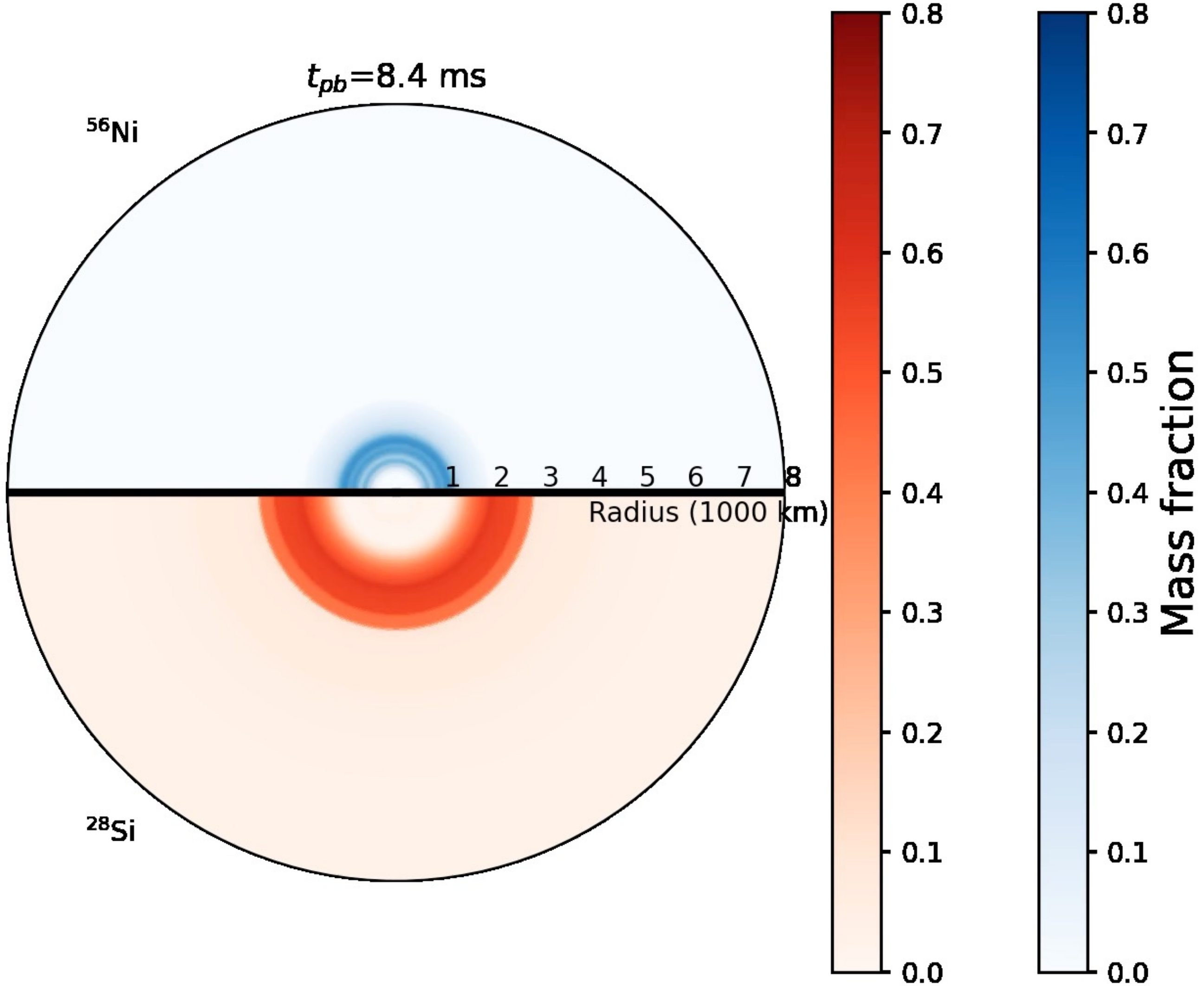
- Core-Collapse supernovae are **neutrino-driven** explosions of massive stars
- Main contributors to the O, Mg, Si, Fe
- Source of radioactive isotopes with observable signatures:
  - ^{56}Ni, ^{60}Fe, ^{44}Ti, ^{26}Al
- ”Explodability” is important for chemical evolution and remnant mass distributions
- Multi-D models show a larger variability of conditions (Ye, entropy)
- 3D models are promising to improve the agreement between observations and theory for ^{44}Ti

Thanks to my collaborators:
H.T. Janka (Max-Planck Insitute for Astrophysics)
W.R.Hix, J.A. Harris, E.J. Lentz (Oak Ridge National Laboratory)
S. Bruenn (Florida Atlantic University)
J. Randhawa, R.J. DeBoer, T. Ahn (University of Notre Dame)
D. Zetterberg (University of Tennessee)
Y.-Z. Qian (University of Minnesota)
B. Müller, A. Heger (Monash University)
G. Martinez-Pinedo, T. Dickel (GSI/TU Darmstadt)
M. Lugaro (Konkoly Observatory)
…

Lawrence Livermore National Laboratory

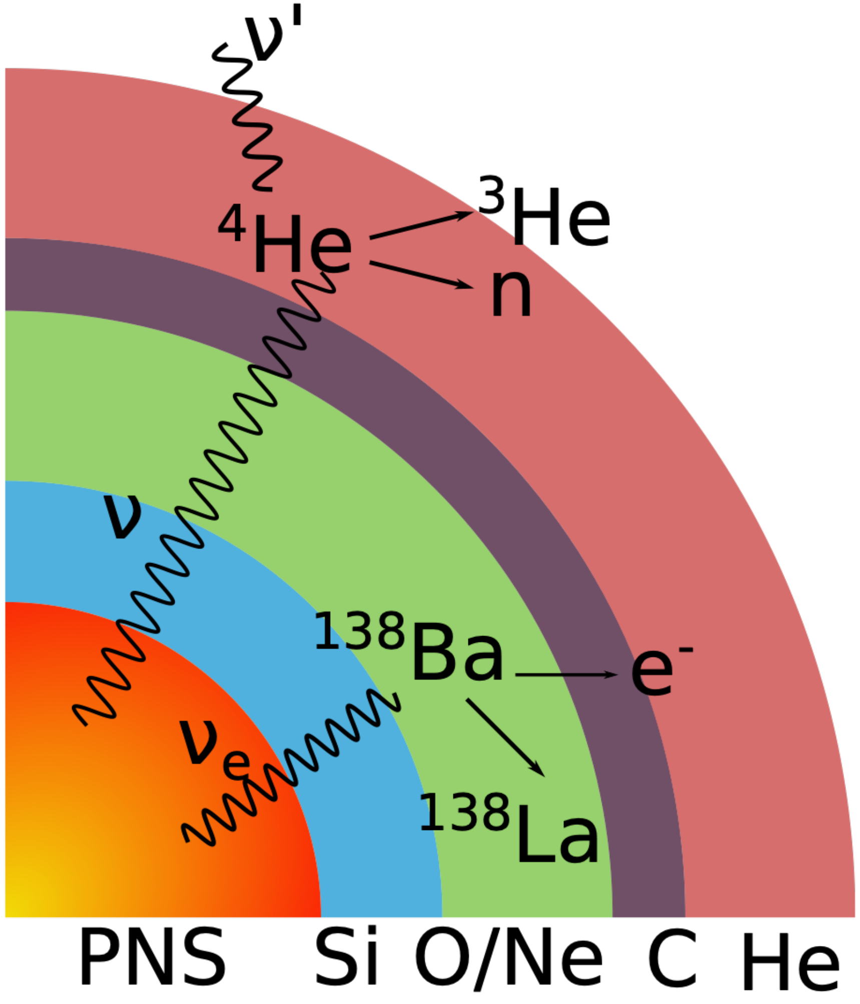
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Neutrinos in Supernova Nucleosynthesis



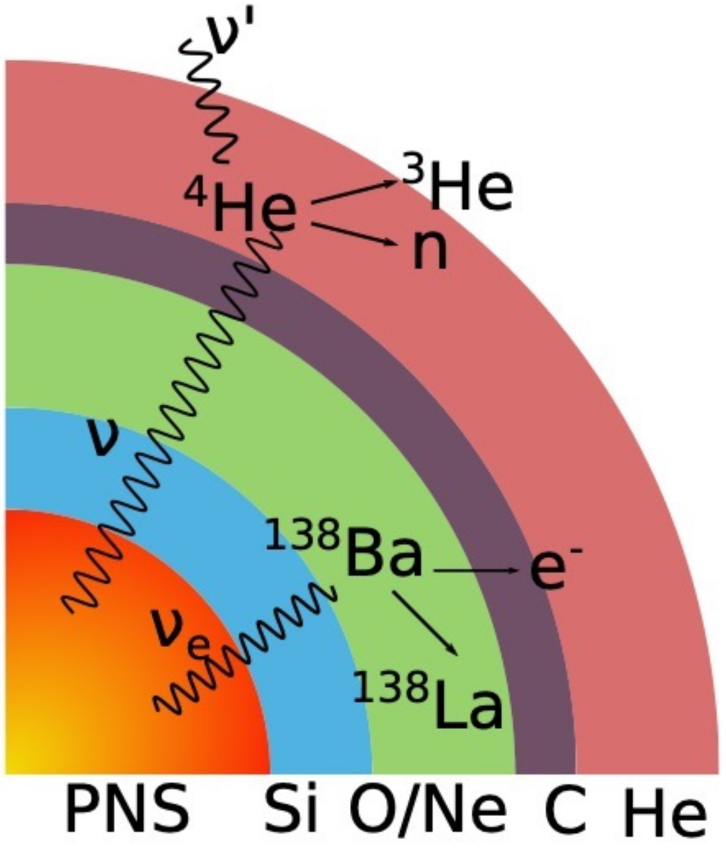
15.78 $M_\odot$ star
Bruenn et al. 2022

The ν process

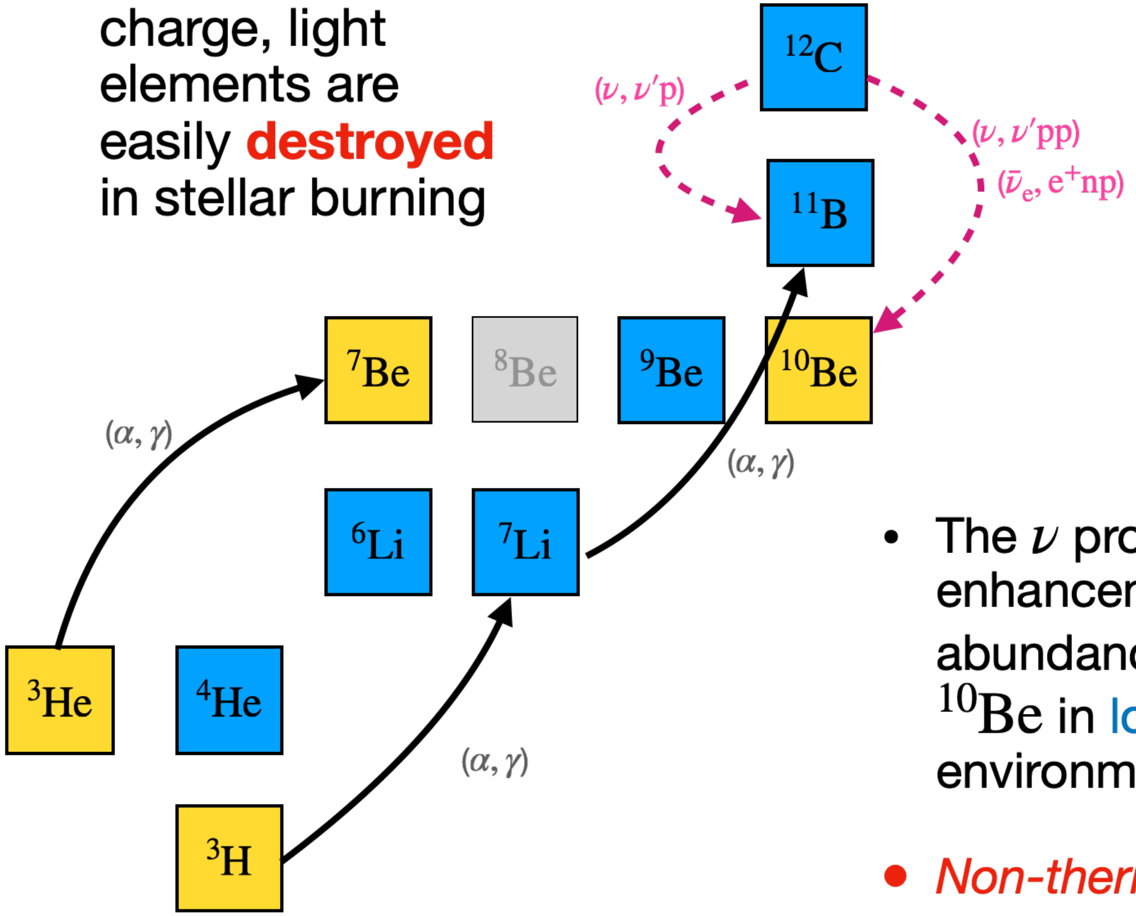


- High energy neutrinos (~10 MeV) induce reaction on abundant nuclei *[Woosely et al. 1990 ...]*
  - Inverse β decay, spallation reactions, supply of light particles
- Contributions to ^{7}Li, ^{11}B, ^{22}Na, ^{26}Al, ^{92}Nb, ^{98}Tc, ^{138}La, ^{180}Ta ...

ν process



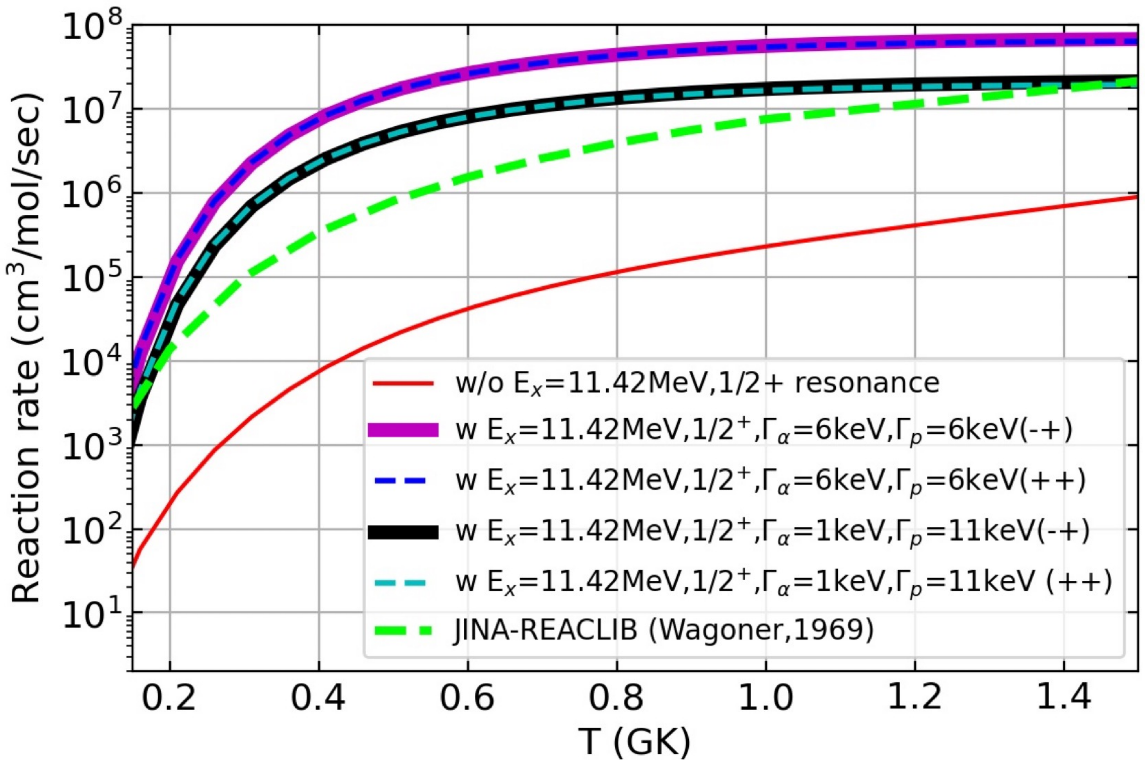
- Due to their small charge, light elements are easily **destroyed** in stellar burning

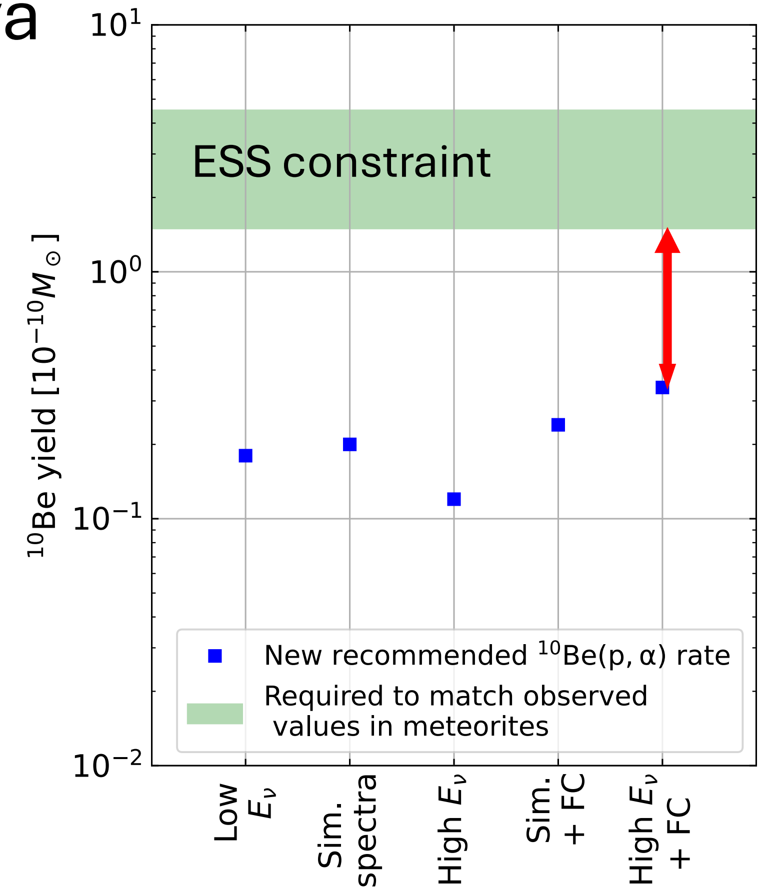


- The ν process allows for enhancement of the abundances of ^{7}Li, ^{11}B and ^{10}Be in low temperature environments
- *Non-thermal nucleosynthesis*

^{10}Be + p resonance

- With the new reaction rate, the 11.8 supernova does not produce enough ^{10}Be

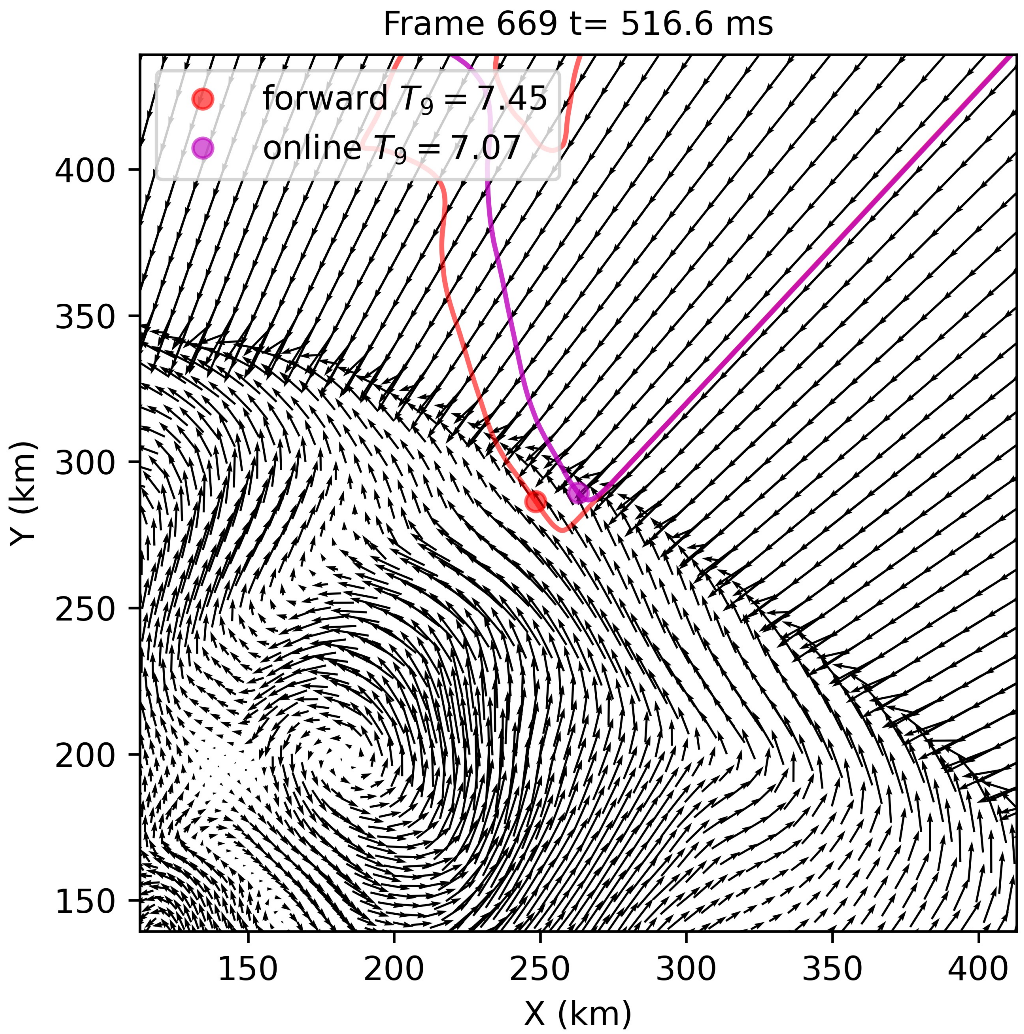




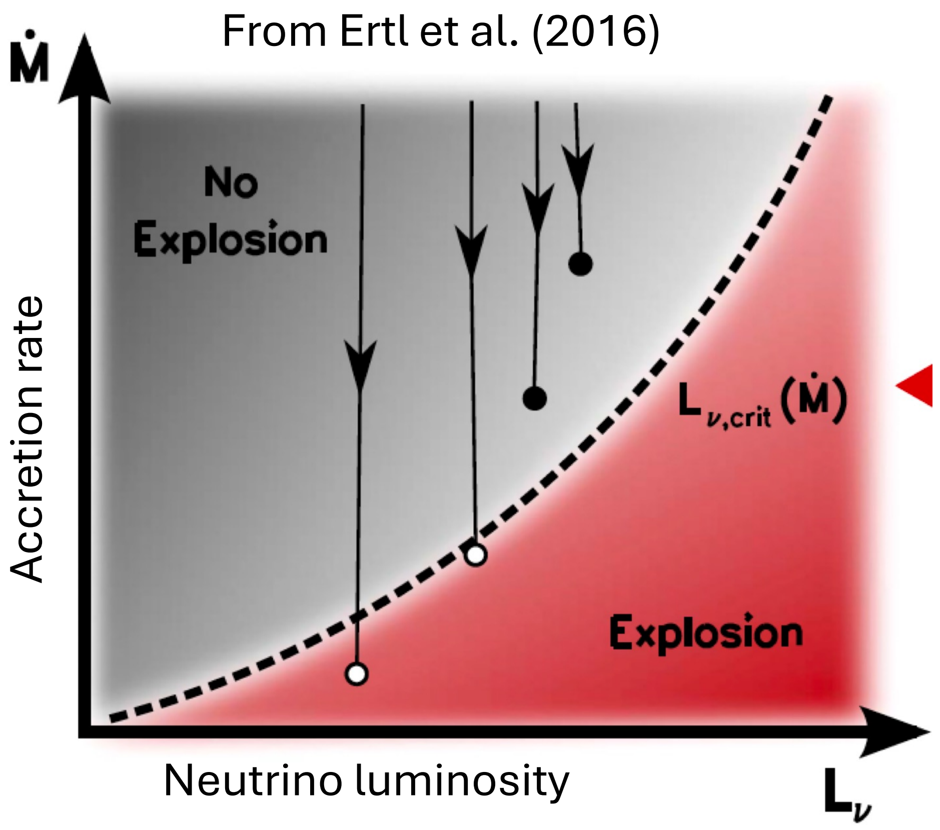
Sieverding et al. (2022)

The tracer particle method

- Follow the fluid velocity of the simulation
- $\frac{d\vec{x}}{dt} = \vec{v}(\vec{x}, t)$
- Ideally: "online" during the simulation with time steps ~ 10^{-6} s
- In practice: Post-processing based on snapshots with time steps ~ 10^{-3} s
- Forward or backward numerical integration



Explodability



- **Competition between neutrino-heating and ongoing collapse**
- **Some supernovae may not be successful**