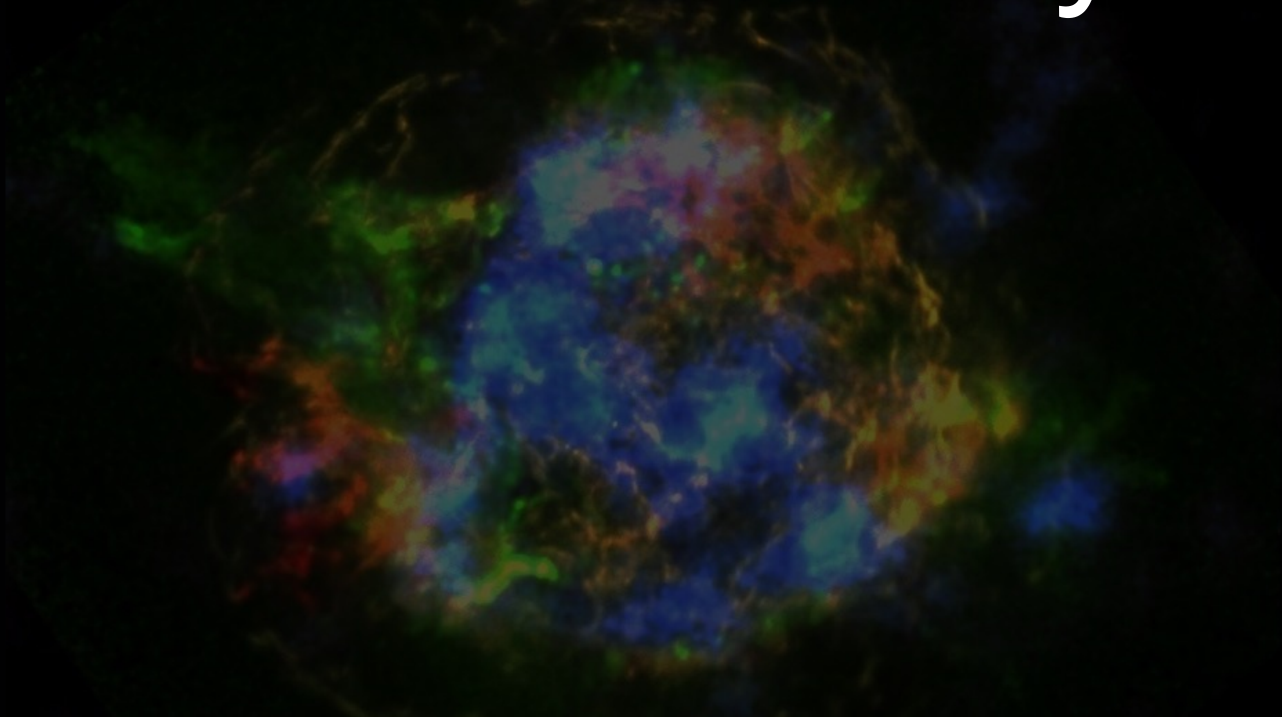
Supernova Nucleosynthesis



Carla Fröhlich

North Carolina State University

U.S. DEPARTMENT OF ENERGY

RESEARCH CORPORATION for SCIENCE ADVANCEMENT

A foundation dedicated to science since 1912.

12th European Summer School on Experimental Nuclear Astrophysics Catania (16-22 June 2024)

About me

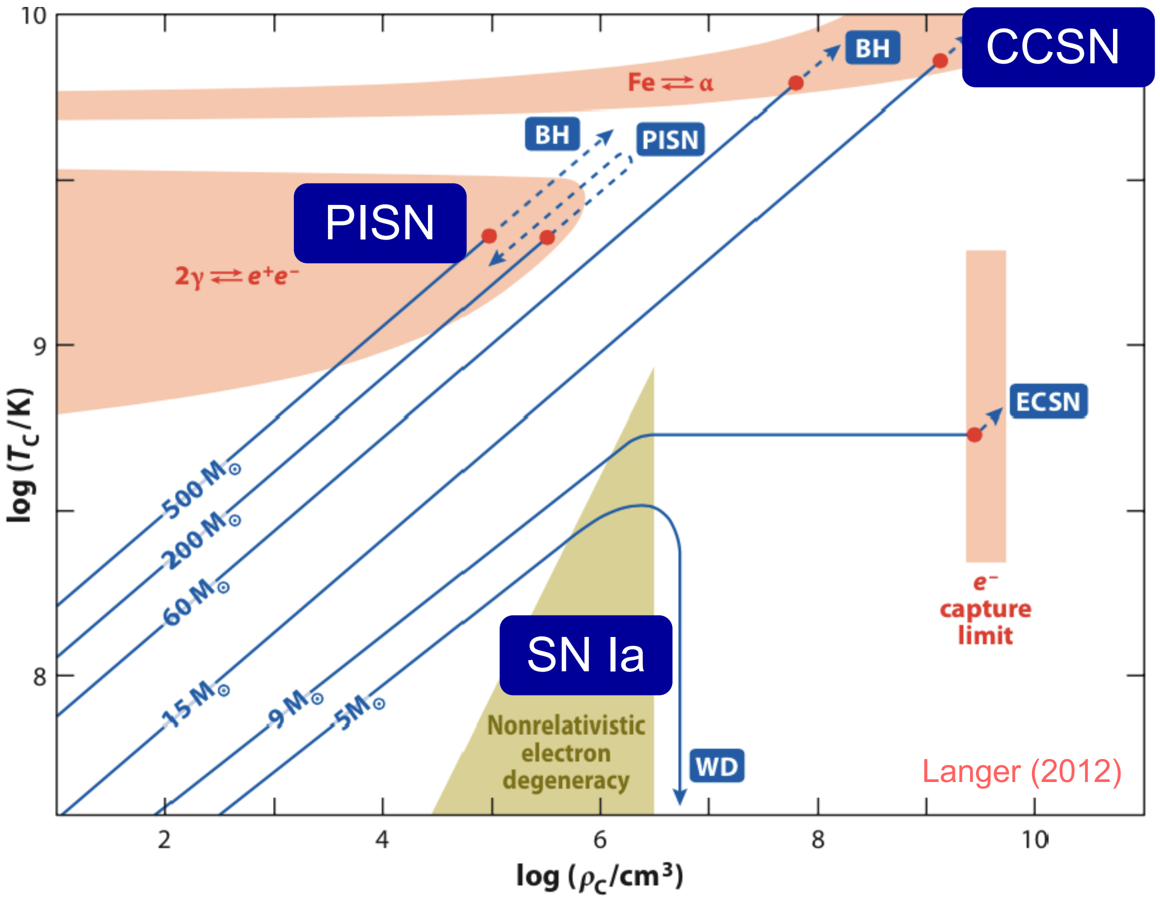
Idea credit: Andreas Korn

- Study of Physics and Computer science
  - University of Basel, Switzerland
  - 2 semesters at Simon Fraser University, Vancouver, Canada
- PhD in theoretical physics (Advisor: Friedel Thielemann)
  - University of Basel, Switzerland
- Enrico Fermi Postdoctoral Fellow
  - University of Chicago, USA

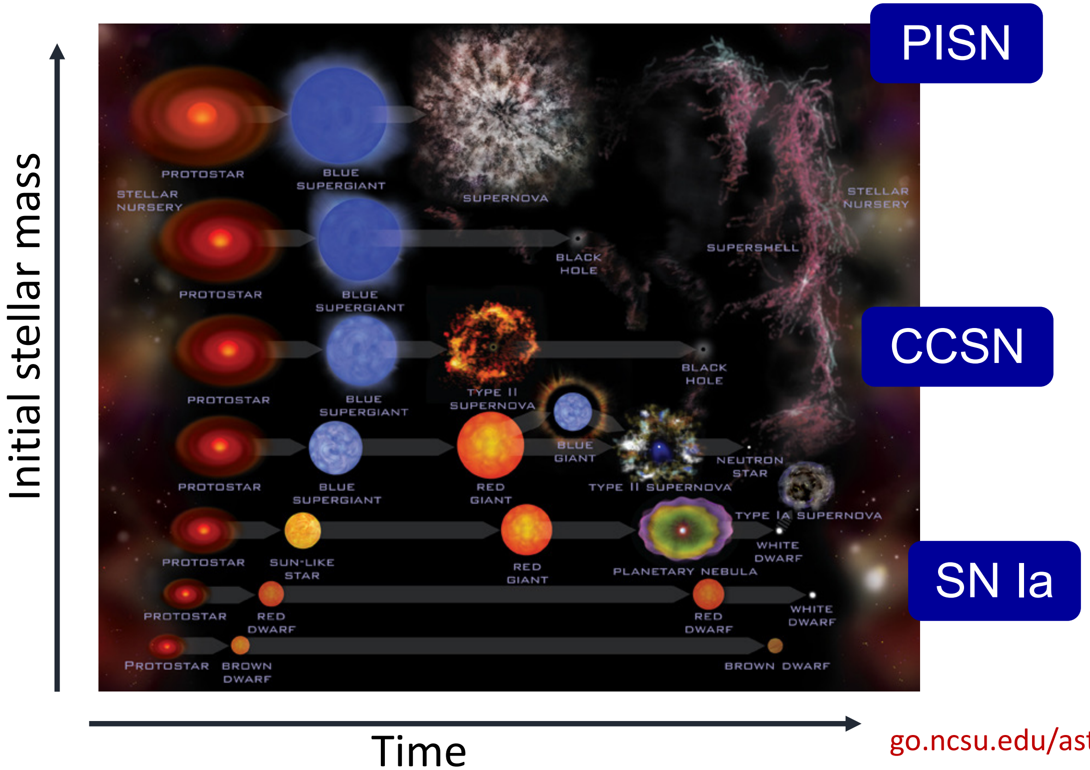
"I'll go to the US for 3 years"

- Since 2010: Professor
  - North Carolina State University, USA

Supernovae

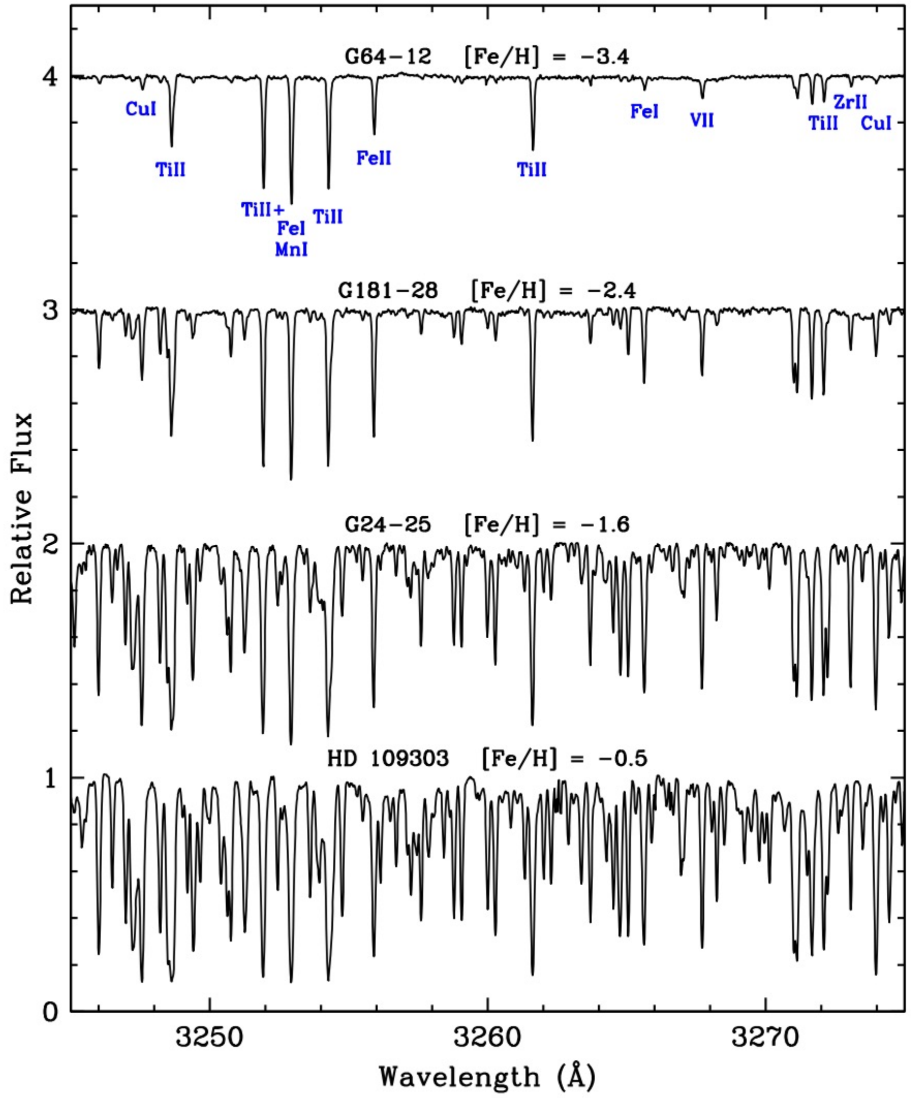


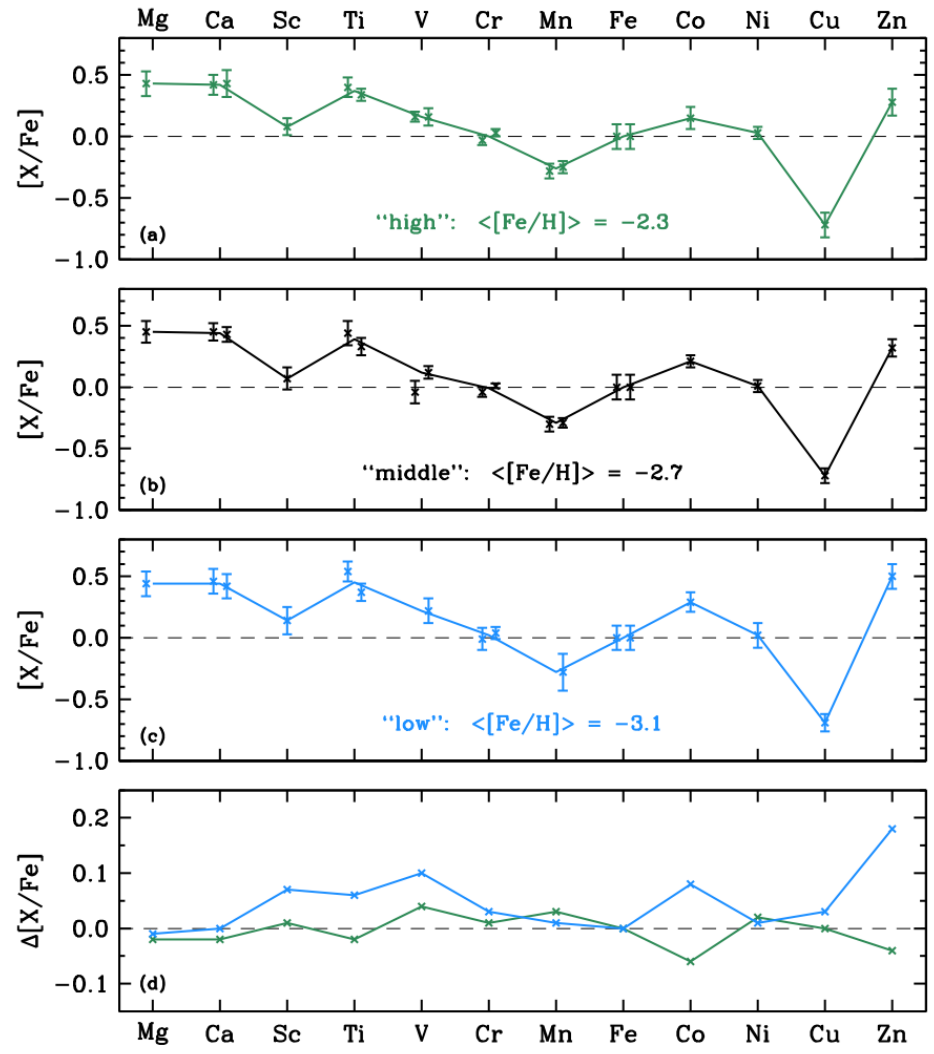
Supernovae happen when stellar evolution reaches a region of instability



Where do we see the nucleosynthetic imprints of CCSNe?

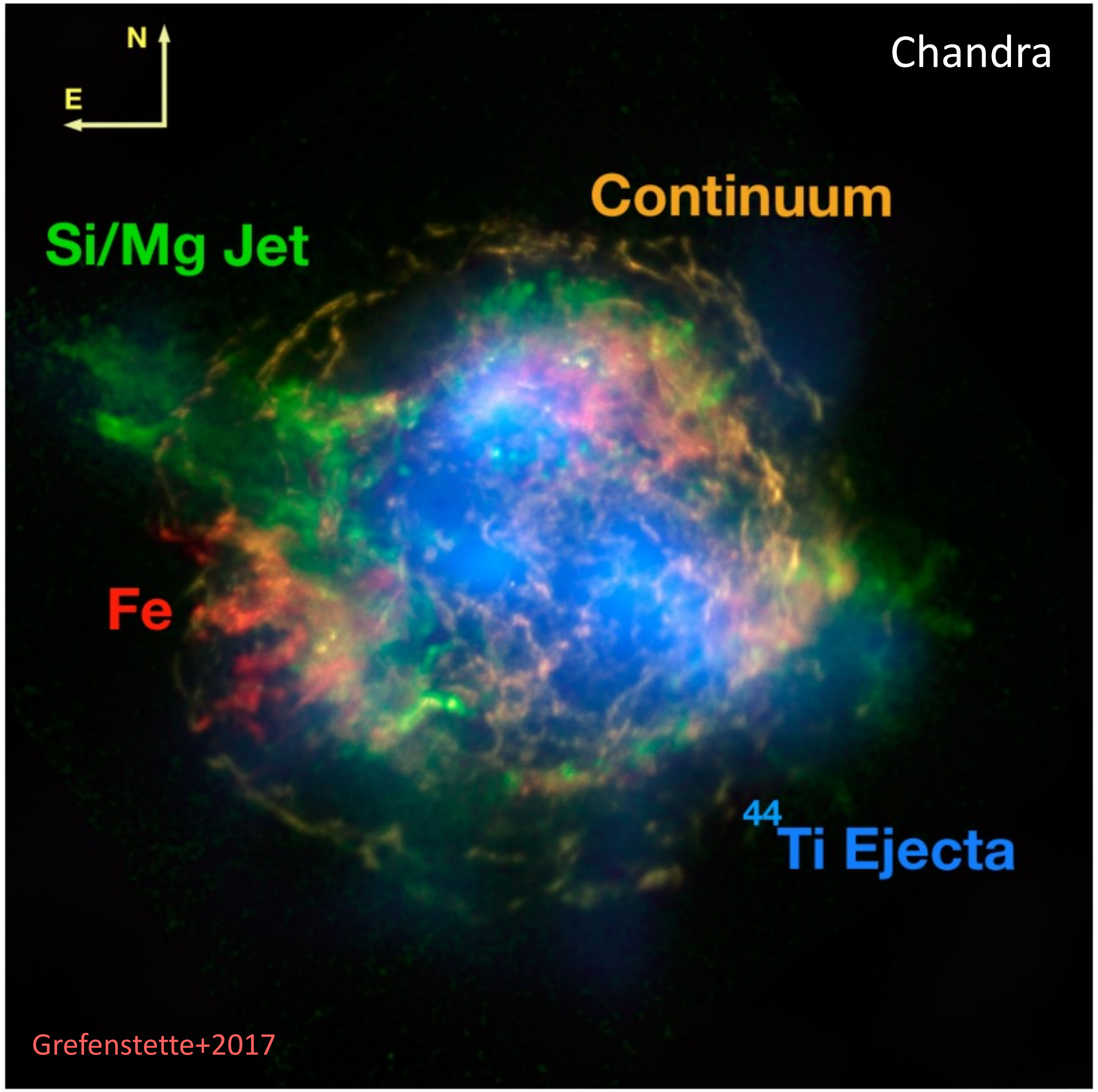
Old Metal Poor Stars



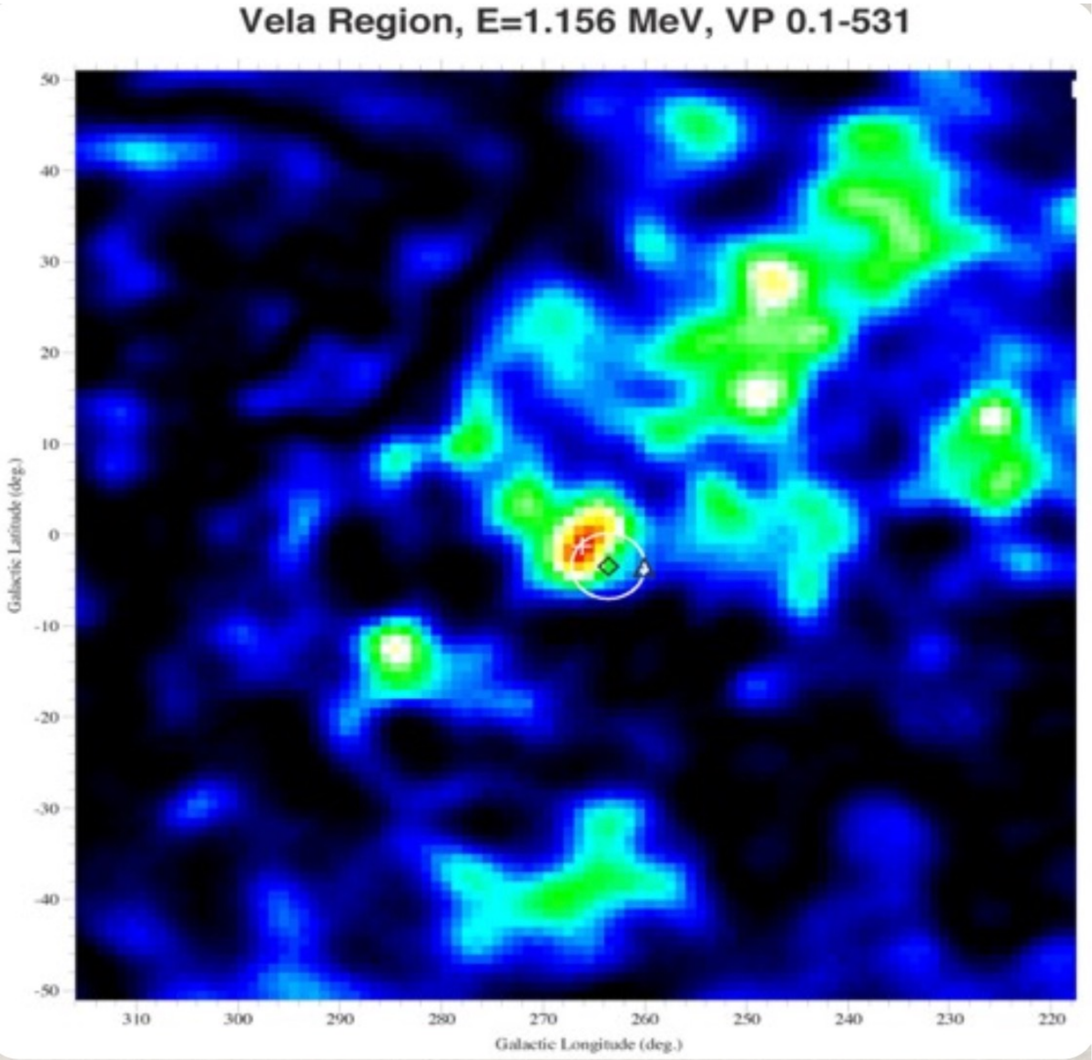


Sneden+2023

Supernova Remnants



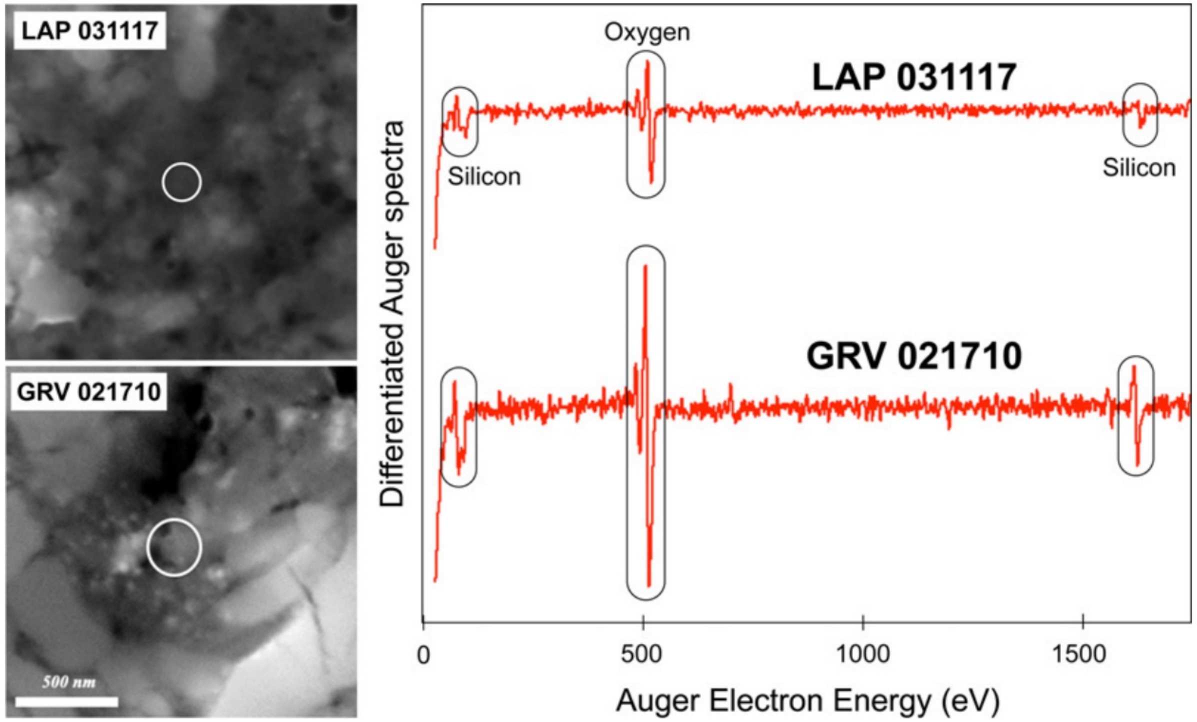
In gamma-rays (signatures of freshly made nuclei)



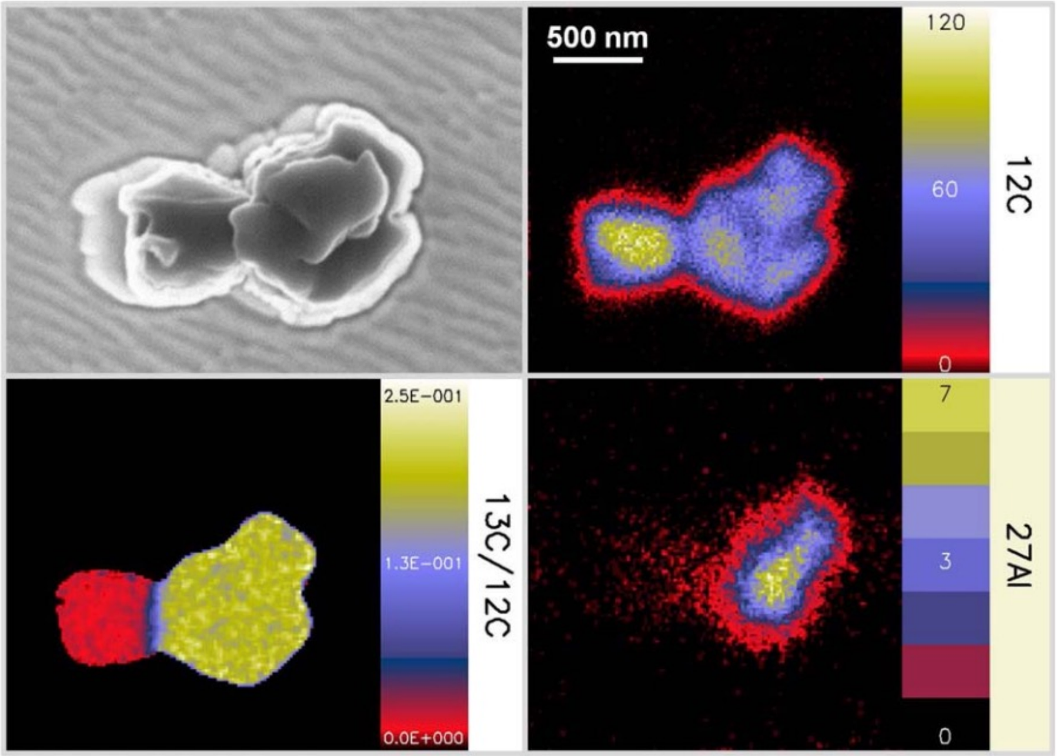
Characteristic gamma-lines:

- 56Ni ($t_{1/2}$ = 6 days)
- 57Ni ($t_{1/2}$ = 36 hrs)
- 56Co ($t_{1/2}$ = 77 days)
- 57Co ($t_{1/2}$ = 272 days)
- 44Ti ($t_{1/2}$ = 60 yrs)

Pre-solar grains

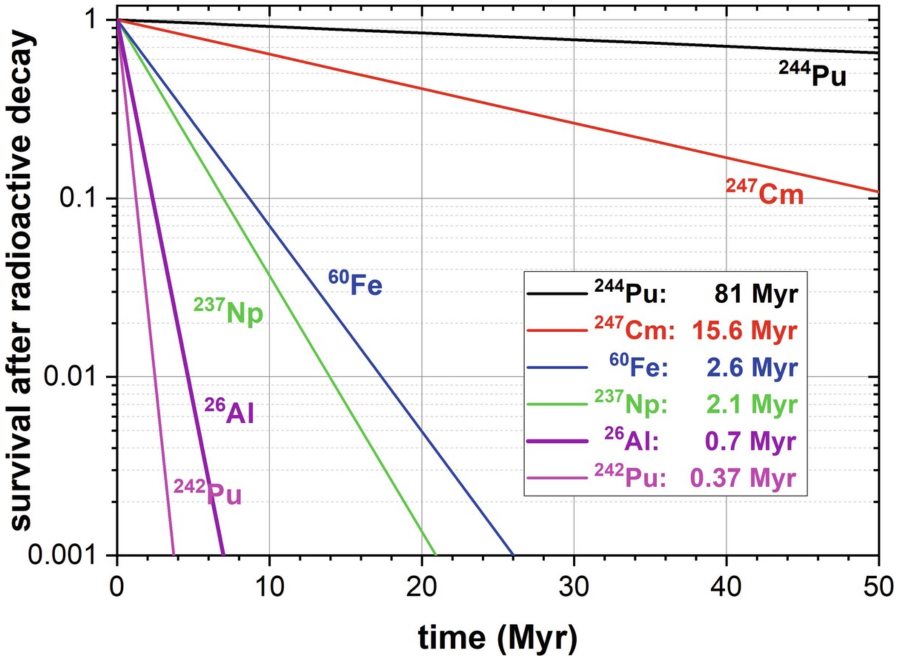


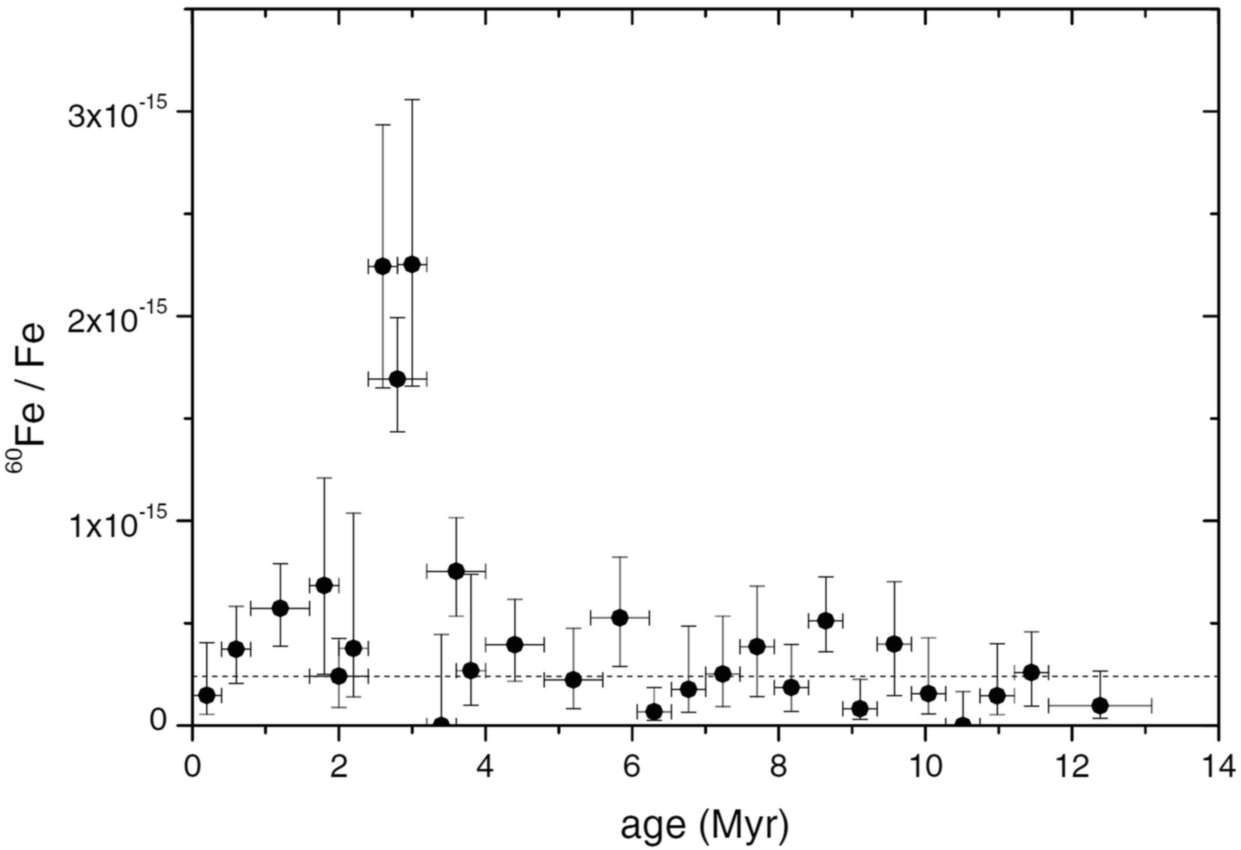
Haenecour+2013



Hoppe+2019

Deep Sea Crust

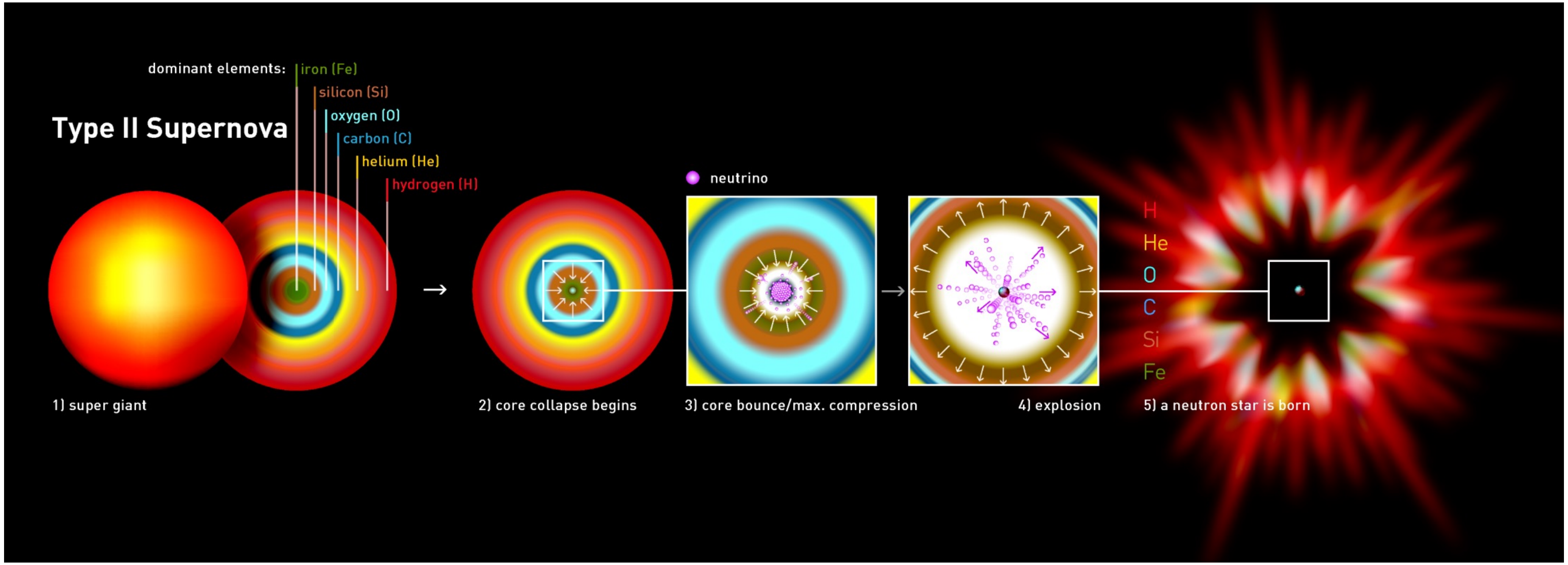




Figures from Wallner 2023

Understanding Core-Collapse Supernovae

Core-collapse supernovae



Massive star
at the end
of its life …

… collapses
under gravity …

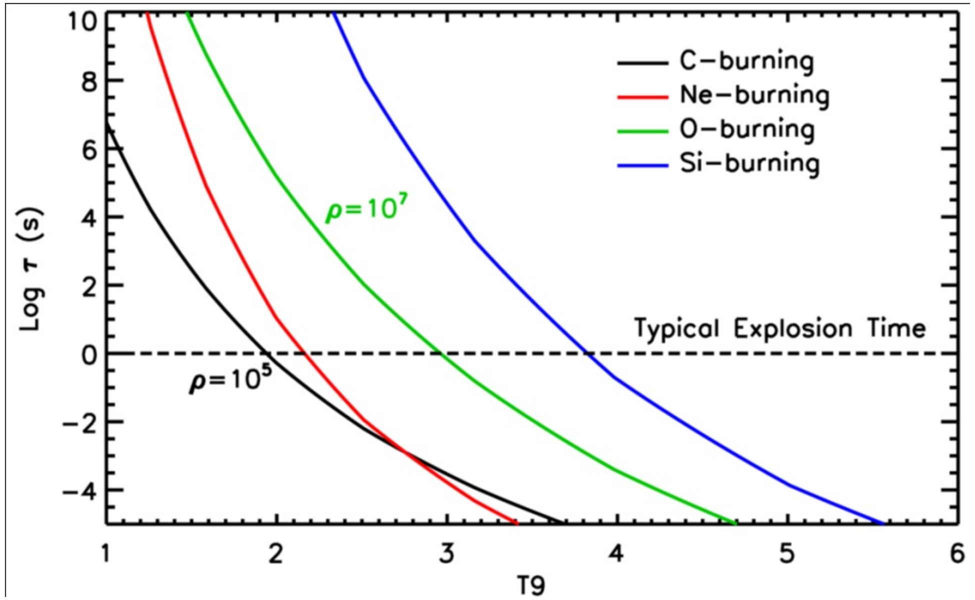
… and
explodes
(sometimes)

Explosive nucleosynthesis

- Typical burning timescales: $\tau \sim \frac{1}{r_{ij}}$
  - Stellar reaction rate: $r_{ij} = n_i \, n_j \, \langle \sigma \, v \rangle_{ij}$

- Typical explosion timescale: 1 second

- Explosive burning:
  - Si burning: $T \gtrsim 4$ GK
  - O burning: $T \gtrsim 3.3$ GK
  - Ne burning: $T \gtrsim 2.1$ GK
  - C burning: $T \gtrsim 1.9$ GK



Explosive nucleosynthesis

- Complete Si-burning:
  - Temperature $T \gtrsim 5$ GK
  - Electron fraction $Y_e > 0.49$
  - Abundances from nuclear statistical equilibrium (NSE)
  - Products: Sc, Ti, Co, Ni, Zn

- Incomplete Si-burning:
  - Temperature between 4 and 5 GK
  - Electron fraction $Y_e > 0.49$
  - Abundances from quasi-statistical equilibrium (QSE)
  - Products: V, Cr, Mn

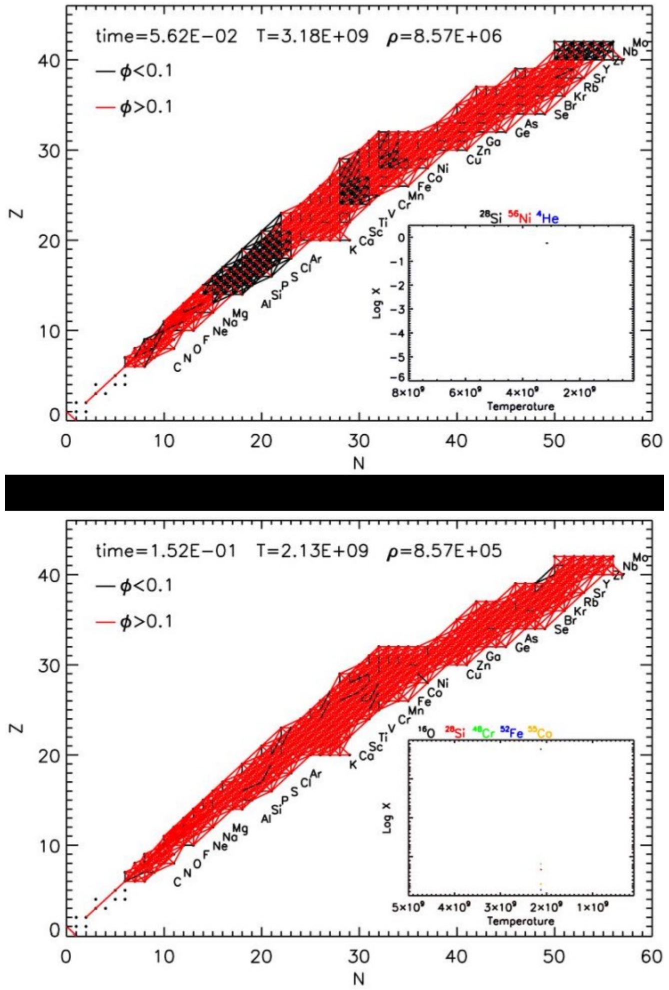


Figure: Limongi

Explosive nucleosynthesis

- Oxygen burning:
  - Temperature between 3.3 and 4 GK
  - Electron fraction $Y_e > 0.49$
  - Abundances from QSE and sequences of nuclear reactions

Products:
Si, S, Ar, K, Ca

- Explosive burning below 3.3 GK
  - Abundances through sequences of nuclear reactions
  - Ne-burning: temperatures between 2.1 and 3.3 GK
  - C-burning: temperatures between 1.9 and 2.1 GK

Products:
Mg, Al, P, Cl
Ne, Na

- Below 1.9 GK: no nuclear processing on explosive timescales

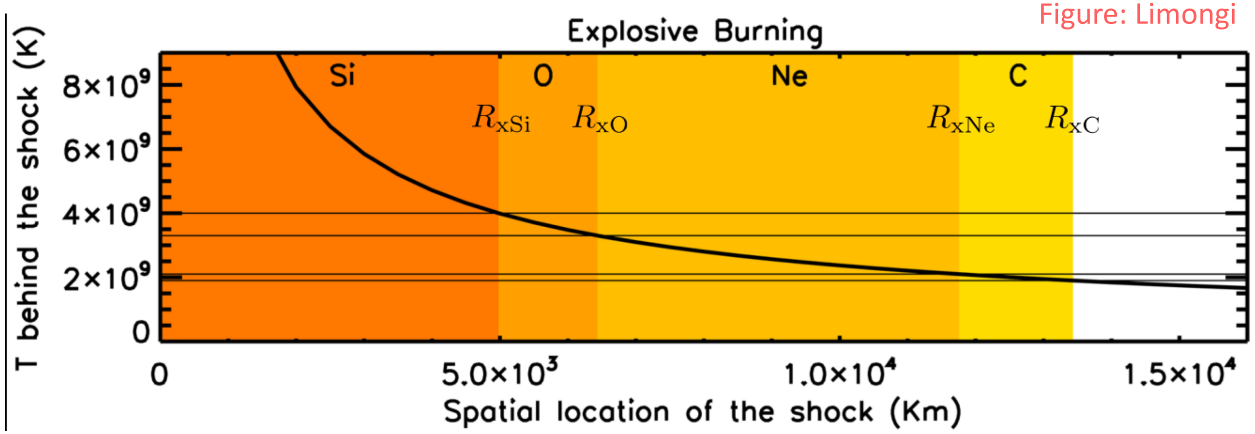
Energy considerations

- Shock temperature can be approximated by:

$$T_{shock} = \left(\frac{3\, E_{expl}}{4\pi a\, R_{shock}^3} \right)^{1/4}$$

- Shock location for a typical explosion energy of 1 Bethe (10^{51} erg):
  - Si-burning: 5000 km
  - O-burning: 6400 km
  - Ne-burning: 11750 km
  - C-burning: 13400 km

Figure: Limongi



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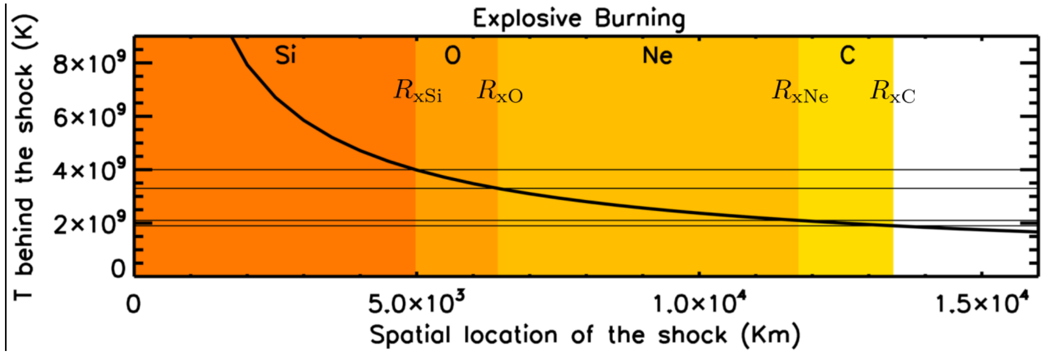


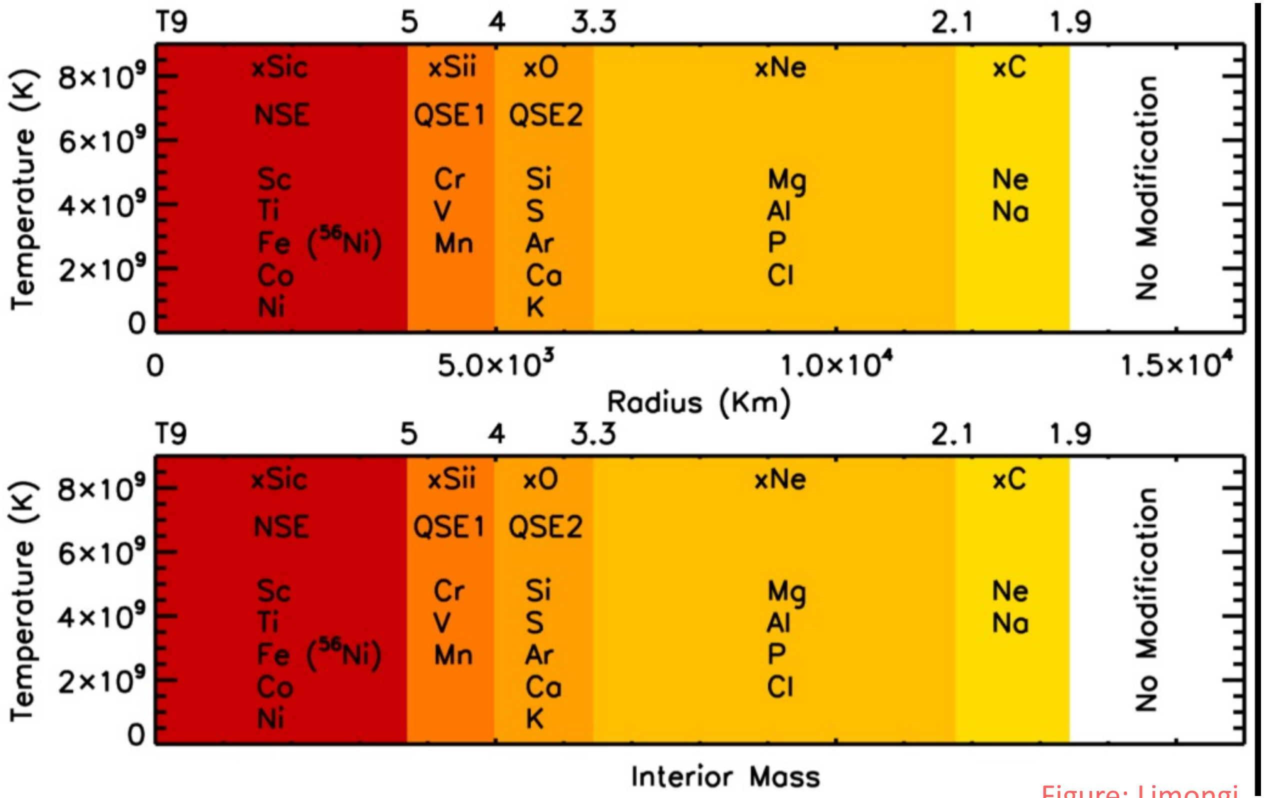


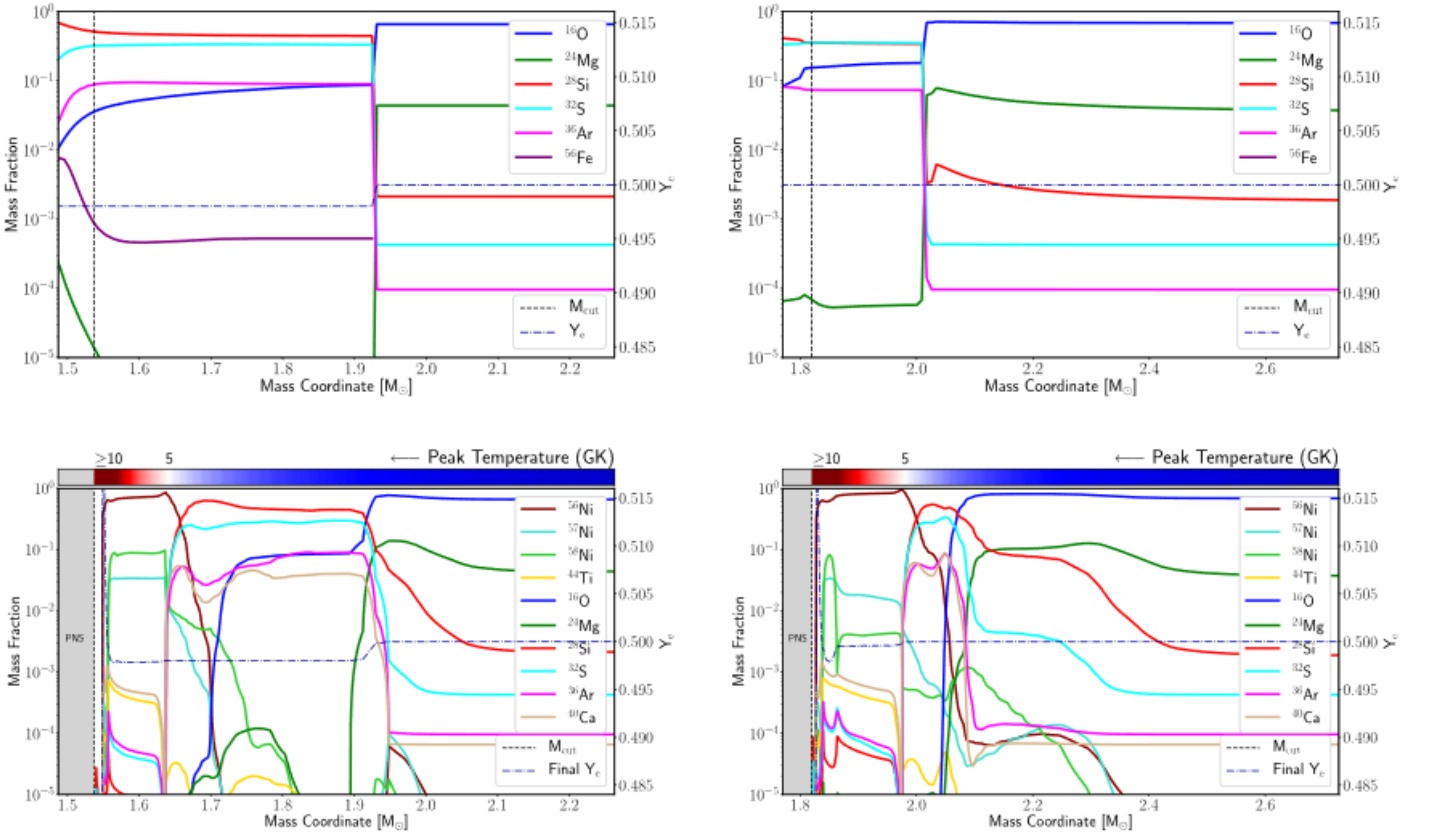
Figure: Limongi

Explosive nucleosynthesis: Now in a simulation

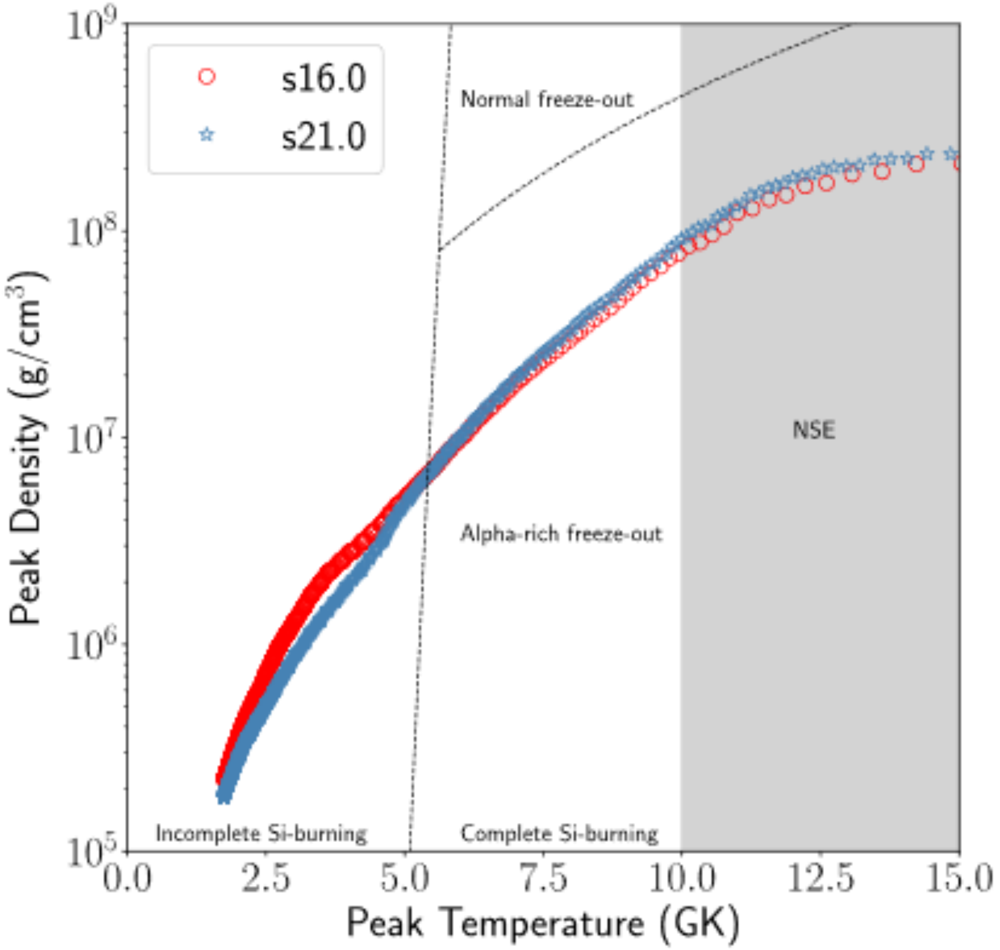
Curtis+2019

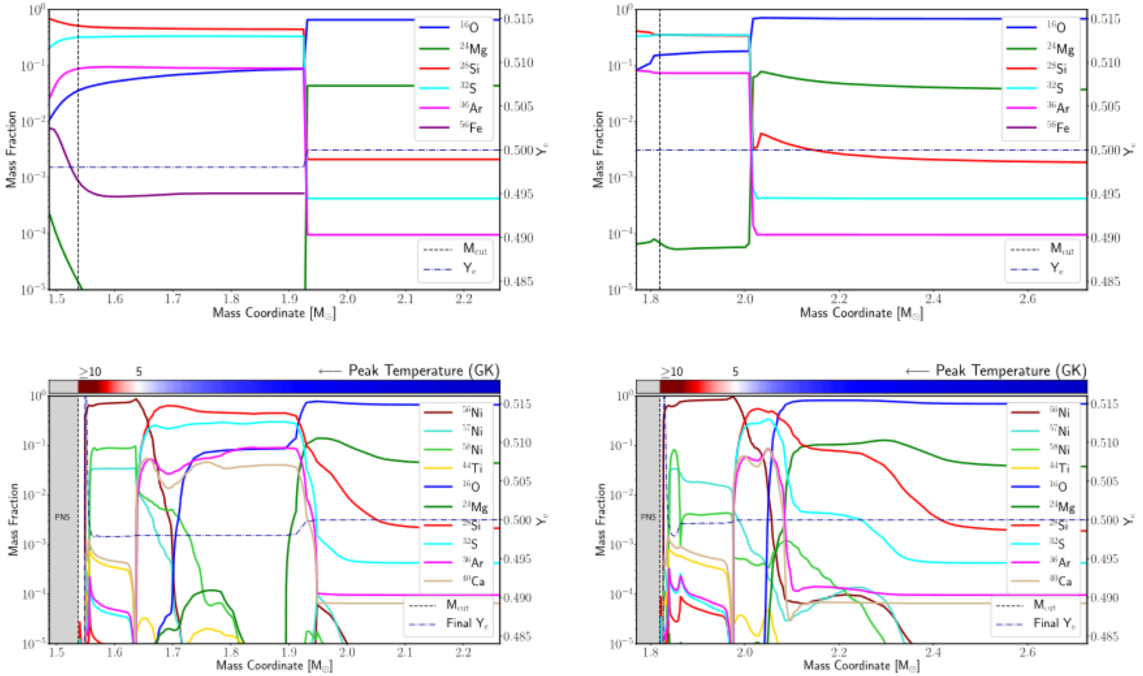
16Msun

21Msun



Explosive nucleosynthesis





Does it matter how we seed the shock wave?

- Inner-most ejecta / iron-group elements: yes!
- Intermediate mass elements: no

- We need a consistent explosion which includes all the physics, not just an explosion energy

→ What is the status of CCSN simulations?

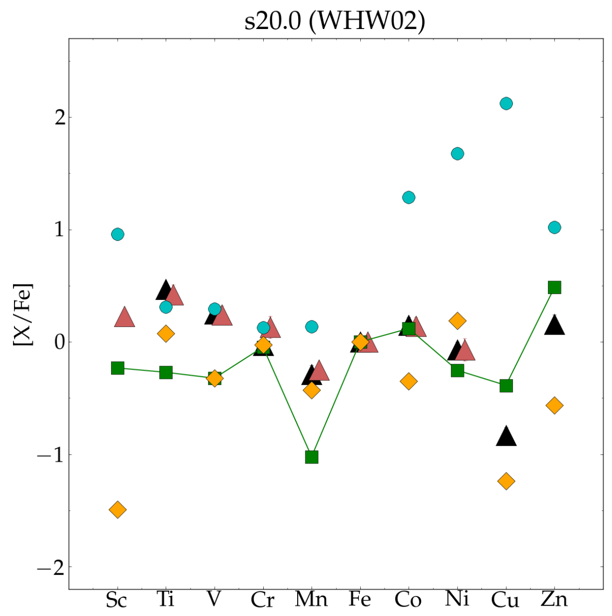
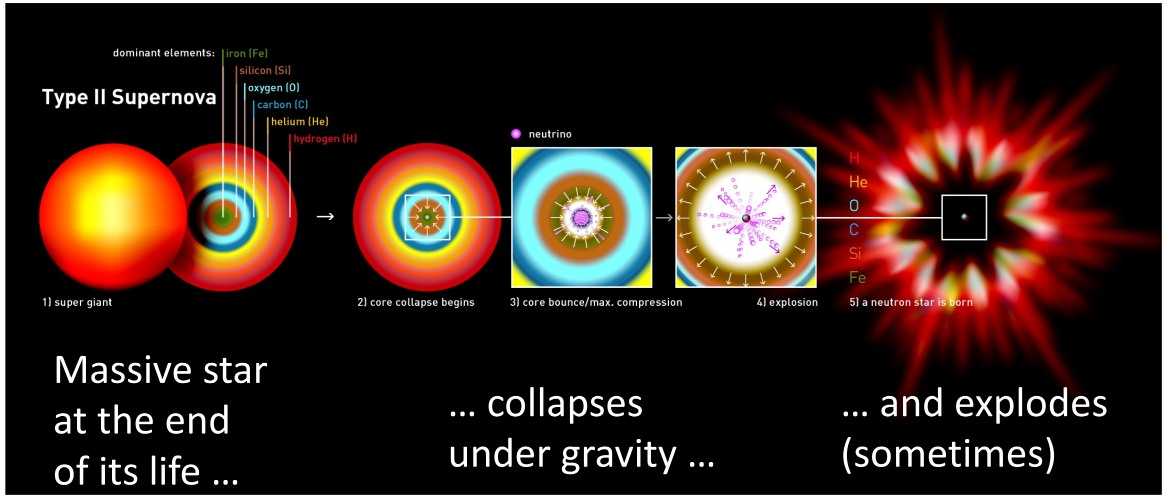
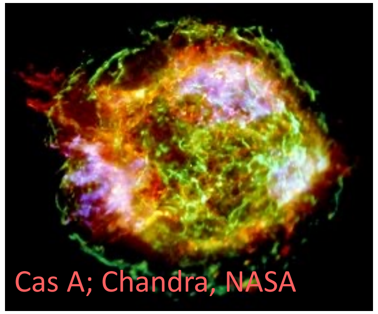


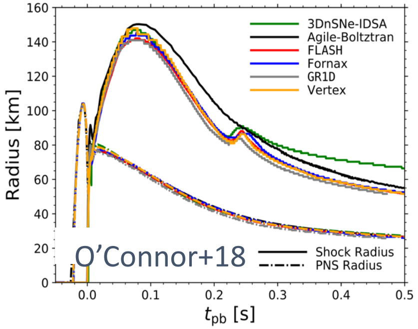
Figure: Curtis

Core-collapse supernova simulations



- Multi-dimensional problem
- Multi-physics problem:
  - General relativity
  - Nuclear physics of dense matter
  - Neutrino transport (trapped, diffusive, free-streaming regimes)
- Multi-scale problem:
  - shock formation at ~200 km vs entire star 10^8 km
  - collapse and shock formation ~1 s vs shock breakout ~1 day



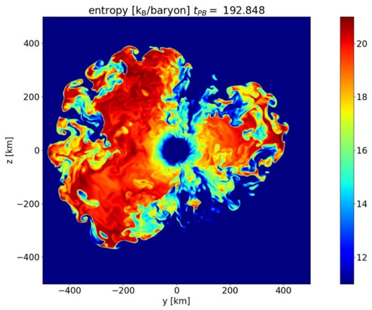


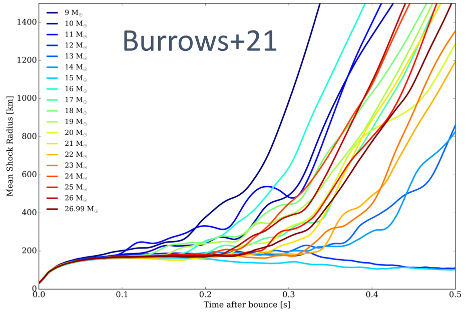
Simulation Status:

1D: in general no self-consistent explosions
~10 CPUh/model

2D: models have converged

3D: mixed results
~ Mio CPUh/model





Current paths forward:
- Self-consistent 3D simulations (few, O(10))
- Effective models (many, O(1000))

The path forward

- Self-consistent 3D simulations
  - The ultimate goal :-)
  - Computationally expensive → can do O(10)
- Effective models
  - Simplify part of the problem, but have free parameters
  - Physically reliable
  - Computationally efficient → can do O(1000)
- We need both path for the open science questions:
  - Prediction of nucleosynthesis yields (and other observables)
  - Connection between progenitor and remnant?
  - Which massive stars explode successfully? Which ones do not?

Effective CCSN Models

- Parametrize a multi-dimensional aspect in 1D simulations
  - Mixing above the PNS, enhanced neutrino heating, etc
- Calibrate parametrization, then apply to many models
  - Eg a suitable model should reproduce observables of SN1987A
  - Predictive within the framework

- PUSH: Parametrized neutrino heating — Perego+15, Ebinger+19, Curtis+19, Ebinger+20, Ghosh+23
- PHOT-B: Parametrized neutrino heating — Ugliano+12, Ertl+15, Sukhbbold+16
- STIR: Parametrized mixing above PNS — Couch+20

- Also: semi-analytic models and remnant mass formulae

O'Connor+13; Mueller+15; Pejcha15; Fryer+12,22; …

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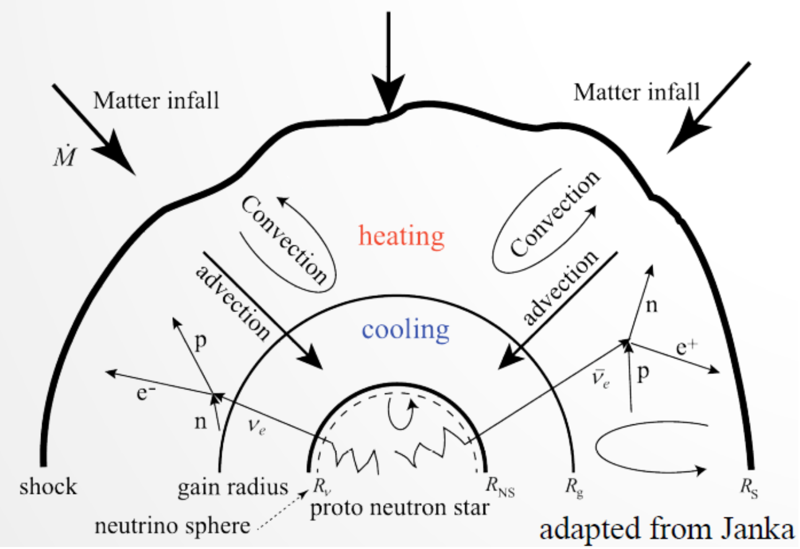

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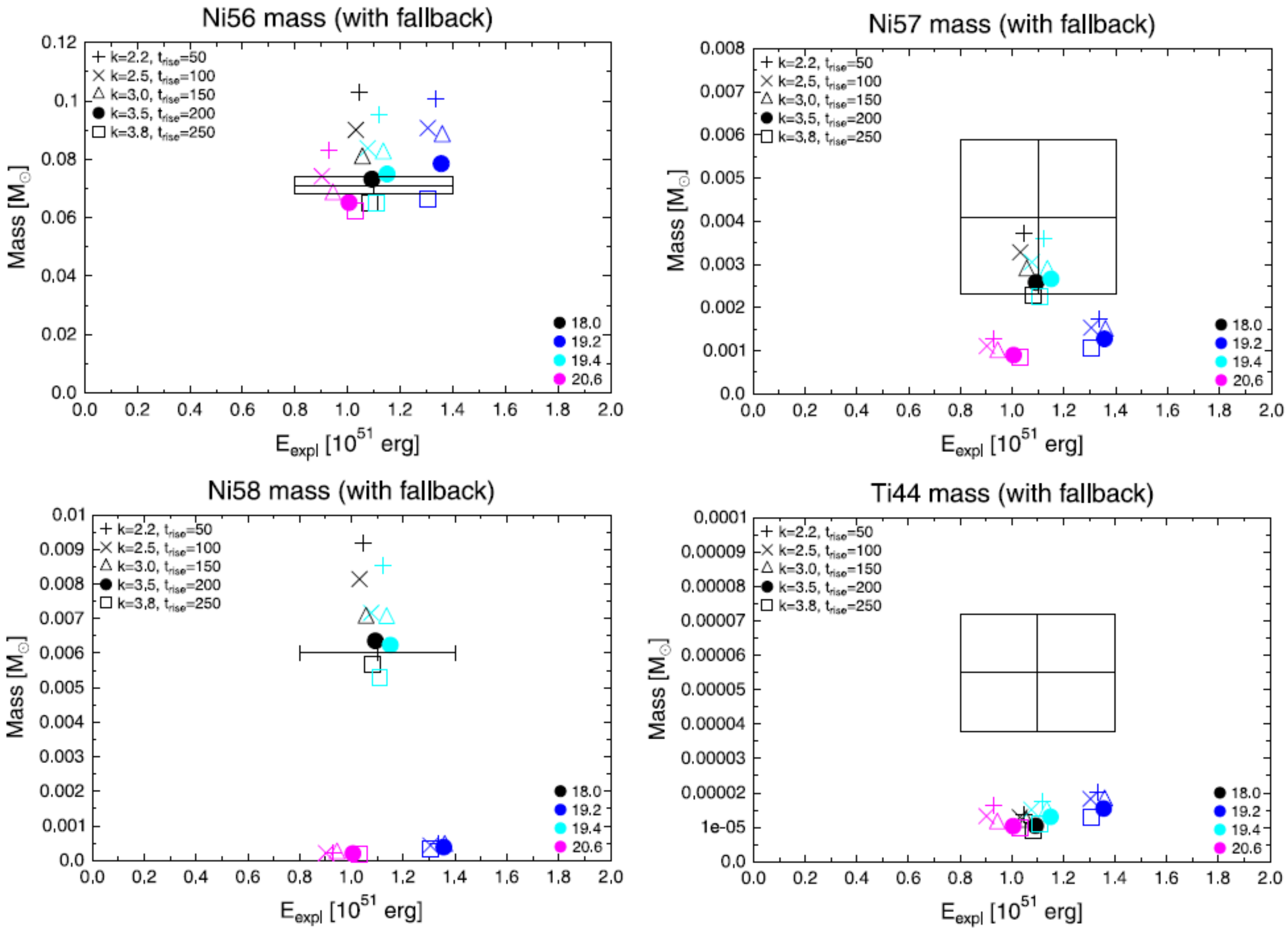
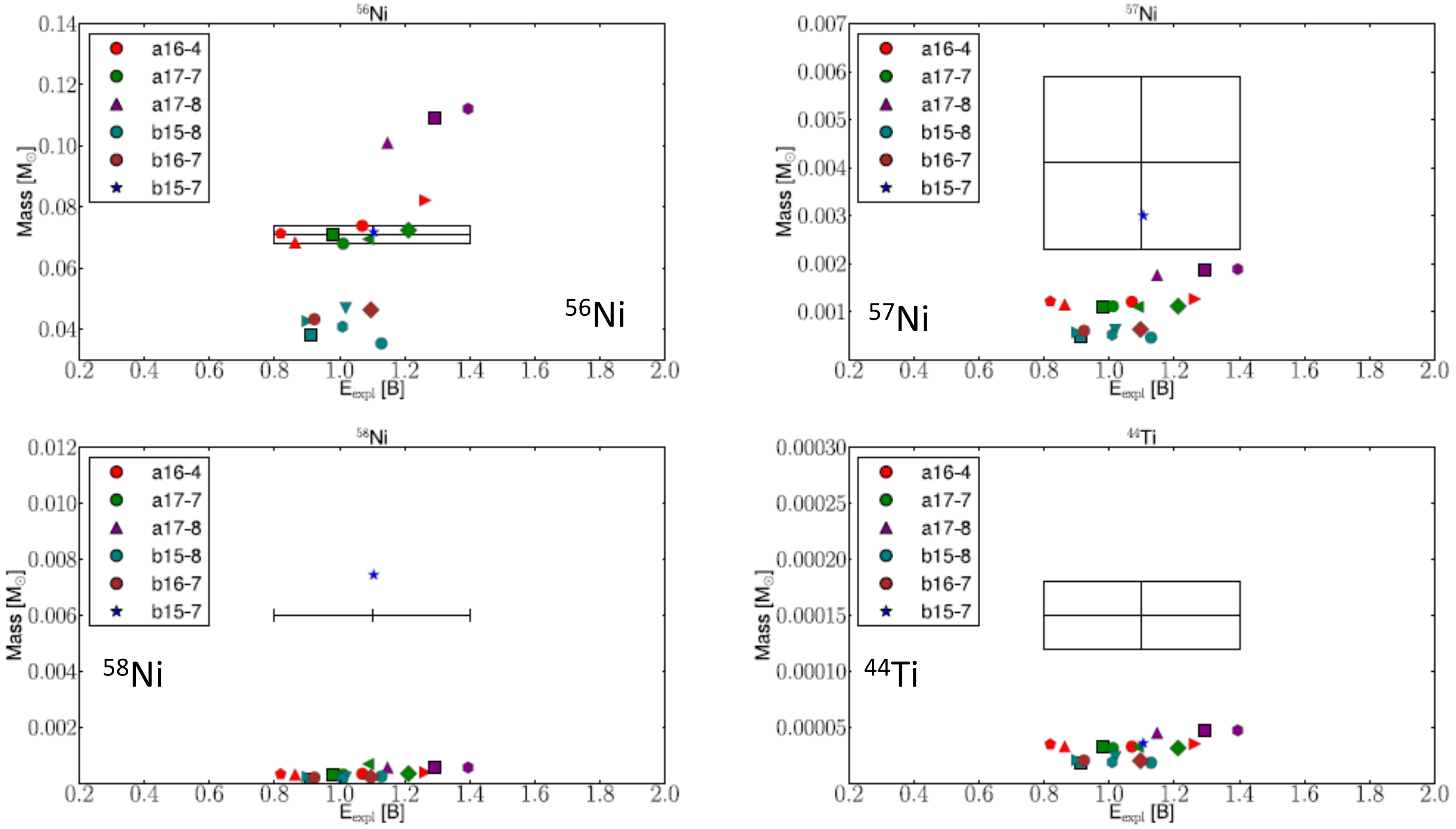
SN1987A: Calibration of PUSH



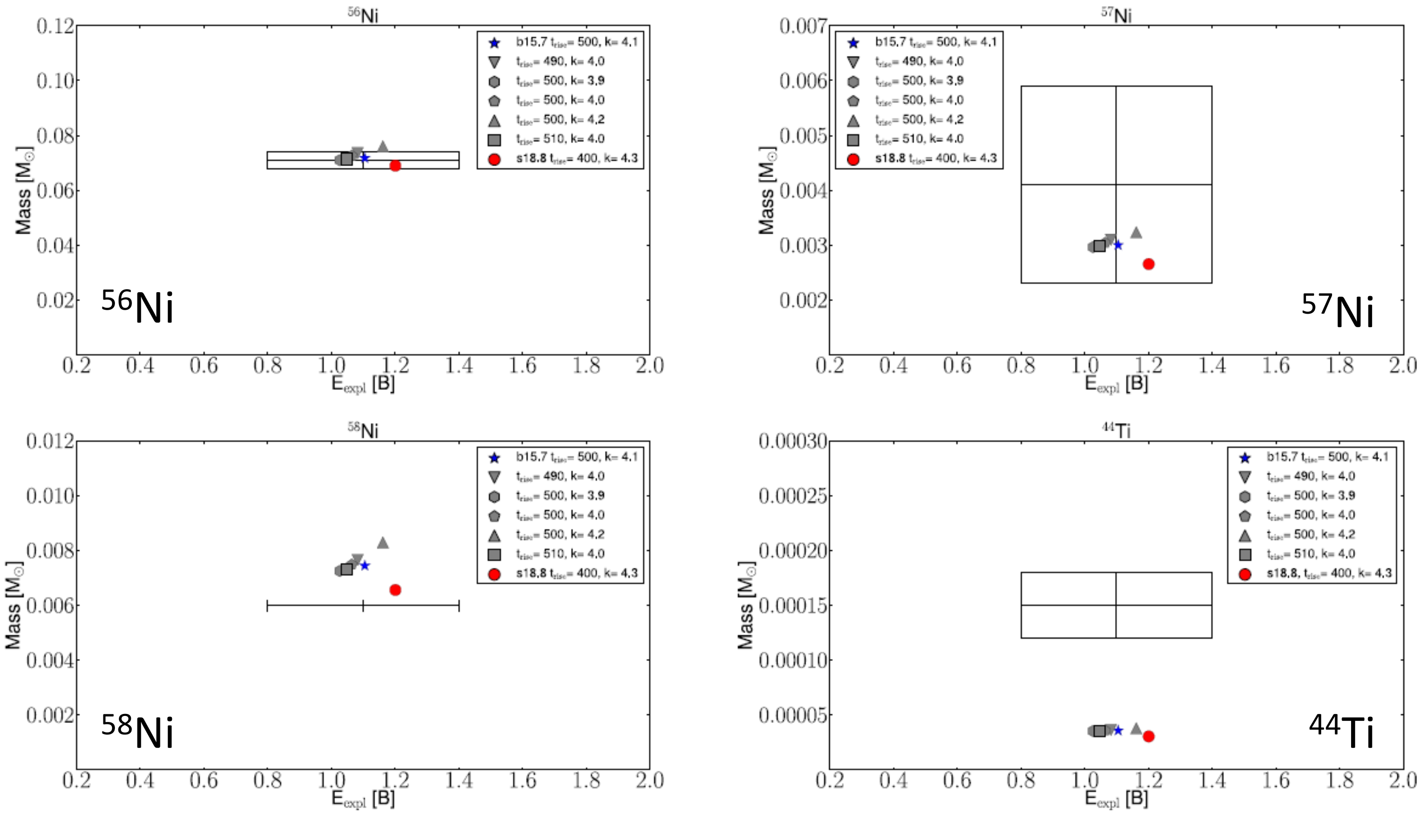
Perego+2015

SN1987A: Calibration of PUSH



Ebinger+19 and CF+19

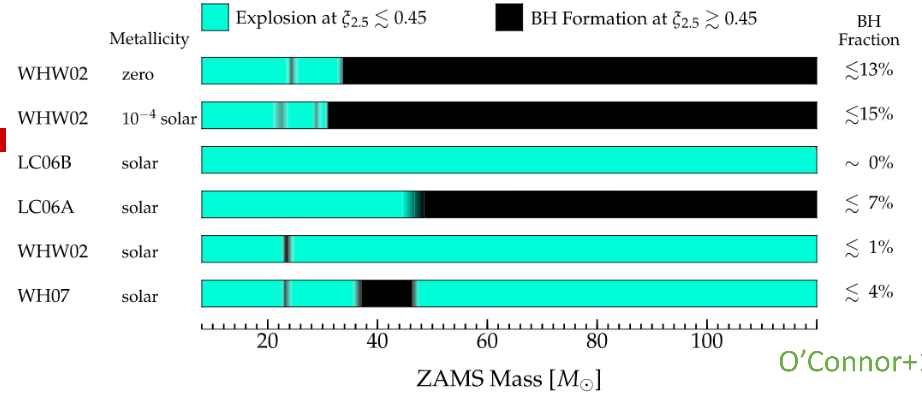
SN1987A: Calibration of PUSH



Comparing calibrations using red supergiants and blue supergiants

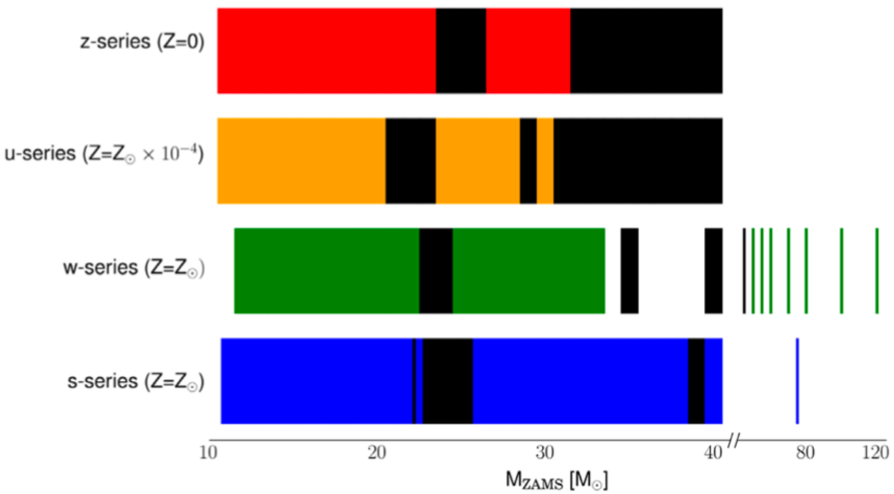
Name	k_{PUSH} (-)	t_{rise} (ms)	E_{expl} (10^{51}erg)	$m(^{56}Ni)$ ($M_{\odot}$)	$m(^{57}Ni)$ ($M_{\odot}$)	$m(^{58}Ni)$ ($M_{\odot}$)	$m(^{44}Ti)$ ($M_{\odot}$)
SN 1987A	—	—	1.1	0.071	0.0041	0.006	1.5×10^{-4}
	—	—	±0.3	±0.003	±0.0018		$\pm 0.3 \times 10^{-4}$
b15-7	4.1	500	1.1	0.072	0.0030	0.0074	3.60×10^{-5}
s18.8	4.3	400	1.2	0.069	0.0027	0.0066	3.05×10^{-5}

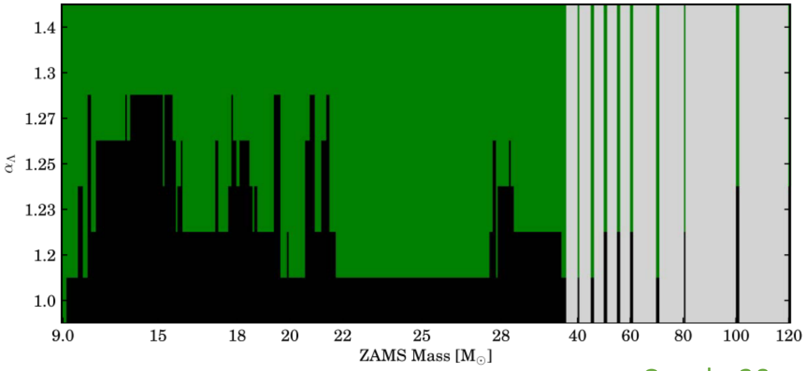
Effective CCSN Models



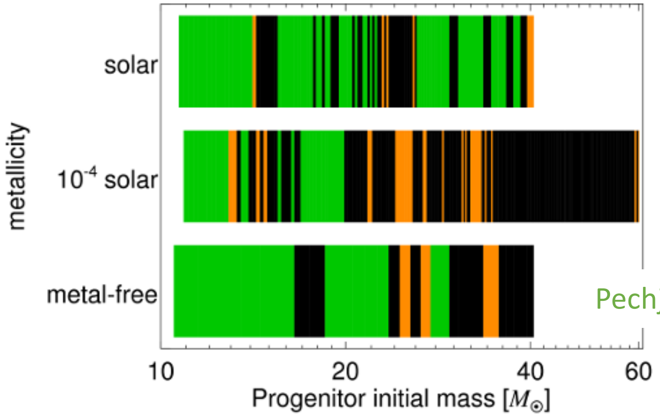
O'Connor+13

Ebinger+20

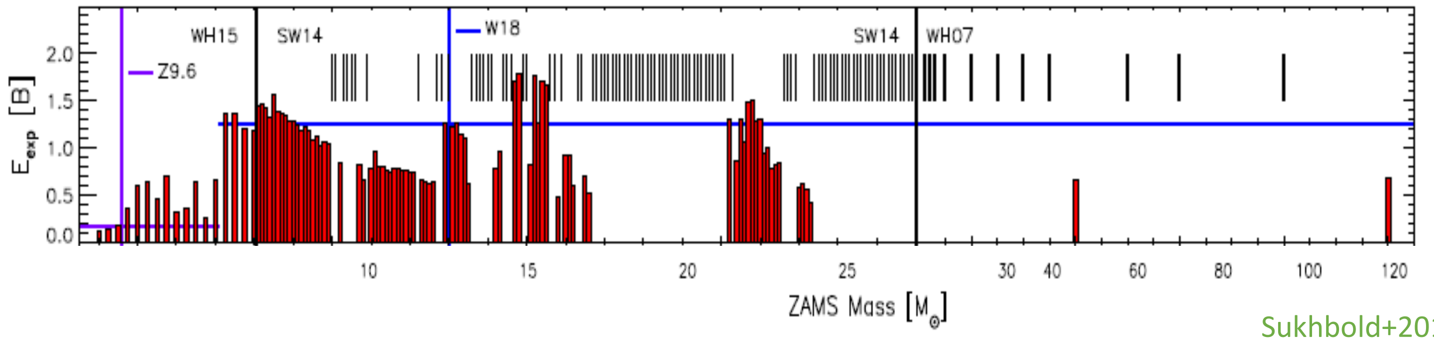




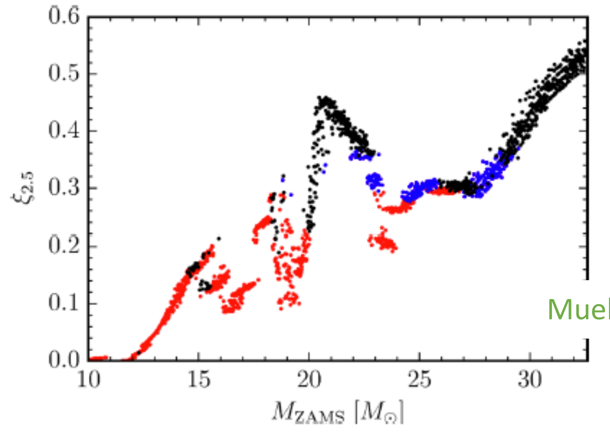
Couch+20



Pechja+15

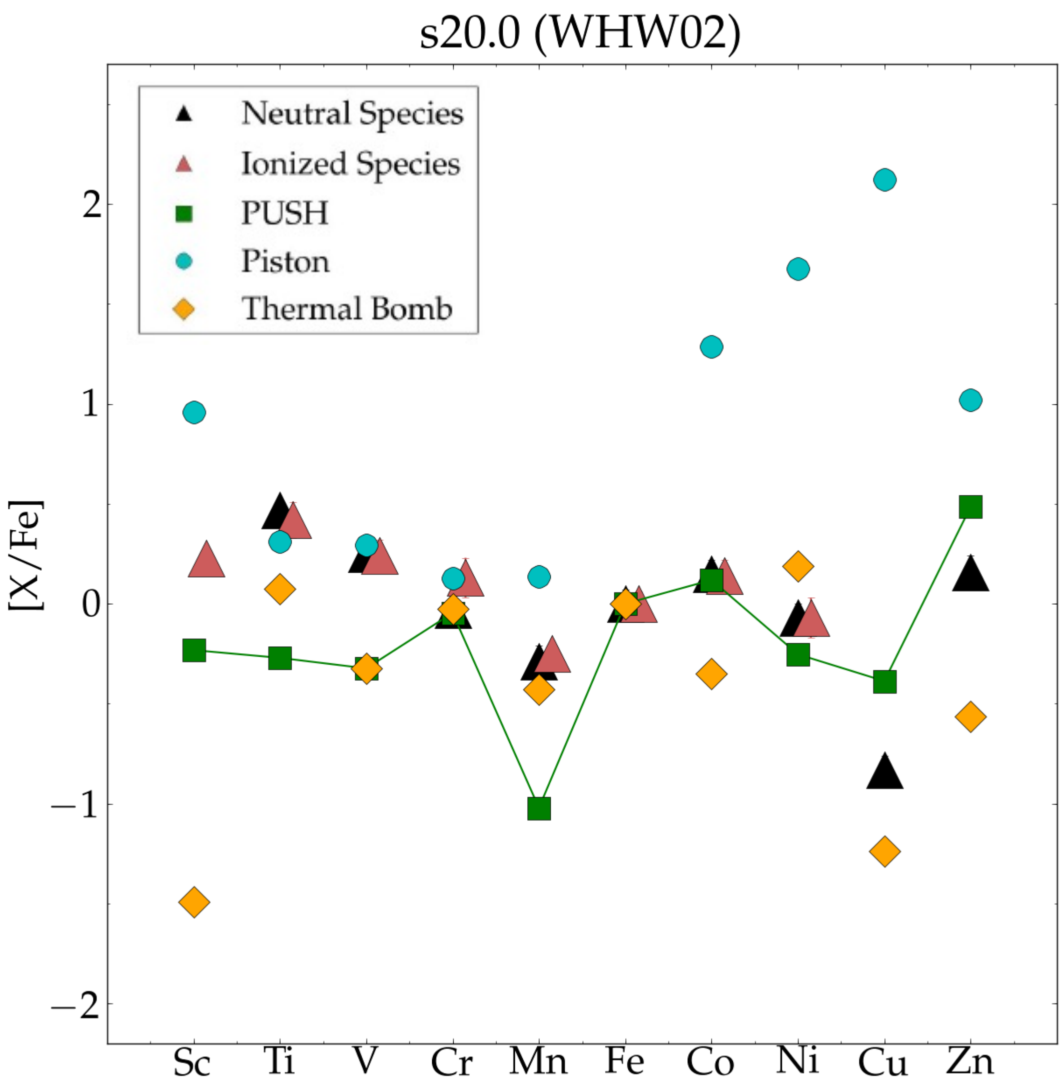


Sukhbold+2016



Mueller+16

Comparison of methods



Thermal bomb:

- Skips the collapse and onset of explosion phase
- Deposits thermal energy over a few interior zones
- Mass cut is determined by integrating the 56Ni yield from the outside in until the desired value is reached

Piston:

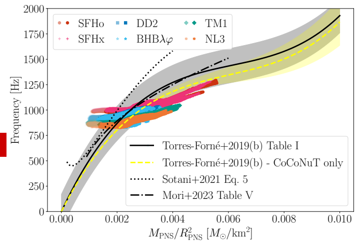
- Skips the weak physics of collapse and onset of explosion
- Trajectory of a particular mass zone is prescribed (infall and outwards motion)
- Mass cut is set by location of the piston

PUSH:

- Mimics a neutrino-driven explosion
- Includes changes in the electron fraction from weak reaction during collapse and neutrino reactions during collapse and explosion
- Calibration required

Some recent results from the NC State University Group

From explosions to observables



progenitor

EOS

PUSH

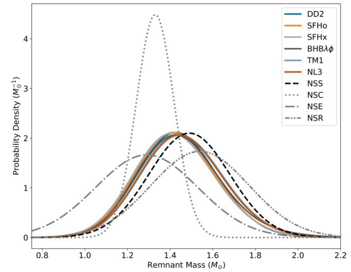
Hydrodynamics simulation With Neutrino transport

GW Frequencies

Wolfe+23

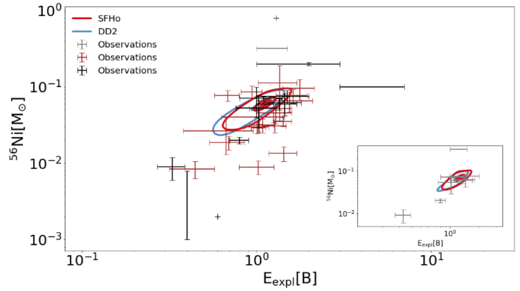
Remnant properties

Meskhi+22



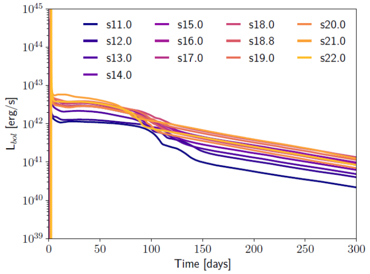
Explosion properties

Ebinger+19; Ebinger+20; Ghosh+22



Bolometric lightcurves

Curtis+21



SNEC Radiation-hydro

SuperNu MC photon transport

Broadband LCs Spectra

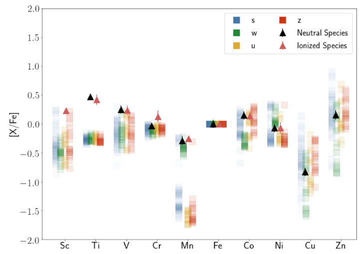
Curtis+21

Mass tracers

Nuclear Reaction Network

Nucleosynthesis Yields

Curtis+19



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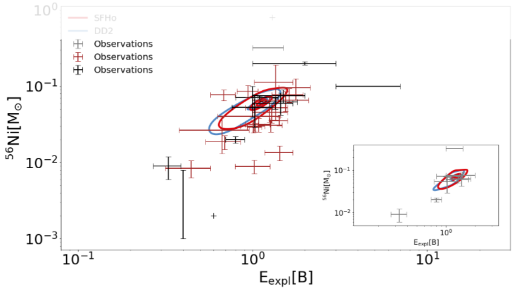

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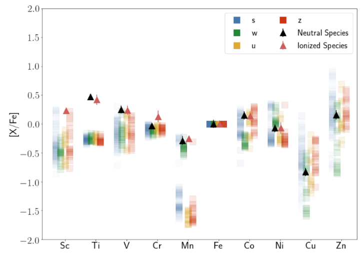
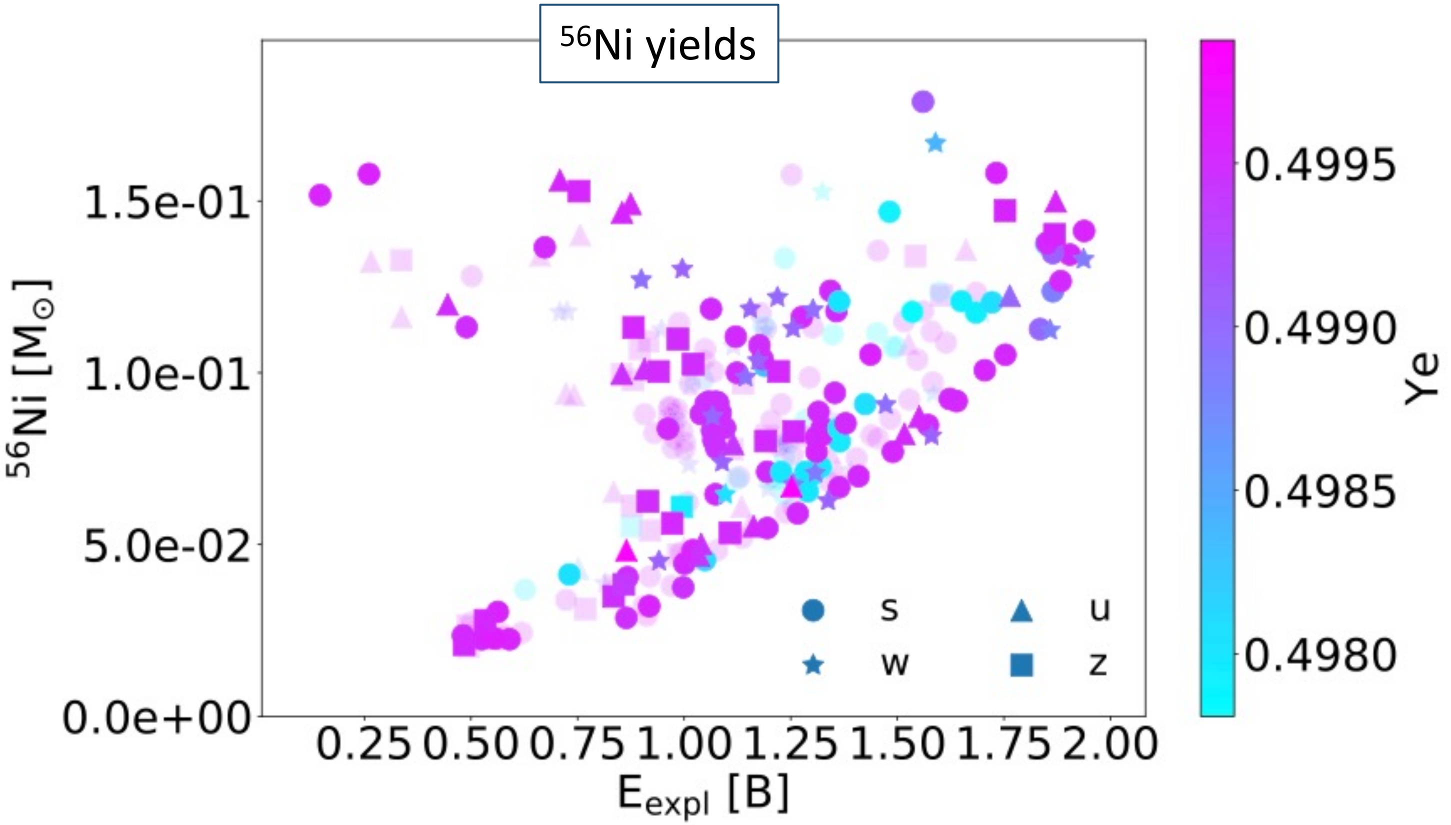


Isotopic and Elemental Nickel Yields

Curtis+19
Ghosh+22



Isotopic and Elemental Nickel Yields

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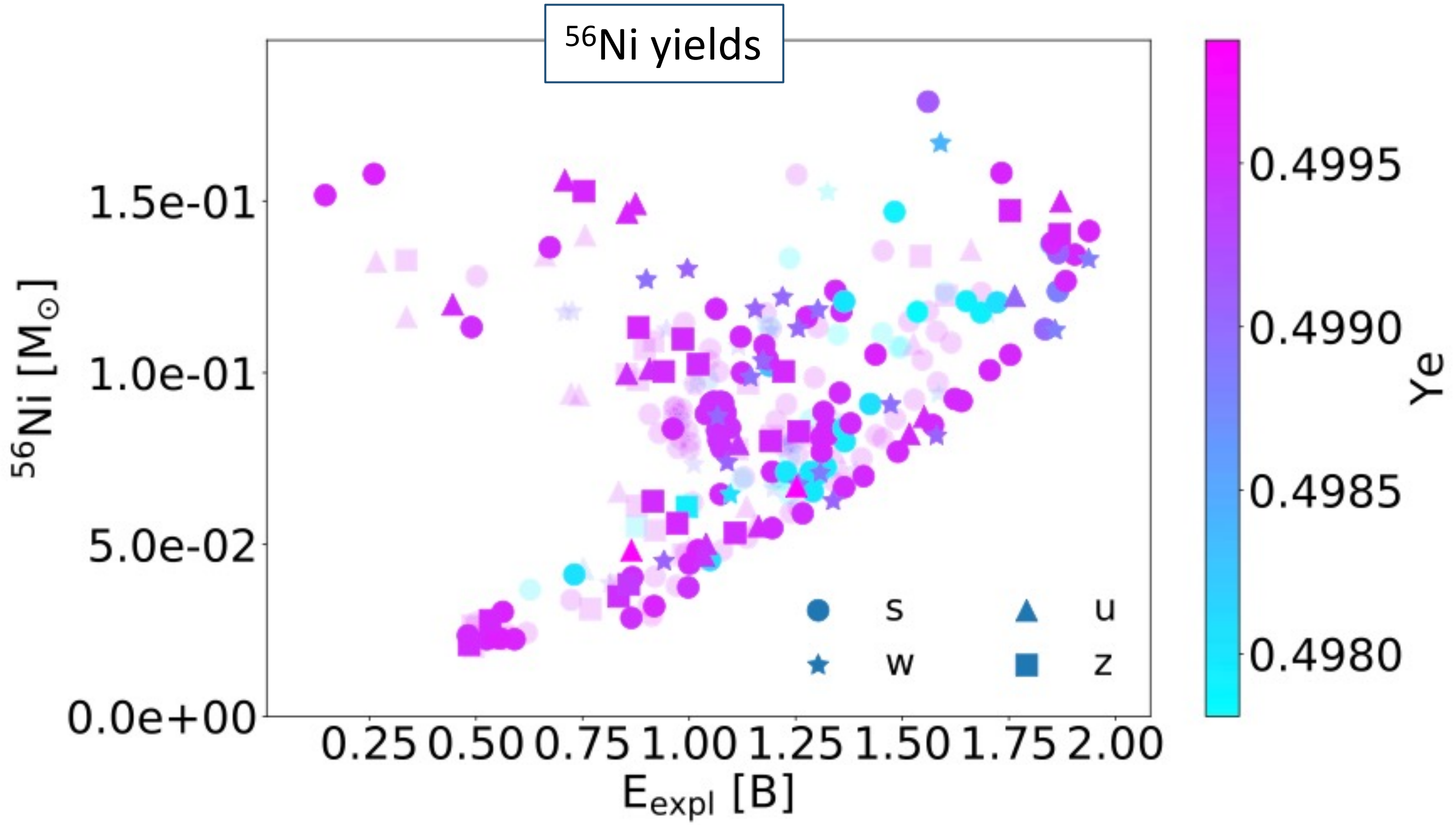

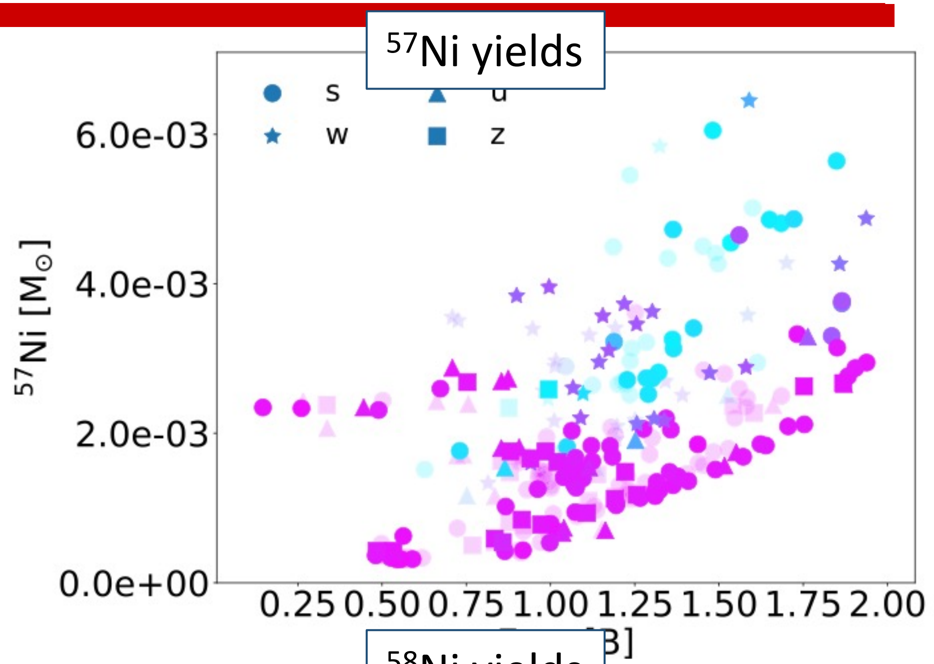

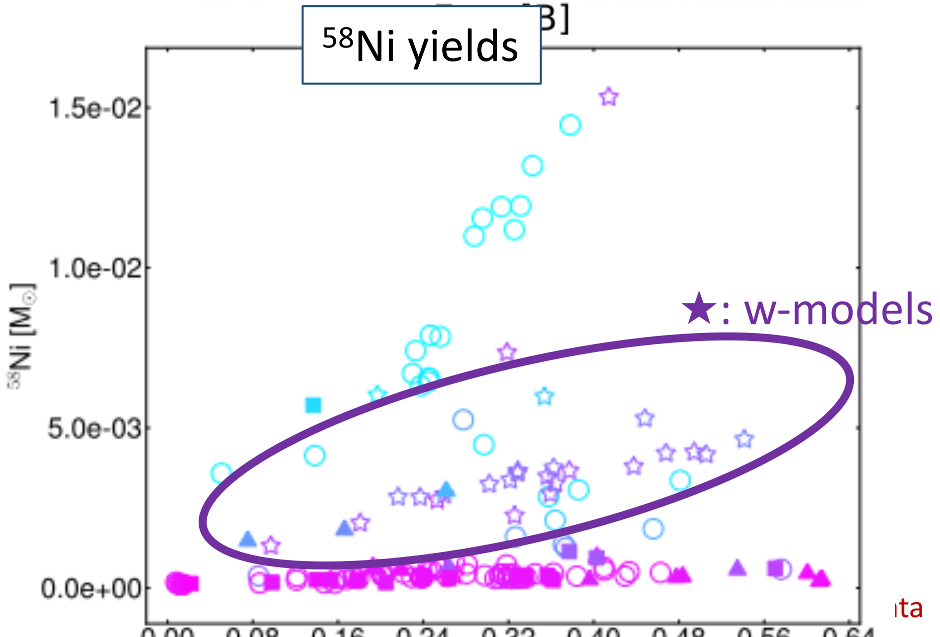

w-models: 100s of isotopes during stellar evolution
s/u/z-models: 21 isotope network during stellar evolution

Isotopic and Elemental Nickel Yields

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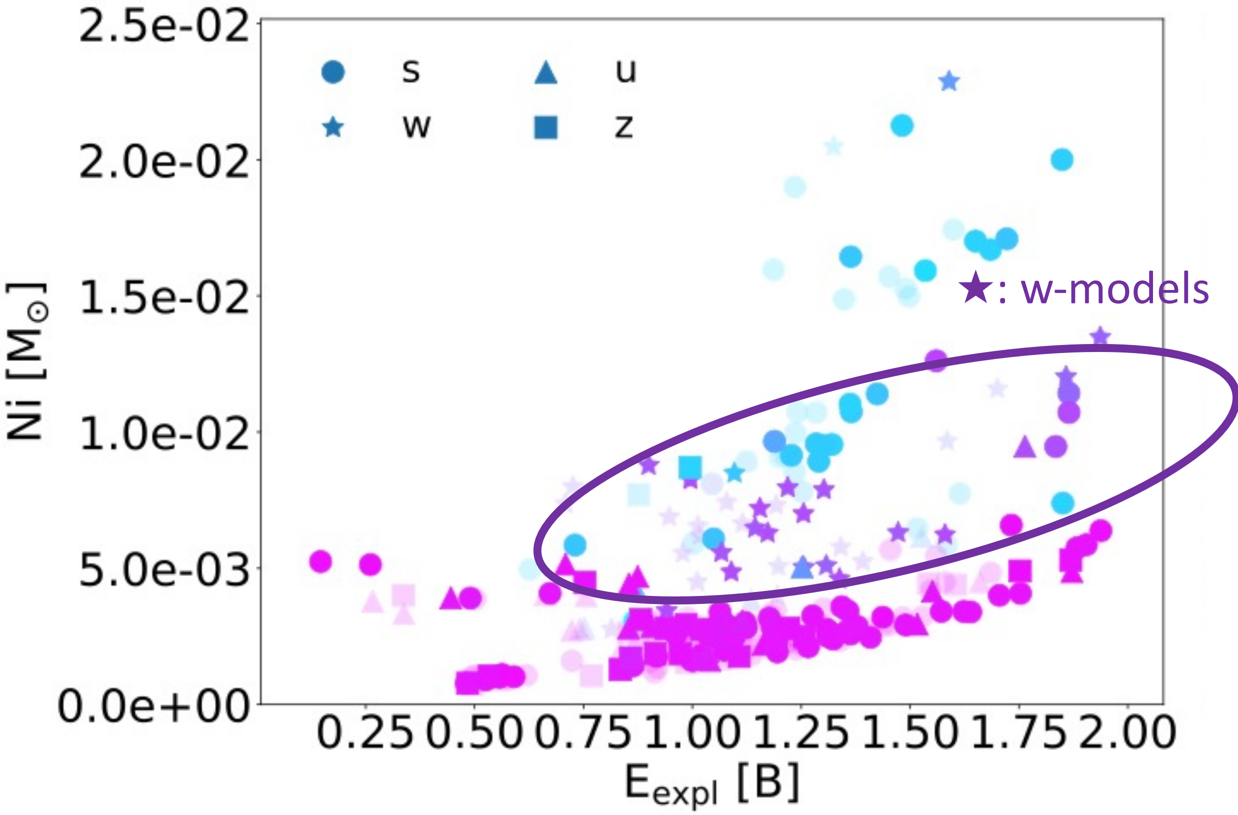
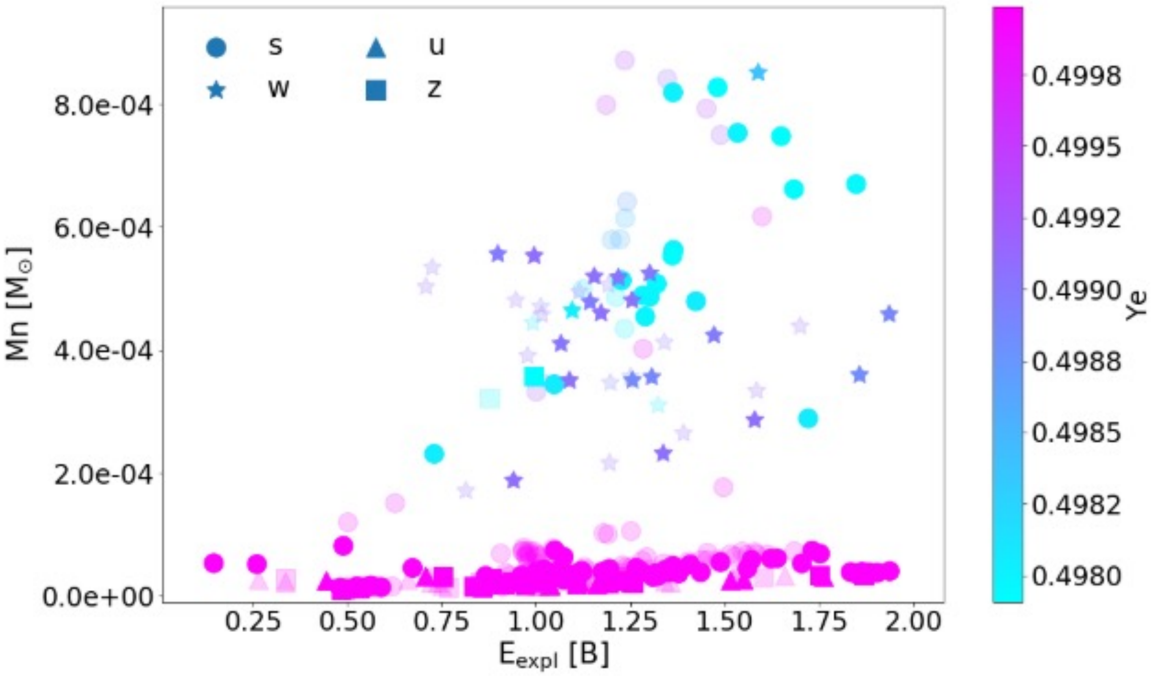


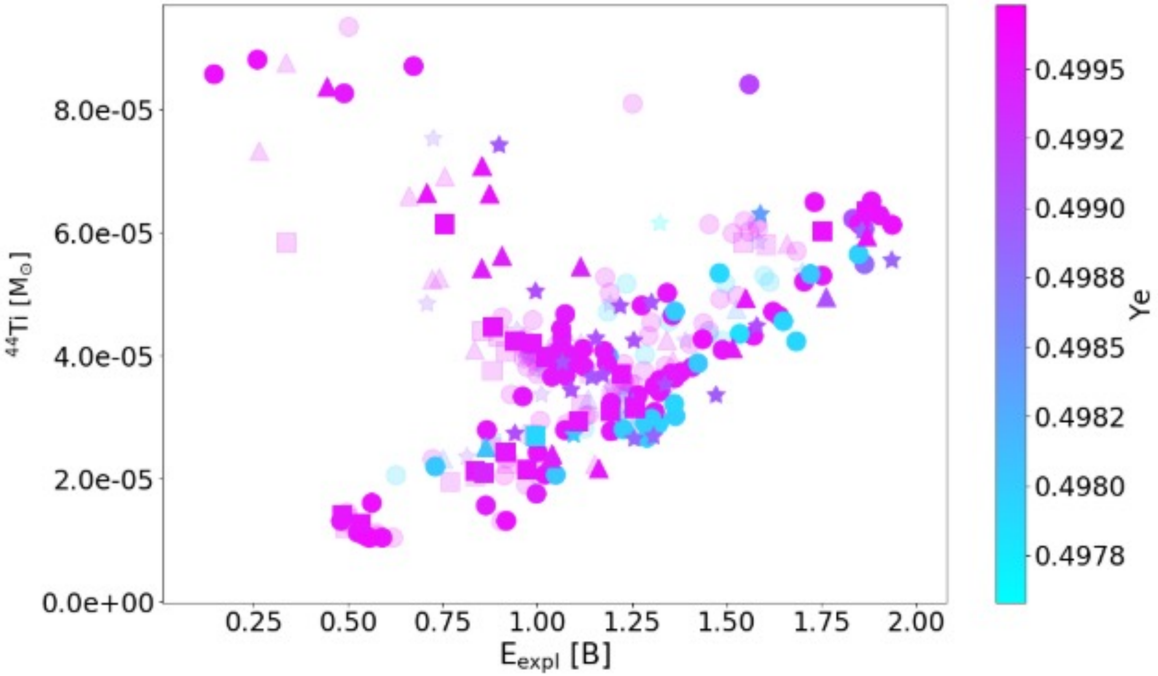
Other Fe-group elements

Ghosh+22

Elemental Mn yields



Isotopic 44Ti yields



★: w-models

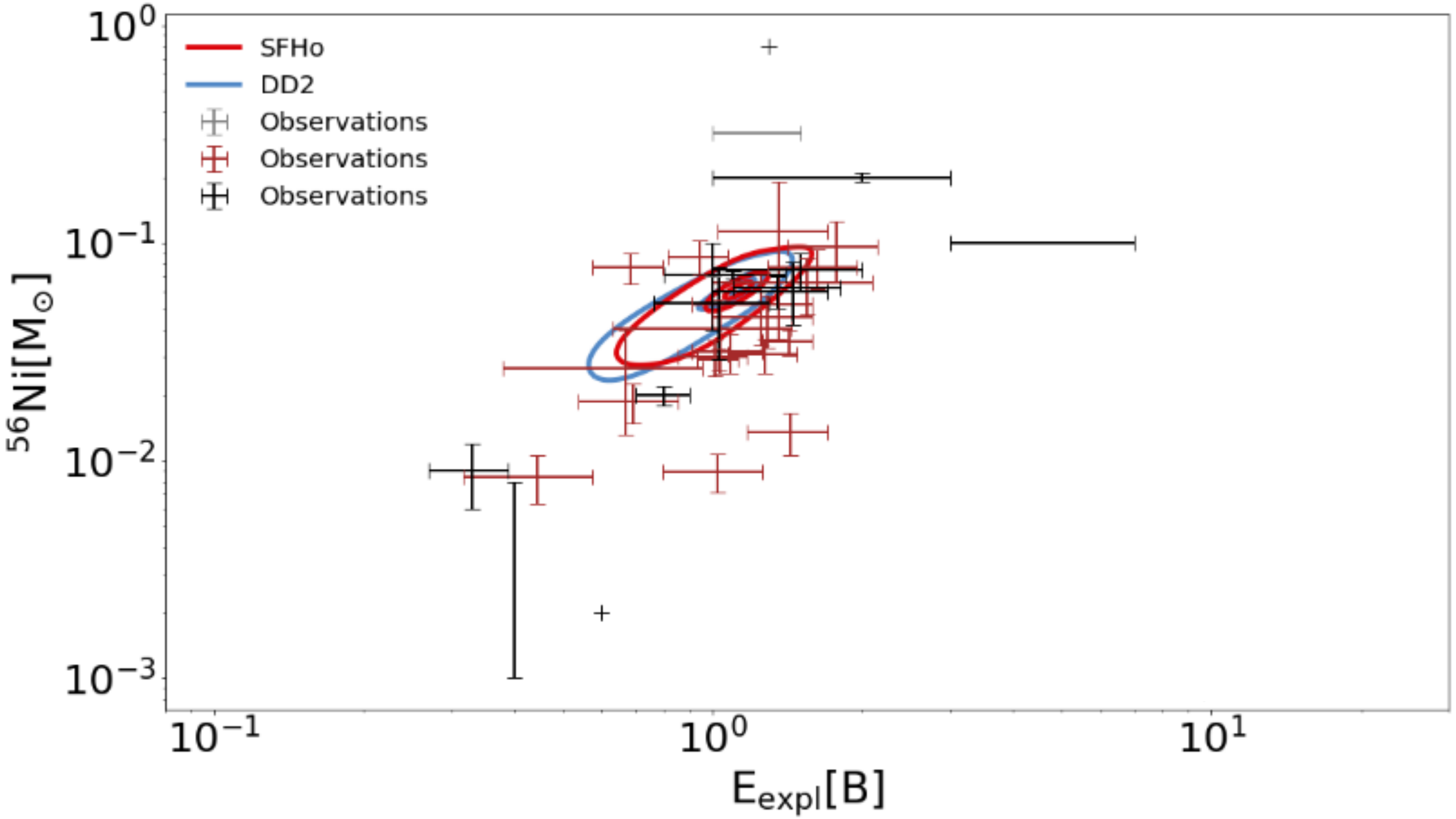
w-models: 100s of isotopes during stellar evolution
s/u/z-models: 21 isotope network during stellar evolution

→ The progenitor (structure and network size) matters

Explosion energy and ^{56}Ni yields

Ghosh+22

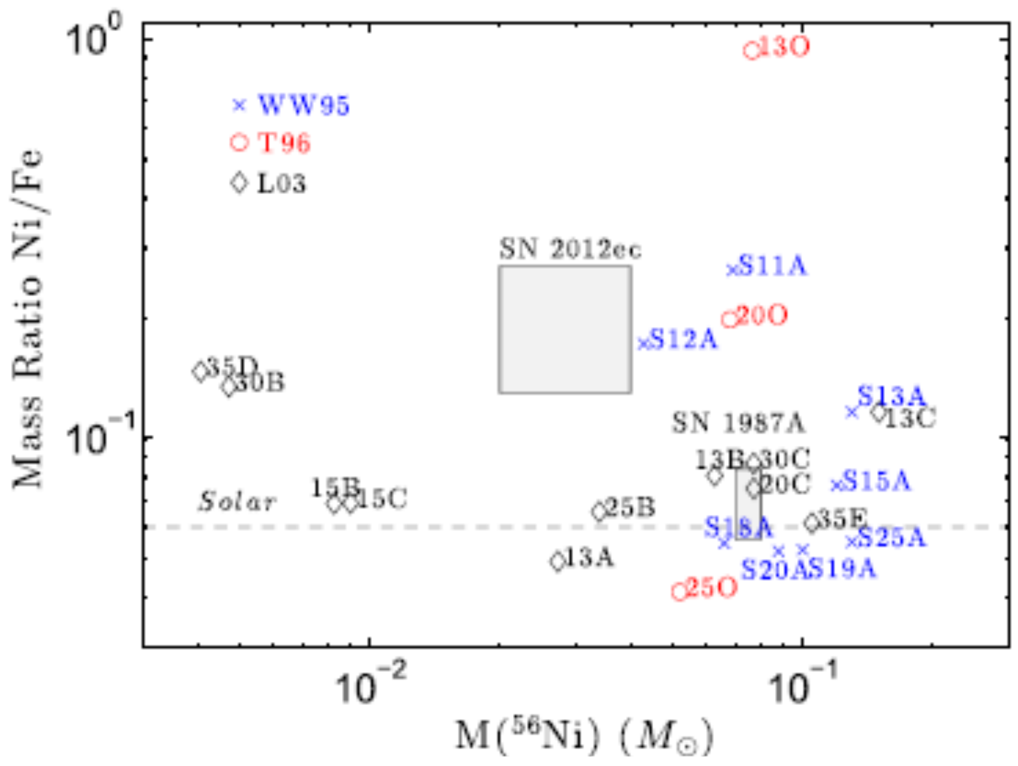
→ In PUSH: Explosion energy and 56Ni mass emerge self-consistently with each other



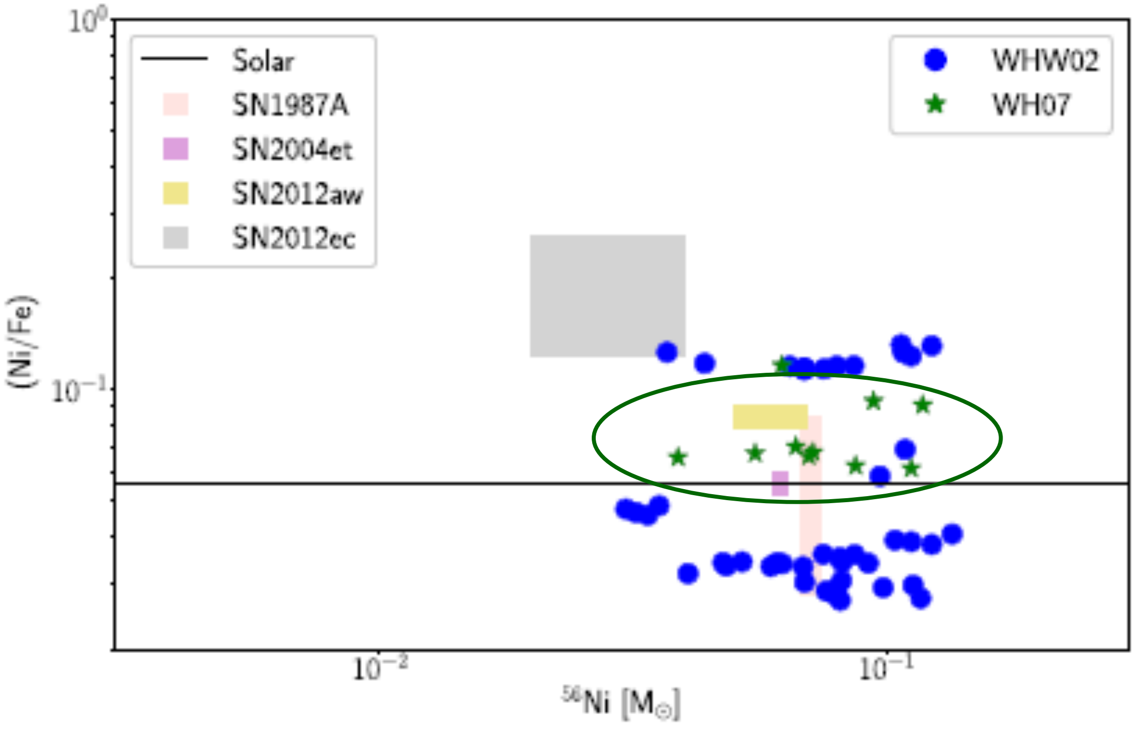
Simulations are IMF weighted for KDE estimation

DD2 data from Ebinger+20
SFHo data from Ghosh+22

Ni/Fe ratio



Jerkstrand+ 2015

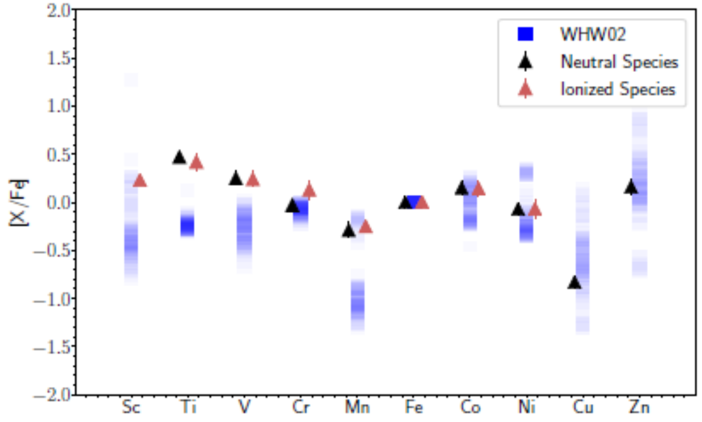


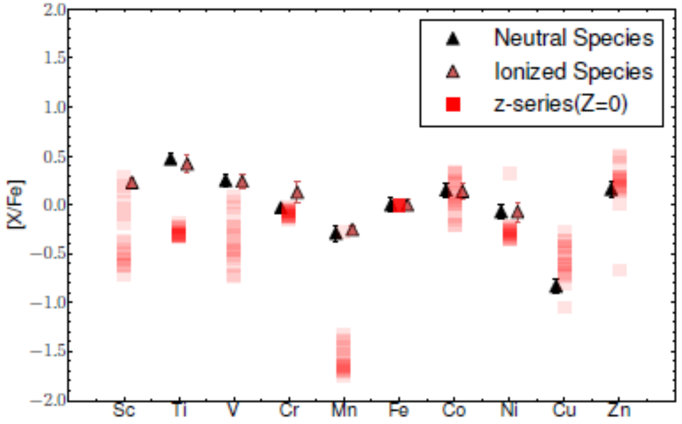
Curtis+19

Fe-group elements and metal-poor stars

Observational data (triangles):
Metal-poor star HD84937

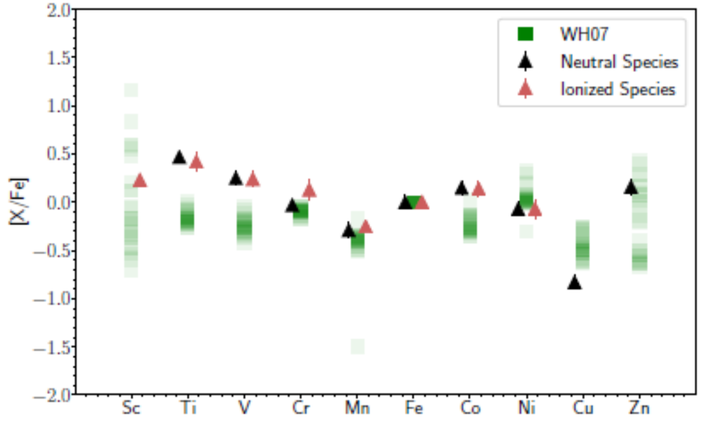
PUSH

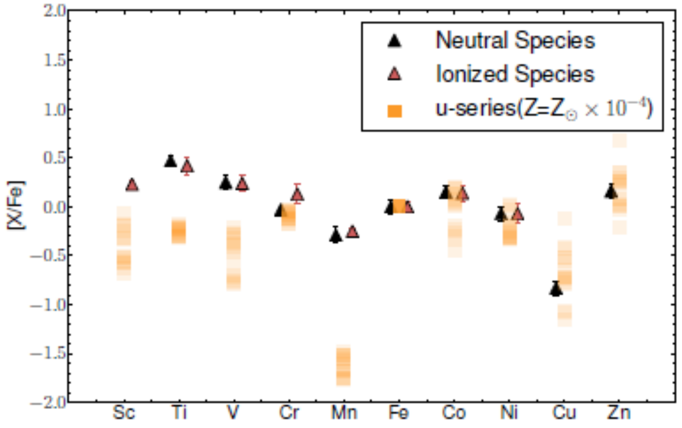




Curtis+19

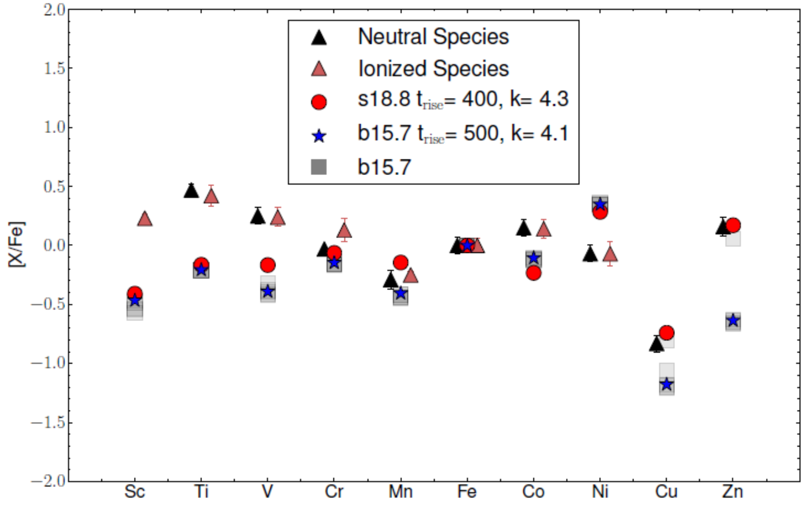
Ebinger,**Curtis**+20



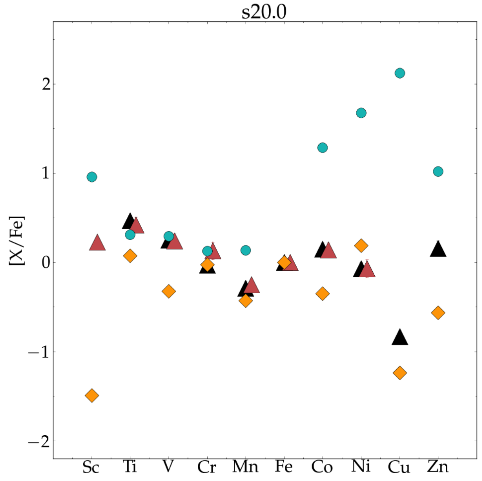


EOS: DD2

PUSH (different models for calibration agianst SN 1987A)



Piston and Thermal Bomb Yields



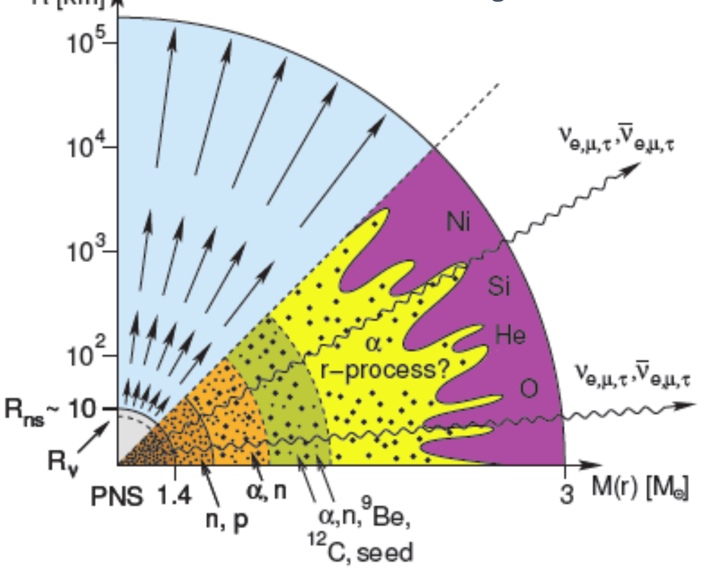
Nucleosynthesis Beyond Iron

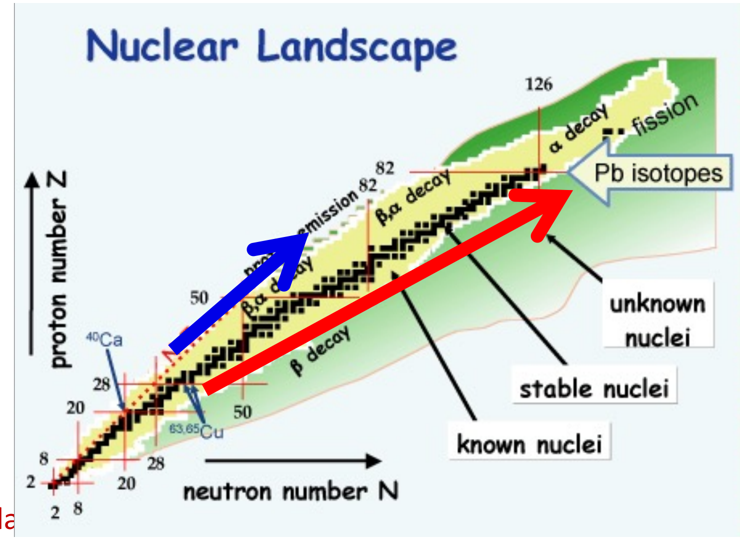
Note, I ran out of time and did not show the following slides during the lecture.

Neutrino-driven winds

- Strong neutrino flux from PNS
- Drives matter-outflow behind shock wave
- Nucleosynthesis:
  - NSE (T=10-8GK)
  - Charged-particle reactions (8-2GK)
  - r-process and νp-process nucleosynthesis (3-1GK)

Figure: Janka





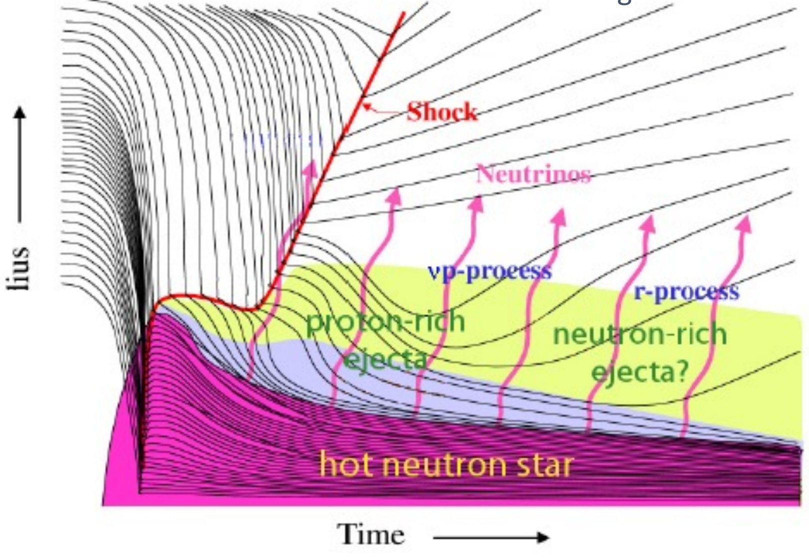
Proton-rich conditions:
- Elements from Zn to Sn
- (p,γ) and (n,p) reactions

→ **νp-process**

Neutron-rich conditions:
- Elements up to uranium
- (n,γ) reactions and β-decays

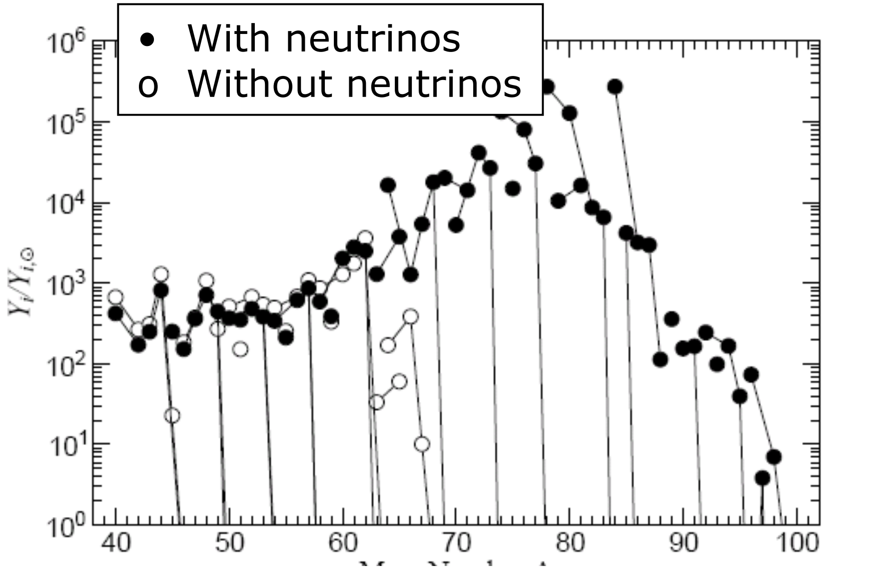
→ r-process

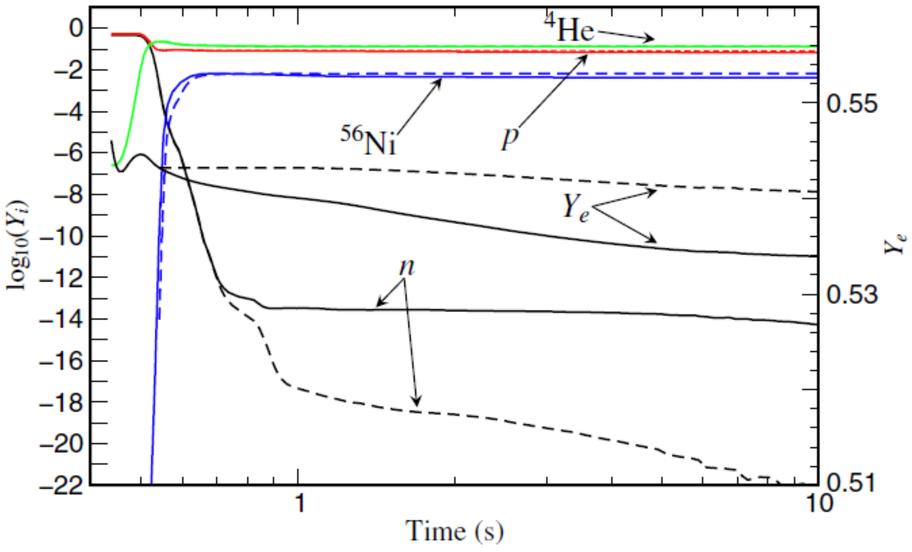
Figure: Bruenn



The neutrino-p Process

- proton-rich matter is ejected under the influence of neutrino interactions
- true rp-process is limited by slow β decays, e.g. τ(64Ge)
- Neutron source: $\bar{\nu}_e + p \rightarrow n + e^+$
- Antineutrinos help bridging long waiting points via (n,p) reactions:
  64Ge (n,p) 64Ga; 64Ga (p,g) 65Ge

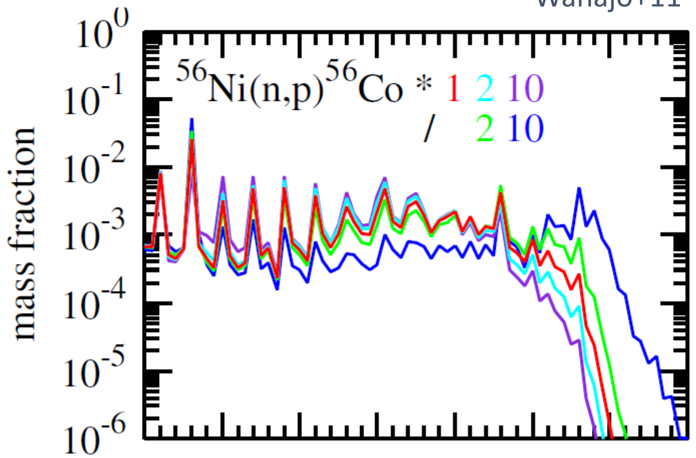




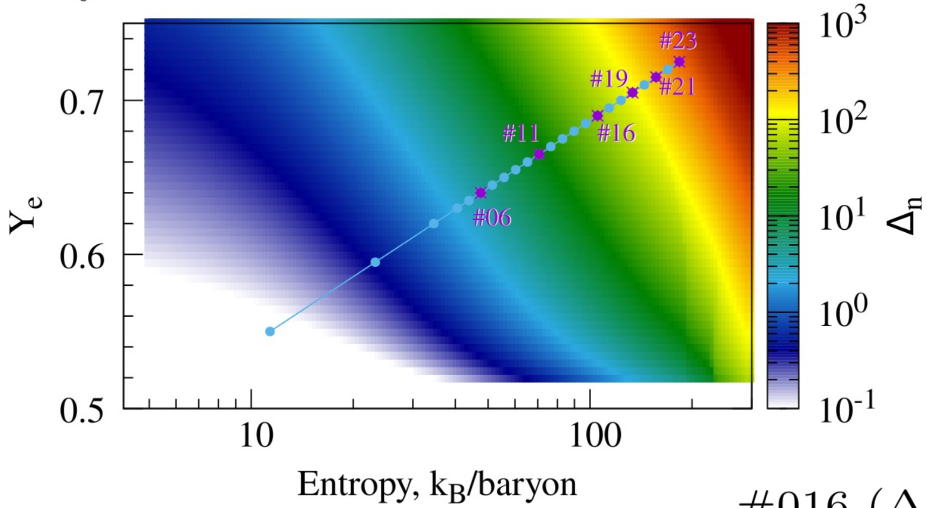
Sensitivity Studies for the neutrino-p process

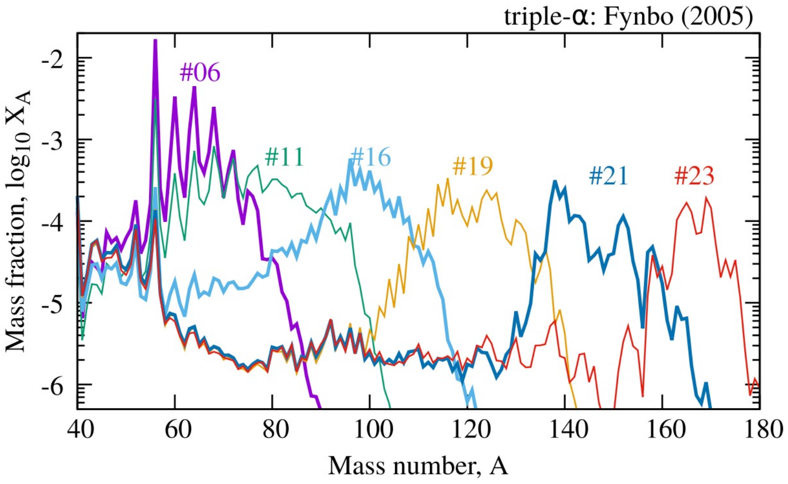
Nishimura+19

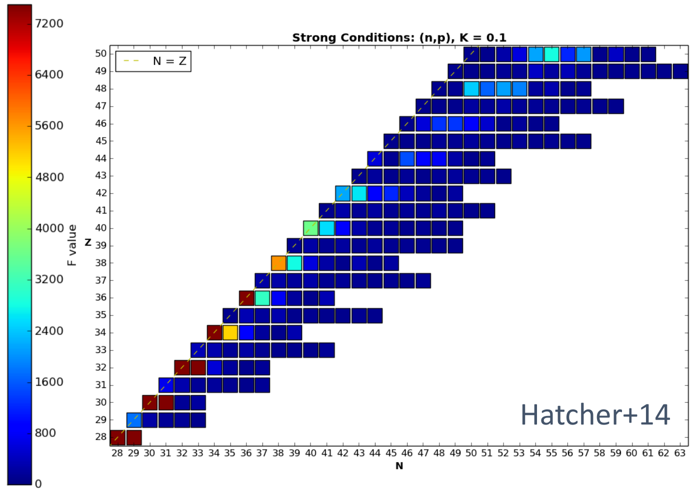
Wanajo+11



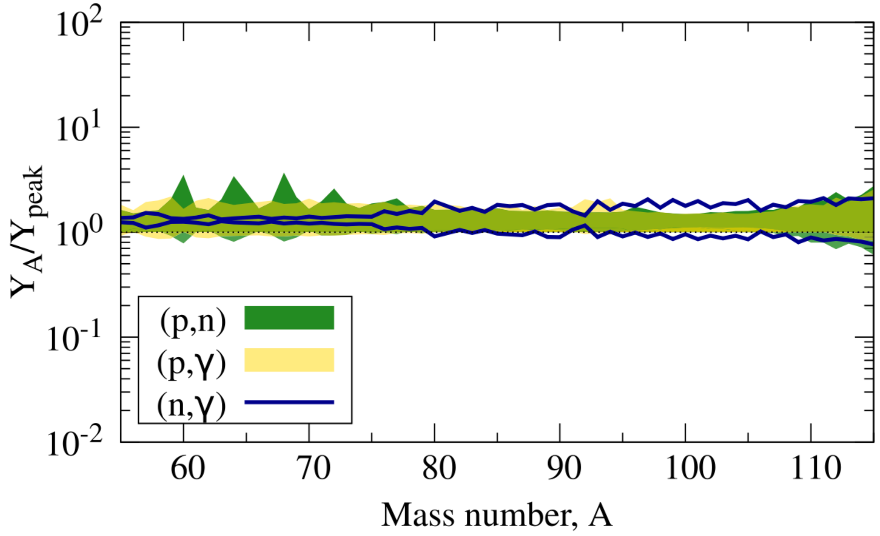
Fynbo-05







#016 (Δ_n = 41.4)



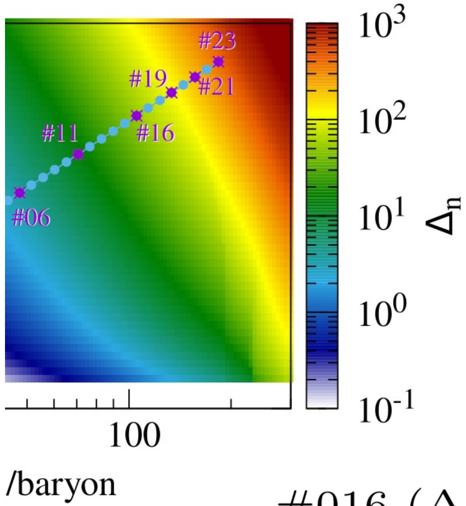
Sensitivity Studies for the neutrino-p process

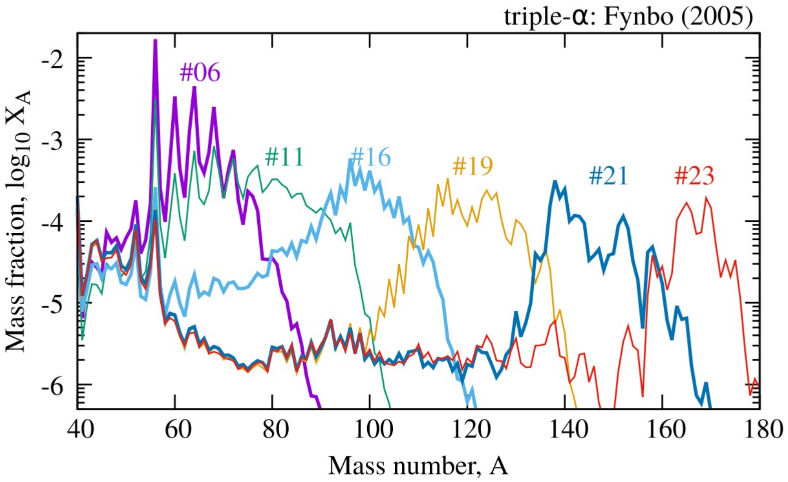
Nishimura+19

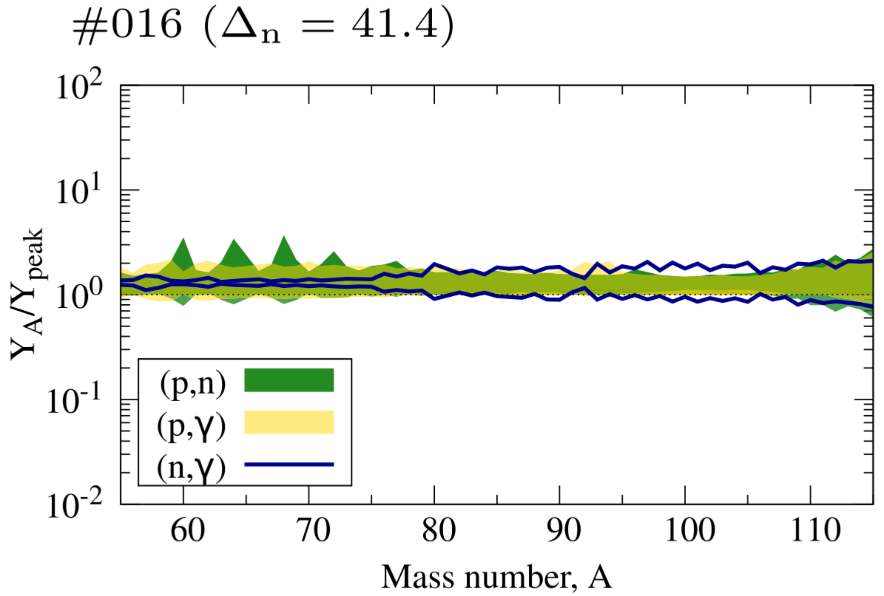
Nishimura et al.

Table 7. Key reaction list sorted by the number of affected nuclides per key rate level and by the counted number of involved trajectories.

Reaction	Level 1	Level 2	Level 3	Number of trajectories
^{60}Zn(n, p)^{60}Cu	^{60}Ni, ^{63}Cu, ^{64}Zn			17
^{64}Ge(n, p)^{64}Ga	^{64}Zn, ^{68}Zn			13
^{68}Se(n, p)^{68}As	^{68}Zn	^{68}Zn, ^{69}Ga, ^{71}Ga, ^{72}Ge	^{69}Ga	16
^{59}Zn(n, p)^{59}Cu	^{59}Co	^{60}Ni, ^{59}Co	^{60}Ni	10
^{63}Ge(n, p)^{63}Ga	^{63}Cu	^{63}Cu, ^{64}Zn	^{63}Cu	5
^{72}Kr(n, p)^{72}Br	^{72}Ge	^{72}Ge	^{72}Ge, ^{75}As	12
^{57}Ni(p,γ)^{58}Cu	^{57}Fe	^{57}Fe	^{57}Fe	13
^{67}As(p,γ)^{68}Se	^{67}Zn	^{67}Zn	^{67}Zn	12
^{70}Se(p,γ)^{71}Br	^{70}Ge	^{70}Ge	^{70}Ge	11
^{77}Sr(n, p)^{77}Rb	^{77}Se	^{77}Se	^{77}Se	8
^{75}Sr(n, p)^{75}Rb	^{75}As	^{75}As	^{75}As	7
^{94}Ru(p,γ)^{95}Rh	^{94}Mo	^{94}Mo	^{94}Mo	3
^{61}Zn(p,γ)^{62}Ga	^{61}Ni	^{61}Ni		12
^{76}Sr(n, p)^{76}Rb	^{76}Se	^{76}Se		7
^{100}Pd(n,γ)^{101}Pd	^{100}Ru	^{100}Ru		2
^{58}Cu(p,γ)^{59}Zn	^{58}Ni		^{58}Ni	12
^{92}Mo(p,γ)^{93}Tc	^{92}Mo			2
^{97}Rh(n,γ)^{98}Rh	^{97}Tc			2
^{113}In(n,γ)^{114}In	^{113}In			1
^{117}In(n,γ)^{118}In	^{117}Sn			1
^{59}Cu(p,γ)^{60}Zn		^{59}Co, ^{60}Ni	^{59}Co, ^{56}Fe	11
^{59}Cu(p,α)^{56}Ni		^{56}Fe	^{56}Fe, ^{60}Ni	9
^{57}Ni(n, p)^{57}Co		^{60}Ni	^{56}Fe, ^{60}Ni	4
^{62}Zn(p,γ)^{63}Ga		^{62}Ni	^{62}Ni	12
^{60}Cu(p,γ)^{61}Zn		^{61}Ni	^{61}Ni	8
^{71}Br(p,γ)^{72}Kr		^{71}Ga	^{71}Ga	7
^{62}Ga(p,γ)^{63}Ge		^{62}Ni	^{62}Ni	6
^{63}Ga(p,γ)^{64}Ge		^{63}Cu	^{63}Cu	6
^{69}Se(p,γ)^{70}Br		^{69}Ga	^{69}Ga	6
^{74}Kr(p,γ)^{75}Rb		^{74}Se	^{74}Se	6
^{73}Kr(p,γ)^{74}Rb		^{73}Ge	^{73}Ge	5



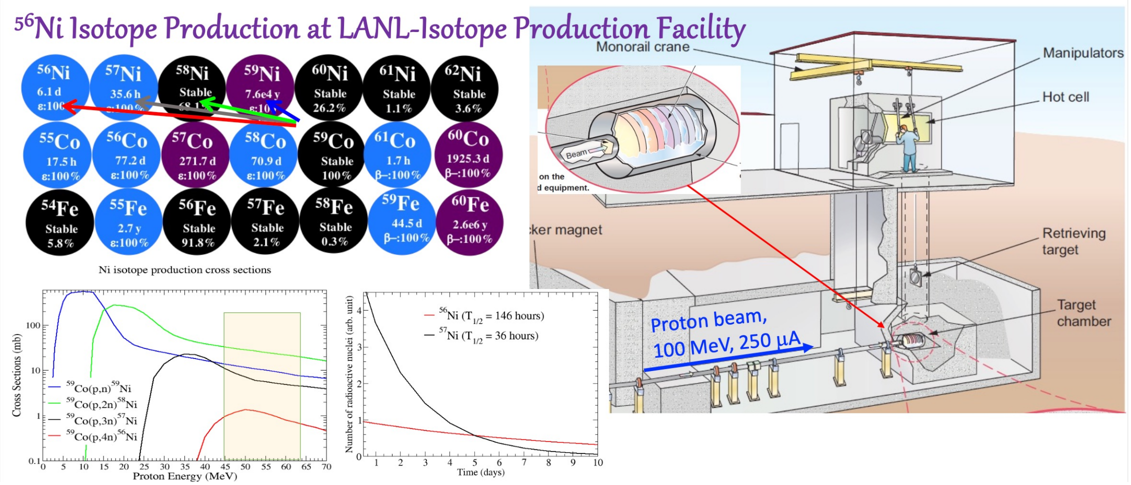


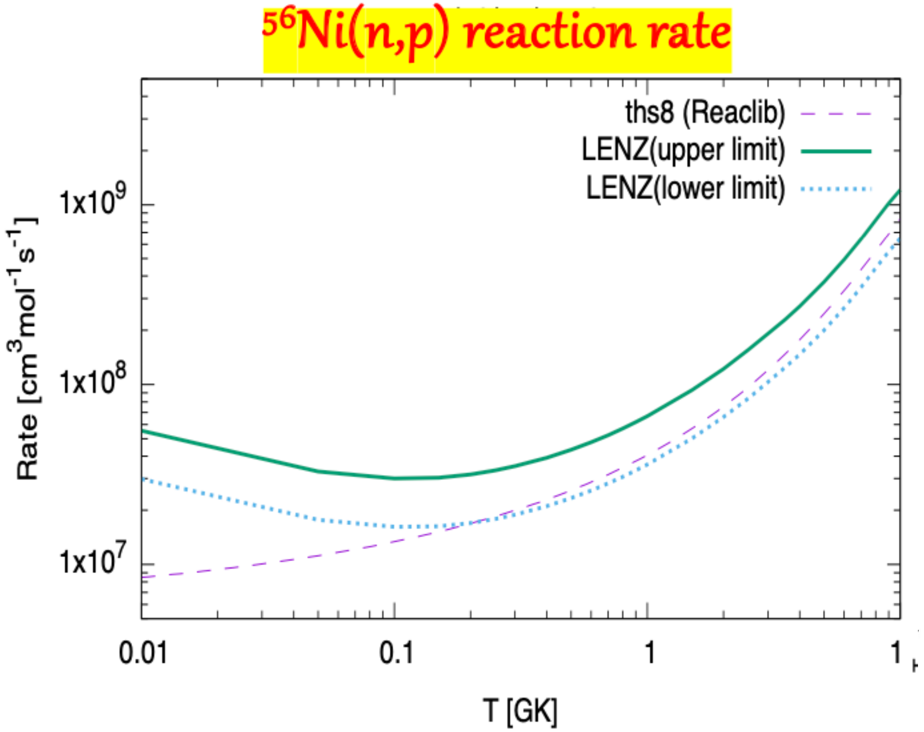


^{56}Ni(n,p)^{56}Co and the neutrino p-process

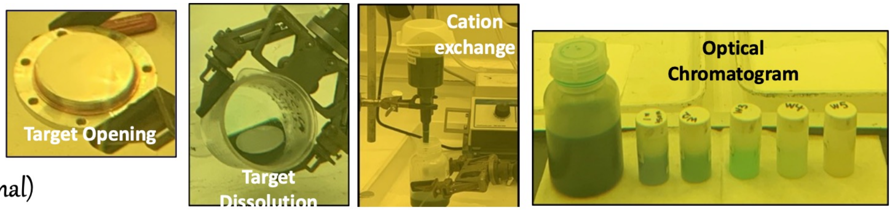
With Hye-Young Lee (LANL)

- Experiment at LANSCE / LANL
- Target production via ^{59}Co(p,4n)



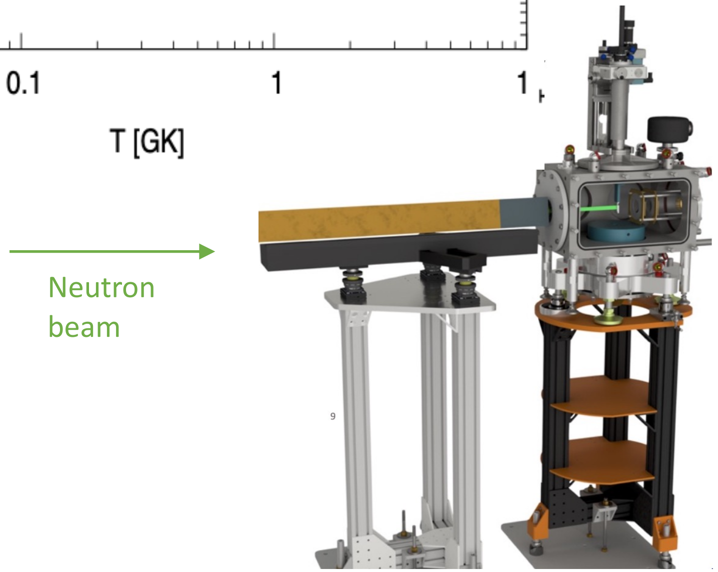


Ni/Co separation and target fabrication

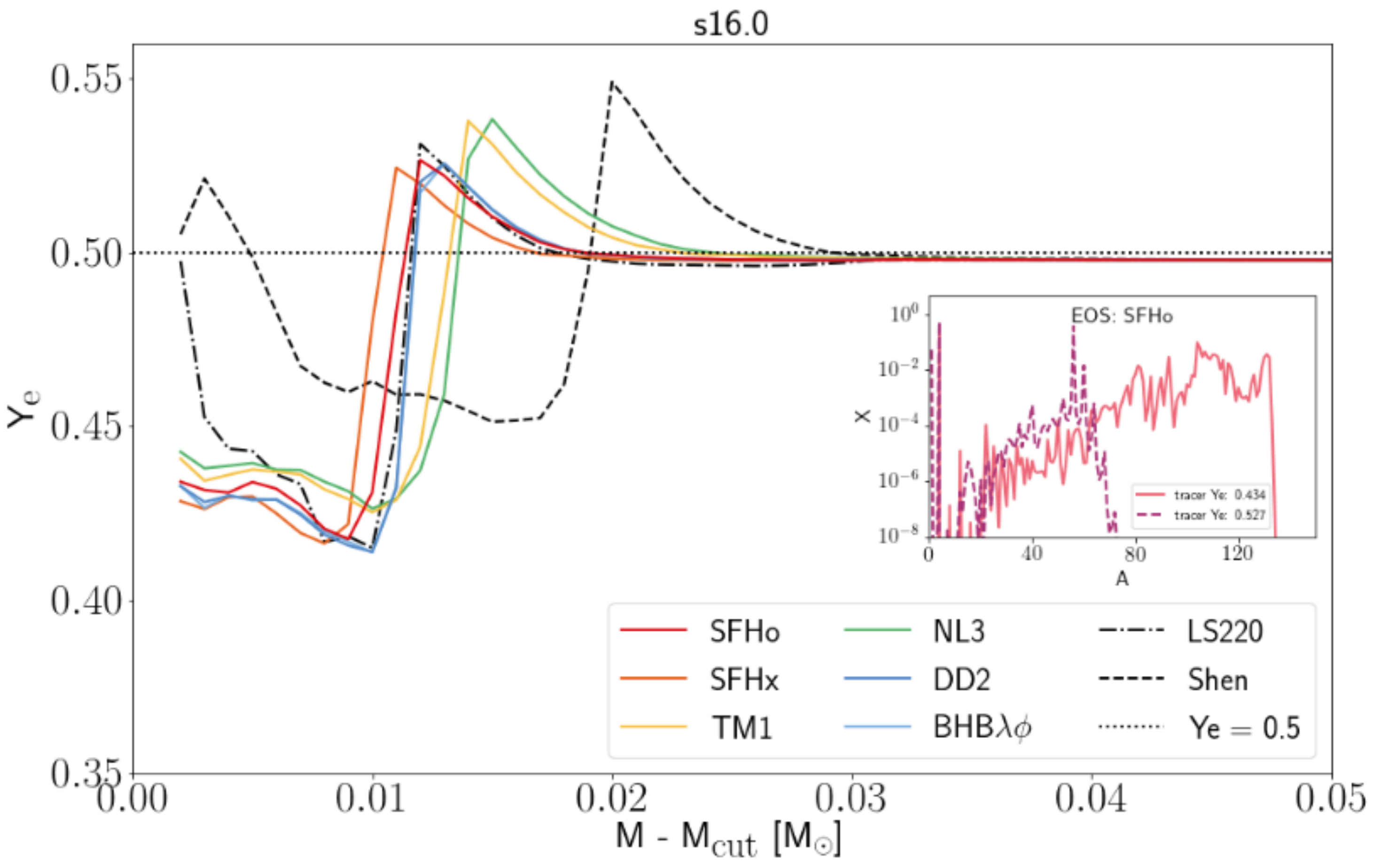


- Improved Ni recovery from 40 % (initial) to 90 % (final)

Neutron beam

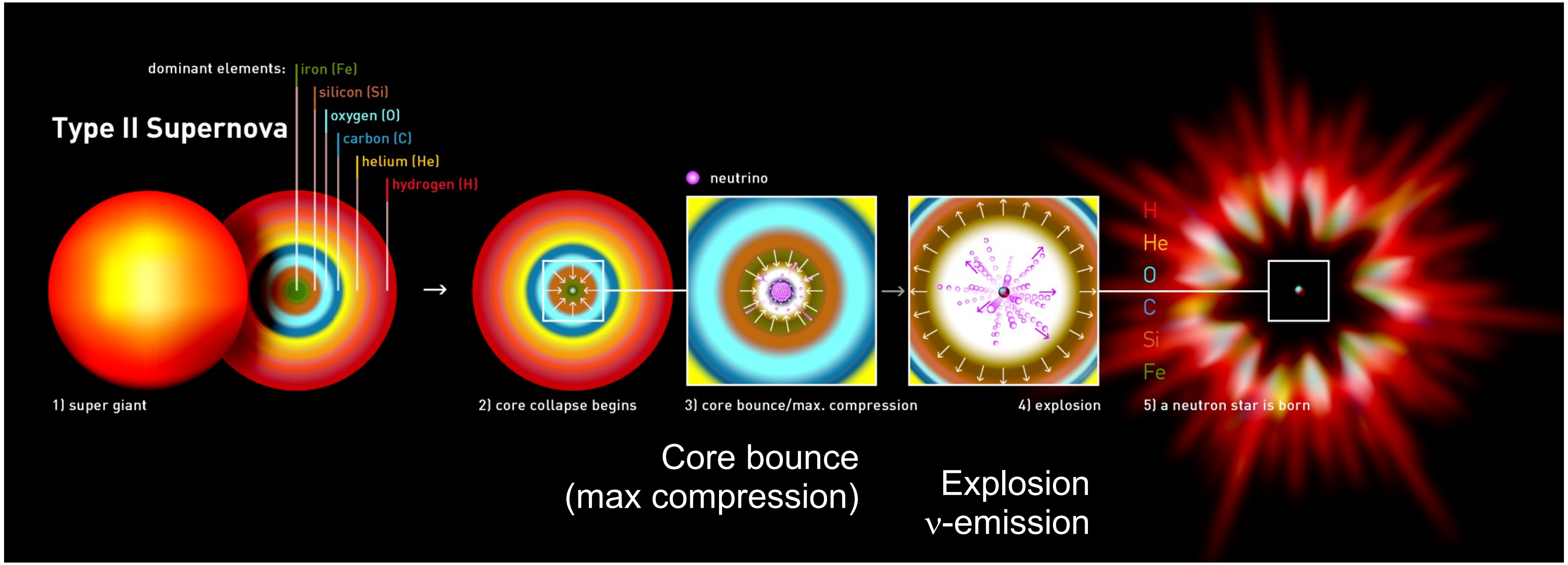


Beyond iron: Nuclear EOS matters



Model	EOS	E_{expl} (B)	M_{cut} ($M_\odot$)
s16.0	SFHo	1.3650	1.5244
	SFHx	1.2413	1.5300
	TM1	1.4071	1.5293
	NL3	1.4607	1.5263
	DD2	1.2365	1.5372
	BHB$\lambda\phi$	1.2362	1.5372
	LS220	1.4177	1.5183
	Shen	1.5861	1.5142

Summary (so far)

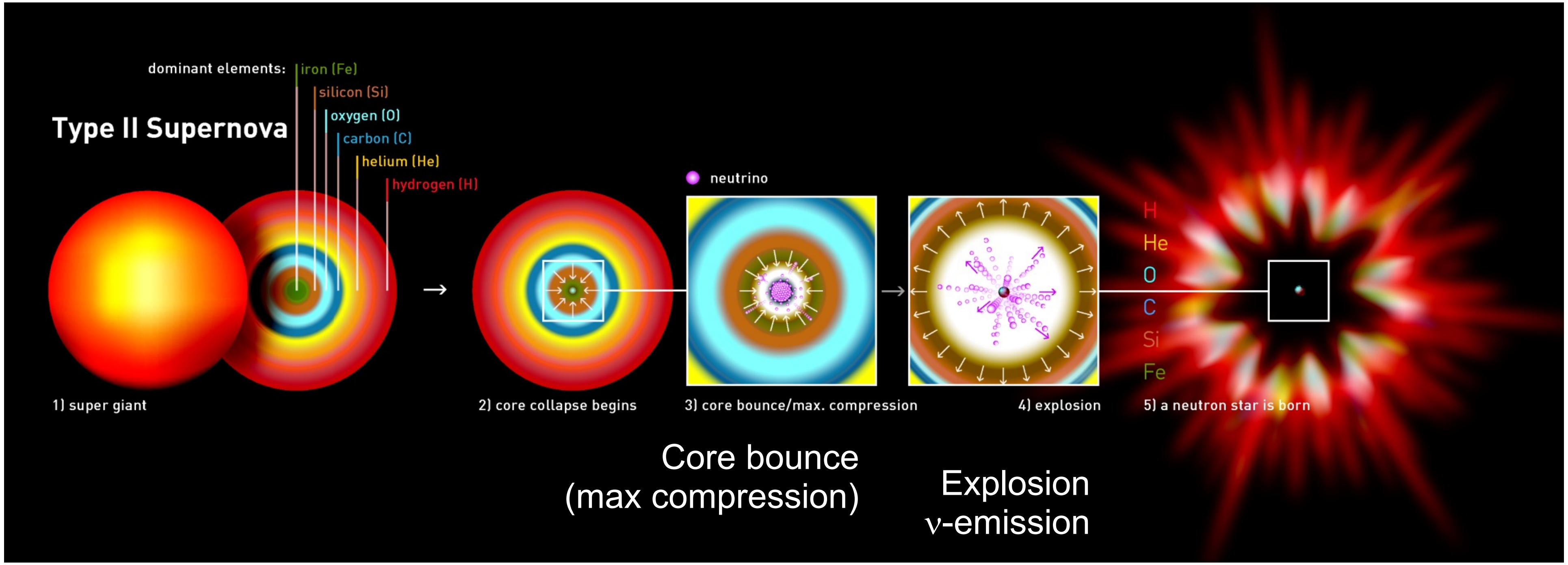


Stellar burning
→ C, O

Explosion mechanism:
Imprint on nucleosynthesis!

Explosive burning
→ Si, S, Ca, Fe, Ni, Zn
νp-process
→ Sr, Y, Zr + Mo, Ru

More CCSN nucleosynthesis



Stellar burning
→ C, O
Weak s-process
→ heavy elements

Explosion mechanism:
Imprint on nucleosynthesis?!

Explosive burning
→ Si, S, Ca, Fe, Ni, Zn
νp-process
→ Sr, Y, Zr + Mo, Ru

r-process ???
γ-process
→ p-nuclides