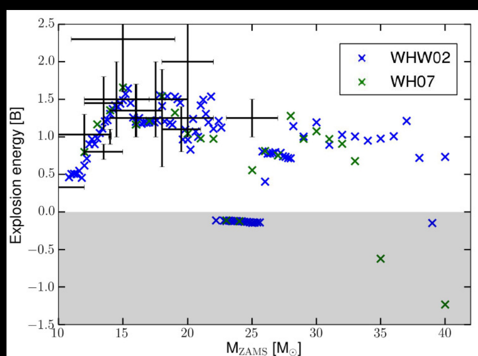
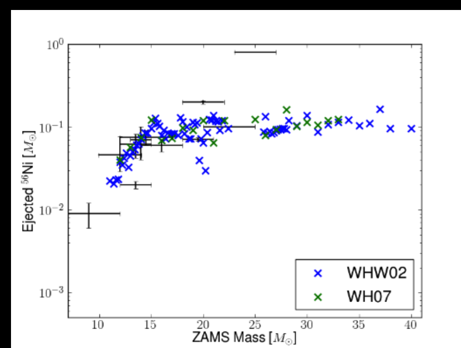
Nucleosynthesis yields from CC supernovae



Ebinger+ (in prep)



Sanjana Sinha+ (in prep)

Sanjana Sinha (NCSU)
Kevin Ebinger (NCSU)
Matthias Hempel (Basel)
Albino Perego (Darmstadt)
Carla Fröhlich (NCSU)

U.S. DEPARTMENT OF ENERGY

Forging Connections Workshop, MSU, 26-29 June 2017

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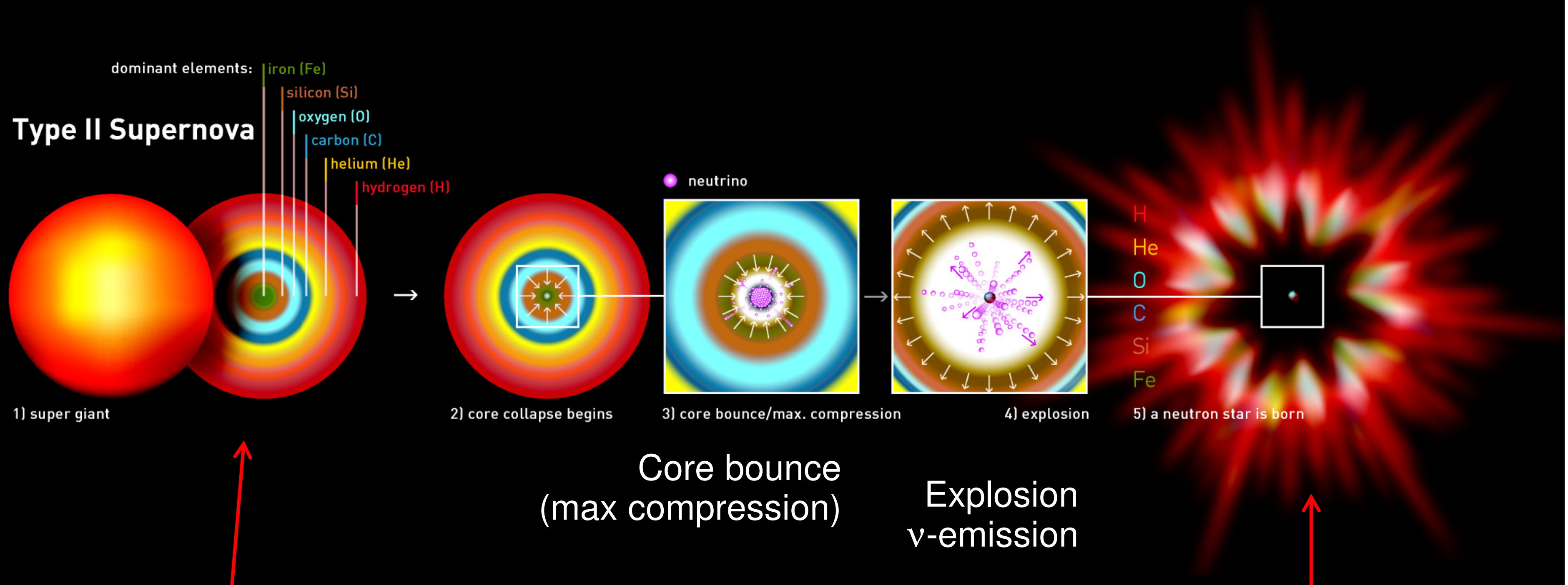
Core-collapse supernovae



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

Explosive burning
→ Si, S, Ca, Fe, Ni, Zn
νp-process
→ Sr, Y, Zr + Mo, Ru
r-process ???
γ-process
→ p-nuclides

➔ Primary sources of chemical enrichment

Core-collapse supernovae

CCSN Simulations

- Spherical symmetry + detailed neutrino transport
- Multi-D: many ongoing efforts

- Need (many) successful explosions for
  - What are conditions for explosive nucleosynthesis?
  - Connection between progenitor and remnant?
  - Prediction of nucleosynthesis yields (→ GCE)

- Strategies
  - Ideal: self-consistent, detailed, long-term 3D models
  - Realistic: parameterized exploding models [This work]
    - Simplify part of the problem, but have free parameters
    - Computationally efficient, physically reliable

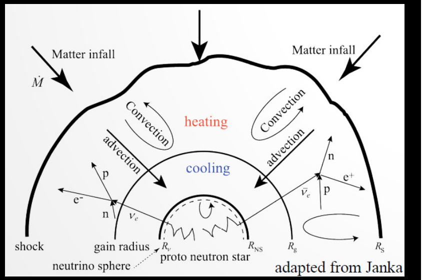
Modelling of CCSN nucleosynthesis

- Piston / thermal bomb
  Woosley&Weaver 95, Rauscher+02
  Thielemann+96, Limongi & Chieffi 06, Umeda&Nomoto 08
  → How much energy?
  → Where is mass cut? Ni yields?
  → Neutrino physics? PNS evolution?
  → Physics of collapse, bounce, onset of explosion?

- Neutrinos methods
  - Light bulb Iwakami+09, Yamamoto+13
    → neutrino luminosities and energies?
  - Modified neutrino reactions Frohlich+06, Fischer+10
    → Ye and PNS evolution?
  - Parameterized PNS contraction Ugliano+12, Ertl+15, Sukhbold+16
    → nuclear physics (EOS; BH formation)?

Modelling of CCSN nucleosynthesis

- Piston / thermal bomb — Woosley&Weaver 95, Rauscher+02; Thielemann+96, Limongi & Chieffi 06, Umeda&Nomoto 08
- Neutrinos methods
  - Light bulb — Iwakami+09, Yamamoto+13
  - Modified neutrino reactions — Frohlich+06, Fischer+10
  - Parameterized PNS contraction — Ugliano+12, Ertl+15, Sukhbold+16
  - **PUSH method** — Perego, Hempel, CF, Ebinger, et al 2015)
    → Based on neutrino-driven mechanism (use neutrinos to obtain explosion)
    → Preserve Ye evolution (no modification of ν_e-transport)
    → Nuclear EOS and PNS evolution included

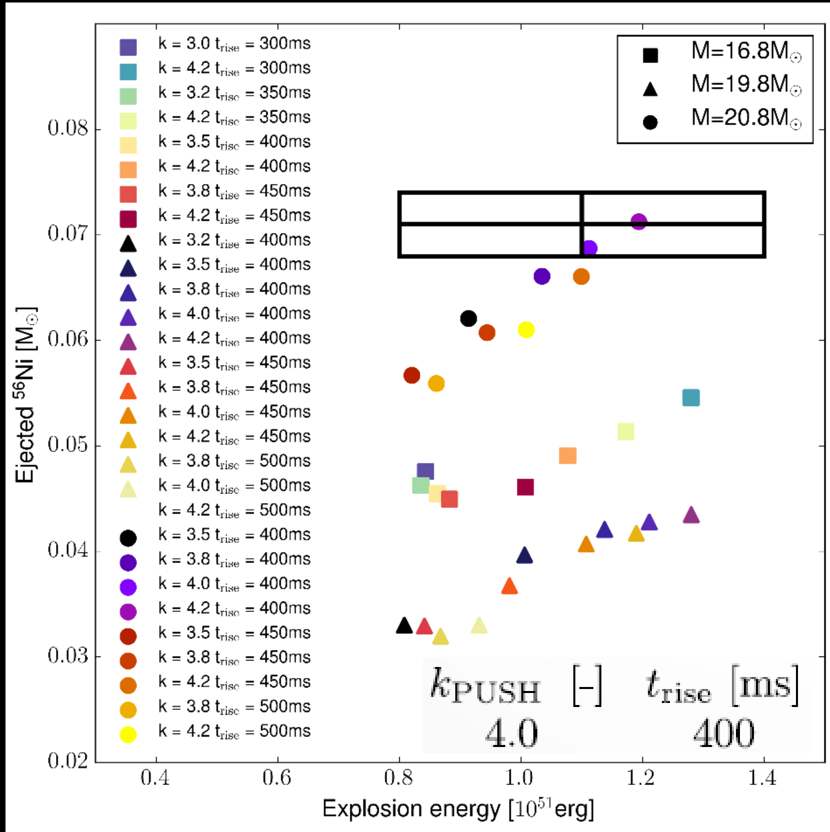


Calibration of PUSH

Observational properties of SN 1987A:

E_{expl}	$(1.1 \pm 0.3) \times 10^{51}$ erg
m_{prog}	18-21$M_\odot$
$m(^{56}Ni)$	$(0.071 \pm 0.003)\ M_\odot$
$m(^{57}Ni)$	$(0.0041 \pm 0.0018)\ M_\odot$
$m(^{58}Ni)$	$0.006\ M_\odot$
$m(^{44}Ti)$	$(0.55 \pm 0.17) \times 10^{-4}\ M_\odot$

Seitenzahl+ 14, Fransson & Kozma 02, Blinnikov+ 00



Progenitor models:

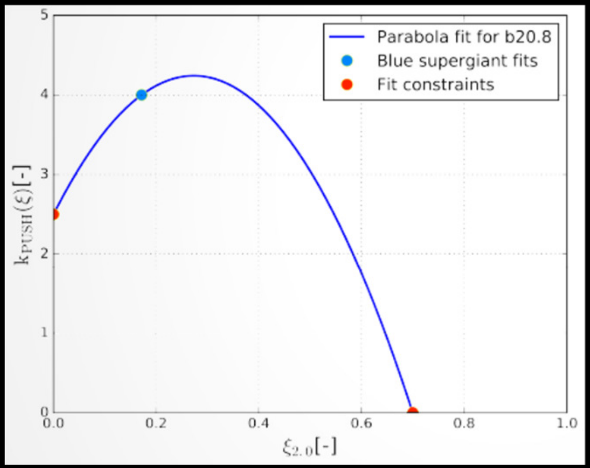
- From A. Menon (Kepler)
- Blue supergiant
- 16.8, 19.8, 20.8 M_{sun}
- Metallicity $Z_{LMC} < Z_{sun}$

Calibration of PUSH

- Observational properties of SN 1987A
- Crab-like supernovae
  - Lower explosion energies at lower end of mass range
- BH formation
  - LIGO finds BHs below 40Msun

- These constraints set the PUSH parameters for entire progenitor set (~11-40 M_{sun})

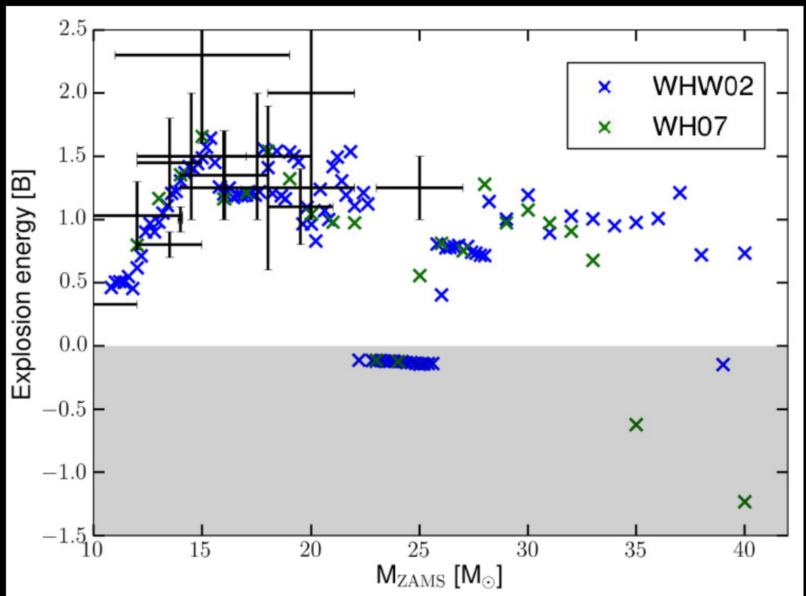
Ebinger+ (in prep), Sanjana Sinha+ (in prep)



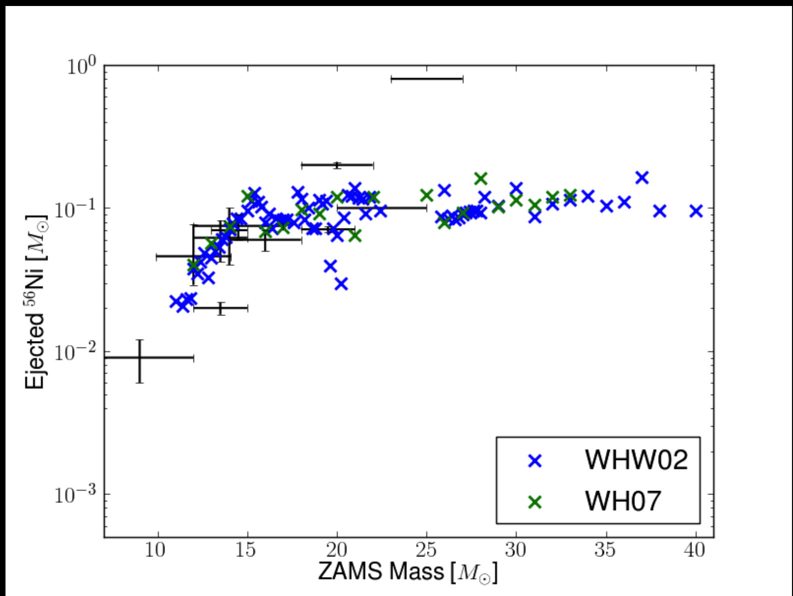
The Faint SN Branch

- Compilation of observational data: Nomoto+2013; Smartt+2015; Bruenn+2016
- Supernova model landscape (two different progenitors sets: WHW02, WH07)

Explosion energy



Nickel ejecta



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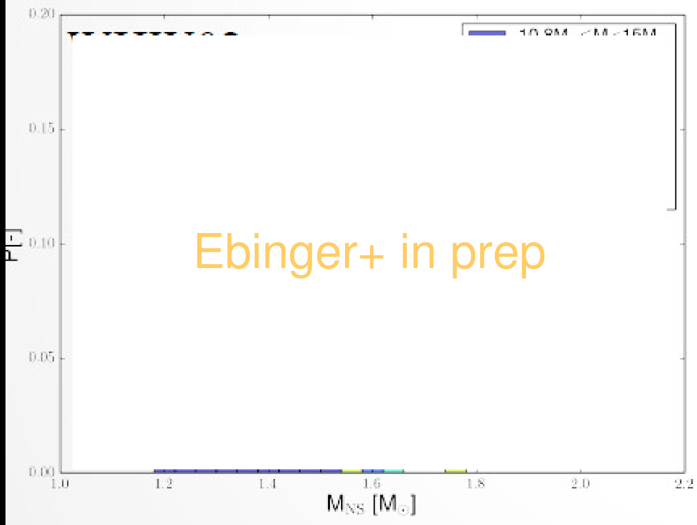
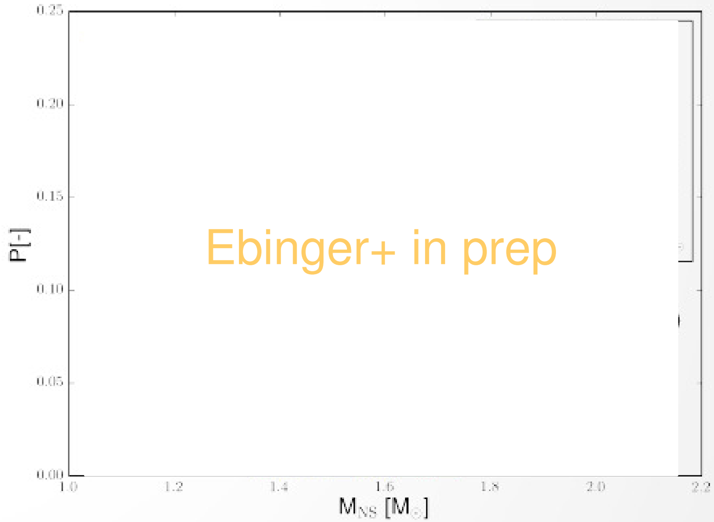
Remnant Mass Distributions

Preliminary:

From the predicted NS masses one can compute the neutron star birth mass distribution in a galaxy, as well as the number of black holes

- With IMF from Salpeter (for massive stars heavier than 10 $M_\odot$)





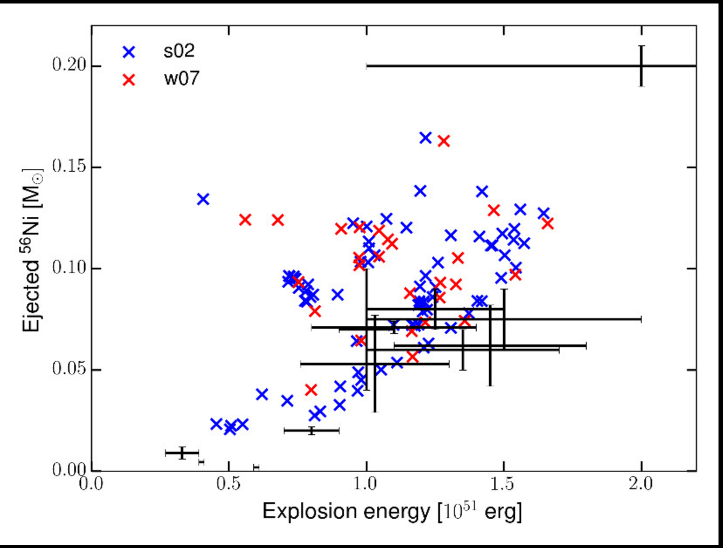
gravitational neutron star mass distribution (cold neutron stars) split in the contributions of the different ZAMS masses of the progenitors

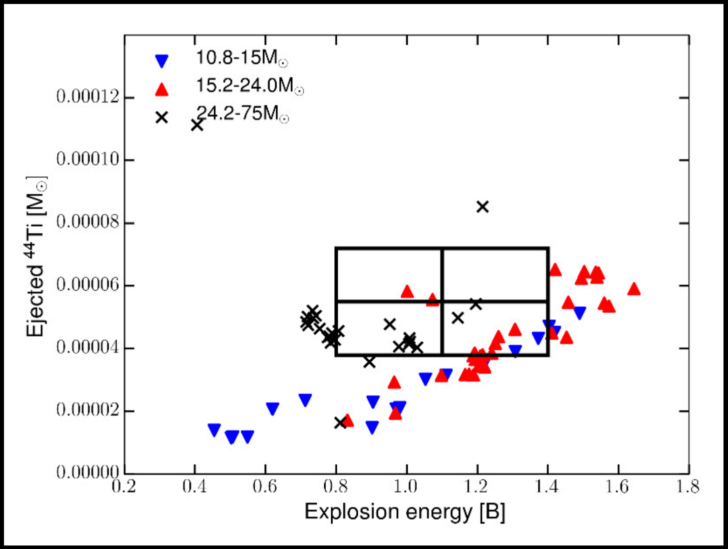
Ejecta Trends

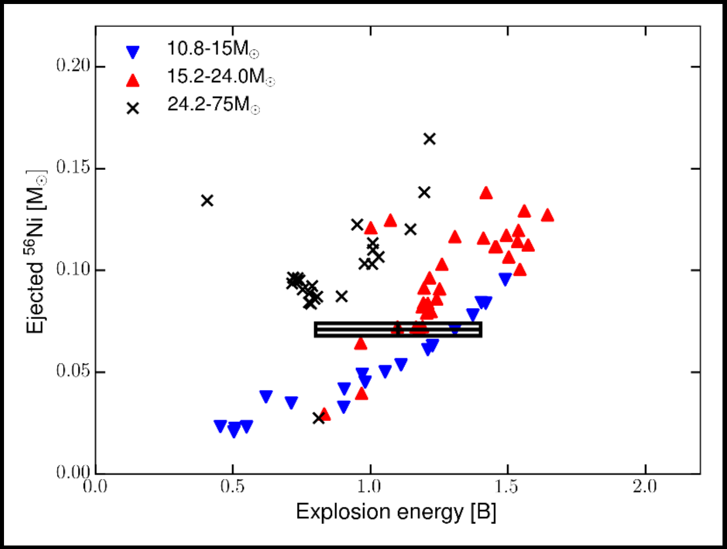
Linear trend of Ni with Eexpl

High Ti yields

Several RSG models fulfilling SN 1987A constraints







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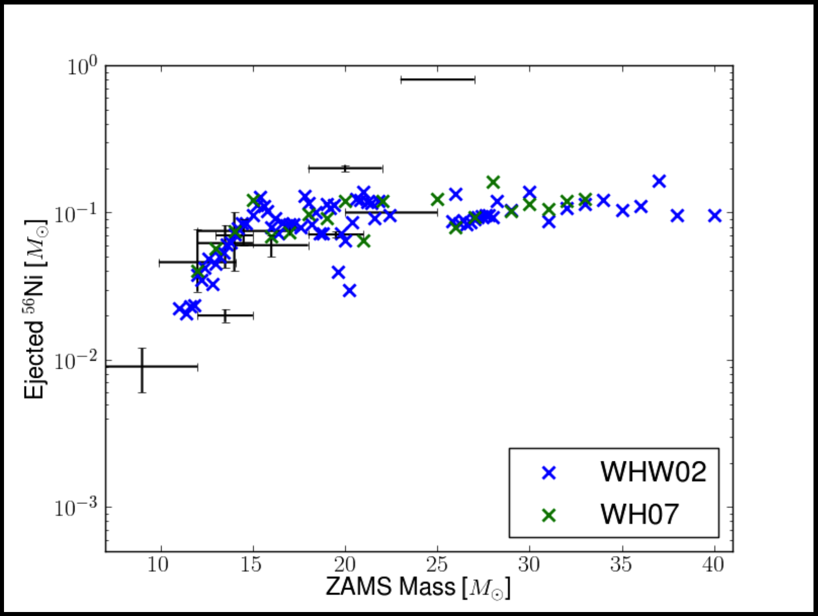
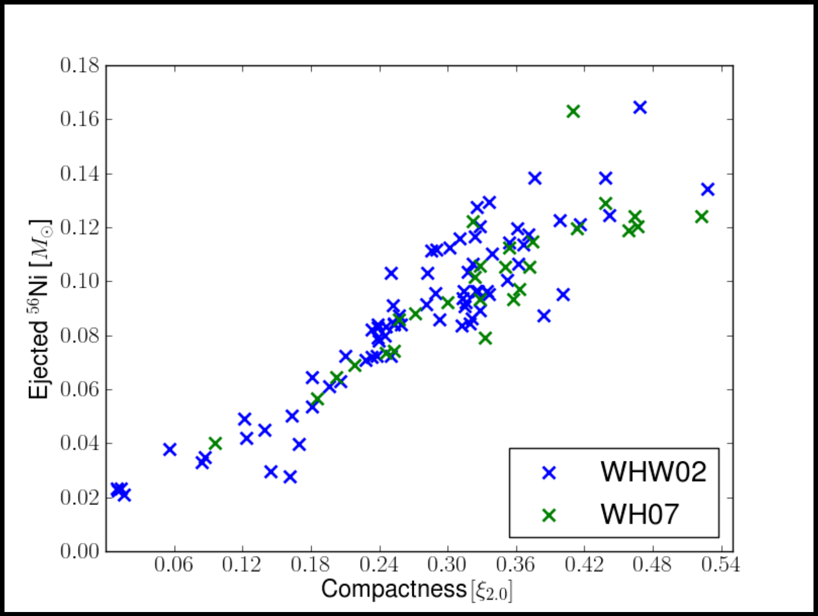
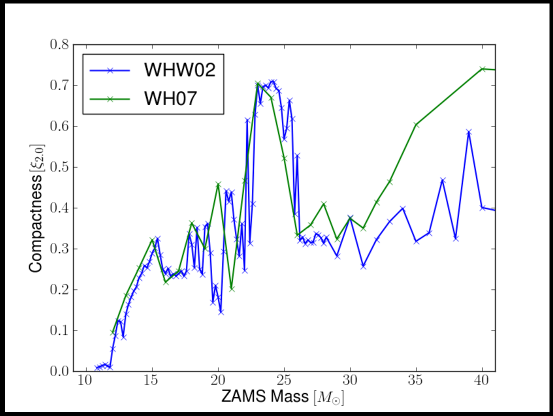
ZAMS vs compactness





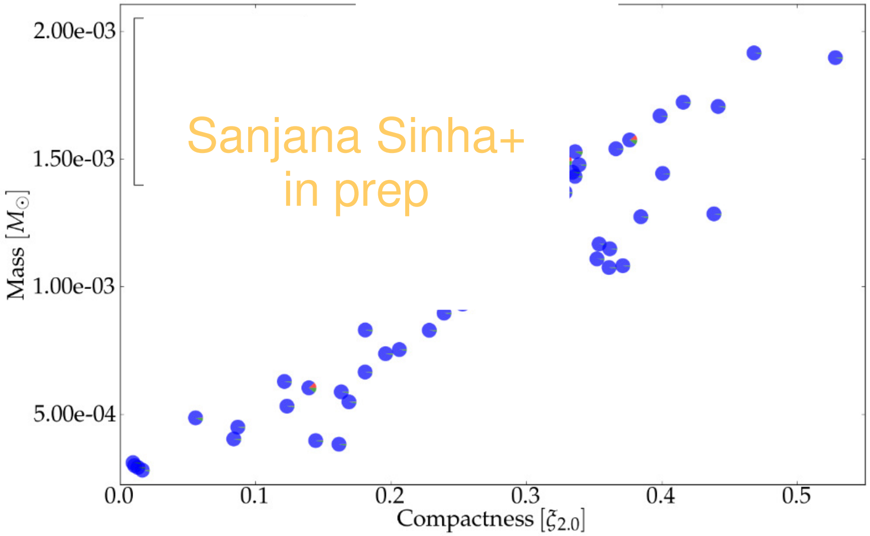
- Compactness:

$$\xi_M \equiv \frac{M/M_\odot}{R(M)/1000\mathrm{km}}$$

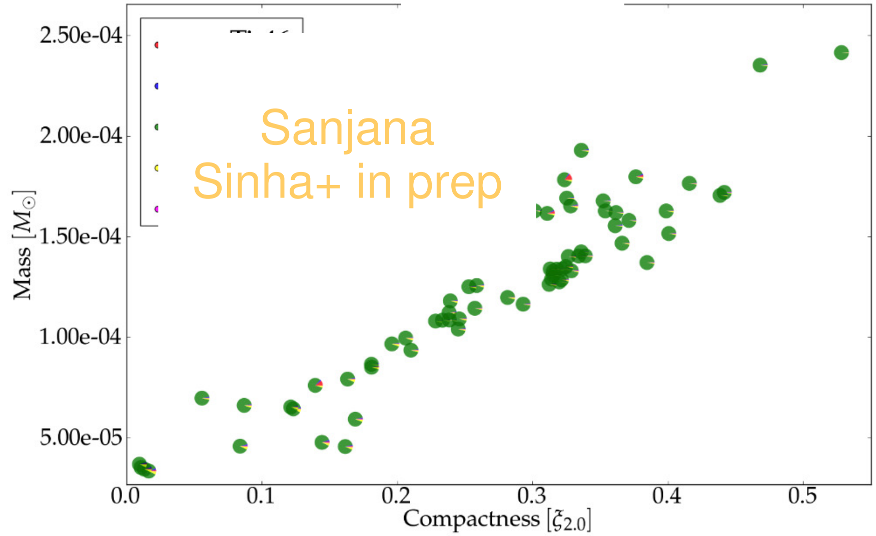


Iron Group Yields

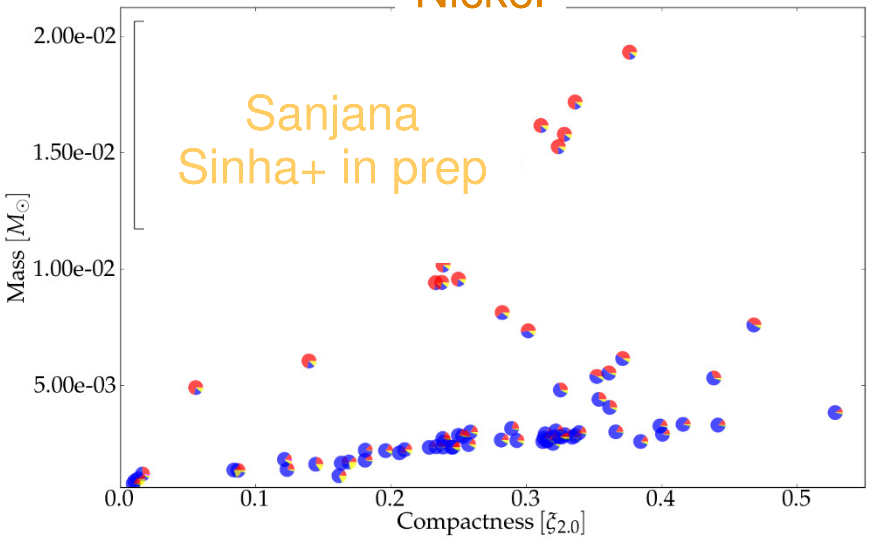
Chromium



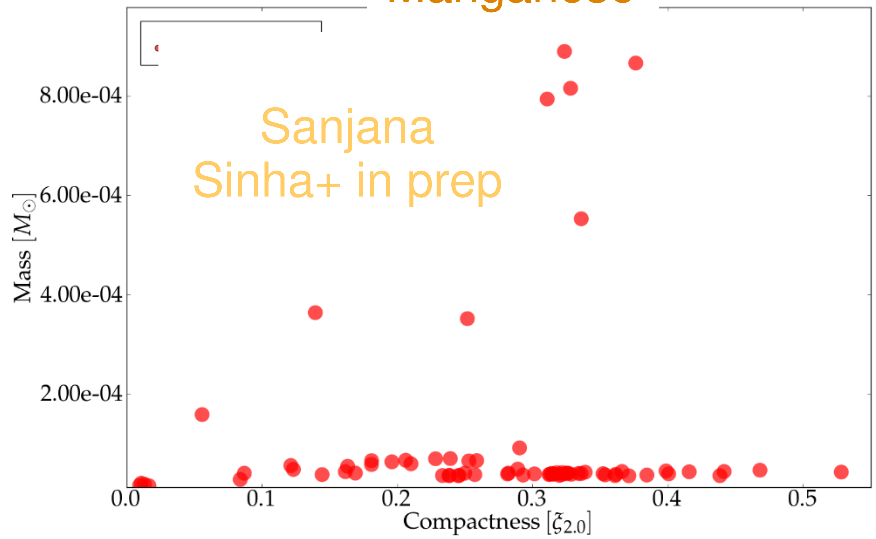
Titanium



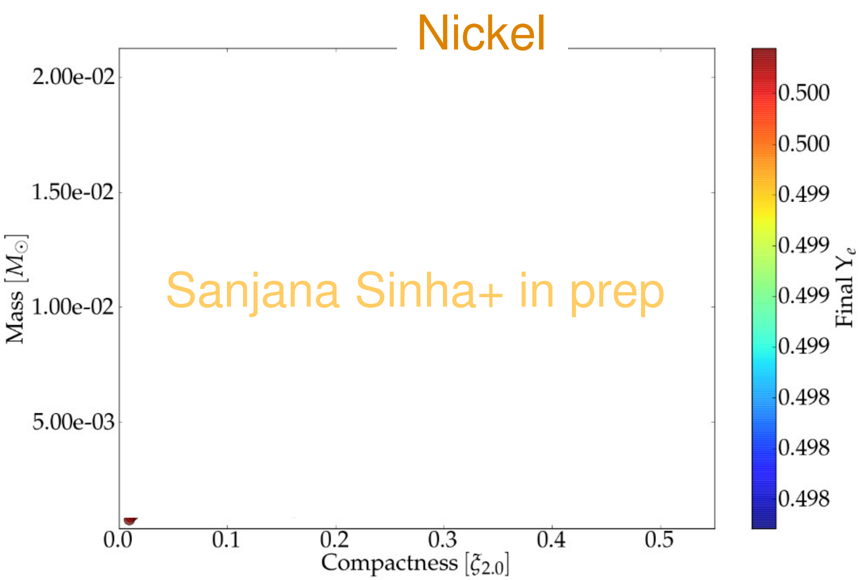
Nickel

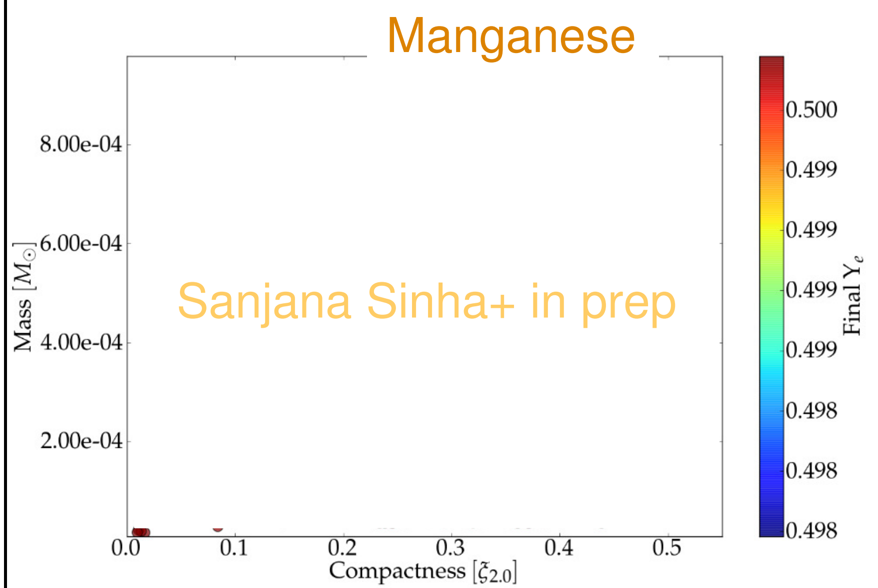


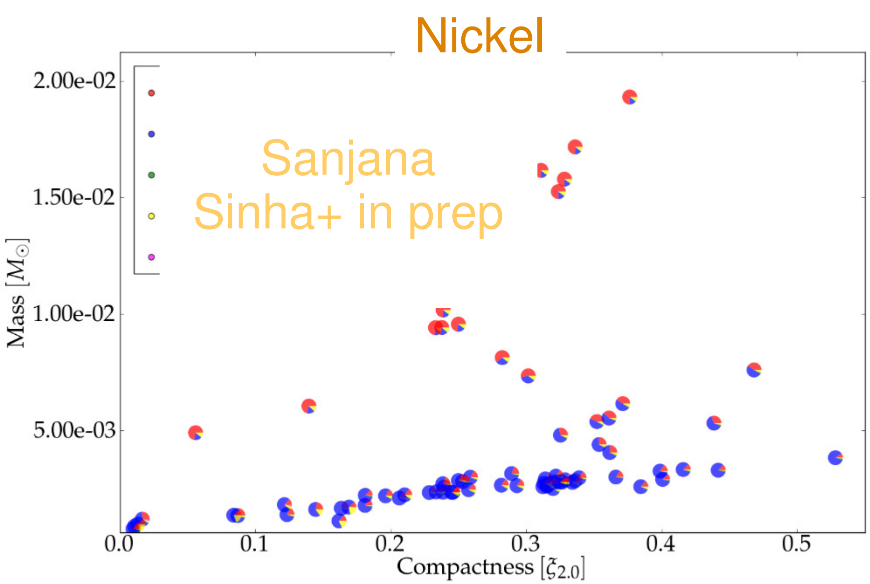
Manganese

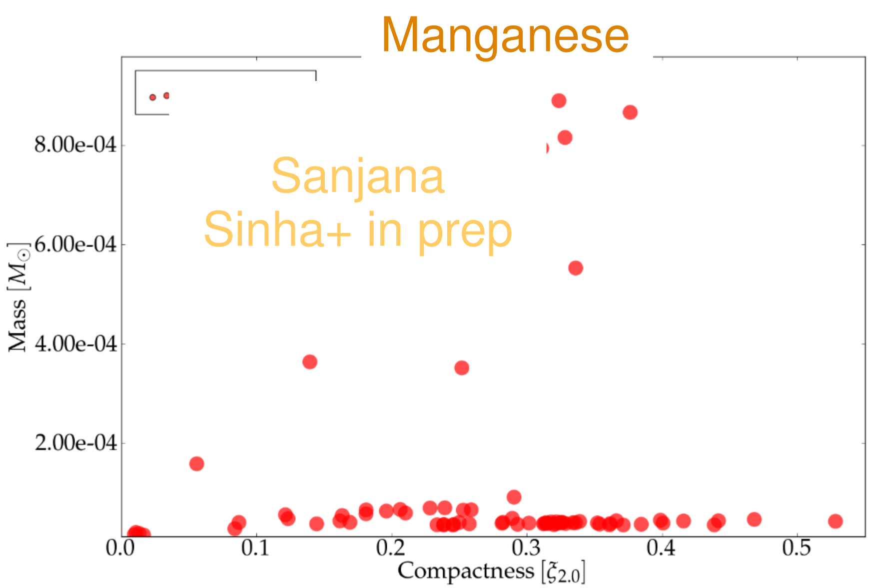


Iron Group Yields



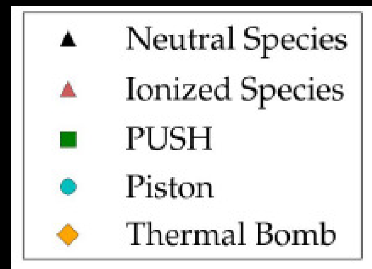




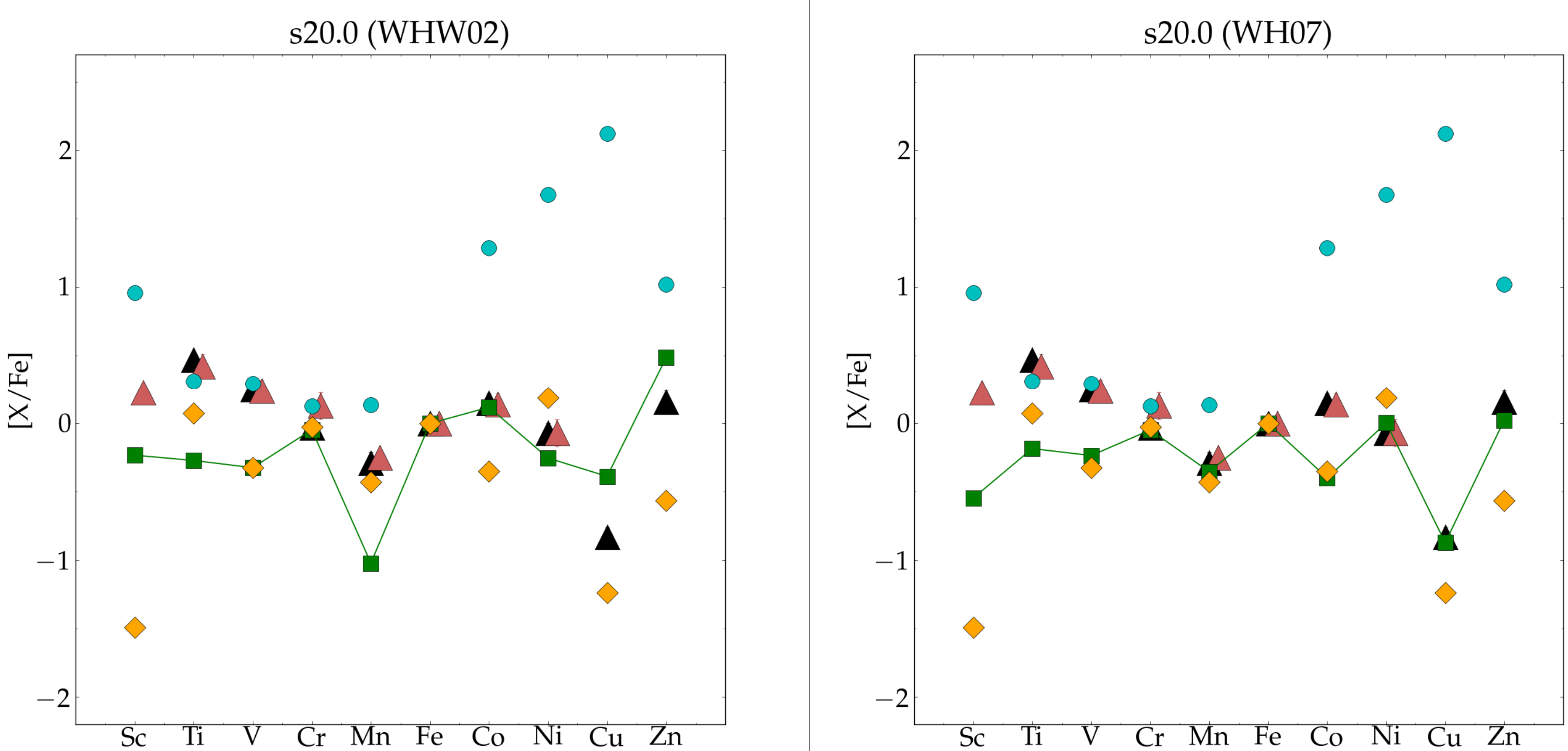


Metal-poor star HD 84937

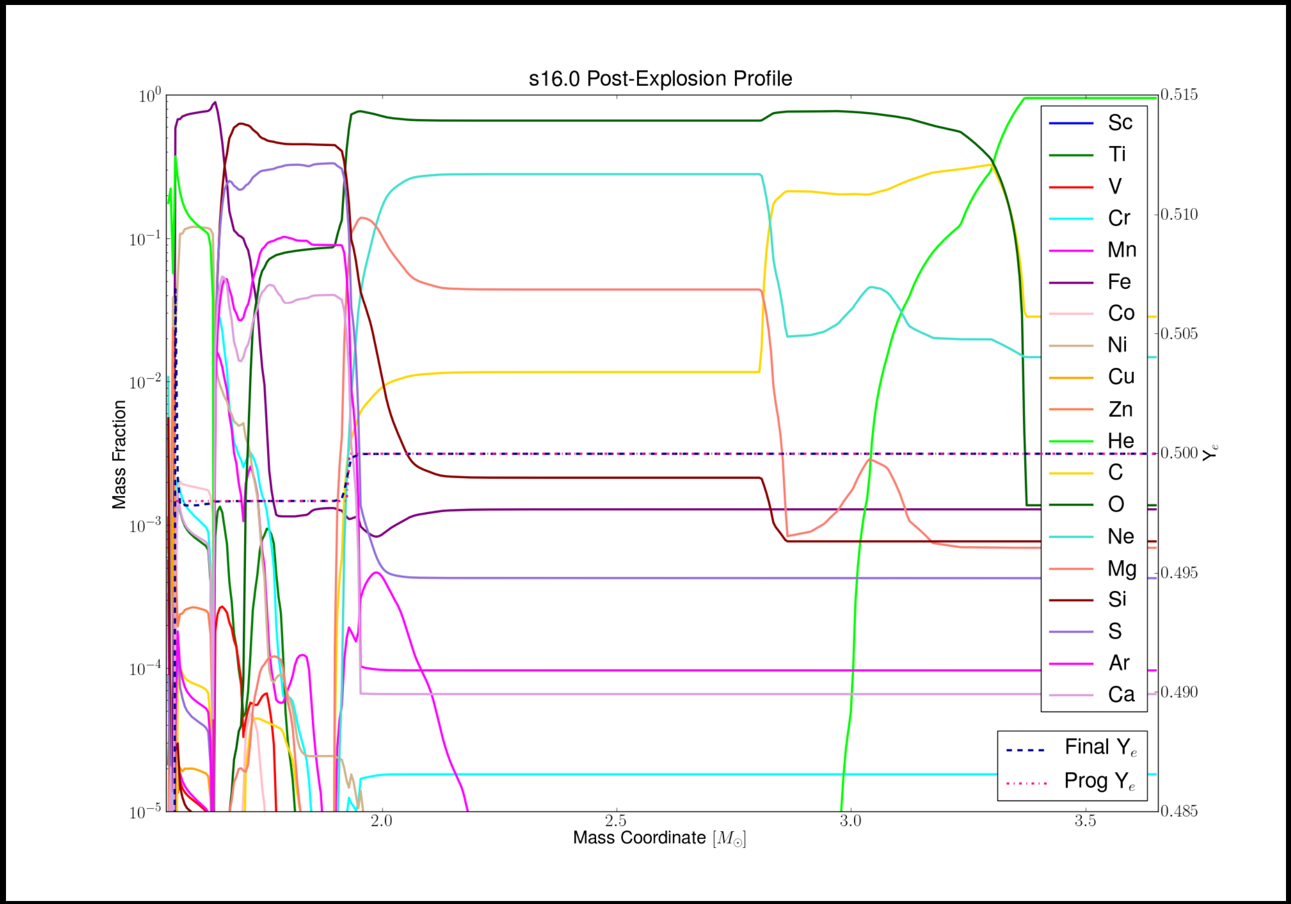
$$\left[\frac{X}{X_{\mathrm{Fe}}}\right] = \log\left(\frac{X}{X_{\mathrm{Fe}}}\right) - \log\left(\frac{X}{X_{\mathrm{Fe}}}\right)_{\odot}$$



Sneden+16



Intermediate mass elements



Conclusions

- Computationally affordable PUSH method
  - Reproduces SN 1987A
  - Two progenitor sets explored (WHW02 & WH07)
- Good agreement with observations of Faint SN branch and metal-poor stars

  → We would like other progenitor models
- Compactness trends
- Predict NS and BH masses
- Have complete isotopic yields for all models
  - Electron fraction is crucial for yields
- Coming soon:
  - Ebinger+2017 [SN landscape, explodability, NS/BH]
  - Sanjana+2017 [detailed nucleosynthesis]