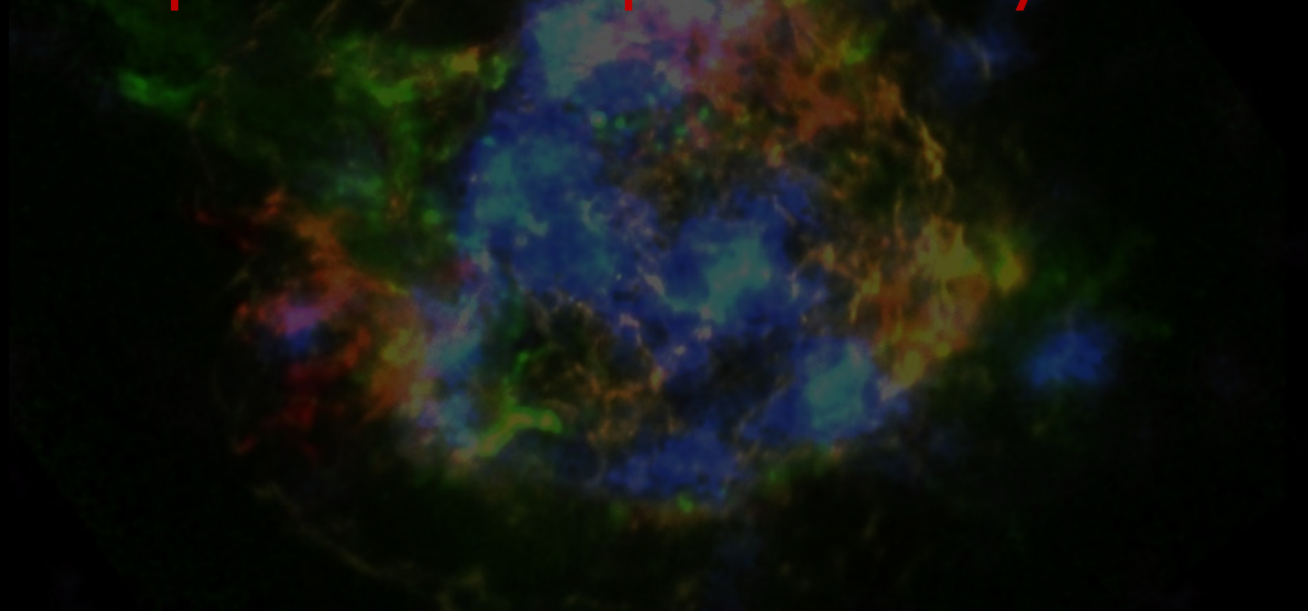
PUSHing Core-Collapse Supernovae to Explosion in spherical symmetry



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U.S. DEPARTMENT OF ENERGY

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Publications

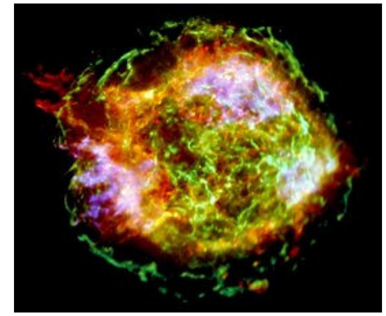
- **Sanjana Curtis (NCSU)**
- **Kevin Ebinger (GSI)**
- Somdutta Ghosh (NCSU)
- Albino Perego (Trento)
- Matthias Hempel (Basel)

- Low and zero metallicity progenitors
  - Ebinger, Curtis, Ghosh, CF et al (in prep)
- Single star vs binary-merger progenitors
  - CF, Curtis, Ebinger, Ghosh, Menon, et al JPG (2019)
- Nucleosynthesis yields across the mass range
  - Curtis, Ebinger, CF, et al ApJ (2019)
- Explosion properties
  - Ebinger, Curtis, CF, et al ApJ (2019)
- The Method
  - Perego, Hempel, CF, et al ApJ (2015)

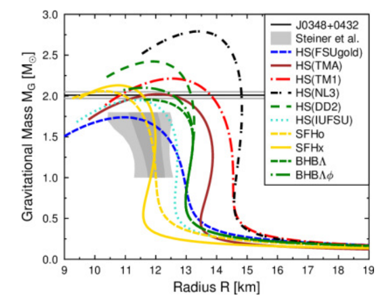
Data available from http://astro.physics.ncsu.edu/~cfrohli/

Core-collapse supernova simulations

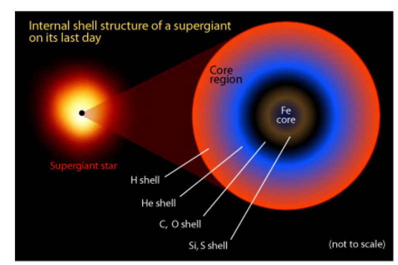
- Computational challenges:
  - Multi-dimensional problem
    (SNe are not spherically symmetric!)
  - Gravitation: general relativistic
  - Nuclear physics of dense matter
    (not very well known)
  - Neutrino transport
    (diffusion and free streaming regimes)
  - Multi-scale problem
    (shock formation: several 100km;
    entire star: 10^8 km)



Cas A; Chandra, NASA



SN EOSs by Hempel



CSIRO

Simulation status

→ See talk by Mezzacappa

- Adequate treatment of physics is important
- 2D models: convergence
  - similar input gives similar results
- 3D models: mixed results
  - Models are close to threshold (some explosions, some failures)
  - Explosions can be code-dependent

- Avenues towards more robust explosions:
  - Ensure stronger turbulent motions (eg convection in the progenitor)
  - More heating by neutrinos, ie get neutrinos out faster and from deeper inside

Bruenn+16, Kuroda+16, Nagakura+16, Radice+16, Pan+16, Roberts+16, Takiwaki+16, Andresen+17, Mueller+17, Radice+17, Suma+17, Wongwanthanarat+17, Kuroda+17, Summa+18, Chan+18, O'Connor+18, Ott+18, Glas+19, Nakamura+19, Vartanyan+19, Burrows+19, … (and several in preparation)

Nucleosynthesis status

- 2D models
  - 12, 15, 20, 25Msun (at Z_{sun}): comparing postprocessing vs in-situ network — Harris+17
  - 8.8, 11, 15, 27Msun (at Z_{sun}), 8.1Msun (at $Z/Z_{sun}=10^{-4}$), 9.6M_{sun} (at Z=0): innermost $10^{-3}M_{sun}$ neutrino-processed ejecta — Wanajo+17
  - 11.2 and 17Msun (at Z_{sun}): detailed processing of representative tracers, extrapolating to other tracers (focus on p-nuclei) — Eichler+17
- 3D models
  - Postprocessing of ~100k tracers (focus on ^{44}Ti and ^{56}Ni for Cas A) — Wongwathanarat+17

Nucleosynthesis status

- 1D models
  - Grids of models using piston or thermal/kinetic bomb
    - Metallicities (Z/Z_{sun}): 10^{-5} to 1
    - ZAMS masses: ~10 – 40 M_{sun}
      plus some < 10 M_{sun} and
      plus some > 40 M_{sun}

Woosley&Weaver 95, Rauscher+02,
Heger+07, Heger+10
Thielemann+96, Nomoto+06, Umeda+08,
Nomoto+13, Nomoto+17
Limongi & Chieffi 06, Limongi+12,
Chieffi+13, Chieffi+17

- But open questions:

→ How much energy?

→ Where is mass cut? Ni yields?

→ Neutrino physics? PNS evolution?

→ Physics of collapse, bounce, onset of explosion?

Nucleosynthesis status

- 1D models
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Limongi & Chieffi 06, Limongi+12, Chieffi+13, Chieffi+17

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

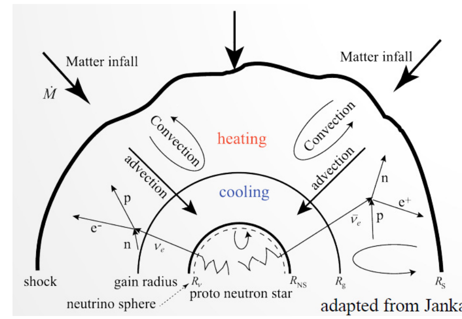
Where to go from here?

- Need (many) successful, **long-term** explosions
  - Connection between progenitor and remnant?
  - Which massive stars explode successfully? Which ones do not?
  - Prediction of nucleosynthesis yields

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

The PUSH method

- Parameterization of the neutrino-driven mechanism

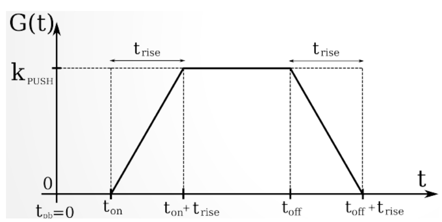


- Basic idea: tap fraction of heavy-neutrino luminosity inside the gain region to mimic the net enhanced heating efficiency of ν_e due to convection and late accretion in multi-D

$$Q^{+}_{\text{push}}(t,r) \propto \mathcal{G}(t) \int_0^\infty q^{+}_{\text{push}}(r,E)\, dE$$

$$q^{+}_{\text{push}}(r,E) \propto \sigma_0 \left(\frac{E}{m_e c^2}\right)^2 \frac{1}{4\pi r^2} \left(\frac{dL_{\nu_x}}{dE}\right) \mathcal{F}(r,E)$$

Temporal evolution
Typical neutrino cross section
Spectral energy flux
Location function



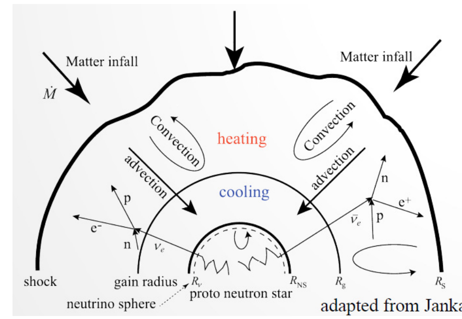
Free parameters:

- $k_{\text{PUSH}} \sim 1$
- $50 \text{ ms} < t_{\text{rise}} < 500 \text{ ms}$

Perego, Hempel, CF, Ebinger, Eichler, Casanova, Liebendoerfer, Thielemann (2015)

The PUSH method

- Parameterization of the neutrino-driven mechanism



- Nuclear EOS and PNS evolution included
- Consistent Ye evolution (electron-flavor transport not modified)
- Predict E_{expl} and mass cut*, nucleosynthesis yields

* Mass cut emerges from the simulation consistent with explosion energy (not put in by hand)

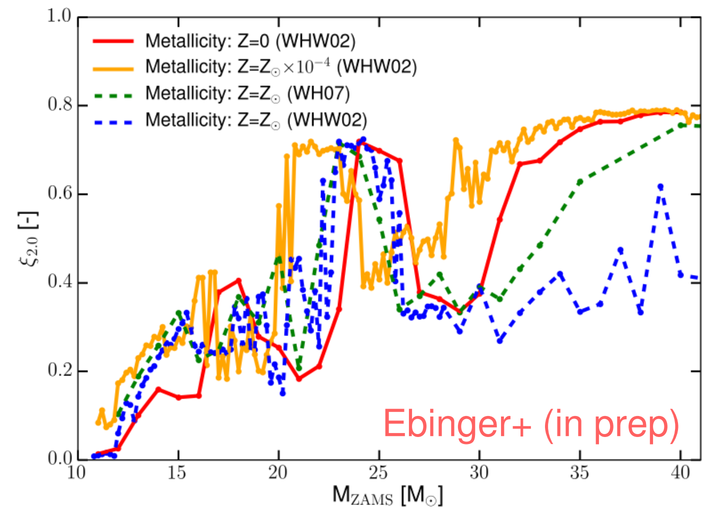
Perego, Hempel, CF, Ebinger, Eichler, Casanova, Liebendoerfer, Thielemann (2015)

Our simulation setup

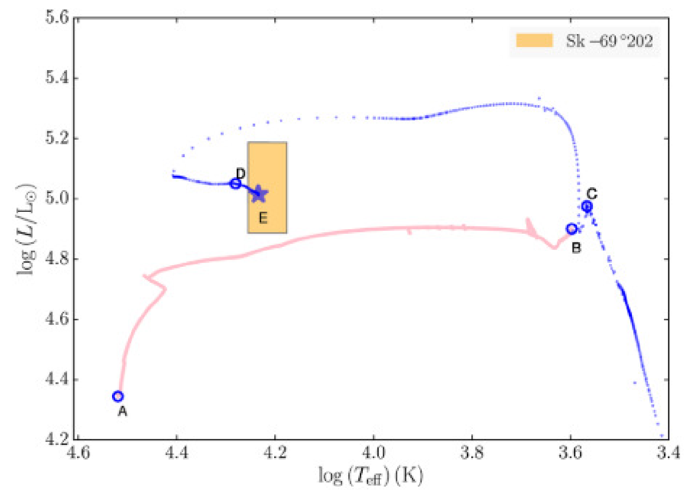
- General relativistic hydrodynamics: Agile — Liebendoerfer+02
- Neutrino transport: IDSA and advanced spectral leakage (ASL) — Lieberdoerfer+09; Perego+16
- Nuclear EOS: HS(DD2) — Hempel+02; Typel+10
- Nucleosynthesis: Postprocessing of tracer particles with nuclear reaction network — CF+06; Curtis+19

Our simulation setup

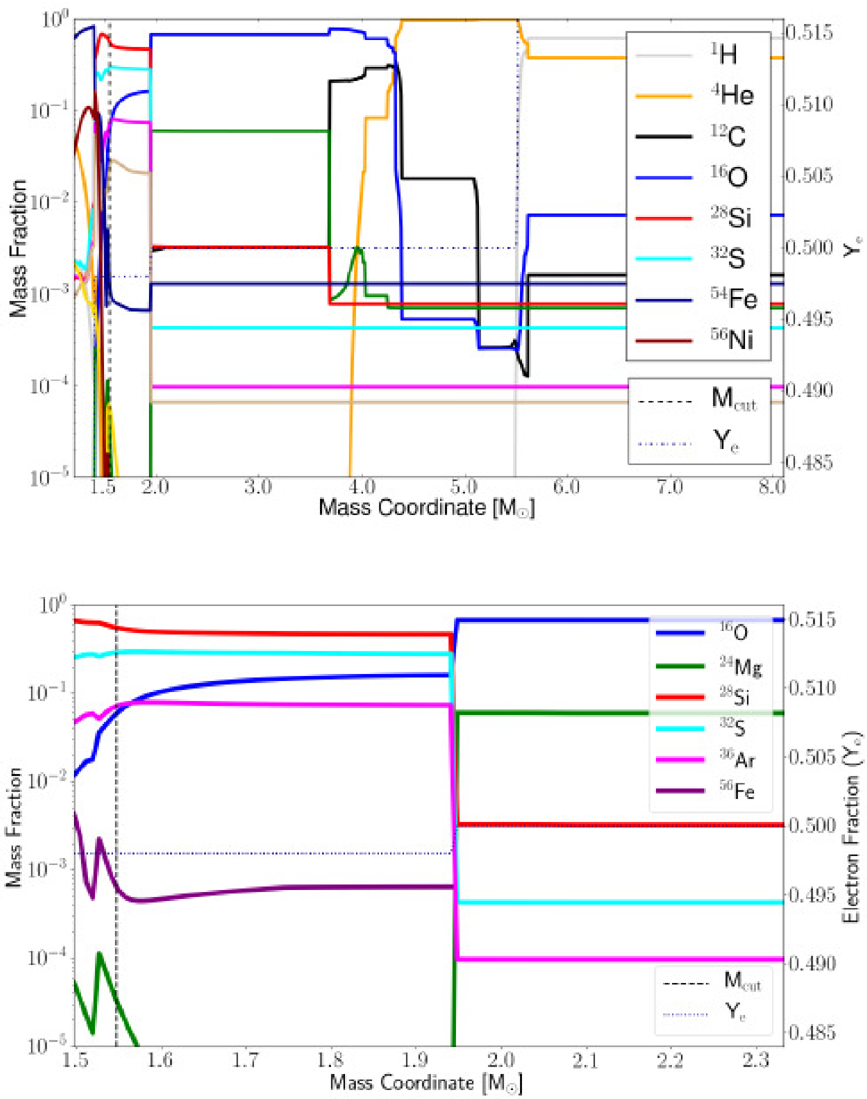
- Progenitor models:
  - Woosley+02 at $Z=Z_{sun}$
  - Woosley+07 at Z_{sun}
  - Woosley+02 at $Z=10^{-4}\ Z_{sun}$
  - Woosley+02 at $Z=0$
  - Menon & Heger 2017 at $Z=Z_{LMC}$



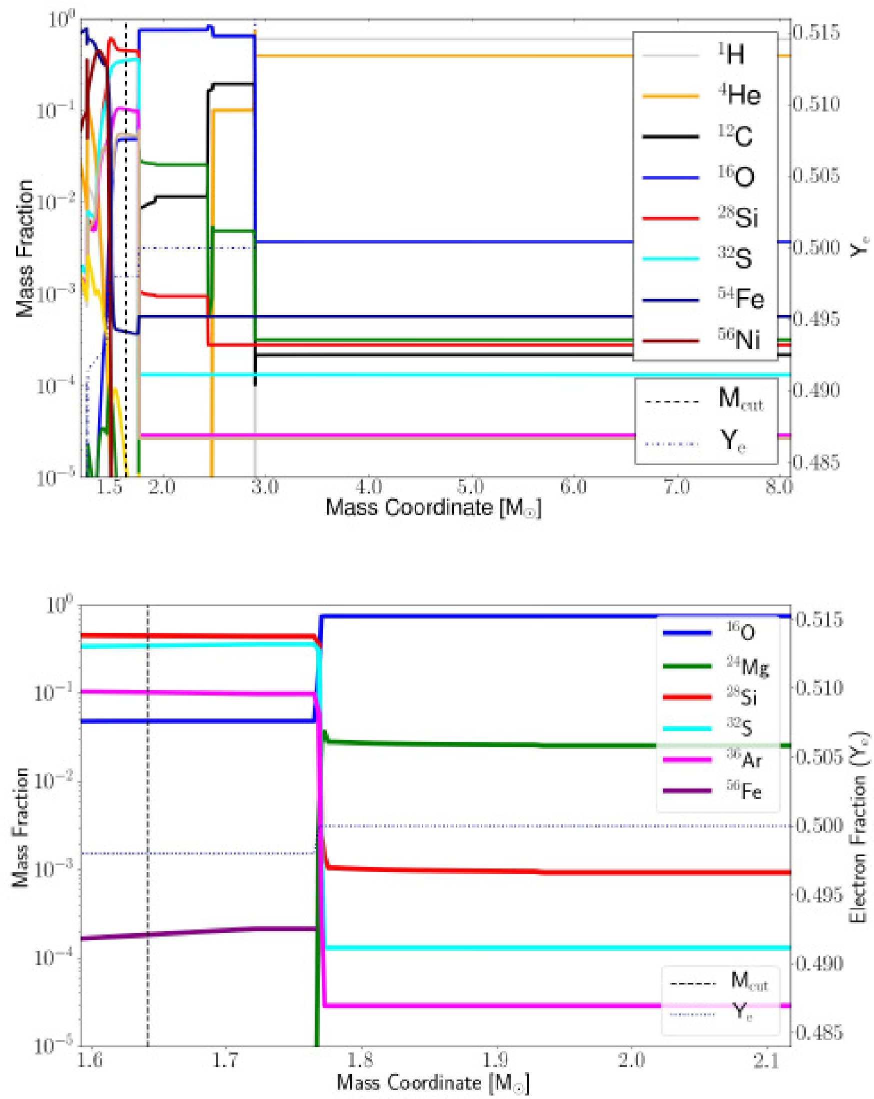
M_1 ($M_\odot$)	M_2 ($M_\odot$)	Final mass ($M_\odot$)	Compactness $\xi_{2.0}$ (-)	Label
16.0	4.0	19.0	0.29843	a16-4
17.0	7.0	22.8	0.28912	a17-7
17.0	8.0	23.8	0.43902	a17-8
15.0	7.0	21.1	0.22154	b15-7
15.0	8.0	22.1	0.12499	b15-8
16.0	7.0	22.0	0.17249	b16-7



RSB versus BSG models

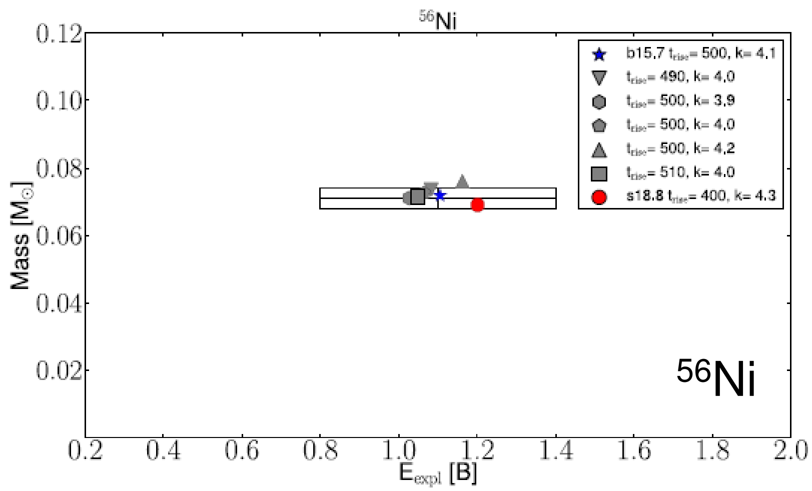


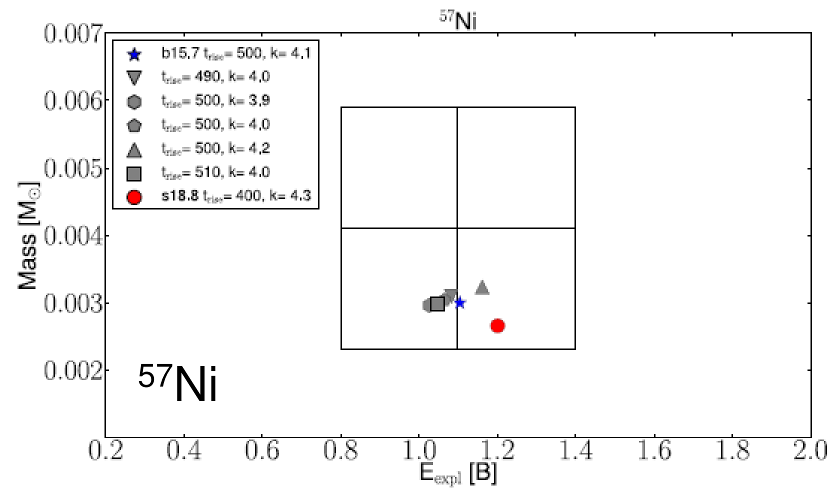
s18.8 (RSG)

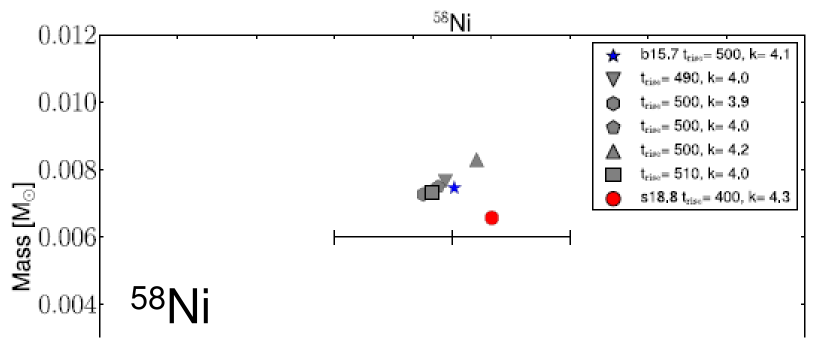


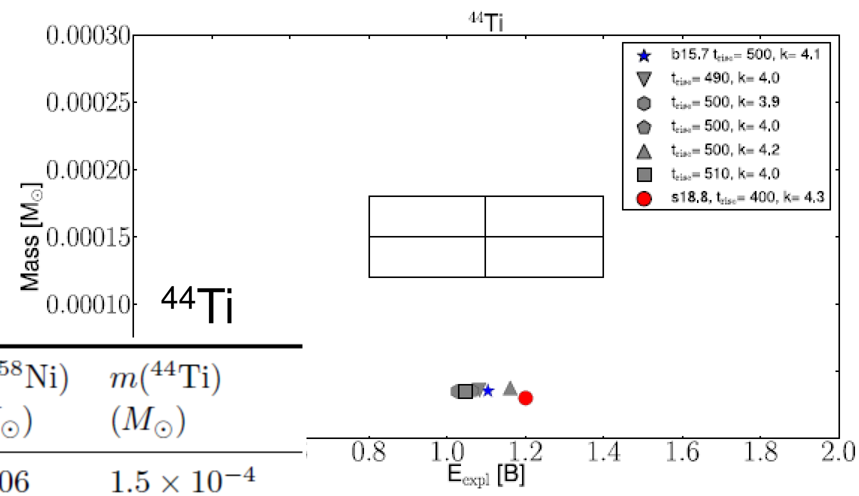
b15-7 (BSG)

SN1987A: Calibration of PUSH





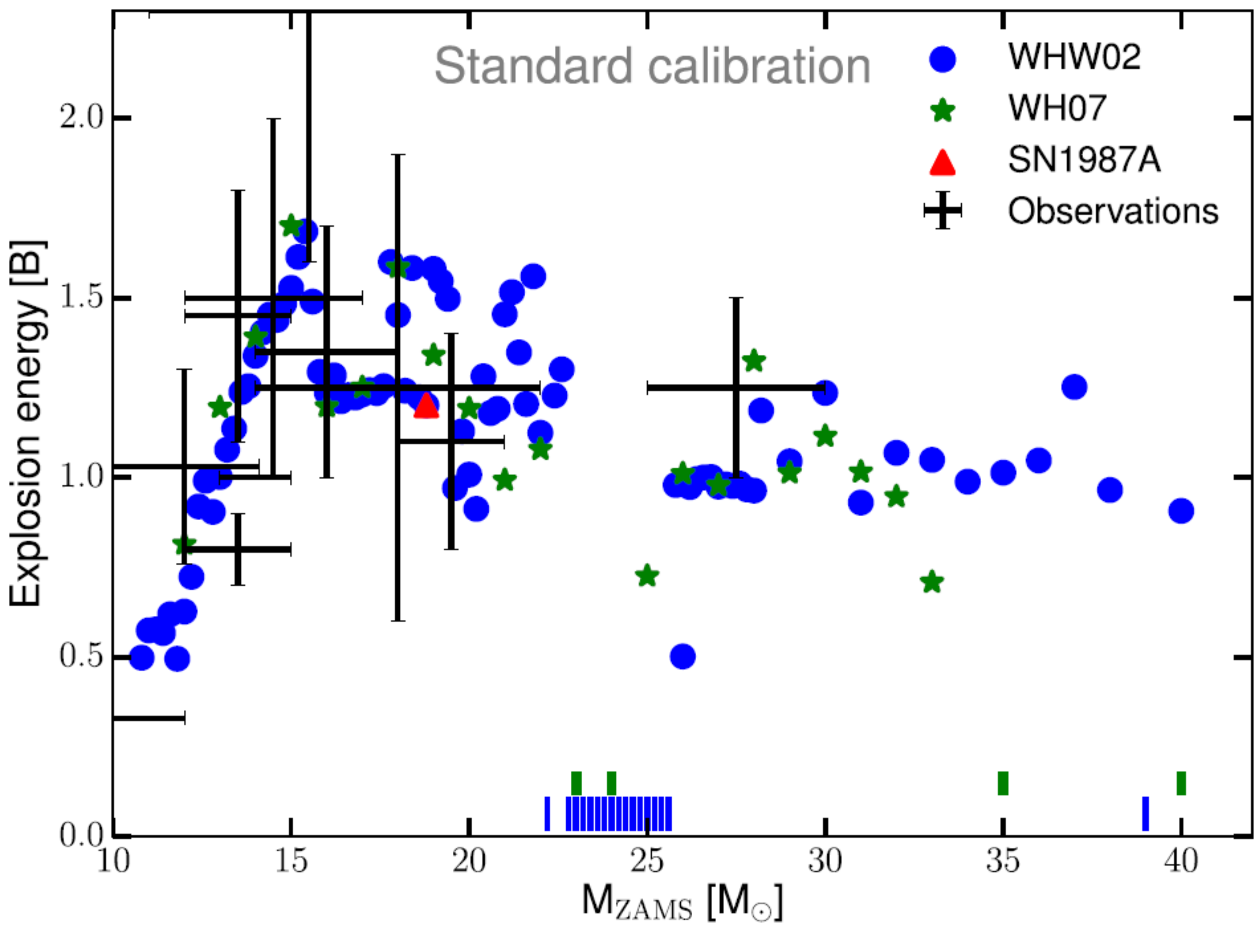




Name	$k_{\rm PUSH}$ (-)	$t_{\rm rise}$ (ms)	$E_{\rm expl}$ (10^{51}erg)	$m(^{56}{\rm Ni})$ ($M_\odot$)	$m(^{57}{\rm Ni})$ ($M_\odot$)	$m(^{58}{\rm Ni})$ ($M_\odot$)	$m(^{44}{\rm Ti})$ ($M_\odot$)
SN 1987A	—	—	1.1	0.071	0.0041	0.006	1.5×10^{-4}
	—	—	±0.3	±0.003	±0.0018		$\pm 0.3 \times 10^{-4}$
b15-7	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}

Ebinger+19 and CF+19

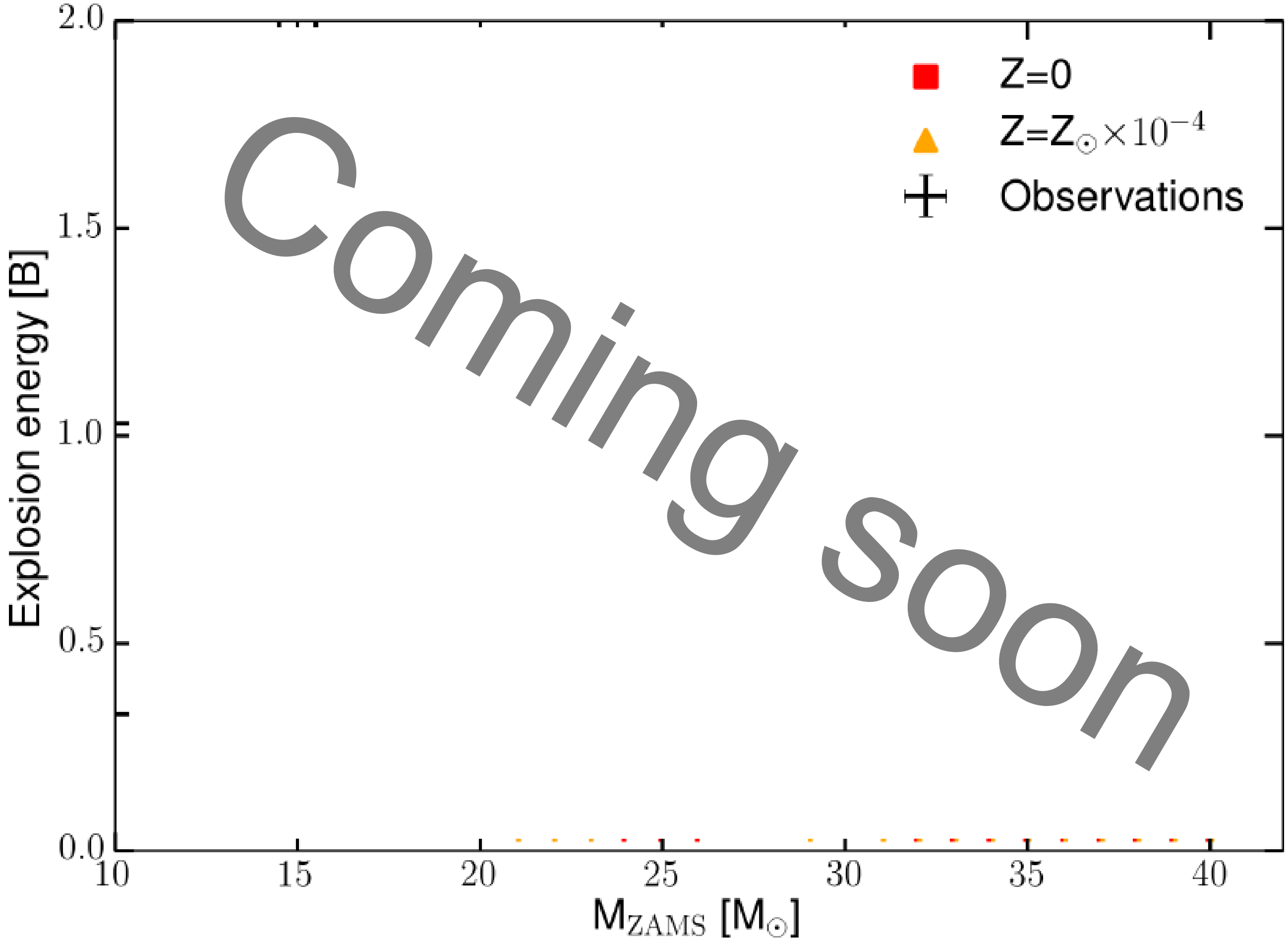
Explosions with PUSH



- Kepler models at Z_{sun} (2002)
  - Small network with mostly alpha-nuclei
- Kepler models at Z_{sun} (2007)
  - Large network

Ebinger+19

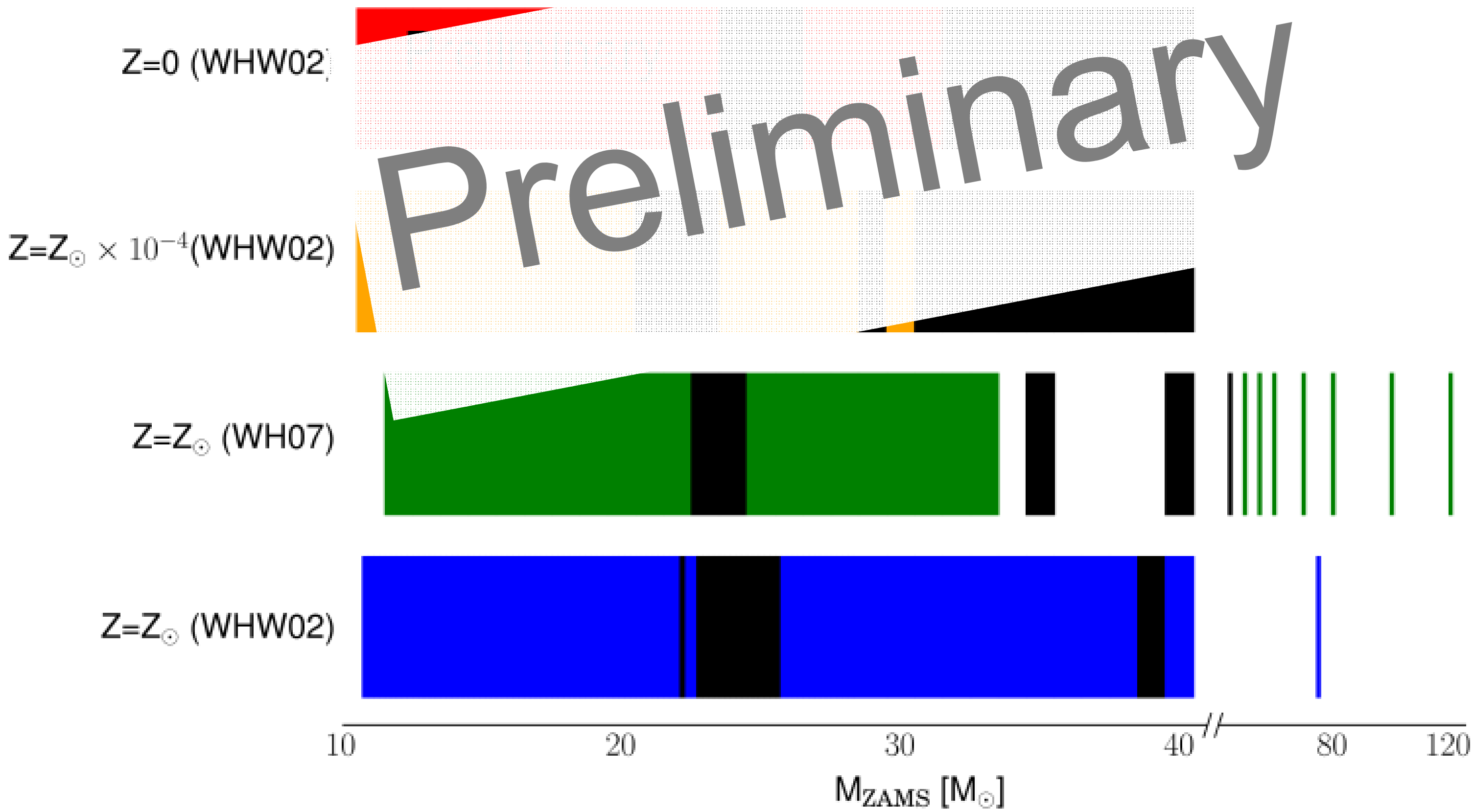
Explosions with PUSH



- Kepler models at 10^{-4} Z_{sun} (2002)
  - Small network with mostly alpha-nuclei
- Kepler models at Z=0 (2002)
  - Small network with mostly alpha-nuclei

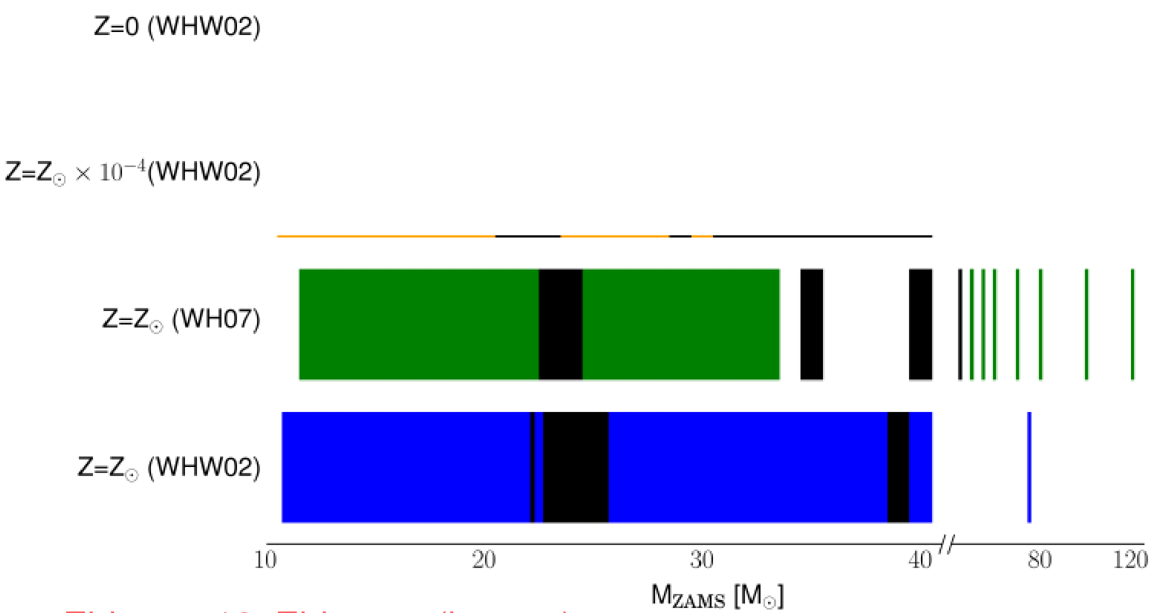
Ebinger+ (in prep)

Explosions with PUSH

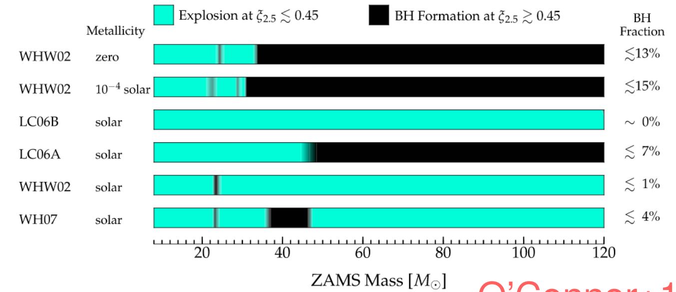


- Lower explosion energies at lower metallicity
- More models forming black holes at lower metallicity

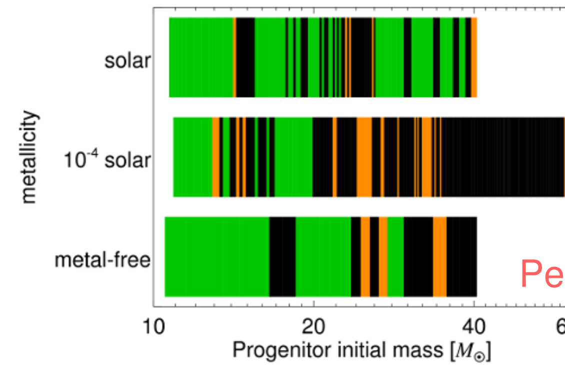
Ebinger+ (in prep)



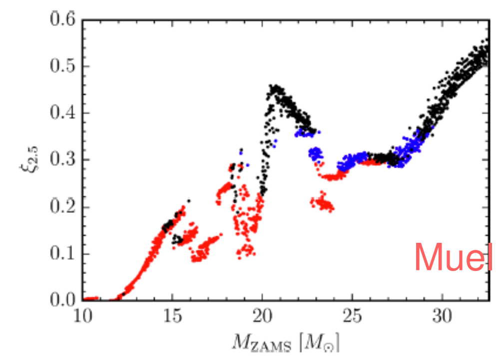
Ebinger+19; Ebinger+ (in prep)



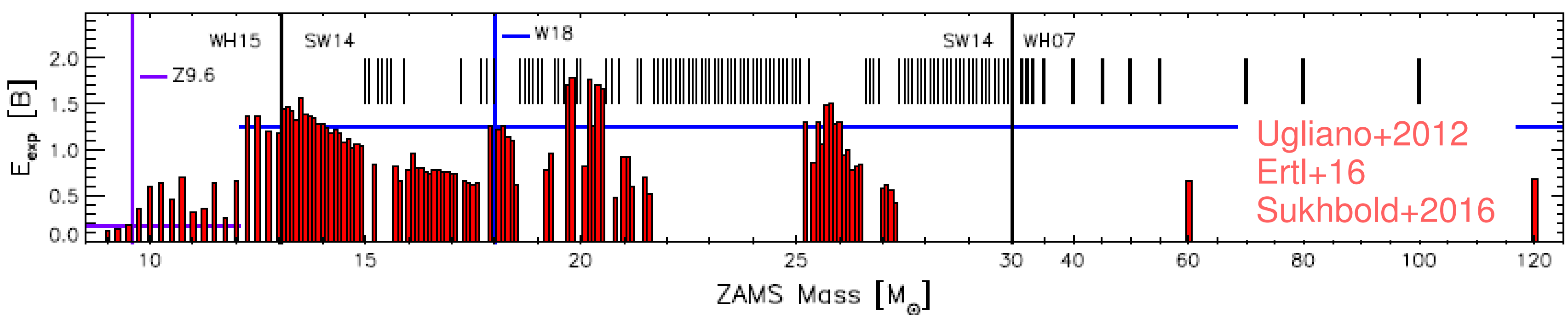
O'Connor+13



Pechja+15

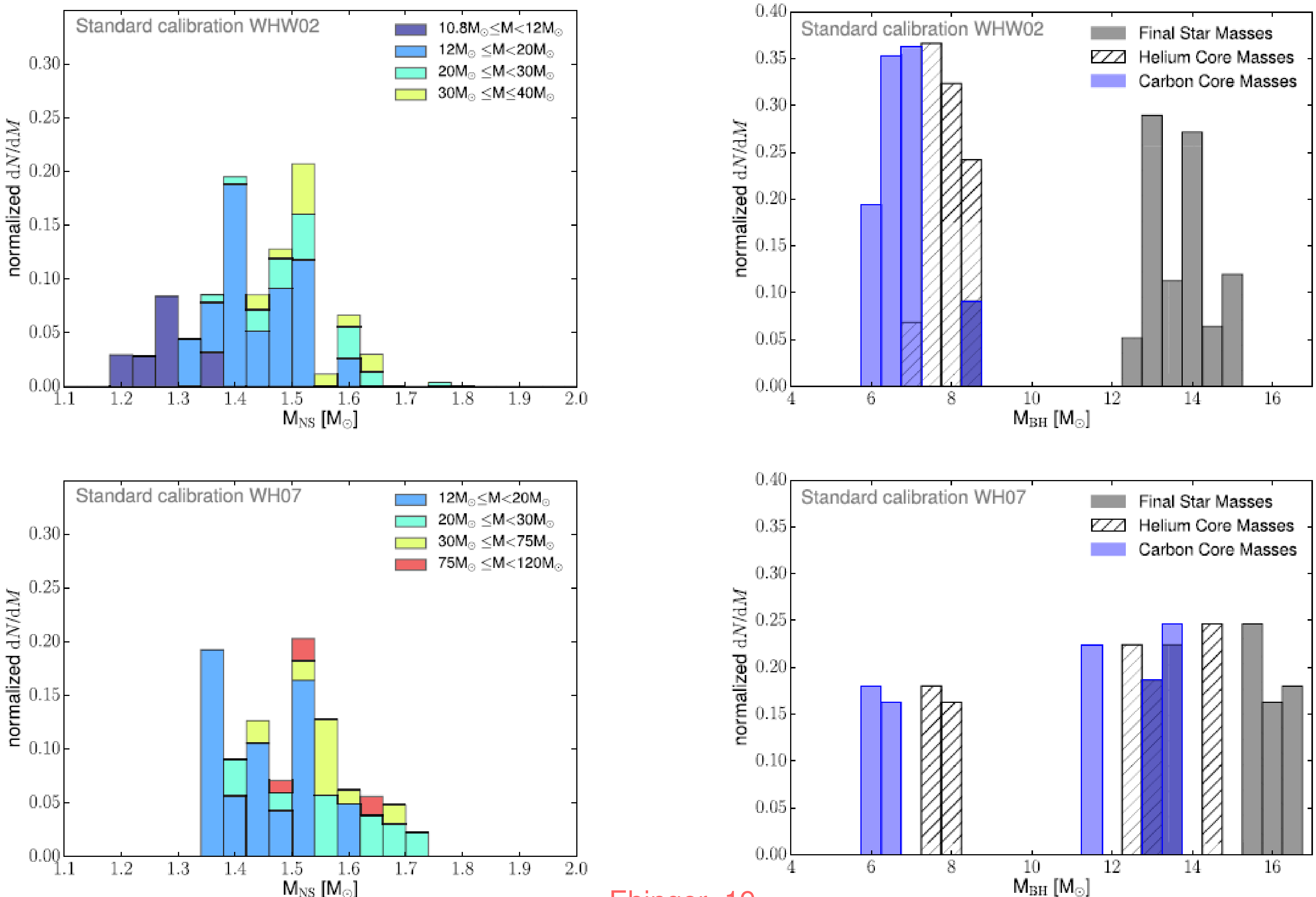


Mueller+16



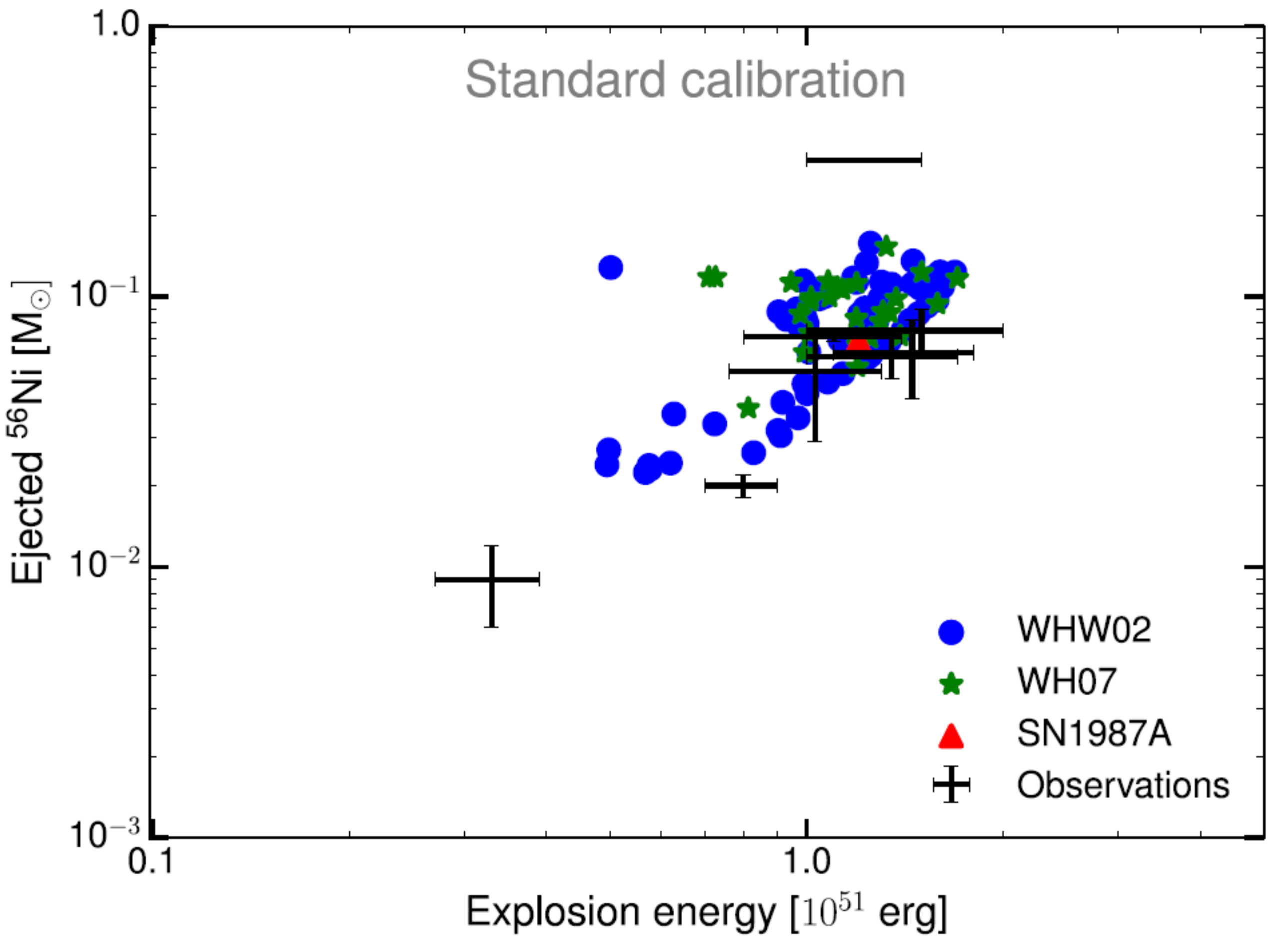
Ugliano+2012
Ertl+16
Sukhbold+2016

NS and BH mass distribution



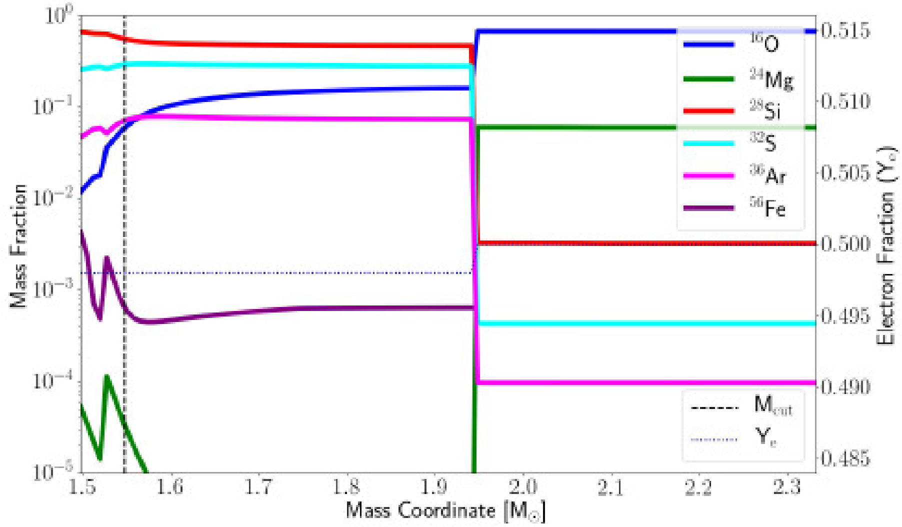
Ebinger+19

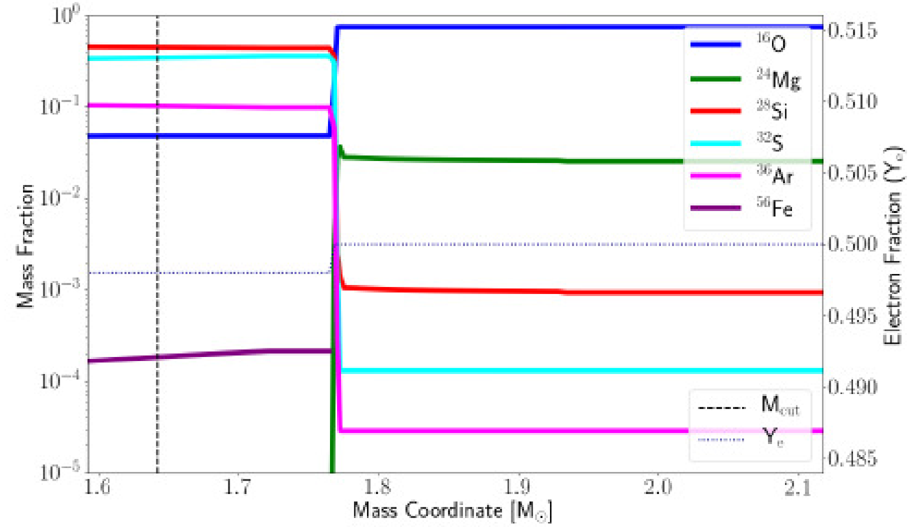
Explosions with PUSH

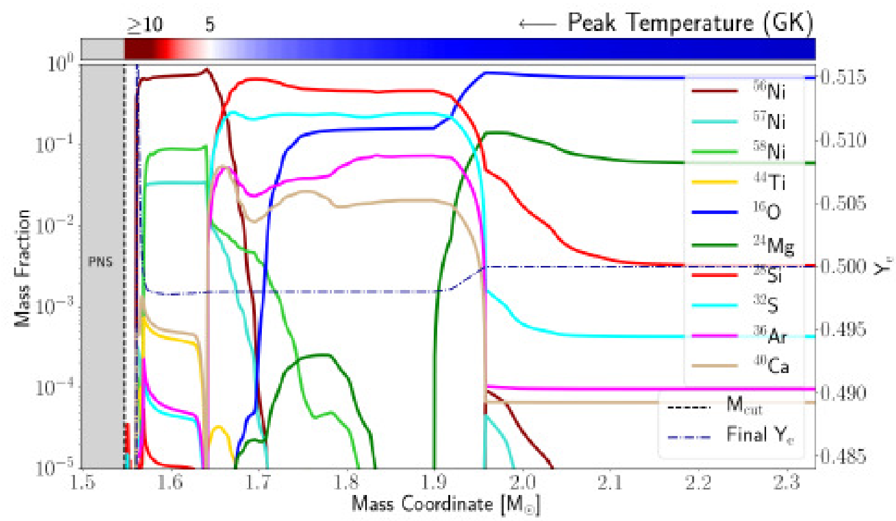


- Kepler models at Z_{sun} (2002)
  - Small network with mostly alpha-nuclei
- Kepler models at Z_{sun} (2007)
  - Large network

Explosive nucleosynthesis







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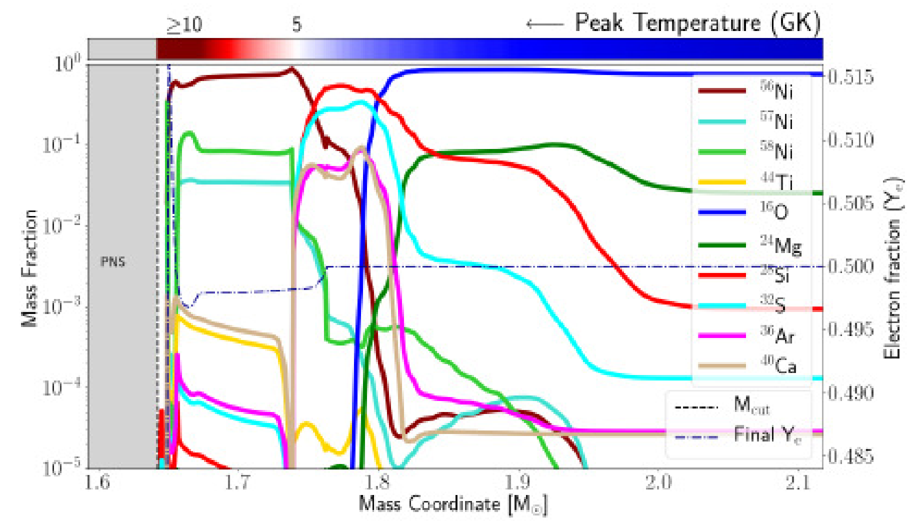
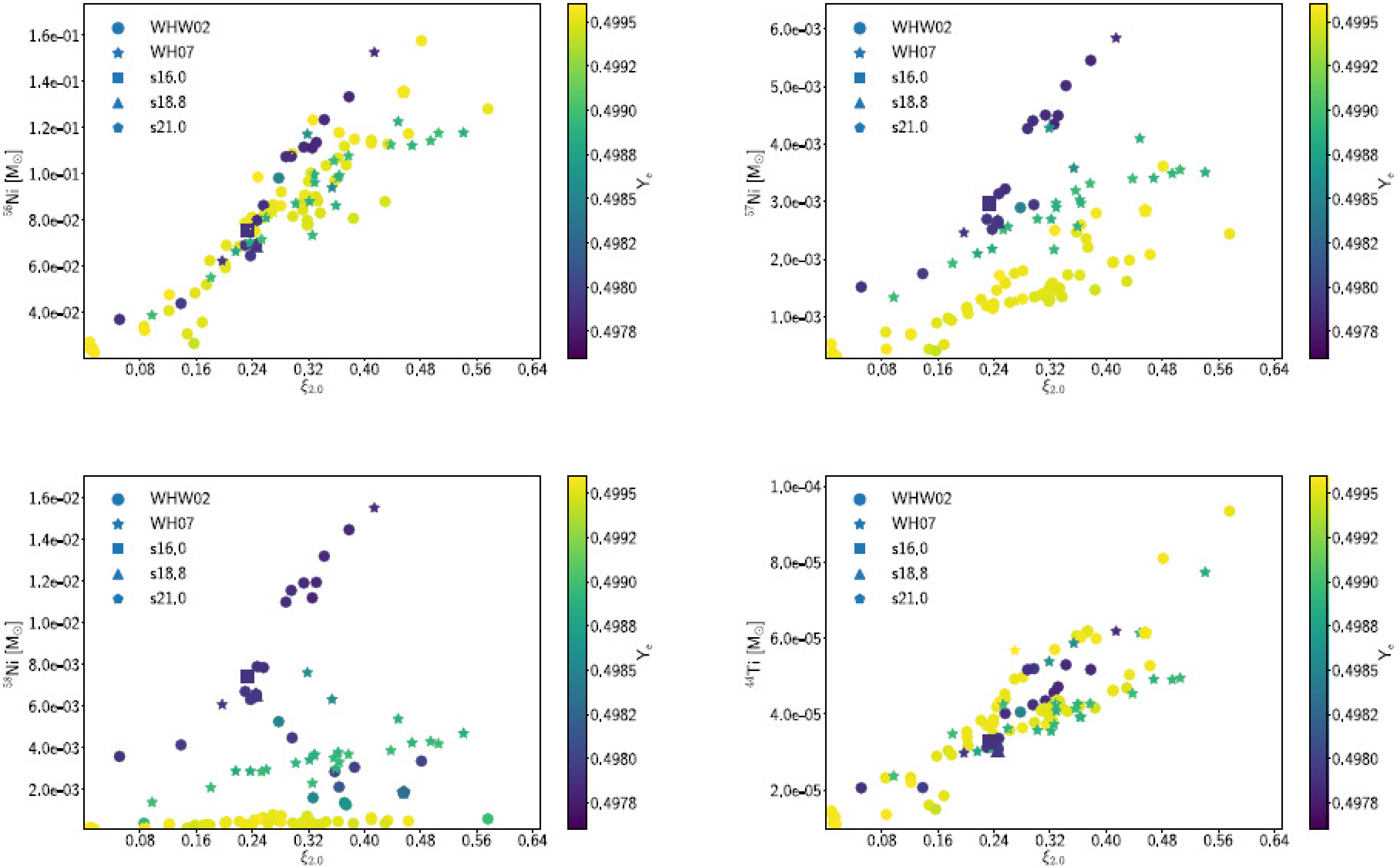


b15-7 (BSG)

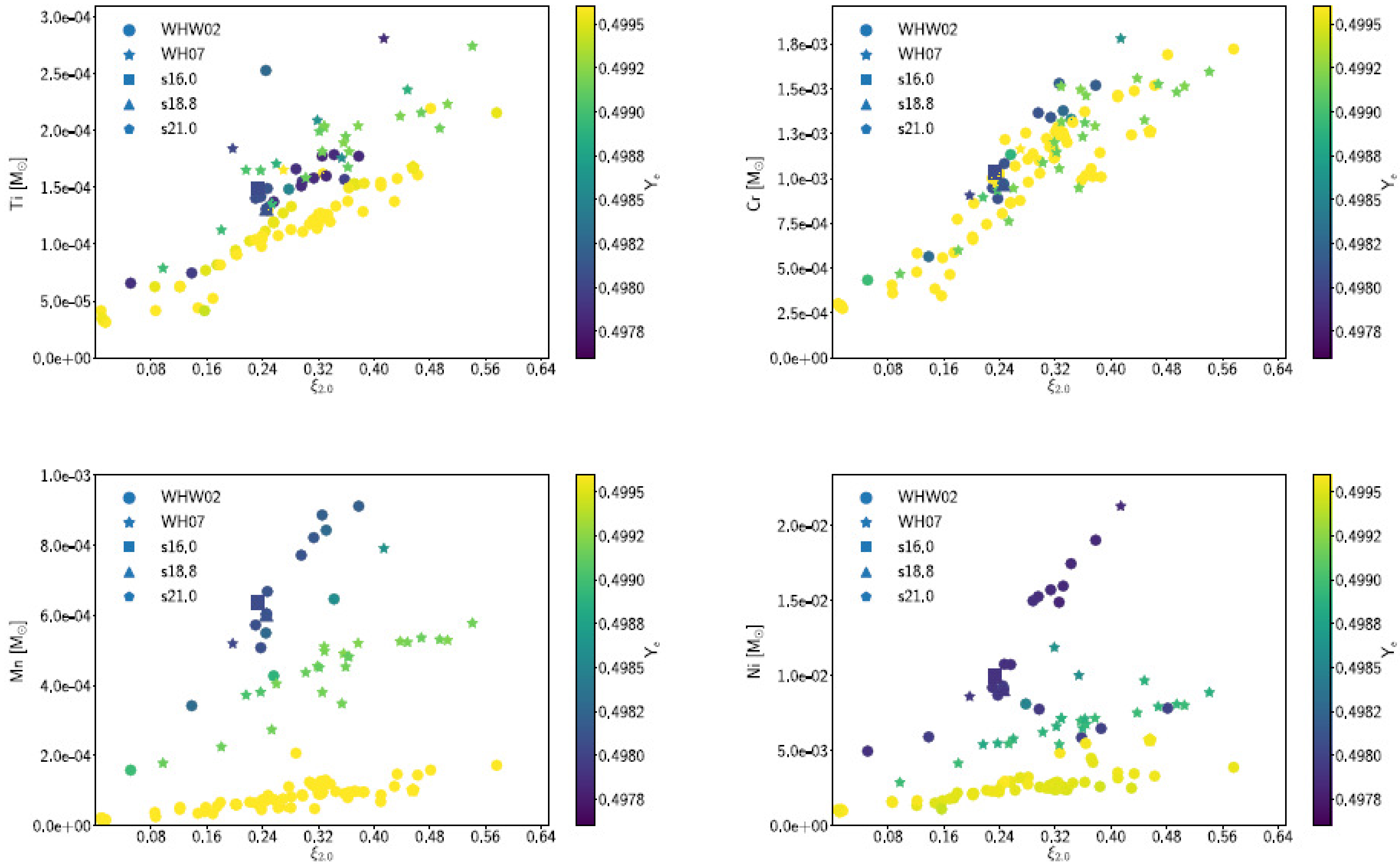
CF+19

Isotopic yields: ^{56,57,58}Ni and ^{44}Ti



Curtis+19

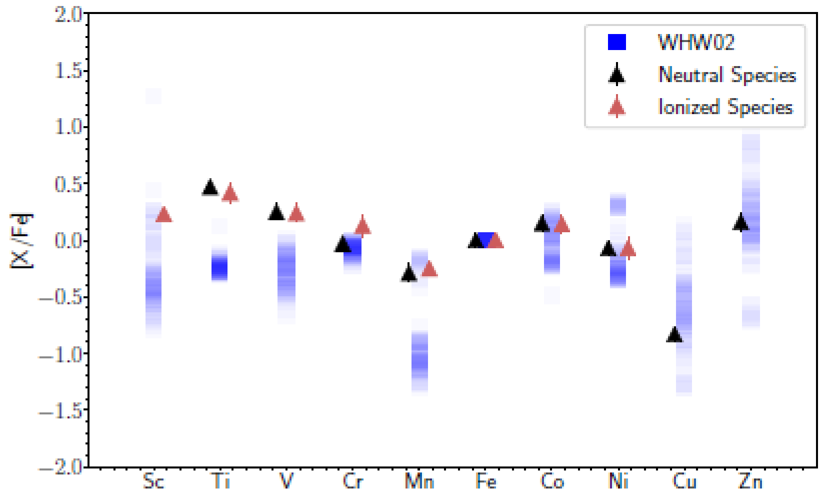
Elemental yields: Ti, Cr, Mn, Ni



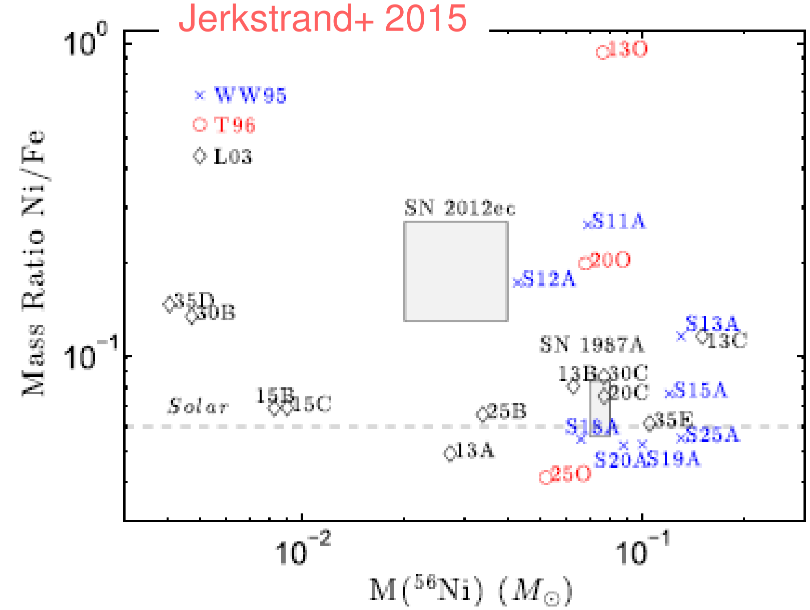
Curtis+19

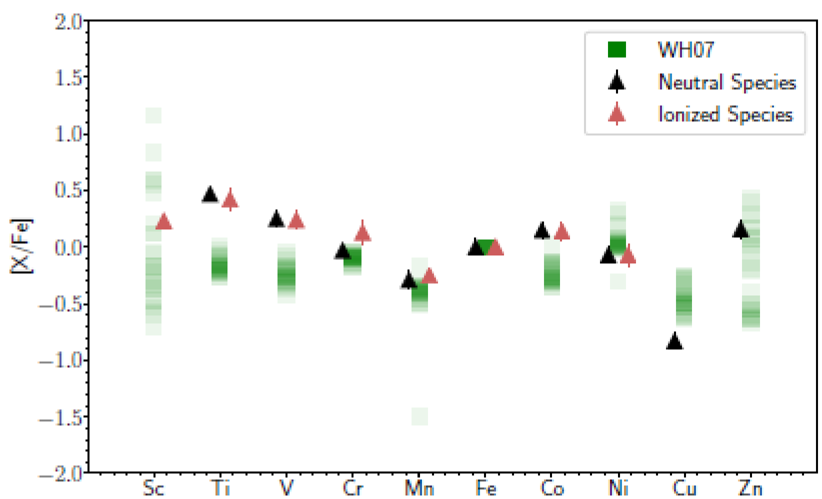
Comparison to observations

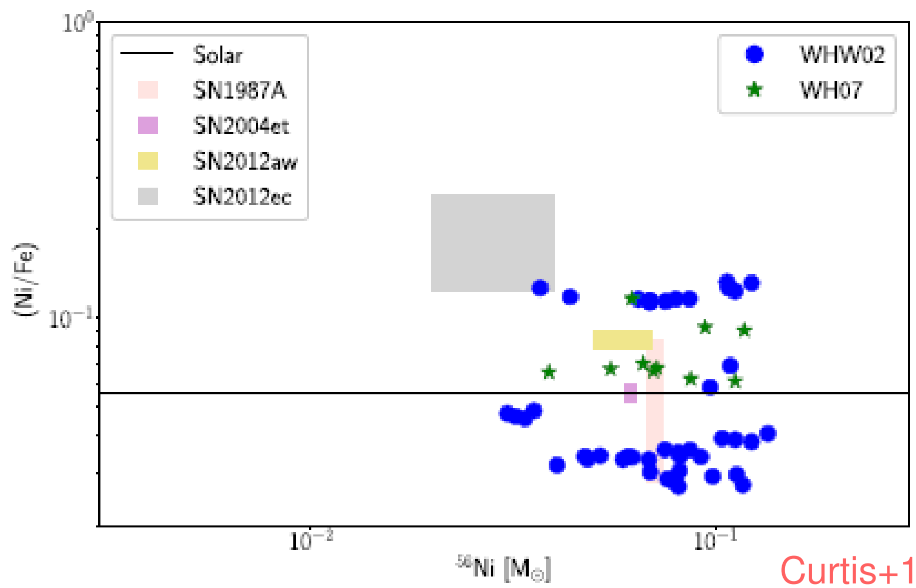
Observational data for HD84937: Sneden+16



Jerkstrand+ 2015







Curtis+19

Curtis+19

Comparison to observations

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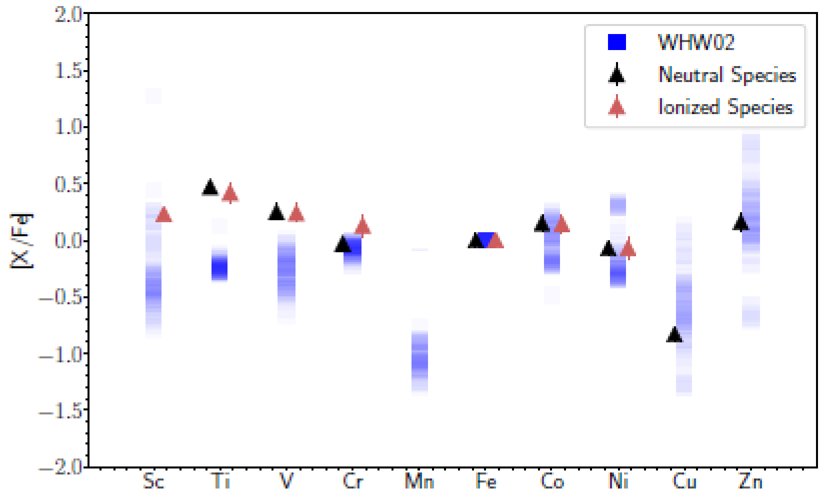
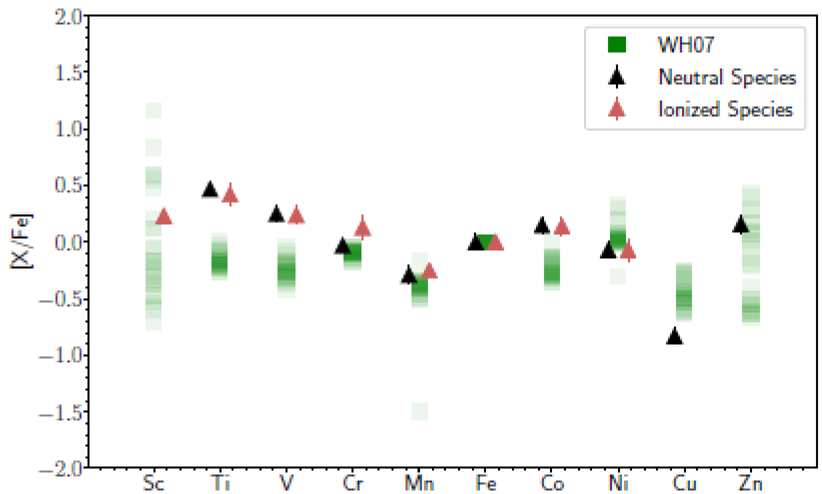
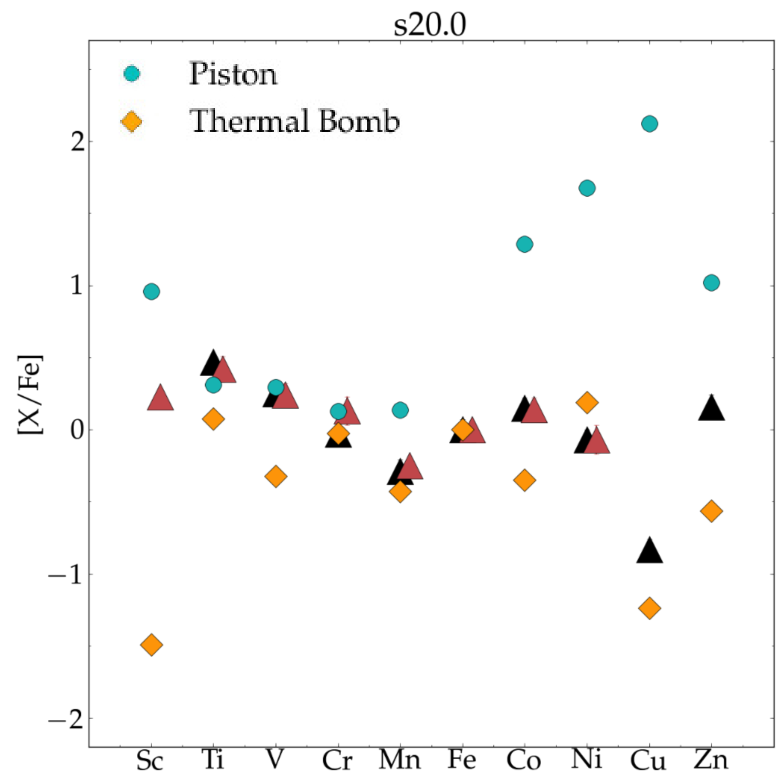




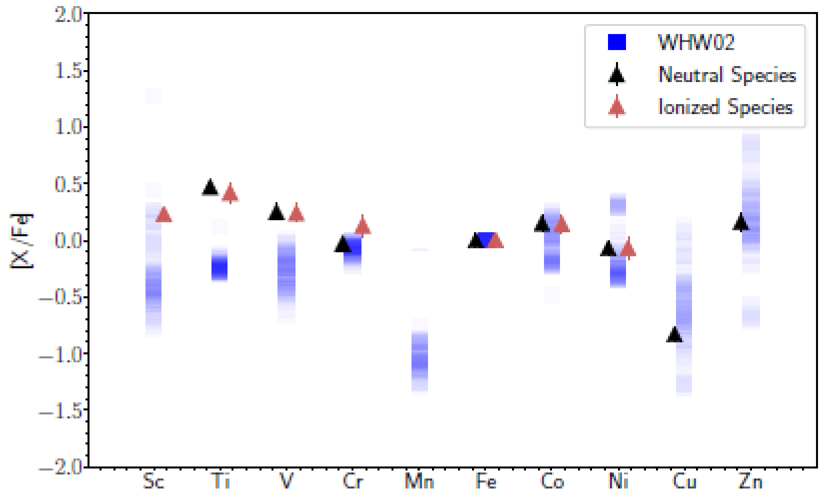
Curtis+19

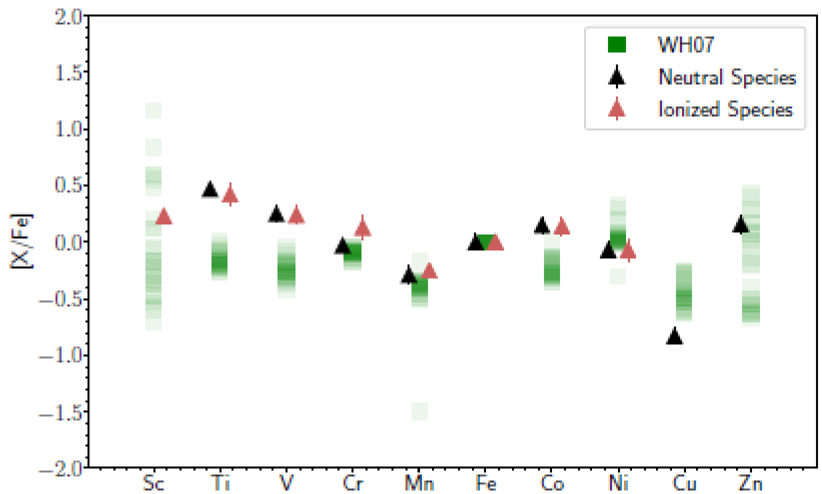
Comparison to previous work:



Comparison to observations

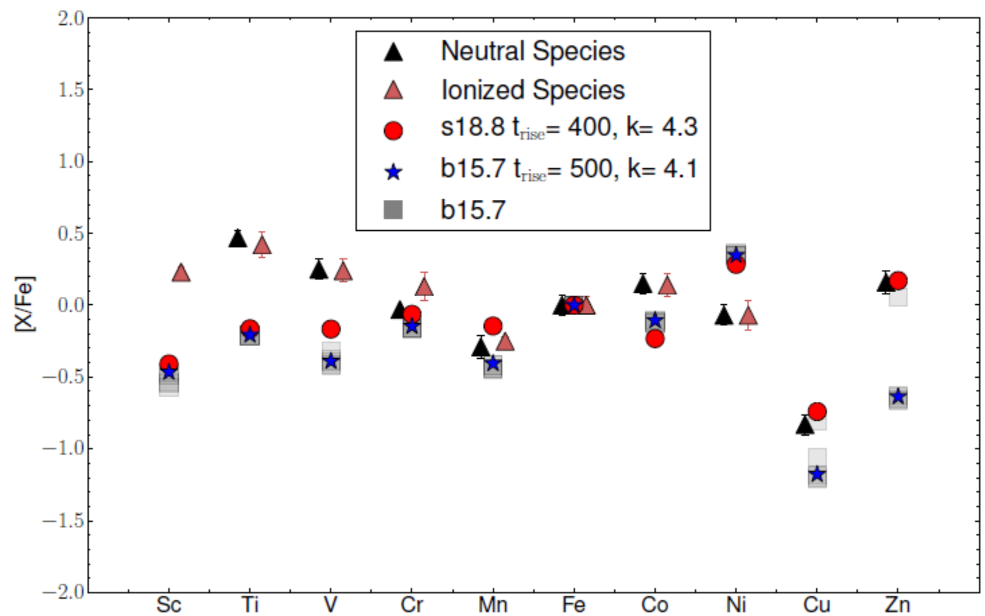
Observational data for HD84937: Sneden+16





Curtis+19

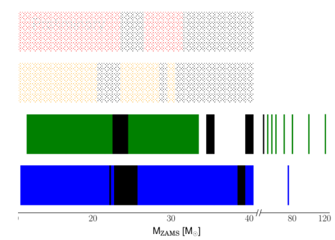
Comparison of RSB and BSG calibration:



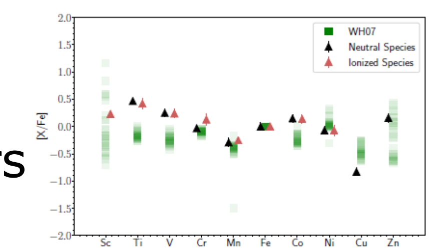
CF+19

Summary (CCSNe)

- Have a tool that allows to study many CCSN models
  - Help bridging the gap from 1s to 10s
  - Explosion properties (dependent on calibration)
  - Prediction of compact remnant masses (NS and BH)
  - Nucleosynthesis yields
- Explosion properties:
  - Metallicity dependent outcomes



- Nucleosynthesis:
  - Electron fraction matters
    especially for non-symmetric Fe-group nuclei
  - Sc and Zn show large scatter
  - Fe-group yields are in agreement with EMP stars
  - The details of the progenitor matter



- Nucleosynthesis is also a messenger