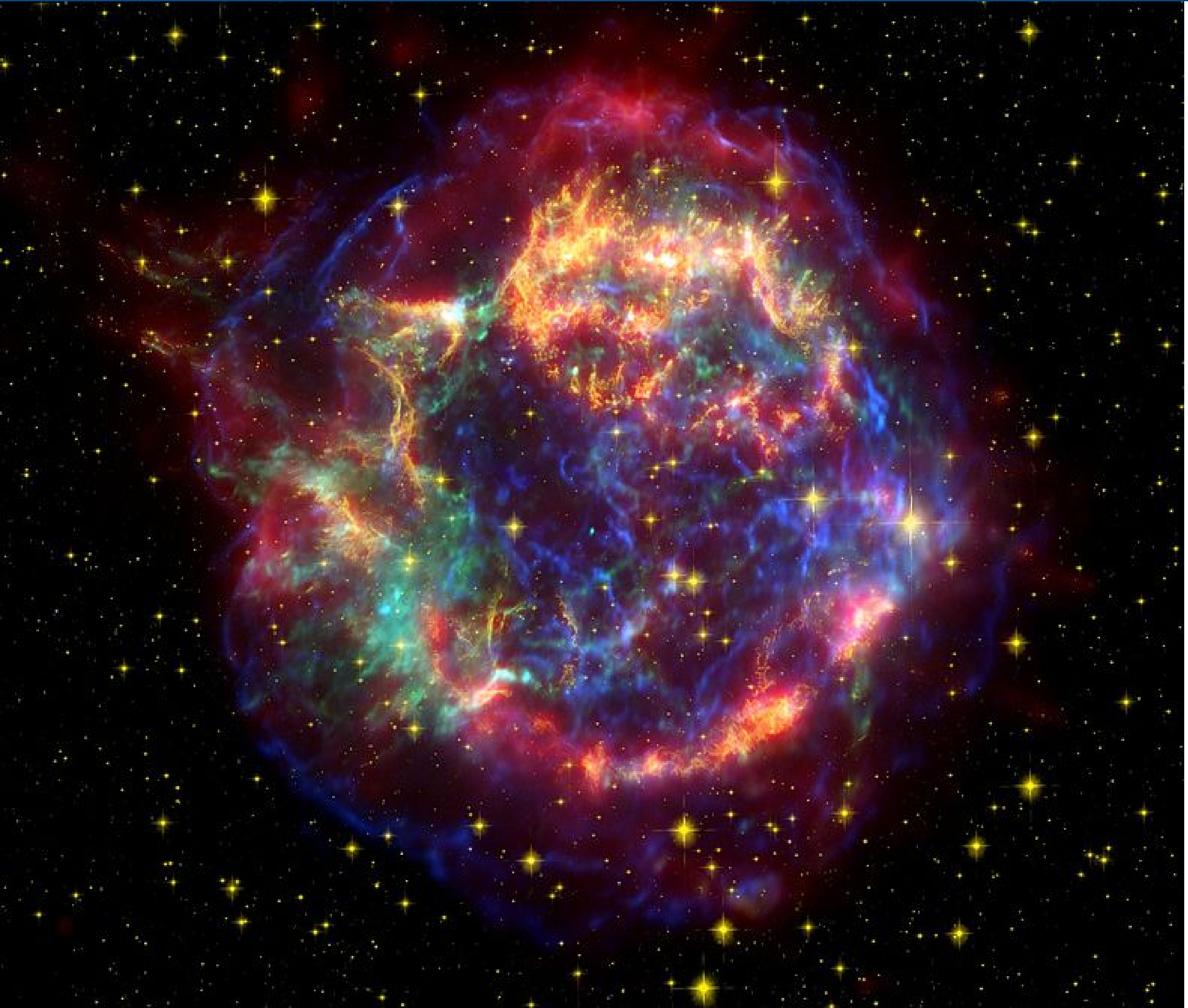
PUSHing Core-Collapse Supernovae to Explosions in Spherical Symmetry



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13.01.2020

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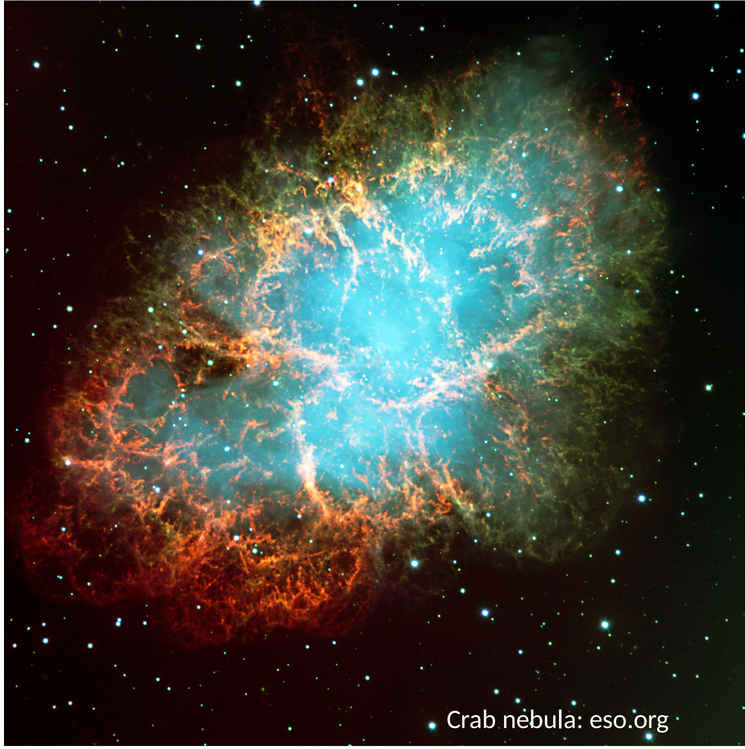
Core-Collapse Supernovae

Massive stars with masses $\mathrm{M} \gtrsim 8-10\mathrm{M}_\odot$:

- CCSNe, among the strongest explosions in the universe
- Source of heavy elements
- Driving force of cosmic cycle of matter



Crab nebula: eso.org

At the end of a massive star‘s life:

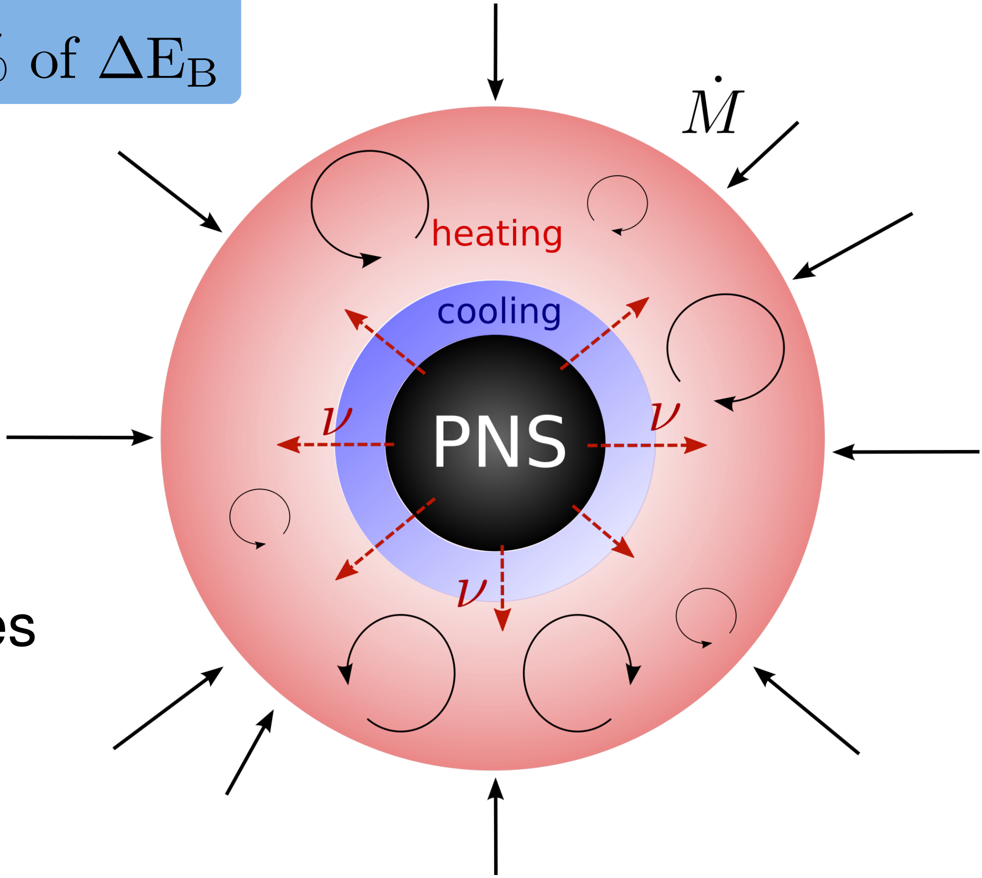
- Onion-shell structure
- Iron core approaches $\mathrm{M}_{\mathrm{CH}}(\mathrm{Y}_\mathrm{e}, \mathrm{s}_\mathrm{e})$
- Collapse → CCSNe

CCSNe: ν-driven Mechanism

Collapse releases gravitational binding energy:

$$\Delta \mathrm{E_B} \sim \frac{GM_{\mathrm{core}}^2}{R} = 3 \times 10^{53} \left(\frac{M_{\mathrm{core}}}{M_\odot}\right)^2 \left(\frac{R}{10\mathrm{km}}\right)^{-1} \mathrm{erg}$$

Explosion energy: $\sim 1\mathrm{B} = 10^{51}$ erg 1% of $\Delta \mathrm{E_B}$



- Core bounce → Prompt shock
- Prompt shock stagnation
- ν-driven mechanism:

  convection and multi-D instabilities

  (e.g. Bethe&Wilson85, Janka12)

Core-Collapse Supernovae

Questions:

- Progenitor-remnant connection, explosion properties?
- Conditions for explosive nucleosynthesis?
- Explosion properties, remnant properties and yields as a function of M_{ZAMS} and Z?

Required:

- Progenitor models (mainly 1D)
- Properties of shock wave (e.g. E_{expl})
- Matter properties of innermost ejecta (Y_e)
- Explosion mechanism (energy injection), mass cut
- SN EOS

CCSN Modeling

Ideal case:

- Self-consistent, detailed, long term, converging 3D models that match observables, for many progenitors

But:

- Multi-D and detailed physics require large resources

Realistic strategy: efficient parametrized exploding models

- Models where a part of the problem is simplified
- Computationally efficient and physically reliable models

CCSN Modeling in 1D

Efficiently study broad range of CCSN progenitors in 1D:

- Induced explosion with different methods

Traditional Methods

(Piston/thermal bomb)

(Woosley&Weaver95, Chieffi & Limongi13, Thielemann+96, Umeda & Nomoto08)

Limitations:

- Physics of collapse, bounce, and onset of explosion
- Neutrinos, PNS
- Remnant mass / mass cut
- Explosion energy and nickel

Using Neutrinos:

- Light bulb models (L_ν) (e.g. Yamamoto+13)
- Enhanced ν reaction rates (e.g. Fröhlich+06, Fischer+10)
- Parametrized L_ν, excised core region

(Ugliano+12, Ertl+16, Sukhbold+16)

CCSN Modeling in 1D: PUSH

Efficiently study broad range of CCSN progenitors in 1D:

- Induced explosion with different methods

PUSH method introduced in ApJ 806, 275 (2015)

Perego, Hempel, Fröhlich, Ebinger, Eichler, Casanova, Liebendörfer, Thielemann

Updated PUSH method, solar metallicity progenitor stars, explosion & remnant properties and nucleosynthesis yields in ApJ 870, 1 & 2 (2019)

Ebinger, Curtis, Fröhlich+ and Curtis, Ebinger, Fröhlich+

Extending study to low and zero metallicity progenitor stars in ApJ (accepted)

Ebinger, Curtis, Ghosh, Fröhlich, Hempel, Perego, Liebendörfer, Thielemann

CCSN Modeling in 1D: PUSH

Efficiently study broad range of CCSN progenitors in 1D:

- Induced explosion with different methods

Aim:

- Parametrization of ν-driven mechanism: ν's determine explosion properties ($\mathrm{E}_{\mathrm{expl}}$, $\mathrm{M}_{\mathrm{rem}}$, nucleosynthesis yields)
- Preserve consistent Y_{e} evolution (no modification of $\nu_{\mathrm{e}}, \bar{\nu}_{\mathrm{e}}$ - transport)
- Nuclear EOS and proto-neutron star evolution included

CCSN Modeling in 1D: PUSH

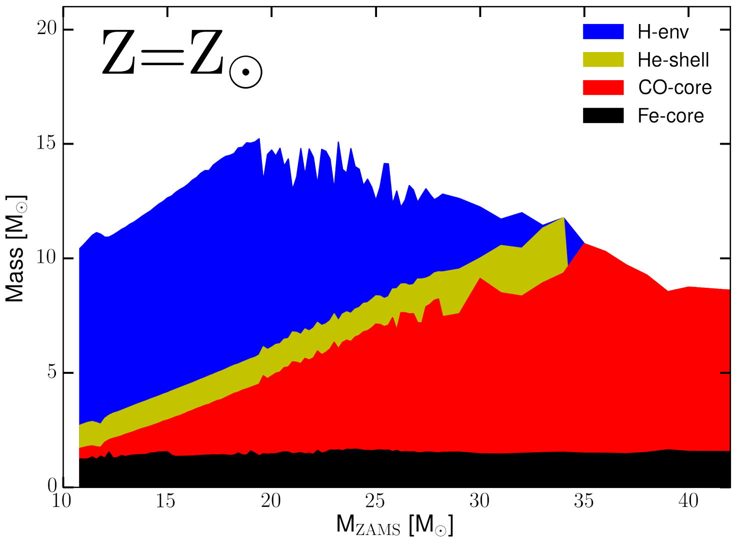
Basic idea: Mimic in 1D simulations the increased heating efficiency of ν_e , $\bar{\nu}_e$ (due to convection and accretion) present in multi-D simulations by parametrizing the heating of $\nu_{\mu,\tau}$, $\bar{\nu}_{\mu,\tau}$

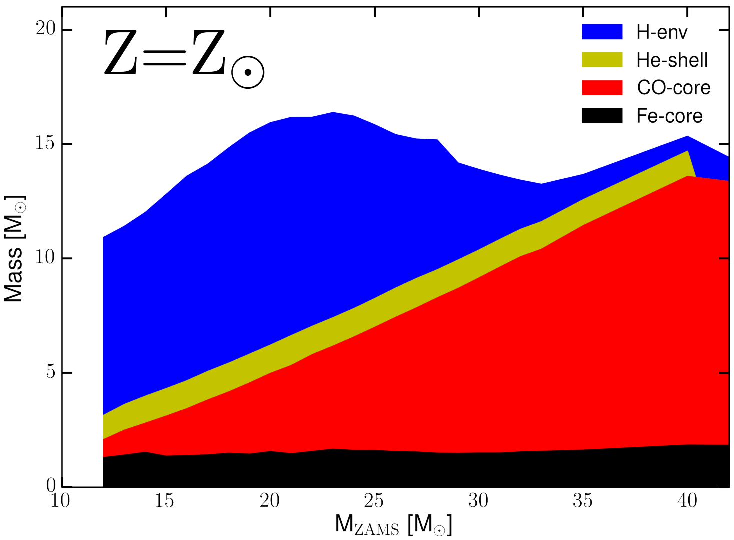
- General relativistic hydrodynamics (AGILE (Liebendörfer+02))
- EOS: nuclear EOS HS(DD2) (Hempel&Schaffner-Bielich+02,Typel+10)
- Neutrino transport: IDSA and advanced spectral leakage

  (Liebendörfer+09, Perego+16)
- Nucleosynthesis yields (Tracer, nuclear network)

  (for details see Curtis+19,KE+19)
- Progenitor models: 1D (Woosley+02, Woosley&Heger07)

CCSN Modeling in 1D: PUSH

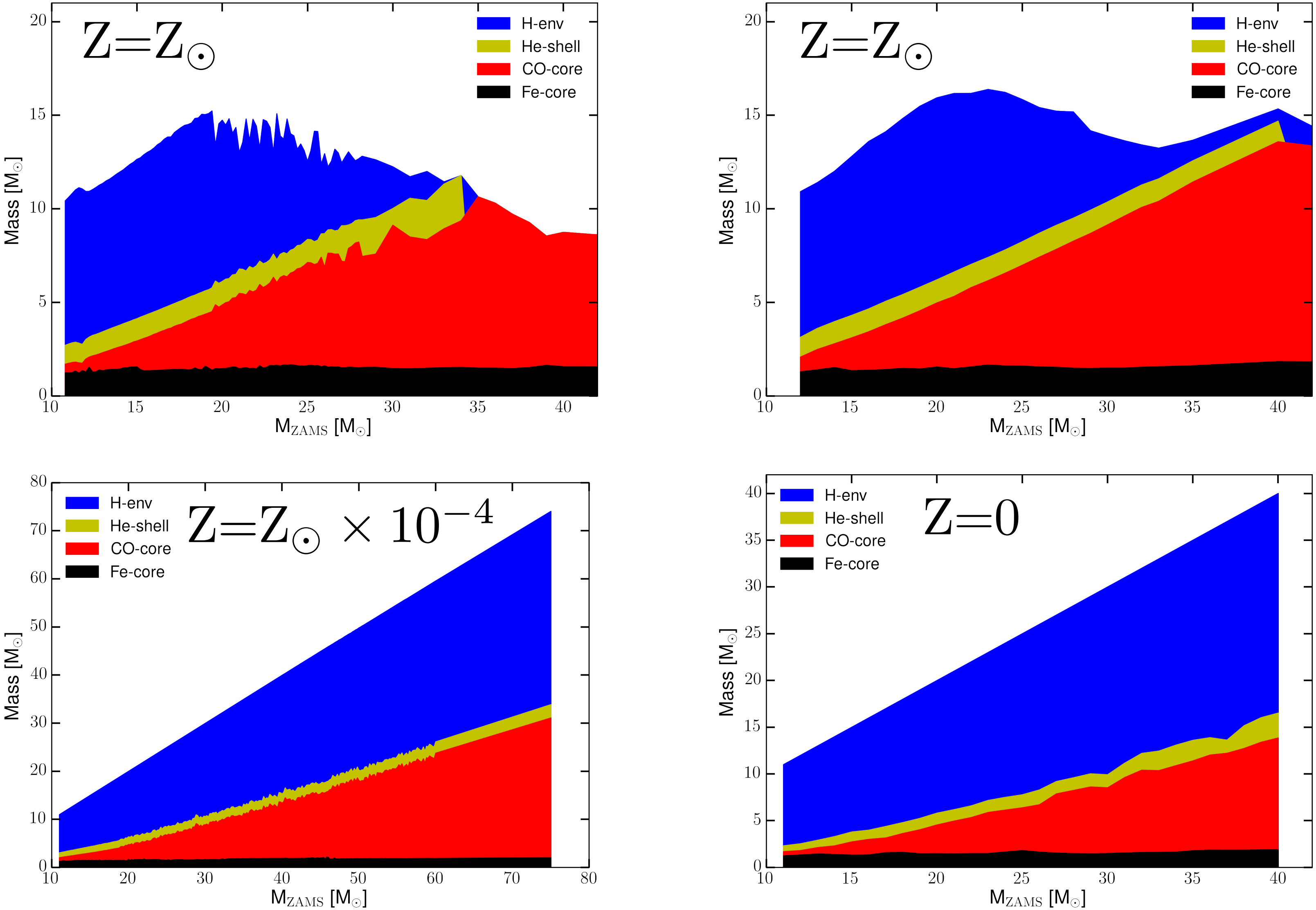




- Uncertainties introduced by differences in the pre-explosion stellar evolution (e.g. WHW02, WH07)

PhD Ebinger 2017

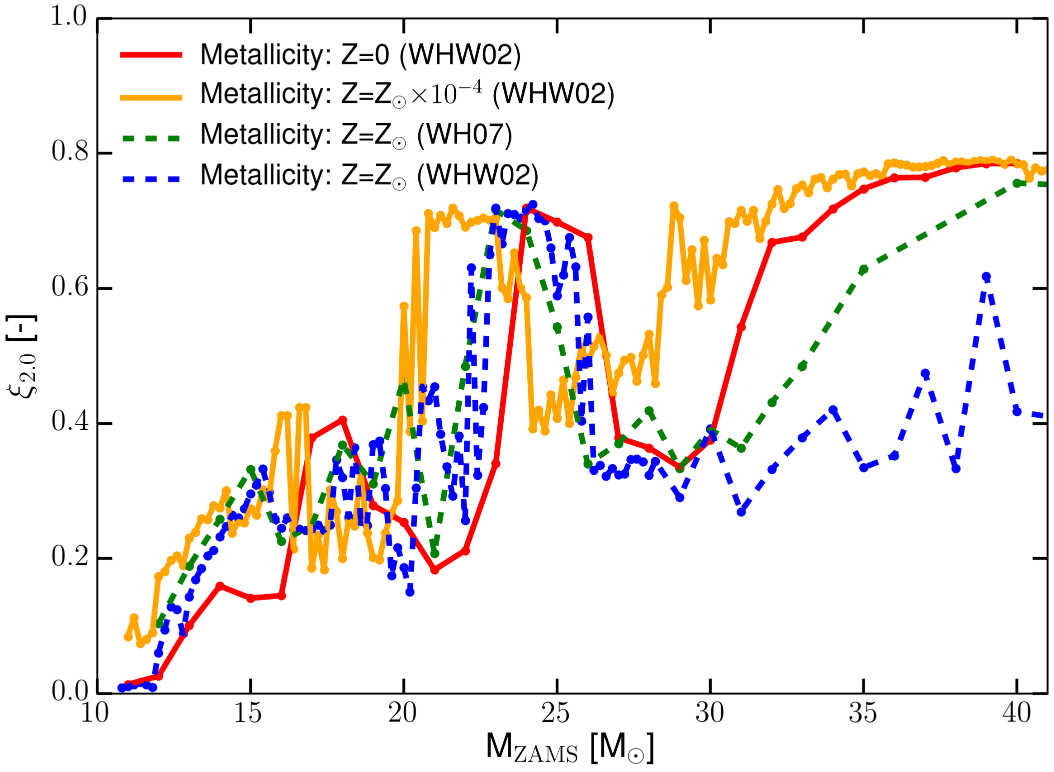
CCSN Modeling in 1D: PUSH



PhD Ebinger 2017

CCSN Modeling in 1D: PUSH

A crucial property of CCSN progenitors is their **compactness**



- Introduced by O'Connor&Ott11

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

- Calibration of PUSH heating with dependence in compactness to fulfill constraints

Calibration of PUSH

- **Reproducing SN 1987A**
- Weaker SNe for lower ZAMS masses
- Possible BH formation

- SN1987A is used as constraint in the investigation of large progenitor samples

Quantity	SN 1987A (observed)	PUSH (s18.8)
E_{expl} $(10^{51}$ erg)	1.1 ± 0.3	1.2
M_{prog} $(\mathrm{M}_\odot)$	18-21	18.8
^{56}Ni $(\mathrm{M}_\odot)$	(0.071 ± 0.003)	0.069
^{57}Ni $(\mathrm{M}_\odot)$	(0.0041 ± 0.0018)	0.0027
^{58}Ni $(\mathrm{M}_\odot)$	0.006	0.0066
^{44}Ti $(\mathrm{M}_\odot)$	$(1.5 \pm 0.3) \times 10^{-4}$	3.05×10^{-5}

Produced well in multi-D modeling of ejected high entropy blobs, e.g. Wongwathanarat+ (2017)

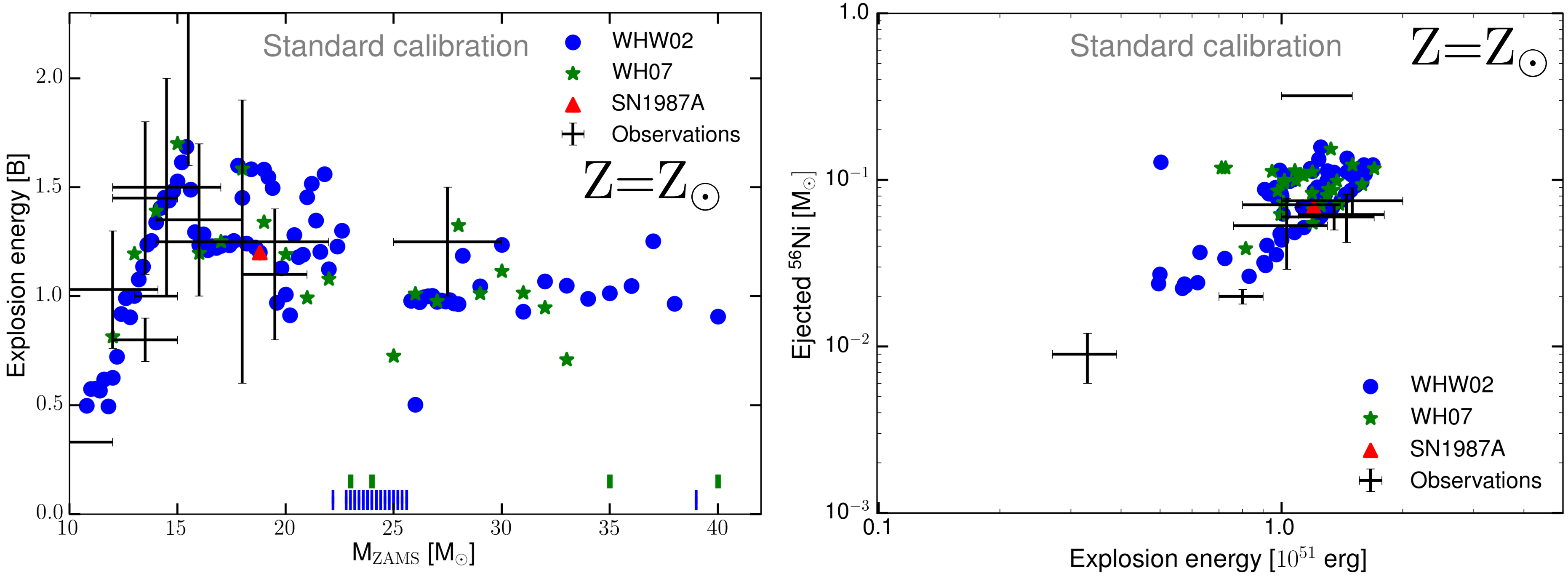
Seitenzahl+ 14, Fransson & Kozma 02, Blinnikov+ 00, Boggs+15, KE+19

Calibration of PUSH

- Reproducing SN 1987A
- **Weaker SNe for lower ZAMS masses**
- **Possible BH formation**

- For higher main-sequence masses:
  branching in Hypernovae and faint SNe
- HNe: very energetic explosions, driven by fast rotation and strong magnetic fields
- **ν-driven SNe** go into **faint branch** around ~25$\mathrm{M}_\odot$
  → Calibration of PUSH to observational properties of CCSNe for lower mass progenitors and faint branch for higher masses

SN Landscape: Explodability and Properties

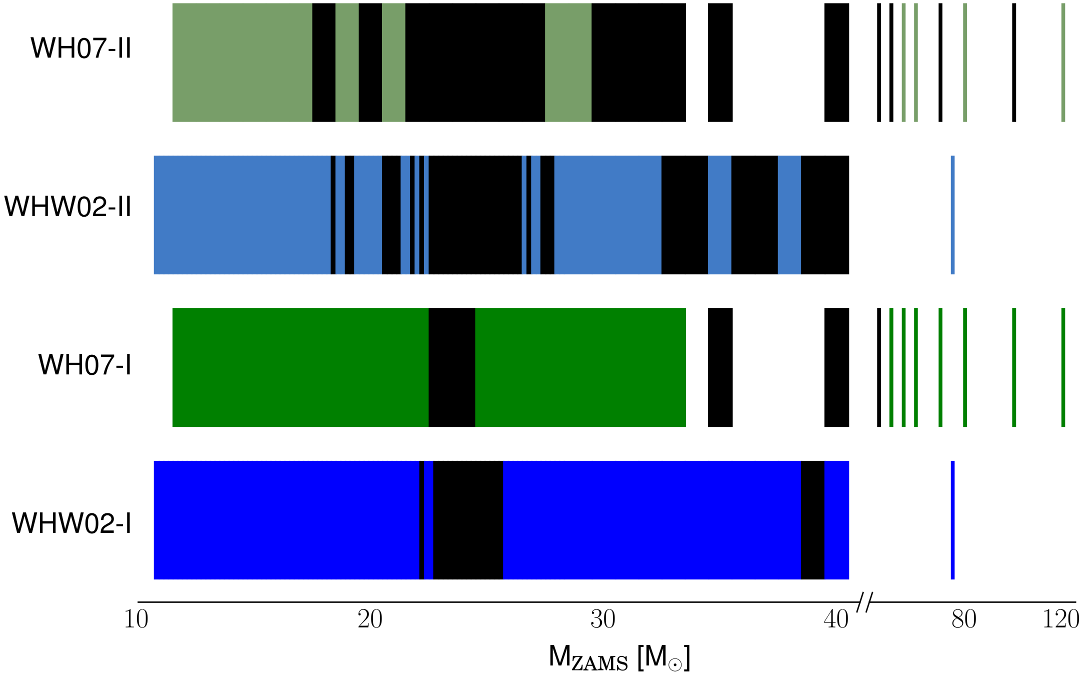


- Good agreement with the observational properties

- Compilation of observational data
  mostly based on Nomoto+13, Bruenn+16 and references therein

Ebinger+19

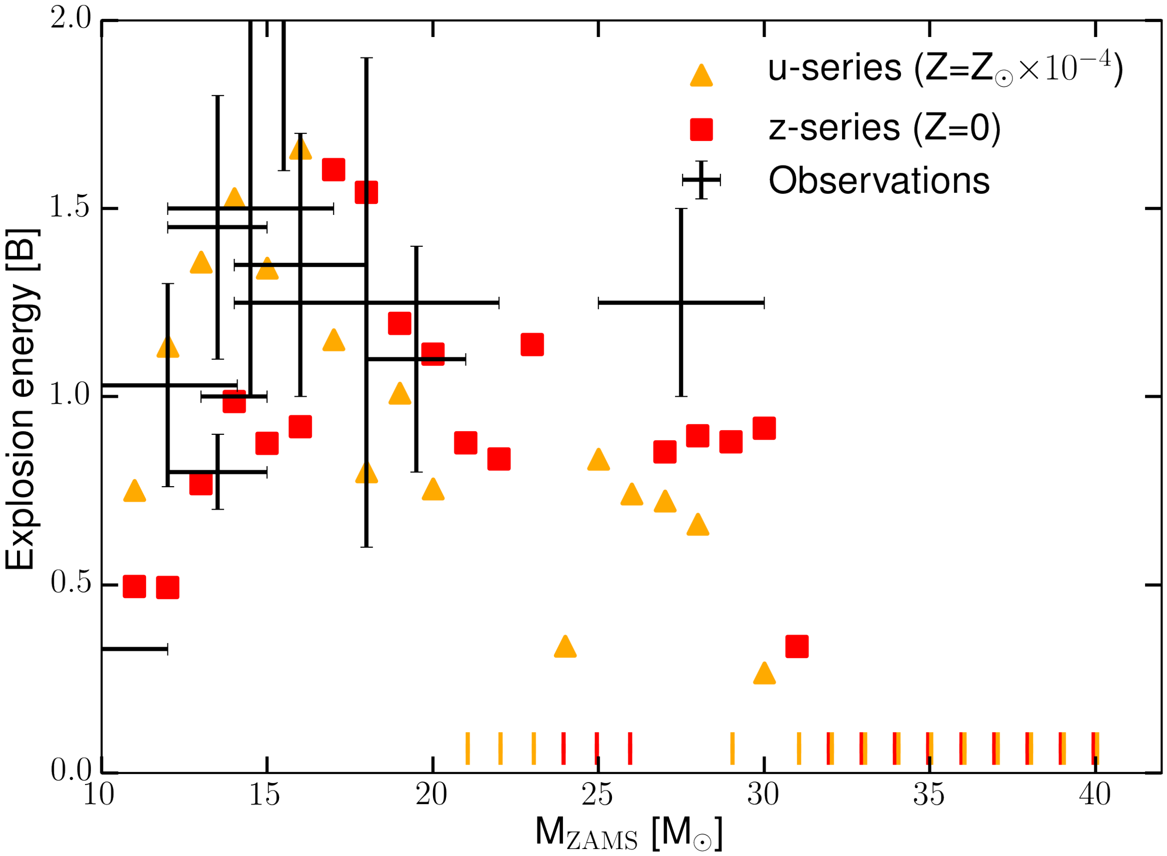
SN Landscape: Explodability and Properties



- Explodability, BH formation (for WHW02 (green) and WH07 (blue))
- Alternative calibration (remnant birth mass distribution)

Ebinger+19

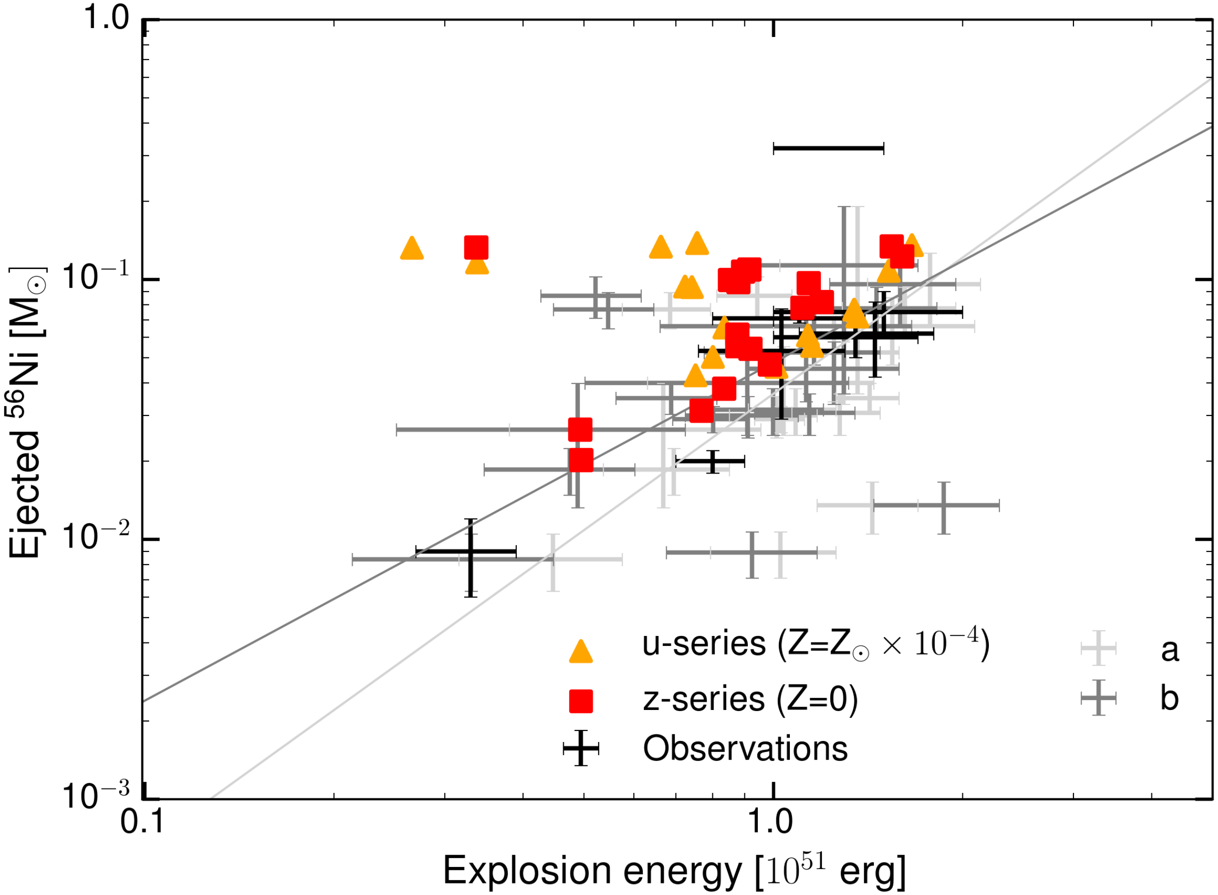
Low Metallicity Stars



- CCSN explosion energies for low metallicity stars (WHW02)
- Lower explosion energies and more BH forming models

Ebinger+ApJ (accepted)

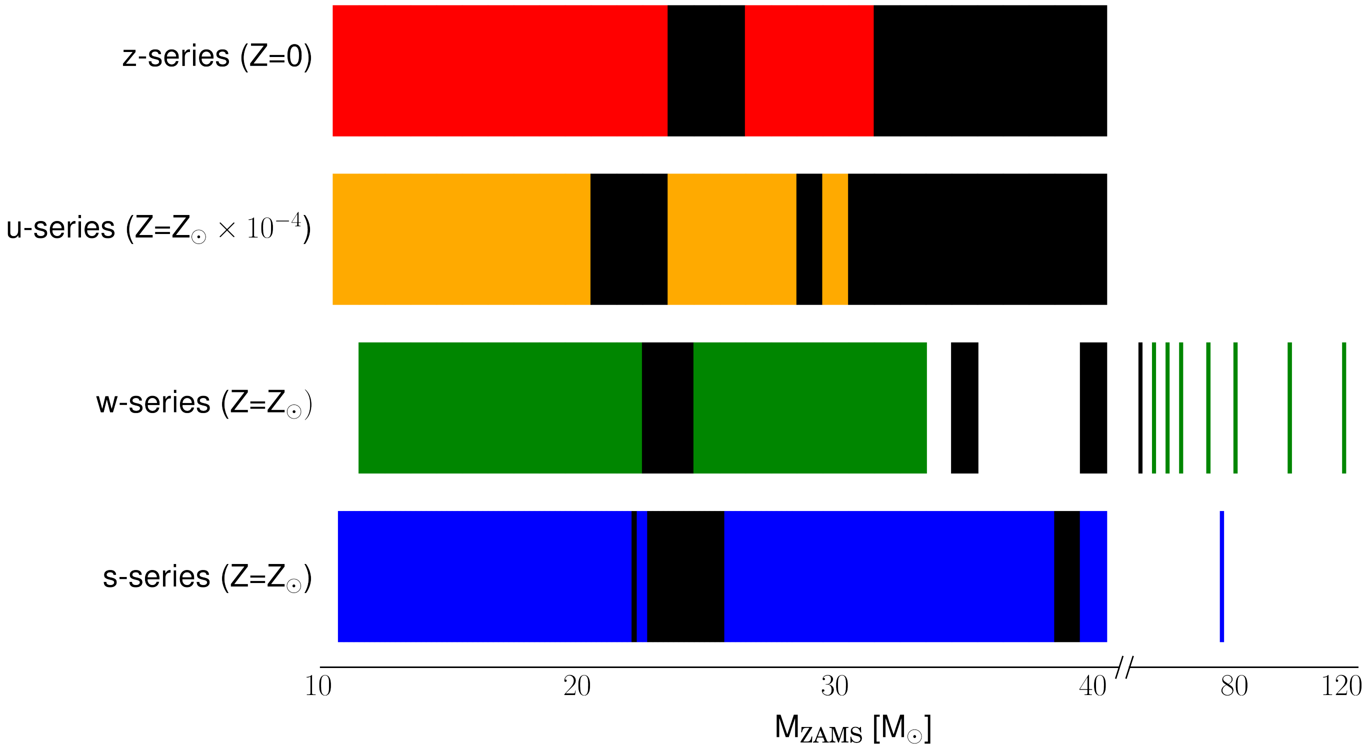
Low Metallicity Stars



- Ejected nickel vs explosion energy (WHW02)
- Comparison with observations (Bruenn+16 and Nomoto+13) and fits (Müller+17)

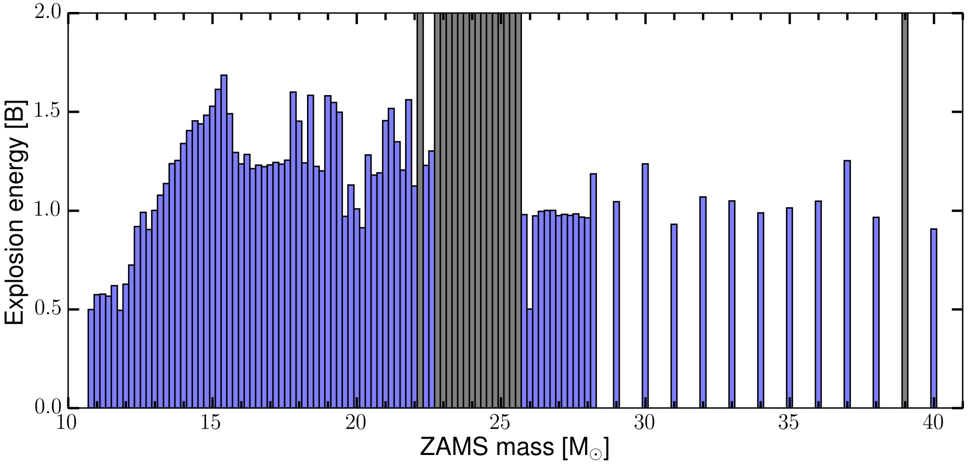
Ebinger+ApJ (accepted)

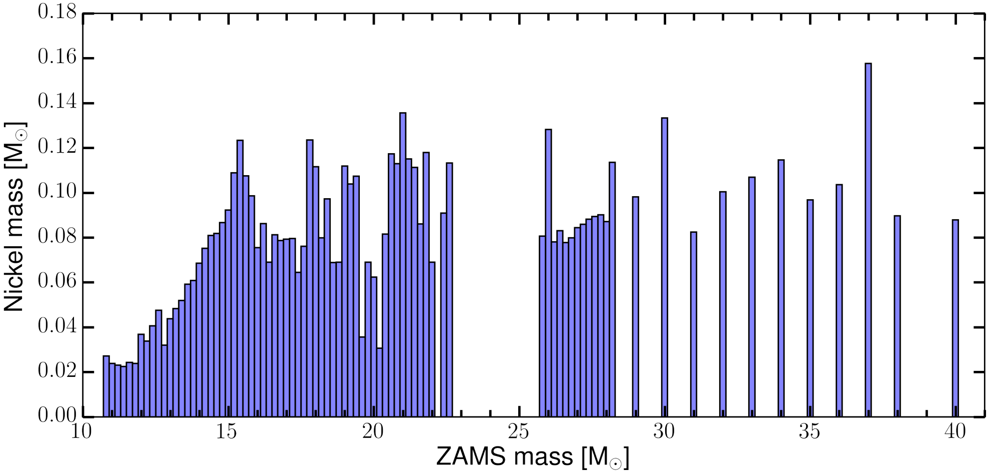
Low Metallicity Stars

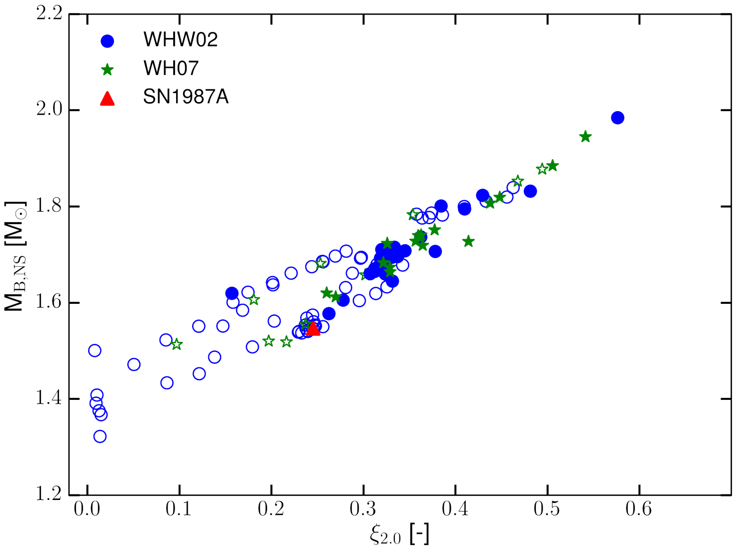


- CCSN explosion energies for low metallicity stars (WHW02)
- Lower explosion energies and more BH forming models

Global Properties of CCSN Simulations







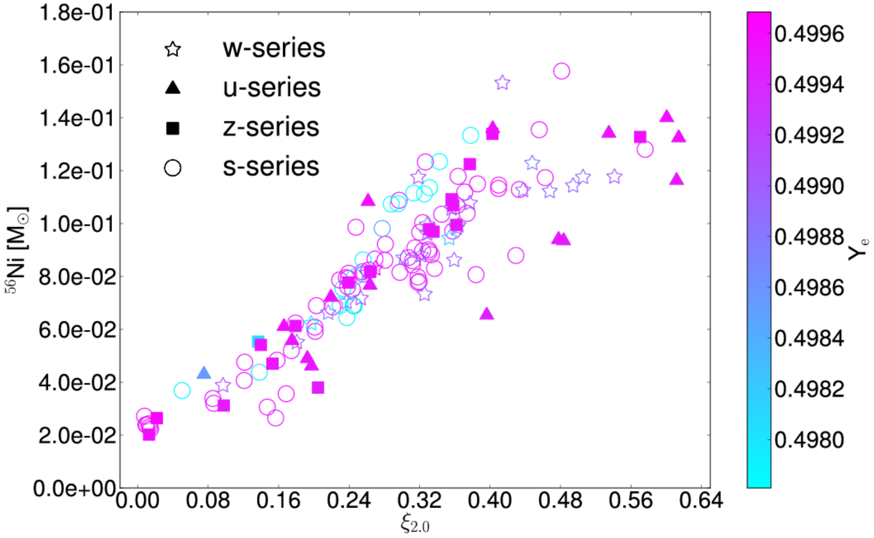
- Trends with compactness

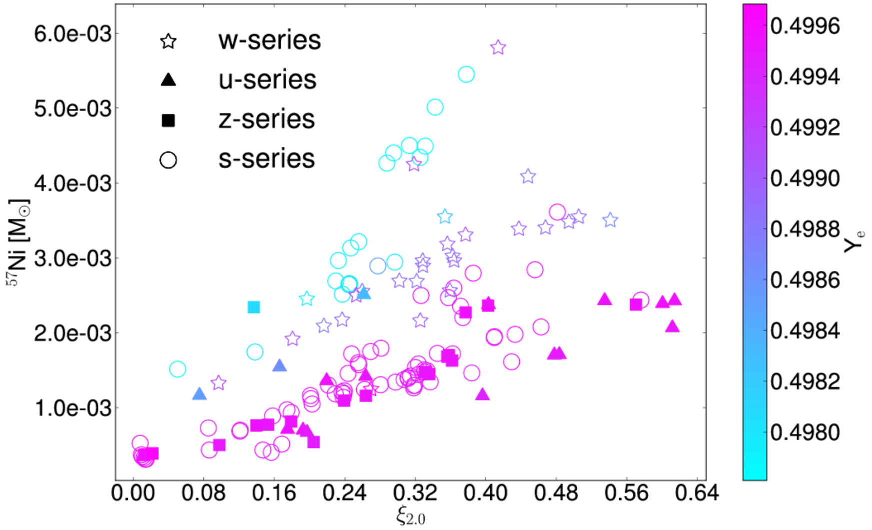
- Resulting properties of CCSNe for all progenitors across the ZAMS mass range

- Postprocessing: nucleosynthesis yields can be used for GCE

Ebinger+19

Global Properties of CCSN Simulations



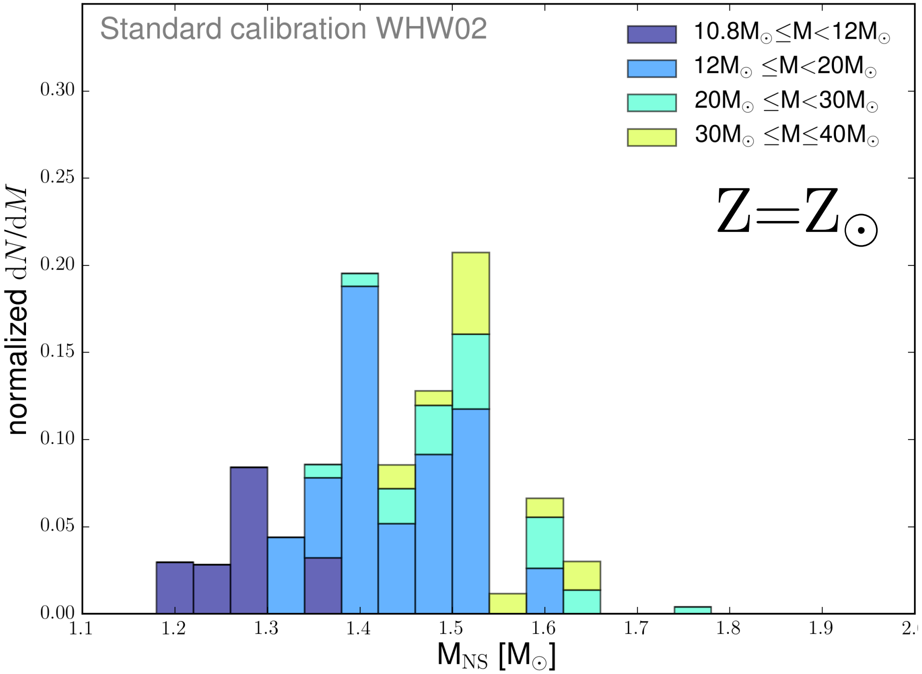


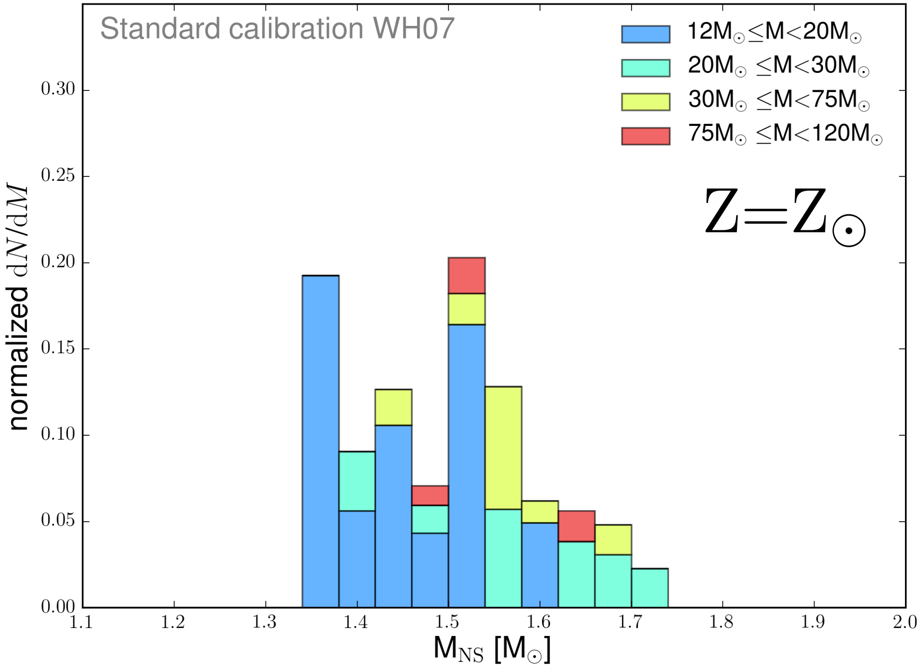
- Trends with compactness
- Resulting properties of CCSNe for all progenitors across the ZAMS mass range
- Postprocessing: nucleosynthesis yields can be used for GCE

Ebinger+ ApJ (accepted)

NS and BH Birthmass Distribution

- Predicted NS masses for ZAMS masses of stars
  → Birth mass distribution
- Initial mass function from Salpeter55 (for massive stars heavier than 10 $\mathrm{M}_\odot$)





- Progenitor range limit at 10.8/12 solar masses. Lighter models would reduce the lower limit of the predicted NS mass distribution range
- Similar distribution for second calibration

Ebinger+19

NS and BH Birthmass Distribution

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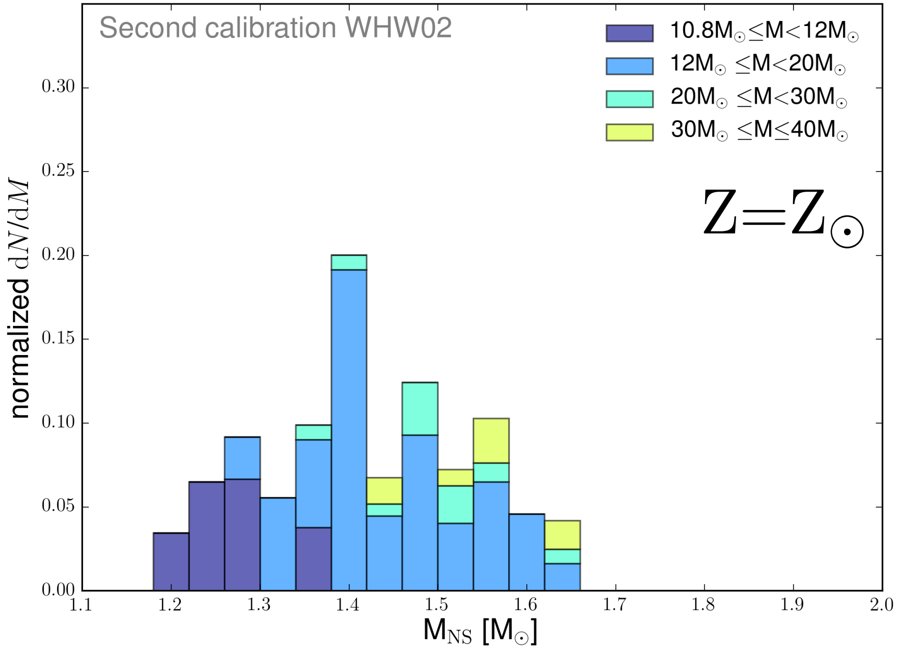

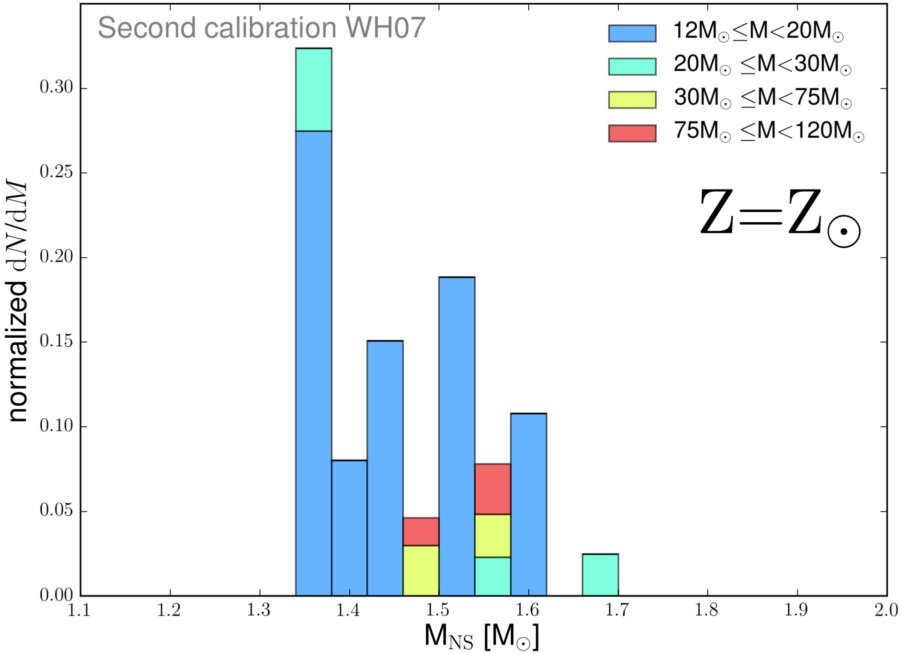

- Progenitor range limit at 10.8/12 solar masses. Lighter models would reduce the lower limit of the predicted NS mass distribution range
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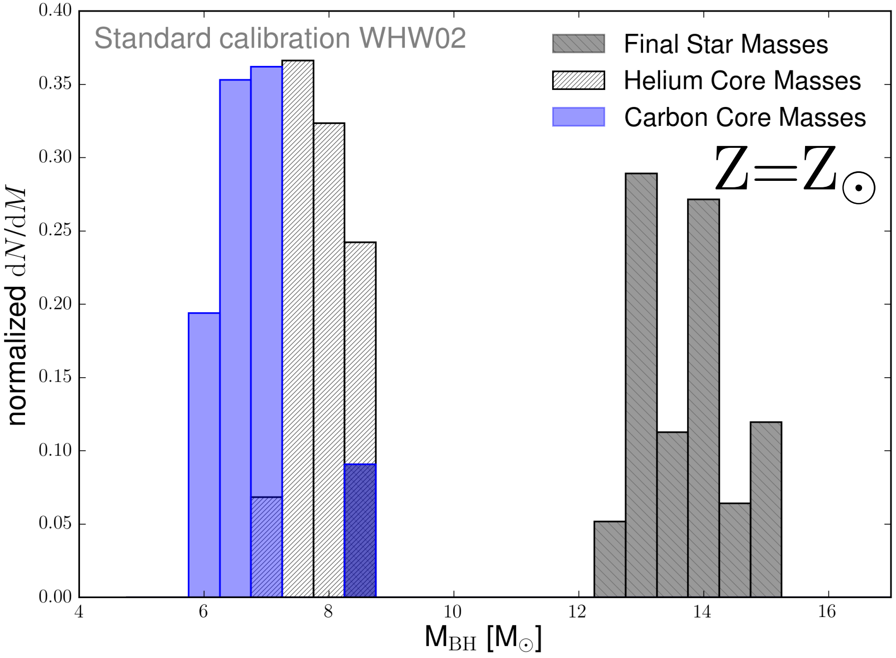
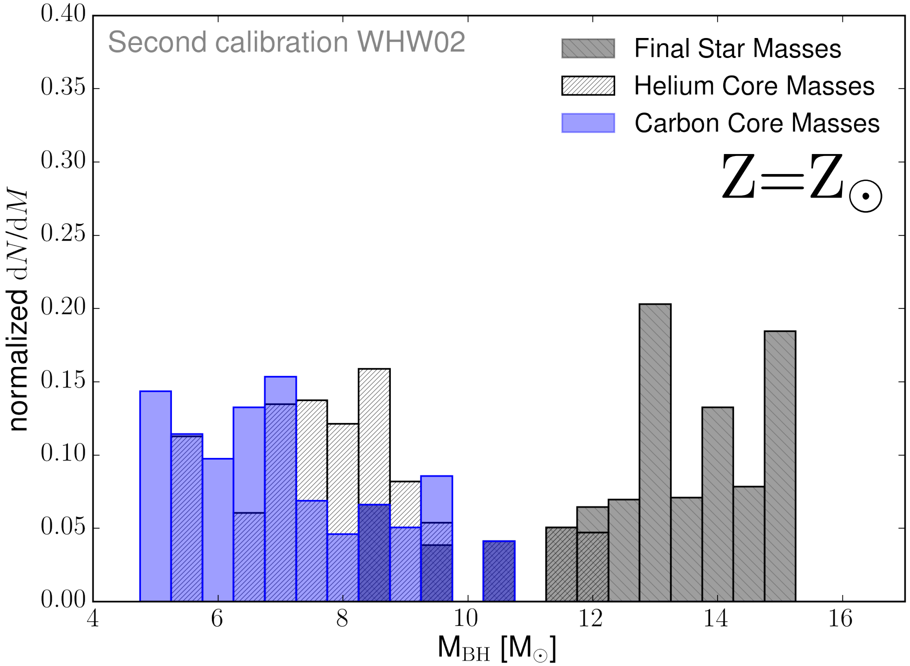
Ebinger+19

NS and BH Birthmass Distribution

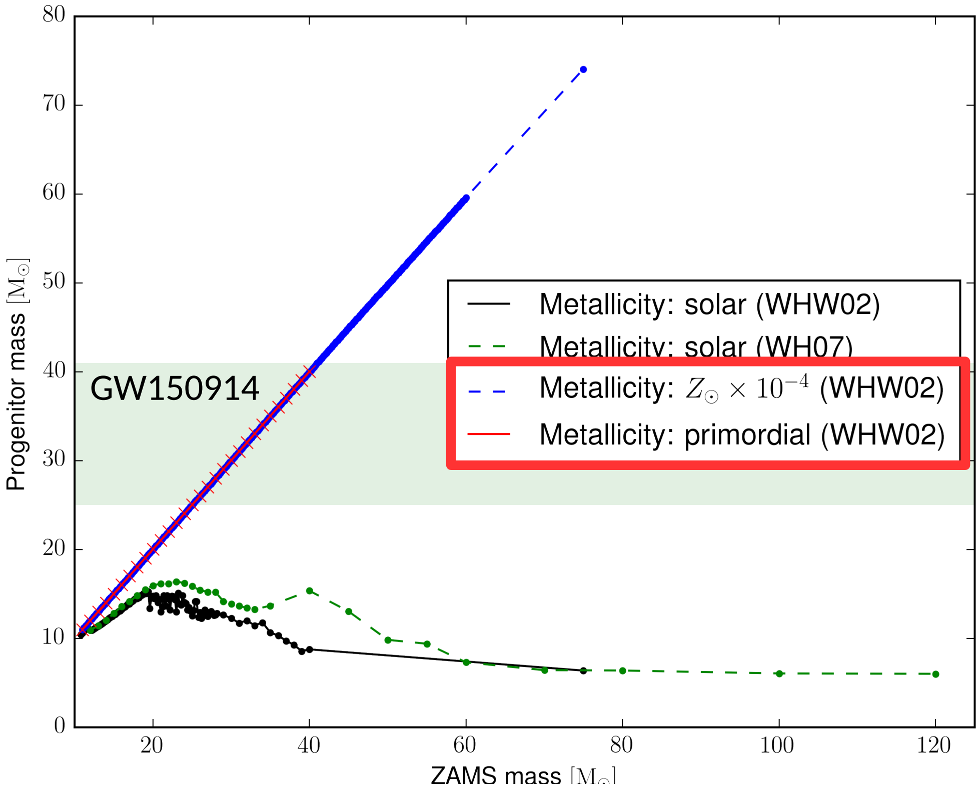
- Predicted BH mass distribution (both calibrations)



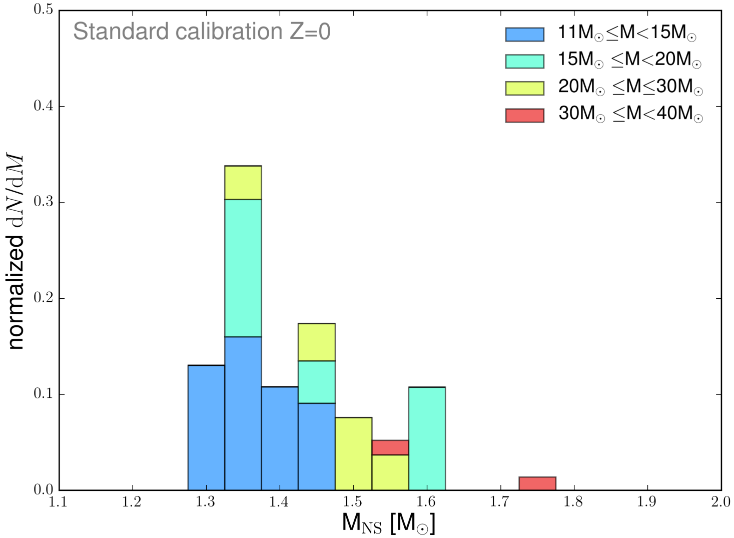


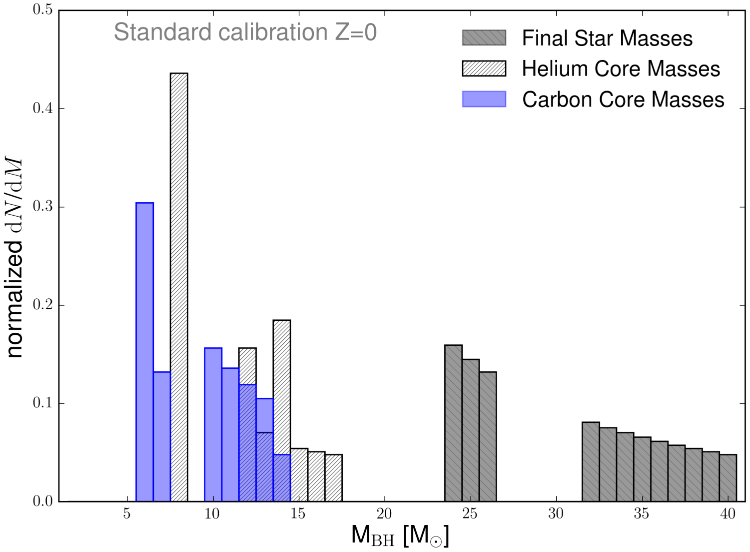
Broadly consistent with observationally determined BH mass distribution (7.8+-1.2 $\mathrm{M}_\odot$, Özel+10), when we assume that the helium core mass sets the BH mass (Kochanek14)

NS and BH Birthmass Distribution



Series	Metallicity $Z/Z_\odot$	Calibration	BH Fraction	Fraction of Mass bound in BH
z	0	I	$\sim 18\%$	$\sim 16-45\%$
u	10^{-4}	I	$\sim 20\%$	$\sim 18-48\%$
s	1	I	$\sim 5\%$	$\sim 1-3\%$
w	1	I	$\sim 8\%$	$\sim 5-6\%$
z	0	II	$\sim 27\%$	$\sim 18-55\%$
u	10^{-4}	II	$\sim 32\%$	$\sim 22-61\%$
s	1	II	$\sim 16\%$	$\sim 4-7\%$
w	1	II	$\sim 21\%$	$\sim 8-14\%$





Conclusion and Outlook

- Calibration of PUSH: observational constraints (SN1987A)
  → Explodability, Supernova landscape, CCSN properties

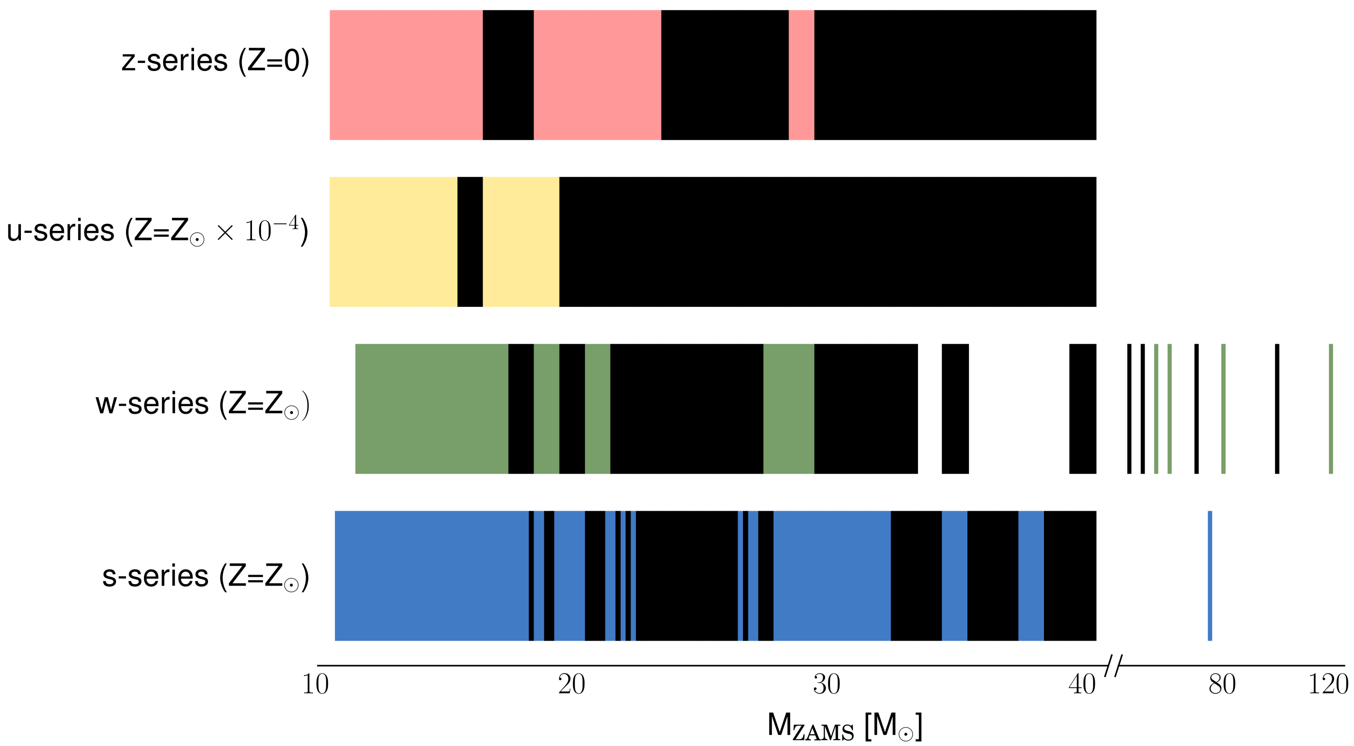
- Good agreement with observational properties of CCSNe

- Influence of progenitor models / EoS

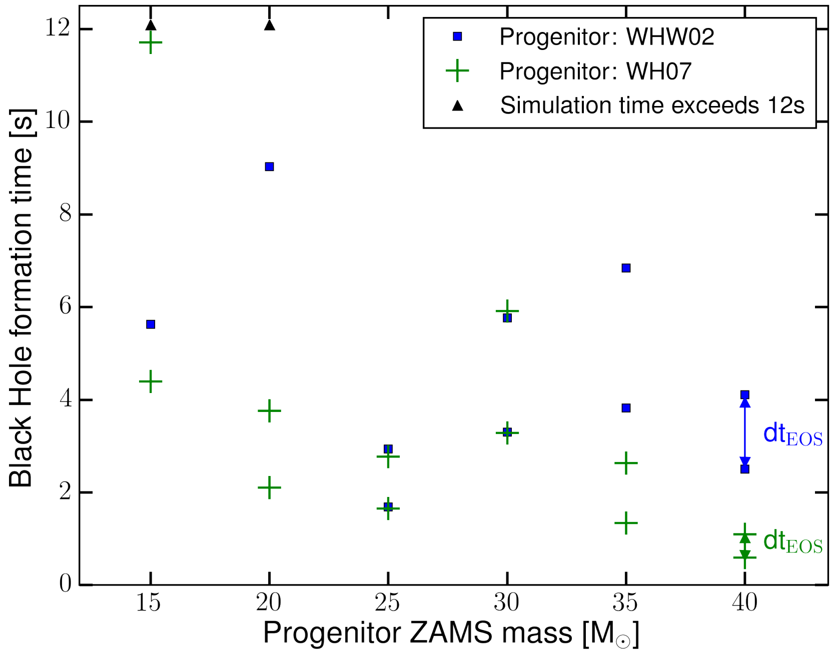
- Compare predicted neutron star and black hole masses to observations

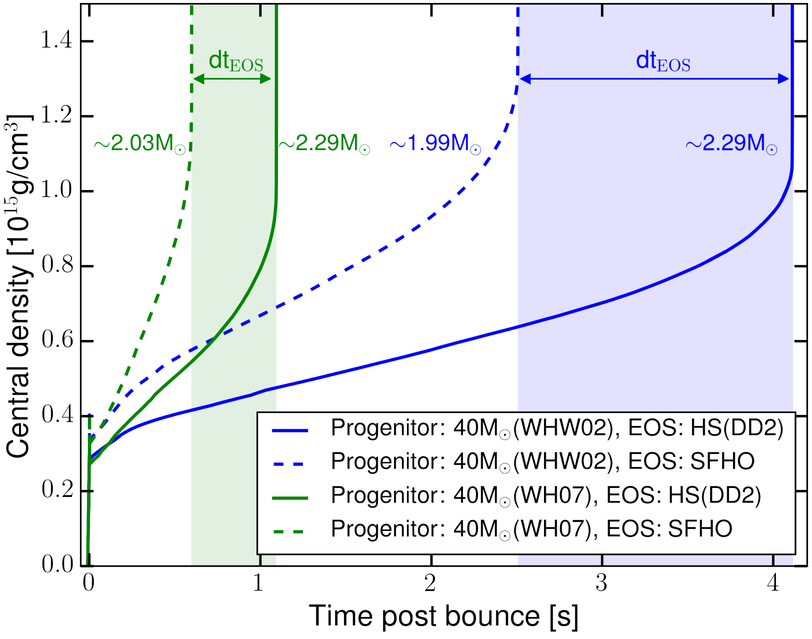
- Explosion/Nucleosynthesis properties can be used in GCE calculations

Second Calibration



Calibration of PUSH



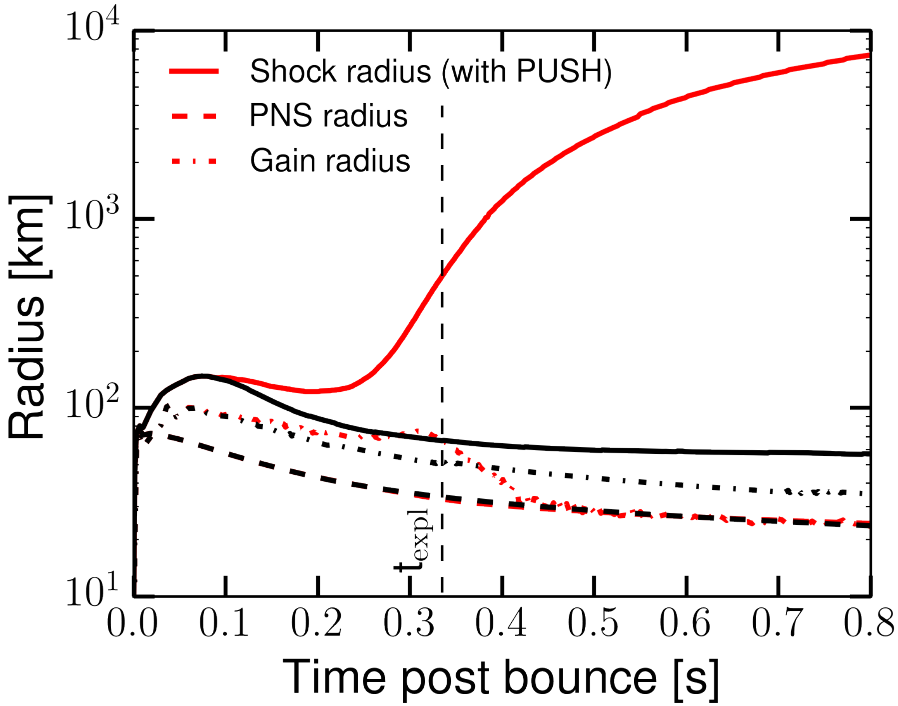


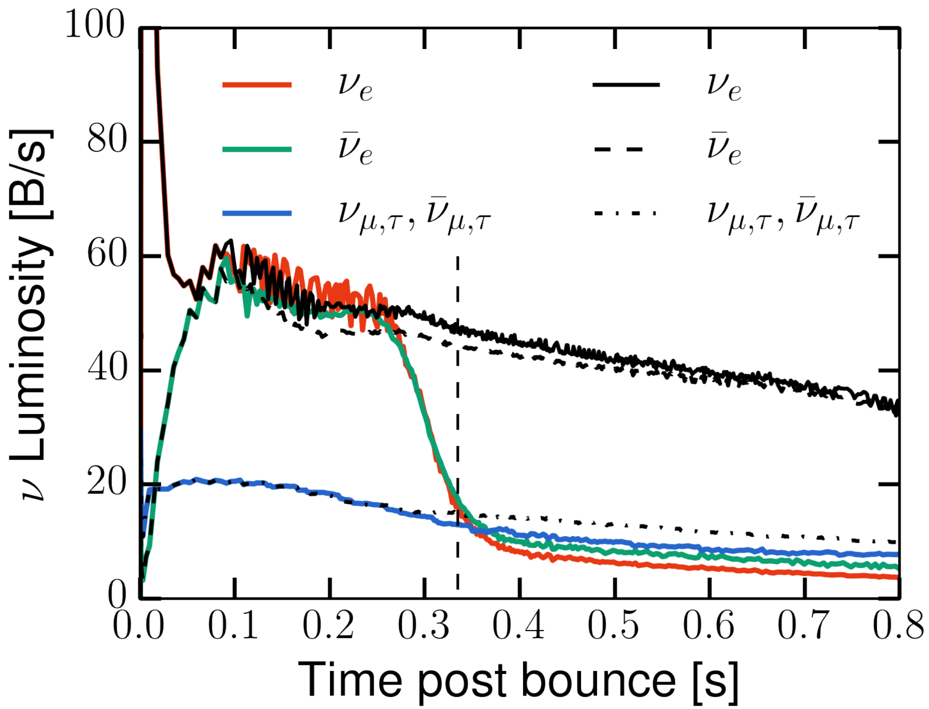
- Black hole formation times of simulations without PUSH (indication of upper limit in time for succesful neutrino-driven mechanism)

- Progenitor uncertainties and EoS have an non-negligible effect

- Higher compactness values coincide with faster BH formation

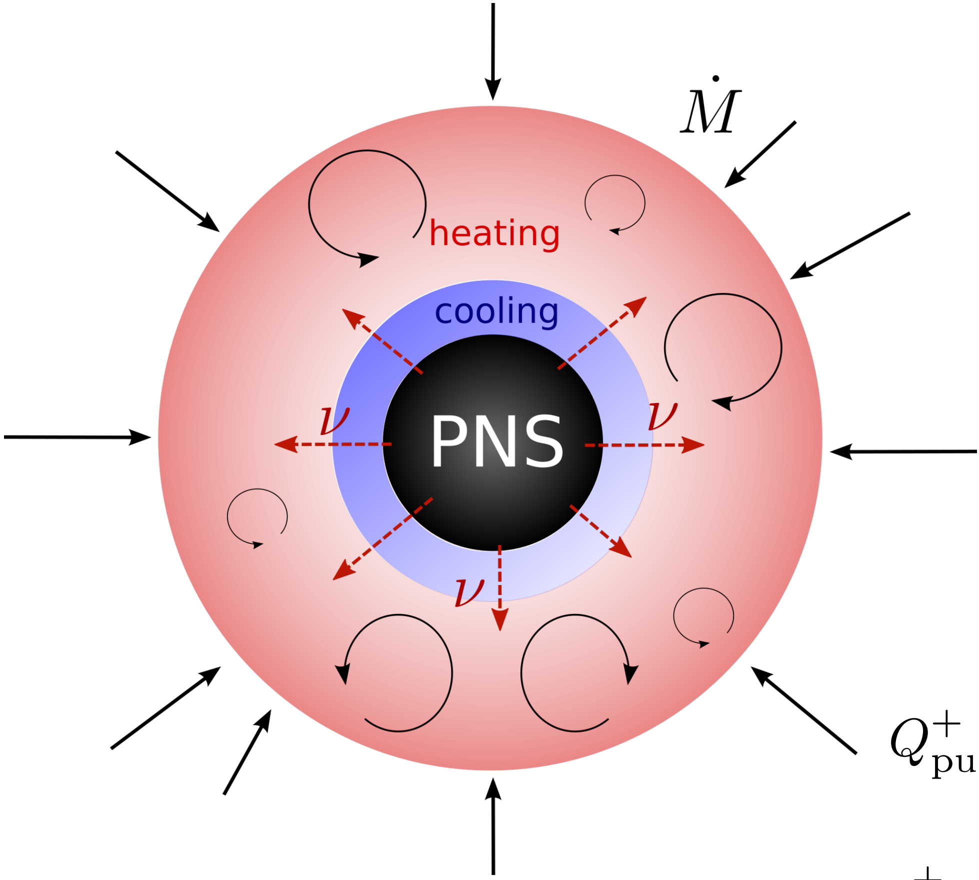
CCSN Modeling in 1D: PUSH





- PUSH model (with and without, 15 $\mathrm{M}_\odot$ star):
  - Additional heating by ν_x, $\bar{\nu}_x$ mimics more efficient ν_e, $\bar{\nu}_e$ heating
  - L_{ν_x} does not suddenly decrease after the onset of explosion

PUSH



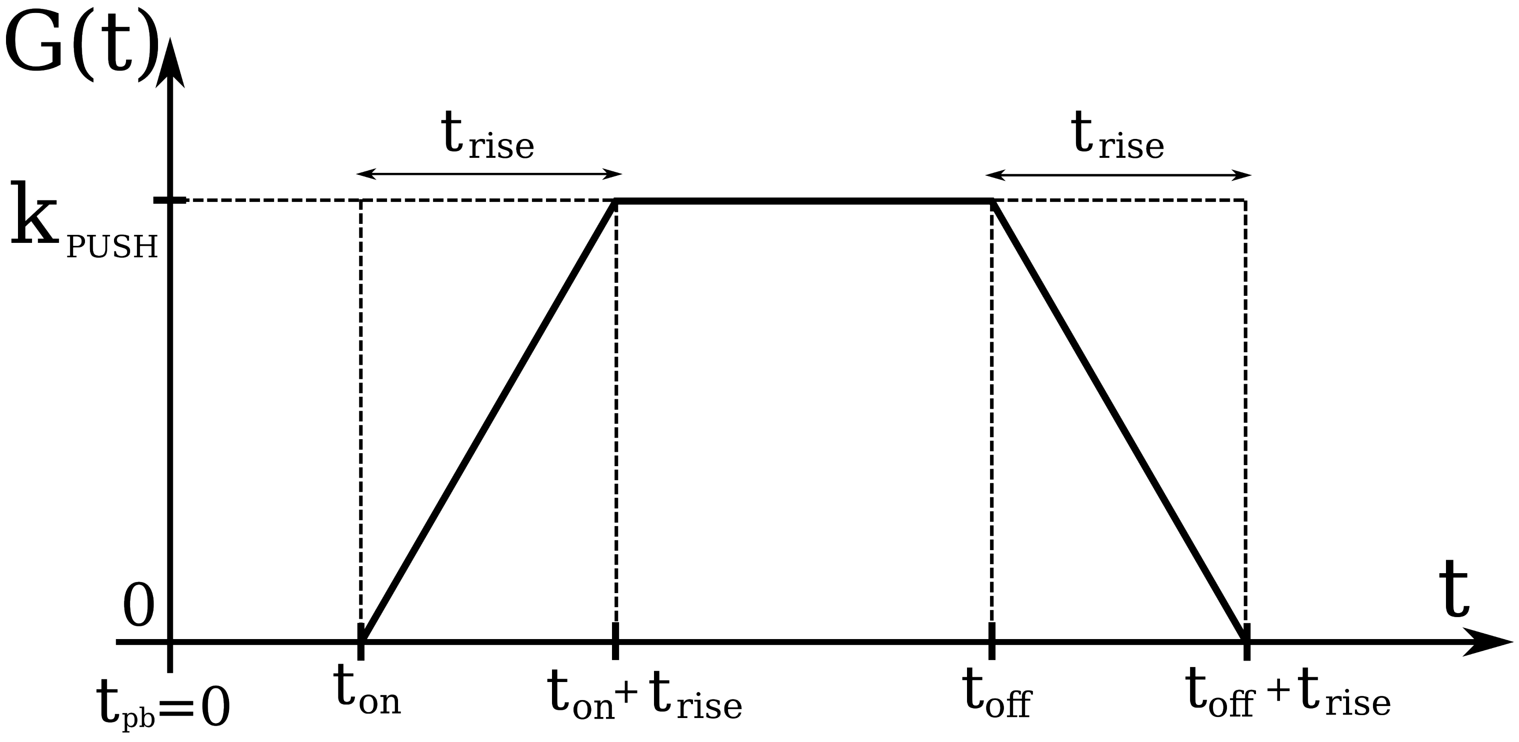
- Temporal evolution
- Typical neutrino cross section
- Spectral energy flux
- Location function

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

$$q^+_{\text{push}}(r,E) \propto E^2 \frac{1}{4\pi r^2} \left(\frac{dL_{\nu_{\mu,\tau}}}{dE}\right) \mathcal{F}(r,E)$$

Temporal Evolution of PUSH

- PUSH parameters inspired by enhanced ν-heating in multi-D simulations



Free parameters:

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

Fixed parameters:

- $t_{on} = 80 \text{ ms}$
- $t_{expl} < t_{off} = 1 \text{ s}$