Core-Collapse Supernovae Across the Stellar Mass Range

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Core-Collapse SNe and their Progenitor Stars

HST

- **SN 1987A**: Identification of the progenitor star for the first time
- Archival data is used to identify progenitors of ever more SNe (cf. Smartt et al. 2009)

Core Collapse and Shock Stagnation

Core collapse

↓

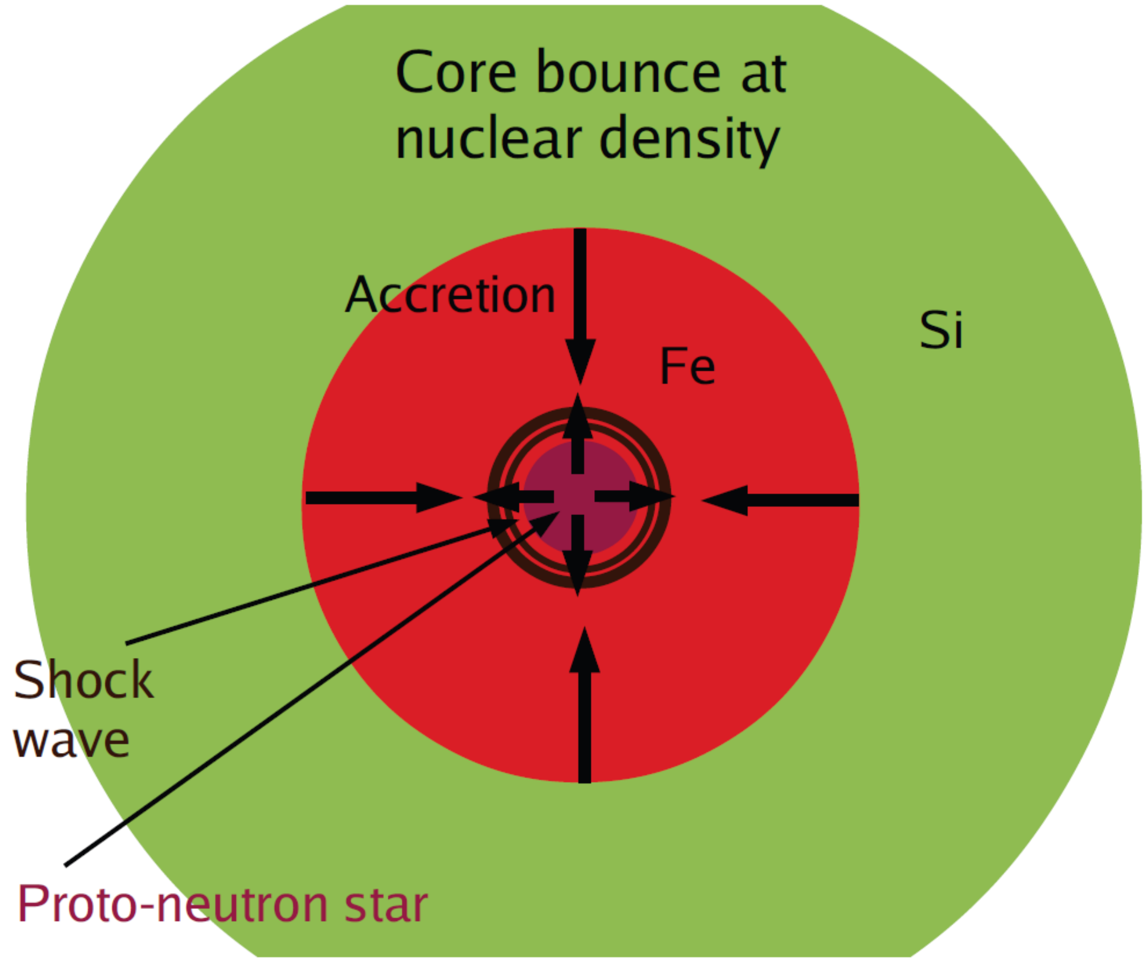
Central density reaches nuclear density

↓

Core bounce

↓

A Shock wave is launched

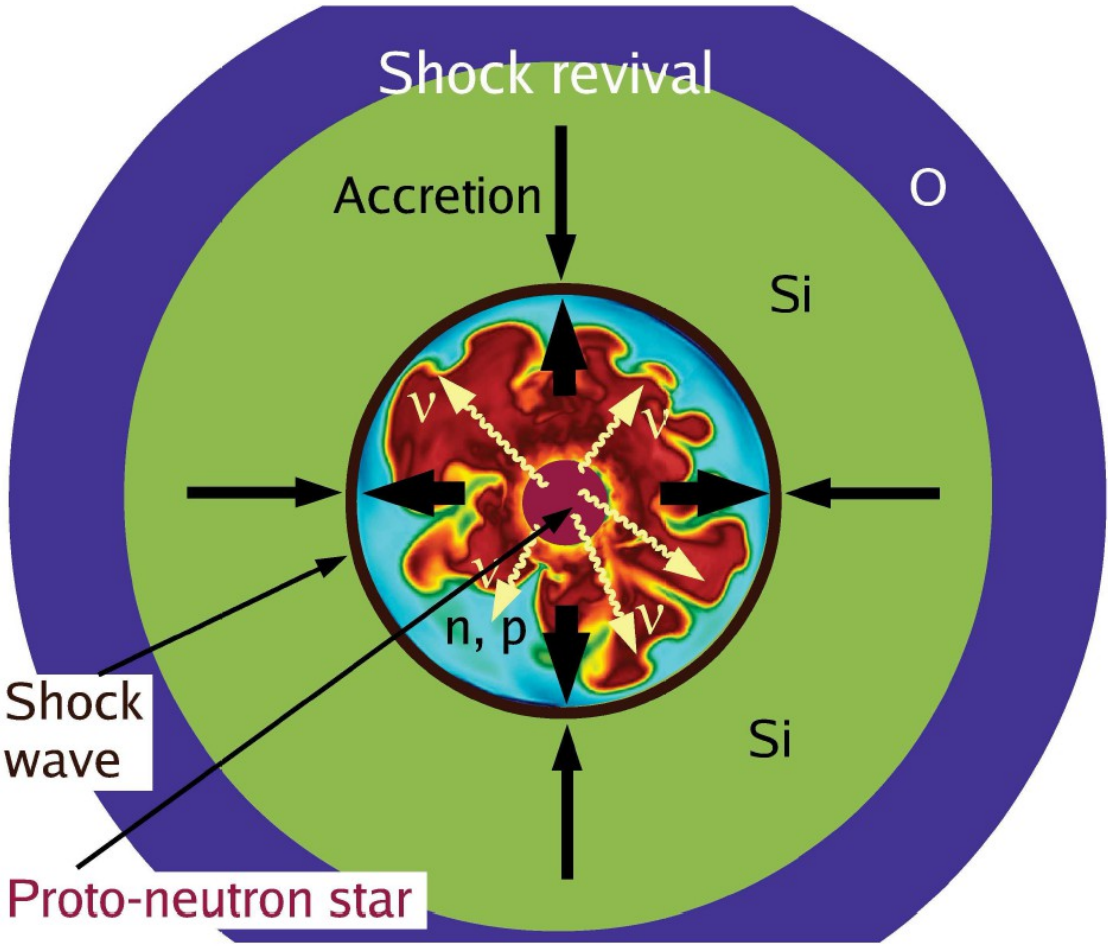


Janka et al. 2012

$$\Delta E_b \approx \frac{GM_{\rm CORE}^2}{R} = 3\times 10^{53}\left(\frac{M_{\rm CORE}}{M_\odot}\right)^2\left(\frac{R}{10\rm km}\right)^{-1}\rm erg$$

The Neutrino-Driven Mechanism

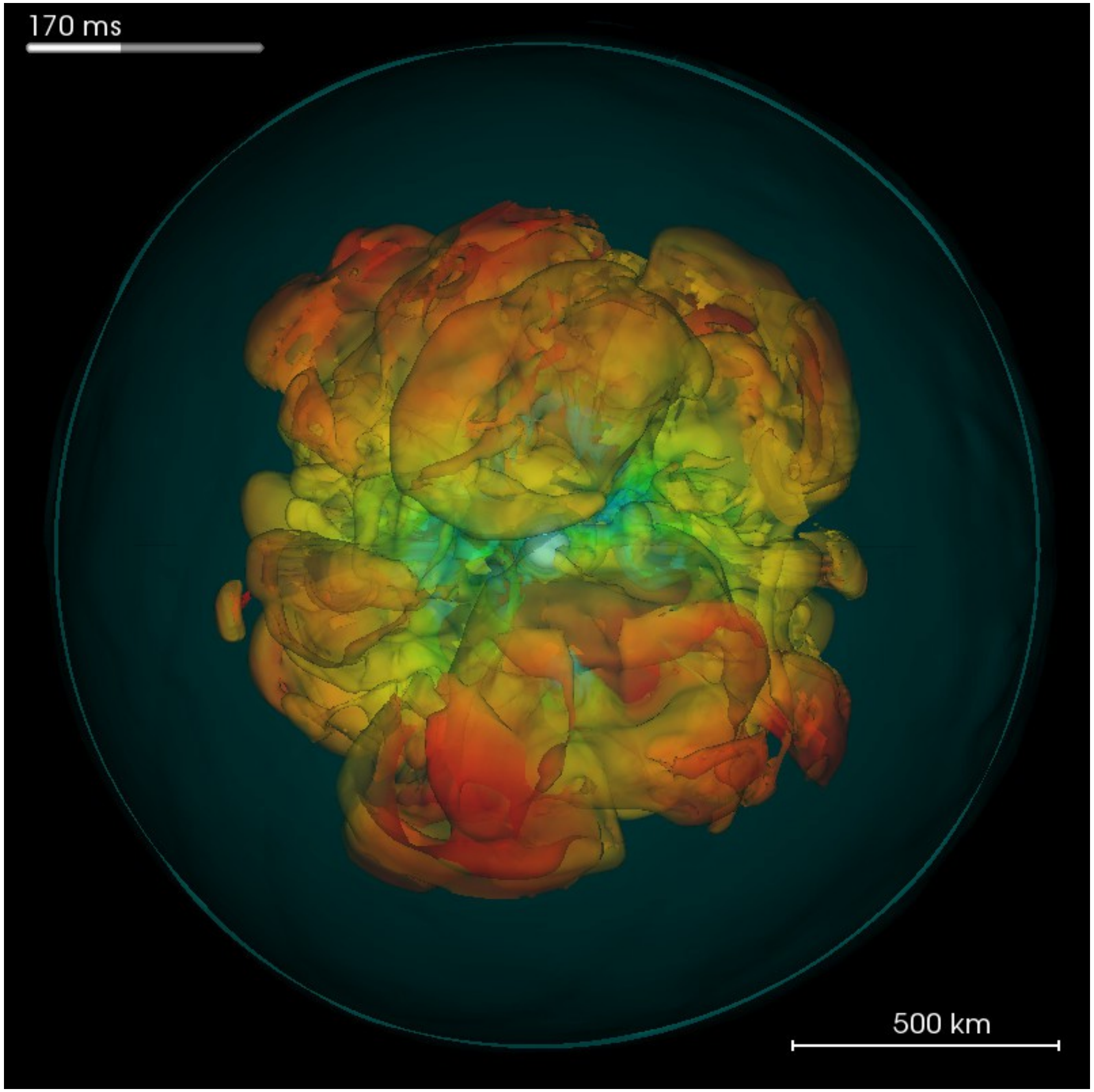
- **Shock stagnates**
- **Critical phase (~ 1s)** for the explosion to set in and success of the mechanism
- **Competing processes:**
  - **Ram pressure** of the infalling material
  - **Neutrino-heating**



Janka et al. 2012

How to Tackle the Supernova Problem?

- First-principle study
  - **Does the mechanism work?**
  - Simulations in 3D
  - Only a **few models**
  - No long-term evolution



Melson et al. 2015

- Systematic parameter study
  - Prediction of **observables**: $M_{Remnant}$, E_{exp}, M_{Ni}, $M_{Fallback}$, ...
  - Explaining the population of core-collapse SNe (CCSNe) and not individual cases

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(ZAMS = Zero-Age Main-Sequence)

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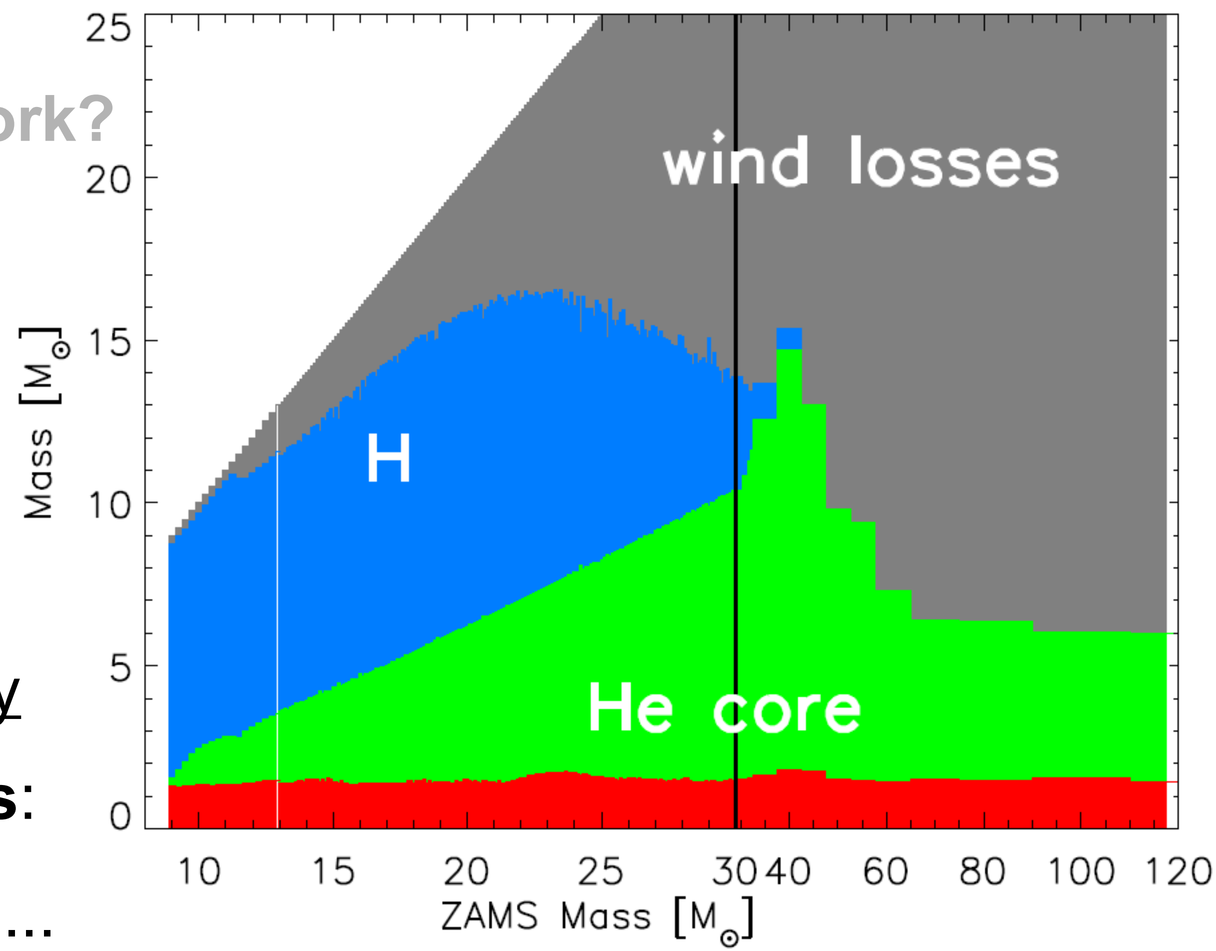

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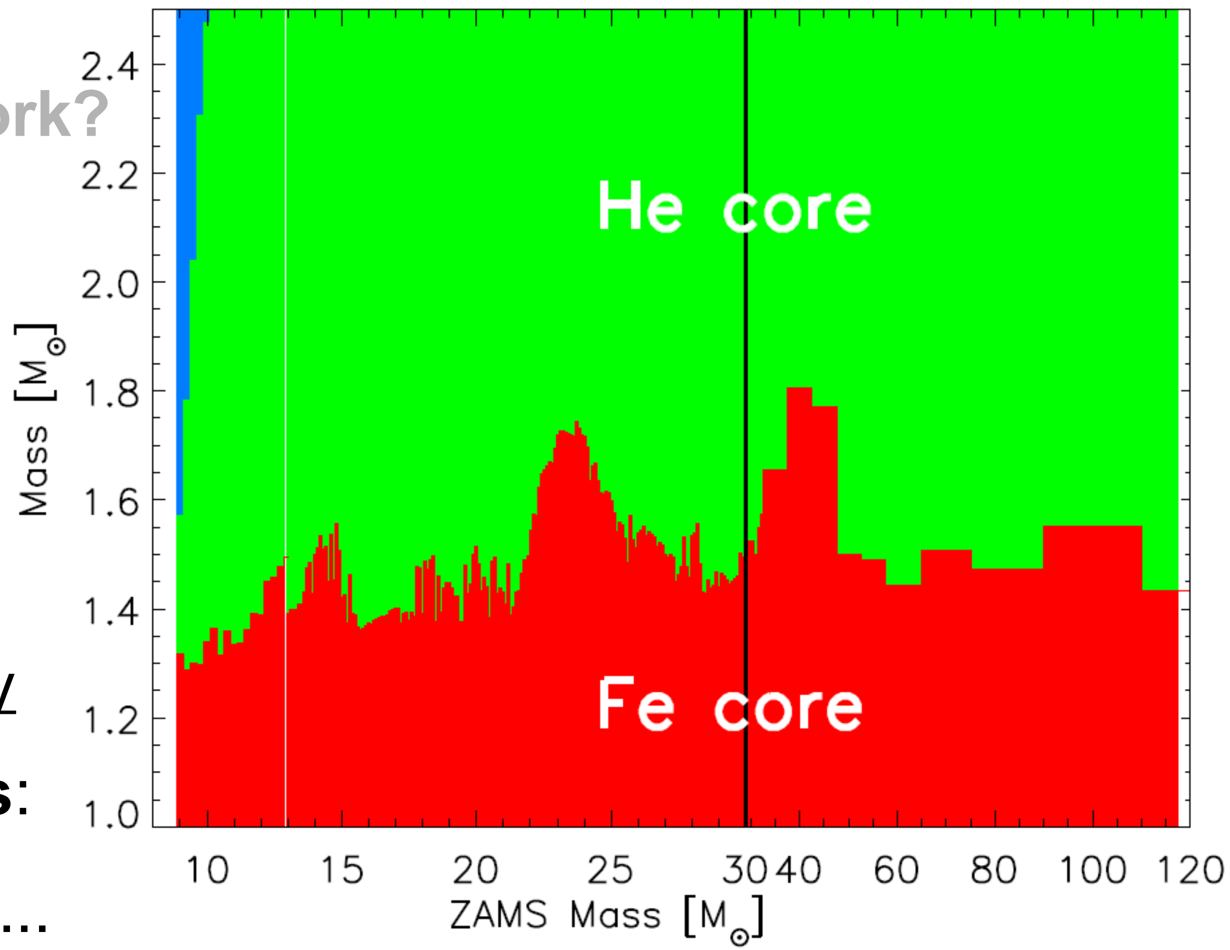

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Efficient Numerical Modeling with **PROMETHEUS-HOTB**

- Hydrodynamics
  - Explicit, finite-volume Eulerian hydrodynamics
  - **GR corrections**
  - **Spherical symmetry** (1D)
- **α-nuclear reaction network**
- **High-density equation of state**

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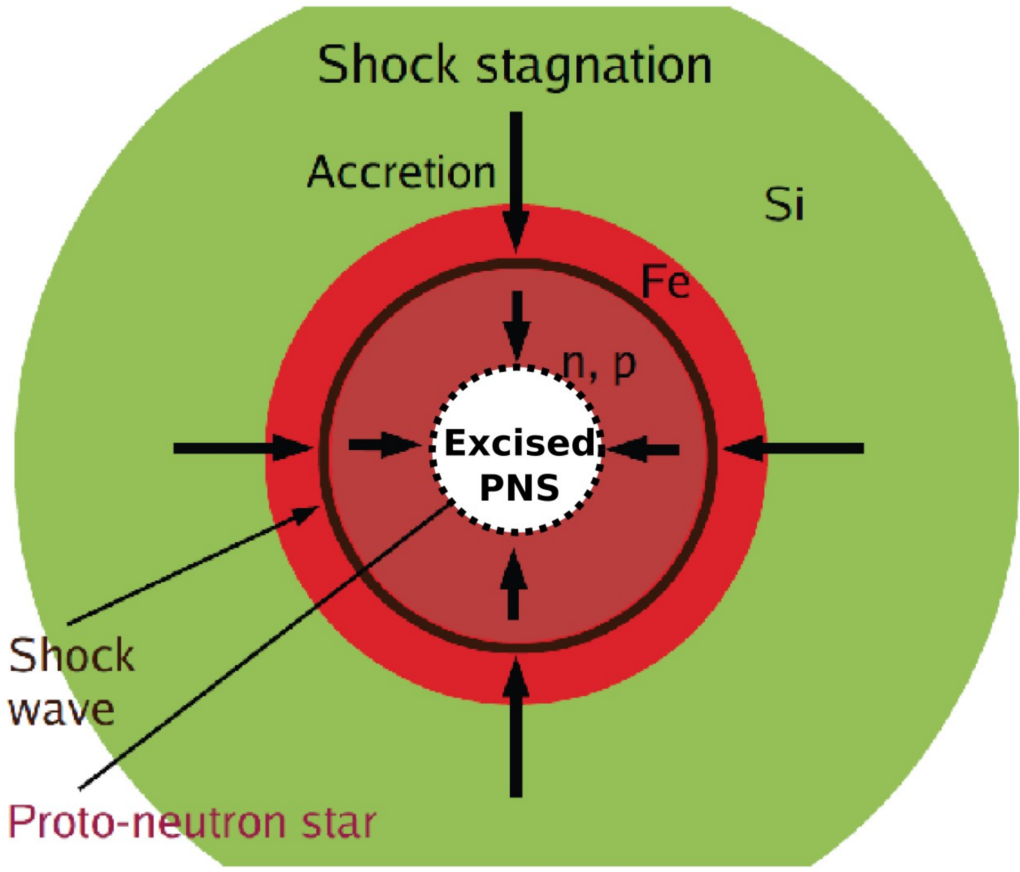
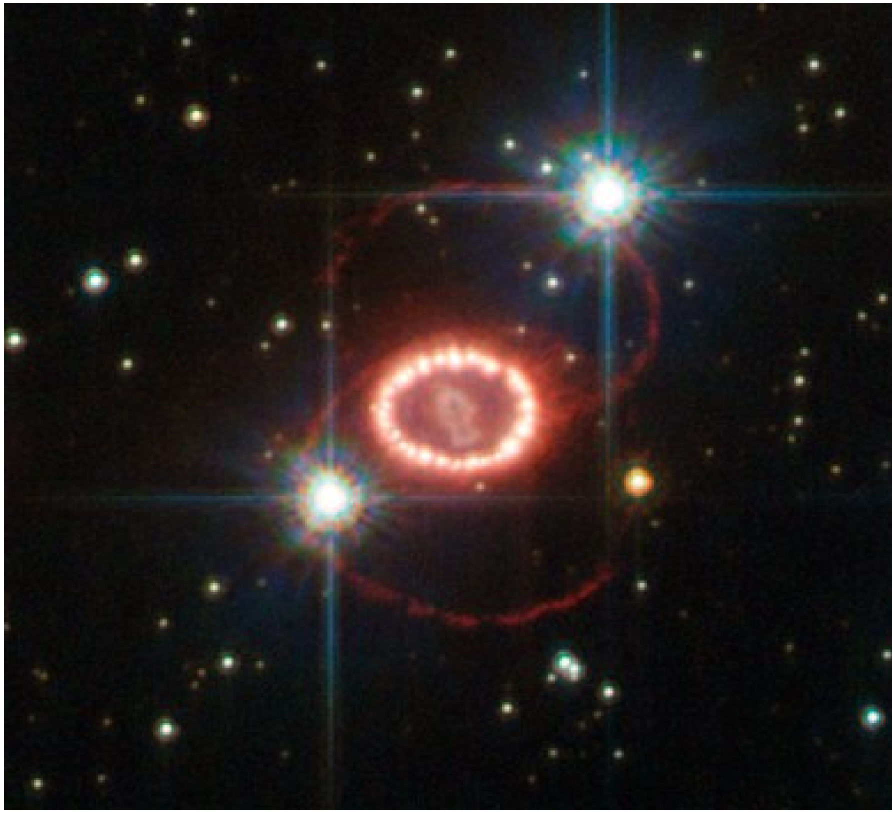
- **High-density equation of state**
- **Gray neutrino transport** solver combined with an **excised proto-neutron star (PNS)**
- **Analytic core-cooling model** with tuneable parameters



Numerical Modeling – Parameter Choice for SN 1987A

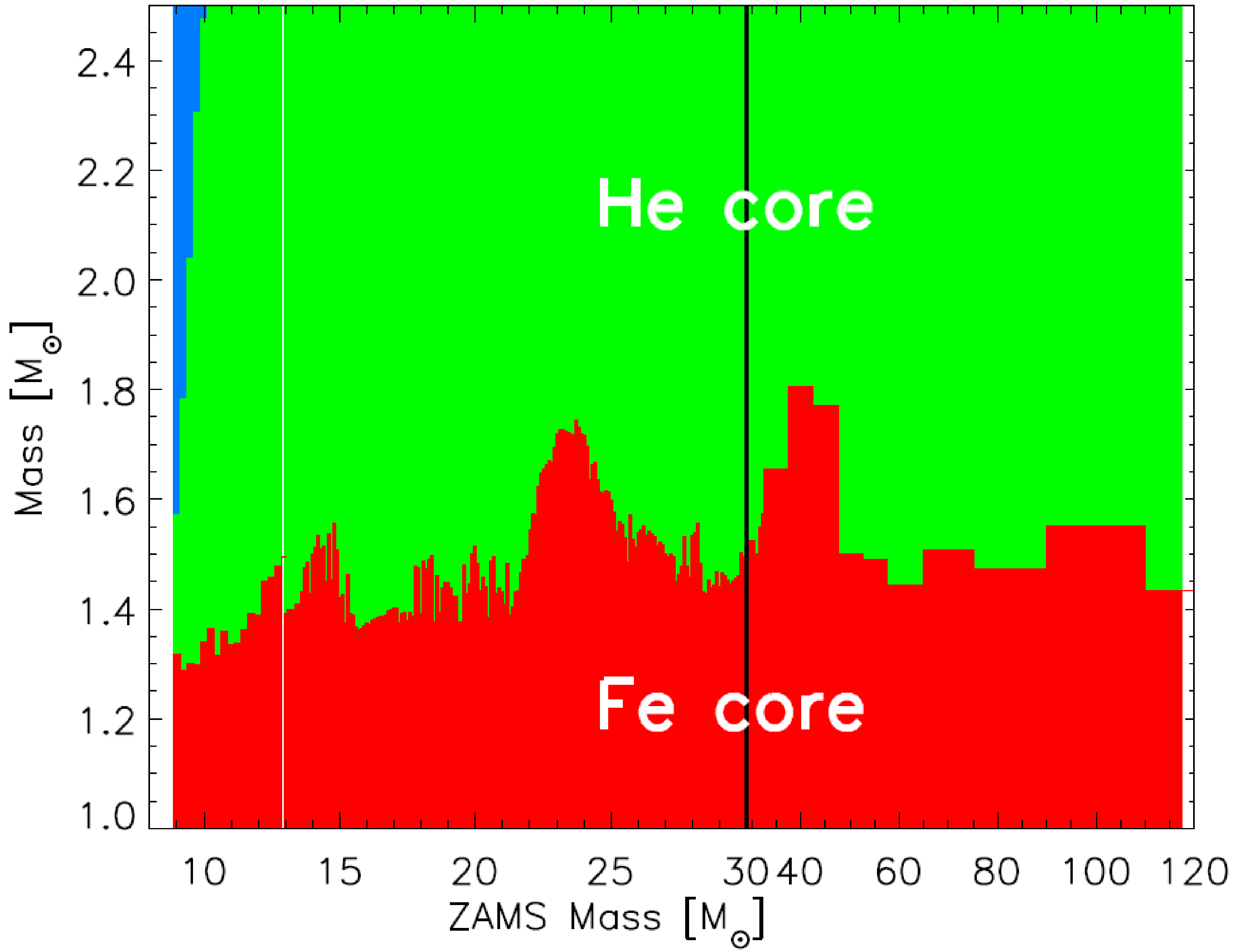
- Parameter chosen to fit the observables of **SN 1987A:**
  - $E_{exp} = (1.3 - 1.5) \times 10^{51}$ erg
  - Nickel ejecta mass of ~0.07 $M_{\odot}$
  - Neutrino signal: Duration and energy
  - Theoretical models for the progenitor star: $M(He) = 6 \pm 1\ M_{\odot}$, $M(H) \sim 10\ M_{\odot}$



HST

15 $M_{\odot}$ Woosley 1988	18 $M_{\odot}$ Woosley 2007	20 $M_{\odot}$ Woosley 1997	20 $M_{\odot}$ Nomoto 1990
W15	W18	W20	N20

Is There a Way to Discriminate Exploding and Non-Exploding Cases Before Core Collapse?



Compactness Parameter

- **Suggestions so far:**

Compactness parameter : $$\xi_M \equiv \frac{M/1M_\odot}{R(M)/1000\,\mathrm{km}}$$

BH formation limit (O'Connor & Ott 2011): $$\xi_{2.5M_\odot} \gtrsim 0.45$$

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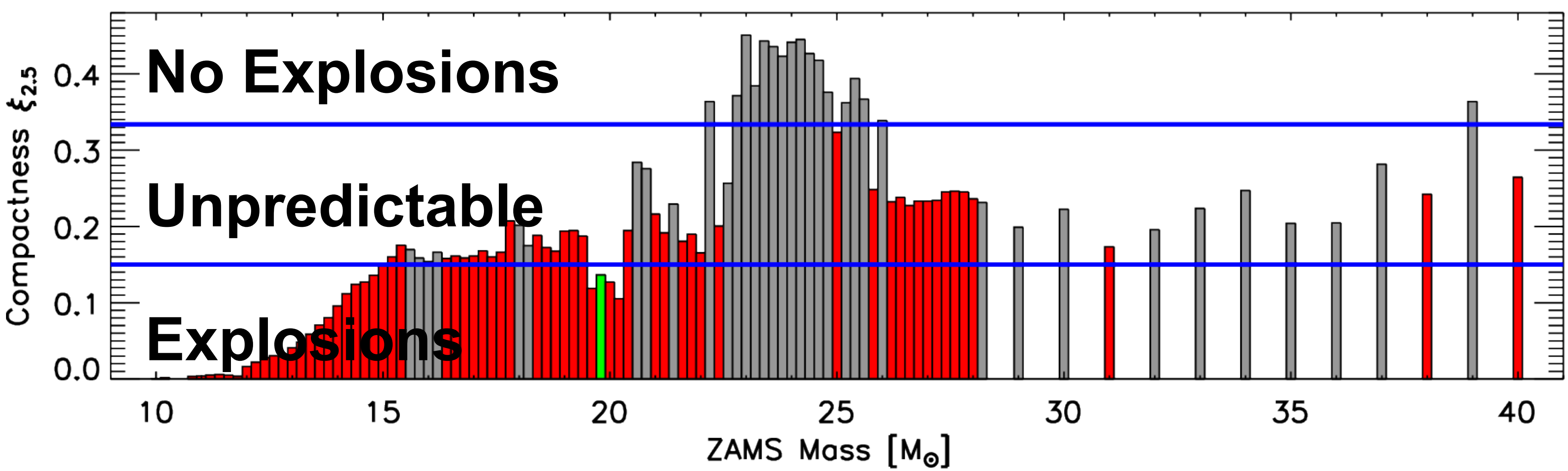
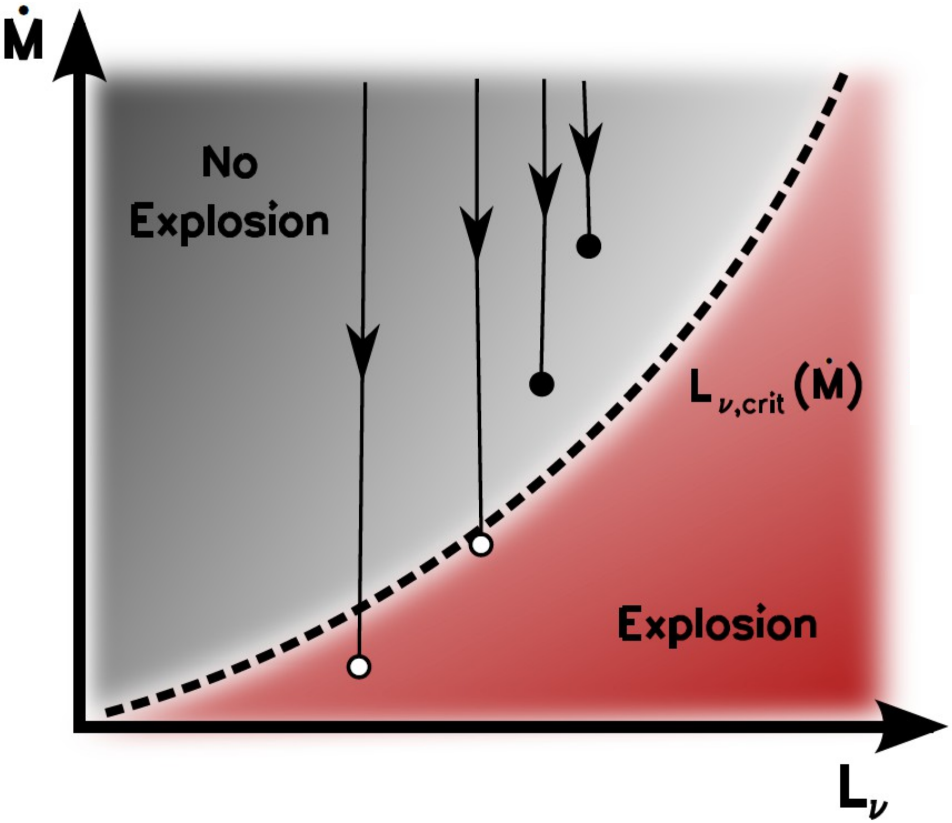
BH formation limit (O'Connor & Ott 2011): $\xi_{2.5M_\odot} \gtrsim 0.45$

- **Problem** (Ugliano et al. 2012):

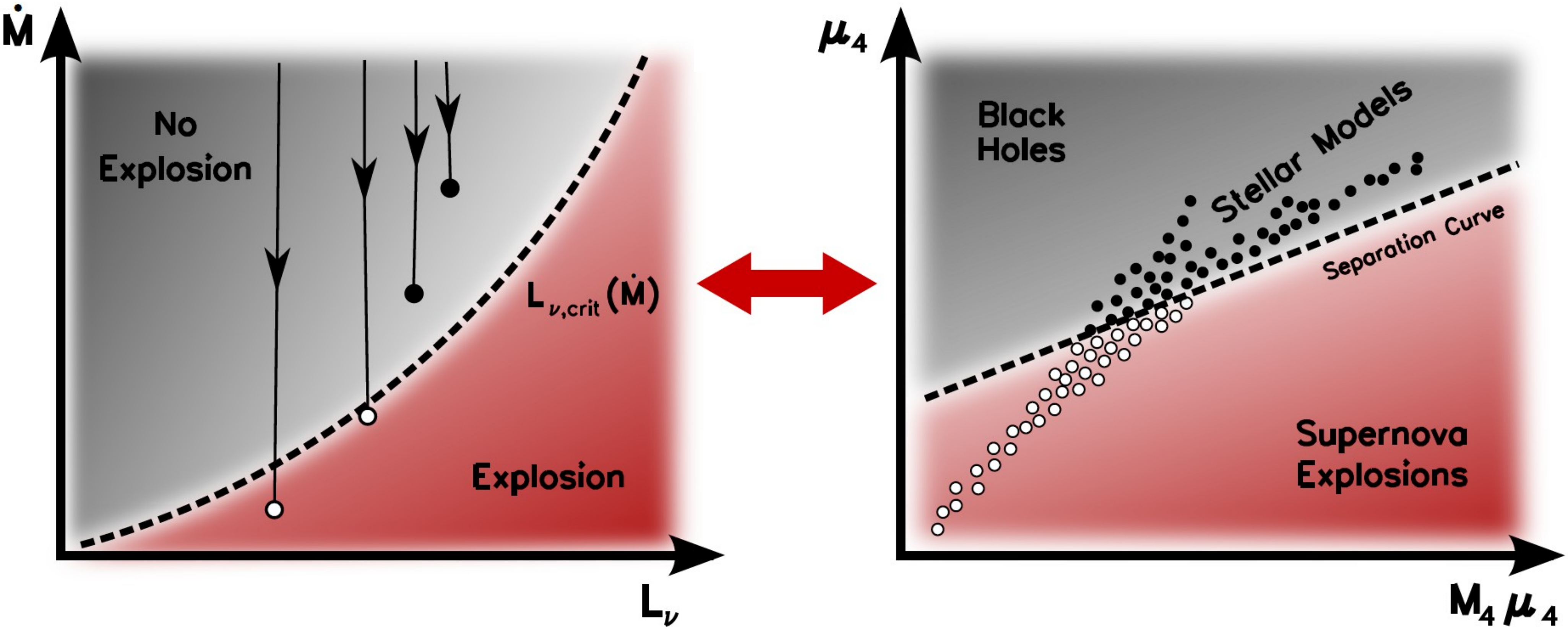


A Two-Parameter Criterion



- **Critical luminosity concept** (Burrows & Goshy 1993)
- **Schematic** evolution of exploding (white circle) and non-exploding (filled circles) models
- **Neutrino luminosity L_ν** versus **mass accretion rate $\dot{M}$**

A Two-Parameter Criterion

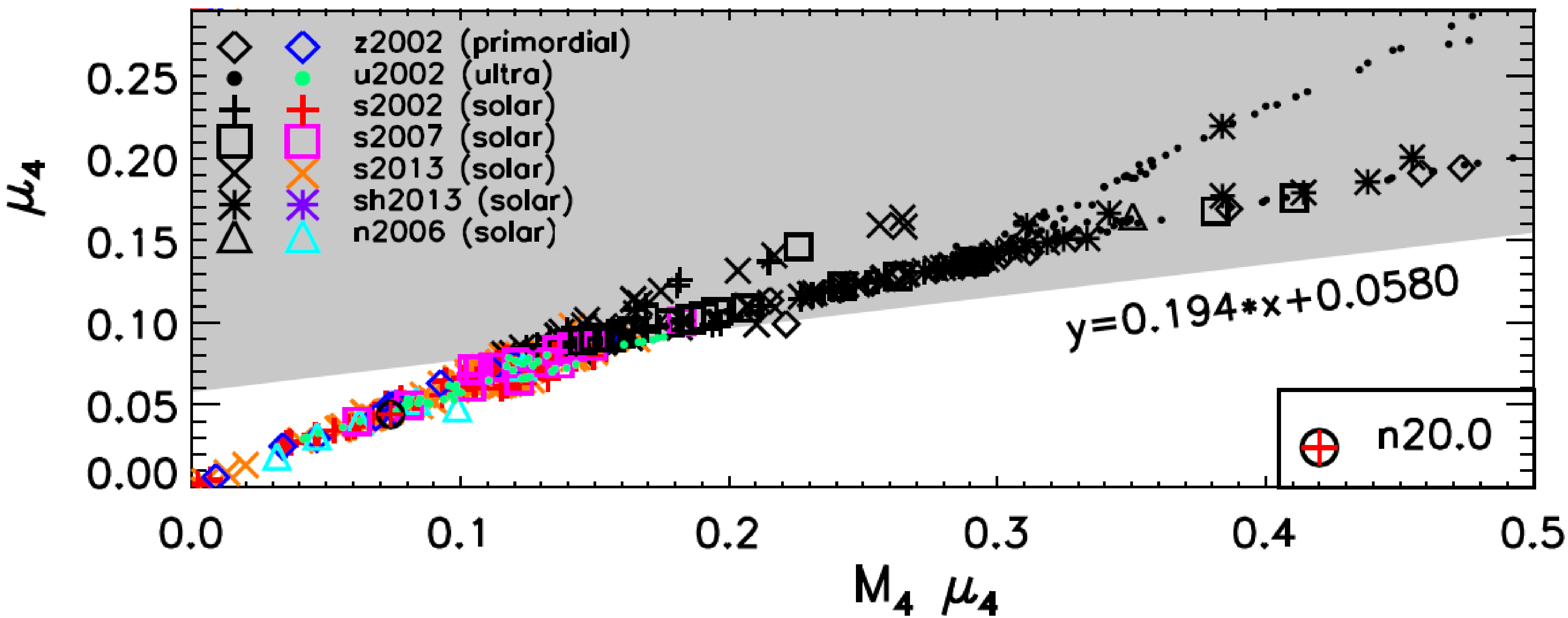


- Measure for the **density gradient outside of** the s=4 interface (**Si-SiO interface**):

$$\mu_4 \equiv \left(\frac{\Delta M}{\Delta R}\right)_{s=4}$$

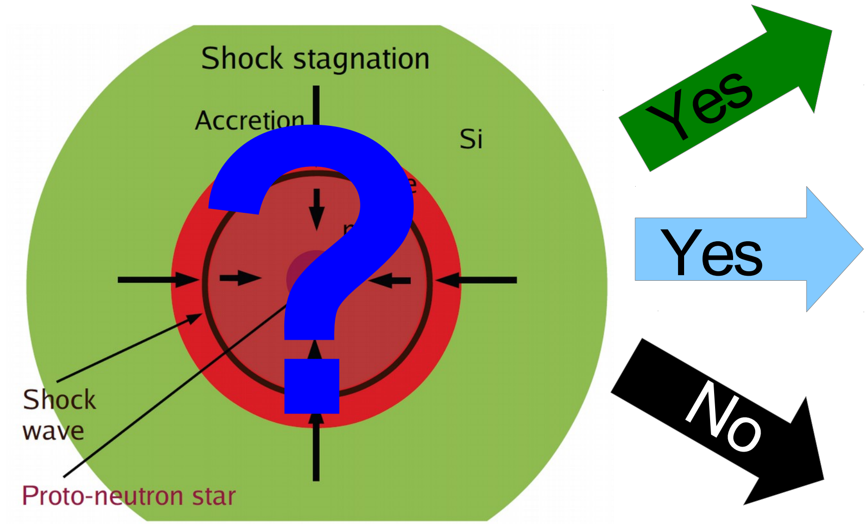
- **M$_4$** is the mass enclosed by the **shell interface** at entropy s=4 k_B

Simulation Results



- Two-Parameter criterion works for **over 600** progenitor models
- A separating line can be found **for every set of core parameters**

What is Left Behind?



Neutron Star (NS)

Black Hole (BH) by late-time fallback

Black Hole (BH)

Is the neutrino-heating strong enough to revive the stalled accretion shock?

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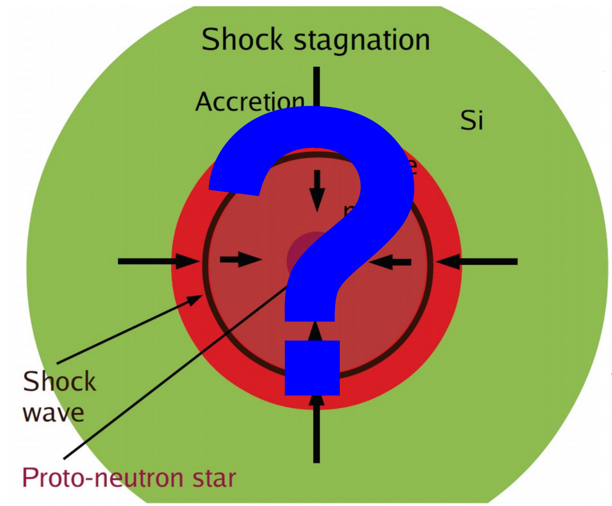

Yes → **Neutron Star (NS)**

Yes → **Black Hole (BH)** by late-time fallback

No → **Black Hole (BH)**

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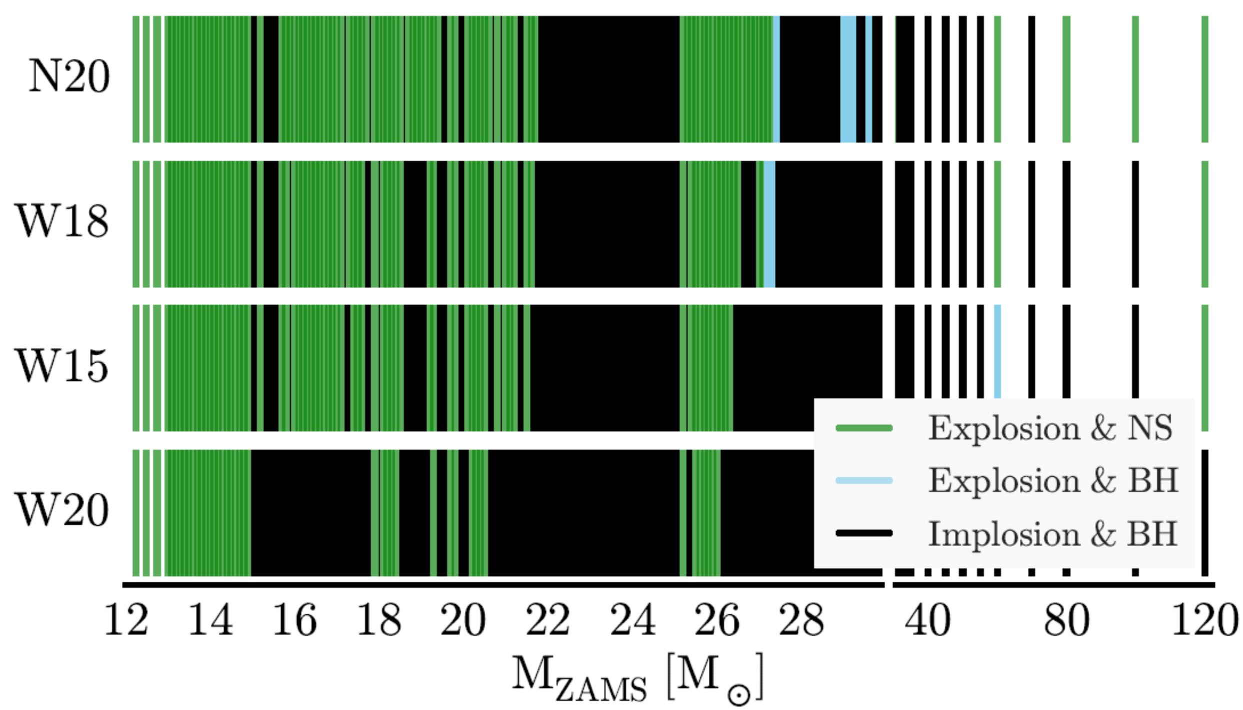
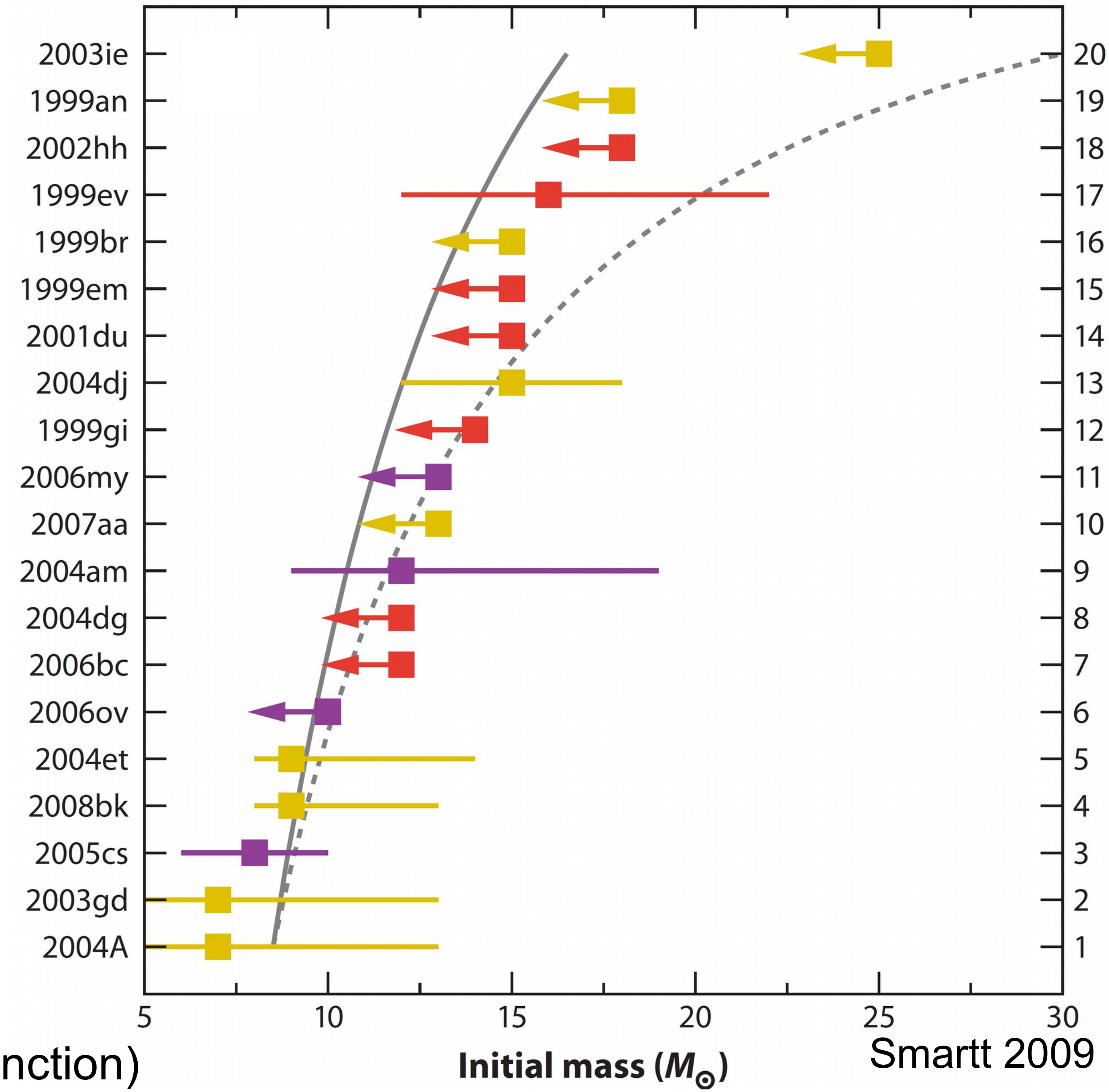


Observed Progenitors of Type IIP SNe

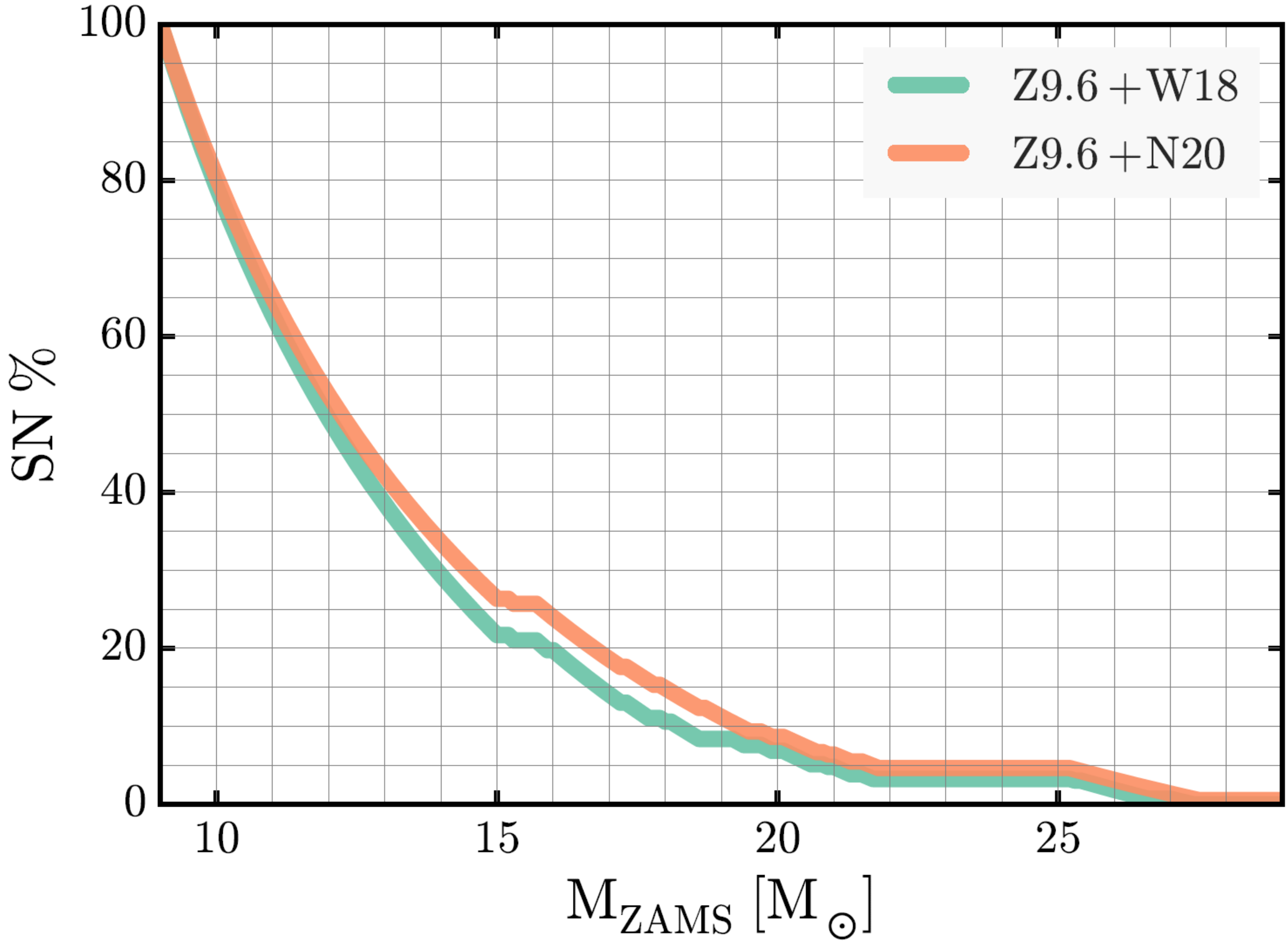
- No Type IIP SN >20 $M_\odot$
- **Line:** Assuming successful explosions only up to16.5 $M_\odot$ (IMF-weighted)
- **Dashed line:** Assuming successful explosions up to 30 $M_\odot$ (IMF-weighted)



Smartt 2009

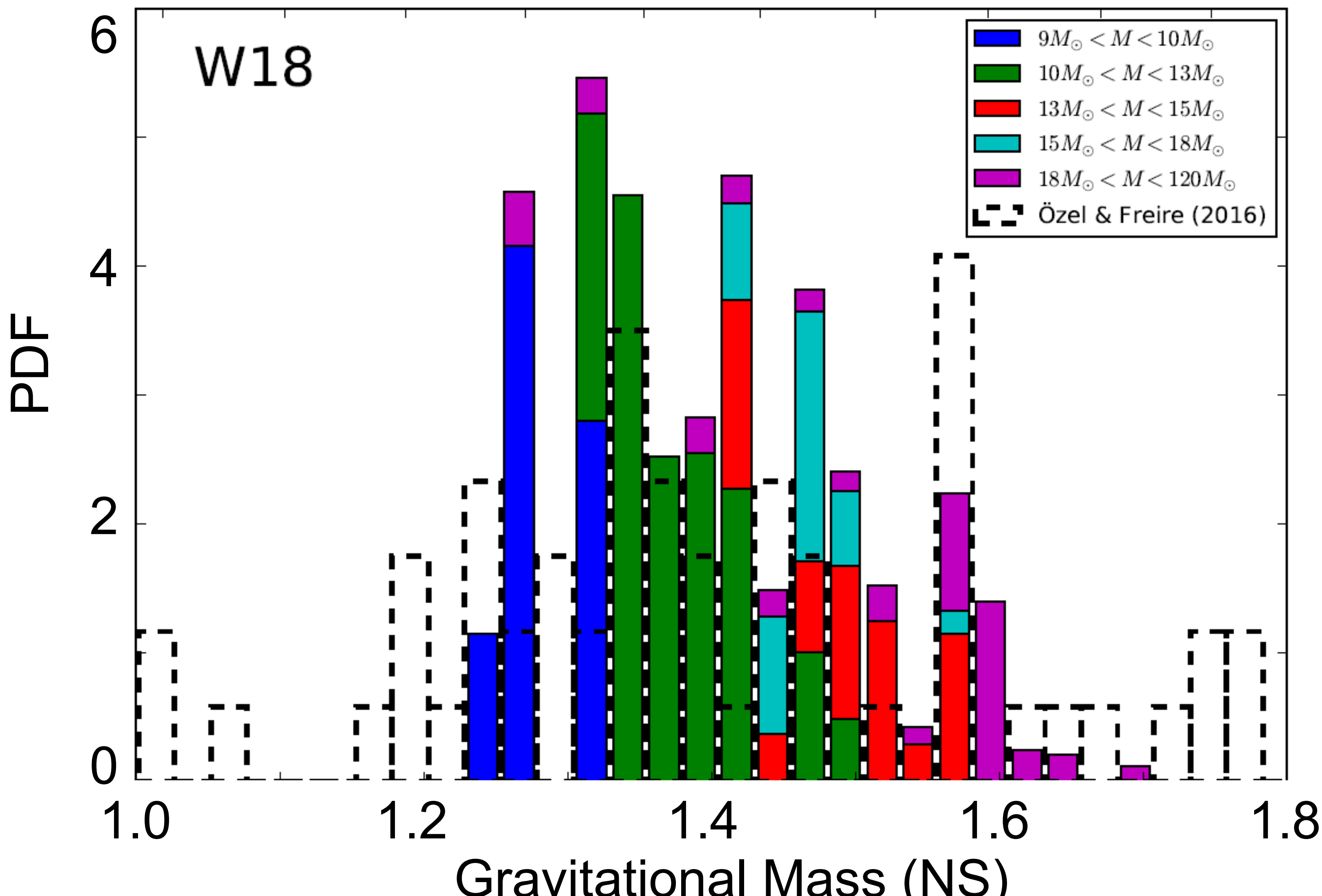
(IMF = Salpeter Initial Mass Function)

Percentage of Type II Supernovae Above a Given Mass



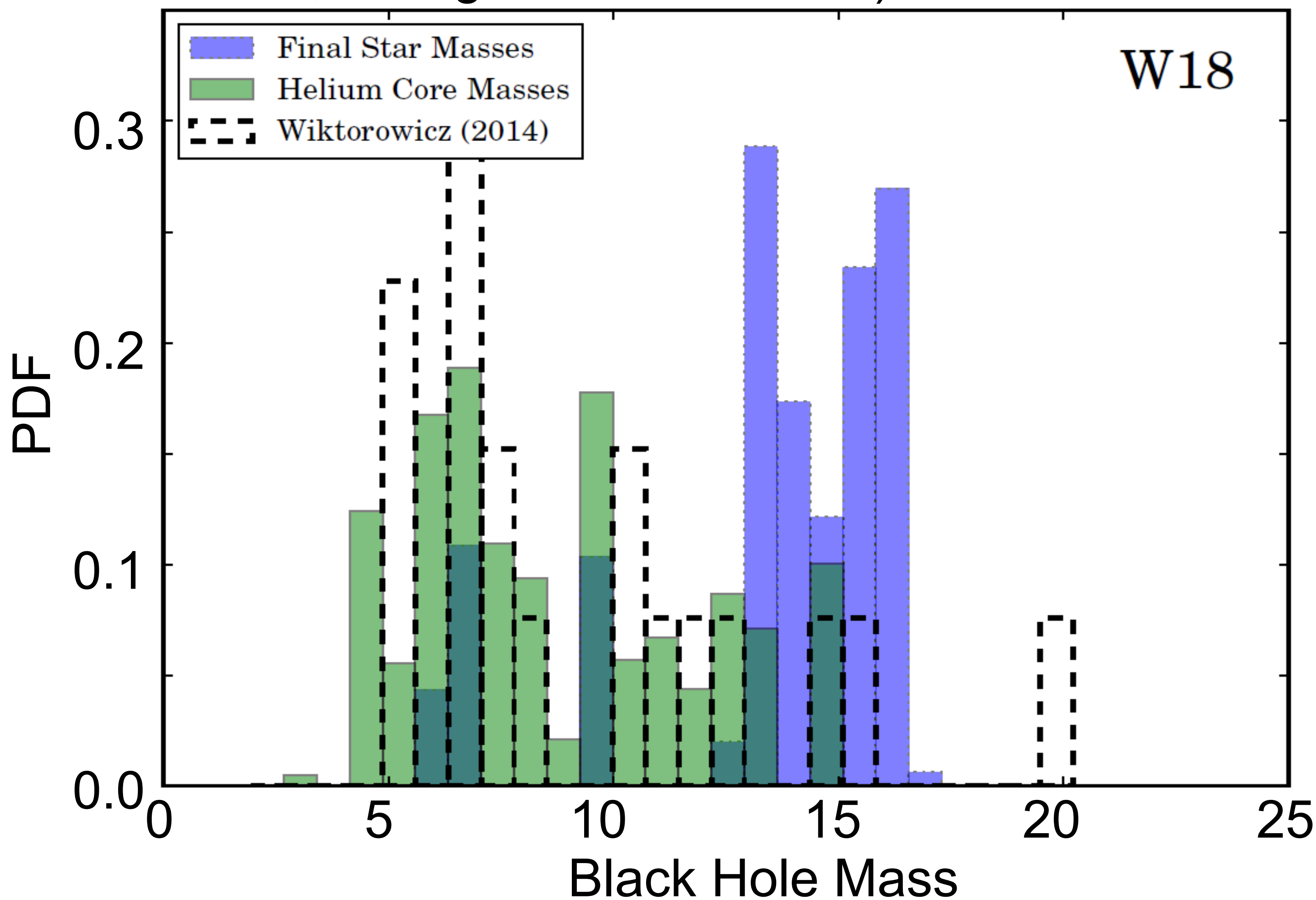
Neutron Stars

- **IMF-weighted** (Salpeter initial mass function) NS masses :

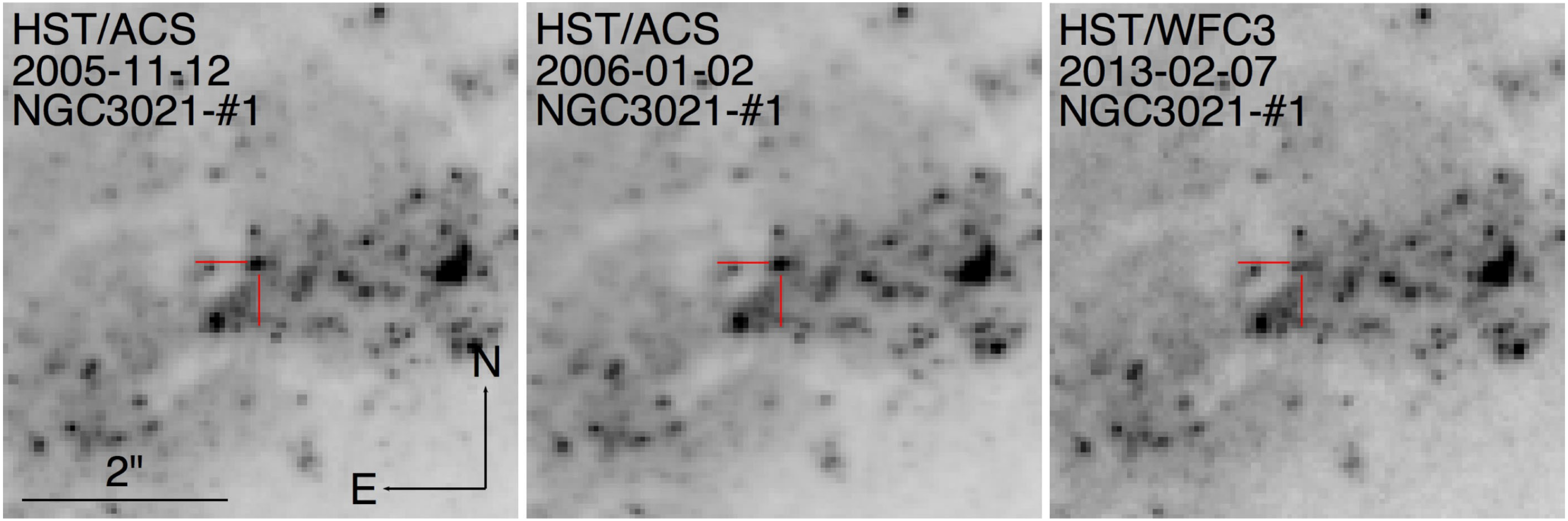


Black Holes

- With/Without ejection of the **loosely bound H-envelope** (Nadezhin 1980, Lovegroove et al. 2013)



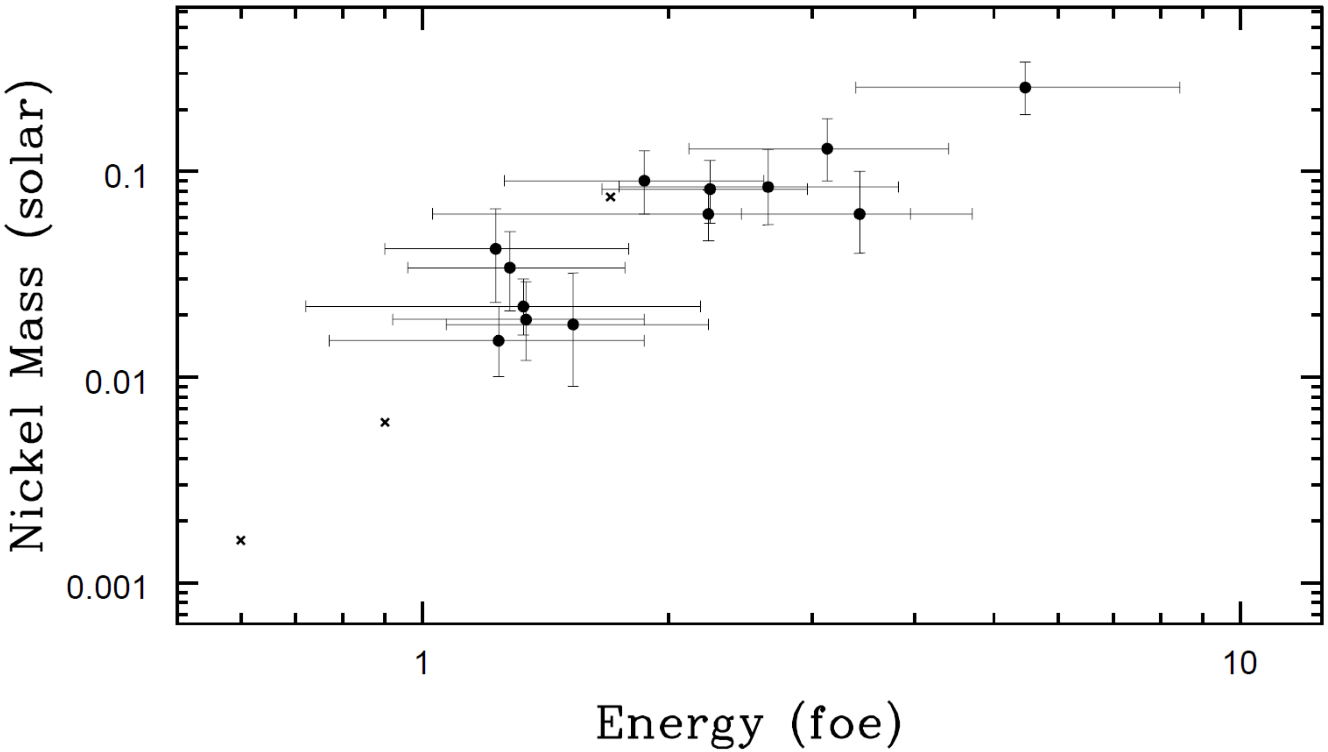
Candidate for a Disappearing Star



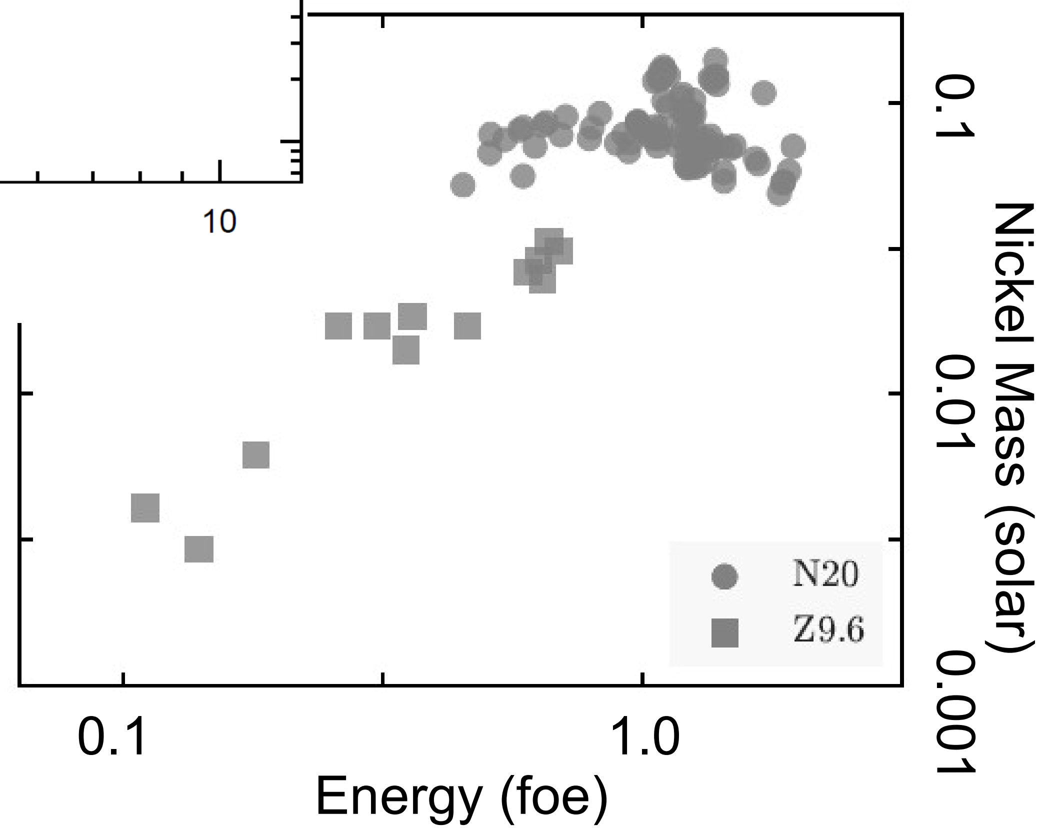
Reynolds et al. 2015

- Efforts to find **failed** CCSNe
- **BUT:** Transients with 10^{39} - 10^{40} erg/s are maybe observable (Nadezhin 1980, Lovegroove et al. 2013)

Nickel Masses and Explosion Energies



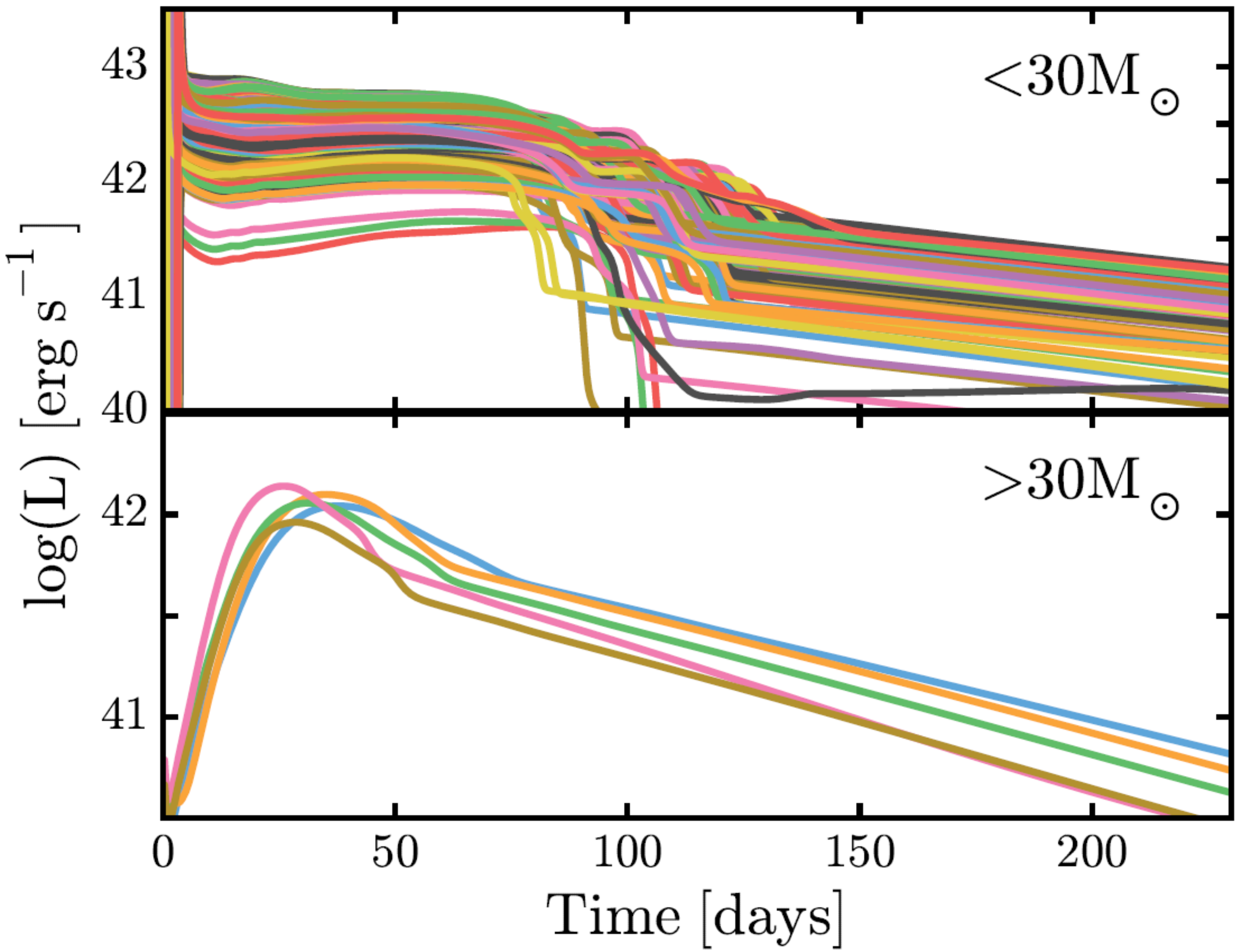
Hamuy 2003



- Explosion energies range from **~10^{50} to 2.0×10^{51} erg**
- 0.0 to 0.15 $M_{\odot}$ of **ejected nickel**

Lightcurves

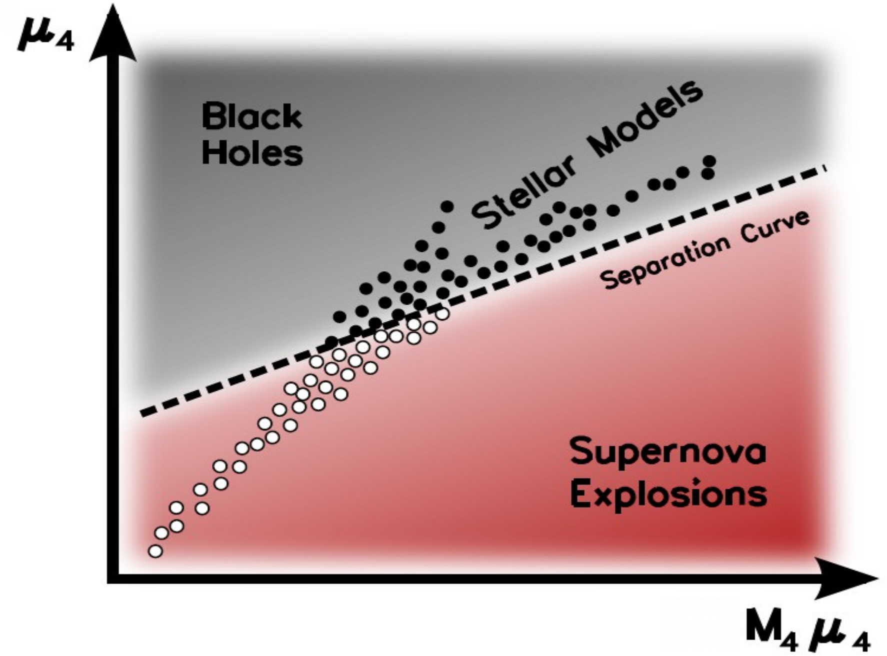
- **95%** of stars result in **Type IIP** supernovae
- No type IIL
- **No common Ibc** (too broad and faint)
  - Stripping in **binary systems**?



Conclusions

- **Two parameters classifyng the explodability** of a star by its structure prior to collapse (Ertl, Janka, Sukhbold and Woosley 2015)

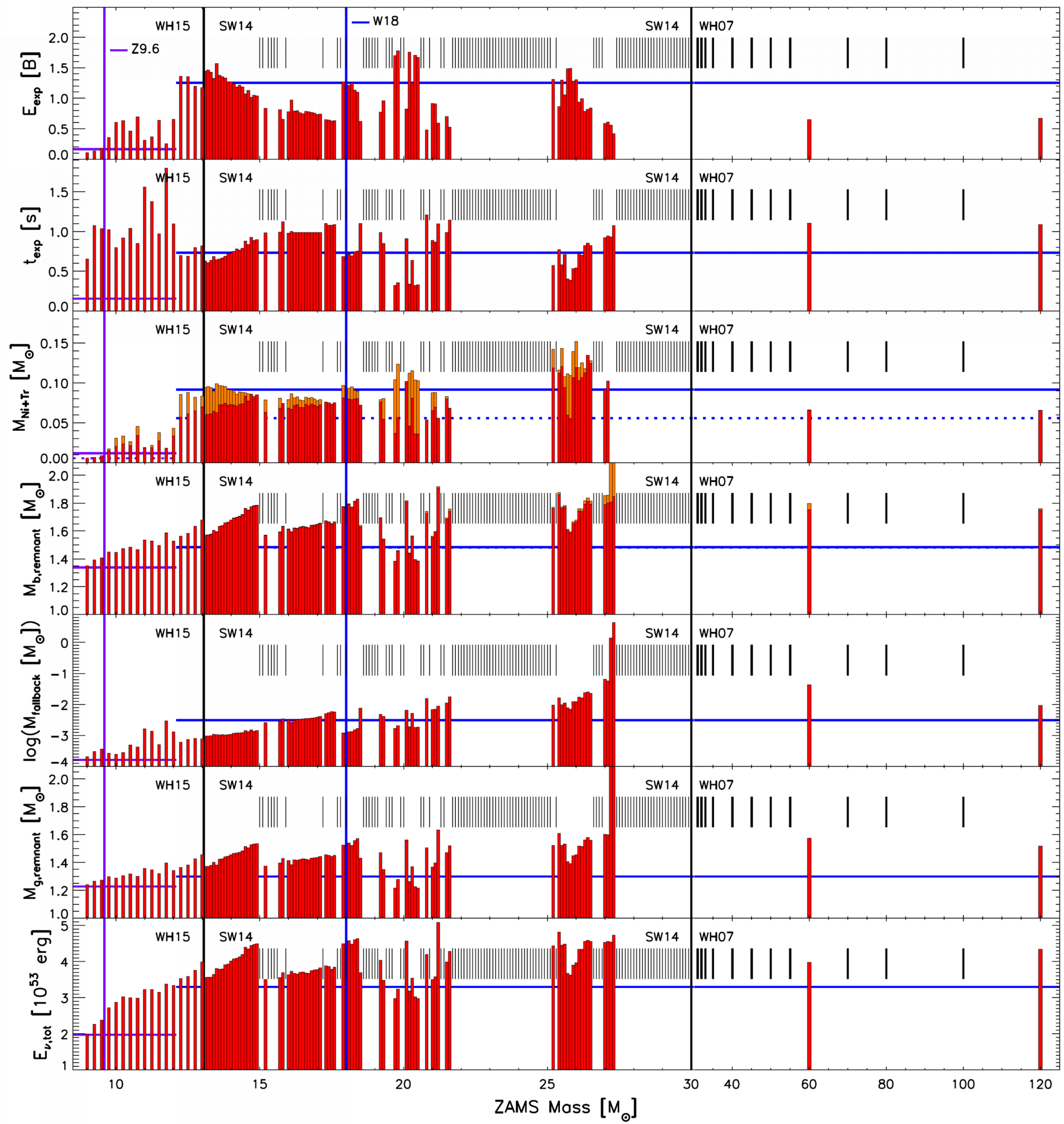
- **Low number** of BH formation cases due to late-time fallback
  - Observed **mass gap** between ~2 $M_\odot$ and ~4 $M_\odot$ **not populated**!



- **Predicting Nucleosynthesis**, **light curves**, **explosion energies**, and **remnant masses** for stars from 9 to 120 $M_\odot$, now **based on neutrino-driven explosions** (Sukhbold, Ertl, Woosley, Brown, and Janka 2015)

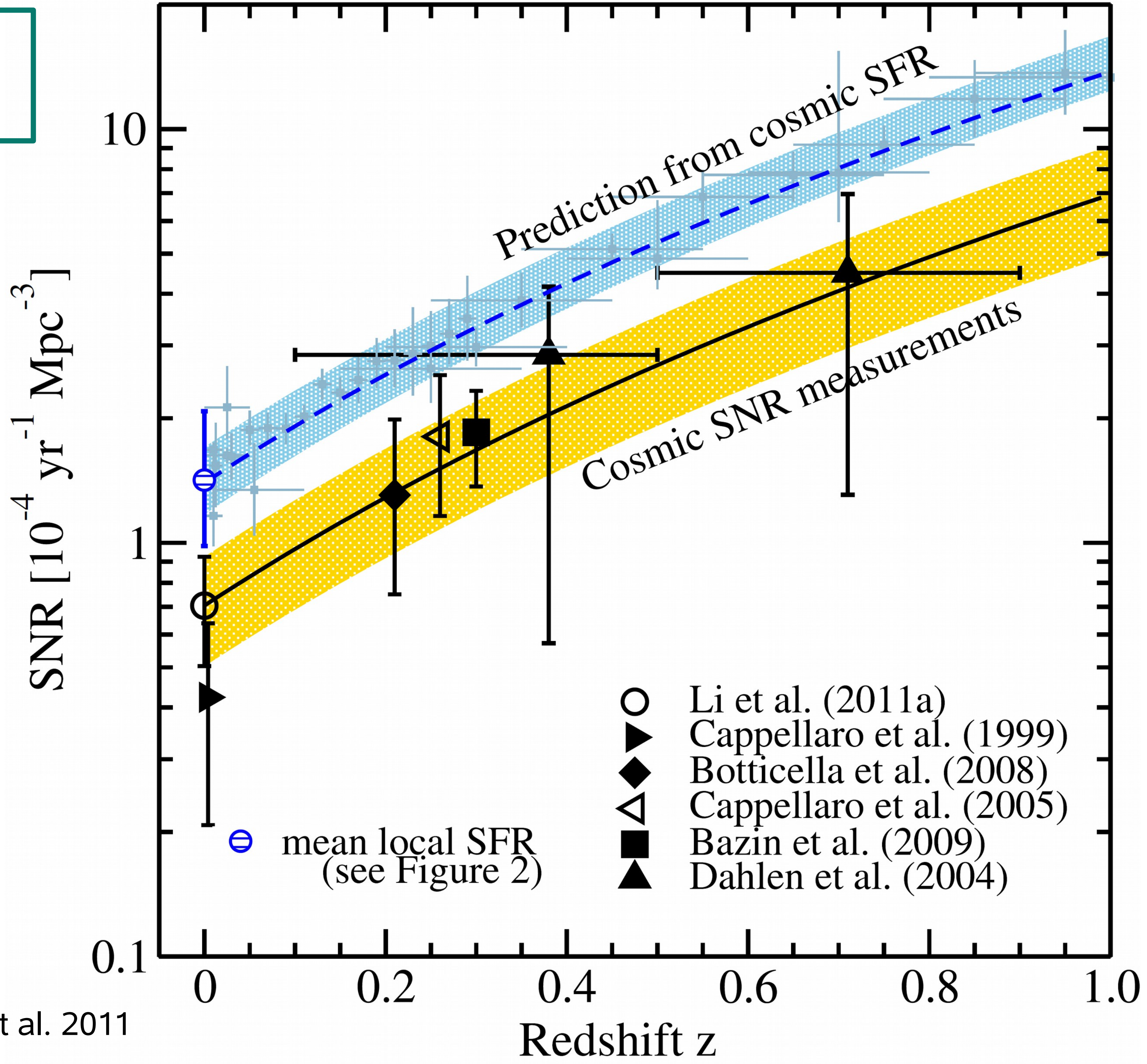
Thank you!

Backup



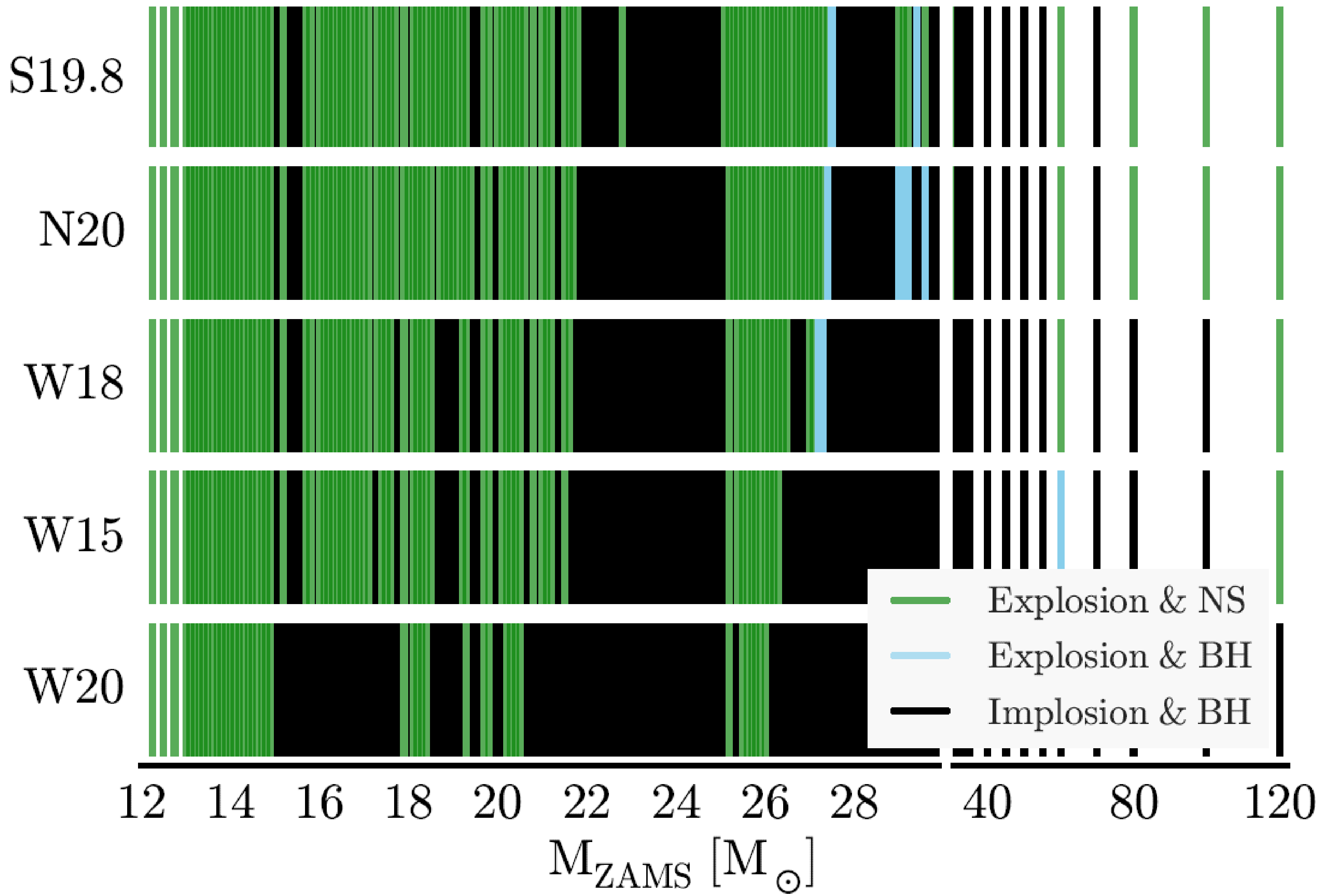
WH15
SW14
W18
SW14
WH07
Z9.6
E_{exp} [B]
t_{exp} [s]
M_{Ni+Tr} [$M_\odot$]
$M_{b,remnant}$ [$M_\odot$]
$\log(M_{fallback}$ [$M_\odot$])
$M_{g,remnant}$ [$M_\odot$]
$E_{\nu,tot}$ [10^{53} erg]
ZAMS Mass [$M_\odot$]

Backup



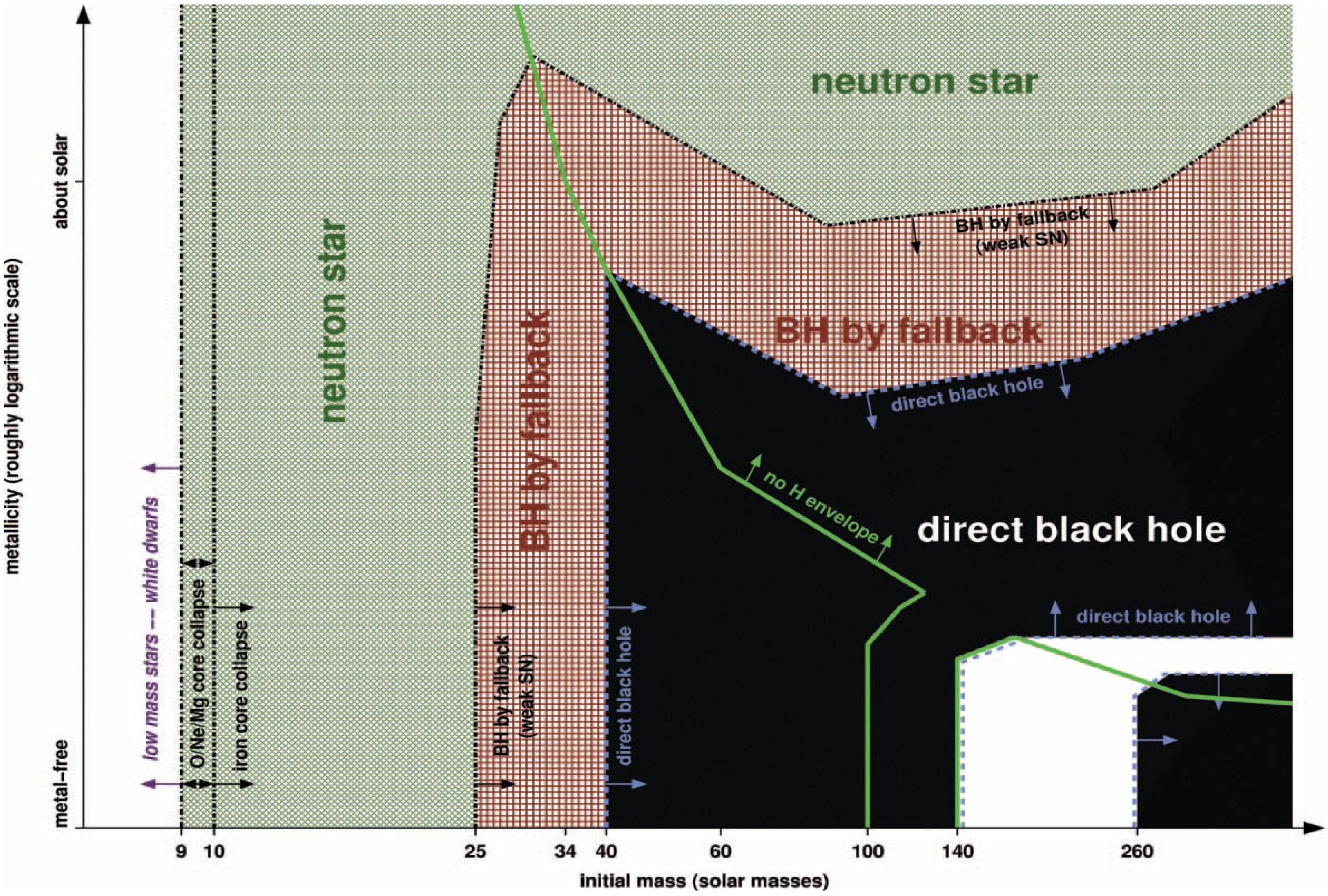
Horiuchi et al. 2011

Backup



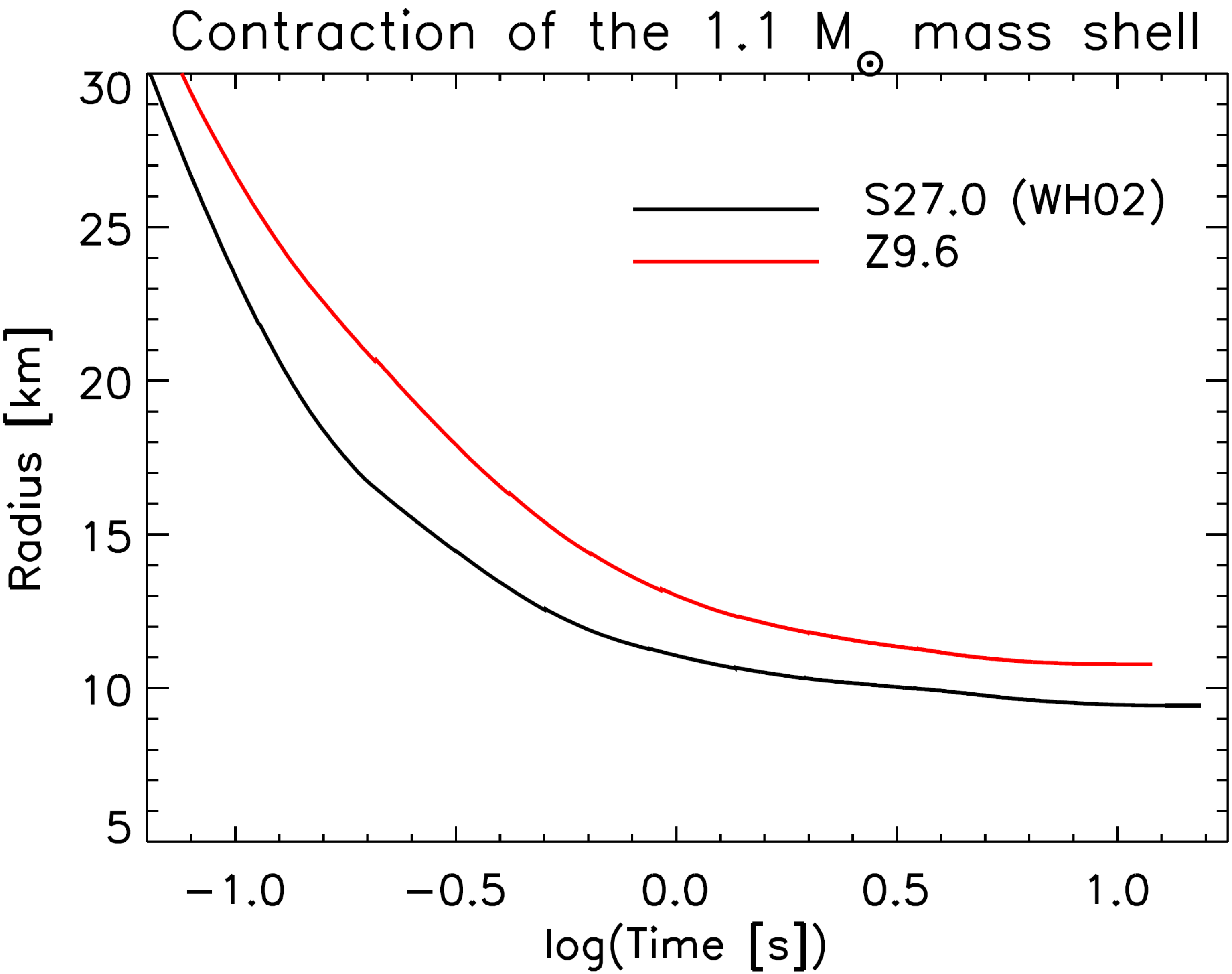
S19.8
N20
W18
W15
W20
Explosion & NS
Explosion & BH
Implosion & BH
12
14
16
18
20
22
24
26
28
40
80
120
M_{ZAMS} [$M_\odot$]

Backup – Paradigm



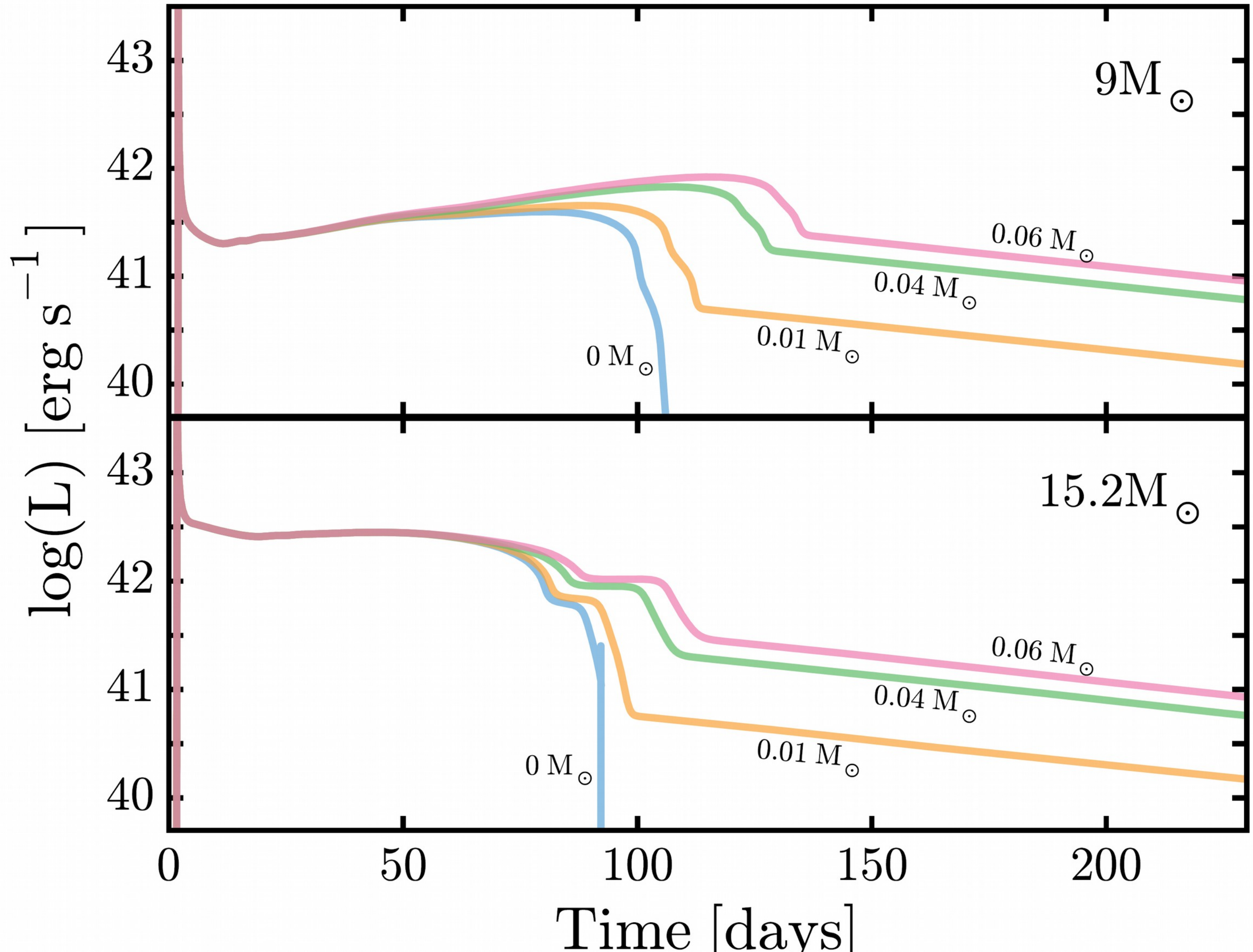
Heger et al. 2013

Backup



Contraction of the 1.1 M☉ mass shell
S27.0 (WH02)
Z9.6
Radius [km]
log(Time [s])
30
25
20
15
10
5
−1.0
−0.5
0.0
0.5
1.0

Backup



9M$_\odot$
15.2M$_\odot$
0.06 M$_\odot$
0.04 M$_\odot$
0.01 M$_\odot$
0 M$_\odot$
43
42
41
40
log(L) [erg s^{-1}]
0
50
100
150
200
Time [days]

Backup