Predictions on the Fates of Stars

Mass – Metallicity - Rotation

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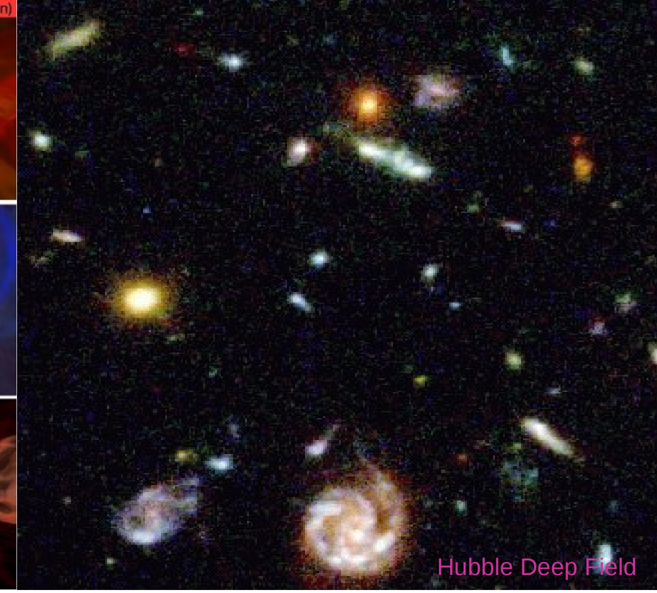
Overview

- **Varieties of Stellar Deaths of Massive Stars**
- **Expected Changes for Different Metallicities**
- **The Impact of Rotation**
- **Binary Stars**
- **Remnant Masses**

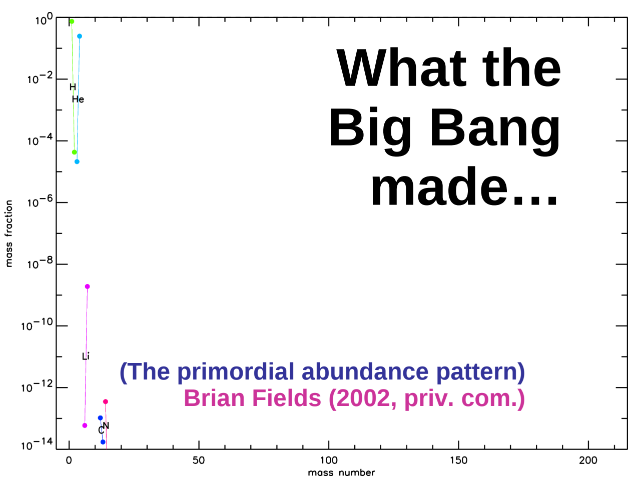
Cosmic Dark Age

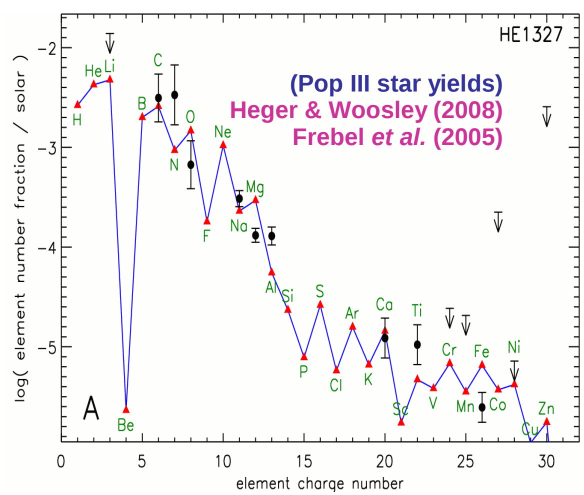
(after recombination)

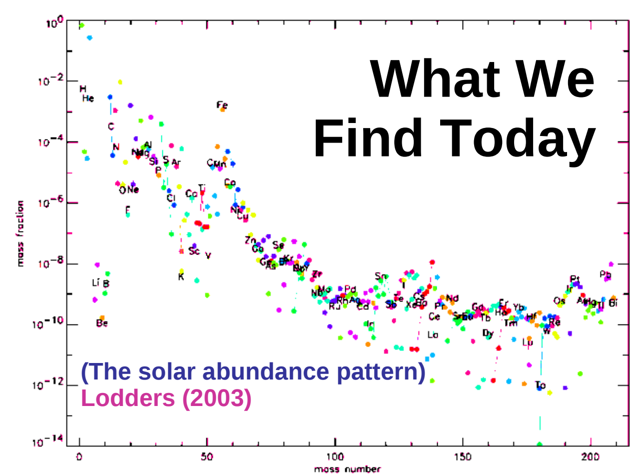
© Alexander Heger



time

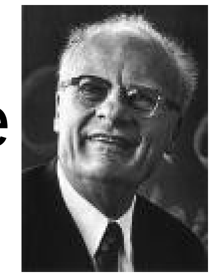






Things that blow up

supernovae



1B=10^{51} erg

MASS

- CO white dwarf → Type Ia SN, E≈ 1Bethe
- MgNeO WD, accretion → AIC, faint SN
- "SAGB" star (AGB, then SN) → EC SN
- "normal" SN (Fe core collapse) → Type II SN
- WR star (Fe CC) → Type Ib/c
- "Collapsar", GRB → broad line Ib/a SN, "hypernova"
- Pulsational pair SN → multiple, nested Type I/II SN
- Very massive stars → pair SN, ≲100B (1B=10^{51} erg)
- Very massive collapsar → IMBH, SN, hard transient
- Supermassive stars → ≳100000 B SN or SMBH

Things that blow up

Neutron star-powered supernovae

- CO white dwarf ➔ Type Ia SN, E≈ 1Bethe
- MgNeO WD, accretion ➔ AIC, faint SN
- “SAGB” star (AGB, then SN) ➔ EC SN
- “normal” SN (Fe core collapse) ➔ Type II SN
- WR star (Fe CC) ➔ Type Ib/c
- “Collapsar”, GRB ➔ broad line Ib/a SN, “hypernova”
- Pulsational pair SN ➔ multiple, nested Type I/II SN
- Very massive stars ➔ pair SN, $\lesssim$100B (1B=10^{51} erg)
- Very massive collapsar ➔ IMBH, SN, hard transient
- Supermassive stars ➔ $\gtrsim$100000 B SN or SMBH

Things that blow up

Thermonuclear supernovae (no *r*-process)

- CO white dwarf ➔ Type Ia SN, E≈ 1Bethe
- MgNeO WD, accretion ➔ AIC, faint SN
- “SAGB” star (AGB, then SN) ➔ EC SN
- “normal” SN (Fe core collapse) ➔ Type II SN
- WR star (Fe CC) ➔ Type Ib/c
- “Collapsar”, GRB ➔ broad line Ib/a SN, “hypernova”
- Pulsational pair SN ➔ multiple, nested Type I/II SN
- Very massive stars ➔ pair SN,≲100B (1B=10^{51} erg)
- Very massive collapsar ➔ IMBH, SN, hard transient
- Supermassive stars ➔ ≳100000 B SN or SMBH

Things that blow up

Black hole-powered supernovae ("Collapsars)

- CO white dwarf ➔ Type Ia SN, E≈ 1Bethe
- MgNeO WD, accretion ➔ AIC, faint SN
- "SAGB" star (AGB, then SN) ➔ EC SN
- "normal" SN (Fe core collapse) ➔ Type II SN
- WR star (Fe CC) ➔ Type Ib/c
- "Collapsar", GRB ➔ broad line Ib/a SN, "hypernova"
- Pulsational pair SN ➔ multiple, nested Type I/II SN
- Very massive stars ➔ pair SN,≲100B (1B=10^{51} erg)
- Very massive collapsar ➔ IMBH, SN, hard transient
- Supermassive stars ➔ ≳100000 B SN or SMBH

First Case: Pop III Stars

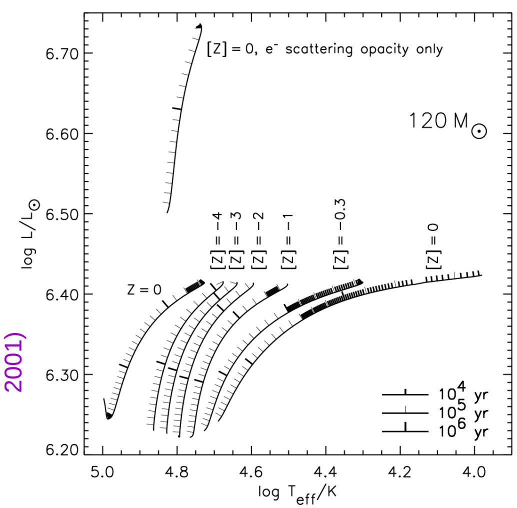
Formation and Properties of the First Stars

No metals ➔ no metal cooling ➔ more massive stars

(Bromm, Coppi, & Larson 1999, 2002; Abel, Bryan, & Norman 2000, 2002;Nakamura & Umemura 2001; **O'Shea & Norman 2006**)

➔ typical mass scale ~100 $M_\odot$

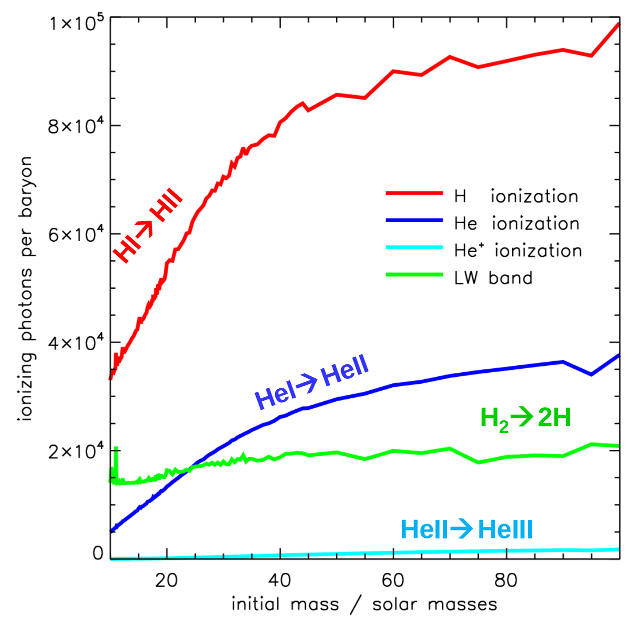
Heating by WIMP annihilation ➔ longer accretion ➔ **even bigger stars**



(Baraffe, Heger, & Woosley 2001)

First stars are very hot and very bright

➔ ionizing radiation



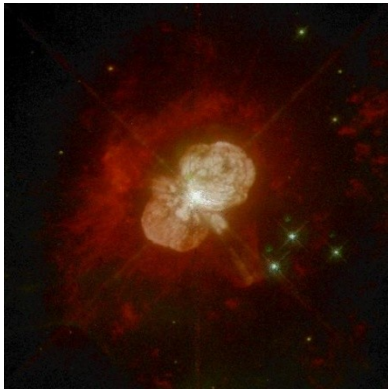
(Heger & Woosley 2007)

No metals ➔ no mass loss ➔ end life as massive stars

Mass Loss in Very Massive Primordial Stars

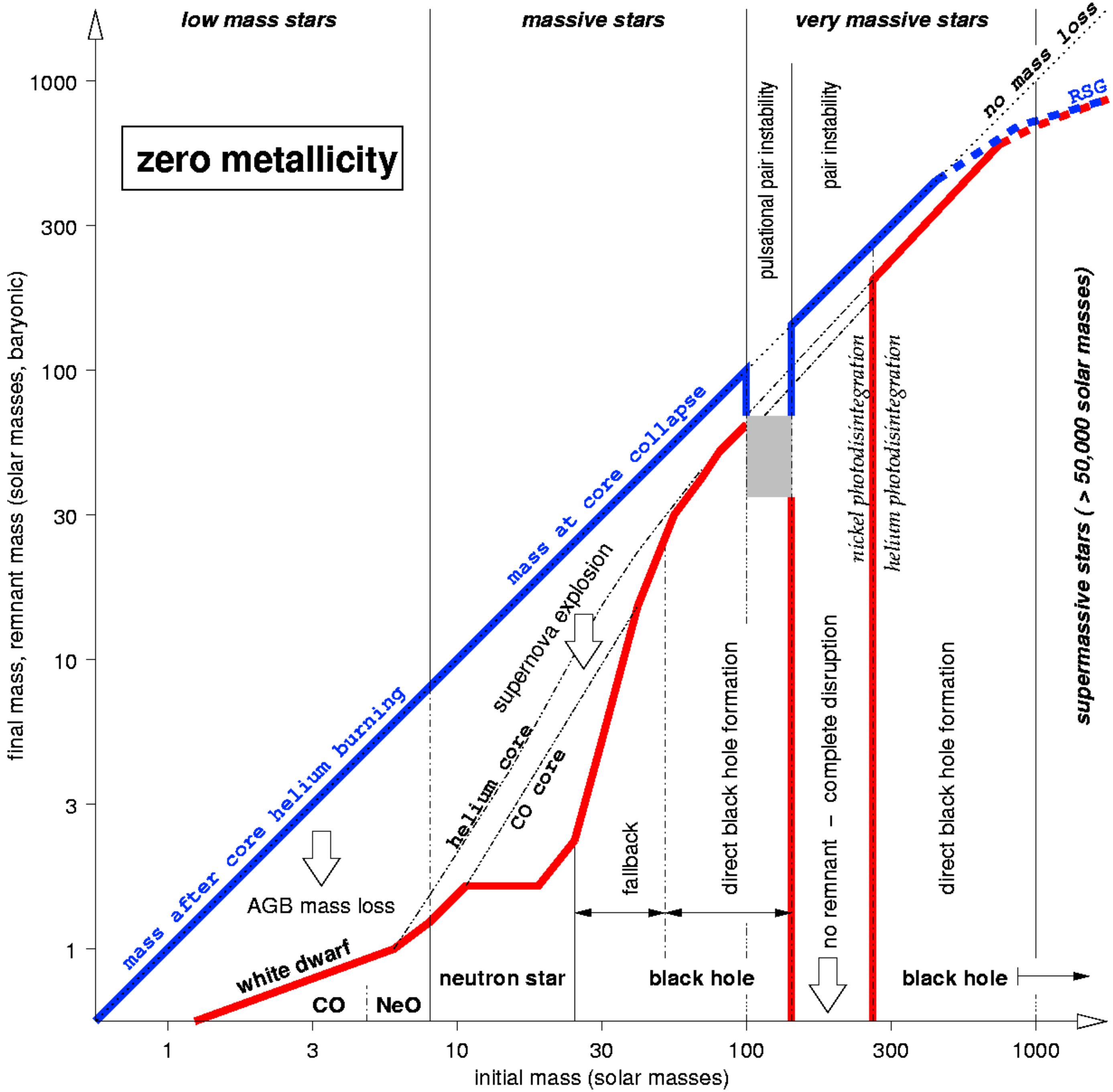
- Negligible line-driven winds
  (mass loss ~ metallicity$^{>1/2}$ – Kudritzki 2002)
- No opacity-driven pulsations (no metals – Baraffe, Heger & Woosley 2001)
- Continuum-driven winds and errptions @ $L \sim L_{Edd}$ have to be explored (Smith, Owocki, Shaviv, *et al. 2005*++)
- Epsilon mechanism inefficient in metal-free stars below ~1000 $M_{\odot}$ (Baraffe *et al.* 2001)
  from pulsational analysis we estimate:
  - 120 solar masses: < 0.2 %
  - 300 solar masses: < 3.0 %
  - 500 solar masses: < 5.0 %
  - 1000 solar masses: < 12. %

  during central hydrogen burning



?

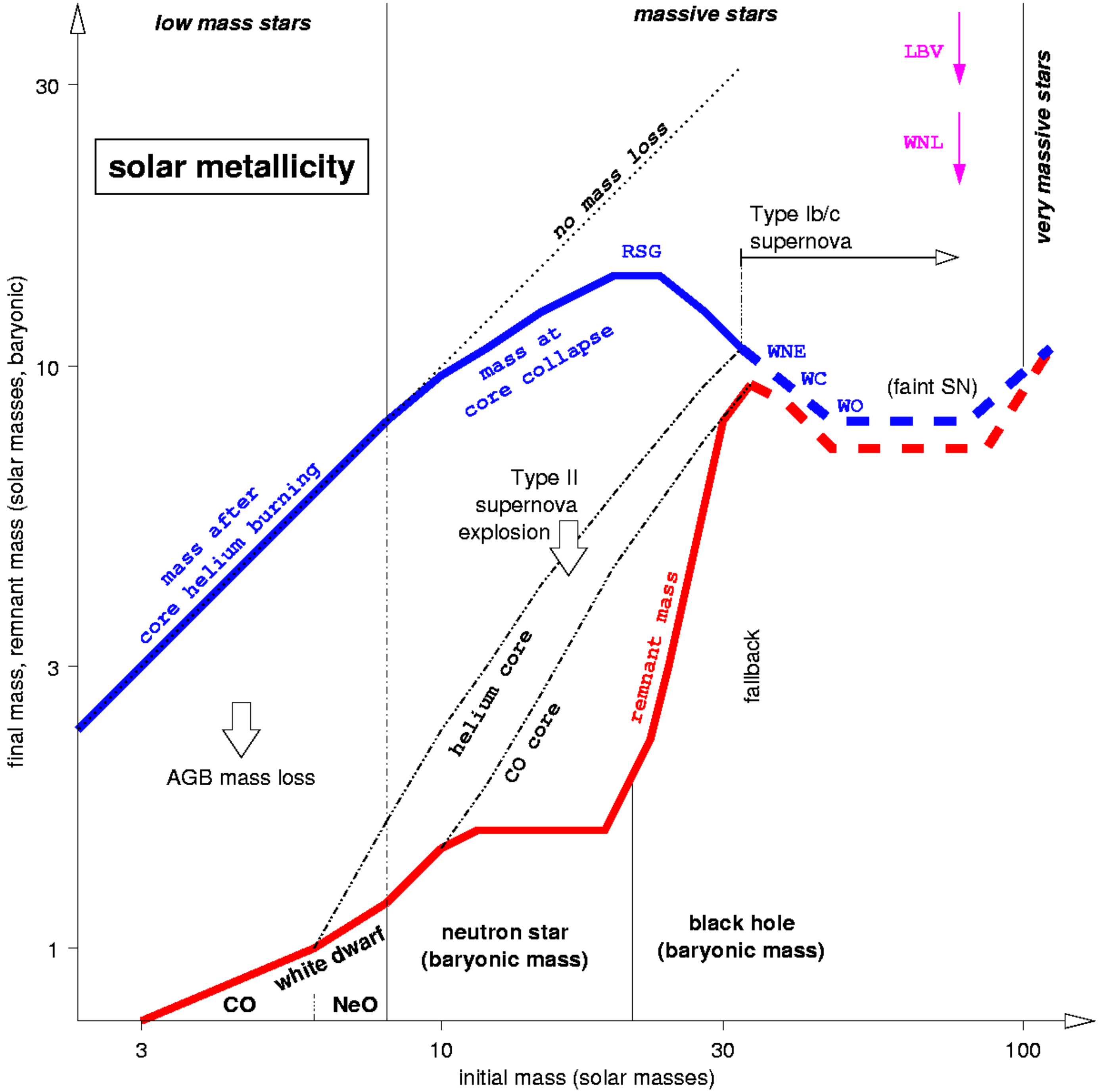
- Red Super Giant pulsations could lead to significant mass loss during helium burning for stars above ~500 $M_{\odot}$
- Rotationally induced ***mixing*** and mass loss, giant eruptions, etc.?



low mass stars
massive stars
very massive stars
zero metallicity
no mass loss
RSG
pulsational pair instability
pair instability
mass at core collapse
mass after core helium burning
supernova explosion
helium core
CO core
AGB mass loss
white dwarf
CO
NeO
neutron star
fallback
direct black hole formation
black hole
no remnant – complete disruption
nickel photodisintegration
helium photodisintegration
direct black hole formation
black hole
supermassive stars (> 50,000 solar masses)
final mass, remnant mass (solar masses, baryonic)
1000
300
100
30
10
3
1
1
3
10
30
100
300
1000
initial mass (solar masses)

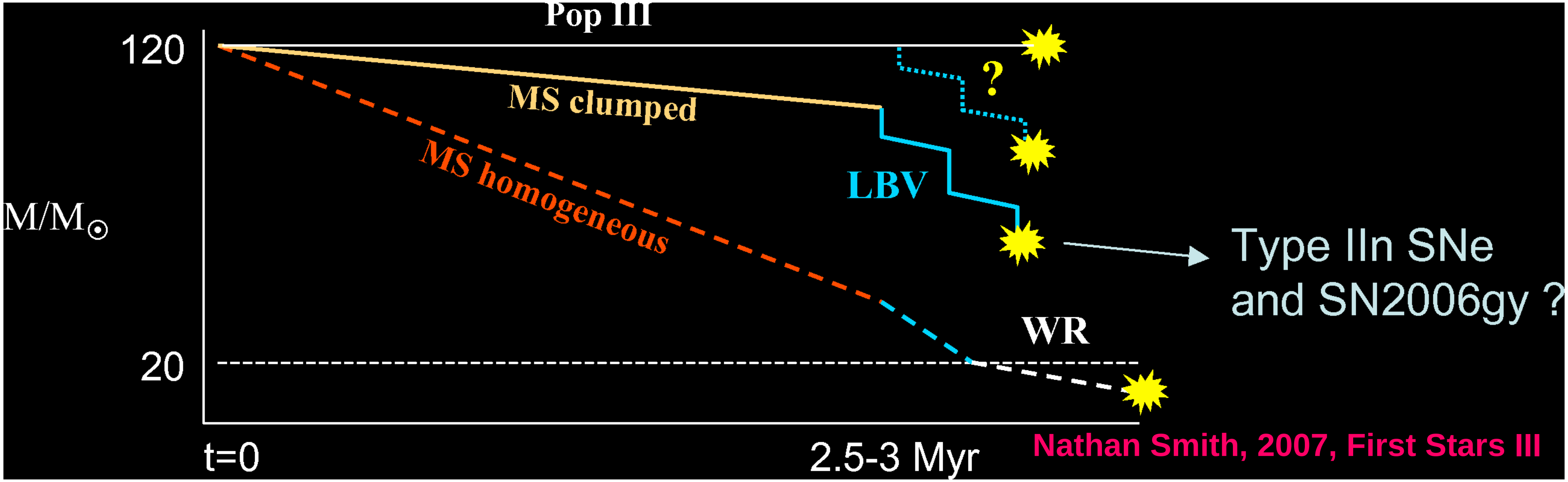
Evolution with Metals

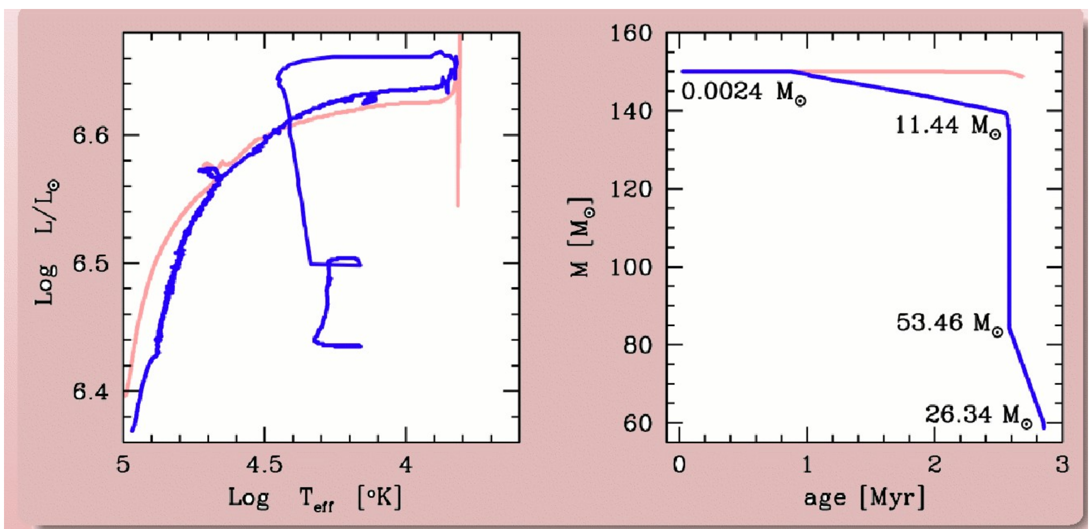
- change initial mass function
- opacity increases
  → increased mass loss, instabilities, outbursts
  larger radius → slower rotation
- hydrogen burning by CNO cycle from seed metals
- massive stars make bare helium stars due to mass loss



low mass stars
massive stars
very massive stars
solar metallicity
LBV
WNL
no mass loss
RSG
Type Ib/c
supernova
WNE
WC
WO
(faint SN)
mass at
core collapse
mass after
core helium burning
Type II
supernova
explosion
helium core
CO core
remnant mass
fallback
AGB mass loss
white dwarf
CO
NeO
neutron star
(baryonic mass)
black hole
(baryonic mass)
30
10
3
1
final mass, remnant mass (solar masses, baryonic)
3
10
30
100
initial mass (solar masses)

Mass Loss by Giant eruptions?





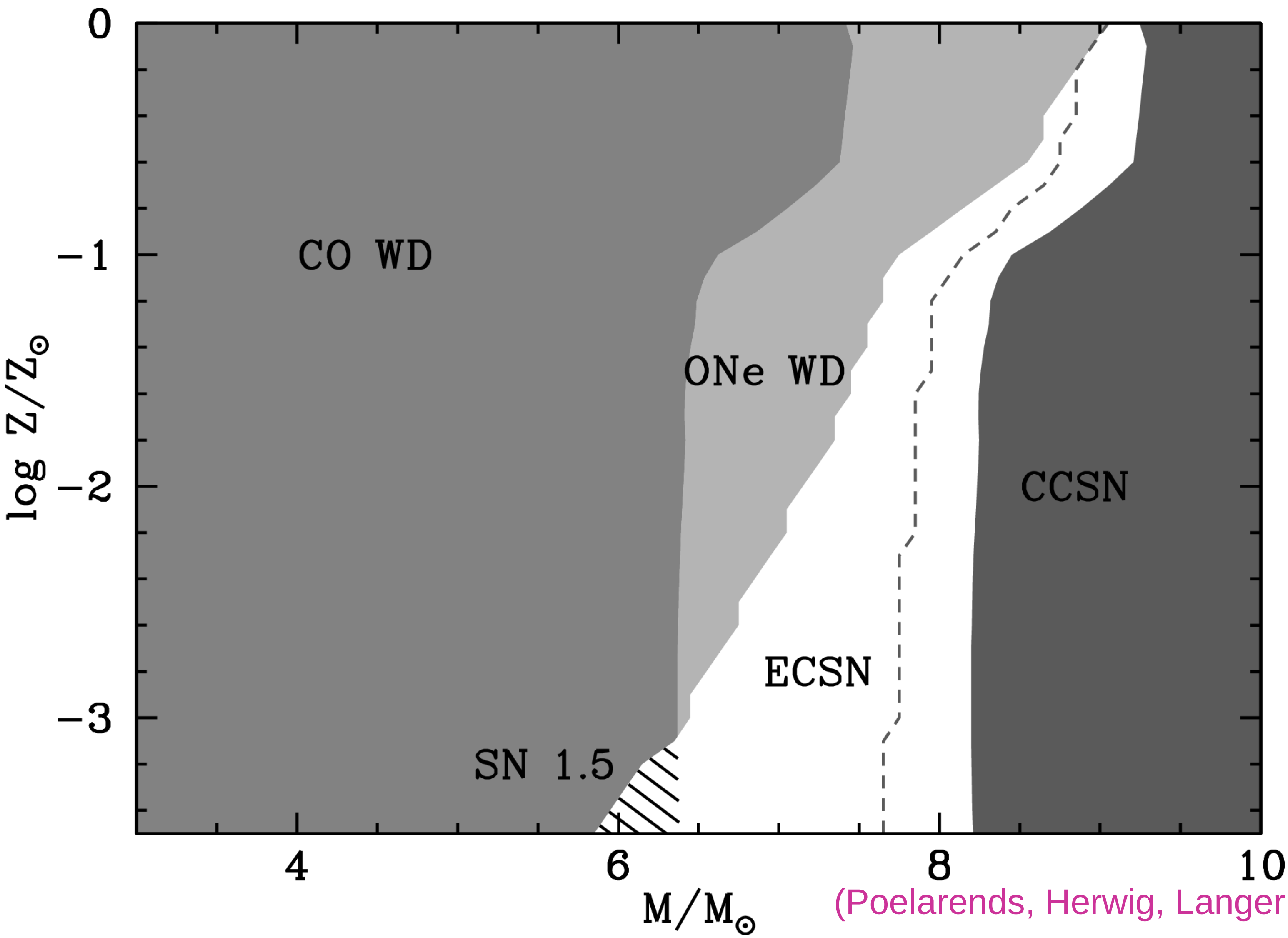
end of central He-burning: $M = 58.05\ M_{\odot}$
back at break-up limit

Mass Loss due to critical rotation?

Eikstroem, 2007, First Stars III

Remnant Types as Function of Mass and Metallicity

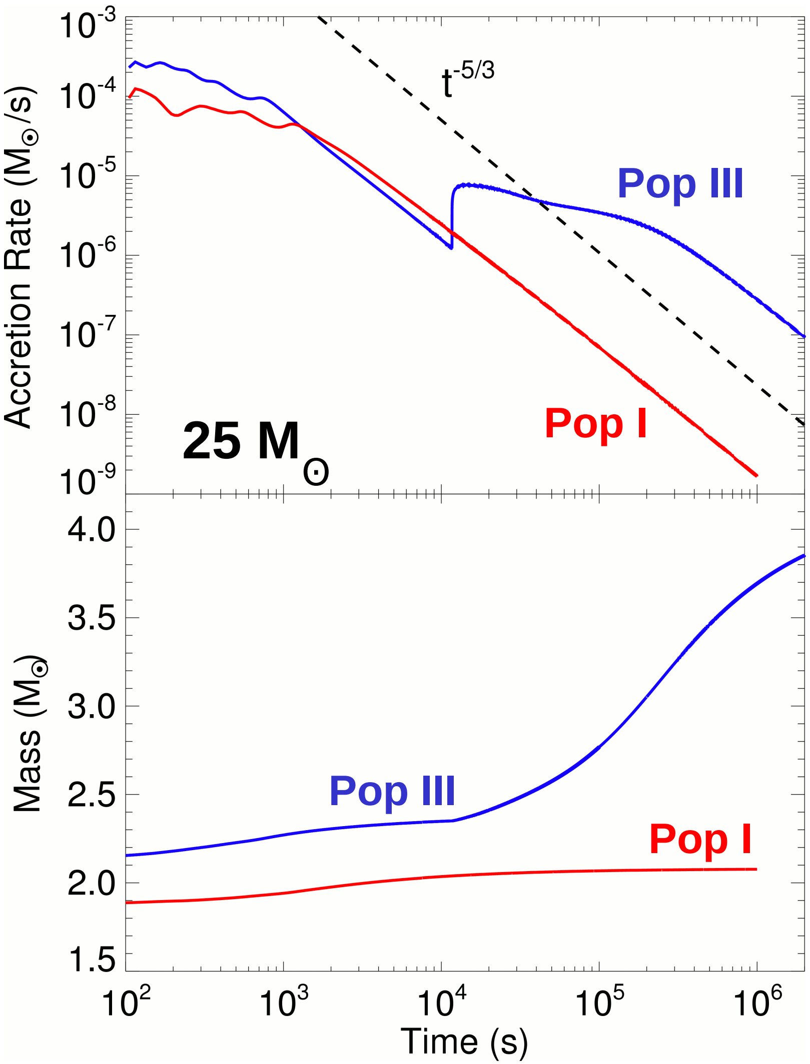
The Lowest Mass Core Collapse SNe

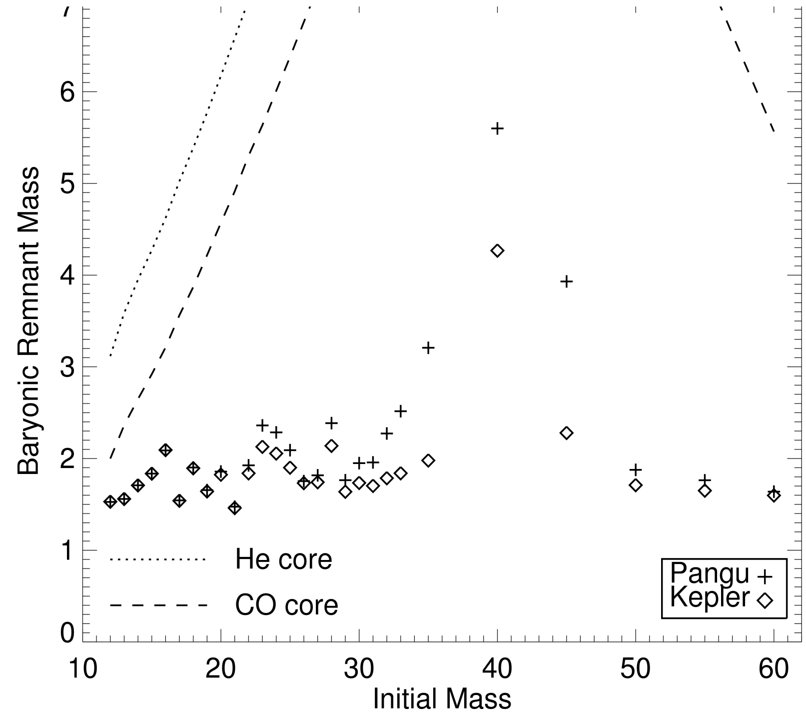


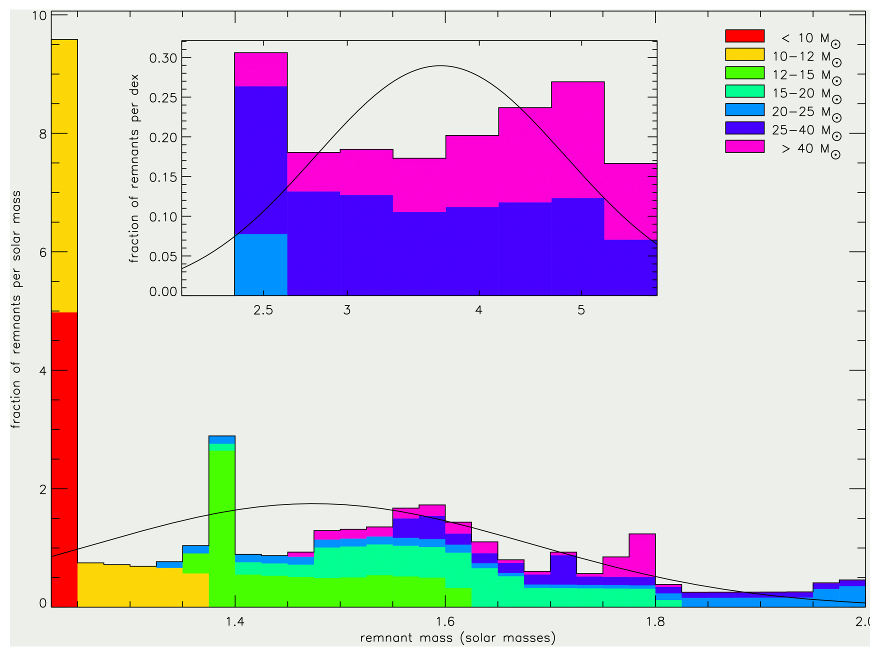
(Poelarends, Herwig, Langer, Heger 2007)

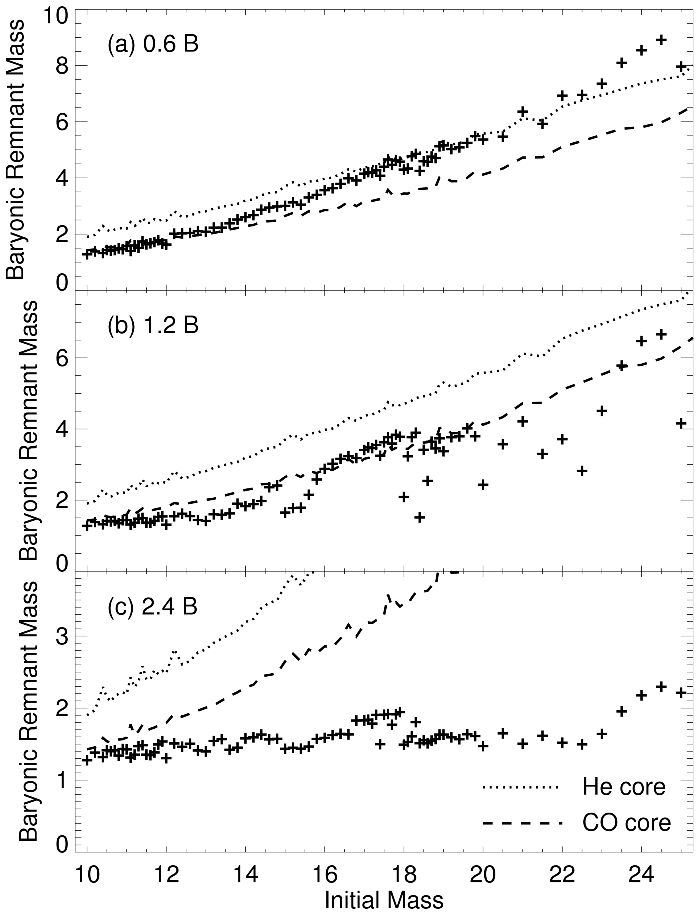
Fallback and Remnants

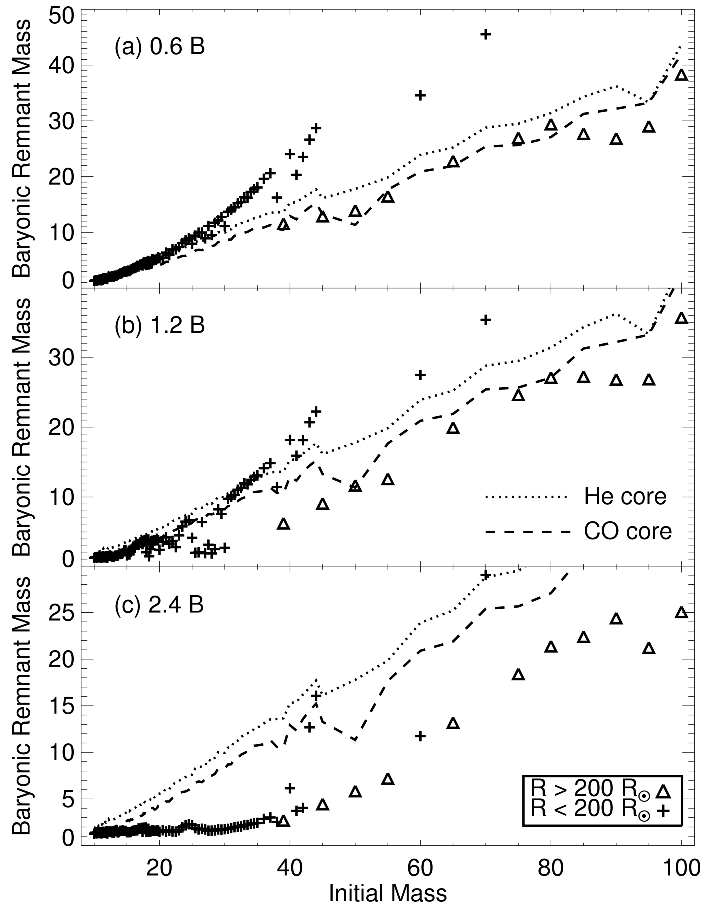
(Zhang, Woosley, Heger 2007)









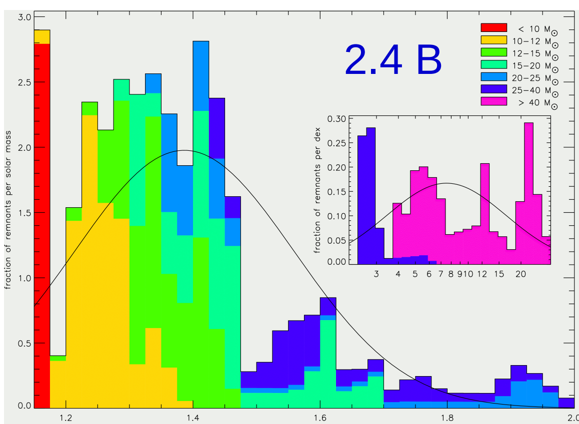


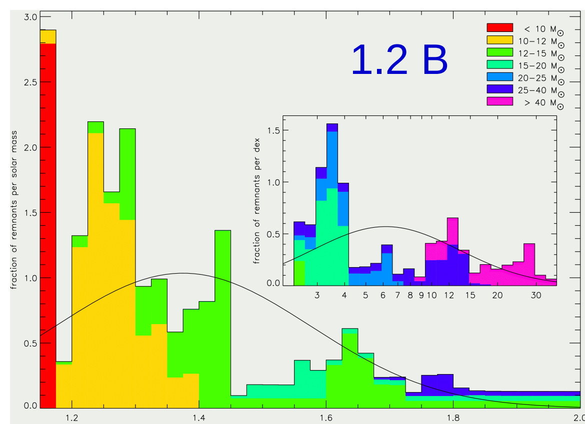
Pop III Stars

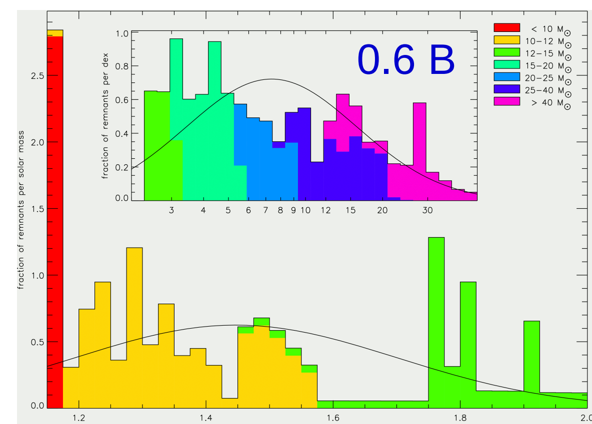
Much fallback for compact stars ("+")

Less fallback for RSG ("Δ")

(Zhang, Woosley, Heger 2007)

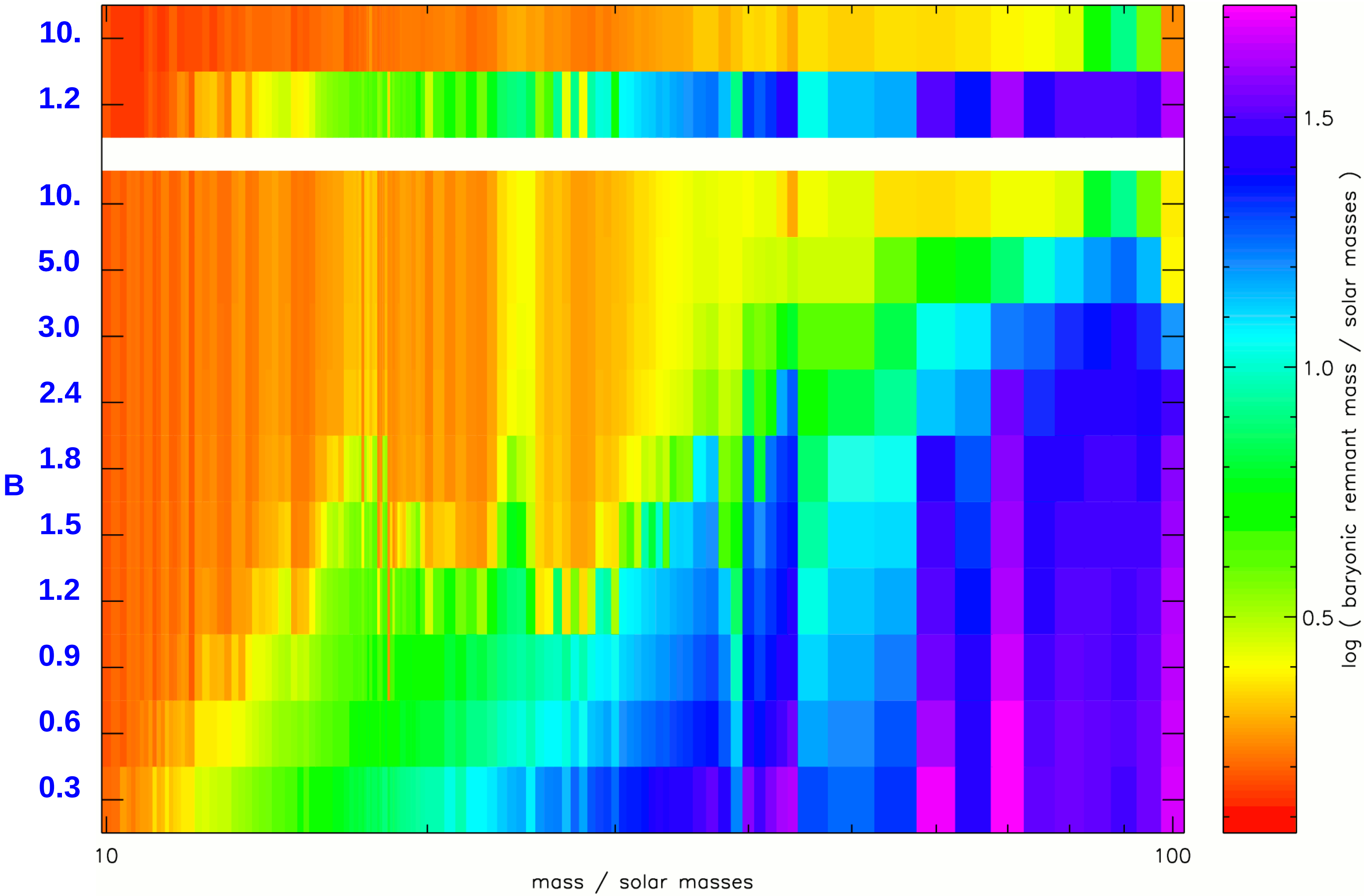






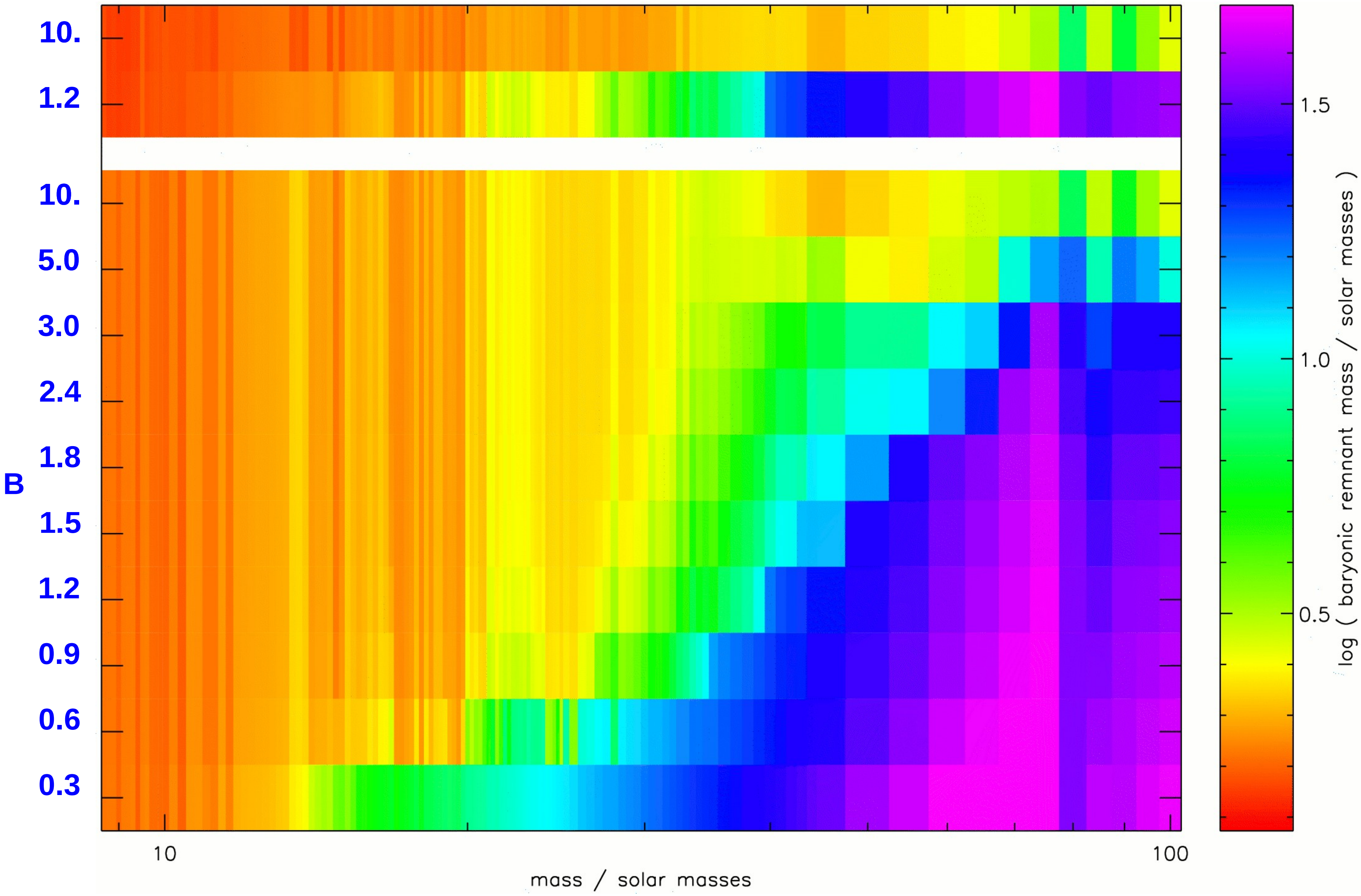
Pop III Star Remnant Masses

(from Zhang, Woosley, Heger 2007)

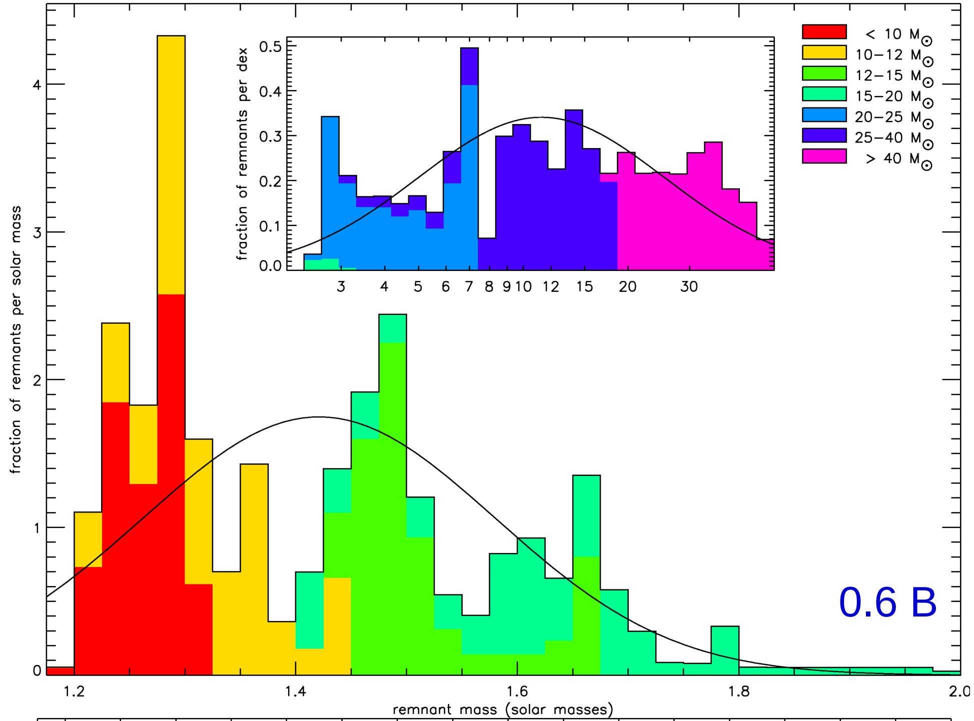


[Z]= -4 Star Remnant Masses

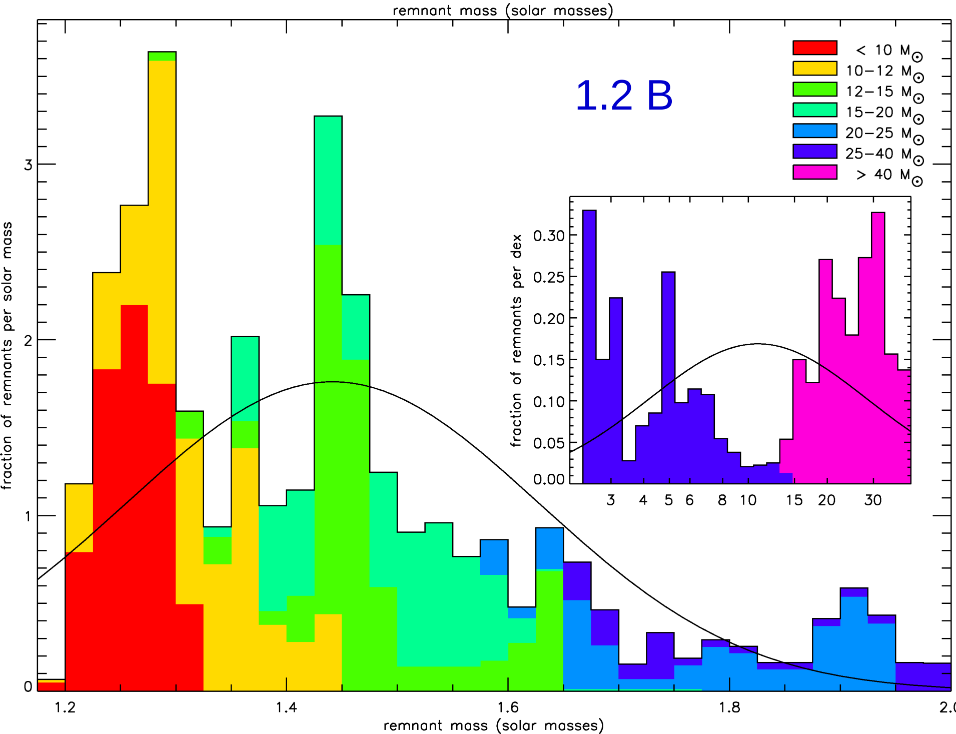
(from Heger, Woosley, Zhang, in prep. 2009)

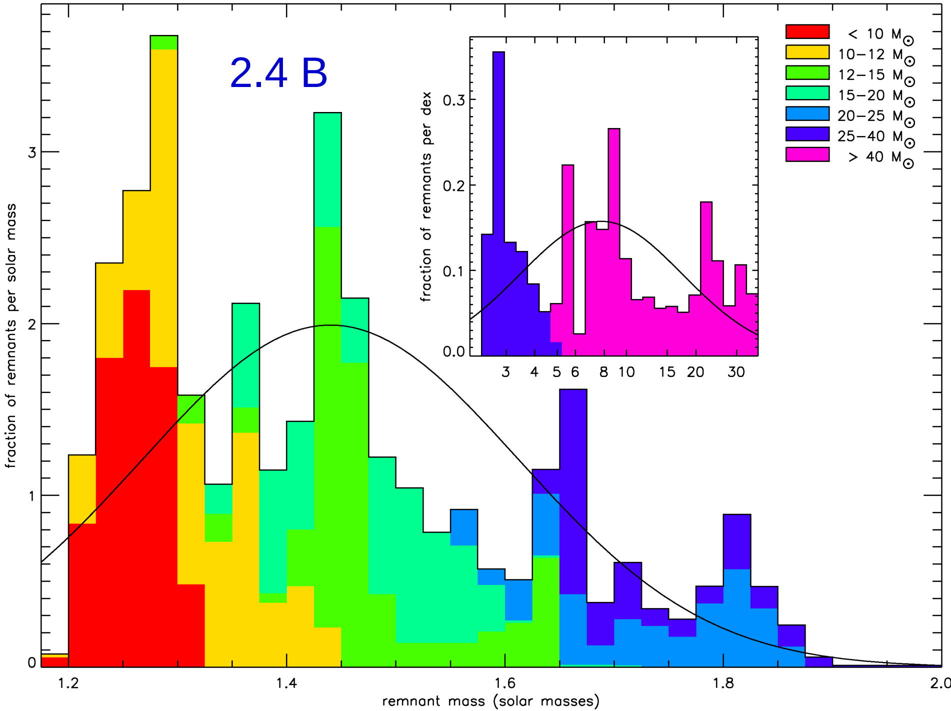


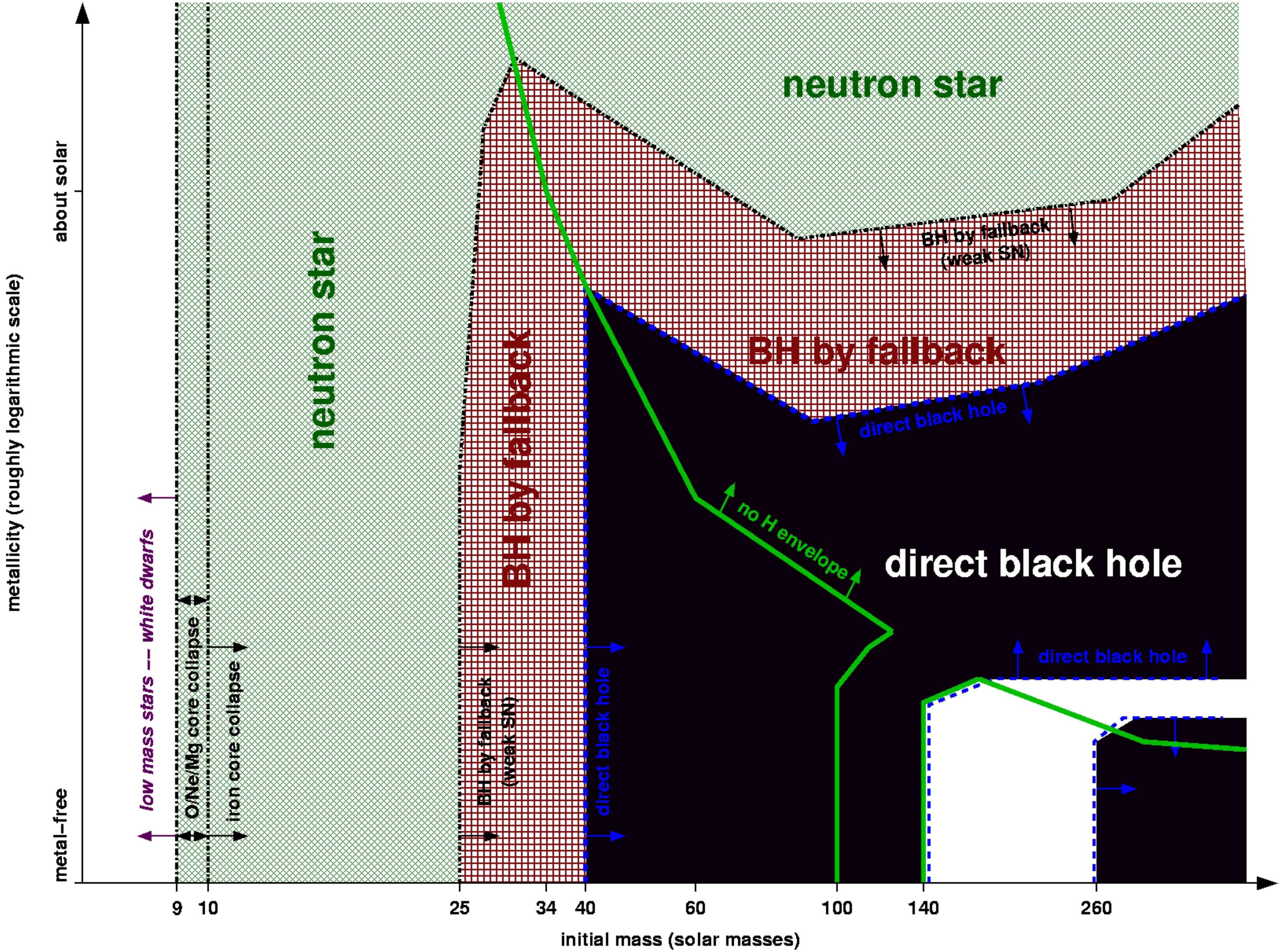
[Z]=-4 Stars



(Heger, Woosley, Zhang in prep 2009)

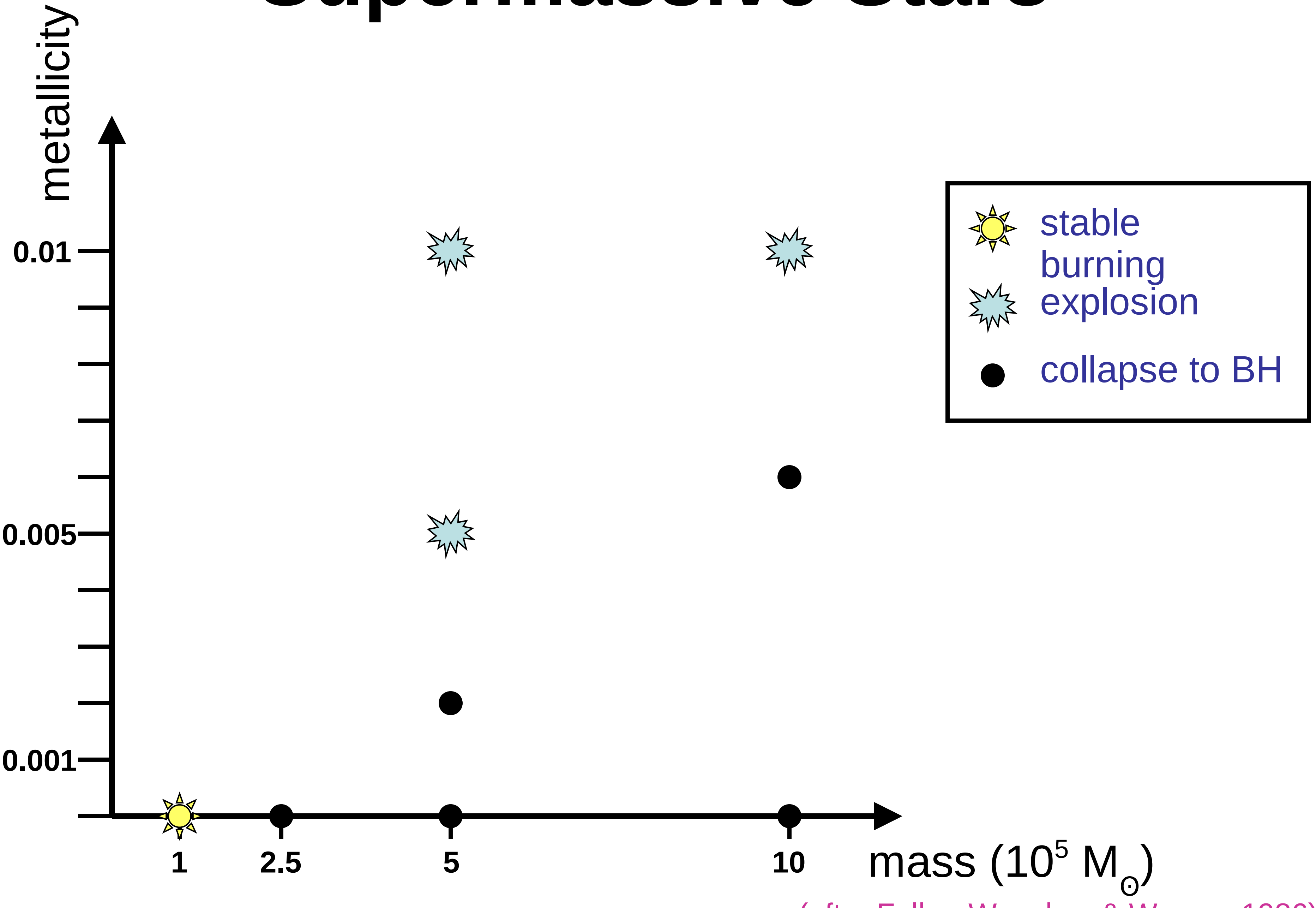






neutron star
neutron star
BH by fallback
BH by fallback
BH by fallback (weak SN)
BH by fallback (weak SN)
direct black hole
direct black hole
direct black hole
direct black hole
no H envelope
low mass stars -- white dwarfs
O/Ne/Mg core collapse
iron core collapse
about solar
metal-free
metallicity (roughly logarithmic scale)
9
10
25
34
40
60
100
140
260
initial mass (solar masses)

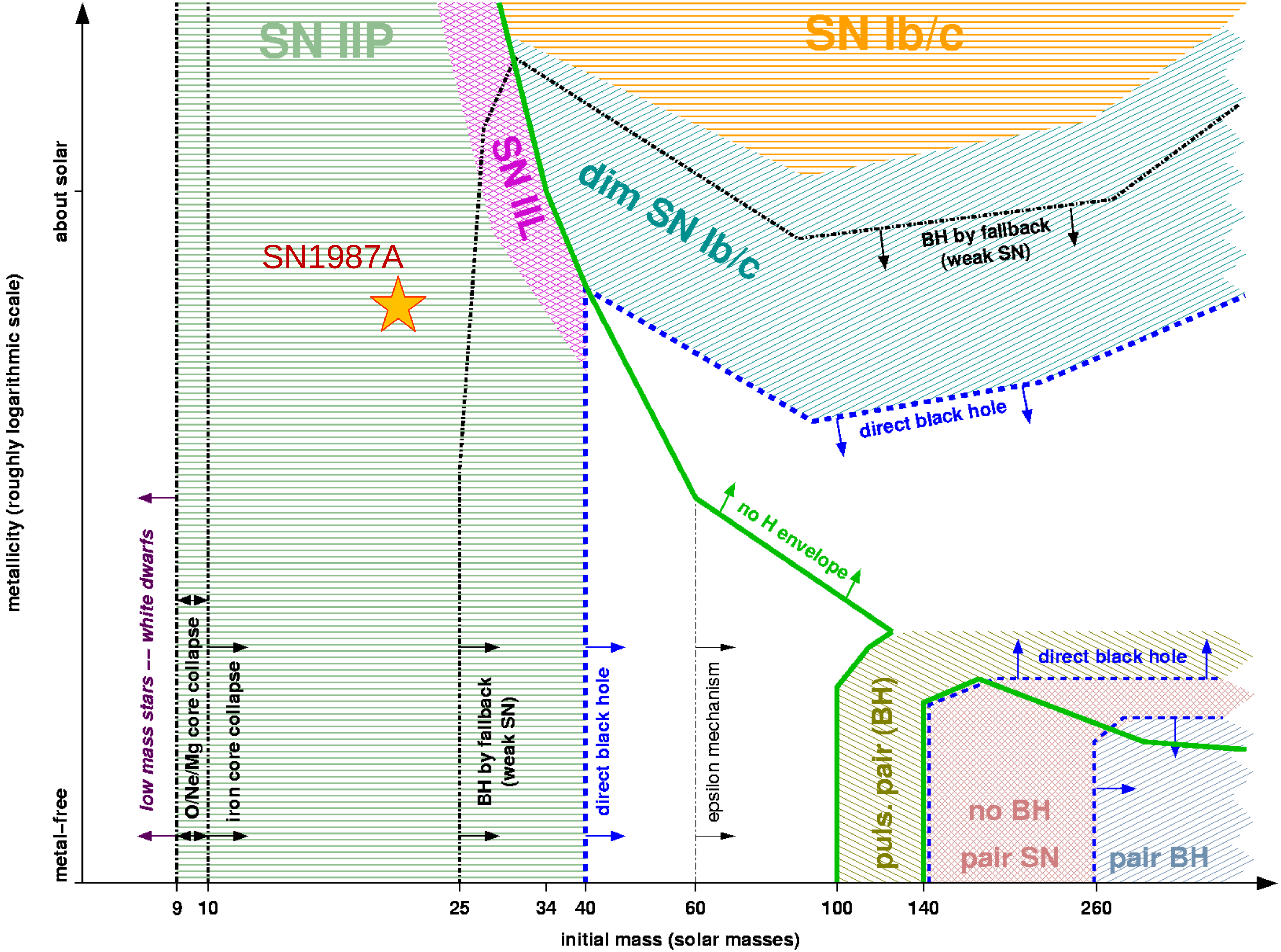
Supermassive Stars



(after Fuller, Woosley, & Weaver 1986)

Massive Star Fates as Function of Mass and Metallicity

(single stars)

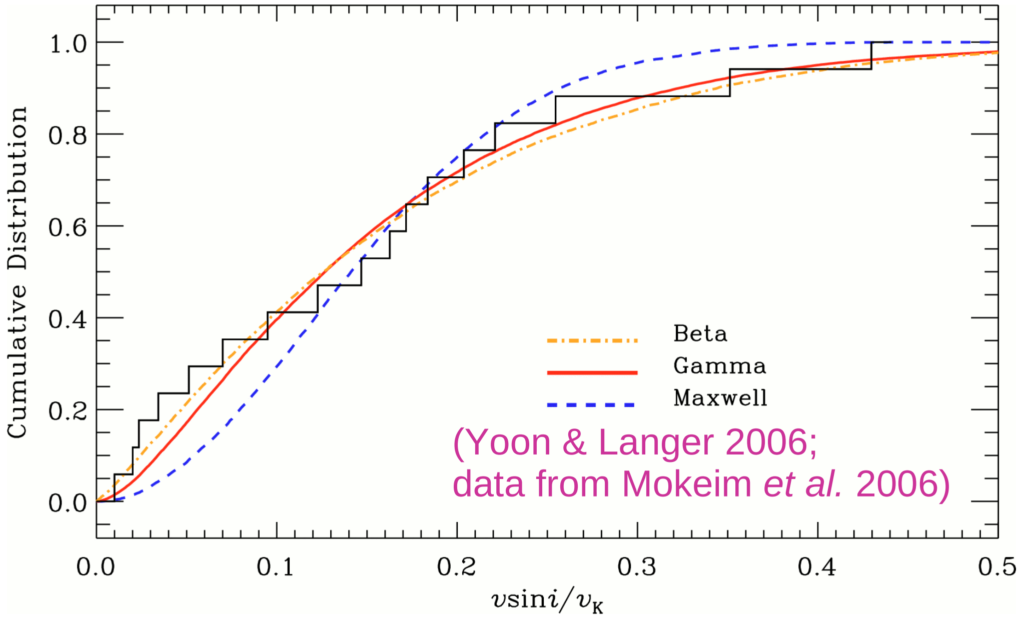


SN IIP
SN Ib/c
SN IIL
dim SN Ib/c
SN1987A
BH by fallback
(weak SN)
direct black hole
no H envelope
direct black hole
puls. pair (BH)
no BH
pair SN
pair BH
low mass stars -- white dwarfs
O/Ne/Mg core collapse
iron core collapse
BH by fallback
(weak SN)
direct black hole
epsilon mechanism
about solar
metallicity (roughly logarithmic scale)
metal-free
9
10
25
34
40
60
100
140
260
initial mass (solar masses)

Evolution with Rotation

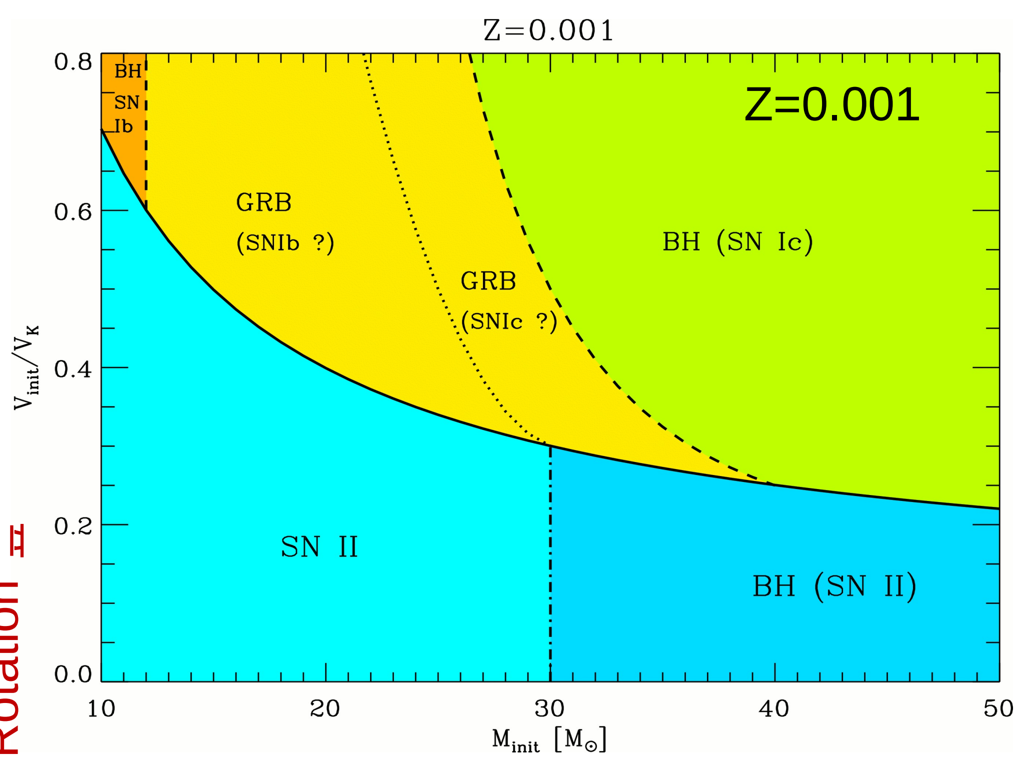
- broadening of main sequence
- change stellar lifetimes
  (more fuel, lower luminosity)
- rotation rates may depend on metallicity
- Rotationally induced mixing processes
  → can lead to chemical homogeneous evolution for extreme cases
  → make helium (WR) stars w/o intermediate RSG/BSG phase

Black Holes and GRBs from Rotating Stars



A small fraction of single stars is born rotating rapidly

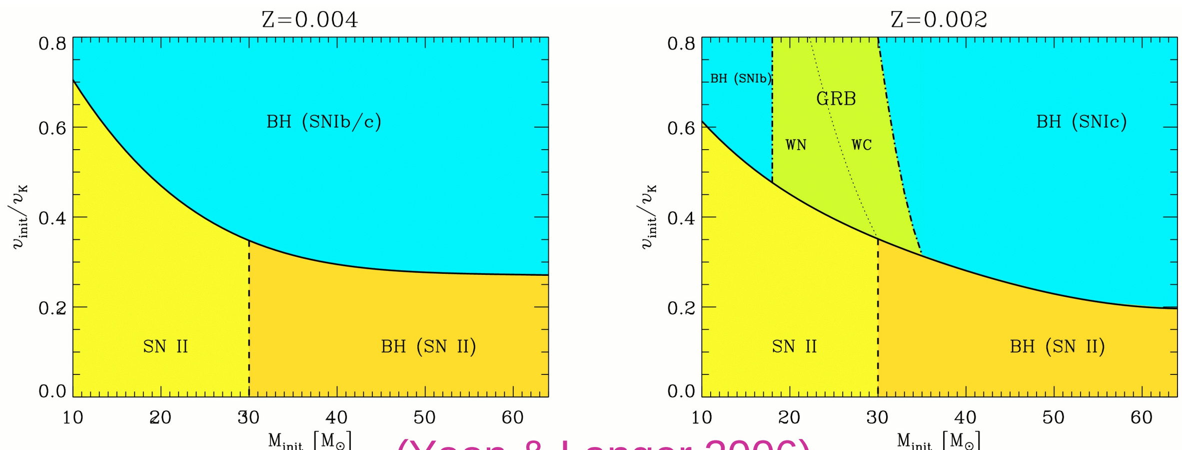
The fastest rotators evolve chemically homogeneously, become WR stars on the MS, and may lose less angular momentum.



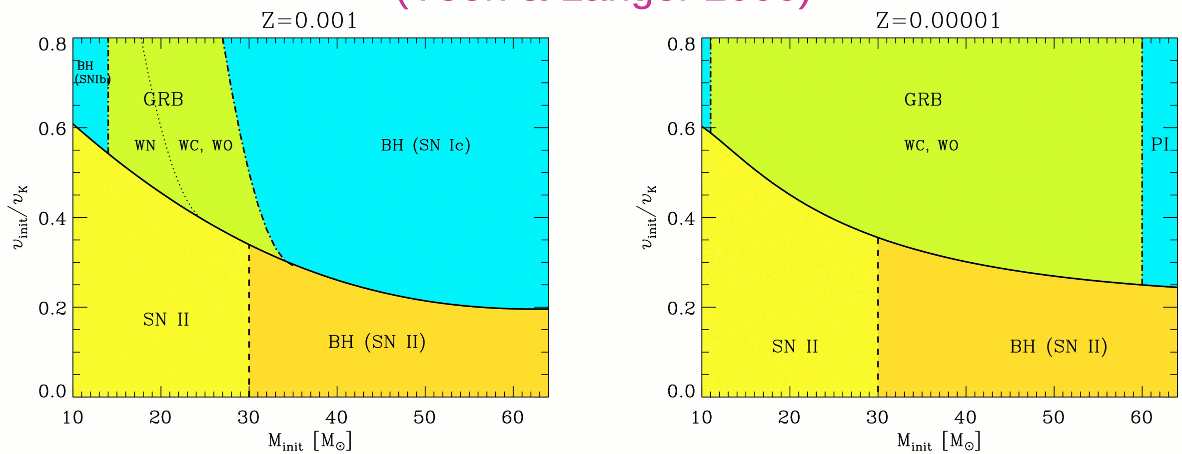
Rotation

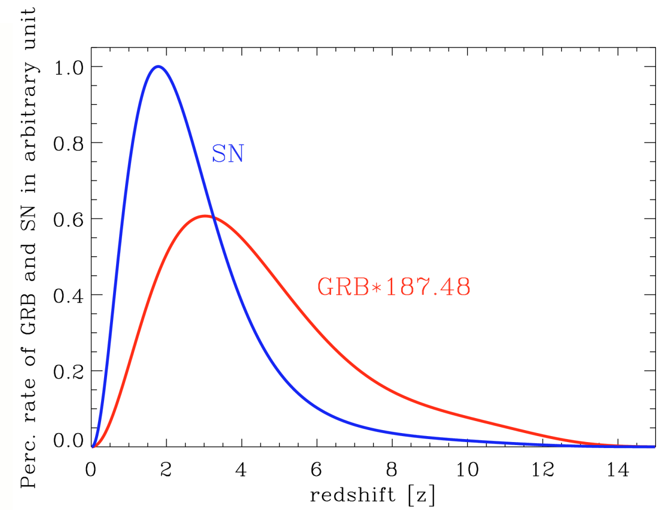
(Yoon & Langer 2006)

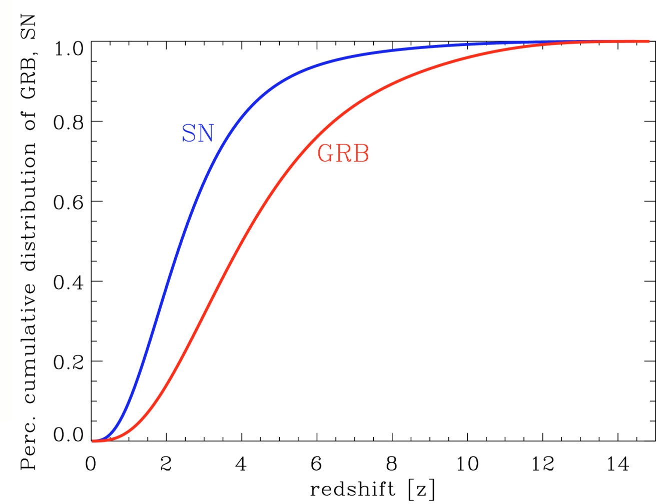
Rapidly Rotating Progenitors for Different Metallicities



(Yoon & Langer 2006)







Similar results, but higher metallicity cut-off, found by Woosley & Heger (2006)

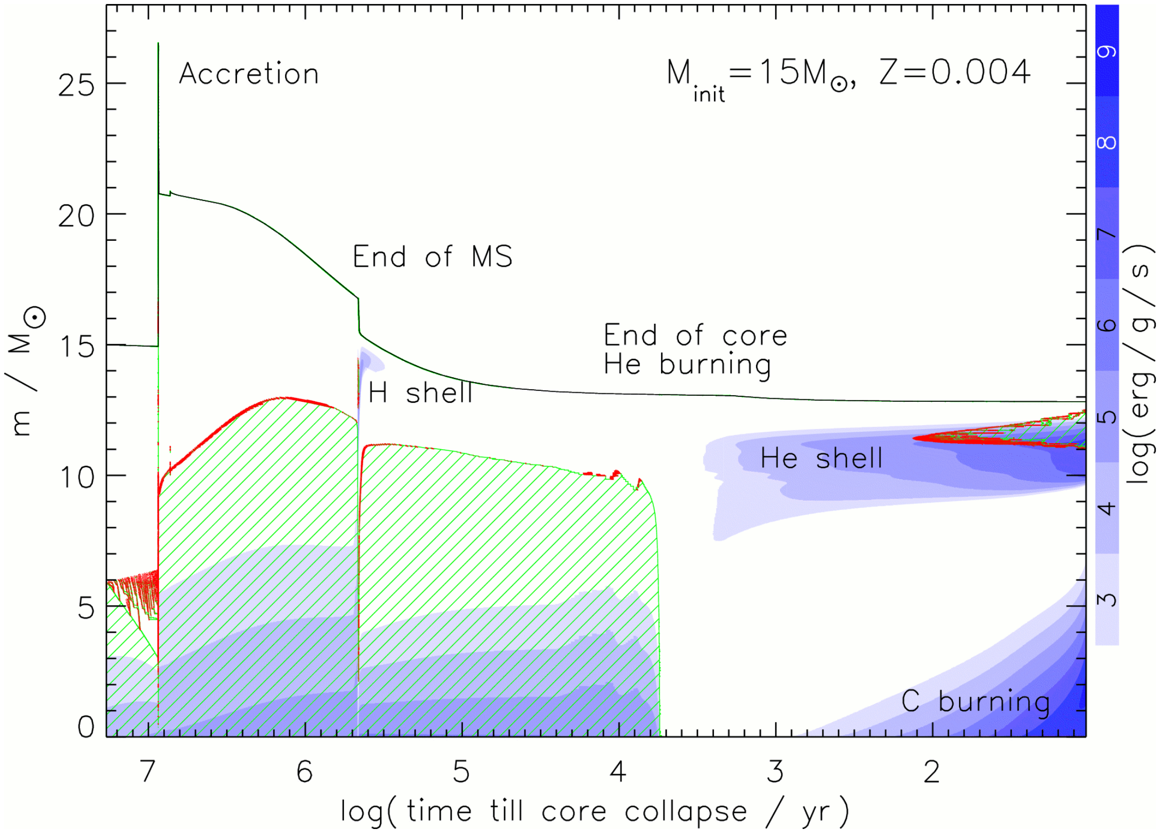
Binaries

initial mass	binary mass transfer			single star
$M_\odot$	Case A	Case B	Case C	
~8…13	WD	WD	SN Ib, NS	SN IIp, NS
~13…16	WD	SN Ib/c, NS	SN Ib, NS	SN IIp, NS
~16…25	SN Ic, NS	SN Ib, NS	SN Ib, NS	SN IIp, NS
~25…35	SN Ic, NS	SN Ic, NS	SN Ib, BH	SN IIL, BH
>35	SN Ic, NS/BH	SN Ic, NS/BH	SN Ib, NS/BH	SN Ic, NS/BH

(solar metallicity)

(after Wellstein & Langer 1999)

Black Holes from Binary Stars



(Cantiello *et al.* 2007)

Model	M_i $M_\odot$	α_{SM}	v_{init}/v_K	$< j_{CO} >$ 10^{15} cm^{2}s^{-1}	M_{CO} $M_\odot$
binary	**15**	**1.0**	**–**	**18.15**	**10.0**
binary	**15**	**0.1**	**–**	**8.90**	**8.4**
binary	15	0.01	–	1.09	2.8
single	**24**	**1.0**	**0.9**	**23.42**	**11.4**
single	**20**	**1.0**	**0.6**	**11.62**	**9.9**
single	20	1.0	0.3	2.09	4.2

15 $M_\odot$ + 16 $M_\odot$ binary star system, early Case B mass transfer from primary to secondary (left)

Binary stars can give different final core masses (black hole masses) and rotation rates than rapidly rotating single stars.

Stellar Forensics

Tracing the fingerprints of nucleosynthesis

(single stars)

Mixing in a 15 $M_\odot$ Stars

E=0.6B E=1.2B E=1.8B

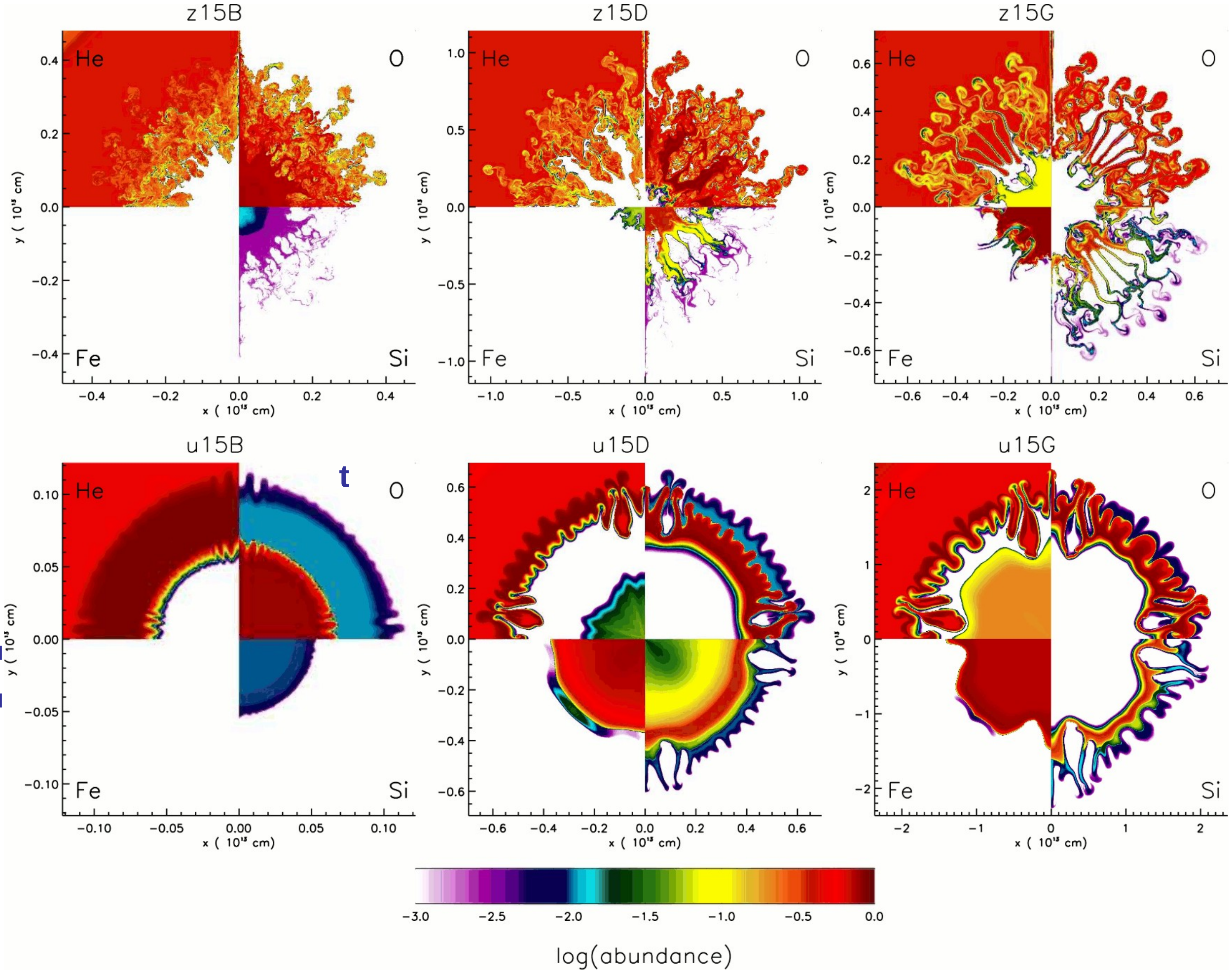
Growth of Rayleigh-Taylor instabilities

Interaction of instabilities (mixing) and fallback determines nucleosynthesis yields

➔ Z=0 stars have more mixing than the [Z]=-4 stars with same rotation rate

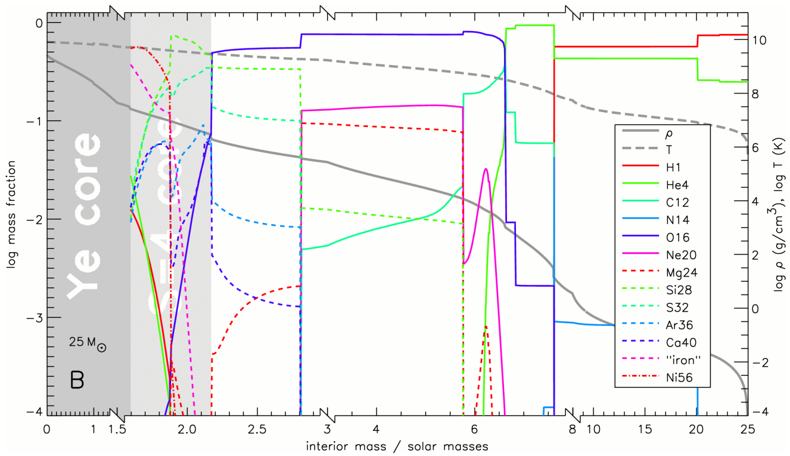
Z=0

[Z]=-4



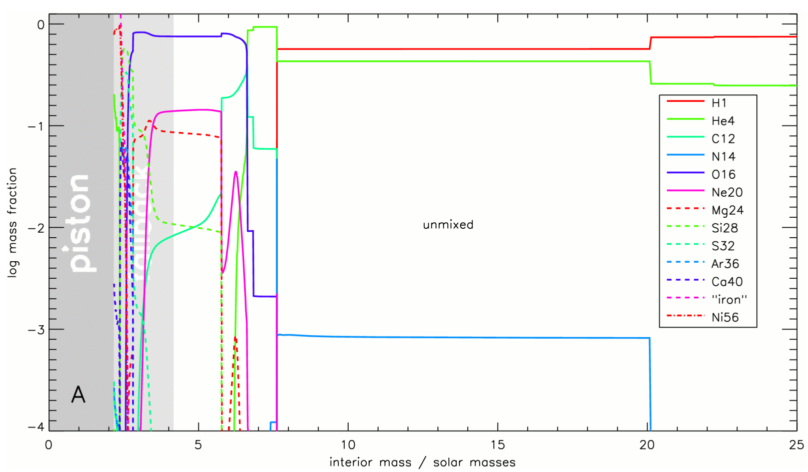
Simulations: Candace Church (UCSC/LANL T-2)

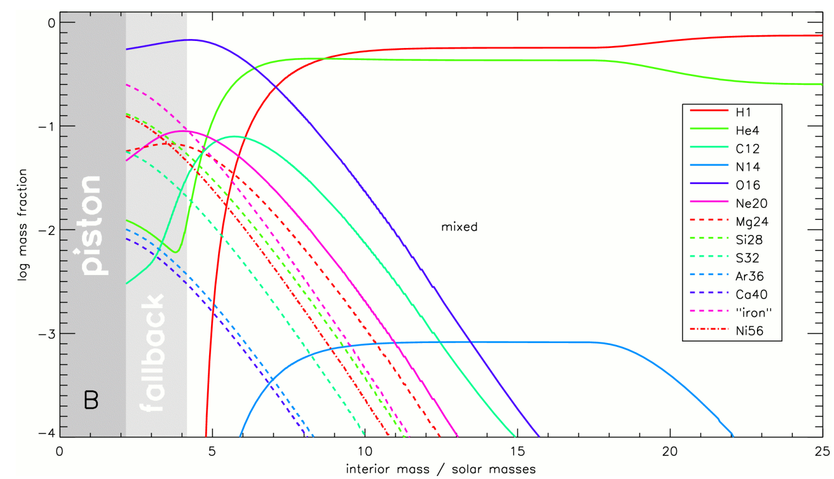
Supernovae, Nucleosynthesis, & Mixing



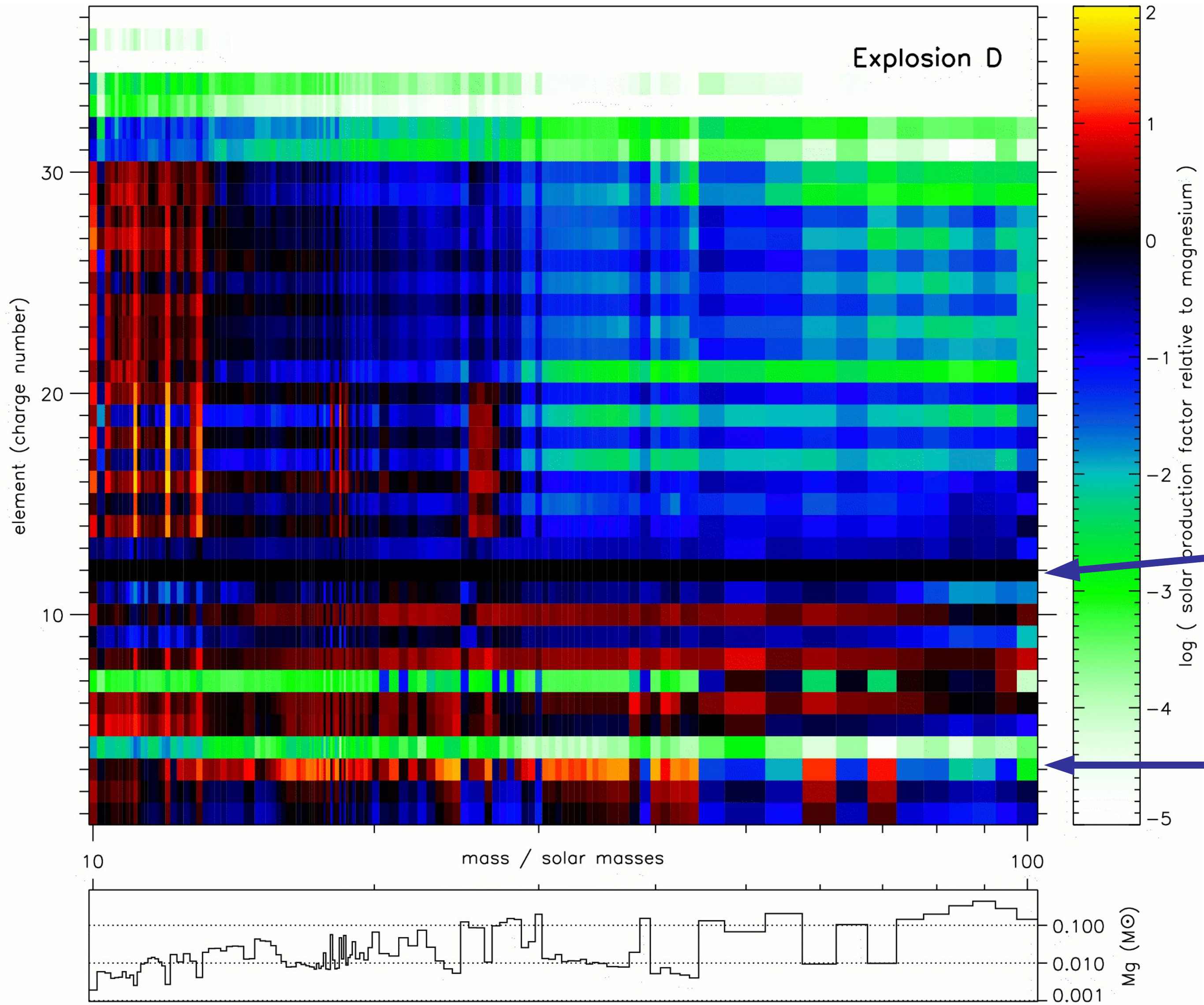
SN, no mixing

SN + mixing





Pop III Nucleosynthesis



Mg yield (ejecta mass fraction)

Elemental Yields as a function of initial mass

non-rotating stars

120 stellar masses

"complete" reaction network

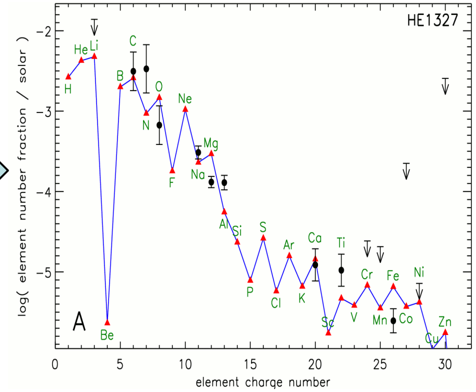
normalized to Mg

RESULTS:
e.g.,
Production of ^{7}Li by neutrino interaction in very compact stellar envelope!

Heger & Woosley, in prep., (2009)

Reconstruction of the IMF

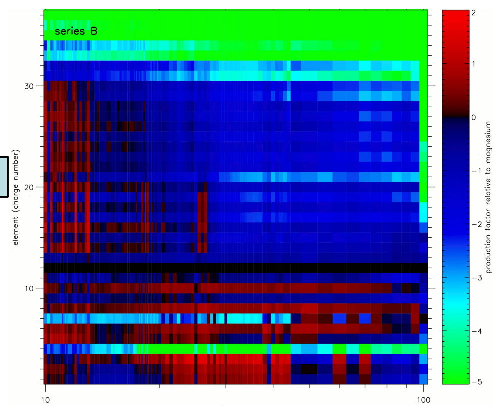
primordial stars form, nucleosynthesis ejected



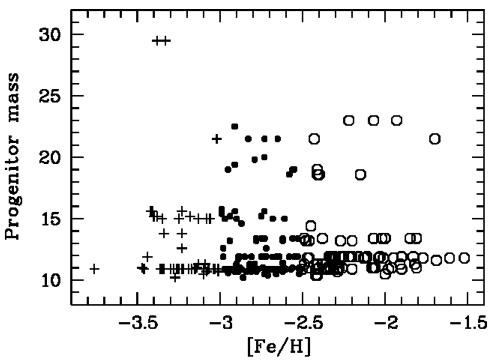
ejecta incorporated in low-Z halo stars

find low-Z halo stars (HERES, SEGUE, ...)

measure abundances (VLT, KECK, ...)



compare abundances to primordial star nucleosynthesis library



obtain IMF of population of progenitor stars

http://starfit.org

Summary

- Metallicity has strong impact on mass loss
  ==> supernova type
  only moderate influence on evolution otherwise
- Fast rotation can significantly change the evolution
  ==> supernova type, explosion mass limits, collapsars/magnetars
- Binary evolution can have similarly strong effect
  ==> stripping, mass transfer, spin-up/spin-down, ...
- Reconstruction of primordial IMF from stellar yields?
  (mixing and explosion energy depend on metallicity)

What we need:

- Reliable predictions of stellar explosion outcome – energy, asymmetry, remnant – from supernova modeling