Deciphering the Violent Universe, Playa Del Charmen, Mexico, 12 December 2017

Stripped Core Collapse Supernovae

MoCA
Monash Centre for Astrophysics

MONASH University

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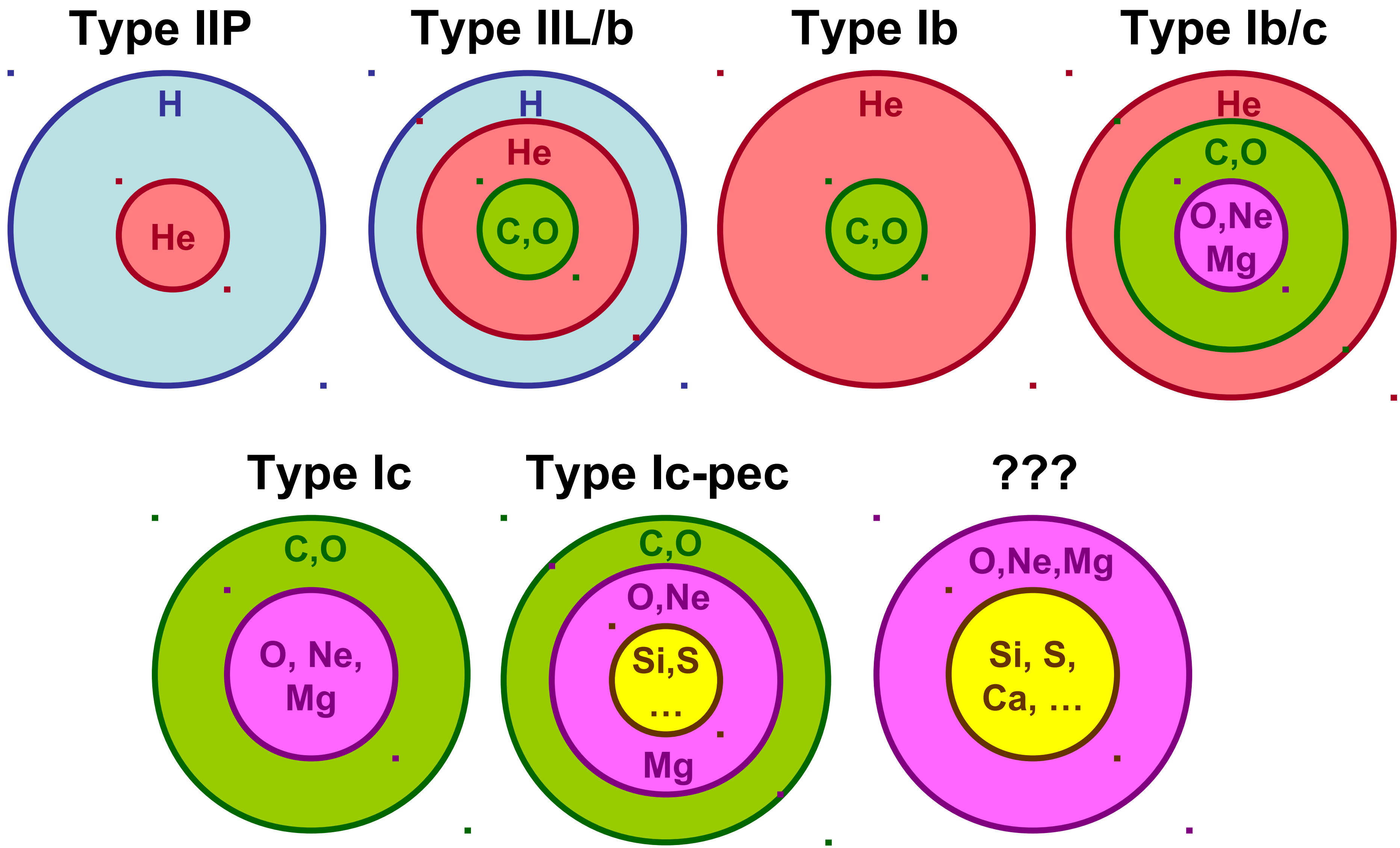
http://CosmicExplosions.org

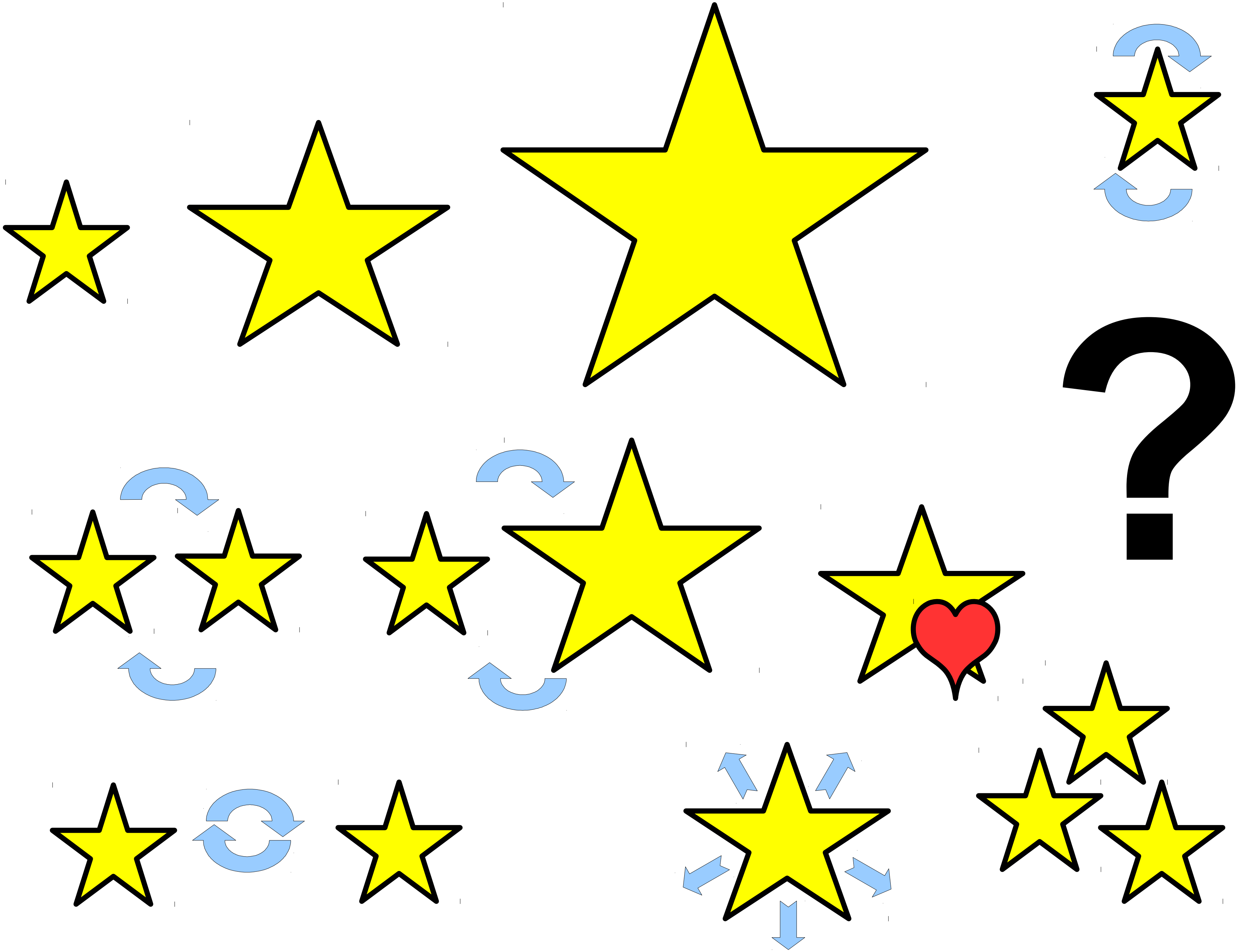
Sequence of increasingly stripped cc SNe



(adopted from Filippenko 2002)

(SN 2002ap?)

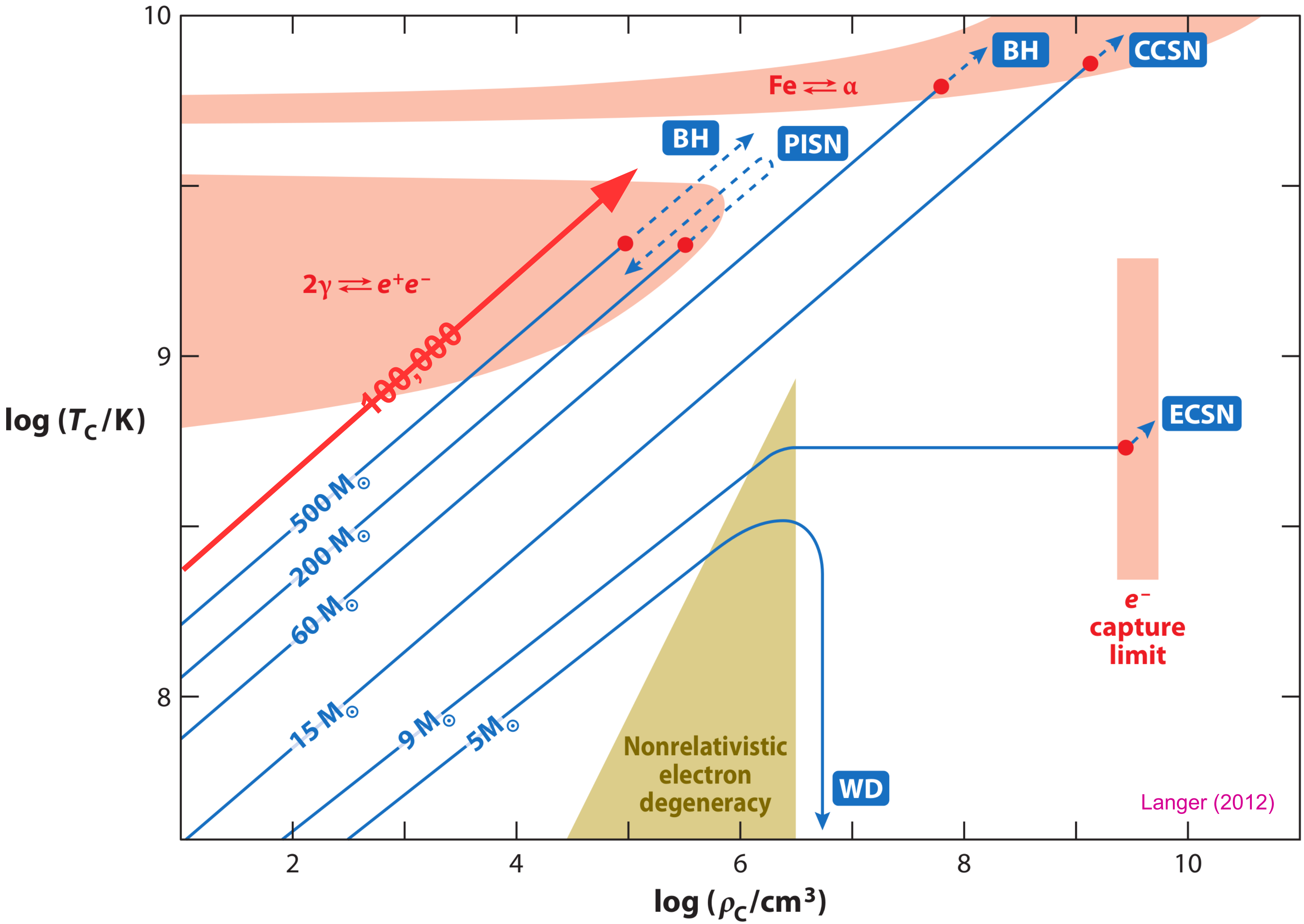
(SN 02ap?, 98bw?)



Paths to Stripped Supernovae

- Winds from massive stars
- Pulsational mass loss
- Pulsational pair instability SNe
- Rotation – Chemical homogeneous evolution
- Binary or multiple star interaction
  - various inflation phases (Case A, B, CE)
  - He giants at low-mass end
- Tidal striping of H envelope (partial disruption)

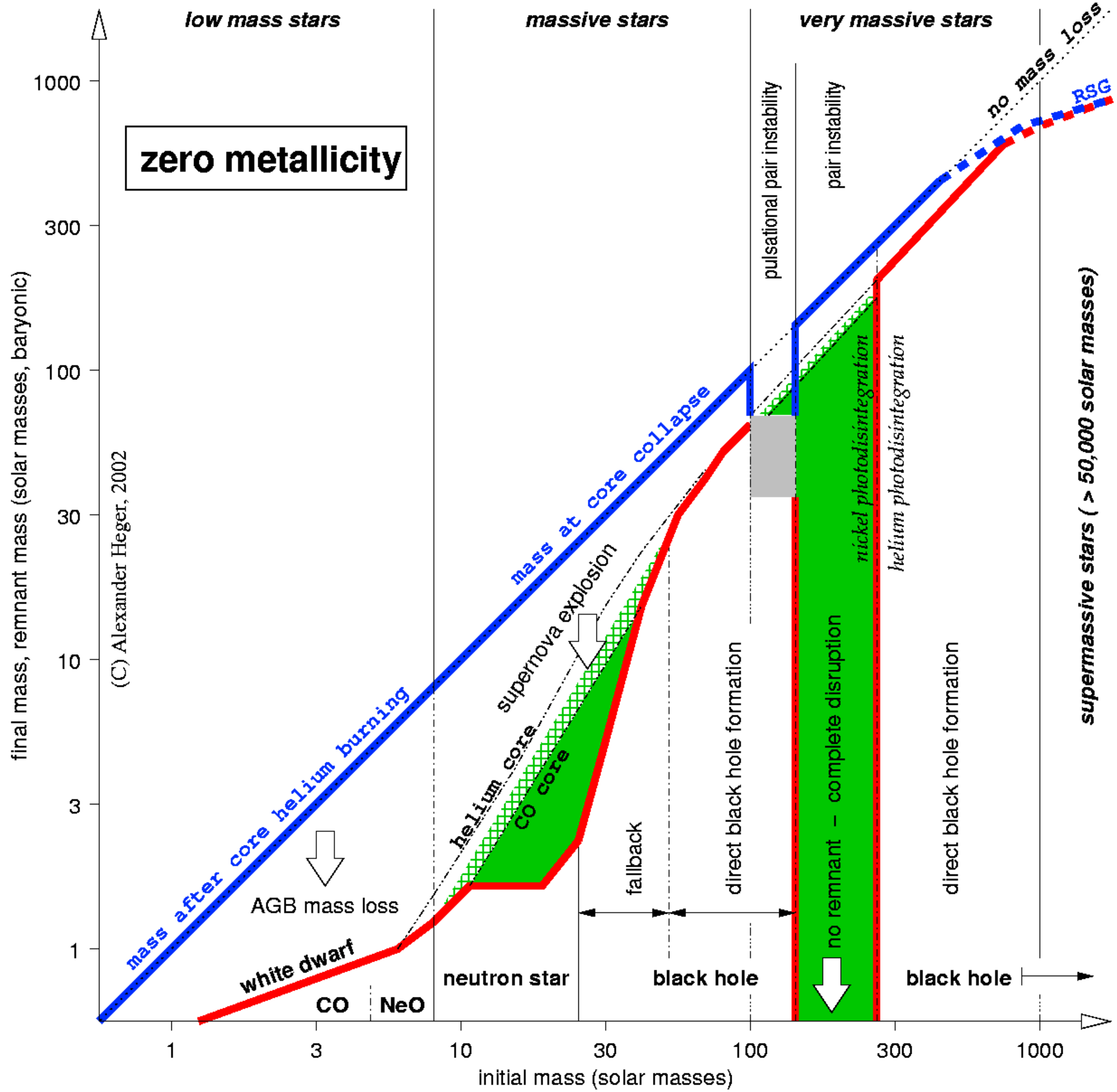
Evolution of Center for Different Initial Masses



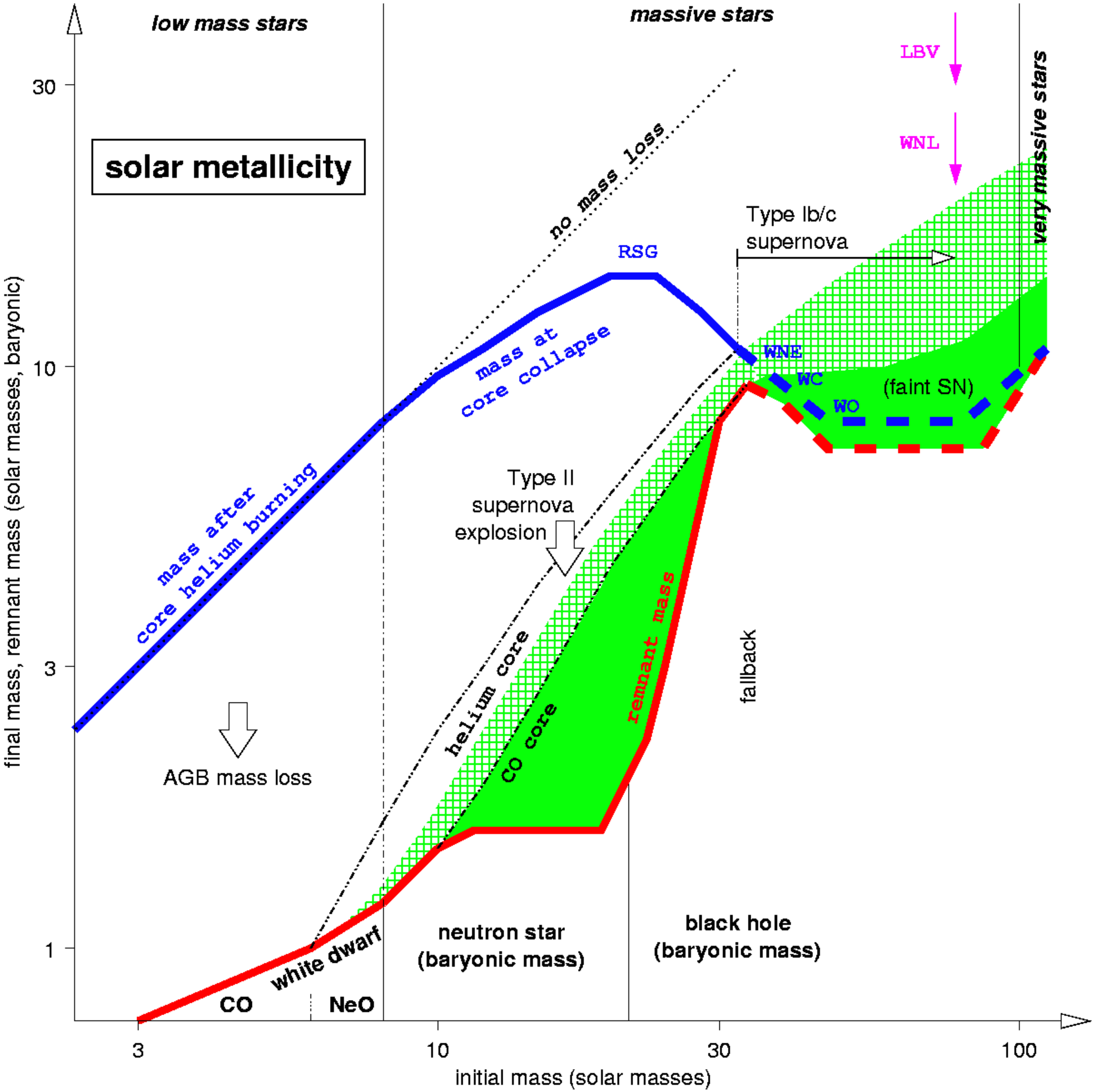
Nuclear burning stages

(20 $M_{\odot}$ stars)

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\,H \xrightarrow{CNO} {}^4He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	$3\,He^4 \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$
O	Si, S	Cl, Ar, K, Ca	2.0	0.8	$^{16}O + {}^{16}O$
Si,S	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	$^{28}Si(\gamma,\alpha)\ldots$

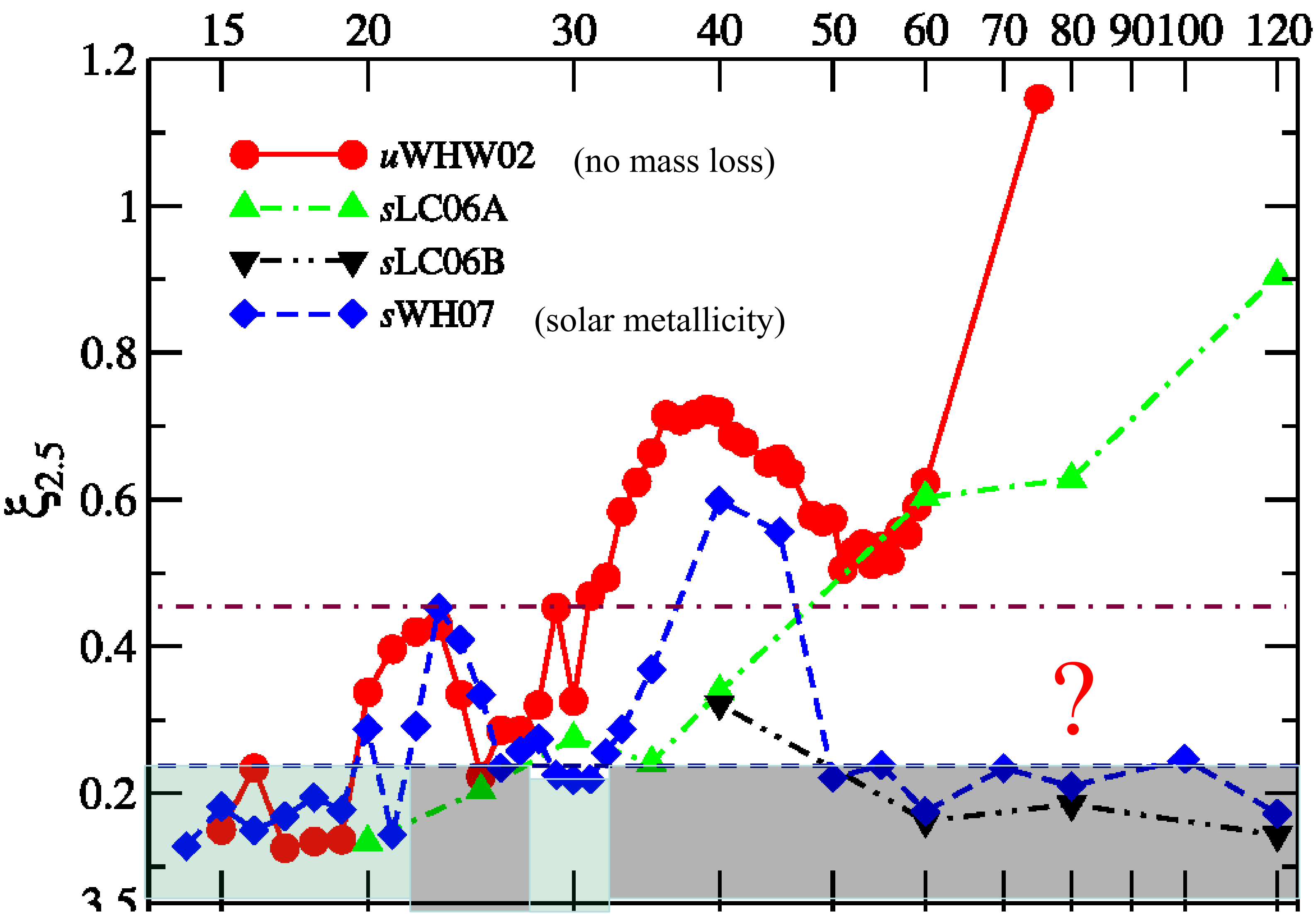


Ejected "metals"



Ejected “metals”

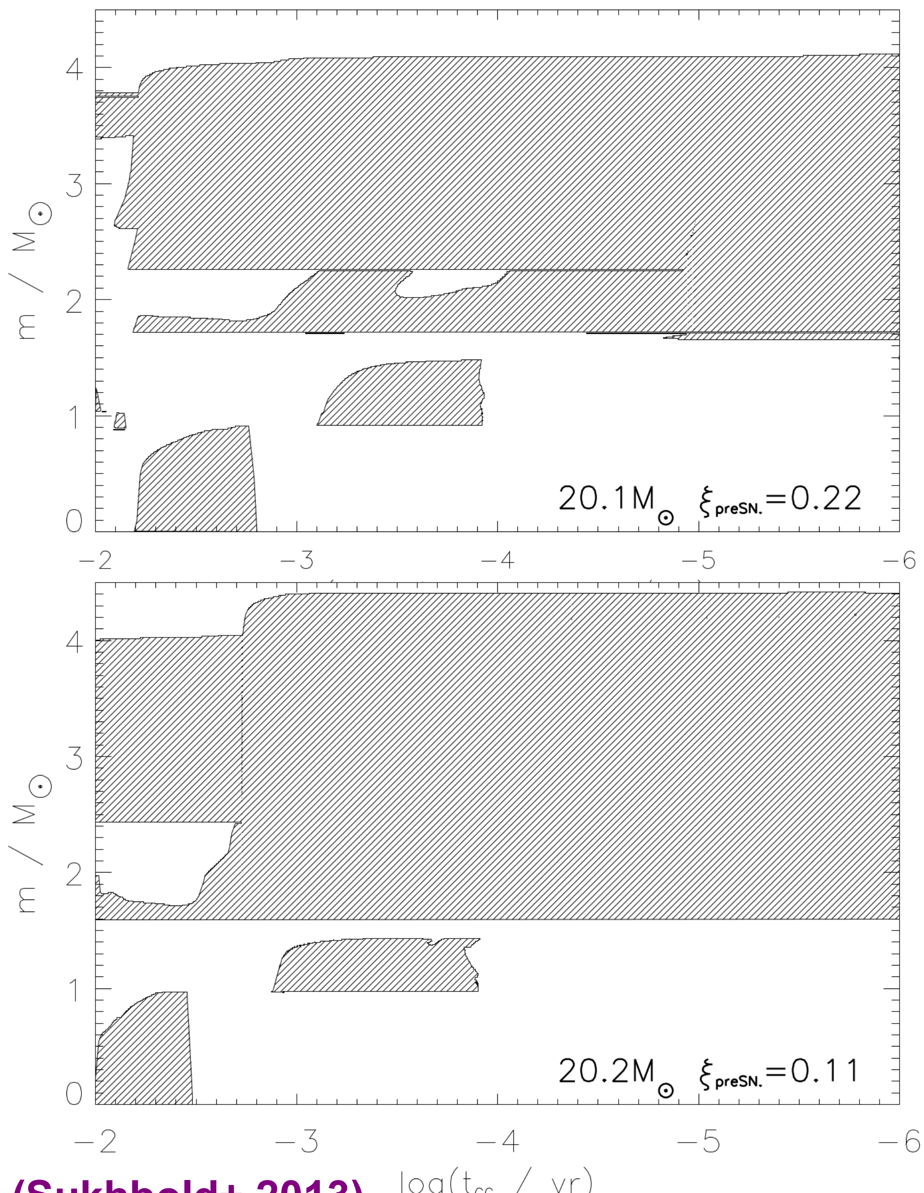
Islands of SN and BH Production



(Woosley 2012, priv. com.)

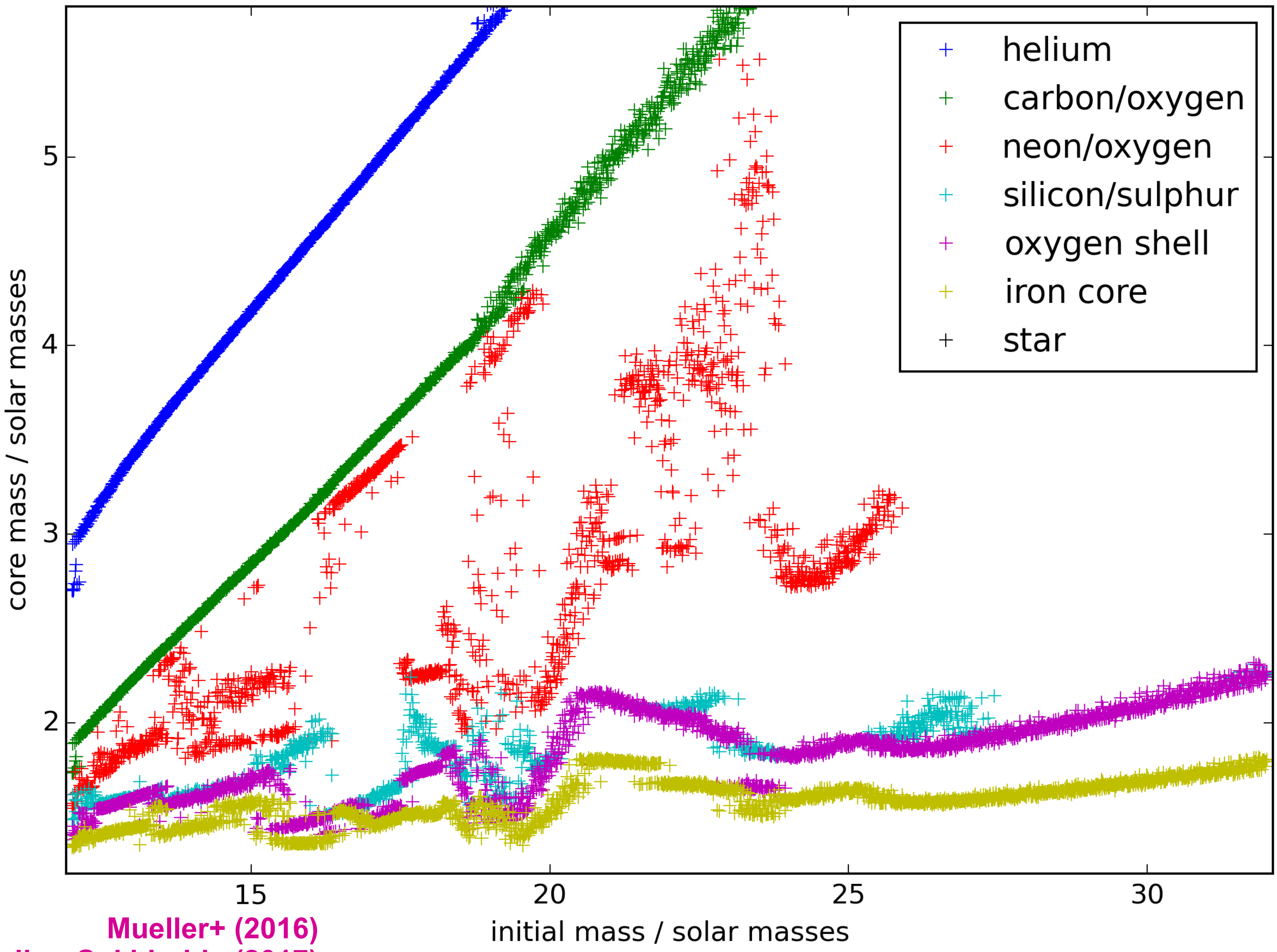
O'Connor and Ott (2011)

Sensitivity of Structure to Initial Mass



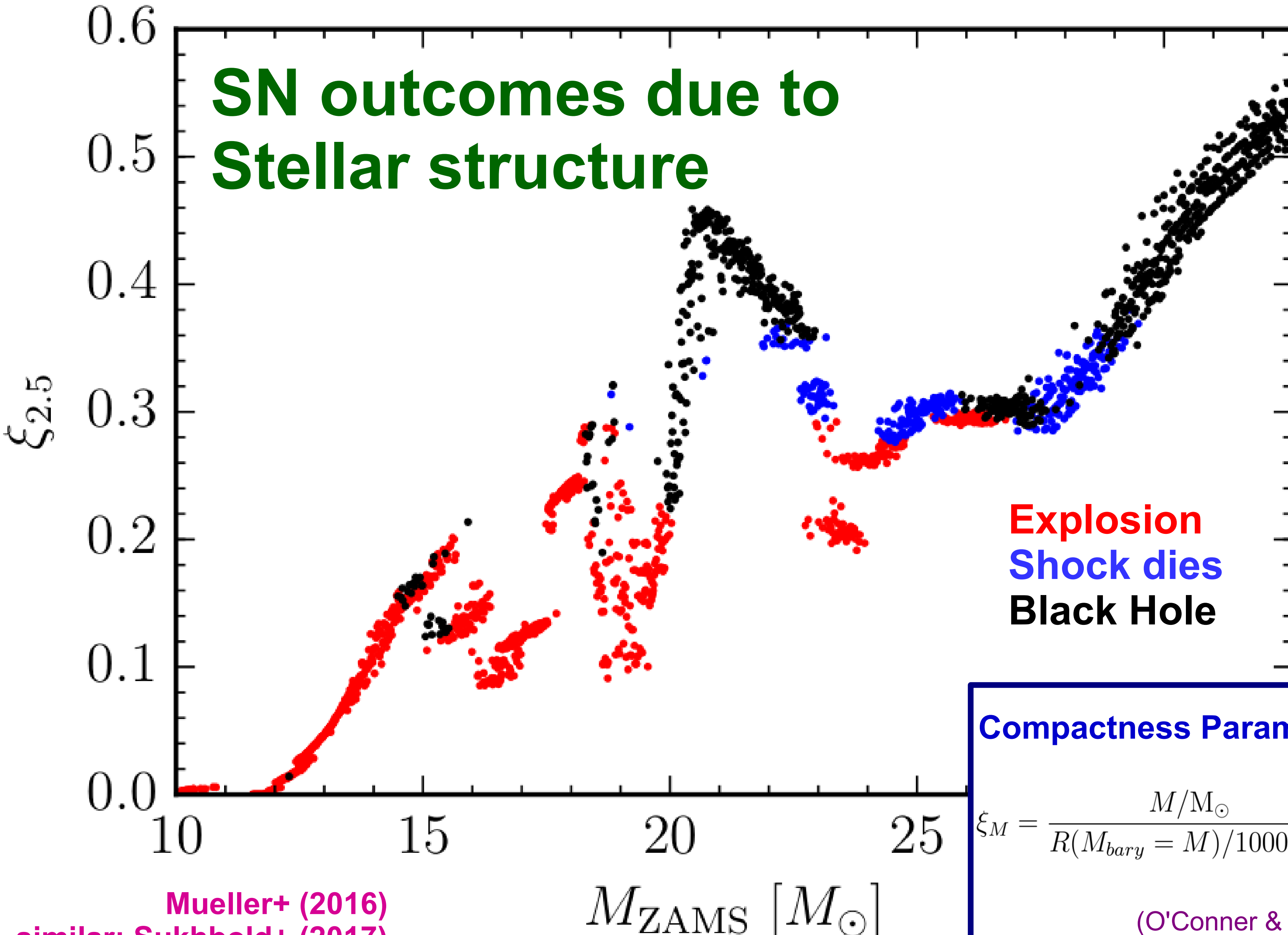
Small changes in initial mass can result in large changes in progenitor structure

(Sukhbold+ 2013)



Mueller+ (2016)
similar: Sukhbold+ (2017)

Signatures of Stellar Structure?



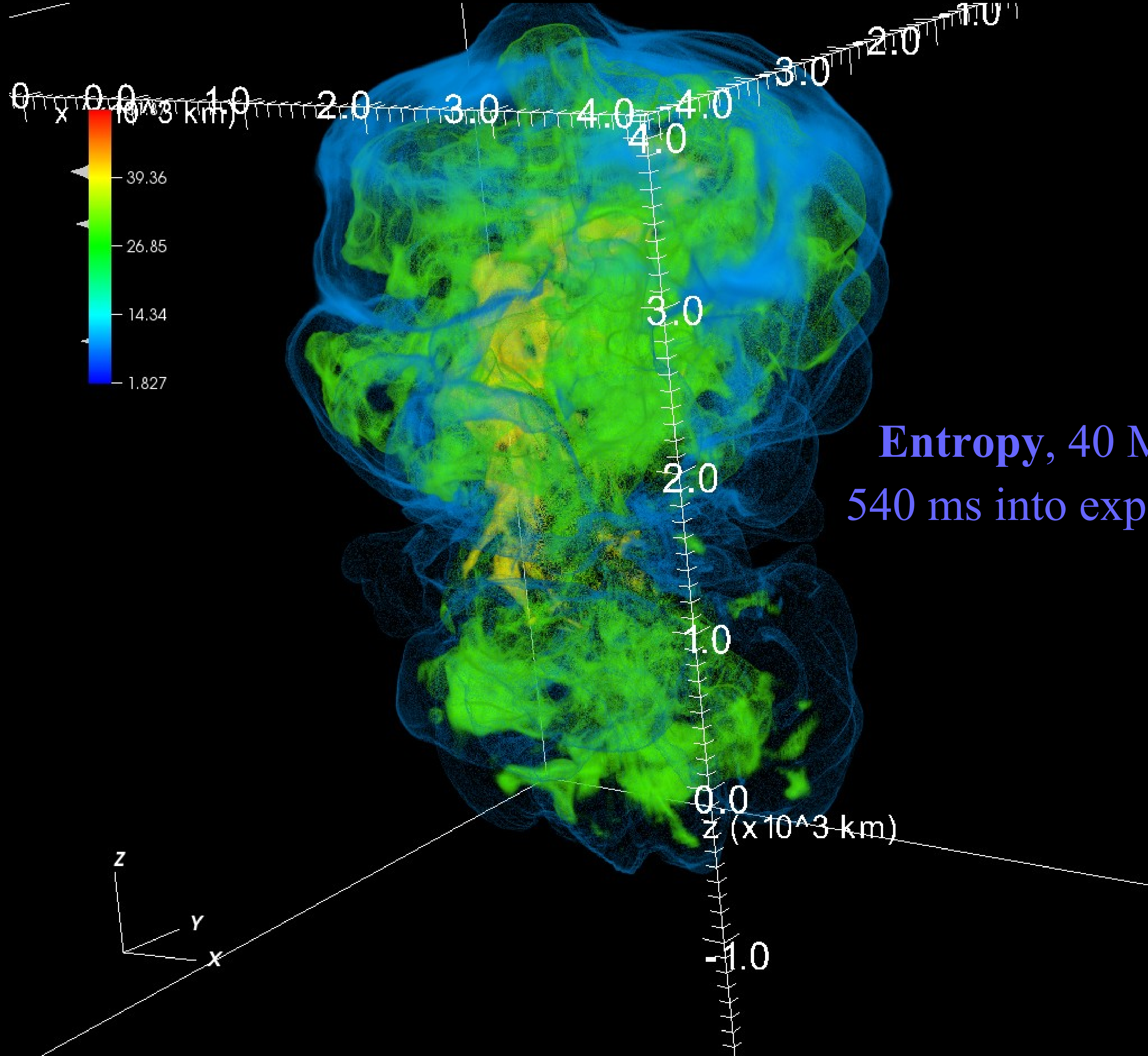
Mueller+ (2016)
similar: Sukhbold+ (2017)

Compactness Parameter

$$\xi_M = \frac{M/\mathrm{M}_\odot}{R(M_{bary} = M)/1000\,\mathrm{km}}\Big|_{t_{bounce}},$$

(O'Conner & Ott 2011)

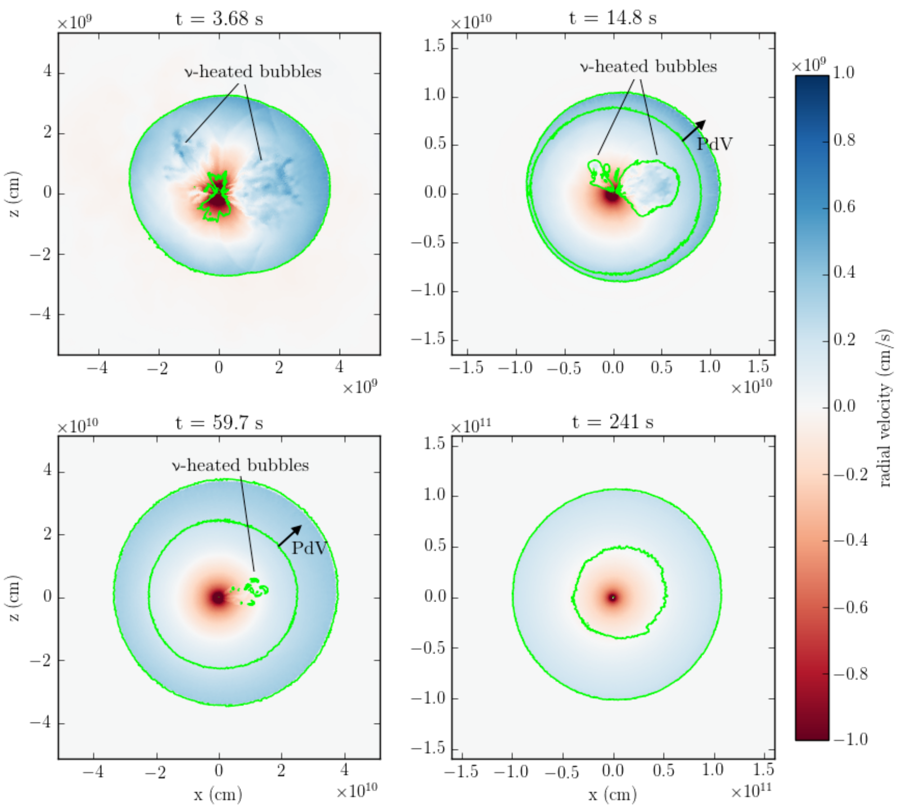

The
Death
of the
Stars

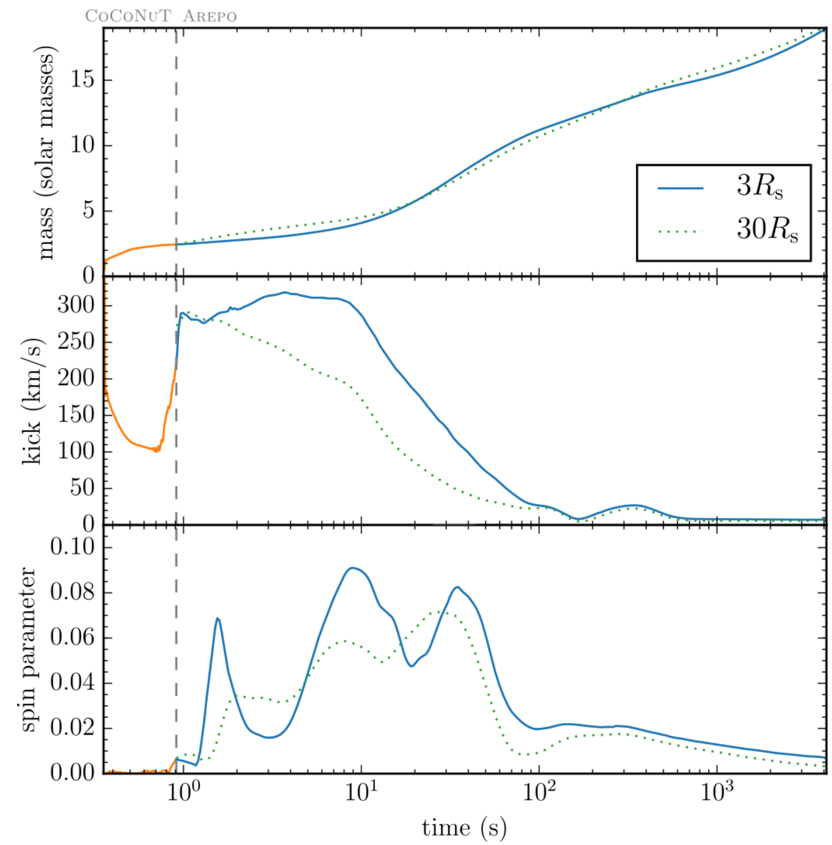


Entropy, 40 $M_{\odot}$ star
540 ms into explosion

Mueller, Chan, Heger 2017 in prep.

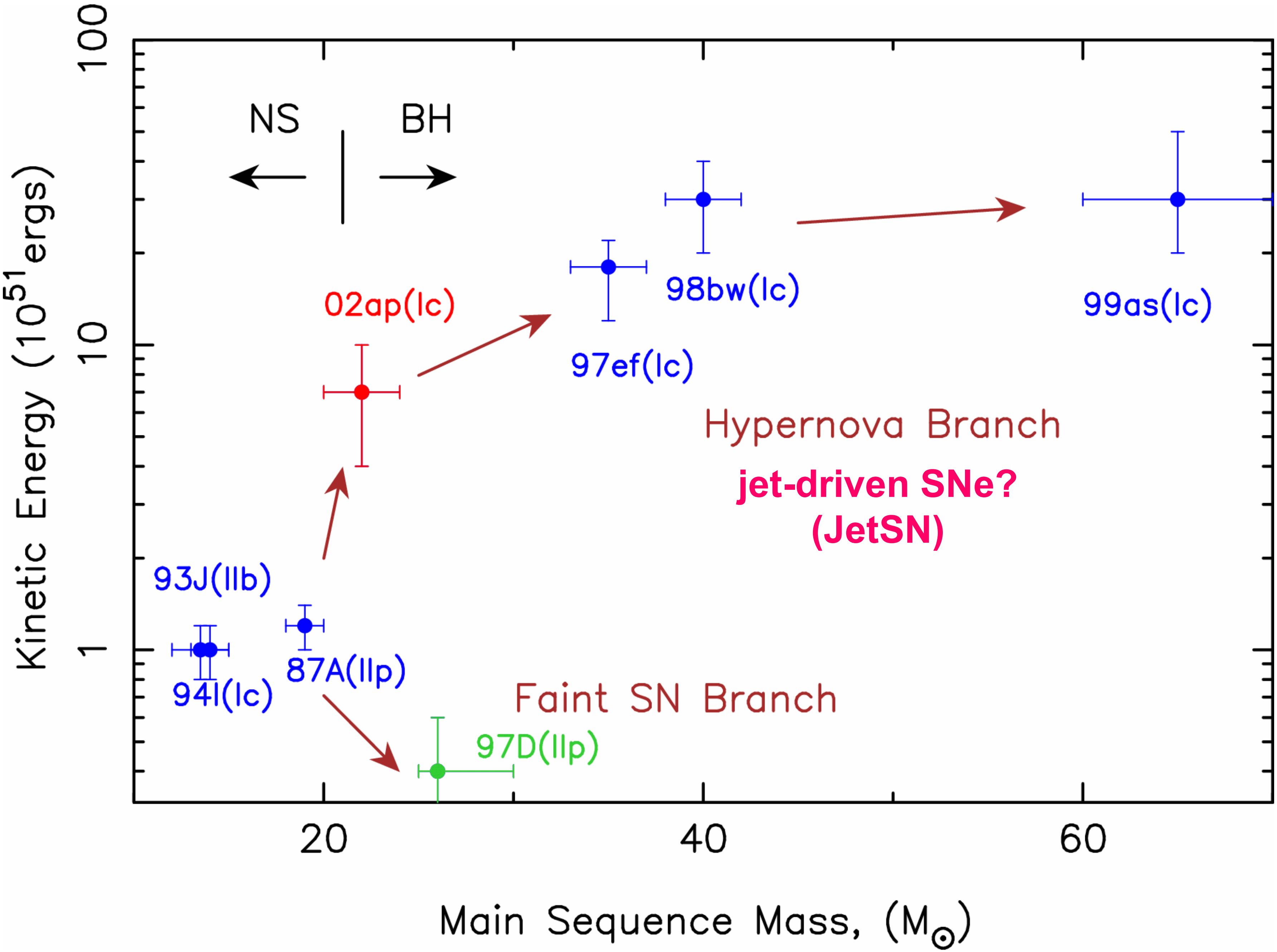
Fallback in a 40 $M_\odot$ Stars





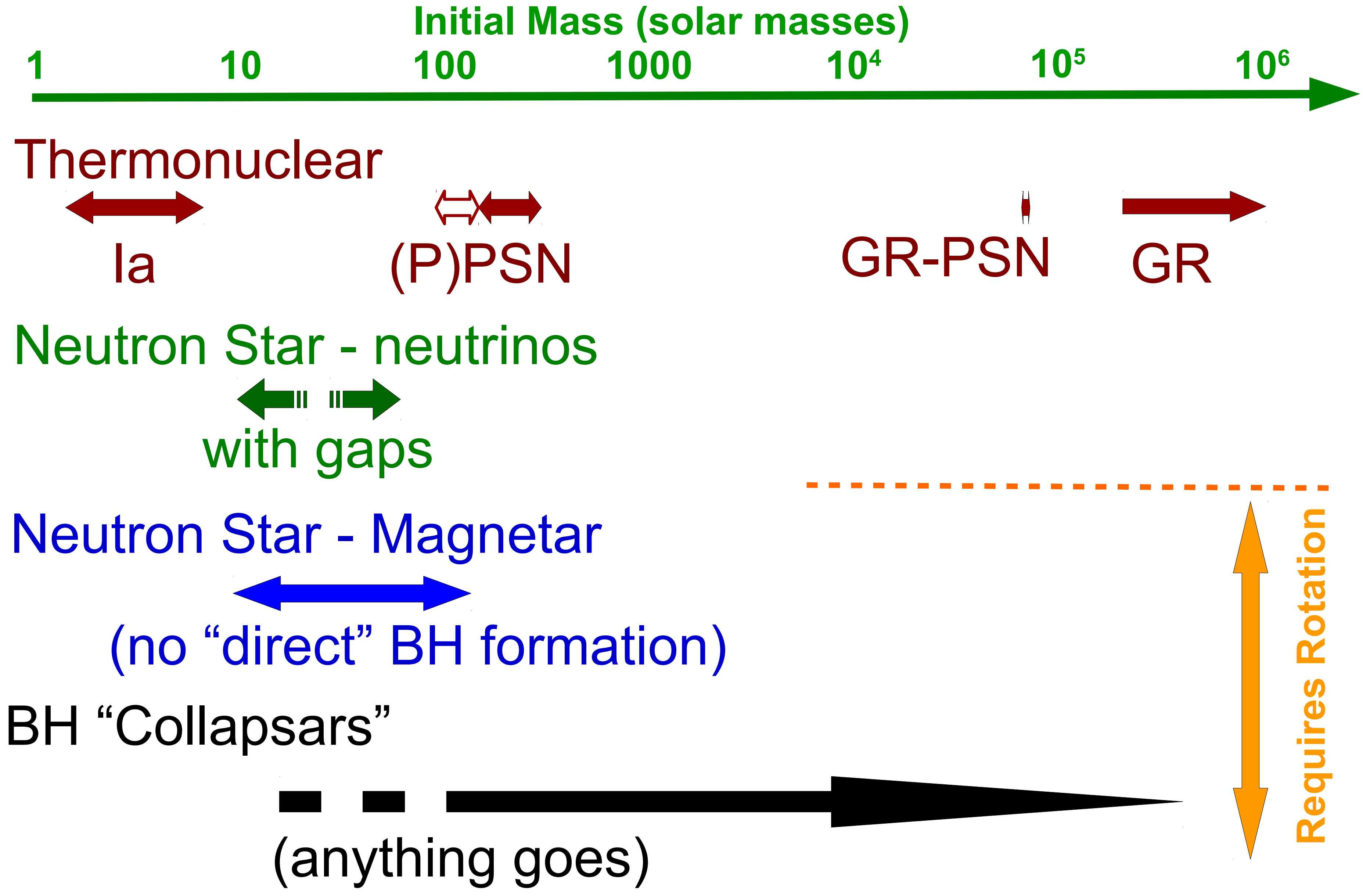
Fallback may impose some spin and kick even in case of BH formation.

Chan+ (2017)



(Nomoto 2002, priv. com.)

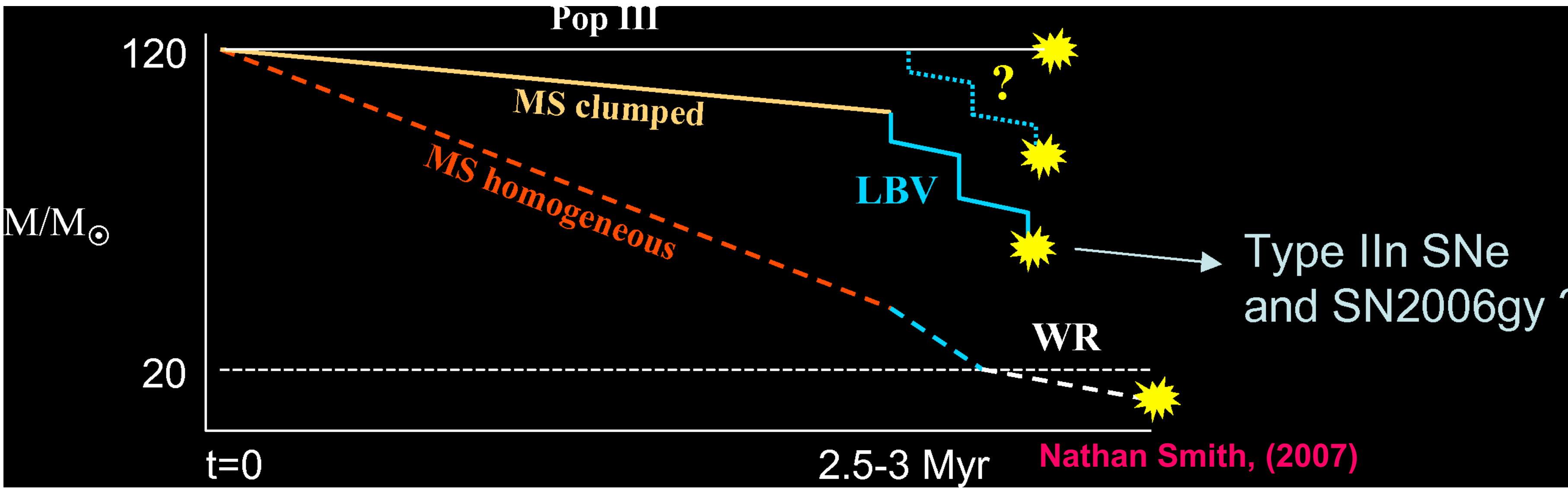
The Engines of SNe

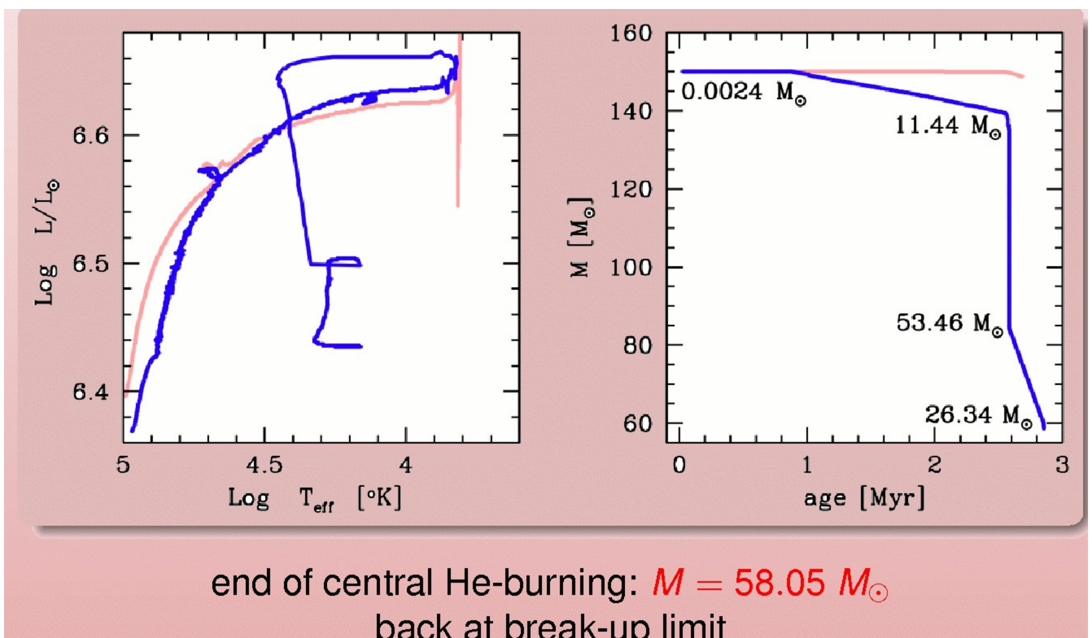


Wind Mass Loss and Eruptions

Eta Car – a really big star in our galaxy today

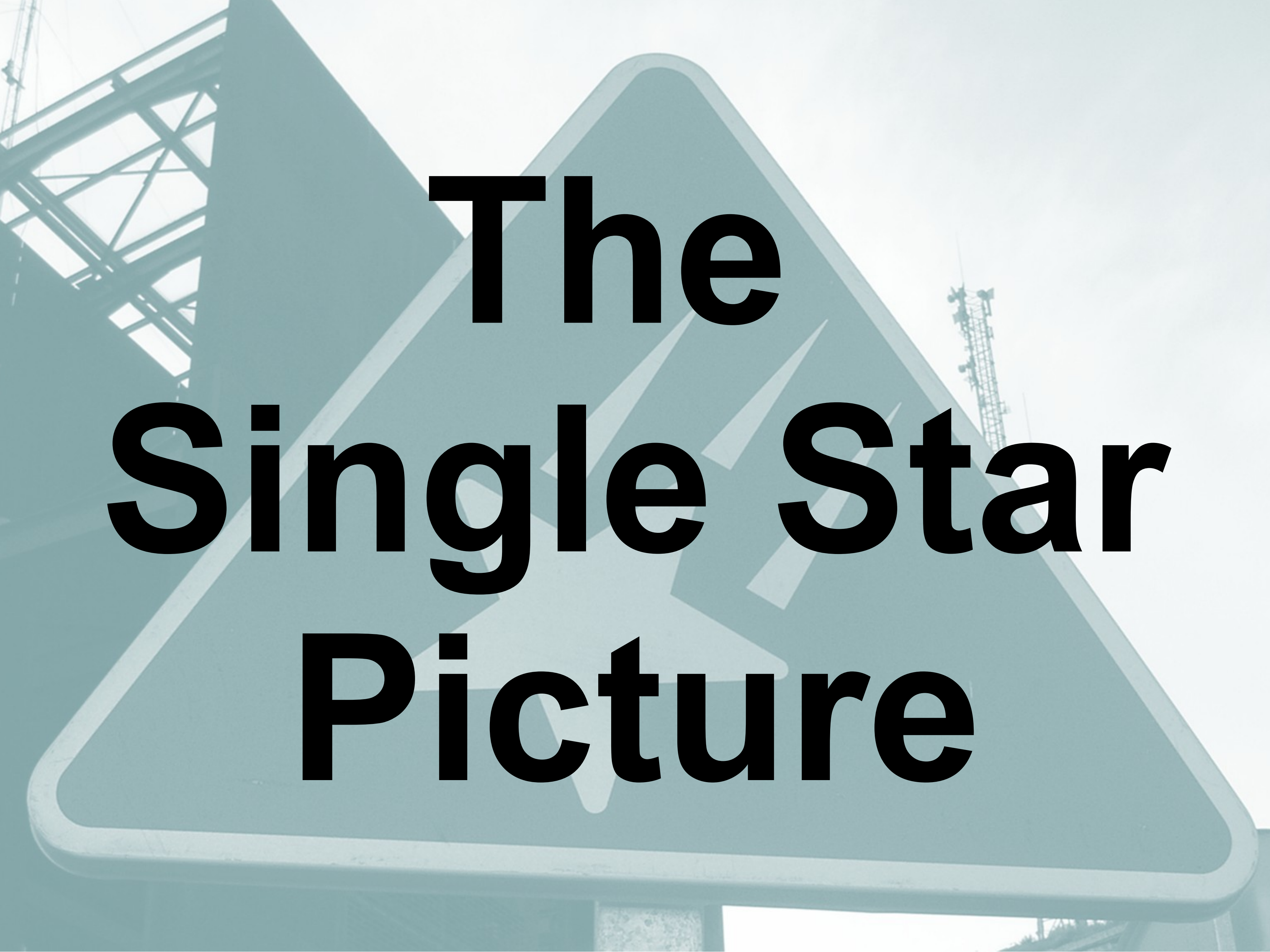
Mass Loss by Giant eruptions?

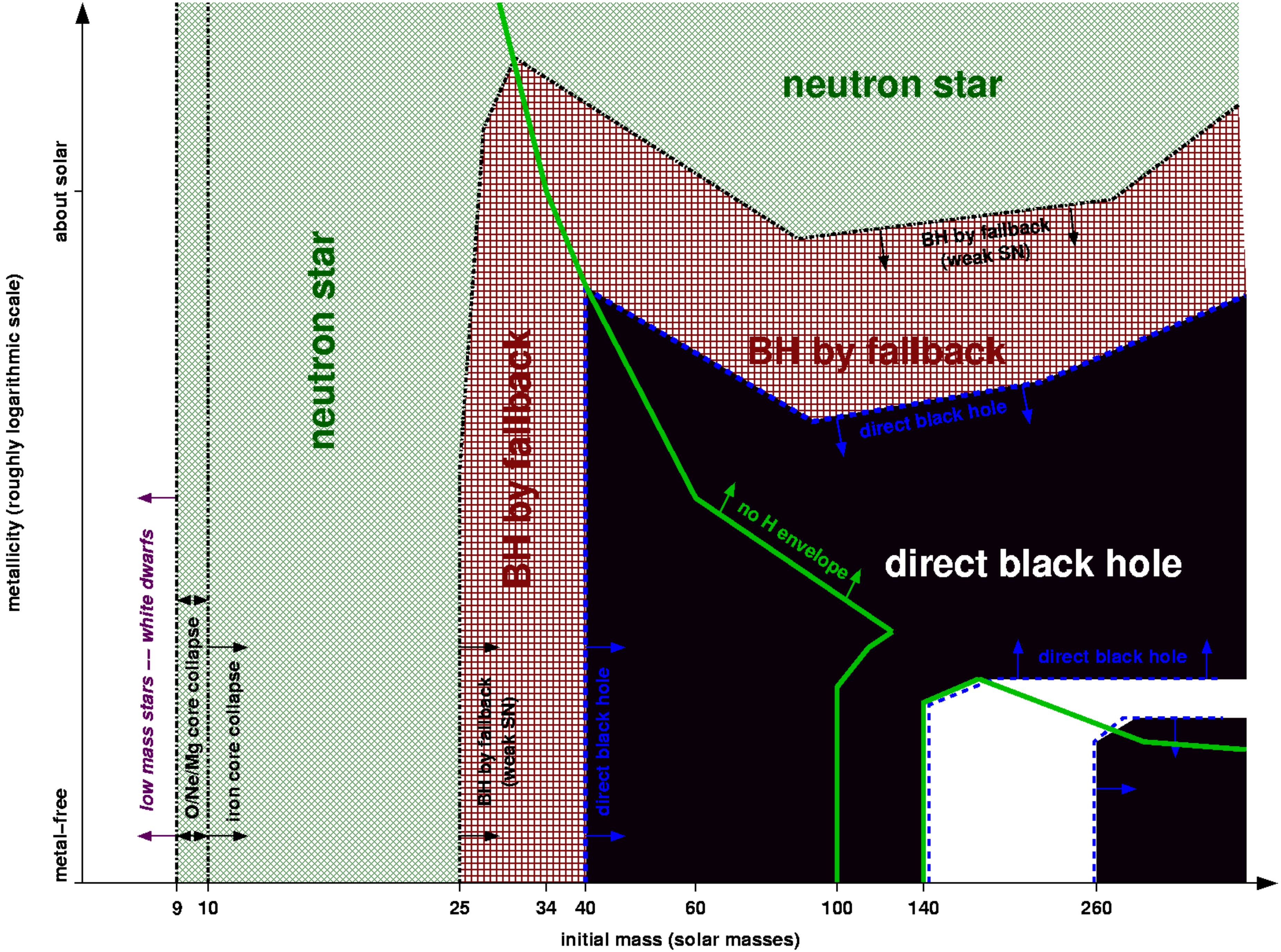




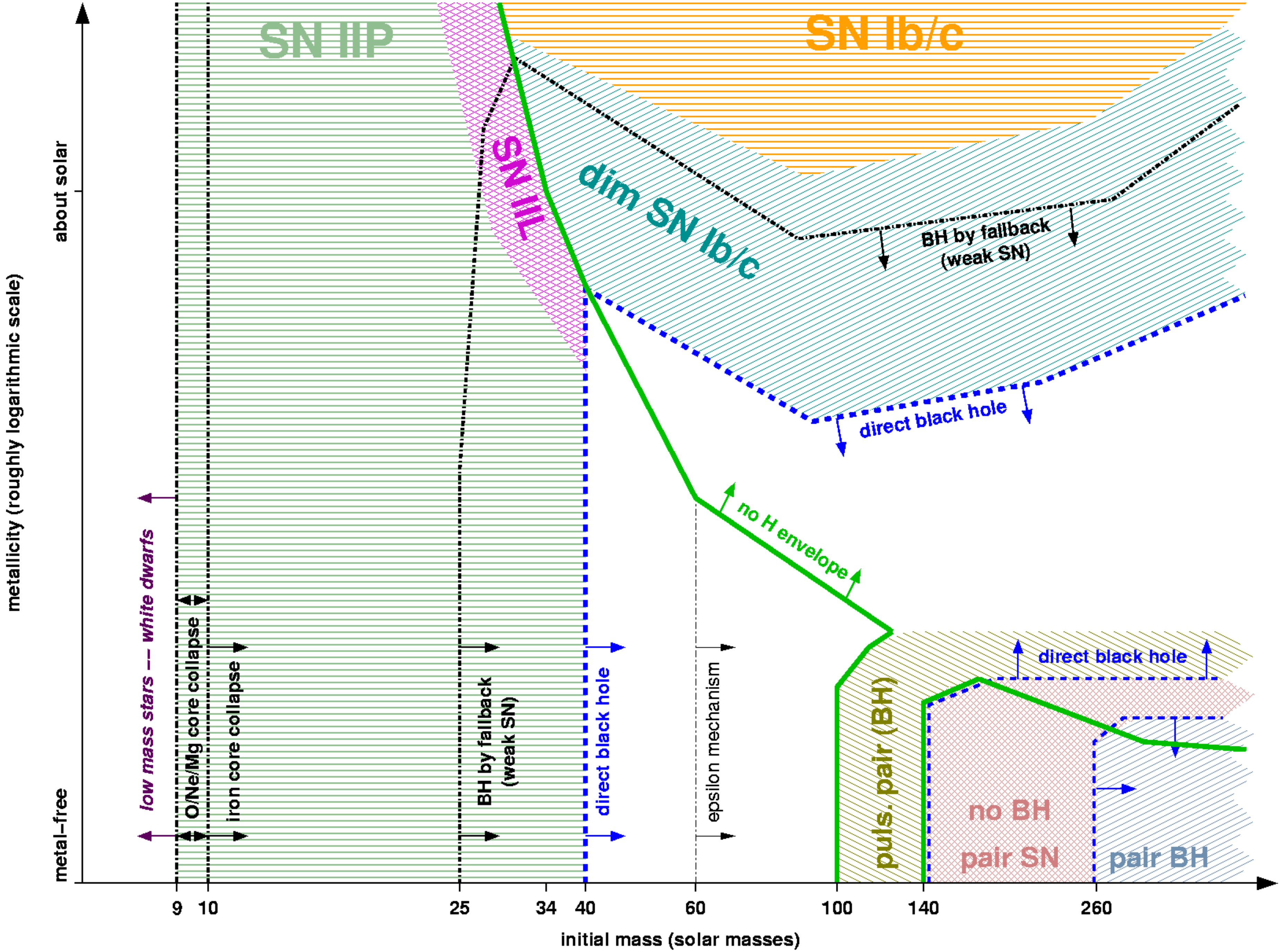
Mass Loss due to critical rotation?

Eikstroem, (2007)


The
Single Star
Picture



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)



SN IIP
SN Ib/c
SN IIL
dim SN Ib/c
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
metal-free
metallicity (roughly logarithmic scale)
9
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40
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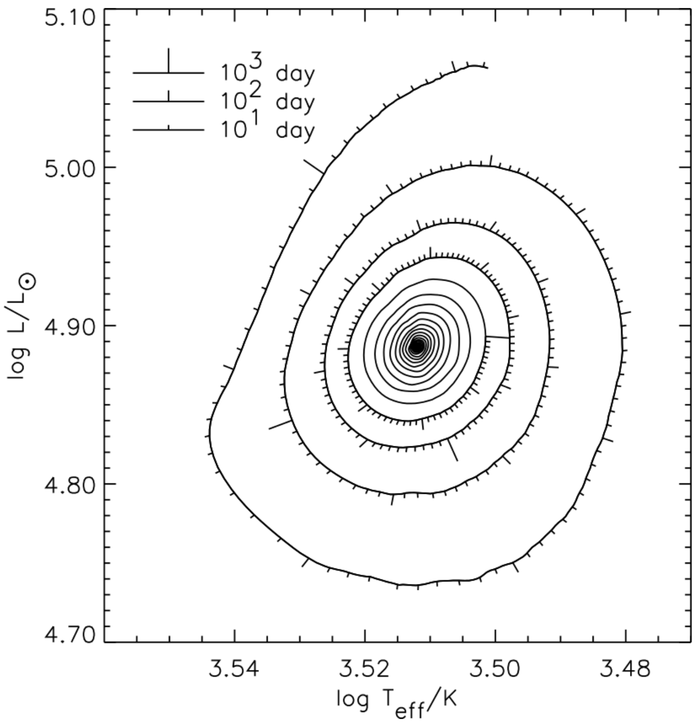
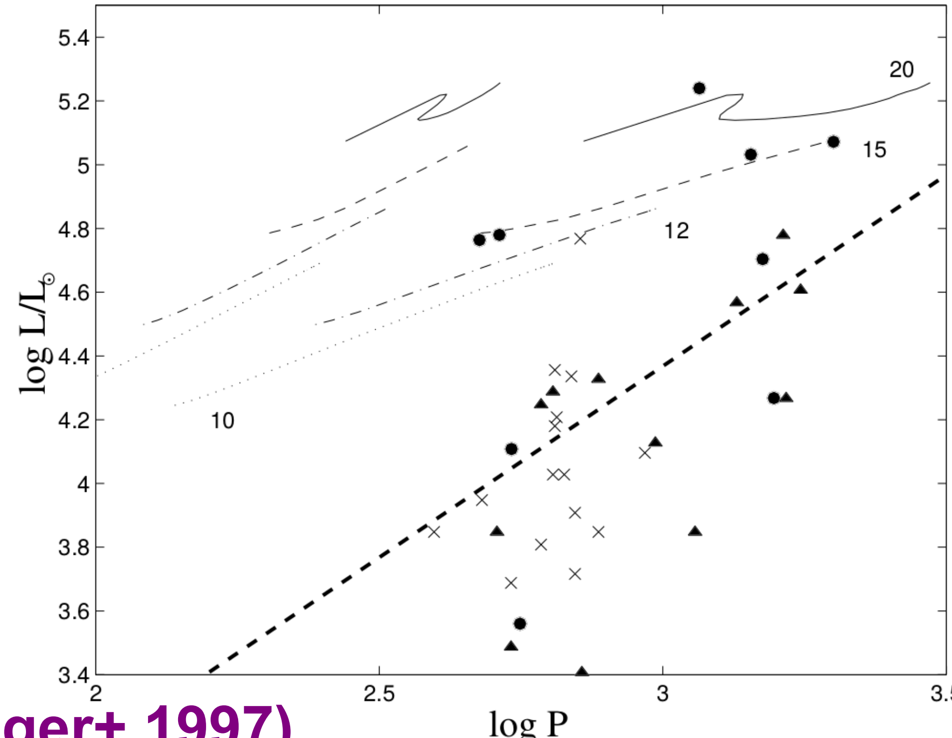
260
initial mass (solar masses)

Advanced Topics

Pulsational Mass Loss

Mass Loss due to Late Pulsations

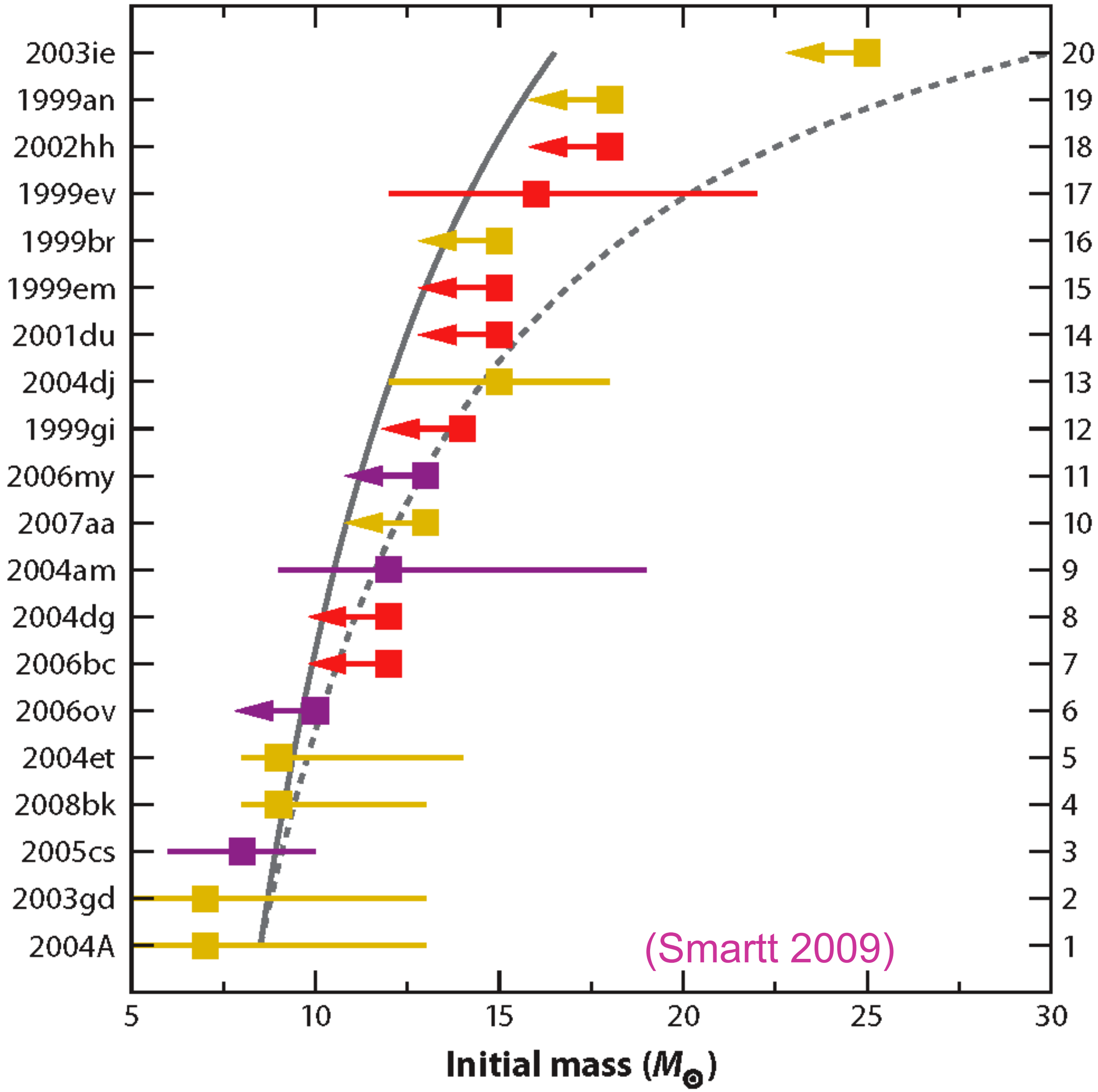




(Heger+ 1997)

- **Red Giants may encounter large-amplitude pulsations post-central He burning (few 10 kyr) which can drive mass loss (OH-IR stars, lost of dust)**
- **Can this remove majority of H envelope in "superwind"? Yoon & Cantiello (2010): this only be efficient above ~17 $M_\odot$**
- **Would make all solar stars above ~17 $M_\odot$ lose H envelope?**

Supernova Progenitor Masses



Presupernova stars for Type IIp and II-L

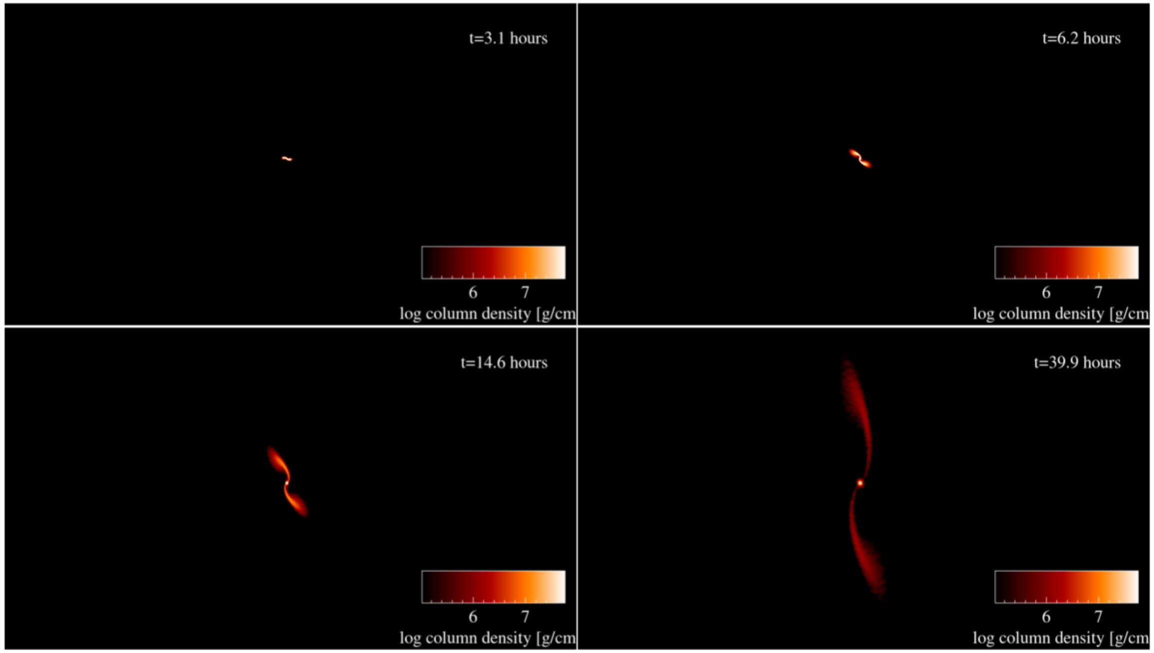
Solid Line:
Salpeter IMF with
16.5 $M_\odot$ cutoff

Dotted Line:
Salpeter IMF with
35 $M_\odot$ cutoff

► Exclude stars with $M_{initial}$ > 20 $M_\odot$ as Type IIP/IIL progenitors at 95% confidence level?

Tidal Stripping

Stripping by Tidal Disruption Events



Rodriguez (2017)

Evolved stars: tidal radius for H envelope much larger than that of He core

→ H envelope may be stripped off

→ high-velocity SN progenitor

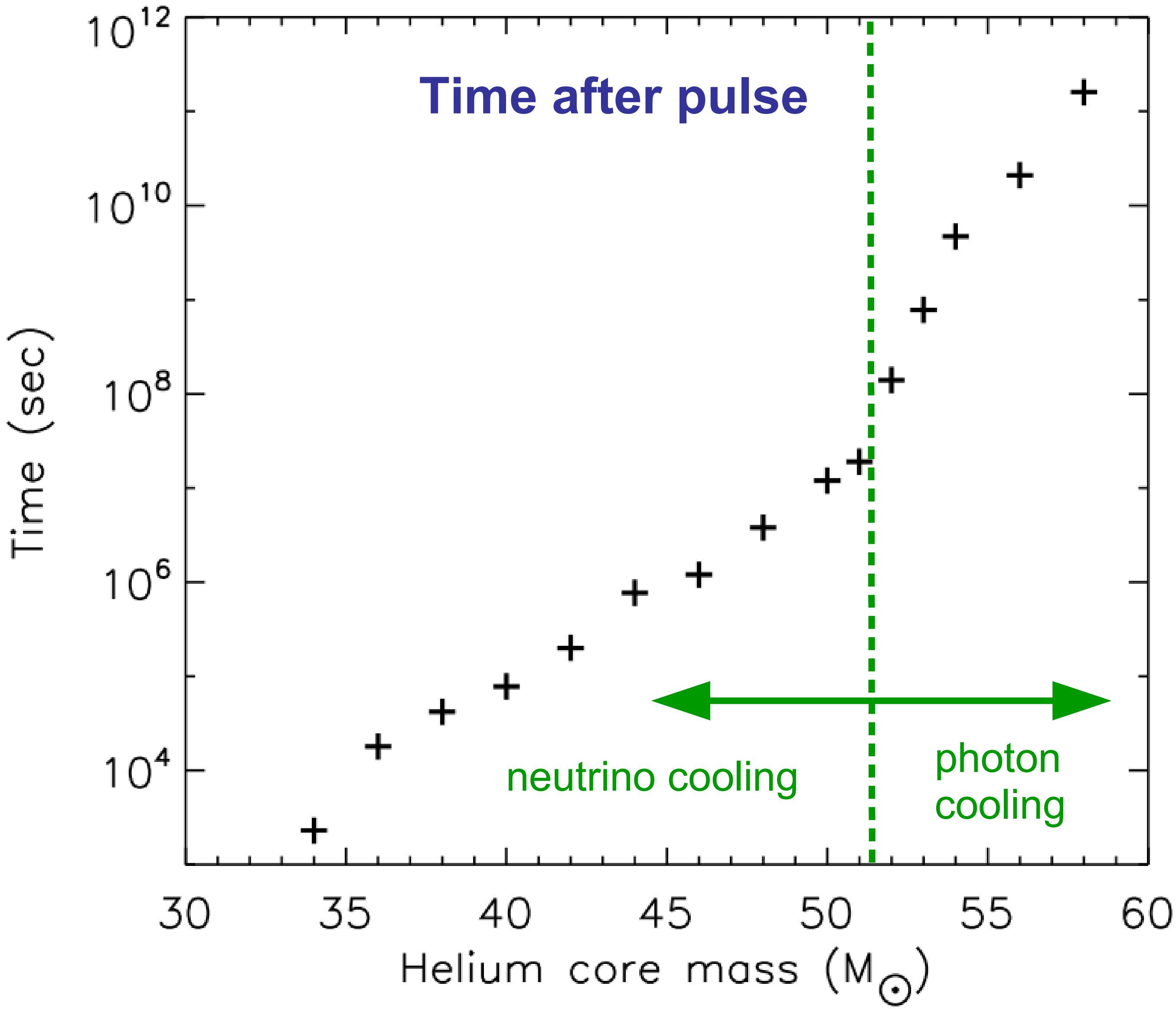
But:

- small time window compared to MS lifetime

- small number compared to TDE events (or binaries)

Pulsational Pair-Instability Supernovae

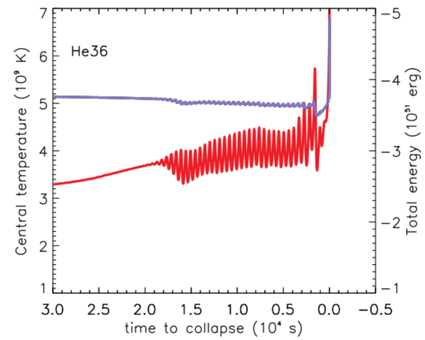
Pulsational Pair Instability Supernovae

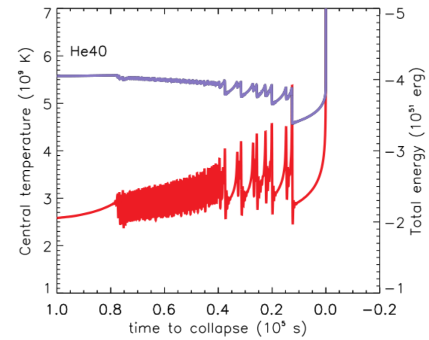


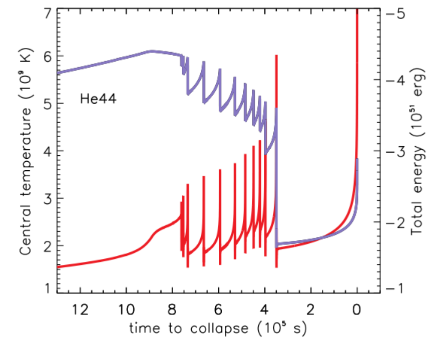
high-power PPSN of more massive cores increase entropy enough to push star outside regime of neutrino cooling

Woosley (2016)

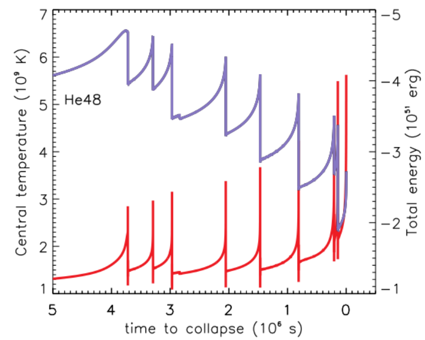
Pulsational Pair Instability Supernovae

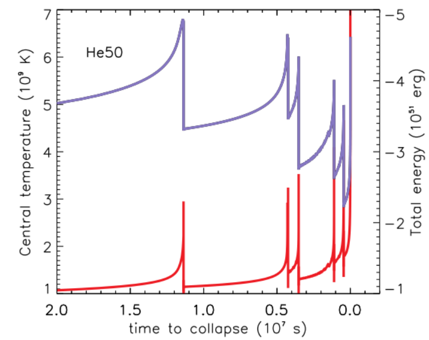


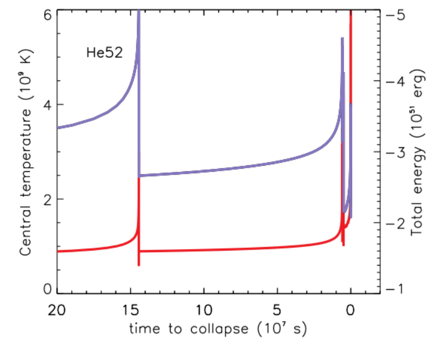


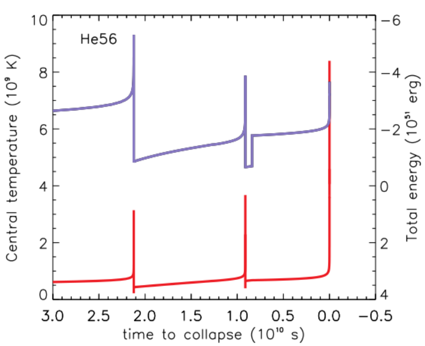


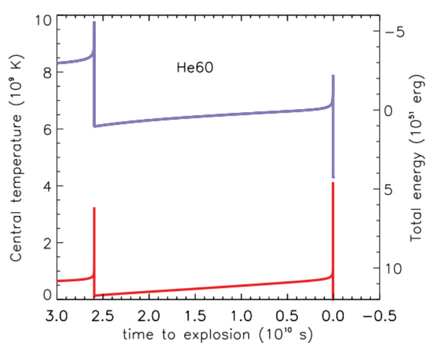
Various Pulse Histories

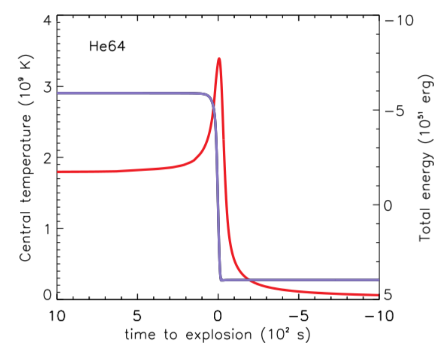






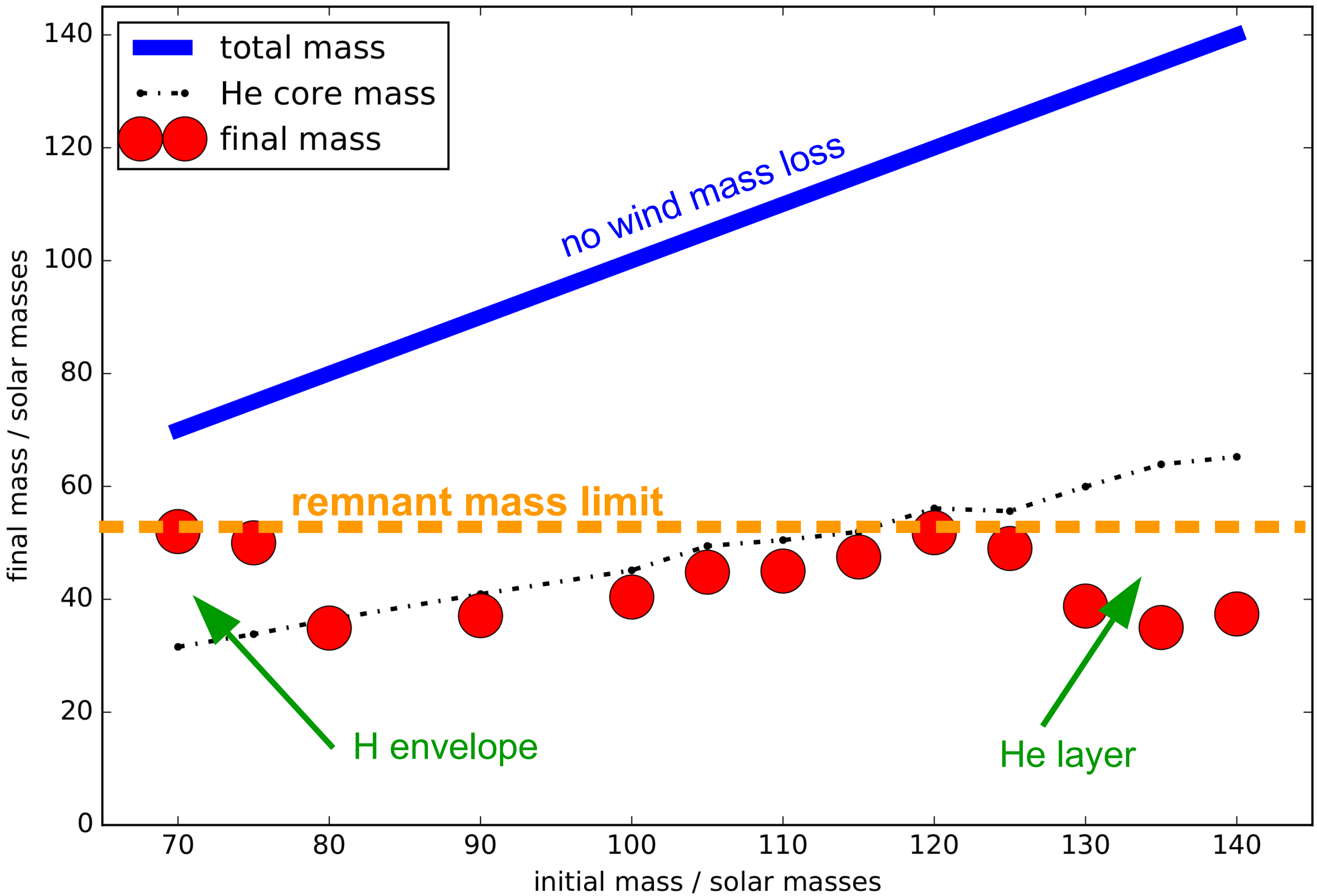






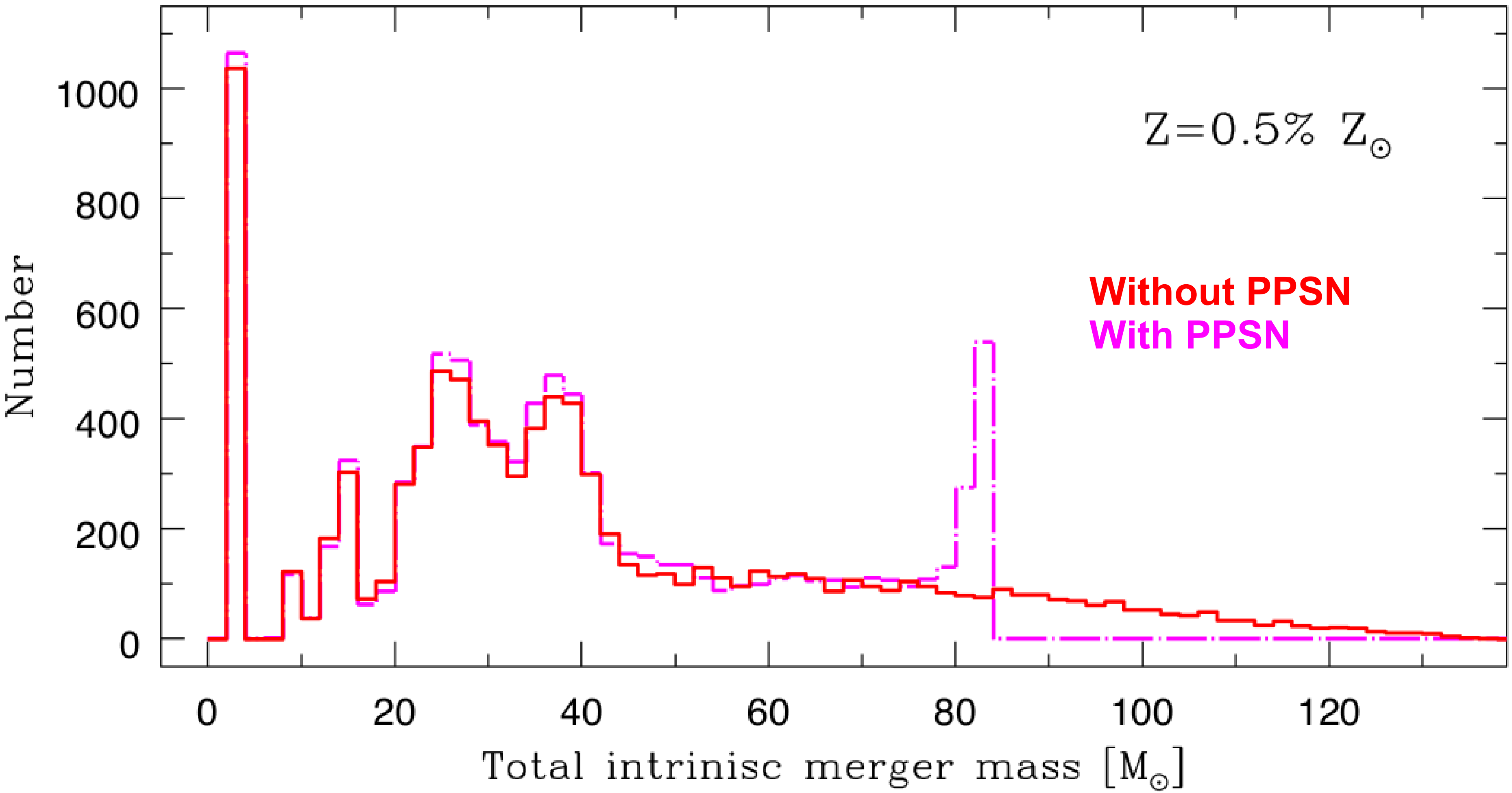
Woosley (2016)

Pulsational Pair Instability Supernovae

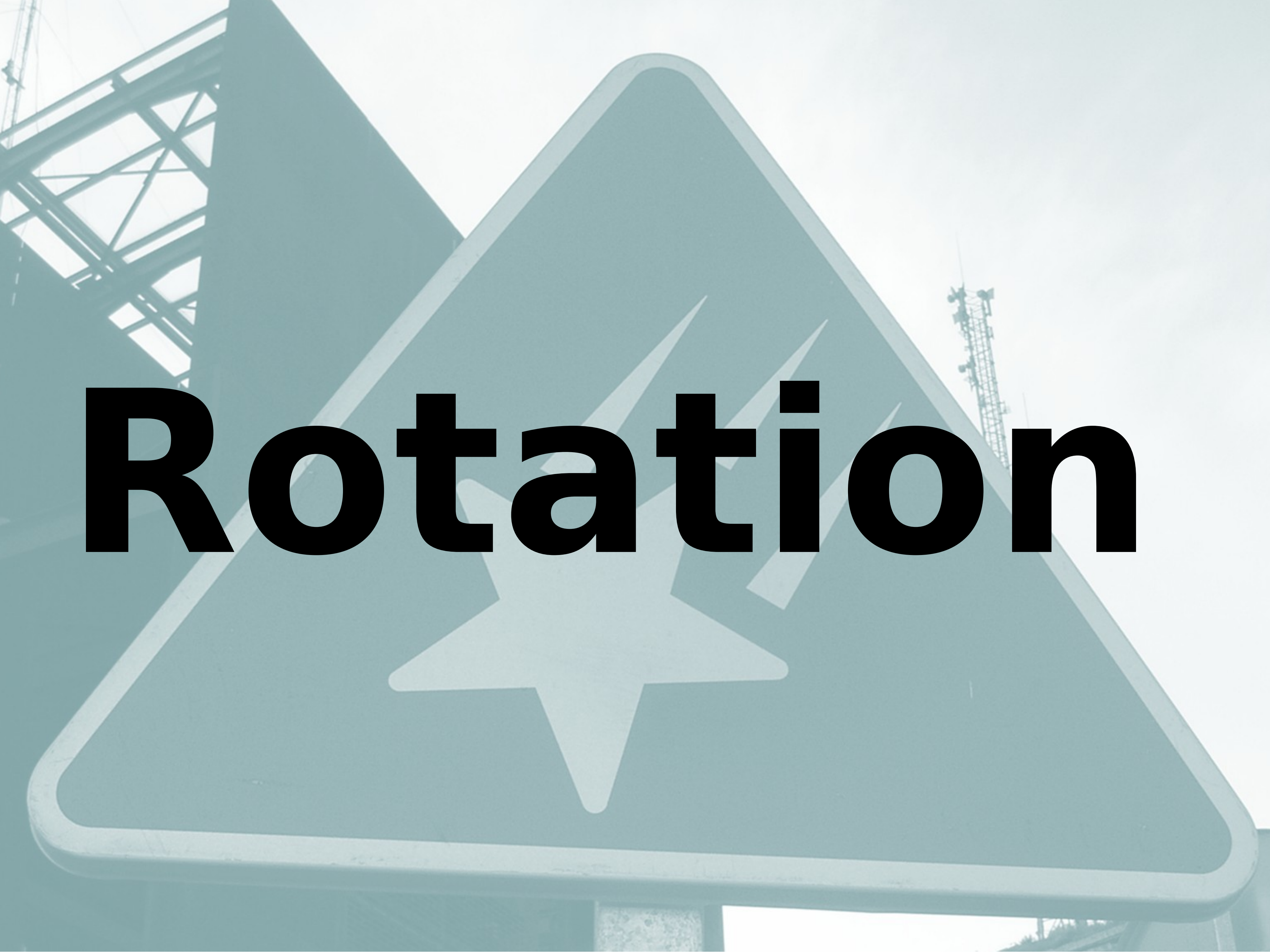


Plot after data from Woosley (2016)

Impact of Pulsational Pair Instability SN On Binary BH Merger Mass

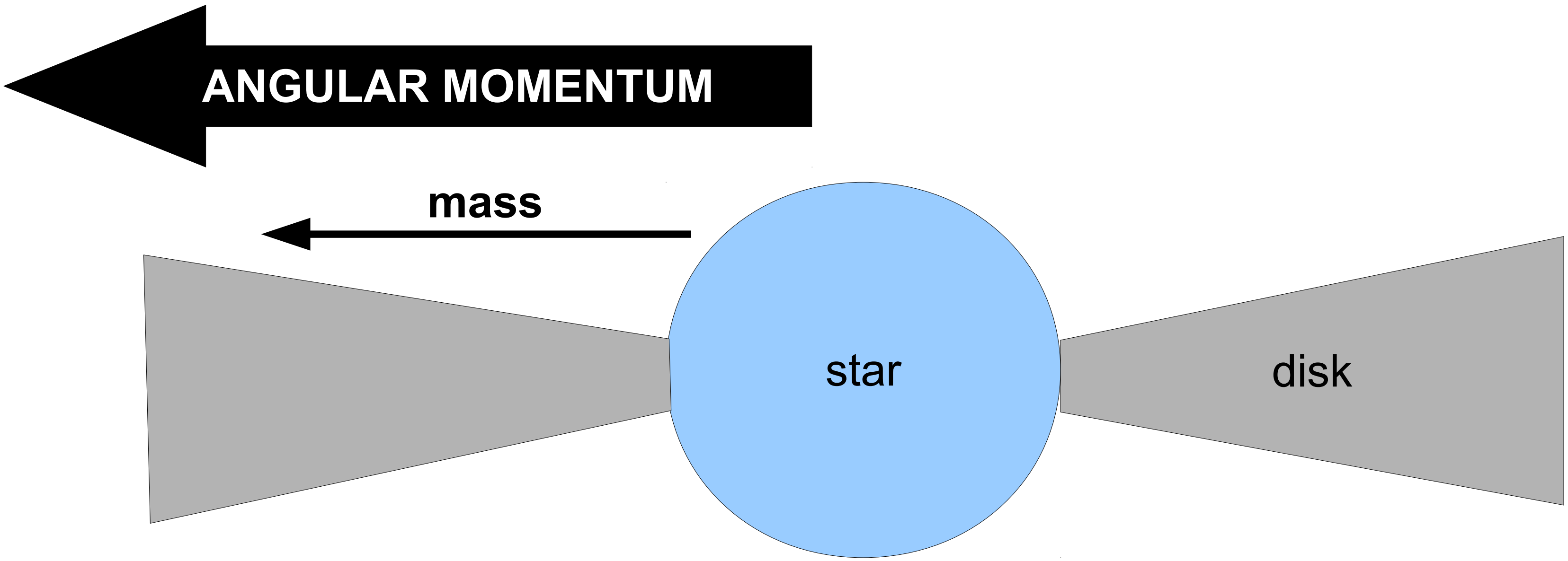


(Belczynski, Heger, Fryer, ... 2016)



Rotation

Mass Loss due to Critical Rotation



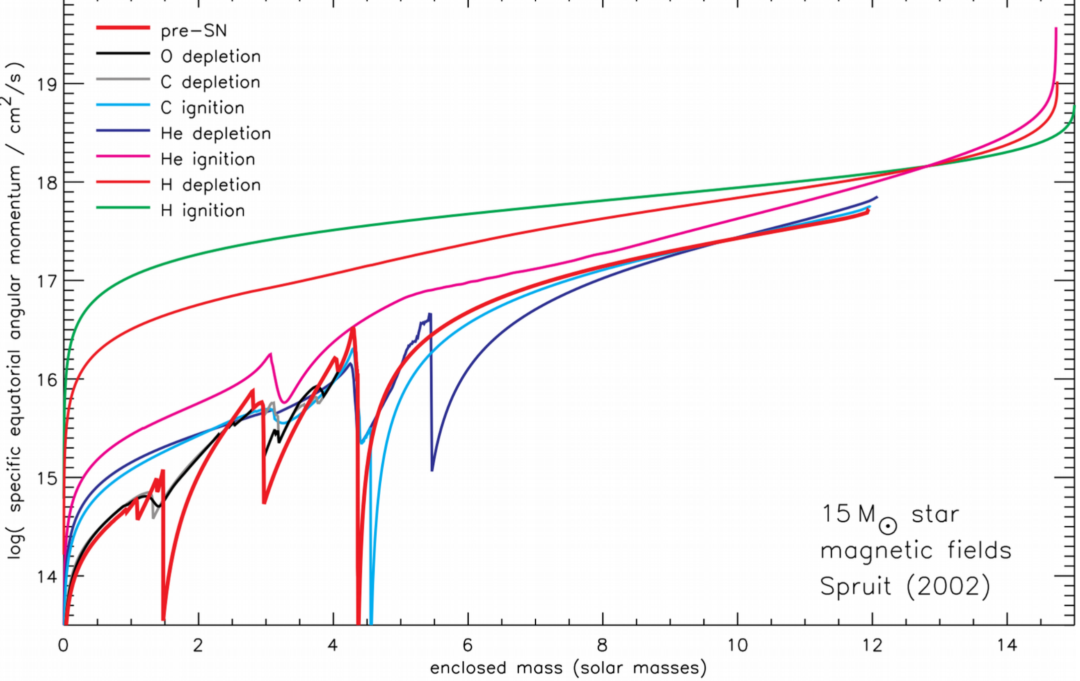
- **How important is mass loss due to critical (or fast) rotation?**
- **How do we quantify mass loss and angular momentum loss?**
- **How does it effect our stellar models?**

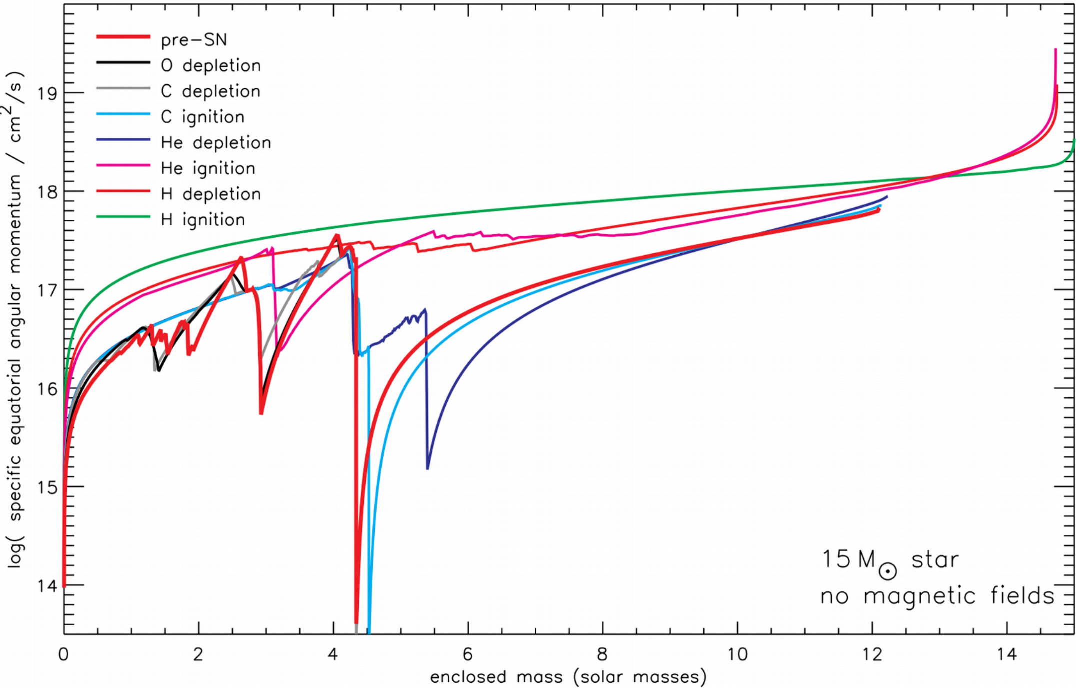
(Langer, Meynet, Maeder, Hirschi,...)

Chemical Homogeneous Evolution

- Typical O/B star rotation rates ~200 km/s
- Extreme rotation rates (300-400 km/s) may keep star chemically homogeneous during central H burning
- Star will end H burning with small H envelope on to top of extended core; H envelope He rich and strong CNO processing
- H envelop likely lost during central H burn as WR star
- (Heger+ 2000, Meynet, Maeder, Hirschi,…)

Angular Momentum Evolution for *Magnetic* and Non-Magnetic Stars



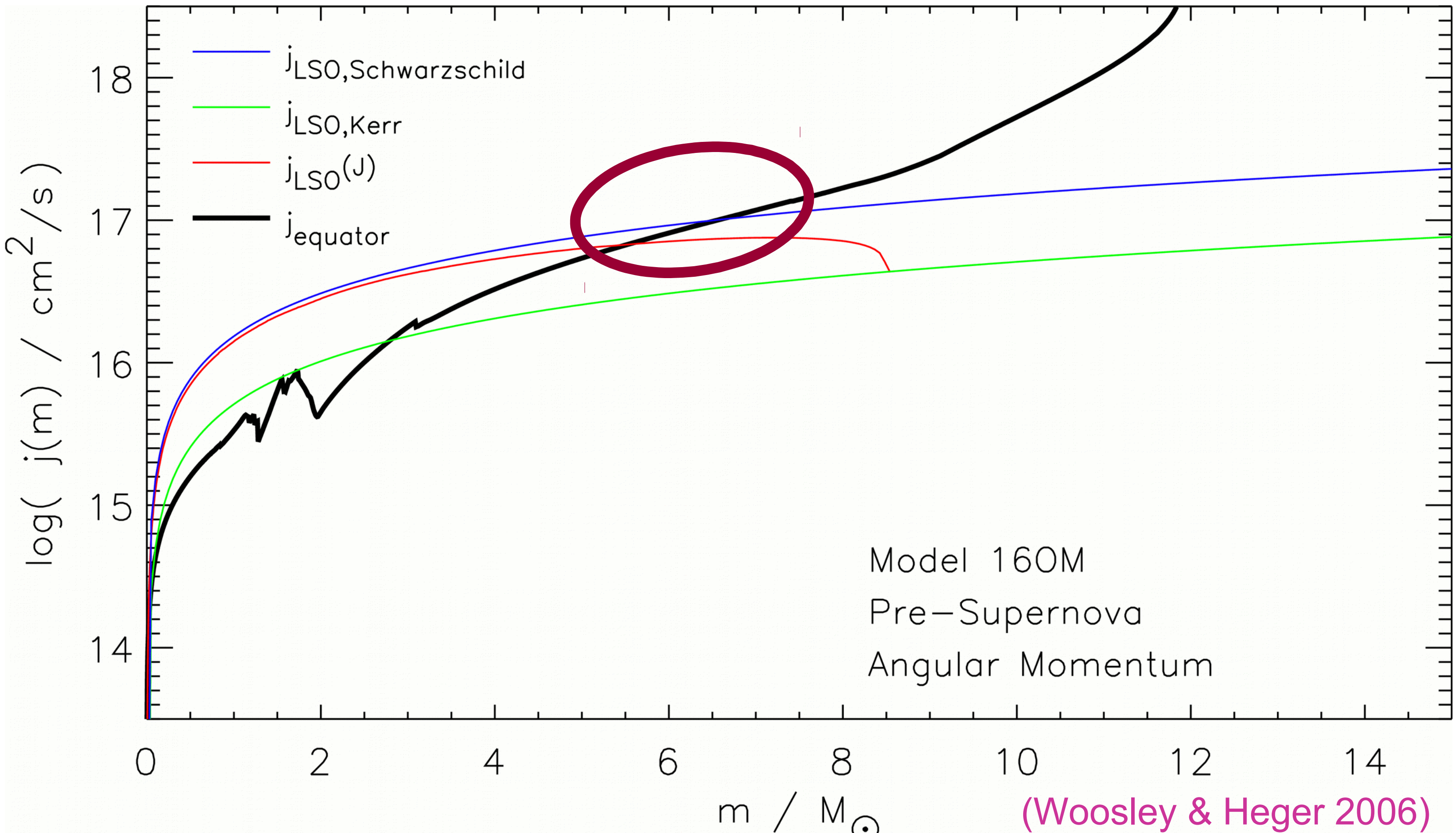


Depending on sensitivity of rotationally induced instabilities and angular momentum transport to composition gradients and magnetic fields, more or less extended parts of the core can obtain centrifugal support around a central black hole.

A Rapidly Rotating Progenitor

16 M_{sun} initial mass, 400 km/s initial rotation rate, Z=0.1 Z_{sun}, 1/3 Vink *et al.* (2005) WR mass loss rate.

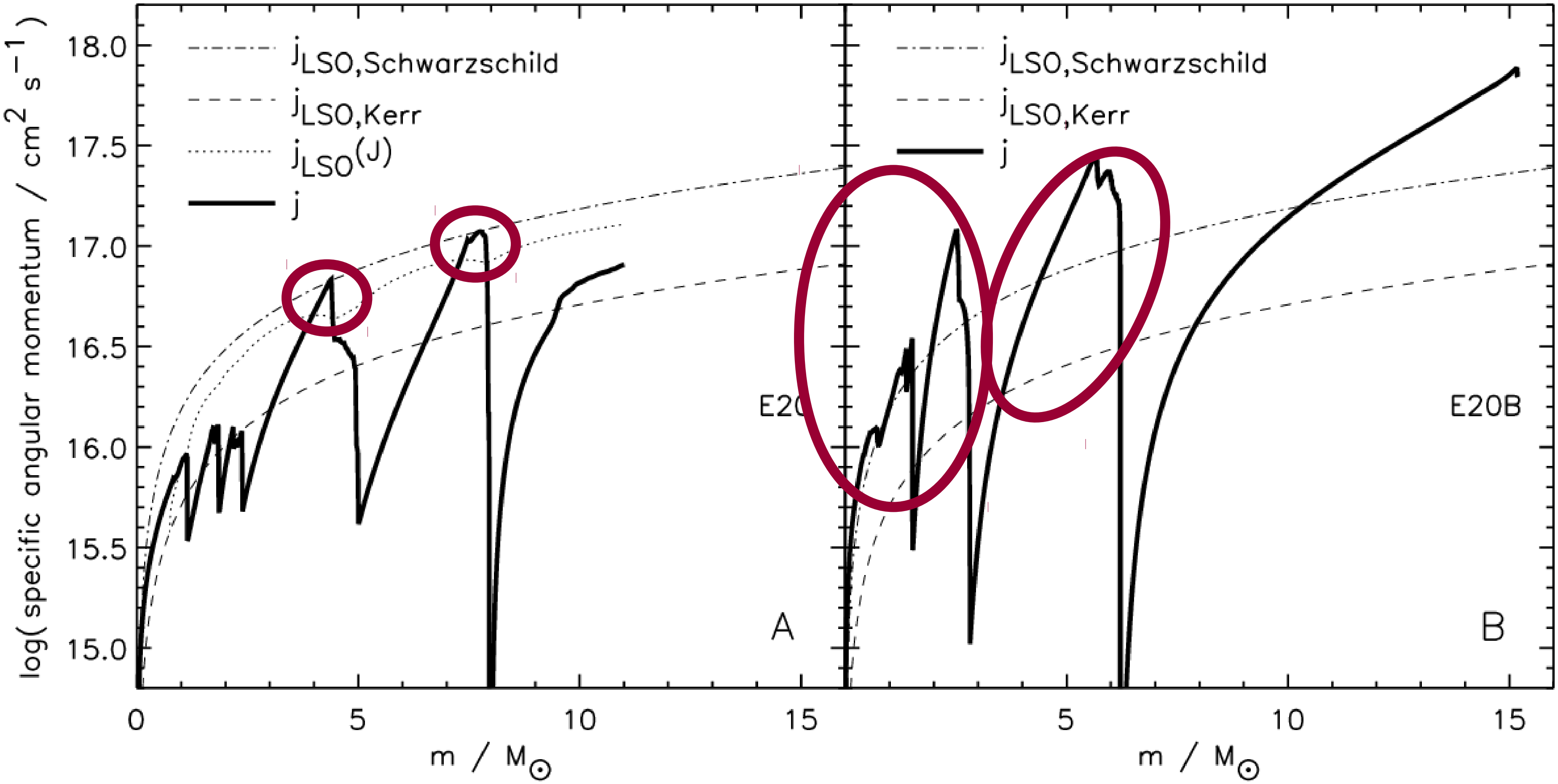
→ angular momentum P ~1.4 ms NS equivalent



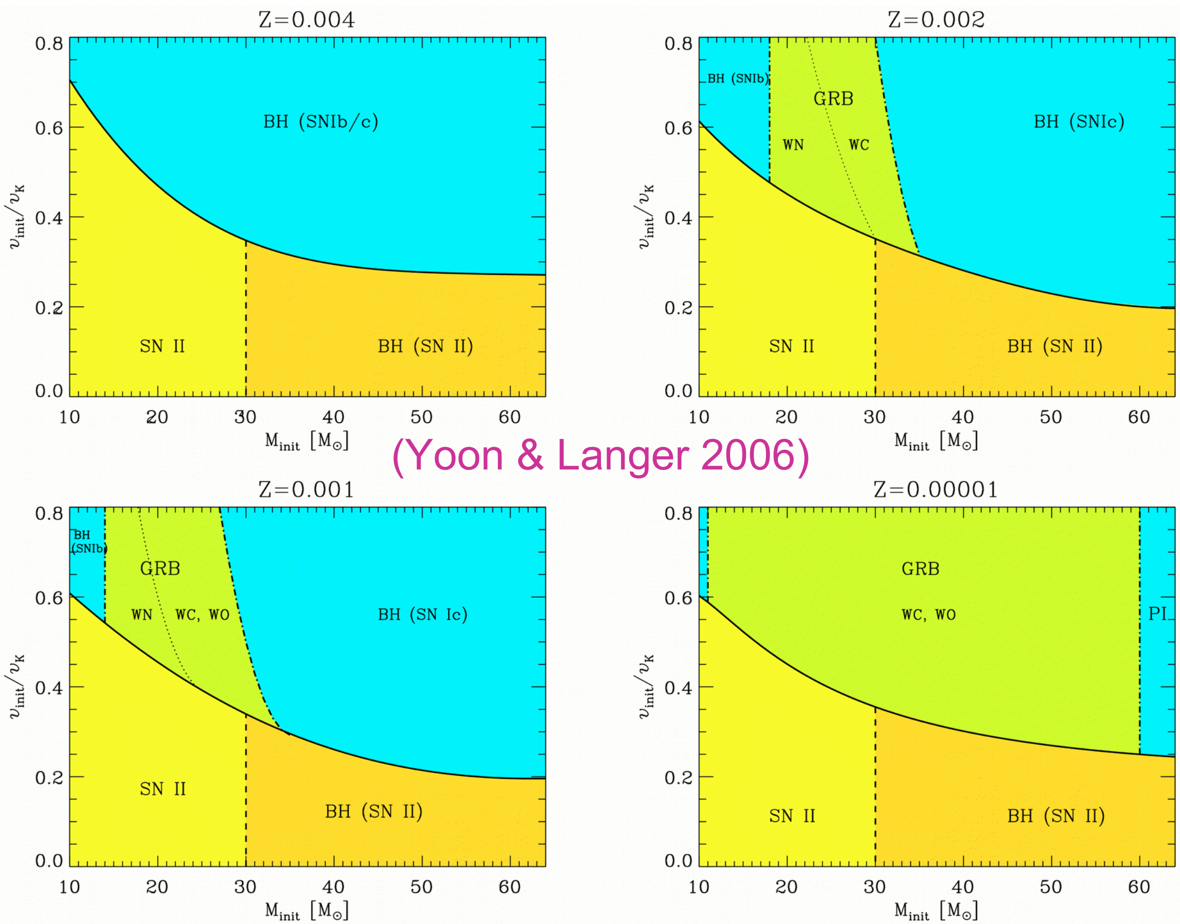
(Woosley & Heger 2006)

Equatorial angular momentum compared to limit for accretion disk formation

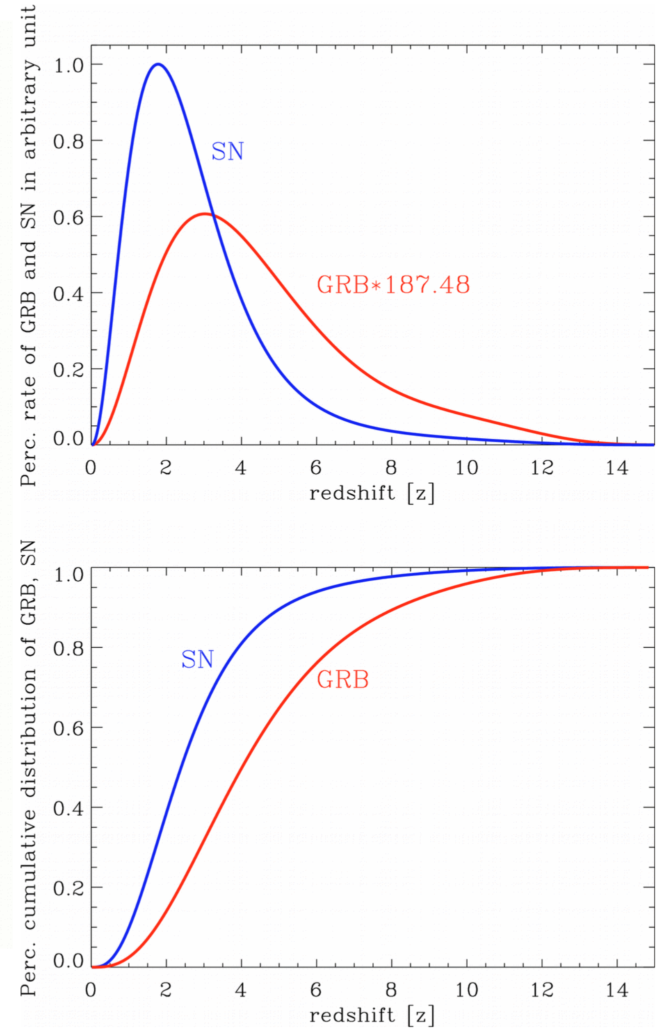
Depending on sensitivity of rotationally induced instabilities and angular momentum transport to composition gradients, more or less extended parts of the core can obtain centrifugal support around a central black hole.



Rapidly Rotating Progenitors for Different Metallicities

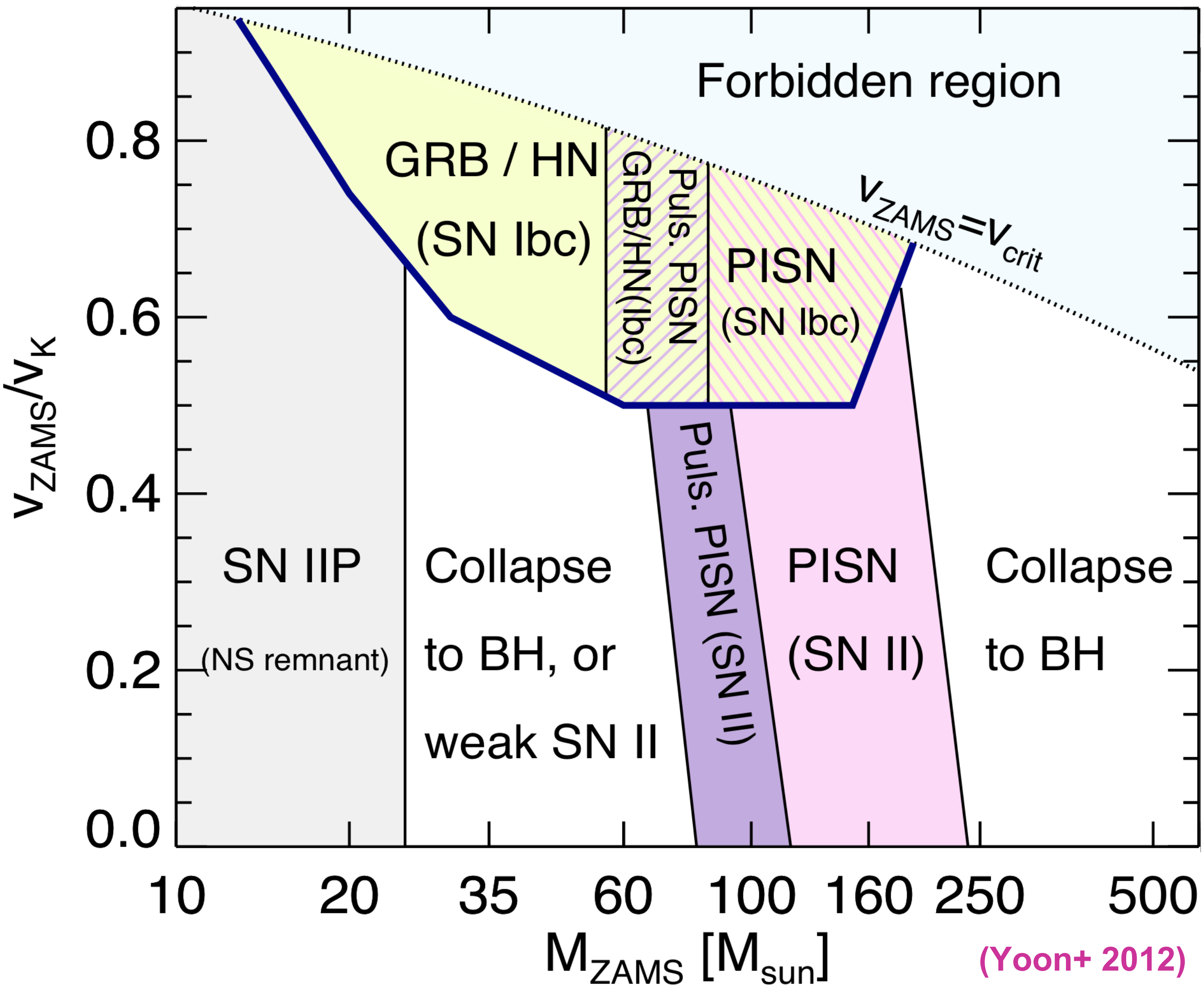


(Yoon & Langer 2006)



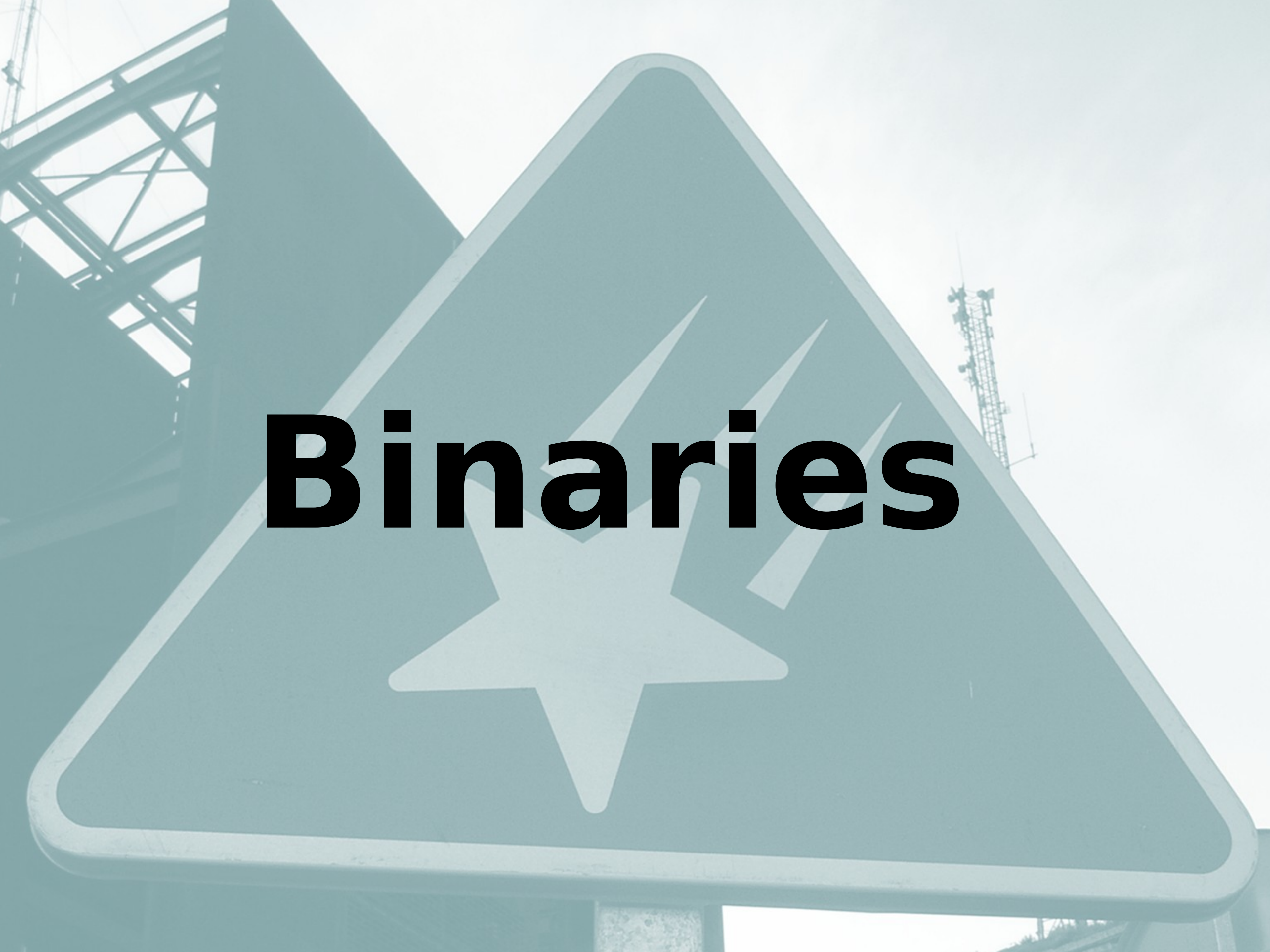
Similar results, but higher metallicity cut-off, found by Woosley & Heger (2006)

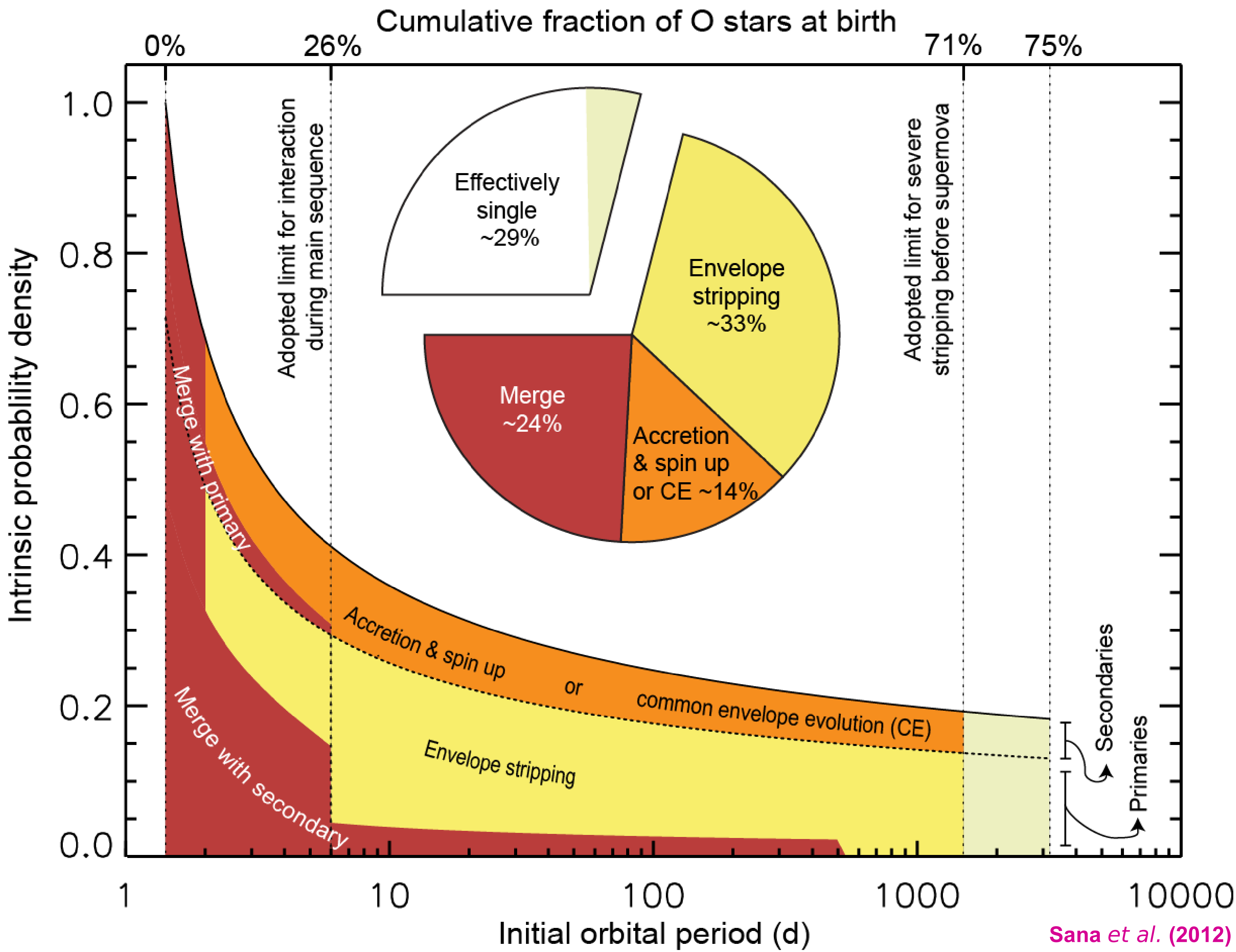
Final fates of rotating massive Pop III stars



(Yoon+ 2012)

Binaries





Cumulative fraction of O stars at birth
0%
26%
71%
75%
Intrinsic probability density
1.0
0.8
0.6
0.4
0.2
0.0
1
10
100
1000
10000
Initial orbital period (d)
Adopted limit for interaction during main sequence
Adopted limit for severe stripping before supernova
Effectively single ~29%
Envelope stripping ~33%
Merge ~24%
Accretion & spin up or CE ~14%
Merge with primary
Merge with secondary
Accretion & spin up or common envelope evolution (CE)
Envelope stripping
Secondaries
Primaries
Sana et al. (2012)

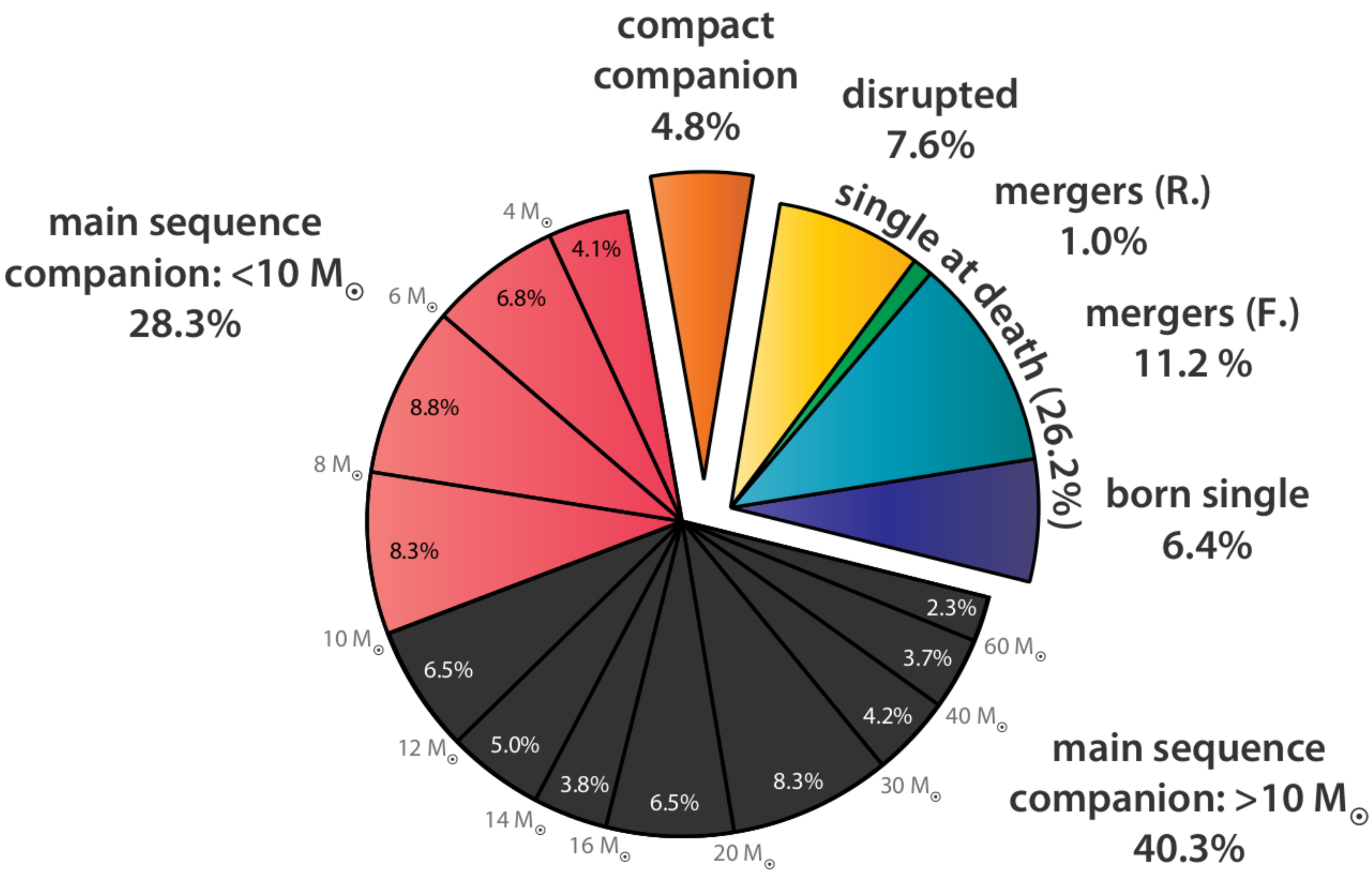
Binaries

initial mass $M_\odot$	binary mass transfer Case A	binary mass transfer Case B	binary mass transfer Case C	single star
~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)

Binary Progenitors of SN Ib/c

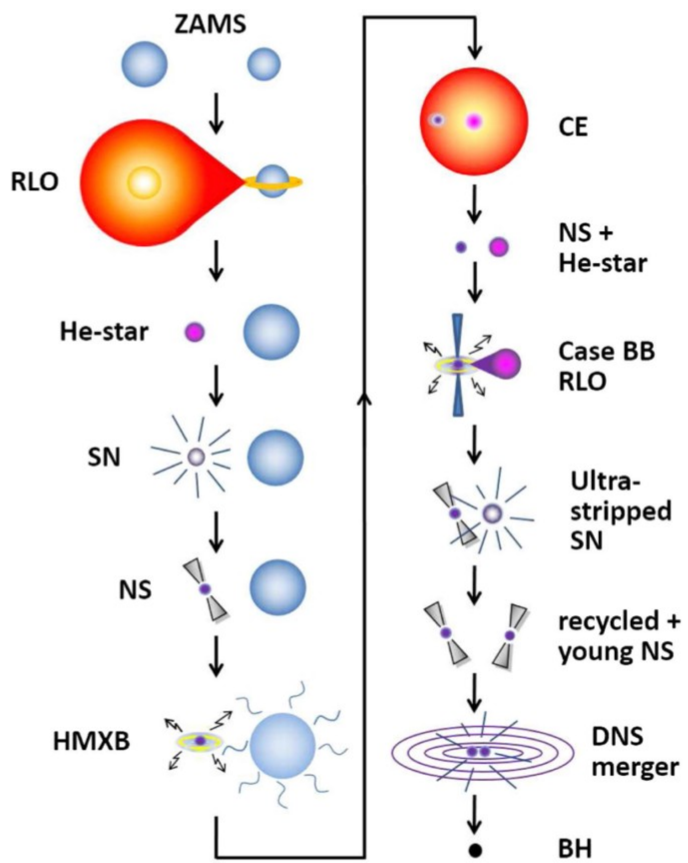


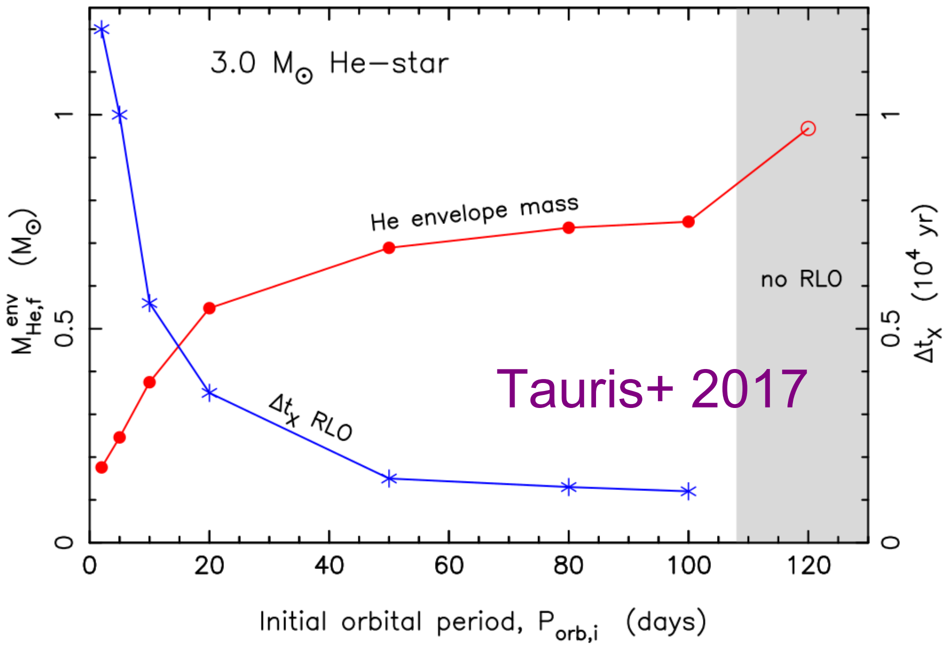
Stripped-envelope SNe (Z = 0.0055)

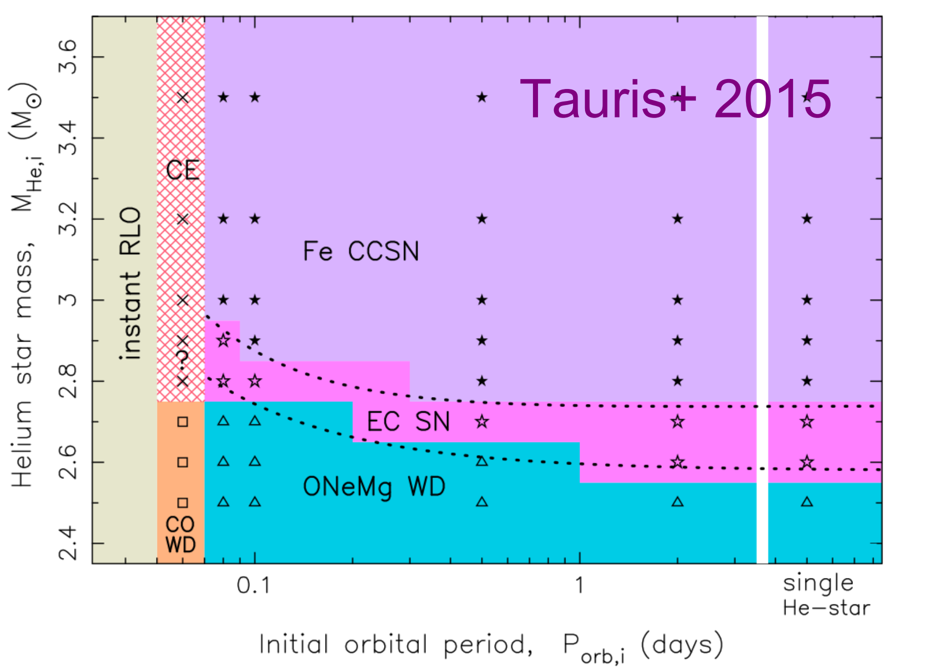
(Zapartas, de Mink, + 2017)

Ultra-Stripped Binaries

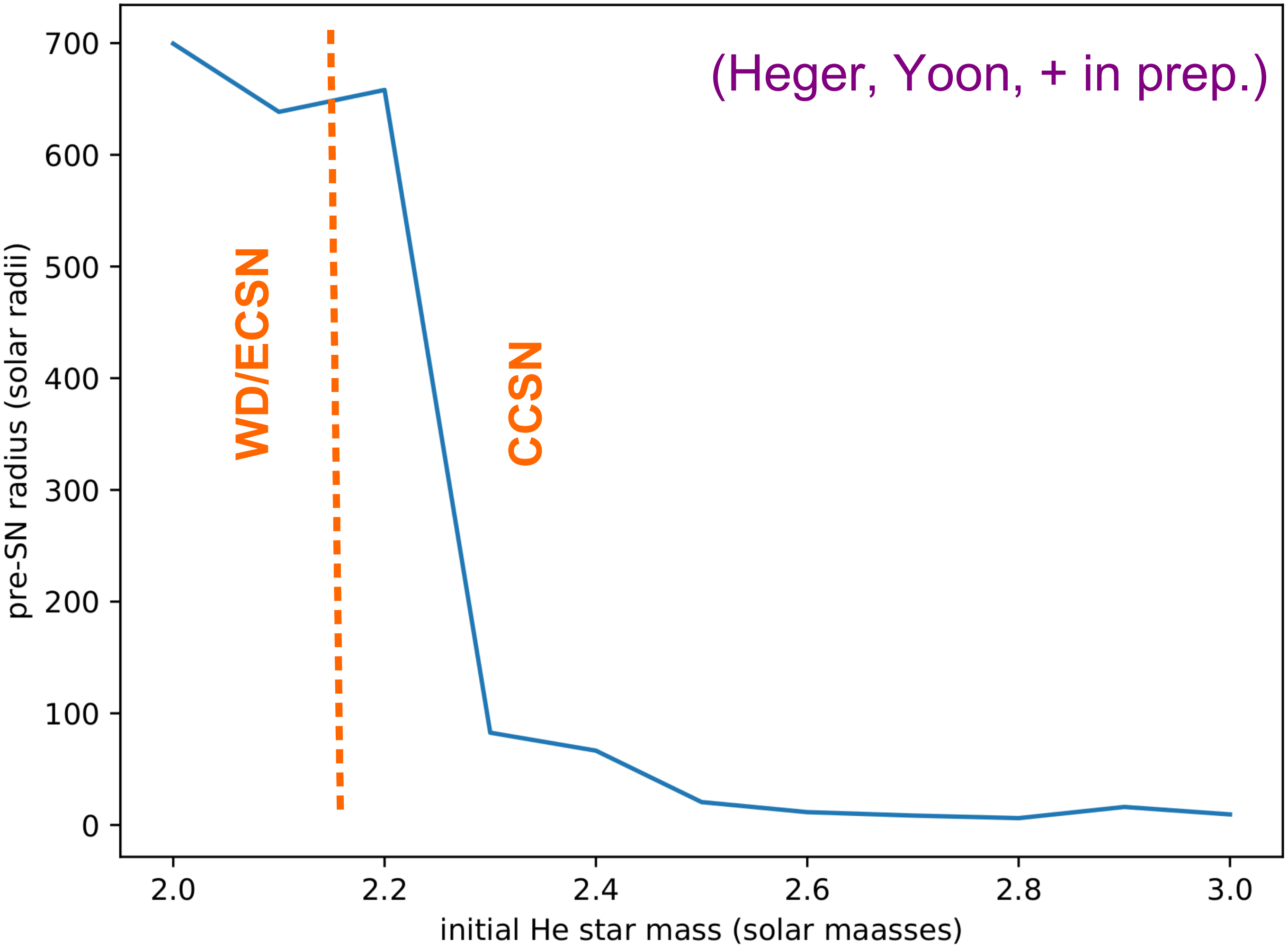
Close Binary interaction may strip much of the He envelope in close binary stars → ultra-stripped SN progenitors.







Radius of in stripped pre-SN



[Explanation]
Model of He stars, evolution to pre-SN.

Experience significant final expansion in just the last few years prior to SN stage
→ **may lead to significant mass loss including must He just prior to explosion.**

(also paper by Woosley, Langer, Podsiadlowski in prep since 1995...)

Perspectives

- *Stripped Core Collapse Supernovae* (SCCSN) can be a variety of objects and have a variety of progenitor sources and evolution paths
- The supernovae and their light curves may give us key insights into the final evolution of their progenitors including binary properties
- SCCSN are likely key stages in the formation of close binary compact objects as progenitors of GW sources and the bulk of the *r*-process
- Origin of the diversity of rotation required for GRB vs. young pulsars – can binary/stripped star evolution paths resolve this?