Big Explosions from Big Stars

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Overview

- Varieties of Stellar Deaths
- Really Big Stars?
- Really Big Supernovae (RBSN)

Formation and Mass 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,...)

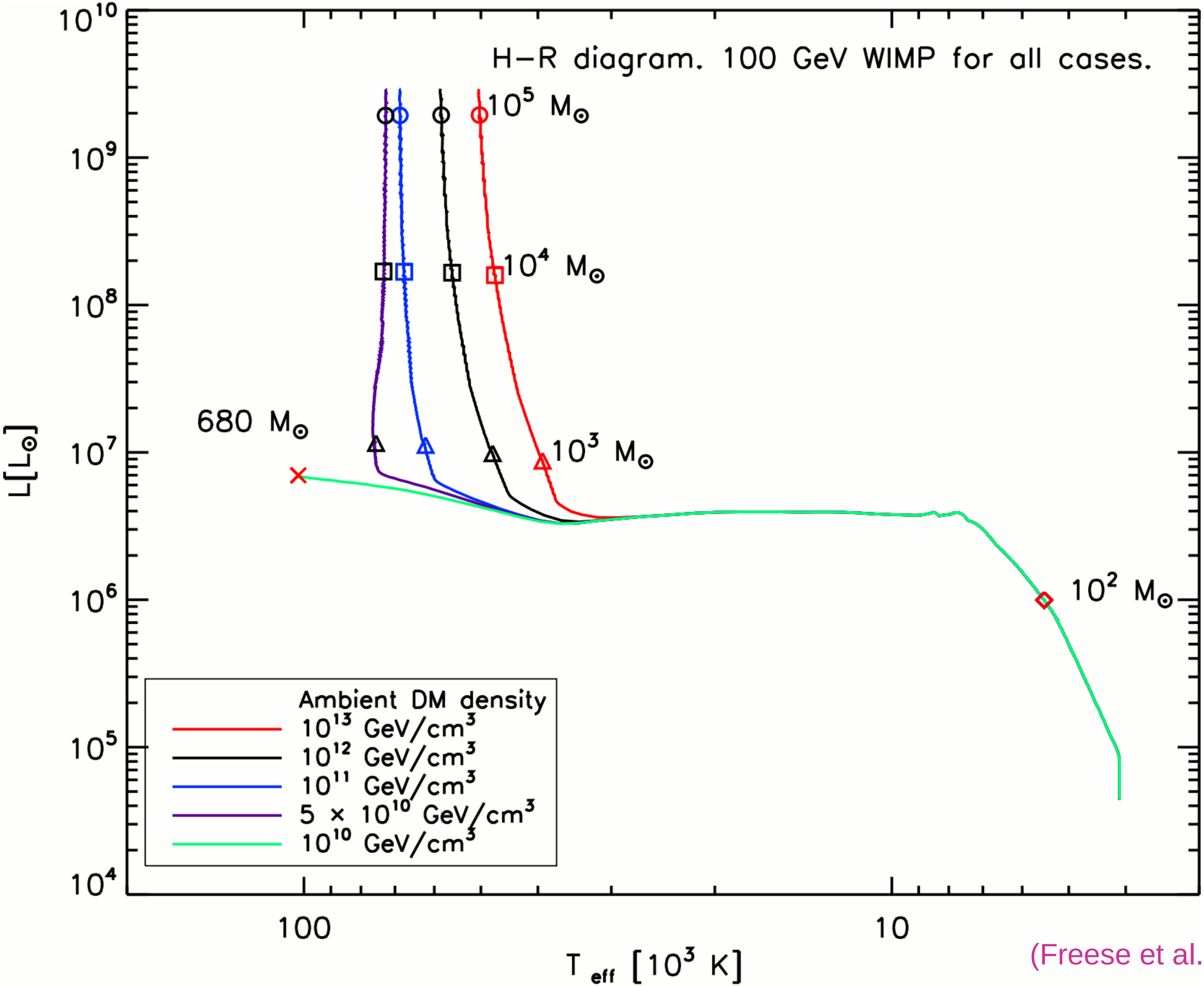
➔ typical mass scale ~100 $M_\odot$ – no binaries

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

- Now simulations indicate binaries may exist
- We still don't have a really strong constrain on Pop III star masses in general
- But what happens in regions of large DM halos collapsing? (these are not the first to collapse)
- Can this make dense star clusters?
- Or really big stars? (supermassive stars)

“Really” Big Stars?

- We observe quasars at high redshift $z > 6$
- Requires supermassive black holes $M \sim 10^9$ solar masses
- Accretion would need to be very efficient to make these
- Other possibility: Make dense cluster for very big primordial cloud, runaway star merging
- Or make big stars with WIMPs...
- We only need a very few of them...

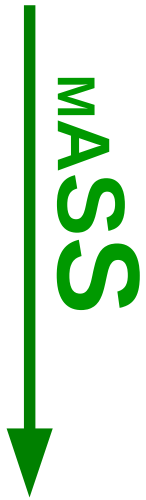


(Freese et al. 2010)

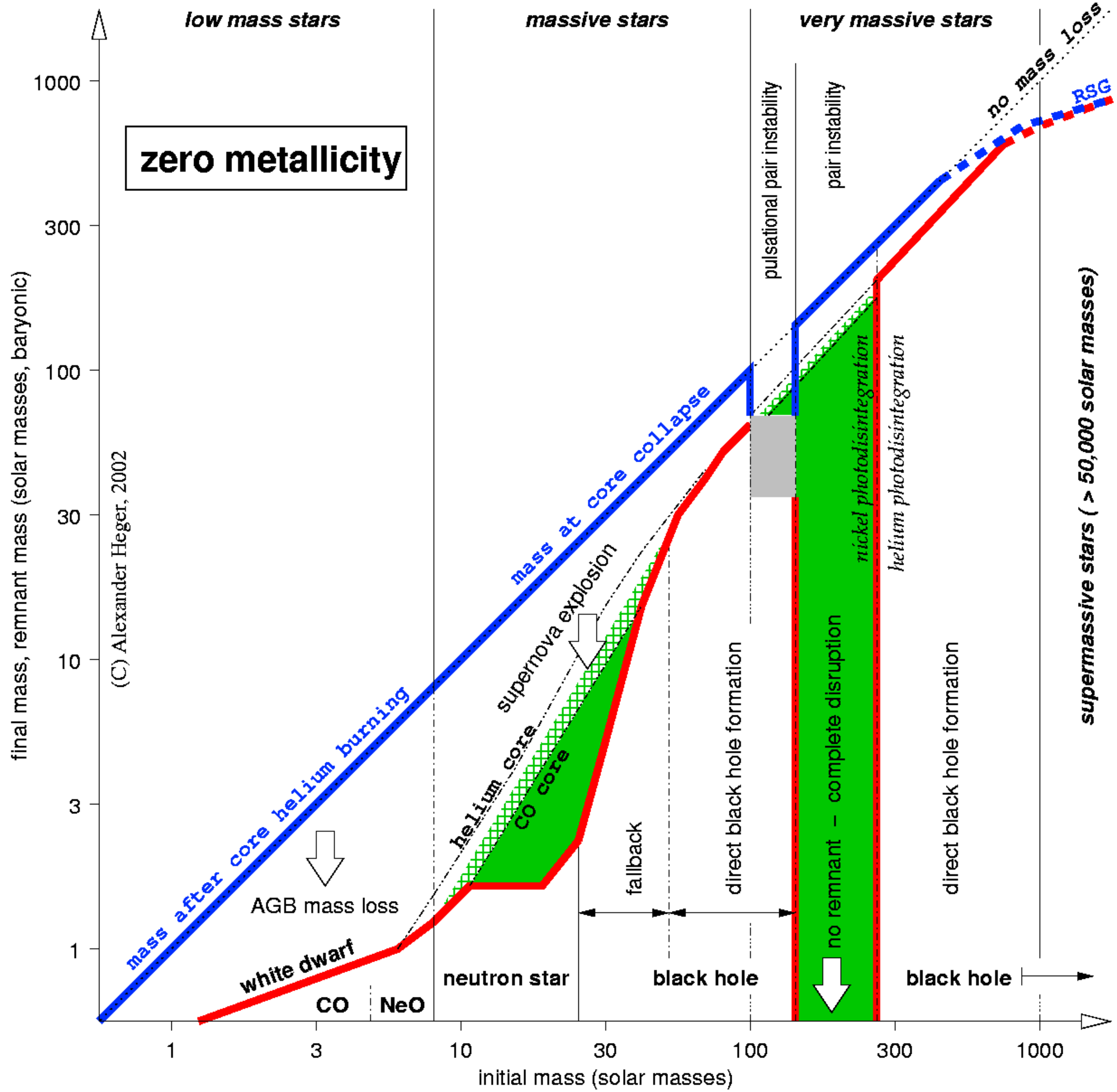
Things that blow up

supernovae

1B=10^{51} erg

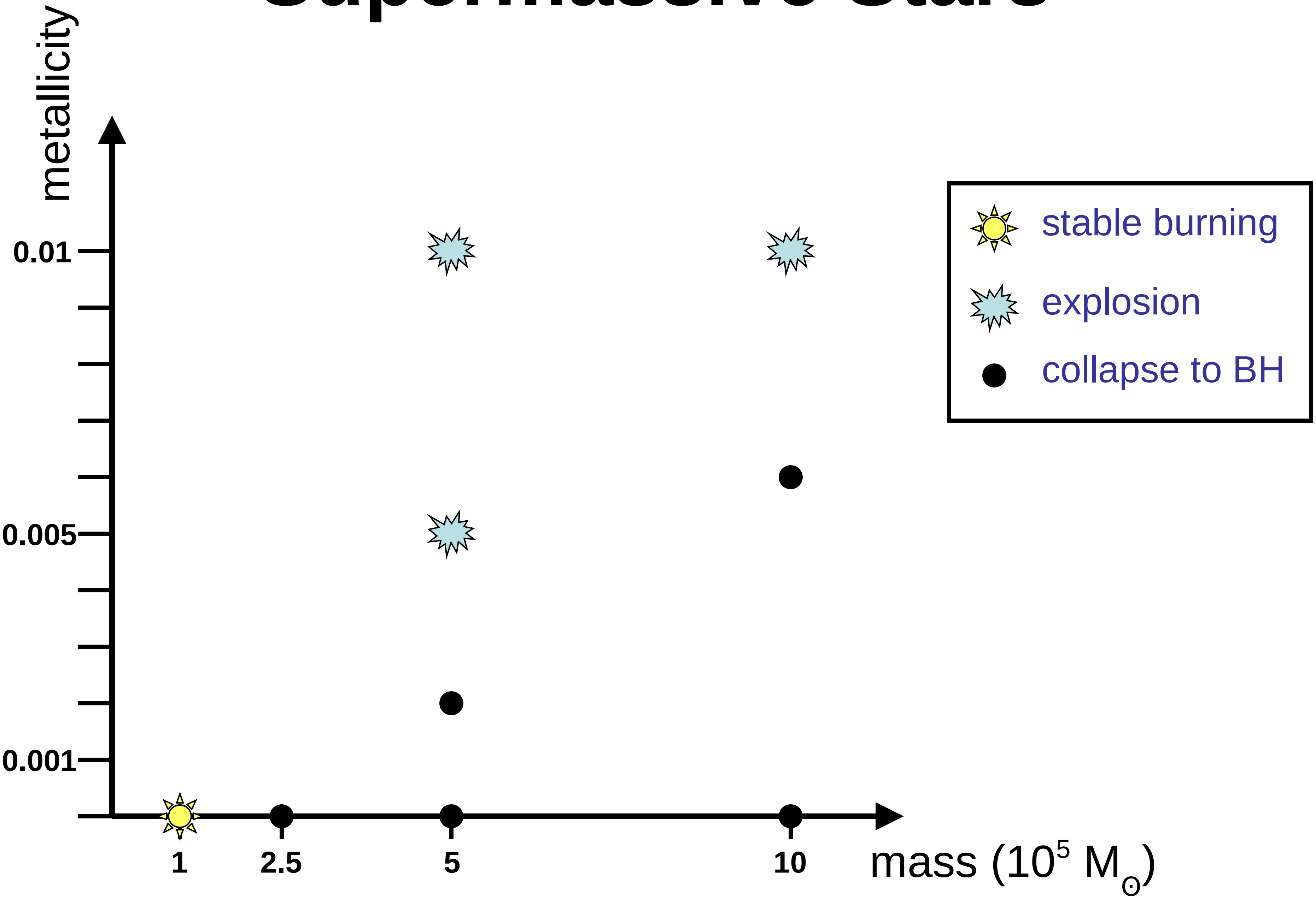


- CO white dwarf ➔ Type Ia SN, E≈ 1Bethe
- MgNeO WD, accretion ➔ AIC, faint SN
- "SAGB" star (AGB, then SN) ➔ EC SN
- "normal" SN (Fe core collapse) ➔ Type II SN
- WR star (Fe CC) ➔ Type Ib/c
- "Collapsar", GRB ➔ broad line Ib/a SN, "hypernova"
- Pulsational pair SN ➔ multiple, nested Type I/II SN
- Very massive stars ➔ pair SN,≲100B (1B=10^{51} erg)
- Very massive collapsar ➔ IMBH, SN, hard transient
- GR He instability ➔ >100 B SN+SMBH, or 10,000 B
- Supermassive stars ➔ ≳100000 B SN or SMBH



Ejected “metals”

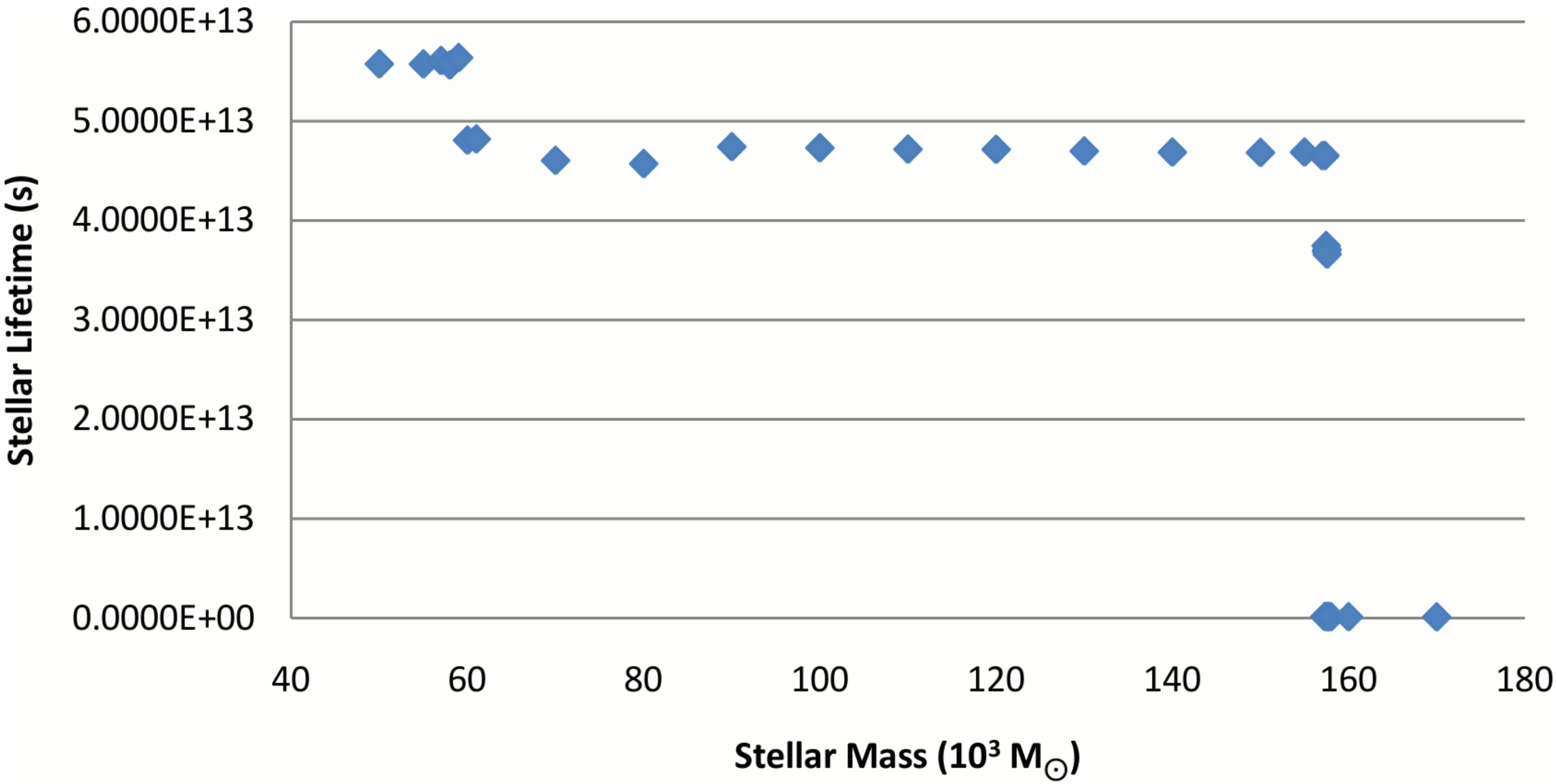
Supermassive Stars



(after Fuller, Woosley, & Weaver 1986)

Lifetime as a Function of Initial Mass (Pop III H stars)

(Ryan Poita, senior thesis, 2010)



Supermassive Stars

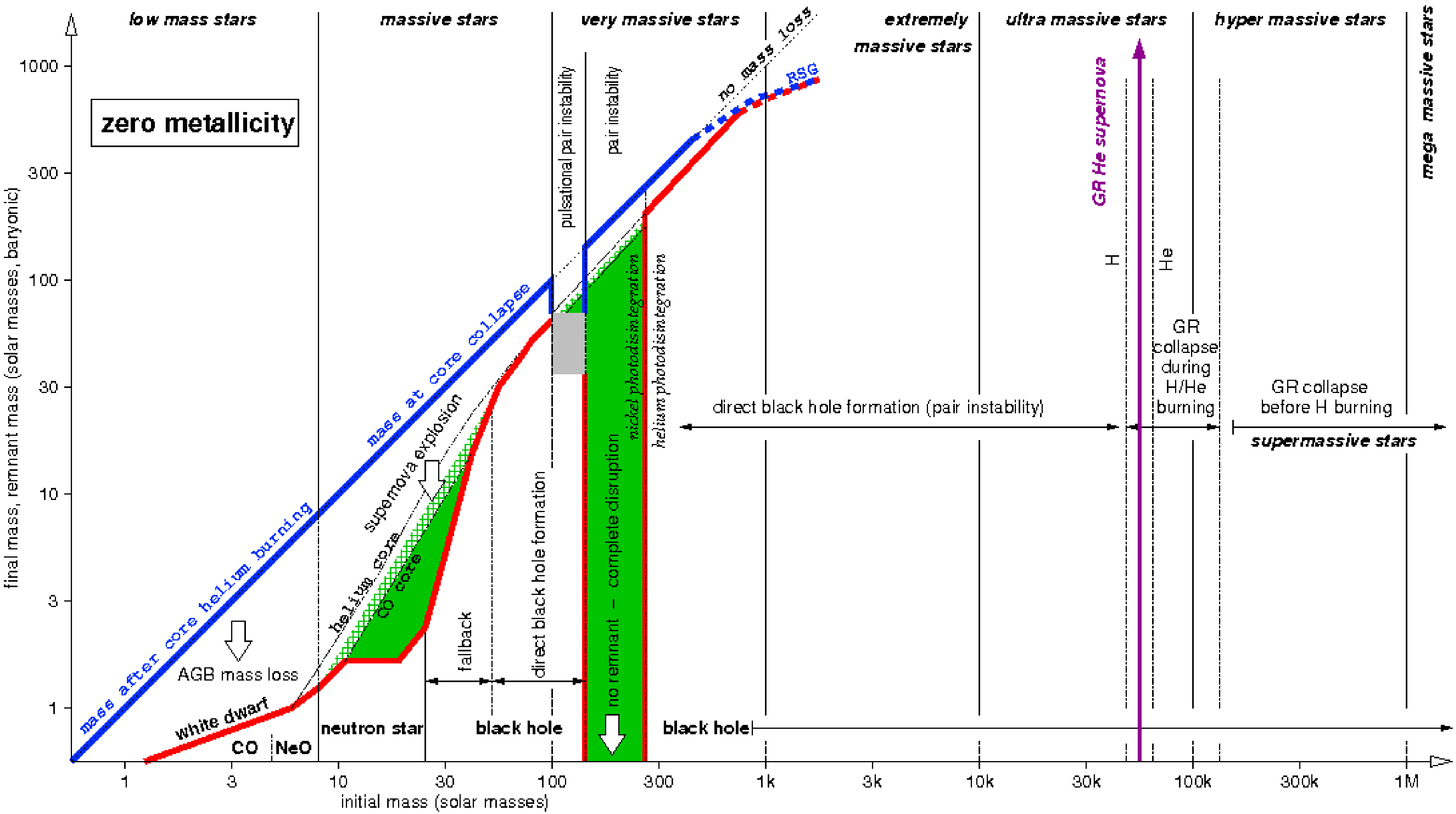
Can they ever form?

- Collapse due to GR instability
- Adiabatic index of gas drops to very close to 4/3, almost entirely dominated by radiation pressure
- Critical adiabatic index γ_{crit} rises above 4/3 due to GR (gravity “stronger”, include internal E in gravitational mass)
  ➔ instability
- Burning has high T-dependence
  ➔ explosion possible?

Supermassive Fates

- Pop III: for $M > 157{,}300\ M_{\odot}$: (sharp transition)
  Collapse before hydrogen burning
- Pop III: for $M \sim 80{,}000\ M_{\odot}$:
  "weak" GR H supernova, E = a few B
- Pop III: for $M > 60{,}000\ M_{\odot}$:
  Collapse before start of helium burning
- Pop III: for $M \sim 60{,}000\ M_{\odot}$:
  "weak" GR He supernova, E = a few 100 B
- Pop III: for $M \sim 55{,}000\ M_{\odot}$:
  "strong" GR He supernova, E ~ 10 kB
- Pop III: for $M > 50{,}000\ M_{\odot}$:
  Collapse before end of helium burning

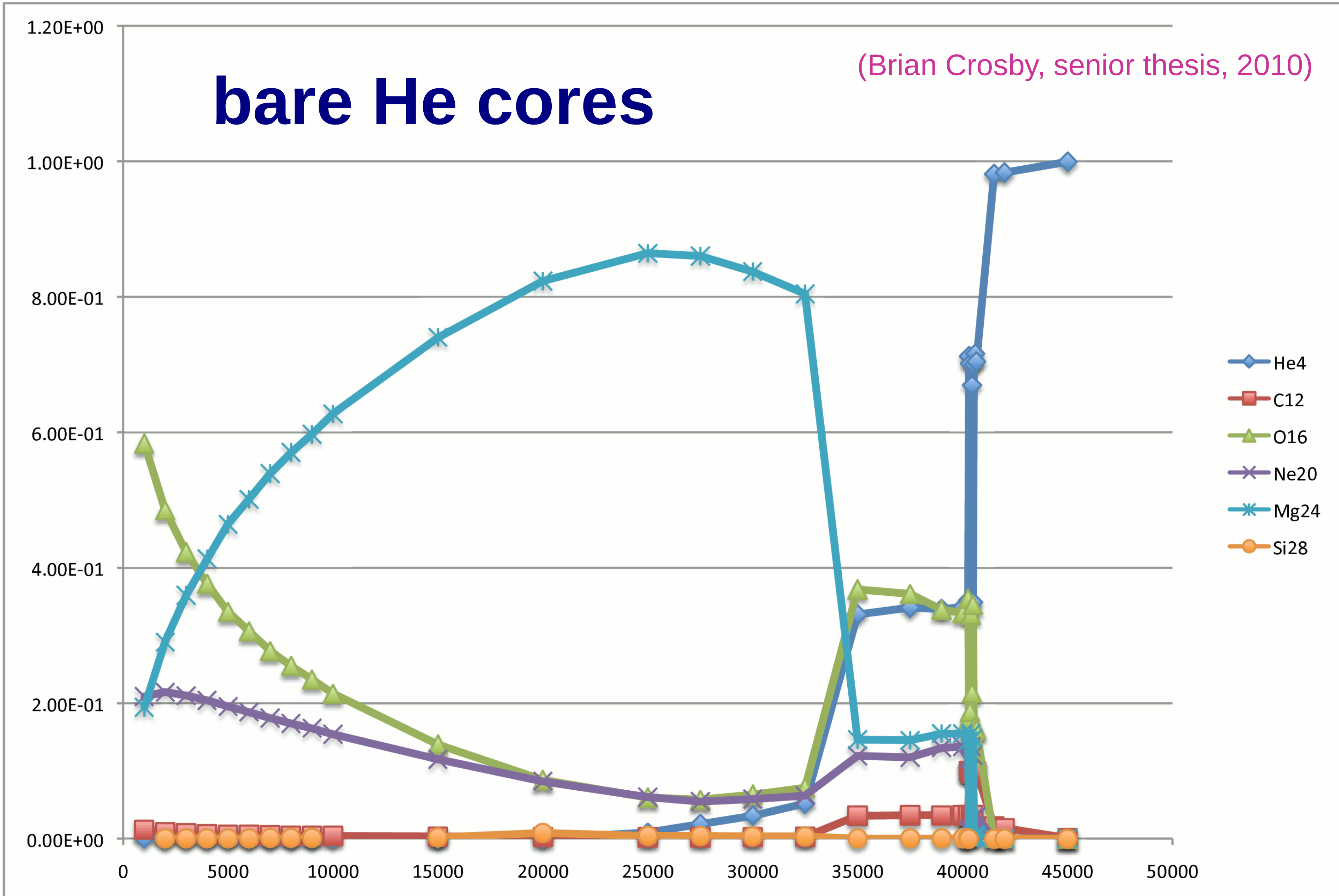
Supermassive Stars



Nuclear burning stages

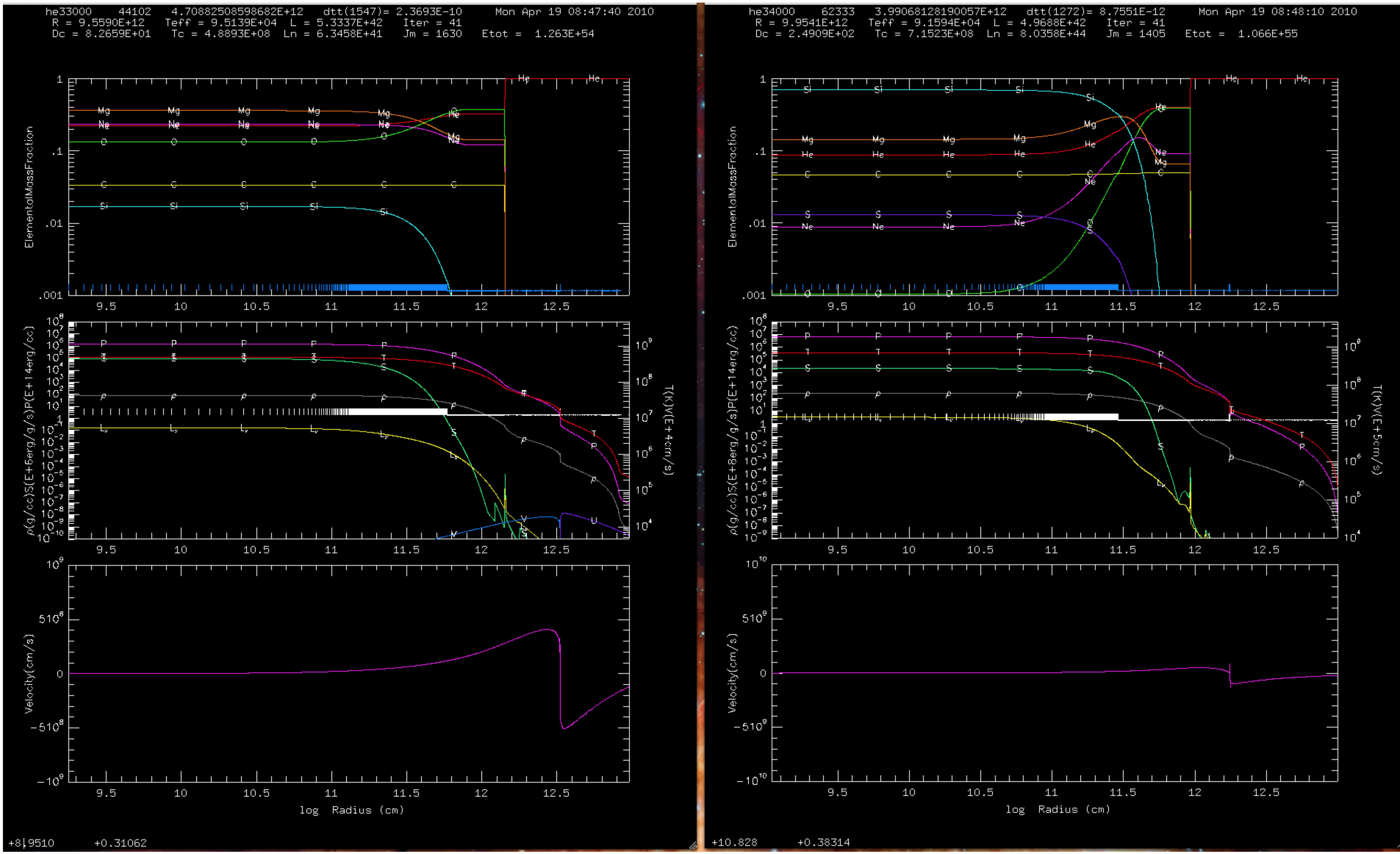
Burning stages		20 $M_\odot$ Star		200 $M_\odot$ Star	
Fuel	Main Product	T (10^9 K)	Time (yr)	T (10^9 K)	Time (yr)
H	He	0.02	10^7	0.1	2×10^6
He	O, C	0.2	10^6	0.3	2×10^5
C	Ne, Mg	0.8	10^3	1.2	10
Ne	O, Mg	1.5	3	2.5	3×10^{-6}
O	Si, S	2.0	0.8	3.0	2×10^{-6}
Si	Fe	3.5	0.02	4.5	3×10^{-7}

Central abundance at end of hydrostatic He burning



Explosion of 33/34kM$_\odot$ He core

(Brian Crosby, senior thesis, 2010)



Big Nucleosynthesis

Hydrostatic burning

- He burning does not just make C+O, but burns all the way to Mg
  ➔ increase He-burning lifetime by 2x!

Explosive burning (RBSN)

- Unique alpha-rich nucleosynthesis up to Si
  ➔ this would be a challenge to GCE
- Burning should be highly unstable
  ➔ mixing
  ➔ do in 2D/3D (CASTRO)

How does this work?

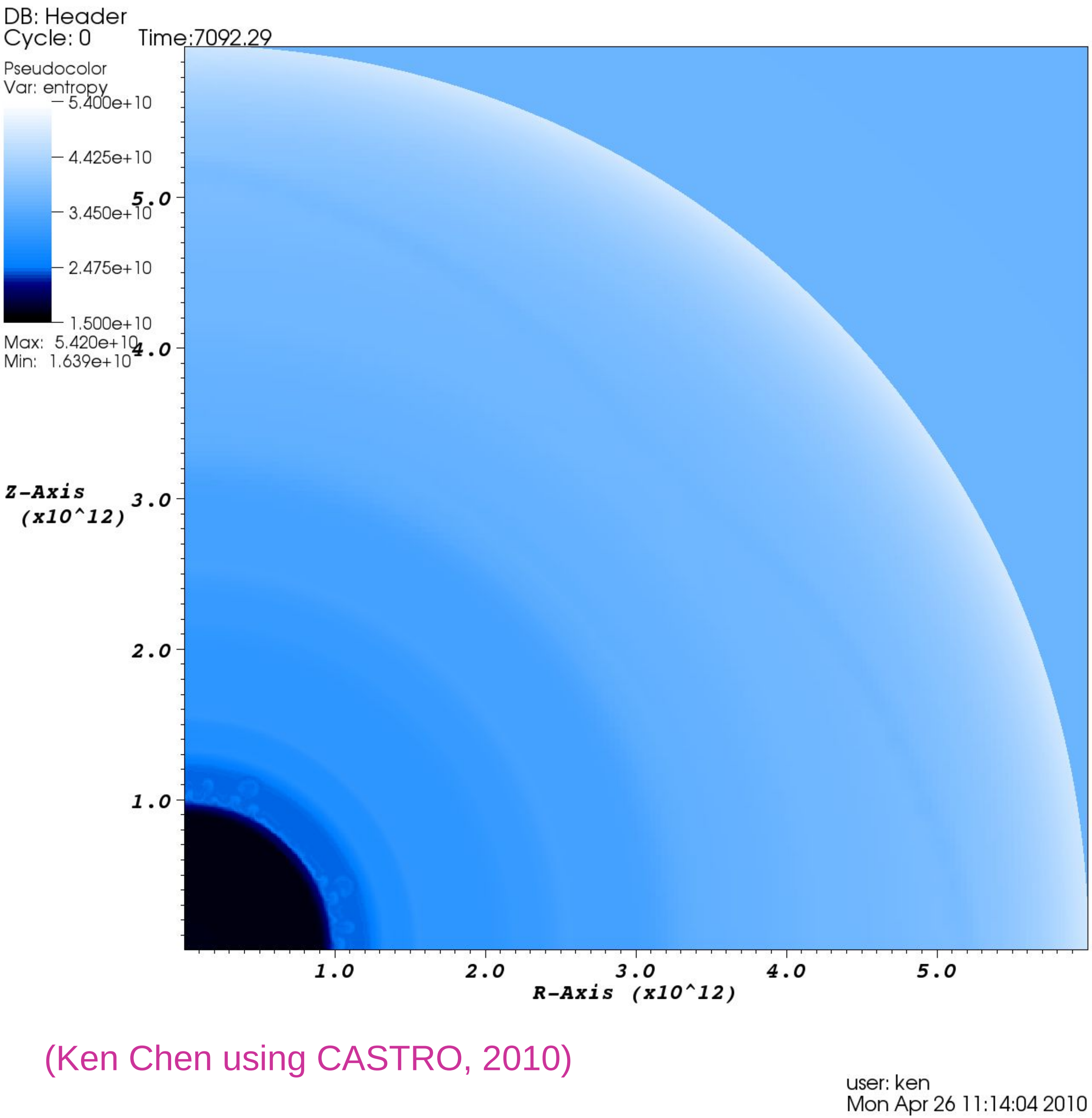
(Really Big Supernovae - DRAFT)

- GR instability sets in during He burning
- Collapse then accelerated by pair-instability
- Explosive burning of He
  ➔ release enough E to give explosion
- Explosions confirmed with CASTRO (GR)

Limits (mass boundaries)

- Low-mass:
  collapse later when too much He is gone
- High-mass:
  collapse “too deep” - photo-disintegration

55kM$_\odot$ H Star



2D simulation using CASTRO:

- 19 isotope network
- monopole gravity
- post-Newtonian corrections (GR)

(Ken Chen using CASTRO, 2010)

Hydrostatic H star limit?

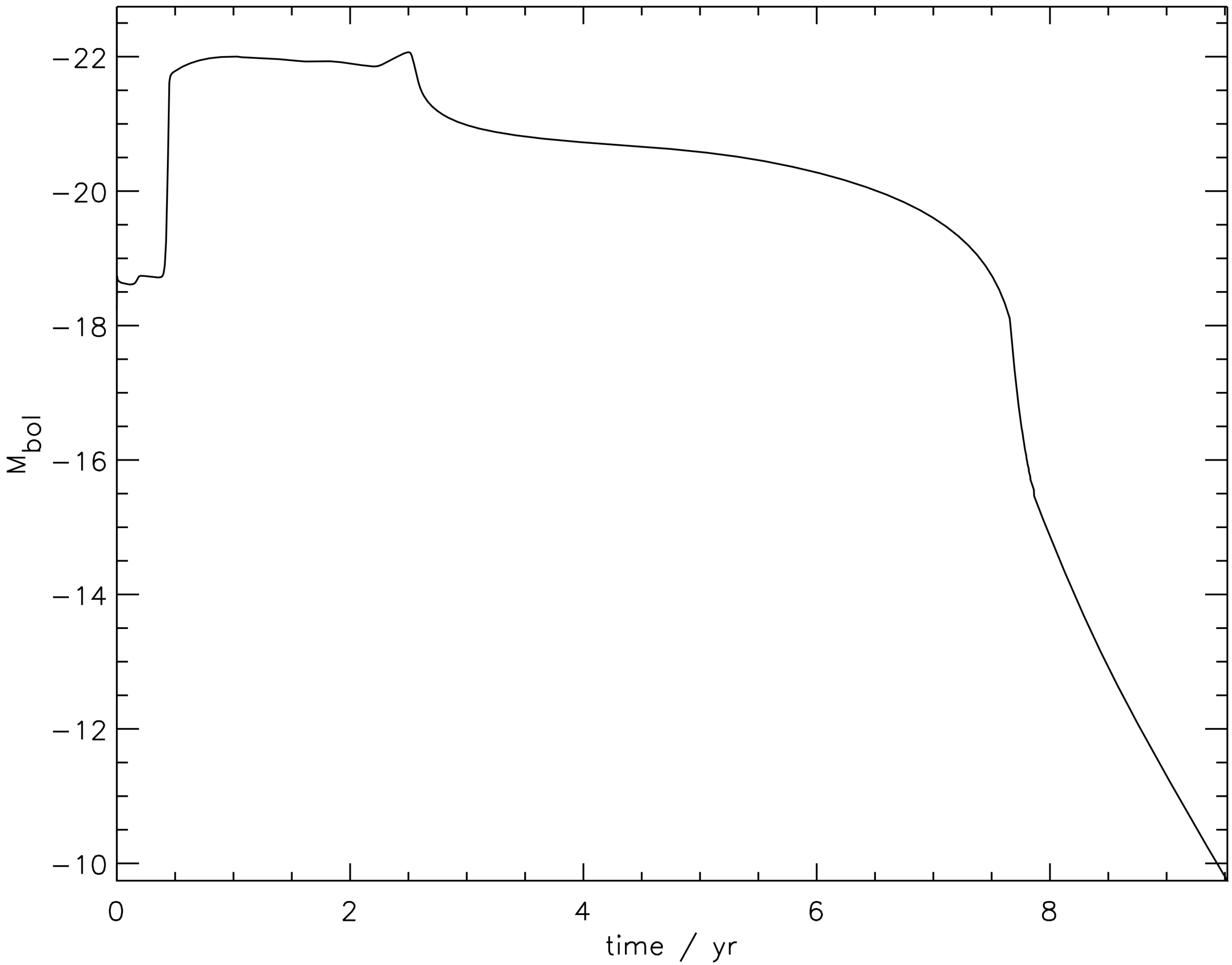
Why is this a sharp transition?

- Why not smooth increase in lifetimes?
- He increases during H-burn lifetime, so density should rise...

Resolution

- Pop III stars make “dense” bounce to create C for CNO burning from 3a
- They continue making more C (at lower pace) so CNO continues to increase, density drops!

Lightcurve of 55k$M_\odot$ H Star



Energy Scales

Log E	**Explosion**	**Thermonuclear**
39	X-ray Bursts	√
40	Long-Duration He Bursts	√
41		
42	X-ray Superbursts	√
43		
44		
45		
46	Classical Novae	√
48	Faint SN (visible LC?)	
49	SN (visible LC)	
50	Bright SN (LC?)	
51	SN (kinetic)	SN Type Ia total
52	Hypernova? GRB?	Pair-SN total (low-mass end)
53	SN (neutrinos – several 10^{53}erg)	Pair-SN total (upper limit)
54	*(a lot of energy - 0.5 $M_\odot c^2$)*	
55	GR He SN	GR He SN (upper limit)
56	GR H SN, Z > 0 (Fuller *et al.* 1986)	√

Summary

Maybe formation of Supermassive black holes at high redshift requires formation of supermassive stars...

- Supermassive stars open up new paths of nucleosynthesis in the interior of the star
- Even stars of several 50,000 $M_{\odot}$ might explode, with as much as 10,000 B

➔**But will be hard to observe...**

- ...they are not really that much brighter, but will persist at virtually constant luminosity for decades (years in rest frame). Confusion with quasars?