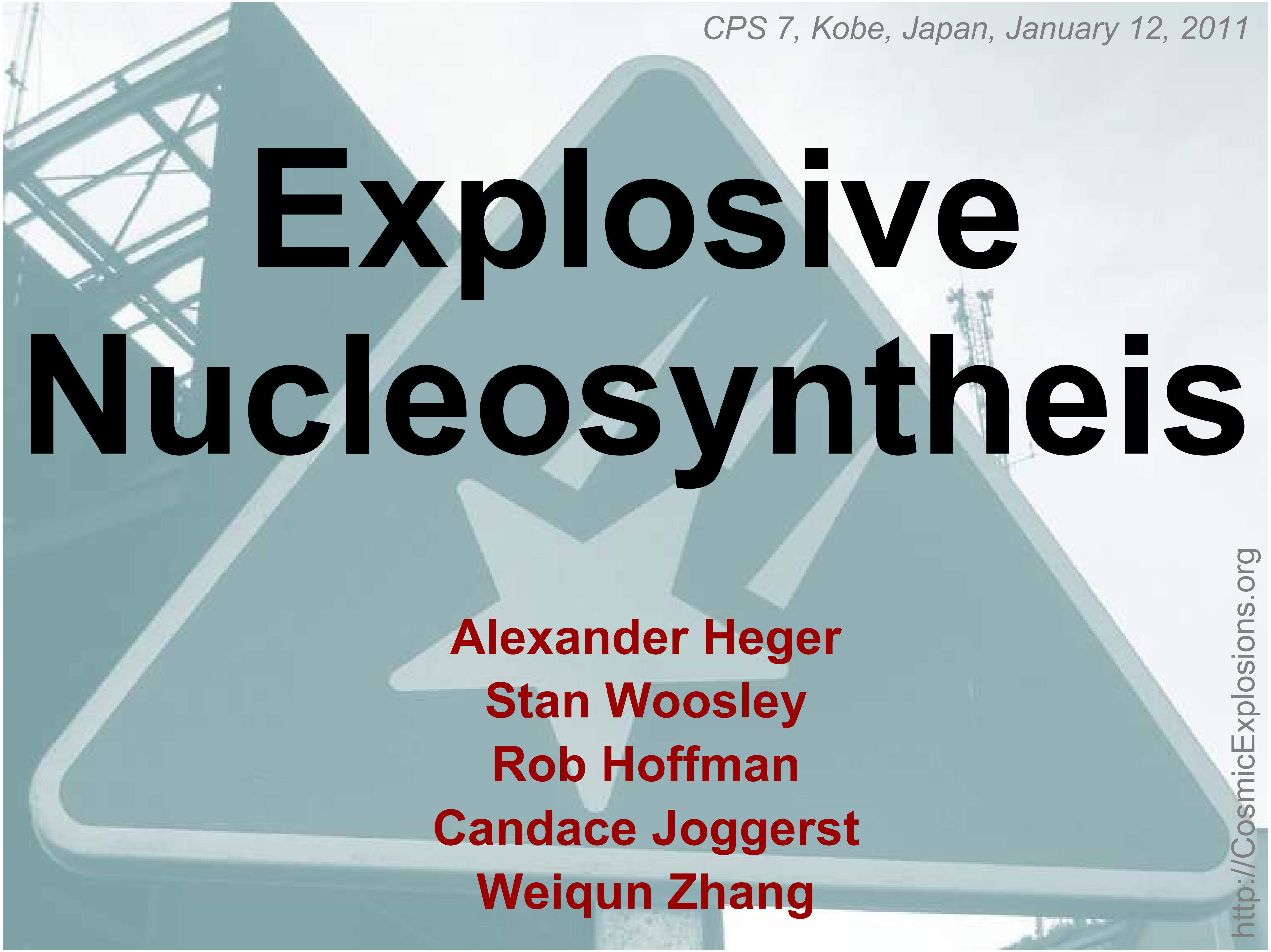
*CPS 7, Kobe, Japan, January 12, 2011*



# Explosive Nucleosyntheis

**Alexander Heger**
**Stan Woosley**
**Rob Hoffman**
**Candace Joggerst**
**Weiqun Zhang**

http://CosmicExplosions.org

# Overview

- Presupernova Evolution and Nucleosynthesis
- Varieties of Stellar Deaths
- Nucleosynthesis
- Uncertianties

## Motivation:

# A Brief History of the Universe

## (Recap)

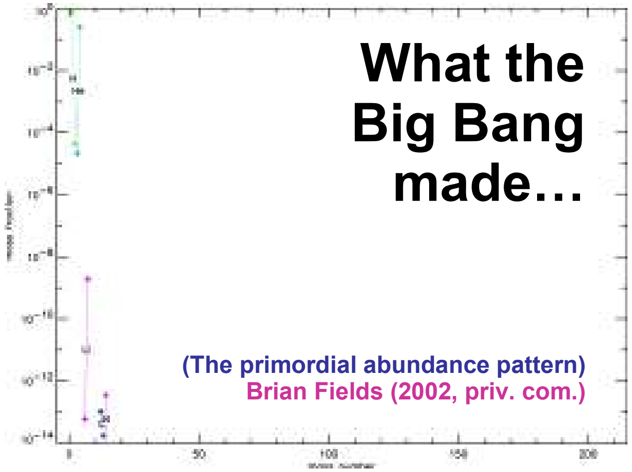
# Cosmic Dark Age

(after recombination)

© Alexander Heger

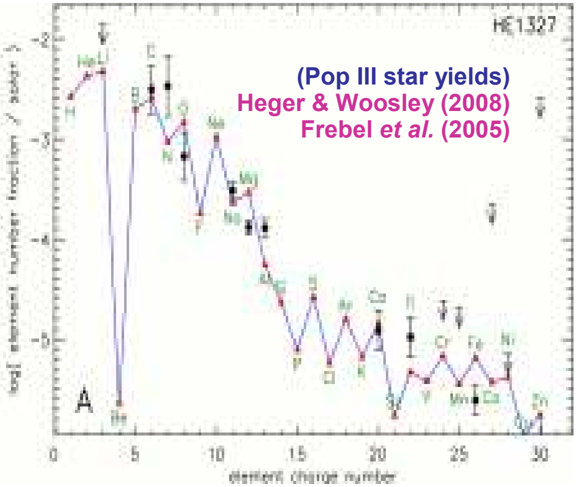

Hubble Deep Field

## time →

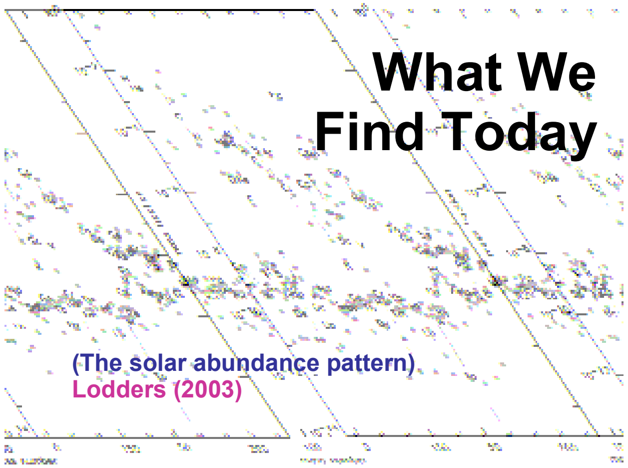


## What the Big Bang made…

(The primordial abundance pattern)
Brian Fields (2002, priv. com.)



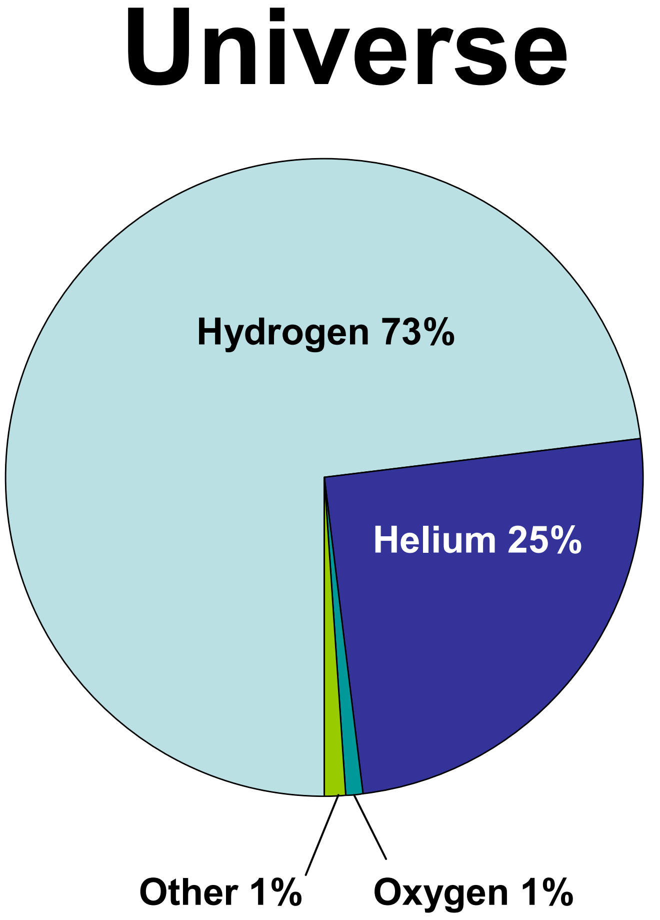
(Pop III star yields)
Heger & Woosley (2008)
Frebel *et al.* (2005)

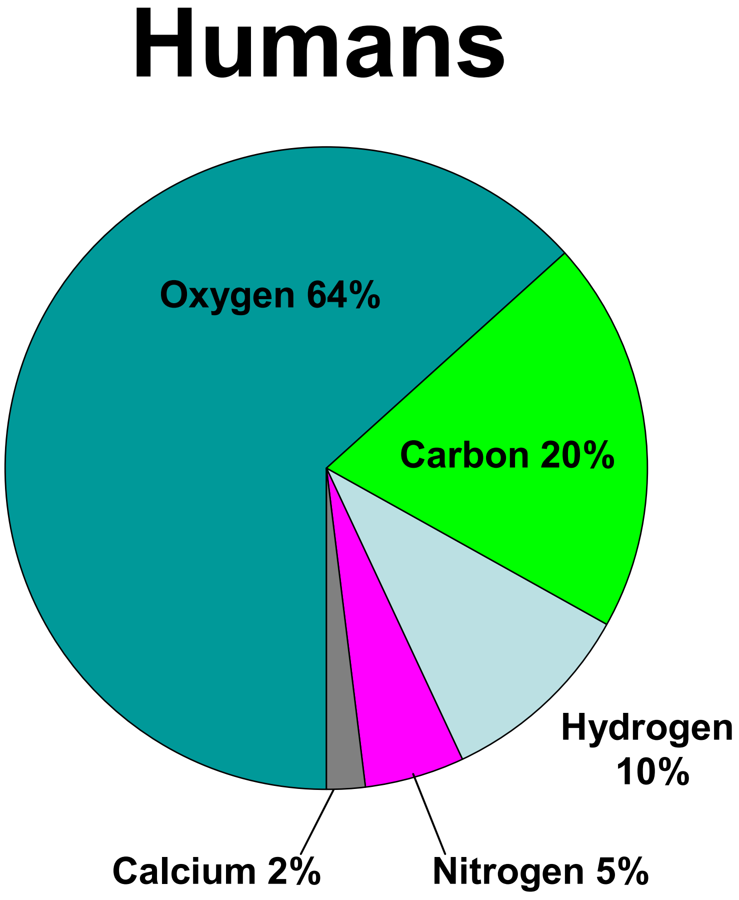


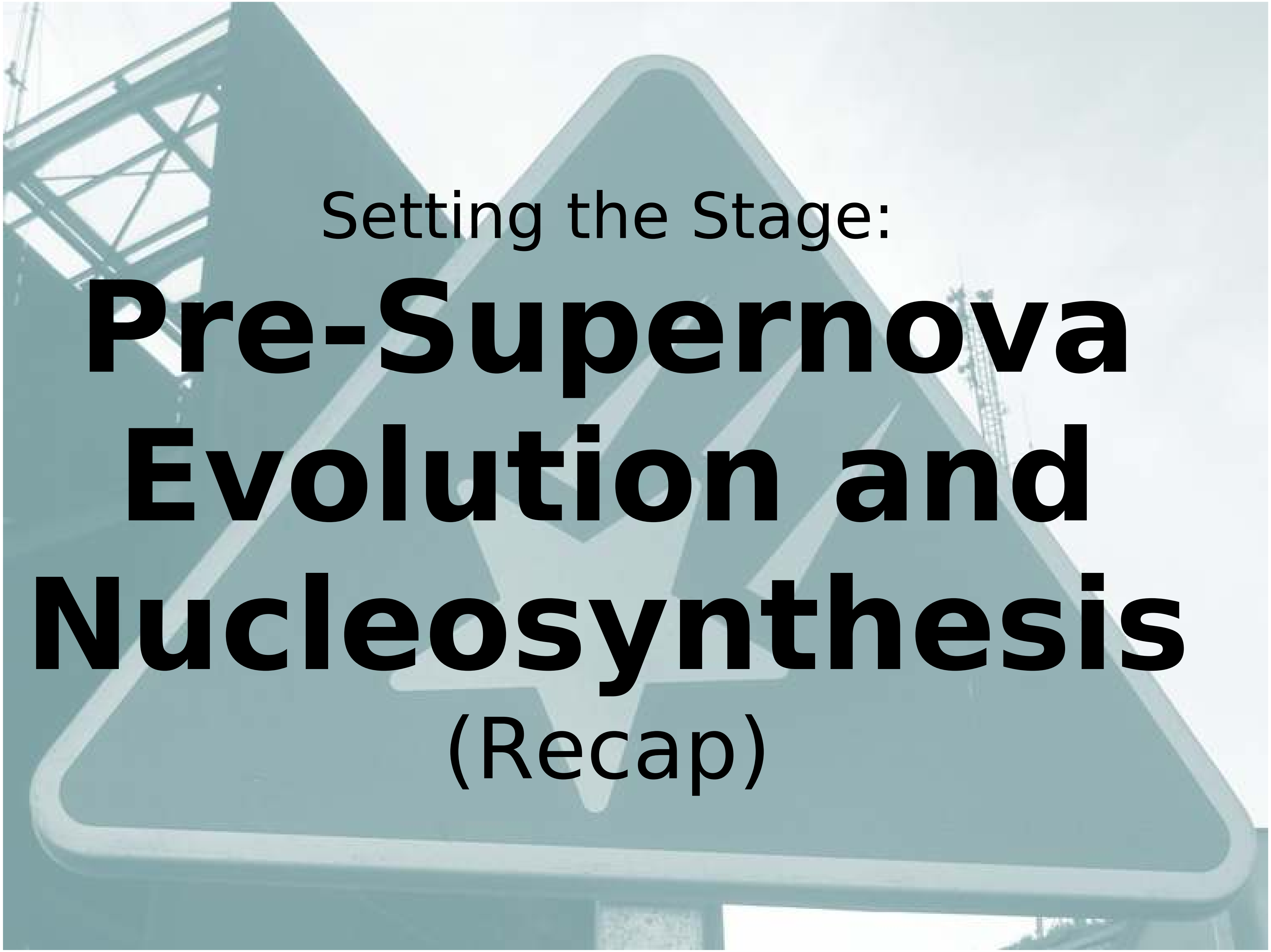
## What We Find Today

(The solar abundance pattern)
Lodders (2003)

# Abundance by Weight



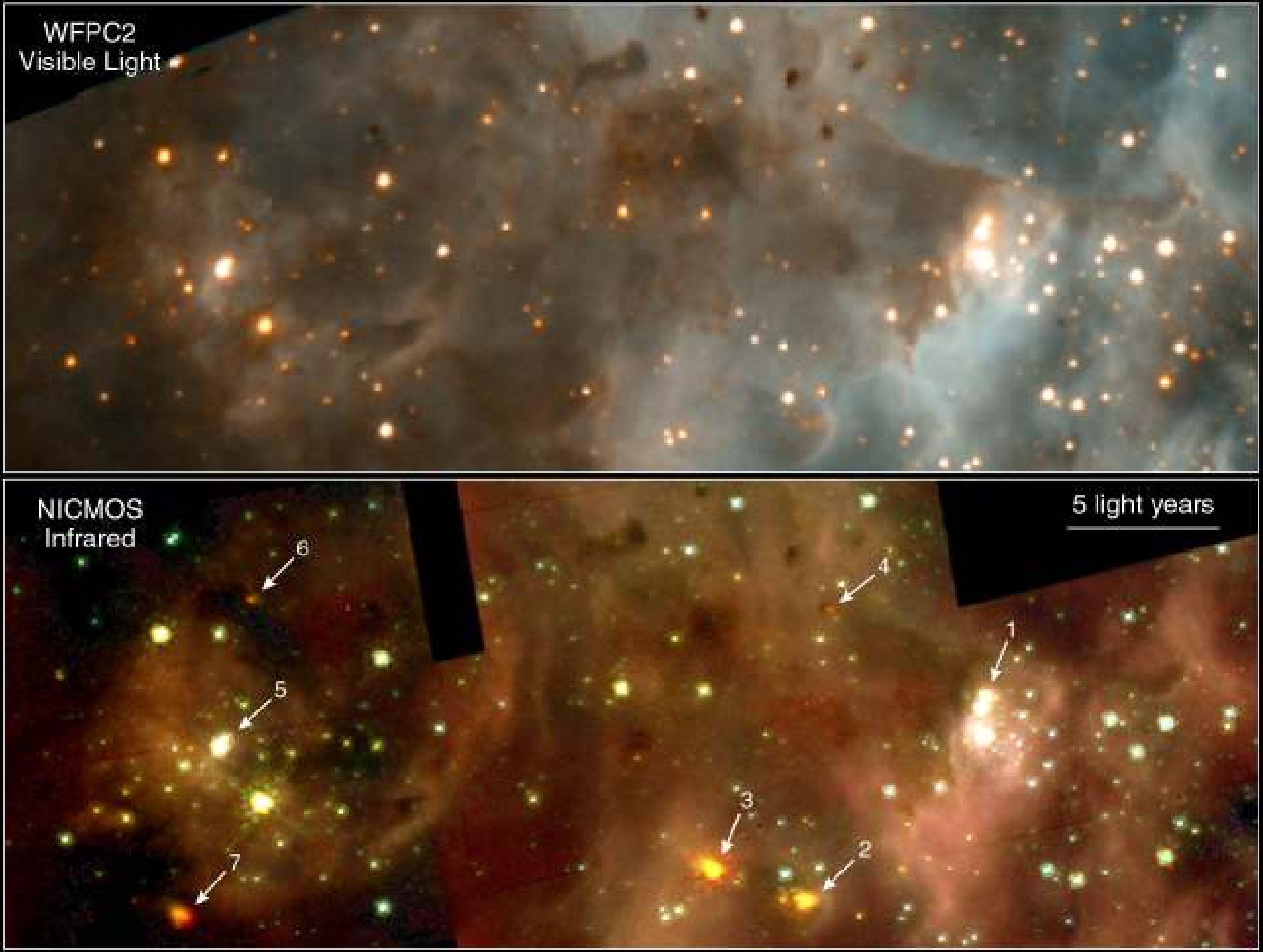




## Setting the Stage:

# Pre-Supernova Evolution and Nucleosynthesis

## (Recap)

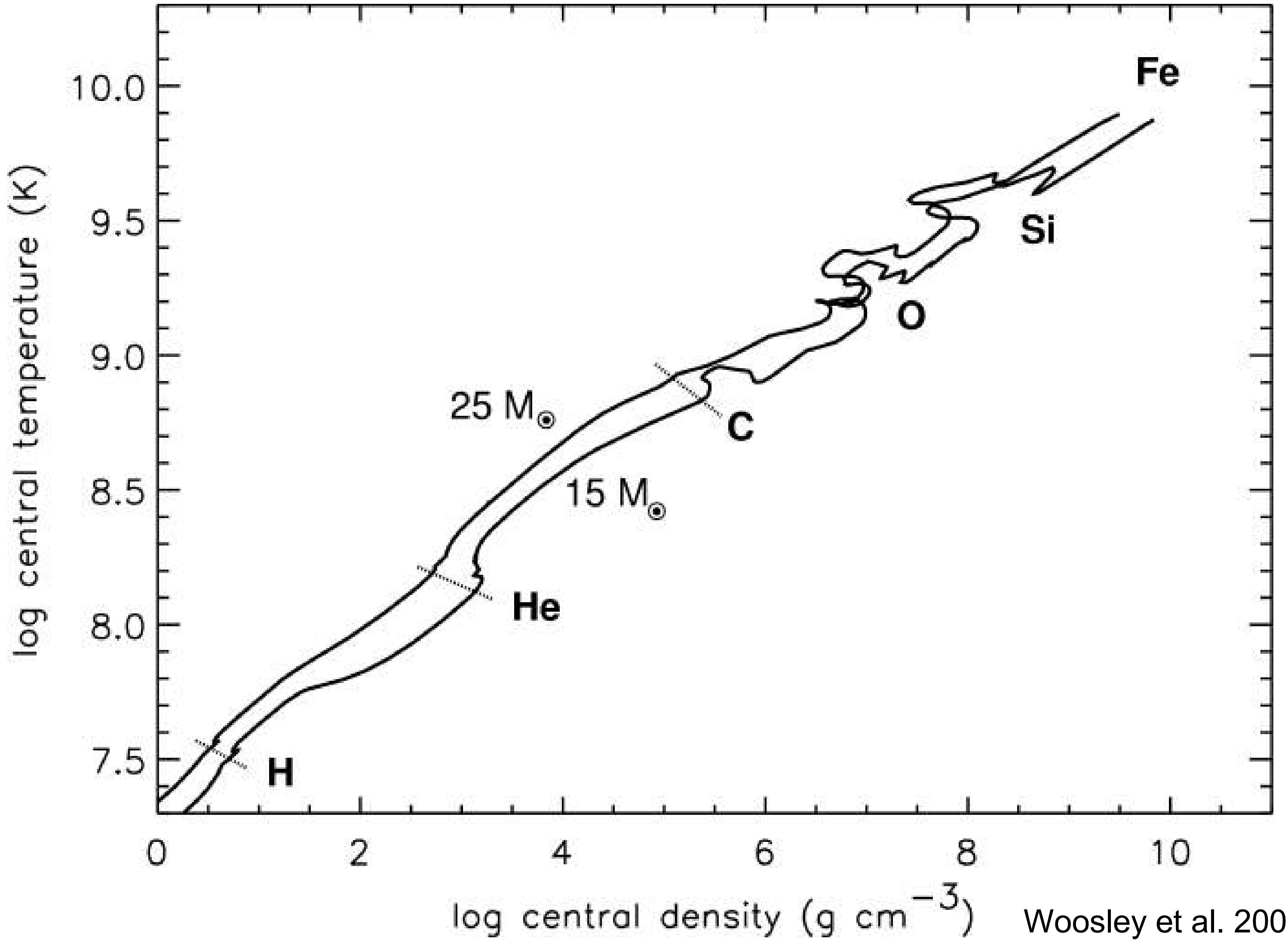


# 30 Doradus Details

Hubble Space Telescope • WFPC2 • NICMOS

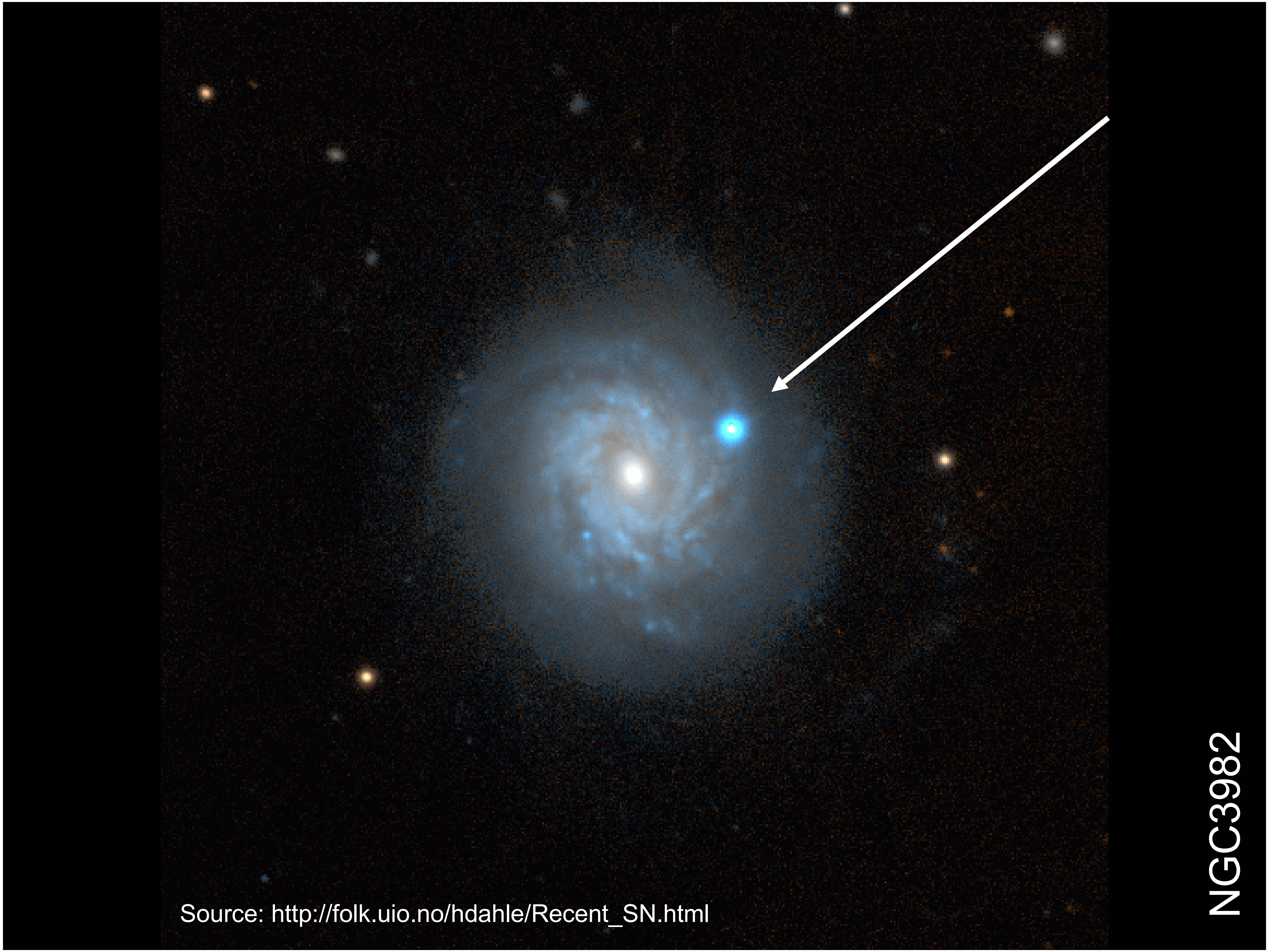
PRC99-33b • STScI OPO • N. Walborn (STScI), R. Barbá (La Plata Observatory) and NASA

# **Once formed, the evolution of a star is governed by gravity:**
*continuing contraction*
to higher central densities and temperatures



Evolution of central density and temperature of 15 M. and 25 M. stars

Woosley et al. 2002, RvMP, 74, 1015



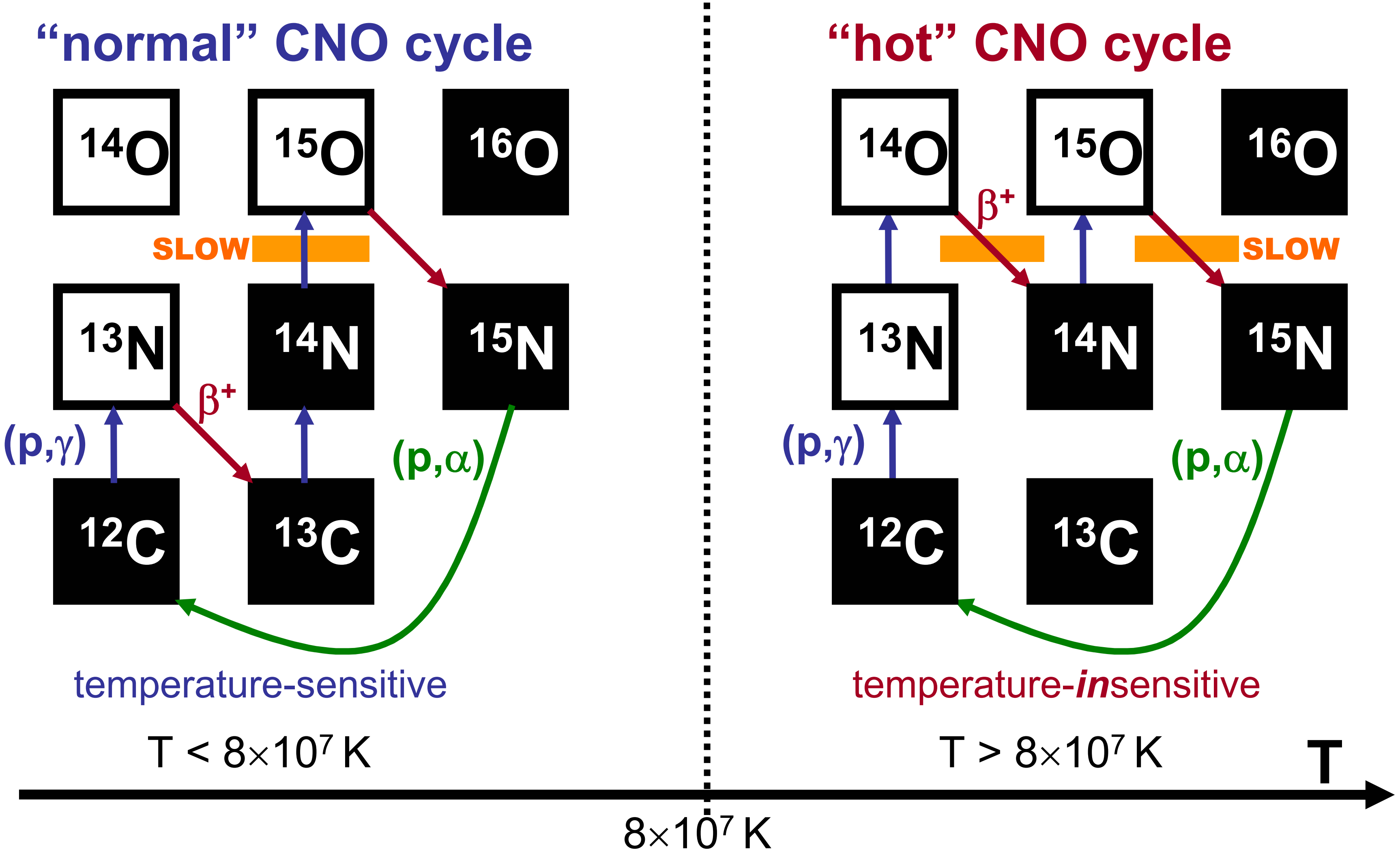
Source: http://folk.uio.no/hdahle/Recent_SN.html

# Nuclear burning stages

(20 M. stars)

| Fuel | Main Product | Secondary Product | T ($10^9$ K) | Time (yr) | Main Reaction |
|---|---|---|---|---|---|
| H | He | $^{14}N$ | 0.02 | $10^7$ | $4\ H \xrightarrow{CNO} {}^{4}He$ |
| He | O, C | $^{18}O$, $^{22}Ne$<br>s-process | 0.2 | $10^6$ | $3\ He^4 \rightarrow {}^{12}C$<br>$^{12}C(\alpha,\gamma)^{16}O$ |
| C | Ne, Mg | Na | 0.8 | $10^3$ | $^{12}C + {}^{12}C$ |
| Ne | O, Mg | Al, P | 1.5 | 3 | $^{20}Ne(\gamma,\alpha)^{16}O$<br>$^{20}Ne(\alpha,\gamma)^{24}Mg$ |
| 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 | $^{28}Si(\gamma,\alpha)$… |

# Hydrogen Burning by CNO Cycle



# Neutrino losses from electron/positron pair annihilation

- Important for carbon burning and beyond
- For T>$10^9$ K (about 100 keV), occasionally:

  $$\gamma \rightarrow e^+ + e^-$$

  and usually

  $$e^+ + e^- \rightarrow 2\gamma$$

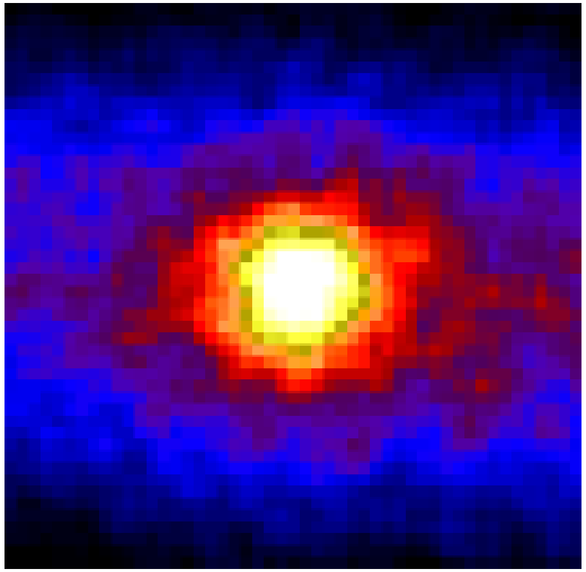
  but sometimes

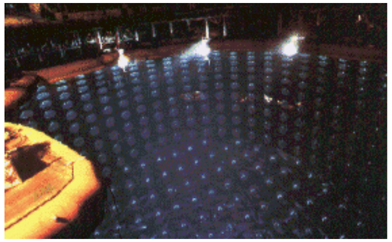
  $$e^+ + e^- \rightarrow \bar{\nu}_e + \nu_e$$

- The neutrinos exit the stars at the speed of light while the $e^+$, $e^-$, and the $\gamma$'s all stay trapped.

- This is an important energy loss with

  $\varepsilon_\nu \approx -10^{15}\ (T/10^9 K)^9$ erg $g^{-1}$ $s^{-1}$
- For carbon burning and beyond, each burning stage gives about the same energy per nucleon, thus the lifetime goes down as $T^{-9}$



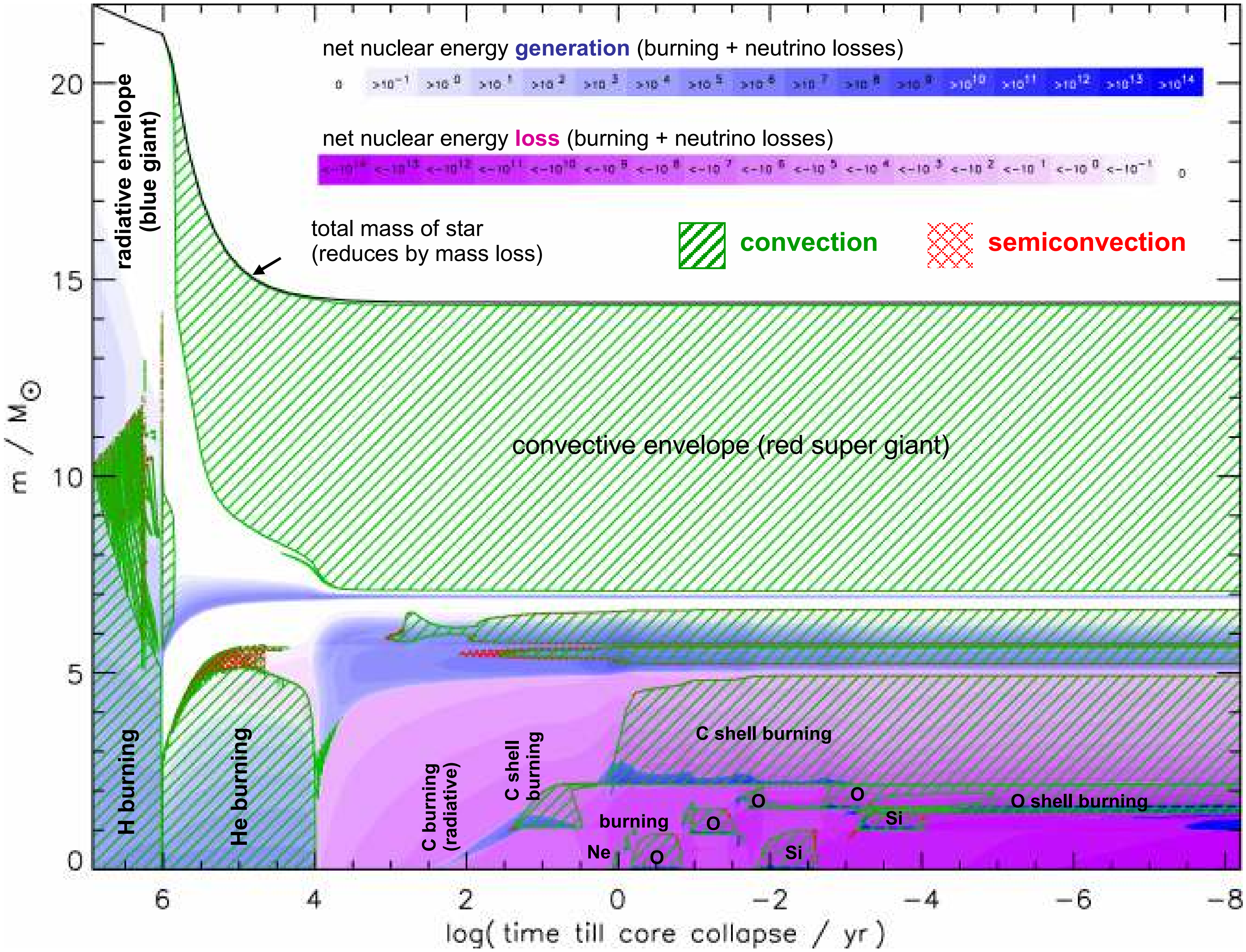


The sun as seen by Kamiokande

# Nitrogen Burning

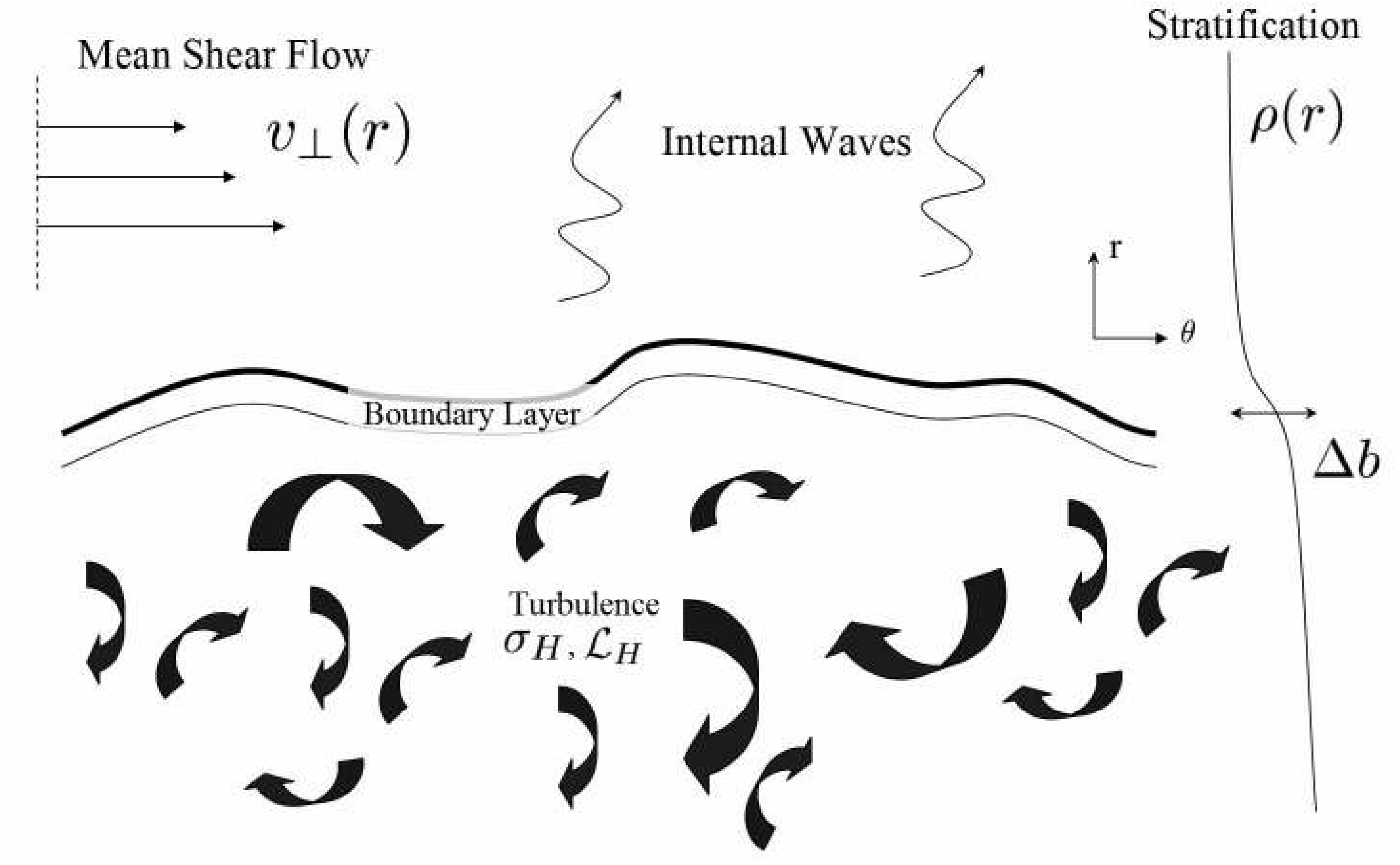
$$^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^{+}\nu_{e})^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$$

- $^{14}$N is made as slowest reactant in CNO cycle
- It is made from initial metals, not as a primary product
- Depending on metallicity, the abundance can be come significant; it will be more important for more metal-rich stars.
- $^{14}$N burning occurs at the onset – before – central helium burning and can have its own convective burning phase, take a few % of helium burning time.



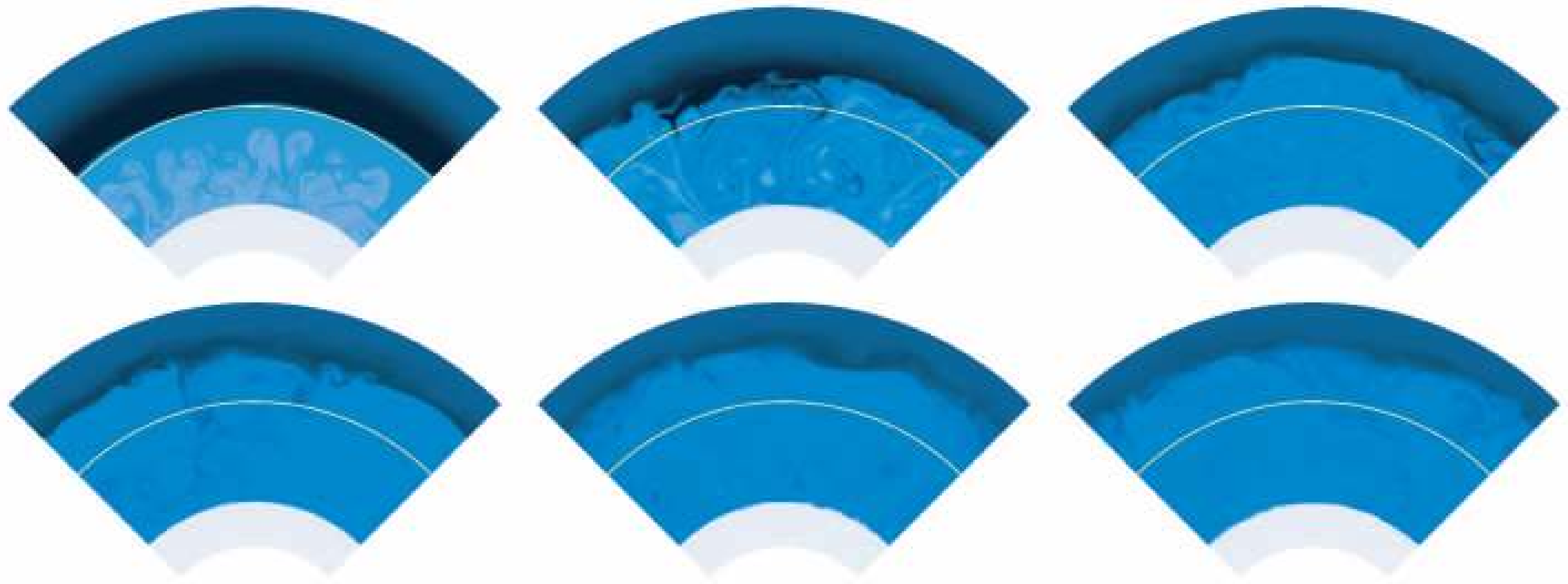
Heger et al. 2003, From Twilight to Highlight: The Physics of Supernovae, Springer-Verlag, 3

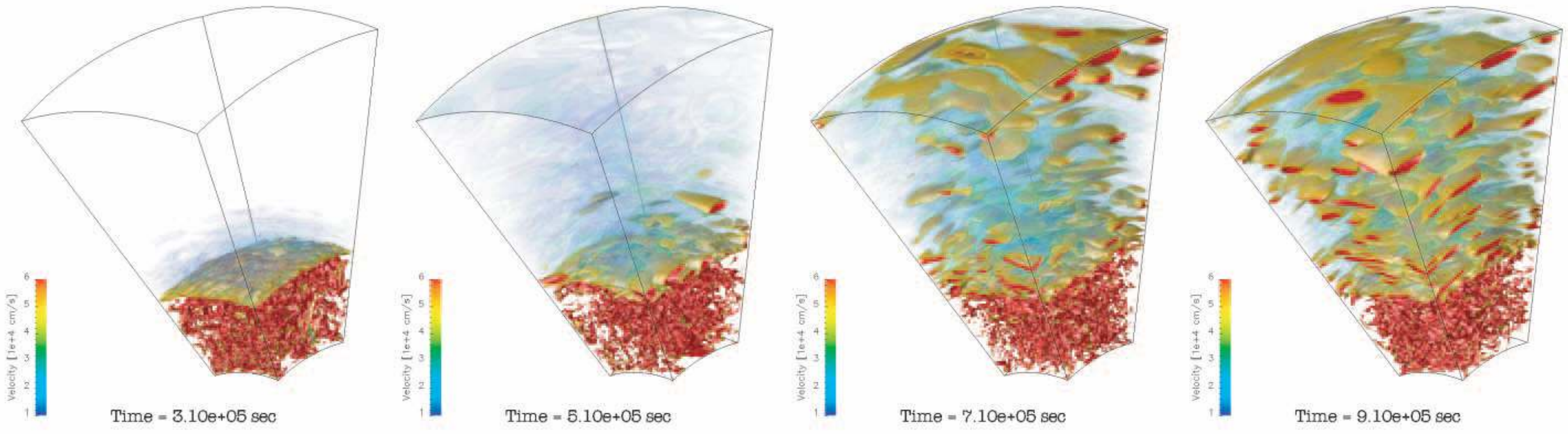
# Multi-Dimensional Convection



(Meaken & Arnett 2007)

# Multi-Dimensional Convection





**(Meaken & Arnett 2007)**

# Change of the stellar structure as a function of initial mass

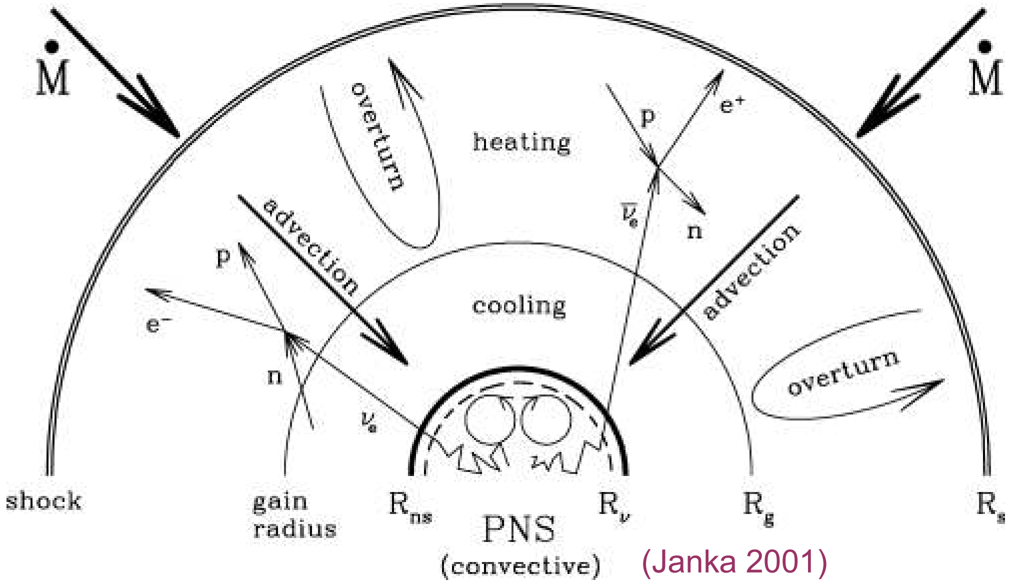
- Mass loss becomes more important
- The “cores” becomes bigger,
  the density gradients more shallow
- The evolution time-scale of all burning phases accelerates
- Central carbon burning becomes radiative, central entropy and $Y_e$ increase

A First Look

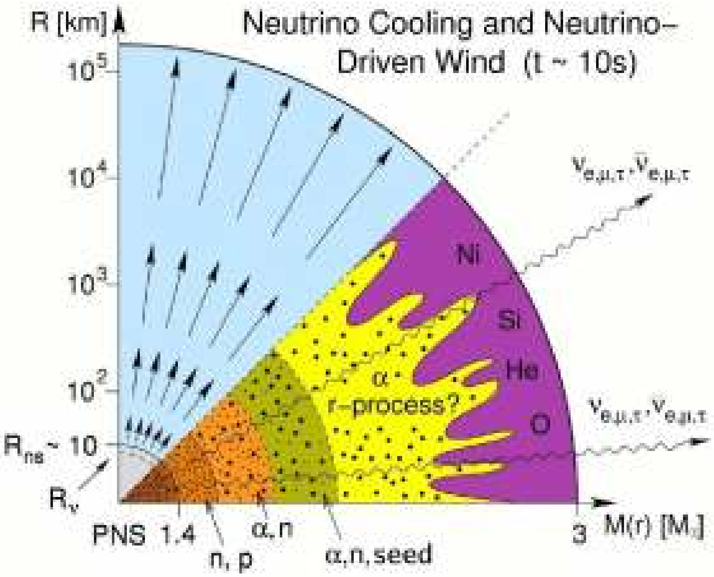
# Core Collapse Supernovae

(Massive Stars, Pop I)

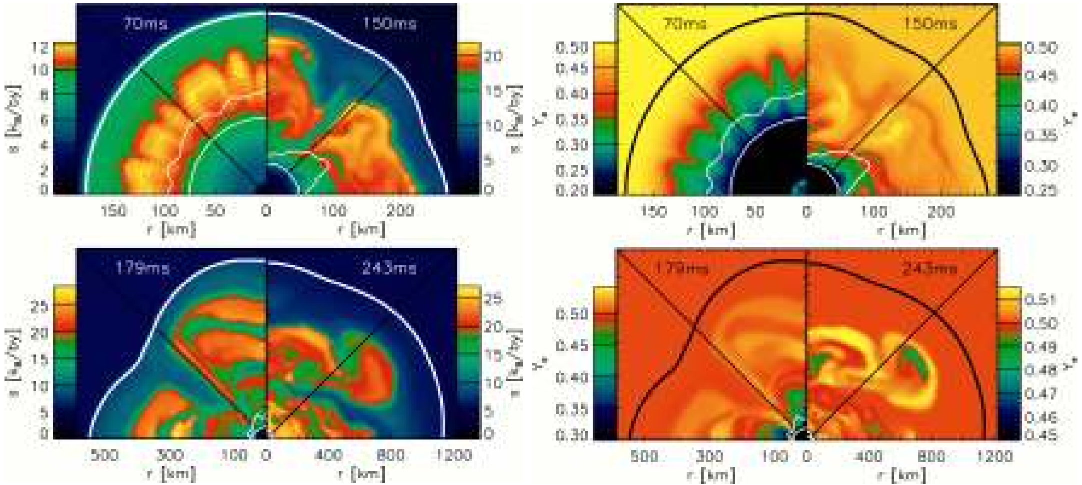
# Core Collapse Supernovae



(Janka 2001)



(Woosley & Janka 2006)



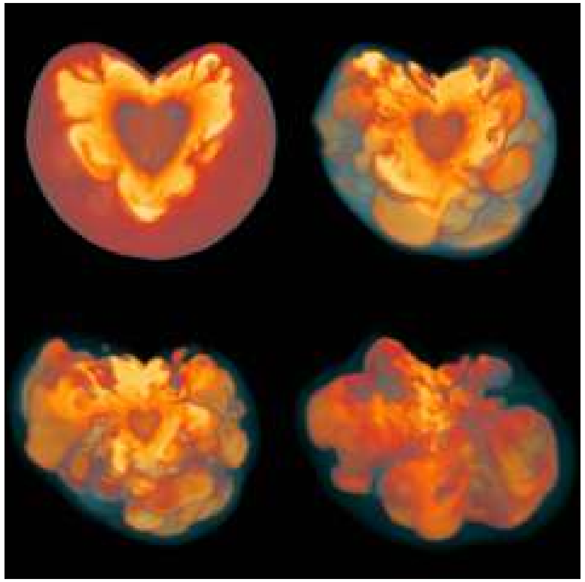
(Buras *et al.* 2006)

←Entropy and electron per baryon ($Y_e$) at different time snapshots in a core collapse supernova

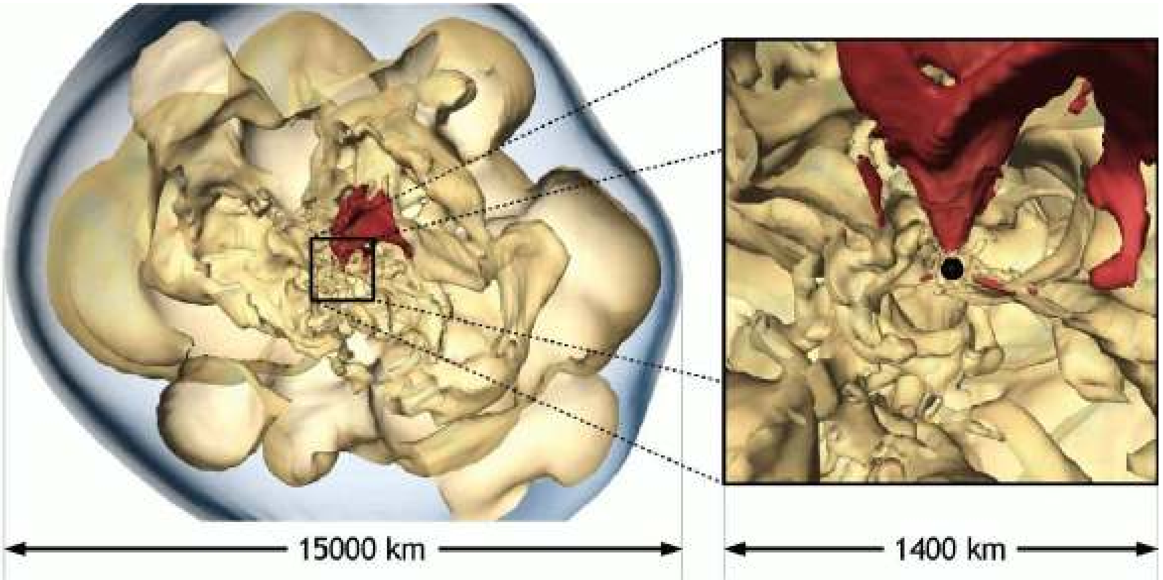
(simulation: equatorial band)

# Core Collapse Supernovae – 3D

**Cold inflow** and **hot outflow** in 3D simulations ➔ similar to dipolar flow pattern observed in 2D rotationally symmetric simulations



(Scheck, Janka, *et al.* 2006)

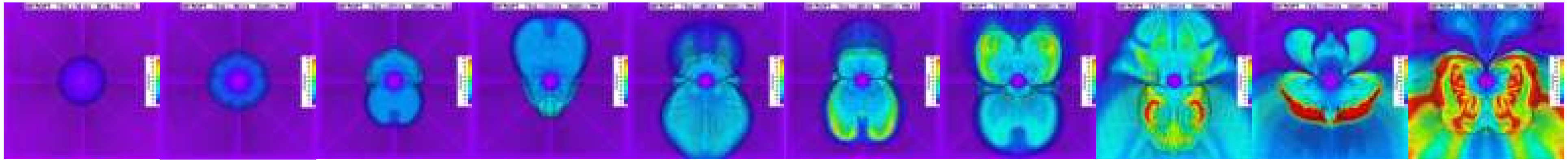


(Janka *et al.* 2005)

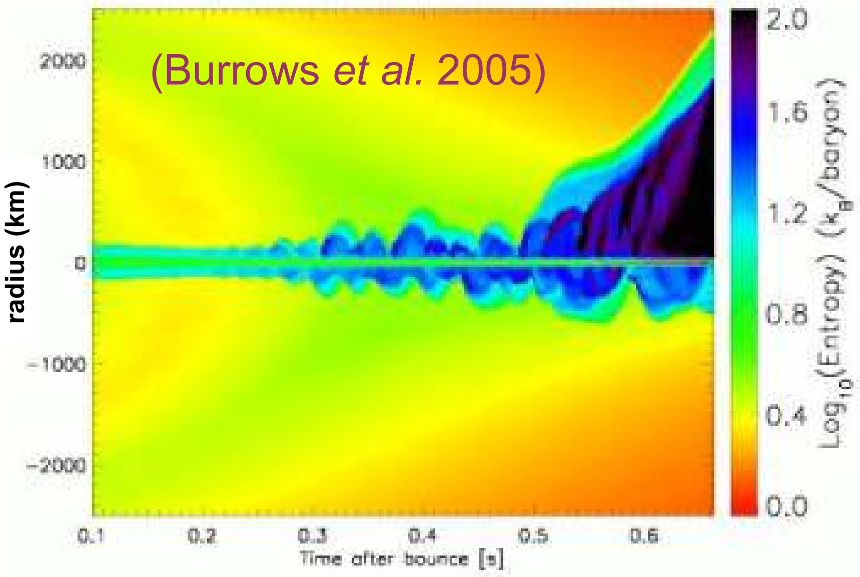
# Singing Supernovae?

Stan Woosley

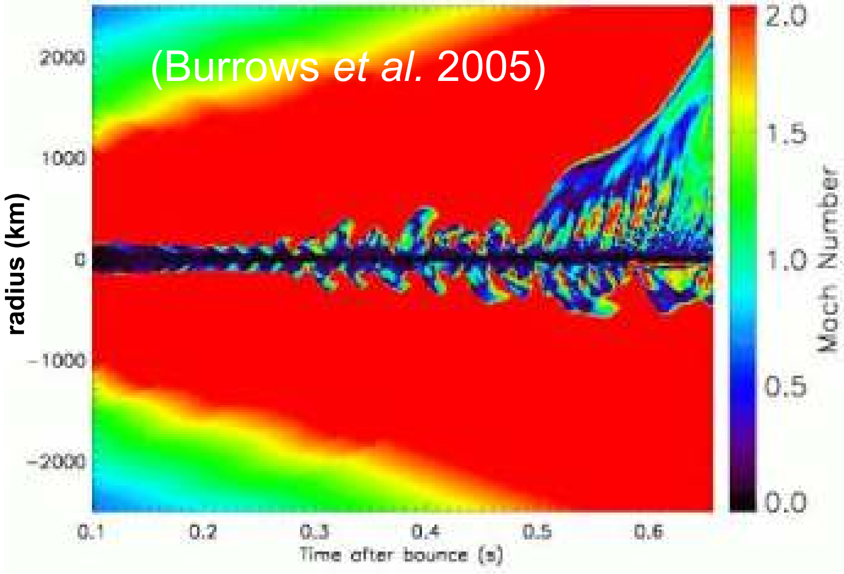
Can sound waves from convection heat bubble and power a supernova explosion?



(Burrows *et al.* 2005)

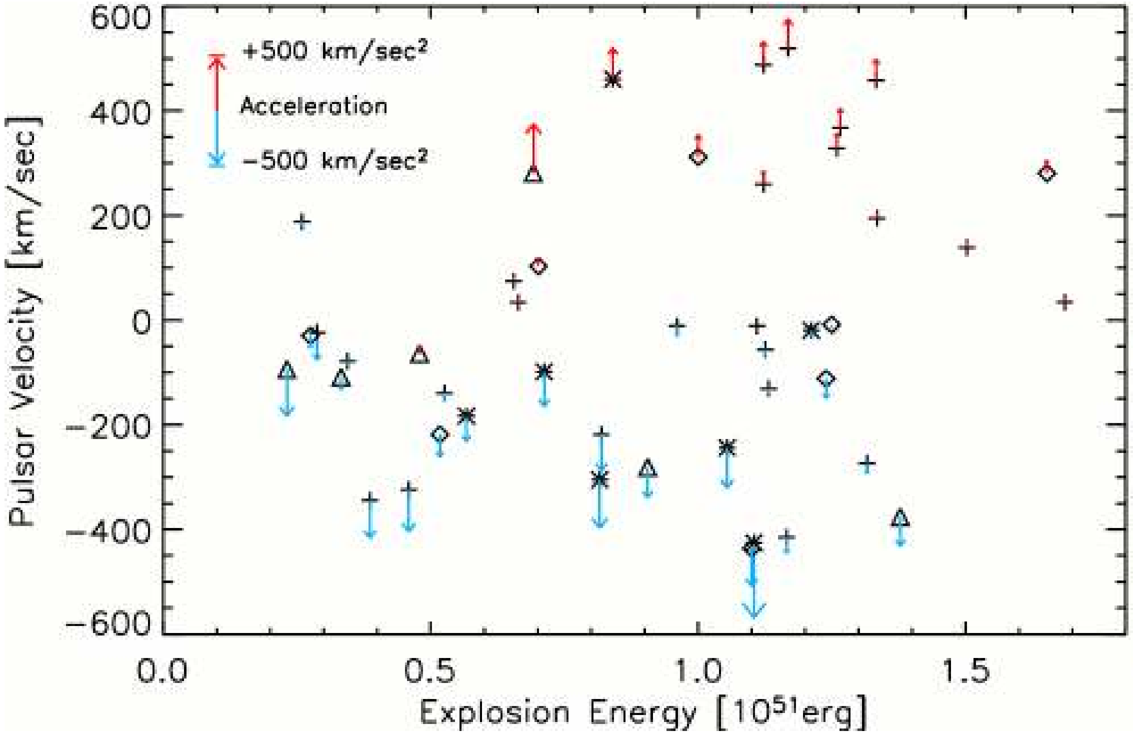


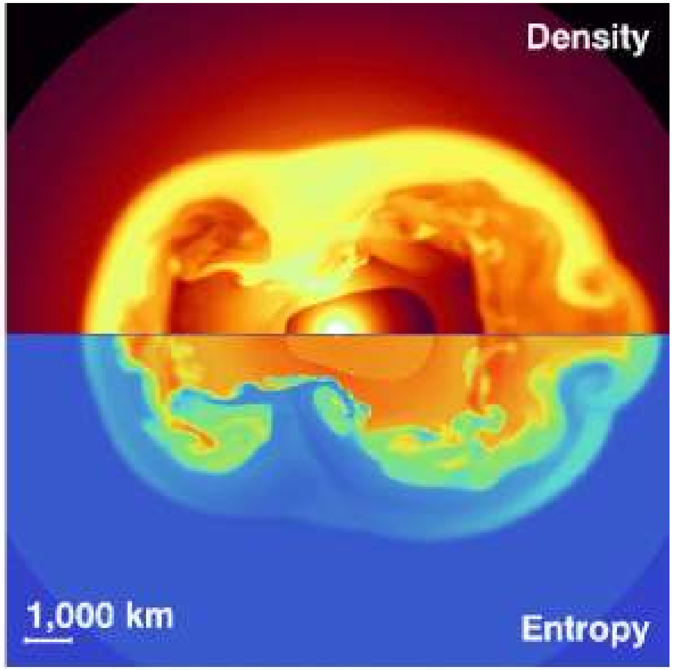
(Burrows *et al.* 2005)



(Burrows *et al.* 2005)

# Neutron Star Kicks





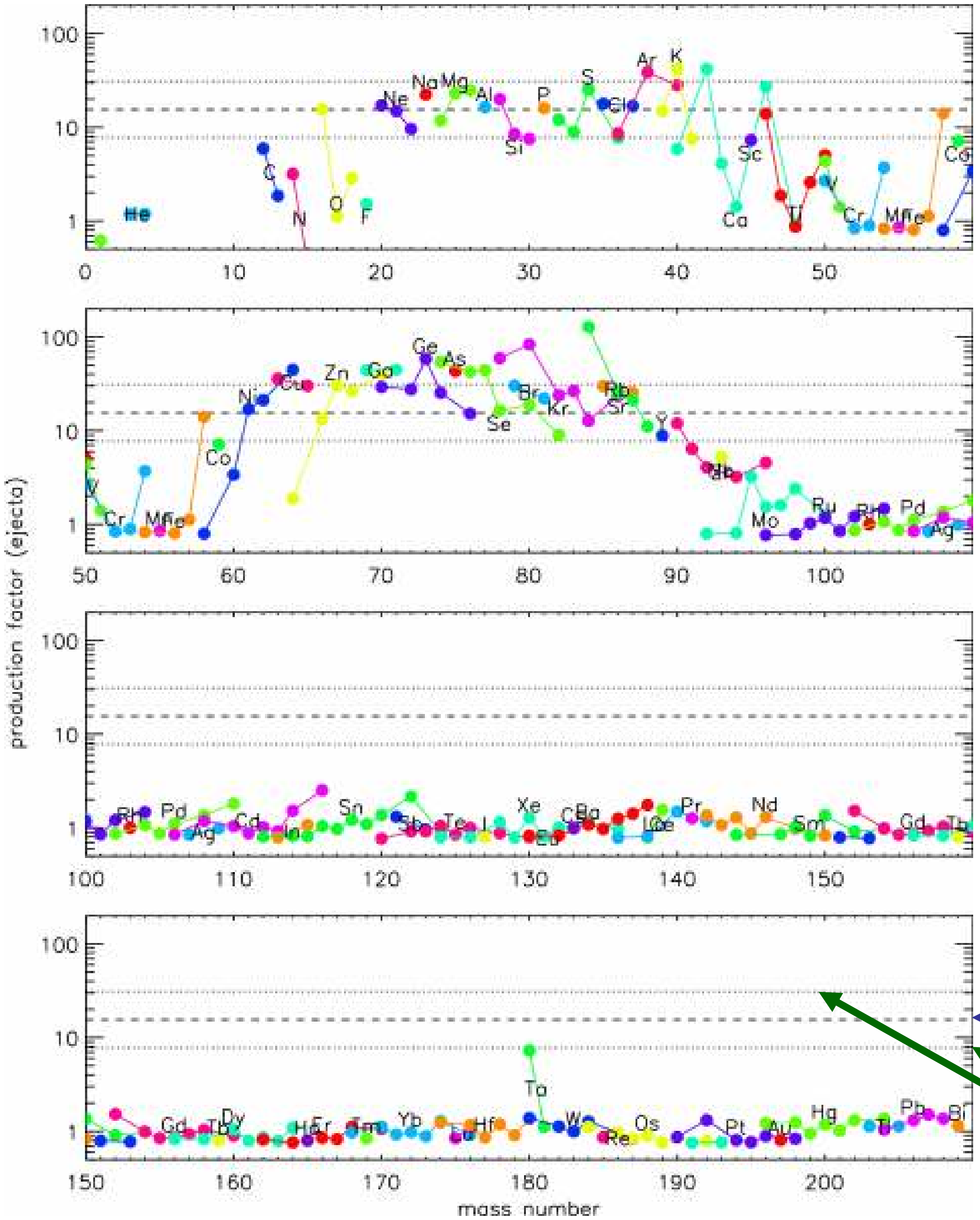
(Janka 2004)

Dipolar oscillation may explain observed neutron star kicks of several 100 km/s.

A First Look

# Supernovae & Nucleosynthesis

(Massive Stars, Pop I)



# 25 $M_\odot$ star

**Presupernova** production factors relative to solar composition

“band of acceptable co-production” defined by $^{16}$O production

(± a factor 2)

Rauscher et al. 2002, ApJ, 576, 323

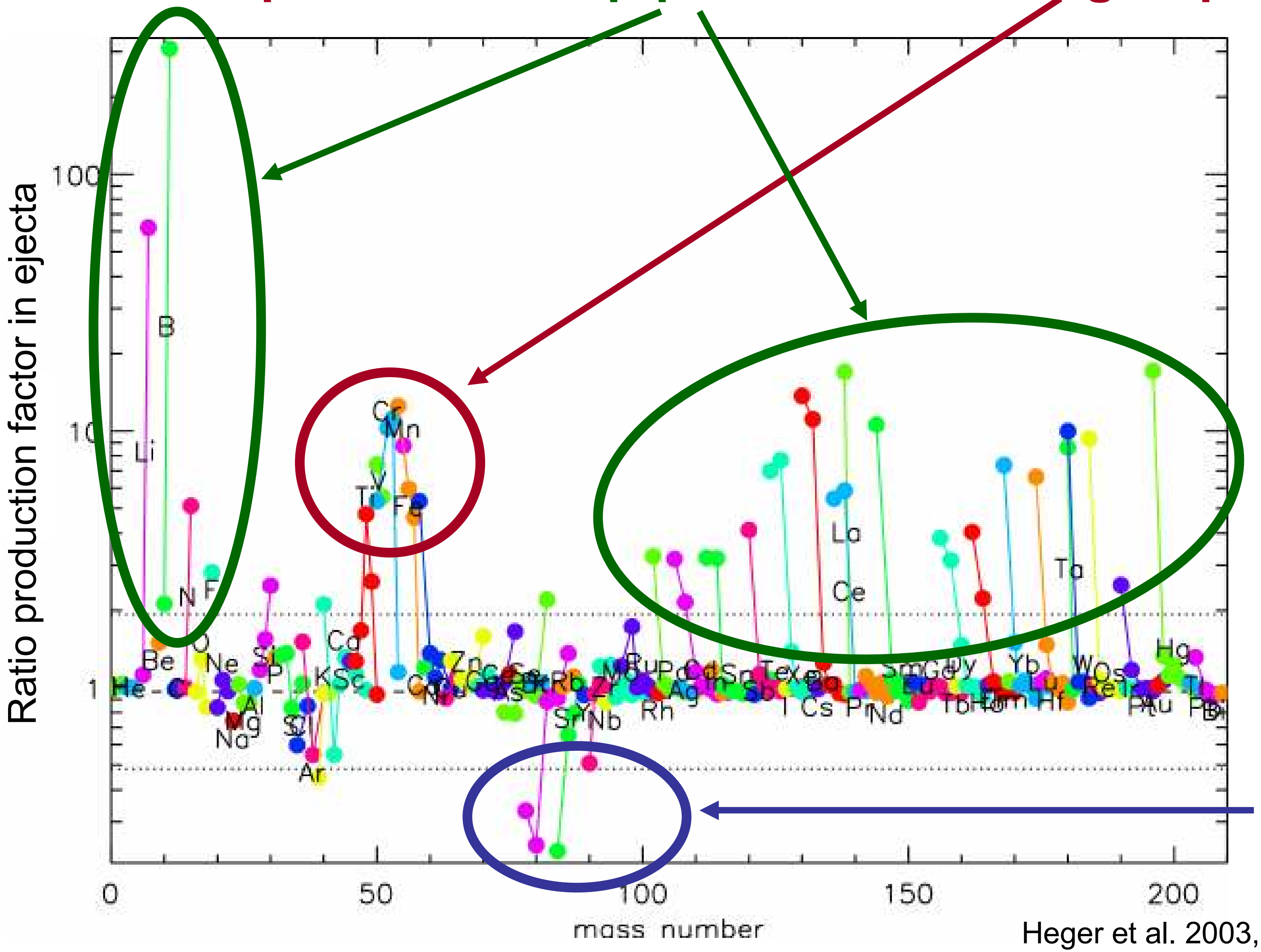
# Explosive Nucleosynthesis

## in supernovae from massive stars

| Fuel | Main Product | Secondary Product | T ($10^9$ K) | Time (s) | Main Reaction |
|---|---|---|---|---|---|
| Innermost ejecta | *r*-process<br>*ν p*-process | - | >10? | 1 | (n,γ), $\beta^-$ |
| Si, O | $^{56}$Ni | iron group | >4 | 0.1 | (α,γ) |
| O | Si, S | Cl, Ar, K, Ca | 3 - 4 | 1 | $^{16}$O + $^{16}$O |
| O, Ne | O, Mg, Ne | Na, Al, P | 2 - 3 | 5 | (γ,α) |
| | | *p*-process | 2 - 3 | 5 | (γ,n) |
| | | $^{11}$B, $^{19}$F, $^{138}$La, $^{180}$Ta<br>*ν*-process | | 5 | (ν, ν'), (ν, $e^-$) |

# Explosive Nucleosynthesis contribution

## →production of p-process and iron group

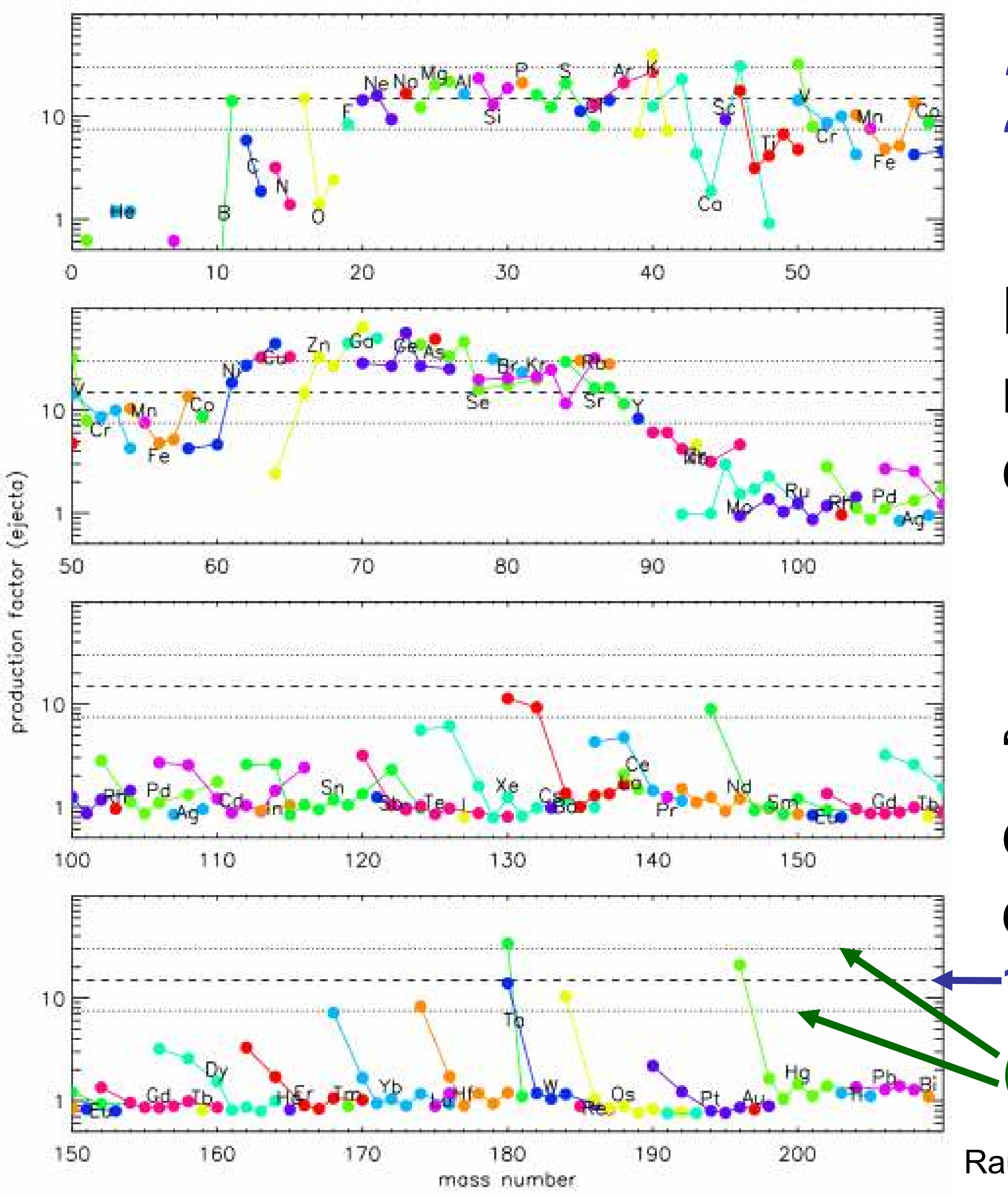


**25 $M_\odot$ star**

**some destruction**

Heger et al. 2003, NuPhA, 718, 159

# 25 $M_\odot$ star



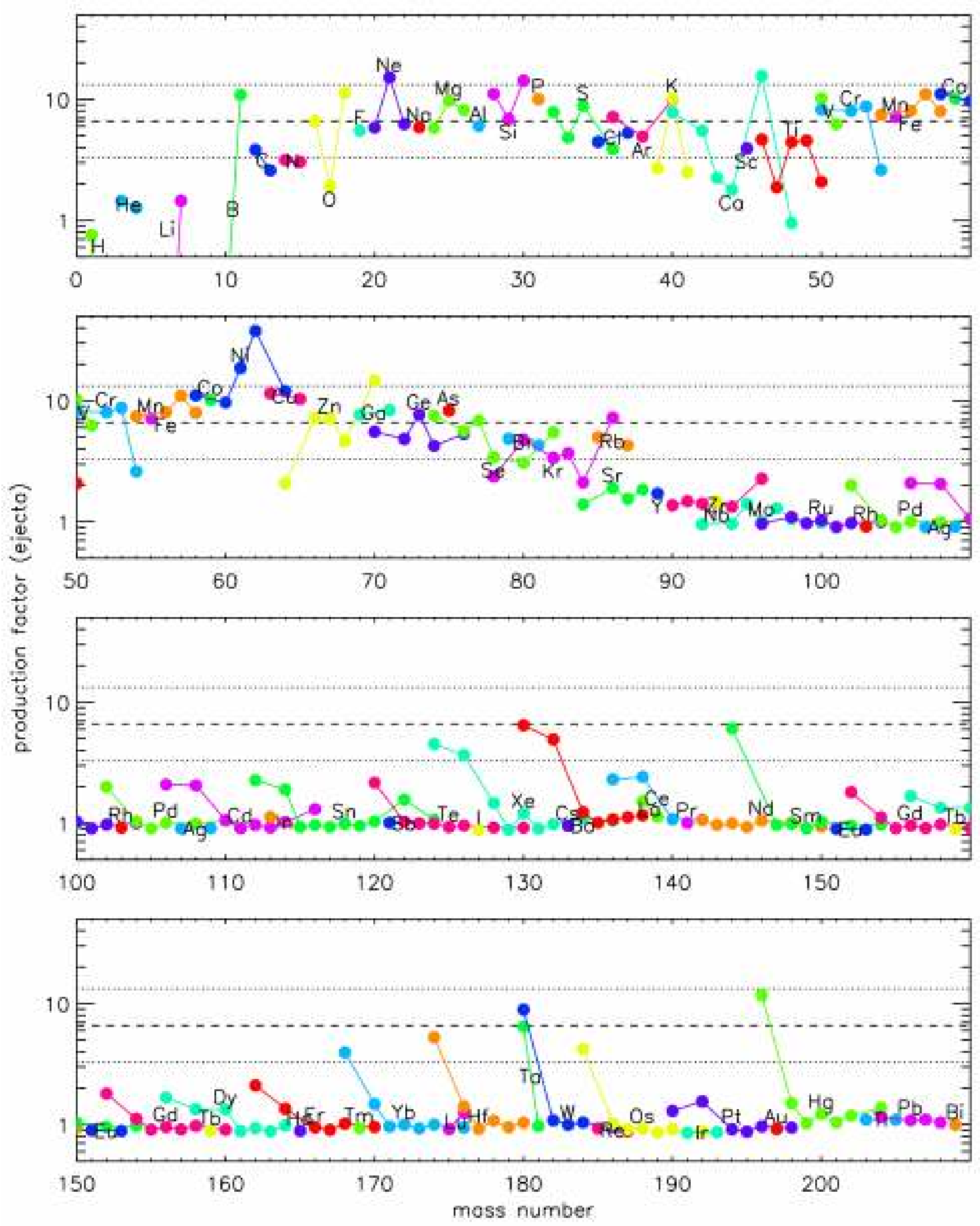
Production factors relative to solar composition

“band of acceptable co-production” defined by

$^{16}$O production

(± a factor 2)

Rauscher et al. 2002, ApJ, 576, 323



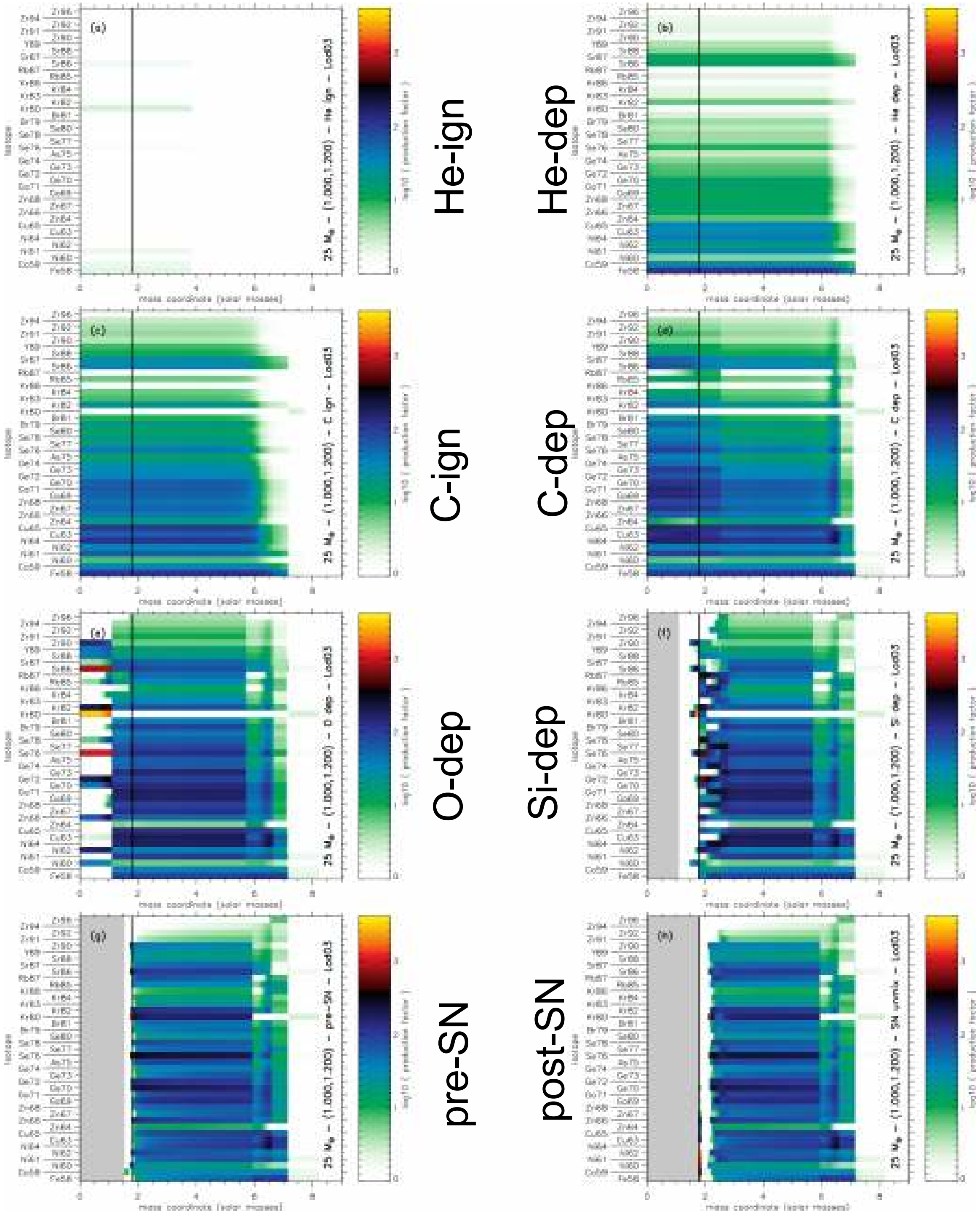
# 15 $M_\odot$ star

Production factors relative to solar composition

"band of acceptable co-production" defined by $^{16}O$ production
(± a factor 2)

Rauscher et al. 2002, ApJ, 576, 323

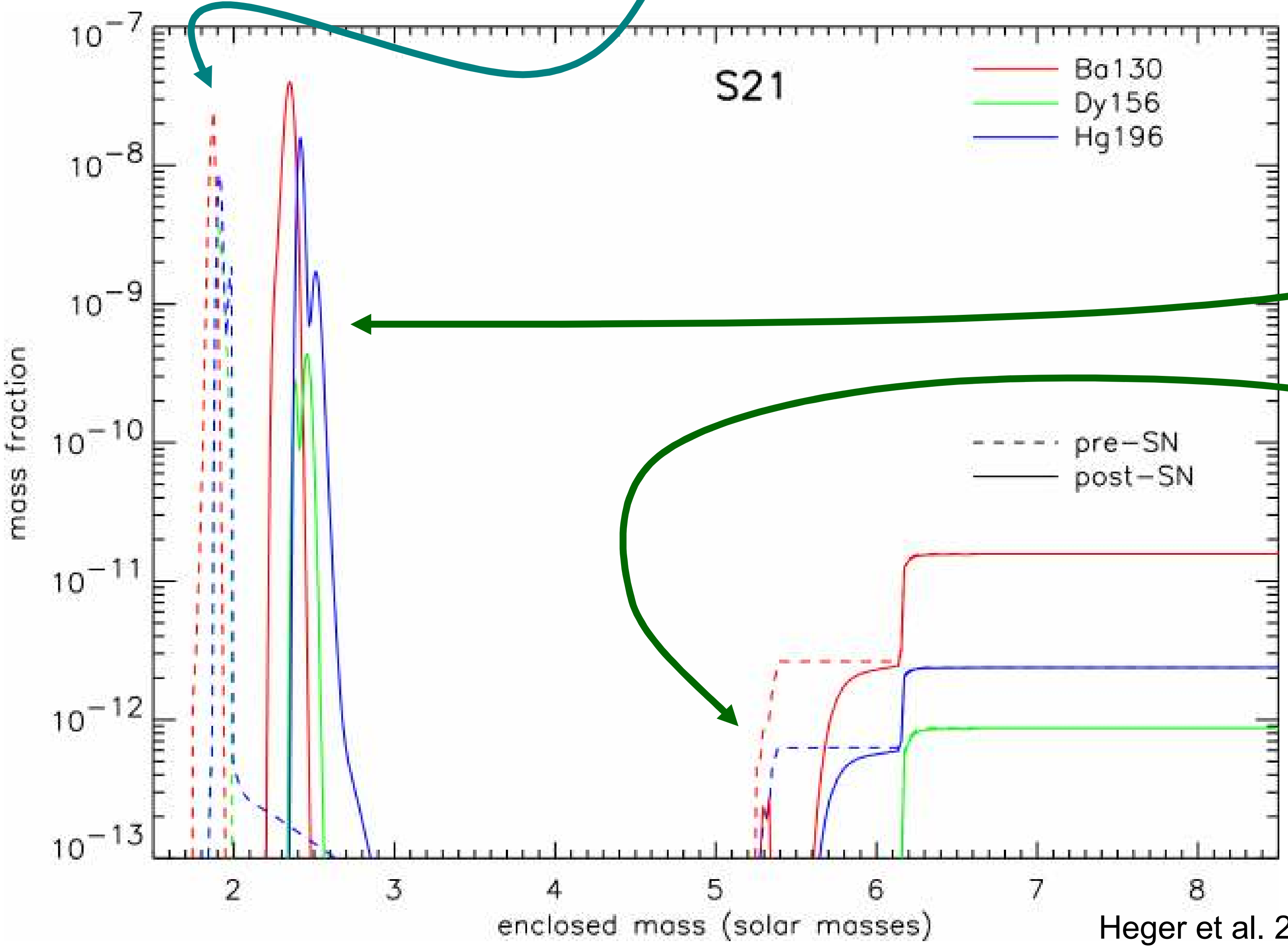
# 25 solar mass star *s*-process yields for different evolution stages



Tur et al. 2009, ApJ, 702, 1068

# “Relocation” of the γ-process

γ-process can be made in implosive O shell burning, but peak abundance is **destroyed by SN** and **recreated further out**



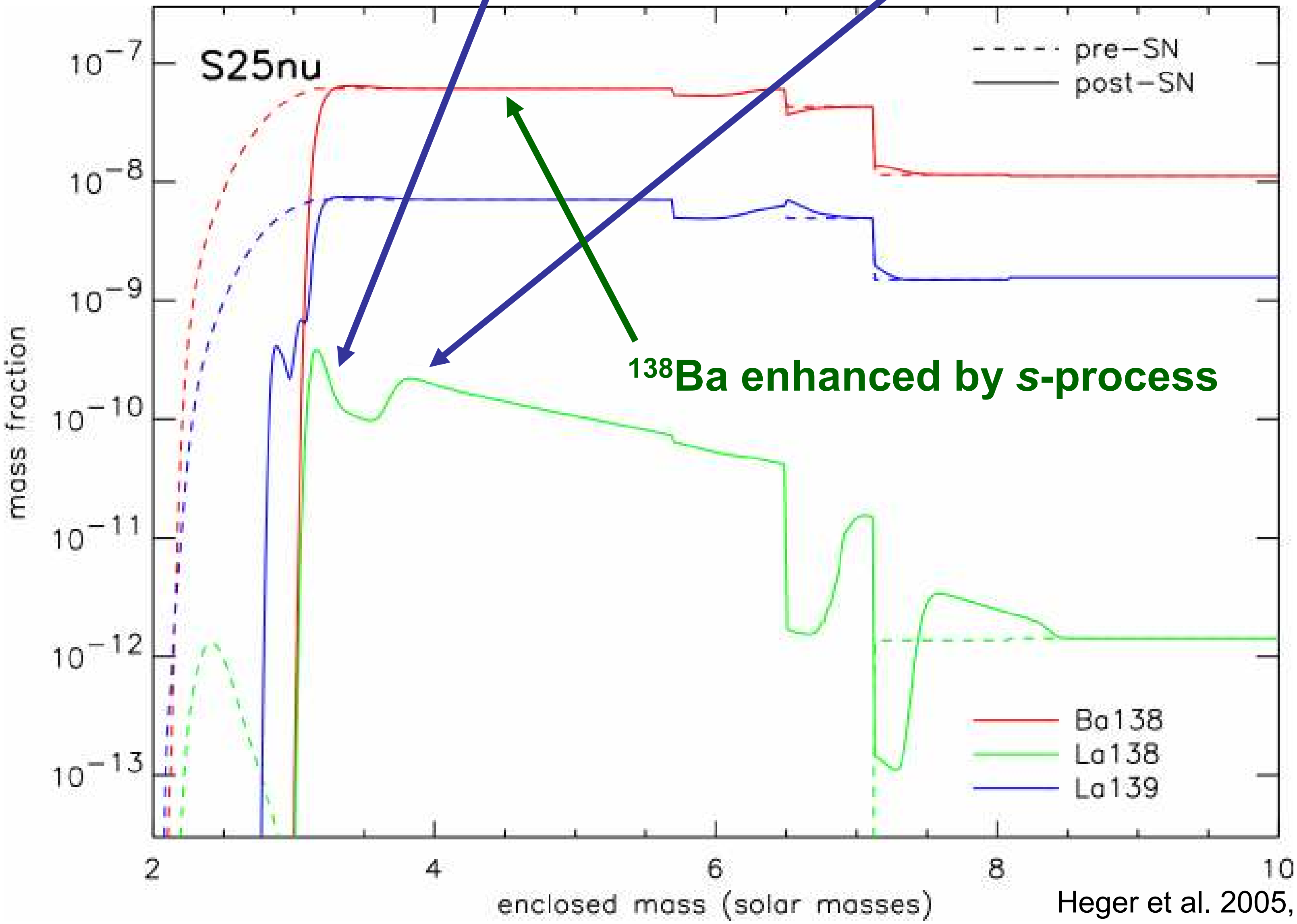
destruction by n-exposure in He shell

21 M. star

Heger et al. 2003, NuPhA, 718, 159

# The Production of $^{138}$La

## by γ-process and ν-process

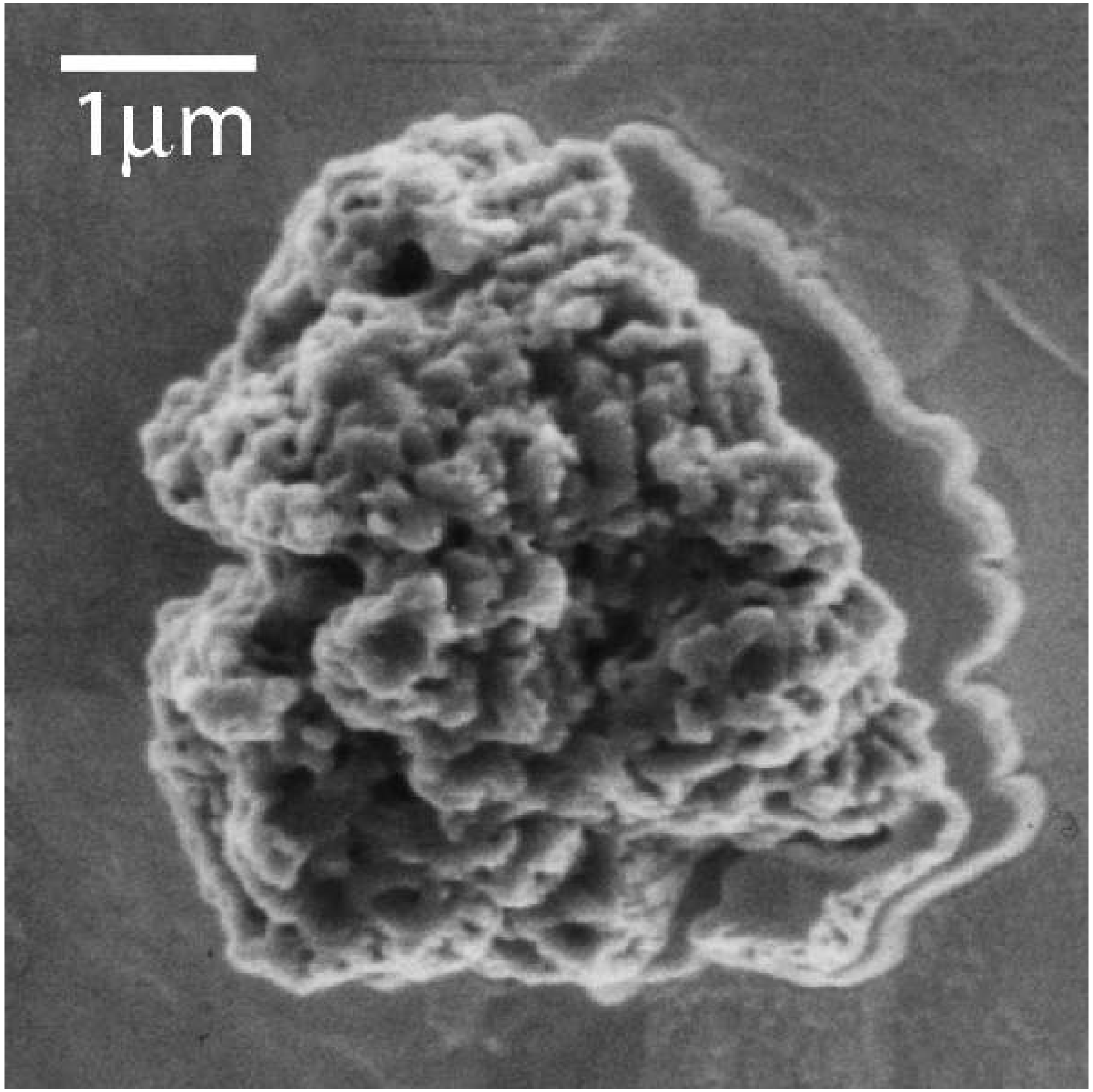


$^{138}$Ba enhanced by *s*-process

Heger et al. 2005, PhLB, 606, 258

# Presolar grains

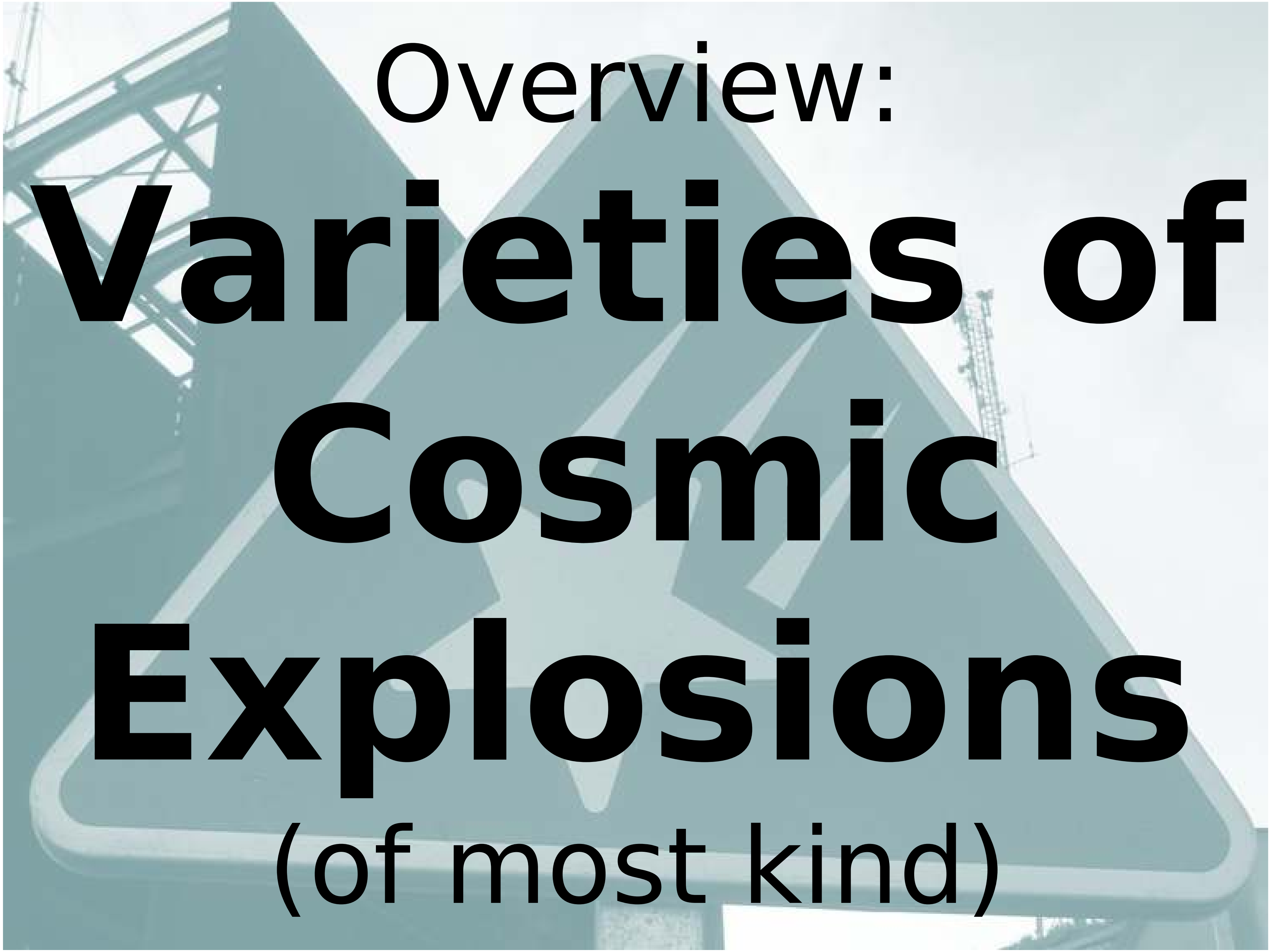
## Direct access to pristine SN nucleosynthesis?



However:
need to understand

- chemistry
- condensation
- SN mixing
- implantation

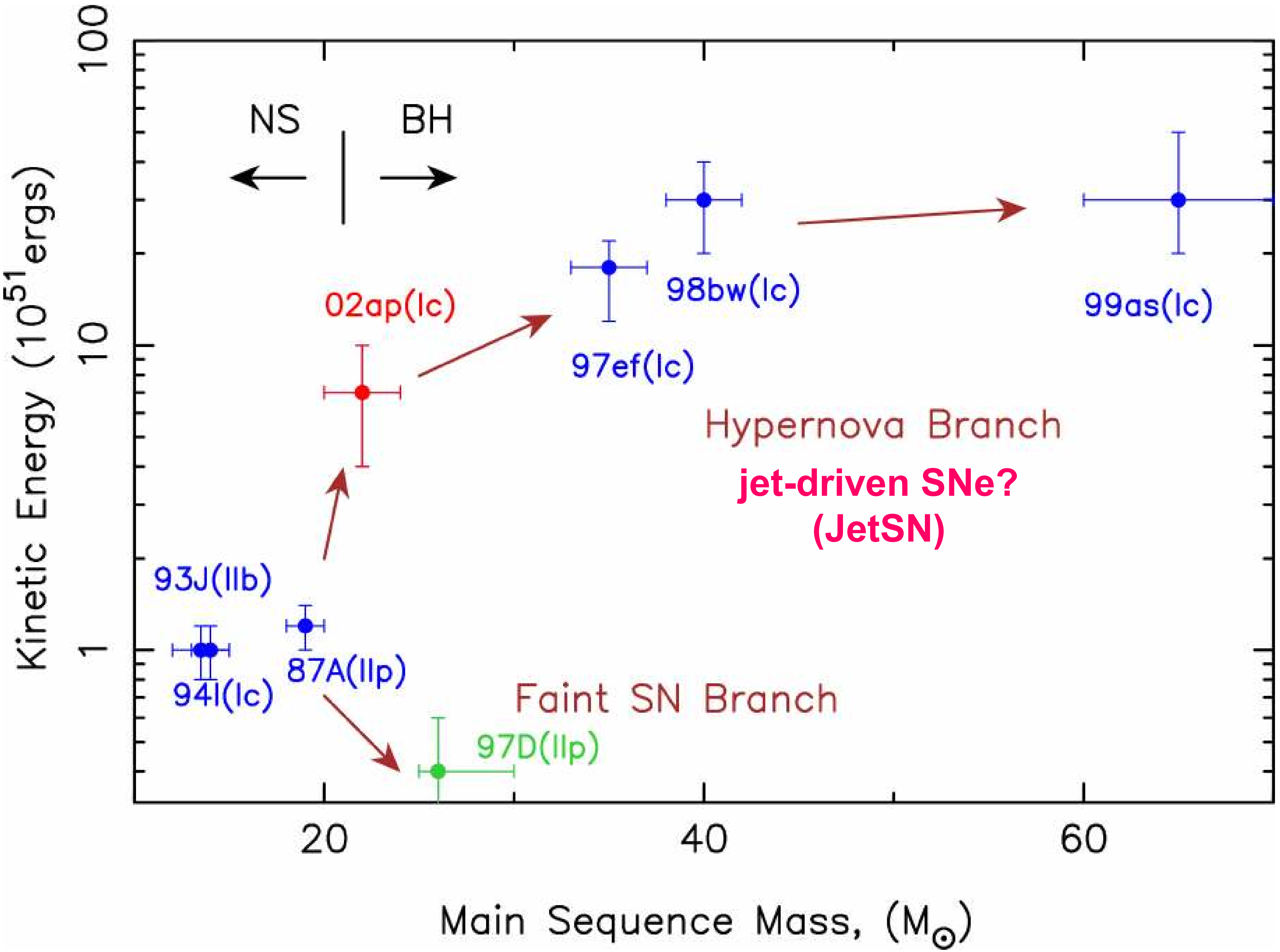
see Denault, Clayton & Heger (2003)



Overview:

# Varieties of Cosmic Explosions

(of most kind)



**jet-driven SNe?**
**(JetSN)**

(Nomoto 2002, priv. com.)

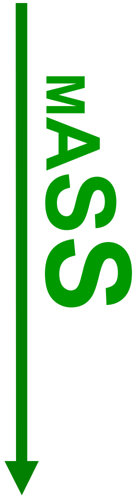
# Energy Scales

| Log E | Explosion | Thermonuclear |
|---|---|---|
| 39 | X-ray Bursts | √ |
| 40 | Long-Duration He Bursts | √ |
| 41 | | |
| 42 | X-ray Superbursts | √ |
| 43 | | |
| 44 | | |
| 45 | Classical Novae | √ |
| 46 | | |
| 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 - $0.5\ M_{.}\ c^2$)* | |
| 55 | GR He SN | GR He SN (upper limit) |
| 56 | GR H SN, $Z > 0$ (Fuller *et al.* 1986) | √ |

# Things that blow up

## supernovae

1B=$10^{51}$ erg



- CO white dwarf ➔ Type Ia SN, $E \approx 1$Bethe
- 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
- GR He instability ➔ >100 B SN+SMBH, or 10,000 B
- Supermassive stars ➔ $\gtrsim$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
- GR He instability ➔ >100 B SN+SMBH, or 10,000 B
- 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
- GR He instability ➔ >100 B SN+SMBH, or 10,000 B
- Supermassive stars ➔ ≳100000 B SN or SMBH

# Things that blow up

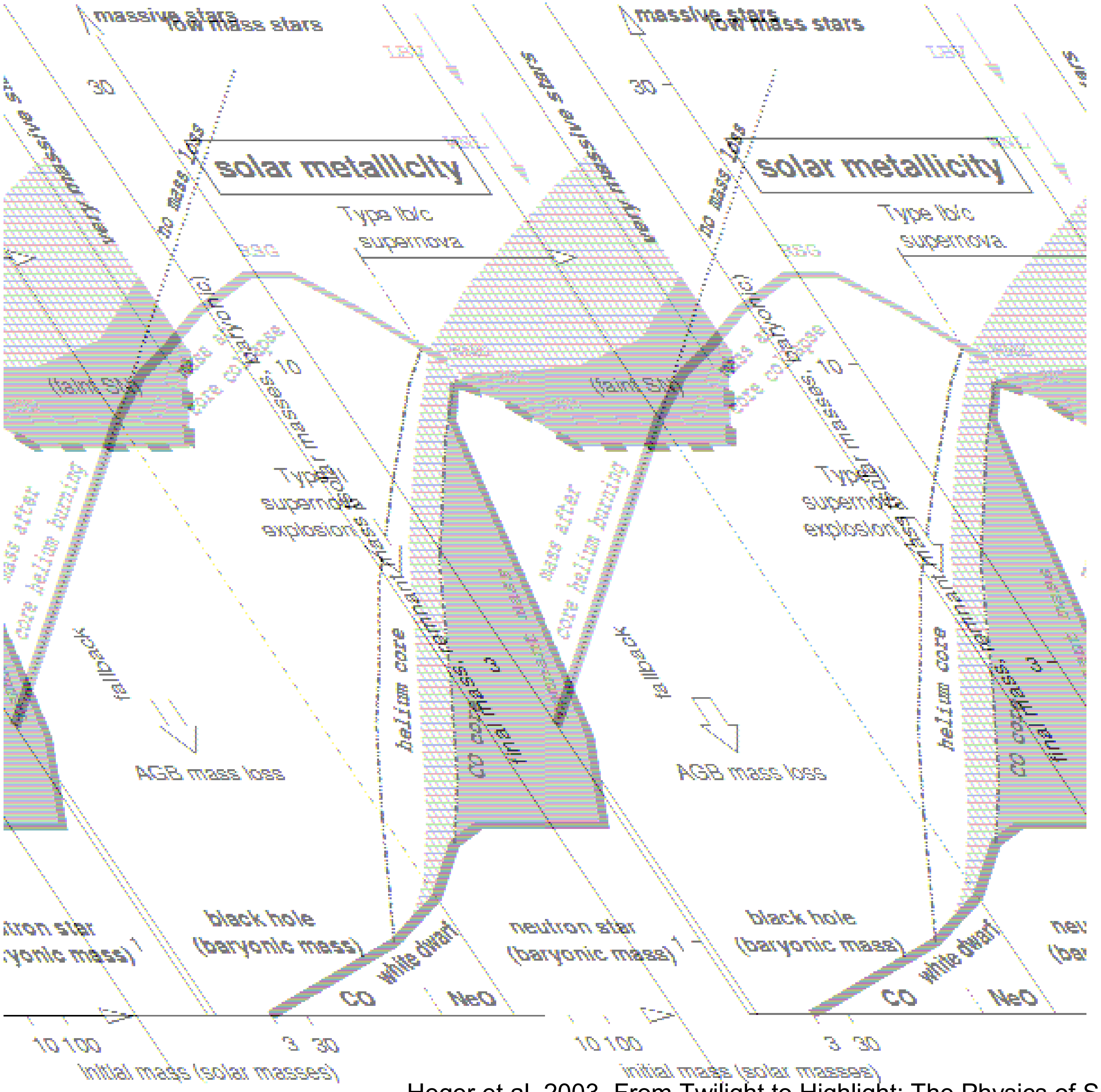
## Black hole-powered supernovae (“Collapsars)

- 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,$\lesssim$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 ➔ $\gtrsim$100000 B SN or SMBH

# Massive Star Fates as Function of Initial Mass

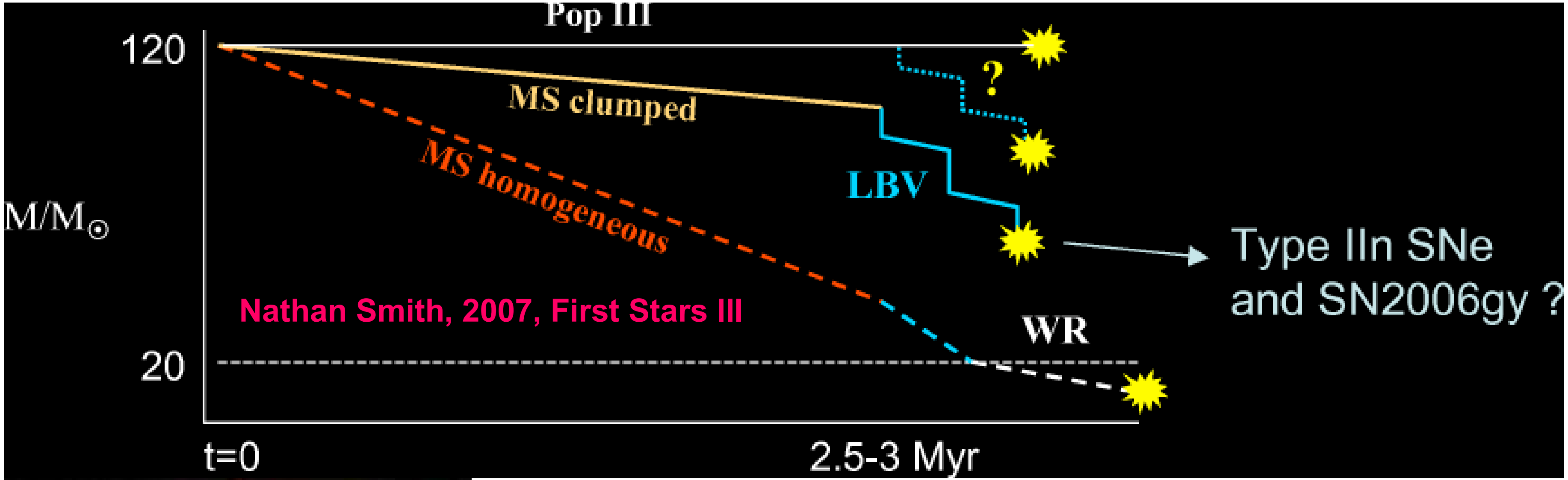
(solar metallicity)

# Ejected “metals”



Heger et al. 2003, From Twilight to Highlight: The Physics of Supernovae, Springer-Verlag, 3

# Mass Loss due to Giant Eruptions?



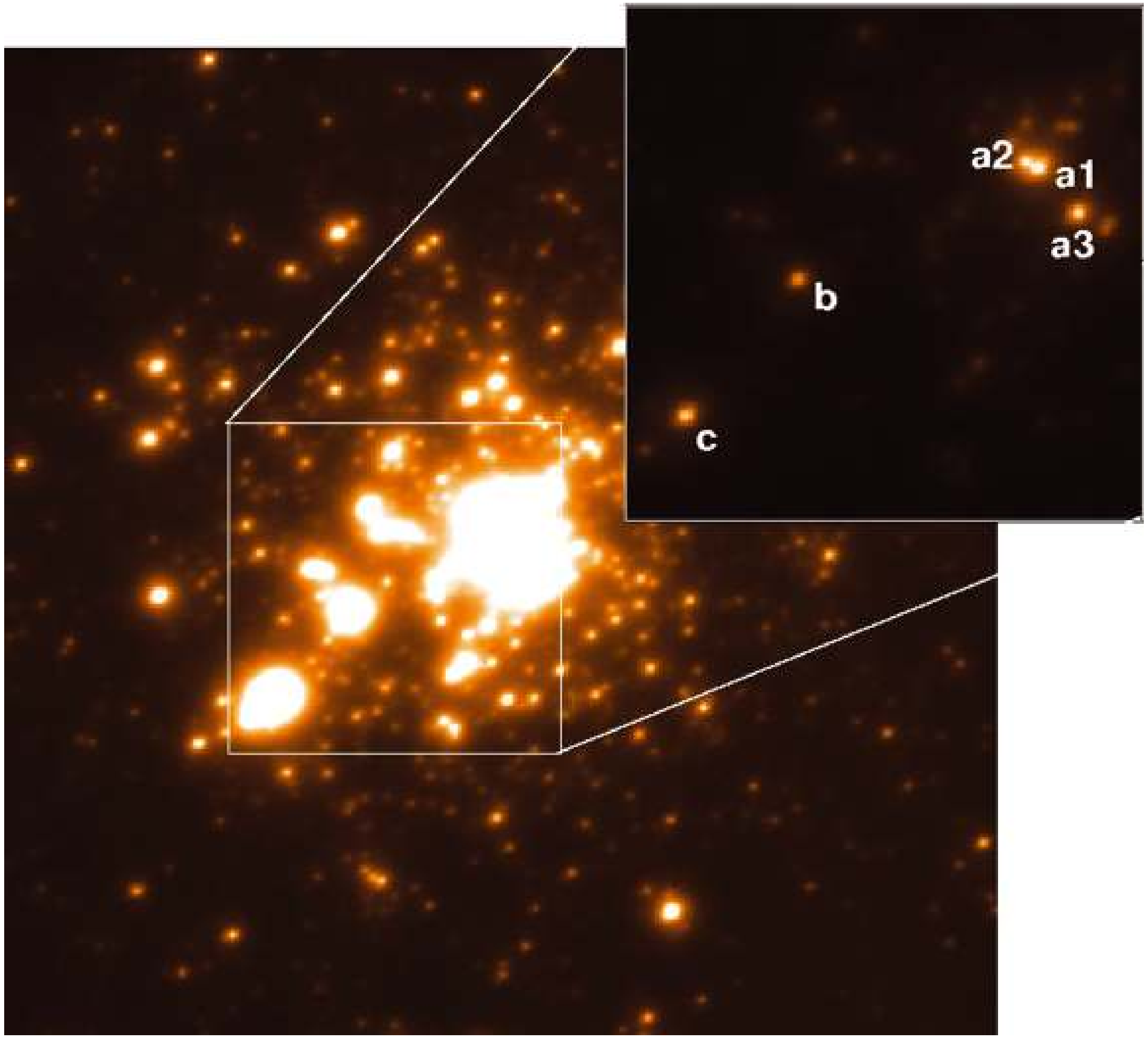
Nathan Smith, 2007, First Stars III

Type IIn SNe and SN2006gy ?

## How do the most massive stars evolve?

- Reduced mass loss on the main sequence followed by LBV & giant eruptions?
- What are these eruptions?
  (physics, number, recurrence)
- When do they occur?
  (internal evolution stage?)
- How do we model these eruptions?
- Pulsational Pair-Instability Supernovae (PPSN)?

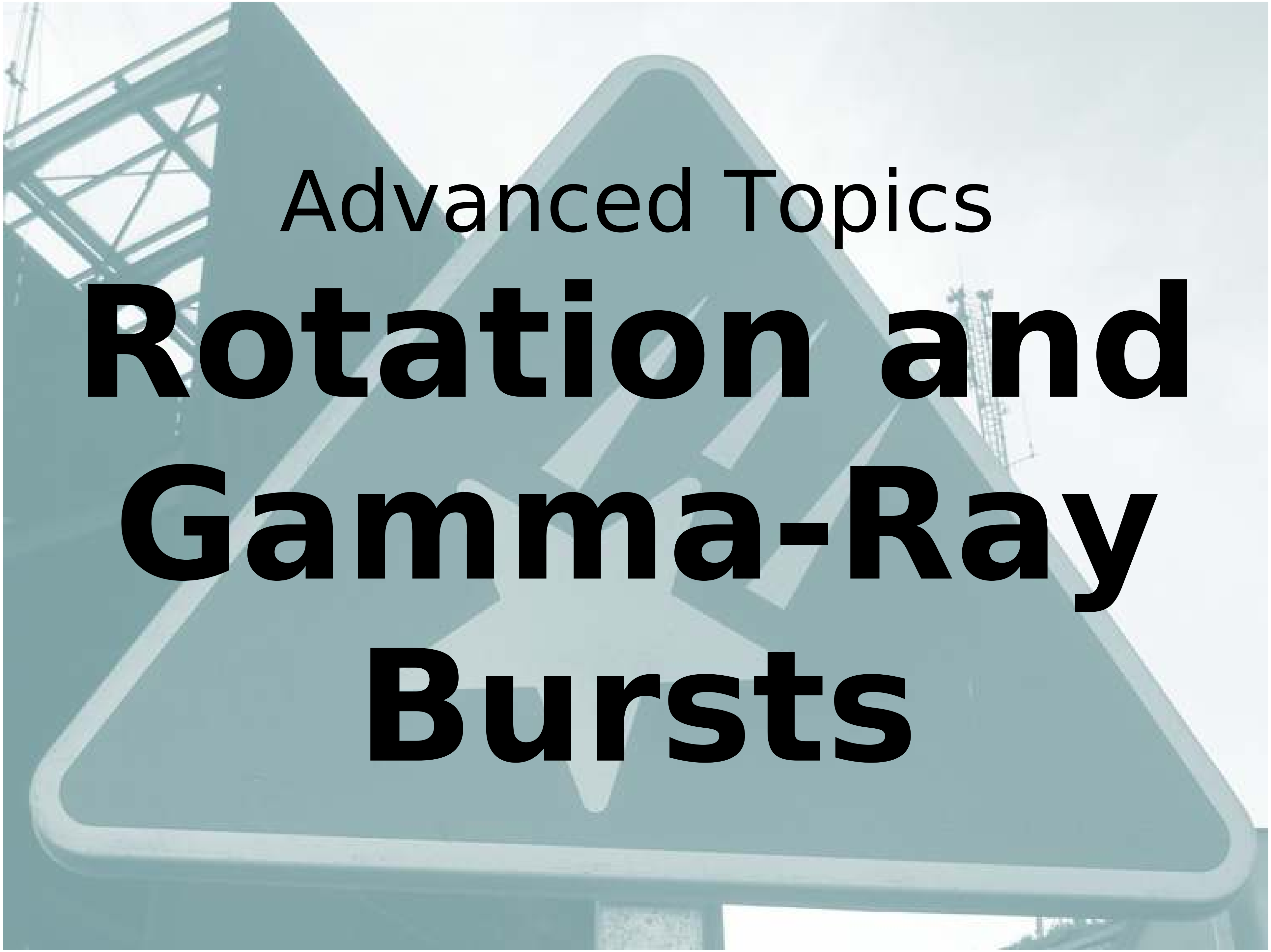
# The Most Massive Stars Today



## R136

- young massive star cluster
- Age around 1.5 Myr
- Star “a1”:
  maybe 200 M.
  initial mass

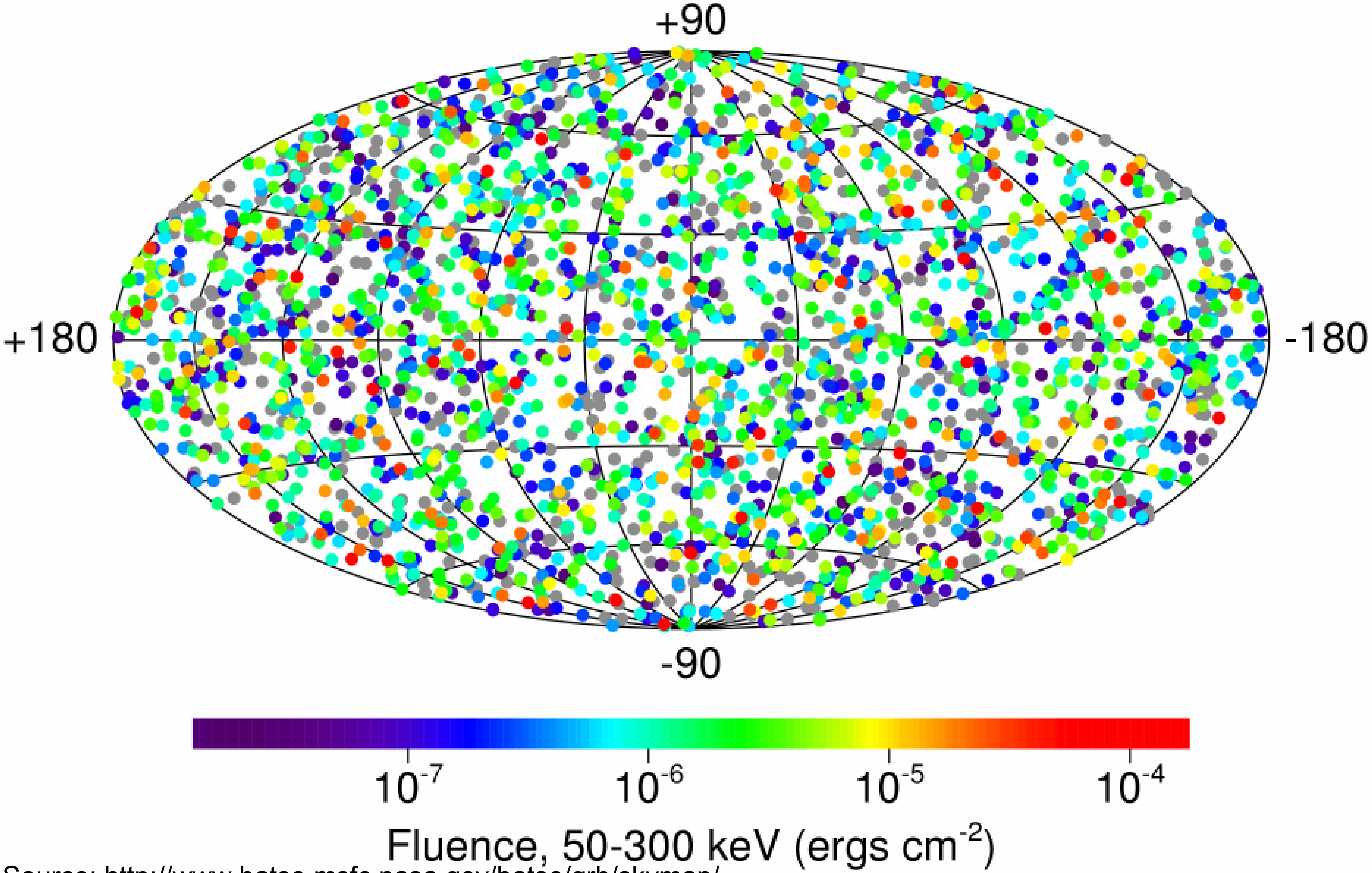
(Crother et al. 2010)



## Advanced Topics

# Rotation and Gamma-Ray Bursts

# 2704 BATSE Gamma-Ray Bursts

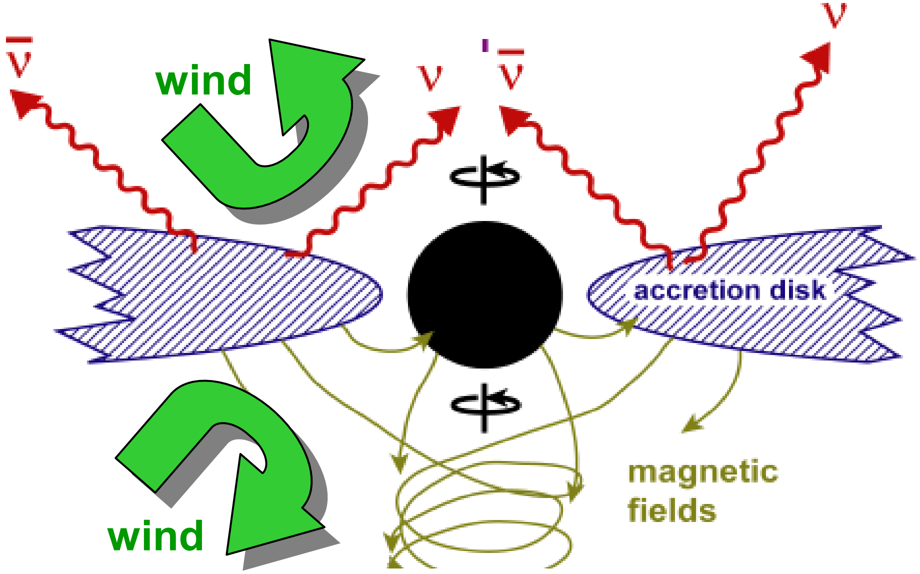


Source: http://www.batse.msfc.nasa.gov/batse/grb/skymap/

# How else can massive stars explode?

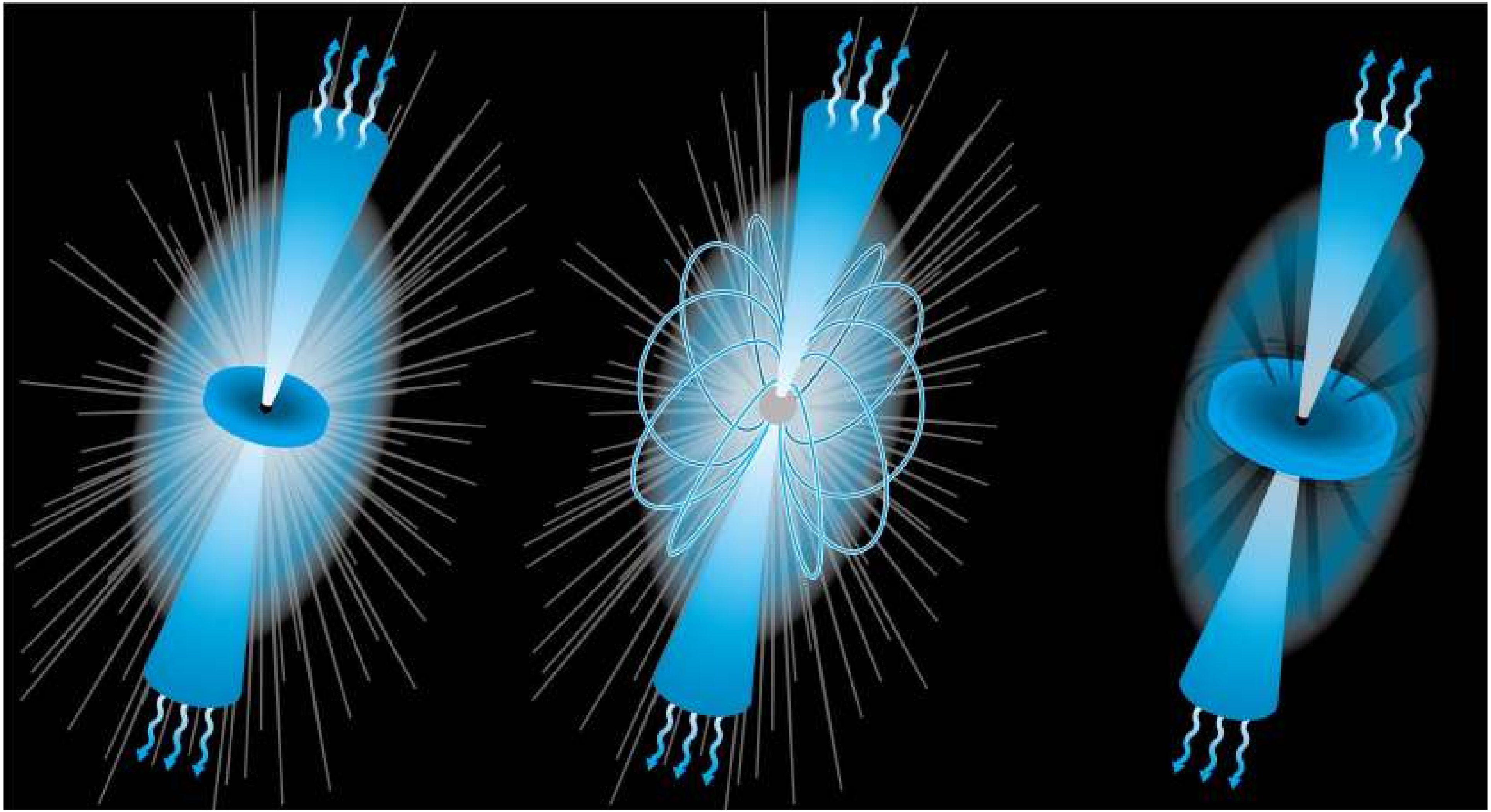
**$25M_\odot < M < 100M_\odot$ ,**
**$M > 250M_\odot$**

## The “Collapsar Engine”

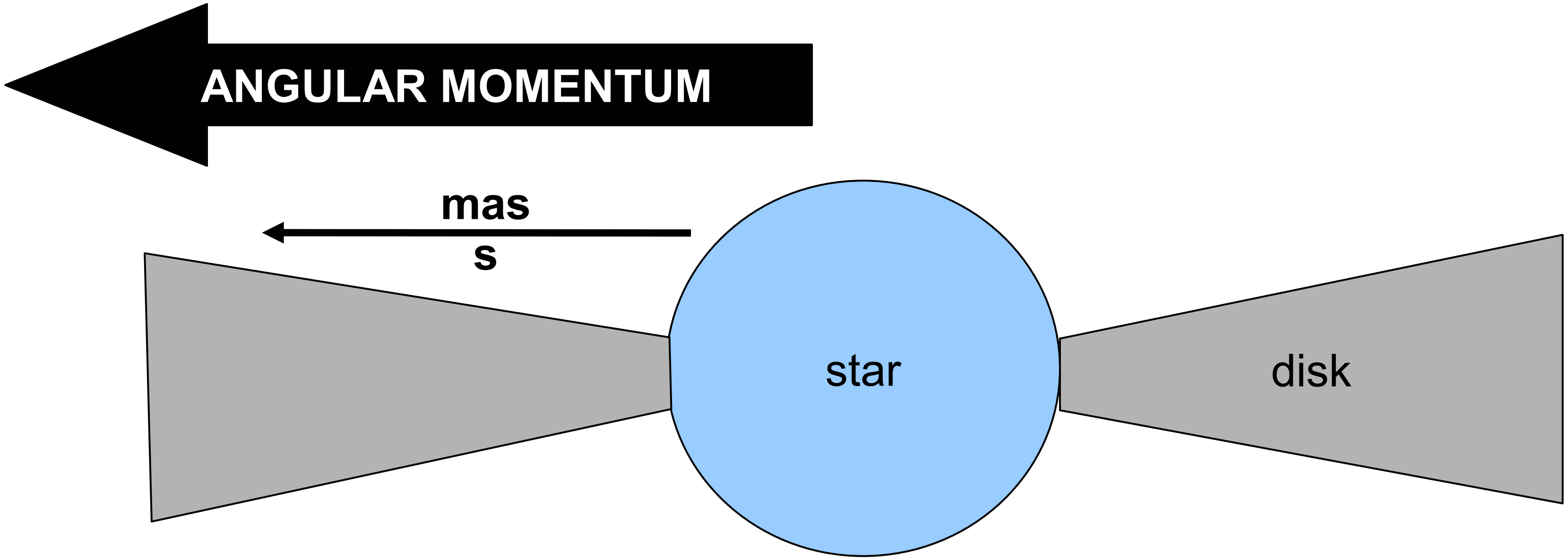


1. black hole forms inside the collapsing star
2. The infalling matter forms and accretion disk
3. The accretion disk releases gravitational energy (up to 42.3% of rest mass for Kerr BH)
4. Part of the released energy or winds off the hot disk explode the star

# GRB Mechanisms



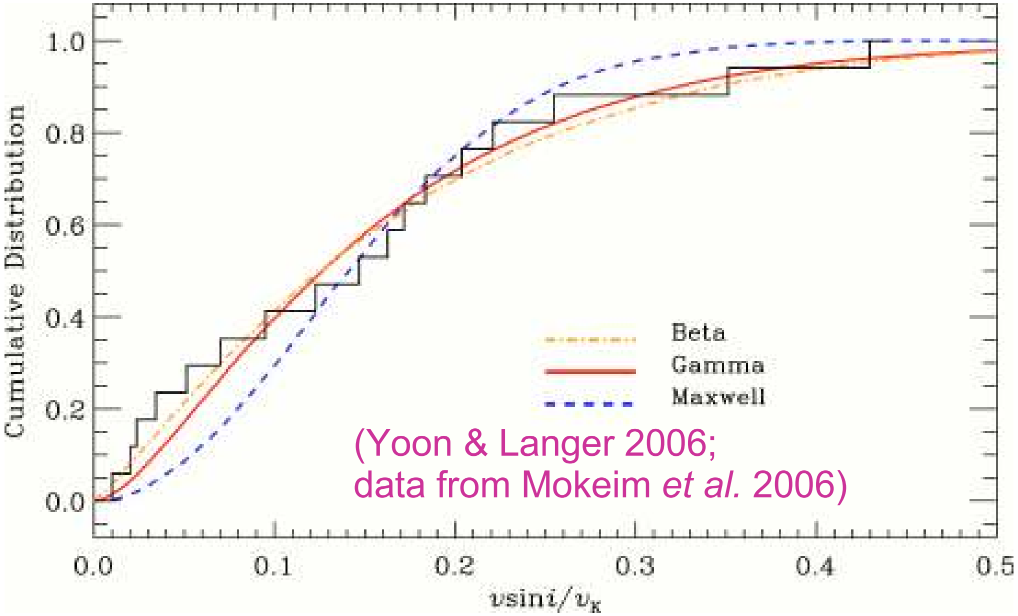
# Mass Loss due to Critical Rotation



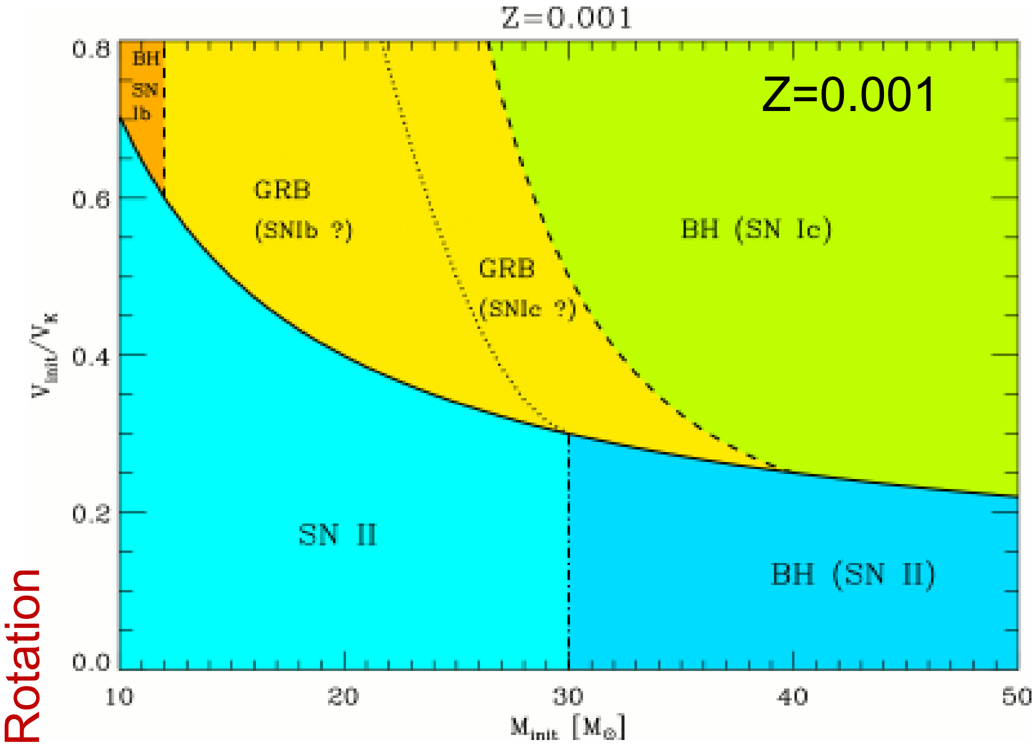
- How important is mass loss due to critical (or fast) rotation?
- How do we quantify mass loss and angular momentum loss?
- How does it effect our stellar models?

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

# Black Holes and GRBs from Rotating Stars



(Yoon & Langer 2006; data from Mokeim *et al.* 2006)



Z=0.001

Rotation

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.

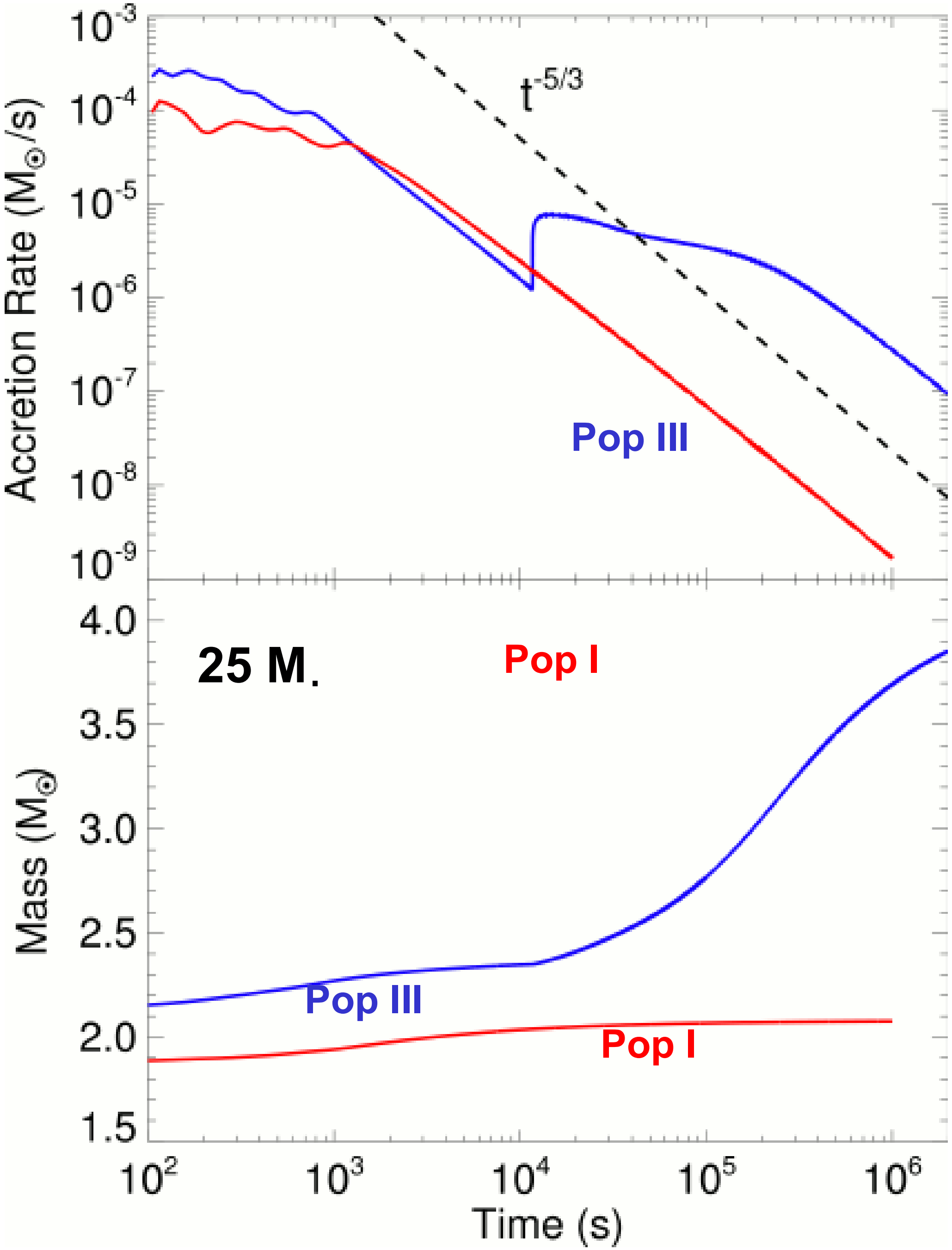
(Yoon & Langer 2006)

Advanced Topics

# Remnant Masses

Of Supernovae

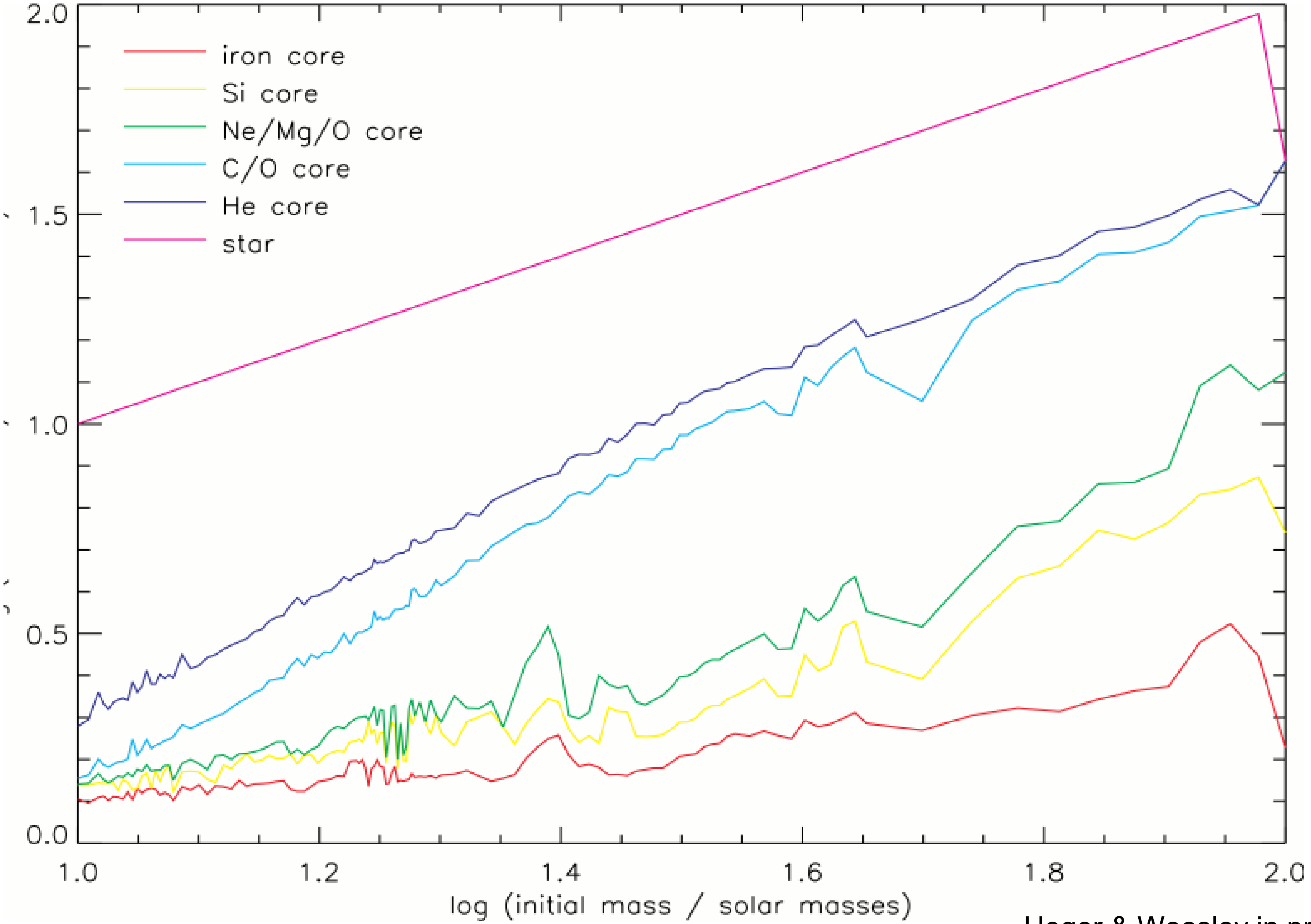
# Fallback and Remnants



➔ **Pop III stars show much more fallback than modern Pop I stars due to their compact hydrogen envelope**

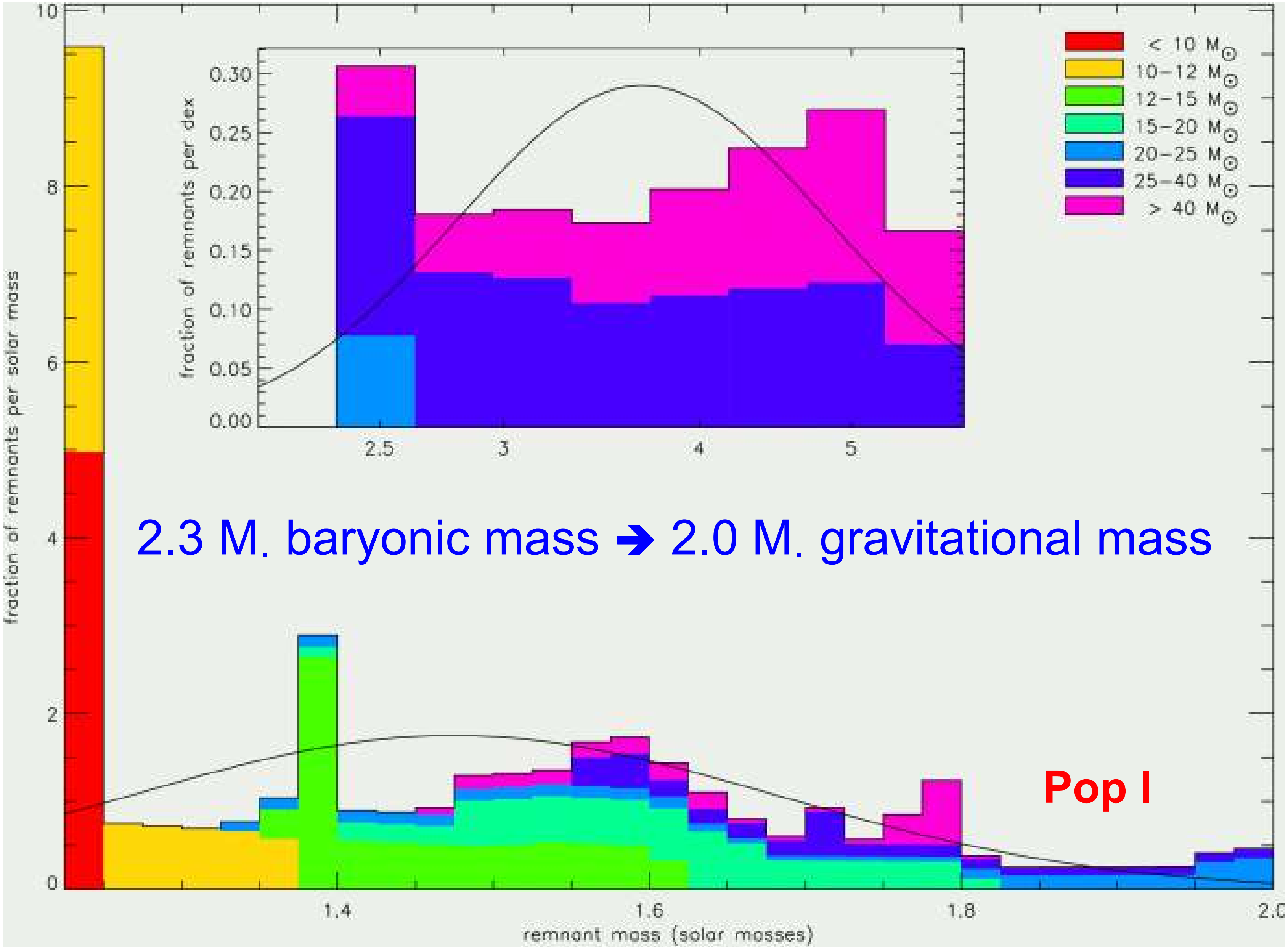
(Zhang, Woosley, Heger 2007)

# Pop III Star Core Masses



Heger & Woosley in prep.

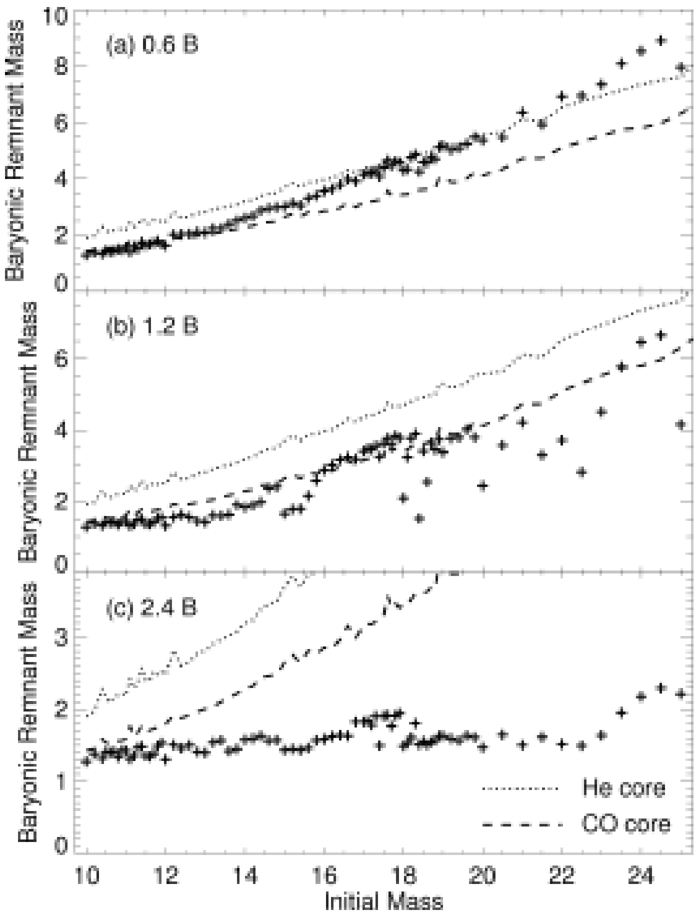
# Fallback and Remnants

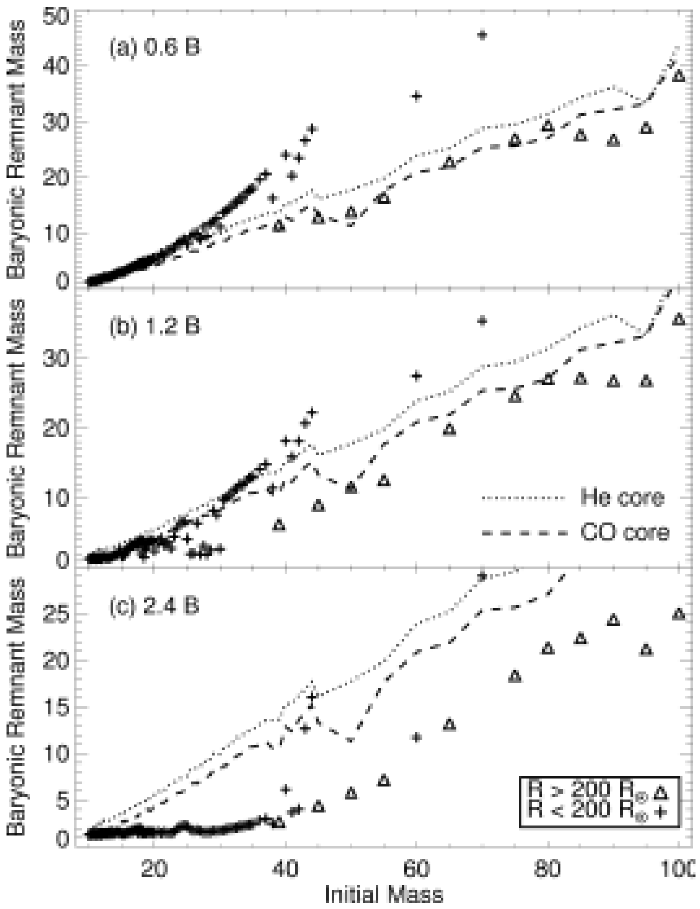


2.3 M. baryonic mass ➔ 2.0 M. gravitational mass

**Pop I**

(Zhang, Woosley, Heger 2007)



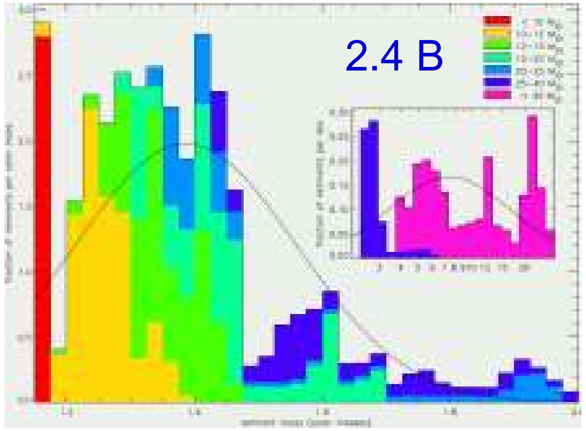


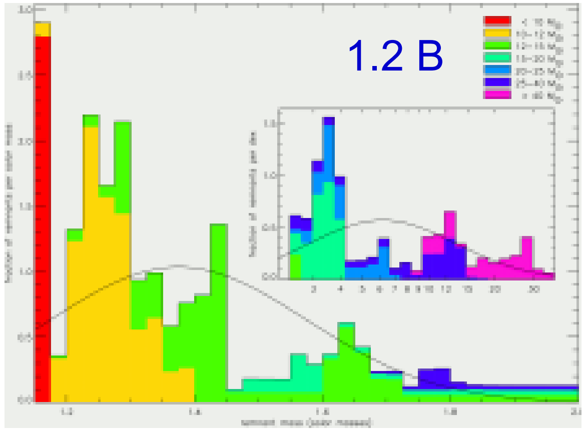
# Pop III Stars

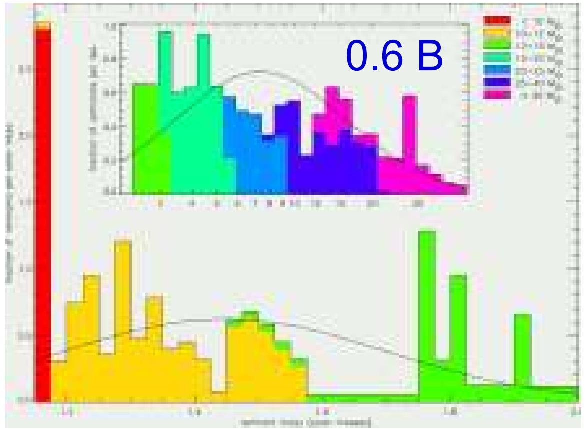
Much fallback for compact stars (“+”)

Less fallback for RSG (“Δ”)

(Zhang, Woosley, Heger 2007)

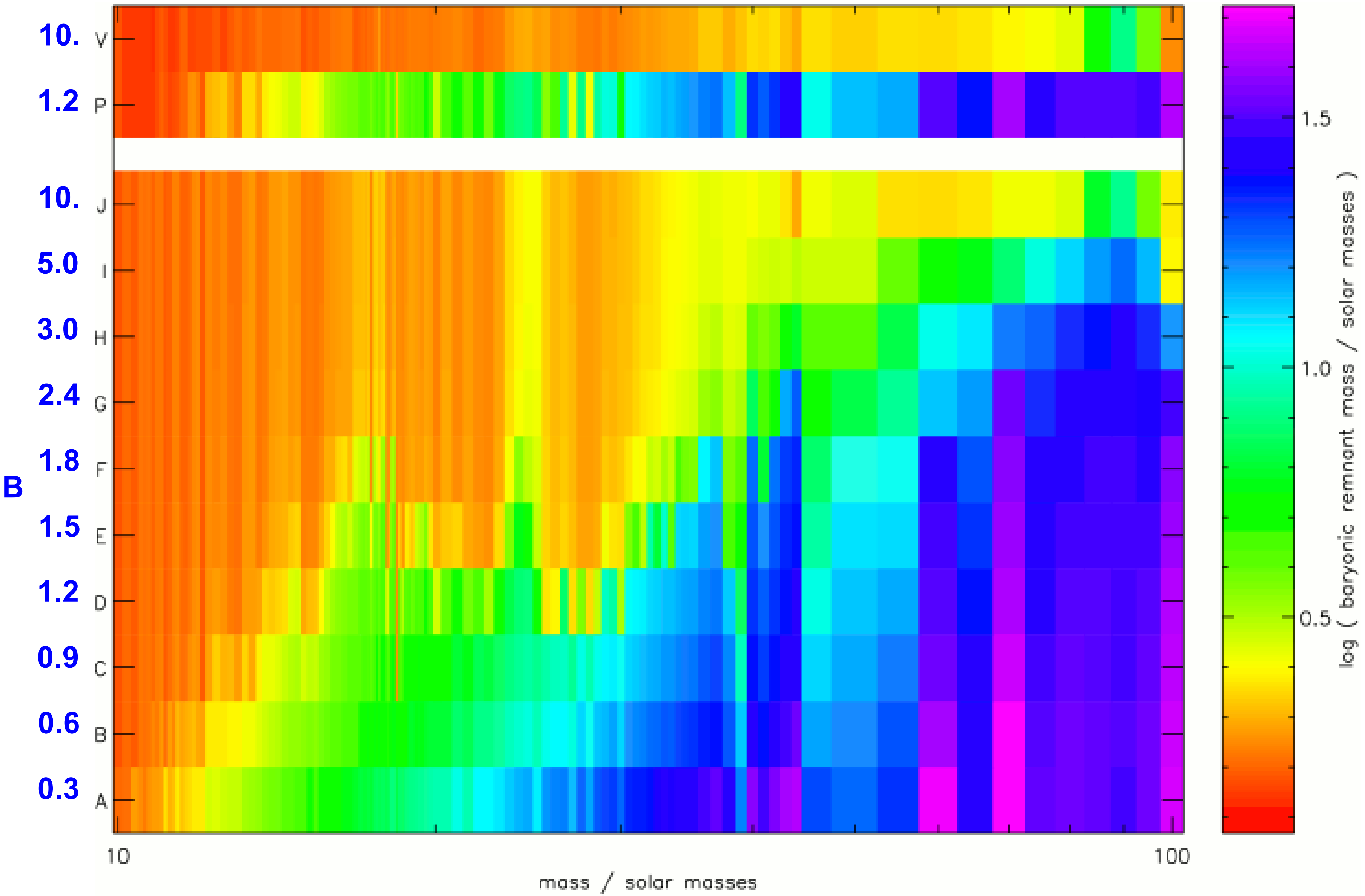






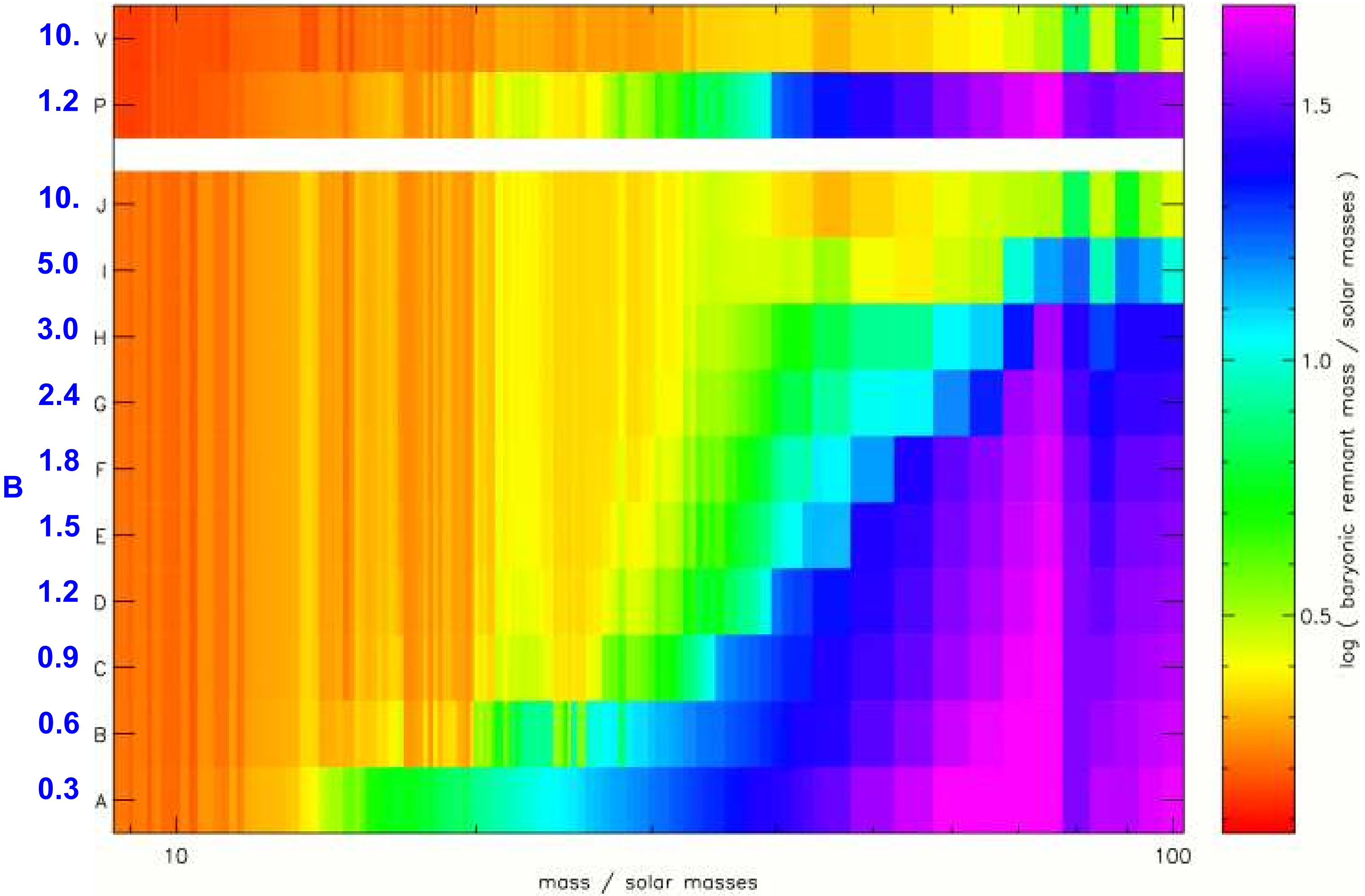
# Pop III Star Remnant Masses

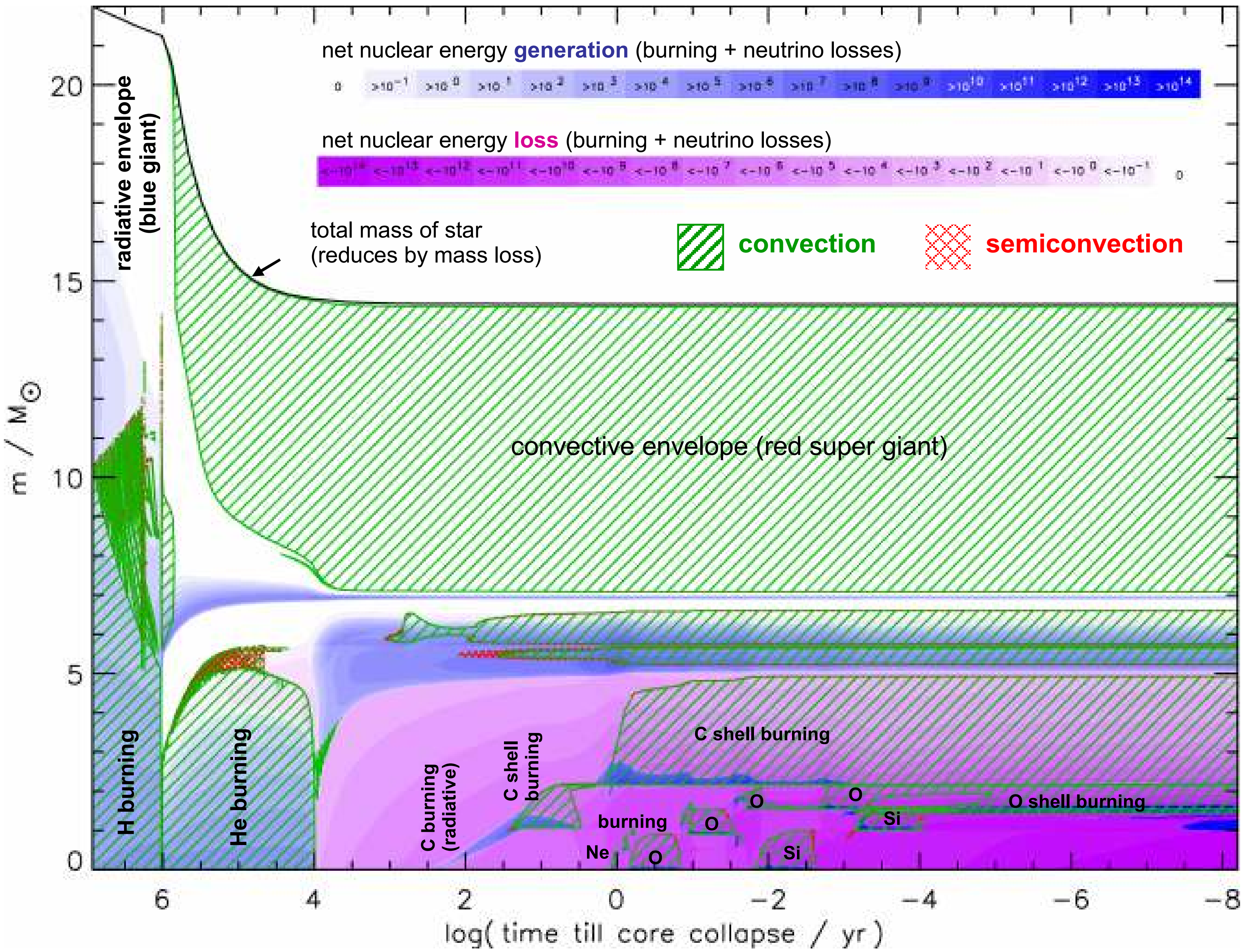
(from Zhang, Woosley, Heger 2007)



# [Z]= -4 Star Remnant Masses

(from Heger, Woosley, Zhang, in prep. 2011)





Heger et al. 2003, From Twilight to Highlight: The Physics of Supernovae, Springer-Verlag, 3

Advanced Topics

# The First Stars

in the Universe

# Formation and Mass of the First Stars

No metals ➔ no metal cooling ➔ more massive stars

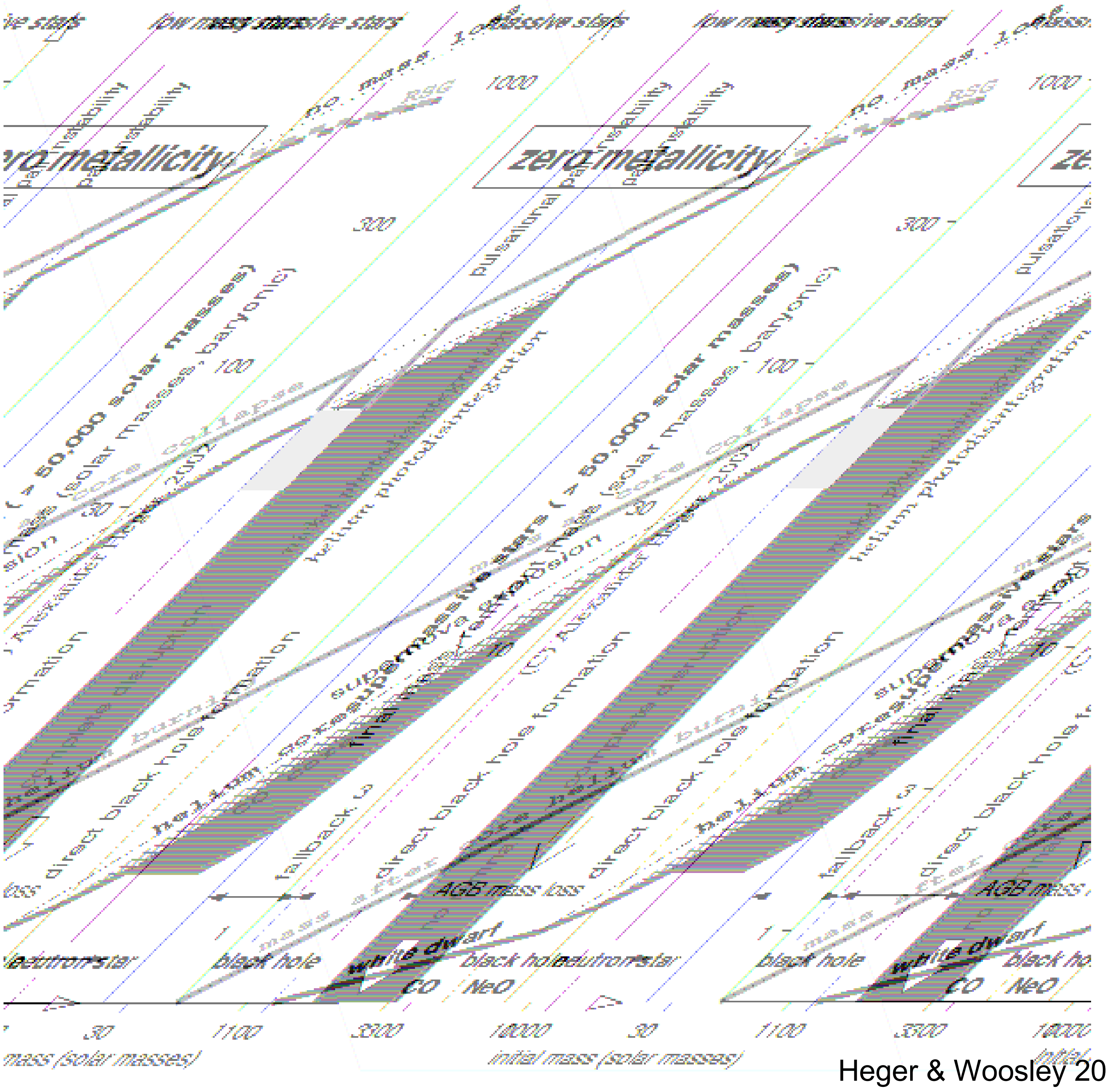
(Bromm, Coppi, & Larson 1999, 2002; Abel, Bryan, & Norman 2000, 2002;Nakamura & Umemura 2001; O'Shea & Norman 2006,...)

➔ typical mass scale ~10...300 $M_{\odot}$?

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)

# Ejected “metals”



Heger & Woosley 2002, ApJ, 567, 532

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