Stellar Evolution Models

Alexander Heger

Overview

- Stellar evolution review
- Uncertainties
- Maybe some examples

Cosmic Dark Age

(after recombination)

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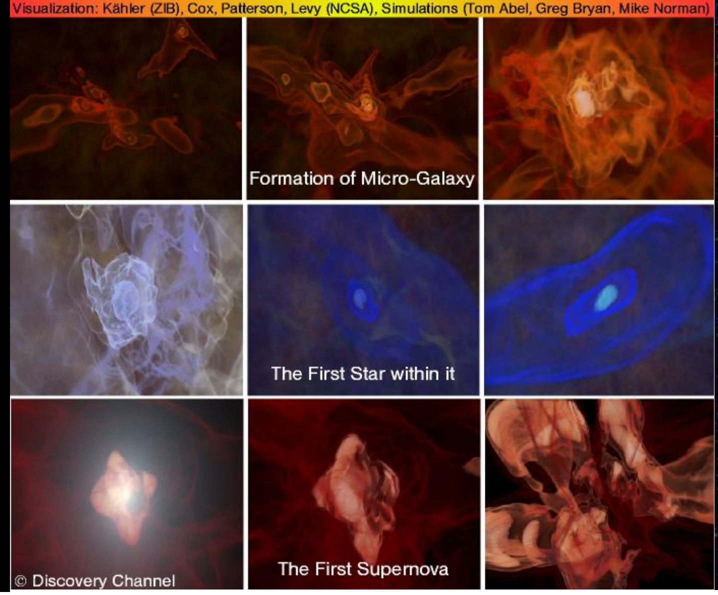
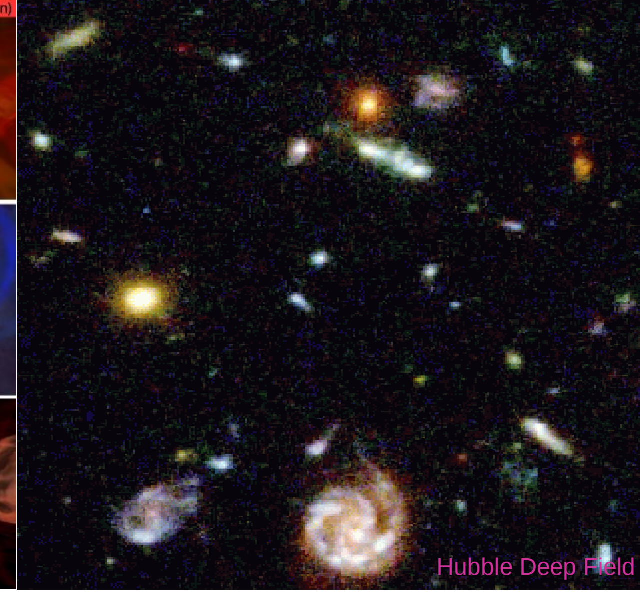
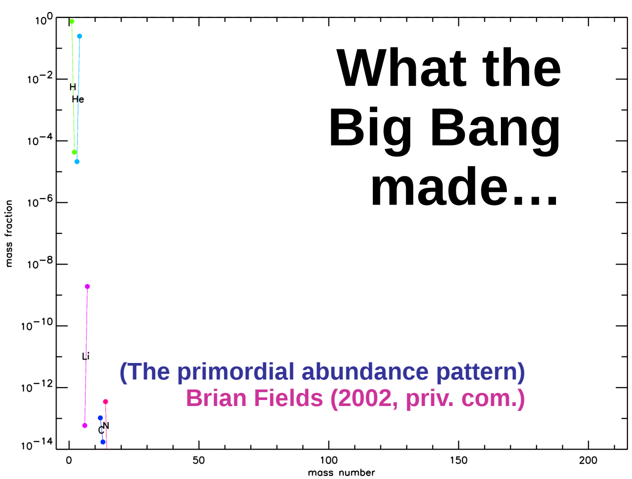
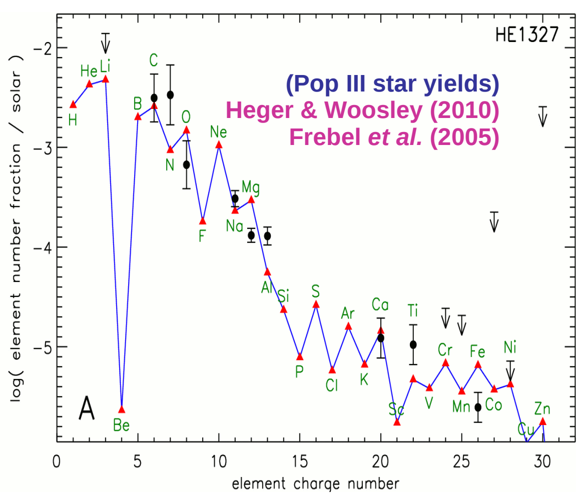
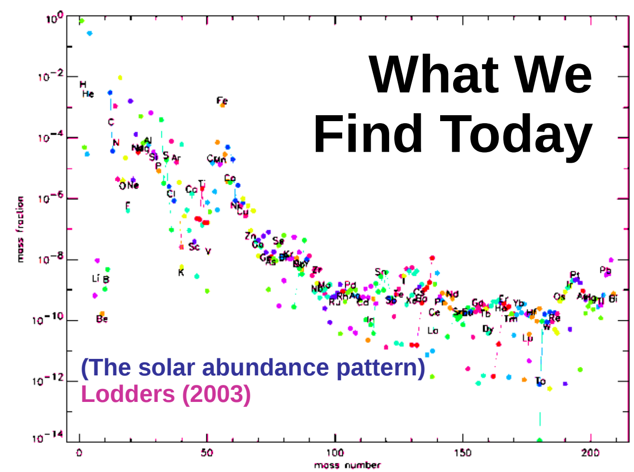




time



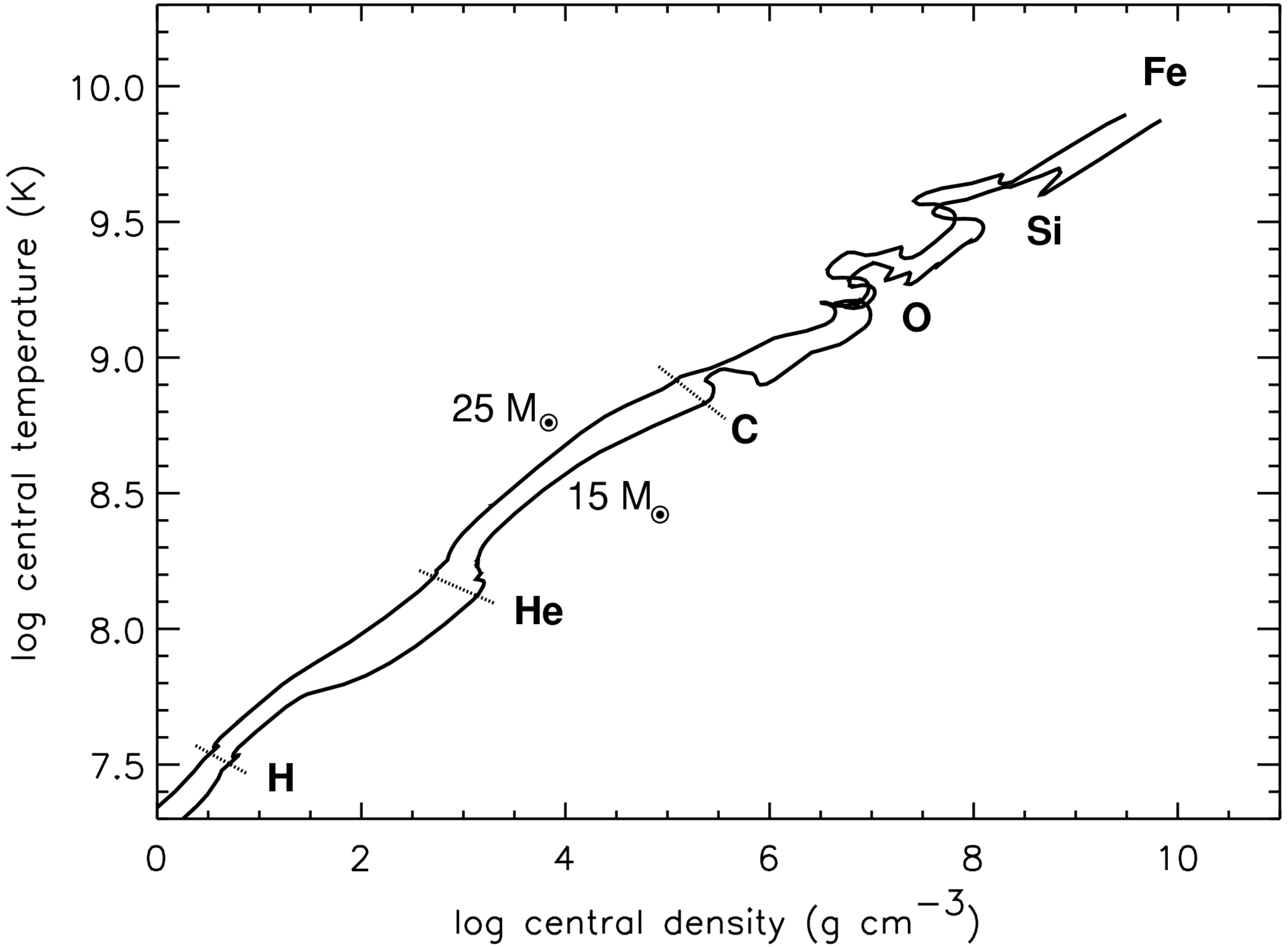




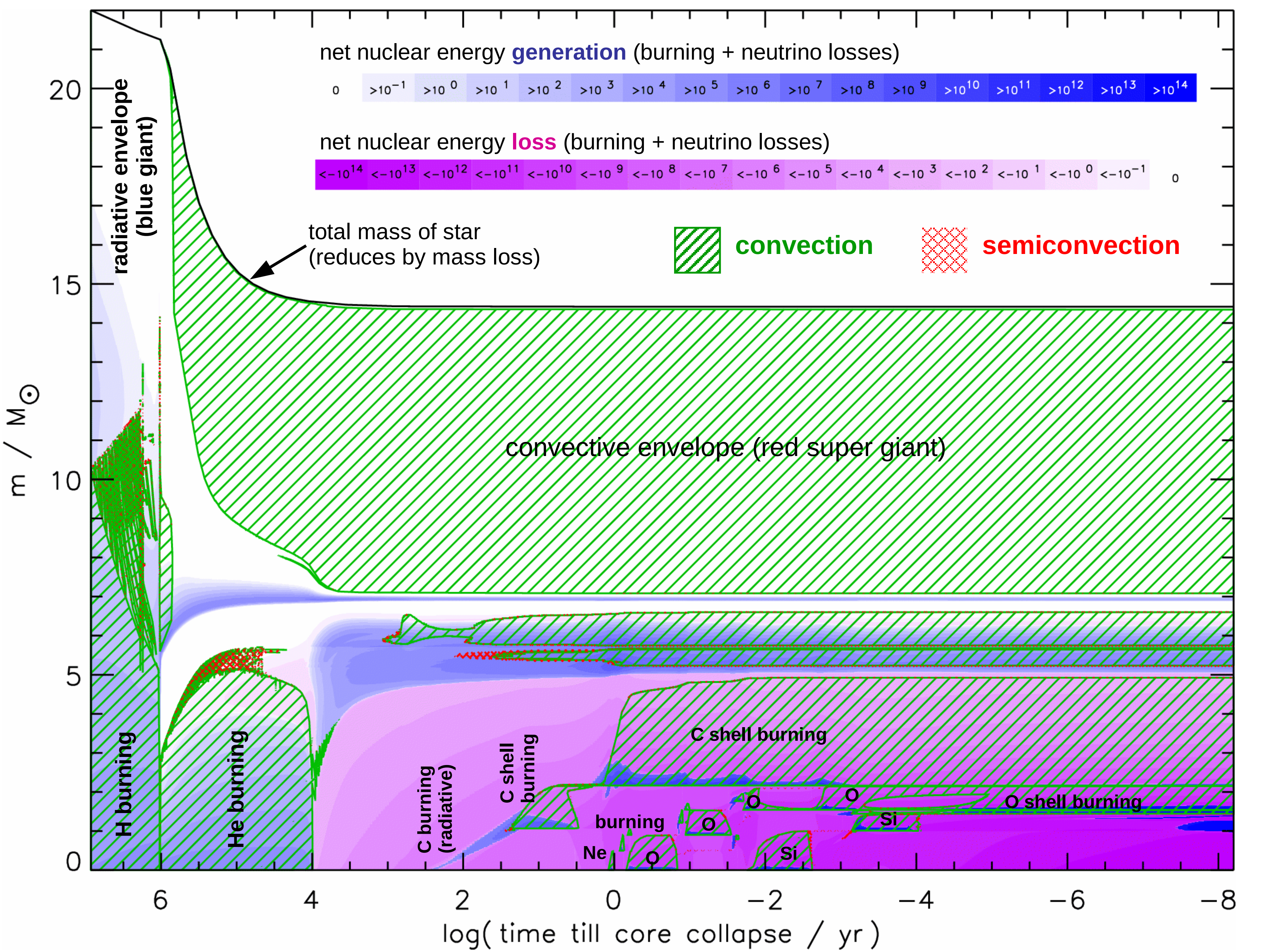
Once formed, the evolution of a star is governed by gravity:

continuing contraction

to higher central densities and temperatures



Evolution of central density and temperature of 15 $M_{\odot}$ and 25 $M_{\odot}$ stars


net nuclear energy generation (burning + neutrino losses)
0
>10^−1
>10^0
>10^1
>10^2
>10^3
>10^4
>10^5
>10^6
>10^7
>10^8
>10^9
>10^10
>10^11
>10^12
>10^13
>10^14
net nuclear energy loss (burning + neutrino losses)
<−10^14
<−10^13
<−10^12
<−10^11
<−10^10
<−10^9
<−10^8
<−10^7
<−10^6
<−10^5
<−10^4
<−10^3
<−10^2
<−10^1
<−10^0
<−10^−1
0
convection
semiconvection
total mass of star
(reduces by mass loss)
radiative envelope
(blue giant)
convective envelope (red super giant)
H burning
He burning
C burning
(radiative)
C shell
burning
C shell burning
Ne
burning
O
O
O
O
O shell burning
Si
Si
m / M_⊙
log(time till core collapse / yr)
20
15
10
5
0
6
4
2
0
−2
−4
−6
−8

(a miracle occurs)

Supernova Explosion

Explosive Nucleosynthesis

in supernovae from massive stars

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (s)	Main Reaction
Innermost ejecta	*r*-process	-	>10 low Y_e	1	(n,γ), β^-
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), (α,γ)
		p-process ^{11}B, ^{19}F, ^{138}La, ^{180}Ta	2 - 3	5	(γ,n)
		ν-process		5	(ν, ν'), (ν, e^-)

Things that blow up

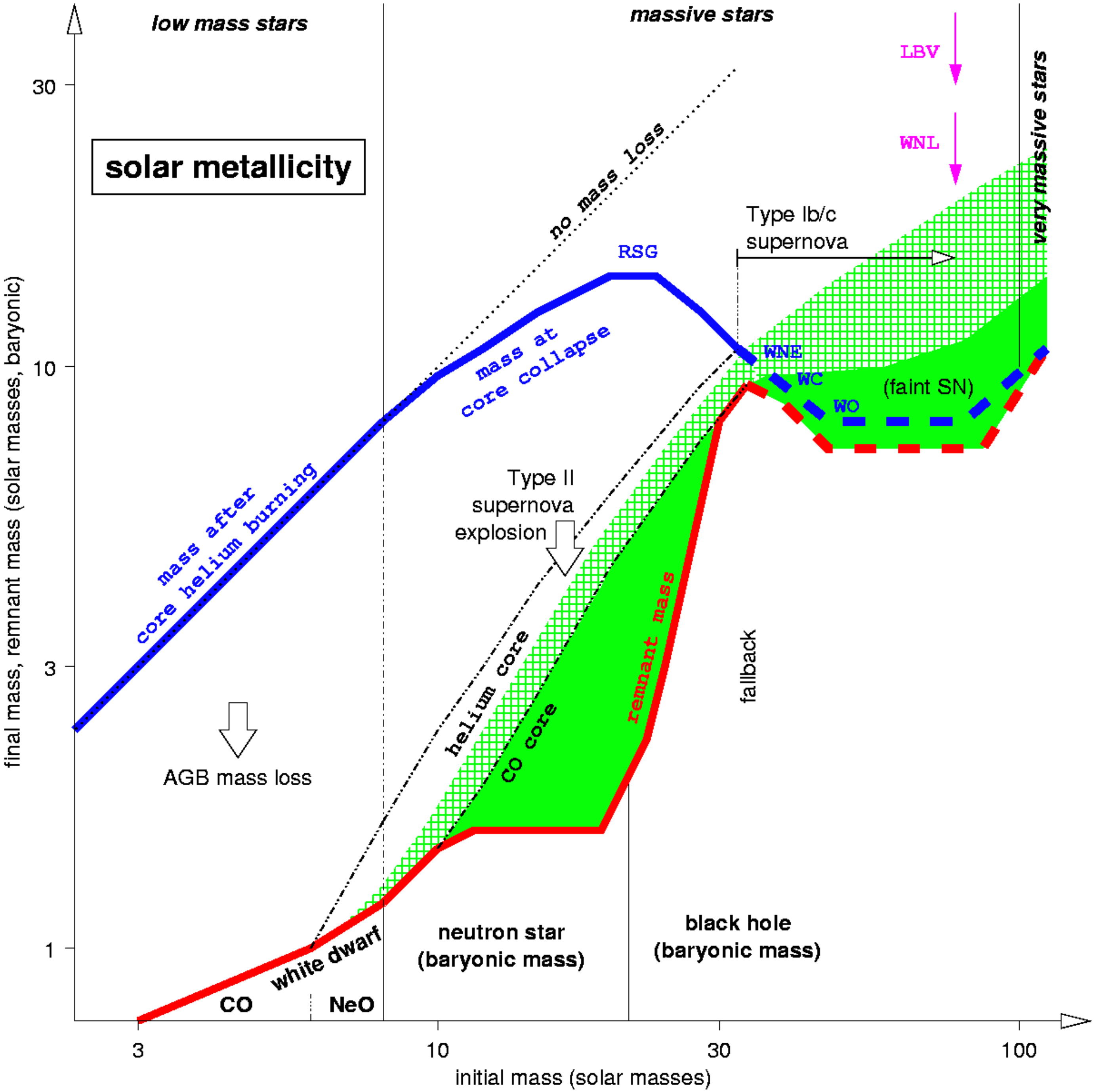
supernovae

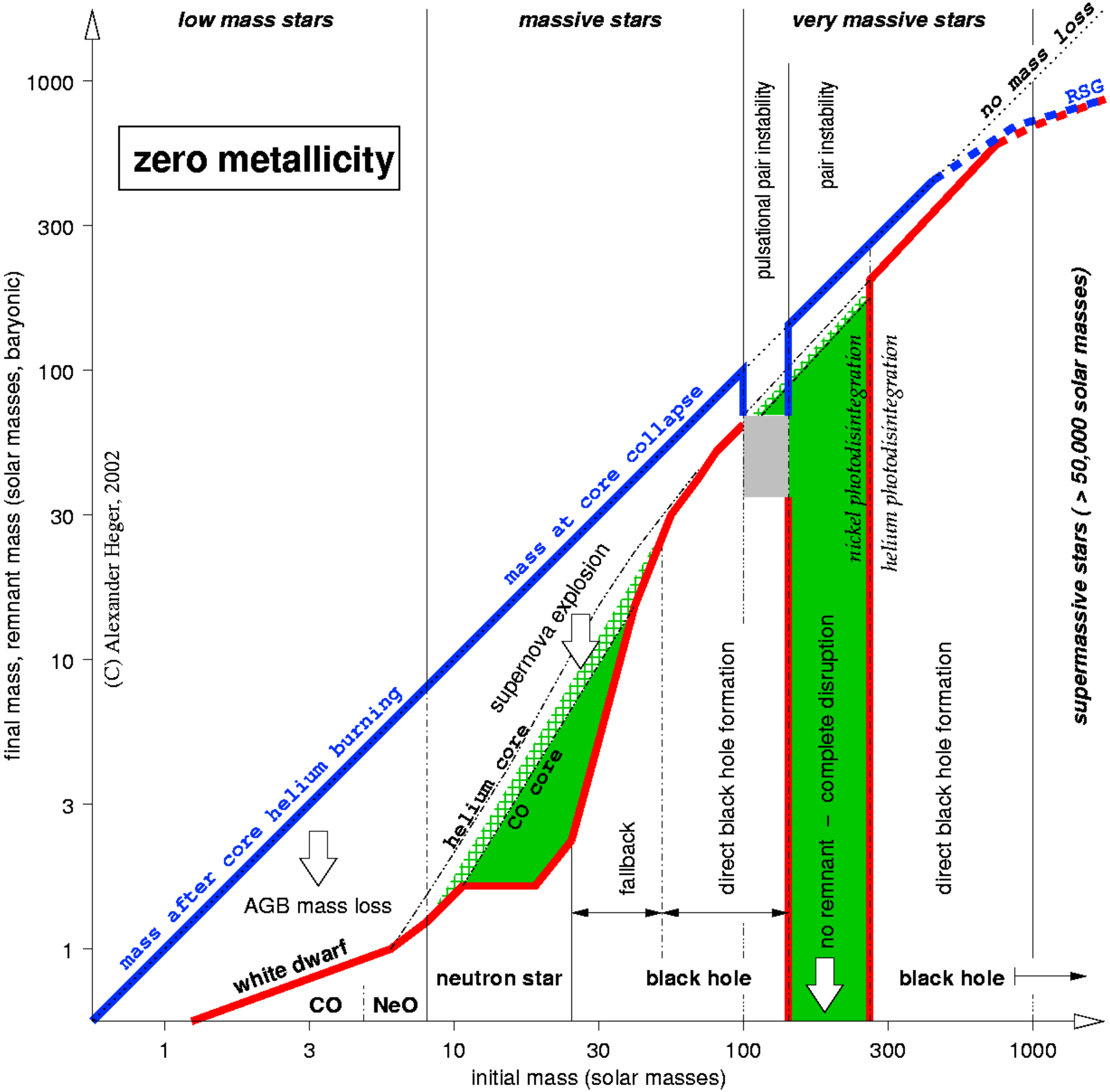
$1B=10^{51}$ erg

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,$\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

Ejected "metals"





Ejected "metals"

What can go wrong?

Three Types of Uncertainty

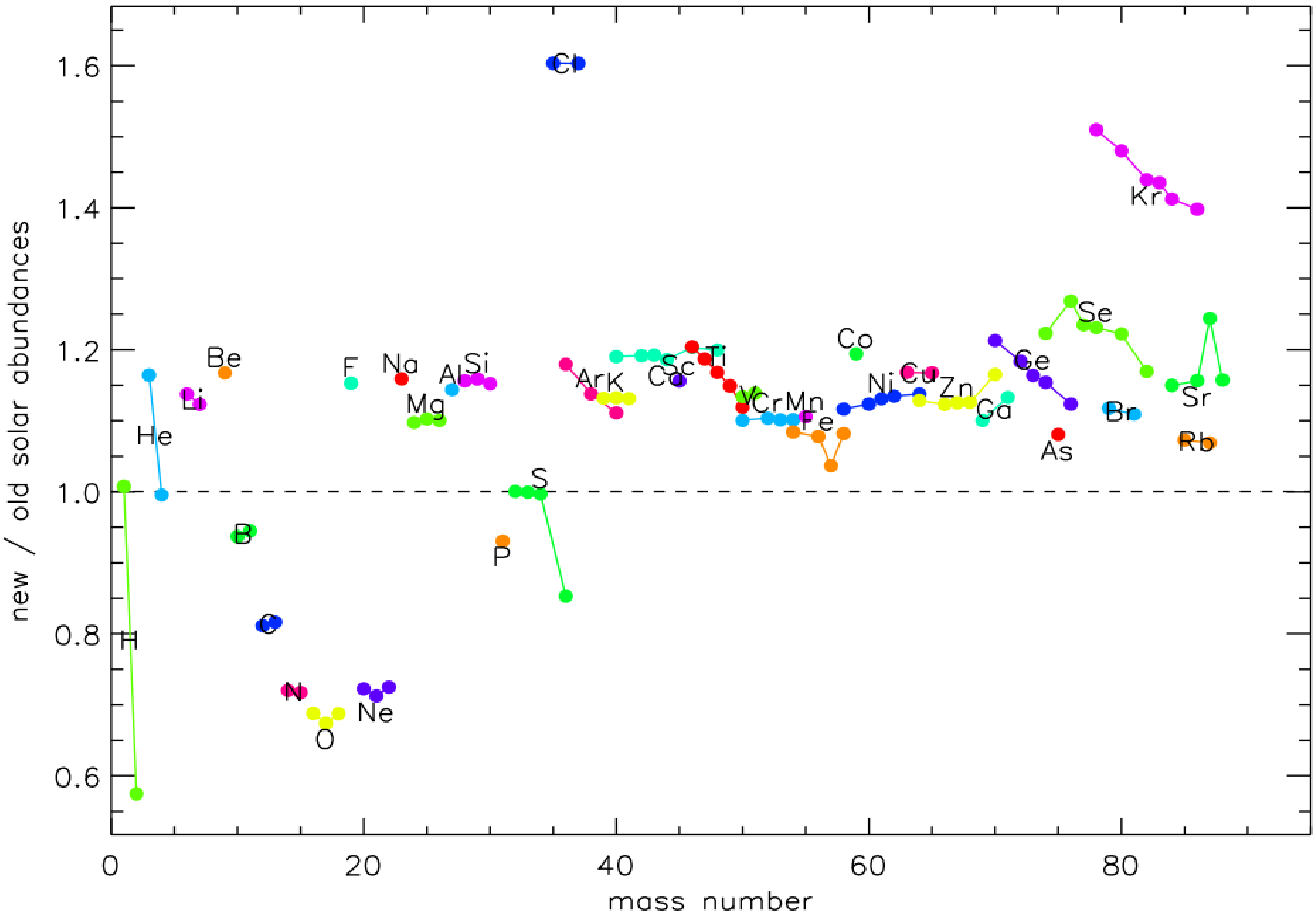
- With what do we start – initial conditions
  composition, rotation rate, ...
    changing solar pattern, GCE: $X_i(Z, *)$?

- Simulations – codes?
  Input physics:
    nuclear data & rates
    "mixing" physics –
      convection, semiconvection, overshooting, "wave"
      mixing, rotation, magnetic fields, mass loss, ...

- What do we compare to?
  Observational data uncertainty

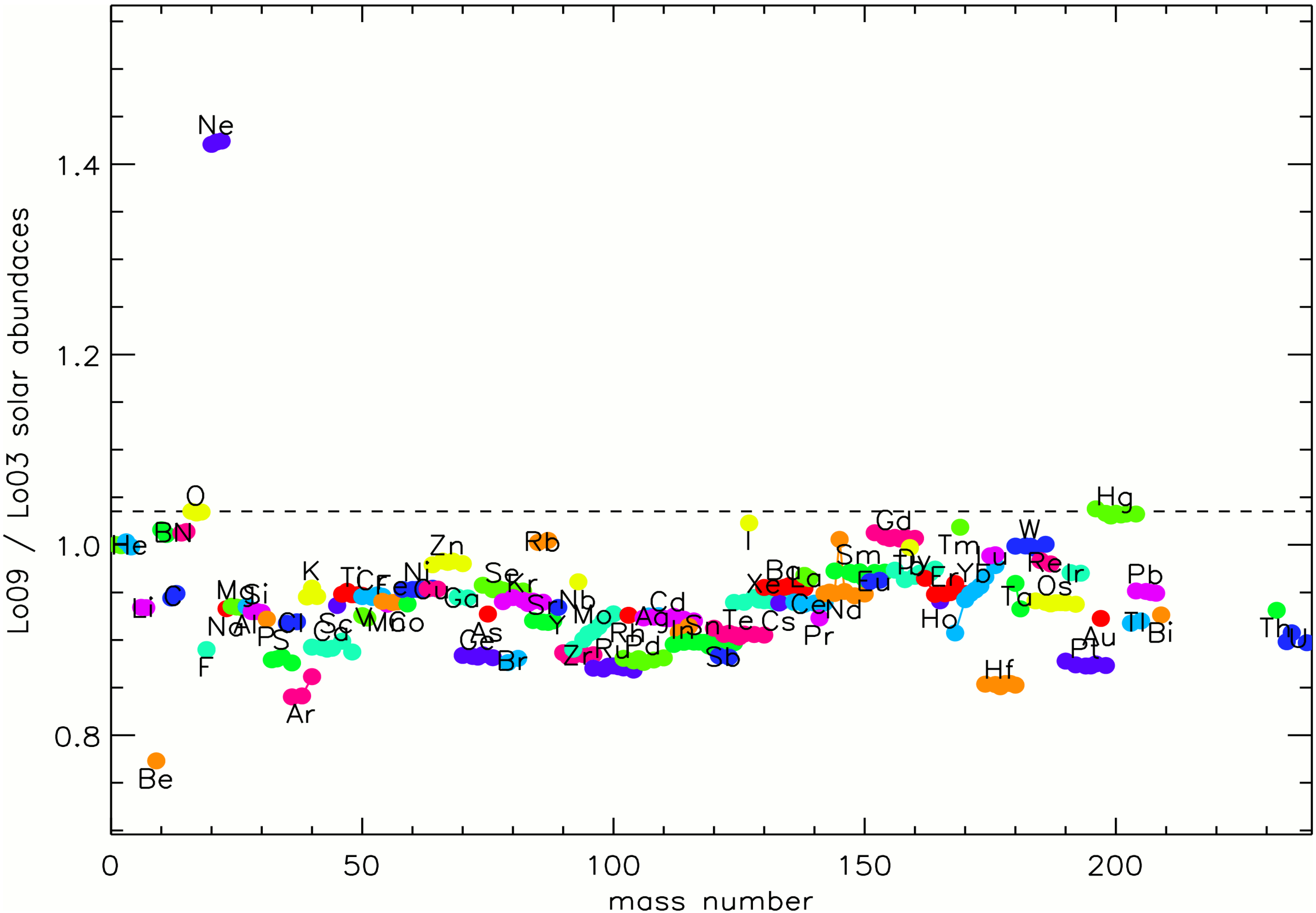
Input

Sun 2.0



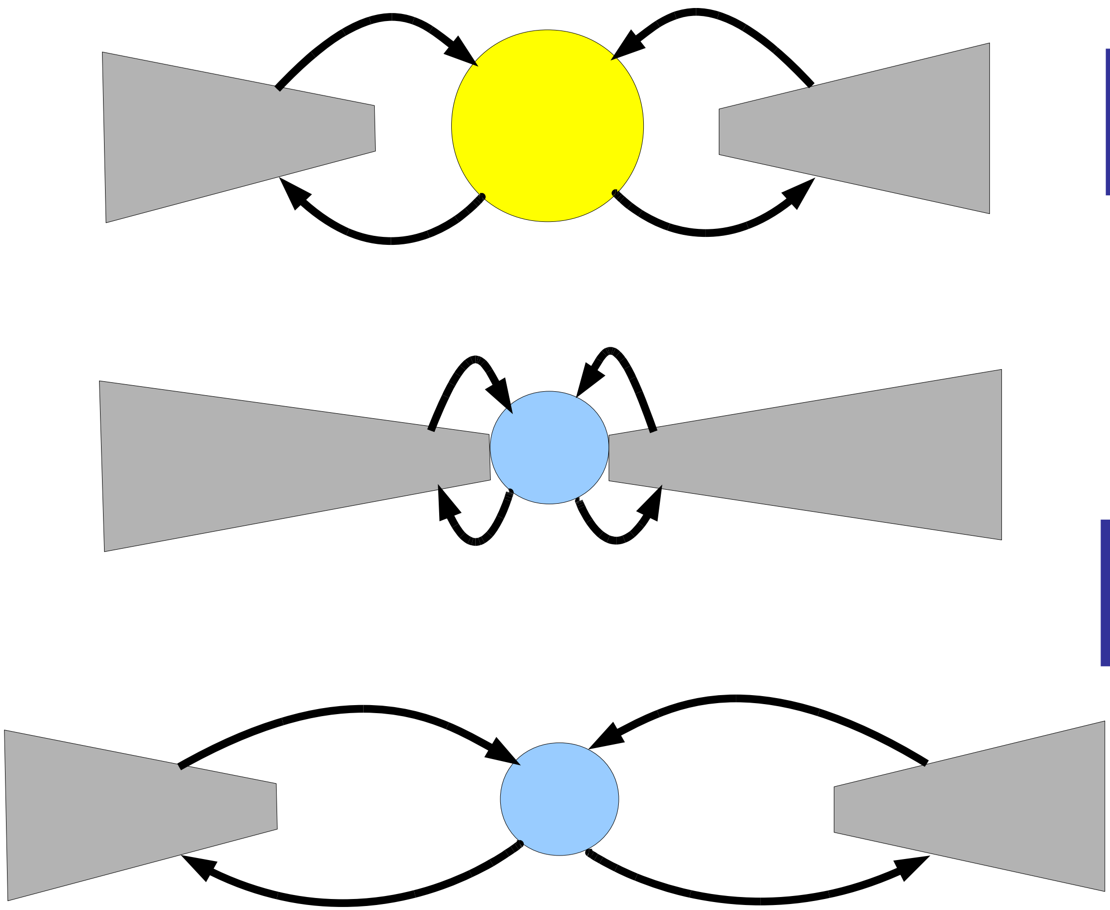
new / old solar abundances
mass number
1.6
1.4
1.2
1.0
0.8
0.6
0
20
40
60
80
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr

Sun 3.0



Lo09 / Lo03 solar abundaces
mass number
0
50
100
150
200
0.8
1.0
1.2
1.4
Ne
O
Hg
Gd
Rb
I
W
Be
Ar
Hf

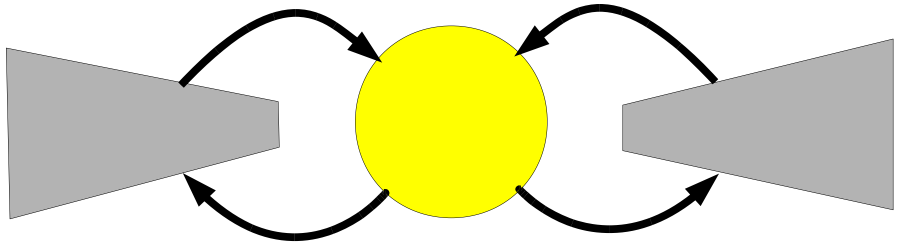
Initial Rotation of Massive Stars



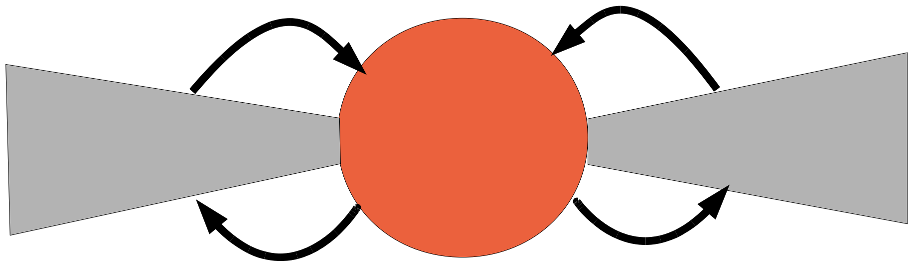
Pop I/II

Pop III

Initial Rotation of Massive Stars

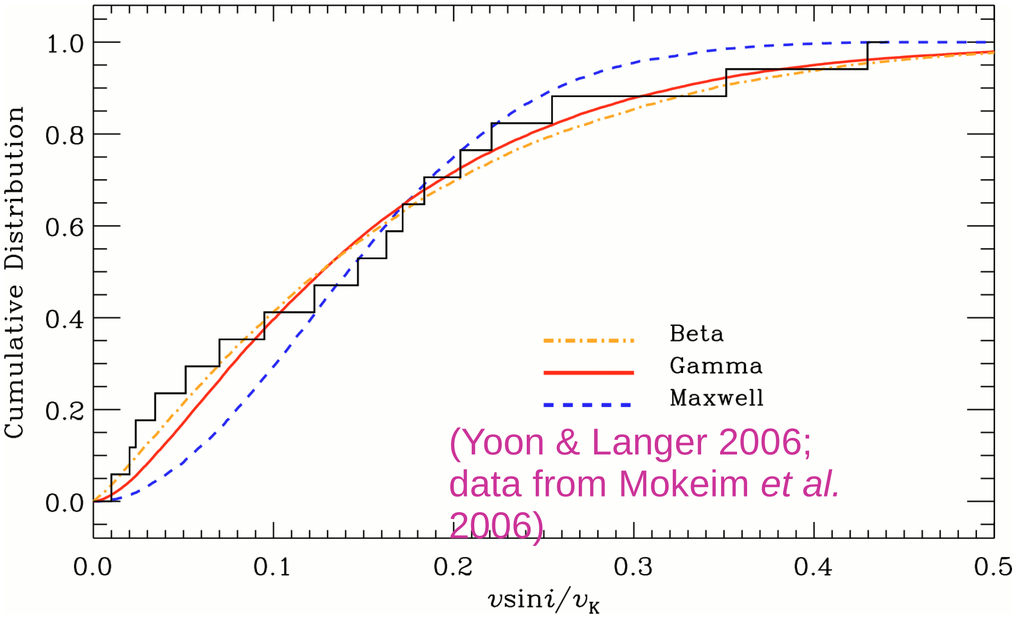


Pop I/II

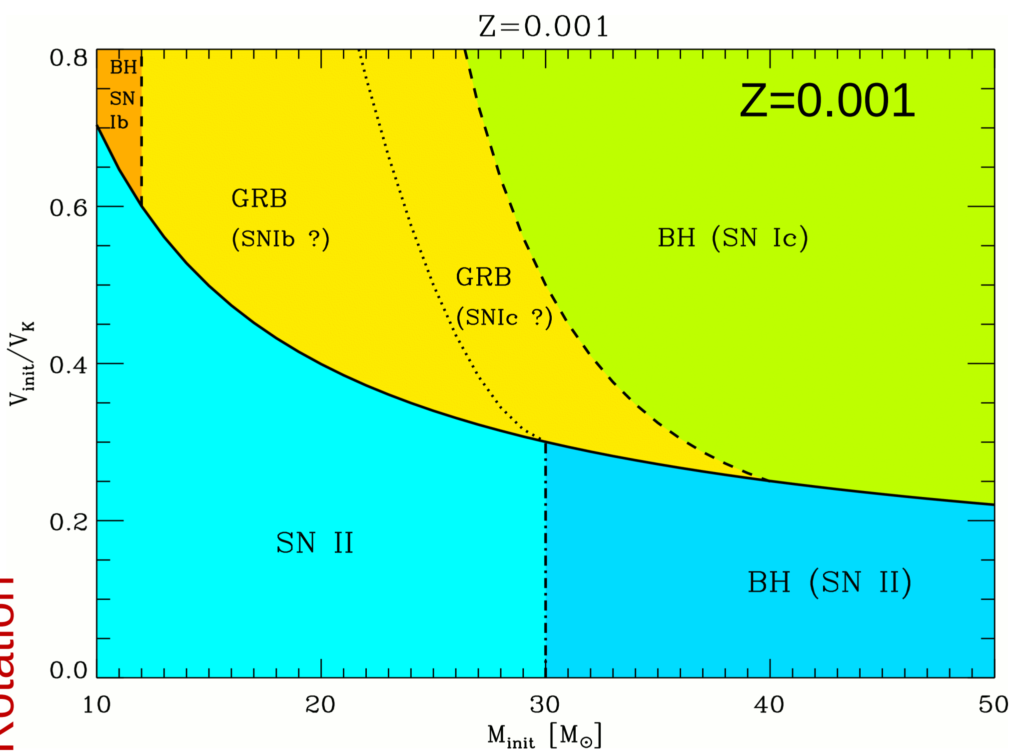


Pop III

Black Holes and GRBs from Rotating Stars



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



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.

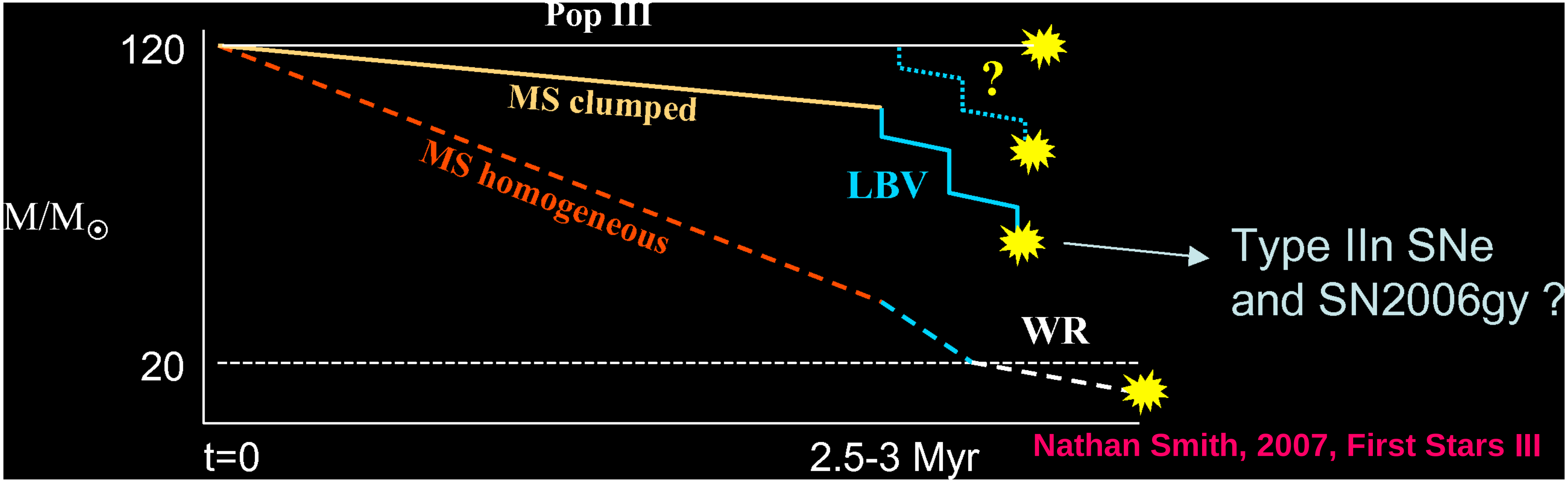
(Yoon & Langer 2006)

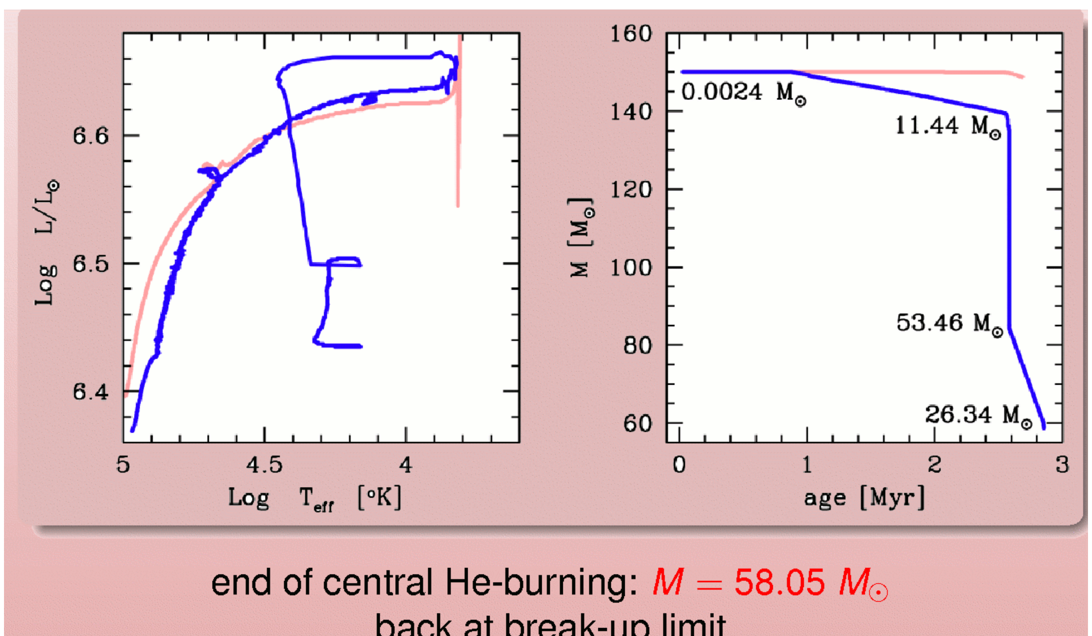
Input

- Rotation rate distributions as a function of mass and metallicity
- Initial composition distribution as a function of metallicity – time (z), environment, ...?
- ***Isotopic*** initial compositions
- Binary star parameters (see later talk)
- Possibly accretion rates if significant part of Main Sequence evolution time.

Modeling

Mass Loss by Giant eruptions?





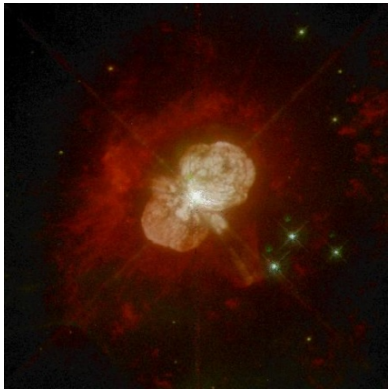
Mass Loss due to critical rotation?

Eikstroem, 2007, First Stars III

Mass Loss in Very Massive Primordial Stars

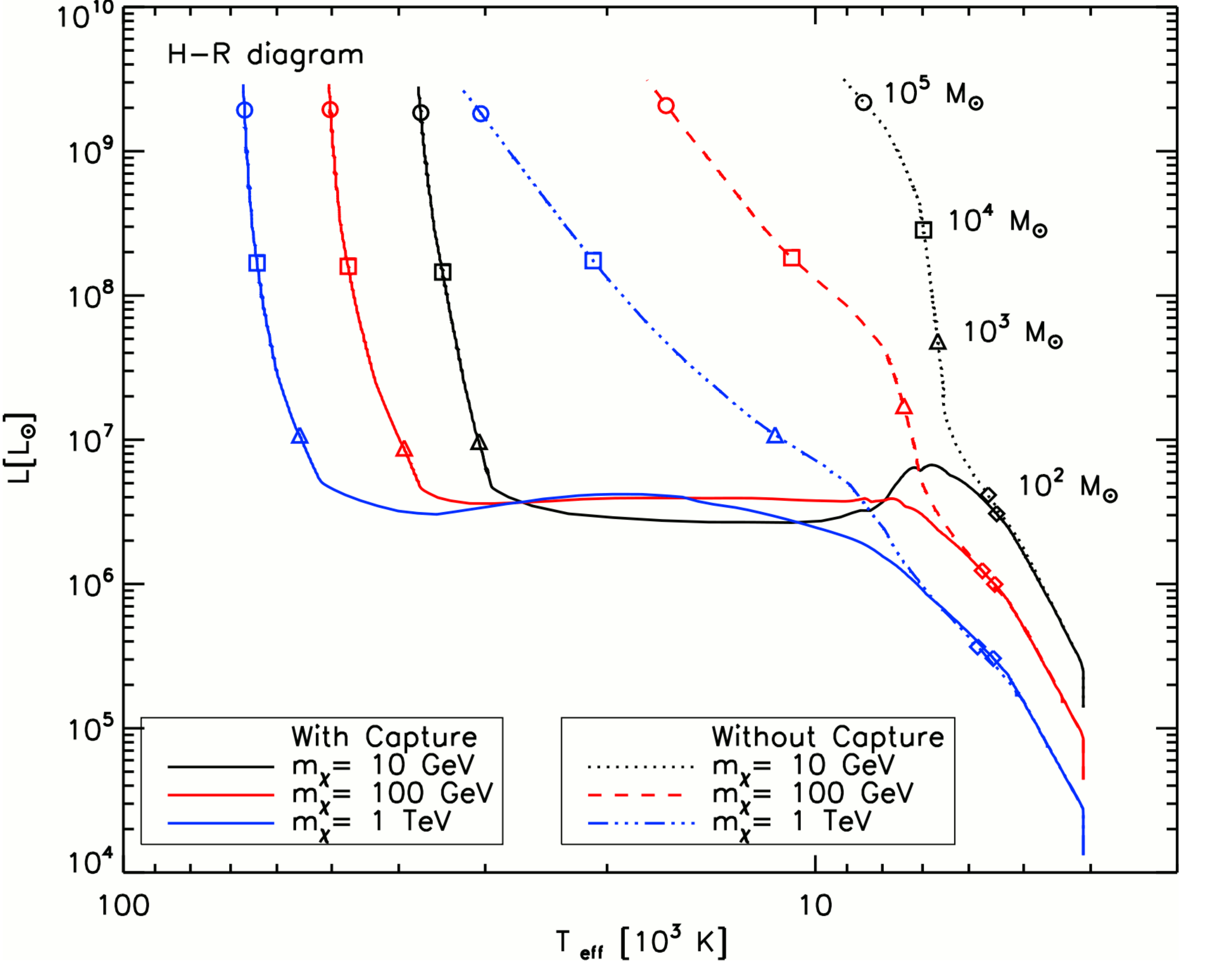
- Negligible line-driven winds
  (mass loss ~ metallicity$^{>1/2}$ – Kudritzki 2002)
- No opacity-driven pulsations (no metals – Baraffe, Heger & Woosley 2001)
- Continuum-driven winds and erruptions @ $L \sim L_{Edd}$ have to be explored (Smith, Owocki, Shaviv, *et al. 2005*++)
- Epsilon mechanism inefficient 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

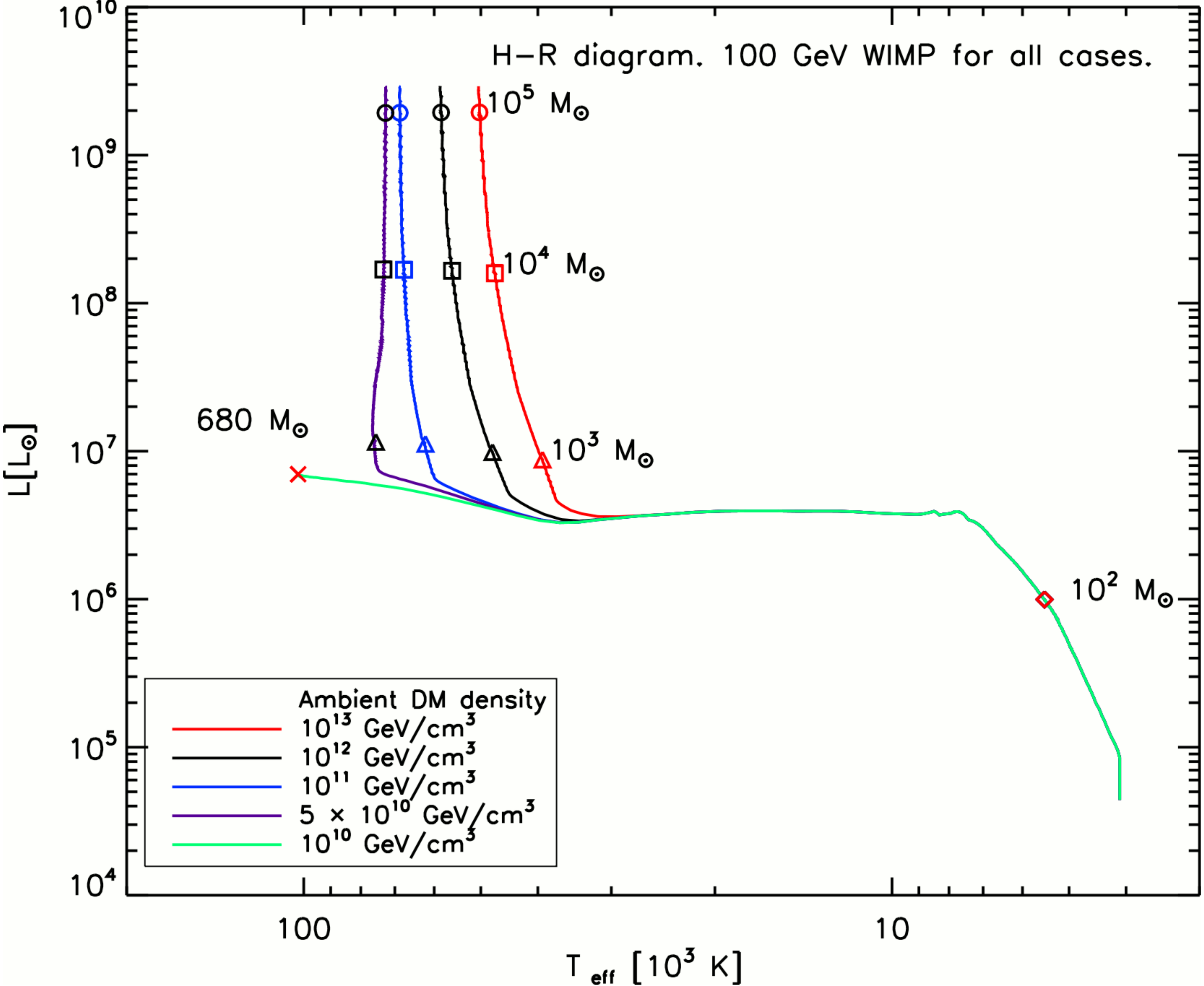


?

- 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.?



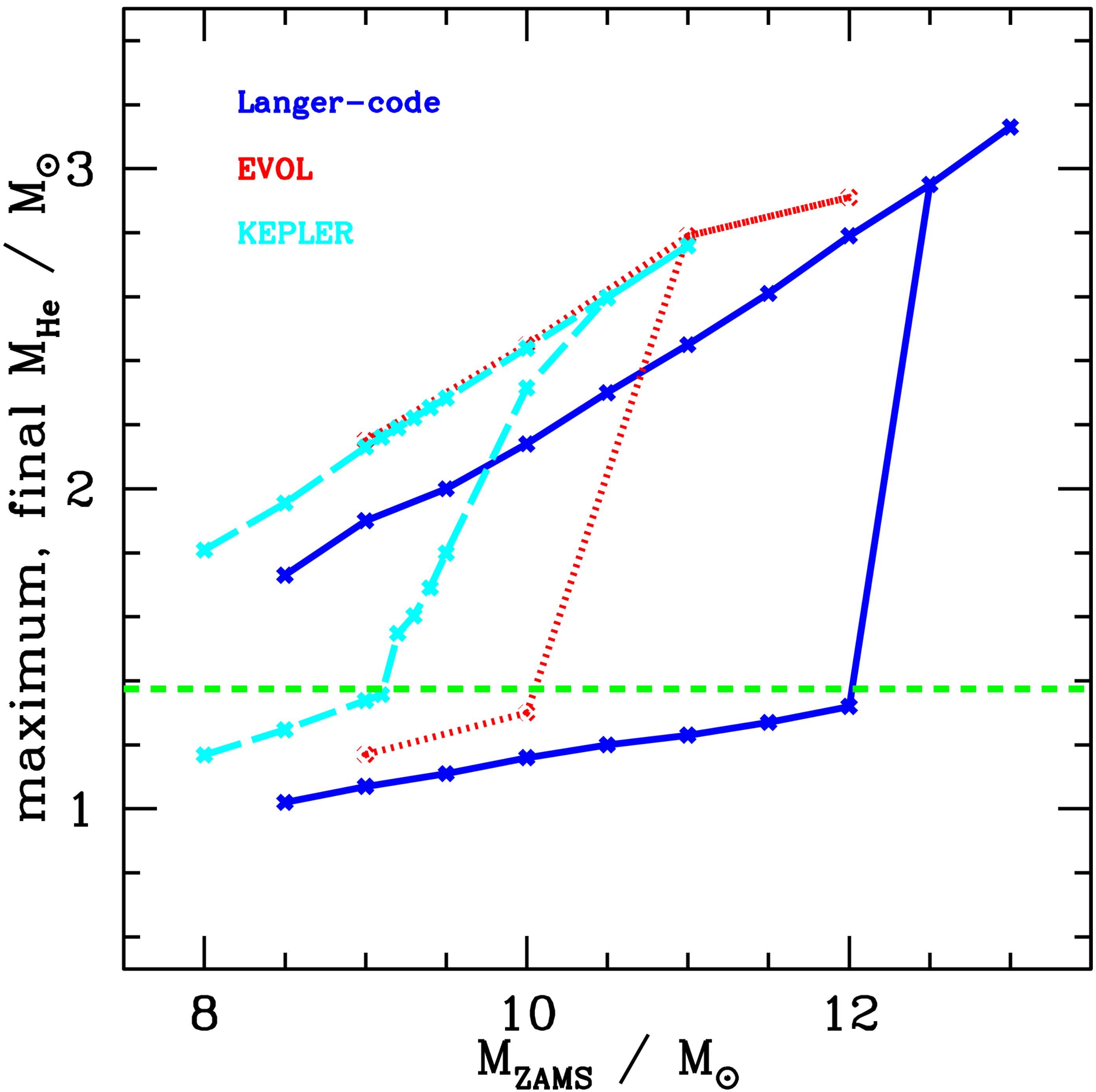
H-R diagram
10^5 $M_\odot$
10^4 $M_\odot$
10^3 $M_\odot$
10^2 $M_\odot$
$L[L_\odot]$
T_{eff} $[10^3$ K$]$
With Capture
m_χ= 10 GeV
m_χ= 100 GeV
m_χ= 1 TeV
Without Capture
m_χ= 10 GeV
m_χ= 100 GeV
m_χ= 1 TeV



H–R diagram. 100 GeV WIMP for all cases.
$10^5\ M_\odot$
$10^4\ M_\odot$
$10^3\ M_\odot$
$10^2\ M_\odot$
680 $M_\odot$
Ambient DM density
10^{13} GeV/cm^3
10^{12} GeV/cm^3
10^{11} GeV/cm^3
5×10^{10} GeV/cm^3
10^{10} GeV/cm^3
$L[L_\odot]$
T_{eff} [10^3 K]
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
100
10

Modeling

- Nuclear reaction rates
- Opacities – molecular, dust, ...
- Mass loss rates – very uncertain for many domains in composition, luminosity, radius.
- Stellar stability – pulsational mass loss, erruptions s-Dorados, LBV.
- Mixing physics – convection, semi-convection, convective overshooting, rotation, magnetic fields, time-dependent mixing and burning, ...
  – 3D modeling (Arnett, Meakin, Young, Dearborn, Woodward, ...)?



Langer-code
EVOL
KEPLER
maximum, final M_{He} / $M_{\odot}$
1
2
3
8
10
12
M_{ZAMS} / $M_{\odot}$

Codes

- Differences in numerical methods
  – discretization, level of approximation (e.g., operator split, choice of time step, networks)

- Disagreement on “input” physics
  – nuclear reaction rates, opacities, mass loss rates, mixing physics

Output

Output

- Realistic error bars for abundances
- Scatter as a function of metallicity (Frank Timmes's comment)
- Isotopic data – not just for ^{13}C
- Observed evolution output, ...

SN

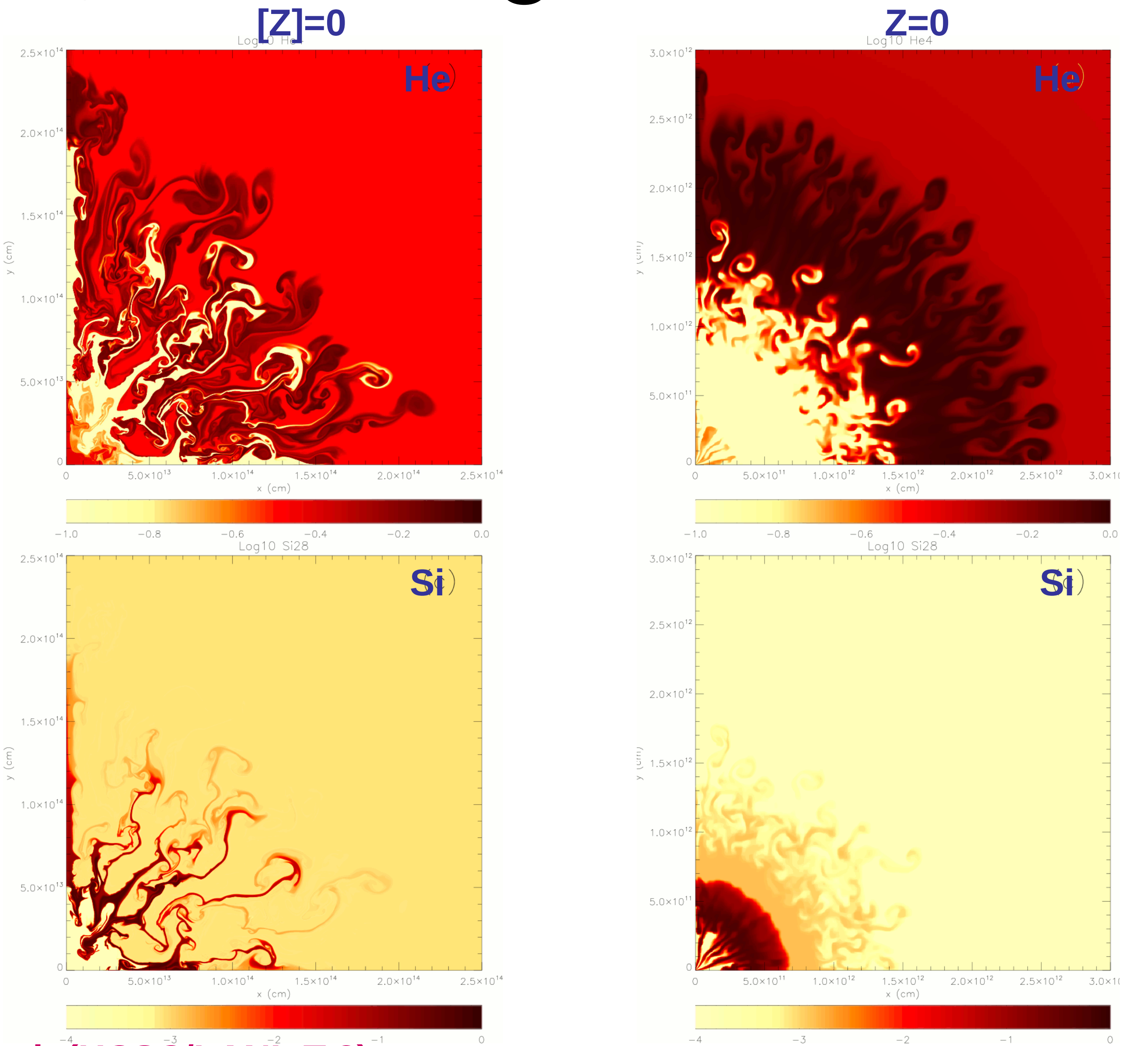
physics

Mixing in 25 $M_\odot$ Stars

Growth of Rayleigh-Taylor instabilities

Interaction of instabilities (mixing) and fallback determines nucleosynthesis yields

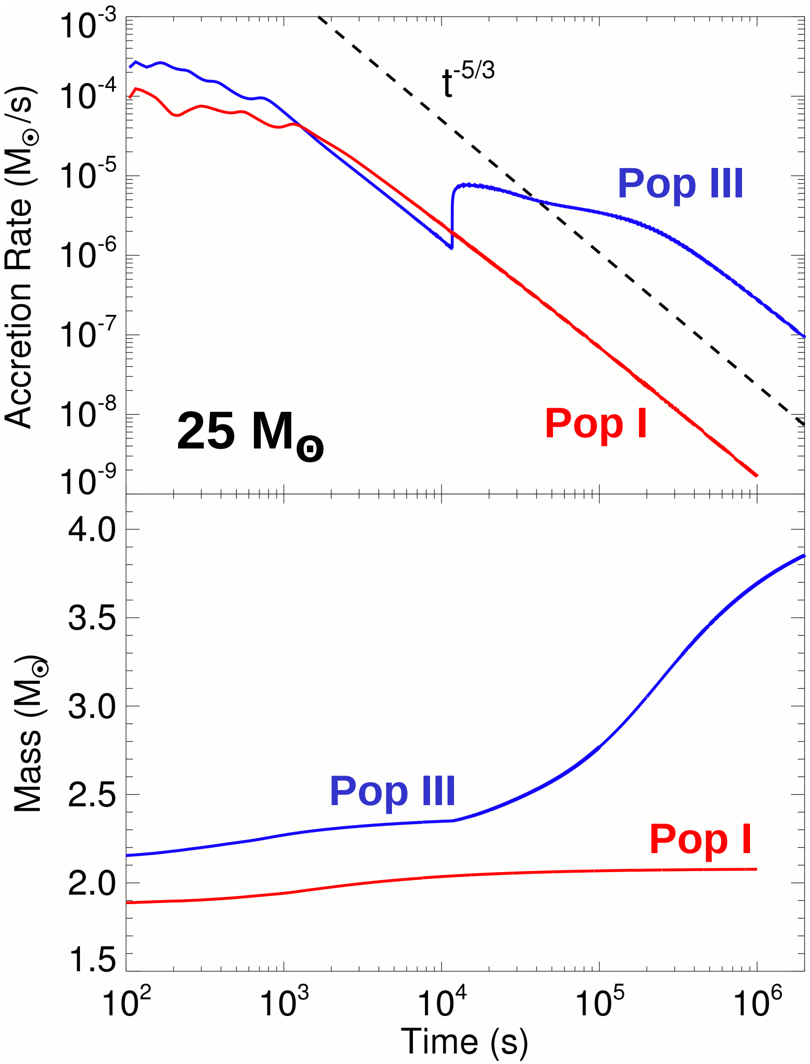
➔ Pop III stars show much less mixing than modern Pop I stars due to their compact hydrogen envelope

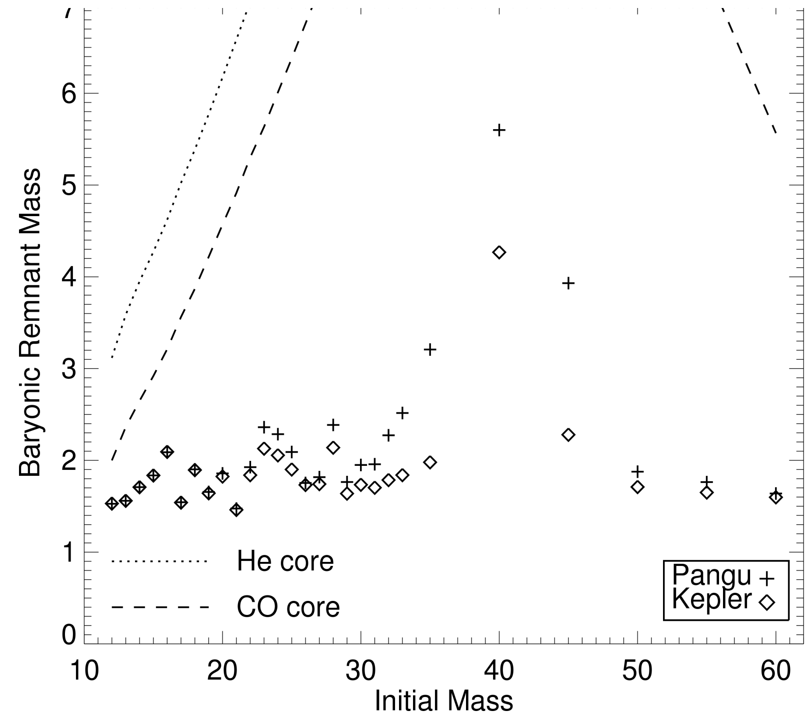


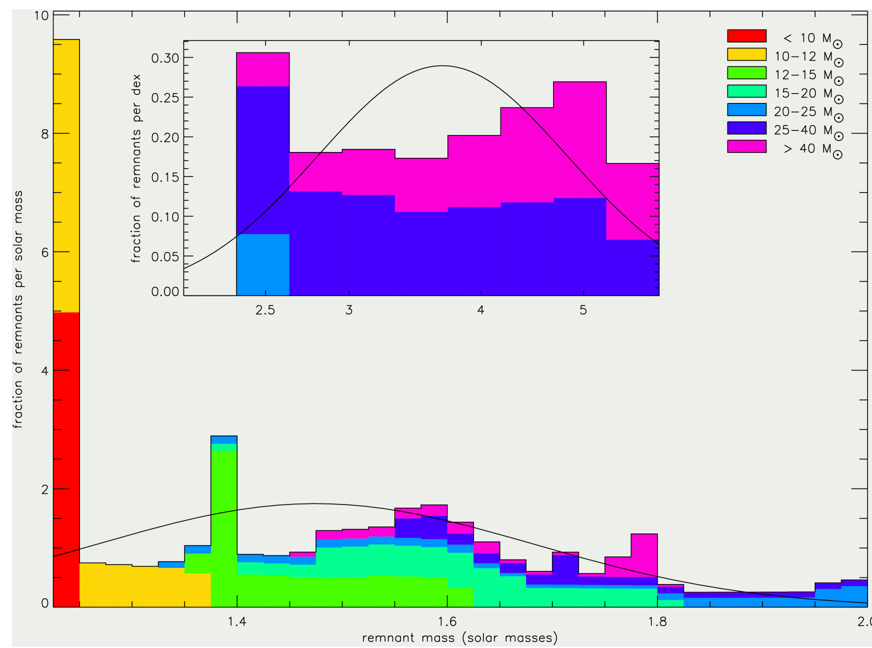
Simulations: Candace Church (UCSC/LANL T-2)

Fallback and Remnants

(Zhang, Woosley, Heger 2007)







Mixing in a 15 $M_\odot$ Stars

Growth of Rayleigh-Taylor instabilities

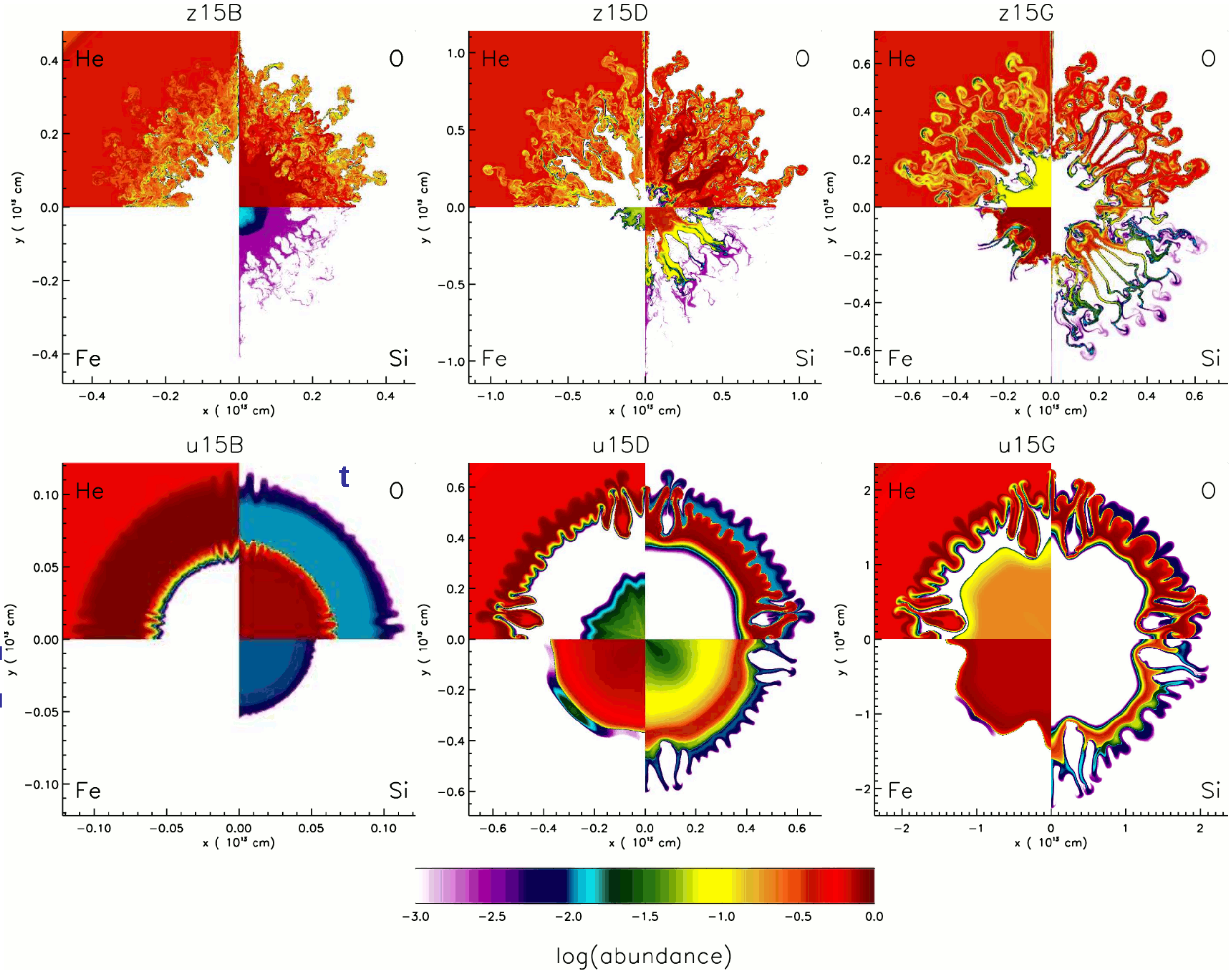
Interaction of instabilities (mixing) and fallback determines nucleosynthesis yields

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

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

Z=0

[Z]=-4



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

Mixing in a 25 $M_{\odot}$ Stars

Growth of Rayleigh-Taylor instabilities

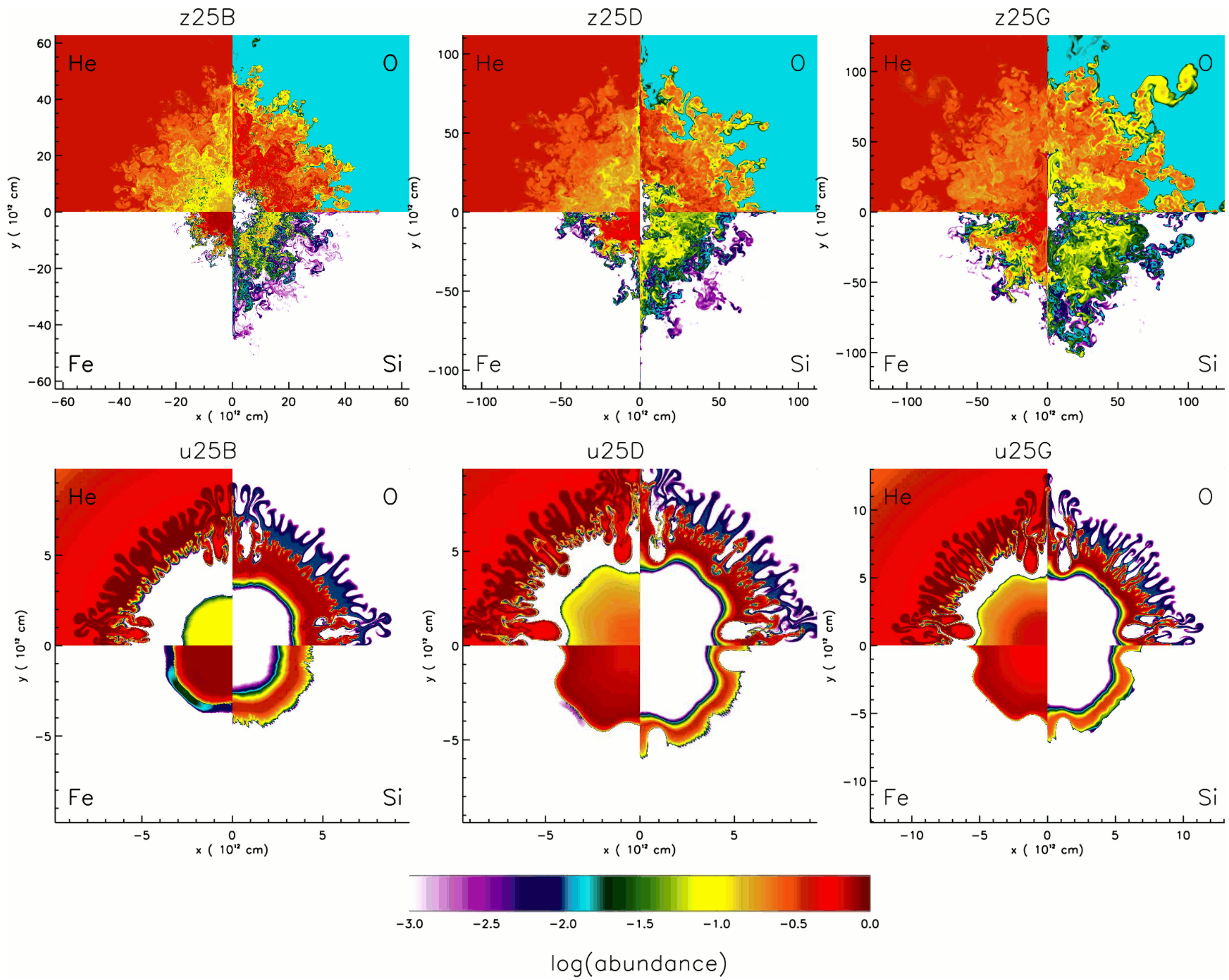
Interaction of instabilities (mixing) and fallback determines nucleosynthesis yields

➔ Z=0 stars have more mixing than the [Z]=-4 stars with same rotation rate; less mixing than in 15 $M_{\odot}$ star

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

Z=0

[Z]=-4



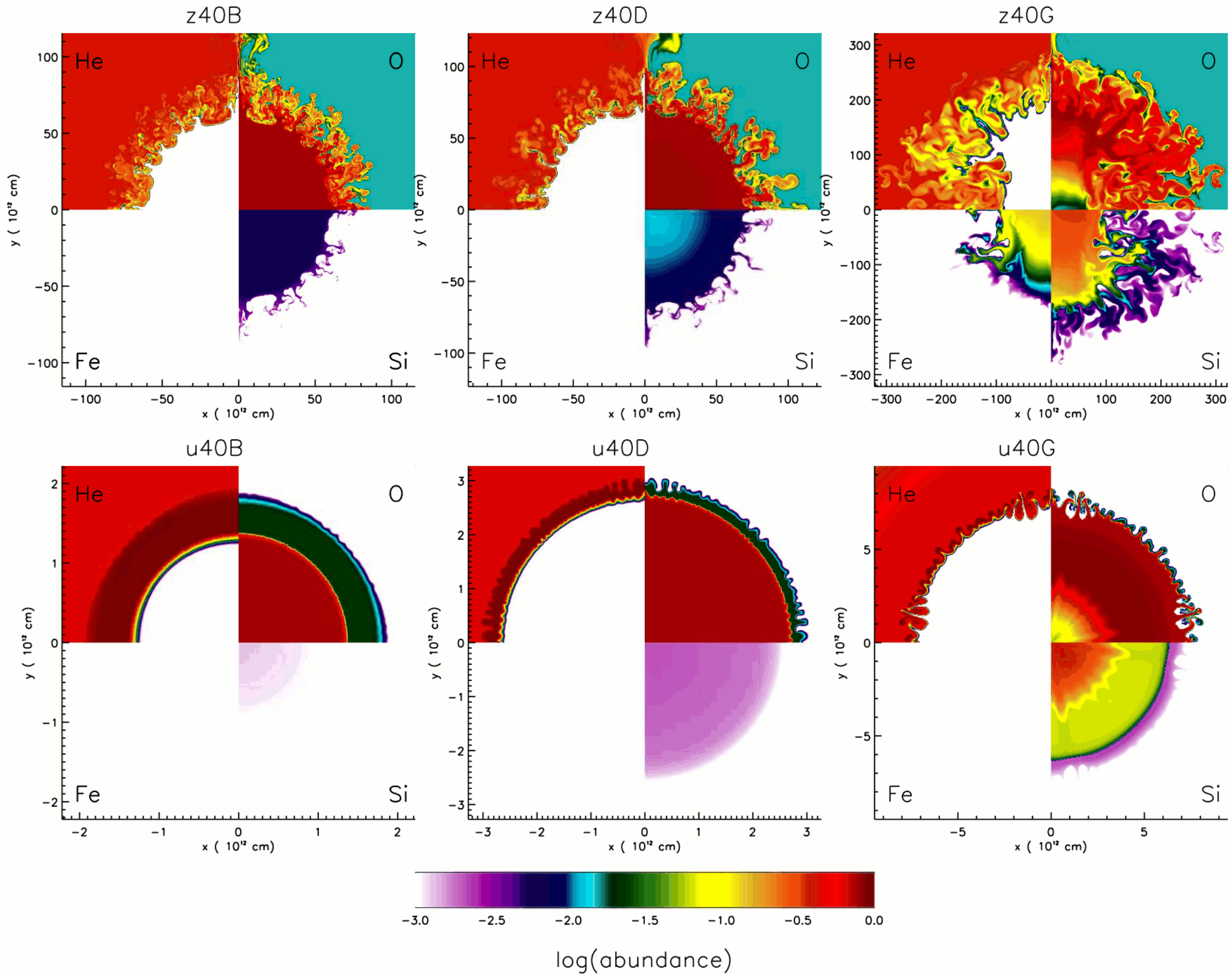
Simulations: Candace Church (UCSC/LANL T-2)

Mixing in a 40 $M_\odot$ Stars

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

Z=0

[Z]=-4



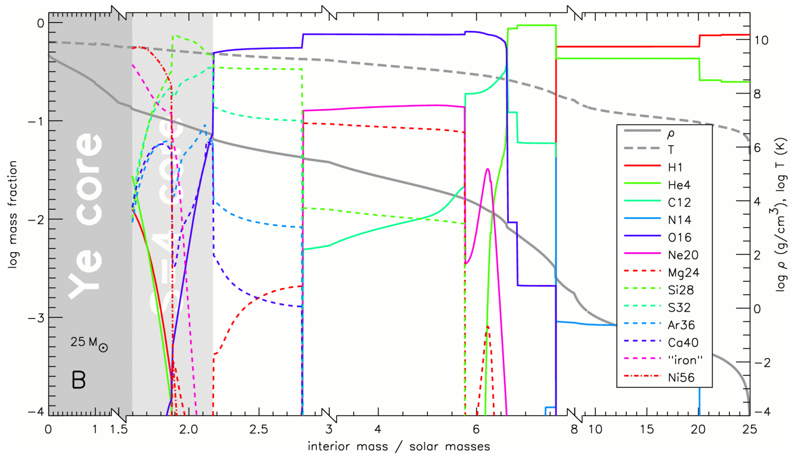
Growth of Rayleigh-Taylor instabilities

Interaction of instabilities (mixing) and fallback determines nucleosynthesis yields

èZ=0 stars have more mixing than the [Z]=-4 stars with same rotation rate; even less mixing

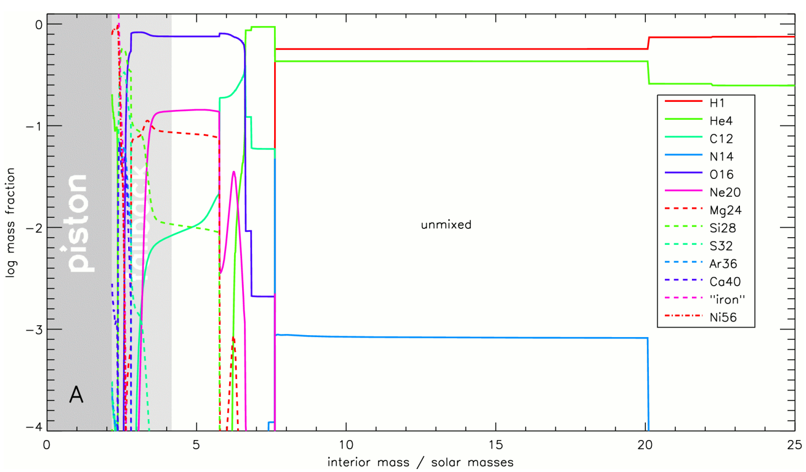
Simulations: Candace Church (UCSC/LANL T-2)

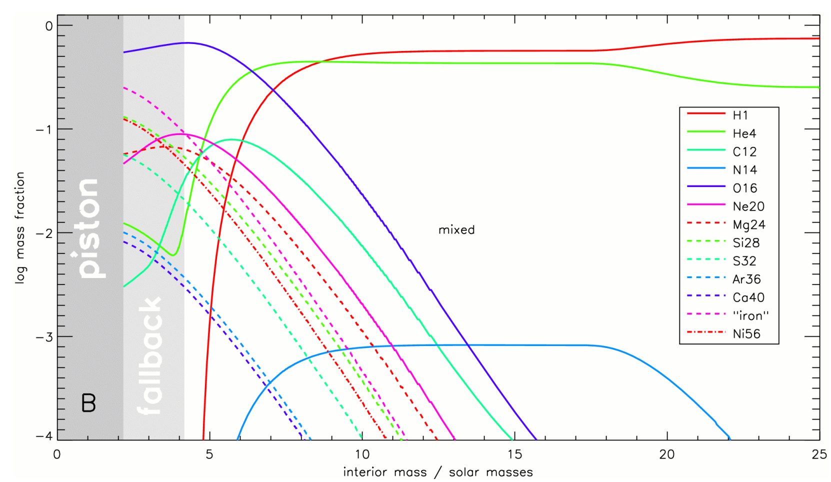
Supernovae, Nucleosynthesis, & Mixing



SN, no mixing

SN + mixing

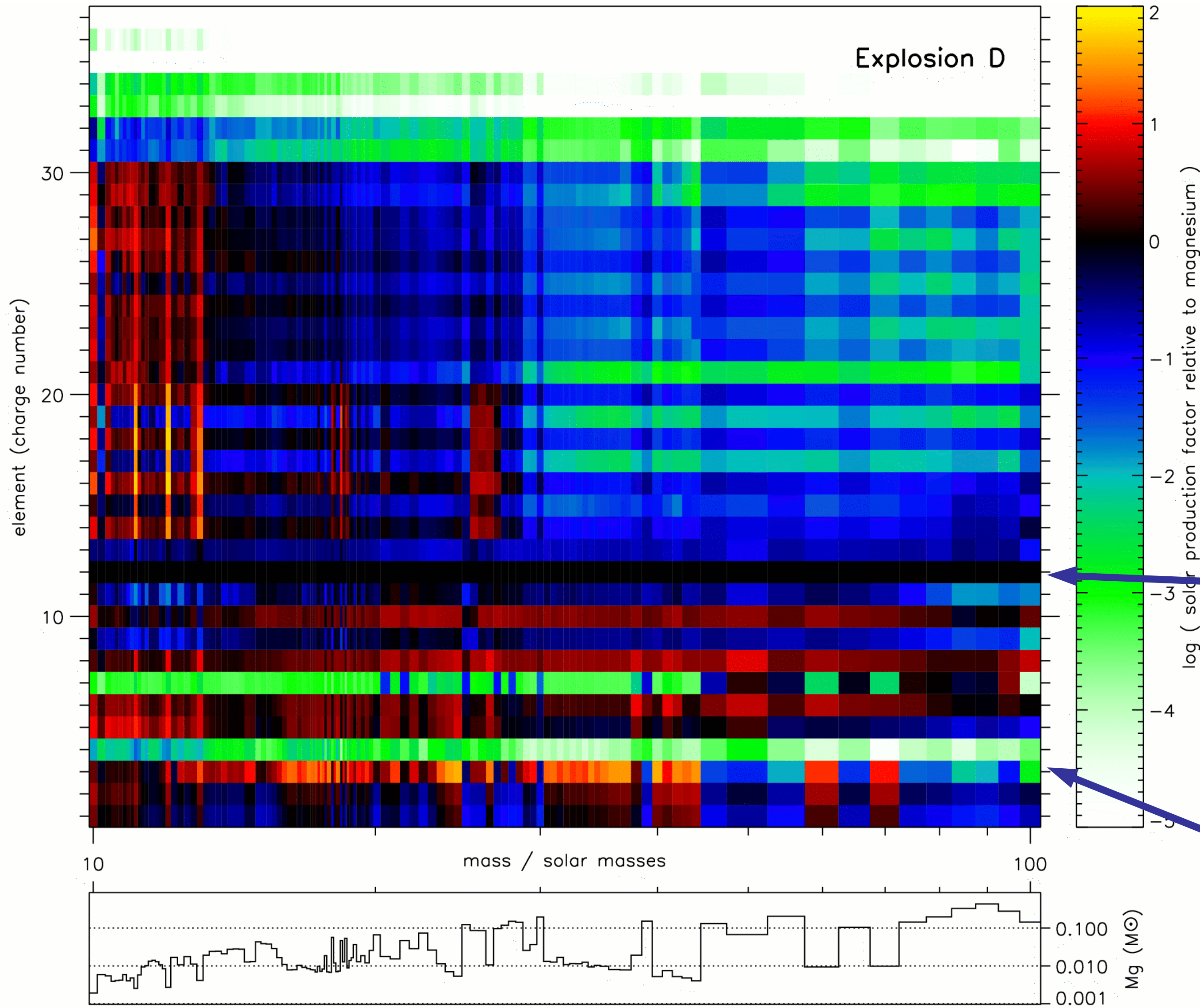




Some Results

Nucleosynthesis from Stars 10-100 $M_{\odot}$

Pop III Nucleosynthesis



Mg yield (ejecta mass fraction)

Elemental Yields as a function of initial mass

non-rotating stars

120 stellar masses

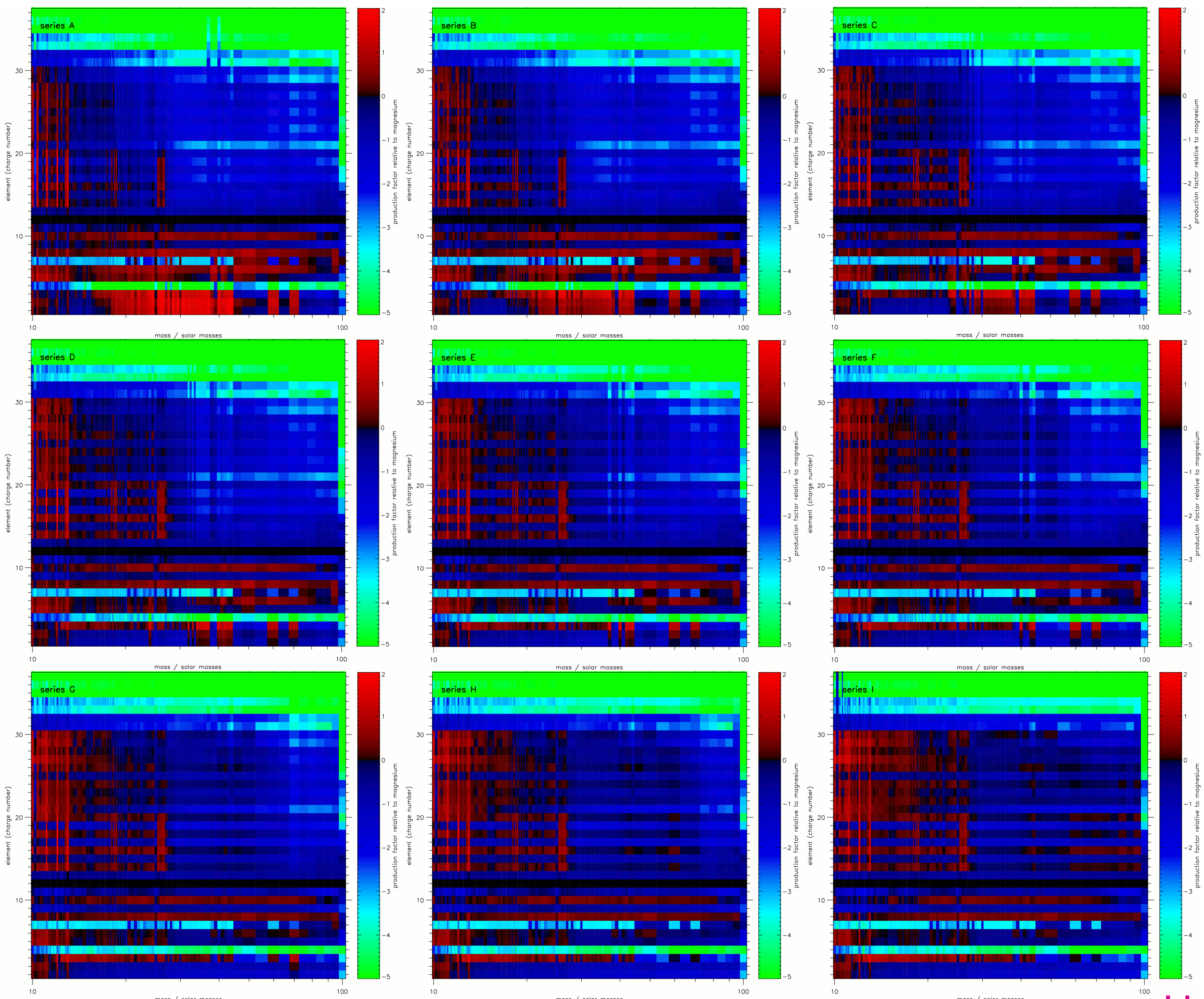
“complete” reaction network

normalized to Mg

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

Heger & Woosley, in prep., (2009)

Pop III Nucleosynthesis Grid

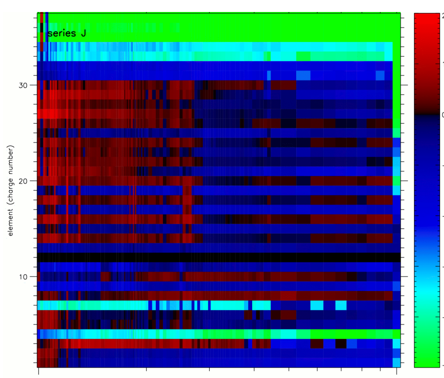


Library of yields as a function of explosion energy

10 explosion energies from 0.3 to 10 B

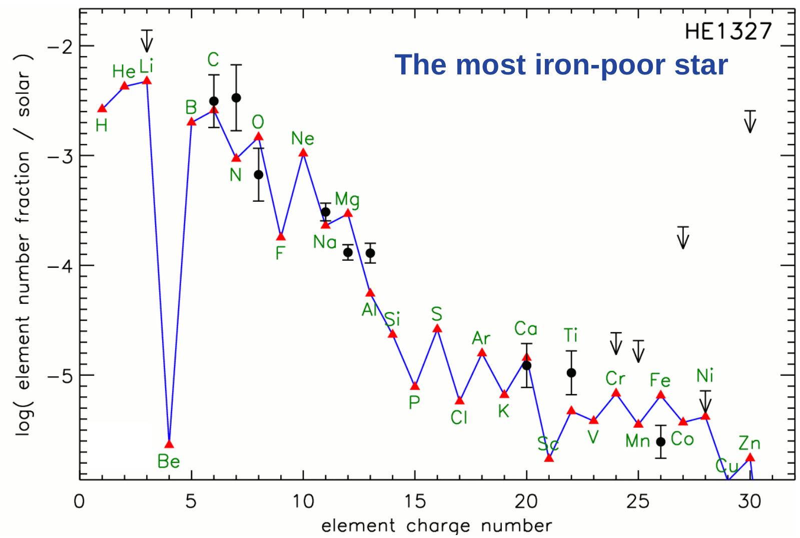
1200 supernova explosions with full stellar/explosive nucleosynthesis

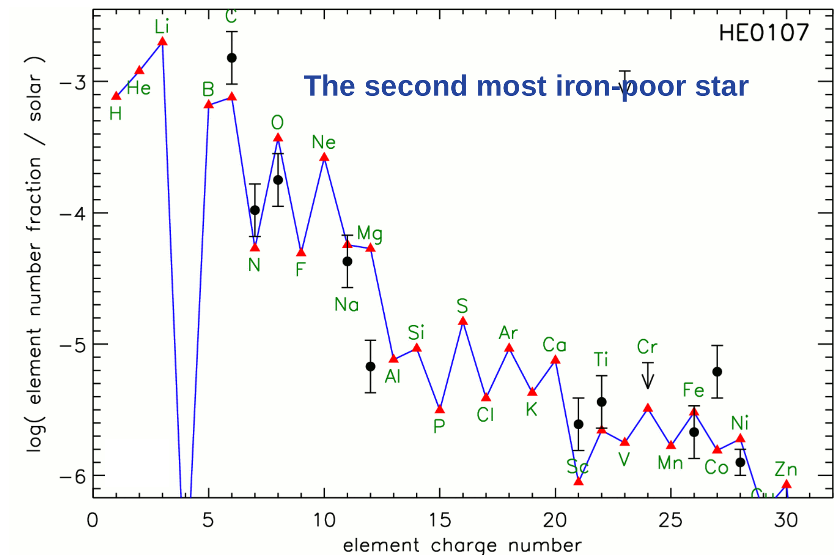
2 different models for piston location



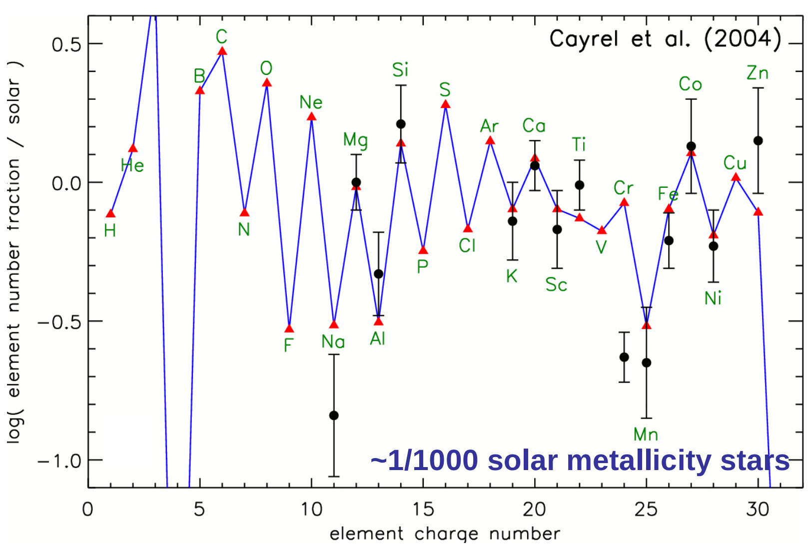
Heger & Woosley (2009)

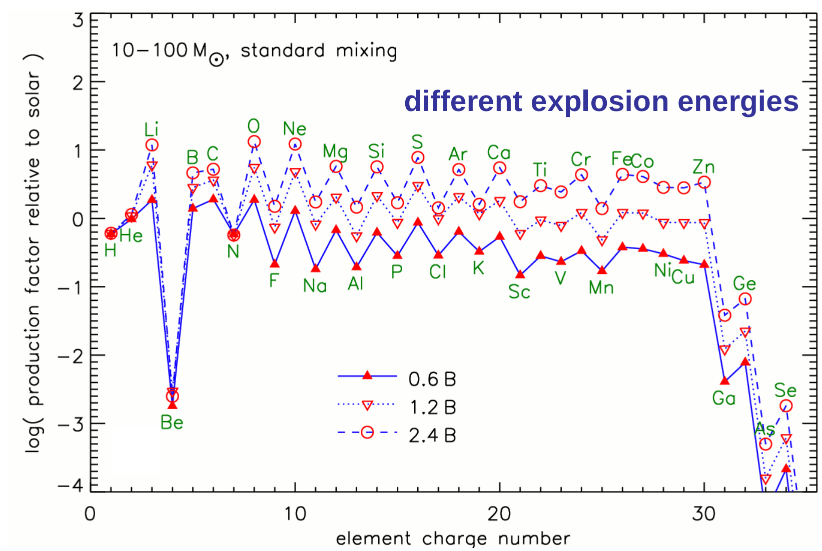
Comparison to Observational Data



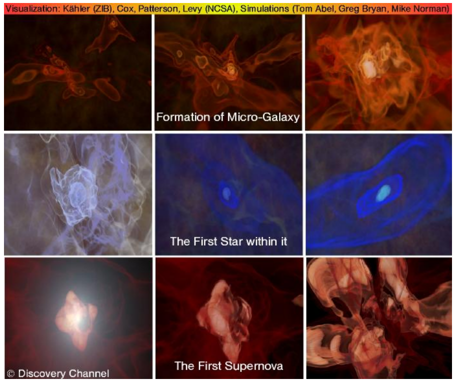


Heger & Woosley (2009)

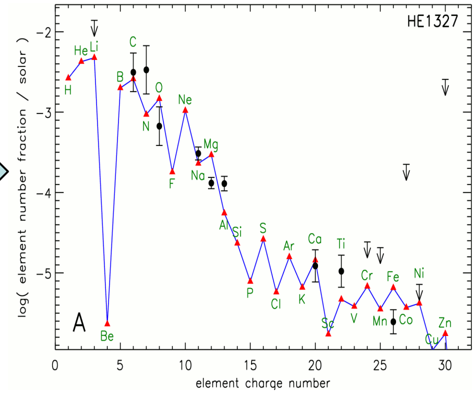




Reconstruction of the IMF



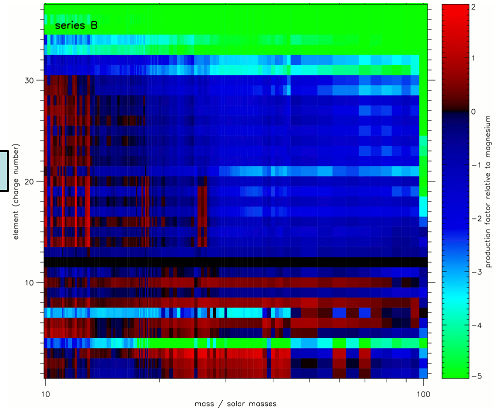
primordial stars form, nucleosynthesis ejected



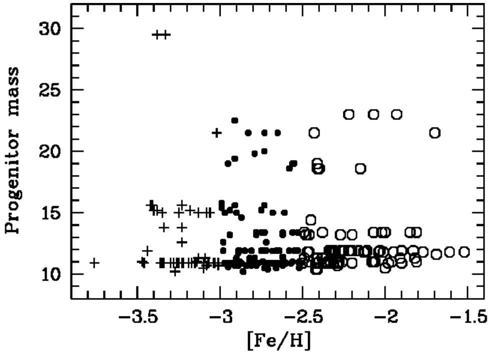
ejecta incorporated in low-Z halo stars

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

measure abundances (VLT, KECK, ...)

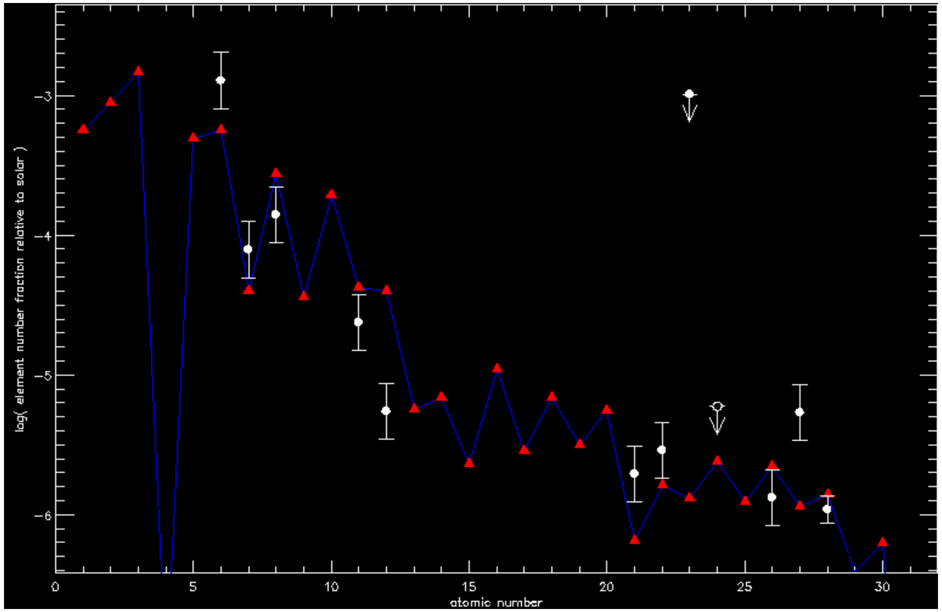


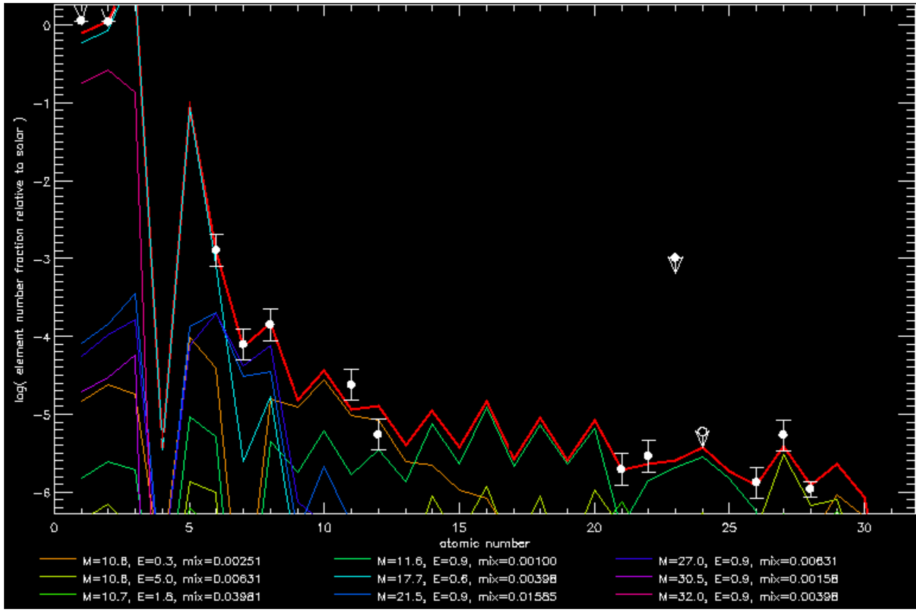
compare abundances to primordial star nucleosynthesis library



obtain IMF of population of progenitor stars

Multi-Star Fit Tool





best single star fit: $\sigma^2 = 4.3974$

sample multi-star fit: $\sigma^2 = 0.5293$

weight	mass	energy	mixing
1.728E-05	10.6	0.3	0.00251
5.036E-07	10.6	5.0	0.00631
1.475E-07	10.7	1.8	0.03981
1.811E-06	11.6	0.9	0.00100
6.472E-01	17.7	0.6	0.00398
9.789E-05	21.5	0.9	0.01585
6.957E-05	27.0	0.9	0.00631
2.211E-05	30.5	0.9	0.00158
2.004E-01	32.0	0.9	0.00398

Yield Data

- Data base format for yield data (**stardb**)
  isotopes, radioactivities, elemental molar, ...
  as function on input parameters
- Single star zonal outputs
  “user” can combine as needed (e.g., pre-solar grains)
- Fit (and plot) tools **starfit** (starfit.org)
- Observers: please provide data in **log ε**,
  better: ***mol fractions (mol/g)***

Summary

- Model grid yields need isotopic initial abundance distributions(!) as function of metallicity and rotation rate distributions
- Author's choices for uncertain stellar physics (including nuclear physics) likely determine main differences
- Some differences in codes/numerical implementation
- Provide output data in several **usable *standardized*** forms?