Explaining globular cluster abundance anomalies with expanded BoOST stellar model grids

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Globular Clusters [1] ESA/Hubble & NASA, G. Piotto et al.

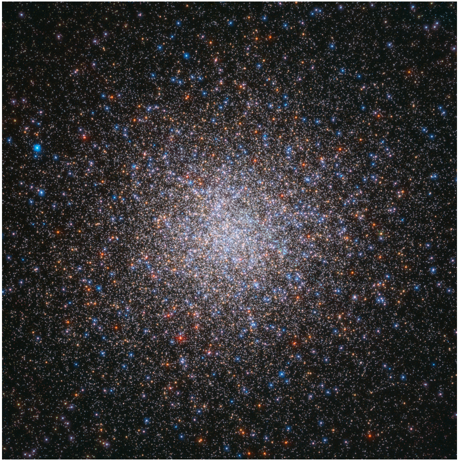
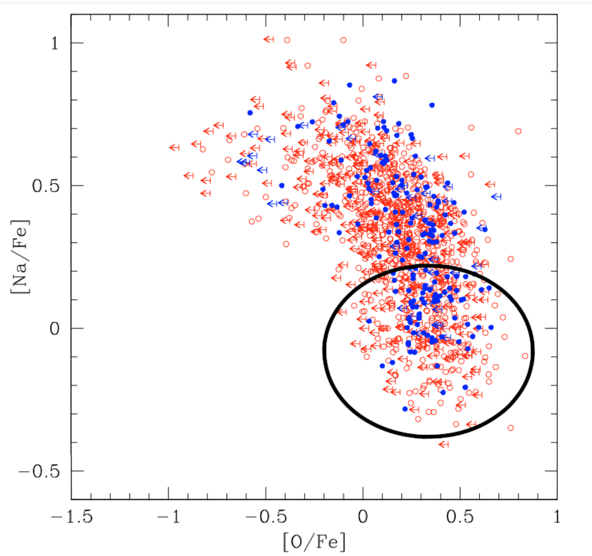
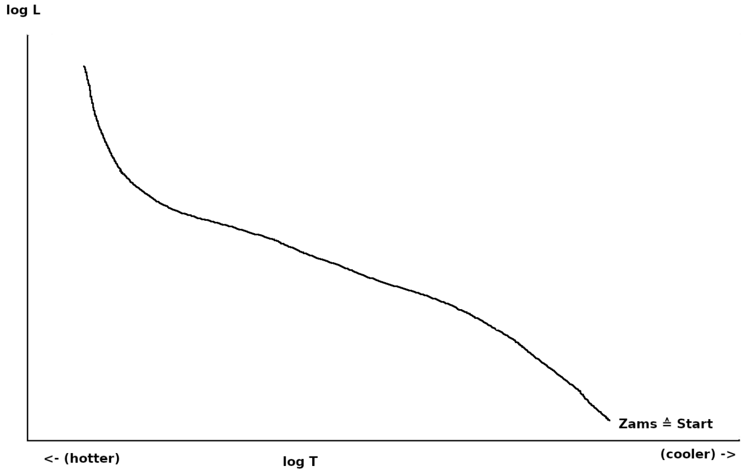


Figure: Messier 2, a globular cluster in the Milky Way

Globular Clusters [2] Caretta et al., 2009, [3] Szécsi & Wünsch (2019)



Massive Stars [4] Robert Hollow, Commonw. Science & Ind. Research Org. (CSIRO), Australia



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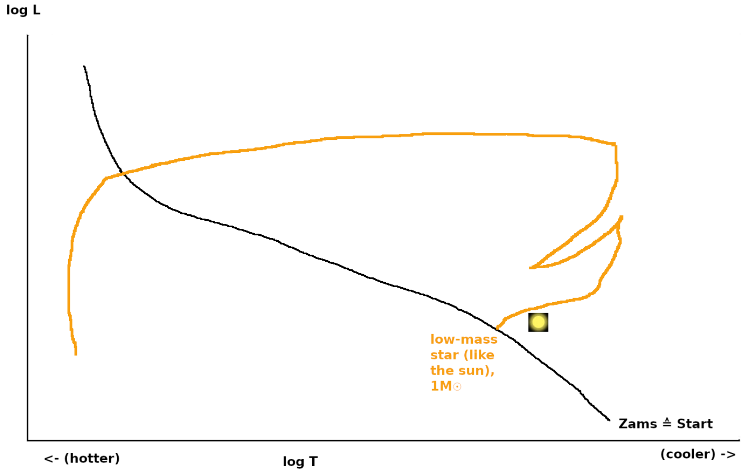
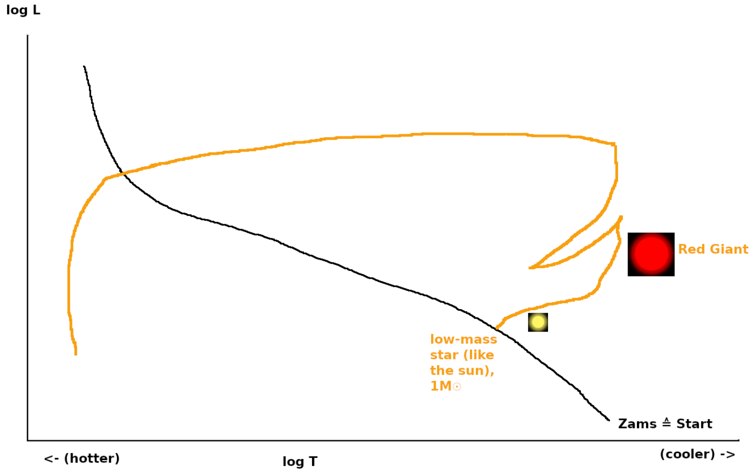
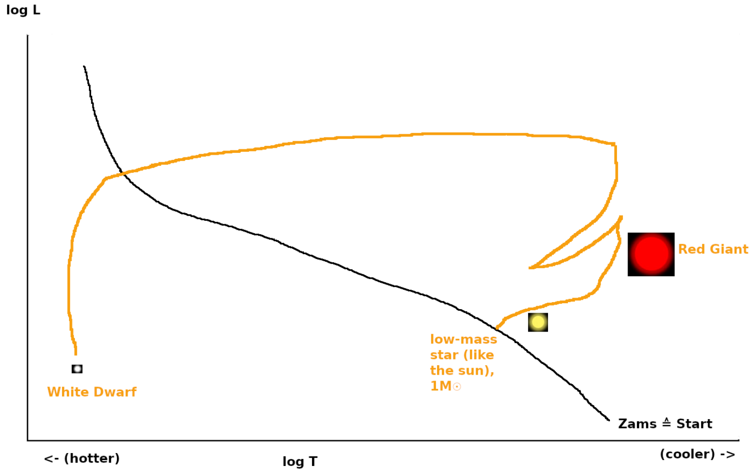
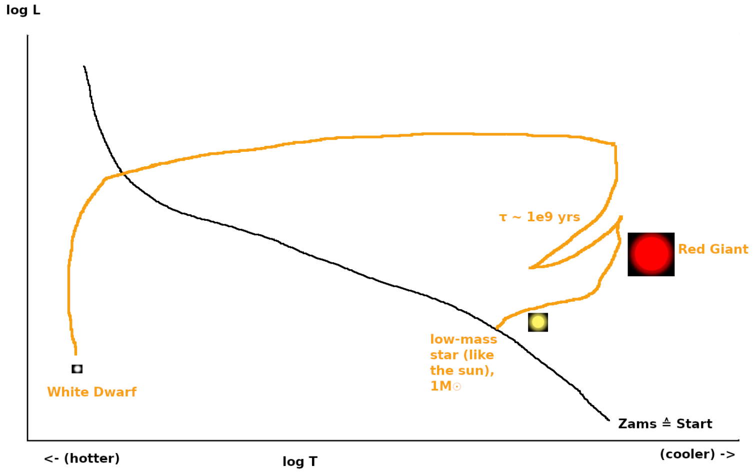
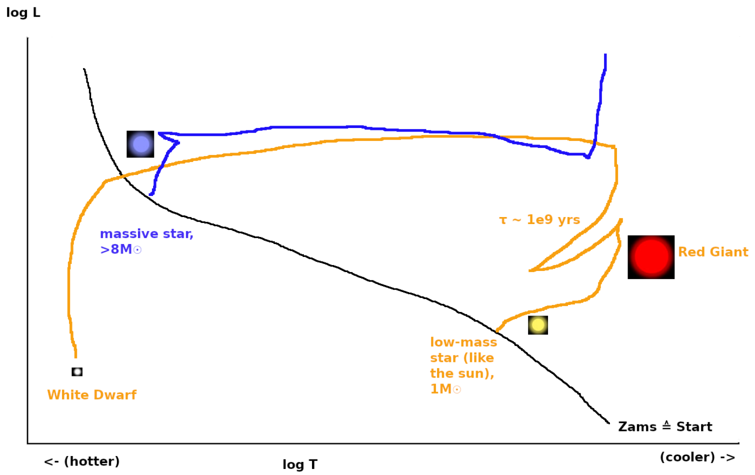


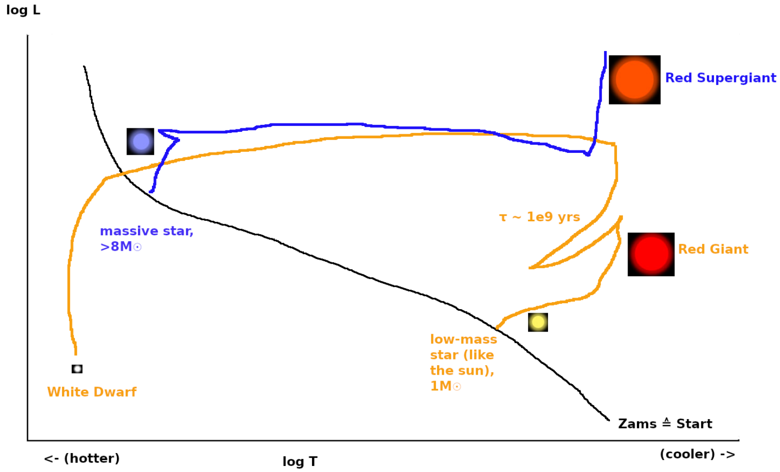
Massive Stars [4] Robert Hollow, Commonw. Science & Ind. Research Org. (CSIRO), Australia



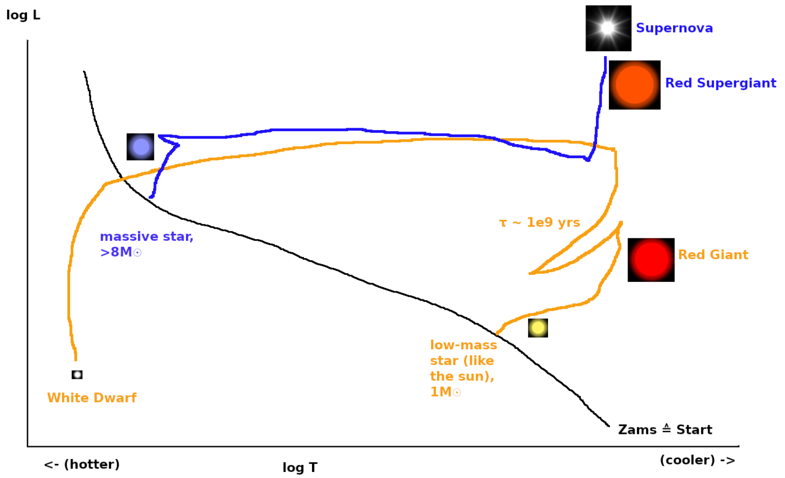

log L
Red Giant
low-mass
star (like
the sun),
1M☉
White Dwarf
Zams ≙ Start
<- (hotter)
log T
(cooler) ->

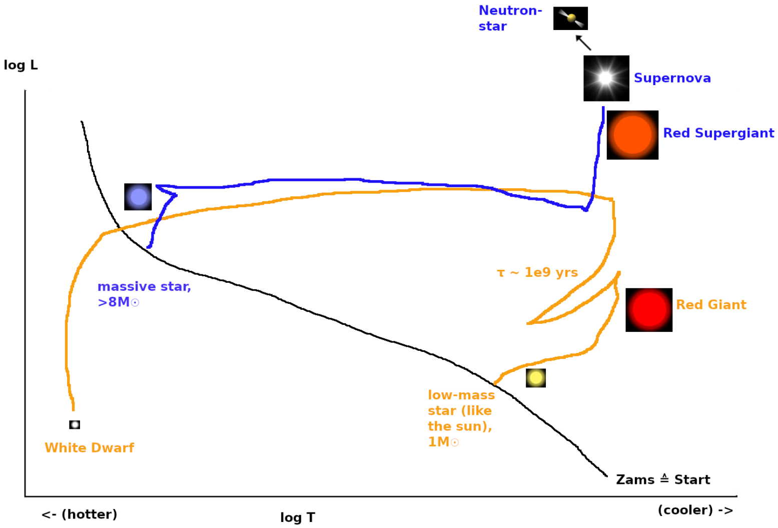

log L
τ ~ 1e9 yrs
Red Giant
low-mass
star (like
the sun),
1M☉
White Dwarf
Zams ≙ Start
<- (hotter)
log T
(cooler) ->

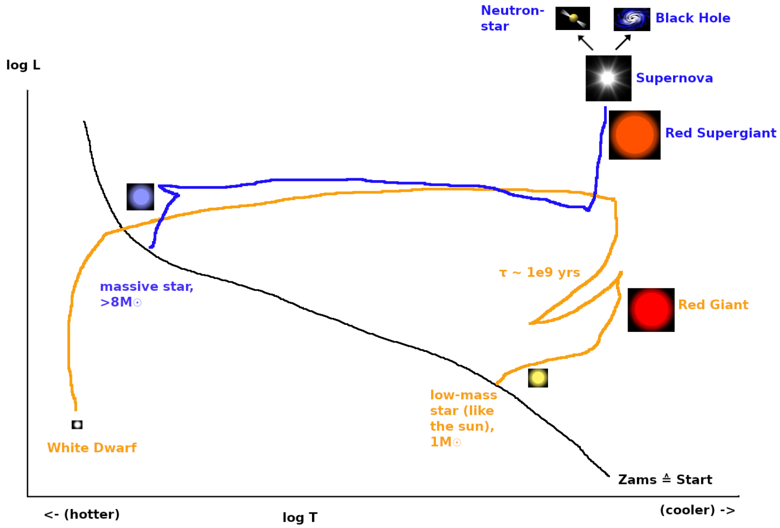

log L
massive star,
>8M☉
τ ~ 1e9 yrs
Red Giant
White Dwarf
low-mass
star (like
the sun),
1M☉
Zams ≙ Start
<- (hotter)
log T
(cooler) ->


log L
Red Supergiant
massive star,
>8M☉
τ ~ 1e9 yrs
Red Giant
low-mass
star (like
the sun),
1M☉
White Dwarf
Zams ≙ Start
<- (hotter)
log T
(cooler) ->

 [4] Robert Hollow, Commonw. Science & Ind. Research Org. (CSIRO), Australia

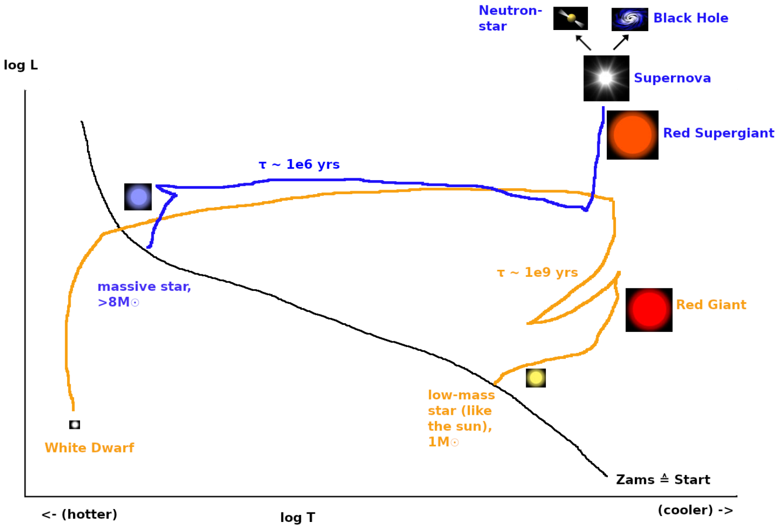



Neutron-
star
Supernova
log L
Red Supergiant
massive star,
>8M☉
τ ~ 1e9 yrs
Red Giant
low-mass
star (like
the sun),
1M☉
White Dwarf
Zams ≙ Start
<- (hotter)
log T
(cooler) ->

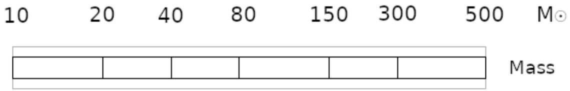


Neutron-star
Black Hole
log L
Supernova
Red Supergiant
τ ~ 1e9 yrs
massive star, >8M☉
Red Giant
low-mass star (like the sun), 1M☉
White Dwarf
Zams ≙ Start
<- (hotter)
log T
(cooler) ->

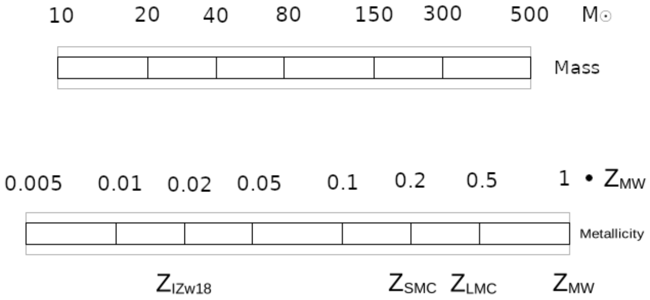
Massive Stars [4] Robert Hollow, Commonw. Science & Ind. Research Org. (CSIRO), Australia



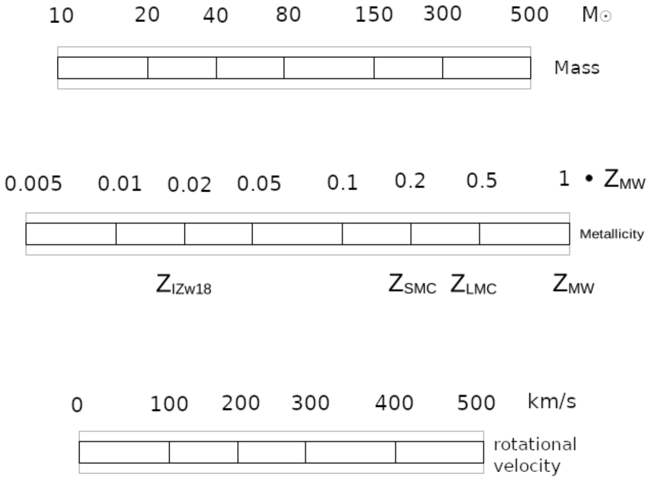
Model Parameter [5] Stinshoff et al., in prep.



Model Parameter [5] Stinshoff et al., in prep.



Model Parameter [5] Stinshoff et al., in prep.



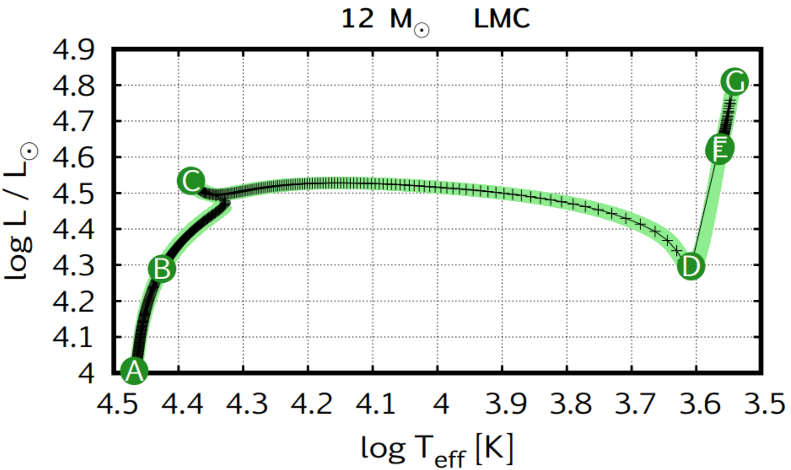
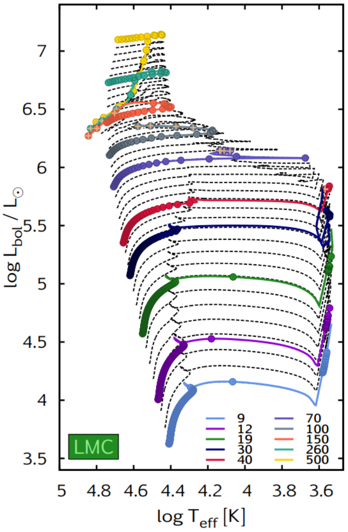
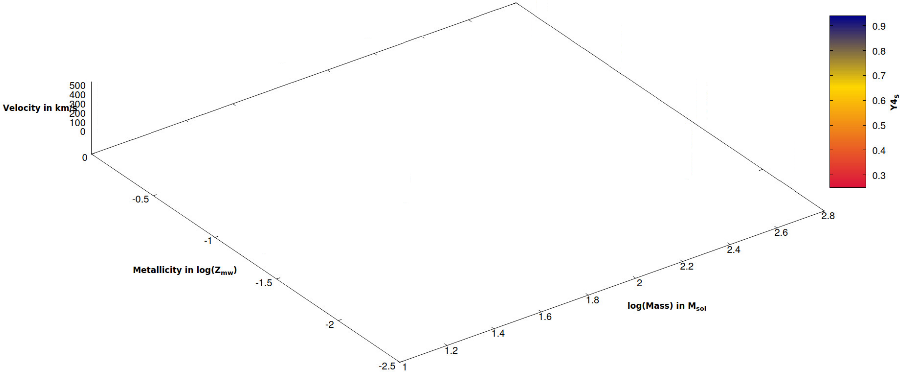


Figure: $v_{rot,ini} = 100km/s$, $Z = Z_{LMC}$

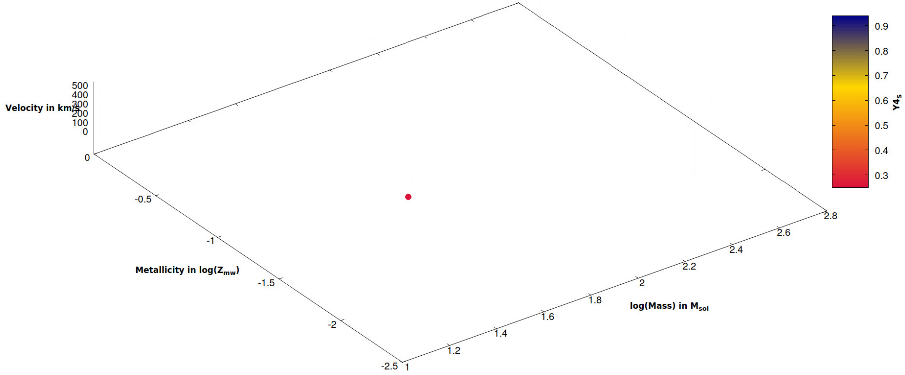
BoOST [6] Szécsi et al., 2022

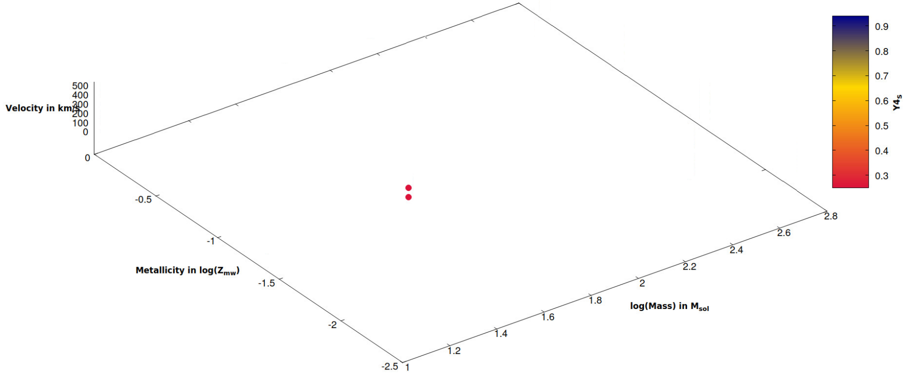


The new models - Y_S at TAMS [5] Stinshoff et al., in prep.



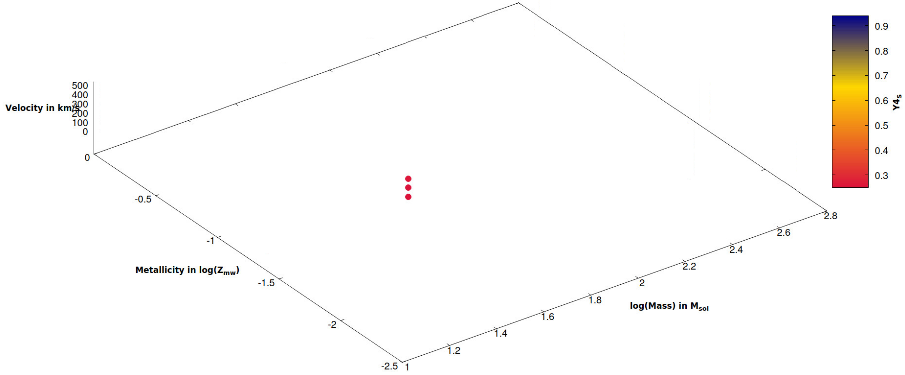
The new models - Y_S at TAMS [5] Stinshoff et al., in prep.



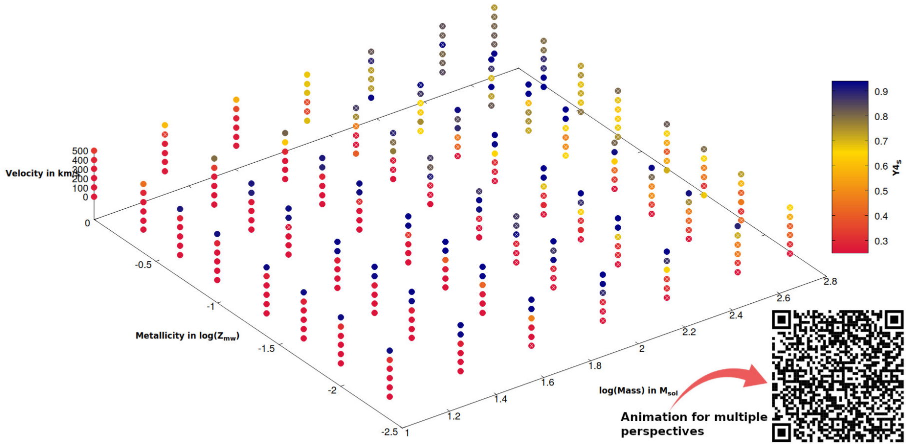


Velocity in km/s
500
400
300
200
100
0
0
-0.5
-1
Metallicity in log(Zmw)
-1.5
-2
-2.5
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
log(Mass) in Msol
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Y4s

The new models - Y_S at TAMS [5] Stinshoff et al., in prep.

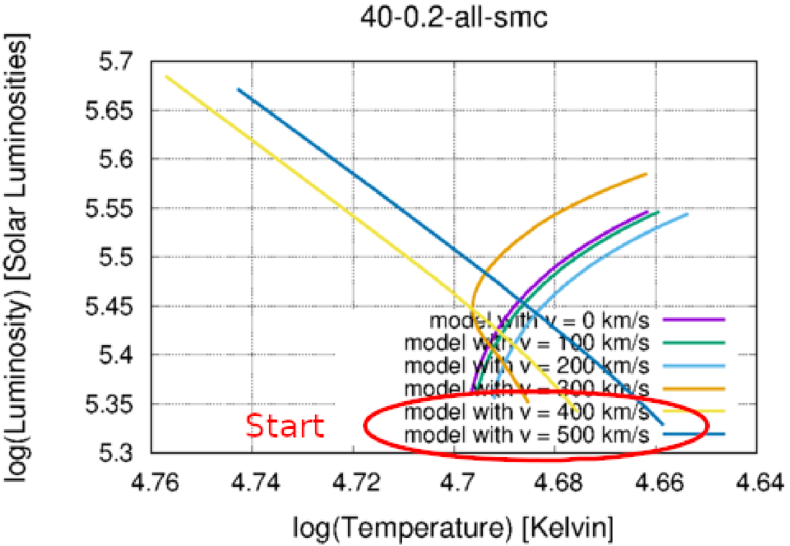


The new models - Y_S at TAMS [5] Stinshoff et al., in prep.

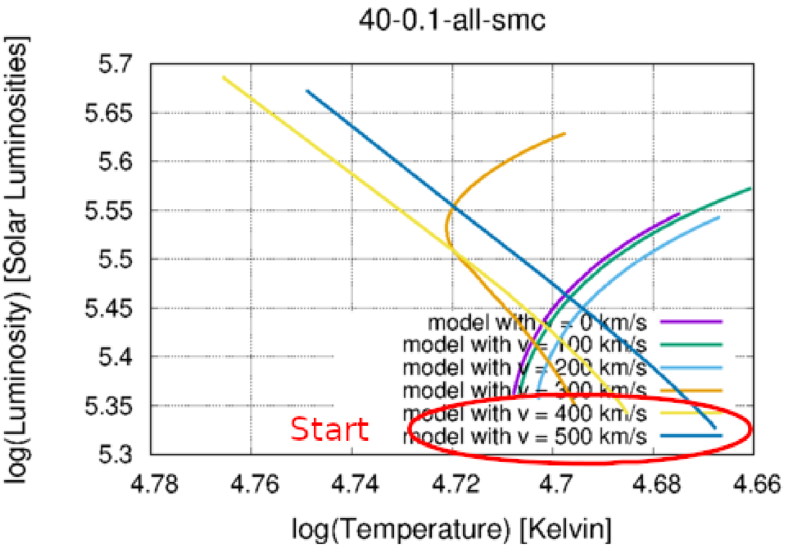


Animation for multiple perspectives

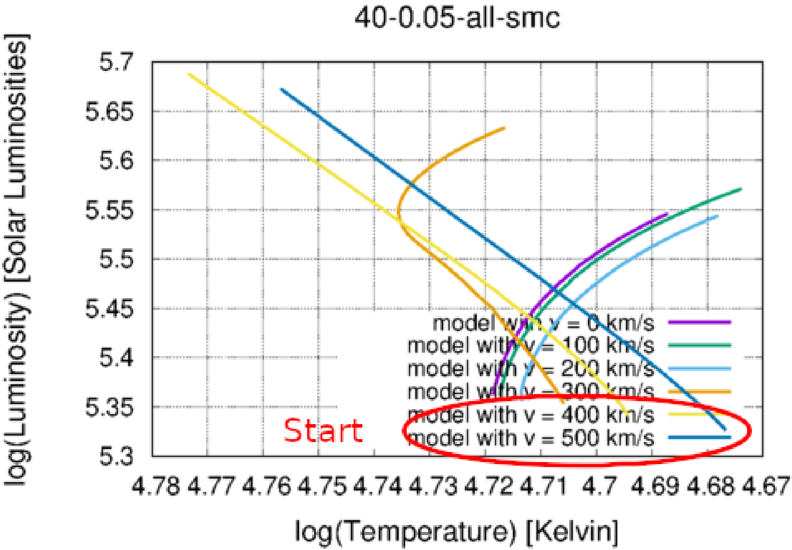
The new models - HRD [5] Stinshoff et al., in prep.



The new models - HRD [5] Stinshoff et al., in prep.



The new models - HRD [5] Stinshoff et al., in prep.



The new models - BoOSTed HRD [5] Stinshoff et al., in prep.

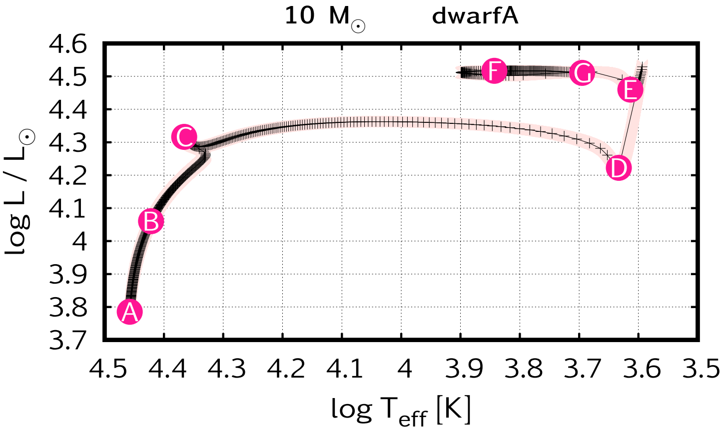


Figure: $v_{rot} = 200\ km/s,\ Z = 0.5 \cdot Z_{SMC}$

The new models - BoOSTed HRD [5] Stinshoff et al., in prep.

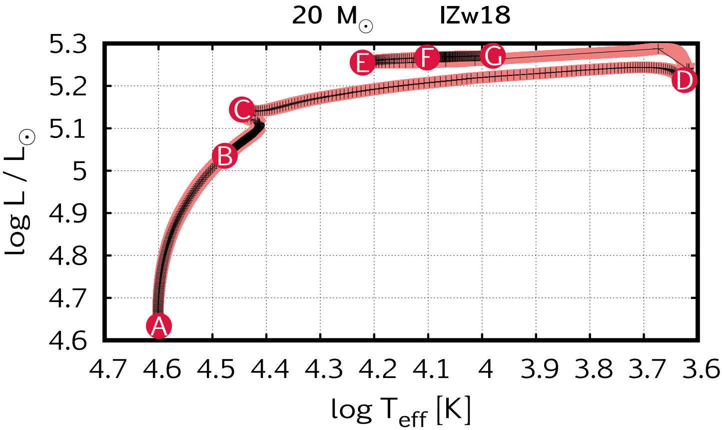


Figure: $v_{rot} = 300\ km/s,\ Z = Z_{IZw18}$

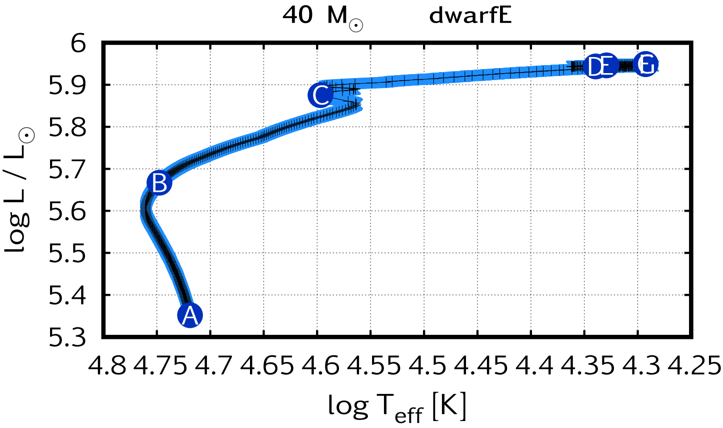


Figure: $v_{rot} = 300\ km/s,\ Z = 0.02 \cdot Z_{SMC}$

Work in Progress

- Finalizing the Boost format for every model

Work in Progress

- Finalizing the Boost format for every model
- Adjusting the A, B, C, D etc Points in problematic cases

Work in Progress [5] Stinshoff et al., in prep.

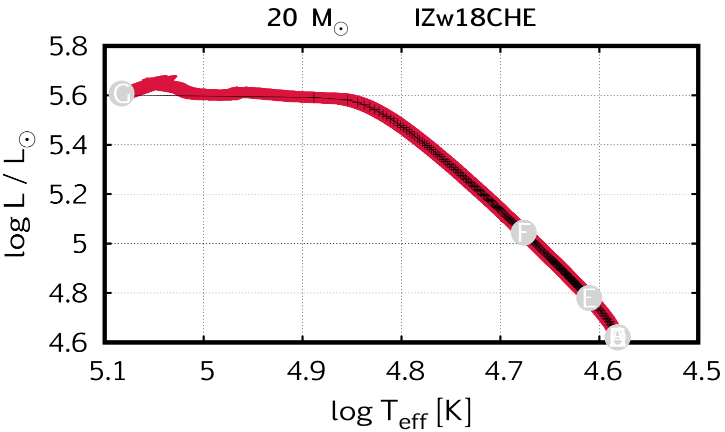


Figure: $v_{rot} = 400\ km/s$, $Z = Z_{IZw18}$

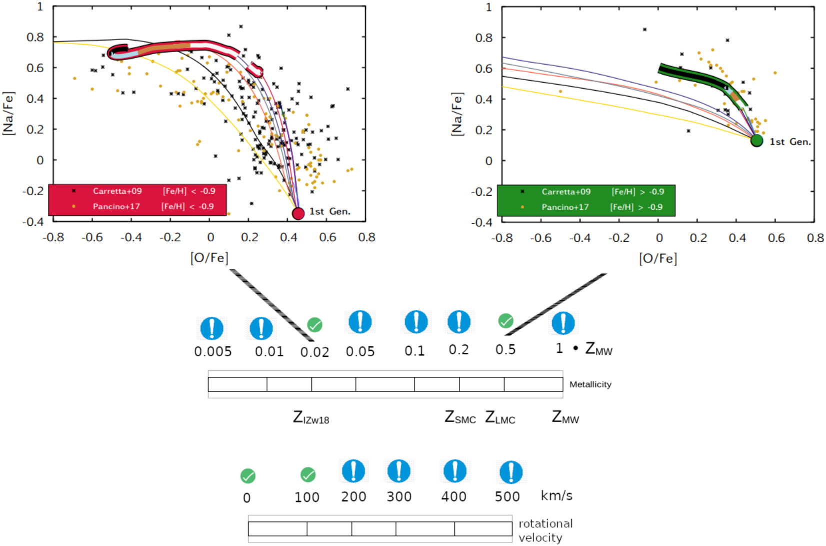
Work in Progress

- Finalizing the Boost format for every model
- Adjusting the A, B, C, D etc Points in problematic cases
- Interpolating with regard to mass, metallicity and velocity

Work in Progress

- Finalizing the Boost format for every model
- Adjusting the A, B, C, D etc Points in problematic cases
- Interpolating with regard to mass, metallicity and velocity
- Reviewing and then applying the models

Application [3] Szécsi & Wünsch (2019)



Sources

- [1] https://commons.wikimedia.org/wiki/File:Messier2_-_HST_-_Potw1913a.jpg, see also: https://esahubble.org/images/potw1913a/ (Picture of Messier 2)

- [2] "Na-O anticorrelation and HB - VII. The chemical composition of first and second-generation stars in 15 globular clusters from GIRAFFE spectra", E. Carretta et al. (2009), A&A, https://www.aanda.org/articles/aa/abs/2009/37/aa12096-09/aa12096-09.html

- [3] "Role of supergiants in the formation of globular clusters, D. Szécsi & R. Wünsch (2019), ApJ, https://iopscience.iop.org/article/10.3847/1538-4357/aaf4be

Sources

- [4] https://www.atnf.csiro.au/outreach/education/senior/astrophysics/stellarevolution_postmain.html
  (HRD comparison low-mass and massive star)

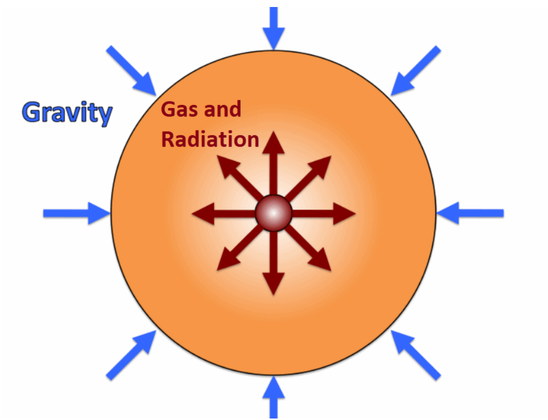
- [5] "*Title tbd*", Stinshoff et al. (2024)

- [6] "Bonn Optimized Stellar Tracks (BoOST). Simulated Populations of Massive and Very Massive Stars for Astrophysical Applications", D. Szécsi et al. (2022), A&A, https://www.aanda.org/articles/aa/full_html/2022/02/aa41536-21/aa41536-21.html

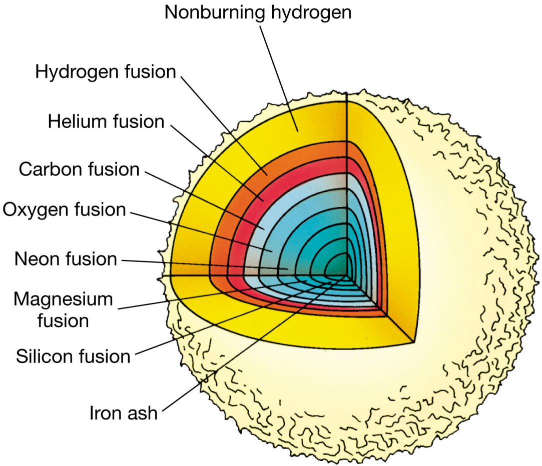
Sources

- https://www.schoolsobservatory.org/learn/astro/stars/cycle (Lifecycle figure used to adapt [4])
- http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/startime.html (Lifetime calculations, used to adapt [4])

Extra

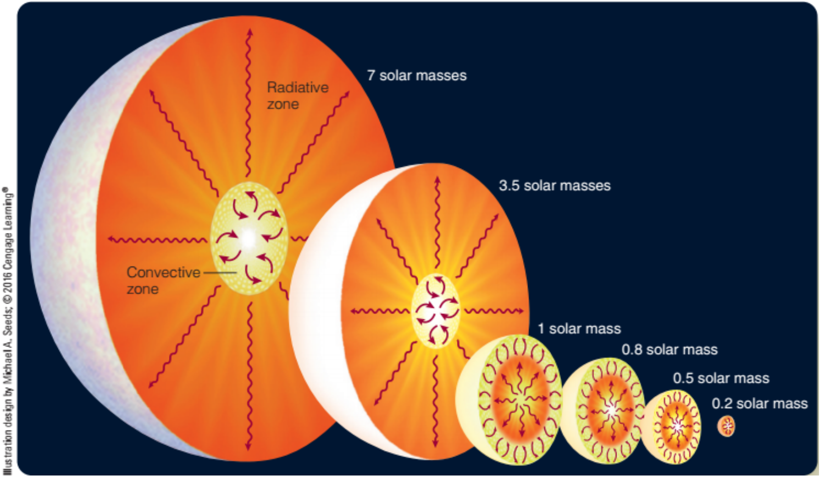


Extra



Nonburning hydrogen
Hydrogen fusion
Helium fusion
Carbon fusion
Oxygen fusion
Neon fusion
Magnesium fusion
Silicon fusion
Iron ash

Extra



7 solar masses
Radiative zone
Convective zone
3.5 solar masses
1 solar mass
0.8 solar mass
0.5 solar mass
0.2 solar mass
Illustration design by Michael A. Seeds; © 2016 Cengage Learning®

Extra

$\mathrm{p} + \mathrm{p} \rightarrow {}^2\mathrm{H} + \mathrm{e}^+ + \nu_\mathrm{e}$

$\mathrm{p} + {}^2\mathrm{H} \rightarrow {}^3\mathrm{He} + \gamma$

83.30% (pp-I)

${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2\mathrm{p}$

16.70%

${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$

99.88% (pp-II)

${}^7\mathrm{Be} + \mathrm{e}^- \rightarrow {}^7\mathrm{Li} + \nu_\mathrm{e}$

${}^7\mathrm{Li} + \mathrm{p} \rightarrow 2\,{}^4\mathrm{He}$

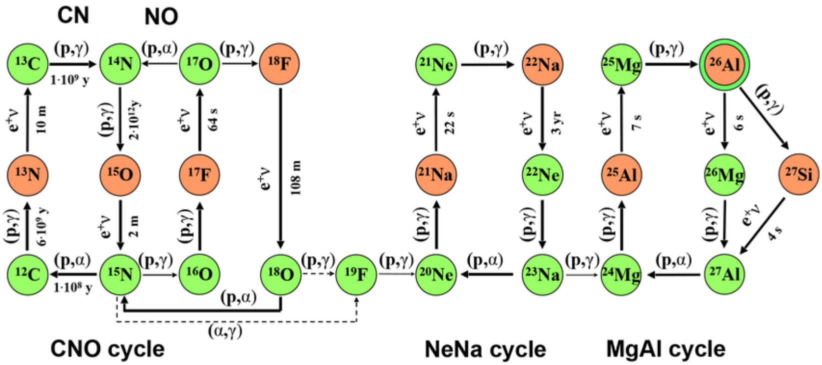
0.12% (pp-III)

${}^7\mathrm{Be} + \mathrm{p} \rightarrow {}^8\mathrm{B} + \gamma$

${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be}^* + \mathrm{e}^+ + \nu_\mathrm{e}$

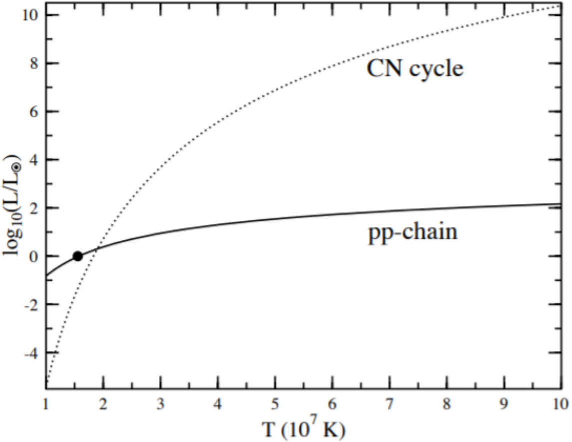
${}^8\mathrm{Be}^* \rightarrow 2\,{}^4\mathrm{He}$

Extra

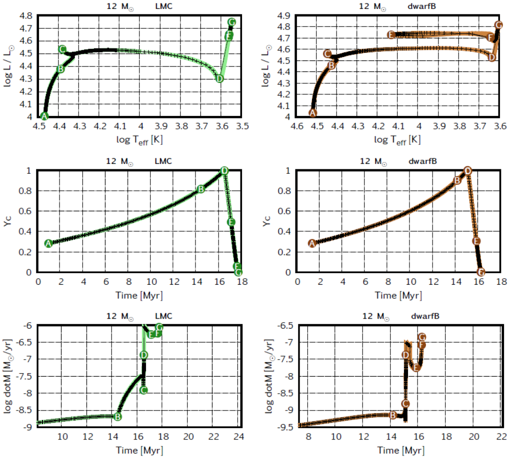


CN
NO
^{13}C
(p,γ)
1·10^9 y
^{14}N
(p,α)
^{17}O
(p,γ)
^{18}F
e$^+$ν
10 m
(p,γ)
2·10^{12}y
e$^+$ν
64 s
e$^+$ν
108 m
^{13}N
^{15}O
^{17}F
(p,γ)
6·10^9 y
e$^+$ν
2 m
(p,γ)
^{12}C
(p,α)
1·10^8 y
^{15}N
(p,γ)
^{16}O
^{18}O
(p,γ)
^{19}F
(p,α)
(α,γ)
CNO cycle
^{21}Ne
(p,γ)
^{22}Na
e$^+$ν
22 s
e$^+$ν
3 yr
^{21}Na
^{22}Ne
(p,γ)
(p,γ)
(p,γ)
^{20}Ne
(p,α)
^{23}Na
(p,γ)
NeNa cycle
^{25}Mg
(p,γ)
^{26}Al
(p,γ)
e$^+$ν
7 s
e$^+$ν
6 s
^{25}Al
^{26}Mg
^{27}Si
(p,γ)
(p,γ)
e$^+$ν
4 s
^{24}Mg
(p,α)
^{27}Al
MgAl cycle

Extra

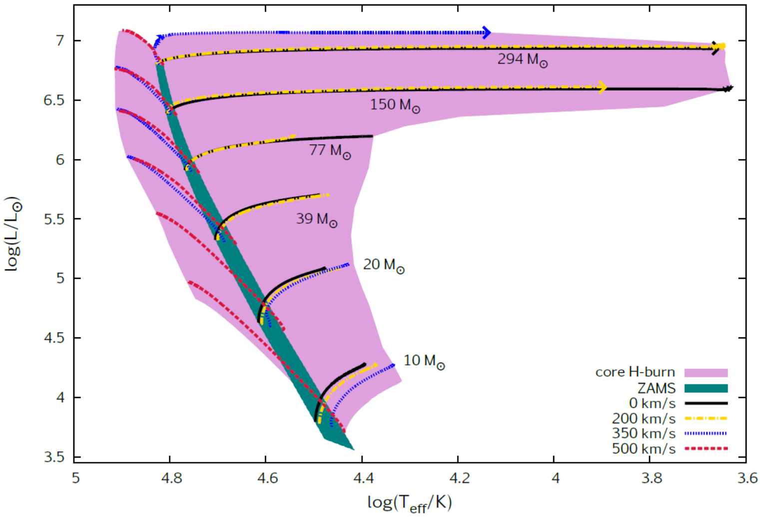

CN cycle
pp-chain
$\log_{10}(L/L_\odot)$
T (10^7 K)
10
8
6
4
2
0
-2
-4
1
2
3
4
5
6
7
8
9
10

Extra



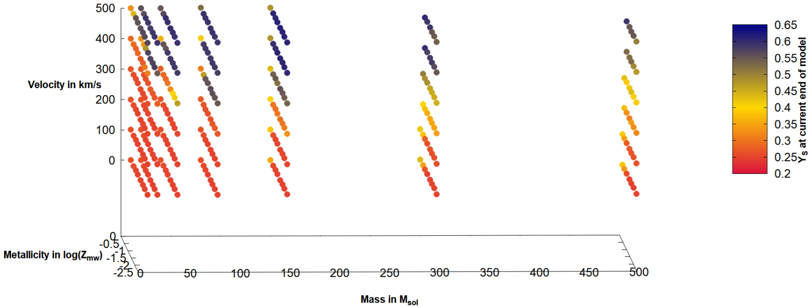
12 M⊙ LMC
log L / L⊙
log T_eff [K]
12 M⊙ dwarfB
log L / L⊙
log T_eff [K]
12 M⊙ LMC
Yc
Time [Myr]
12 M⊙ dwarfB
Yc
Time [Myr]
12 M⊙ LMC
log dotM [M⊙/yr]
Time [Myr]
12 M⊙ dwarfB
log dotM [M⊙/yr]
Time [Myr]

Extra

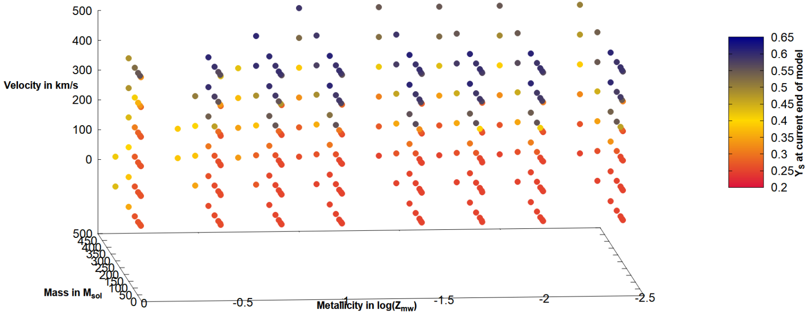


7
6.5
6
5.5
5
4.5
4
3.5
$\log(L/L_{\odot})$
5
4.8
4.6
4.4
4.2
4
3.8
3.6
$\log(T_{eff}/K)$
294 $M_{\odot}$
150 $M_{\odot}$
77 $M_{\odot}$
39 $M_{\odot}$
20 $M_{\odot}$
10 $M_{\odot}$
core H-burn
ZAMS
0 km/s
200 km/s
350 km/s
500 km/s

Extra

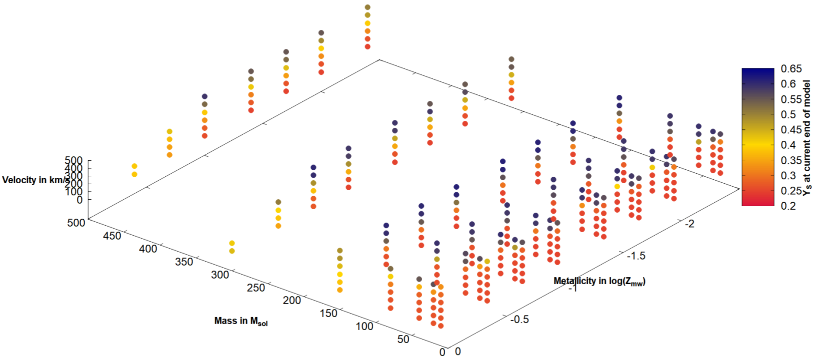

Velocity in km/s
500
400
300
200
100
0
Metallicity in log(Z_{mw})
0
-0.5
-1
-1.5
-2
-2.5
0
50
100
150
200
250
300
350
400
450
500
Mass in M_{sol}
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
Y_s at current end of model

Extra



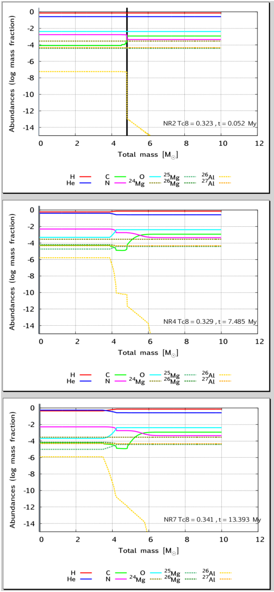
Velocity in km/s
500
400
300
200
100
0
Mass in M_{sol}
500 450 400 350 300 250 200 150 100 50 0
Metallicity in $\log(Z_{mw})$
0 -0.5 -1 -1.5 -2 -2.5
Y_s at current end of model
0.65 0.6 0.55 0.5 0.45 0.4 0.35 0.3 0.25 0.2

Extra



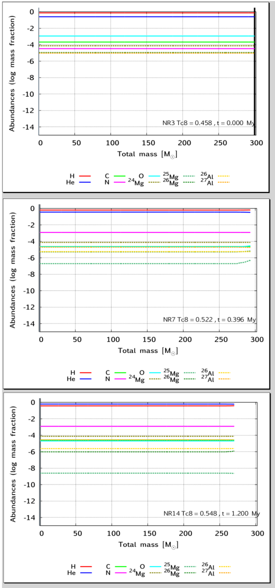
Velocity in km/s
500
400
300
200
100
0
Mass in M_{sol}
500
450
400
350
300
250
200
150
100
50
0
Metallicity in $\log(Z_{mw})$
0
-0.5
-1
-1.5
-2
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
Y_s at current end of model

Extra



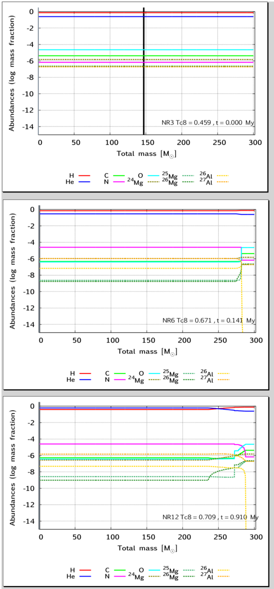
Abundances (log mass fraction)
Total mass [M☉]
NR2 Tc8 = 0.323 , t = 0.052 My
NR4 Tc8 = 0.329 , t = 7.485 My
NR7 Tc8 = 0.341 , t = 13.393 My
H
He
C
N
O
24Mg
25Mg
26Mg
26Al
27Al

Extra



Abundances (log mass fraction)
Total mass [M☉]
NR3 Tc8 = 0.458 , t = 0.000 My
NR7 Tc8 = 0.522 , t = 0.396 My
NR14 Tc8 = 0.548 , t = 1.200 My
H
He
C
N
O
24Mg
25Mg
26Mg
26Al
27Al

Extra


NR3 Tc8 = 0.459 , t = 0.000 My
NR6 Tc8 = 0.671 , t = 0.141 My
NR12 Tc8 = 0.709 , t = 0.910 My
Abundances (log mass fraction)
Total mass [M⊙]
H
He
C
N
O
24Mg
25Mg
26Mg
26Al
27Al

Extra

- young massive clusters have winds

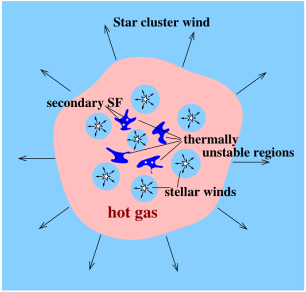
  stellar winds $\rightarrow$ collisions $\rightarrow$ shocked wind $\rightarrow$ outflow
- thermal instability, rapid cooling

  if the cluster is massive and compact enough
- dense warm/cold clumps are formed

  cluster gravity $\Rightarrow$ clumps fall to the centre;

  accumulation $\Rightarrow$ self-shielding against EUV radiation
- 2nd generation (2G) stars formed

  enriched by products of massive stars chem. evolution

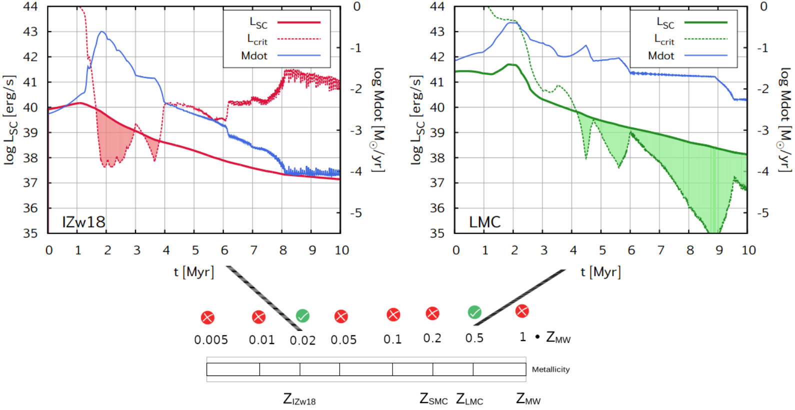


Credit: R. Wünsch (ASU)

Basic parameters:

- L_{SC}, $\dot{M}_{SC} \leftarrow M_{1G}$, stellar evolution tracks
- R_{SC} + eventually radial profile (R_c, β)

Extra



IZw18
LMC
L_{SC}
L_{crit}
Mdot
log L_{SC} [erg/s]
log Mdot [$M_\odot$/yr]
t [Myr]
0.005
0.01
0.02
0.05
0.1
0.2
0.5
1 • Z_{MW}
Metallicity
Z_{IZw18}
Z_{SMC}
Z_{LMC}
Z_{MW}

Extra

STATUS | RESOURCES | DOCUMENTATION

The BONNSAI project

Select Stellar Models: Choose stellar model...

Observables | Correlations | Priors | Output Setting | Further Settings | Submit Page

Welcome to the BONNSAI web-service.

BONNSAI, the BONN Stellar Astrophysics Interface, is a Bayesian statistical method that is capable of comparing all available observables simultaneously to stellar models while taking observed uncertainties and prior knowledge such as initial mass functions and distributions of stellar rotational velocities into account. BONNSAI can be used to (1) determine probability distributions of fundamental stellar parameters such as initial masses and stellar ages from complex datasets, (2) predict stellar parameters that were not yet observationally determined and (3) test stellar models to further advance our understanding of stellar evolution. A full description of BONNSAI is published in Schneider et al. (2014, A&A, 570, 66).

There are only four steps involved to submit a job:

1. Select stellar models to which the observables shall be matched.
2. Provide the observables including their uncertainties.
3. Choose priors and output quantities.
4. Submit your request.

Once your job is finished, you will receive an email with a link to your results.

To start submitting a job, select the stellar models to match your observables to from the above drop-down menu. In case you have any questions, comments or suggestions do not hesitate to contact us. We hope you enjoy using BONNSAI.