# Expanding the BoOST massive star models to explain the formation of globular clusters - Midterm Evaluation of Hanno Stinshoff -

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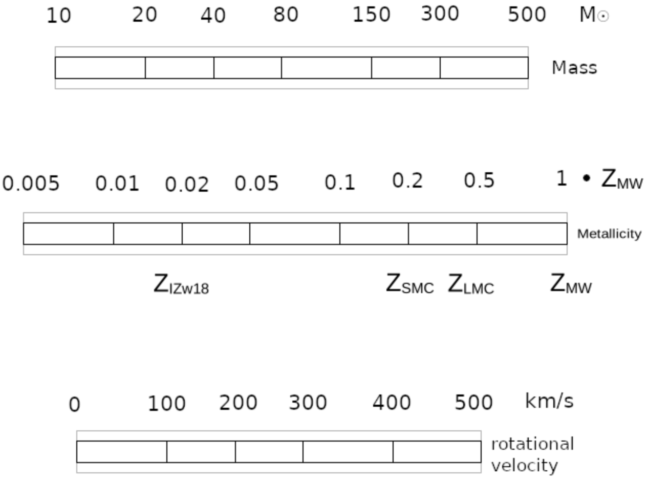
# Project 1

Expanding the BoOST model grids


10 20 40 80 150 300 500 M☉
Mass
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
0 100 200 300 400 500 km/s
rotational velocity

# The new models - The BoOST format [1] Stinshoff et al., in prep., [2] Szécsi et al., 2022

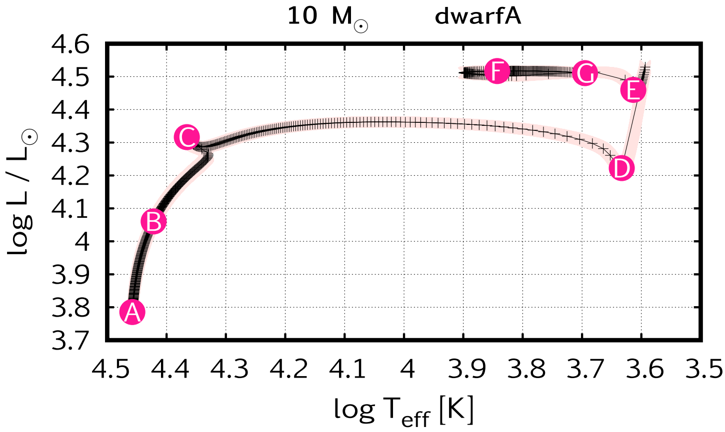
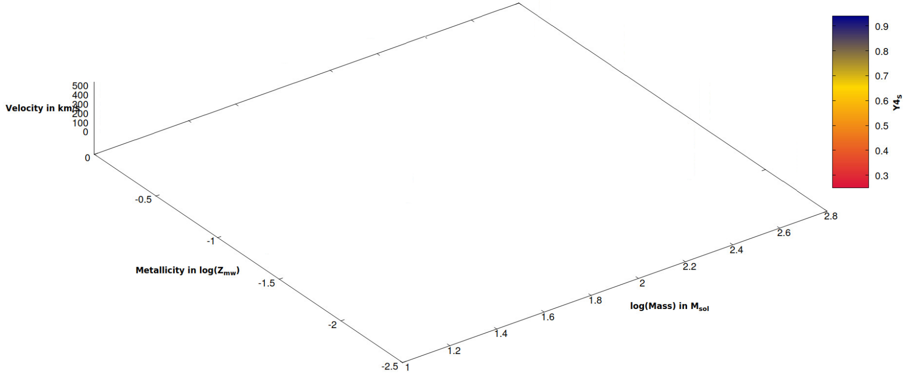



Figure: $v_{rot} = 200\ km/s,\ Z = 0.5 \cdot Z_{SMC}$

# The new models - $Y_S$ at TAMS [1] Stinshoff et al., in prep.



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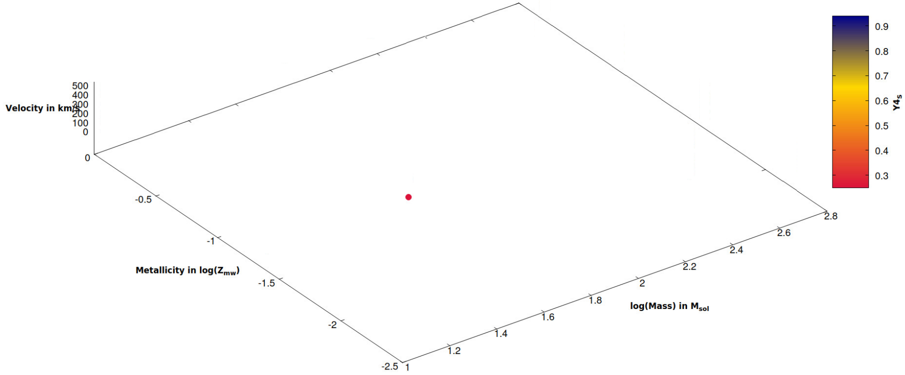
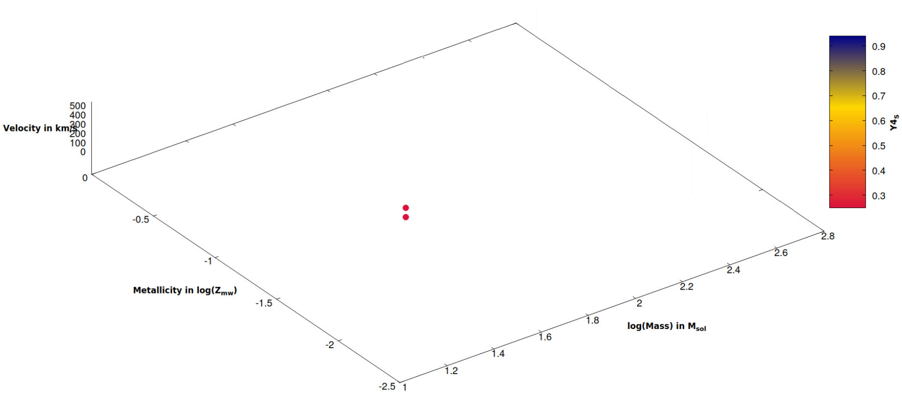


# The new models - $Y_S$ at TAMS [1] Stinshoff et al., in prep.



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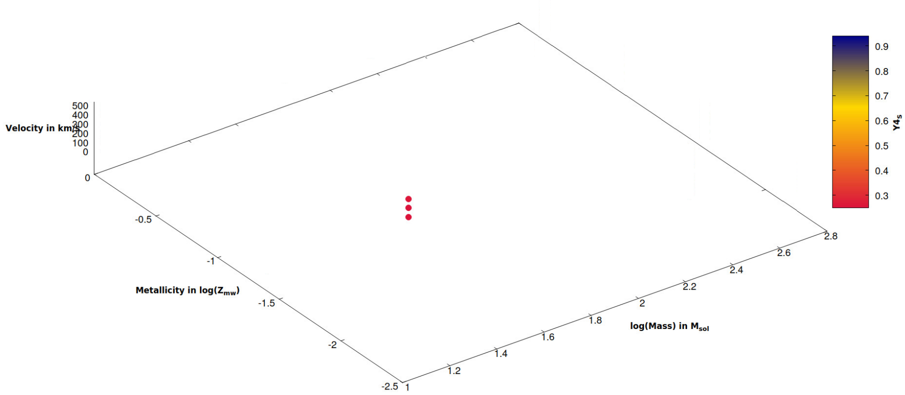
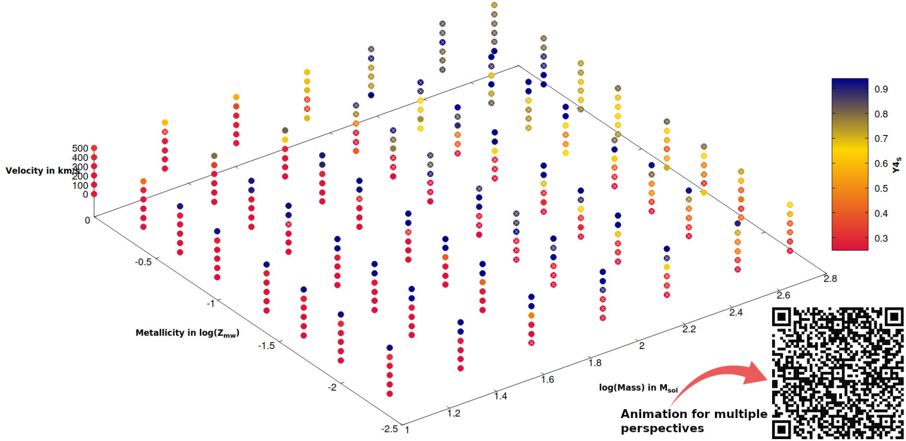


# The new models - $Y_S$ at TAMS [1] Stinshoff et al., in prep.




Animation for multiple perspectives

# The new models - BoOSTed HRD [1] Stinshoff et al., in prep.

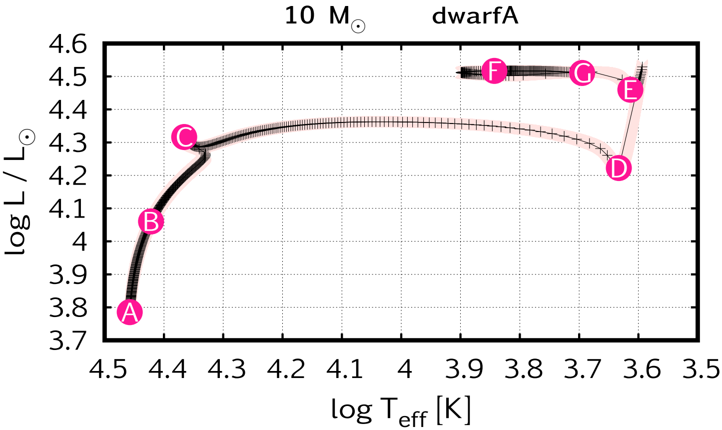



Figure: $v_{rot} = 200\ km/s,\ Z = 0.5 \cdot Z_{SMC}$

# The new models - BoOSTed HRD [1] Stinshoff et al., in prep.

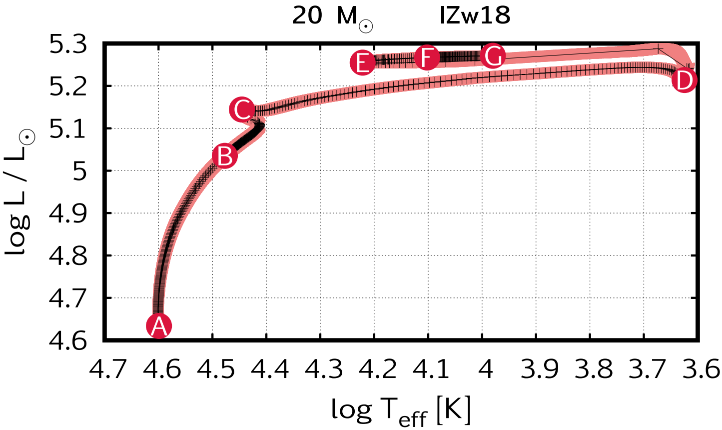



Figure: $v_{rot} = 300\ km/s,\ Z = Z_{IZw18}$

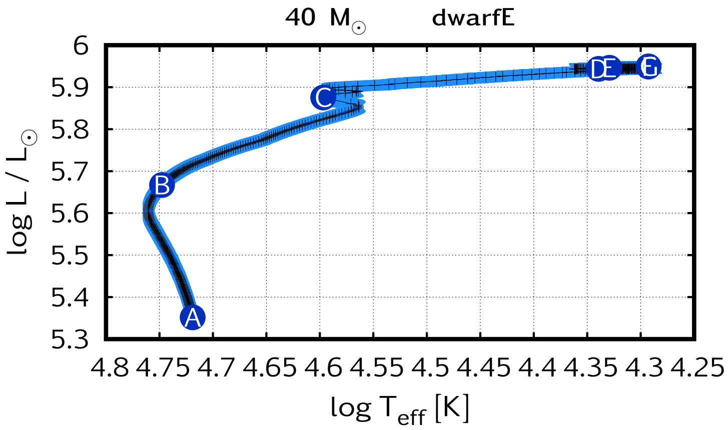


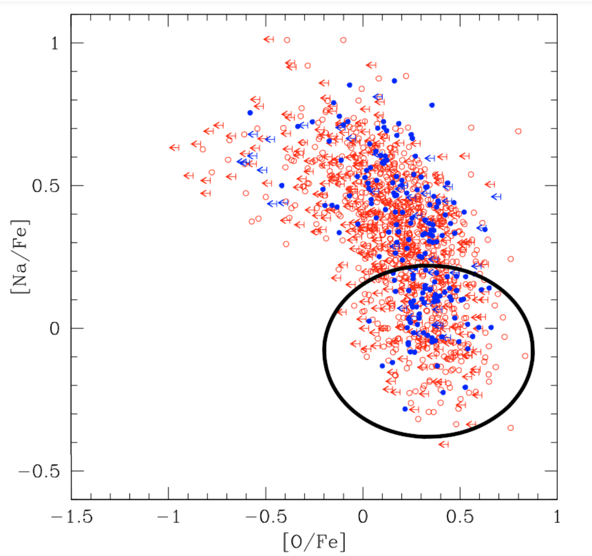

Figure: $v_{rot} = 300\ km/s,\ Z = 0.02 \cdot Z_{SMC}$

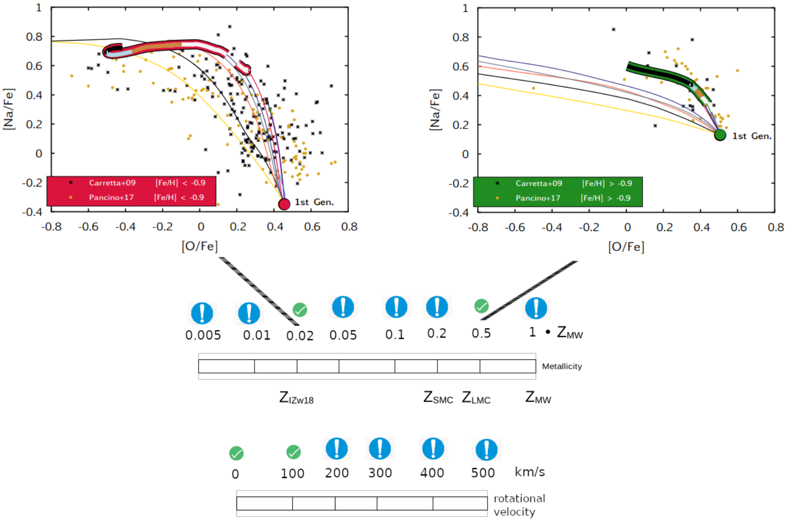
# Project 2

Expanding the BoOST model grids

Investigating the winds of stellar populations with varying wind descriptions

# Globular Clusters [3] Caretta et al., 2009, [4] Szécsi & Wünsch, 2019





[Na/Fe]
[O/Fe]
1st Gen.
Carretta+09 [Fe/H] < -0.9
Pancino+17 [Fe/H] < -0.9
Carretta+09 [Fe/H] > -0.9
Pancino+17 [Fe/H] > -0.9
0.005
0.01
0.02
0.05
0.1
0.2
0.5
1 • $Z_{MW}$
Metallicity
$Z_{IZw18}$
$Z_{SMC}$ $Z_{LMC}$
$Z_{MW}$
0
100
200
300
400
500
km/s
rotational velocity

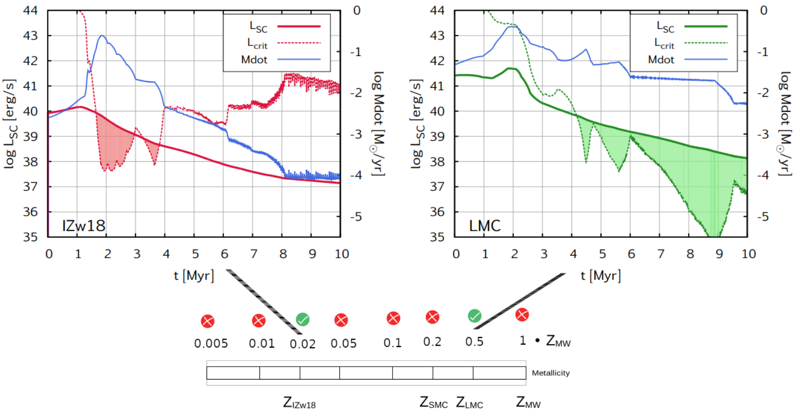



Figure: Population with Kroupa IMF (cf. [5]), 0.02 $Z_{MW}$ (red) and $Z = 0.5\, Z_{MW}$ (green), $L_{SC} = \int \log(0.5 * \dot{M} * v_{wind}^2)$

 [1] Stinshoff et al., in prep., [6], [7], [8] (see figure legend)

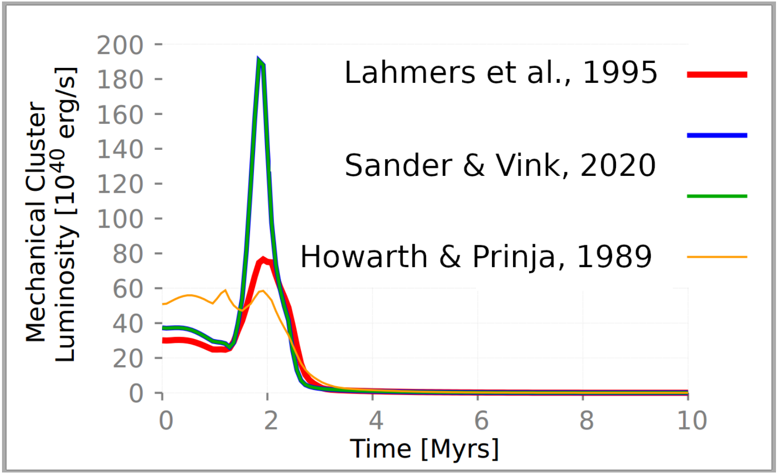



Figure: Population with Kroupa IMF (cf. [5]), 500 $M_\odot$ upper mass limit, $Z = 0.5\, Z_{MW}$, $L_{SC} = \int \log(0.5 * \dot{M} * v_{wind}^2)$

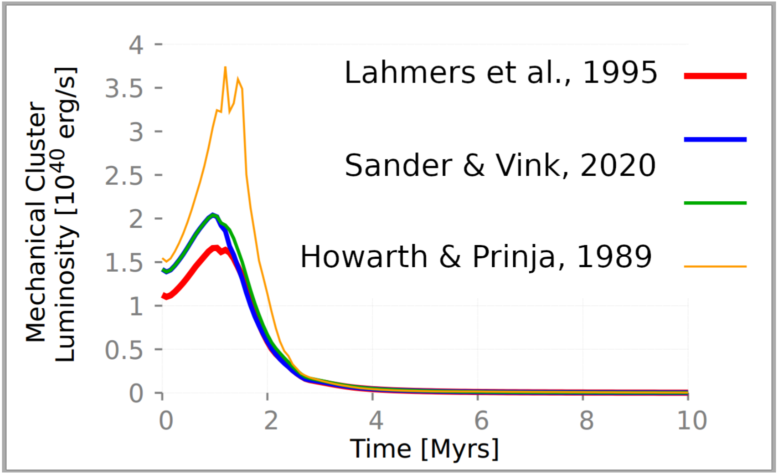



Figure: Population with Kroupa IMF (cf. [5]), $\sim$ 500 $M_\odot$ upper mass limit, 0.02 $Z_{MW}$, $L_{SC} = \int \log(0.5 * \dot{M} * v_{wind}^2)$

# Outlook - Project 3

Expanding the BoOST model grids

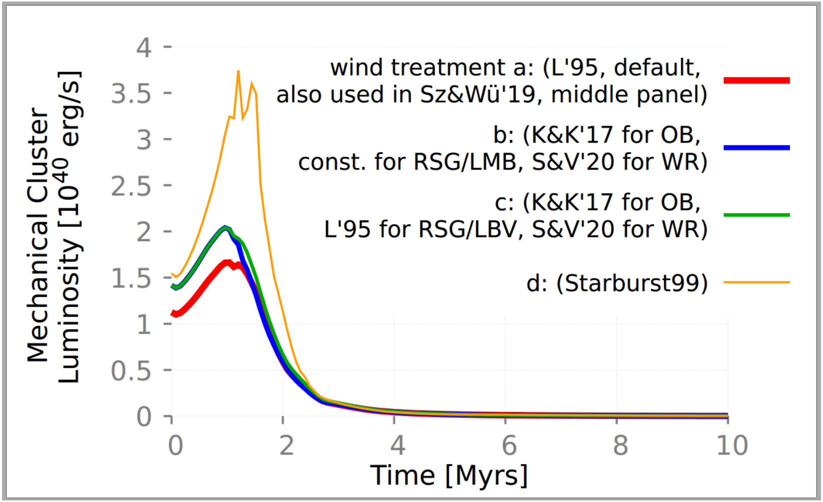
Investigating the winds of stellar populations with varying wind descriptions

Creating new populations to investigate the mass budget for second generations of star formation

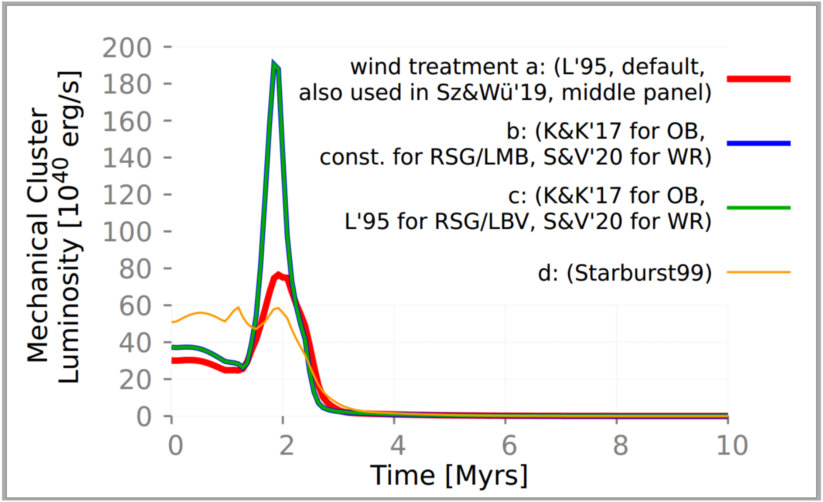
# Outlook

- Improvement on/Choices of the wind prescriptions
- Improving the resolution in critical areas of the parameter space
- Investigations of different IMFs

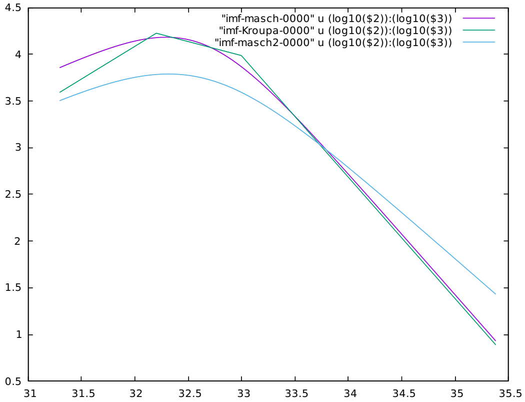
# Wind Prescriptions [1] Stinshoff et al., in prep., [2] Szécsi et al., 2022, [6], [7], [8], [9], [10] (see figure legend)



# Wind Prescriptions [1] Stinshoff et al., in prep., [2] Szécsi et al., 2022, [6], [7], [8], [9], [10] (see figure legend)



# Outlook - IMF [1] Stinshoff et al., in prep., [5] Kroupa, 2001, [11] Maschberger, 2013



# Sources


- [1] H. N. Stinshoff et al. (in prep.)
- [2] D. Szécsi, P. Agrawal, R. Wünsch, and N. Langer: "Bonn Optimized Stellar Tracks (BoOST) - Simulated populations of massive and very massive stars for astrophysical applications", Astronomy & Astrophysics, vol. 658, 2022, doi:10.1051/0004-6361/202141536
- [3] E. Carretta, A. Bragaglia, R. G. Gratton, S. Lucatello, G. Catanzaro, F. Leone, M. Bellazzini, R. Claudi, V. D'Orazi, Y. Momany, S. Ortolani, E. Pancino, G. Piotto, A. Recio-Blanco, and E. Sabbi: "Na-O anticorrelation and HB - VII. The chemical composition of first and second-generation stars in 15 globular clusters from GIRAFFE spectra", Astronomy & Astrophysics, vol. 505, July 2009, doi:10.1051/0004-6361/200912096
- [4] D. Szécsi and R. Wünsch: "Role of Supergiants in the Formation of Globular Clusters", The Astrophysical Journal, vol. 871, January 2019, p. 20, doi:10.3847/1538-4357/aaf4be

# Sources


- [5] P. Kroupa: "On the variation of the initial mass function", Monthly Notices of the Royal Astronomical Society, vol. 322, 2001, doi:10.1046/j.1365-8711.2001.04022.x.

- [6] H. J. G. L. M. Lamers, T. P. Snow, and D. M. Lindholm: "Terminal Velocities and the Bistability of Stellar Winds", The Astrophysical Journal, vol. 455, 1995. doi:10.1086/176575.

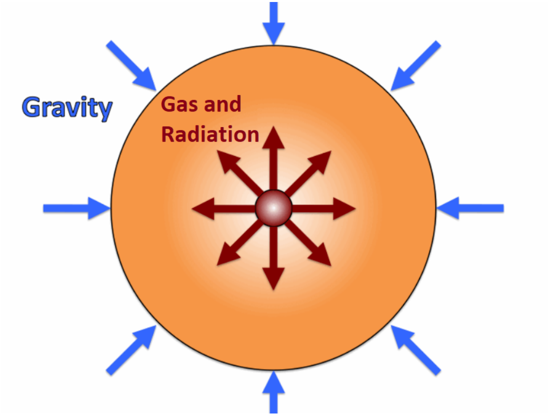
- [7] A. A. C. Sander and J. S. Vink: "On the nature of massive helium star winds and Wolf-Rayet-type mass-loss", Monthly Notices of the Royal Astronomical Society, vol. 499, 2020, https://doi.org/10.1093/mnras/staa2712

- [8] I. D. Howarth and R. K. Prinja: "The Stellar Winds of 203 Galactic O Stars: A Quantitative Ultraviolet Survey", The Astrophysical Journal Supplement Series, vol. 69, 1989, doi:10.1086/191321.

# Sources


- [9] J. Krtička, J. Kubát, and I. Krtičková: "New mass-loss rates of B supergiants from global wind models", Astronomy & Astrophysics, vol. 647, 2021, doi:10.1051/0004-6361/202039900
- [10] C. Leitherer, D. Schaerer, J. D. Goldader, R. M. G. Delgado, C. Robert, D. F. Kune, D. F. de Mello, D. Devost, and T. M. Heckman: "Starburst99: Synthesis Models for Galaxies with Active Star Formation", The Astrophysical Journal Supplement Series, vol. 123, no. 1, IOP, pp. 3-40, 1999, doi:10.1086/313233
- [11] T. Maschberger: "On the function describing the stellar initial mass function", Monthly Notices of the Royal Astronomical Society, vol. 429, 2013, doi:10.1093/mnras/sts479

# Extra



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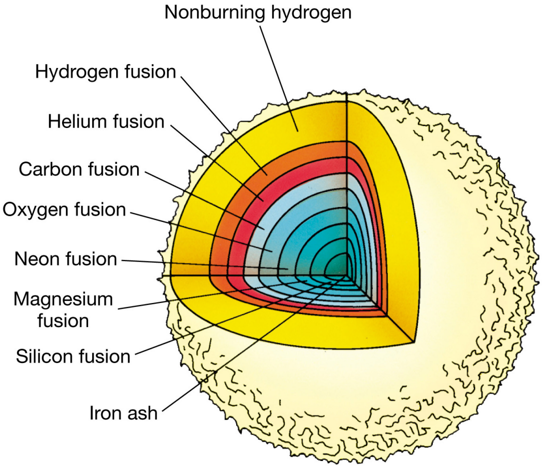
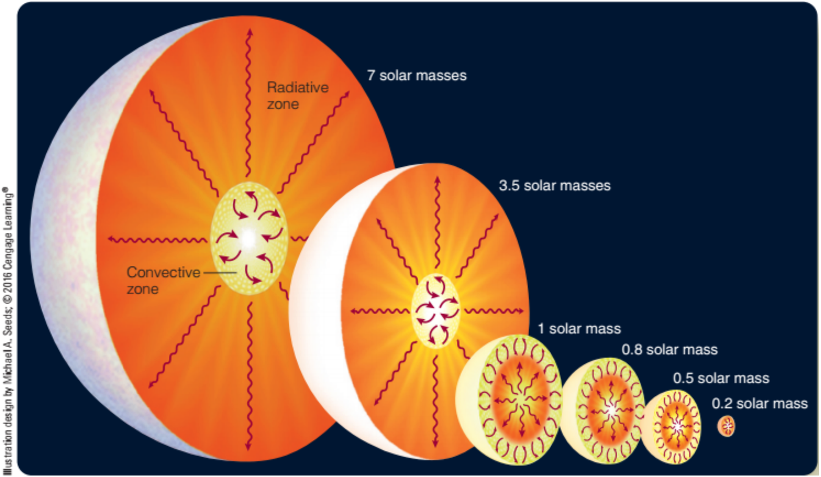


Nonburning hydrogen
Hydrogen fusion
Helium fusion
Carbon fusion
Oxygen fusion
Neon fusion
Magnesium fusion
Silicon fusion
Iron ash

# 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

$$p + p \rightarrow {}^{2}H + e^{+} + \nu_e$$

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

83.30% (pp-I)

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

16.70%

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

99.88% (pp-II)

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

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

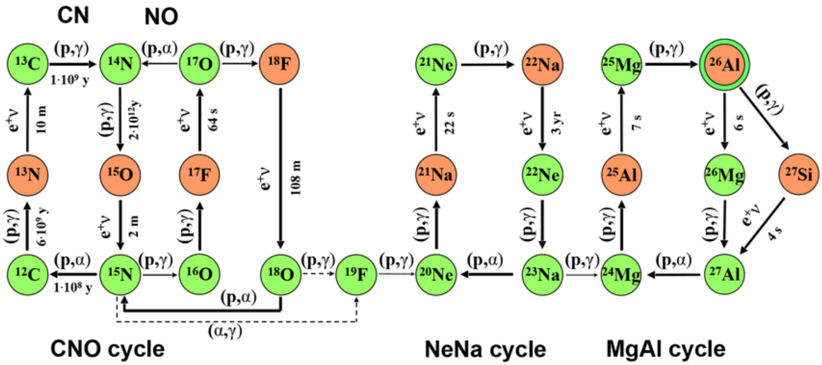
0.12% (pp-III)

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

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

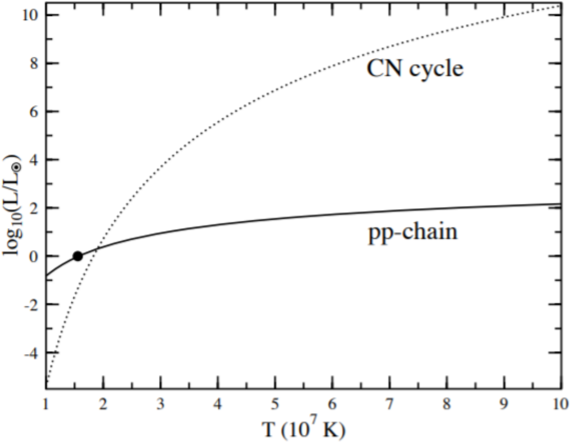
$${}^{8}Be^{*} \rightarrow 2{}^{4}He$$

# Extra

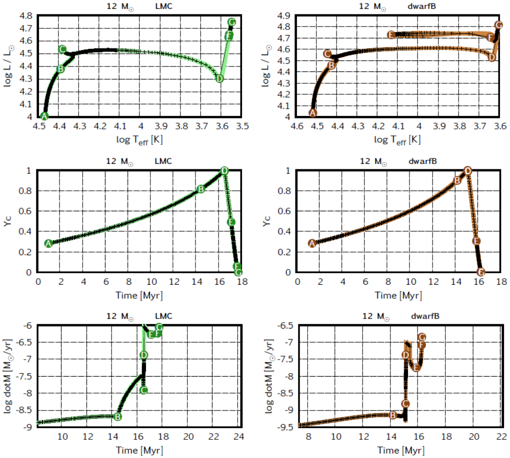


CN
NO
$^{13}$C
(p,γ)
1·10⁹ y
$^{14}$N
(p,α)
$^{17}$O
(p,γ)
$^{18}$F
e⁺ν
10 m
(p,γ)
2·10¹²y
e⁺ν
64 s
e⁺ν
108 m
$^{13}$N
$^{15}$O
$^{17}$F
(p,γ)
6·10⁹ y
e⁺ν
2 m
(p,γ)
$^{12}$C
(p,α)
1·10⁸ y
$^{15}$N
(p,γ)
$^{16}$O
$^{18}$O
(p,γ)
$^{19}$F
(p,α)
(α,γ)
CNO cycle
$^{21}$Ne
(p,γ)
$^{22}$Na
e⁺ν
22 s
e⁺ν
3 yr
$^{21}$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

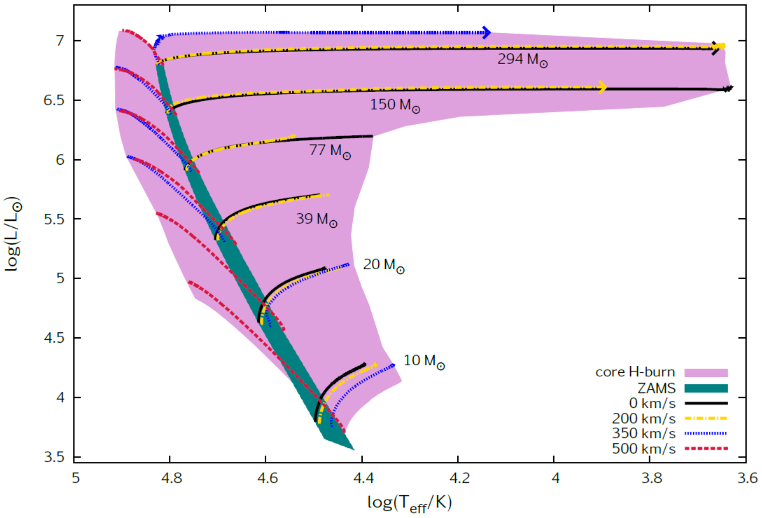

CN cycle
pp-chain
$\log_{10}(L/L_\odot)$
T ($10^7$ K)
10
8
6
4
2
0
-2
-4
1
2
3
4
5
6
7
8
9
10

# Extra



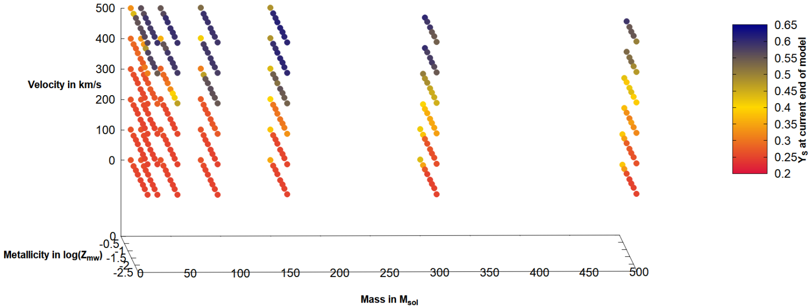
12 M☉ LMC
log L / L☉
log Teff [K]
12 M☉ dwarfB
Yc
Time [Myr]
log dotM [M☉/yr]
A
B
C
D
E
F
G

# Extra



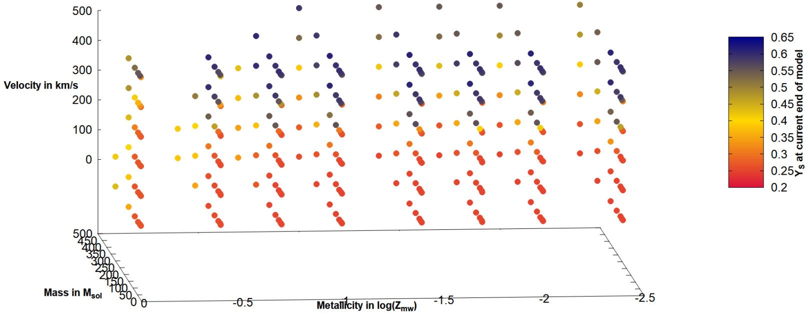
7
6.5
6
5.5
5
4.5
4
3.5
log(L/L☉)
5
4.8
4.6
4.4
4.2
4
3.8
3.6
log(T_eff/K)
294 M☉
150 M☉
77 M☉
39 M☉
20 M☉
10 M☉
core H-burn
ZAMS
0 km/s
200 km/s
350 km/s
500 km/s

# Extra



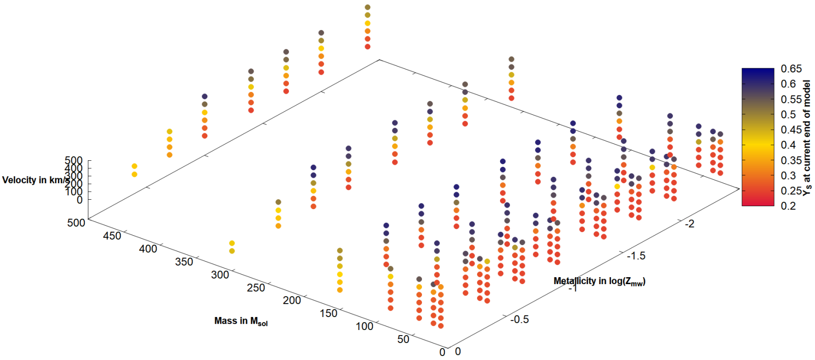
Velocity in km/s
500
400
300
200
100
0
Metallicity in log(Z_mw)
0
-0.5
-1
-1.5
-2
-2.5
0
50
100
150
200
250
300
350
400
450
500
Mass in M_sol
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
Y_s at current end of model

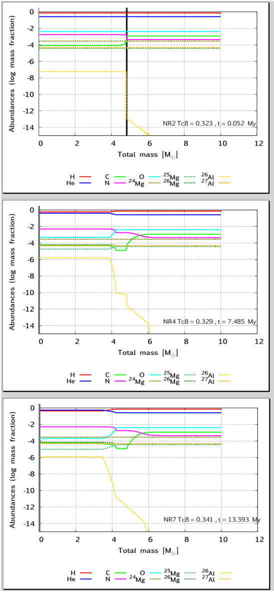
# Extra



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

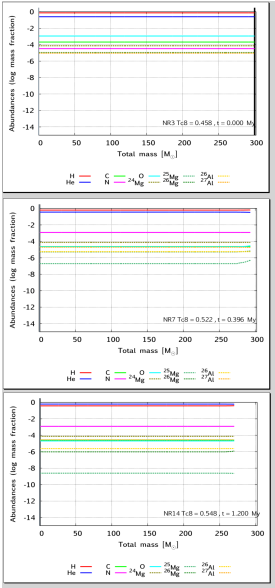
# Extra


Velocity in km/s
500
400
300
200
100
0
500
450
400
350
300
250
200
150
100
50
0
Mass in $M_{sol}$
0
-0.5
-1
-1.5
-2
Metallicity in $\log(Z_{mw})$
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

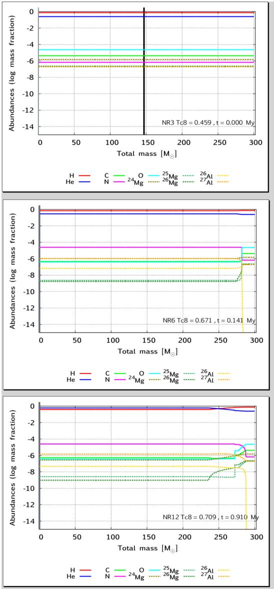


Abundances (log mass fraction)
Total mass [M☉]
NR2 Tc8 = 0.323 , t = 0.052 My
NR4 Tc8 = 0.329 , t = 7.485 My
NR7 Tc8 = 0.341 , t = 13.393 My
H
He
C
N
O
24Mg
25Mg
26Mg
26Al
27Al

# Extra


Abundances (log mass fraction)
Total mass [M$_\odot$]
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
$^{24}$Mg
$^{25}$Mg
$^{26}$Mg
$^{26}$Al
$^{27}$Al

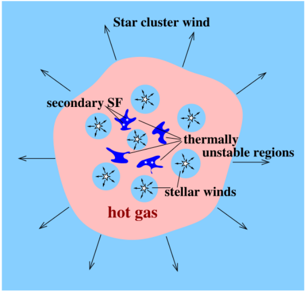
# Extra



Abundances (log mass fraction)
Total mass [M⊙]
NR3 Tc8 = 0.459 , t = 0.000 My
NR6 Tc8 = 0.671 , t = 0.141 My
NR12 Tc8 = 0.709 , t = 0.910 My
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 ($R_c$, $\beta$)

# 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.