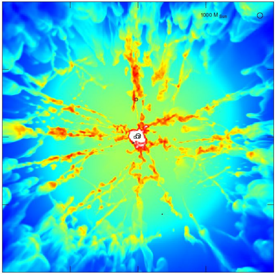
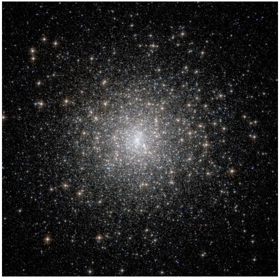
Rapidly cooling shocked stellar winds

On the Origin of Globular Clusters and their multiple populations

Richard Wünsch

Edinburgh, 7th September 2018





In collaboration with:

J. Palouš, G. Tenorio-Tagle, S. Silich, D. Szécsi, S. Martínez González, S. Ehlerová, C. Muñoz-Tuñón, S. Walch

Multiple stellar populations in GCs

- photometric evidence:

  → split main-sequence (also RGB, SGB, EHB, turn-off points) (Bedin+04, Piotto+07, Bellini+10, Milone11,12,13,15, . . .)

- spectroscopic evidence:

  → variations in light elements abundances

  → anticorrelations among pairs of them (e.g. Na-O, Mg-Al, . . .) Carreta+06,09

- correspondence between both (Milone+15)

- constant Fe (and other hevier elements):

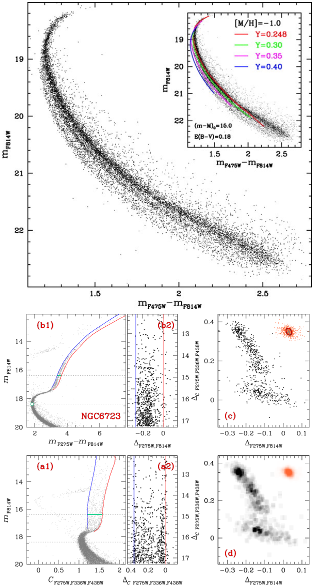
  (except.: ωCen, Terzan 5, M2, M22, M54 . . .)

  → no SN enrichment; origin from one cloud

- universal for GCs (and intermed. age clusters):

  → determined by: M, [Fe/H], M/R?

  → age limit 2 Gyr?



Multiple stellar populations in GCs

- photometric evidence:

  → split main-sequence (also RGB, SGB, EHB, turn-off points) (Bedin+04, Piotto+07, Bellini+10, Milone11,12,13,15, . . .)

- spectroscopic evidence:

  → variations in light elements abundances

  → anticorrelations among pairs of them (e.g. Na-O, Mg-Al, . . .) Carreta+06,09

- correspondence between both (Milone+15)
- constant Fe (and other hevier elements):

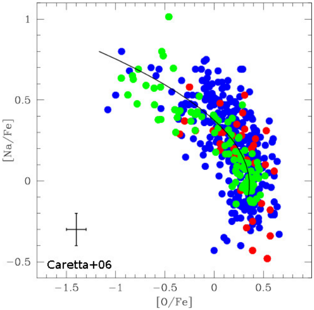
  (except.: ωCen, Terzan 5, M2, M22, M54 . . .)

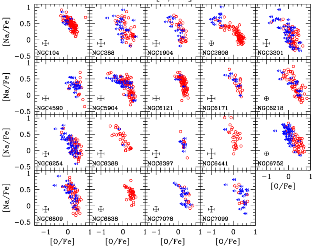
  → no SN enrichment; origin from one cloud

- universal for GCs (and intermed. age clusters):

  → determined by: M, [Fe/H], M/R?

  → age limit 2 Gyr?





Multiple stellar populations in GCs

- photometric evidence:

  → split main-sequence (also RGB, SGB, EHB, turn-off points) (Bedin+04, Piotto+07, Bellini+10, Milone11,12,13,15, . . .)

- spectroscopic evidence:

  → variations in light elements abundances

  → anticorrelations among pairs of them (e.g. Na-O, Mg-Al, . . .) Carreta+06,09

- correspondence between both (Milone+15)

- constant Fe (and other hevier elements):

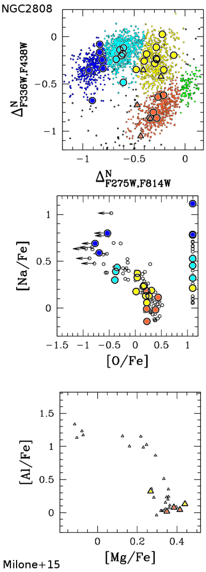
  (except.: ωCen, Terzan 5, M2, M22, M54 . . .)

  → no SN enrichment; origin from one cloud

- universal for GCs (and intermed. age clusters):

  → determined by: M, [Fe/H], M/R?

  → age limit 2 Gyr?



Multiple stellar populations in GCs

- photometric evidence:

  → split main-sequence (also RGB, SGB, EHB, turn-off points) (Bedin+04, Piotto+07, Bellini+10, Milone11,12,13,15, . . .)
- spectroscopic evidence:

  → variations in light elements abundances

  → anticorrelations among pairs of them (e.g. Na-O, Mg-Al, . . .) Carreta+06,09
- correspondence between both (Milone+15)
- constant Fe (and other hevier elements):

  (except.: ωCen, Terzan 5, M2, M22, M54 . . .)

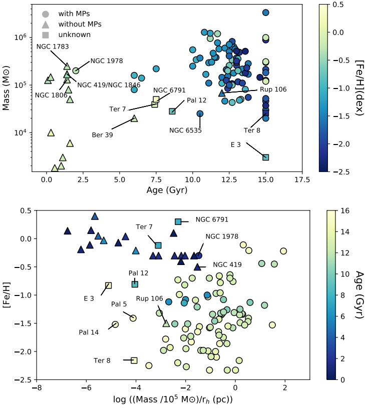
  → no SN enrichment; origin from one cloud
- universal for GCs (and intermed. age clusters):

  → determined by: M, [Fe/H], M/R?

  → age limit 2 Gyr?

Multiple stellar populations in GCs

- photometric evidence:
  → split main-sequence (also RGB, SGB, EHB, turn-off points) (Bedin+04, Piotto+07, Bellini+10, Milone11,12,13,15, . . .)
- spectroscopic evidence:
  → variations in light elements abundances
  → anticorrelations among pairs of them (e.g. Na-O, Mg-Al, . . .) Carreta+06,09
- correspondence between both (Milone+15)
- constant Fe (and other hevier elements):
  (except.: ωCen, Terzan 5, M2, M22, M54 . . .)
  → no SN enrichment; origin from one cloud
- universal for GCs (and intermed. age clusters):
  → determined by: M, [Fe/H], M/R?
  → age limit 2 Gyr?



Bastian&Lardo18

(see review in ARA&A)

Self-enrichment scenario

- chem. composition suggests enrichment by hot H burning
  (e.g. Gratton+04, Charbonnel+05)
- objects burning hydrogen at high T (20MK+):
  - massive stars
    (Decressin+07, de Mink+09, Elmegreen17, Wünsch+17, Recchi+17, Szécsi+16 . . .)
  - AGB stars (d'Ercole+08,10,16, Bekki+17)
  - super massive stars (Denissenkov+13, Gieles+18)

Problems:

- mass budget problem
  - $\sim 50 - 70\%$ of enriched stars
  - winds/outflows not enough
  - 1G escaped?, top-heavy IMF?
- He abundance over-predicted
- $N_1/N_{\mathrm{tot}} = f(M, \dots)$,
  but $N_1/N_{\mathrm{tot}} \neq (R_G, \dots)$

Self-enrichment scenario

- chem. composition suggests enrichment by hot H burning
  (e.g. Gratton+04, Charbonnel+05)
- objects burning hydrogen at high T (20MK+):
  - massive stars
    (Decressin+07, de Mink+09, Elmegreen17, Wünsch+17, Recchi+17, Szécsi+16 . . .)
  - AGB stars (d'Ercole+08,10,16, Bekki+17)
  - super massive stars (Denissenkov+13, Gieles+18)

Problems:

- mass budget problem
  - $\sim 50 - 70\%$ of enriched stars
  - winds/outflows not enough
  - 1G escaped?, top-heavy IMF?
- He abundance over-predicted
- $N_1/N_{\rm tot} = f(M, \dots)$,
  but $N_1/N_{\rm tot} \neq (R_G, \dots)$

Self-enrichment scenario

- chem. composition suggests enrichment by hot H burning
  (e.g. Gratton+04, Charbonnel+05)
- objects burning hydrogen at high T (20MK+):
  - massive stars
    (Decressin+07, de Mink+09, Elmegreen17, Wünsch+17, Recchi+17, Szécsi+16 ...)
  - AGB stars (d'Ercole+08,10,16, Bekki+17)
  - super massive stars (Denissenkov+13, Gieles+18)

Problems:

- mass budget problem
  - $\sim 50-70\%$ of enriched stars
  - winds/outflows not enough
  - 1G escaped?, top-heavy IMF?
- He abundance over-predicted
- $N_1/N_{\rm tot} = f(M,\dots)$,
  but $N_1/N_{\rm tot} \neq (R_G,\dots)$

Self-enrichment scenario

- chem. composition suggests enrichment by hot H burning
  (e.g. Gratton+04, Charbonnel+05)
- objects burning hydrogen at high T (20MK+):
  - massive stars
    (Decressin+07, de Mink+09, Elmegreen17, Wünsch+17, Recchi+17, Szécsi+16 . . .)
  - AGB stars (d'Ercole+08,10,16, Bekki+17)
  - super massive stars (Denissenkov+13, Gieles+18)

Problems:

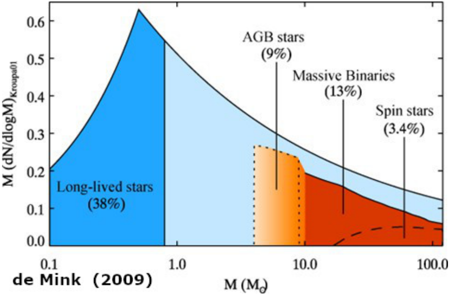
- mass budget problem
  - $\sim 50-70\%$ of enriched stars
  - winds/outflows not enough
  - 1G escaped?, top-heavy IMF?
- He abundance over-predicted
- $N_1/N_{\rm tot} = f(M, \ldots)$,
  but $N_1/N_{\rm tot} \neq (R_G, \ldots)$

Self-enrichment scenario

- chem. composition suggests enrichment by hot H burning
  (e.g. Gratton+04, Charbonnel+05)
- objects burning hydrogen at high T (20MK+):
  - massive stars
    (Decressin+07, de Mink+09, Elmegreen17, Wünsch+17, Recchi+17, Szécsi+16 . . .)
  - AGB stars (d’Ercole+08,10,16, Bekki+17)
  - super massive stars (Denissenkov+13, Gieles+18)

Problems:

- mass budget problem
  - $\sim 50 - 70\%$ of enriched stars
  - winds/outflows not enough
  - 1G escaped?, top-heavy IMF?
- He abundance over-predicted
- $N_1/N_{\mathrm{tot}} = f(M, \dots)$,
  but $N_1/N_{\mathrm{tot}} \neq (R_G, \dots)$



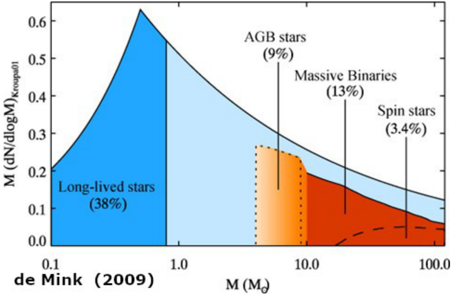
de Mink (2009)

Self-enrichment scenario

- chem. composition suggests enrichment by hot H burning
  (e.g. Gratton+04, Charbonnel+05)
- objects burning hydrogen at high T (20MK+):
  - massive stars
    (Decressin+07, de Mink+09, Elmegreen17, Wünsch+17, Recchi+17, Szécsi+16 . . .)
  - AGB stars (d'Ercole+08,10,16, Bekki+17)
  - super massive stars (Denissenkov+13, Gieles+18)

Problems:

- mass budget problem
  - $\sim 50 - 70\%$ of enriched stars
  - winds/outflows not enough
  - 1G escaped?, top-heavy IMF?
- He abundance over-predicted
- $N_1/N_{\rm tot} = f(M, \ldots)$, but $N_1/N_{\rm tot} \neq (R_G, \ldots)$



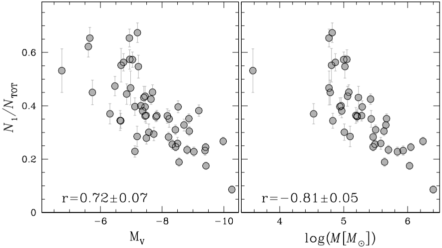
de Mink (2009)

Self-enrichment scenario

- chem. composition suggests enrichment by hot H burning
  (e.g. Gratton+04, Charbonnel+05)
- objects burning hydrogen at high T (20MK+):
  - massive stars
    (Decressin+07, de Mink+09, Elmegreen17, Wünsch+17, Recchi+17, Szécsi+16 . . .)
  - AGB stars (d'Ercole+08,10,16, Bekki+17)
  - super massive stars (Denissenkov+13, Gieles+18)

Problems:

- mass budget problem
  - $\sim 50 - 70\%$ of enriched stars
  - winds/outflows not enough
  - 1G escaped?, top-heavy IMF?
- He abundance over-predicted
- $N_1/N_{\rm tot} = f(M, \dots)$,
  but $N_1/N_{\rm tot} \neq (R_G, \dots)$



Milone+16

- young massive clusters have winds

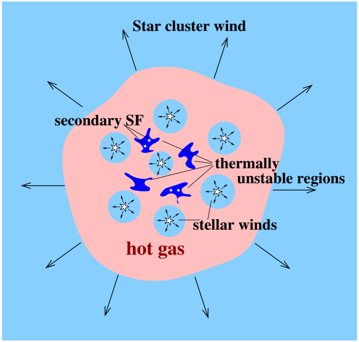
  stellar winds → collisions → shocked wind → outflow
- thermal instability, rapid cooling

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

  cluster gravity ⇒ clumps fall to the centre;

  accumulation ⇒ self-shielding against EUV radiation
- 2nd generation (2G) stars formed

  enriched by products of massive stars chem. evolution



Basic parameters:

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

Rapidly cooling shocked stellar winds model

- young massive clusters have winds

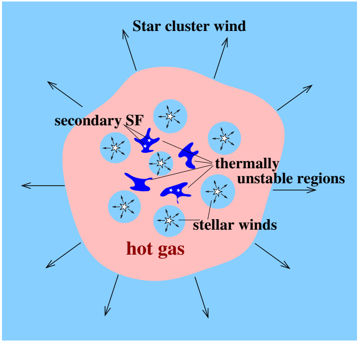
  stellar winds → collisions → shocked wind → outflow
- thermal instability, rapid cooling

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

  cluster gravity ⇒ clumps fall to the centre;

  accumulation ⇒ self-shielding against EUV radiation
- 2nd generation (2G) stars formed

  enriched by products of massive stars chem. evolution

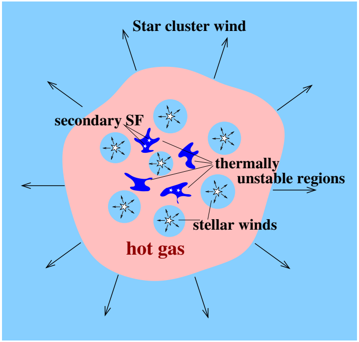


Basic parameters:

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

Rapidly cooling shocked stellar winds model

- young massive clusters have winds
  stellar winds → collisions → shocked wind → outflow
- thermal instability, rapid cooling
  if the cluster is massive and compact enough
- dense warm/cold clumps are formed
  cluster gravity ⇒ clumps fall to the centre;
  accumulation ⇒ self-shielding against EUV radiation
- 2nd generation (2G) stars formed
  enriched by products of massive stars chem. evolution

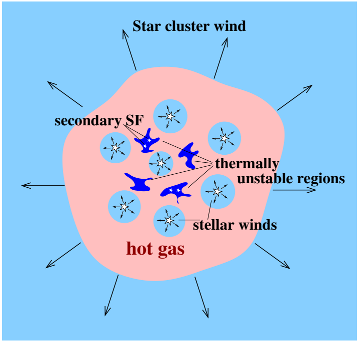


Basic parameters:

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

Rapidly cooling shocked stellar winds model

- young massive clusters have winds
  stellar winds → collisions → shocked wind → outflow
- thermal instability, rapid cooling
  if the cluster is massive and compact enough
- dense warm/cold clumps are formed
  cluster gravity ⇒ clumps fall to the centre;
  accumulation ⇒ self-shielding against EUV radiation
- 2nd generation (2G) stars formed
  enriched by products of massive stars chem. evolution

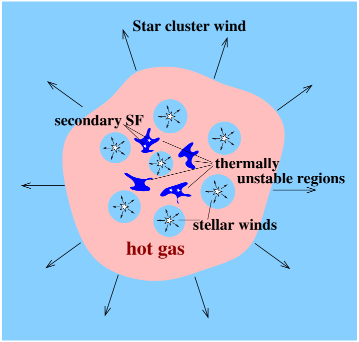


Basic parameters:

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

Rapidly cooling shocked stellar winds model

- young massive clusters have winds
  stellar winds → collisions → shocked wind → outflow
- thermal instability, rapid cooling
  if the cluster is massive and compact enough
- dense warm/cold clumps are formed
  cluster gravity ⇒ clumps fall to the centre;
  accumulation ⇒ self-shielding against EUV radiation
- 2nd generation (2G) stars formed
  enriched by products of massive stars chem. evolution



Basic parameters:

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

Semi-analytic and fully numeric implementation

Semianalytic model:

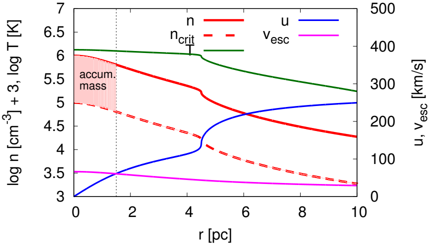
(Chevalier&Clegg+85, Silich+04, Wünsch+17)

$$\frac{1}{r^2}\frac{d}{dr}(\rho u r^2) = q_m$$

$$\rho u \frac{du}{dr} = -\frac{dP}{dr} - q_m u - \nabla\Phi$$

$$\frac{1}{r^2}\frac{d}{dr}\left[\rho u r^2\left(\frac{u^2}{2} + \frac{\gamma}{\gamma-1}\frac{P}{\rho}\right)\right] = q_e - Q$$

$$q_m, q_e \propto (1 + (r/R_c)^2)^{-\beta} \text{ for } r < R_{SC}$$



Mass accumulation:

$$M_{\rm acc}(t) = \int_{t_{bs}}^{t}\int_0^{R_{\rm esc}}[q_m(r,t') - q_{m,crit}(r,t')]drdt'$$

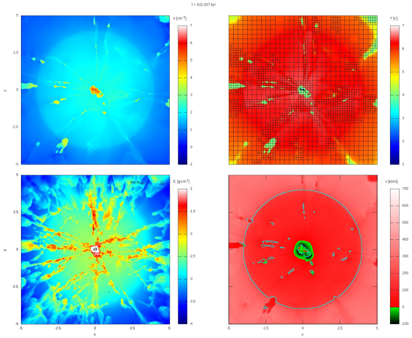
rate of the clump formation is given by $q_m - q_{m,crit}$

only clumps formed with $v < v_{\rm esc}$ accumulate

RHD simulations:

(Wünsch+17):

- AMR code Flash, 512^3 (finest) (Fryxell+00)
- opt. thin cooling (Schure+09)
- fixed stellar gravity, self-gravity
  → tree code (Wünsch+18)
- ionising radiation
  → TreeRay (Wünsch, in prep.)



Semianalytic model:

(Chevalier&Clegg+85, Silich+04, Wünsch+17)

$$\frac{1}{r^2}\frac{d}{dr}(\rho u r^2) = q_m$$

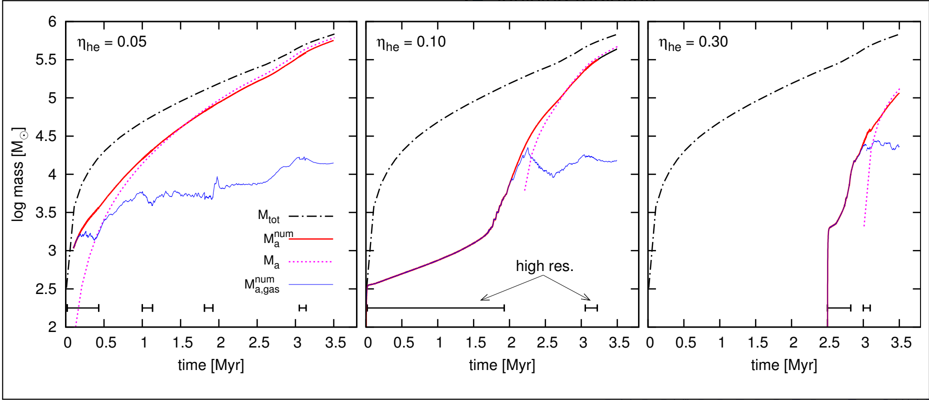
$$\rho u \frac{du}{dr} = -\frac{dP}{dr} - q_m u - \nabla\Phi$$

$$\frac{1}{r^2}\frac{d}{dr}\left[\rho u r^2\left(\frac{u^2}{2} + \frac{\gamma}{\gamma-1}\frac{P}{\rho}\right)\right] = q_e - Q$$

RHD simulations:

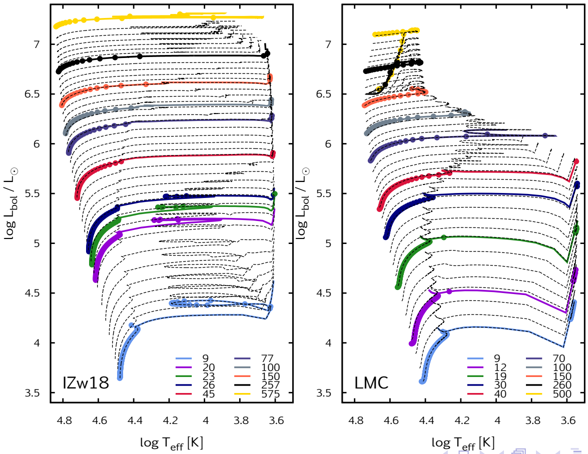
(Wünsch+17):

- AMR code Flash, 512^3 (finest) (Fryxell+00)
- opt. thin cooling (Schure+09)
- fixed stellar gravity, self-gravity → tree code (Wünsch+18)
- ionising radiation



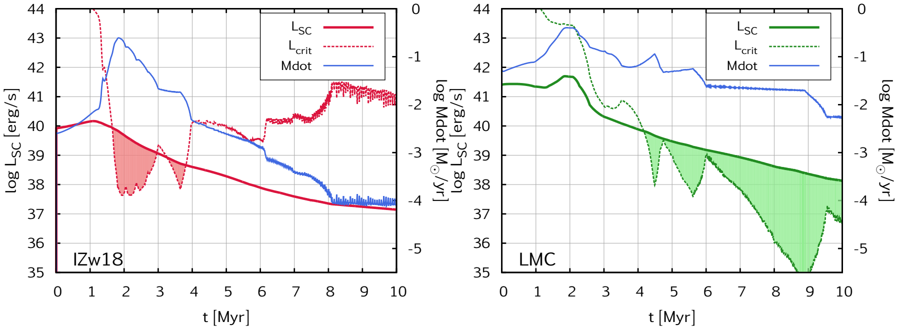
Stellar evolution

- tracks by D. Szécsi (Bonn stellar evol. code)
  → Szécsi & Wünsch (submitted, arXiv:1809.01395)
- $M_{\rm max} = 500\,{\rm M}_\odot$, $Z = 0.02\,{\rm Z}_\odot$ (IZw18) vs. $Z = 0.4\,{\rm Z}_\odot$ (LMC)



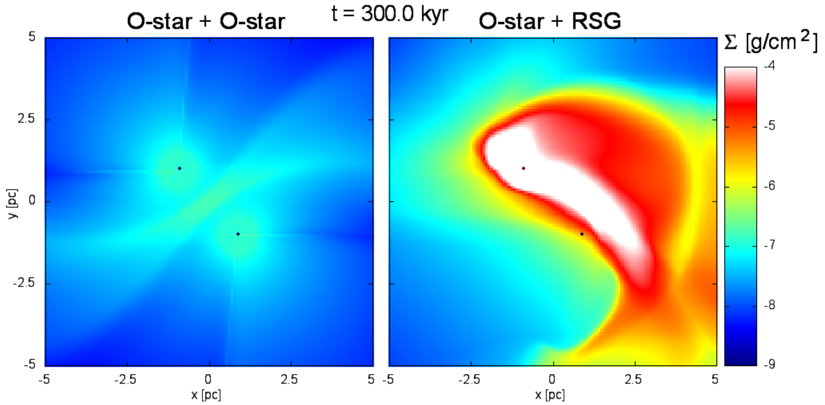
Star cluster wind evolution

- period of instability: $L_{SC} > L_{crit} \rightarrow$ mass accumulation
- low Z: 1.8 – 3.8 Myr (before SNe)
- high Z: 4.2 – 10 Myr (during SNe)

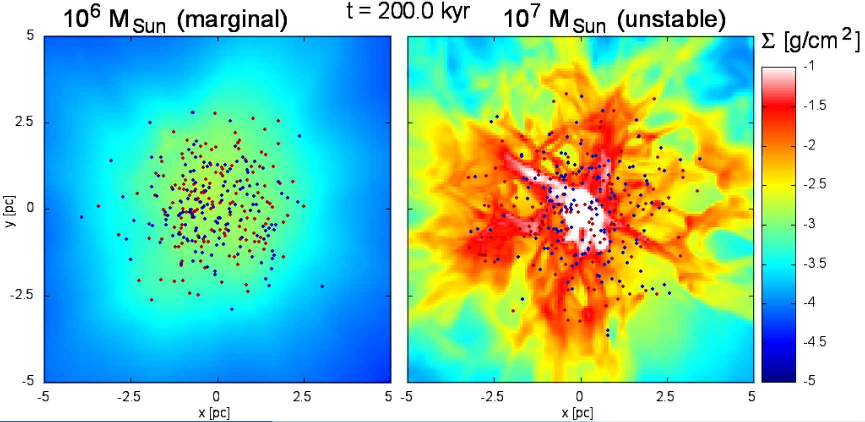


RSG wind + hot star wind → cluster wind?

- convergence of the cluster consisting of hot stars to the smooth wind solution tested by Cantó+00, Raga+01,. . .
- however, does it work also for hot stars mixed with RSGs?
- mass and momentum inserted into a sphere with $r = 4$ cells

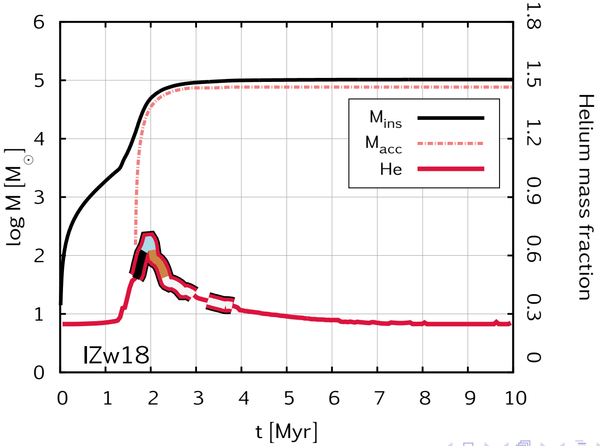


- cluster with $M = 10^6\,\mathrm{M}_\odot$ 2.4 Myr includes:
  150 RSGs $\rightarrow$ representedi with 150 sources
  $\sim$ 7000 massive MS stars $\rightarrow$ represented with 150 sources
  $\Rightarrow$ marginally unstable (left)
- cluster with $M = 10^7\,\mathrm{M}_\odot$ 2.4 Myr includes:
  $10\times$ more RSGs and hot stars $\rightarrow$ represented y 2×150 sources
  $\Rightarrow$ fully thermally unstable (right)



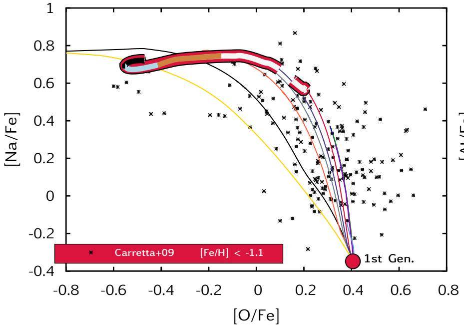
Accumulated mass (for $M_{1G} = 10^7\,M_\odot$)

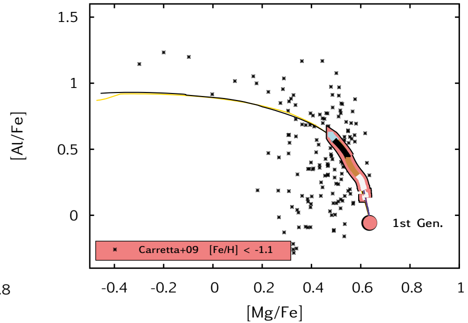
- inserted $M_{ins} = 10^5\,M_\odot$, accumulated $M_{acc} = 8 \times 10^4\,M_\odot$ (80%)
- C+N+O constant $\Rightarrow$ no He burning products (good!)
- He mass fraction in accum. mass: 0.7 (max), 0.52 (mean)



Chemical composition

- Na-O: range reproduced well
- Mg-Al: predicted range smaller
  (some stars have correct chem. composition, however, their mass is not accumulated)

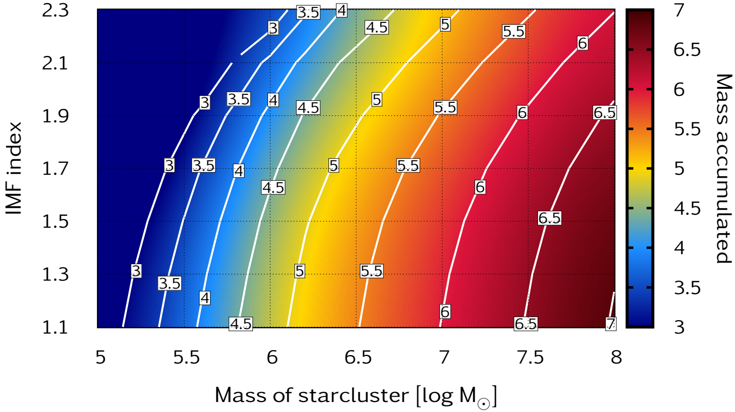




Param. space: mass budget

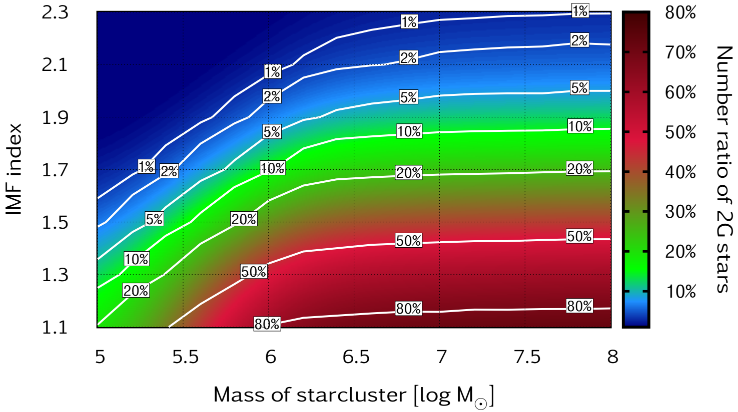
Varied parameters:

- first generation mass: M_{1G}
- IMF high-mass slope: α (Salpeter = 2.35)



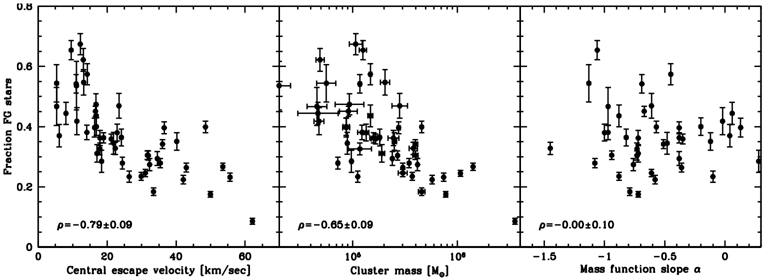
Param space: population ratio N_2/N_{tot}

- 2G stars form with standard IMF (not only low mass stars)
- only stars between 0.08 and 0.8 $M_\odot$ considered for N_1 and N_2
- no dynamical mass loss of the first generation assumed



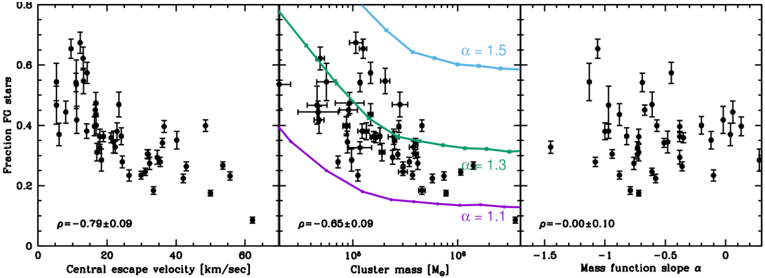
Population ratio correlations

- GC structural params. determined by fitting N-body sims. (Baumgardt & Hilker18)
- $N_1/N_{\rm tot}$ correlates best with $v_{\rm esc}$; does not correlate with present mass function
- suggests that ability to keep wind ejecta determines N_1, and not dynamical mass loss



Population ratio correlations

- GC structural params. determined by fitting N-body sims. (Baumgardt & Hilker18)
- $N_1/N_{\rm tot}$ correlates best with $v_{\rm esc}$; does not correlate with present mass function
- suggests that ability to keep wind ejecta determines N_1, and not dynamical mass loss



Summary

Rapidly cooling shocked stellar winds + low Z stellar evolution models

- almost all massive stars winds (including fast ones) can be captured
- 2G stars predicted to form in the cluster centre
- chemical composition of the accumulated mass:
  - C+N+O = const, Na-O anticorrelation → OK
  - He mass fraction, Mg-AL anticorrelation → not so well
- mass budget:
  - correct population ratios can be obtained with IMF slope 1.3; (Salpeter = 2.35)
  - with reasonable assumption about 2G IMF
  - dynamical mass lost of 1G can make this slope closer to the standard IMF
- fraction of second generation correlates with GC mass
  →in agreement with observations

Thank you!