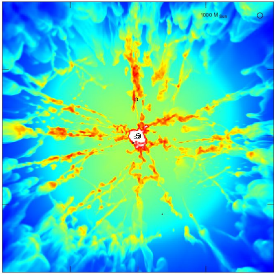
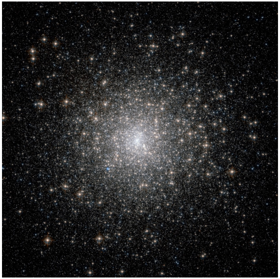
Multiple stellar populations in globular clusters from winds of massive stars

Richard Wünsch

Zooming in on Star Formation, Nafplio, 13th June 2019



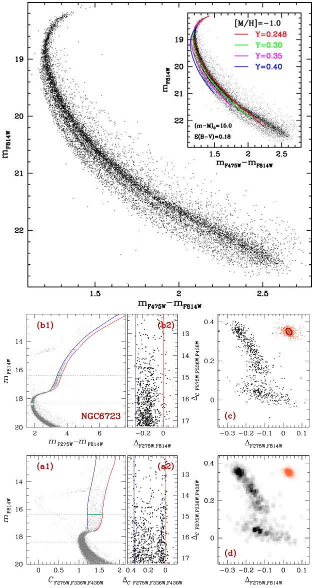


In collaboration with:

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

Multiple stellar populations in GCs

- photometric evidence:
  $\rightarrow$ split main-sequence (also RGB, SGB, EHB, TO)
  (Bedin+04, Piotto+07, Milone11,12,13,15, . . .)
- spectroscopic evidence:
  $\rightarrow$ anticor. among pairs of light elements
  (e.g. Na-O, Mg-Al, . . .) Carreta+06,09 $\rightarrow$ signature of hot H burning (massive stars, AGB, SMS)
  (e.g. Gratton+04, Charbonnel+05)
- correspond. between both (Milone+15)
- constant Fe (and other heavier elements):
  (exceptions: ωCen, . . . $\rightarrow$ anomalous GC)
  $\rightarrow$ no SN enrichment; origin from one cloud
- universal for GCs:
  $\rightarrow$ determined: M, [Fe/H], M/R?, age (2Gyr?)
- variable pop. fraction:
  $N_1/N_{\rm tot} = f(M, \dots)$, but $N_1/N_{\rm tot} \neq (R_G, \dots)$



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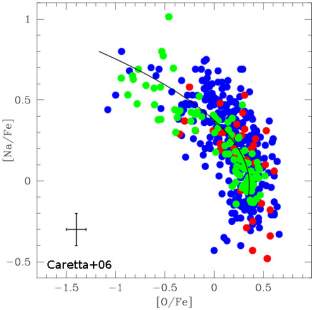

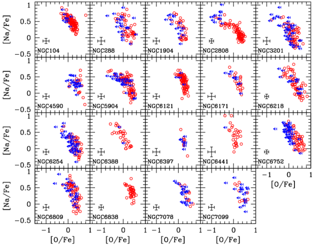

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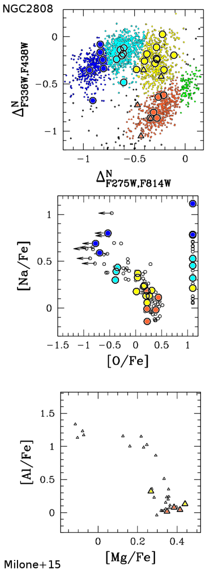

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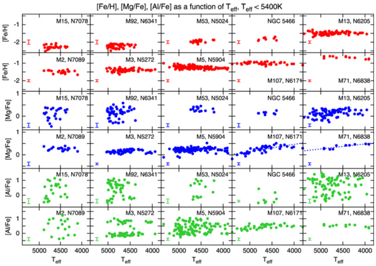

Mészáros+15

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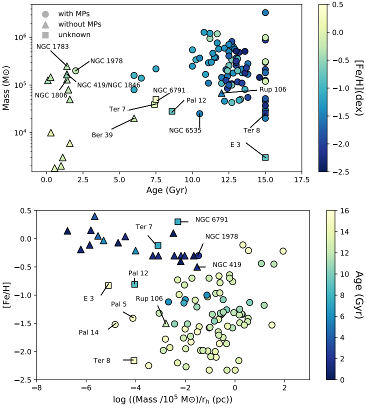

Bastian&Lardo18

(see review in ARA&A)

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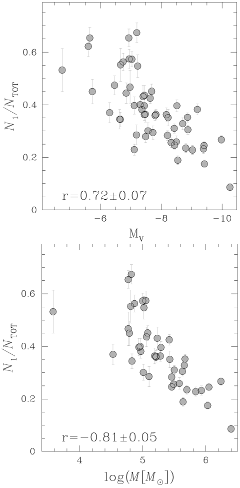

Milone+17

Rapidly cooling shocked stellar winds model

- self-enrichment scenario: 2G stars are form out of winds of 1G stars
  $\rightarrow$ mass budget problems: how to (i) produce enough enriched mass, and (ii) capture it?
- 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

Basic parameters:

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

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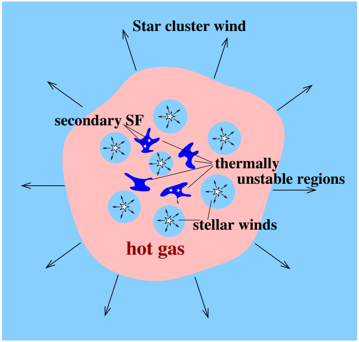

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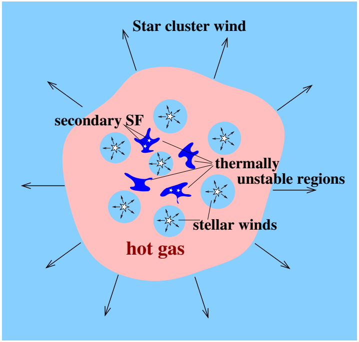

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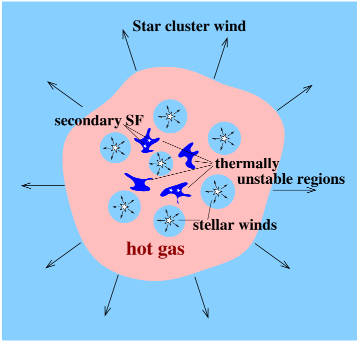

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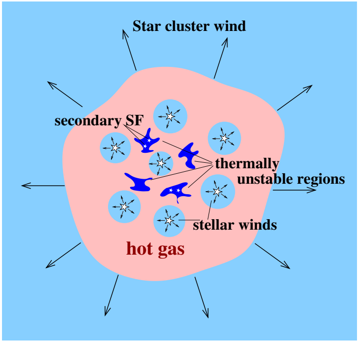

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Semi-analytic and fully numeric implementation

Semi-analytic model:

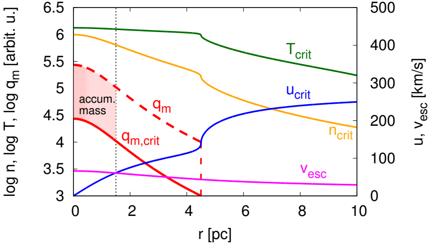
(Chevalier&Clegg+85, Silich+04, Wünsch+17)

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

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

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

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



Mass accumulation:

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

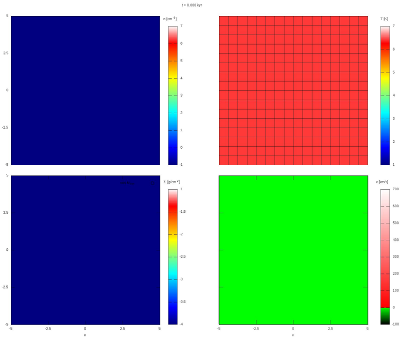
rate of the clump formation is given by $q_m - q_{m,crit}$

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.)



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Semi-analytic model: , RHD simulations:

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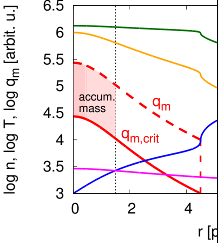
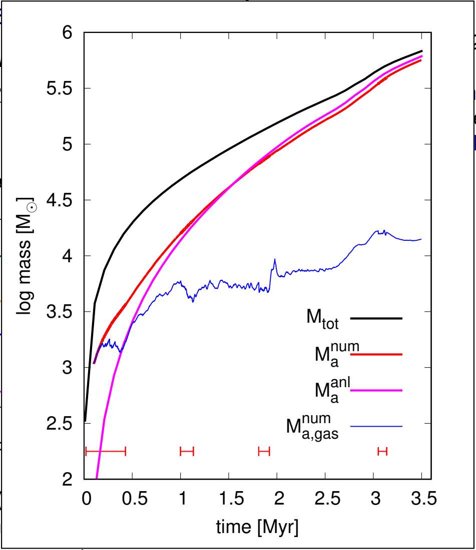
$q_m, q_e \propto (1 + (r/R$





2^3 (finest)

ure+09)

elf-gravity

h+18)

, in prep.)

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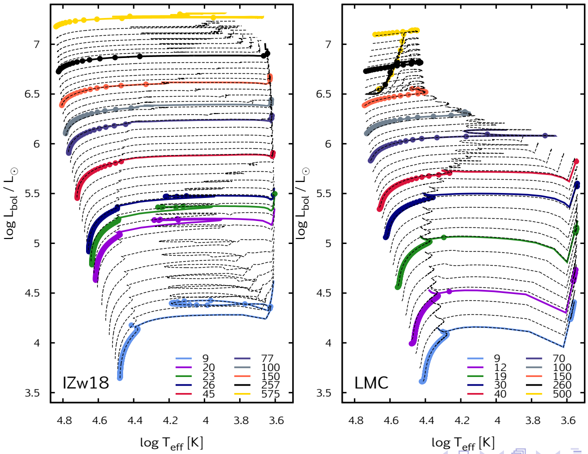
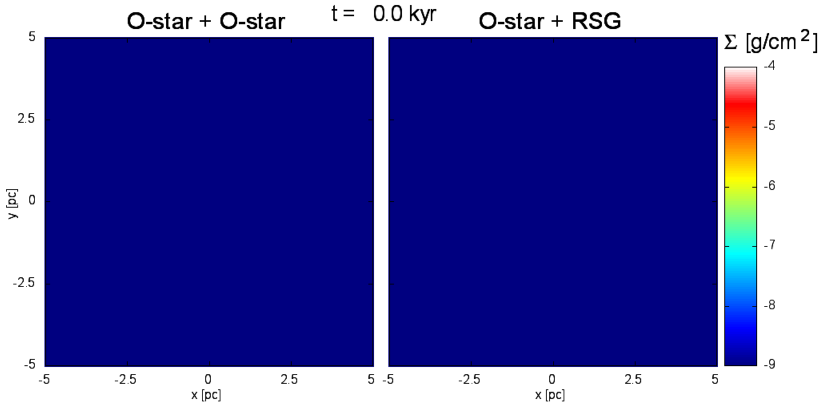
- tracks by D. Szécsi (Bonn stellar evol. code)
  → Szécsi & Wünsch (2019)
- $M_{\rm max} = 500\,{\rm M}_\odot$, $Z = 0.02\,{\rm Z}_\odot$ (IZw18) vs. $Z = 0.4\,{\rm Z}_\odot$ (LMC)



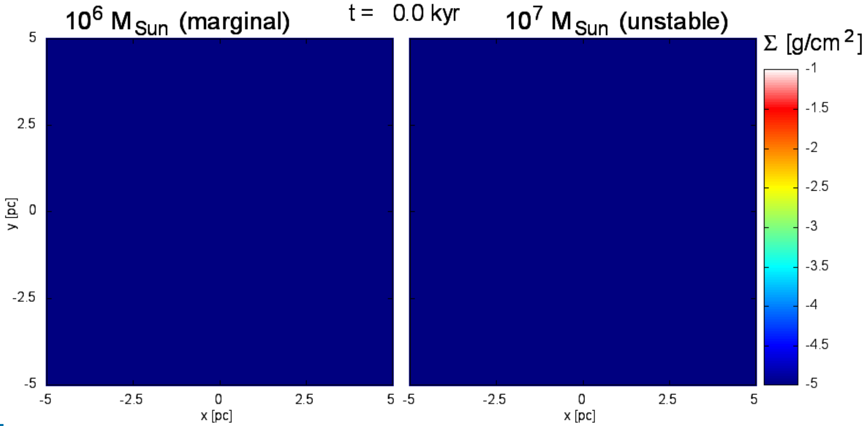
RSG wind + hot star wind → cluster wind?

- 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



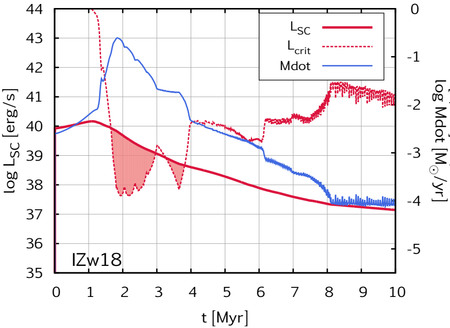
Simulations with individual sources

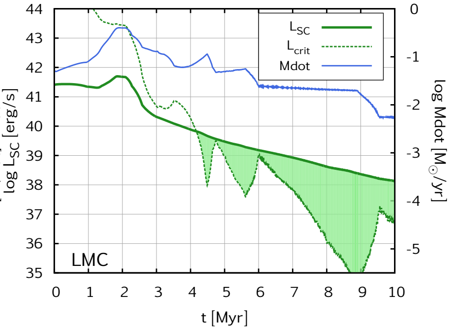
- cluster with $M = 10^6\,\mathrm{M}_\odot$ 2.4 Myr includes:
  150 RSGs $\rightarrow$ represented with 150 sources
  $\sim$ 7000 massive MS stars $\rightarrow$ represented with 150 sources
  $\Rightarrow$ marginally unstable (left)
- cluster with $M = 10^7\,\mathrm{M}_\odot$ 2.4 Myr includes:
  10$\times$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



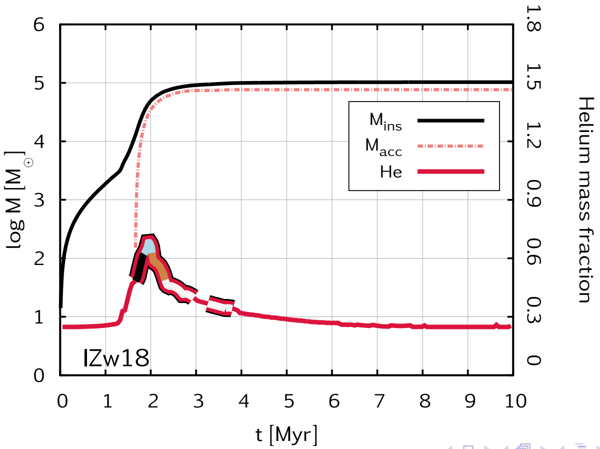
Star cluster wind evolution

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



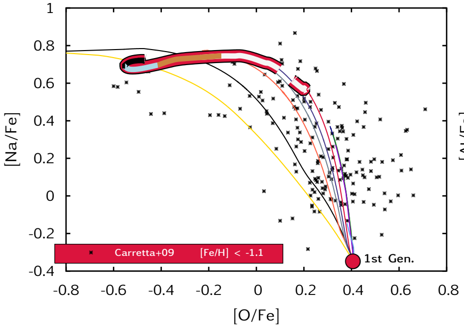


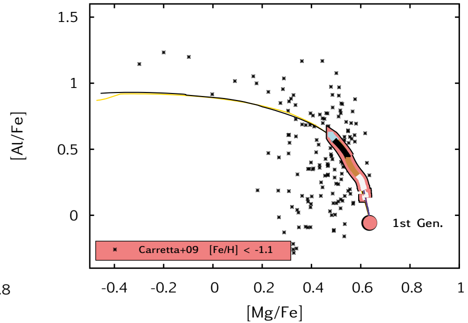
- inserted $M_{\rm ins} = 10^5\,\mathrm{M}_\odot$, accumulated $M_{\rm acc} = 8 \times 10^4\,\mathrm{M}_\odot$ (80%)
- C+N+O constant $\Rightarrow$ no He burning products (good!)
- He mass fraction in accum. mass: 0.7 (max), 0.52 (mean)



- Na-O: range reproduced well
- Mg-Al: predicted range smaller

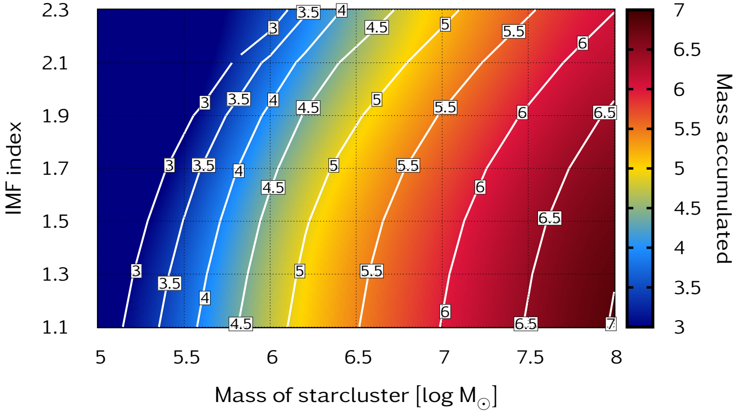
  (some stars have correct chem. composition, however, their mass is not accumulated)





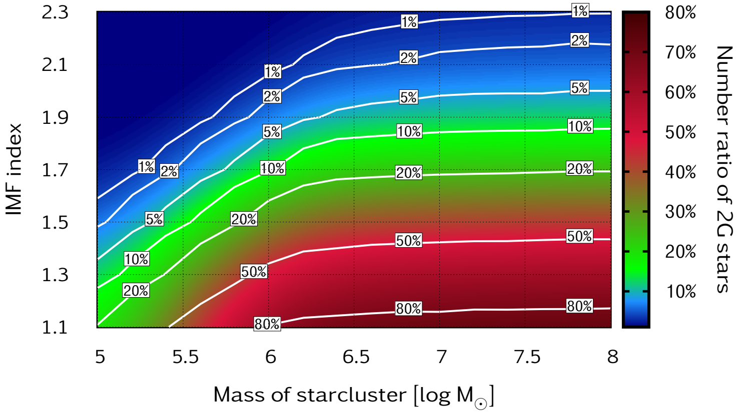
Varied parameters:

- 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



Predicted IMF slope for Galactic GC

What IMF slope is needed to get the observed population ratios?

- N_{2+}/N_{tot} for MW GC (Milone+17)
- $M_{\rm GC}$ and $R_{\rm GC}$ (Baumgardt&Hilker18)
- stellar evolution:
  - $M_{\rm GC} \rightarrow M_{\rm 1G}$ ($\leftarrow$IMF slope)
  - $R_{\rm GC} \rightarrow R_{\rm 1G}$ ($\leftarrow M_{\rm 1G}/M_{\rm GC}$, virial th.)
- for each GC, find IMF slope so that:

$$\left.\frac{N_{2+}}{N_{tot}}\right|_{\rm pred} = \left.\frac{N_{2+}}{N_{tot}}\right|_{\rm obs}$$

- IMF shallower for higher mass clusters (with higher N_{2+}):
  - shallow IMF $\rightarrow$ more massive stars $\rightarrow$ more enriched mass
  - shallow IMF $\rightarrow$ more massive cluster capture winds more efficiently
- caveats: no dynamical mass loss, const $Z_{\rm 1G} = 0.02 Z_{\odot}$

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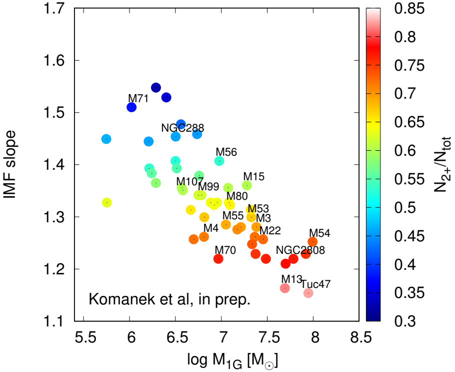

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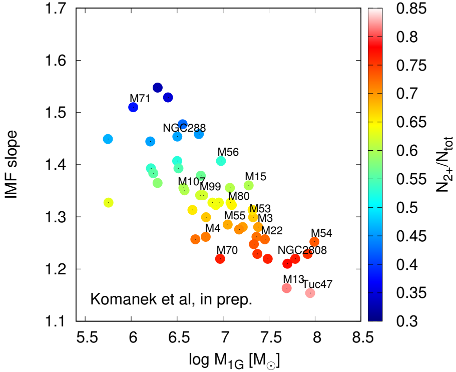

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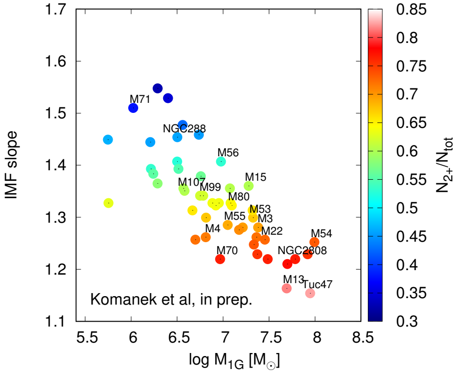

- IMF shallower for higher mass clusters (with higher N_{2+}):
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  - shallow IMF → more massive cluster capture winds more efficiently
- caveats: no dynamical mass loss, const $Z_{\rm 1G} = 0.02 Z_\odot$

What IMF slope is needed to get the observed population ratios?

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- $M_{\rm GC}$ and $R_{\rm GC}$ (Baumgardt&Hilker18)
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  - $M_{\rm GC} \rightarrow M_{\rm 1G}$ (←IMF slope)
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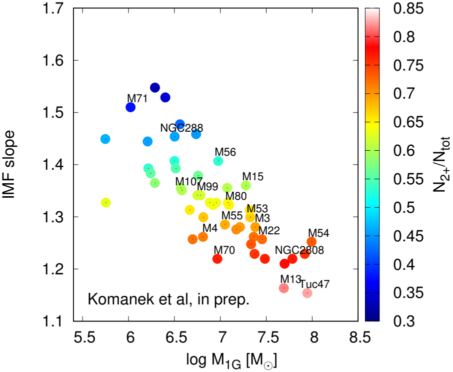

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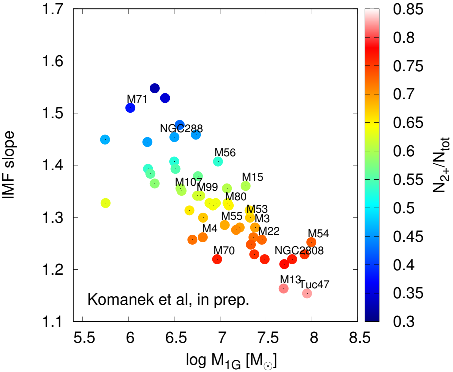

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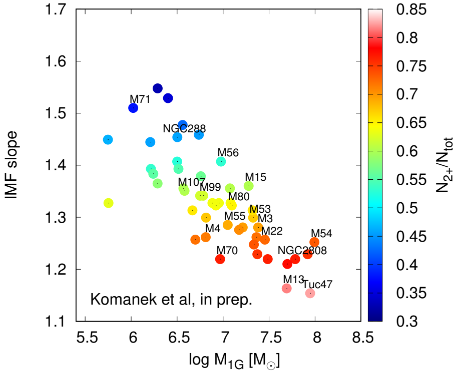

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Summary

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 $\rightarrow$ OK
  - He mass fraction, Mg-AL anticorrelation $\rightarrow$ not so well
- mass budget:
  - observed population ratios can be obtained with IMF slope $\sim 1.1 - 1.6$; (Salpeter = 2.35)
  - with reasonable assumption about 2G IMF
  - dynamical mass lost of 1G can make this slope closer to the standard IMF
- more massive clusters (with higher fraction of enriched population) need shallower IMF to form

Thank you!