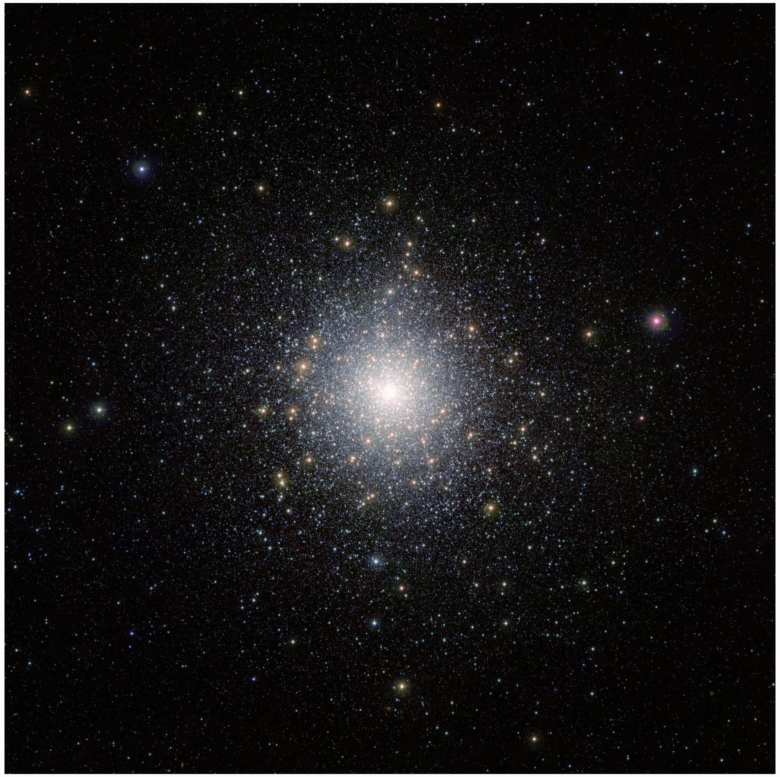
Multiple stellar populations and their evolution in globular clusters



Part II – Multiple Populations

Towards a new paradigm

- ✓ Heavy elements in GCs
- ✓ Light elements and the presence of multiple populations
- ✓ Photometric signatures
- ✓ Potential polluters
  - Details on AGB physics
  - Details on massive star physics
- ✓ GC initial masses
- ✓ Early dynamical and chemical evolution

Towards a global scenario (?)

Corinne Charbonnel
Dept of Astronomy, Univ. of Geneva
& IRAP CNRS, Univ. of Toulouse

C-N, O-Na, Mg-Al, F-Na, Li-Na anticorrelations
[(C+N+O)] ~ constant within experimental errors
[Fe/H] constant

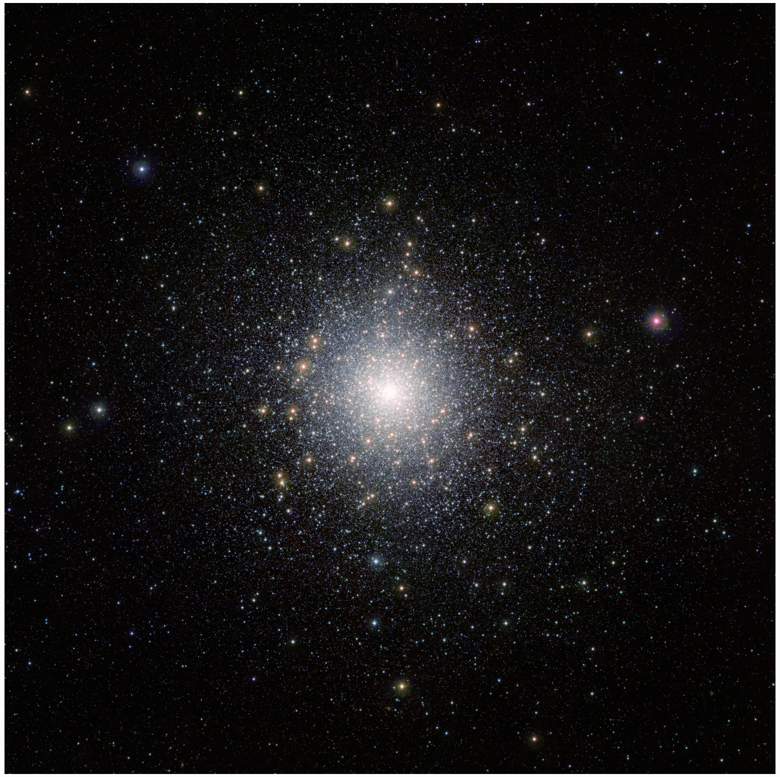
H-burning through CNO, NeNa, MgAl
H-burning ashes mixed with pristine gas

} →2d generation

No recycling of He-burning products

No recycling of supernovae ejecta,
except in some rare (most massive) cases (e.g., Ω Cen or M22)

Multiple stellar populations and their evolution in globular clusters



Part II – Multiple Populations

Towards a new paradigm

- ✓ Heavy elements in GCs
- ✓ Light elements and the presence of multiple populations
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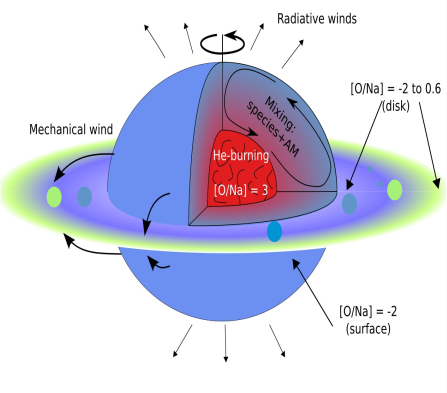
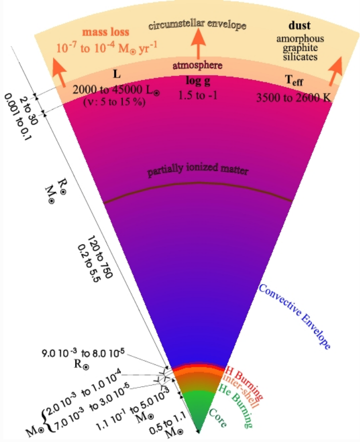
  Towards a global scenario (?)

Proposed polluters (H-burning at T ~ 72 to 78 MK)



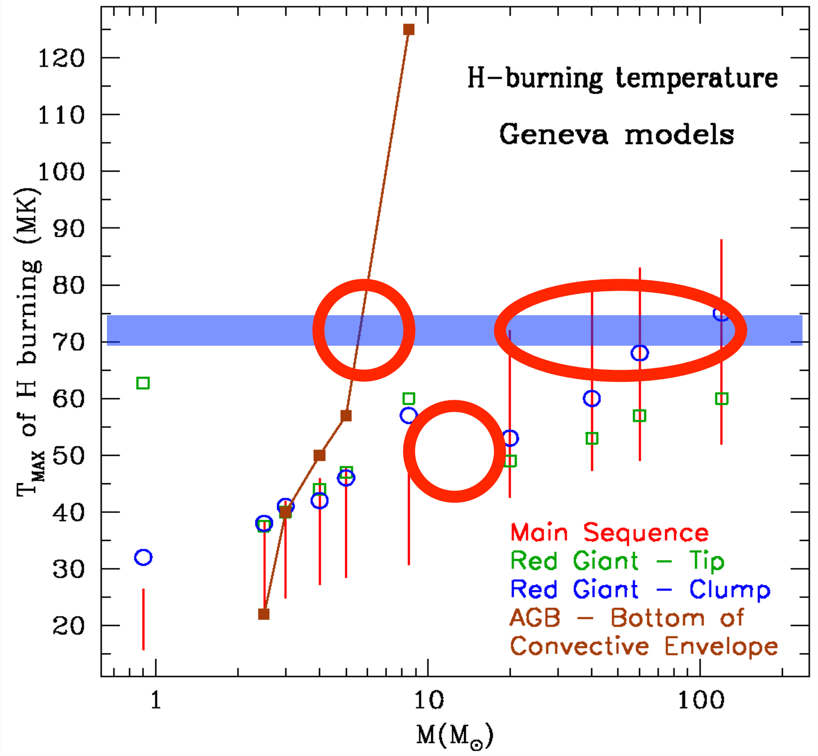
Fast Rotating
Massive Stars
(FRMS)
$\geq 25\ M_\odot$

Prantzos & Charbonnel (06)
Decressin *et al.* (07a,b), Krause *et al.* (12,13)



Massive
AGB
$\sim 5 - 6\ M_\odot$

Ventura *et al.* (01, 11, 13)
D'Ercole *et al.* (11)

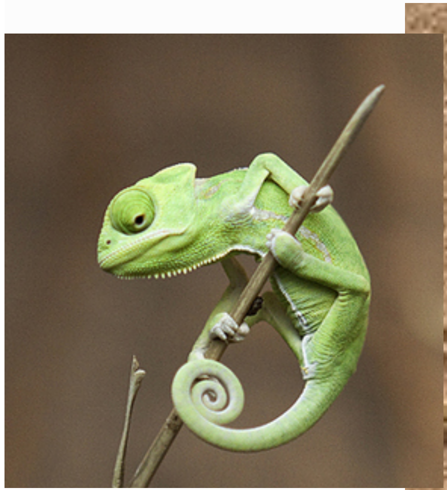


Massive binaries
$\sim 10 - 20\ M_\odot$
De Mink *et al.* (10)

Supermassive stars
$\sim 10^4\ M_\odot$
Denissenkov & Hartwick (14)

Who is the culprit?
When and how did it happen?

AGB



FRMS

Supermassive star

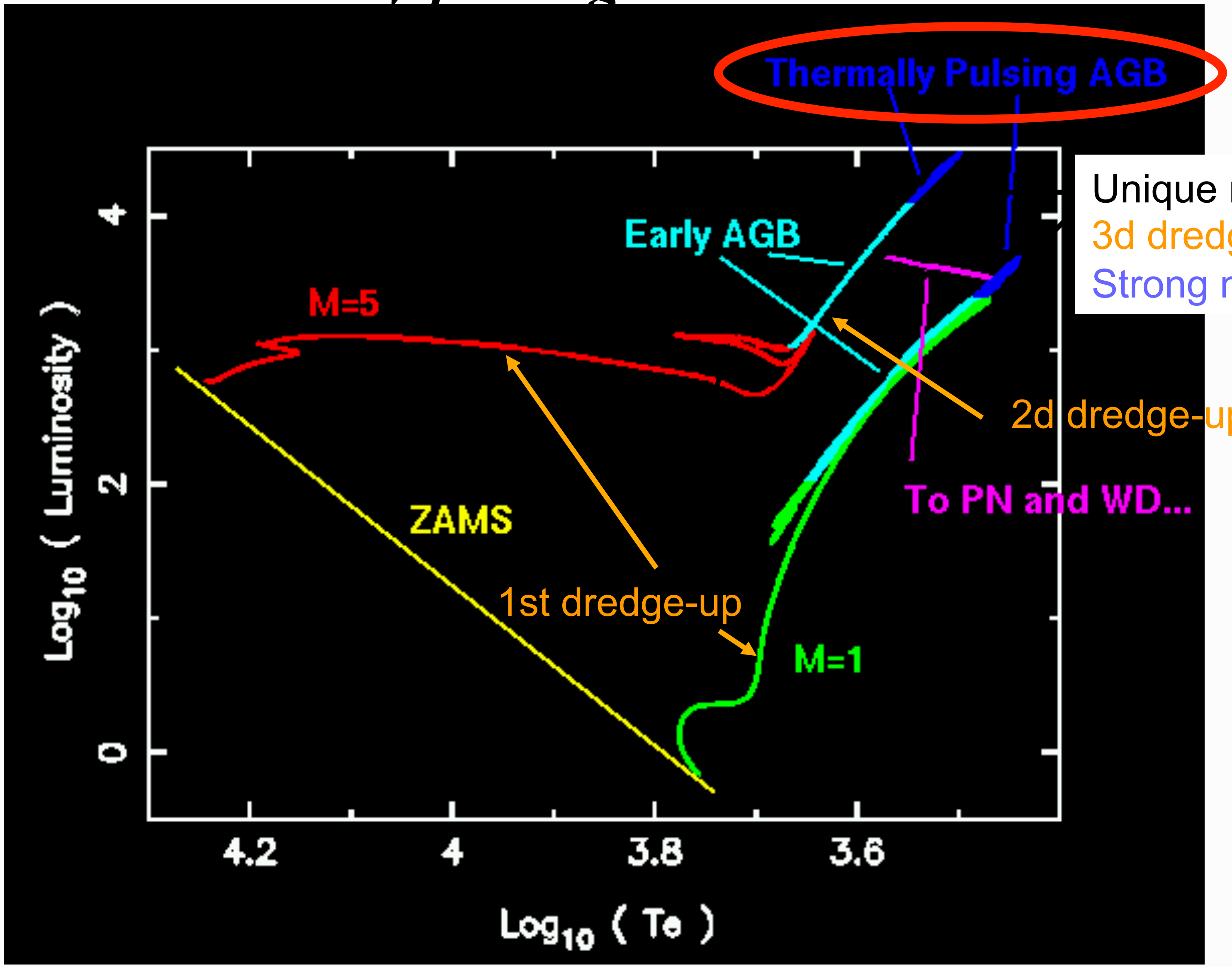
Massive binaries

Who is the culprit?

When and how did it happen?

AGB

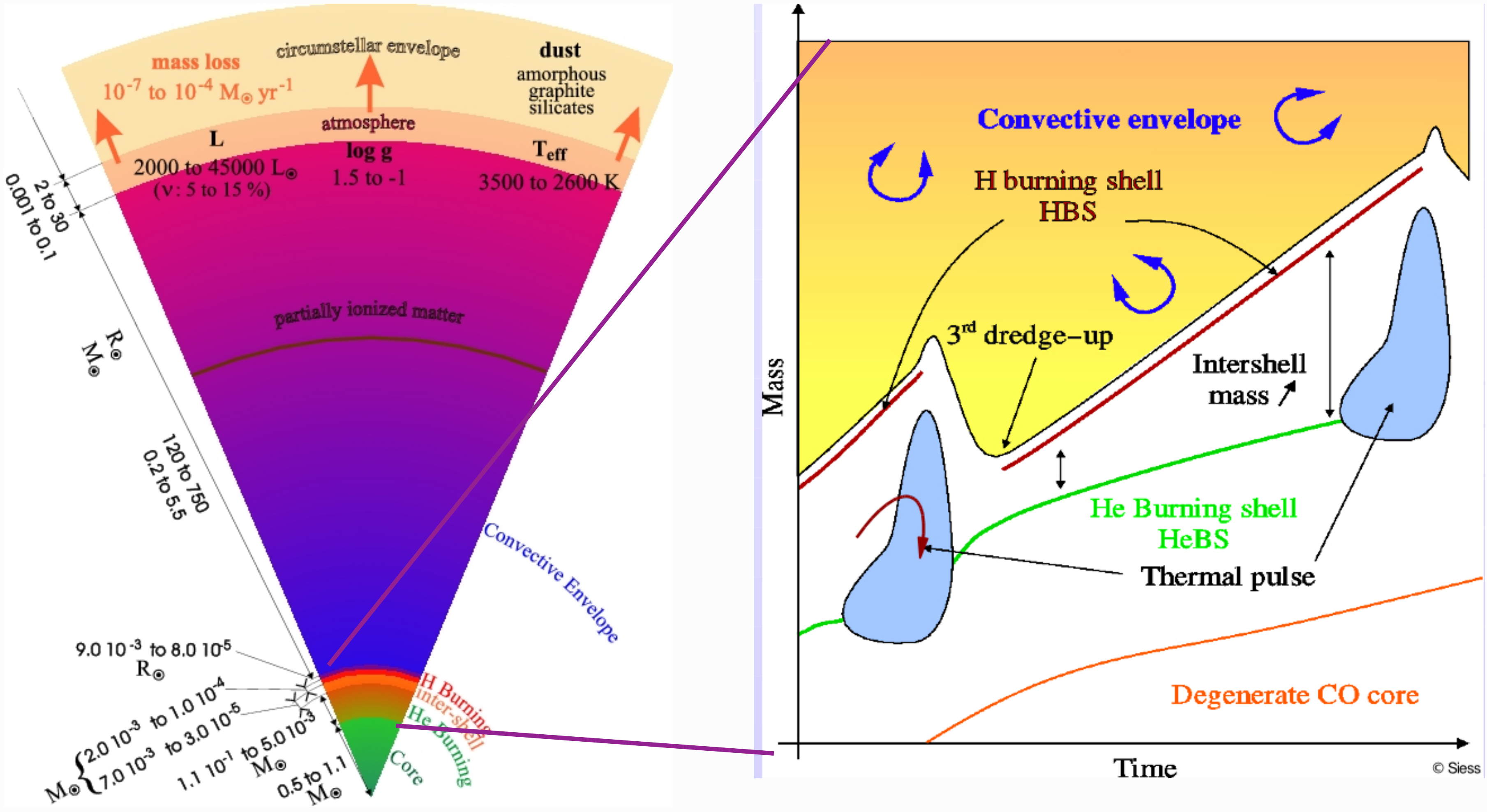
Thermally-pulsing AGB stars



Unique nucleosynthesis
3d dredge-up
Strong mass loss

Adapted from Lattanzio

TP-AGB



Figures by Forestini (AGB slice) & Siess (Kippenhahn diagram)

TP-AGB

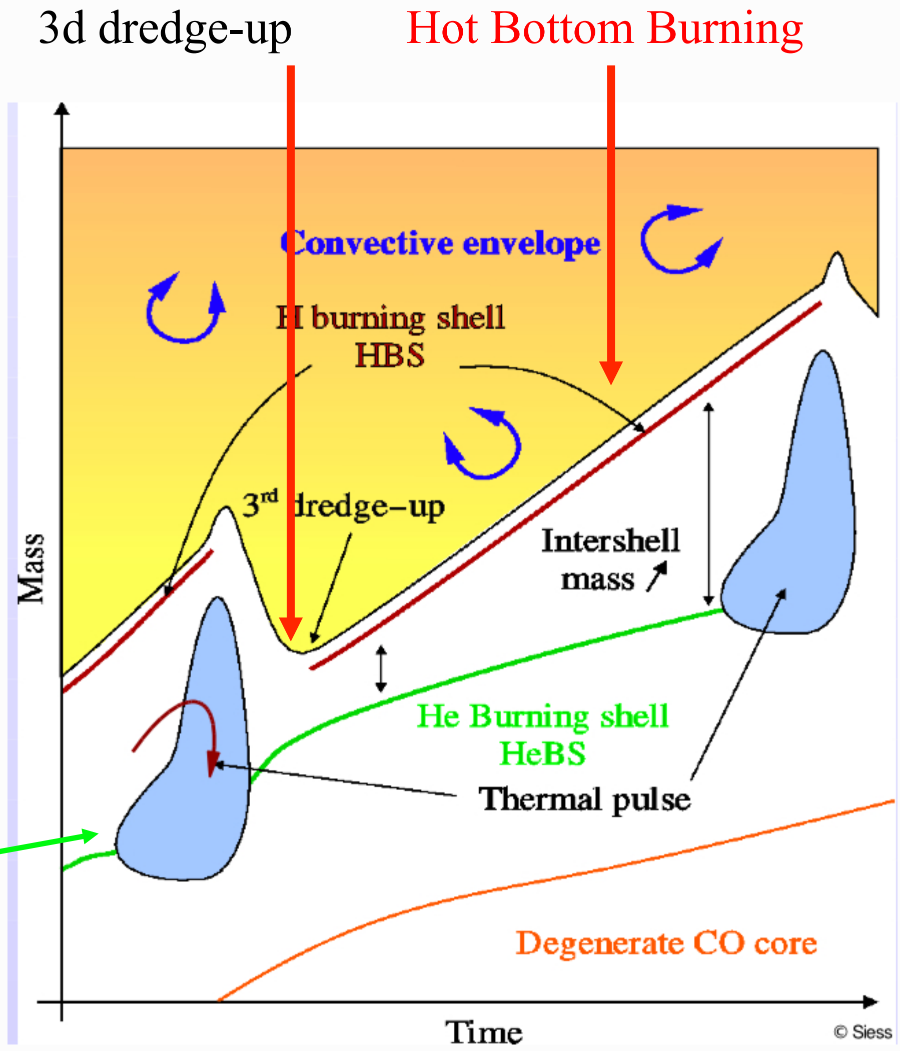
HBB (M > 4M$_{\odot}$) CNO, NeNa, MgAl

At high T, ^{23}Na(p,γ)^{24}Mg

^{26}Al **producted from** ^{25}Mg

At very high T : ^{24}Mg ↓

3d dredge-up of the
ashes of the
thermal pulse
into the
convective
envelope
↗ ^{16}O, ^{22}Ne
↗ C+N+O



He burning

$3\alpha \rightarrow {}^{12}C \rightarrow {}^{12}C(\alpha,\gamma)\mathbf{^{16}O}$

^{14}N (CNO) $\rightarrow {}^{14}N(\alpha,\gamma){}^{18}F(\beta+){}^{18}O(\alpha,\gamma)\mathbf{^{22}Ne}$

↗ C+N+O

Figure by Siess

AGB

Subtle competition between

✓ **Third dredge-up** ($M \geq 1.5 M_\odot$ at $Z_\odot$)

products of He-burning in the TP ↑

^{4}He, ^{12}C, ^{16}O, ^{22}Ne, ^{25,26}Mg (s-process elements) ↑

✓ **Hot-bottom burning** ($M \geq 4 - 4.5 M_\odot$)

CN-cycle : $^{12}\mathrm{C} \rightarrow {}^{14}\mathrm{N}$ ON-cycle : $^{16}\mathrm{O} \rightarrow {}^{14}\mathrm{N}$

NeNa : → Na ↑ and ↓ at higher T

MgAl : Al ↑ at the expense of ^{25,26}Mg and

eventually of ^{24}Mg

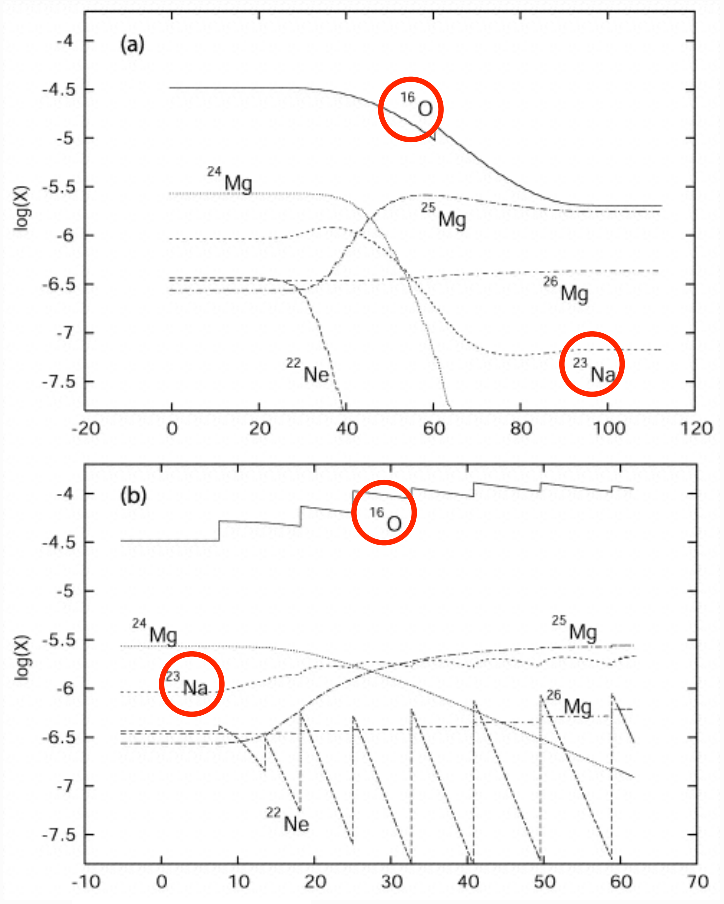
Difficult to get the O-Na anticorrelation (rather a correlation)

Impact of mass loss, convection treatment, metallicity, etc …

Ventura & D'Antona (02, 05a,b,c, 06, 07, 08a,b, 09, 10)

Evolution of the surface abundances of O and Na

Delicate interplay of 3d dredge-up and hot bottom burning



t/1000yr
(t=0 : 1st TP)
5M$_\odot$

(a) <u>No 3DUP, only HBB</u>

→ Large ^{16}O depletion

→ ^{23}Na depletion

(due to the lack of primary ^{22}Ne dredged-up)

(b) <u>Strong 3DUP, HBB, no mass loss</u>

→ 3DUP of the ^{16}O-rich layers below the TP

→ ^{23}Na increase (from dredged-up ^{22}Ne)

→ O-Na CORRELATION

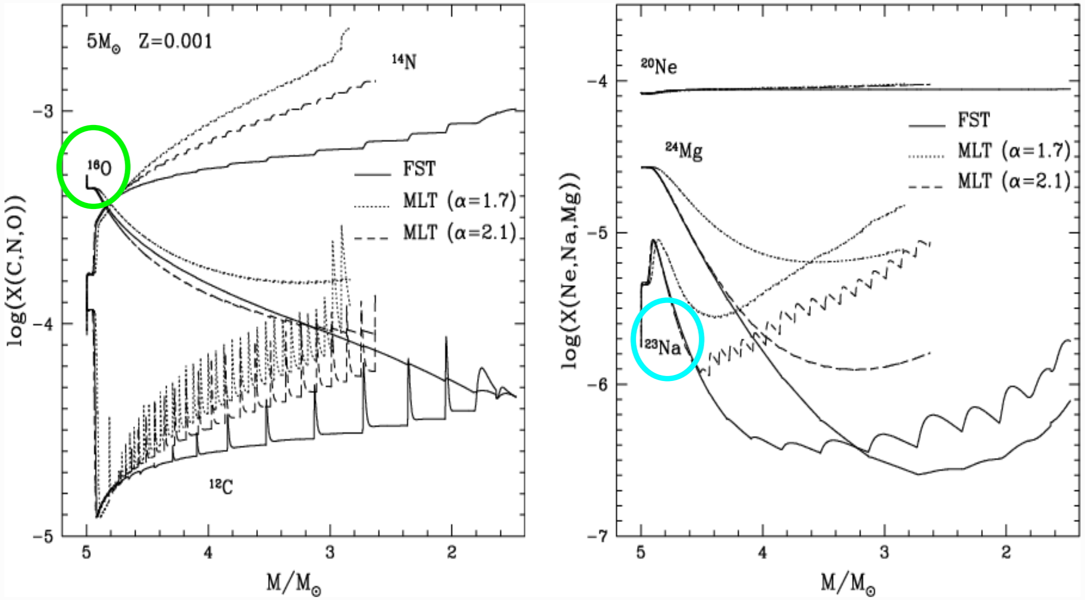
See also the models by
Ventura, D'Antona et al.,
Lattanzio, Karakas, Fenner et al.,
Decressin, Charbonnel et al.

Denissenkov & Herwig (03) Full evolution models

Treatment of convection

Ventura & D' Antona (05a)
See also Renzini & Voli (81), Sackmann & Boothroyd (91)
Blöcker & Schönberner (91), D'Antona & Mazzitelli (96)

Full Spectrum of Turbulence (Canuto & Mazzitelli 91)
→ **<u>much more efficient HBB</u>** than with MLT
(on the AGB : higher L, stronger mass loss, less 3DUPs)



<u>MLT17</u> : ⋯⋯⋯⋯⋯
Little O depletion (factor of ~2)
Increase of Na and N
C+N+O increase by ~ 0.8 dex

<u>FST</u> : ———
Larger O depletion
Slight decrease of Na
C+N+O ~ conserved

Evolution of the surface abundances of O and Na

Delicate interplay of 3d dredge-up and hot bottom burning

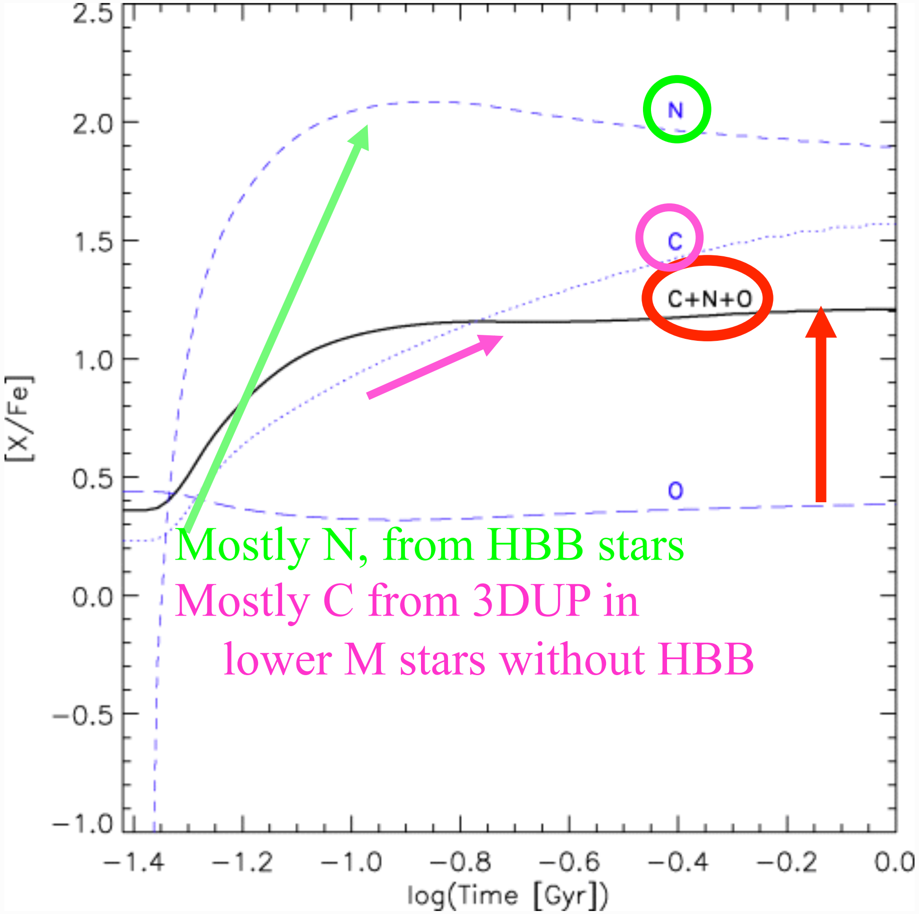
→ O-Na CORRELATION

« While Na and O appear to be anticorrelated in the cluster stars, from the stellar models they turn out to be correlated into the AGB ejecta…
Thus the 2d generation stars should exhibit an O-Na correlation, in glaring conflict with the observations.»

D'Ercole, D'Antona, Vesperini (11)

GCCE model including AGB predictions

Fenner et al. (04)



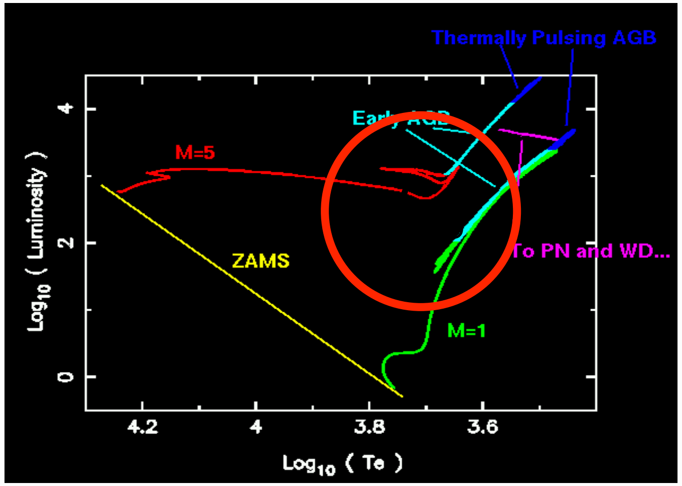
Mostly N, from HBB stars

Mostly C from 3DUP in
lower M stars without HBB

Almost 1 order of magnitude rise
of [C+N+O / Fe]
within 1Gyr of formation
(due to the DUP of the products
of He-burning)

C+N+O is found to be ~ constant
in many GCs
(Pilachowski et al. 88,
Dickens et al. 91,
Smith et al. 96, Ivans et al. 99)

Before the TP-AGB - Rotating models



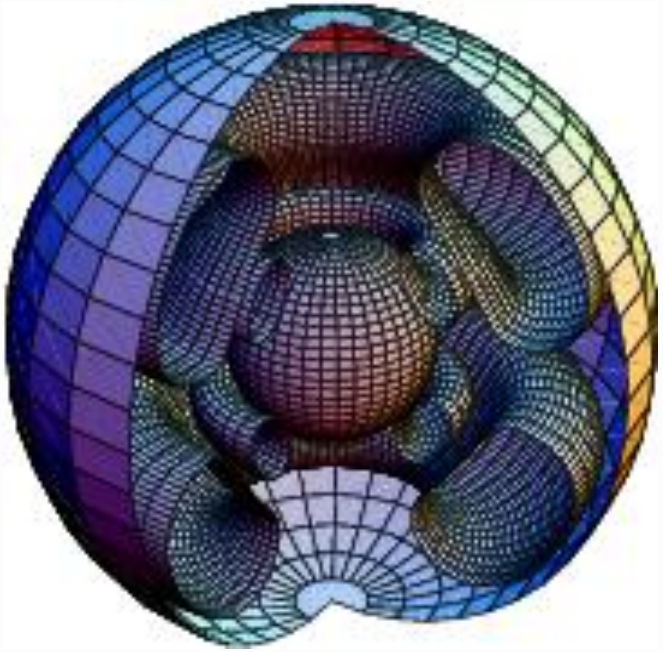


Fig. courtesy
G.Meynet

Meridional circulation and
shear turbulence
Transport of angular momentum
and of chemicals
Zahn (92), Chaboyer & Zahn (95)
Talon & Zahn (97), Maeder & Zahn (98)

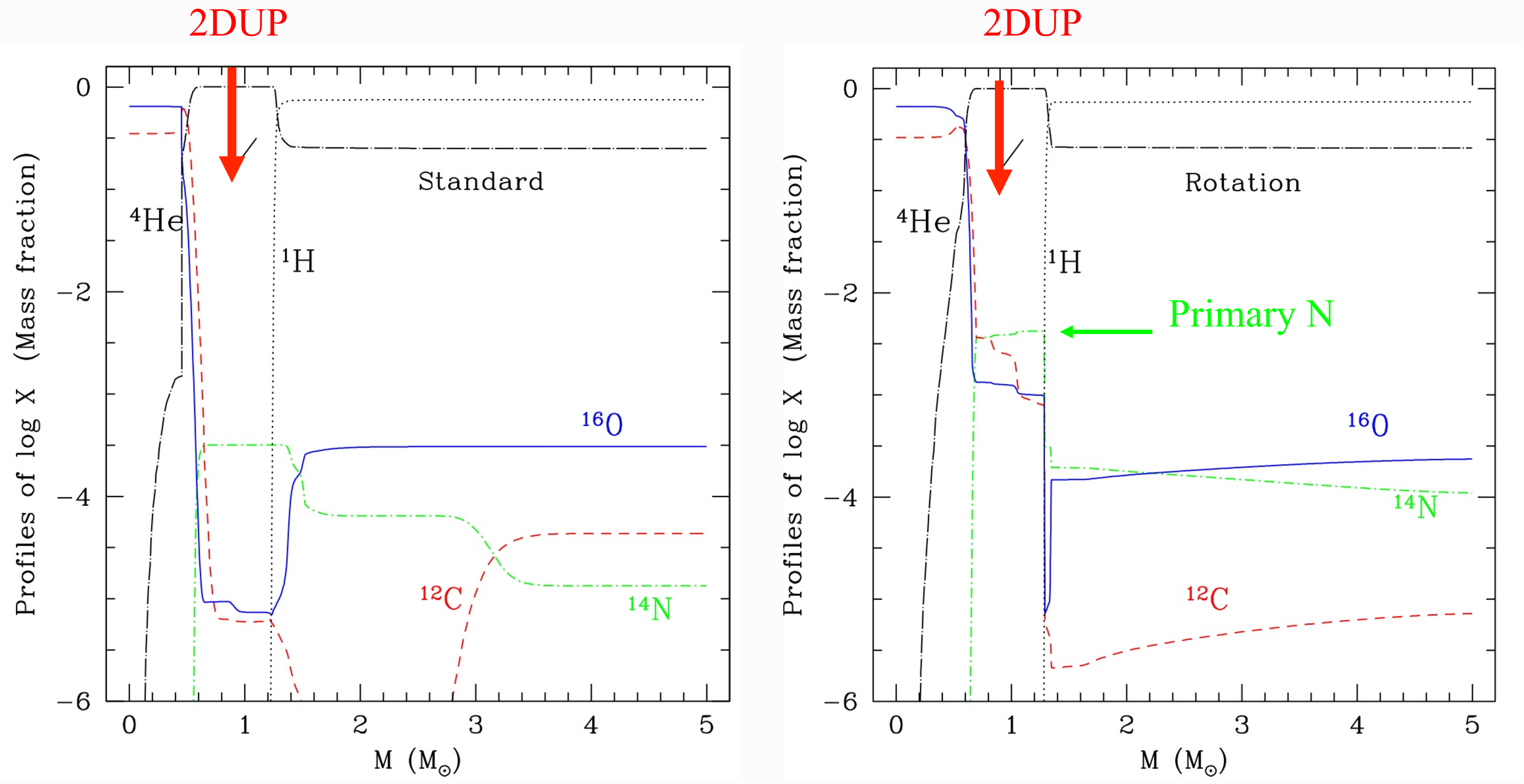
Same physics successfully applied to
Massive stars : HeBCN anomalies (Maeder & Meynet 00)
Low-mass stars : Hot side of the Li dip, Li in subgiants (Charbonnel & Talon 99,
Palacios et al.03, Pasquini et al.04)
Intermediate-mass stars : Primary N production at low Z (Chiappini et al. 06)

Decressin, Charbonnel, Siess, Palacios, Meynet & Georgy (09)

Before the TP-AGB - Rotating models

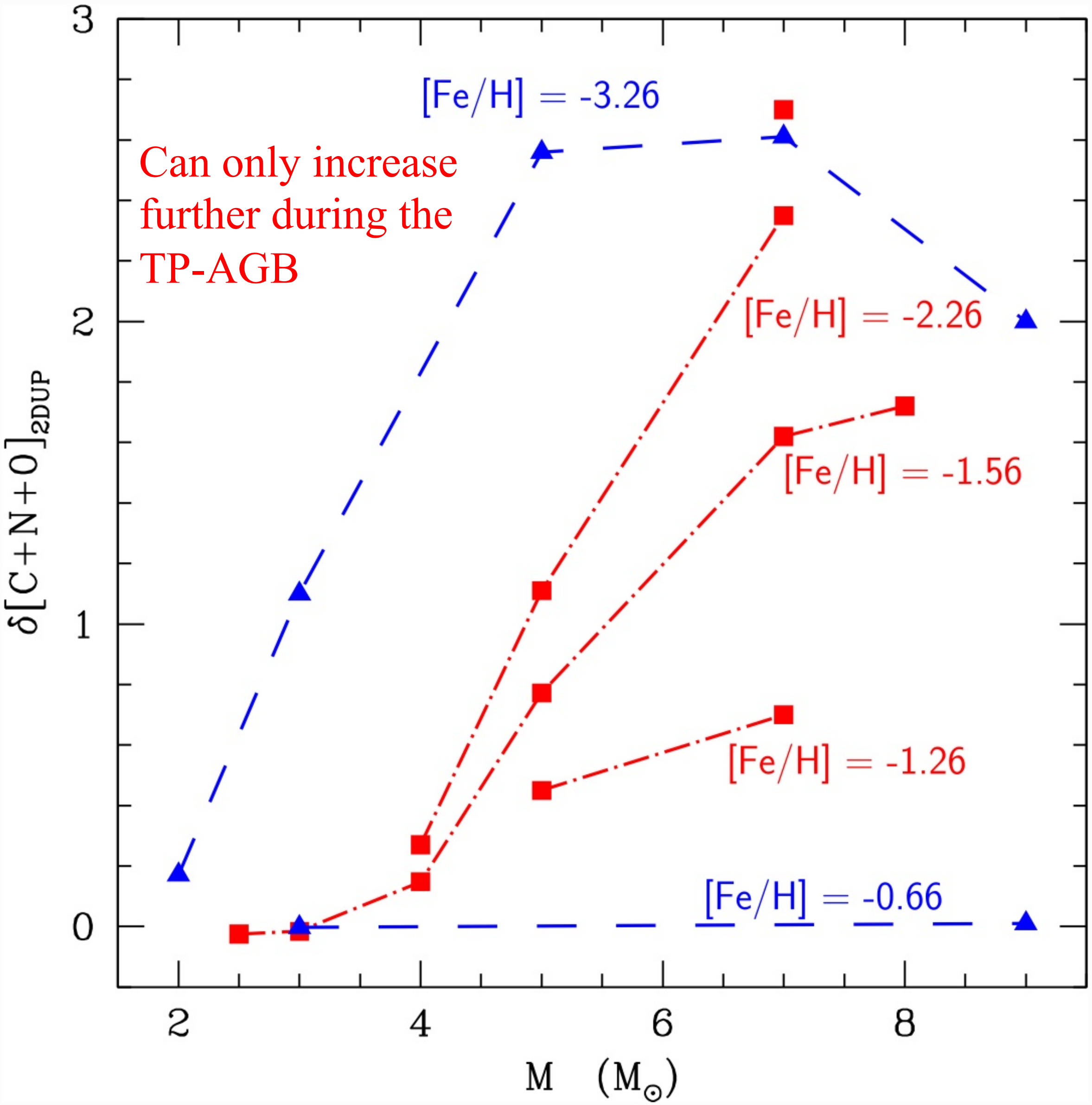
5M$_\odot$, [Fe/H] = -2

Abundance profiles at the end of central He-burning



Decressin, Charbonnel, Siess, Palacios, Meynet & Georgy (09)

Before the TP-AGB - Rotating models



Can only increase further during the TP-AGB

✓ Incompatible with C+N+O ~ ct within a factor 2

Need for C+N+O observations in M15, M92

C+N+O ~ constant
M13 & M3 (Smith et al. 96,
Cohen & Melendez 05)
NGC 6752 & 6397 (Carretta et al. 05)

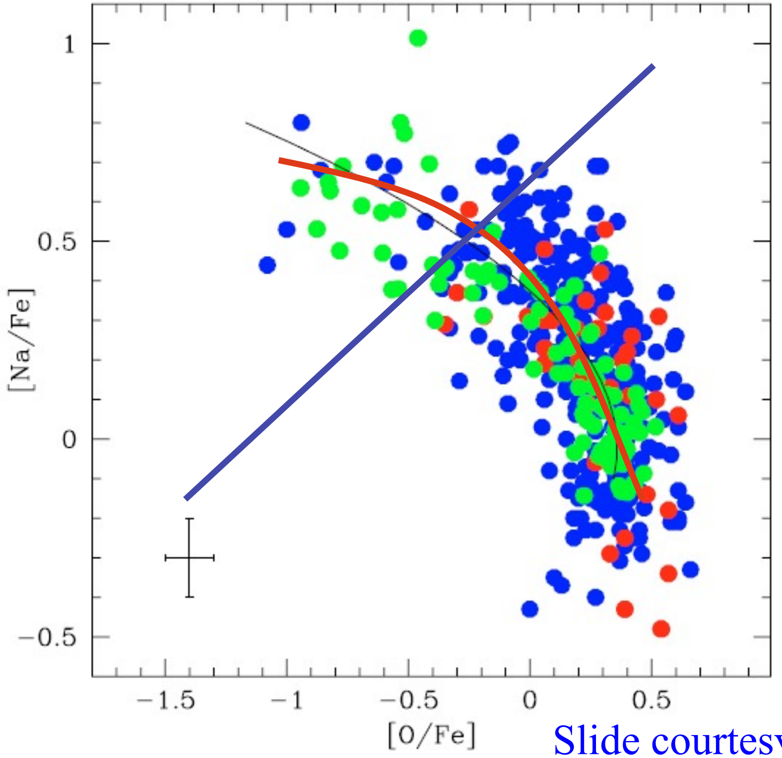
C+N+O ~ constant
NGC 288 & 362 (Dickens et al. 91)
M4 (Ivans et al. 99, Smith et al. 05)
NGC 1851 (Yong et al. 09): 1 star with CNO increased by 0.57+/-0.15 dex
What about unevolved stars in 1851?

C+N+O ~ constant
47 Tuc (Carretta et al. 05)
NGC 6712 (Yong et al. 08)

Decressin, Charbonnel, Siess, Palacios, Meynet & Georgy (09)

AGB scenario – Anticorrelation possible only by dilution

→ Need to **re-accrete original gas** to turn the O-Na correlation into an anticorrellation (D'Ercole + 11)

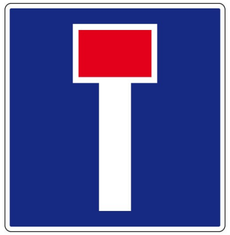


models!!

anticorrelation

AGB yields → O-Na correlation
in glaring conflict with observations

Slide courtesy D'Antona (Sexten 2014)

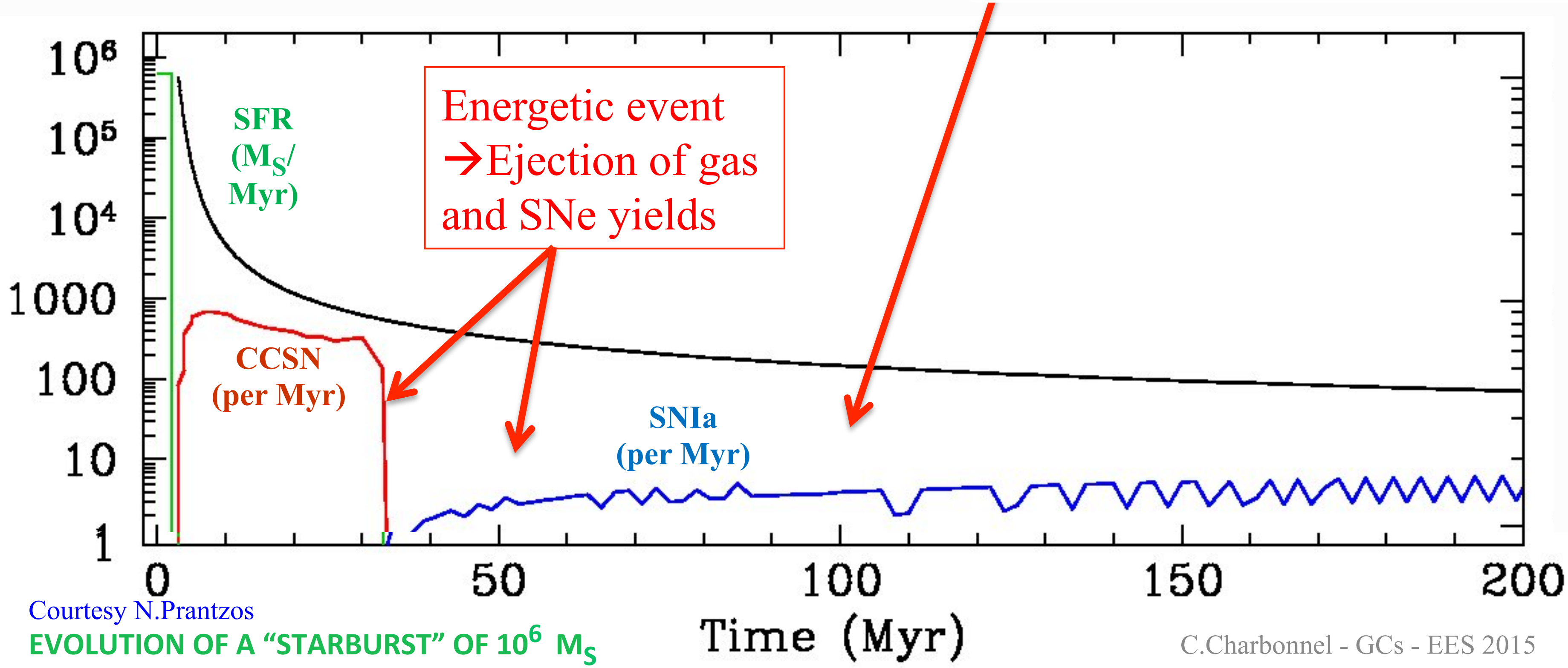


AGB scenario

Survey of 130 Galactic and extra-galactic YMCs
($10^4 < M/M_\odot < 10^8$; $10 <$ age/Myr < 1000):
No evidence for extended or multiple SF episodes
within 30 – 100 Myr

Bastian *et al.* (13); Cabrera-Ziri *et al.* (14)

Massive AGB scenario
1st-2nd generations: Δt ~ 50 - 100 Myr



Energetic event
→Ejection of gas
and SNe yields

Courtesy N.Prantzos

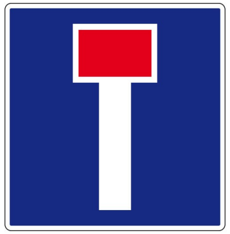
EVOLUTION OF A "STARBURST" OF 10^6 M_S

AGB scenario

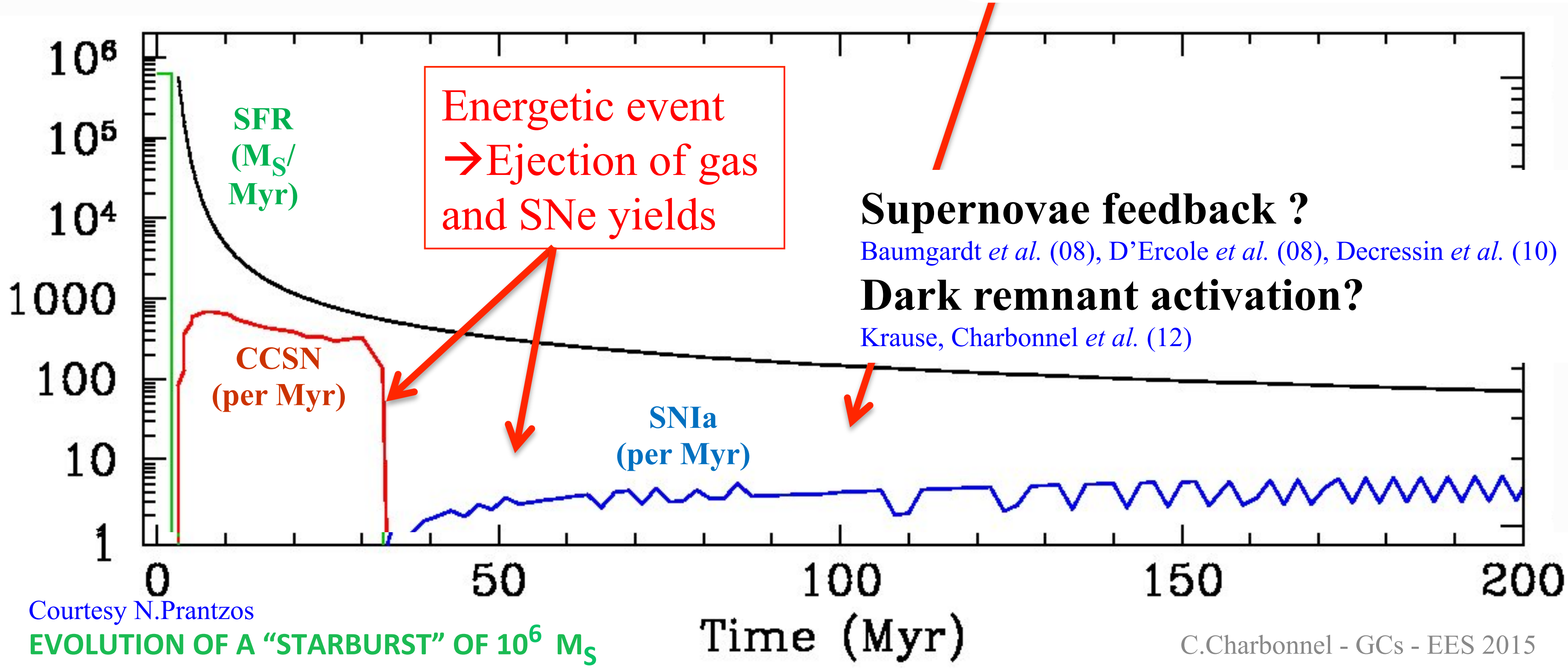
Distinct stellar **generations**
but no recycling of the SNe ejecta

→ Need to **re-accrete gas**
to form the 2G and to turn the
correlation into an anticorrelation
(D'Ercole + 11)

How do all the GCs manage to re-accrete gas
with exactly the same [Fe/H] than the one of the proto-GC,
after having travelled around for ~ 50 – 100Myrs?



Massive AGB scenario
1^{st}-2^{nd} generations: Δt ~ 50 - 100 Myr



Energetic event
→Ejection of gas
and SNe yields

Supernovae feedback ?
Baumgardt *et al.* (08), D'Ercole *et al.* (08), Decressin *et al.* (10)

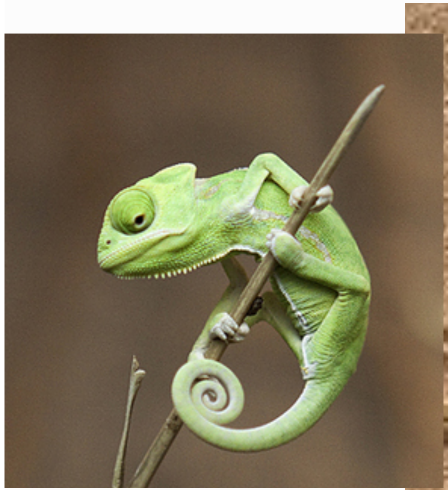
Dark remnant activation?
Krause, Charbonnel *et al.* (12)

Courtesy N.Prantzos

EVOLUTION OF A "STARBURST" OF 10^6 M_S

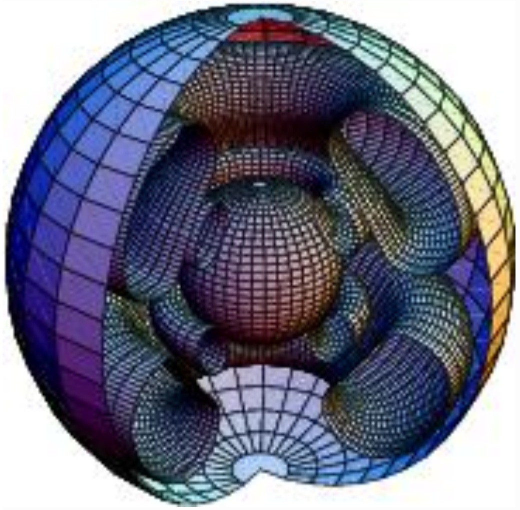
Who is the culprit?

When and how did it happen?



FRMS

Fast Rotating Massive Stars scenario



Prantzos & Charbonnel (06), Decressin *et al.* (07a,b,09,10)
Schaerer & Charbonnel (10), Krause *et al.* (12,13)

Transport of angular momentum and chemicals by meridional circulation and shear turbulence
Zahn (92), Maeder & Zahn (98), Meynet & Maeder (00)

Same physics successfully applied to
Massive stars : HeBCN anomalies (Maeder & Meynet 00)
Intermediate-mass stars : Primary N production at low Z (Chiappini *et al.* 06)
Low-mass stars : Hot side of the Li dip, Li in subgiants (Charbonnel & Talon 99, Palacios *et al.*03, Pasquini *et al.* 04)

Higher rotational velocities in young massive clusters than in the field

(Huang & Gies 06; Strom *et al.* 05; Dufton *et al.* 06)

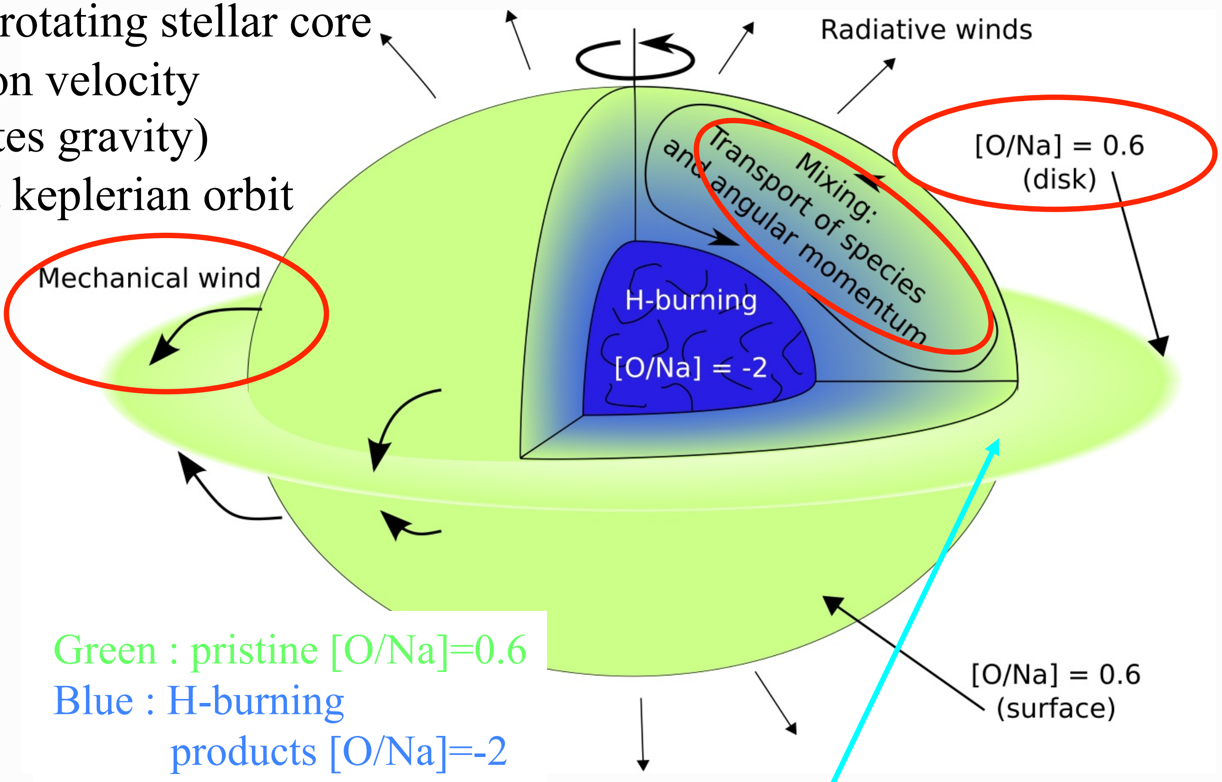
Be-type stars

FRMS – Main sequence

Meridional circulation and turbulence extract angular momentum from the fast rotating stellar core

→ The star reaches critical rotation velocity (centrifug acceleration compensates gravity)

→ Equatorial matter released in a keplerian orbit

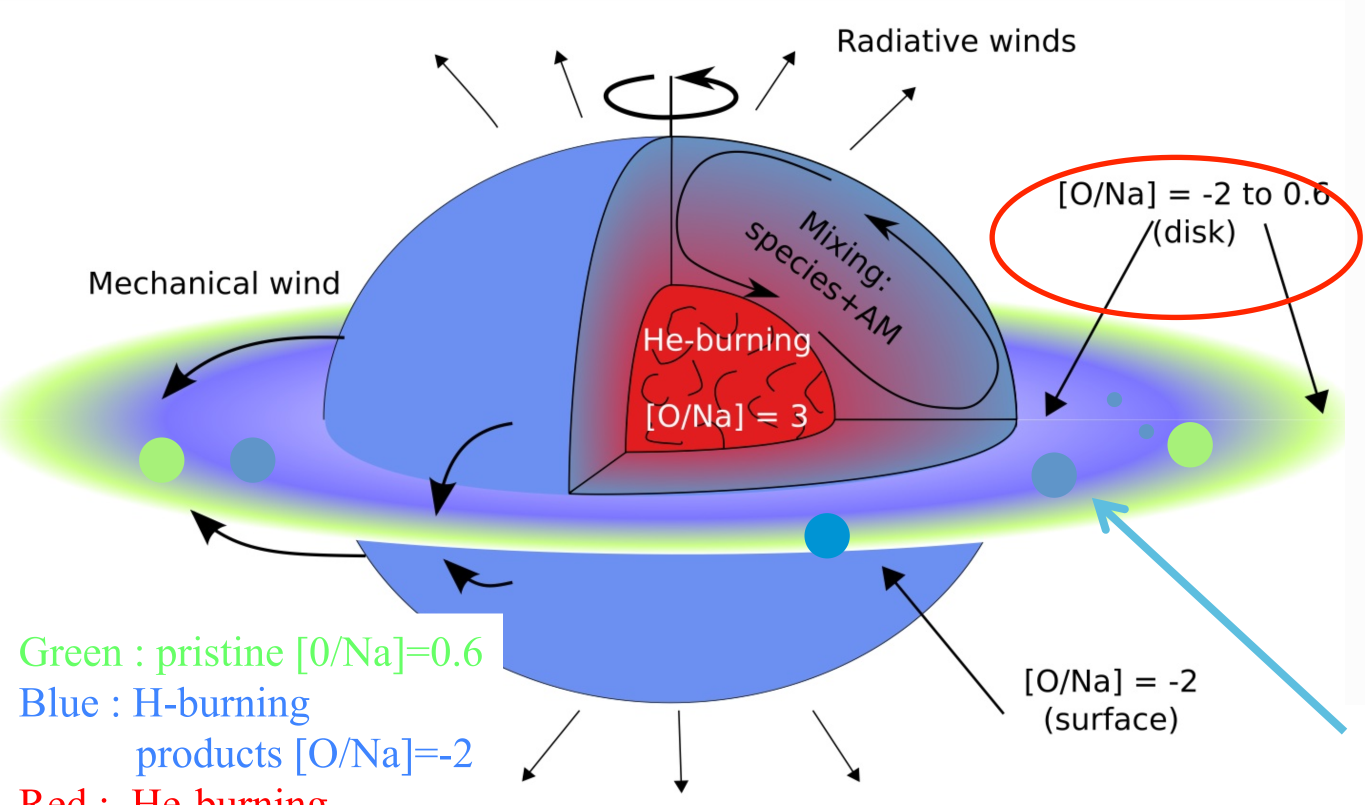


Green : pristine [O/Na]=0.6
Blue : H-burning
products [O/Na]=-2

Formation of a slow outflowing disk (Be stars)

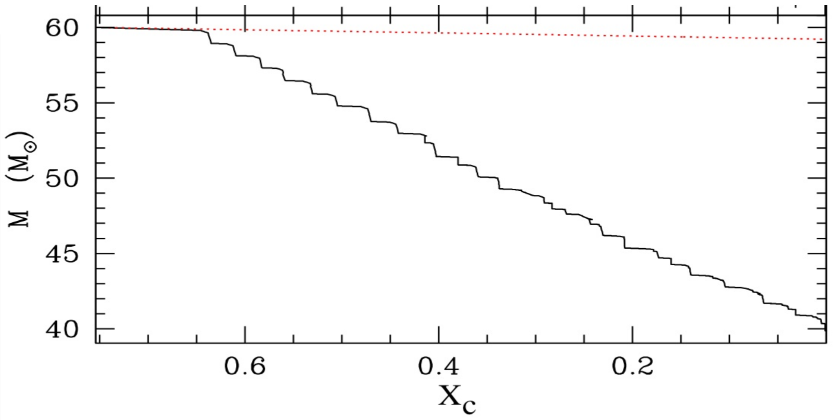
Decressin *et al.* (07)

Main sequence and LBV phase at break-up :
Transport of H-burning-products from the core to the surface and disk



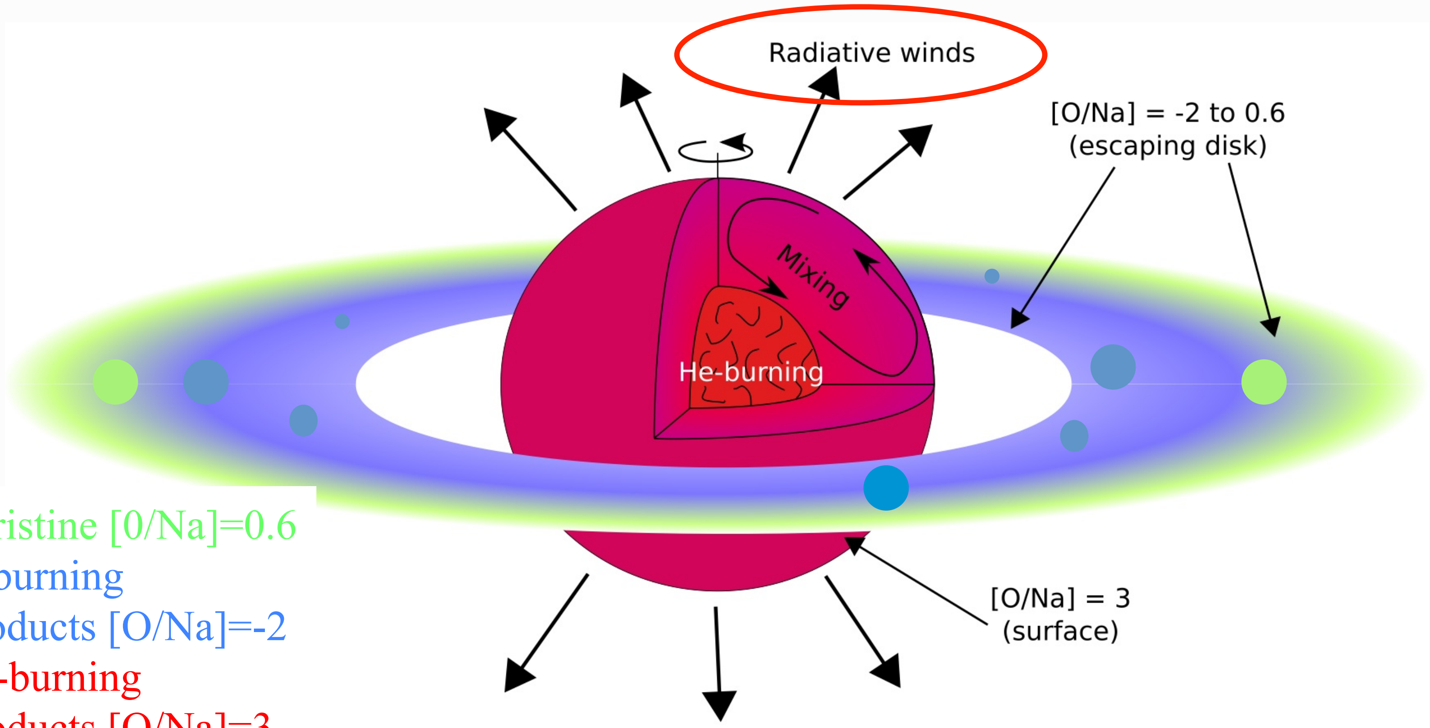
Star formation in the "decretion disc"

Green : pristine [0/Na]=0.6
Blue : H-burning products [O/Na]=-2
Red : He-burning products [O/Na]=3



Decressin *et al.* (07)

After the LBV phase, the star moves away from break-up



Green : pristine [0/Na]=0.6

Blue : H-burning
products [O/Na]=-2

Red : He-burning
products [O/Na]=3

The disk is disconnected from the star,
and the classical radiatively-driven fast winds (≥ 1000 km.sec^{-1}) take over

⇓

No recycling of the stellar ejecta
of more advanced phases (He-burning products and metals)

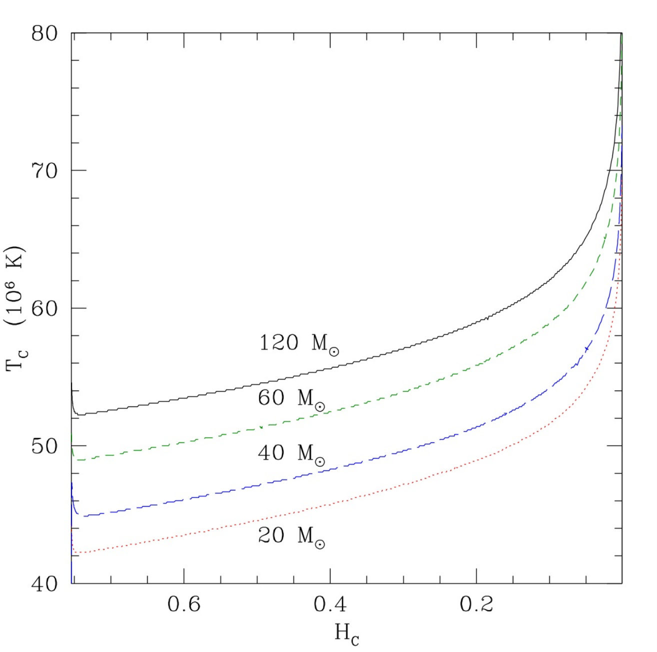
Decressin *et al.* (07)

FRMS – Evolution of the central Abundances during the main sequence

60 M$_\odot$

[Fe/H] = -1.5

Tc ∈ [48 ; 75] x 10^6 K



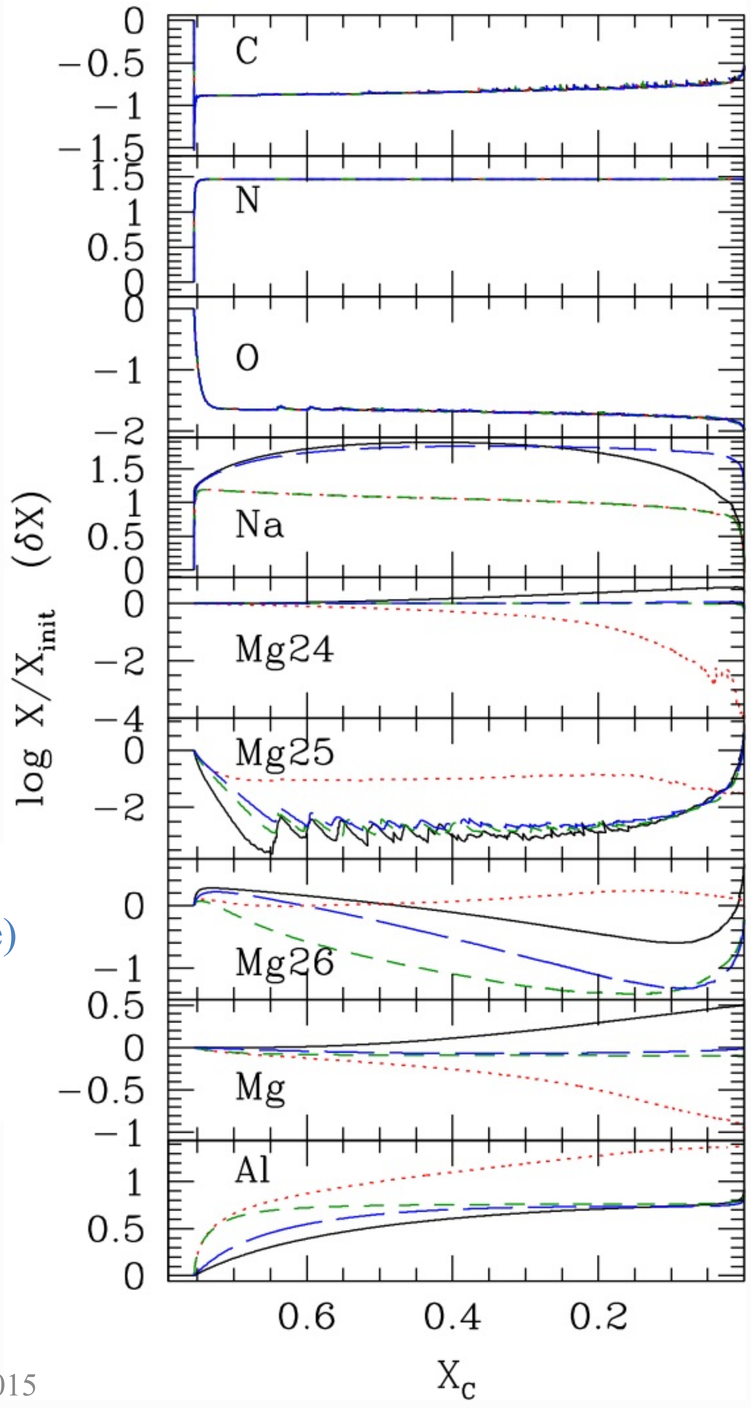
NACRE (full black)

Illiadis et al. (01), Hale et al. (02, 04) nominal (long dashed blue)

Id experimental limits (short dashed green)

Id & 24Mg(p,γ) (Illiadis et al. 01)

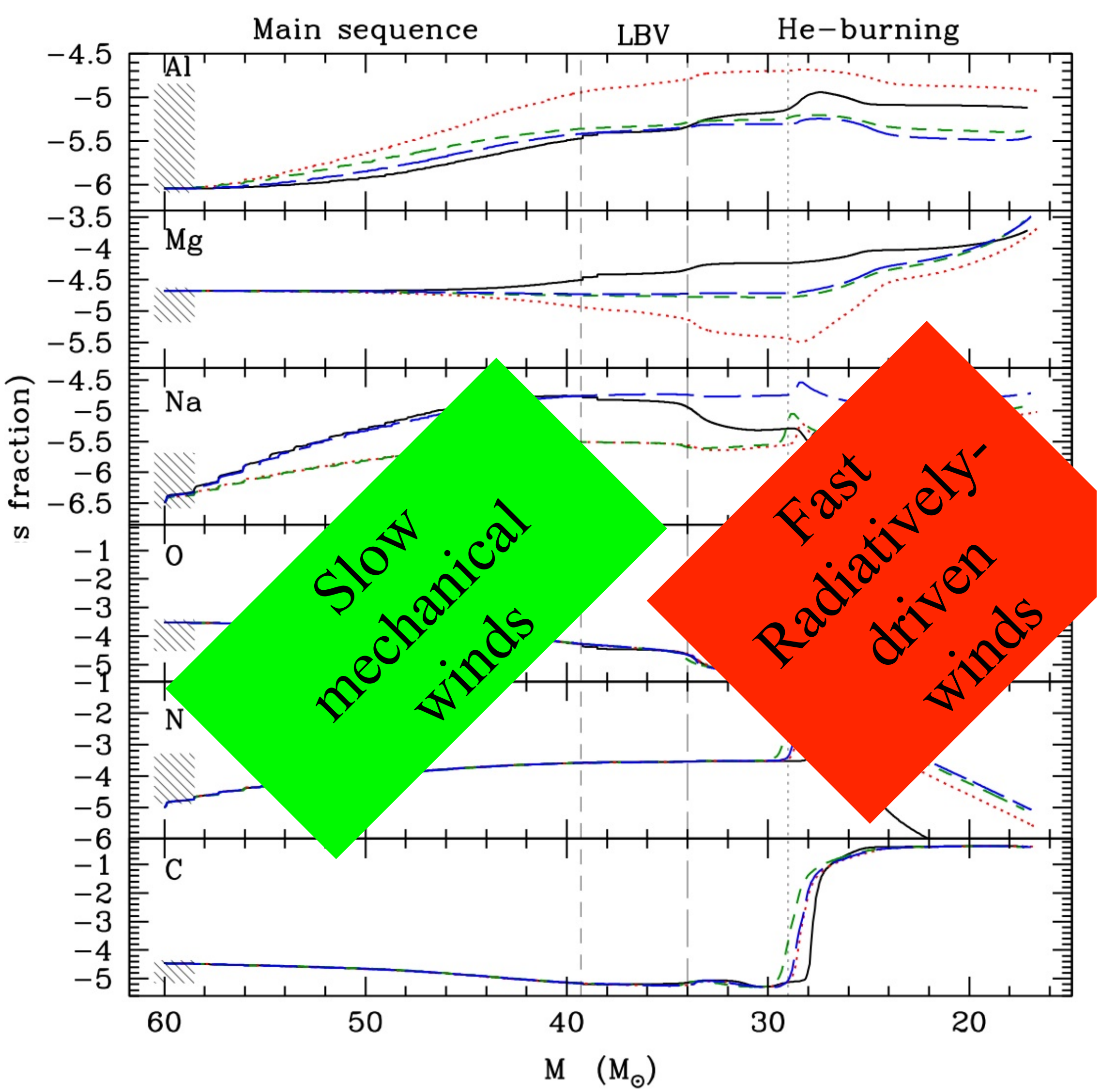
x 10^3 @ ~ 50MK and x $10^{1.5}$ @ ~ 60MK (dotted red)



Decressin *et al.* (07a)

FRMS – Evolution of the surface abundances

60 $M_\odot$, Z = 5 x 10 $^{-4}$
$\Omega/\Omega c$ = 0.95
Meridional circulation
and shear turbulence



Slow mechanical winds

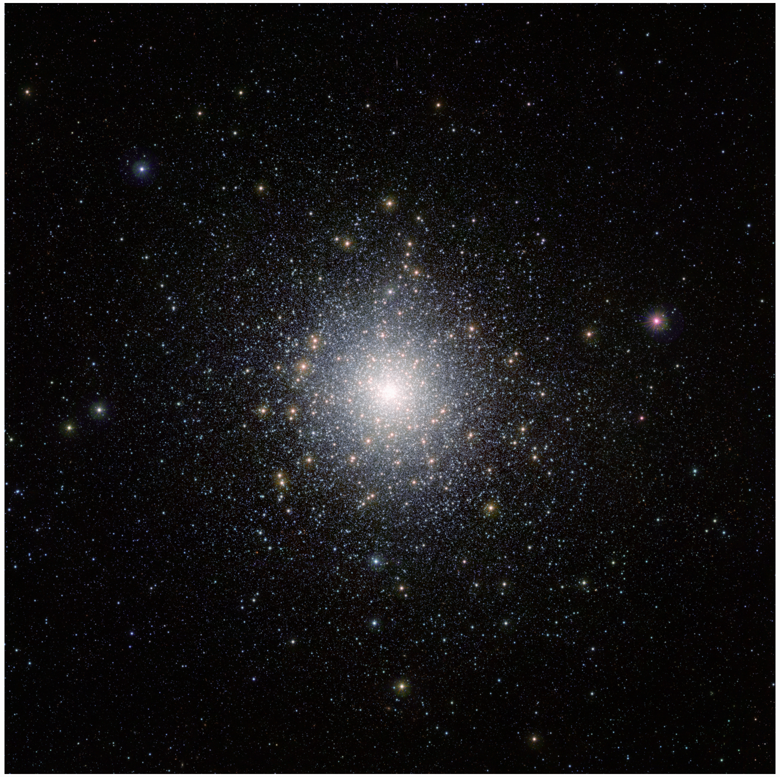
Fast Radiatively-driven winds

NACRE (full black)
Illiadis et al. (01), Hale et al. (02, 04)
nominal (long dahed blue)
Id experimental limits (short dashed green)
Id &
^{24}Mg(p,γ) (Iliadis et al. 01) x 10^3 (dotted red)

▨ Magnitude of abundance variations in NGC 6752 stars

Decressin *et al.* (07)

Multiple stellar populations and their evolution in globular clusters



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- ✓ **Light elements and the presence of multiple populations**
- ✓ **Photometric signatures**
- ✓ **Potential polluters**
  - **Details on AGB physics**
  - **Details on massive star physics**
- ✓ **GC initial masses**
- ✓ **Early dynamical and chemical evolution**

Towards a global scenario (?)

Mass budget issue

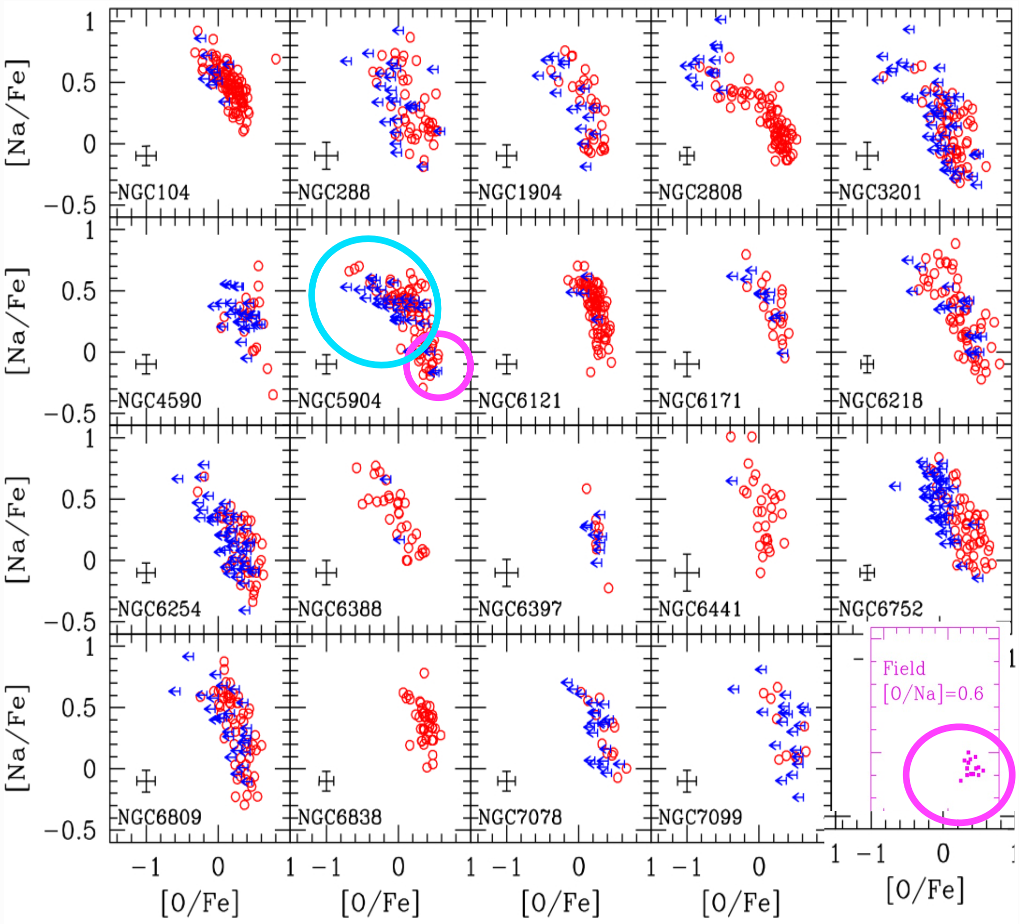
1st population ~ 30 ± 7 %

2d population ~ 70 ± 7 %

If 1G polluters follow a standard IMF
(Salpeter X=1.35 or Kroupa)
today's ratio 1G:2G should be ~ 90:10
Decressin *et al.* (07), D'Ercole *et al.* (08)

Flat polluter IMF
X ~ 0.6 - 0.8 ($\geq 20\ M_\odot$)
X < -0.65 ($5 - 6.5\ M_\odot$)

Compare with Salpeter X = 1.35
Prantzos & Charbonnel (06)
Smith & Norris (82, C-N data) D'Antona & Caloi (04)
Downing & Sills (07) Marks & Kroupa (10) Marks *et al.* (12)



Carretta *et al.* (10, VII)

Delayed (~ 2 – 4 Myr) star formation
Original gas : only 1P massive stars
Polluted gas : only 2P low-mass stars
Initial GC mass ~ 2 – 4 x present-day mass

Charbonnel *et al.* (14)

Mass budget issue

1st population ~ 30 ± 7 %

2d population ~ 70 ± 7 %

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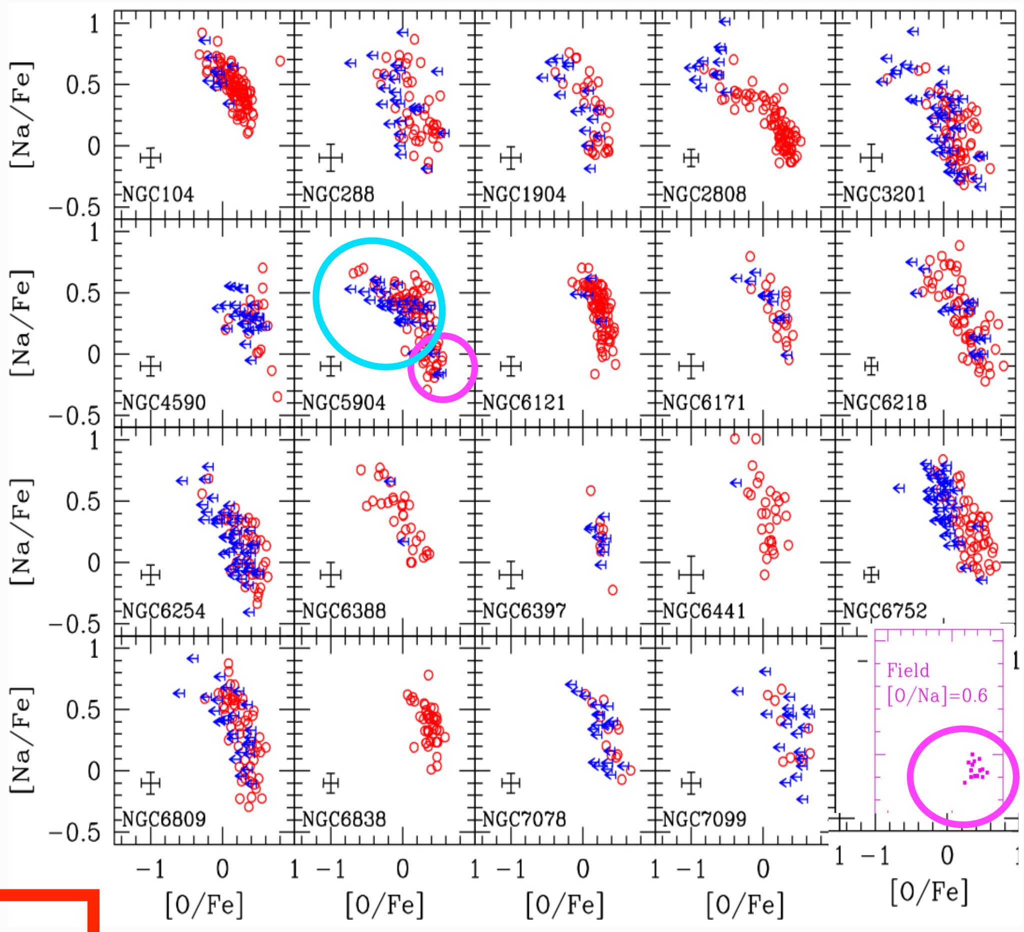
(Salpeter X=1.35 or Kroupa)
today’s ratio 1G:2G should be ~ 90:10
Decressin *et al.* (07), D’Ercole *et al.* (08)

Standard IMF →
Loss of ~ 95 % of 1G low-mass stars

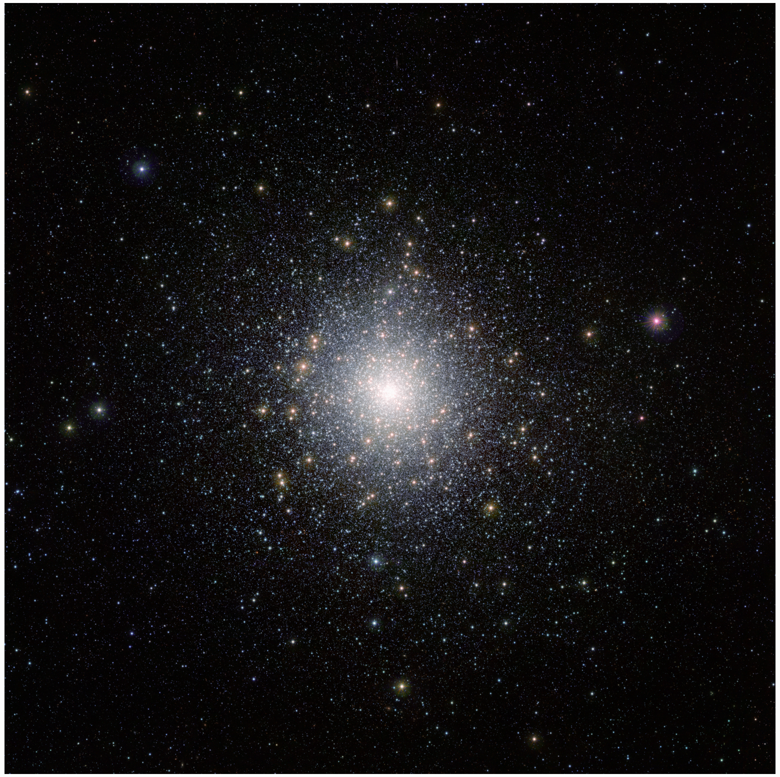
Prantzos & Charbonnel (06), Decressin *et al.* (07)
D’Ercole *et al.* (08, 10), Carretta (10) Vesperini *et al.* (10)
Schaerer & Charbonnel (11), Conroy (12)

8 – 25 x present-day mass
→ 6 – 20 % of the stellar mass of the Galactic halo



Carretta *et al.* (10, VII)

Multiple stellar populations and their evolution in globular clusters



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- ✓ Photometric signatures
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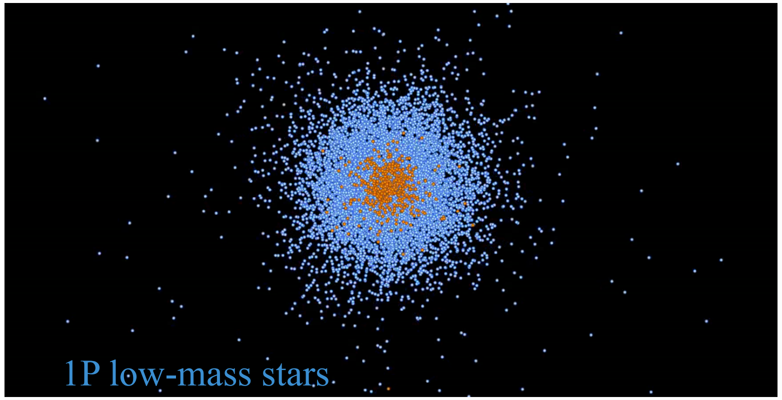
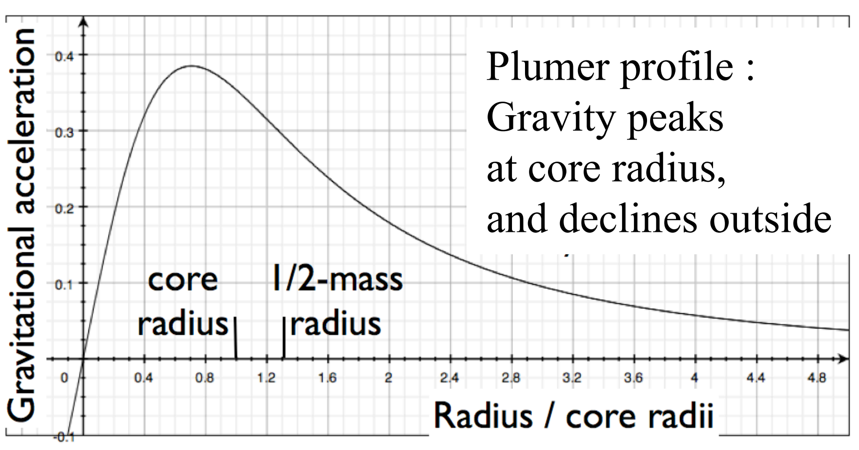
  - Details on massive star physics
- ✓ GC initial masses
- ✓ Early dynamical and chemical evolution
  Towards a global scenario (?)
  Or at least possible effects to take into account

A typical proto-GC
in the framework of the self-enrichment with standard IMF

NGC 6752 (today's M ~ 3 x 10^5 $M_\odot$, no Fe spread)
Proto-GC cloud of M_{tot} = 9 x 10^6 $M_\odot$
Half-mass radius $r_{1/2}$ = 3pc
SFE = 1/3



1P massive stars and 2P low-mass stars



Plumer profile :
Gravity peaks
at core radius,
and declines outside

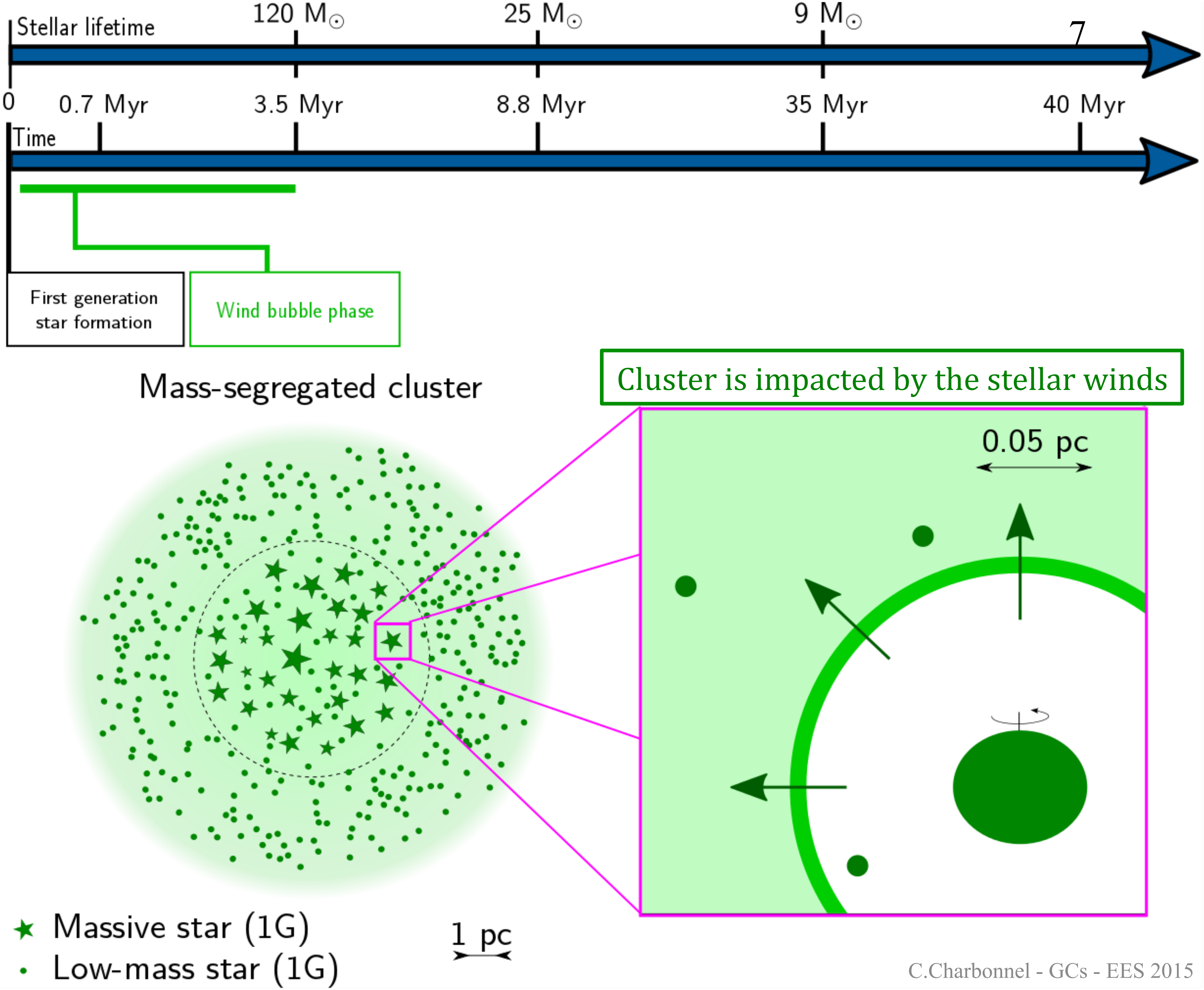
Salpeter IMF for 1G stars with Mi>0.8$M_\odot$
~ 5700 massive stars between 25 and 120 $M_\odot$
log-normal IMF for 1&2G stars with Mi≤0.8$M_\odot$

Mass-segregated cluster (Hillenbrand 97; de Grijs+02; Klessen 01; Bonnel+01)

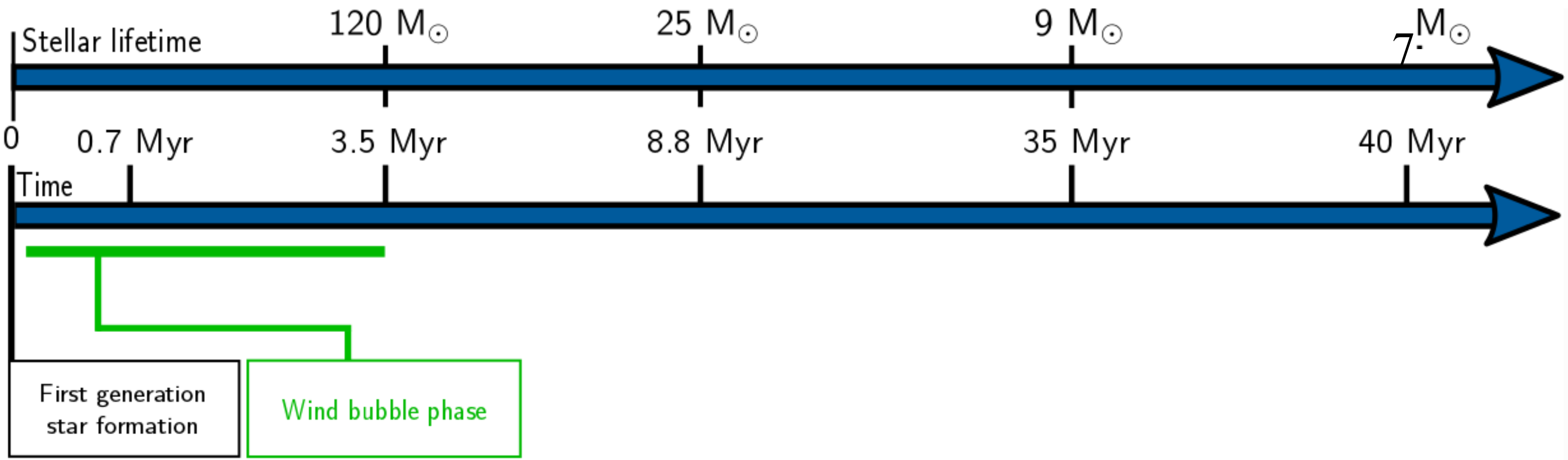
Plummer profile for mass distribution
(Baumgardt+08; Decressin et al. 10; Baumgardt & Khalaj 14)

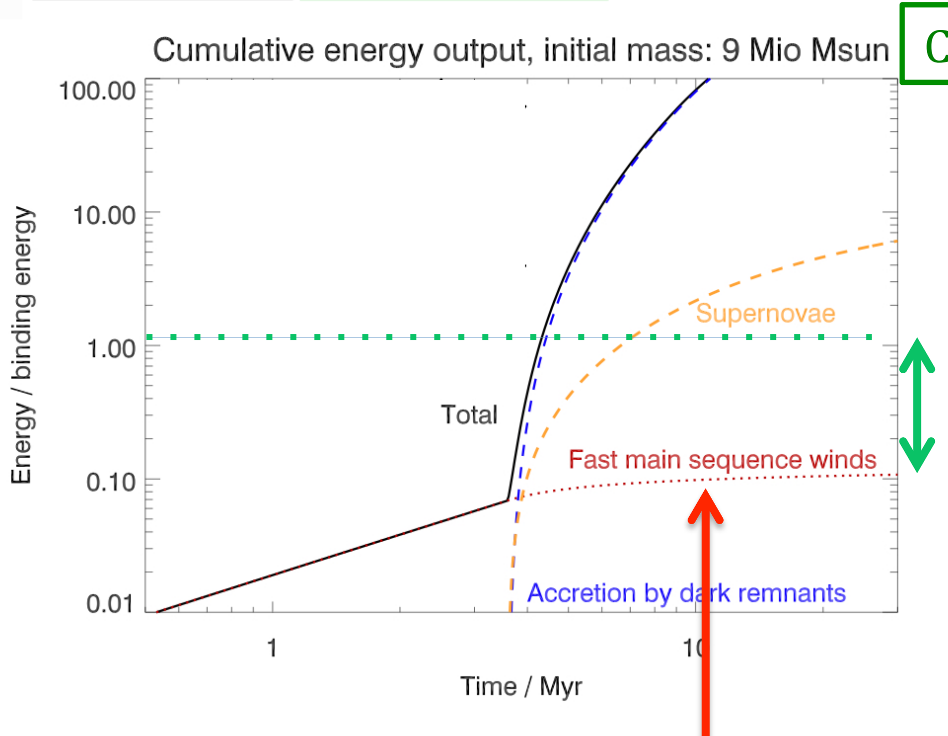
Gas mass proportional to
M_{tot} , SFE, core radius

Stellar properties (energy, winds, radiation, lifetimes) and feedback to ISM



Cluster is impacted by the stellar winds





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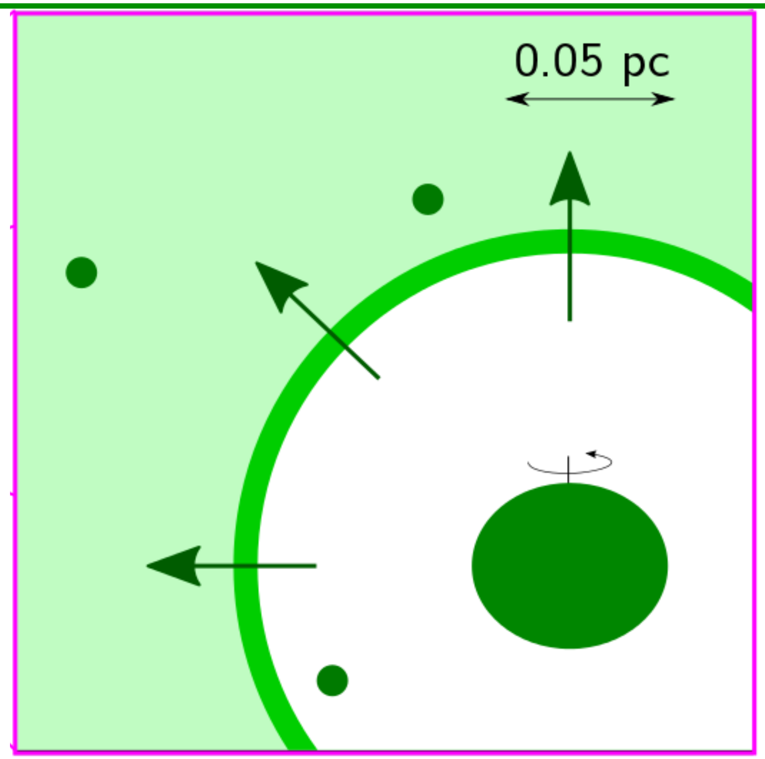
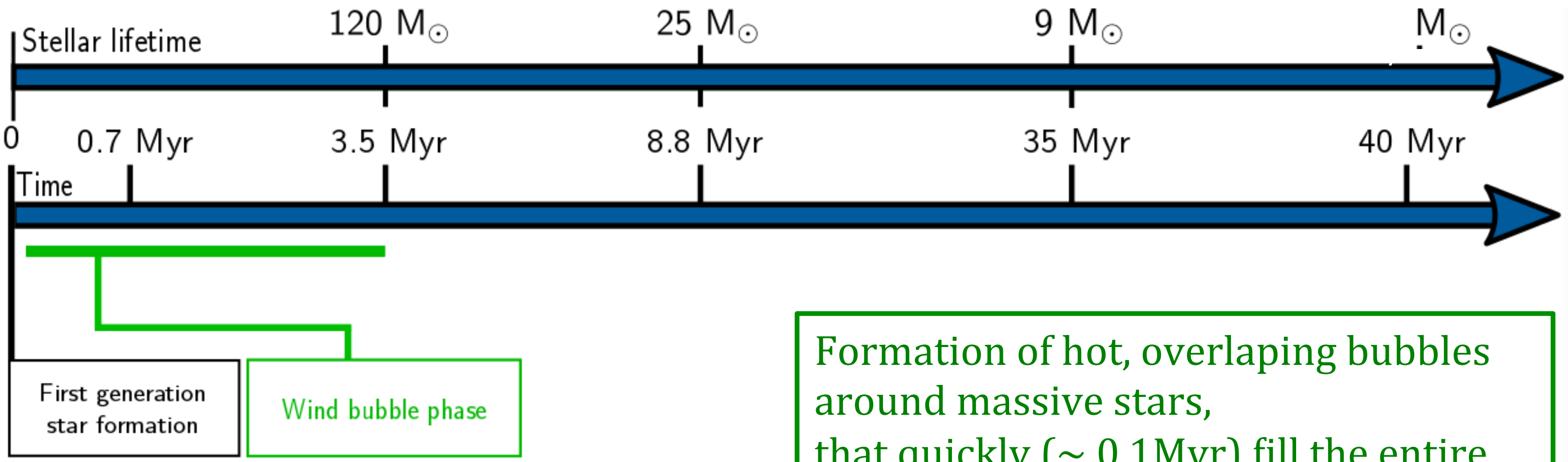
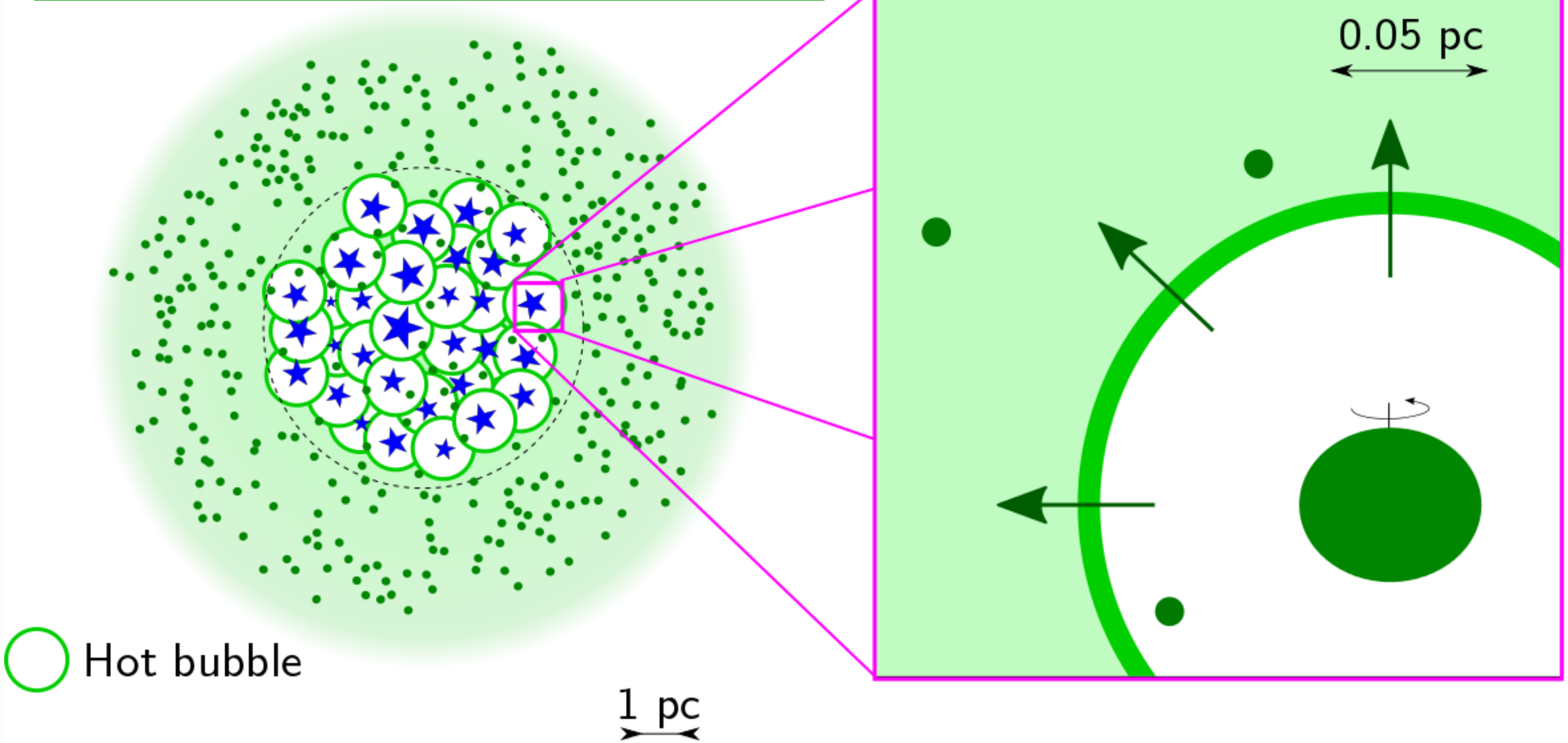


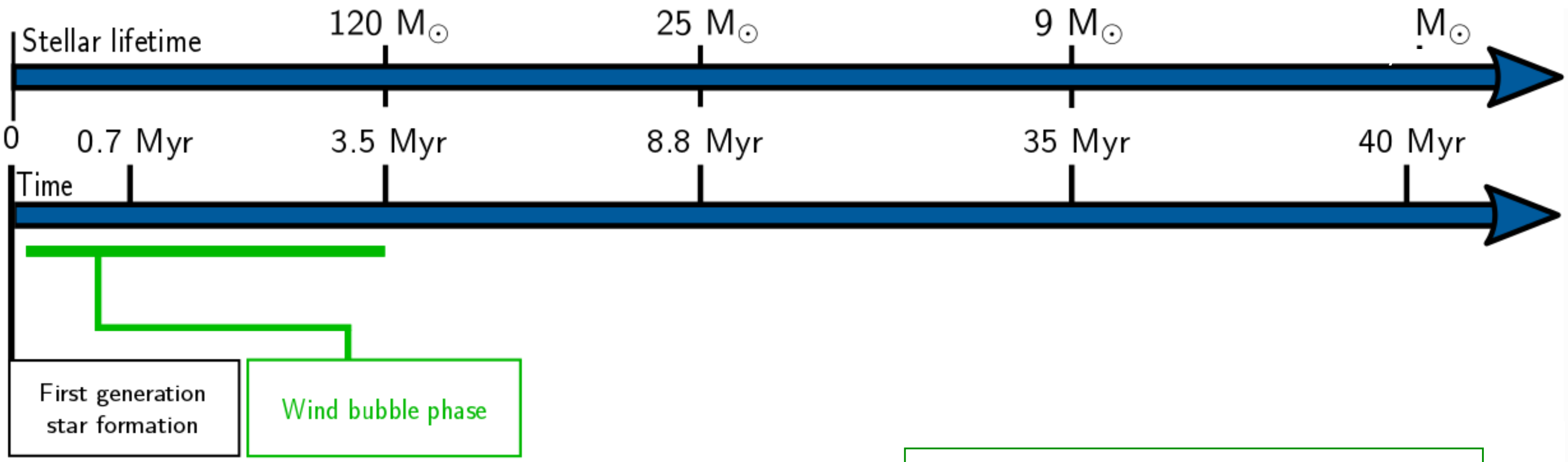
Stellar winds unable to lift any noteworthy amount of gas out of the GC on a relevant timescale



Spongy structure for ISM

Formation of hot, overlaping bubbles around massive stars,
that quickly (~ 0.1Myr) fill the entire volume within the half mass radius





Lyman-Werner photons

$Q_{LW}(M) = 7 \times 10^{43} \, (M/M_\odot)^{2.9} \, s^{-1}$

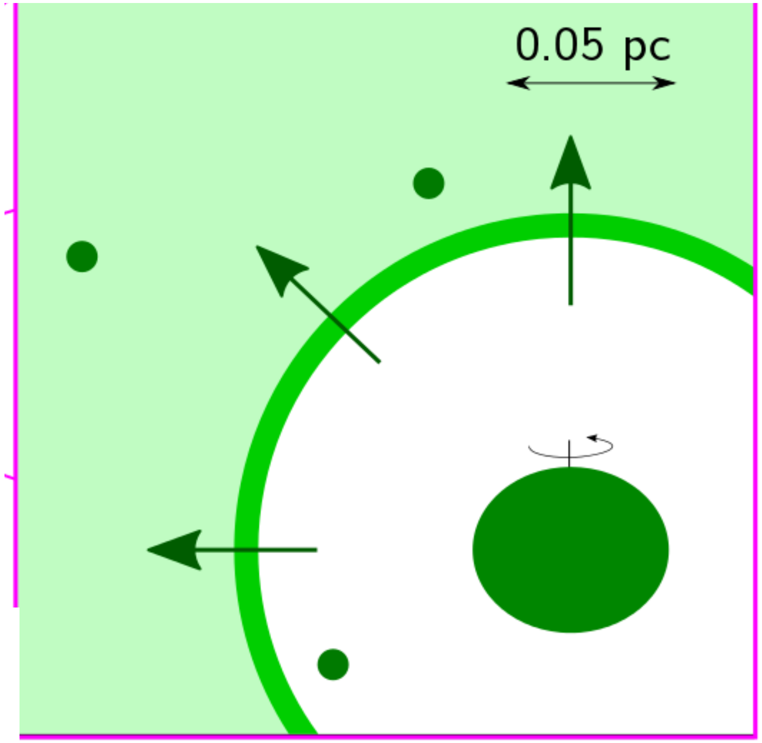
→ Photodissociation of molecular H

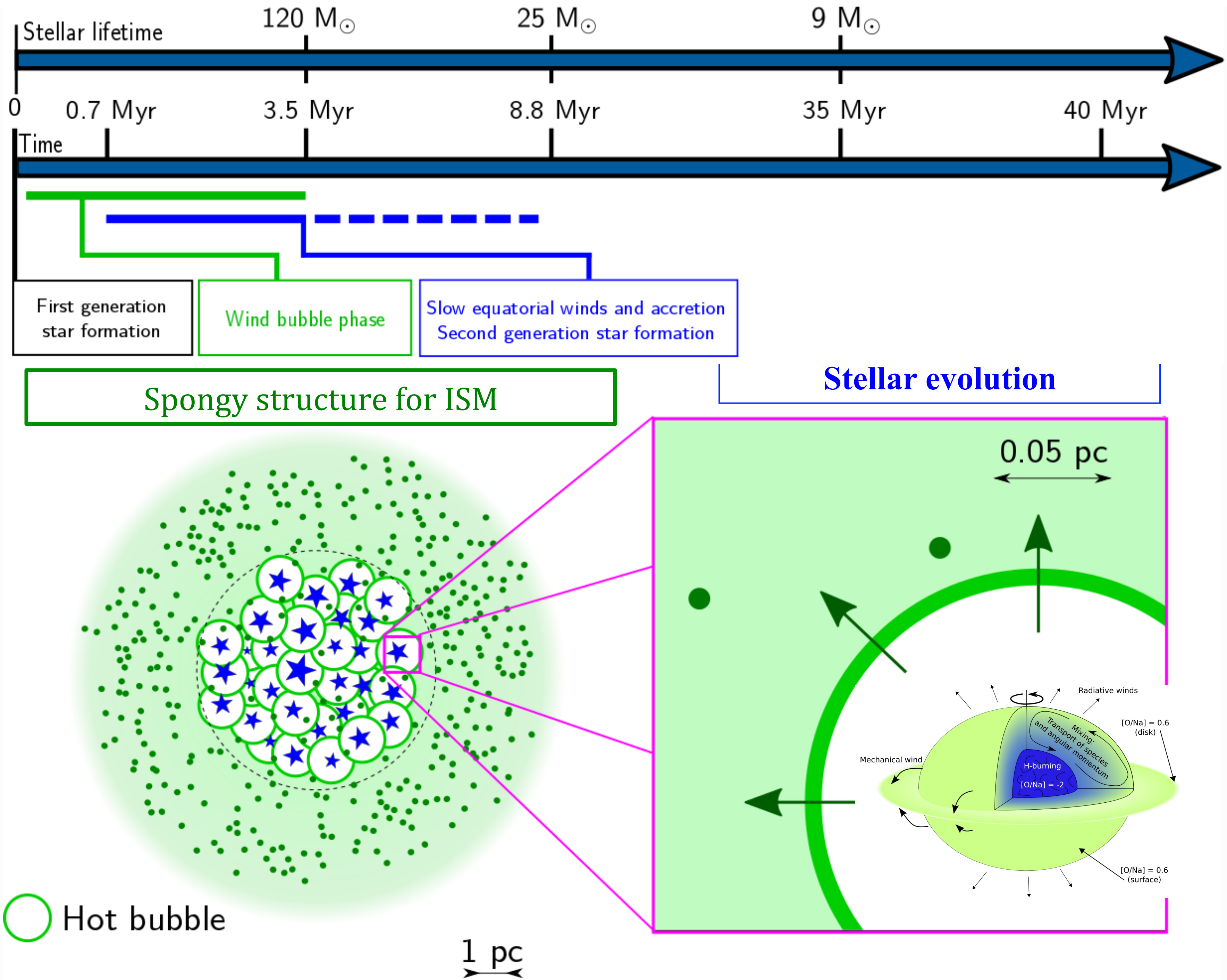
$T_{gaz} \sim 100K$

→ No « classical » star formation

Conroy & Spergel (11)
Schaerer & Charbonnel (11)
Krause *et al.* (13)

High ultraviolet radiation





Stellar lifetime

120 M$_\odot$ 25 M$_\odot$ 9 M$_\odot$

0 0.7 Myr 3.5 Myr 8.8 Myr 35 Myr 40 Myr

Time

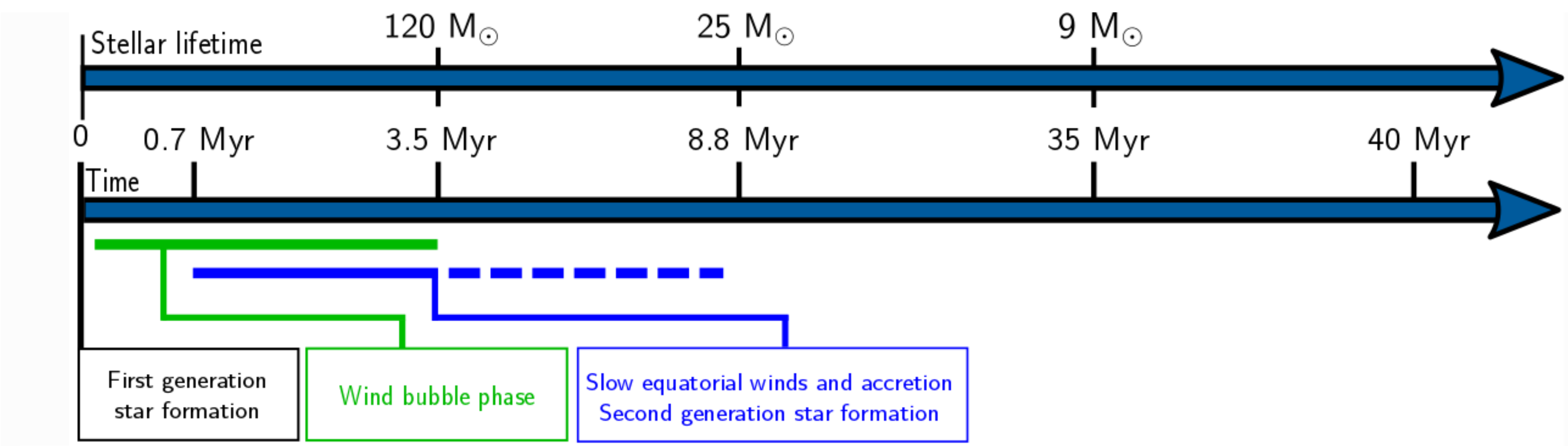
First generation star formation

Wind bubble phase

Slow equatorial winds and accretion
Second generation star formation

Spongy structure for ISM

Stellar evolution



Stellar lifetime

120 M☉

25 M☉

9 M☉

0

0.7 Myr

3.5 Myr

8.8 Myr

35 Myr

40 Myr

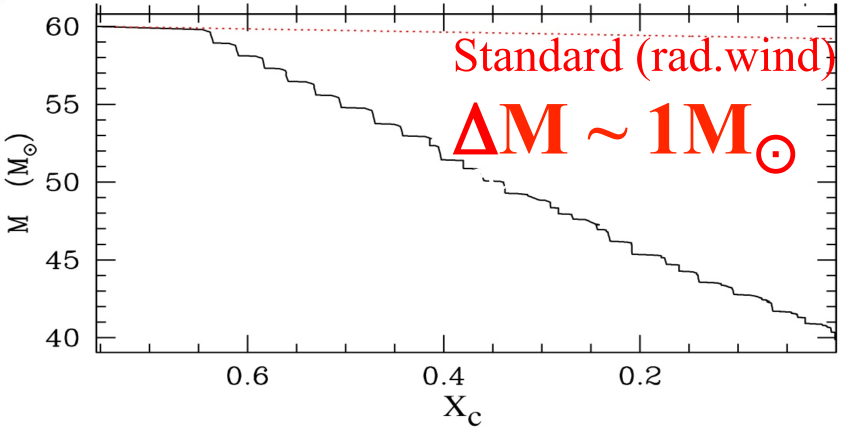
Time

First generation
star formation

Wind bubble phase

Slow equatorial winds and accretion
Second generation star formation

Slow equatorial mass ejection
at critical rotation velocity

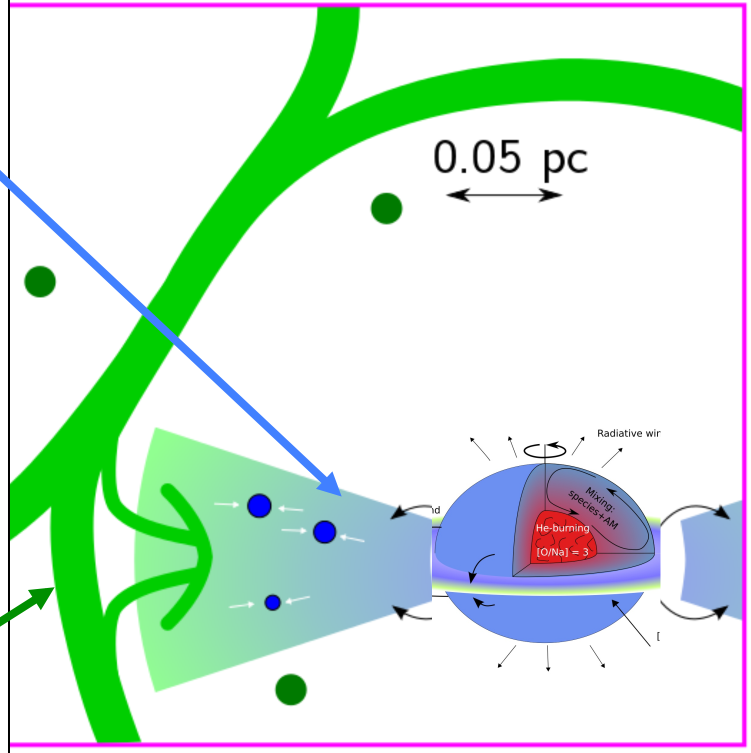


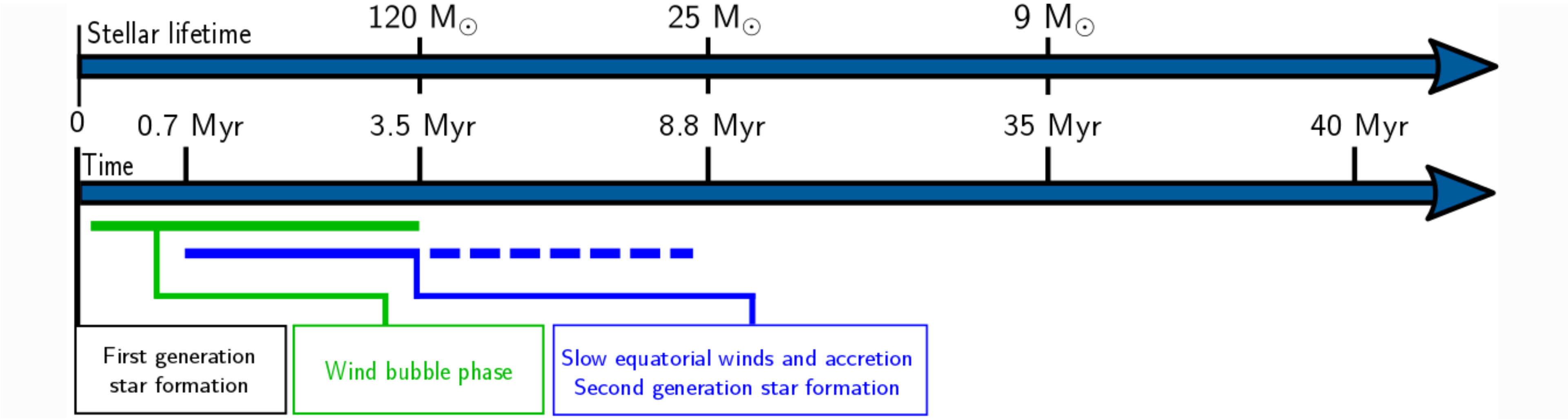
Shadowing of the disc frees the equatorial region from radiation pressure

→ Establishment of an accretion flow of surrounding dense original gas

→ Time- and orbit-averaged Bondi accretion rate ~ 10^4 M☉ /Myr

Equatorial mass ejection

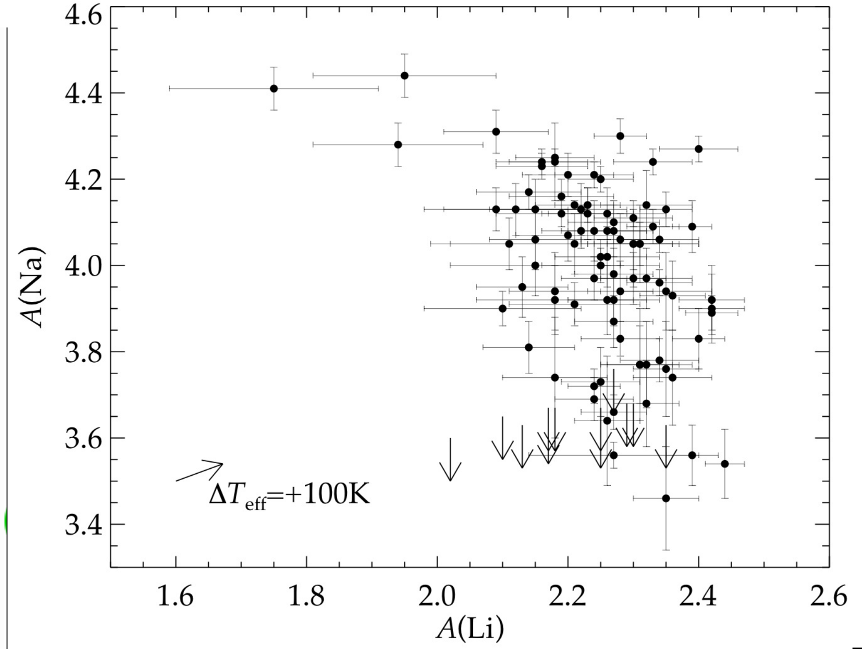




Disc fed both by stellar processed matter and original material

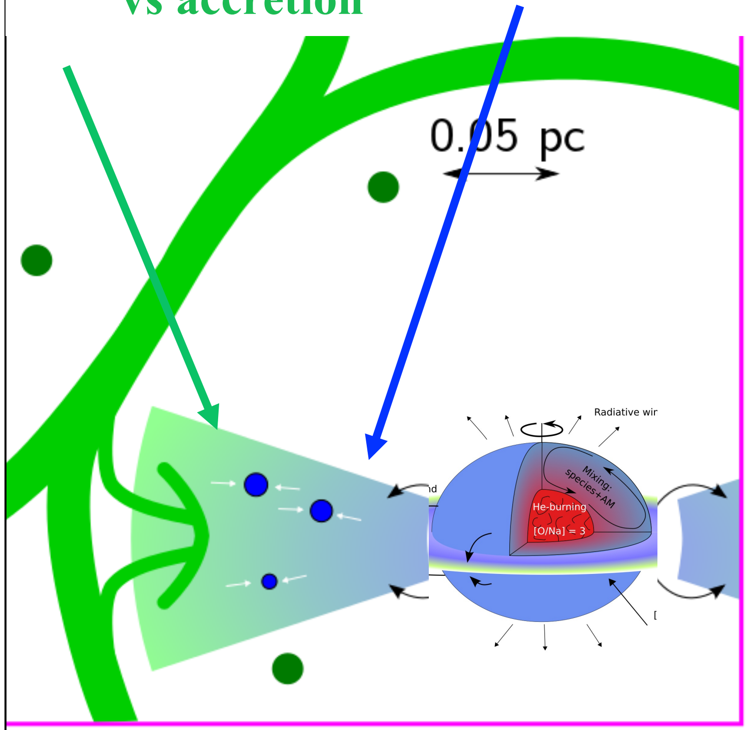
Mixture of gas within the disk:

~ ½ pristine – ½ ejecta (on average)

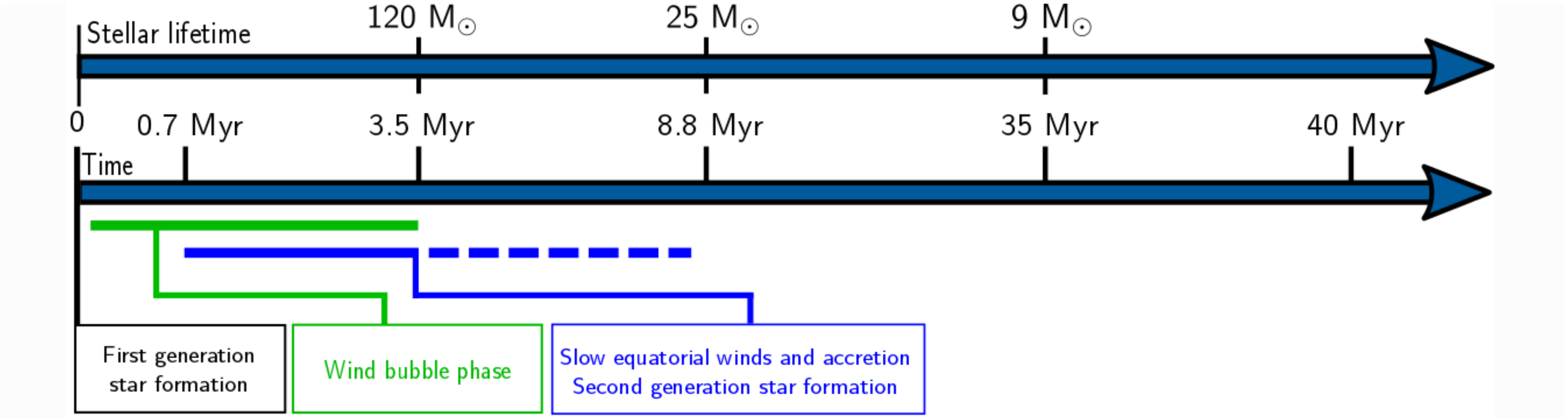


Equatorial mass ejection

vs accretion

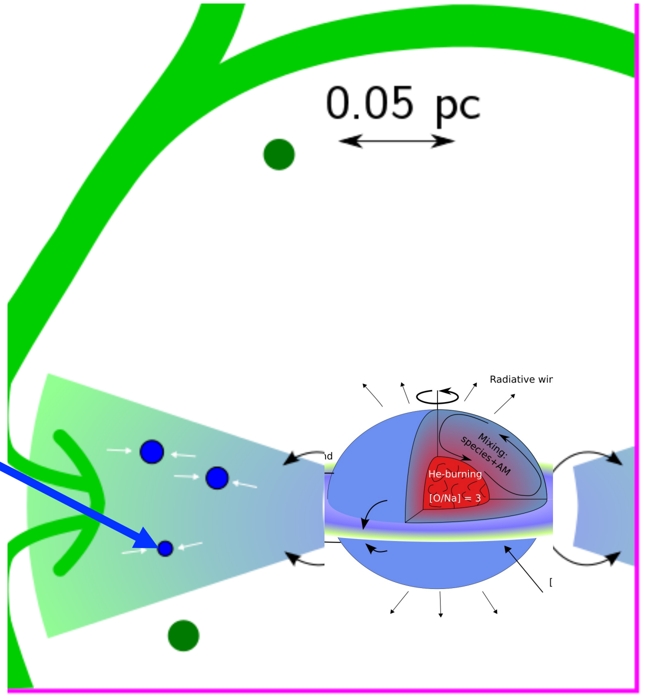


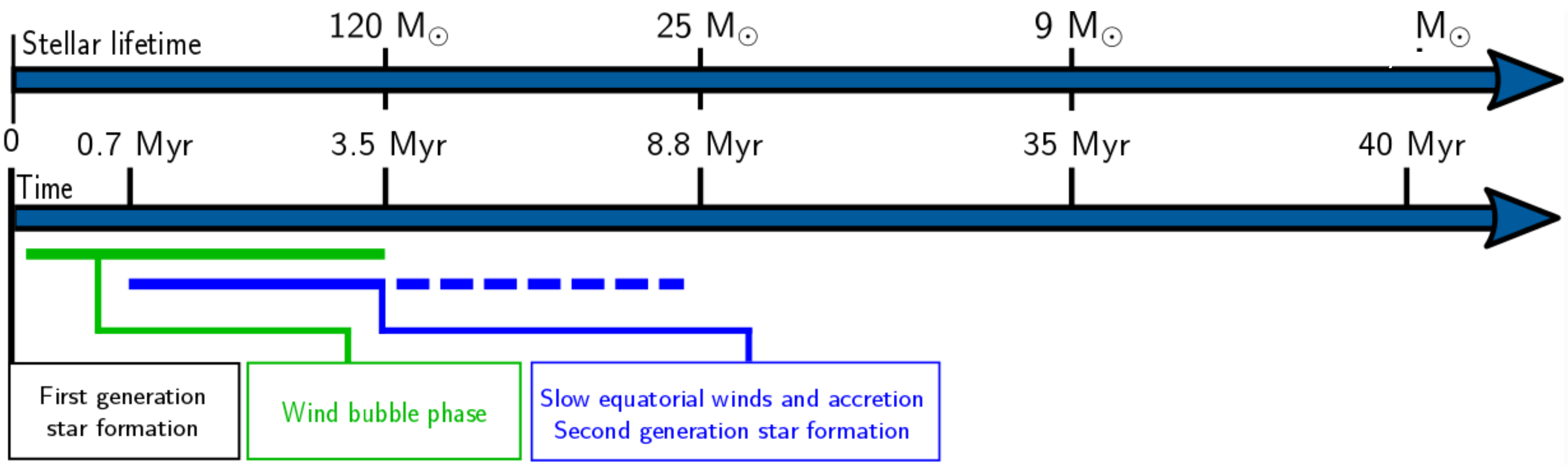
Lind, Primas, Charbonnel, Grundahl & Asplund (09)



Self-gravitating discs
(mass similar to the central star) (eg Armitage 11)
Toomre criterion (Shu 92)
→ The disc reach the critical mass for gravitational instability on timescale of $\leq 10^6$ yrs
→ Formation of 2G low-mass stars
Studied in the context of planet
(eg review by Kley & Nelson 12)
Very complex problem, lots of physics:
Transport/exchange of matter and angular momentum, role and influence of disk self-gravity and magnetohydrodynamic turbulence, …

Gravitational instability and star formation in the disk





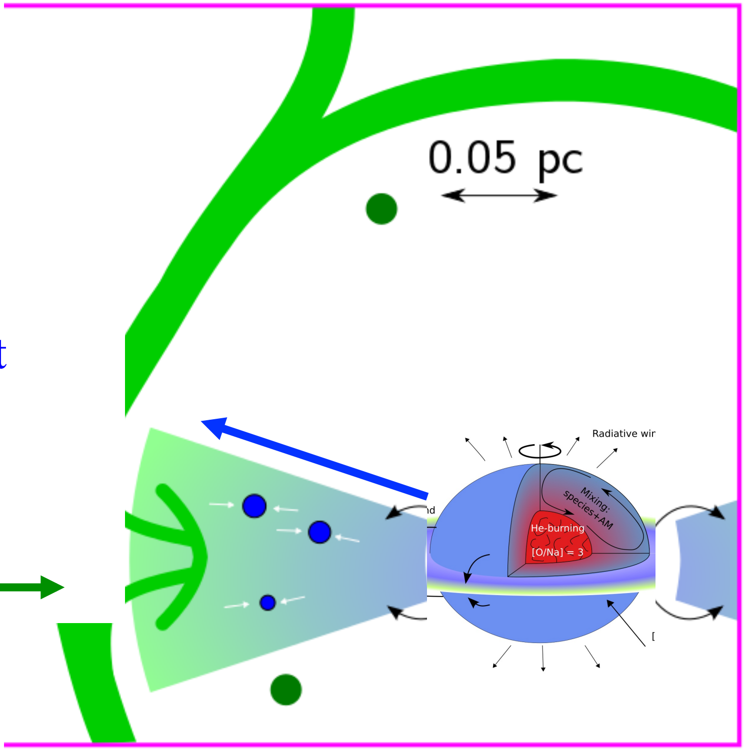
First generation star formation

Wind bubble phase

Slow equatorial winds and accretion
Second generation star formation

Fast Rotating Massive Star scenario
Stars with masses > 25 $M_\odot$
1^{st}-2^{nd} populations: Δt ~ 3.5 - 10 Myr

2P stars formation around individual massive stars:
H-burning ashes ejected by slow equatorial winds at critical rotation velocity
mixed with
Accretion flow of
surrounding dense pristine gas



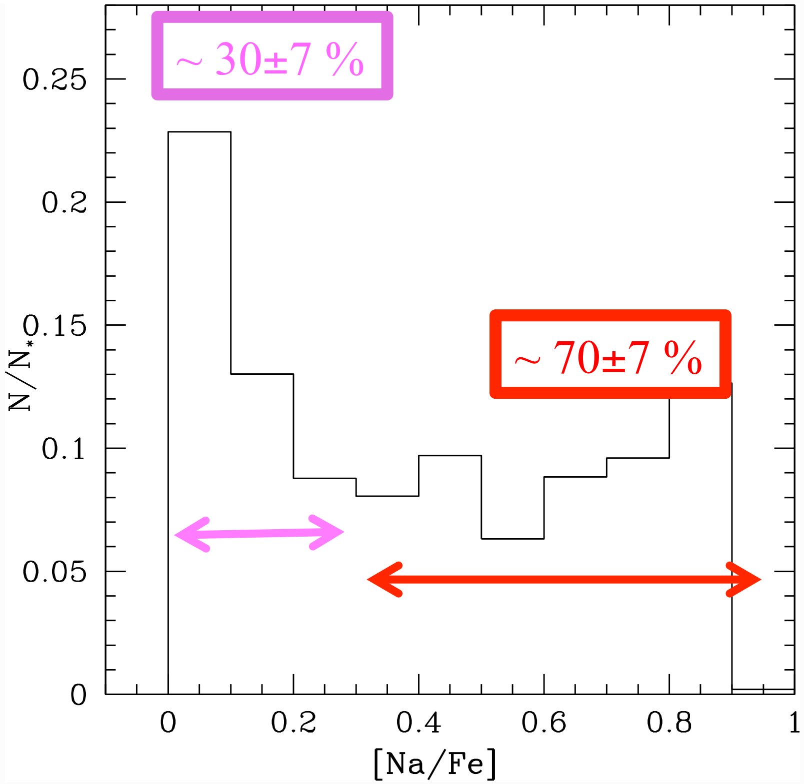
Prantzos & Charbonnel (06)
Decressin *et al.* (07a,b), Krause *et al.* (12,13)

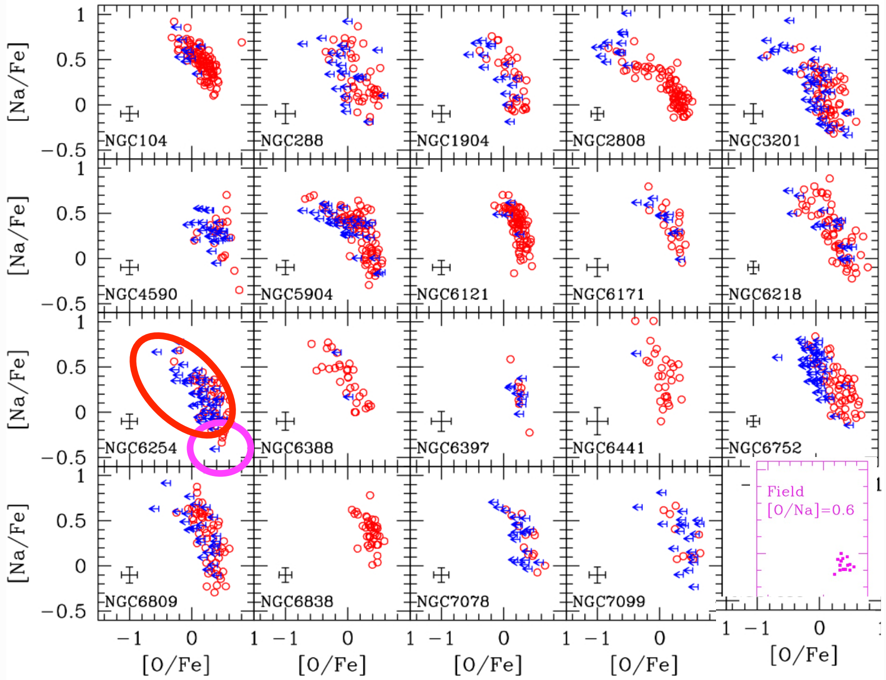
Are there any 1st generation stars in GCs today?

Disc fed both by stellar processed matter and original material

Mixture of gas within the disk:
~ ½ pristine – ½ ejecta (on average)
(actual dilution is time-dependent)

Theoretical distribution of Na abundance for low-mass “2d generation” stars at birth
Assuming
- Salpeter IMF for massive stars
- Log normal distribution Paresce & De Marchi 00





“Fake” 1st generation stars

1st generation : [Na/Fe]min + 0.3 dex

Charbonnel *et al.* (14)

Are there any 1st generation stars in GCs today?

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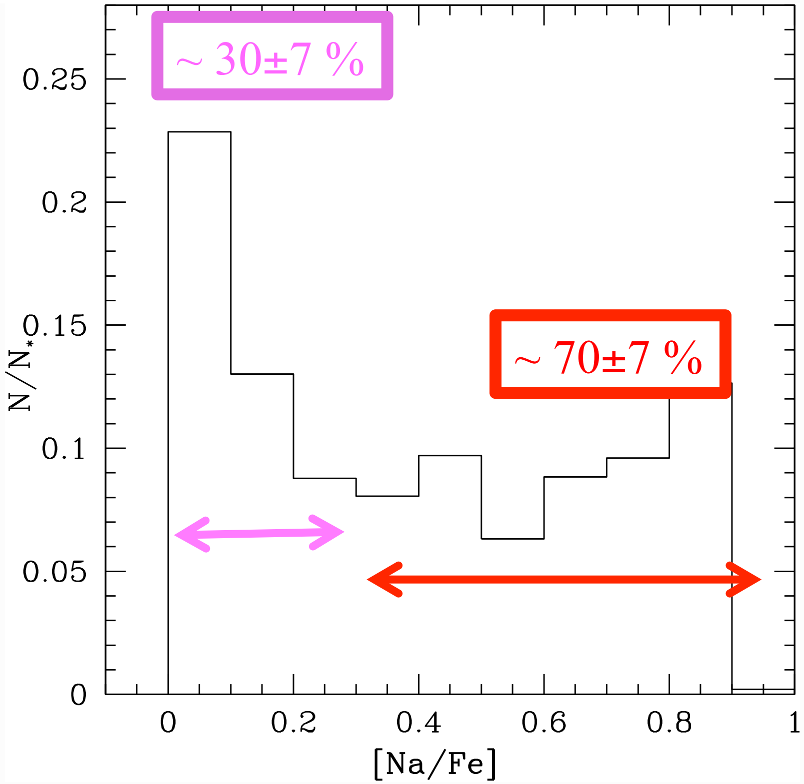
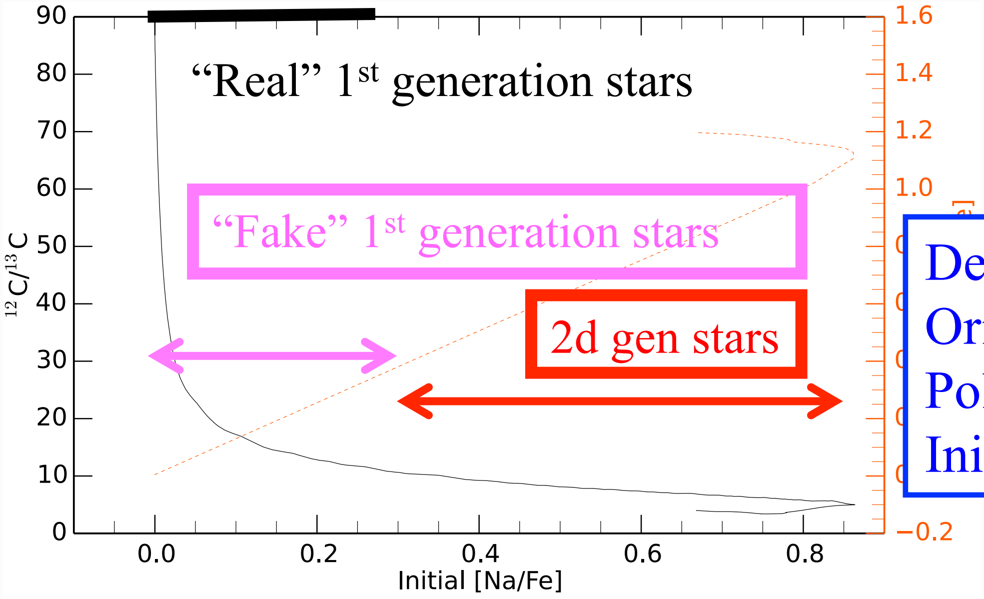
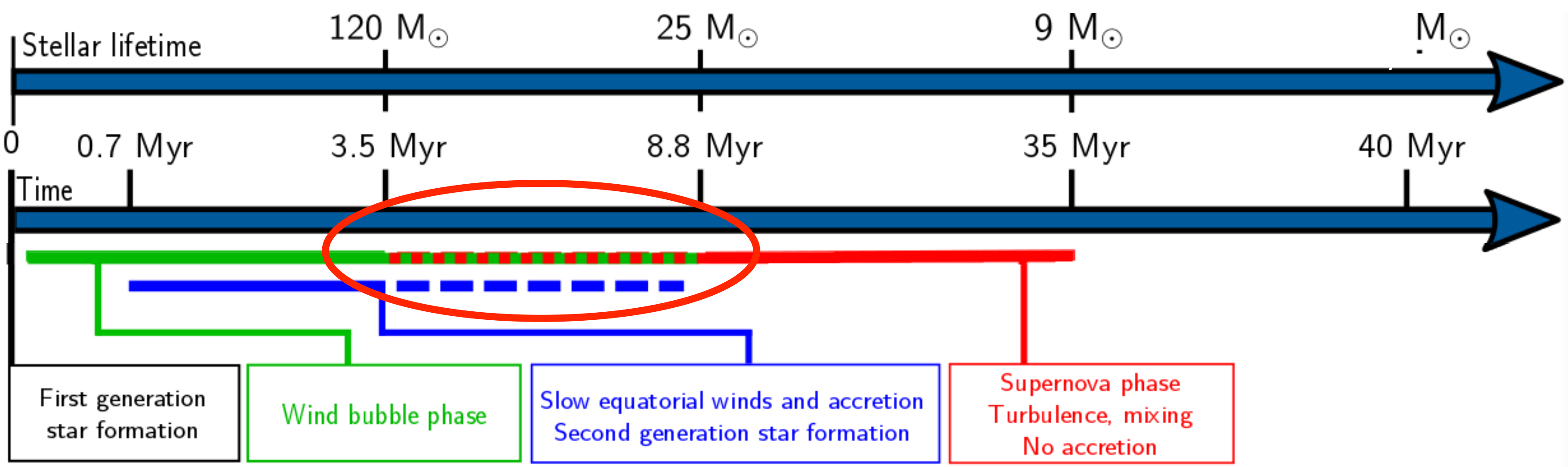




Delayed (~ 2 – 4 Myr) star formation
Original gas : only massive stars
Polluted gas : only low-mass stars
Initial GC mass ~ 2 – 4 x present-day mass

Charbonnel *et al.* (14)



Mass limit for stars to explode as SNe ?

$M \geq 25\ M_{\odot}$ may to turn silently into black holes

(Portegies Zwart *et al.* 97; Ergma & van der Heuvel 98; Kobulnicky & Skillman 97; Fryer 99; Belczynski *et al.* 12)

Loss of 1G stars during the supernovae phase ?

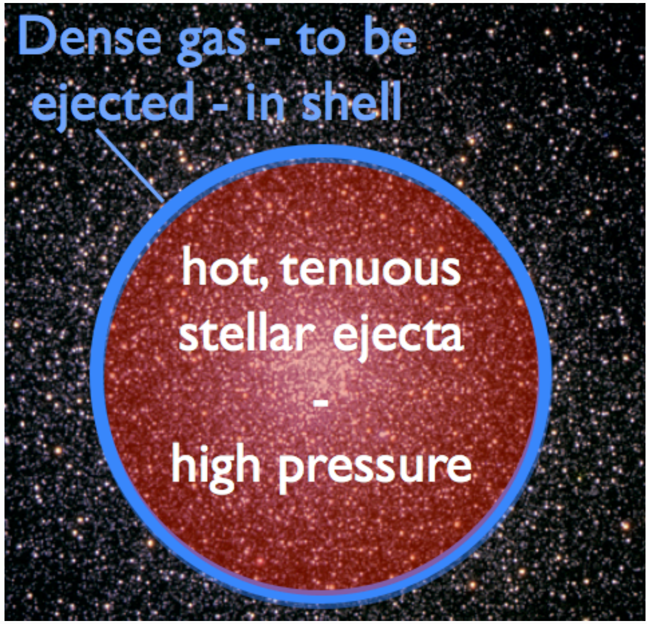
Energetic arguments: SNe: agents of gas expulsion

→Fast ejection of gas and SNe yields

→Sudden change of gravitational potential and loss of 1G stars

Baumgardt *et al.* (08), D' Ercole *et al.* (08), Decressin *et al.* (10)

Fast gas expulsion and loss of 1G stars – Superbubble



Growth of the superbubble via spherically symmetric thin shell approximation

Brown, Burkert & Truran (91,95)

$$\frac{\partial}{\partial t}(\mathcal{M}v) = pA - \mathcal{M}g$$

Shell momentum given by the applied forces:

p : bubble pressure depends on energy injection law E(t) and efficiency parameter for the transfer of energy to the gas (20%)

g : gravitational acceleration

M : mass in the shell, *v* : shell velocity, A : surface area of the shell

$$\lambda = (a - g)\tau^2$$

Rayleigh-Taylor scale

τ : time for the Ity to grow

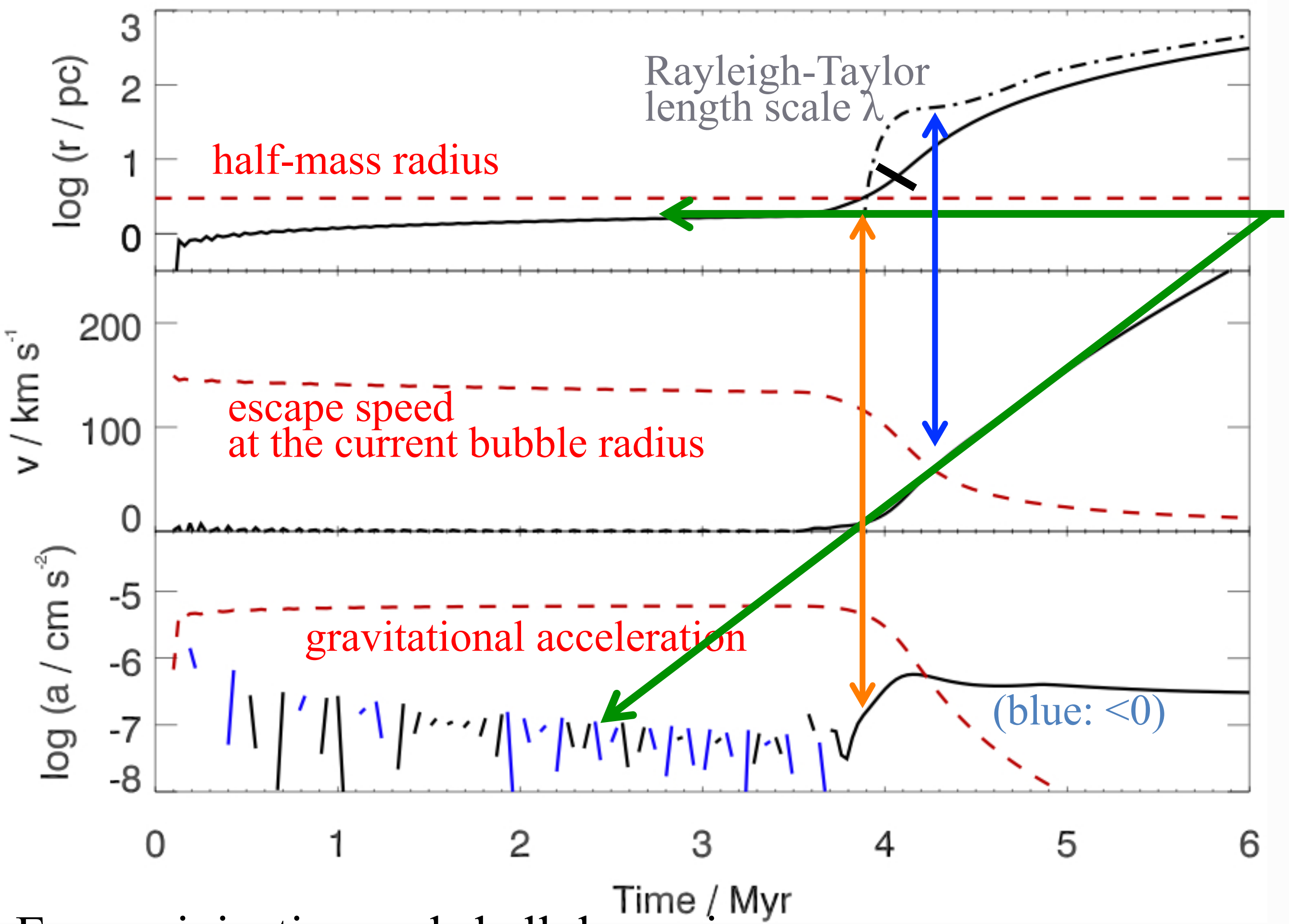
Rayleigh-Taylor instability
develops whenever shell acceleration overcomes
gravitational acceleration (a-g > 0)
and disrupts the shell when λ > shell radius

→ This favours fall back towards the cluster centre, and in this case gas expulsion fails

Energy sources: Stellar winds and SNe explosions

Winds of massive stars

SNe explosions (10^{51} erg per explosion, with an efficiency parameter for the transfer of energy to the gas of 20%)



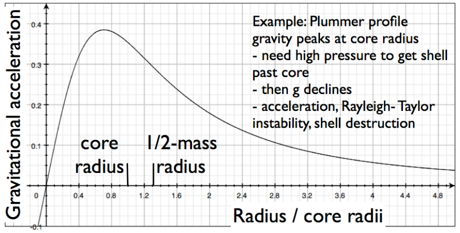
Energy injection and shell dynamics

Krause, Charbonnel *et al.* (12)

Slow and oscillatory shell expansion (<4Myr) (gravitational pull)

Gravity declines sharply around $r_{1/2}$

→ shell acceleration



Rayleigh-Taylor Ity

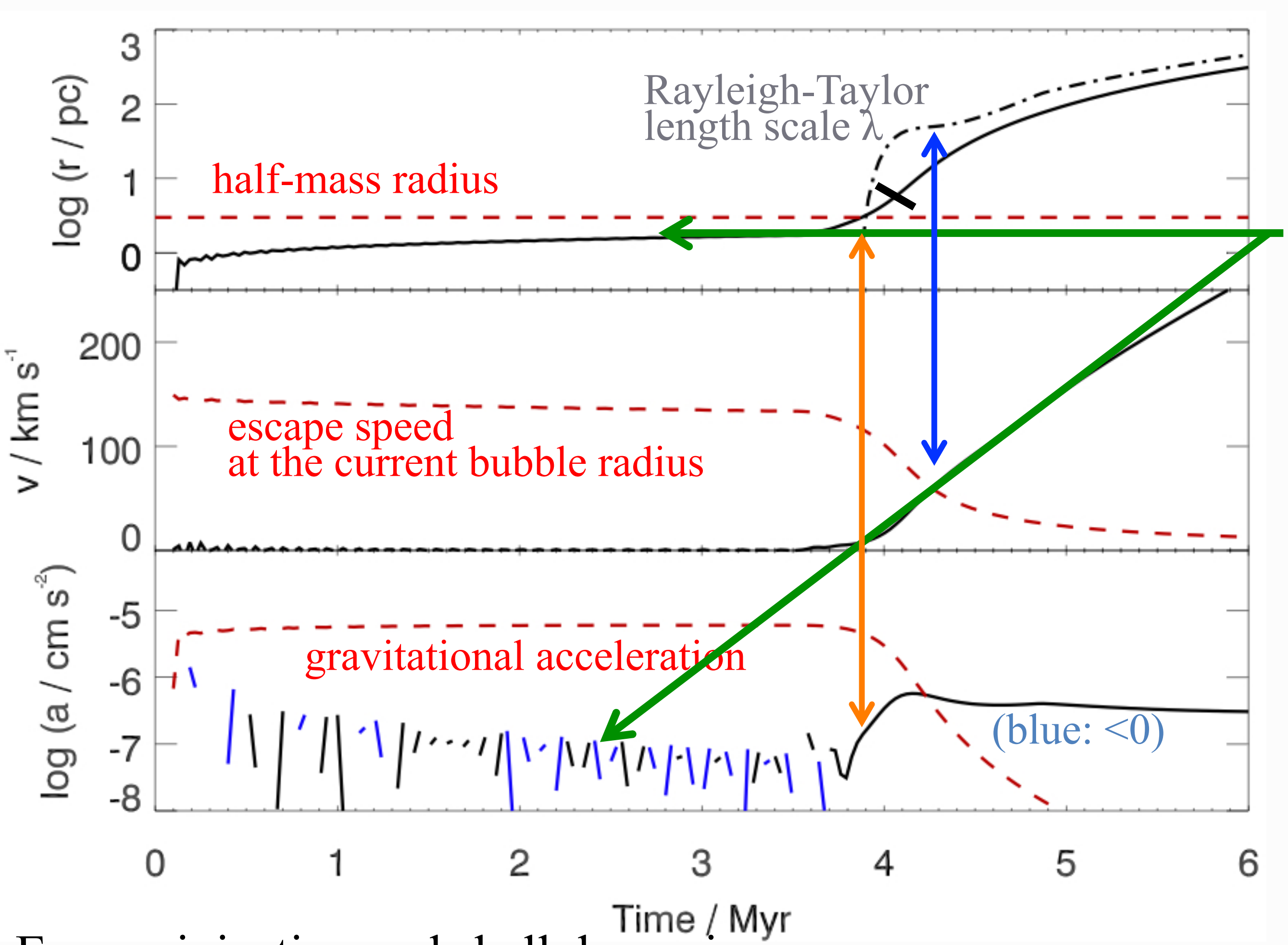
length scale $\lambda = (a-g)\,\tau^2$

→ Shell is burst and disrupted before it reaches the escape speed

→ Shell fragments fall back

Energy sources: Stellar winds and SNe explosions

While the energy injected by the SNe in total is sufficient, it is not delivered fast enough to overcome the RT instability



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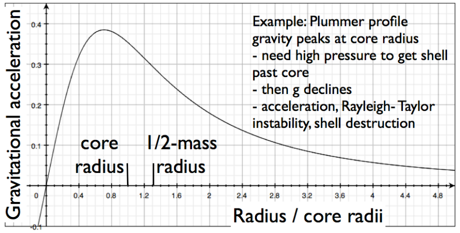


Example: Plummer profile
gravity peaks at core radius
- need high pressure to get shell past core
- then g declines
- acceleration, Rayleigh- Taylor instability, shell destruction

Rayleigh-Taylor Ity
length scale $\lambda = (a-g)\,\tau^2$

→ Shell is burst and disrupted before it reaches the escape speed

→ Shell fragments fall back

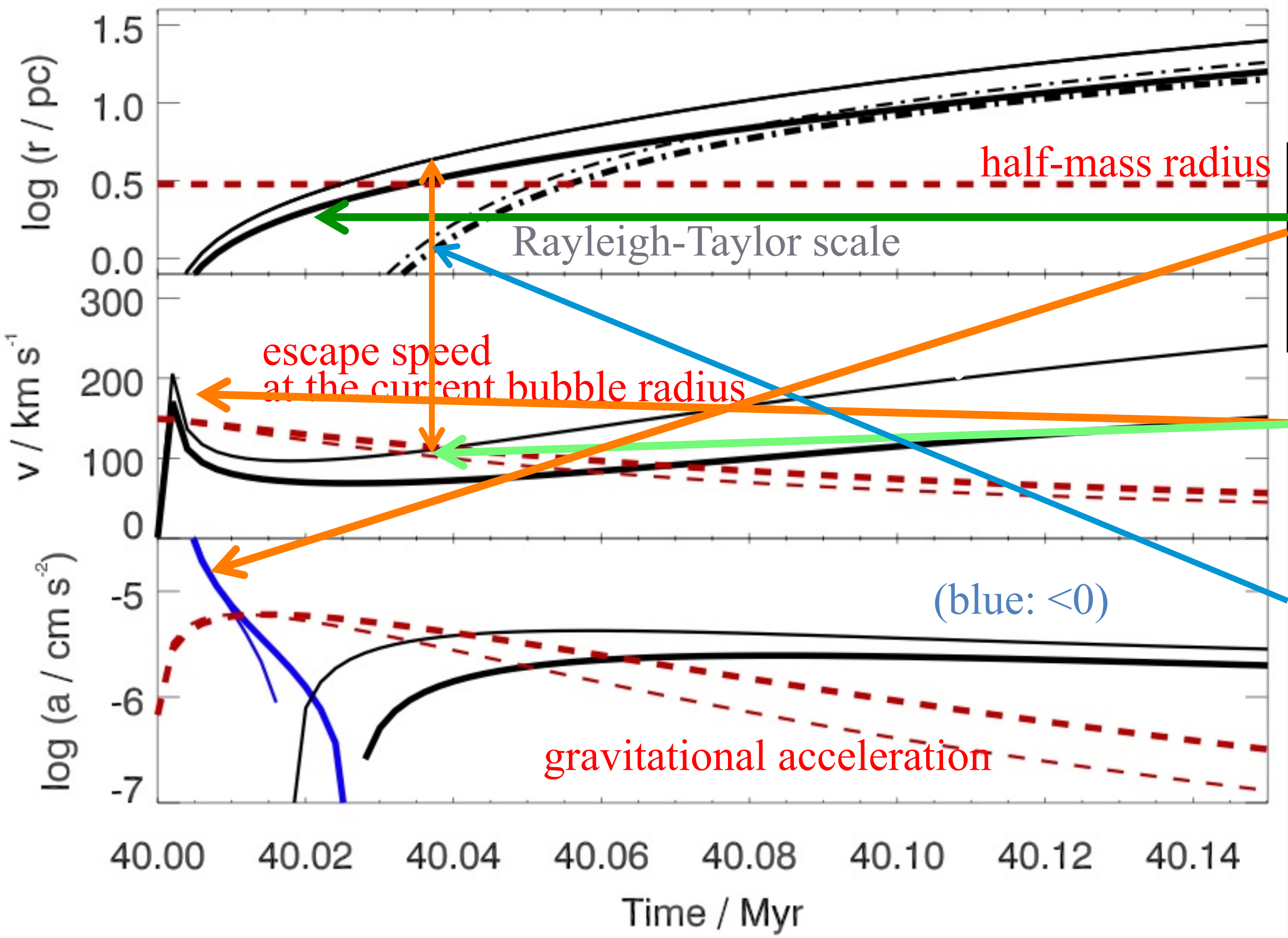
Energy injection and shell dynamics

Krause, Charbonnel *et al.* (12)

Energy source: Sudden activation of dark remnants

$> 25M_\odot \rightarrow 3M_\odot$BH, accretion of local gas adds energy to the gas at a rate of 20% of Eddington L

10-25$M_\odot \rightarrow 1.5\ M_\odot$ neutron stars, contribute 20% of Eddington L



Shell expands immediatly due to sudden power increase

Shell soon (0.03-0.06Myr) reaches escape velocity

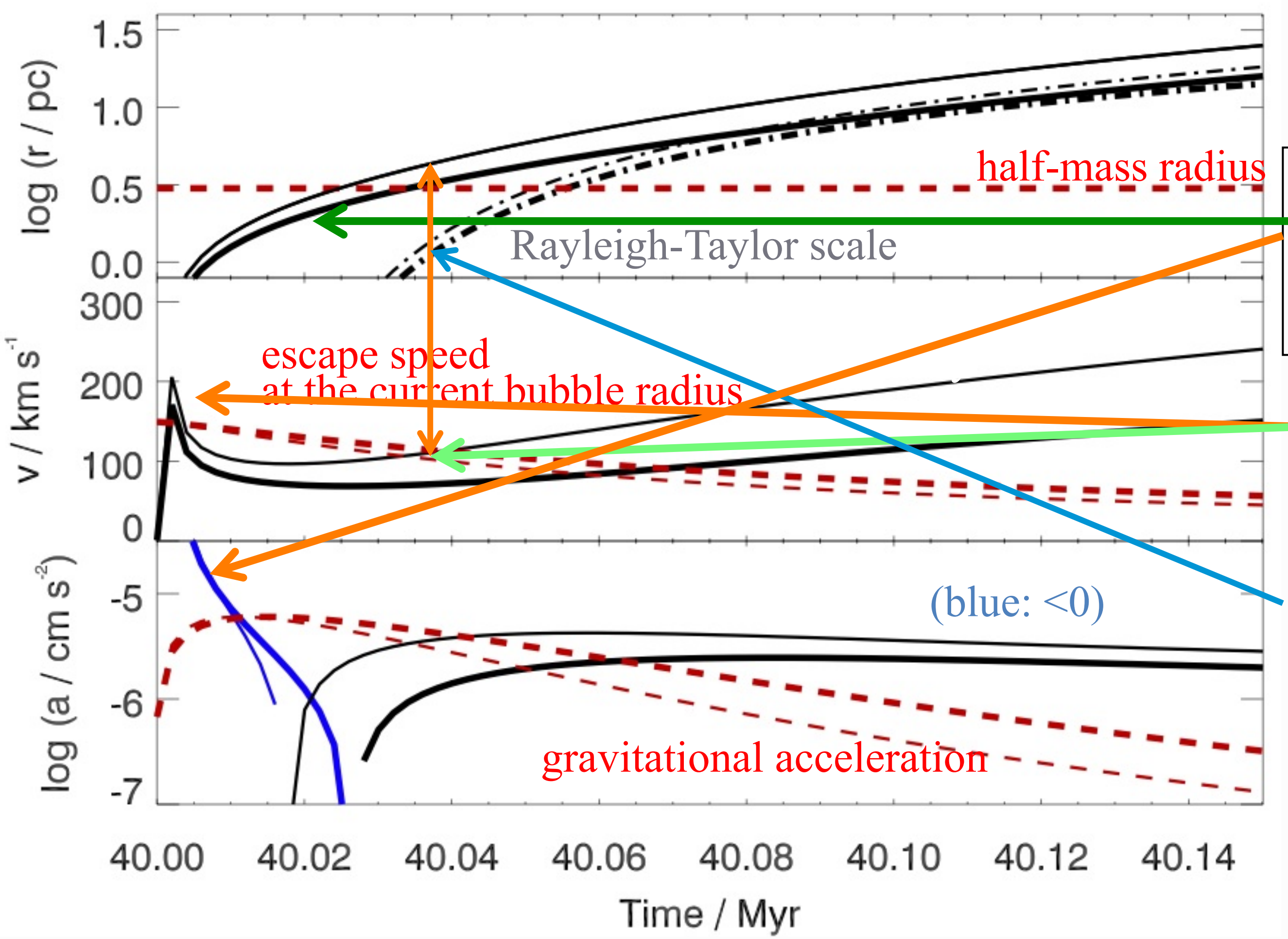
Rayleigh-Taylor Ity not able to affect the entire shell

→ Gas is expelled from the cluster

Krause, Charbonnel *et al.* (12)

Energy source: Sudden activation of dark remnants

Only coherent onset of accretion of local ISM onto the stellar remnants succeeds in expelling cold gas and unbinds 1st generation stars



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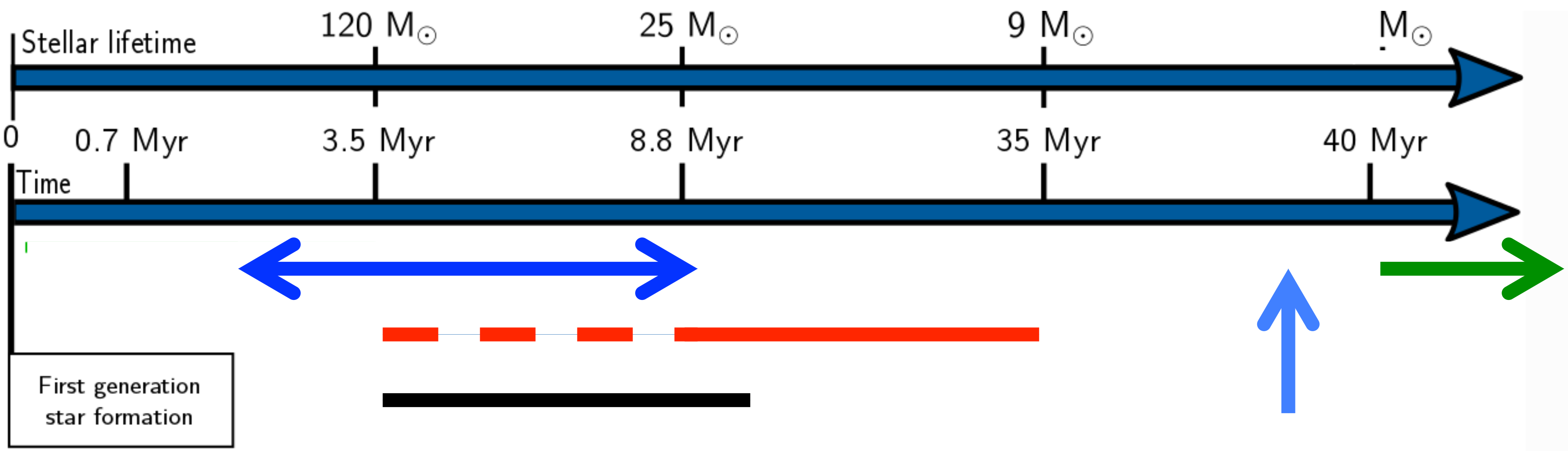
Krause, Charbonnel *et al.* (12)



FRMS scenario
Stars with masses > 25 $M_\odot$
1^{st}-2^{nd} populations: $\Delta t \sim 3.5 - 10$ Myr

Massive AGB scenario
Stars with masses ~ $6.5 M_\odot$
Gas re-accretion and 2G * formed in a cooling flow

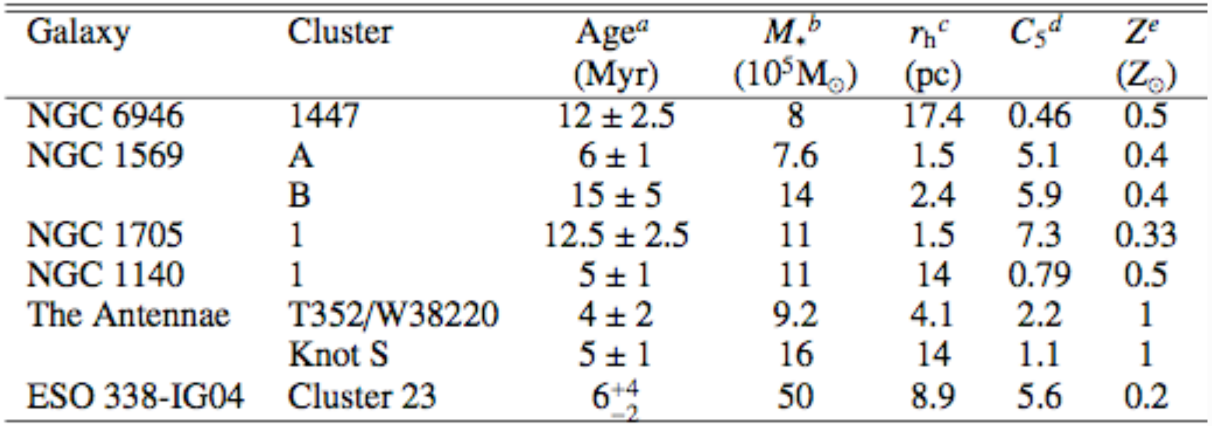
SNe energy not released quickly enough

Accretion onto and activation of dark remnants
at the end of the SNe phase (turbulence decreases in the ISM)

Challenge:
Gas-free
young massive star clusters

When and how did gas and 1G * ejection happen?

Challenge: Gas-free young massive star clusters



Galaxy	Cluster	Age^a (Myr)	$M_*{}^b$ ($10^5 M_\odot$)	$r_h{}^c$ (pc)	$C_5{}^d$	Z^e ($Z_\odot$)
NGC 6946	1447	12 ± 2.5	8	17.4	0.46	0.5
NGC 1569	A	6 ± 1	7.6	1.5	5.1	0.4
	B	15 ± 5	14	2.4	5.9	0.4
NGC 1705	1	12.5 ± 2.5	11	1.5	7.3	0.33
NGC 1140	1	5 ± 1	11	14	0.79	0.5
The Antennae	T352/W38220	4 ± 2	9.2	4.1	2.2	1
	Knot S	5 ± 1	16	14	1.1	1
ESO 338-IG04	Cluster 23	6^{+4}_{-2}	50	8.9	5.6	0.2

Bastian *et al.* (14)

YMCs in starburst and merging galaxies
with no gas and no star formation

Ages < ~ 15 Myr (although largely uncertain)
Masses and radii comparable to the values postulated for GCs from self-enrichment considerations
Very compact

Compactness index : $C_5 = (M_*/10^5\ M_\odot) / (r_h / \mathrm{pc})^{-1}$

Higher metallicity than old GCs

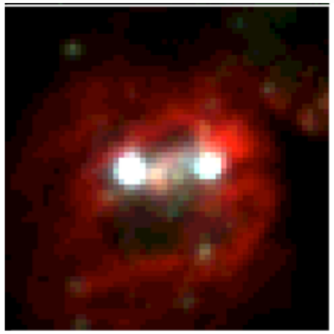
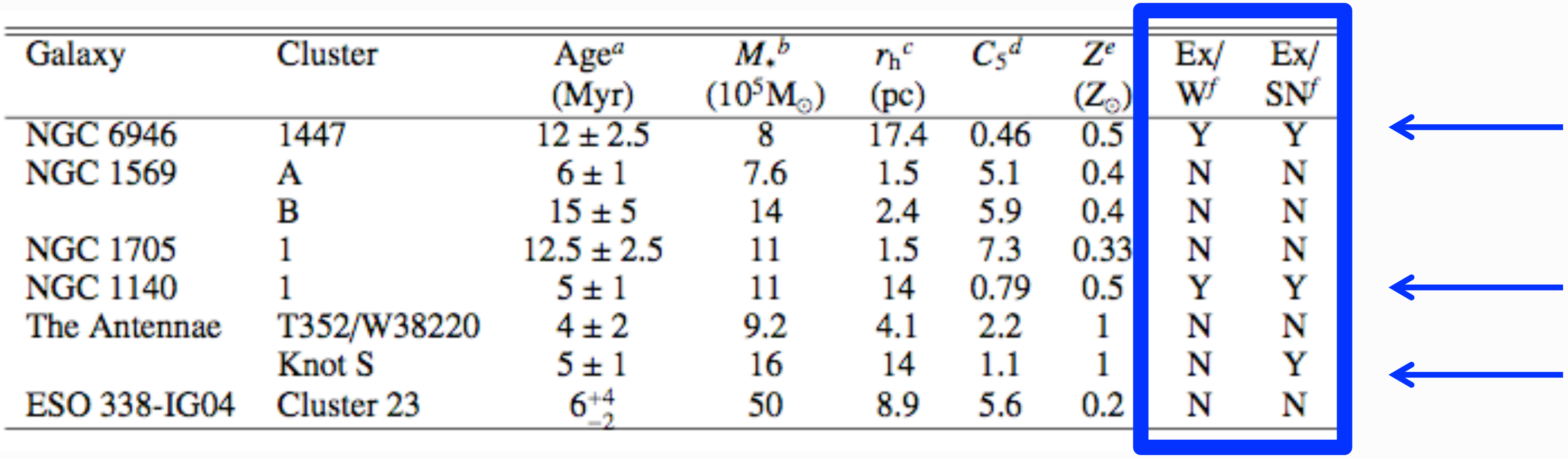


Figure 1. Top panel: a three-colour *HST*/ACS image of T352 in the Antennae galaxies; blue, green, and red represent images in the *F435W*, *F550M*, and *F658N* (Hα) filters, respectively. The ID from Whitmore et al. (2010) is also shown. Bottom panel: a zoom in on the region in the box in the top panel.

T352 in the Antennae

Gas-free YMCs – Individual gas expulsion modelling



Galaxy	Cluster	Age[a] (Myr)	M_*[b] ($10^5 M_\odot$)	r_h[c] (pc)	C_5[d]	Z[e] ($Z_\odot$)	Ex/ W[f]	Ex/ SN[f]
NGC 6946	1447	12 ± 2.5	8	17.4	0.46	0.5	Y	Y
NGC 1569	A	6 ± 1	7.6	1.5	5.1	0.4	N	N
	B	15 ± 5	14	2.4	5.9	0.4	N	N
NGC 1705	1	12.5 ± 2.5	11	1.5	7.3	0.33	N	N
NGC 1140	1	5 ± 1	11	14	0.79	0.5	Y	Y
The Antennae	T352/W38220	4 ± 2	9.2	4.1	2.2	1	N	N
	Knot S	5 ± 1	16	14	1.1	1	N	Y
ESO 338-IG04	Cluster 23	6^{+4}_{-2}	50	8.9	5.6	0.2	N	N

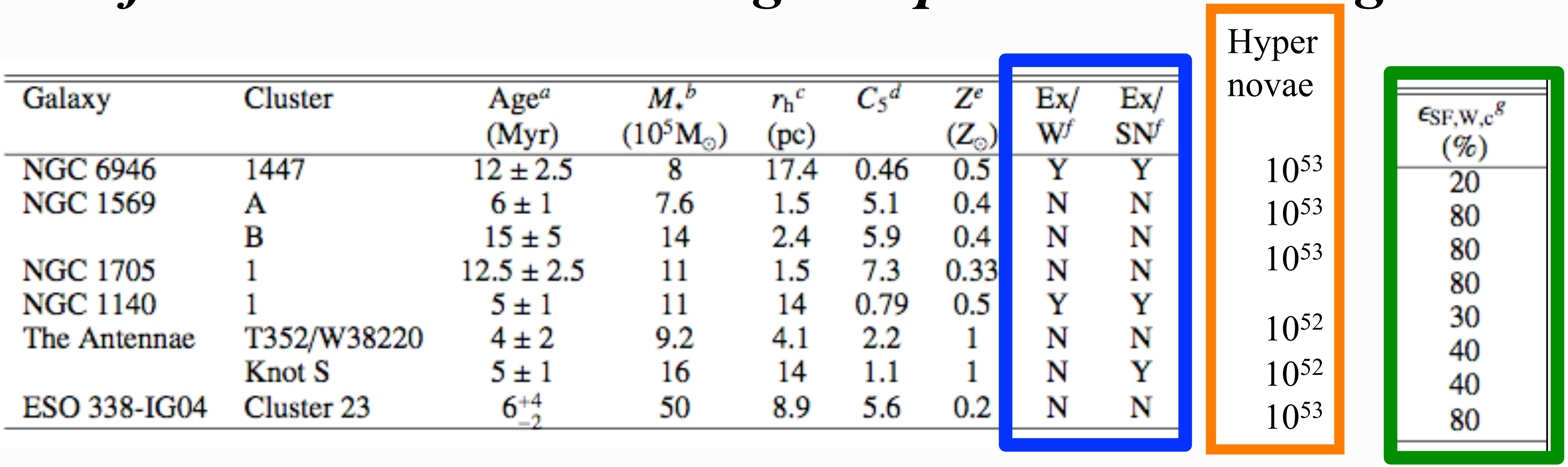
Krause, Charbonnel, Bastian, Diehl (15)

Gas expulsion efficient
only for the less compact objects
Compactness index : $C_5 = (M_*/10^5\ M_\odot) / (r_h / \mathrm{pc})^{-1}$

(Y) Success of gas expulsion by
- Stellar winds (W)
- SNe 10^{51} erg

with 20% feedback efficiency
and assuming SFE = 0.3

Gas-free YMCs – Individual gas expulsion modelling



Galaxy	Cluster	Age[a] (Myr)	M_*[b] ($10^5 M_\odot$)	r_h[c] (pc)	C_5[d]	Z[e] ($Z_\odot$)	Ex/ W[f]	Ex/ SN[f]	$\epsilon_{SF,W,c}$[g] (%)
NGC 6946	1447	12 ± 2.5	8	17.4	0.46	0.5	Y	Y	20
NGC 1569	A	6 ± 1	7.6	1.5	5.1	0.4	N	N	80
	B	15 ± 5	14	2.4	5.9	0.4	N	N	80
NGC 1705	1	12.5 ± 2.5	11	1.5	7.3	0.33	N	N	80
NGC 1140	1	5 ± 1	11	14	0.79	0.5	Y	Y	30
The Antennae	T352/W38220	4 ± 2	9.2	4.1	2.2	1	N	N	40
	Knot S	5 ± 1	16	14	1.1	1	N	Y	40
ESO 338-IG04	Cluster 23	6^{+4}_{-2}	50	8.9	5.6	0.2	N	N	80

Hyper novae

10^{53}
10^{53}
10^{53}
10^{52}
10^{52}
10^{53}

Krause, Charbonnel, Bastian, Diehl (15)

Gas expulsion efficient
only for the less compact objects
Compactness index : $C_5 = (M_*/10^5\ M_\odot) / (r_h / \mathrm{pc})^{-1}$

(Y) Success of gas expulsion by
- Stellar winds (W)
- SNe 10^{51} erg

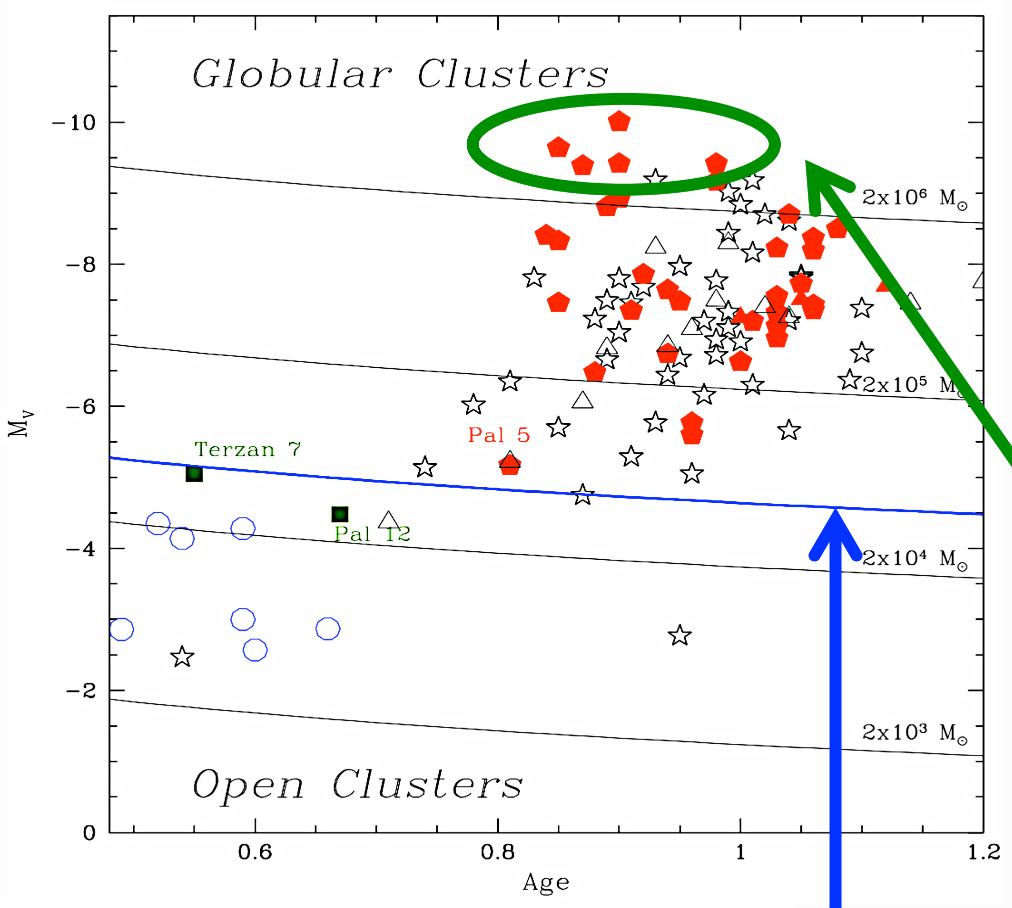
when assuming SFE = 0.3
and 20% feedback efficiency

For the more compact YMCs, need hypernovae (10^{52} and 10^{53} erg) if SFE = 0.3

Or for a much higher SFE ≥ 0.8 for the most compact clusters
(less gas to be expelled)

→ However in this case, no loss of 1G stars, as the potential well does not change significantly

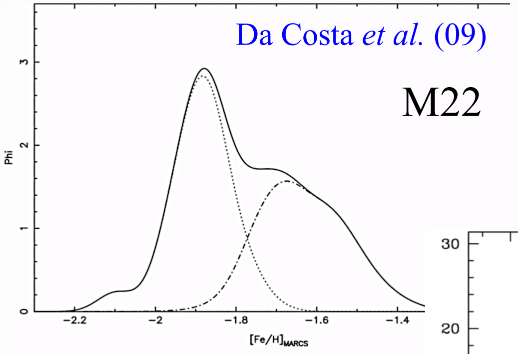
Abundance properties – The key role of initial cluster mass

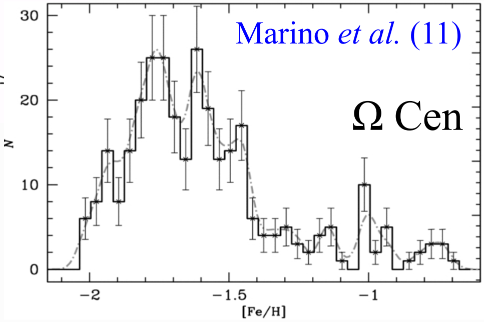


MW and LMC GCs with anticorrelation
Sagittarius dSph GC without anticorrelation
Old open clusters
No or too few data

Carretta *et al.* (10)

M22

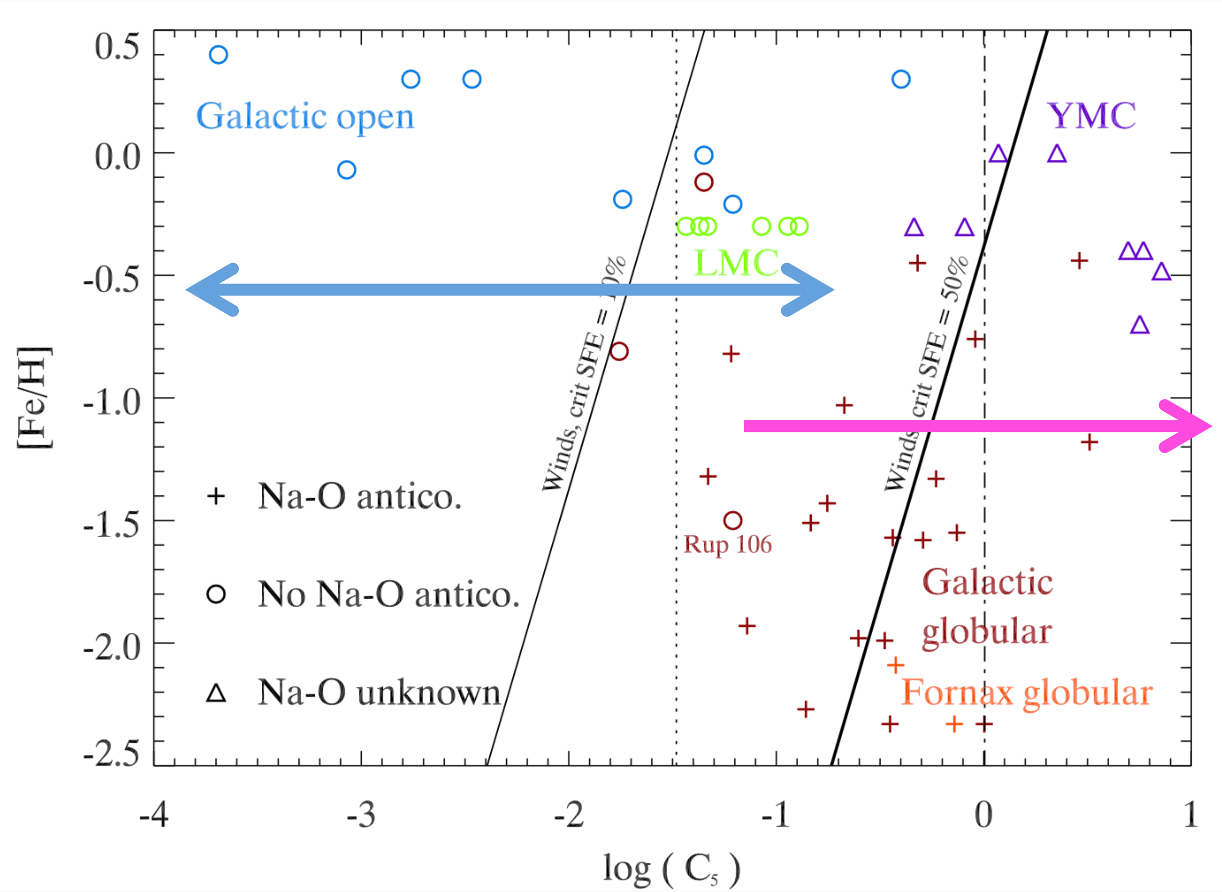




Minimum present-day mass for a star cluster to exhibit [Fe/H] dispersion

Minimum present-day mass for a star cluster to exhibit the O-Na anticorrelation (but no [Fe/H] dispersion)

Abundances and gas ejection – The key role of compactness



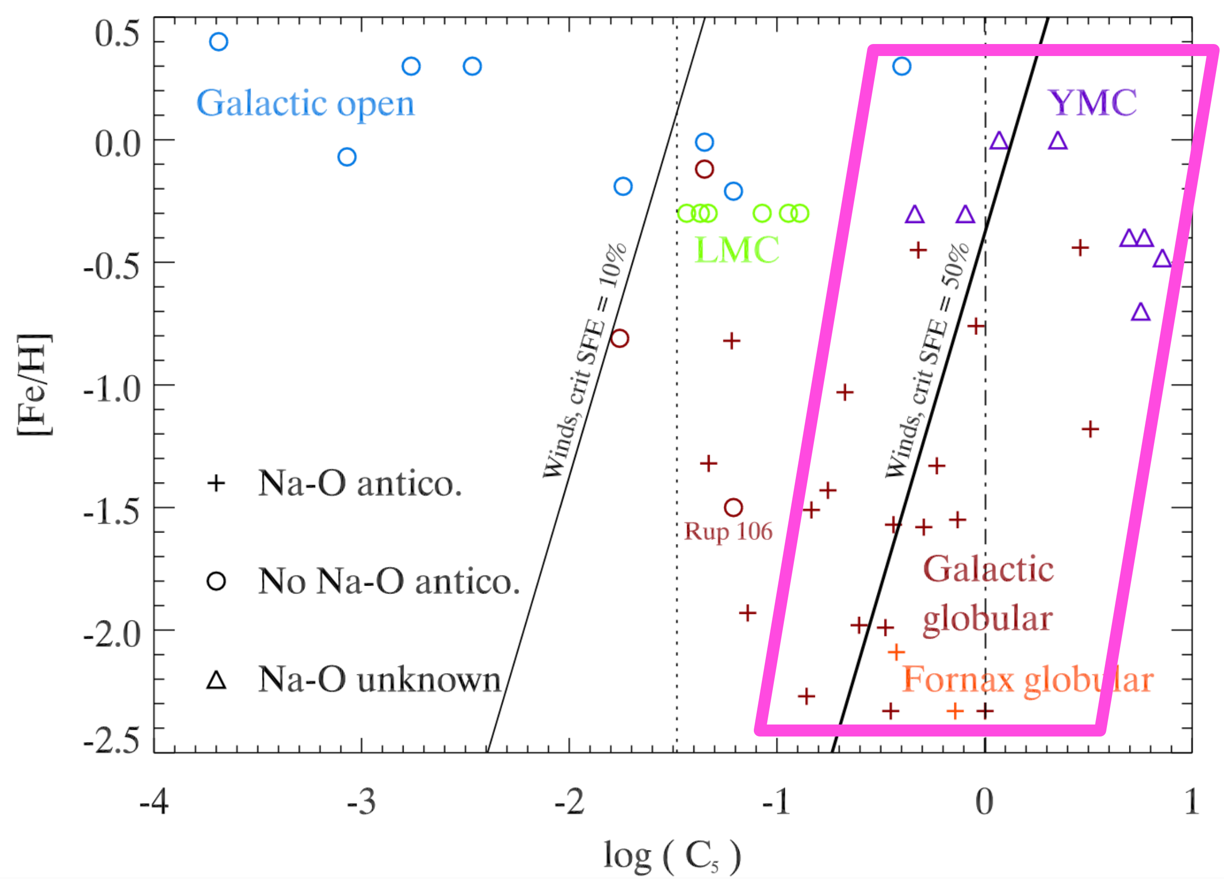
Single stellar population :
No problem to expulse the gas
but no O-Na anticorrelation

Multiple stellar populations
with O-Na anticorrelation :
Gas expulsion under very
special conditions
Or
High SFE

Lines indicate the critical SFE for a given compactness index and energy scheme
Compactness index : $C_5 = (M_*/10^5\ M_\odot) / (r_h / pc)^{-1}$

Krause, Charbonnel, Bastian, Diehl (15)

Abundances and gas ejection – The key role of compactness

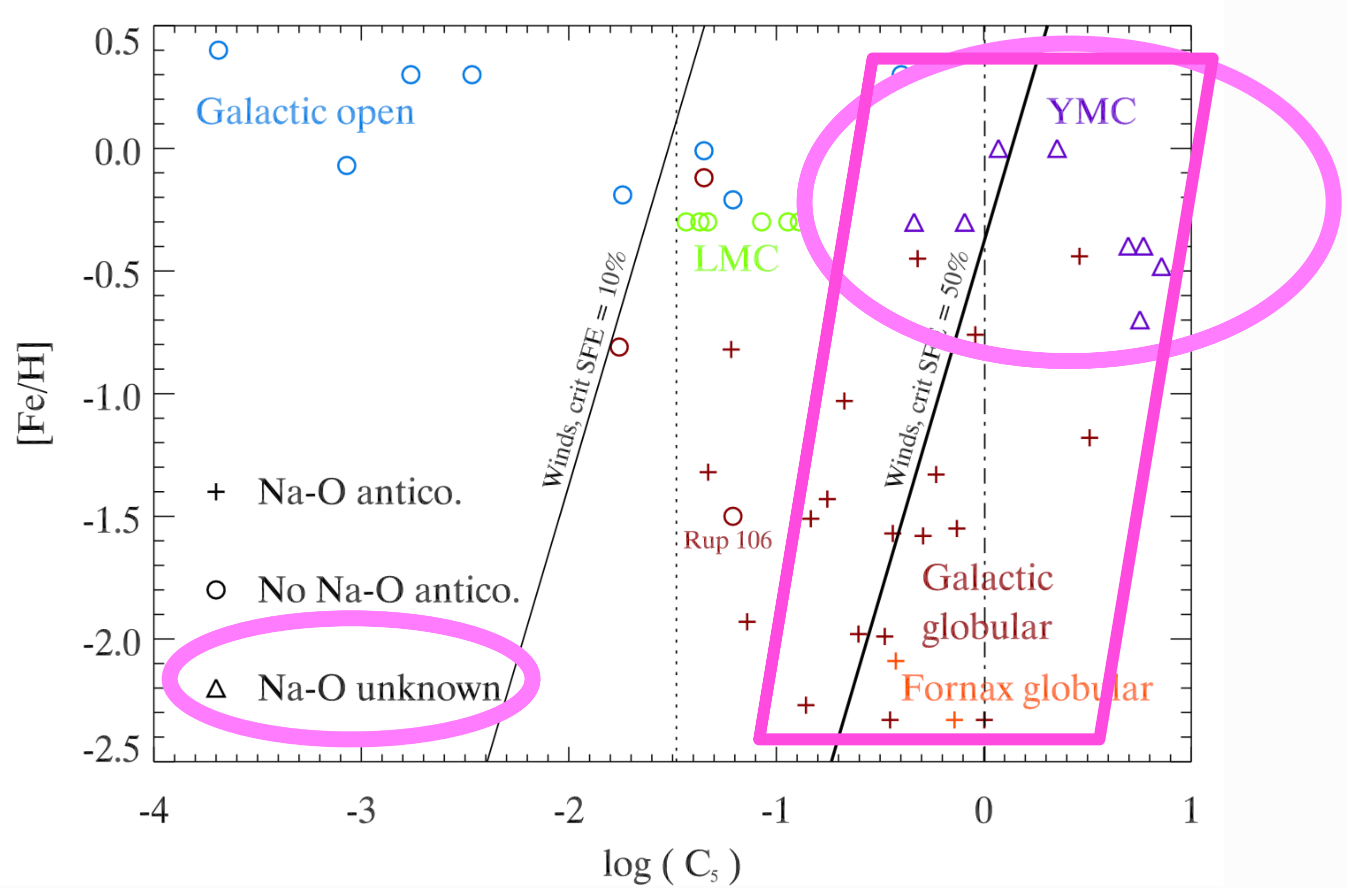


Multiple stellar populations with O-Na anticorrelation : Gas expulsion under very special conditions
Or
High SFE

GC constraints : Require runaway gas accretion onto BH and NS @ ~ 40Myrs
If YMCs ~ GC progenitors, i.e., early gas loss or consumption :
Require hypernovae,
or SFE > 50 – 80 %, thus no loss of 1G stars

Krause, Charbonnel, Bastian, Diehl (15)

Are YMSCs comparable to GC progenitors?



?

Yes – **Universal process for the formation and evolution of MSCs**

No – **Importance of metallicity (ISM physics) ?**
Importance of environment?
Very unique conditions in the early Universe ?

Krause, Charbonnel, Bastian, Diehl (15)

Formation, evolution, and survival of massive star clusters

Universal processes in the early and present-day universe?
→ Importance of comparative studies !
→ Key role of multiple stellar populations !

(Some of the) Theoretical challenges of the next decade

→ Tailor-made models for MSC member stars

→ Models of MSCs (N-body and chemodynamical) coupling stellar evolution, ISM physics, and feedback

→ Advanced population synthesis models accounting for the chemical and photometric peculiarities of multiple stellar populations