The early life of globular clusters
Chemistry and dynamics

Pillar and Jets HH 901/902
Hubble Space Telescope • WFC3/UVIS

Star-Forming Region 30 Doradus
Hubble Space Telescope • WFC3/UVIS

Star-Forming Region S106

NASA, ESA, and the Hubble Heritage Team (STScI/AURA) • *HST* WFC3/UVIS • STScI-PRC11-38

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

Main collaborators
Prantzos (IAP)
Chantereau, Meynet, Schaerer (Geneva)
Krause (MPE) Decressin (Rome)
Primas, Wang (ESO)

O-Na anticorrelation in Galactic globular clusters
A general property

"Anomalous",
[O/Na] ~ -2
2^{d} generation/
population

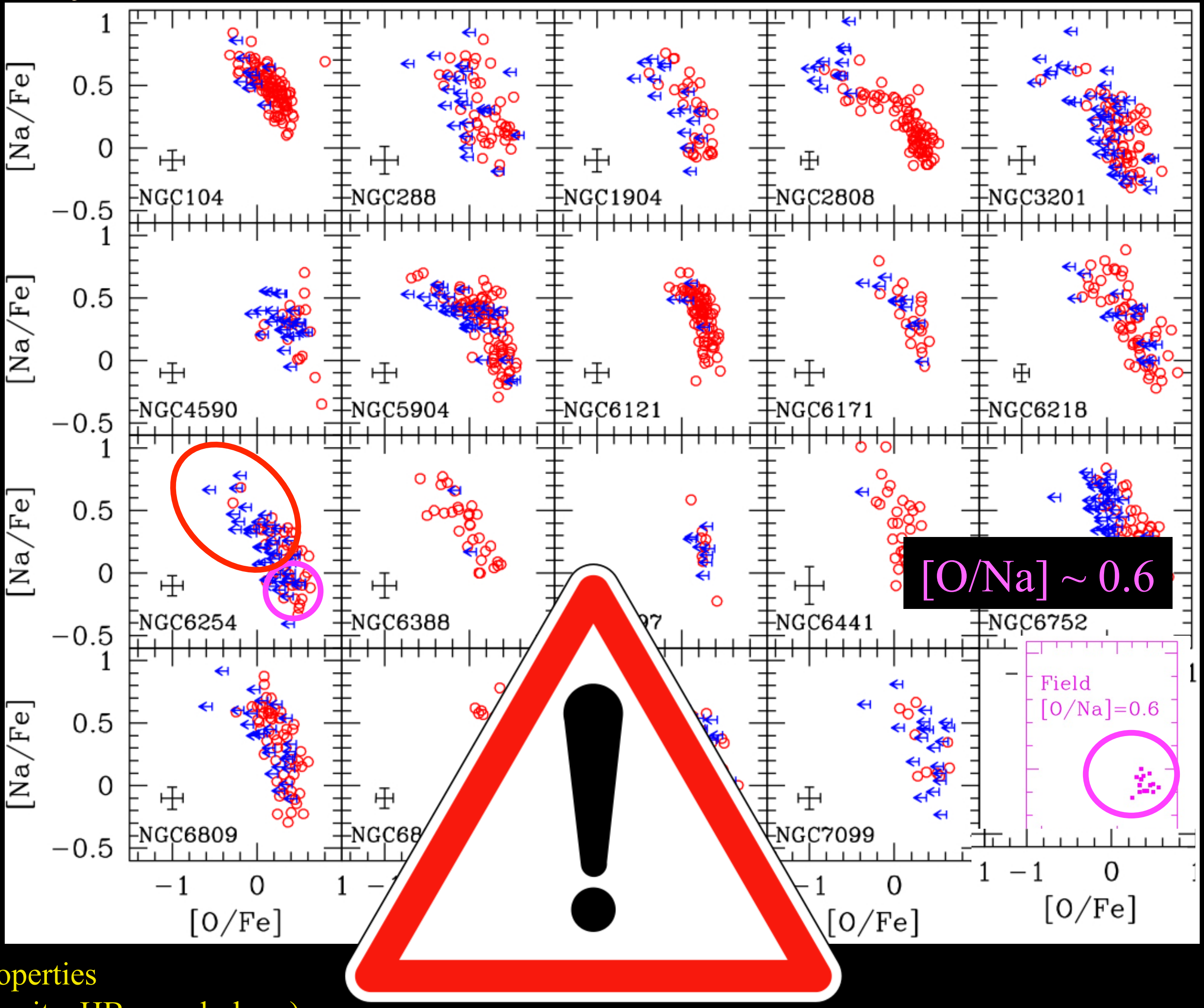
~ 70±7 %

"Normal" ,
[O/Na] ~ 0.6
formed out of
original GC material

1st generation/
population

~ 30±7 %

Prantzos & Charbonnel (06)



[O/Na] ~ 0.6

MW GCs with

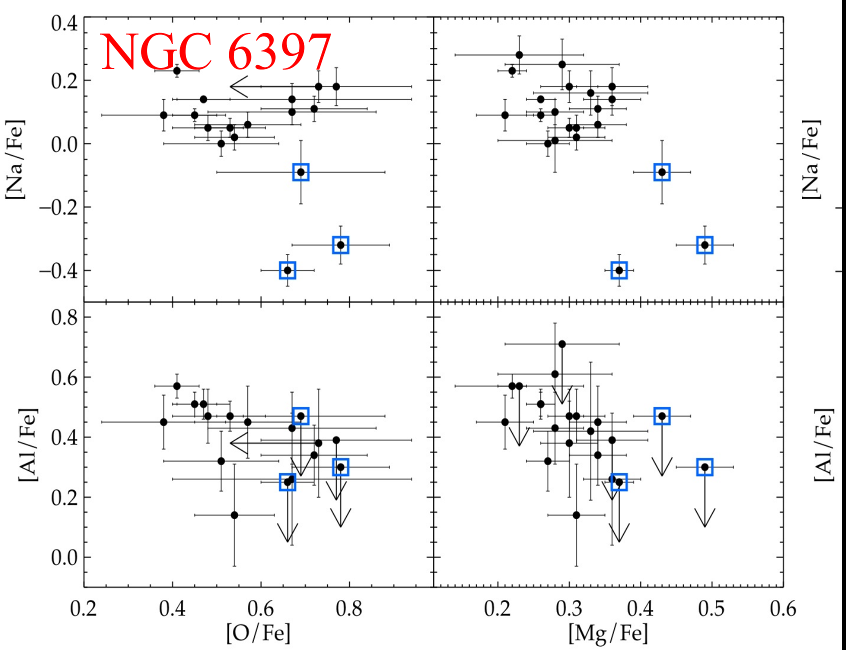
- -2.16 ≤ [Fe/H] ≤+0.07
- a large range of physical properties
  (≠ total M, concentration, density, HB morphology)
- disk and halo population

Carretta *et al.* (10, VII)

O-Na, Mg-Al anticorrelations

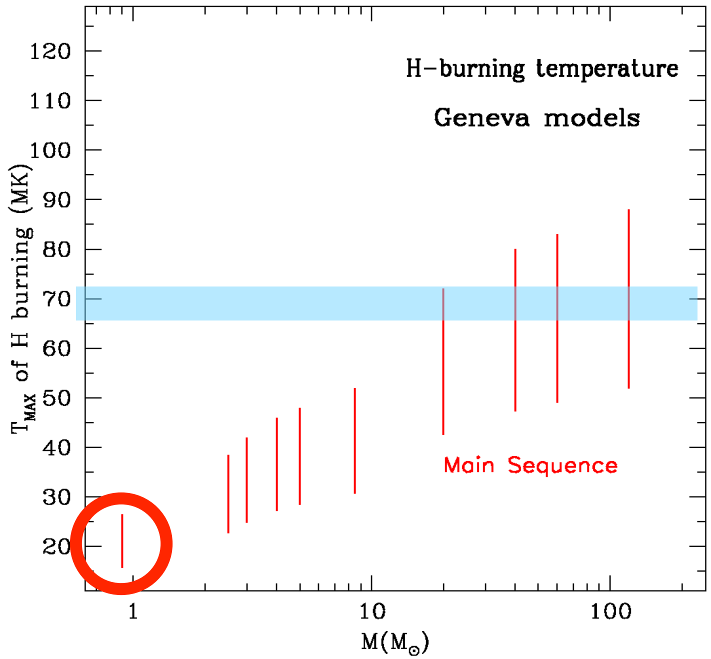
H-burning (CNO, NeNa, MgAl) at T ~ 72 to 78 MK

Denissenkov & Denissenkova (90), Prantzos, Charbonnel & Iliadis (07)



Lind, Charbonnel, Decressin, Primas, Asplund & Grundahl (11)

The observed patterns *pre-existed*
in the material out of which
the presently surviving stars formed

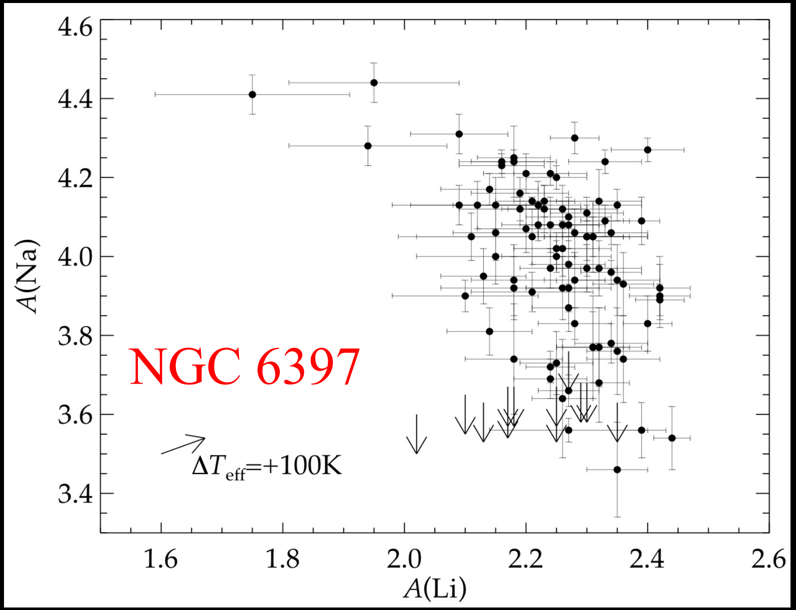


The chemically anomalous
(“second”) stellar population
formed from “non pristine” intracluster gas
that was polluted by
first generation massive, rapidly evolving stars
in which H burned at ~ 72-78 MK

O-Na, Mg-Al anticorrelations

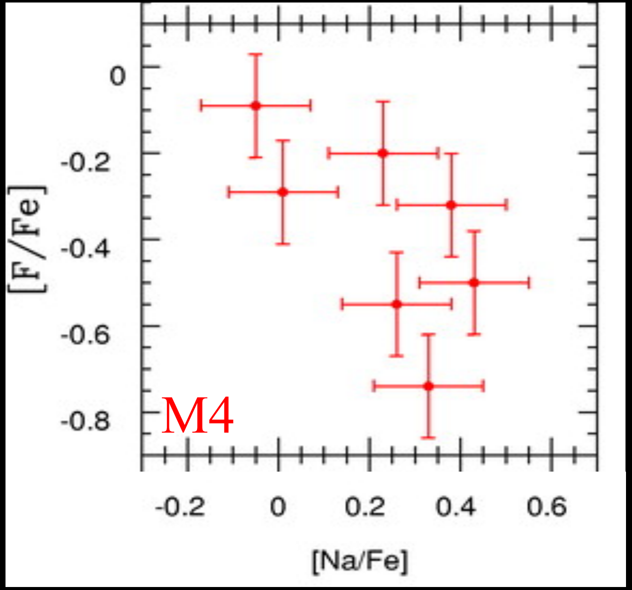
H-burning (CNO, NeNa, MgAl) at T ~ 72 to 78 MK

Li, F



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

H-burning ashes devoid of light elements (LiBeBF)
→ *2G stars form from*
H-burning ashes mixed with pristine gas

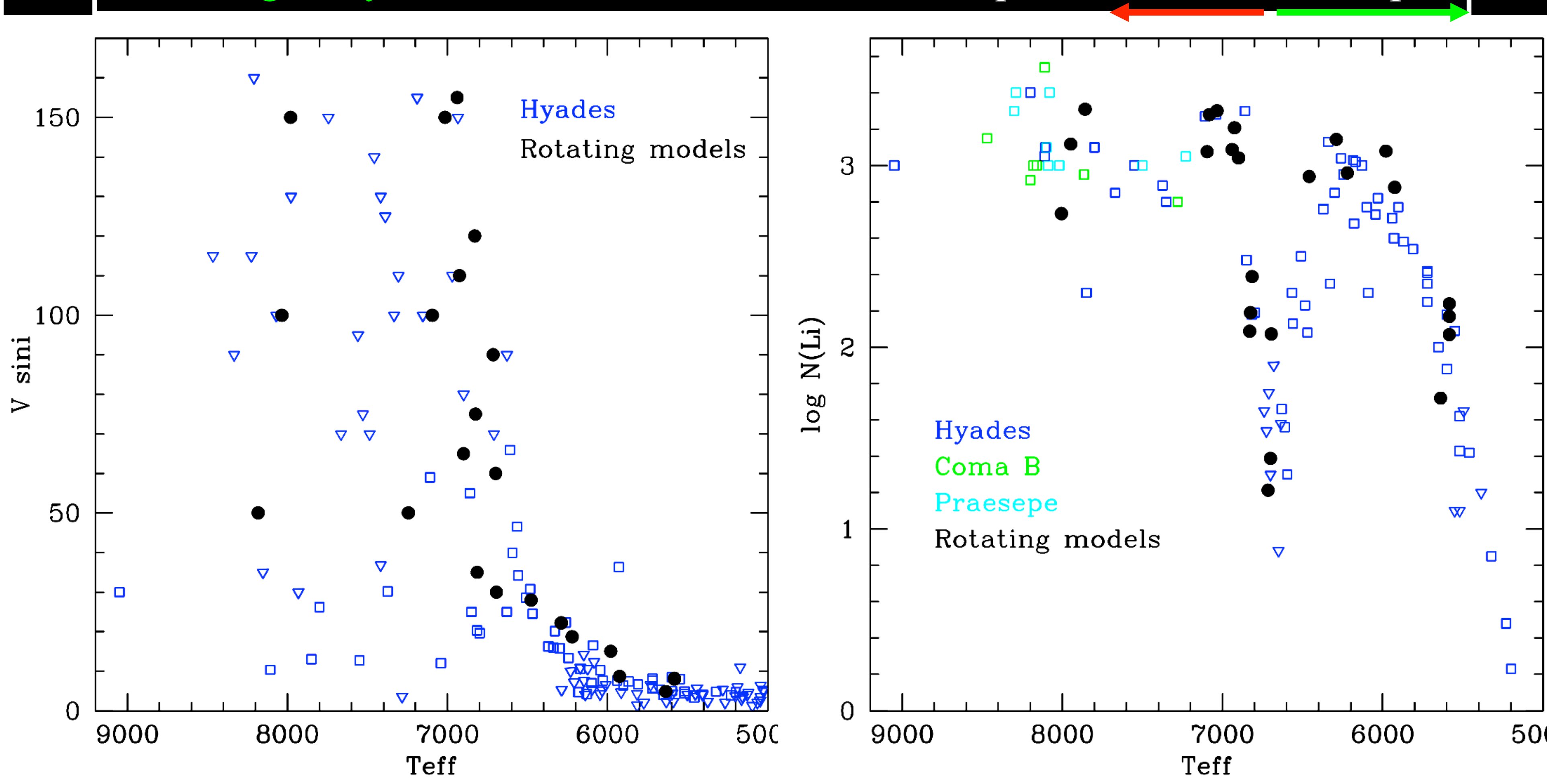


Smith *et al.* (05)

~ 50 % of original gas (LiBeBF-rich)
& 50 % of stellar ejecta (LiBeBF-free)

Lithium in Pop I stars

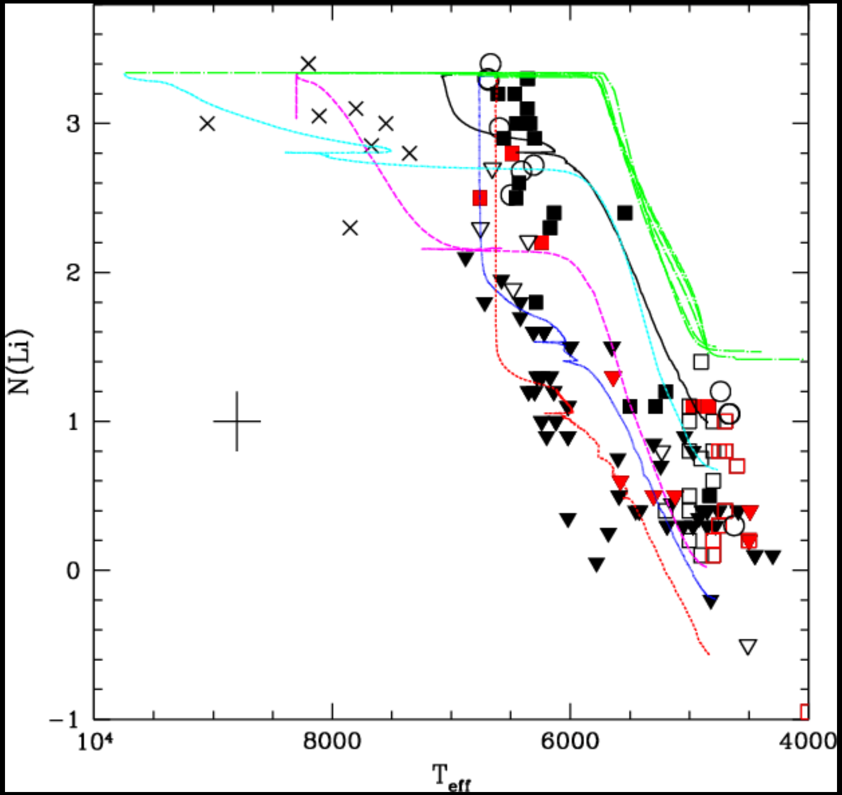
Transport of angular momentum dominated by
Circulation and turbulence in massive stars down to the Li dip
Internal gravity waves in low mass stars with deeper convective envelopes



Charbonnel, Decressin & Talon (in prep.)

Lithium in Pop I stars

Rotation-induced mixing in low-mass main subgiant stars



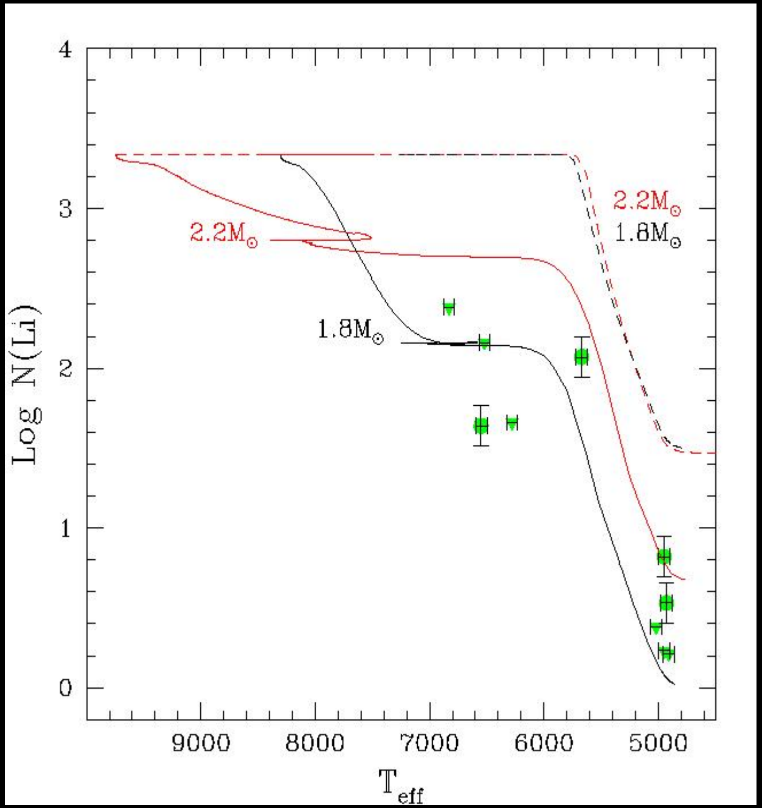
Standard models : green lines

Rotating models of various M_* : other colored lines

Observations : Field and
open cluster evolved stars

Lèbre et al. (99), Wallerstein et al. (94), Gilroy (89)
Pasquini et al. (01), Burkhart & Coupry (98, 00)

Palacios et al. (03), Pasquini et al. (04)



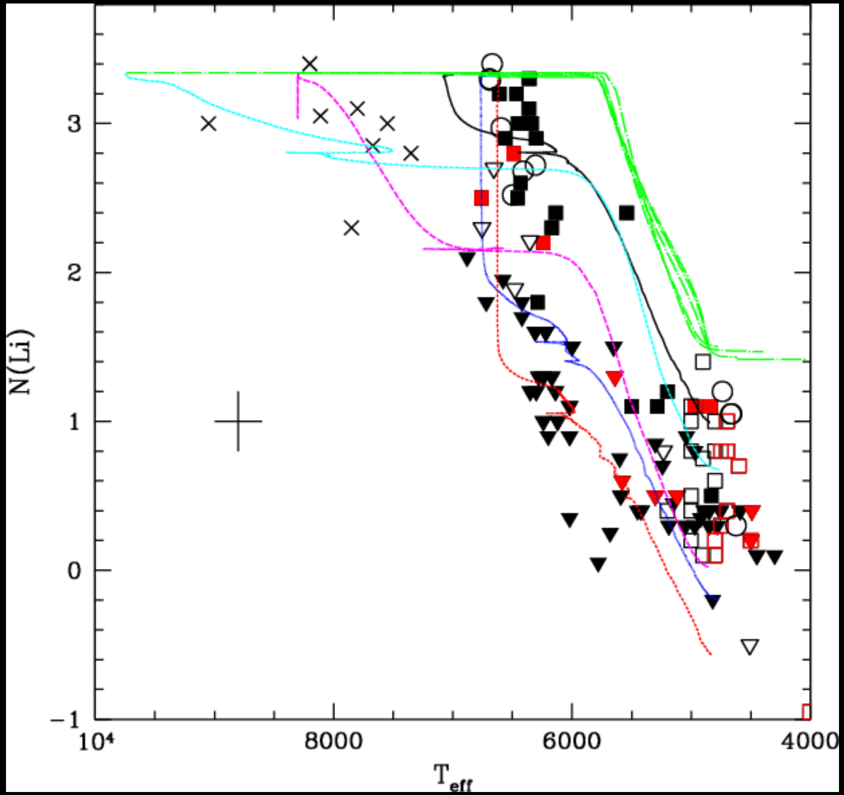
Standard models : dotted lines

Rotating models : full lines (Palacios et al. 03)

Observations : IC 4651 evolved stars

Pasquini et al. (05)

Lithium in Pop I stars



Standard models : green lines

Rotating models of various M_* : other colored lines

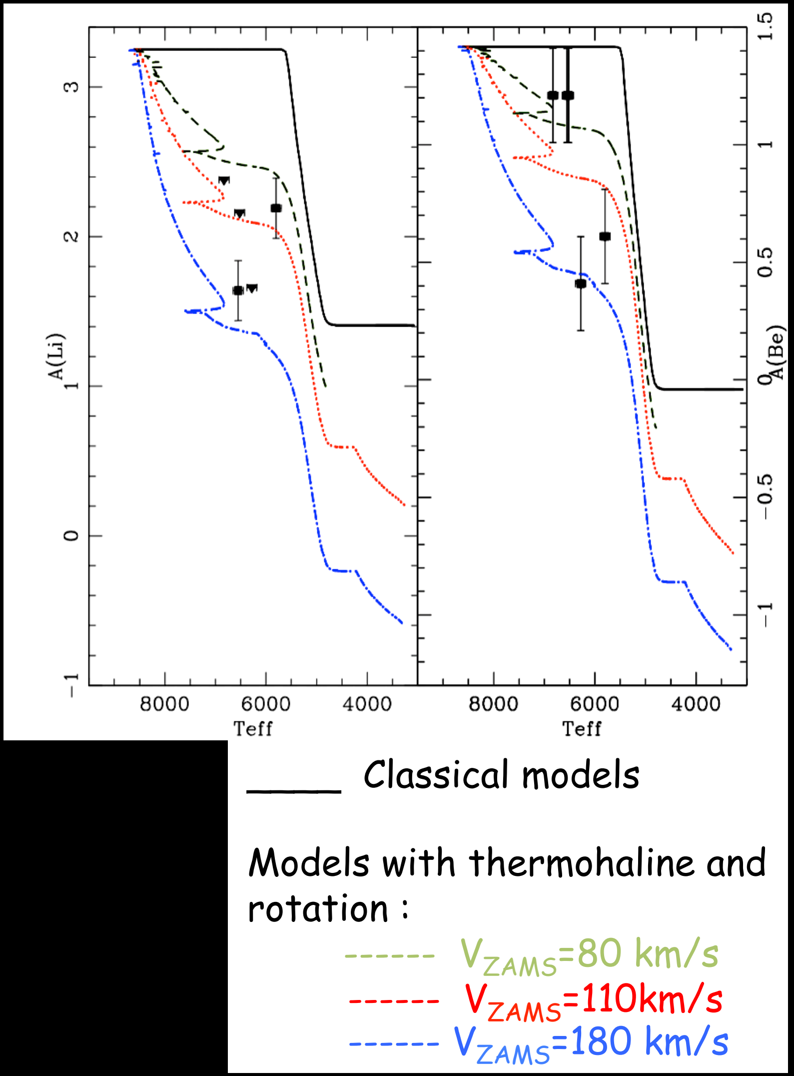
Observations : Field and
open cluster evolved stars

Lèbre et al. (99), Wallerstein et al. (94), Gilroy (89)

Pasquini et al. (01), Burkhart & Coupry (98, 00)

Palacios et al. (03), Pasquini et al. (04)

Rotation-induced mixing in low-mass main subgiant stars



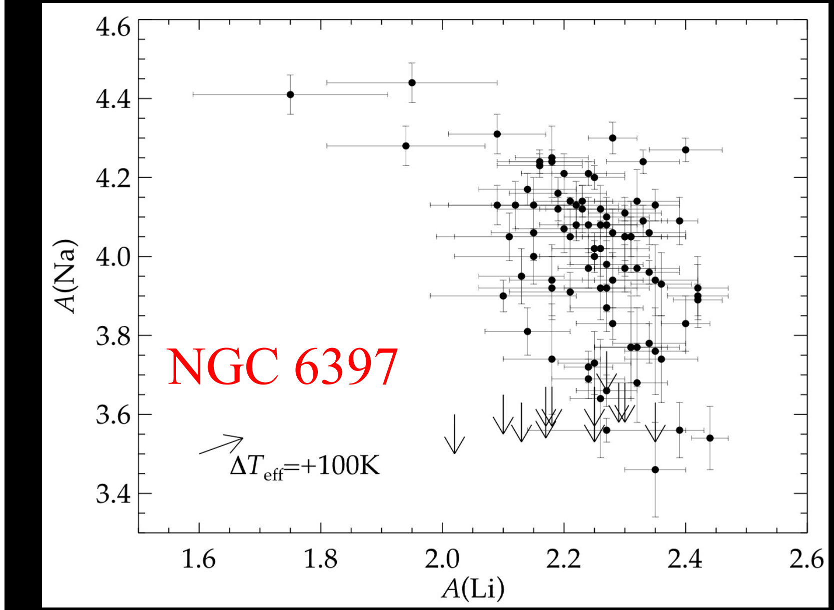
Observations : IC 4651

Smiljanic, Pasquini, Charbonnel & Lagarde (09)

O-Na, Mg-Al anticorrelations

H-burning (CNO, NeNa, MgAl) at T ~ 72 to 78 MK

Li, F and Be

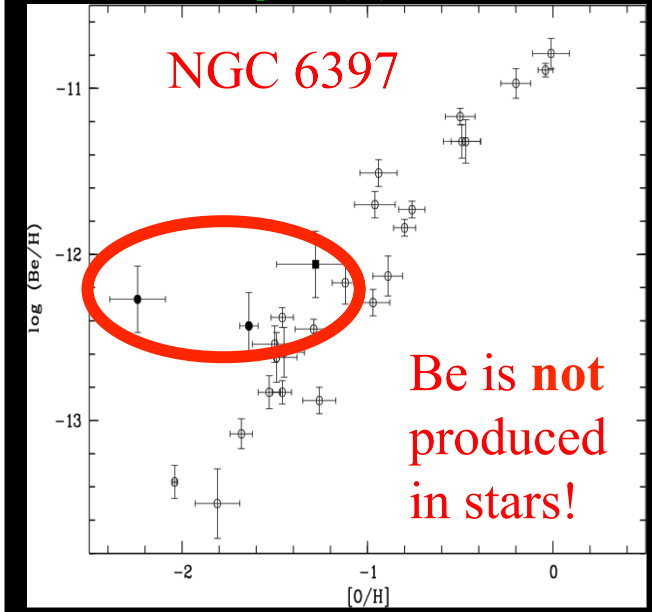


Lind, Primas, Charbonnel,
Grundahl & Asplund (09)

H-burning ashes devoid of light elements (LiBeBF)

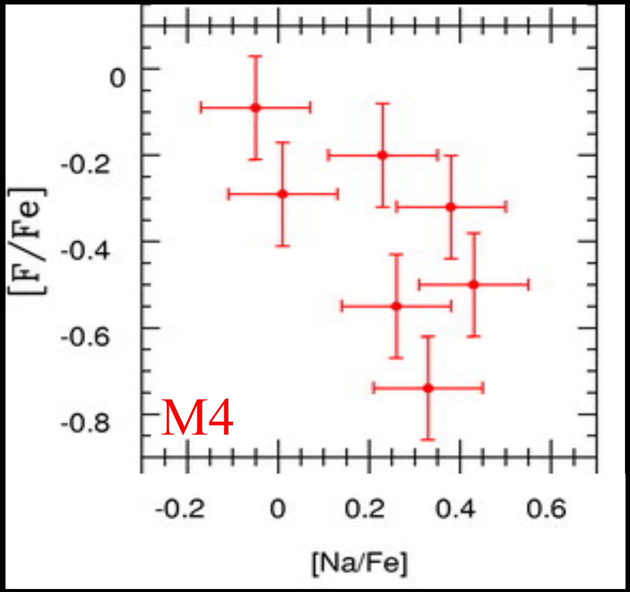
→ *2G stars form from*

H-burning ashes mixed with pristine gas



Be is **not** produced in stars!

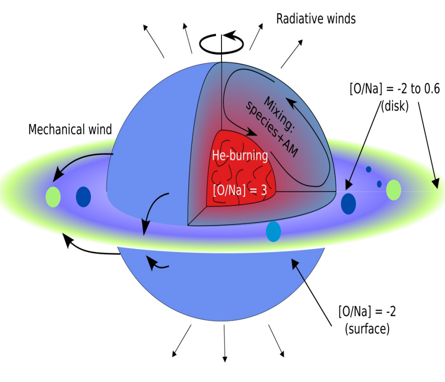
Pasquini *et al.* (07)



Smith *et al.* (05)

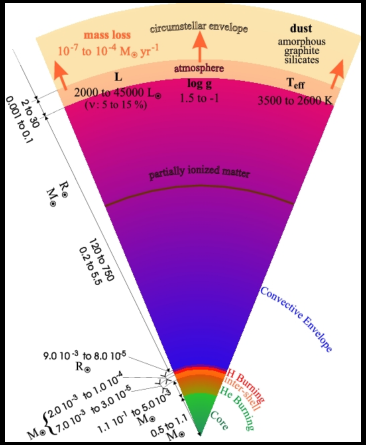
~ 50 % of original gas
(LiBeBF-rich)
& 50 % of stellar ejecta
(LiBeBF-free)

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



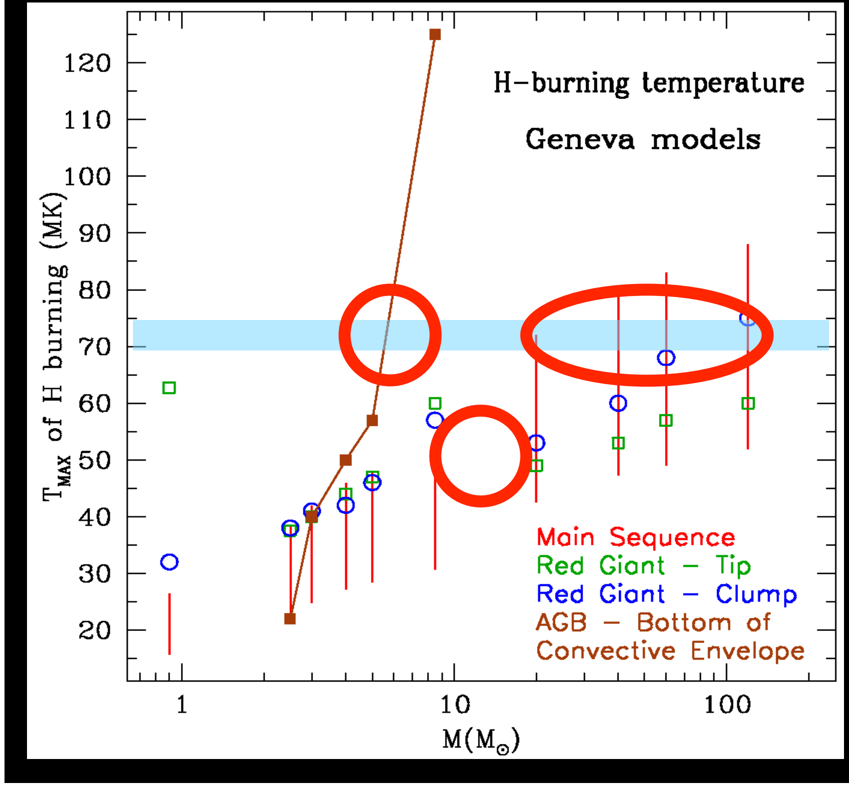
Fast Rotating Massive Stars (FRMS)
$\geq 25\ M_\odot$

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)



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?

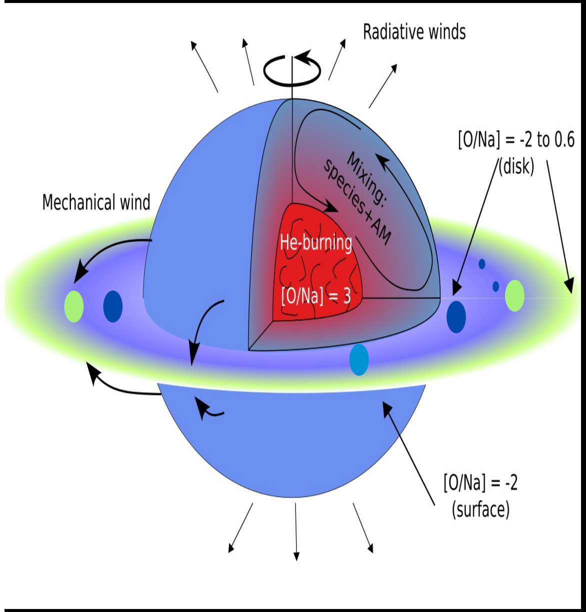
FRMS

AGB

Supermassive star

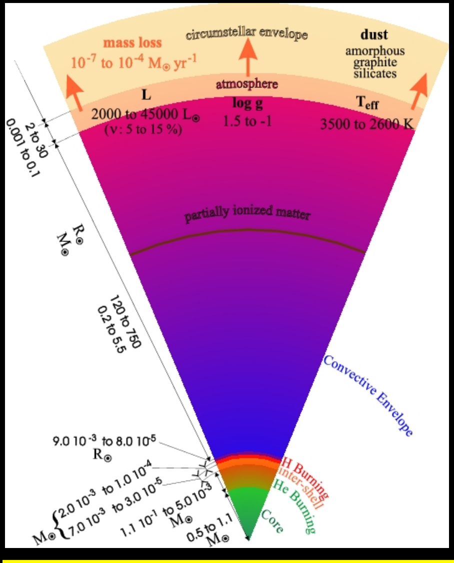
Massive binaries

Mass budget issue



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)

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)

Observed ratio 1G:2G ~ 30:70 Prantzos & CC (06)
Carretta *et al.* (10)

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

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

Standard IMF →
Loss of ~ 95 % of 1G low-mass stars
Much higher initial GC mass
8 – 25 x present-day mass
→ 6 – 20 % Galactic halo made of 1G GC stars

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

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)

Consequences for the initial conditions

Standard IMF →
Much higher initial GC mass
(8 – 25 x present-day mass)
Loss of ~ 95 % of 1G low-mass stars
(6 – 20 % of the Galactic halo)

Typical GC:
NGC 6752 (today's M ~ 3 x 10^5 $M_\odot$, no Fe spread)
Proto-GC cloud of $M_{tot} = 9 \times 10^6 M_\odot$

N-body models (Decressin et al. 10; Baumgardt & Khalaj 14) →
Mass-segregated cluster (Hillenbrand 97; de Grijs+02; Klessen 01; Bonnel+01)
Plummer profile for mass distribution (eg Baumgardt+08)
Half-mass radius $r_{1/2} = 3$pc
Average ρ(gas) ~ $10^6 m_p \, cm^{-3}$
SFE = 1/3
Extremely fast gas expulsion (~ 10^3 yrs)

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 low-mass stars
Stellar parameters (lifetimes, winds, …)
(Decressin et al. 07b; Krause et al. 12, 13)

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

AGB

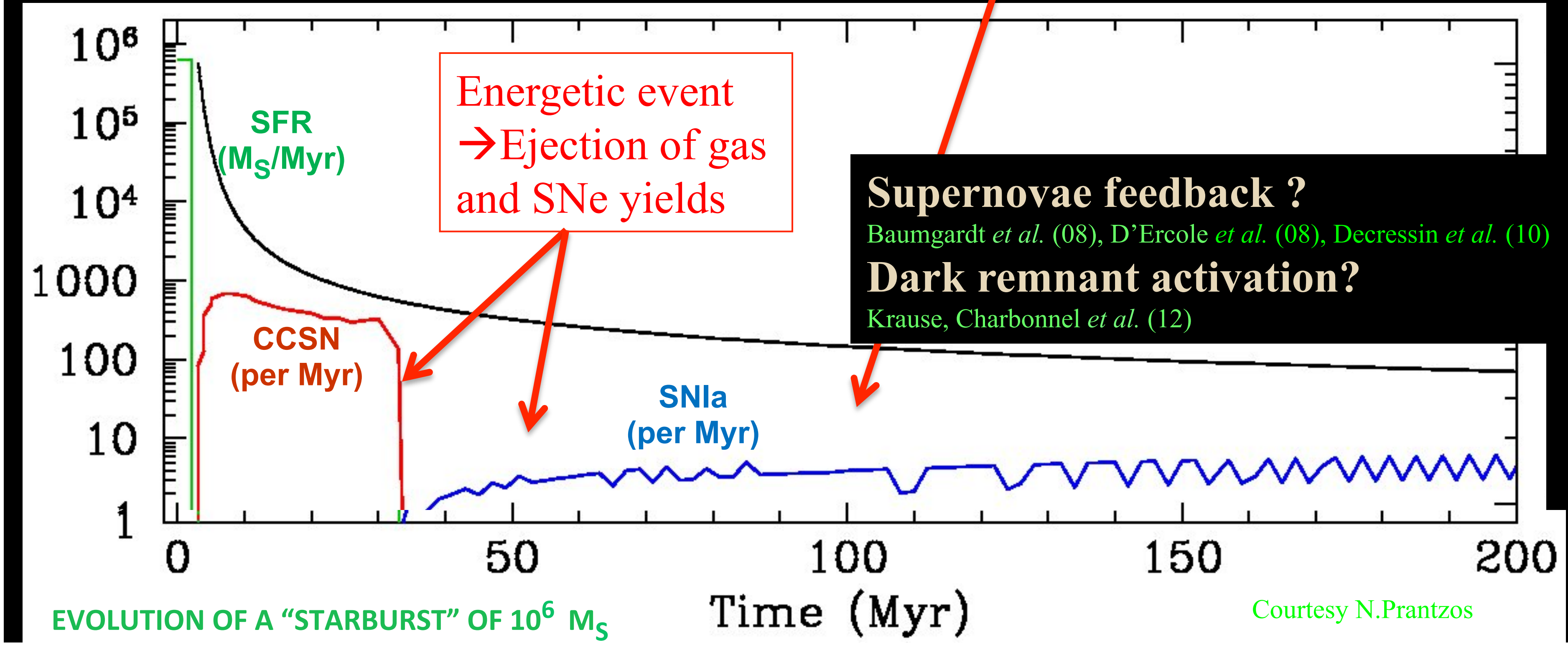
AGB scenario

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

Survey of 130 Galactic and extra-galactic YMCs
($10^4 < M/M_\odot < 10^8$; $10 < \text{age/Myr} < 1000$):
No evidence for extended or multiple SF episodes
within 30 – 100 Myr
Bastian *et al.* (13); Cabrera-Ziri *et al.* (14)

→ Need to **re-accrete gas to form the 2G**
(D'Ercole + 11)

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



Energetic event
→Ejection of gas and SNe yields

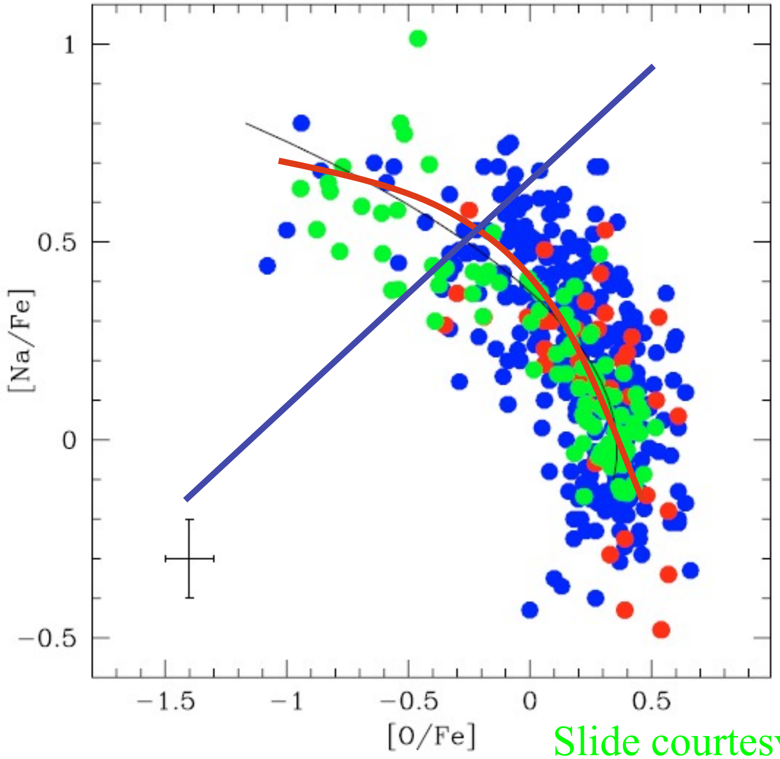
Supernovae feedback ?
Baumgardt *et al.* (08), D'Ercole *et al.* (08), Decressin *et al.* (10)

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

EVOLUTION OF A "STARBURST" OF 10^6 M_S

Courtesy N.Prantzos

AGB scenario – Anticorrelation possible only by dilution



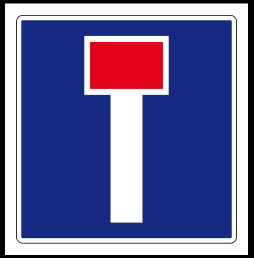
→ Need to **re-accrete original gas** to turn the O-Na correlation into an anticorrellation (D'Ercole + 11)

models!!

anticorrelation

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

Slide courtesy D'Antona (Sexten 2014)



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?

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

FRMS

Fast-rotating massive stars

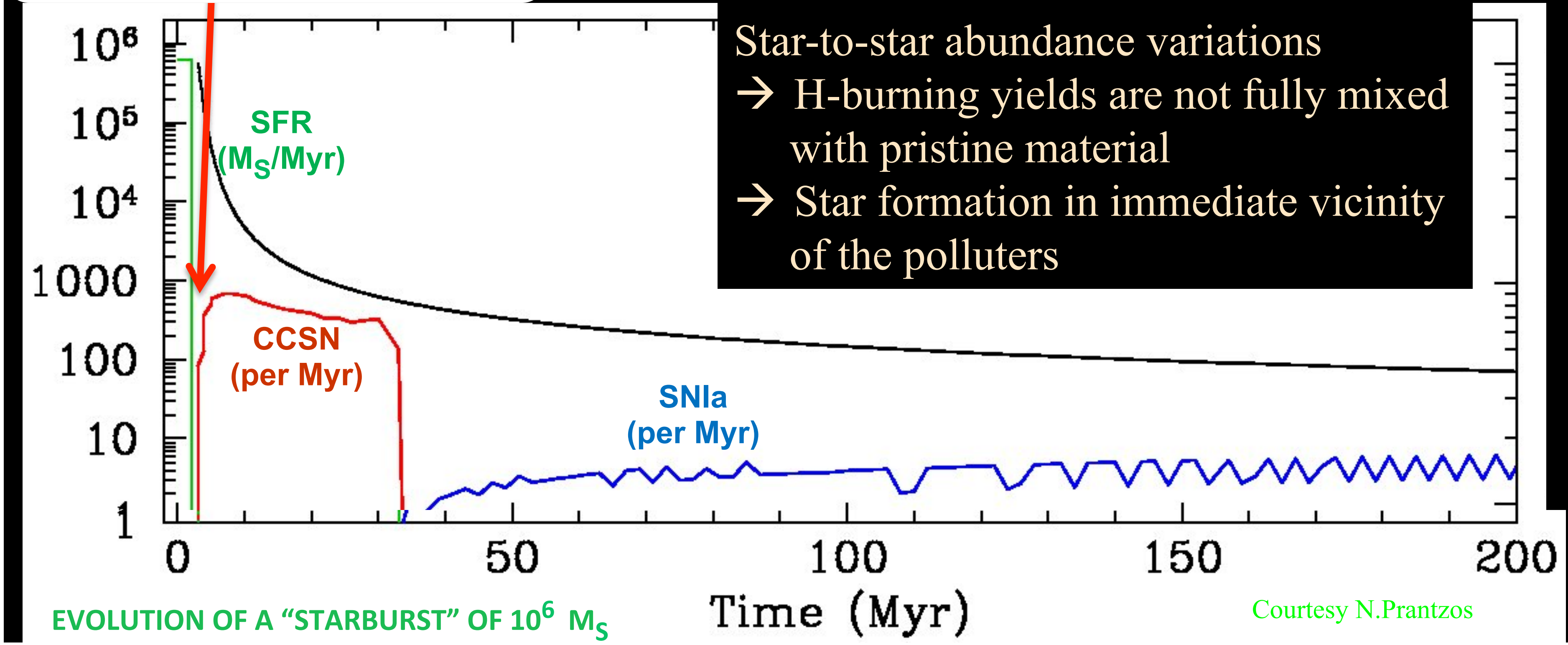
Shorter than PMS timescale
for low-mass stars
→ Almost coeval populations

(Decressin +07ab; Bastian +13; Charbonnel +14)

Original gas is still present

FRMS scenario:
1^{st}-2^{nd} populations: $\Delta t < 10$ Myr

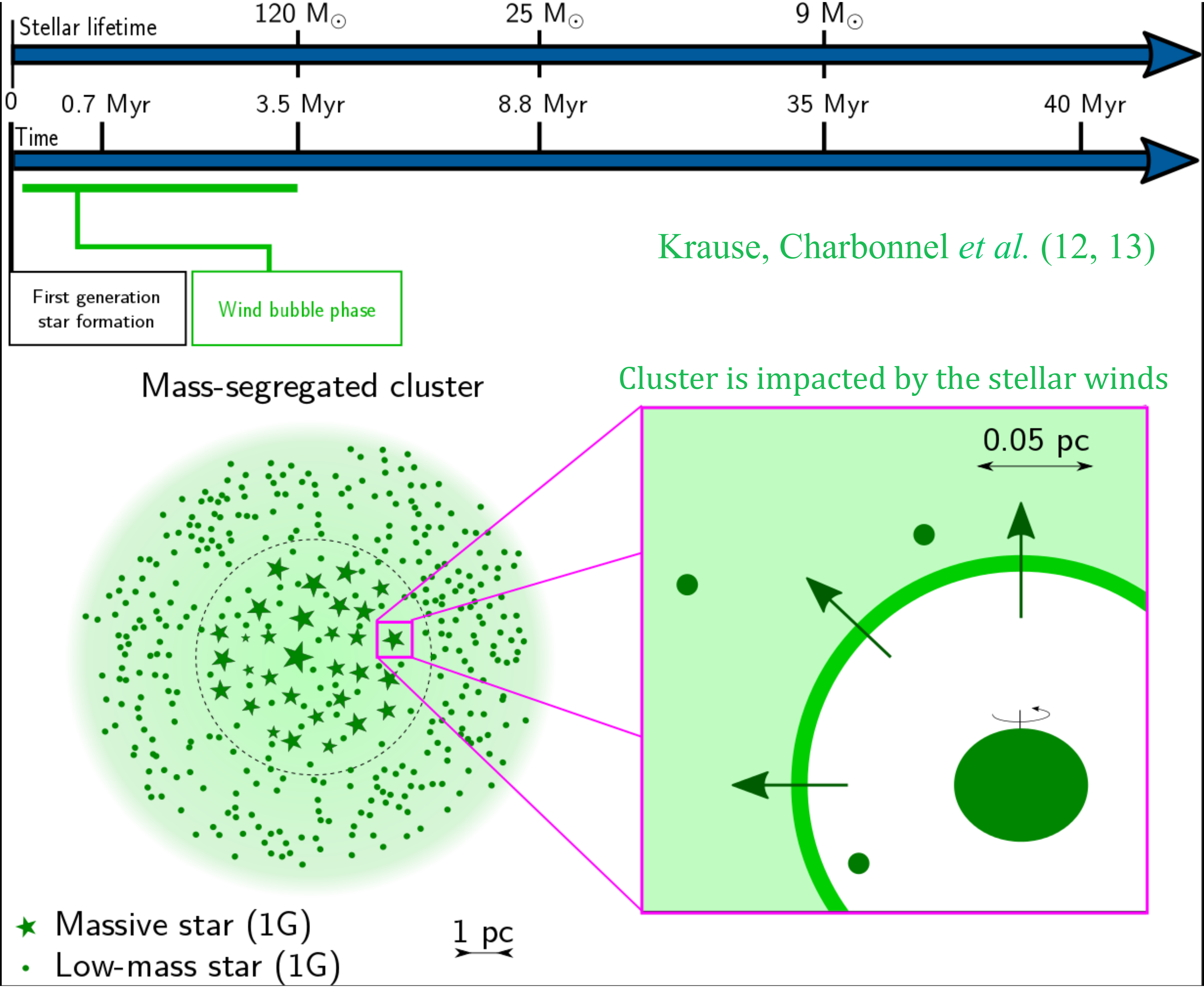
YMCs (~ 10^6 $M_\odot$)
in nearby dwarf and spiral galaxies
with ages between a few and ~ 15 Myr
have already cleared out their natal material
Bastian *et al.* (13)



Star-to-star abundance variations
→ H-burning yields are not fully mixed with pristine material
→ Star formation in immediate vicinity of the polluters

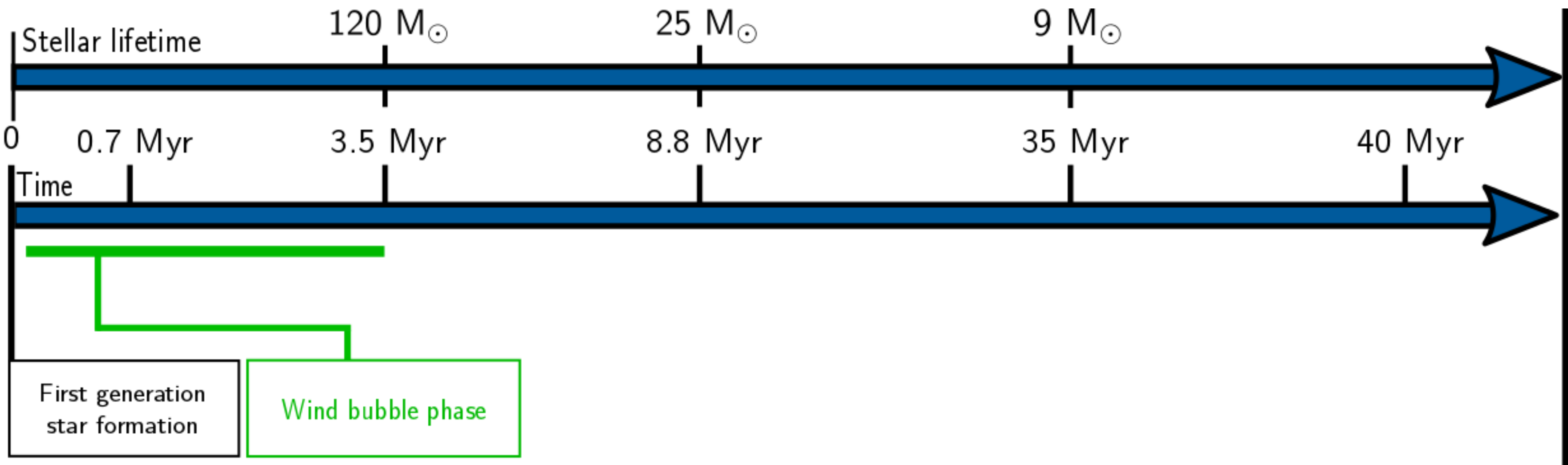
EVOLUTION OF A “STARBURST” OF 10^6 M_S

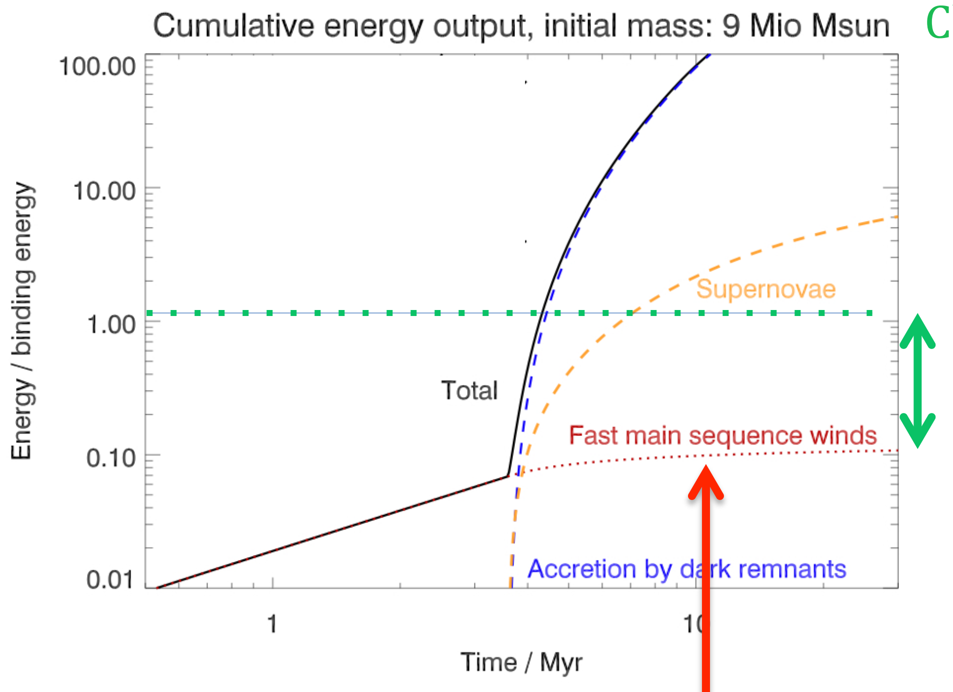
Courtesy N.Prantzos



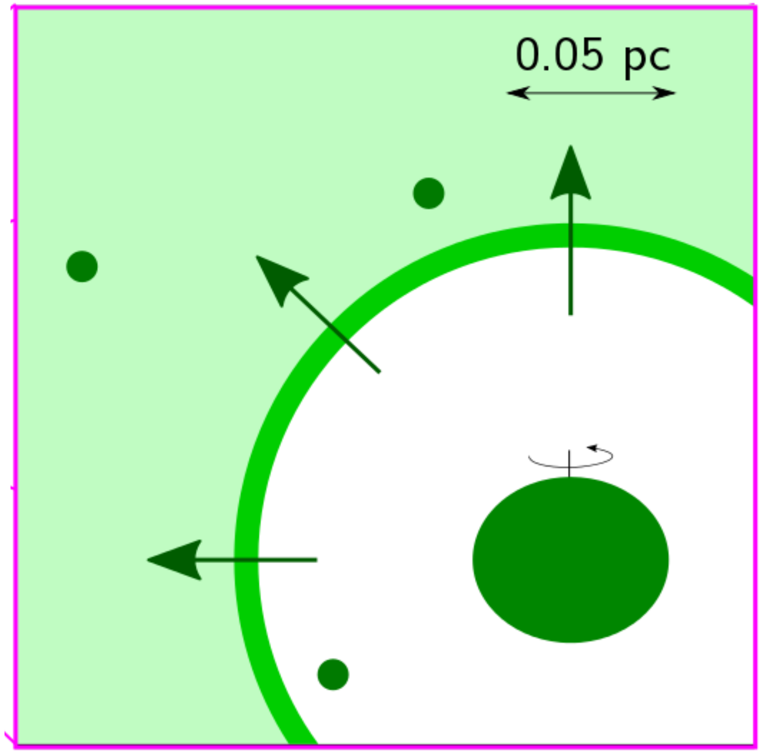
Krause, Charbonnel *et al.* (12, 13)

Cluster is impacted by the stellar winds

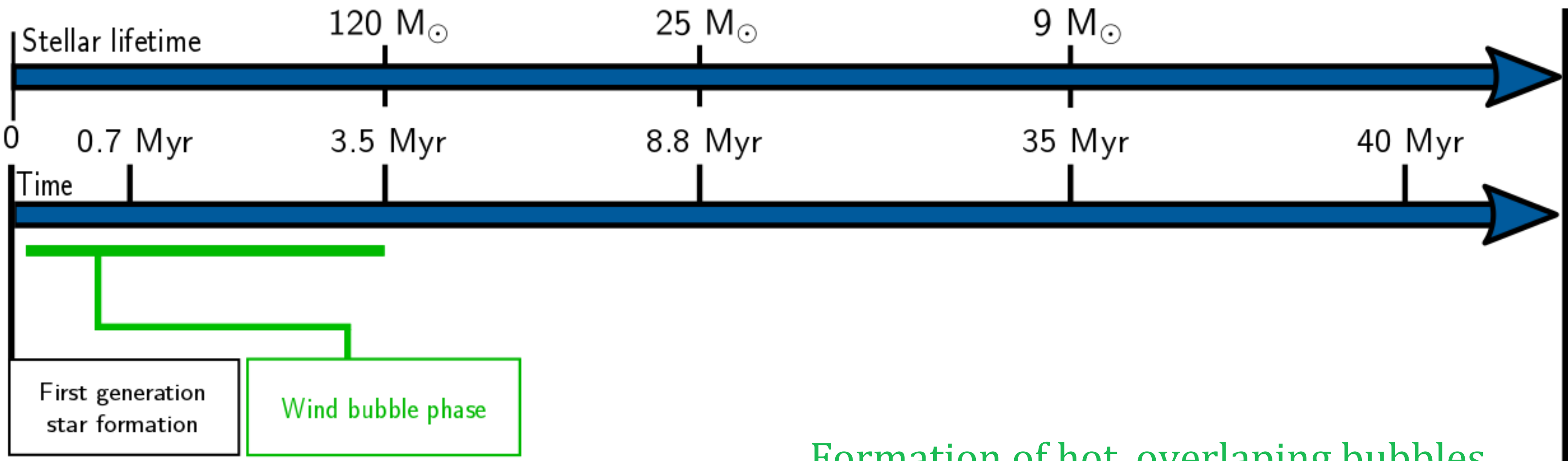

Stellar lifetime
120 M☉
25 M☉
9 M☉
0
0.7 Myr
3.5 Myr
8.8 Myr
35 Myr
40 Myr
Time
First generation
star formation
Wind bubble phase



Cluster is impacted by the stellar winds



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

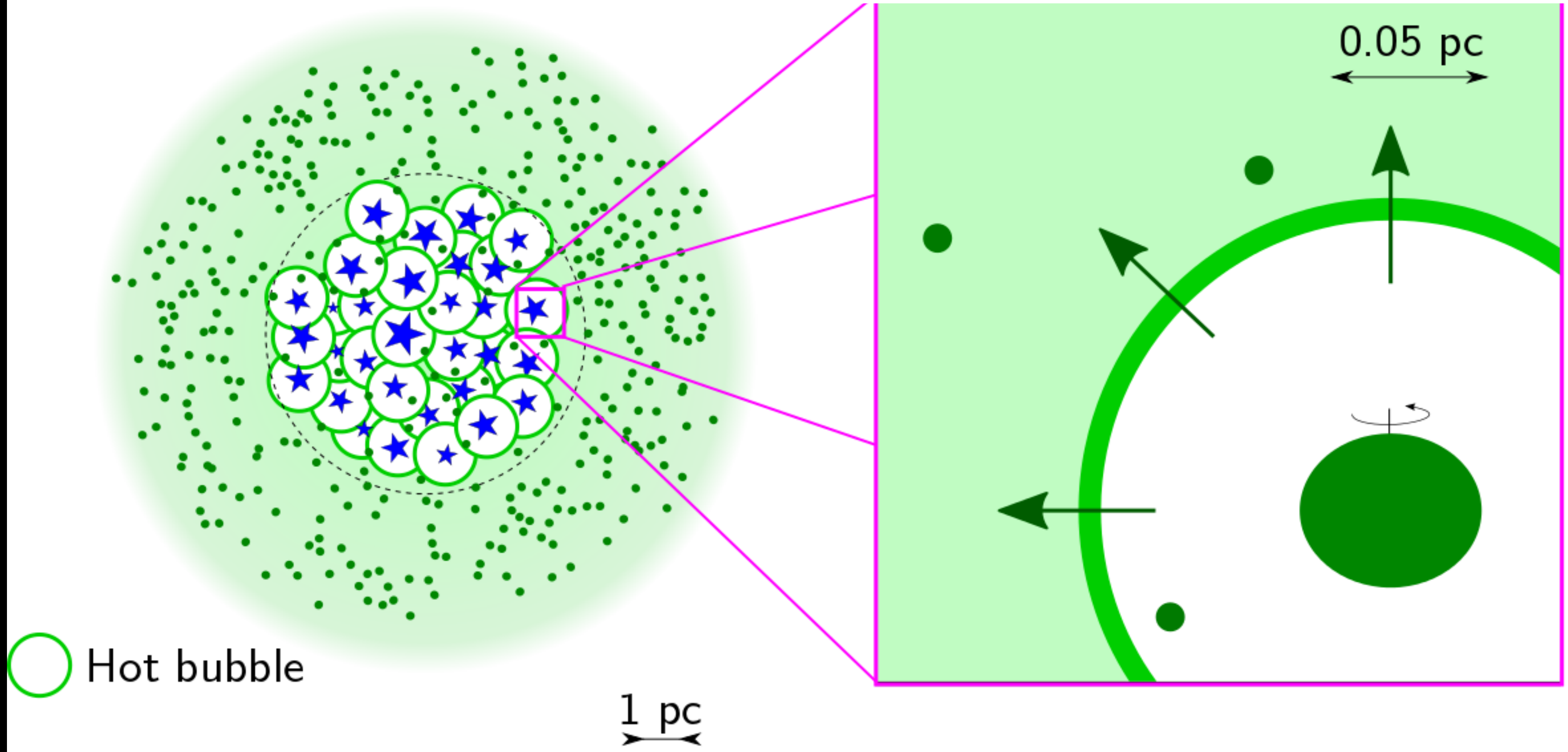


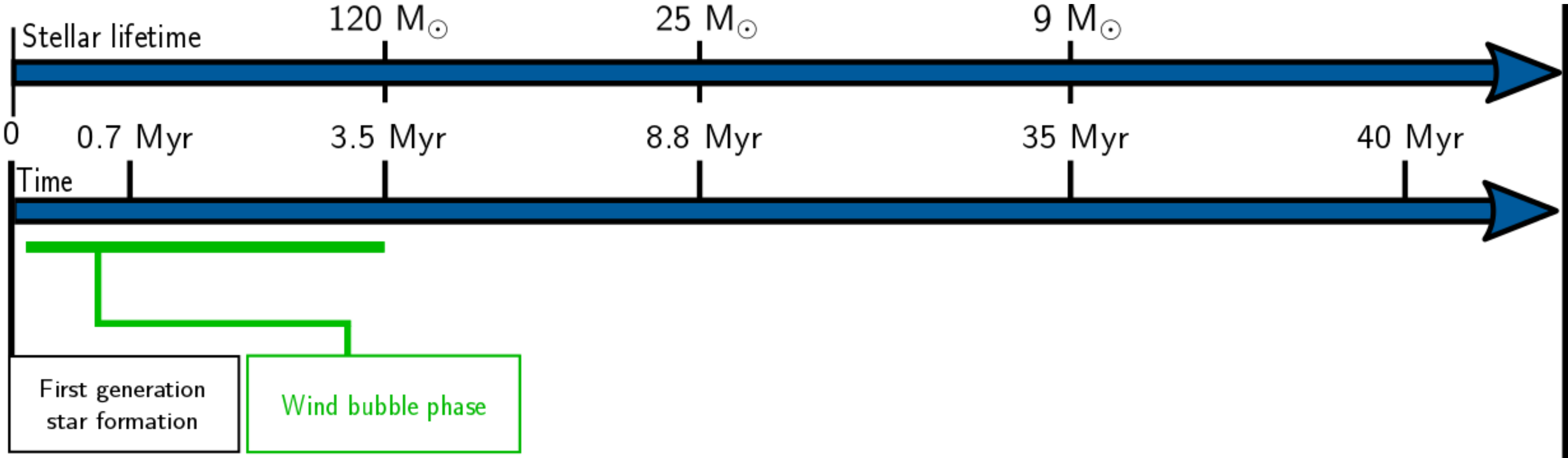
First generation star formation

Wind bubble phase

Spongy structure for ISM

Formation of hot, overlaping bubbles around massive stars





Lyman-Werner photons

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

→ Photodissociation of molecular H

$T_{gaz} \sim 100K$

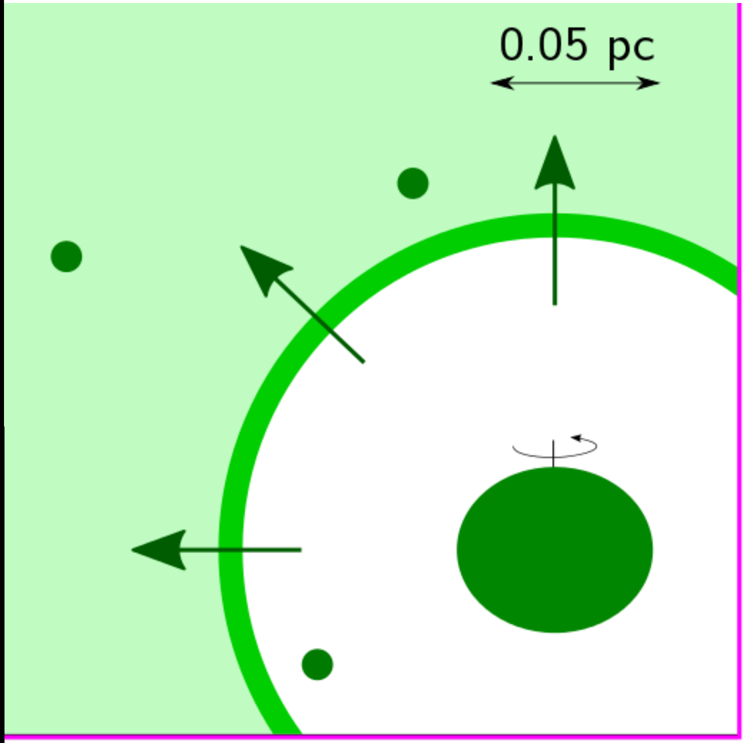
→ No « classical » star formation

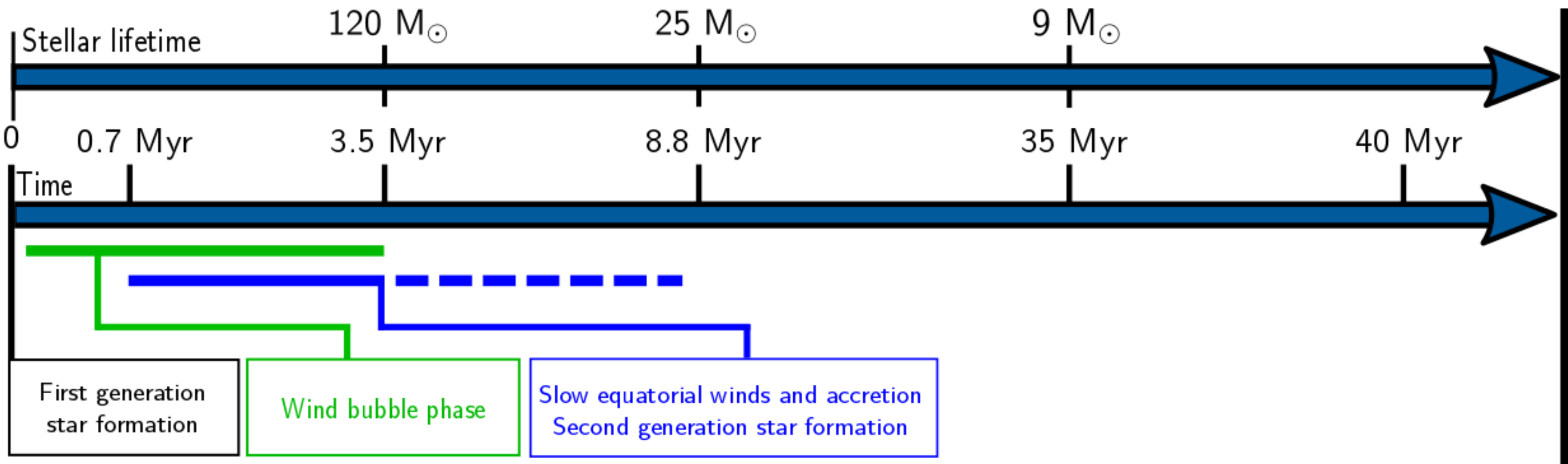
(confirm Conroy & Spergel 11)

→ Formation of 2P low-mass stars in the decretion discs of individual massive stars « Fast Rotating Massive Stars » scenario

(Decressin, Charbonnel *et al.* 07, Krause, Charbonnel *et al.* 13)

High ultraviolet radiation





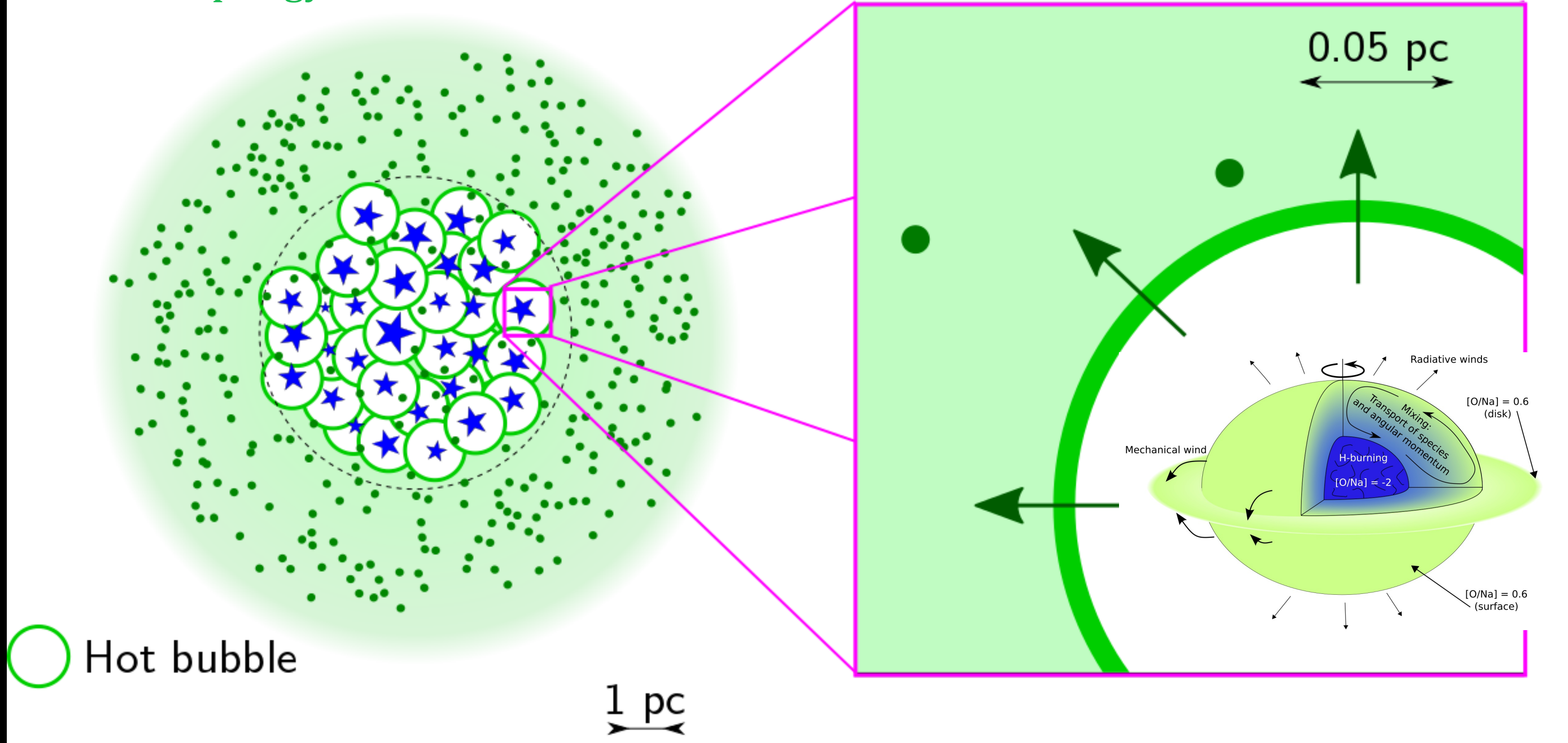
First generation star formation

Wind bubble phase

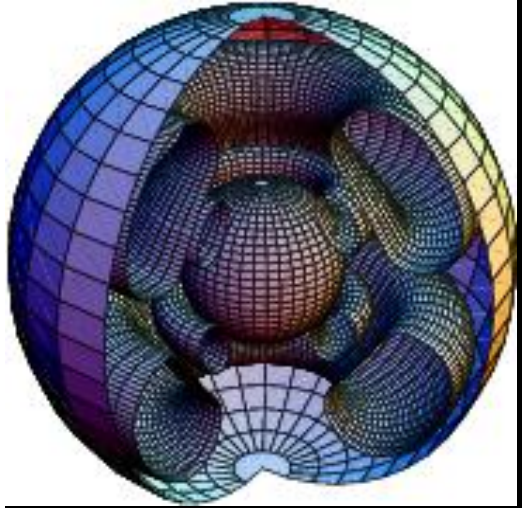
Slow equatorial winds and accretion
Second generation star formation

Spongy structure for ISM

Stellar evolution → FRMS



Fast-rotating massive stars



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)

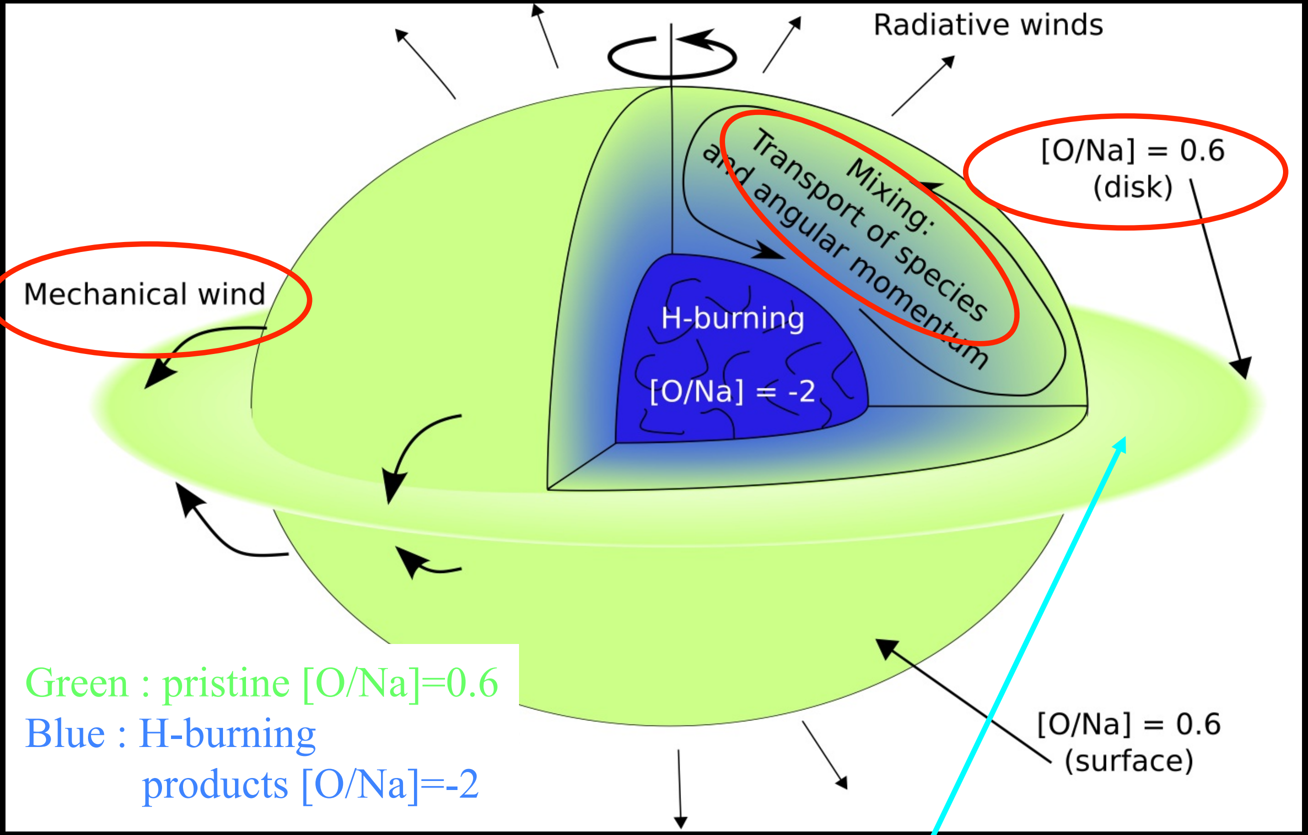
Be-type stars

Early main sequence

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

⇒ **The star reaches the break-up velocity** (Centrif. acc. compensates gravity)

⇒ **Equatorial matter released in a keplerian orbit**

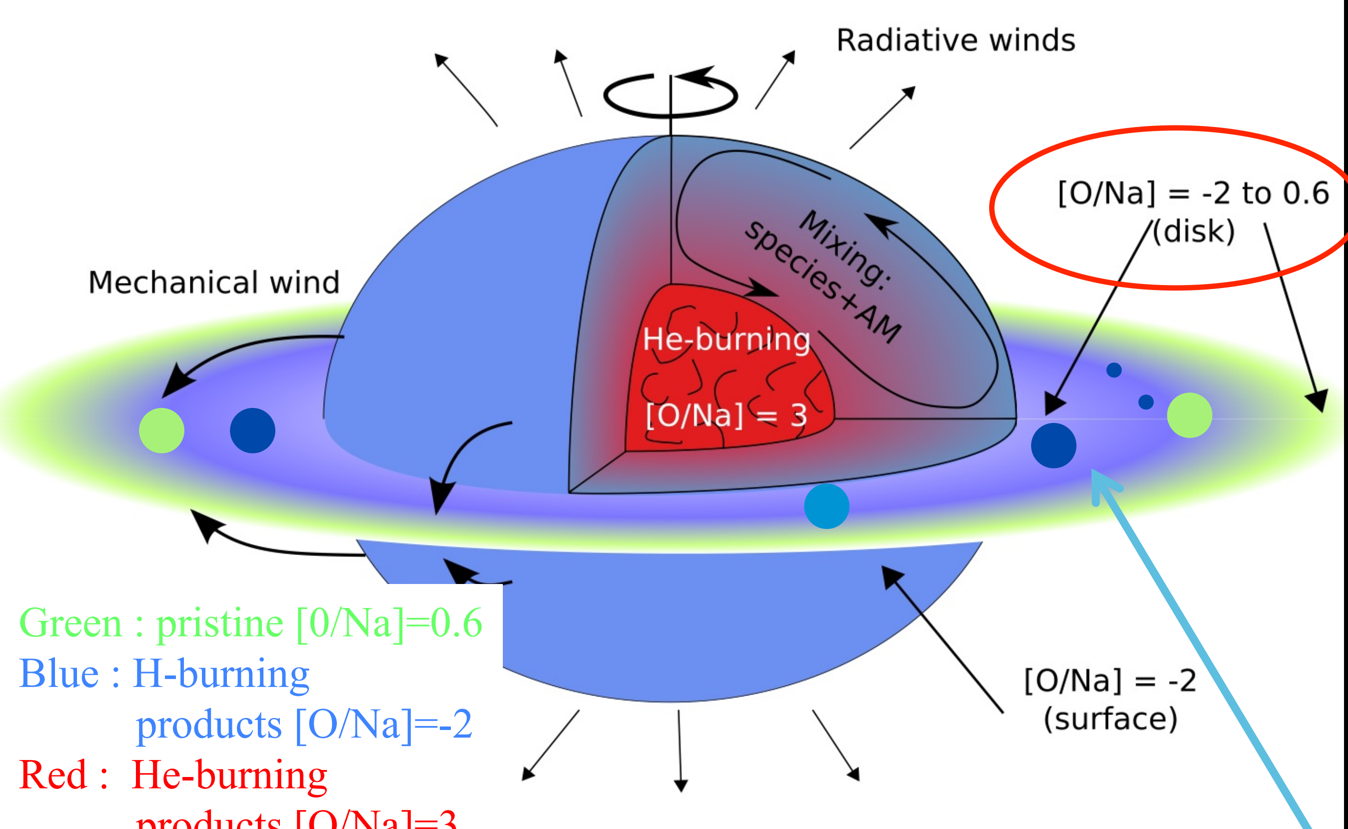


Green : pristine [O/Na]=0.6
Blue : H-burning
products [O/Na]=-2

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

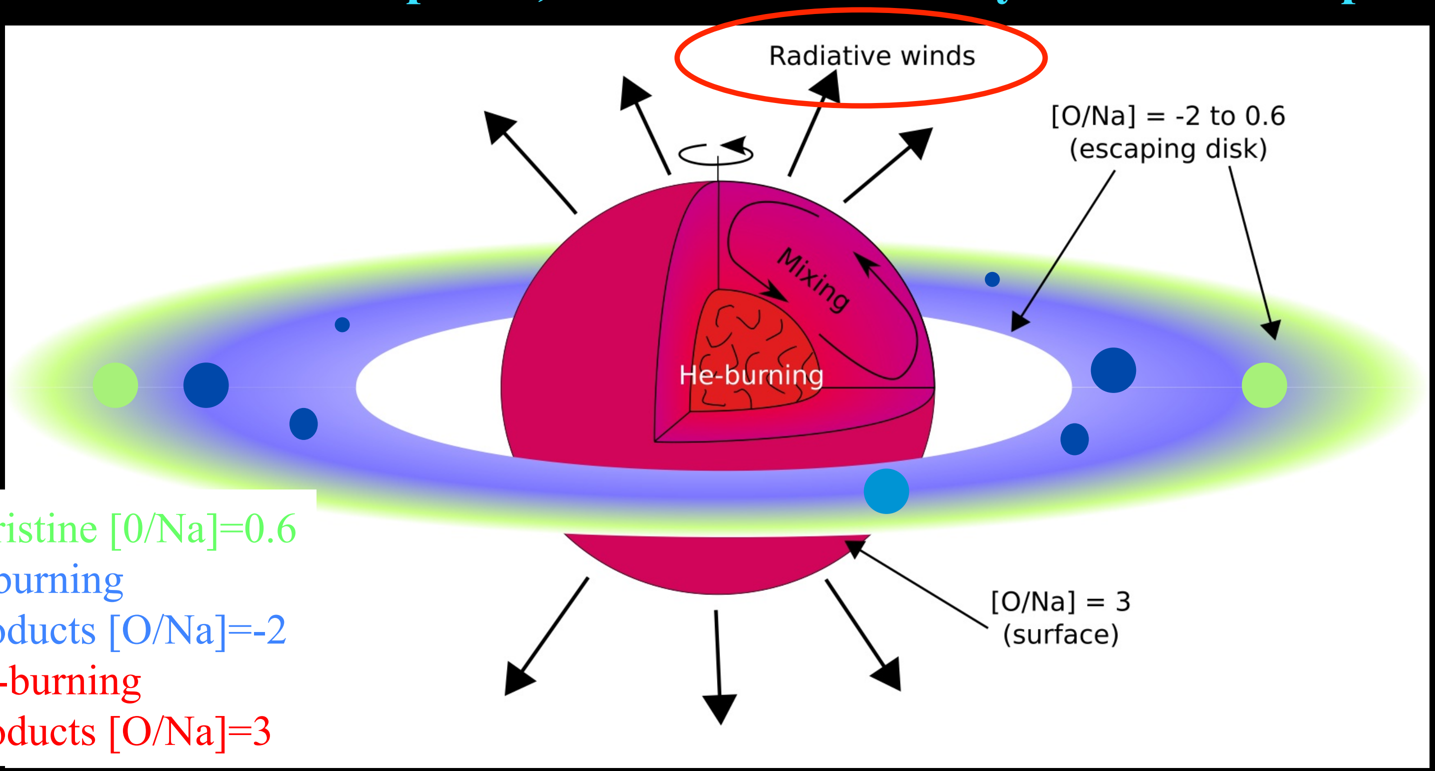


Green : pristine [0/Na]=0.6
Blue : H-burning
products [O/Na]=-2
Red : He-burning
products [O/Na]=3

Star formation in the "decretion disc"
Clumps or protostars
observed in the disk
of the Be star MWC 1080
(Wang *et al.* 07)

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

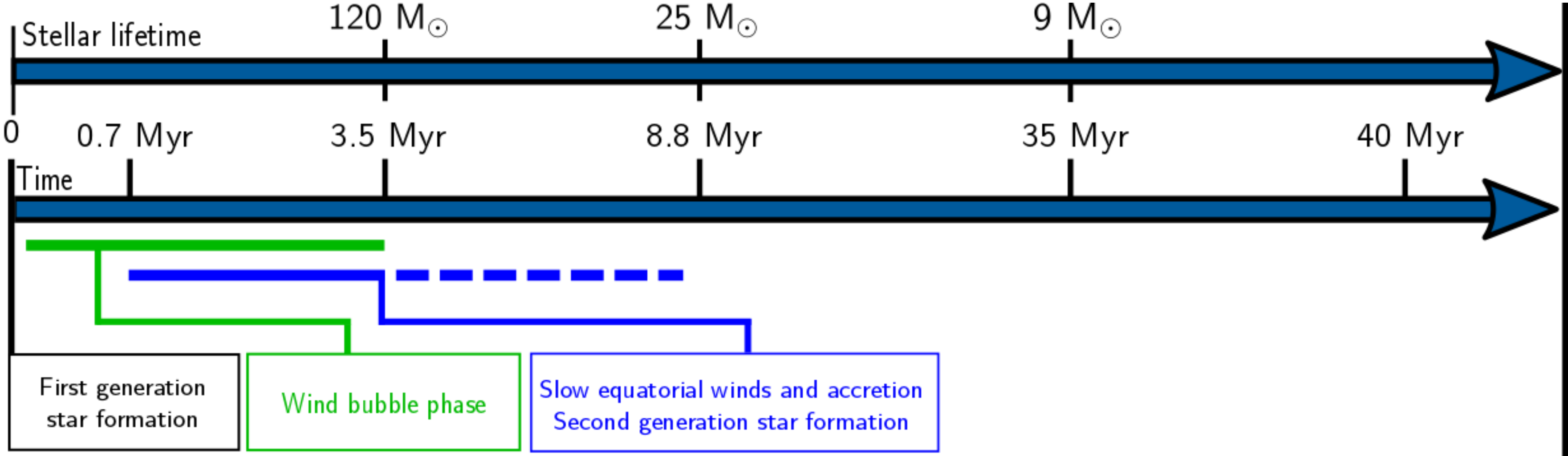
⇓

The disk is disconnected from the star,
and the classical radiatively-driven fast winds ($\geq$ 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)

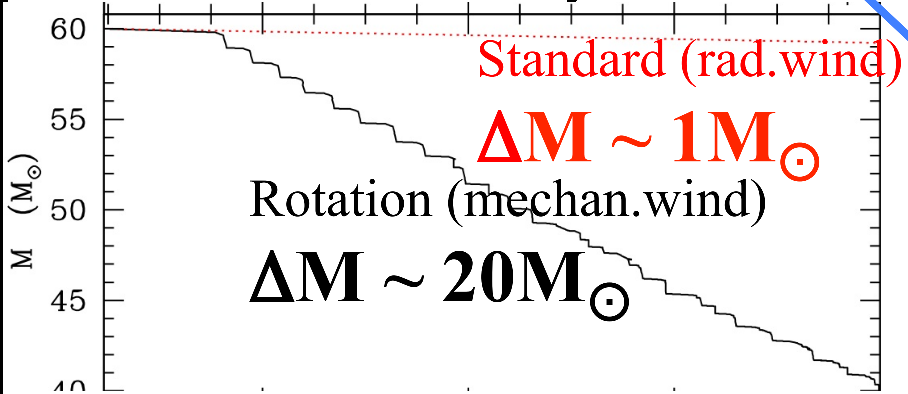


First generation star formation

Wind bubble phase

Slow equatorial winds and accretion
Second generation star formation

Slow equatorial mass ejection
at critical rotation velocity



Standard (rad.wind)

$\Delta M \sim 1M_\odot$

Rotation (mechan.wind)

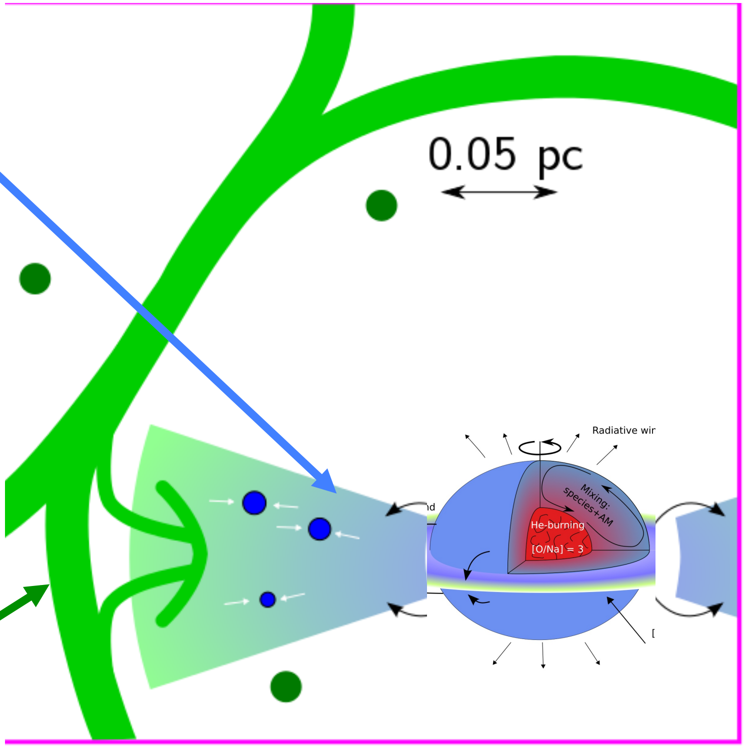
$\Delta M \sim 20M_\odot$

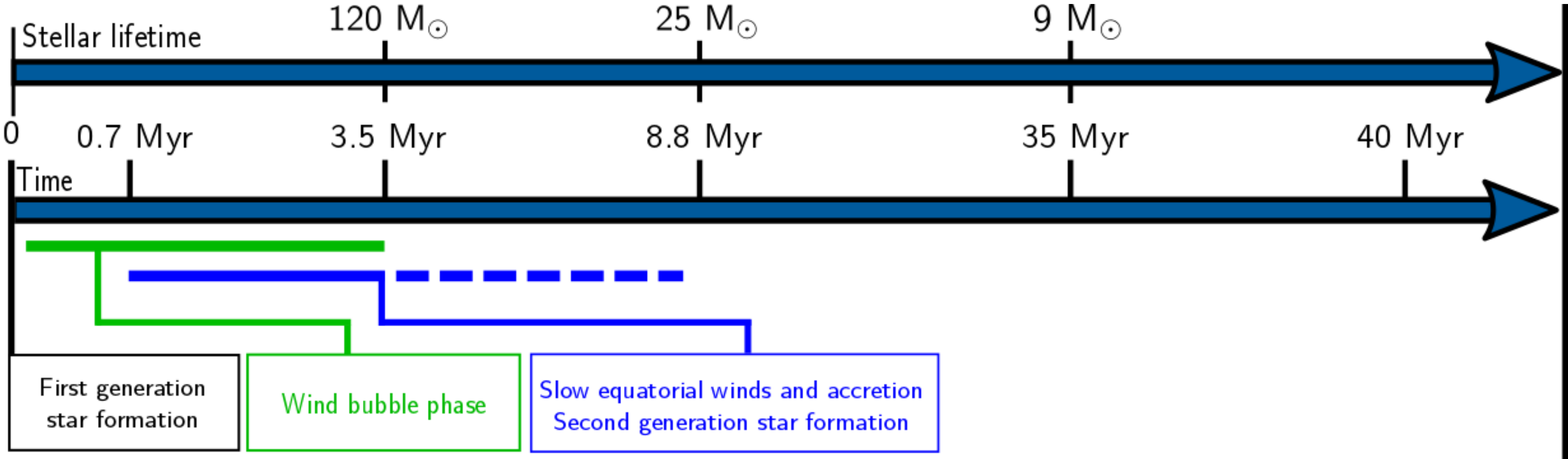
Shadowing of the disc frees the equatorial region from radiation pressure

→ Establishment of an accretion flow of surrounding dense original gas

→ Time- and orbit-averaged Bondi accretion rate ~ 10^4 $M_\odot$ /Myr

Equatorial mass ejection





First generation star formation

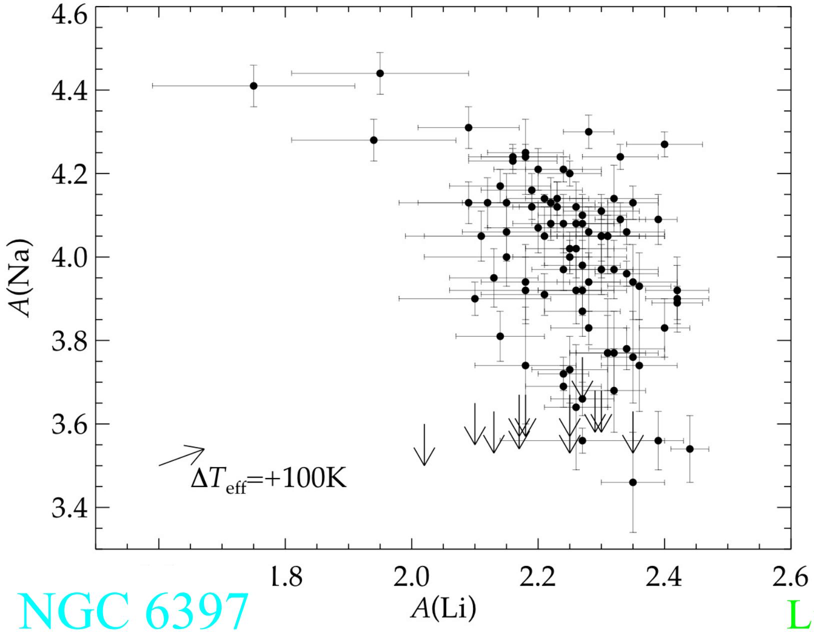
Wind bubble phase

Slow equatorial winds and accretion
Second generation star formation

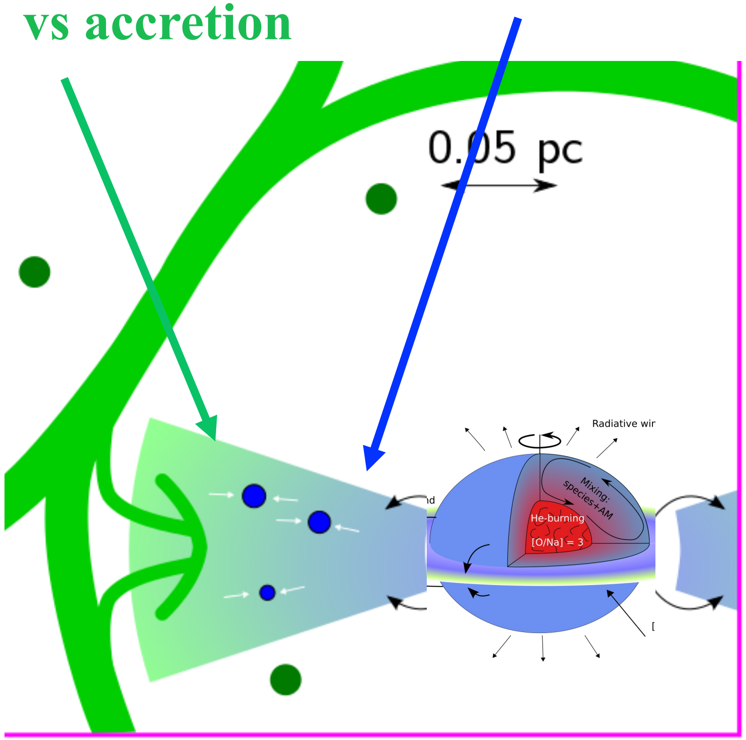
Disc fed both by stellar processed matter and original material

Mixture of gas within the disk:
~ ½ pristine – ½ ejecta (on average)

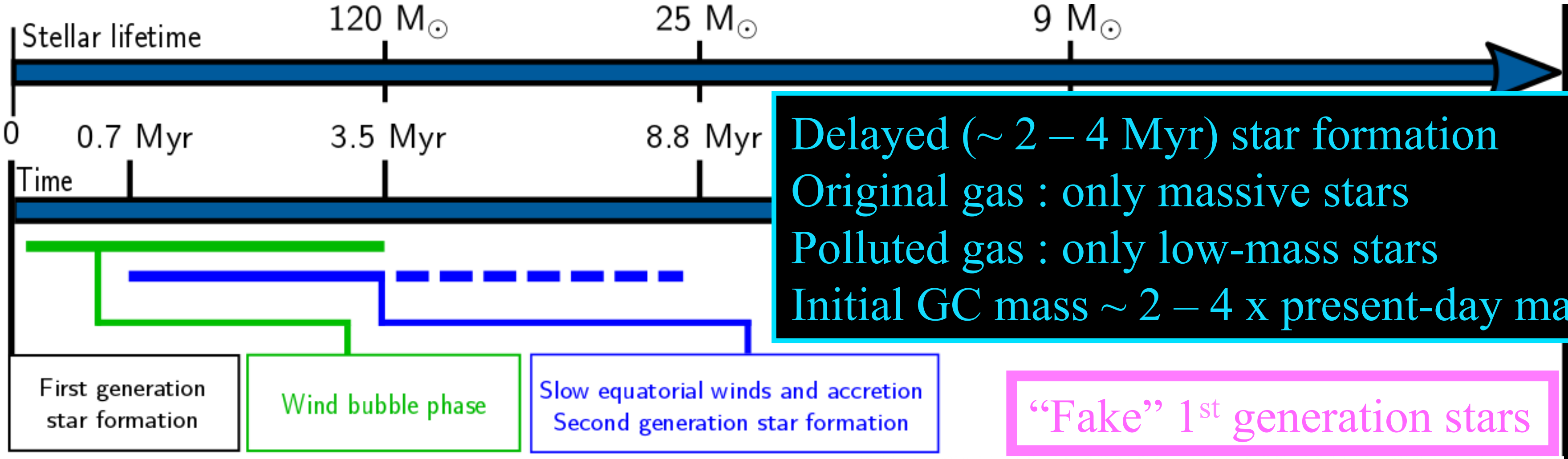
Equatorial mass ejection
vs accretion



NGC 6397



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



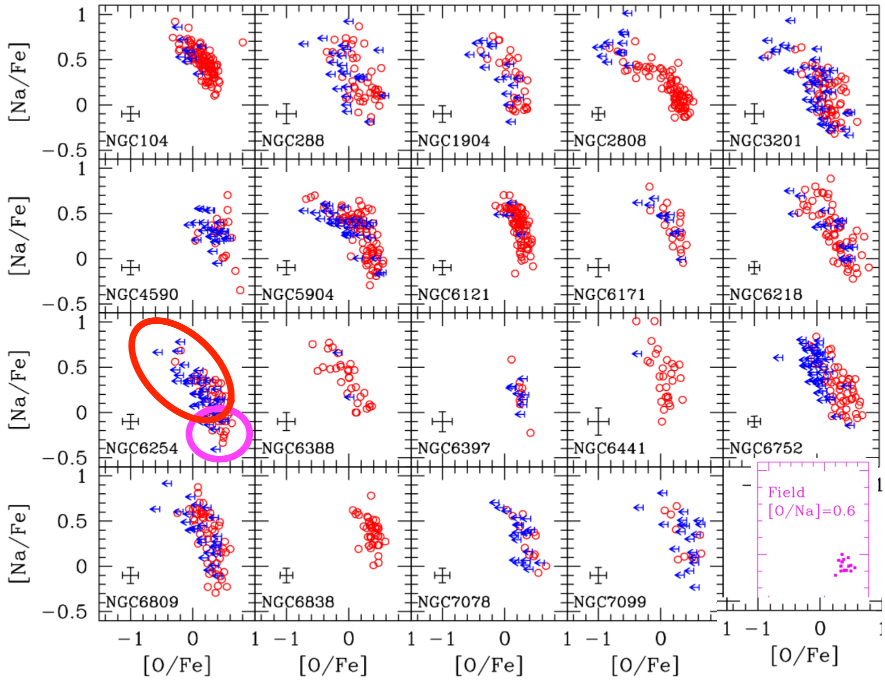
Delayed (~ 2 – 4 Myr) star formation
Original gas : only massive stars
Polluted gas : only low-mass stars
Initial GC mass ~ 2 – 4 x present-day mass

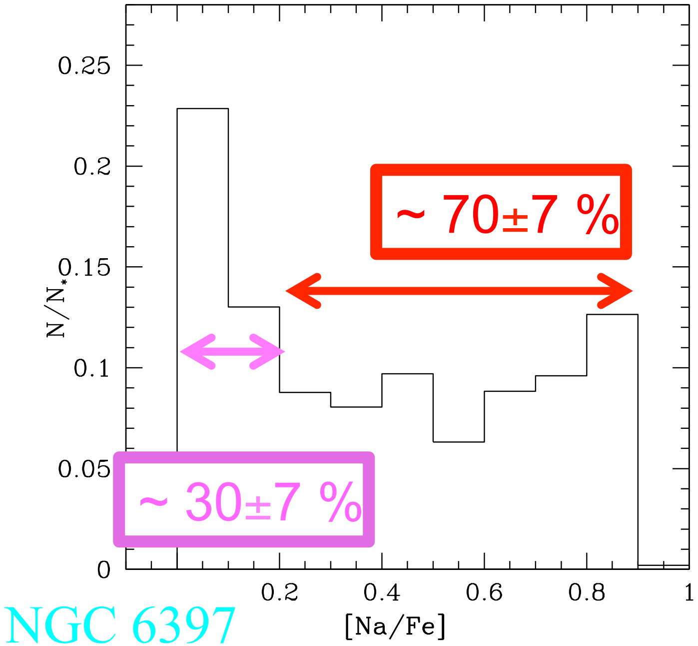
“Fake” 1st generation stars

Disc fed both by stellar processed matter and original material

Mixture of gas within the disk:

~ ½ pristine – ½ ejecta (on average)





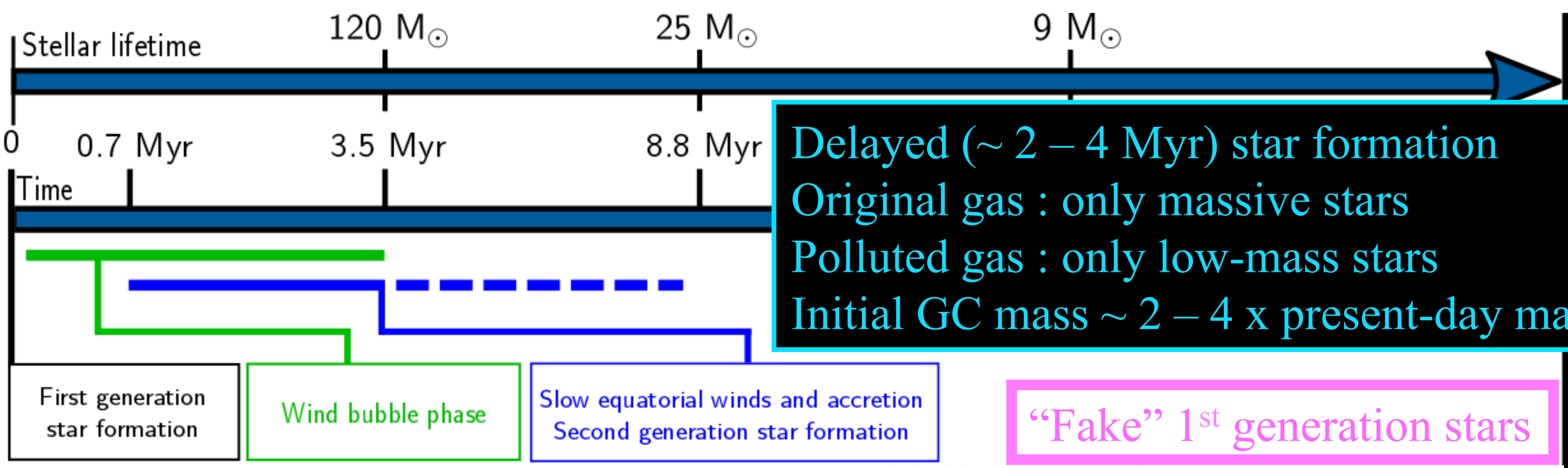
~ 70±7 %

~ 30±7 %

NGC 6397

Theoretical distribution of Na abundance for low-mass “2d generation” stars at birth

Charbonnel *et al.* (14)



First generation star formation

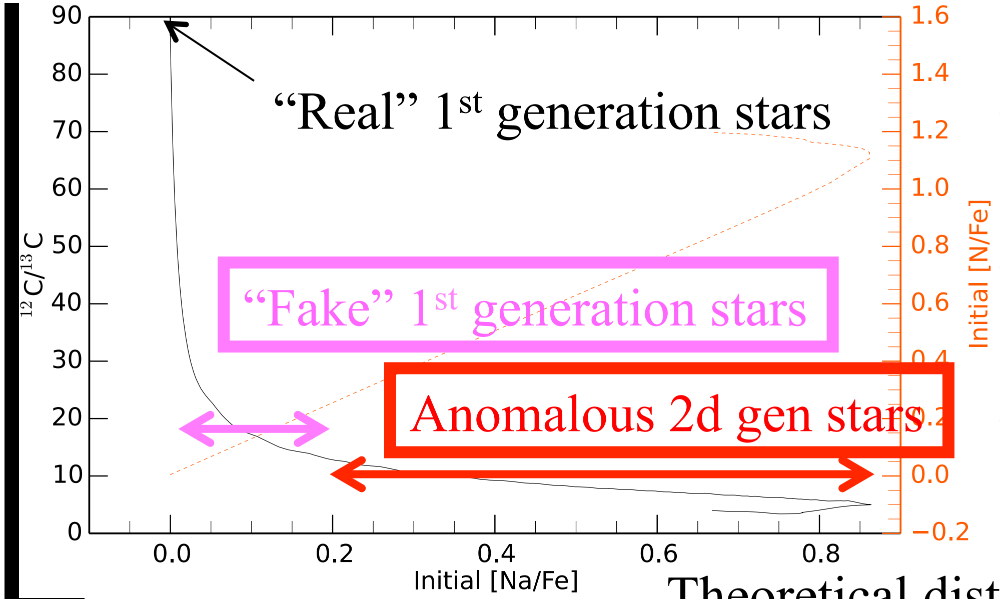
Wind bubble phase

Slow equatorial winds and accretion
Second generation star formation

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

“Fake” 1st generation stars

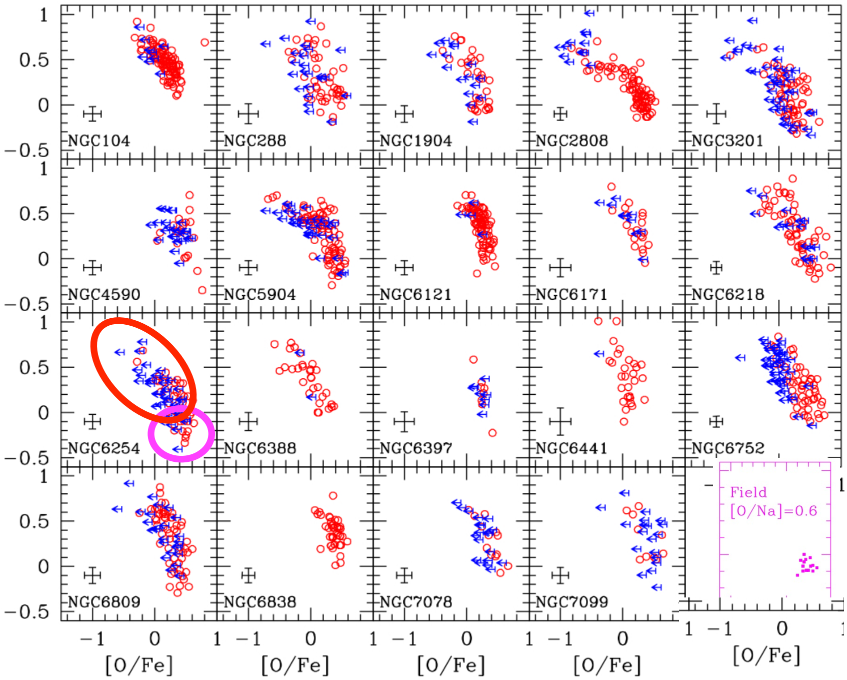
Observational test
(submitted @ ESO/VLT/FLAMES/UVES)



“Real” 1st generation stars

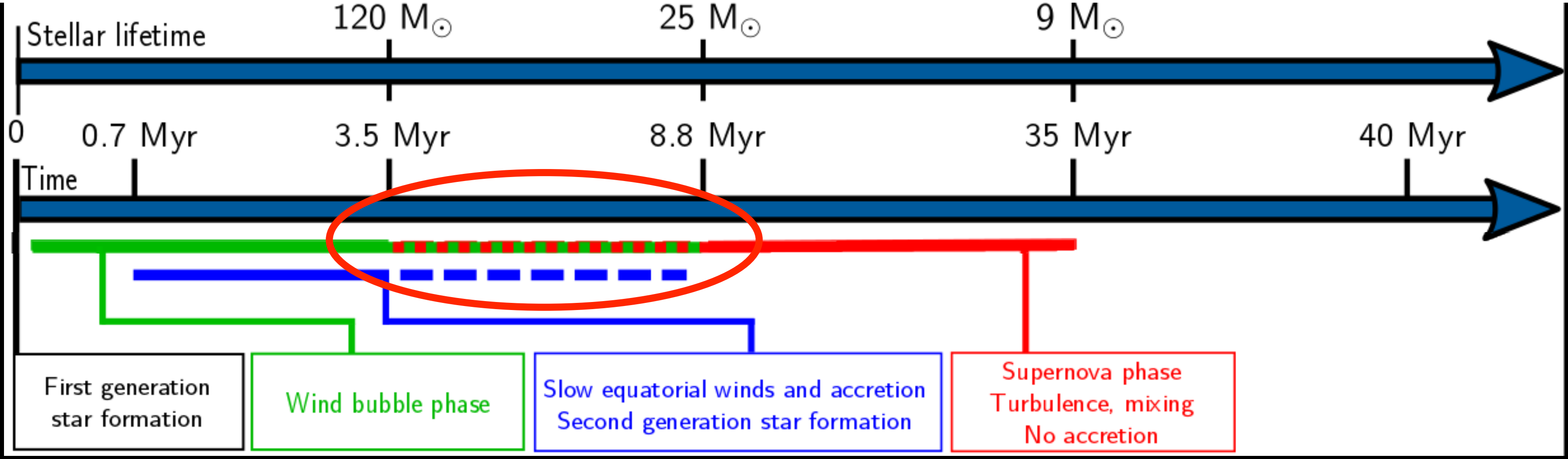
“Fake” 1st generation stars

Anomalous 2d gen stars



Theoretical distribution of ^{12}C/^{13}C vs Na
for low-mass “2d generation” stars at birth

Charbonnel *et al.* (14)



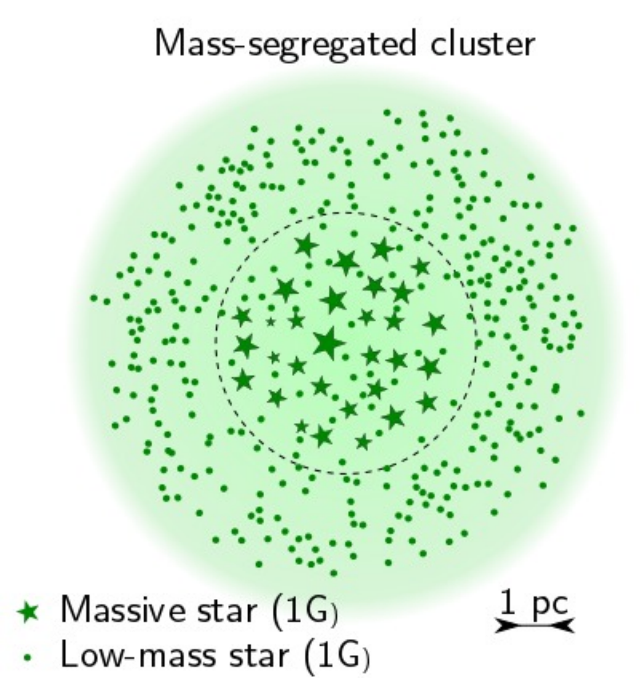
Mass limit for stars to explode as SNe ?
$M \geq 25\ M_{\odot}$ may to turn silently into black holes

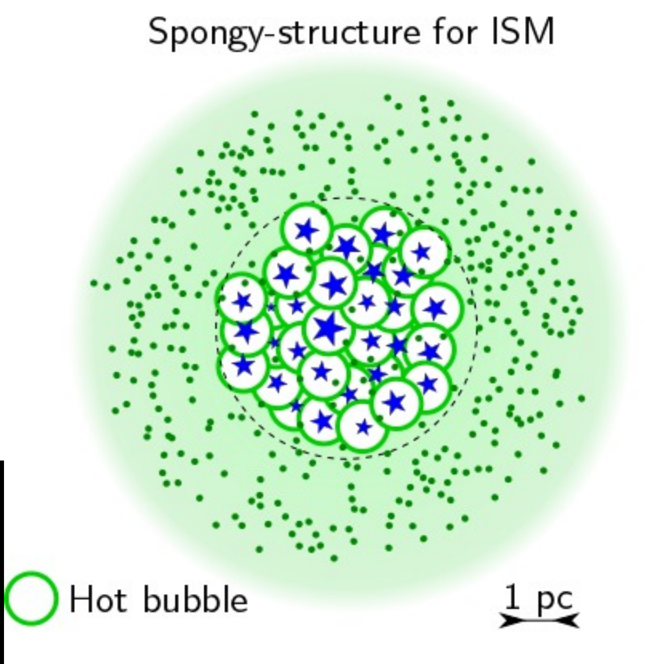
(Portegies Zwart *et al.* 97; Ergma & van der Heuvel 98;
Kobulnicky & Skillman 97; Fryer 99; Belczynski *et al.* 12)

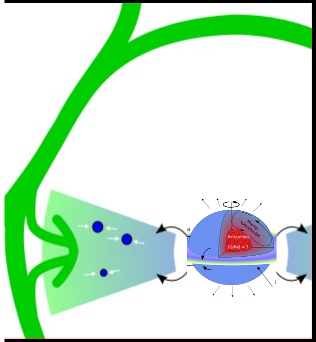
Fast gas expulsion and loss of 1G stars?

Baumgardt *et al.* (08), D'Ercole *et al.* (08), Decressin *et al.* (10)
Krause, Charbonnel, Decressin, Prantzos, Meynet & Diehl (12a)

Multiple stellar generations in GCs
Towards a global scenario?





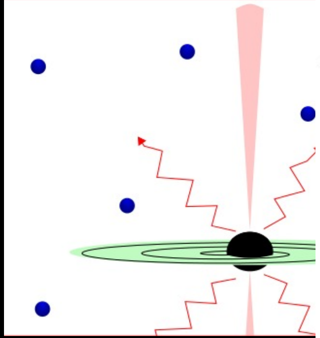


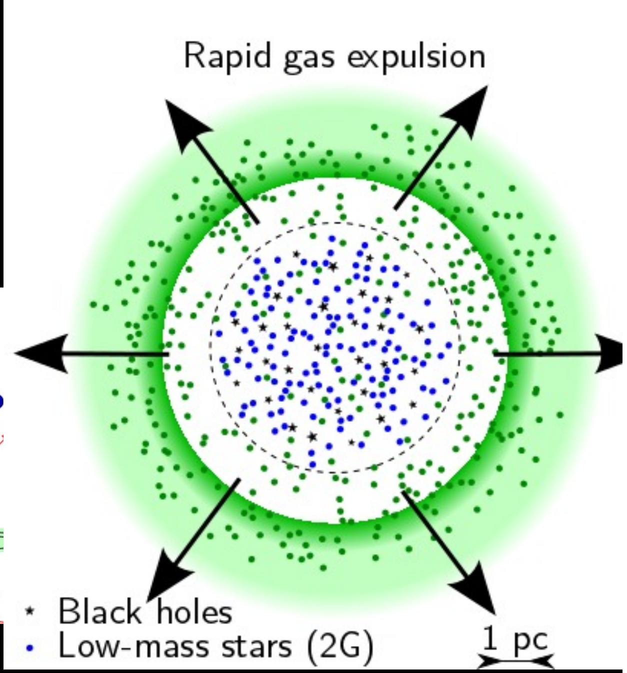
Important role of the physics of the intra-cluster medium and of the star-ISM interactions

Star formation in immediate vicinity of Massive stars

Which process can evacuate the bulk of gas and of 1G stars?

Different IMF in different environments?





Massive star clusters across the Hubble time

Team Members

Prof. **Corinne Charbonnel** (University of Geneva, Switzerland & CNRS France) - Team leader
Stellar evolution and nucleosynthesis, stellar hydrodynamics, chemical evolution

Dr **Holger Baumgardt** (University of Queensland, Australia)
N-body simulations of star clusters, stellar dynamics

Dr **Ben Davis** (Liverpool John Moores University, Birkenhead, UK)
Chemical evolution of star-forming galaxies, massive star clusters, formation and evolution of mas

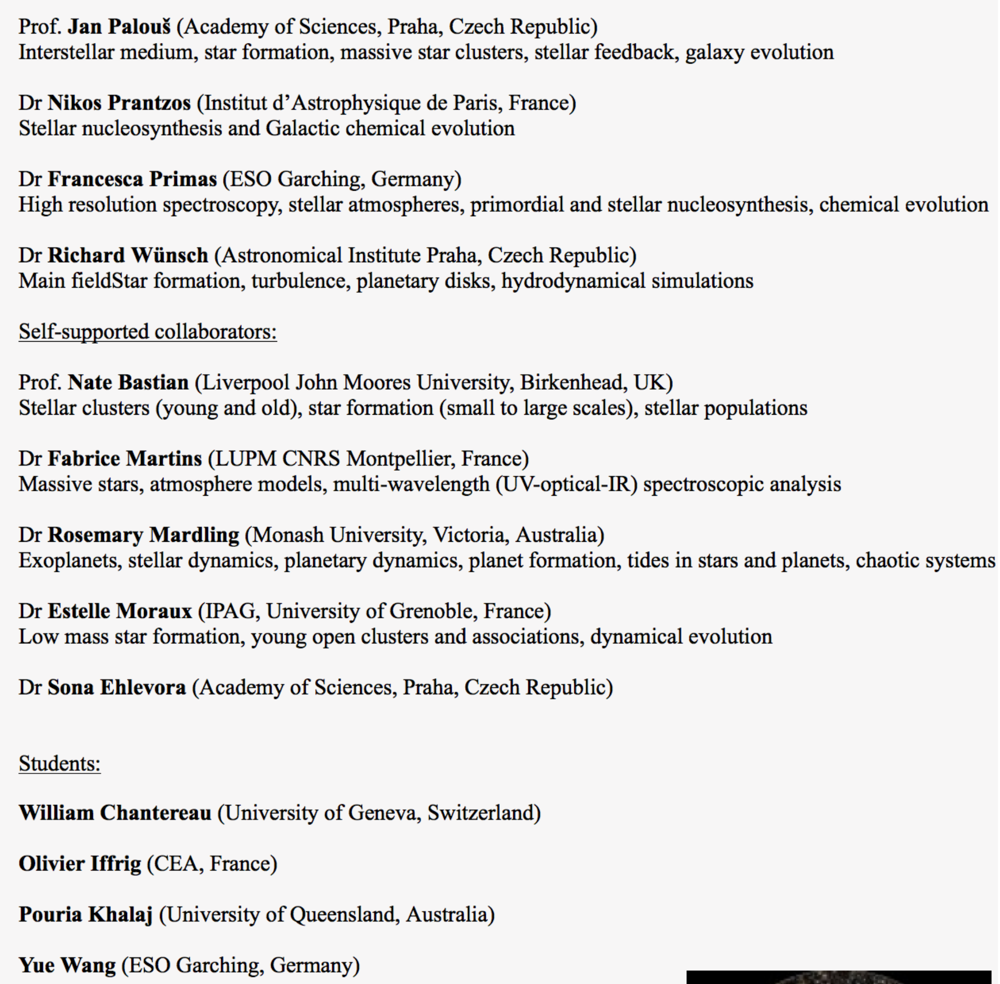
Dr **Thibaut Decressin** (Osservatorio di Roma, Italy)
Stellar evolution, stellar hydrodynamics, N-body simulation

Dr **Patrick Hennebelle** (CEA/IRFU/SAp, France)
Star formation, dynamics of the interstellar medium, numerical simulations

Prof. **Ralf S. Klessen** (Heidelberg University, Germany)
Theoretical star formation studies and ISM dynamics, numerical astrophysics

Dr **Martin Krause** (MPE, Germany)
Interstellar medium, feedback in star clusters, galaxies and galaxy clusters, magnetohydrodynamic

Prof. **Georges Meynet** (University of Geneva, Switzerland)
Massive star evolution and nucleosynthesis



Prof. **Jan Palouš** (Academy of Sciences, Praha, Czech Republic)
Interstellar medium, star formation, massive star clusters, stellar feedback, galaxy evolution

Dr **Nikos Prantzos** (Institut d'Astrophysique de Paris, France)
Stellar nucleosynthesis and Galactic chemical evolution

Dr **Francesca Primas** (ESO Garching, Germany)
High resolution spectroscopy, stellar atmospheres, primordial and stellar nucleosynthesis, chemical evolution

Dr **Richard Wünsch** (Astronomical Institute Praha, Czech Republic)
Main fieldStar formation, turbulence, planetary disks, hydrodynamical simulations

Self-supported collaborators:

Prof. **Nate Bastian** (Liverpool John Moores University, Birkenhead, UK)
Stellar clusters (young and old), star formation (small to large scales), stellar populations

Dr **Fabrice Martins** (LUPM CNRS Montpellier, France)
Massive stars, atmosphere models, multi-wavelength (UV-optical-IR) spectroscopic analysis

Dr **Rosemary Mardling** (Monash University, Victoria, Australia)
Exoplanets, stellar dynamics, planetary dynamics, planet formation, tides in stars and planets, chaotic systems

Dr **Estelle Moraux** (IPAG, University of Grenoble, France)
Low mass star formation, young open clusters and associations, dynamical evolution

Dr **Sona Ehlevora** (Academy of Sciences, Praha, Czech Republic)

Students:

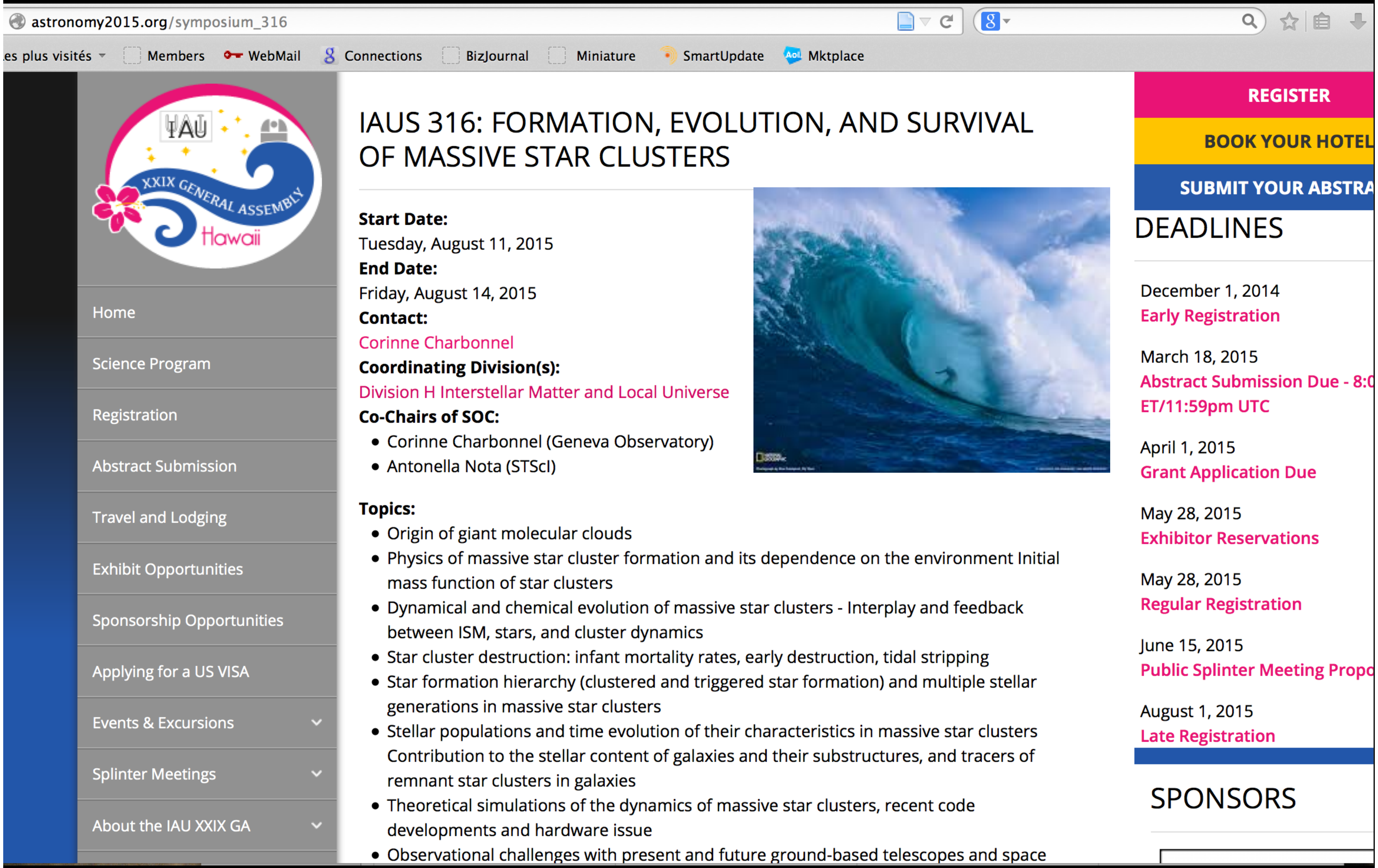
William Chantereau (University of Geneva, Switzerland)

Olivier Iffrig (CEA, France)

Pouria Khalaj (University of Queensland, Australia)

Yue Wang (ESO Garching, Germany)

INTERNATIONAL
SPACE
SCIENCE
INSTITUTE



IAUS 316: FORMATION, EVOLUTION, AND SURVIVAL OF MASSIVE STAR CLUSTERS

Start Date:
Tuesday, August 11, 2015
End Date:
Friday, August 14, 2015
Contact:
Corinne Charbonnel
Coordinating Division(s):
Division H Interstellar Matter and Local Universe
Co-Chairs of SOC:

- Corinne Charbonnel (Geneva Observatory)
- Antonella Nota (STScI)

Topics:

- Origin of giant molecular clouds
- Physics of massive star cluster formation and its dependence on the environment Initial mass function of star clusters
- Dynamical and chemical evolution of massive star clusters - Interplay and feedback between ISM, stars, and cluster dynamics
- Star cluster destruction: infant mortality rates, early destruction, tidal stripping
- Star formation hierarchy (clustered and triggered star formation) and multiple stellar generations in massive star clusters
- Stellar populations and time evolution of their characteristics in massive star clusters Contribution to the stellar content of galaxies and their substructures, and tracers of remnant star clusters in galaxies
- Theoretical simulations of the dynamics of massive star clusters, recent code developments and hardware issue
- Observational challenges with present and future ground-based telescopes and space

DEADLINES

December 1, 2014
Early Registration

March 18, 2015
Abstract Submission Due - 8:0
ET/11:59pm UTC

April 1, 2015
Grant Application Due

May 28, 2015
Exhibitor Reservations

May 28, 2015
Regular Registration

June 15, 2015
Public Splinter Meeting Propo

August 1, 2015
Late Registration

SPONSORS