Lund Observatory: Källén Seminar for Young Astronomers - 06.09.2022

Rebounding Cores to Build

Star Cluster Multiple Populations

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Multiple Stellar Populations in Star clusters

Multiple stellar populations:
Two aspects

First aspect:
- Chemical abundance variations
- Observed In globular star clusters

Second aspect:
- Multiple star formation episodes
- Observed in young star clusters

First Aspect: Light-Element Abundance Variations

- Observed in old Globular Clusters and other compact massive clusters of intermediate age

- Mostly light elements CNONaMgAl
  - Correlations: N-Na-Al
  - Anti-correlations: C-N, O-Na, Mg-Al

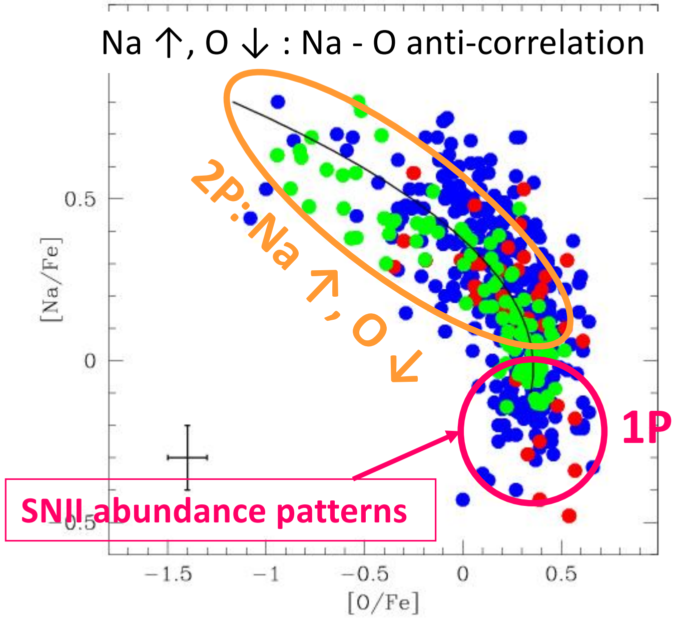

Fig5, Carretta+2006
Green points: RGB stars in NGC2808
Blue points: RGB stars from lit.
Red points: TO or SG stars from lit.

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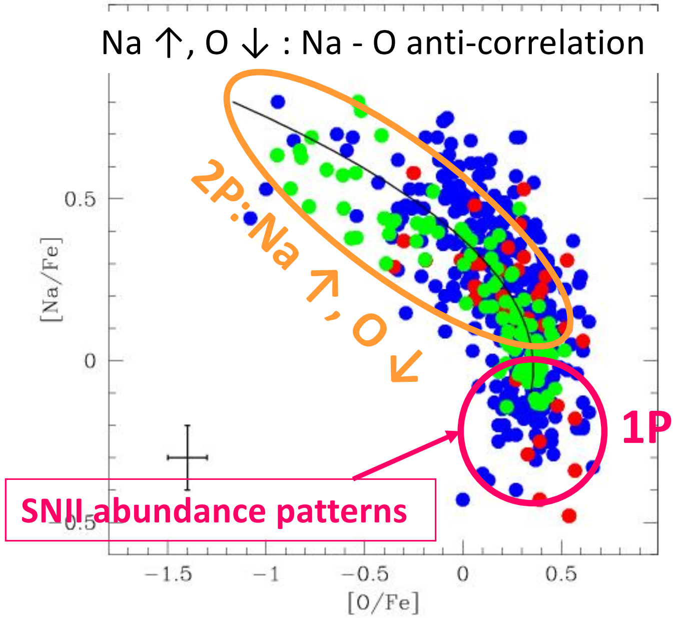
  - Imprint of hot hydrogen burning, i.e. burning of hydrogen at temperatures higher than for the pp-chain, that is:
    - CNO cycle (20MK)
    - NeNa cycle (40MK)
    - MgAl cycle (70MK)



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First Aspect: Light-Element Abundance Variations

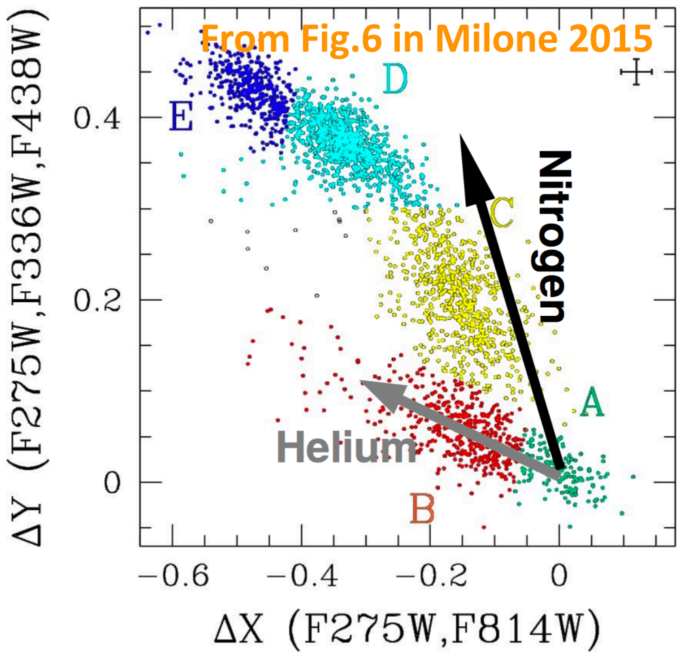
- CNONaMgAl abundance variations
  - Site of the nucleosynthesis?
    - AGB stars (D'Ercole et al 2008, D'Antonna et al 2016)
    - Fast-rotating massive stars (Decressin et al. 2007)
    - Super massive stars (mass $\gtrapprox$1E4M_{sun}, Denissenkov & Hartwick 2014)

- Star formation history of old globular clusters:
  - Virtually unkown
  - Relative age-dating of their stars remains difficult (star formation duration very short compared to their old age)
  - So far: only upper limit on their star formation duration – Oliveira et al 2020

First Aspect: Light-Element Abundance Variations

- Chromosome maps (Milone+2015):
  - Powerful **mapping tool** of multiple stellar populations in star clusters
  - **Photometry-based** (exploits the high sensitivity of stellar UV-colours to CNO abundances)
  - **Identification of the pristine and polluted populations**
    - Presence of subgroups in both groups
    - Large diversity of morphologies

NGC2808



First Aspect: Light-Element + Iron Abundance Variations

- Chromosome maps have revealed that **each globular cluster has its own specifics**, an aspect that models of multiple stellar populations in clusters must be able to explain
- Branch made of the polluted stars is:
  - Clumpy or smooth
  - Extended or short
- Some ChMaps also present redder stars (presumably more iron-rich)

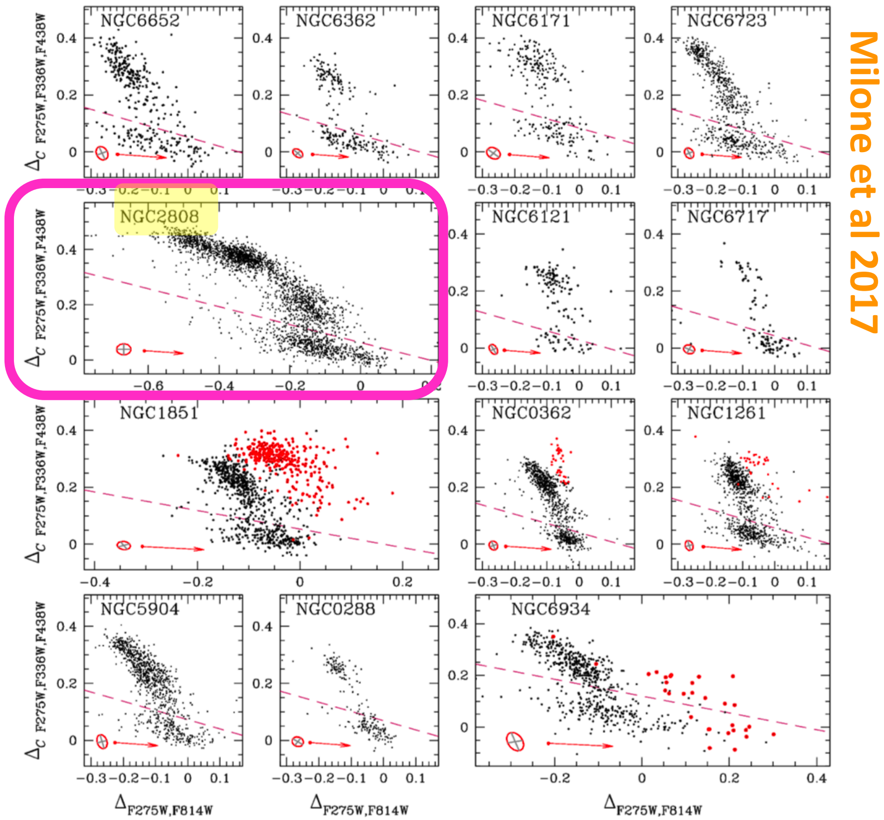


Figure 4. As in Figure 3, but for NGC 6652, NGC 6362, NGC 6171 (M 107), NGC 6723, NGC 2808, NGC 6121 (M 4), NGC 6717, NGC 1851, NGC 362, NGC 1261, NGC 5904 (M 5), NGC 288, and NGC 6934.

Second Aspect: Multiple Episodes of Star Formation

- Noticeable in young star clusters, for which relative age-dating of stars is doable, e.g
  - Orion Nebula Cluster (ONC)
    - 3 consecutive star formation episodes (Beccari et al 2017)
    - With Δt≅1Myr
    - Of decreasing amplitude

- Two features to explain:
  - Globally-decreasing star formation rate
  - Successive star formation episodes

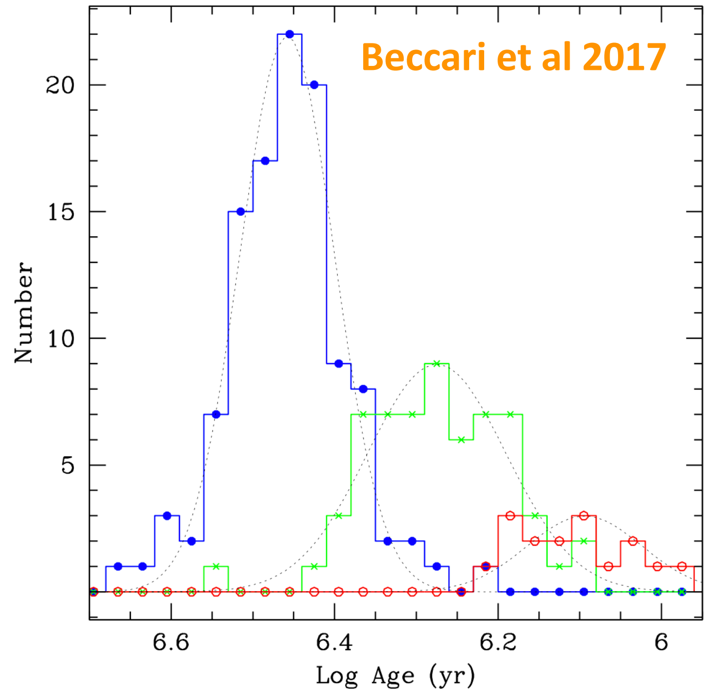
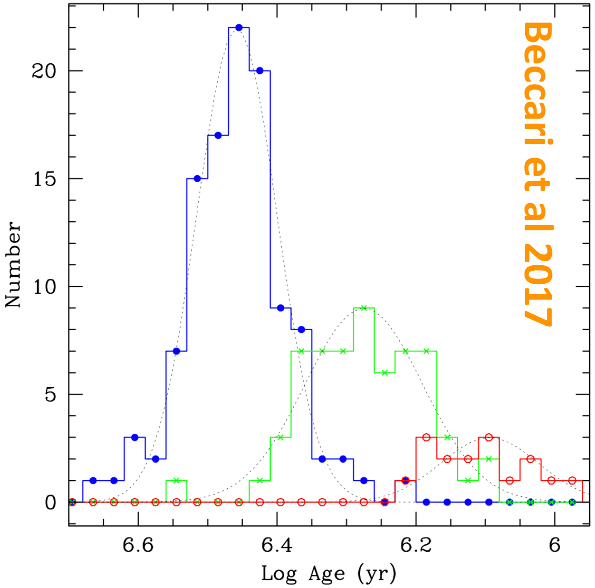


Fig. 6. Distribution of the logarithm of the spectroscopically determined ages for stars from the three populations, old (in blue), young (in green), and very young (in red) with the best Gaussian fits indicated.

Young Cluster Bumpy Stellar Age Distribution vs. Old Globular Cluster Clumpy Chromosome Map

We know: **ONC**
→ 3 consecutive episodes
of star formation



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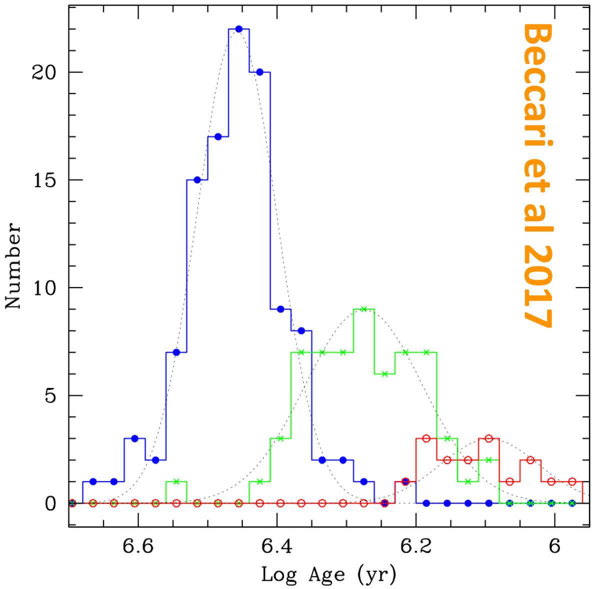

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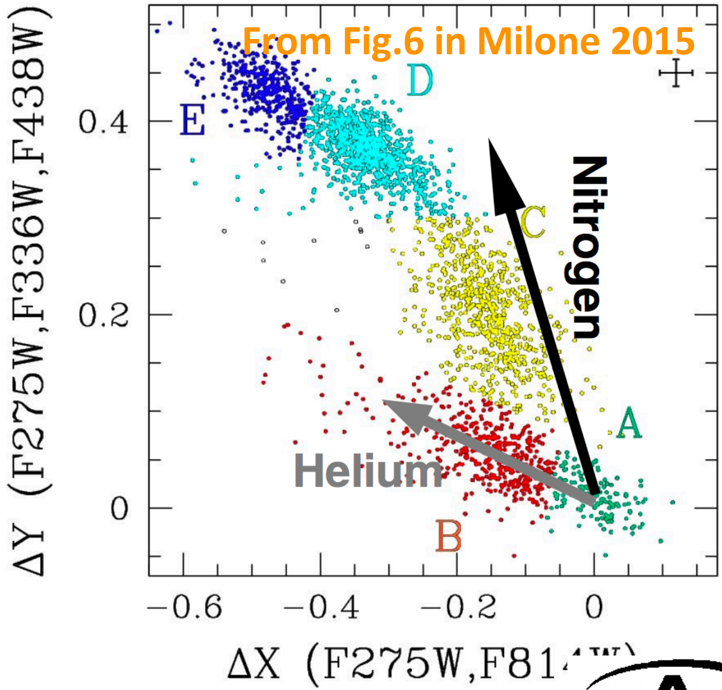
We assume: **NGC2808**
→ 3 consecutive episodes of polluted star formation



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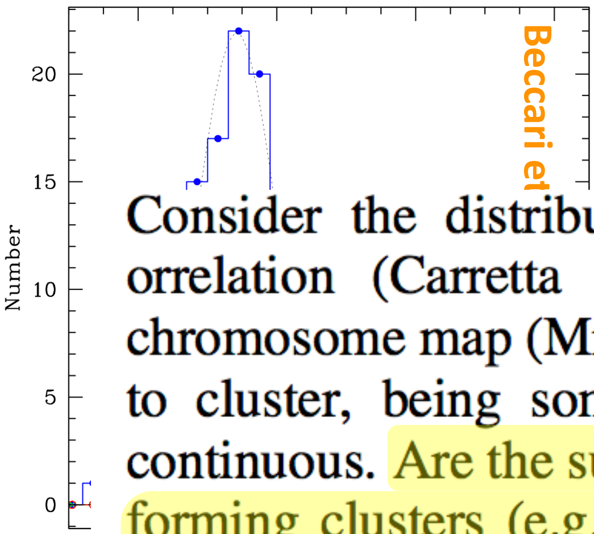
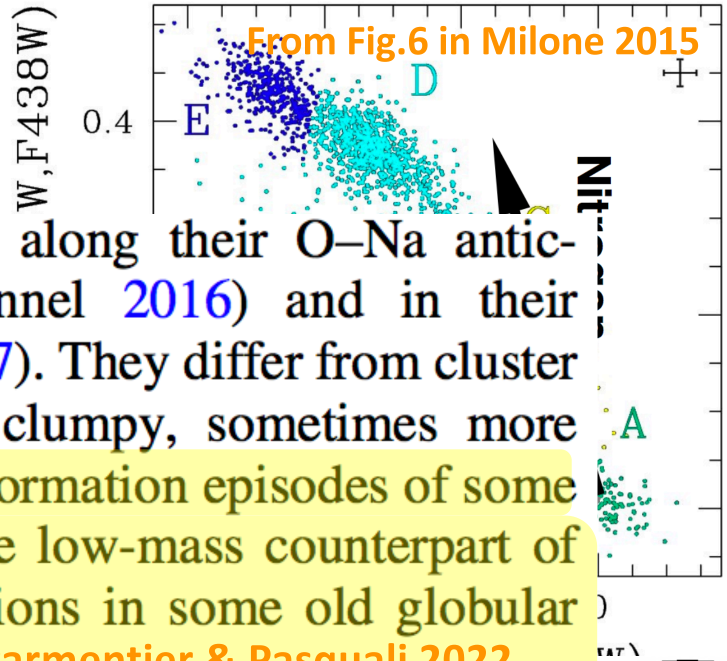




Consider the distributions of stars along their O–Na anticorrelation (Carretta 2015; Charbonnel 2016) and in their chromosome map (Milone et al. 2017). They differ from cluster to cluster, being sometimes more clumpy, sometimes more continuous. Are the successive star formation episodes of some forming clusters (e.g., the ONC) the low-mass counterpart of the clumpy multiple stellar populations in some old globular clusters?

Parmentier & Pasquali 2022

Fig. 6. Distri… ages for stars … and very you…

How to create bumpy star formation histories in clusters?

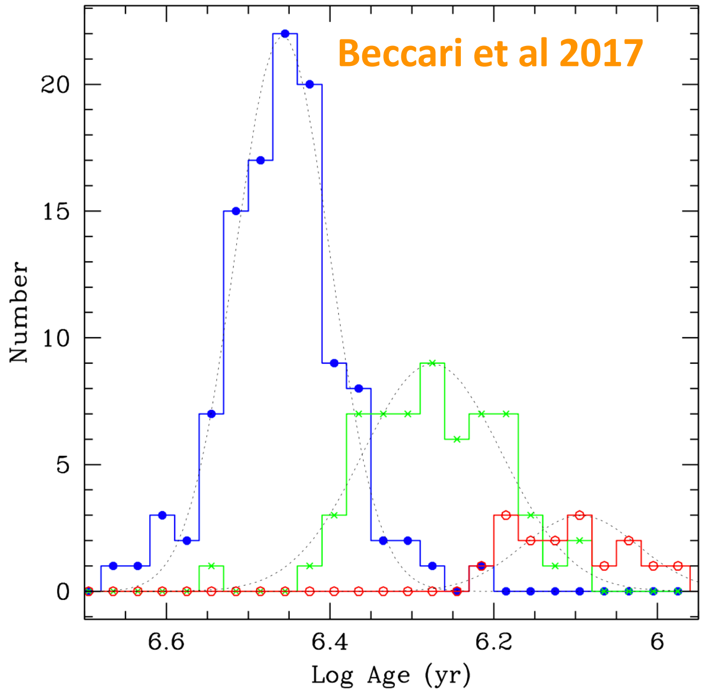
- Obvious **triple of conditions** for multiple star formation episodes to emerge
  1. First episode of star formation,
  2. Which must be somehow stopped,
  3. And followed by star formation resumption (2nd episode of star formation)
  4. And so forth …

- That is, we need a switch to turn star formation on and off several times

- Models of accelerated star formation inadequate here (e.g. Palla & Stahler 2000; takes only self-gravity into account): how do you jam the brake?

How to create bumpy star formation histories in clusters?

- In contrast, **a declining star formation rate provides a natural switch off** (1.+2.)
- Interestingly, **in the ONC**, the star formation rate has been **globally decreasing**
- For the ONC, two features to explain:
  - Globally-decreasing star formation rate
  - Successive star formation episodes



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Decreasing star formation rate in clusters

- A declining star formation rate is a **natural feature** of the cluster-formation model of
  Parmentier & Pfalzner (2013) and
  Parmentier, Pfalzner & Grebel (2014)

Eq. from Krumholz & McKee (2005)

$$SFR \searrow = \frac{\varepsilon_{ff} m_{gas} \searrow}{\tau_{ff} \nearrow}$$

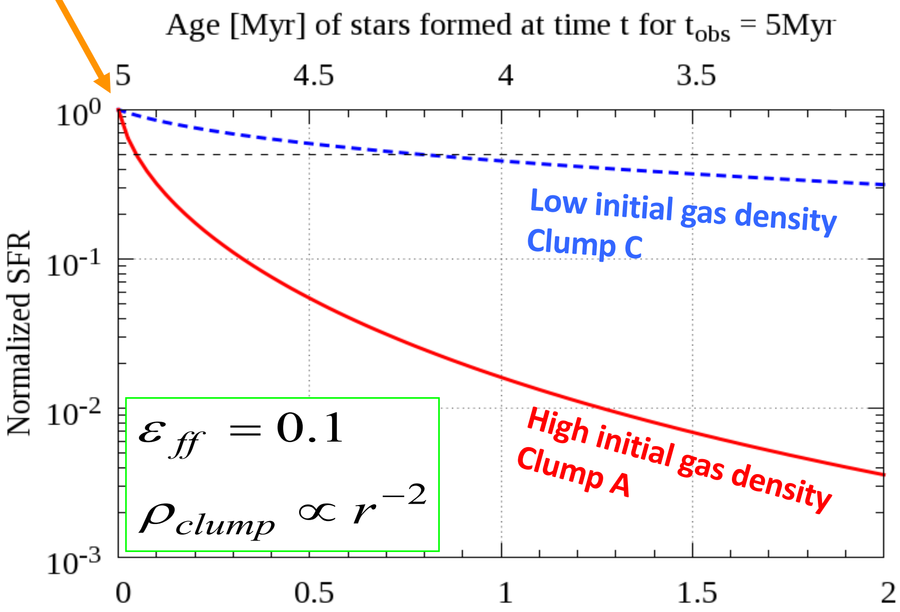
$m_{gas}(t)$ decreases

$\tau_{ff}(t)$ gets longer

SFR decreases with time

(assuming constant clump size)

Clump SFR evolution normalized to initial value



Onset of star formation

Figure adapted from Parmentier, Pfalzner & Grebel (2014)

Bumpy star formation histories in clusters

- But a steadily decreasing star formation history is not yet enough
- **How to „re-activate“ star formation** for a 2nd episode to emerge ?
- New concept: “**star formation bouncing back with rebounding cores**“ (Parmentier & Pasquali 2022)
- Little reminder:
  - Parmentier & Pfalzner (2013) model describes a 1-step SF process

Initial gas mass → **Stars**

Star formation efficiency per free-fall time ε_{ff} = 1%

$$SFR = \frac{\varepsilon_{ff} m_{gas}}{\tau_{ff}}$$

Krumholz & McKee (2005)

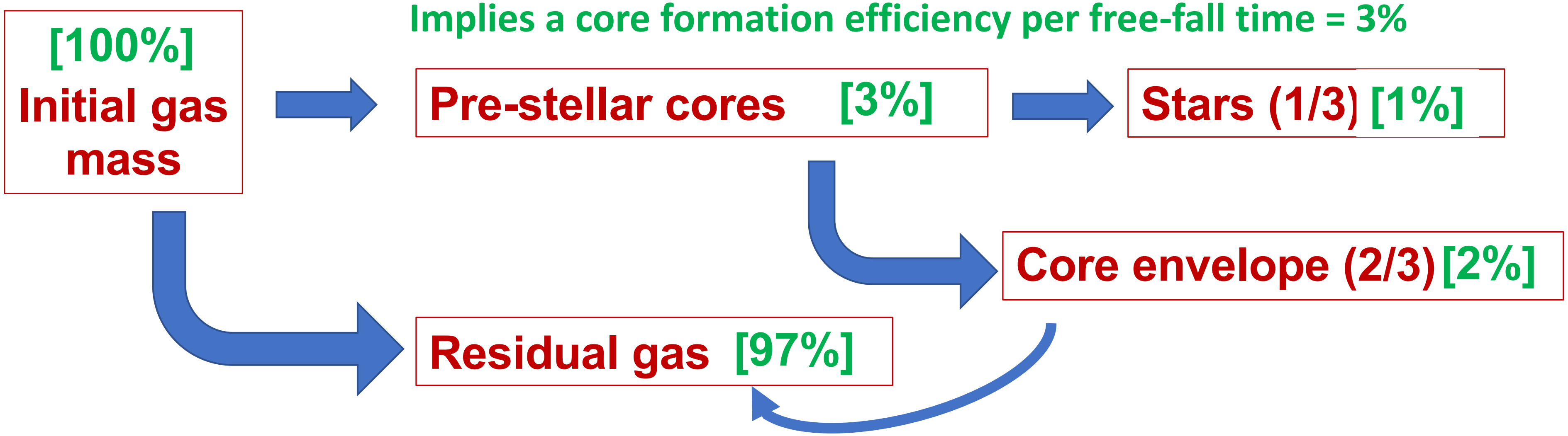
15

Star formation bouncing back with rebounding cores

- Stars do not form straight out of the gas: star formation is a 2-step process
- **Core formation as an intermediate stage**

Star formation efficiency per free-fall time = 1%

Implies a core formation efficiency per free-fall time = 3%



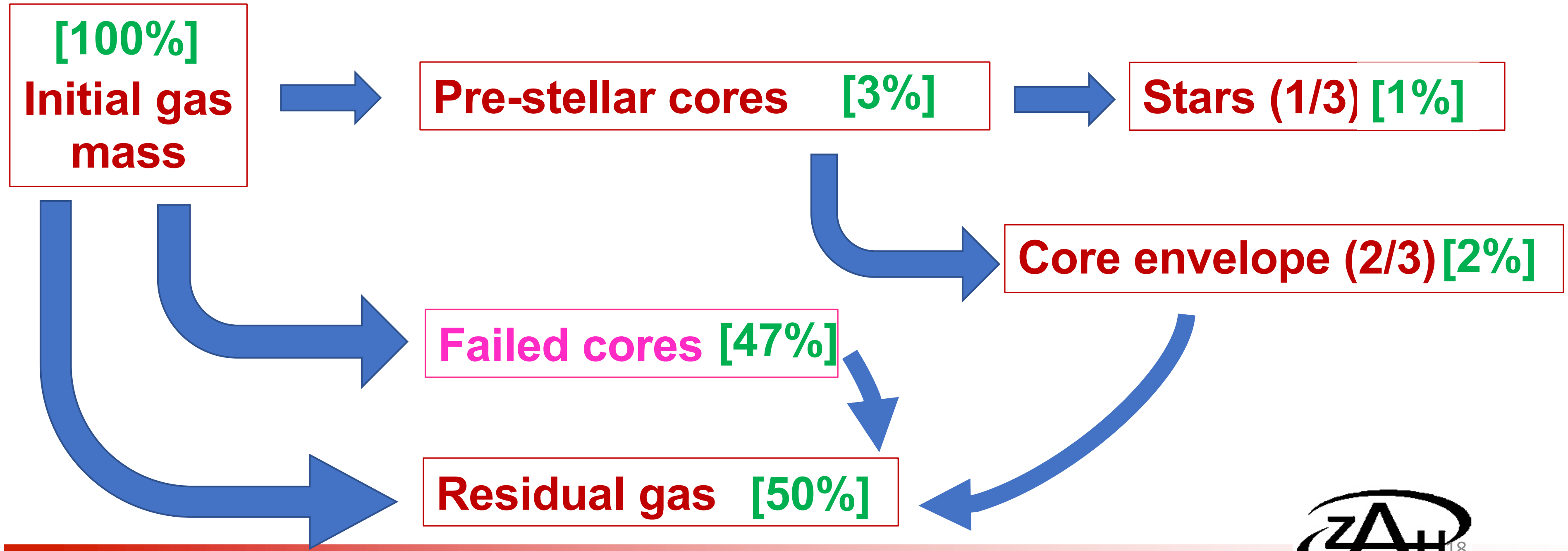
Star formation bouncing back with rebounding cores

- But sometimes the chain of events gas → core → star fails
  - **Some cores do not collapse: they fail to form stars and, eventually, disperse into the ambient gas out of which they initially formed**
  - Rebounding/Failed/Dispersing cores
  - Vast amount of literature about star-forming cores, but little about failed cores
  - Yet their existence has been known for 15+ years
    - in simulations: e.g. Vazquez-Semadini+2005
    - and in observations: e.g. Belloche+2011
    - [additional references in Parmentier & Pasquali 2022]
  - On top of that: **they could be the dominant species**
- We therefore need to revise/complete our time-line diagram

Star formation bouncing back with rebounding cores

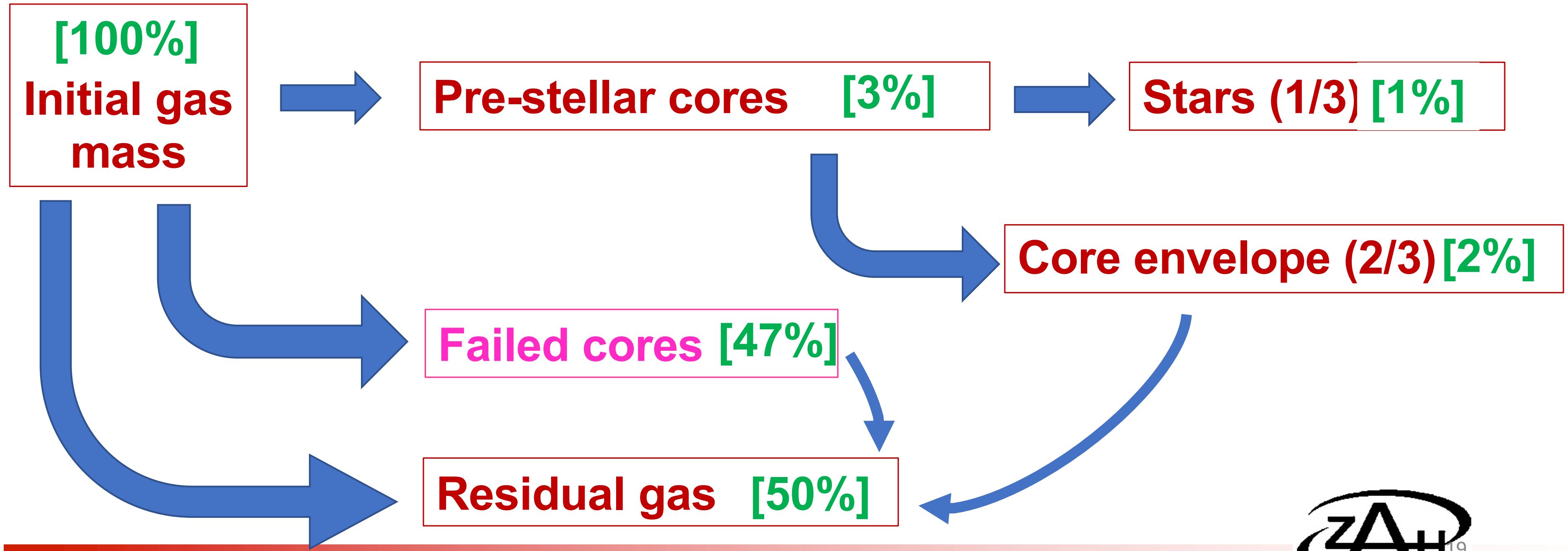
Star formation efficiency per free-fall time: 1%

Total core formation efficiency per free-fall time: 50%

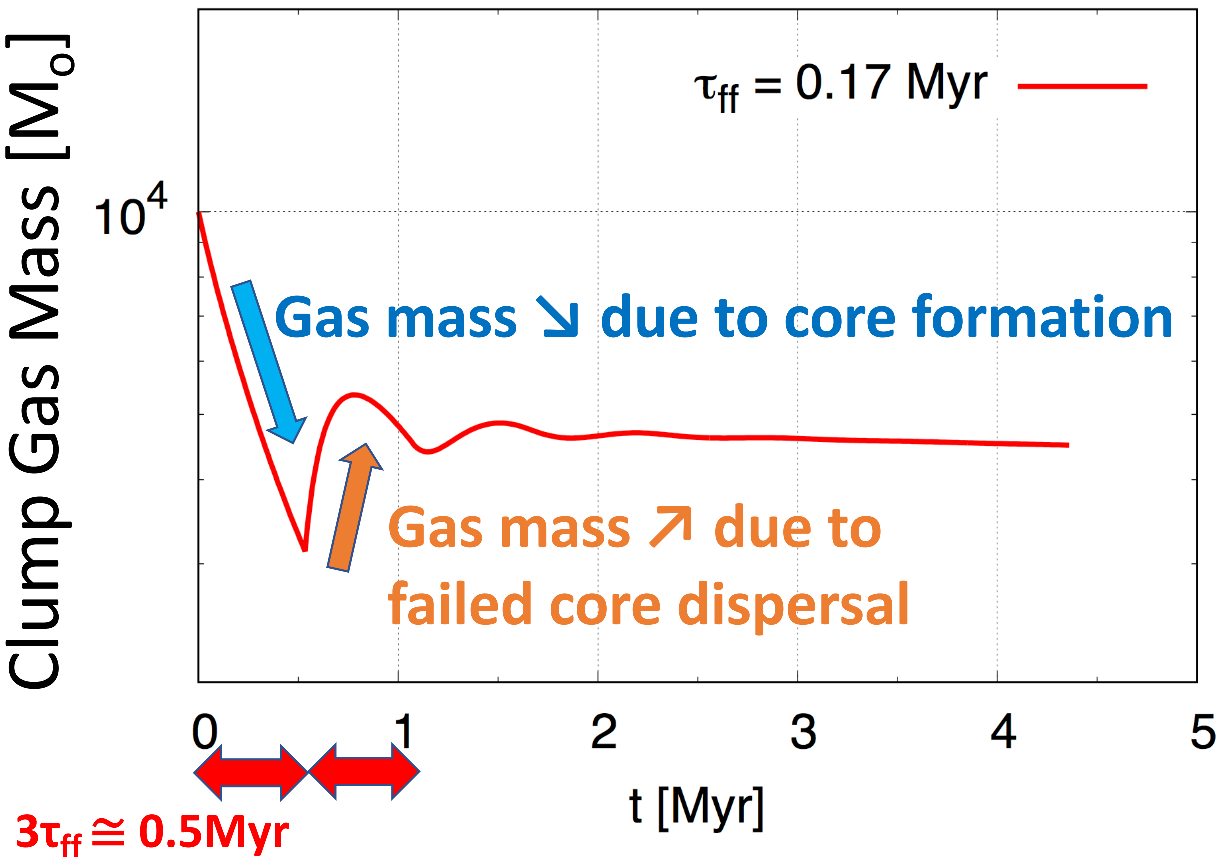


Star formation bouncing back with rebounding cores

- With such a picture, we expect the **gas mass to experience some ups and downs**
  - Down when cores form
  - **Up when failed cores disperse (rejuvenation of the gas mass reservoir)**



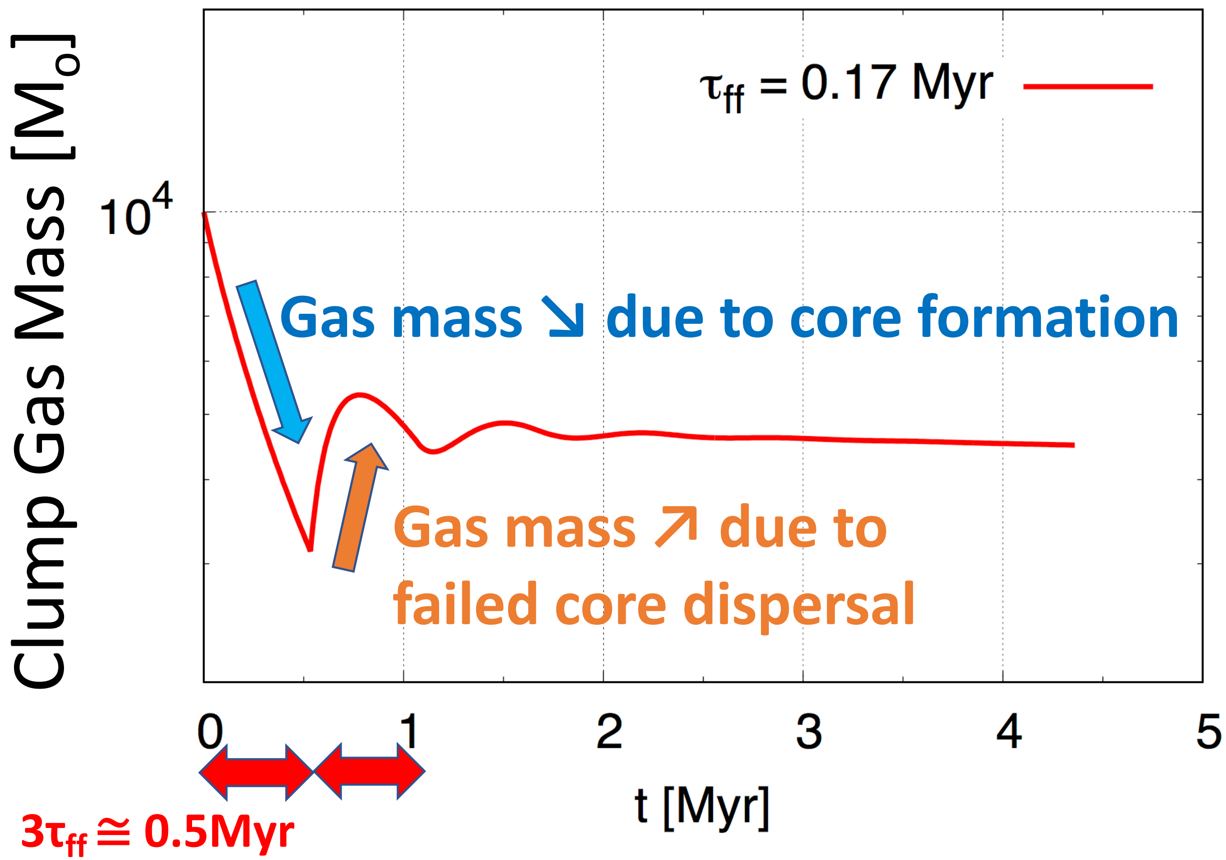
Gas mass and the formation-dispersal cycle of failed cores



$$CoFR = \frac{\varepsilon_{ff,co} m_{gas}}{\tau_{ff}}$$

Adapted from Fig. 1 in Parmentier & Pasquali (2022)

Gas mass and the formation-dispersal cycle of failed cores

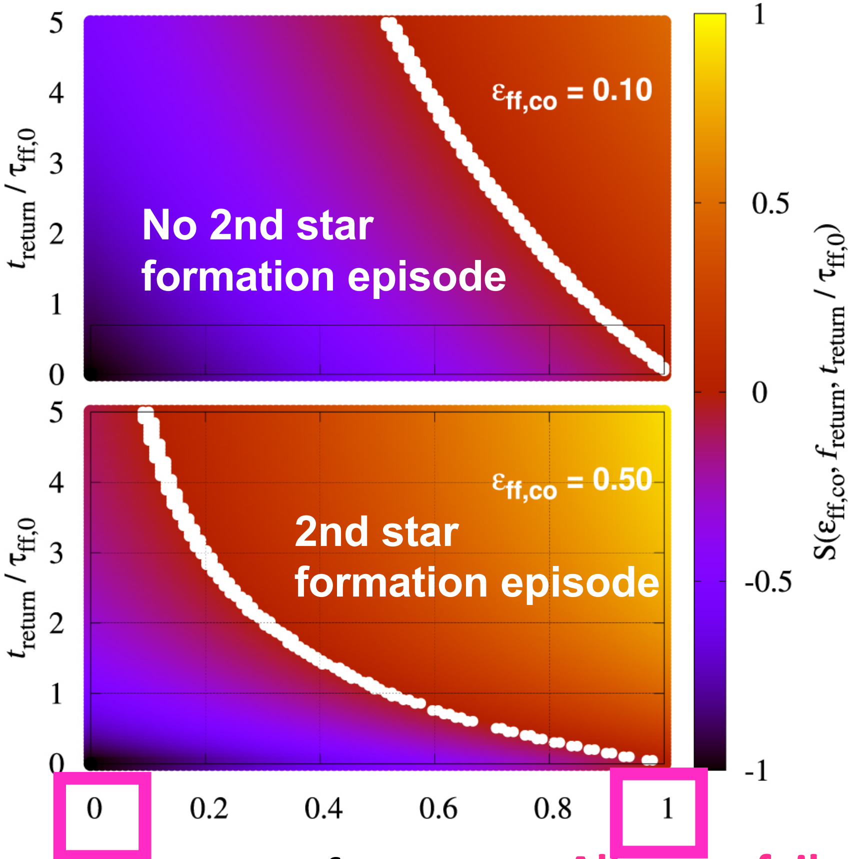


$$CoFR = \frac{\varepsilon_{ff,co} m_{gas}}{\tau_{ff}}$$

- If the mass and free-fall time of the clump gas vary with time,
- Then:
  - So does the CoFR
  - So does the SFR

Adapted from Fig. 1 in Parmentier & Pasquali (2022)

3 dimensionless parameters to quantify the failed-core activity



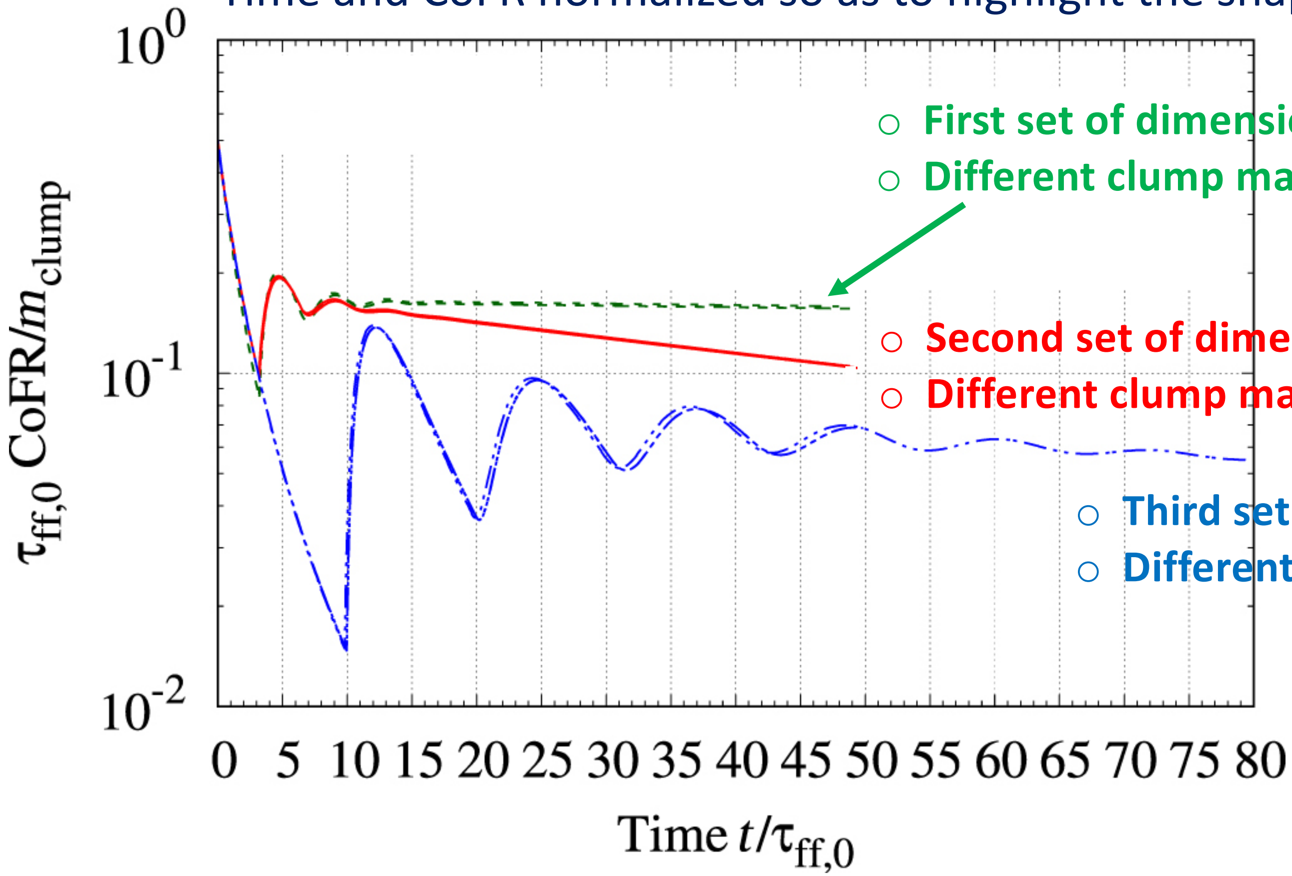
All cores form stars (efficiency=100%)

All cores fail to form stars

- Three parameters to determine whether a 2nd star formation episode emerges:
  - $\varepsilon_{ff,co}$ >>: many cores must form
  - f_{return} >>: most cores must fail at forming stars
  - $\frac{t_{return}}{\tau_{ff,0}}$ >>: the ambient gas density/mass must be given as much time as possible to decrease
- These are 3 **dimensionless** parameters
- **The clump mass is irrelevant**
- The ONC is as likely to form multiple SF episodes as NGC2808

Shape of SFH imposed by dimensionless parameters only

Time and CoFR normalized so as to highlight the shape of the SFH only



- First set of dimensionless of parameters
- Different clump masses and densities

- Second set of dimensionless of parameters
- Different clump masses and densities

- Third set of dimensionless of parameters
- Different clump masses and densities

Fig9, Parmentier & Pasquali (2022)

The Young ONC Cluster as a Test-Bed

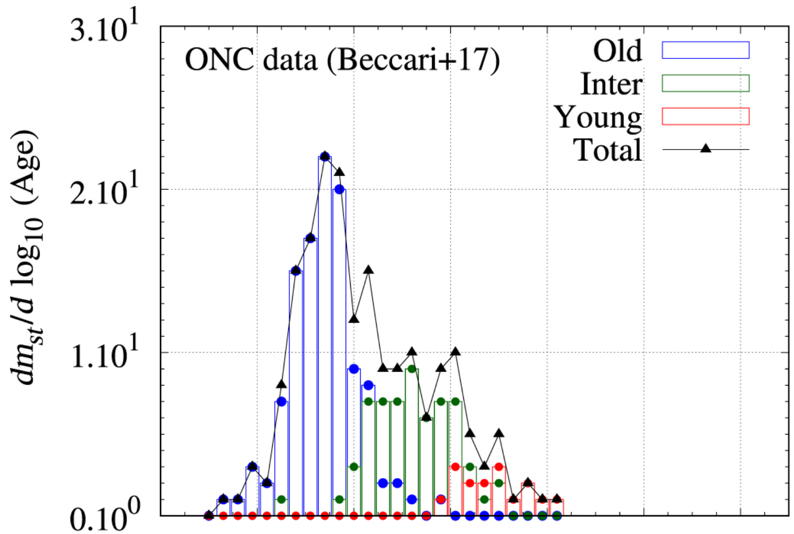
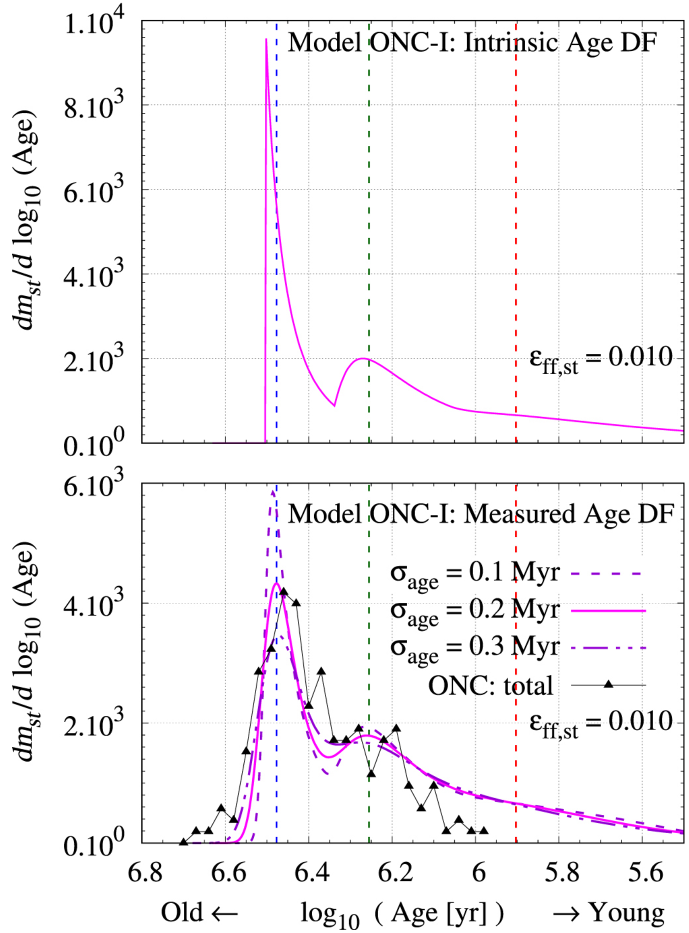


Fig6, Parmentier & Pasquali 2022



But now what about the nucleosynthesis?

- **Back to the first aspect: Chemical abundance variations**

➢ **Super Massive Stars (SMS, mass $\gtrapprox 10^4 M_o$)** as the assumed polluters

➢ **Formation of SMSs :**

- Via runaway stellar collisions of pre-existing „normal“ stars
  - Restricted to massive and dense stellar systems (stellar-collision likelihood must be high enough)
  - Central regions of dense massive clusters (e.g. globular clusters)
- 1 SMS per cluster
- **Formation time-span of order 2-3Myr** (Gieles+2018)
- That is, comparable to the cluster star formation duration

Super Massive Stars as the assumed polluters

- **Super Massive Stars (SMS, mass $\gtrsim 10^4 M_{\odot}$)** as the assumed polluters
- **Nucleosynthetic yields of SMSs:**
  - High enough temperatures in their stellar interiors to trigger the CNO, NeNa, MgAl cycles
  - SMS stellar winds then pollute the intra-cluster star-forming gas
- **SMS formation criterion?**
  - Light-element abundance variations observed
    - in old, initially massive, globular clusters
    - not in low-mass open clusters of the Galactic disk

⟶ **Suggests a cluster stellar mass threshold**

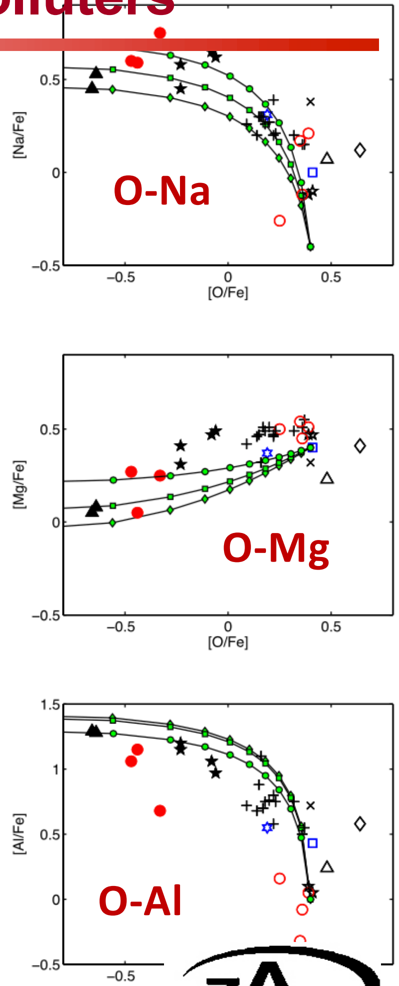


Fig1, Denissenkov & Hartwick 2014

Super Massive Stars as the assumed polluters

- **A stellar mass threshold as the SMS formation criterion?**
  - Sensible choice since **more massive globular clusters host a greater fraction of polluted stars**
  - Simulations of Gieles+2018:
    - $N=10^5$ stars (mass $\cong 0.5 \cdot 10^5 M_o$): no SMS
    - $N=10^6$ stars (mass $\cong 0.5 \cdot 10^6 M_o$): almost there
    - $N=10^7$ stars (mass $\cong 0.5 \cdot 10^7 M_o$): SMS active 2-3Myr after SF onset

- **The ability of a cluster to form a SMS and, therefore, polluted stars then depends on a dimensional parameter, namely, its stellar mass**

Decoupling SFH and chemical-abundance aspects

- The <u>shape</u> of the Star Formation History of a cluster and its chemical evolution are now two decoupled issues (Parmentier & Pasquali 2022)

Star Formation History shape

↕

dimensionless parameters:
$\varepsilon_{ff,co}$, f_{return}, $t_{return}/\tau_{ff,0}$

Light-element abundance variations

↕

dimensional parameter:
cluster stellar mass

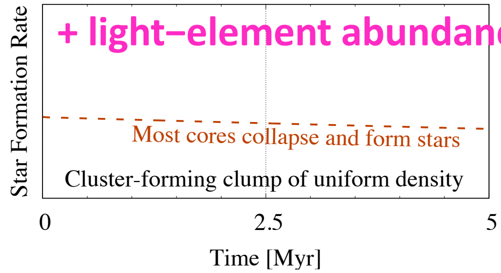
Decoupling SFH and chemical-abundance aspects

Illustration of Section 7.2 in Parmentier & Pasquali 2022

Cluster stellar mass (∝ likelihood of SMS formation)

- SC massive enough to form a SMS

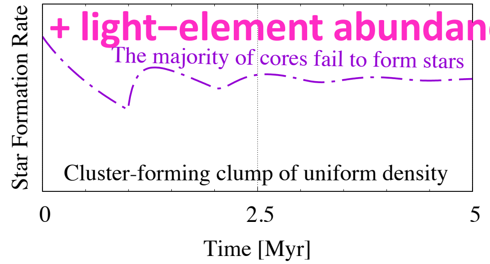
\+ light–element abundance variations



E.g. old GC with smooth chromosome map

- SC massive enough to form a SMS

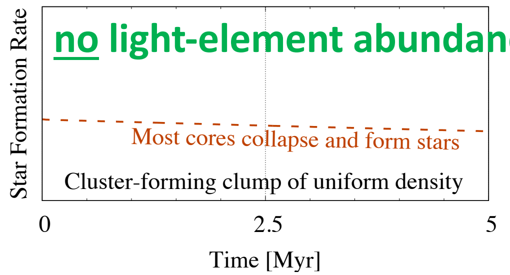
\+ light–element abundance variations



E.g. old GC with clumpy chromosome map

- SC not massive enough to form a SMS

<u>no</u> light-element abundance variations



- SC not massive enough to form a SMS

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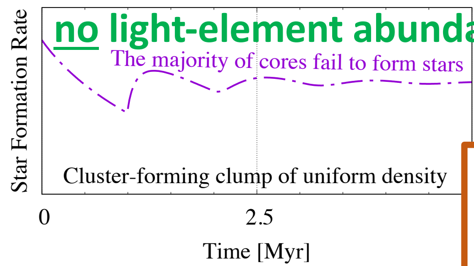

E.g. the Orion Nebula Cluster

Failed-core "activity"

$(\epsilon_{ff,co}, f_{return}, \frac{t_{return}}{\tau_{ff,0}})$