ARI Colloquium – 06.02.2025

Cracking the Relation between Mass and 1P-Star Fraction of Globular Clusters

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Project initiated under
SFB B5, PI: Anna Pasquali

SFB
881

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SEIT 1386

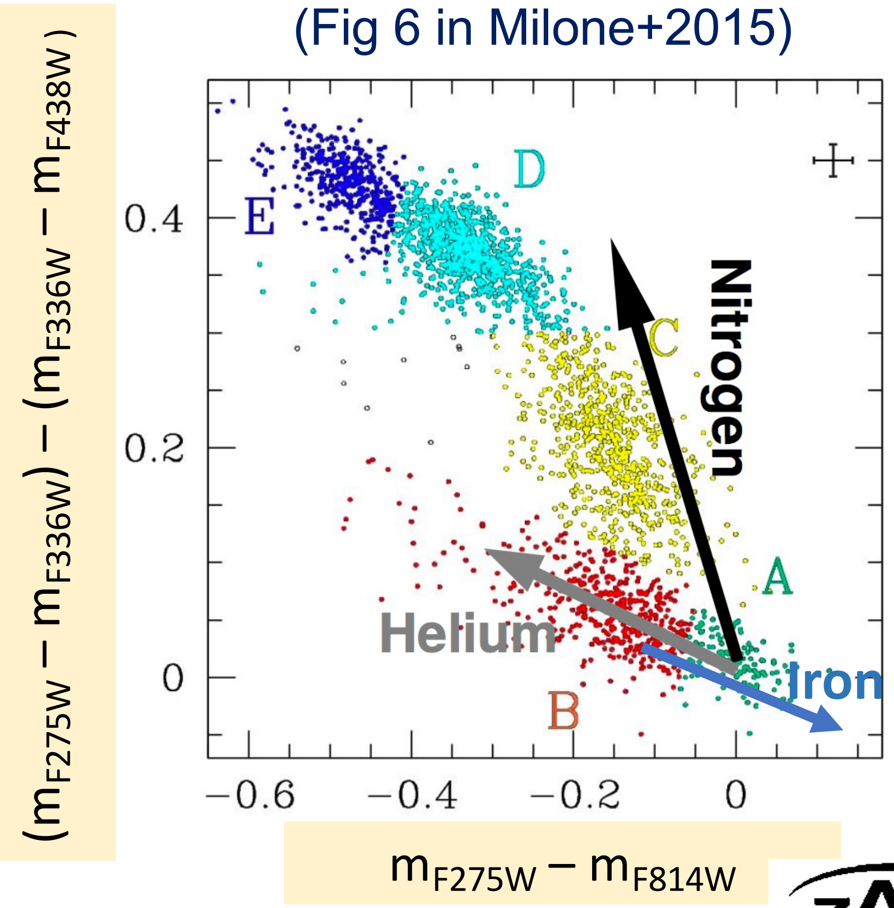
Light-Element Abundance Variations

- Observed in old globular clusters and in intermediate-age compact massive clusters
- Mostly light elements:
  He, CNONa (MgAl)
- First insights from spectroscopy …

Light-Element Abundance Variations

- … Today powerfully completed by the data from the Chromosome Map of star clusters (Milone+2015)
  - **Mapping tool** of multiple stellar populations in star clusters
  - **Photometry-based** (exploits the high sensitivity of stellar UV-colours to CNO abundances)

Chromosome map of NGC2808
(Fig 6 in Milone+2015)



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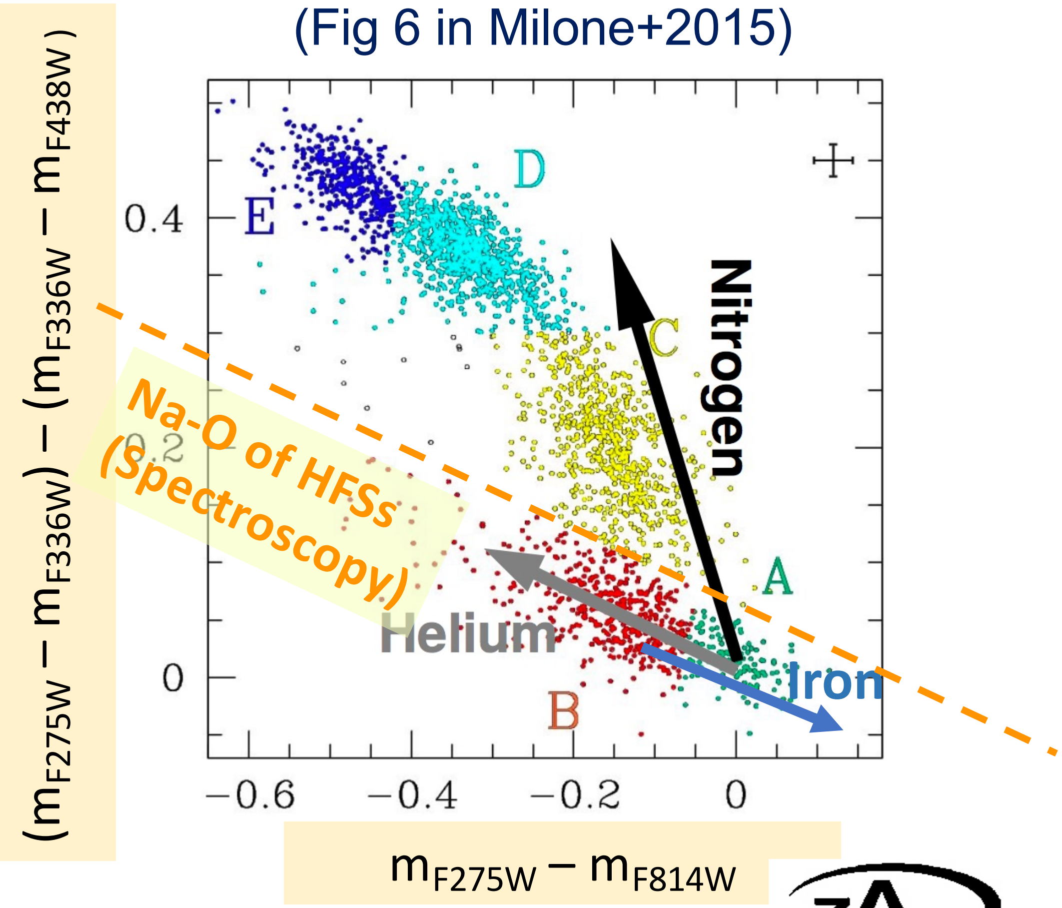

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  - **Mapping tool** of multiple stellar populations in star clusters
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- Two main populations:
  - 1P stars (pristine stars)
  - 2P stars (polluted stars)

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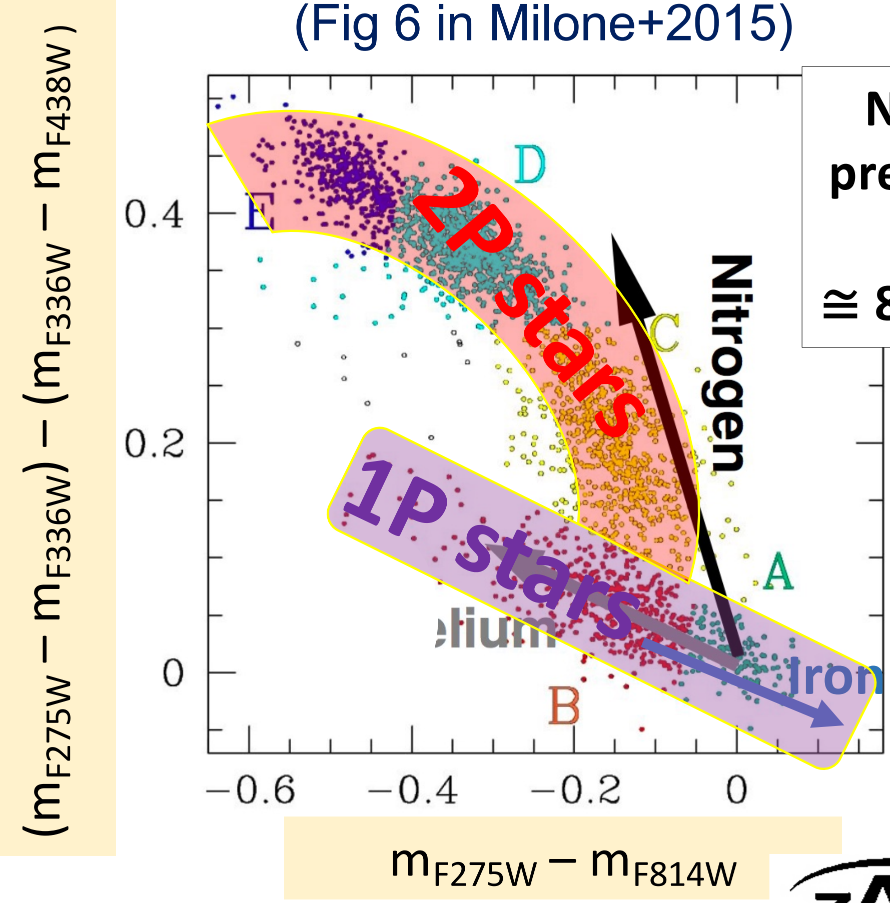


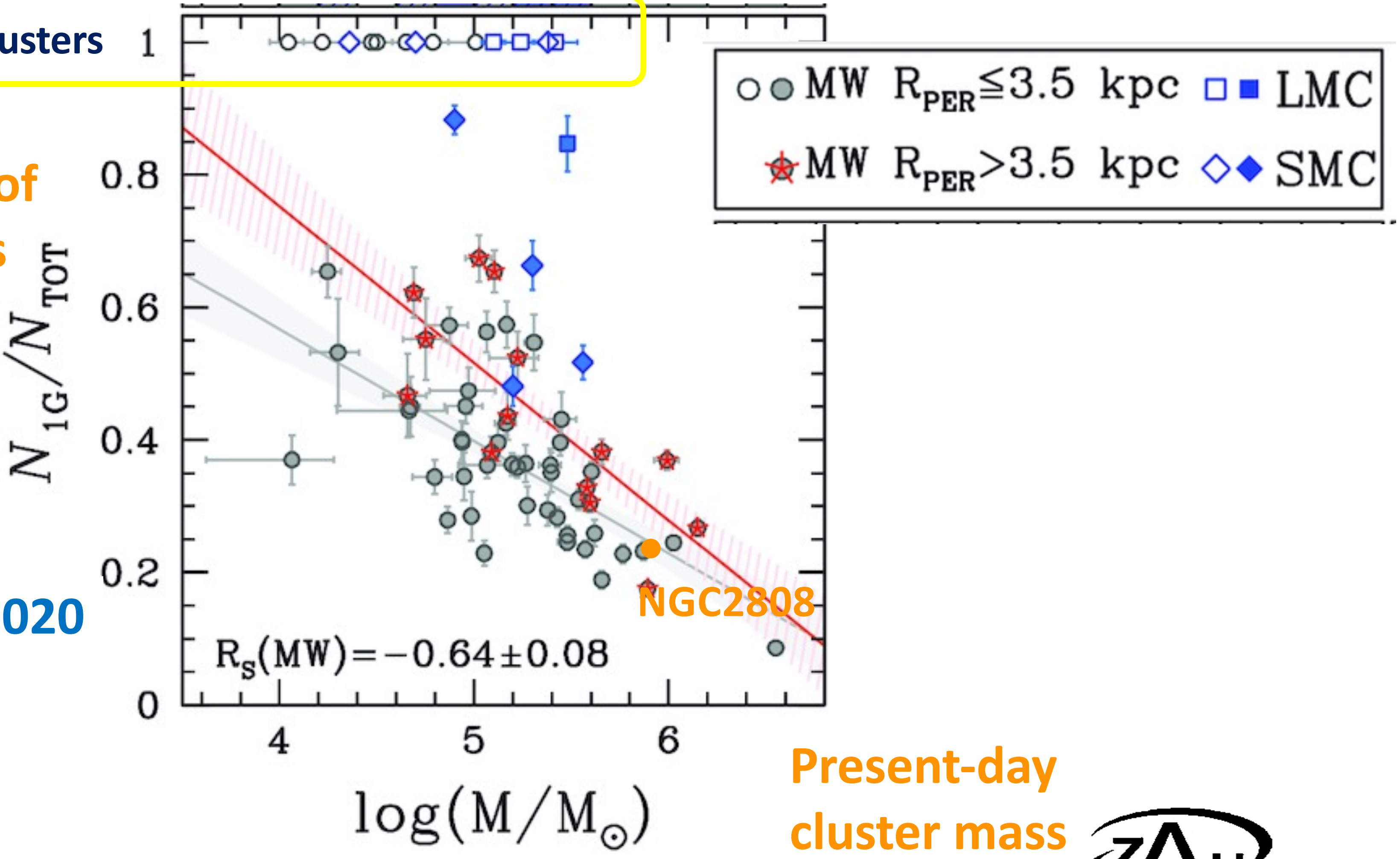
NGC2808 present-day mass $\cong 8 \cdot 10^5\ M_\odot$

The Multi-Pops Phenomenon … A Massive-Cluster Story

Single-population clusters

Number fraction of pristine/1P stars in clusters

F_{1P}^{obs}



NGC2808

Present-day cluster mass

Fig7a, Milone+2020

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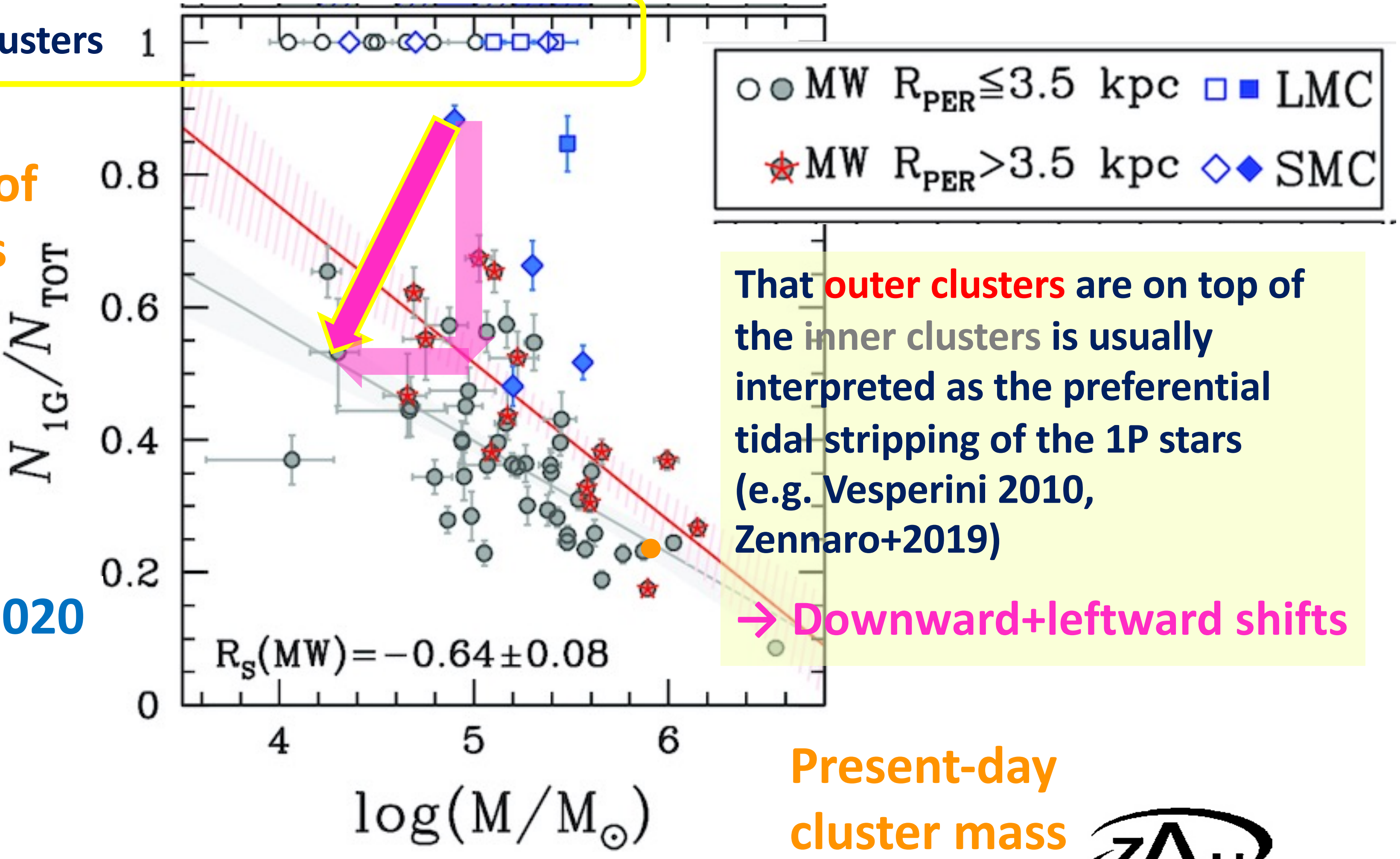


Fig7a, Milone+2020

That outer clusters are on top of the inner clusters is usually interpreted as the preferential tidal stripping of the 1P stars (e.g. Vesperini 2010, Zennaro+2019)

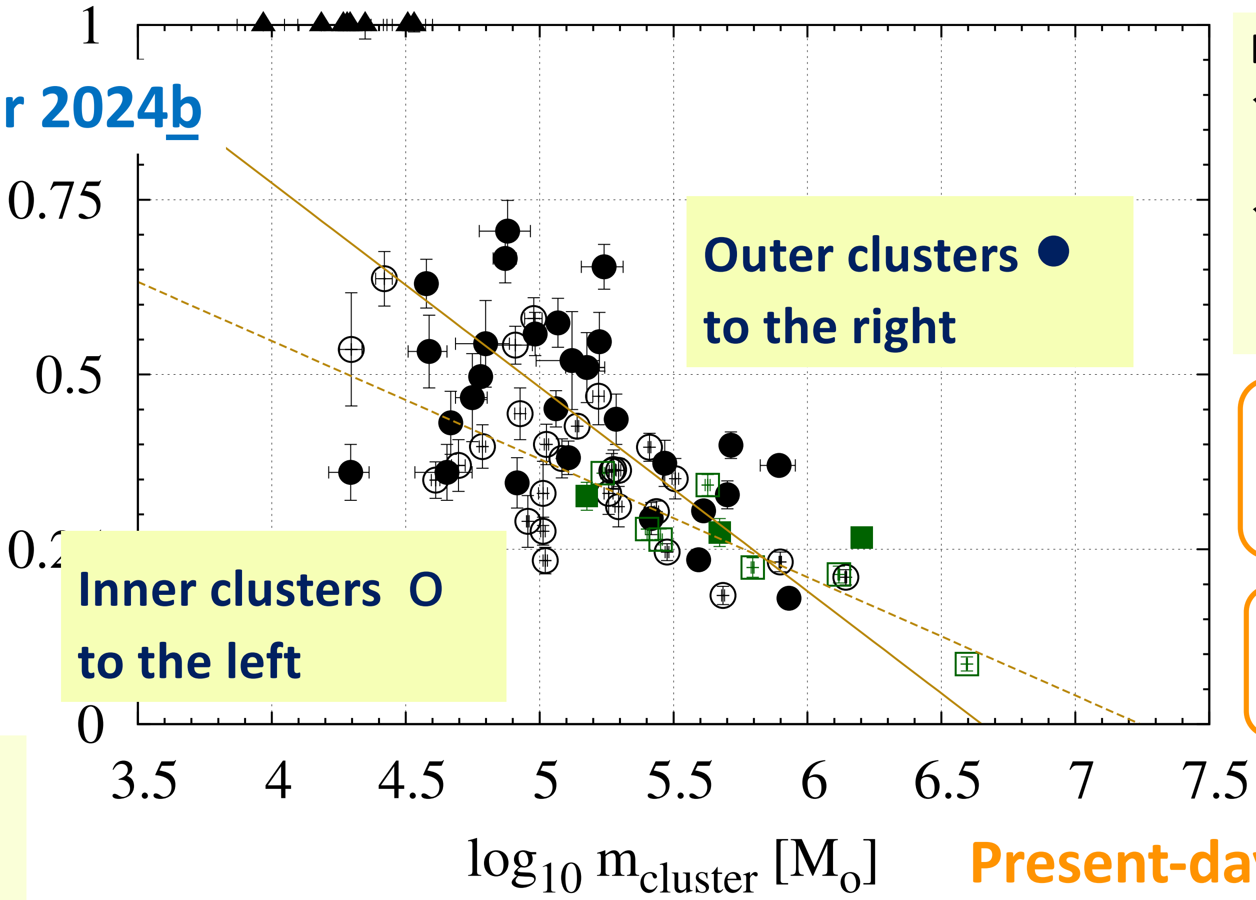
→ Downward+leftward shifts

Present-day cluster mass

Note: “outer” or “inner” clusters refers to their outer or inner location in the Galaxy

Data Points: Location and Desert, Shape of their Distribution

Fig1b, Parmentier 2024b



F^{obs}_{1P}

Outer clusters ●
to the right

Inner clusters O
to the left

Present-day
cluster mass

Data set assembly:
- ✓ Sec. 3,
  Parmentier 2024a,
- ✓ Updated in Sec. 2.2,
  Parmentier 2024b

Dynamical mass
estimates from
Baumgardt+ 2019

F^{obs}_{1P} from Milone 's
collaboration

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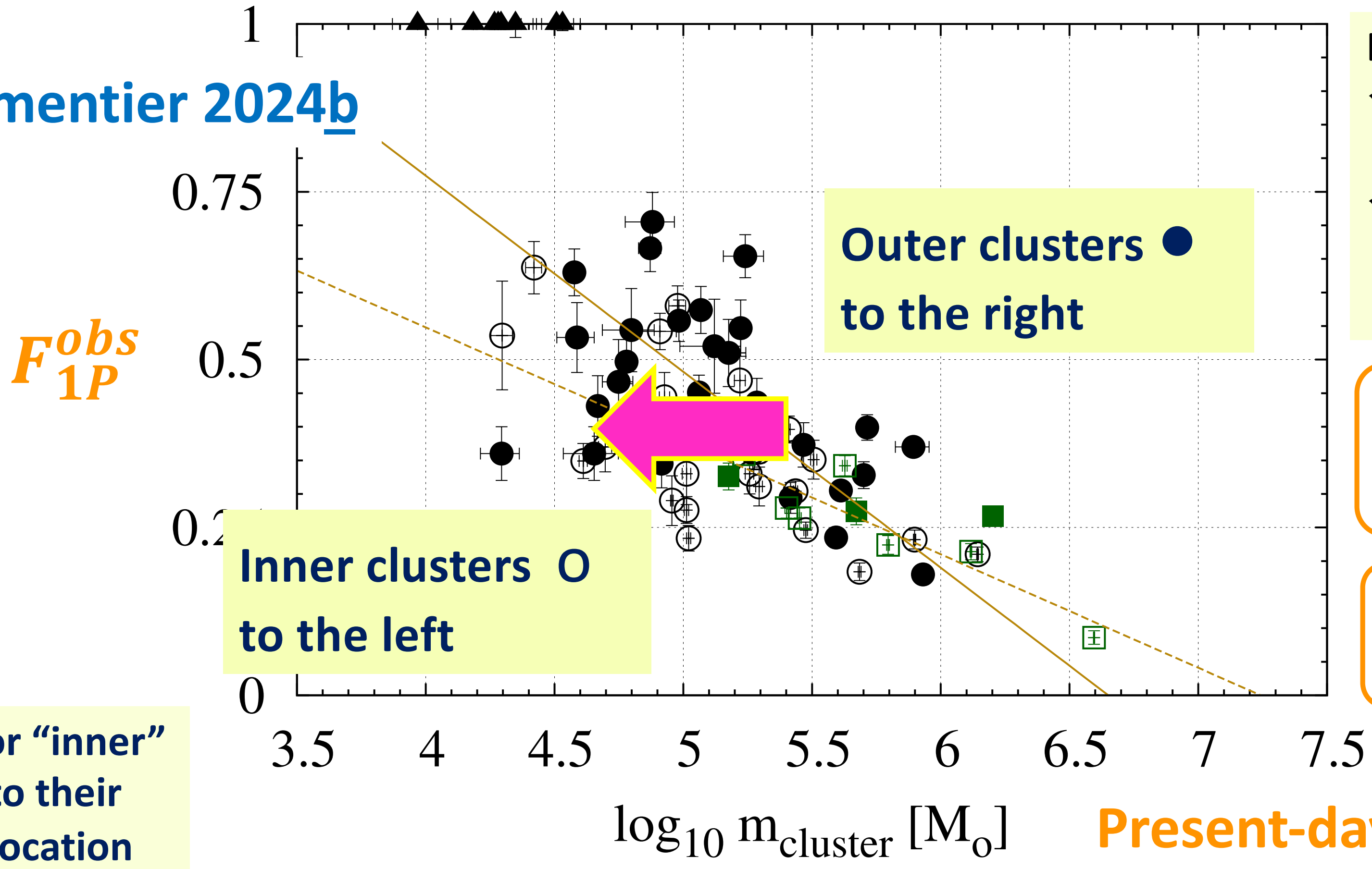
Explaining the Data with a Pure Mass (Leftward) Shift

Fig1b, Parmentier 2024b



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Present-day cluster mass

A Sharpened Read of the Data

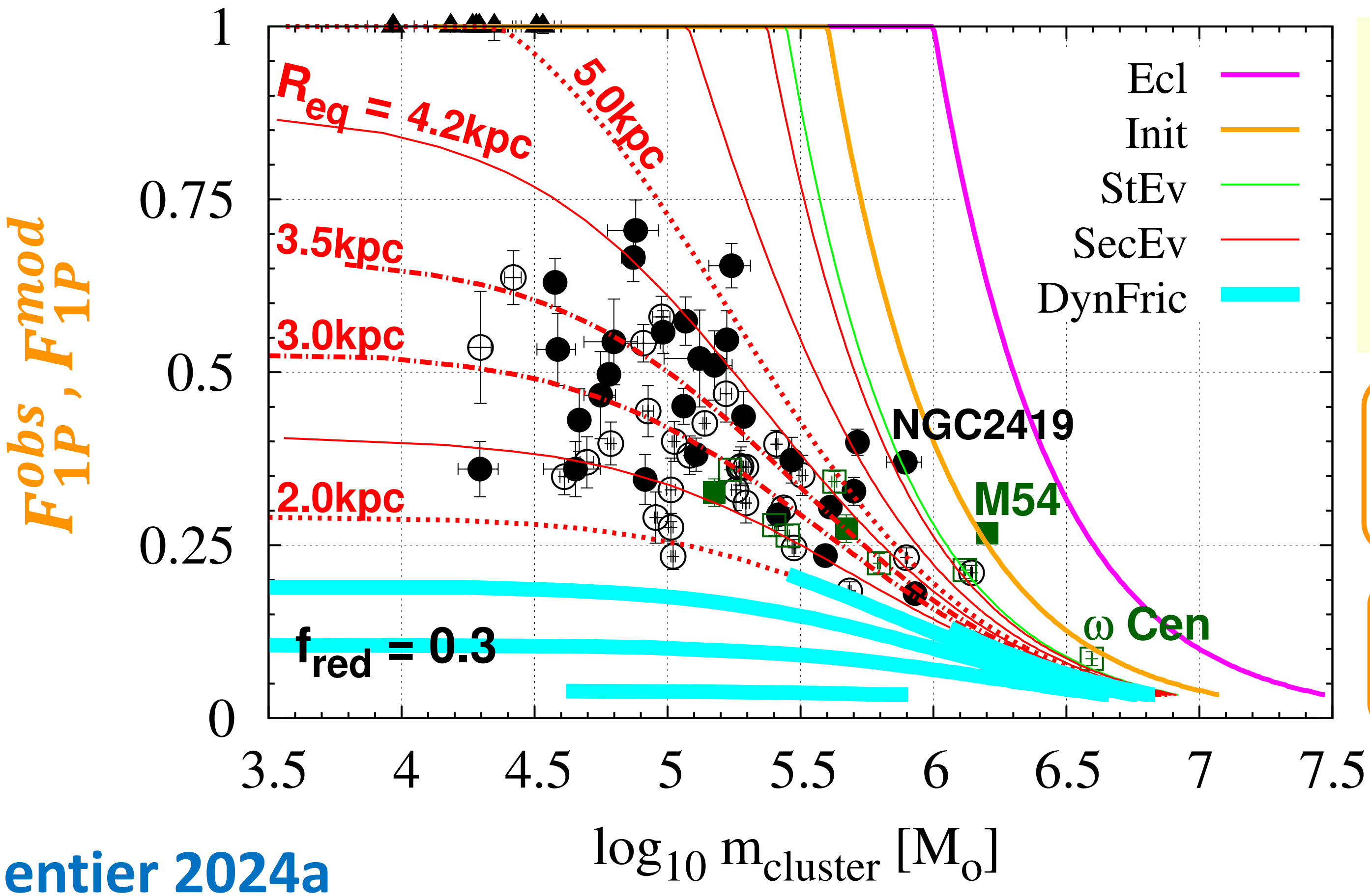

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Fig7 , Parmentier 2024a

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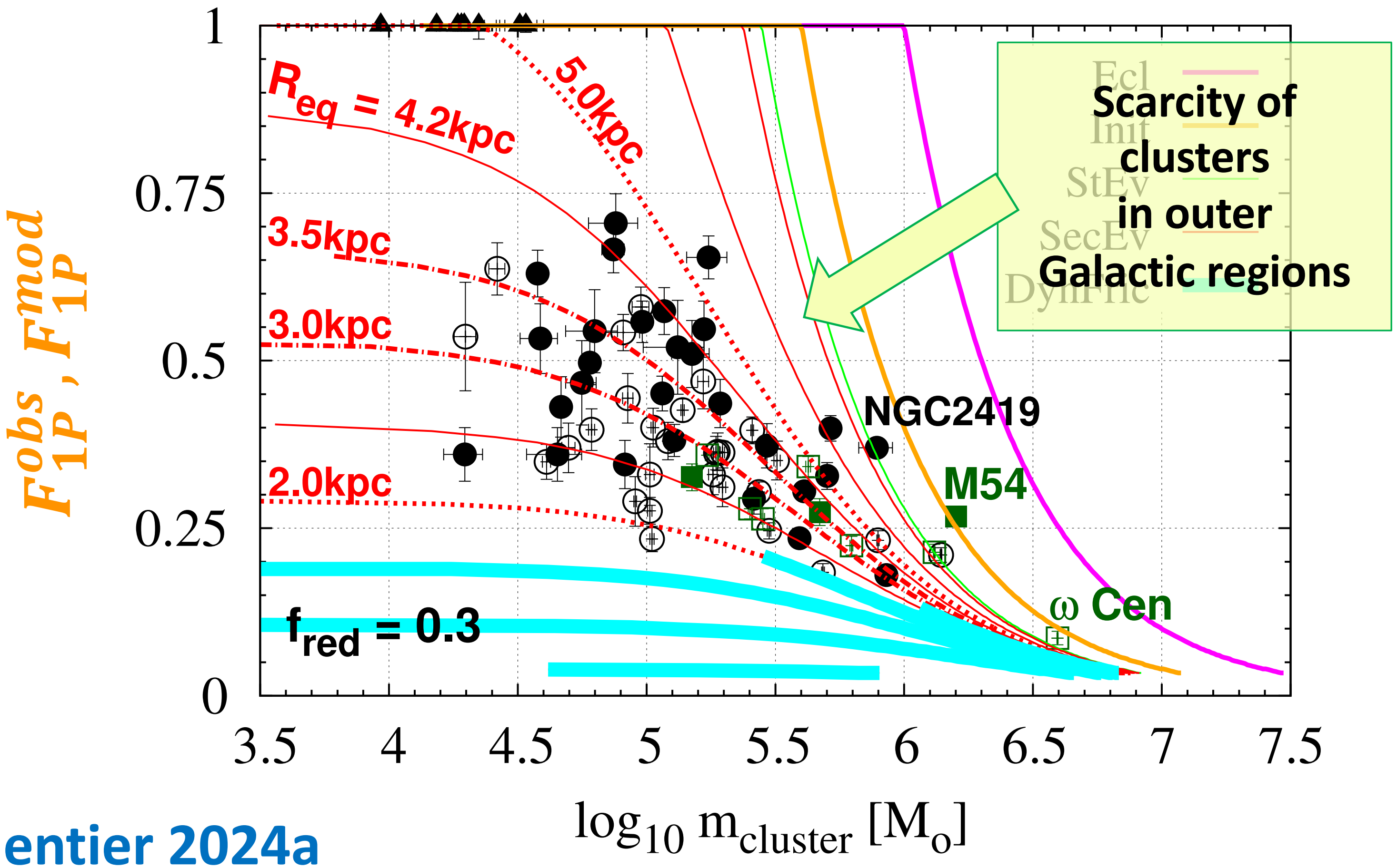

Scarcity of clusters in outer Galactic regions

Fig7 , Parmentier 2024a

Fig1a, Parmentier 2024b

A Sharpened Read of the Data

Destruction by dynamical friction + size-of-sample effect applied to cluster mass spectrum

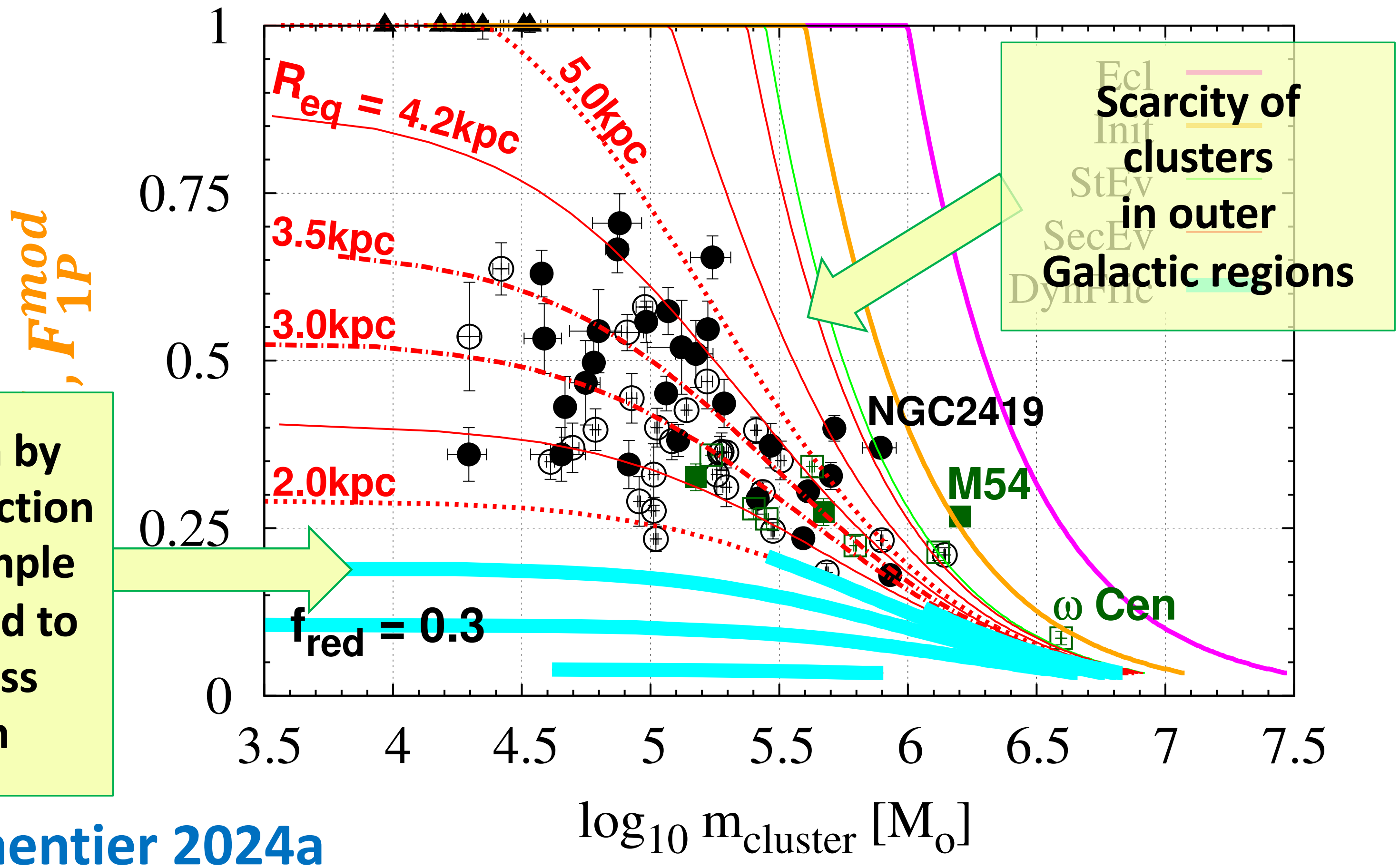

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Fig7 , Parmentier 2024a

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Three Key Hypotheses

I. **A stellar mass threshold for 2P-star formation**

For a cluster to start its self-pollution,
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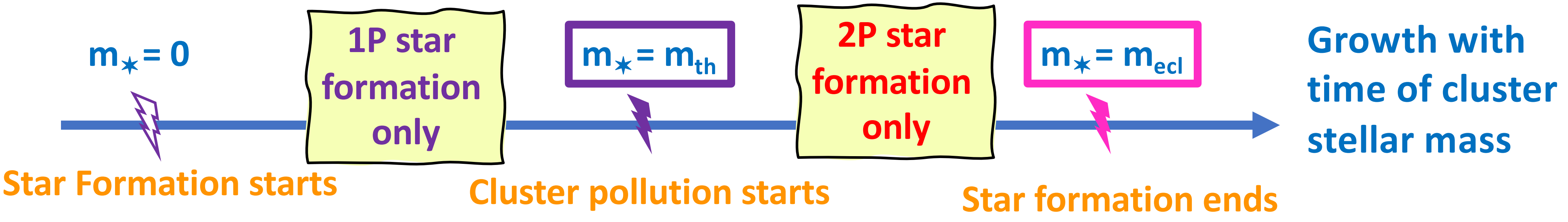
III. **Clusters evolve at constant F_{1P}**

1P and 2P stars form spatially well-mixed;
they are therefore lost equally likely

Step 1 - Cluster Formation → m_{ecl}



$m_\star = 0$

Star Formation starts

1P star formation only

$m_\star = m_{th}$

Cluster pollution starts

2P star formation only

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Star formation ends

Growth with time of cluster stellar mass

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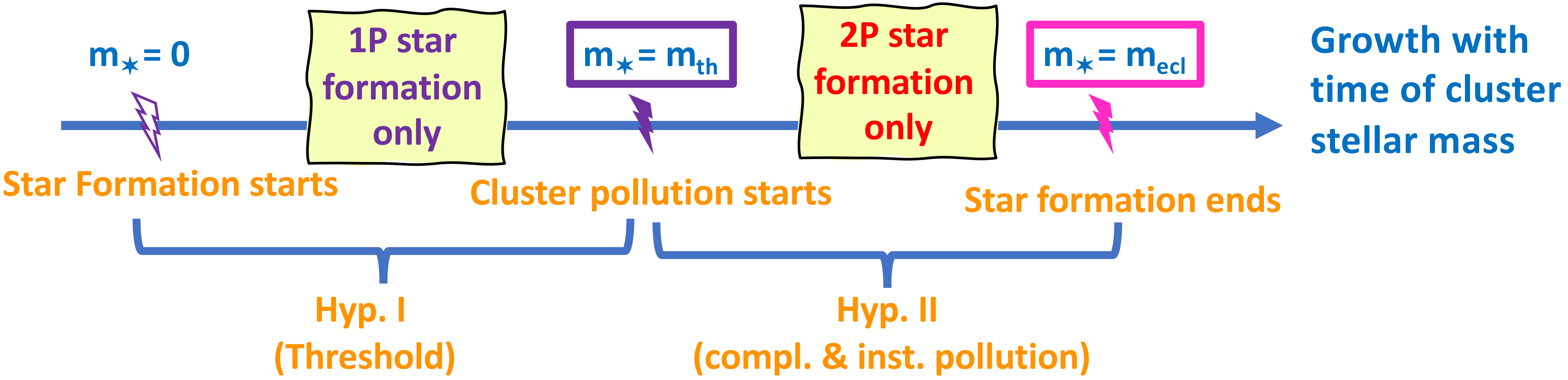

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Hyp. I
(Threshold)

Hyp. II
(compl. & inst. pollution)

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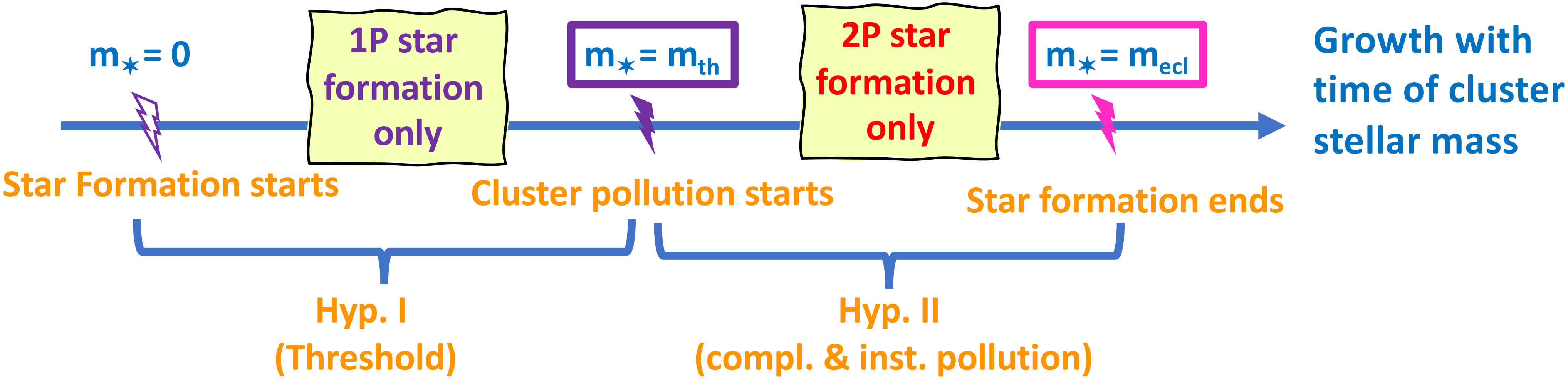

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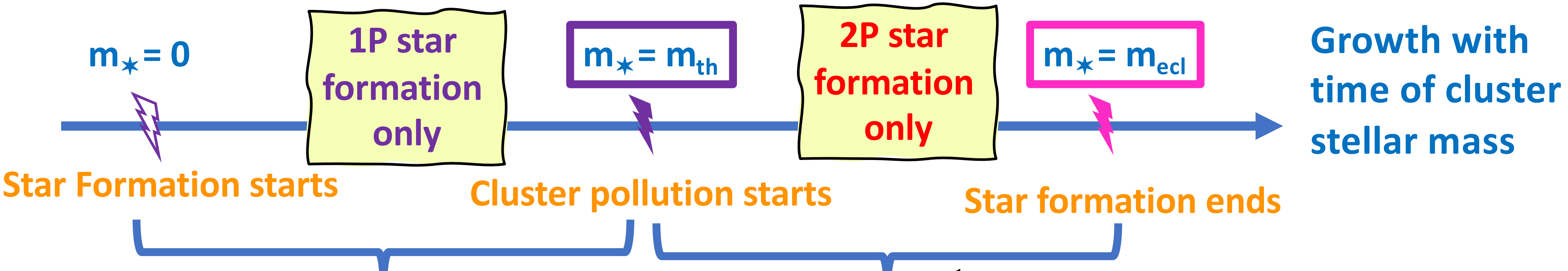

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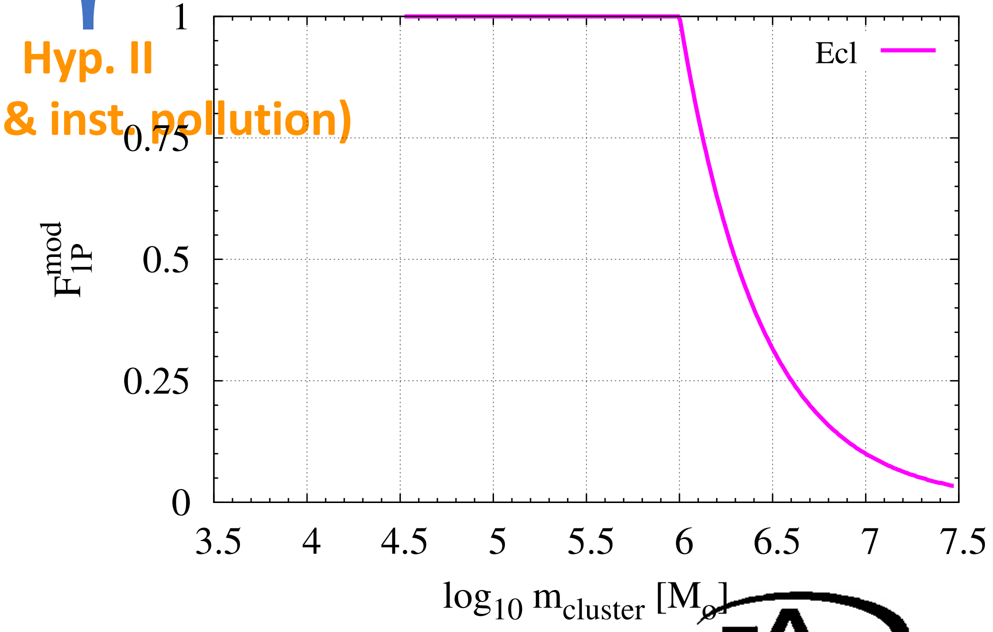

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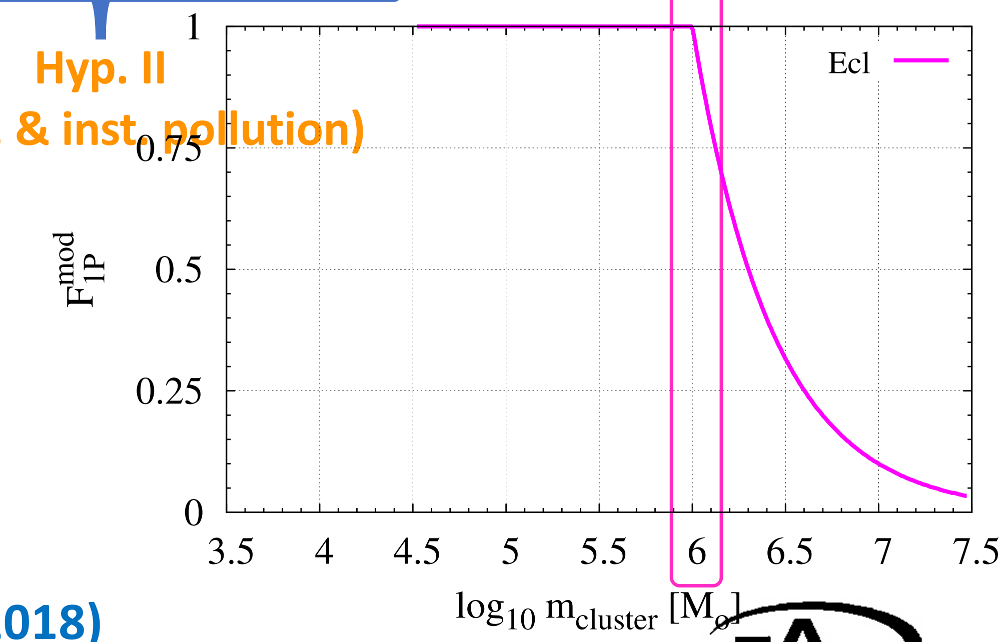
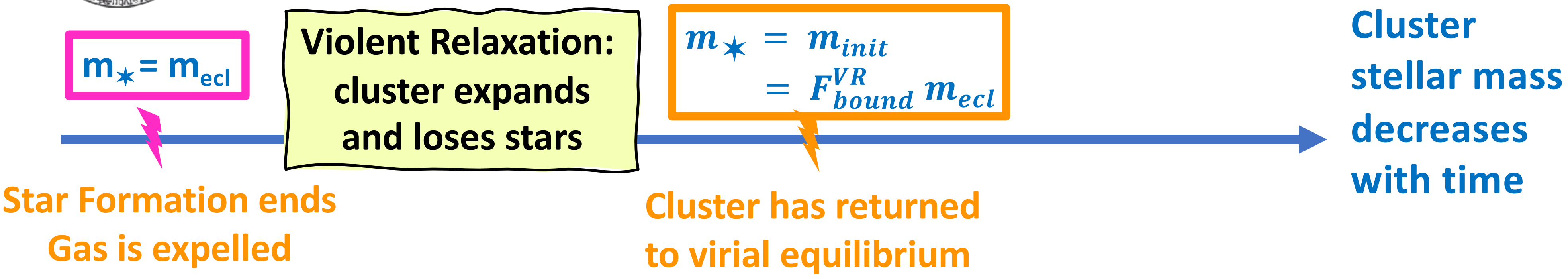
$$F_{1P} = \frac{m_{1P}}{m_{1P} + m_{2P}} = \frac{m_{th}}{m_{ecl}}$$

$$m_{th} = 10^6 M_\odot$$



SMS formation via stellar collisions (Gieles+ 2018)

Step 2 – Violent Relaxation Following Gas Expulsion → m_{init}



$m_\star = m_{ecl}$

Star Formation ends
Gas is expelled

Violent Relaxation:
cluster expands
and loses stars

$$m_\star = m_{init} = F^{VR}_{bound}\, m_{ecl}$$

Cluster has returned
to virial equilibrium

Cluster
stellar mass
decreases
with time

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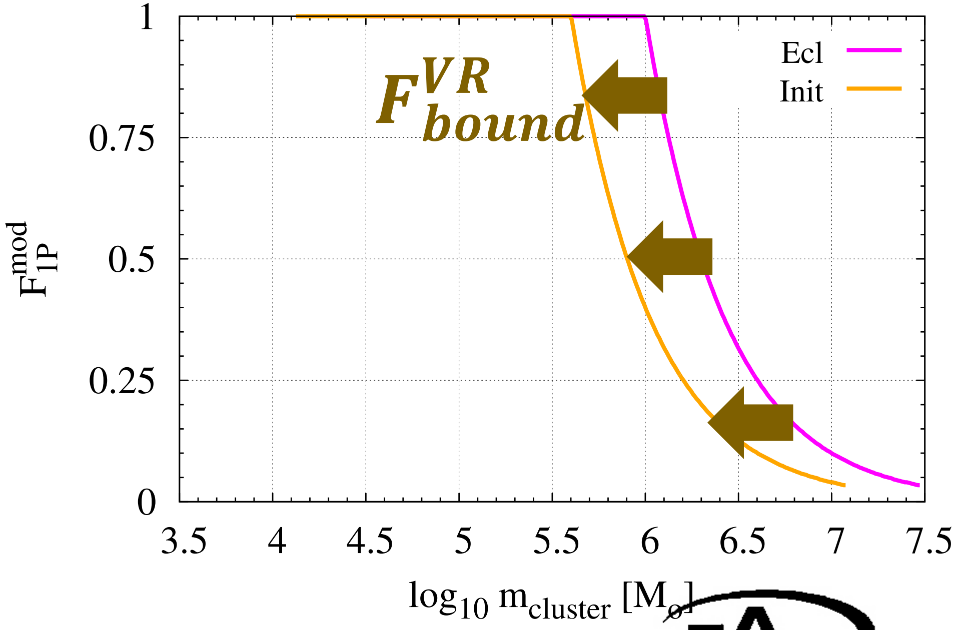

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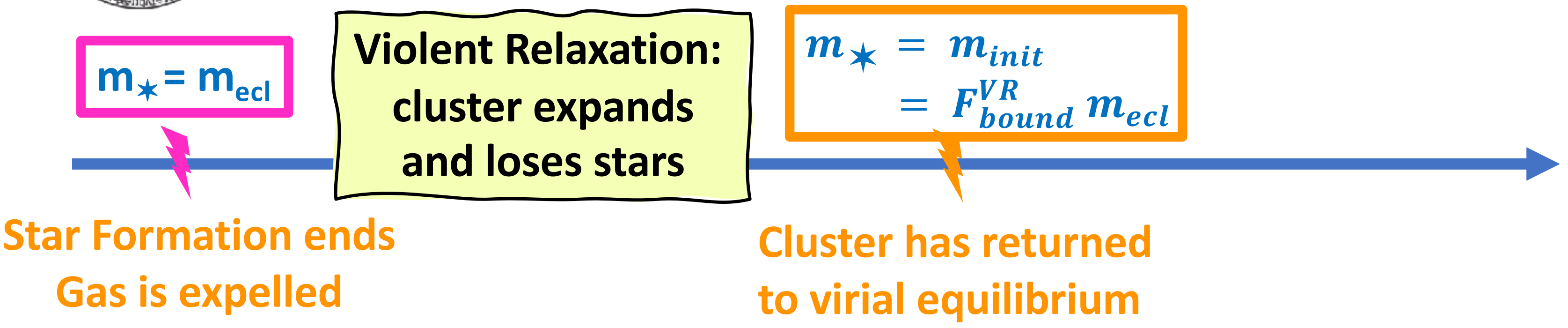

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Violent Relaxation: cluster expands and loses stars

$$\begin{aligned} m_{\star} &= m_{init} \\ &= F^{VR}_{bound}\, m_{ecl} \end{aligned}$$

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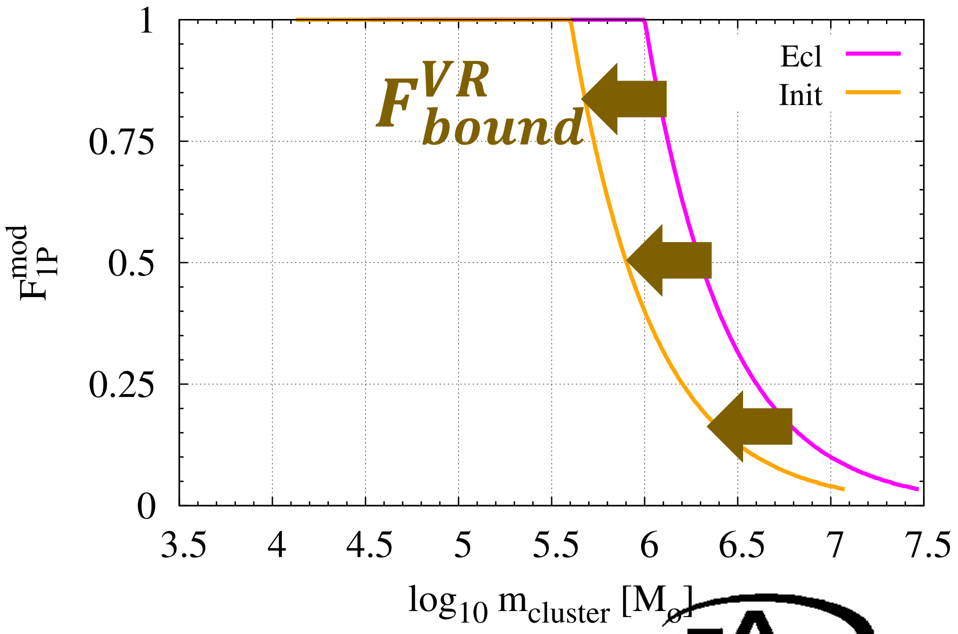

$$m_{init} = F^{VR}_{bound}\, m_{ecl}$$
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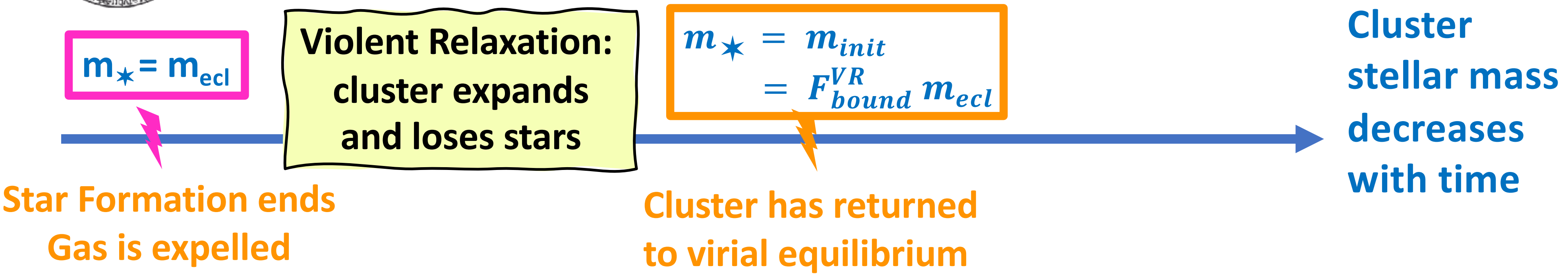

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a. Hyp. III: 1P and 2P stars spatially well-mixed at formation
→ Evolution with F_{1P} = constant

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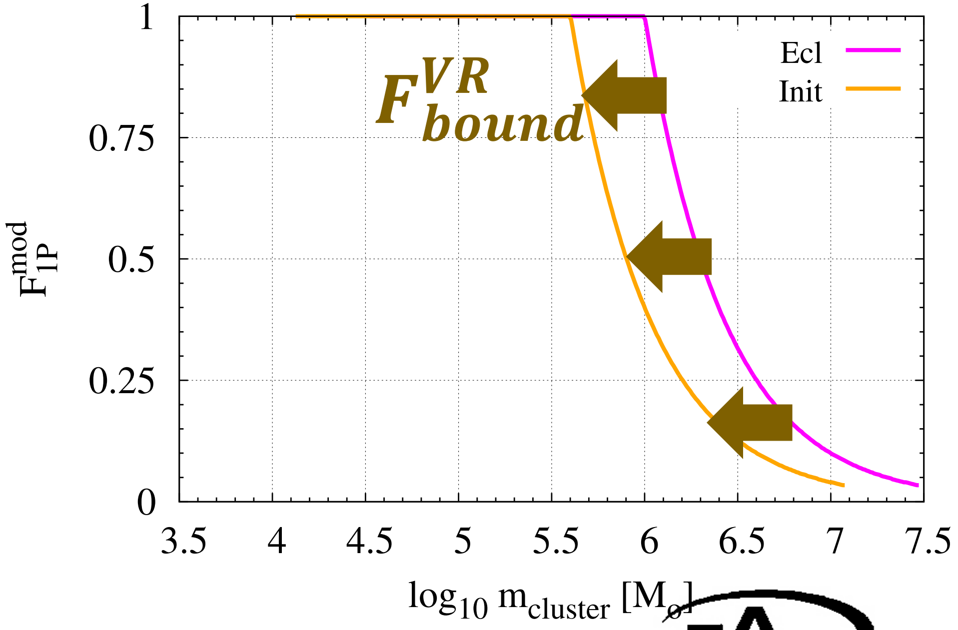

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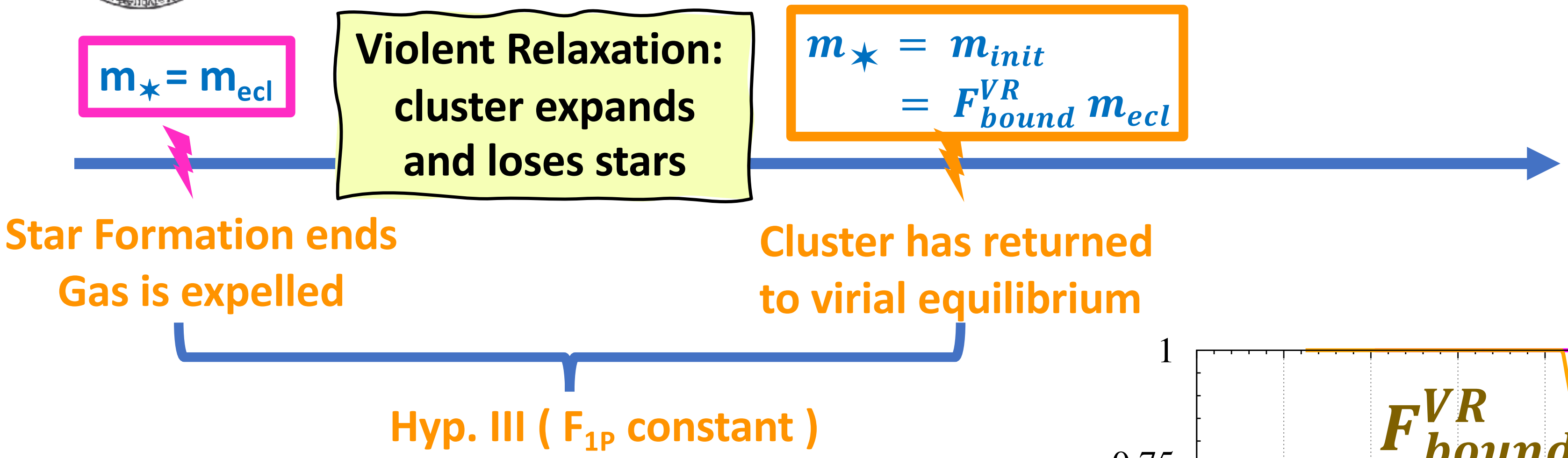

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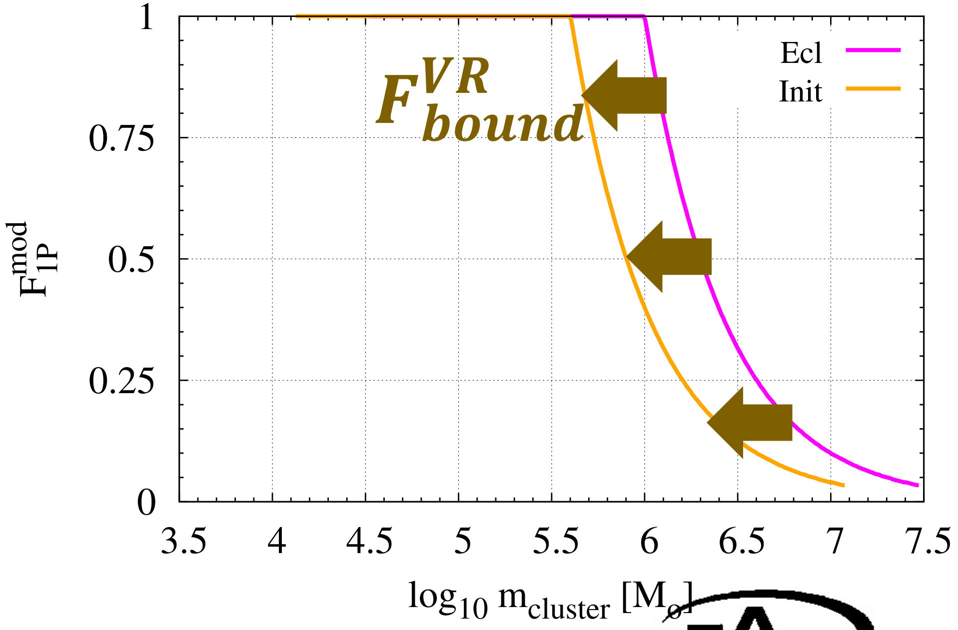
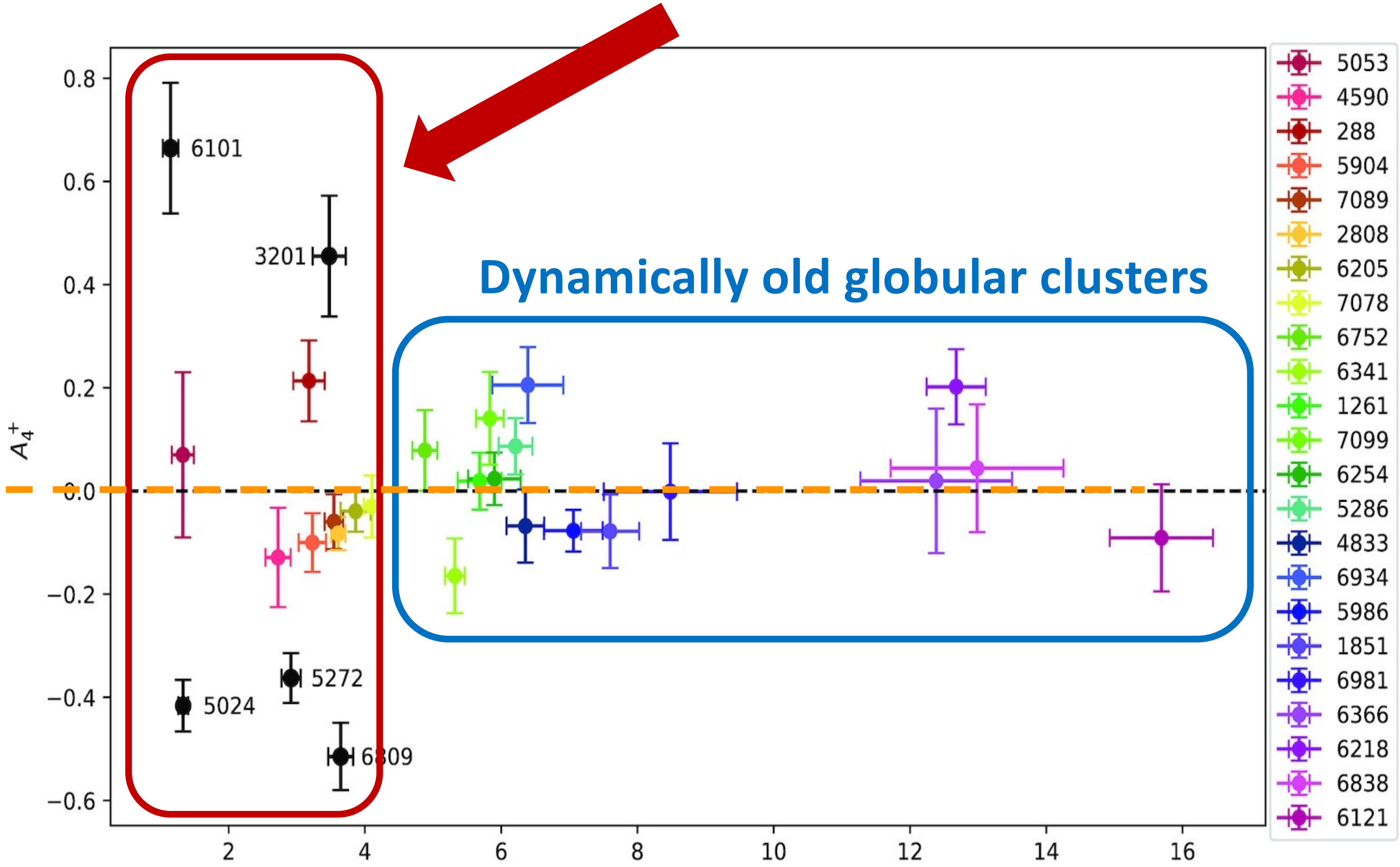


Evolution with F_{1P} = constant (Hyp. III)
Insights from Dynamically Young Globular Clusters



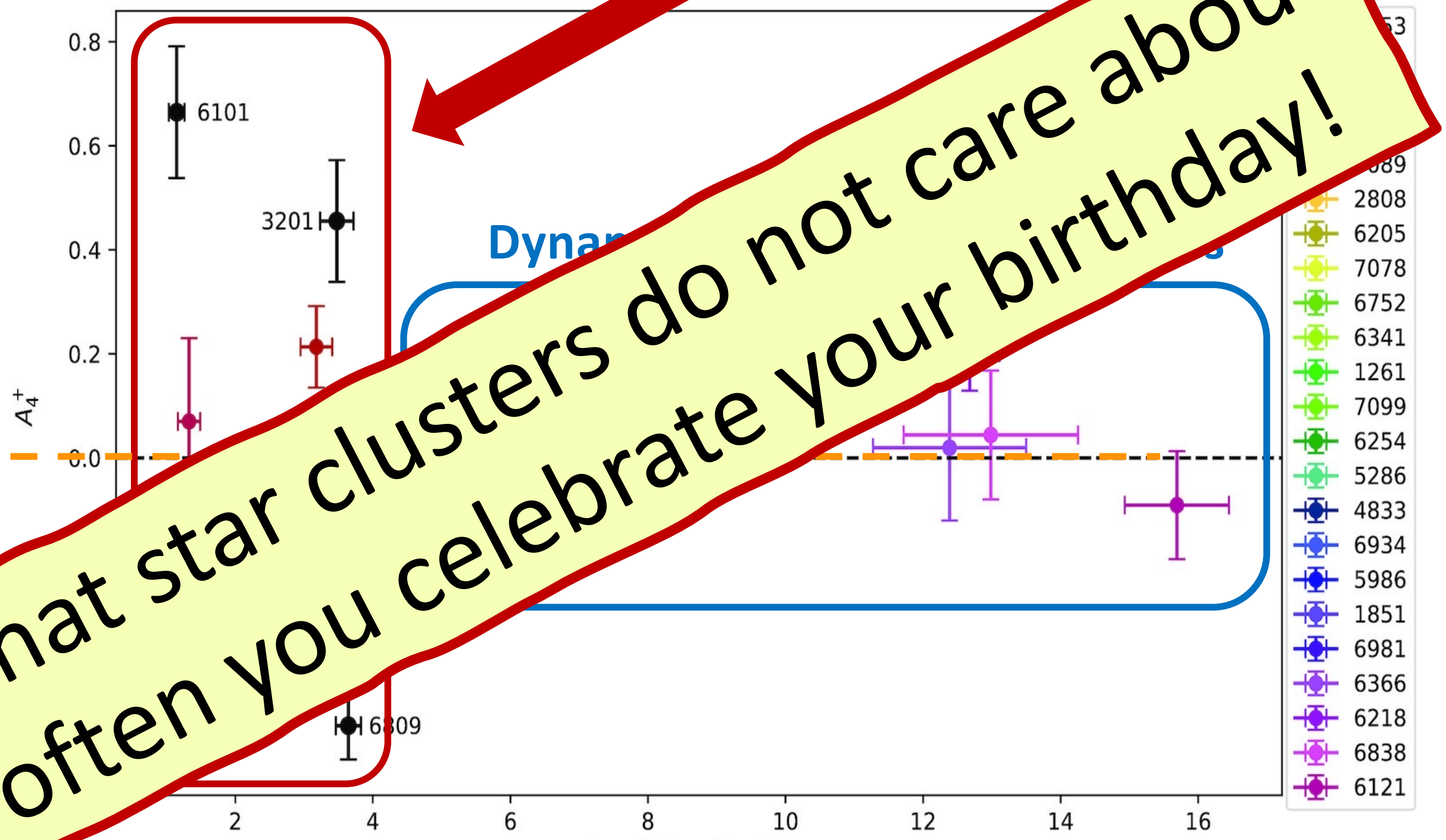
Dynamically old globular clusters

Age / Relaxation Time

Fig15, Leitinger+2023

Evolution with F_{1P} = constant (Hyp. III)

Insights from Dynamically Young Globular Clu s



Recall that star clusters do not care about how often you celebrate your birthday!

Fig15 2023

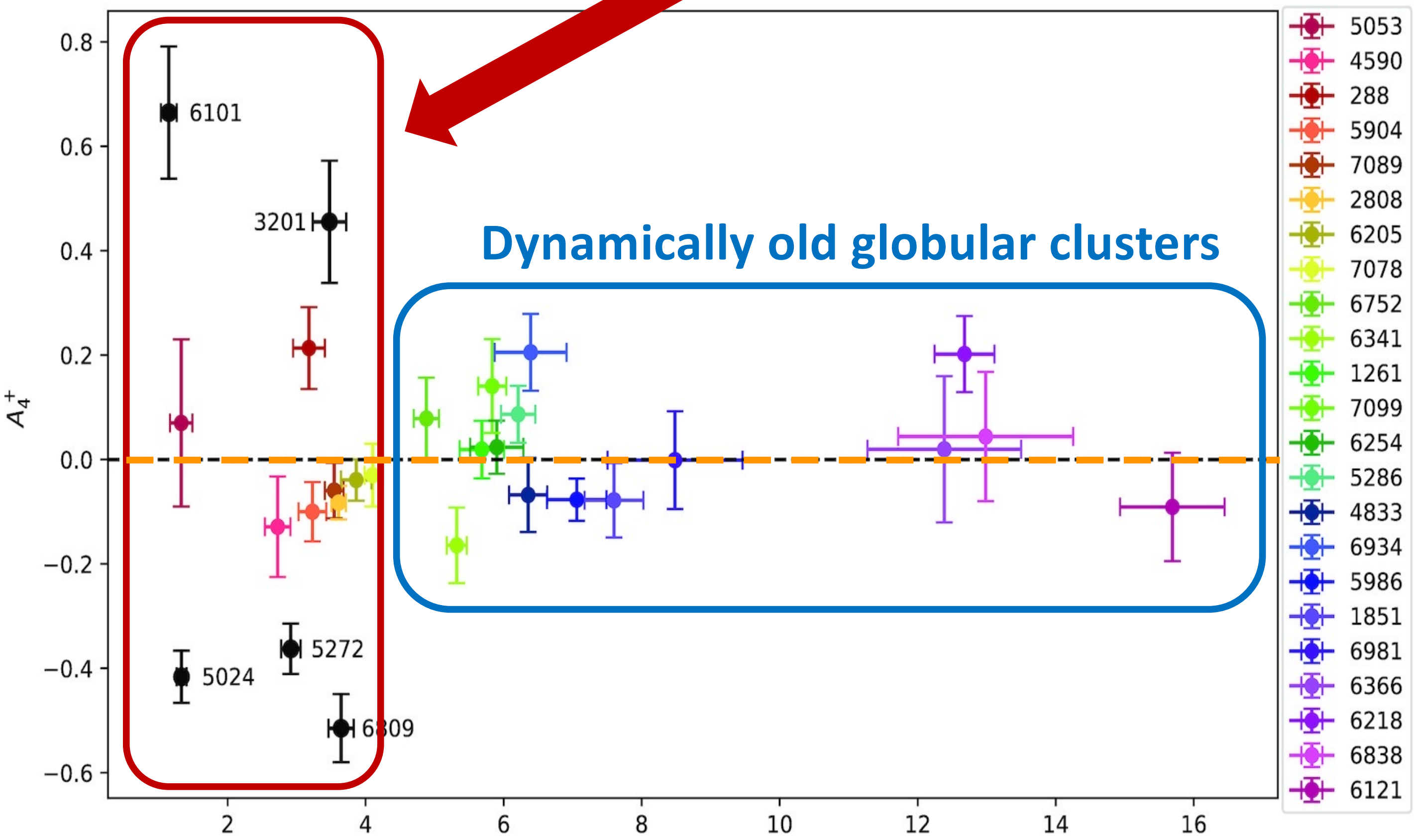
Age / Relaxation Time

Evolution with F_{1P} = constant (Hyp. III)
Insights from Dynamically Young Globular Clusters

Outer 2P stars:
F_{1P} ↗ with time

Well-mixed
1P and 2P stars

Outer 1P stars:
F_{1P} ↘ with time



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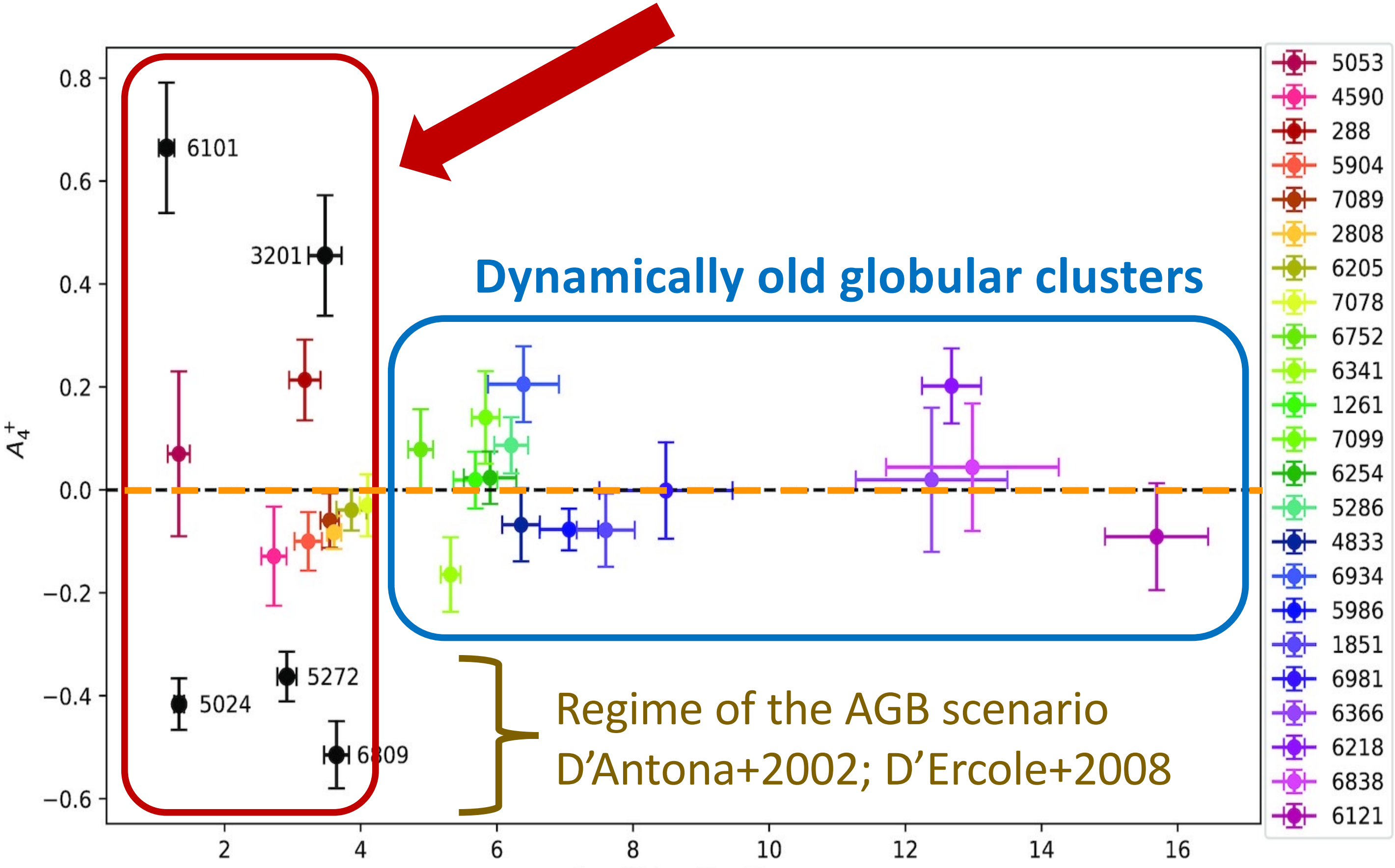

Dynamically old globular clusters

Regime of the AGB scenario
D'Antona+2002; D'Ercole+2008

Age / Relaxation Time

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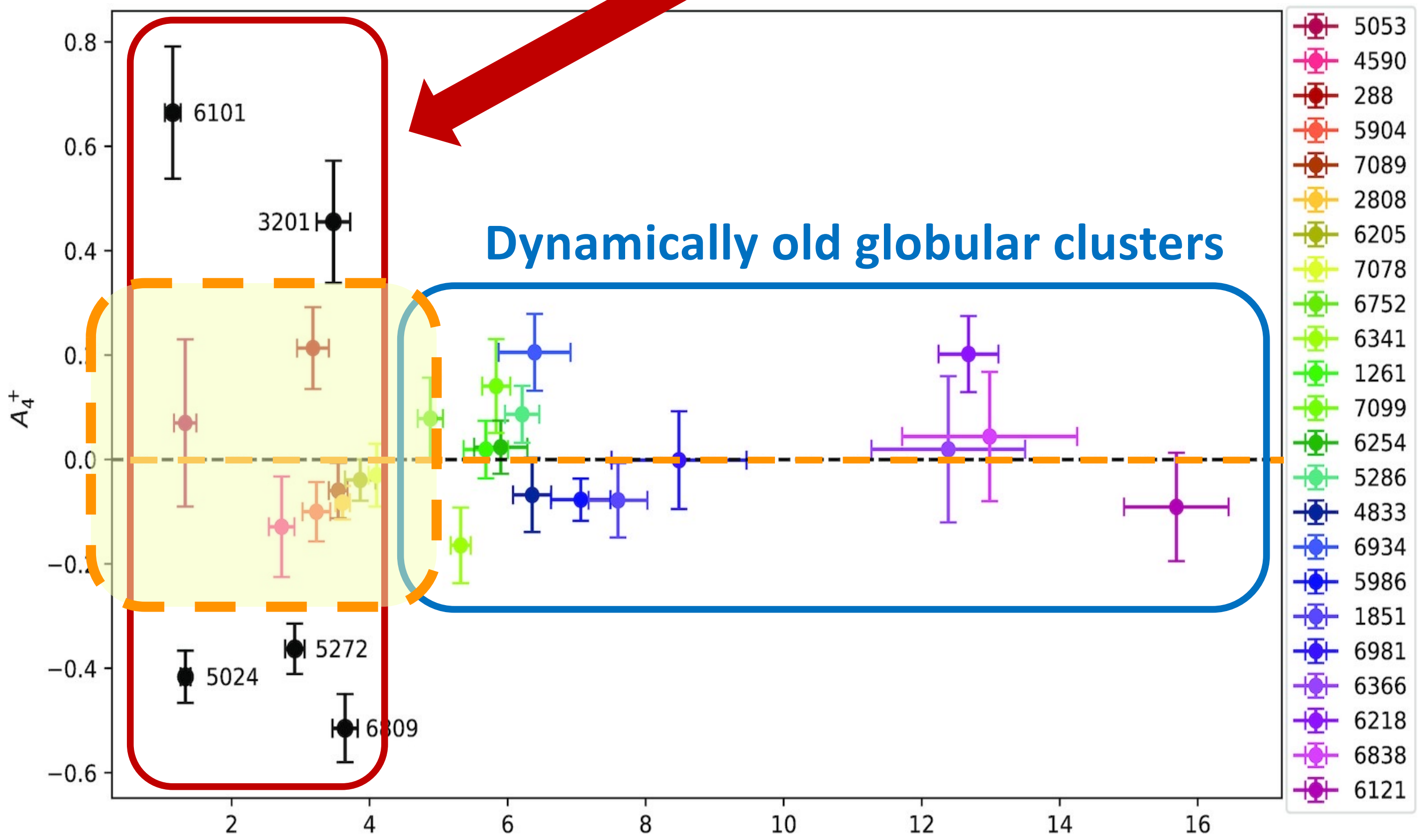

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Step 2 – Violent Relaxation Following Gas Expulsion → m_{init}

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Violent Relaxation: cluster expands and loses stars

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Cluster stellar mass decreases with time

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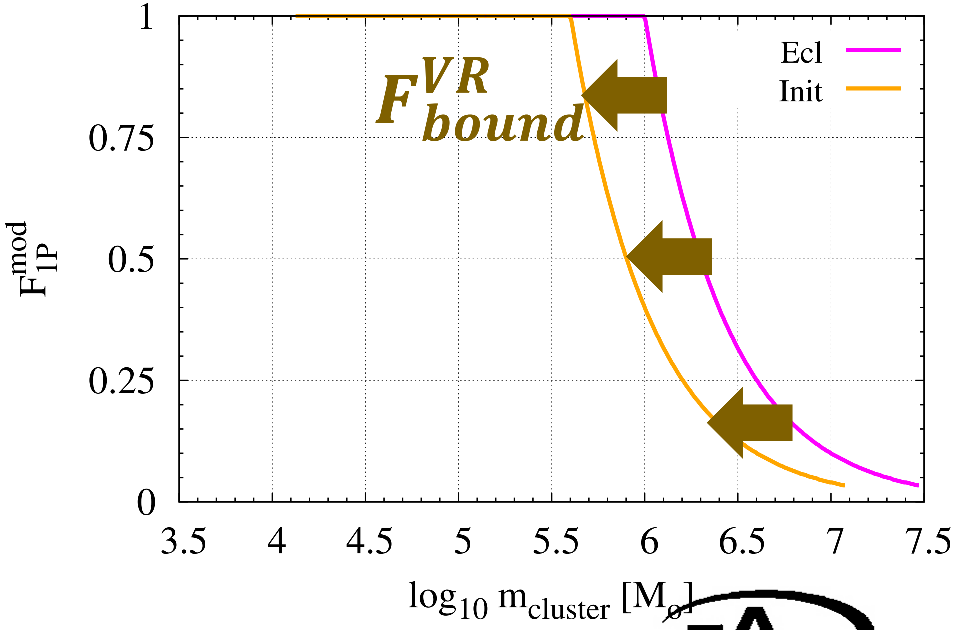

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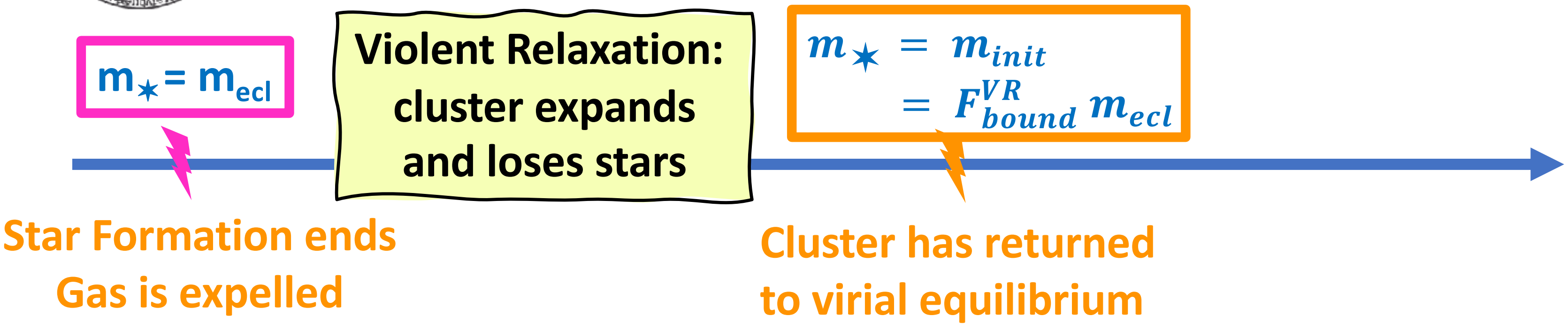

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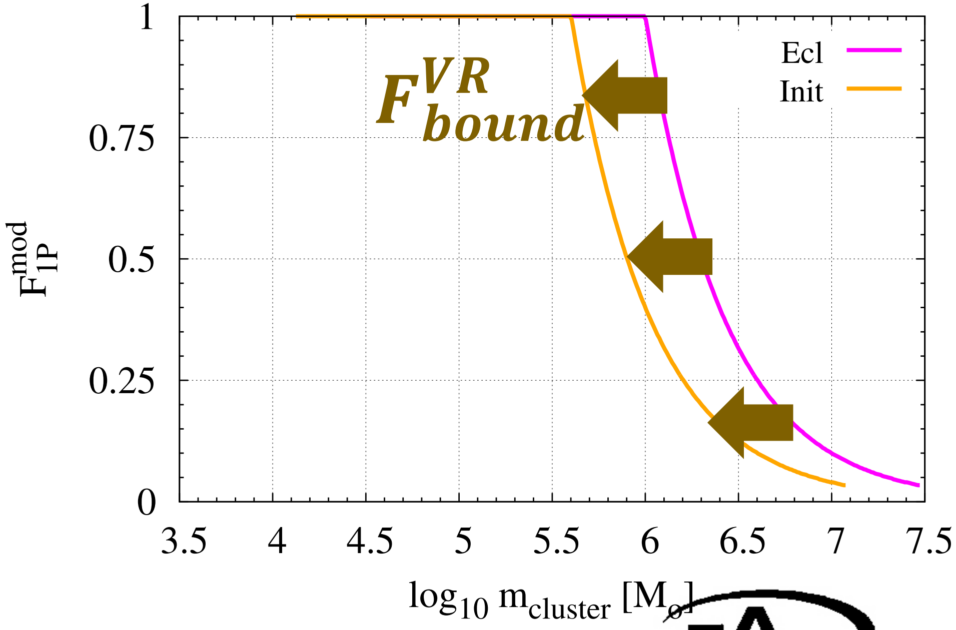

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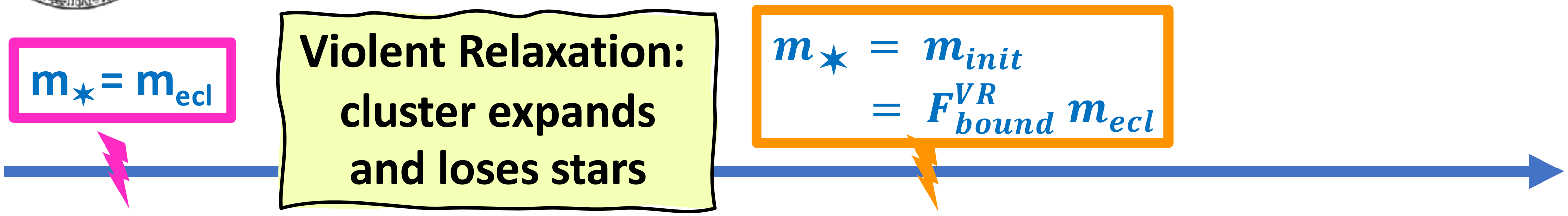

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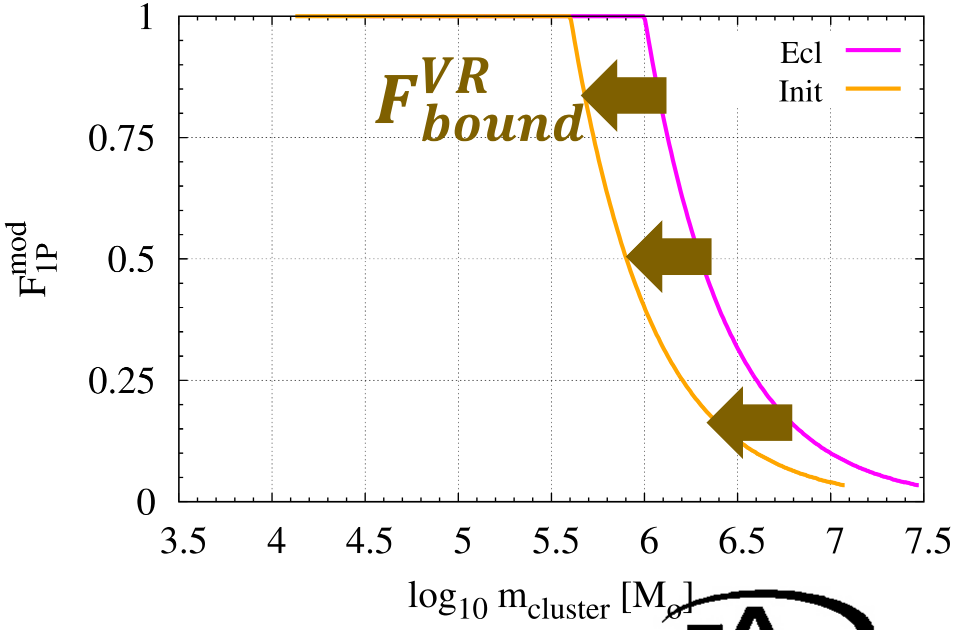
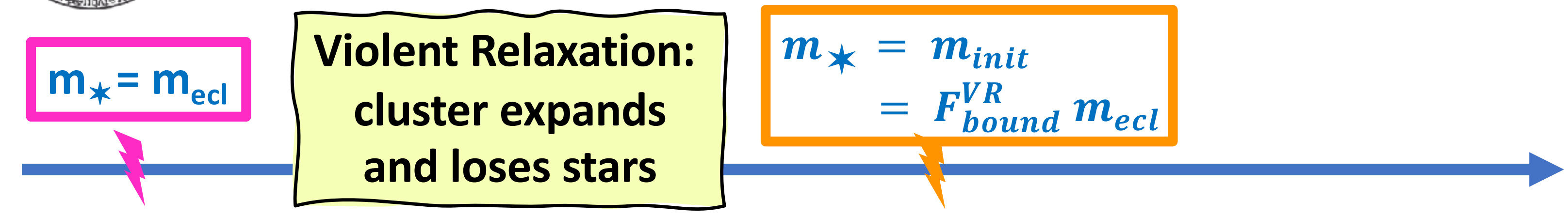
- F^{VR}_{bound} more robust to the tidal field impact than thought in the past (Shukirgaliyev, Parmentier+2019)
- Could violent relaxation be a non-event for newly formed compact massive clusters?
  If SFE → 1 (Polak+2023),
  F^{VR}_{bound} → 1



Step 2+ – Anchoring the Initial Track



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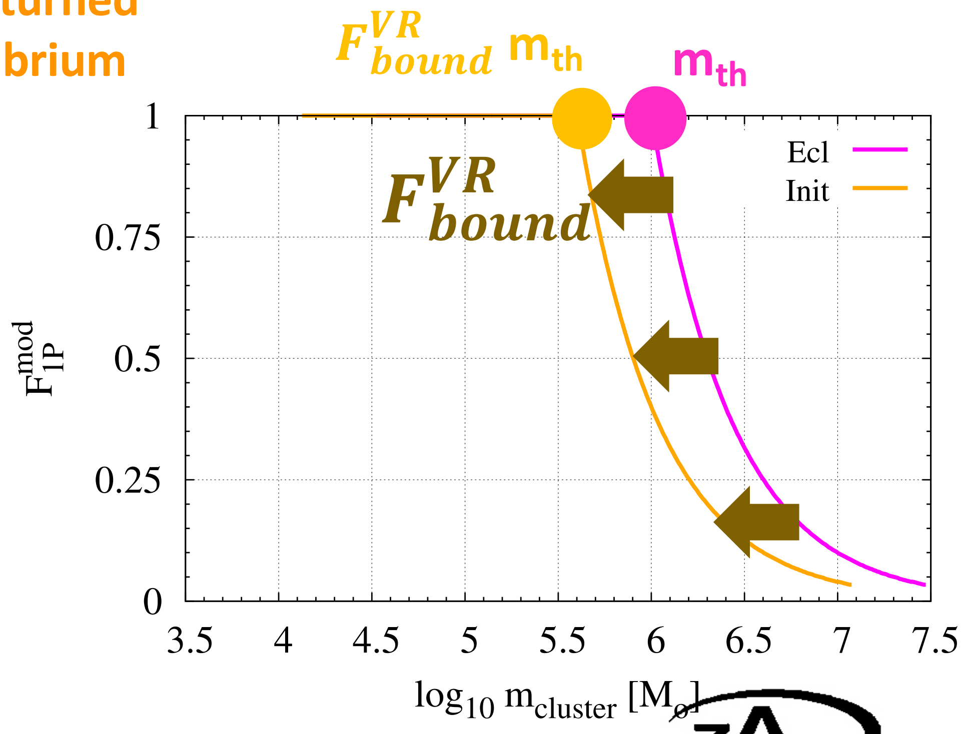
- Neither m_{th} nor F^{VR}_{bound} are well-constrained (if at all!)
- How to „anchor" the initial track ?



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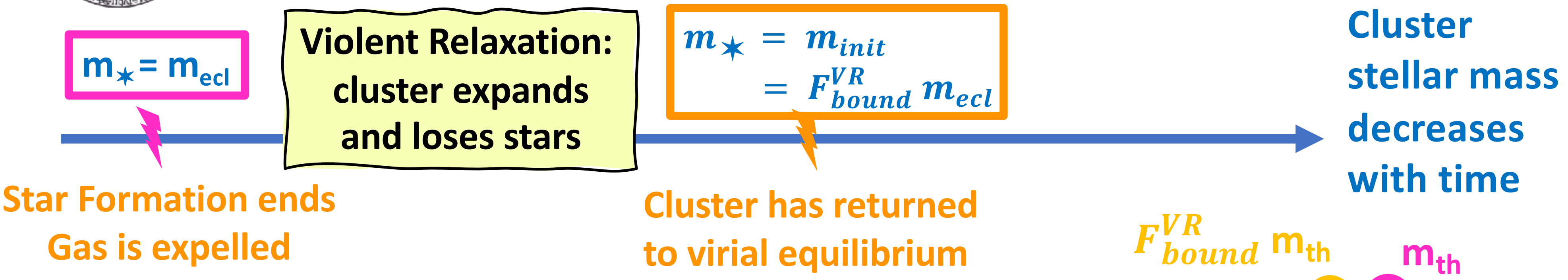

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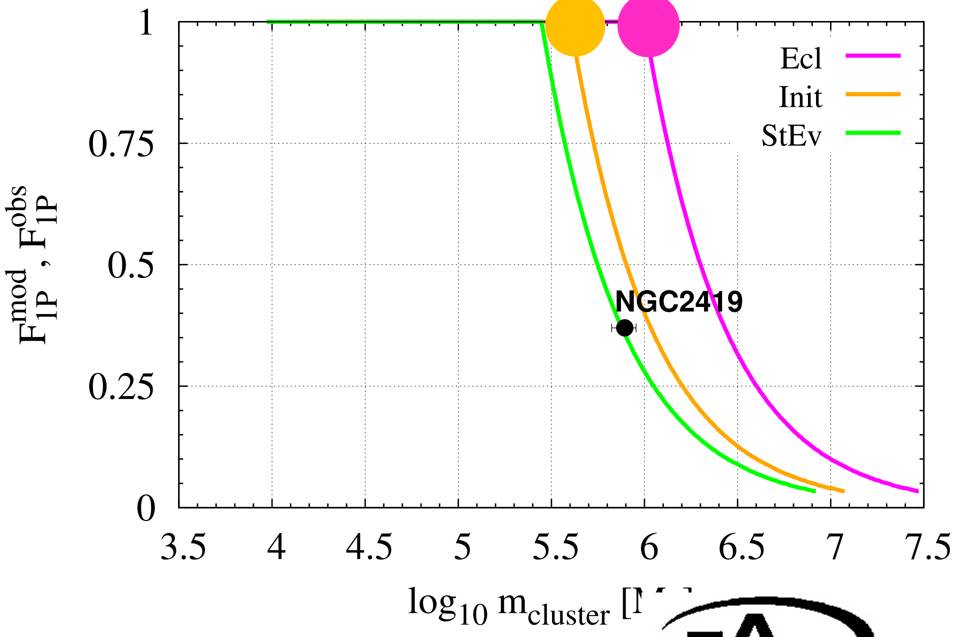
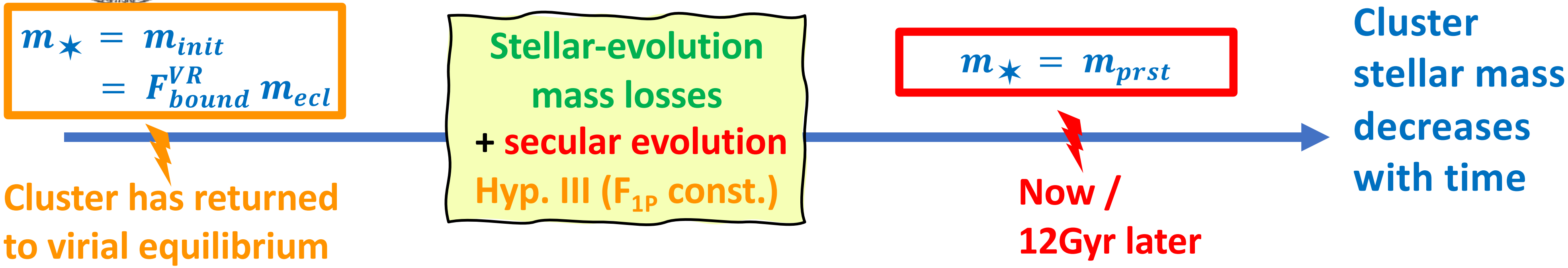
- Neither m_{th} nor F^{VR}_{bound} are well-constrained (if at all!)
- How to „anchor“ the initial track ?
- With NGC2419, a globular cluster that is both remote and massive
- We may know neither m_{th} nor F^{VR}_{bound} , but at least we know $F_{StEv}F^{VR}_{bound}$ m_{th}



Step 3 – Secular Evolution → m_{prst}



$$m_\star = m_{init}$$
$$= F^{VR}_{bound}\, m_{ecl}$$

Cluster has returned to virial equilibrium

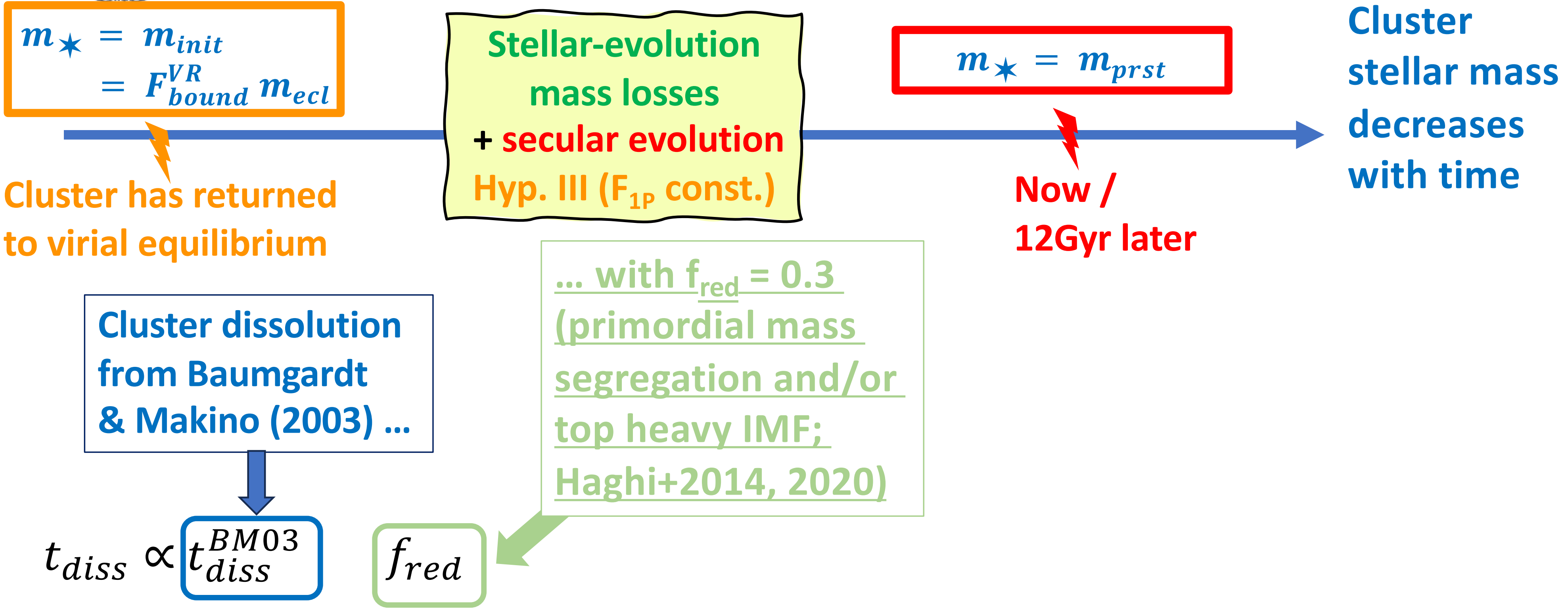
Stellar-evolution mass losses
+ secular evolution
Hyp. III (F_{1P} const.)

$$m_\star = m_{prst}$$

Now / 12Gyr later

Cluster stellar mass decreases with time

Step 3 – Secular Evolution → $\mathrm{m_{prst}}$



$$m_\star = m_{init} = F_{bound}^{VR}\, m_{ecl}$$

Cluster has returned to virial equilibrium

Stellar-evolution mass losses

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Now / 12Gyr later

Cluster stellar mass decreases with time

Cluster dissolution from Baumgardt & Makino (2003) …

$$t_{diss} \propto \boxed{t_{diss}^{BM03}}$$

… with $f_{red} = 0.3$ (primordial mass segregation and/or top heavy IMF; Haghi+2014, 2020)

$$\boxed{f_{red}}$$

Step 3 – Secular Evolution → m_{prst}

$$\boxed{\begin{aligned} m_\star &= m_{init} \\ &= F_{bound}^{VR}\, m_{ecl} \end{aligned}}$$

Cluster has returned to virial equilibrium

Stellar-evolution mass losses
+ secular evolution
Hyp. III (F_{1P} const.)

$$\boxed{m_\star = m_{prst}}$$

Now / 12Gyr later

Cluster stellar mass decreases with time

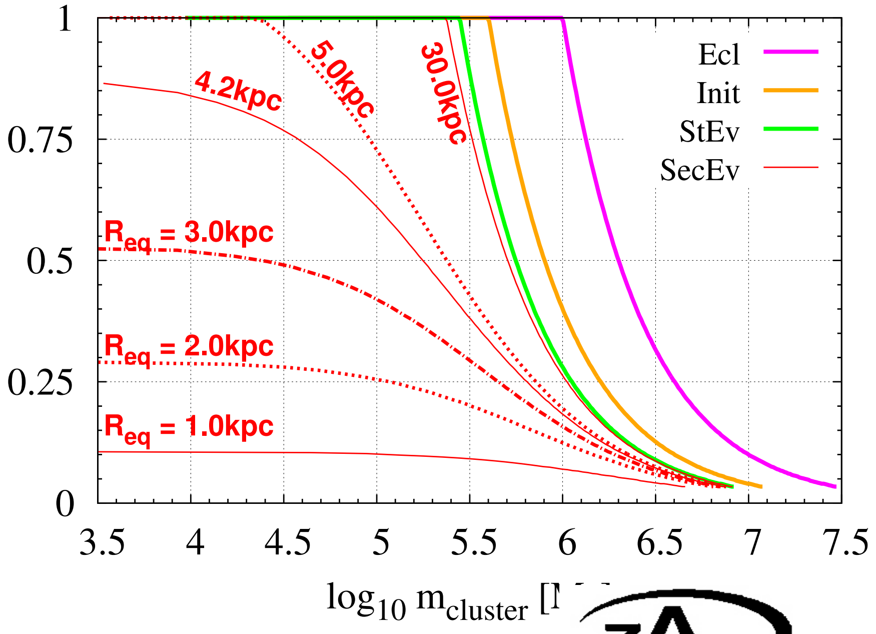
Cluster dissolution from Baumgardt & Makino (2003) …

… with f_{red} = 0.3 (primordial mass segregation and/or top heavy IMF; Haghi+2014, 2020)

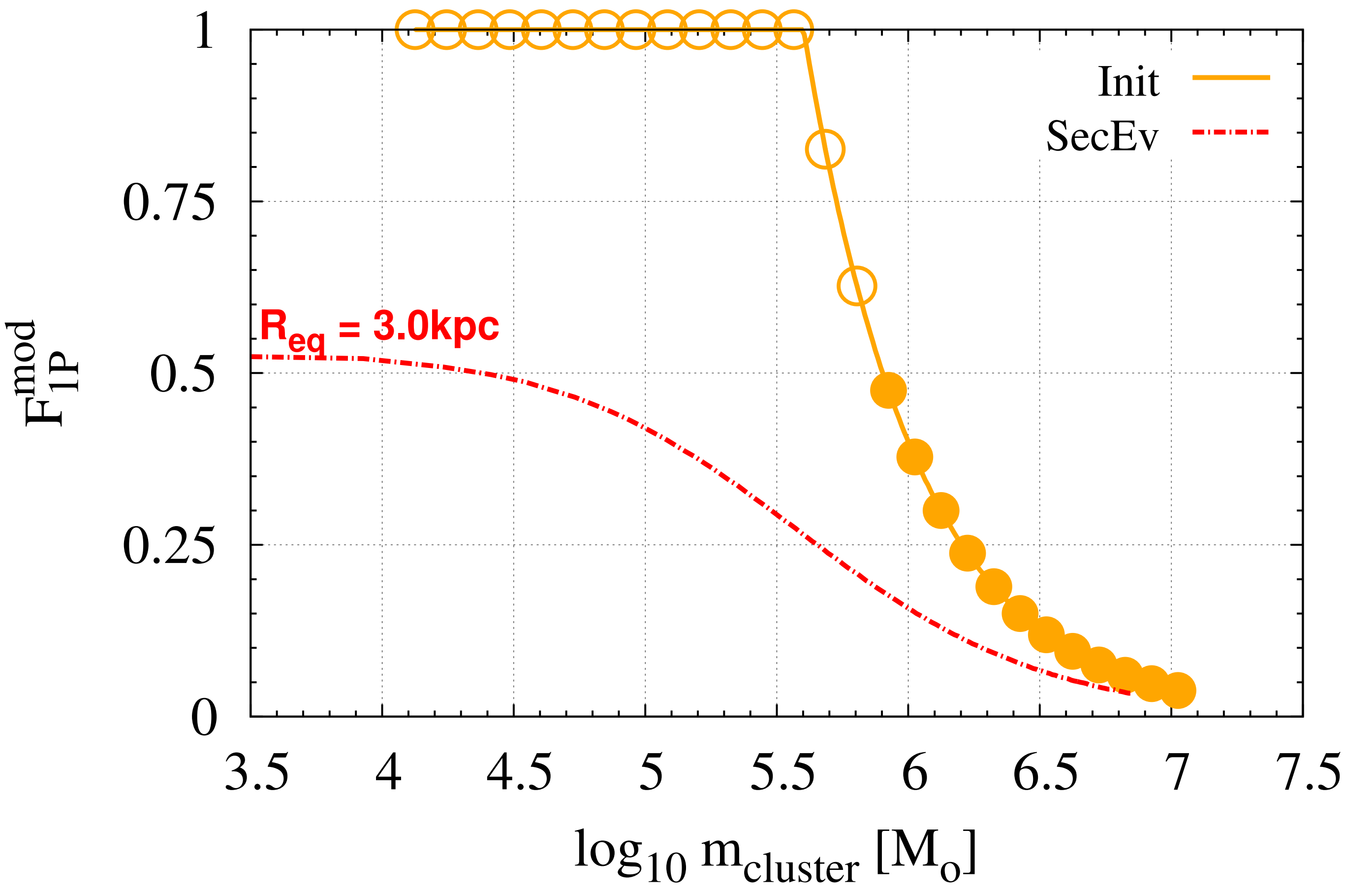
R_{eq}

$$t_{diss} \propto \boxed{t_{diss}^{BM03}} \quad \boxed{f_{red}}$$

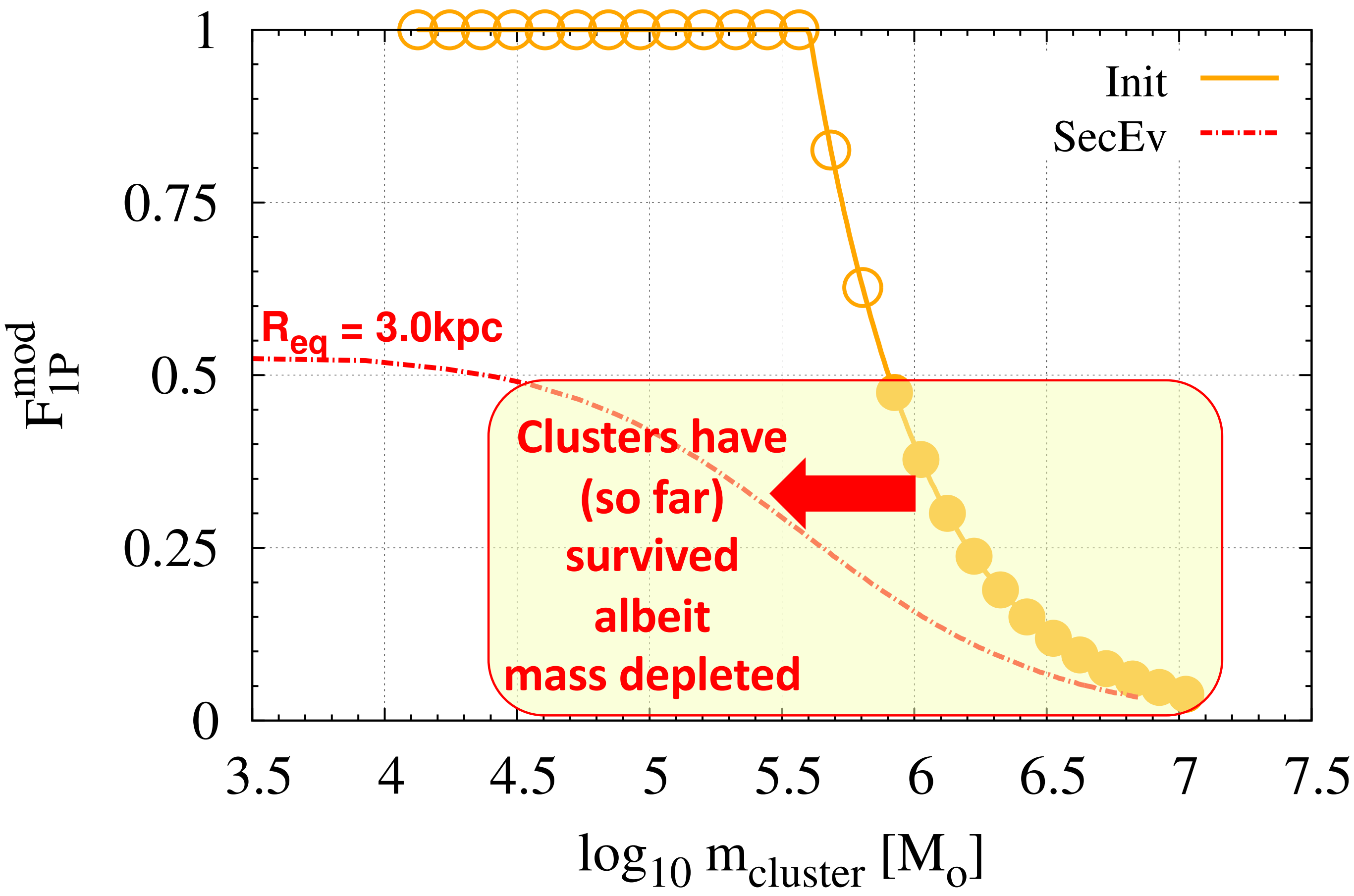
$$\propto \underline{f(m_{init}, x, \beta)\,\frac{\boxed{(1-e)D_{apo}}}{V_c}} \cdot \boxed{f_{red}}$$



Step 3 – Secular Evolution → m_{prst}

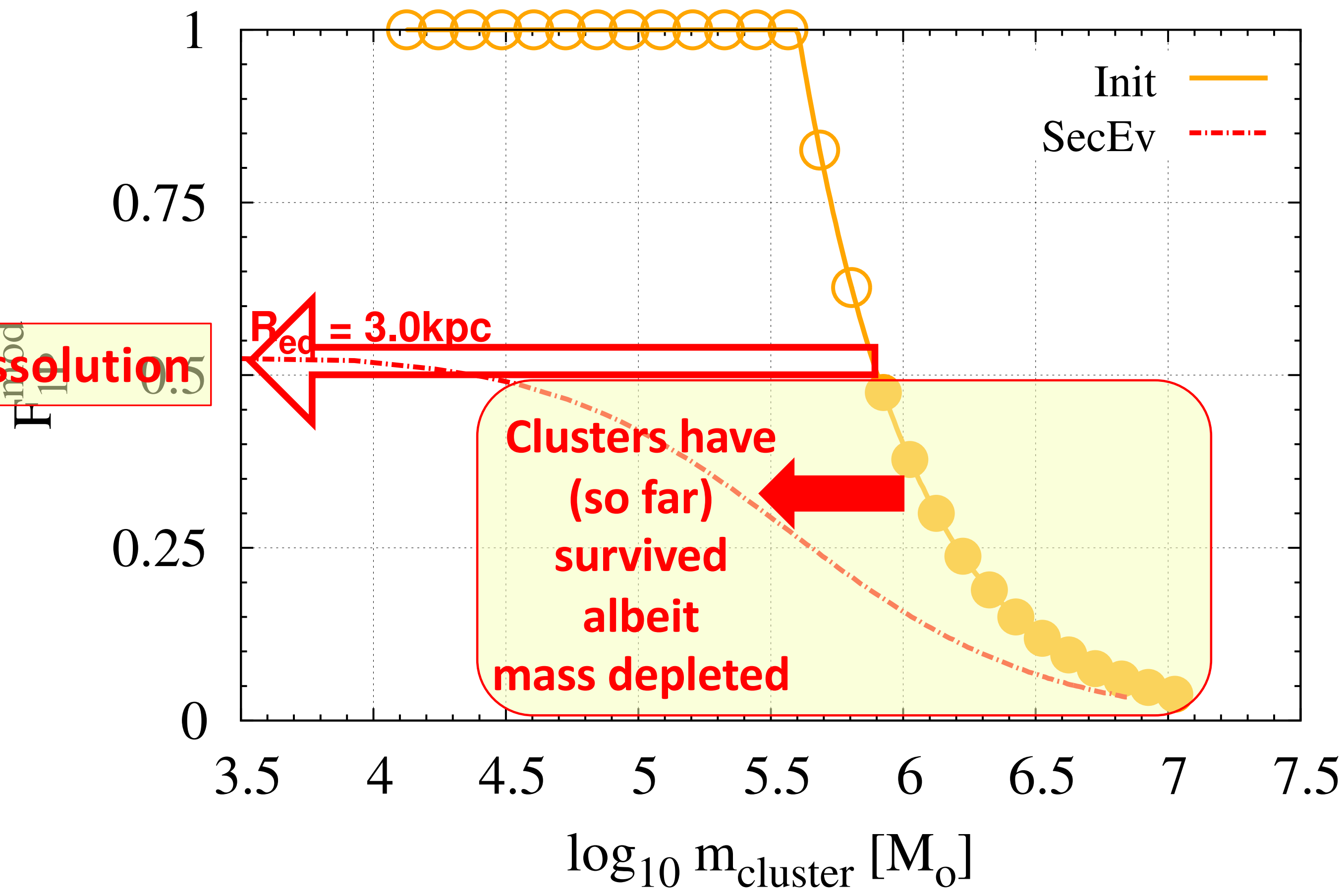


Step 3 – Secular Evolution → m_{prst}



Clusters have (so far) survived albeit mass depleted

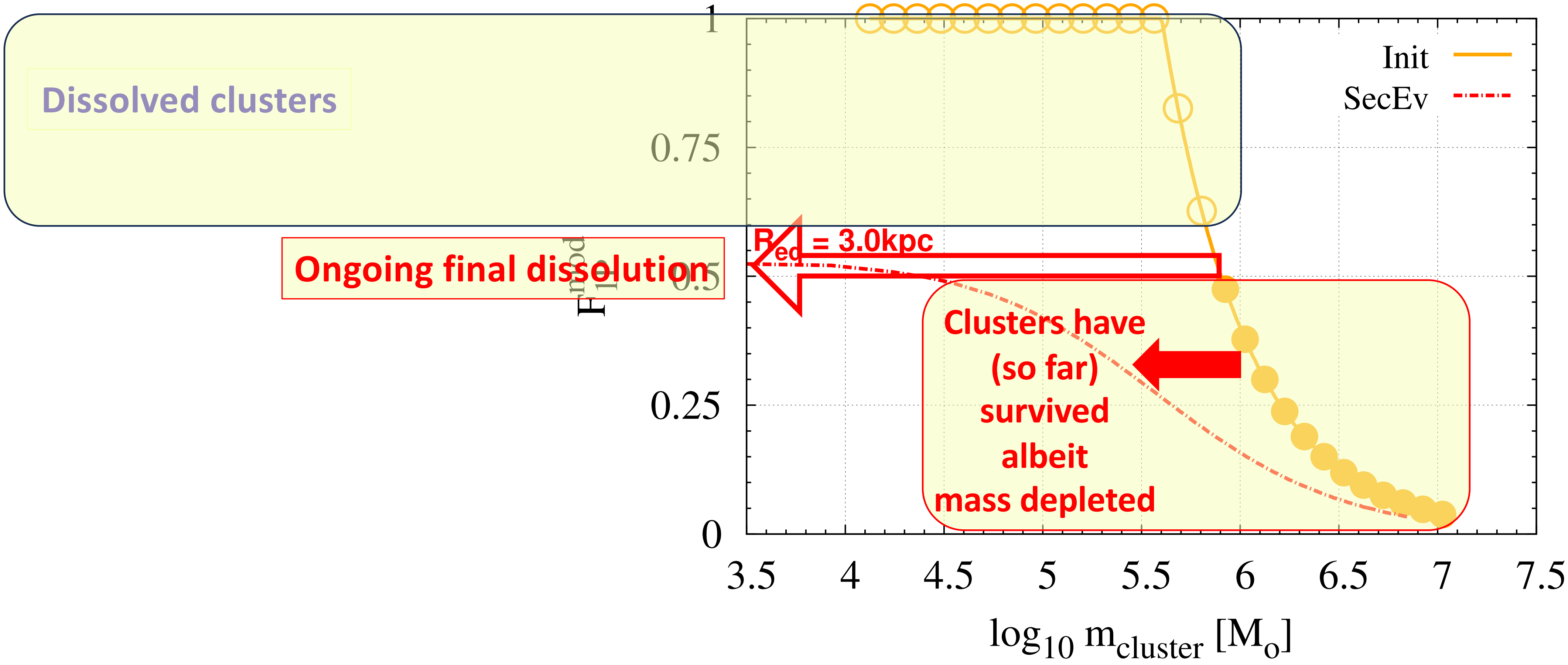
Step 3 – Secular Evolution → m_{prst}



Ongoing final dissolution

Clusters have (so far) survived albeit mass depleted

Step 3 – Secular Evolution → m_{prst}



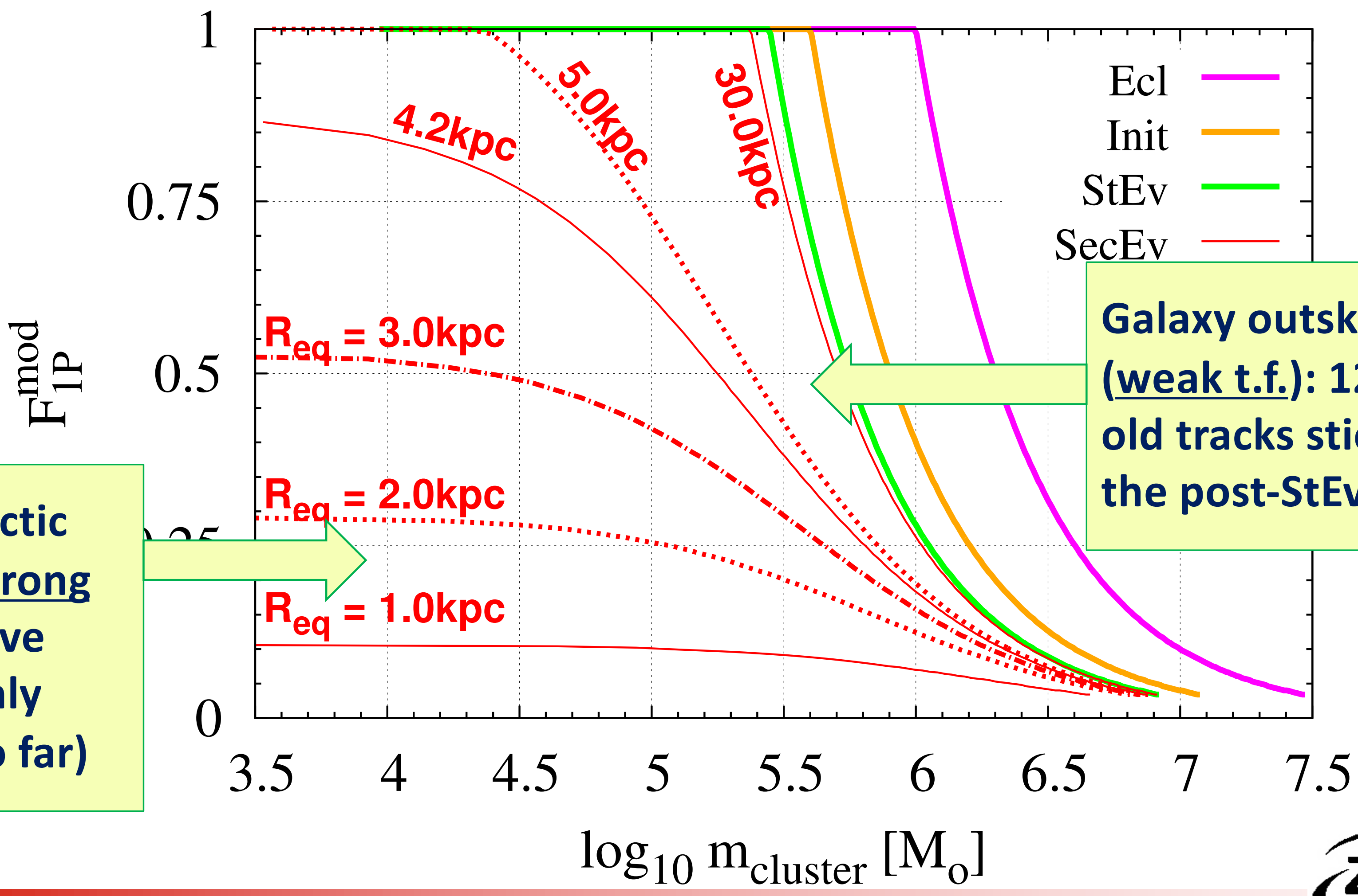
Dissolved clusters

Ongoing final dissolution

R_{ed} = 3.0kpc

Clusters have (so far) survived albeit mass depleted

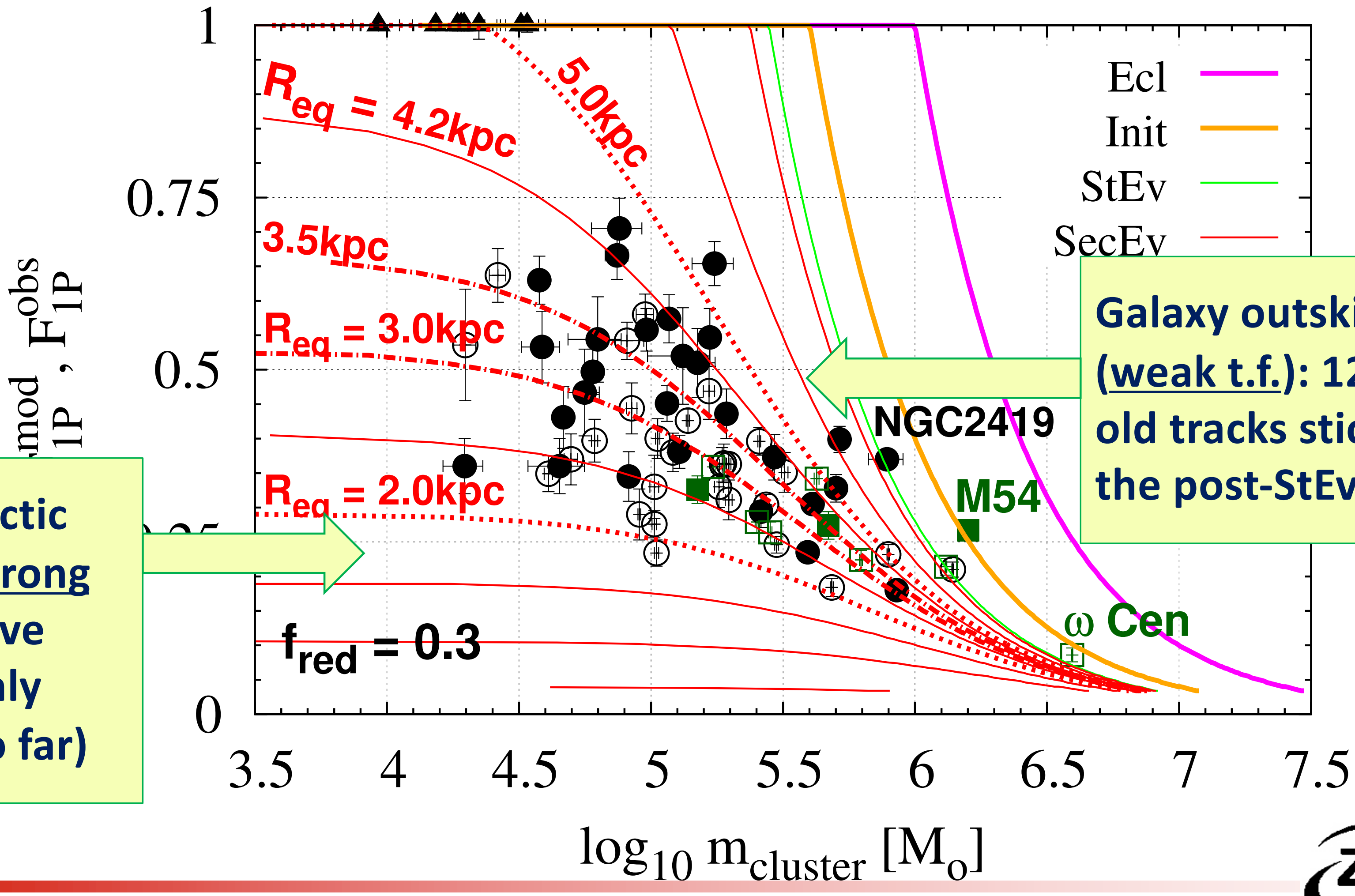
Step 3 – Secular Evolution – Two Extreme Behaviors



Galaxy outskirts (<u>weak t.f.</u>): 12Gyr-old tracks stick to the post-StEv track

Inner Galactic regions (<u>strong t.f.</u>): massive clusters only survive (so far)

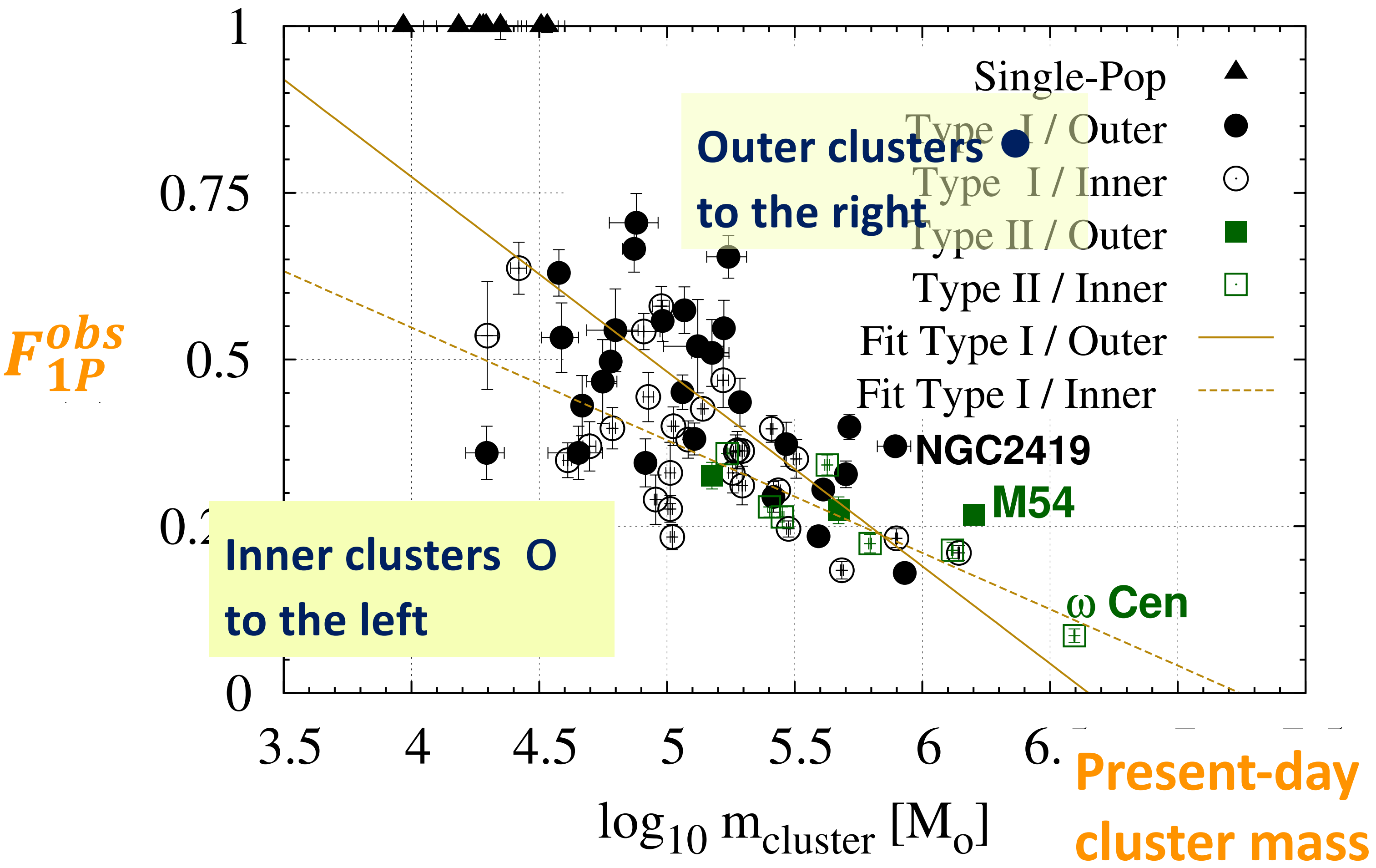
Step 3 – Secular Evolution – Two Extreme Behaviors



Galaxy outskirts (weak t.f.): 12Gyr-old tracks stick to the post-StEv track

Inner Galactic regions (strong t.f.): massive clusters only survive (so far)

Step 3 – Secular Evolution
Inner / Outer is Here a Pure Left / Right Effect



Outer clusters ● to the right

Inner clusters O to the left

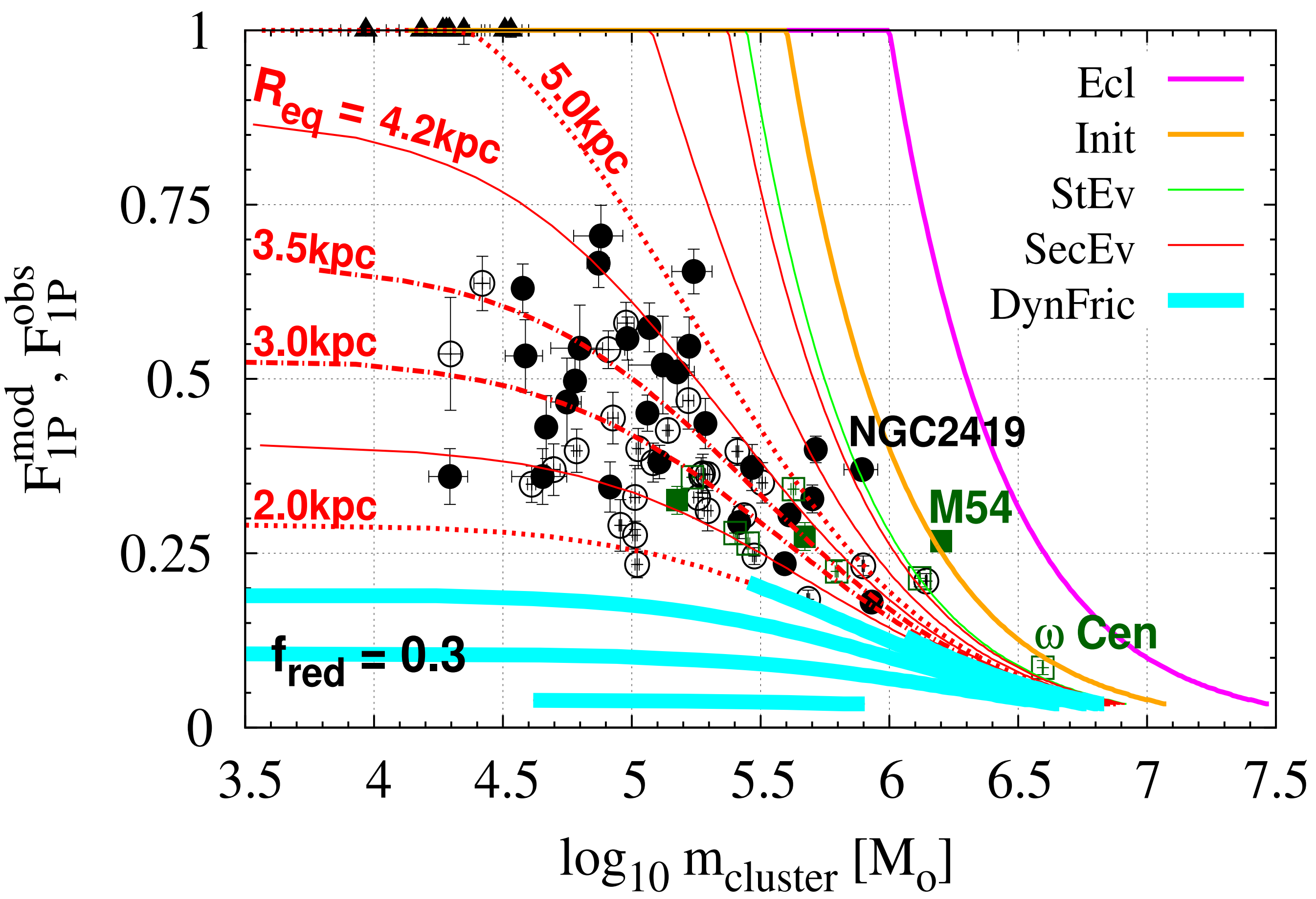
Present-day cluster mass

Step 3+ – On the High-Mass Side: Dynamical Friction

Close to the Galactic center, massive clusters do have a hard time too.

Cyan tracks: $t_{DynFric} < 12\text{Gyr}$

with $t_{DynFric}$ from Binney & Tremaine



What about the Magellanic Clouds Clusters ?

- Star clusters of the Magellanic Clouds
  - are younger and
  - have evolved in a milder tidal field

  than most Galactic globular clusters

- We thus expect to find them among the large R_{eq} tracks

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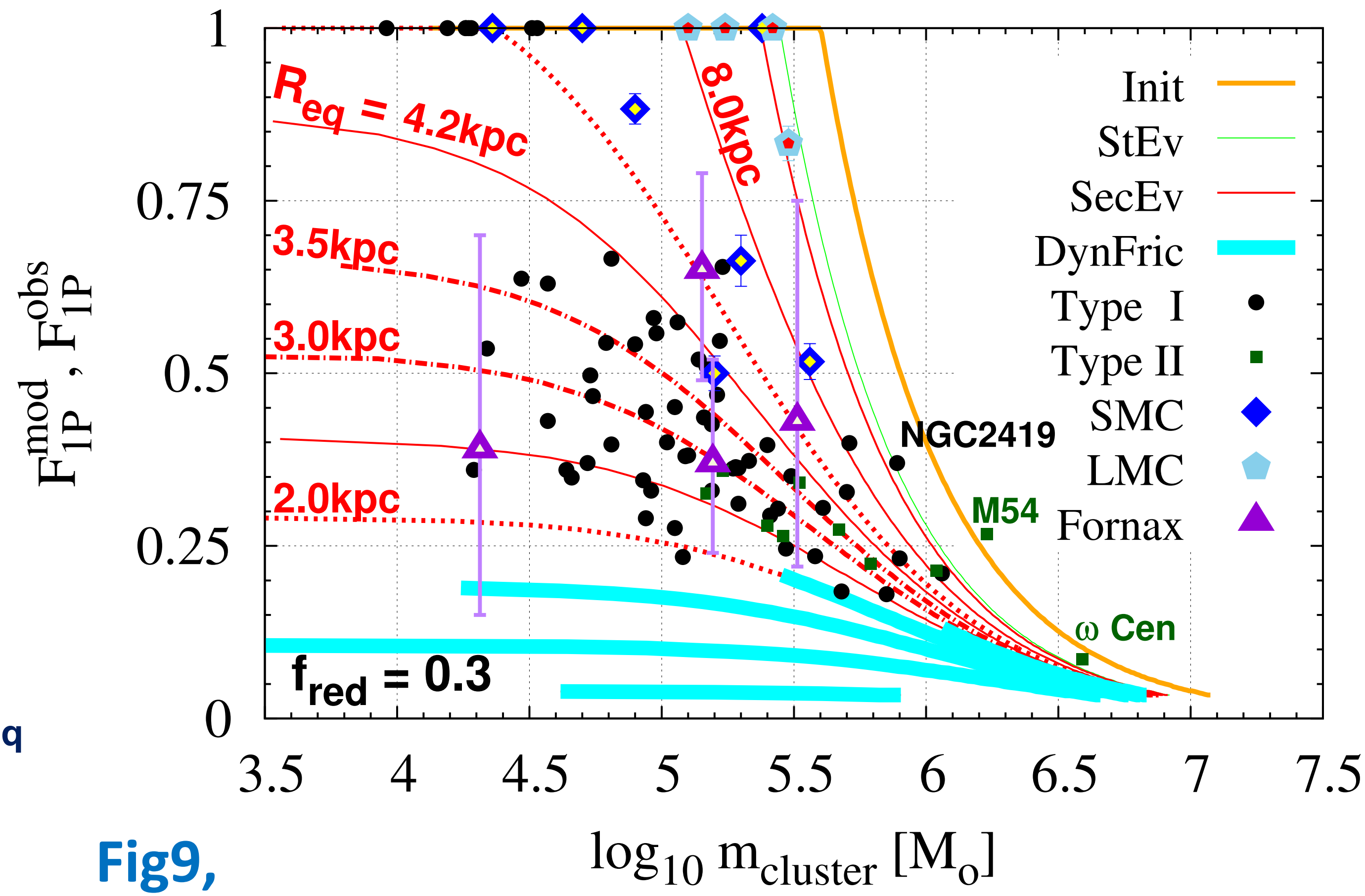

Fig9, Parmentier 2024a

An Observational Constraint …

The fraction of 2P stars in the Galactic halo field is low:
1-3%
Carretta+ 2010 - Martell+ 2011

That multiple-populations clusters are assumed
to lose equally-likely their 1P and 2P stars
may therefore be perceived as a problem.

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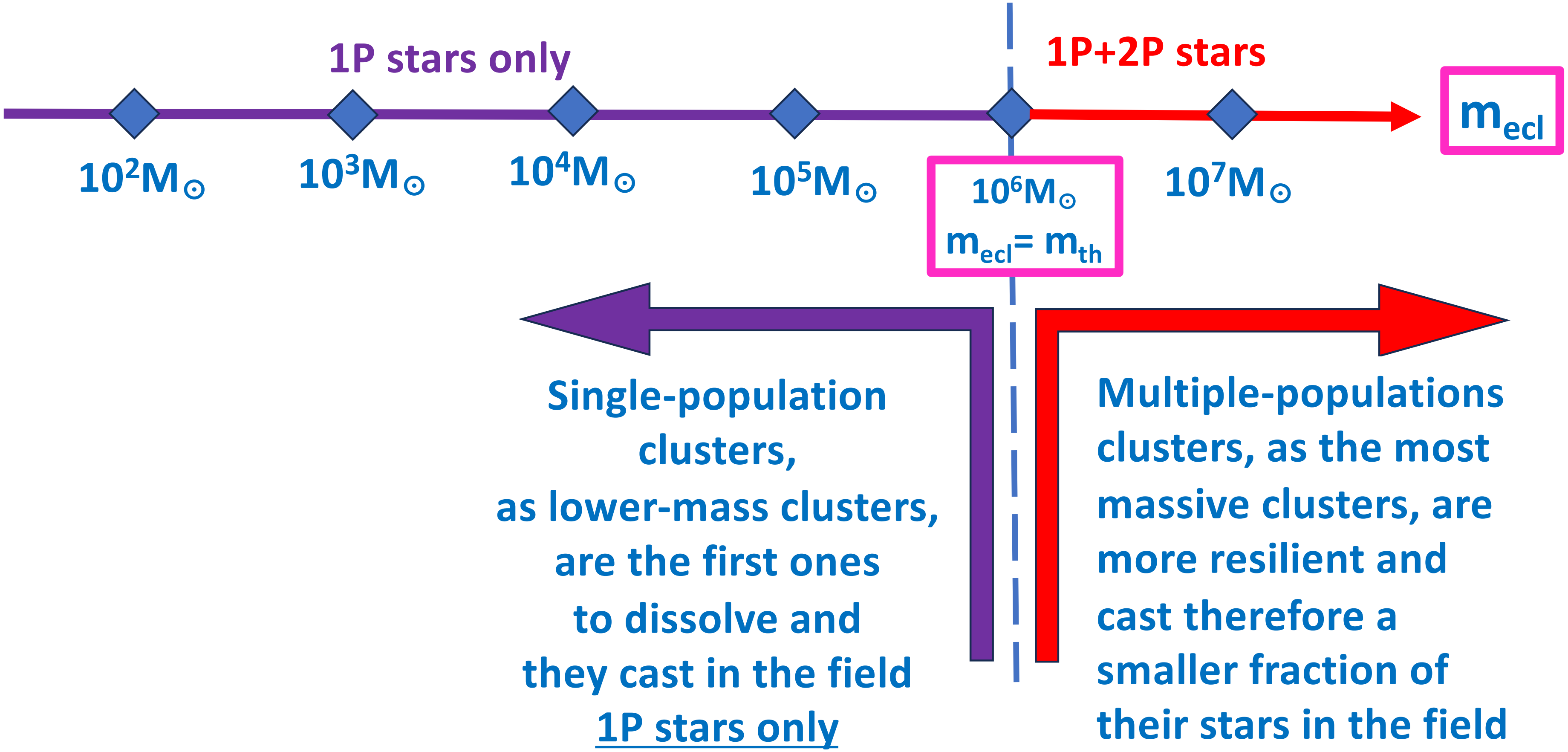
Yet, it is not

2P stars are released by multiple-populations clusters only,
and multiple-populations clusters are the most massive clusters,
hence the most resilient to evaporation

The Low Fraction of 2P Stars in the Galactic Halo Field



1P stars only

1P+2P stars

m_{ecl}

$10^2 M_\odot$ $10^3 M_\odot$ $10^4 M_\odot$ $10^5 M_\odot$

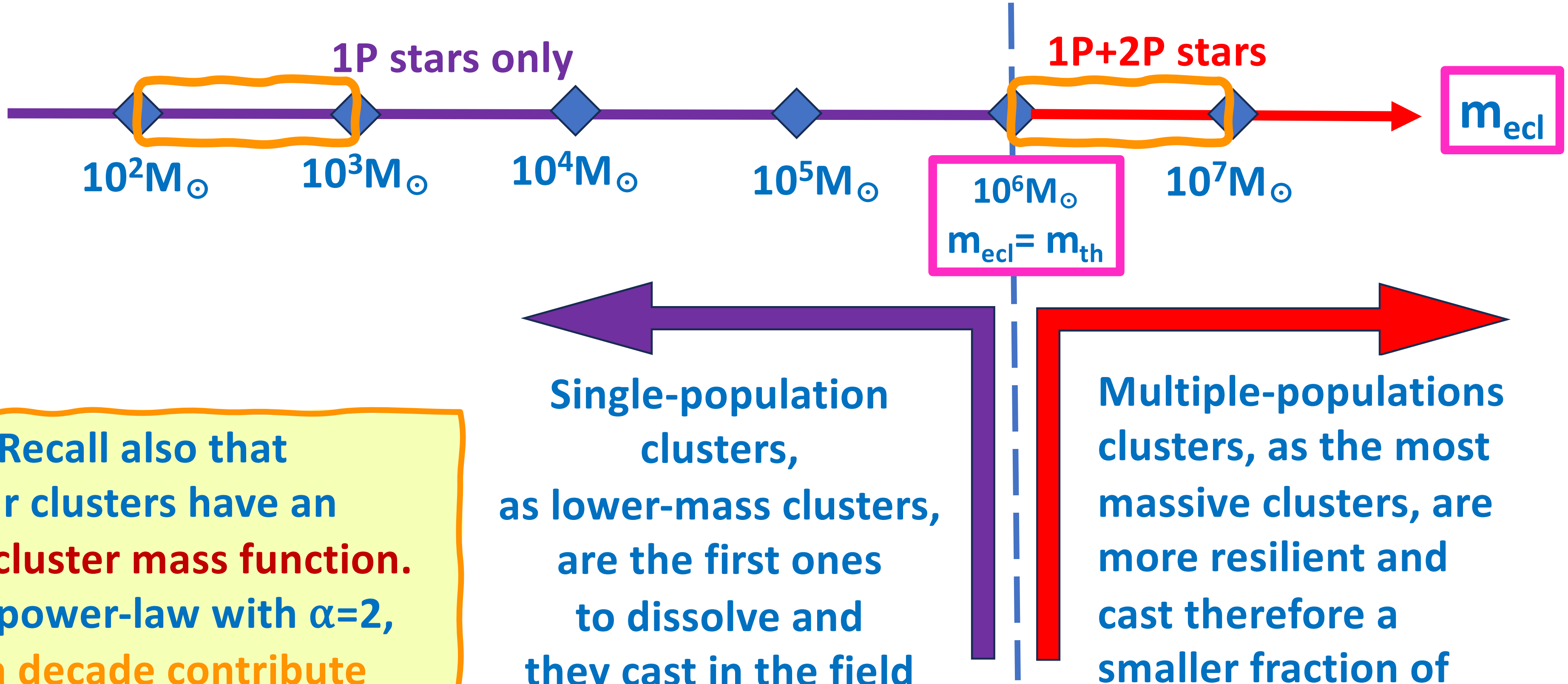
$10^6 M_\odot$
$m_{ecl} = m_{th}$

$10^7 M_\odot$

Single-population clusters, as lower-mass clusters, are the first ones to dissolve and they cast in the field 1P stars only

Multiple-populations clusters, as the most massive clusters, are more resilient and cast therefore a smaller fraction of their stars in the field

The Low Fraction of 2P Stars in the Galactic Halo Field



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Recall also that
star clusters have an
initial cluster mass function.
For a power-law with $\alpha=2$,
each decade contribute
the same fraction
to the total initial cluster mass

Take-Home Messages

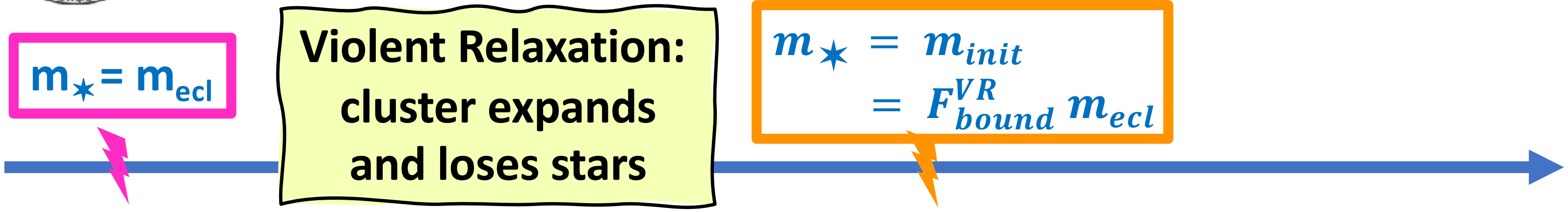
- The present-day distribution of Galactic globular clusters in the $F_{1P}(m_{prst})$ space is straightforwardly explained if:
  I. There is a cluster-mass threshold for 2P star formation
  II. Upon reaching this threshold, clusters form 2P stars exclusively
  III. Globular clusters retain a constant pristine-star fraction F_{1P} as they evaporate, i.e. their 1P and 2P stars are spatially well-mixed initially
    - ✓ This does not contradict the small fraction of 2P stars in the halo field as single-population, lower-mass, clusters are the first ones to dissolve

- The location of the Magellanic Clouds clusters with respect to their Galactic siblings follows naturally
- Hyp.II and Hyp.III are being relaxed in ongoing work

Supplementary Material

Supplementary Material

Step 2+ – Anchoring the Initial Track



$m_\star = m_{ecl}$

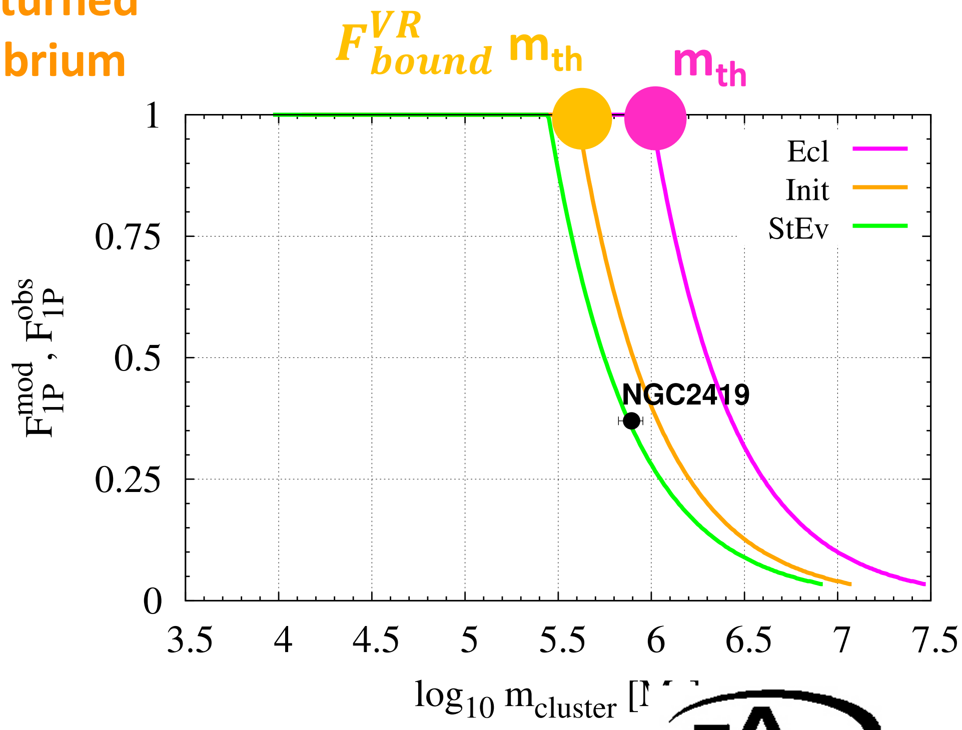
Violent Relaxation: cluster expands and loses stars

$$m_\star = m_{init} = F^{VR}_{bound}\, m_{ecl}$$

Star Formation ends
Gas is expelled

Cluster has returned
to virial equilibrium

Cluster
stellar mass
decreases
with time



❖ m_{th} value
→ implications for the mass of the pollution source, e.g.
VMSs or SMS ?

Higgins+2023
Gieles+2018
Charbonnel+2023
Lahen+2024

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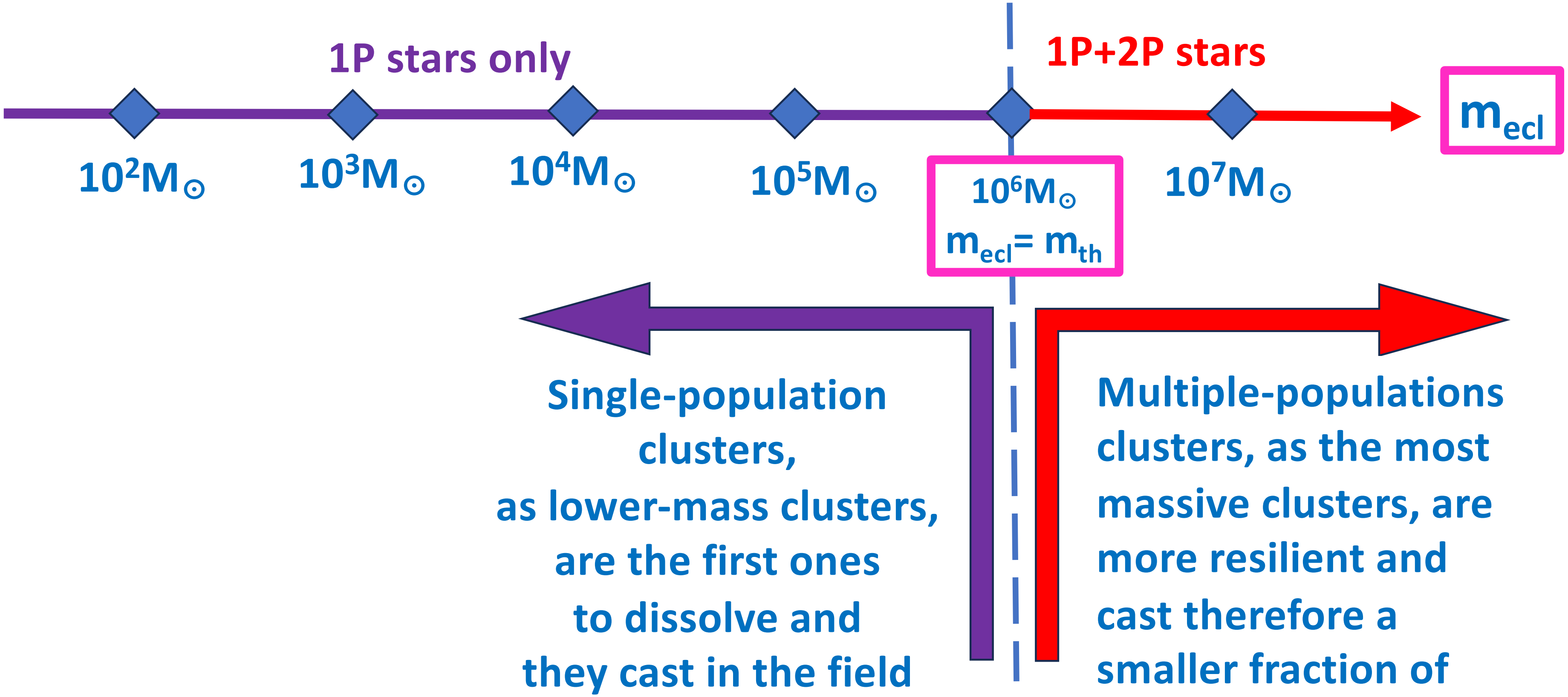
The Low Fraction of 2P Stars in the Galactic Halo Field



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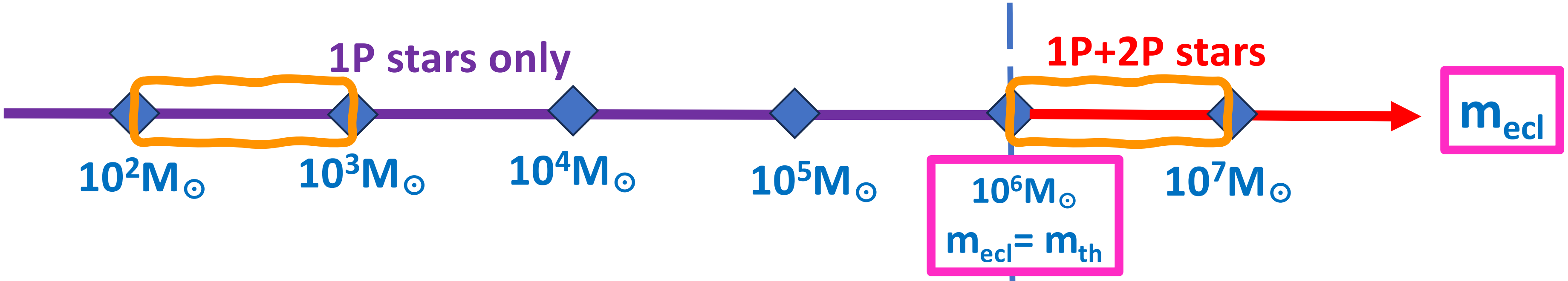

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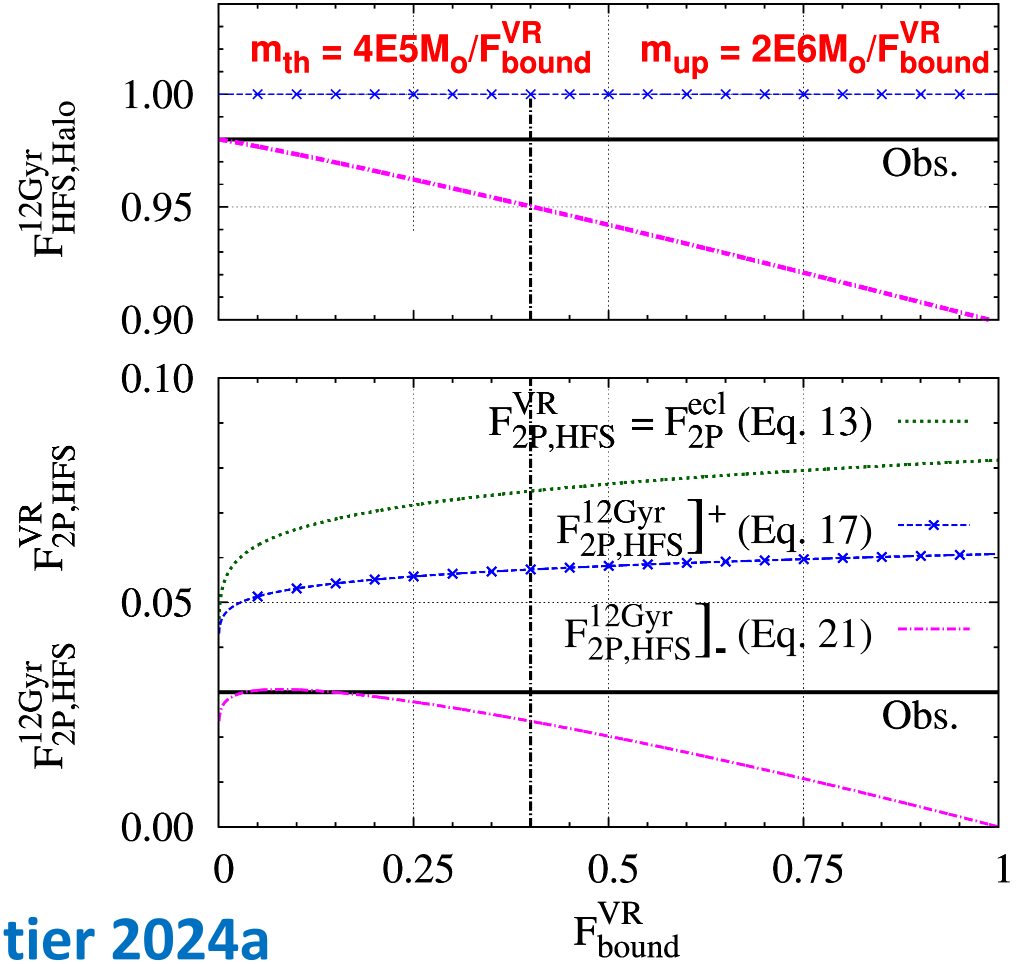
An Observational Constraint … That is Met



$\left.F^{12Gyr}_{HFS,Halo}\right]^{+}$

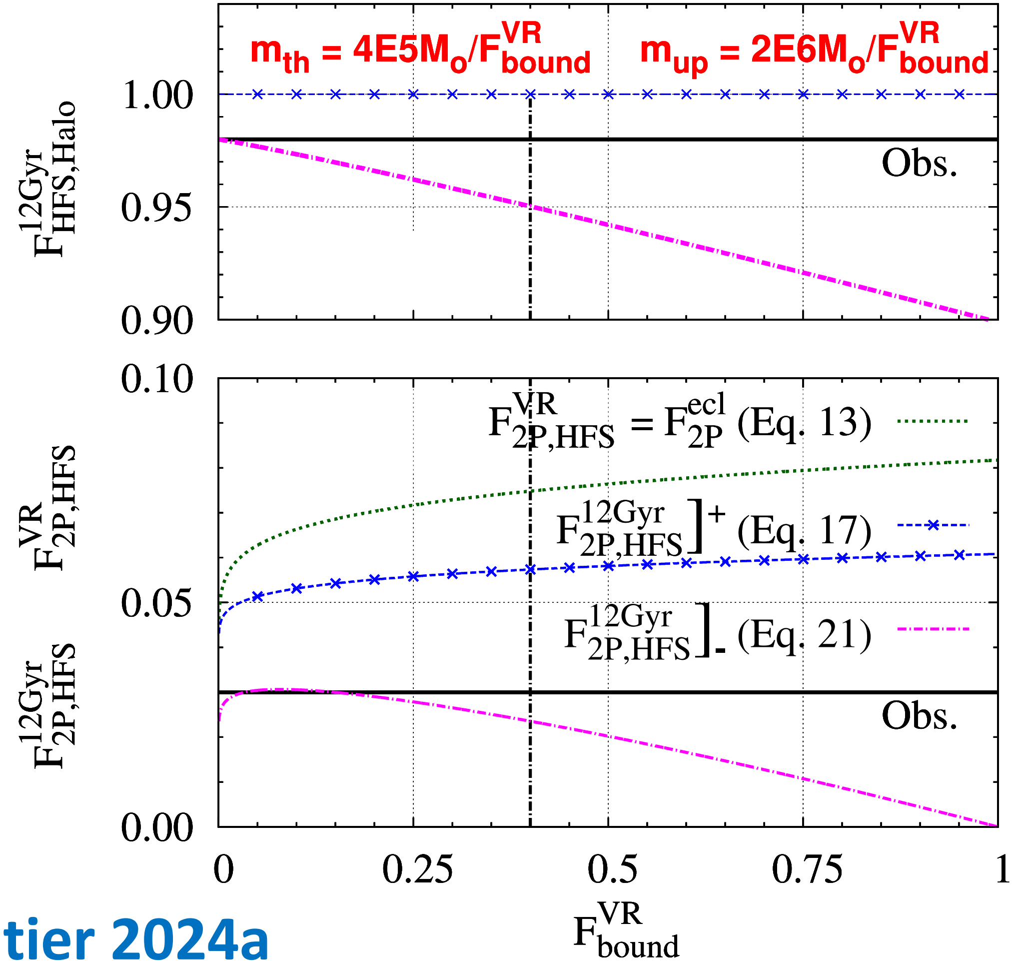
All clusters have dissolved

$\left.F^{12Gyr}_{2P,HFS}\right]^{+}$

All clusters have dissolved

Fig10, Parmentier 2024a

An Observational Constraint … That is Met



$F^{12Gyr}_{HFS,Halo}]^+$

All clusters have dissolved

$F^{12Gyr}_{HFS,Halo}]^-$

SP clusters only have dissolved

$F^{12Gyr}_{2P,HFS}]^+$

All clusters have dissolved

$F^{12Gyr}_{2P,HFS}]^-$

SP clusters only have dissolved

Fig10, Parmentier 2024a

Top-Heavy IMF

Tracks for top-heavy IMFs based on the cluster dissolution time-scales of Haghi+2020

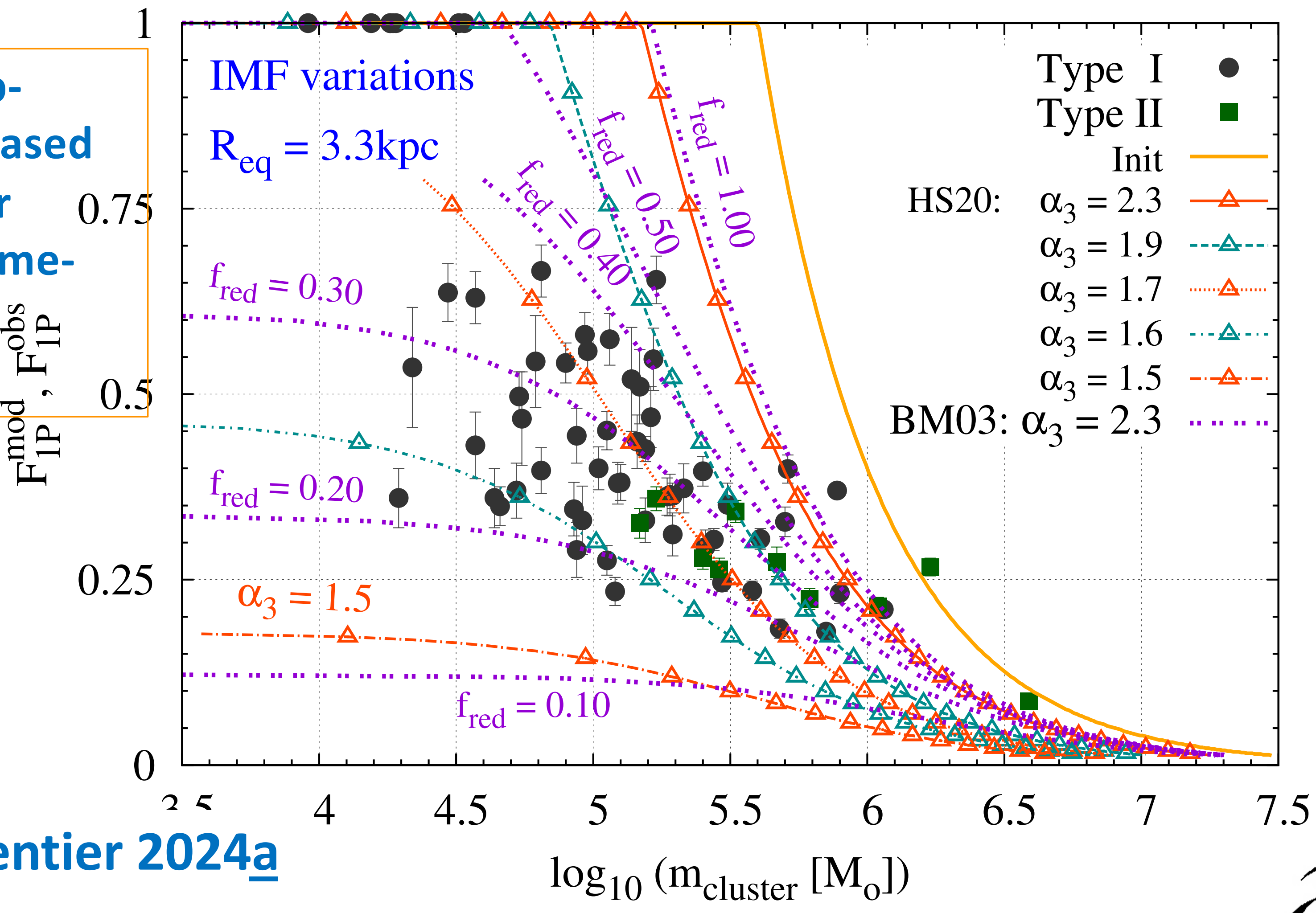


Fig6, Parmentier 2024a

Reading the Data Anew … From Different Viewing Points

$F_{1P}(m_{1P})$ $F_{1P}(m_{prst})$ $F_{1P}(m_{2P})$

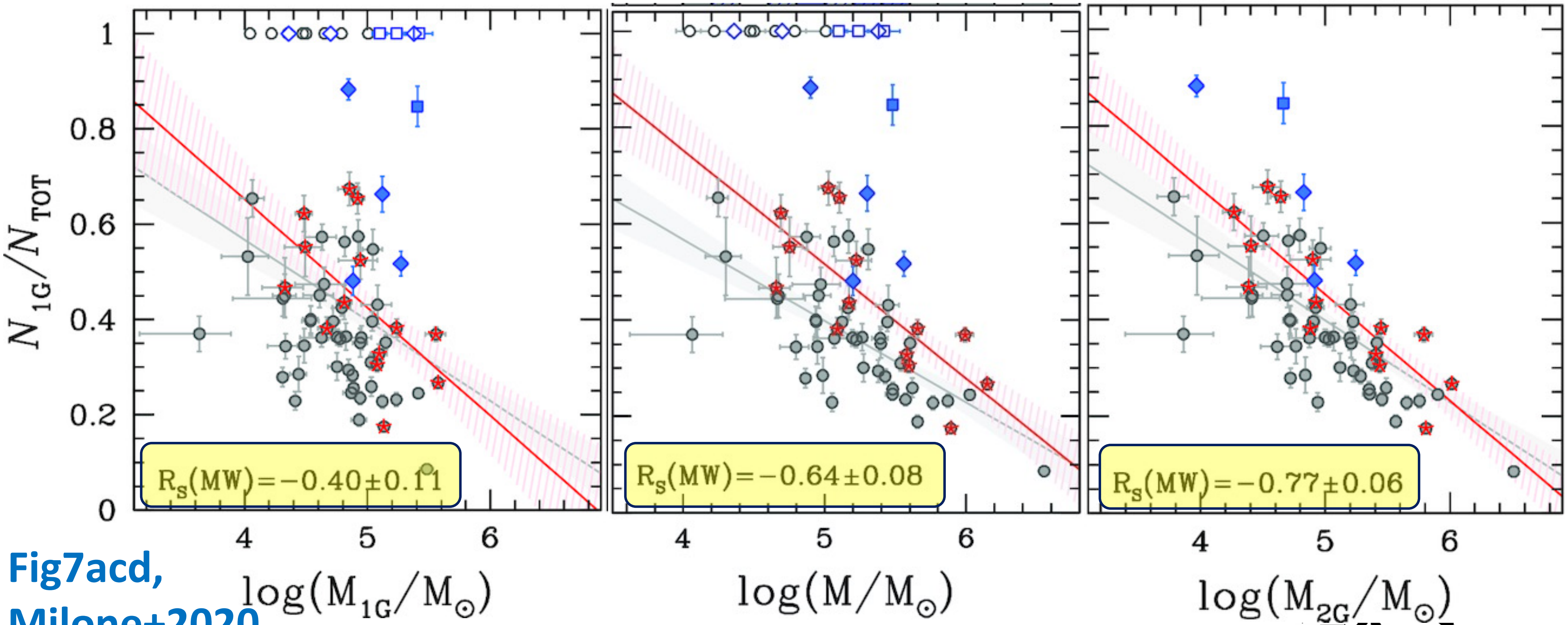
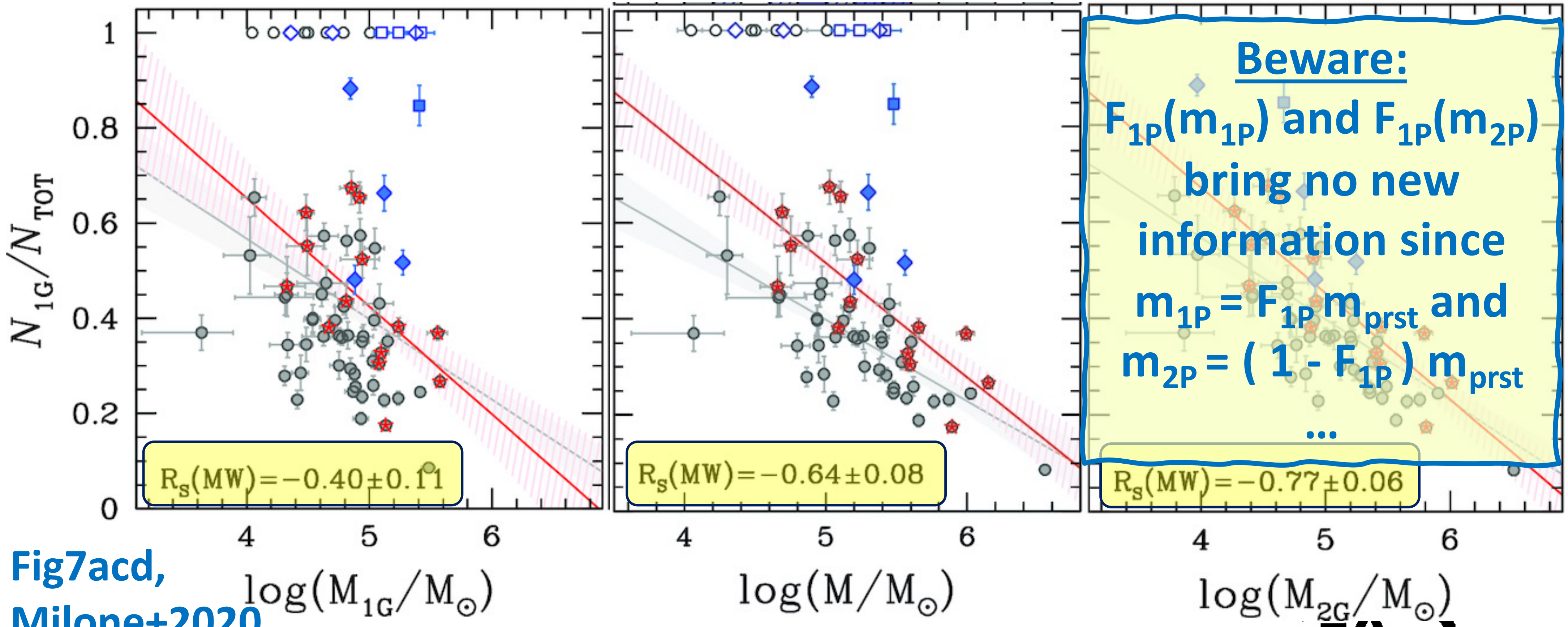


Fig7acd, Milone+2020

Reading the Data Anew … From Different Viewing Points

$F_{1P}(m_{1P})$ $F_{1P}(m_{prst})$ $F_{1P}(m_{2P})$



$R_S(MW) = -0.40 \pm 0.11$

$R_S(MW) = -0.64 \pm 0.08$

$R_S(MW) = -0.77 \pm 0.06$

Beware:

$F_{1P}(m_{1P})$ and $F_{1P}(m_{2P})$ bring no new information since

$m_{1P} = F_{1P}\, m_{prst}$ and

$m_{2P} = (1 - F_{1P})\, m_{prst}$

…

Fig7acd, Milone+2020

Reading the Data Anew … From Different Viewing Points

… but they allow additional and insightful readings of the data

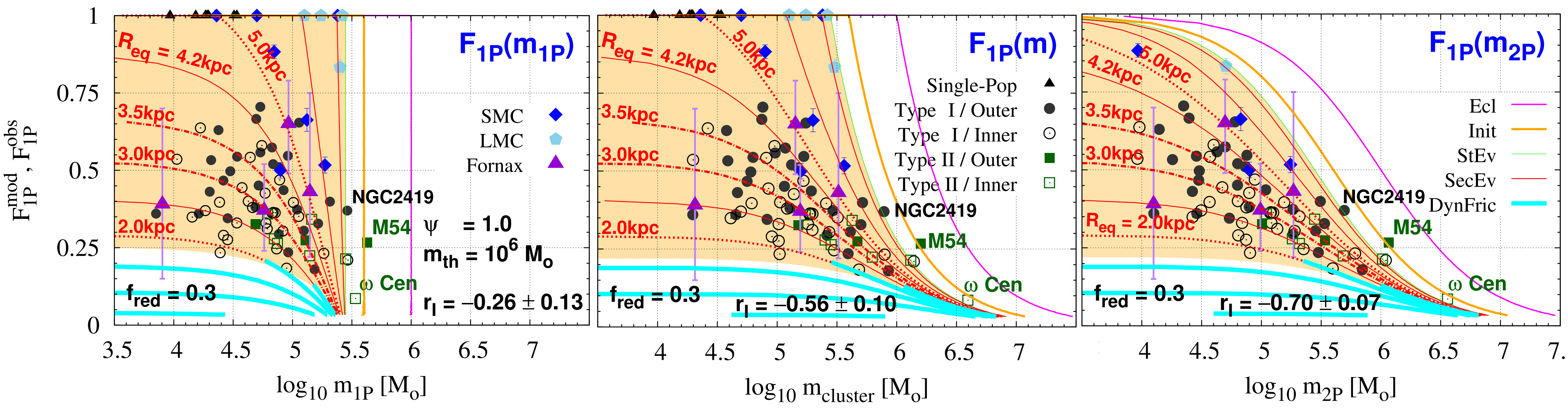
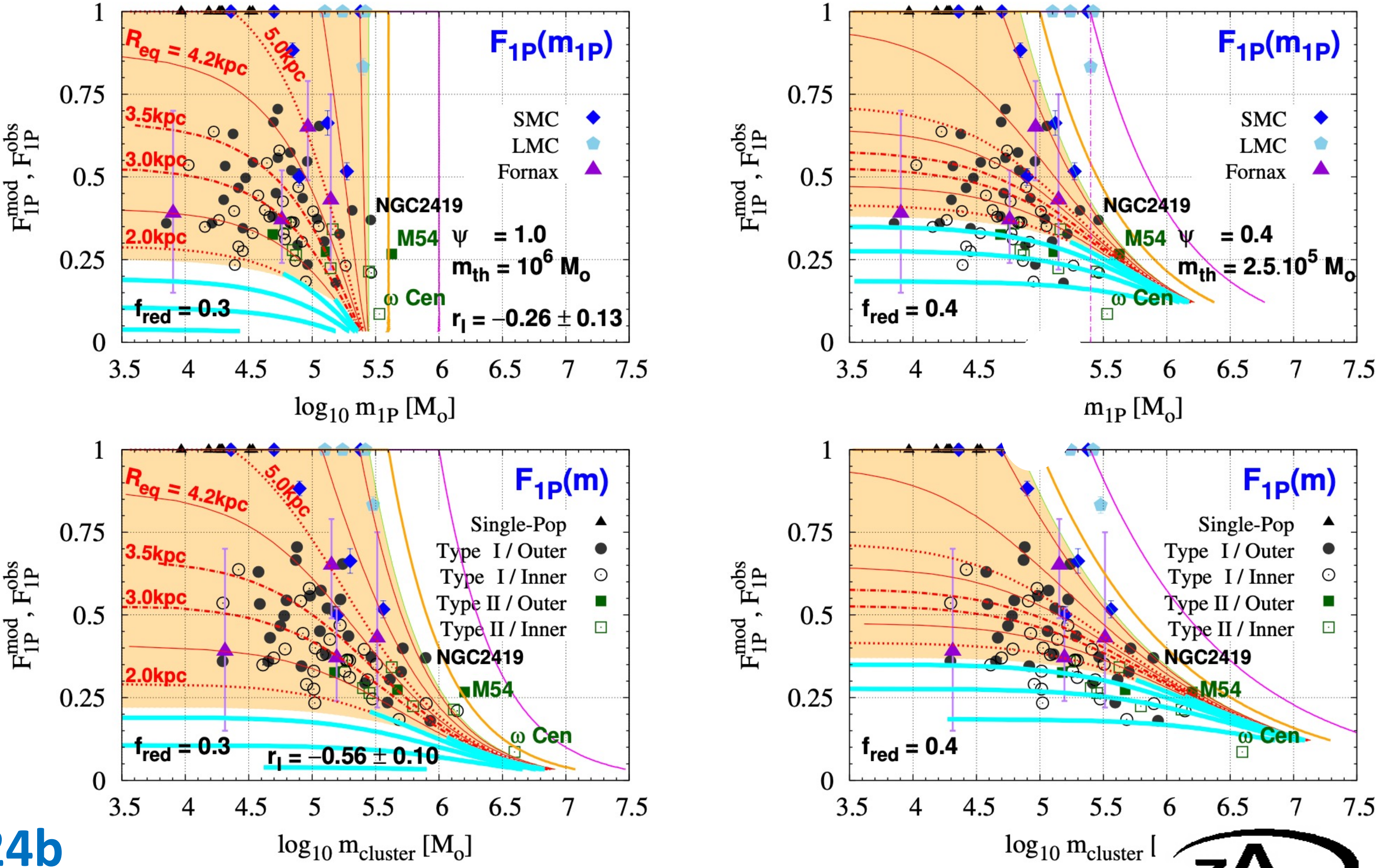


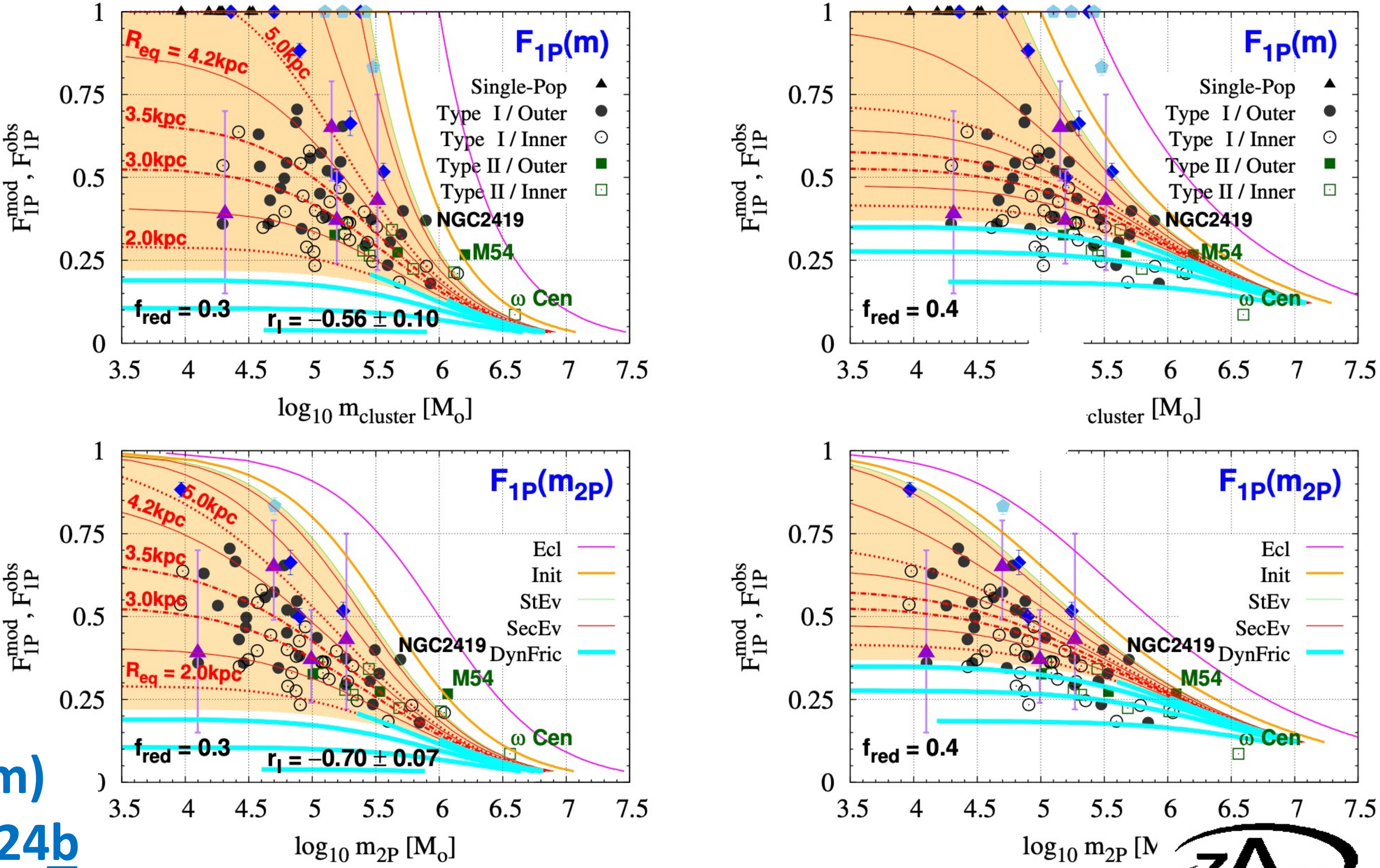
Fig4abc, Parmentier 2024b

Non-Instantaneous Pollution of the Cluster



Figs4-5 (top)
Parmentier 2024b

Non-Instantaneous Pollution of the Cluster



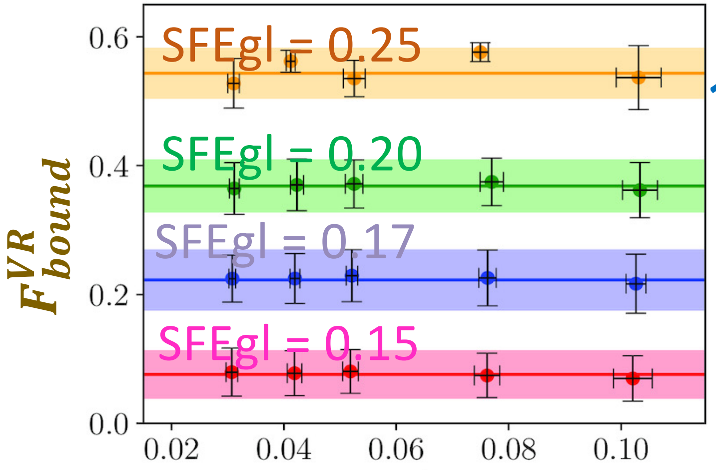
Figs4-5 (bottom)
Parmentier 2024<u>b</u>

Evolution with $F_{bound}^{VR} = constant$ during Violent Relaxation

- F_{bound}^{VR} more robust to environmental variations (e.g. external tidal field; Shukirgaliyev, Parmentier et al. 2019) than thought in the past once the steeper density profile of clusters, as compared to their embedding gas, is taken into account (Parmentier & Pfalzner 2013)

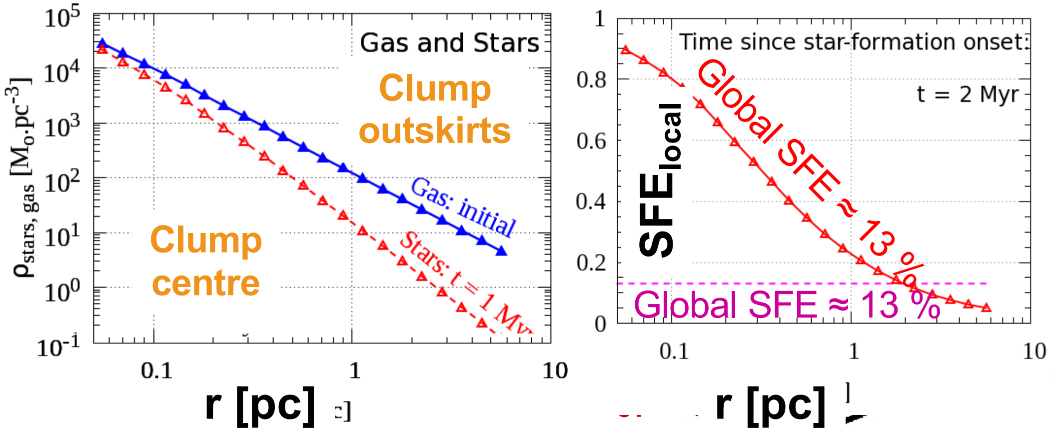
- Could violent relaxation be a non-event for newly formed compact massive clusters?

  If SFE → 1 (Polak+2023),
  $F_{bound}^{VR} \rightarrow 1$



r_{hm} / r_J at gas expulsion
(= tidal field impact)

Fig4, Shukirgalyiev, Parmentier + 2019



Figs 1&10, Parmentier & Pfalzner 2013