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

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The Multi-Pops Phenomenon … A Massive-Cluster Story

74 Galactic GCs

$$F_{1P} = \frac{N_{1P}}{N_{1P} + N_{2P}}$$

F_{1P}^{obs}

Fraction of pristine/1P/1G stars in clusters

F_{1P}^{obs} from Milone's collaboration

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The Multi-Pops Phenomenon … A Massive-Cluster Story

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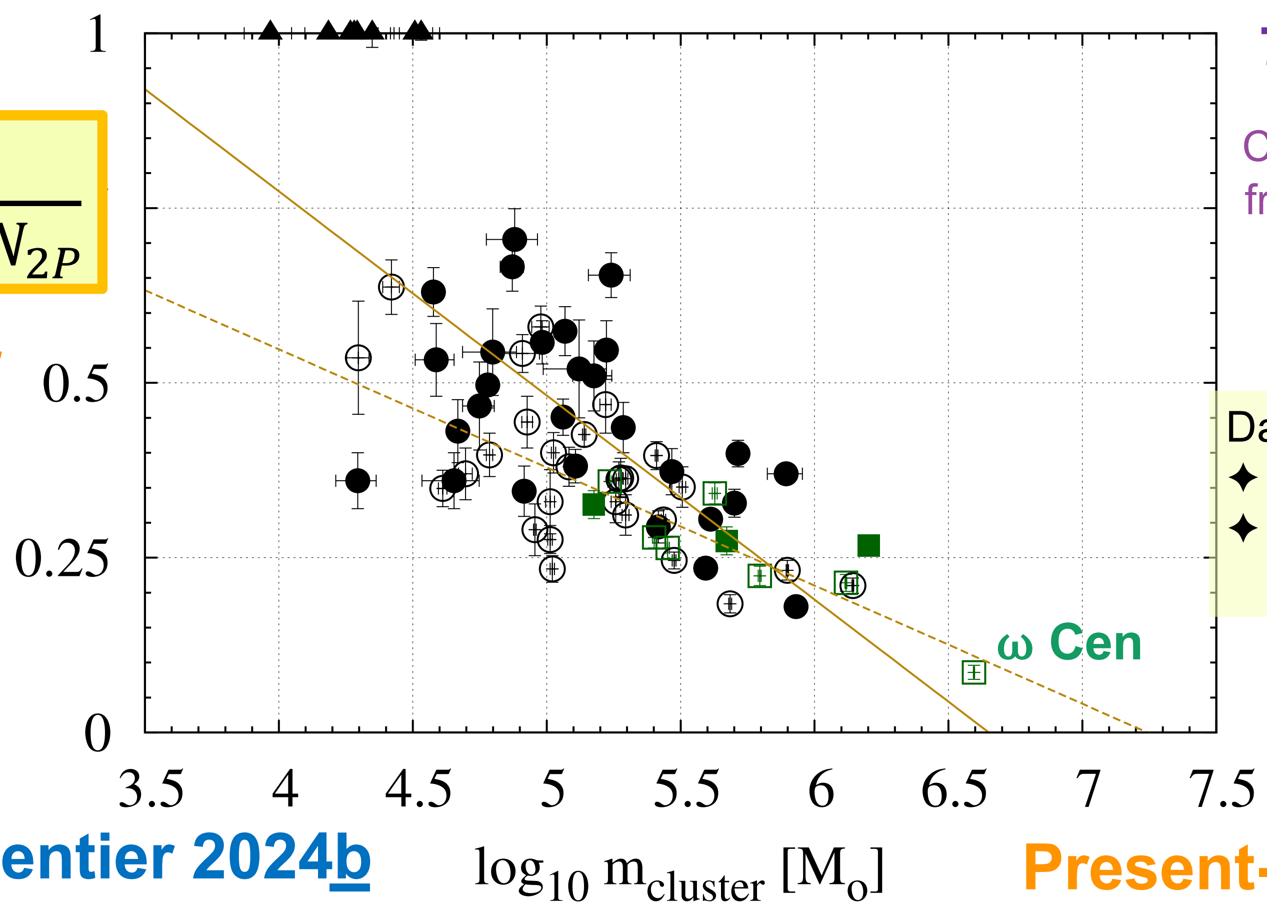

74 Galactic GCs

Cluster mass estimates from Baumgardt+ 2019

F_{1P}^{obs} from Milone's collaboration

Data set assembly:
- ✦ Parmentier 2024a, Sec.3
- ✦ Updated Parmentier 2024b, Sec.2

Fig1b, Parmentier 2024b

Present-day cluster mass

The Multi-Pops Phenomenon … A Massive-Cluster Story

Single-population clusters

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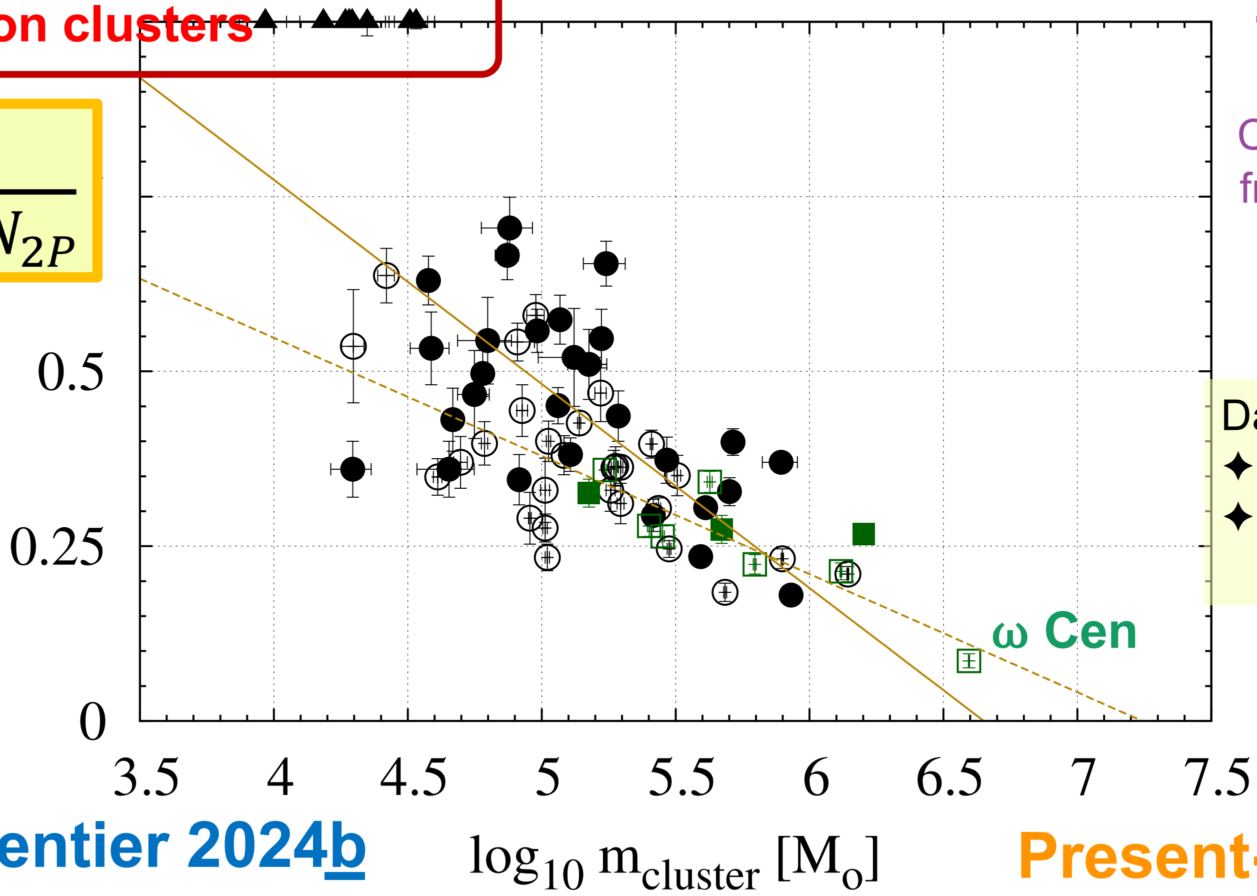

74 Galactic GCs

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Fig1b, Parmentier 2024b

Present-day cluster mass

A Sharpened Read of the Data

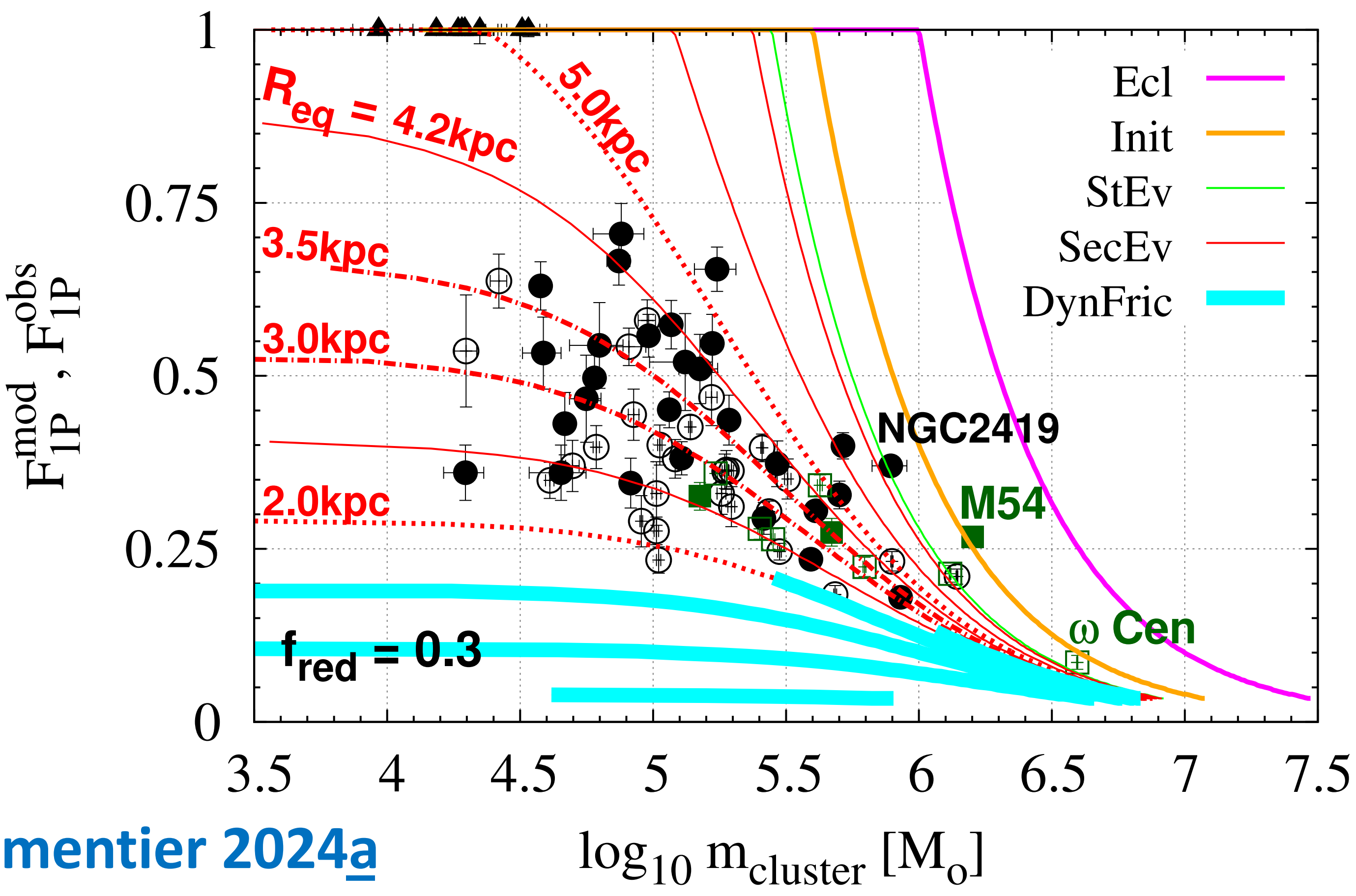

Fig7 , Parmentier 2024a

Fig1a, Parmentier 2024b

Three Key Hypotheses

I. A fixed stellar mass **threshold** for 2P-star formation: m_{th}

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Once 2P-star formation starts

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$$\boxed{m_{1P} = m_{th}}$$

Hypotheses I + II ⇒ F_{1P}(mass) for newly formed clusters

I. **A fixed stellar mass threshold for 2P-star formation: m_{th}**

II. **An instantaneous and complete cluster pollution**

Once 2P-star formation starts

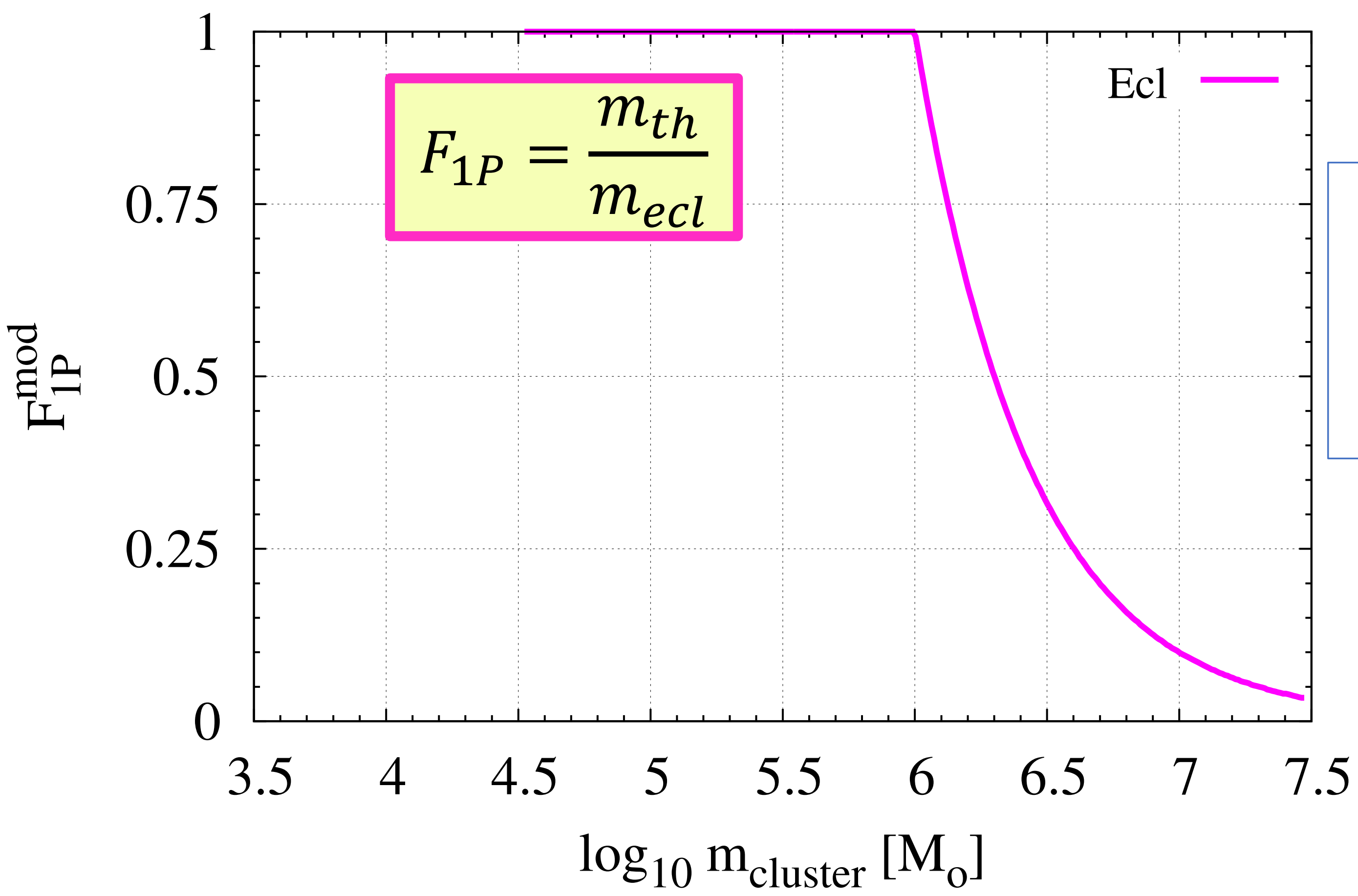
1P-star formation stops

$$\boxed{m_{1P} = m_{th}}$$

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

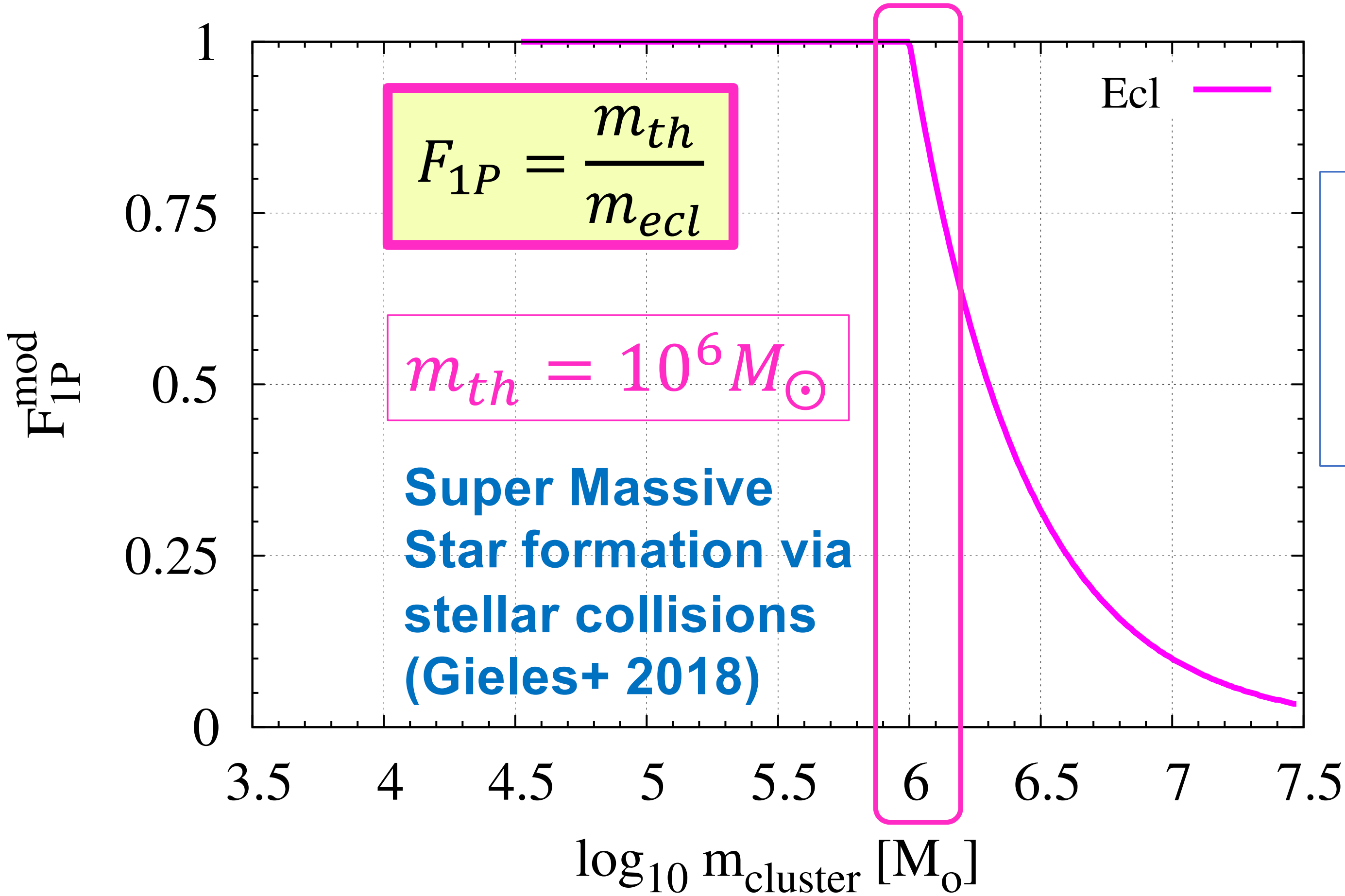
with m_{ecl} the stellar mass of newly formed clusters

Hypotheses I + II ⇒ F_{1P}(mass) for newly formed clusters



m_{ecl}:
stellar mass of newly formed clusters

Hypotheses I + II ⇒ F_{1P}(mass) for newly formed clusters



m_{ecl}: stellar mass of newly formed clusters

Three Key Hypotheses

I. A fixed stellar mass threshold for 2P-star formation: m_{th}

II. An instantaneous and complete cluster pollution

Once 2P-star formation starts

1P-star formation stops

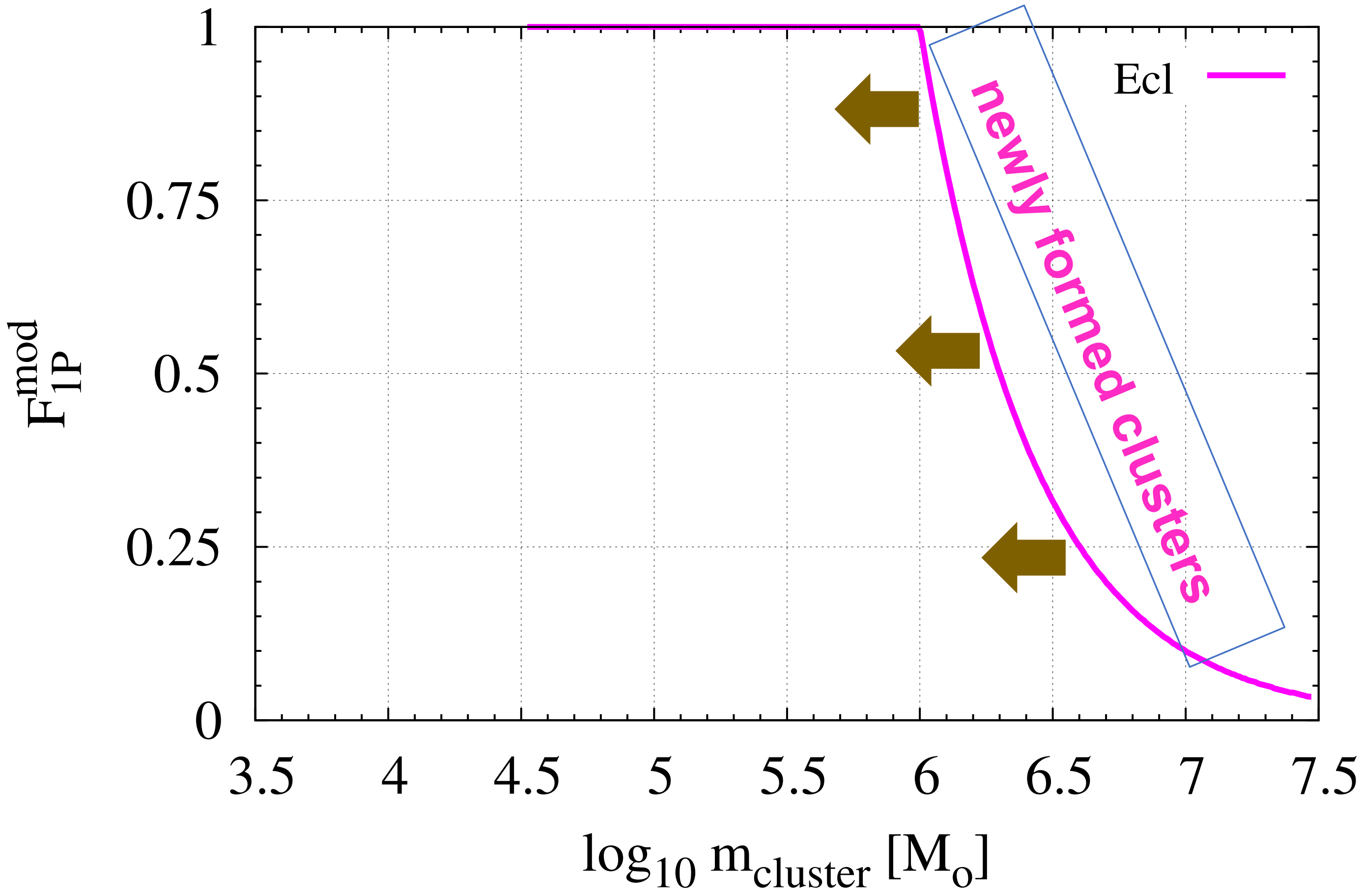
III. Clusters evolve at constant F_{1P}

1P and 2P stars form spatially well-mixed;

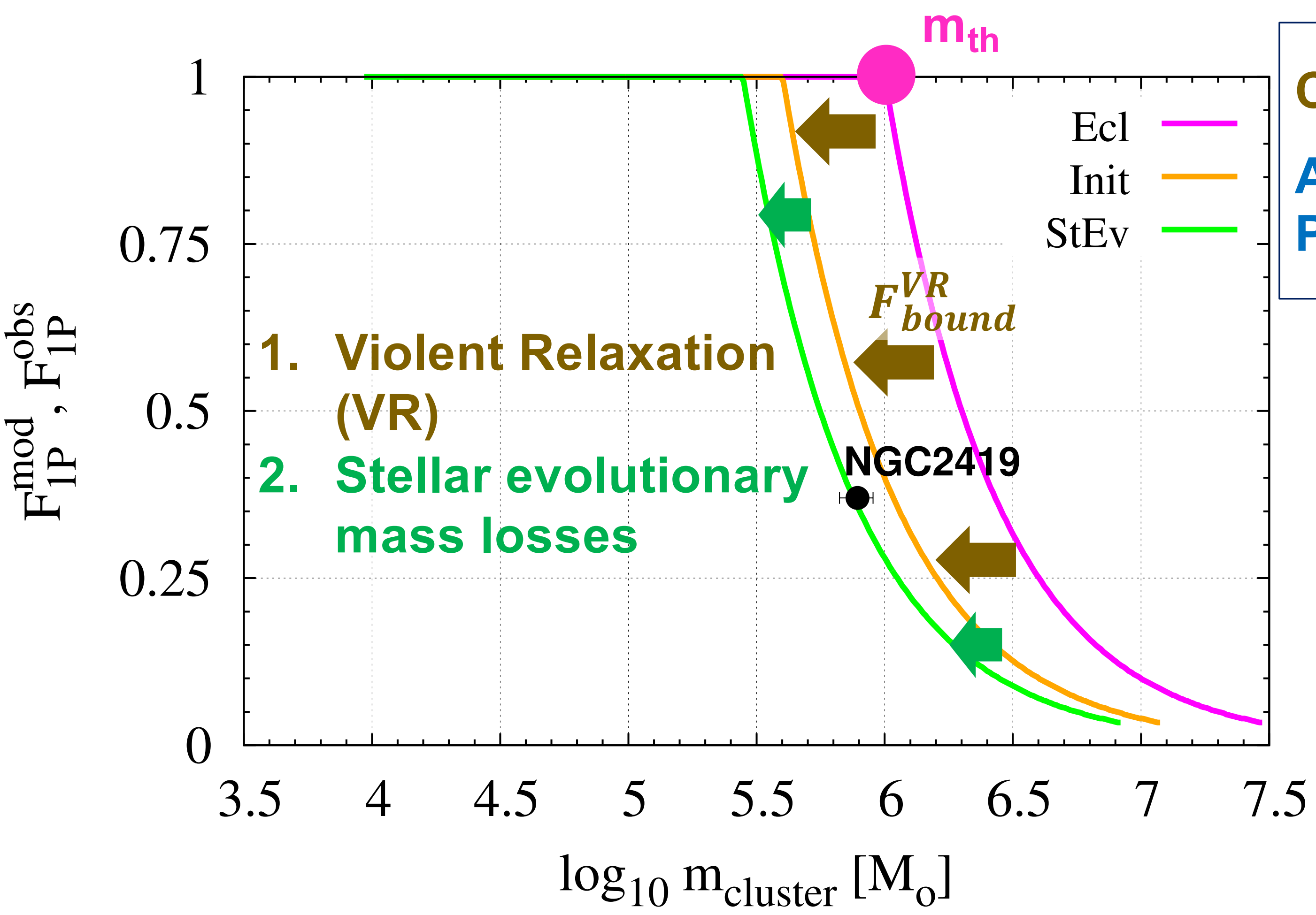
they are lost equally likely

Leitinger+2023, Fig15

Hyp III ⇒ Cluster Data Points Move Horizontally Leftward



Violent Relaxation - Stellar Evolutionary Mass Losses



Constancy of F_{bound}^{VR}:

Appendices A+B in Parmentier 2024a

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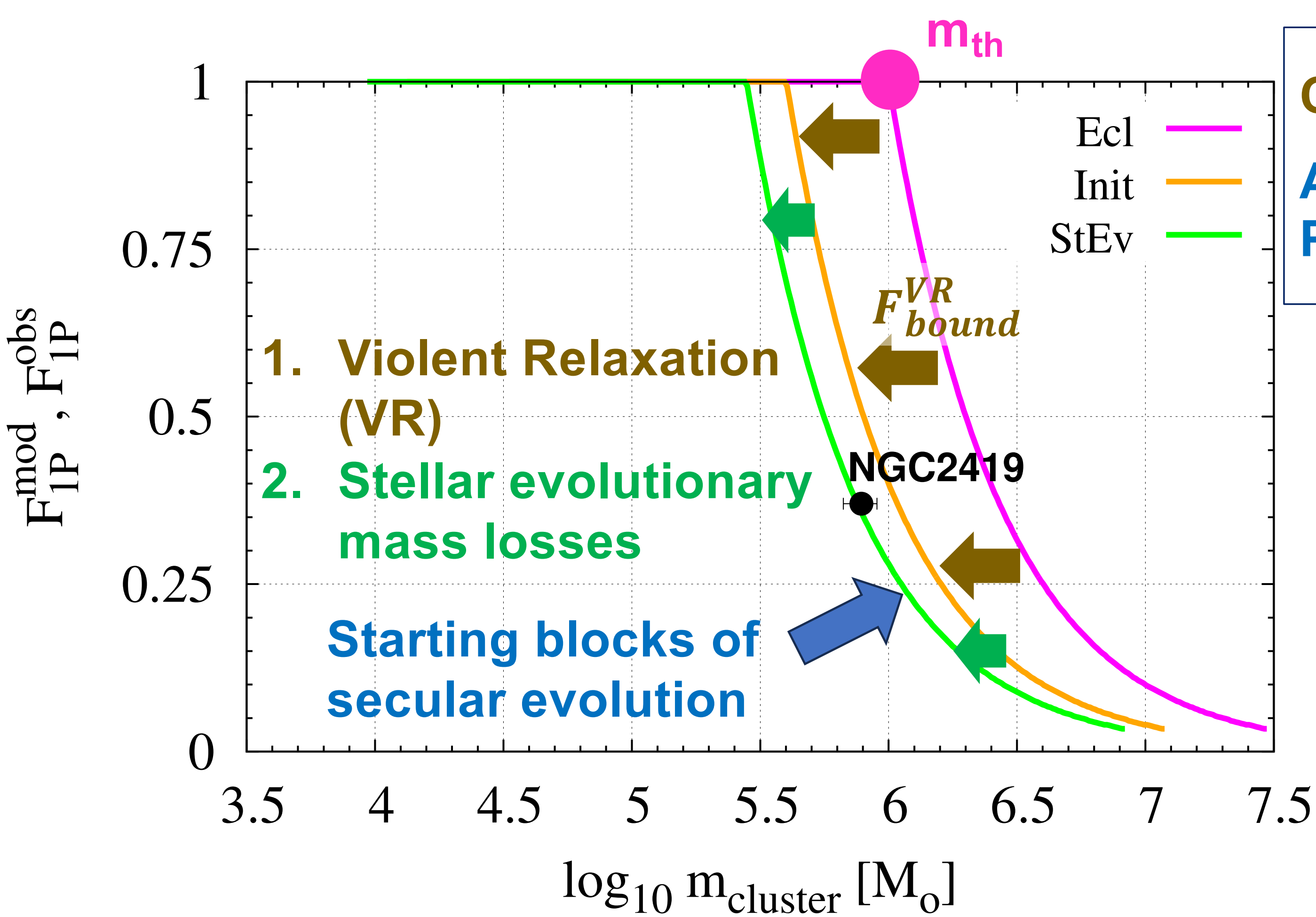

Constancy of F^{VR}_{bound}:

Appendices A+B in Parmentier 2024a

With Secular Evolution up to the Age of 12Gyr

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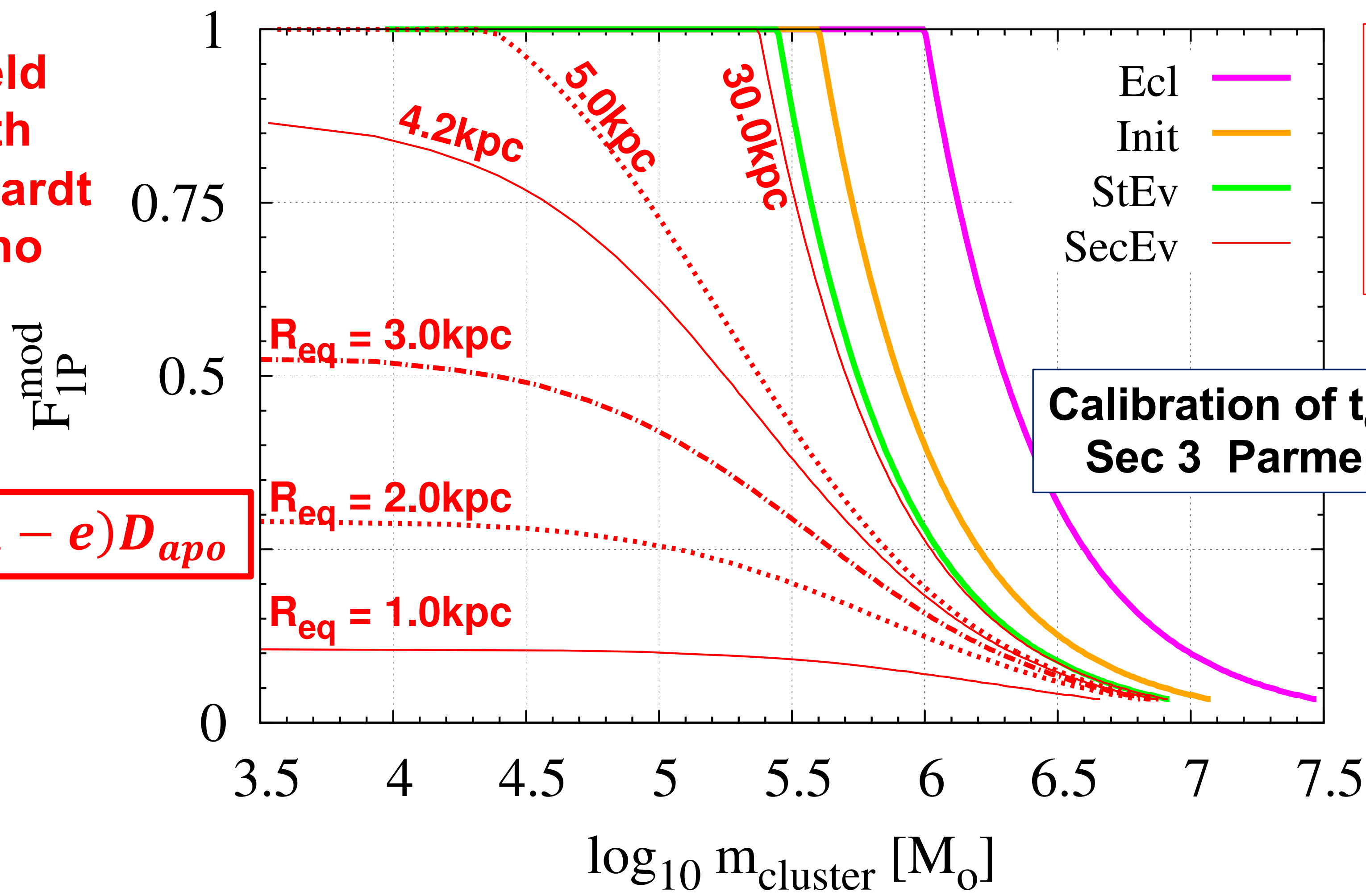
Tidal field strength in Baumgardt & Makino 2003

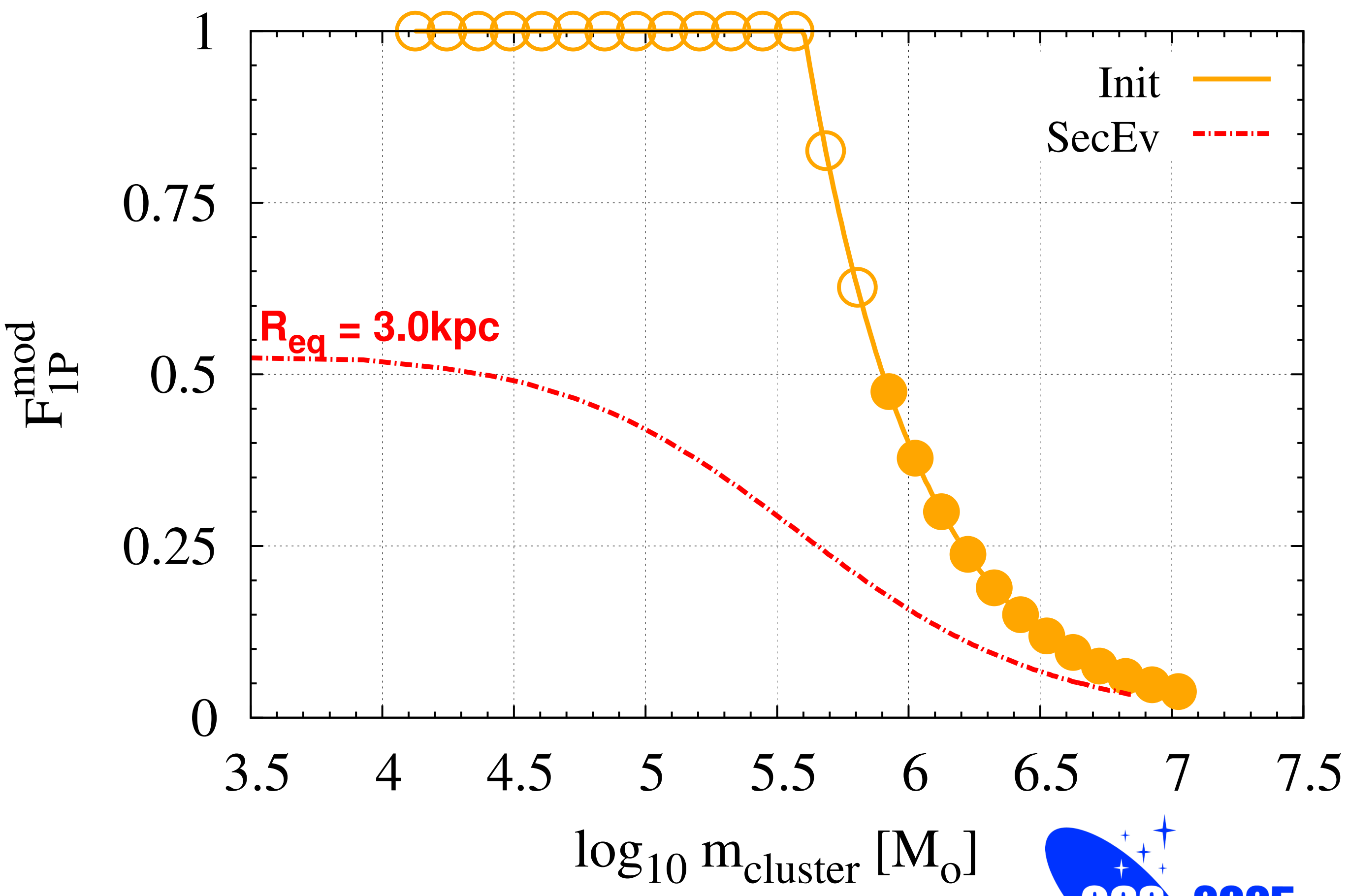
$$R_{eq} = (1 - e)D_{apo}$$



Red tracks = 12Gyr-old tracks

Calibration of t_{diss}:
Sec 3 Parmentier 2024a

Given Tidal Field: Low-Mass Clusters Dissolve Faster



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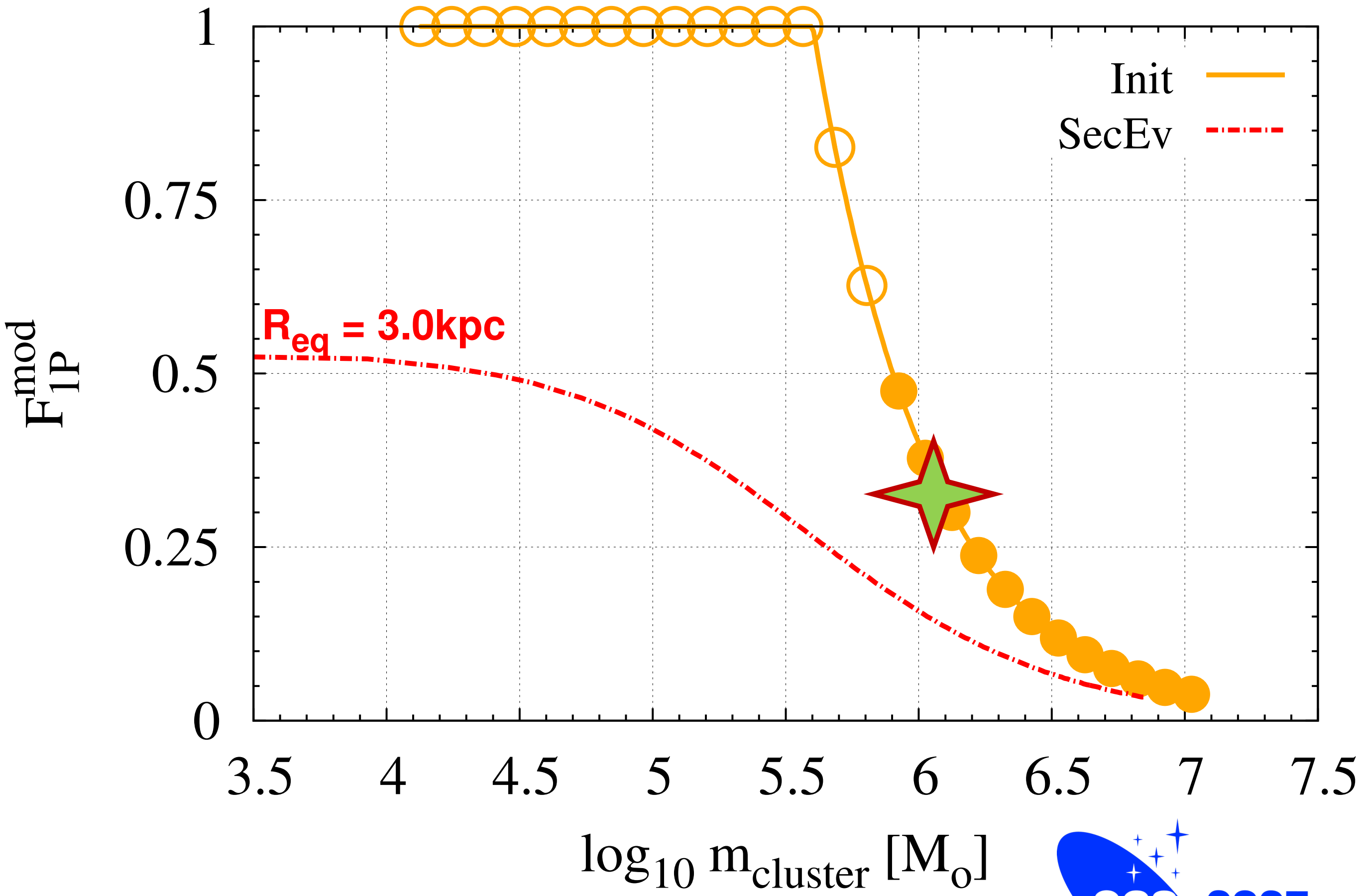

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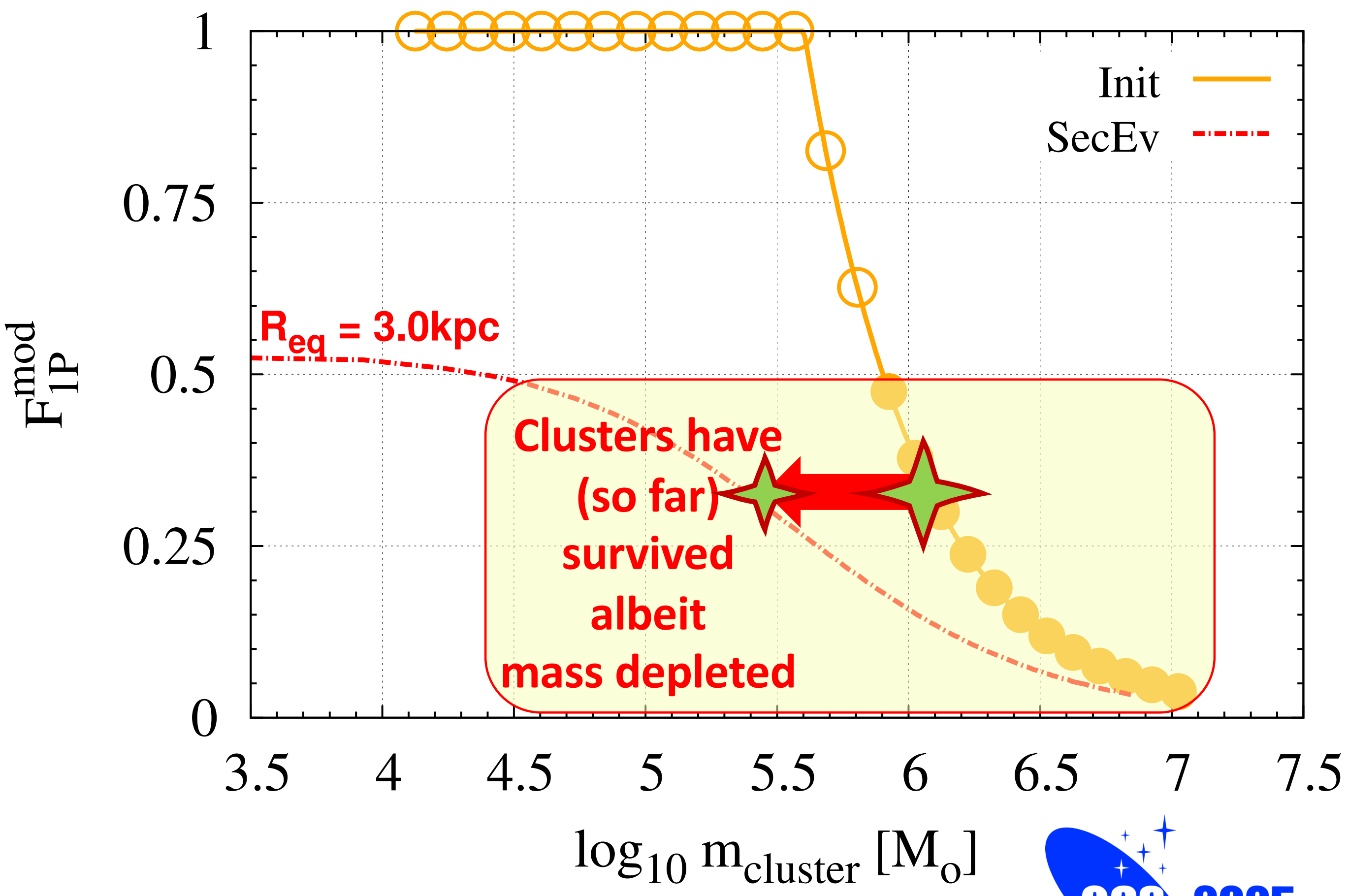

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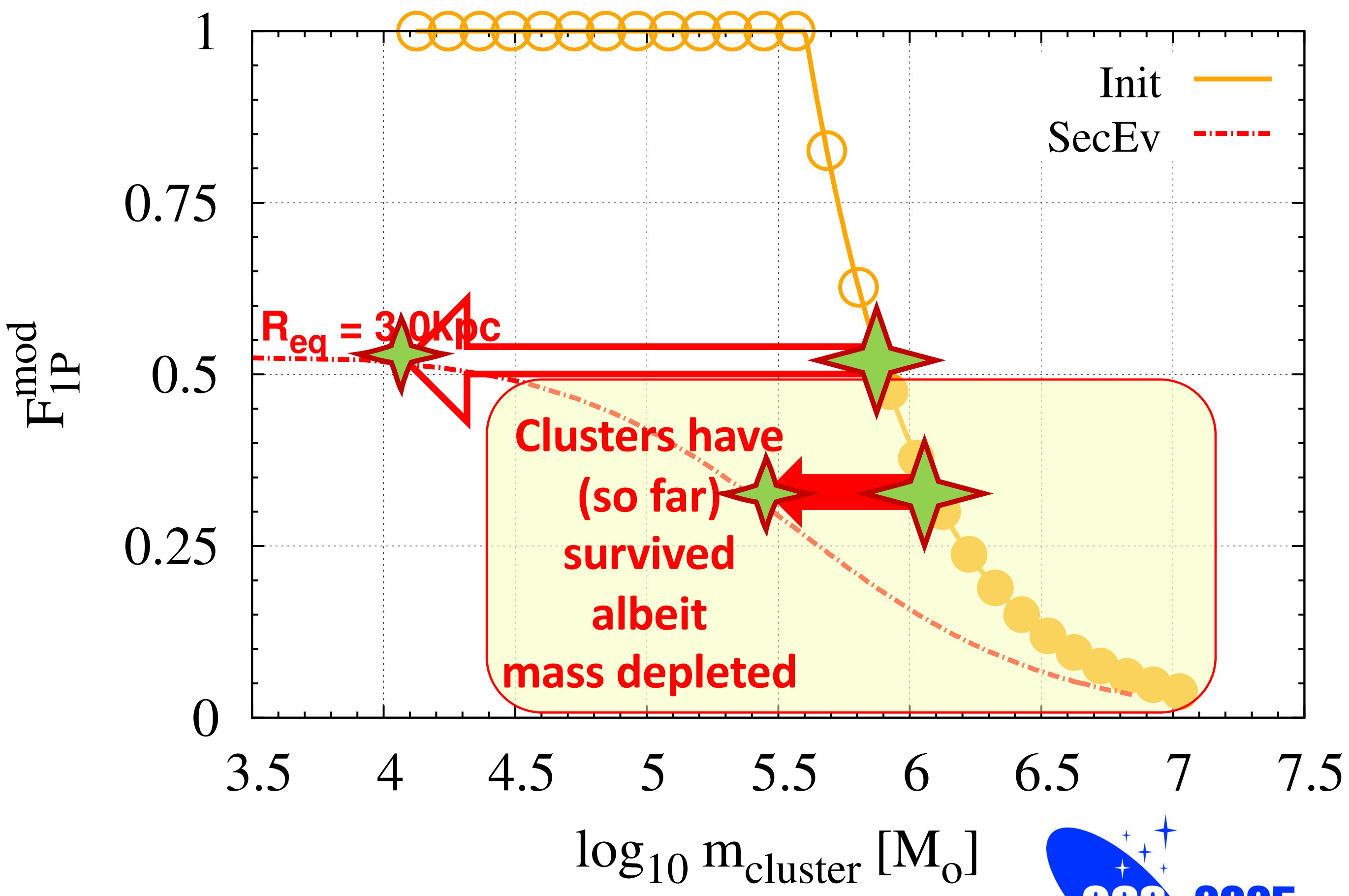

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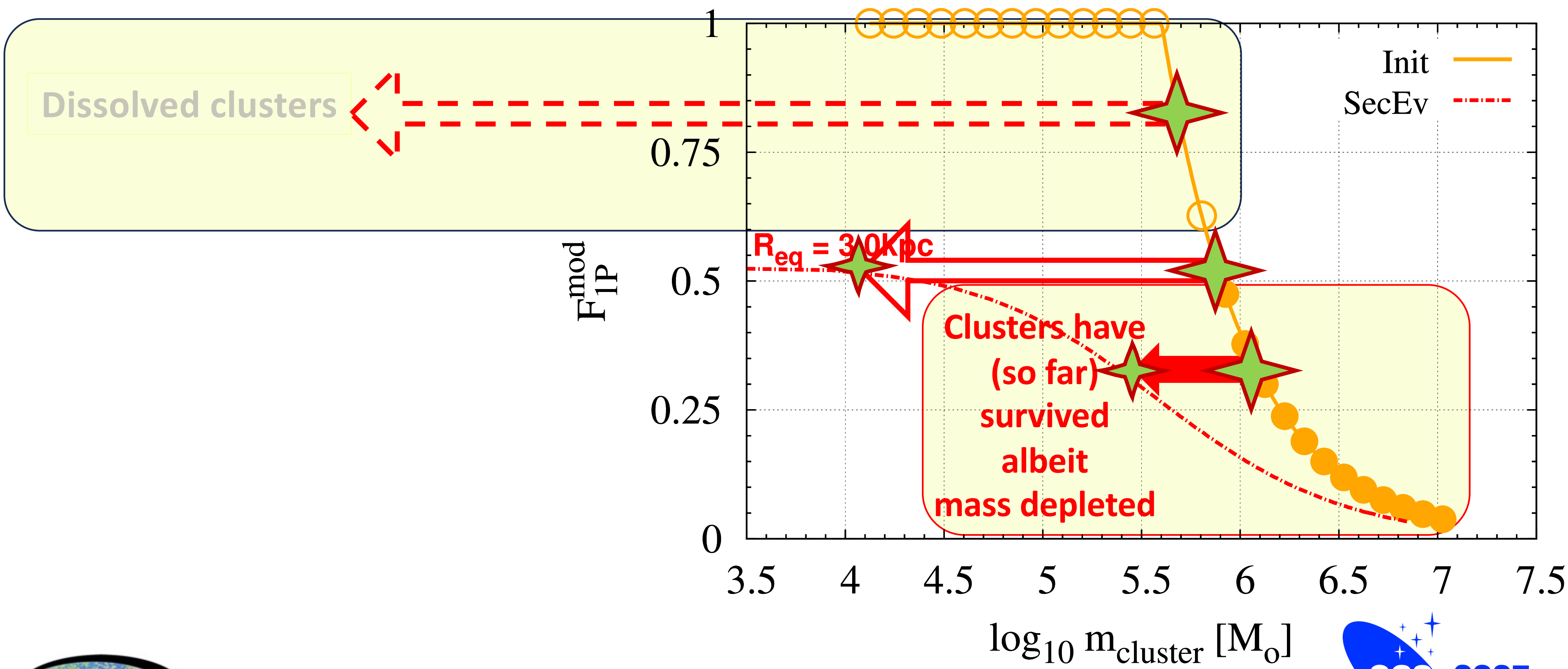

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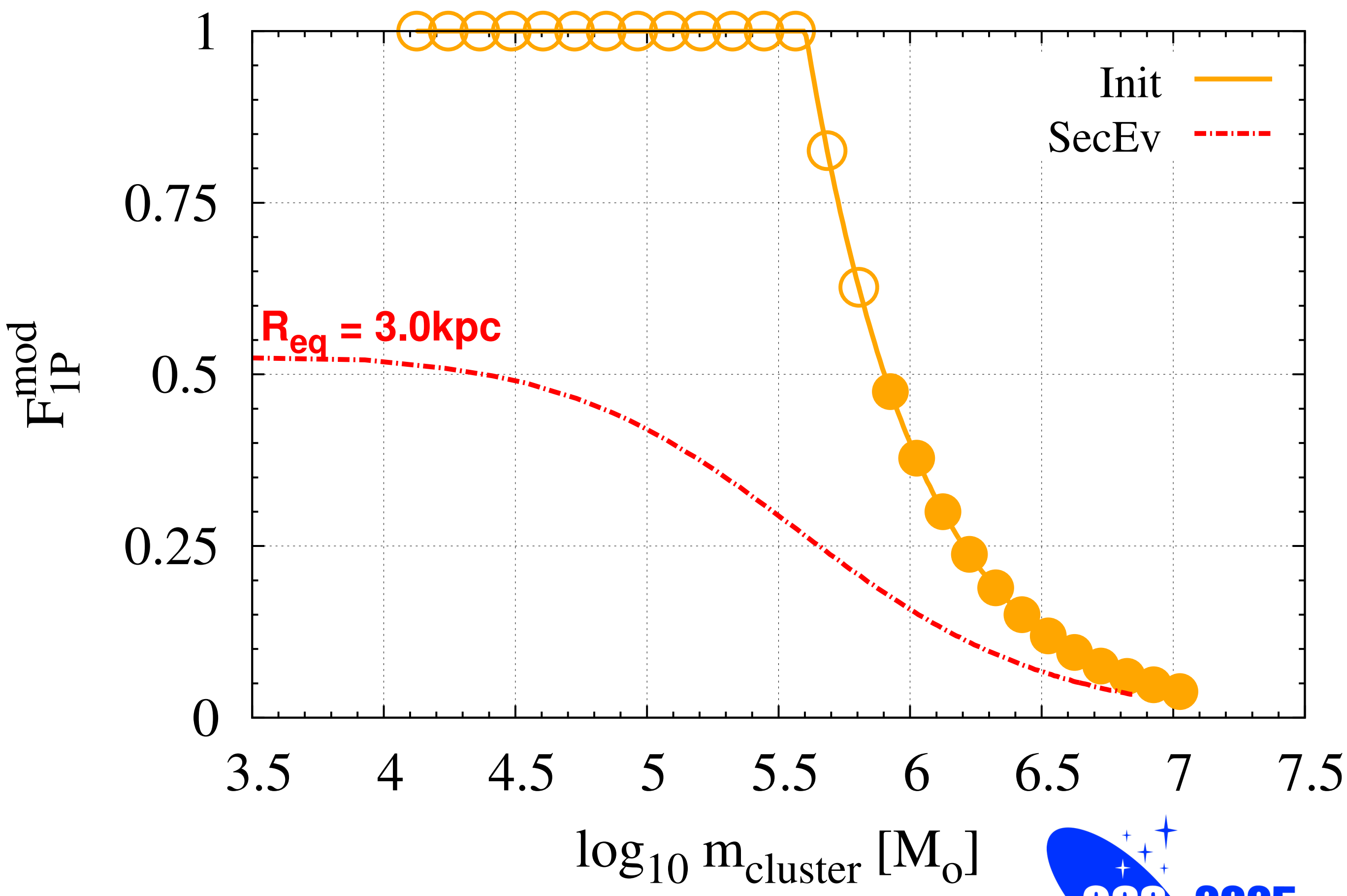
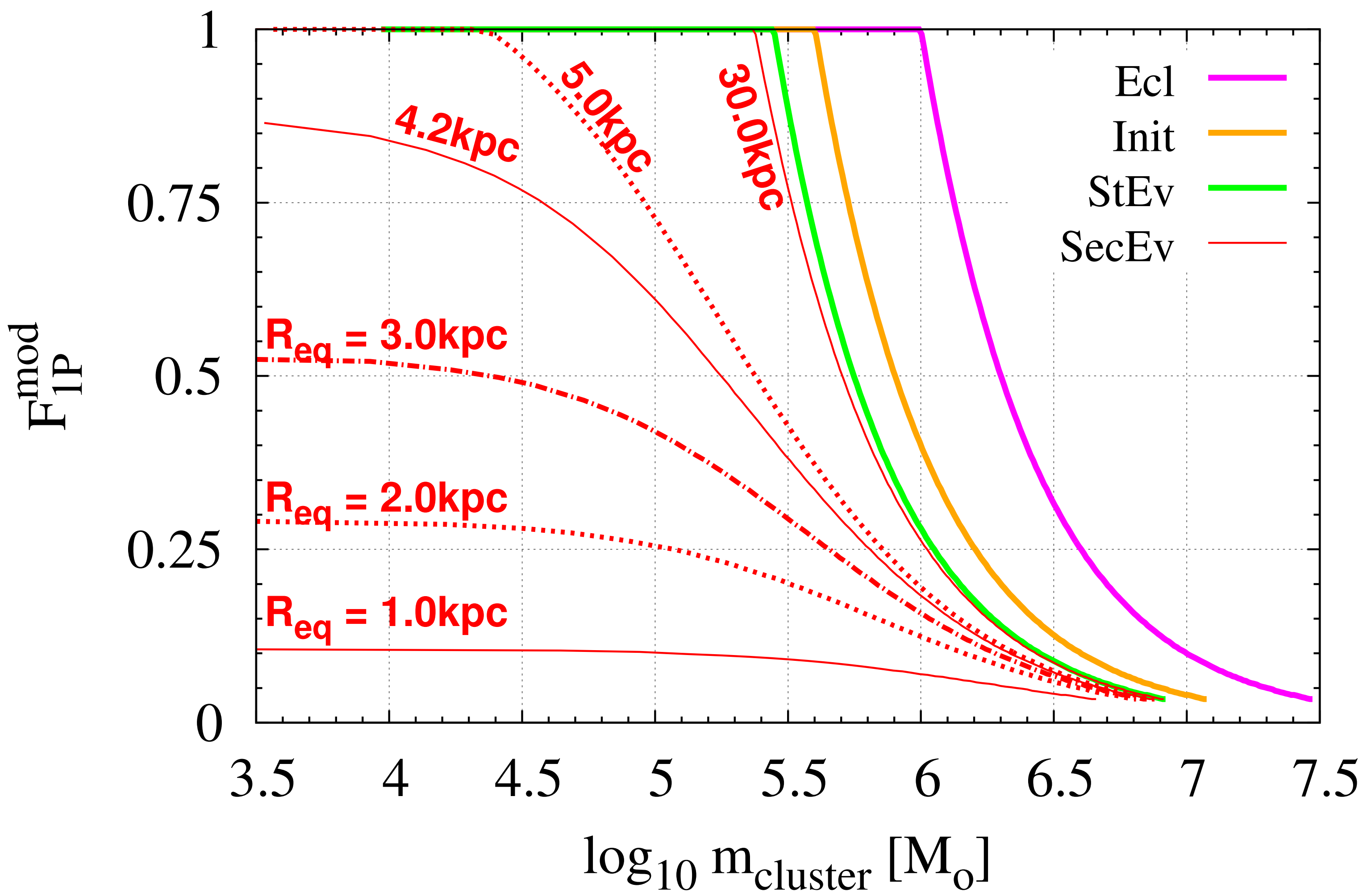


Secular Evolution: Two Extreme Behaviours



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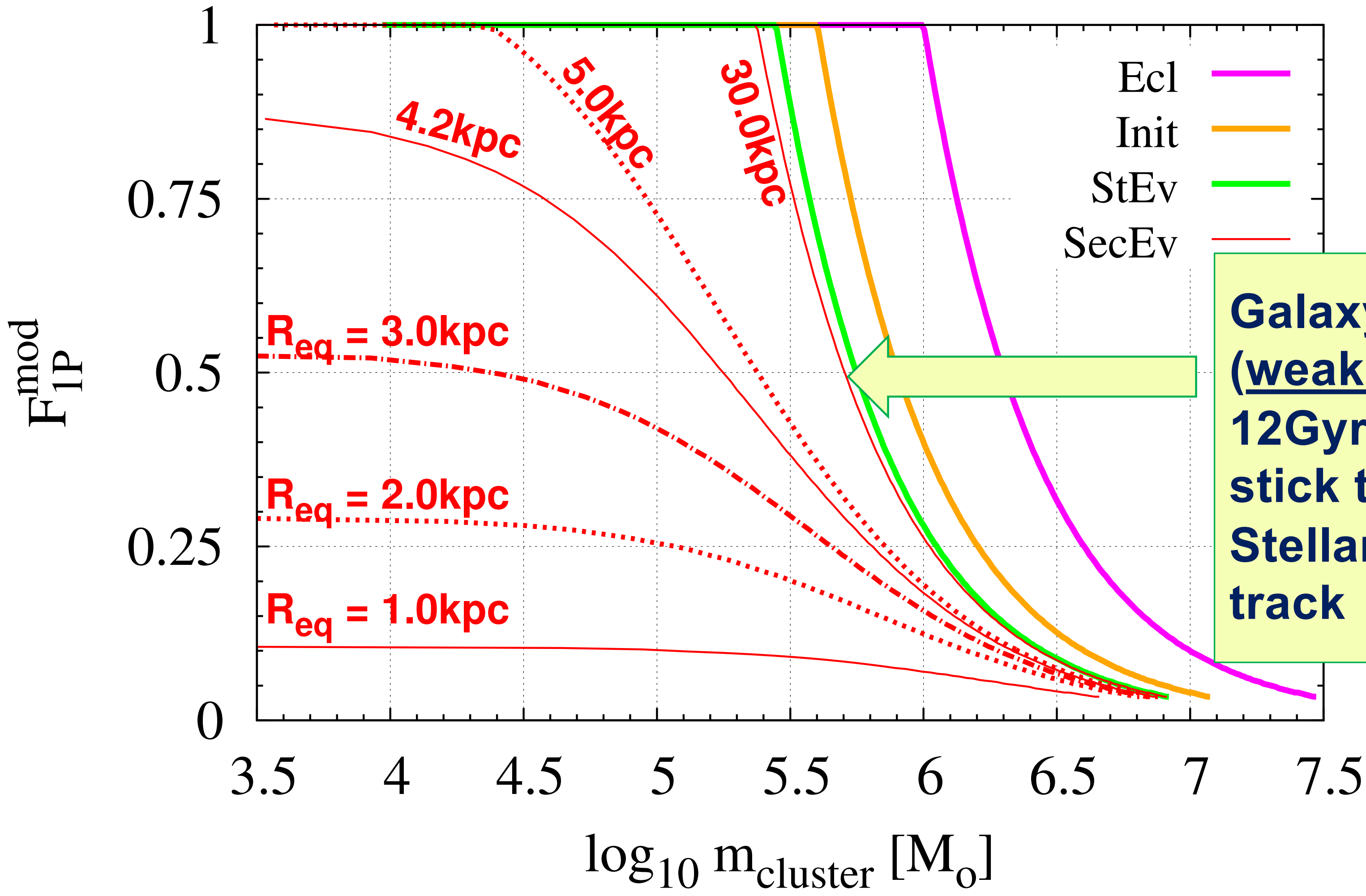
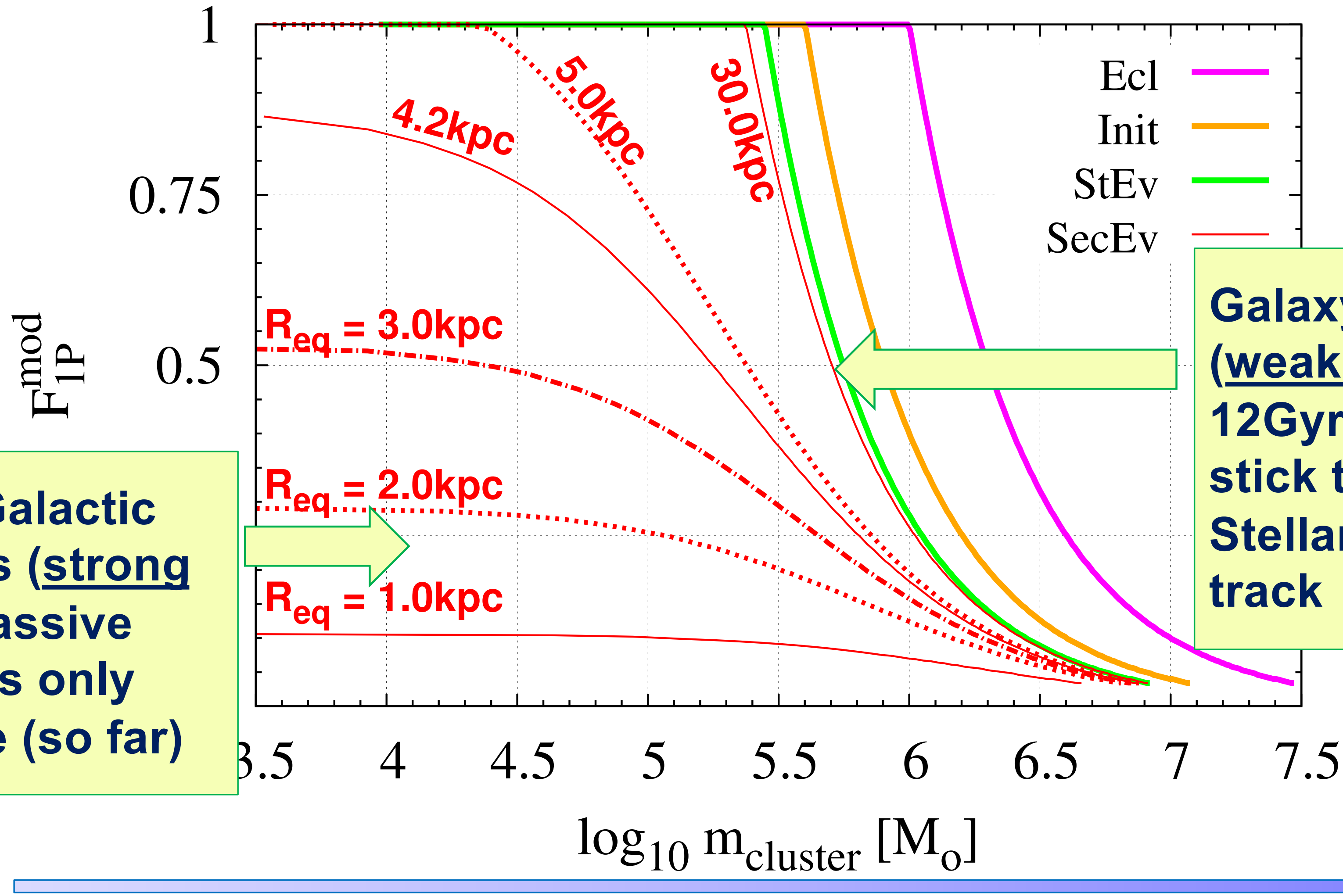


Galaxy outskirts (<u>weak tidal field</u>): 12Gyr-old tracks stick to the post-Stellar-Evolution track

Secular Evolution: Two Extreme Behaviours

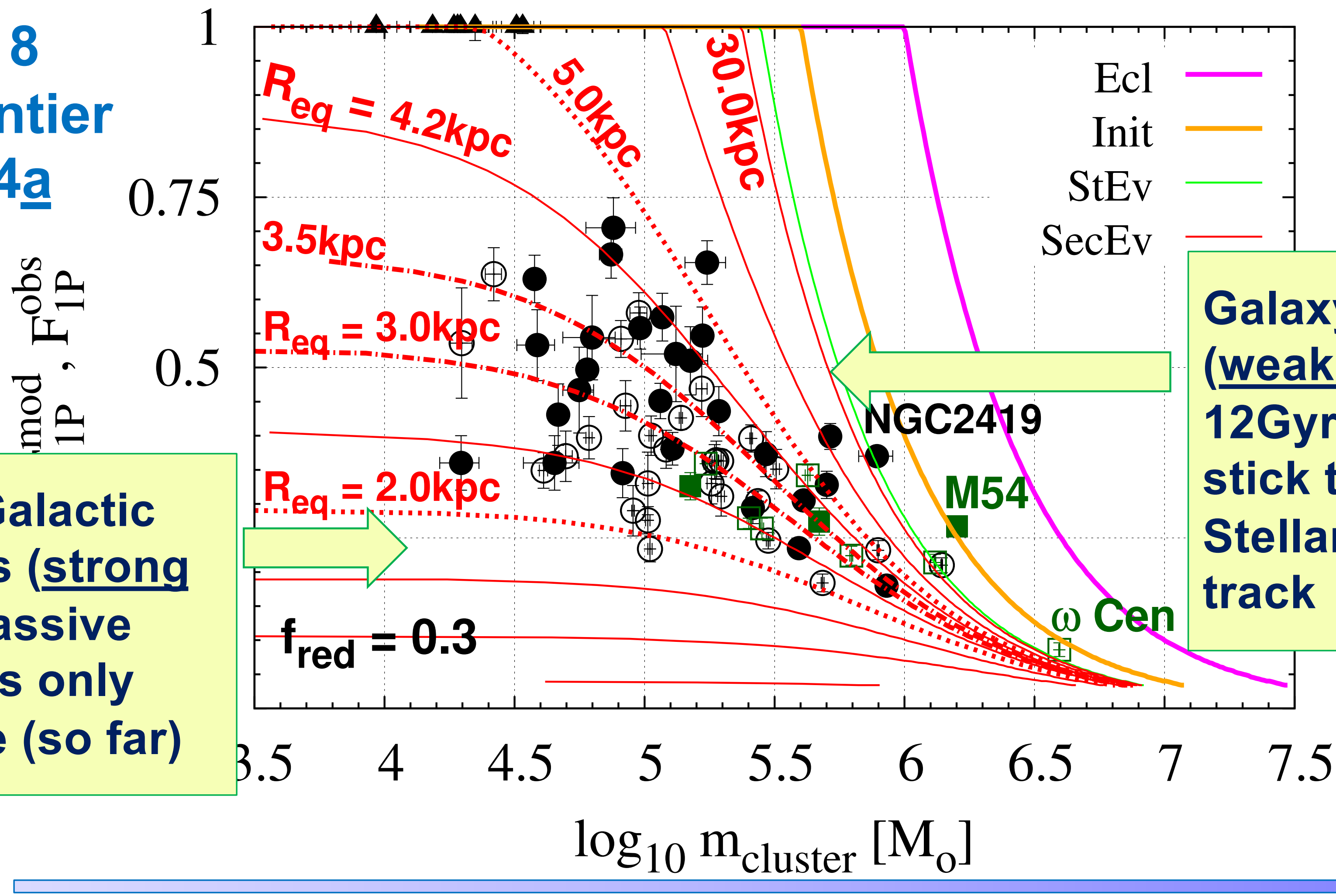


Inner Galactic regions (<u>strong t.f.</u>): massive clusters only survive (so far)

Galaxy outskirts (<u>weak tidal field</u>): 12Gyr-old tracks stick to the post-Stellar-Evolution track

Secular Evolution: Two Extreme Behaviours

Fig 8
Parmentier
2024a



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

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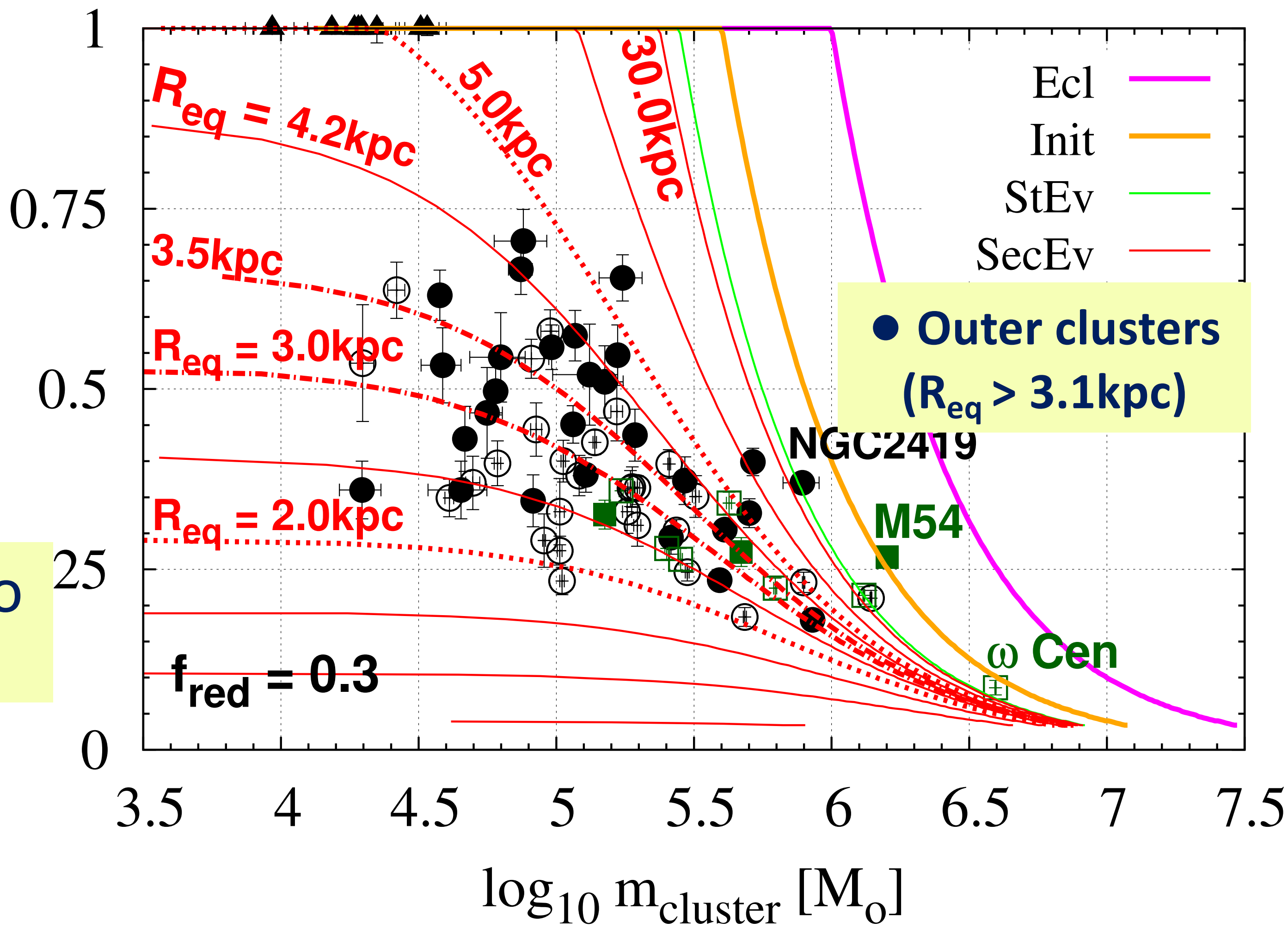
Inner versus Outer/Remote Clusters

Fig 8 Parmentier 2024a

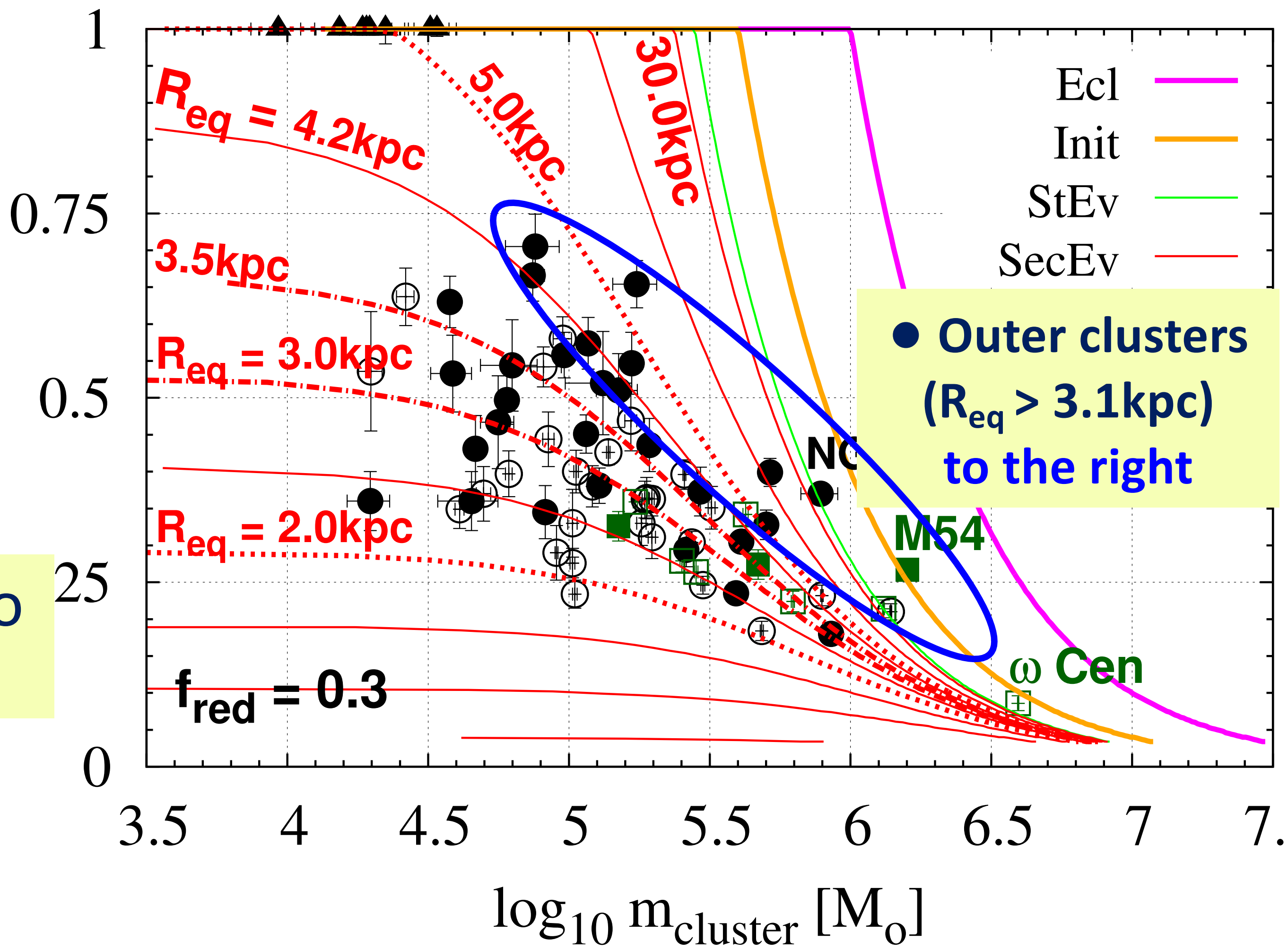


● Outer clusters (R_{eq} > 3.1kpc)

Inner clusters O (R_{eq} < 3.1kpc)

Inner versus Outer/Remote Clusters

Fig 8
Parmentier
2024a



Inner clusters O
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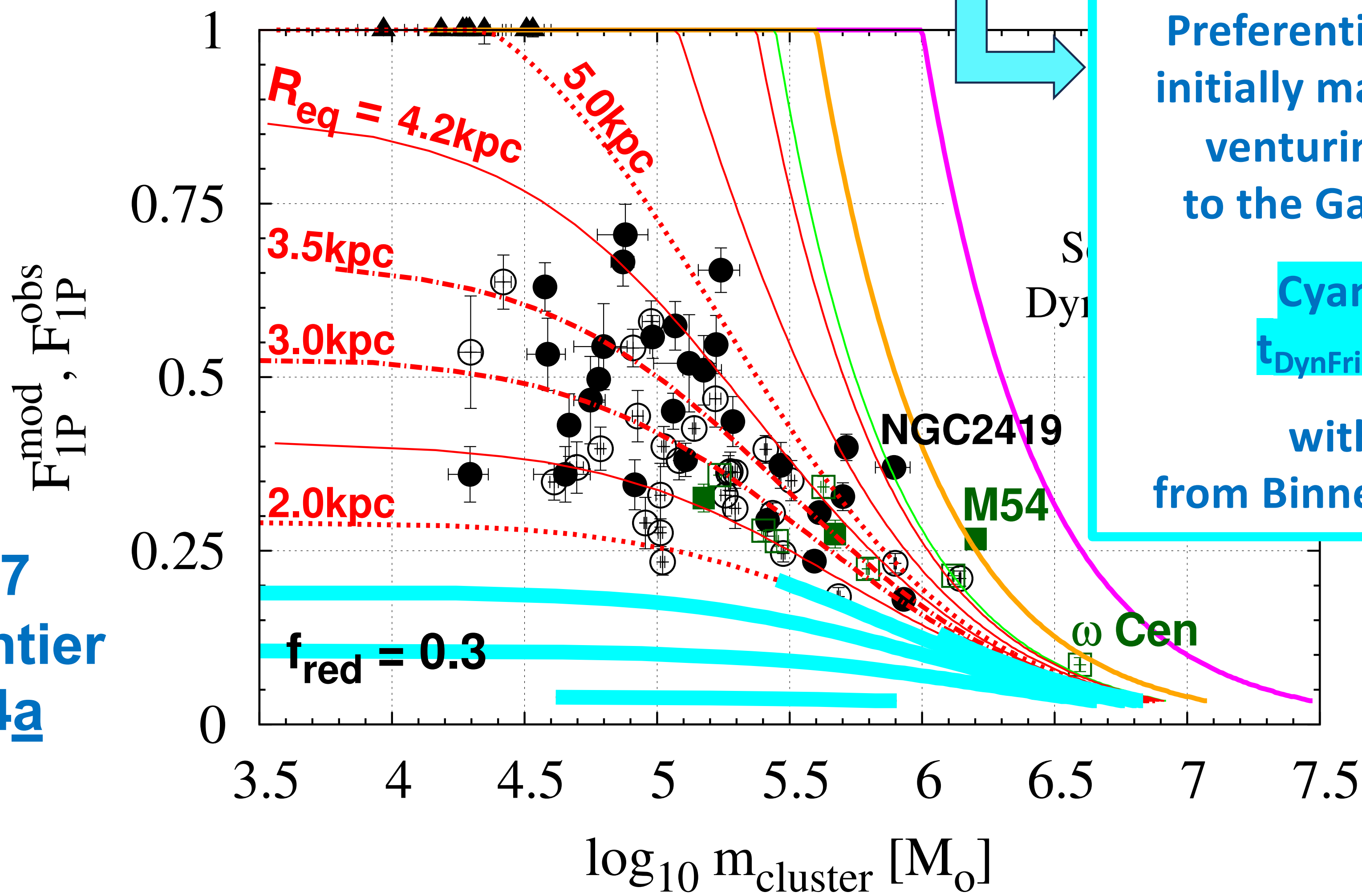
Dynamical Friction



Preferential removal of initially massive clusters venturing too close to the Galactic center

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

with $t_{DynFric}$ from Binney & Tremaine

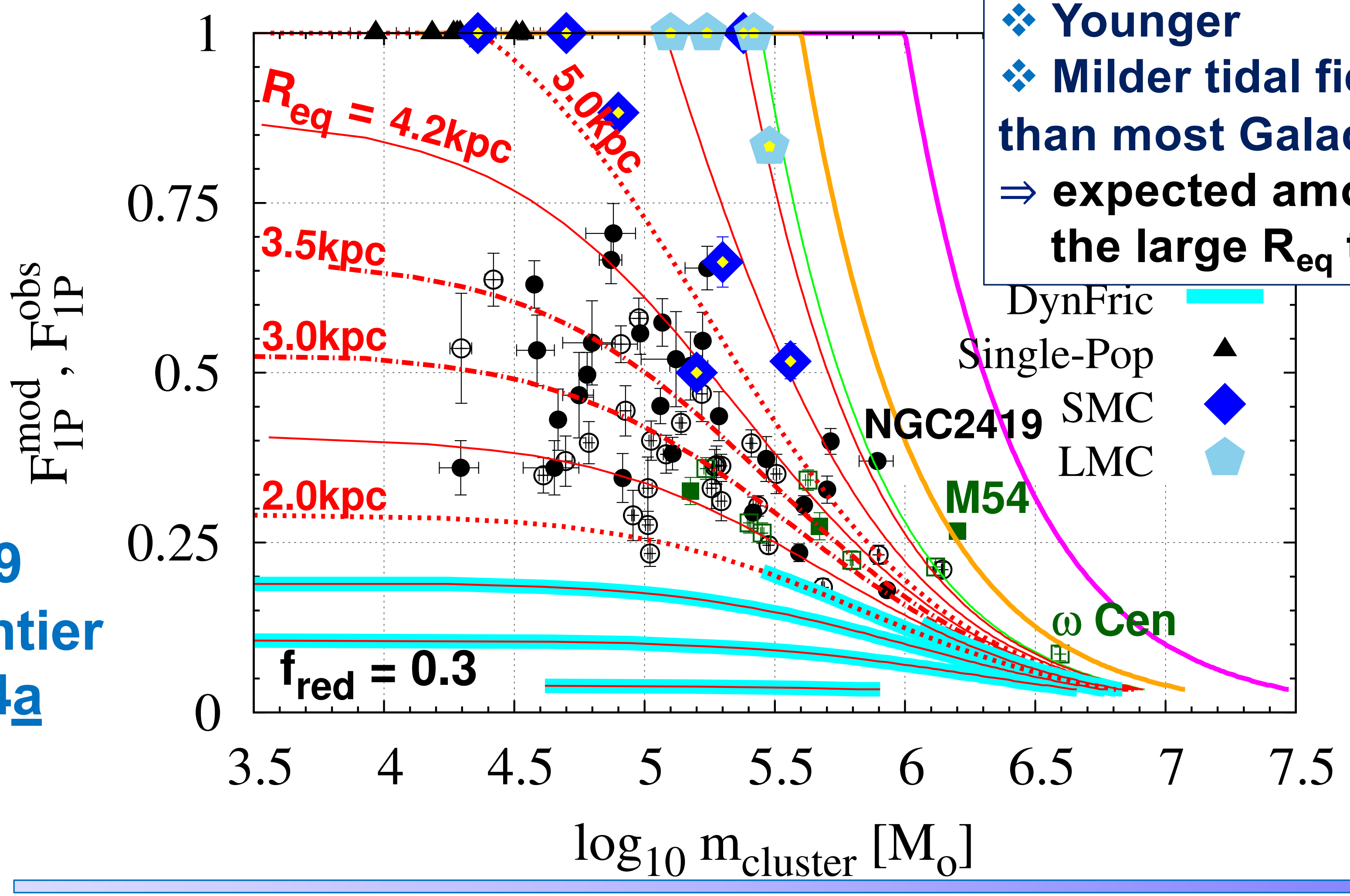
Fig 7 Parmentier 2024a

Magellanic Cloud Clusters

- Younger
- Milder tidal field than most Galactic GCs

$\Rightarrow$ expected among the large R_{eq} tracks

Magellanic Cloud Clusters



- Younger
- Milder tidal field than most Galactic GCs

⇒ expected among the large R_{eq} tracks

Fig9 Parmentier 2024a

What About Bringing the Data Points Back in Time ?

Present-Day, Disk group from Massari+2019 — **12Gyr ago, with primordial mass segregation**

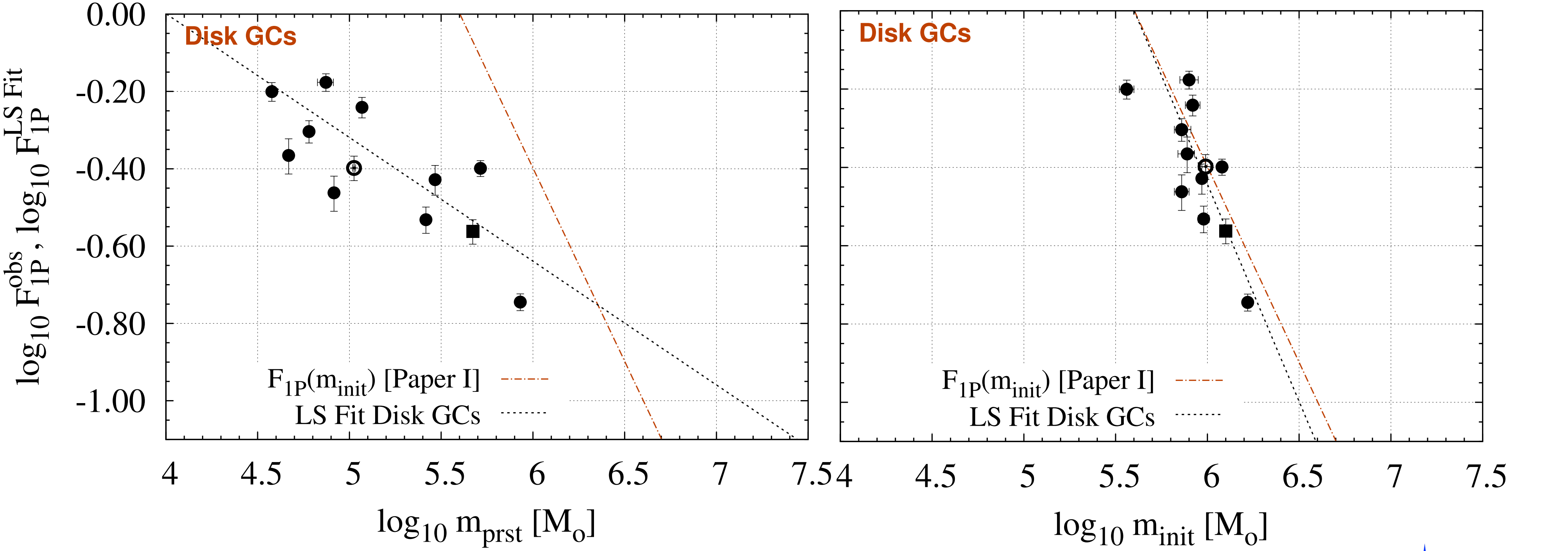


Fig4, Parmentier 2025

What About Bringing the Data Points Back in Time ?

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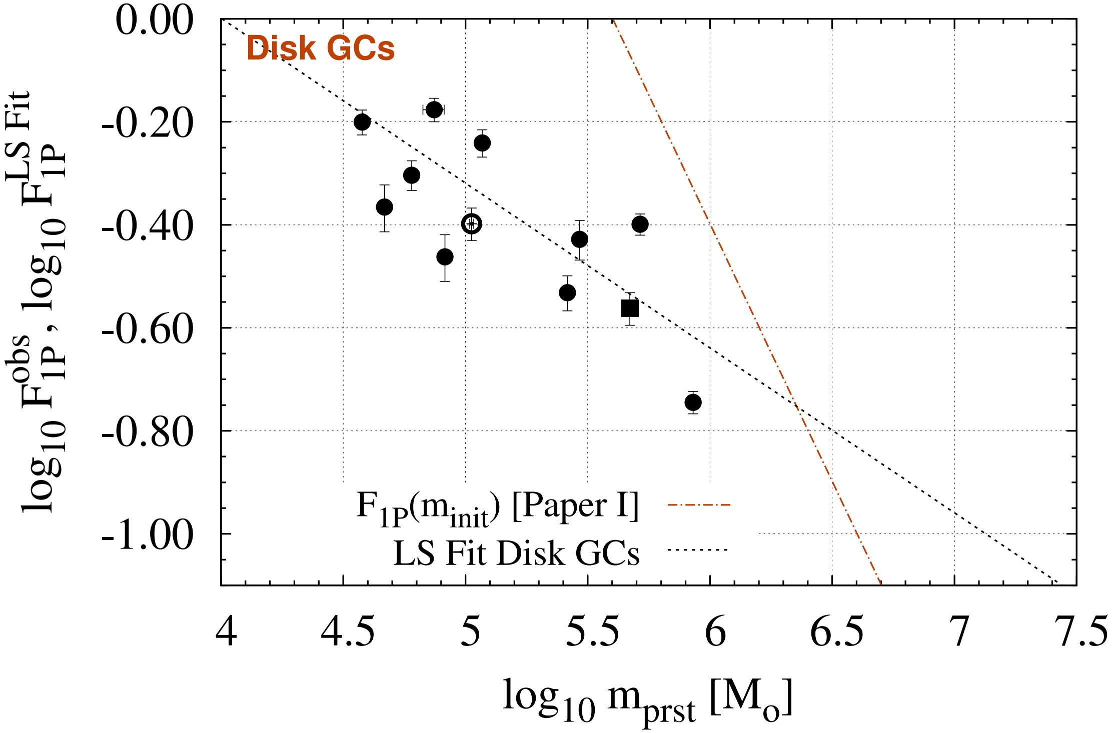
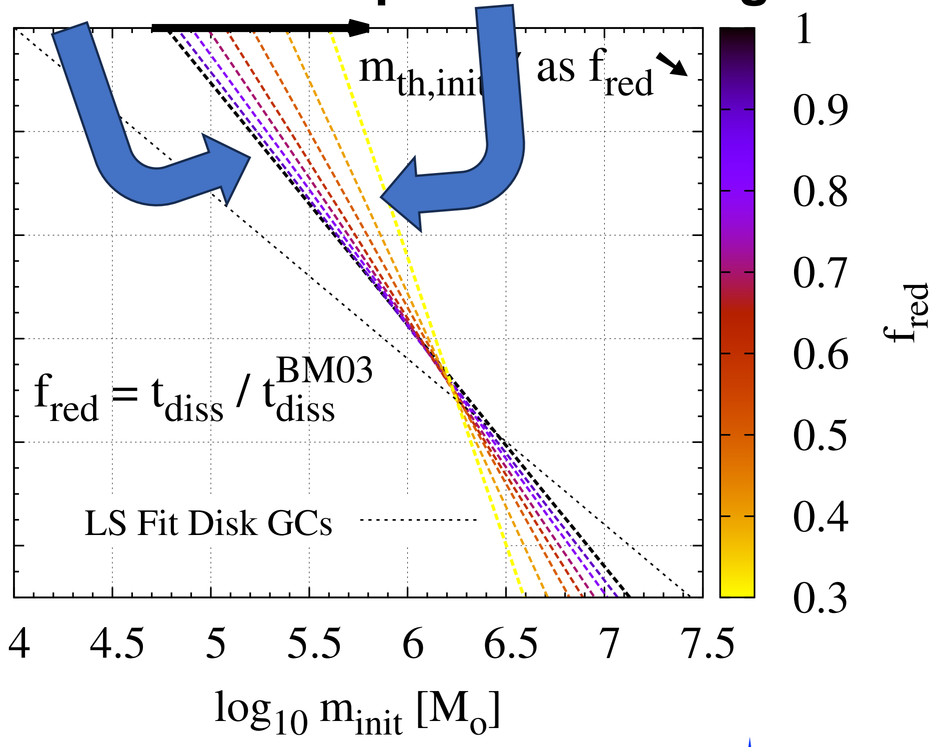


12Gyr ago,
without / with prim. mass seg.



Figs 4-5, Parmentier 2025

Take-Home Messages

- The observed (mass, F_{1P}) distribution of Galactic globular clusters

  could stem from $$\boxed{F_{1P} = \frac{m_{th}}{m_{ecl}}}$$ → instantaneous cluster pollution

  Parmentier 2024<u>a</u>

- Generalisation as $$\boxed{F_{1P} = \left(\frac{m'_{th}}{m_{ecl}}\right)^{\psi<1}}$$ → <u>non</u>-instantaneous cluster poll. (drop Hyp.II)

  Parmentier 2024<u>b</u>

  Parmentier 2025

What About Bringing the Data Points Back in Time ?

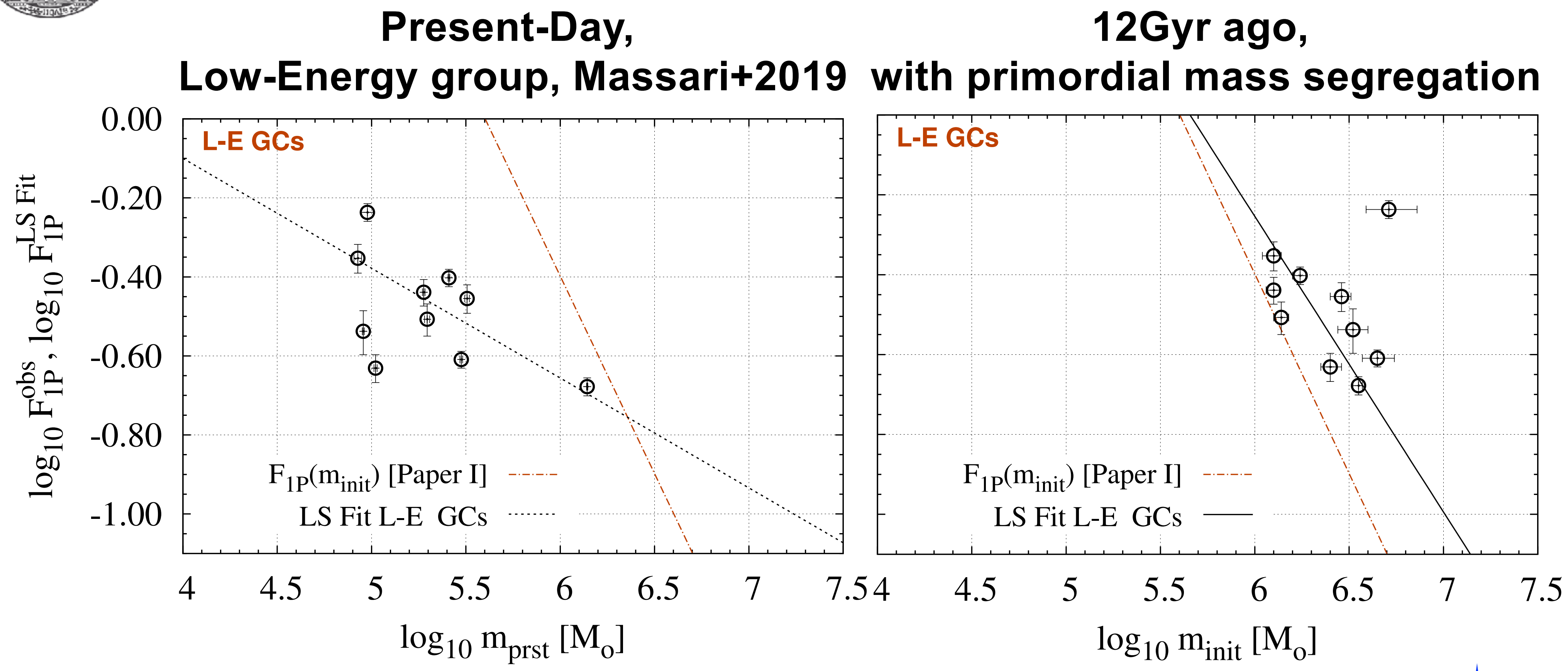


Fig 7 (left) , Parmentier 2025

Supplementary Material

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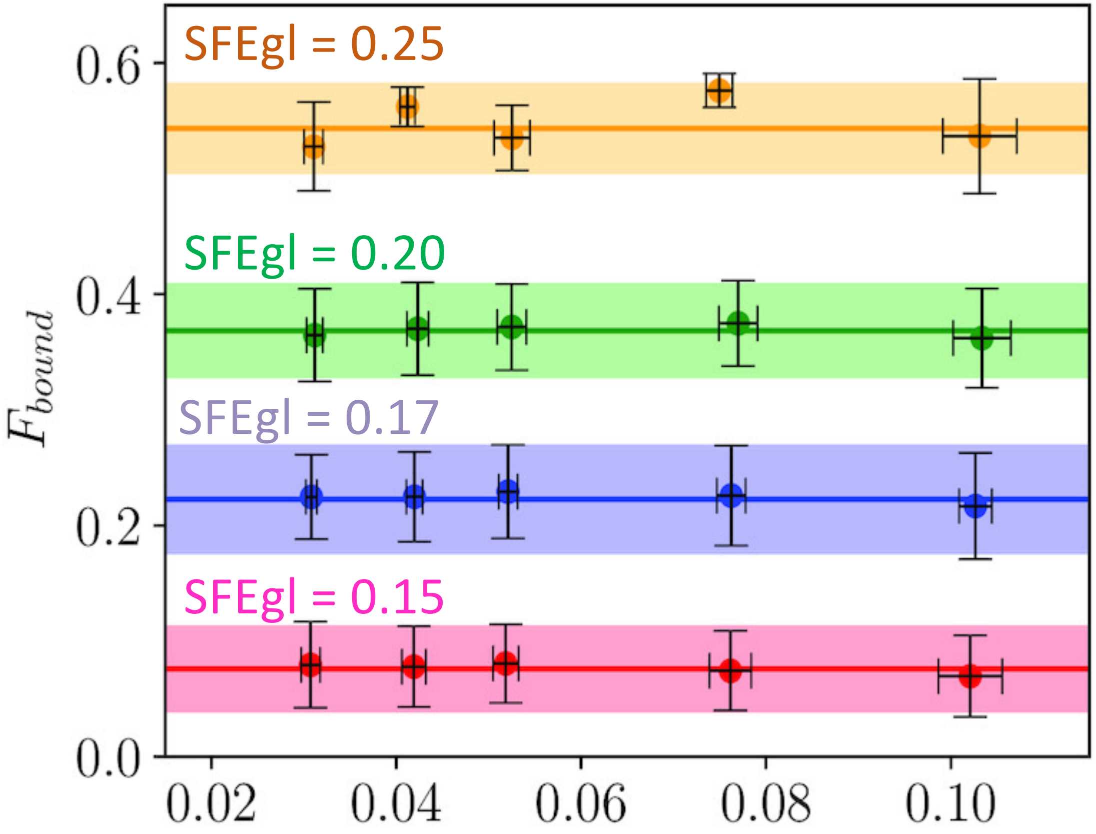
Evolution with $F_{bound}^{VR} = constant$ during Violent Relaxation

- F_{bound}^{VR} more robust to environmental variations than thought in the past (e.g. external tidal field)

- Could violent relaxation be a non-event for newly formed compact massive clusters?
  If SFE → 1 (Polak+2023), $F_{bound}^{VR} \rightarrow 1$

Fig4, Shukirgalyiev, Parmentier + 2019



r_{hm} / r_J at gas expulsion onset

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

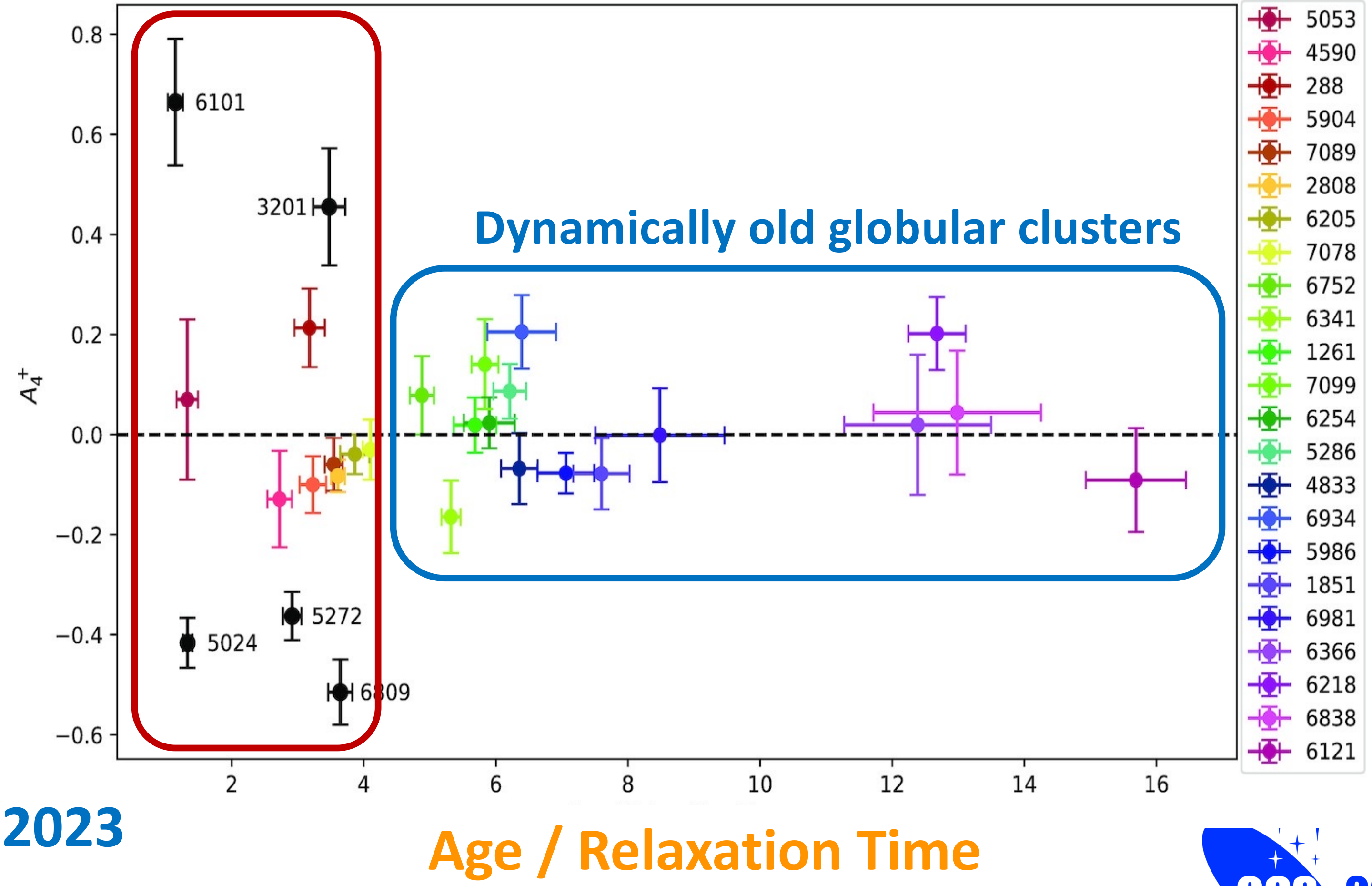
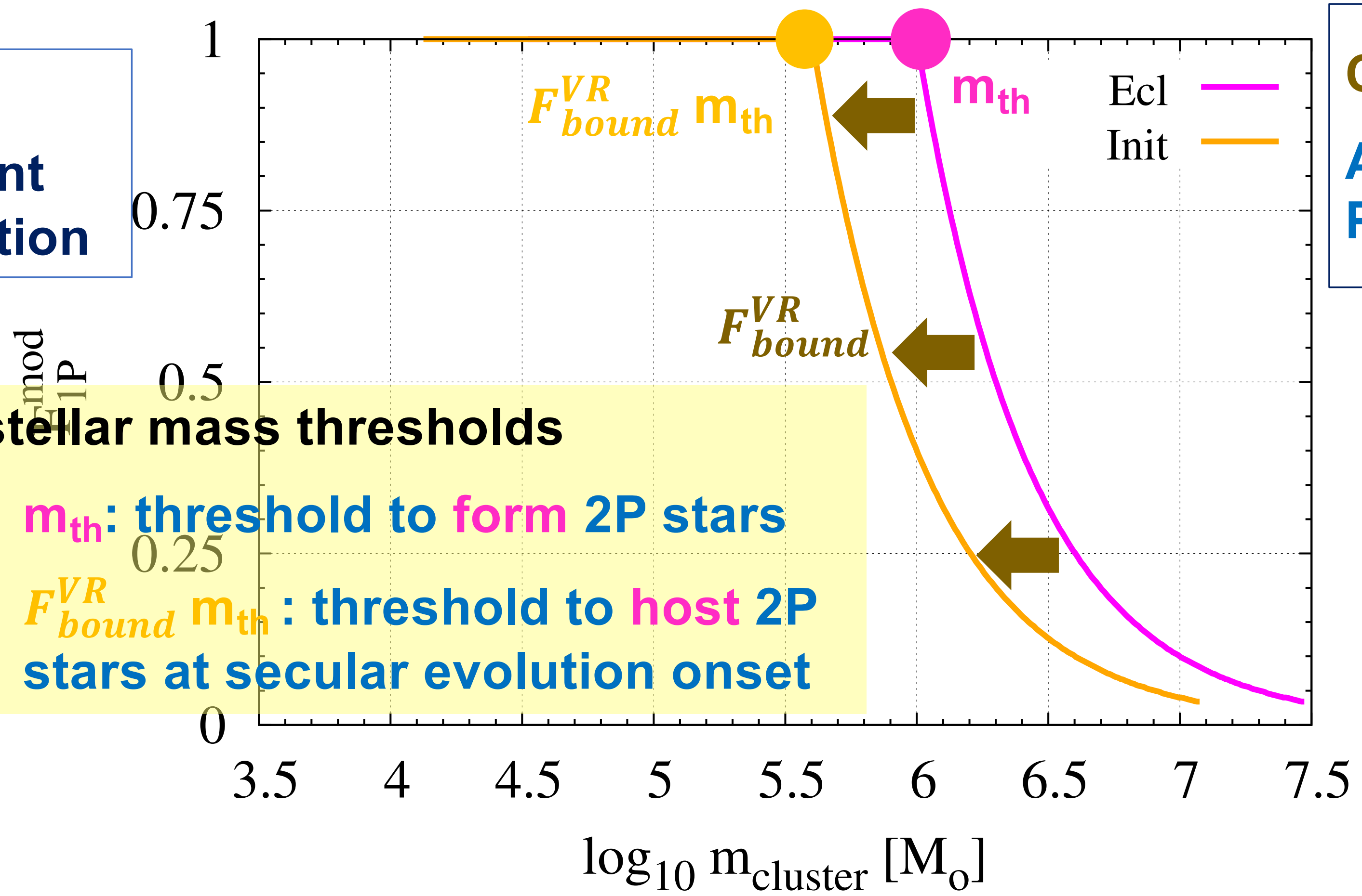


Fig15, Leitinger+2023

Residual Star-Forming Gas Expulsion & Violent Relaxation

VR: Violent Relaxation



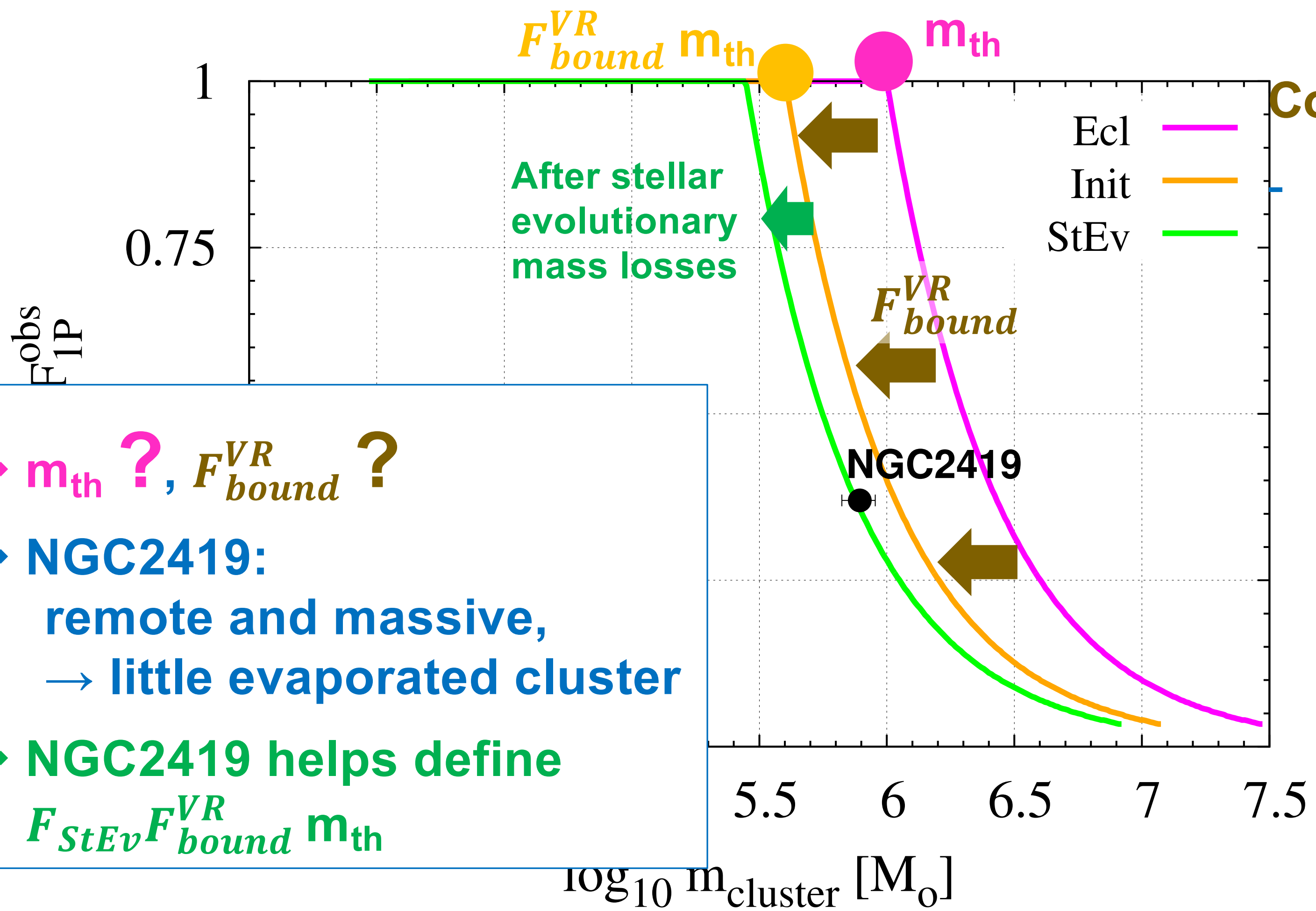
2 stellar mass thresholds

- m$_{th}$: threshold to form 2P stars
- F^{VR}_{bound} m$_{th}$: threshold to host 2P stars at secular evolution onset

Constancy of F^{VR}_{bound}:

Appendices A+B in Parmentier 2024a

NGC2419 as a Calibrator



- m$_{th}$?, F_{bound}^{VR} ?
- NGC2419:
  remote and massive,
  → little evaporated cluster
- NGC2419 helps define
  $F_{StEv}F_{bound}^{VR}$ m$_{th}$

Constancy of F_{bound}^{VR}:

- Appendices A1-A2 in Parmentier 2024a

Secular Evolution up to the Age of 12Gyr

Cluster evaporation
in the Galactic tidal field,
aka secular evolution

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

Cluster dissolution time-scale of Baumgardt & Makino (2003)

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

Calibration of f_{red}: Sec. 3 in Parmentier 2024a

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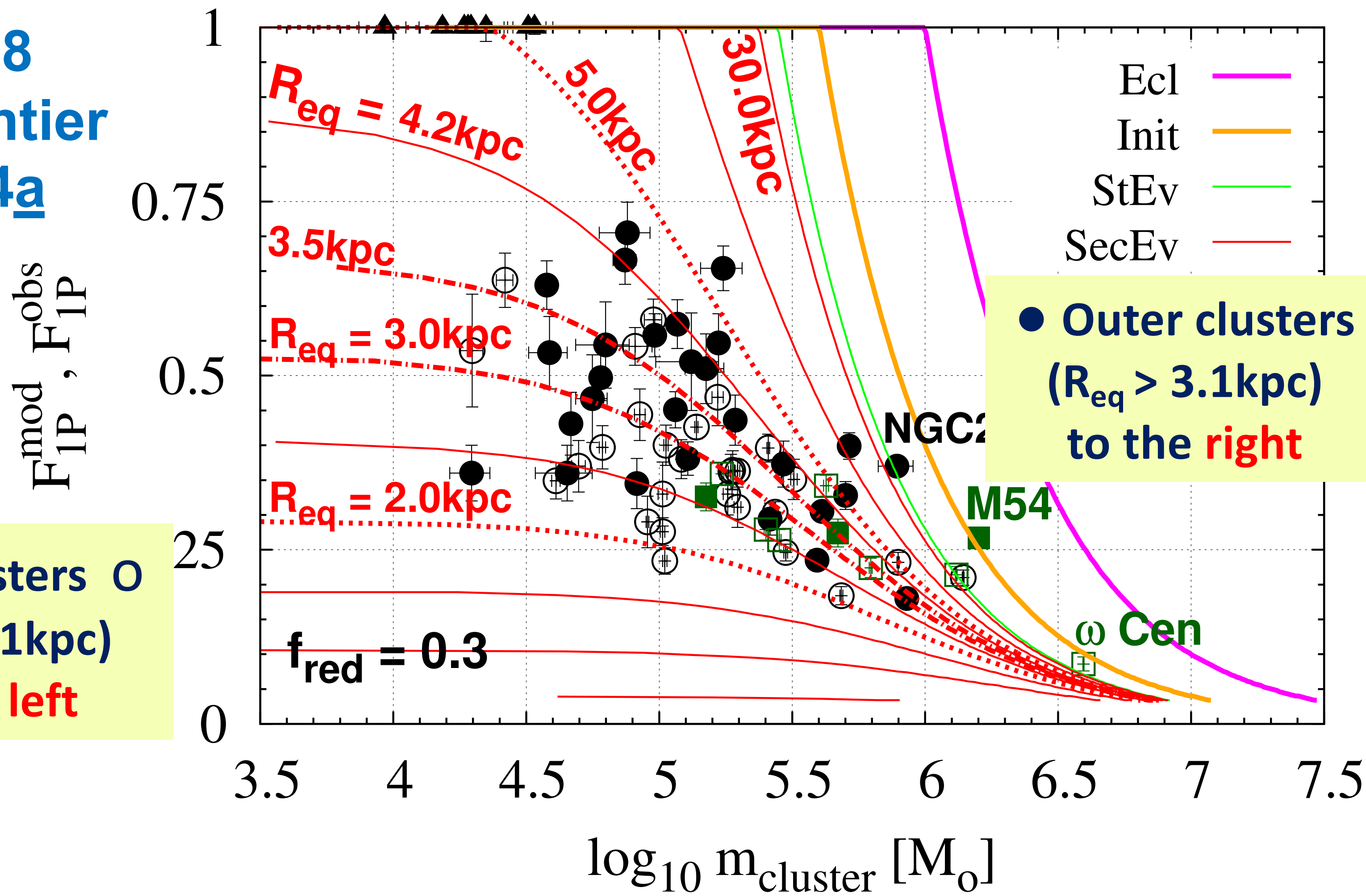
Inner versus Outer/Remote Clusters

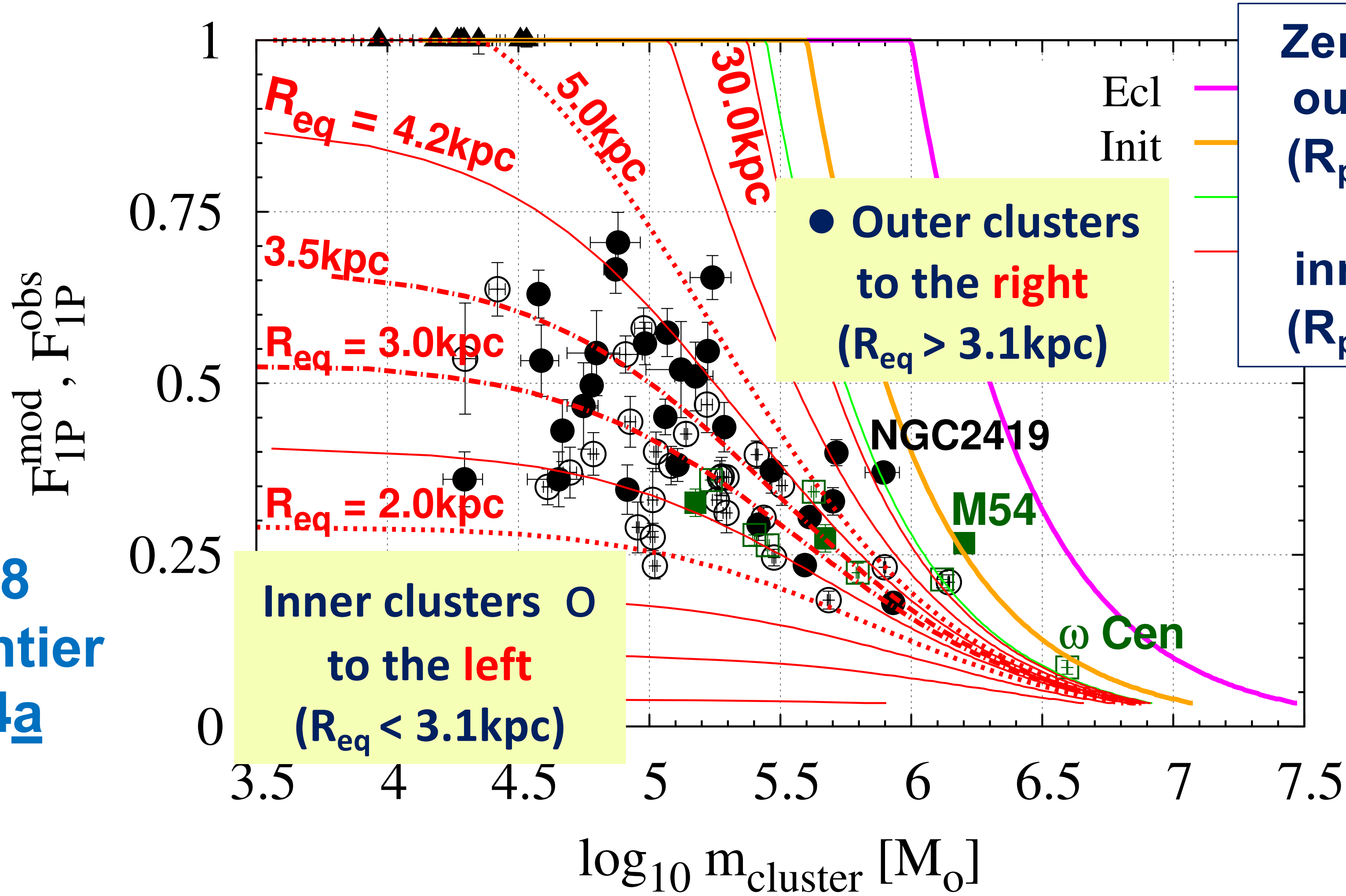
Fig 8 Parmentier 2024a



● Outer clusters (R_{eq} > 3.1kpc) to the right

Inner clusters O (R_{eq} < 3.1kpc) to the left

Inner versus Outer/Remote Clusters



Zennaro+2019: outer clusters (R_{peri} > 3.5kpc) on top of inner clusters (R_{peri} < 3.5kpc)

Fig 8 Parmentier 2024a

An Observational Constraint …

The fraction of 2P stars in the Galactic halo field is low:
3%-10%
Carretta+ 2010 - Martell+ 2011 – Horta+21

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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to lose equally-likely their 1P and 2P stars
may therefore be perceived as a problem.

Yet, it is not

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