Orbiting globular clusters formed in dark matter mini-halos

Eduardo Vitral & Pierre Boldrini - submitted to MNRAS (in review)

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How do globular clusters form?

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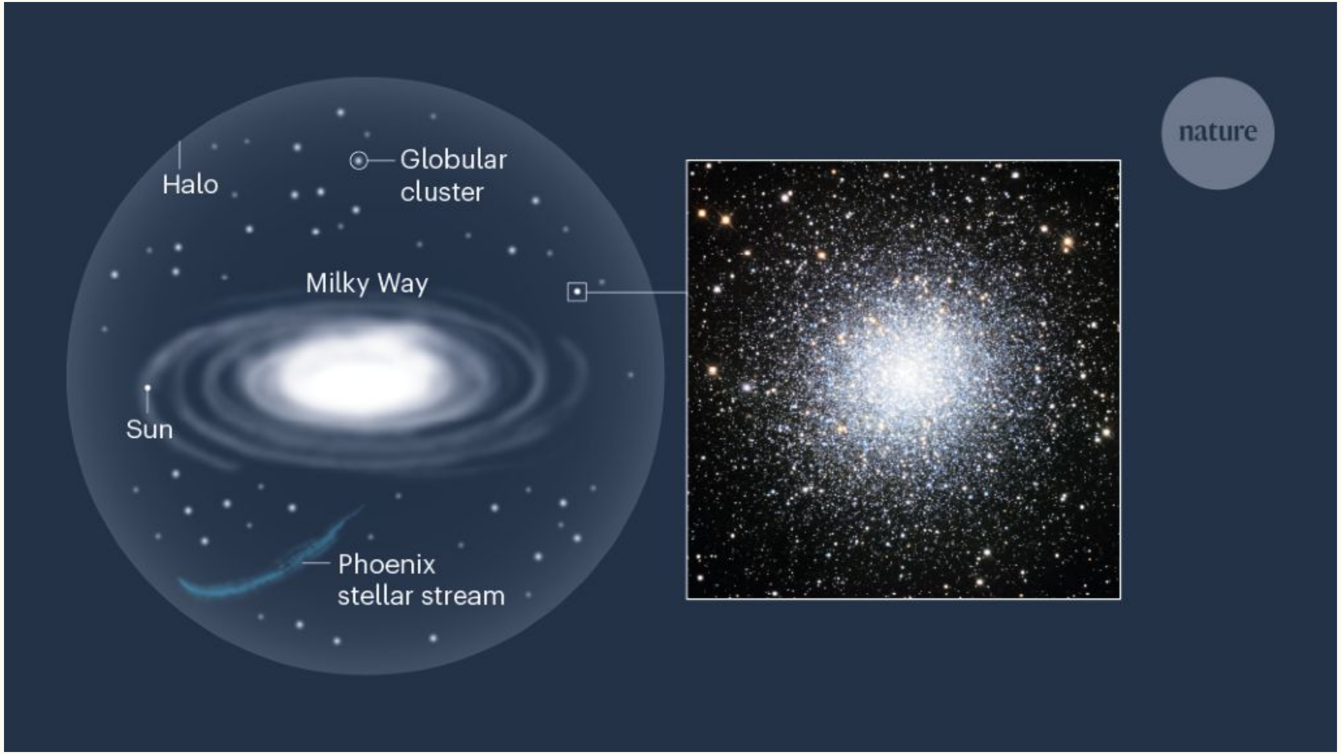

Image credits: *Nature*

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Different formation scenarios:

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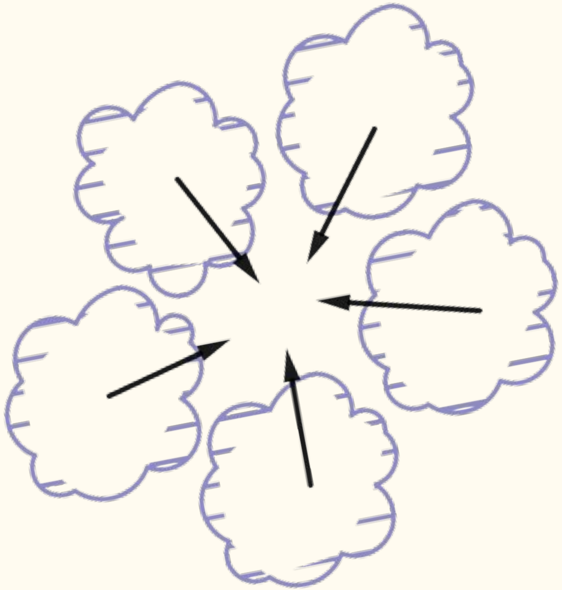

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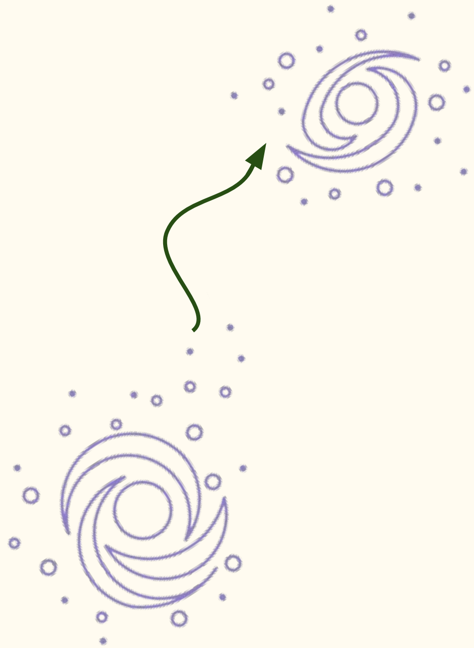

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Image credits: *ESA/Hubble & NASA*

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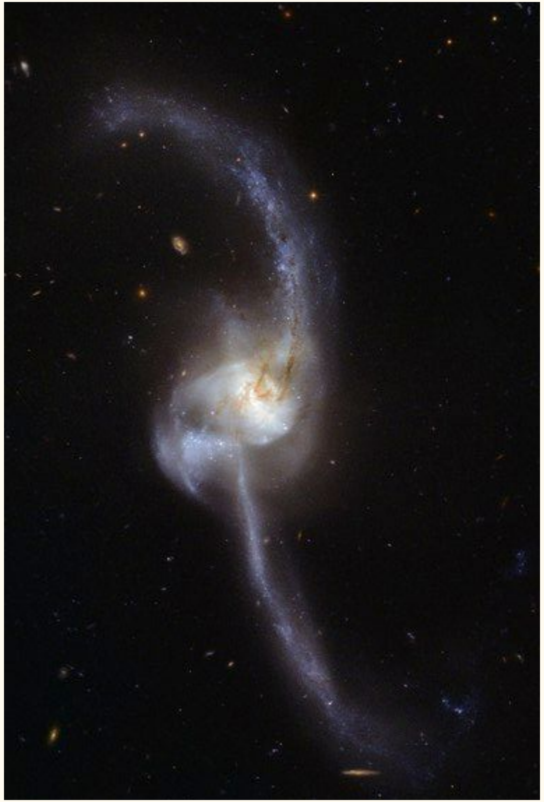

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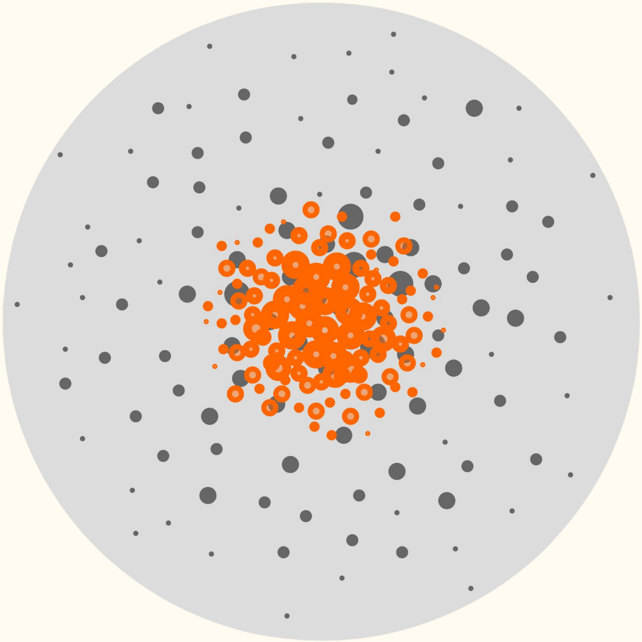
- **Formed inside their own DM mini-halo, such as galaxies** (Peebles 1984).



How to model a mini-halo?

Dark matter mini-halos

Main difficulties and previous attempts:

- Cosmological simulations: poor resolution.

  e.g.: Keller et al., 2020, E-MOSAIC → $10^4\ M_\odot$

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- Milky Way: live N-body particles not feasible.

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- Influence of tides.

  e.g.: Peñarrubia et al., 2017 → Isolated globular clusters.

Dark matter mini-halos

Solution:

➢ We use a dwarf galaxy to constrain tidal effects (realistic initial conditions from Boldrini et al., 2020).

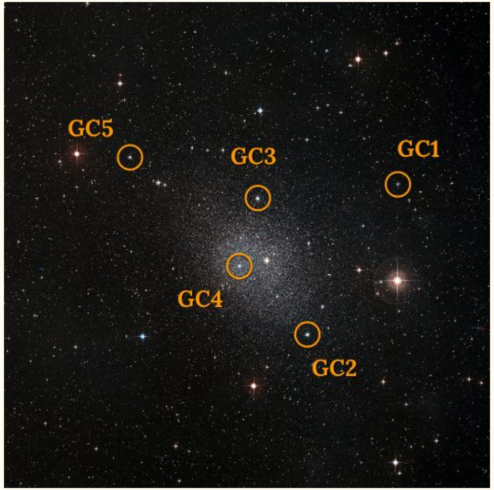

Image credits: *Giuseppe Donatiello & ESO/Digitized Sky Survey 2*

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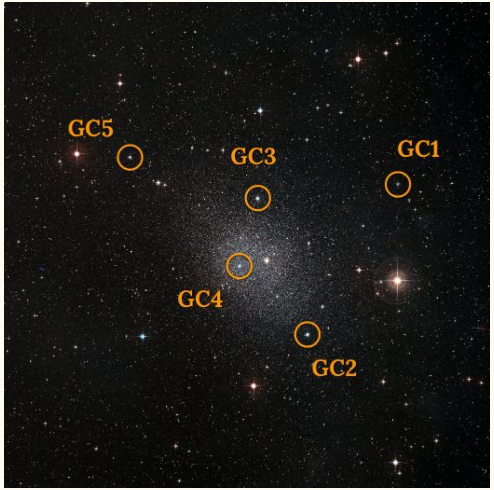

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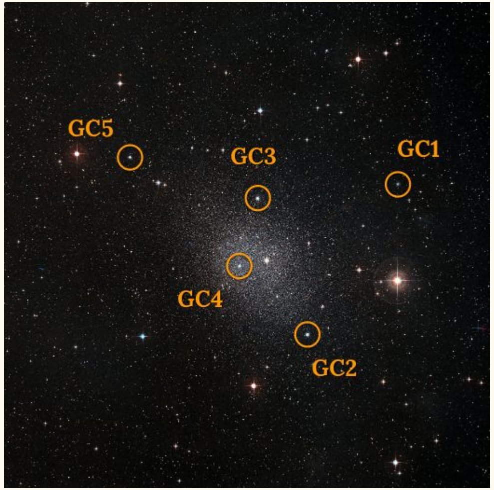

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- $m_{\star,GC} = m_{\star,Fornax} = m_{DM,GC} = m_{DM,Fornax} = 50\ M_{\odot}$
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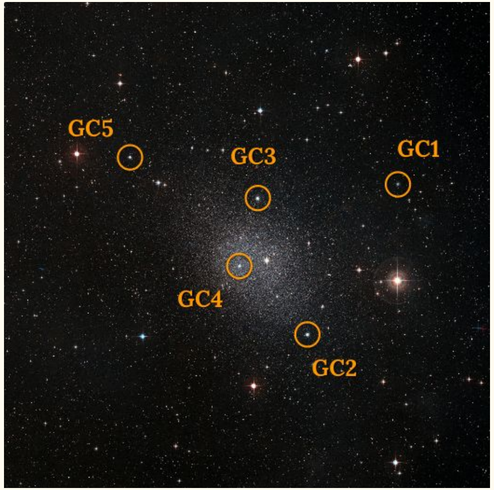
  $M_{DM,GC} = 2 \times 10^7\ M_{\odot}$



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What to expect?

Dynamical implications

Dynamical heating from dark matter: Higher mass → More velocity dispersion → More stars manage to escape the globular cluster potential

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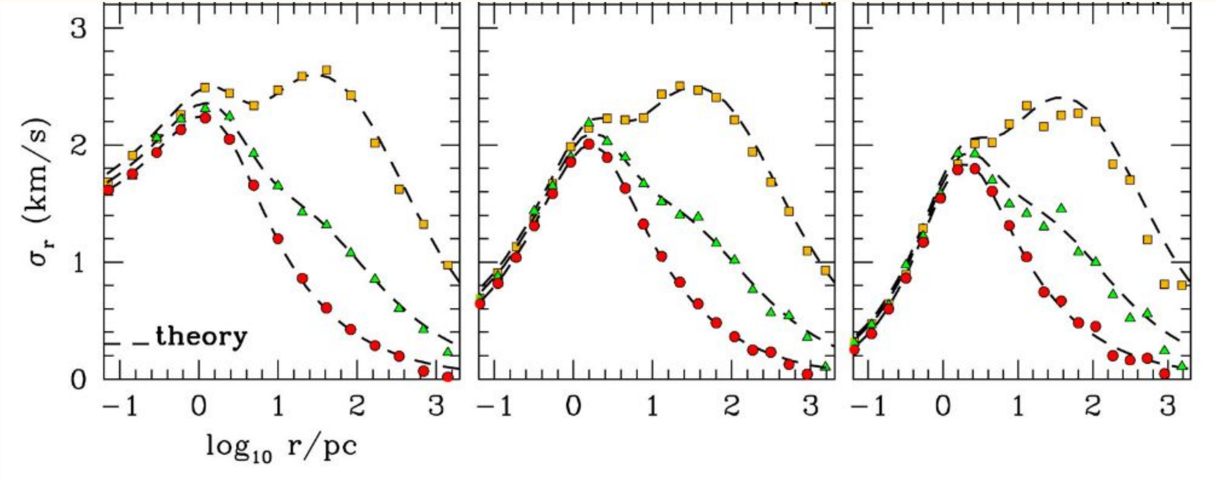

Peñarrubia et al., 2017

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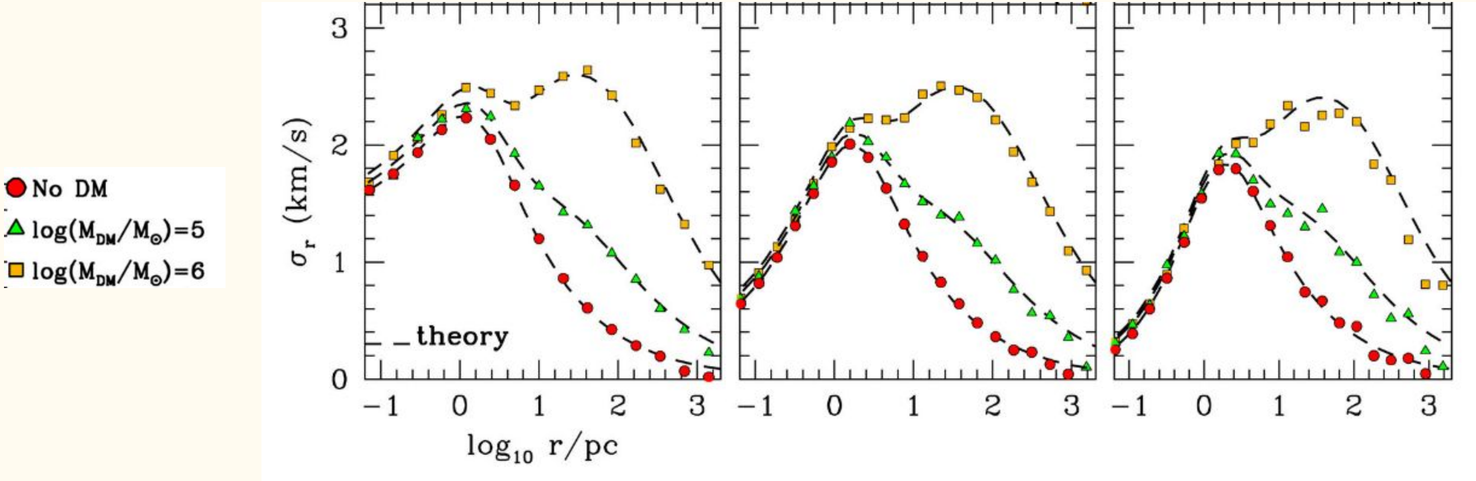

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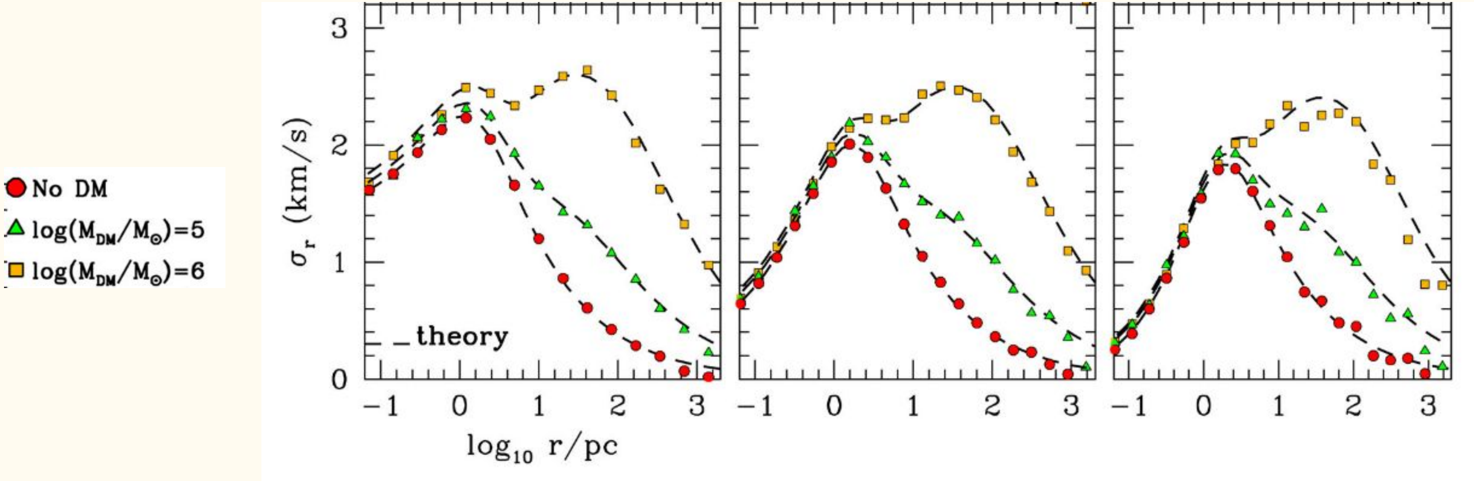
Different velocity distributions



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Dynamical implications

Faster orbital decay: Higher mass → More dynamical friction

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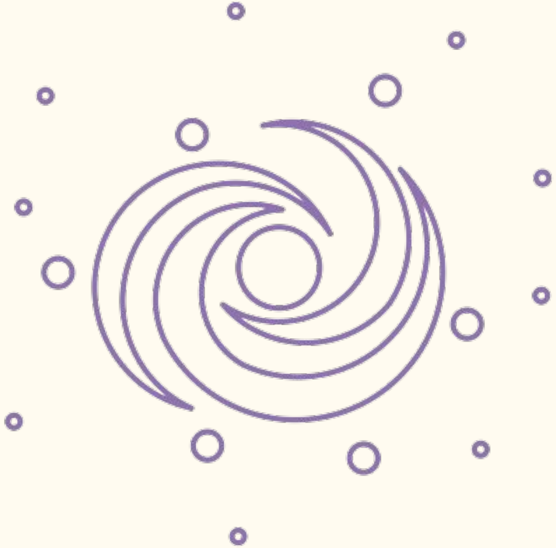

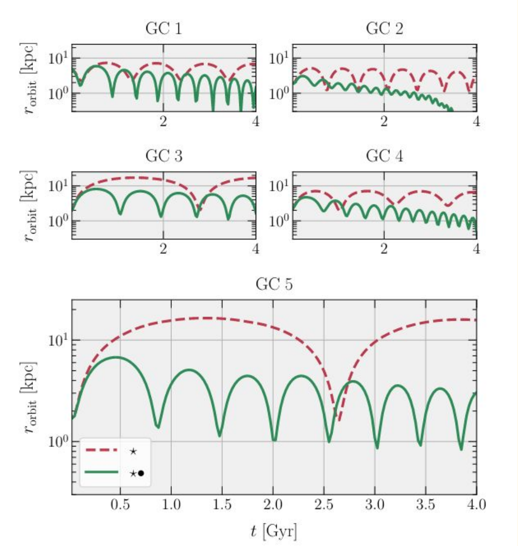

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Increase of the tidal radius: $r_t \propto M^{1/3}$

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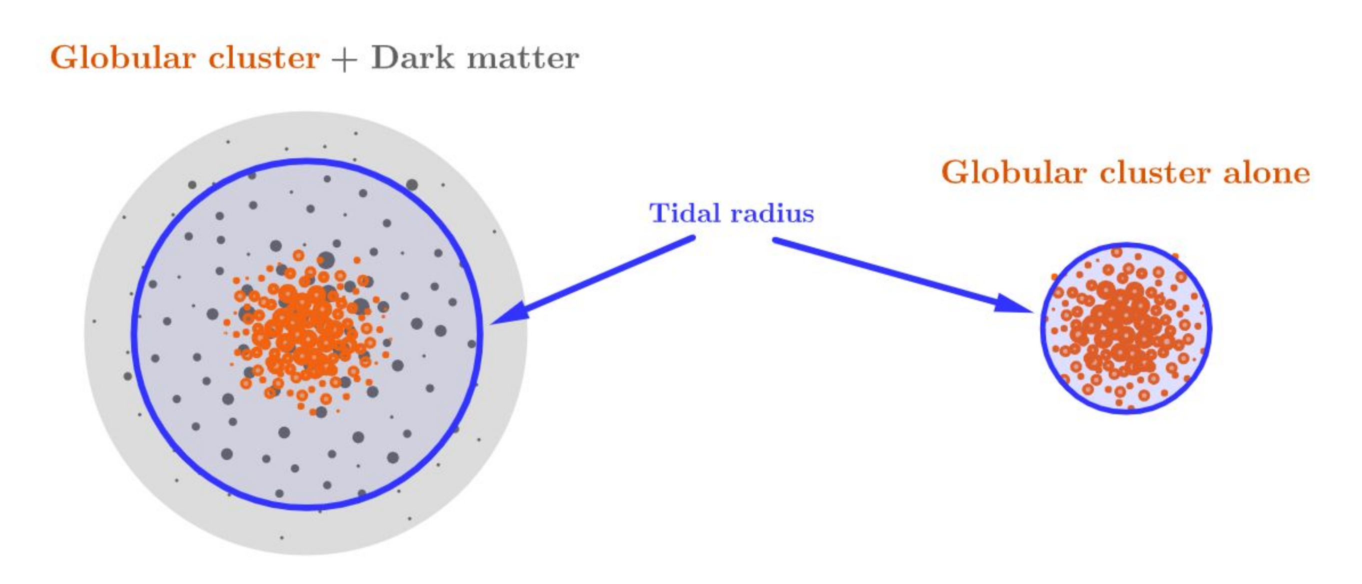

Dynamical implications

Dynamical heating
(disruptive)

Orbital decay
(disruptive)

Tidal radius growth
(protective)

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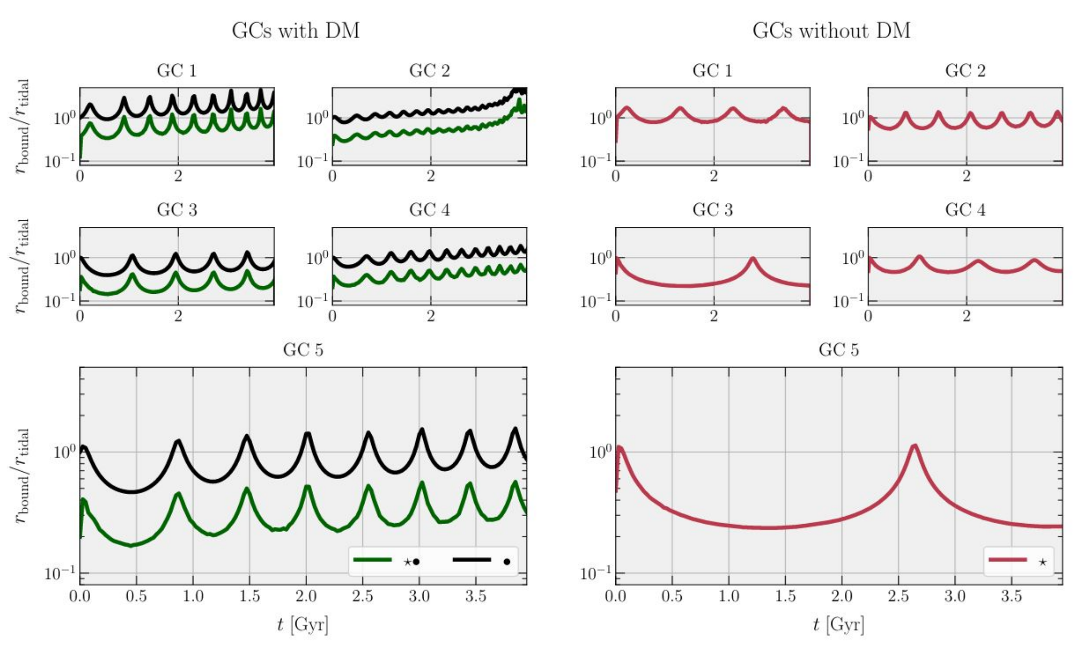
→ **Which one prevails?**

What do our simulations tell?

Dark matter shield

→ The mini-halo undertakes most of the tidal effects in the place of the stellar components



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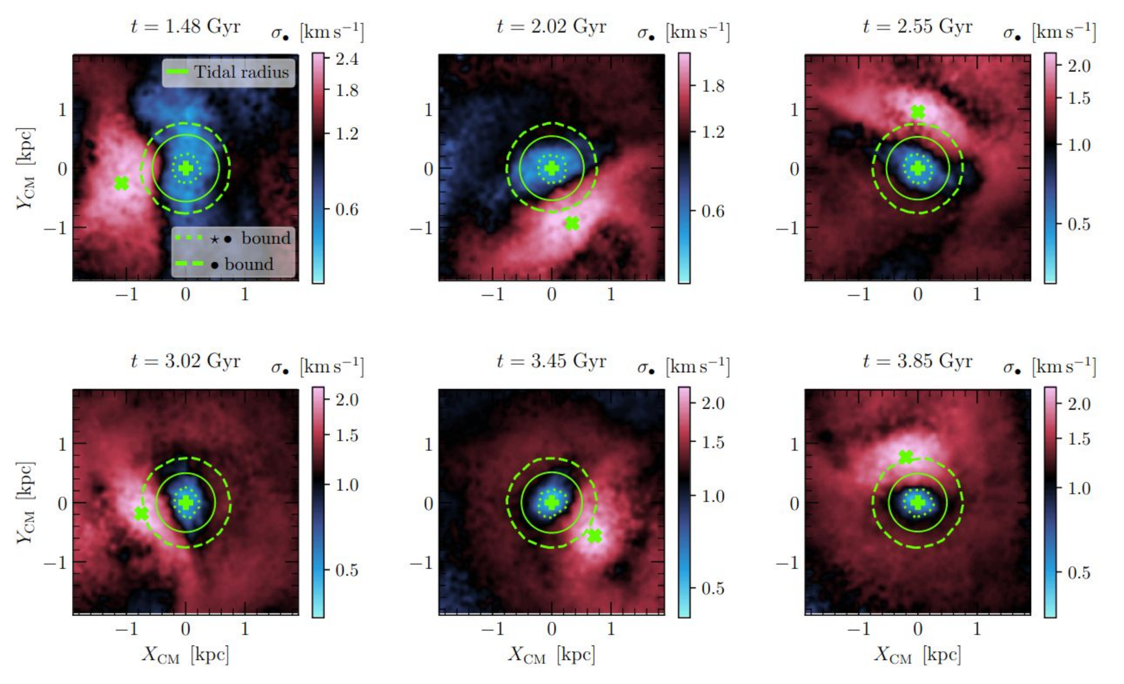

Dynamical heating

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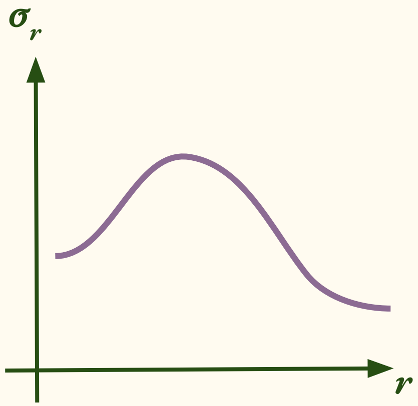

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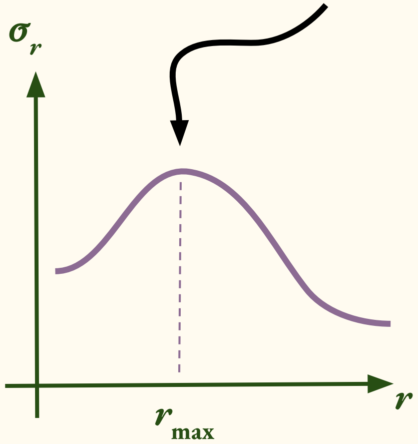

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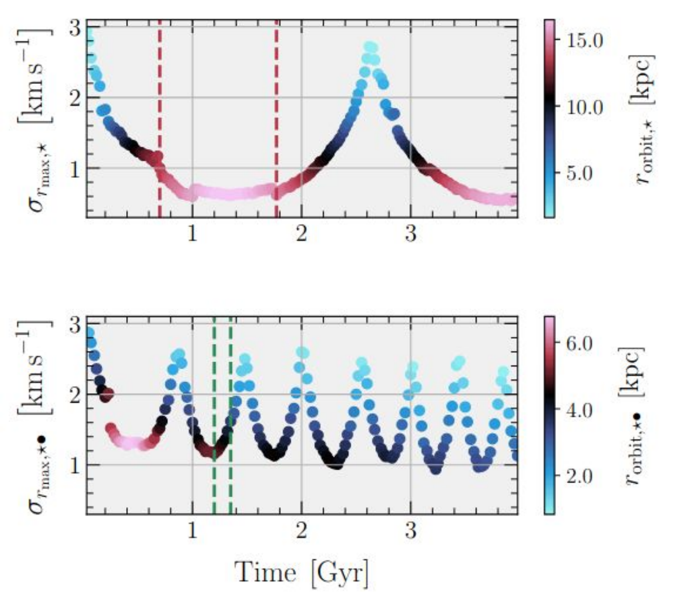
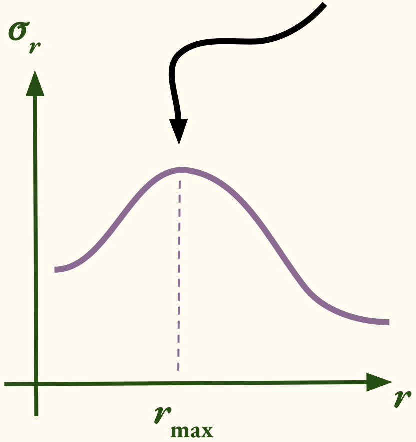
Without DM

With DM





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→ The tides heat the system much more than an eventual mini-halo

→ Without a protective shield, the stars feel the tides more intensively

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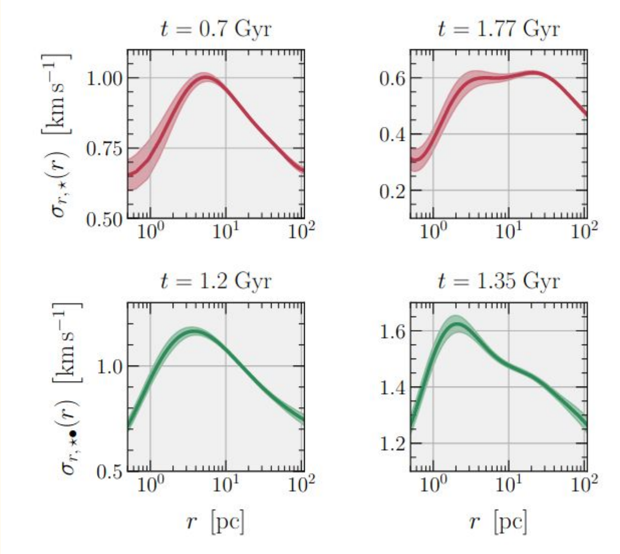

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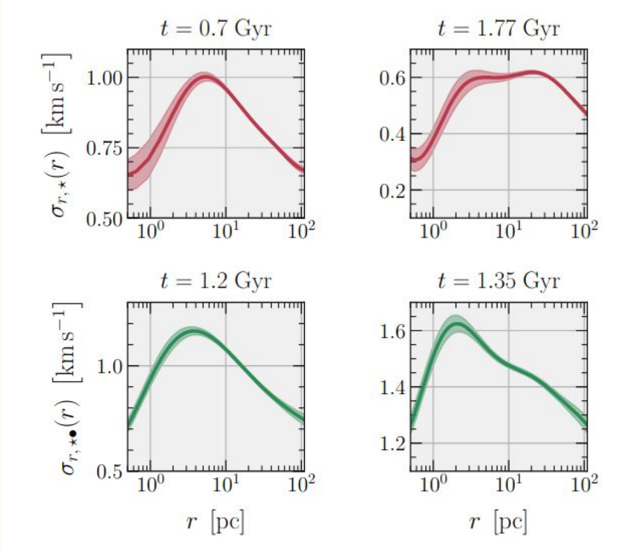
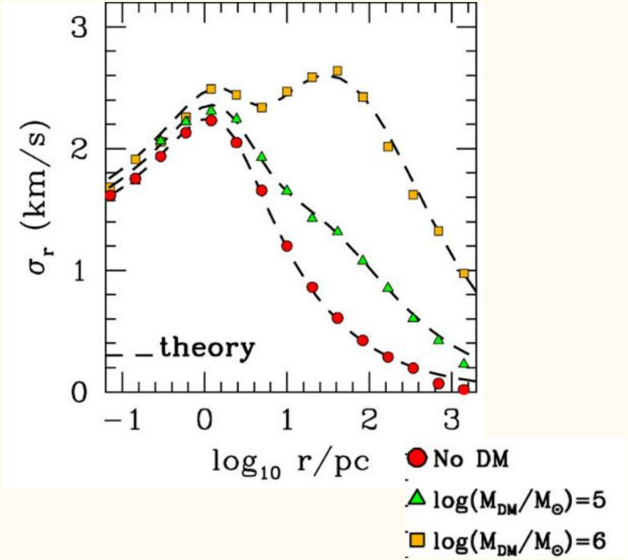
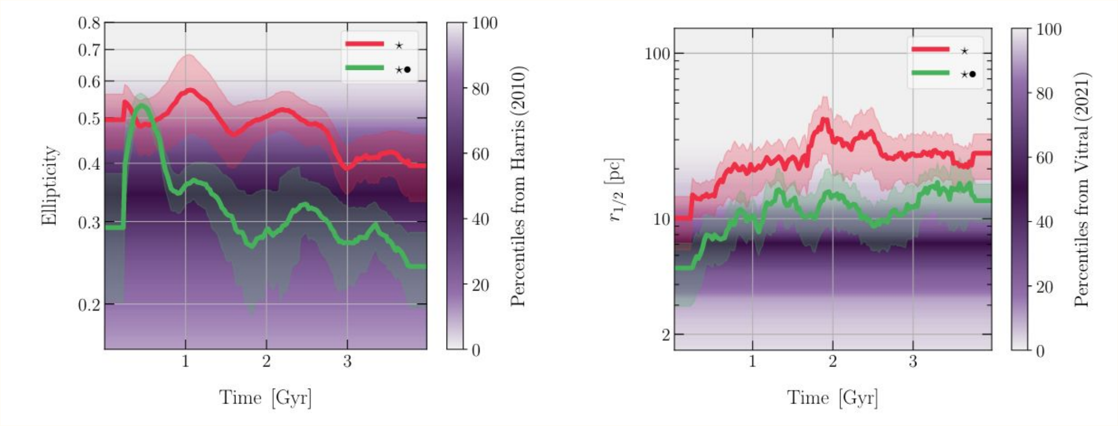


Comparison with
Peñarrubia et al., 2017
(isolated clusters)



Ellipticity and size

→ The dark matter shield renders its cluster rounder and smaller



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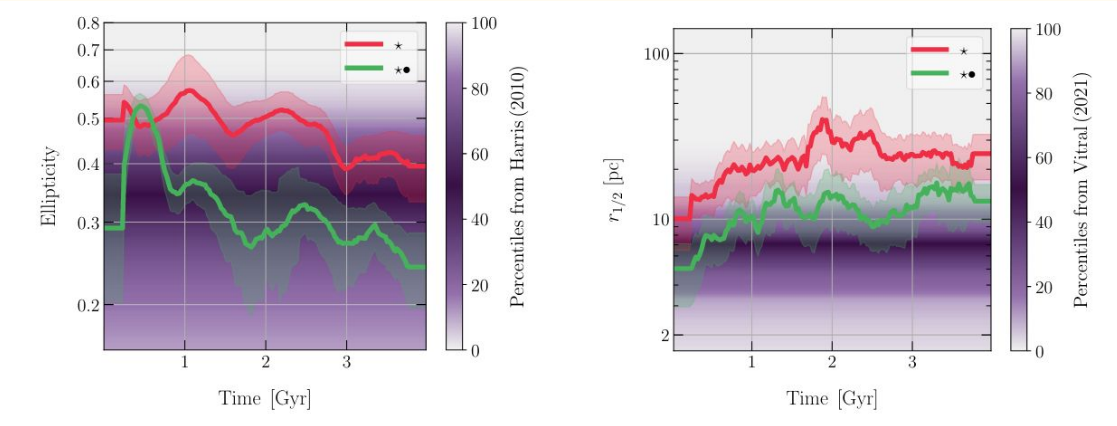
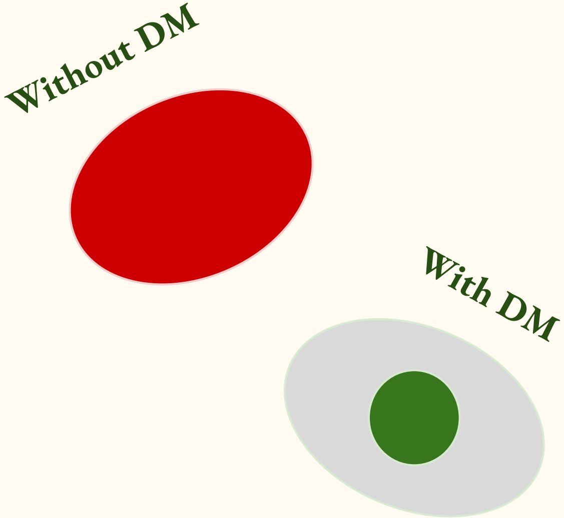
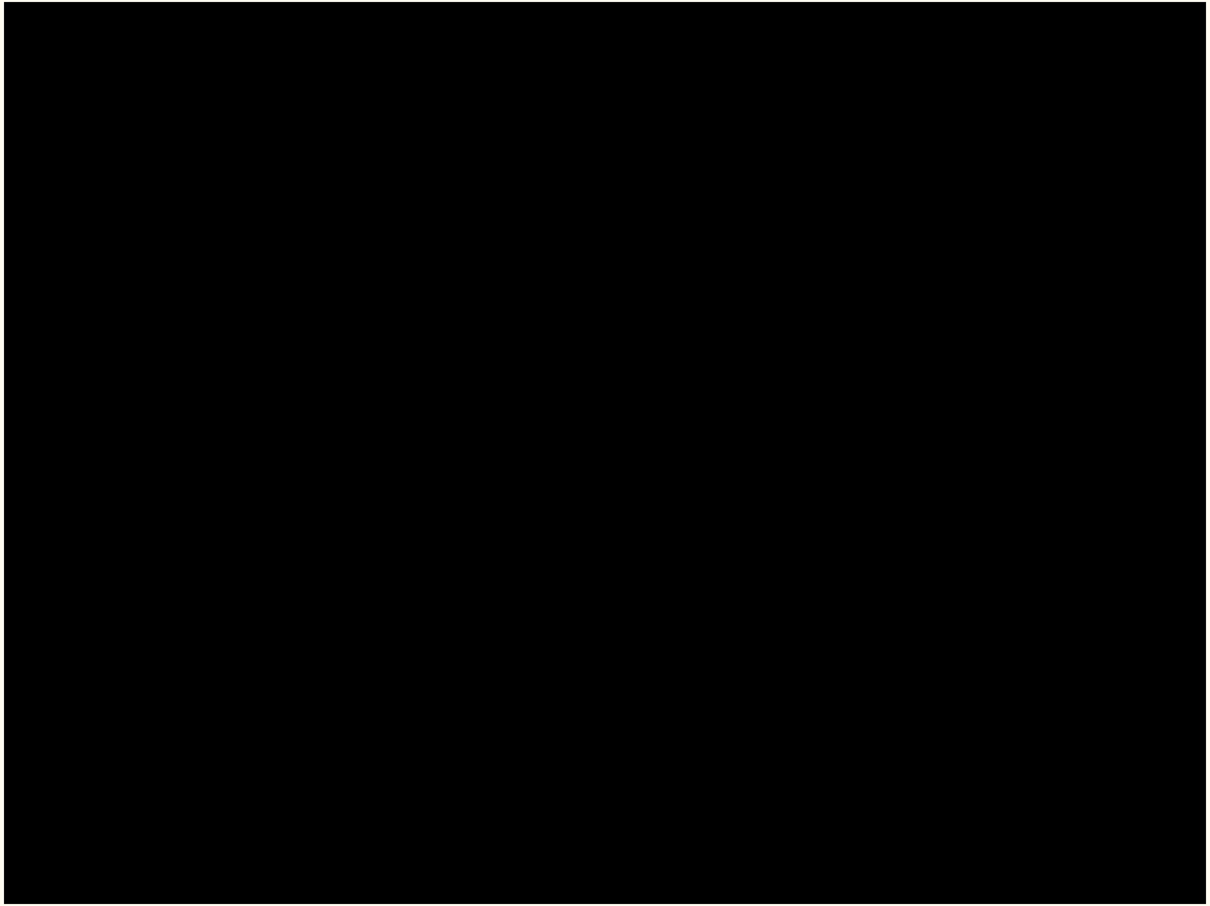




Tidal tails and stellar streams



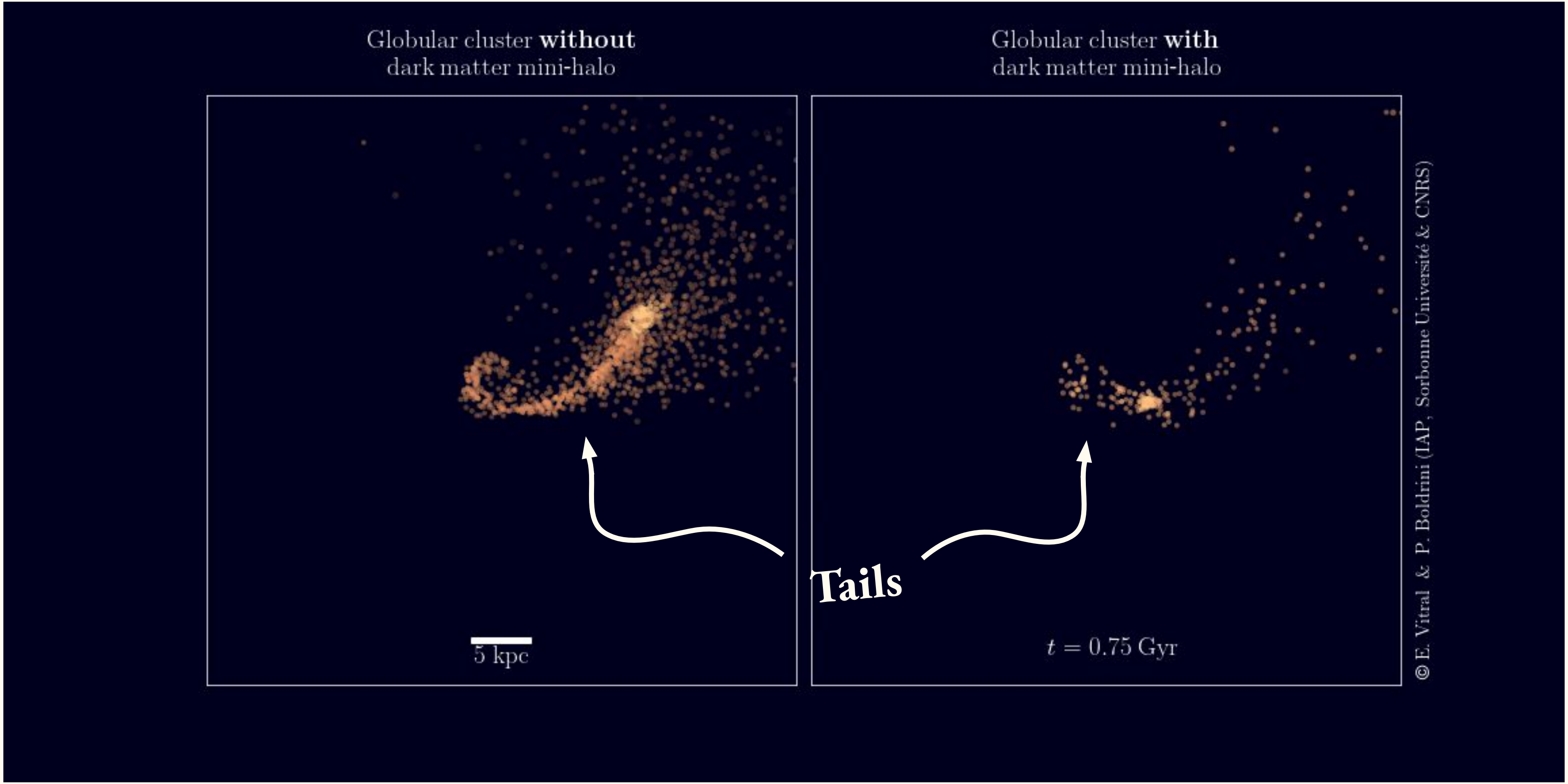
Tidal tails and stellar streams

Without DM

- ➢ Tail formation

With DM

- ➢ Tail formation


Globular cluster **without** dark matter mini-halo
Globular cluster **with** dark matter mini-halo
Tails
5 kpc
$t = 0.75$ Gyr
© E. Vitral & P. Boldrini (IAP, Sorbonne Université & CNRS)

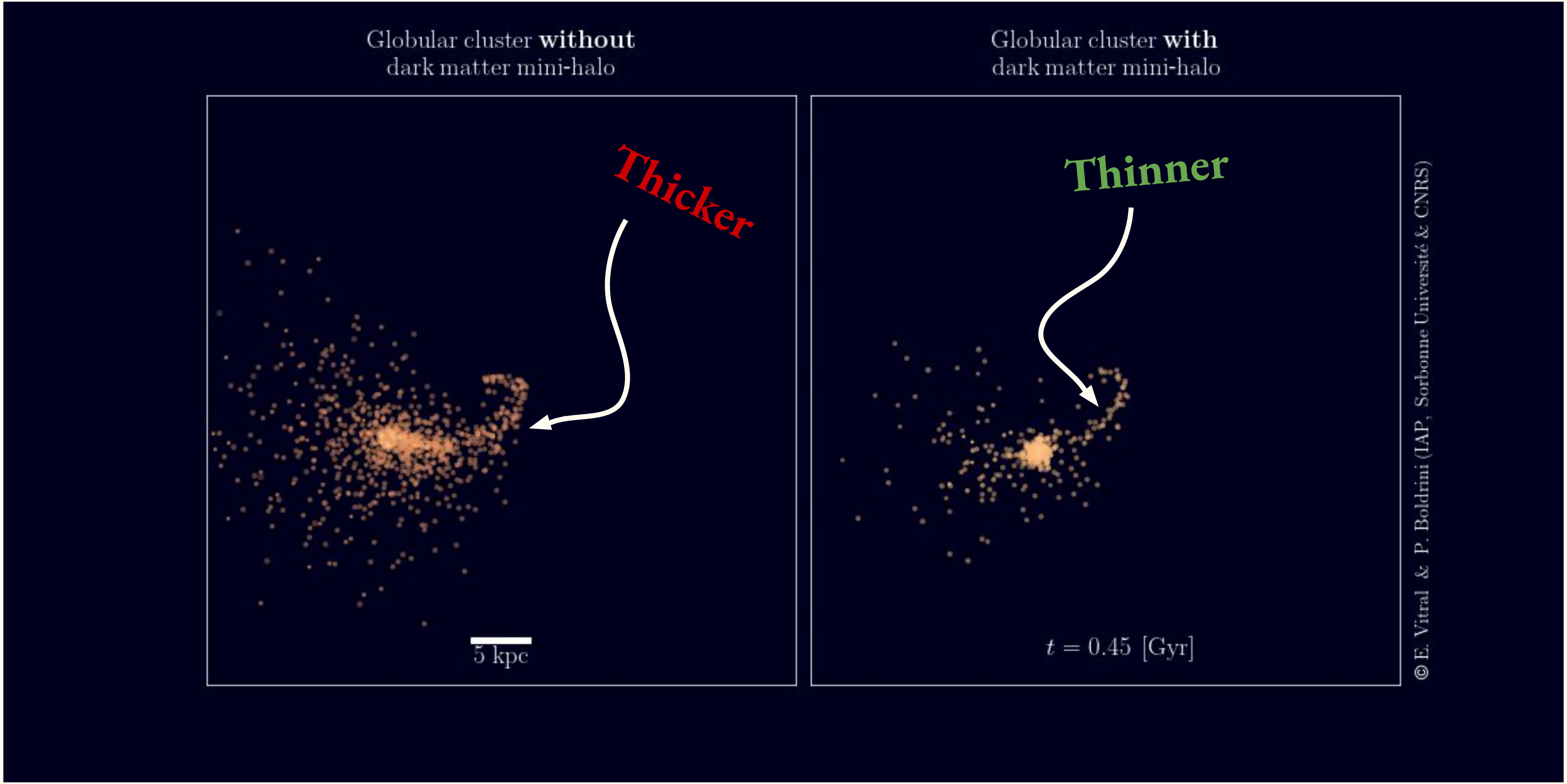
Tidal tails and stellar streams

Without DM

- ➢ Tail formation
- ➢ Thicker tails / Less coherent
(more dispersion in the perpendicular direction of tail formation)

With DM

- ➢ Tail formation
- ➢ Thinner tails / More coherent


Globular cluster without dark matter mini-halo
Globular cluster with dark matter mini-halo
Thicker
Thinner
5 kpc
t = 0.45 [Gyr]
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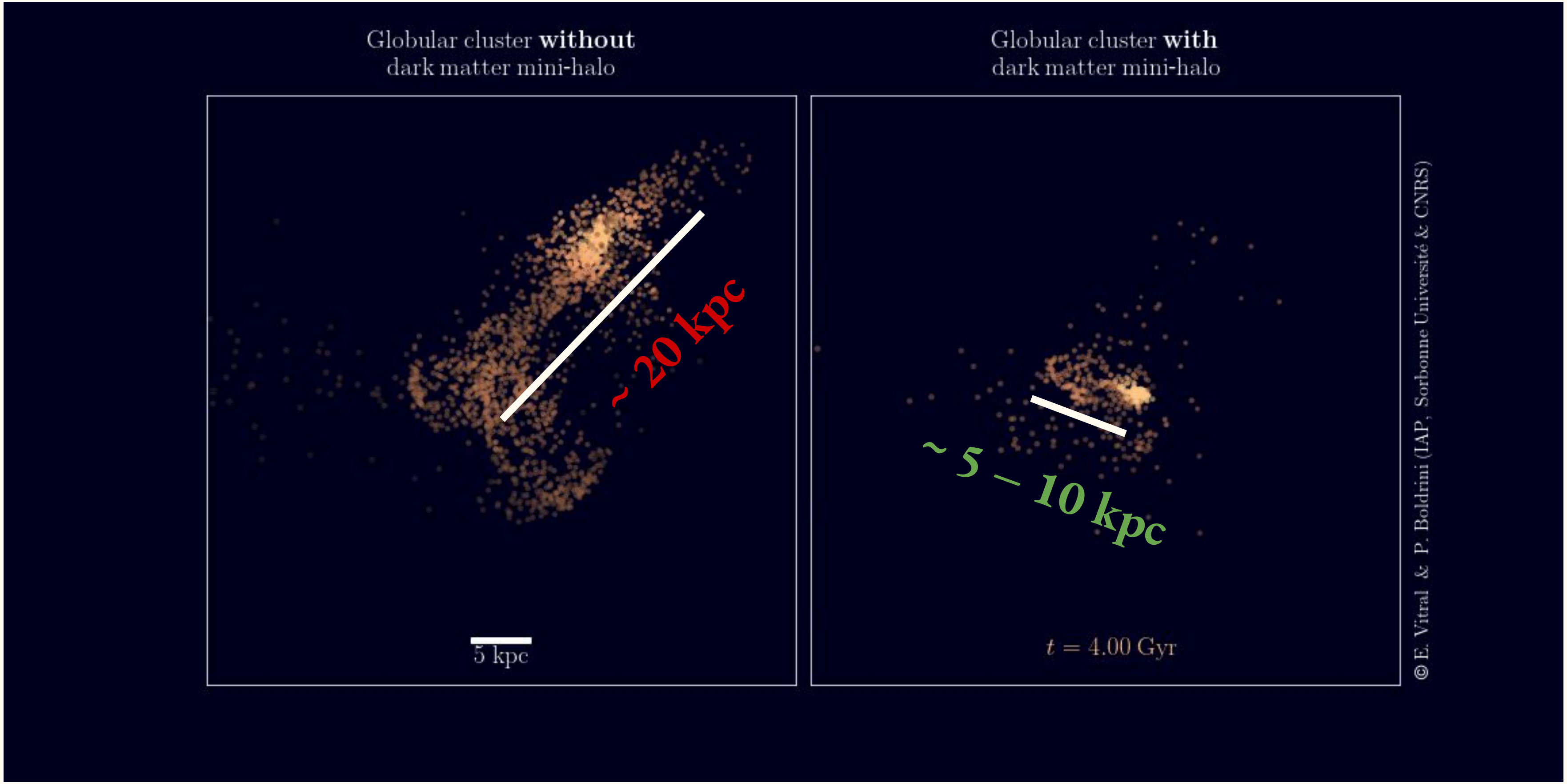
Tidal tails and stellar streams

Without DM

- ➢ Tail formation
- ➢ Thicker tails / Less coherent
  (more dispersion in the perpendicular direction of tail formation)
- ➢ Longer tails
  (distances as great as ~20 kpc)

With DM

- ➢ Tail formation
- ➢ Thinner tails / More coherent
- ➢ Milder tails
  (length between ~5 – 10 kpc)



Globular cluster **without** dark matter mini-halo
Globular cluster **with** dark matter mini-halo
~ 20 kpc
5 kpc
~ 5 – 10 kpc
t = 4.00 Gyr
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Tidal tails and stellar streams

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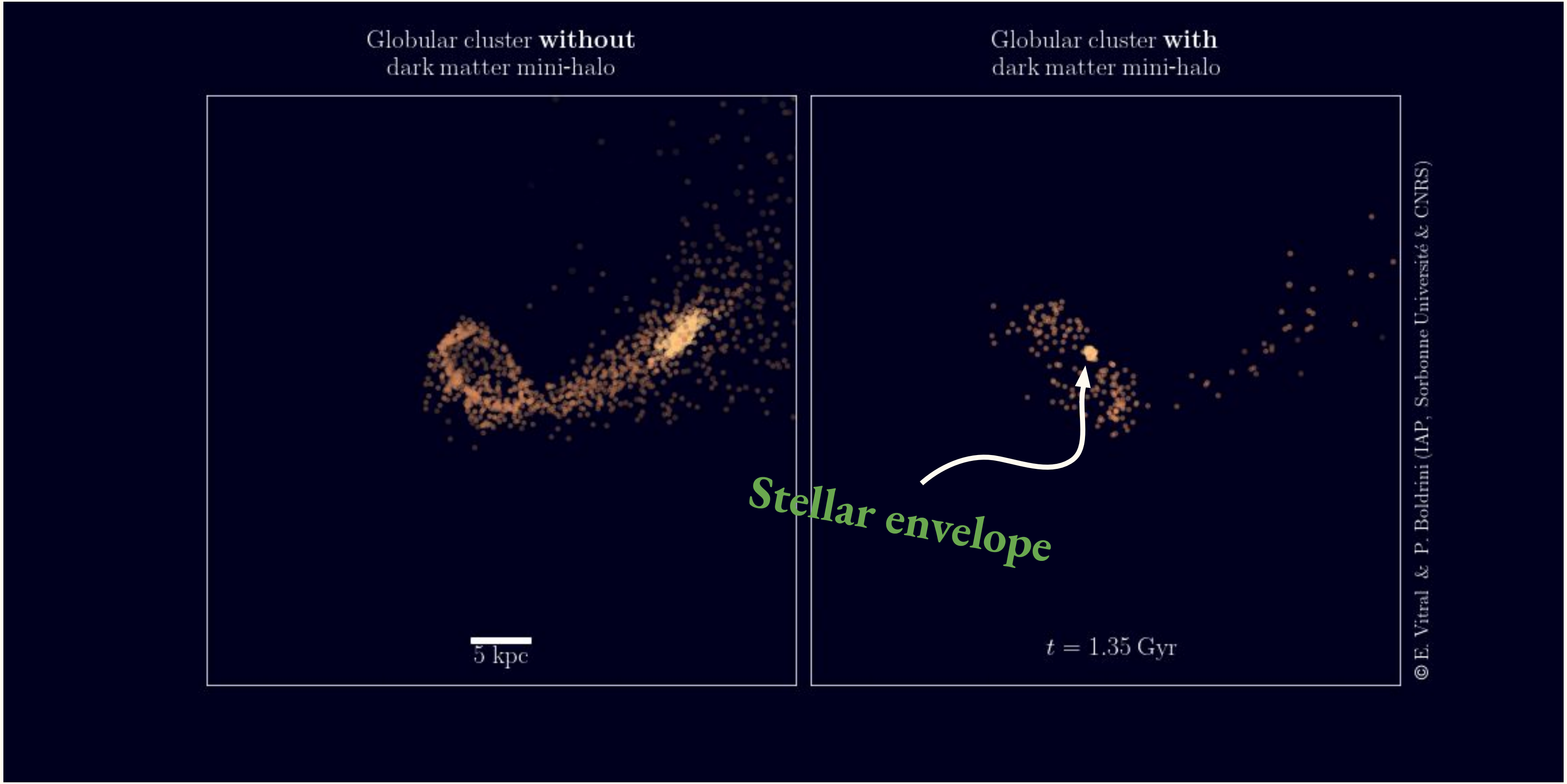
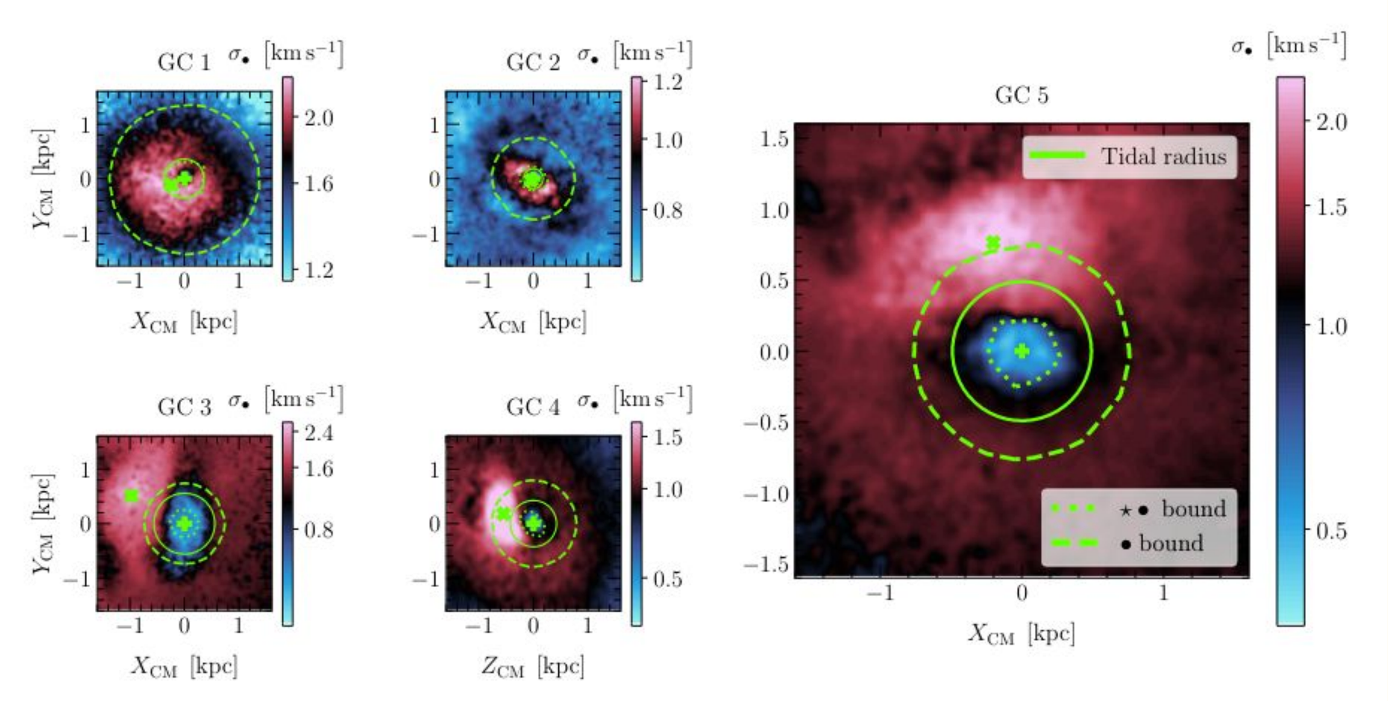
- ➢ ~1 kpc stellar envelope


Globular cluster **without**
dark matter mini-halo
Globular cluster **with**
dark matter mini-halo
5 kpc
$t = 1.35$ Gyr
Stellar envelope
© E. Vitral & P. Boldrini (IAP, Sorbonne Université & CNRS)

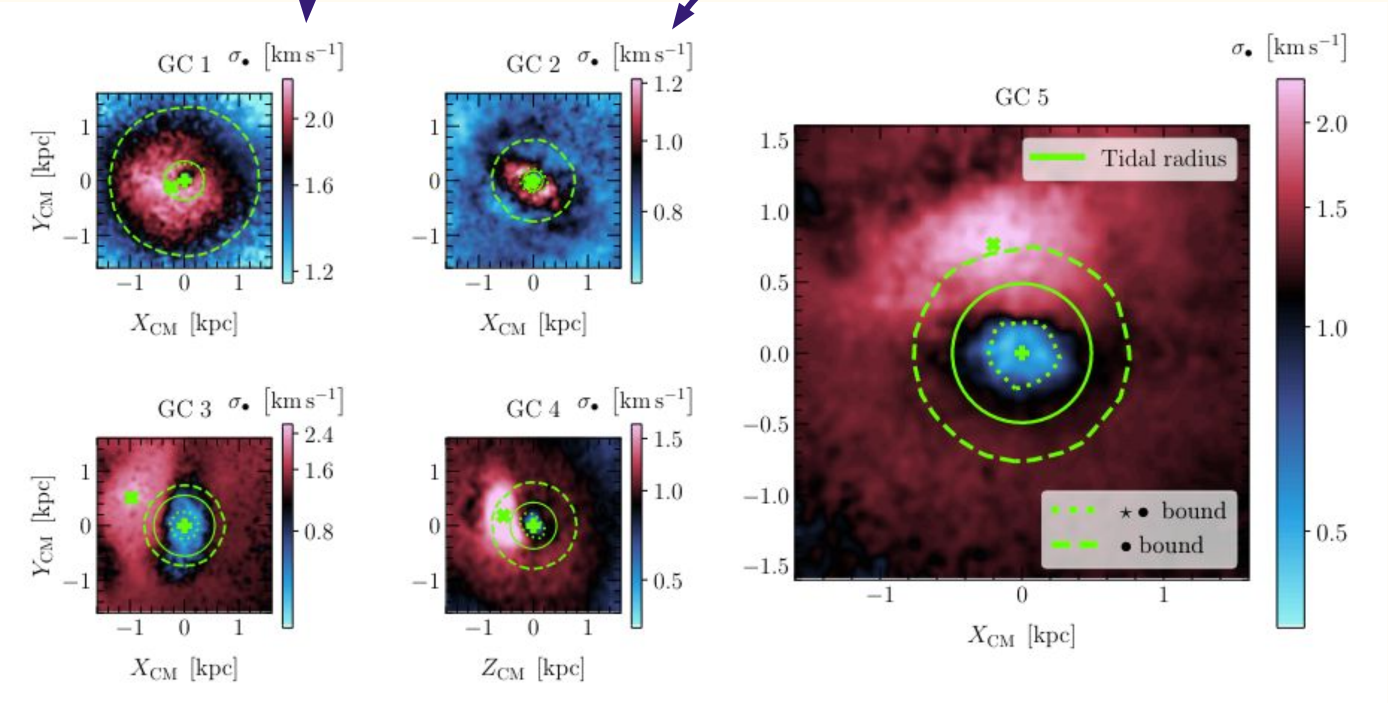
What about the long run?

Mini-halo dissolution



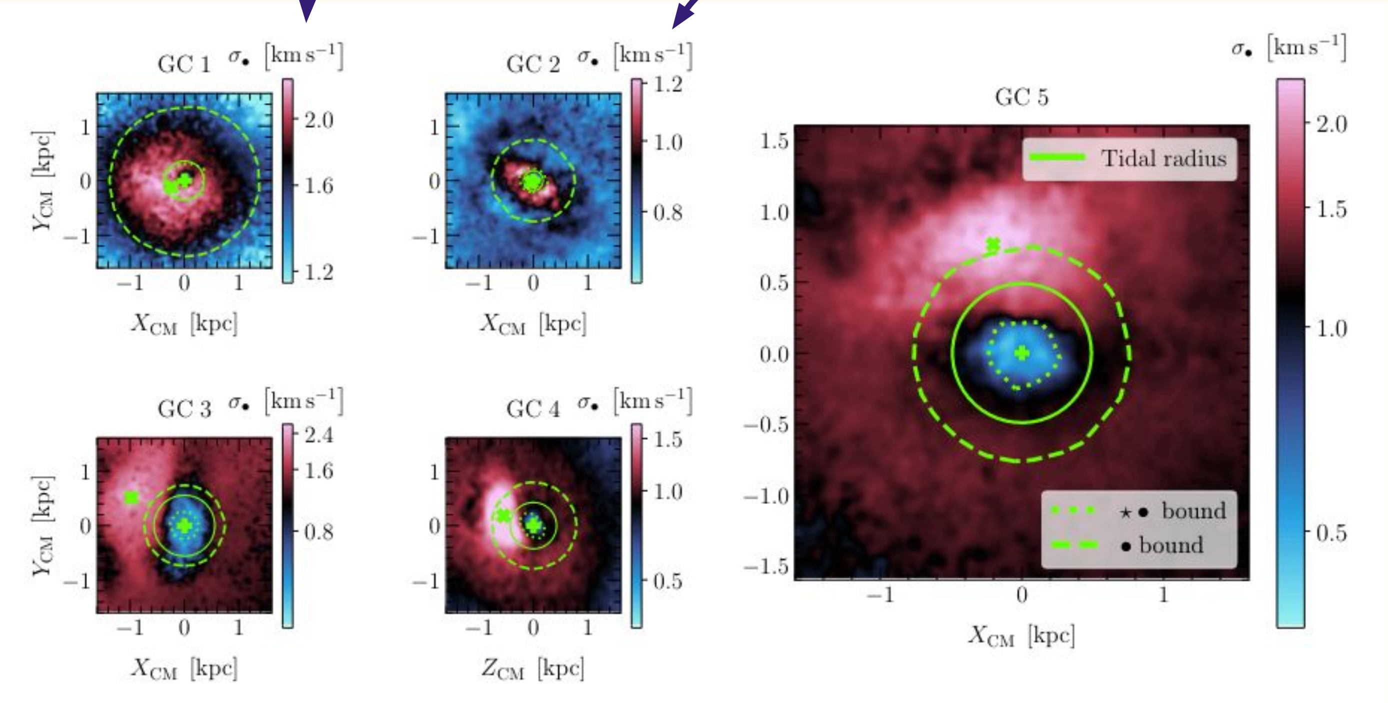
Mini-halo dissolution

No dark matter shield



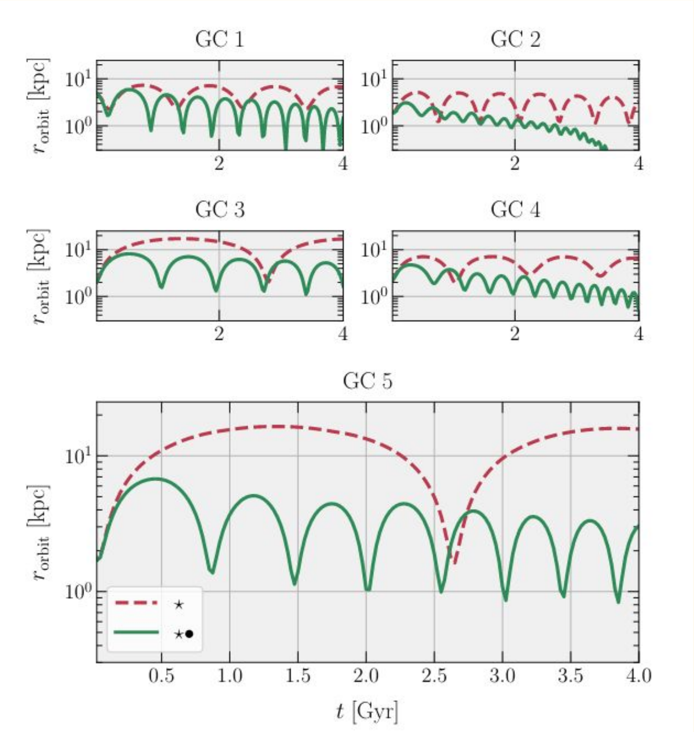
Mini-halo dissolution

No dark matter shield → **Why?**



Mini-halo dissolution

→ Orbital past plays a major role in the shield retention

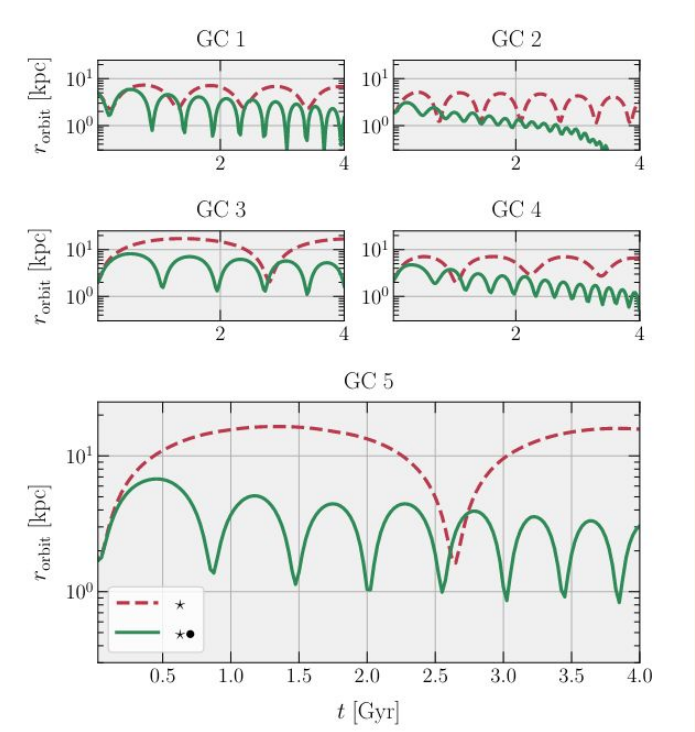


Mini-halo dissolution

→ Orbital past plays a major role in the shield retention

Table 1. Mean of structural parameters from the last ten snapshots, considering only bound particles and stars.

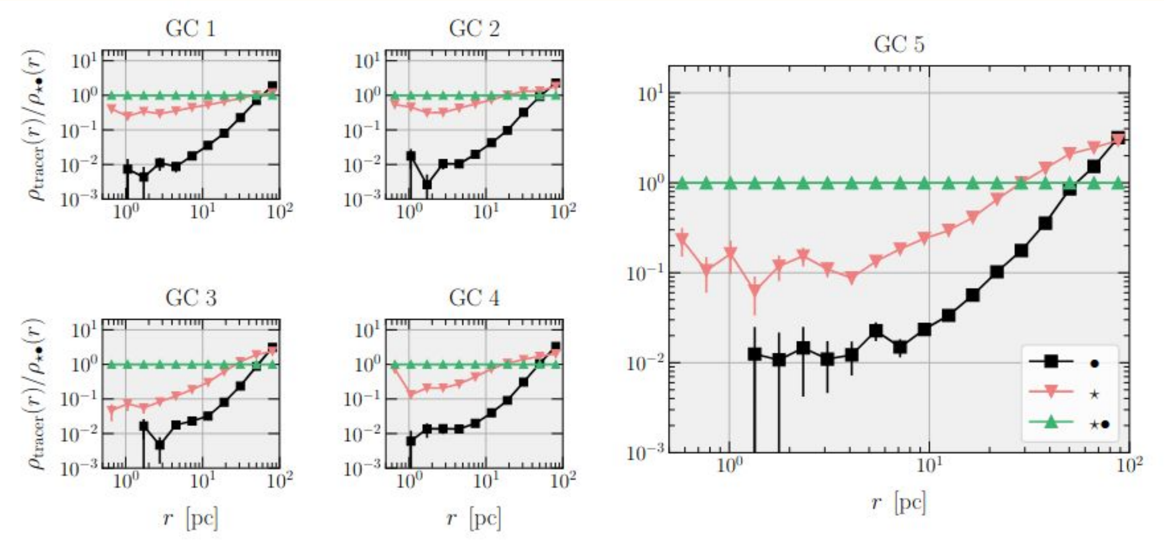
ID (1)	$M_{\bullet}$ [10^5 $M_{\odot}$] (2)	$M_{\star\bullet}$ [10^5 $M_{\odot}$] (3)	$M_{\star}$ [10^5 $M_{\odot}$] (4)	$r_{1/2,\bullet}$ [pc] (5)	$r_{1/2,\star\bullet}$ [pc] (6)	$r_{1/2,\star}$ [pc] (7)	$r_{\mathrm{bound},\bullet}$ [pc] (8)	$r_{\mathrm{bound},\star\bullet}$ [pc] (9)	$r_{\mathrm{bound},\star}$ [pc] (10)
GC1	10.2	8.7	6.1	415.8	12.2	11.7	1391.0	508.5	508.1
GC2	8.2	9.1	8.0	269.7	13.2	22.4	770.1	282.6	281.5
GC3	14.6	9.6	8.8	158.2	11.9	31.6	745.2	273.7	274.4
GC4	11.4	9.7	9.0	317.2	11.9	13.8	795.4	289.6	292.1
GC5	9.9	9.8	8.6	164.2	14.9	45.0	766.7	280.1	282.2



How easy is it to spot a mini-halo?

Dark matter detectability

→ The answer is in the outskirts!



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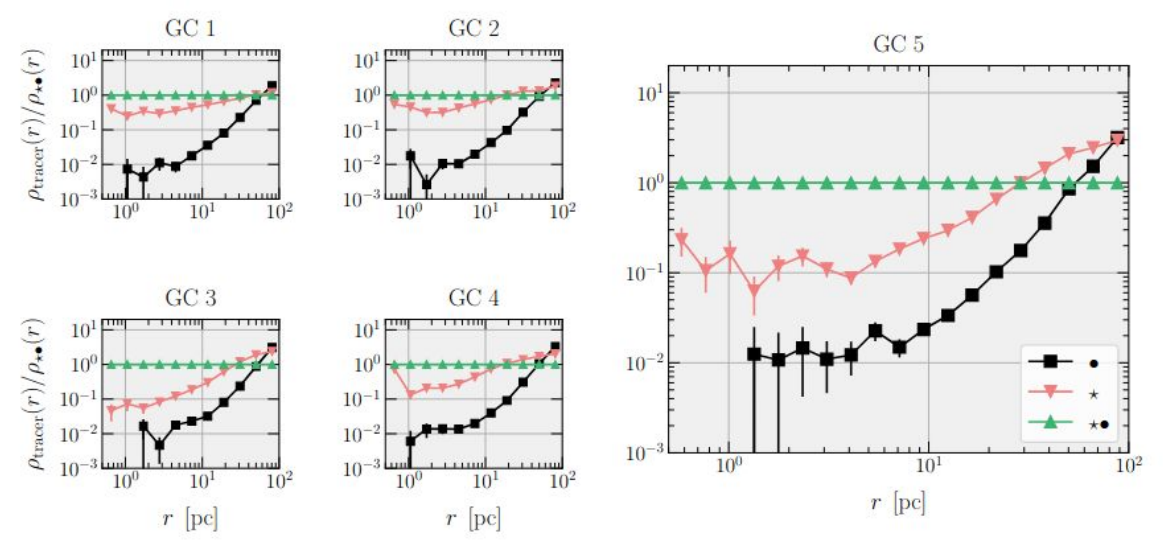
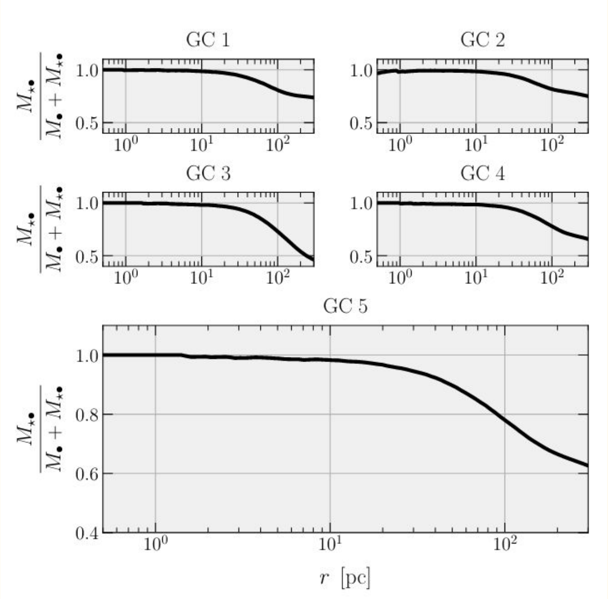
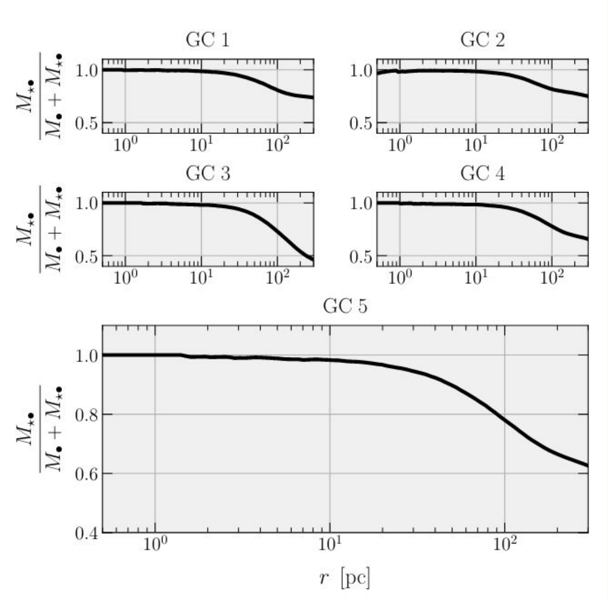




Dark matter detectability

→ The answer is in the outskirts!

→ Relatively low mass-to-light ratios do not imply lack of dark matter.

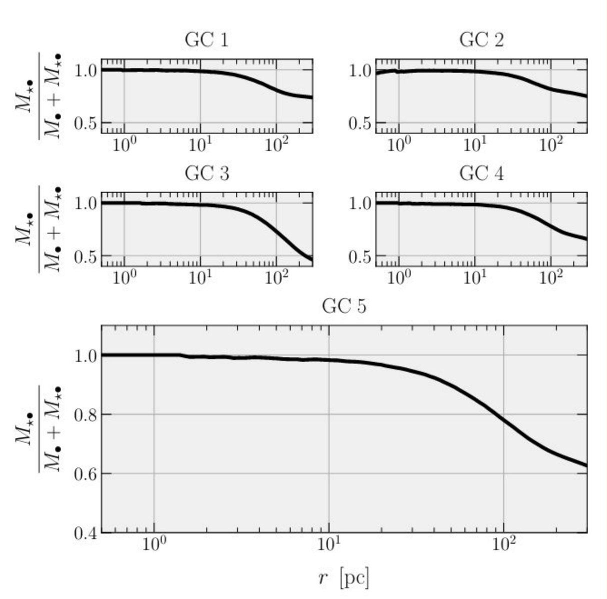


Dark matter detectability

→ The answer is in the outskirts!

→ Relatively low mass-to-light ratios do not imply lack of dark matter.

→ Only after a few hundreds of pc, the dark matter mass budget becomes important.



What is next?

Targets for dark matter search

- Is NGC 2419 a good candidate?

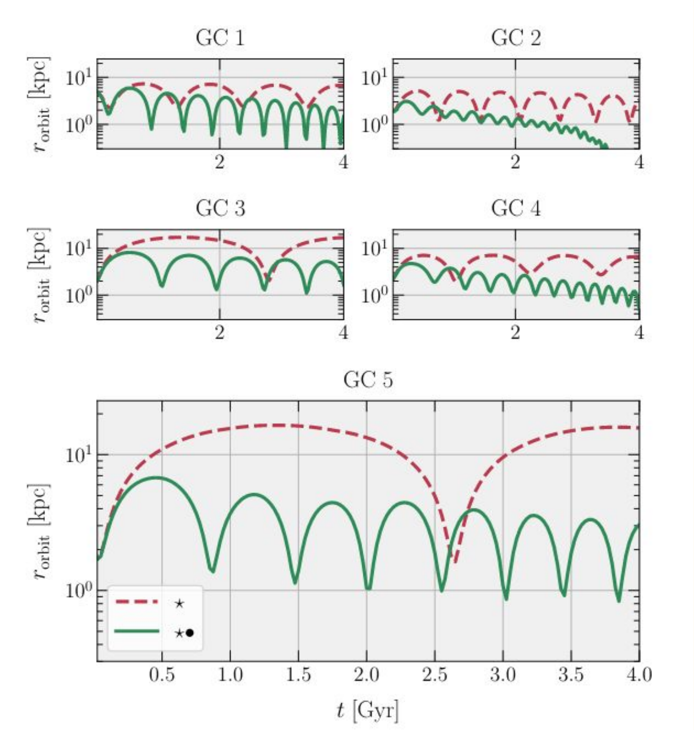
e.g.: Conroy et al., 2011; Ibata et al., 2013;
Baumgardt et al., 2009.

→ Galactocentric distance of 95 kpc (very distant).

Targets for dark matter search

- ➢ Is NGC 2419 an ideal candidate?

If NGC 2419 was formed inside a dark matter mini-halo, dynamical friction should have driven it more inwards.



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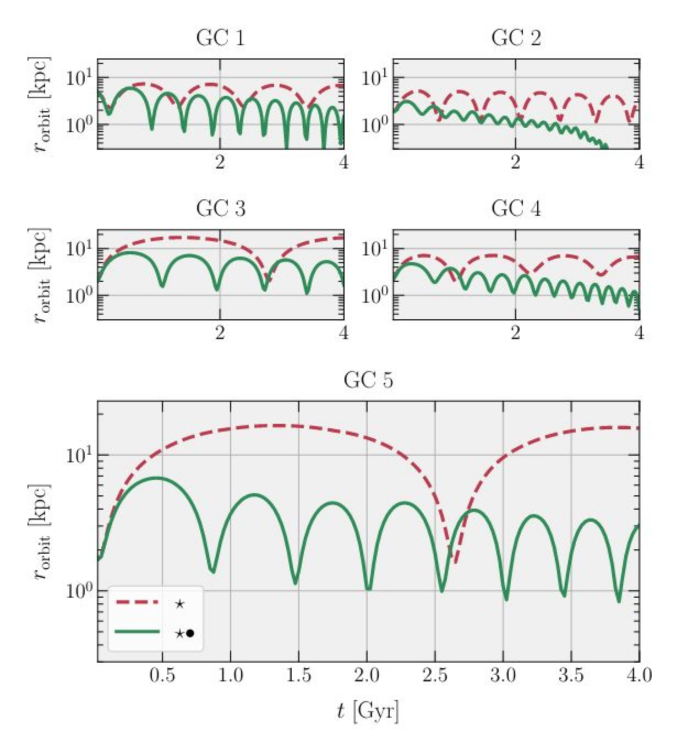
- Ex-situ origin?



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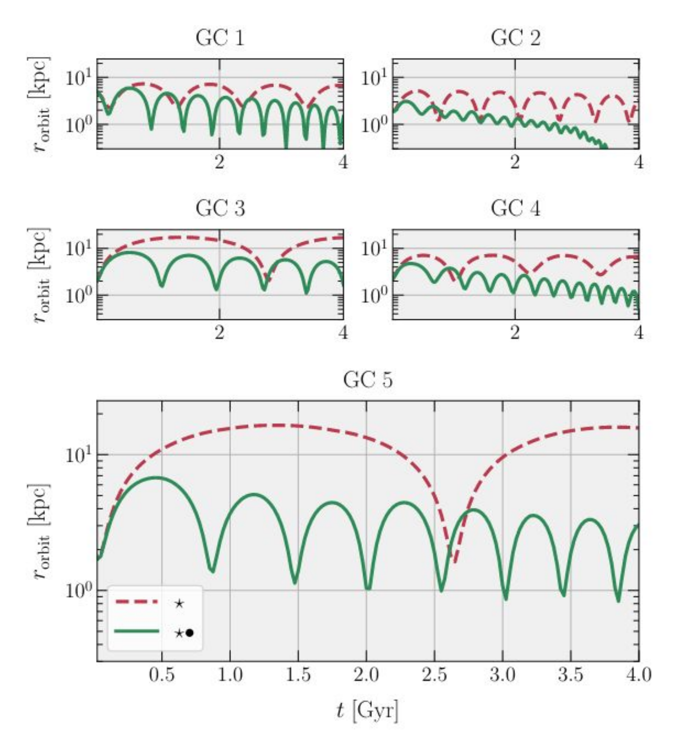

Not *ideal*...

Targets for dark matter search

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see Martin et al., 2022

LETTER

A stellar stream remnant of a globular cluster below the metallicity floor

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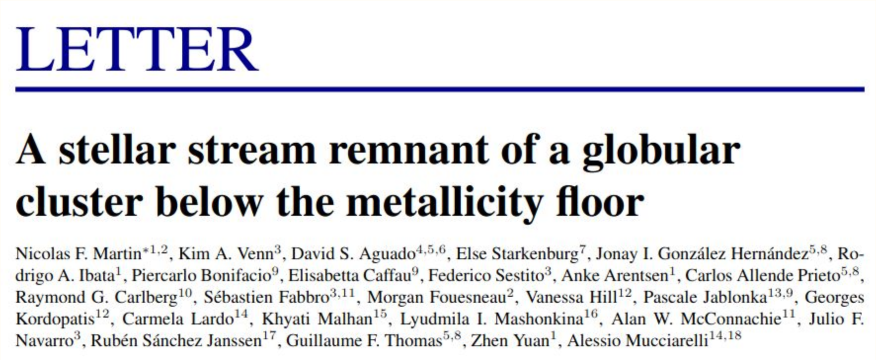

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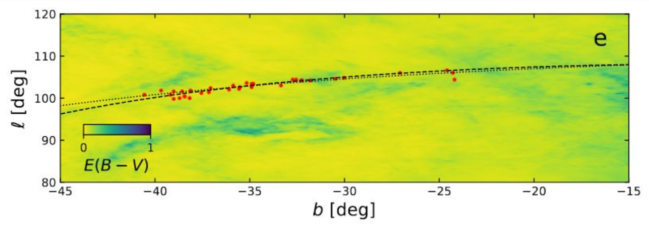

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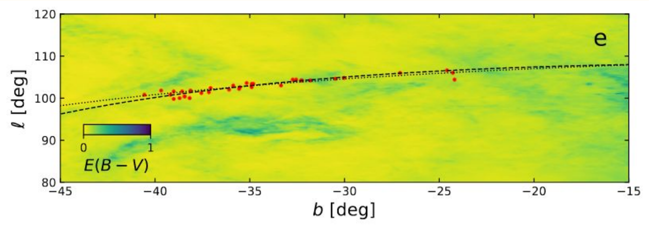

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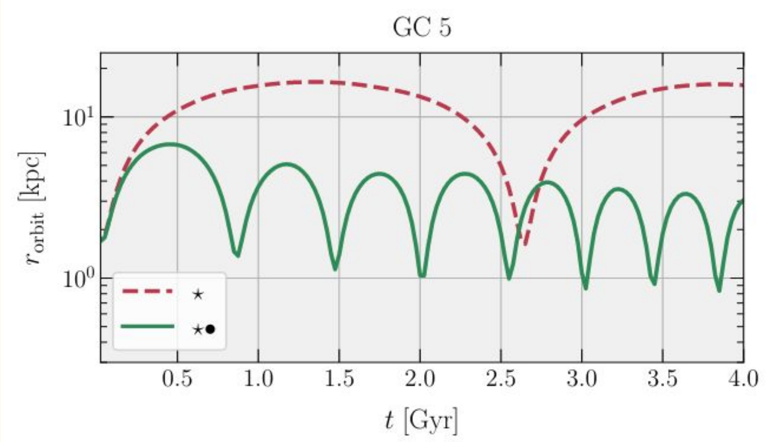

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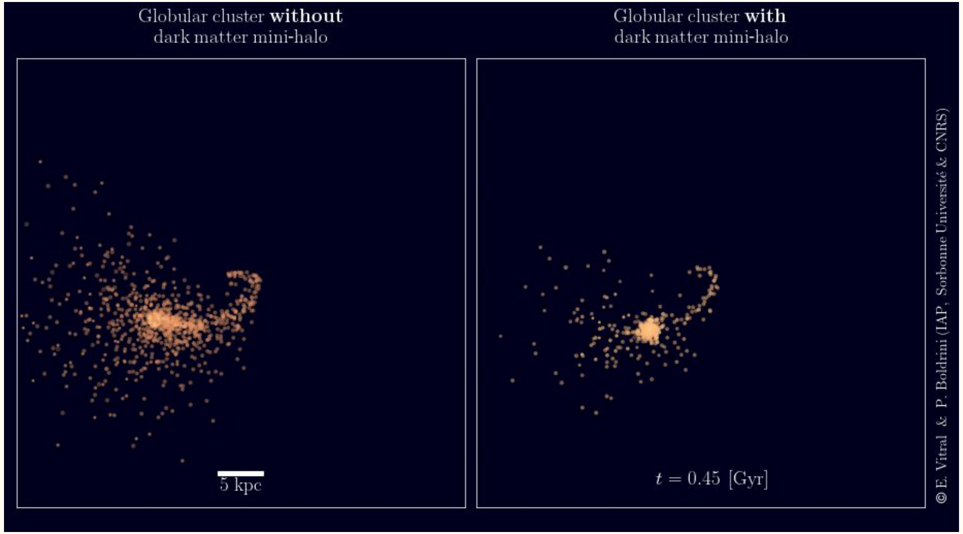

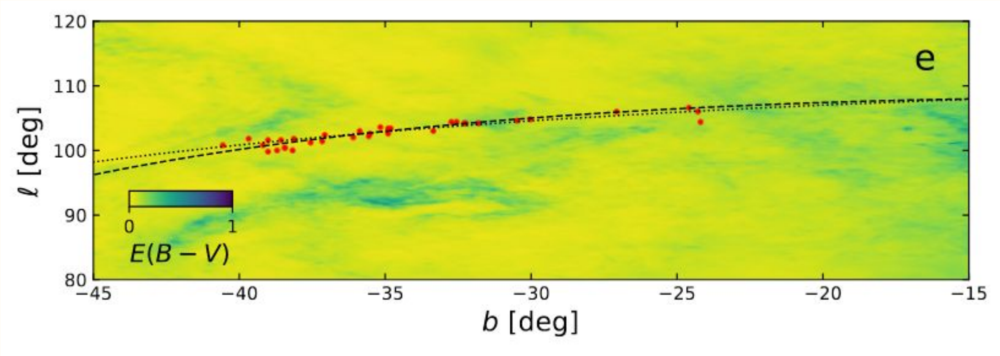

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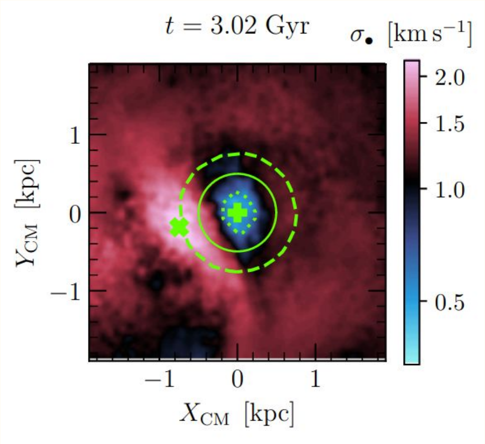

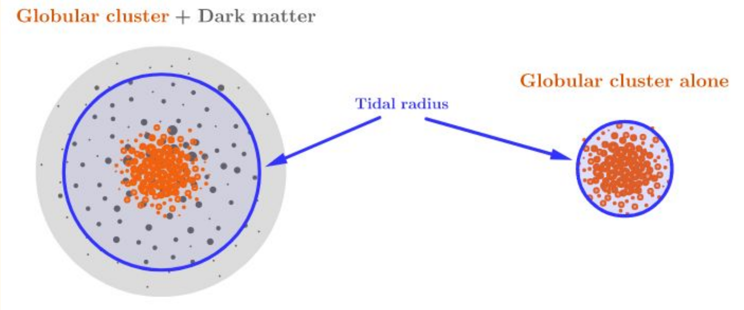

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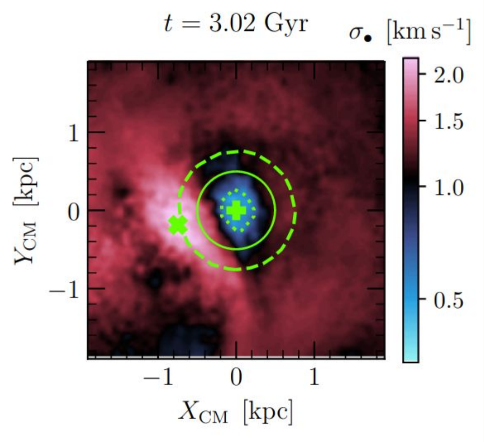
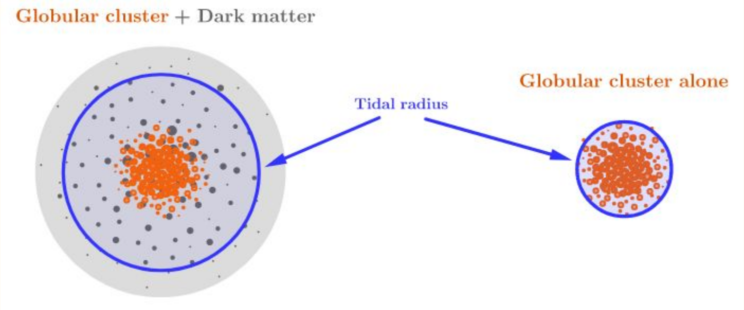
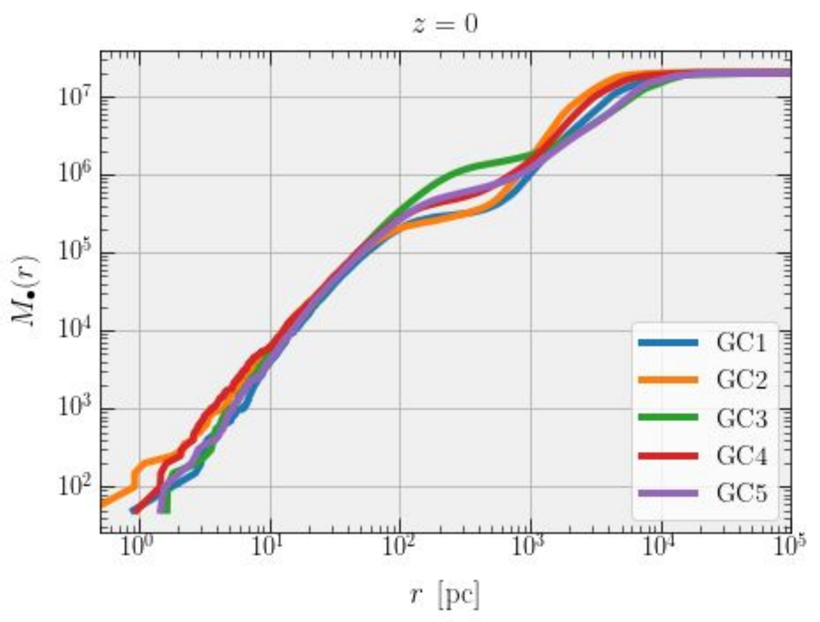




Dark matter mass profiles

- ➢ Jeans mass-modelling

- ➢ Orbital integrations



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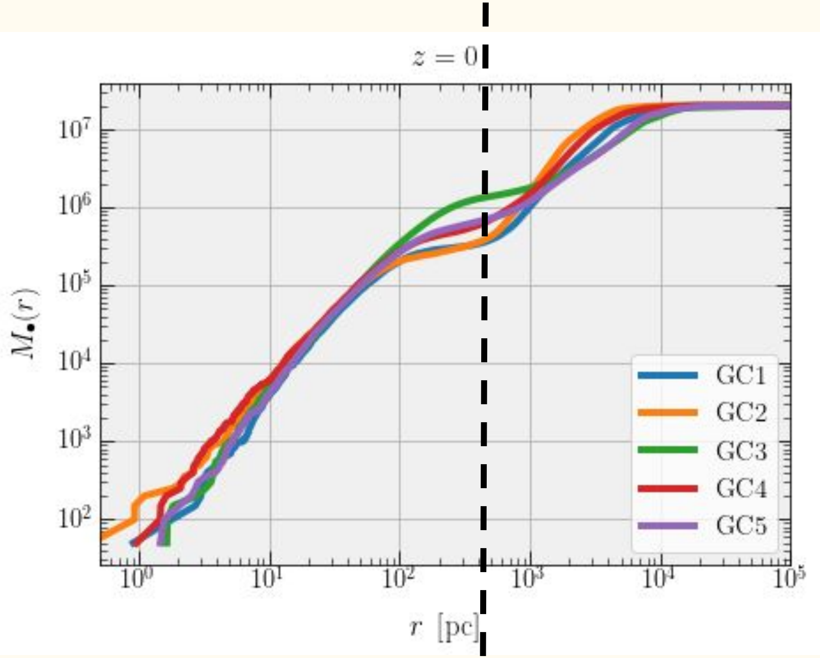

Thank you!