

TRACING THE NATURE OF DARK MATTER WITH GLOBULAR CLUSTERS



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Exchange Workshop, September 2025

Dark matter theories [1/2]

- ◆ Cosmological model —> Cold dark matter
- ◆ Axions or WIMPs have so far not been detected
- ◆ Very successful at large scales

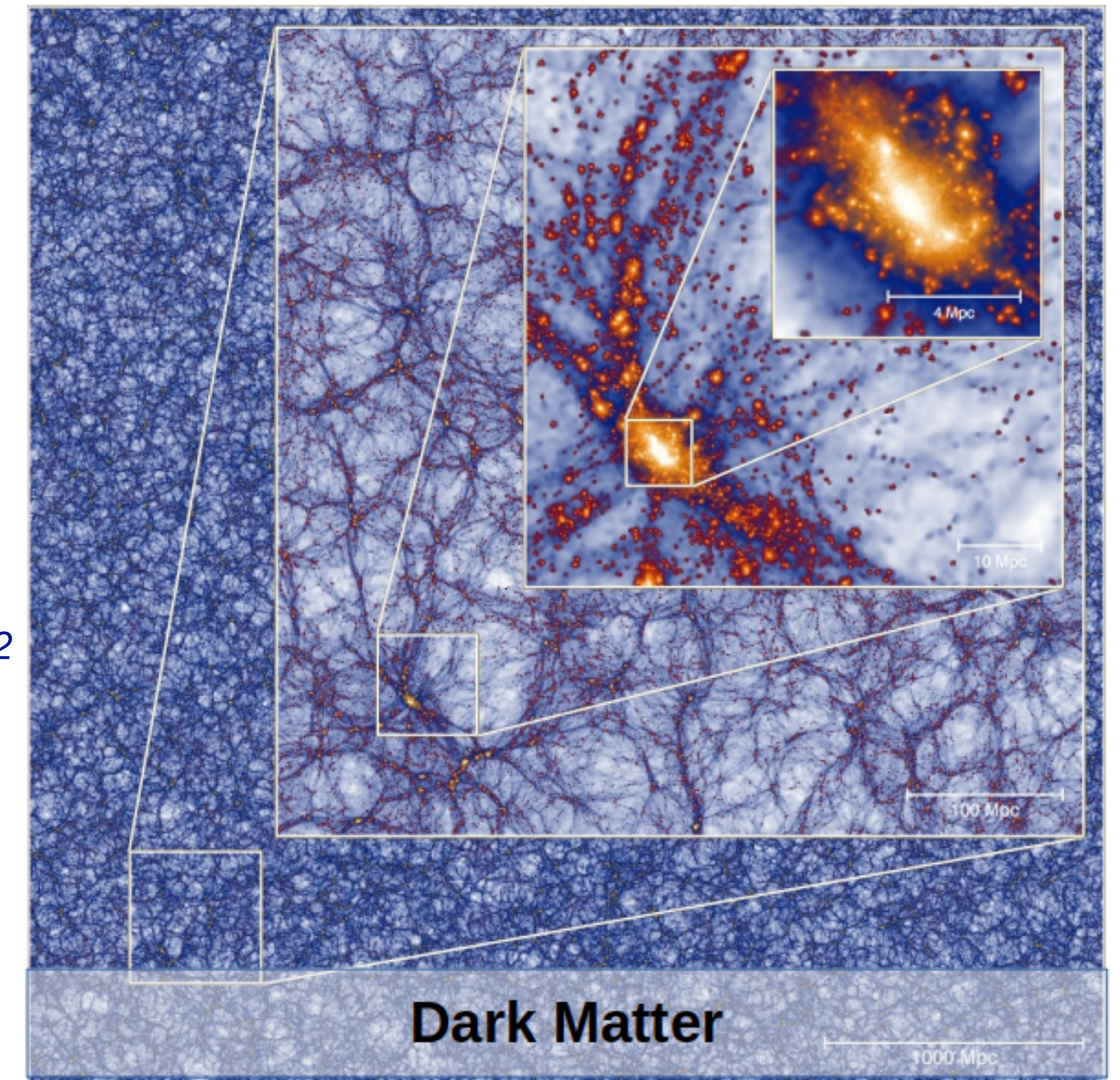
Planck Collaboration+14

CDM tensions:

Reviews: Bullock & Boylan-Kolchin+17, Boldrini+22

- ◆ Cusp-core problem *Boldrini+22*
- ◆ Too-big-to-fail problem *Boylan-Kolchin+11*
- ◆ Diversity of rotation curves *Kaplinghat+20*
- ◆ Lensing properties of subhalos

Minor+17, Ballard+24; Despali+24, Enzi+24, Ragagnin+22, Meneghetti+20, +23



Angulo+21

How to resolve these tensions?

Dark matter theories [2/2]

Solution proposed to tensions:

- ◆ Including baryonic processes or missing elements in the sub-grid physics
- ◆ New physics in the dark sector —> viable alternative dark matter theories

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Colín et al+00

Warm DM

WDM particles have higher velocities than CDM particles

particle mass m_ν (in keV)

Kochanek & White+00

Self-interacting DM

Additional force than gravity which consist of DM self-interactions

cross-section σ_m (in cm^2/g)

Hu et al.+00

Fuzzy DM

The wave-like nature of FDM introduces quantum pressure effects that counteract gravity on small scales.

particle mass m_χ (in 10^{-22} eV)

Which one is the most likely?

This talk

How to constrain DM? Why globular clusters?
How to simulate their dynamics?

I) Our approach: GC semi-analytical model in
post-processing of cosmological simulations

II) Origin of our Galactic GCs

III) GC dynamics in FDM universe: impact of the
DM core profile

IV) GC dynamics in FDM universe: impact of
FDM dynamical friction

Future works



◆ P. Di Matteo, LIRA



◆ C. Laporte, LIRA



◆ A. Szpilfidel, LIRA



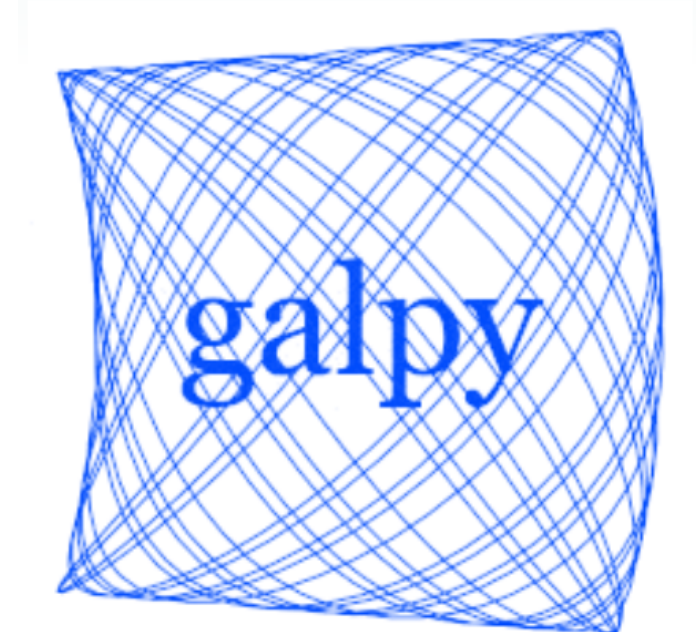
◆ O. Agertz, Lund Observatory



◆ S. Khoperskov, AIP



◆ J. Bovy (GALPY PI), University of Toronto



Globular clusters as DM tracers?

- ◆ More numerous than satellite galaxies (200 GCs versus 20 satellites in MW-like galaxies)
- ◆ Found in virtually all types of galaxies across a wide range of masses
- ◆ Span a wide range of galactocentric distances
- ◆ Essentially DM-free

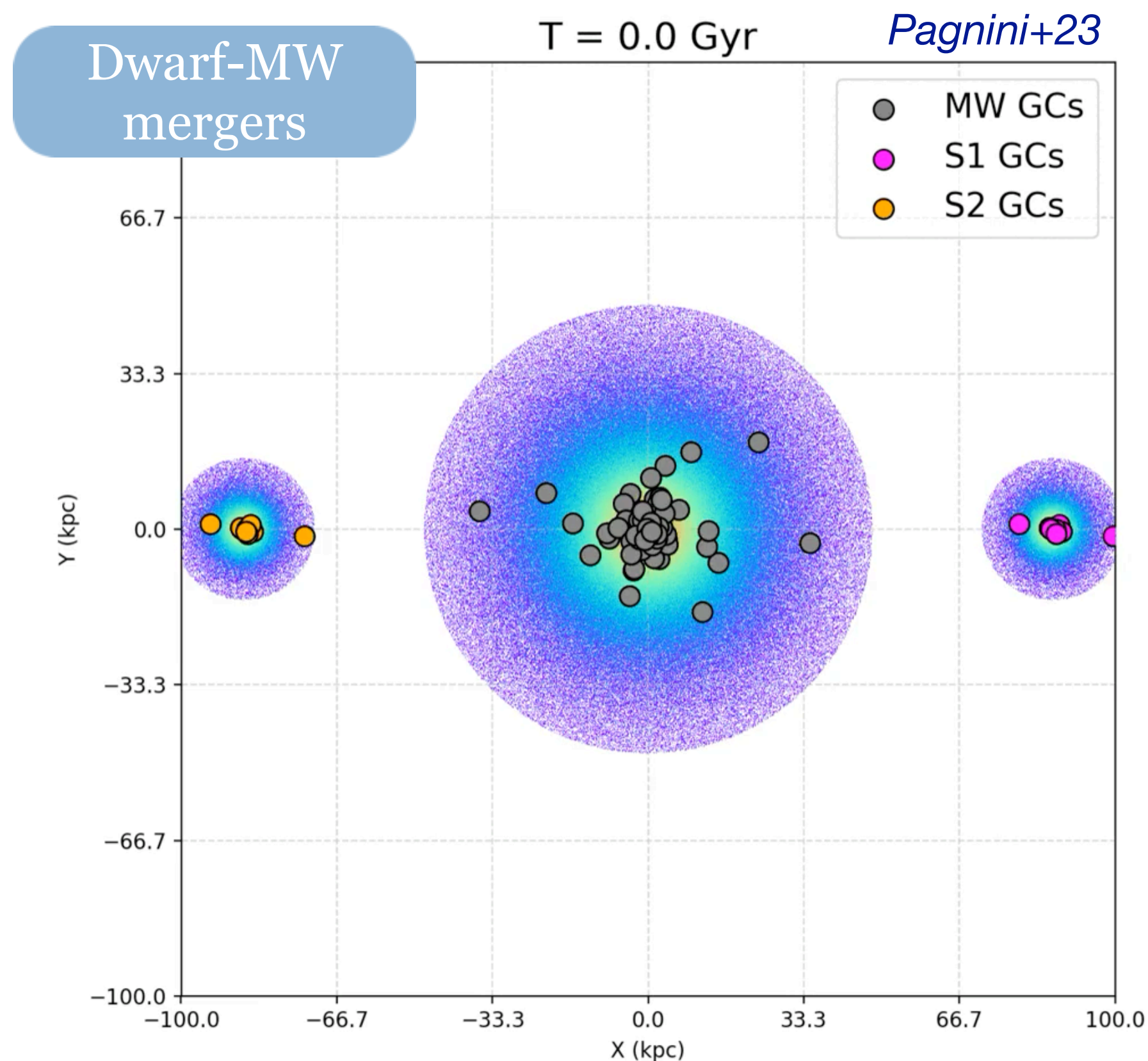
Similar to CDM Deviation from CDM	Density profile		Dynamical friction		Satellite population (low mass halos)
	Massive galaxies	Dwarf galaxies	Massive galaxies	Dwarf galaxies	
SIDM Collisional dark matter	DM core with size depending on the DM free parameter		Inefficient due to the huge mass ratio with GC	Reduced by the presence of a DM core	Less abundant <i>Bullock+17, Marsh+15</i>
WDM High velocity dark matter				Erased or reduced by quantum fluctuations <i>Hui+17, Lancaster+19</i>	
FDM Quantum wave-like nature					

GCs will be sensitive to DM theory properties

How to simulate GC in a cosmological context?

In galaxies, GCs experience:

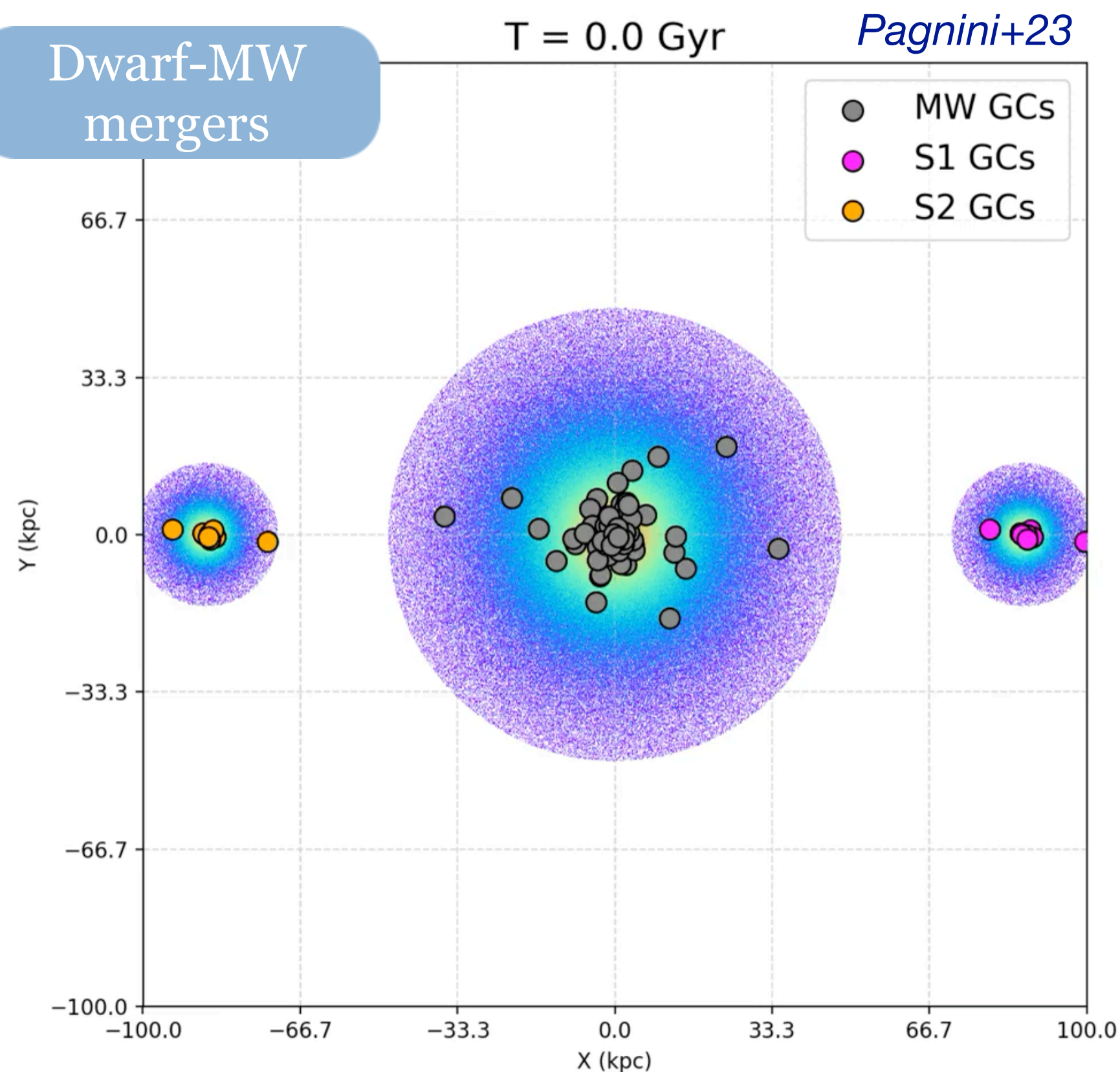
- ◆ Gravity (and heating mechanisms by exotic DM particles)
- ◆ Dynamical friction
- ◆ Mass loss



How to simulate GC in a cosmological context?

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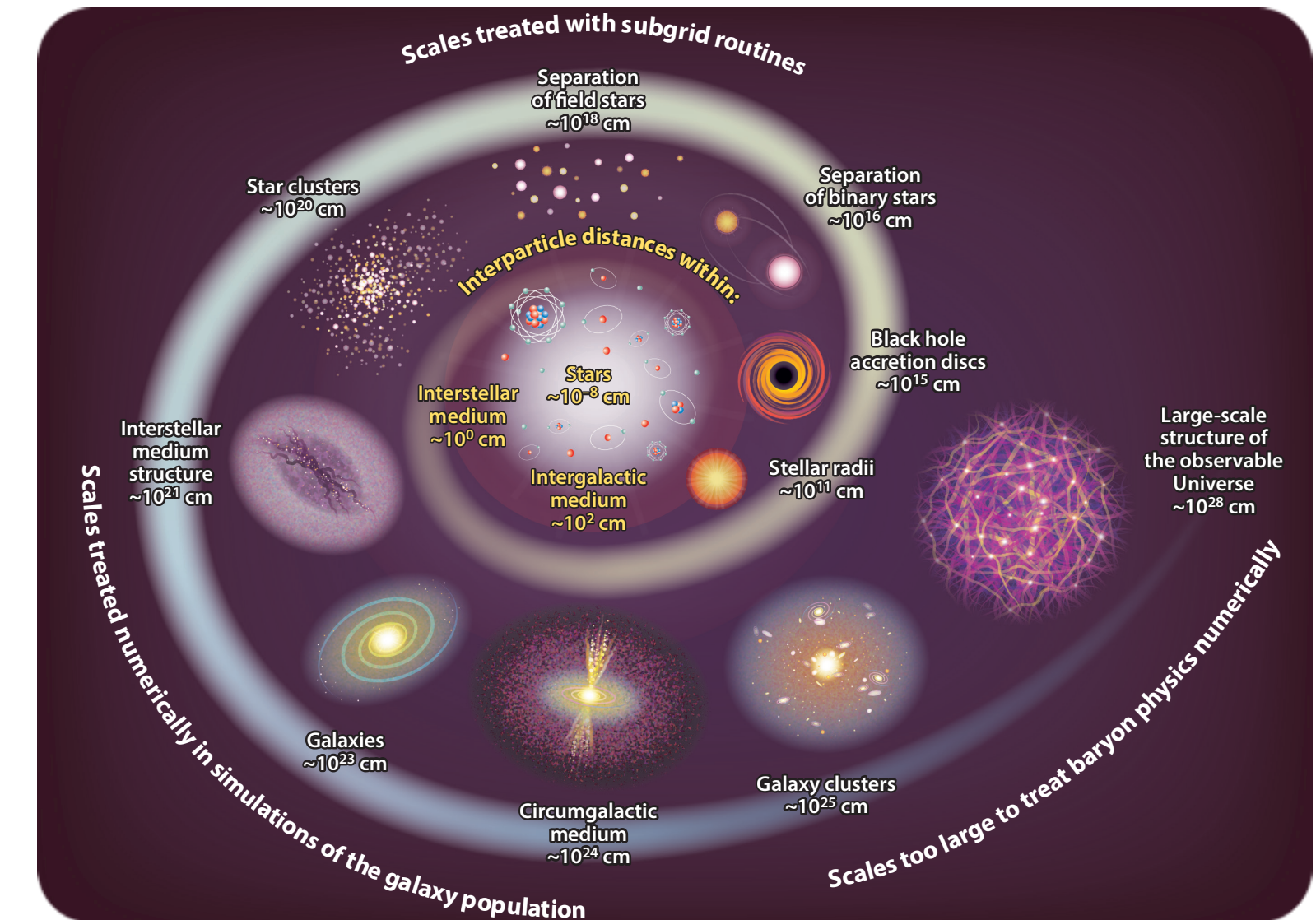
- ◆ Gravity (and heating mechanisms by exotic DM particles)
- ◆ Dynamical friction
- ◆ Mass loss



A challenging problem:

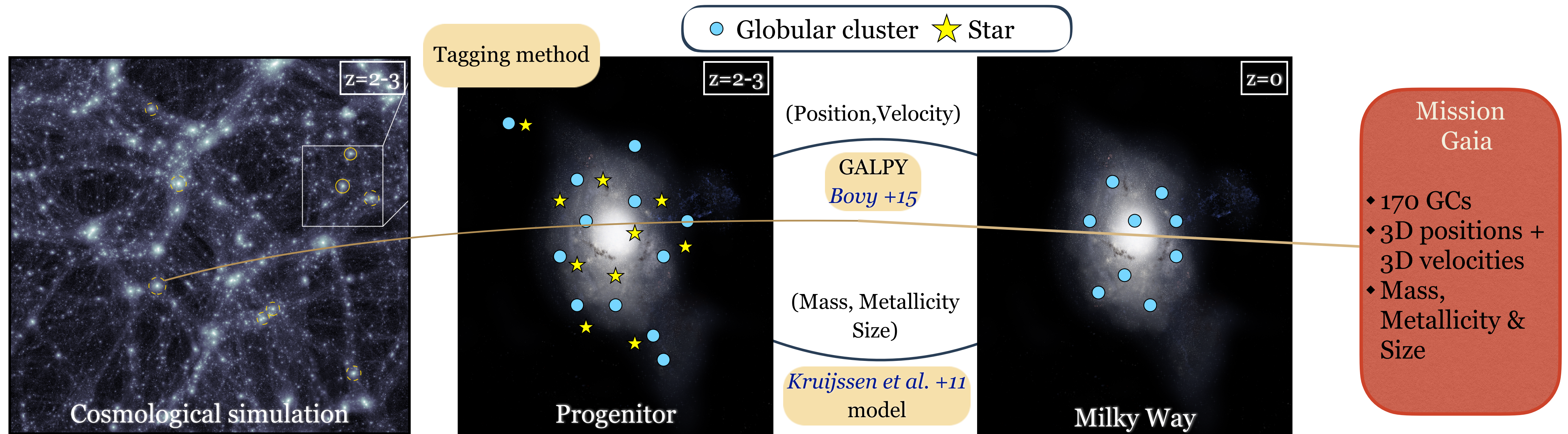
- ◆ Spatial resolution $\sim$ sub-pc
- ◆ Mass resolution $\sim 1 M_{\odot}$
- ◆ Cosmological context: large range of space (pc - Mpc) and time-scales (Myr - Gyr)

Resolution requirements make this presently impossible to do in direct calculations that track the formation of individual stars



Crain+23

Our approach [1/2]

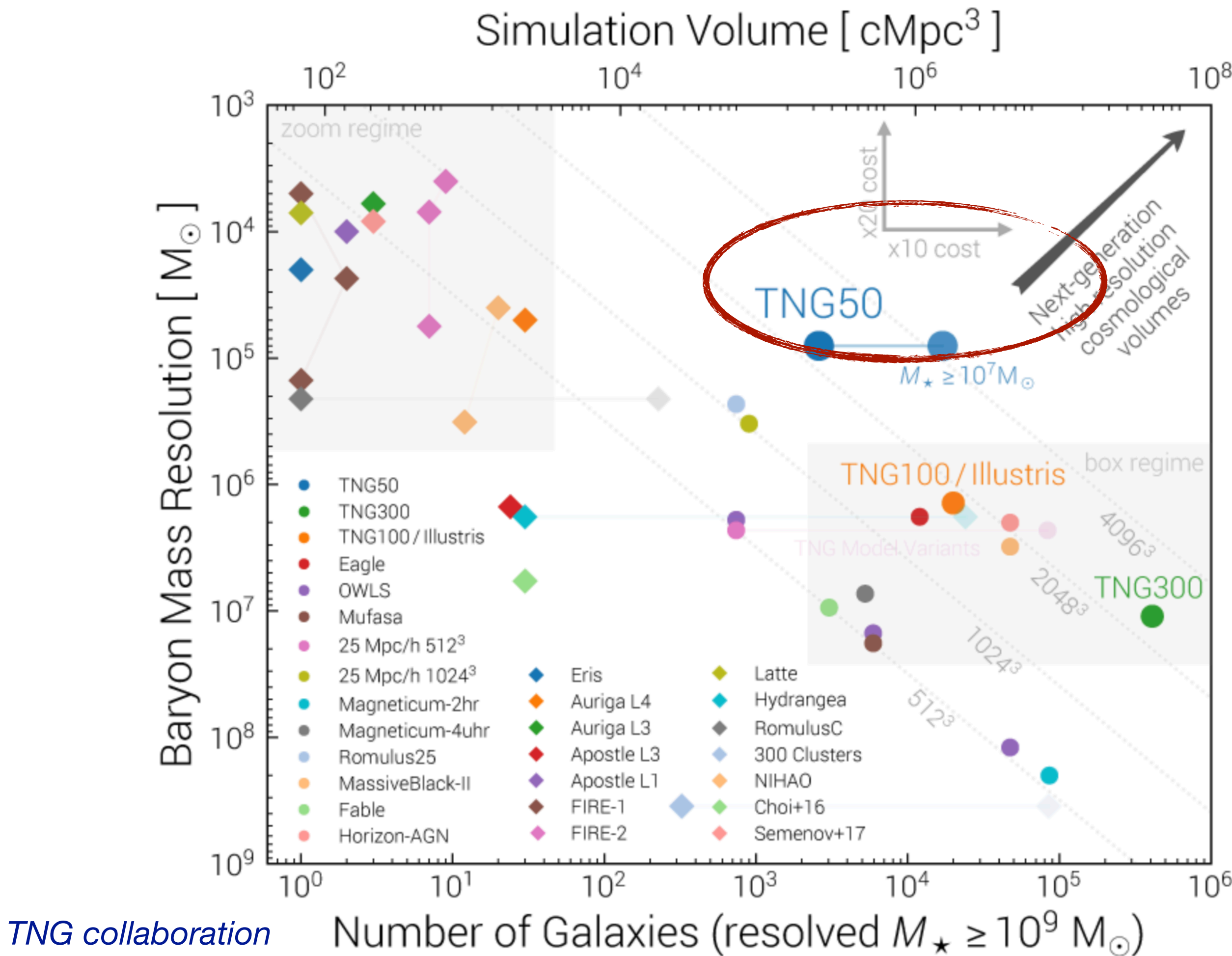


- ◆ Using existing cosmological simulations
- ◆ Computationally inexpensive
- ◆ Statistics

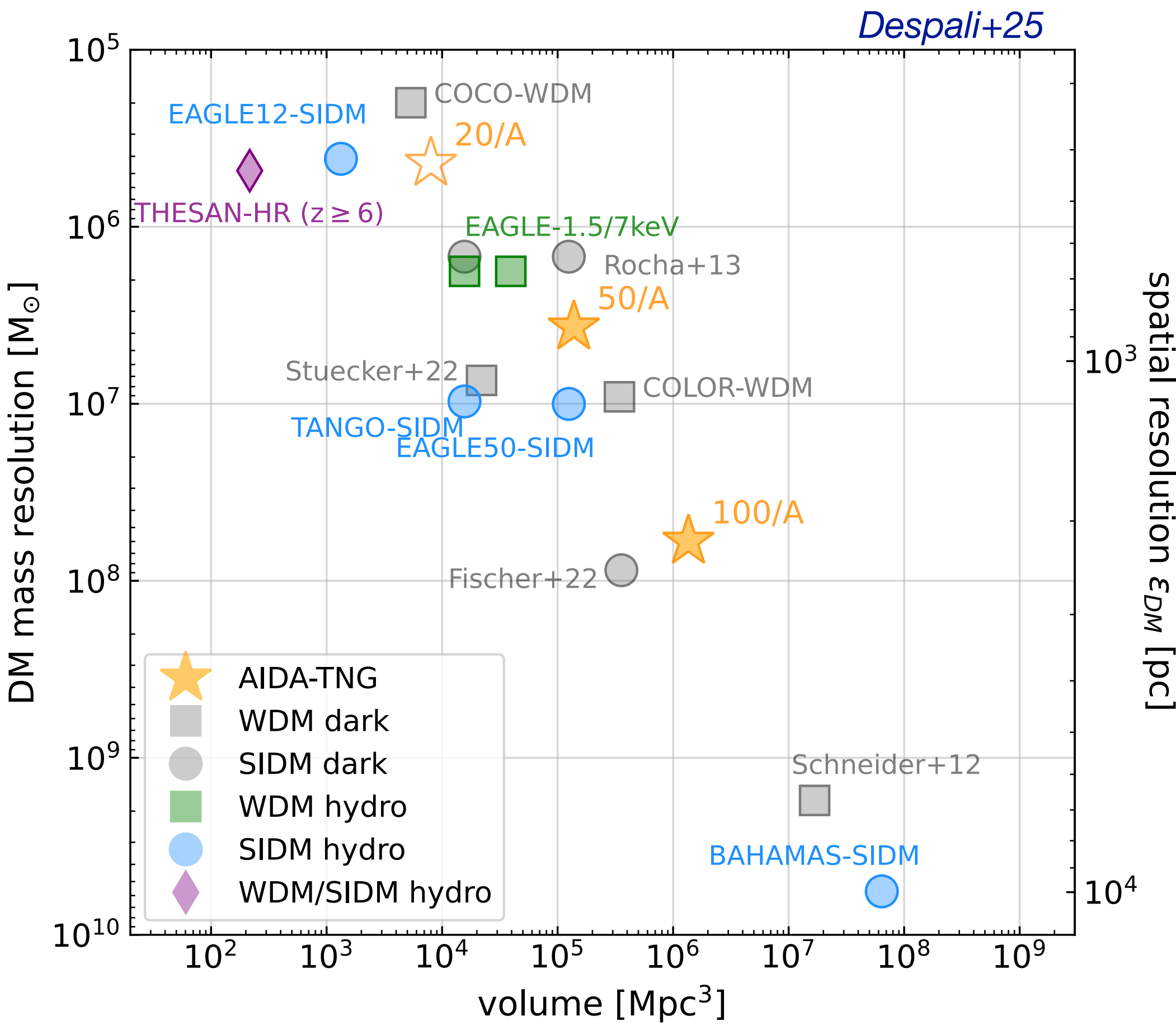
Flexible semi-analytical model in post-processing of simulations

Our approach [2/2]

CDM



ADM



A lot of cosmological simulations are available

This talk



◆ P. Di Matteo, LIRA



◆ C. Laporte, LIRA



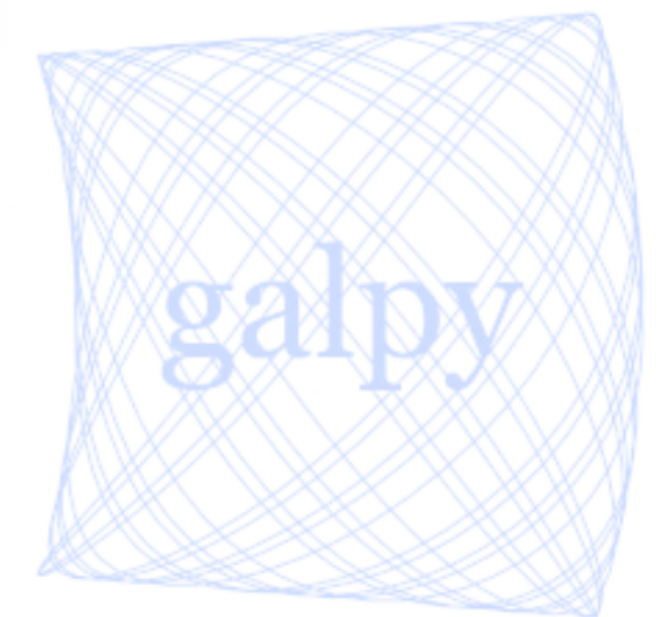
II) Origin of our Galactic GCs



◆ O. Agertz, Lund Observatory



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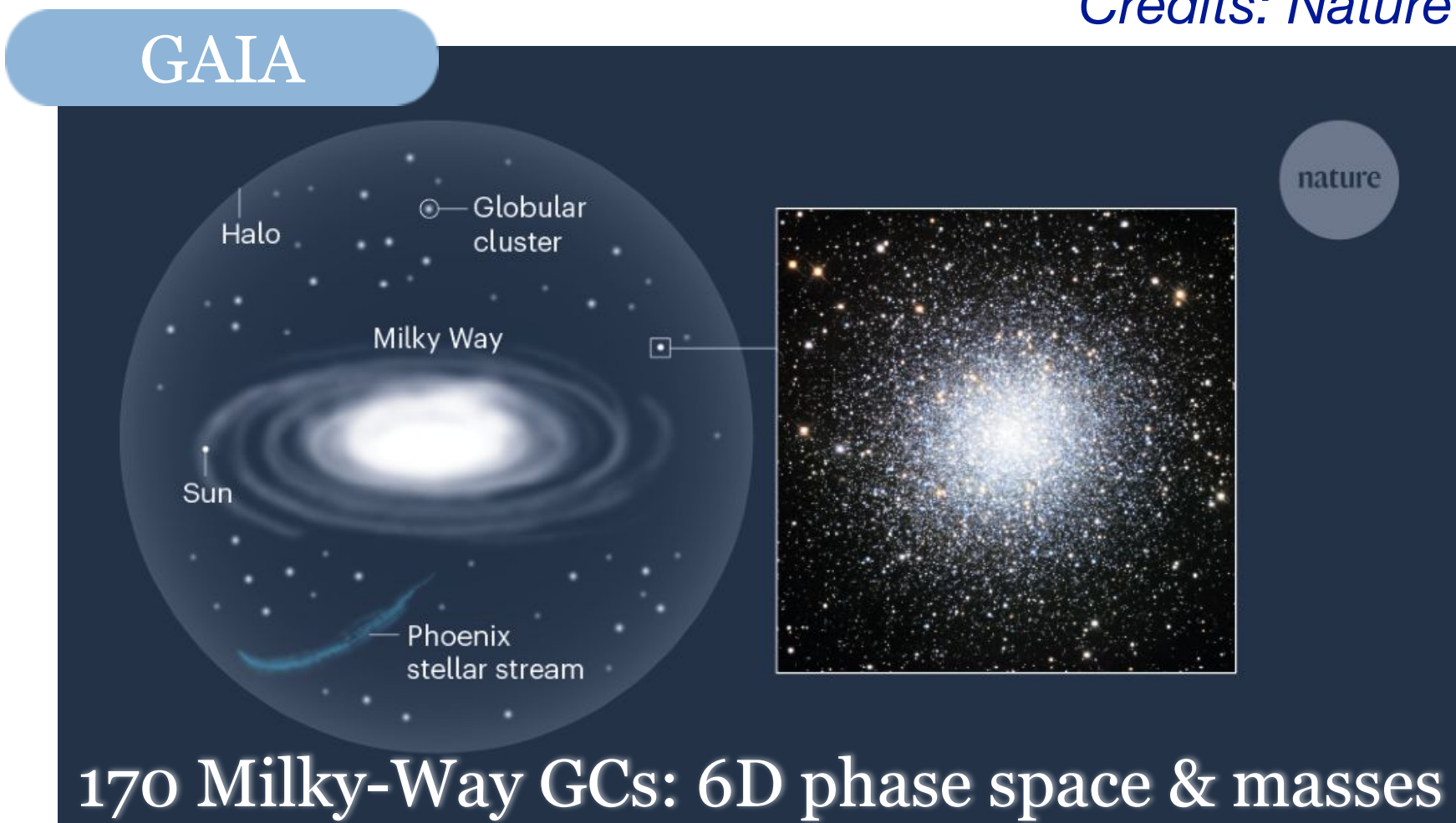


Boldrini, Di Matteo, Laporte et al. +25, submitted to A&A

arXiv:2506.13254

Origin of Galactic globular clusters: in-situ or ex-situ?

Credits: Nature

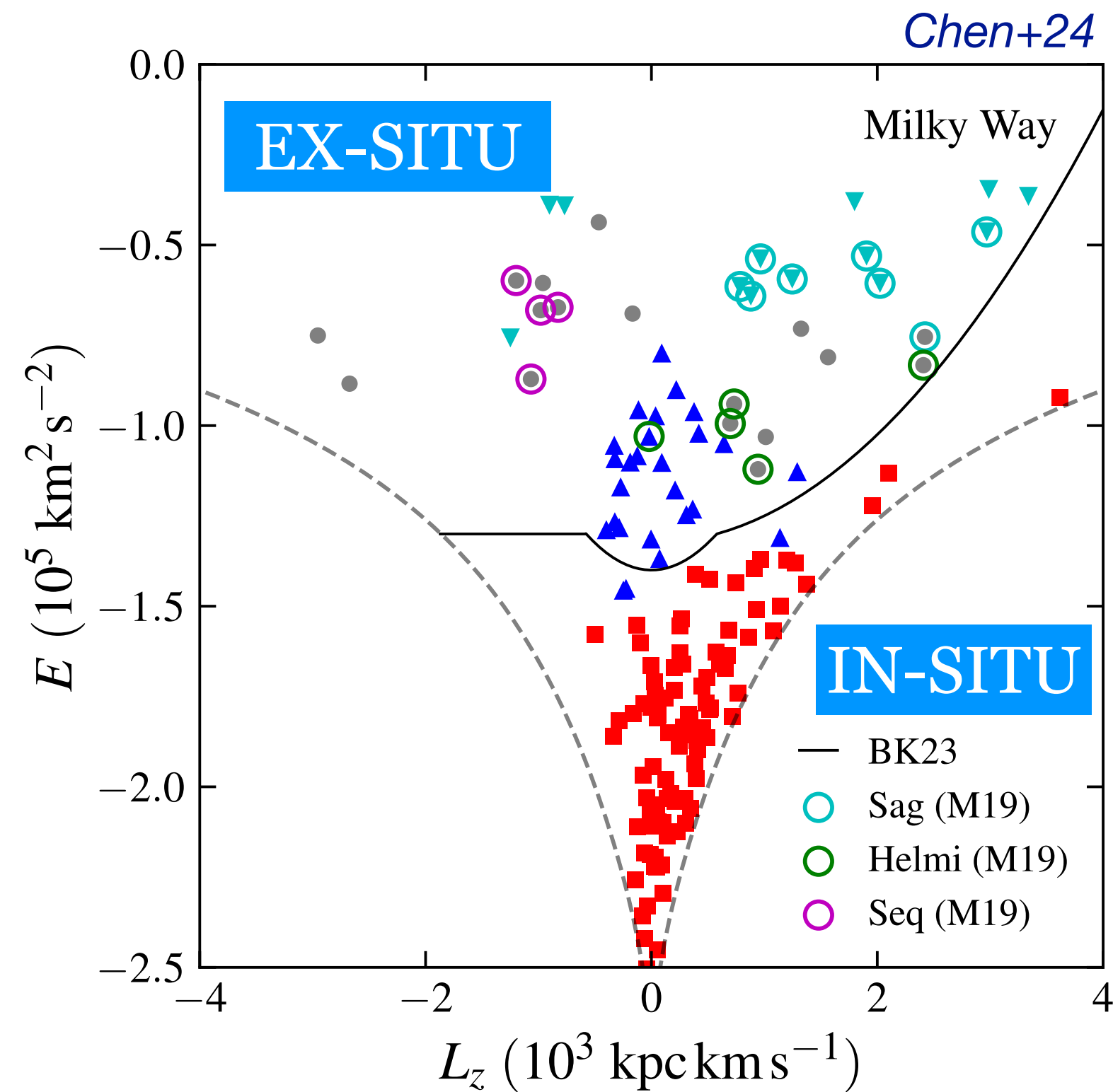


EX-SITU

Formed in
satellite galaxies

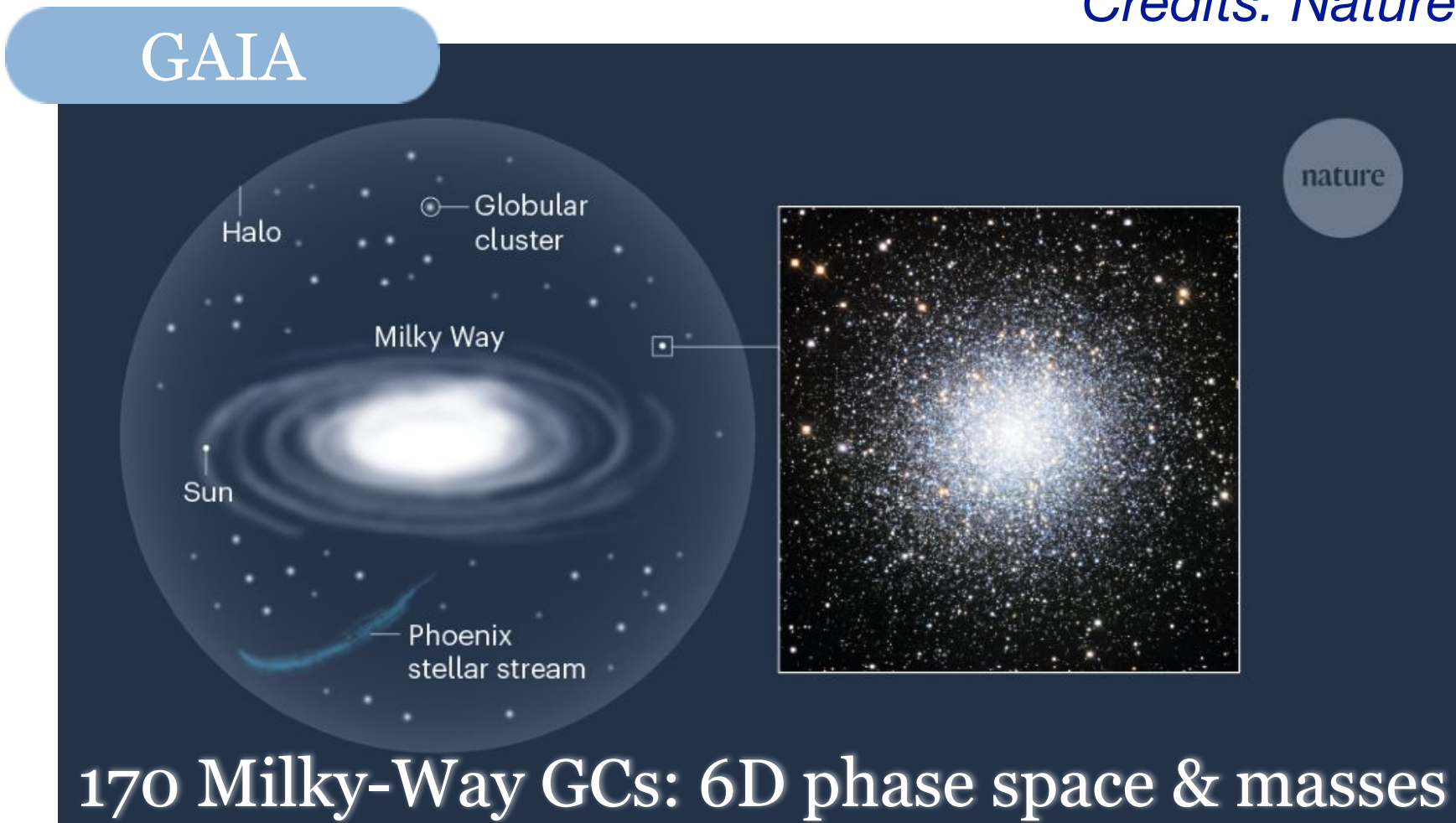
IN-SITU

Formed within
the MW



Origin of Galactic globular clusters: in-situ or ex-situ?

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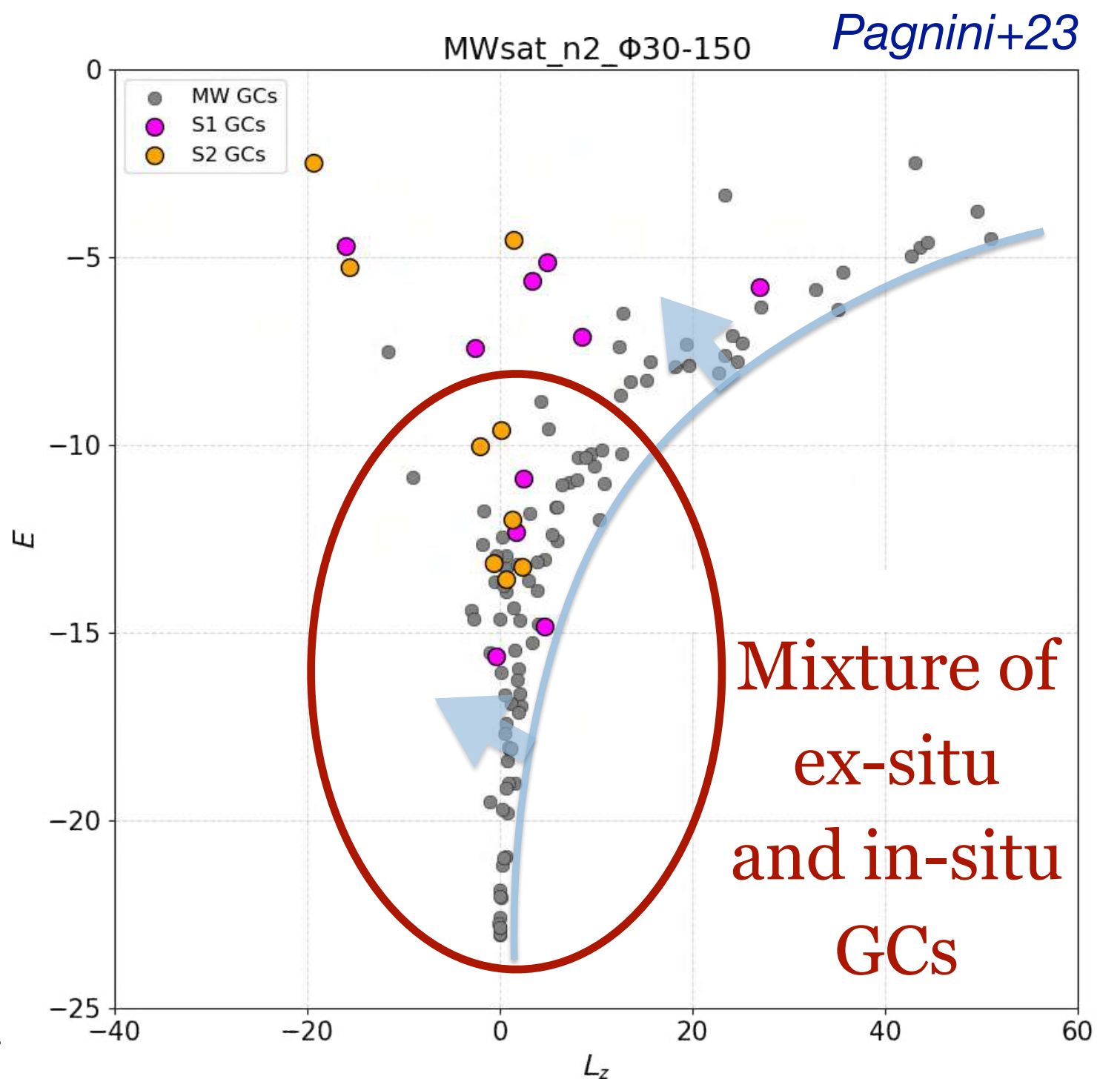
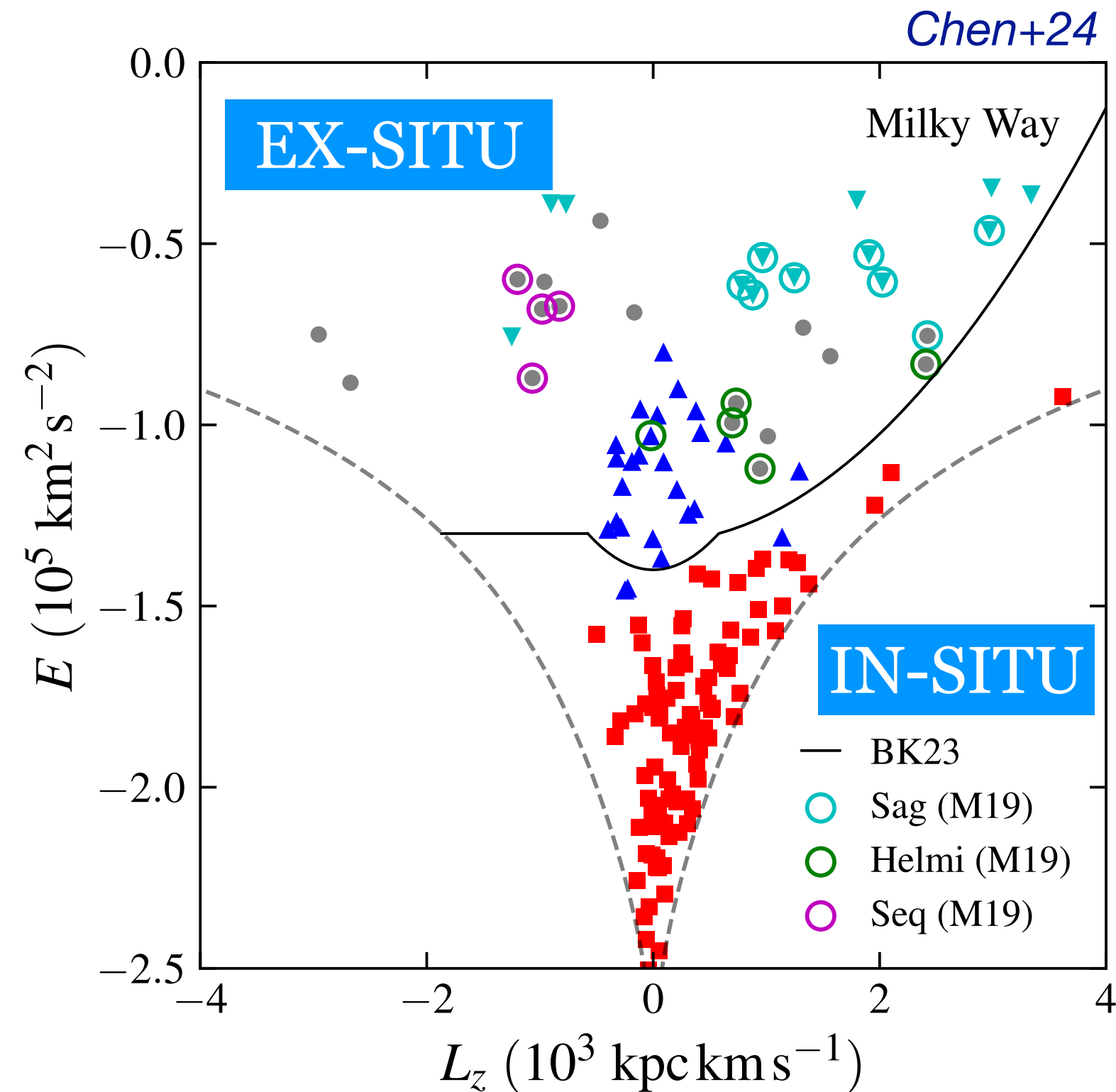


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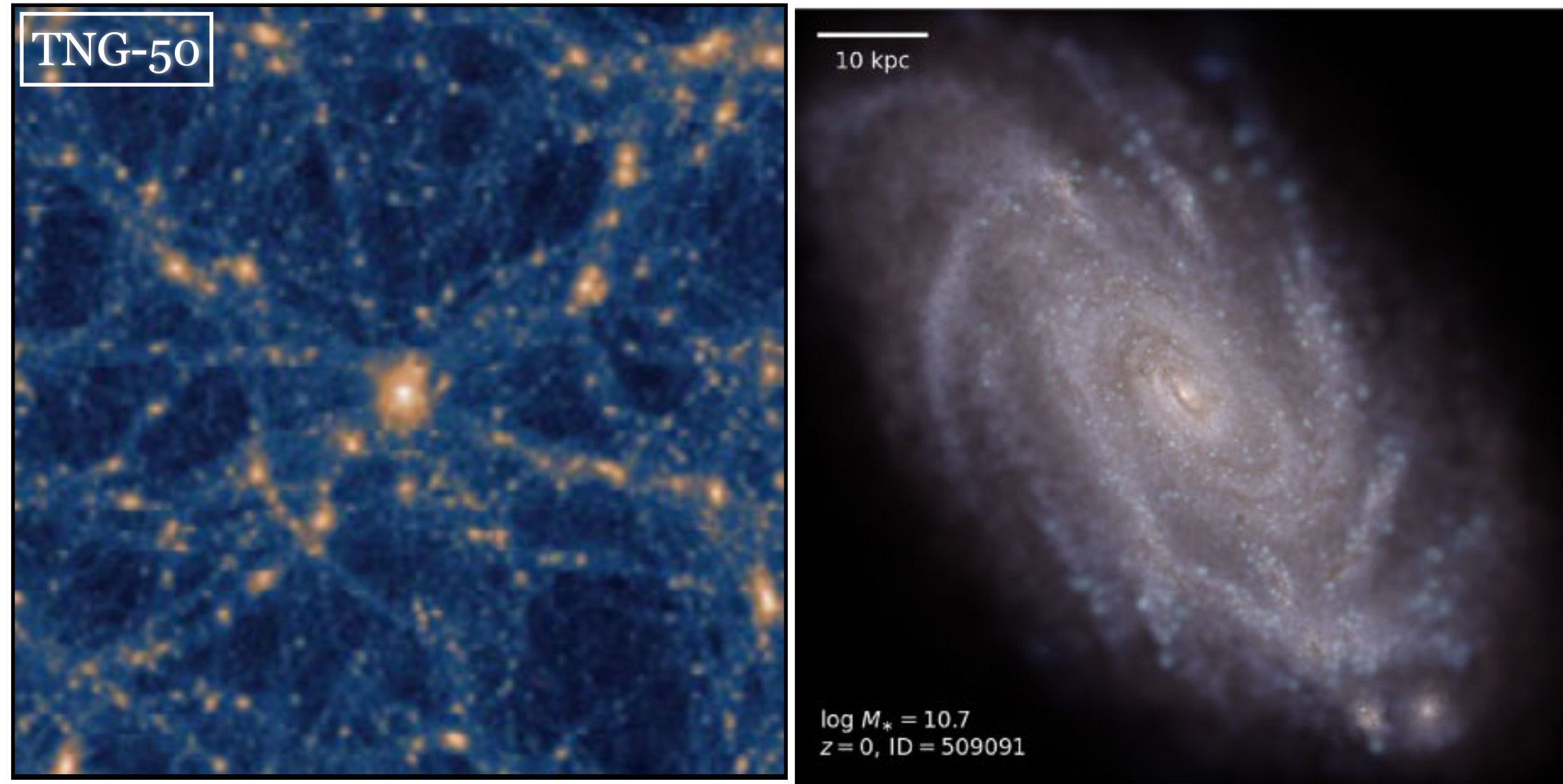


Previous studies found a clear separation between the two GC populations and it is based only on quantities at $z=0$!

What is missing?

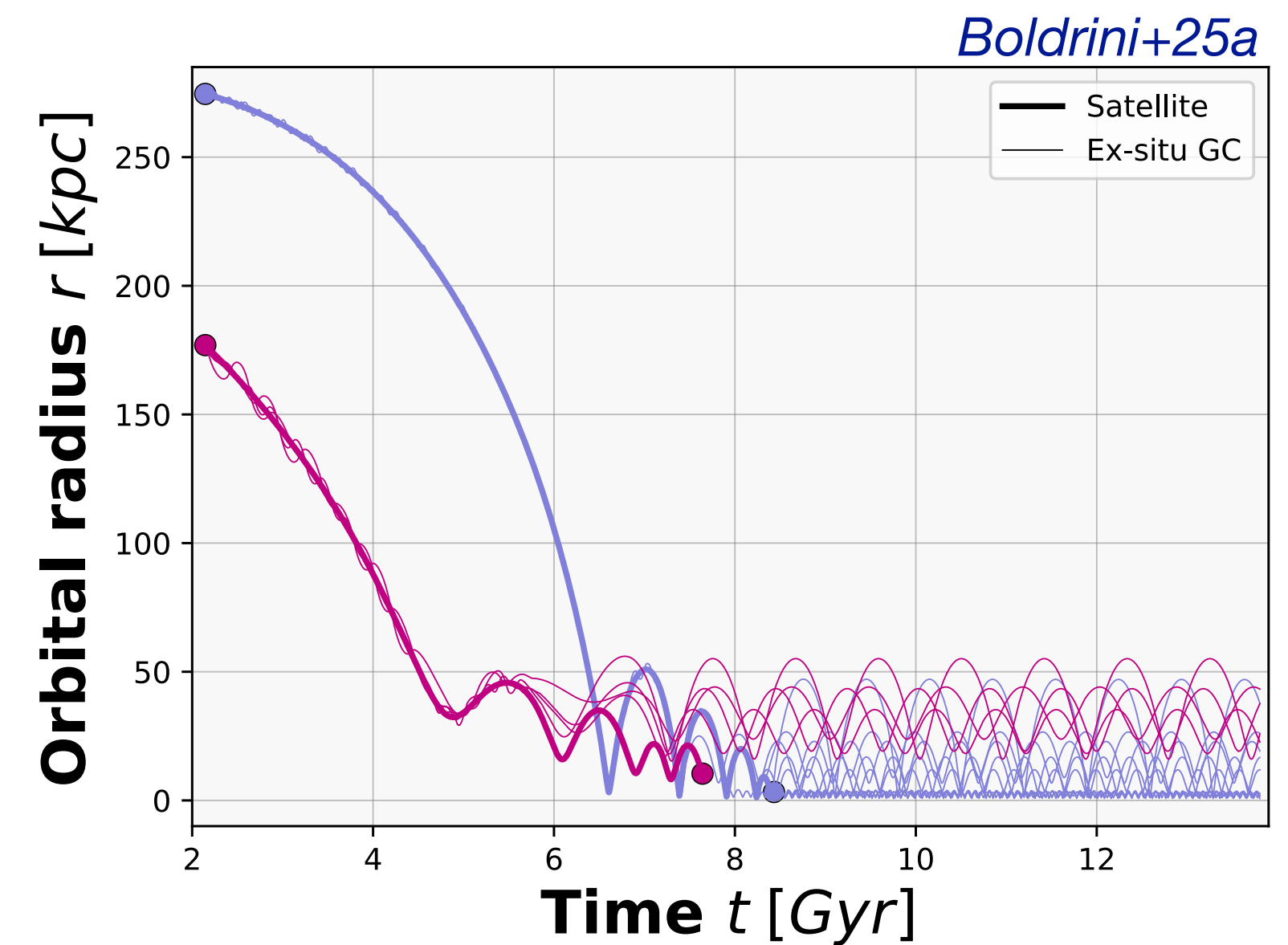
- 1) Long-term evolution of the MW
- 2) Cosmological context

Globular cluster in TNG MW-like galaxies: methods



50 Mpc

- ◆ Galactic spherical potentials are extracted from TNG50 cosmological simulations containing **198** Milky Way-like galaxies.
- ◆ GCs are tagged between $z=3$ and 2 according to [Burkert & Forbes+20](#) relation

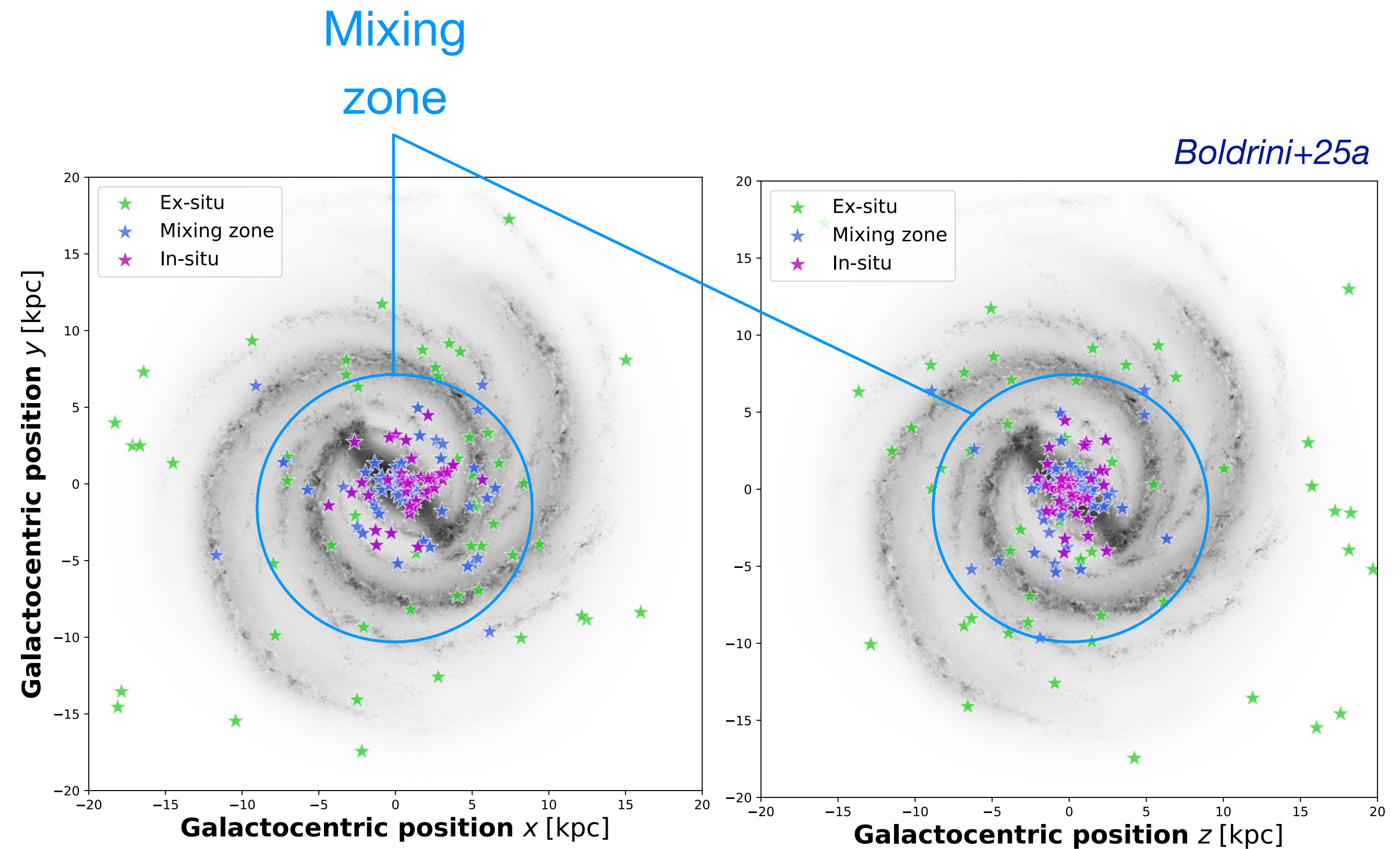
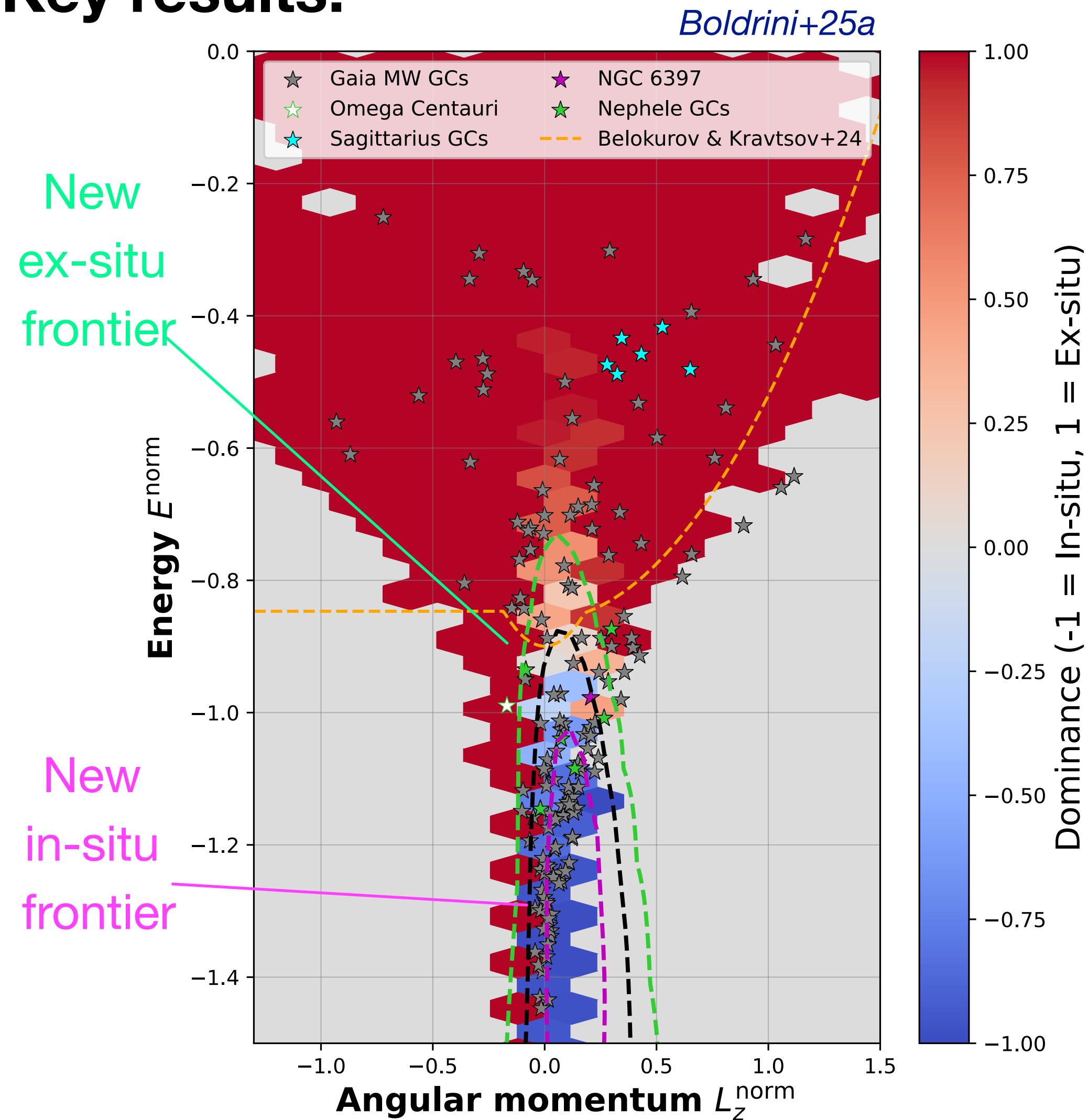


- ◆ Combined with orbit integrations with GALPY of **18,000** globular clusters from redshift $z = 3$ to 0
- ◆ Track mass loss and dynamical friction in evolving galactic environments.

198 MW systems, 18 000 GCs, from redshift $z=3$ to $z=0$, 3 physical properties

New classification of the two GC populations in our Galaxy

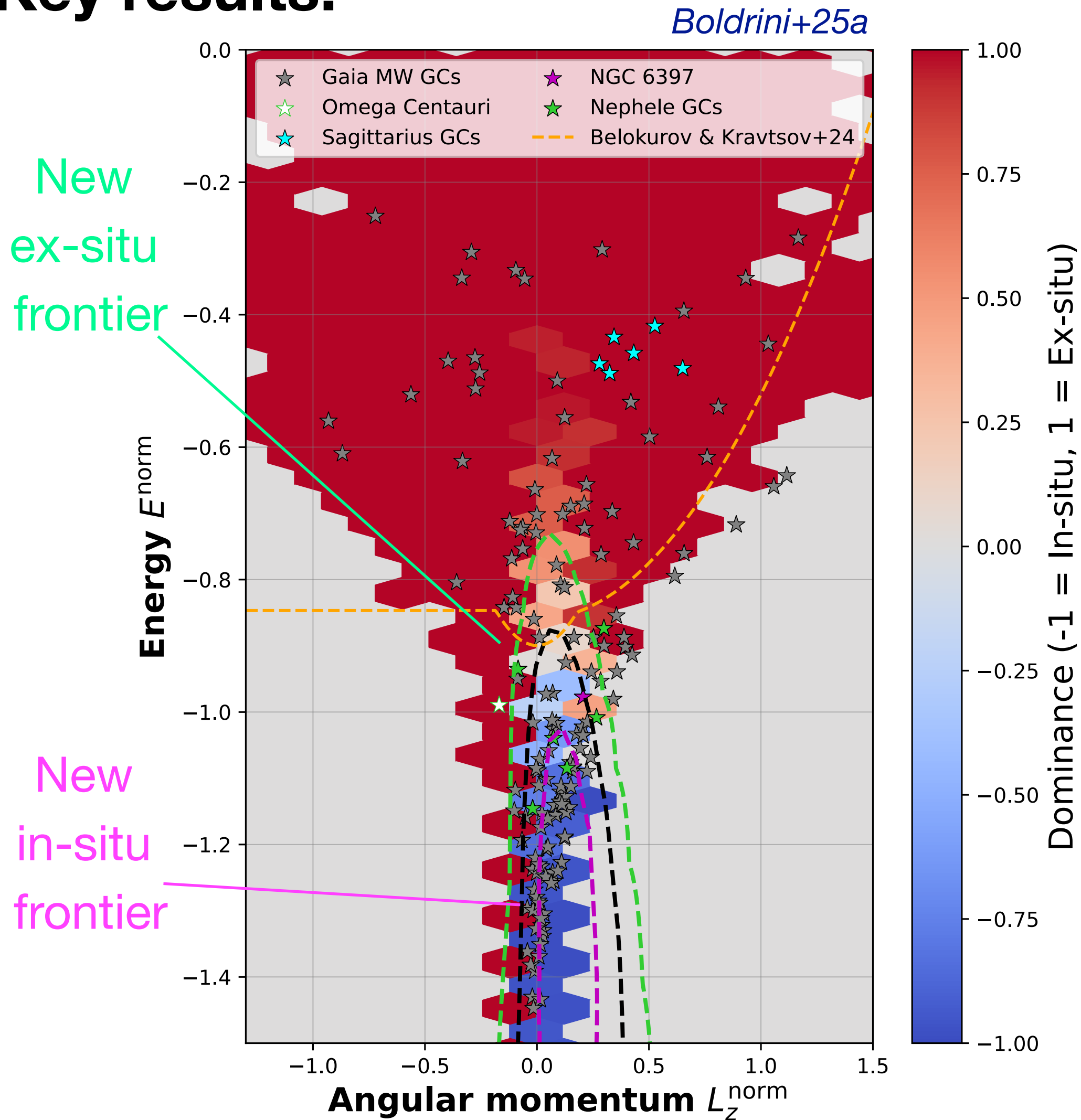
Key results:



Mixture of the two GC populations —> Challenges previous separation methods

New classification of the two GC populations in our Galaxy

Key results:



	Our work	<i>Belokurov+24</i>	<i>Chen+24</i>	<i>Sun+23</i>
ex-situ to in-situ number ratio	1.02	0.52	0.6	1.2

- ◆ **New classification:** 79 in-situ versus 81 ex-situ GCs — more ex-situ than previously thought.
- ◆ Kinematics alone are insufficient to trace GC origins —> chemical abundance could provide additional constraints (see *Pagnini+25b*).
- ◆ Full cosmological modeling is essential to understand the globular cluster population's assembly history.

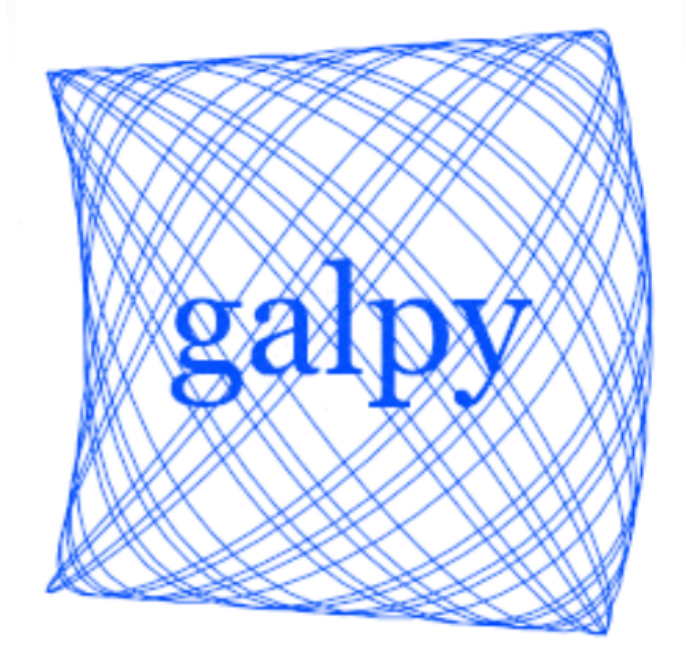
This talk



◆ P. Di Matteo, LIRA



III) GC dynamics in FDM universe: impact of the DM core profile

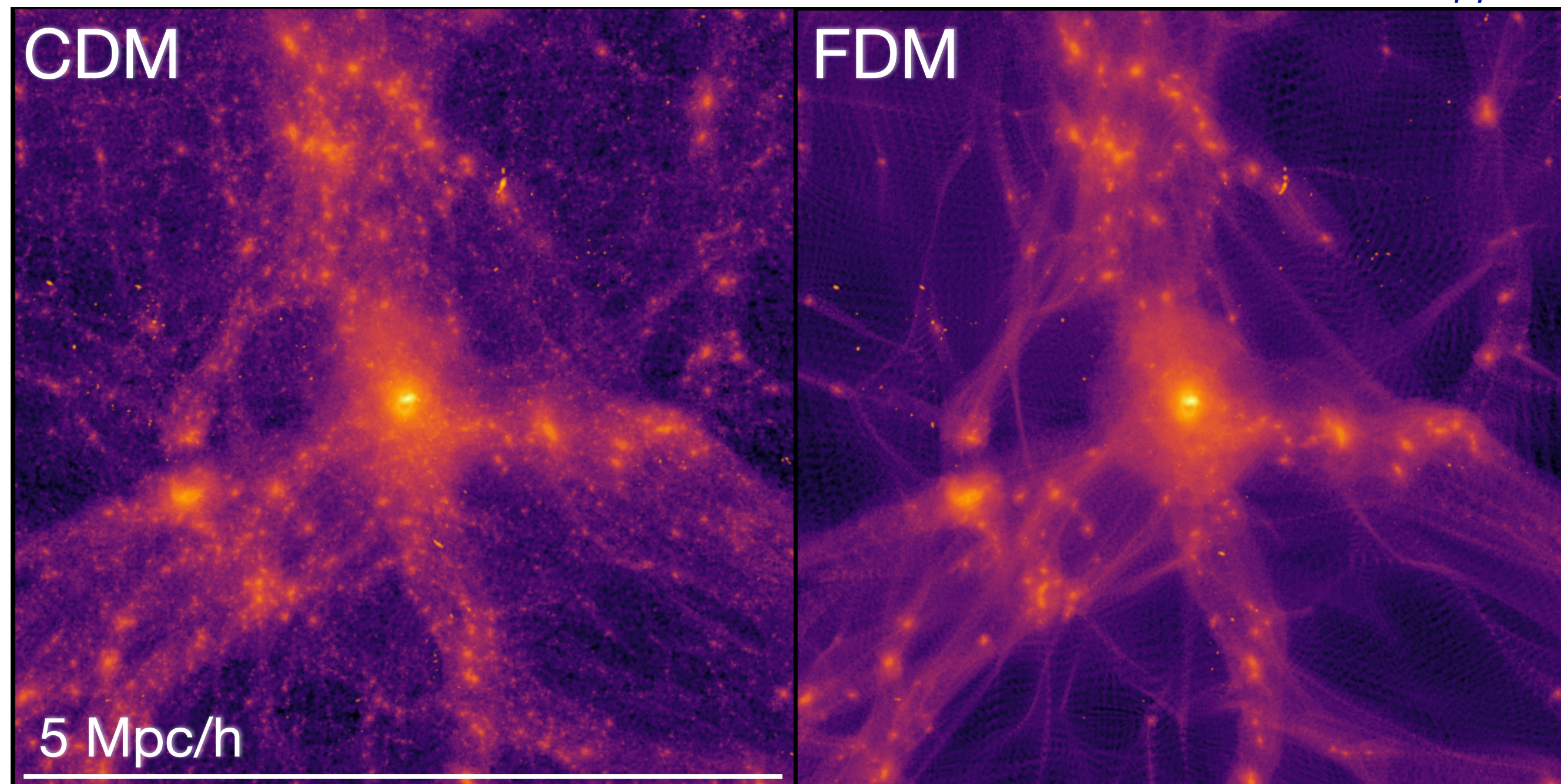


Boldrini & Di Matteo +25, in prep.

GC dynamics in fuzzy dark matter universe [1/2]

- ◆ A different DM halo density profile, with a central core instead of a cusp
- ◆ A suppression of small-scale structure formation compared to CDM
- ◆ A fluctuating potential that induces dynamical heating of infalling objects → Dynamical friction

Sipp+22



Review: Eberhardt & Ferreira+25

- ◆ Free parameter: **FDM particle mass**

$$m_{22} = m_{\chi} / 10^{-22} \text{ eV}$$

- ◆ $m_{22} = 0.1 - 100$
- ◆ Low m_{22} → Maximise FDM effects
- ◆ High m_{22} → CDM
- ◆ Galactic constraints: $m_{22} = 0.5 - 1.5$
streams, MW disc *Amorisco+18a, Chiang+23b*
- ◆ Cosmological constraints: $m_{22} = 7 - 20$
Lyman- α forest

Iršić+17, Kobayashi+17, Nori+19, Armengaud+17, Rogers+21

Deviations from CDM at galaxy scales

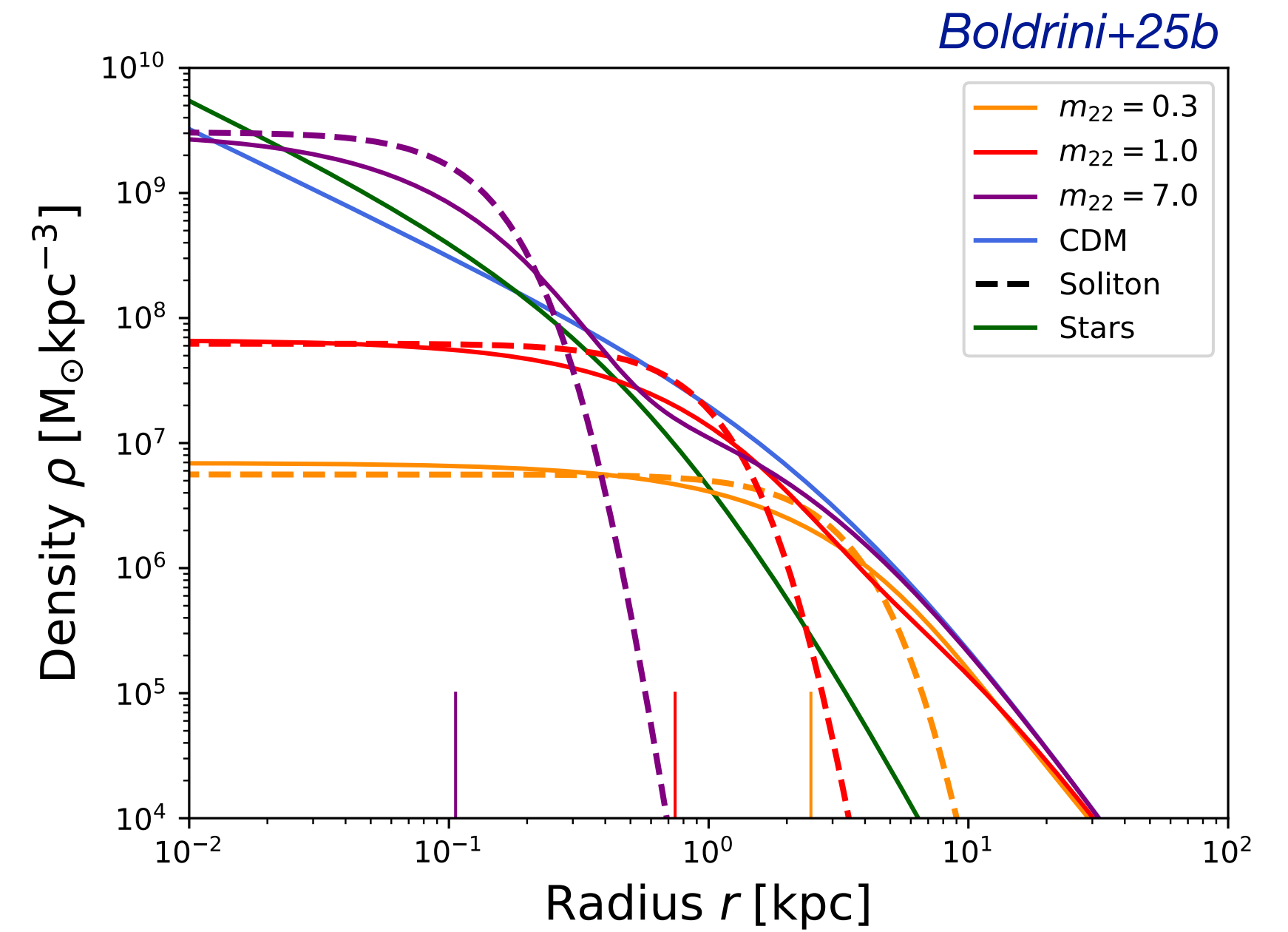
GC dynamics in FDM universe: impact of DM core

FDM MW-like galaxies from TNG50

- ◆ Solitonic core + NFW
- ◆ TNG50 Milky Way mass growth
- ◆ 198 MWs

$$\rho(r) = \frac{\rho_0(z, r_c, m_{22})}{(1 + 0.091 (r/r_c(z, M_h, m_{22}))^2)^8}$$

Schive+14



GC dynamics in FDM universe: impact of DM core

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Schive+14

In-situ globular cluster population

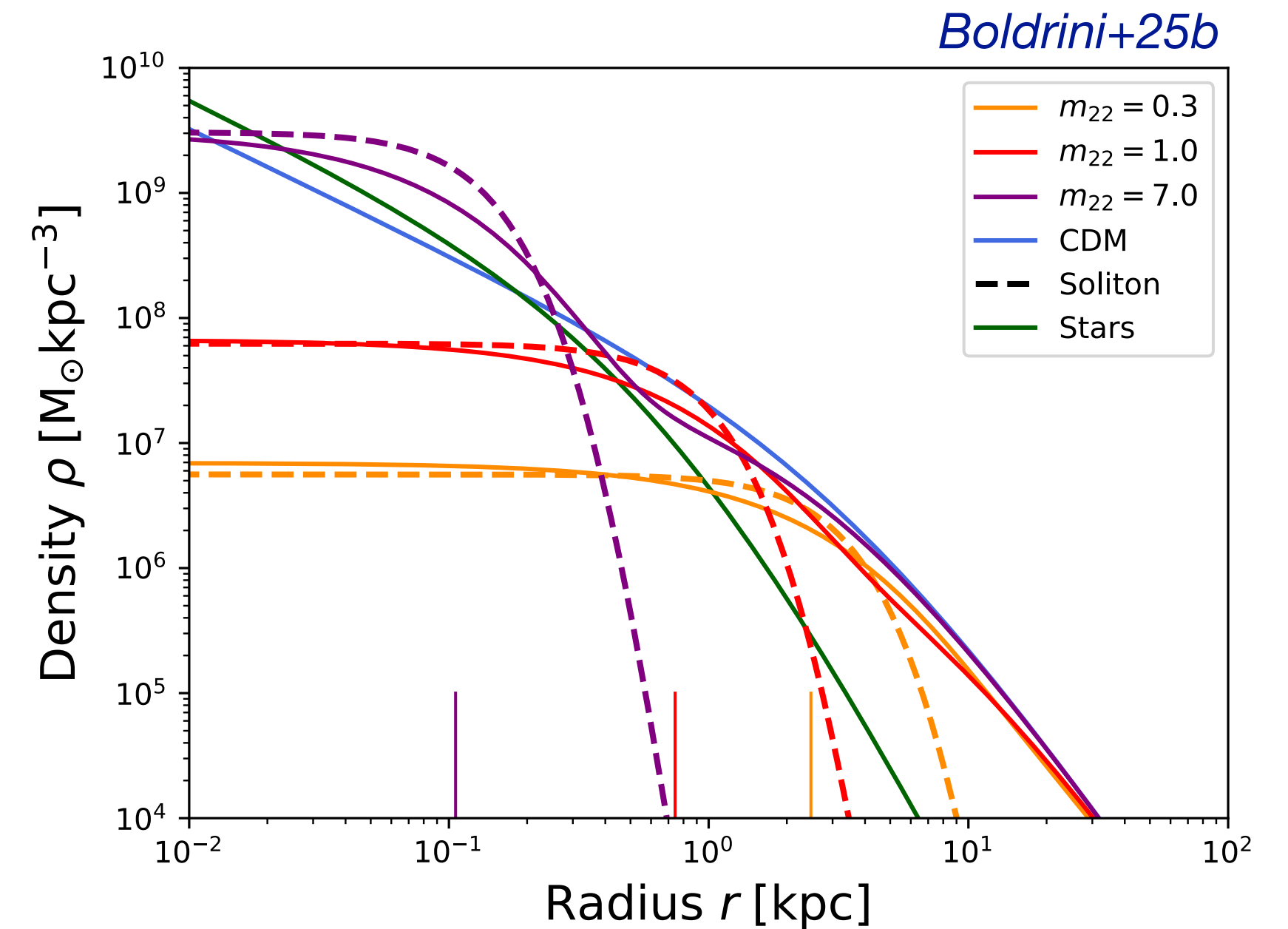
- ◆ 7709 GCs tagged at $z=2$ within MW progenitor according to *Burkert & Forbes+20* relation
- ◆ Initially located within the stellar half-mass radius of each galaxy and have disc-like distribution ($L_z > 0.6 L_{\text{circ}}$)
- ◆ Absence of dynamical friction but mass loss

$$t_{\text{fric}} \sim \left(M_{\text{gal}}(r) / M_{\text{GC}} \right) \times t_{\text{dyn}}$$

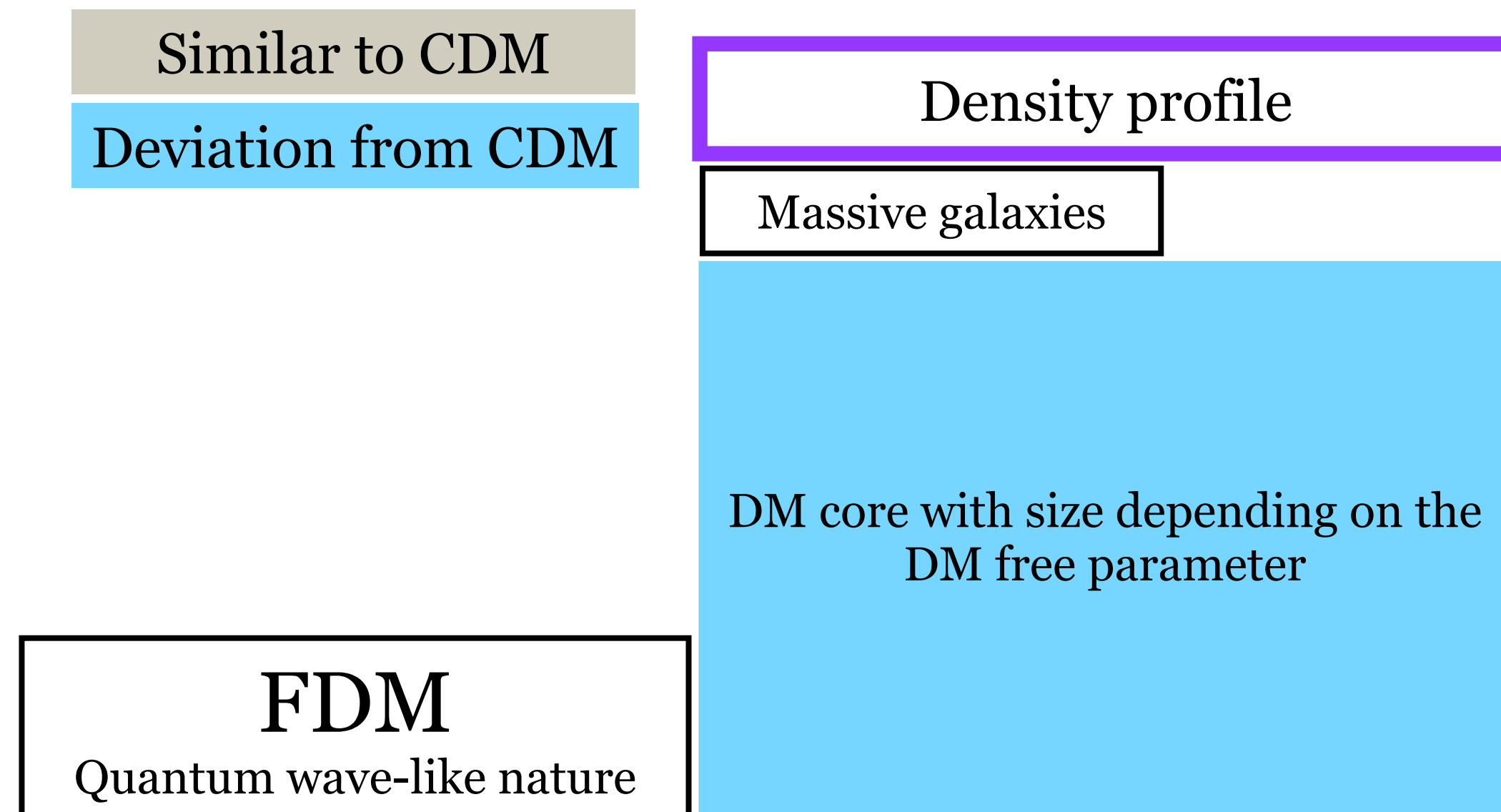
FDM parameter space

- ◆ Four different FDM particles masses: $m_{22} = 0.3, 1, 7$ and 30

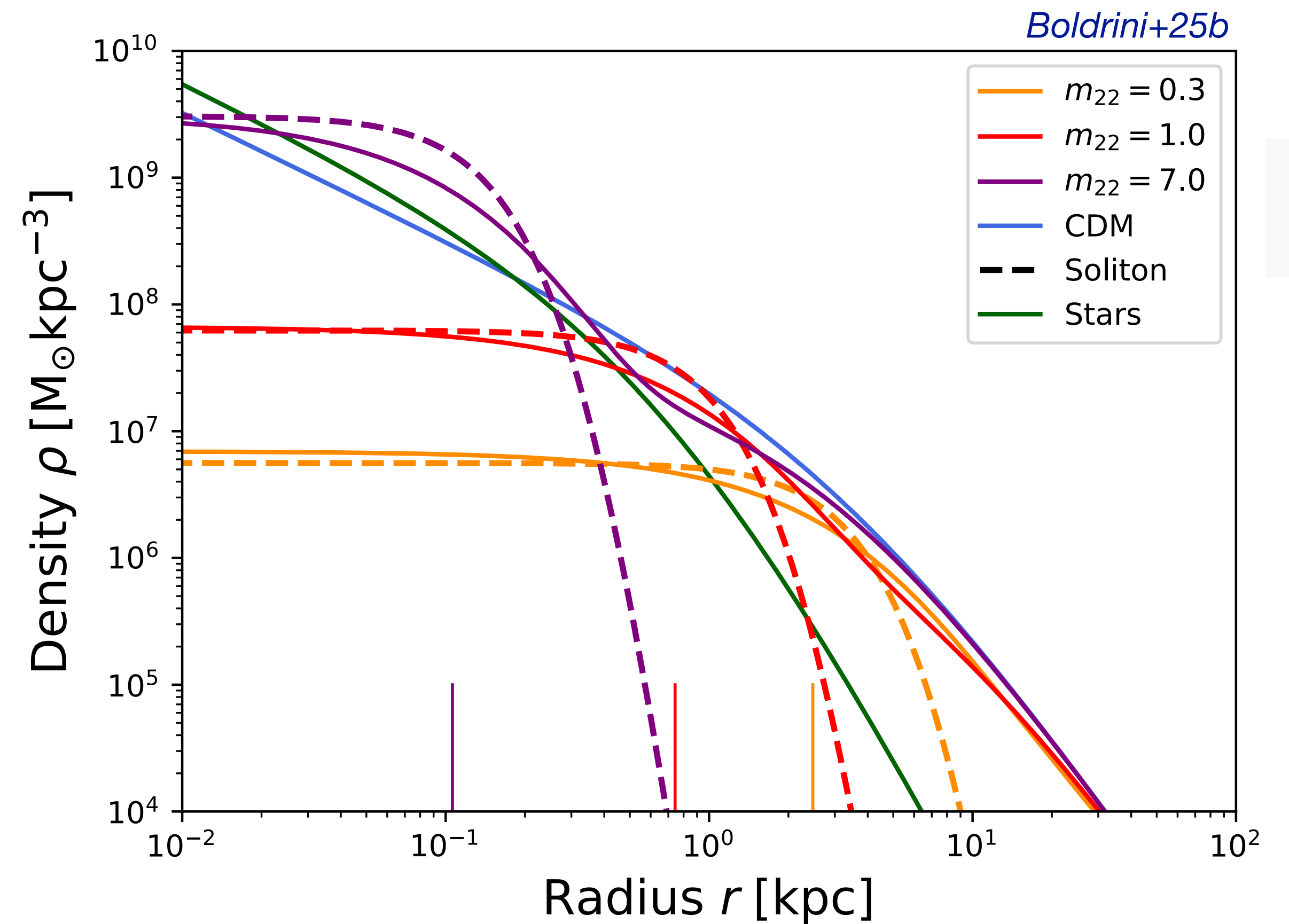
198 MW systems, 7709 GCs, from redshift $z=2$ to $z=0$, 3 physical properties



GC dynamics in FDM universe: impact of DM core

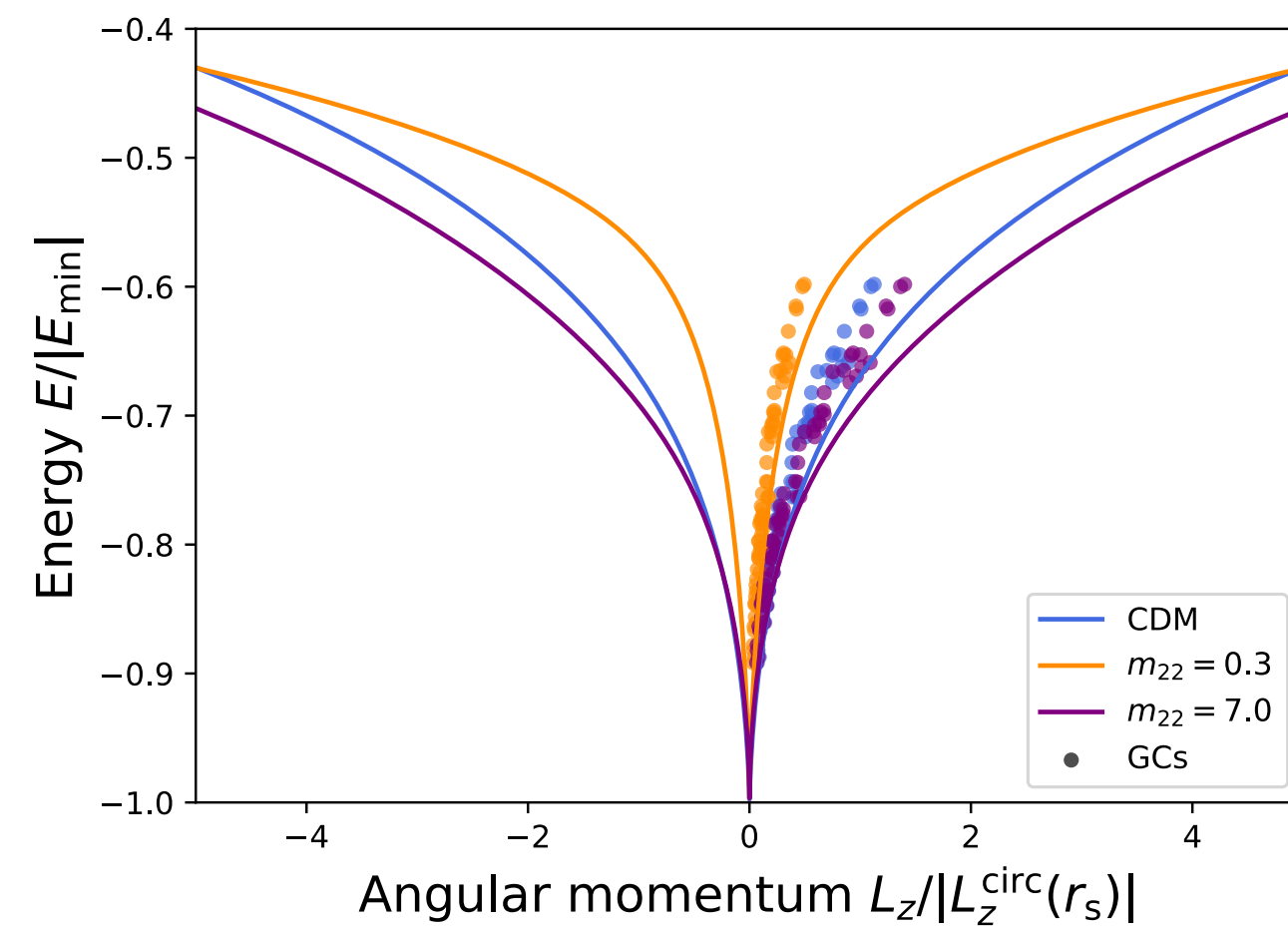


if $M_h \searrow$ or $m_{22} \searrow \Rightarrow$ Core size $\nearrow$



GC dynamics in FDM universe: impact of DM core

Initial conditions

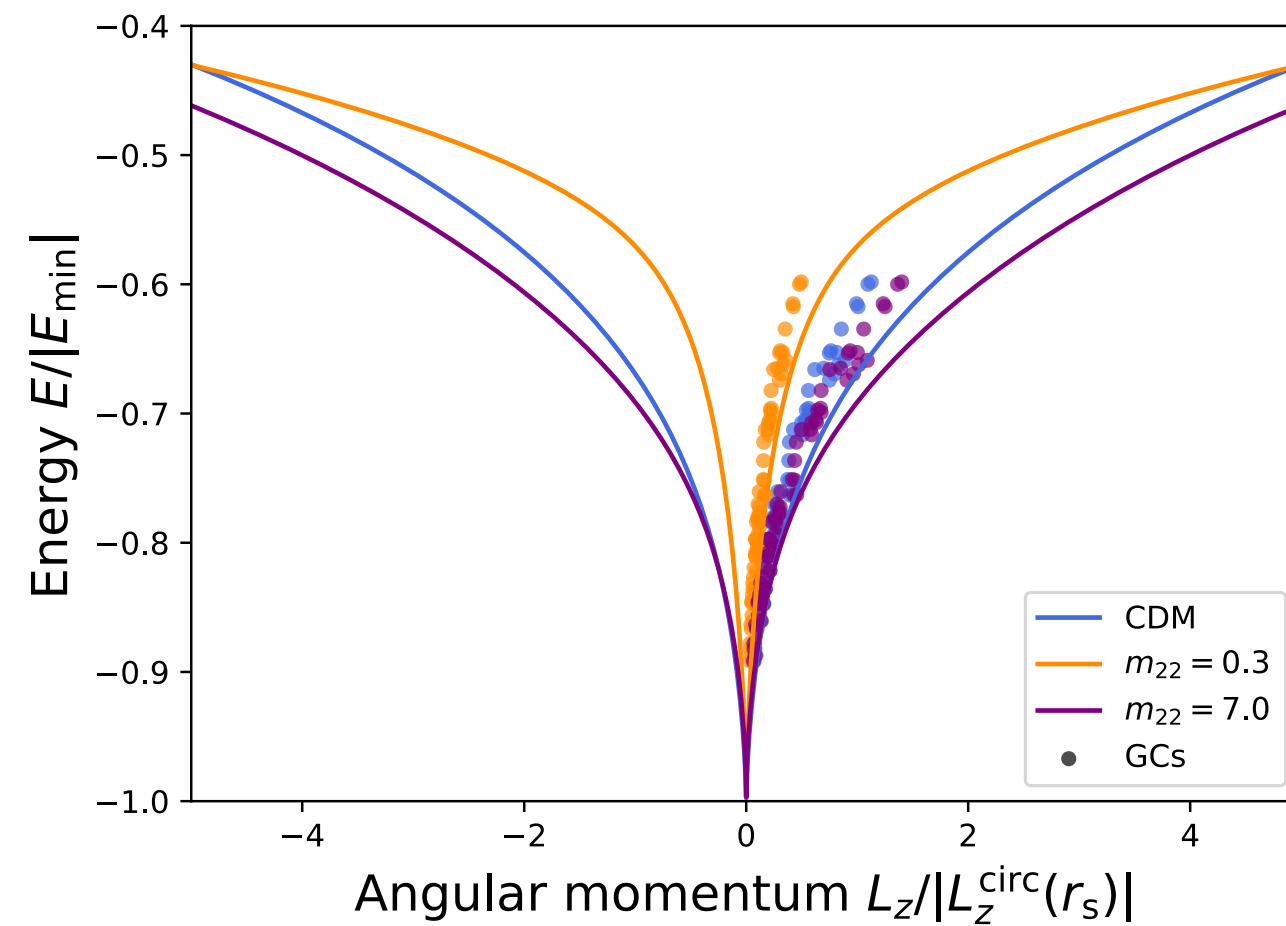


- ◆ Distributed equivalently of normalized E - L_z
- ◆ Fair comparison between DM potentials (core vs cusp)

GC dynamics in FDM universe: impact of DM core

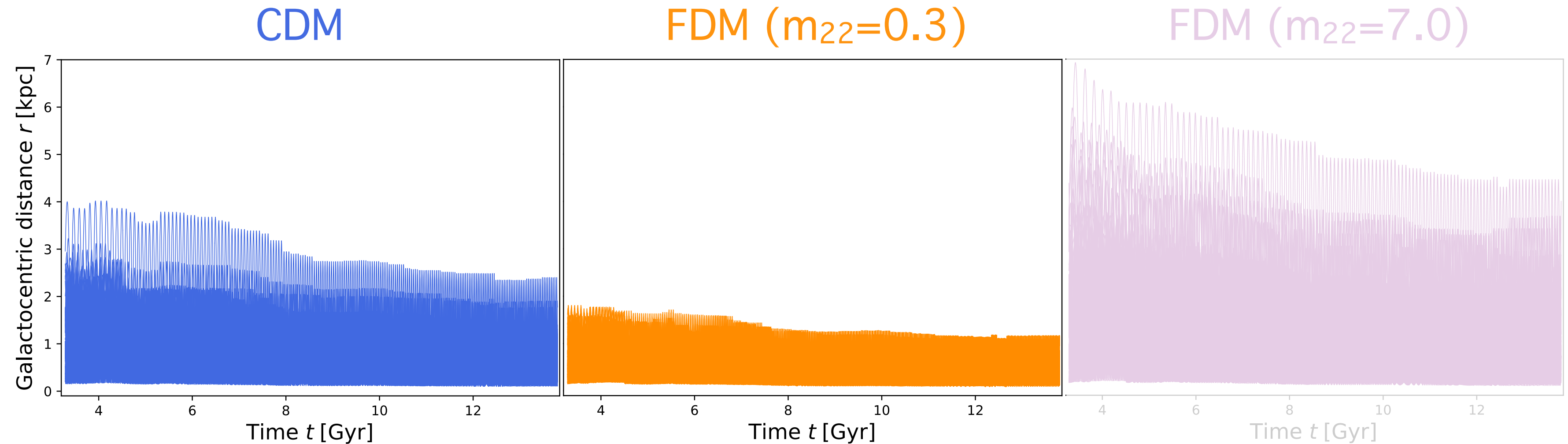
Boldrini+25b

Initial conditions



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Time evolution in

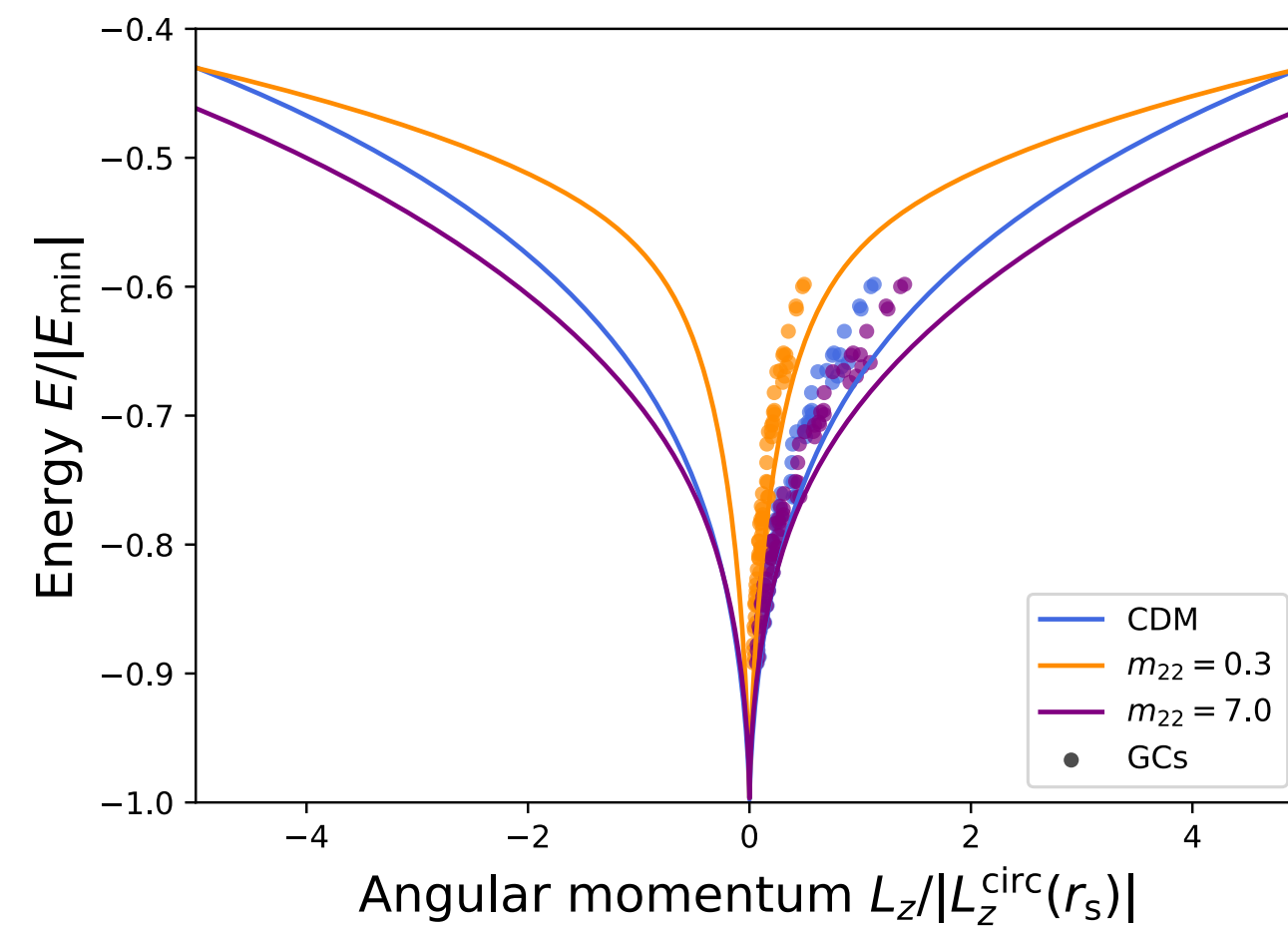


- ◆ **Low m_{22} :** steepest slope in the $E(L_z)$ is explained by the dominant baryonic contribution in the central regions of the galaxy
- ◆ Energy barrier to escape the central region is harder to overcome in FDM
—> **orbital confinement**

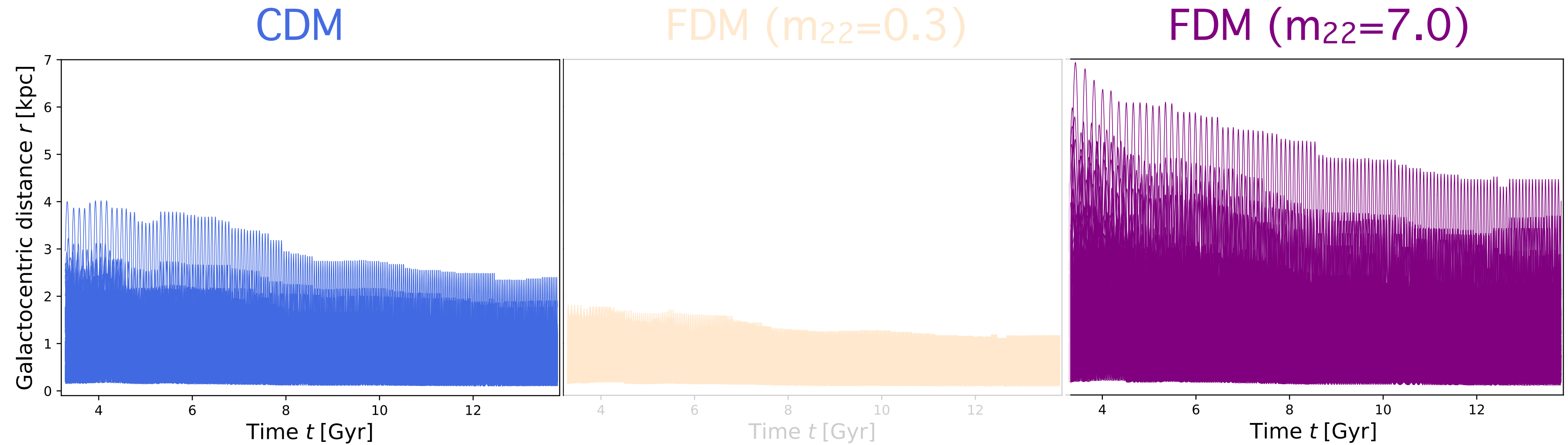
GC dynamics in FDM universe: impact of DM core

Boldrini+25b

Initial conditions



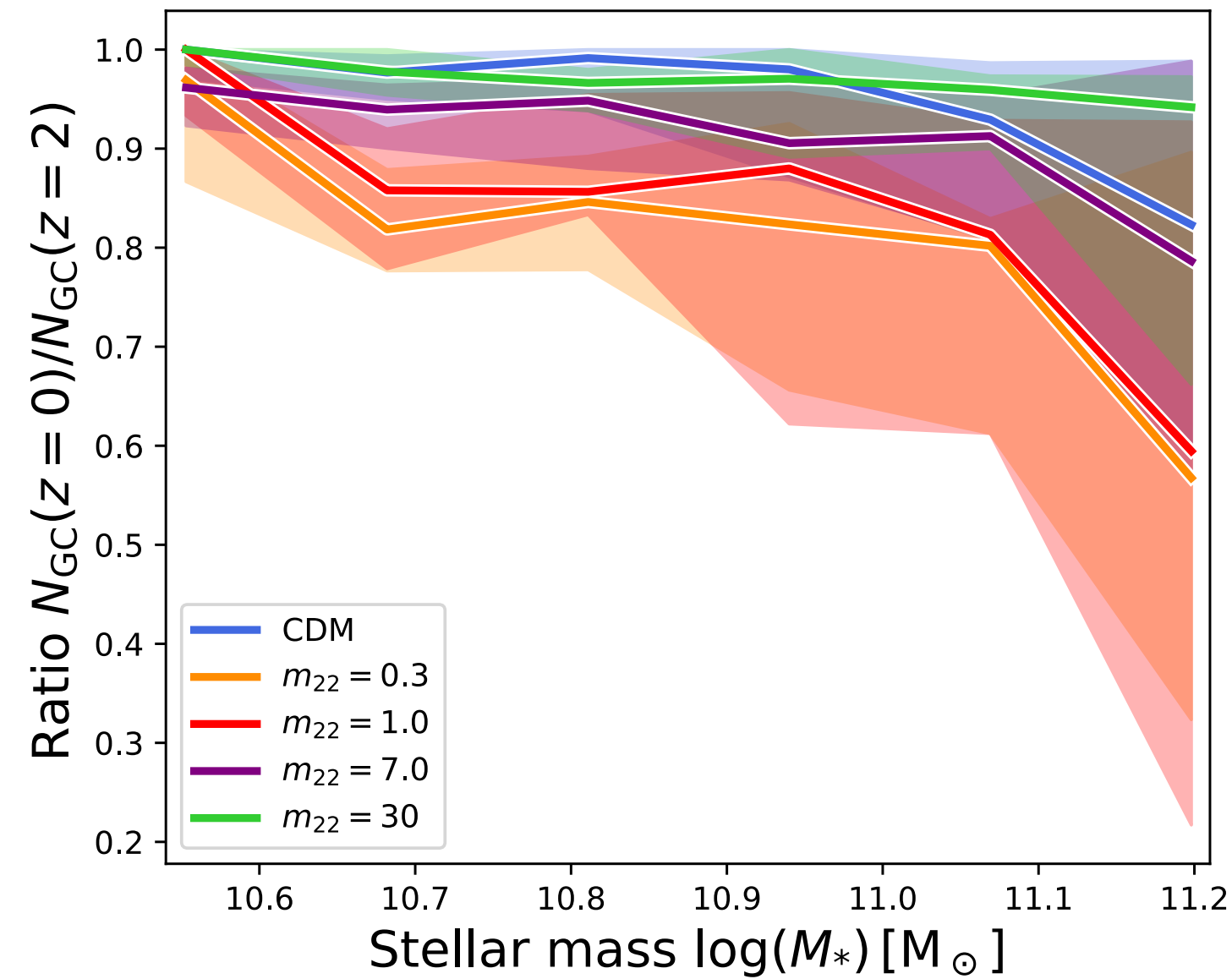
Time evolution in



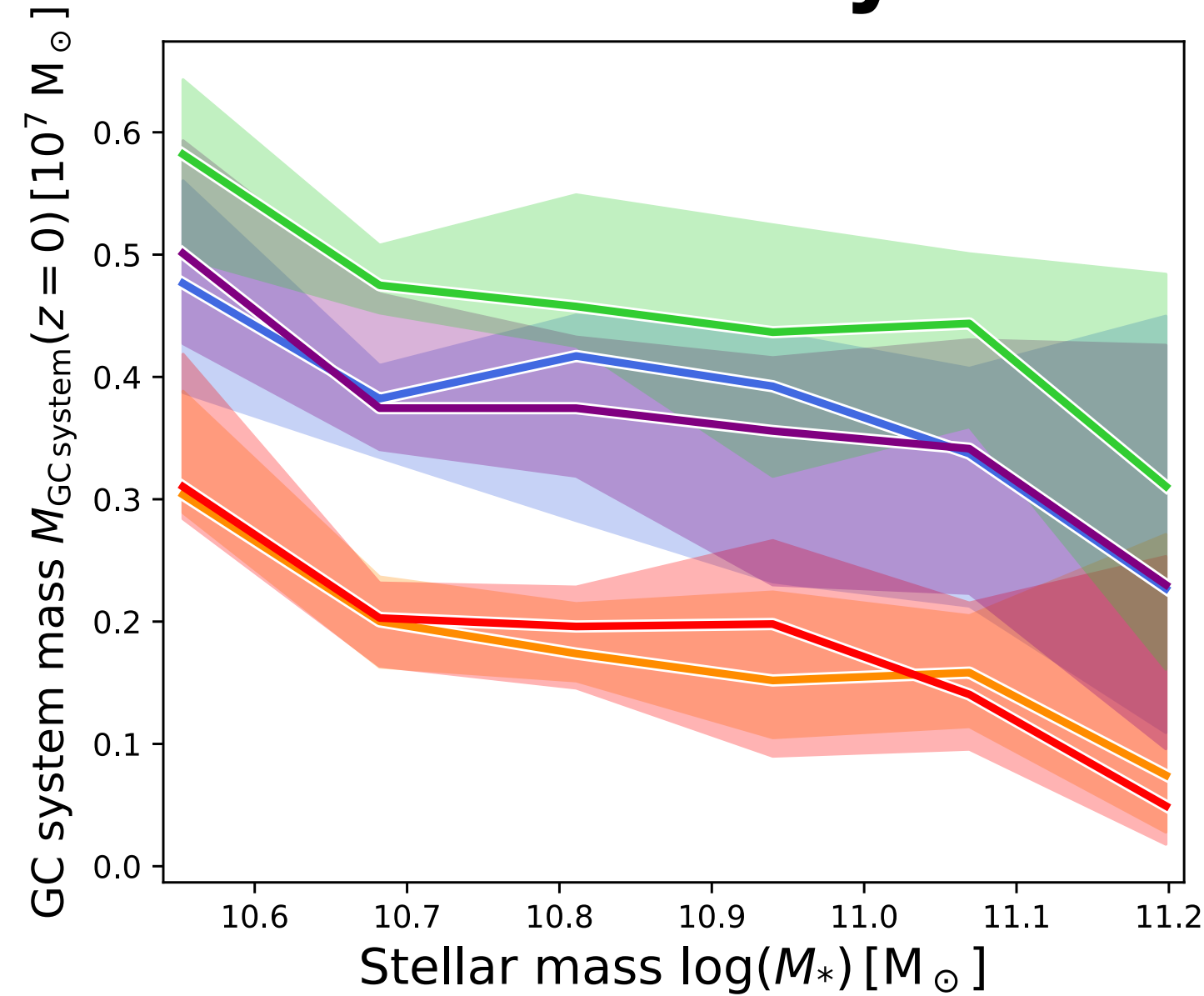
- ◆ **High m_{22} :** DM core becomes more compact and denser and the relative contribution of baryons to the total potential decrease.
- ◆ The accessible area in the (E, L_z) plane expands in FDM
—> **orbital expansion**

GC dynamics in FDM universe: impact of DM core

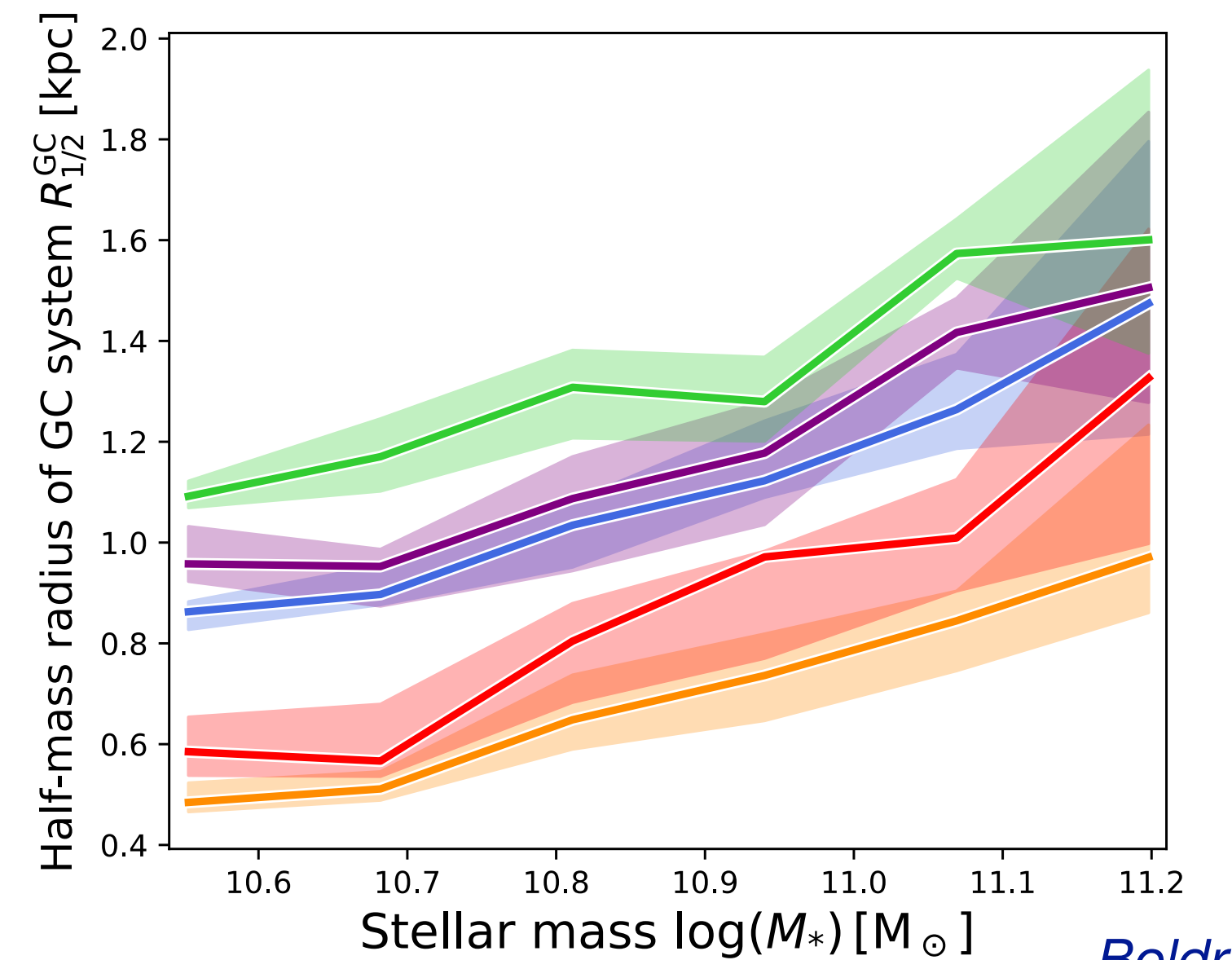
At $z=0$: Surviving GCs



Mass of GC system



Half-mass radius



Boldrini+25b

♦ $m_{22} < 7$: Fewer and individually less massive GCs.

GC system $\rightarrow$ less massive and more spatially concentrated than in CDM

♦ $m_{22} \sim 7$: Similar to CDM, both in terms of total mass and spatial distribution.

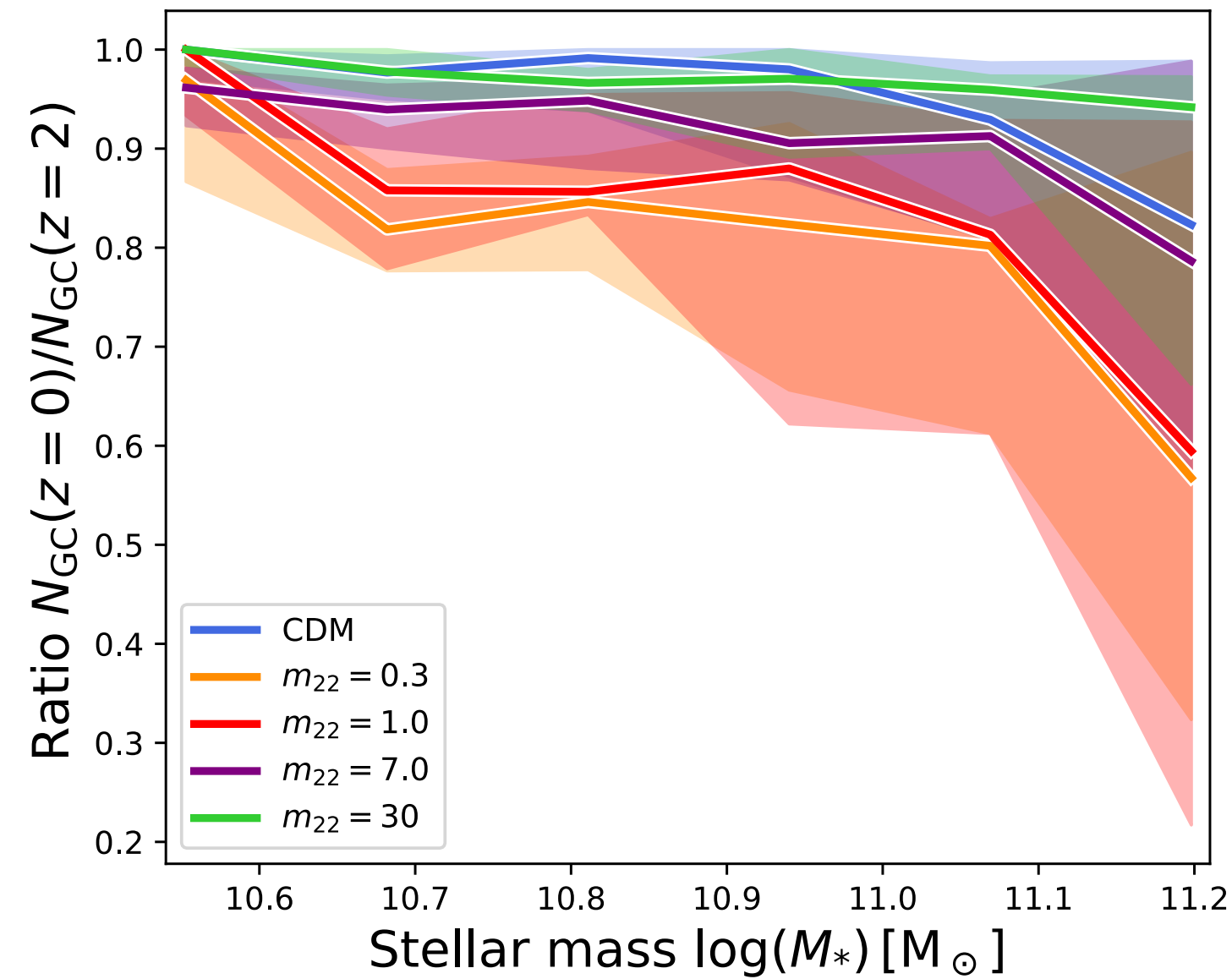
♦ $m_{22} > 7$: Larger number of surviving clusters, generally more massive.

GC system $\rightarrow$ more massive and more extended than in CDM

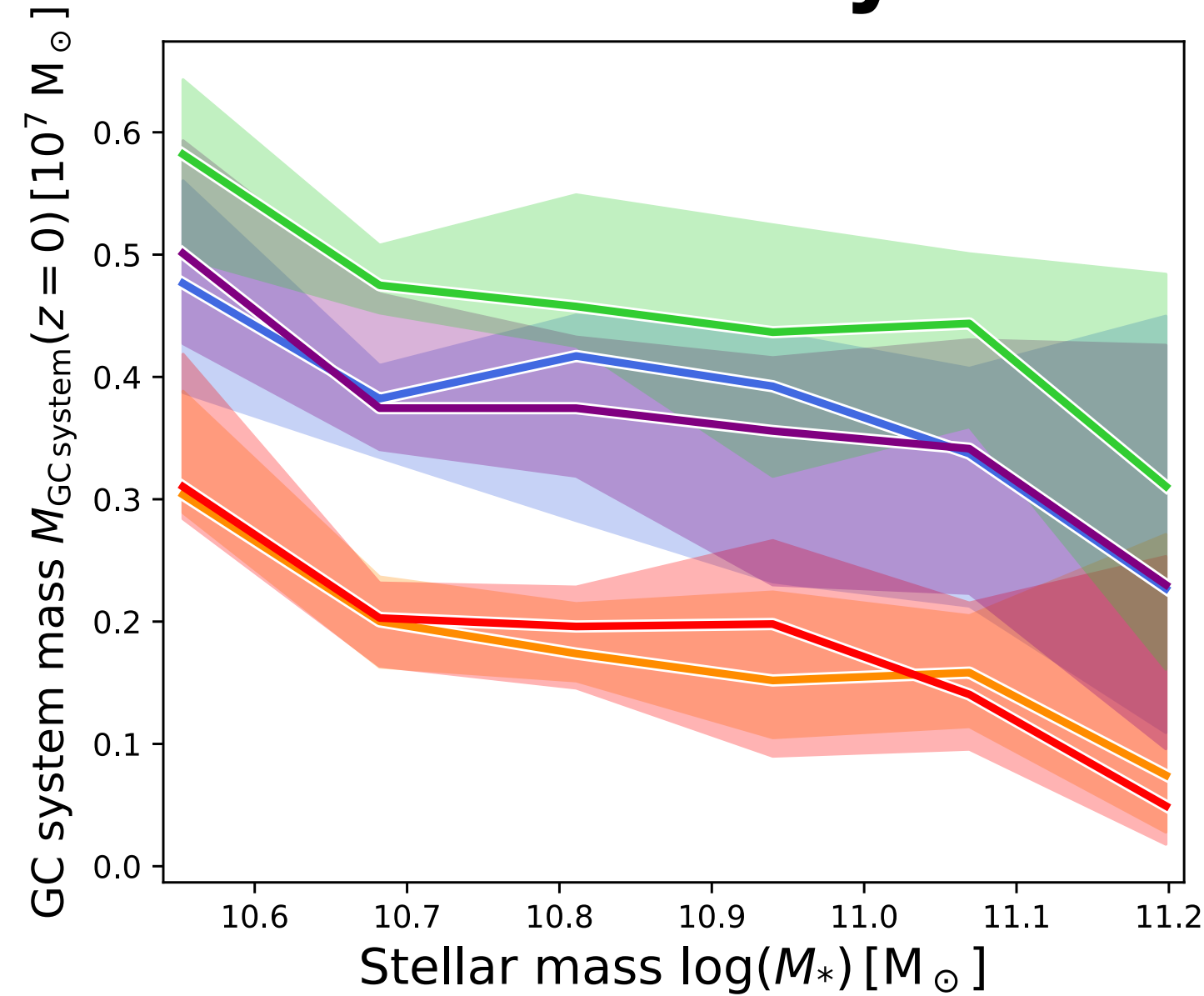
3 regimes for the in-situ GC population

GC dynamics in FDM universe: impact of DM core

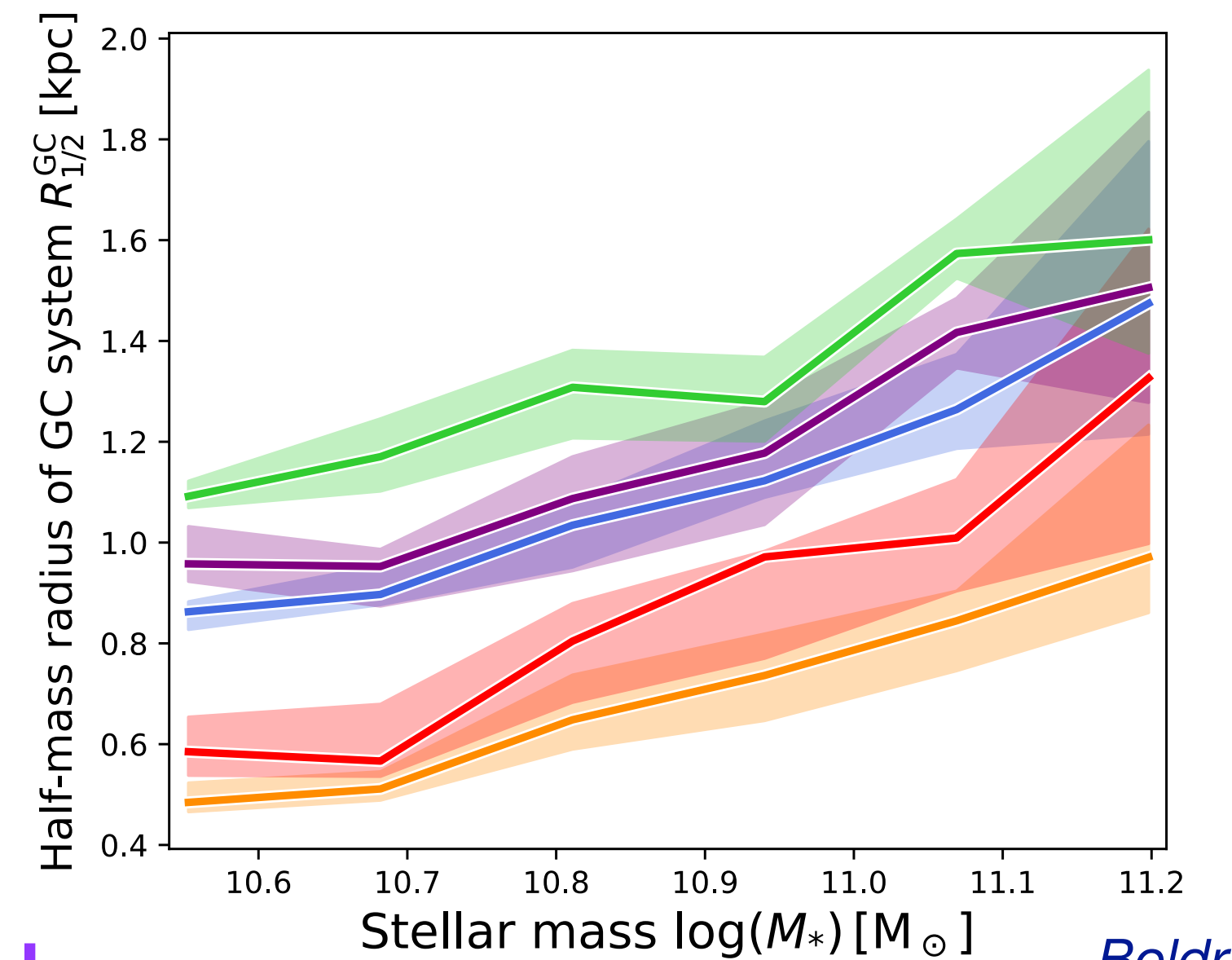
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Boldrini+25b

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Favored by galactic constraints

- ◆ $m_{22} \sim 7$: Similar to CDM, both in terms of total mass and spatial distribution

- ◆ $m_{22} > 7$: Larger number of surviving clusters, generally more massive.

GC system $\rightarrow$ more massive and more extended than in CDM

Favored by cosmological constraints

3 regimes for the in-situ GC population

This talk

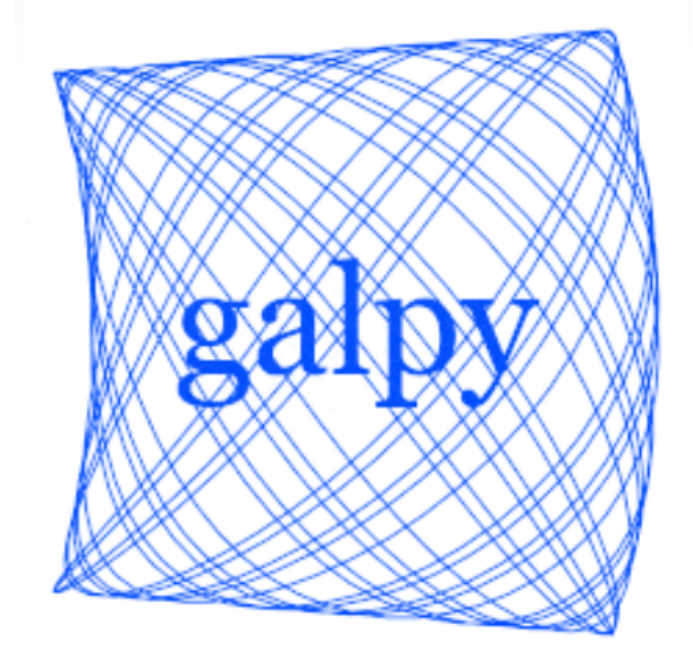


◆ P. Di Matteo, LIRA



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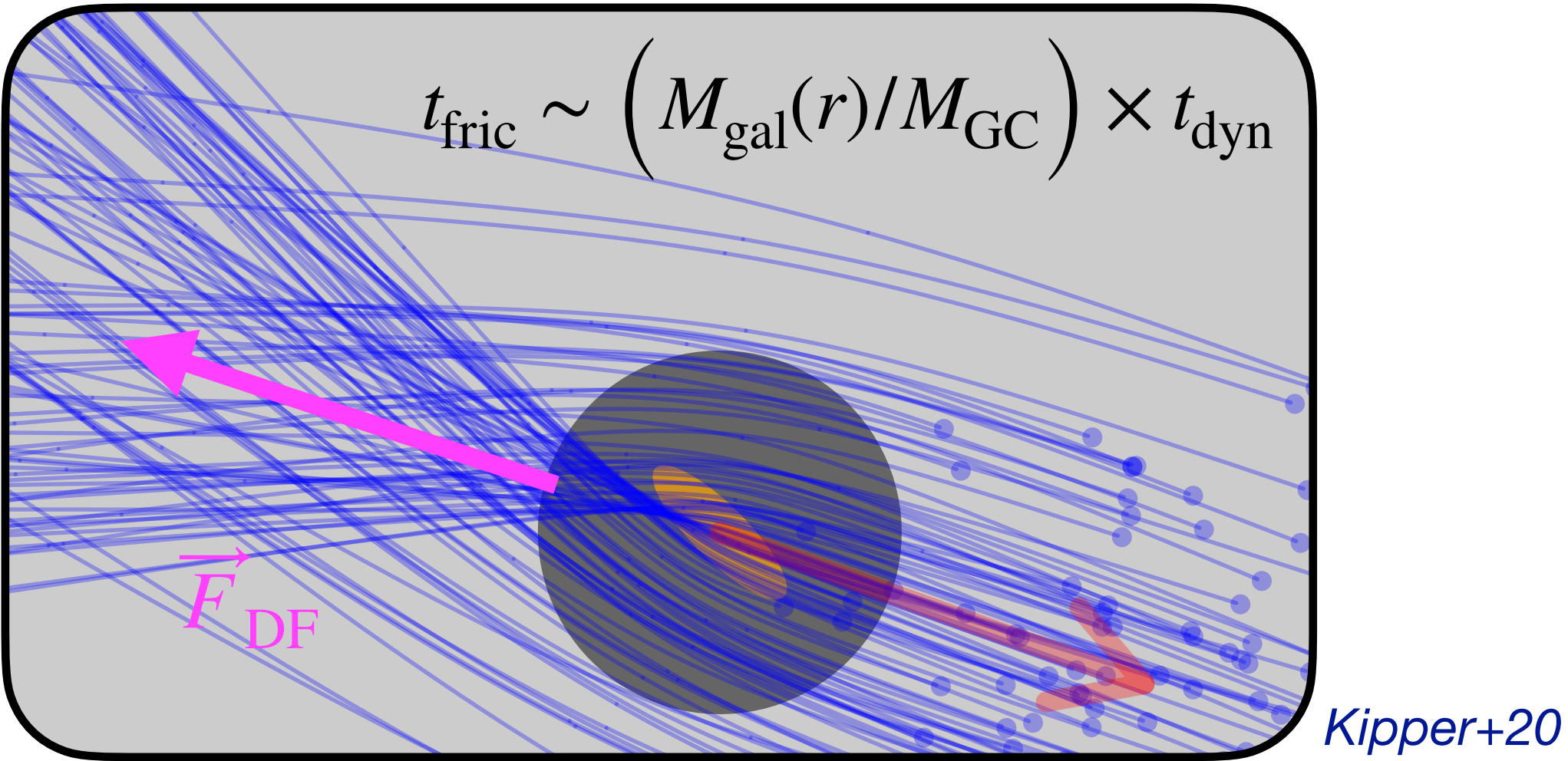
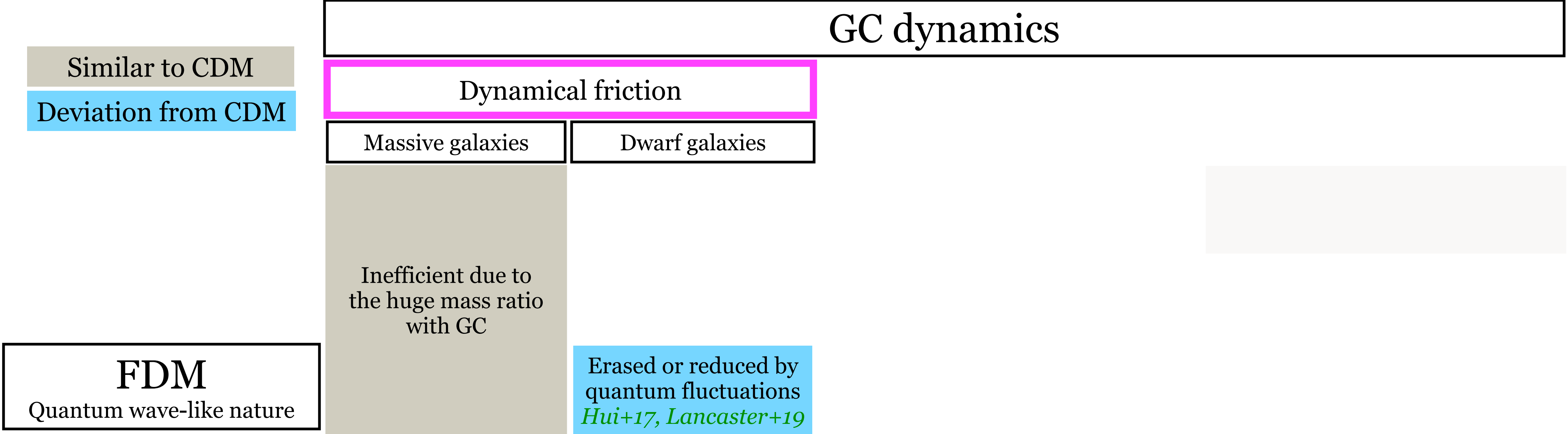
IV) GC dynamics in FDM universe: impact of FDM dynamical friction



◆ J. Bovy (GALPY PI), University of Toronto

Szpilfidel, Boldrini, Bovy, Di Matteo +25, in prep.

GC dynamics in FDM universe: impact of specific dynamical friction



GC dynamics in FDM universe: impact of specific dynamical friction

- ◆ Implementation in both Python and C of [Lancaster+20](#) formulation in GALPY
- ◆ Documentation available at <https://docs.galpy.org/en/latest/reference/potentialfdmdynfric.html>
- ◆ Included in the next release of galpy in November 26
- ◆ Very efficient: 1000 GCs over 10 Gyr $\rightarrow$ 0.01 CPU hour



◆ A. Szpilfidel, LIRA

$$\vec{F}_{\text{CDM}} = -4\pi G^2 M_{\text{GC}}^2 \rho(r) \frac{\vec{v}}{v^3} \mathcal{C}(r, v)$$

X

CDM: $\mathcal{C}_{\text{CDM}}(r, v) = \frac{1}{2} \ln(1 + \Lambda^2) \left[\text{erf} \left(\frac{v}{\sqrt{2}\sigma} \right) - \frac{2v}{\sqrt{2\pi}\sigma} e^{-\frac{v^2}{2\sigma^2}} \right]$

FDM: $\mathcal{C}_{\text{FDM}}(r, v, m_{22}, M_\sigma)$ (2 regimes depending on the velocity dispersion of the FDM medium)

Fuzzy-dark-matter dynamical friction

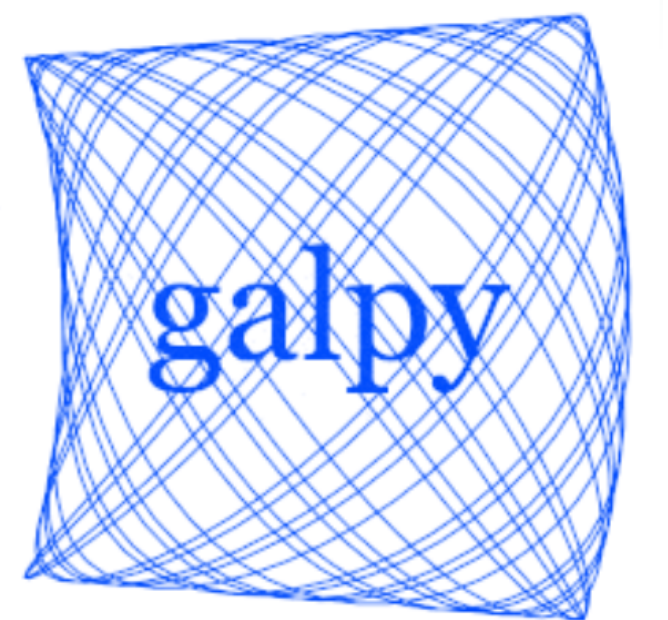
```
class galpy.potential.FDMDynamicalFrictionForce(amp=1.0, GMs=0.1, gamma=1.0, rhm=0.0,
m=1e-99, dens=None, sigmar=None, const_lnLambda=False, const_FDMfactor=False, minr=0.0001,
maxr=25.0, nr=501, ro=None, vo=None)
```

[source]

Implements the fuzzy dark matter (FDM) dynamical friction force.

The force is given by:

$$\vec{F}_{\text{FDM}} = -\frac{4\pi G^2 M_{\text{obj}}^2 \rho}{v^3} C_{\text{FDM}}(kr) \vec{v}$$

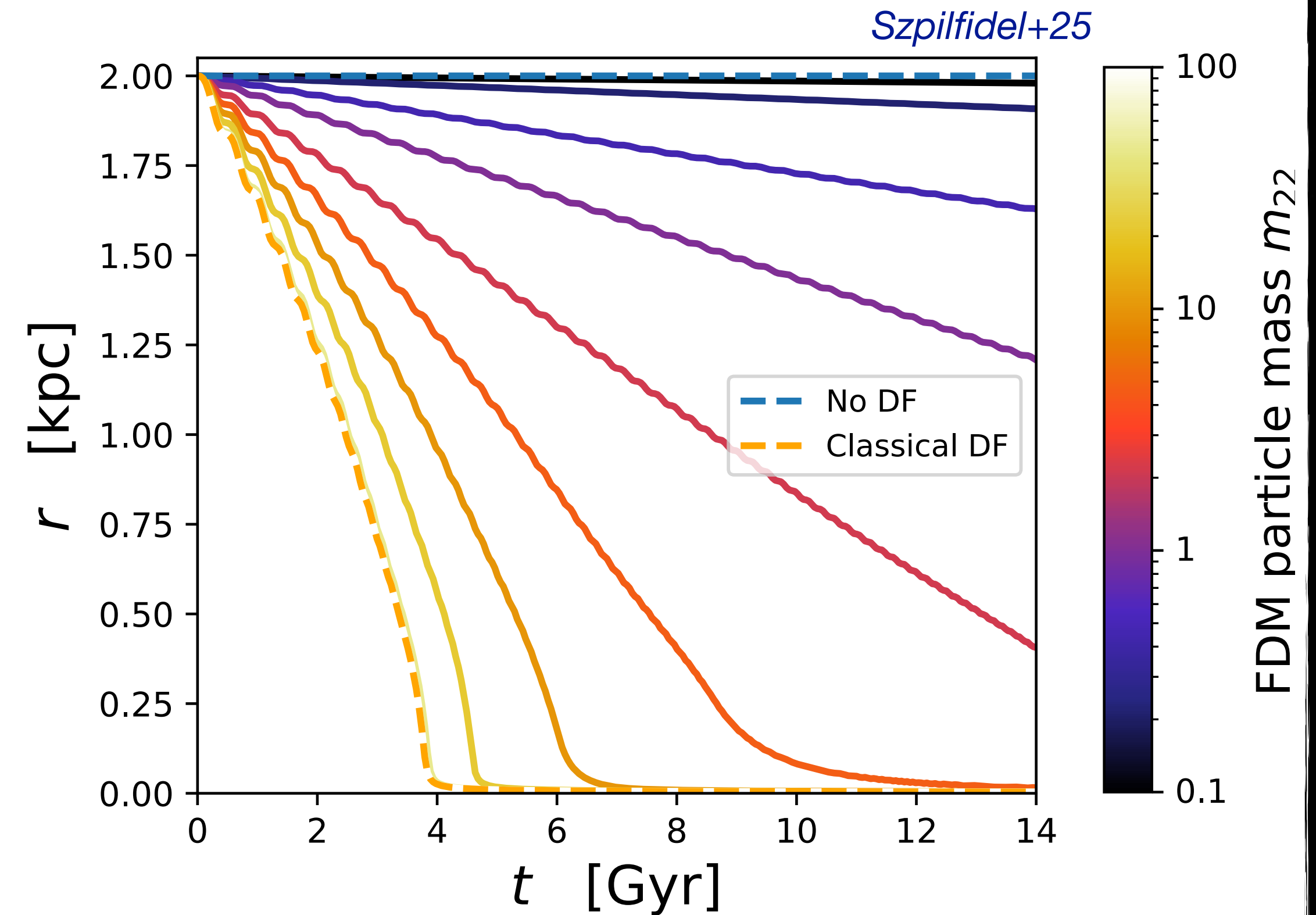


New public Galpy package for FDM dynamical friction

GC dynamics in FDM universe: impact of specific dynamical friction

Why dynamical friction is reduced in FDM galaxies?

- ◆ Not intrinsically reduced in the sense of a vanishing frictional force
- ◆ Persistent stochastic density fluctuations of the FDM halo dynamically heat the GC
- ◆ This heating counteracts the energy loss due to DF by injecting kinetic energy into the GC
- ◆ Heating stronger as GCs approach the galactic center



if $Density \nearrow$ or $m_{22} \searrow \Rightarrow Heating \nearrow$

- ◆ Low $m_{22} \rightarrow$ no dynamical friction
- ◆ High $m_{22} \rightarrow$ CDM dynamical friction

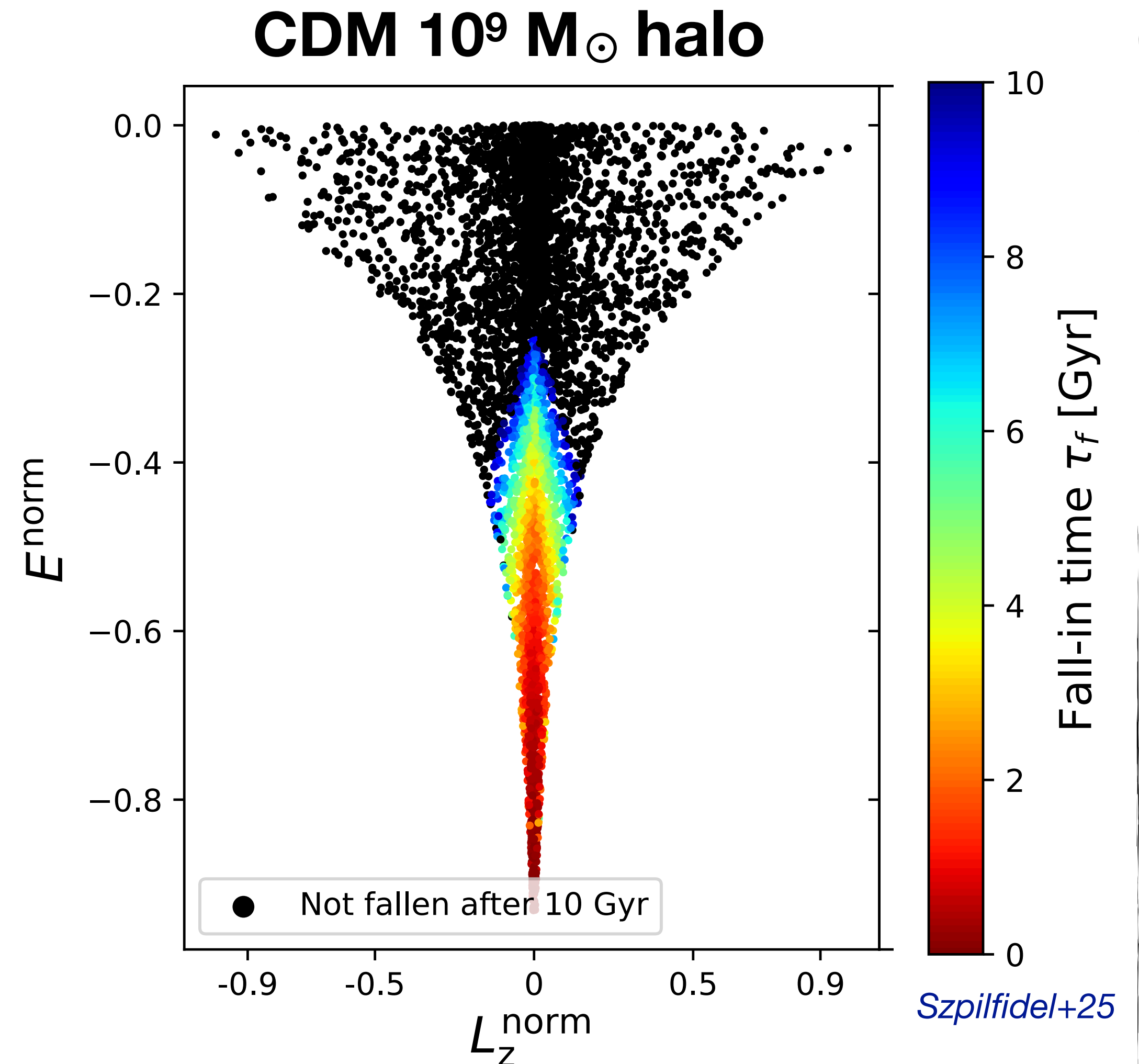
GC dynamics in FDM universe: impact of specific dynamical friction

- ♦ GCs: $10^6 M_\odot$, half-mass radius of 10 pc, $N=4500$, initially uniformly distributed in log space between 0.1 and $10 r_s$, populated the E - L_z space
- ♦ Halo: 10^9 (dwarfs) - $10^{12} M_\odot$ (MWs), r_s from cosmological simulations, fixed potential
- ♦ 10 Gyr of evolution
- ♦ 3 models

CDM = NFW + DF

FDM only friction = NFW + FDM DF

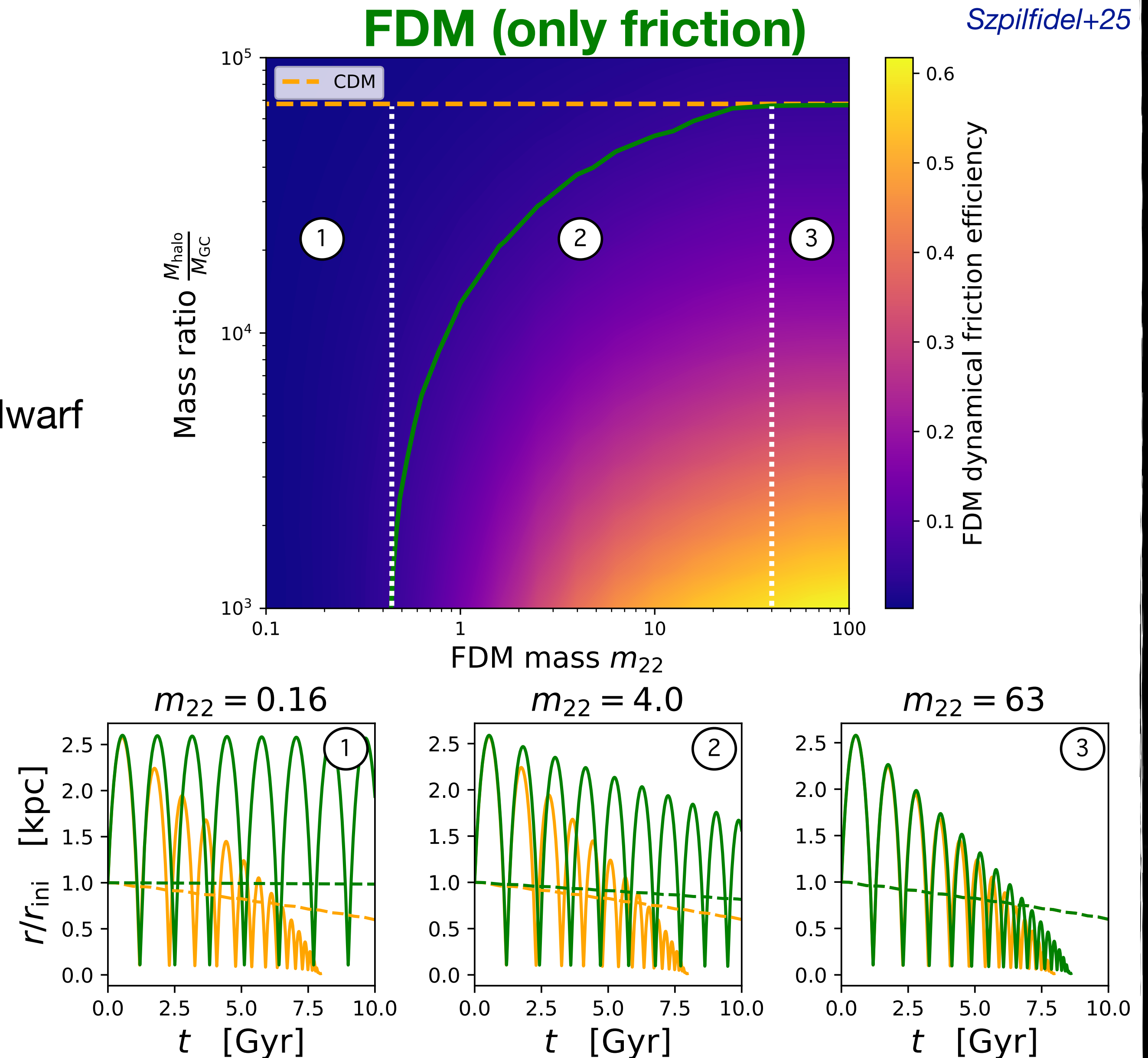
FDM = Core + FDM DF



GC dynamics in FDM universe: impact of specific dynamical friction

$$DF \text{ efficiency} = \frac{2 \left| r_{apo}^{DF} - r_{apo}^{no DF} \right|}{r_{apo}^{DF} + r_{apo}^{no DF}} > 5 \%$$

- ◆ **Classical DF:** above a mass ratio of 7×10^4 , friction becomes negligible
- ◆ Regime of interest for significant FDM signatures: dwarf galaxies

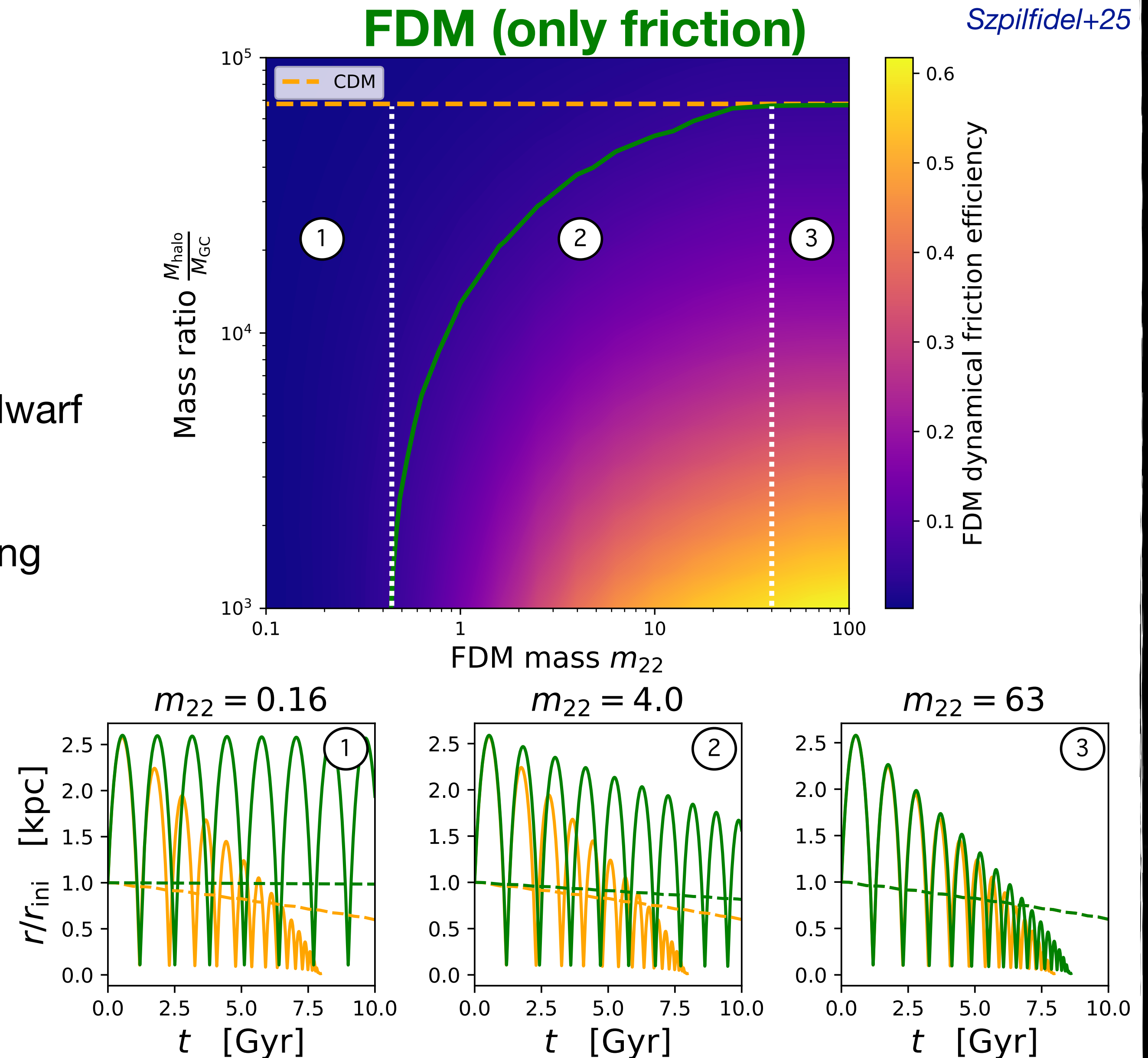


GC dynamics in FDM universe: impact of specific dynamical friction

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- ◆ Regime of interest for significant FDM signatures: dwarf galaxies
- ◆ **Zone 1:** FDM DF is highly inefficient $\rightarrow$ orbital stalling
- ◆ **Zone 2:** Effective but reduced compared to CDM
- ◆ **Zone 3:** Converge back to CDM

FDM stalling mechanism challenges the expected galactic cannibalism of GCs

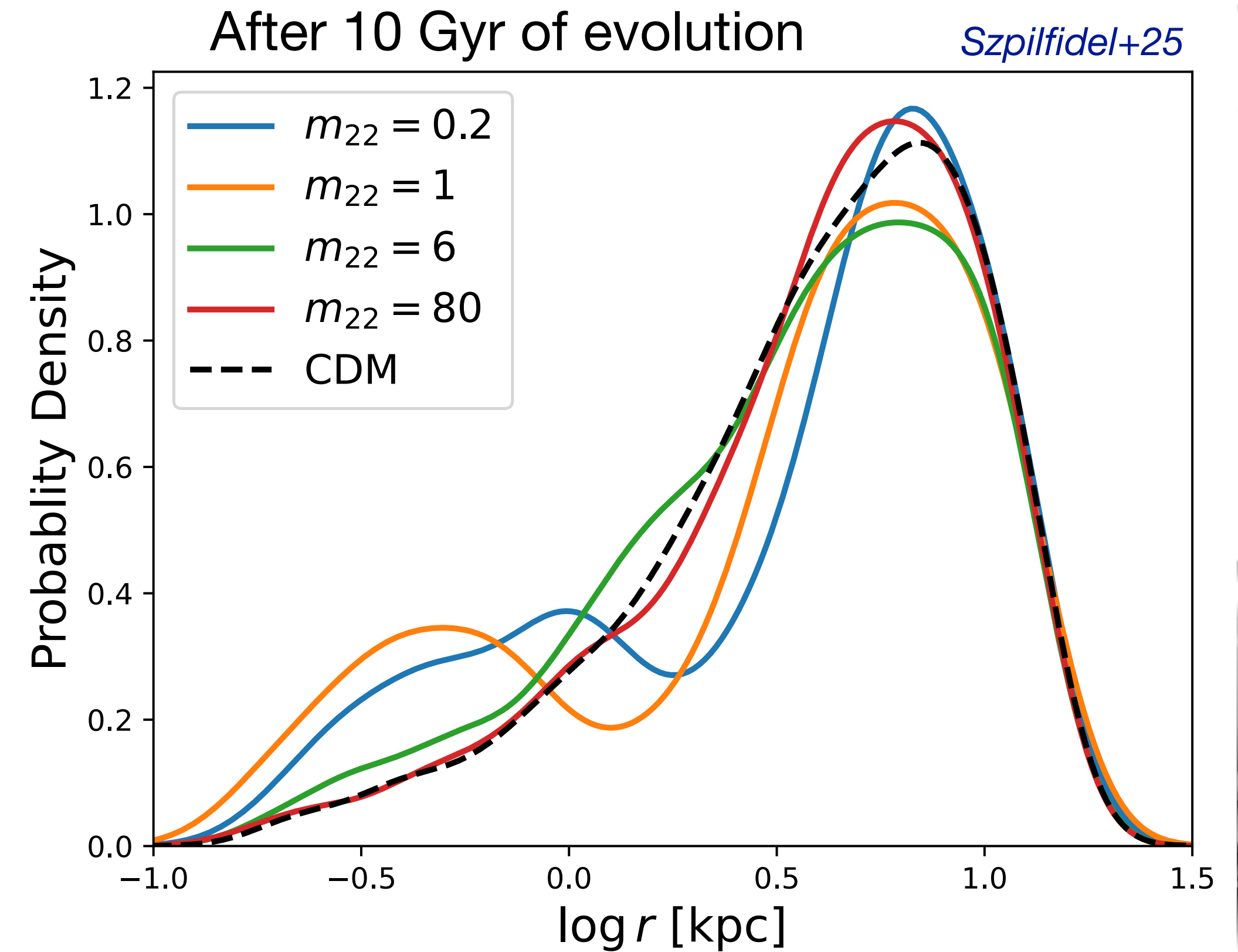


GC dynamics in FDM universe: impact of specific dynamical friction

Impact of FDM GC system demographics in dwarfs

- ◆ stalling mechanism from **quantum heating** counteracting DF and from the presence of a **DM core**
 - > implications for the galactic cannibalism of GCs
- ◆ Artificially construct in-situ and an ex-situ GC populations

X

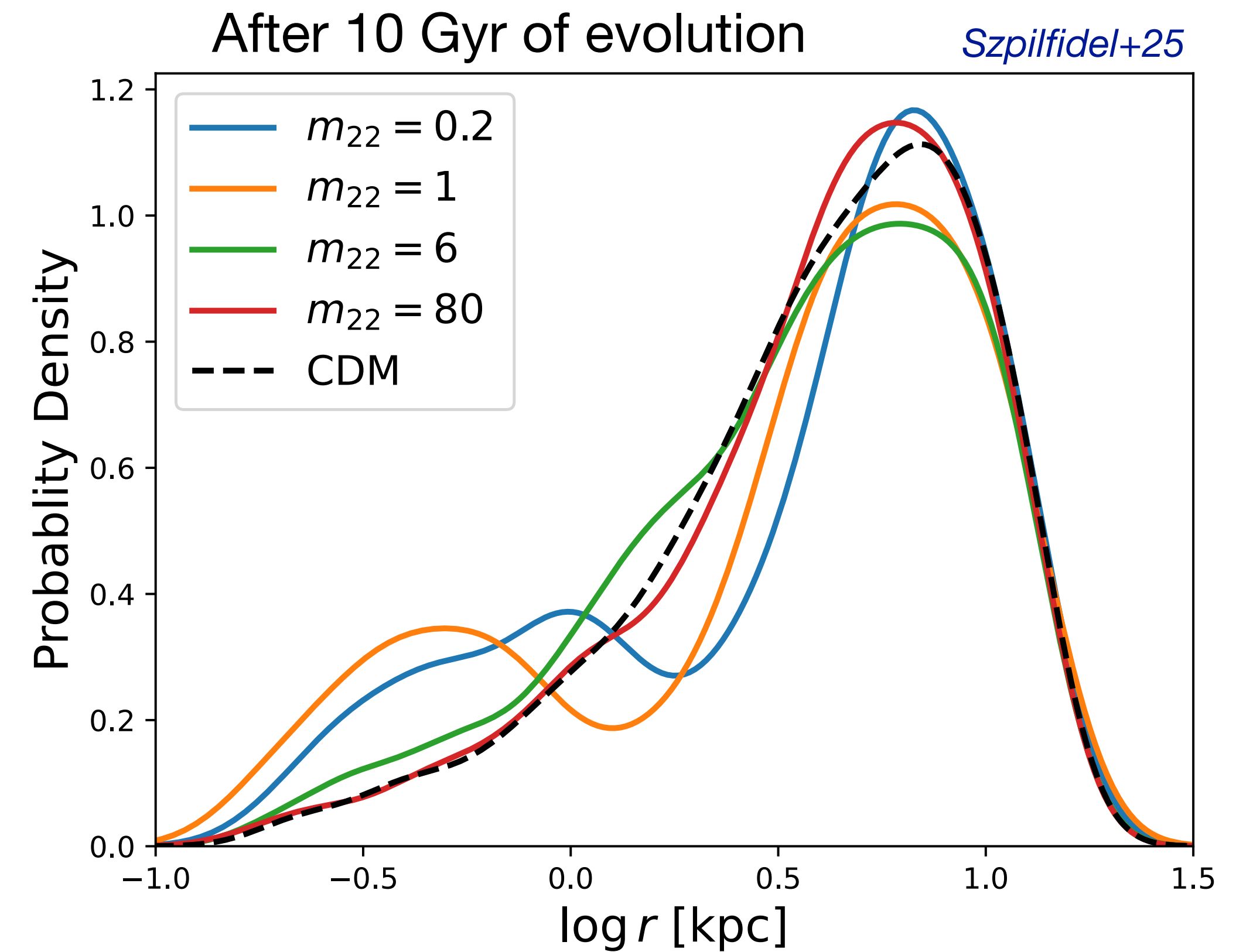


- ◆ **In-situ:** $r_{\text{apo}}^{\text{init}} < r_s$
- ◆ **Ex-situ:** $3r_s < r_{\text{apo}}^{\text{init}} < 10r_s$

GC dynamics in FDM universe: impact of specific dynamical friction

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 - > implications for the galactic cannibalism of GCs
- ◆ Artificially construct in-situ and an ex-situ GC populations
- ◆ **CDM**: indiscernible mixture of populations
- ◆ **FDM**: In-situ survived in the central regions, whereas ex-situ clusters remain at larger radii
- ◆ Absence of galactic cannibalism
 - > bimodal radial distribution for $m_{22} < 6$



Presence or absence of this bimodal signature in dwarf GC population
=
sensitive indicator of the nature of DM

- ◆ **In-situ:** $r_{\text{apo}}^{\text{init}} < r_s$
- ◆ **Ex-situ:** $3r_s < r_{\text{apo}}^{\text{init}} < 10r_s$

Conclusions

GC dynamics				
Similar to CDM Deviation from CDM	Density profile		Dynamical friction	
	Massive galaxies	Massive galaxies	Dwarf galaxies	Satellite population (low mass halos)
SIDM Collisional dark matter	DM core with size depending on the DM free parameter		Reduced by the presence of a DM core	
WDM High velocity dark matter				
FDM Quantum wave-like nature	Orbital confinement or expansion depending on m_{22} <i>Boldrini+25b</i>	Inefficient due to the huge mass ratio with GC	2 regimes: resilient to galactic cannibalism and absence of mixing <i>Szpilfidel+25</i>	Less abundant <i>Bullock+17, Marsh+15</i>

Conclusions

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WDM High velocity dark matter					
FDM Quantum wave-like nature					

- ◆ **Density profile:** SIDM produces larger and less dense cores than FDM - WDM cores have higher central densities than SIDM and are similar to FDM, but never exceed NFW profile → MWs
- ◆ **Dynamical friction:** Similar to CDM in SIDM and WDM → dwarfs



Thank you!