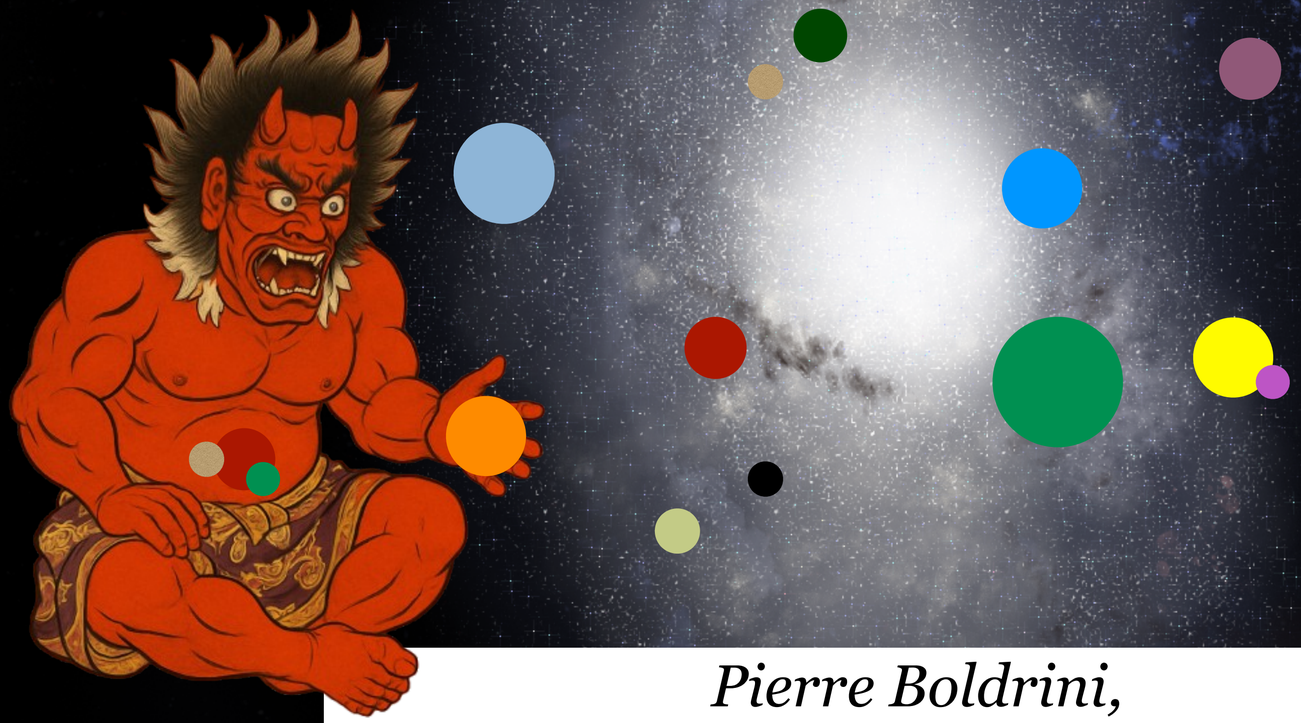
# TRACING THE NATURE OF DARK MATTER WITH GLOBULAR CLUSTERS



*Pierre Boldrini,*
*CNES fellow at LIRA*
ObAS seminar, June 2025

LIRA Observatoire de Paris | PSL

*Boldrini et al. +25, A&A (2510.00927)*
*Boldrini & Di Matteo +25, A&A (2510.02130)*
*Szpilfidel et al. +26, A&A (2510.00927)*

# Dark matter theories [1/2]

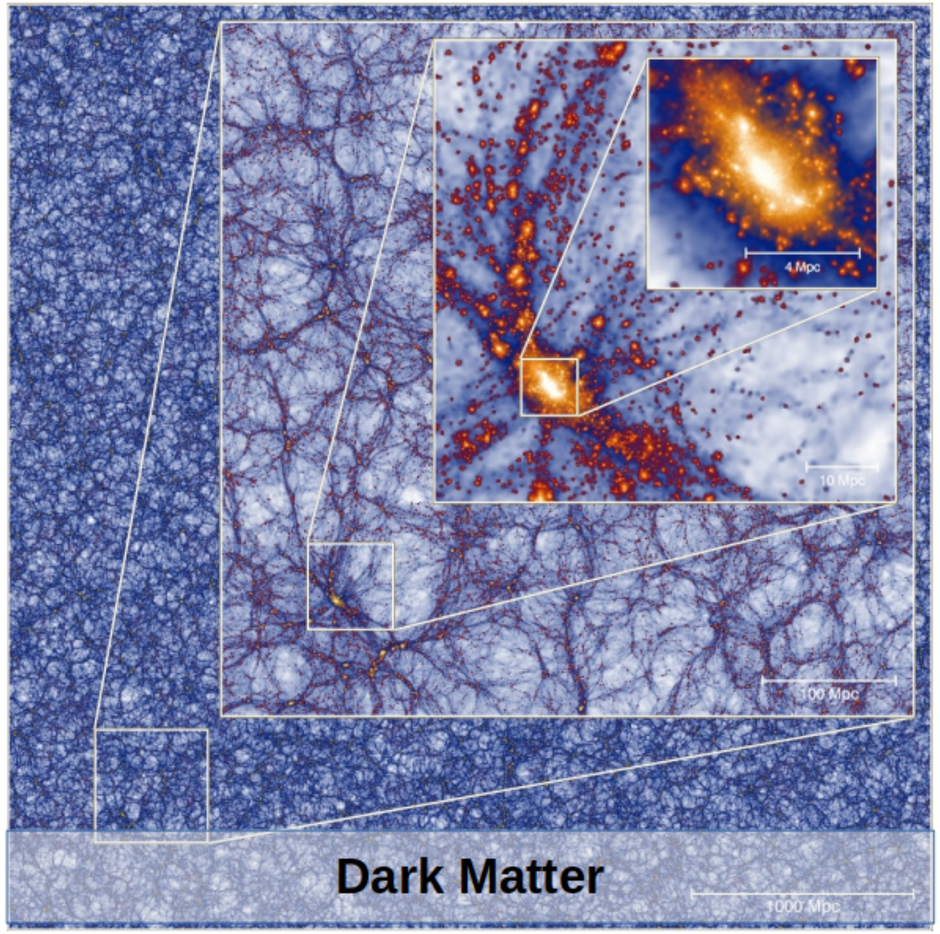
- Cosmological model —> Cold dark matter
- Axions or WIMPs have so far not been detected
- Very successful at large scales *Planck Collaboration+14*

**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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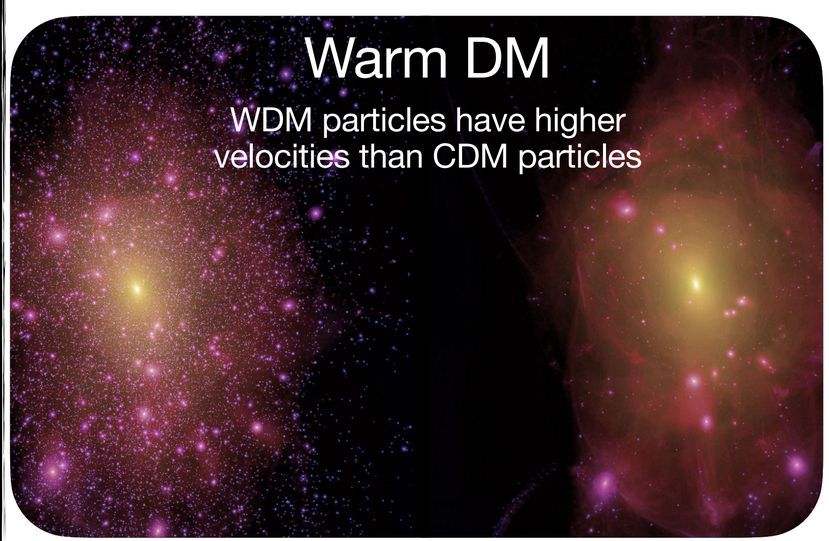
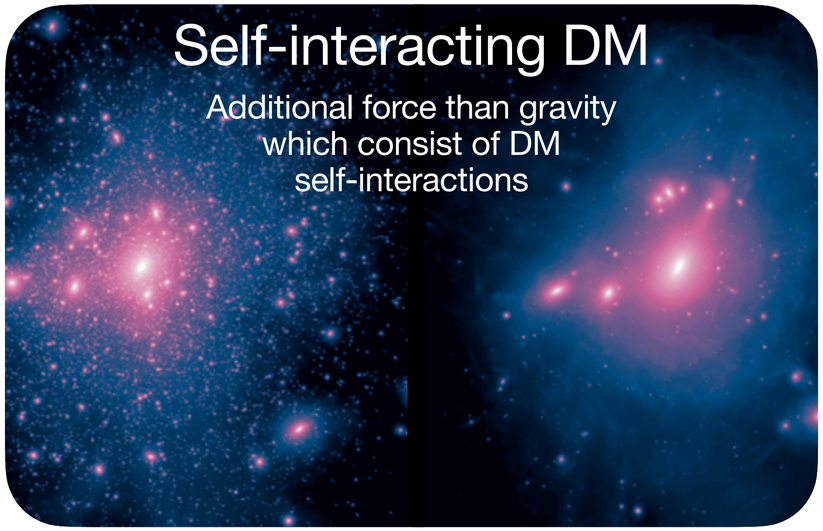
*Colín et al+00*



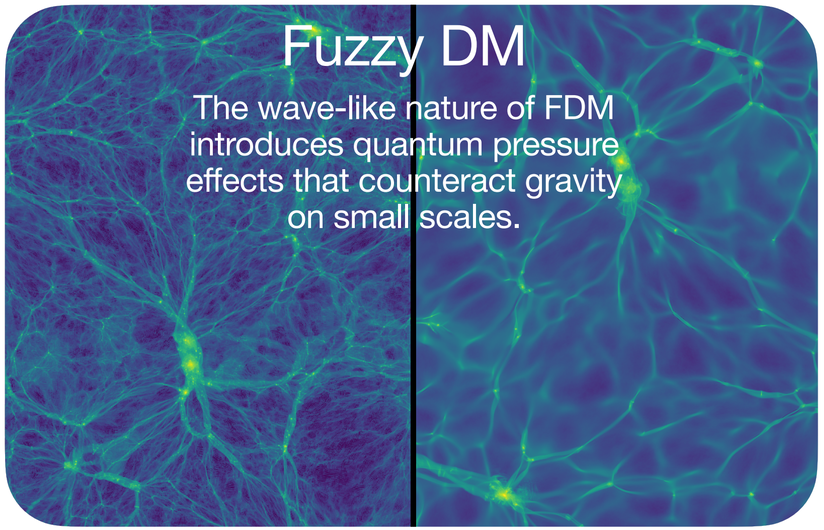

particle mass $m_v$ (in keV)

*Kochanek & White+00*




cross-section $\sigma_m$ (in $cm^2/g$)

*Hu et al.+00*




particle mass $m_\chi$ (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

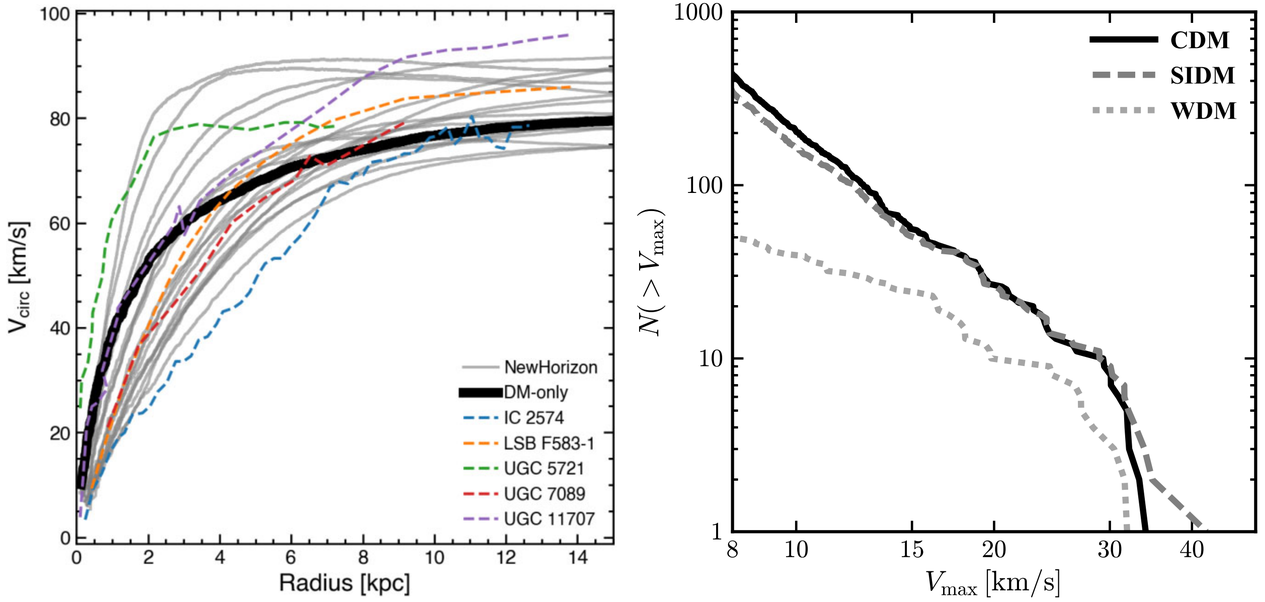
◆ J. Bovy (GALPY PI), University of Toronto

# Constraining the dark matter nature

## Classical methods:

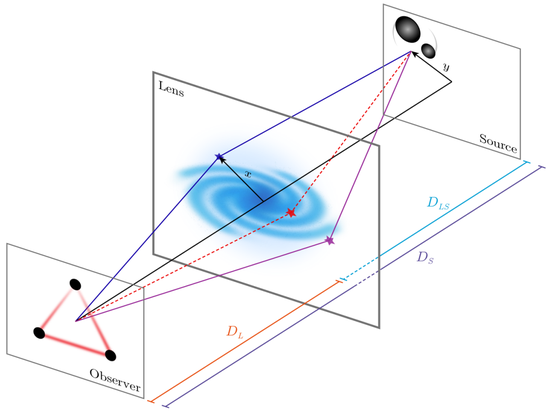
- Rotation curves of galaxies
- Analyzing gravitational lenses
- Velocity dispersion of stars in satellite galaxies

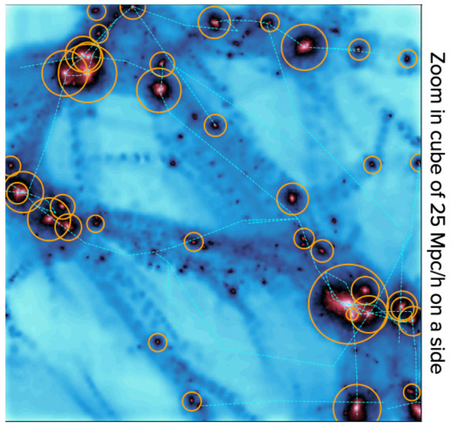
*Jackson+25, Bullock & Boylan-Kolchin+17*




## New DM probes:

- Gravitational wave lensing *Singh+25*
- Cosmic web via filament connectivity *Boldrini & Laigle+25*
- Globular cluster dynamics



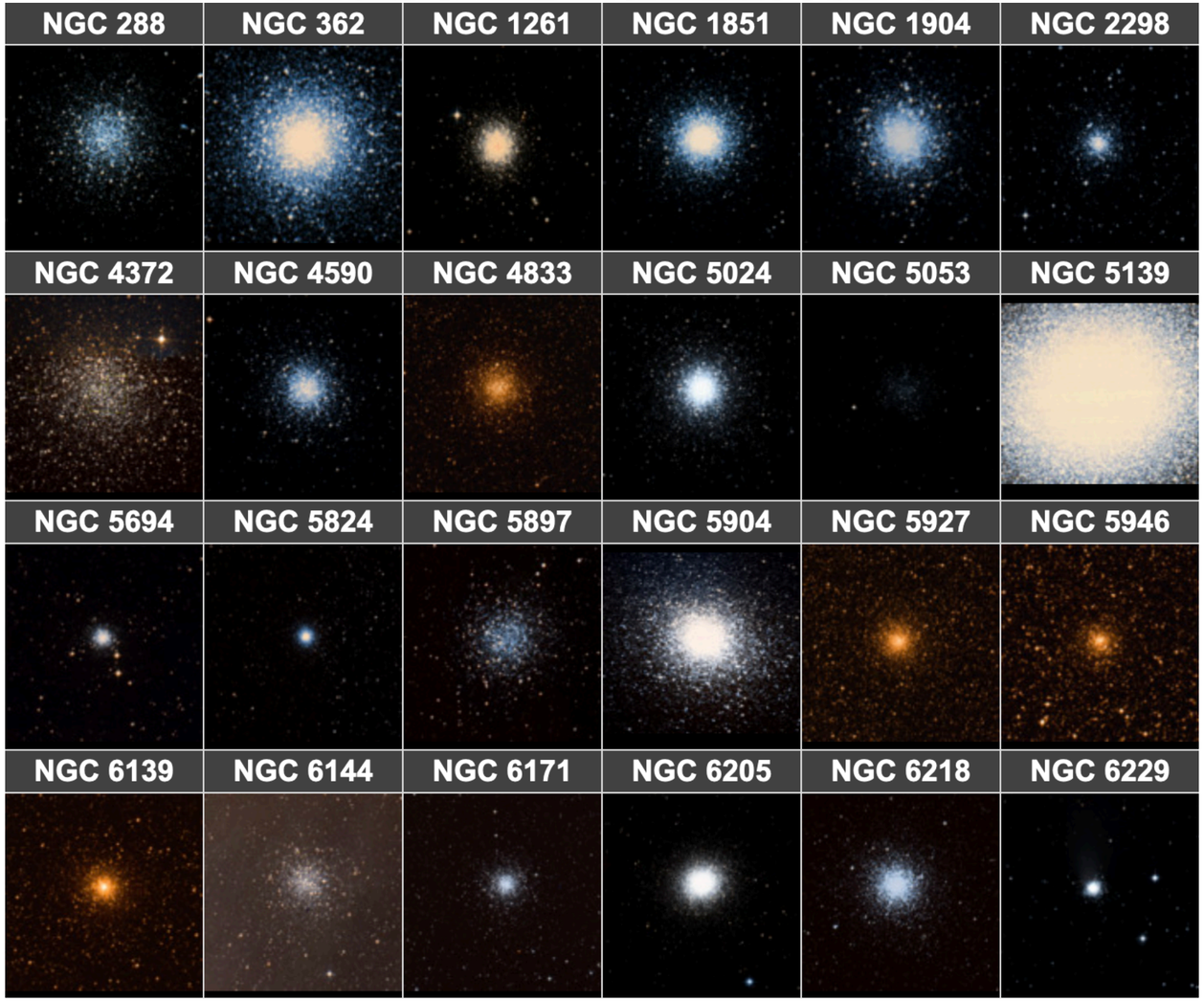

GCs as DM tracers?

*Singh+25, Boldrini & Laigle+25*

# Why globular clusters? [1/2]

- Compact gravitationally bound stellar system
- Oldest systems in the Universe > 10 Gyr
- Half-mass radius: ~ 10 pc
- $10^4$ -$10^6$ $M_\odot$
- Origin of GCs: in-situ or ex-situ?

| IN-SITU | EX-SITU |
|---|---|
| Formed within the present-day host galaxy | Formed in satellite galaxies that were accreted |

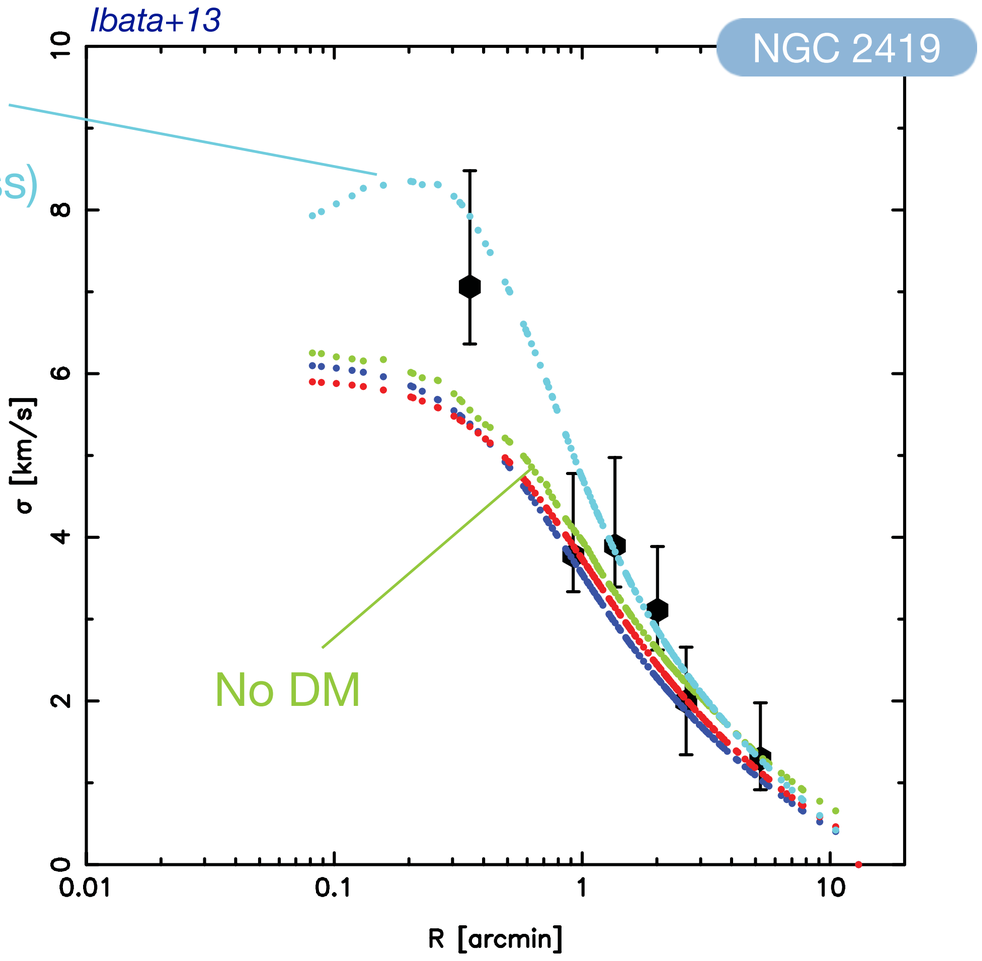



*Baumgardt GC database*

Relics of galaxy formation and evolution

# Globular clusters as DM tracers? [3/5]

With a DM halo
of $5 \times 10^4$ $M_\odot$
( 6% of stellar mass)




- Essentially DM-free at z=0

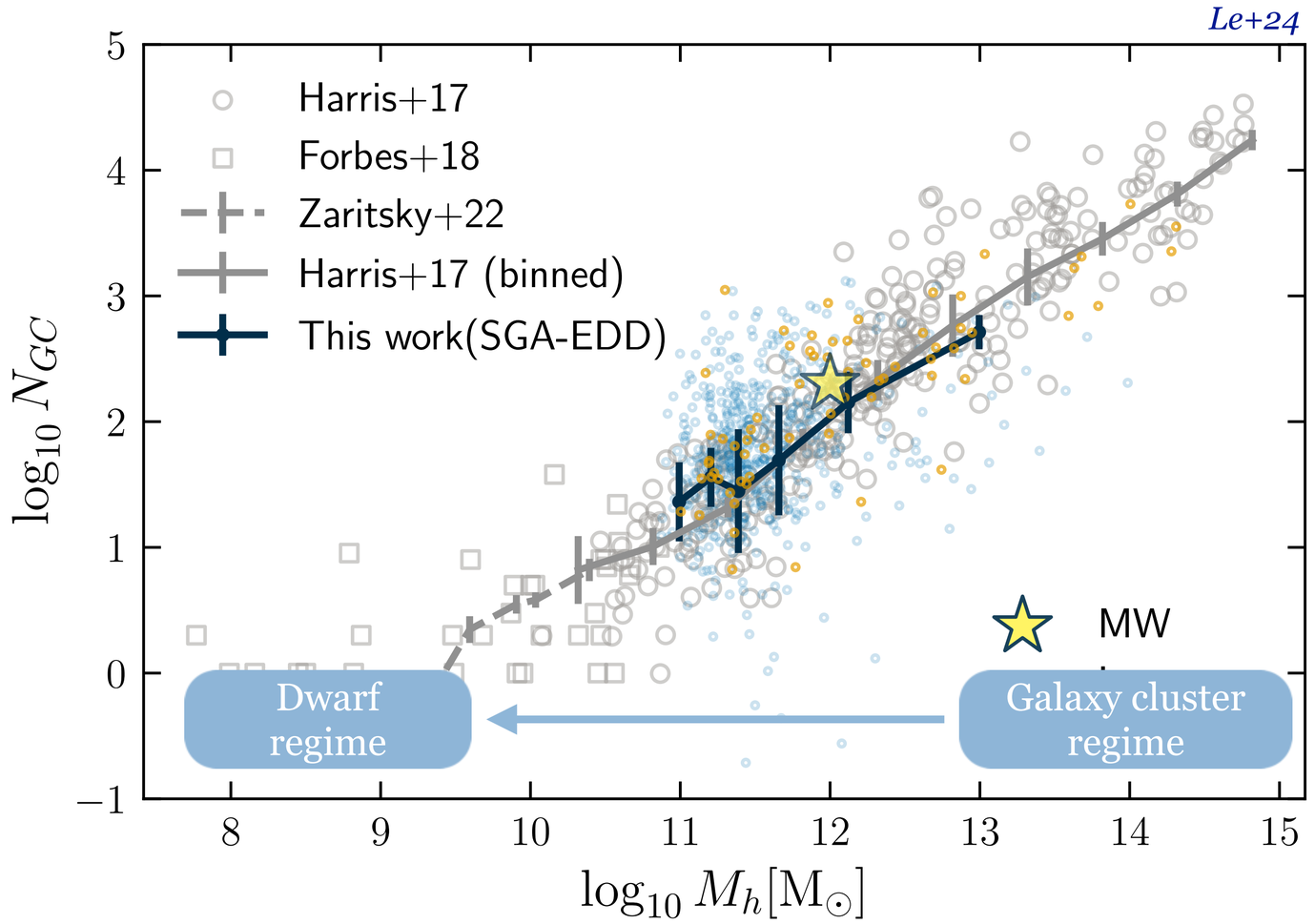
—> internal dynamics are driven solely by stars

—> not significantly perturb the host gravitational potential

No significant amount of DM at z=0

# Globular clusters as DM tracers? [1/5]

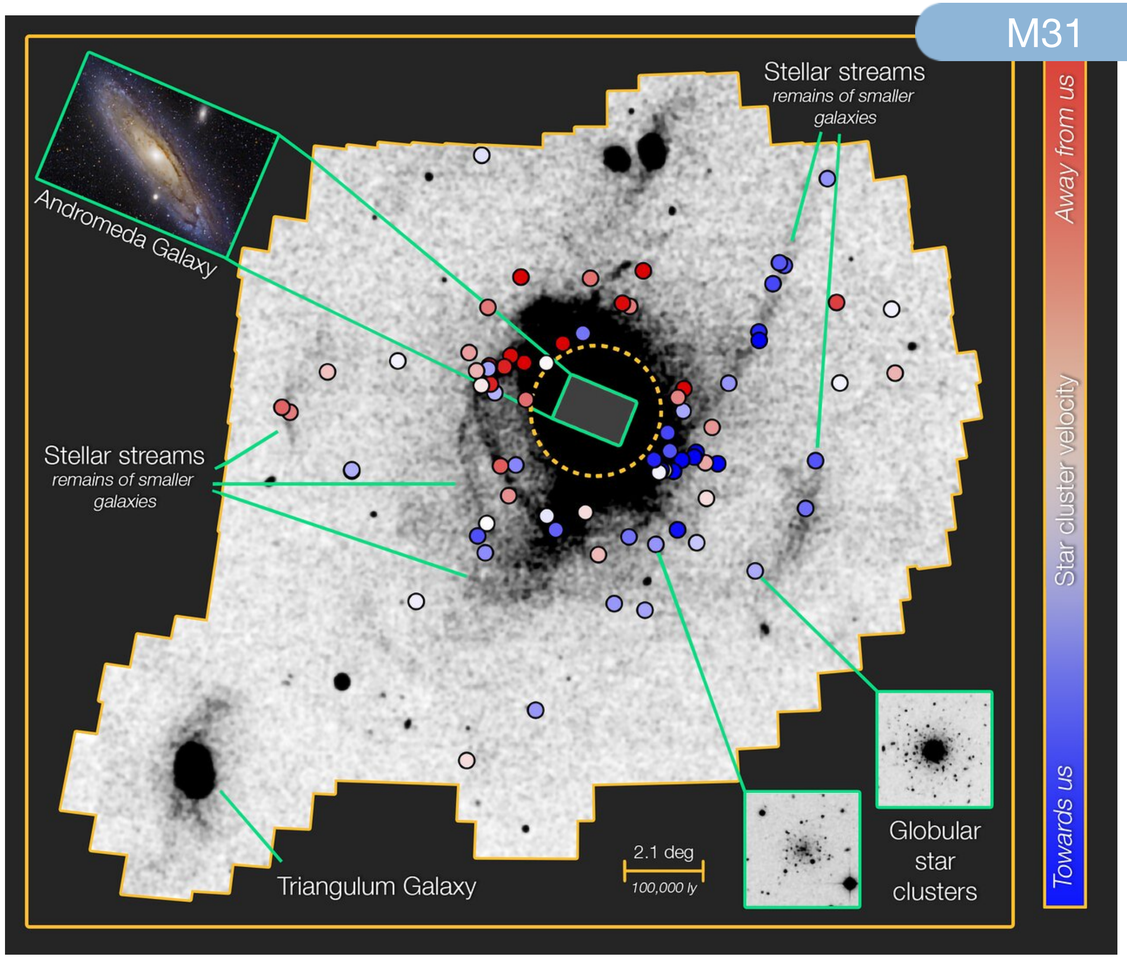
- Very numerous ( **200 GCs** in the Milky Way)
- Found in virtually all types of galaxies across a wide range of masses




Exist in almost all systems from galaxy clusters down to dwarfs

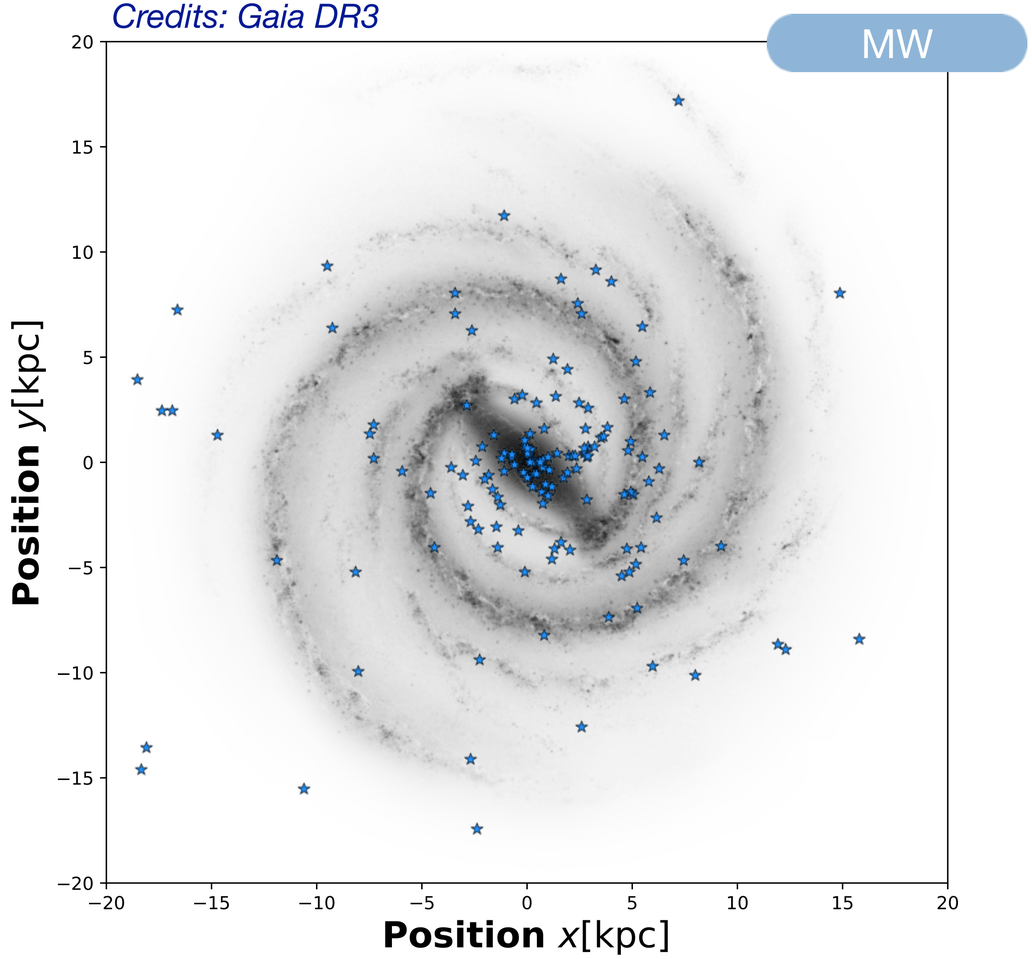
# Globular clusters as DM tracers? [2/5]

- Span a wide range of galactocentric distances




*Credits: Nature, PAndAS data*

*Credits: Gaia DR3*

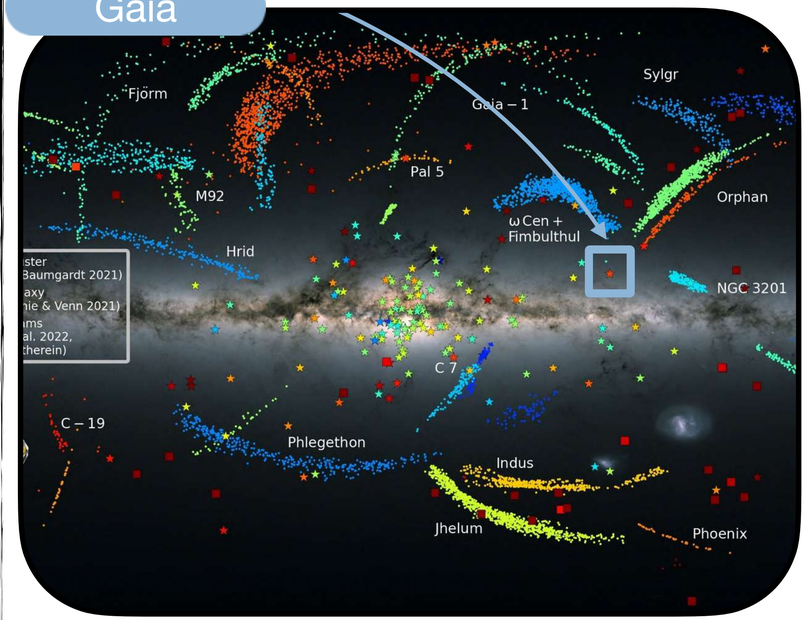



Galactic & extragalactic GCs

# Why globular clusters? [2/2]

Gaia

*Malhan+22*



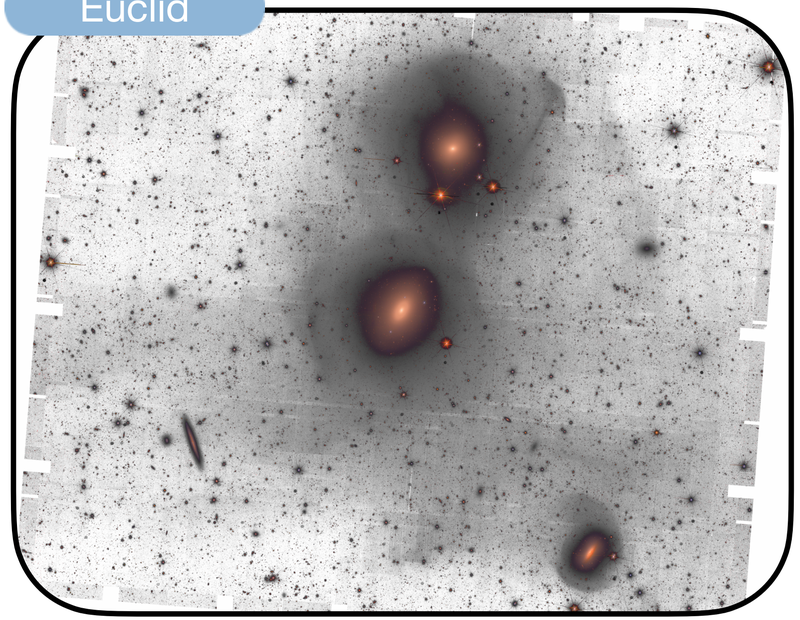

**171 Milky-Way GCs**

6D phase space

Mass, metallicity and size

Euclid

*Urbano+25*



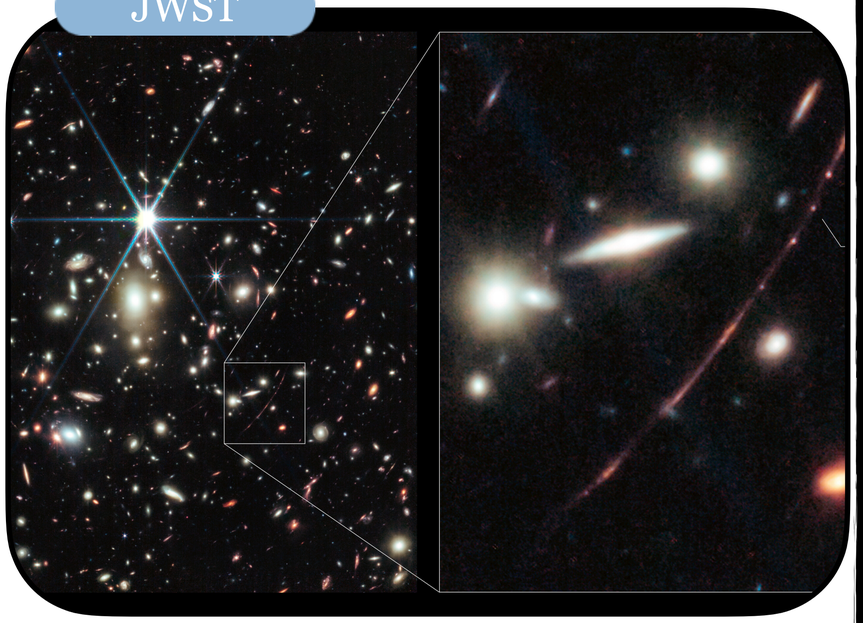
**Half-million extragalactic GCs**

in 4000 galaxies

within <100 Mpc

JWST

*Vanzella+22*



**Proto-GCs**

detected with strong gravitational lensing

of high-redshift galaxies

Golden age for studying globular clusters

# Globular clusters as DM tracers? [5/5]

- Very numerous
- 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 | |
| **WDM** High velocity dark matter | | | | | Less abundant *Bullock+17 , Marsh+15* |
| **FDM** Quantum wave-like nature | | | | Erased or reduced by quantum fluctuations *Hui+17, Lancaster+19* | |

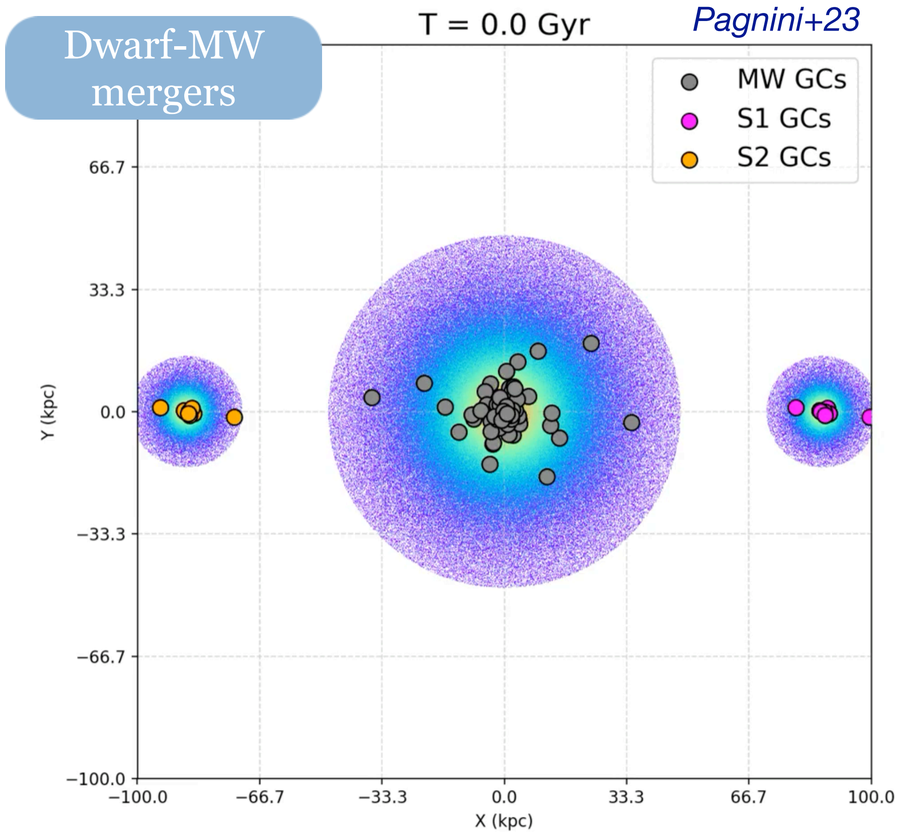
GCs will be sensitive to DM theory properties

# How to simulate GC in a cosmological context?

**In galaxies, GCs experience:**

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

Dwarf-MW mergers




*Pagnini+23*

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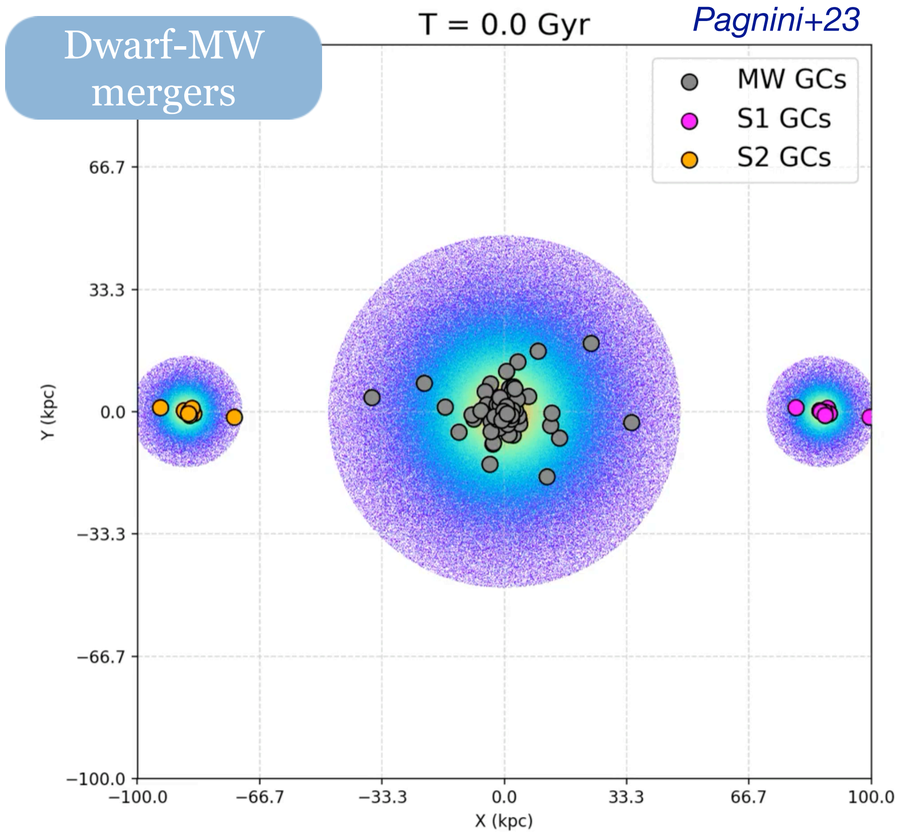
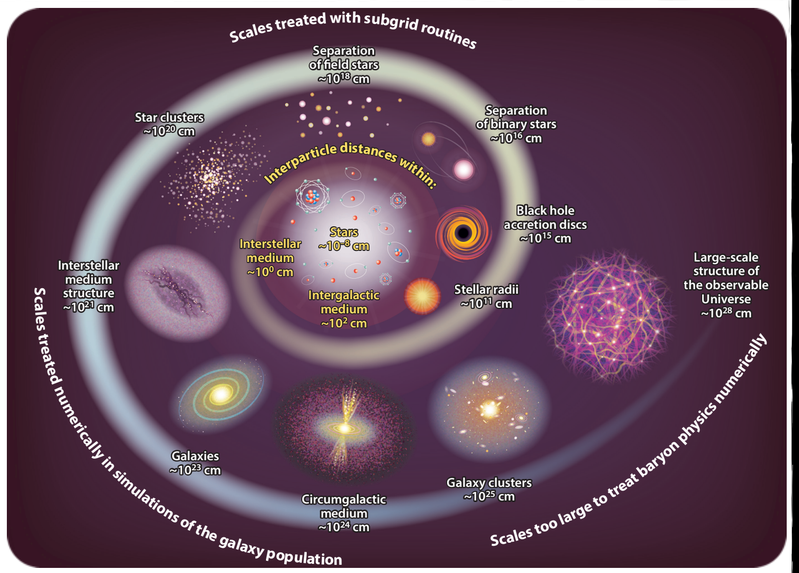



*Pagnini+23*




*Crain+23*

## A challenging problem:

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

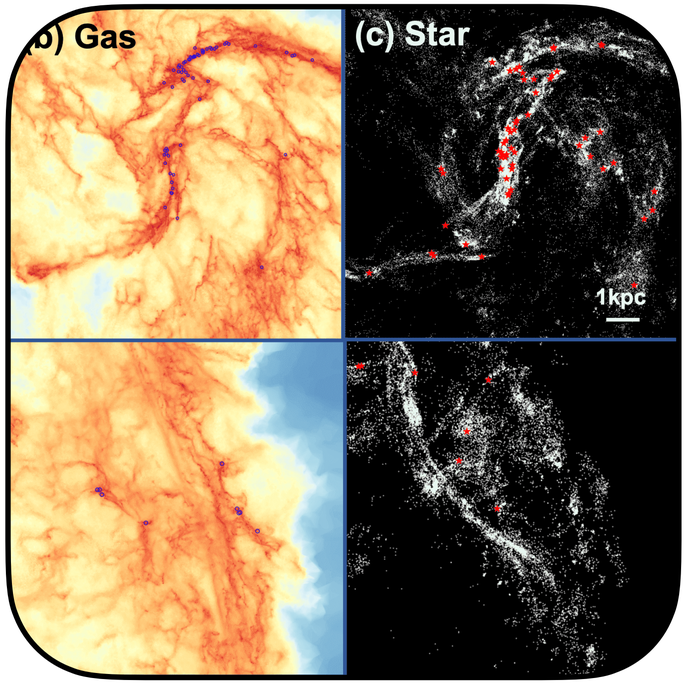
Resolution requirements make this presently impossible to do in direct calculations that track the formation of individual stars

# Current limitations of simulations [1/3]

**Main strategies:** Beasley+20, Renaud+19 for reviews

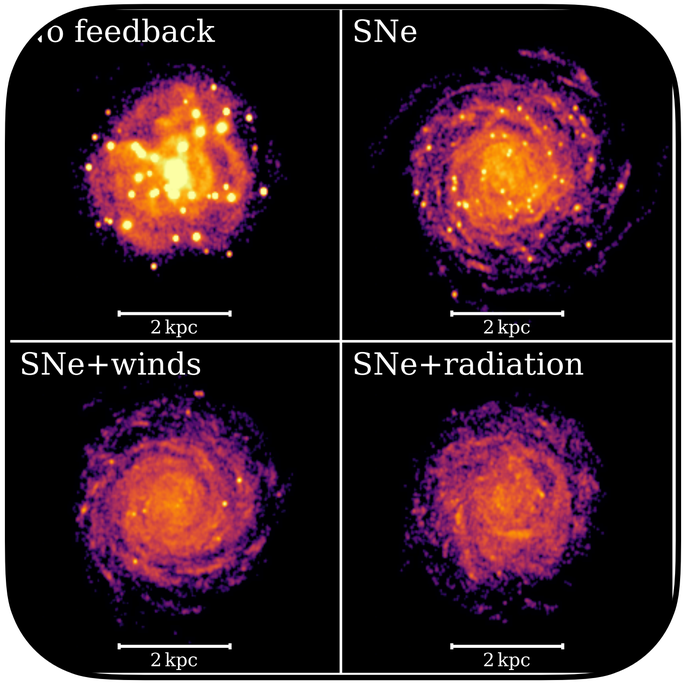
- Idealized high-resolution galaxy simulations *Lahen+20, Li+22, Andersson+24, Deng+24, …*

*Li+22*



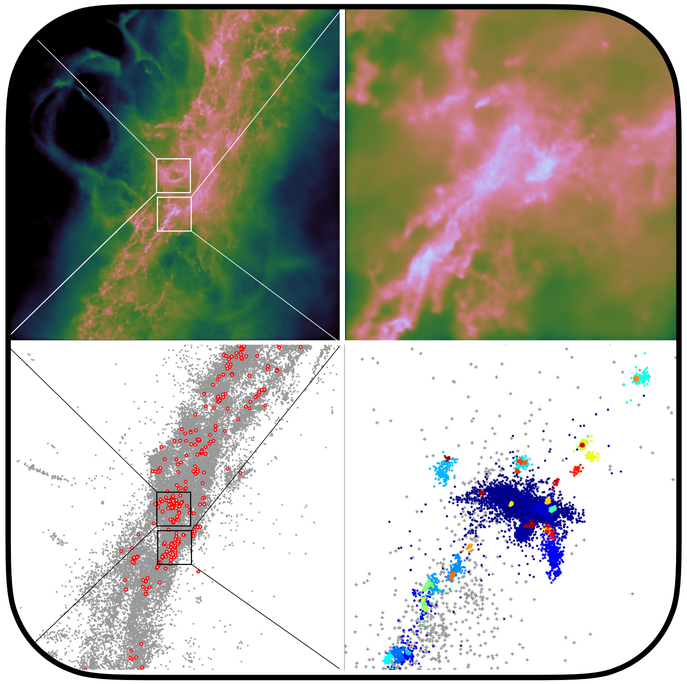

2 MWs over 1 Gyr, ~ 3 pc

*Andersson+24*




1 dwarf over 1 Gyr, ~ 3 pc

*Lahen+20*



2 dwarfs over 0.3 Gyr, ~ 0.1 pc

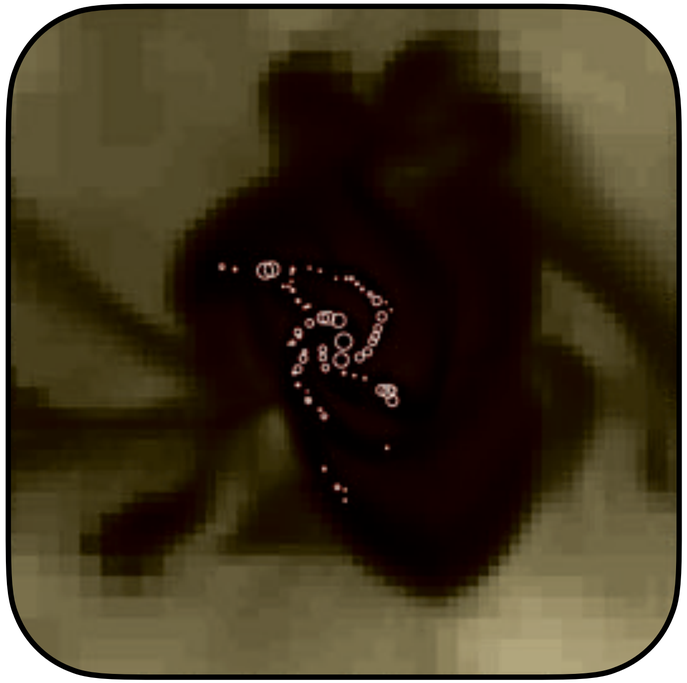
Modeling only few galaxies and limited in their evolution due to huge computational costs

# Current limitations of simulations [2/3]

**Main strategies:**

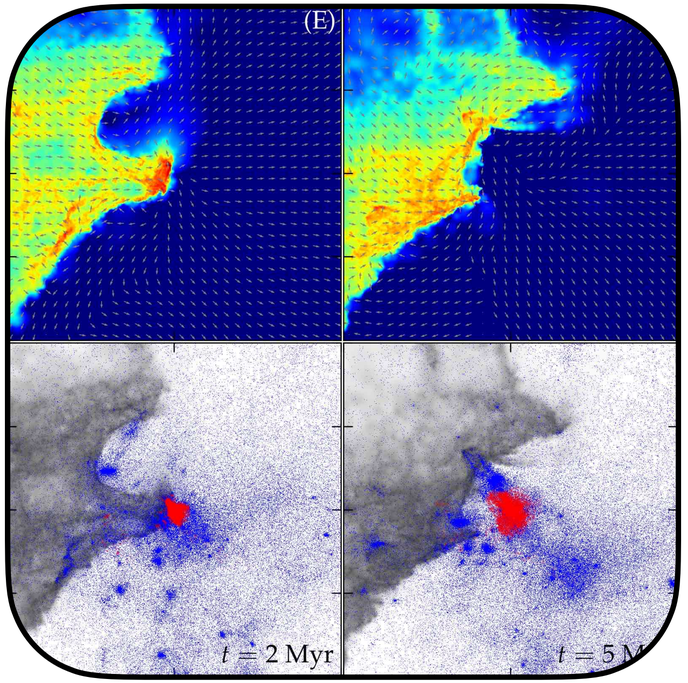
- High-resolution cosmological simulations *Kravtsov +05, Li +17, Kim +18, Ma +20, Meng +22, Sameie +22, …*

*Kravtsov+05*



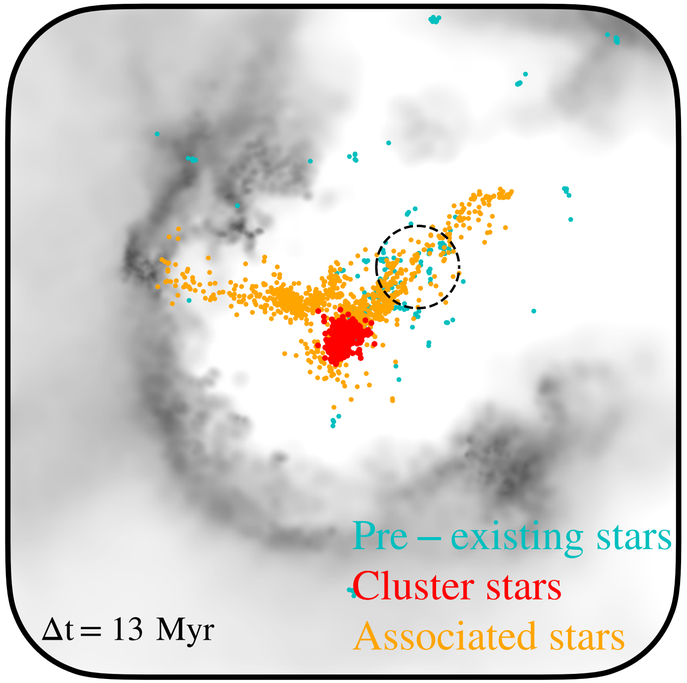
MW galaxy —> z=3, ~ 80 pc

*Ma+20*




Dwarfs —> z=5, ~ 10 pc

*Sameie+22*




Dwarfs —> z=4, ~ 3 pc

Limited to high redshifts with extremely high spatial & mass resolution

# Current limitations of simulations [3/3]

**Main strategies:**

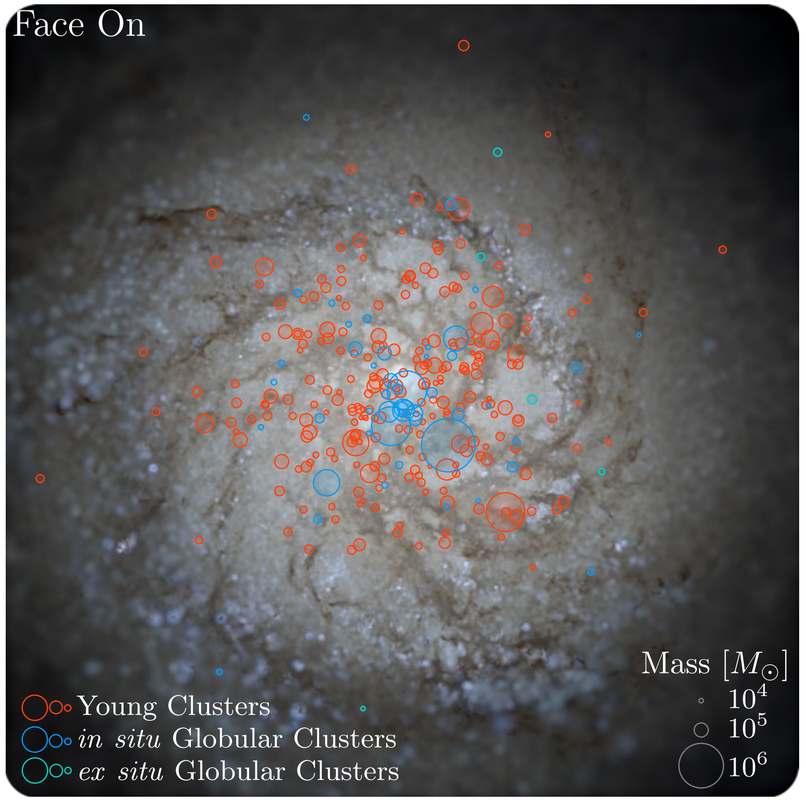
- **Tagging methods in post-treatment of simulations such as** *Illustris TNG-50, FIRE, EAGLE, AURIGA, …*

- Formation efficiency parameter based on gas and stellar quantities resolved in the simulation *Pfeffer+17, Reina-Campos+22, Grudic+23, Rodriguez+23*

- Identification of the most DM bound particles *Creasey+18*

- DM halo properties *Ramos+20, Halbesma+20, Park+22, Rodriguez+23, Doppel+23, Chen+23, +24*

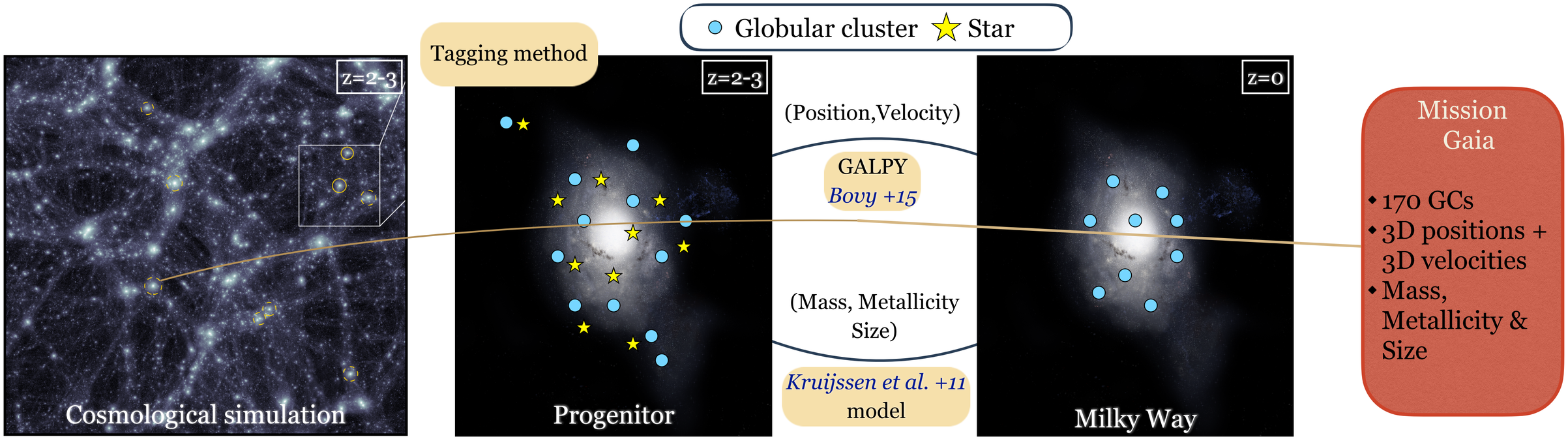
- Defining GC candidates as all star particles older than 10 Gyr *Halbesma+20*




*Rodriguez+23*

Computationally inexpensive with large statistics and several environments

# Our approach [1/2]

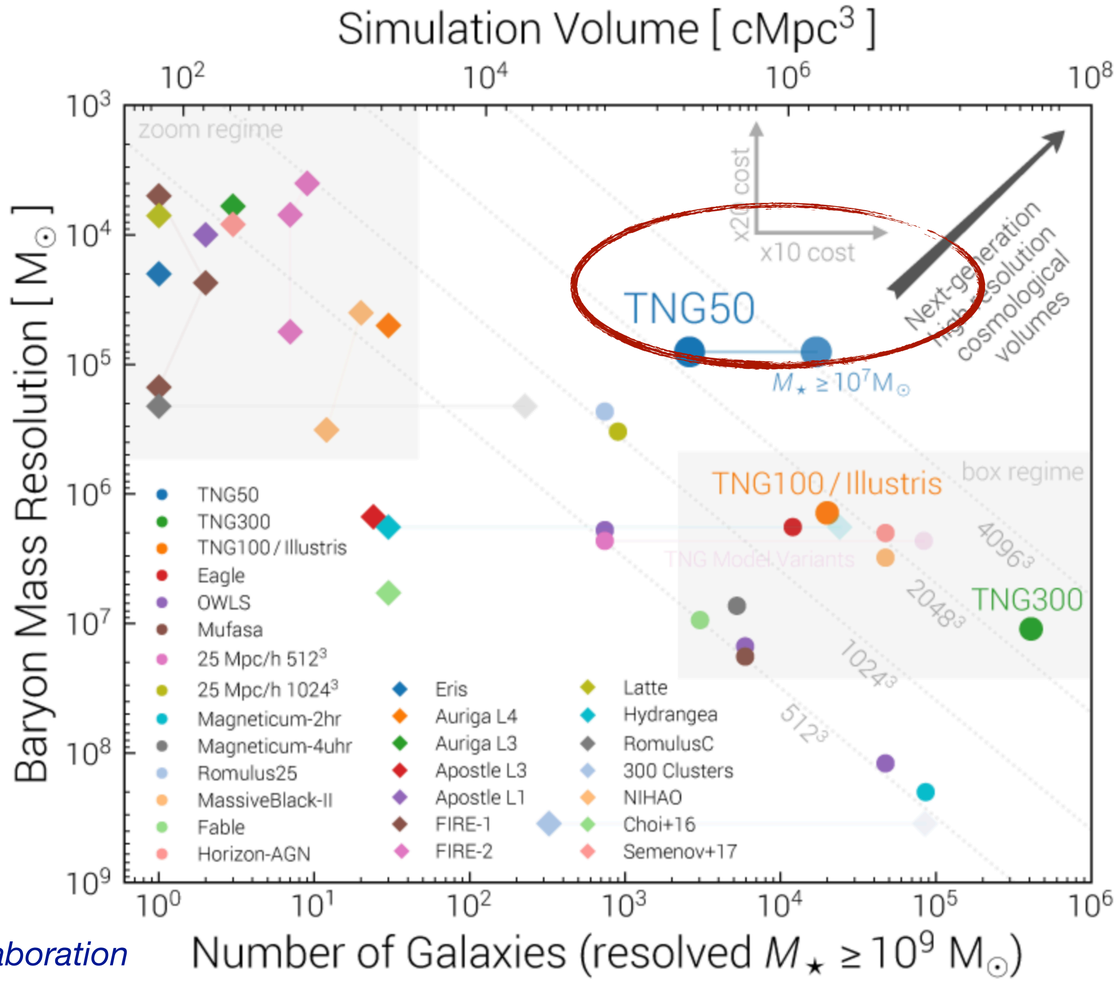



- Using existing cosmological simulations
- Computationally inexpensive
- Statistics

Flexible semi-analytical model in post-processing of simulations

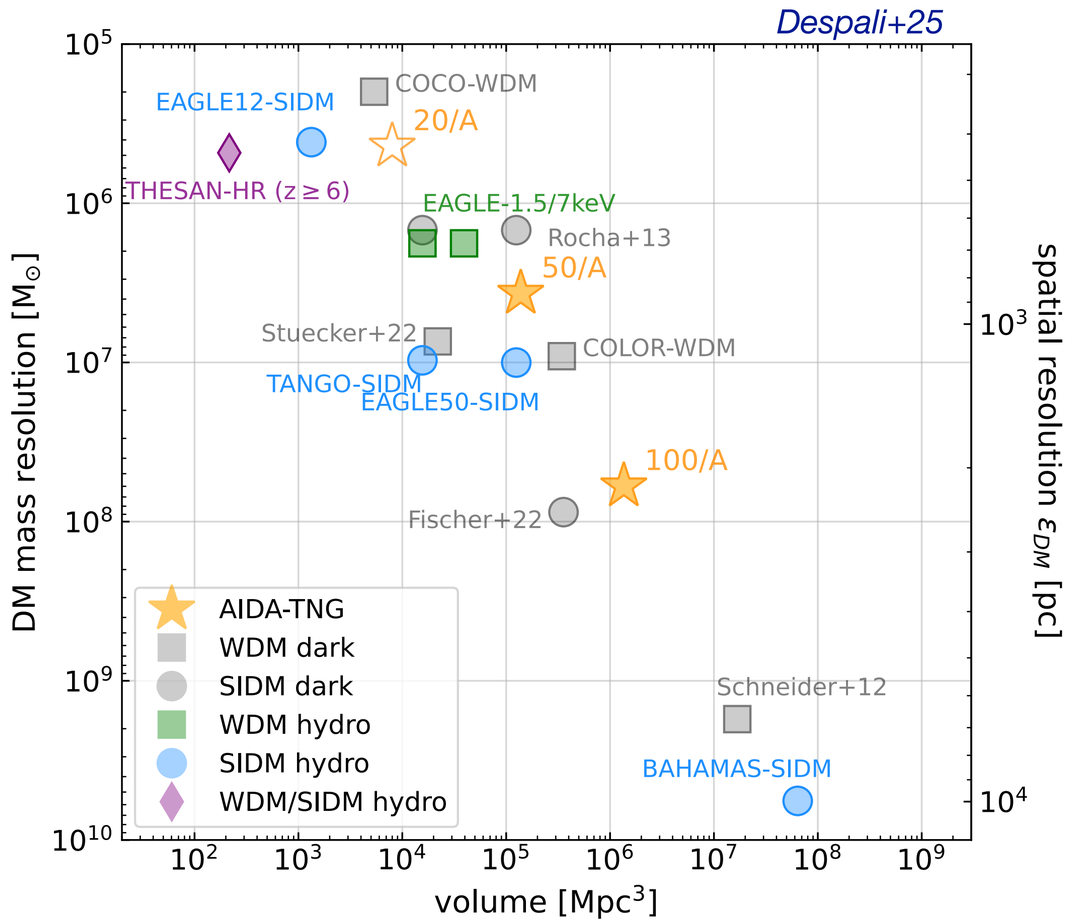
# Our approach [2/2]

## CDM




*TNG collaboration*

## 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

◆ S. Khoperskov, AIP



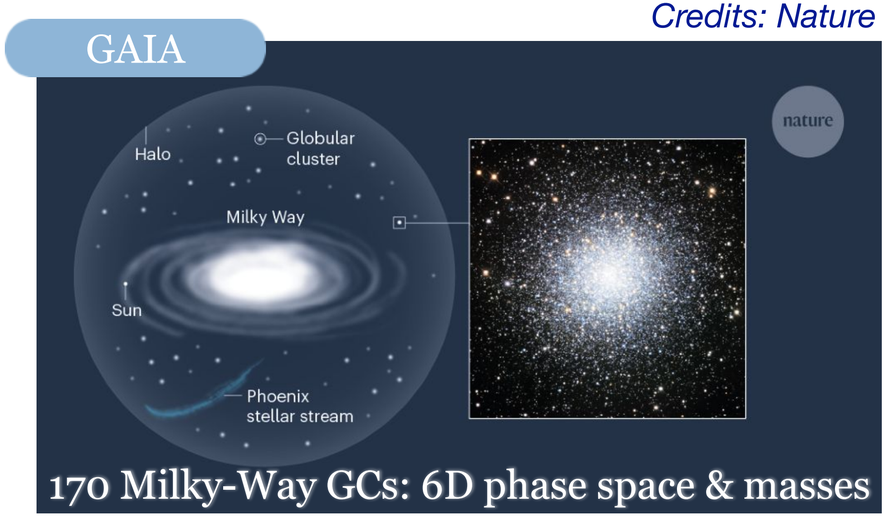
galpy

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

***arXiv:2506.13254***

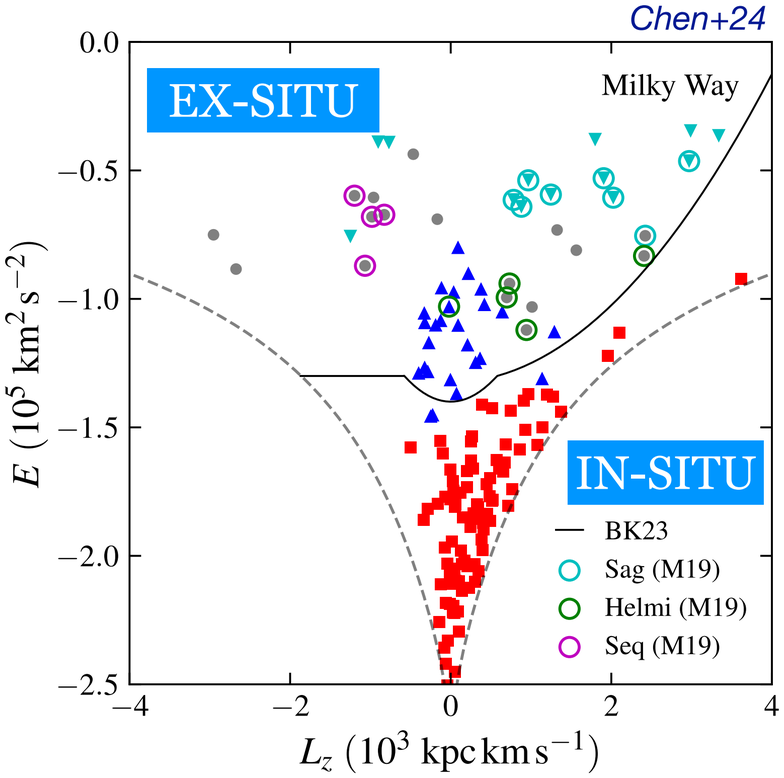
# Origin of Galactic globular clusters: in-situ or ex-situ?

*Credits: Nature*




| EX-SITU | IN-SITU |
|---|---|
| Formed in satellite galaxies | Formed within the MW |

*Chen+24*



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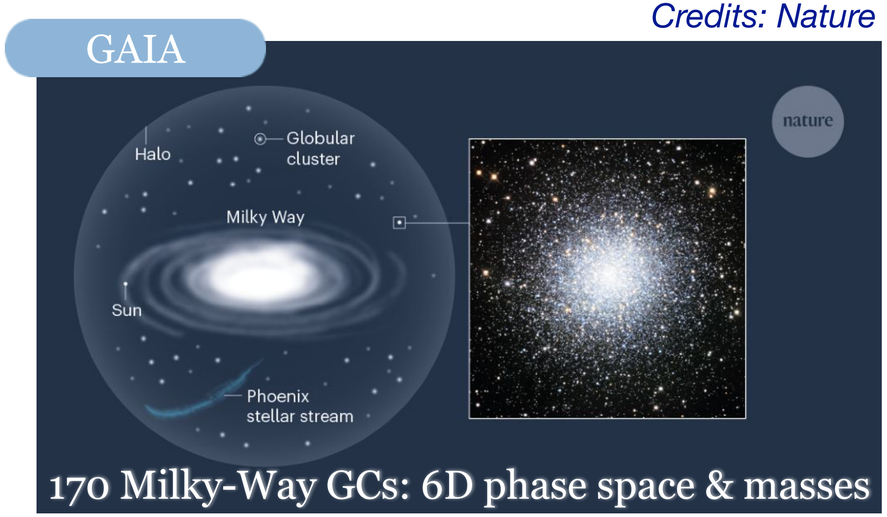


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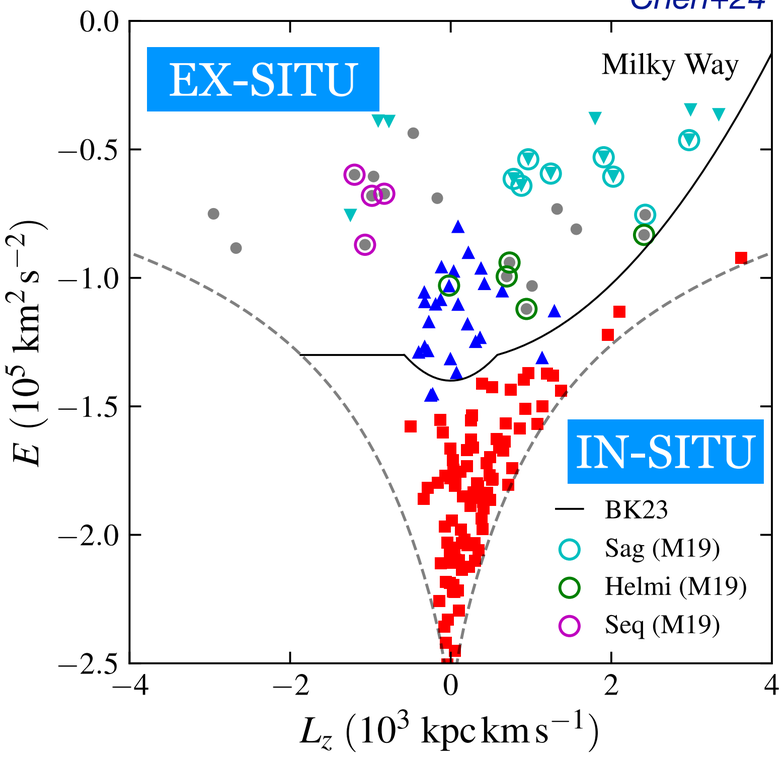
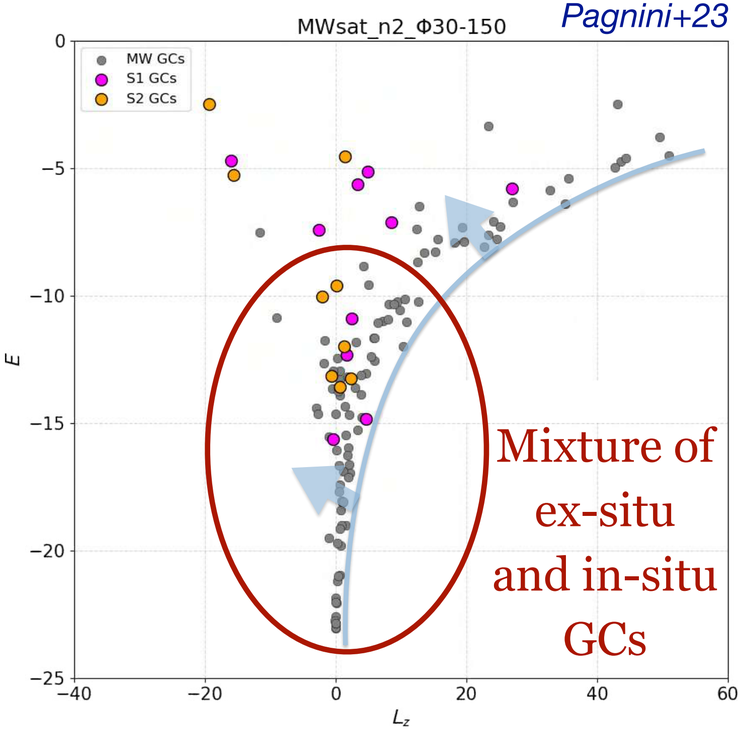



Pagnini+23

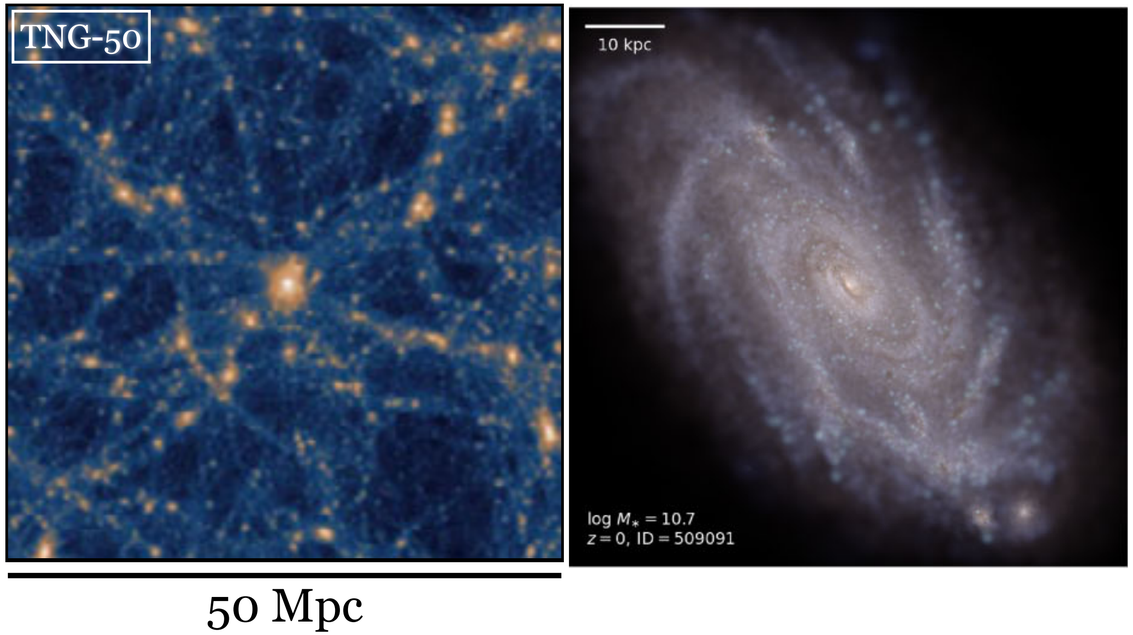


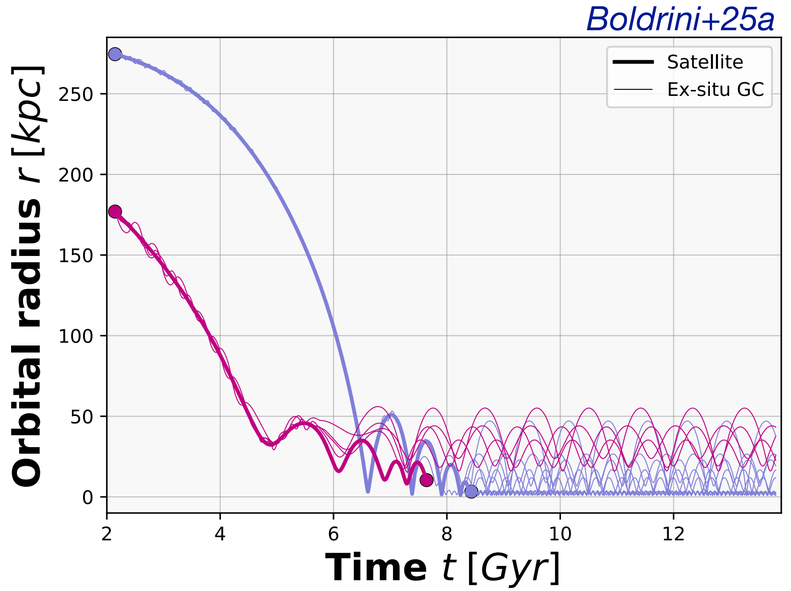

Previous studies found a clear separation between the two GC populations and it is based only on quantities at z=0!

What is missing?

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

# Globular cluster in TNG MW-like galaxies: methods



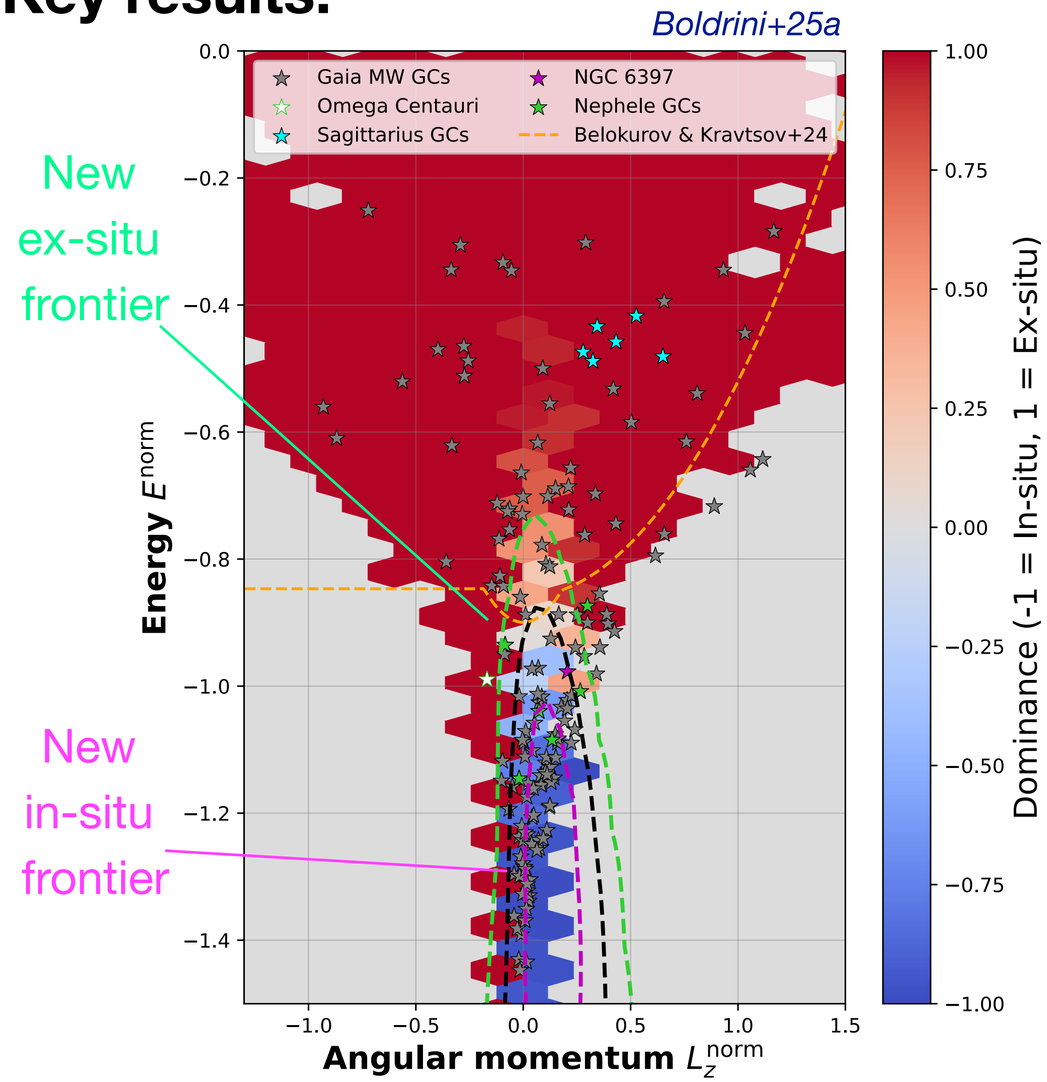



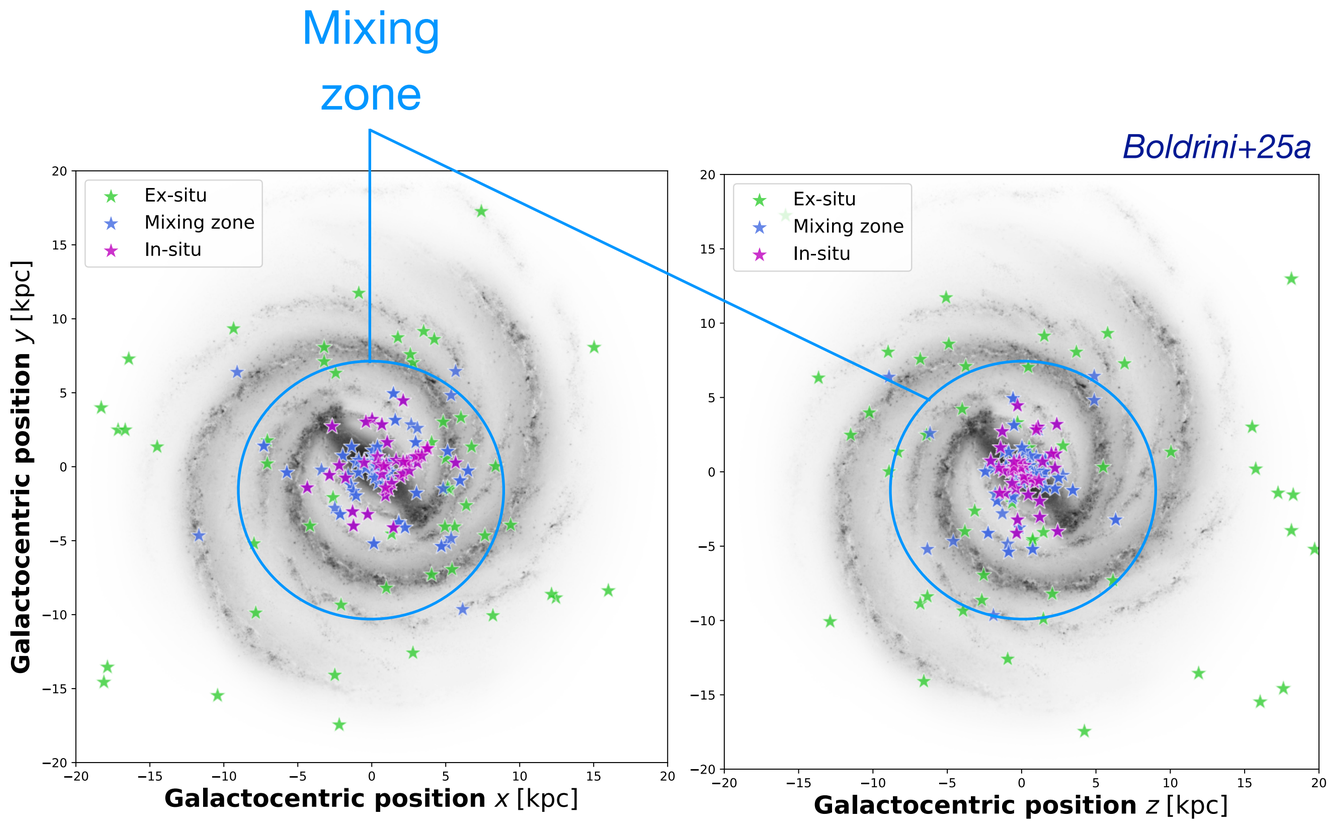

- Galactic spherical potentials are extracted from TNG50 cosmological simulations containing **198** Milky Way-like galaxies.
- GCs are tagged between z=3 and 2 according to Burkert & Forbes+20 relation
- Combined with orbit integrations with GALPY of **18,000** globular clusters from redshift z = 3 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:**



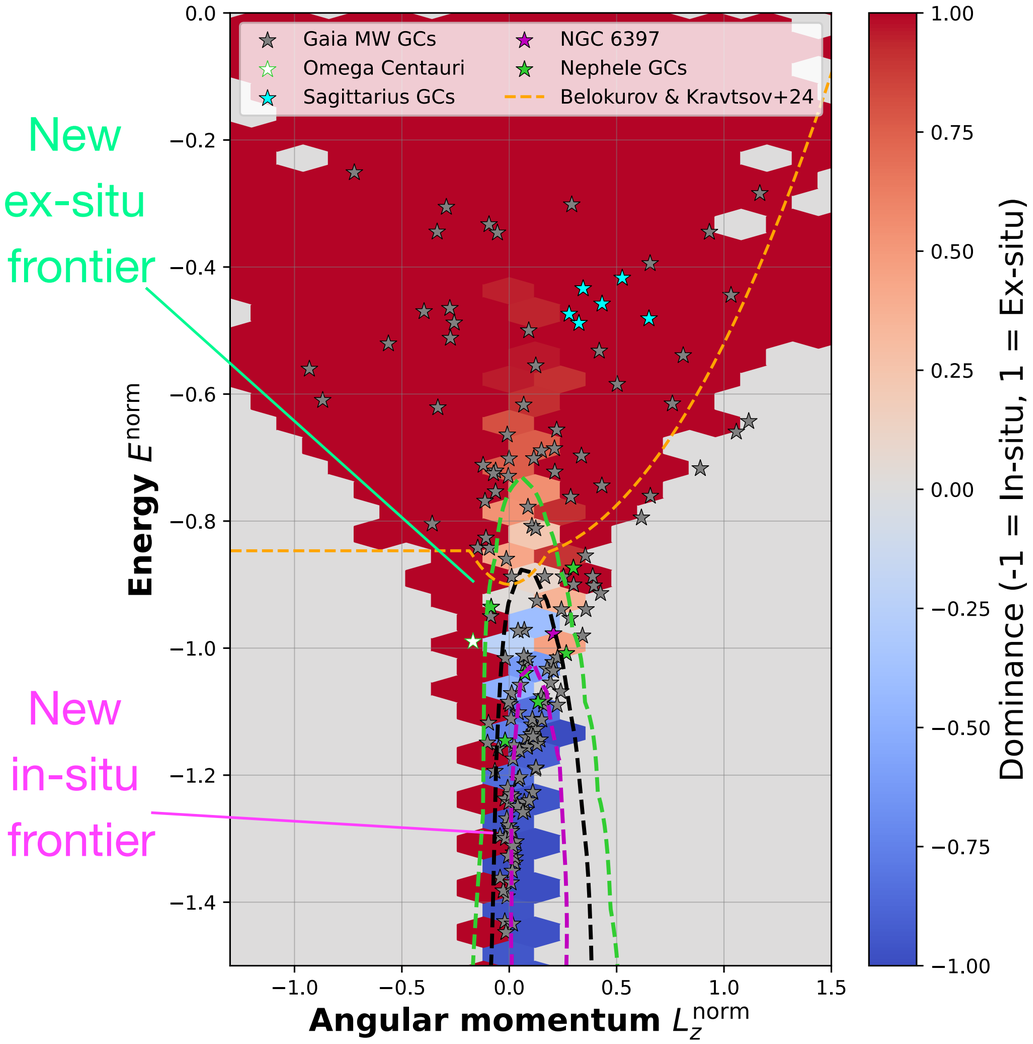




Mixture of the two GC populations —> Challenges previous separation methods

# New classification of the two GC populations in our Galaxy

## Key results:

*Boldrini+25a*




| | Our work | *Belokurov+24* | *Chen+24* | *Sun+23* |
|---|---|---|---|---|
| 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

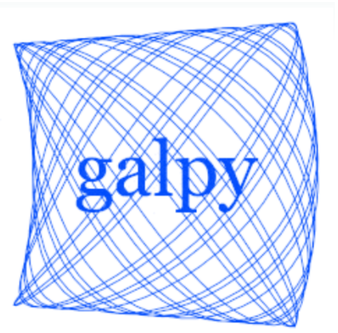
- P. Di Matteo, LIRA





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



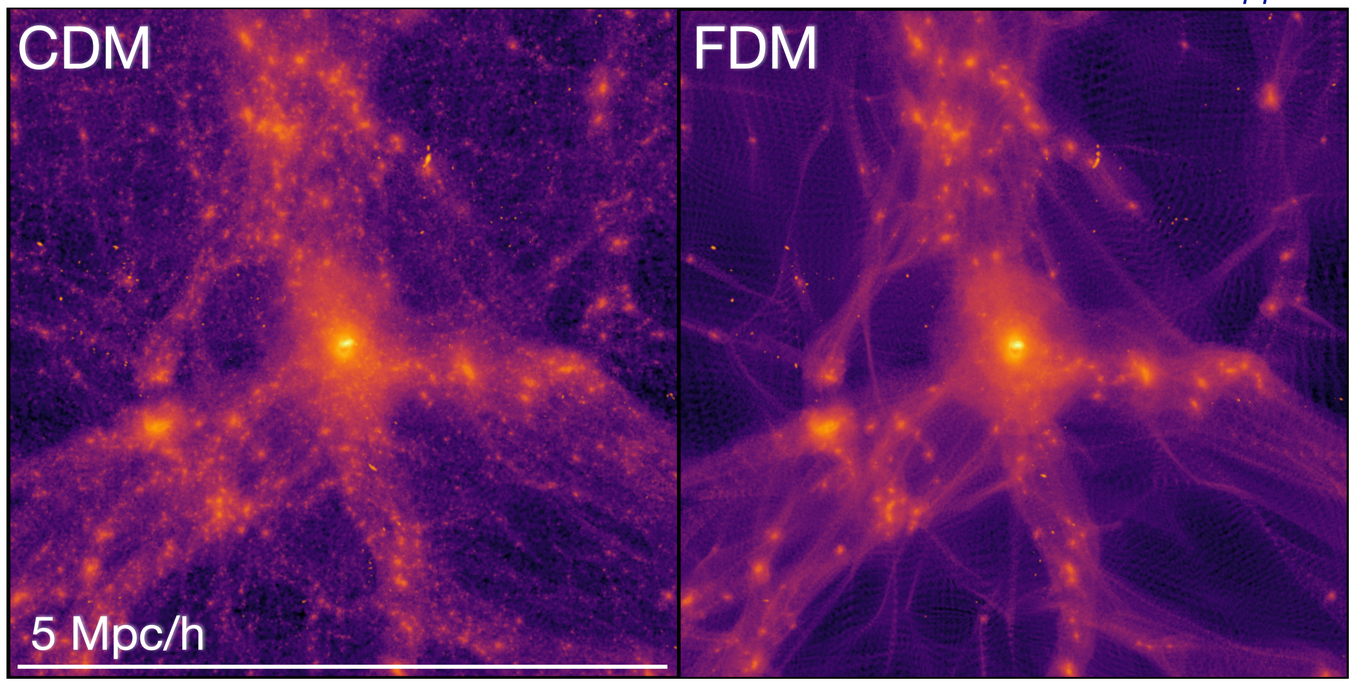



*Boldrini & Di Matteo +25, in prep.*

# 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*




- Free parameter: **FDM particle mass**

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

- $m_{22}$ = 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

*Iršic+17, Kobayashi+17, Nori+19, Armengaud+17, Rogers+21*

*Review: Eberhardt & Ferreira+25*

Deviations from CDM at galaxy scales

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

## State-of-the art for FDM simulations

- Stringent numerical requirements: small time steps, small spatial resolution
- Limited to small boxes at z=0 (1.4 Mpc/h) and to high redshift (z=3) *Schive+14, Mina+20, May & Springel+21,+23*
- $8192^3$ cells simulation down to z = 0 limited to 10 Mpc/h box —> $10^7$ CPU hours
- Absence of baryonic model for FDM

Similar to CDM

Deviation from CDM

| | Density profile | | Dynamical friction | | Satellite population (low mass halos) |
|---|---|---|---|---|---|
| | Massive galaxies | Dwarf galaxies | Massive galaxies | Dwarf galaxies | |
| FDM<br>Quantum wave-like nature | 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<br>Erased or reduced by quantum fluctuations *Hui+17, Lancaster+19* | Less abundant *Bullock+17 , Marsh+15* |

No proof of concept for GC dynamics in alternative DM theories

# GC dynamics in FDM universe: impact of DM core

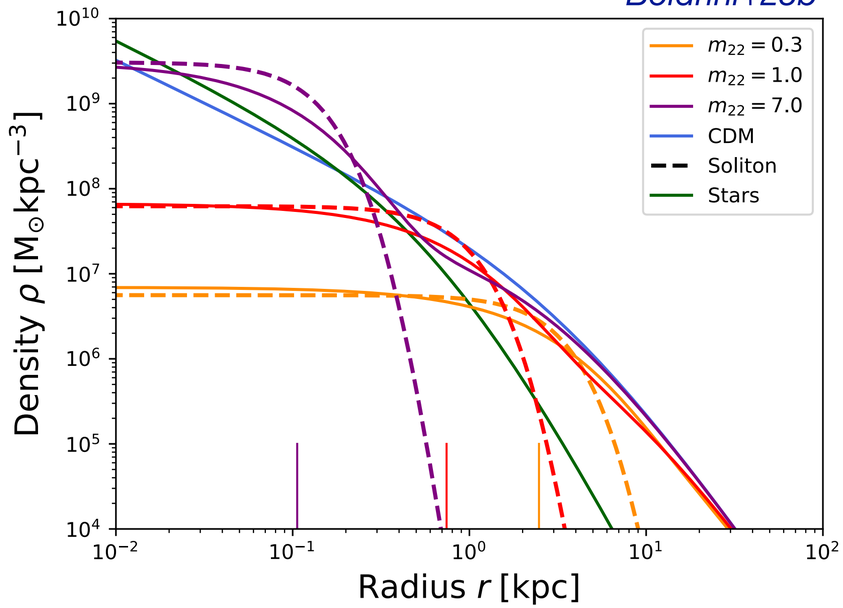
## FDM MW-like galaxies from TNG50

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

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

*Schive+14*

*Boldrini+25b*



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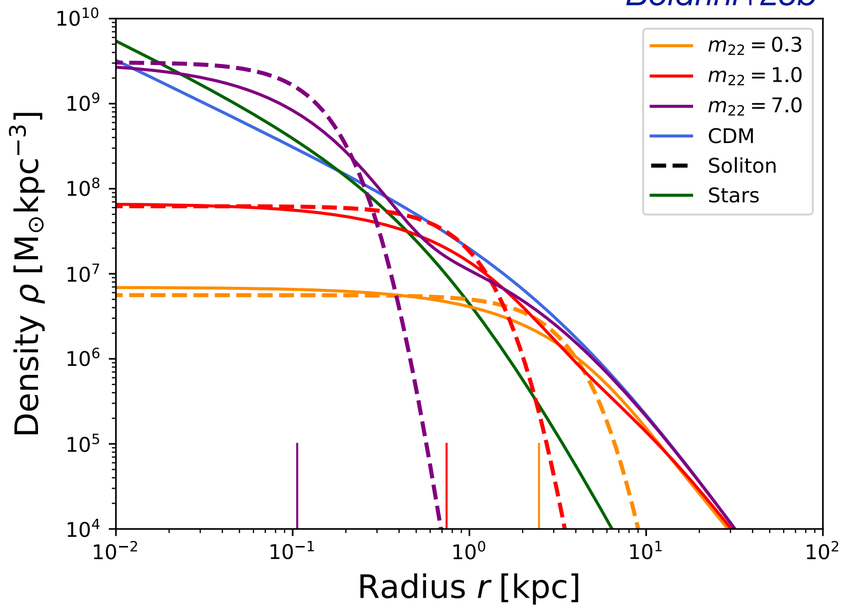



## In-situ globular cluster population

- 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 ($L_z > 0.6\ L_{circ}$)
- Absence of dynamical friction but mass loss

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

## 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

Similar to CDM

Deviation from CDM

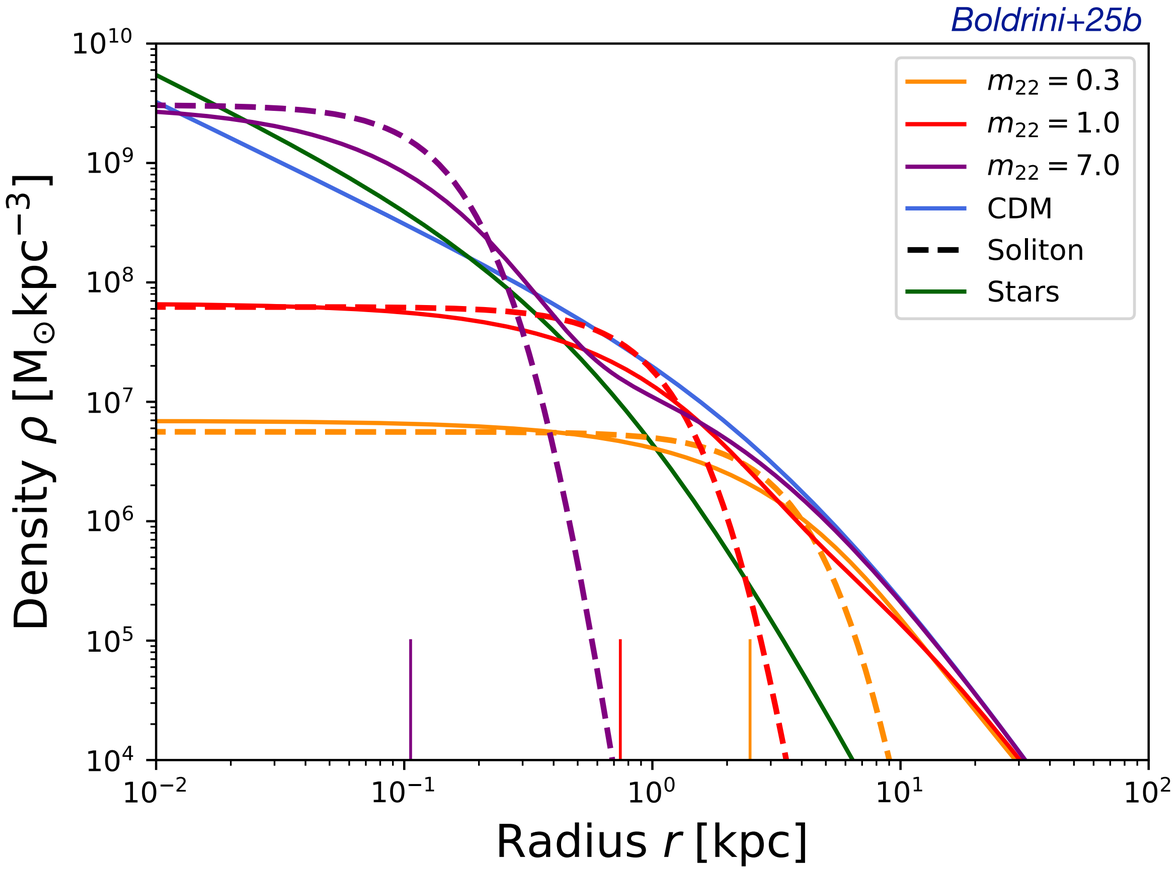
Density profile

Massive galaxies

DM core with size depending on the DM free parameter

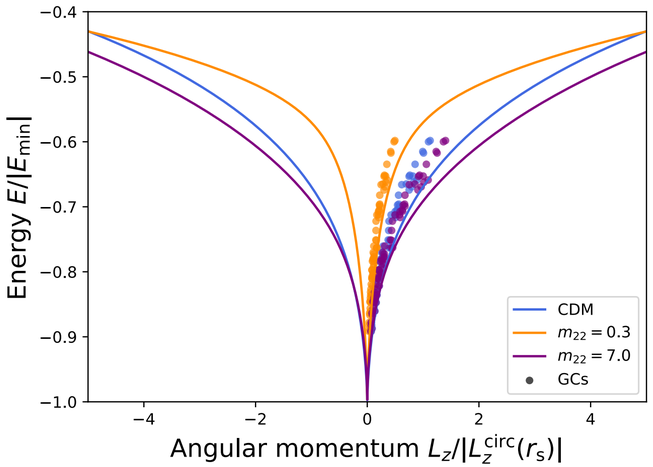
**FDM**
Quantum wave-like nature

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



# GC dynamics in FDM universe: impact of DM core

## Initial conditions

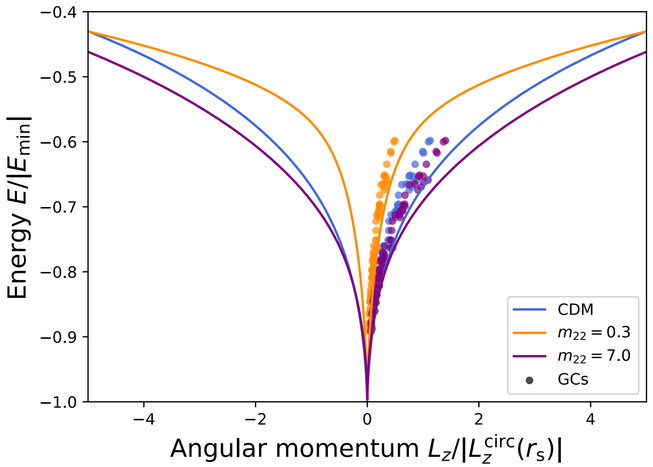



- Distributed equivalently of normalized E-$L_z$
- Fair comparison between DM potentials (core vs cusp)

# GC dynamics in FDM universe: impact of DM core

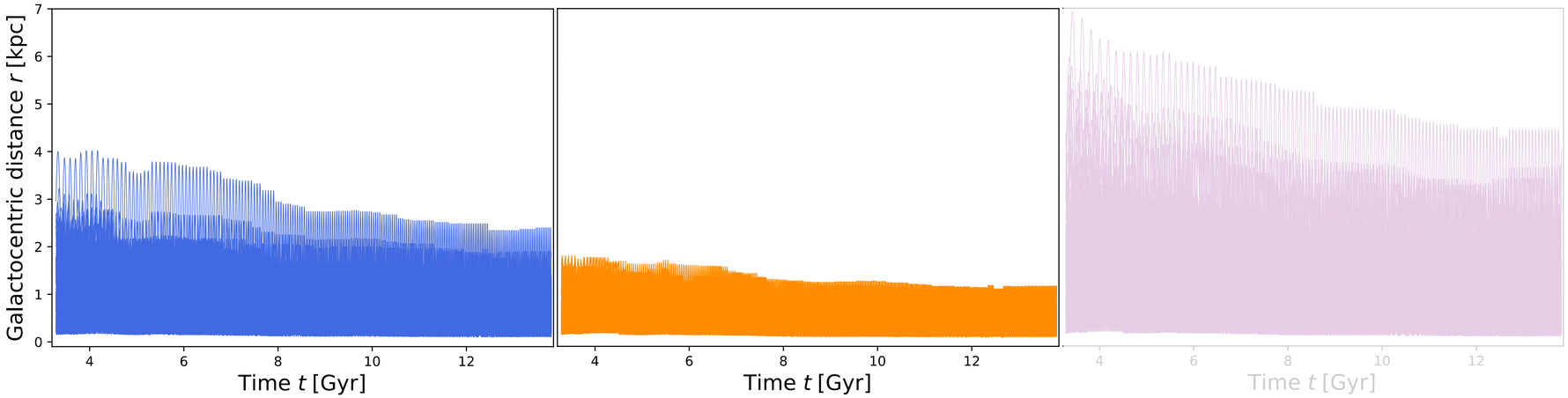
*Boldrini+25b*

## Initial conditions




## Time evolution in

CDM | FDM ($m_{22}$=0.3) | FDM ($m_{22}$=7.0)



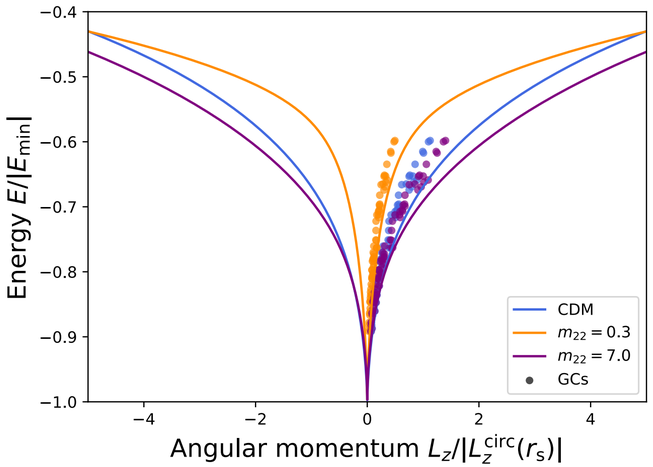

- Distributed equivalently of normalized E-$L_z$
- Fair comparison between DM potentials (core vs cusp)

- **Low m22:** 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

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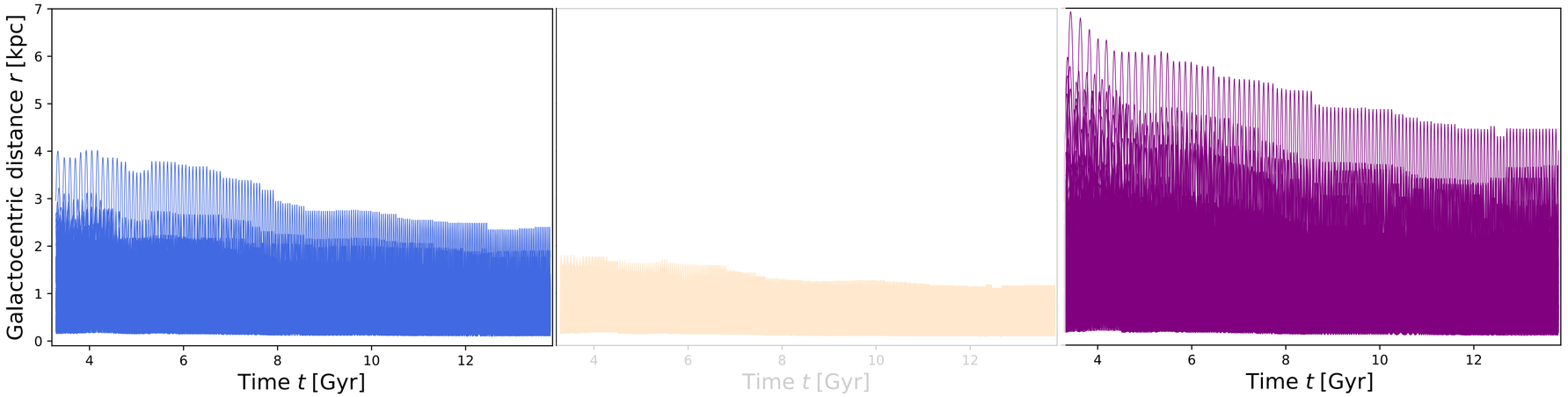



- **High m22:** DM core becomes more compact and denser and the relative contribution of baryons to the total potential decrease.
- The accessible area in the (E,$L_z$) plane expands in FDM —> **orbital expansion**

# GC dynamics in FDM universe: impact of DM core

- **Low $m_{22}$:** baryons dominate which confines the orbital space to a narrow region

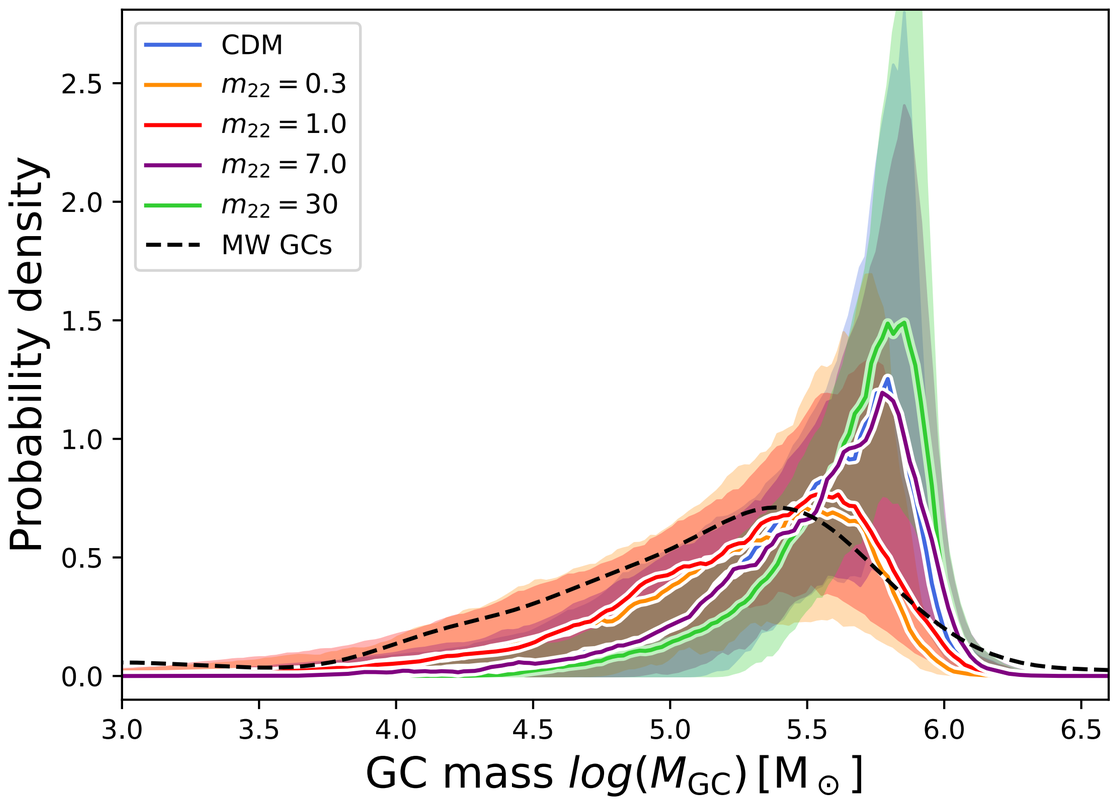
—> GCs confined near the center are much more susceptible to tidal effects and ultimately to disruption

—> FDM models produce broader mass distributions, with a significant number of low-mass clusters

- **High $m_{22}$:** DM dominate which allows for a wider variety of stable orbits

—> GCs can migrate to larger galactocentric distances and remain protected from strong tidal forces

*Boldrini+25b*




Confinement or expansion mechanism appears as a clear dynamical signature of FDM

# GC dynamics in FDM universe: impact of DM core

- **Low $m_{22}$:** baryons dominate which confines the orbital space to a narrow region.

—> GCs confined near the center are much more susceptible to tidal effects and ultimately to disruption

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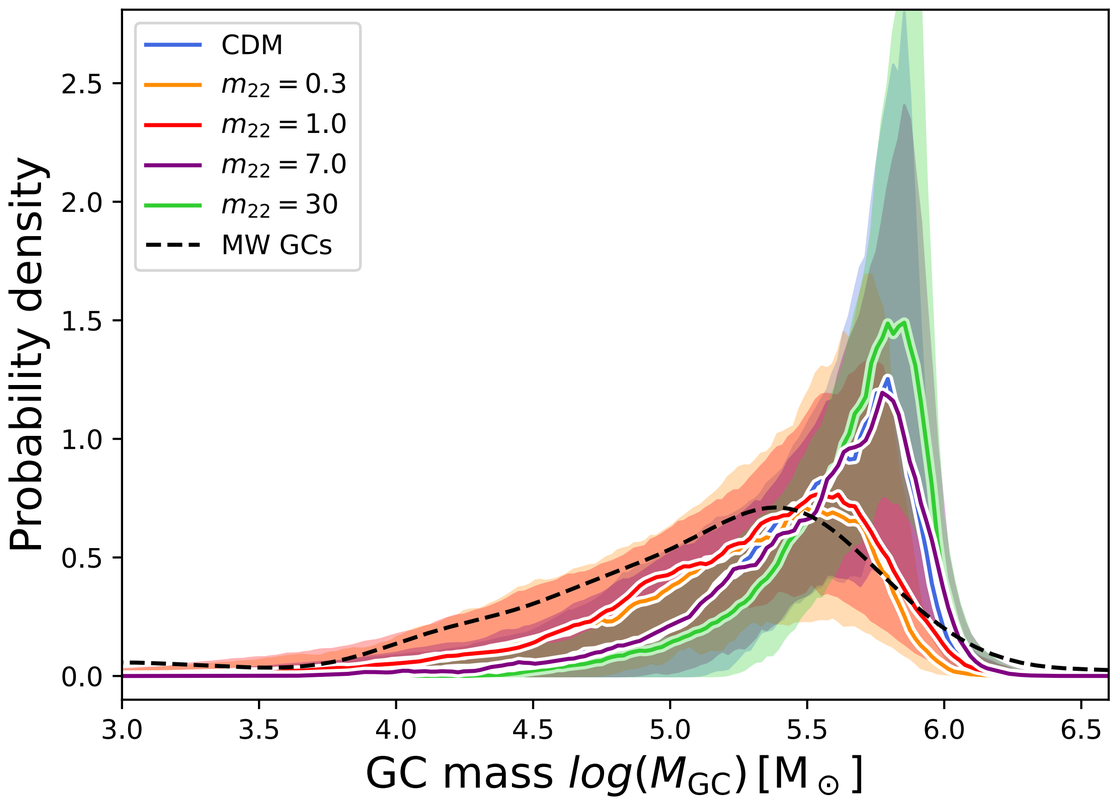
- **High $m_{22}$:** DM dominate which allows for a wider variety of stable orbits

—> GCs can migrate to larger galactocentric distances and remain protected from strong tidal forces

—> FDM models shows the highest peak in the mass distribution

*Boldrini+25b*

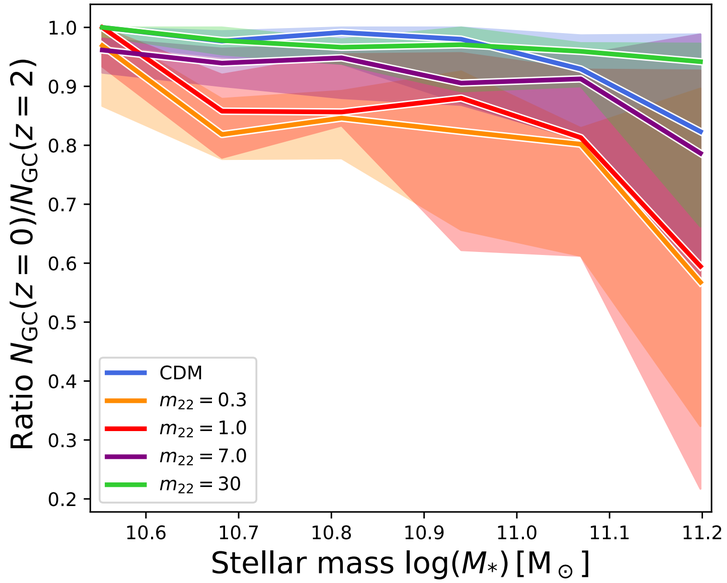



Confinement or expansion mechanism appears as a clear dynamical signature of FDM

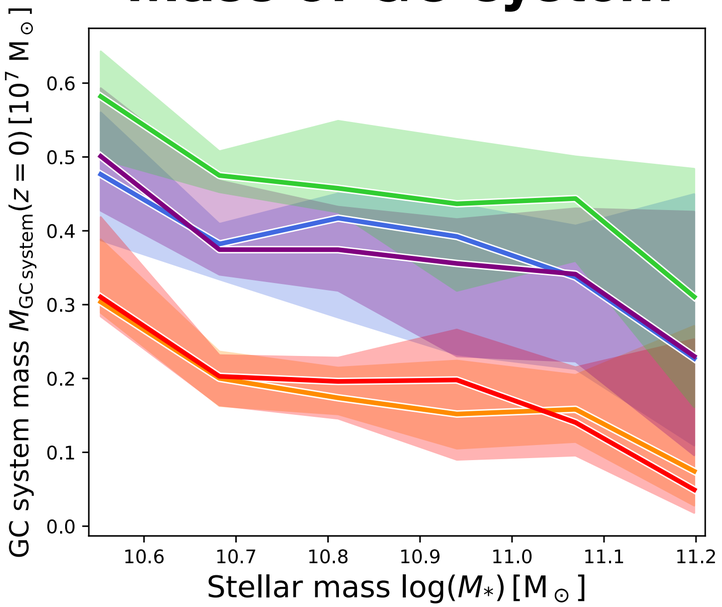
# GC dynamics in FDM universe: impact of DM core

**At z=0:**

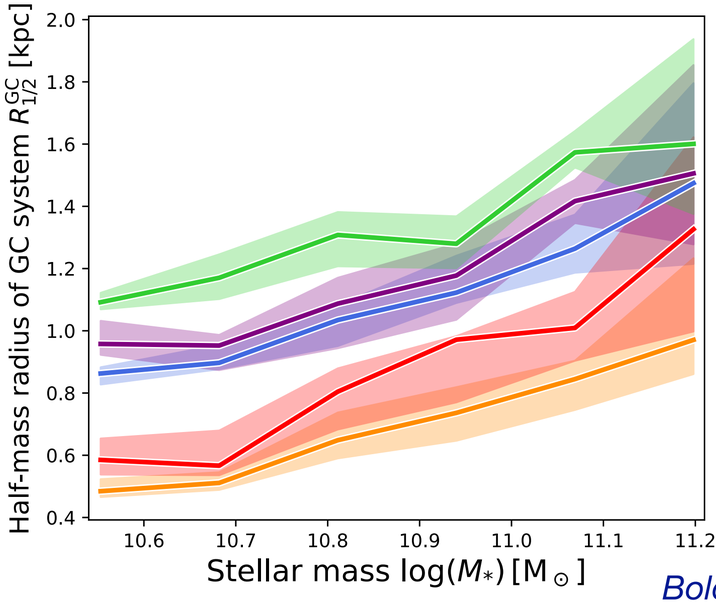
**Surviving GCs**




**Mass of GC system**




**Half-mass radius**




*Boldrini+25b*

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

GC system —> less massive and more spatially concentrated than in CDM

- **$m_{22}$** ~7: Similar to CDM, both in terms of total mass and spatial distribution.

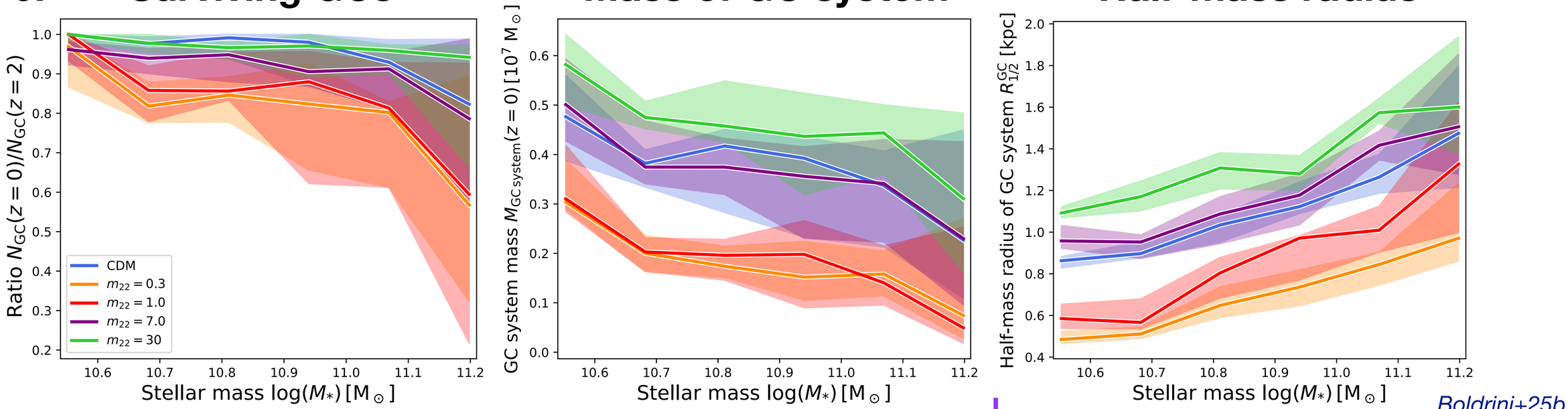
- **$m_{22}$** >7: Larger number of surviving clusters, generally more massive.

GC system —> 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

**At z=0:** **Surviving GCs** **Mass of GC system** **Half-mass radius**




*Boldrini+25b*

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Favored by galactic constraints

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Favored by cosmological constraints

3 regimes for the in-situ GC population

# This talk

◆ P. Di Matteo, LIRA

◆ A. Szpilfidel, LIRA





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

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

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

# GC dynamics in FDM universe: impact of specific dynamical friction

Similar to CDM

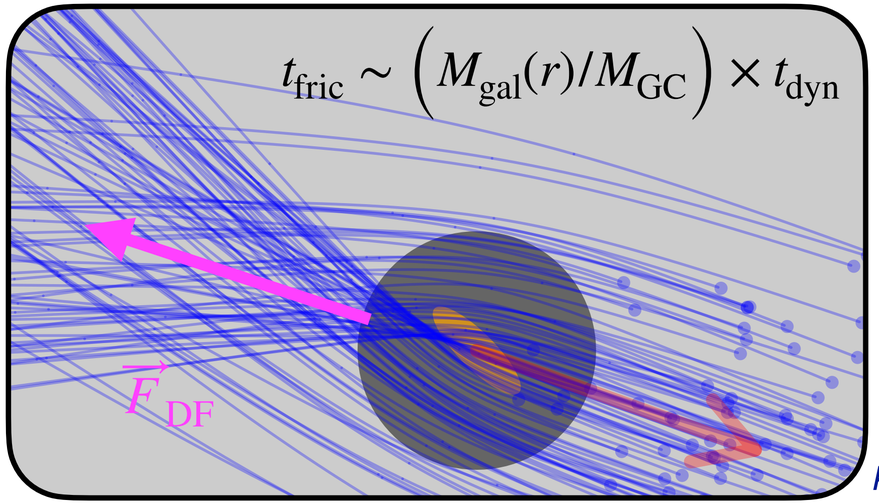
Deviation from CDM

**GC dynamics**

**Dynamical friction**

| Massive galaxies | Dwarf galaxies |
|---|---|
| Inefficient due to the huge mass ratio with GC | Erased or reduced by quantum fluctuations *Hui+17, Lancaster+19* |

**FDM**
Quantum wave-like nature




*Kipper+20*

# 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 —> 0.01 CPU hour

- A. Szpilfidel, LIRA

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

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

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

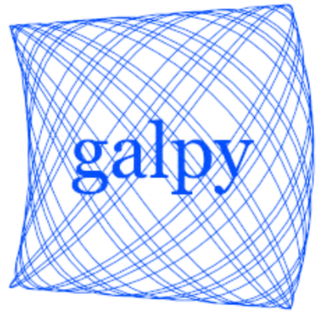
### Fuzzy-dark-matter dynamical friction

*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:

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

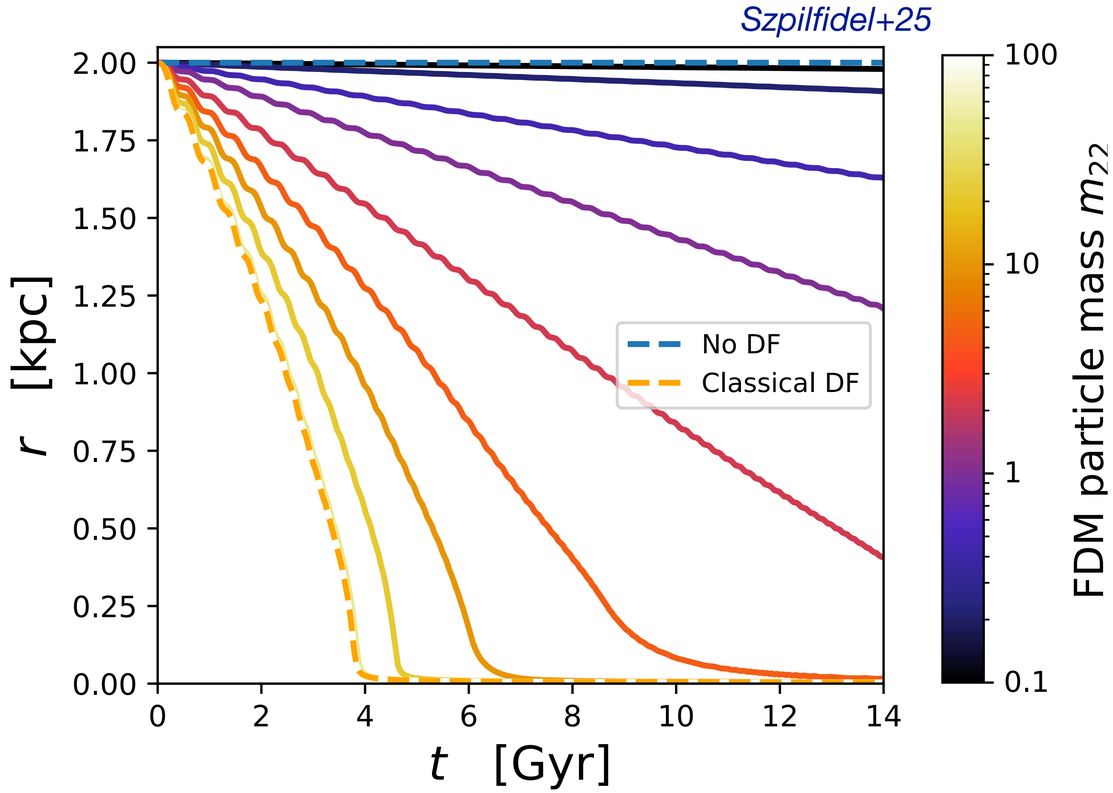



New public Galpy package for FDM dynamical friction

# 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




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

- Low $m_{22}$ —> no dynamical friction
- High $m_{22}$ —> CDM dynamical friction

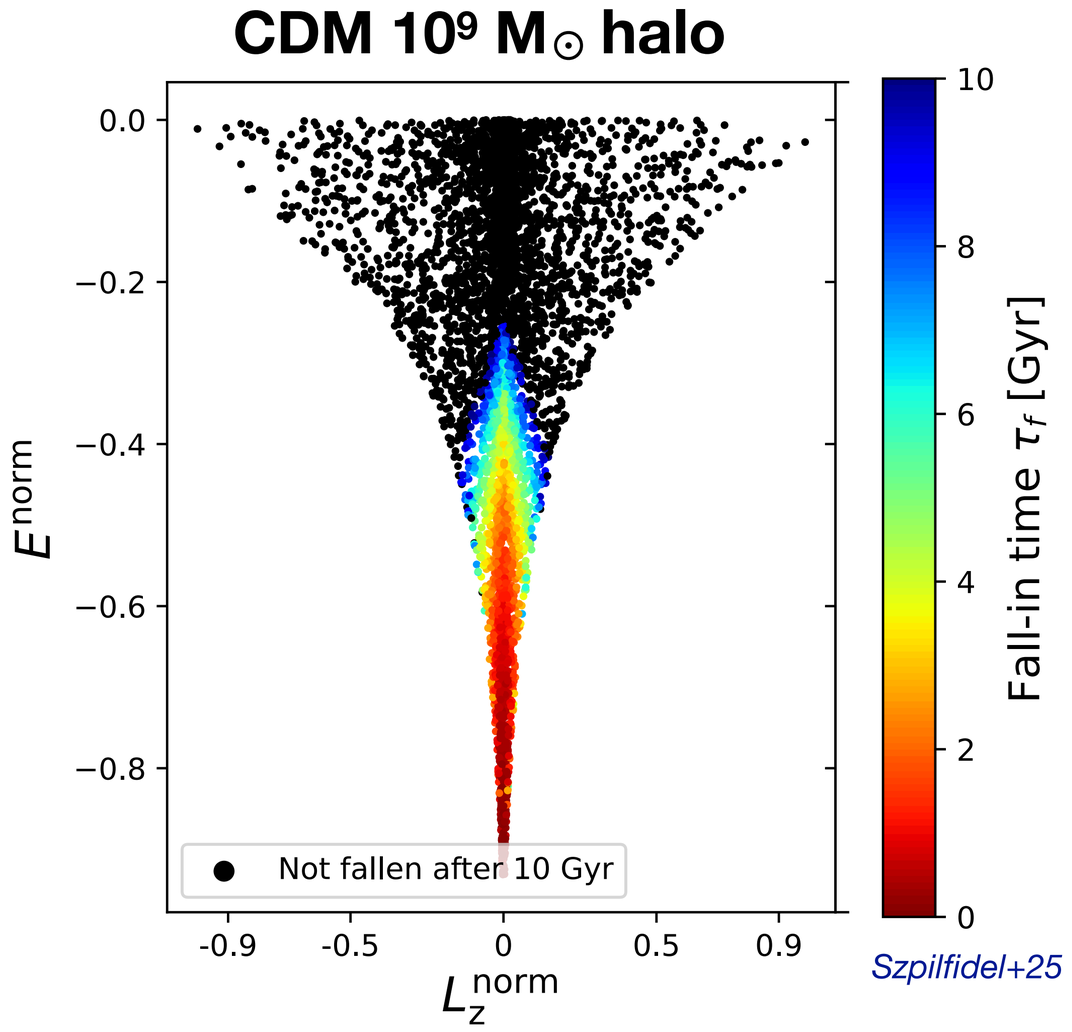
# GC dynamics in FDM universe: impact of specific dynamical friction

- 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**

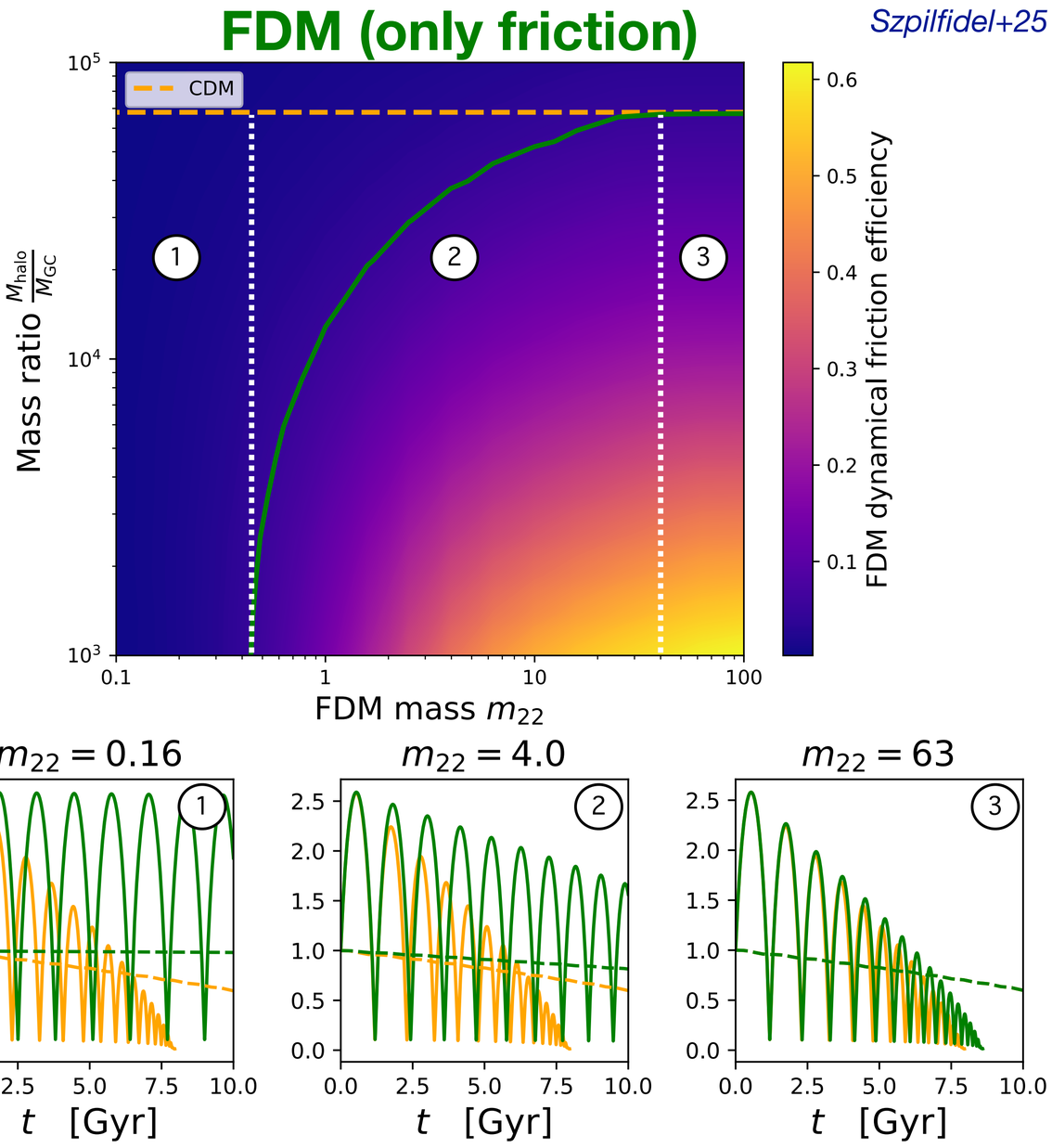
**FDM = Core + FDM DF**



# GC dynamics in FDM universe: impact of specific dynamical friction

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

- **Classical DF:** above a mass ratio of 7 ×10⁴, friction becomes negligible
- Regime of interest for significant FDM signatures: dwarf galaxies



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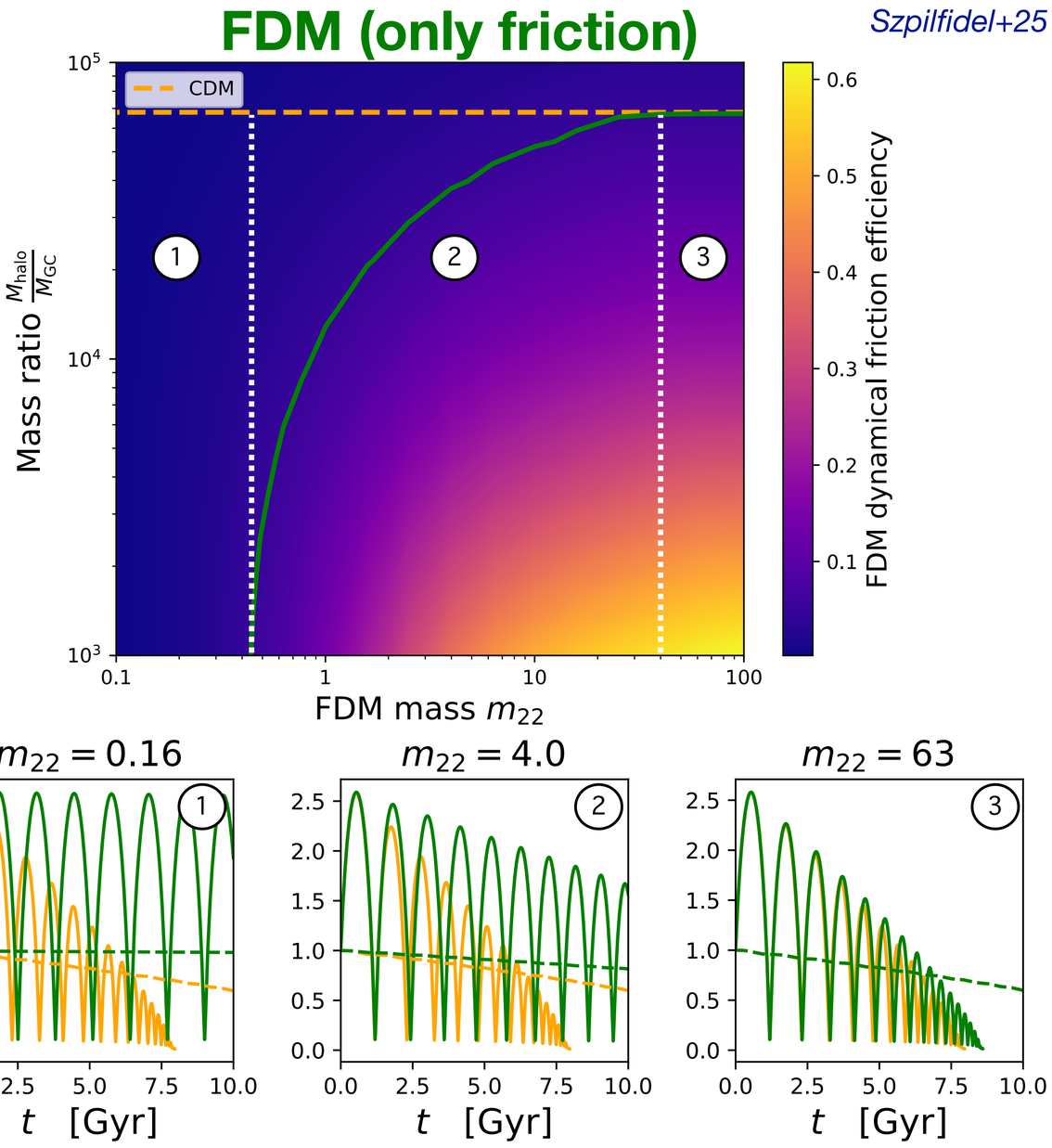
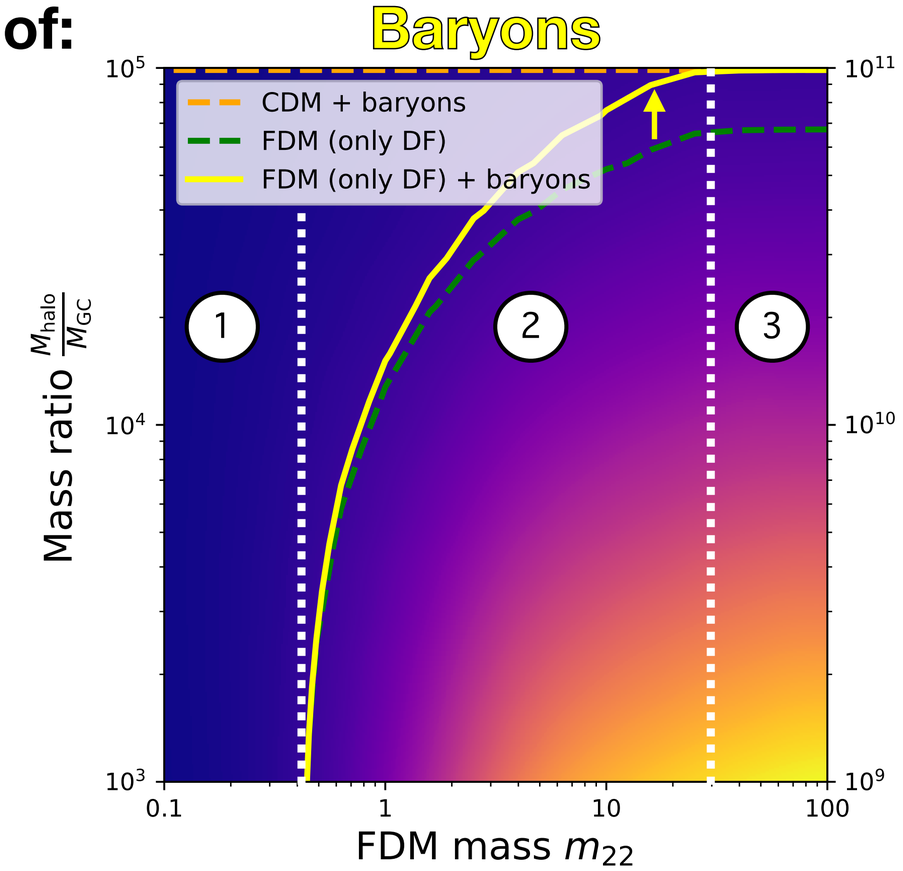
- **Classical DF:** above a mass ratio of 7 ×10⁴, friction becomes negligible
- Regime of interest for significant FDM signatures: dwarf galaxies
- **Zone 1:** FDM DF is highly inefficient —> orbital stalling
- **Zone 2:** Effective but reduced compared to CDM
- **Zone 3:** Converge back to CDM

FDM stalling mechanism challenges the expected galactic cannibalism of GCs



# GC dynamics in FDM universe: impact of specific dynamical friction

**Impact of:**

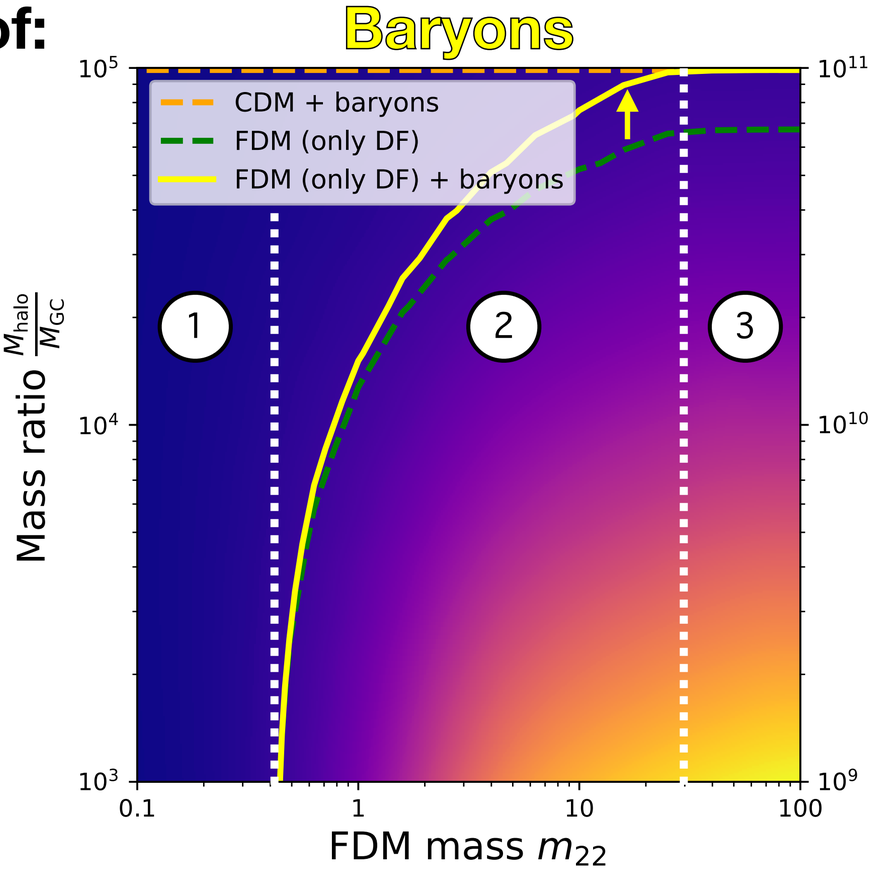


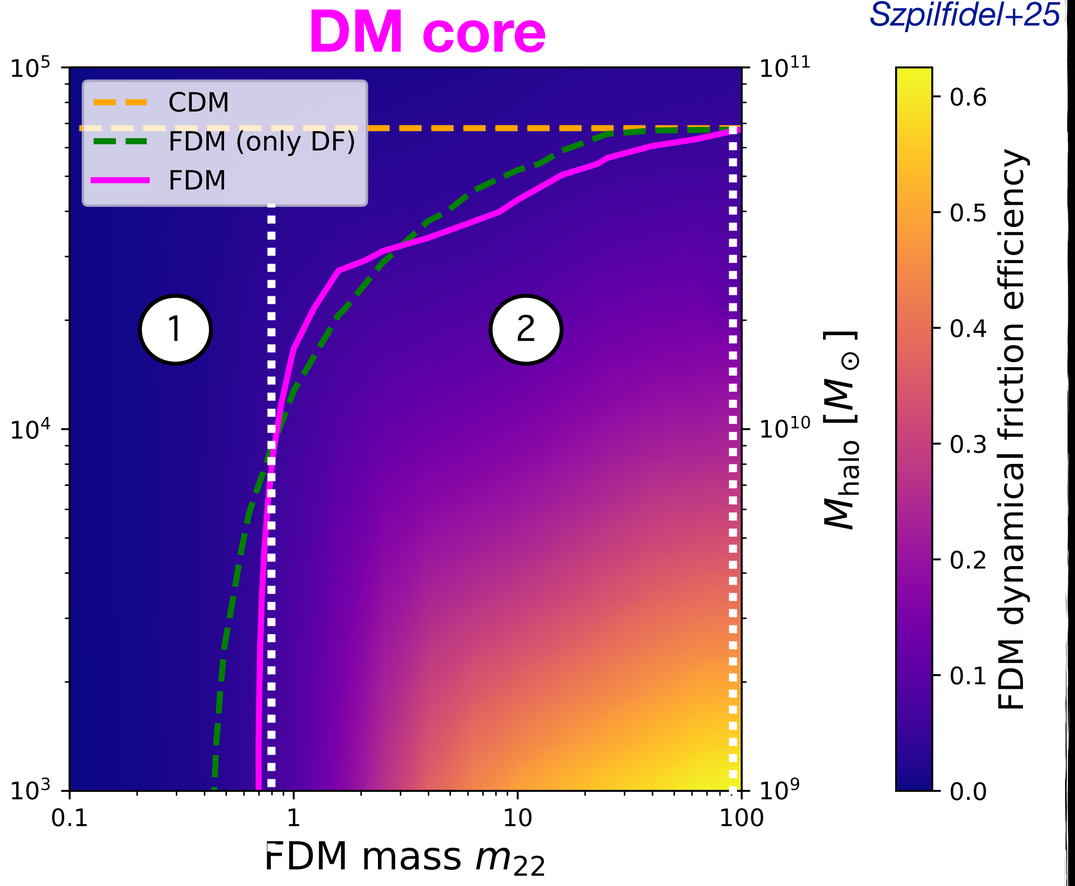

*Szpilfidel+25*

- **Hypothesis:** stellar mass from *Behroozi+10* and effective radius from *Shen+03*
- Addition of baryons broadens the range of mass ratios over which DF is efficient, since we add extra density

# GC dynamics in FDM universe: impact of specific dynamical friction

**Impact of:**




- **Hypothesis:** stellar mass from *Behroozi+10* and effective radius from *Shen+03*
- Addition of baryons broadens the range of mass ratios over which DF is efficient, since we add extra density

- Only two regimes: inclusion of the core reinforces the DF inefficiency and nearly suppresses the convergence toward the CDM regime
- Enlarges the regime in which DF is reduced

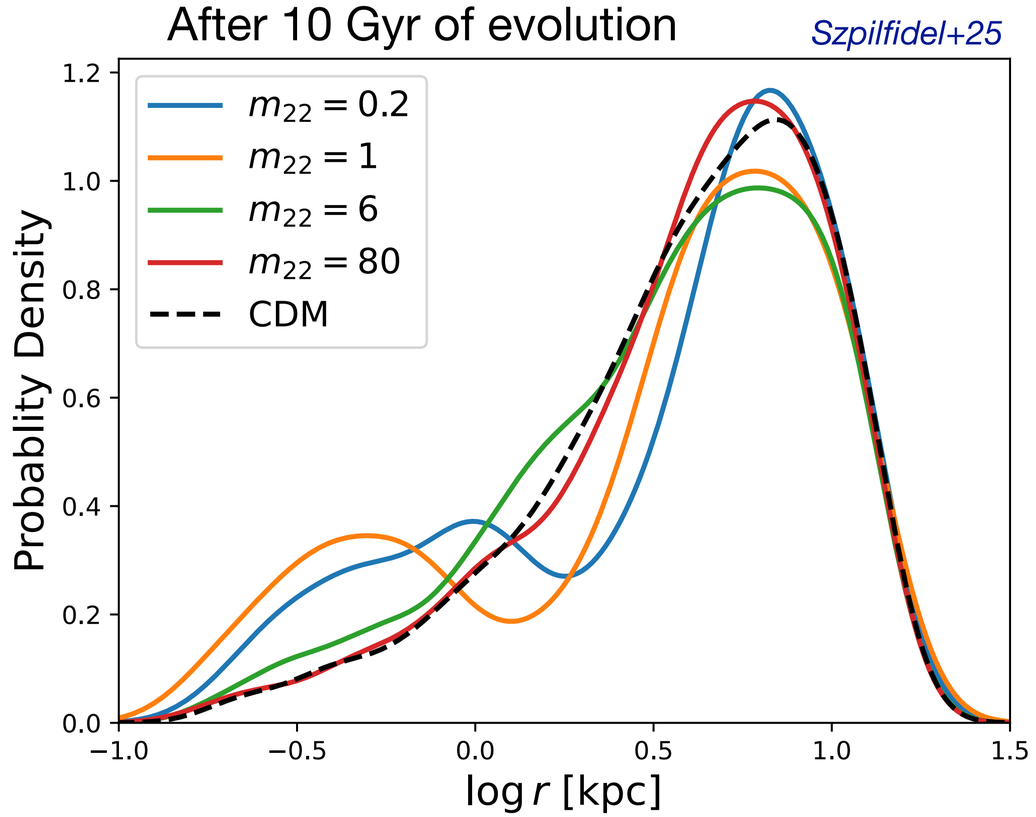
# GC dynamics in FDM universe: impact of specific dynamical friction

## 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




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

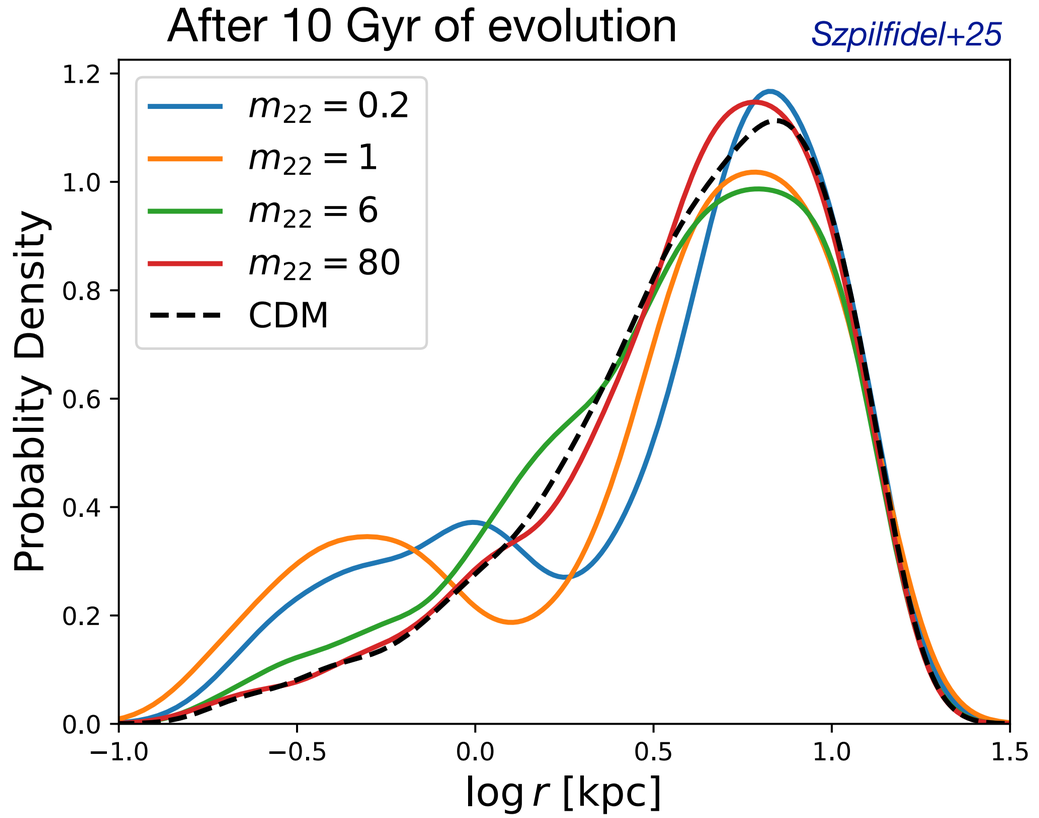
# GC dynamics in FDM universe: impact of specific dynamical friction

## 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
- **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 m22 < 6




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

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

# Conclusions

Similar to CDM

Deviation from CDM

| | GC dynamics | | | |
|---|---|---|---|---|
| | Density profile | Dynamical friction | | Satellite population (low mass halos) |
| | Massive 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 | |
| **WDM** High velocity dark matter | | | | Less abundant *Bullock+17 , Marsh+15* |
| **FDM** Quantum wave-like nature | Orbital confinement or expansion depending on $m_{22}$ *Boldrini+25b* | | 2 regimes: resilient to galactic cannibalism and absence of mixing *Szpilfidel+25* | |

# Conclusions

Similar to CDM

Deviation from CDM

| | GC dynamics | | | |
|---|---|---|---|---|
| | Density profile | Dynamical friction | | Satellite population (low mass halos) |
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- **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

# Futur works [1/2]

## Applying the model to CDM simulations:

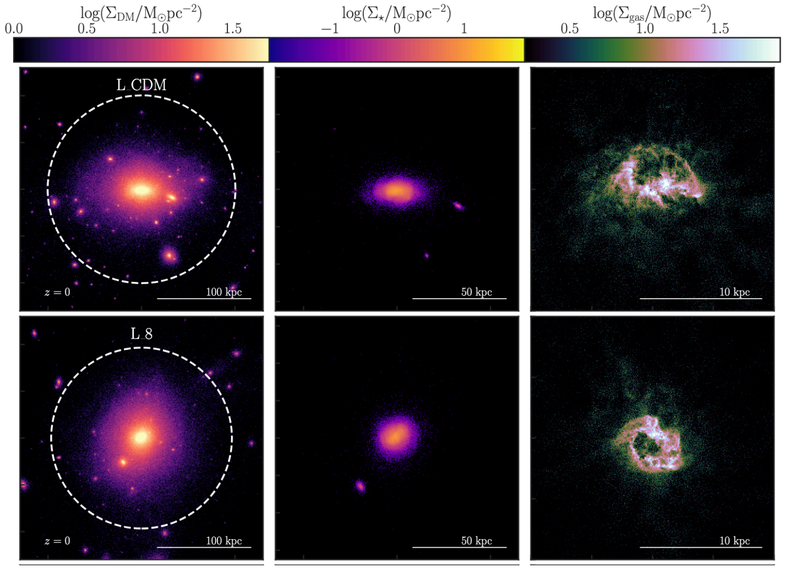
- Local group simulation —> Hestia 2
- How did MW-like galaxies form and assemble over cosmic time?

*Khoperskov+23*

- S. Khoperskov, AIP

## Applying the model to ADM simulations:

- Fuzzy dark matter simulations —> Fuzzy Gasoline ( dwarf galaxies + hydrodynamics)
- Warm and self-interacting dark matter also needs to be investigated —> using existing cosmological simulations such as *Darkium* (SIDM) and not need of specific formulation of DF



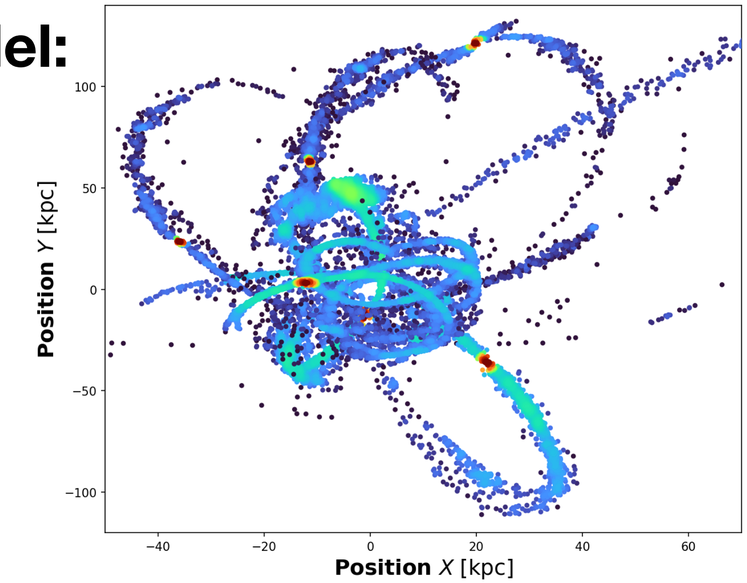

*Nori+24*

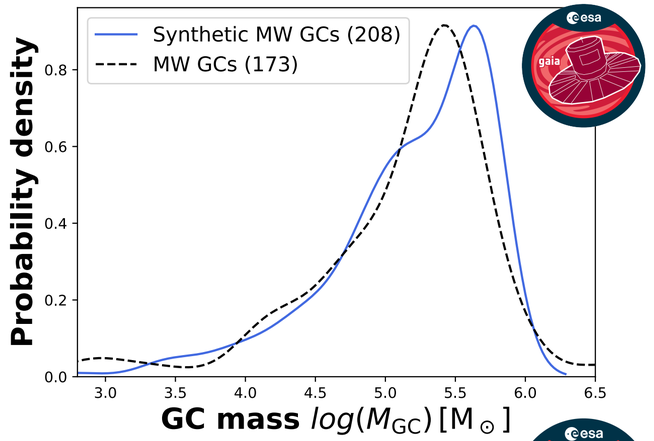
- A. Maccio, NYUAD

# Futur works [2/2]

## Concerning our post-processing model:

- Formation of globular clusters streams
- Basis function expansion methods instead of spherical potentials
- Initial conditions to match with Gaia globular clusters

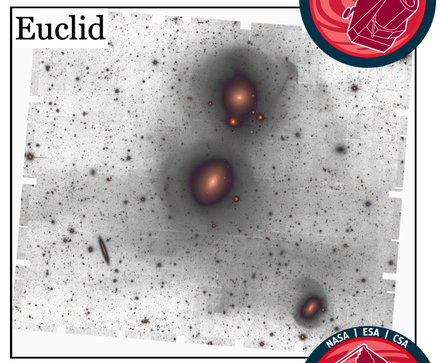



## Comparing with observational data:

- Euclid ERO data for Fornax and Perseus galaxy clusters ~ 5000 GCs in dwarf galaxies with T. Saifollahi and A. Lançon (ObAS)

*Saifollahi+25*




- ~2000 compact clumps identified at 0.7< z <10 with JWST

*Claeyssens+25*

- A. Claeyssens, CRAL

Thank you!