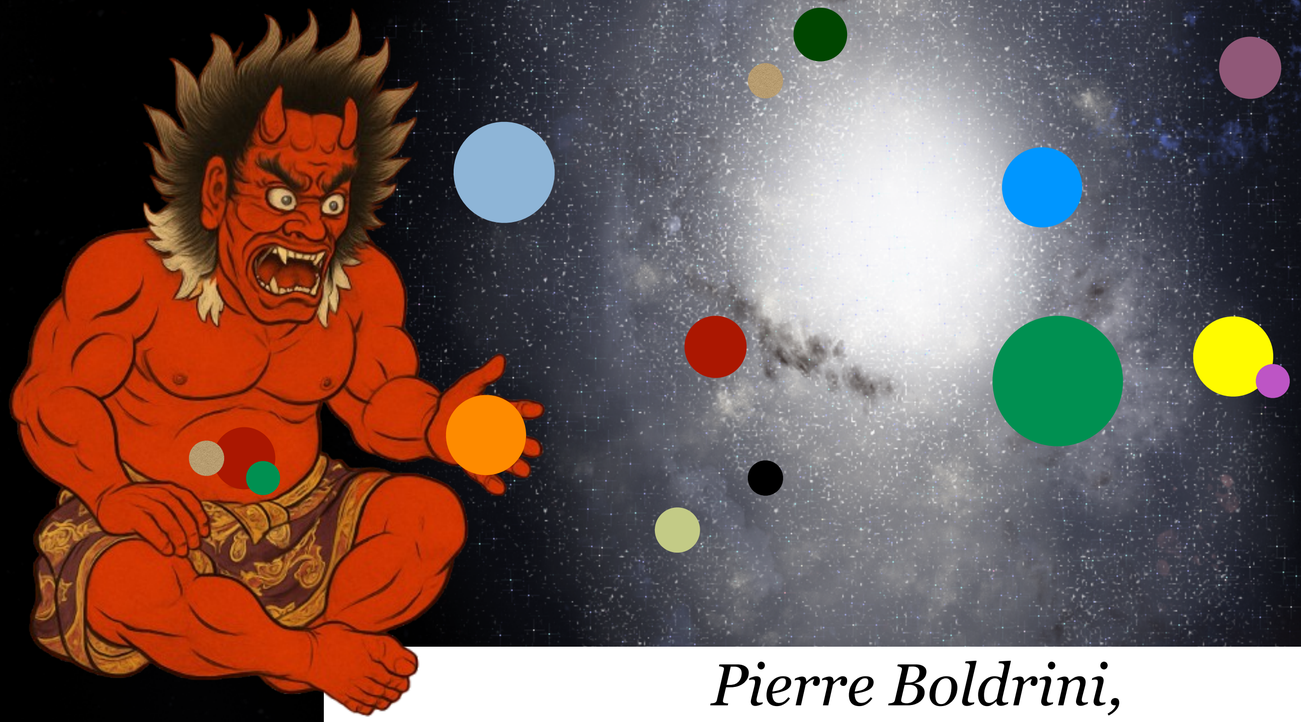
TRACING THE NATURE OF DARK MATTER WITH GLOBULAR CLUSTERS



Pierre Boldrini,
CNES fellow at LIRA

COSGAL seminar, September 2025

LIRA Observatoire de Paris | PSL

Boldrini, Di Matteo, Laporte et al. +25, submitted to A&A
Boldrini & Di Matteo +25, in prep.
Szpilfidel, Boldrini, Bovy, Di Matteo +25, in prep.

Dark matter theories [1/2]

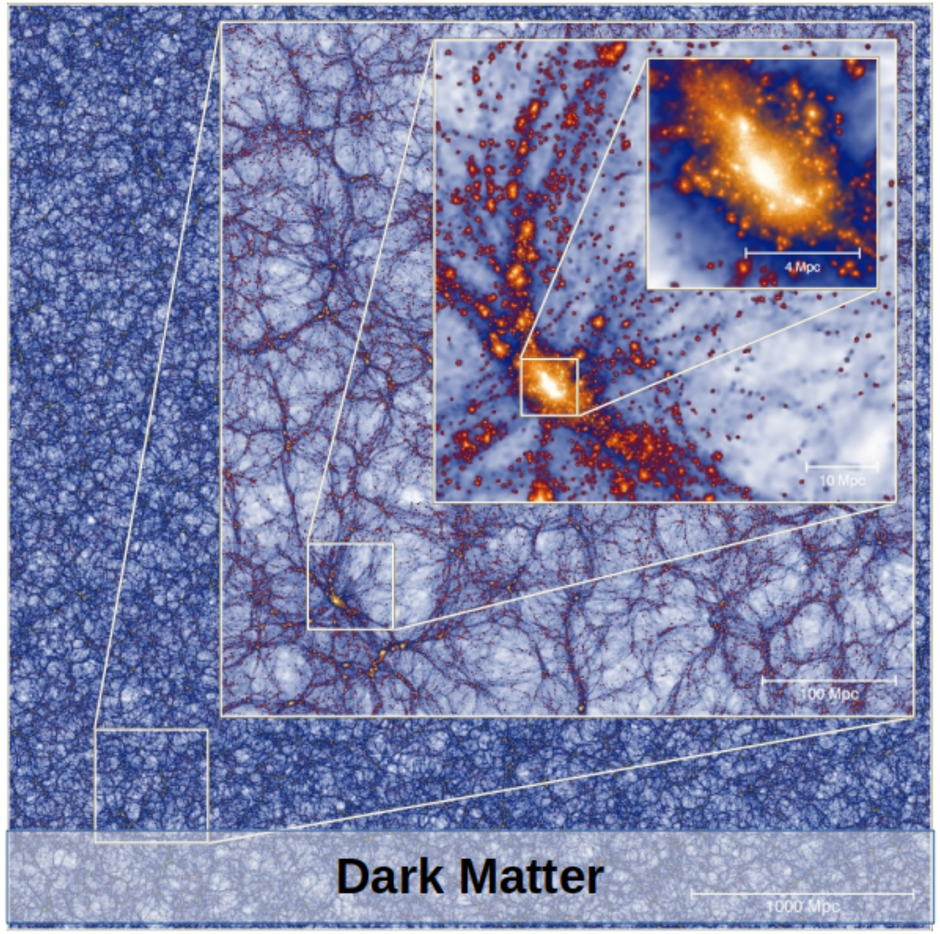
- Cosmological model —> Cold dark matter
- Axions or WIMPs have so far not been detected
- Very successful at large scales *Planck Collaboration+14*

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:

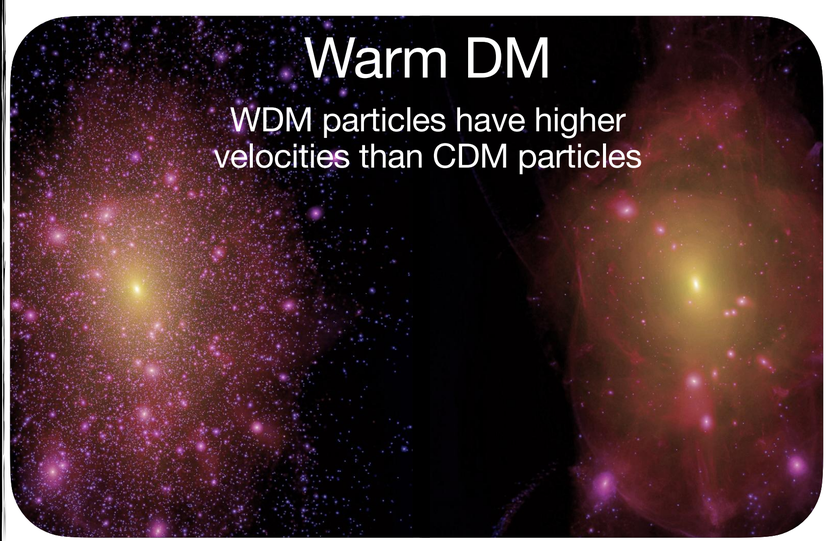
- Including baryonic processes or missing elements in the sub-grid physics
- New physics in the dark sector —> viable alternative dark matter theories

Dark matter theories [2/2]

Solution proposed to tensions:

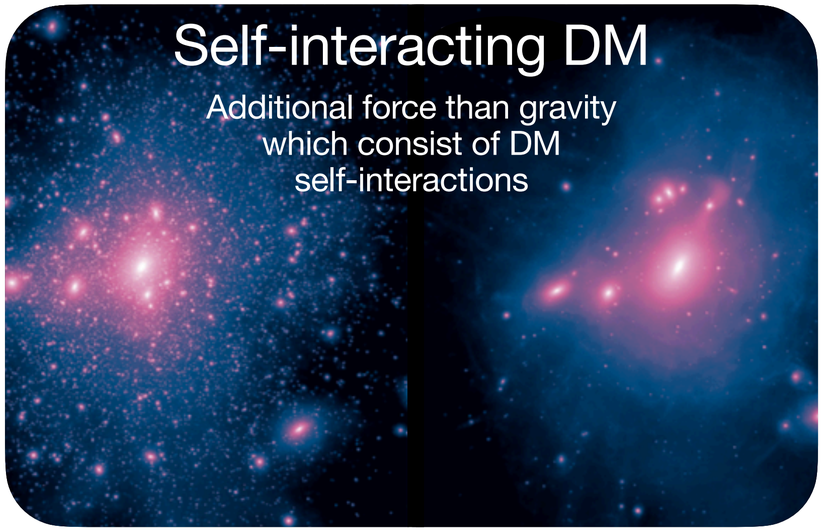
- Including baryonic processes or missing elements in the sub-grid physics
- New physics in the dark sector —> viable alternative dark matter theories

Colín et al+00



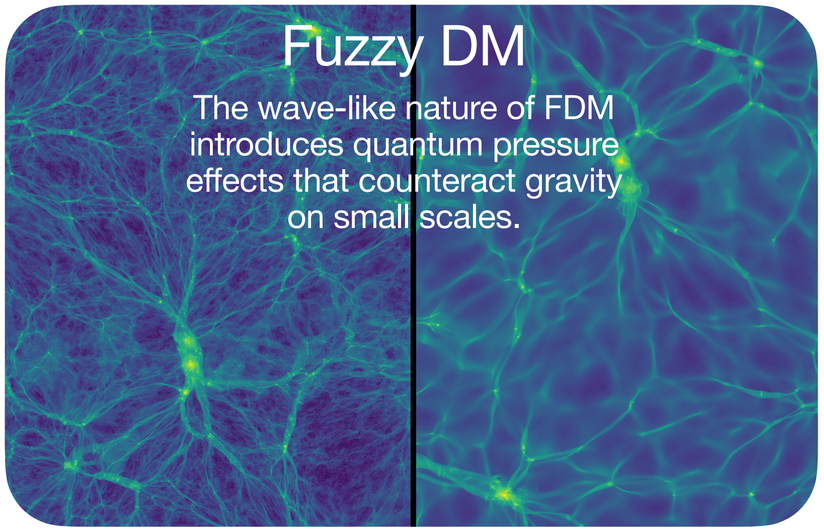
particle mass m_v (in keV)

Kochanek & White+00



cross-section σ_m (in cm^2/g)

Hu et al.+00



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

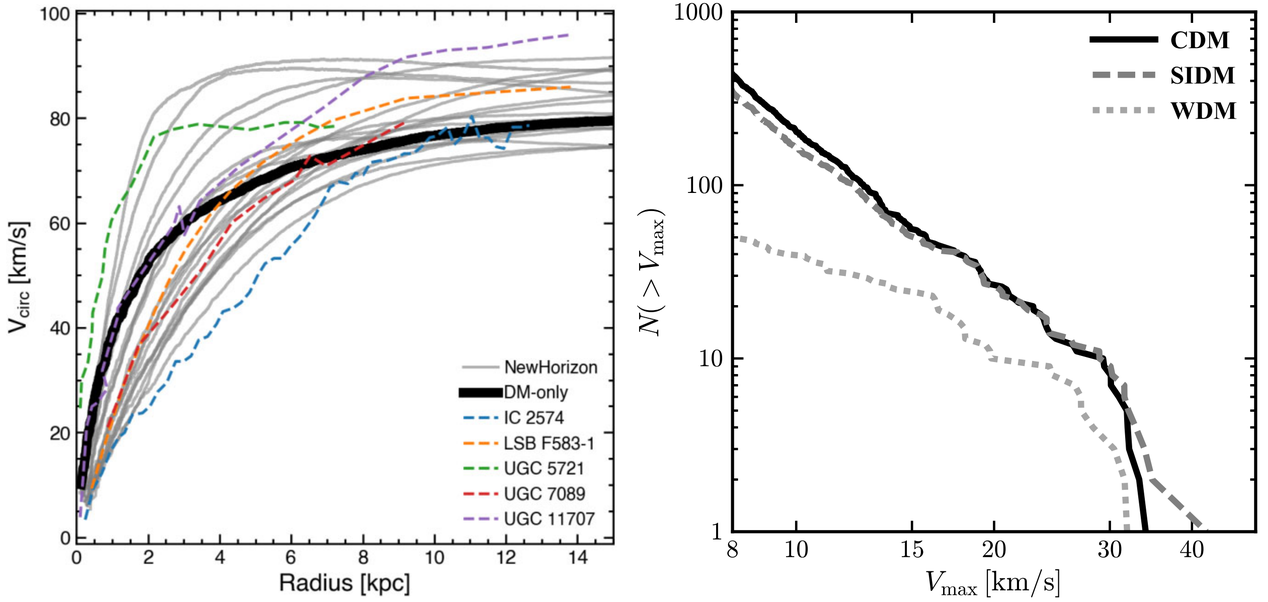
◆ J. Bovy (GALPY PI), University of Toronto

Constraining the dark matter nature

Classical methods:

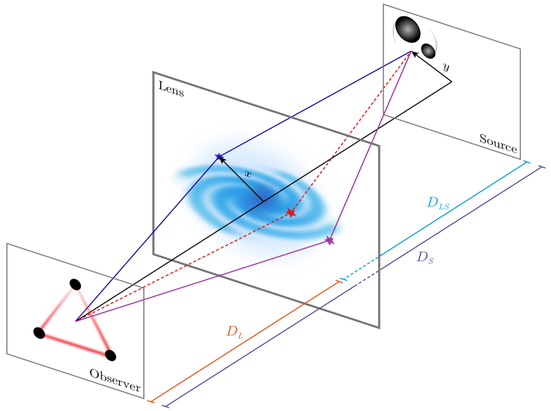
- Rotation curves of galaxies
- Analyzing gravitational lenses
- Studying the dynamics of small satellite galaxies around large galaxies

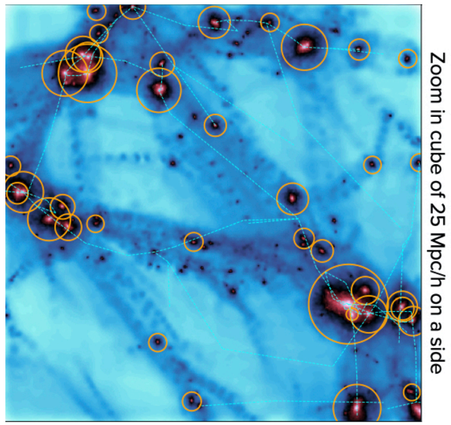
Jackson+25, Bullock & Boylan-Kolchin+17



New DM probes:

- Gravitational wave lensing *Singh+25*
- Cosmic web via filament connectivity *Boldrini & Laigle+25*
- Globular cluster dynamics *Reina-Campos+22a,b*





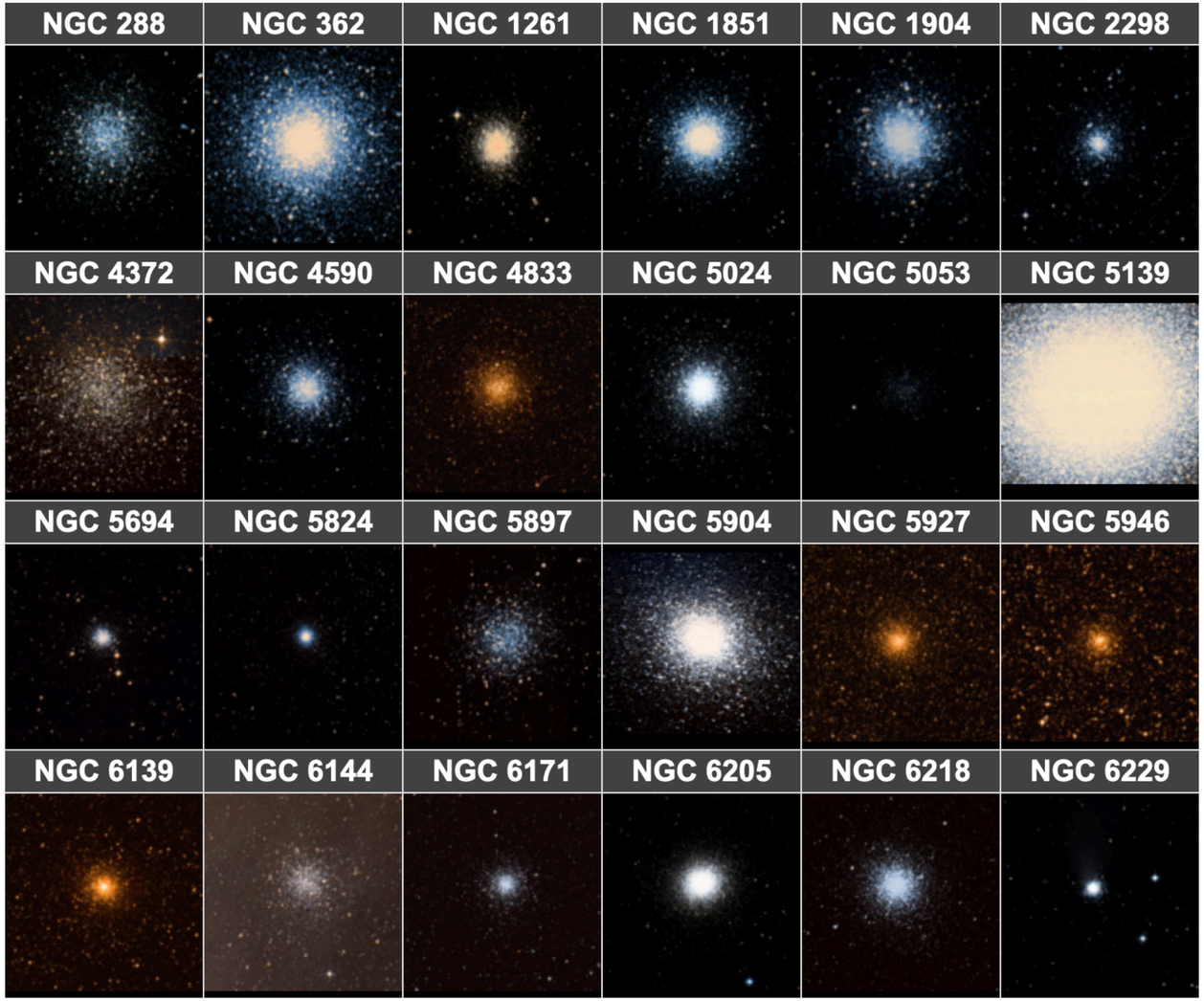
GCs as DM tracers?

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

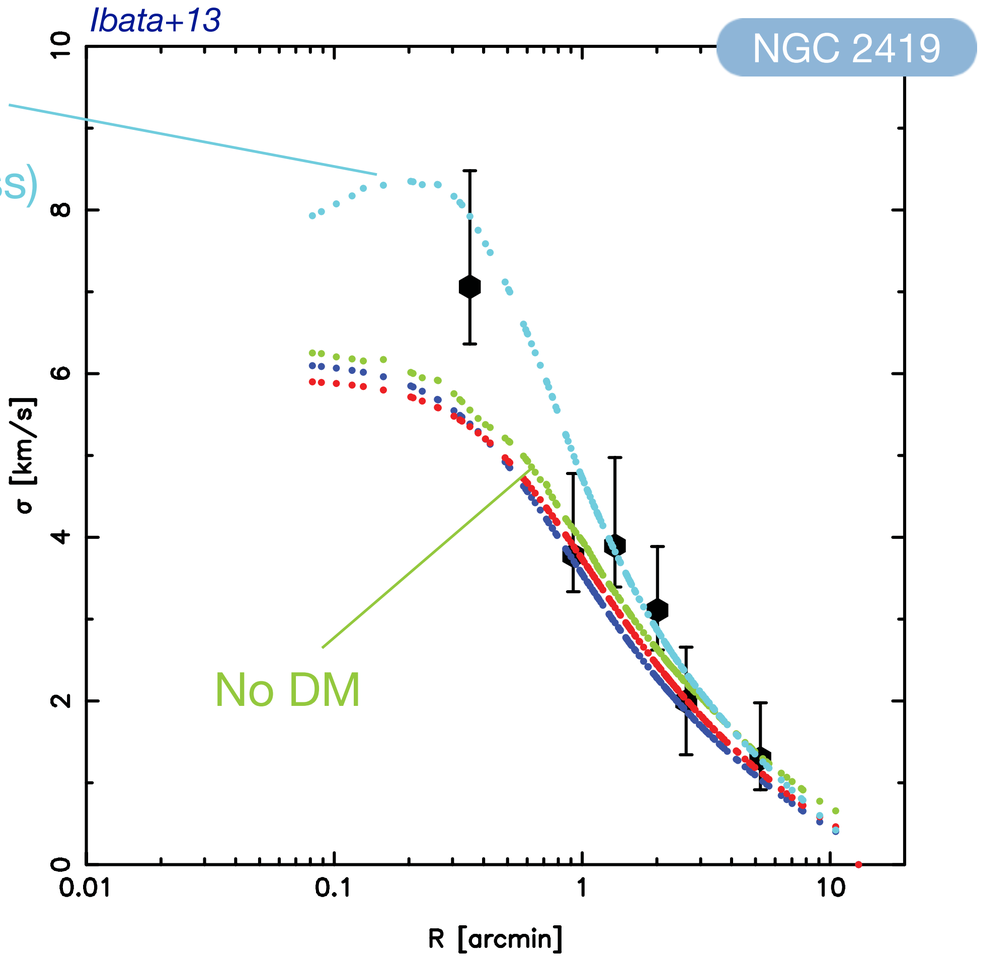


Baumgardt GC database

Relics of galaxy formation and evolution

Globular clusters as DM tracers? [3/5]

With a DM halo
of 5×10^4 $M_\odot$
(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

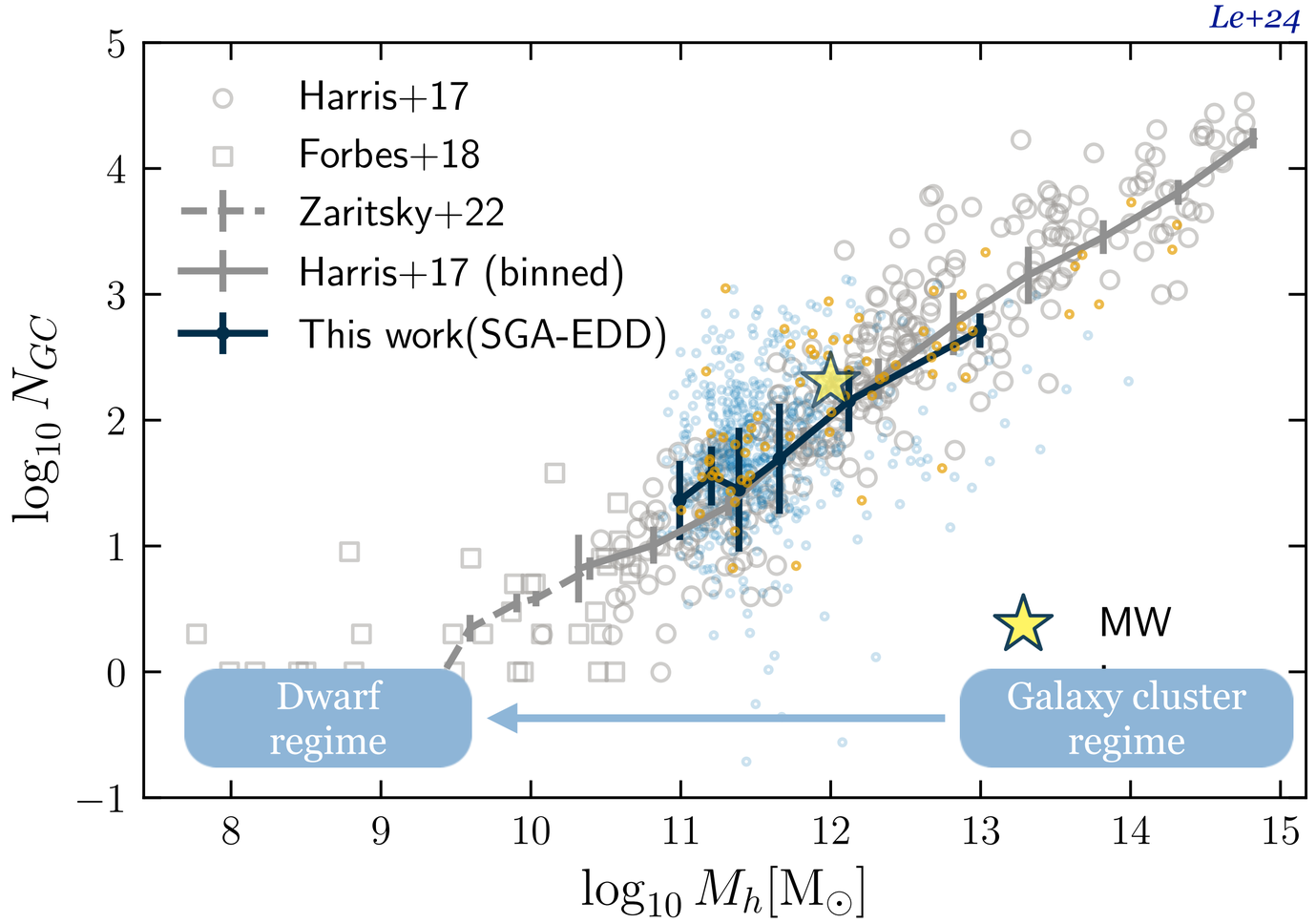
Globular clusters as DM tracers? [1/5]

- More numerous than satellite galaxies

(**200 GCs** vs **20 satellites** in MW-likes galaxies)

- Found in virtually all types of galaxies across a

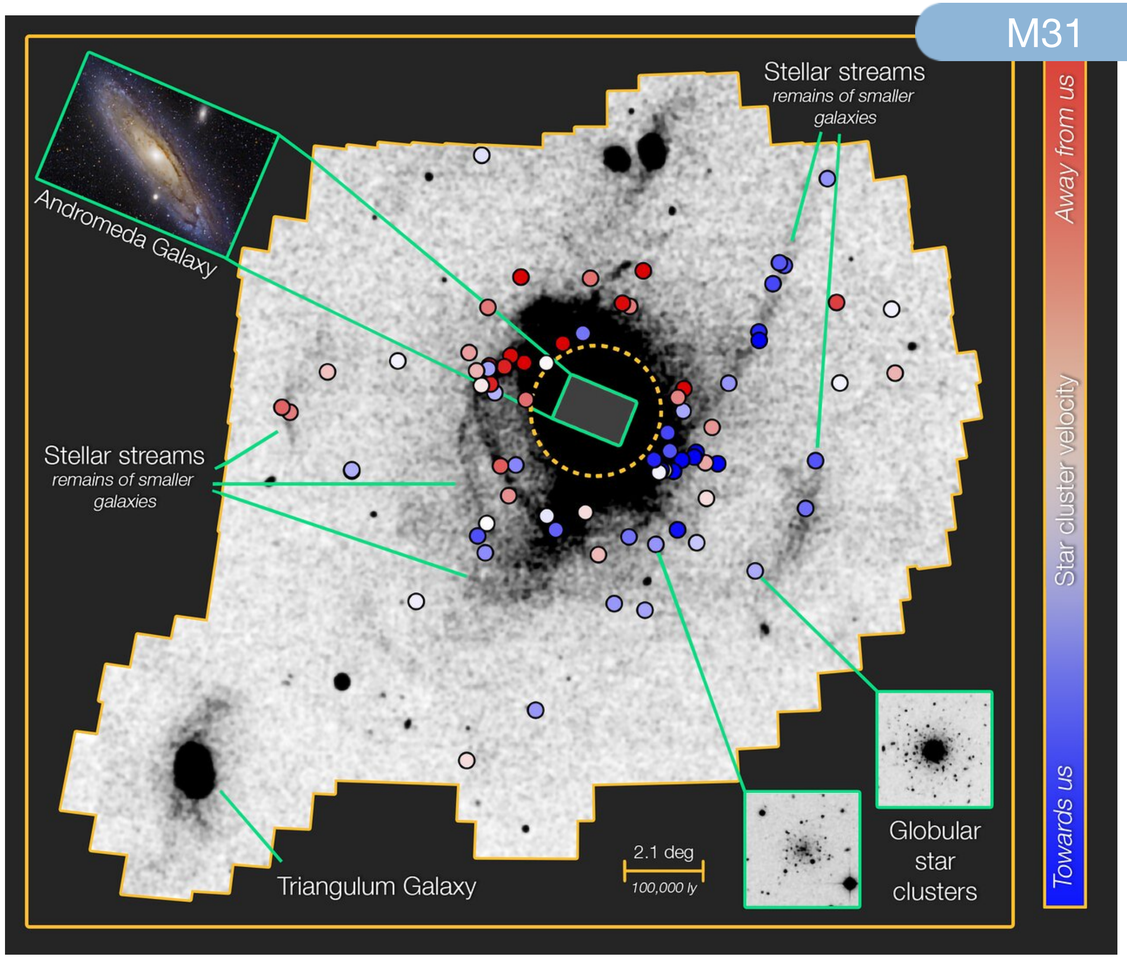
  wide range of masses



Exist in almost all systems from galaxy clusters down to dwarfs

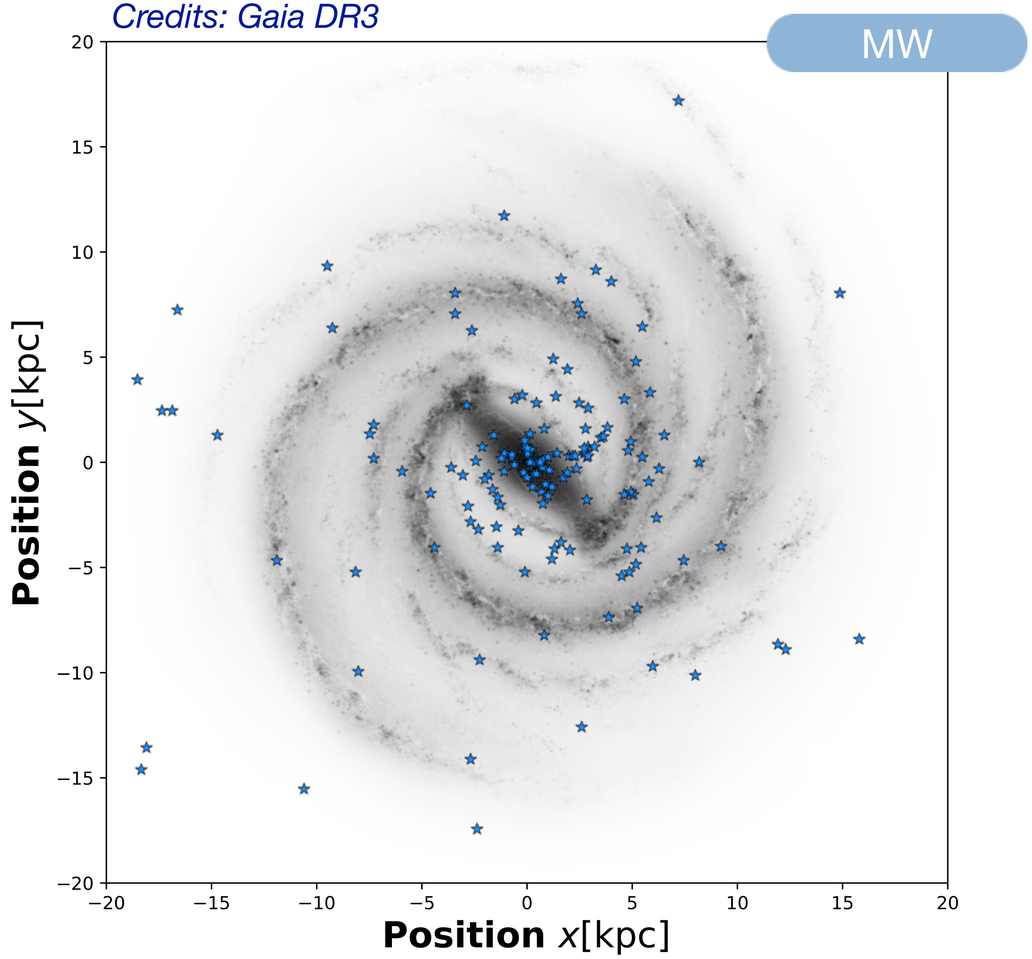
Globular clusters as DM tracers? [2/5]

- Span a wide range of galactocentric distances



Credits: Nature, PAndAS data

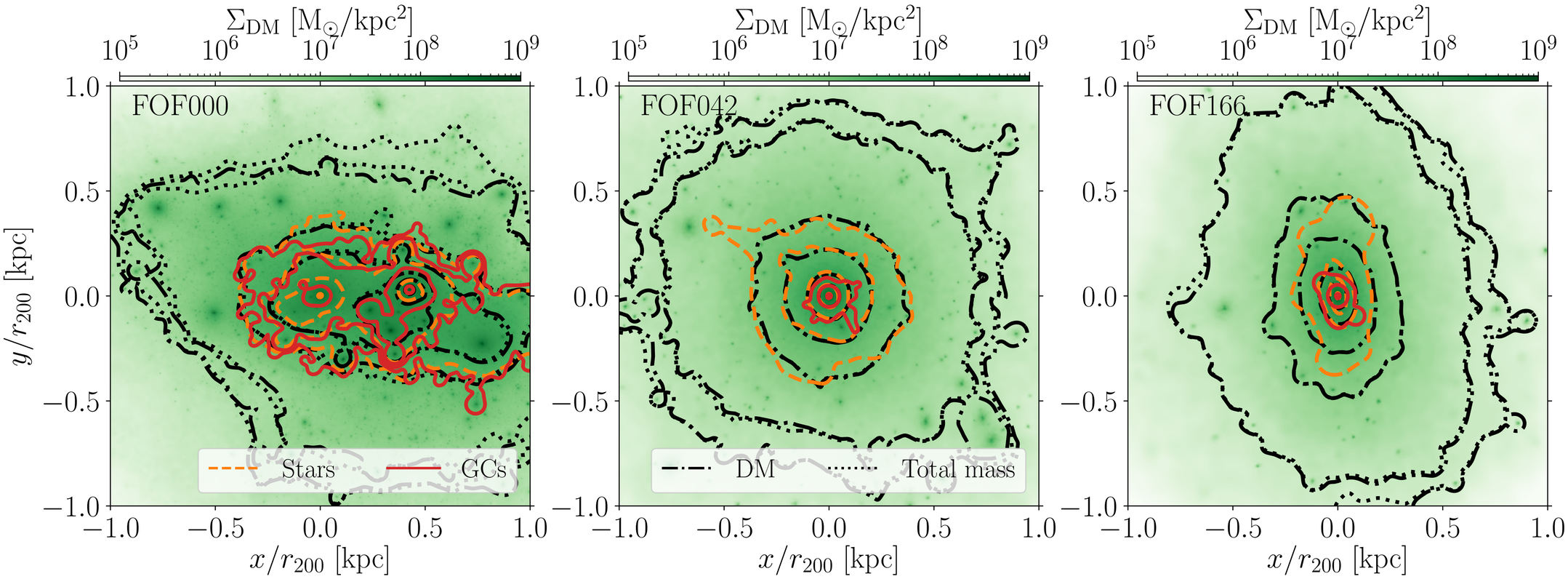
Credits: Gaia DR3



Galactic & extragalactic GCs

Globular clusters as DM tracers? [4/5]

- Already been used to explore the structural properties of DM halos in galaxies
- In most of halos, the structures identified in the GC populations agree with those in the DM

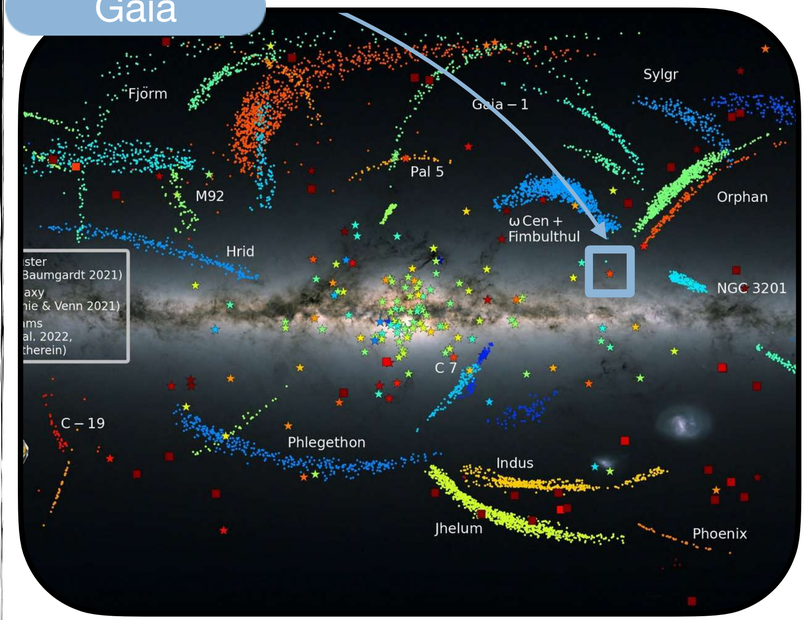


Reina-Campos+22

Why globular clusters? [2/2]

Gaia

Malhan+22



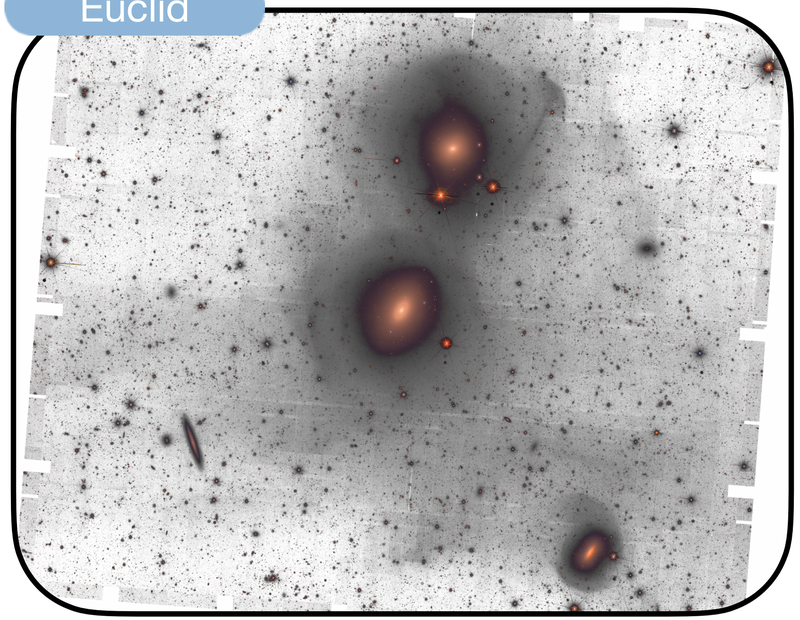
171 Milky-Way GCs

6D phase space

Mass, metallicity and size

Euclid

Urbano+25



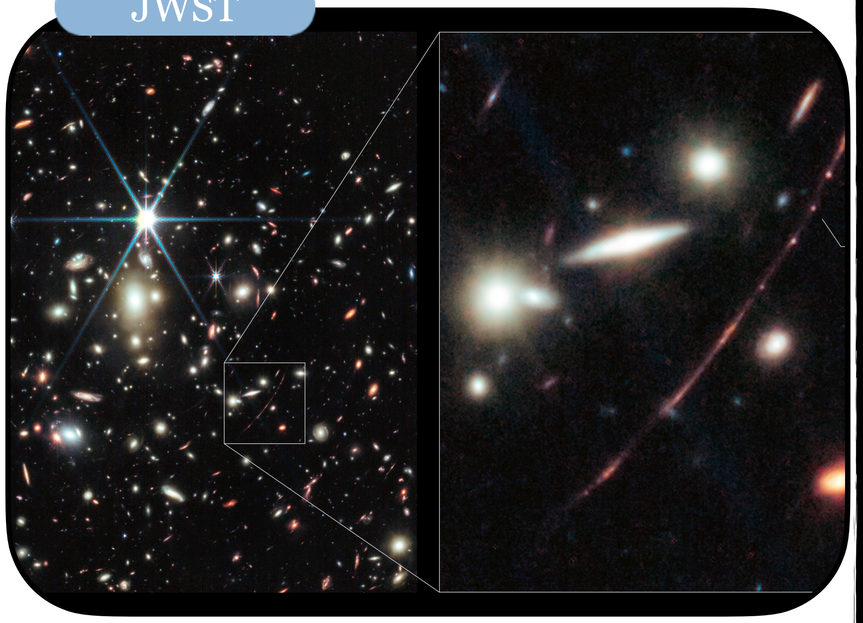
Half-million extragalactic GCs

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]

- More numerous than satellite galaxies (200 GCs versus 20 satellites in MW-likes 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	
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*	

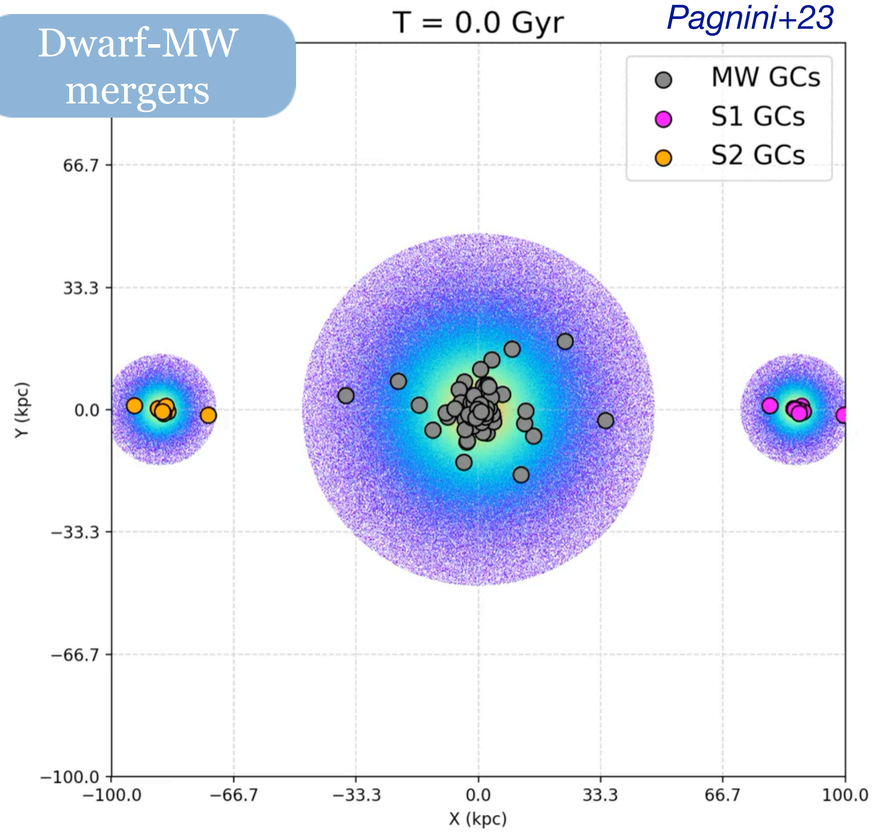
GCs will be sensitive to DM theory properties

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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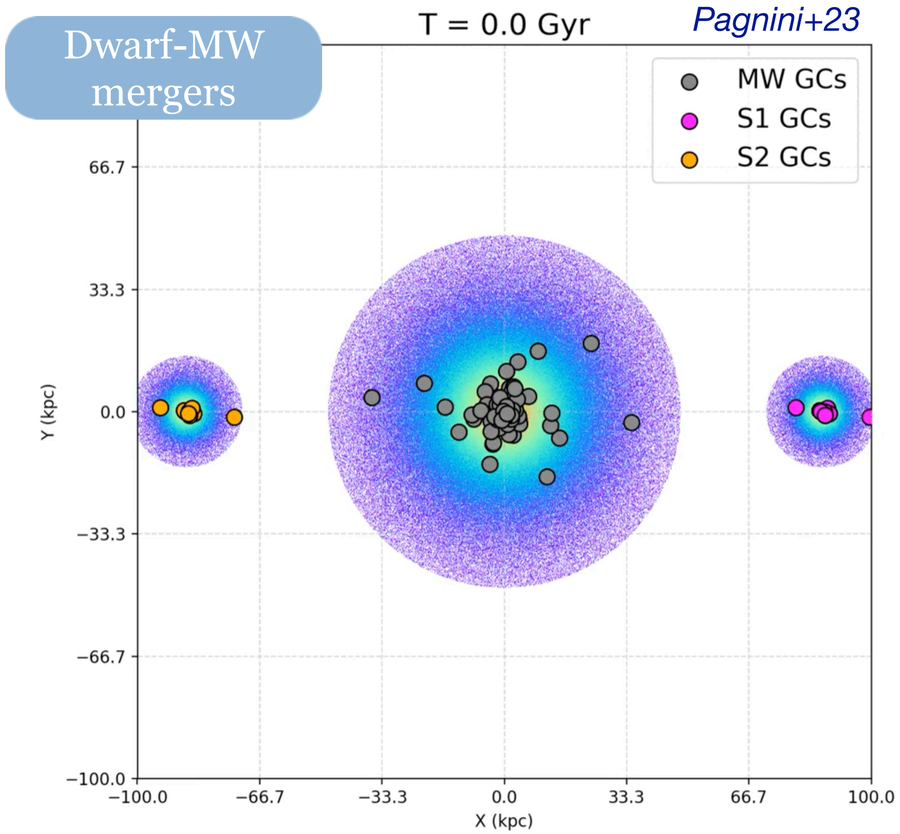
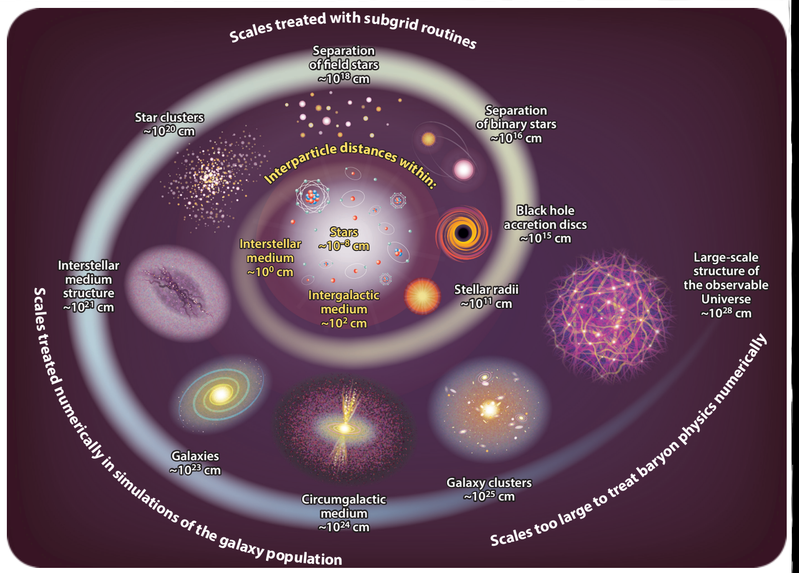


Pagnini+23



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)

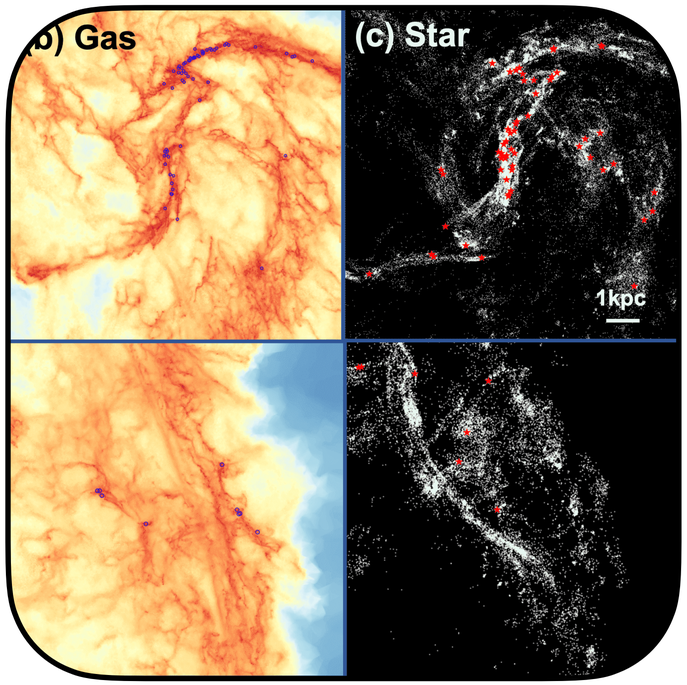
Resolution requirements make this presently impossible to do in direct calculations that track the formation of individual stars

Current limitations of simulations [1/3]

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

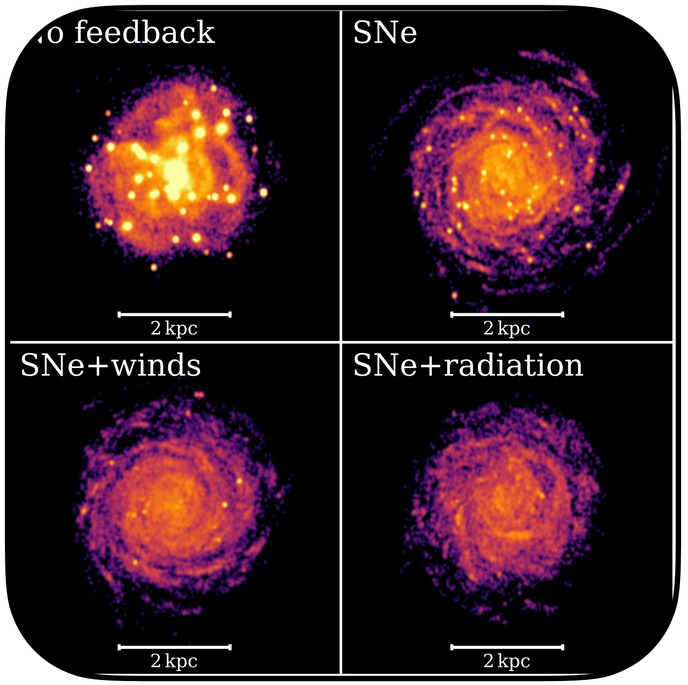
- Idealized high-resolution galaxy simulations *Lahen+20, Li+22, Andersson+24, Deng+24, …*

Li+22



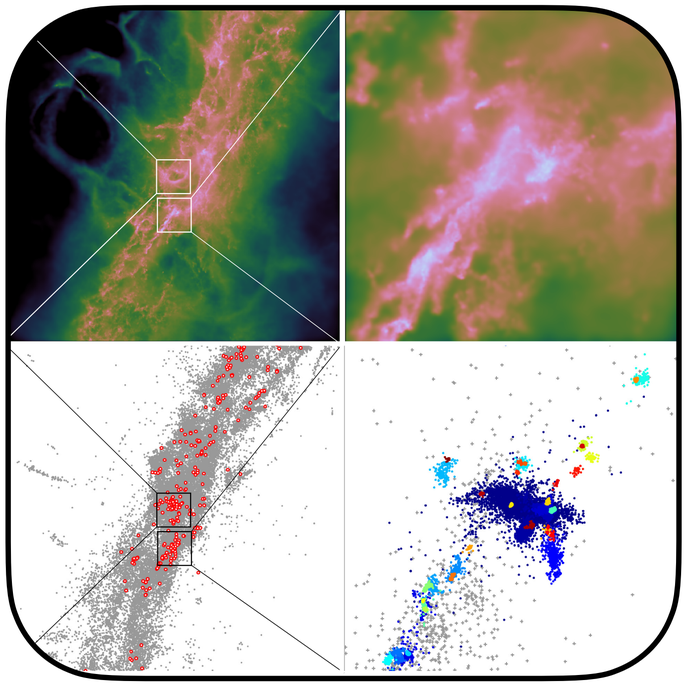
2 MWs over 1 Gyr, ~ 3 pc

Andersson+24



1 dwarf over 1 Gyr, ~ 3 pc

Lahen+20



2 dwarfs over 0.3 Gyr, ~ 0.1 pc

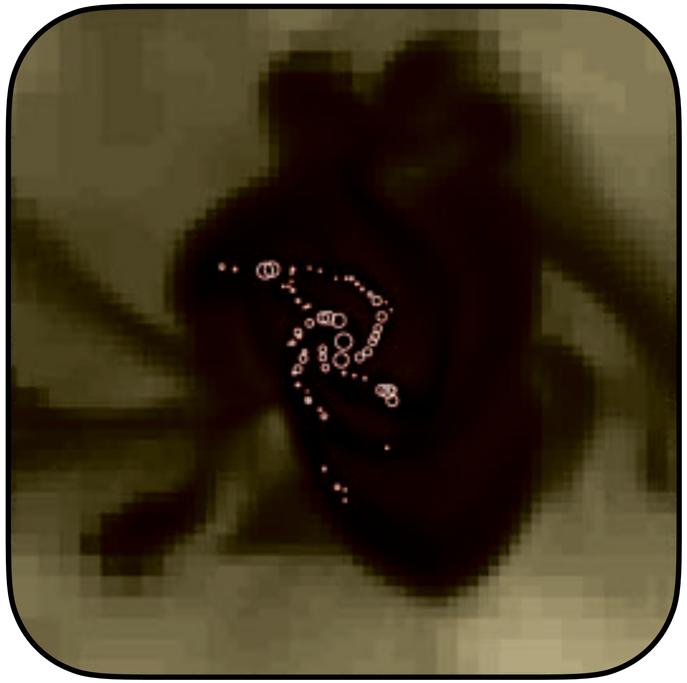
Modeling only few galaxies and limited in their evolution due to huge computational costs

Current limitations of simulations [2/3]

Main strategies:

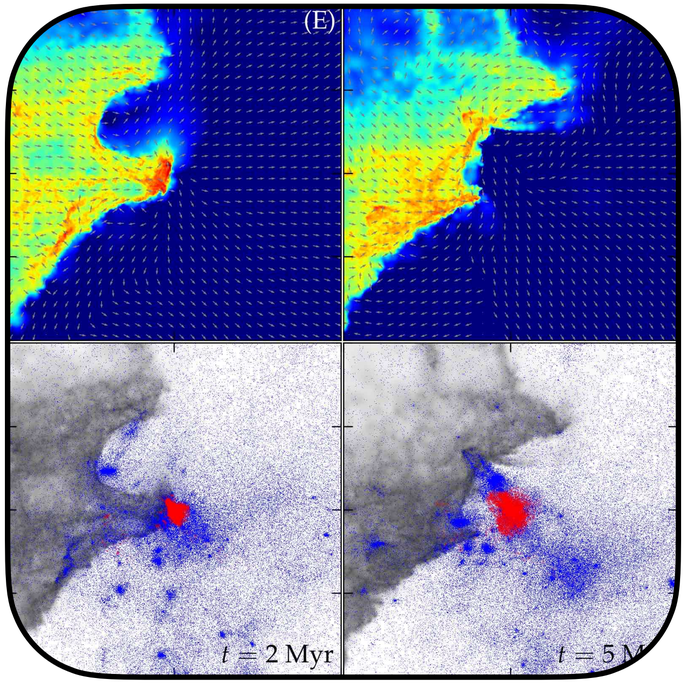
- High-resolution cosmological simulations *Kravtsov +05, Li +17, Kim +18, Ma +20, Meng +22, Sameie +22, …*

Kravtsov+05



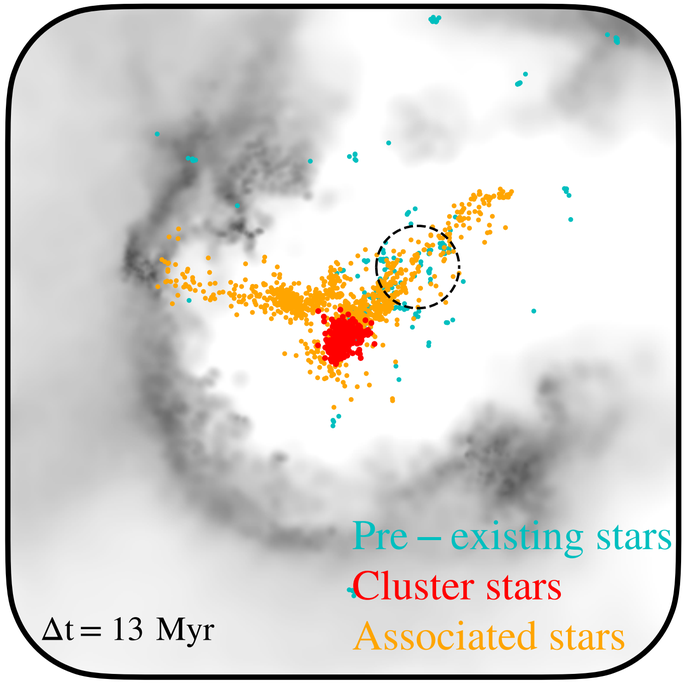
MW galaxy —> z=3, ~ 80 pc

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:

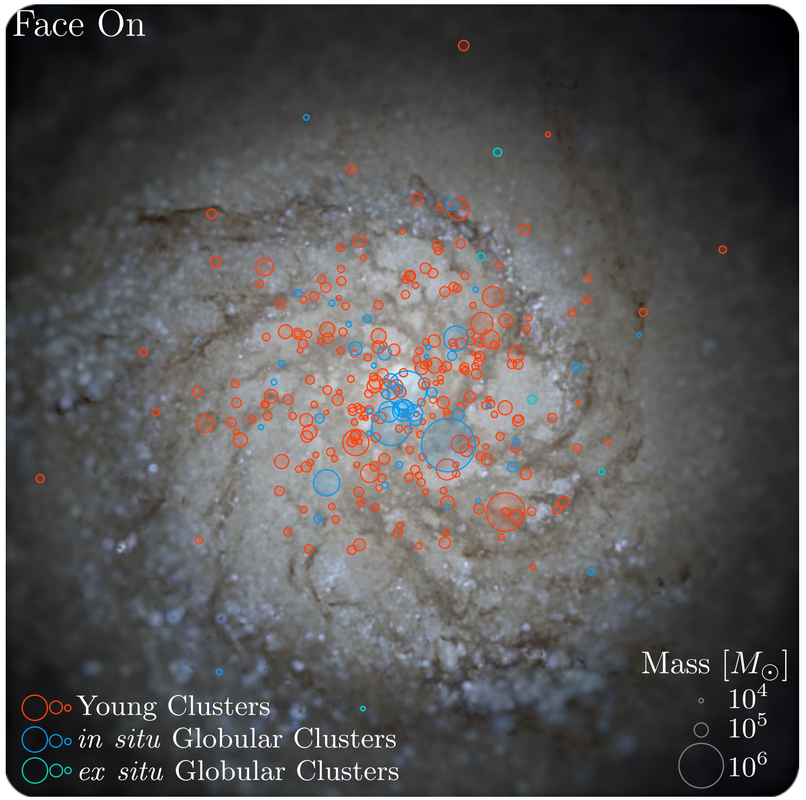
- **Tagging methods in post-treatment of simulations such as** *Illustris TNG-50, FIRE, EAGLE, AURIGA, …*

- 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*

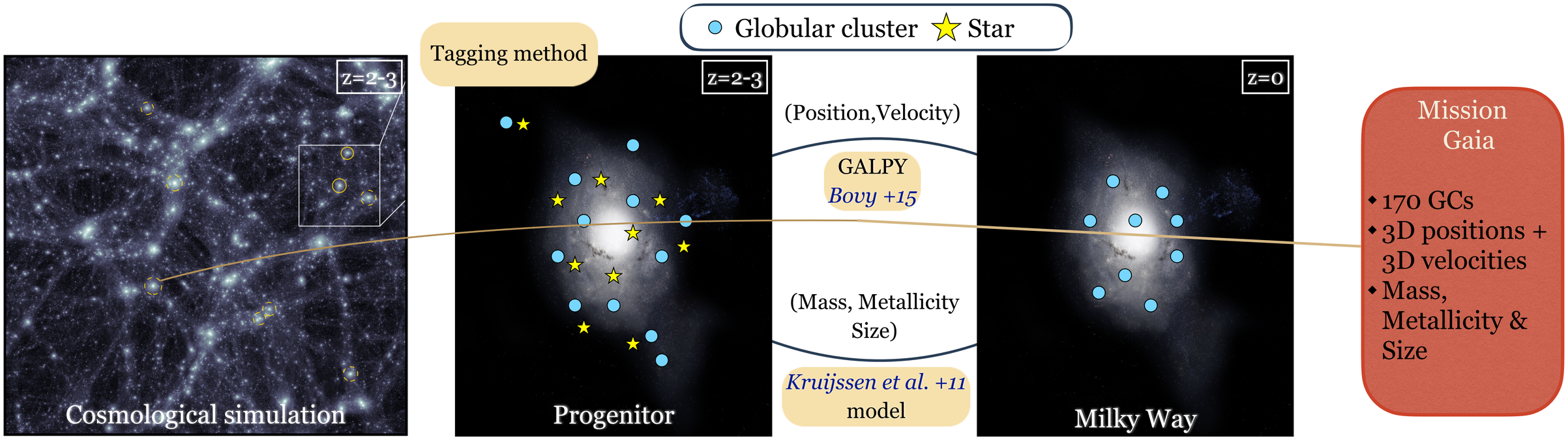
- Defining GC candidates as all star particles older than 10 Gyr *Halbesma+20*



Rodriguez+23

Computationally inexpensive with large statistics and several environments

Our approach [1/2]

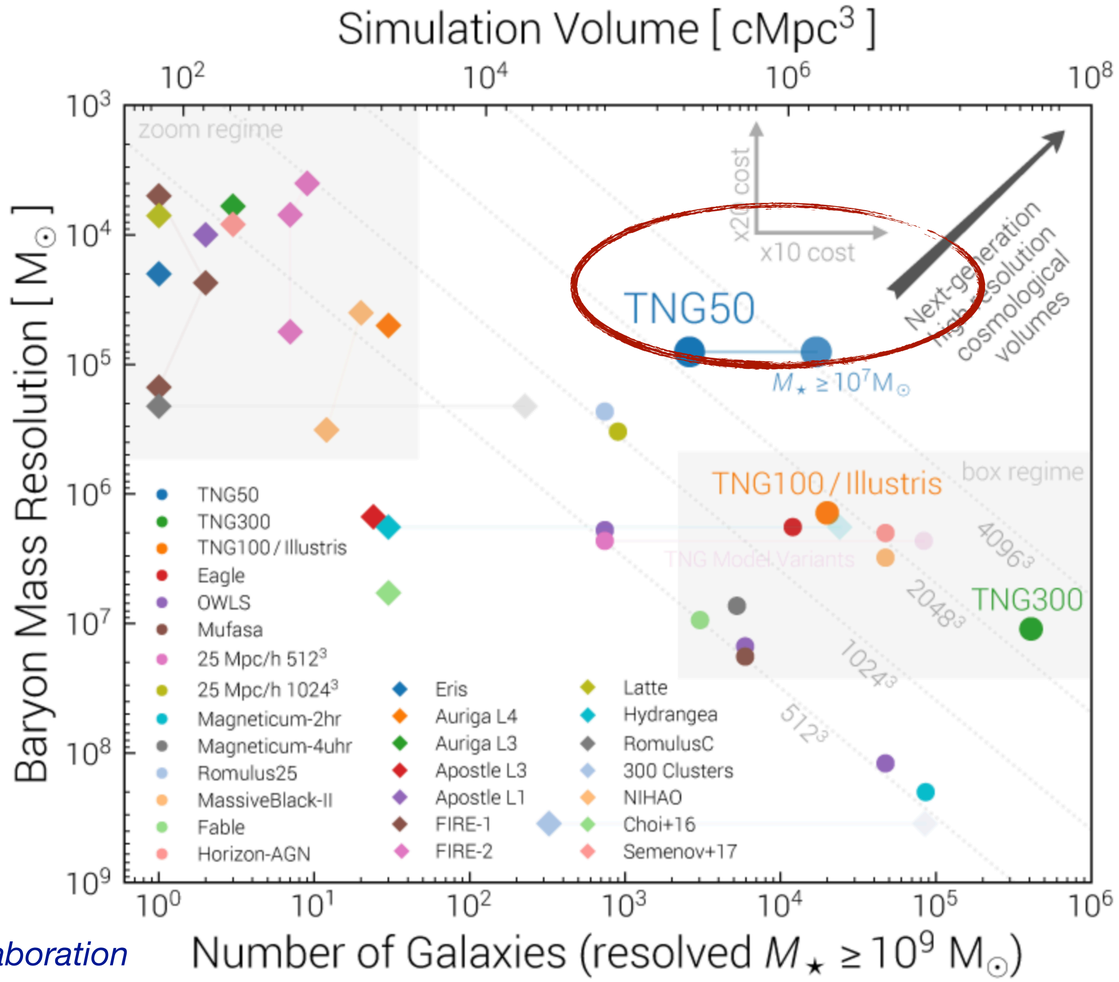


- Using existing cosmological simulations
- Computationally inexpensive
- Statistics

Flexible semi-analytical model in post-processing of simulations

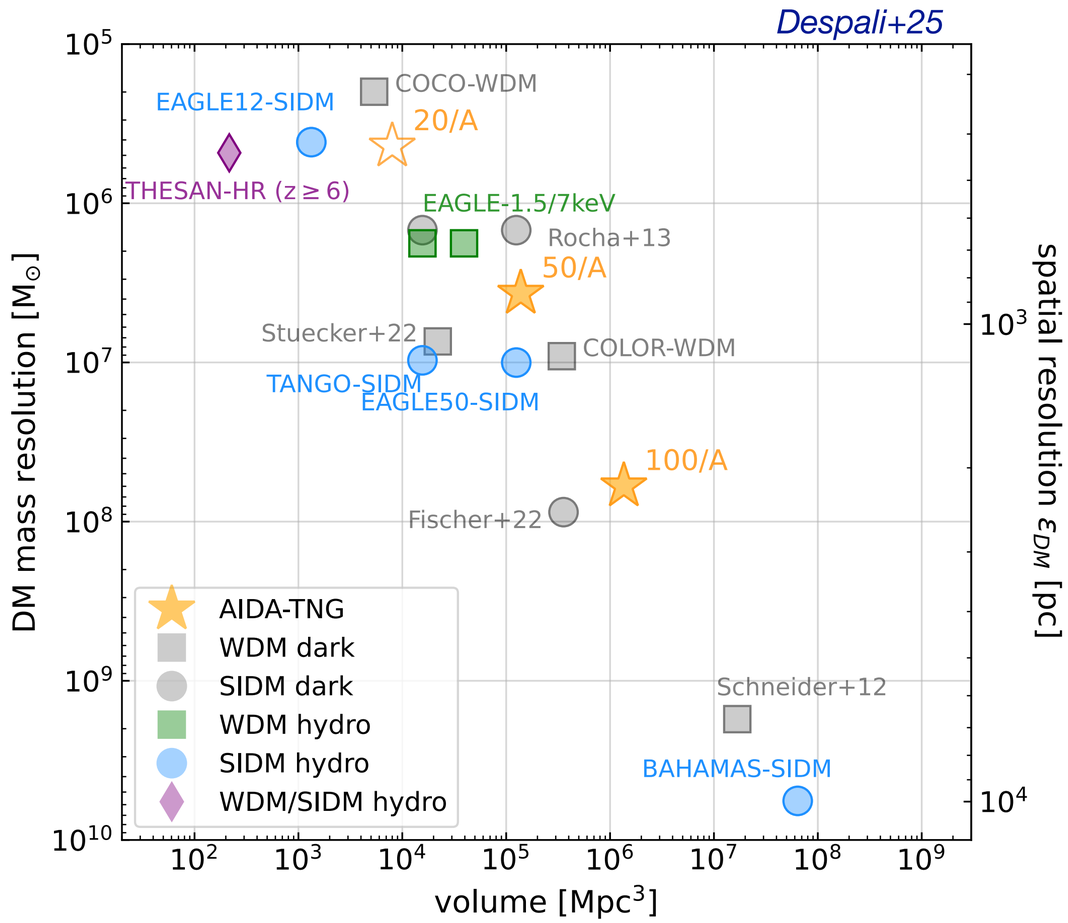
Our approach [2/2]

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

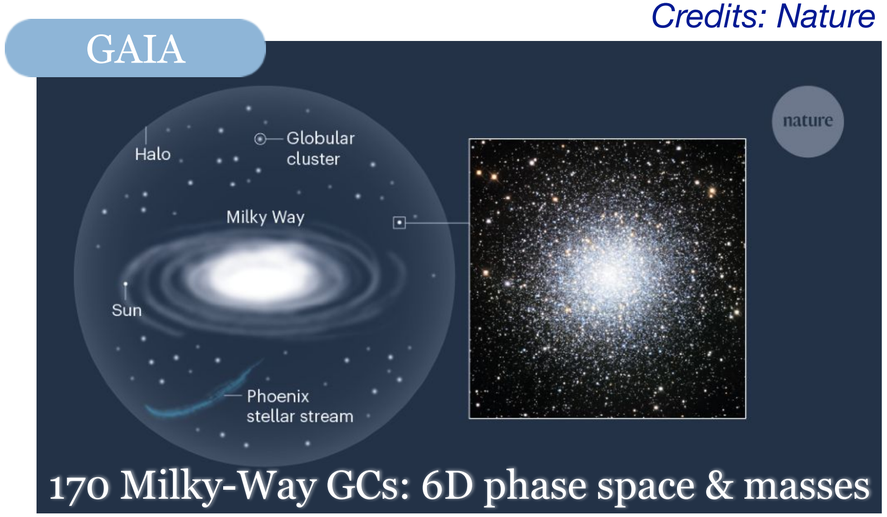
galpy

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

arXiv:2506.13254

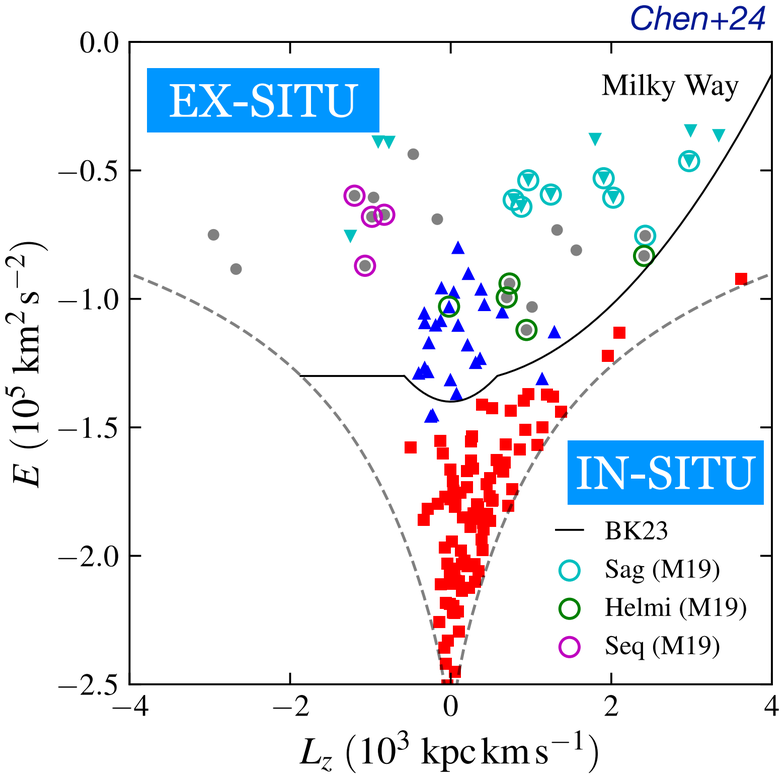
Origin of Galactic globular clusters: in-situ or ex-situ?

Credits: Nature



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

Chen+24



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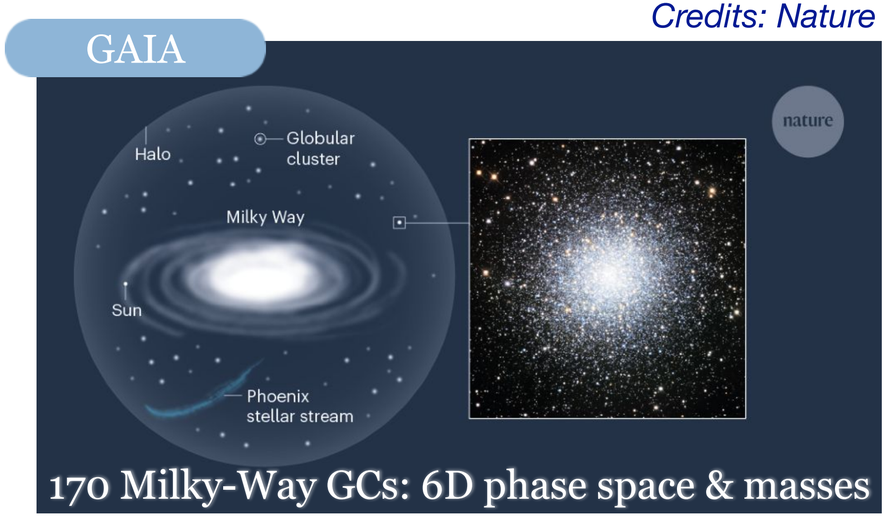

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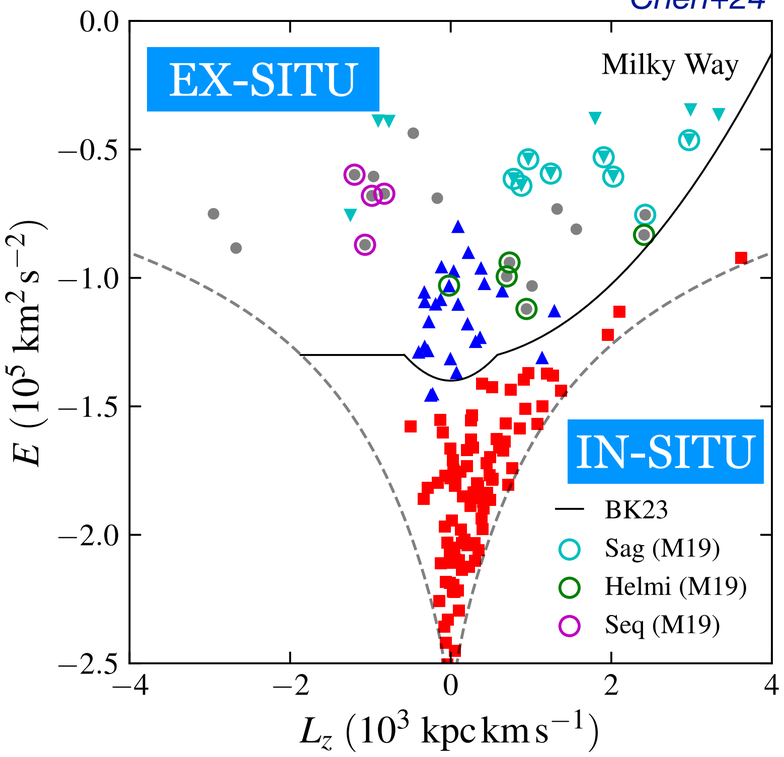
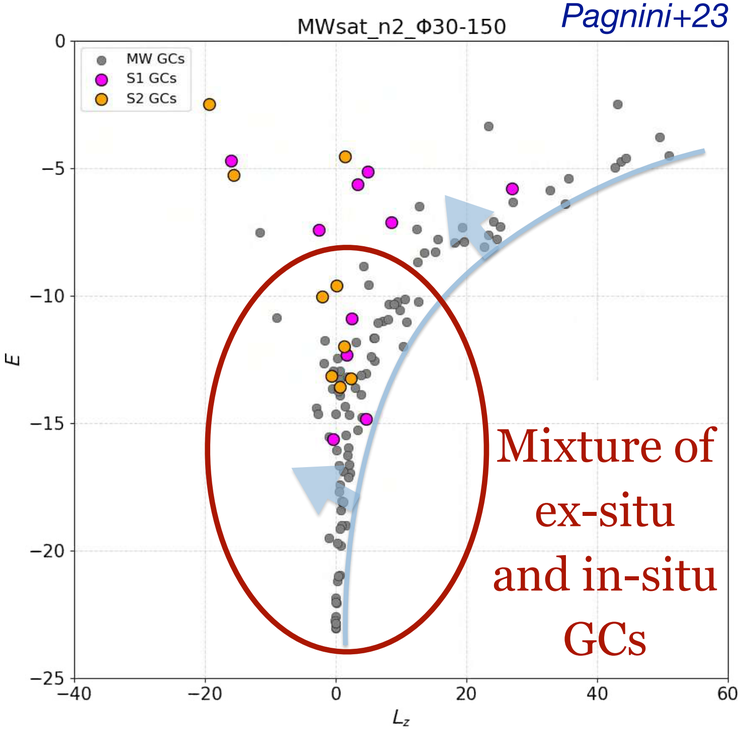


Pagnini+23

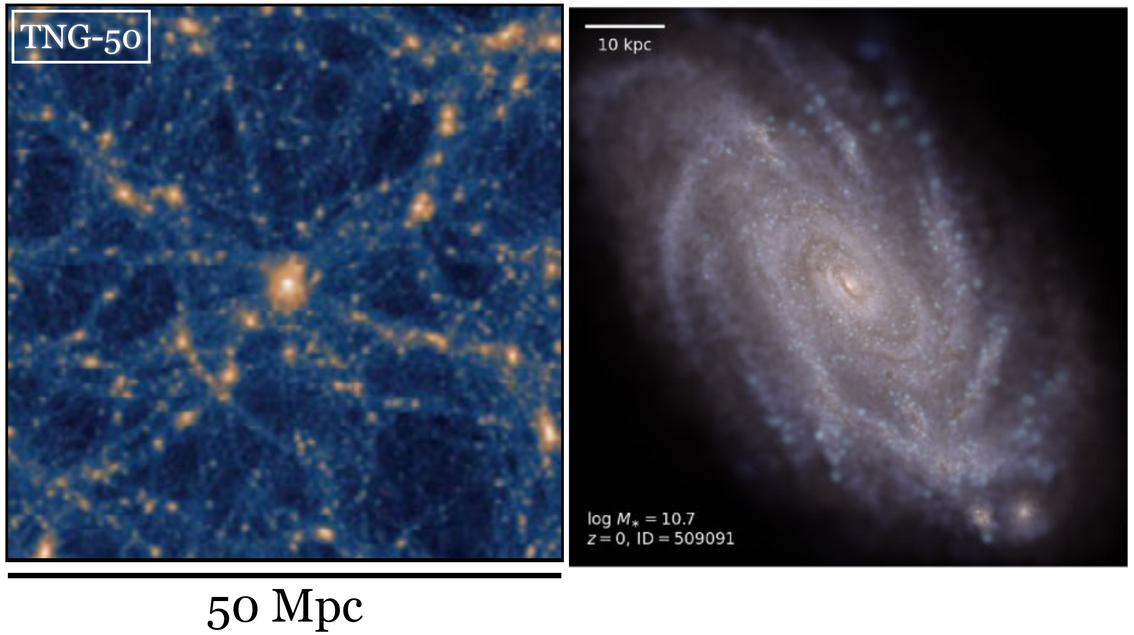


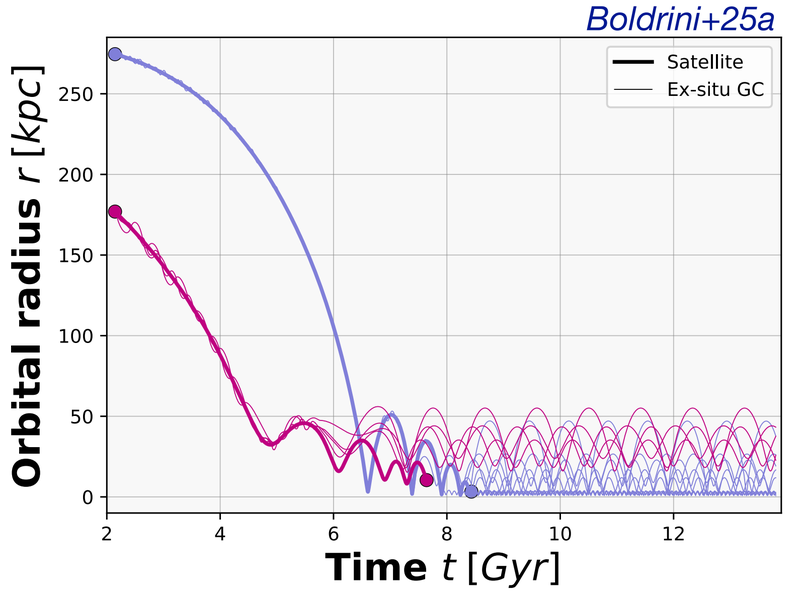
Previous studies found a clear separation between the two GC populations and it is based only on quantities at z=0!

What is missing?

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

Globular cluster in TNG MW-like galaxies: methods





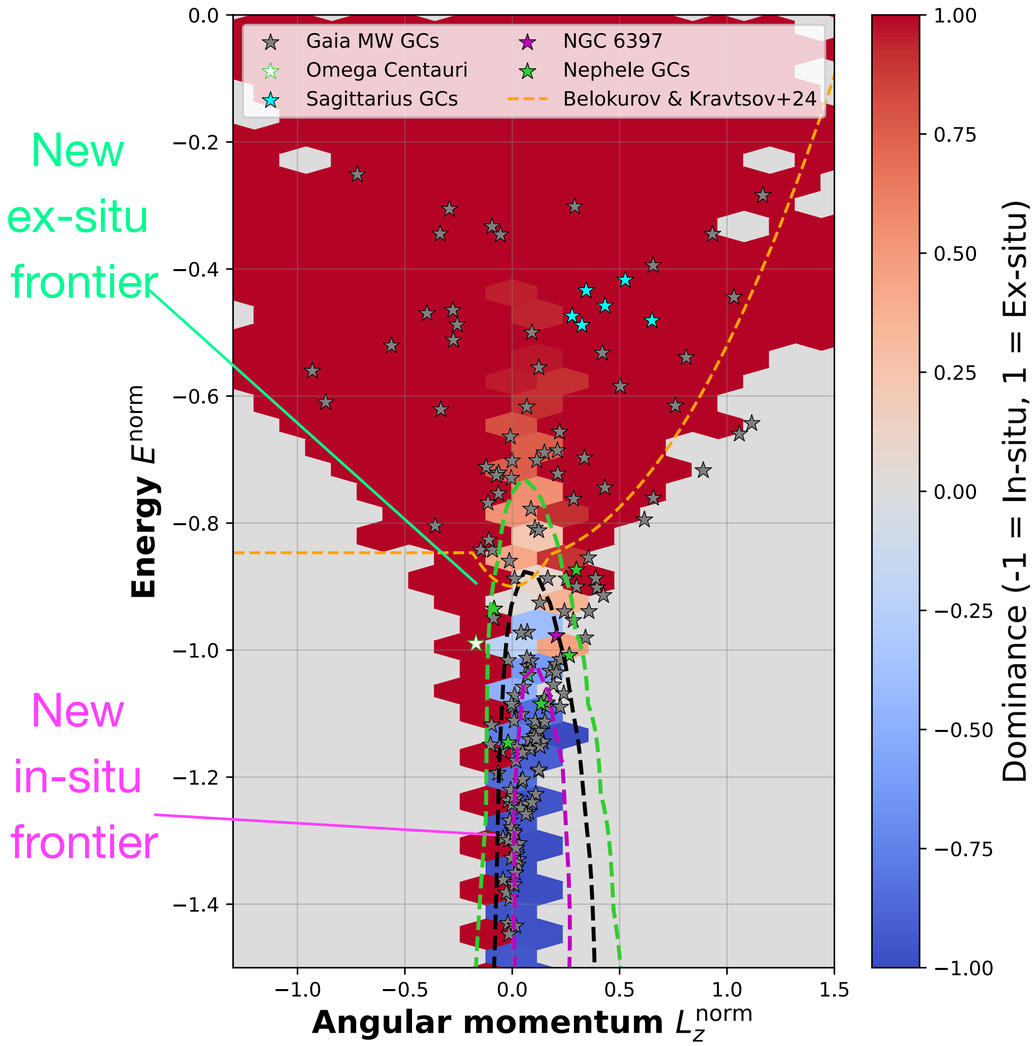
- Galactic spherical potentials are extracted from TNG50 cosmological simulations containing **198** Milky Way-like galaxies.
- GCs are tagged between z=3 and 2 according to Burkert & Forbes+20 relation
- Combined with orbit integrations with GALPY of **18,000** globular clusters from redshift z = 3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

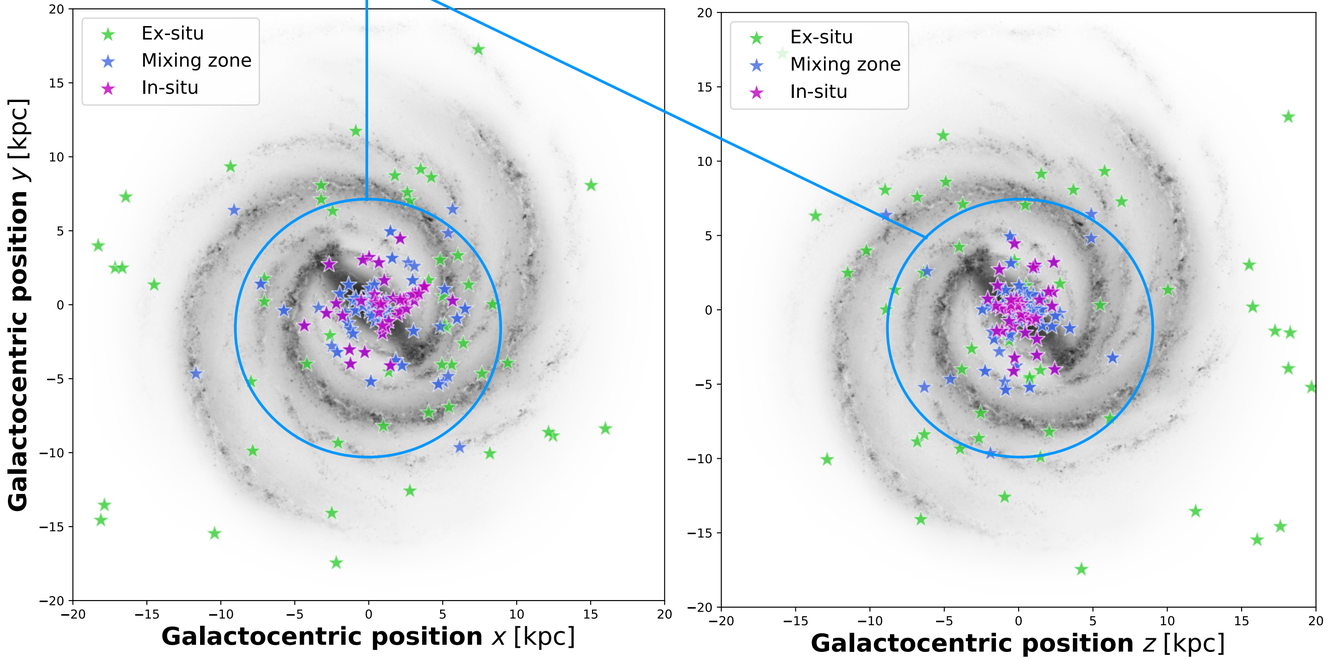
Key results:

Boldrini+25a



Mixing zone

Boldrini+25a

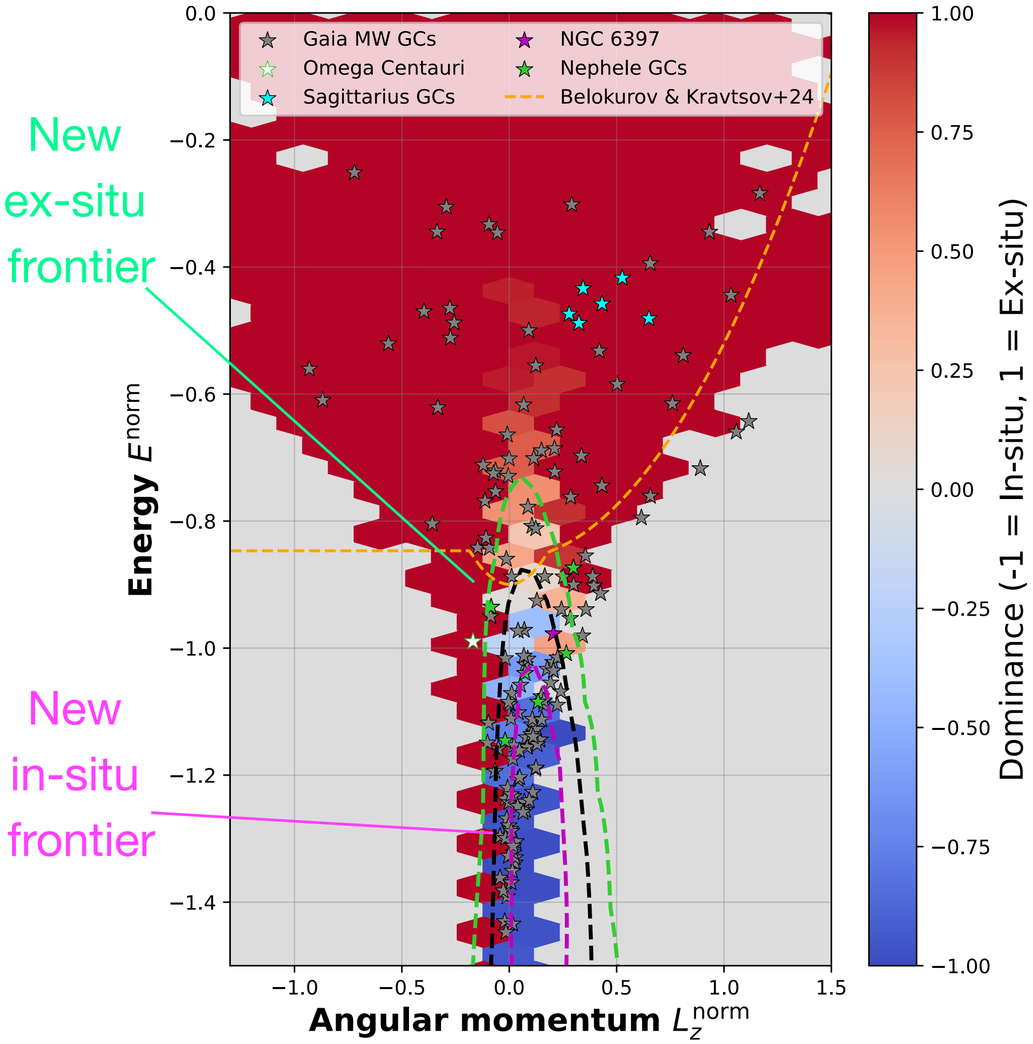


Mixture of the two GC populations —> Challenges previous separation methods

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

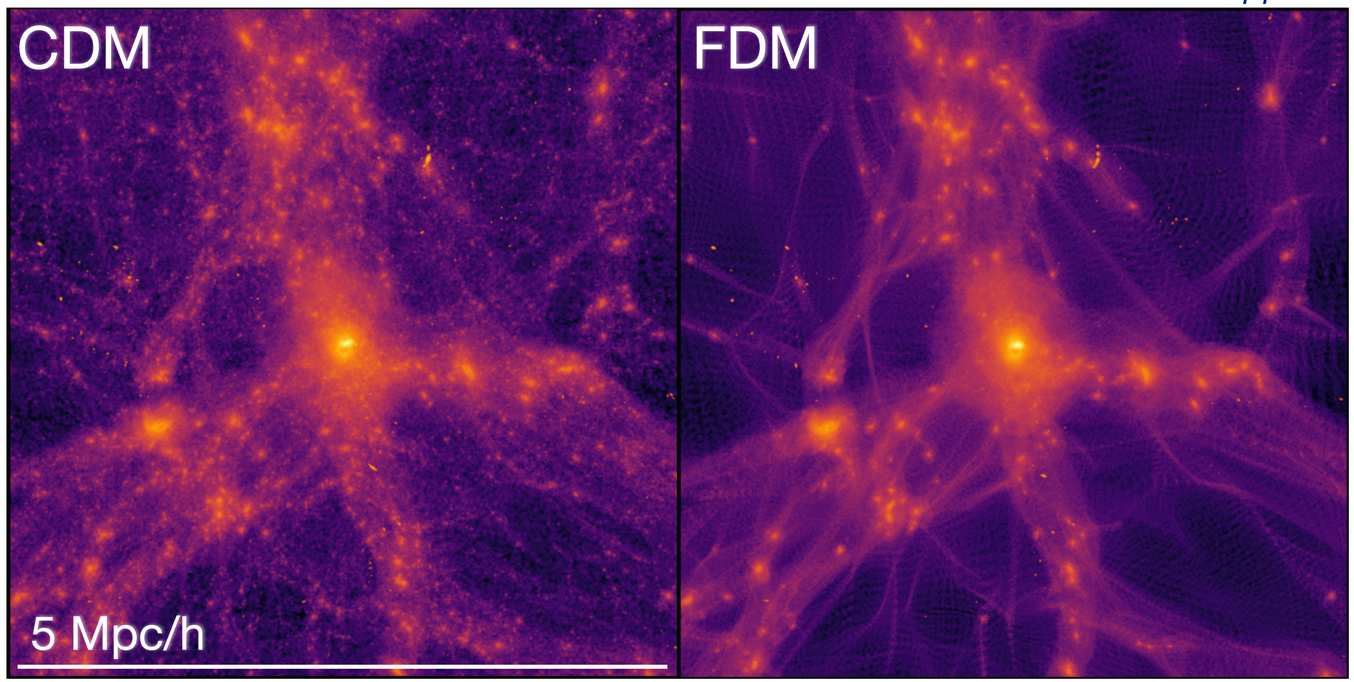
galpy

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 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 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

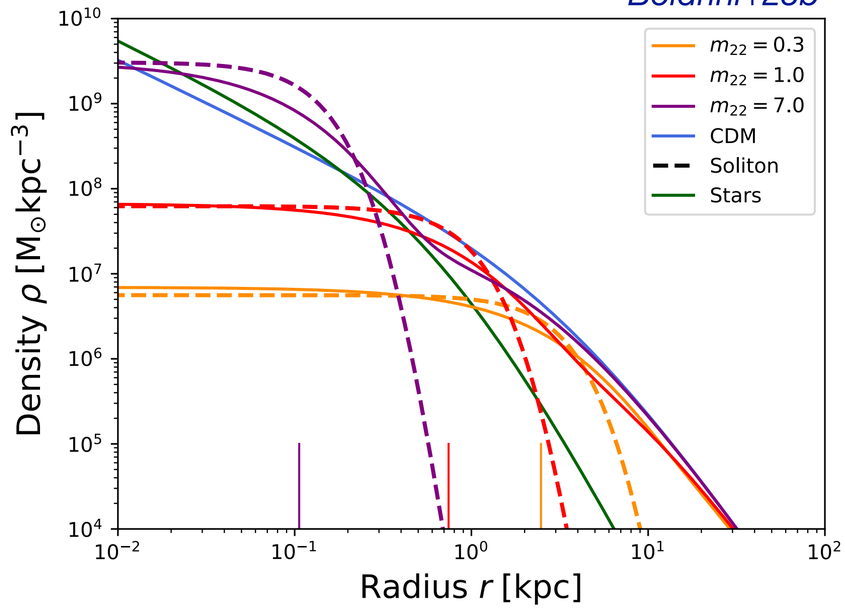
FDM MW-like galaxies from TNG50

- 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



GC dynamics in FDM universe: impact of DM core

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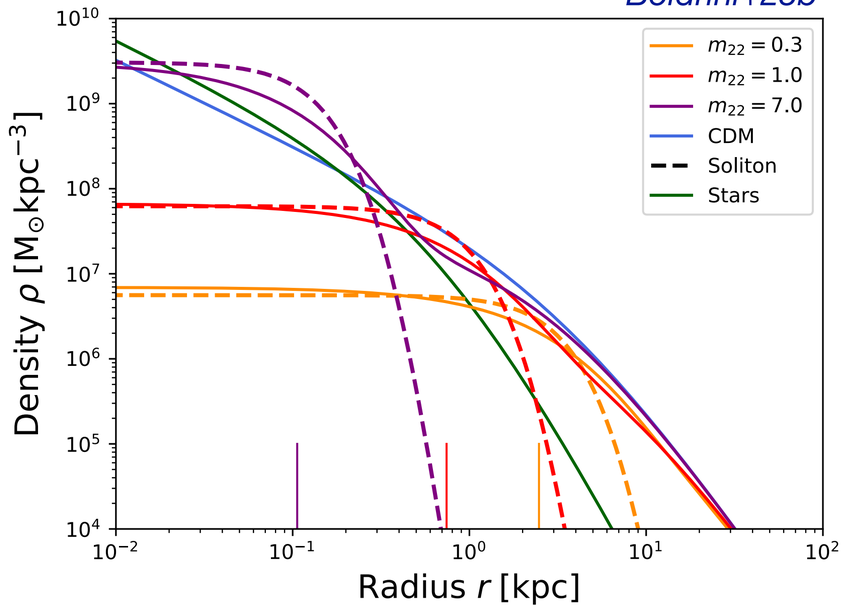


In-situ globular cluster population

- 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

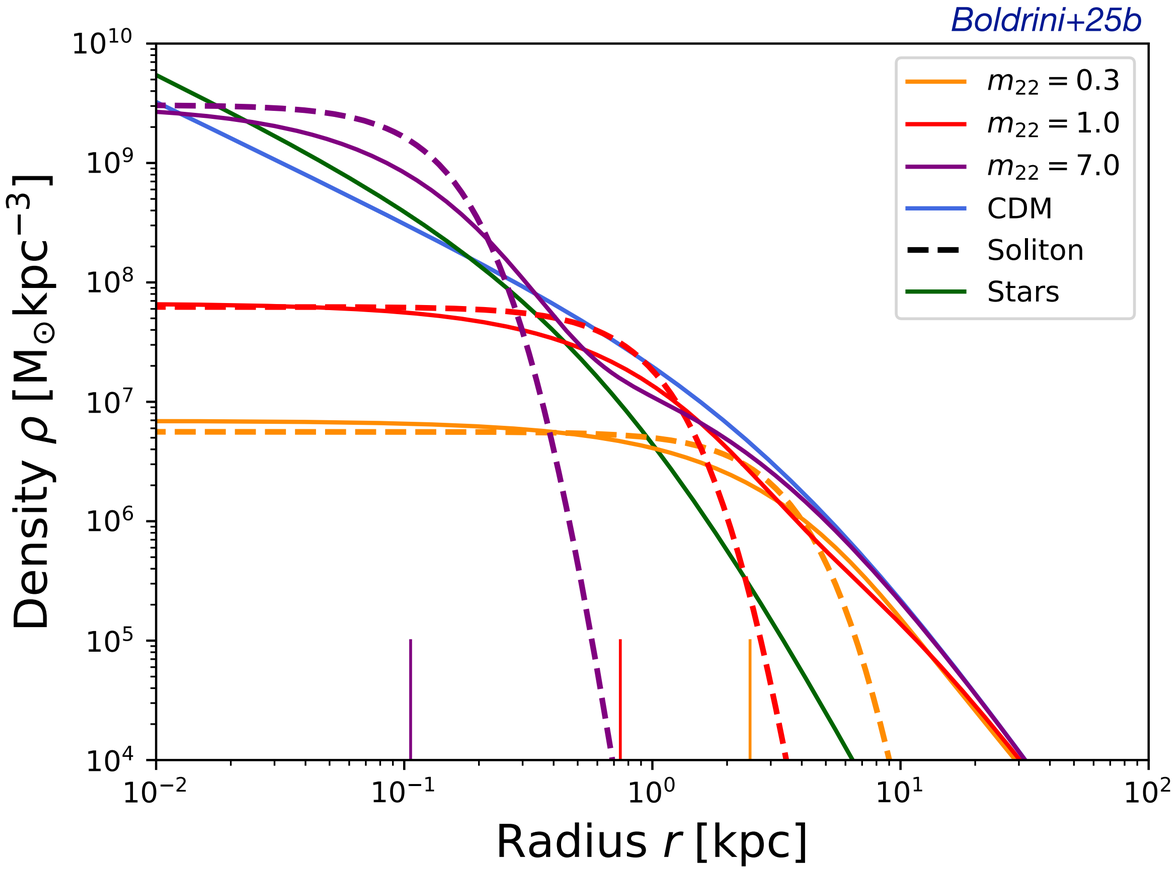
Density profile

Massive galaxies

DM core with size depending on the DM free parameter

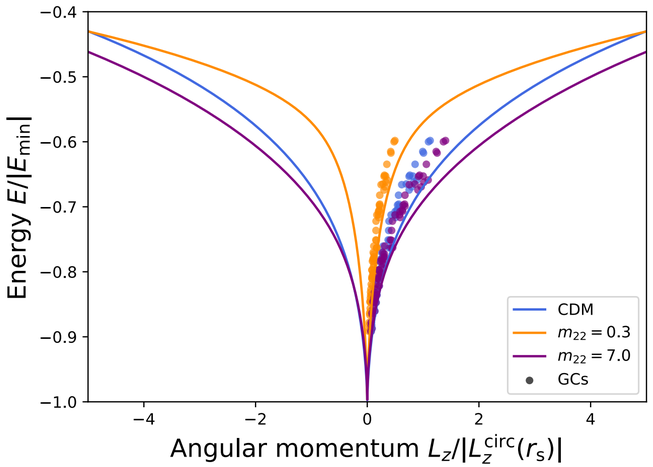
FDM
Quantum wave-like nature

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



GC dynamics in FDM universe: impact of DM core

Initial conditions

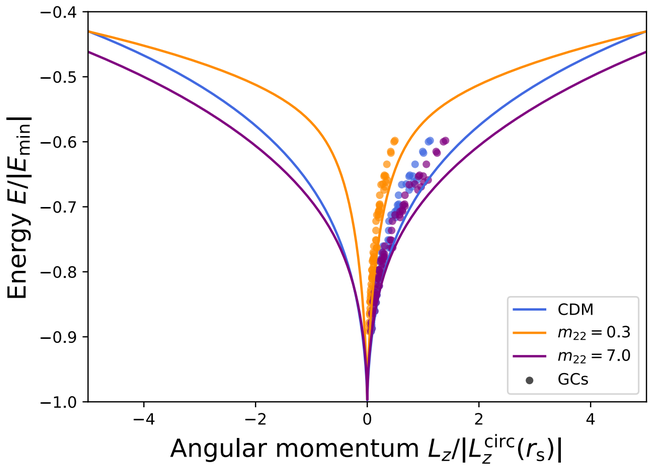


- Distributed equivalently of normalized E-L_z
- Fair comparison between DM potentials (core vs cusp)

GC dynamics in FDM universe: impact of DM core

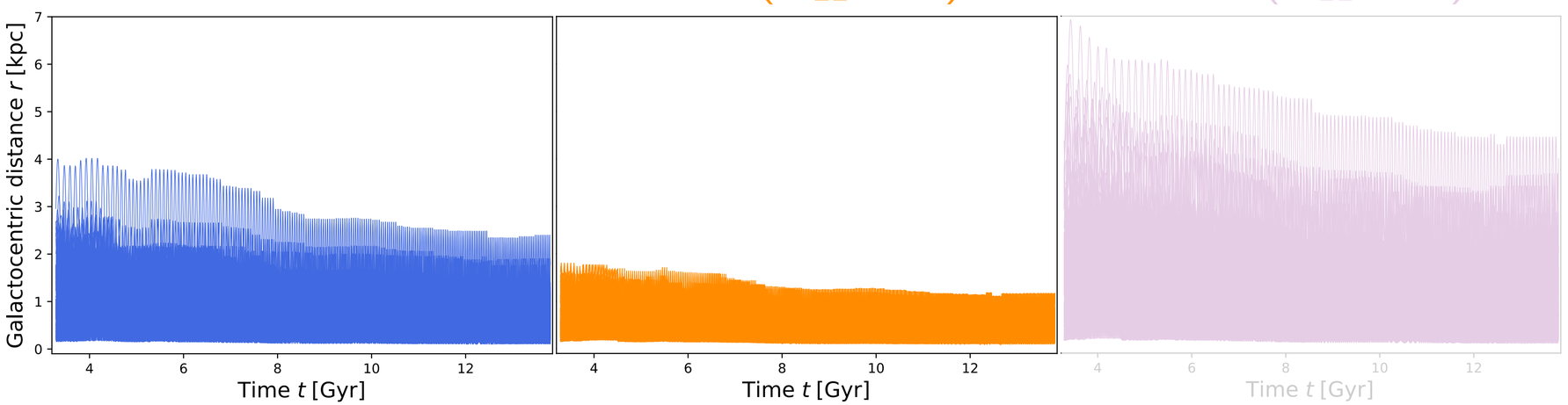
Boldrini+25b

Initial conditions



Time evolution in

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



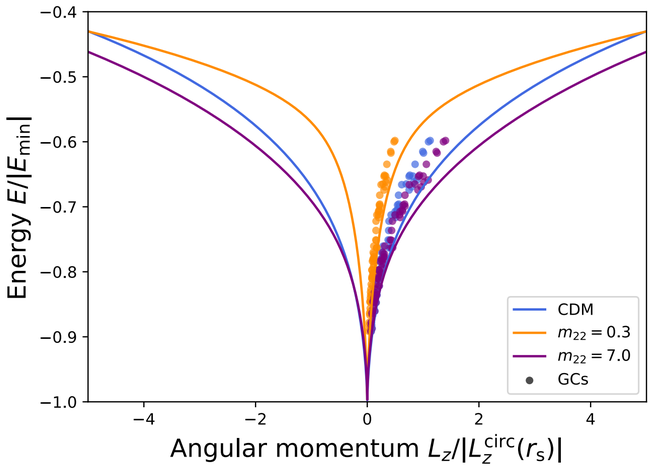
- Distributed equivalently of normalized E-L_z
- Fair comparison between DM potentials (core vs cusp)

- **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**

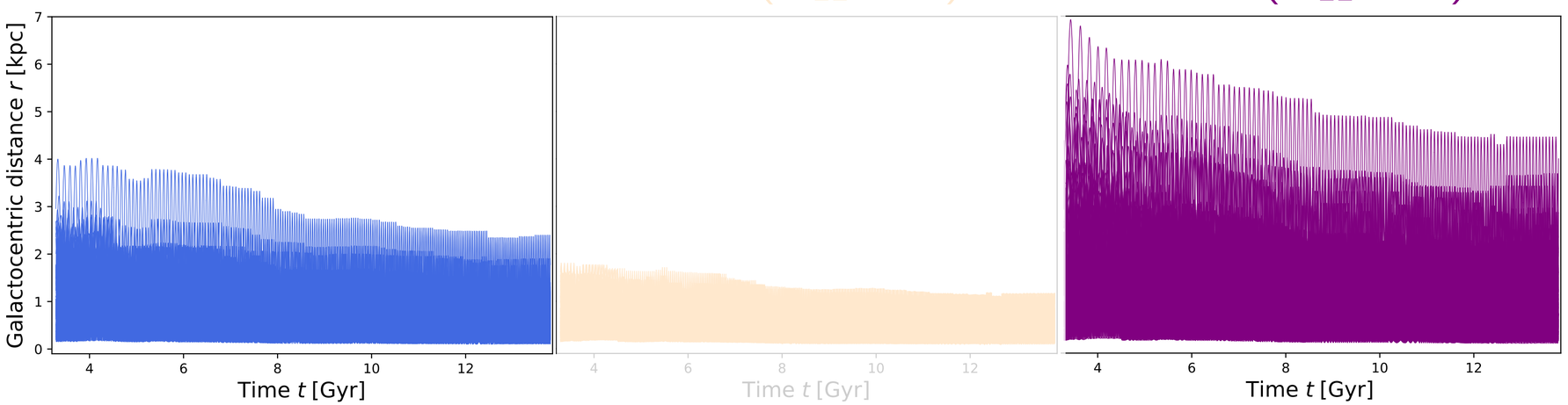
GC dynamics in FDM universe: impact of DM core

Boldrini+25b

Initial conditions



Time evolution in



- **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

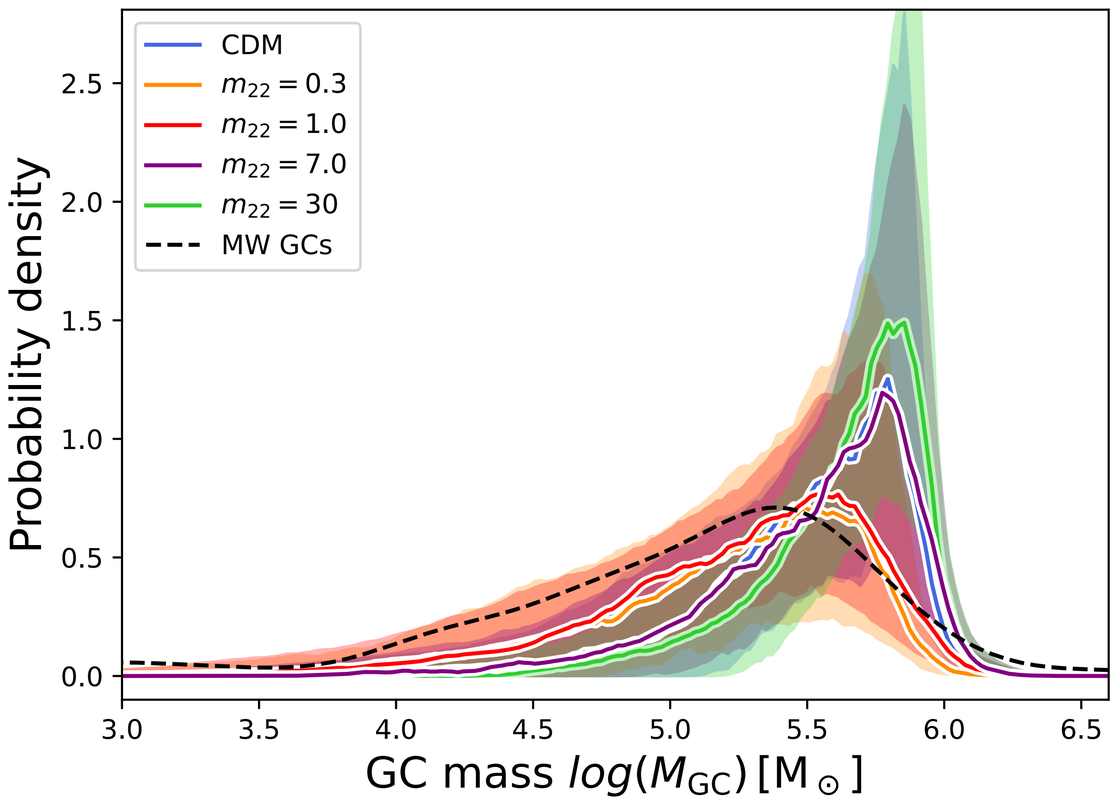
—> GCs confined near the center are much more susceptible to tidal effects and ultimately to disruption

—> 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

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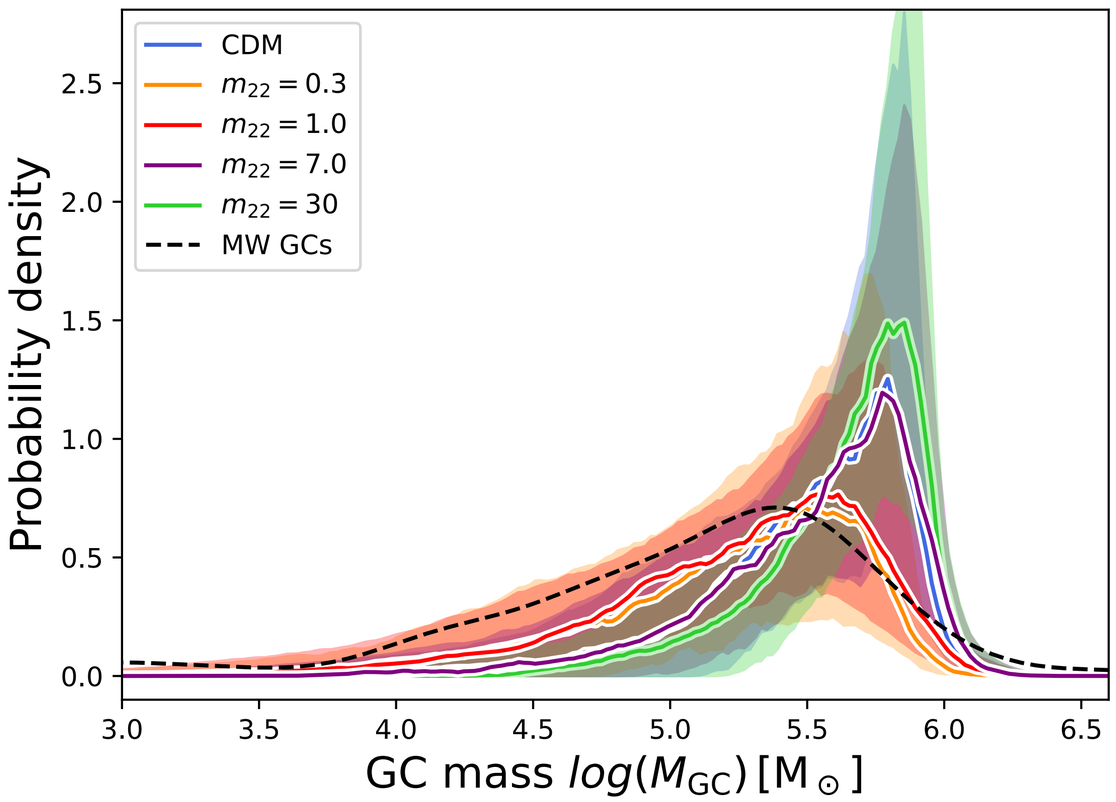
- **High m_{22}:** DM dominate which allows for a wider variety of stable orbits

—> 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

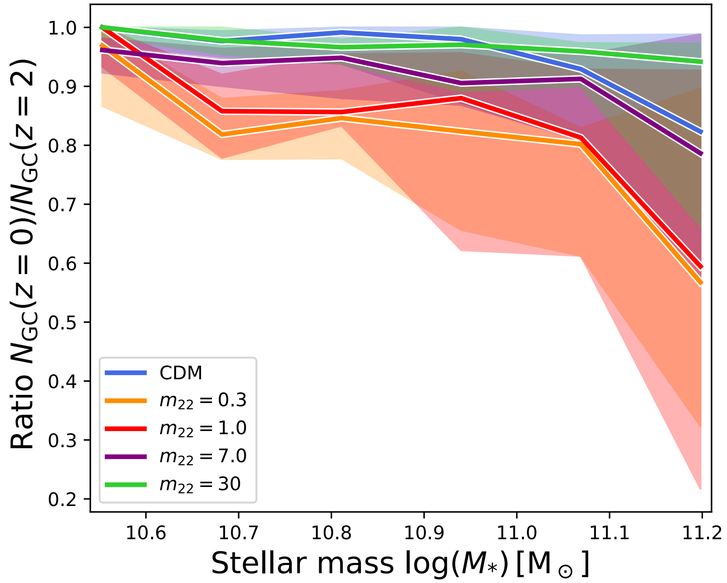


Confinement or expansion mechanism appears as a clear dynamical signature of FDM

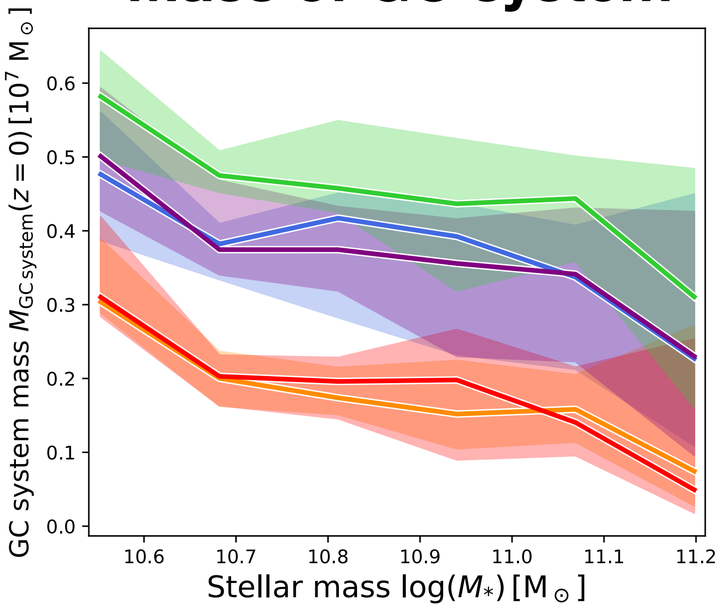
GC dynamics in FDM universe: impact of DM core

At z=0:

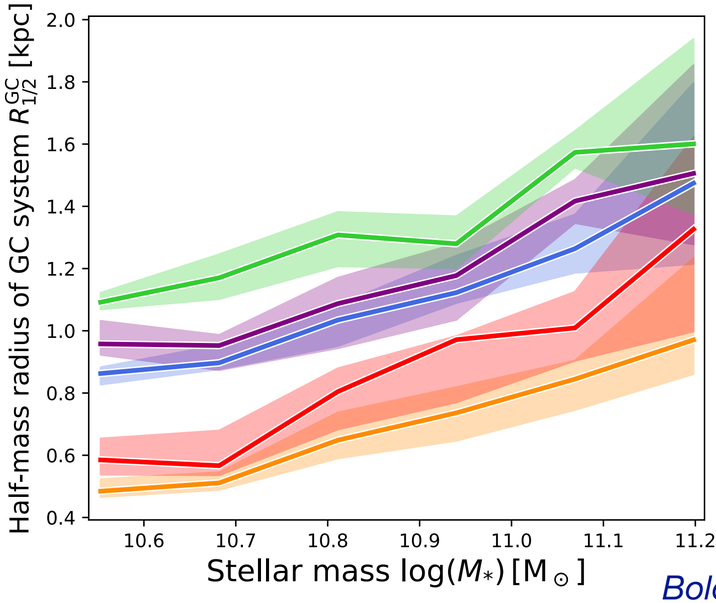
Surviving GCs



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:

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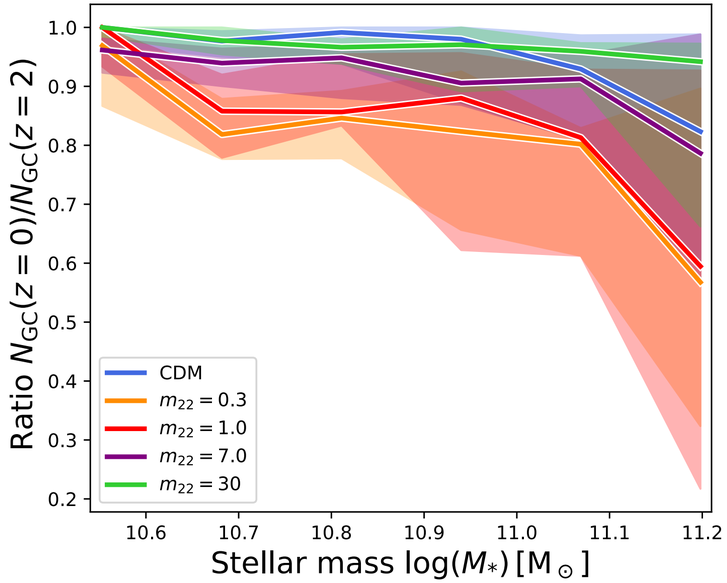
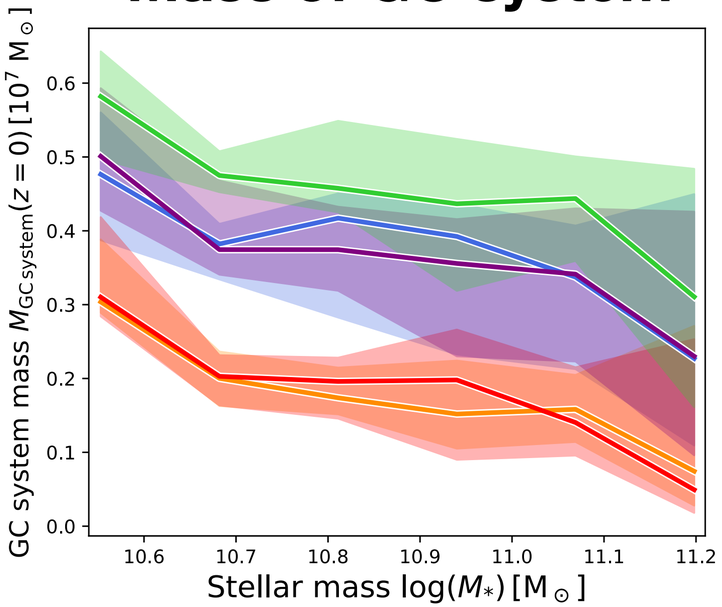
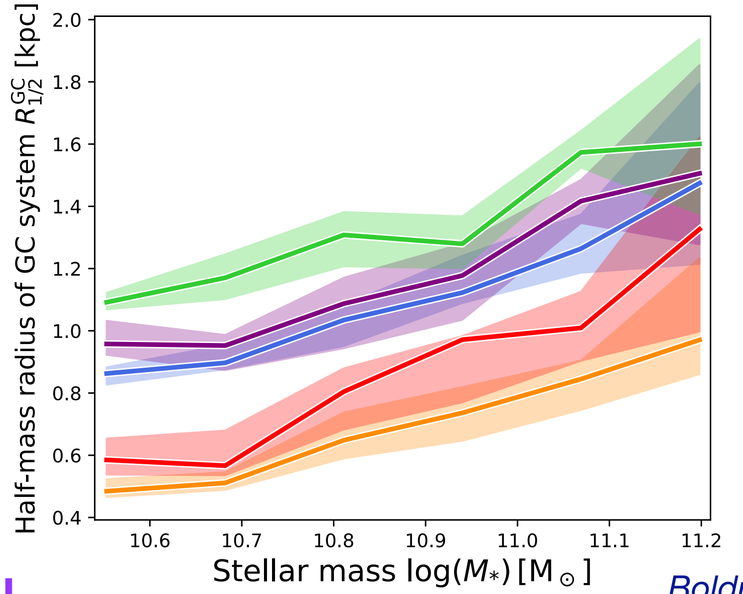


Mass of GC system



Half-mass radius



Boldrini+25b

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

Favored by galactic constraints

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

GC system —> 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

◆ 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

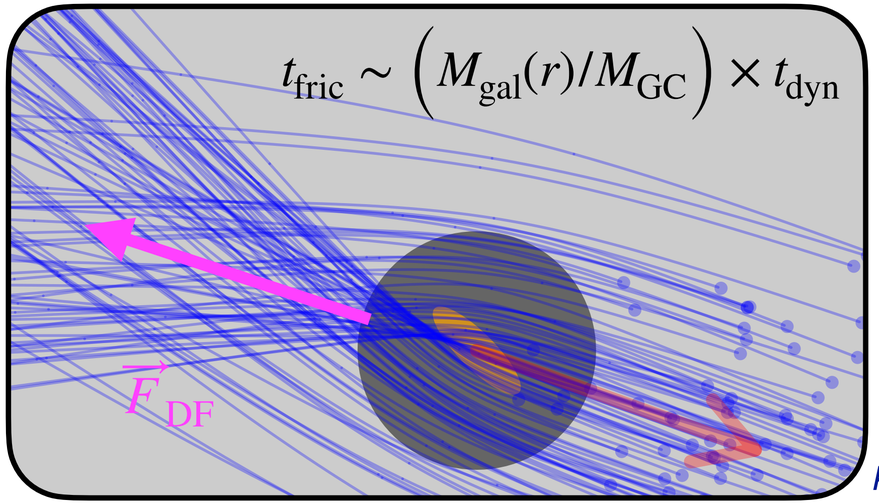
Deviation from CDM

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)

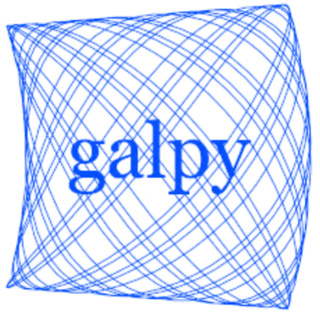
Fuzzy-dark-matter dynamical friction

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:

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

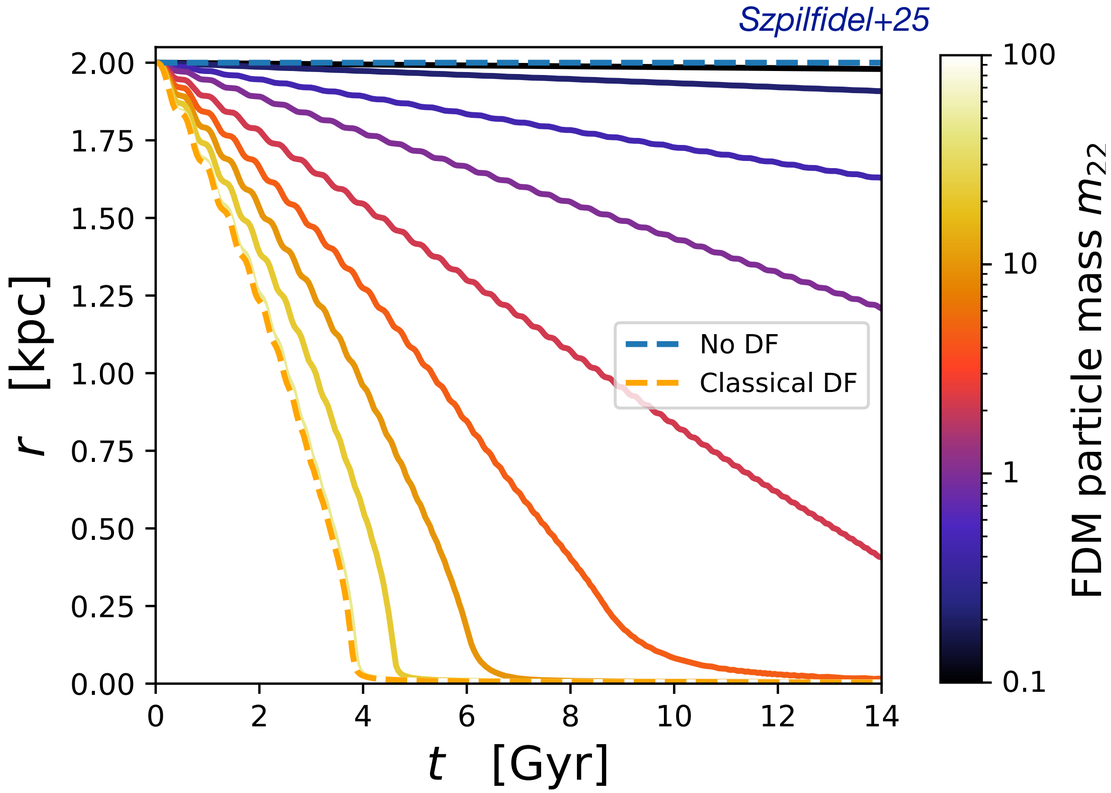


New public Galpy package for FDM dynamical friction

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

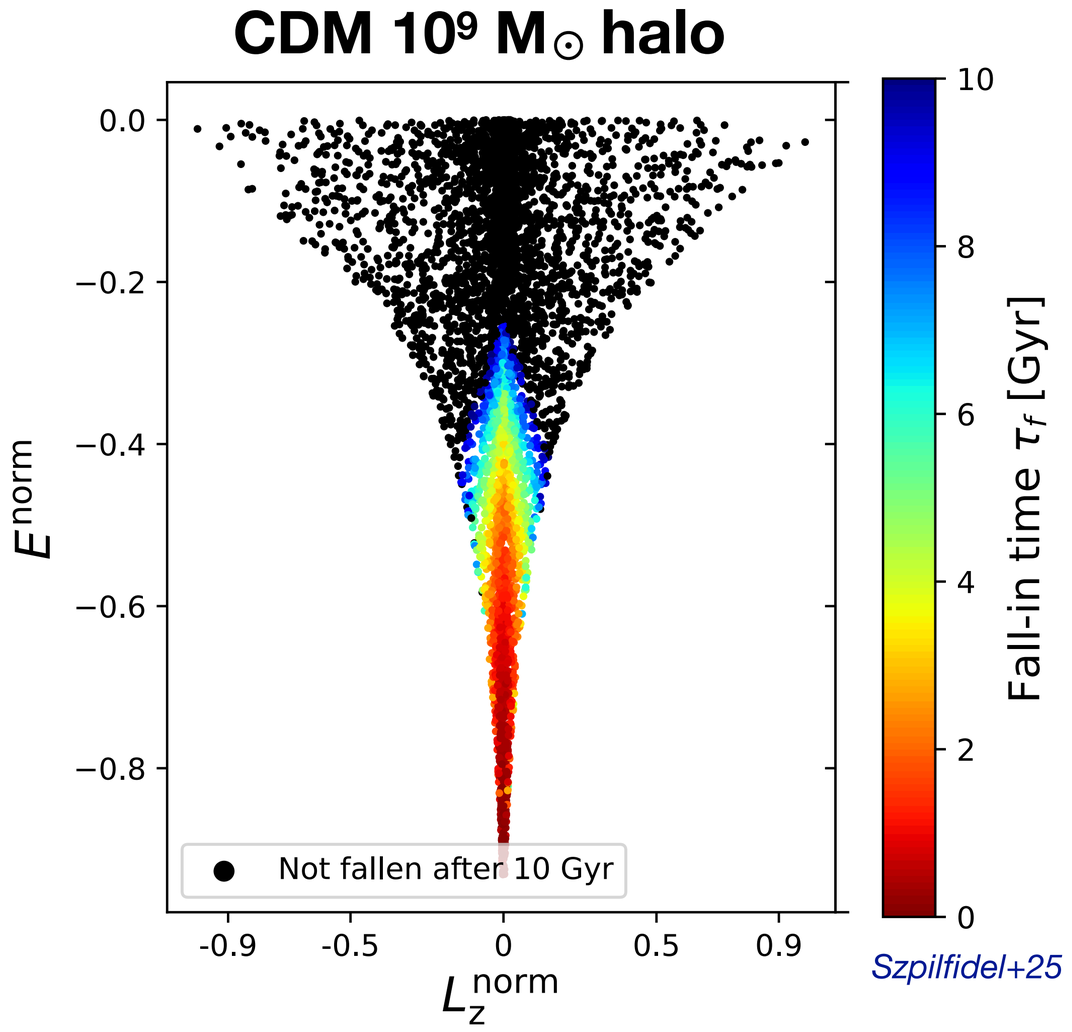
GC dynamics in FDM universe: impact of specific dynamical friction

- 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

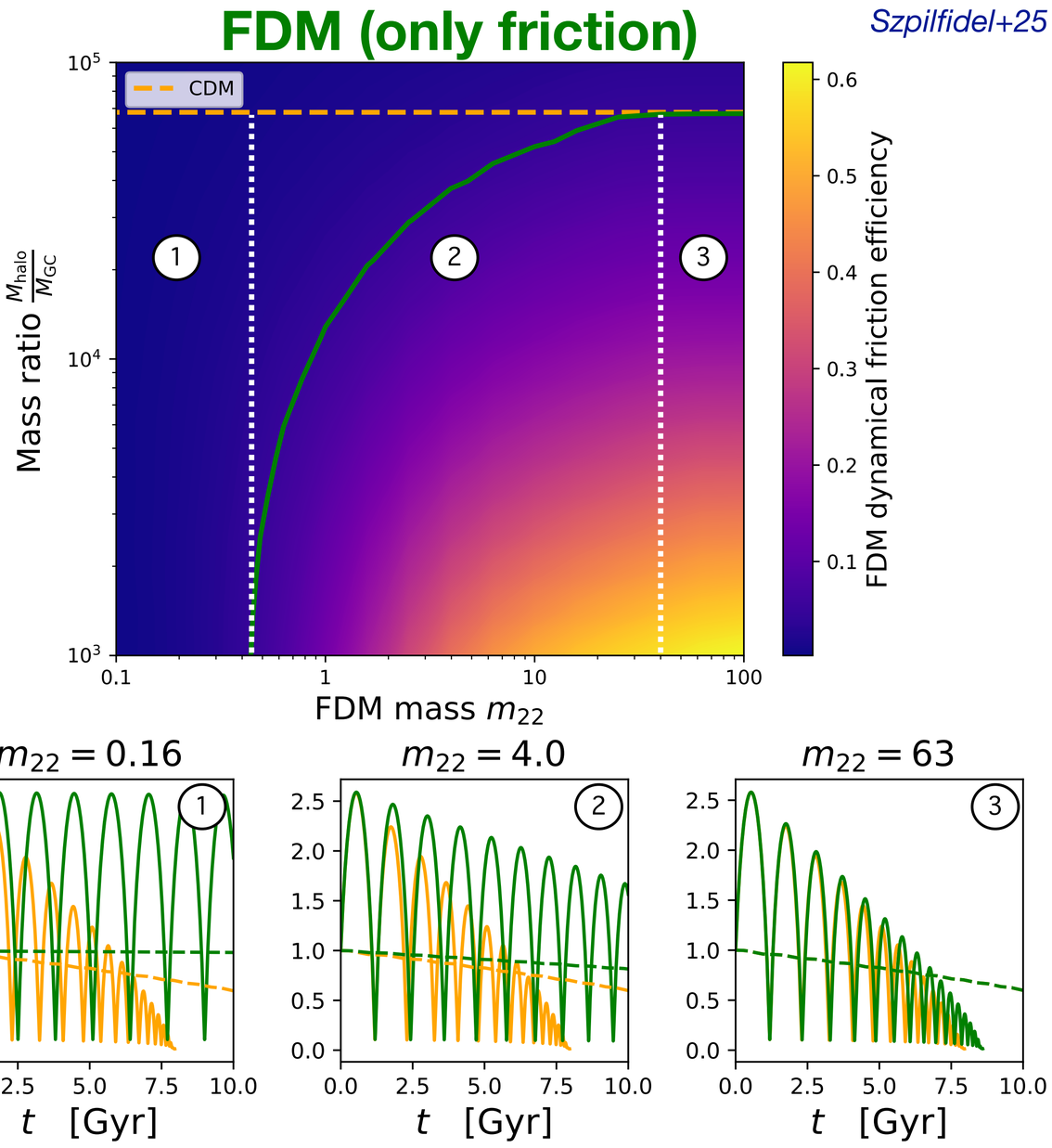
FDM = Core + FDM DF



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



GC dynamics in FDM universe: impact of specific dynamical friction

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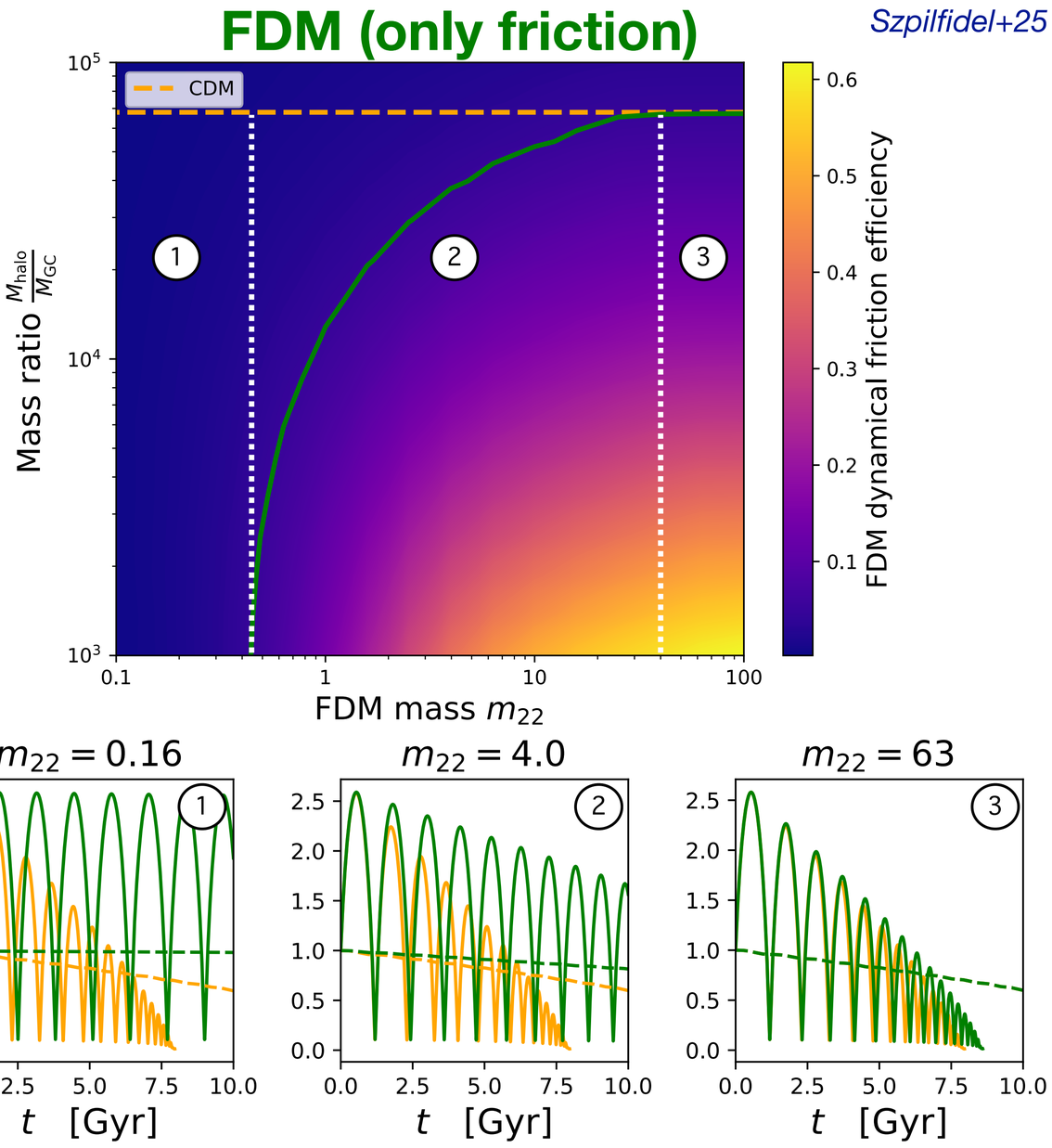
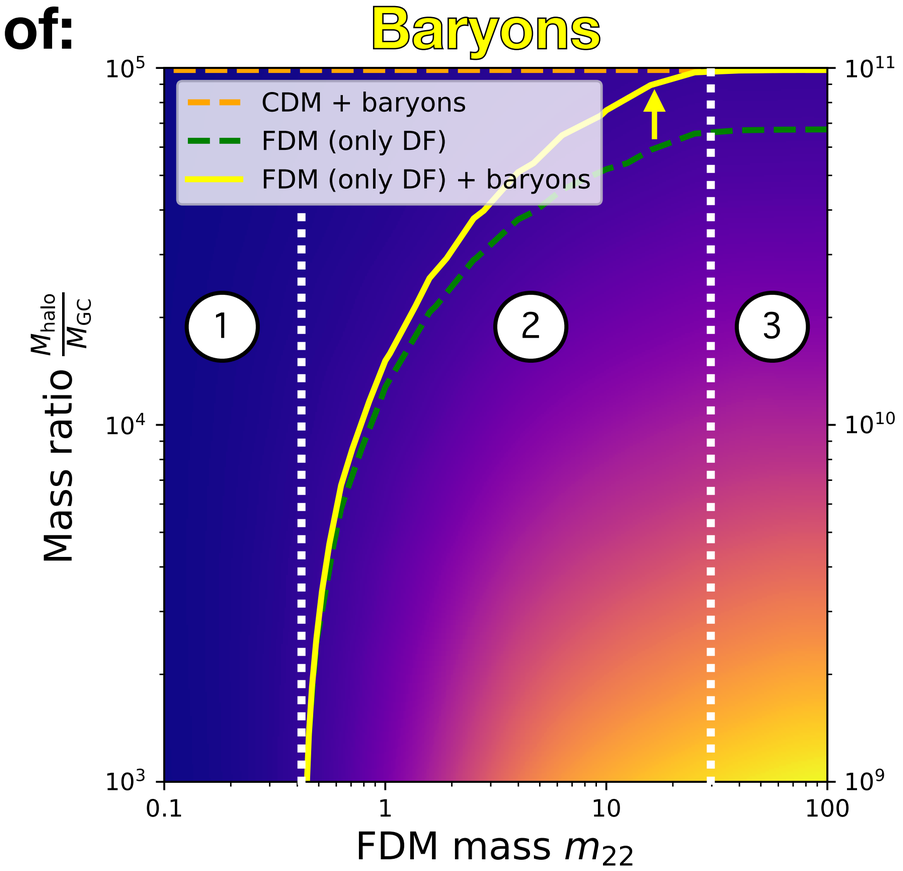
- **Classical DF:** above a mass ratio of 7 ×10⁴, friction becomes negligible
- Regime of interest for significant FDM signatures: dwarf galaxies
- **Zone 1:** FDM DF is highly inefficient —> orbital stalling
- **Zone 2:** Effective but reduced compared to CDM
- **Zone 3:** Converge back to CDM

FDM stalling mechanism challenges the expected galactic cannibalism of GCs



GC dynamics in FDM universe: impact of specific dynamical friction

Impact of:

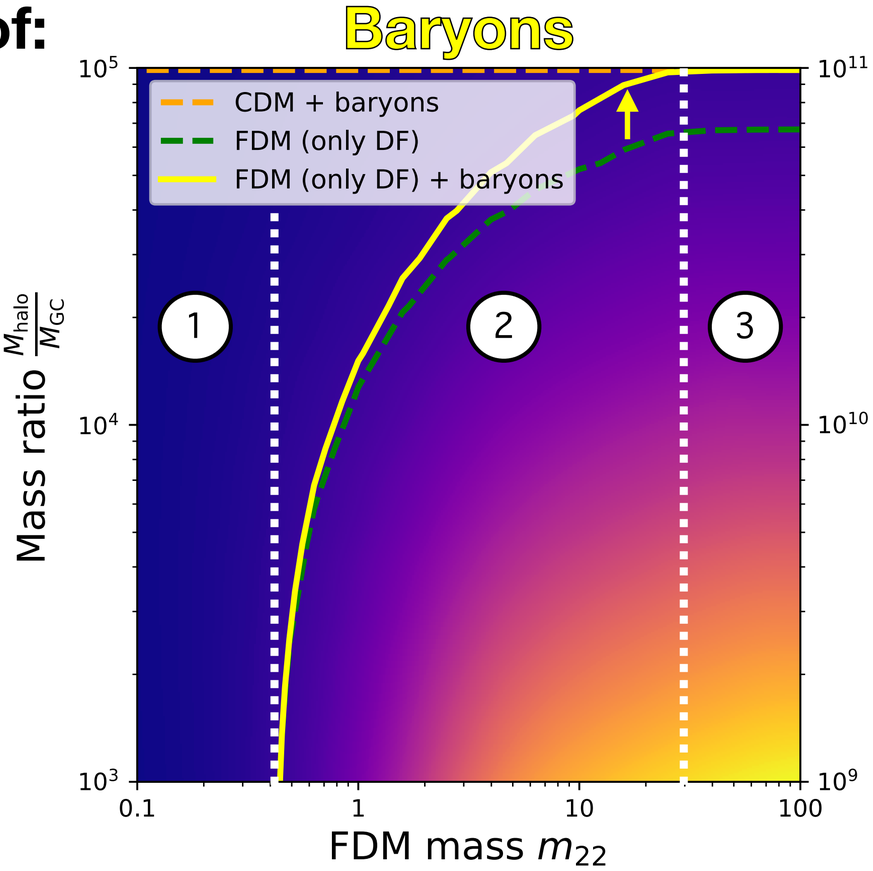


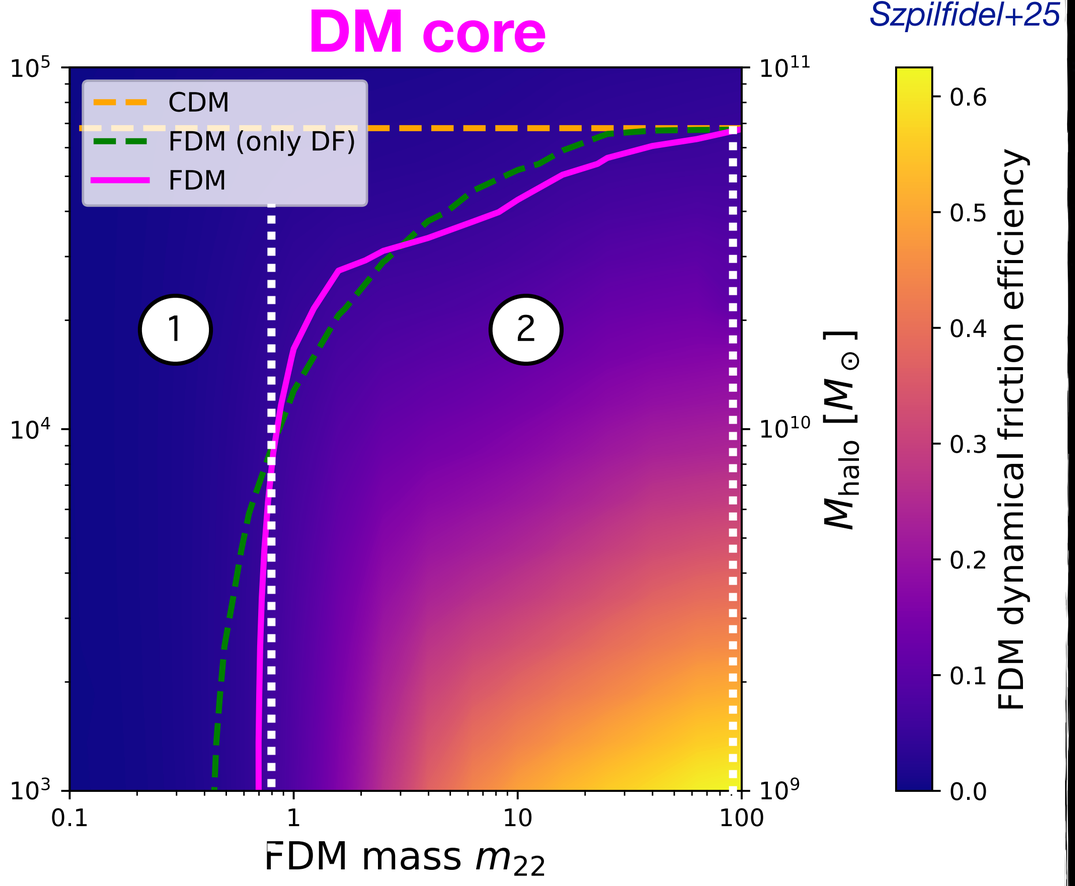
Szpilfidel+25

- **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

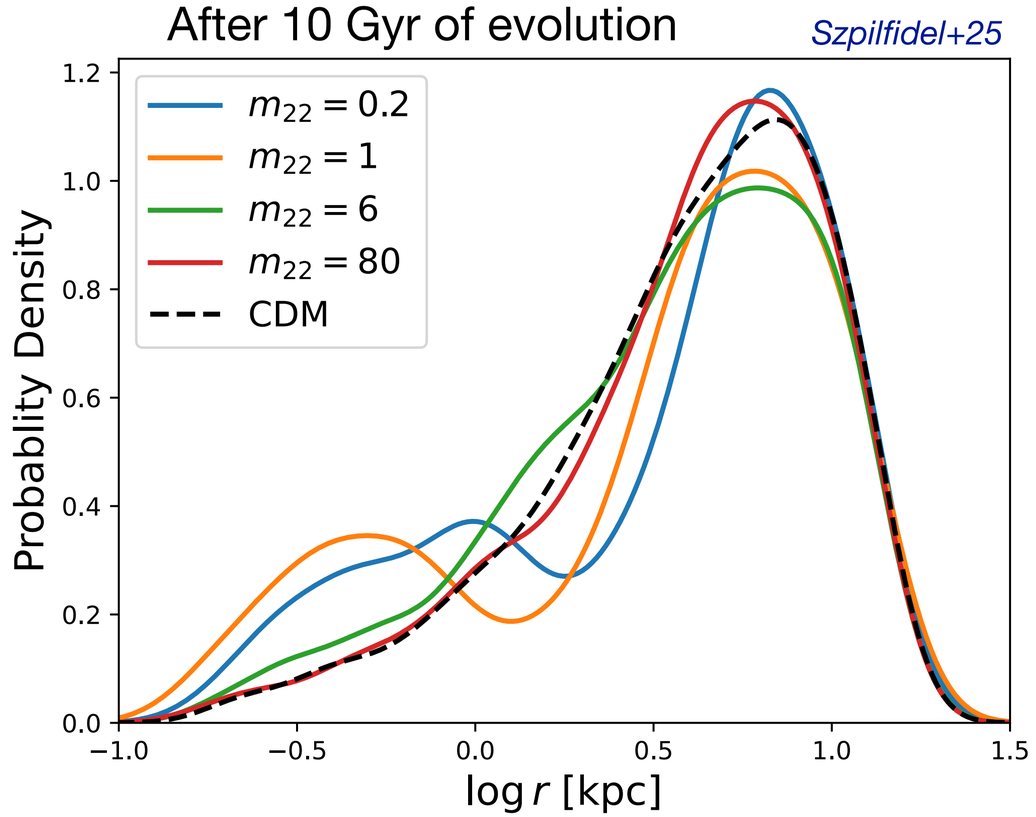
GC dynamics in FDM universe: impact of specific dynamical friction

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:** $3r_s < r_{\rm apo}^{\rm init} < 10r_s$

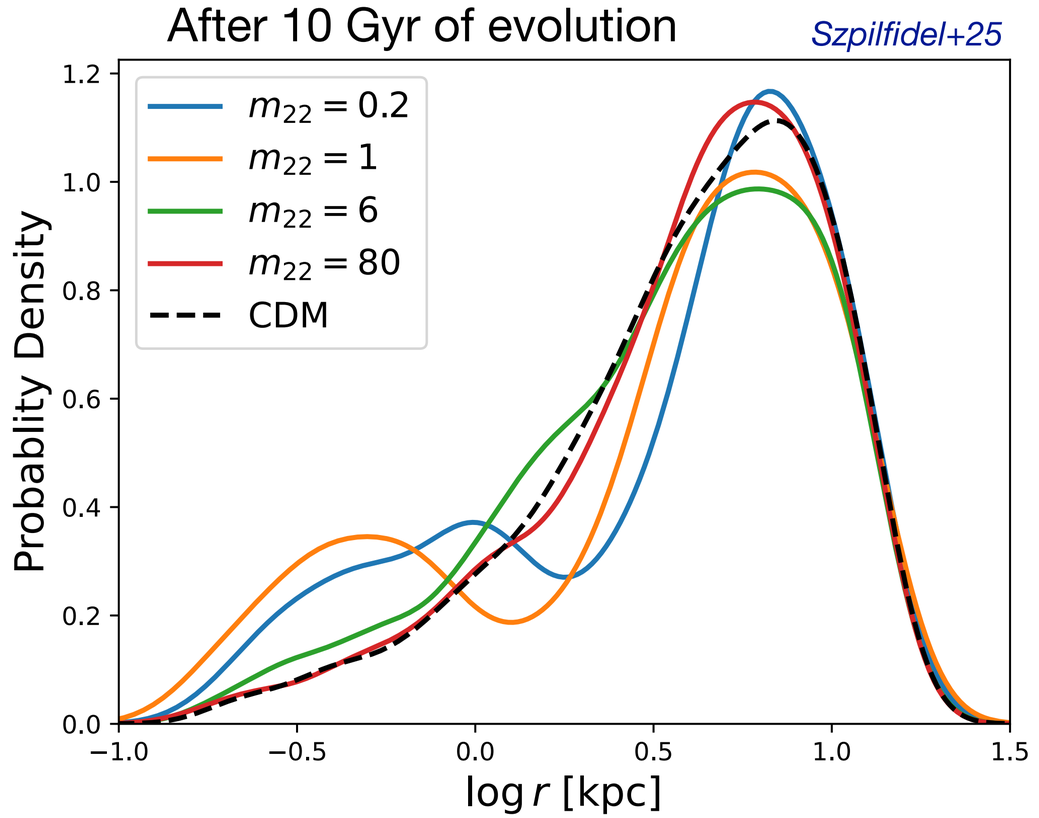
GC dynamics in FDM universe: impact of specific dynamical friction

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*	

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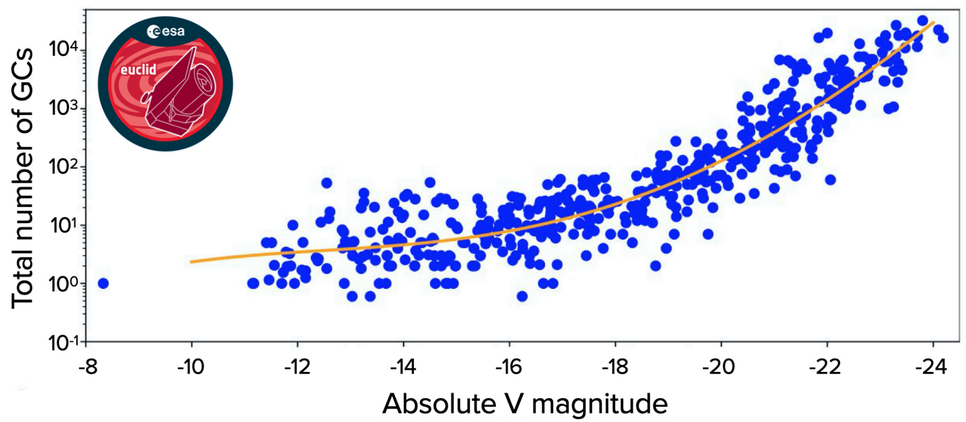
- **Density profile:** SIDM produces larger and less dense cores than FDM - WDM cores have higher central densities than SIDM and are similar to FDM, but never exceed NFW profile —> MWs
- **Dynamical friction:** Similar to CDM in SIDM and WDM —> dwarfs

Futur works [1/2]

Concerning globular cluster dynamics:

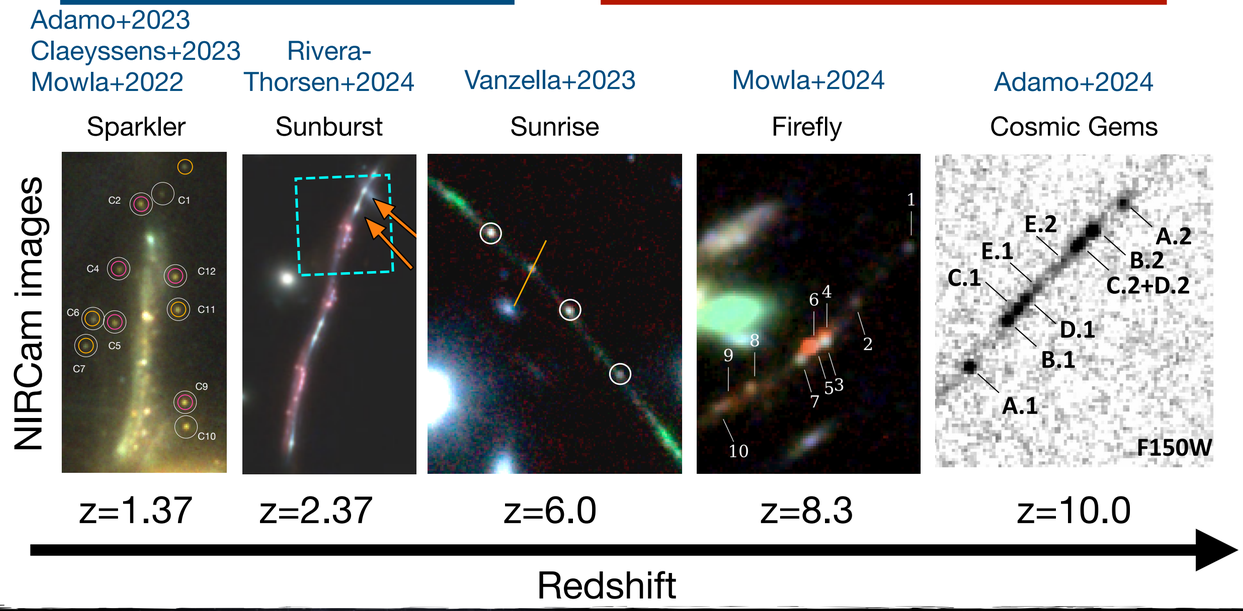
- Improving our post-processing GC formation and evolution model in the pursuit of a realistic and robust model to compare with Euclid data
- **Euclid data:** half-million extragalactic GCs in 4000 nearby galaxies (< 100 Mpc) spanning stellar masses from 10^9 to 10^{12} M⊙ *Voggel+24*
- **GC formation model:** using local quantities in cosmological simulations such as Obelisk or NewHorizon *Trebitsch+21, Dubois+21*
- **Constraints:** mass distribution of MW GCs, high-redshift GC candidates with JWST, EUCLID+MOSAIC?
- **GC evolution model:** using basis function expansion methods (AGAMA) instead of spherical potentials

Voggel+24



Credits: A. Claeyssens' SF2A talk

(Proto)-globular clusters | Young and massive star clusters

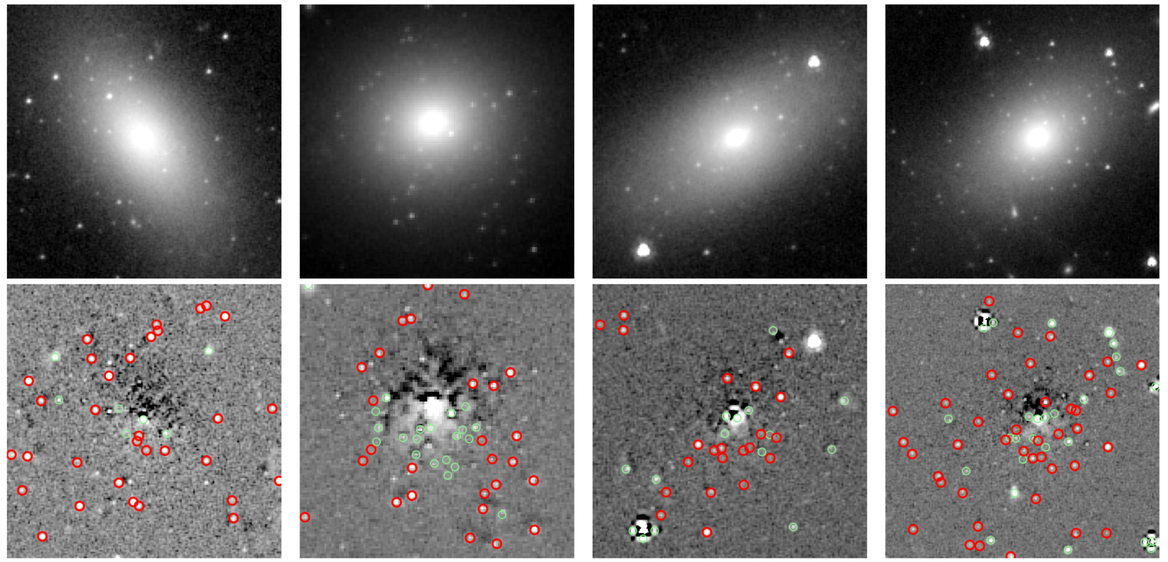


Futur works [2/2]

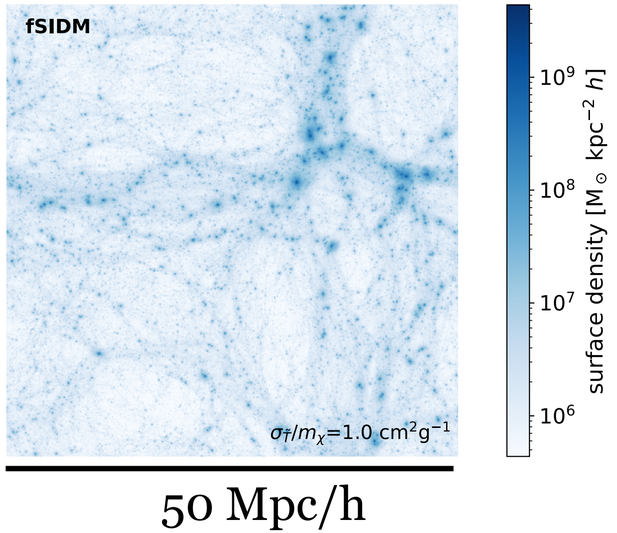
Concerning constraining DM:

- **FDM:** confirming the bimodality signature in dwarfs by taking into account hierarchical assembly with mass loss as in Boldrini25a
- **Euclid EROs:** Perseus galaxy cluster —> 11370 candidate GCs associated with more than 1000 dwarf galaxies (10^6 and 10^{10} M$\odot$)
- More statistics with the upcoming **Euclid DR1** in autumn 2026
- 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

Saifollahi+25



Fischer+24



Thank you!