

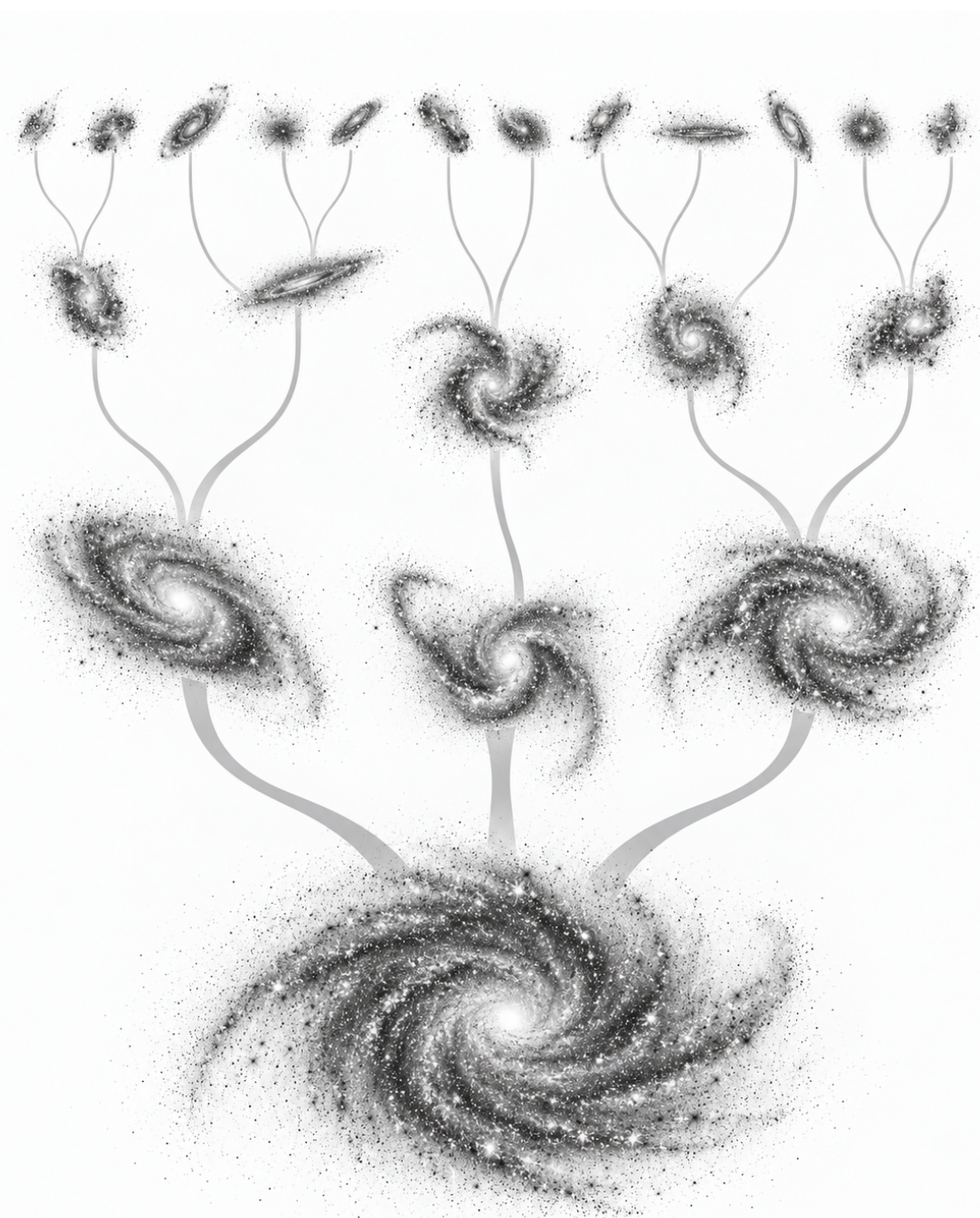
SIMULATING COMPACT OBJECTS IN A COSMOLOGICAL CONTEXT



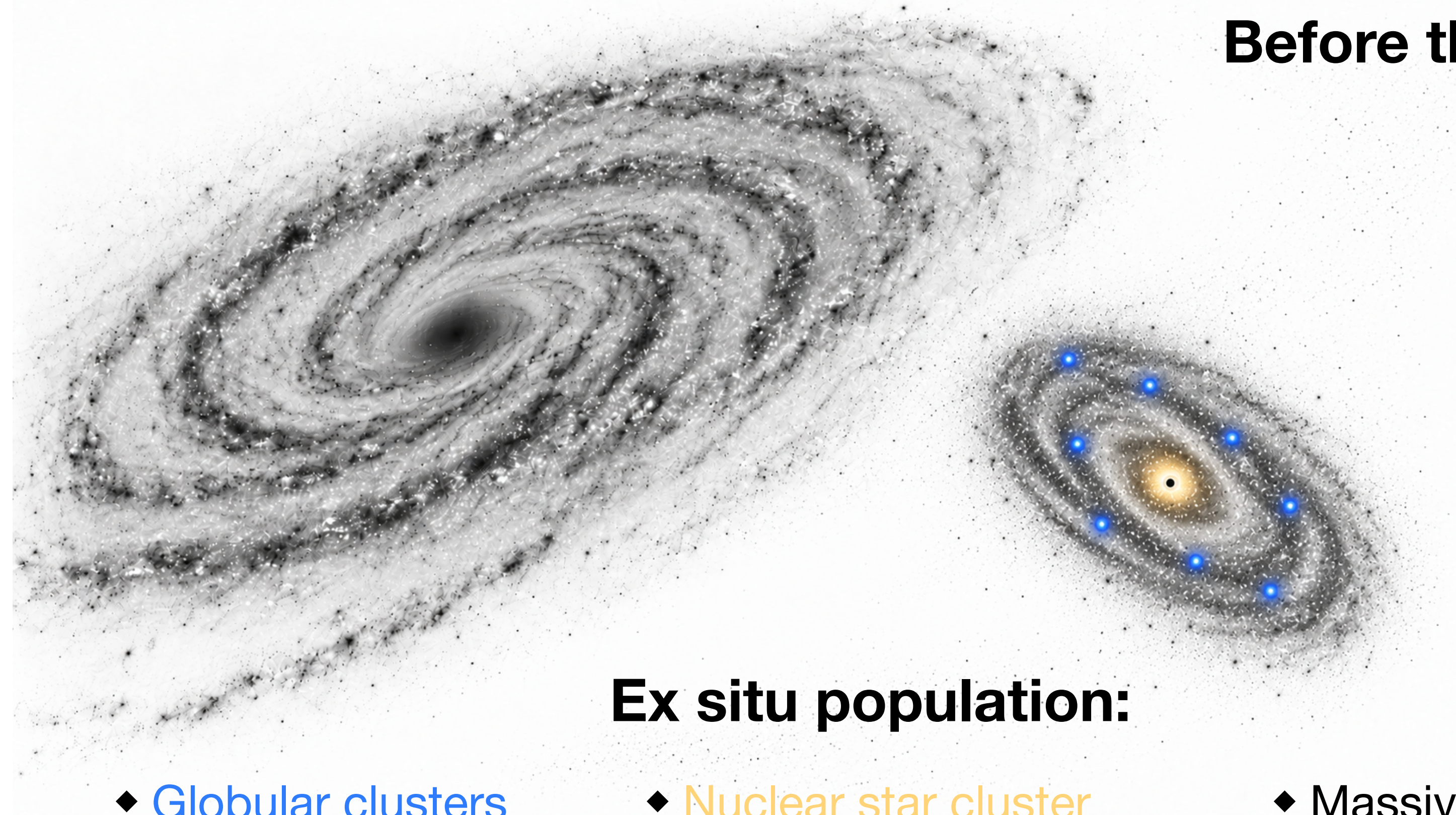
Pierre Boldrini,
CNES fellow at LIRA —> NYUAD, UAE
IRAP seminar, September 2026

Merger with a satellite galaxy

Hierarchical galaxy formation



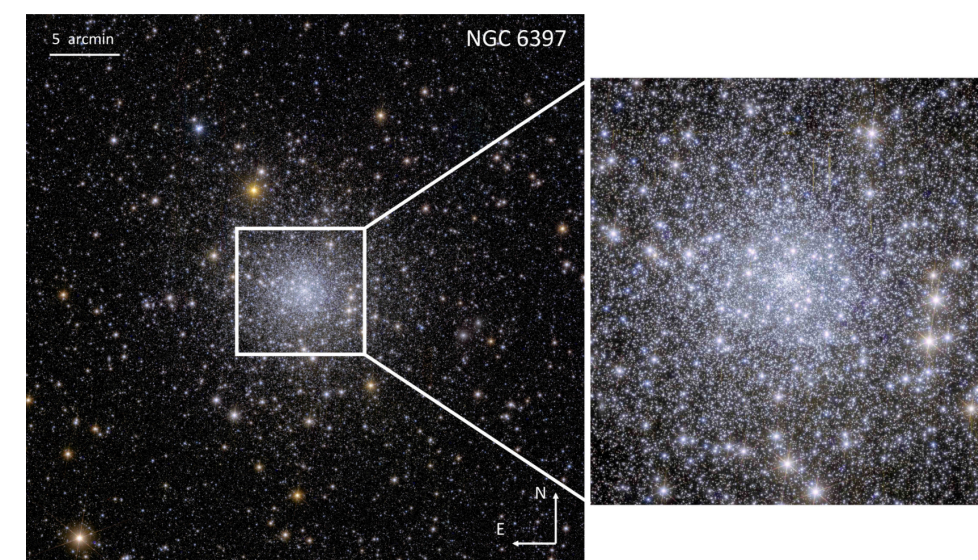
Before the merger



Ex situ population:

◆ Globular clusters

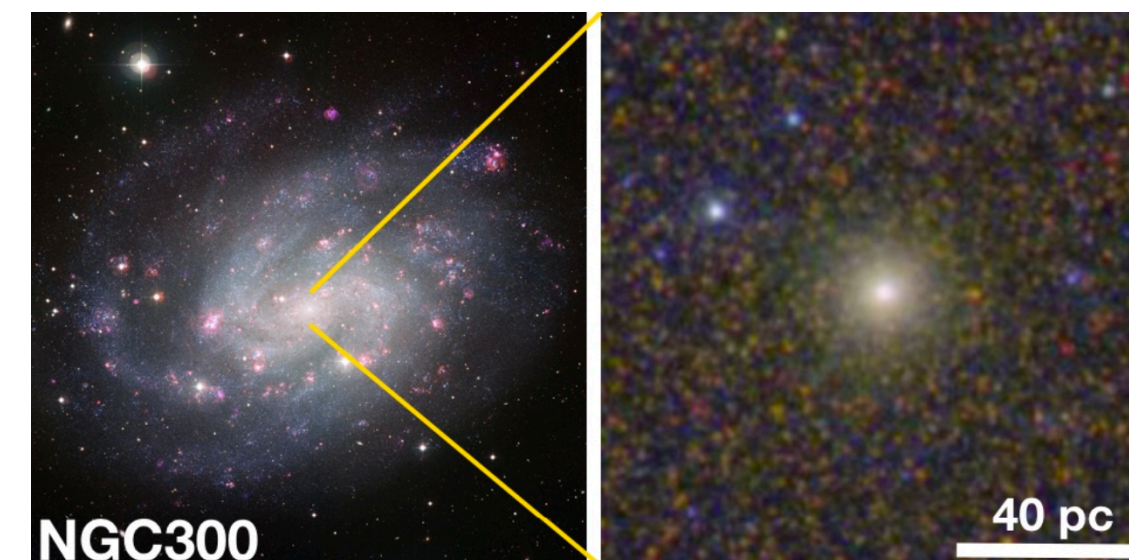
$10^4 - 10^6 M_{\odot}$



Euclid: Massari+24

◆ Nuclear star cluster

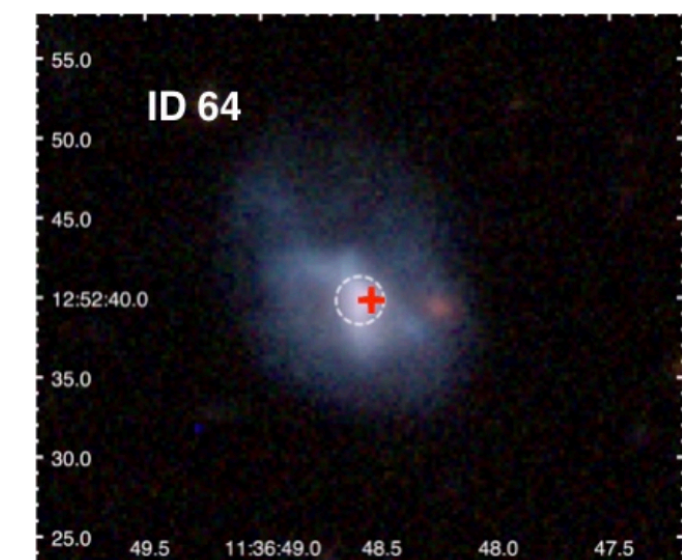
$10^5 - 10^8 M_{\odot}$



Neunmayer+20

◆ Massive black hole

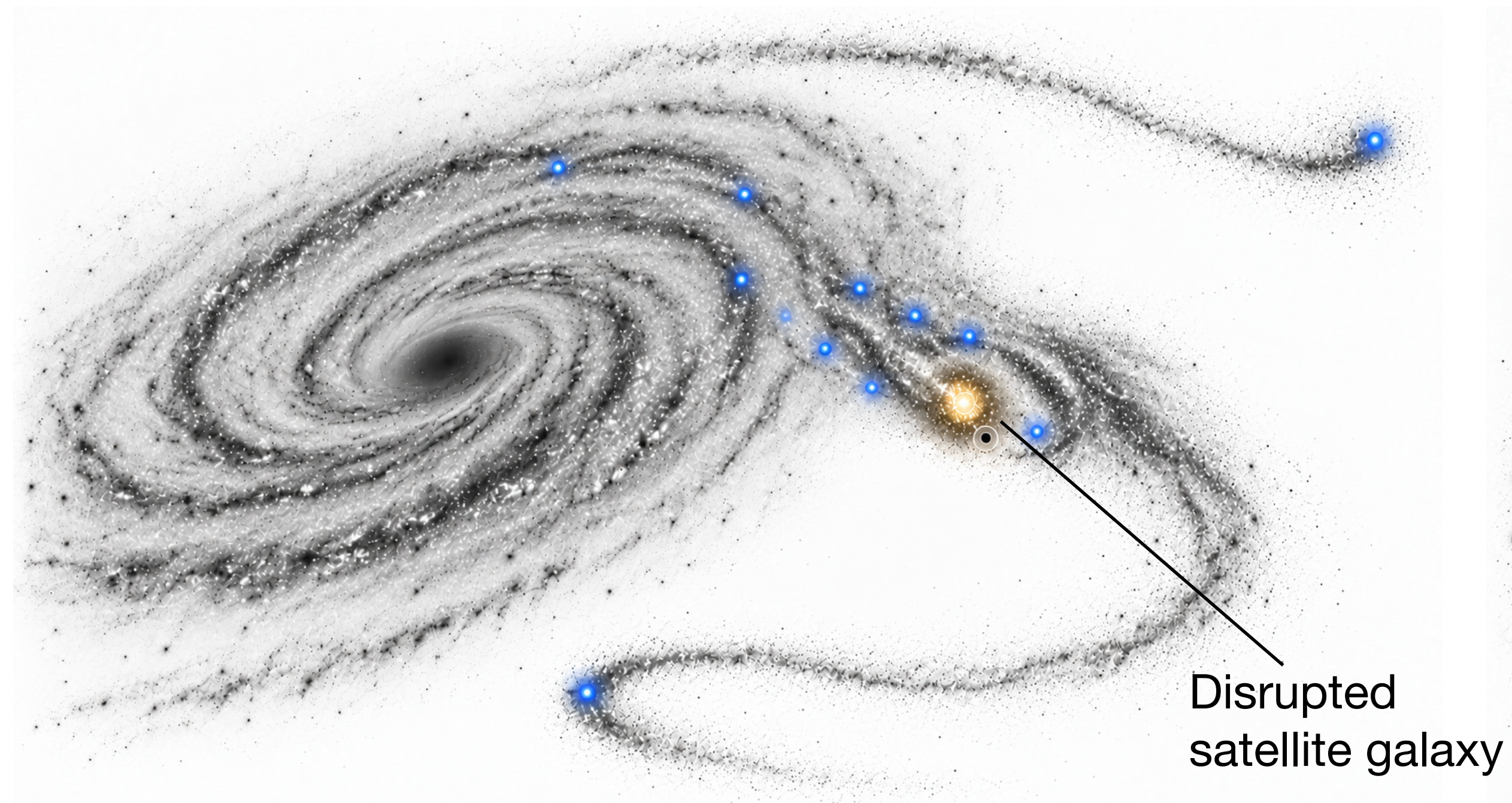
$10^4 - 10^7 M_{\odot}$



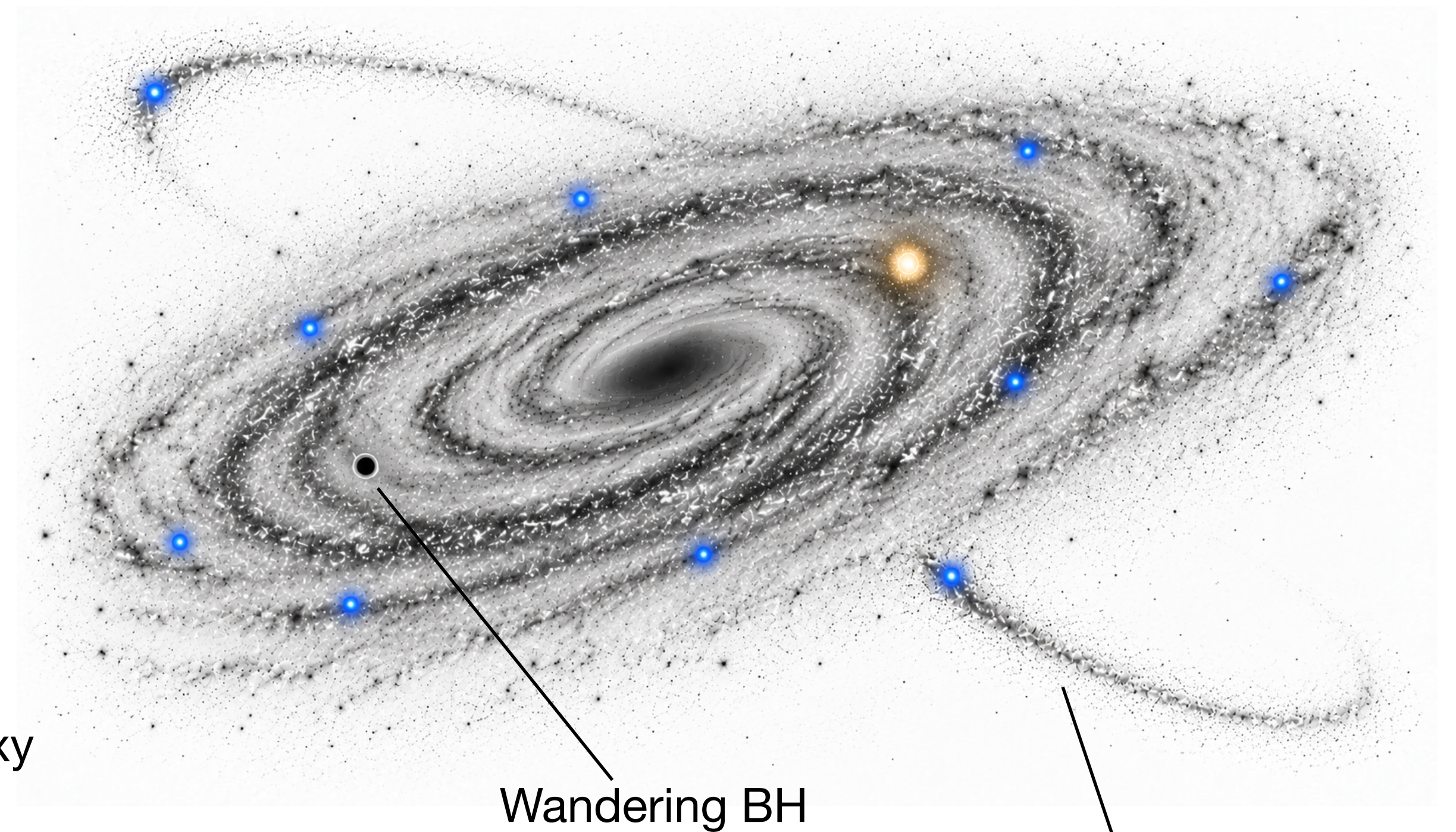
Reines+19

Merger with a satellite galaxy

During the merger

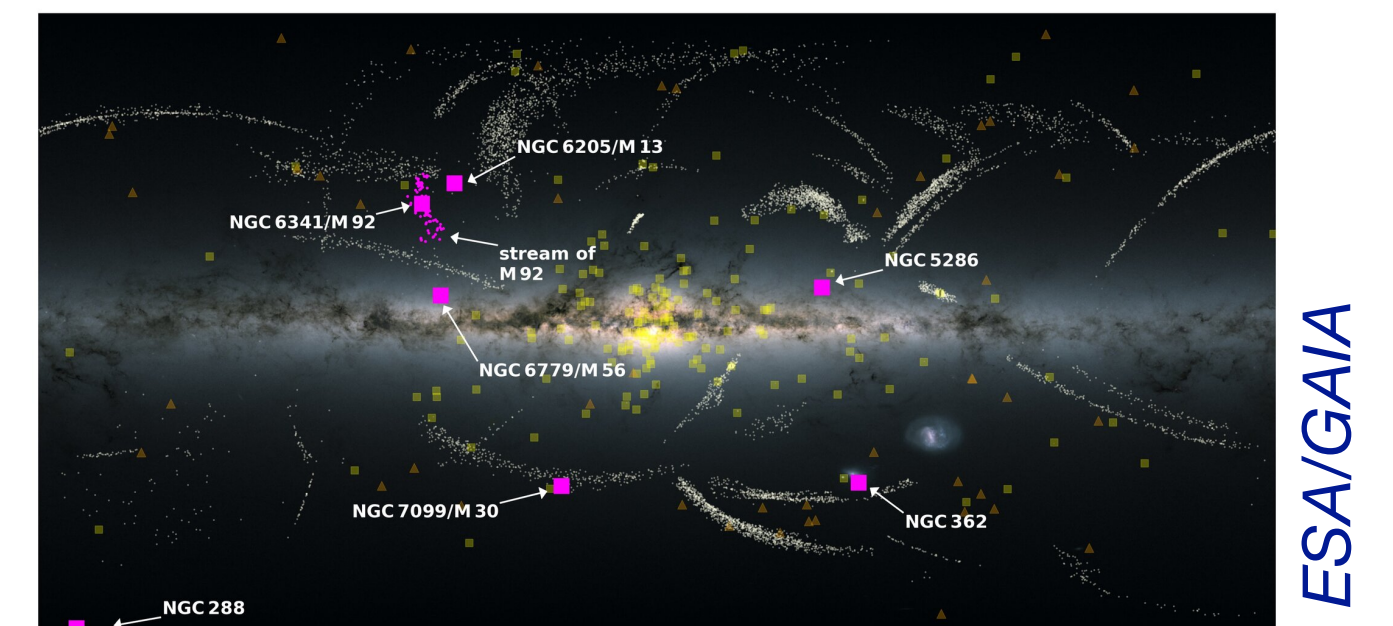


After the merger



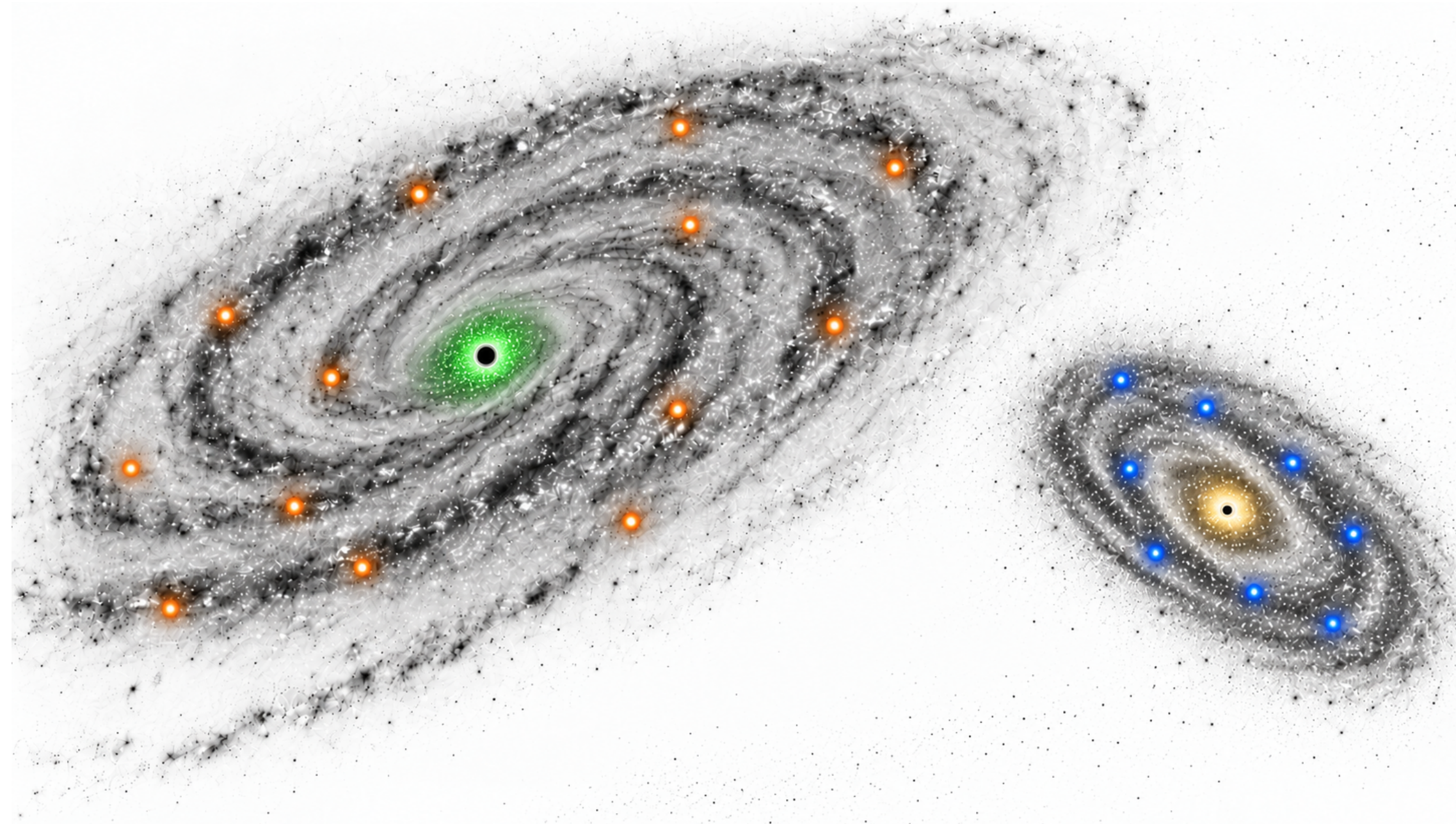
Key physical processes:

- ◆ Gravity
- ◆ Dynamical friction
- ◆ Mass loss
- ◆ Tidal stream formation



Merger with a satellite galaxy

During the merger



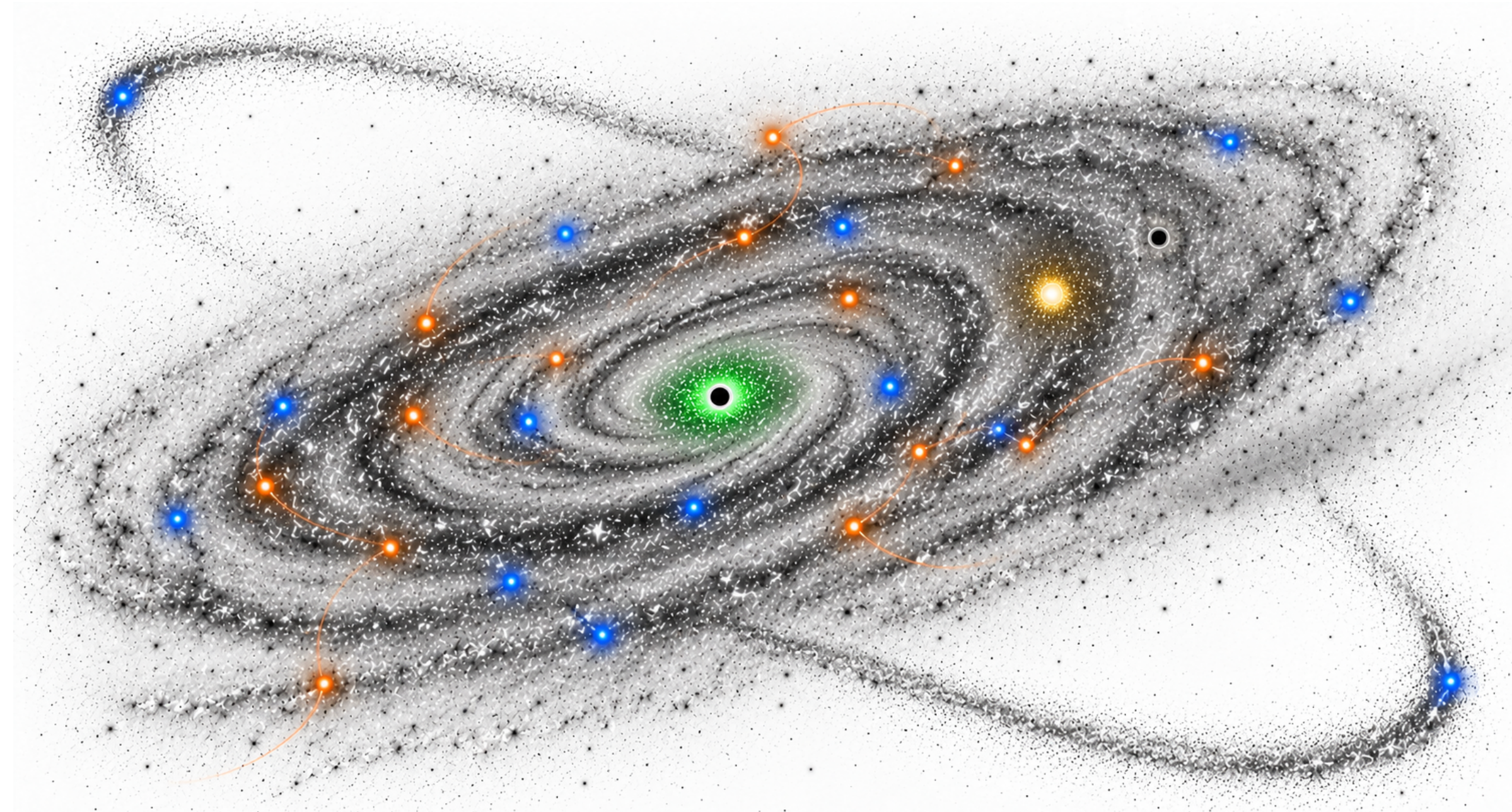
In situ population:

- ◆ GCs
- ◆ NSC
- ◆ MBH

Ex situ population:

- ◆ GCs
- ◆ NSC
- ◆ MBH

After the merger



Present-day population

=

mixture of in situ and ex situ
populations

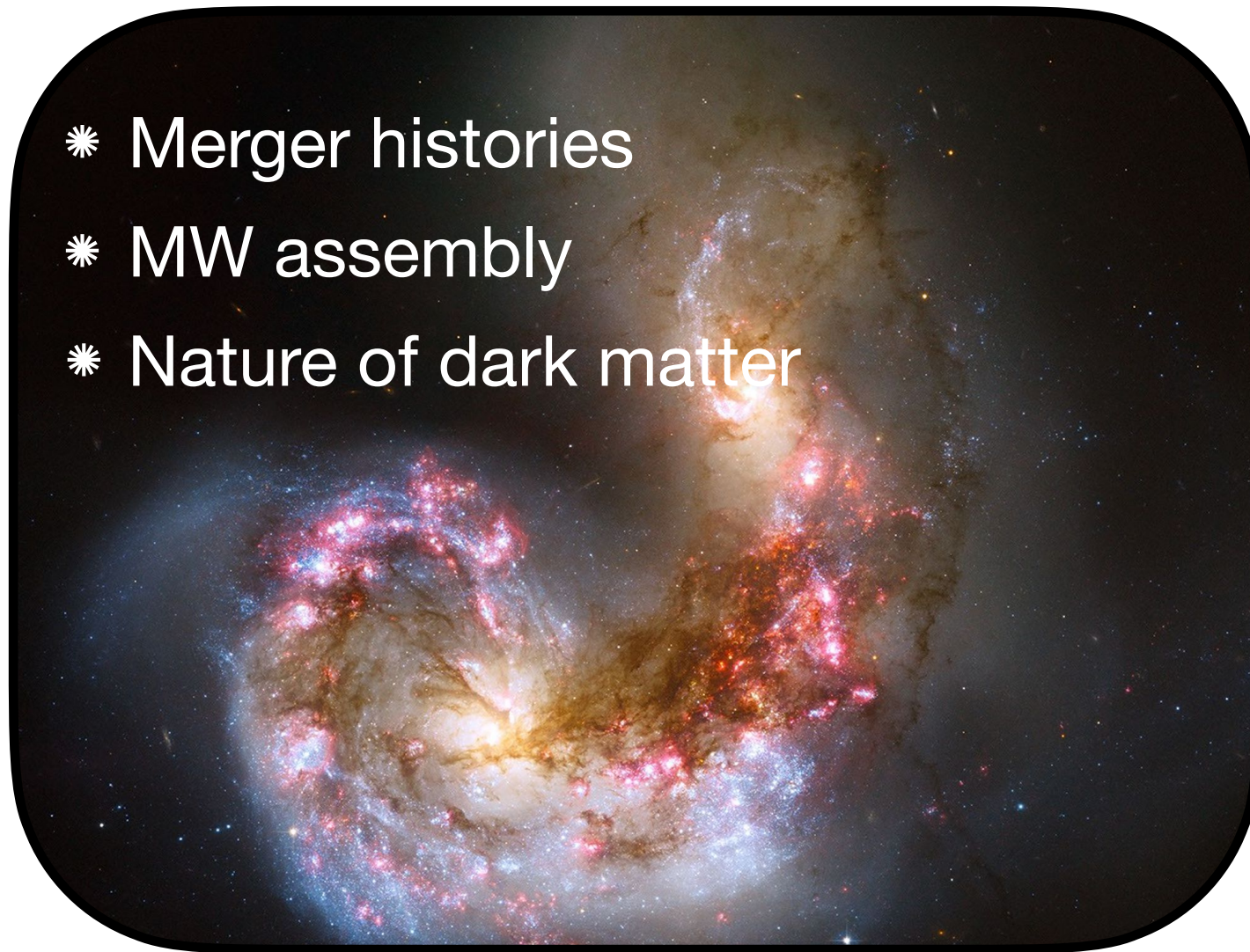
Relics of galaxy formation and evolution

Why study compact objects?

Relics of galaxy formation and evolution

How do galaxies assemble?

- * Merger histories
- * MW assembly
- * Nature of dark matter

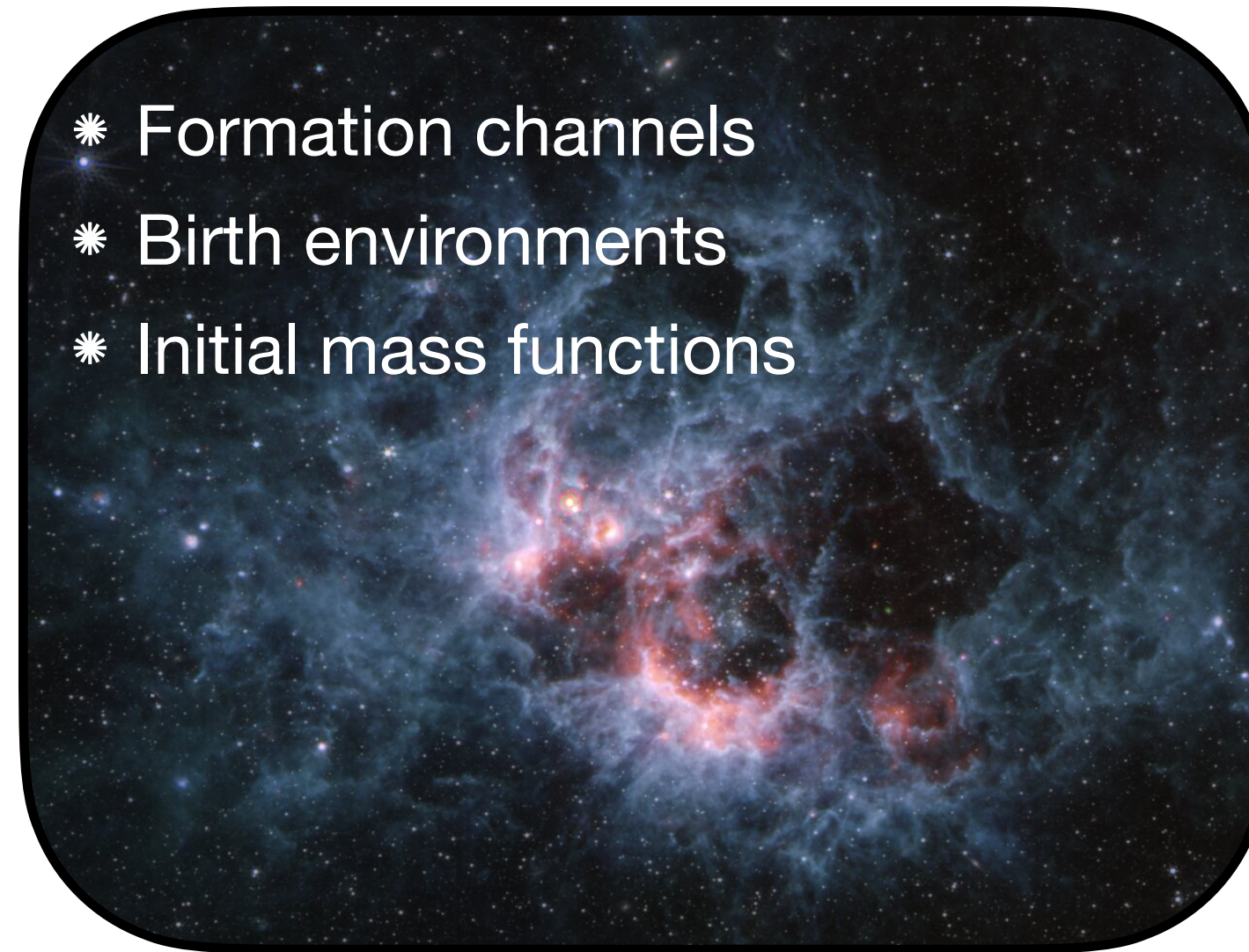


NASA-ESA

Products of extreme formation environments

How do they form?

- * Formation channels
- * Birth environments
- * Initial mass functions

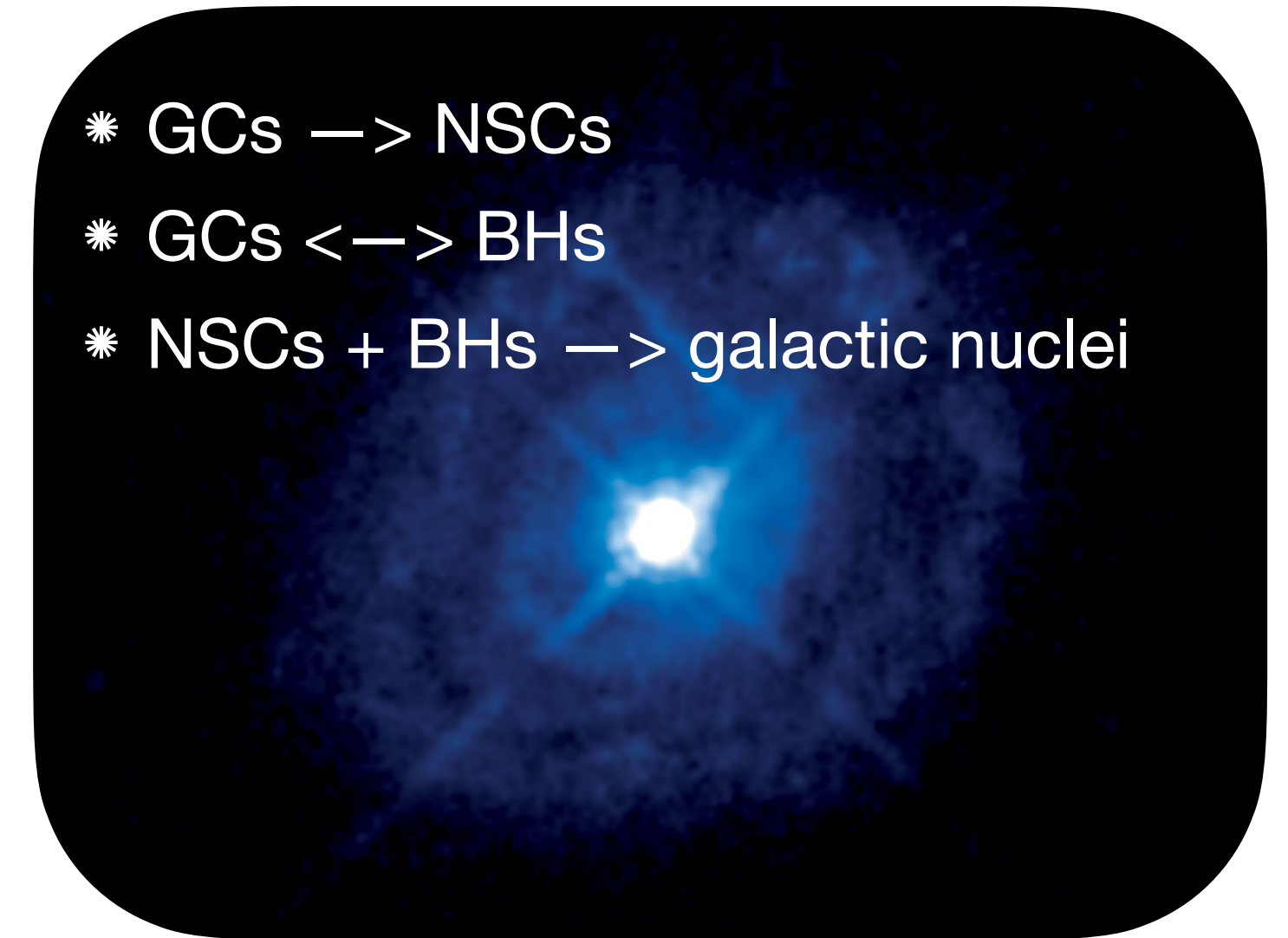


NASA-ESA

An interconnected ecosystem

How do they interact?

- * GCs $\rightarrow$ NSCs
- * GCs $\leftrightarrow$ BHs
- * NSCs + BHs $\rightarrow$ galactic nuclei

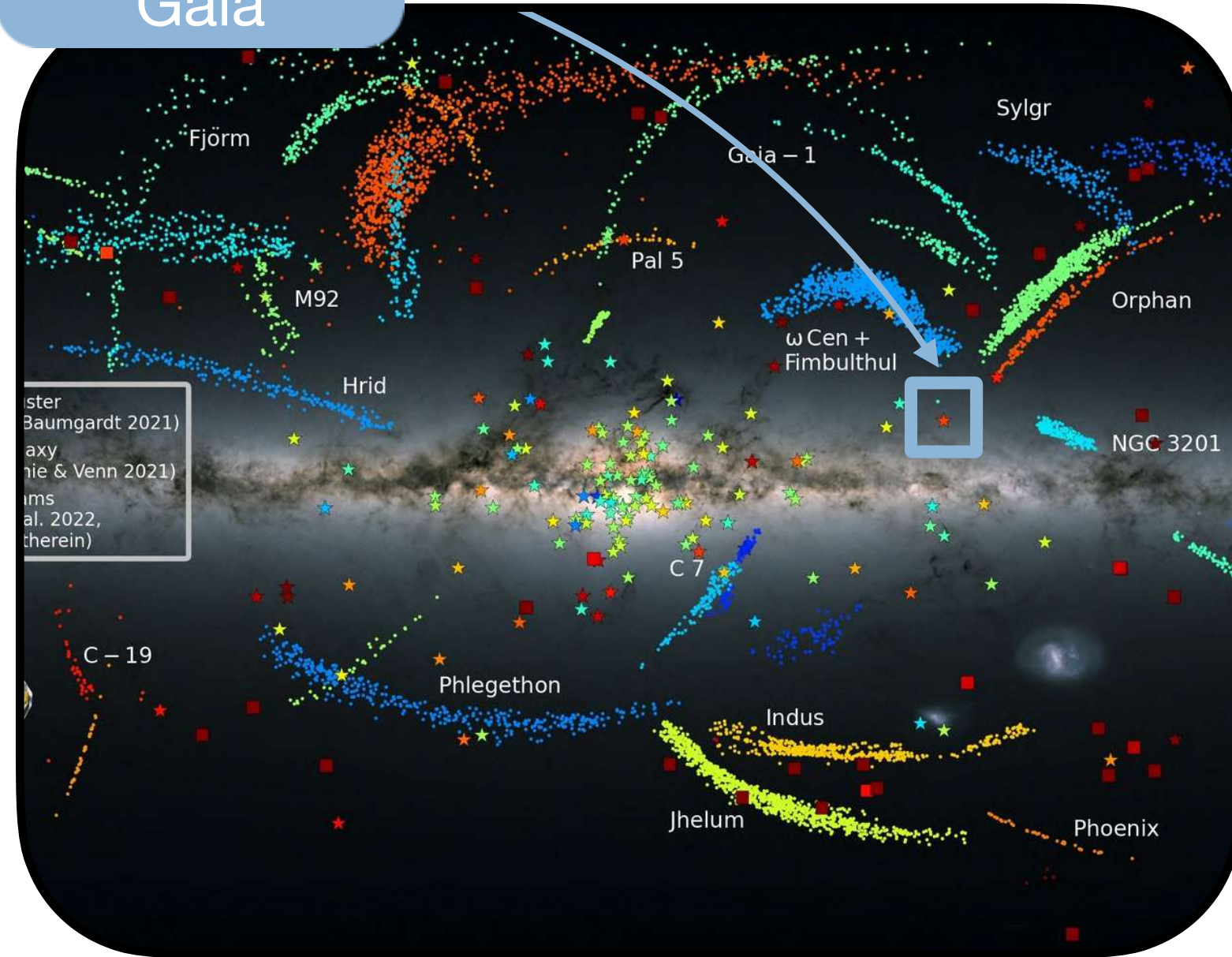


NASA-ESA

Why now?

Gaia

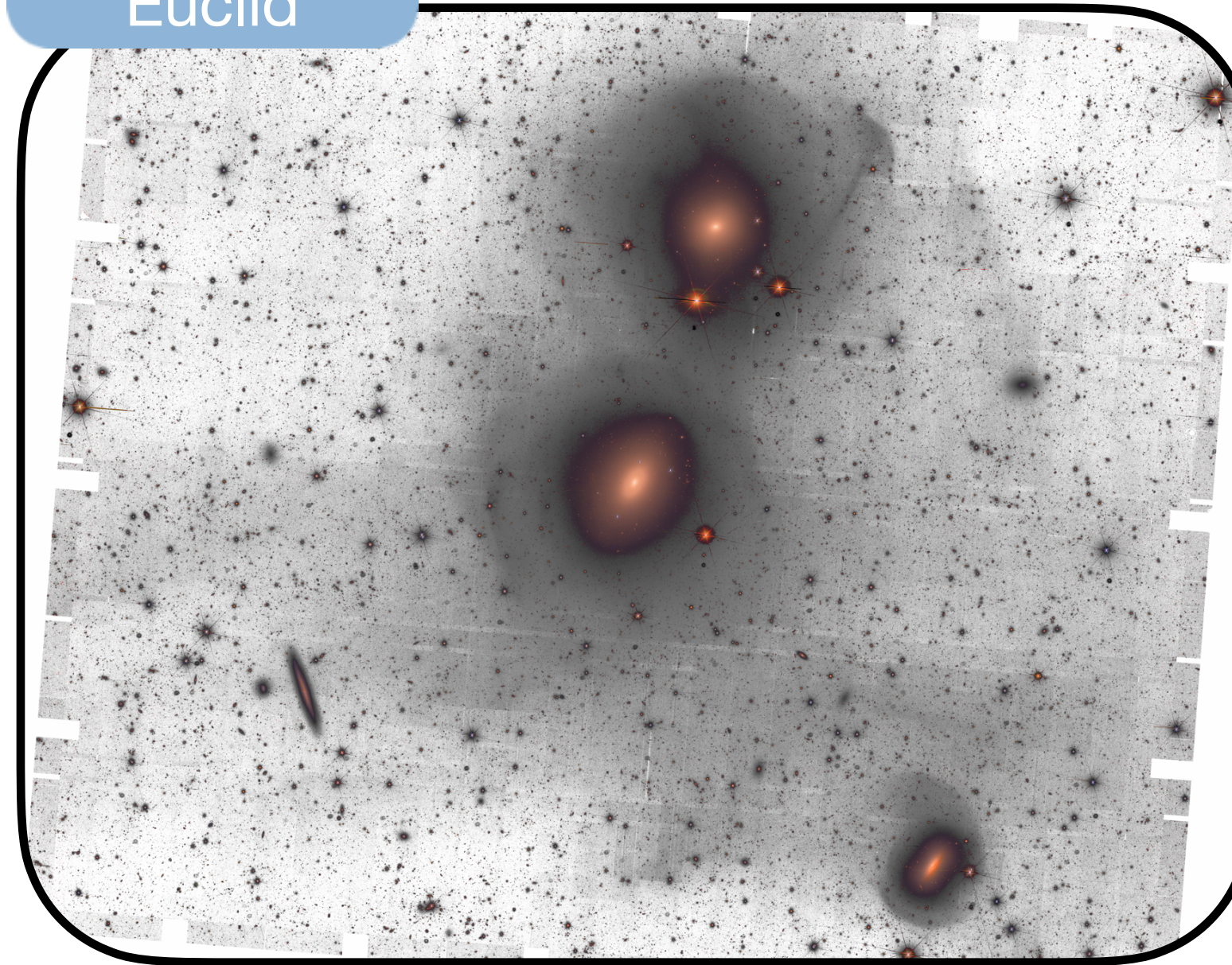
Malhan+22



171 GCs,
41 stellar streams,
3000 open clusters
6D phase space

Euclid

Urbano+25



Half-million extragalactic
GC and NSC candidates
in 4000 galaxies
within <100 Mpc
ERO data: ~7000 GCs in dwarf galaxies

JWST

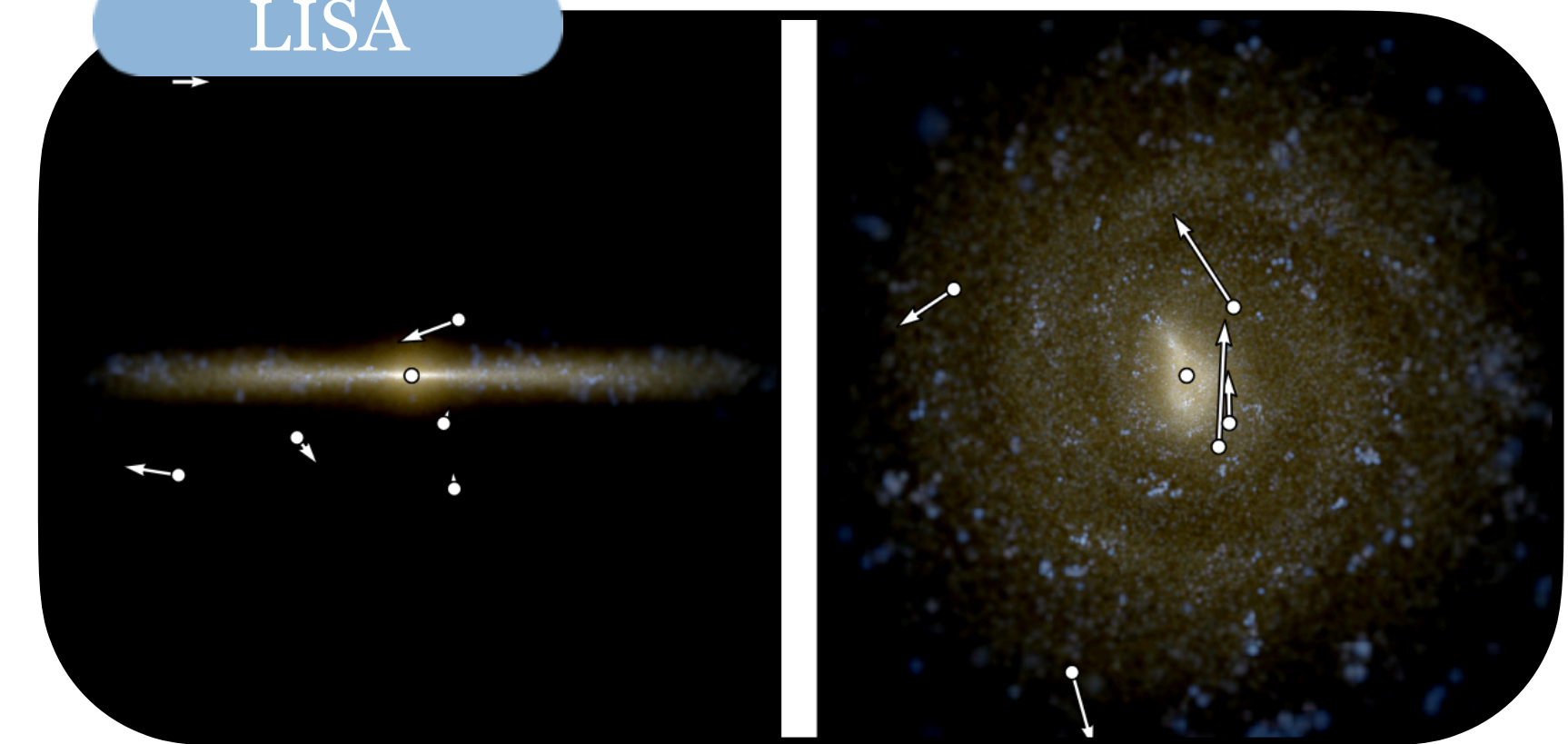
Vanzella+22



~ 2000 compact stellar clumps
in Abell 2744 and Abell S1063
galaxy clusters

LISA

Tremmel+18



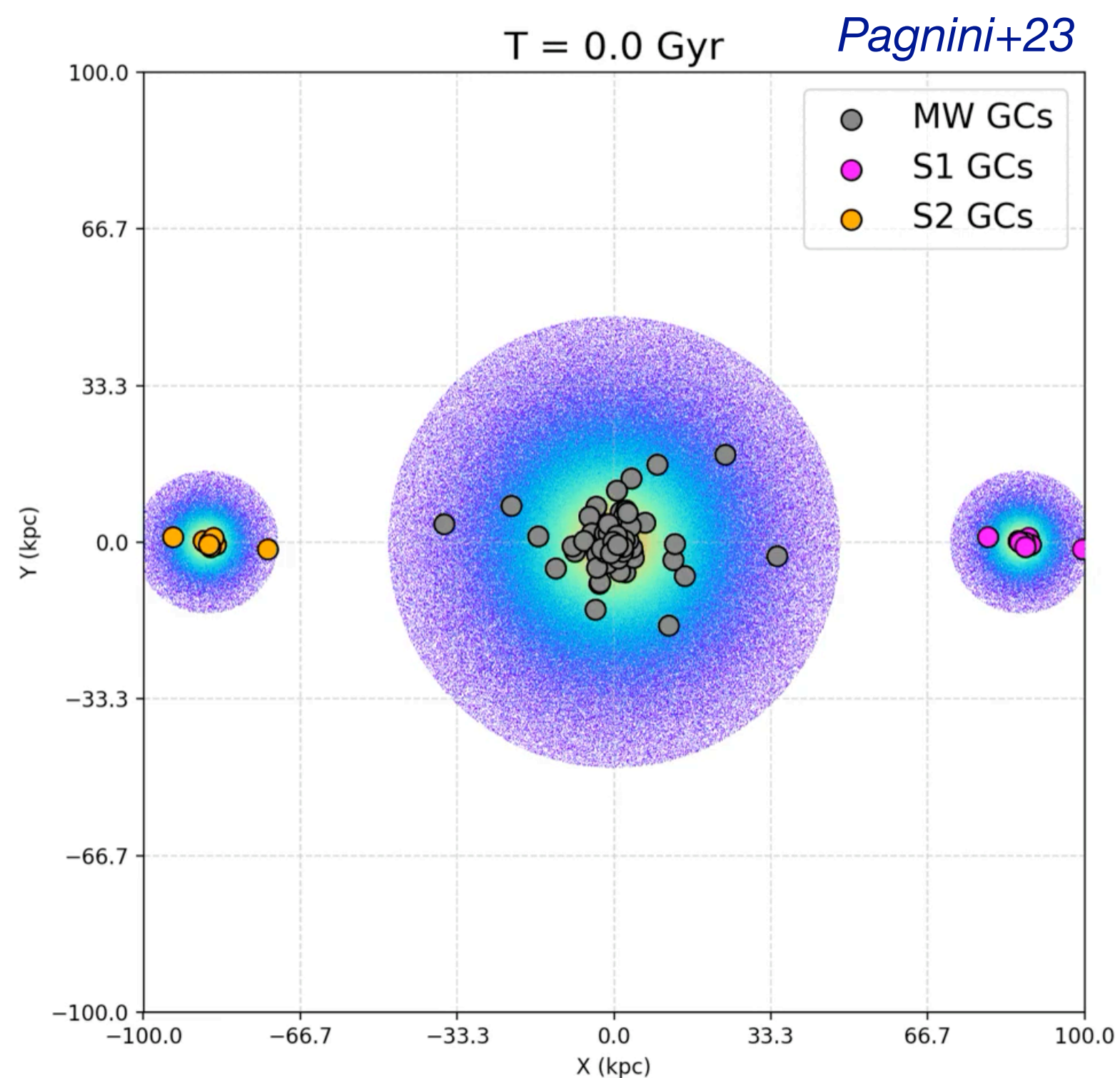
$10^4 - 10^7 M_{\odot}$ (from 2035)

Golden age for these compact objects

Why now?

During a merger, compact objects experience:

- ◆ Gravity
- ◆ Dynamical friction
- ◆ Mass loss
- ◆ Tidal stream formation



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

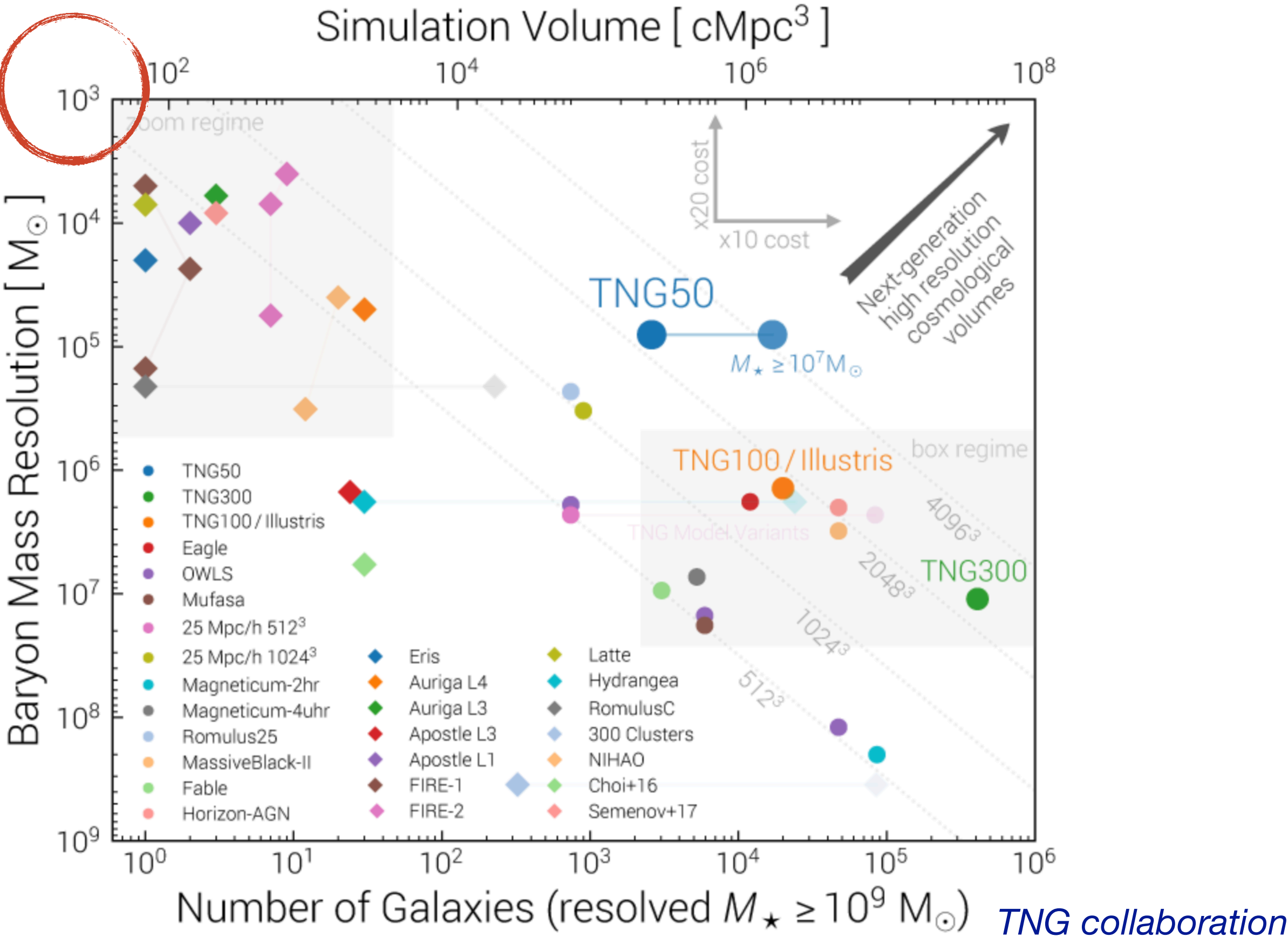
Current limitations in cosmological simulations

not resolved in cosmological simulations —> below the mass and spatial resolution

Globular clusters

Nuclear star clusters

Needed to resolve
GCs and NSCs

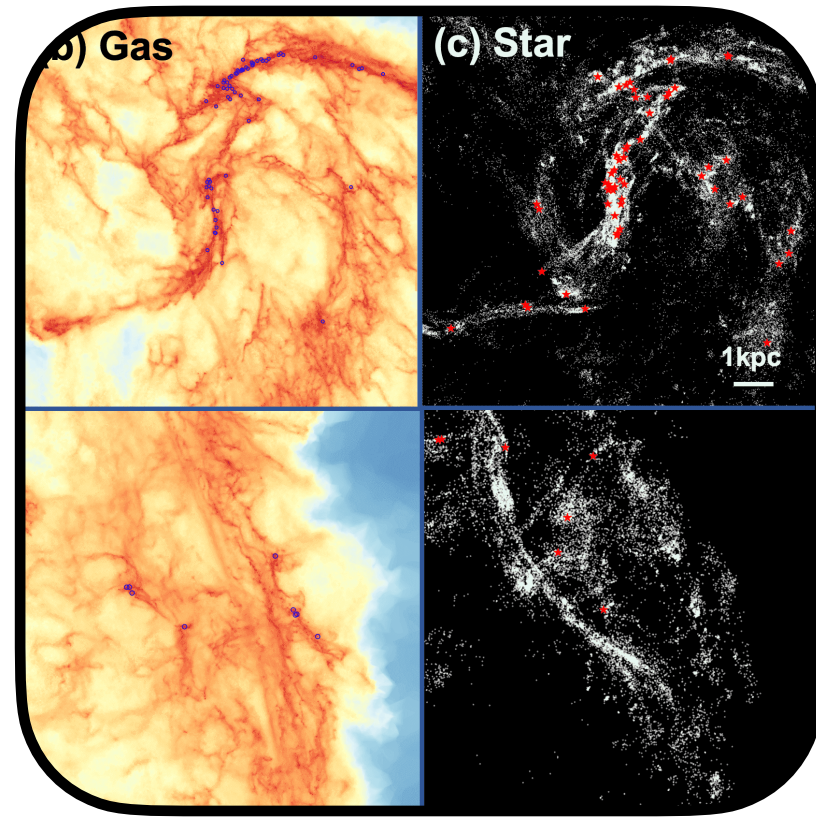


Current limitations in cosmological simulations

If resolved

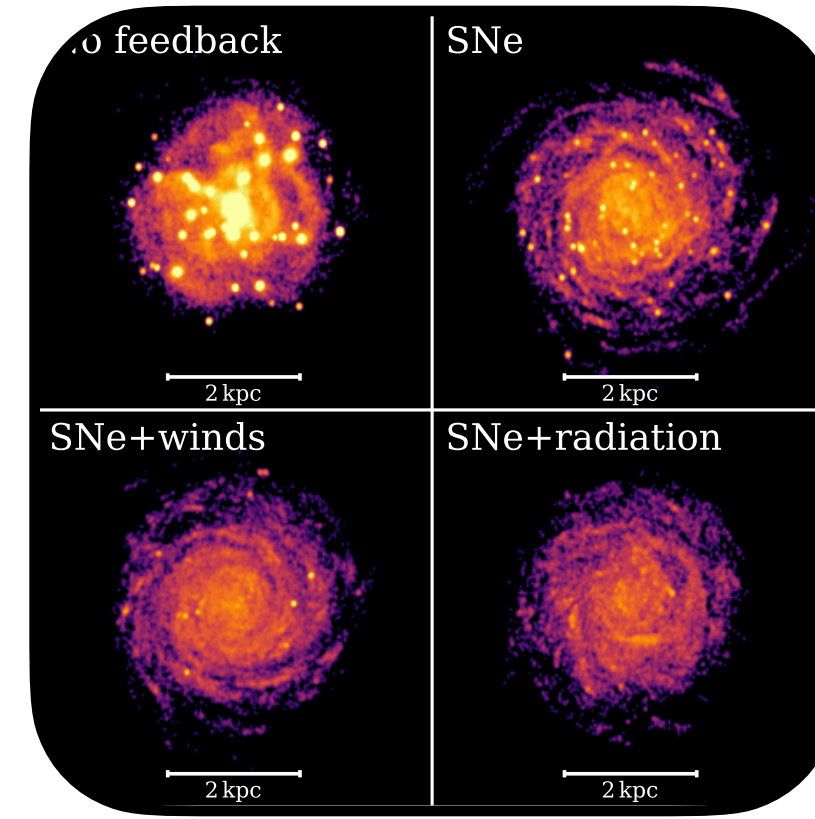
Idealized high-resolution galaxy simulations —> **limited to a few galaxies (1-2)**

Li+22



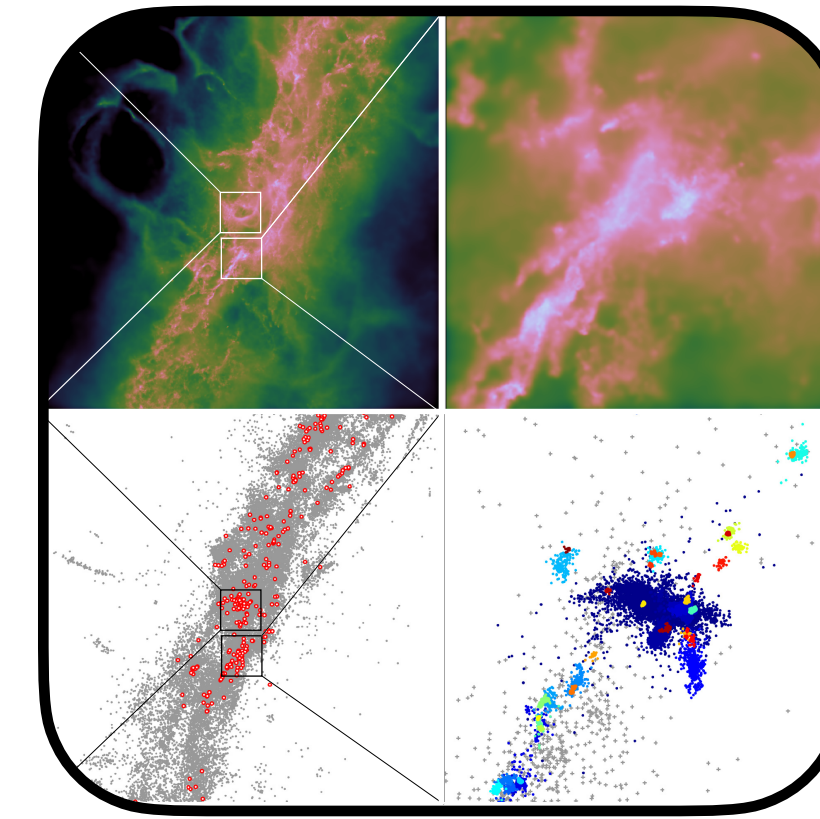
2 MWs over 1 Gyr

Andersson+24



1 dwarf over 1 Gyr

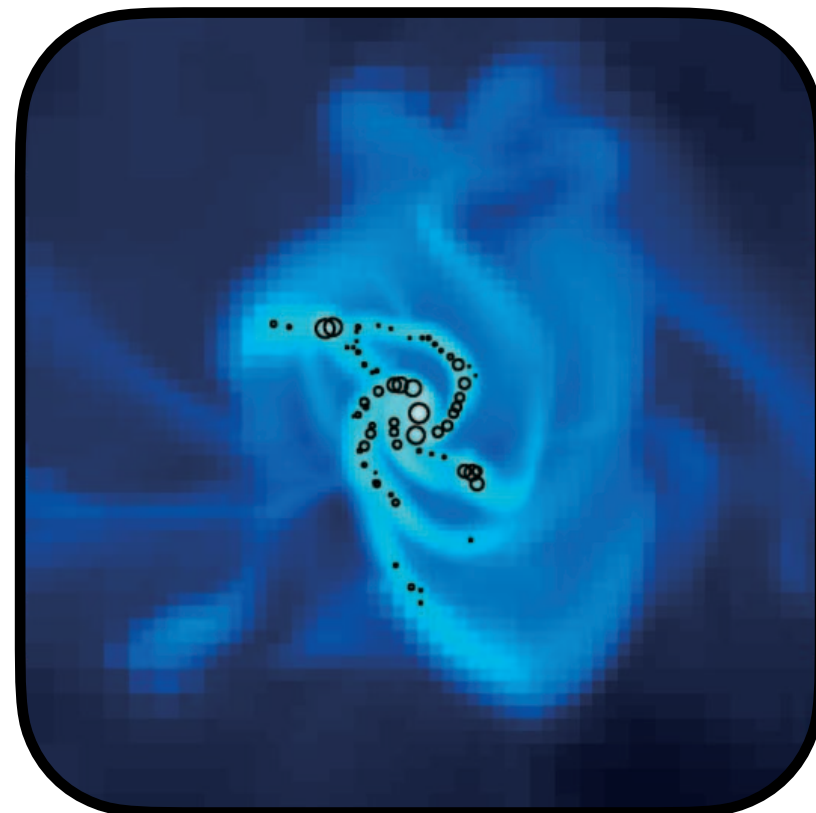
Lahen+20



2 dwarfs over 0.3 Gyr

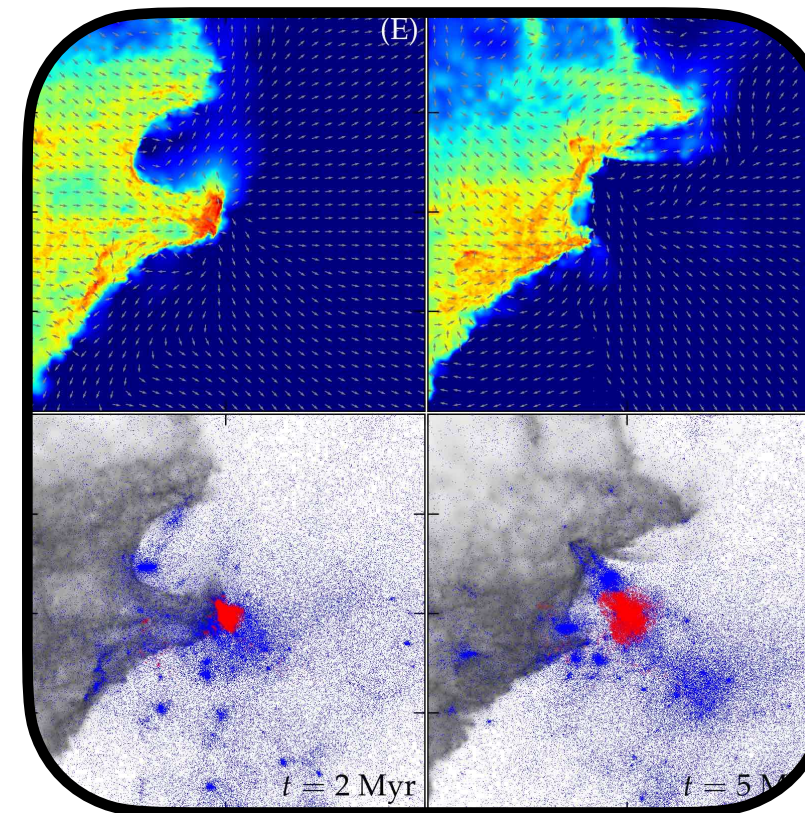
High-resolution cosmological simulations —> **limited to high redshift ($z=3-5$)**

Kravtsov+05



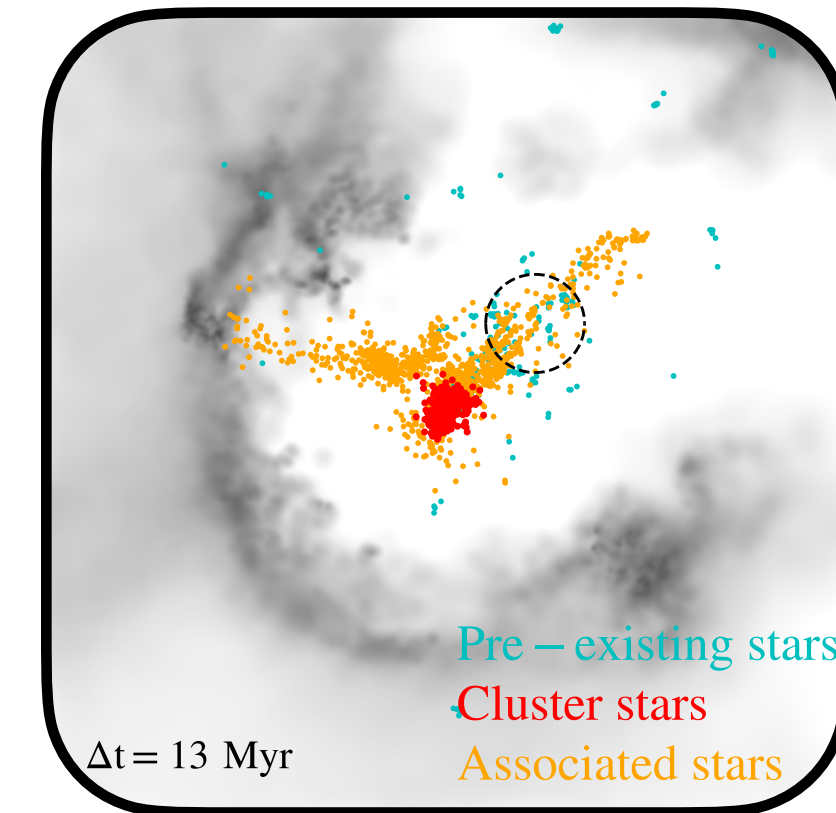
MW galaxy —> $z=3$

Ma+20



Dwarfs —> $z=5$

Sameie+22



Dwarfs —> $z=4$

Globular clusters

Nuclear star clusters

Current limitations in cosmological simulations

Resolved but

BH particles are artificially repositioned toward the local potential minimum

—> **Prevents numerical scattering and enables efficient subgrid modelling of BH accretion and feedback** *Bahé+21*

Black holes

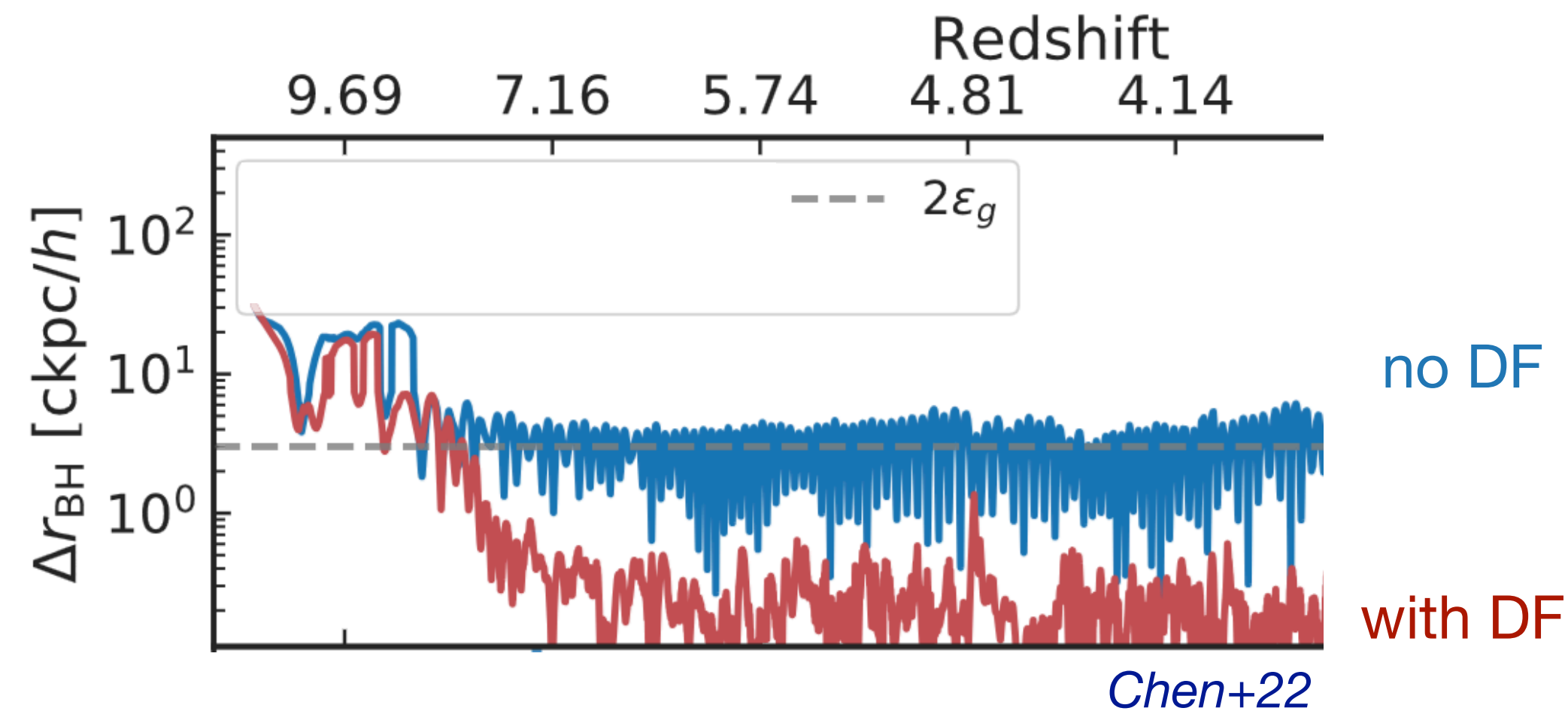
Unresolved dynamical friction is treated using subgrid prescriptions

—> **BH dynamics down to sub-kpc scales**

Chen+22

Interactions between BHs and nuclear star clusters are not modeled

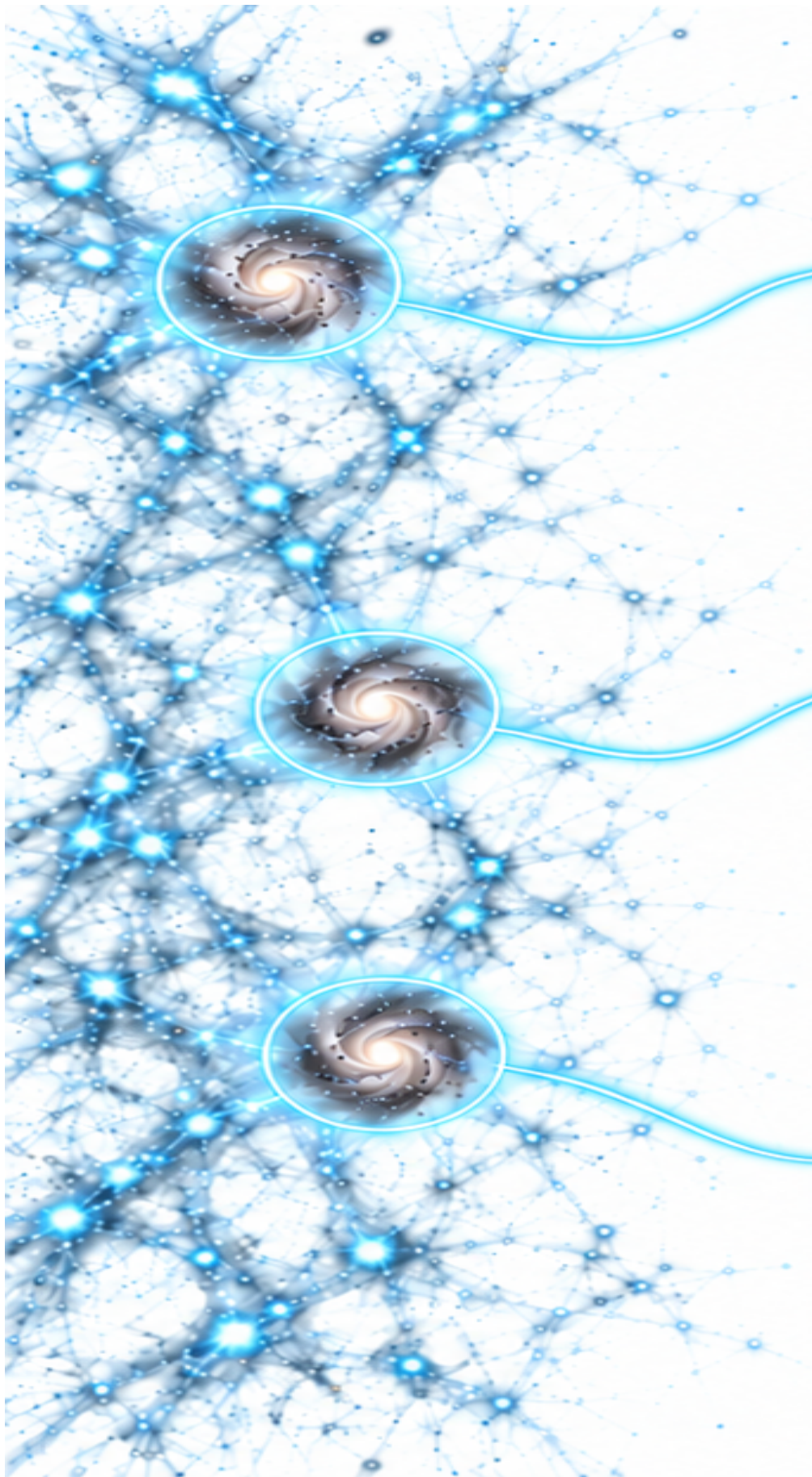
—> **insufficient spatial and mass resolution**



Overcoming these numerical limitations?

Our approach

Cosmological simulation

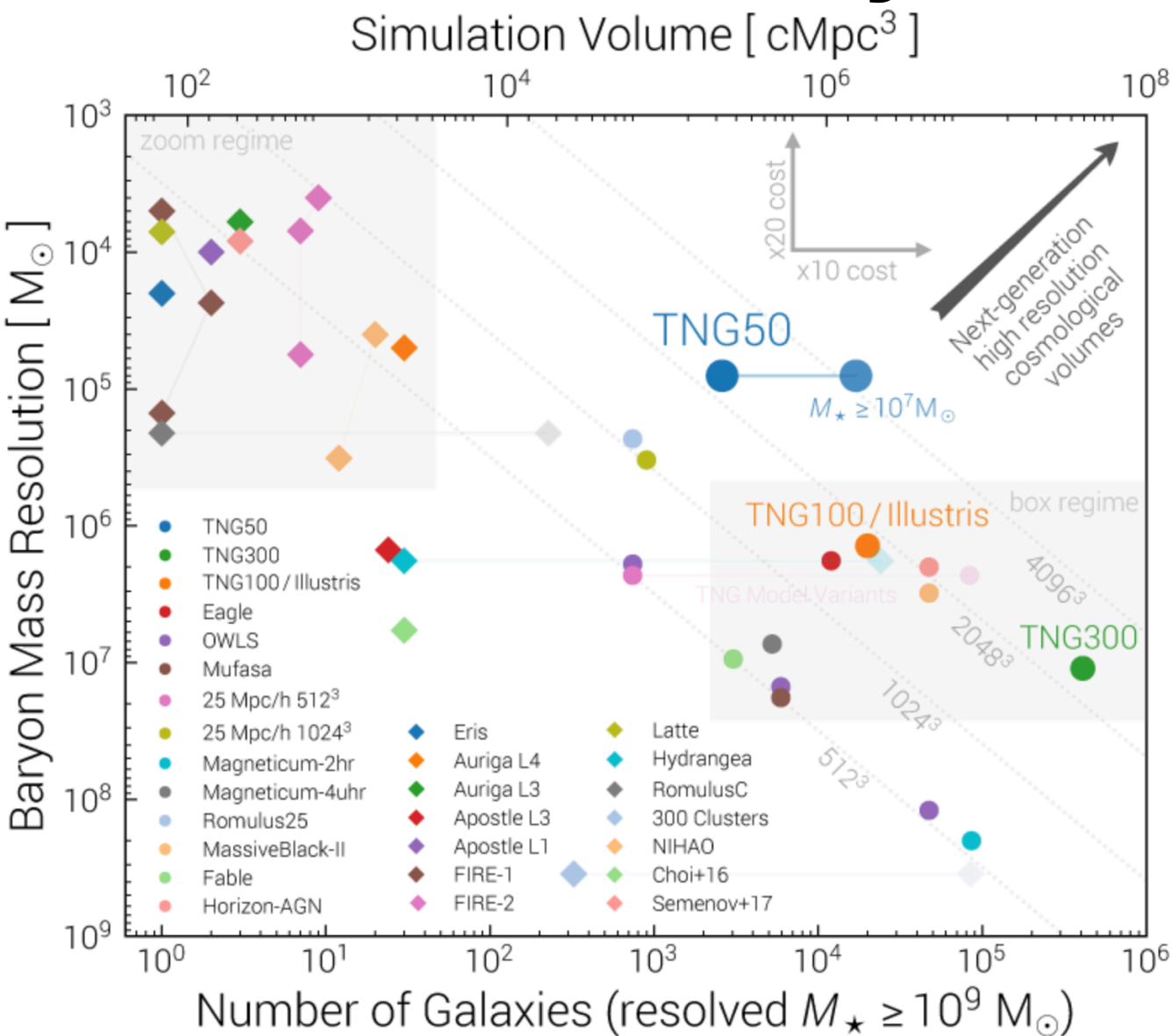


TNG50
200 MW-like galaxies

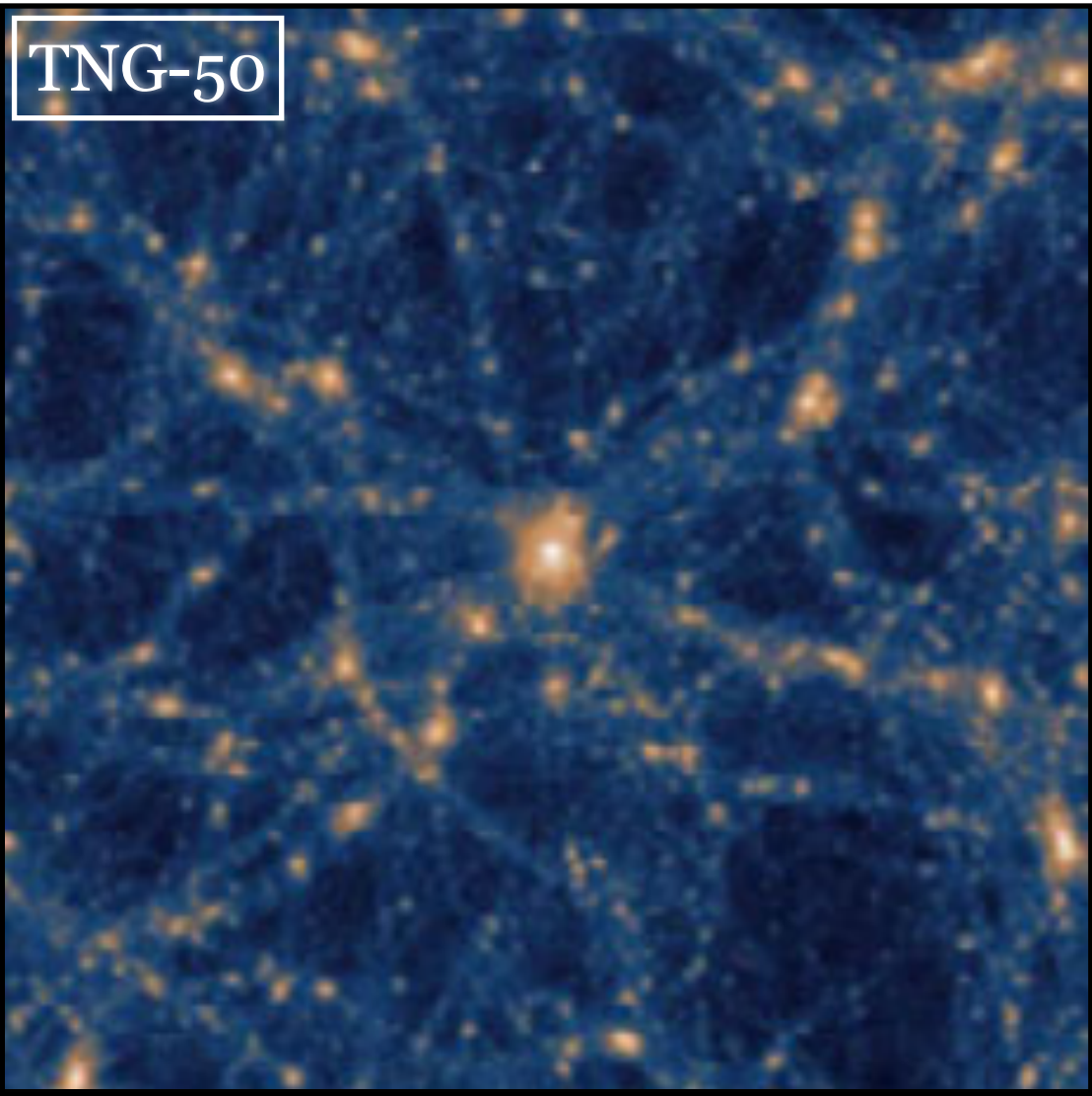
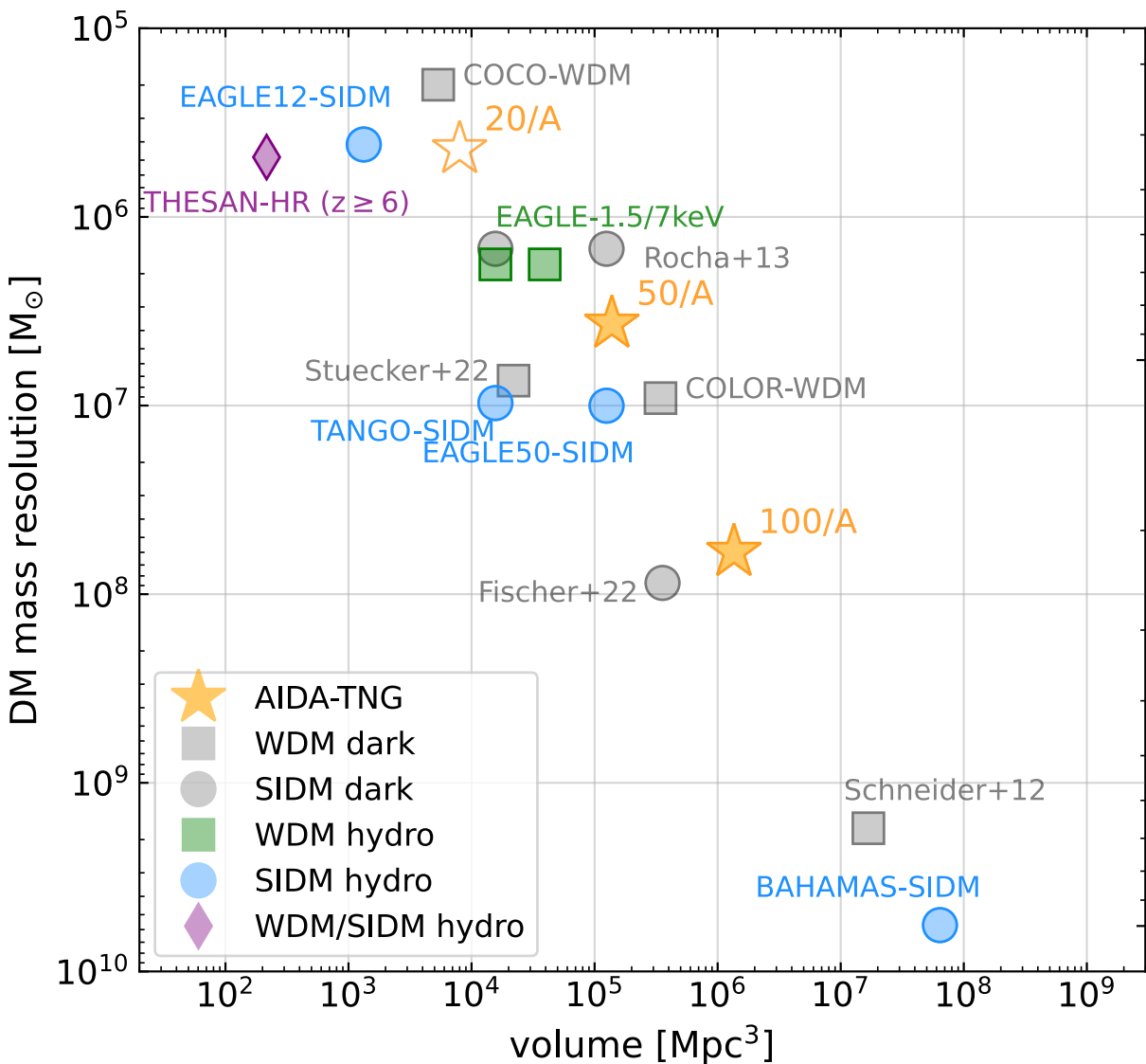
Cosmological context:

- ◆ realistic galaxy formation model
- ◆ realistic galaxy assembly
- ◆ statistics

CDM theory



Other DM theories

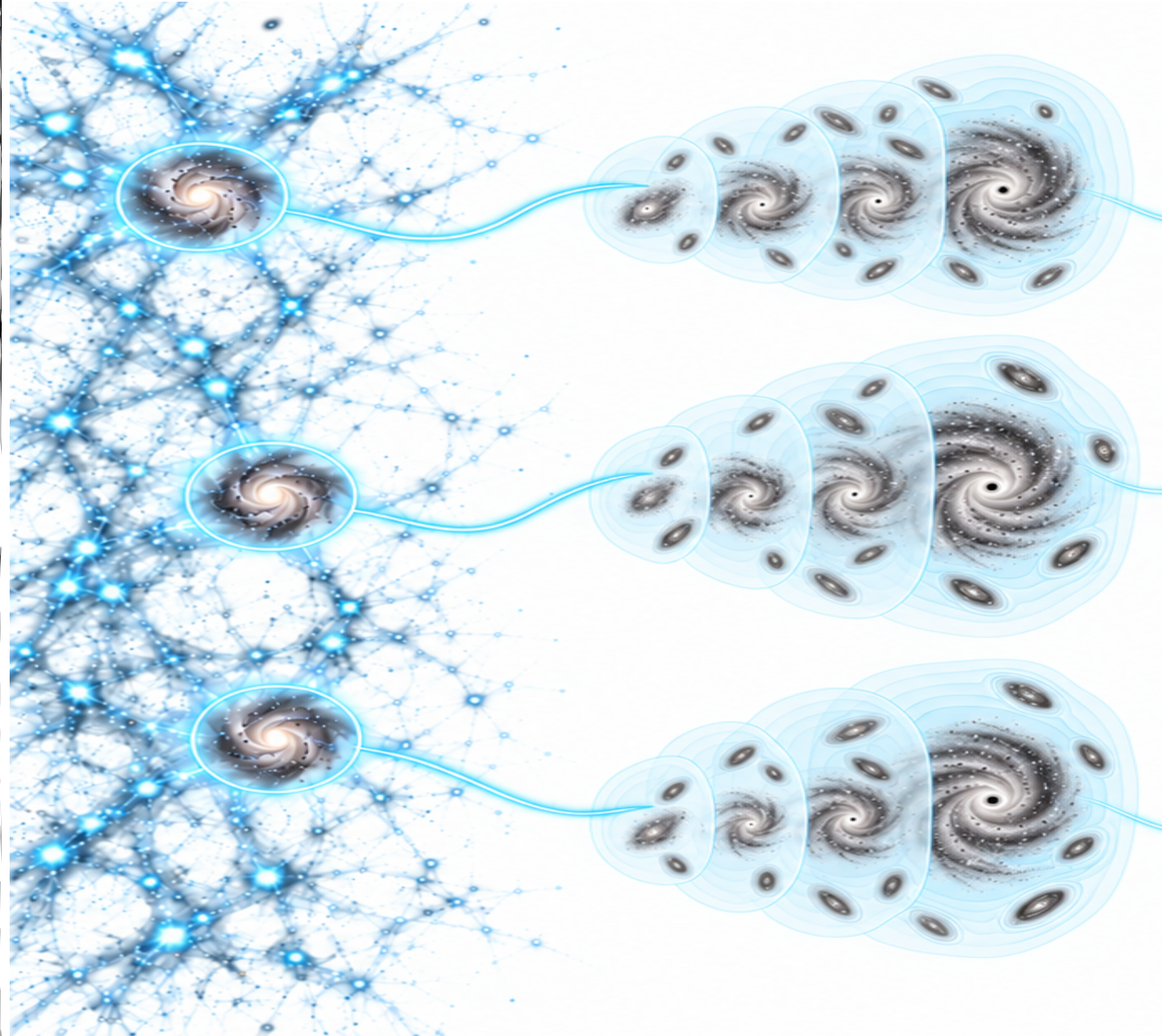


TNG collaboration

Our approach

Cosmological simulation

Reconstructing the evolving
cosmological environment



TNG50
200 MW-like galaxies

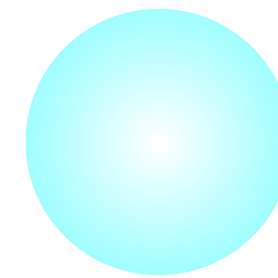
$$\Phi_{\text{env}}(t) = \Phi_{\text{host}}(t) + \sum_i \Phi_{\text{sat},i}(t)$$

Galaxy profiles:

◆ Global shape

Spherical potentials:

$$\rho_{\text{DM}}(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right) \left(1 + \frac{r}{r_s}\right)^2}$$



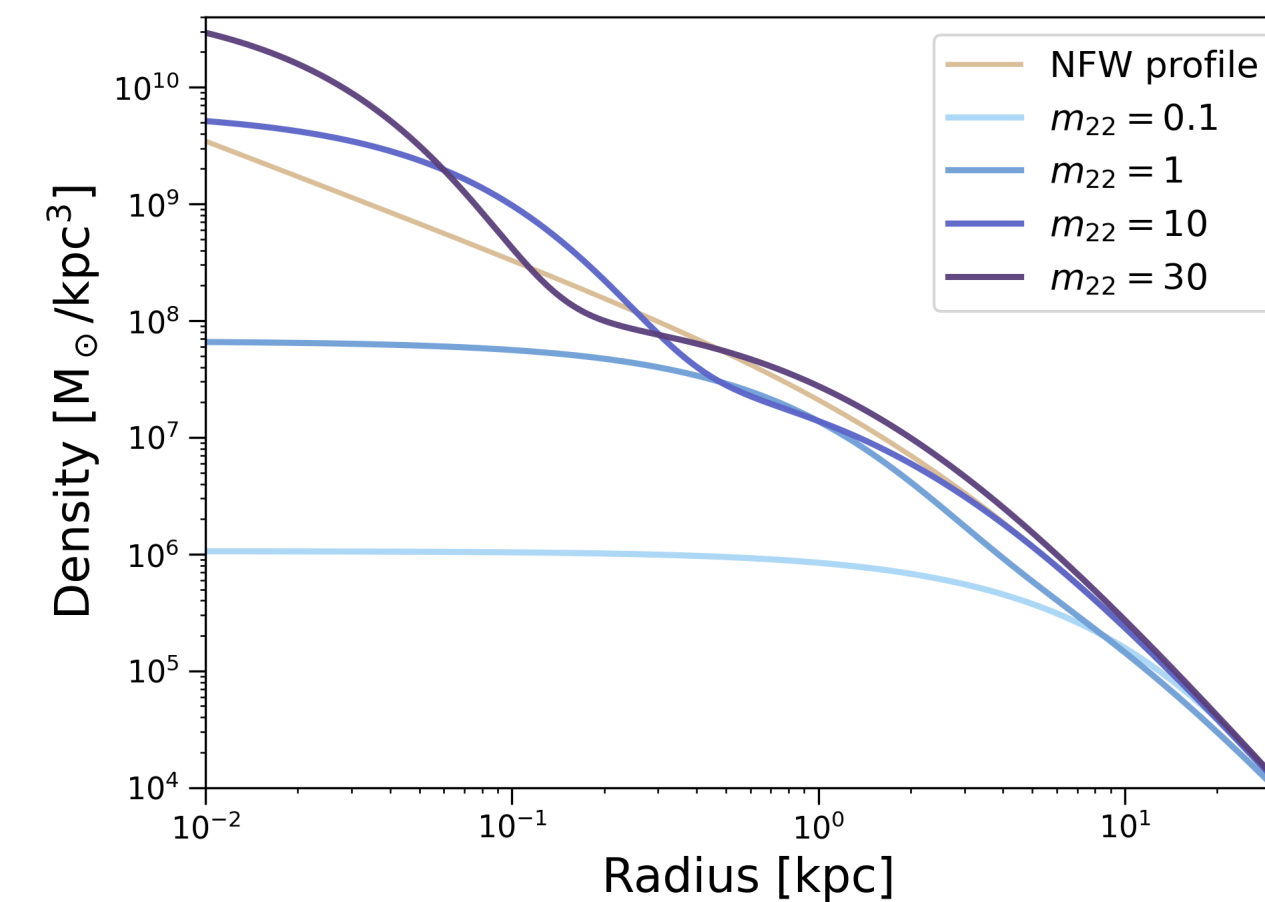
Non-spherical potentials:

$$\rho_{\text{DM}}(x, y, z) = \frac{\rho_0}{(m/r_s)^\alpha (1 + m/r_s)^{\beta-\alpha}}$$



◆ Internal shape

Cuspy profile
(CDM)



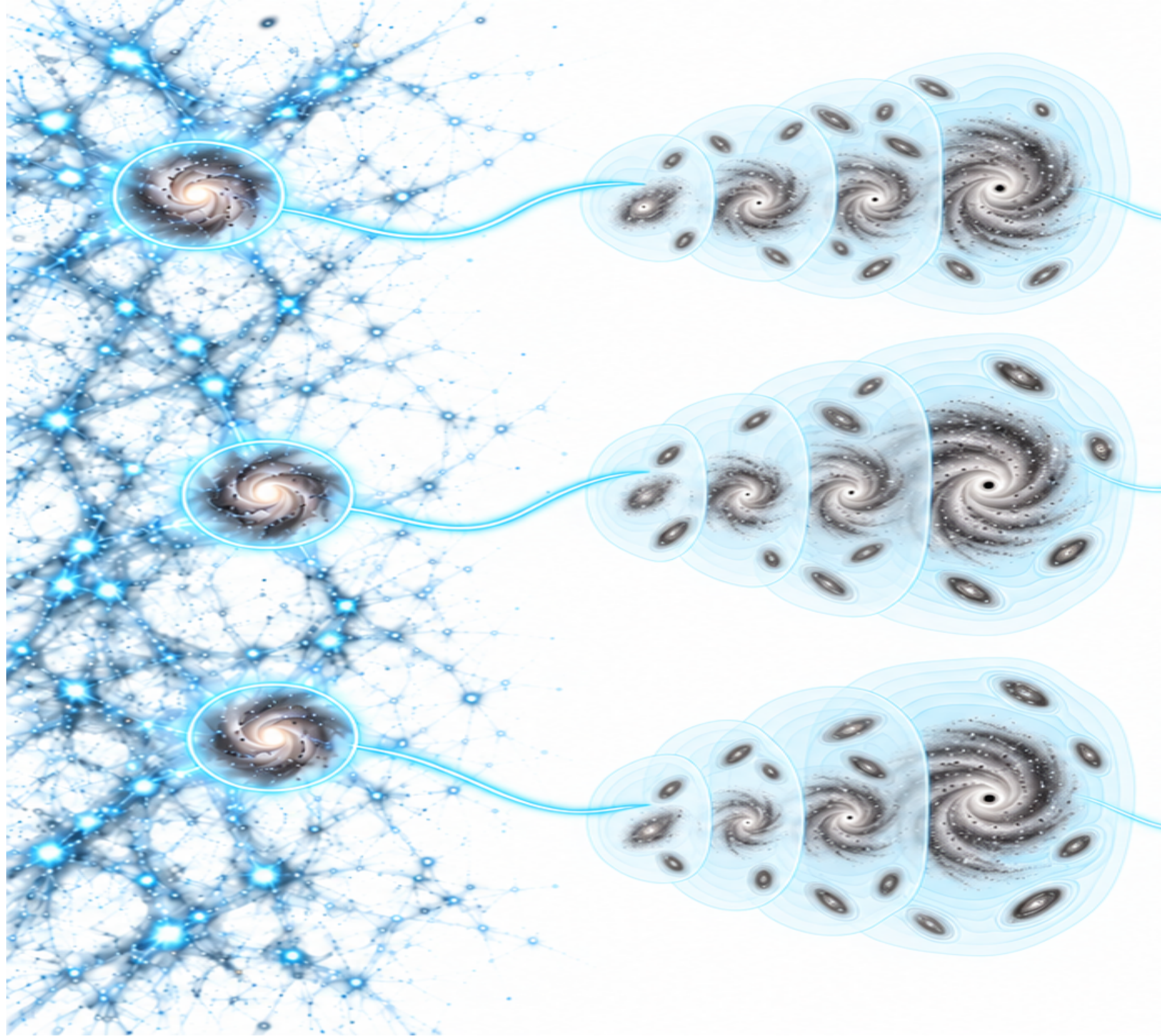
Besnard+26

Core profile
(baryons or
FDM)

Our approach

Cosmological simulation

Reconstructing the evolving
cosmological environment

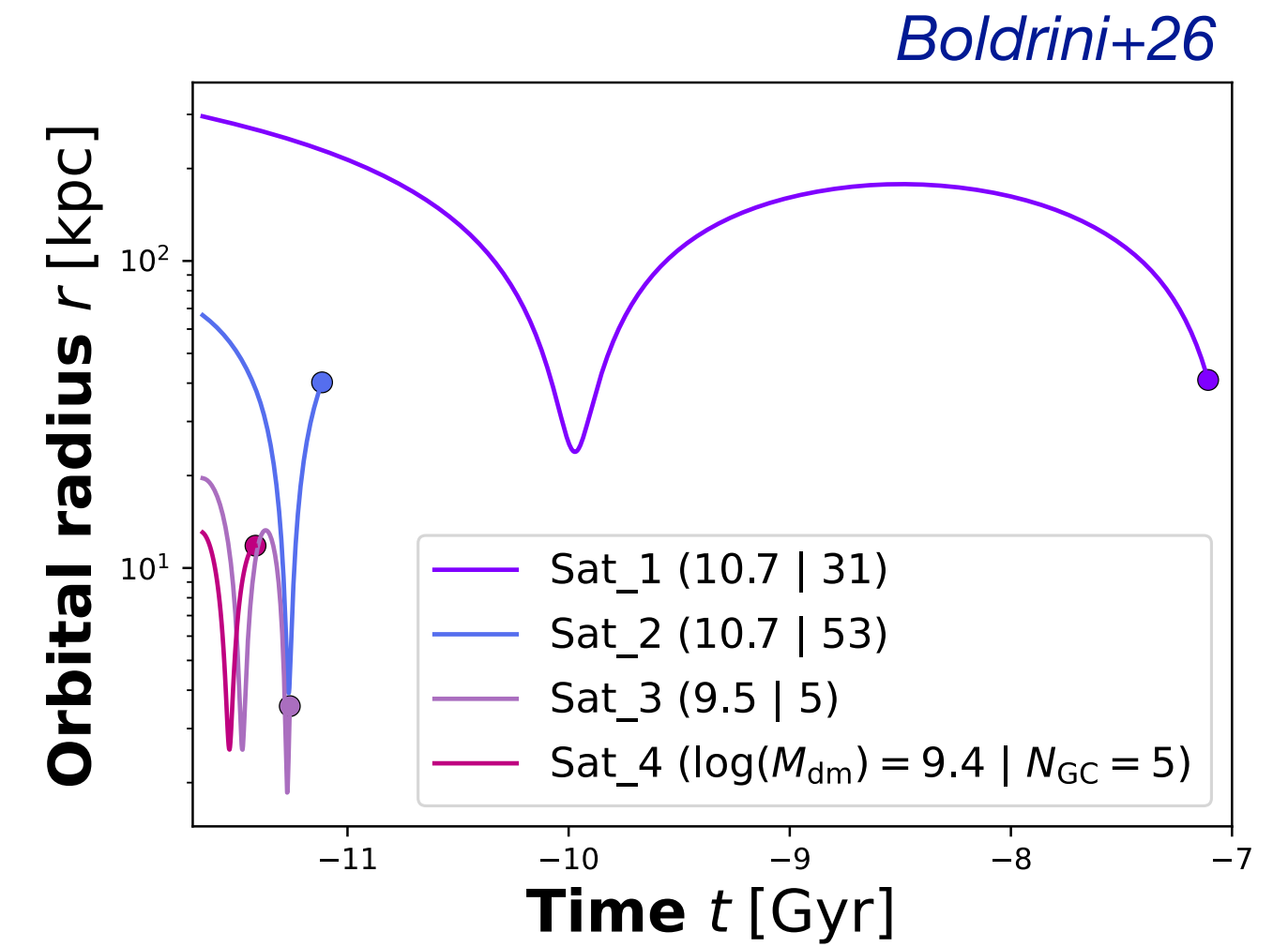
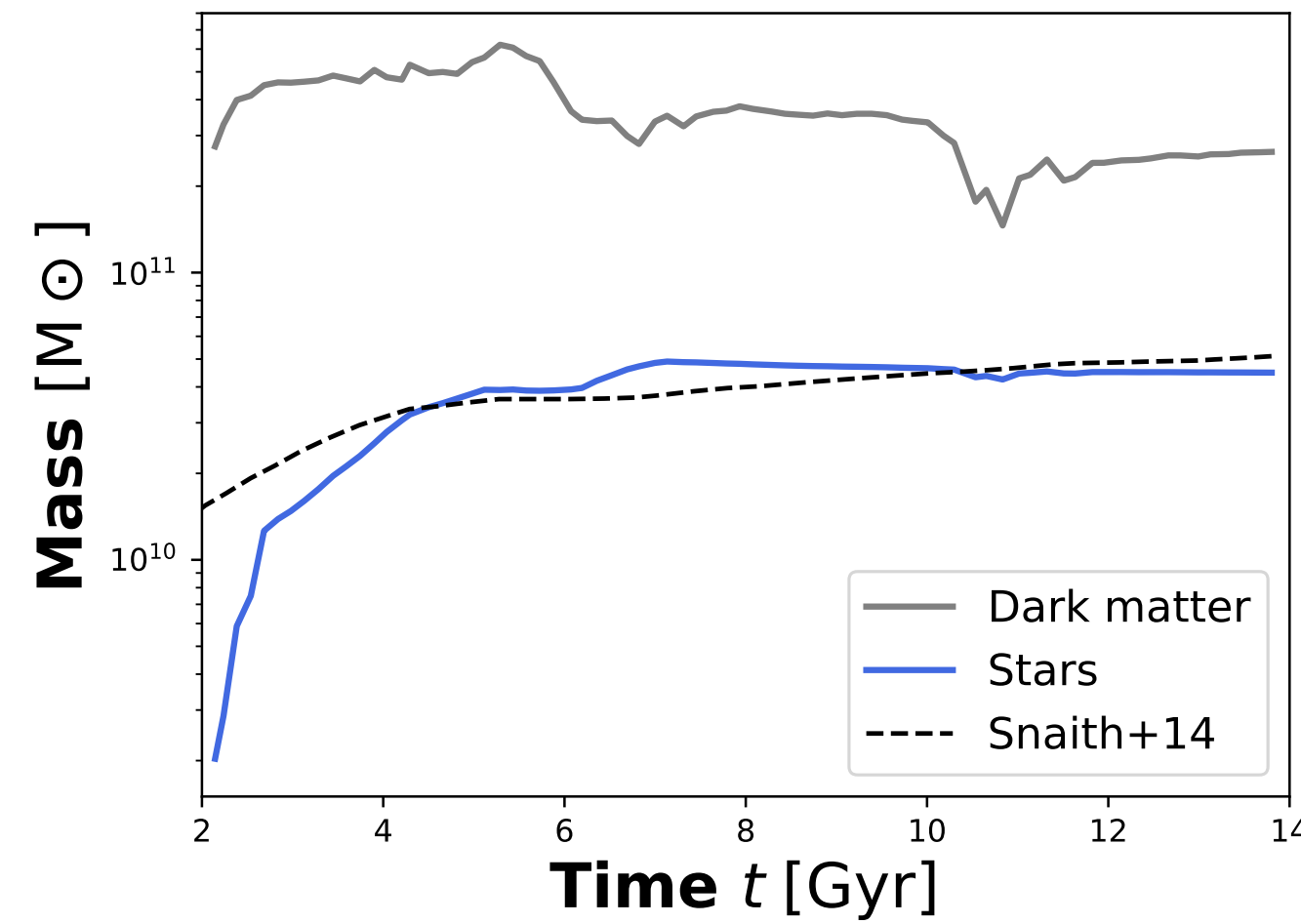


TNG50
200 MW-like galaxies

$$\Phi_{\text{env}}(t) = \Phi_{\text{host}}(t) + \sum_i \Phi_{\text{sat},i}(t)$$

Galaxies are modeled:

- ◆ between $z=3$ and $z=0$
- ◆ via analytical spherical potentials for dark matter and stars extracted from the simulation
- ◆ with their merging satellite galaxies represented by moving potential



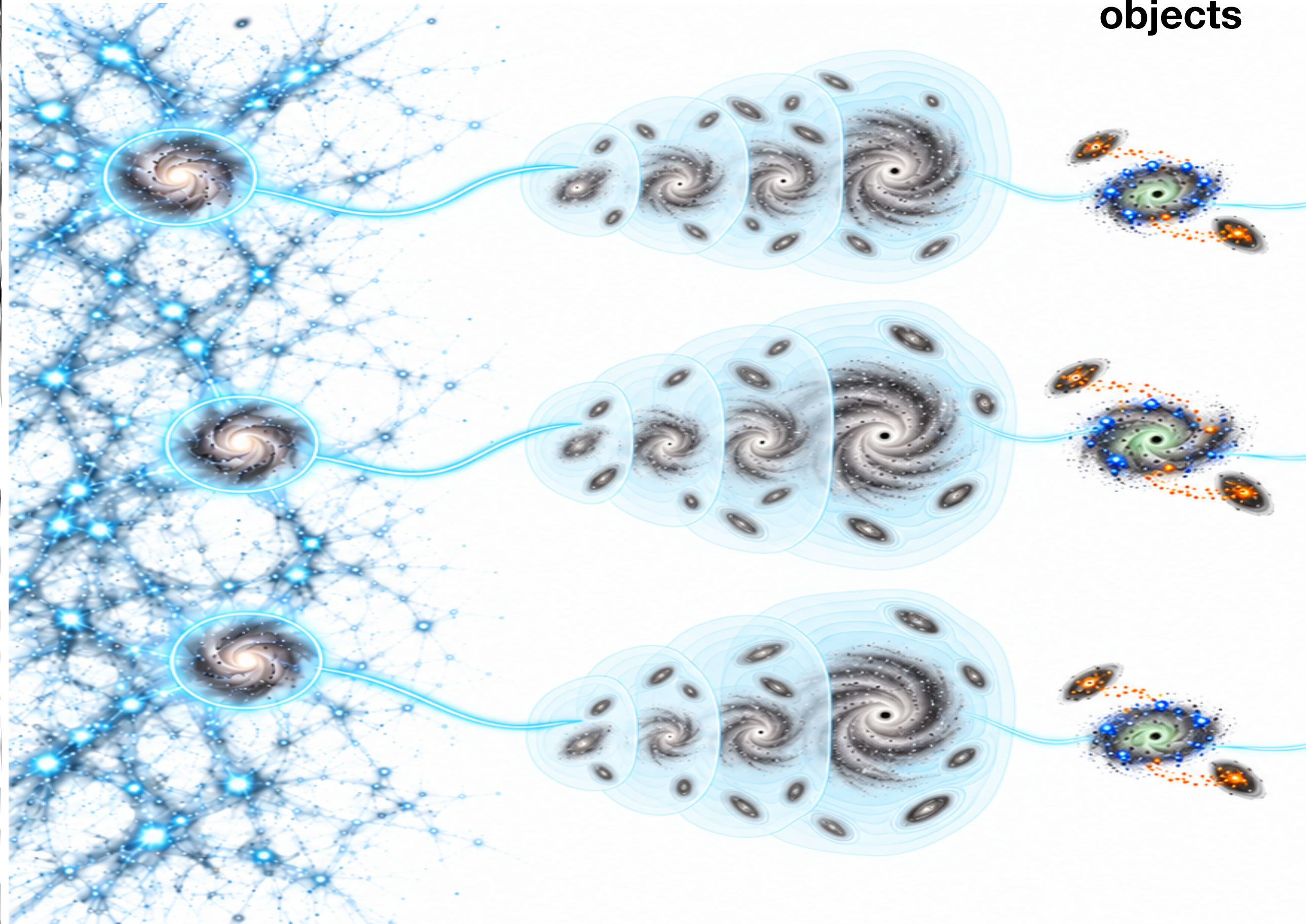
Our approach

Cosmological simulation

Reconstructing the evolving cosmological environment

Tagging compact objects

Pfeffer+17, Reina-Campos+22, Grudic+23, Creasey+18, Ramos+20, Halbesma+20, Park+22, Rodriguez+23, Doppel+23, Chen+23, +24



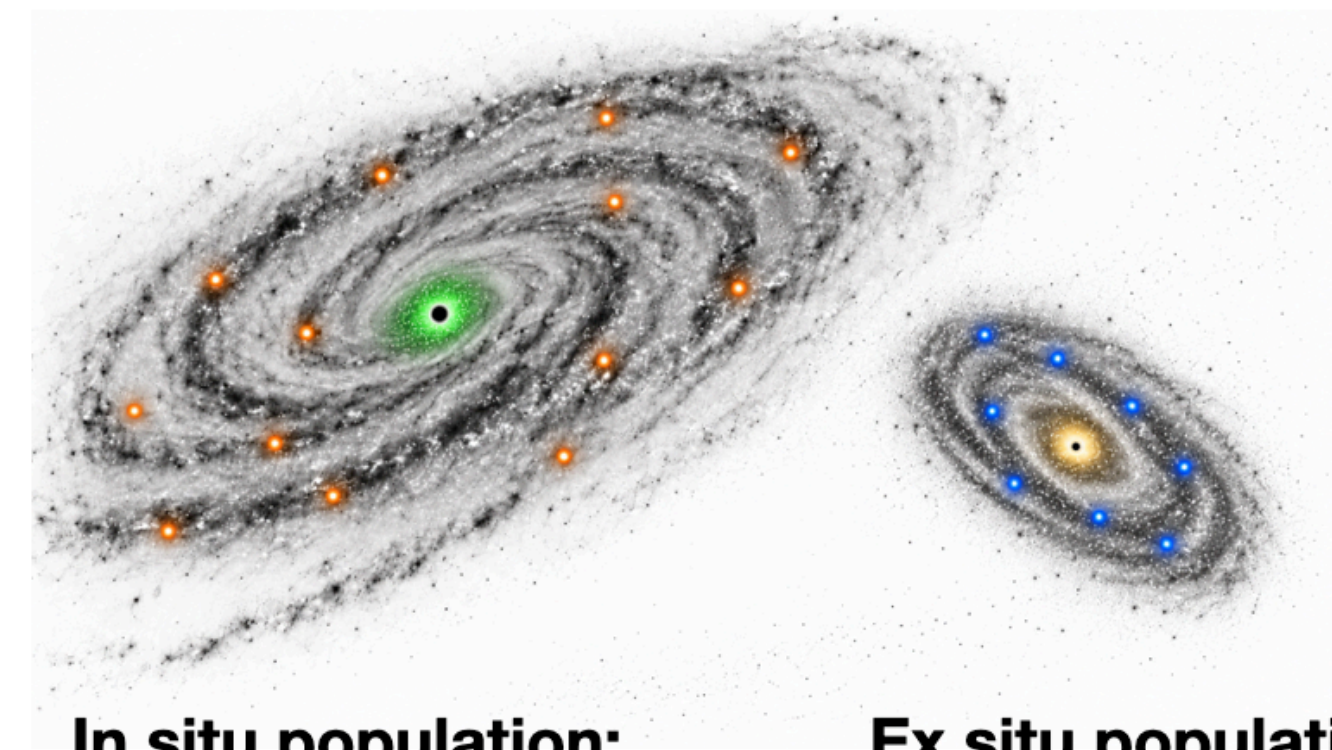
TNG50
200 MW-like galaxies

$$\Phi_{\text{host}}(t) + \sum_i \Phi_{\text{sat},i}(t)$$

$$X(t_0), V(t_0), M(t_0)$$

Tagging methods:

- ◆ in post-processing → no need to rerun simulations
- ◆ already done in cosmological simulations such as *Illustris TNG-50, FIRE, EAGLE, AURIGA, ...*
- ◆ new: first time on a large statistical sample (200 MWs)
- ◆ new: compact stellar systems and black holes



In situ population:

- ◆ GCs
- ◆ NSC
- ◆ MBH

Ex situ population:

- ◆ GCs
- ◆ NSC
- ◆ MBH

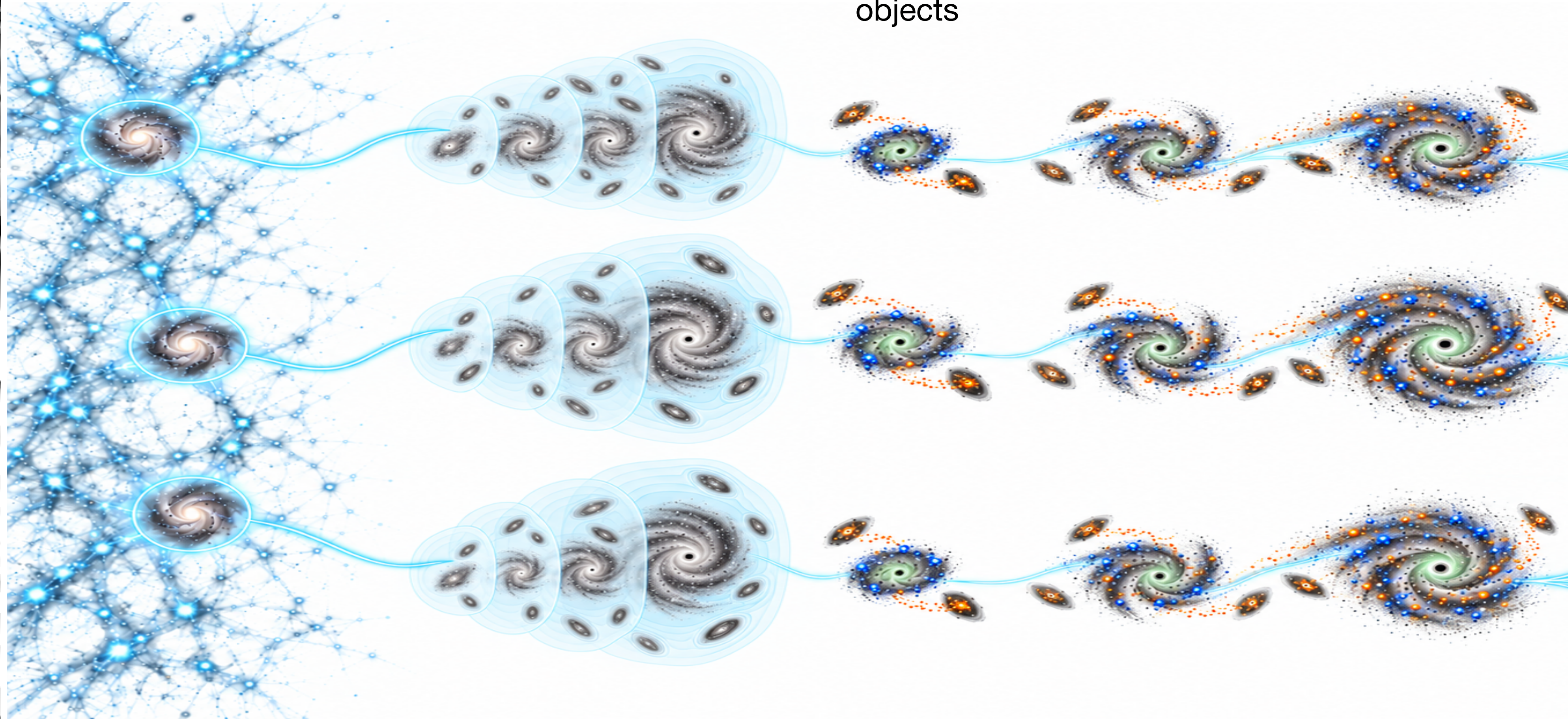
Our approach

Cosmological simulation

Reconstructing the evolving
cosmological environment

Tagging
compact
objects

Following their dynamics



TNG50
200 MW-like galaxies

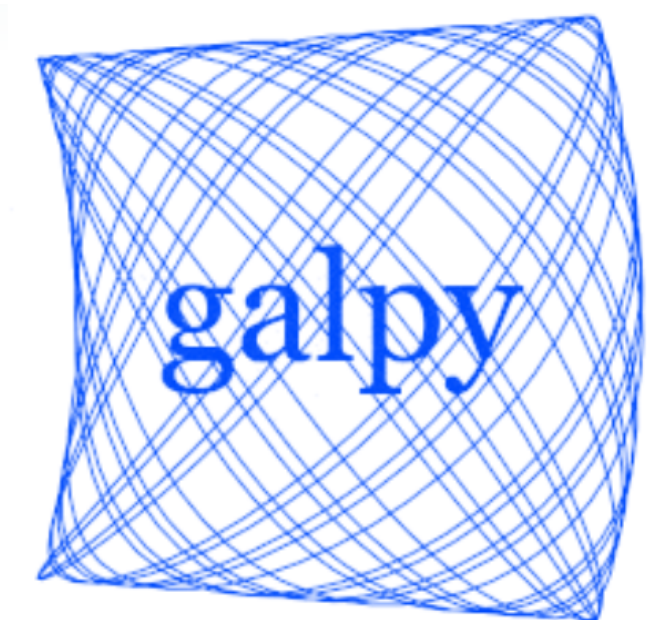
$$\Phi_{\text{host}}(t) + \sum_i \Phi_{\text{sat},i}(t)$$

$$X(t_0), V(t_0), M(t_0)$$

$$X(t), V(t), M(t)$$

Physics:

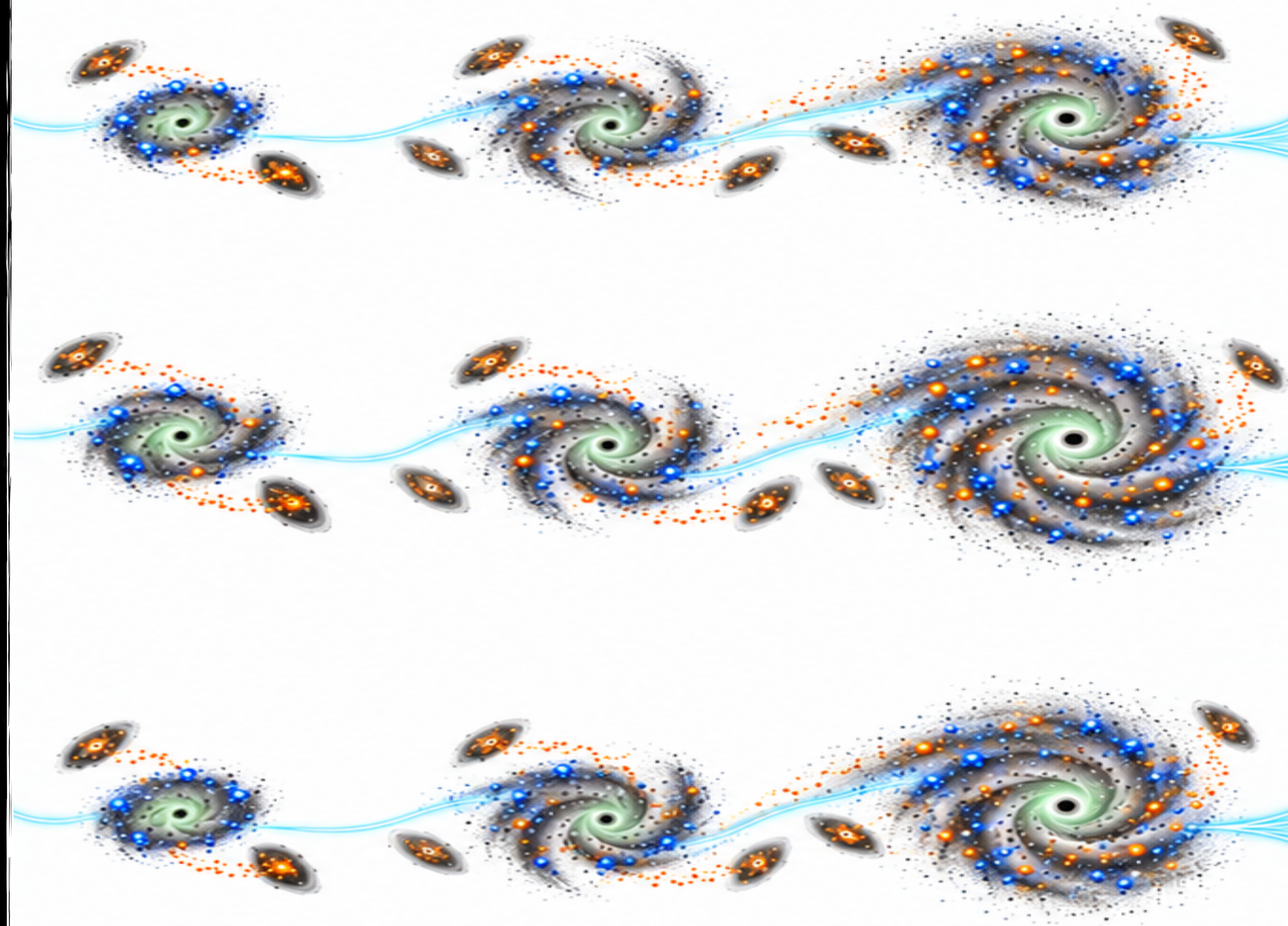
- ◆ Orbital integrations
- ◆ Dynamical friction (3)
- ◆ Mass loss (1)
- ◆ Tidal streams



Bovy+15

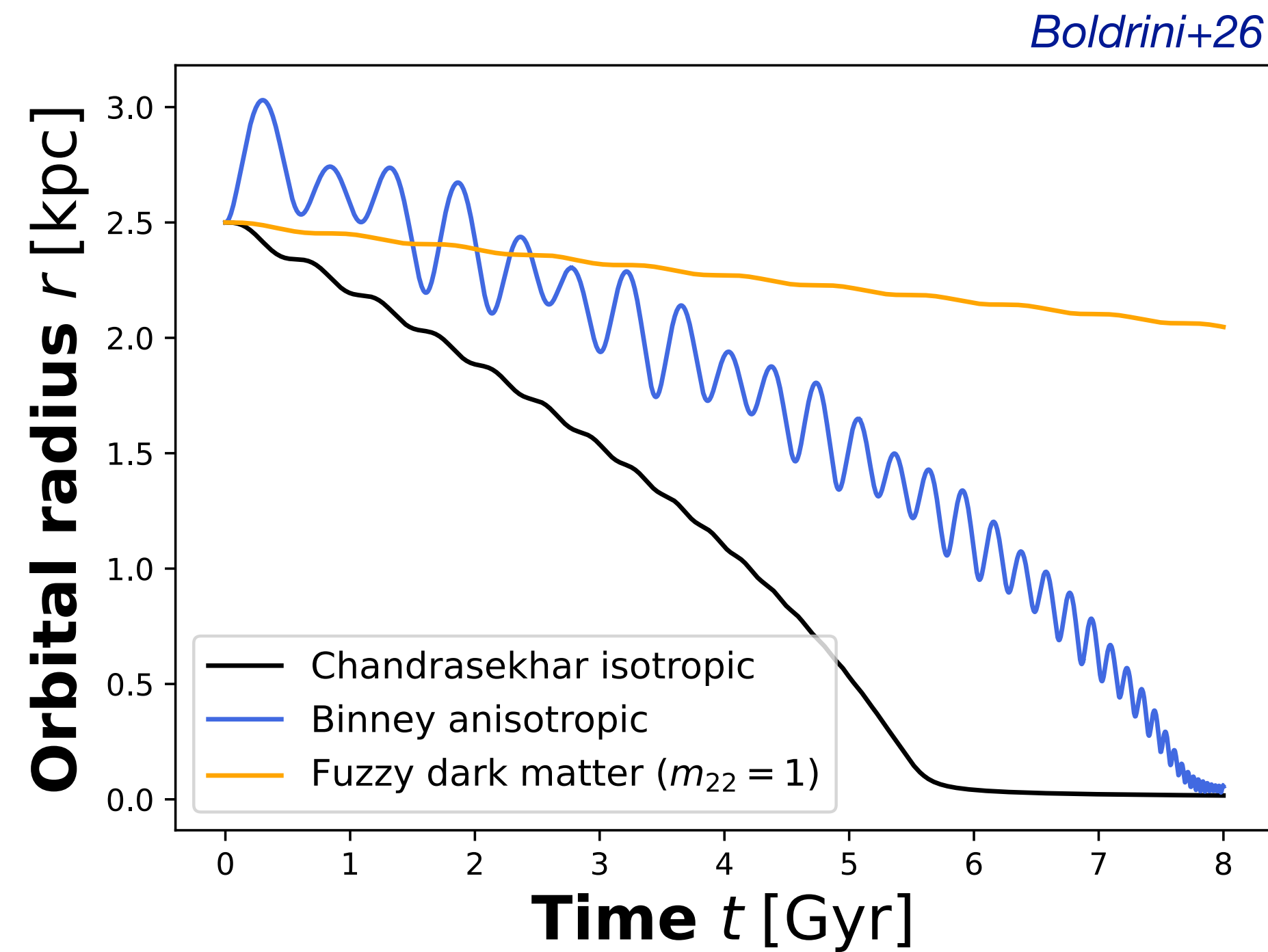
Our approach

Following their dynamics



Dynamical friction (3):

- ◆ Chandrasekhar formulation for spherical systems *Petts+15*
- ◆ Binney formulation for non-spherical systems *Assuerus in prep.*
- ◆ Dynamical friction in alternative DM theory (Fuzzy Dark Matter) *Szpilfidel+25*



Our approach

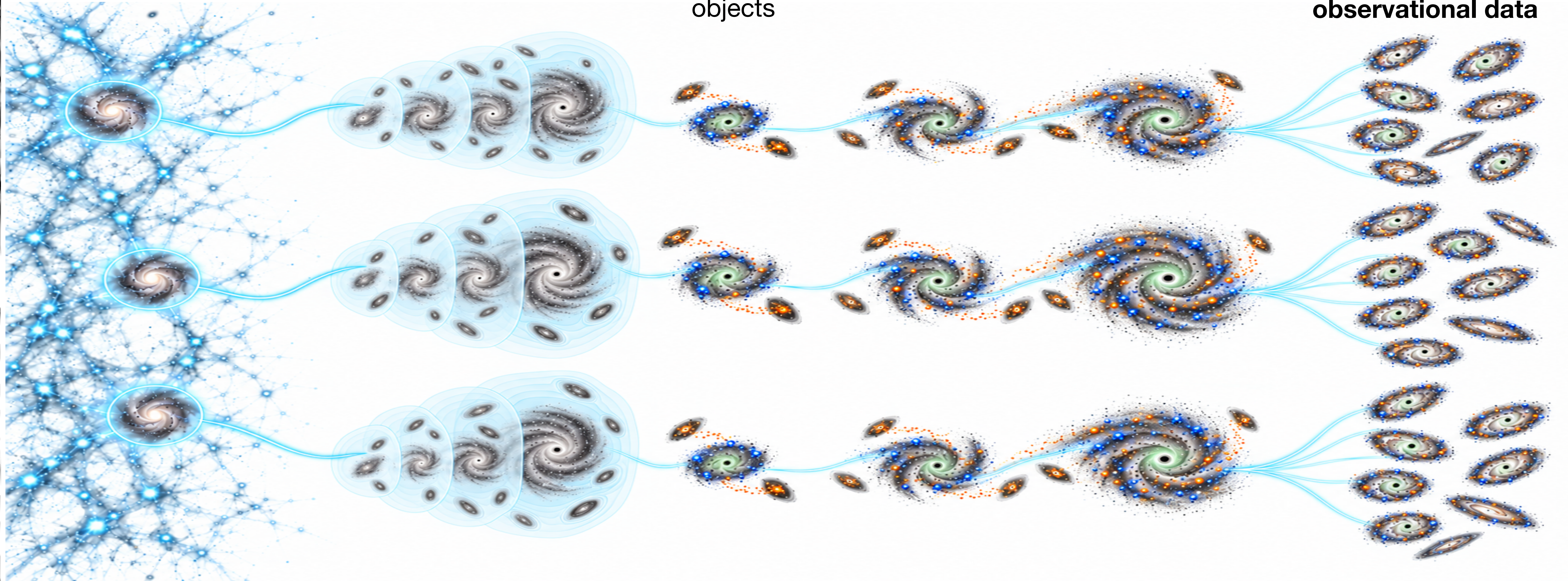
Cosmological simulation

Reconstructing the evolving
cosmological environment

Tagging
compact
objects

Following their dynamics

**Statistical predictions
to compare with
observational data**



TNG50
200 MW-like galaxies

$$\Phi_{\text{host}}(t) + \sum_i \Phi_{\text{sat},i}(t)$$

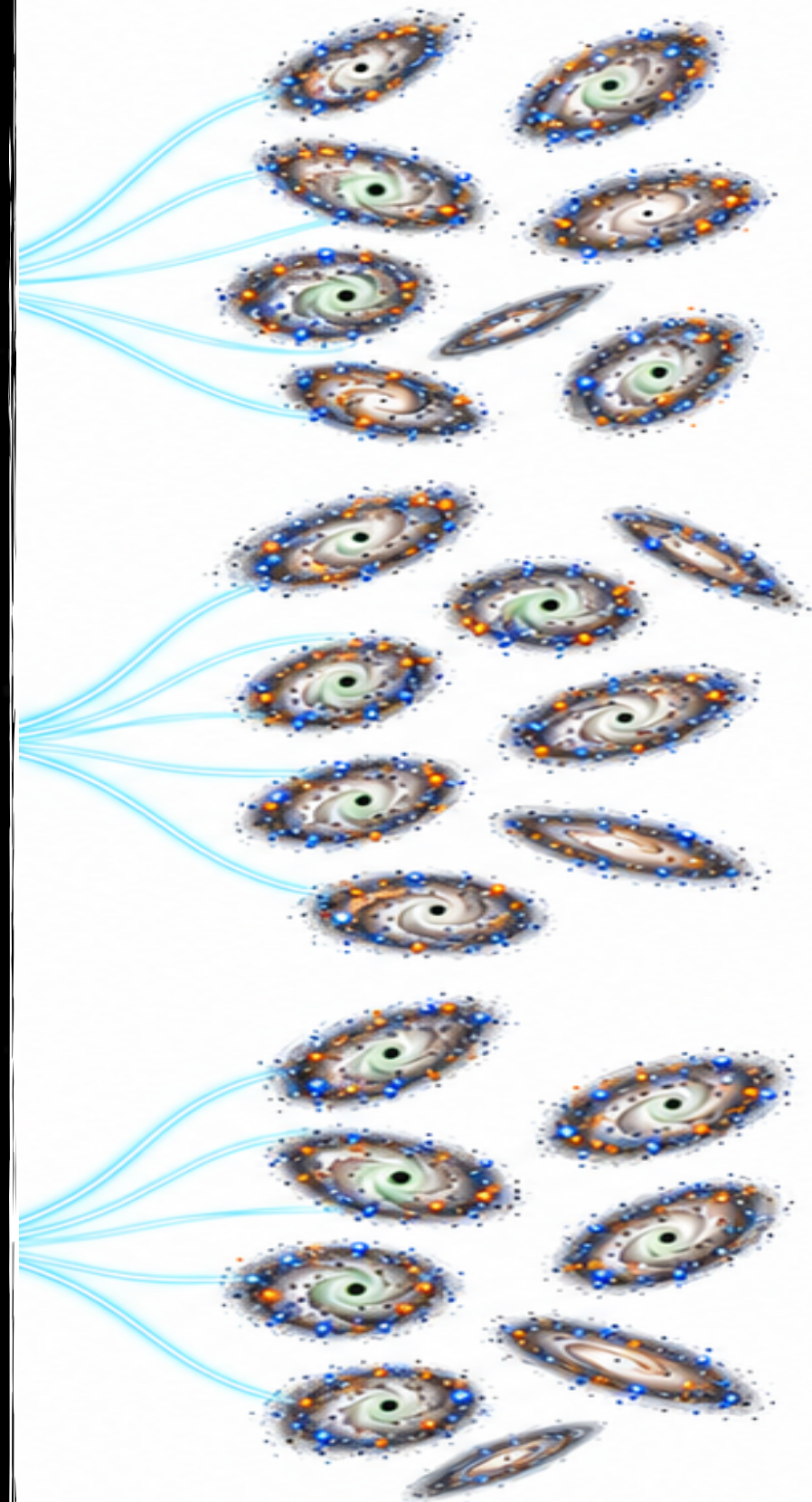
$$X(t_0), V(t_0), M(t_0)$$

$$X(t), V(t), M(t)$$

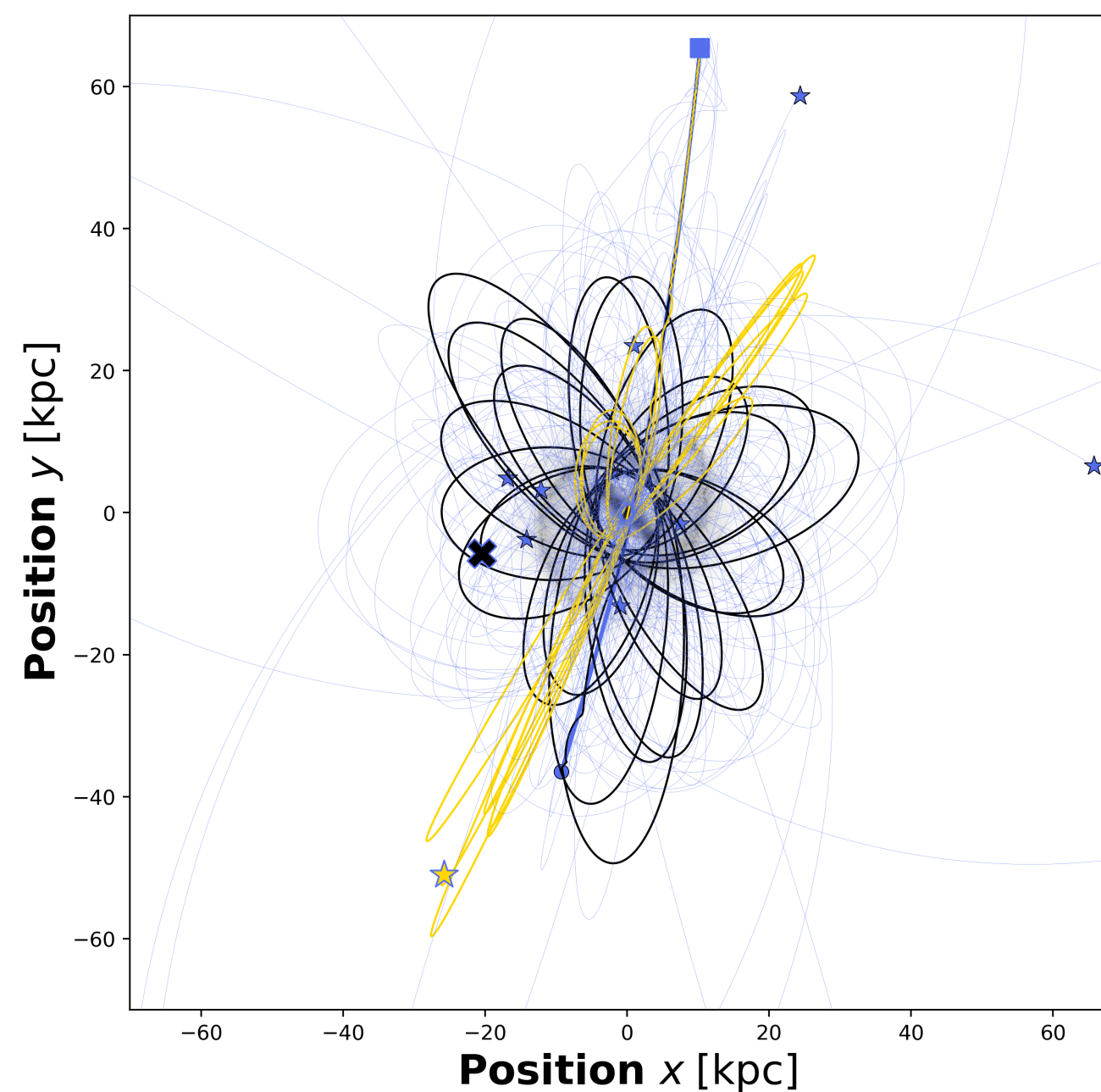
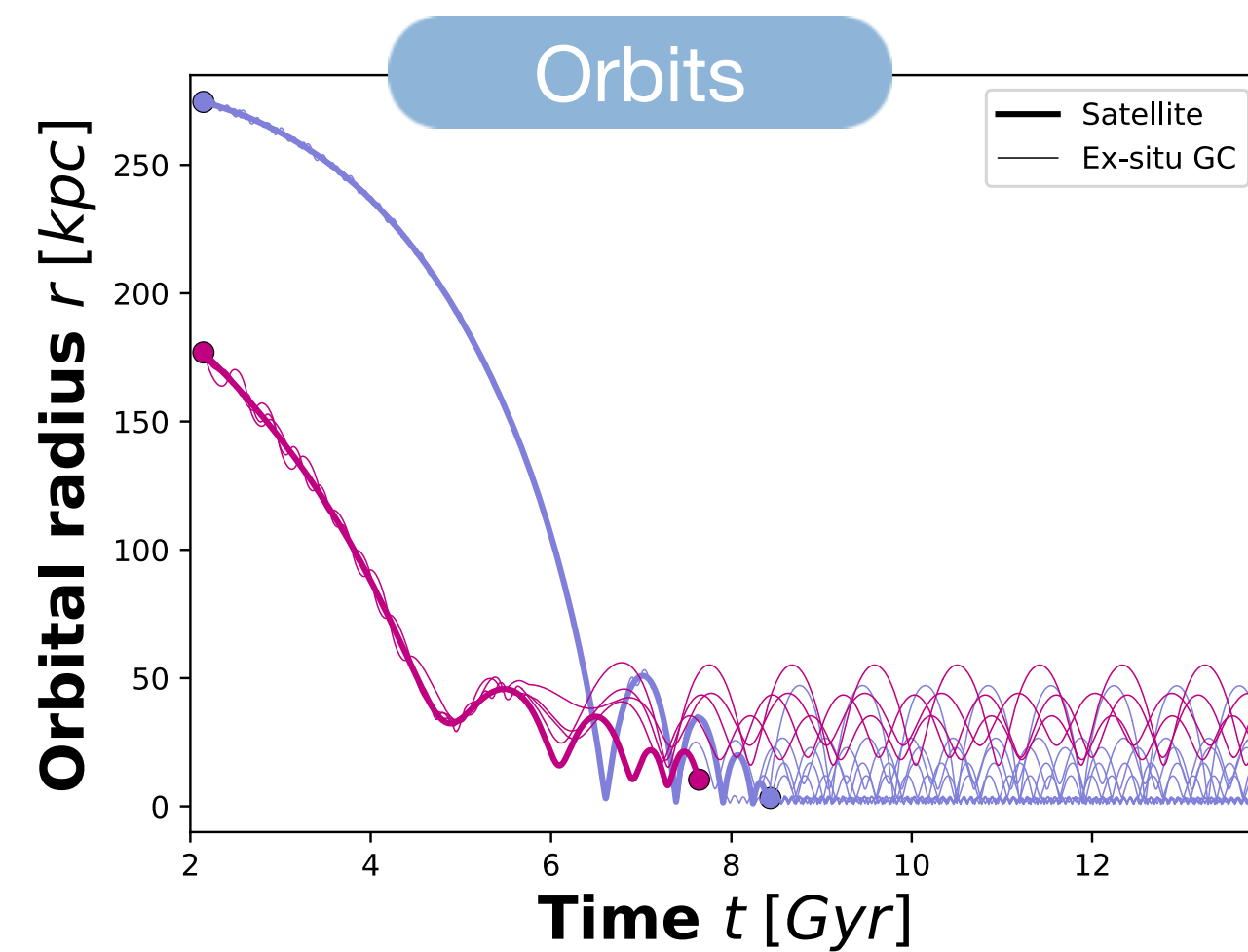
18000 GCs
+ 200 BHs
+ 200 NSCs

Our approach

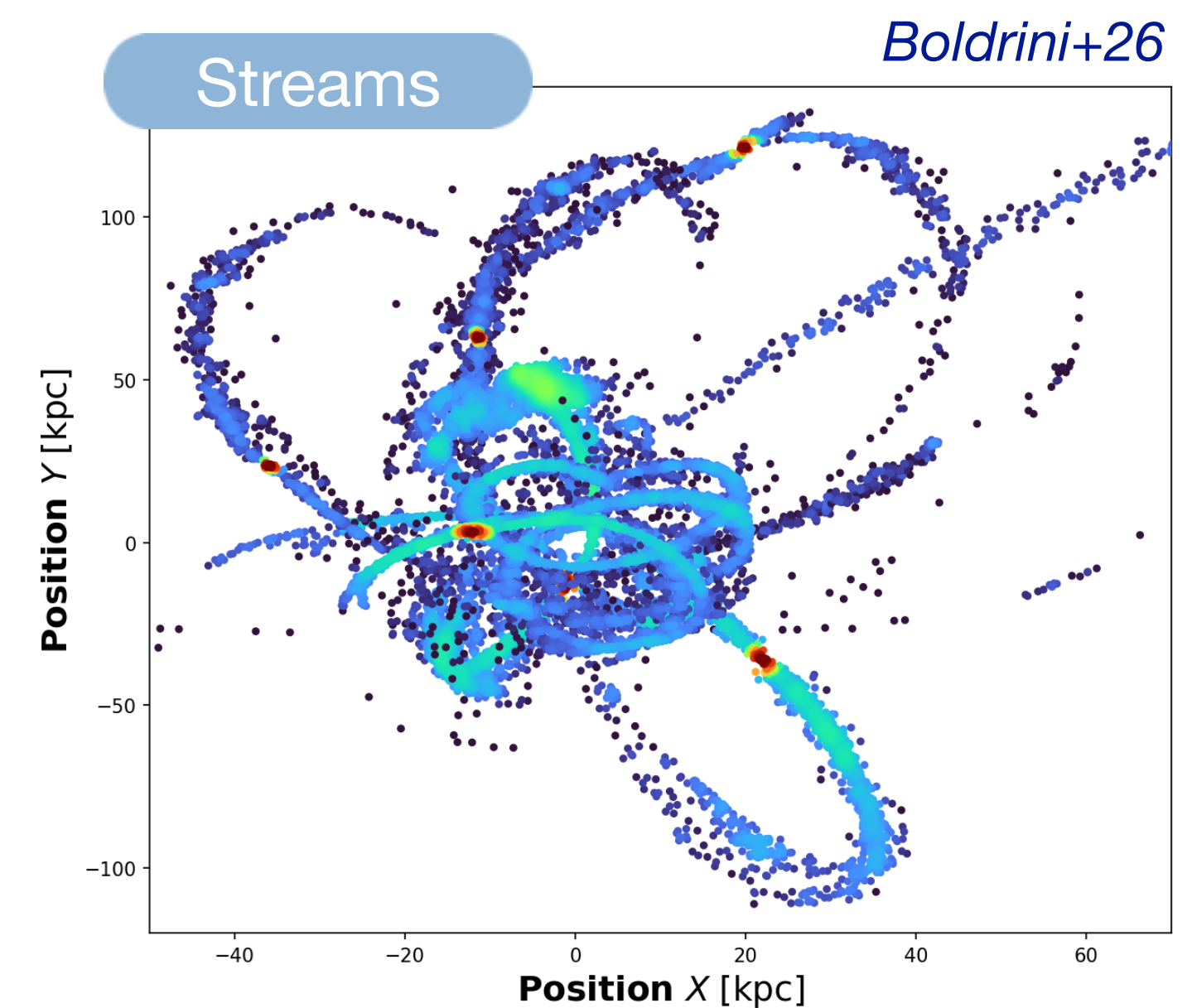
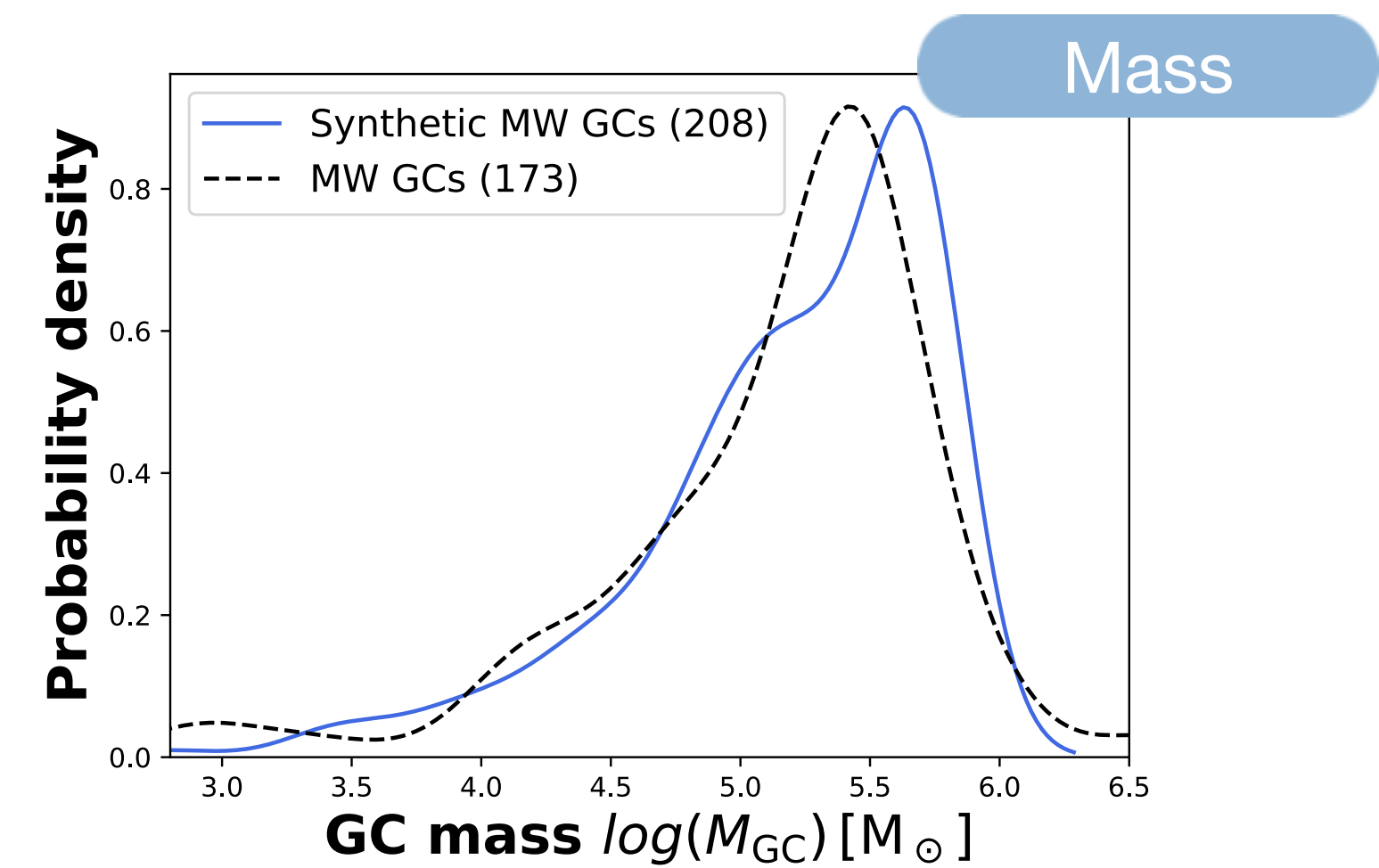
Statistical predictions
to compare with
observational data



18000 GCs
+ 200 BHs
+ 200 NSCs



Outputs $X(t)$, $V(t)$, $M(t)$



Our approach

Boldrini+26

CosmoDyn

License MIT Python 3.10+

CosmoDyn is an open-source Python framework designed to reconstruct **time-dependent galactic potentials** from cosmological simulations and model the dynamical evolution of compact stellar systems such as **globular clusters (GCs)**, **nuclear star clusters (NSCs)** and **massive black holes (MBHs)**.

publicly available on GitHub

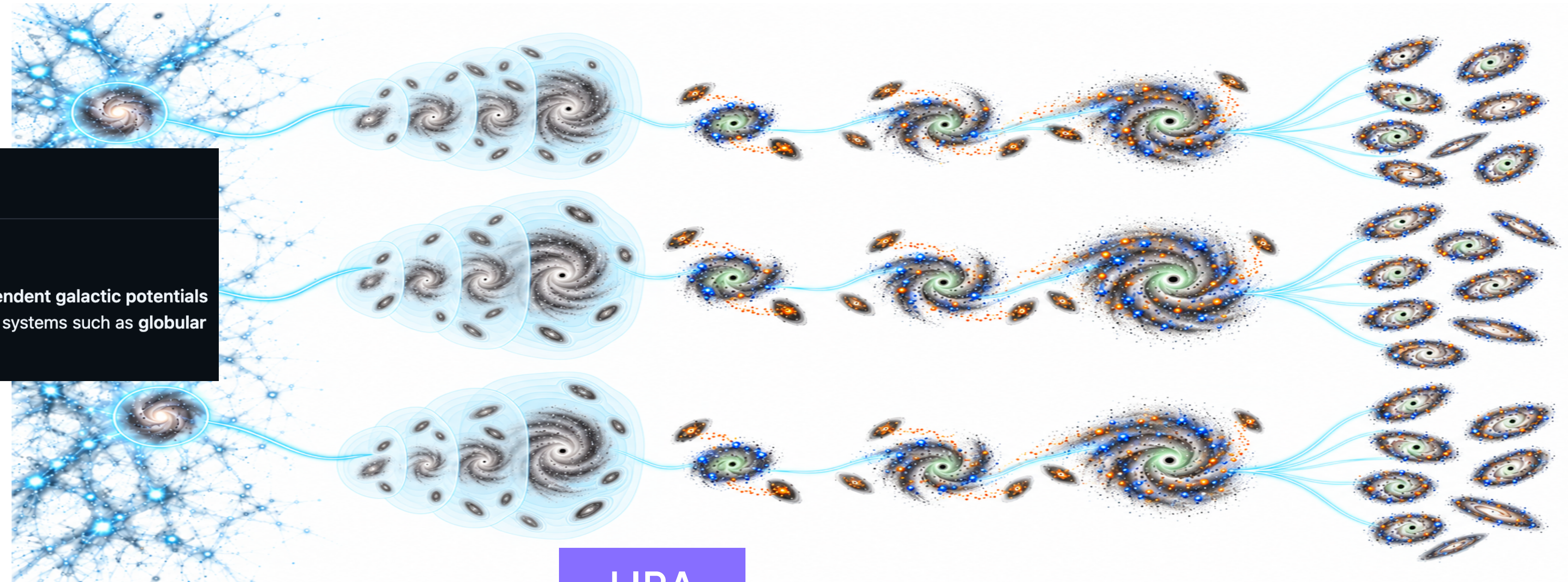
Cosmological
simulation

Cosmological
environment

Tagging
objects

Dynamics

Statistical
predictions



LIRA



universität
wien



SAPIENZA
UNIVERSITÀ DI ROMA

- ◆ Using any existing cosmological simulations (no need to rerun)
- ◆ Complete cosmological environment (host + satellites)
- ◆ Computationally inexpensive (400 CPU hours - 2 days on my laptop)
- ◆ Statistics (well suited for Gaia, JWST, and Euclid data)

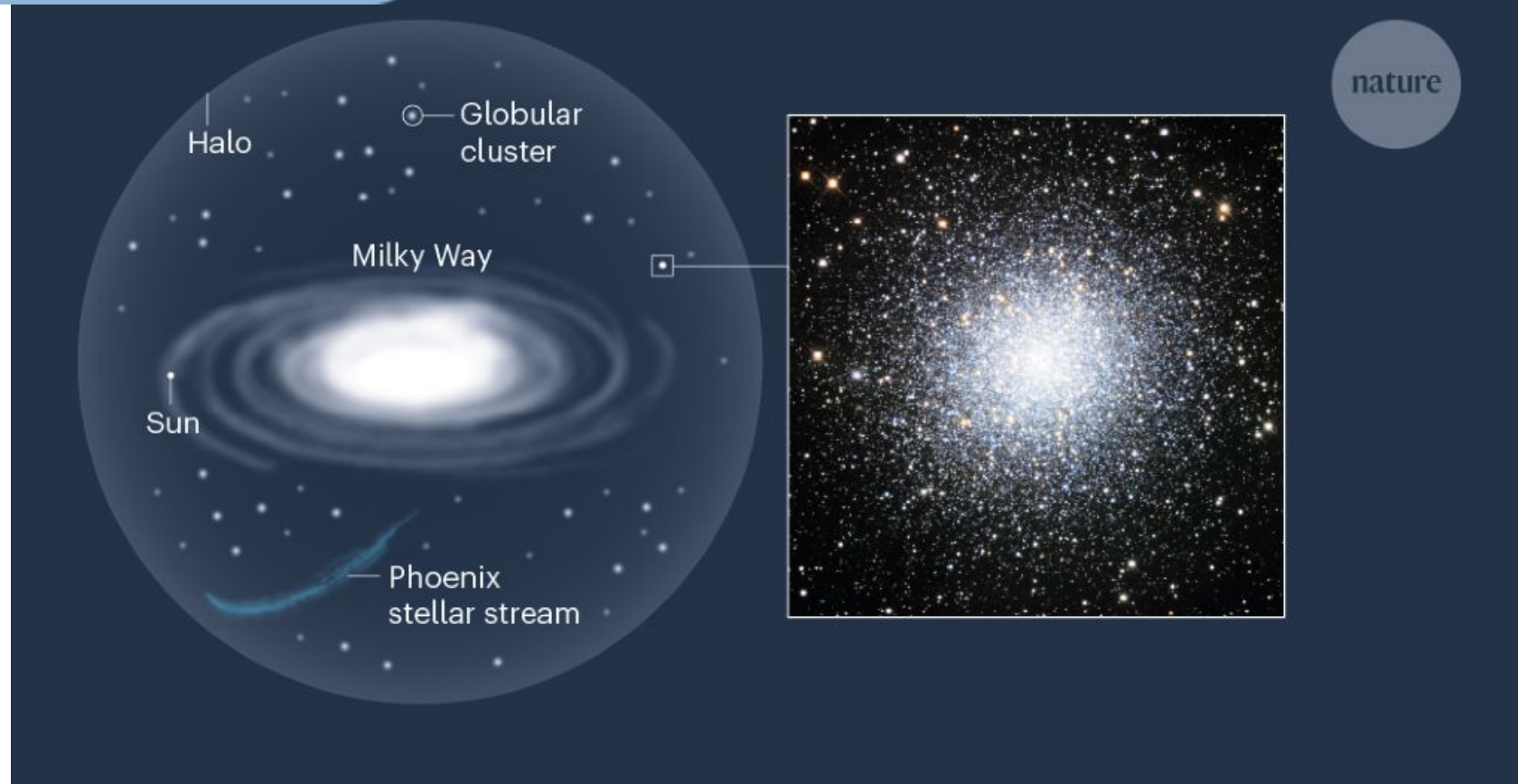
- ◆ **LIRA, Observatoire de Paris:** P. Di Matteo, D. Katz, C. Laporte, L. Casamiquela, M. Assuerus
- ◆ **Sapienza (Italy):** M. Montuori
- ◆ **University of Vienna (Austria):** G. van den Ven

Flexible semi-analytical model in post-processing of simulations

Application 1: Origin of MW globular clusters

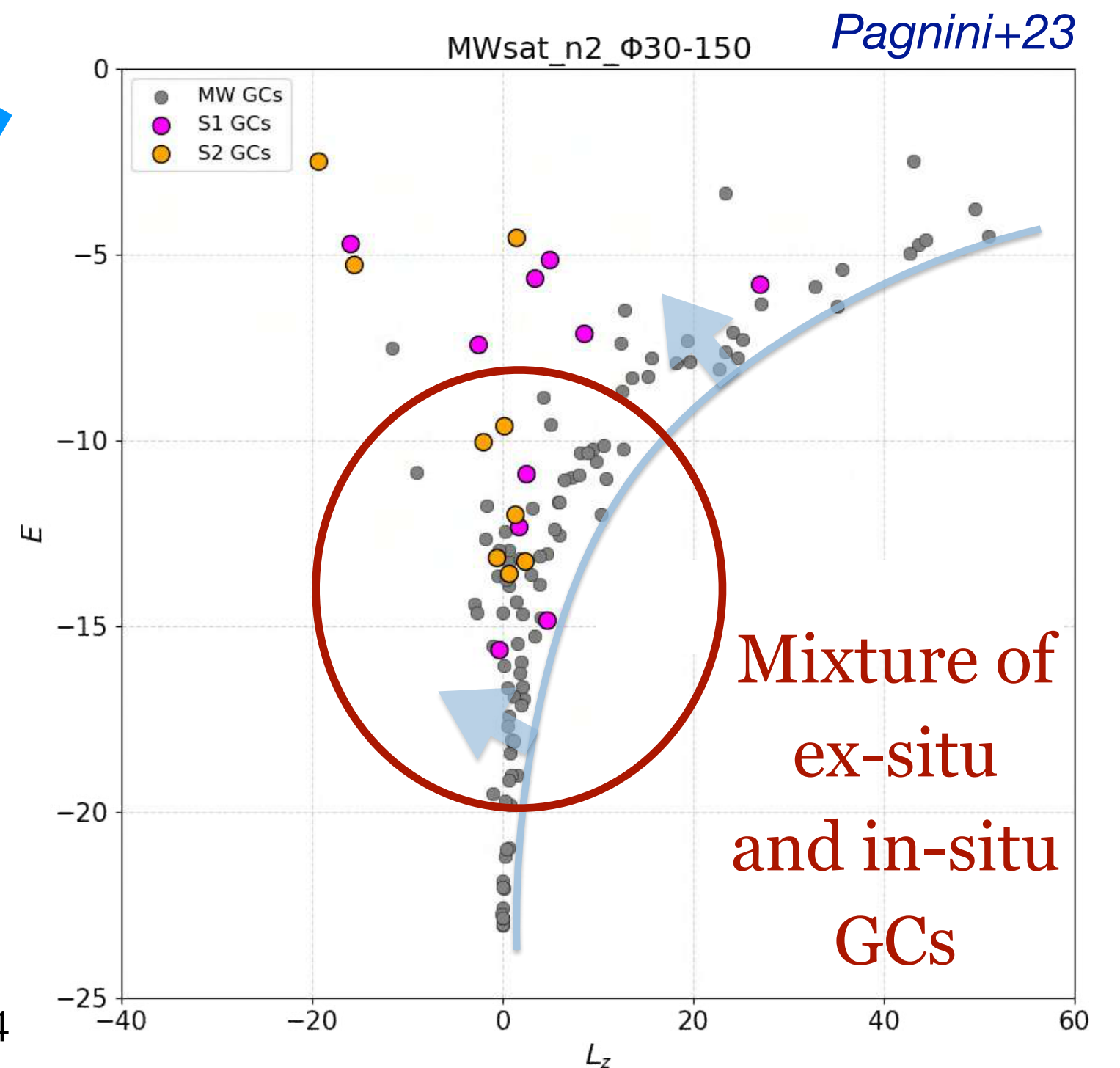
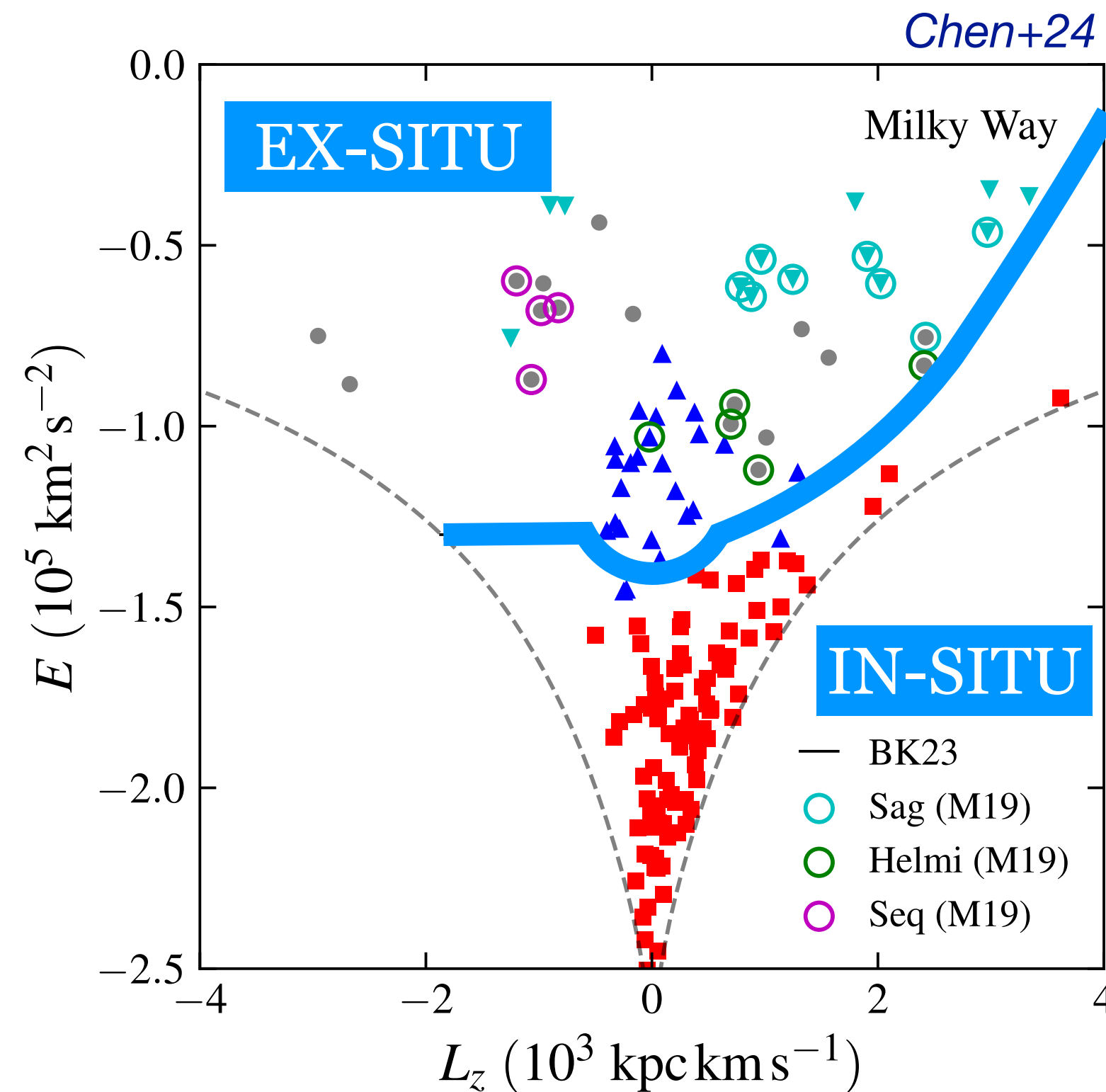
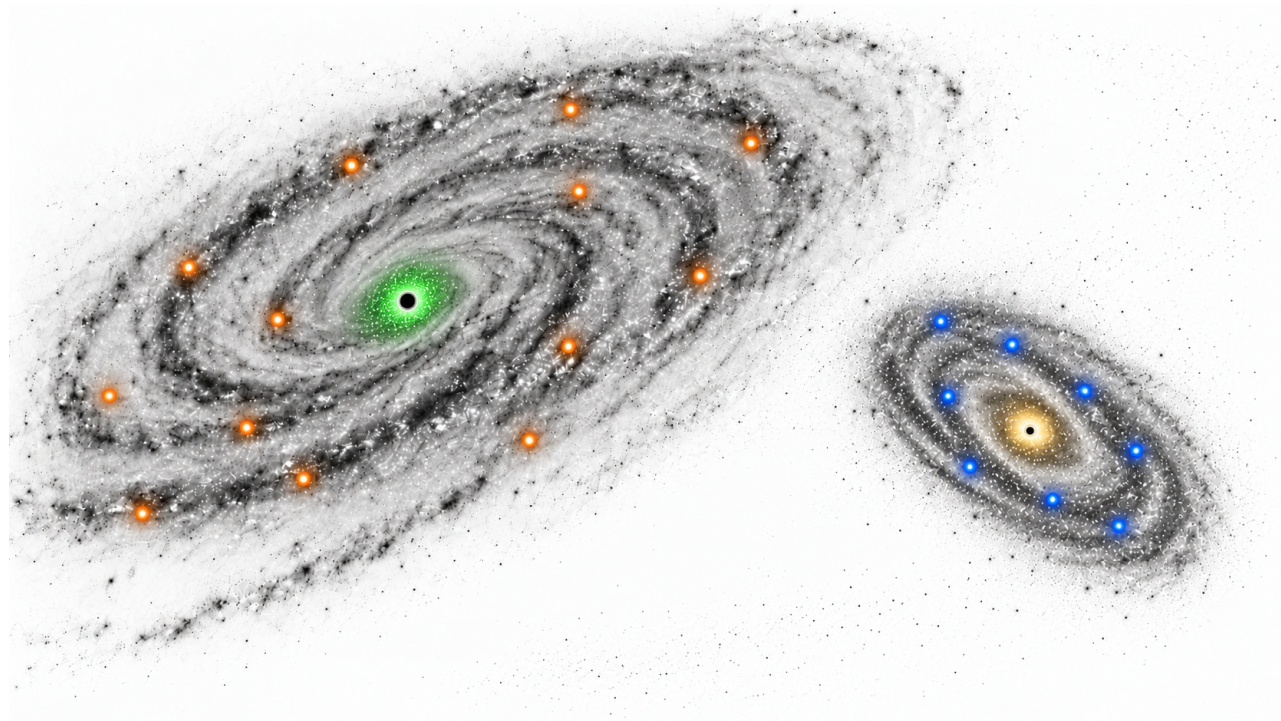
Credits: Nature

GAIA



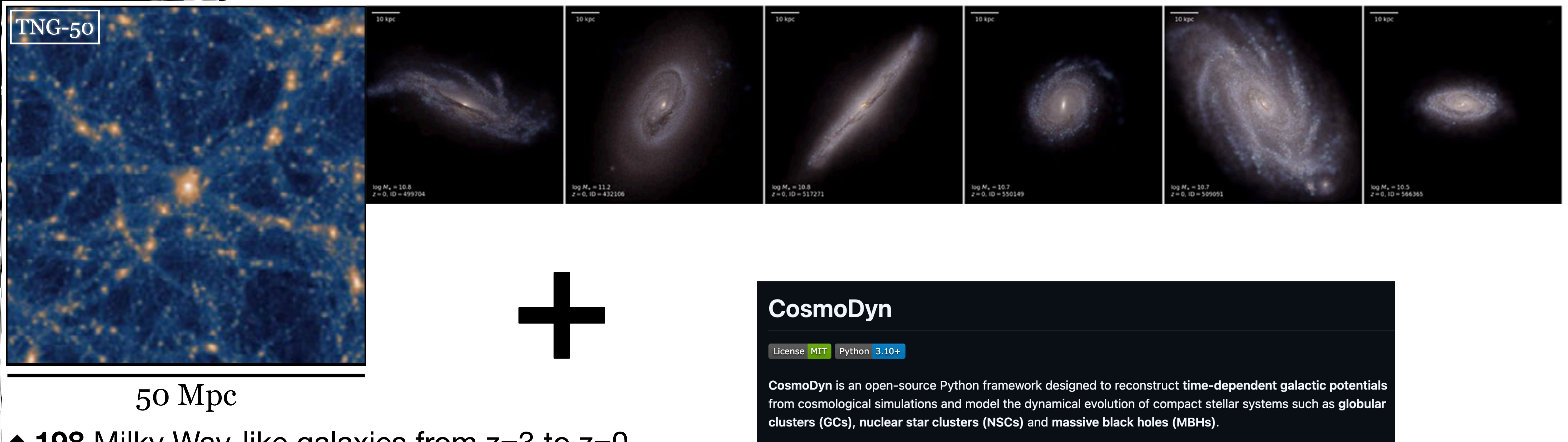
Origin of the 171 MW GCs:

- ◆ **In situ**: formed within the MW
- ◆ **Ex situ**: formed within satellite galaxies



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

Application 1: Origin of MW globular clusters



- ◆ **198** Milky Way-like galaxies from $z=3$ to $z=0$

- ◆ DM halo (NFW profile) + stellar component (Hernquist profile) $\rightarrow$ spherical potentials

- ◆ Cosmological environment: $\Phi_{\text{host}}(t) + \sum_i \Phi_{\text{sat},i}(t)$

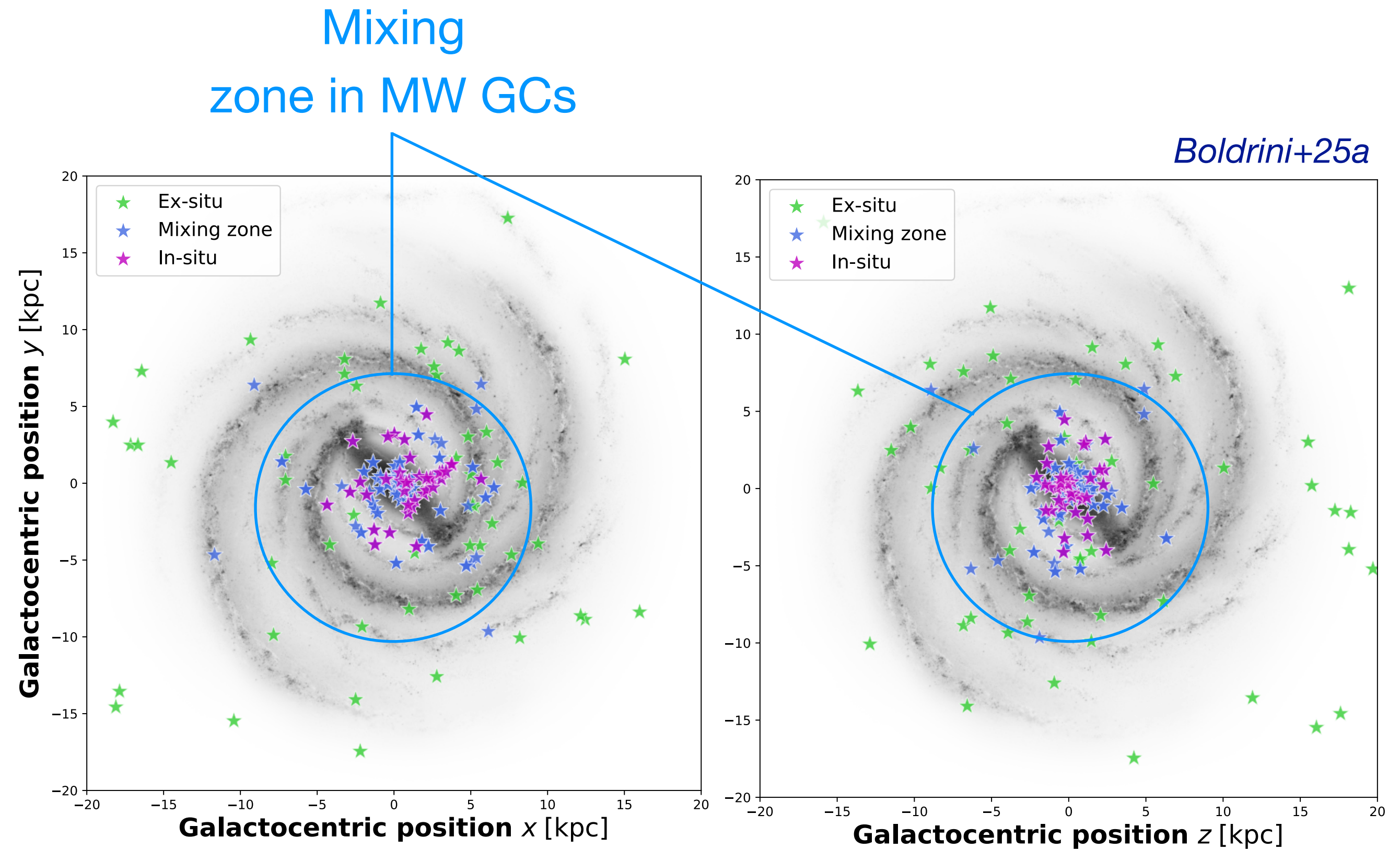
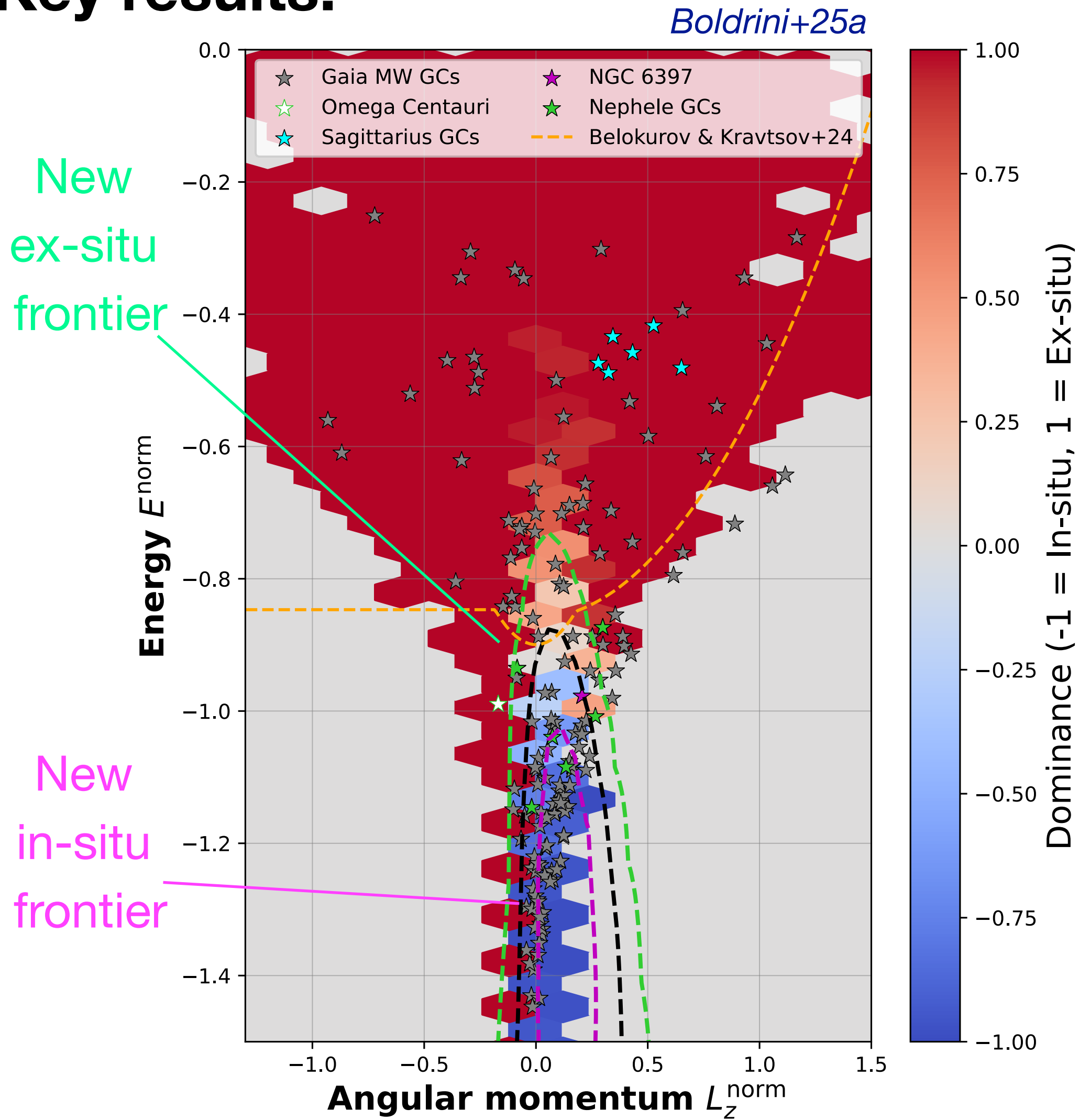
- ◆ GCs are tagged at $z=3$ according to [Burkert&Forbes+20](#) relation

- ◆ **18,000** globular clusters from redshift $z = 3$ to 0 by incorporating dynamical friction and mass loss

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

Application 1: Origin of MW globular clusters

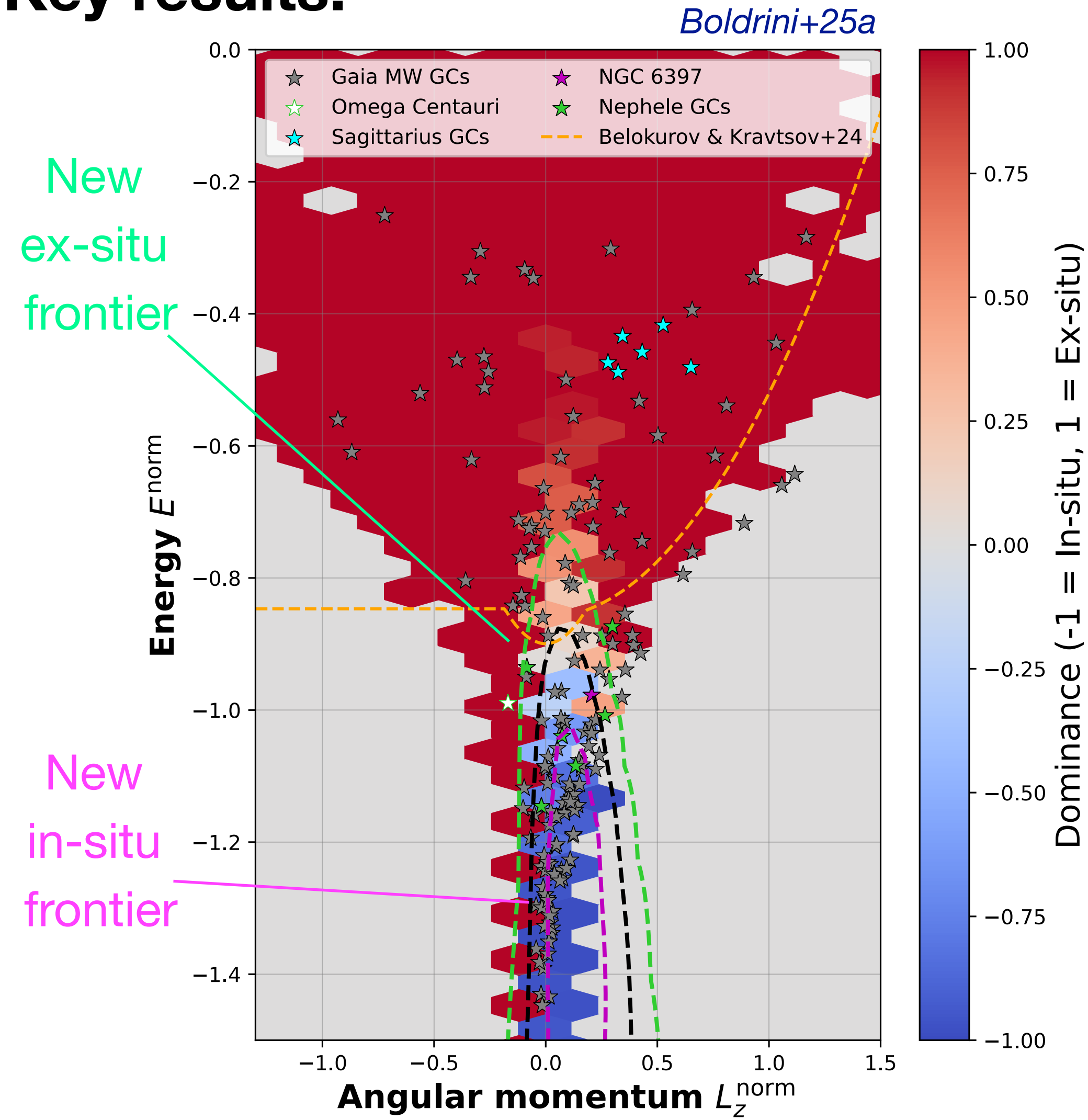
Key results:



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

Application 1: Origin of MW globular clusters

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

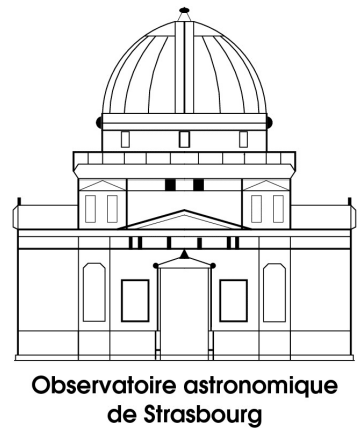
- ◆ **New classification:** 79 in-situ versus 81 ex situ GCs —> more ex situ than previously thought.
- ◆ Kinematics alone are insufficient to trace GC origins —> chemical abundances could provide additional constraints (*Pagnini+25b*).
- ◆ Full cosmological modeling is essential to understand the globular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



Leibniz-Institut für
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- ◆ **LIRA, Observatoire de Paris:** P. Di Matteo, C. Laporte
- ◆ **Lund University (Sweden):** O. Agertz
- ◆ **AIP (Germany):** S. Khoperskov
- ◆ **Observatoire de Strasbourg:** G. Pagnini

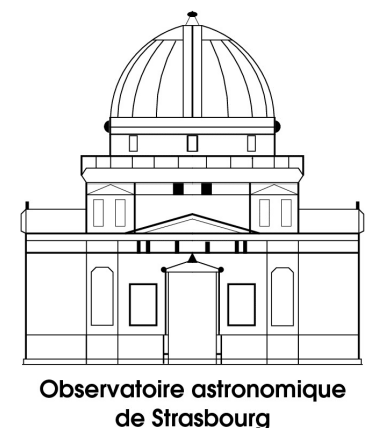
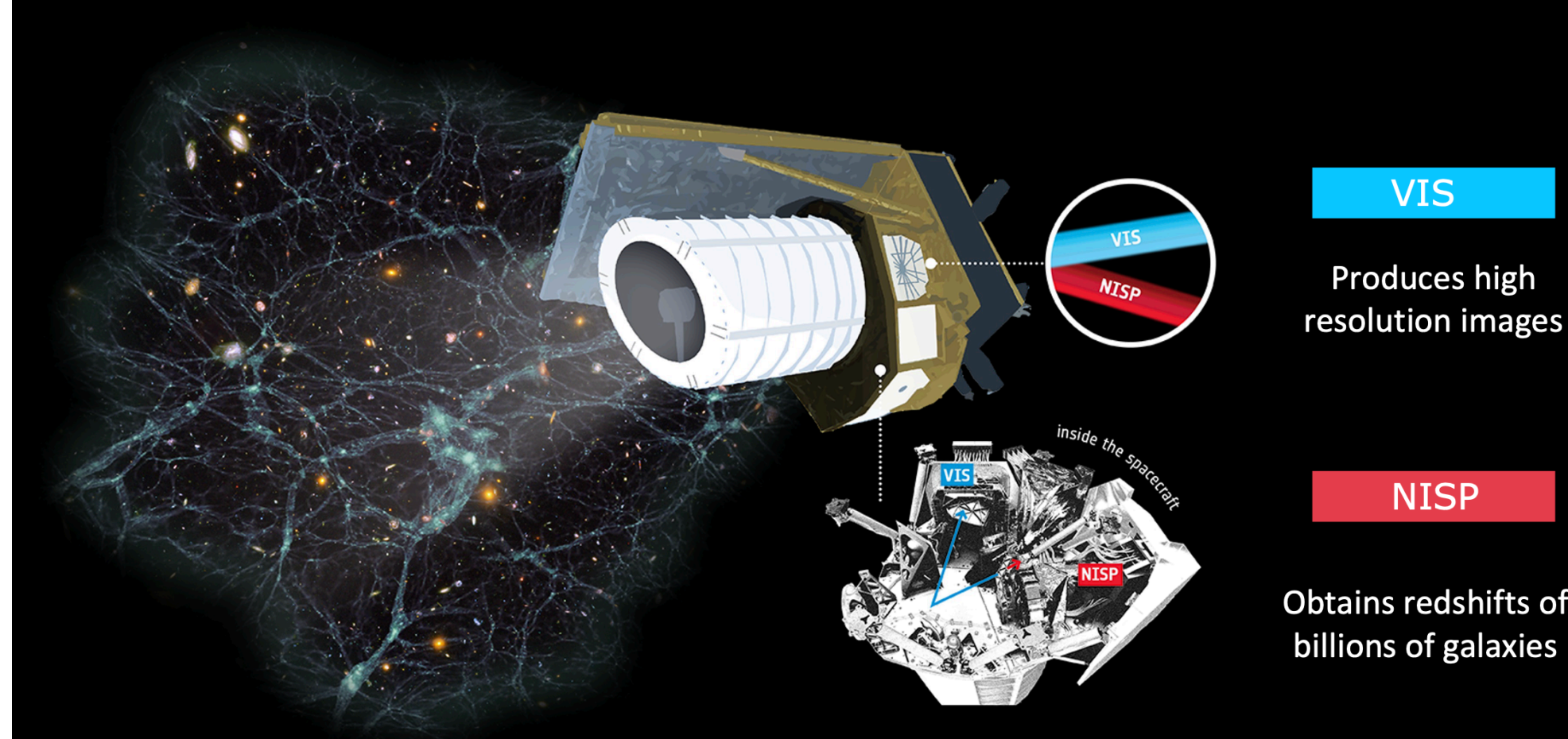
Application 2: Euclid globular clusters in dwarf galaxies

Euclid space telescope

GC detection and identification:

- ◆ Deep imaging
- ◆ High spatial resolution
- ◆ Optical + NIR photometry

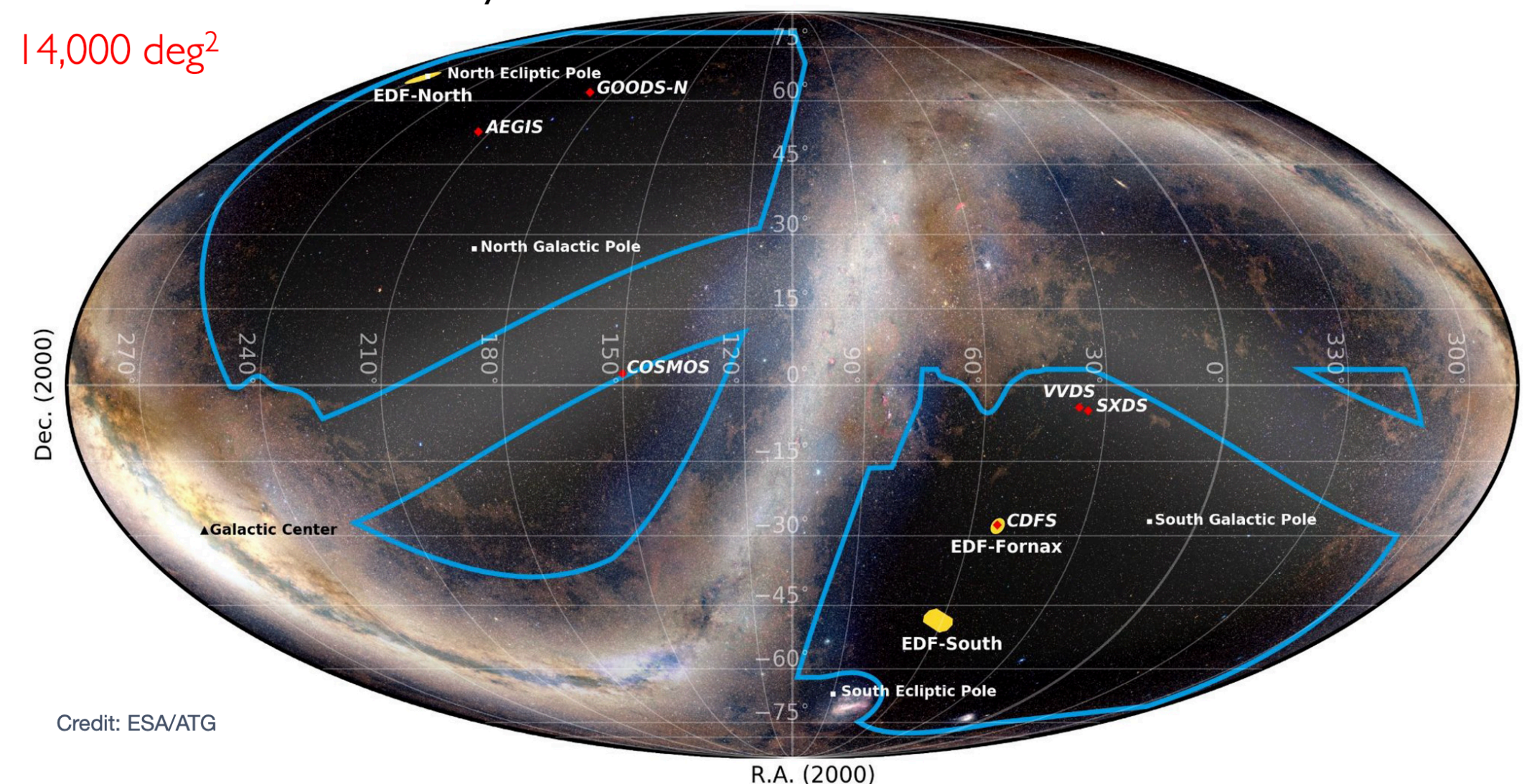
Euclid instruments (VIS + NISP)



- ◆ **Observatoire de Strasbourg:** A. Lançon, T. Saifollahi
- ◆ **CRAL, Lyon:** A. Claeysens
- ◆ **Euclid working group:** Extragalactic Globular Clusters (EGC)

Euclid Wide Survey

14,000 deg²

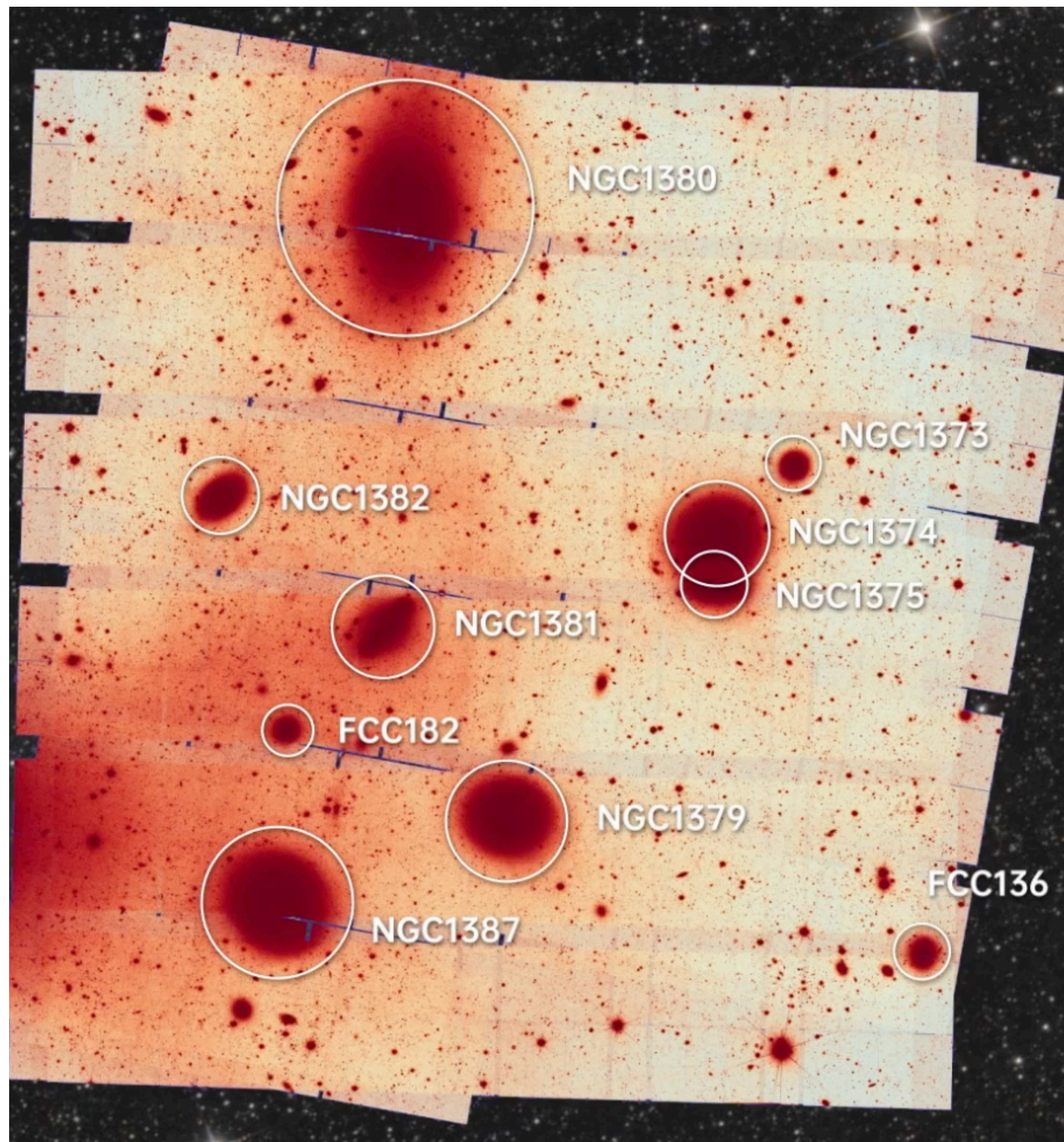


Large sky coverage —> Large sample of galaxies

Application 2: Euclid globular clusters in dwarf galaxies

Euclid Early Release Observations (ERO) data *Cuillandre+24*

Fornax galaxy cluster at 20 Mpc



Spatial resolution: 10-20 pc

Perseus galaxy cluster at 73 Mpc

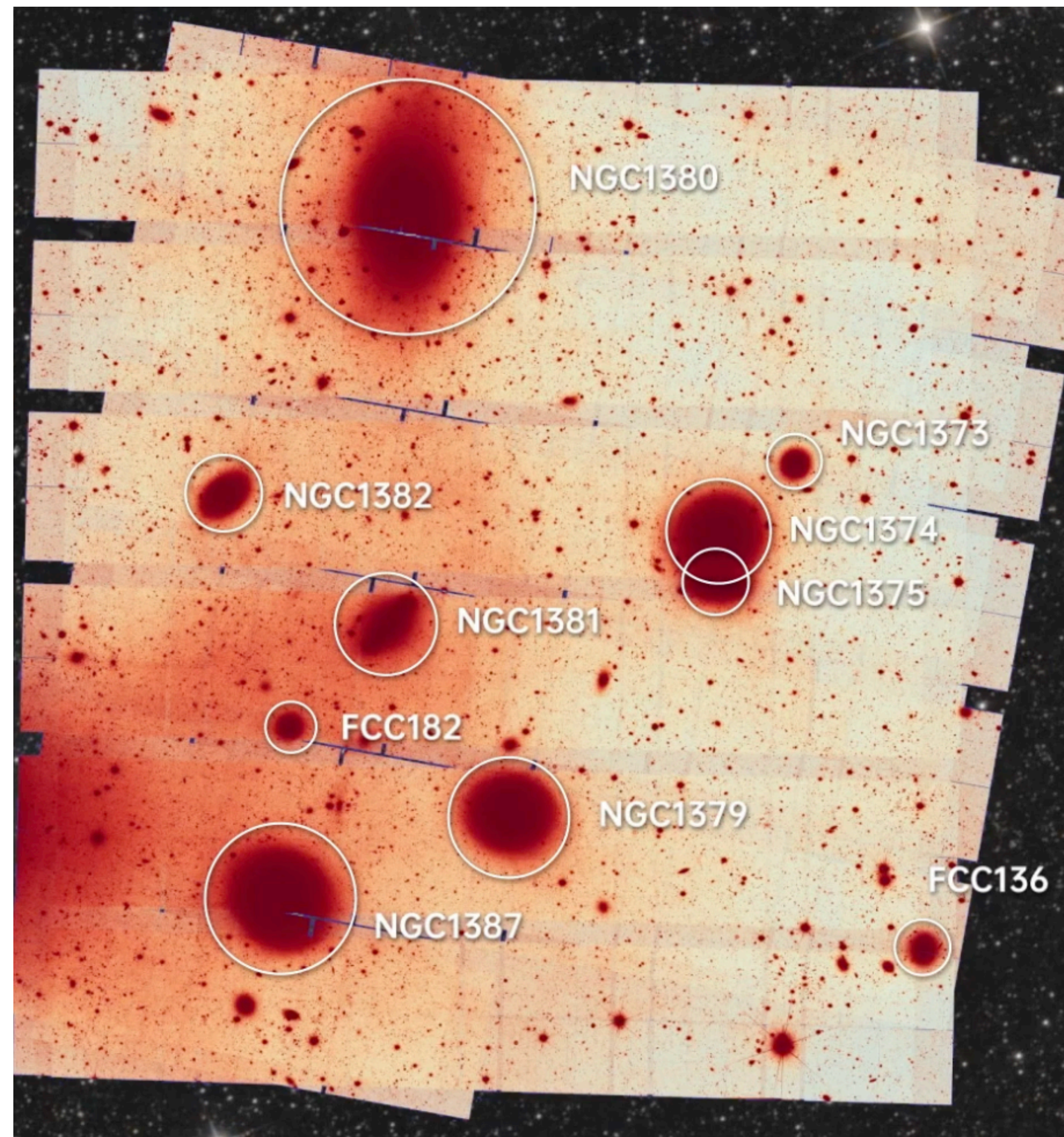


35-70 pc

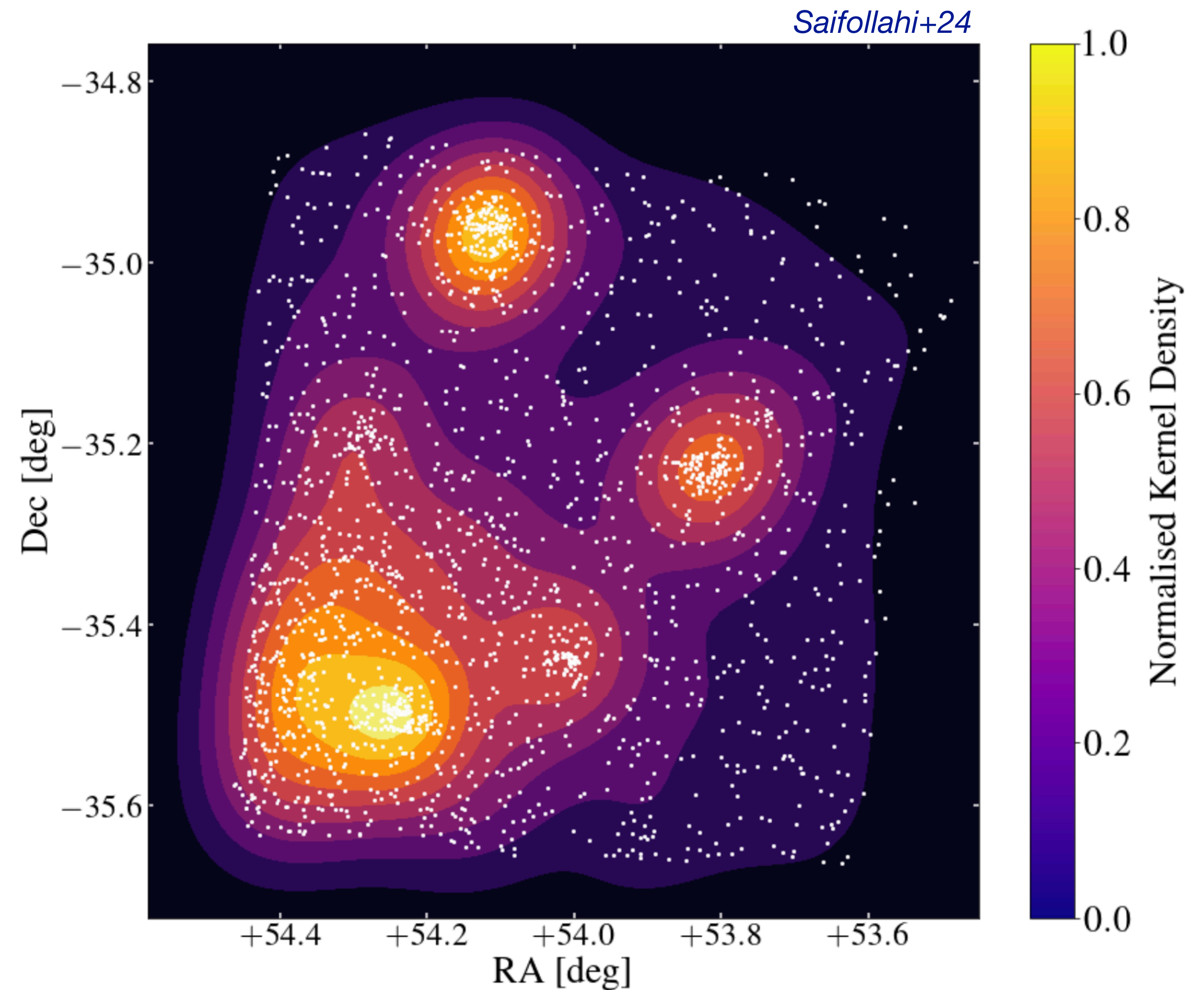
Application 2: Euclid globular clusters in dwarf galaxies

Euclid Early Release Observations (ERO) data

Fornax galaxy cluster at 20 Mpc



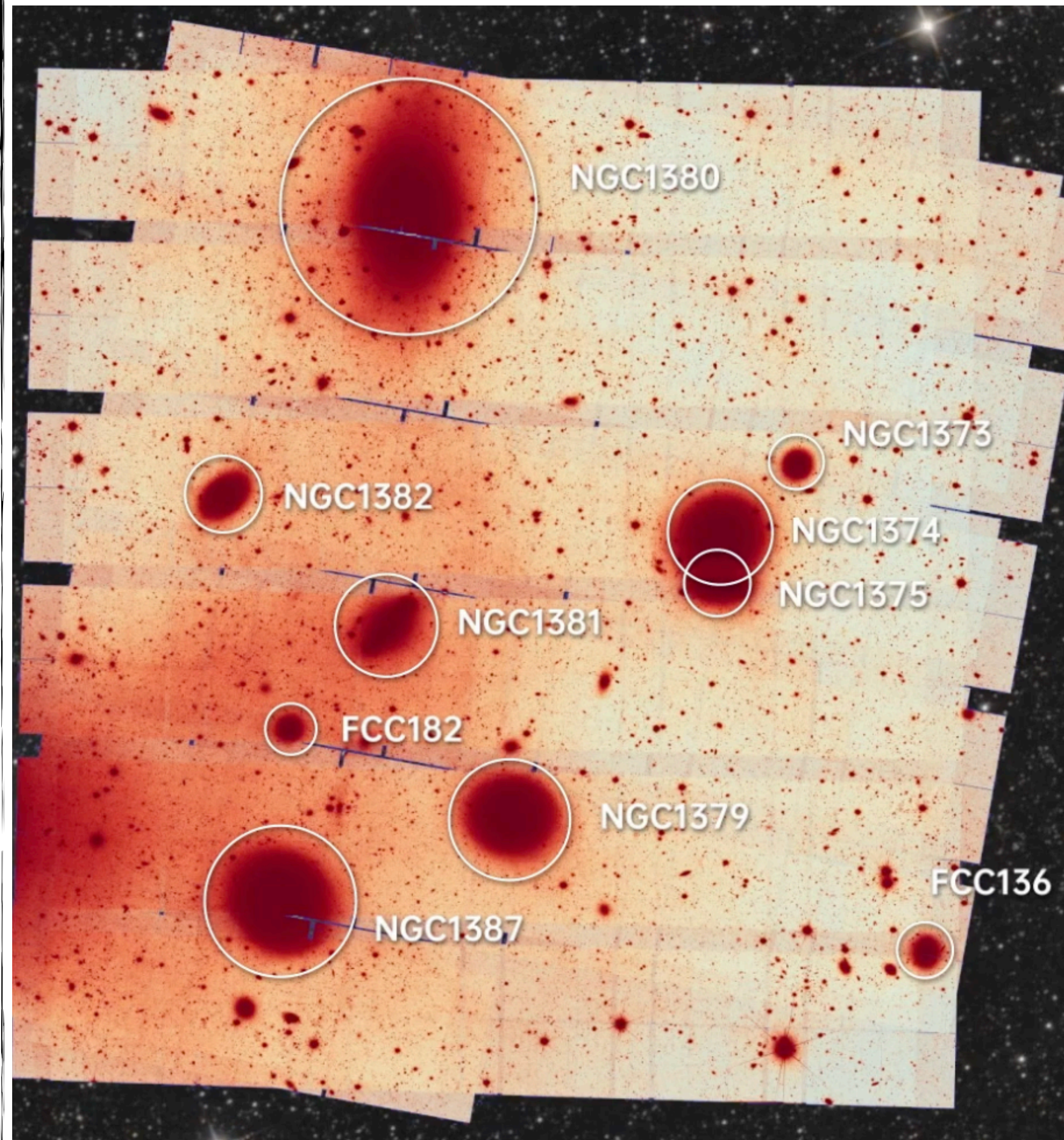
Where are the GCs?



Application 2: Euclid globular clusters in dwarf galaxies

Euclid Early Release Observations (ERO) data *Cuillandre+24*

Fornax galaxy cluster at 20 Mpc



30 dwarf galaxies, 47 GC candidates

Saifollahi+24

Perseus galaxy cluster at 73 Mpc



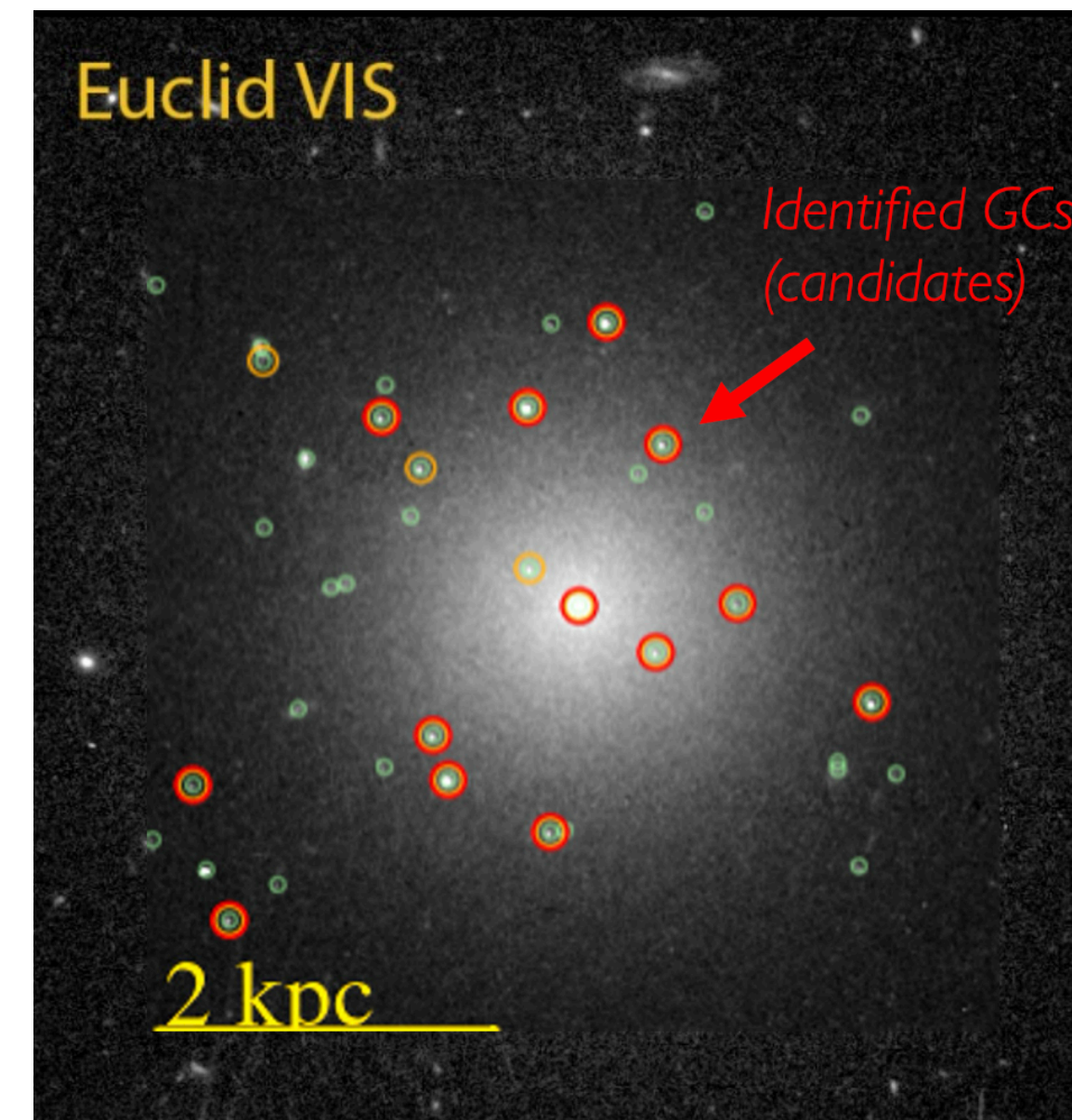
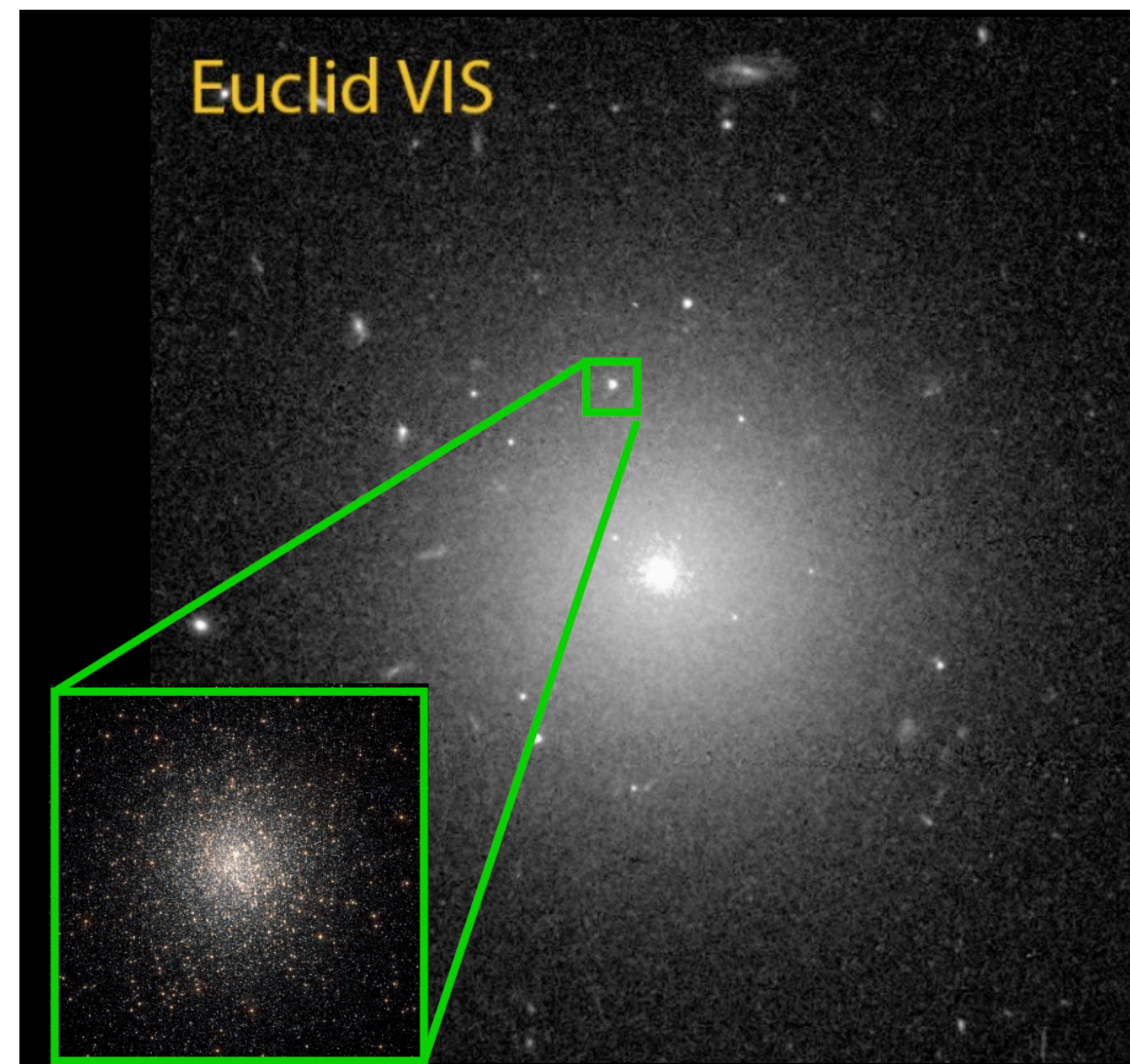
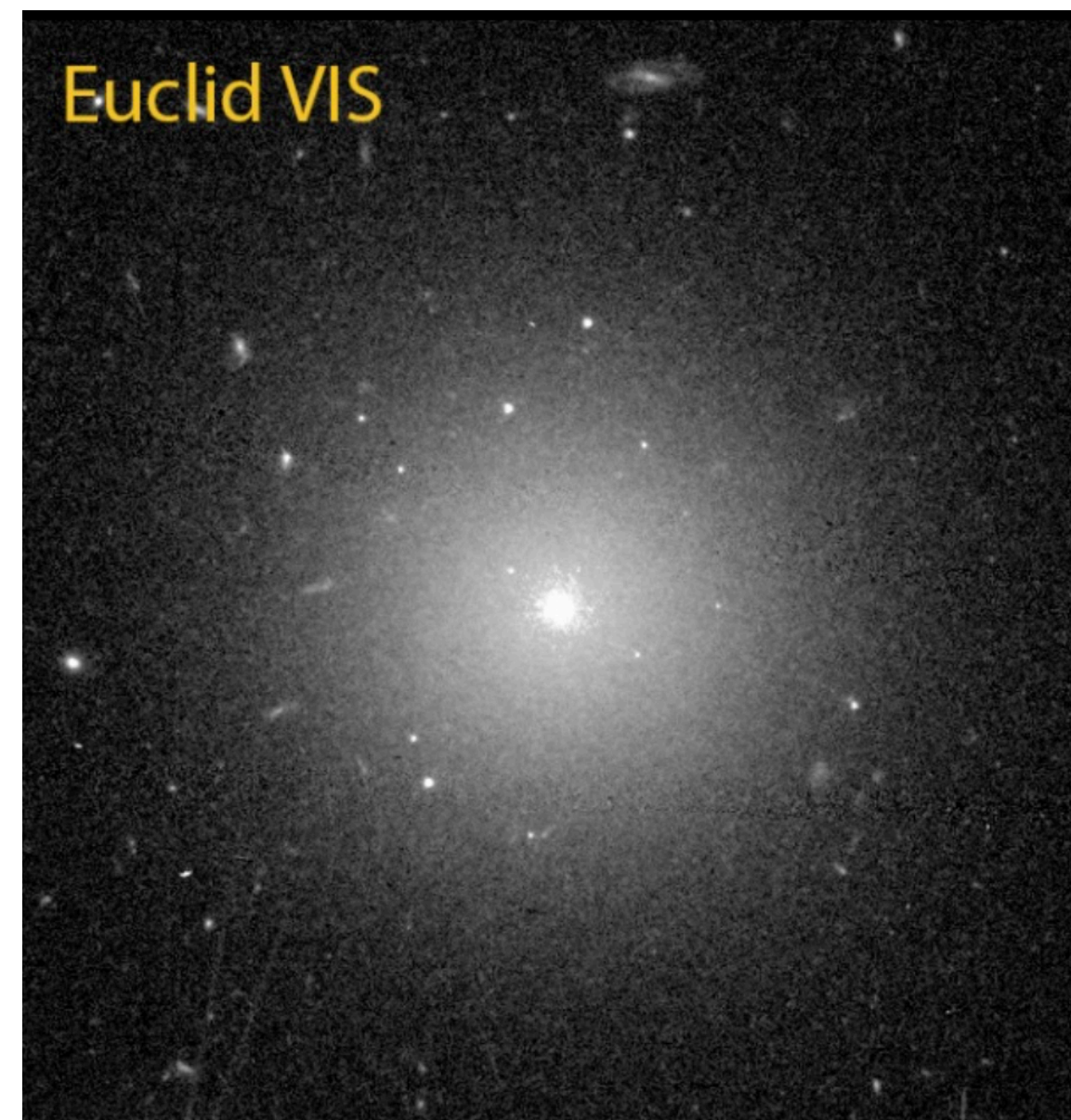
826 dwarf galaxies, 6553 GC candidates

Saifollahi+25

- ◆ $-11.2 < \text{VIS Magnitude} < -7$
- ◆ GC catalogues: $> 90\%$ and $> 80\%$ complete
- ◆ $1\text{-}30 \times 10^5 M_{\odot}$

Application 2: Euclid globular clusters in dwarf galaxies

Euclid Early Release Observations (ERO) data



Observed properties:

- ◆ GC projected distance
- ◆ GC mass
- ◆ Galaxy stellar mass

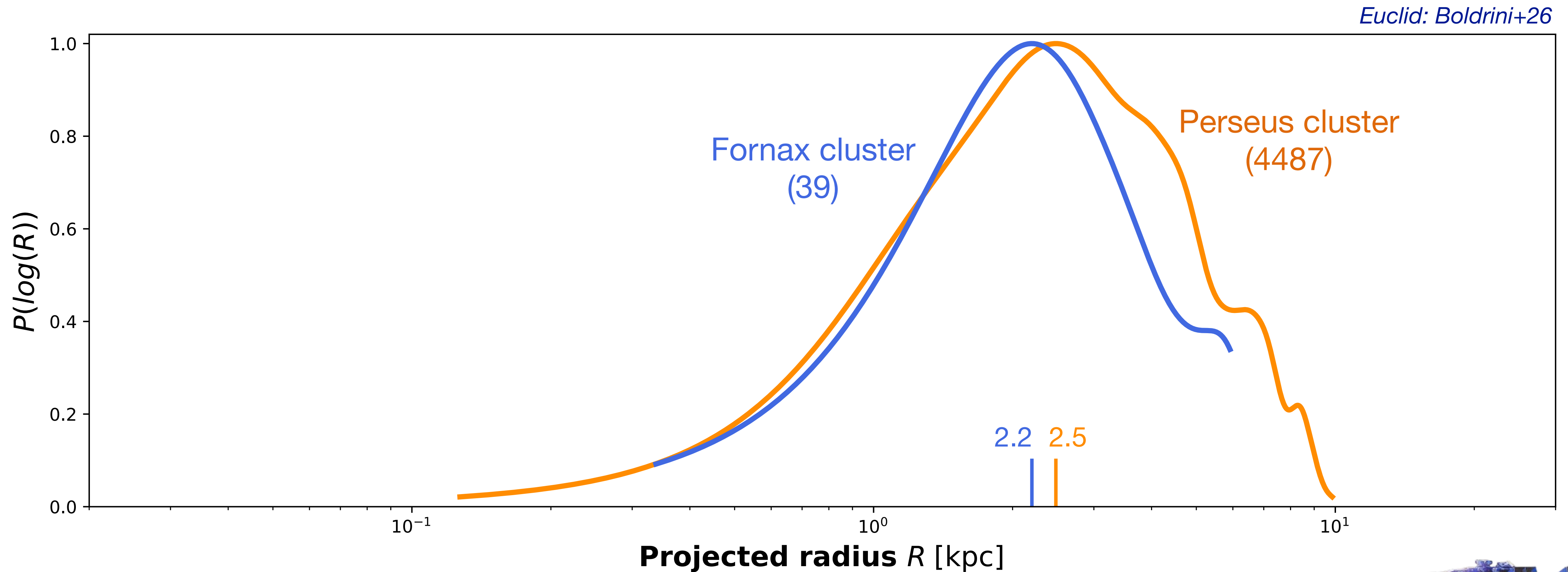
Set of selection criteria:

- ◆ VIS Magnitude < -8 $\rightarrow$ More massive GCs
- ◆ Exclude objects with galactocentric radius below 0.2 kpc $\rightarrow$ Remove NSC candidates

A sample of 4500 GC candidates

Application 2: Euclid globular clusters in dwarf galaxies

Euclid GCs at $z=0$



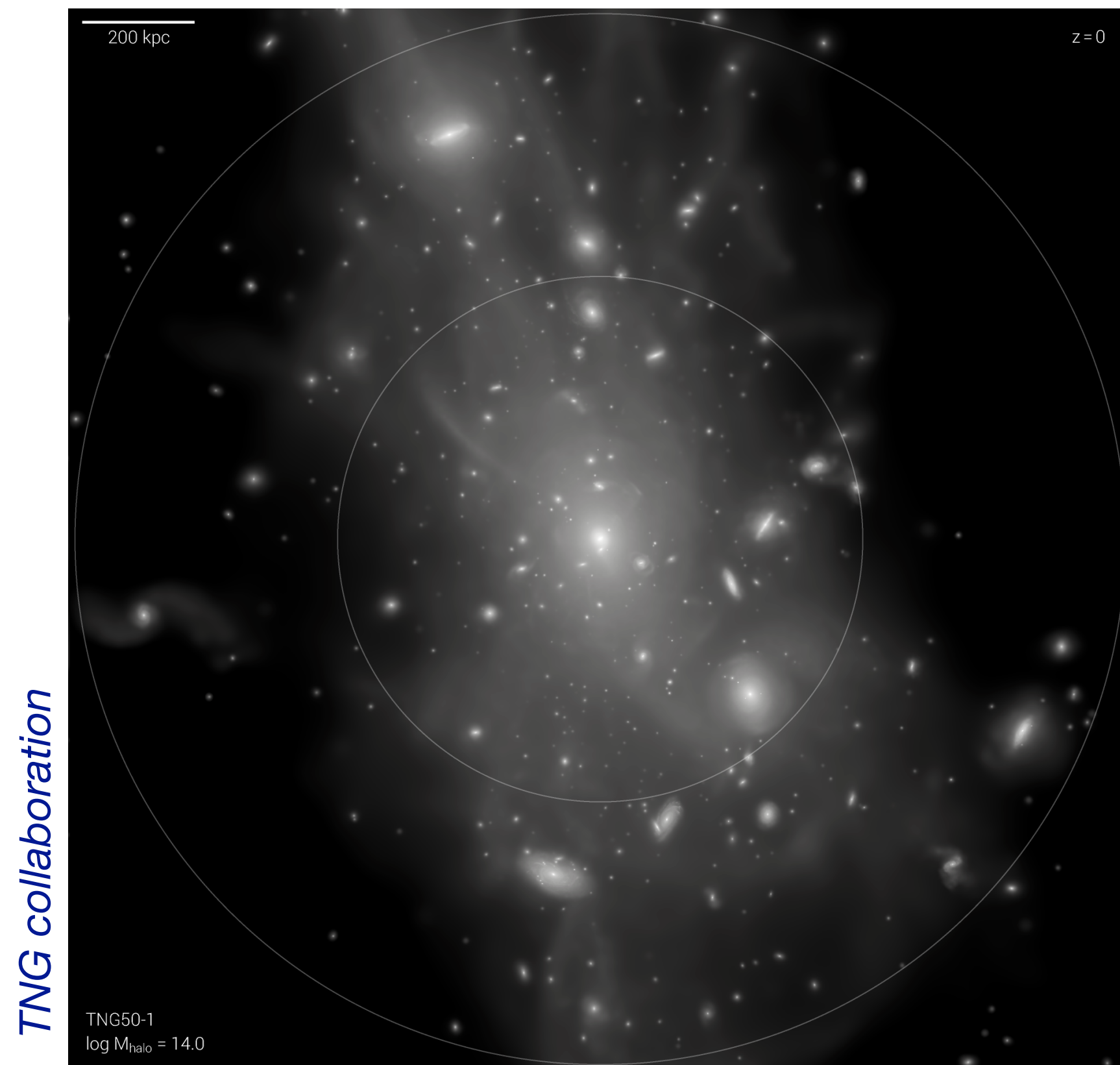
We should not go forward in time, but backward ...



Application 2: Euclid globular clusters in dwarf galaxies

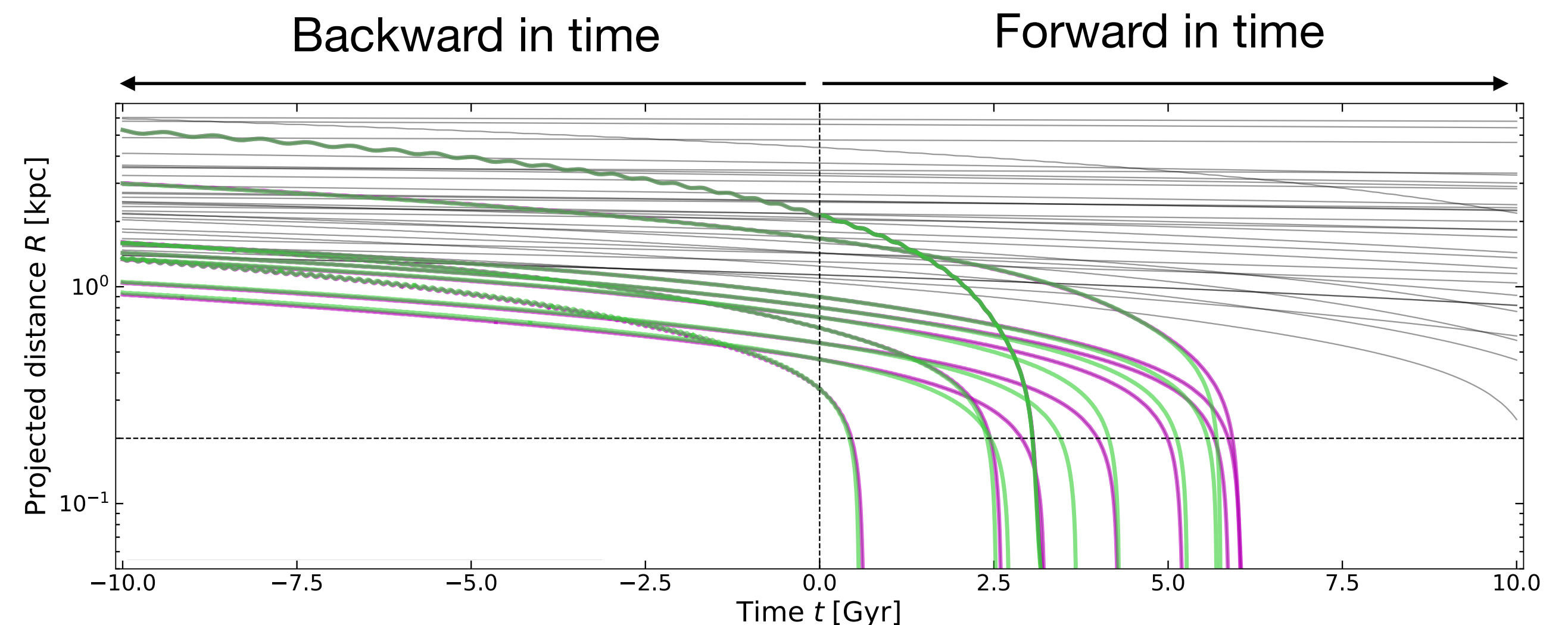
Integrating GC trajectories backward in time within realistic dwarf galaxy potentials

TNG50 most massive galaxy cluster ($10^{14} M_{\odot}$)



848 dwarfs ($10^6 - 10^{9.5} M_{\odot}$)

- ◆ Identified dwarf analogues based on the stellar mass
- ◆ Time-evolving potential between $z=3$ and $z=0$
- ◆ Account for the evolution of dwarf galaxies within the TNG cluster environment

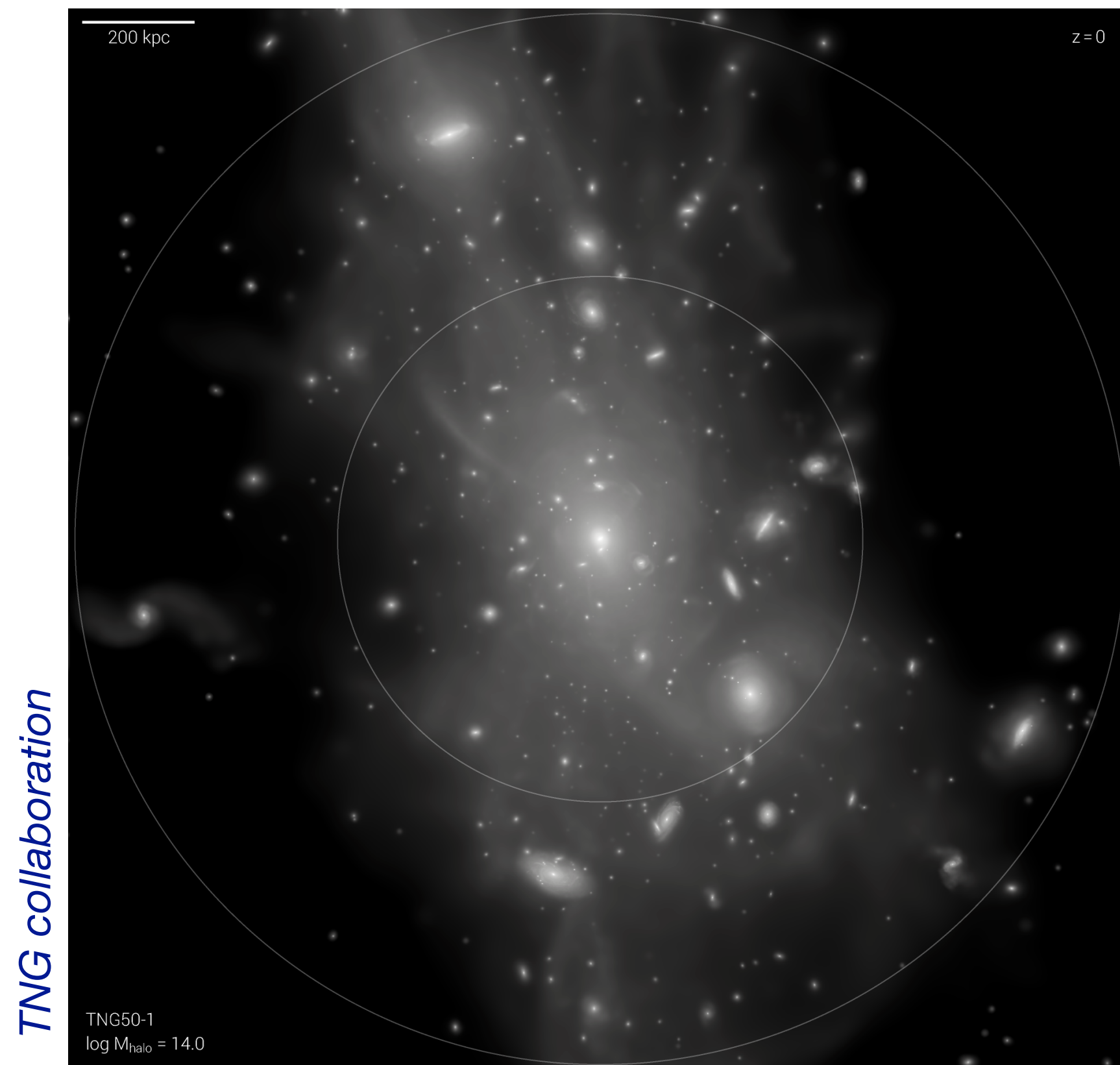


Backward orbital integrations effectively reverse the role of dynamical friction $\rightarrow$ energy gain

Application 2: Euclid globular clusters in dwarf galaxies

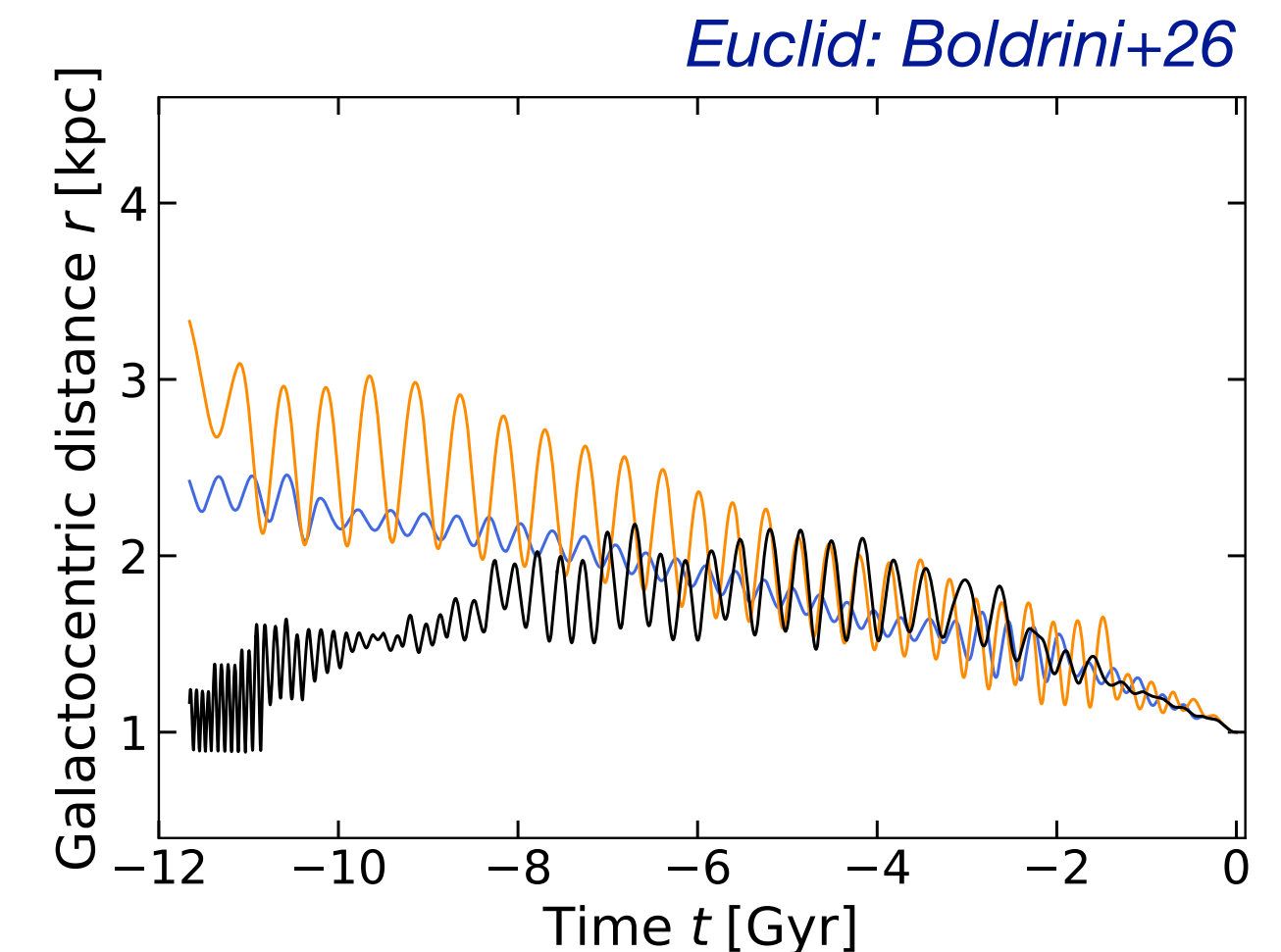
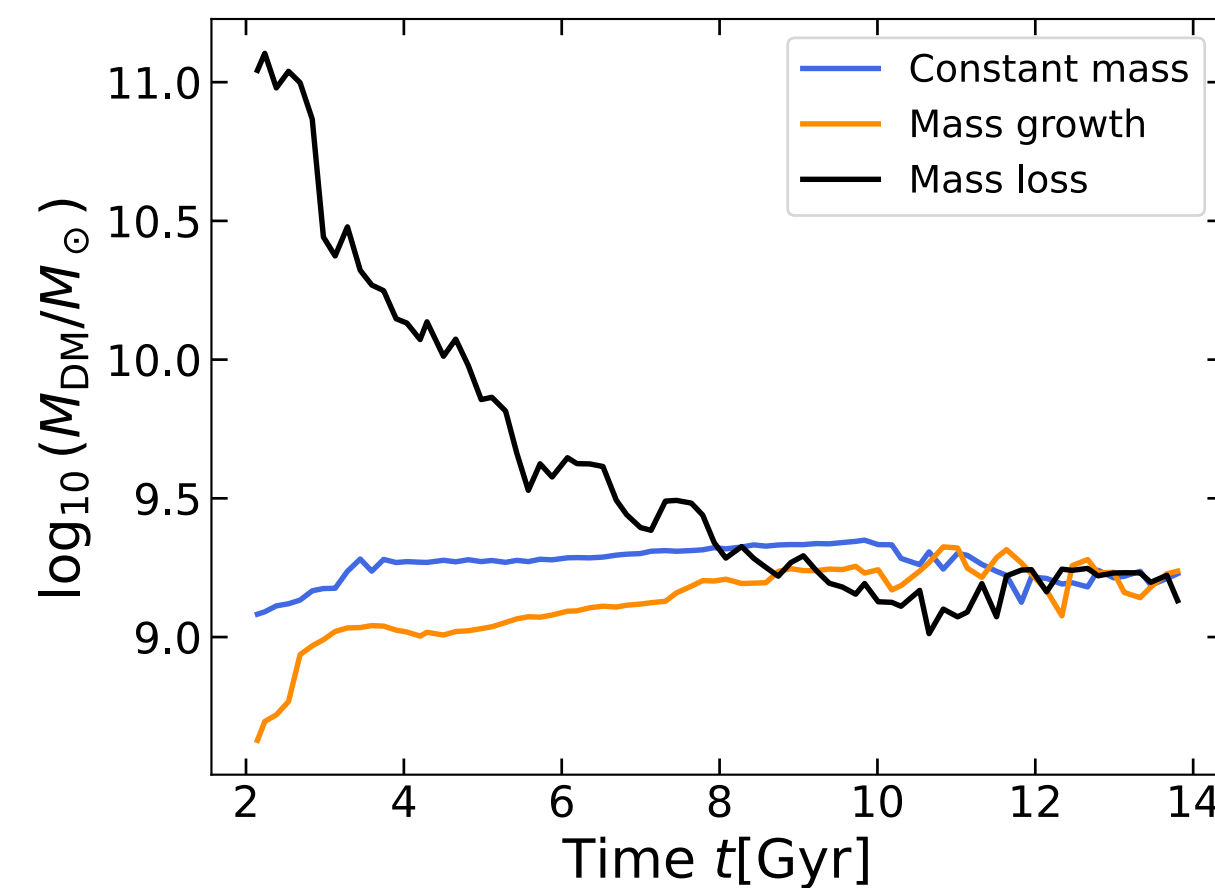
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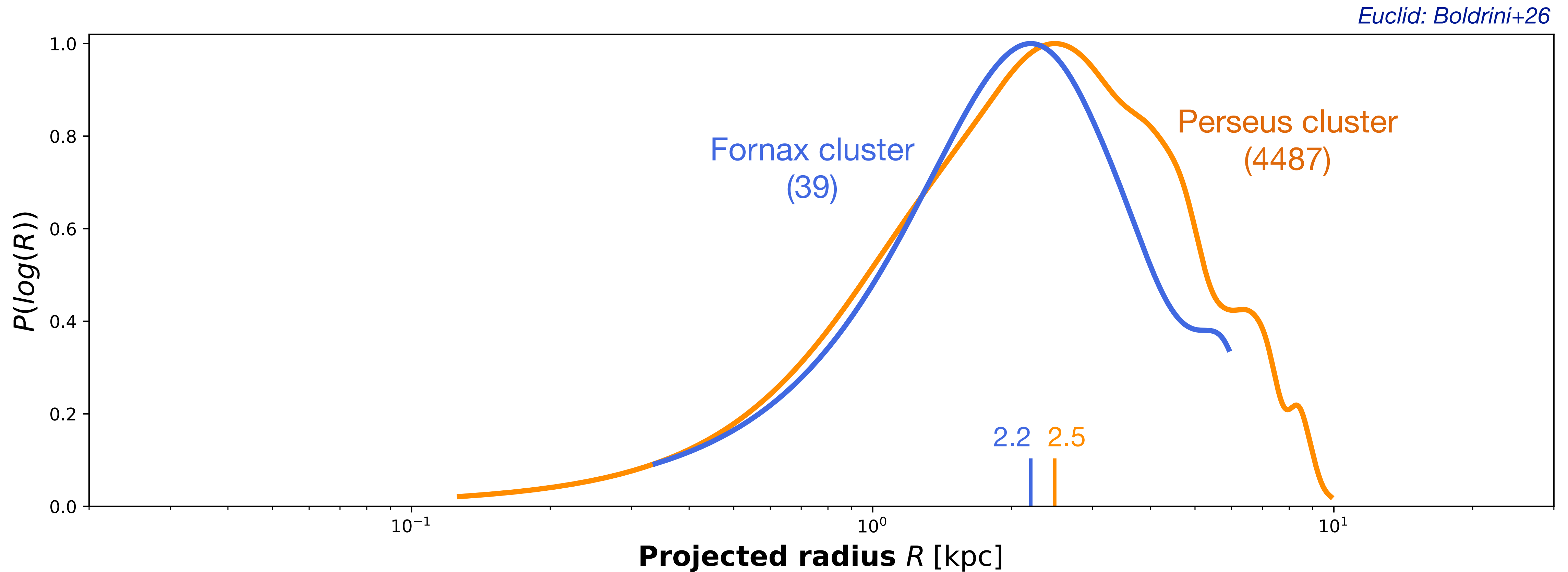
- ◆ Time-evolving potential between $z=3$ and $z=0$
- ◆ Account for the evolution of dwarf galaxies within the TNG cluster environment



Different mass-evolution scenario in galaxy cluster environment

Application 2: Euclid globular clusters in dwarf galaxies

Euclid GCs from $z=0$ to $z=3$



Application 2: Euclid globular clusters in dwarf galaxies

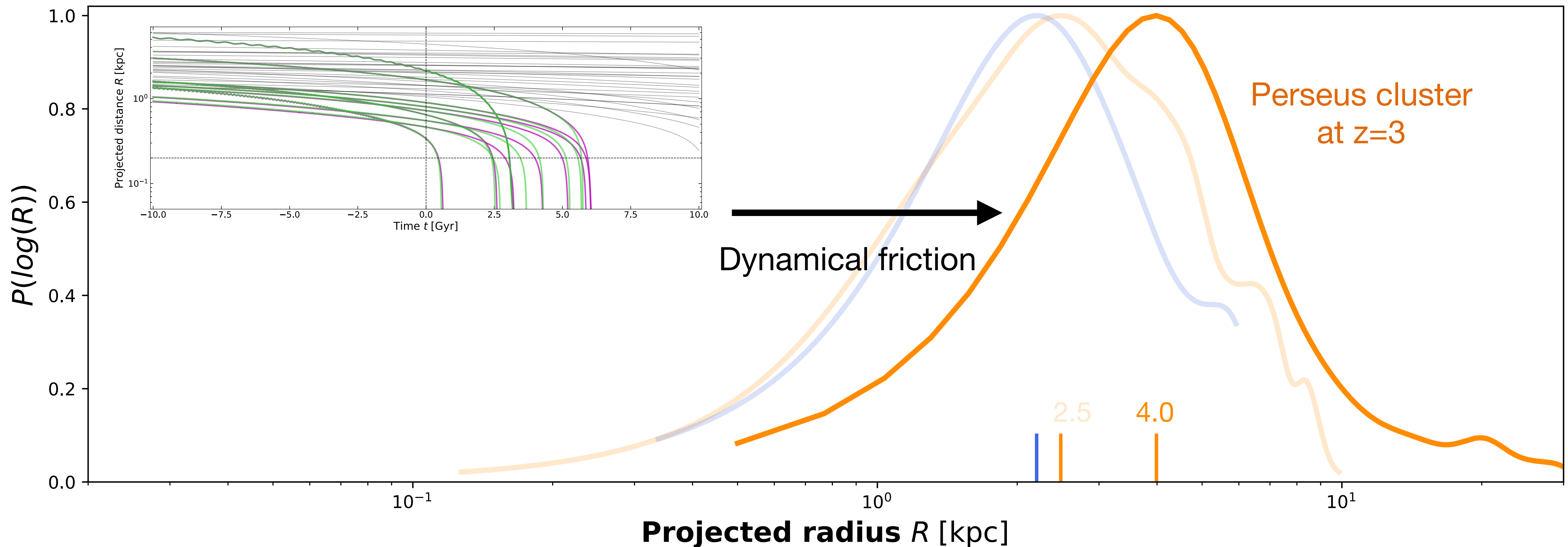
Euclid GCs from $z=0$ to $z=3$

CosmoDyn

License MIT Python 3.10+

CosmoDyn is an open-source Python framework designed to reconstruct time-dependent galactic potentials from cosmological simulations and model the dynamical evolution of compact stellar systems such as globular clusters (GCs), nuclear star clusters (NSCs) and massive black holes (MBHs).

Euclid: Boldrini+26



GCs would have been located at much larger galactocentric distances

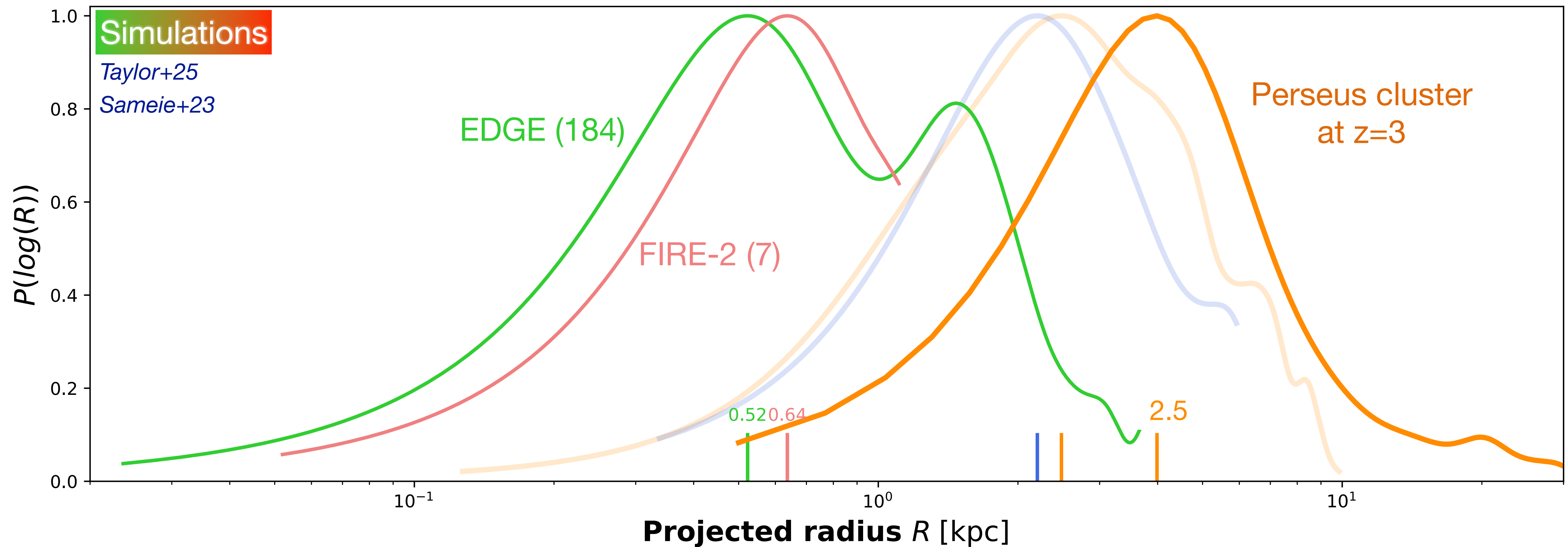
Application 2: Euclid globular clusters in dwarf galaxies

What do the simulations tell us?

- ◆ Most GCs should form within 1 kpc of the galaxy centre

Elmegreen+97, Kruijssen+15

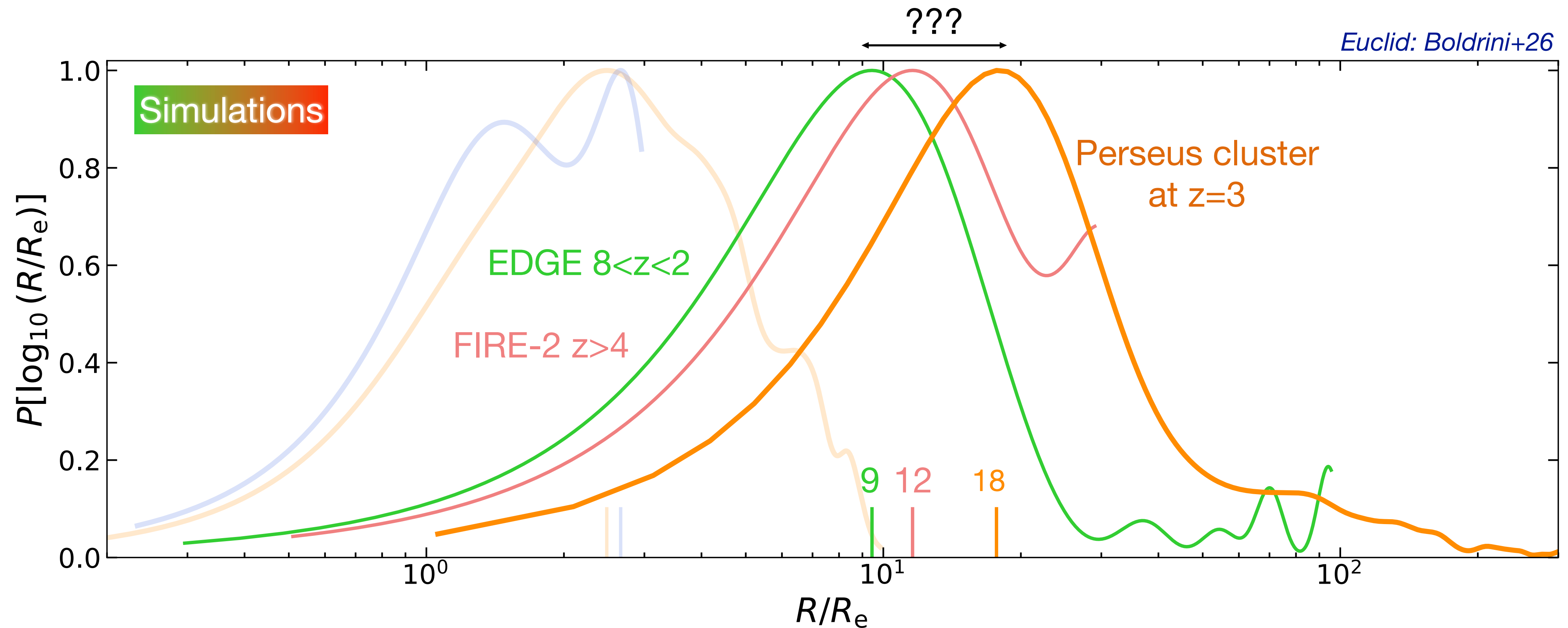
Euclid: Boldrini+26



Discrepancy between simulations and reconstructed Euclid data?

Application 2: Euclid globular clusters in dwarf galaxies

Normalised by the galaxy size



Discrepancy between simulations and reconstructed Euclid data?

Application 2: Euclid globular clusters in dwarf galaxies

JWST data on GC birth radii

Abell 2744 galaxy cluster



NASA/ESA

573 galaxies between $z=0.7$ and $z=10$
—> **1956 compact stellar clumps**

Claeysens+25

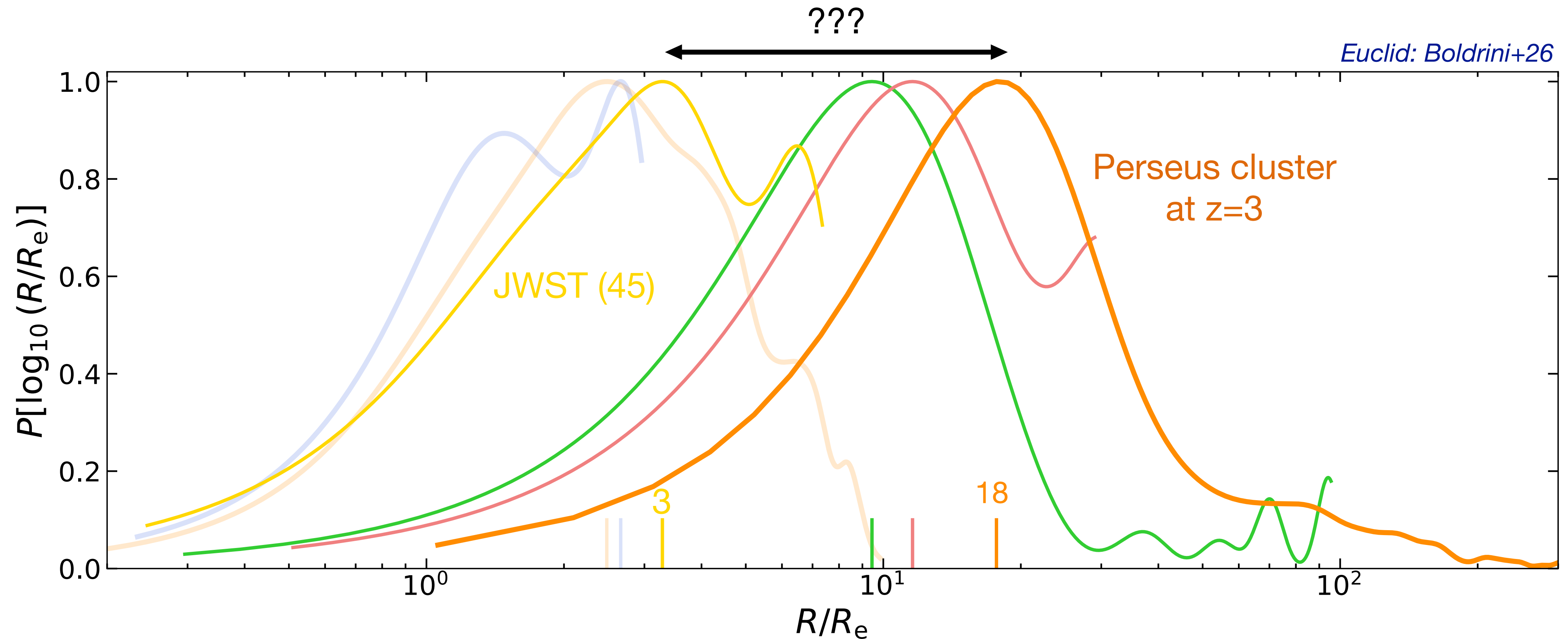
Set of selection criteria:

- ◆ $0.2 \text{ kpc} < R < 10 \text{ kpc}$ —> excluding both NSCs and distant outliers
- ◆ $z > 2$ —> high-redshift systems
- ◆ $\text{Size} < 40 \text{ pc}$ —> removing overly extended structures
- ◆ $\text{Mass} > 6 \times 10^6 M_{\odot}$ —> massive compact star-forming regions

45 regions potentially hosting the formation of one or several GCs

Application 2: Euclid globular clusters in dwarf galaxies

JWST data on GC birth radii



Even stronger discrepancy, as the peak of the distribution lies very close to the present-day Euclid distribution

Application 2: Euclid globular clusters in dwarf galaxies

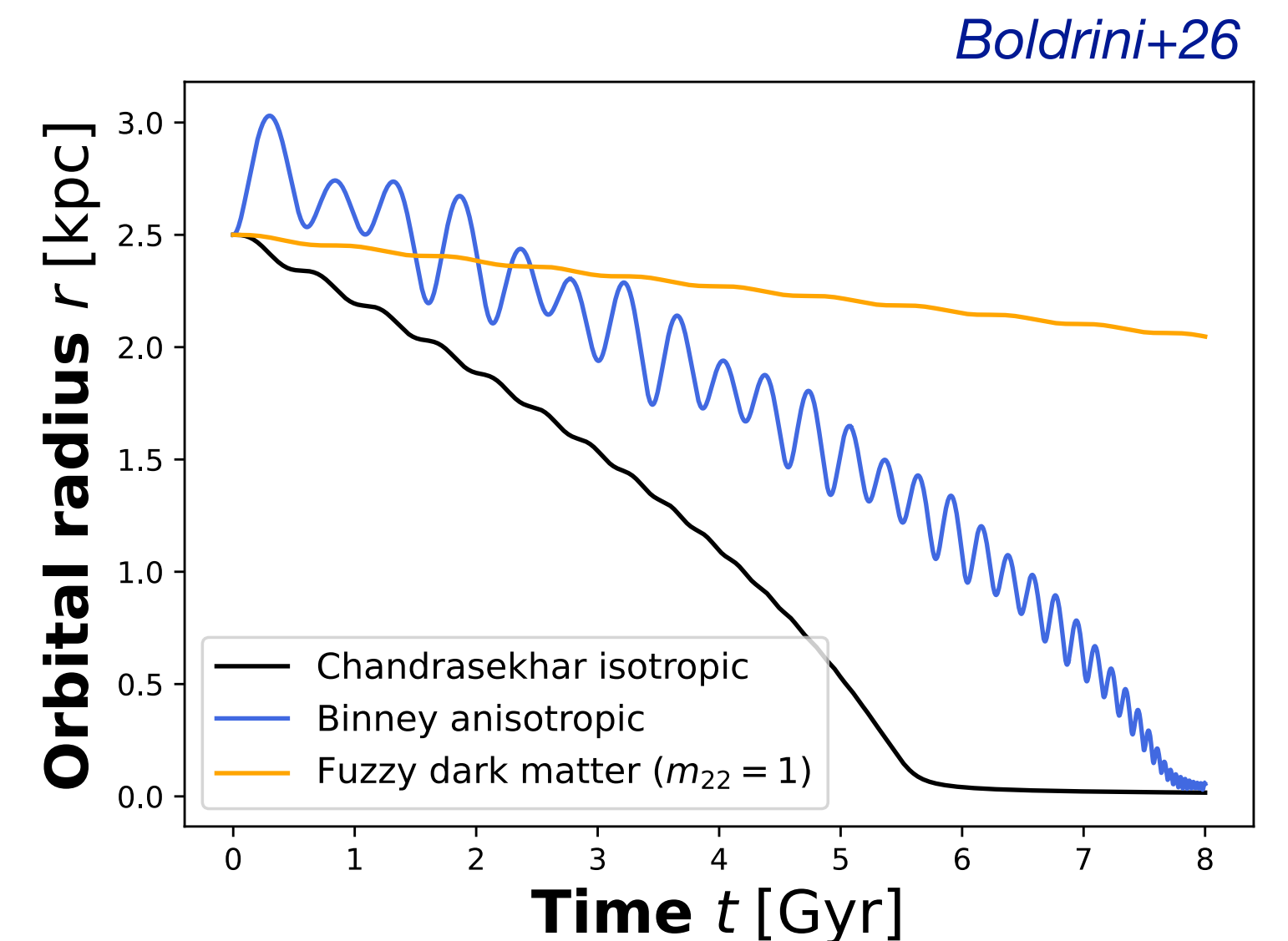
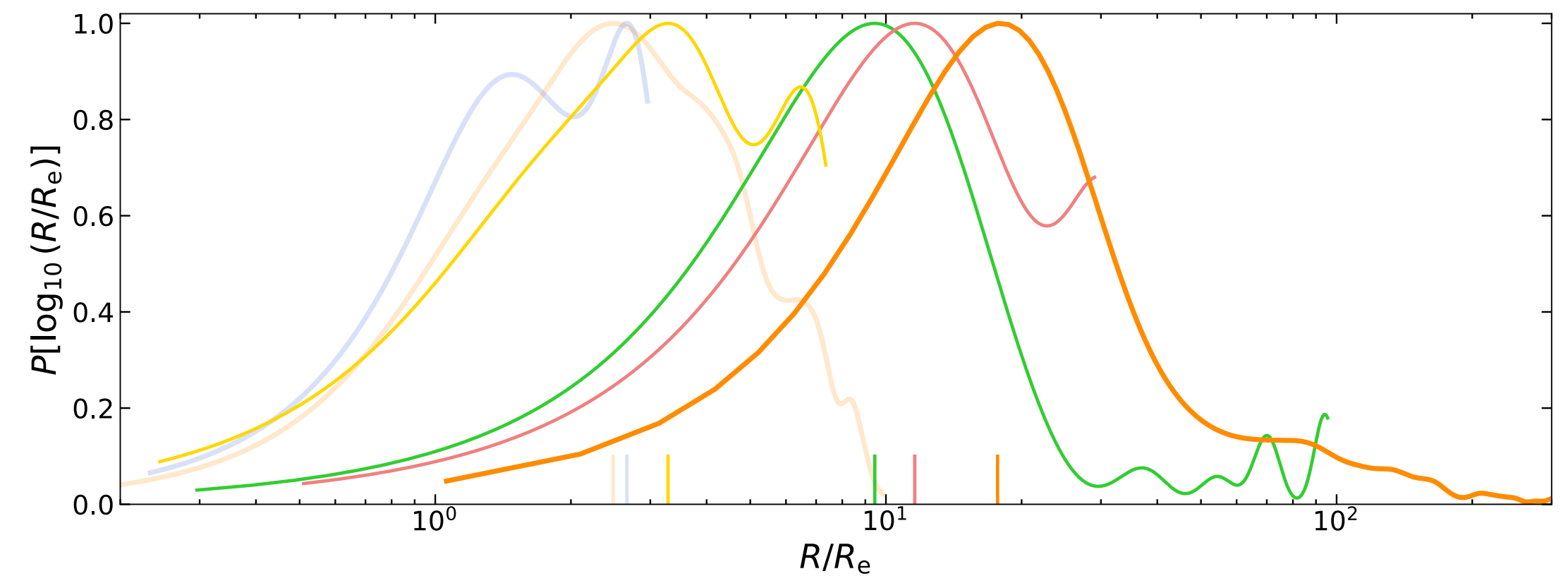
Problem: tension between the backward-integrated positions of Euclid Perseus GCs and the expected birth locations inferred from simulations

Solution 1: survivorship bias inherent to $z=0$ GCs

- ◆ Largely dominated by ex situ GCs $\rightarrow$ Extreme scenario
- ◆ Estimated missing in situ population: 9000 in situ $\rightarrow$ high probability of sinking
- ◆ Only 27% of Perseus dwarfs host an NSC
- ◆ 67% of dwarfs have not experienced a merger in TNG50 galaxy cluster

Solution 2: reduce or counteract dynamical friction

- ◆ Allow GCs to leave the central region after their formation
- ◆ Expected mixed population of in situ and ex-situ, as in MW
- ◆ **Candidates:** DM mass loss, DM subhalo-GC interactions, non-spherical potential, mergers, core profile, alternative DM theory (FDM), ...



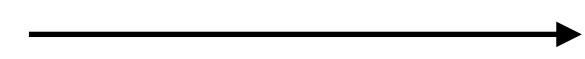
Combined action of several of these processes operating simultaneously over cosmic time

Futur work [1/2]

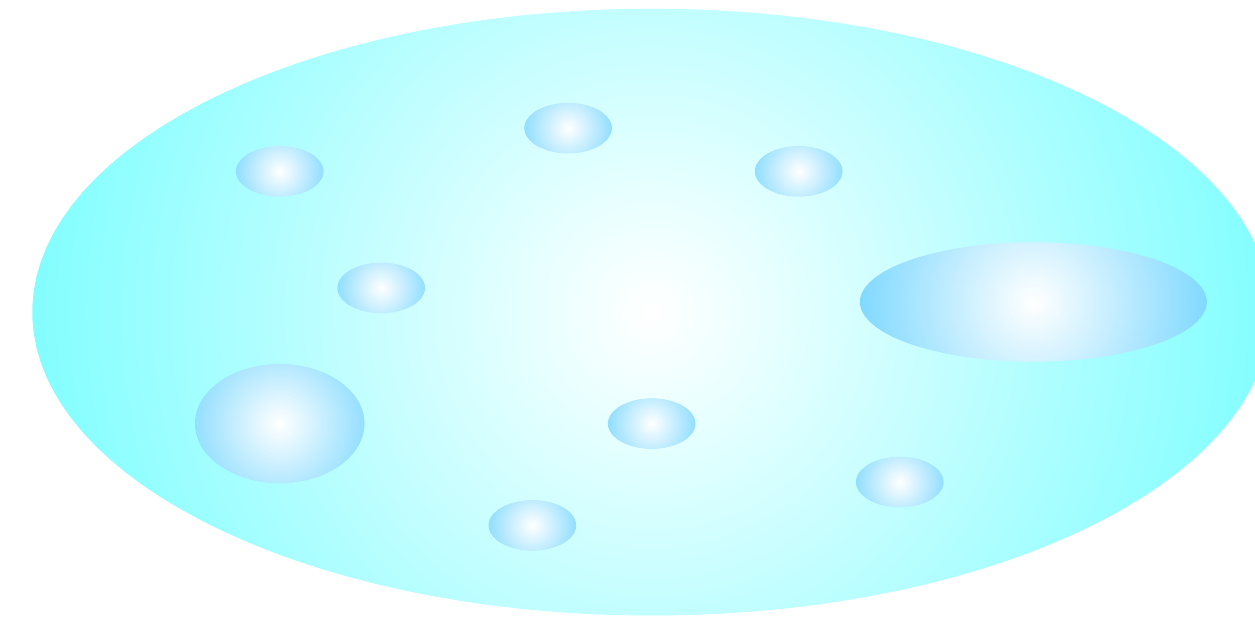
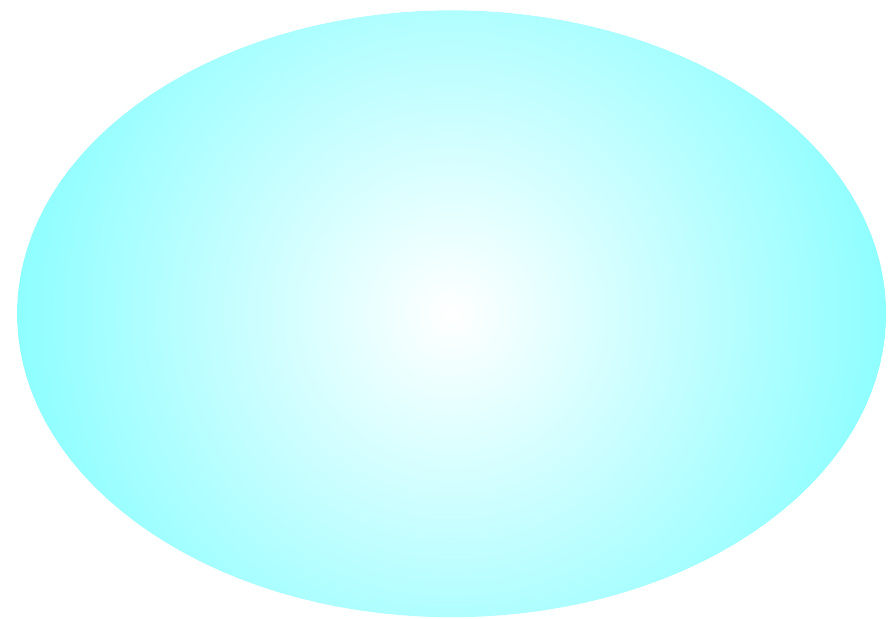
CosmoDyn 2.0:

- ♦ GCs tagged based on DM halo mass and distribution functions
 - > **NEW:** incorporating physically motivated GC-formation models *Leaman+17*
- ♦ Fixed analytical density profiles
 - > **NEW:** basis-function expansion method from particles of the simulation *Hernquist&Ostriker+92*

$$\rho(r) = \frac{\text{amp}}{4\pi a^3} \frac{1}{(r/a)(1+r/a)^2}$$



$$\rho(r, \theta, \phi) = \frac{\text{amp}}{2} \sum_{n=0}^{\infty} \sum_{l=0}^{\infty} \sum_{m=0}^l N_{lm} P_{lm}(\cos(\theta)) \tilde{\rho}_{nl}(r) (A_{\cos,nlm} \cos(m\phi) + A_{\sin,nlm} \sin(m\phi))$$



New observational data:

- ♦ Euclid ERO: 39 GCs in Fornax galaxy clusters —> **DR1: several thousand new GCs**
- ♦ 45 star forming regions of GCs in Abell 2744 —> **NEW:** 23 in AbellS1063 *Claeysens+26*



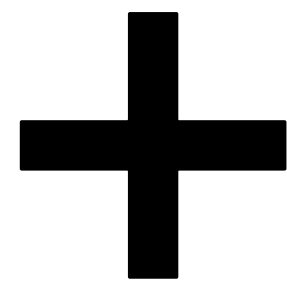
Futur work [2/2]

Applying the model to CDM simulations:

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

Applying the model to ADM simulations:

- ◆ Fuzzy dark matter simulations —> Fuzzy Gasoline (dwarf galaxies + hydrodynamic)



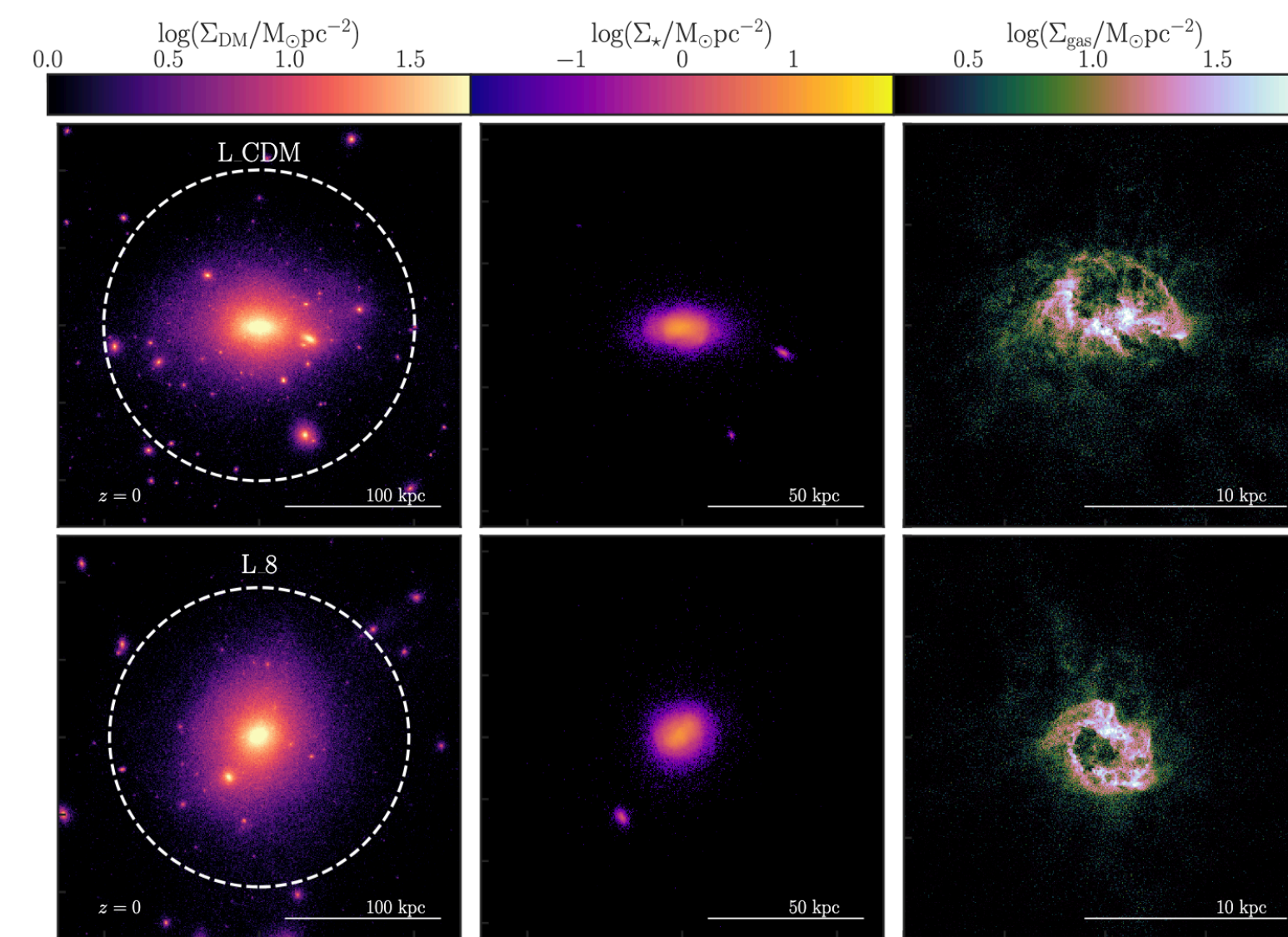
CosmoDyn 2.0

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Khoperskov+23



Nori+24



◆ A. Maccio



Thank you!

Current limitations in cosmological simulations

Globular clusters

Not resolved in cosmological simulations —> **below the mass and spatial resolution**

Nuclear star clusters

If resolved

Idealized high-resolution galaxy simulations —> **limited to a few galaxies (1-2)**

Lahen+20, Li+22, Andersson+24, Deng+24, ...

High-resolution cosmological simulations —> **limited to high redshift ($z=3-5$)**

Kravtsov +05, Li +17, Kim +18, Ma +20, Meng +22, Sameie +22, ...

Black holes

Artificially repositioned toward the local potential minimum —> **in many simulations** *Bahé+21*

Dynamical friction prescriptions —> **limited to kpc scales** *Chen+22*

Interactions between BHs and nuclear star clusters —> **not modeled**

Overcoming these numerical limitations?