Observational Astrophysics Group Seminar, *Lancaster*, *23/02/2026*

# What can intracluster light tell us about dark matter?

Garreth Martin
*University of Nottingham*

***with:*** **Harley Brown, Joe Butler, Nina Hatch, Frazer Pearce, Tutku Kolcu, Adela Fernandez, Yannick Bahe, Ilin Lazar and Sugata Kaviraj**

# The Nottingham ICL group

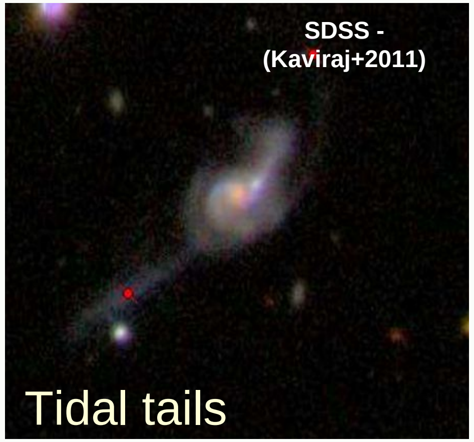
- **Observations:**
  - **Low-surface-brightness image processing** — optimising Euclid postprocessing pipelines for LSB science
  - **ICL measurement techniques** — multi-galaxy fitting, BCG–ICL separation, surface brightness profiles
  - **ICL shape compared with mass maps** — measuring ICL morphology from Euclid and comparing with dark matter distributions
  - **ICL across cosmic time** — tracing ICL evolution out to z ~ 1, including links to hierarchical BCG assembly
  - **Kinematic BCG–ICL separation —** using IFU data to kinematically decompose the BCG and ICL and test whether ICL kinematics trace the dark matter
- **Theory / Simulations:**
  - **ICL formation mechanisms** — tracking ICL progenitors through cosmological simulations
  - **Phase-space relationship with dark matter** — characterising the energy and angular momentum offsets between ICL and DM; understanding why the ICL is a biased DM tracer

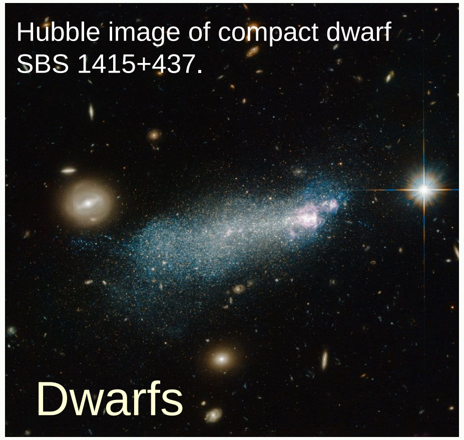
# Tidal debris as a probe of dark matter

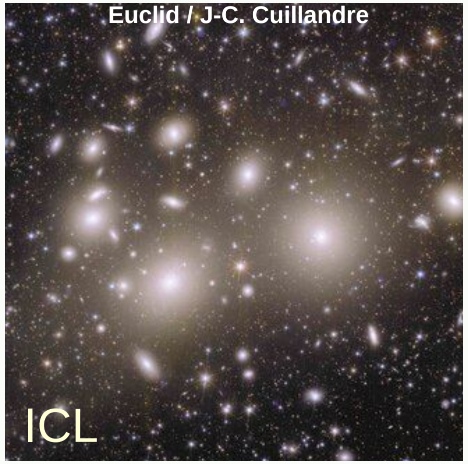
- When galaxies fall into larger systems, tidal forces strip their stars and dark matter. The resulting debris — streams, tails, shells, and diffuse haloes — traces the gravitational potential of the host.

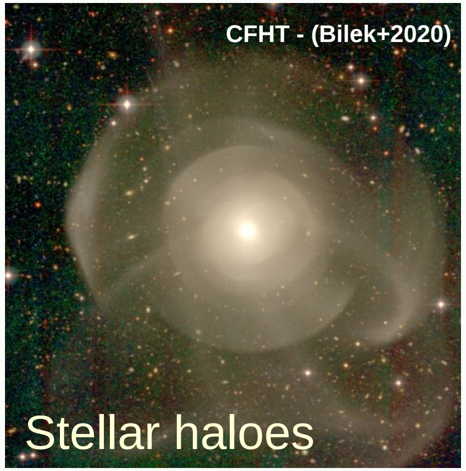
- **This is now possible across the full mass hierarchy:**
  - Milky Way: ~100 stellar streams from Gaia constrain the Galactic potential and DM substructure
  - Galaxy scale: the SSLS catalogues tidal features around thousands of nearby galaxies; The STRRINGS survey aims to robustly measure and model their geometry; ARRAKIHS will target streams and satellite systems from space
  - **Cluster scale: intracluster light — stars stripped from infalling galaxies — traces the cluster DM potential**

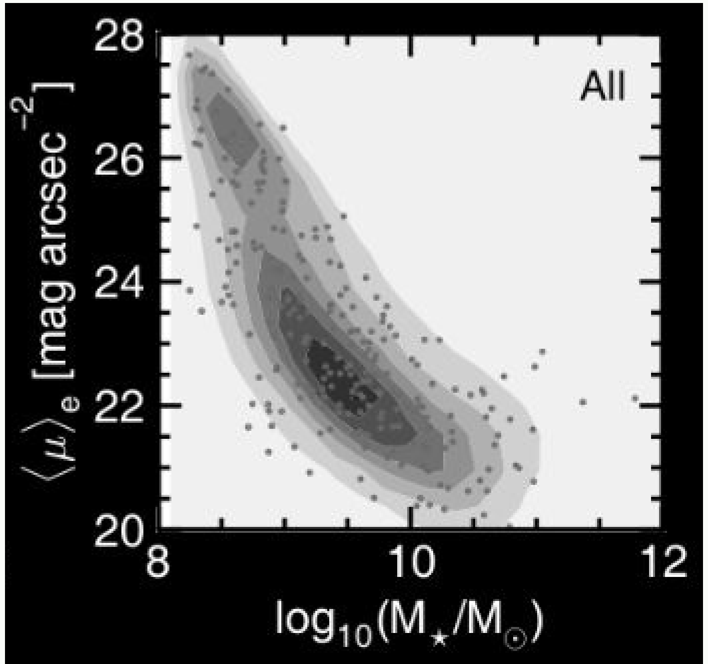
- **Tidally stripped stars are collisionless tracers of the gravitational potential, just like dark matter itself.**



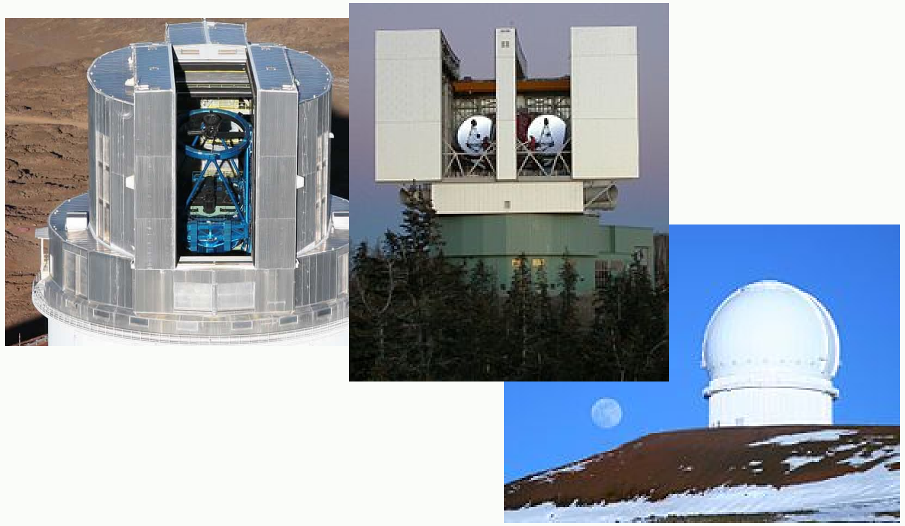



Martin et al. 2019

Duc+14

- We always observe the Universe at **finite depth**
  - The objects and structures that we detect are a **biased subset** of the true underlying distribution
  - Most of these structures **lie far SB limits achievable by contemporary surveys** (e.g. Impey+1988)

- New surveys are expanding LSB discovery space in depth, resolution, and area.

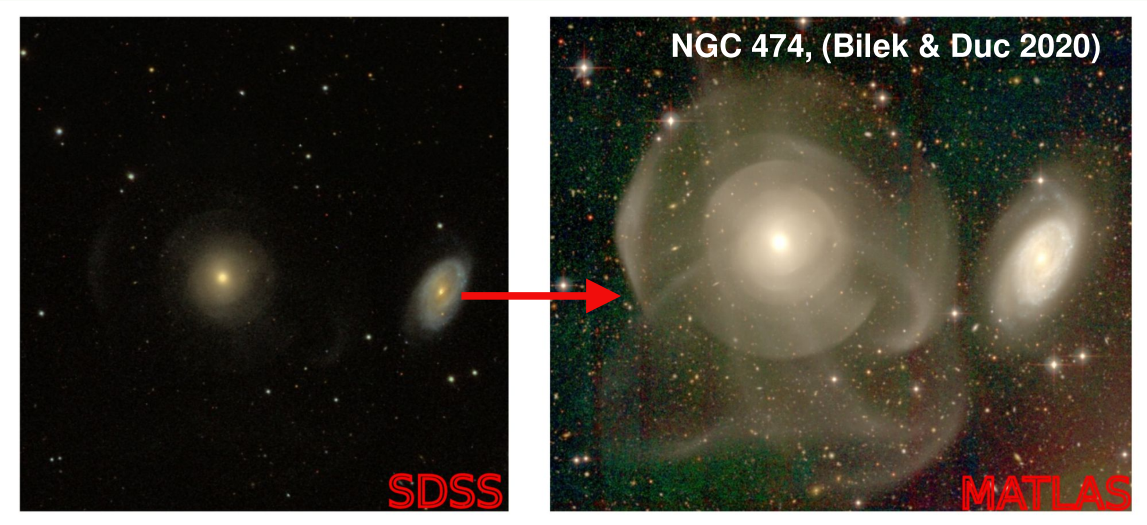


Euclid: WFD underway

JWST

Rubin: LSSTCam now on-sky

Existing and upcoming deep small-to-medium area surveys including CFIS, LIGHTS, HSC-SSP have given us a preview of the the kind of imaging we can achieve



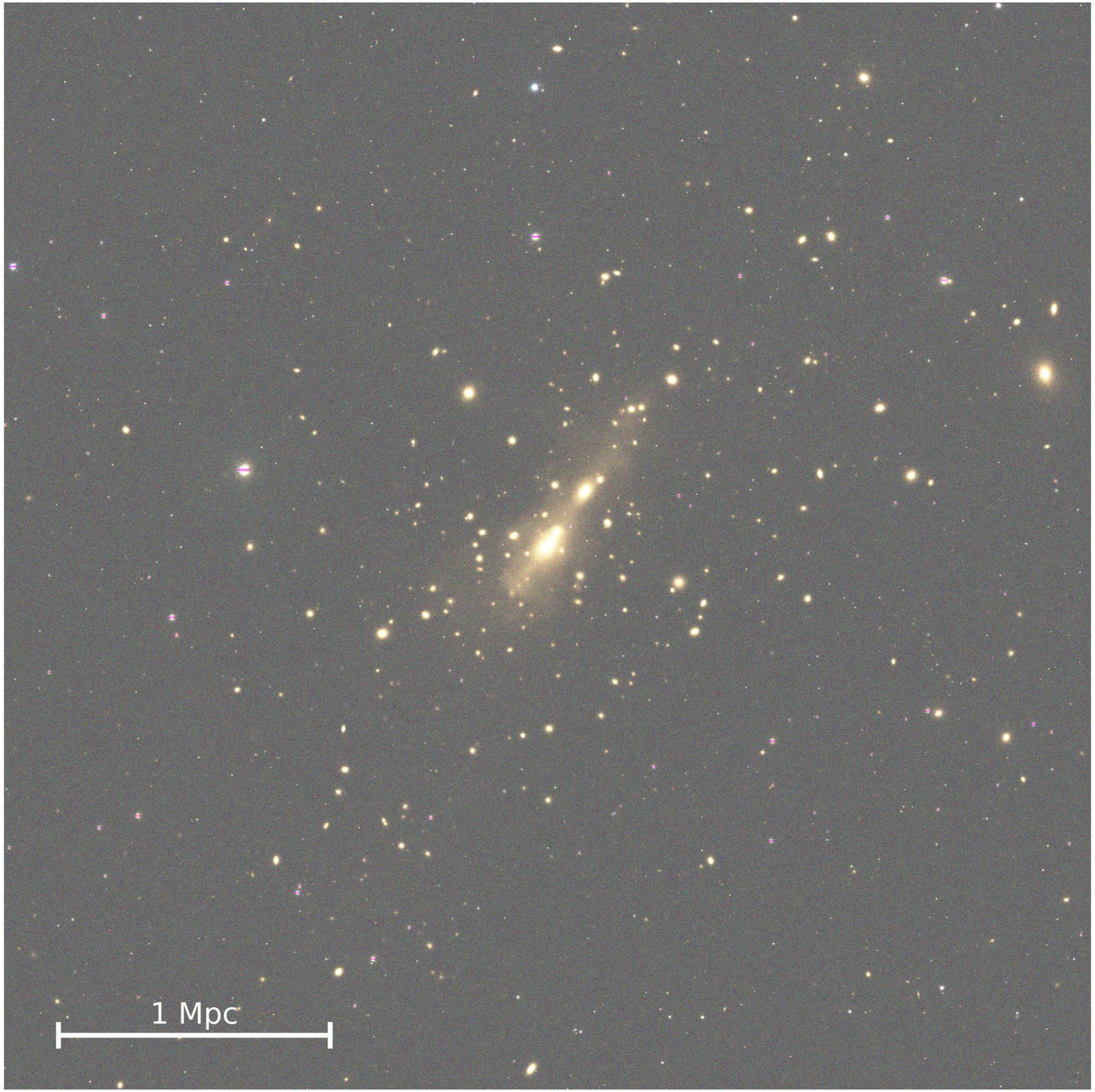

## Expanding Discovery Through Deep-Wide Surveys

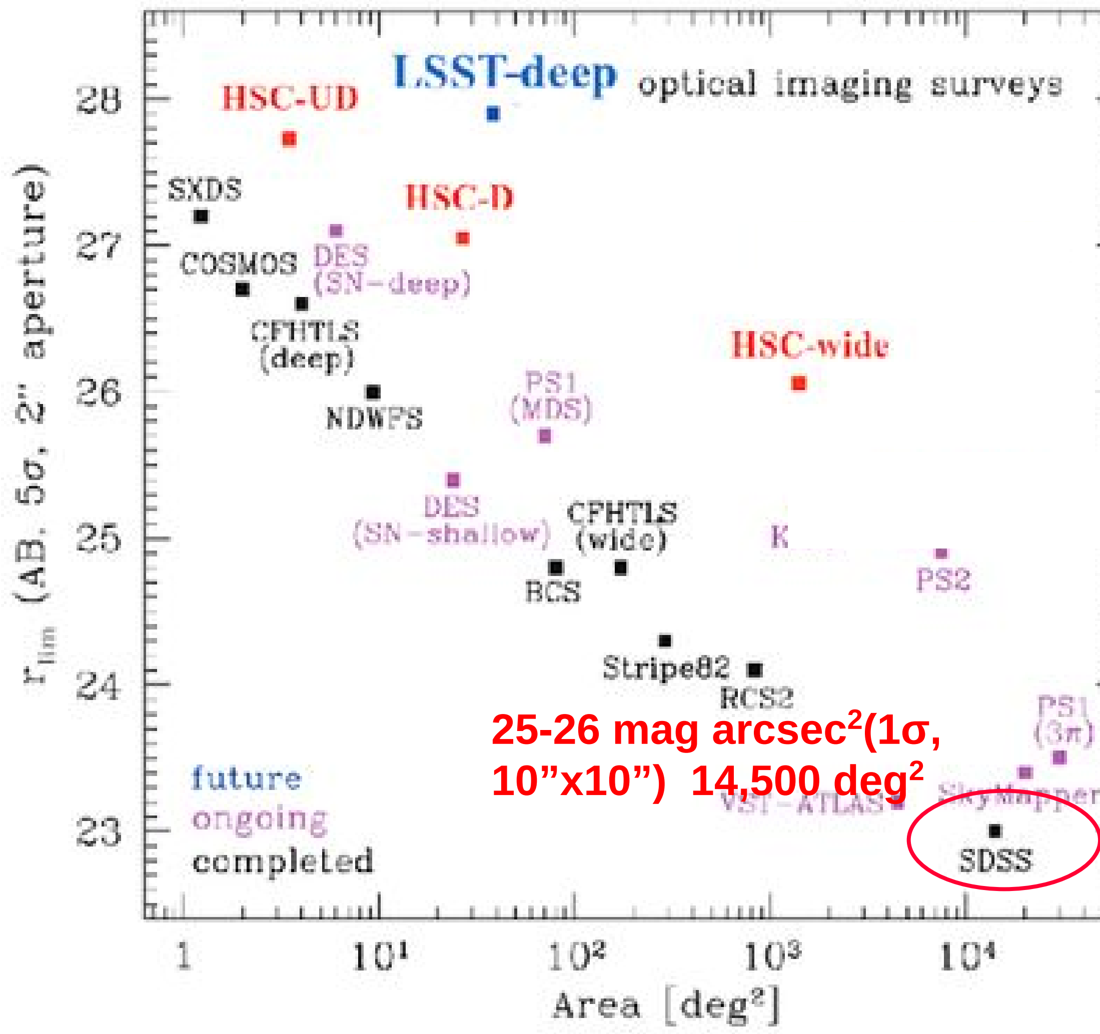
- Pathfinder surveys already demonstrate the potential of deep imaging over smaller areas of the sky.

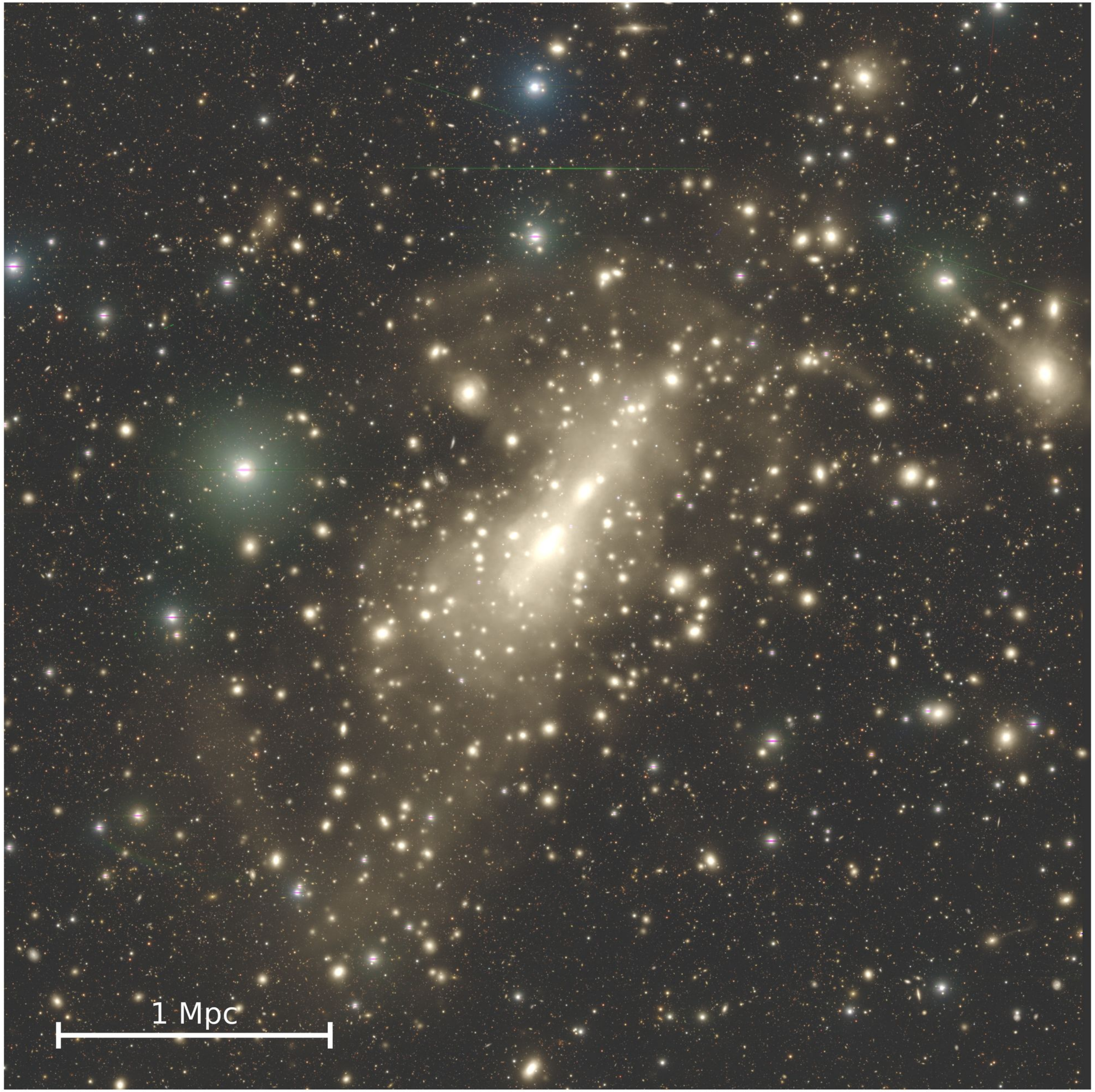
– Next-generation “deep-wide” datasets will enable systematic studies across much larger samplesmost

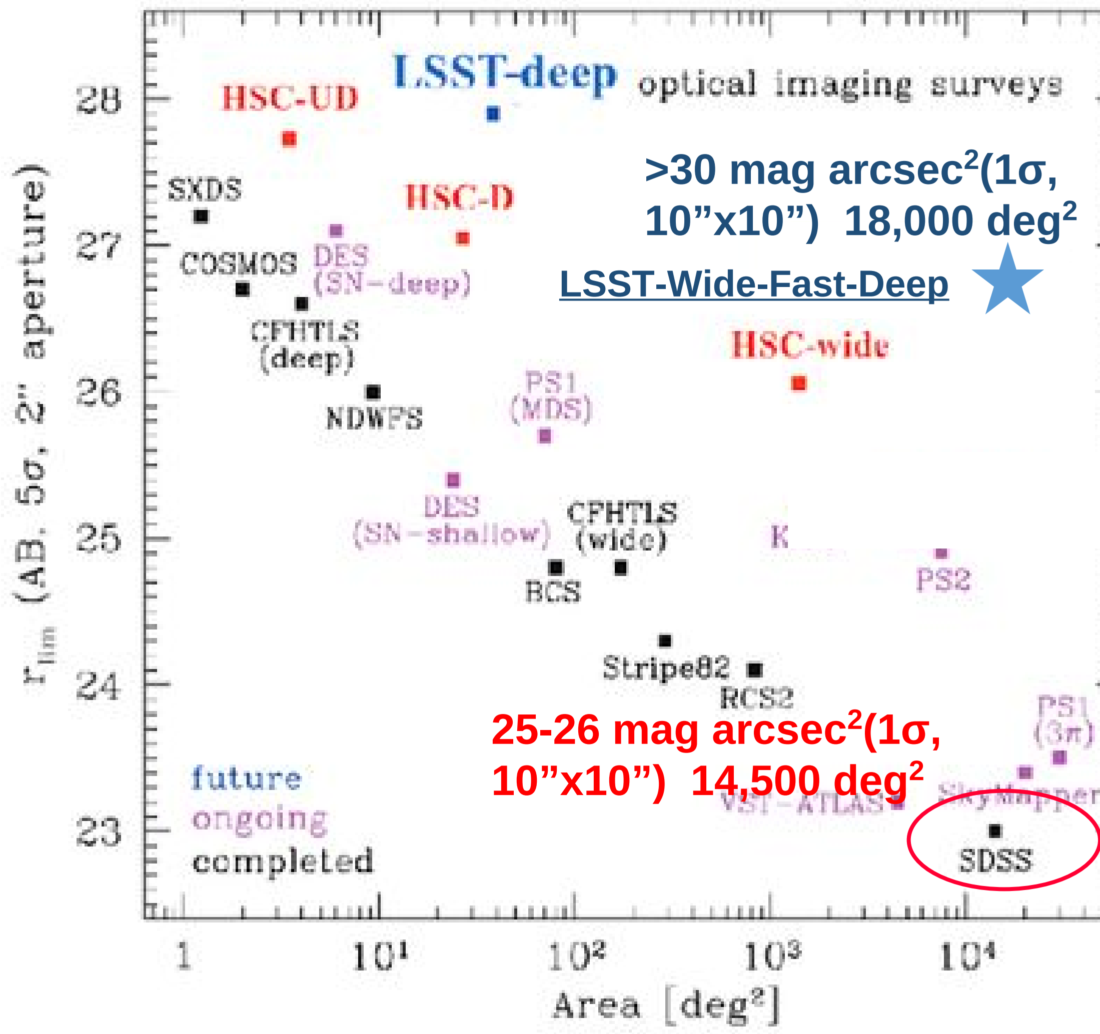
- Coverage over thousands of square degrees enables broad and statistically robust exploration.

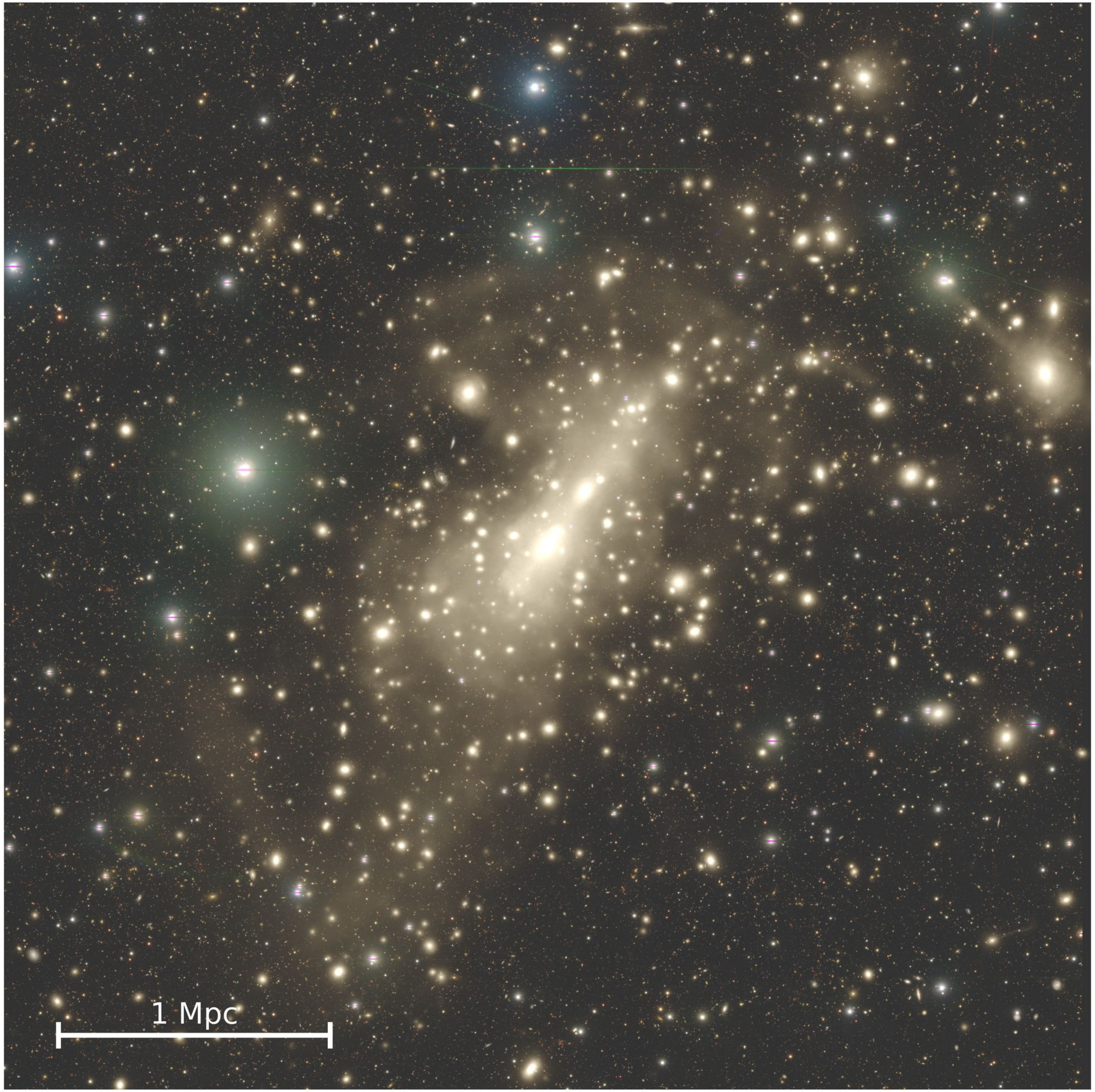
- Combining depth and area maximises discovery potential for LSB phenomena.

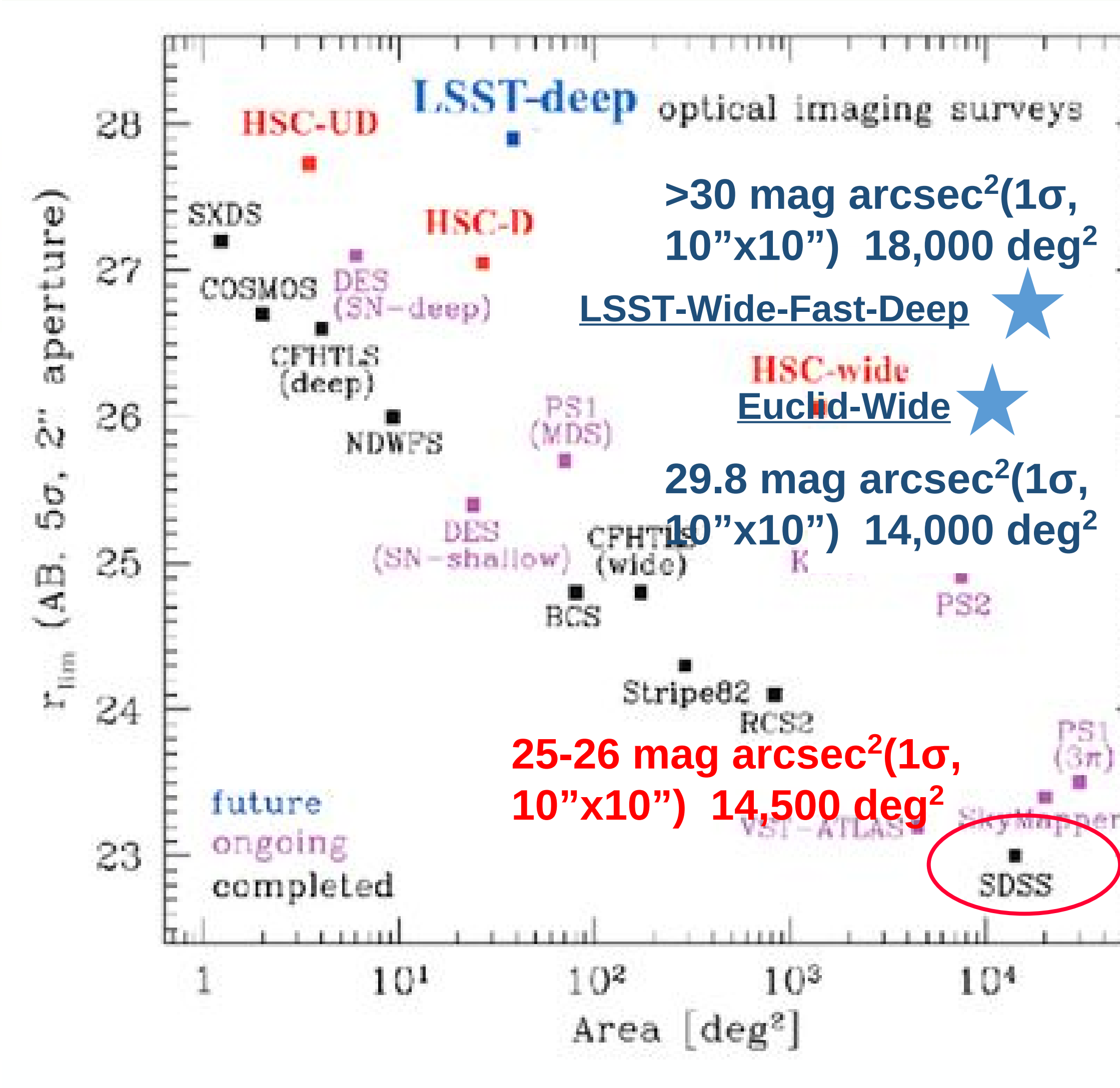

1 Mpc

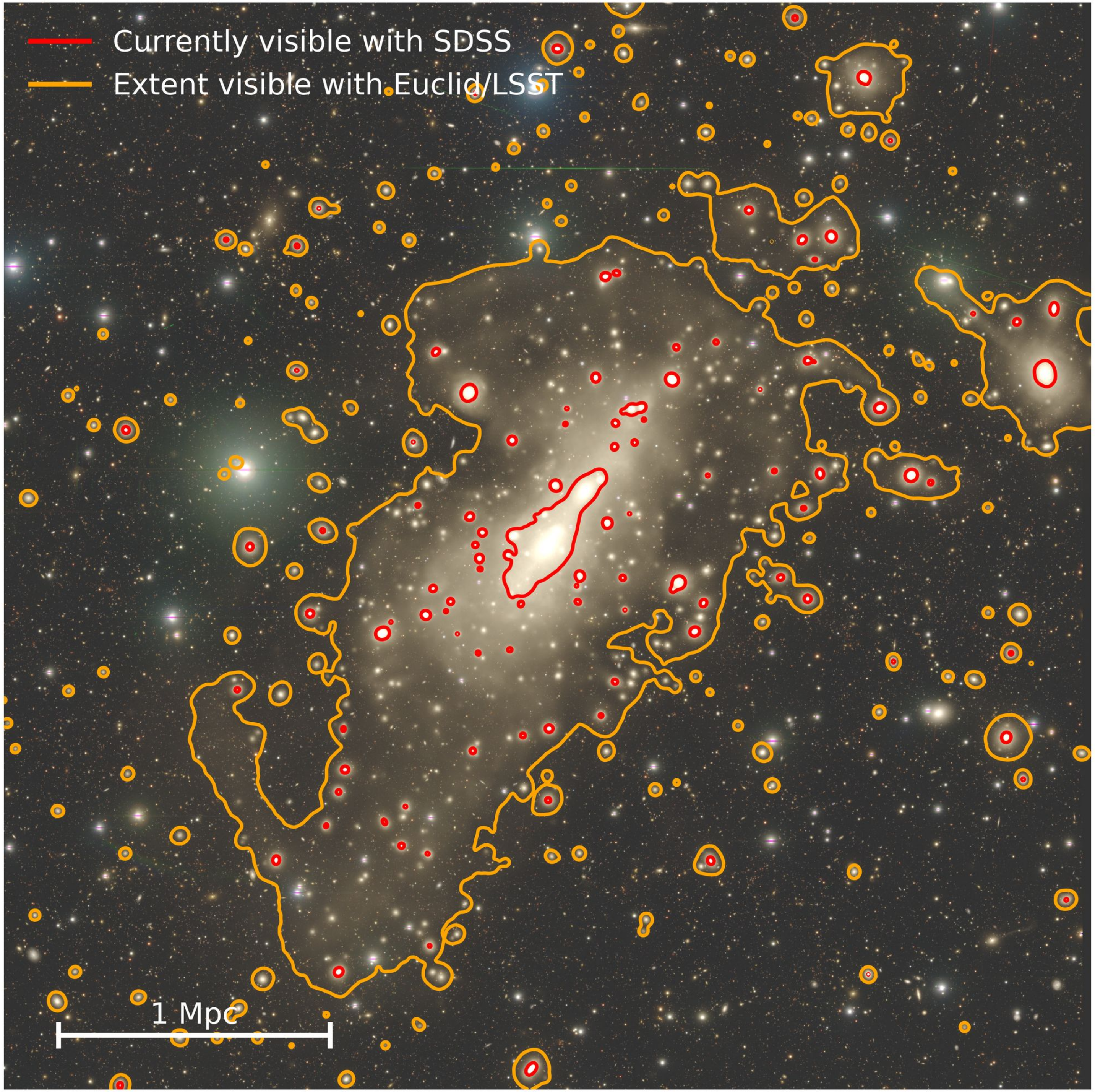

LSST-deep
optical imaging surveys
HSC-UD
HSC-D
HSC-wide
SXDS
COSMOS
DES (SN-deep)
CFHTLS (deep)
NDWFS
PS1 (MDS)
DES (SN-shallow)
CFHTLS (wide)
BCS
K
PS2
Stripe82
RCS2
PS1 (3π)
VST-ATLAS
SkyMapper
SDSS
future
ongoing
completed
25-26 mag arcsec$^2$(1σ, 10”x10”) 14,500 deg$^2$
$r_{lim}$ (AB, 5σ, 2” aperture)
Area [deg$^2$]

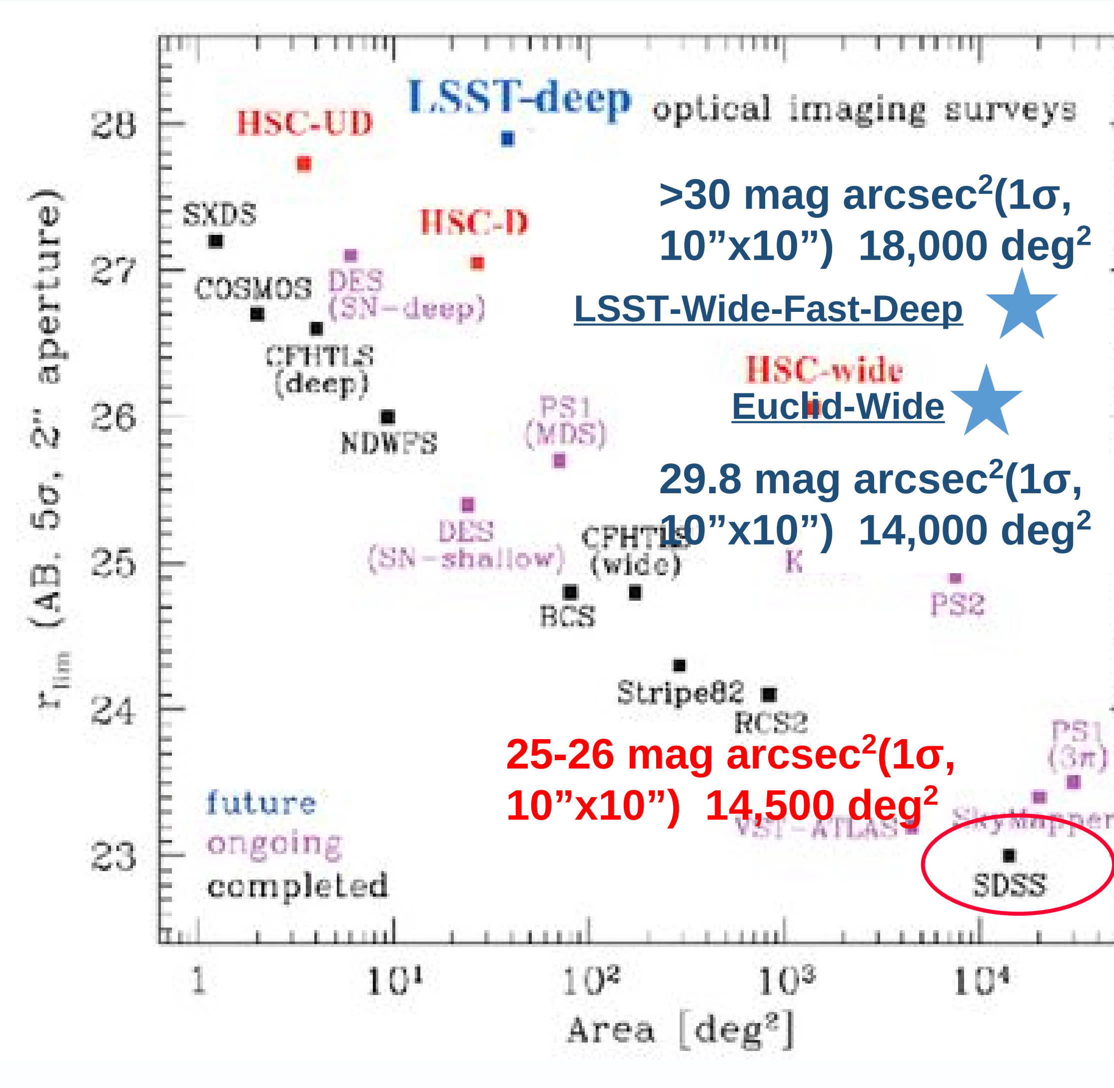

1 Mpc


LSST-deep
optical imaging surveys
HSC-UD
HSC-D
HSC-wide
SXDS
COSMOS
DES (SN-deep)
CFHTLS (deep)
NDWFS
PS1 (MDS)
DES (SN-shallow)
CFHTLS (wide)
BCS
K
PS2
Stripe82
RCS2
PS1 (3π)
VST-ATLAS
SkyMapper
SDSS
future
ongoing
completed
$r_{lim}$ (AB, 5σ, 2″ aperture)
Area [deg$^2$]
>30 mag arcsec$^2$(1σ, 10”x10”) 18,000 deg$^2$
LSST-Wide-Fast-Deep
25-26 mag arcsec$^2$(1σ, 10”x10”) 14,500 deg$^2$


1 Mpc


LSST-deep
optical imaging surveys
HSC-UD
HSC-D
HSC-wide
SXDS
COSMOS
DES (SN-deep)
CFHTLS (deep)
NDWFS
PS1 (MDS)
DES (SN-shallow)
CFHTLS (wide)
BCS
Stripe82
RCS2
PS2
PS1 (3π)
SDSS
future
ongoing
completed
$r_{lim}$ (AB, 5σ, 2" aperture)
Area [deg$^2$]
>30 mag arcsec$^2$(1σ, 10"x10") 18,000 deg$^2$
LSST-Wide-Fast-Deep
Euclid-Wide
29.8 mag arcsec$^2$(1σ, 10"x10") 14,000 deg$^2$
25-26 mag arcsec$^2$(1σ, 10"x10") 14,500 deg$^2$


Currently visible with SDSS
Extent visible with Euclid/LSST
1 Mpc

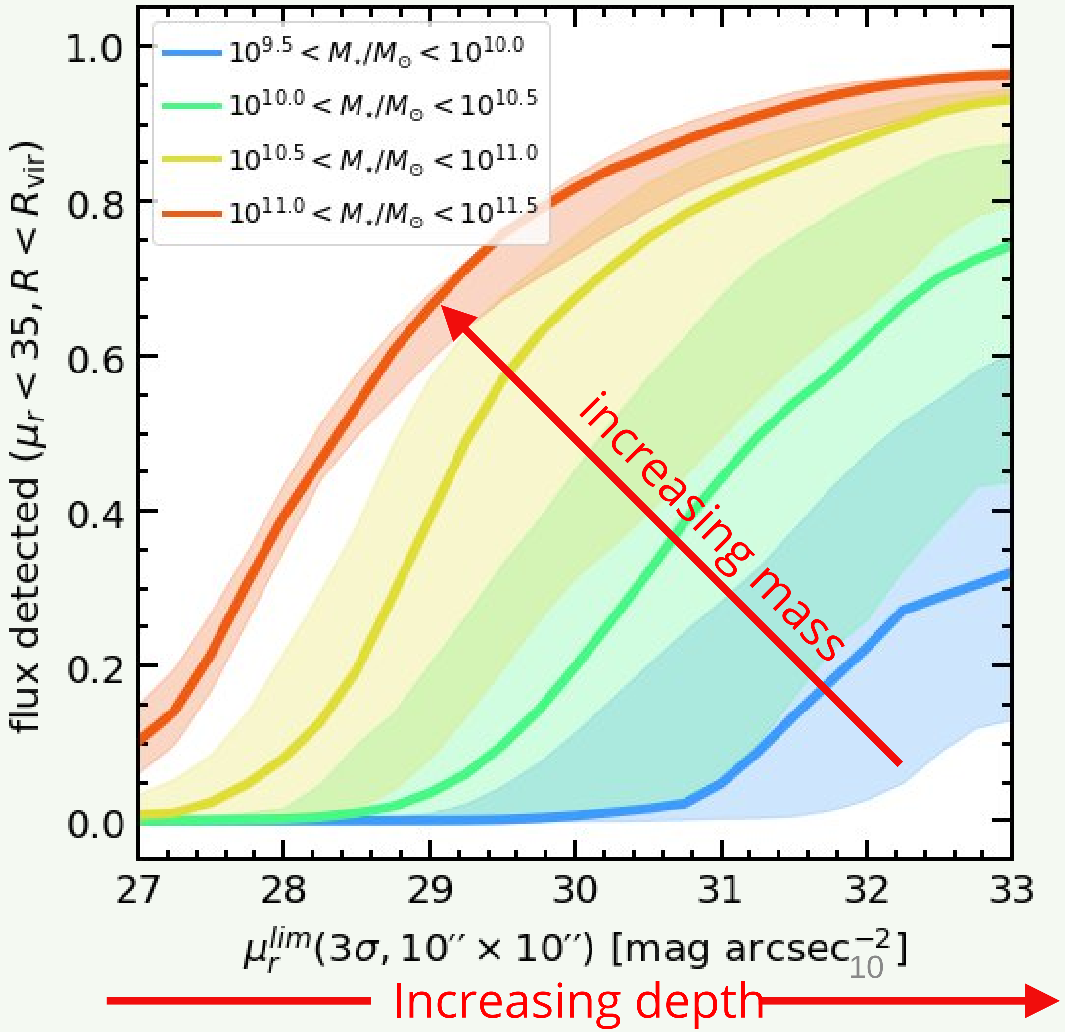

LSST-deep
optical imaging surveys
HSC-UD
HSC-D
SXDS
COSMOS
DES (SN-deep)
CFHTLS (deep)
NDWFS
PS1 (MDS)
HSC-wide
DES (SN-shallow)
CFHTLS (wide)
RCS
PS2
Stripe82
RCS2
PS1 (3π)
VST-ATLAS
SDSS
future
ongoing
completed
$r_{lim}$ (AB, 5σ, 2" aperture)
Area [deg²]
>30 mag arcsec²(1σ, 10”x10”) 18,000 deg²
LSST-Wide-Fast-Deep
Euclid-Wide
29.8 mag arcsec²(1σ, 10”x10”) 14,000 deg²
25-26 mag arcsec²(1σ, 10”x10”) 14,500 deg²

# Depth reveals the diffuse universe

– With Euclid and LSST, we can detect the diffuse light in the outskirts of galaxies and clusters — including the ICL — across the full mass scale.

– Euclid and LSST will trace detect a large fraction of flux in the diffuse outskirts of galaxies and clusters across the mass scale (Martin+2022).

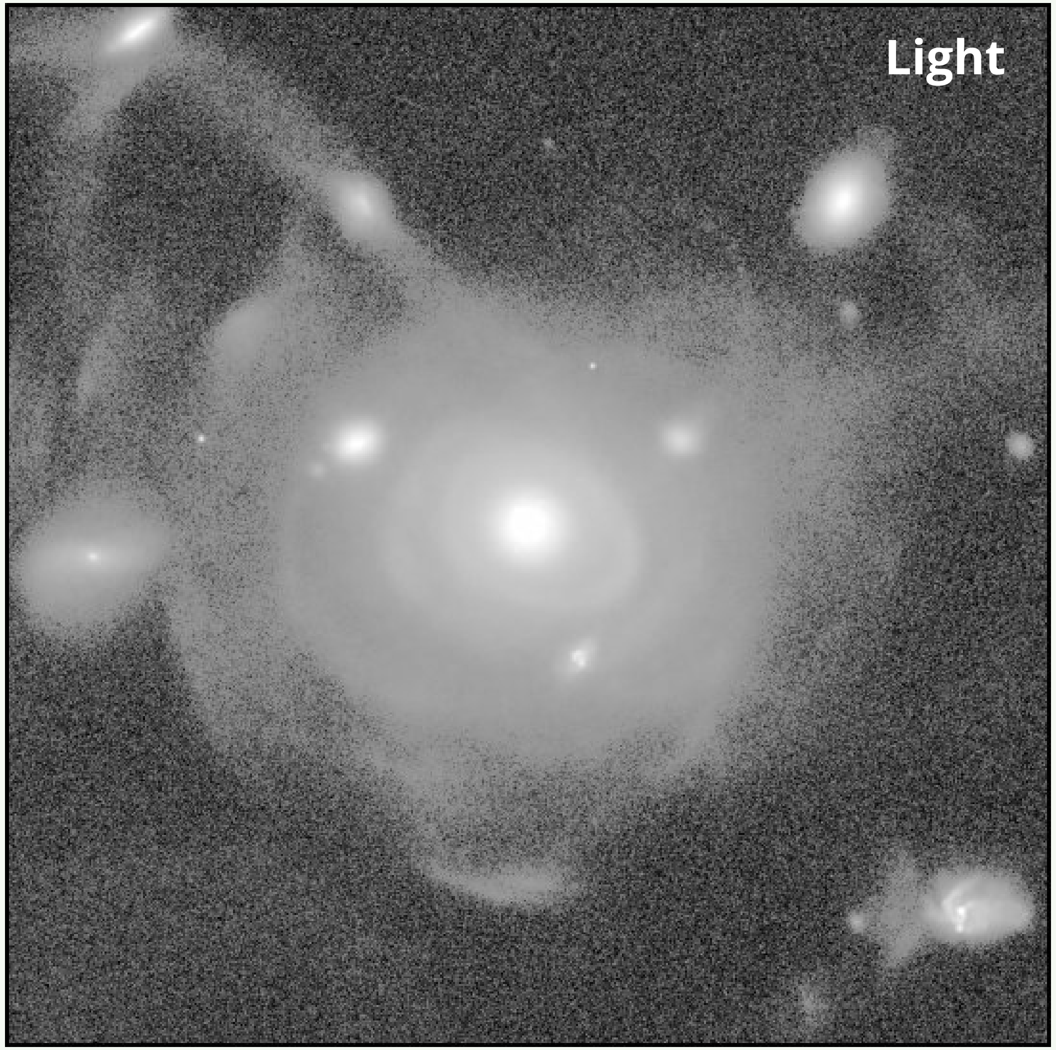

Martin+2022



# From stripped stars to dark matter

Martin+ in prep

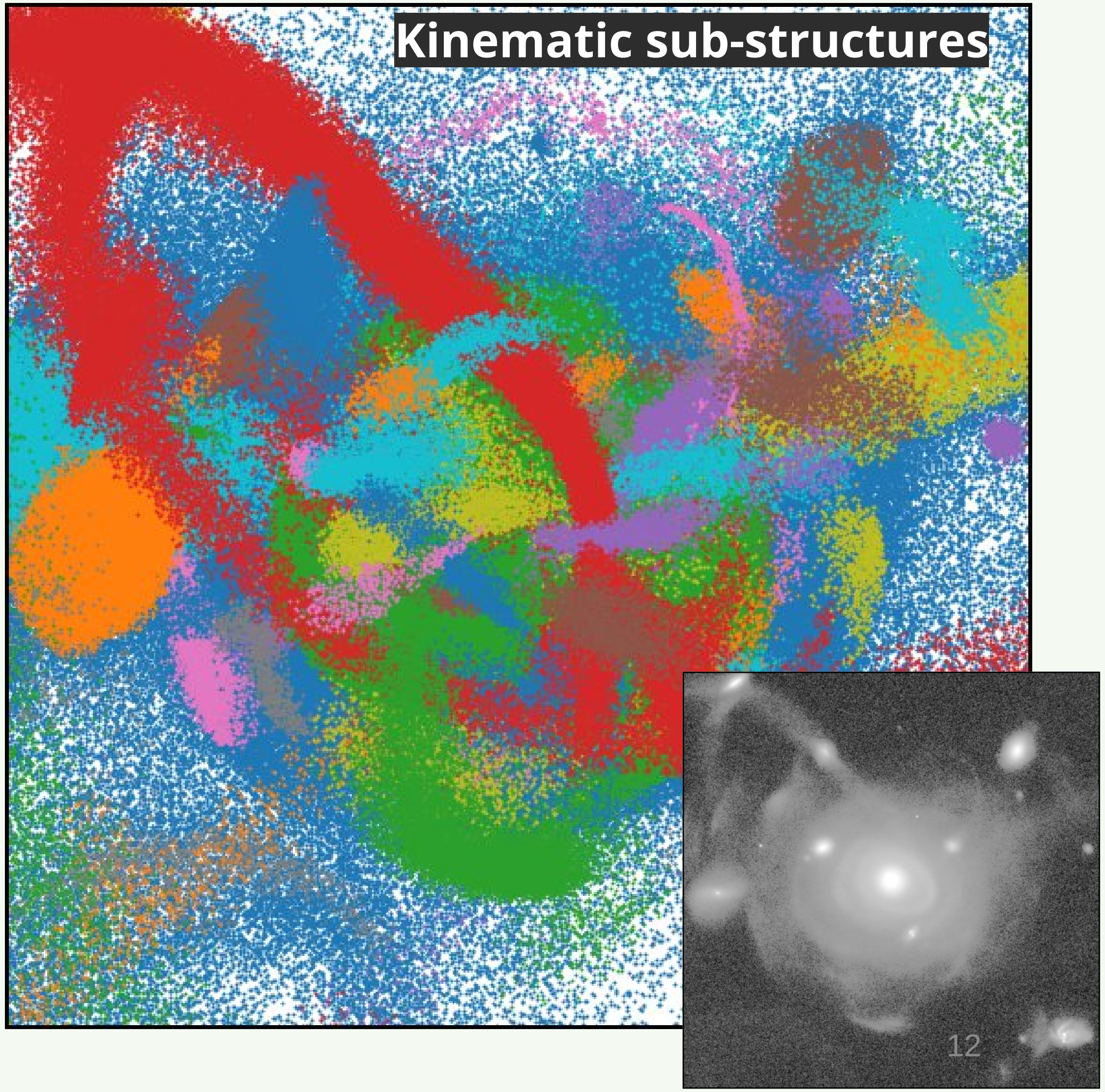
- Tidal debris and dark matter dynamics
  - Deeper imaging reveals tidal streams, shells, and diffuse haloes that encode information about the host dark matter potential and mass assembly history.



# From stripped stars to dark matter

Martin+ in prep

- Tidal debris and dark matter dynamics
  - Deeper imaging reveals tidal streams, shells, and diffuse haloes that encode information about the host dark matter potential and mass assembly history.

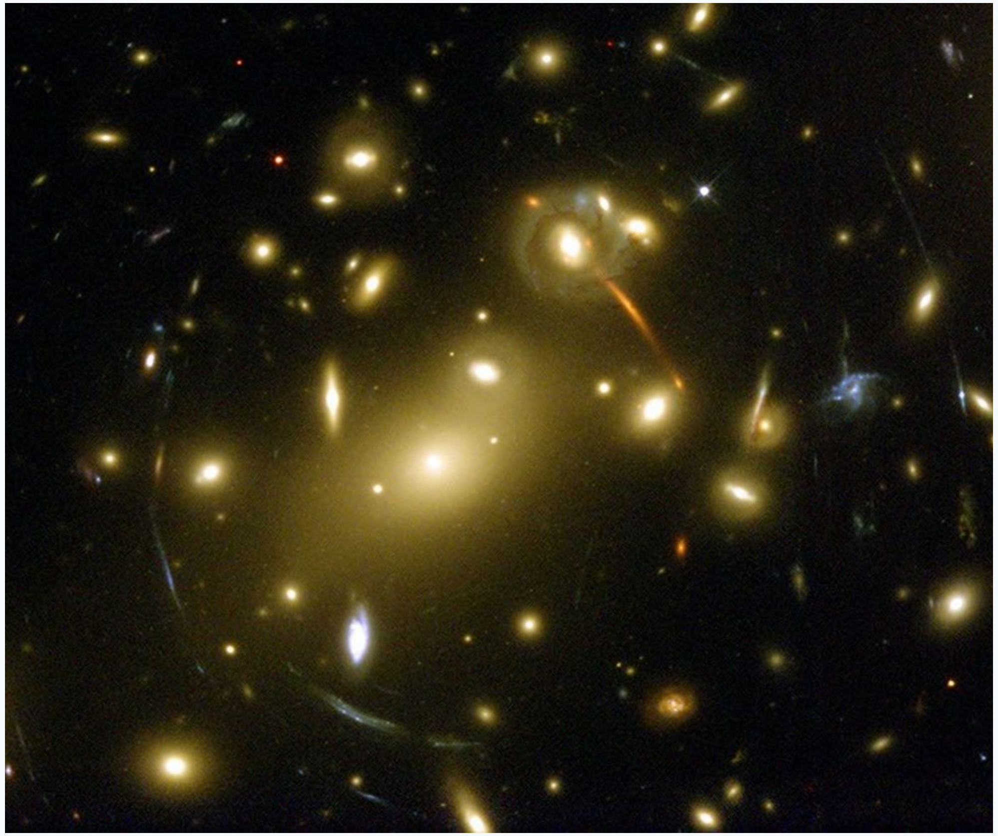


**Intracluster light**

- Stellar haloes formed primarily from the stars stripped from infalling satellites (10-40% of total cluster stellar mass)
- Forms a diffuse component whose dynamics are dominated by the DM halo
- Both a tracer of the underlying dark matter distribution and the heirarchical assembly of the halo

# Intracluster light

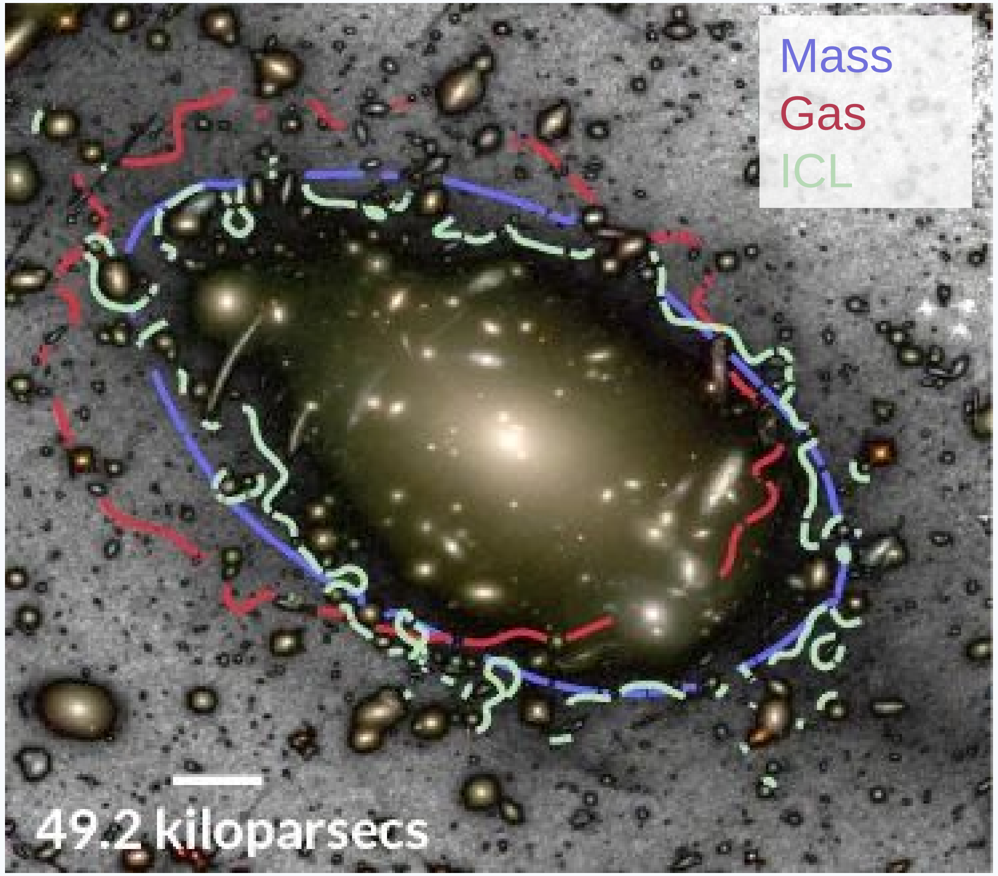
- Gravitational lensing directly probes mass
  - Strong lensing limited to small samples
  - Weak lensing requires deep imaging/stacking and many background sources
- X-ray emission:
  - Gas is collisional, disturbed during mergers (sloshing)
  - May not reliably trace collisionless dark matter
- Intracluster light as a complimentary probe
  - Effectively collisionless like dark matter
  - Abundant signal distributed across cluster
  - Should trace time-averaged gravitational potential
  - Simulations and observations show morphological alignment with dark matter



Abell 2218: NASA/Hubble, Andrew Fruchter and the ERO Team

# Intracluster light

- Gravitational lensing directly probes mass
  - Strong lensing limited to small samples
  - Weak lensing requires deep imaging/stacking and many background sources
- X-ray emission:
  - Gas is collisional, disturbed during mergers (sloshing)
  - May not reliably trace collisionless dark matter
- Intracluster light as a complimentary probe
  - Effectively collisionless like dark matter
  - Abundant signal distributed across cluster
  - Should trace time-averaged gravitational potential
  - Simulations and observations show morphological alignment with dark matter




Montes and Trujilo 2018

## Intracluster light

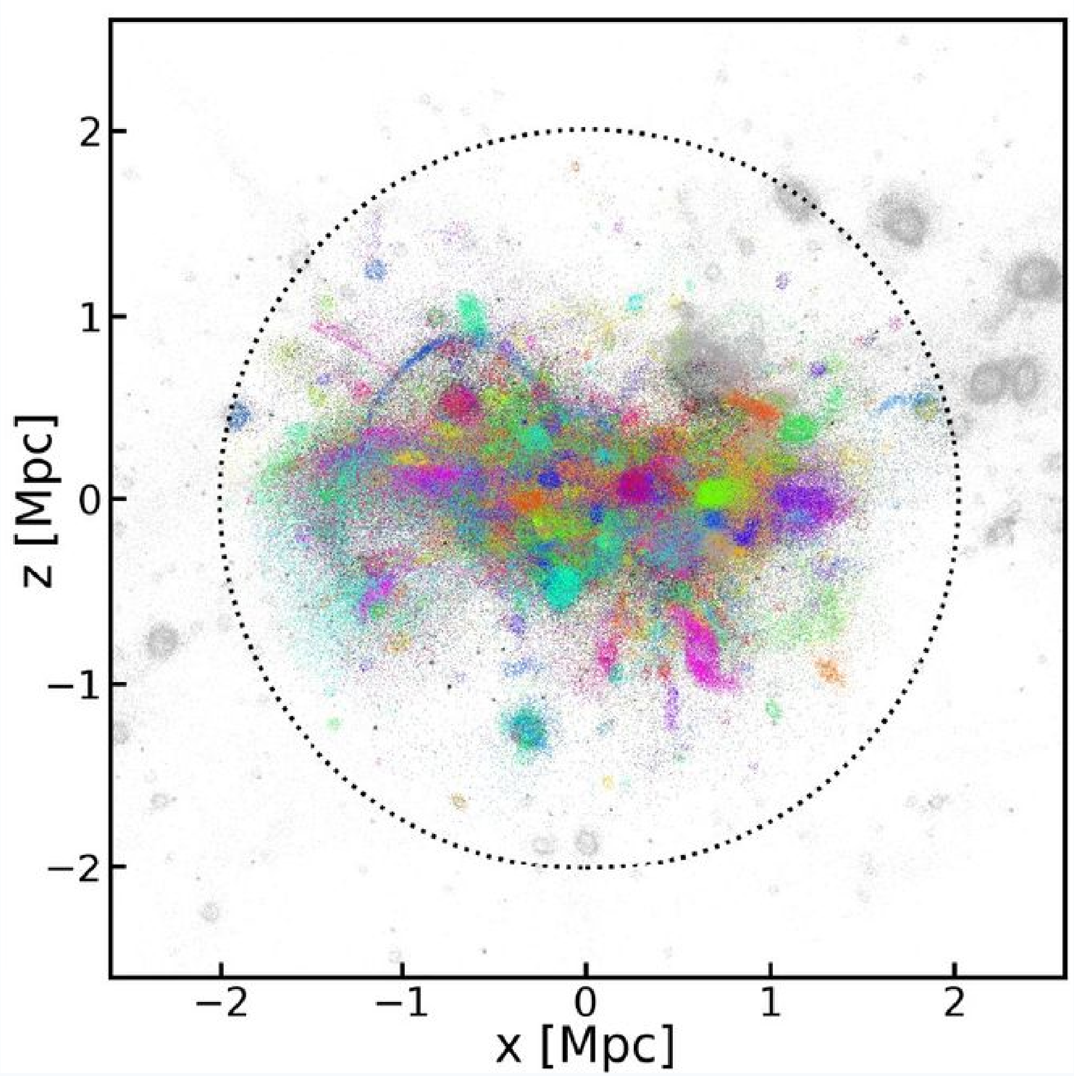
- The radial profile, colour gradient and morphology of the ICL reflect its dynamical history and progenitor satellite populations (**Kimmig+2025**)

- Potential luminous tracer of dark matter in clusters

- ICL could reveal information about the central mass distribution, testing DM models

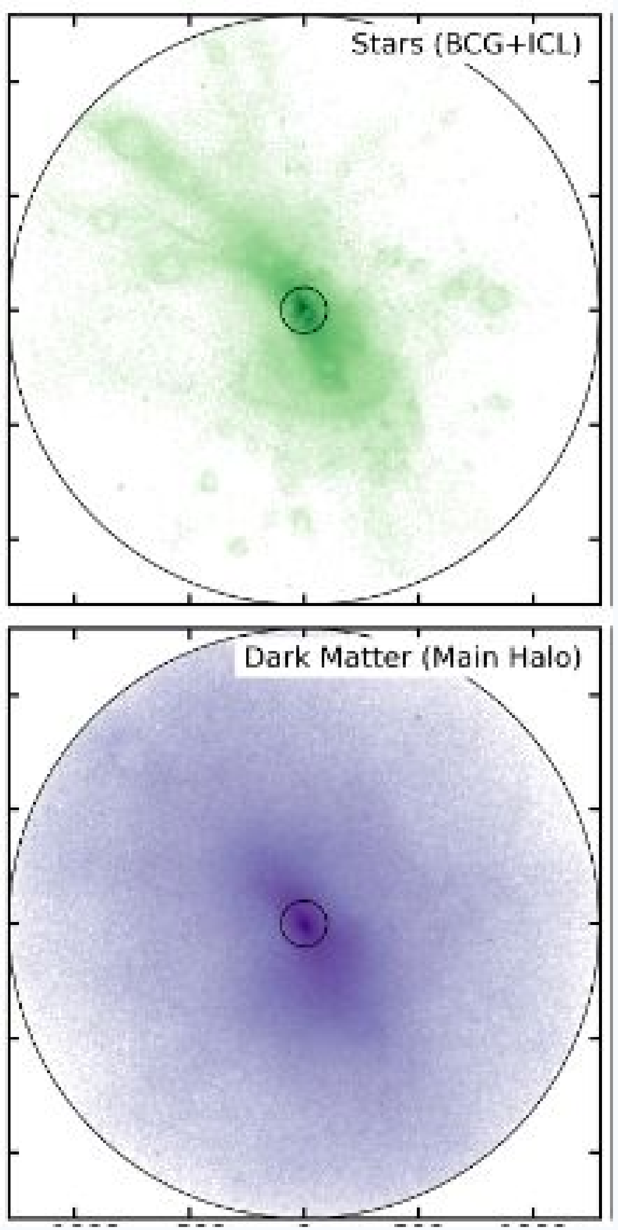
- Assembly history encoded in the kinematics and stellar populations

- We can measure the ICL shape of ~70% of clusters at 0.1 < z < 0.8.
  - To test dark matter models we need 1000's of clusters




Brown+2024

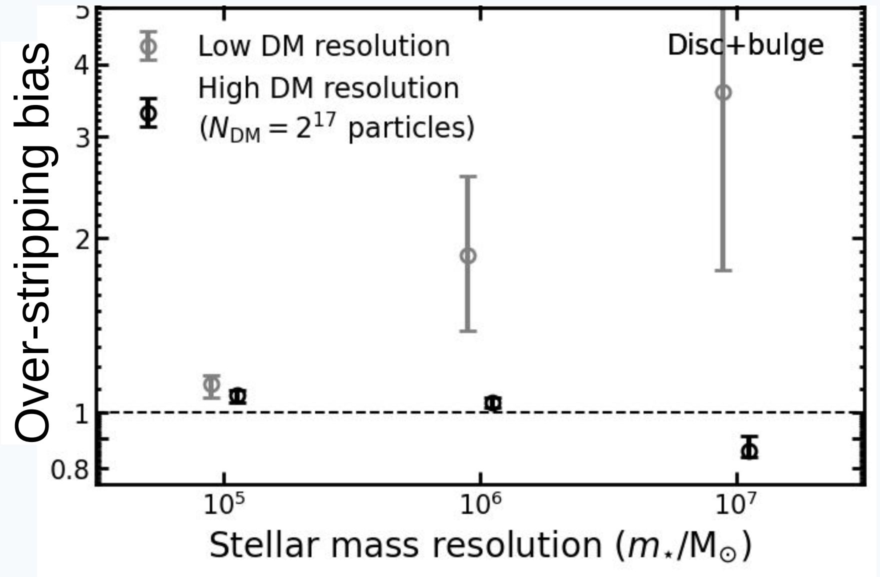
- **<u>Key Challenge:</u> ICL is a biased tracer of the underlying potential**
  - Spatial distributions differ
  - An understanding of the physical processes that produce the ICL is needed to correct for this




Butler et al. 2024

**<u>Key Challenge:</u> Simulating Diffuse Light Requires High Fidelity**

- Stripped stars, tidal debris, and diffuse components form from the loosely bound outskirts of satellites making them extremely sensitive to mass resolution.
- High resolutions are required to resolve these processes

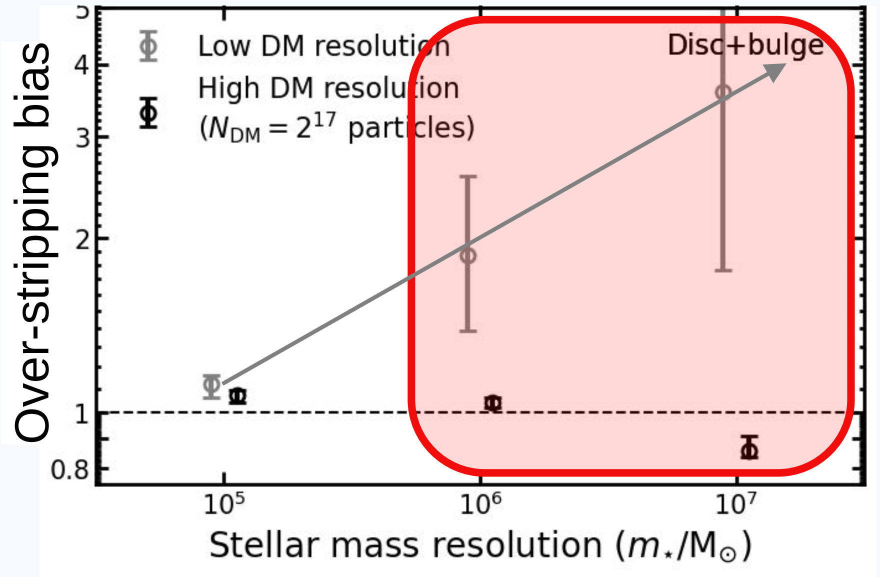



Martin et al. 2024

## <u>Key Challenge:</u> Simulating Diffuse Light Requires High Fidelity

- Stripped stars, tidal debris, and diffuse components form from the loosely bound outskirts of satellites making them extremely sensitive to mass resolution.
- High resolutions are required to resolve these processes
  - Many large cosmological simulations **overestimate the bulk quantity of stellar mass** removed from satellite galaxies

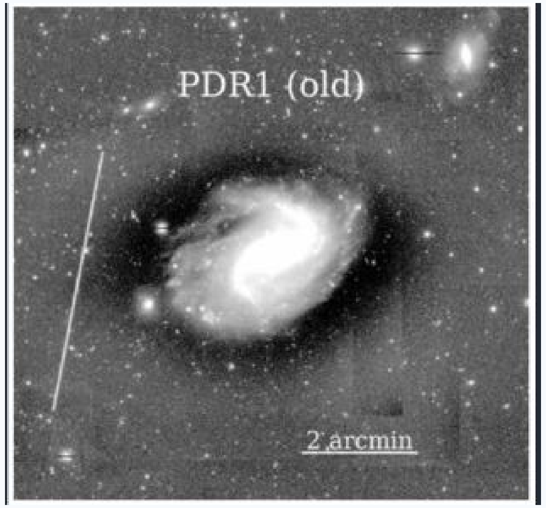
State-of-the-art large cosmological sims (e.g. TNG)



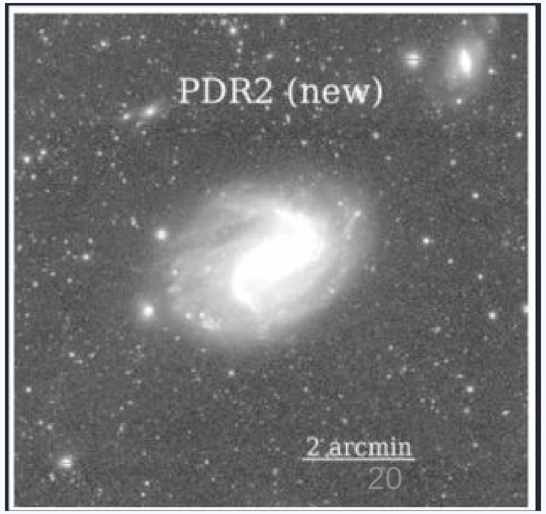

Martin et al. 2024

- **<u>Key Challenge:</u> Observational Biases and Data Quality**
  - The recovery of LSB features depends critically on background estimation, flat-fielding, PSF modelling, and deblending.
  - Standard pipelines are not optimised for diffuse light, often filtering out or mischaracterising extended structures, but the underlying data is perfect for our science goals.

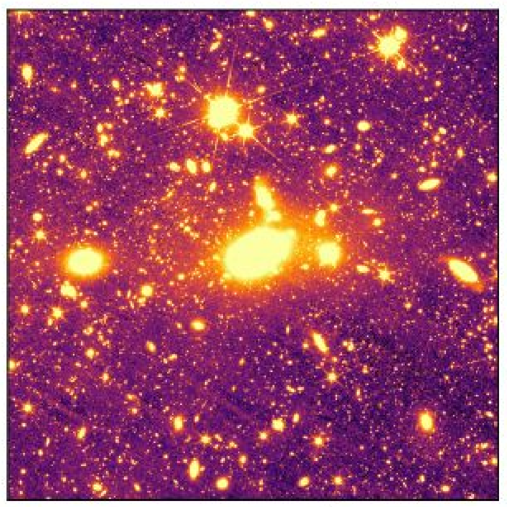
HSC-SSP (LSST-like): aggressive background subtraction



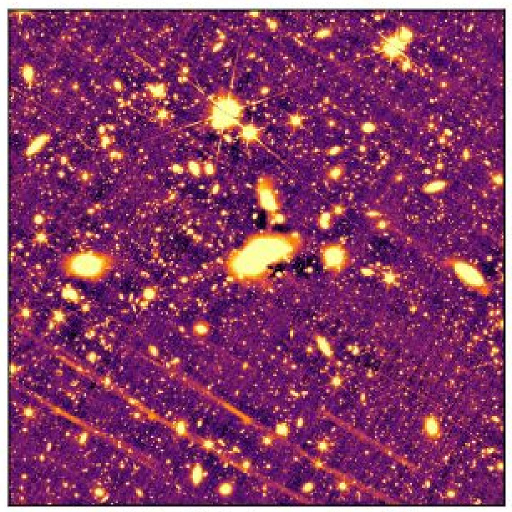

Background subtraction with larger binning



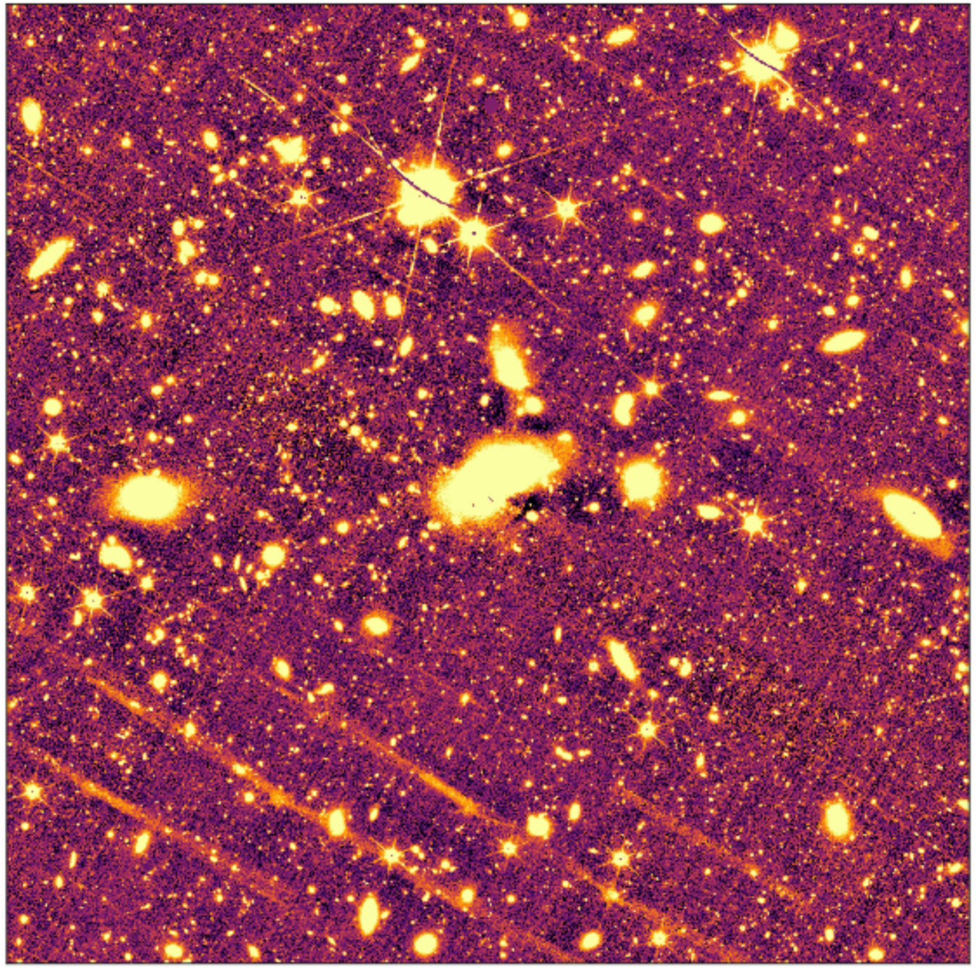

Bespoke reduction



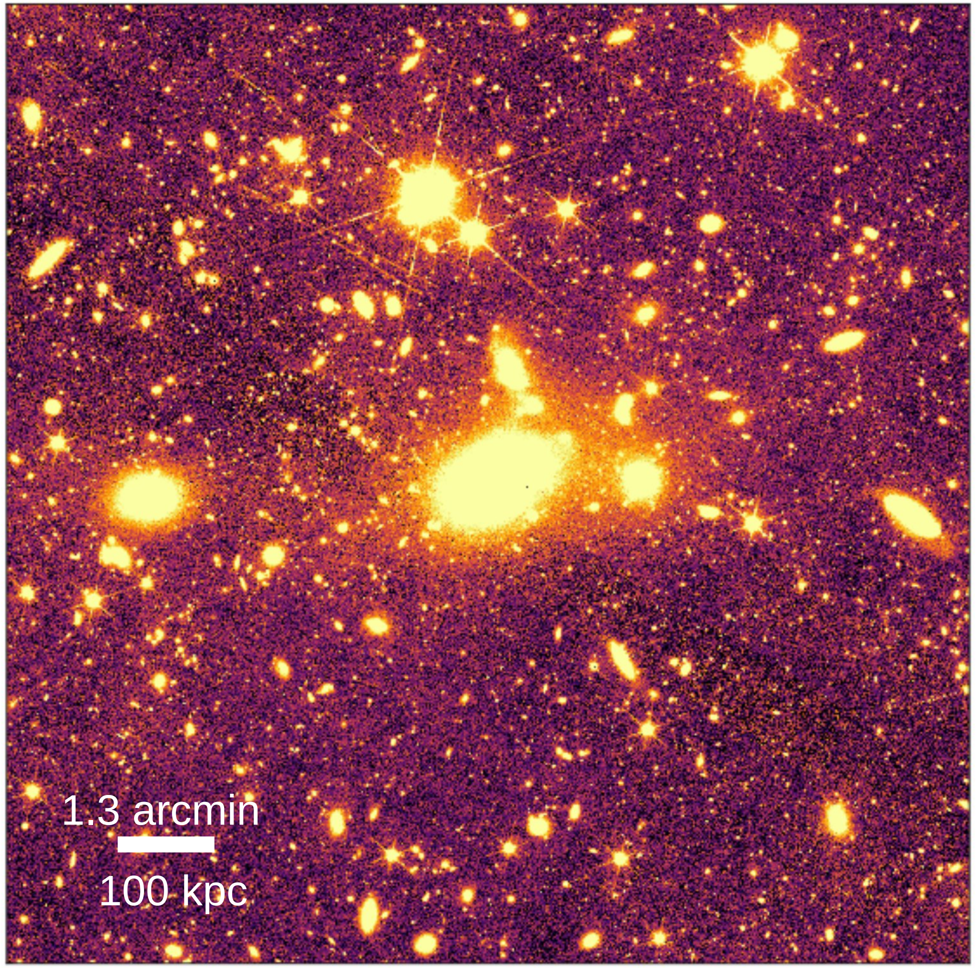
Euclid MER



Standard final product (MER)



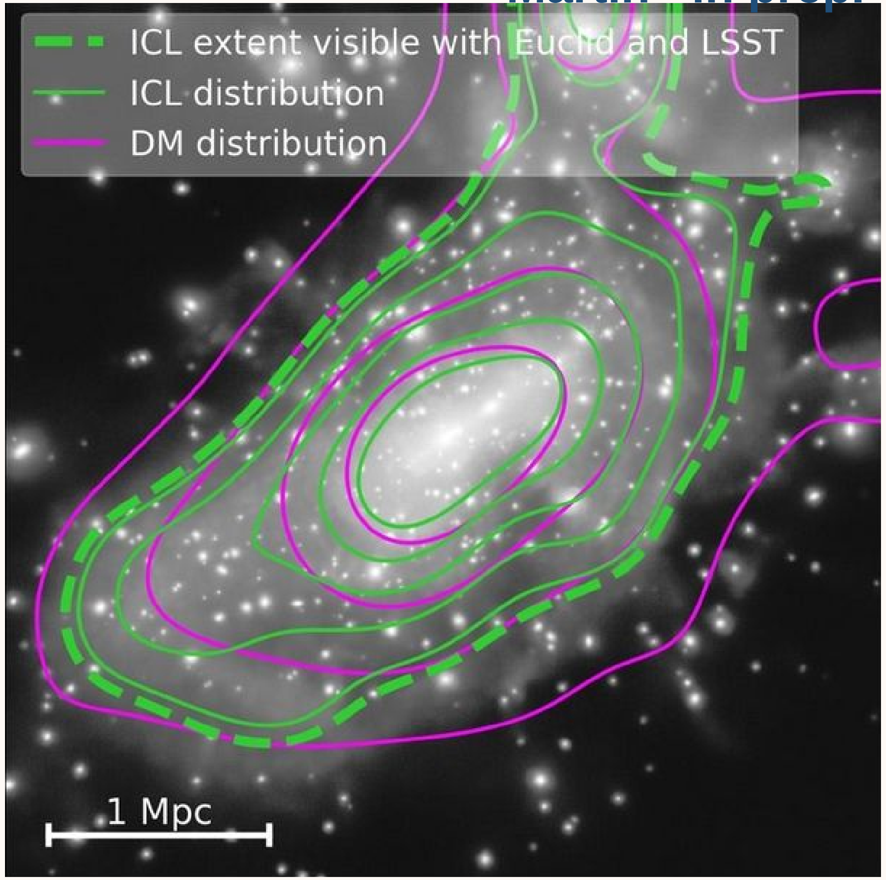
Fully post-processed




**Bamford, Gao, Urbano et al.**

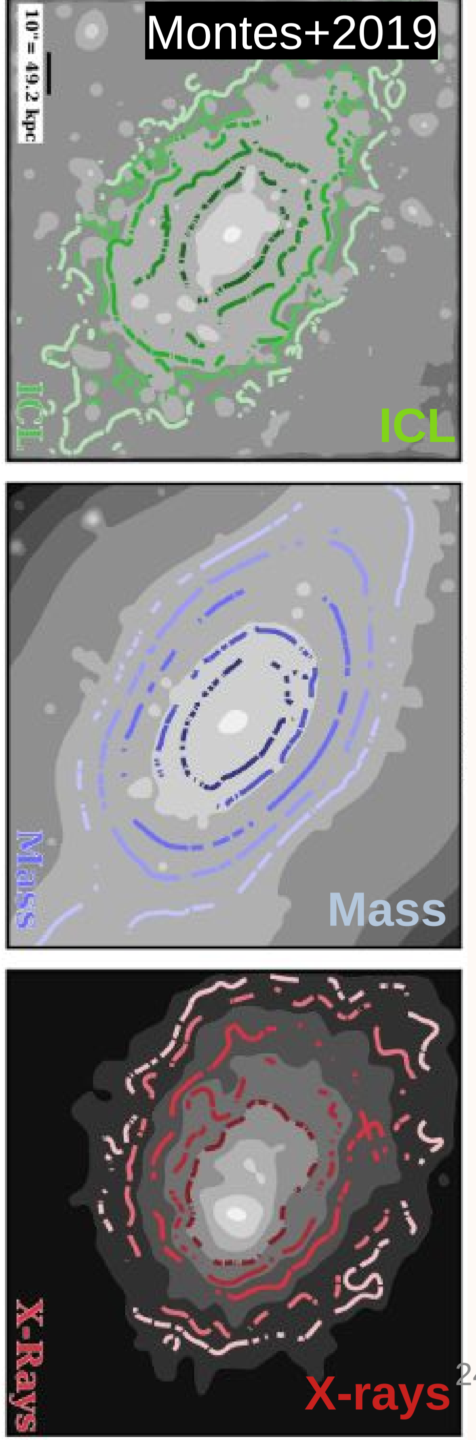
- **Why the ICL is special for physics:**
  - Gravity dominates the dynamics
  - Should reflect underlying dark matter distribution
  - Minimal influence from baryonic processes

Martin+ in prep.

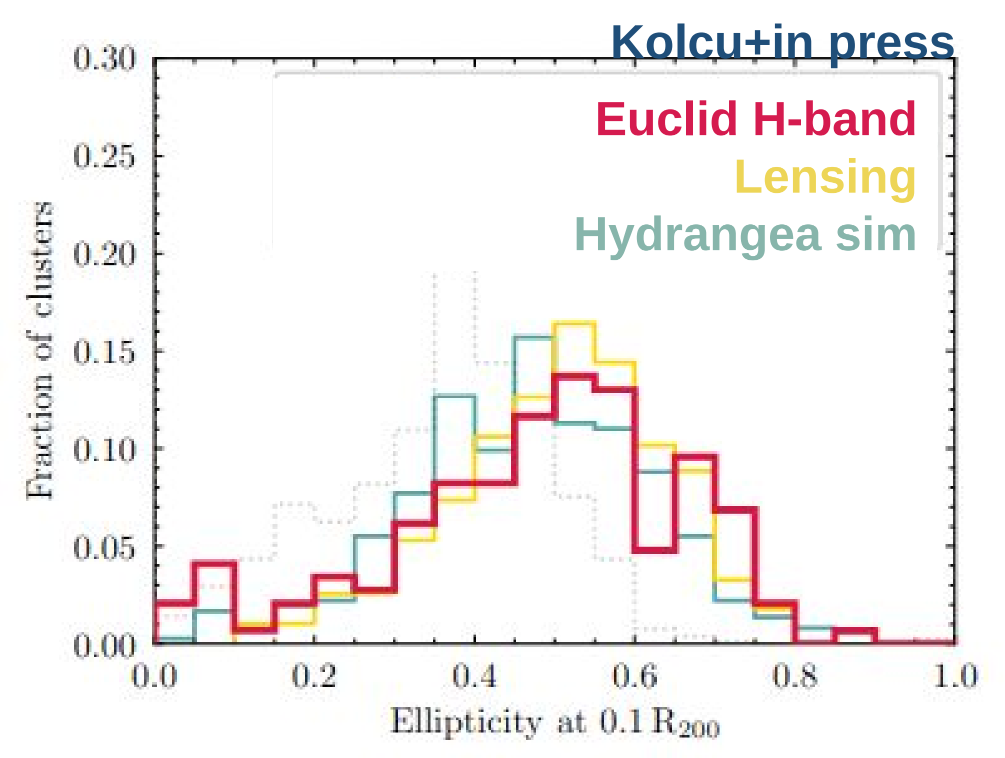


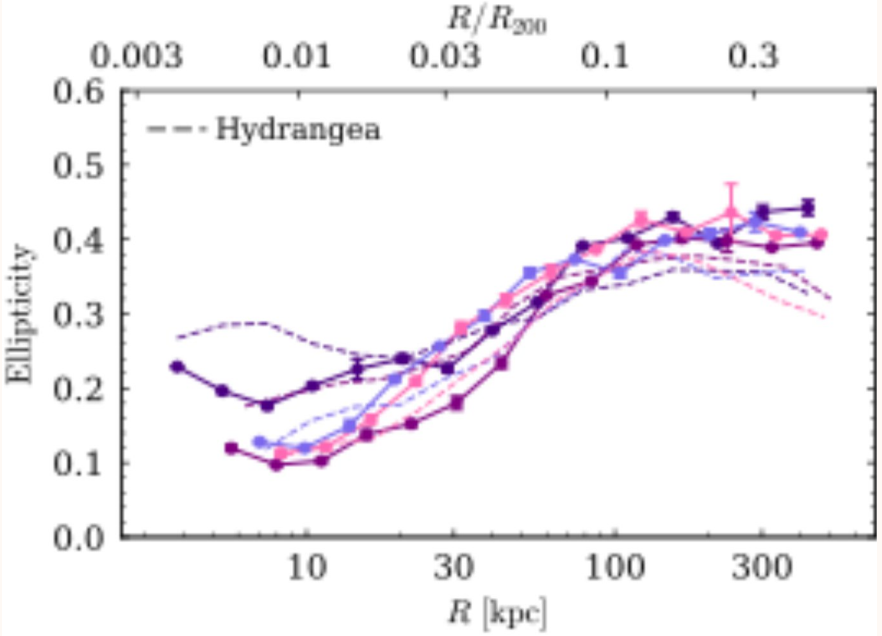

DM vs Light distribution in a simulated cluster. Dashed line shows extent accessible by Euclid/LSST.

- **Why the ICL is special for physics:**
  - Gravity dominates the dynamics
  - Should reflect underlying dark matter distribution
  - Minimal influence from baryonic processes
  - Observations indicate that ICL traces the lensing derived mass distribution much more closely than X-ray observations of the hot intracluster medium

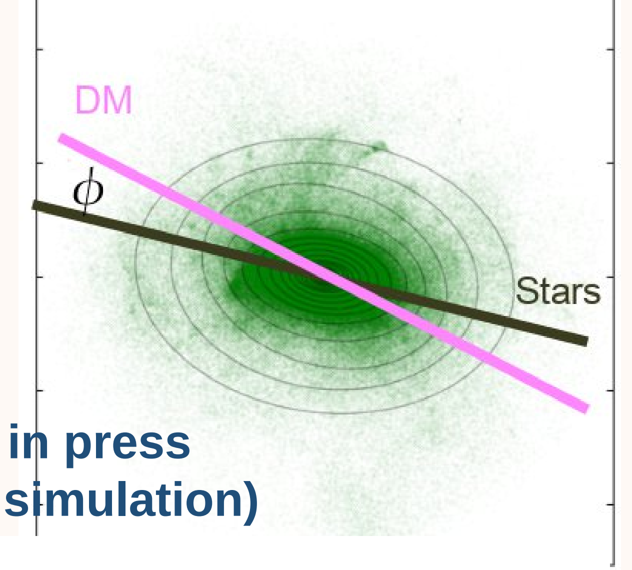


- **Why the ICL is special for physics:**
    - The ellipticity distribution of the ICL isocontours are in good agreement with lensing maps

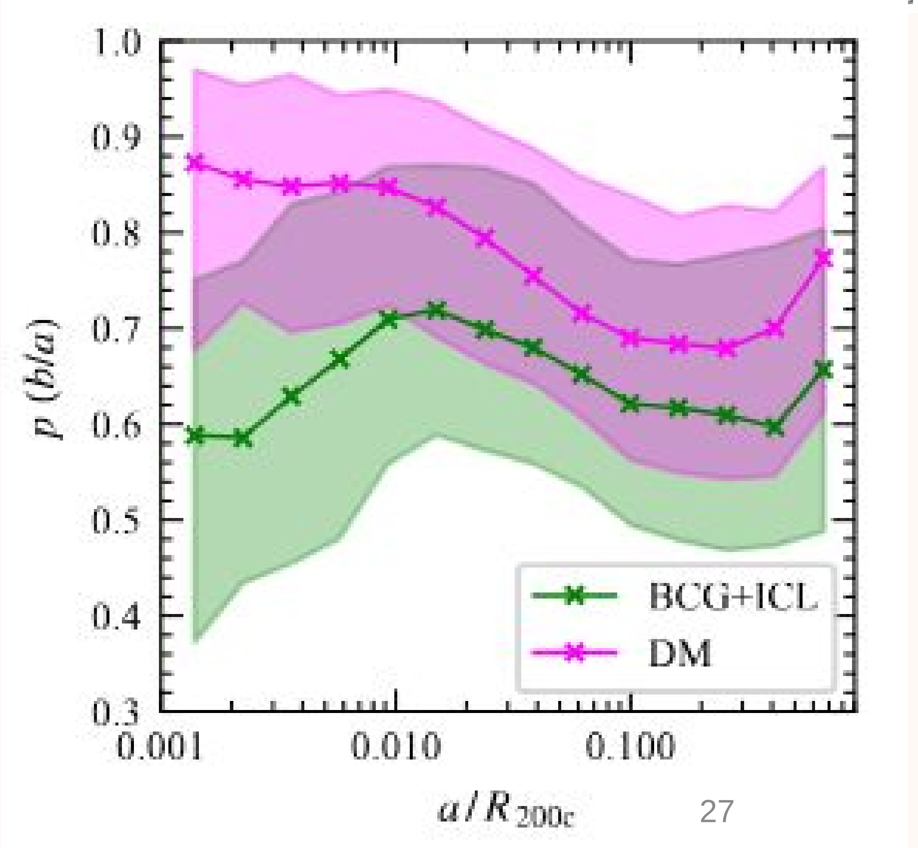


- **Why the ICL is special for physics:**
  - The ellipticity distribution of the ICL isocontours are in good agreement with lensing maps
  - And simulations agree that the ellipticity and position angles of the ICL should be very similar




Fernandez+ in press
(Hydrangea simulation)

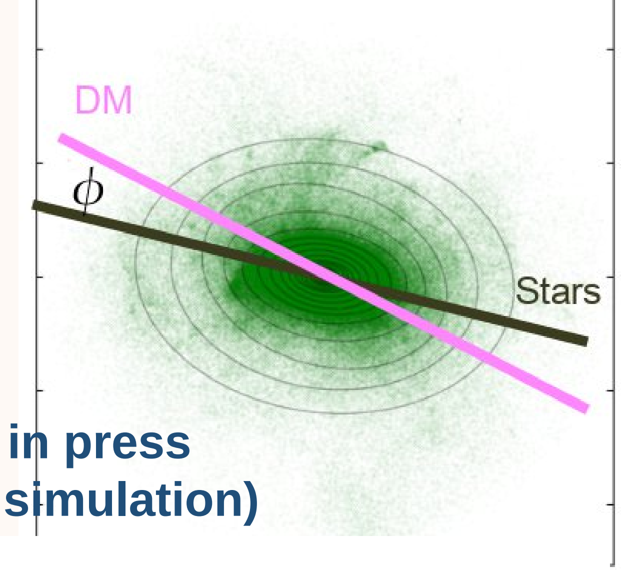


- **Why the ICL is special for physics:**

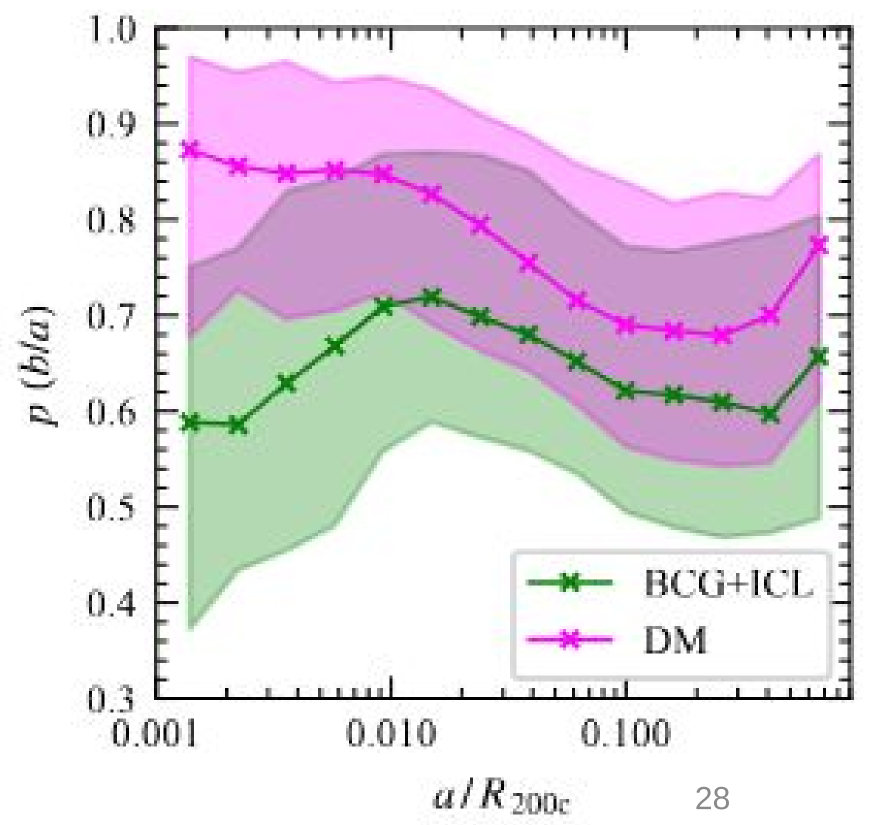
  - The ICL is an excellent tracer of the orientation of a dark matter halo
    - And a very good tracer of the ellipticity of a dark matter halo

  - The shape of the ICL is similar to cluster haloes measured via weak-lensing

  - Suggests a common origin for the ICL and cluster DM halo




Fernandez+ in press
(Hydrangea simulation)



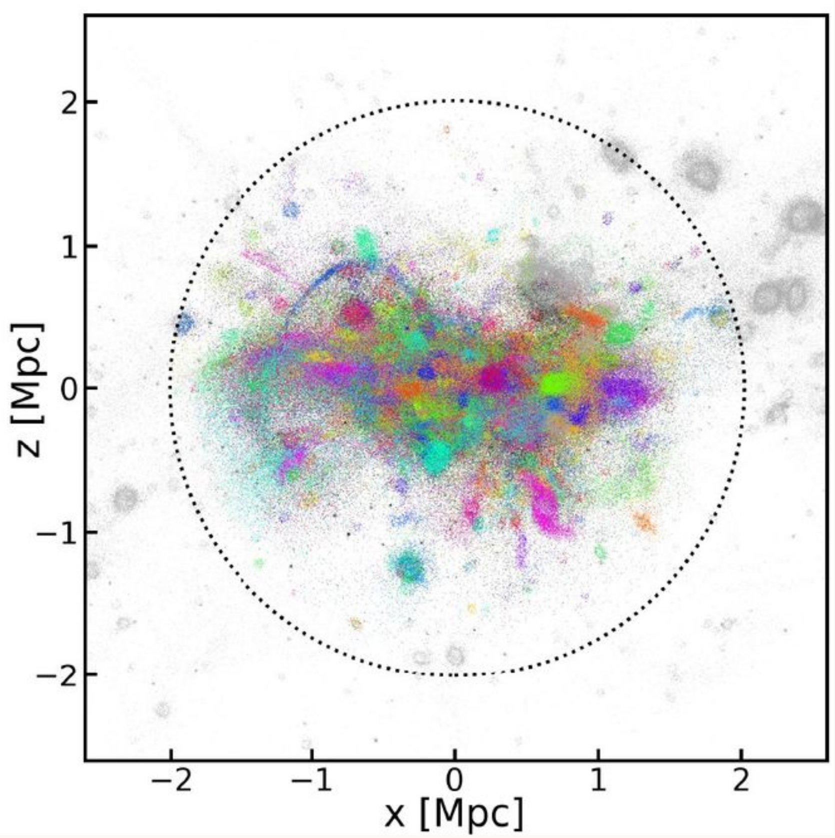
Cluster haloes are built hierarchically from repeated mergers of satellite galaxies

ICL is built up from the stars stripped from these infalling satellites so they are linked

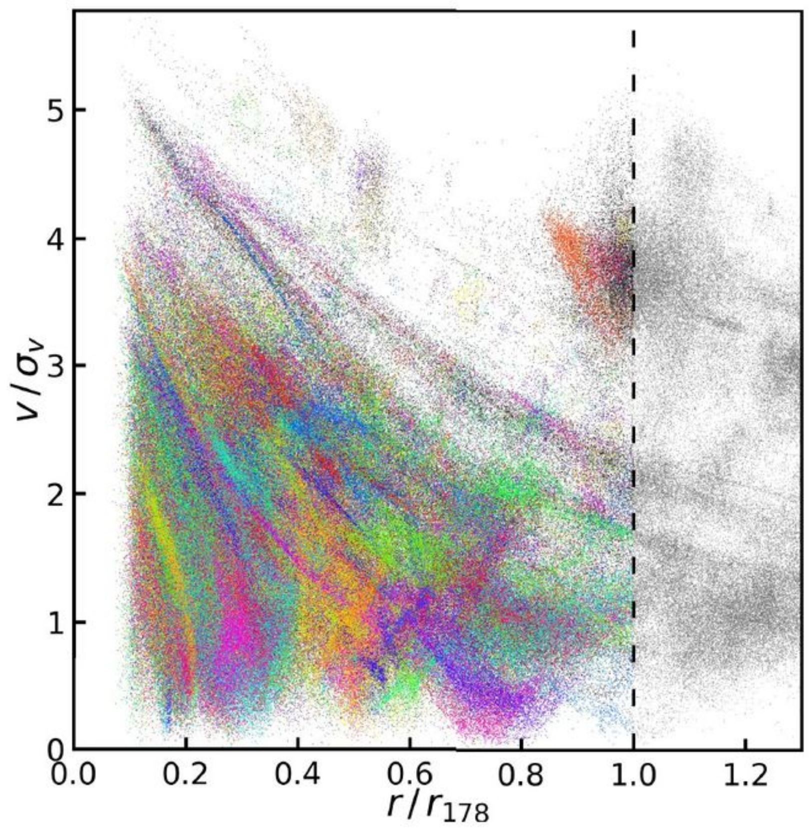
When decomposed into the contributions from indvidual infallers, they show persistent structures in phase space

**Brown+24**

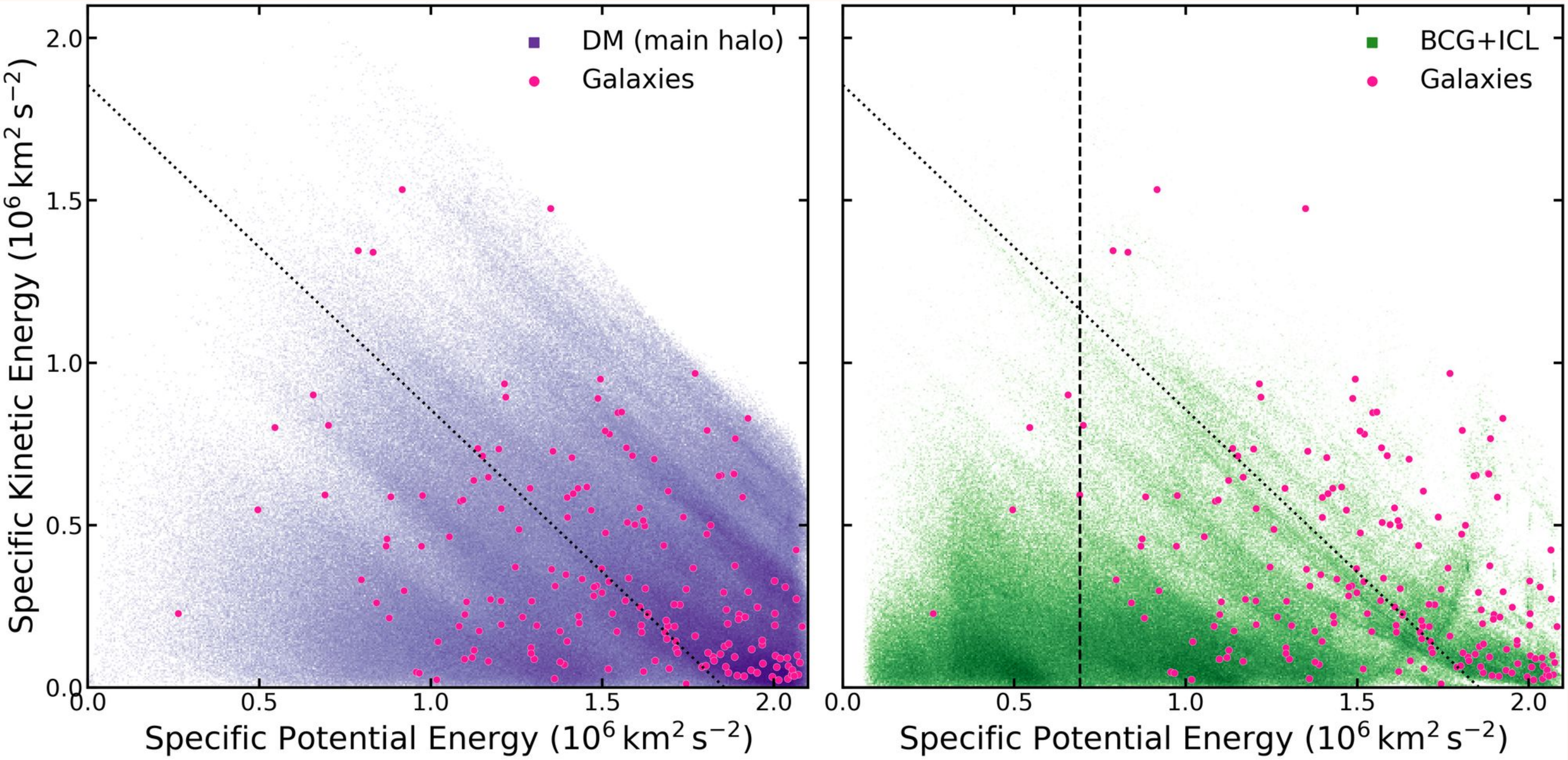
ICL configuration space split by substructure




ICL phase space split by substructure



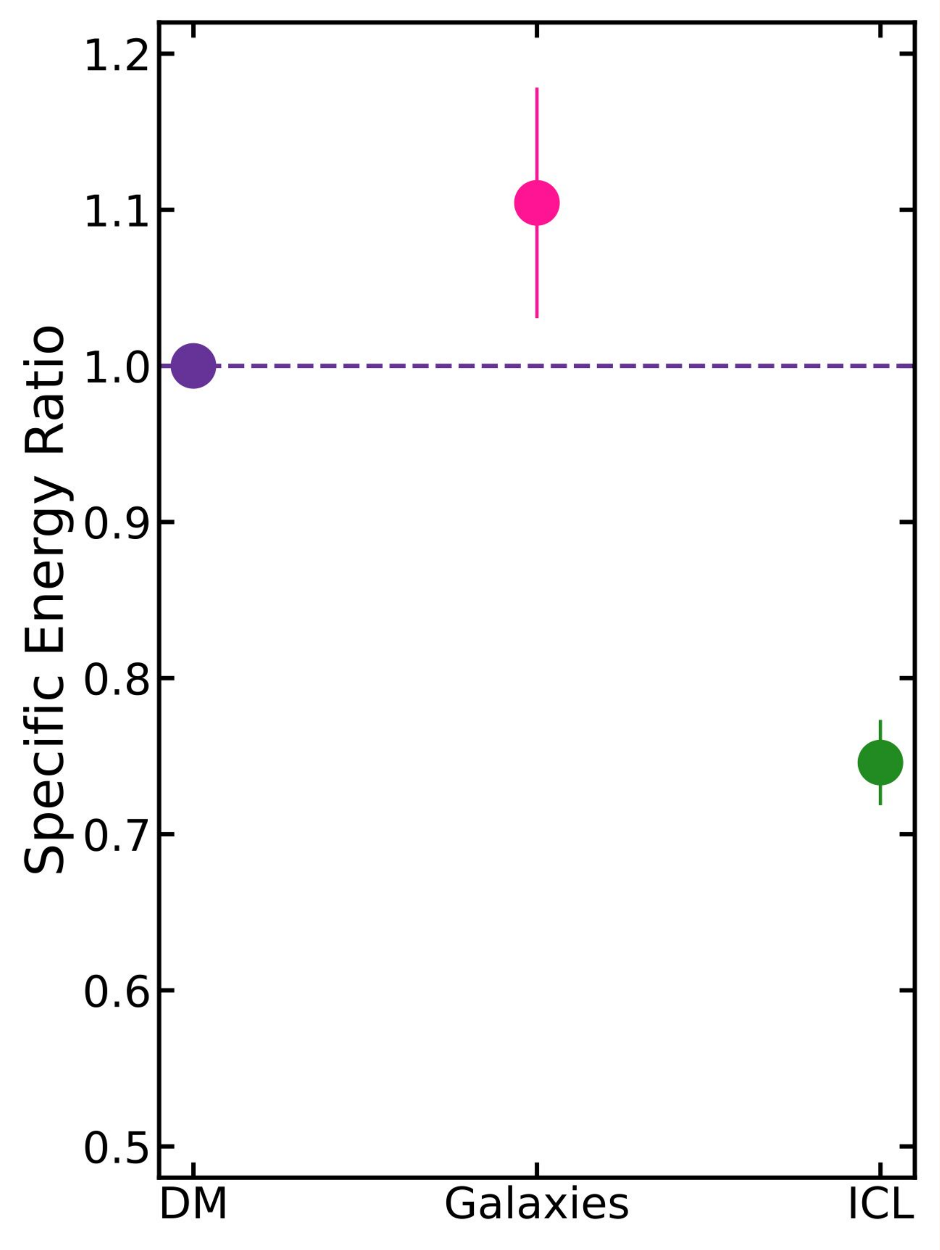
# But DM and ICL still don’t share indentical phase-space distributions




Butler+25

Butler+25

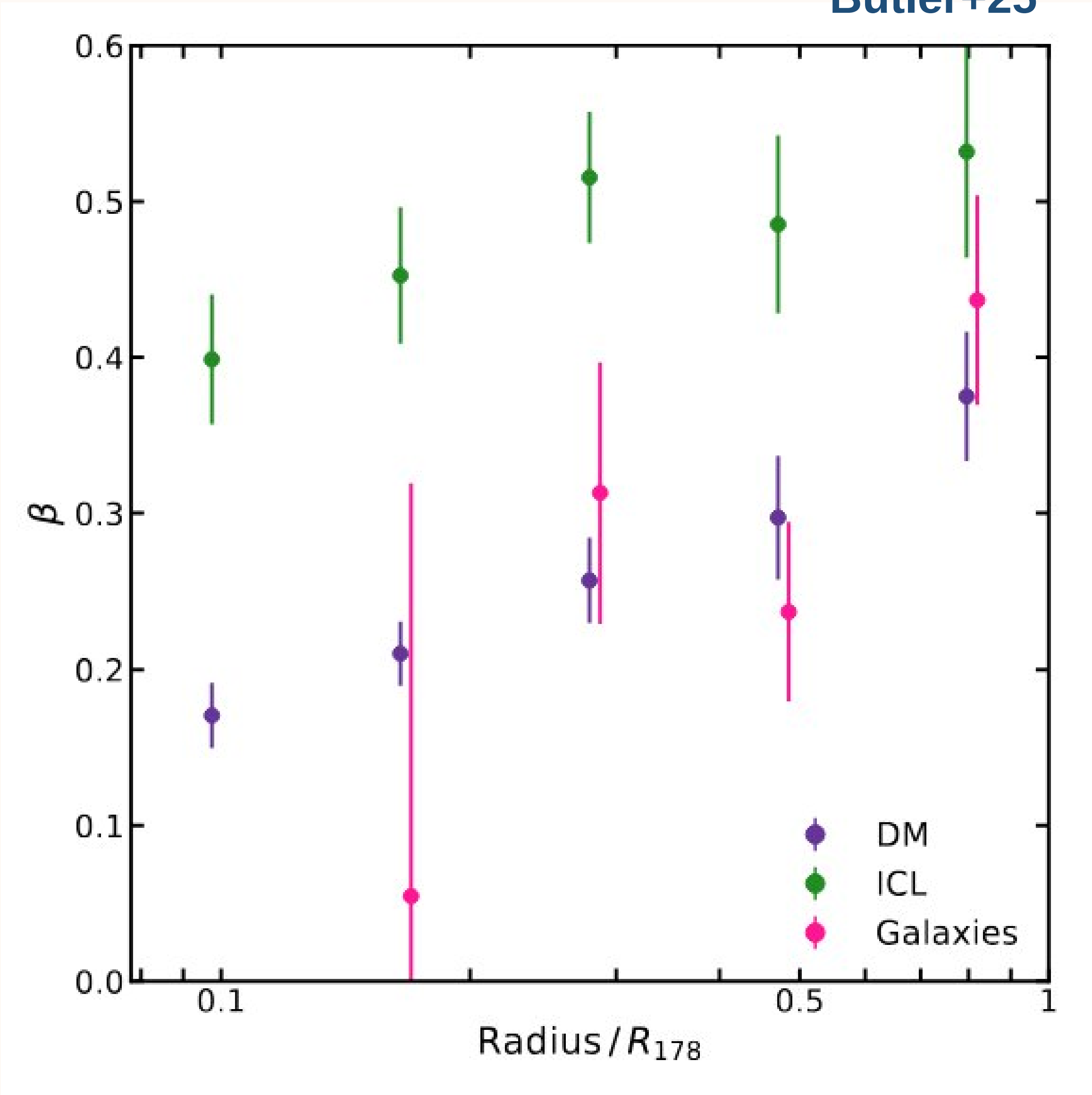
Compared to the DM halo, ICL stars have smaller orbital energies



Butler+25

Compared to the DM halo, ICL stars have smaller orbital energies

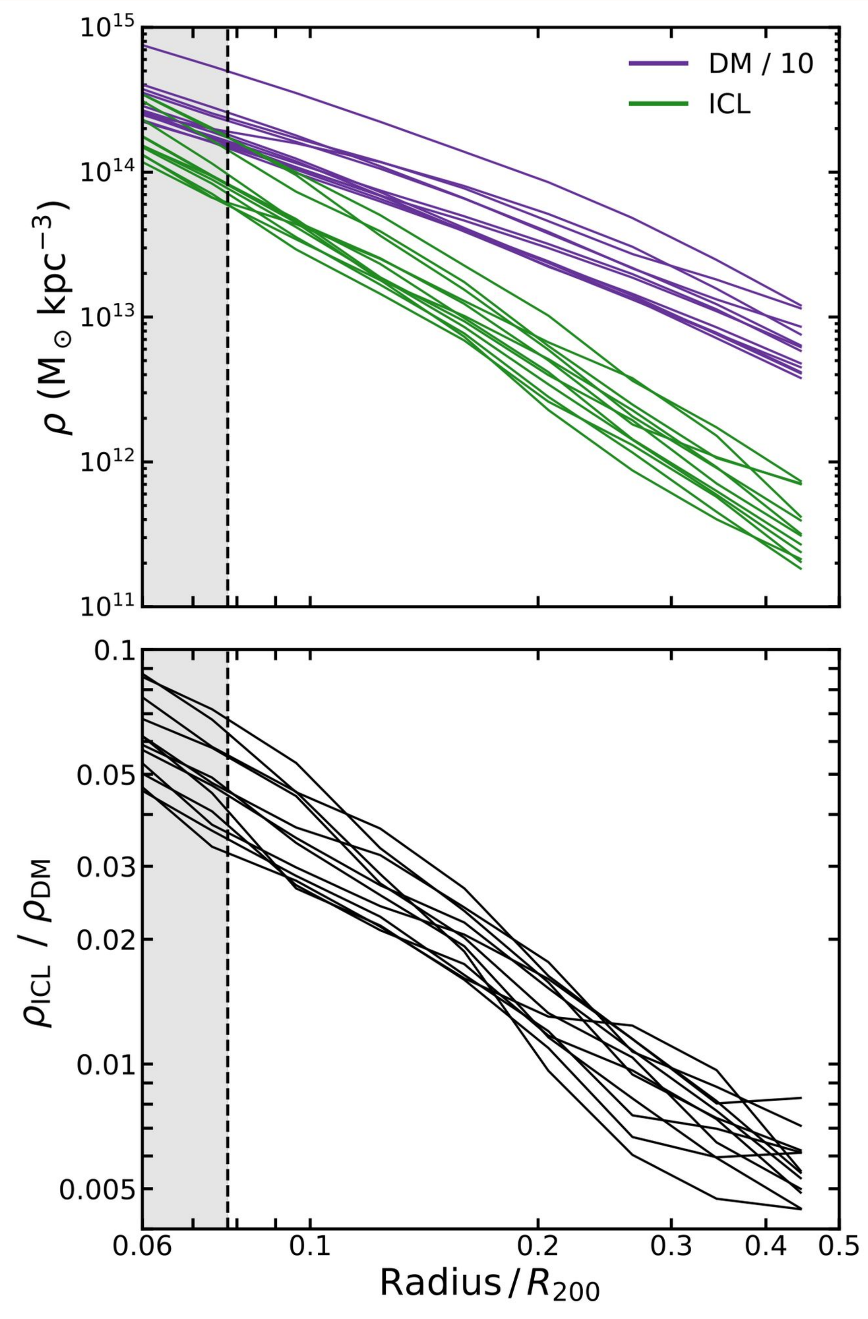
And a more anisotropic distribution (i.e. individual orbits are more elliptical)



Compared to the DM halo, ICL stars have smaller orbital energies

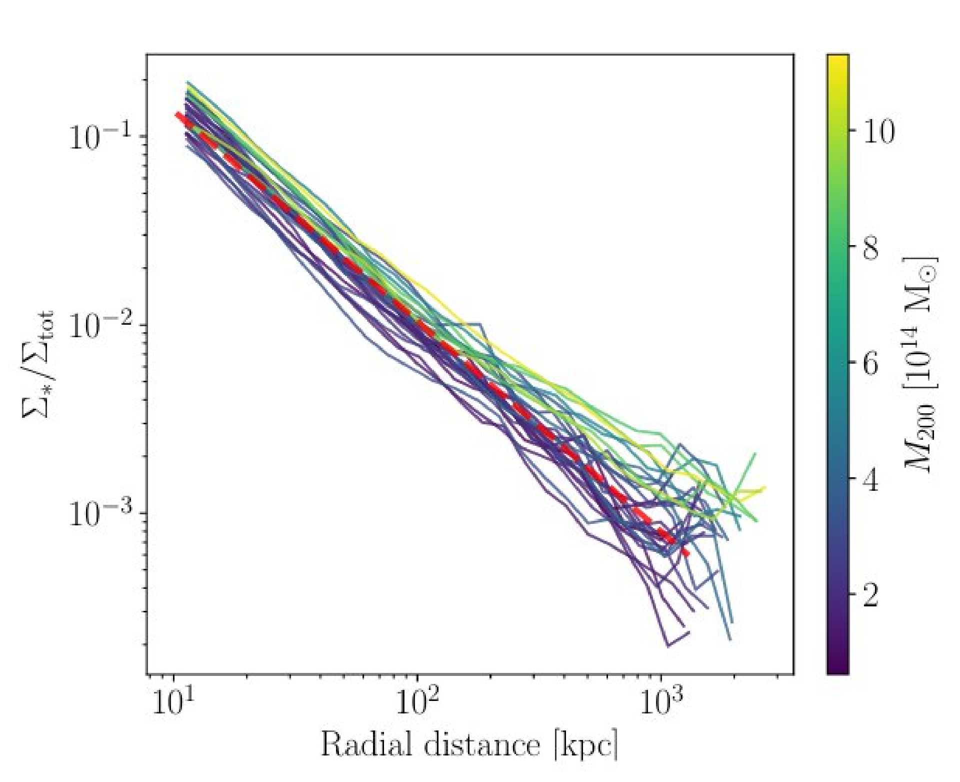
And a more anisotropic distribution (i.e. individual orbits are more elliptical)

These phase-space differences result in different slopes in the two density profiles




Butler+25

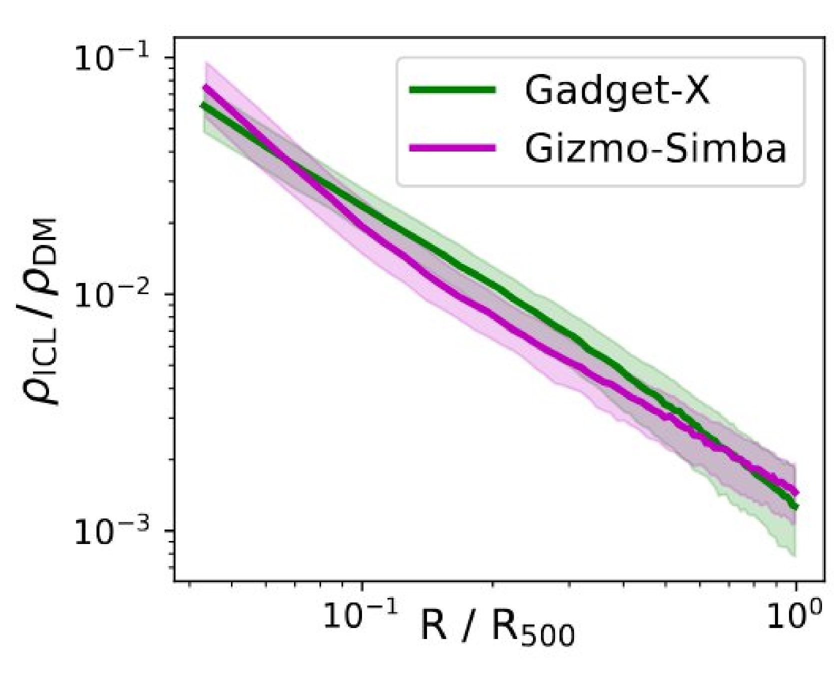
Approximate power-law ratio between the DM and ICL density slope established in literature (e.g. Alonso-Asensio+2020




Alonso-Asensio+2020

Approximate power-law ratio between the DM and ICL density slope established in literature (e.g. Alonso-Asensio+2020, Contreras-Santos+2024).

The physical origin of this slope is not well understood.



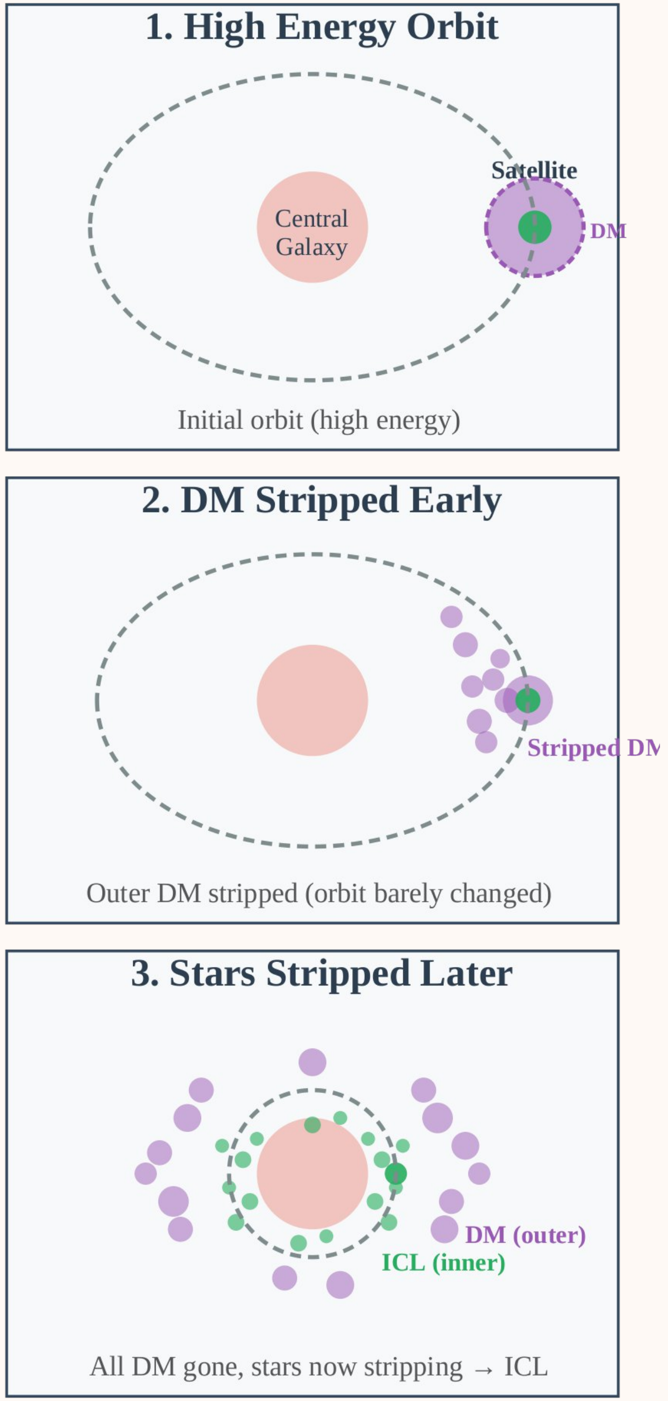

Contreras-Santos+2024

- One possible mechanism to explain the physical origin of th and a driver of  is dynamical friction

- Dynamical friction causes satellite orbits to decay
  - Driven primarily by the mass ratio between the infalling satellite and the cluster

- Satellites DM is stripped more efficiently than more centrally concentrated stars

- So DM is stripped on high energy-orbits and stars are stripped on low-energy orbits

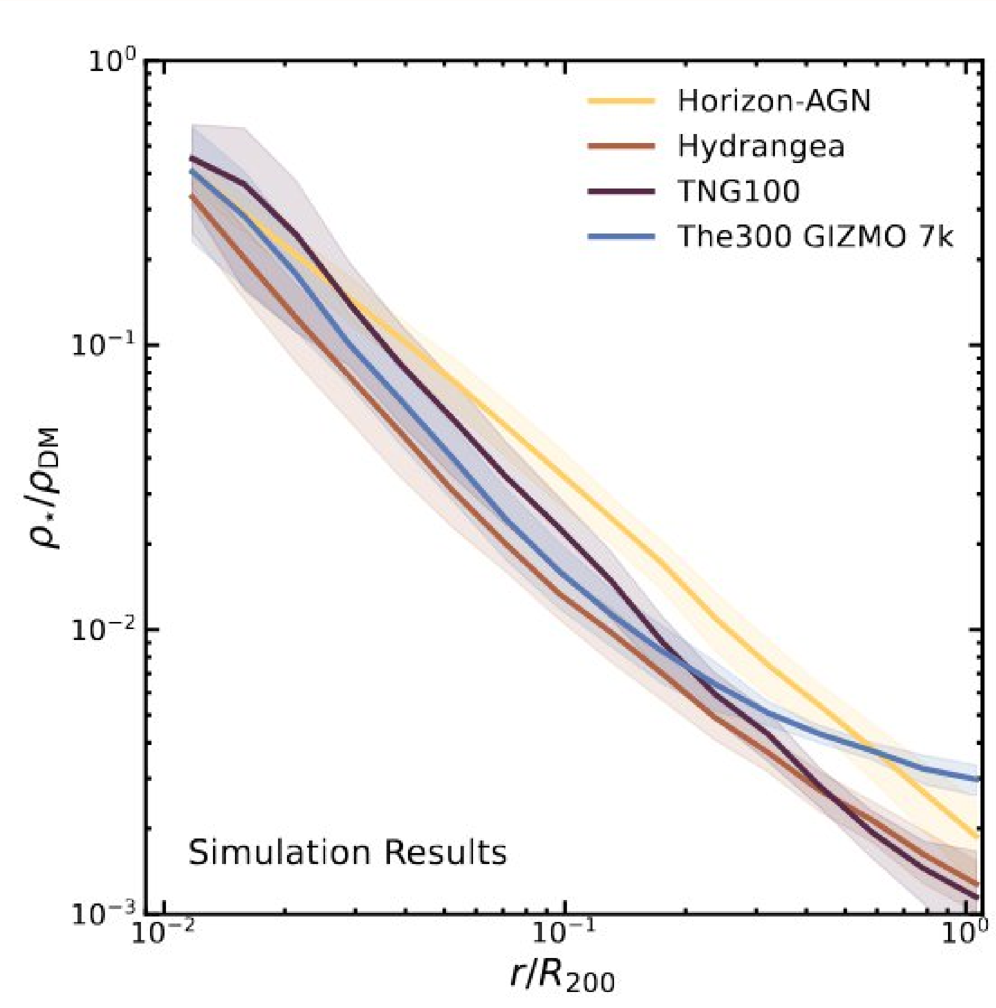


- If we standardise the measurement of the DM and ICL slopes we don't find an identical relationship between different simulation suites

- A similar relationship is observed across simulations, but with scatter both between clusters and between different simulation suites.

- Sensitive to:
  - Cluster assembly history

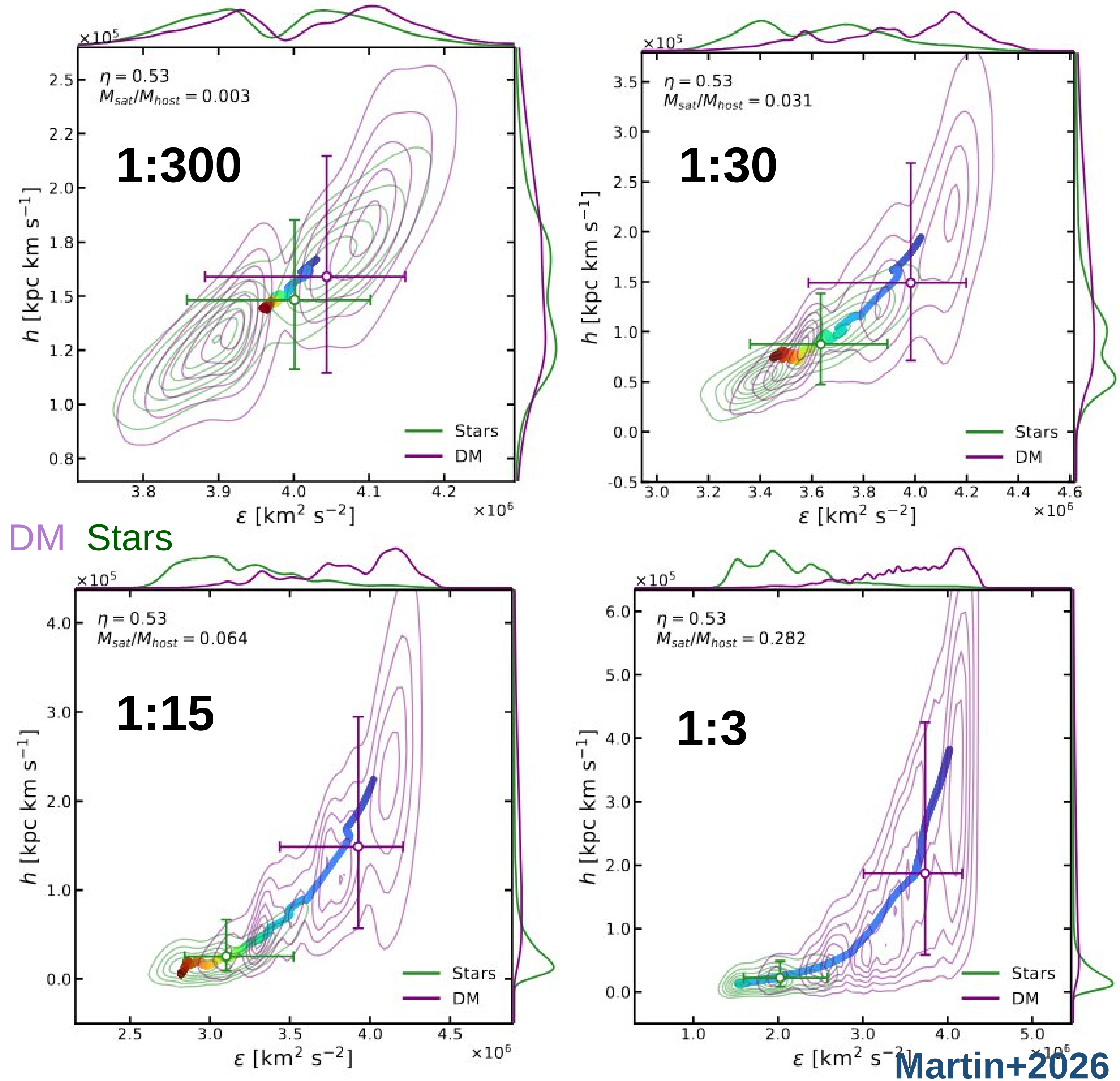
  - Infalling satellite properties
    - Mass and orbital distribution




Martin+2026

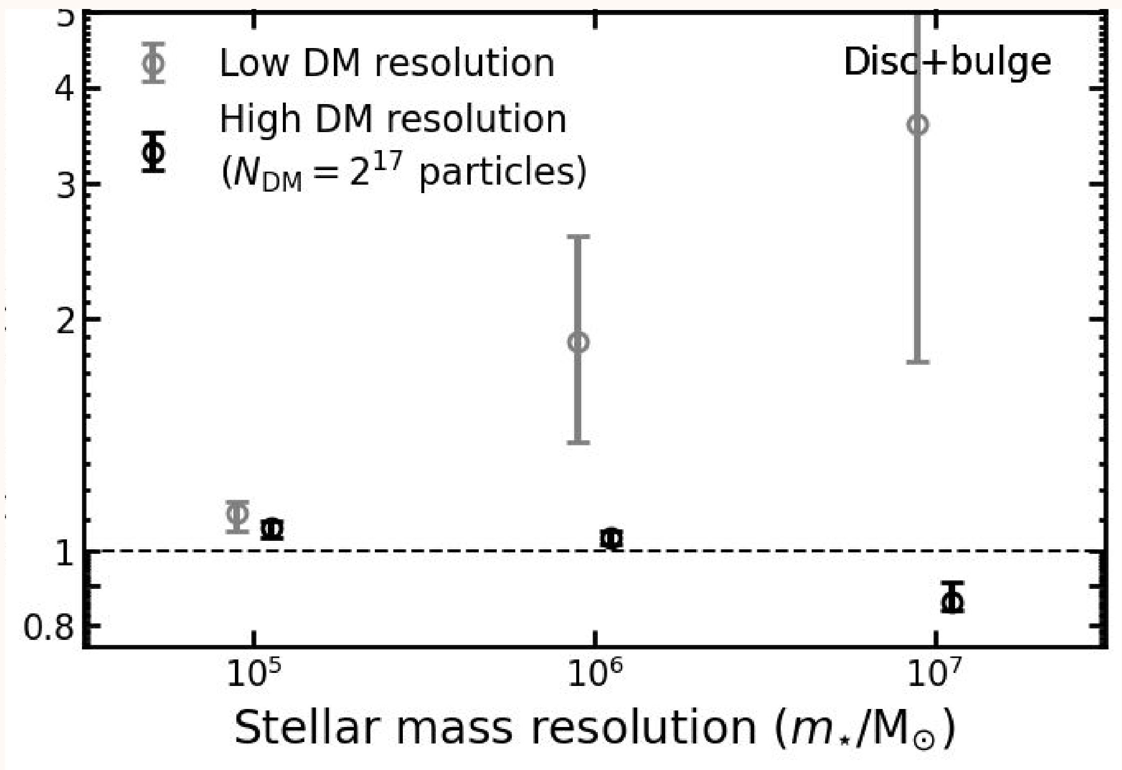
The final kinematic and spatial distribution of the stars relative to the dark matter stripped from satellites depends on the properties of the infalling satellites and their orbital configuration.

So the relative spatial distribution and radial slope of the ICL and DM is dependent on the distribution of these properties.




Martin+2026

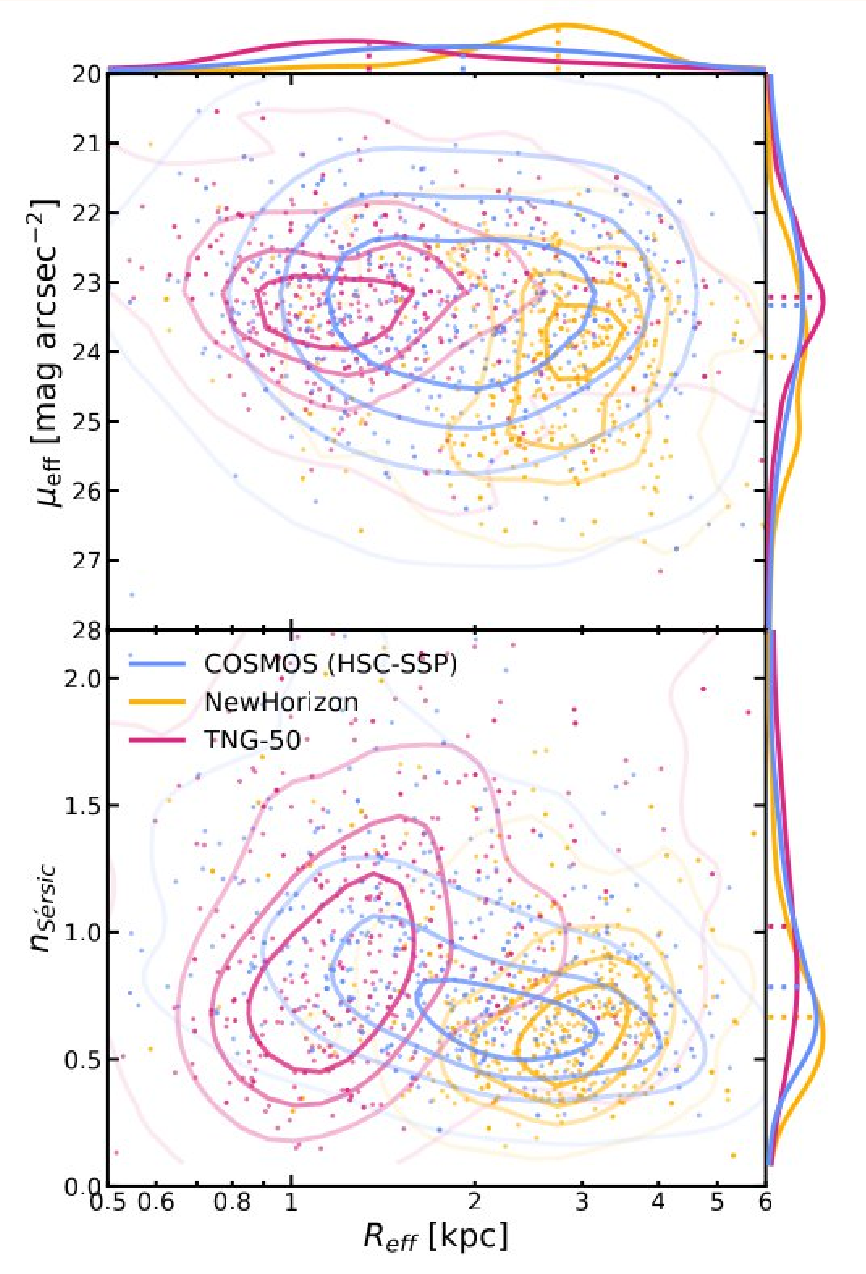
- Also sensitive to:
  - Numerical resolution




Martin et al. 2024

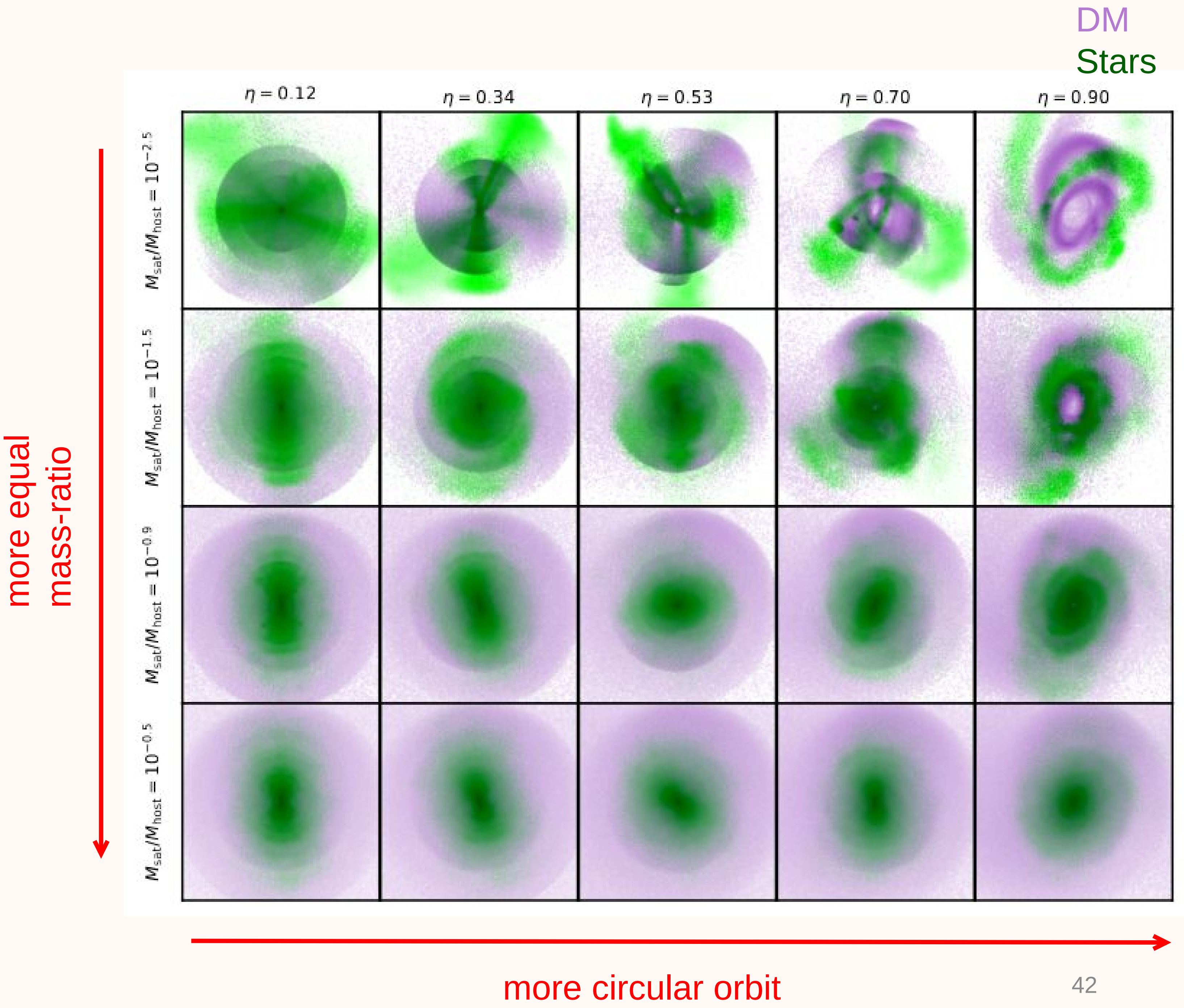
- Also sensitive to:
  - Numerical resolution

  - Galaxy evolution model and galaxy structure
    - Star formation efficiency
    - Feedback processes
    - ISM

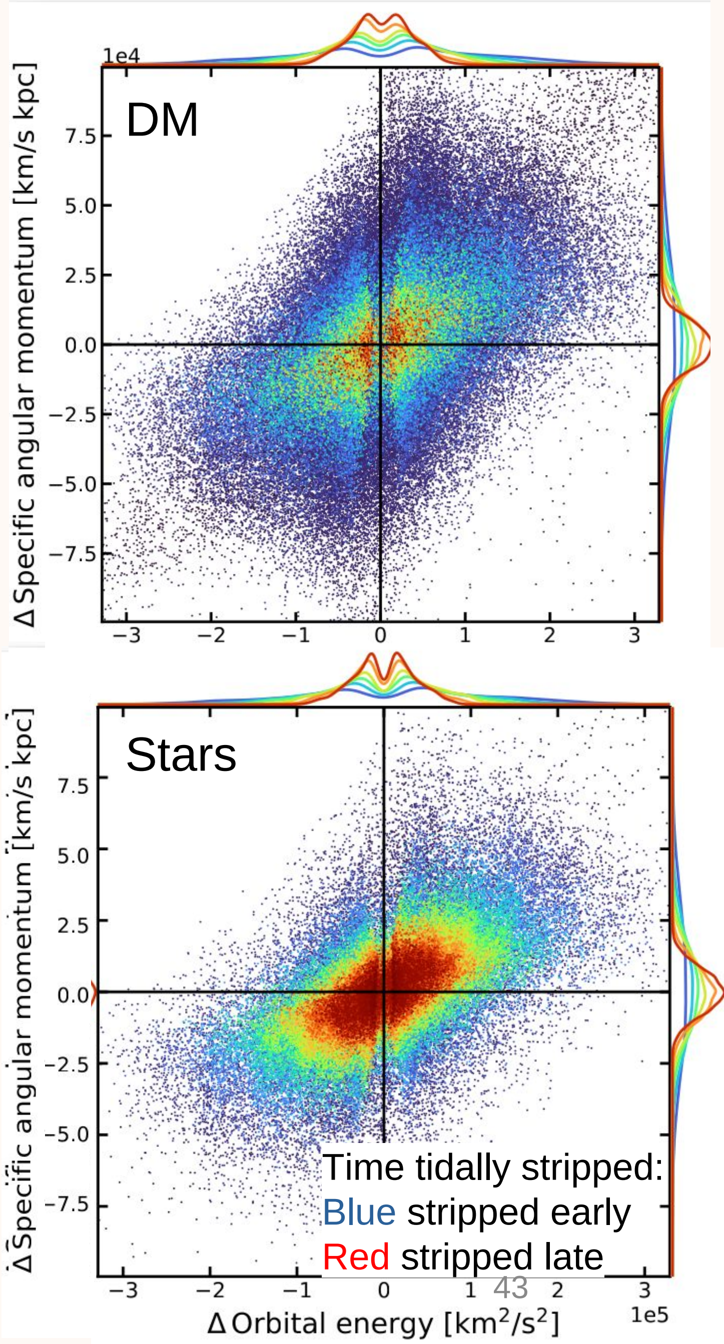



Martin et al. 2025

- We set up a series of controlled numerical experiments
- We injected simulated satellites into a cluster halo
  - Efficient enough that we can ensure sufficient resolution to resolve stripping processes
- We explore a grid of satellite masses and orbital configurations



- In our models we find that DM is always stripped rapidly compared with stars

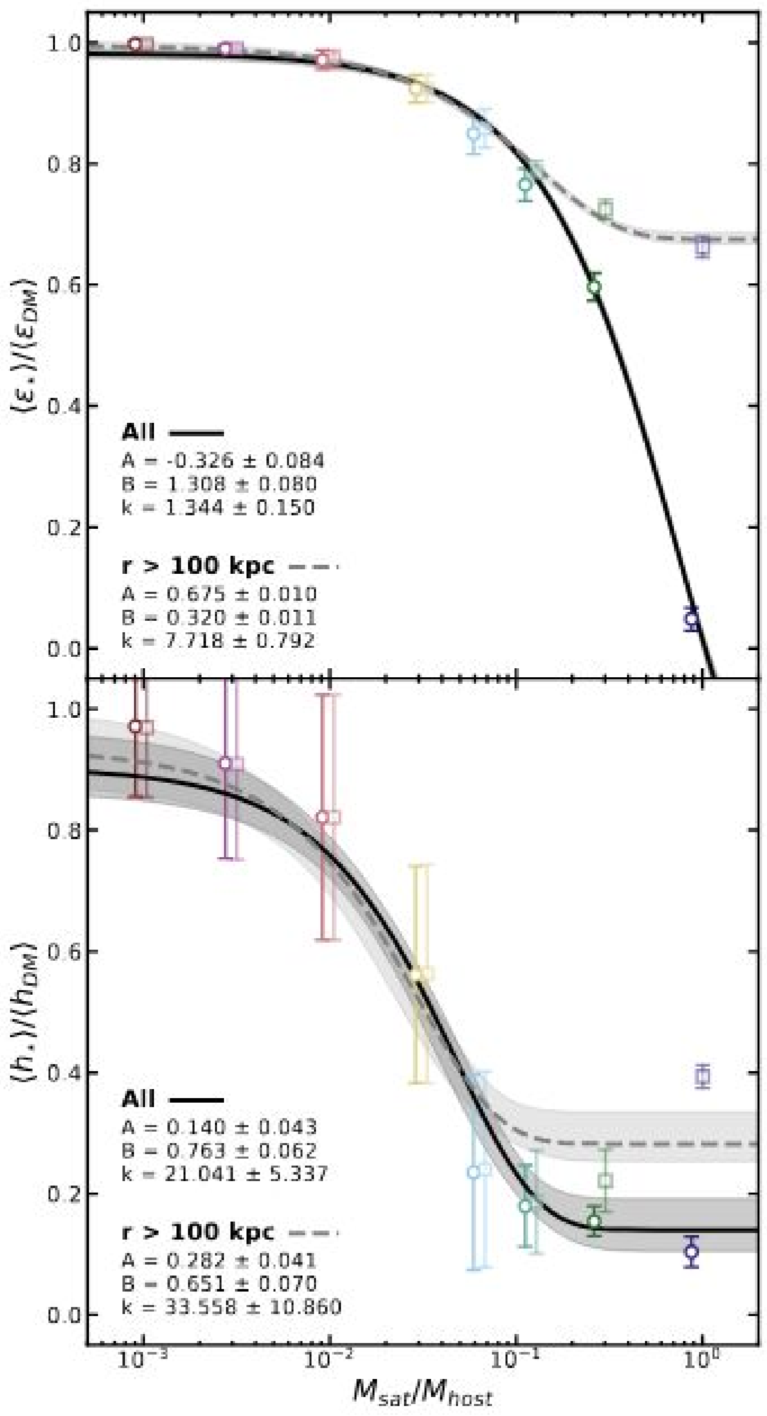


- In our models we find that DM is always stripped rapidly compared with stars

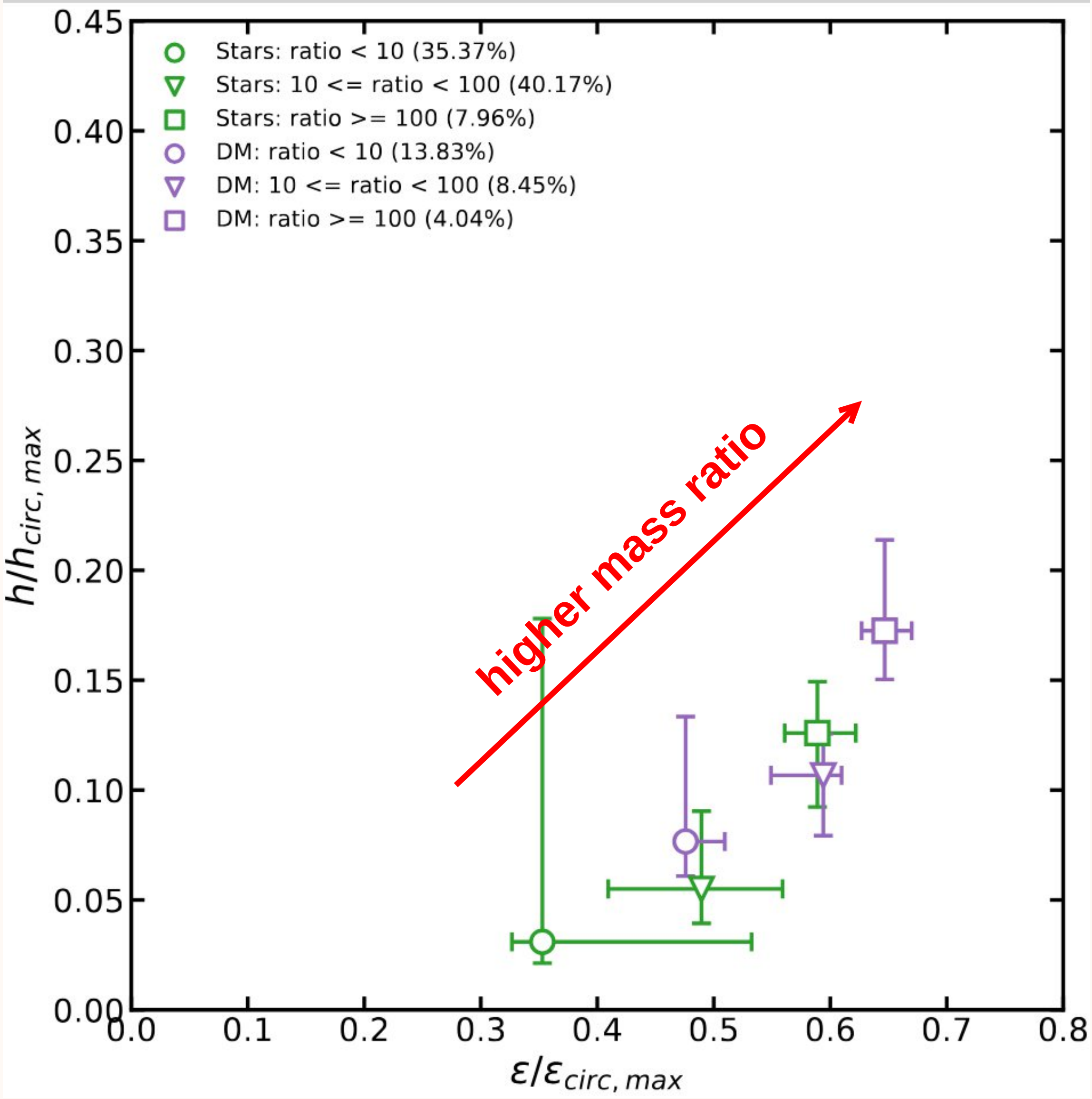
- Difference in the energy and angular momentum of stripped stars vs DM is strongly dependent on mass.

- No strong offset for low-mass satellites

- And limited dependence on circularity of the initial orbit



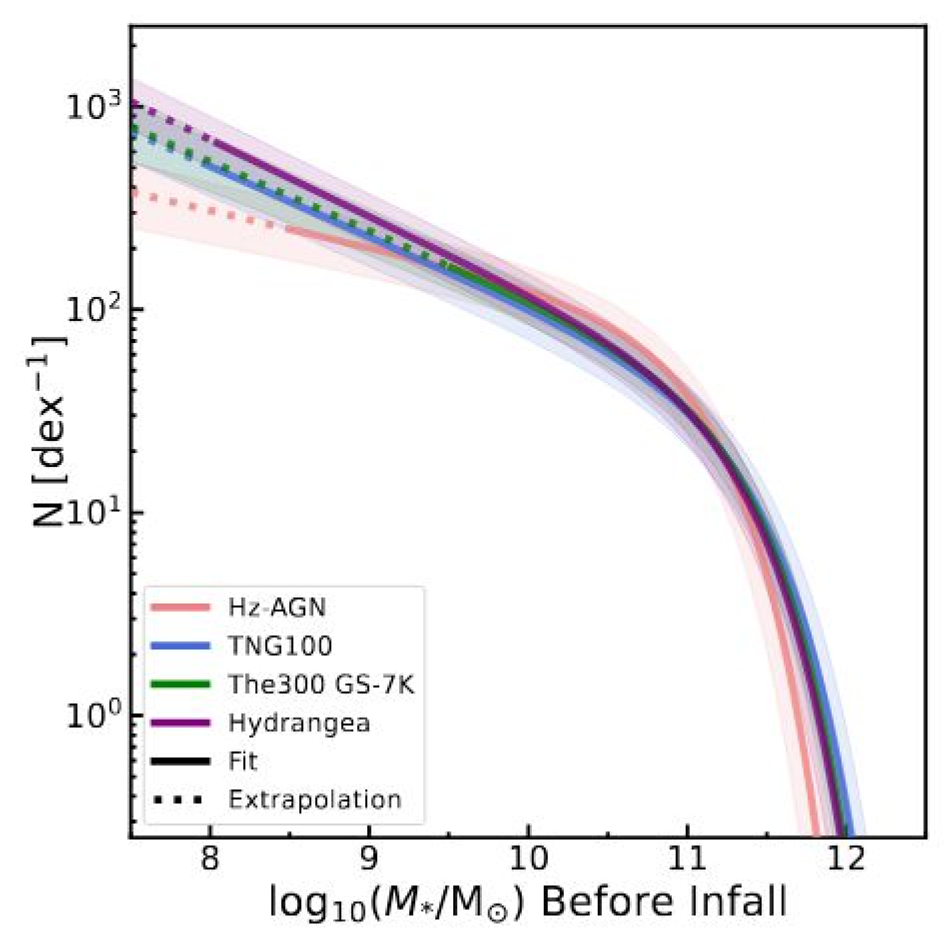
- Similar trends in cosmological simulations
- More equal mass mergers result in the DM and stars sinking deeper into the cluster (losing more orbital energy and angular momentum)
- The offset between the stars and DM shrinks  as satellite mass gets smaller.




Butler et al. in prep

- Cosmological simulations predict a range of infalling satellite stellar mass functions

Brown in prep.

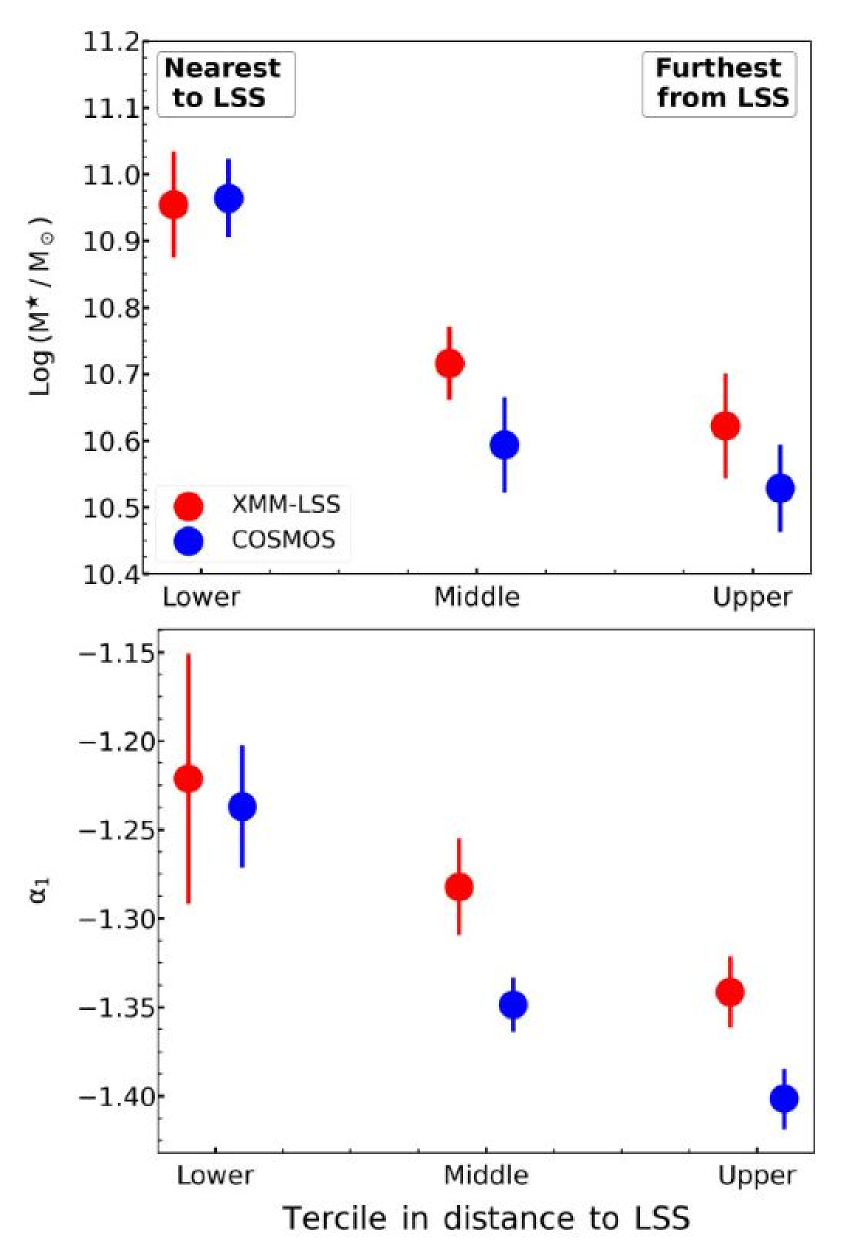


Lazar+2025

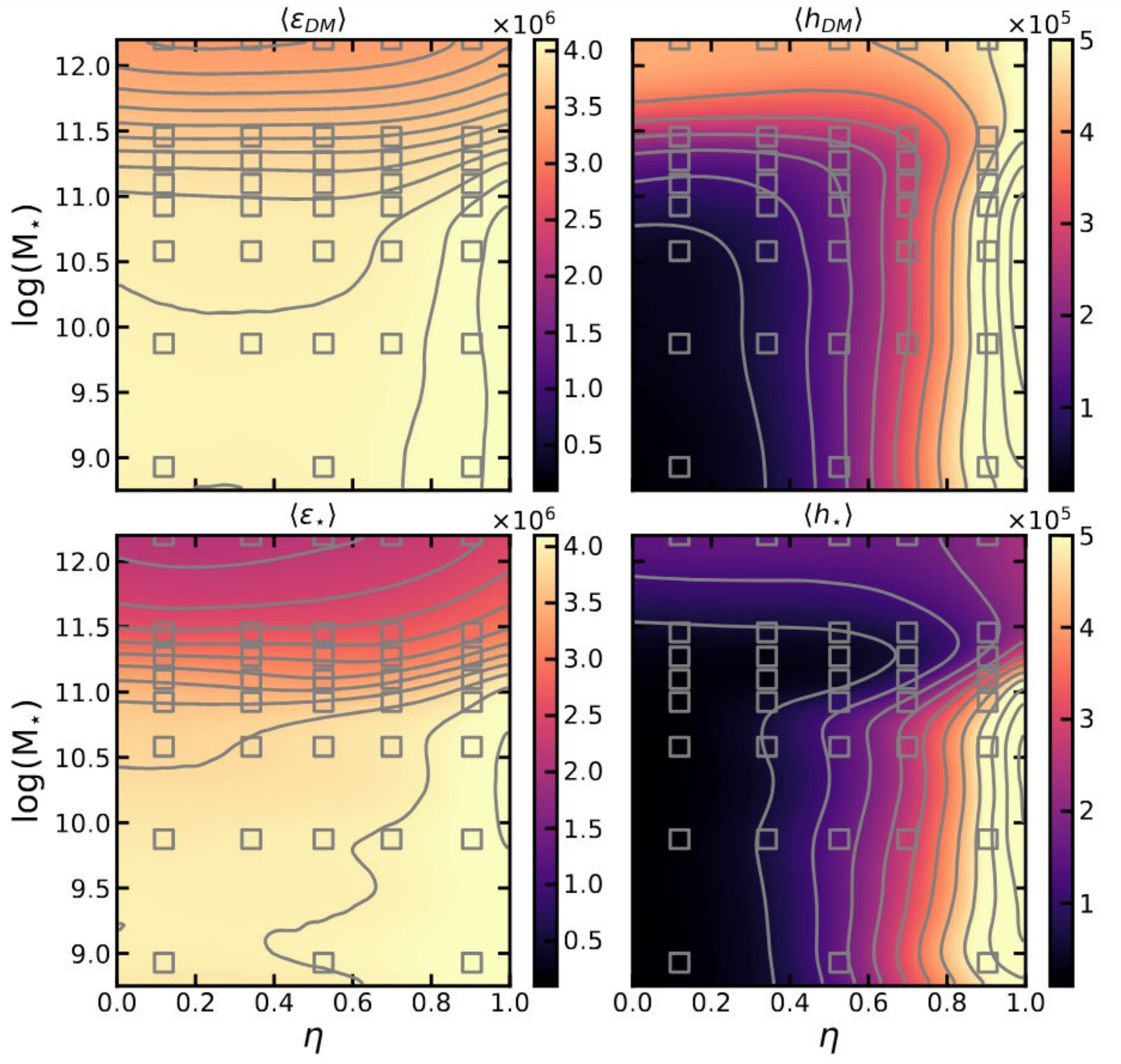
- Cosmological simulations predict a range of infalling satellite stellar mass functions

- Also observational evidence that both the low-mass slope and characteristic mass of galaxy mass functions vary across cosmic environment

- Differences in the objects that contribute to ICL production modify its spatial and kinematic distribution



Based on our numerical experiments, we constructed a Bayesian model that predicts the phase space distribution of stripped stars and DM produced by a given satellite orbit and mass ratio

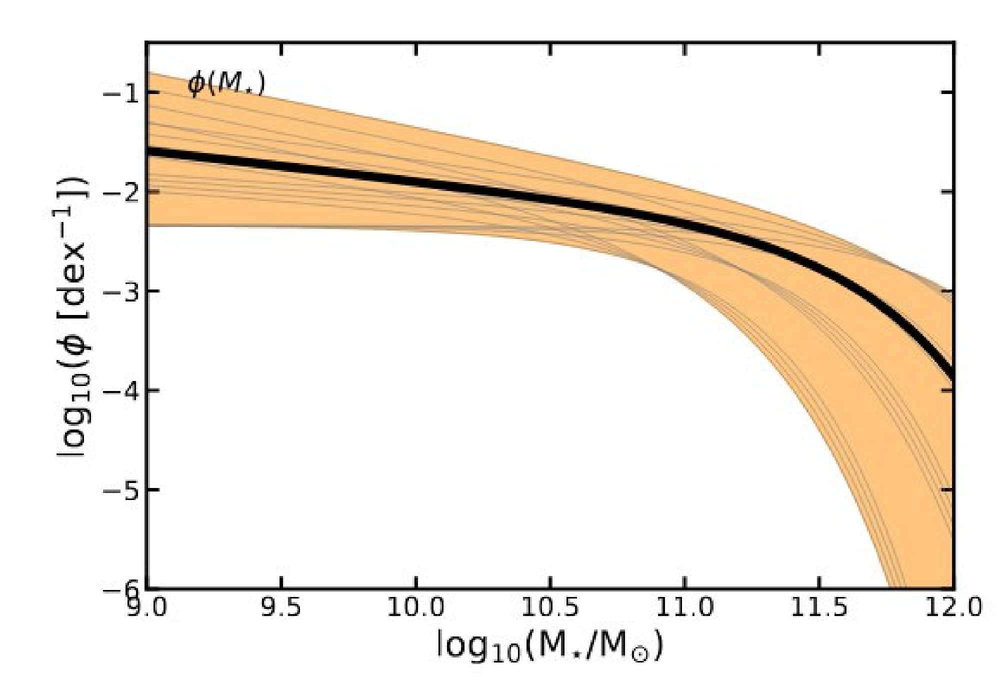



Martin+2026

We can convolve our model over a range of plausible infalling satellite mass functions to understand the dependence on satellite population.

We vary the characteristic mass and low-mass slope and predict the resulting radial density profiles of the DM and ICL

**Martin+2026**

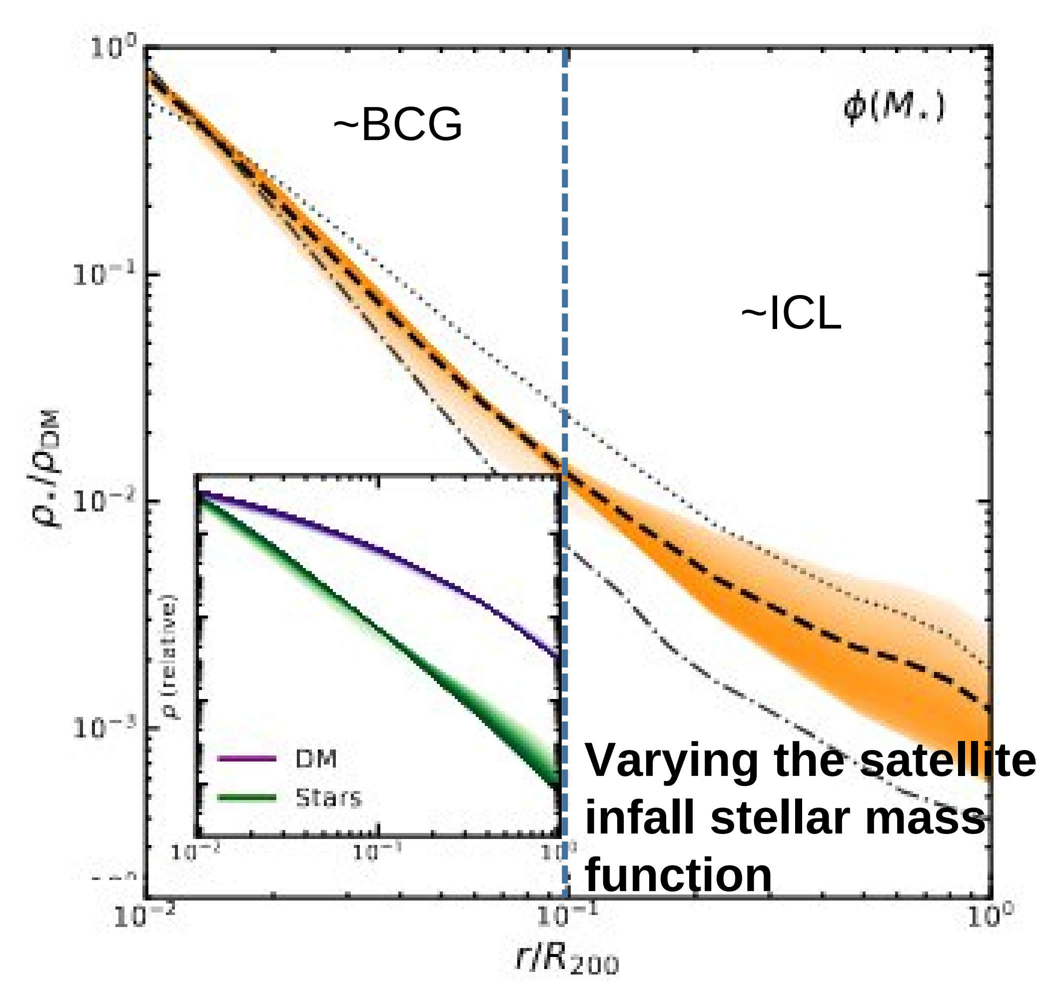


We can convolve our model over a range of plausible infalling satellite mass functions to understand the dependence on satellite population.

We vary the characteristic mass and low-mass slope and predict the resulting radial density profiles of the DM and ICL

This gives us quite a wide range of plausible slopes in the density ratio

Martin+2026

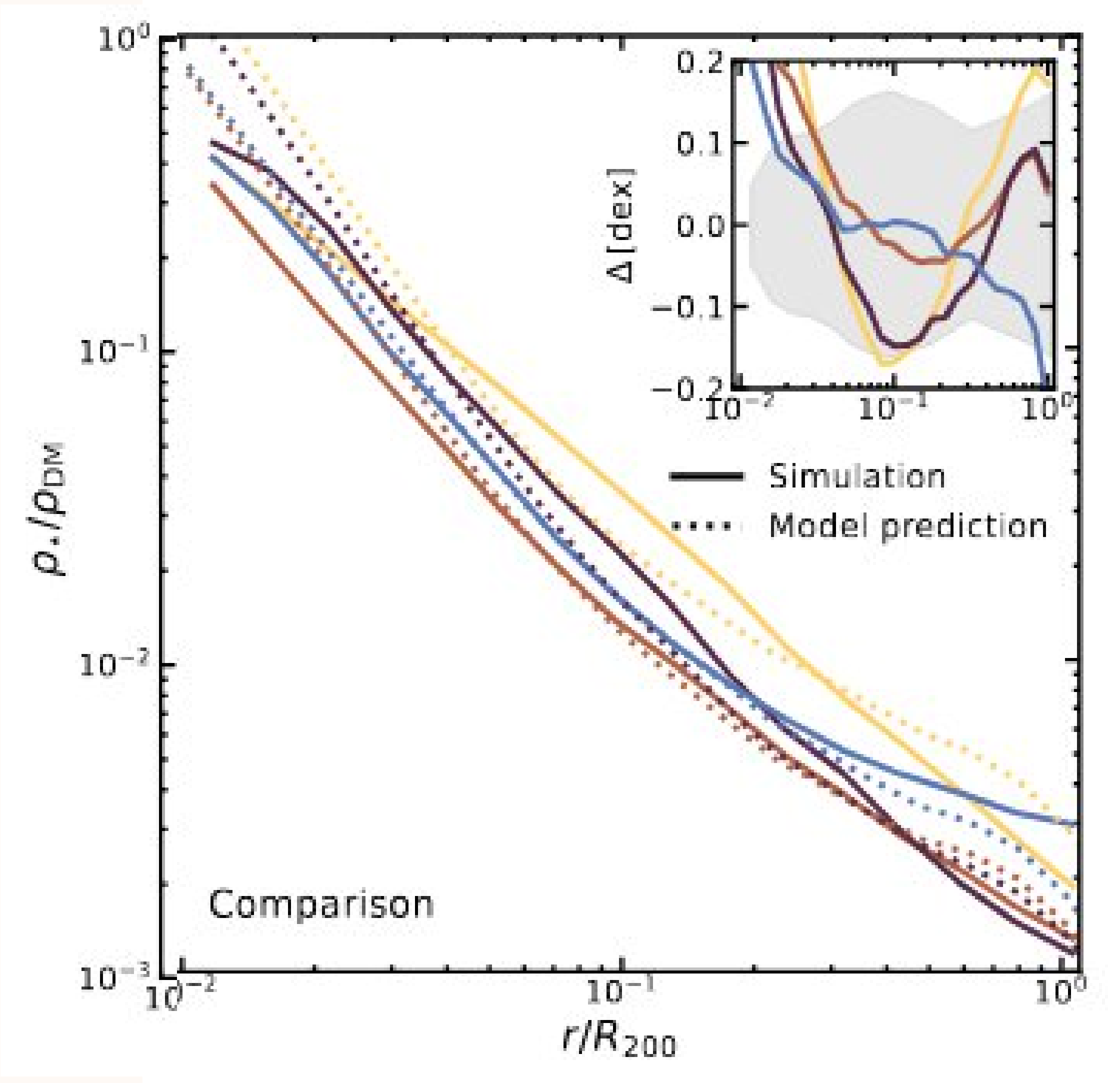


If we only constrain the satellite mass function, our model does a good job at recovering the ICL/DM density profile ratios from the cosmological simulations

The remaining residual is due to differences in resolution/numerical differences and sub grid-physics implementations.

Must be less important compared with the satellite mass function.

Martin+2026

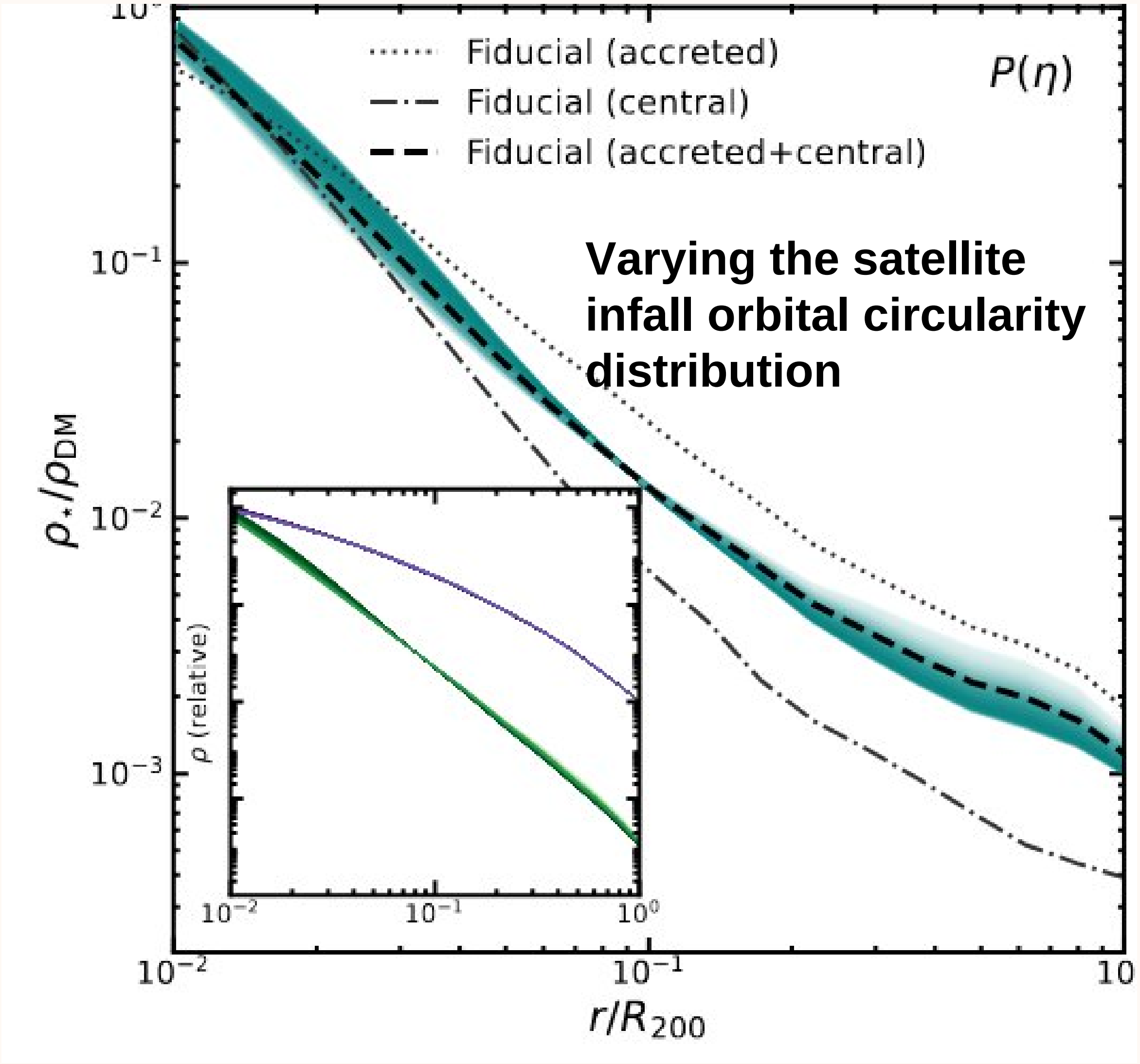


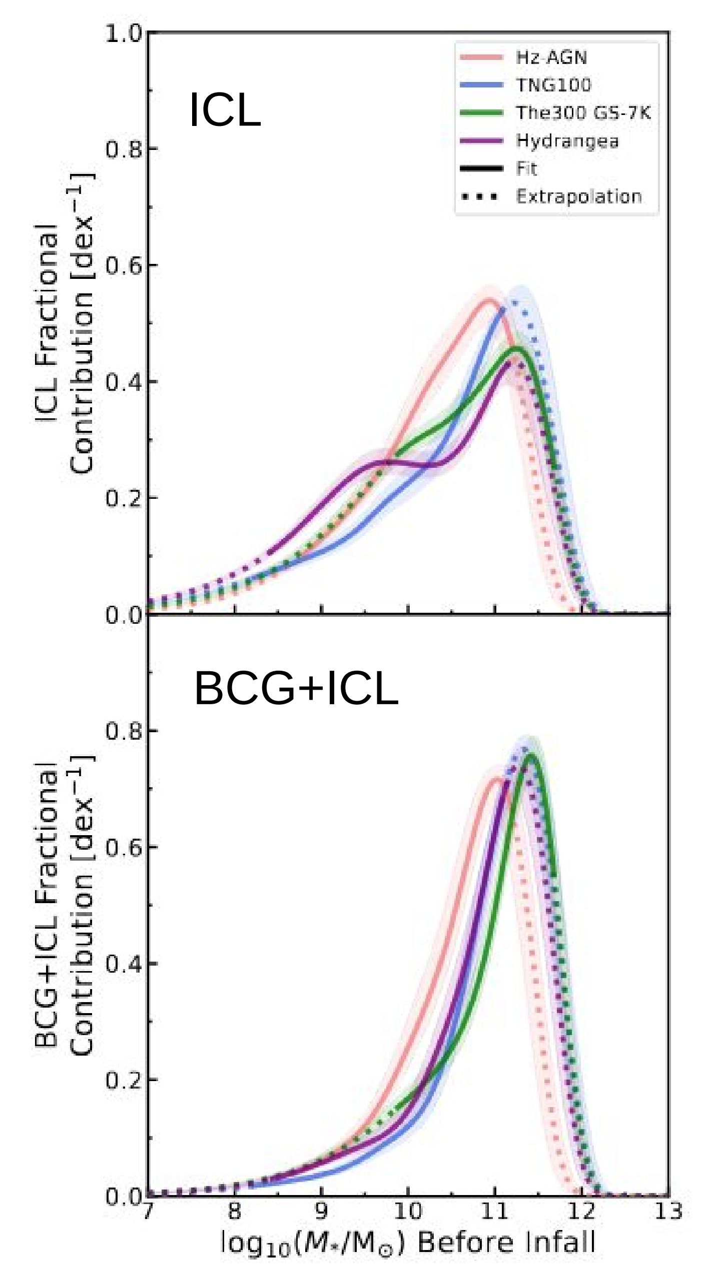
The most important parameter determining the slope of this relation is the characteristic mass of the satellite stellar mass function

Satellites below $10^{10}$ $M_{sun}$ contribute negligibly

The initial orbital distribution of the satellites plays a negligible role

**Martin+2026**






**Brown+ in prep**

Lines up with our understanding that the ICL is formed from a narrow range of satellite stellar masses

The ICL mass budget is dominated by the characteristic mass (knee) of the infalling satellite stellar mass function

Low-mass galaxies contribute relatively little

We saw these low-mass satellite also produce a negligible offset between the stars and DM

$M^\star$ is the primary parameter we need to constrain in order to recover the underlying DM distributionn

- **We should be able to recover the underlying DM potential from ICL observations**
  - Once we constrain the infalling satellite population:
  - We predict stellar-to-DM radial offset with ~0.2 dex precision
  - Better than inter-simulation scatter

- **Requirement:** Characterize M★ of dominant ICL contributors
  - Observable through stellar population gradients
  - Visible tidal streams from massive satellites
  - Cluster dynamical state

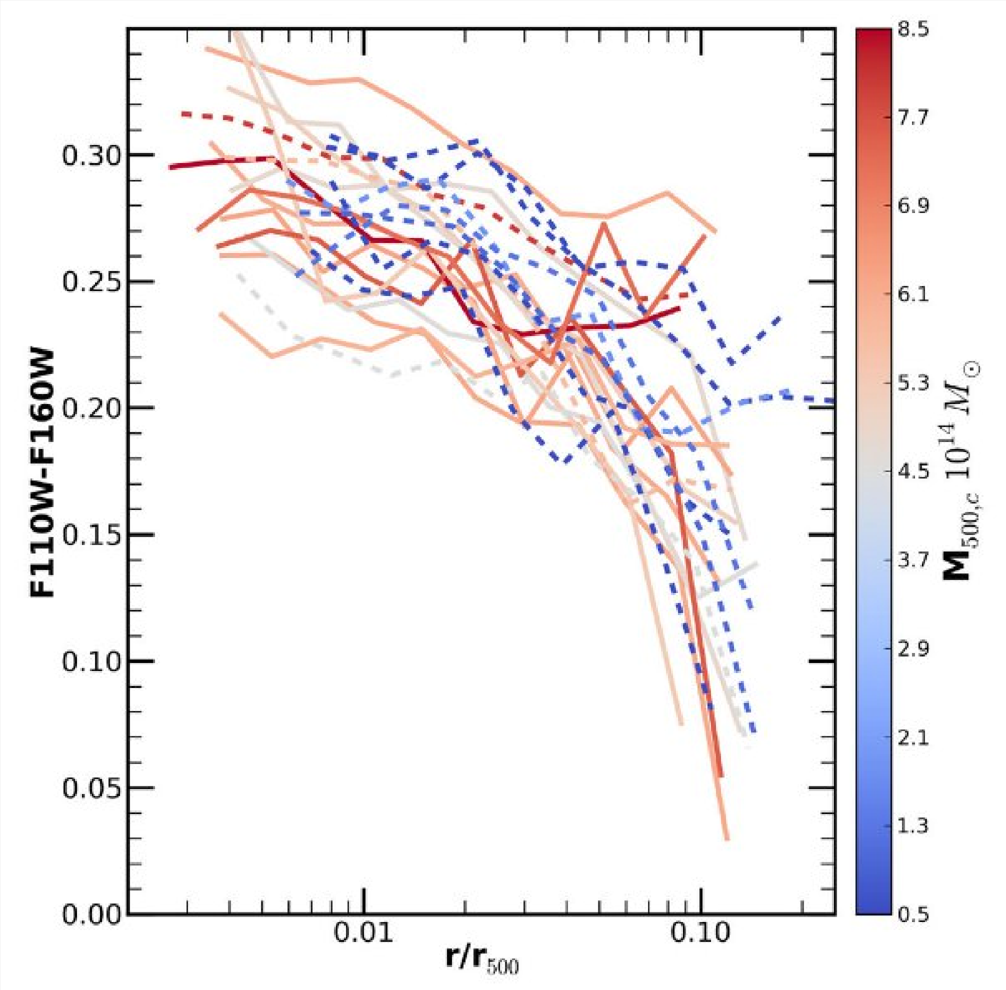
- **Euclid (operational):**
  - ~10,000s of clusters with ICL detection to z=1.5 (Bellhouse+25)
  - Deep imaging (μ ~ 29-30 mag arcsec^-2)
  - Combined with weak lensing → direct calibration

- **LSST (soon):**
  - Unprecedented depth (μ = 30-31 mag arcsec^-2)
  - Large cluster samples across cosmic time

✓ ICL works at high redshift (z > 1) where source density drops
✓ No background source requirement
✓ Traces mass in individual clusters without requiring stacking
✓ Abundant, widely distributed signal

Observationally, we can infer the ICL progenitor masses from stellar populations or colour/metalicty gradients in the ICL

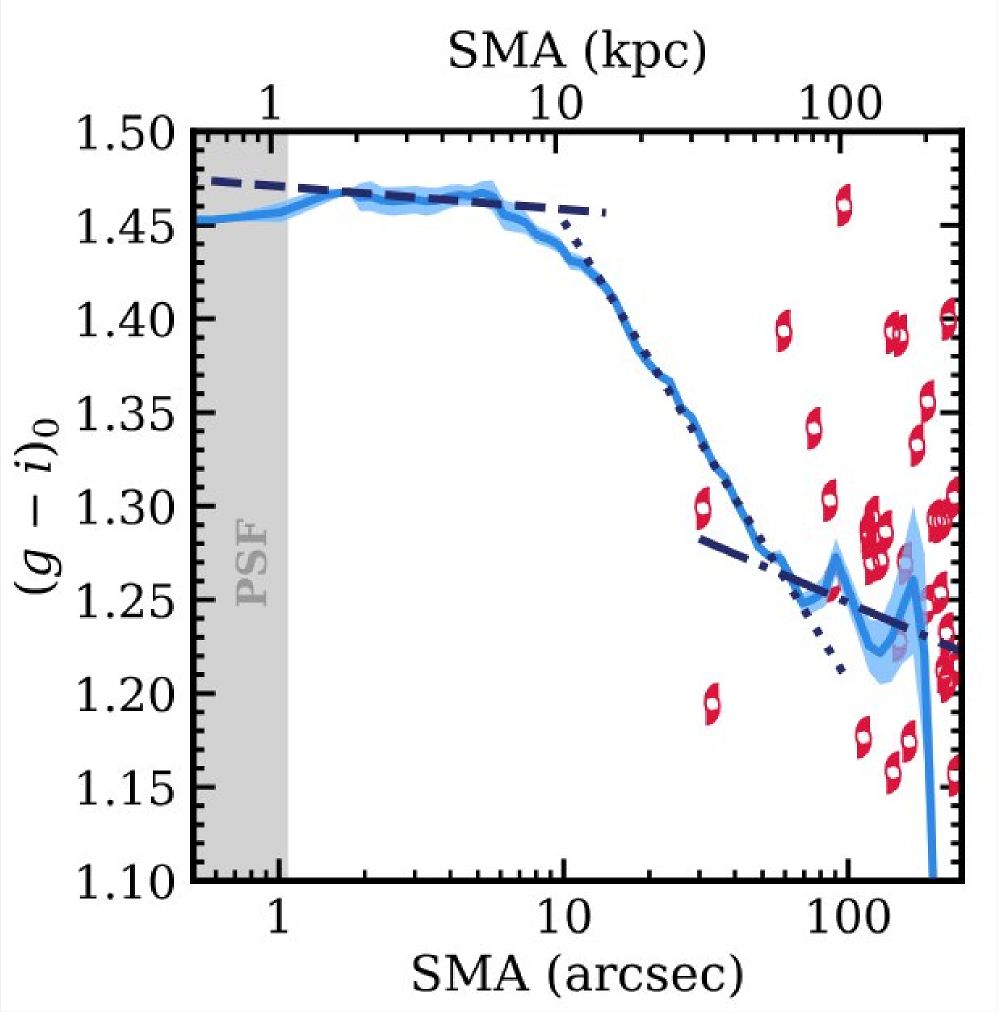
With self-consistent modeling of the cluster assembly history and ICL properties, we should be able to simultaneously infer the key measurements of cluster assembly history and underlying DM halo.




**DeMaio+2018**

Observationally, we can infer the ICL progenitor masses from stellar populations or colour/metalicty gradients in the ICL

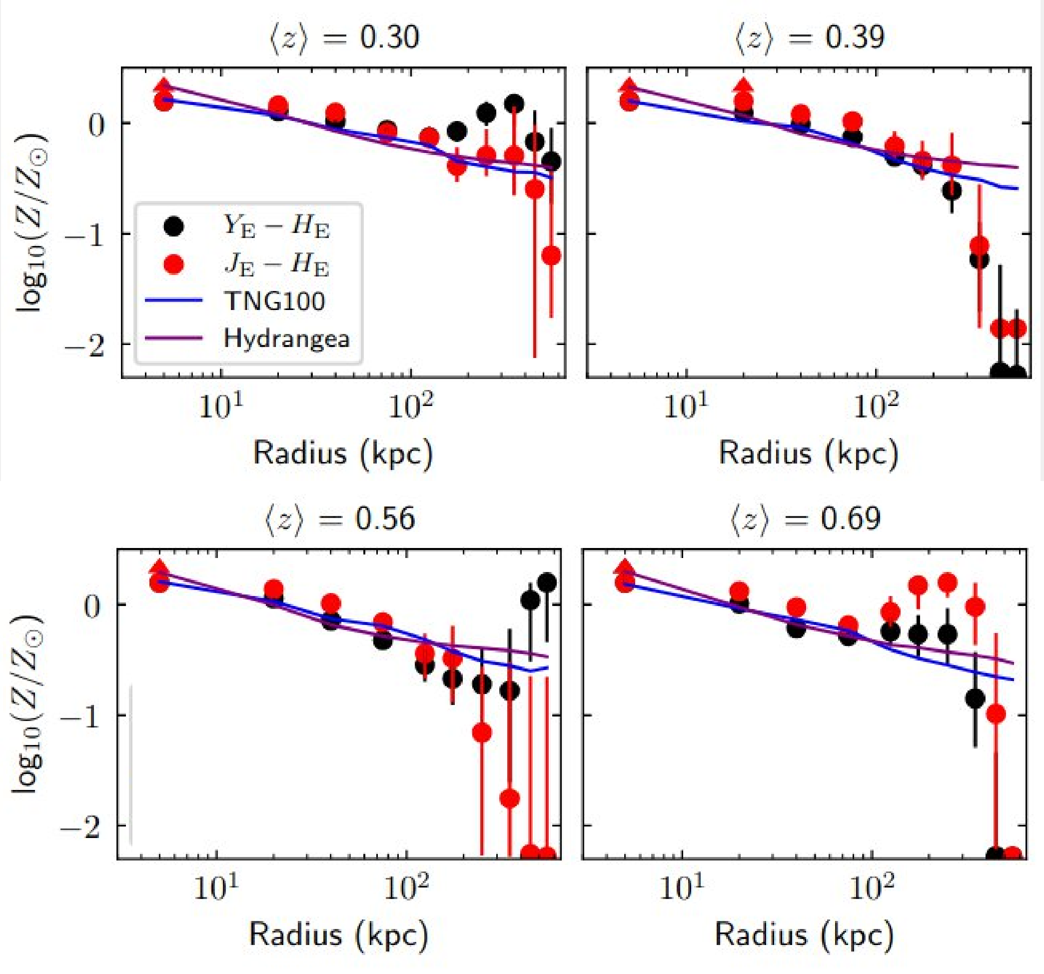
With self-consistent modeling of the cluster assembly history and ICL properties, we should be able to simultaneously infer the key measurements of cluster assembly history and underlying DM halo.




**Montes+2021**

Observationally, we can infer the ICL progenitor masses from stellar populations or colour/metalicty gradients in the ICL

With self-consistent modeling of the cluster assembly history and ICL properties, we should be able to simultaneously infer the key measurements of cluster assembly history and underlying DM halo.

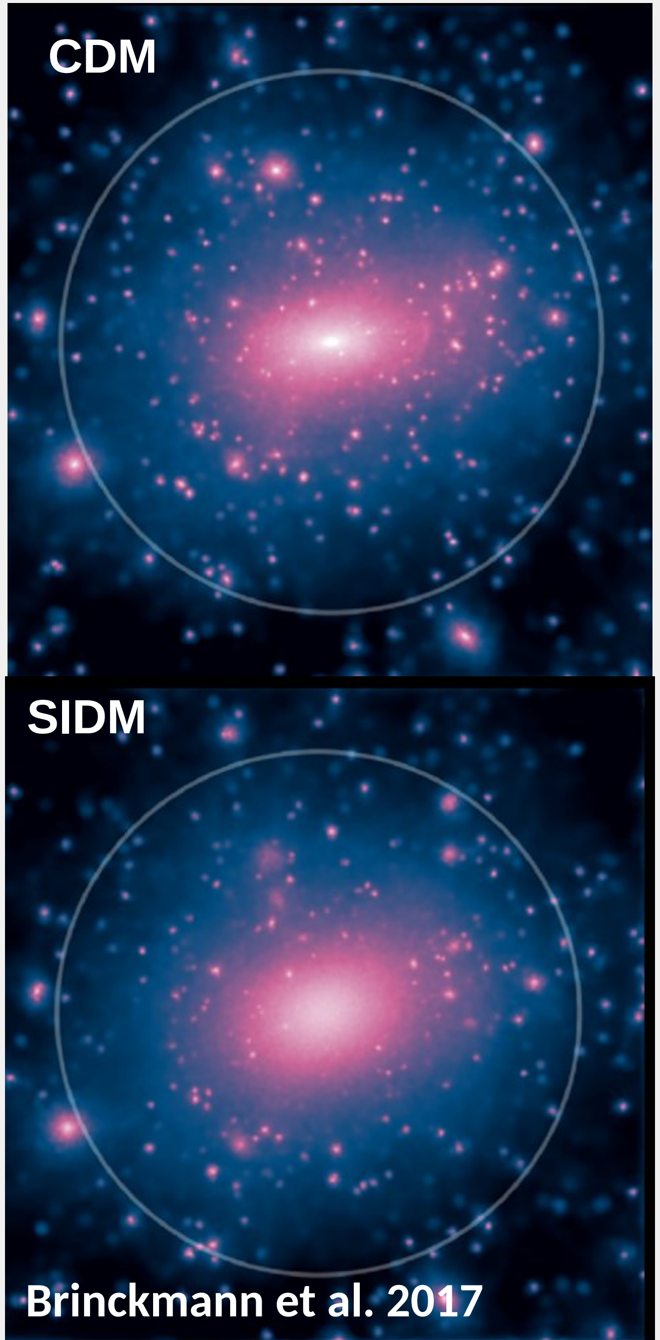



Golden-Marx+in prep

- **Cluster Mass Profiles**
  - Measure radial DM distribution in individual clusters
  - Probe inner regions where lensing is challenging

- **Dark Matter Physics:**
  - Halo concentrations → constraints on DM nature
  - Substructure abundance → warm vs. cold DM
  - Inner slope → self-interacting DM signatures

- **Cluster Assembly Histories:**
  - ICL encodes record of major mergers
  - Constrain mass ratios of key accretion events
  - Can we connect present-day structure to formation history?



**Physical Understanding:**
Stripped stars and DM occupy systematically different phase-space
Driven by differential stripping + orbital decay of massive satellites
Satellite demographics (especially $M_\star$) control ICL-DM relationship
**Model Success:**
Reproduces cosmological simulations within inter-simulation scatter
Once infalling satellite population is matched
Simplifying assumptions capture dominant physics
**Practical Impact:**
ICL can be quantitative tracer of cluster DM halos
Requires constraining infalling satellite population ($M_\star$)
Advantages: high-z, disturbed systems, no background sources needed

**A new precision tool for cluster astrophysics and cosmology?**

# Thank you!