New challenges for cosmological simulations in the low-mass and low-surface-brightness Universe

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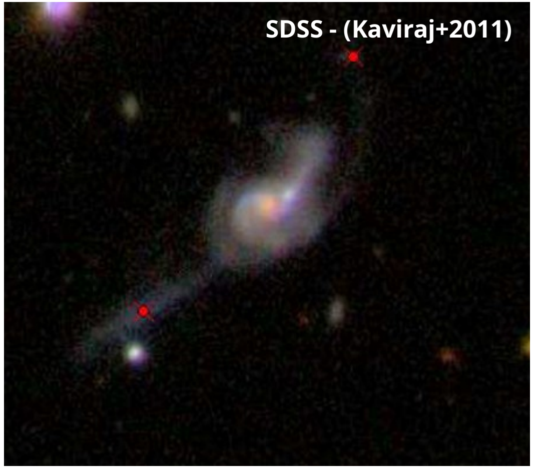
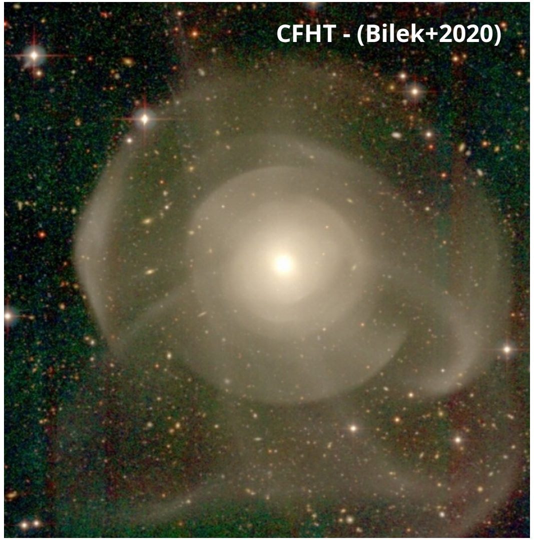




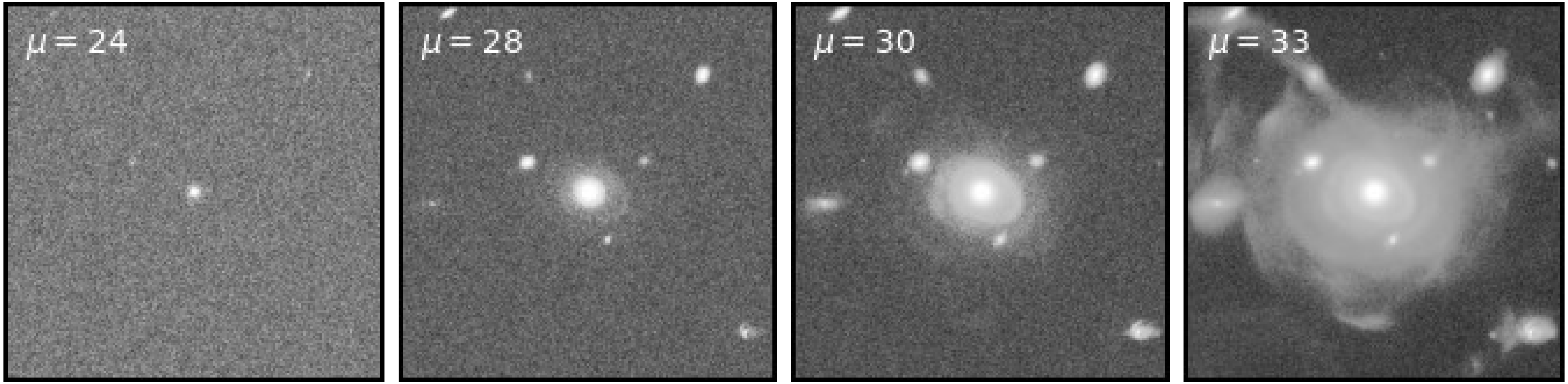
Background

Tidal tails, stellar streams and intragroup/intracluster light are signatures of **accretion events** or interactions

Most LSB structures detected in previous surveys are a **biased subset** of especially bright (μ^{lim}_r(3σ,10″×10″) > 26 mag arcsec^{-2}) and recent events (e.g. **Impey+1988**)

Fainter halo substructures and intragroup/intracluster light contain a more **complete record of past accretion -** μ^{lim}_r(3σ,10″×10″) ~ 30 mag

Background



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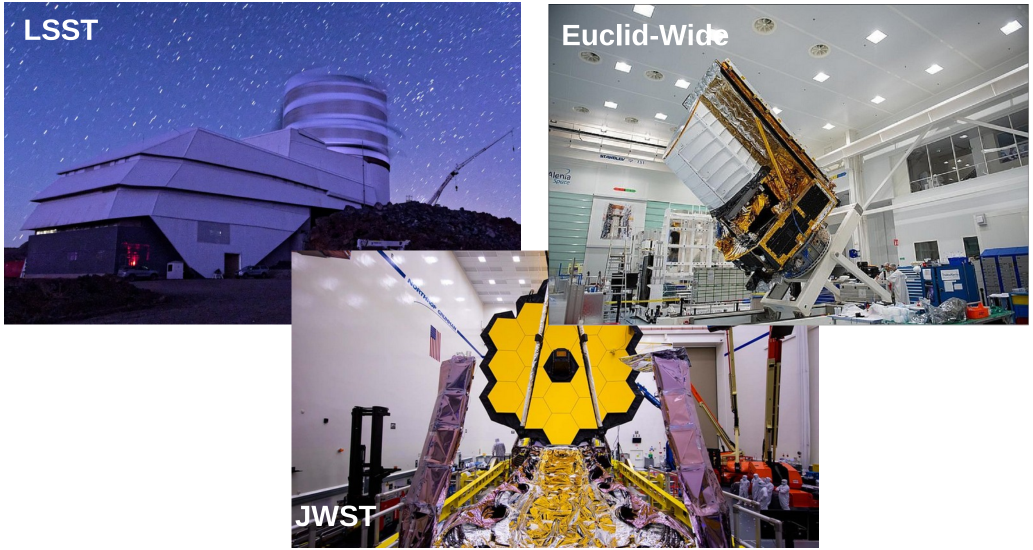
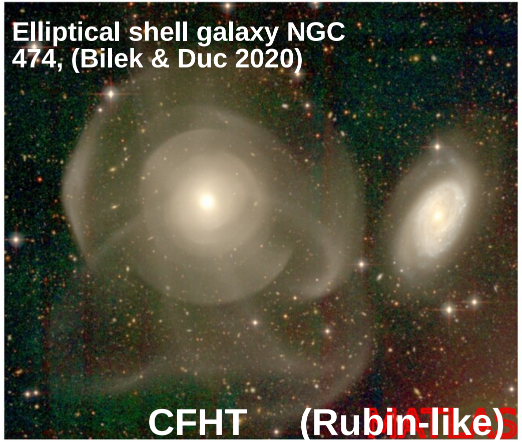


Past surveys



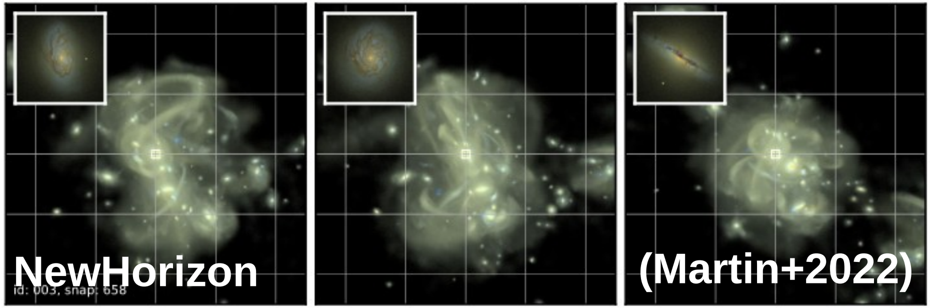
Current state-of-the-art

Deep-wide imaging from **Rubin/LSST**, **Euclid-Wide** and other facilities will be a significant step from previous wide surveys

Deeper imaging for billions of galaxies revealing many intricate structures

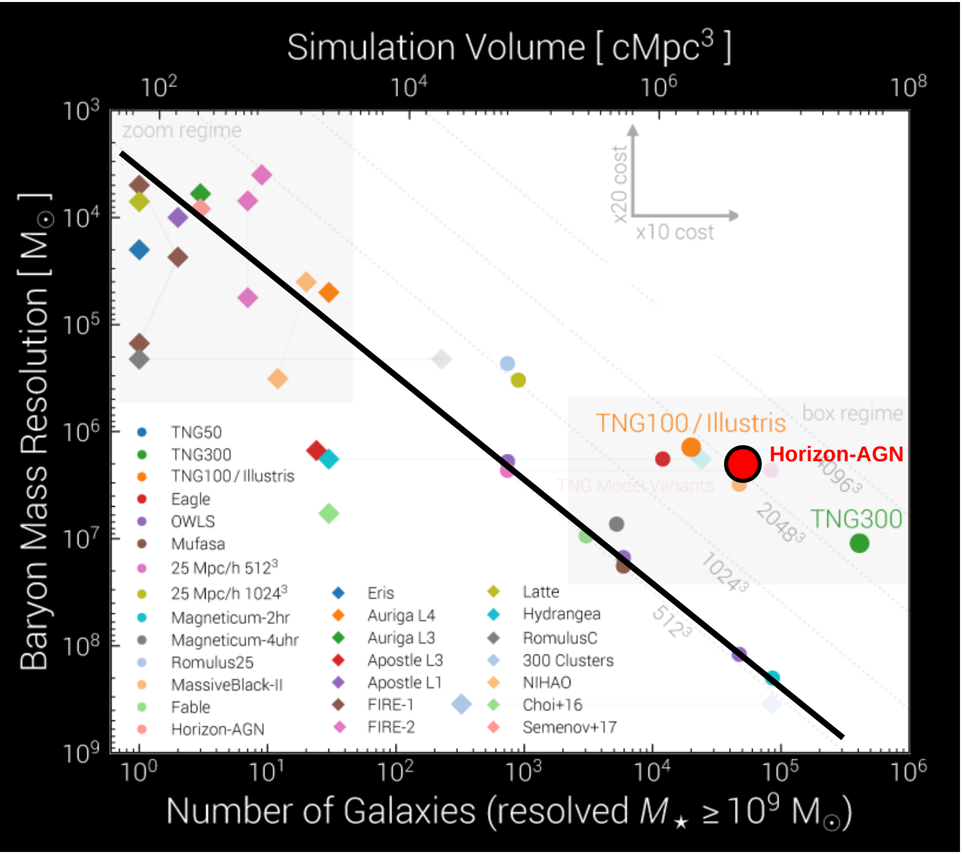
A much **less biased understanding of galaxy assembly** at key epochs their evolutionary history

Background



Next-generation simulations reproduce a variety of low-surface-brightness features

Background

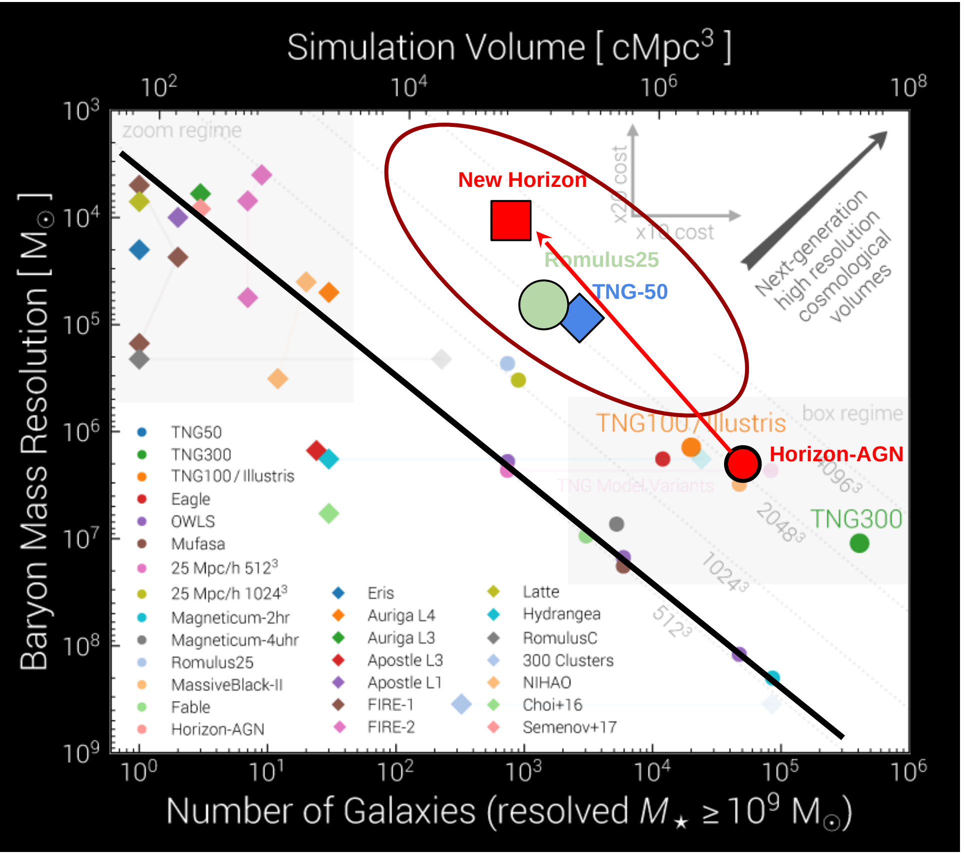


Next-generation simulations reproduce a variety of low-surface-brightness features

It is becoming possible to simulate **larger volumes at higher resolution**

Adapted from plot by Illustris collaboration

Background



Next-generation simulations reproduce a variety of low-surface-brightness features

It is becoming possible to simulate **larger volumes at higher resolution**

Resolutions comparable to high-res zoom-ins (e.g. **New Horizon, Romulus25 and Illustris TNG-50**)

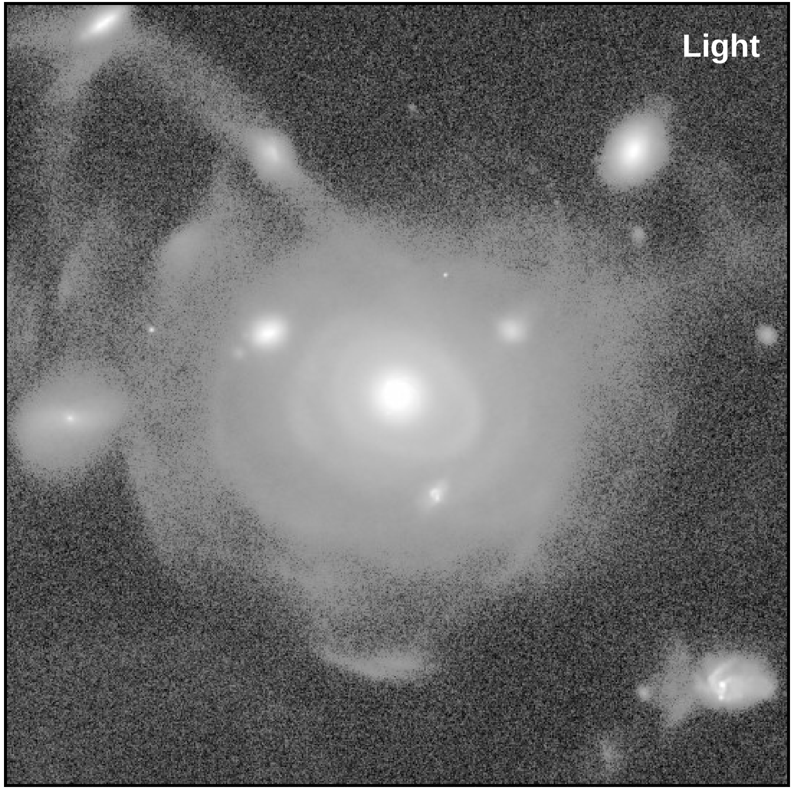
Currently limited to **intermediate volumes** of 10s of Mpc

Adapted from plot by Illustris collaboration

Background

Stellar stripping: stars removed from satellite galaxies by **tidal forces**.

Contributes to **intracluster light** (ICL) and **evolution of galaxies** in clusters.



Background

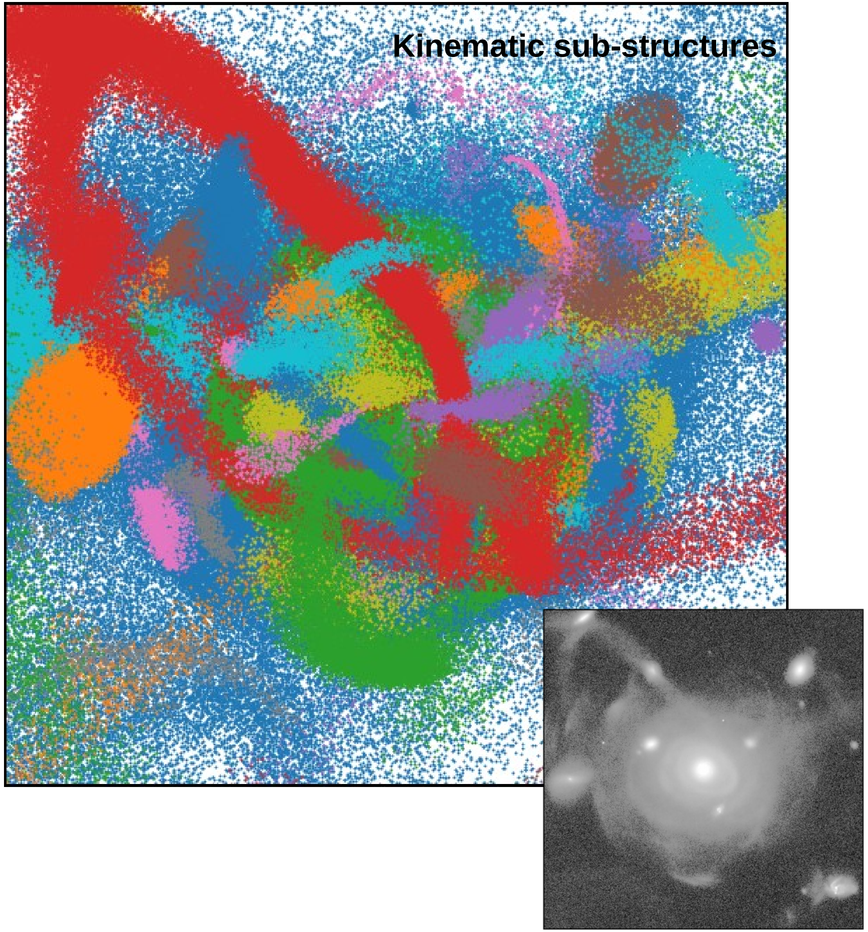
Stellar stripping: stars removed from satellite galaxies by **tidal forces**.

Contributes to **intracluster light** (ICL) and **evolution of galaxies** in clusters.

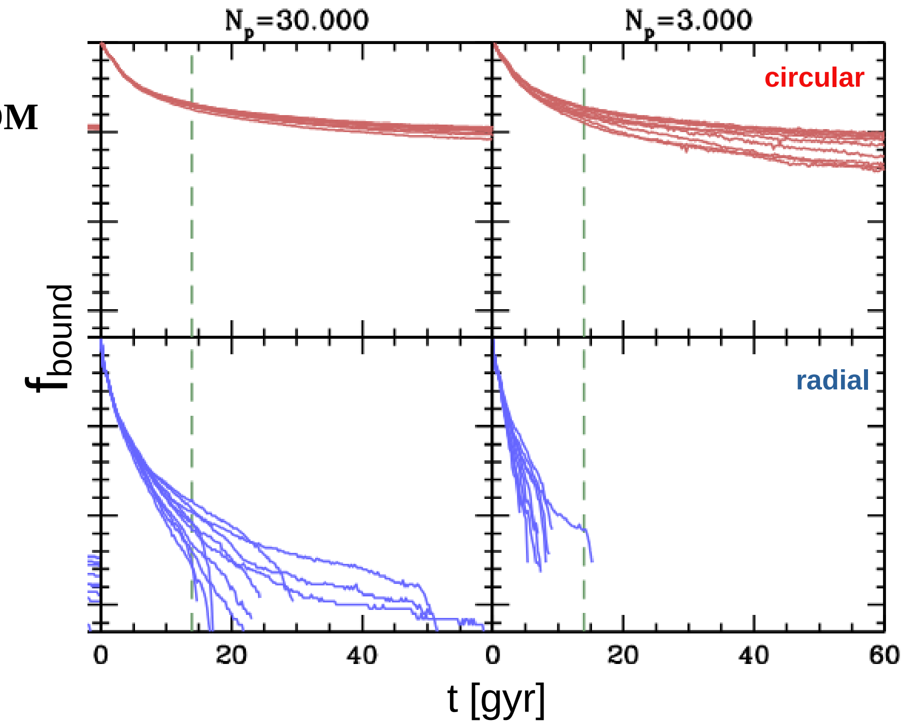
A majority of intracluster/intragroup light is generated by **tidal stripping**

Originating from many small objects

Simulations need to resolve the processes affecting each of these objects to make accurate predictions about the quantity and properties of ICL



Previous work has shown that resolving mass loss from **DM haloes** requires a **minimum number of particles** to avoid artificial disruption

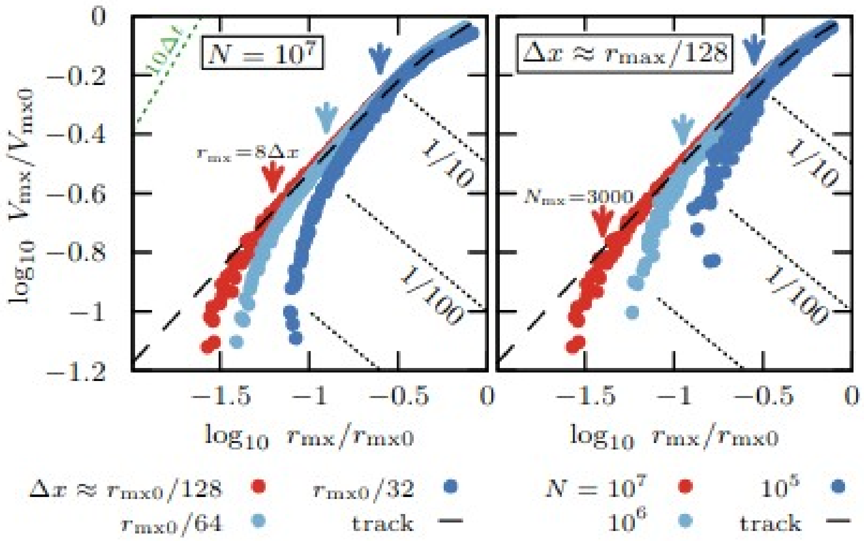


van den Bosch & Ogiya (2018)

Previous work has shown that resolving mass loss from **DM haloes** requires a **minimum number of particles** to avoid artificial disruption

High numerical resolution is also required to properly resolve the **density profile of stripped remnants**

The impact of poor resolution on **stellar mass loss rates** has not been explored so-far



Errani & Navarro (2020)

Background

Numerical and spatial resolution affects the accuracy of various **physical processes** in simulations, including **tidal stripping**

Different resolutions produce **varying mass loss** outcomes

In cosmological simulations convergence is tested on the properties of **galaxy populations**.

The convergence of physical processes like stripping is not typically tested

Inaccurate stellar mass loss rates may impact **tuning of the galaxy evolution model** to reproduce the GSMF – currently different tuning is required to accurately reproduce the GSMF in clusters vs the field

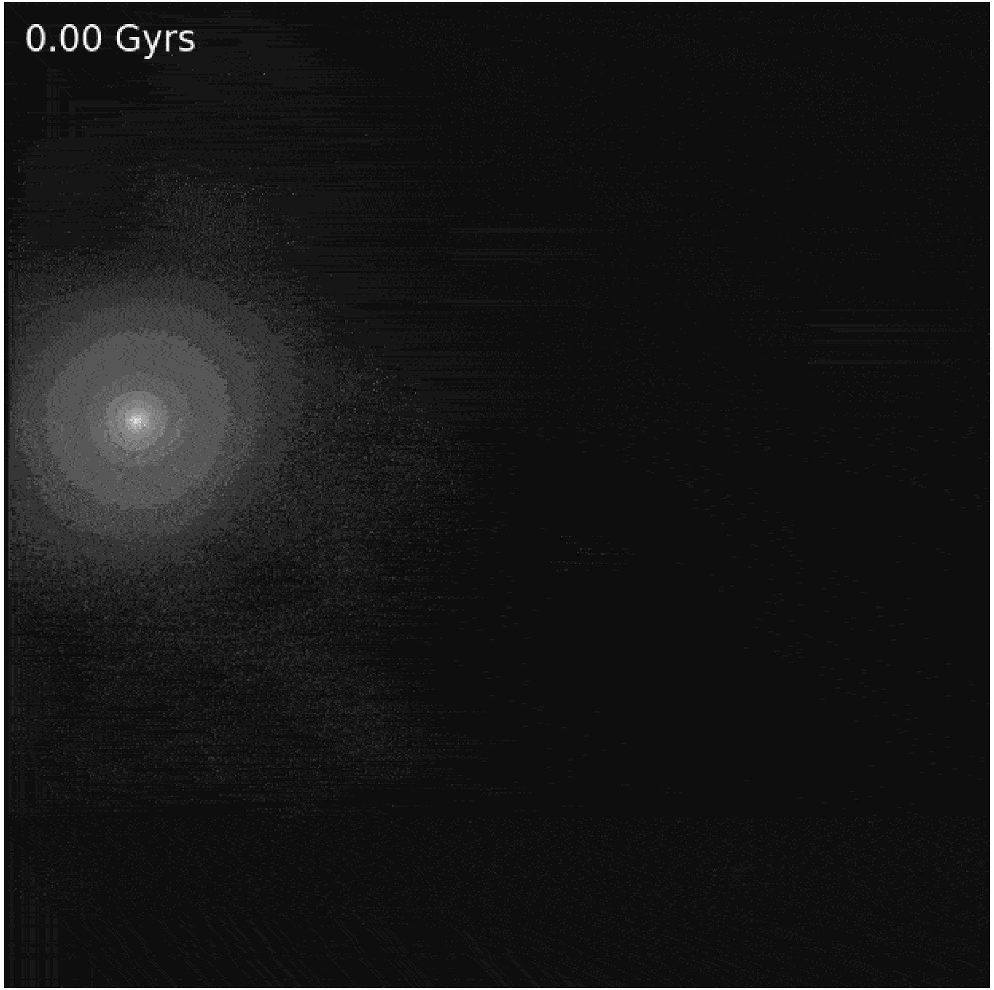
Simulation setup

Model satellites galaxies in a $10^{14.5}$ Msun **static potential**

DM halo with stellar component (spheroid or bulge+disc) using GalIC (**Yurin & Springel, 2014**)

Grid of **orbital parameters** and **satellite stellar masses**

Grid of **spatial and mass resolutions** over a range corresponding to contemporary cosmological simulations



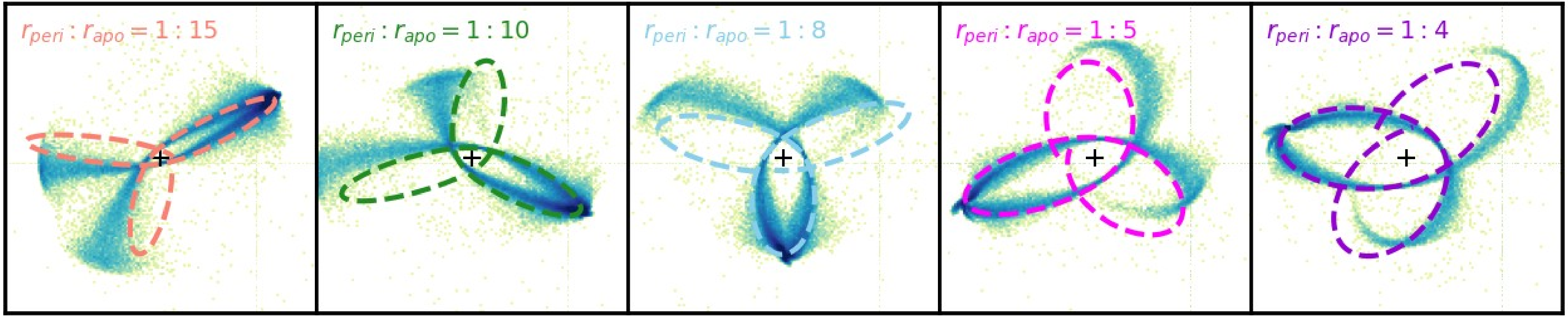
Simulation setup

Masses: 10^7 Msun < M* < 10^{11} Msun

Morphologies: Spheroidal, Disc dominated

Orbits: 1:15 < r_{peri}/r_{apo} < 1:4

Mass resolution (m^*/m_{DM}): $10^5/10^6$, $10^6/10^7$, $10^7/10^8$ Msun



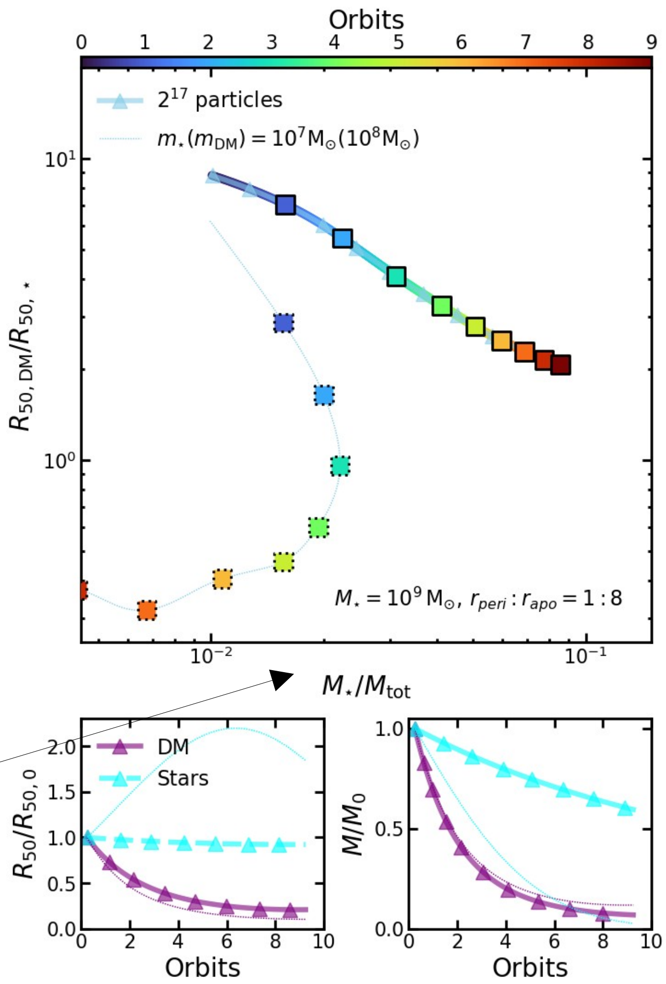
DM vs stellar stripping

The properties of the **satellite DM halo** significantly influence stellar stripping efficiency.

The slope of the inner DM profile near the stellar component impacts stripping rates with poorly resolved haloes leading to **over-efficient stripping**

DM to stellar radius ratio

DM to stellar mass ratio



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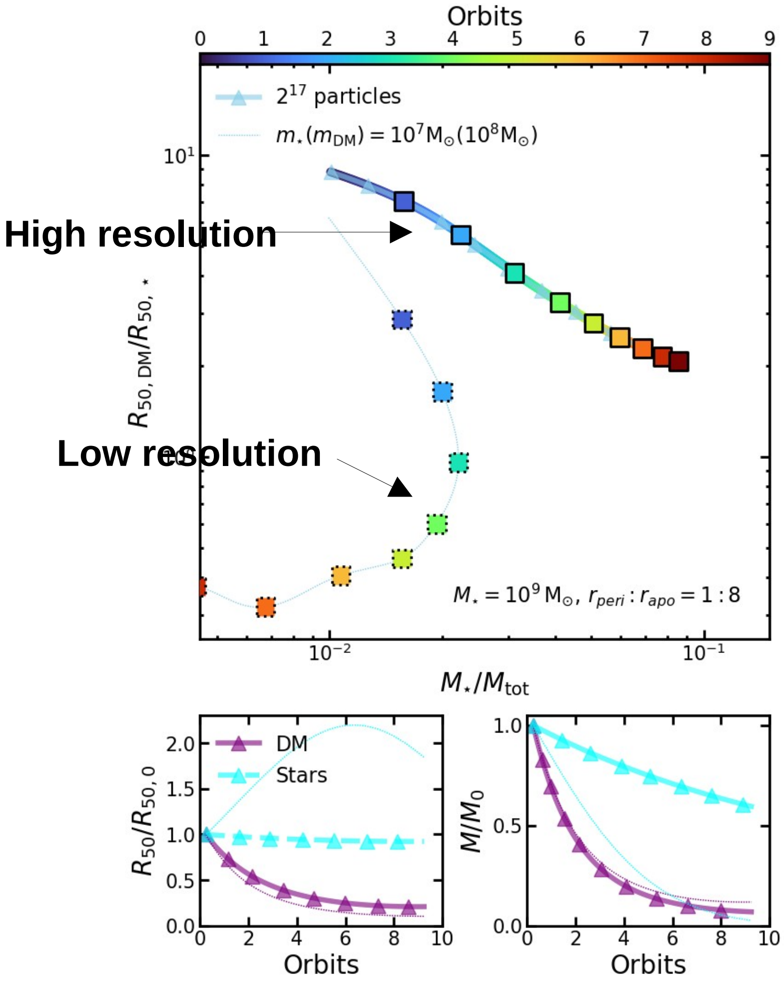

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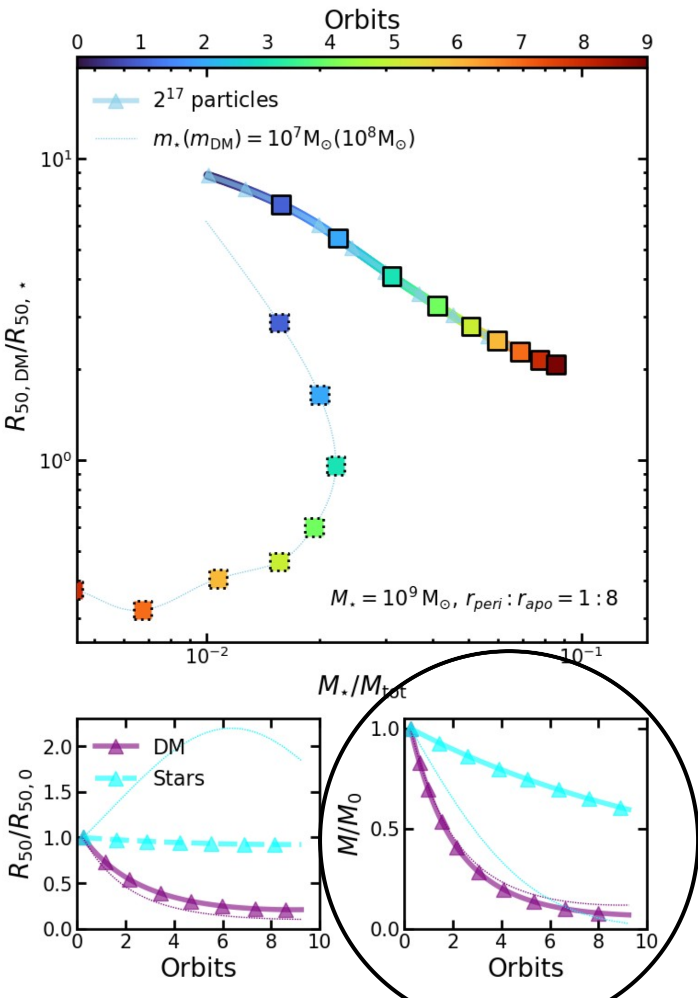

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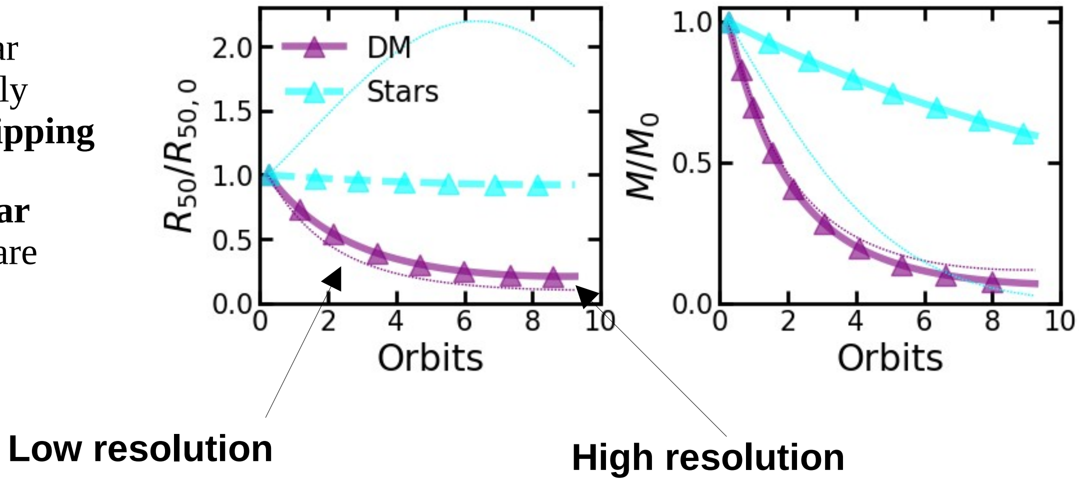
DM resolution has a large influence on the **stellar component** but **integrated DM properties** are largely unchanged



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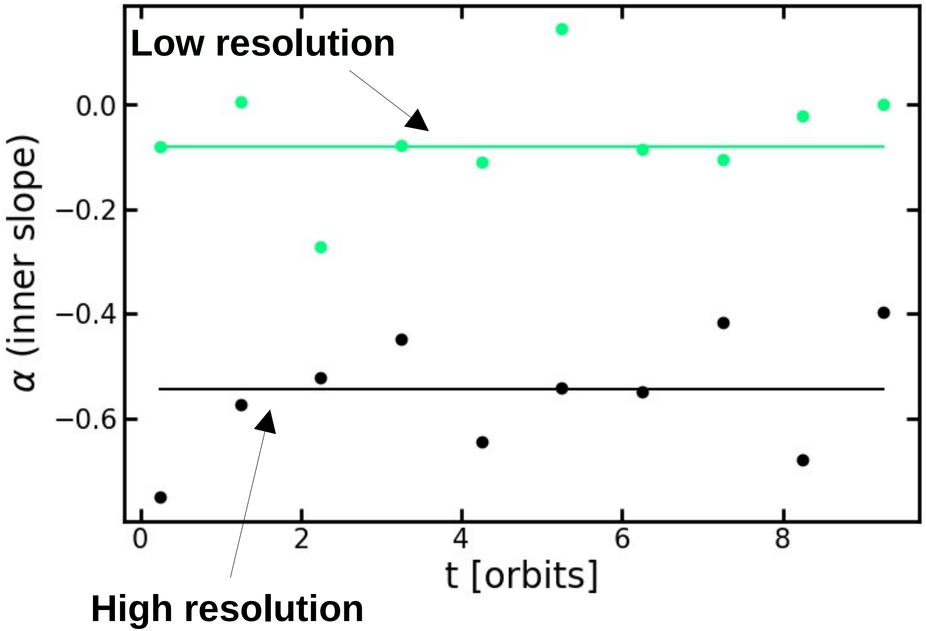
Looking closer: well-resolved DM haloes maintain their structure, while poorly resolved haloes lead to **cored central profiles**.



DM vs stellar stripping

Well-resolved DM haloes maintain their structure, while poorly resolved haloes (<1000 DM particles) lead to **cored central profiles**.

The properties of the **satellite DM halo** significantly influence stellar stripping efficiency.

The slope of the inner DM profile near the stellar component impacts stripping rates with poorly resolved haloes leading to **over-efficient stripping**

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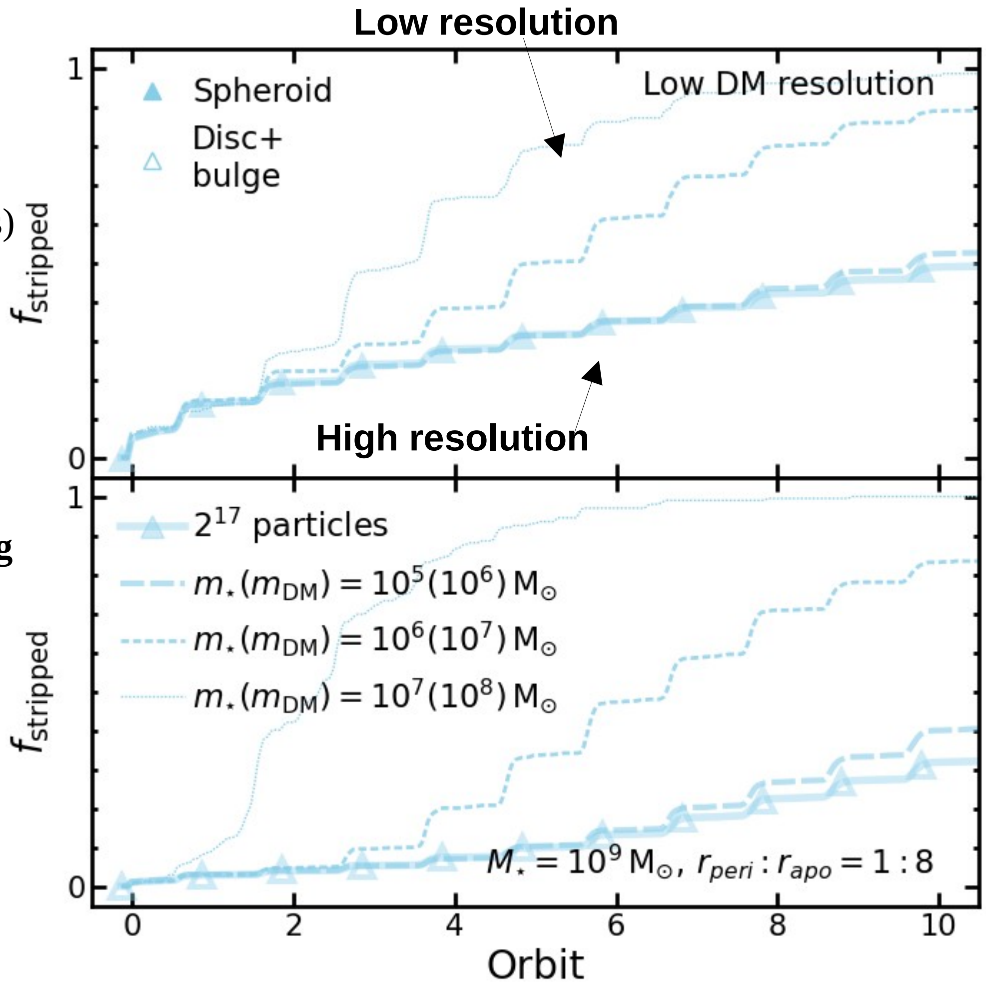
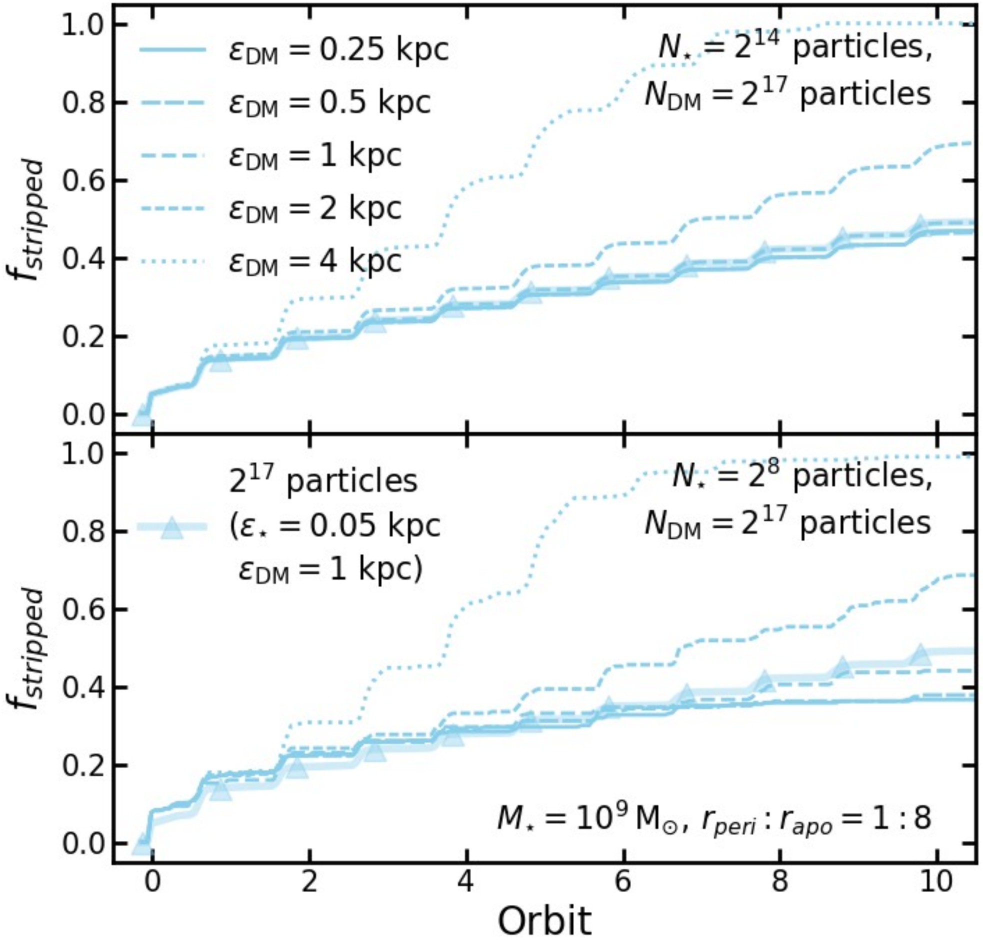


Force resolution

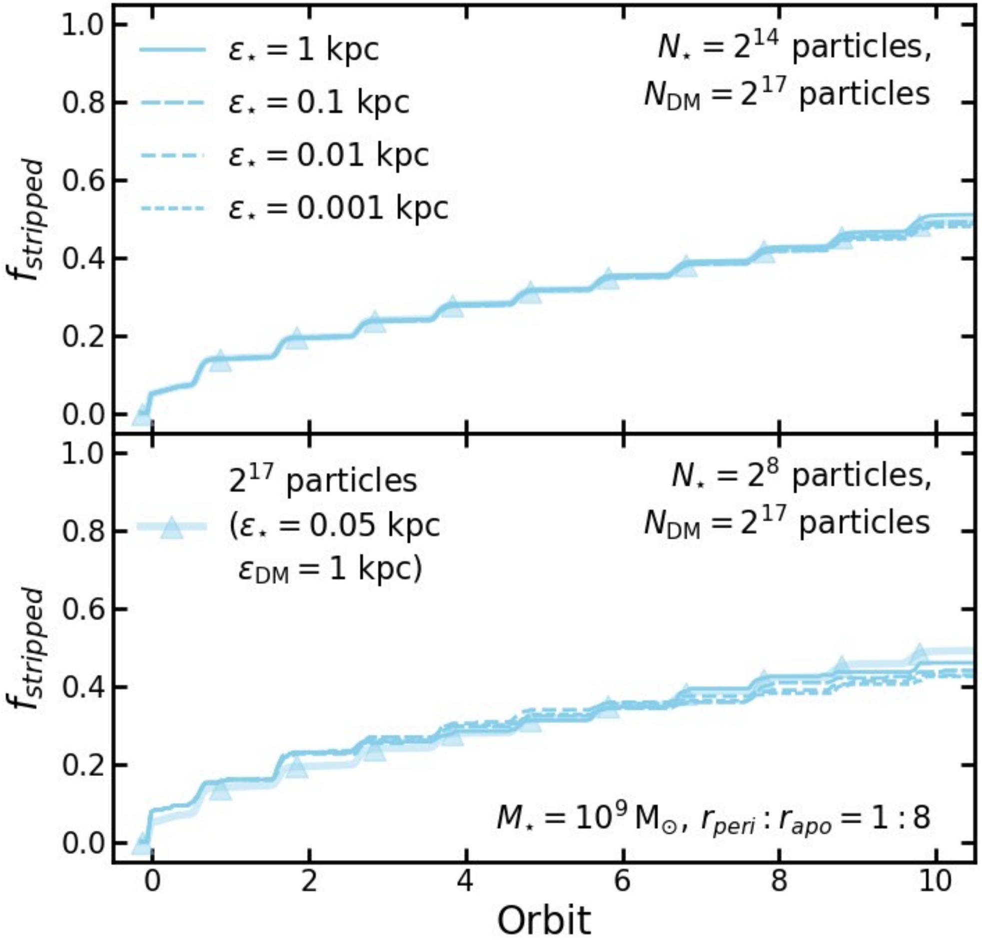
Larger **DM force softening lengths** also increase stripping artificially.



Force resolution

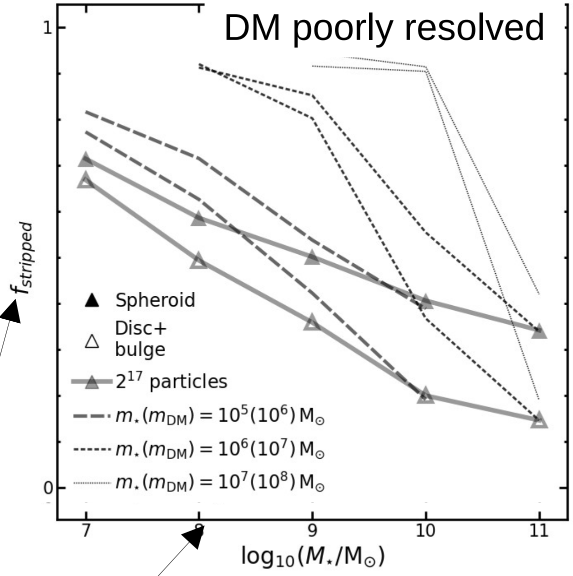
Larger **DM force softening lengths** also increase stripping artificially.

But choice of **stellar softening length** makes little difference



Impact of resolution on ICL production

Accurate stripping rates require **numerical and spatial resolution** for the DM.



Fraction stripped after 5 Gyrs

Satellite stellar mass

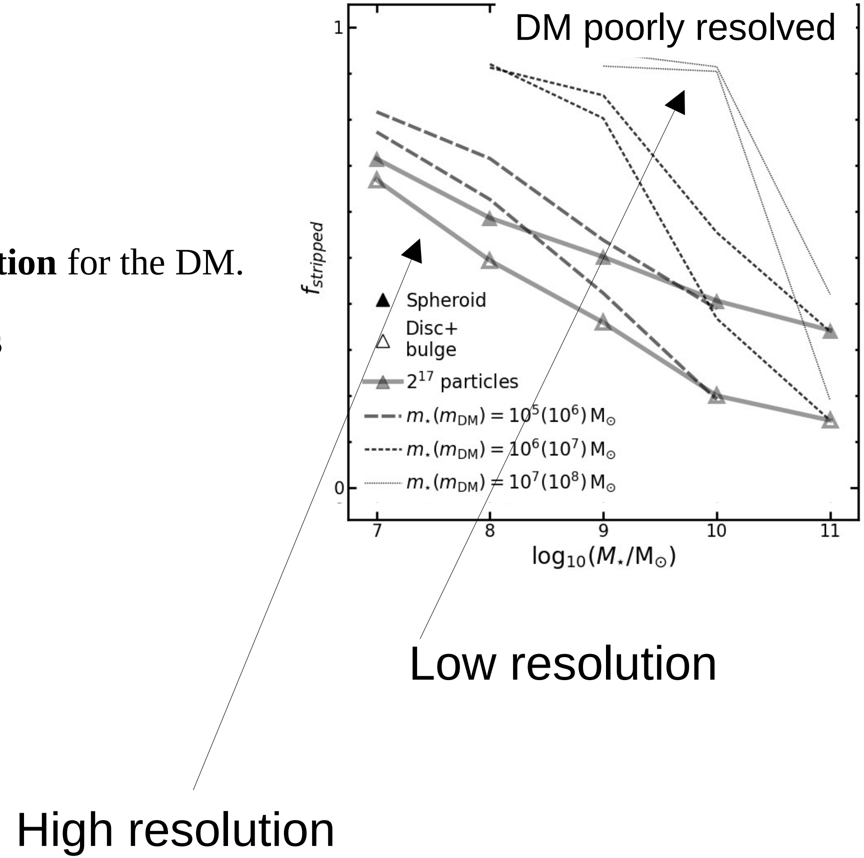
Impact of resolution on ICL production

Accurate stripping rates require **numerical and spatial resolution** for the DM.

High-resolution DM results in **convergence of mass loss rates**

True even when the **stellar component** is poorly resolved.

Lowest mass galaxies are significantly overstripped



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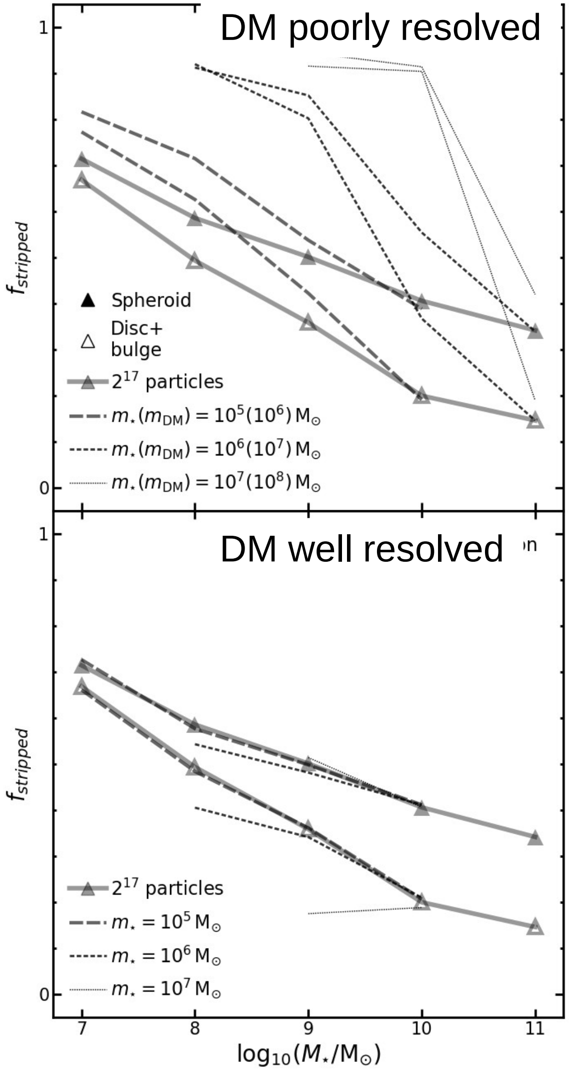
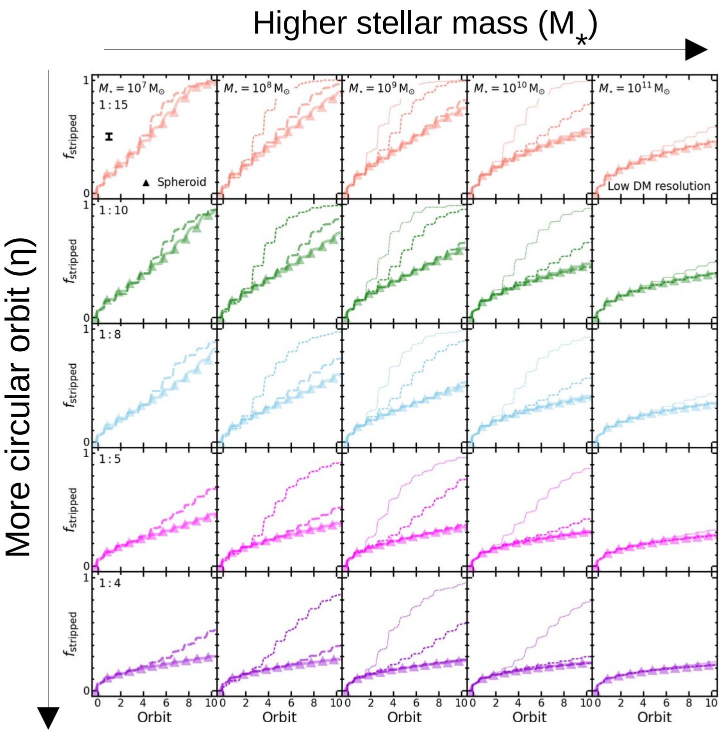
Good convergence regardless of stellar mass resolution when the DM halo is well resolved



Impact of resolution on ICL production

$$M_{ICL} \approx \text{mass stripped}(M_*,\eta) \times P(\eta) \times \text{GSMF}(M^*,\alpha)$$



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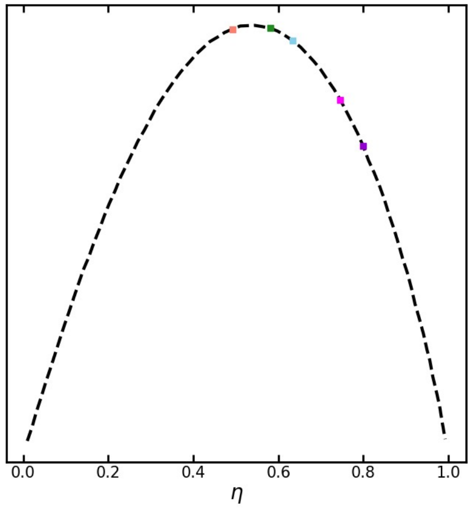

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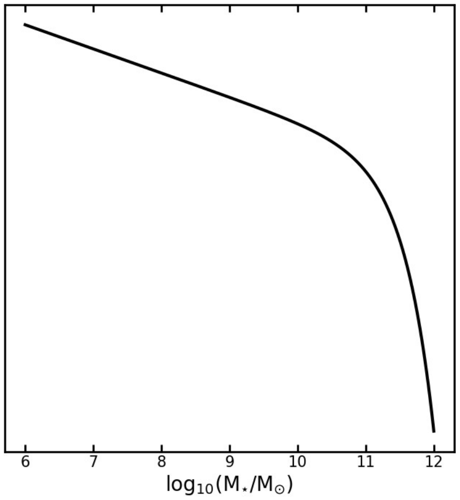


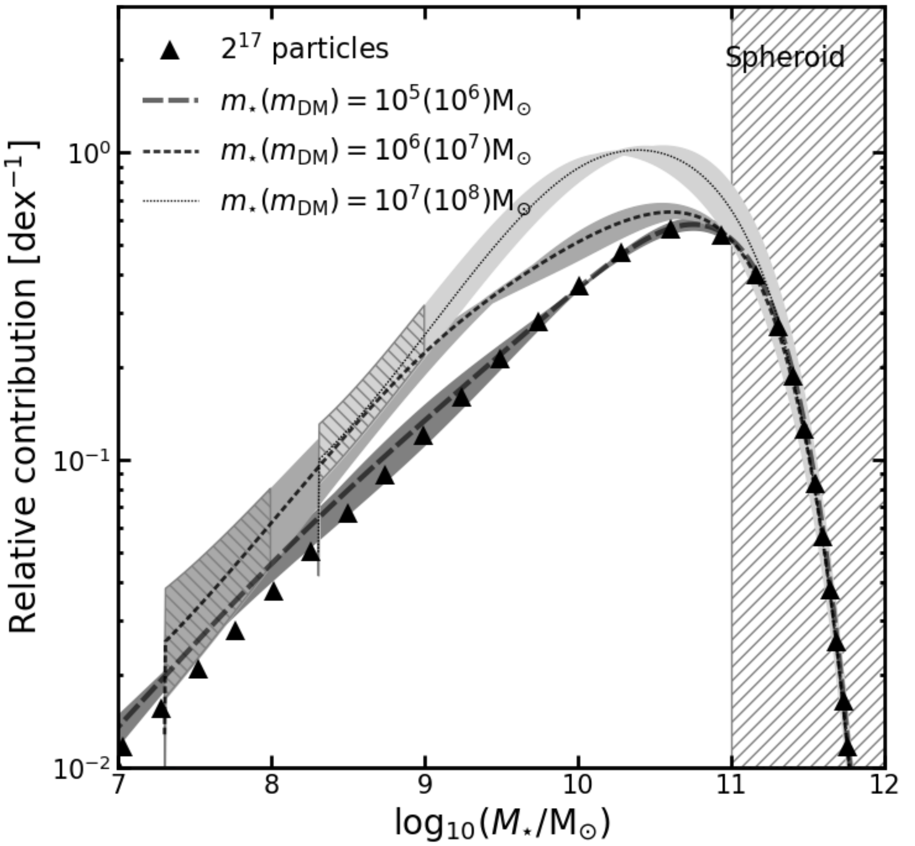
Impact of resolution on ICL production

Low mass galaxies are overstripped, but account for a small fraction of the **total stellar mass budget**

Most of the stripped stellar mass contributing to ICL originates from **satellites with intermediate stellar masses** (10^{10} - 10^{11} solar masses).

Low-resolution shifts contribution toward **lower-mass satellites**.

Biases observational predictions for **which objects** are responsible for originating the ICL.



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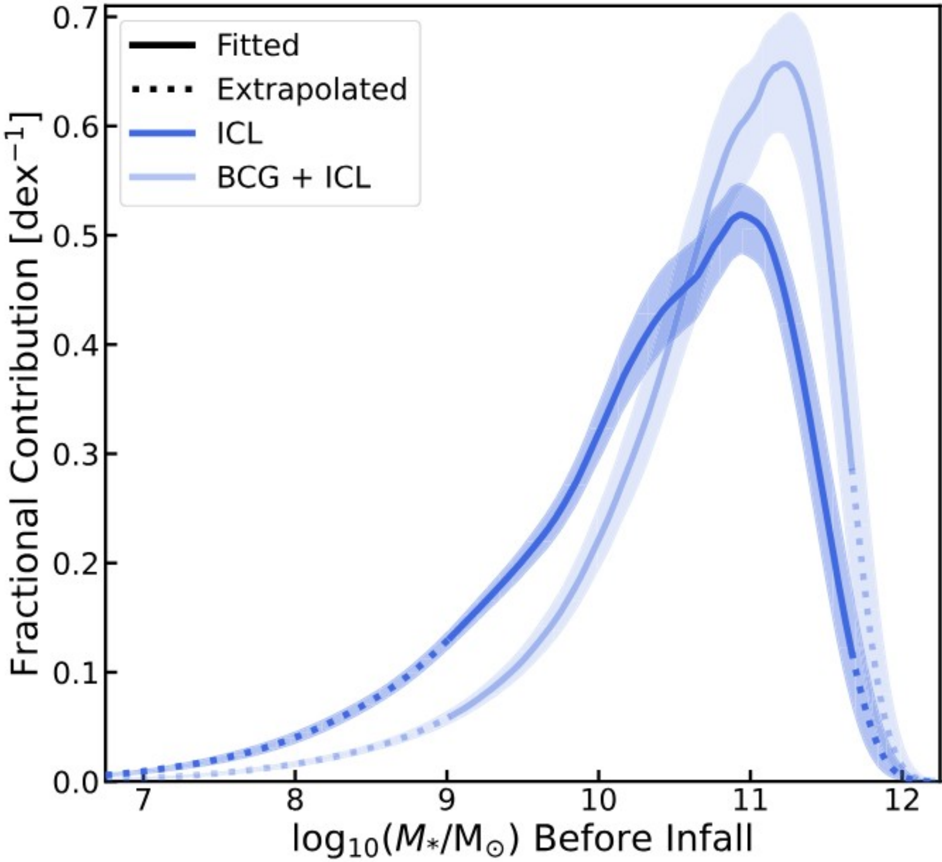
We see a very similar trend in HorizonAGN (**Brown, Martin+, 2024**) – note y-axis is linear!



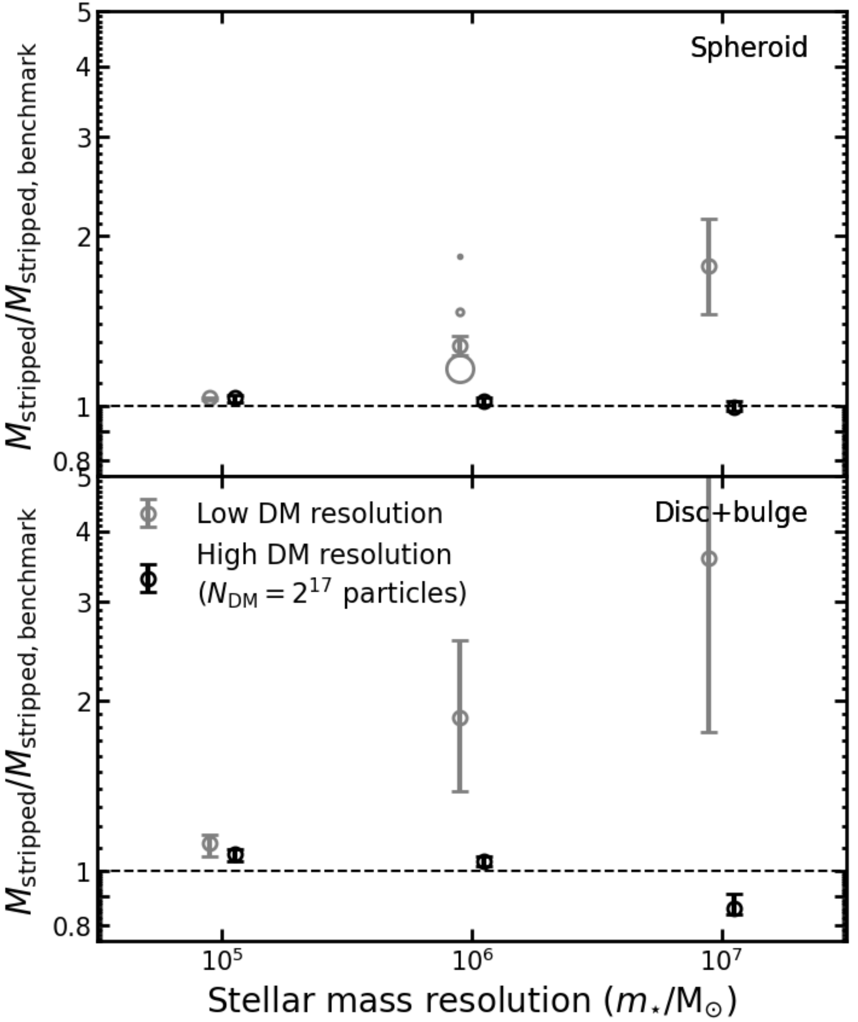
Brown et al (2024)
Horizon-AGN simulation

Impact of resolution on ICL production

Poor resolution overestimates the **bulk quantity** of stellar mass stripped.

Over-stripping less severe in spheroidal galaxies than discs.

Many cosmological simulations likely **overestimate the bulk quantity of stellar mass** stripped from satellite galaxies, especially in **disc-dominated** systems.



Impact of resolution on ICL production

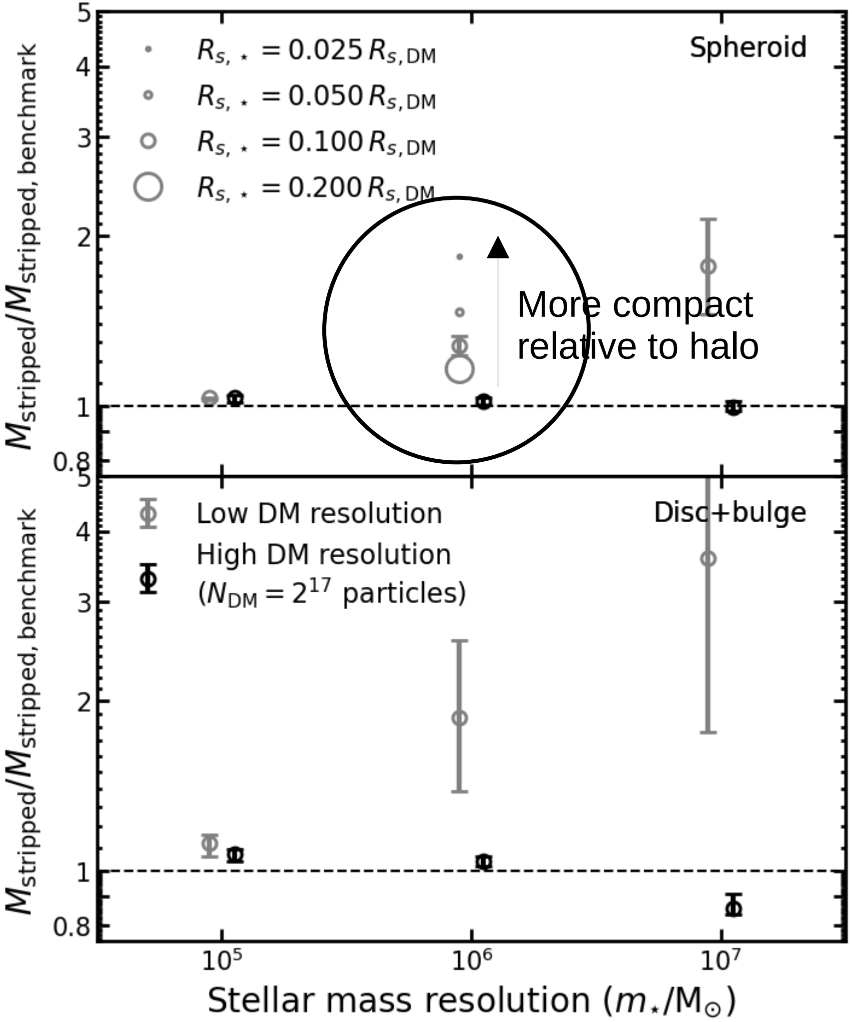
Poor resolution overestimates the **bulk quantity** of stellar mass stripped.

Over-stripping more common in spheroidal galaxies than discs.

Important to avoid inflated ICL predictions.

Many cosmological simulations likely **overestimate the bulk quantity of stellar mass** stripped from satellite galaxies, especially in **disc-dominated** systems.

Stripping rate is also strongly dependent on **satellite morphology and size**



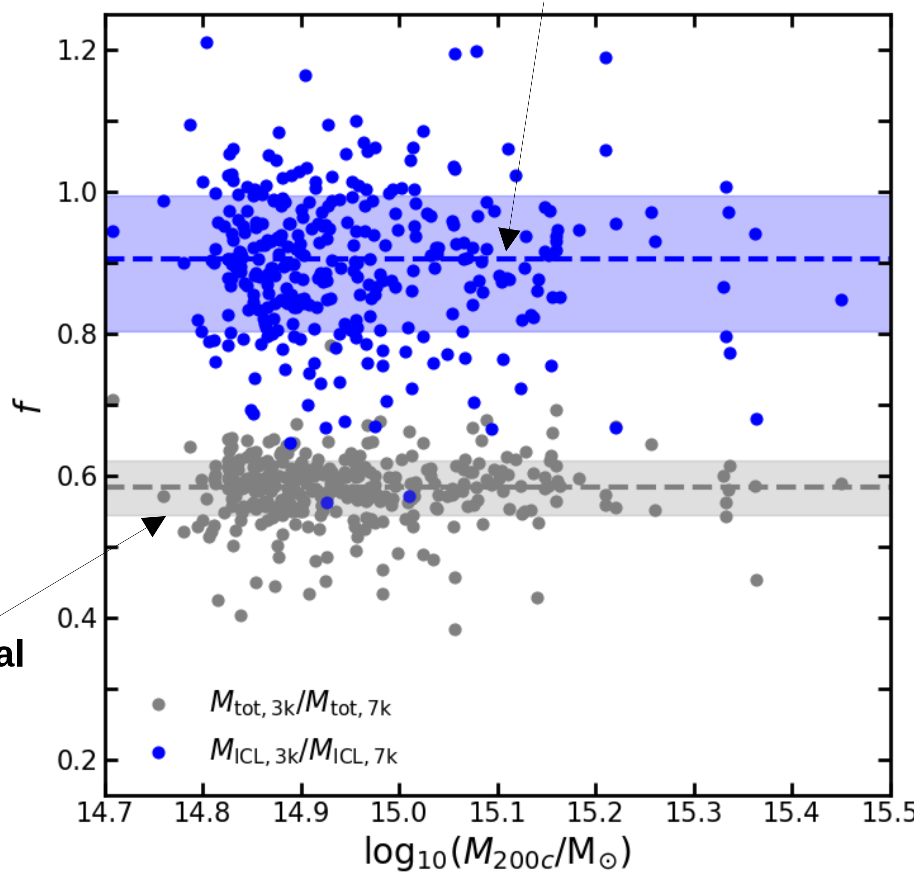
Comparison with real cosmological simulations

Observed in real hydrodynamical cosmological cluster simulations

At two different resolution levels, **TheThreeHundred** clusters show similar amounts of ICL despite significant differences in total stellar mass

ICL is **overproduced at lower resolution** as predicted

Difference in ICL mass



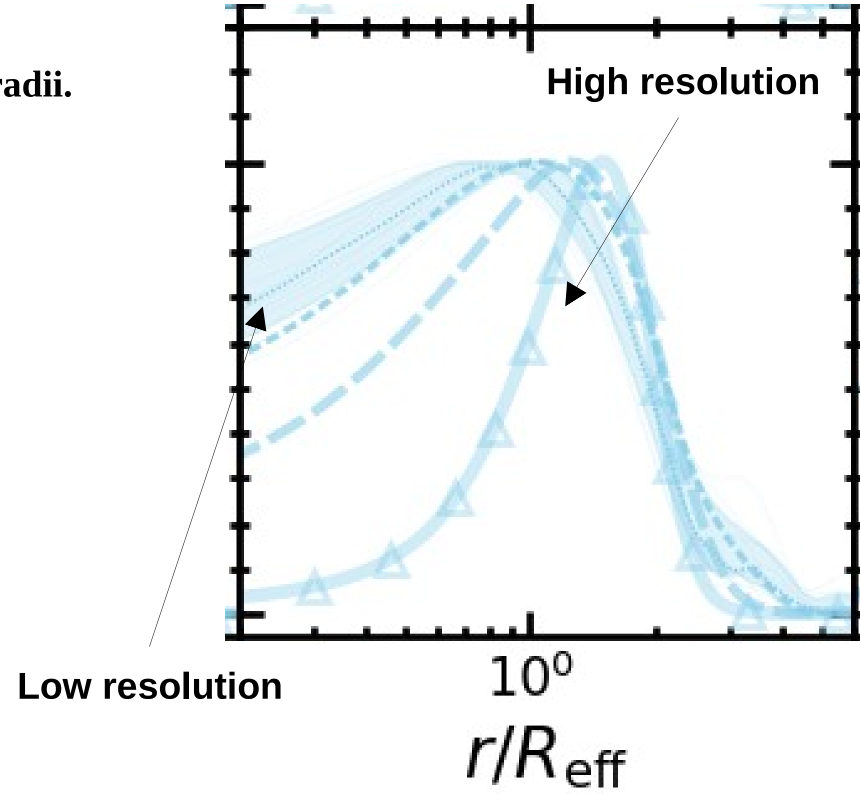
Difference in total stellar mass

Resolved properties of the ICL and stripped remnant

Stripping radius is also sensitive to numerical resolution.

Poor resolution strips stars originating from **artificially small radii.**

Impacts final galaxy morphology and ICL properties.



Resolved properties of the ICL and stripped remnant

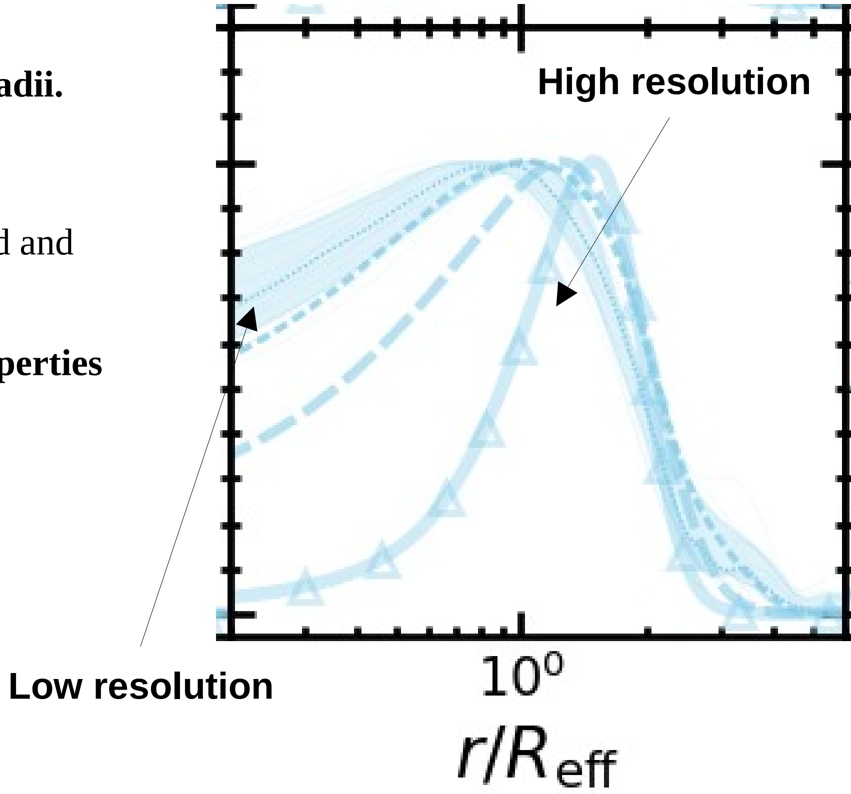
Stripping radius is also sensitive to numerical resolution.

Poor resolution strips stars originating from **artificially small radii.**

Impacts final galaxy morphology and ICL properties.

Inaccuracy occurs even where bulk quantity of ICL is converged and even when the **DM is well resolved**

Stellar mass resolution becomes important for the **resolved properties** of the remnant, but less so for mass loss rate



Part 1: summary

DM resolution is the most important factor impacting stellar stripping accuracy.

Poorly resolved DM haloes lead to **over-stripping.**

High DM resolution needed for **accurate bulk ICL quantities**

Stellar mass resolution matters for the **resolved stellar properties** of the tidally stripped remnant

Inaccurate stellar mass loss rates may impact **tuning of the galaxy evolution model** to reproduce the GSMF, especially in cluster simulations

Standard resolution schemes with **fixed m_*/m_{DM}** are not ideal for resolving stellar stripping due to evolution of the **SM-HM relation** – **Galaxy Replacement Technique** (e.g. **Chun+2022**) may be a good solution

Part 2: dwarf galaxy properties

Field dwarfs: progenitors of cluster satellites.

Their internal structure and feedback processes influence evolution.

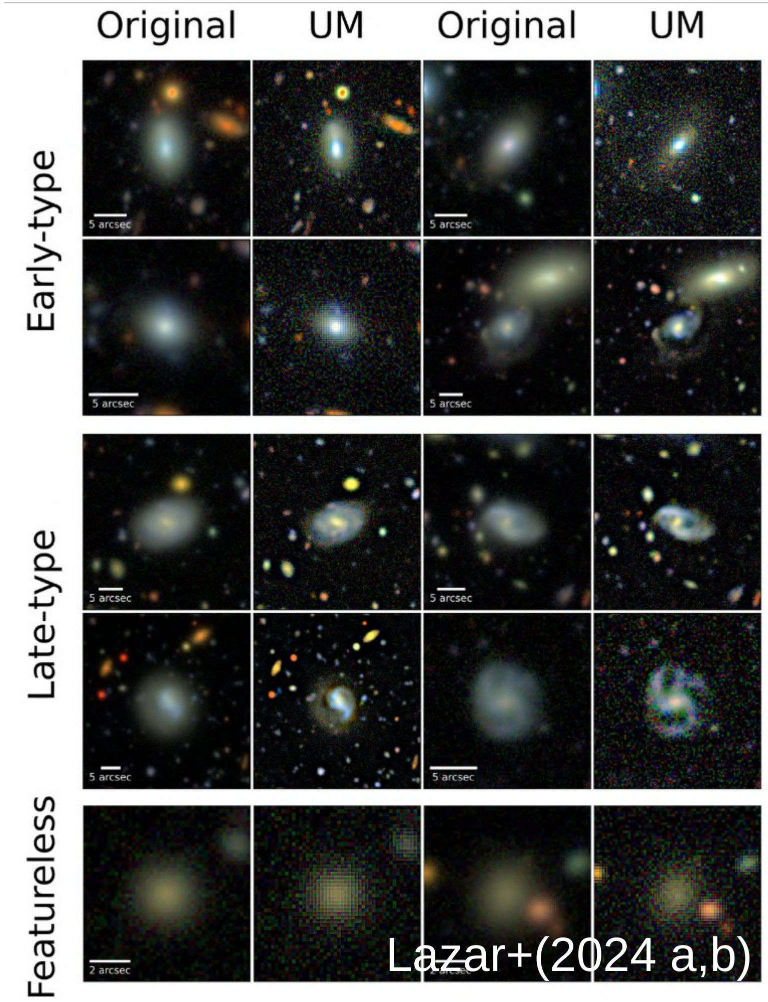
Their **structure** determines how they will respond to **tidal stripping** if/when they eventually fall into clusters or groups

Part 2: dwarf galaxy properties

Dwarfs do not appear to be solely an extension of high-mass populations

Some morphological features present in the high-mass regime extend to dwarf galaxies

But we also observe dwarfs with **morphologies** and **structural properties** only found in the low-mass regime



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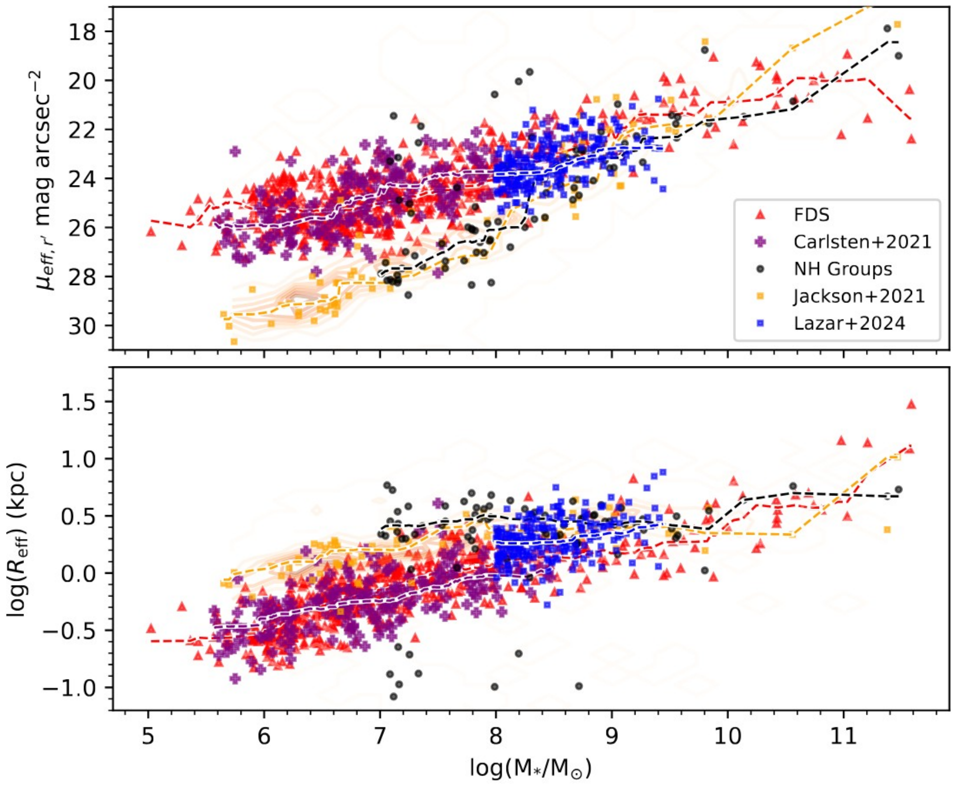
Cosmological simulations are tuned to reproduce **high mass galaxy populations**, but not the low mass Universe, which is **observationally incomplete**



Watkins (in prep.)

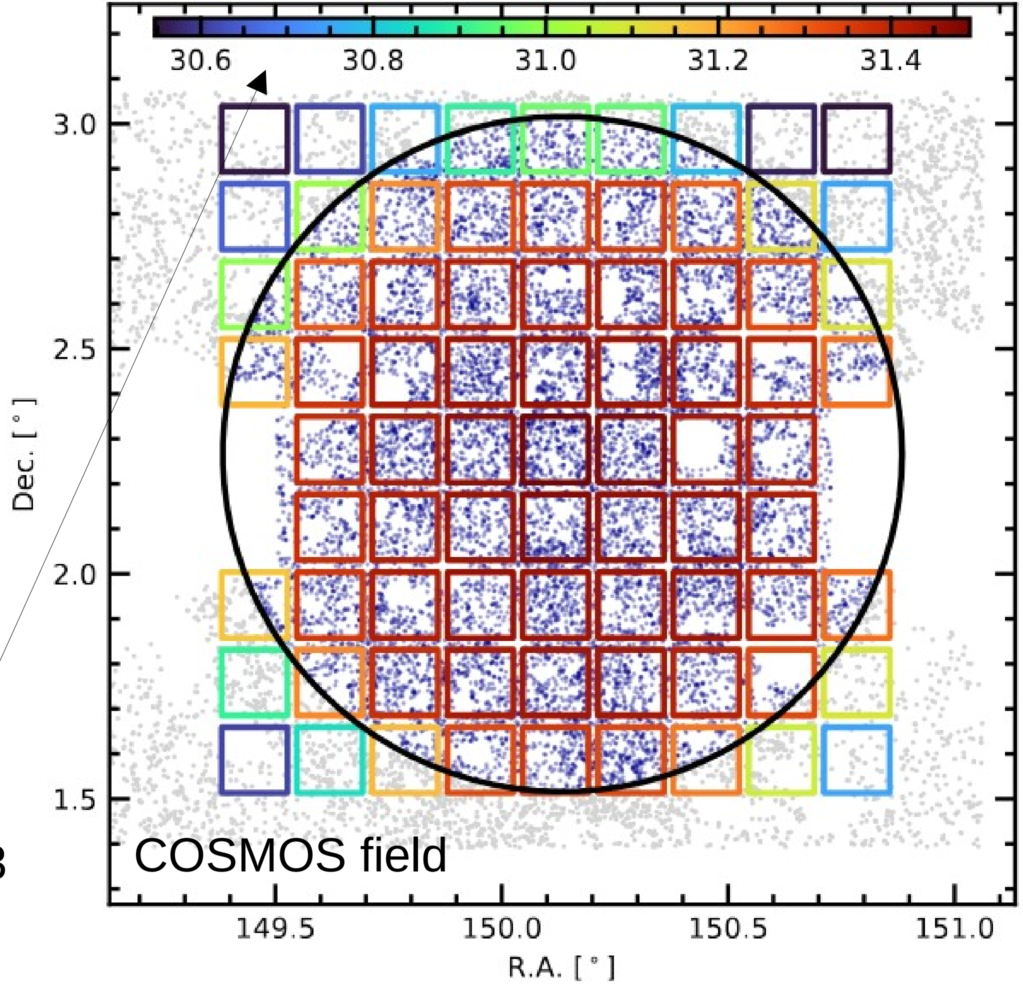
Observational sample

- Recent **deep surveys** like HSC-SSP and high-resolution cosmological simulations (e.g., **TNG-50** and **NewHorizon**) allow a detailed comparison of dwarf galaxy properties.

- Limit our study to COSMOS field centre imaged to a depth of **31.5 mag/sq. arcsec** by HSC

- A **complete sample of dwarfs** out to z<0.3 and $M_{*}>10^{7.5}$ Msun

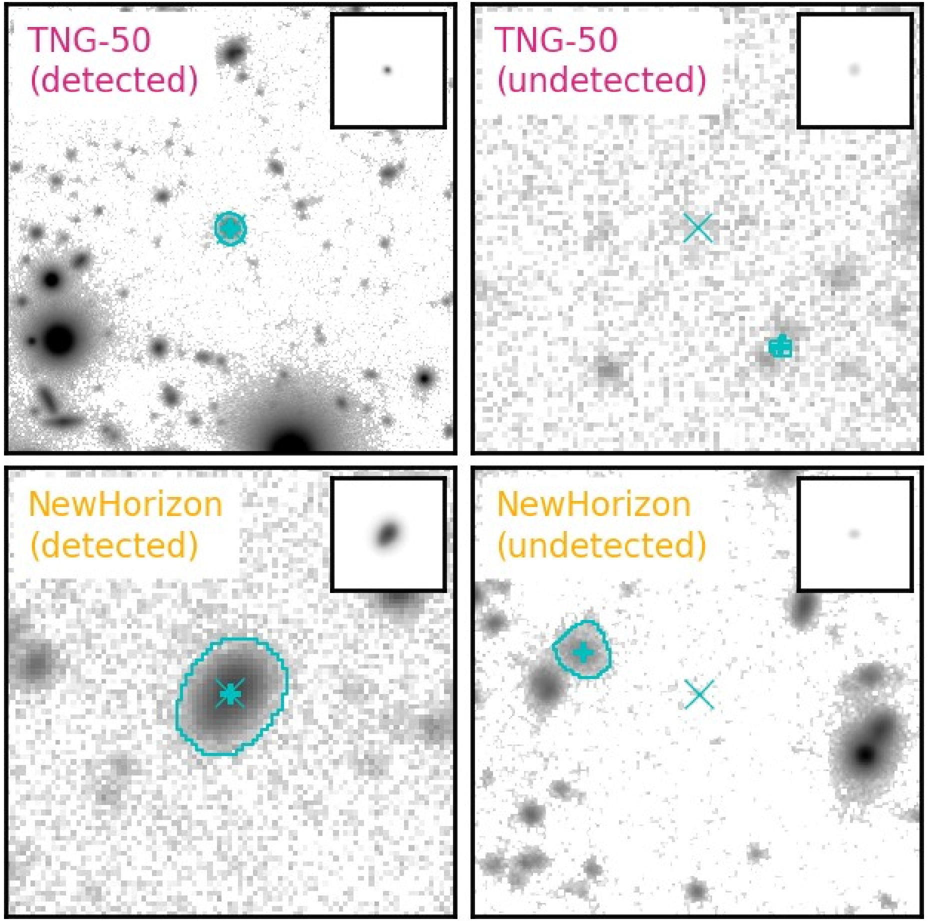
- Key parameters: Sersic parameters, Gini, M20, asymmetry, and concentration.



i-band SB limit (3 sigma 10”x10”)

Simulated sample

- Synthetic images of dwarf galaxies from **NewHorizon** and **TNG-50** simulations injected into HSC-SSP backgrounds
- Identical detection, segmentation and measurement of structural properties performed on observed and simulated dwarfs

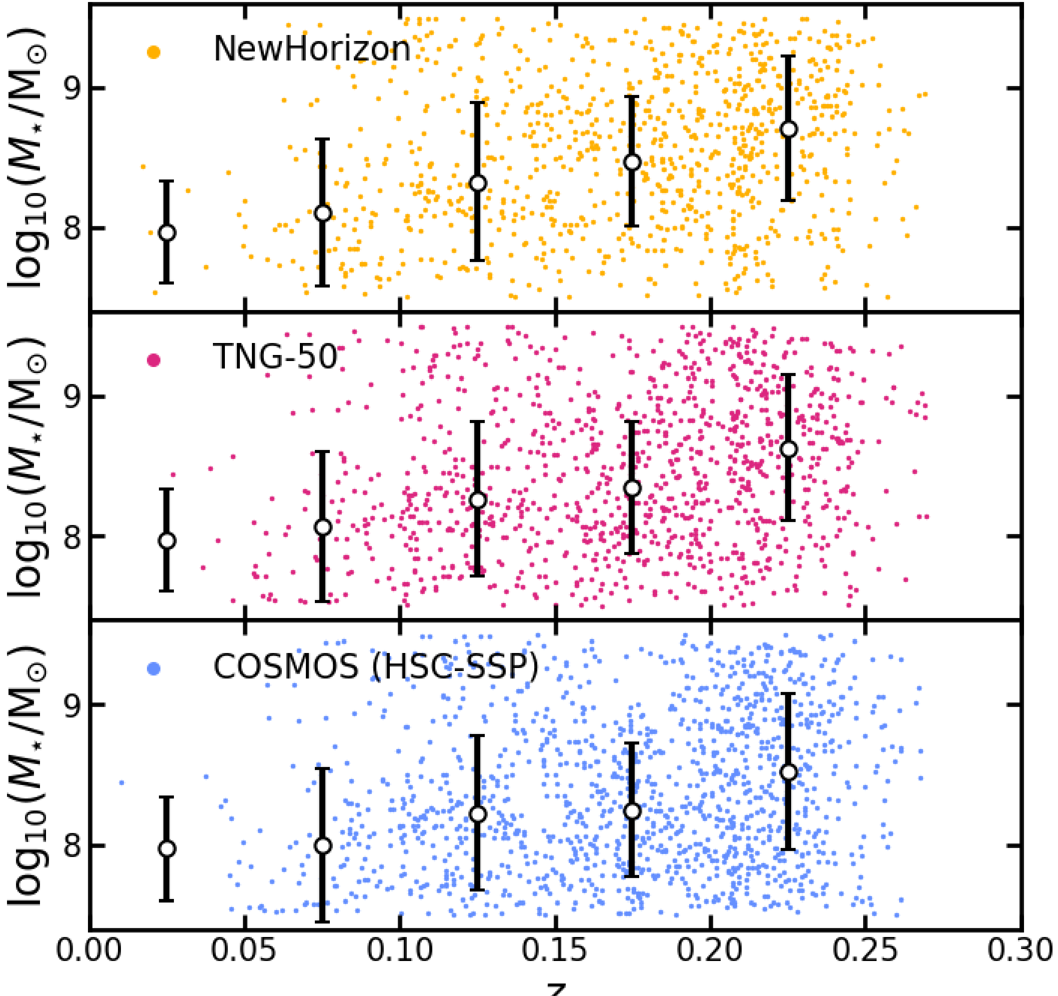


Matched sample

Synthetic images of dwarf galaxies from **NewHorizon** and **TNG-50** simulations injected into HSC-SSP backgrounds

Identical detection, segmentation and measurement of structural properties performed on observed and simulated dwarfs

Select **mass and redshift matched samples** corresponding to the distribution from COSMOS

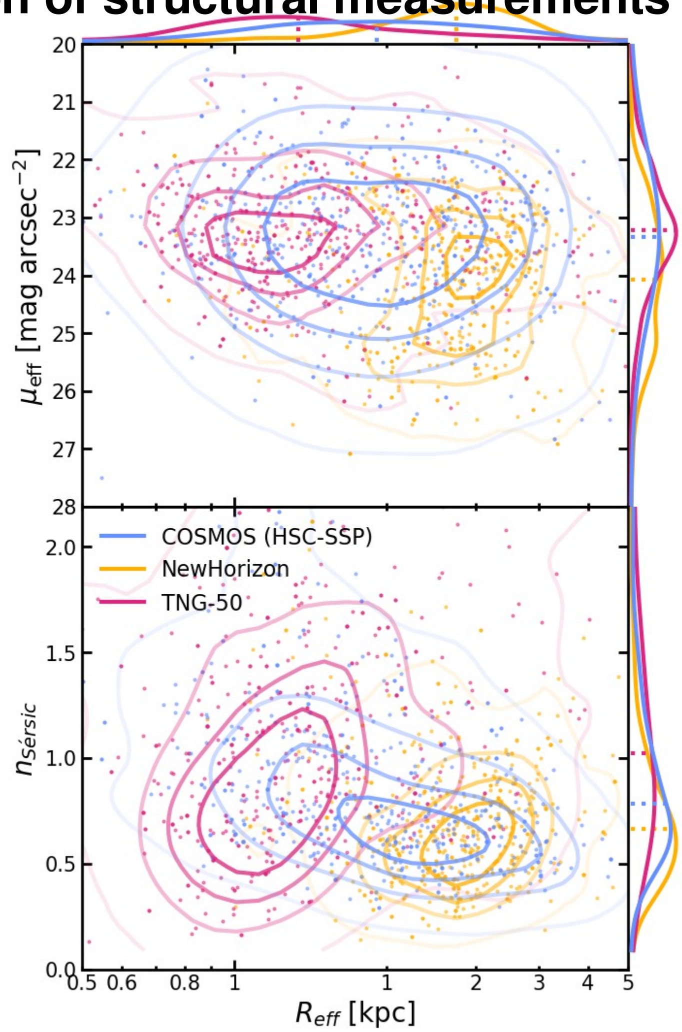


Comparison of structural measurements

Field dwarfs show distinct structural differences in simulations.

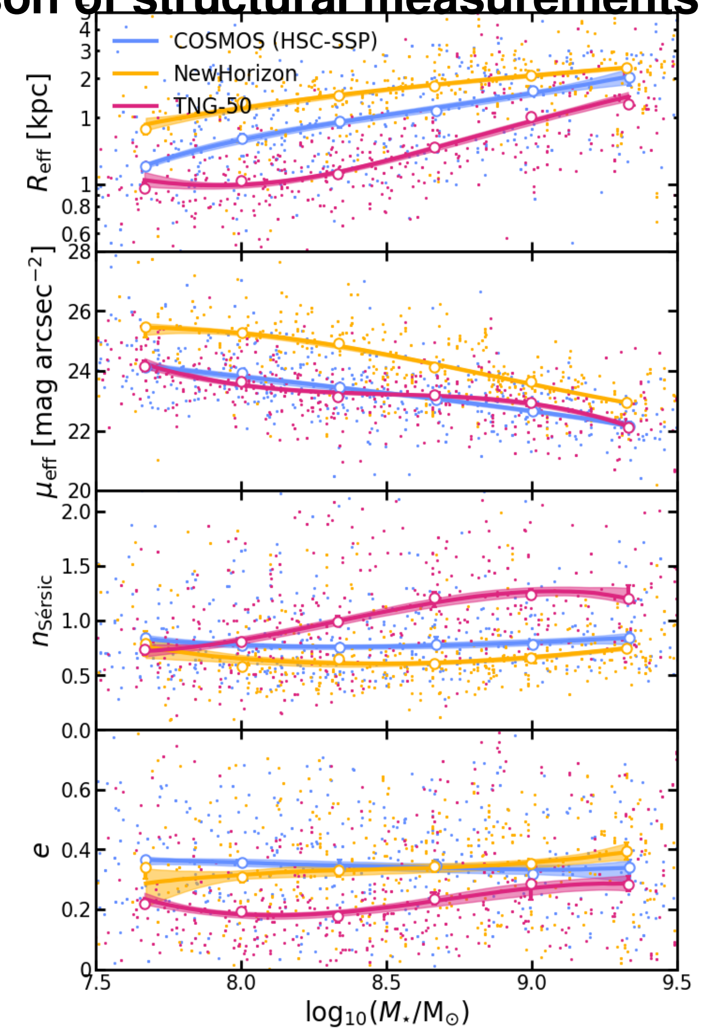
The **Sérsic fits** of simulated dwarf galaxies in TNG-50 and NewHorizon place them at extremes compared to observed galaxies.

TNG-50 galaxies appear more **compact**, while NewHorizon galaxies are more **diffuse**.

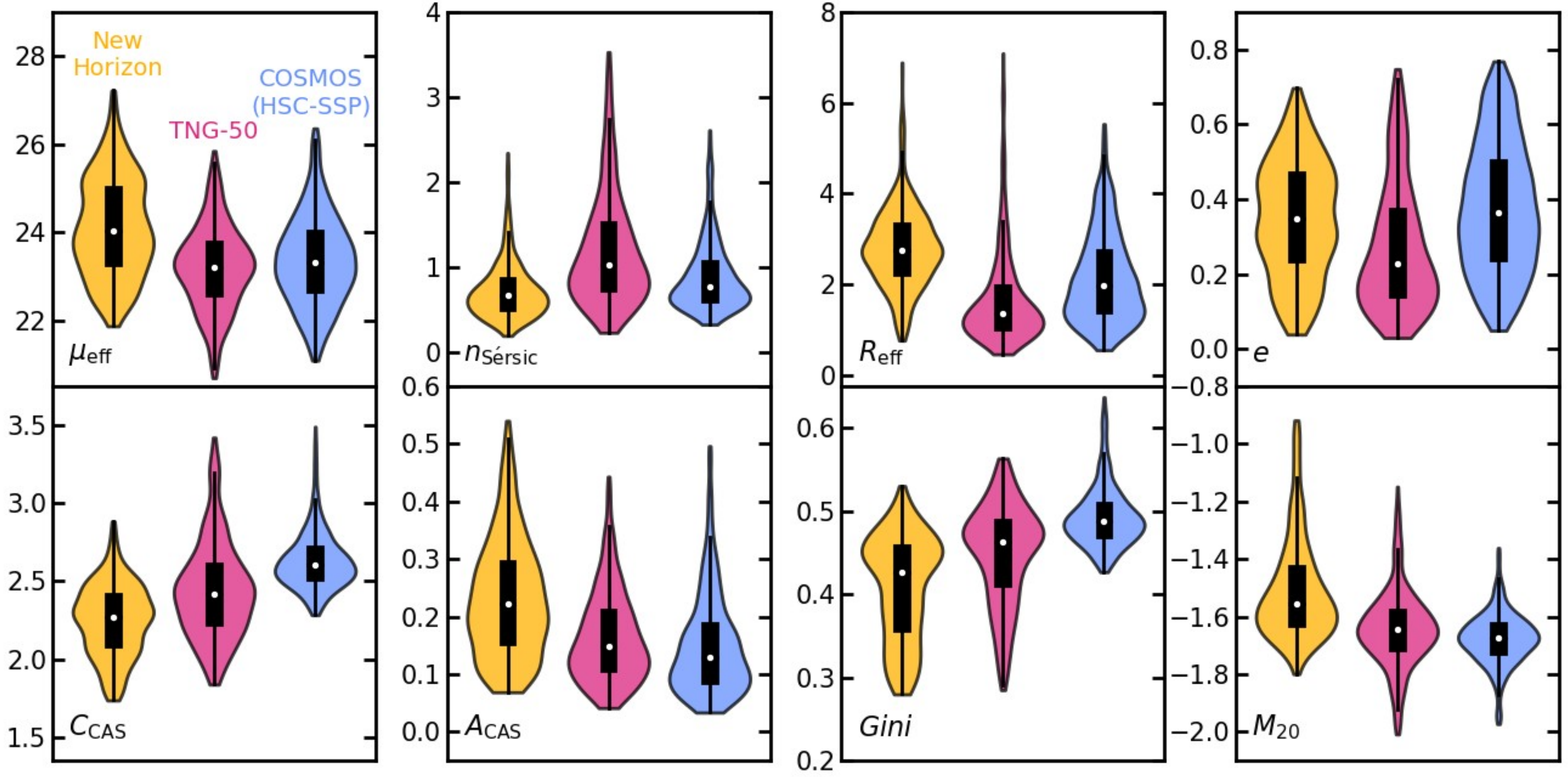


Comparison of structural measurements

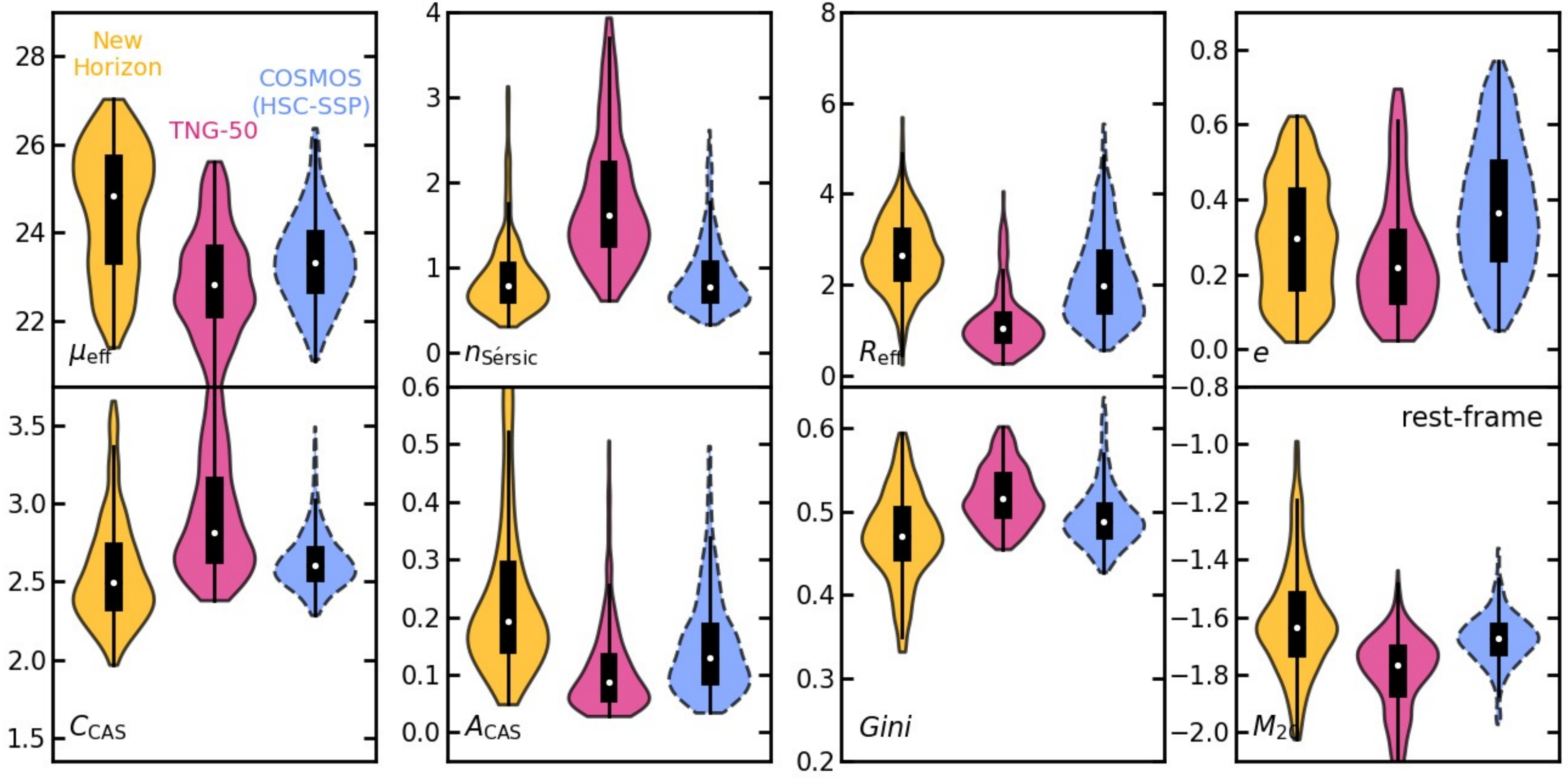
Mass-size relation has been shown to hold well at higher masses in both simulations, but **discrepancies emerge in the low-mass regime**.



Observed frame structural properties



Rest frame structural properties

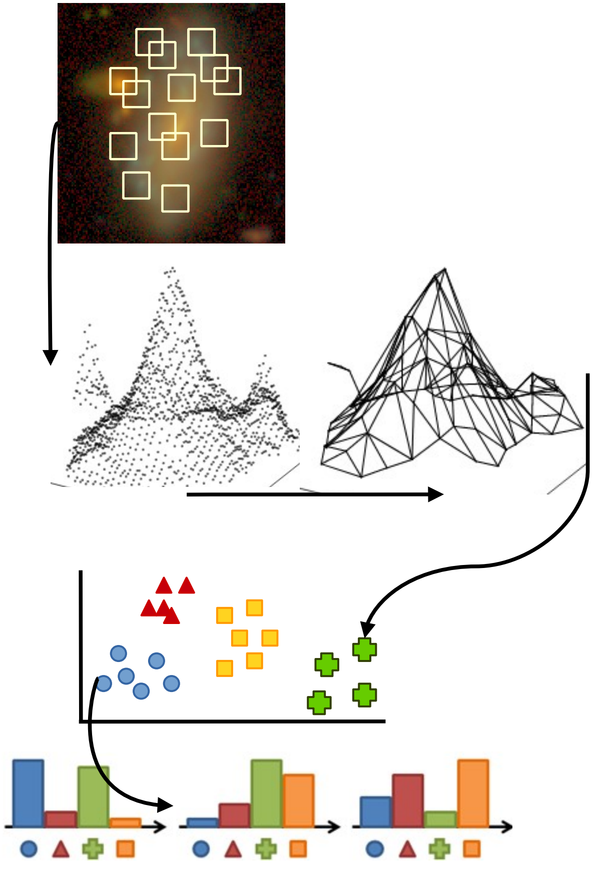


Visual similarity

We applied an **unsupervised clustering technique** to define how similar galaxies appear relative to each other based on their **visual appearance**

Correlation between the **visual appearance of simulated galaxies** and their **star-formation histories** is seen, even controlling for mass and environment.

Understanding this link is key to understanding the differing dwarf galaxy evolution between the two simulation



Martin+2019

Visual similarity

Differences in **visual appearance** of dwarfs in TNG-50 vs NewHorizon vs COSMOS field

What are their nearest neighbours

Simulated galaxies tend to have nearest neighbours that are **also simulated**

Observed galaxies tend to have nearest neighbours that are **also observed**

But at least some simulated galaxies have appearances **consistent** with observed ones

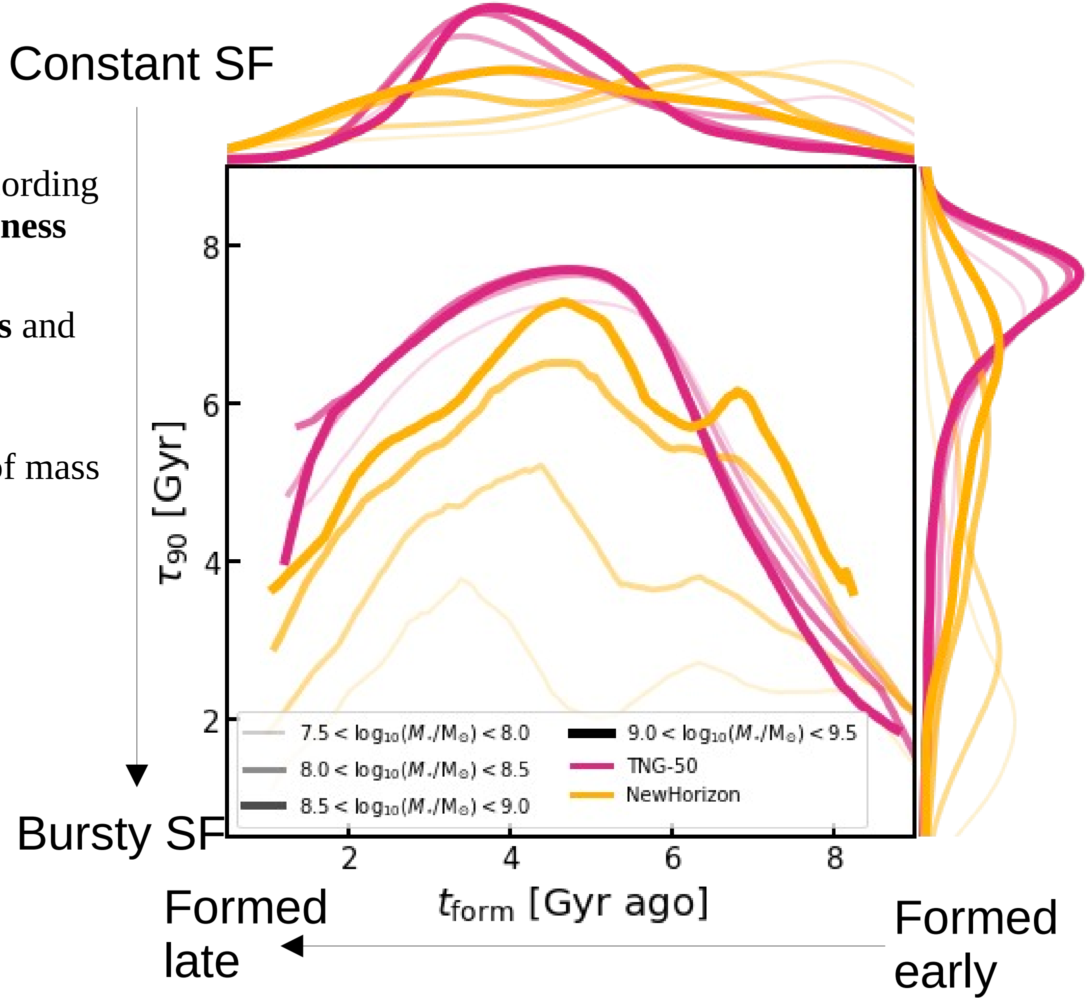
	Random forest				**Pearson correlation**			
Multiband		**COSMOS**	**NH**	**TNG-50**		**COSMOS**	**NH**	**TNG-50**
	COSMOS	0.774	0.198	0.175	**COSMOS**	0.822	0.210	0.121
	NH	0.127	0.864	0.118	**NH**	0.173	0.803	0.146
	TNG-50	0.169	0.217	0.781	**TNG-50**	0.168	0.175	0.786
Monochromatic		**COSMOS**	**NH**	**TNG-50**		**COSMOS**	**NH**	**TNG-50**
	COSMOS	0.663	0.245	0.331	**COSMOS**	0.738	0.213	0.284
	NH	0.278	0.748	0.198	**NH**	0.262	0.751	0.217
	TNG-50	0.398	0.268	0.634	**TNG-50**	0.392	0.258	0.621

Star formation history

Parameterize galaxy star formation history according to their **formation time** and level of **burstiness**

NewHorizon galaxies have **more bursty SFHs** and **formed earlier**

No evolution in SFH observed as a function of mass for TNG-50 dwarf galaxies



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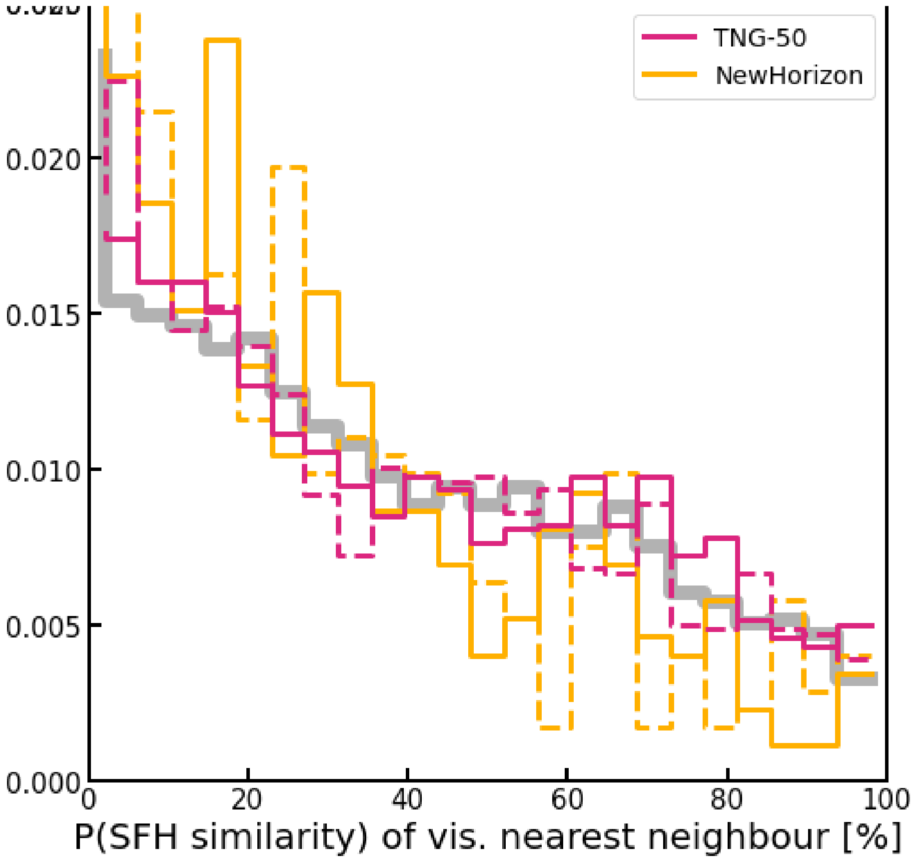
We can measure the level of **correlation between SFH and visual similarity**



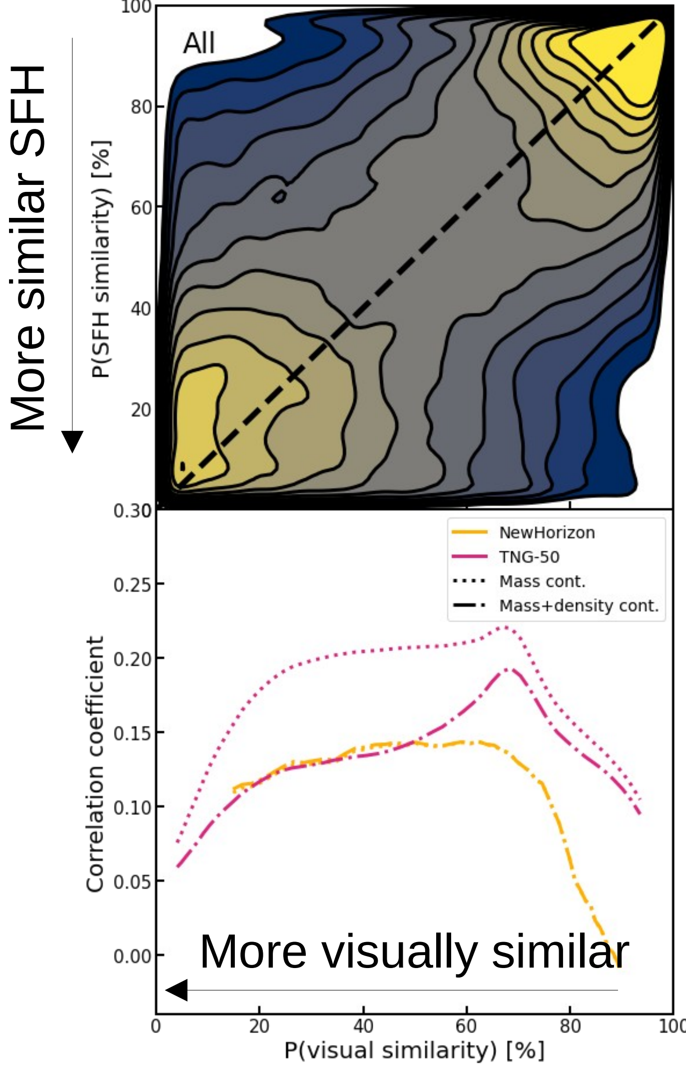
Star formation history vs visual similarity

Correlation between the **visual appearance of simulated galaxies** and their **star-formation histories** is seen, even controlling for mass and environment.

Understanding this link is key to understanding the **differing dwarf galaxy properties** between the two simulations

Observe general correlation between more **visually similar** galaxies are more likely have **similar star-formation histories**

When **controlling for environment** only TNG-50 shows a decrease in strength of correlation



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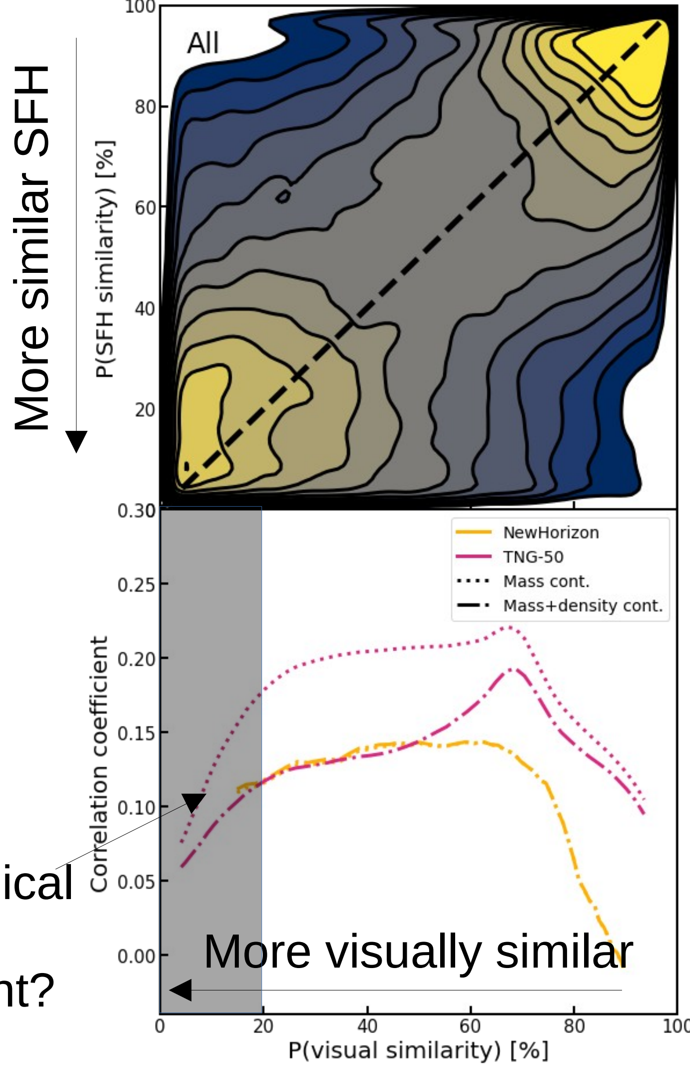
Due to morphological transformation by dense environment?



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Correlation of morphology and SFH with local density disappears when restricted to **less dense environments –** dominated by internal processes in the field

Partial correlations

NewHorizon	Morph.	SFH	$M_\star$	ρ
Morph.	-			
SFH	0.240	-		
$M_\star$	0.208	0.242	-	
ρ	0.027	-0.016	-0.0280	-

TNG-50	Morph.	SFH	$M_\star$	ρ
Morph.	-			
SFH	0.308	-		
$M_\star$	0.167	0.015	-	
ρ	0.238	0.475	-0.006	-

TNG (low density)	Morph.	SFH	$M_\star$	ρ
Morph.	-			
SFH	0.142	-		
$M_\star$	0.232	0.022	-	
ρ	-0.006	0.022	-0.022	-

Part 2: summary

The properties of **field dwarfs** set the stage for understanding stripping in cluster environments.

State-of-the-art simulations still get **dwarf galaxy properties** wrong – they were **not tuned** to reproduce these populations due to incomplete observational data

Implications for inaccurate galaxy modelling of **structural evolution** (compactness, morphology) impacts stellar mass loss rate (**Chang+2013**, **Martin+2019...**).

Differences in galaxy formation models, gas physics etc give rise to **very different star formation histories** between TNG-50 and NewHorizon

Discrepancy between SFH in the simulations is likely responsible for very different structural properties in the low-mass populations

New **deep-wide observations** may help us to refine galaxy evolution physics in the future with l**arge representative samples** of dwarf galaxies