http://arxiv.org/abs/2505.04509

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The structural diversity of simulated and observed low-mass galaxies

<u>NAM 2025</u>

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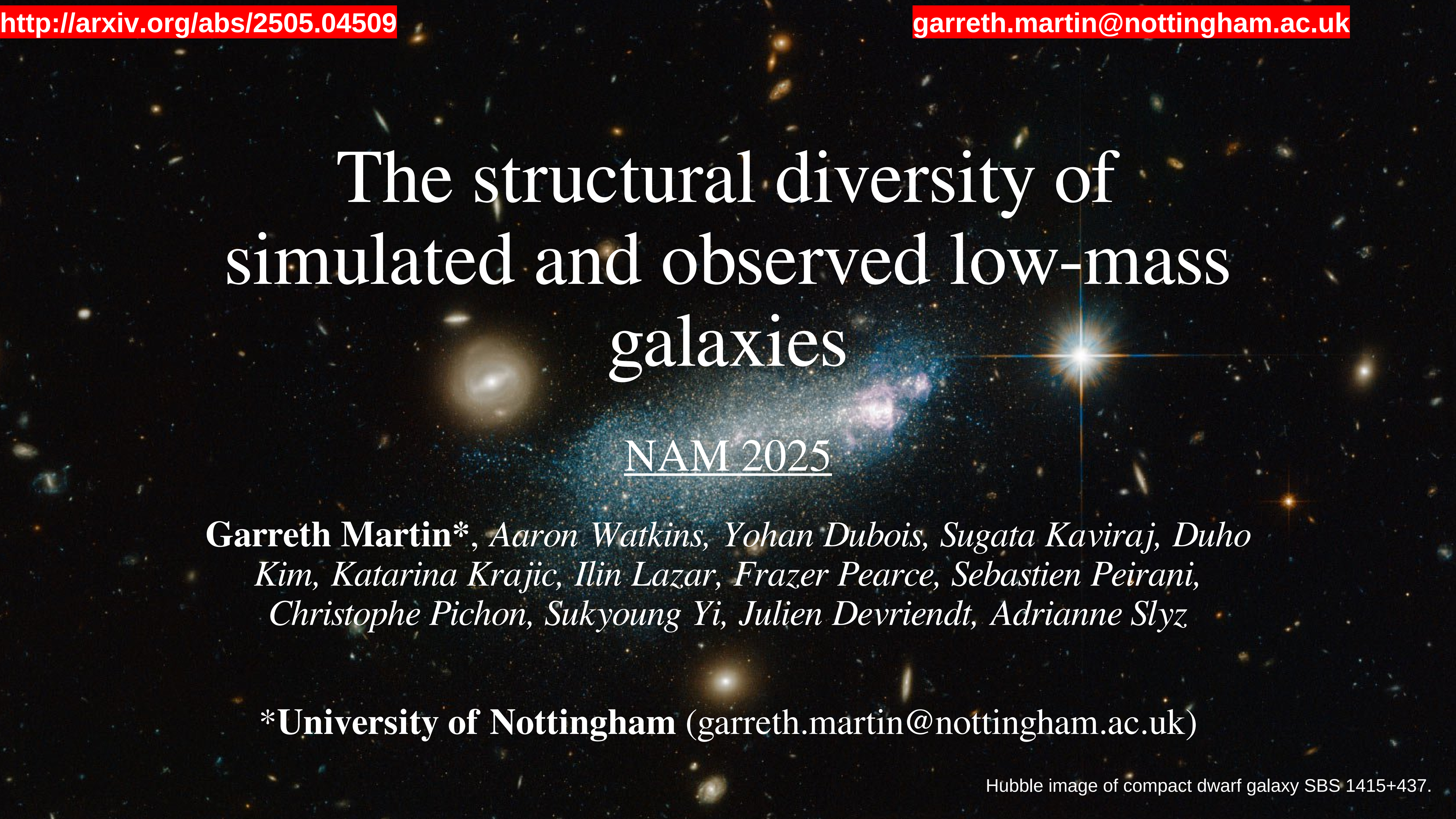

Hubble image of compact dwarf galaxy SBS 1415+437.

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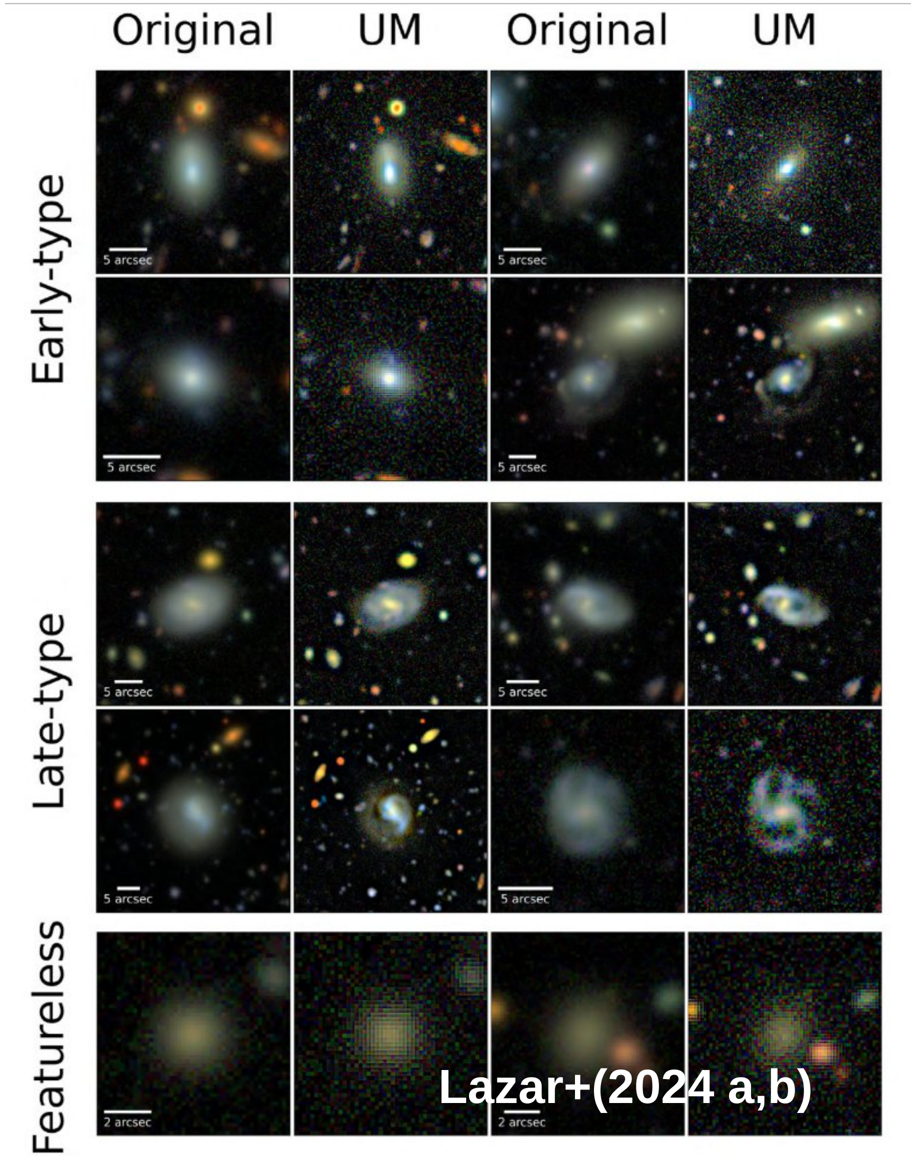
Low-mass galaxies as Laboratories for Galaxy Evolution

- 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 (**Lazar+2024a, 2024b**)
- Cosmological simulations are tuned to reproduce **high mass galaxy populations**, but not the low mass Universe, which is **observationally incomplete**



Lazar+(2024 a,b)

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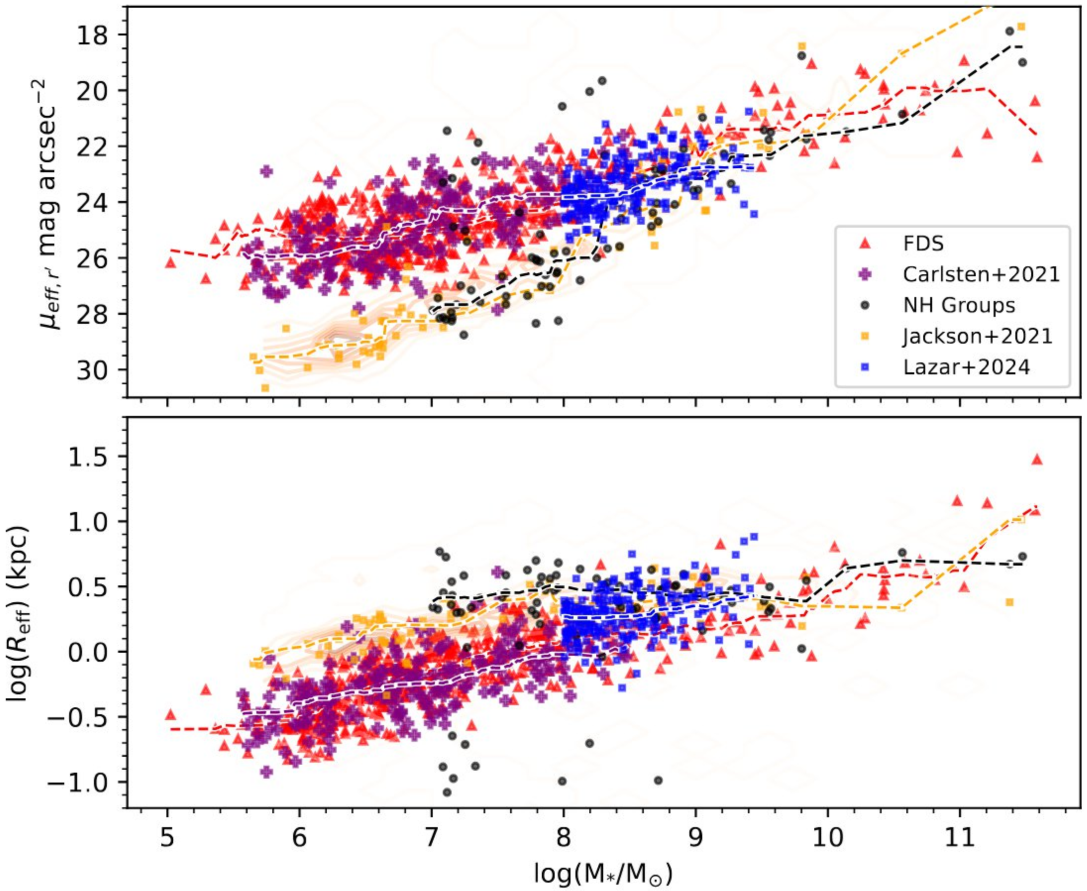

Watkins+2025

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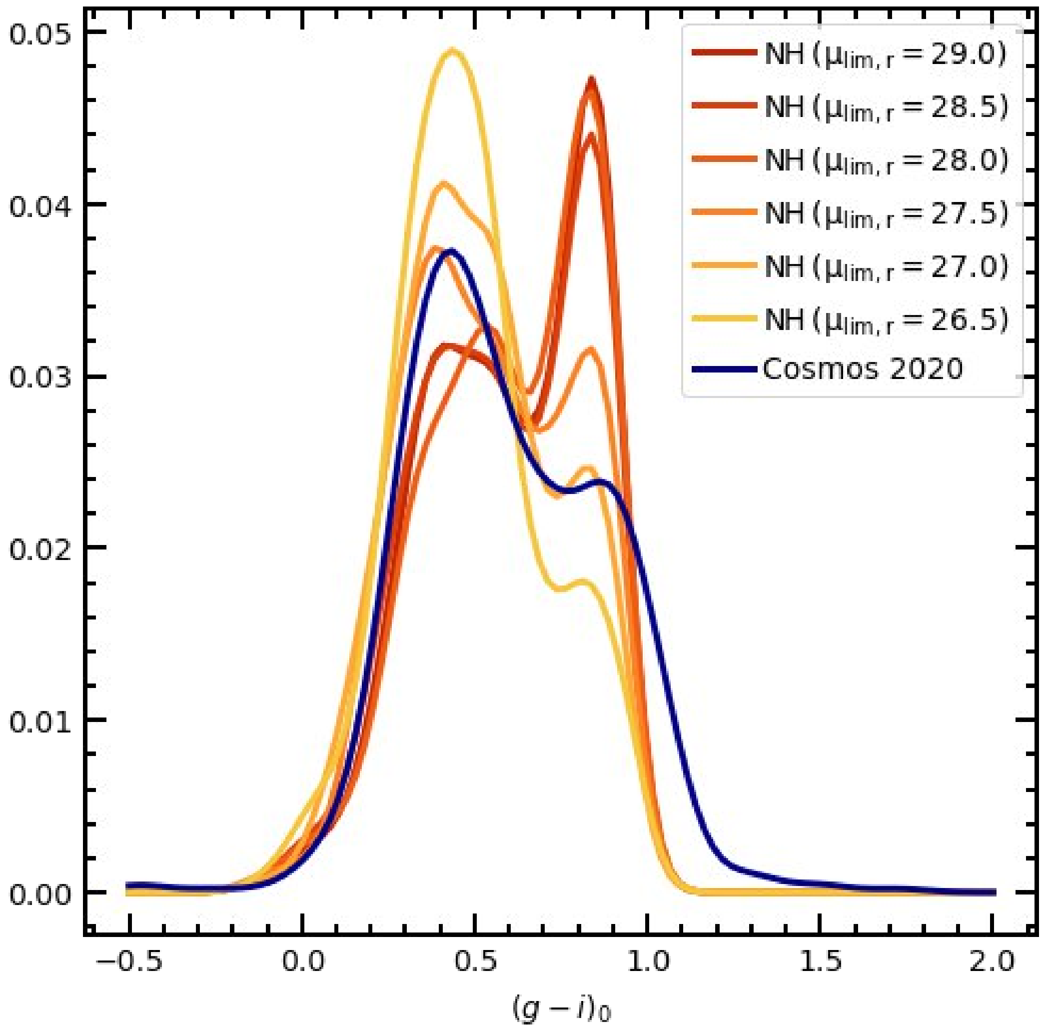
Low-mass galaxies as Laboratories for Galaxy Evolution

- Deep-wide imaging reveals that previous wide-area surveys (e.g. SDSS) missed many low-mass galaxies due to surface brightness limits.
  - e.g. “Ultra-diffuse galaxies” (**van Dokkum+2015**) highlight significant selection biases in past observations.
  - Biased towards the most star-forming objects (**Kaviraj+2025**)

- Dwarf galaxies are very sensitive to feedback and environmental processes due to shallow potential wells
  - Stellar feedback
  - Indication that AGN play some role (e.g. **Reines+2013**, **Kaviraj+2019**, **Bichang'a+2024**)
  - Interactions with environment



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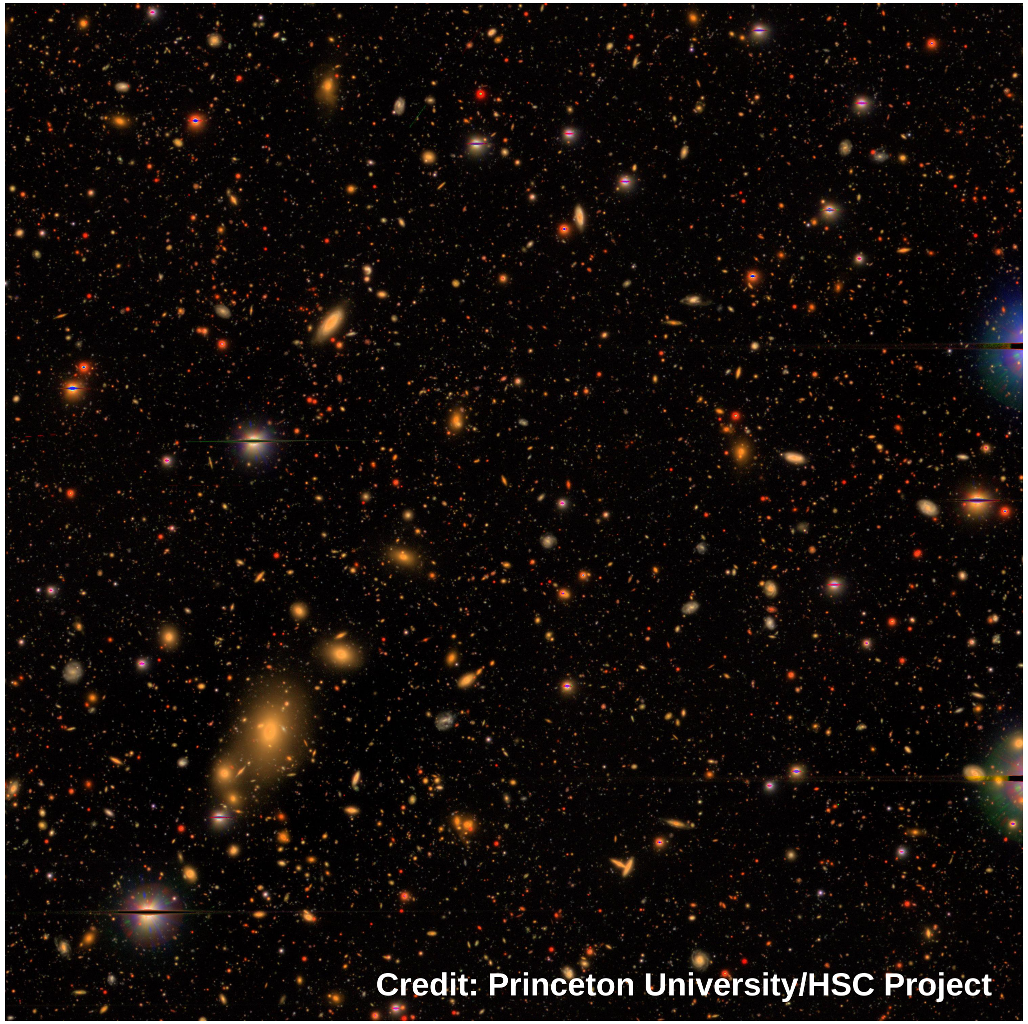
A New Era of Observations and Simulations

- Next-generation surveys (Rubin, Euclid, JWST) are revolutionizing our view of low-mass galaxies with unprecedented depth.
- The COSMOS field (HSC-SSP) provides one of the deepest current datasets for studying faint dwarfs (μ_i (3σ, 10″×10″) > 31 mag arcsec^{-2}).
- Cosmological simulations (e.g. NewHorizon, TNG50, FIREbox) now resolve low-mass galaxies over relatively large volumes.
- Forward modelling allows direct comparison between real and simulated galaxies.


Credit: Princeton University/HSC Project

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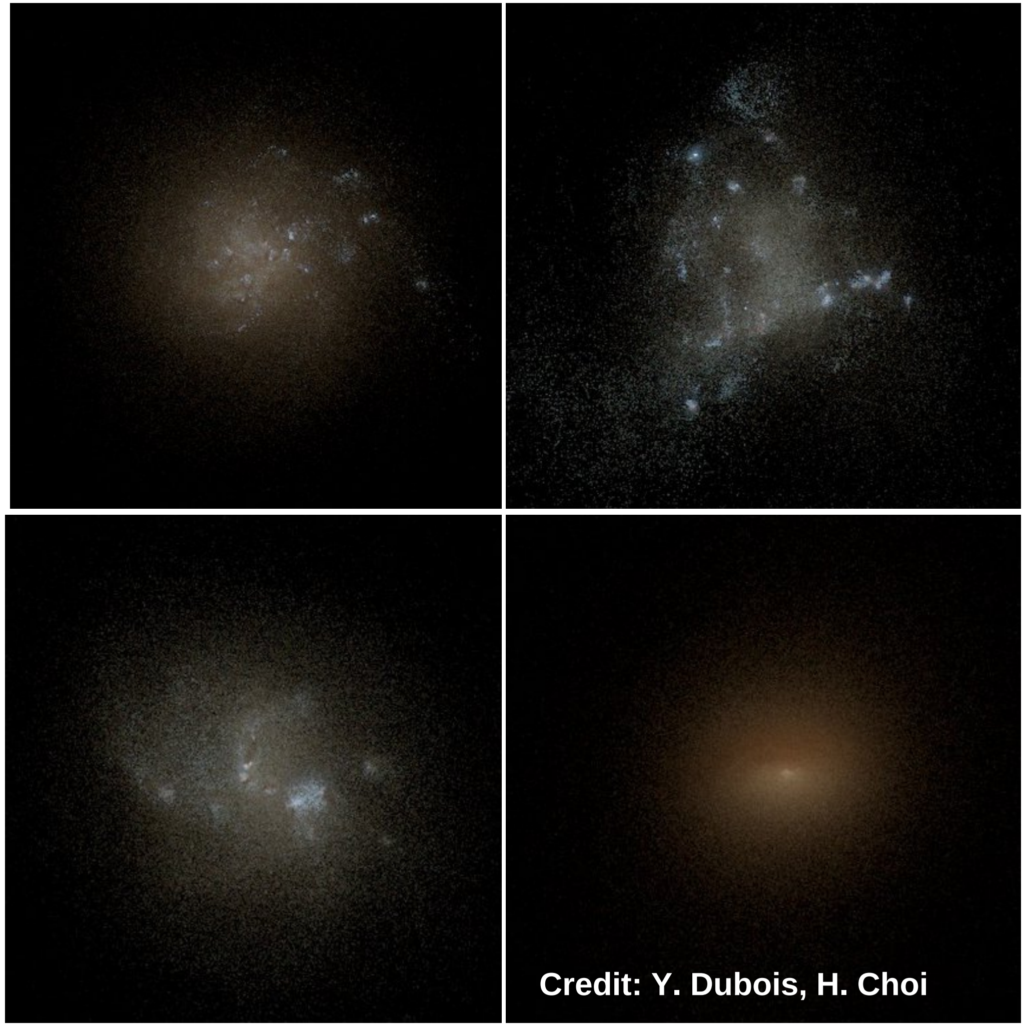

Simulations

	NewHorizon (Dubois+2021)	**TNG50 (Nelson+2019, Pillepich+2019)**
Code	RAMSES (AMR)	AREPO (moving mesh)
Volume	Zoom-in of 20 Mpc spherical region from Horizon-AGN	50 Mpc box
Resolution	~1.3×10^4 $M_\odot$ (stars), ~34 pc (spatial)	~8.5×10^4 $M_\odot$ (stars/gas), 100–140 pc (spatial)
Environment Coverage	Field and group (max halo ~10^{13} $M_\odot$)	Field, group & poor clusters (~10^{14} $M_\odot$)
Star Formation	Turbulence-regulated	Schmidt law
ISM Physics	Multiphase ISM	Idealised two-phase model
SN Feedback	Mechanical feedback from SN Type II (**Kimm & Cen 2014**)	Direct heating + delayed kinetic winds (**Springel & Hernquist 2003**)
Extras		MHD

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Observations

We use data from the COSMOS field, supported by deep Hyper Suprime-Cam (HSC) imaging:

- **COSMOS2020 (Weaver+2021)**
  - Provides stellar masses, redshifts, and rest-frame properties via comprehensive (40-band) multiwavelength photometry.
  - Photometric redshifts reach <1% precision for bright sources.
- **HSC-SSP Imaging (Aihara+2019)**
  - Deep *i*-band imaging ($\mu \approx 31$ mag arcsec^{-2}) over the central 1.5° of COSMOS.
  - We use the DR2 deepCoadd images to preserve extended flux.
  - COSMOS probes relatively average environments, with a galaxy number density similar to TNG50 and NewHorizon volumes at $0.05 < z < 0.3$.

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Connecting Observations and Theory

- Galaxy morphology encodes key information about formation history, feedback, and environment.
- Morphological comparisons between observations and simulations help test physical prescriptions.
- In this work, we:
  - Generate realistic synthetic HSC-like images from TNG50 and NewHorizon.
  - Measure structural properties of COSMOS dwarf galaxies.
  - Compare structural diversity across observed and simulated samples.
- Our aim: to assess how well current simulations reproduce the diversity of dwarf galaxy structure, and what this reveals about feedback and ISM physics.

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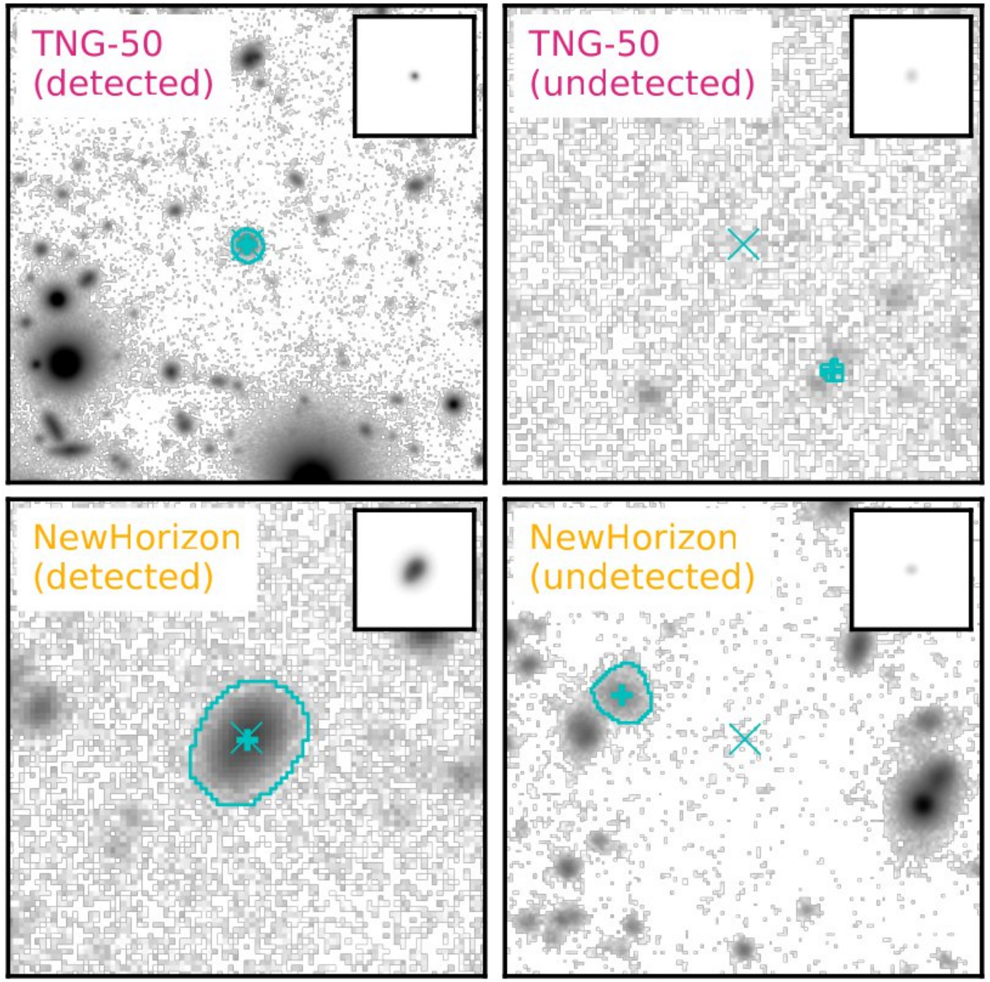
Detection, Segmentation & Sample

- **Synthetic imaging:**
  - Generate *i*-band flux maps from SEDs, convolved with HSC PSF (**Montes+2021**)
  - Match HSC pixel scale (0.168″), photometric zero-points, and image noise characteristics
- **Source Injection & Detection:**
  - Synthetic galaxies injected into random, source-free regions of HSC images
  - Detections performed with PhotUtils — same pipeline for real and synthetic sources
- **Observed Sample Selection:**
  - COSMOS2020 dwarfs with:
  - $0.05 < z < 0.25$, $10^{7.5} < M^*/M_\odot < 10^{9.5}$
  - Final sample: 1320 observed galaxies
- **Matching Simulations to Observations:**
  - Simulated samples matched in mass and redshift to COSMOS
  - Non-detections become notable only for NewHorizon at $z > 0.2$, $M^*/M_\odot < 10^8$



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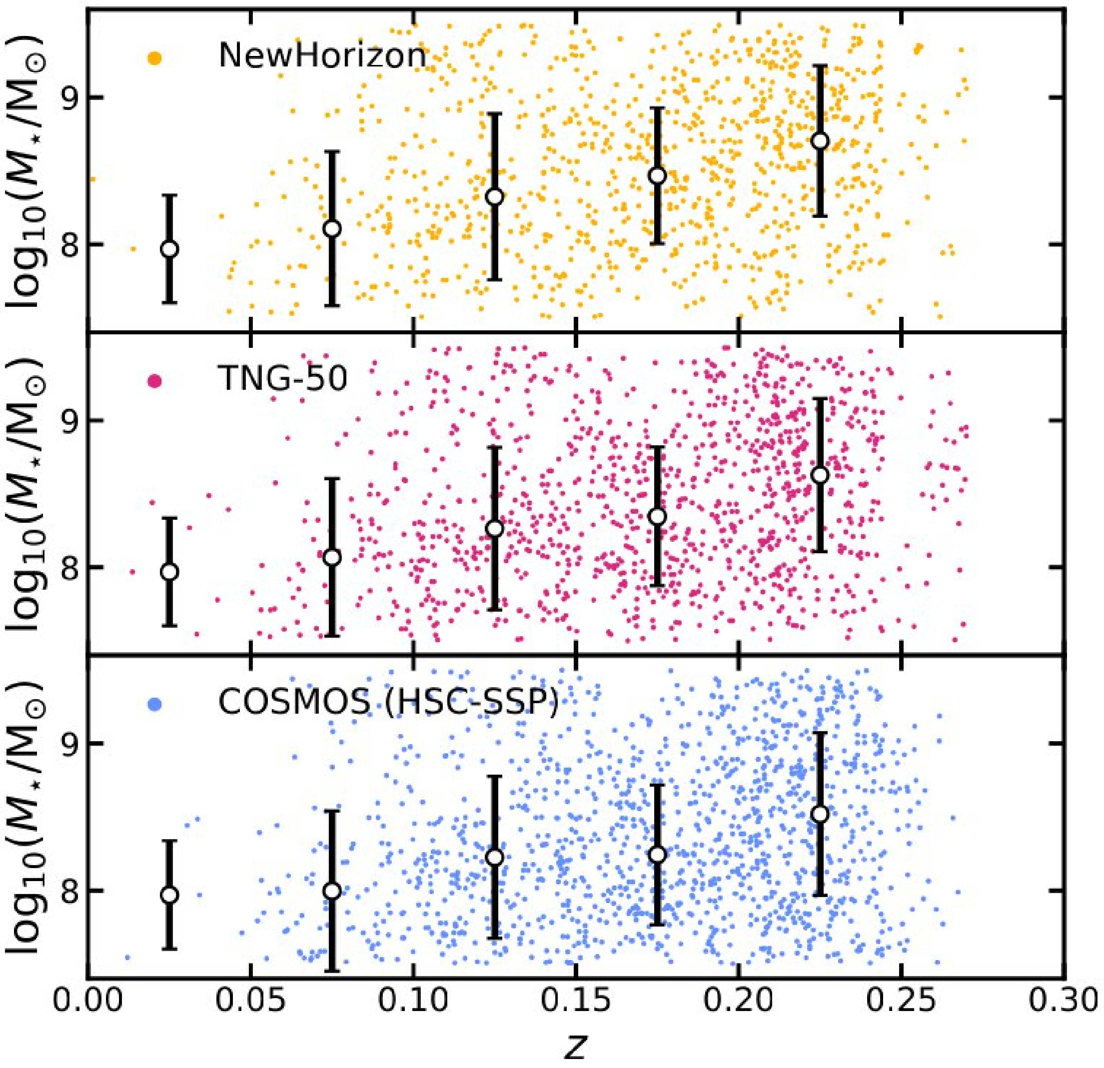

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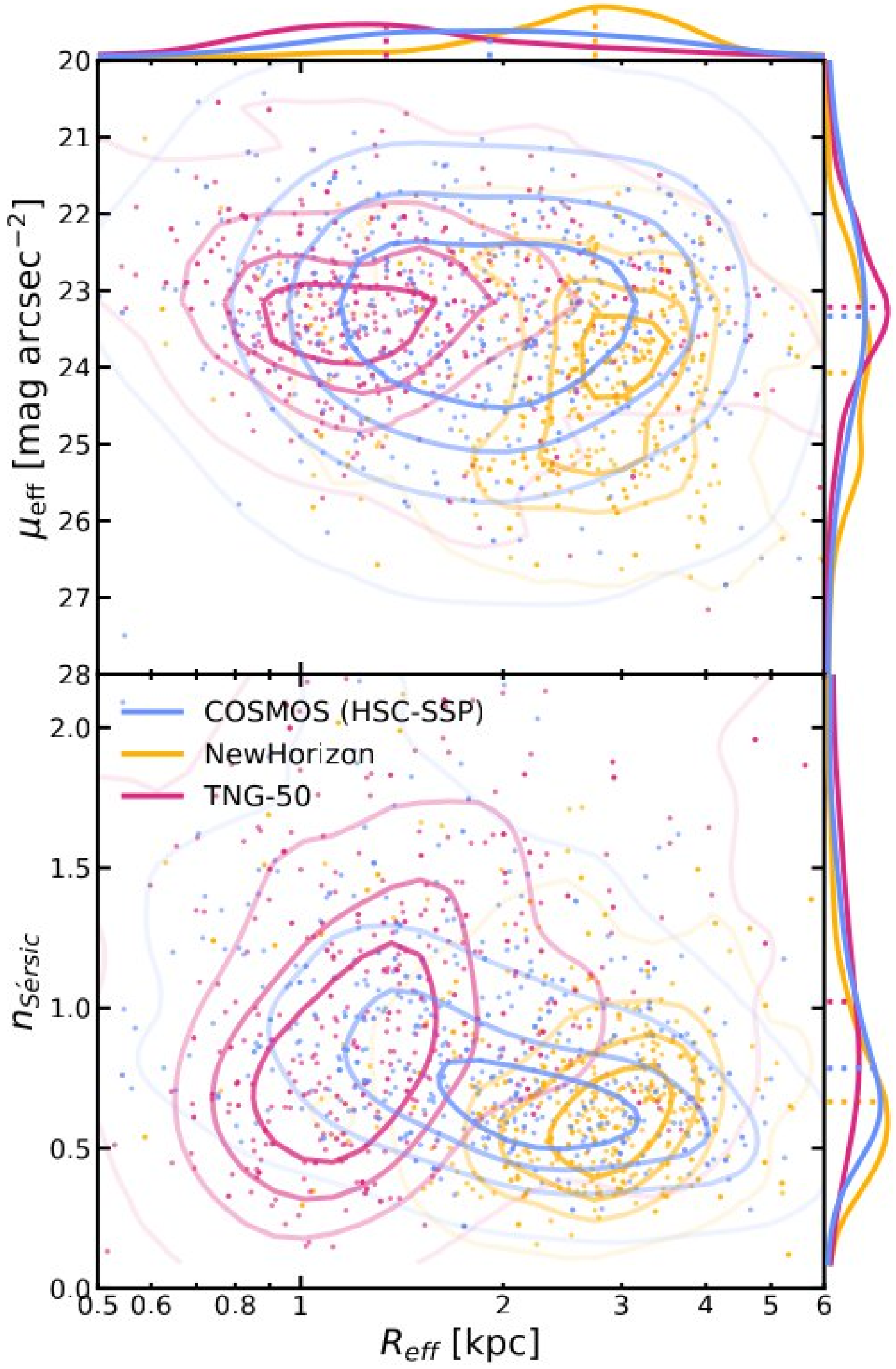
Comparing Simulated and Observed Dwarf Galaxy Structure

- **Method:**
  - Non-parametric: Gini, M20, Concentration–Asymmetry–Smoothness (CAS) (**Conselice+2003**)
  - Parametric: Single-component Sersic fits
  - All calculated using statmorph (**Rodriguez-Gomez+2019**)
  - Same selection, detection and measurement process applied to both observed and simulated galaxies → **ensures structural differences reflect physics, not observational/systematic bias**

- *Key Question:* Do current galaxy formation models reproduce observed dwarf galaxy structure and morphology?

Simulated vs. Observed Dwarf Structures Diverge

- **TNG50**:
  - Too compact, high concentration and steep Sérsic indices
- **NewHorizon**:
  - Too diffuse, large sizes, shallow Sérsic indices
- **COSMOS dwarfs**:
  - Span a *broad, intermediate* range not captured by either simulation
- **Non-parametric metrics**:
  - NewHorizon → more asymmetric & clumpy
  - TNG50 → smoother but overly concentrated
- *Neither simulation captures full observed structural diversity.*



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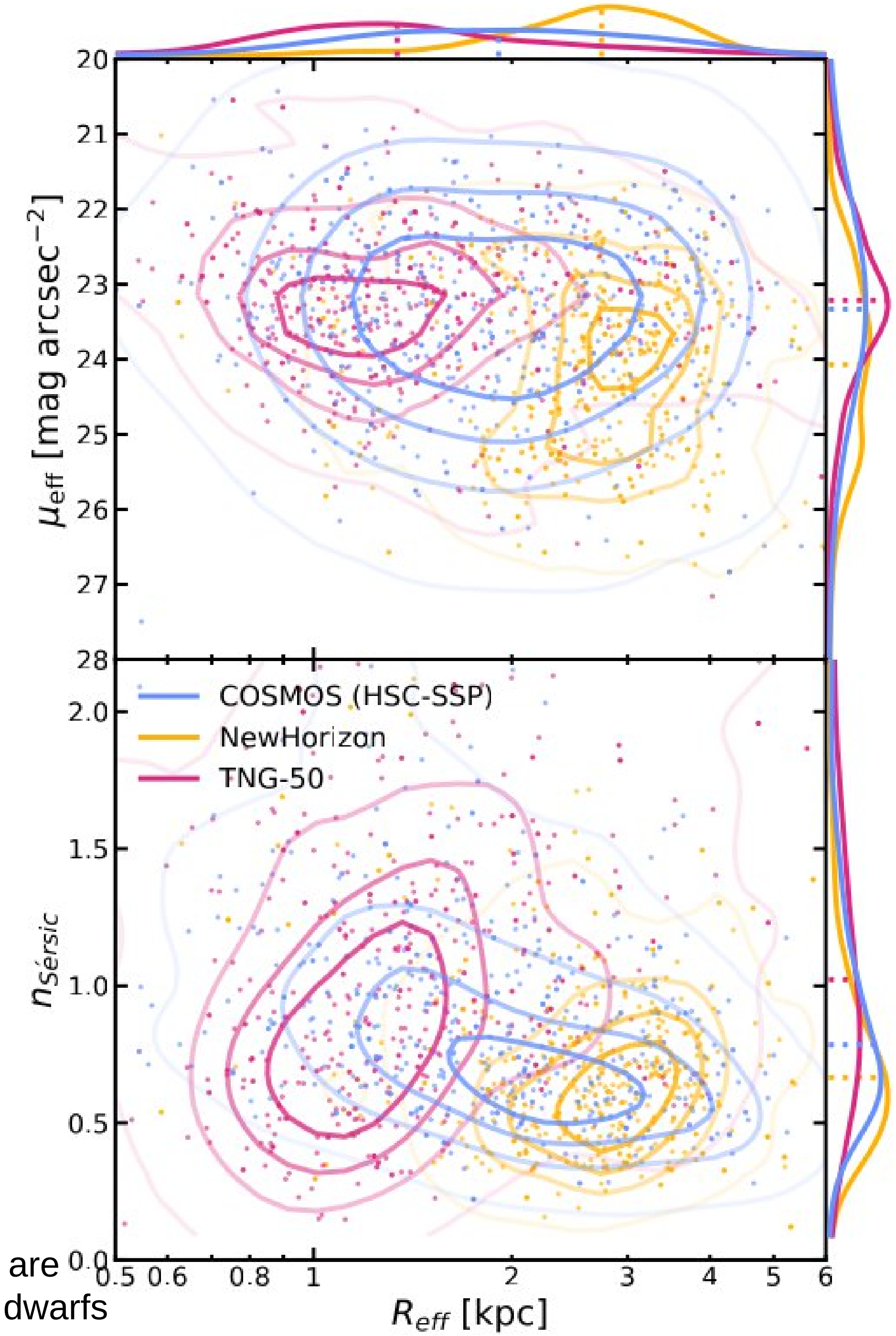

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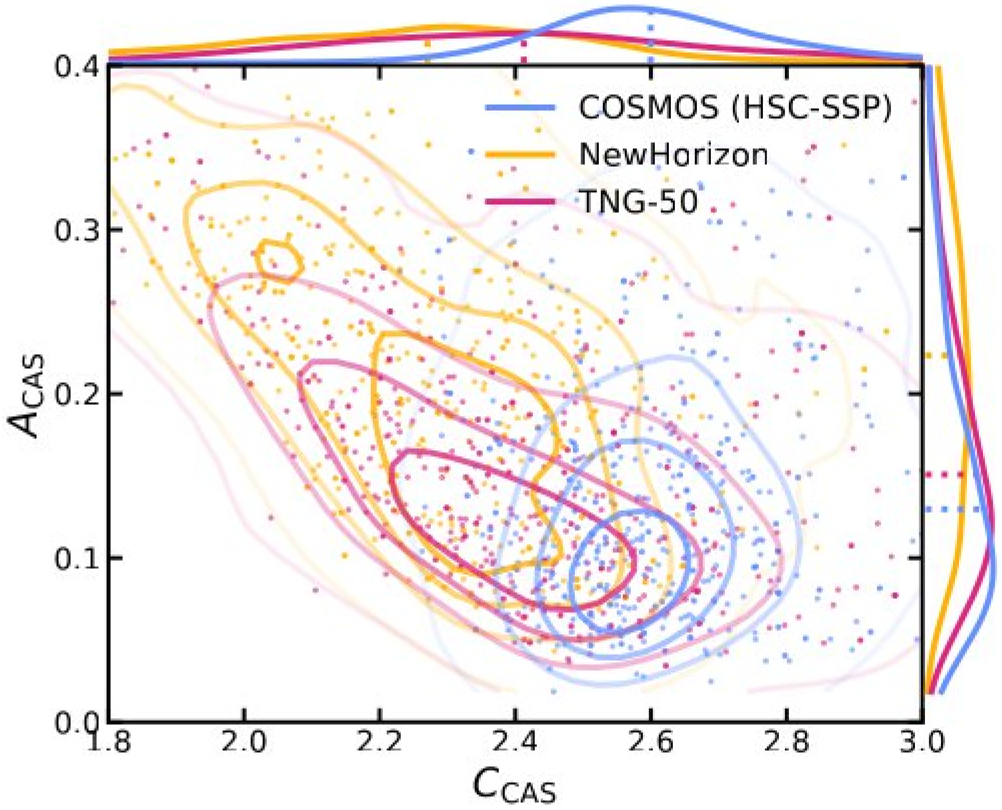

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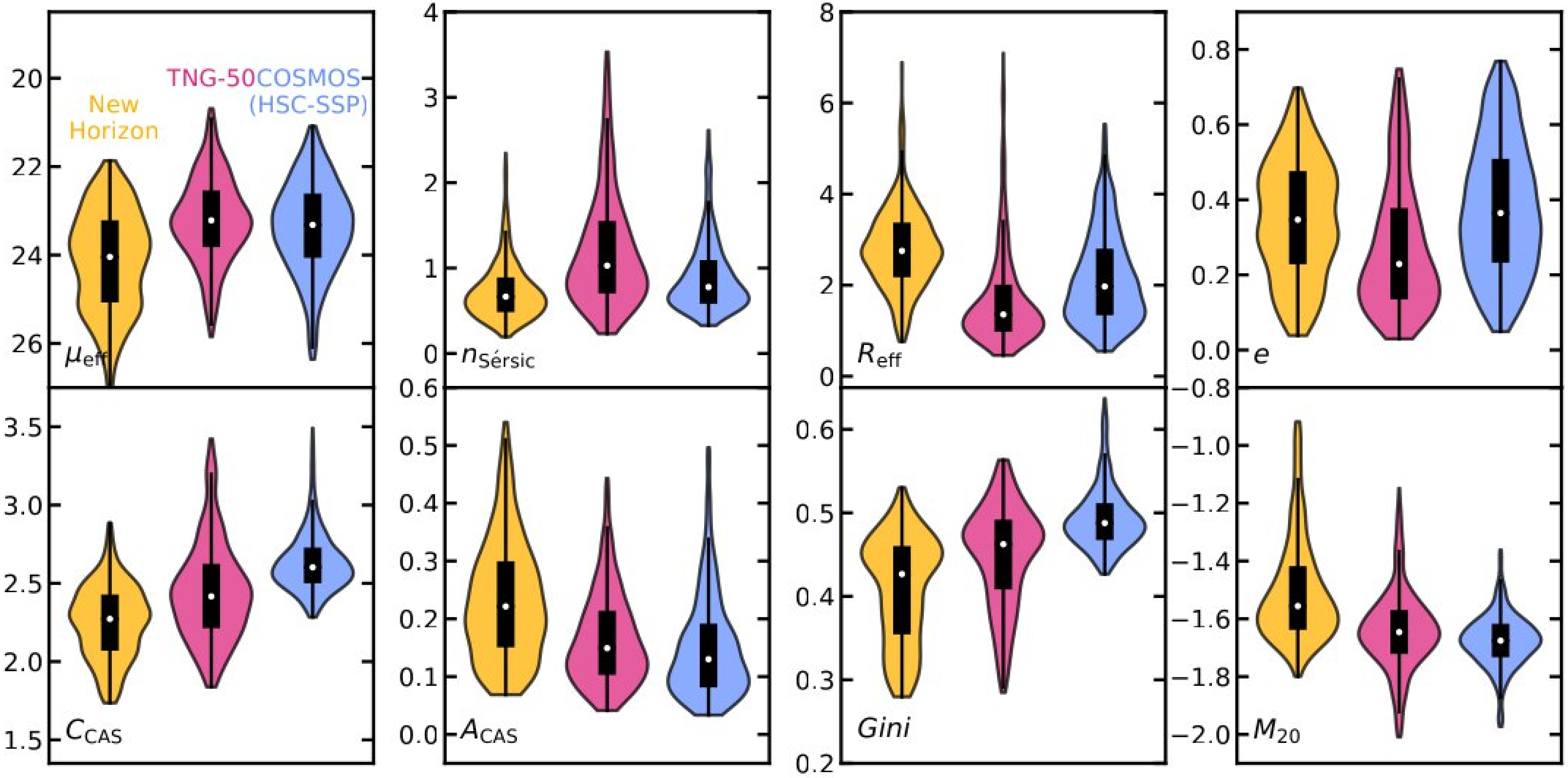

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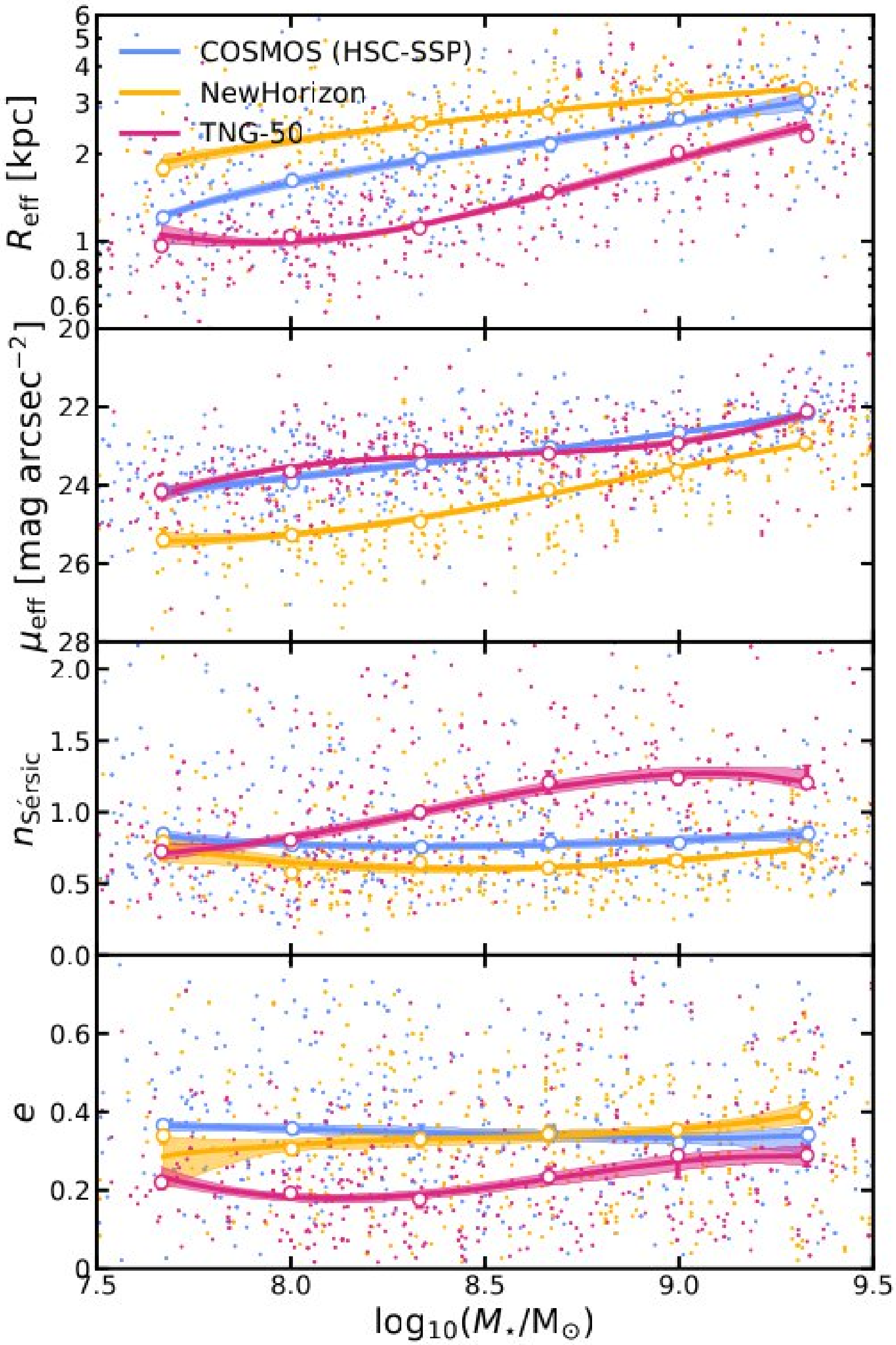
Mass Evolution Trends Differ

- At high mass end (~$10^{9.5}$ M☉), simulations begin to converge toward observed values but still differ systematically
- **TNG50**:
  - Strong increase in concentration and Sérsic index with mass. Large discrepancy with both NewHorizon and COSMOS
- **NewHorizon**:
  - Remains somewhat too diffuse even at higher masses
- **COSMOS dwarfs**:
  - Weak trends with mass — structural properties are relatively *stable*
- Much better agreement has been shown at higher masses (e.g. **Dubois 2021, Wang & Lilly 2023**)
- *Highlights limitations in how feedback and star formation scale in simulations.*



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Feedback & ISM Physics Drive Divergence

- **TNG50**:
  - Smooth ISM, continuous star formation, SN feedback, and MHD processes → retention of low AM gas
  - Promotes central gas accumulation → compact, concentrated structures
  - Insufficient angular momentum redistribution leads to overly compact galaxies
- **NewHorizon**:
  - Multiphase ISM, bursty star formation, local SN feedback → low angular momentum gas ejected from central regions
  - Efficient redistribution of gas results in more diffuse, irregular galaxies
- **Impact of Feedback**:
  - **NewHorizon**'s bursty SF leads to **irregular morphologies** and less compact structures
  - **TNG50**'s continuous SF results in **smoother, more compact galaxies.** Differences also influenced by resolution, PSF biases, and environment
- *Feedback and ISM models, not resolution or observational bias, are primary drivers.*

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Summary

- **Structural Differences**:
  - **Low-mass galaxies are highly sensitive** to ISM, star formation, and feedback implementations
    - Reproducing global observables (e.g. stellar mass functions) isn't sufficient— resolved morphology adds crucial constraints especially given aparrent degeneracies between models in reproducing integrated properties like stellar mass (Wright+2024).
  - **NewHorizon**: Produces diffuse, extended galaxies with **low concentration**, **burstier star formation**
  - **TNG50**: Produces compact, concentrated galaxies with **high central density**, **smoother star formation**
- **Feedback and ISM Physics**:
  - **NewHorizon**: Burstier SF, dynamic ISM leads to **more asymmetric** and **less compact** galaxies as low AM gas ejected efficiently
  - **TNG50**: Continuous SF with feedback uncoupled from the central parts of galaxies, smooth ISM results in **more compact**, concentrated structures
- **Discrepancy with Observations**:
  - Both simulations show **divergent trends** compared to observed COSMOS dwarf galaxies, with neither fully capturing the observed structural diversity
  - Structural mismatch in dwarfs is a powerful diagnostic of sub-grid physics in simulations
- **Future Insights**:
  - **Next-generation surveys** like LSST and Euclid will provide larger, deeper and higher-resolution datasets to constrain and refine simulations and better understand the **physical mechanisms** driving dwarf galaxy evolution.

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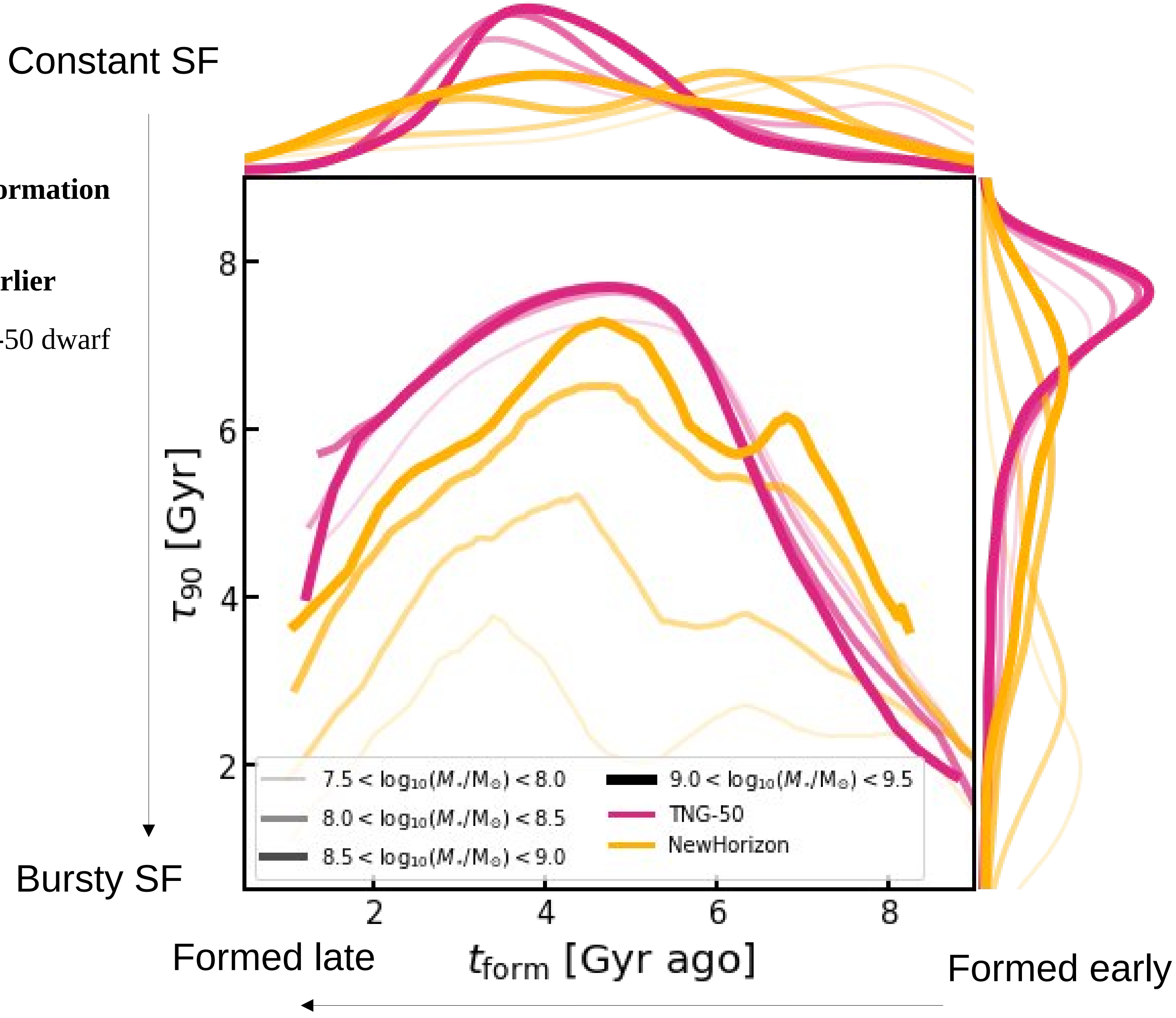
Additional slides

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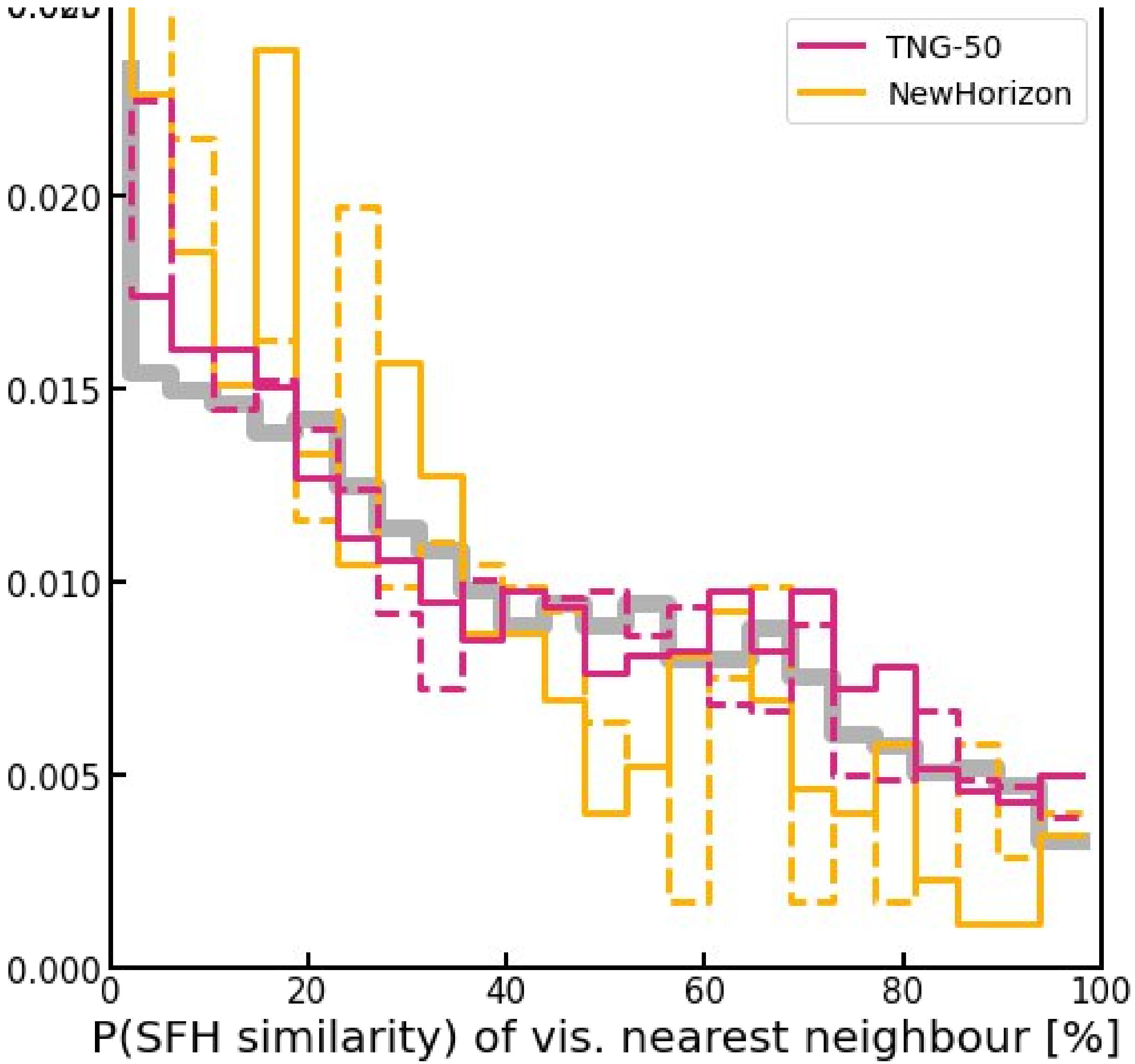
We can measure the level of **correlation between SFH and visual similarity**



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

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	-