

Non-Thermal Physics Drives Compact, Self- Regulated Galaxies at Cosmic Dawn



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The James Webb Space Telescope revealed **surprisingly bright, large galaxies** a ~few hundred million years after the Big Bang.

Predicted: Diffuse, faint

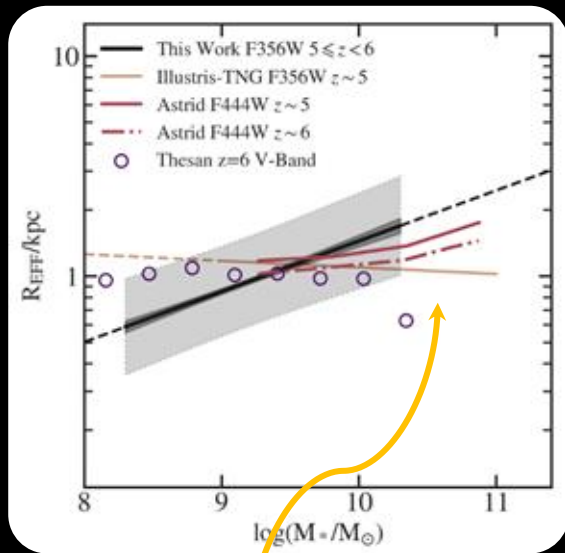


Observed: Structured, bright



The James Webb Space Telescope revealed surprisingly bright, large galaxies a ~few hundred million years after the Big Bang.

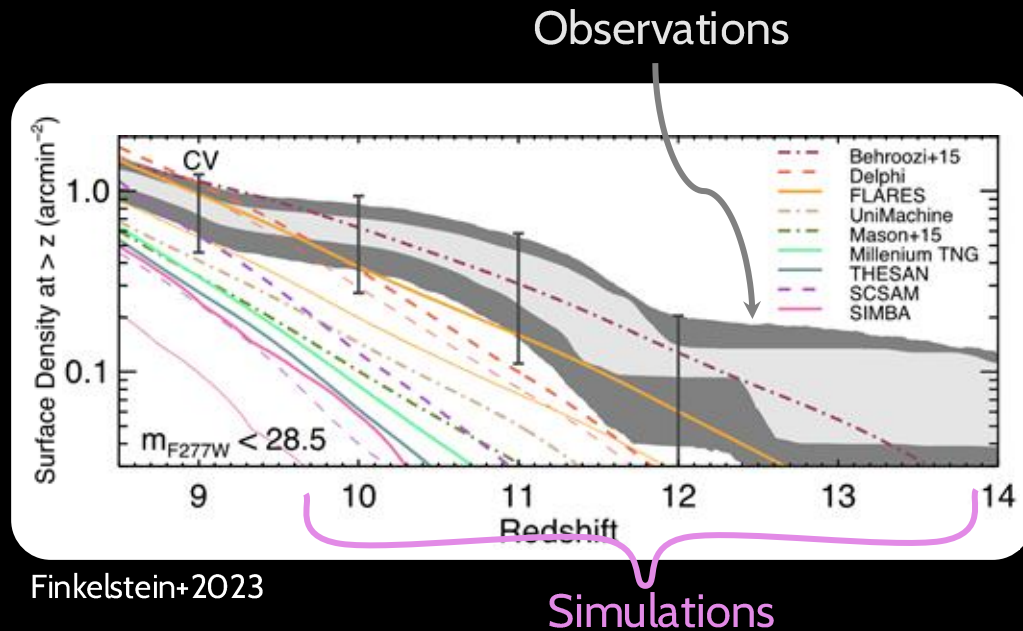
1. Rapid stellar mass assembly at $z > 10$



Allen+2025

Simulated galaxies are smaller than observed!

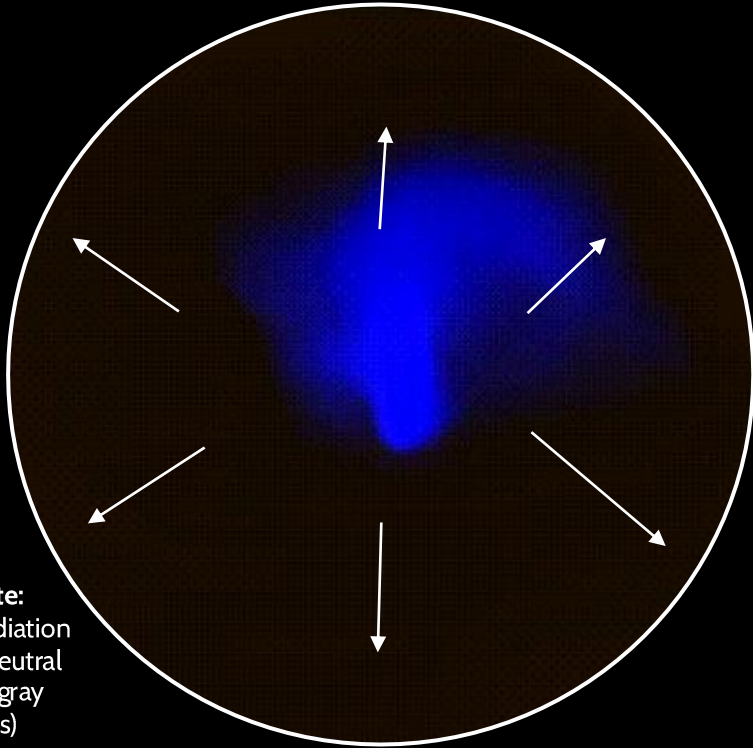
2. Unexpectedly bright UV galaxies



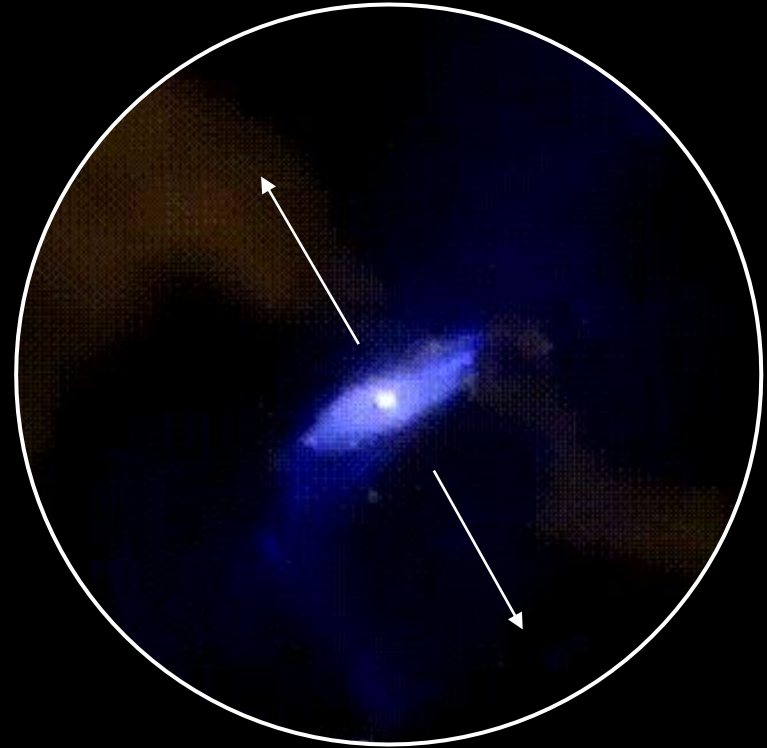
Finkelstein+2023

Galaxy shapes, sizes, structures offer direct clues to the physical processes that regulate their growth.

Before disk: Isotropic outflows



After disk: Perpendicular outflows



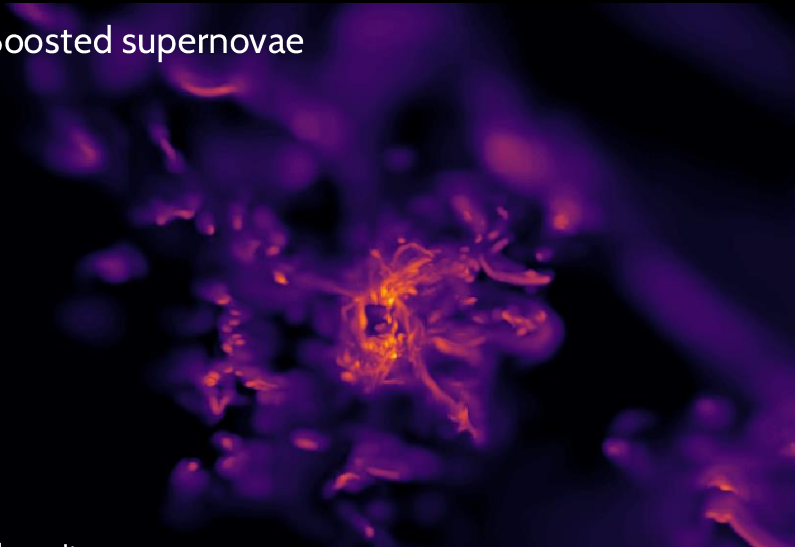
Azahar suite:
Ionizing radiation
(orange), neutral
gas (blue), gray
(ionized gas)

Two Challenges in measuring early galaxy shapes

PSF
□

Simulations

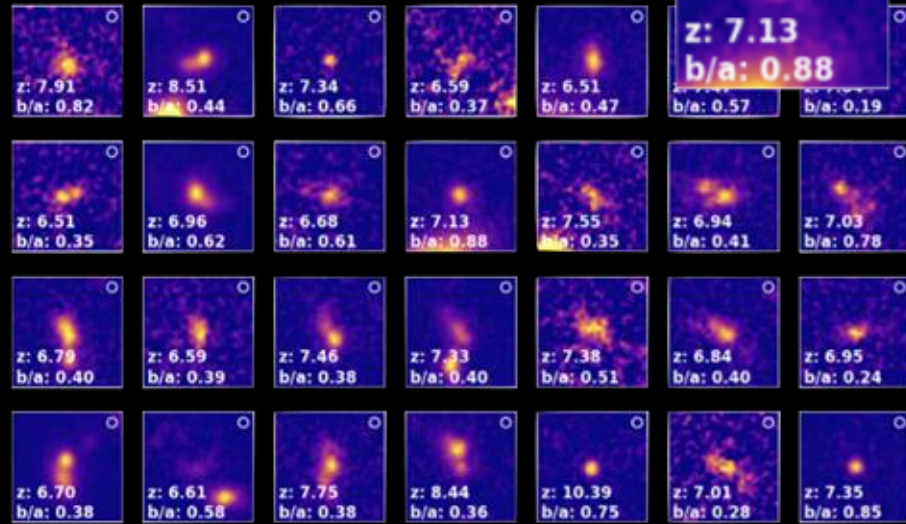
Boosted supernovae



Azahar suite

**Supernovae calibrated models
form galaxies too late with incorrect
sizes**

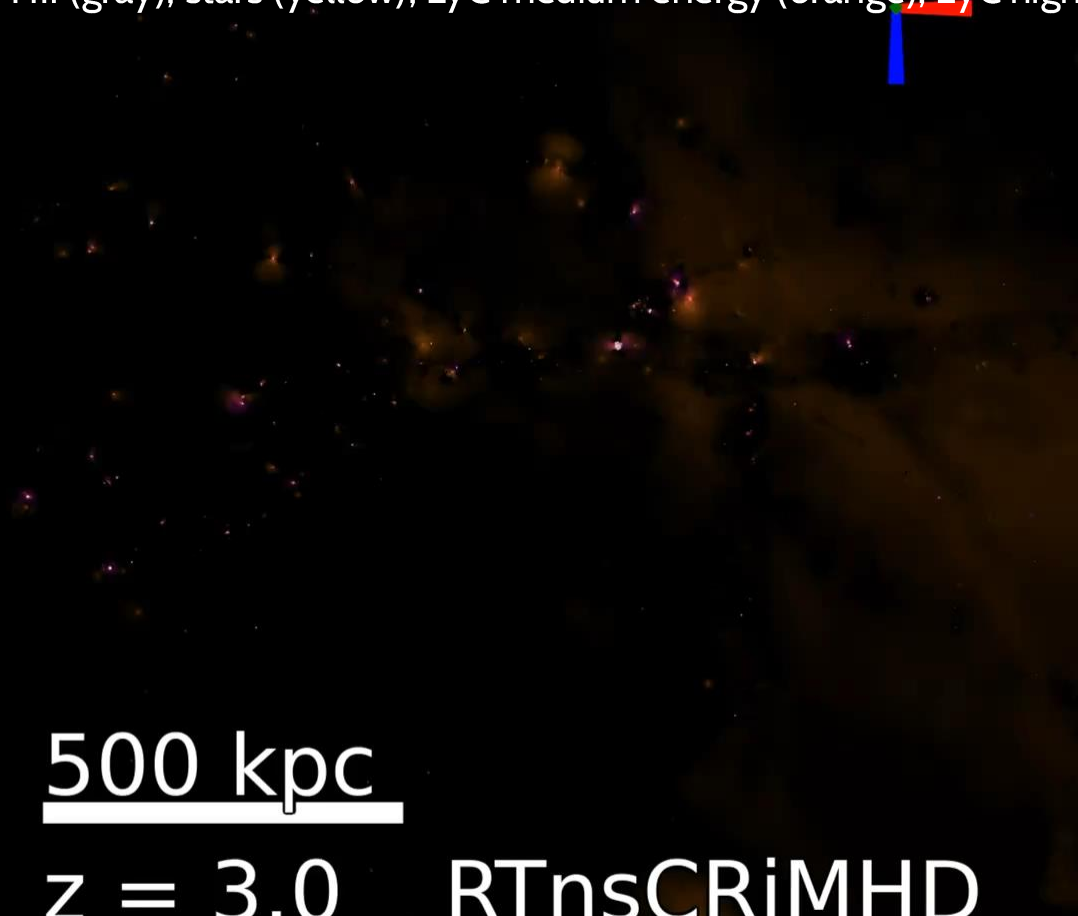
Observations



Westcott+25

**Challenging to recover galaxy
morphologies at $z > 10$, under the
resolution limit of JWST**

Zoom-in of galaxies in the **Azahar simulation suite** at $z = 3$
HI (blue), HII (gray), stars (yellow), LyC medium energy (orange), LyC high energy (pink)



500 kpc

$z = 3.0$

RTnsCRiMHD



Azahar simulation suite

3 physics models isolate role of feedback

HD

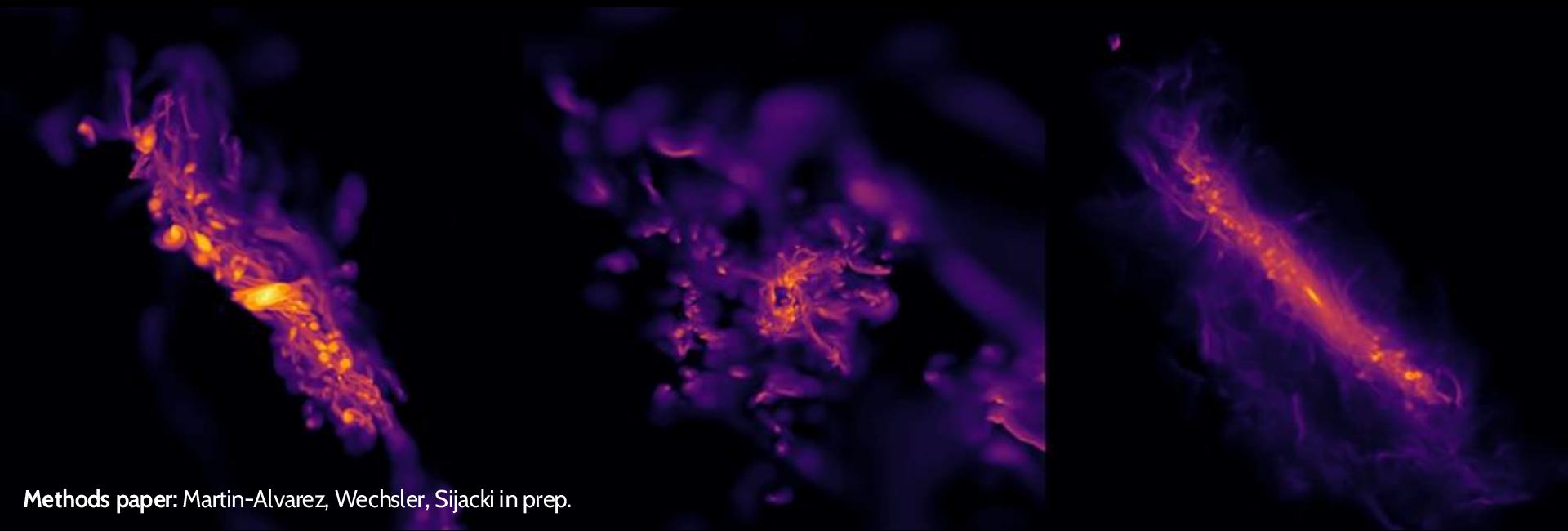
Standard hydrodynamics
physics

HD-Boost

HD + boosted supernovae
calibrated to stellar mass
function at $z = 3$

Full-Physics

HD + radiative transfer, cosmic
rays, & magnetic fields



Can we explain the sizes & morphologies of early galaxies ($3 < z < 12$) with the Azahar simulation suite?



1. **Full-Physics** reproduces observed galaxy sizes & morphologies

□ Predicts **compact, starburst scenario** that explains abundance of bright $z > 10$ galaxies



2. We predict galaxies smaller than JWST resolution, and **instrumental effects** produce larger observed sizes

Can we explain the sizes & morphologies of early galaxies ($3 < z < 12$) with the Azahar simulation suite?



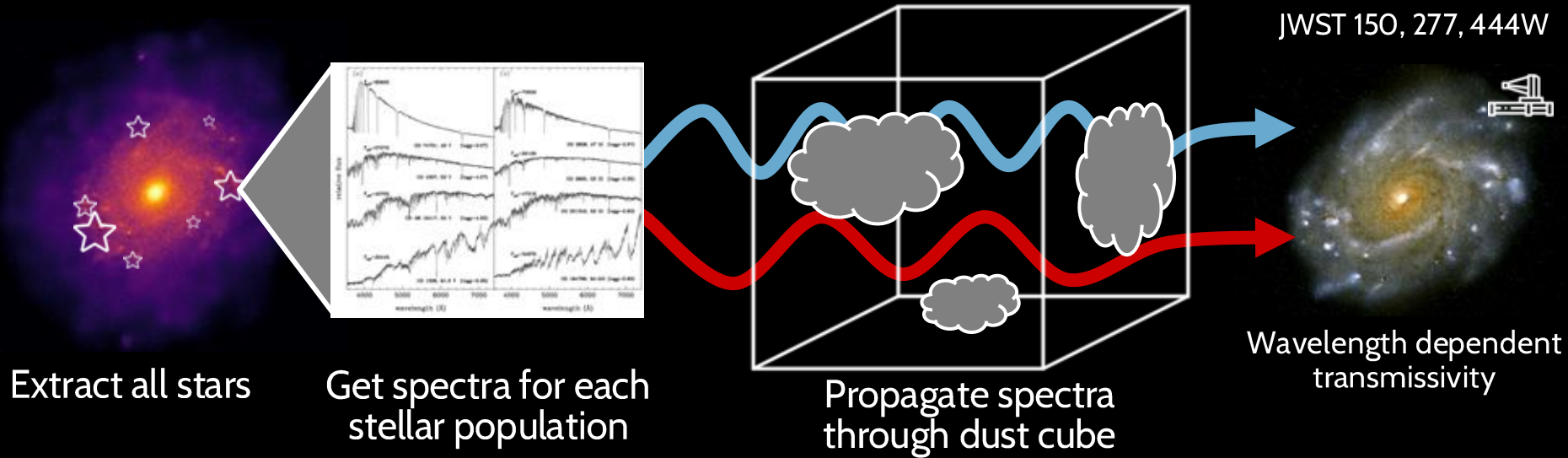
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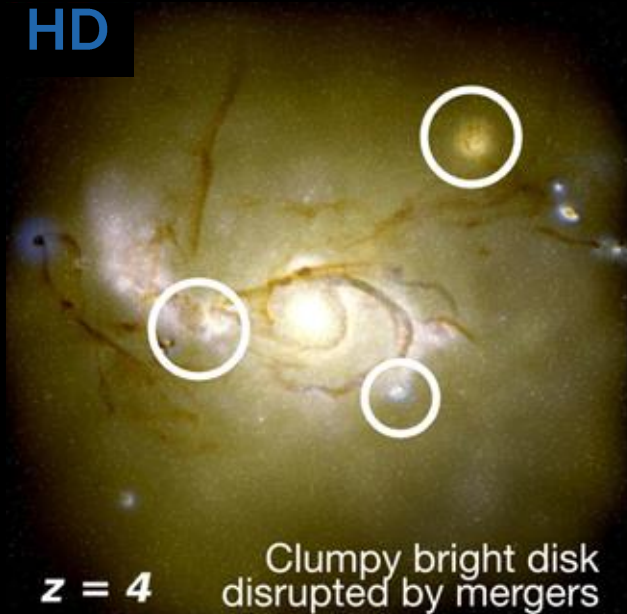
Synthetic observations of simulated Azahar galaxies



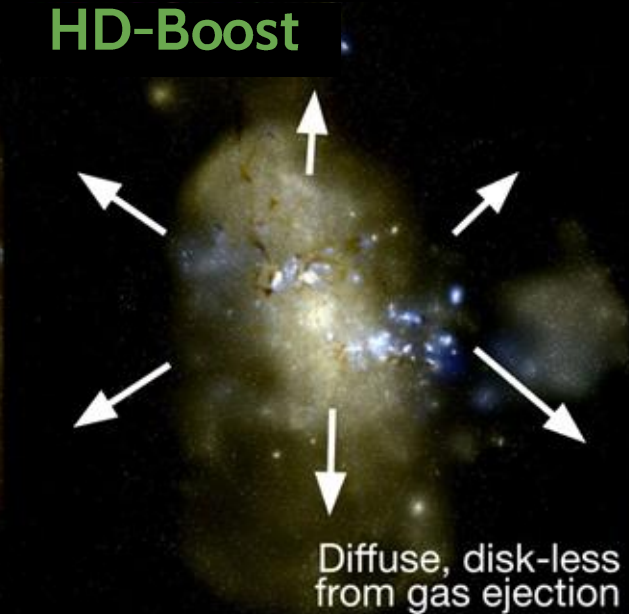
Directly compare with surveys under JWST filters & instrumental effects
(dust, resolution limits)

Different feedback physics produce different galaxy morphologies

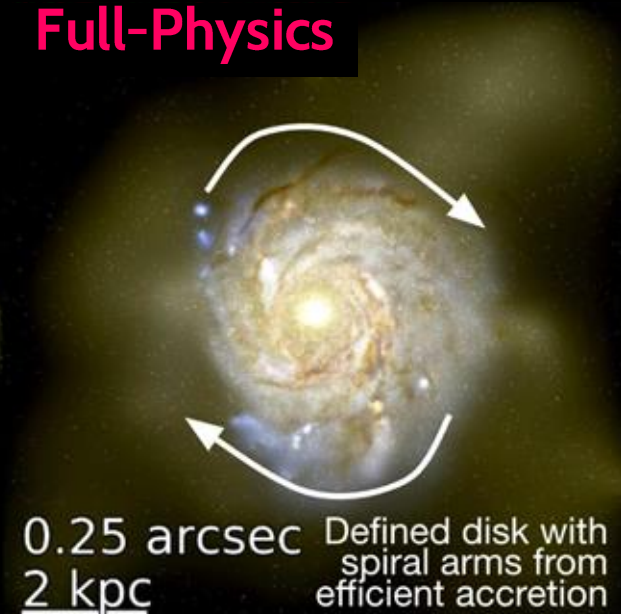
HD



HD-Boost



Full-Physics



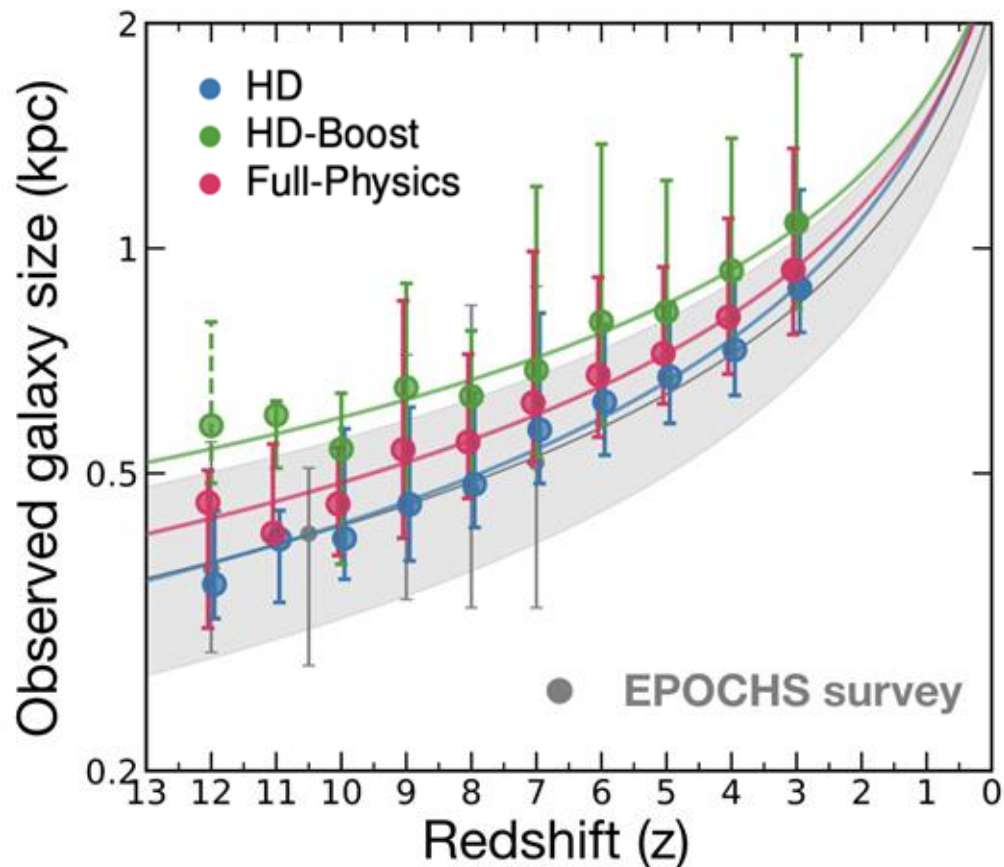
Park, Martin-Alvarez, Wechsler 2026

1000s of galaxies:

Which model reproduces observed galaxy sizes & morphologies across populations?



Full-Physics reproduces observed sizes and morphologies



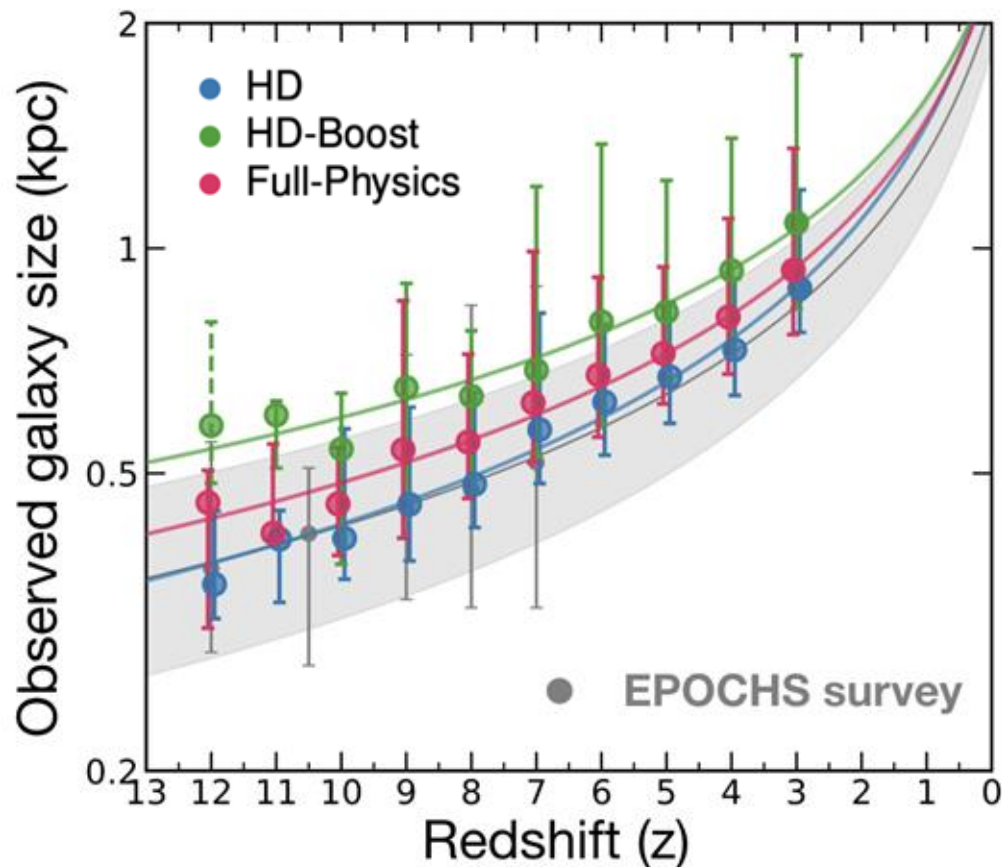
More feedback yields larger galaxies.

HD-Boost produces galaxy sizes ~ 2 $\times$ observations

Full-Physics regulates stellar mass, which matches JWST observations at early and late times.



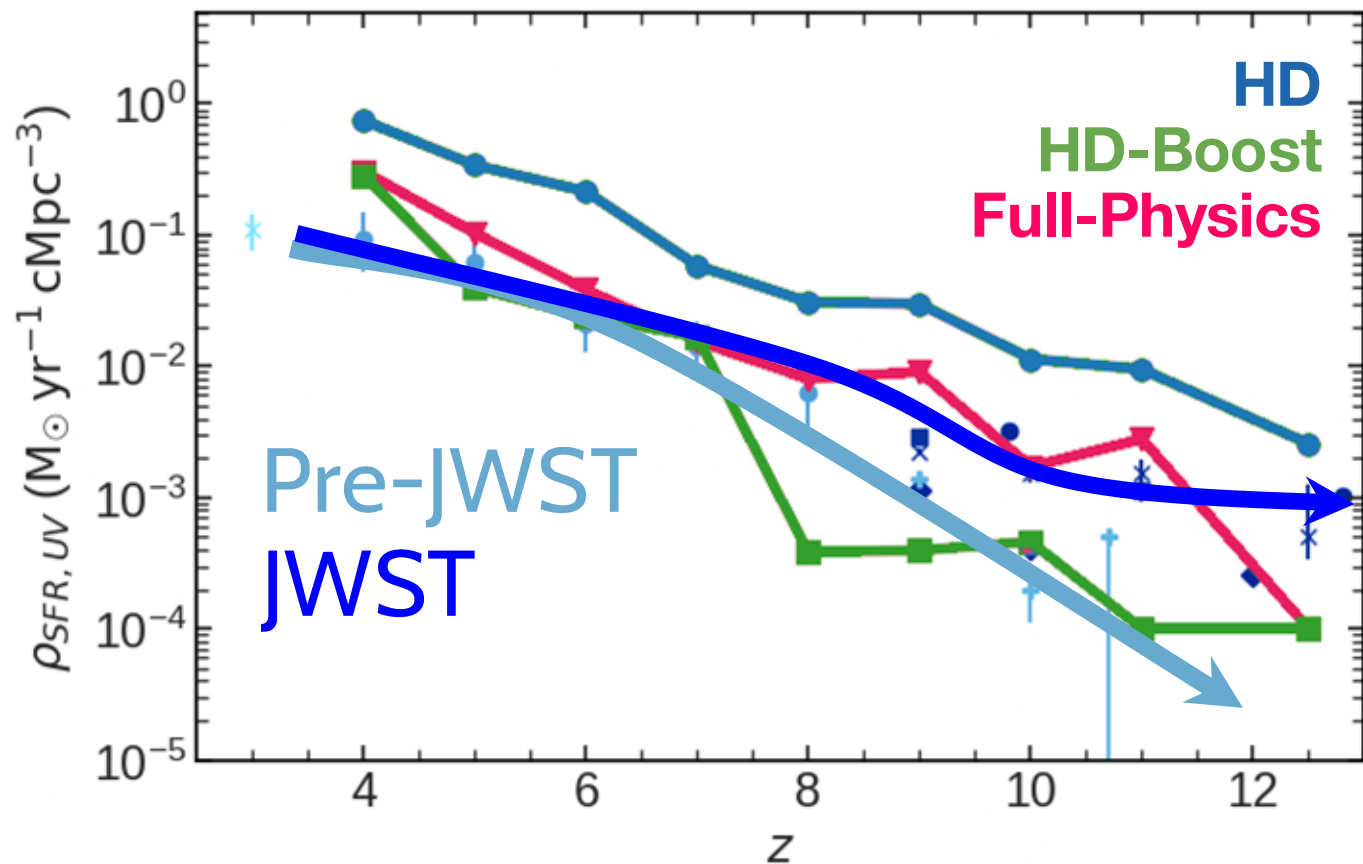
Full-Physics reproduces observed sizes and morphologies



HD & Full-Physics
match with
observations, but **HD**
produces galaxies that
are **too bright in UV**.



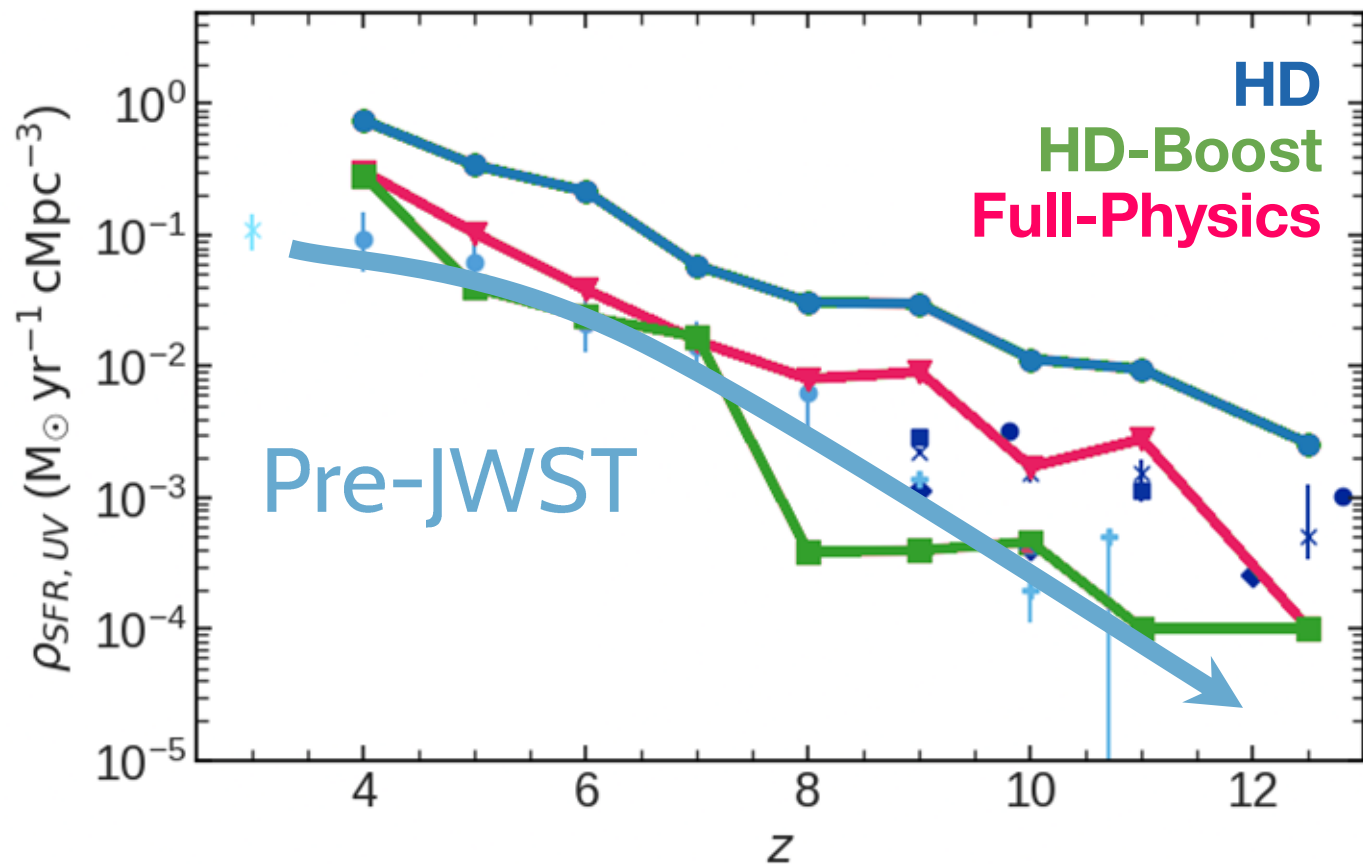
Full-Physics reproduces observed sizes and morphologies



HD produces galaxies with higher UV luminosities



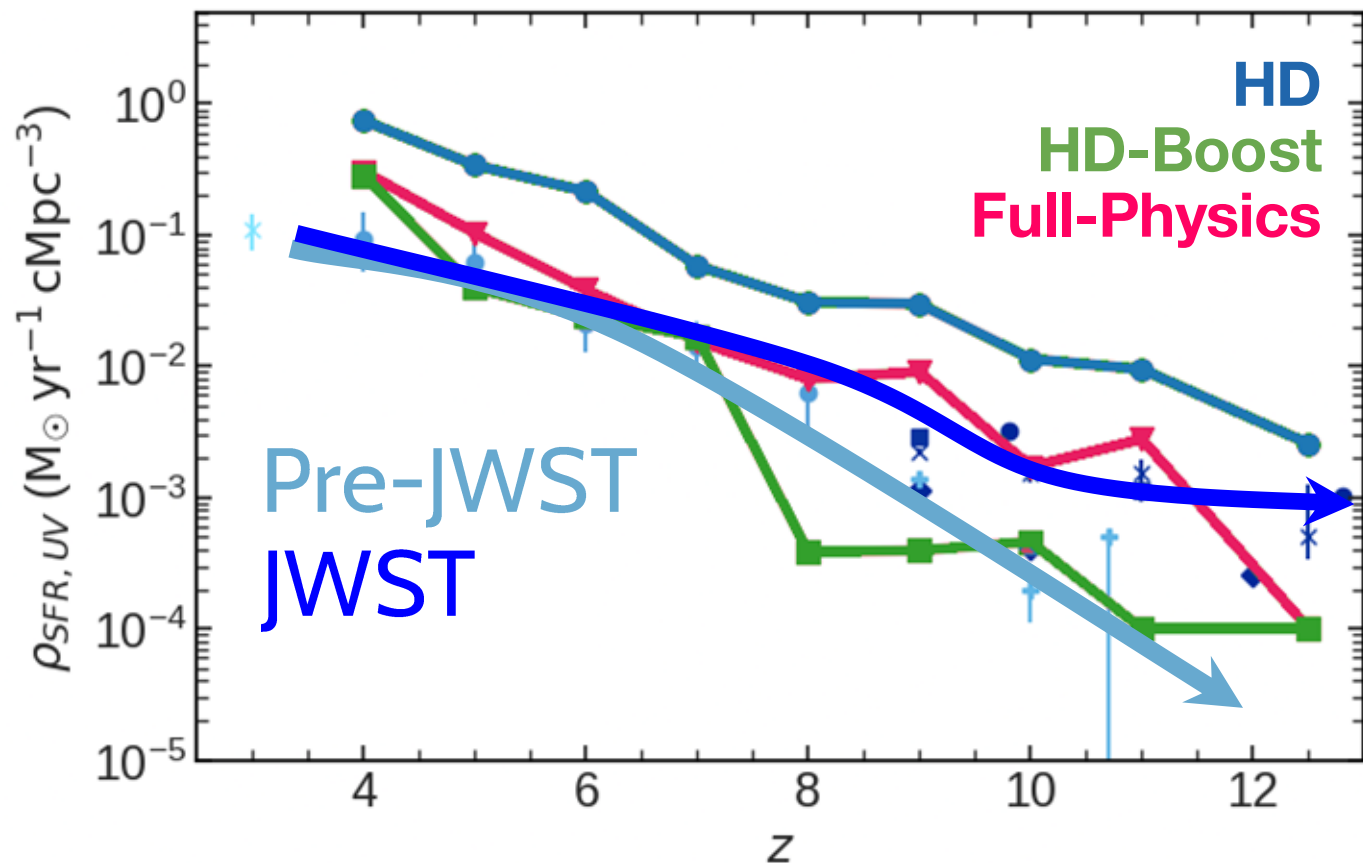
Full-Physics reproduces observed sizes and morphologies



HD-Boost's calibrated supernovae explosions matched **pre-JWST** surveys



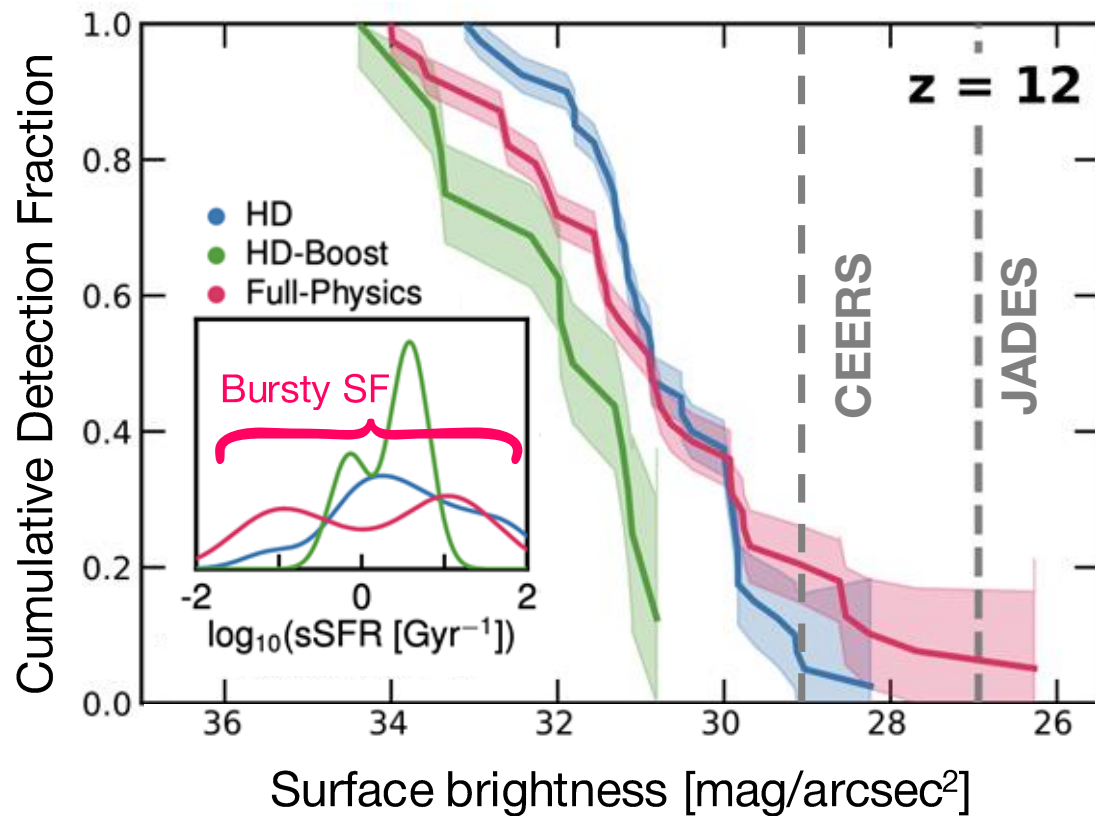
Full-Physics reproduces observed sizes and morphologies



Full-Physics regulates sizes and brightnesses correctly in the early universe!



Full-Physics explains the abundance of bright galaxies found by JWST.



Full-Physics model predicts:

Observed high- z galaxies are **bright, compact, starbursting** end of a broader distribution.

Significant population of **fainter** galaxies yet to be uncovered.

Can we explain the sizes & morphologies of early galaxies ($3 < z < 12$) with the Azahar simulation suite?



1. **Full-Physics** reproduces observed galaxy sizes & morphologies

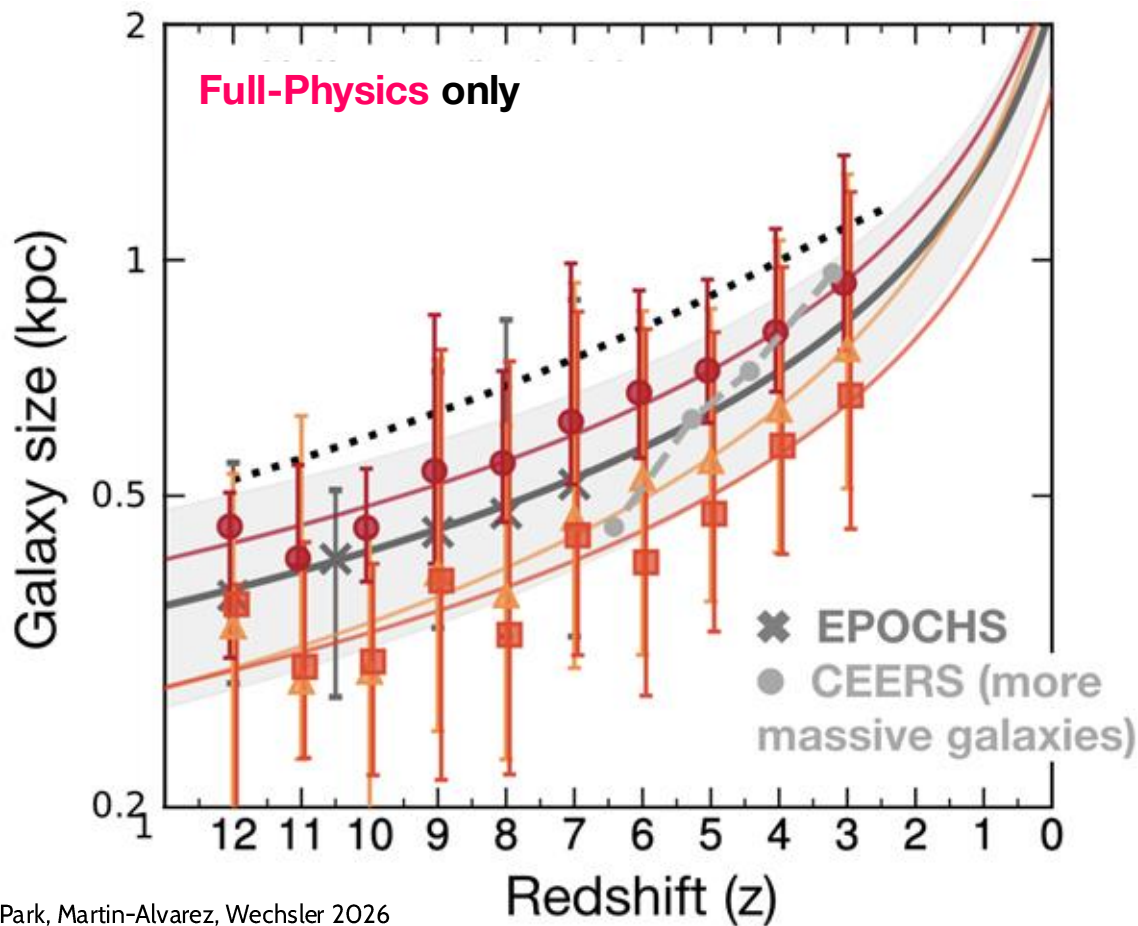
□ Predicts **compact, starburst scenario** that explains abundance of bright $z > 10$ galaxies



2. We predict galaxies smaller than JWST resolution, and **instrumental effects** produce larger observed sizes



Instrumental effects produce larger observed sizes



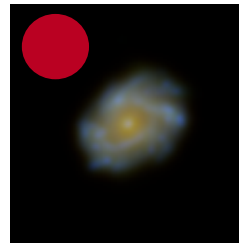
3 sizes are all different!



Half-Mass Radius
Intrinsic



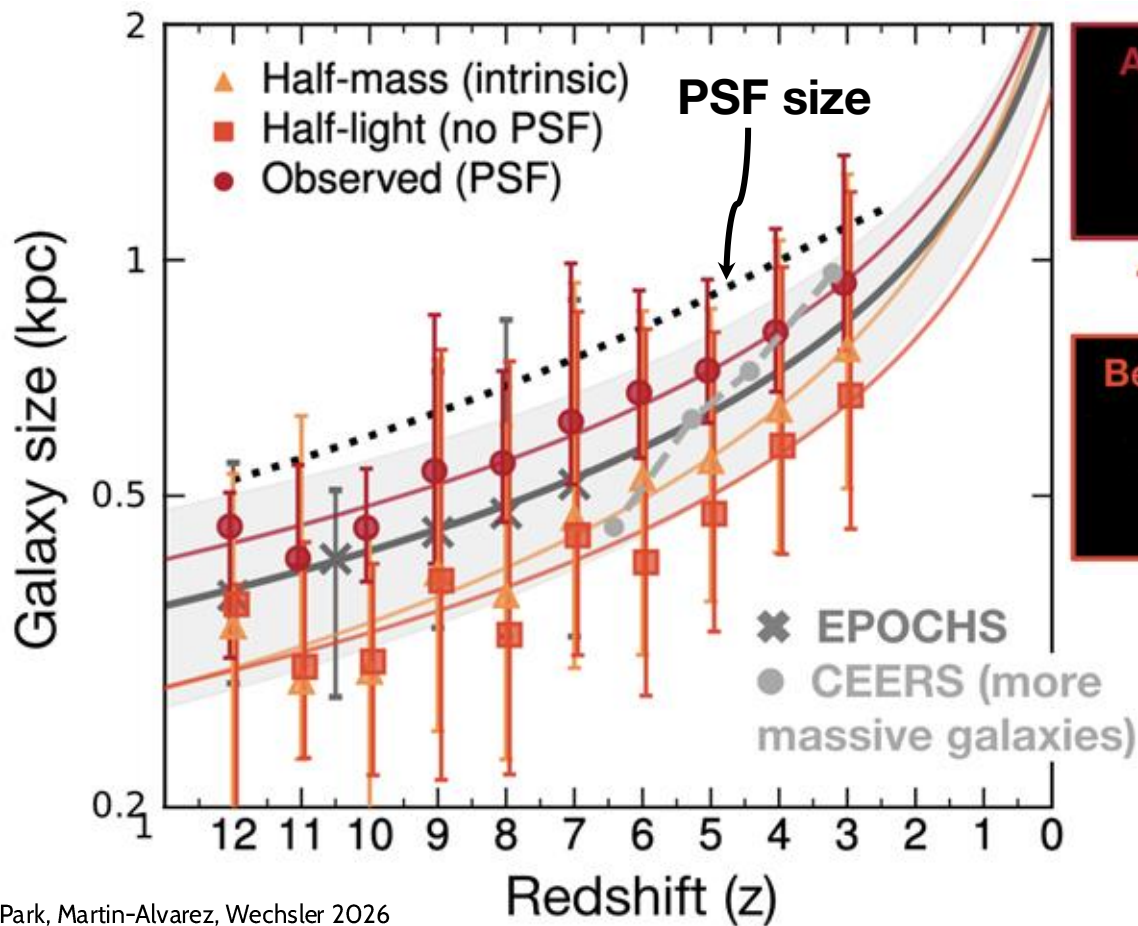
Half-Light Radius
Synthetic
observation, no PSF



Observed Radius
Synthetic
observation, PSF



Instrumental effects produce larger observed sizes



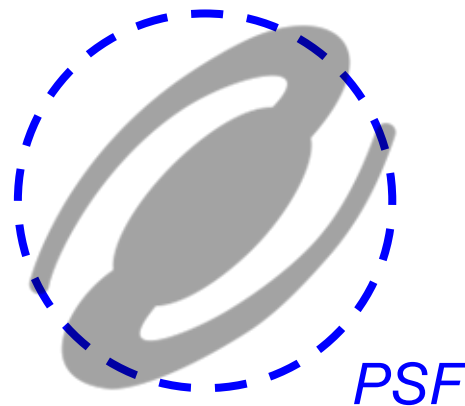
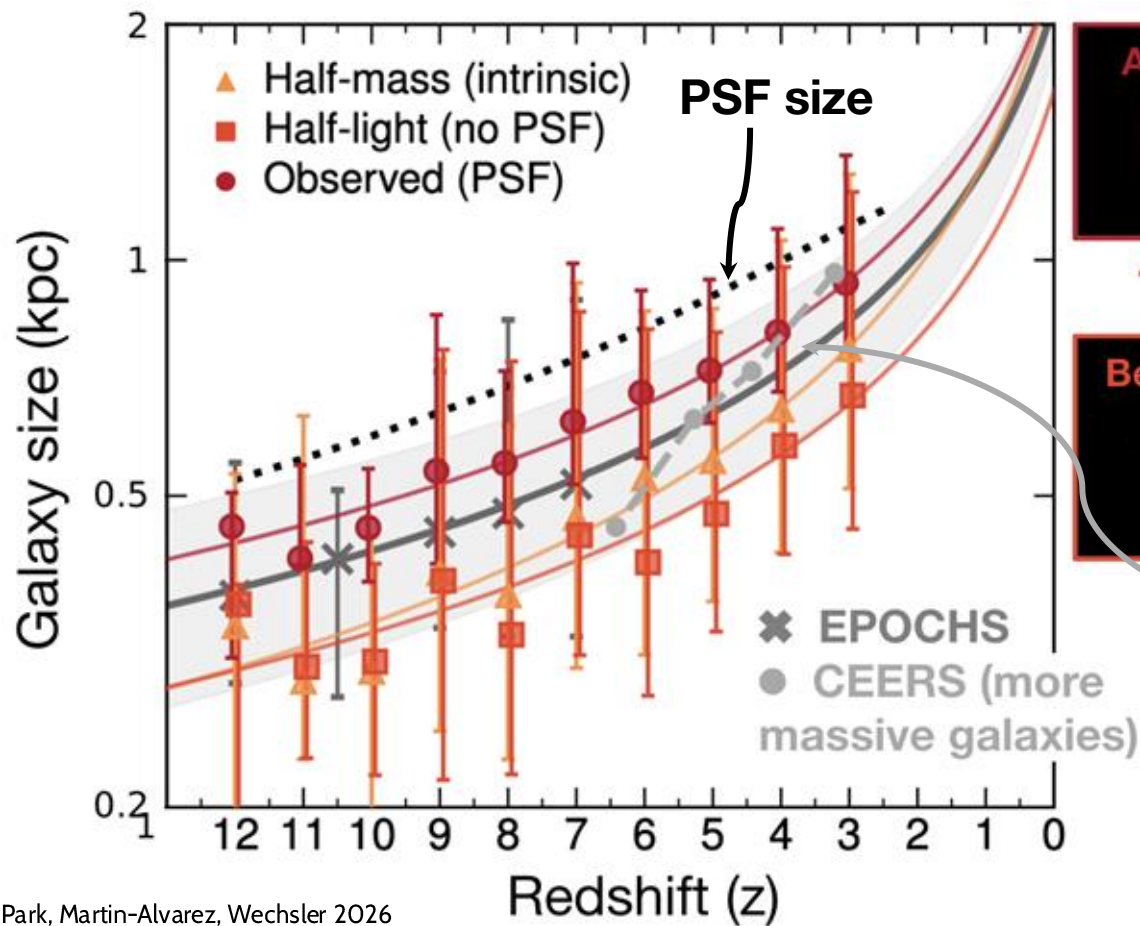
However, the predicted sizes are **below JWST resolution limits**

~ 1/2 PSF size!

Compact galaxies
most affected: high-z
& **HD** model



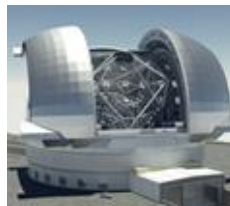
Instrumental effects produce larger observed sizes



Higher-mass, well-resolved systems match intrinsic sizes at high redshift



Next-gen observatories will resolve ~ 100 pc galaxies at $z \sim 10$



Extremely Large Telescopes:
 $R_e/R_{\text{PSF}} \square 3\text{--}7$, or $>10\times$
resolution improvement

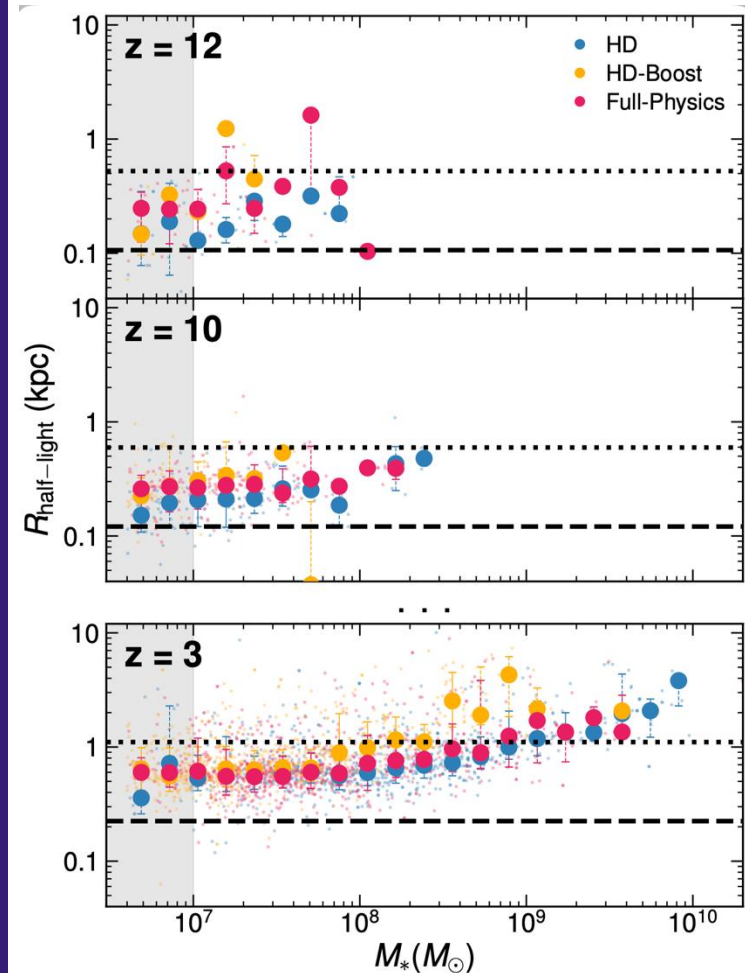
JWST PSF

at F444W

ELT PSF

Davies+2018

Estimated at F444W



We use synthetic observations of simulated **Azahar** galaxies in three feedback models to explain the unexpectedly bright, rapidly growing first galaxies.



Full-Physics produces self-regulated galaxies that...

- Match observed sizes & morphologies from $z = 12$ to $z = 3$
- Predicts **compact, starburst scenario** that explains abundance of bright $z > 10$ galaxies



Instrumental effects yield larger observed sizes

- Predicted sizes are **smaller** than JWST resolution
- Consistent with extrapolations from higher mass systems

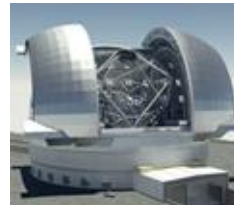


Park, Martin-Alvarez,
Wechsler 2026
Published in ApJ

Azahar Simulations



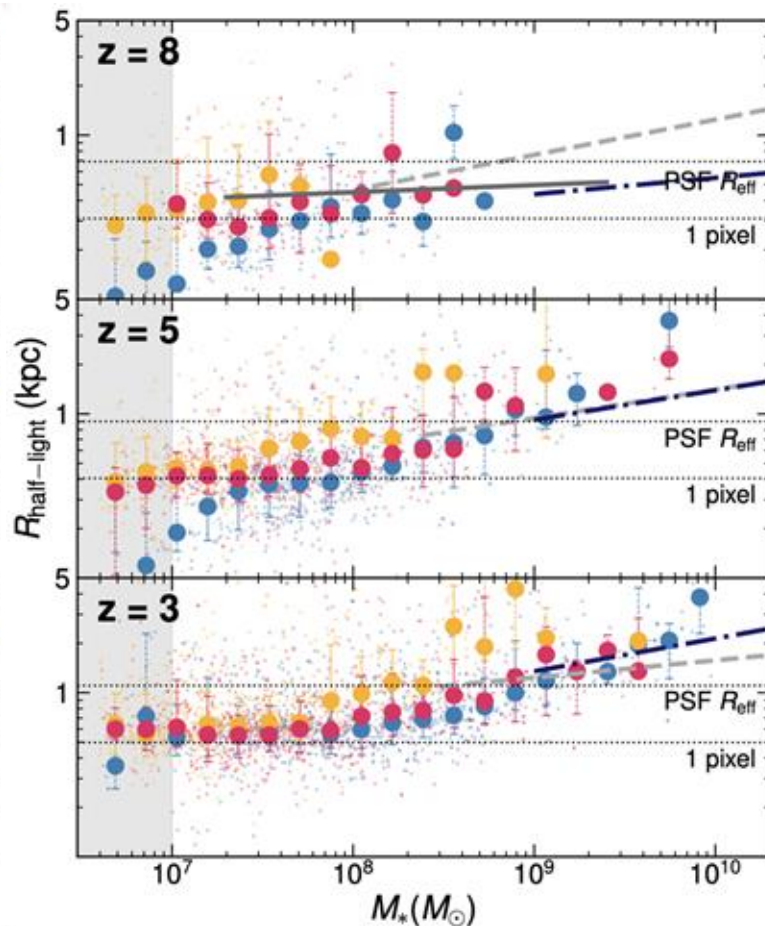
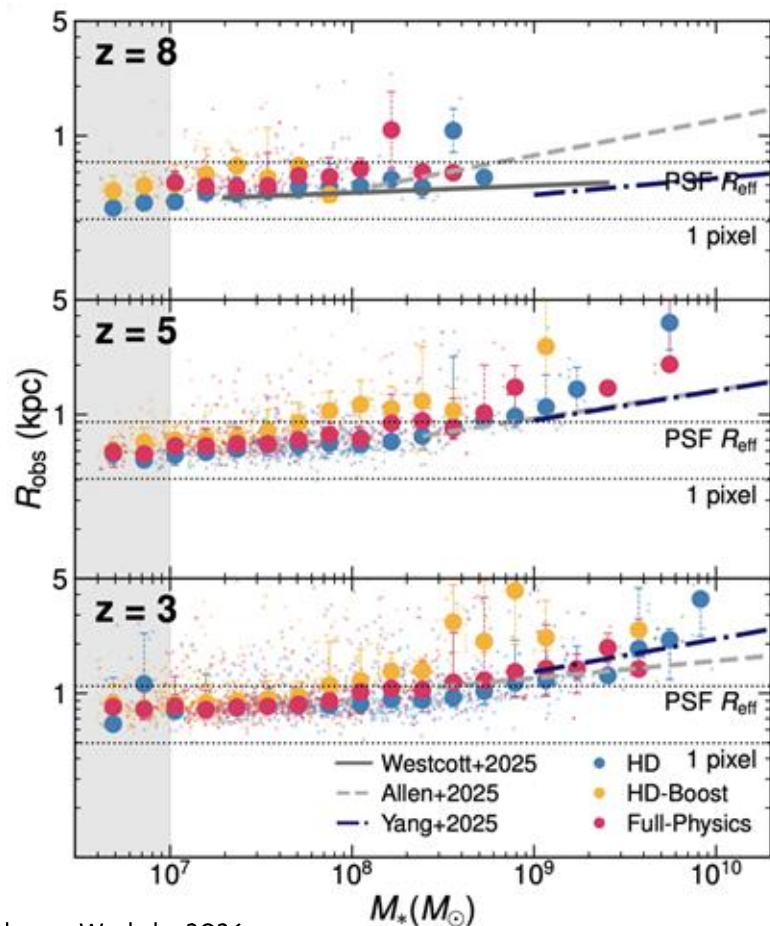
Martin-Alvarez,
Wechsler, Sijacki 2026
Submitted to ApJ

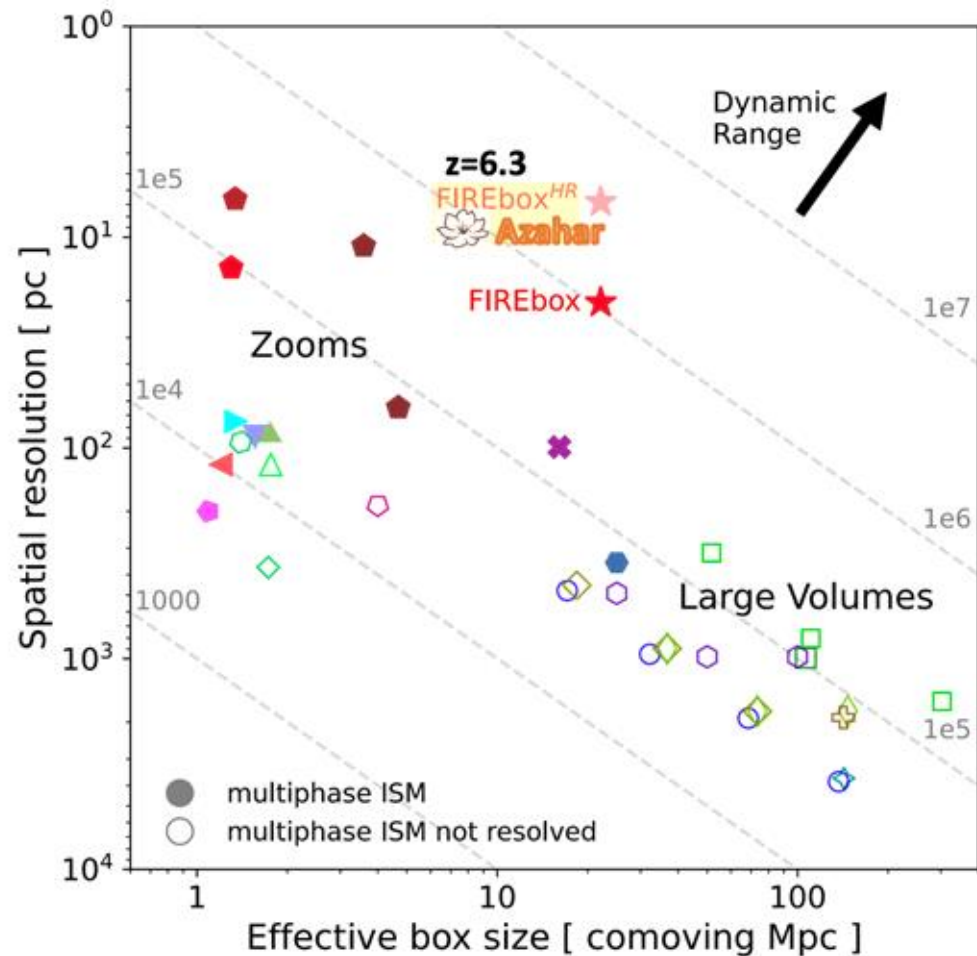


Next-gen observatories
could resolve this population
 ~ 100 pc at $z \sim 10$

Supplementals

Size–Mass Relation with observed size (PSF) & half-light size (no PSF)





- **10 pc half-cell resolution + 4x Jeans refinement**
- **Non-parametric local magneto-thermoturbulent star formation**
- **Mechanical supernova feedback**
- **Constraint Transport MHD**
- **On-the-fly radiative transfer for HI, HeI and HeII**
- **Cosmic rays diffusion and streaming**
- **10 different models, down to $z = 0.8$. More upcoming!**

$z = 10$

$z = 6$

$z = 5$

$z = 4$

$z = 3$

HD

HD-Boost

Full-Physics

0.06 arcsec
0.5 kpc

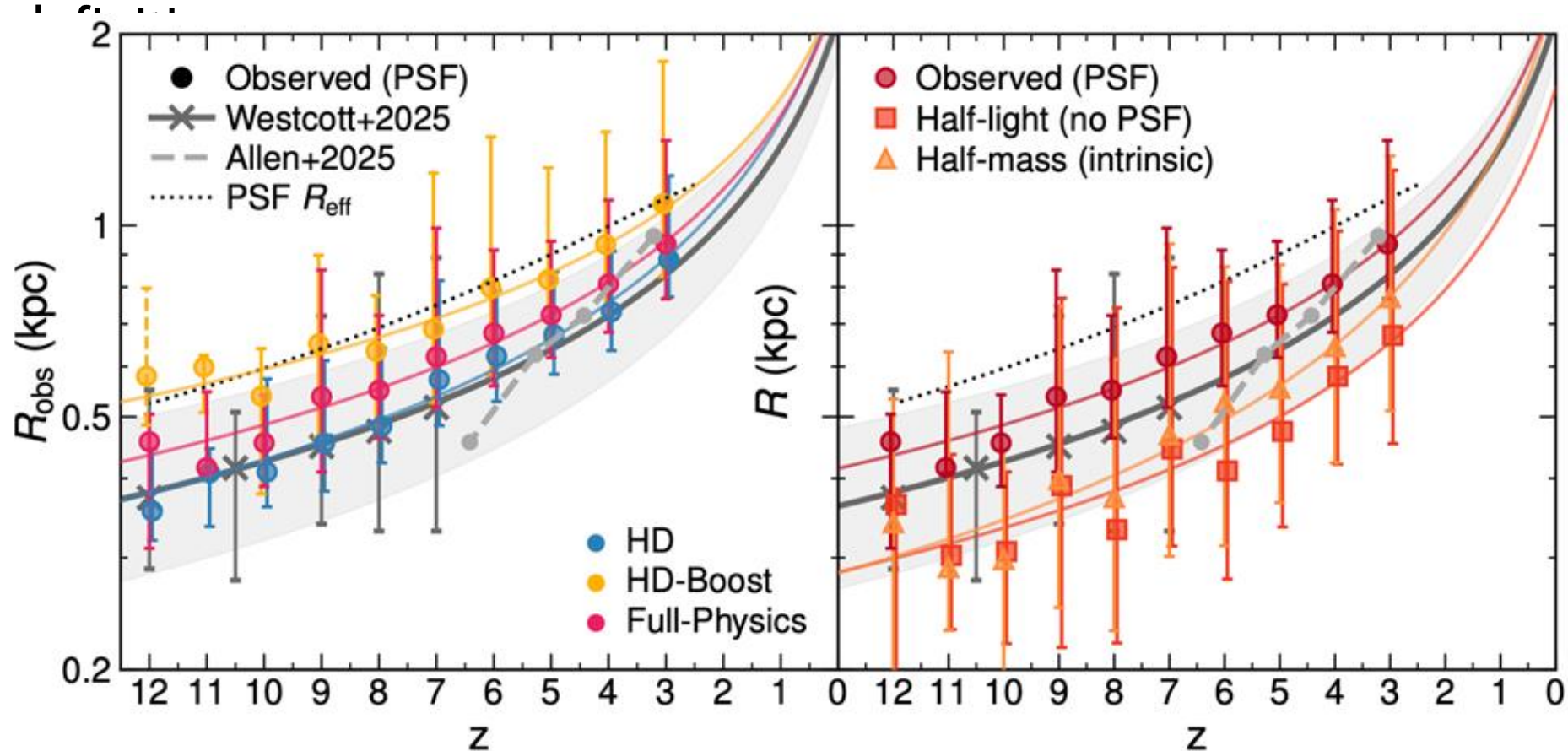
0.06 arcsec
0.5 kpc

0.06 arcsec
0.5 kpc

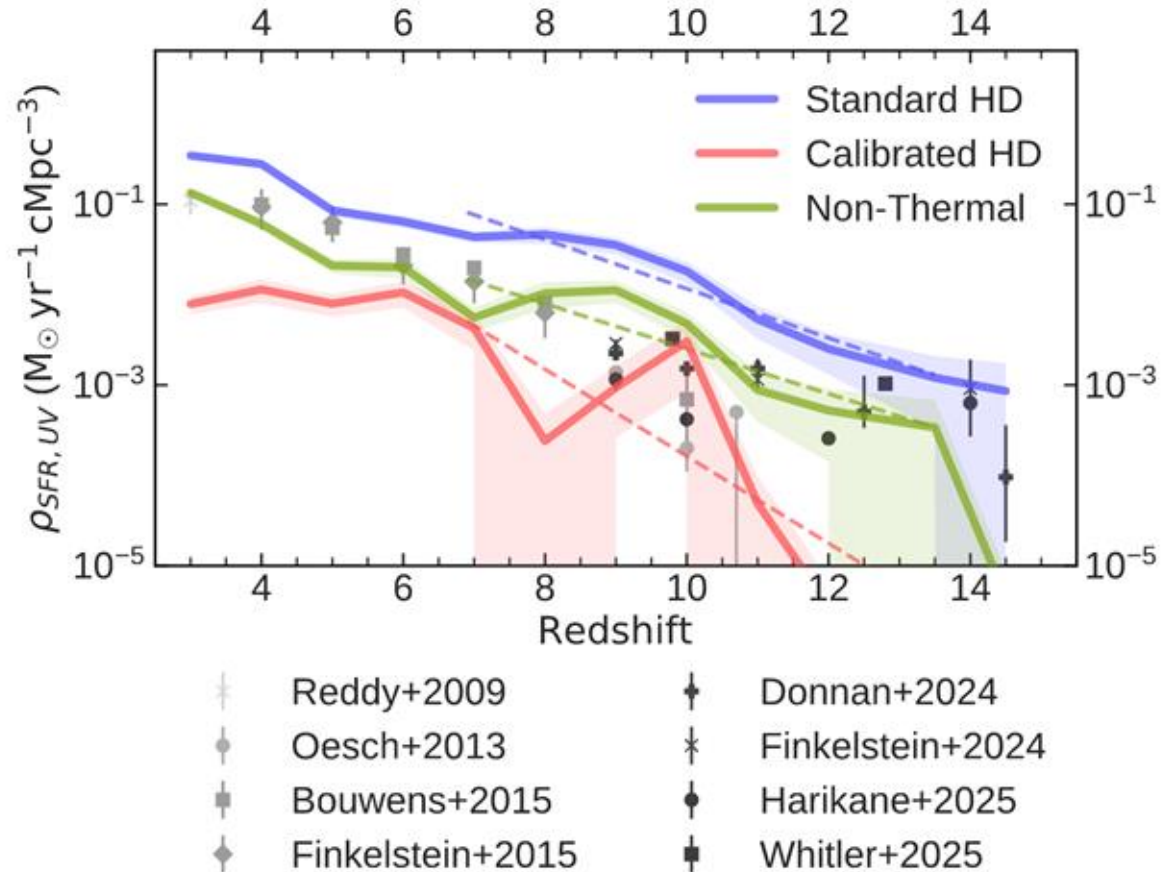
0.25 arcsec
2 kpc

0.63 arcsec
5 kpc

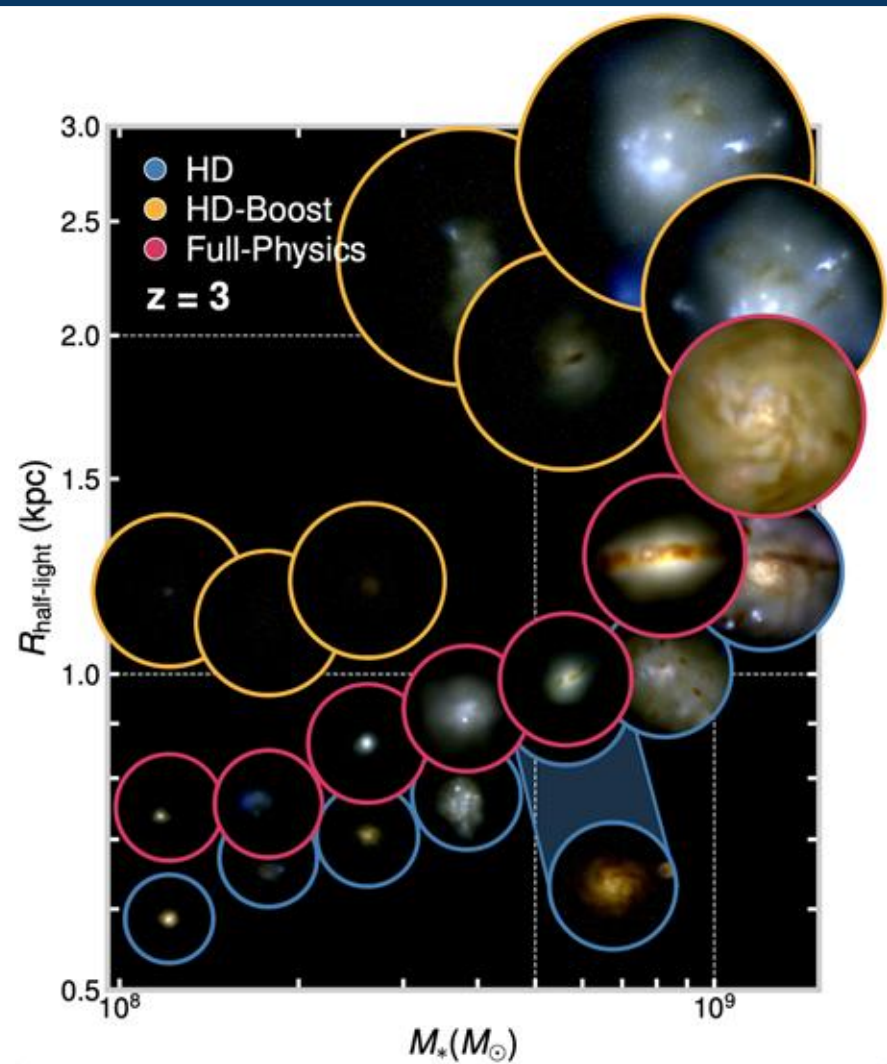
Redshift–Size Relation for all feedback models & size



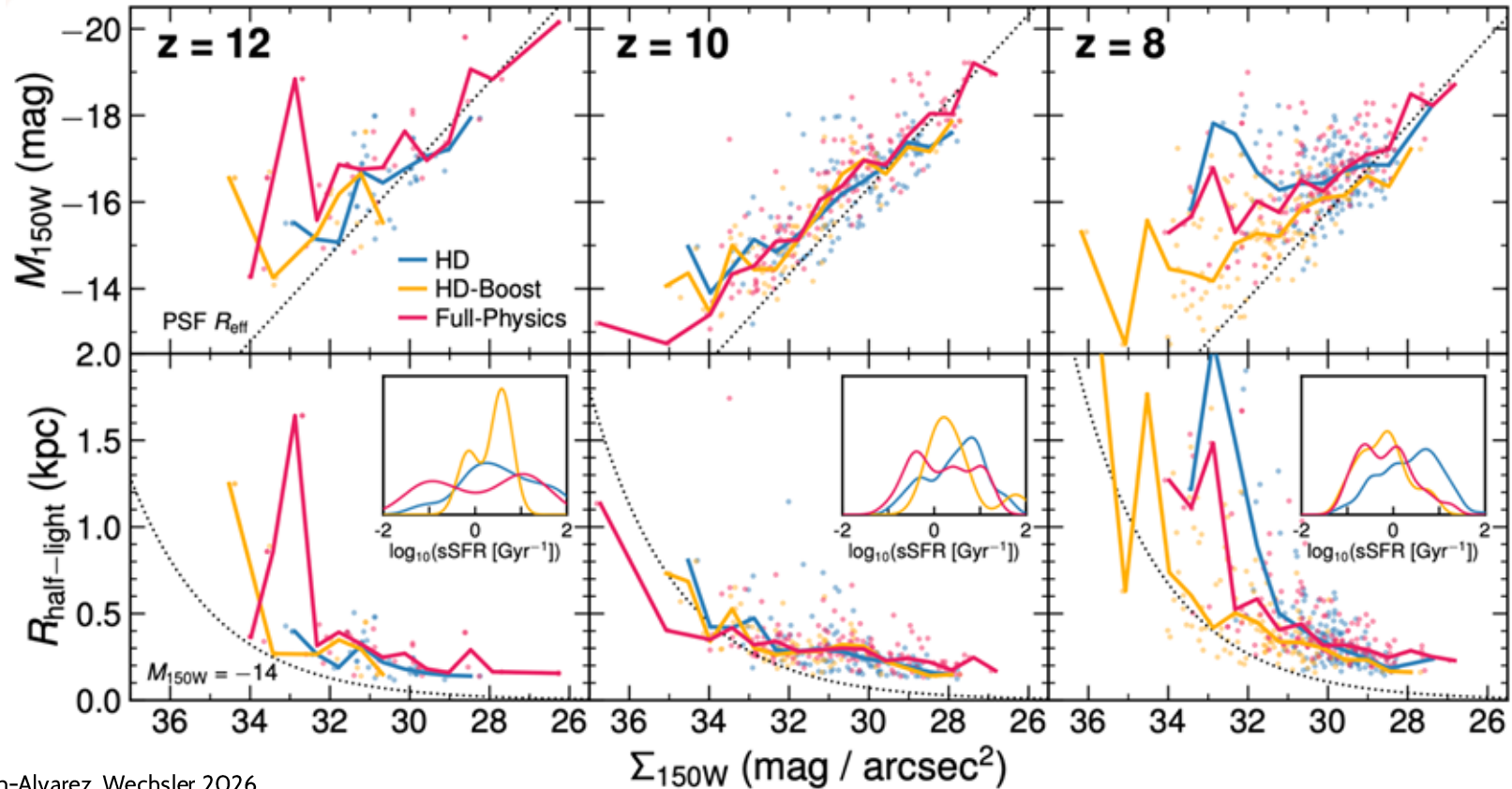
Cosmic SFR Density up to $z \sim 14$



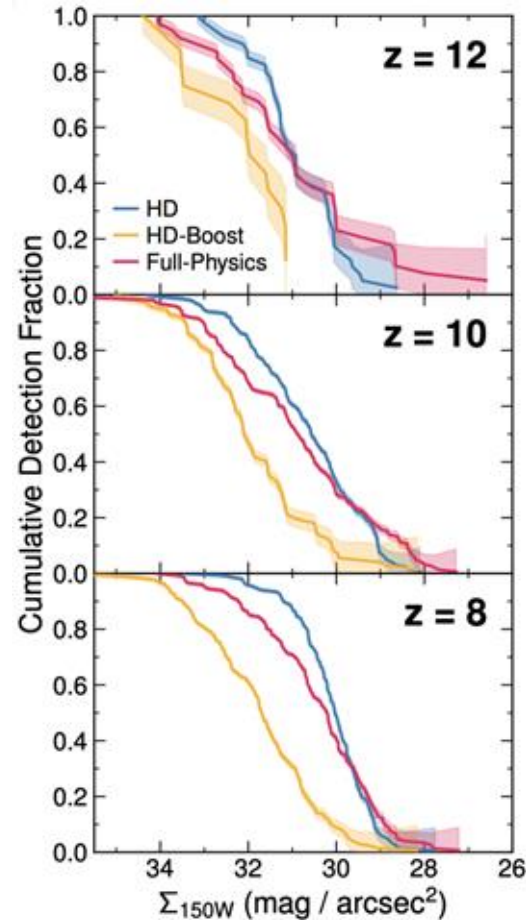
Size–Mass Relation with representative galaxy images



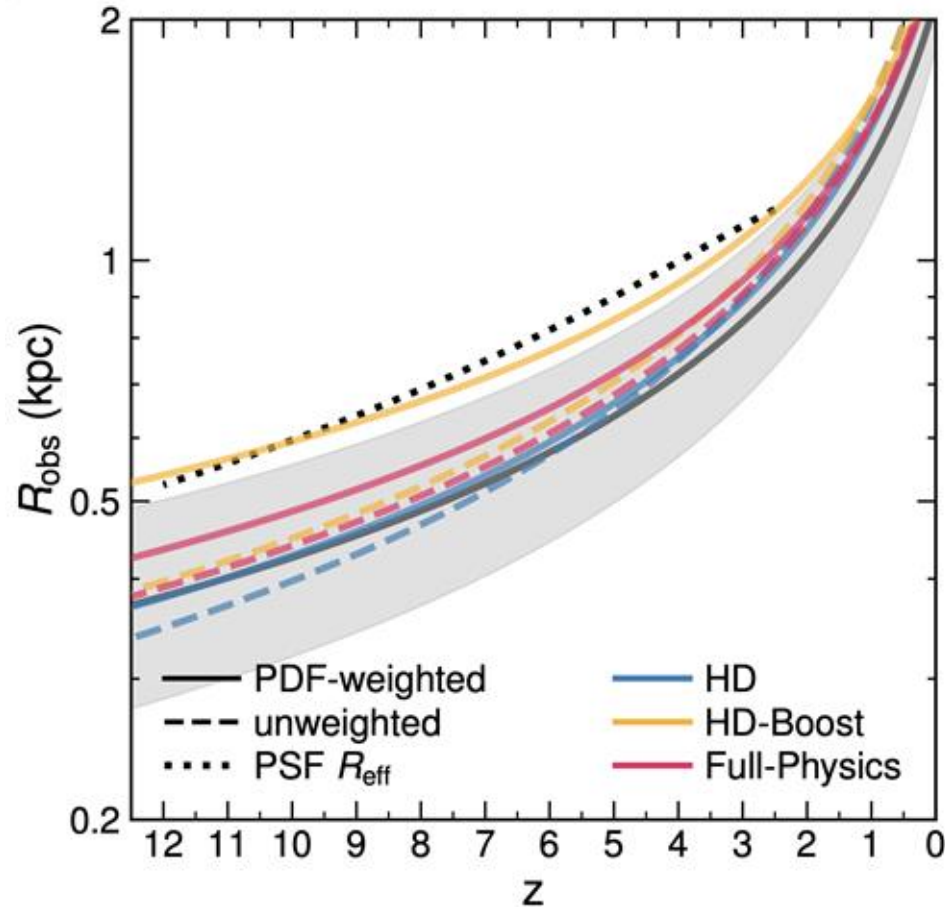
Surface Brightness Distribution with apparent magnitude in F150W & half-light size



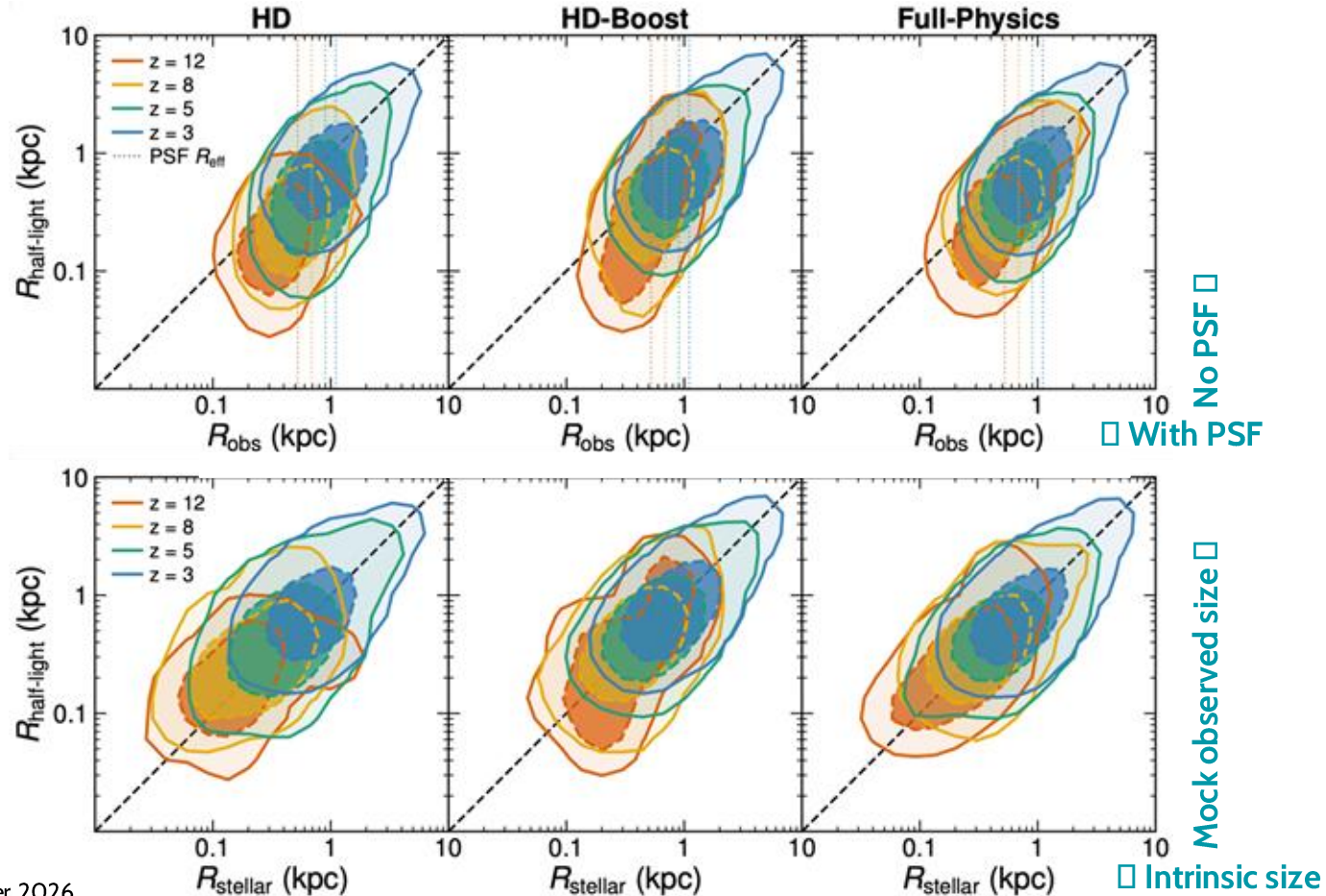
Cumulative Detection Fraction with surface brightness in F150W



With & Without Weighting to the EPOCHS Mass Distribution

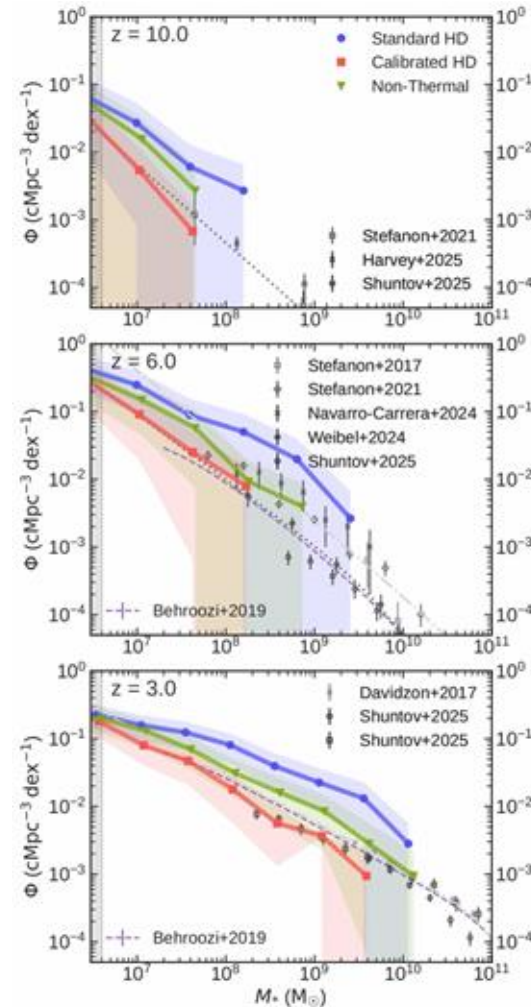


Size Comparison: with PSF $\neq$ without PSF, intrinsic $\neq$ observed

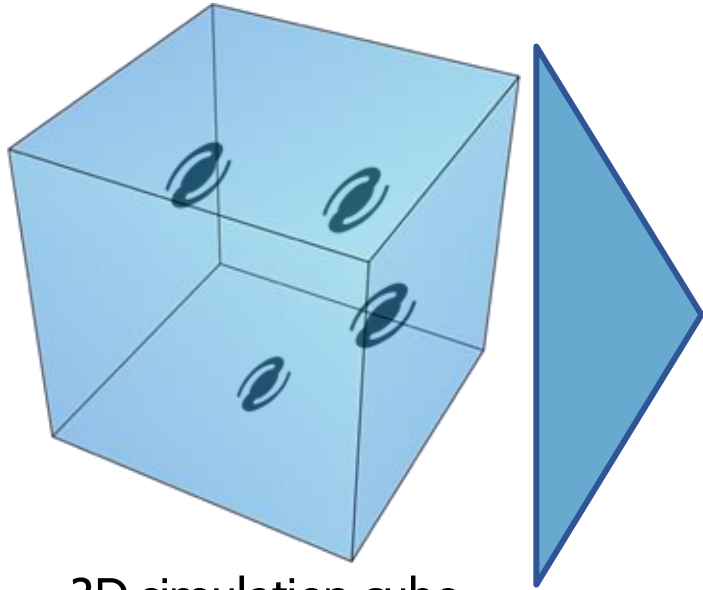


Galaxy Stellar Mass Function

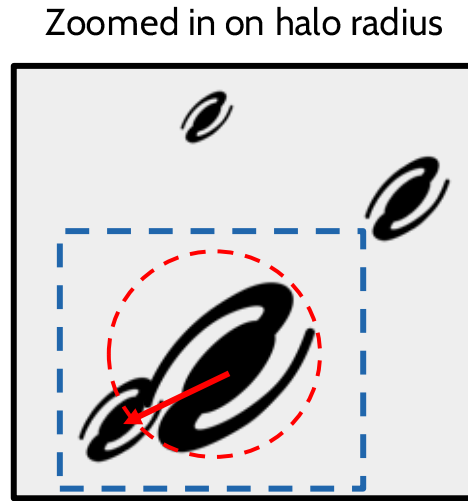
HD-Boost is the best fit by construction at $z = 3$.
The next-best is Full-Physics, which slightly over-predicts stellar masses.



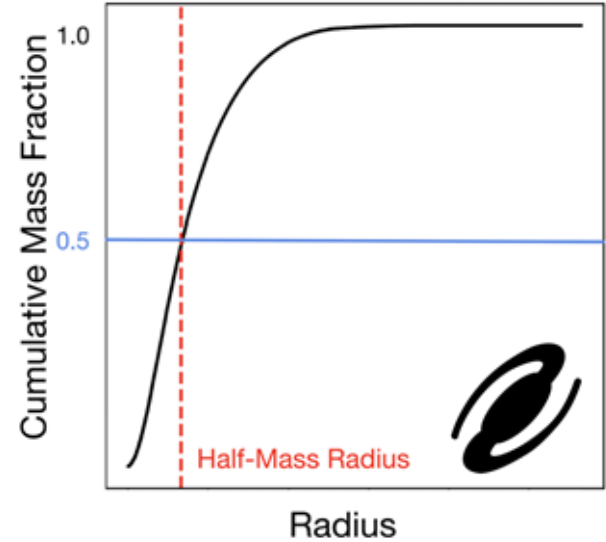
Measuring Galaxy Sizes



3D simulation cube

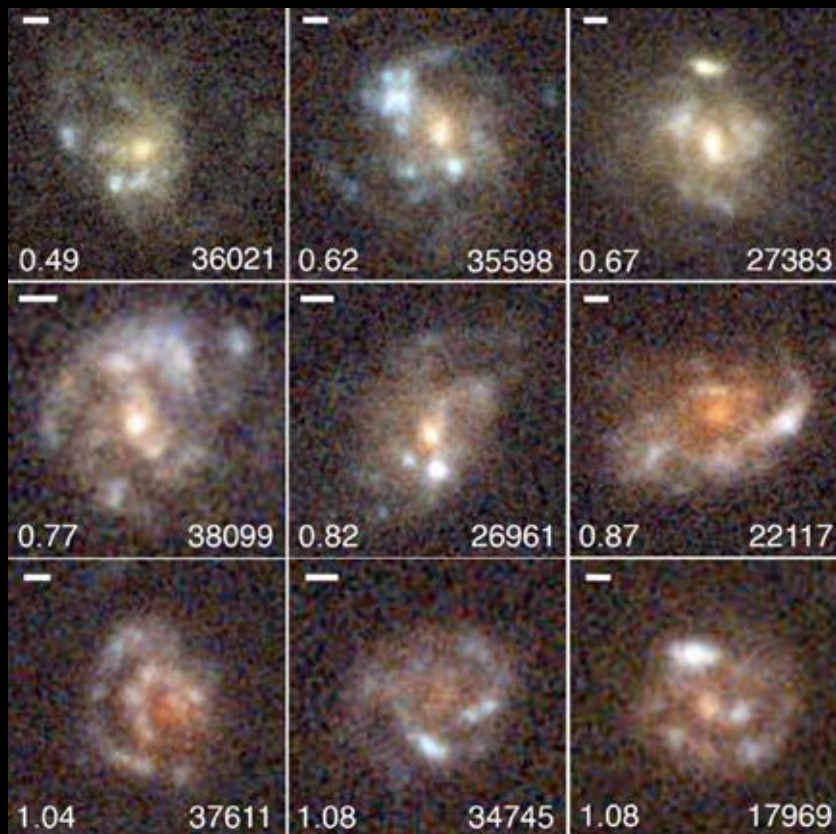


2D projection



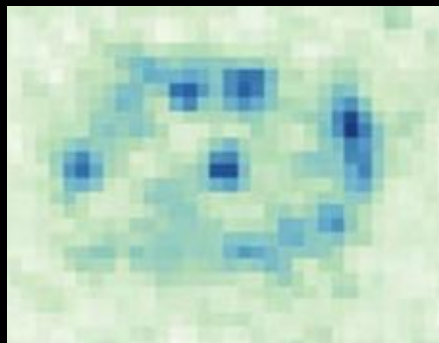
Measuring radius

Can we reproduce **clumpy galaxies** in the early universe?



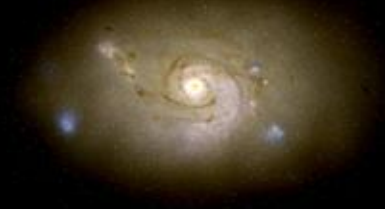
Elmegreen+2009

Observations



Sattari+2023

vs. HD
HD-Boost



vs. Full-Physics



and



Full-Physics produces **bright, clumpy galaxies** that match the early universe.