Understanding Galaxy Formation from Deep Hubble Images: The Forward-Modeling Approach

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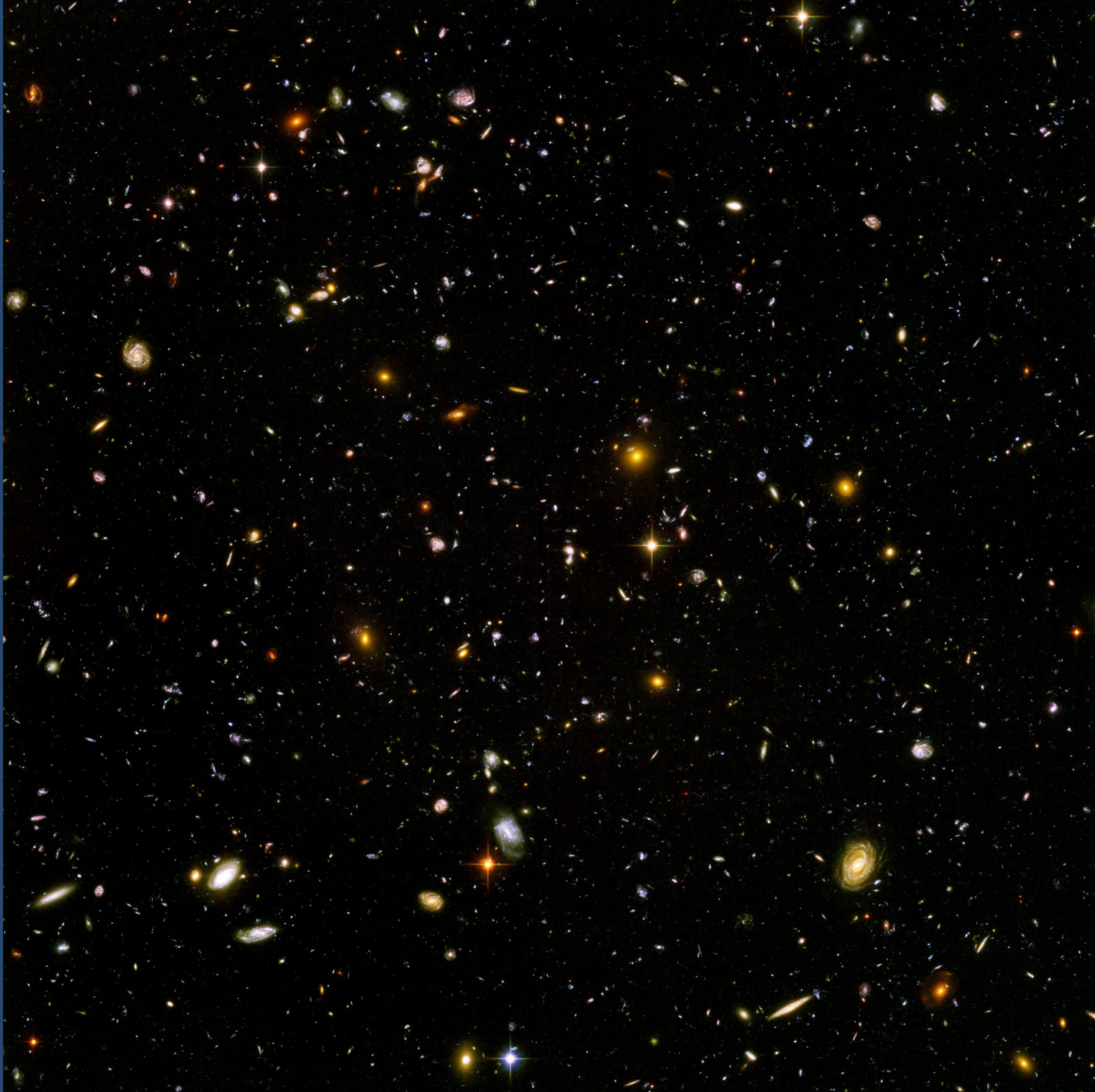
HUDF



Selection Biases

1. Flux limit: $f > f_{\text{lim}}$

2. Surface brightness limit: $I > I_{\text{lim}}$

Cosmological dimming in intensity: $I/I_0 = (1 + z)^{-4}$

$\Rightarrow$ I/I_0 = 1/256, 1/2401, 1/10,000 at z = 3, 6, 9

Cosmological dimming in magnitudes: $\Delta\mu = 10 \log (1 + z)$

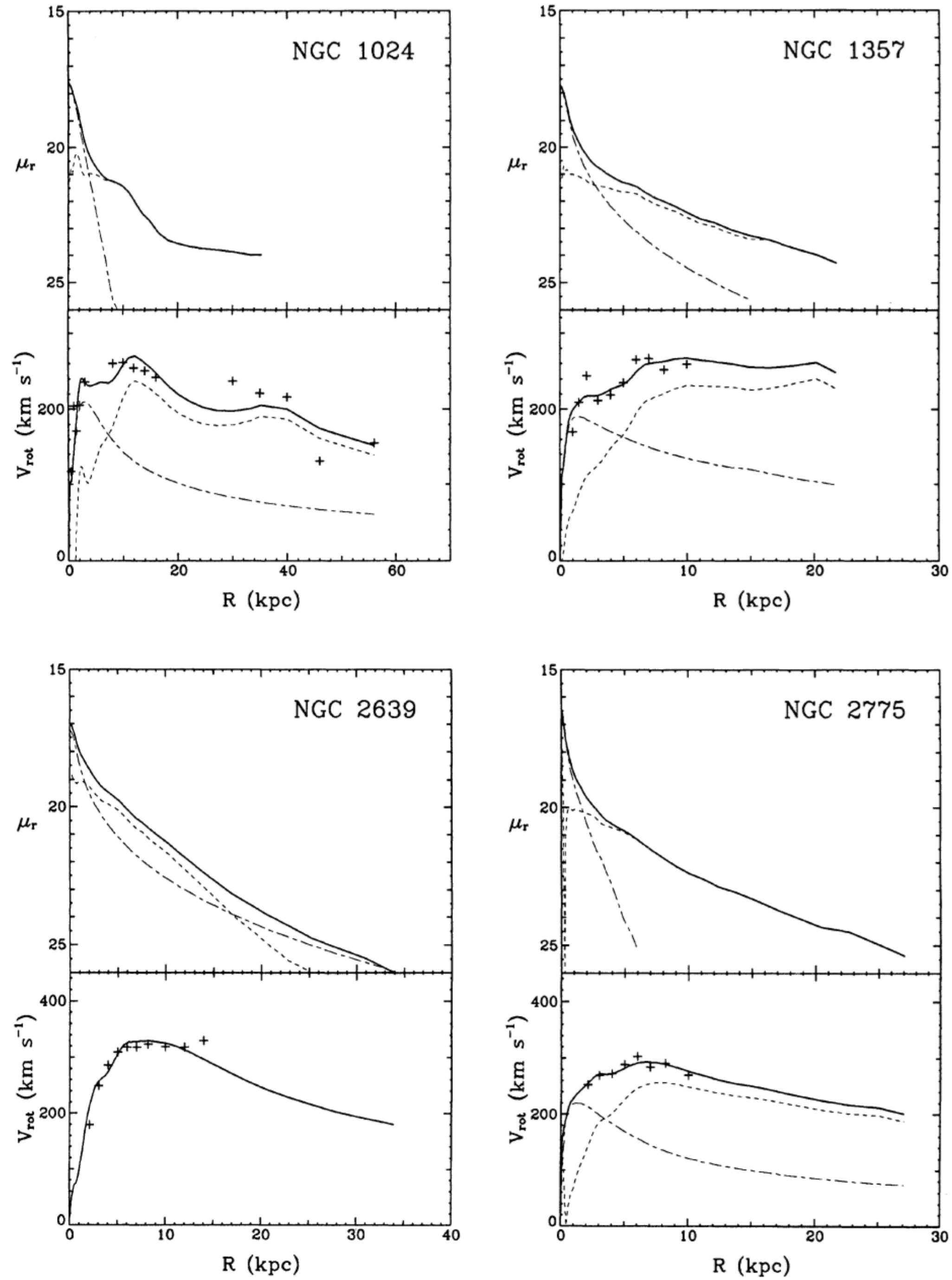
$\Rightarrow$ $\Delta\mu$ = 6.0, 8.5, 10.0 mag at z = 3, 6, 9

Typical Nearby Sa galaxies

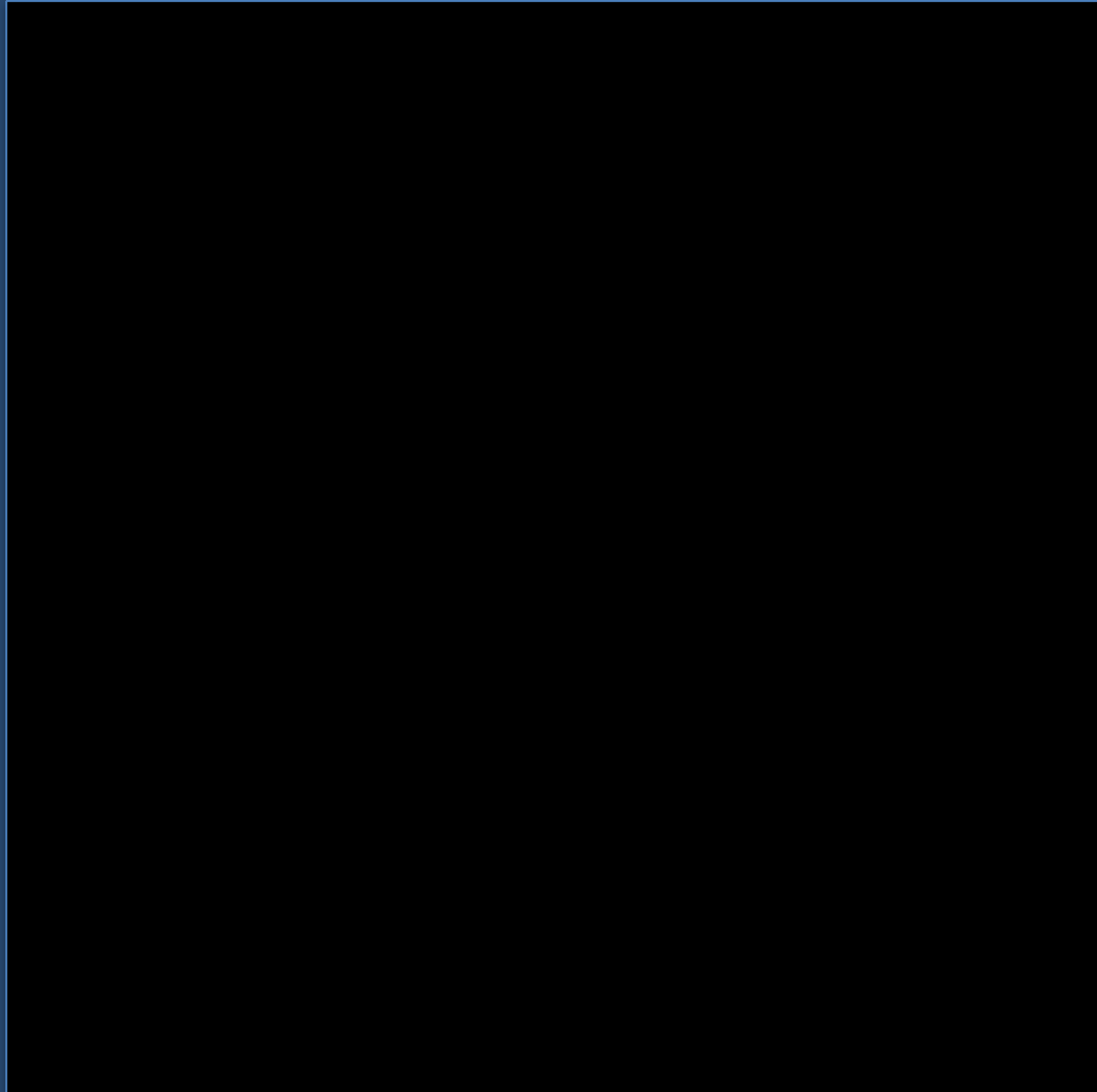
Surface brightness (mag) vs radius: upper panels

Rotation velocity vs radius: lower panels

Note: $\Delta\mu \sim 5$—10 mag



Mock HUDF for a galaxy popn at $z > 6$ like the one at $z = 0$



Degeneracy Among Models

M1(z) = model designed to match the observed properties of galaxies

M0(z) = any model with $f(\mathrm{z}) < f_{\mathrm{lim}}$ and $I(\mathrm{z}) < I_{\mathrm{lim}}$

M2(z) = M1(z) + M0(z)

Models M1 and M2 have exactly the same goodness of fit to observations (likelihood, chi-square, etc)

Forward Modeling

- Project theoretical models into the observational domain by creating mock images
- Impose the same selection biases on mock images as on real images
- Measure mock images in same way as real images
- Compare distributions of quantities measured from mock and real images
- Vary parameters of models and repeat above steps
- Determine which combinations of parameters give satisfactory agreement between mock and real distributions

Forward Modeling

In principle, FM can be applied to any type of model:

- Hydrodynamical
- Semi-Analystical
- Semi-Empirical

Illustrative semi-empirical models:

Manu Taghizadeh-Popp, Mike Fall, Rick White, Alex Szalay

Methods and first results published in ApJ, 801: 14 (2015)

A Toy Universe

- Merger trees from a cosmological dark matter simulation (Millennium in our case)
- An imposed stellar mass-halo mass relation for galaxies, $M_s(M_h,z)$ (four options in our case)
- An imposed stellar radius-halo radius relation for galaxies, $R_s(R_h,z)$ (three options in our case)
- A prescription for the internal structure of galaxies (rescaled images of SDSS galaxies in our case)
- Software to generate mock images, including all relevant cosmological and instrumental effects

Illustrative Models

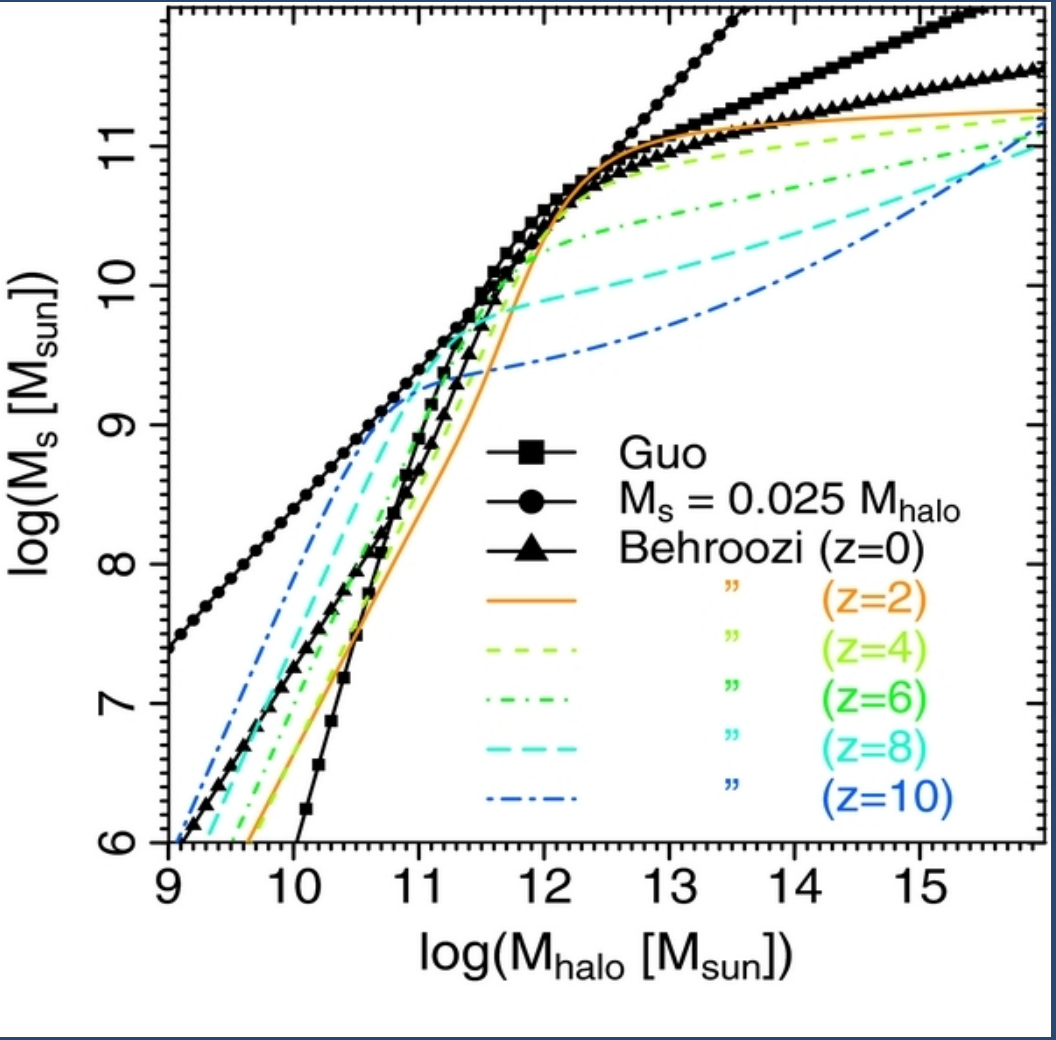
Reference model:

- Non-evolving SMHM relation
- Solar metallicity
- Dust included
- Galaxy size proportional to halo size

Other models change one parameter at a time:

- Evolving SMHM relation
- Low metallicity
- No dust
- Non-evolving galaxy size-mass relation

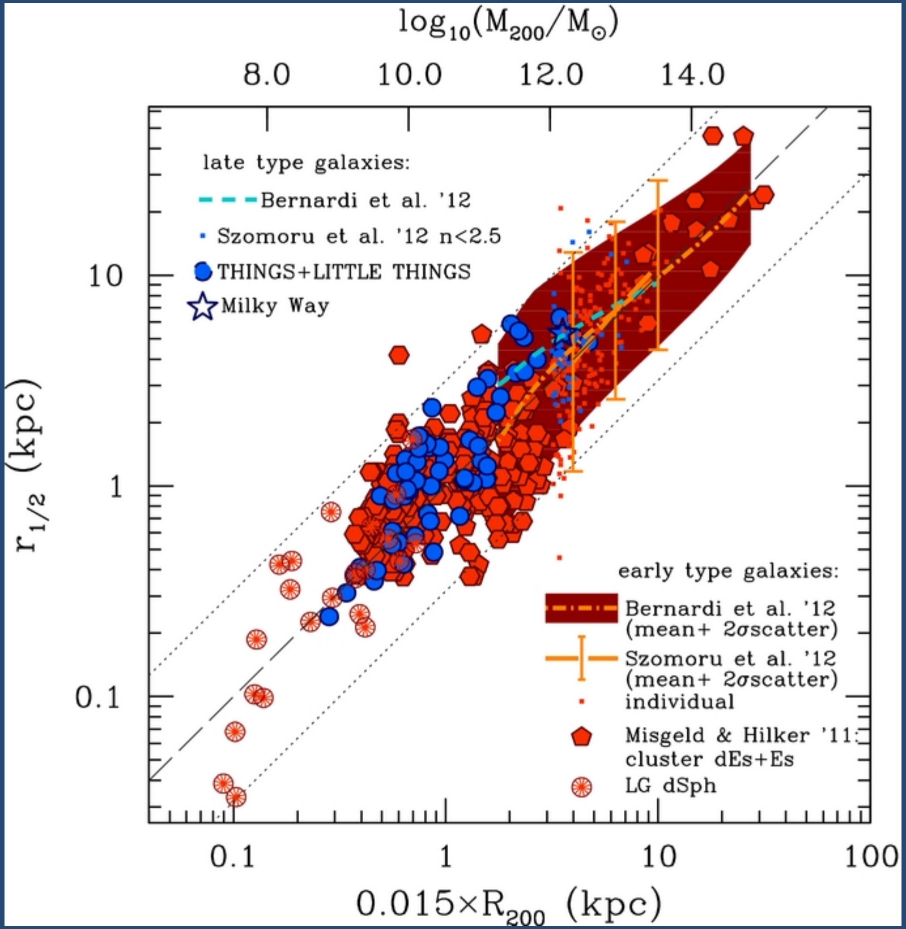
Adopted Stellar Mass-Halo Mass Relations



Adopted Galaxy Size-Halo Size Relations

Reference model
$R_s = \text{const} \times R_h$
(Kravtsov 2013)

Alternative model
$R_s = R_s(M_s, z = 0)$
present-day radius-mass relation

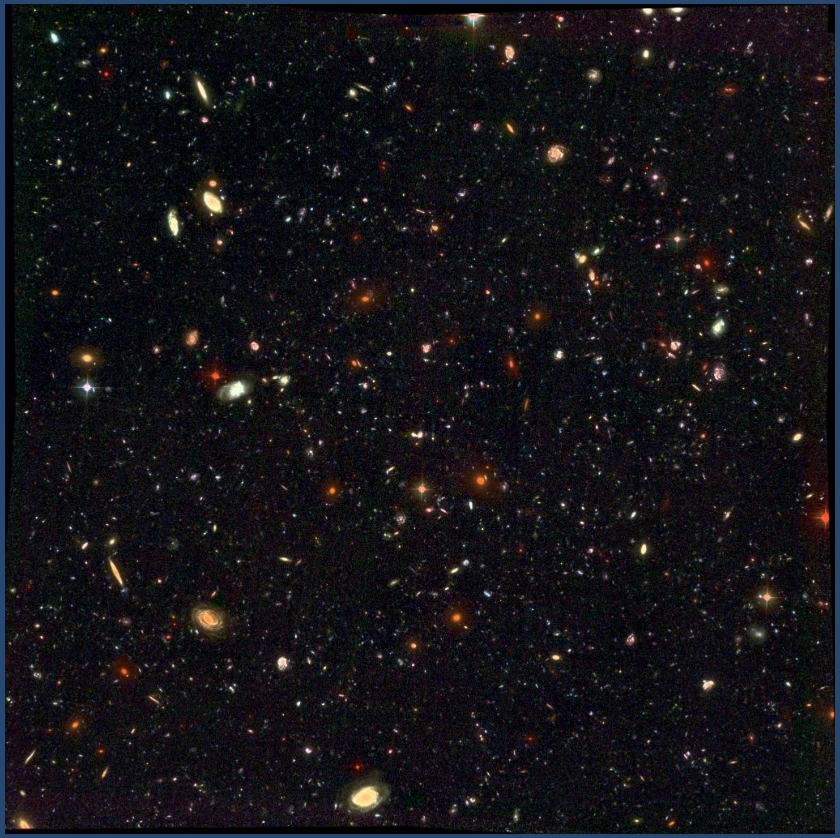


Comparison of Mock Image with Real Image

HUDF depth: f850lp, f606w, f435w filters

Mock HST image

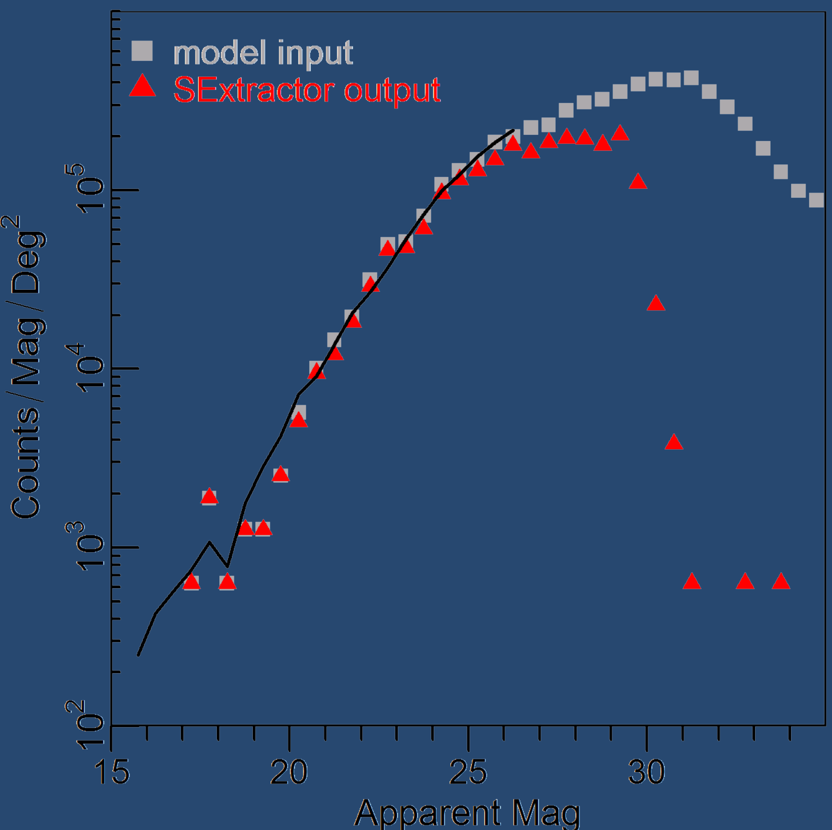
Reference model



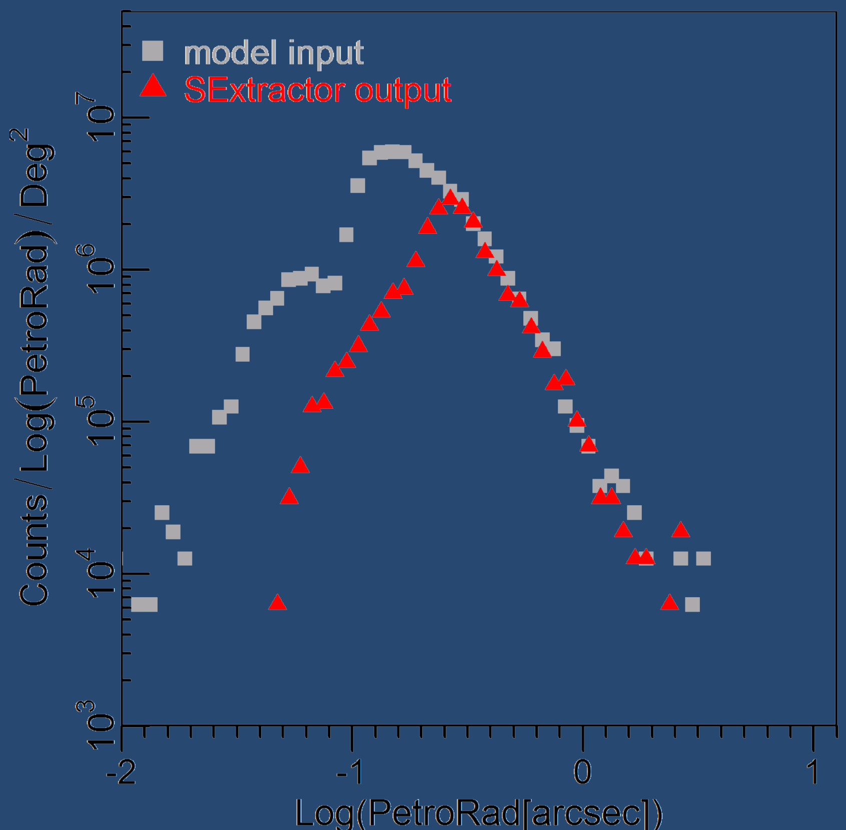
Real HST image

Comparison of Input and Output Distributions

Mock HST image, Reference model
HUDF depth, f160w filter



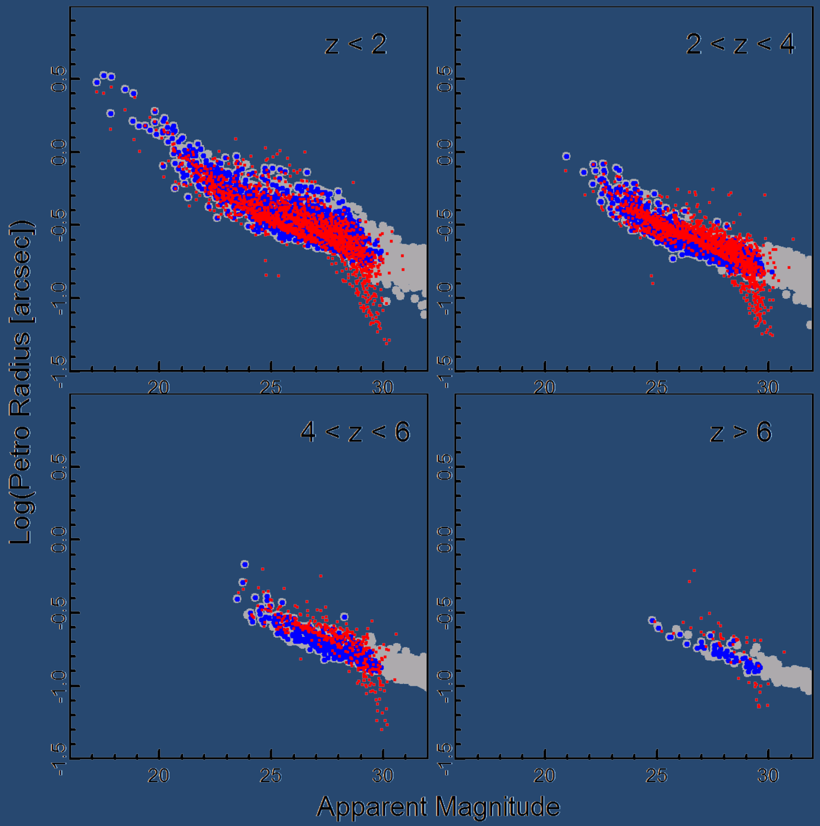
Apparent luminosity distribution (from SExtractor)



Apparent size distribution (from SExtractor)

Detection Efficiency with SExtractor

Mock HST image, Reference model
HUDF depth (f160w), Redshift slices



GRAY: all galaxies, input values

BLUE: SExtracted galaxies, input values

RED: SExtracted galaxies, output values

Lessons Learned

1. For $z < 3$, a constant SMHM relation $M_s(M_h,z)$ and a constant GSHS relation $R_s(R_h,z)$ provide good fits to deep HST images.

2. For $z > 3$ (especially $z > 6$), forward modeling and backward modeling (the usual method) give different results.

3. For $z > 6$, be skeptical of any statistical results not derived by forward modeling.

Merci

Selection Biases

1. Flux limit:

   Familiar

2. Surface brightness limit:

   Cosmological dimming in intensity: $I/I_0 = (1 + z)^{-4}$

   $\Rightarrow$ $I/I_0 = 1/256,\ 1/2401,\ 1/10{,}000$ at $z = 3, 6, 9$

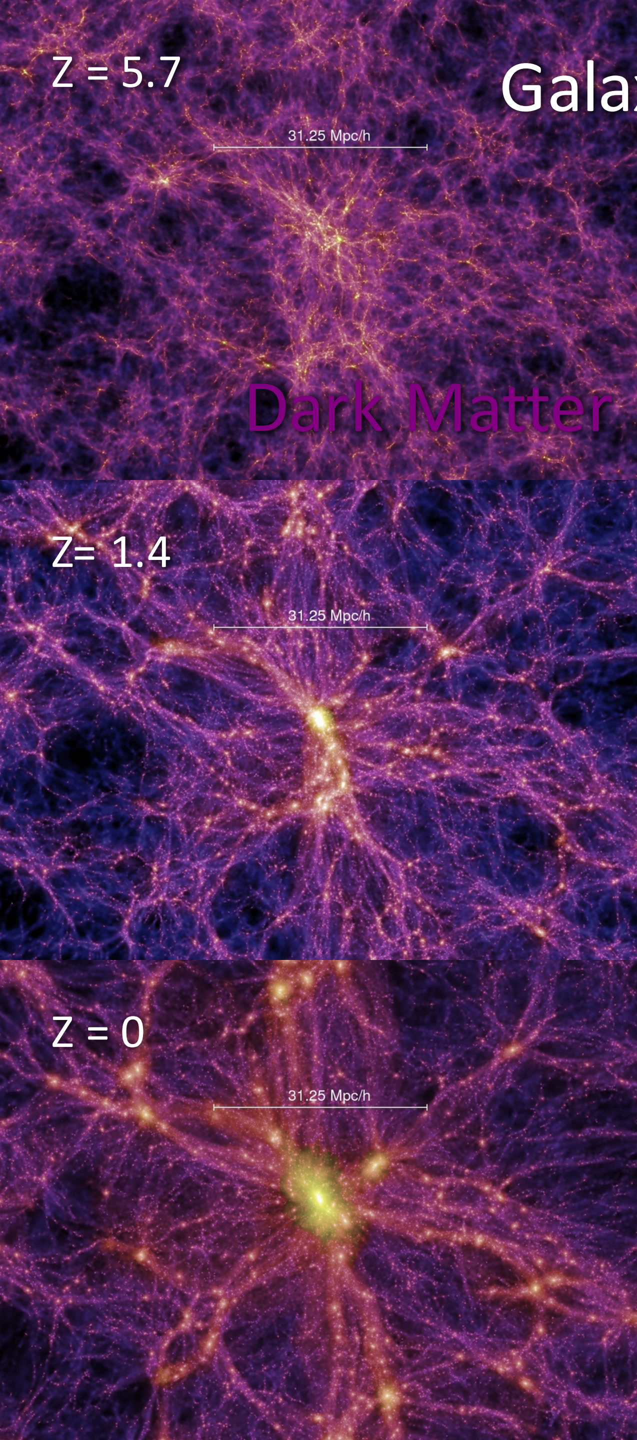
   Cosmological dimming in magnitudes: $\Delta\mu = 10 \log (1 + z)$

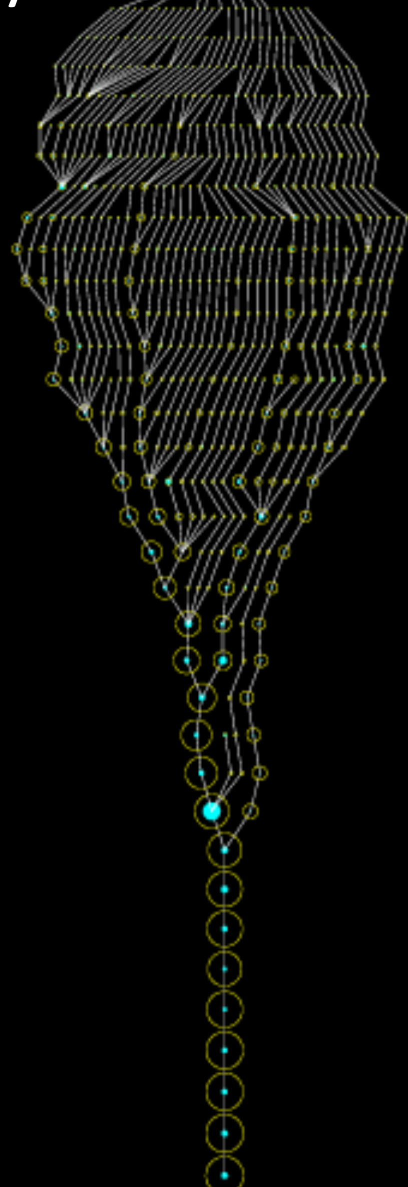
   $\Rightarrow$ $\Delta\mu = 6.0,\ 8.5,\ 10.0$ mag at $z = 3, 6, 9$

   Radial factor for exponential profile: $r/r_d = 4 \ln (1 + z)$

   => $r/r_d = 5.5,\ 7.8,\ 9.2$ at $z = 3, 6, 9$

Galaxy Formation Ingredients



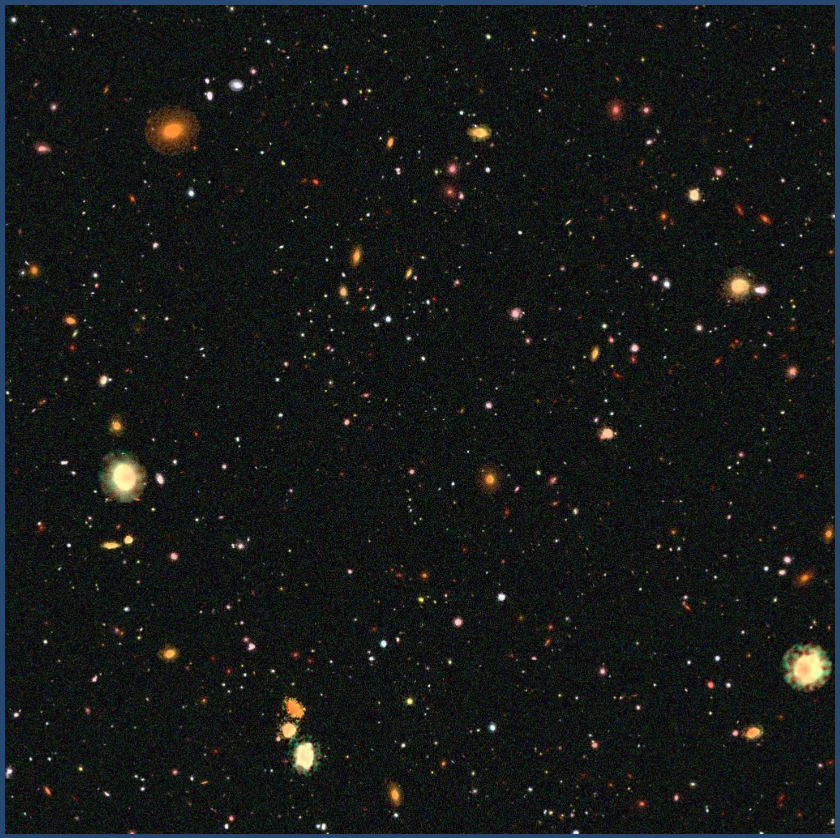


Baryons

- Shock heating and radiative cooling
- Merging and Inflow
- Star formation: quiescent and burst
- Feedback: stellar and AGN
- Chemical evolution
- Stellar populations
- Radiative transfer: dust
- BH and AGN evolution

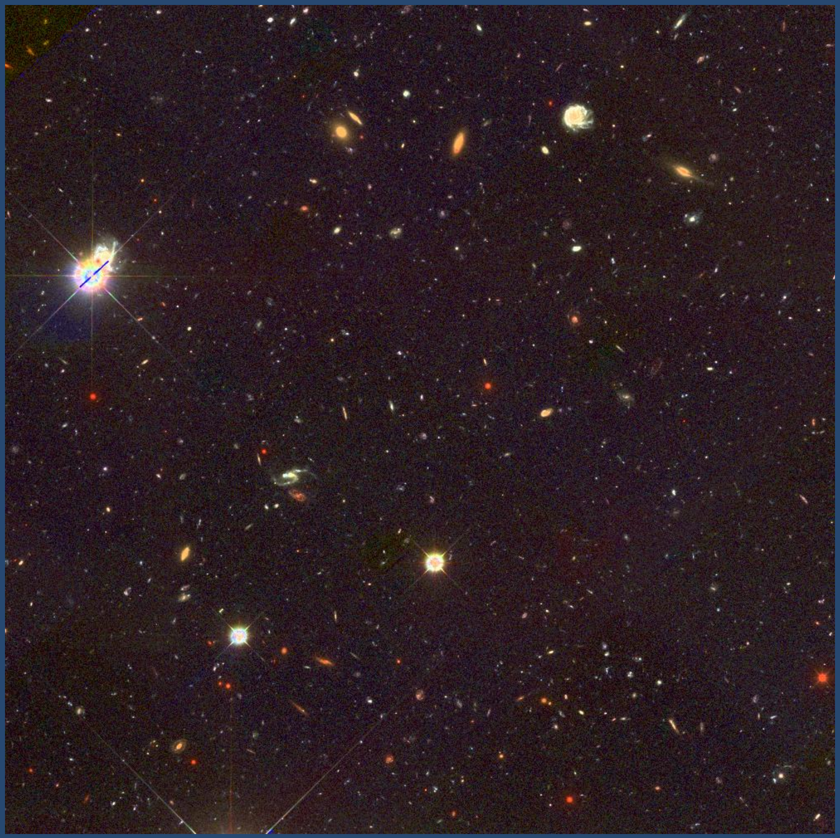
Comparison of mock image with real image

GOODS depth: f850lp, f606w, f435w filters



Mock HST image

Reference model



Real HST image

Comparison of mock images

HUDF depth: f850lp, f606w, f435w filters

Mock HST image

Reference model

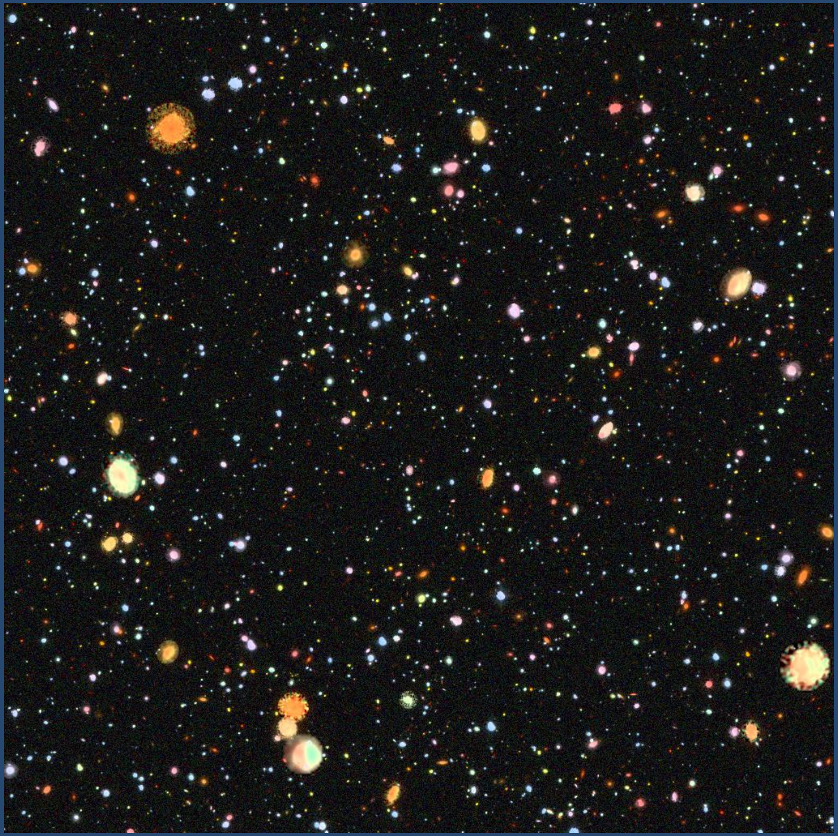
Mock HST image

Low metallicity

Comparison of mock images

HUDF depth: f850lp, f606w, f435w filters

Mock HST image
Reference model



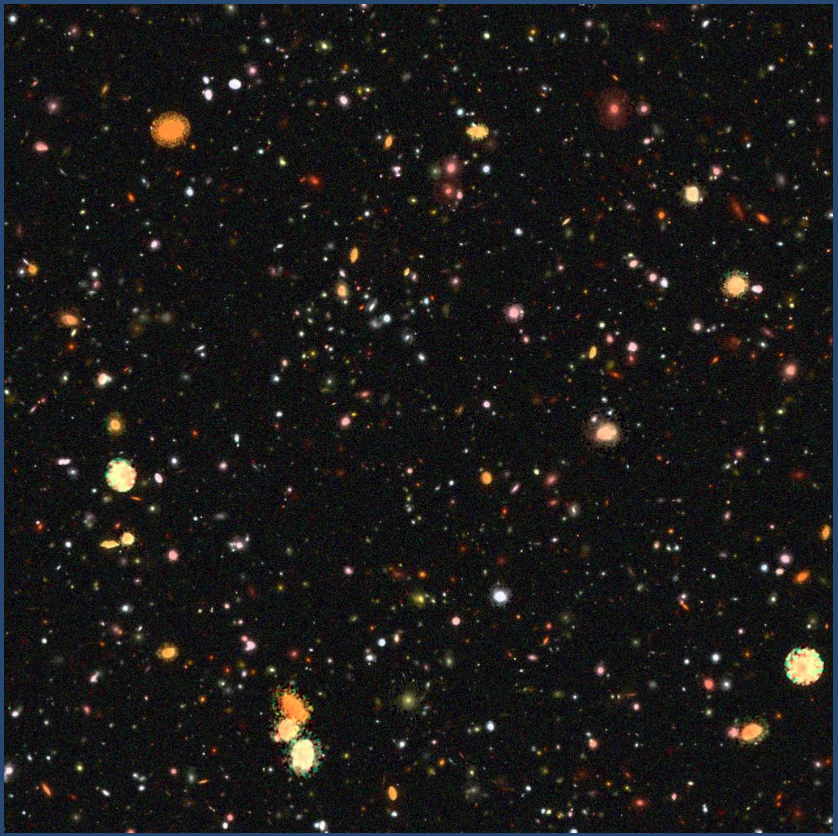
Mock HST image
No dust

Comparison of mock images

HUDF depth: f850lp, f606w, f435w filters

Mock HST image

Reference model

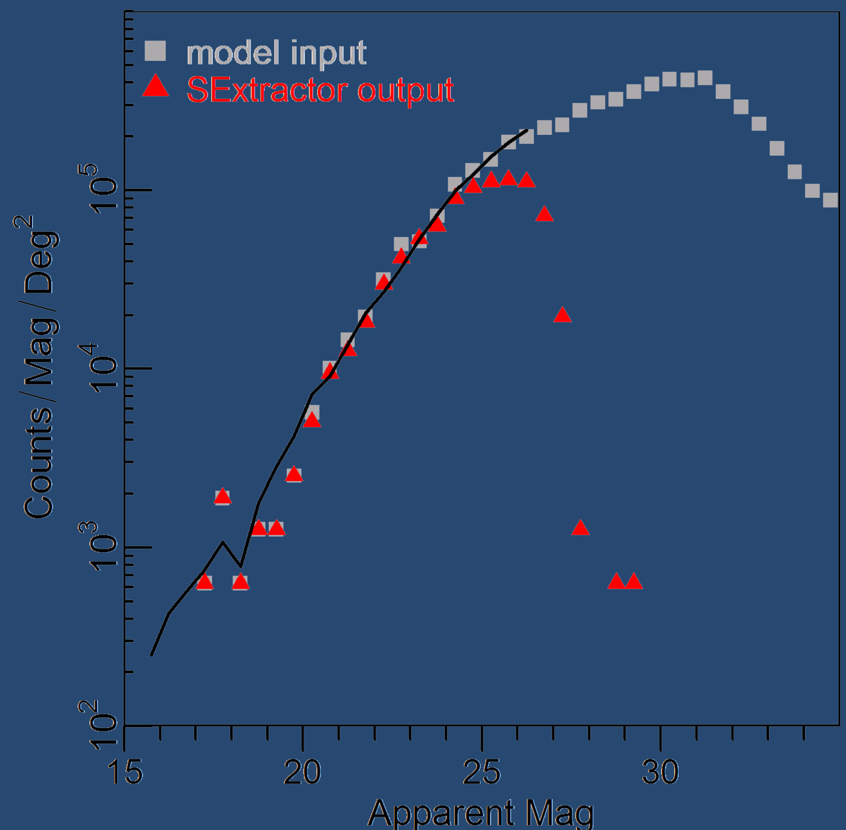


Mock HST image

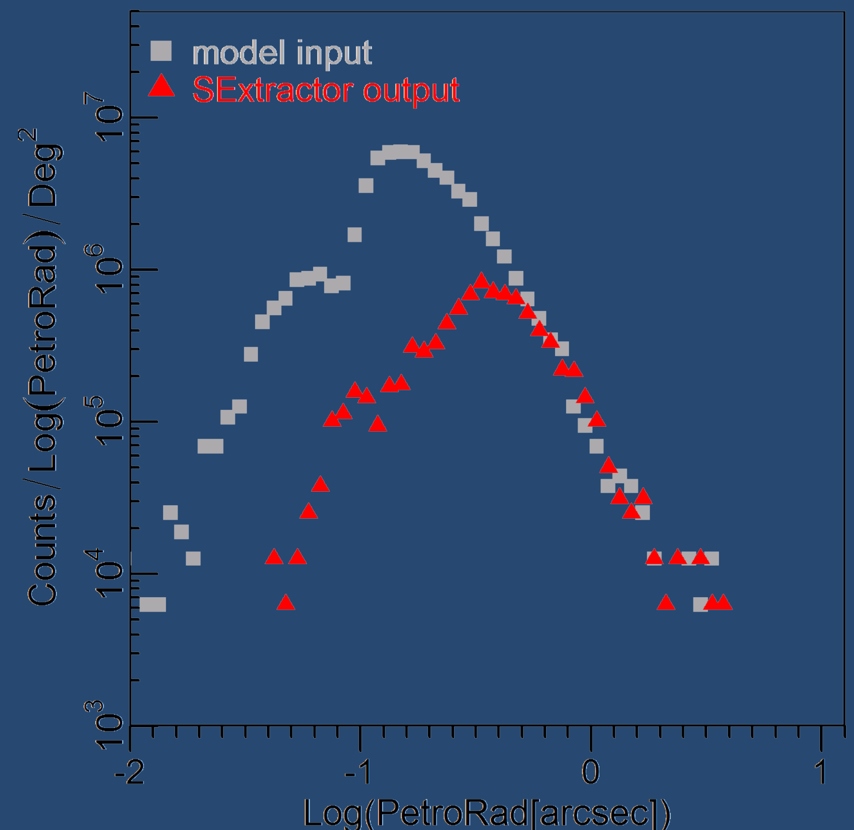
No scaling to halo size

Comparison of input and output distributions

Mock HST image, Reference model
GOODS depth, f160w filter



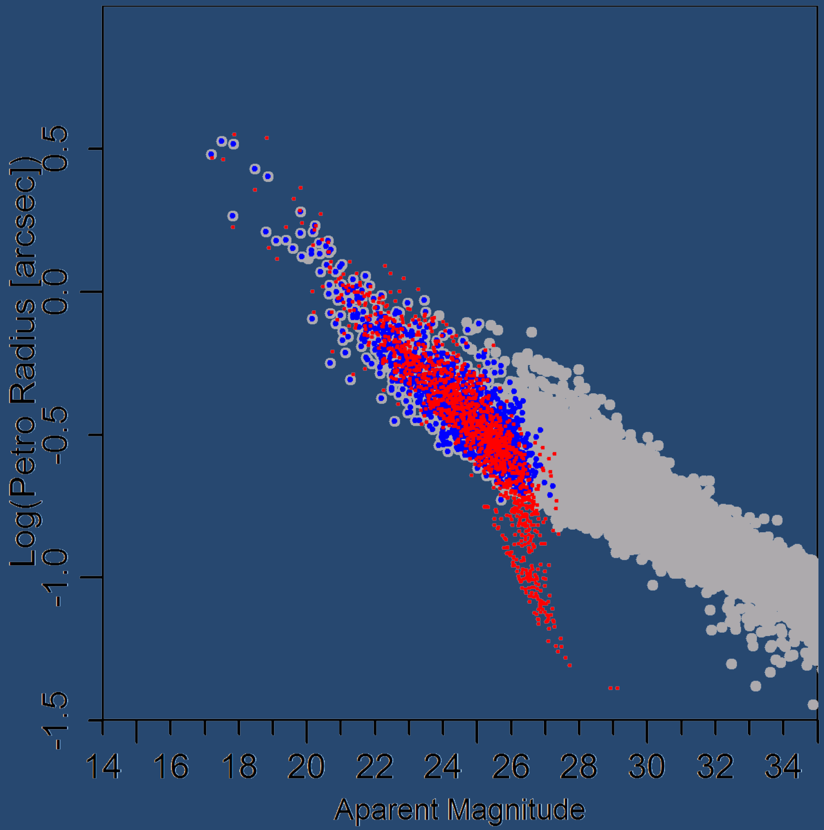
Apparent luminosity distribution
(from SExtractor)



Apparent size distribution
(from SExtractor)

Detection efficiency with SExtractor

Mock HST image, Reference model
GOODS depth (f160w), All redshifts



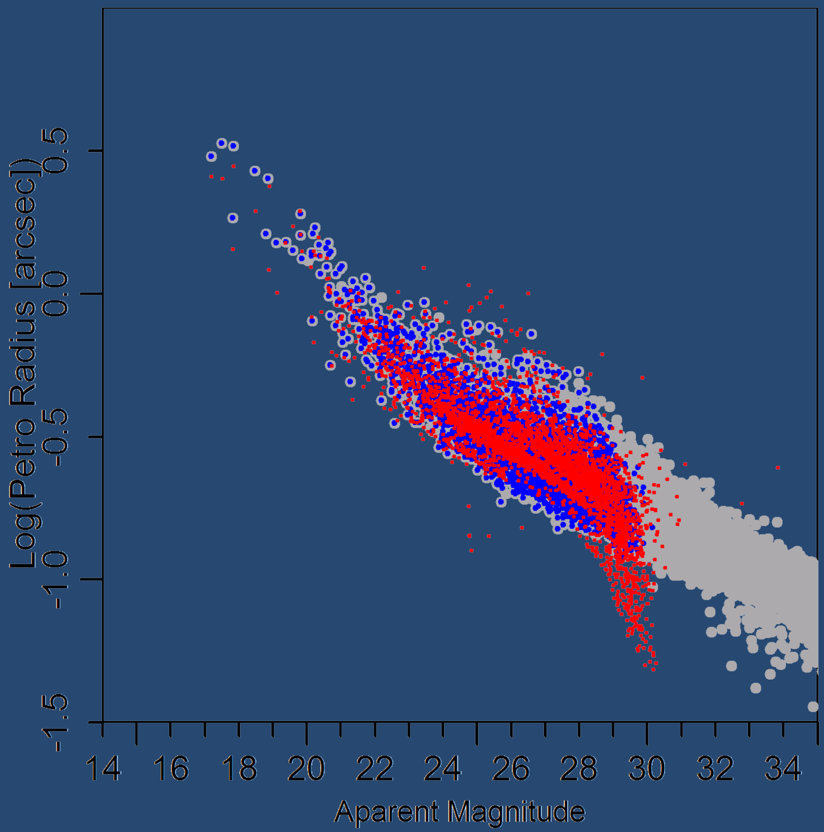
GRAY: all galaxies, input values

BLUE: SExtracted galaxies, input values

RED: SExtracted galaxies, output values

Detection efficiency with SExtractor

Mock HST image, Reference model
HUDF depth (f160w), All redshifts



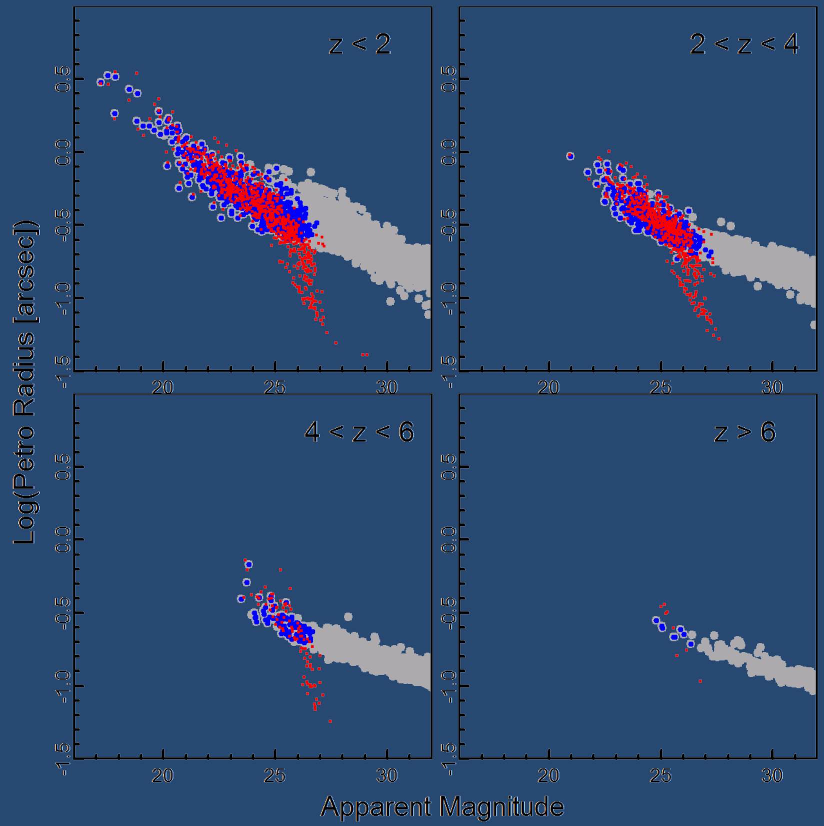
GRAY: all galaxies, input values

BLUE: SExtracted galaxies, input values

RED: SExtracted galaxies, output values

Detection efficiency with SExtractor

Mock HST image, Reference model
GOODS depth (f160w), Redshift slices



GRAY: all galaxies, input values

BLUE: SExtracted galaxies, input values

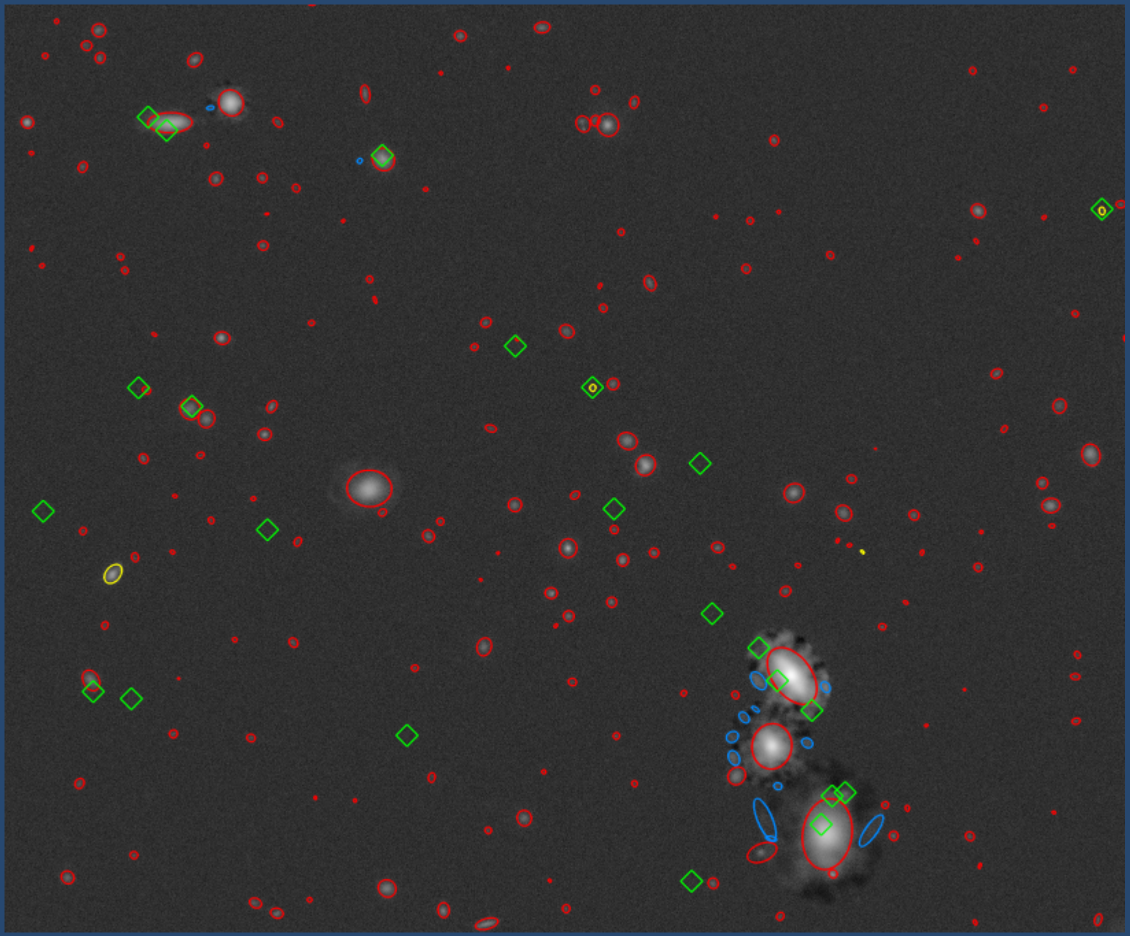
RED: SExtracted galaxies, output values

Mock HST image detail

GREEN : galaxies not detected by SExtractor in the range 24 < f160w < 26

BLUE : Spurious SExtractor detections

RED: Unique match between model input and SExtractor output



Conclusions

1. Proof of concept. We have a working model. Software written and tested.

2. For $z < 3$, a constant SMHM relation $M_s(M_h,z)$ and a constant SRHR relation $R_s(R_h,z)$ provide good fits to deep HST images according to the forward-modeling approach.

Future I

1. Determine the "optimal" SMHM and SRHR relations, $M_s(M_h,z)$ and $R_s(R_h,z)$, as functions of M_h, R_h, and z, by forward modeling.

2. Technical improvements:

   - Larger dark matter simulation
   - Evolving metal and dust content
   - Alternative internal structures of galaxies

Future II

1. JWST

2. Apply FM to other types of simulation:
   - Hydrodynamical
   - Semi-analytical

Number and light detection efficiencies