Tests of ΛCDM on small scales

Carlos S. Frenk
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Observational tests of ΛCDM

Fundamental prediction of ΛCDM

→ Primordial power spectrum of density perturbations

+ random phases

Can test this in two regimes:

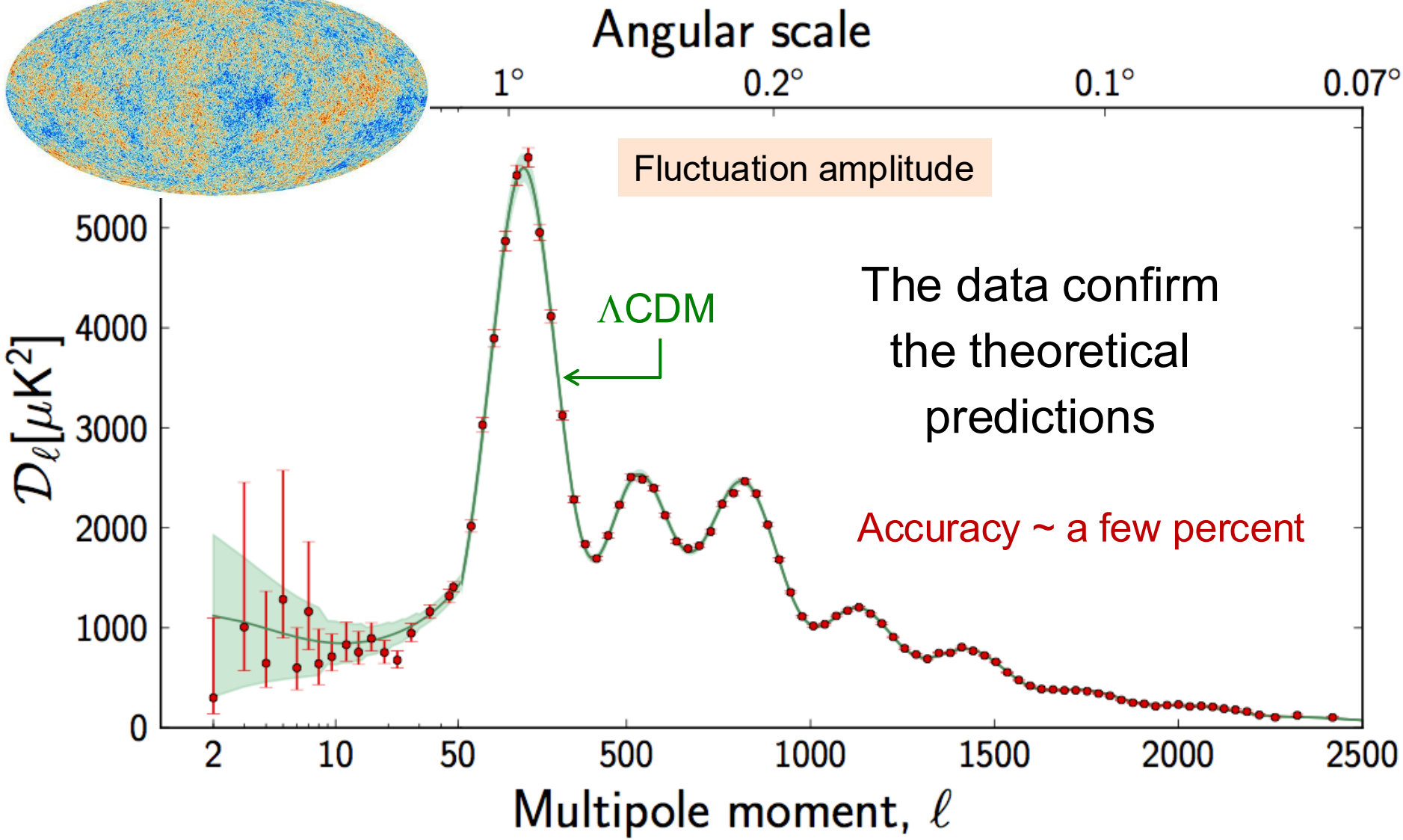
Linear regime: cosmic microwave background (z~1000)

large-scale structure (z~3 - 0)

Evolved non-linear regime: dark matter halos →

- abundance (z~15 – 0)
- structure
- clustering

Planck: CMB temperature anisotropies

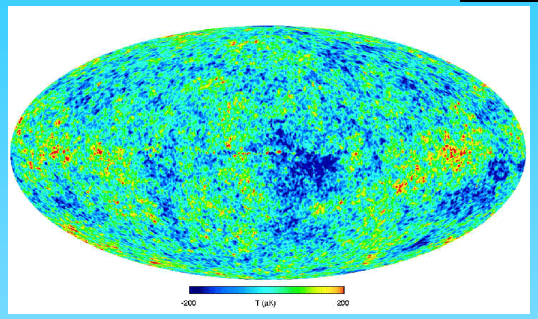


The data confirm the theoretical predictions

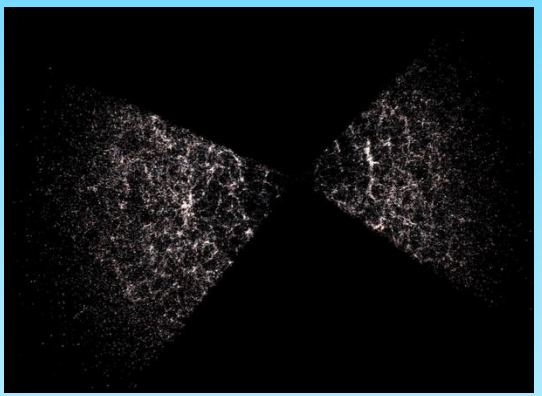
Accuracy ~ a few percent

Planck coll. 2015

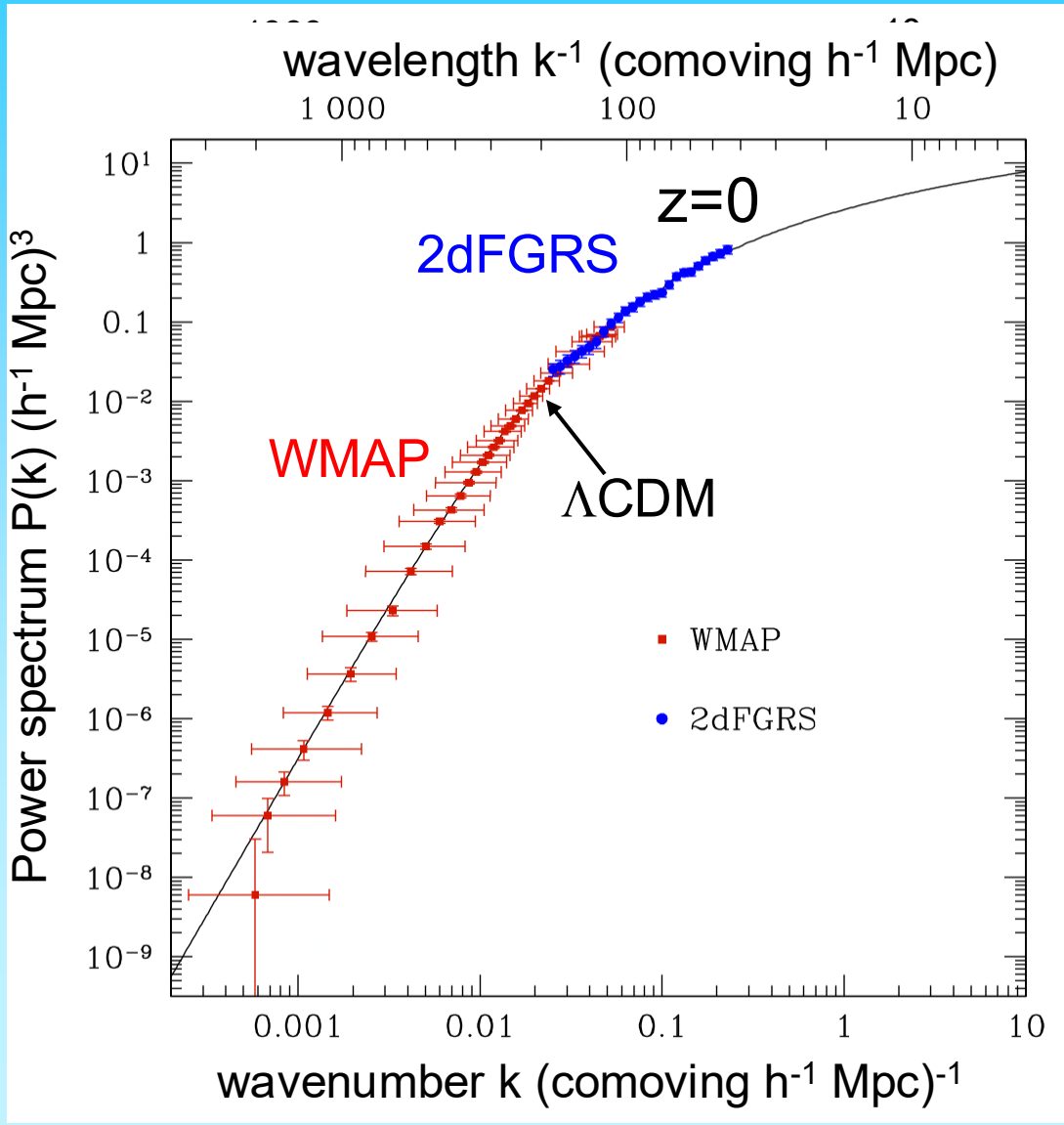
The cosmic power spectrum: from the CMB to the 2dFGRS



z~1000



z~0



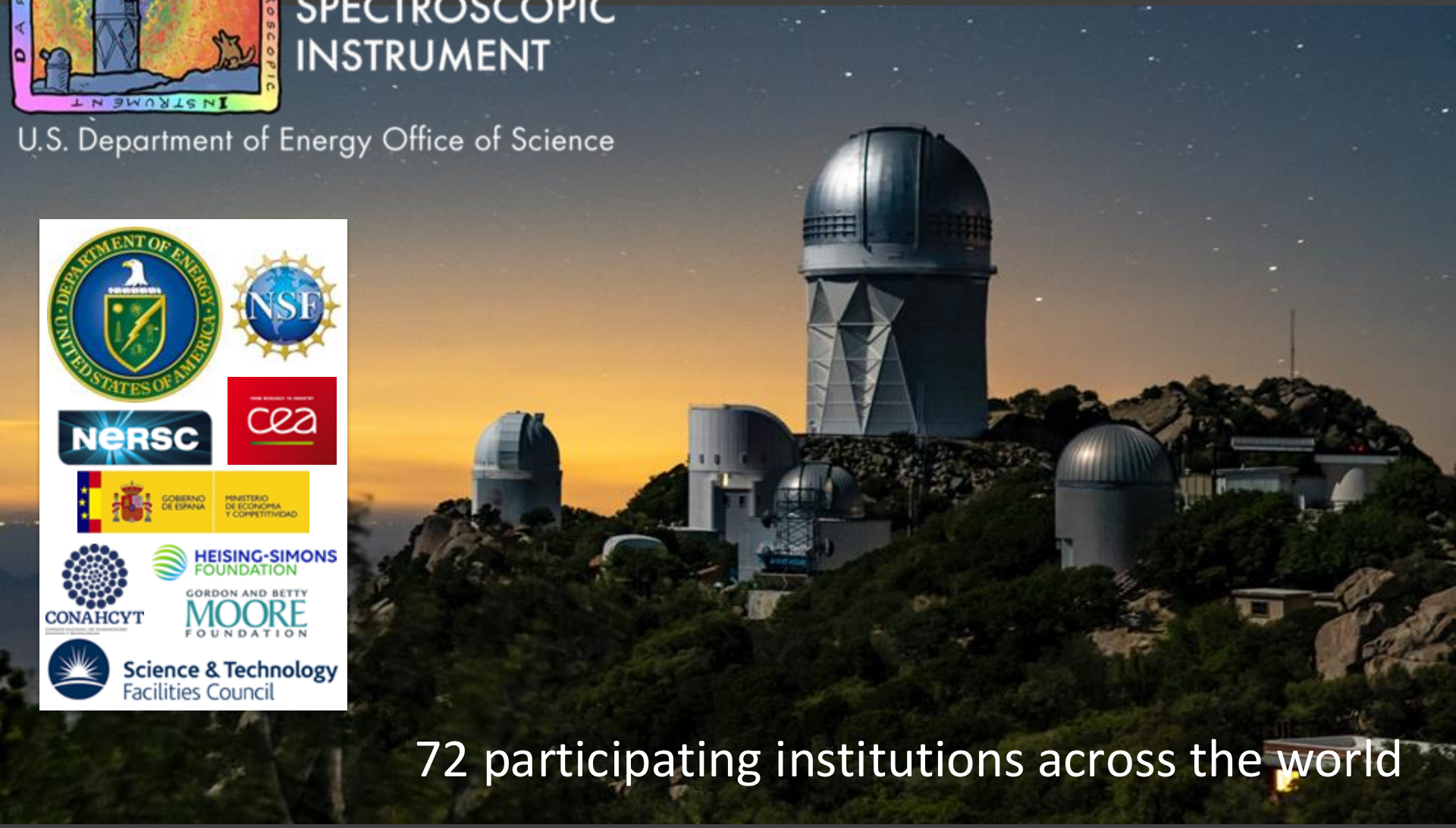
⇒ ΛCDM provides an excellent description of mass power spectrum from 10-1000 Mpc

Sanchez et al 06

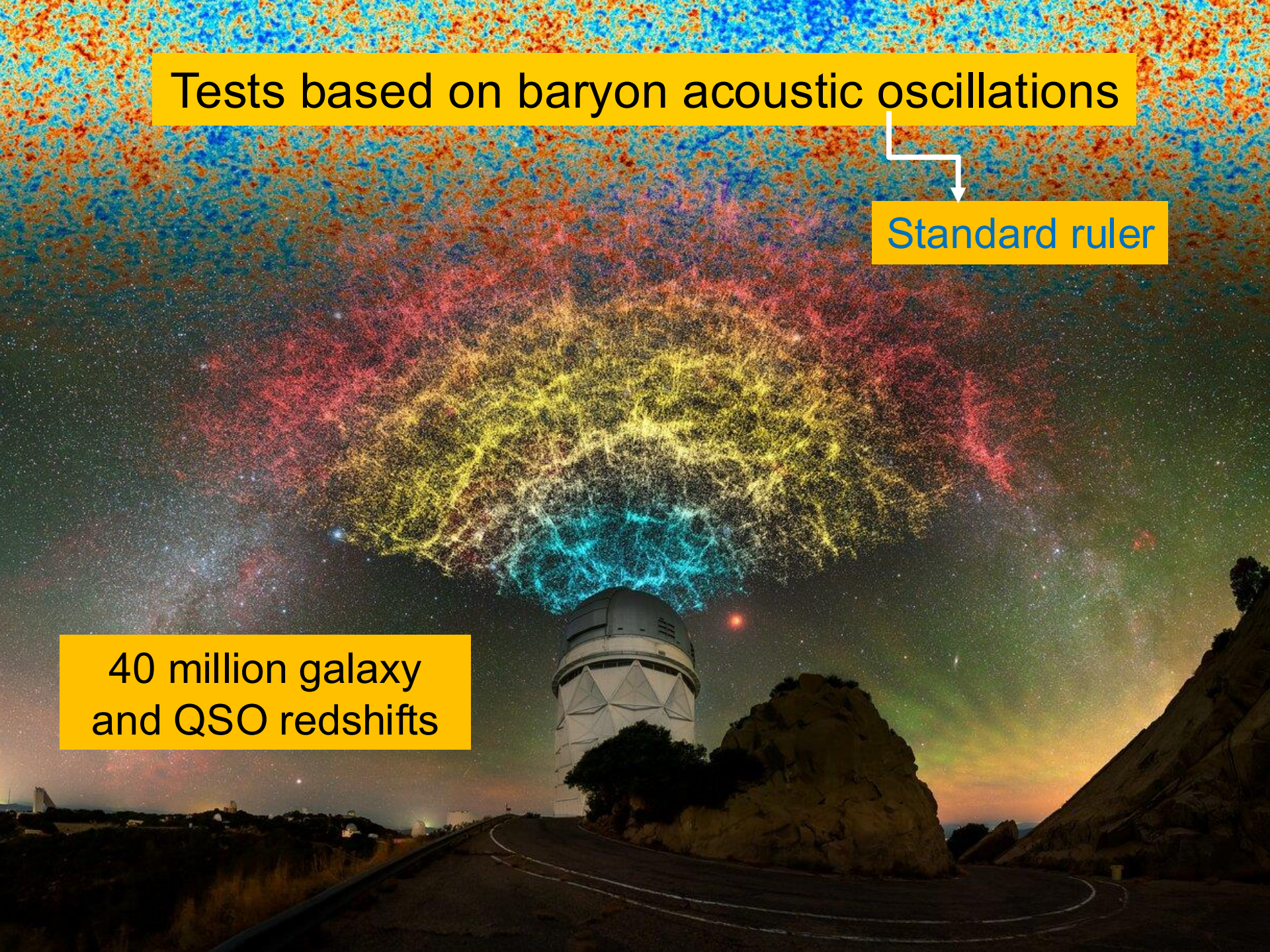
Tests of ΛCDM a subpercent accuracy?

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science



72 participating institutions across the world


Tests based on baryon acoustic oscillations
Standard ruler
40 million galaxy and QSO redshifts

Dynamical dark energy

Dark energy has a negative pressure:

$$P = w\rho$$

Simplest case:

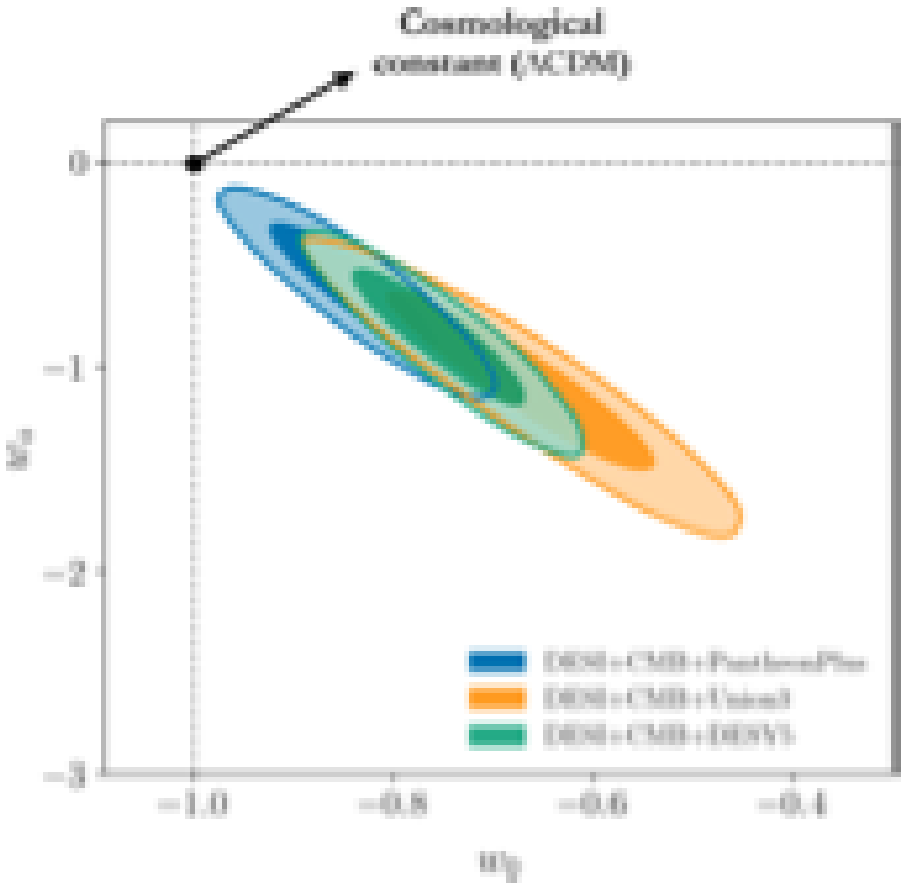
$$w = -1 \quad (\Lambda)$$

Introducing a time-varying equation of state:

$$w(a) = w_0 + w_a(1-a)$$

Significance of rejection of ΛCDM:

- DESI+CMB+Pantheon+: 2.8σ
- DESI+CMB+Union3: 3.8σ
- DESI+CMB+DESY5: 4.2σ



DESI collaboration: Adame+ '24

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Observational tests of ΛCDM

Fundamental prediction of ΛCDM

→ Primordial power spectrum of density perturbations

+ random phases

Can test this in two regimes:

Linear regime: cosmic microwave background (z~1000)

large-scale structure (z~3 - 0)

Evolved non-linear regime:

Depends v. weakly on Λ;
Test of CDM!

dark matter halos →

- abundance (z~15 – 0)
- structure
- clustering

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The small-scale "crisis" of ΛCDM

Four old problems:

		"Solved" in:	
1.	"Missing satellites"	2002	baryon effects
2.	"Too-big-to-fail"	2015	
3.	"Core-cusp"	1996	
4.	"Plane of satellites"	2023	→ Cosmic web + statistics

and a new one:

5. Galaxies at z > 10 discovered by JWST

JWST galaxies at z= 8 -15

arXiv:2211.05792v2 [astro-ph.GA] 4 Nov 2023

CEERS Key Paper I:
An Early Look into the First 500 Myr of Galaxy Formation with *JWST*

Steven L. Finkelstein,[1] Micaela B. Bagley,[1] Henry C. Ferguson,[2] Stephen M. Wilkins,[3,4] Jeyhan S. Kartaltepe,[5] Casey Papovich,[6,7] L. Y. Aaron Yung,[8,*] Pablo Arrabal Haro,[9] Peter Behroozi,[10,11] Mark Dickinson,[9] Dale D. Kocevski,[12] Anton M. Koekemoer,[13] Rebecca L. Larson,[14,1] Aurélien Le Bail,[15] Alexa M. Morales,[1] Pablo G. Pérez-González,[16] Denis Burgarella,[17] Romeel Davé,[18,19] Michaela Hirschmann,[20,21] Rachel S. Somerville,[22] Stijn Wuyts,[23] Volker Bromm,[1] Caitlin M. Casey,[1] Adriano Fontana,[24] Seiji Fujimoto,[1,25,26,†] Jonathan P. Gardner,[27] Mauro Giavalisco,[28] Andrea Grazian,[29] Norman A. Grogin,[2] Nimish P. Hathi,[2] Taylor A. Hutchison,[8,*] Saurabh W. Jha,[30] Shardha Jogee,[1] Lisa J. Kewley,[31] Allison Kirkpatrick,[32] Arianna S. Long,[1,†] Jennifer M. Lotz,[33] Laura Pentericci,[24]

ABSTRACT

We present an investigation into the first 500 Myr of galaxy evolution from the Cosmic Evolution Early Release Science (CEERS) survey. CEERS, one of 13 *JWST* ERS programs, targets galaxy formation $z \sim 0.5$ to $z > 10$ using several imaging and spectroscopic modes. We make use of the first epoch of CEERS NIRCam imaging, spanning 35.5 sq. arcmin, to search for candidate galaxies at $z > 9$. Following a detailed data reduction process implementing several custom steps to produce high-quality reduced images, we perform multi-band photometry across seven NIRCam broad and medium-band (and six *Hubble* broadband) filters focusing on robust colors and accurate total fluxes. We measure photometric redshifts and devise a robust set of selection criteria to identify a sample of 26 galaxy candidates at $z \sim 9$–16. These objects are compact with a median half-light radius of ~0.5 kpc. We present an early estimate of the $z \sim 11$ rest-frame ultraviolet (UV) luminosity function, finding that the number density of galaxies at $M_{UV} \sim -20$ appears to evolve very little from $z \sim 9$ to $z \sim$ 11. We also find that the abundance (surface density [arcmin^{-2}]) of our candidates exceeds nearly all theoretical predictions. We explore potential implications, including that at $z > 10$ star formation may

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JWST galaxies at z= 8 -15

The Complete CEERS Early Universe Galaxy Sample: A Surprisingly Slow Evolution of the Space Density of Bright Galaxies at $z \sim 8.5$–14.5

Steven L. Finkelstein,[1] Gene C. K. Leung,[2] Micaela B. Bagley,[1] Mark Dickinson,[3] Henry C. Ferguson,[4] Casey Papovich,[5,6] Hollis B. Akins,[7] Pablo Arrabal Haro,[3] Romeel Davé,[8,9] Avishai Dekel,[10] Jeyhan S. Kartaltepe,[11] Dale D. Kocevski,[12] Anton M. Koekemoer,[13] Nor Pirzkal,[14] Rachel S. Somerville,[15] L. Y. Aaron Yung,[16,13,*] Ricardo O. Amorín,[17,18] Bren E. Backhaus,[19] Peter Behroozi,[20,21] Laura Bisigello,[22,23] Volker Bromm,[1] Caitlin M. Casey,[1] Óscar A. Chávez Ortiz,[1] Yingjie Cheng,[24] Katherine Chworowsky,[1,†] Nikko J. Cleri,[5,6] M. C. Cooper,[25] Kelcey Davis,[19] Alexander de la Vega,[26] David Elbaz,[27] Maximilien Franco,[1] Adriano Fontana,[28] Seiji Fujimoto,[29,30] Mauro Giavalisco,[24] Norman A. Grogin,[4] Benne W. Holwerda,[31] Marc Huertas-Company,[32,33,34] Michaela Hirschmann,[35] Kartheik G. Iyer,[36] Shardha Jogee,[1] Intae Jung,[37] Rebecca L. Larson,[38,39] Ray A. Lucas,[40] Bahram Mobasher,[26] Alexa M. Morales,[41] Caroline V. Morley,[42] Sagnick Mukherjee,[43] Pablo G. Pérez-González,[44] Swara Ravindranath,[45,46] Giulia Rodighiero,[47,48] Melanie J. Rowland,[49] Sandro Tacchella,[50,51] Anthony J. Taylor,[1] Jonathan R. Trump,[19] and Stephen M. Wilkins[52,53]

arXiv:2311.04279v1 [astro-ph.GA] 7 Nov 2023

ABSTRACT

We present a sample of 88 candidate $z \sim 8.5$–14.5 galaxies selected from the completed NIRCam imaging from the Cosmic Evolution Early Release Science (CEERS) survey. These data cover ~90 arcmin^2 (10 NIRCam pointings) in six broad-band and one medium-band imaging filter. With this sample we confirm at higher confidence early *JWST* conclusions that bright galaxies in this epoch are more abundant than predicted by most theoretical models. We construct the rest-frame ultraviolet

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JWST galaxies at z= 8 -15

A population of red candidate massive galaxies ~600 Myr after the Big Bang

Ivo Labbé[1], Pieter van Dokkum[2], Erica Nelson[3], Rachel Bezanson[4], Katherine A. Suess[5,6], Joel Leja[7,8,9], Gabriel Brammer[10], Katherine Whitaker[10,11], Elijah Mathews[7,8,9], Mauro Stefanon[12,13], Bingjie Wang[7,8,9]

Galaxies with stellar masses as high as ~ 10^{11} solar masses have been identified[1–3] out to redshifts z ~ 6, approximately one billion years after the Big Bang. It has been difficult to find massive galaxies at even earlier times, as the Balmer break region, which is needed for accurate mass estimates, is redshifted to wavelengths beyond 2.5 μm. Here we make use of the 1-5 μm coverage of the *JWST* early release observations to search for intrinsically red galaxies in the first ≈ 750 million years of cosmic history. In the survey area, we find six candidate massive galaxies (stellar mass > 10^{10} solar masses) at $7.4 \leq z \leq 9.1$, 500–700 Myr after the Big Bang, including one galaxy with a possible stellar mass of ~10^{11} solar masses. If verified with spectroscopy, the stellar mass density in massive galaxies would be much higher than anticipated from previous studies based on rest-frame ultraviolet-selected samples.

issue is that these stellar mass densities are difficult to realize in a standard LCDM cosmology, as pointed out by several recent studies.[31,32] Our fiducial mass densities push against the limit set by the number of available baryons in the most massive dark matter halos.

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Galaxies at z= 6 – 8

THE IMPOSSIBLY EARLY GALAXY PROBLEM

CHARLES. L. STEINHARDT [1,2], PETER CAPAK[1,2], DAN MASTERS[1,2], JOSH S. SPEAGLE[3,2,4]

Draft version June 12, 2018

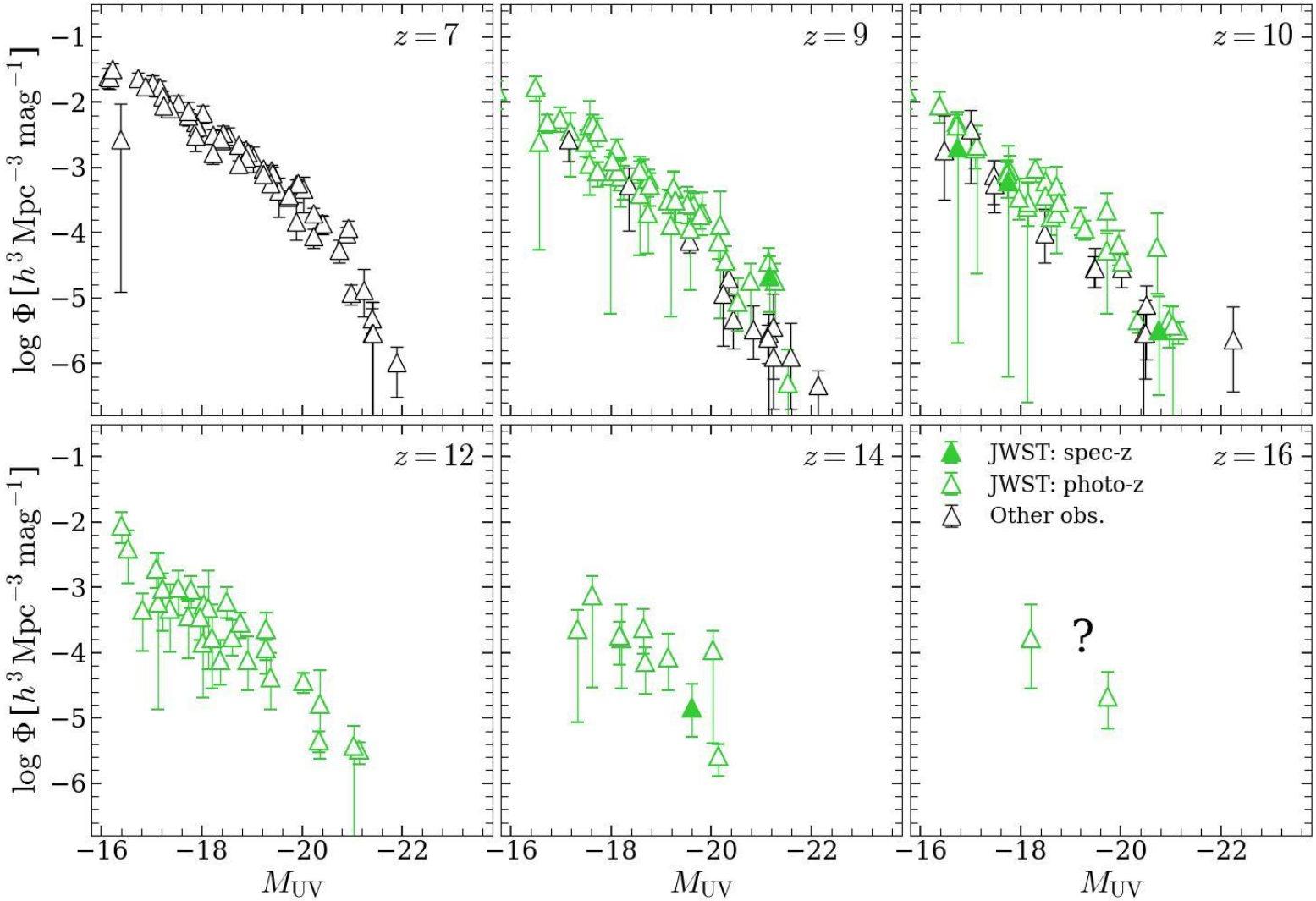
arXiv:1506.01377v2 [astro-ph.GA] 8 Apr 2016

ABSTRACT

The current hierarchical merging paradigm and ΛCDM predict that the $z \sim 4-8$ universe should be a time in which the most massive galaxies are transitioning from their initial halo assembly to the later baryonic evolution seen in star-forming galaxies and quasars. However, no evidence of this transition has been found in many high redshift galaxy surveys including CFHTLS, CANDELS and SPLASH, the first studies to probe the high-mass end at these redshifts. Indeed, if halo mass to stellar mass ratios estimated at lower-redshift continue to $z \sim 6-8$, CANDELS and SPLASH report several orders of magnitude more $M \sim 10^{12-13} M_{\odot}$ halos than are possible to have formed by those redshifts, implying these massive galaxies formed impossibly early. We consider various systematics in the stellar synthesis models used to estimate physical parameters and possible galaxy formation scenarios in an effort to reconcile observation with theory. Although known uncertainties can greatly reduce the disparity between recent observations and cold dark matter merger simulations, even taking the most conservative view of the observations, there remains considerable tension with current theory.

Subject headings: galaxies: evolution

JWST galaxies at z=7-16



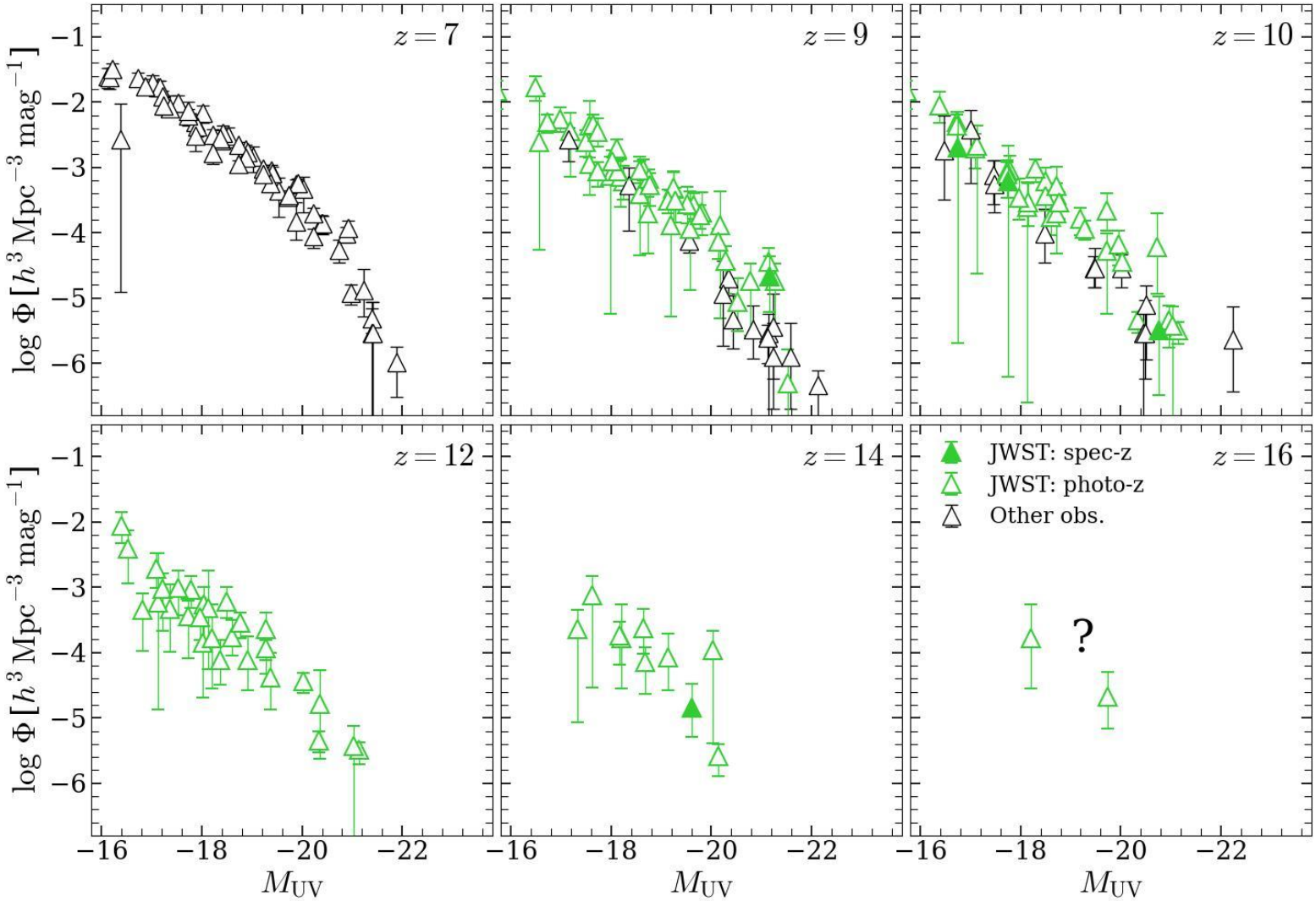
JWST galaxies at z=7-16

What do these authors mean by “most theoretical models”, “merger simulations”, etc?

→Existing hydro simulations (e.g. TNG50)

The simulations used do not have enough resolution and/or volume (or the right physics)!

JWST galaxies at z=7-16



JWST galaxies at z=7-16

Hydro simulations?

- Abundance of brightest ones: $n \sim 3 \times 10^{-7}$ /Mpc^3

  → Need cube side-length, $L > 500$ Mpc
  (to get a few tens)

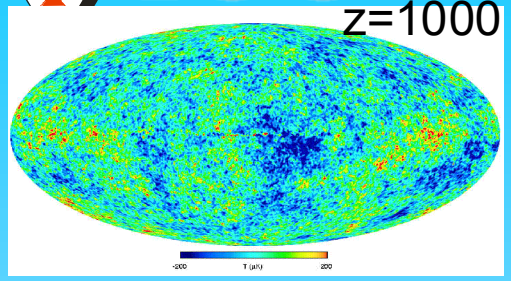
- Mass of faintest: $M \sim$ a few $\times 10^6 M_o$

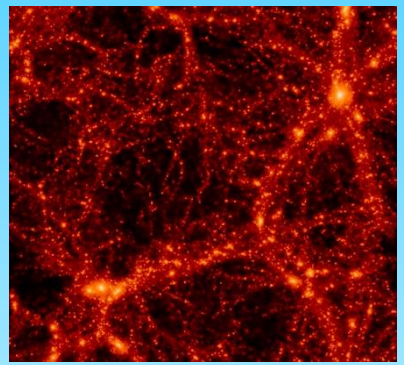
  → Need $m_{gas} < 10^5 M_o$

Not currently feasible (by a factor of 10-1000)!

JWST galaxies at z=7-16

What do we really expect in ΛCDM?





Cosmological model

(Ω_m, Ω_Λ, h); dark matter

↓

Primordial fluctuations

$\delta\rho/\rho$(M, t)

↓

Dark matter halos

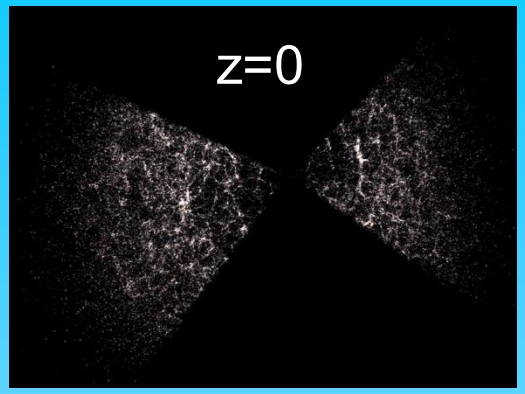
(N-body simulations)

↓

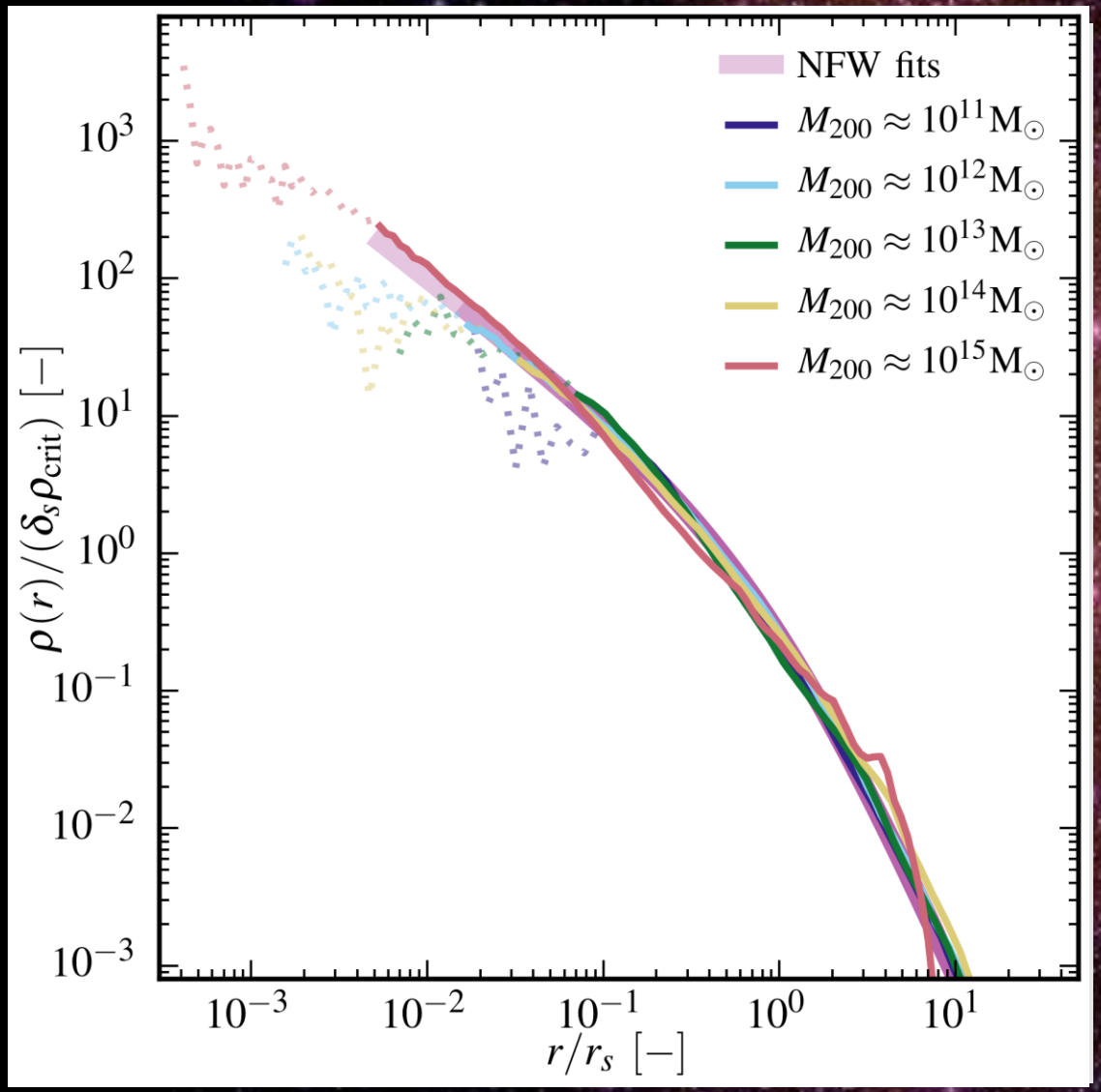
Gas processes

(cooling, star formation, feedback)

Well understood



The density profile of cold dark matter halos



Shape of halo profiles ~independent of halo mass & cosmological parameters

Density profiles are "cuspy" - no `core' near the centre

Fitted by simple formula:

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

(Navarro, Frenk & White '97)

More massive halos and halos that form earlier have higher densities (bigger δ)

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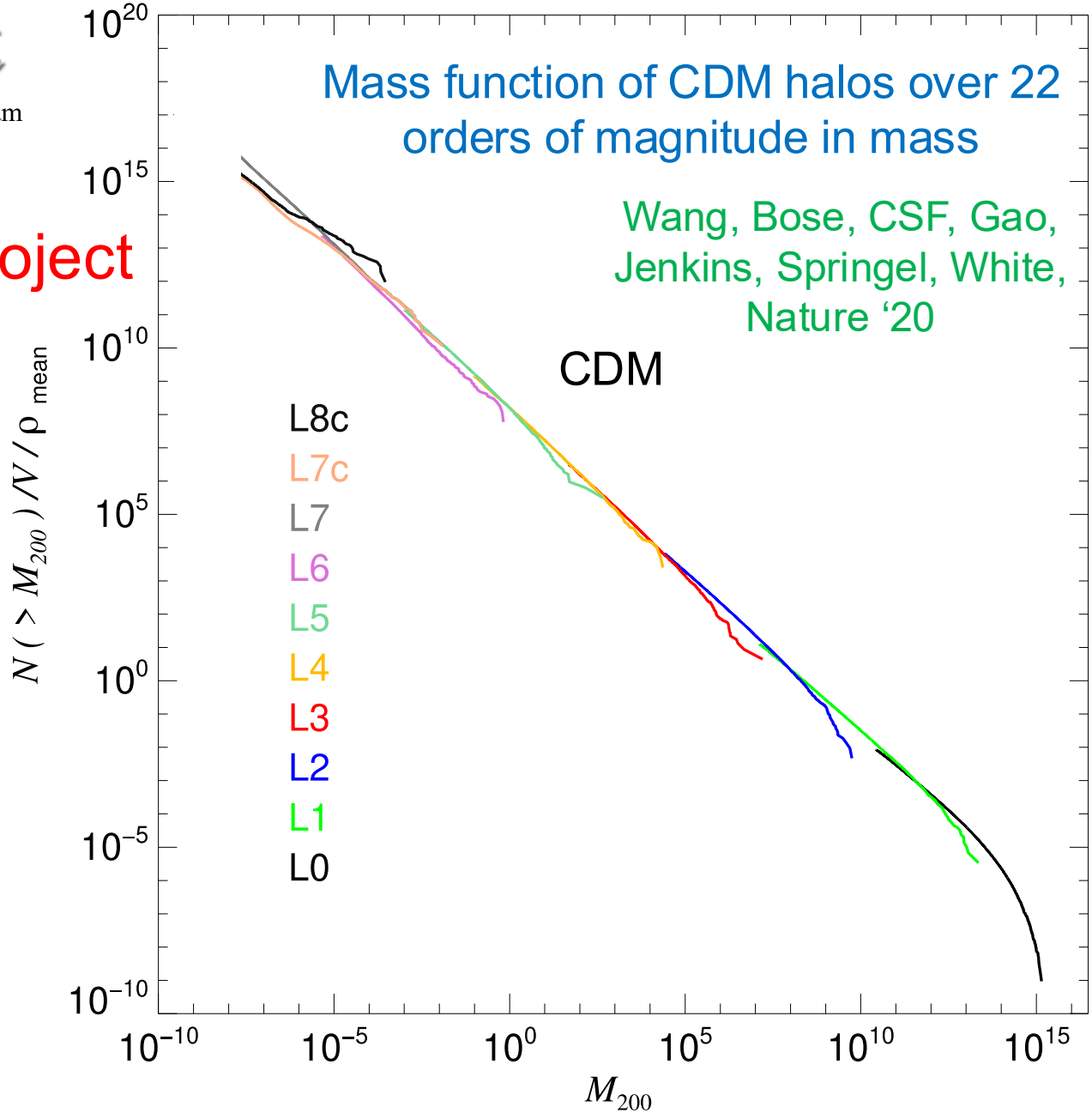
The VVV project



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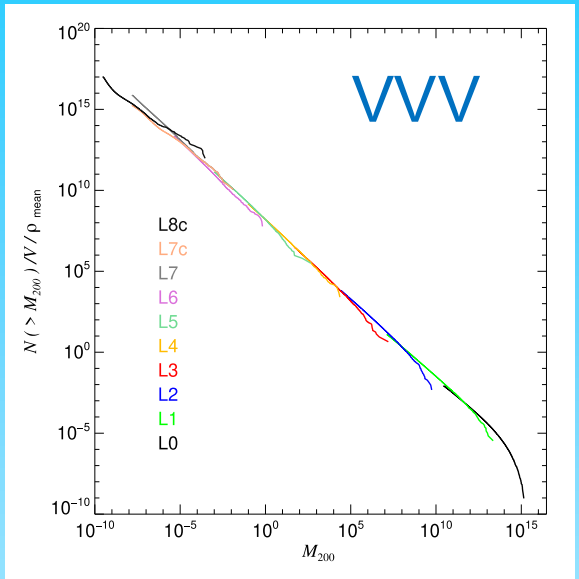
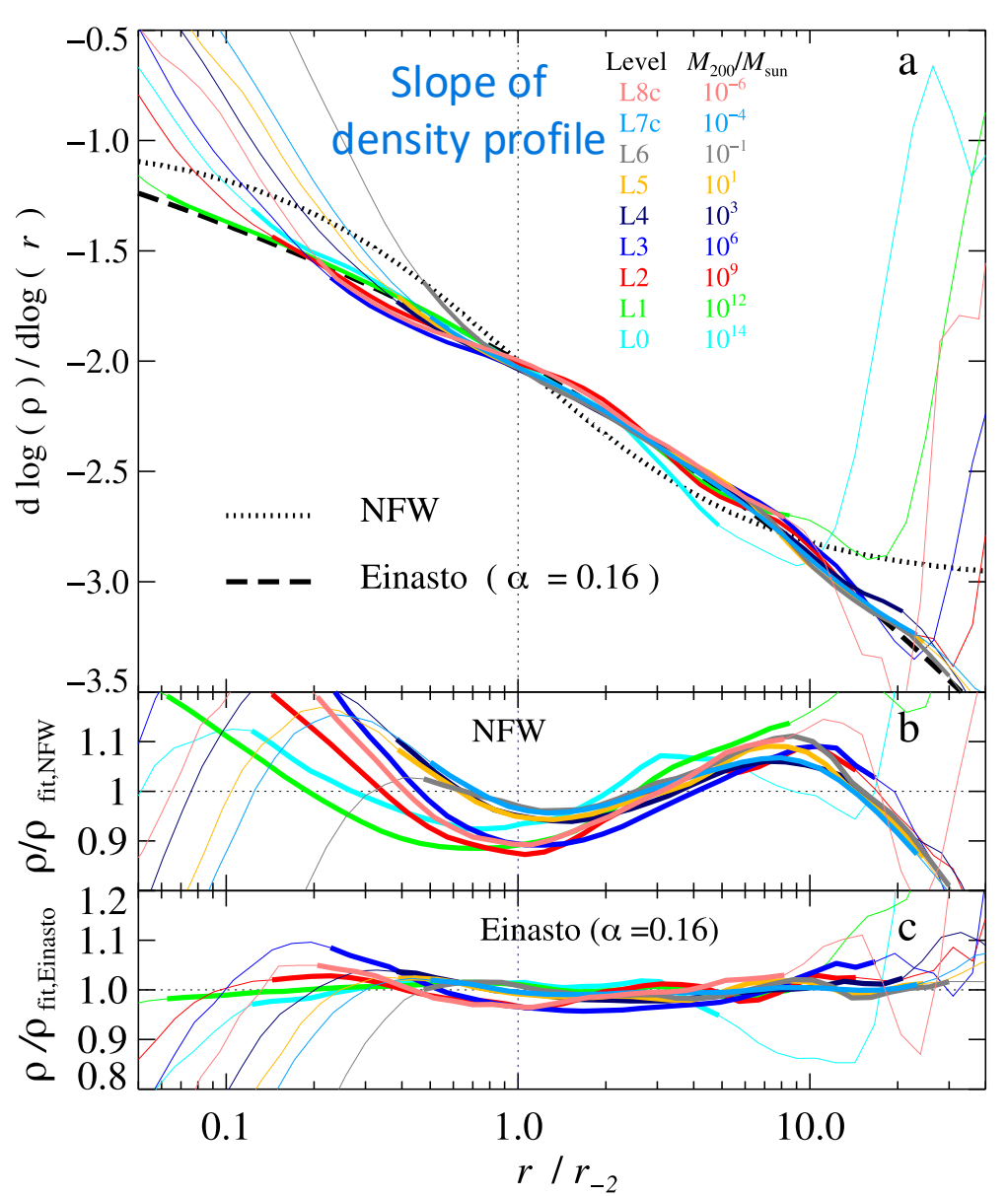
Density profiles of ALL halos

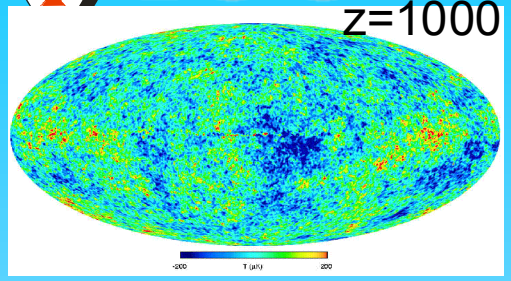




Over 25 orders of magnitude in halo mass and 4 orders of magnitude in density, the mean density profiles of halos are fit by NFW to within 20% and by Einasto (α =0.16) to within 7%

Wang, Bose, CSF + '20

$\rho(r) = \frac{\rho_0}{\frac{r}{r_0}\left(1+\frac{r}{r_0}\right)^2}$



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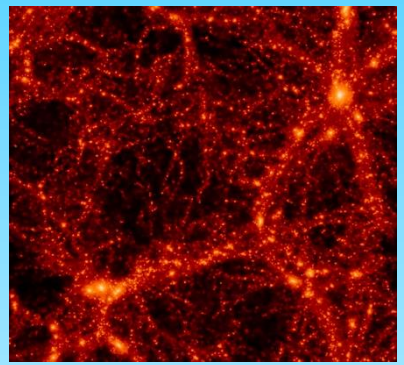


Dark matter halos

(N-body simulations)

Well understood

↓

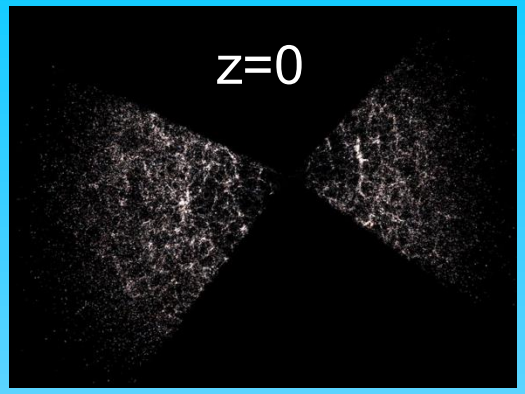
Gas processes

(cooling, star formation, feedback)

Semi-analytics

Hydro simulations

Formation and evolution of galaxies



Evolution of baryons

Basic differential rate equations of Durham SA model (GALFORM):

$$
\begin{aligned}
\dot{M}_\star &= (1-R)\psi \\
\dot{M}_{\rm hot} &= -\dot{M}_{\rm cool} + \beta\psi \\
\dot{M}_{\rm cold} &= \dot{M}_{\rm cool} - (1-R+\beta)\psi \\
\dot{M}^Z_\star &= (1-R)Z_{\rm cold}\psi \\
\dot{M}^Z_{\rm hot} &= -\dot{M}_{\rm cool}Z_{\rm hot} + (pe+\beta Z_{\rm cold})\psi \\
\dot{M}^Z_{\rm cold} &= \dot{M}_{\rm cool}Z_{\rm hot} \\
&+ (p(1-e) - (1+\beta-R)Z_{\rm cold})\psi,
\end{aligned}
$$

Mass conservation

R = recycled fraction

ψ = star formation rate

Conservation of metals

β = SN feedback parameter

p = metal yield

e = fraction of metals ejected

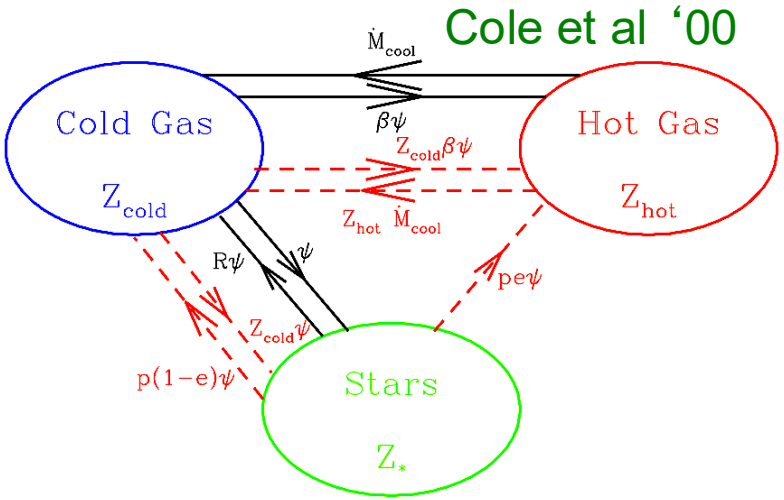
White & Frenk '91,
Kauffmann et al '93
Cole et al '00

SFR & mass ejection

SFR $\quad \psi = \dfrac{M_{\rm cold}}{\tau_\star(r_{\rm disk}, V_{\rm disk})}$

SN feedback $\quad \dot{M}_{\rm eject} = \beta(V_{\rm disk})\,\psi$

AGN feedback $\quad \dot{M}_{BH} = f_{BH}\psi_{burst} + \dfrac{L_{cool}}{c^2\varepsilon_{SMBH}}$



Free parameters in SA models

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Semi-analytics

White & Frenk ' 91; Kauffmann et al ' 93; Cole et al. '00

SFR & mass ejection

SFR $$\psi = \frac{M_{\rm cold}}{\tau_\star(r_{\rm disk}, V_{\rm disk})}$$

SN feedback $$\dot{M}_{\rm eject} = \beta(V_{\rm disk})\,\psi$$

AGN feedback $$\dot{M}_{BH} = f_{BH}\psi_{burst} + \frac{L_{cool}}{c^2\varepsilon_{SMBH}}$$

SFR timescale

$$\tau_\star \propto \tau_{\rm dyn,disk} V_{\rm disk}^{\alpha_\star}$$

SN feedback efficiency

$$\beta = (V_{\rm disk}/V_{\rm hot})^{-\alpha_{\rm hot}}$$

AGN feedback efficiency

f_{BH}, ε_{SMBH}

Basic SA model has 6 free parameters (plus IMF):

SFR: τ_0, α_*; SN feedback: α_{hot}, V_{hot} ; AGN feedback: f_{BH}, ε_{SMBH}

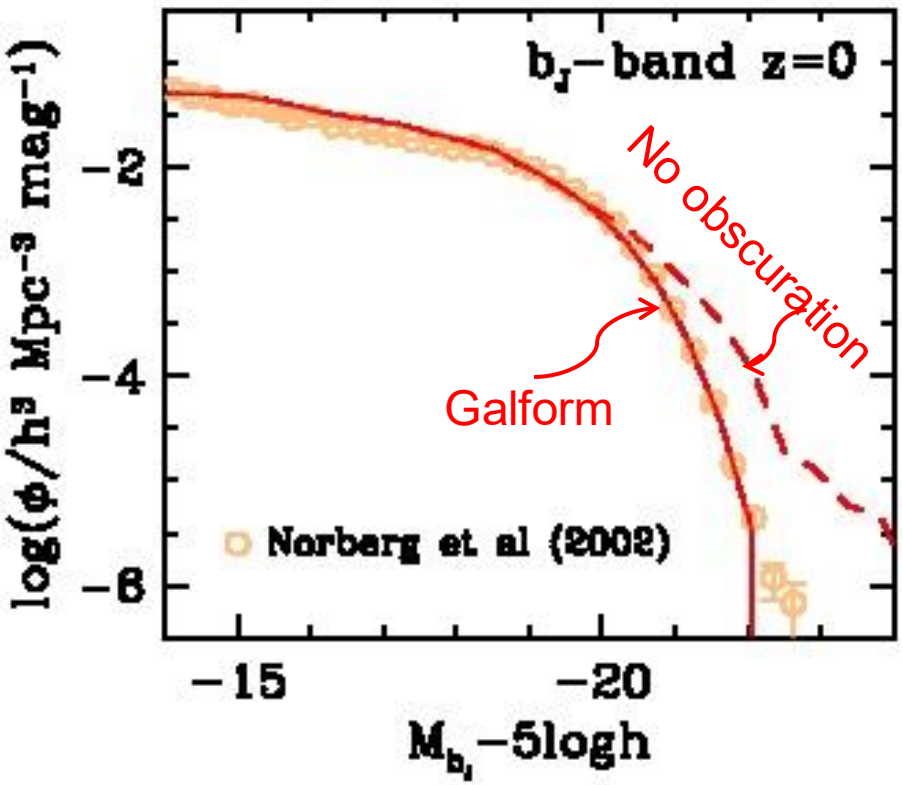
→ gives mass in stars, gas and metals at all times

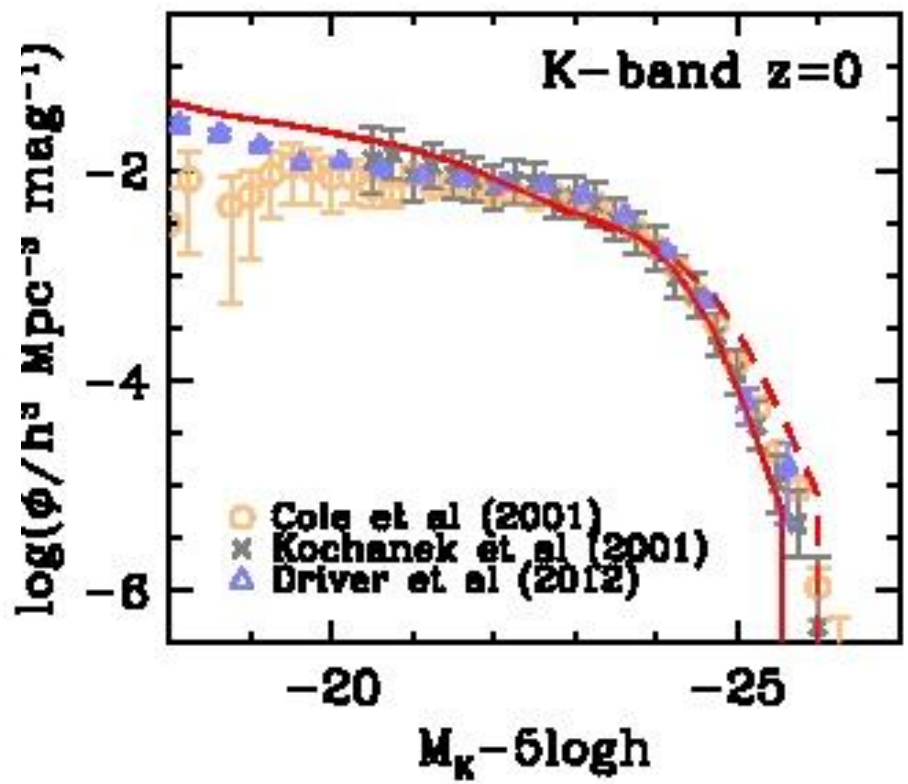
To turn into observables, need extra modelling: dust, morpholgy…

The galaxy luminosity function

Philosophy (since 1994) → fix model parameters by matching subset of z=0 basic data

Not a "prediction" of the model – parameters adjusted to get this match!





Lacey et al. '15

Evolution of the luminosity fn.

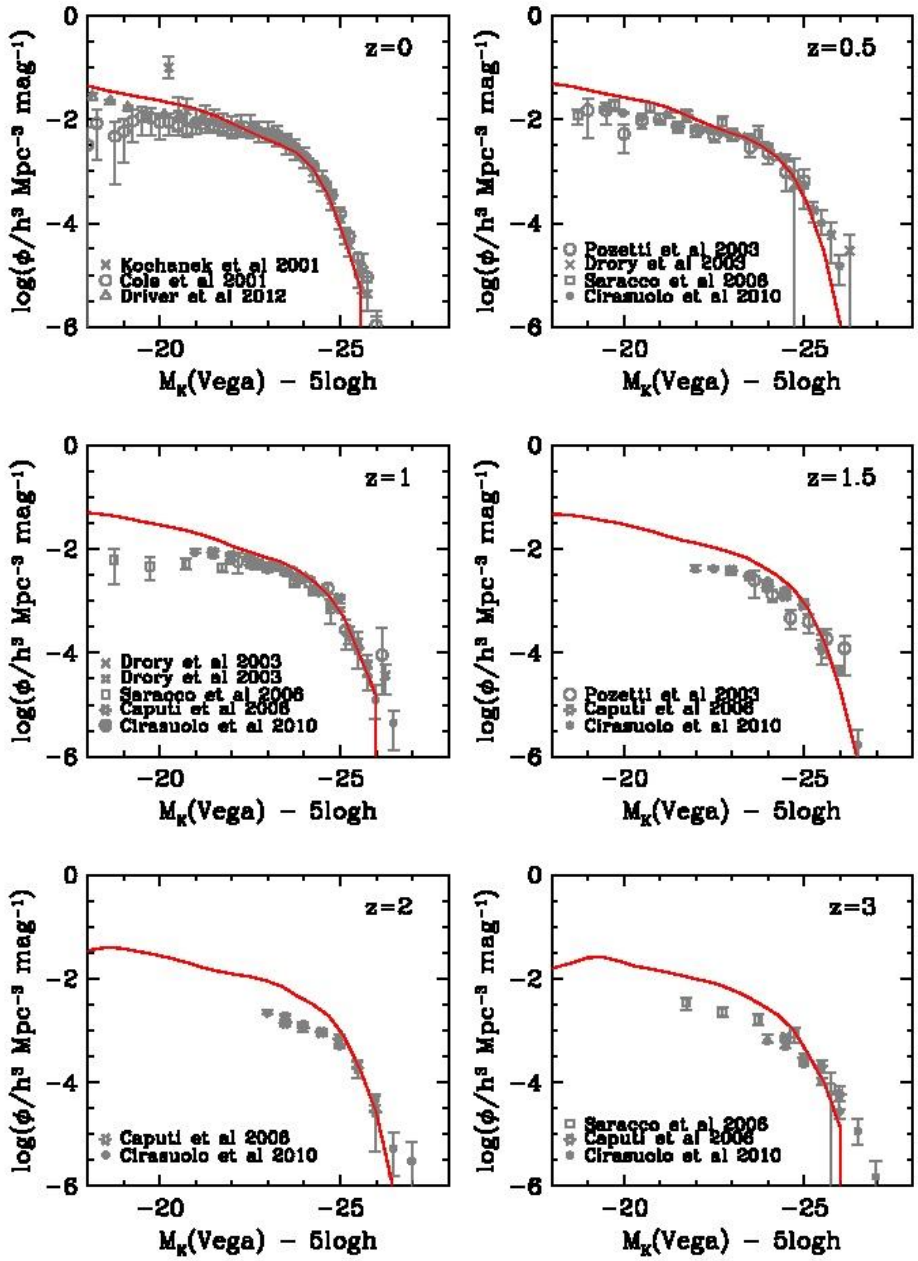
University of Durham

GALFORM

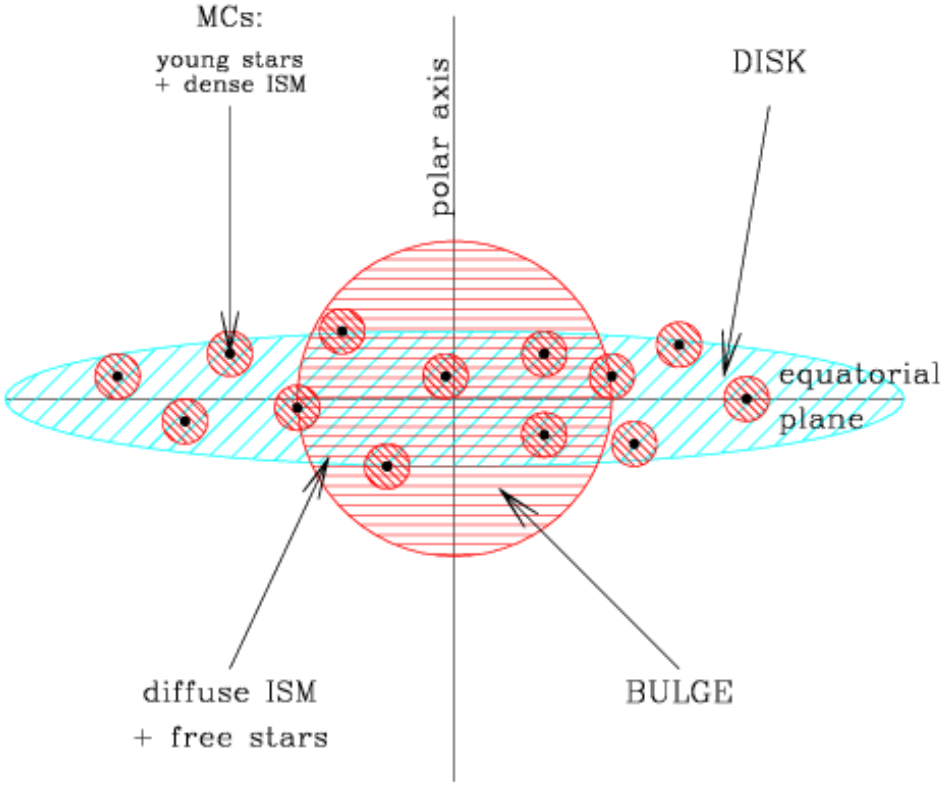
GALFORM gives excellent match to the evolution of the K-band galaxy luminosity function to z=3

This is a genuine prediction!

Lacey, Baugh, Frenk et al. '15



Dust emission and absorption



Absorption and emission by dust

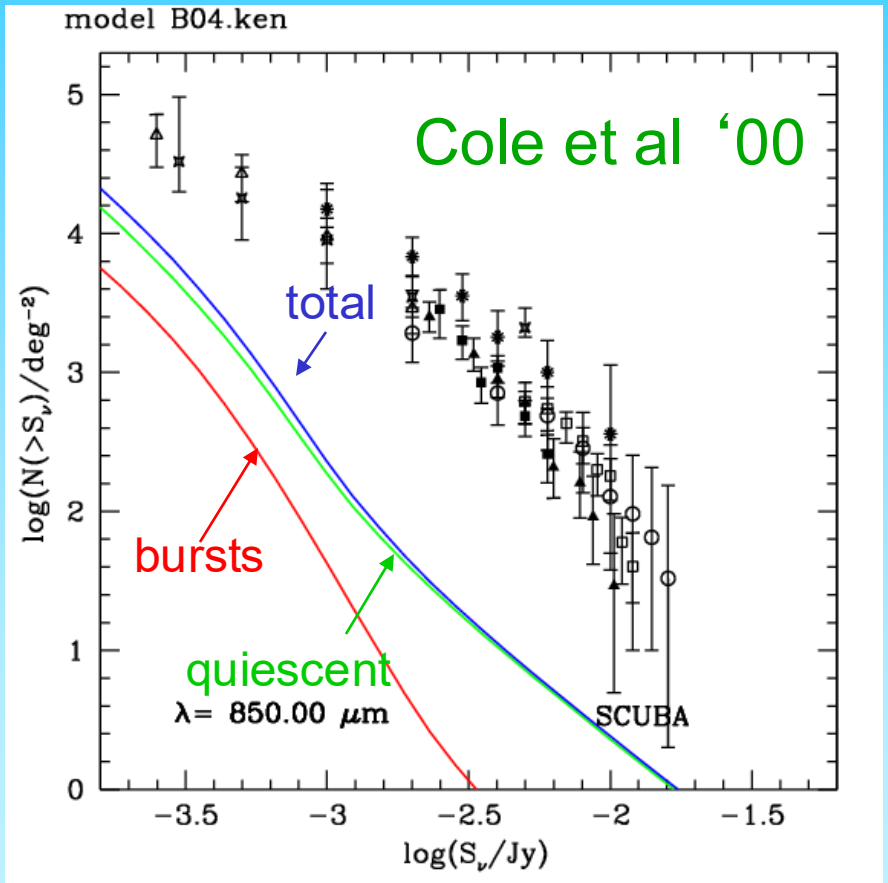
- Dust in diffuse medium and molecular clouds
- Phys. dust grain model +PAHs
- Radiative transfer of starlight through clumpy dust medium
- Heating of dust grains → dust temp. distribution
- Grains with distri. of size/T → IR/submm emission

Granato, Lacey, Silva, Baugh, Bressan, Cole & Frenk '00

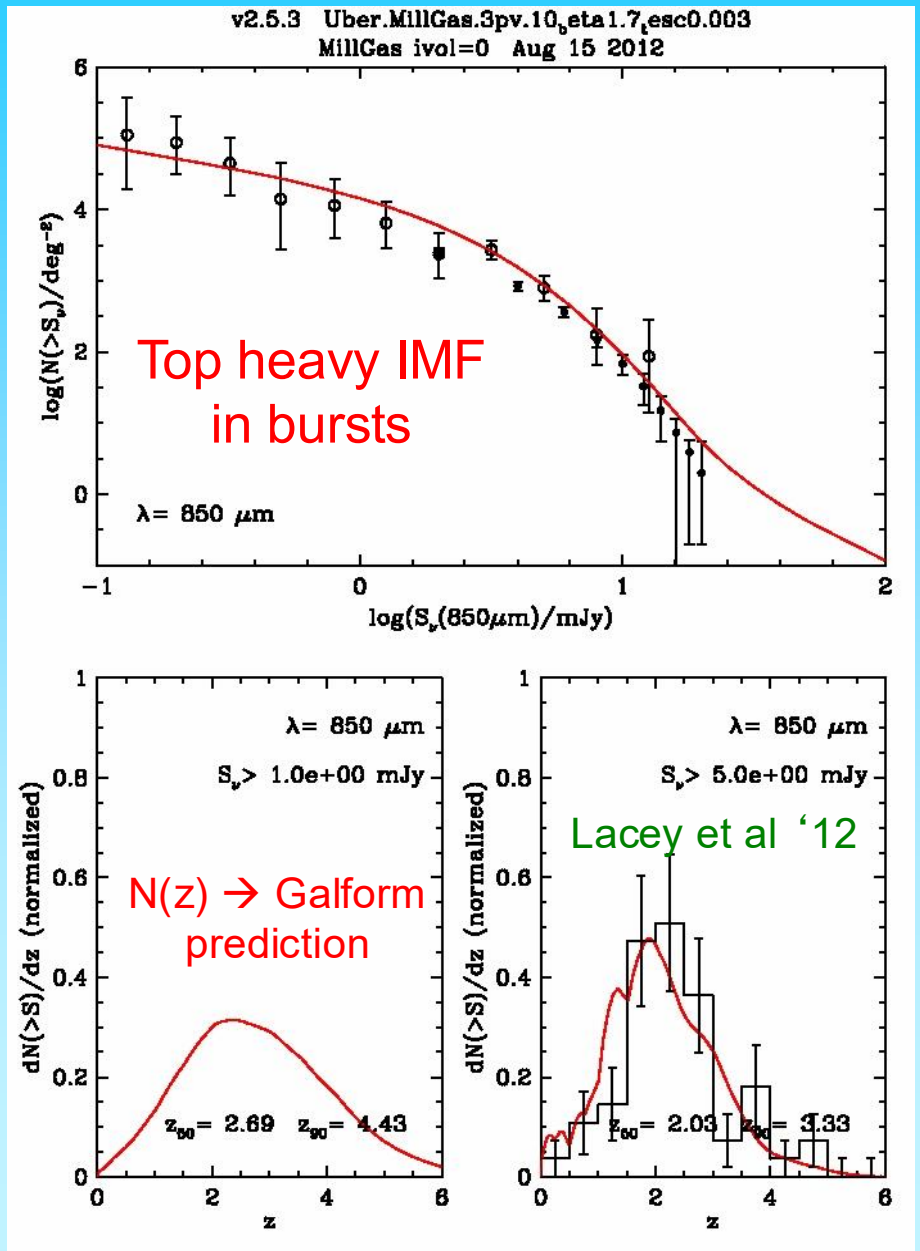
A big failure in GALFORM

Sub-mm galaxies

Normal IMF



Sub-mm counts too low by factor ~30 for normal IMF



JWST galaxies at z=7-16

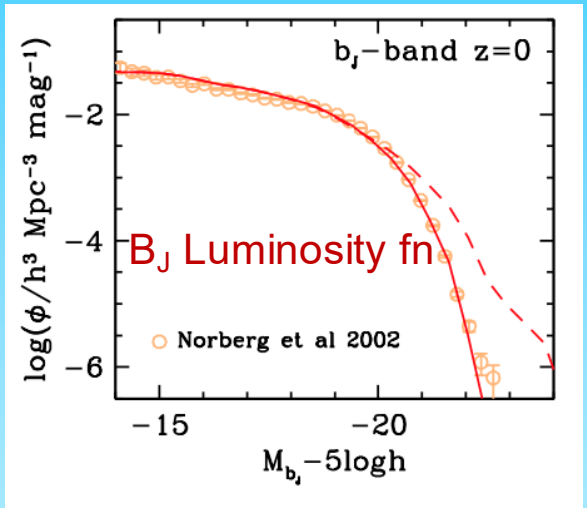
Two crucial components of GALFORM

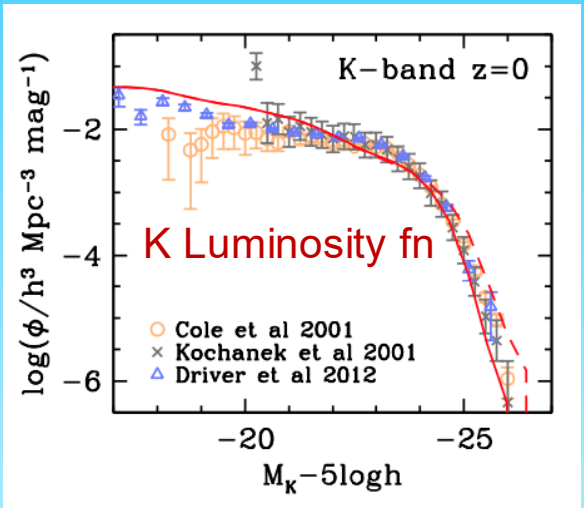
1. A top-heavy IMF in starbursts (only)
2. A detailed dust obscuration model

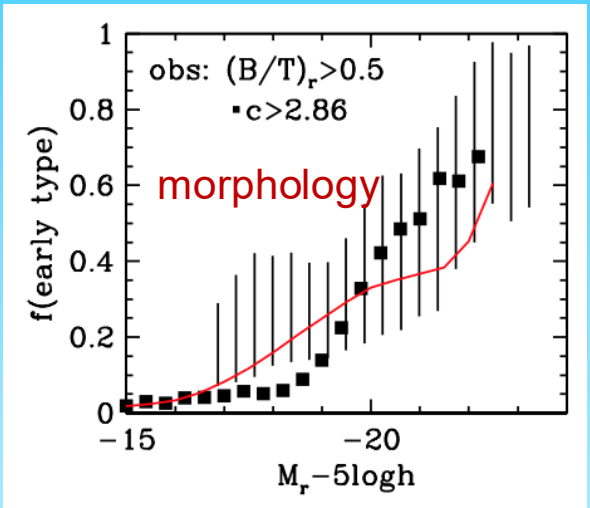
Galform calibration

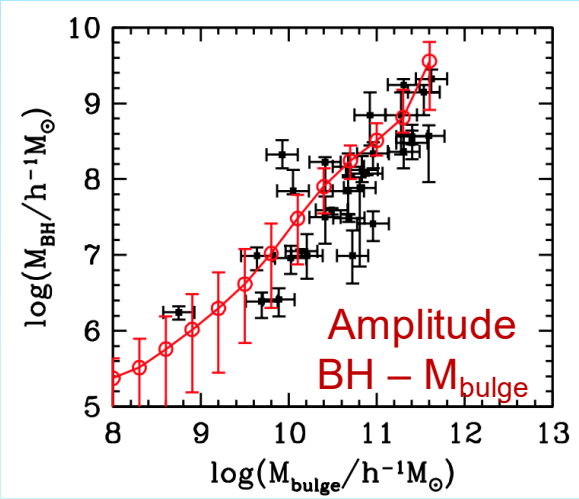
Philosophy (since 1994) → fix model parameters by matching subset of z=0 basic data

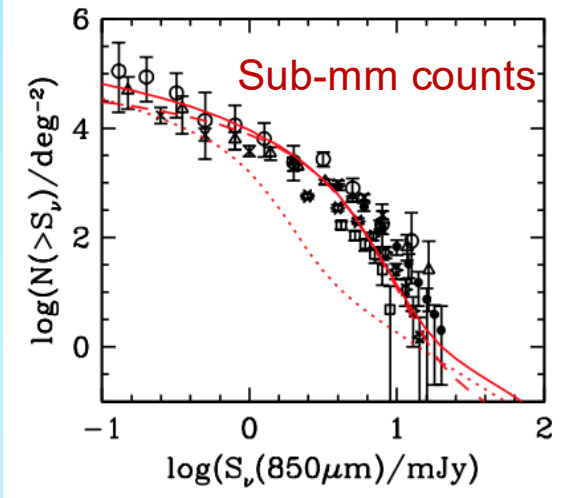
Cole et al '00
Lacey et al '16

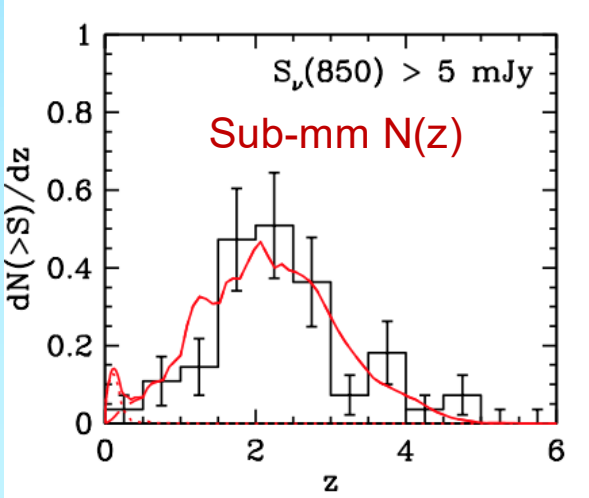




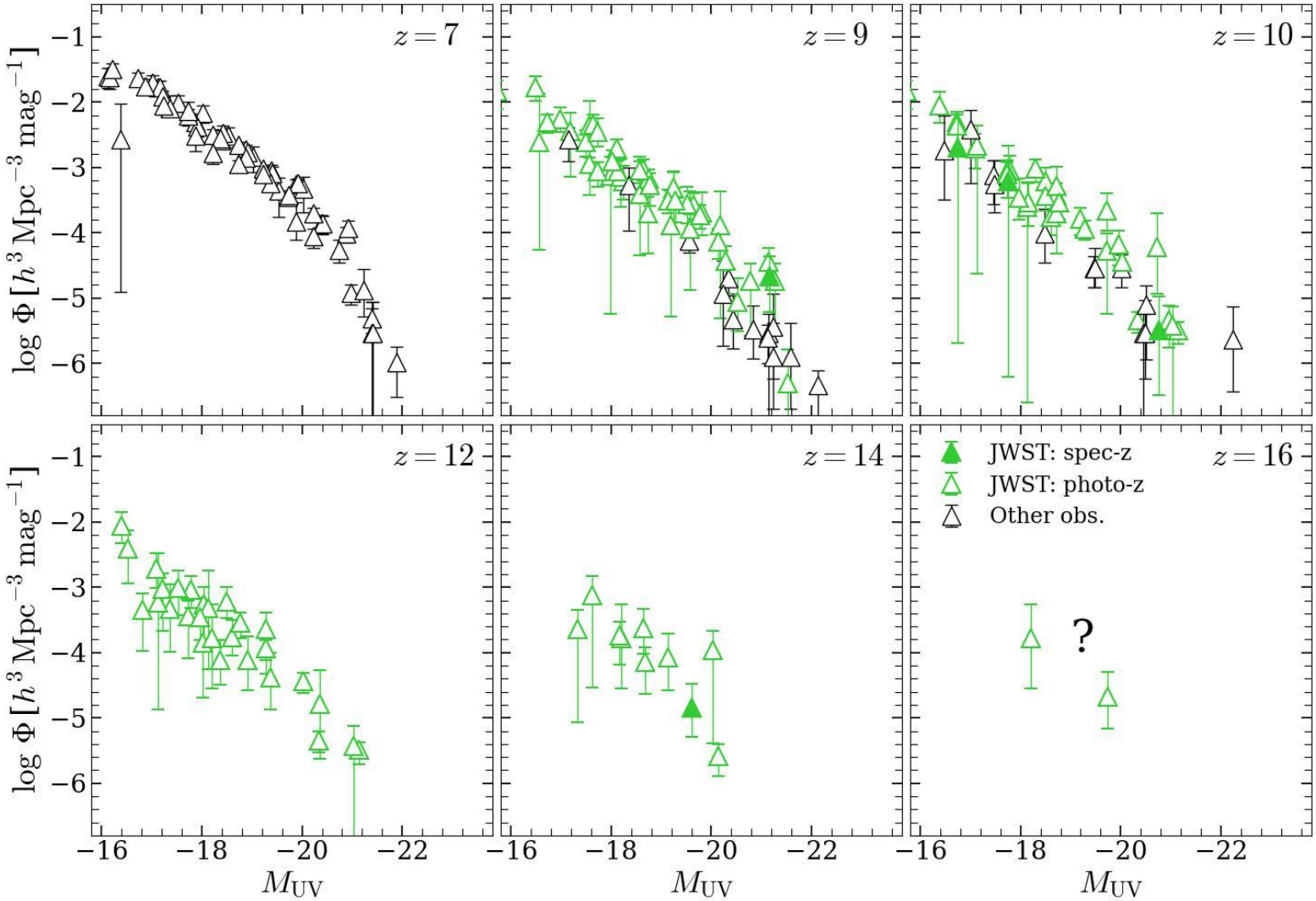


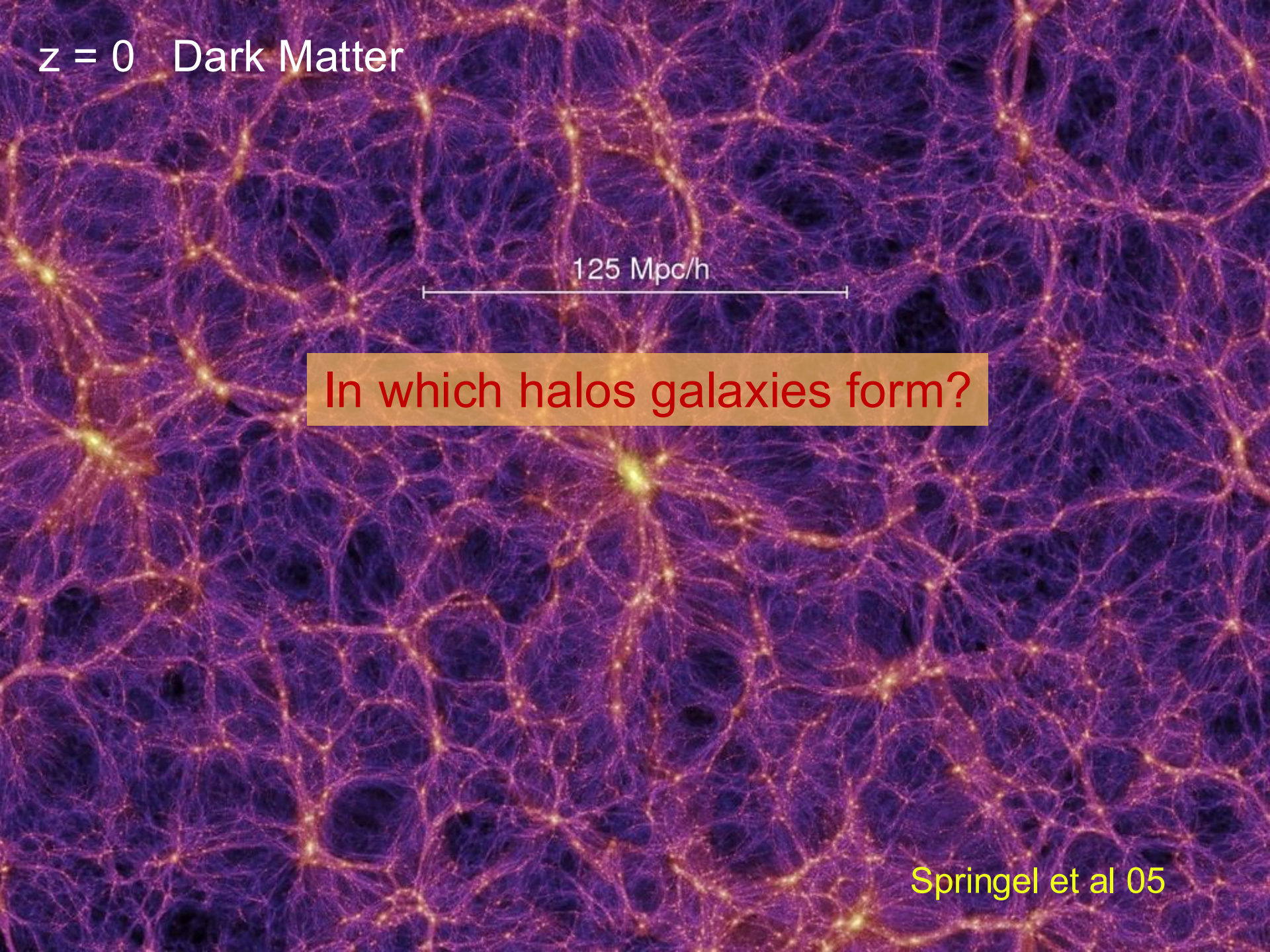






JWST galaxies at z=7-16




z = 0 Dark Matter
125 Mpc/h
In which halos galaxies form?
Springel et al 05

A galaxy formation primer

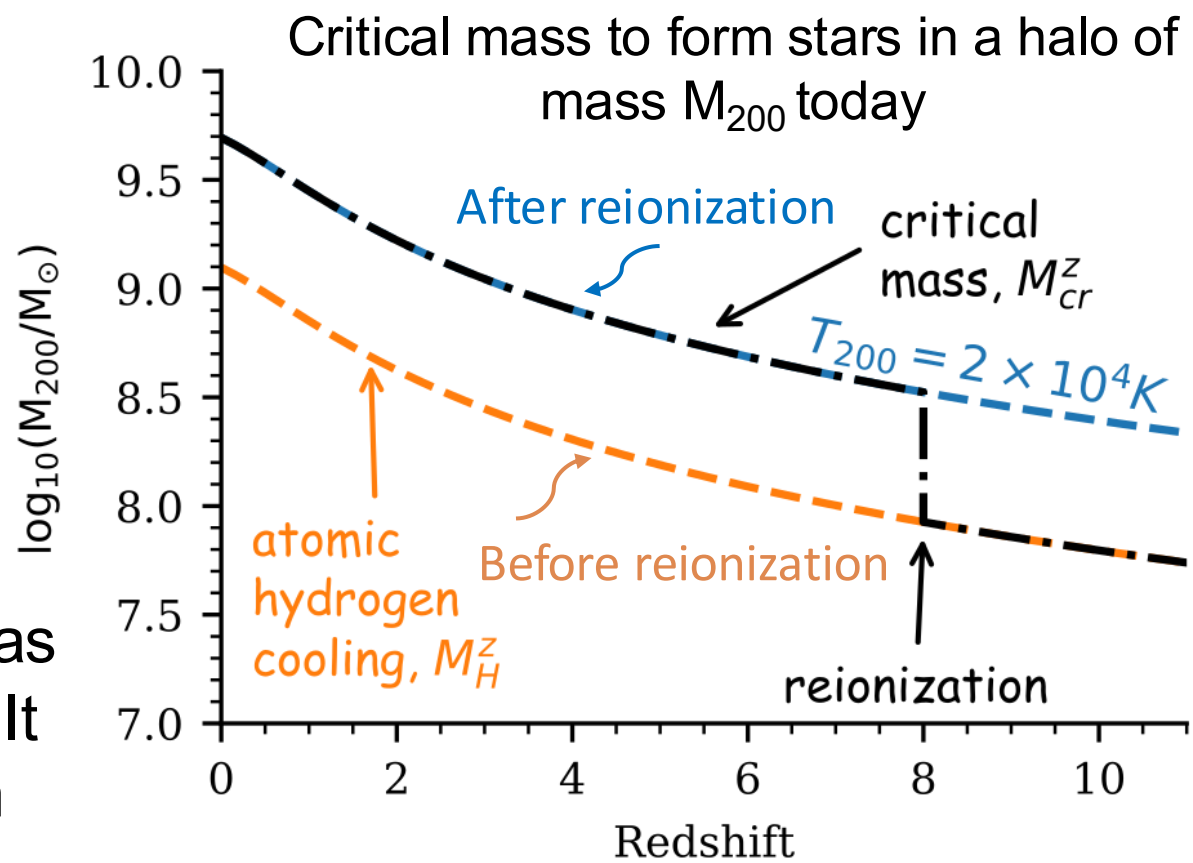
In which halos do galaxy form?

1. Before reionization, stars can only form if atomic H cooling is effective: → T>7000 K

$$M_H^z \sim (4 \times 10^7\ M_\odot) \left(\frac{1+z}{11}\right)^{-3/2}$$

2. After H reionization, gas is heated to T=2x10^4 K. It can only cool and form stars in halos with:

$T_{vir} > T_{IGM} = 2x10^4$ K



Benitez-Llambay & CSF '20

See also Efstathiou '82, Thoul & Weinberg '95

Institute for Computational Cosmology

A galaxy formation primer

1. Before reionization, stars can only form if gas can cool for which

→ T>7000 K

$$M_H^z \sim (4 \times 10^7\ M_\odot) \left(\frac{1+z}{11}\right)^{-3/2}$$

2. After H reionization, gas is heated to T=2x10^4 K. It can only cool and form stars in halos with:

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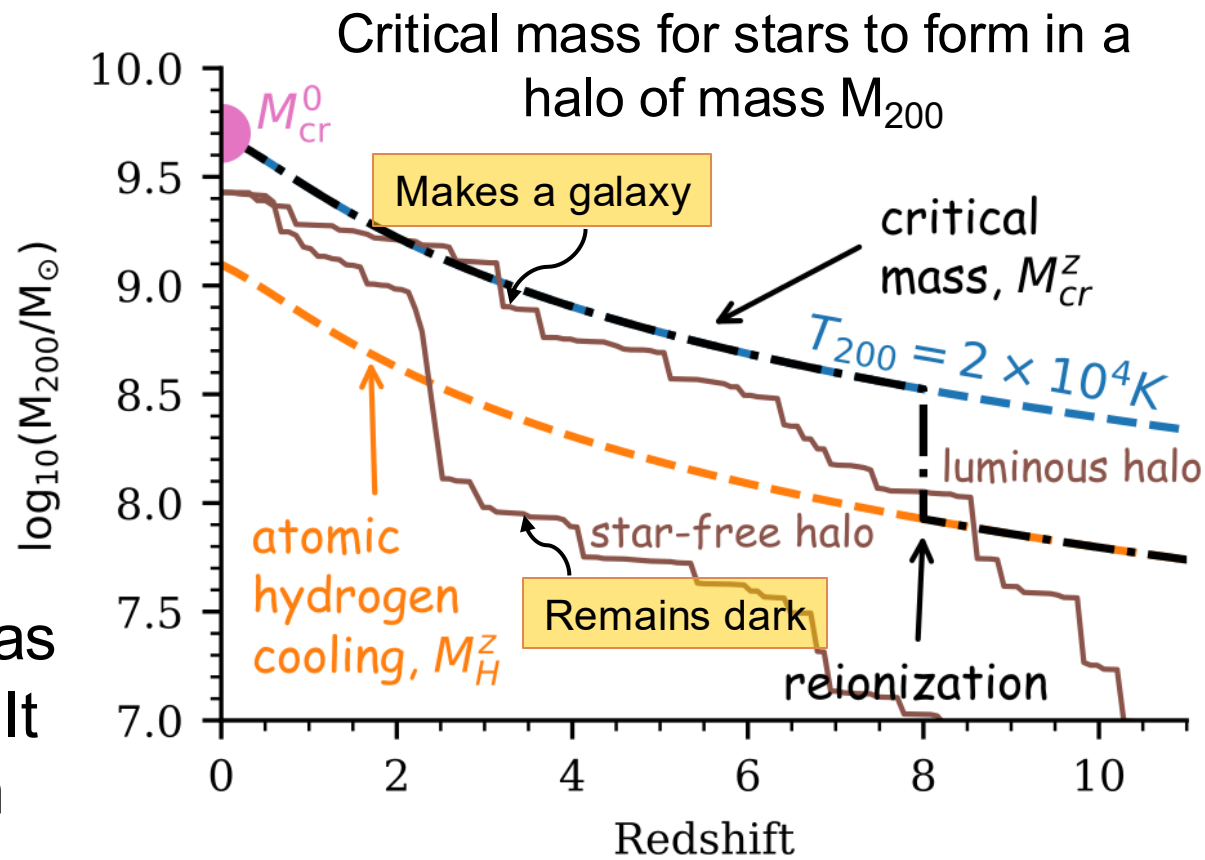
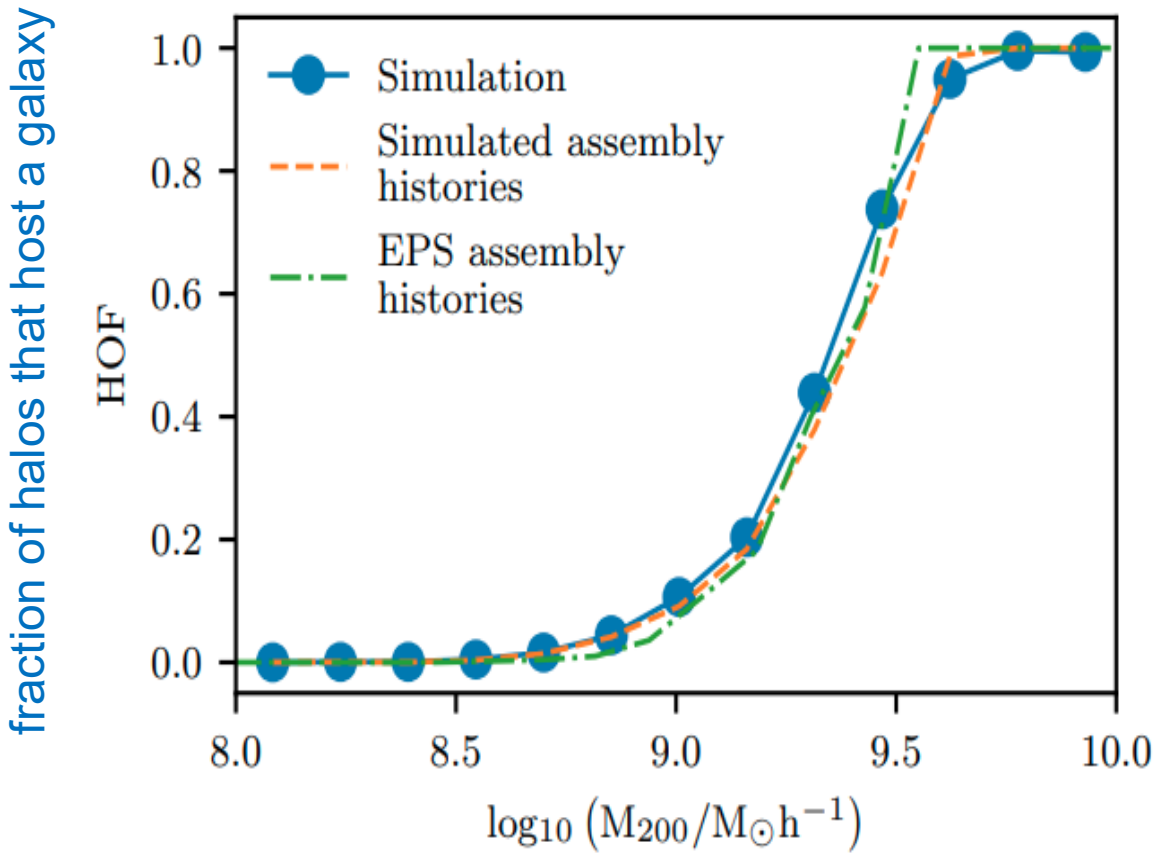


Benitez-Llambay & CSF '20

A galaxy formation primer

Halo Occupation Fraction (HOF): fraction of halos of a given mass today that host a galaxy

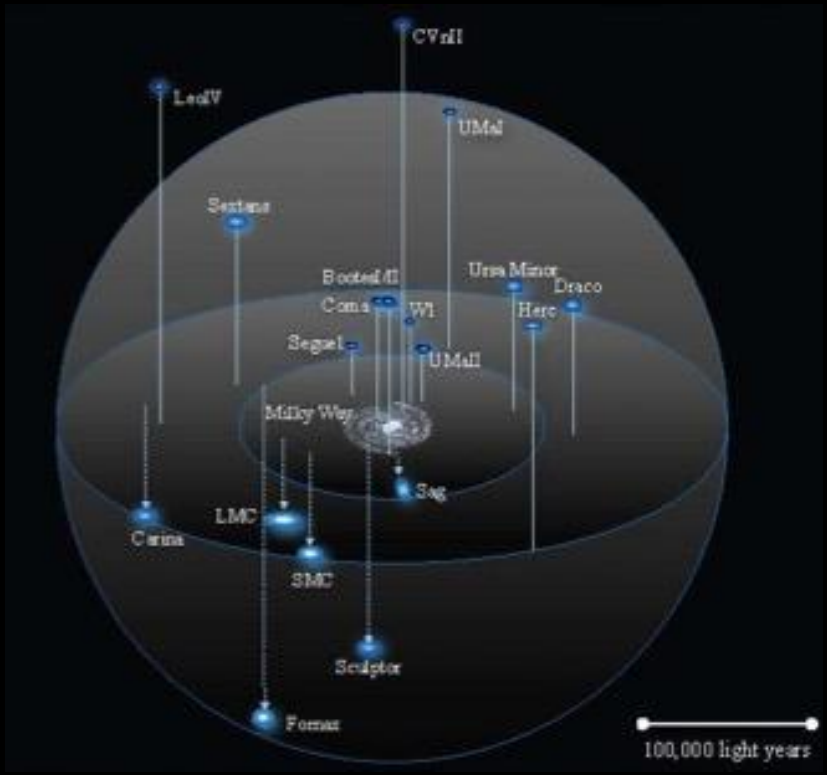


$M<3\times10^8 M_o$
→ dark

$M>3\times10^9 M_o$
→ visible

Benitez-Llambay & CSF '20

These physics works

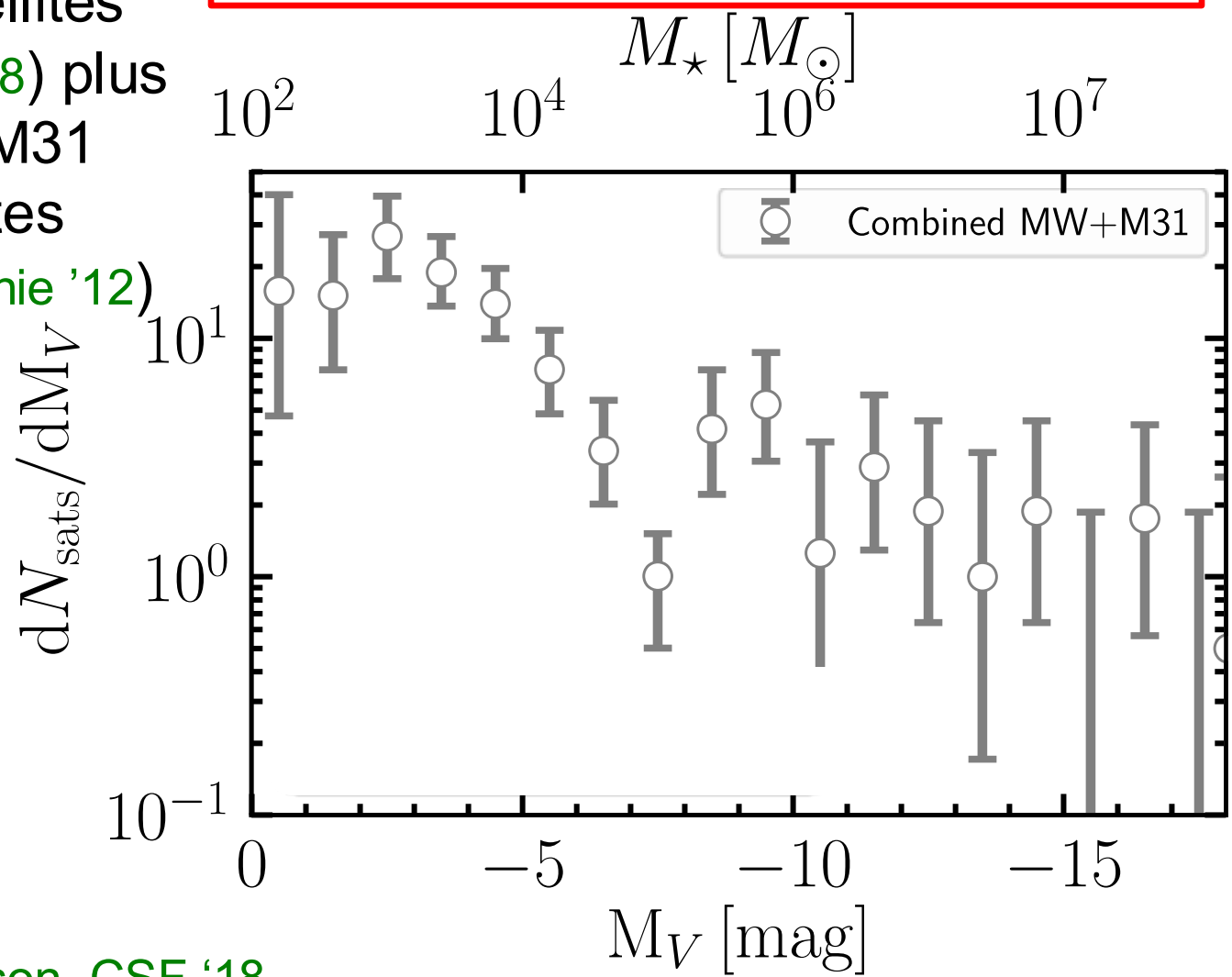


In the MW: ~60 satellites discovered so far

The MW/M31 sat. luminosity function

Differential satellite luminosity function

MW satellites (Newton+ '18) plus M_V<-8 M31 satellites (Mcconnachie '12)

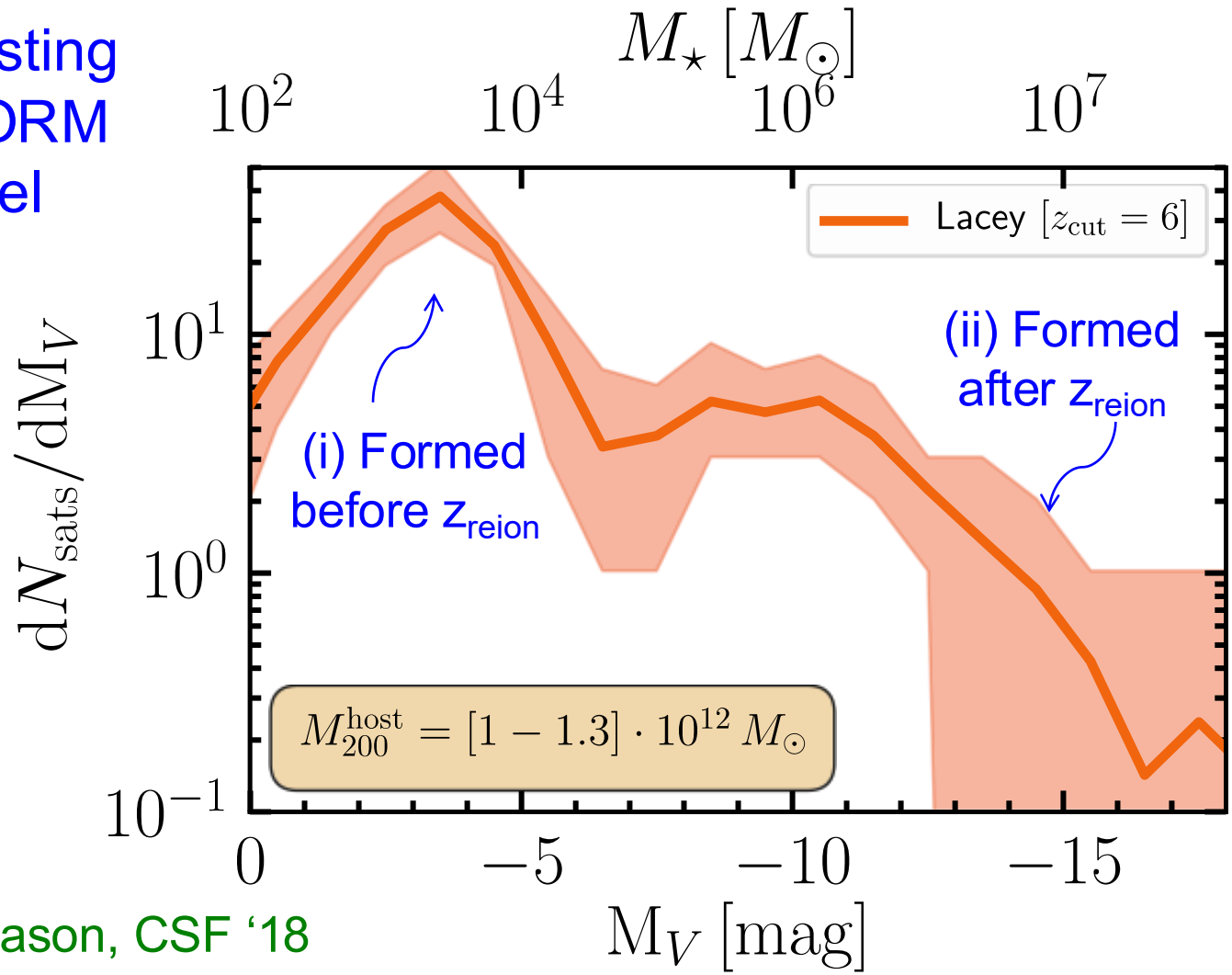


Bose, Deason, CSF '18

The satellite luminosity function

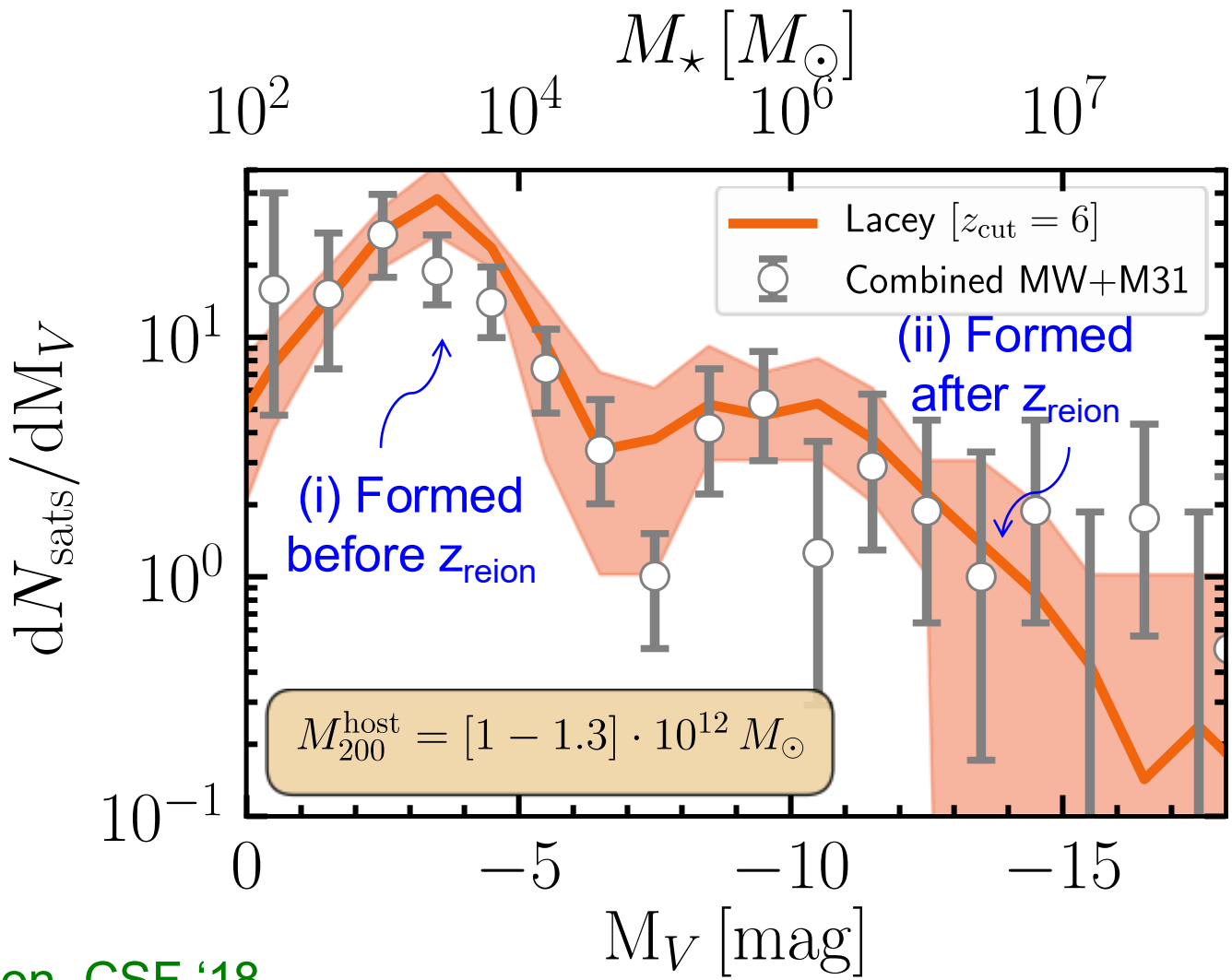
Two populations of sats formed: (i) before and (ii) after reionization

Pre-existing GALFORM model



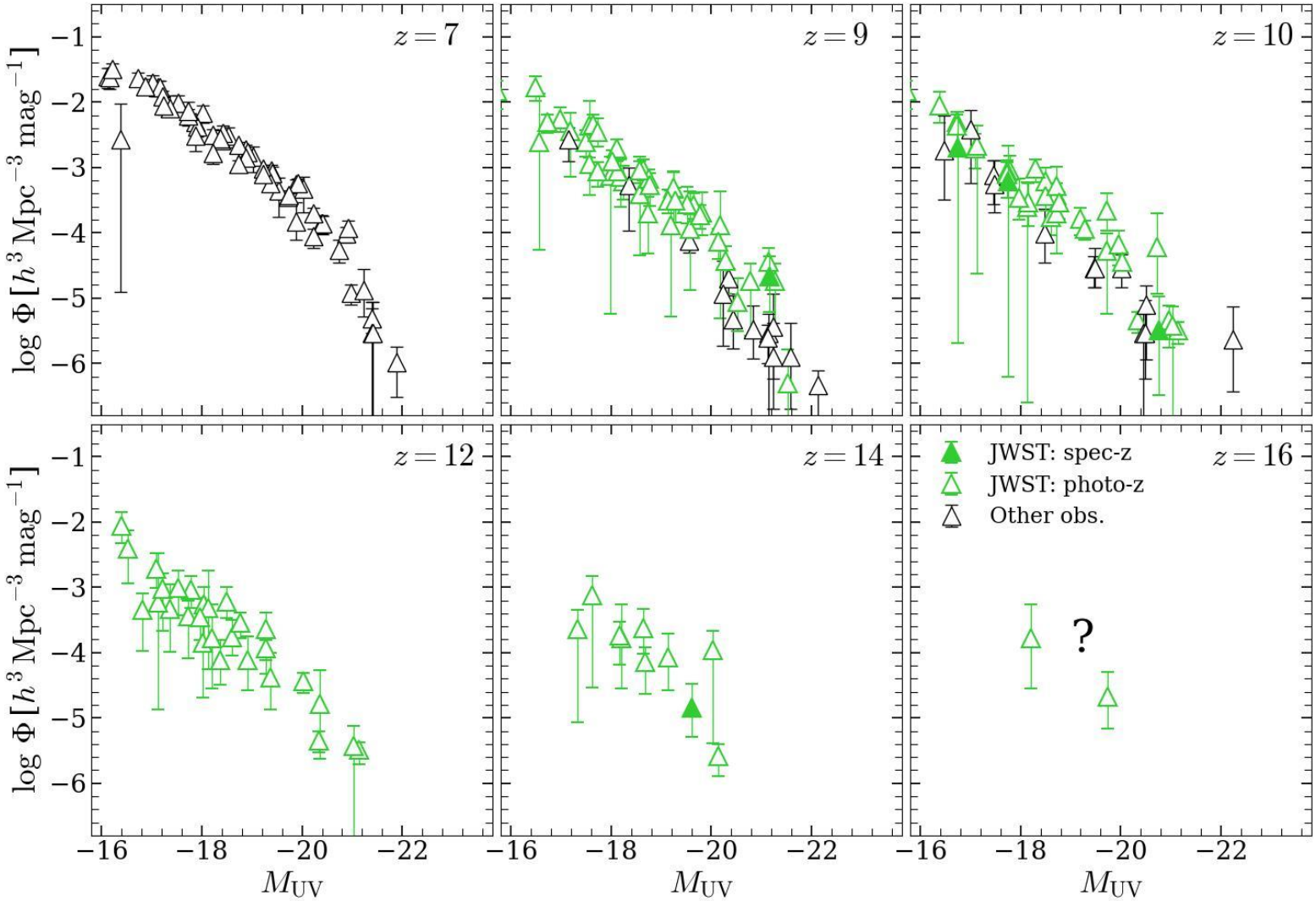
Bose, Deason, CSF '18

Theory *vs* data: test of CDM prediction



Bose, Deason, CSF '18

JWST galaxies at z=7-16



JWST galaxies at z= 8 -15

arXiv:2211.05792v2 [astro-ph.GA] 4 Nov 2023

CEERS Key Paper I:
An Early Look into the First 500 Myr of Galaxy Formation with *JWST*

Steven L. Finkelstein,[1] Micaela B. Bagley,[1] Henry C. Ferguson,[2] Stephen M. Wilkins,[3,4] Jeyhan S. Kartaltepe,[5] Casey Papovich,[6,7] L. Y. Aaron Yung,[8,*] Pablo Arrabal Haro,[9] Peter Behroozi,[10,11] Mark Dickinson,[9] Dale D. Kocevski,[12] Anton M. Koekemoer,[13] Rebecca L. Larson,[14,1] Aurélien Le Bail,[15] Alexa M. Morales,[1] Pablo G. Pérez-González,[16] Denis Burgarella,[17] Romeel Davé,[18,19] Michaela Hirschmann,[20,21] Rachel S. Somerville,[22] Stijn Wuyts,[23] Volker Bromm,[1] Caitlin M. Casey,[1] Adriano Fontana,[24] Seiji Fujimoto,[1,25,26,†] Jonathan P. Gardner,[27] Mauro Giavalisco,[28] Andrea Grazian,[29] Norman A. Grogin,[2] Nimish P. Hathi,[2] Taylor A. Hutchison,[8,*] Saurabh W. Jha,[30] Shardha Jogee,[1] Lisa J. Kewley,[31] Allison Kirkpatrick,[32] Arianna S. Long,[1,†] Jennifer M. Lotz,[33] Laura Pentericci,[24]

ABSTRACT

We present an investigation into the first 500 Myr of galaxy evolution from the Cosmic Evolution Early Release Science (CEERS) survey. CEERS, one of 13 *JWST* ERS programs, targets galaxy formation $z \sim 0.5$ to $z > 10$ using several imaging and spectroscopic modes. We make use of the first epoch of CEERS NIRCam imaging, spanning 35.5 sq. arcmin, to search for candidate galaxies at $z > 9$. Following a detailed data reduction process implementing several custom steps to produce high-quality reduced images, we perform multi-band photometry across seven NIRCam broad and medium-band (and six *Hubble* broadband) filters focusing on robust colors and accurate total fluxes. We measure photometric redshifts and devise a robust set of selection criteria to identify a sample of 26 galaxy candidates at $z \sim 9$–16. These objects are compact with a median half-light radius of ~0.5 kpc. We present an early estimate of the $z \sim 11$ rest-frame ultraviolet (UV) luminosity function, finding that the number density of galaxies at $M_{UV} \sim -20$ appears to evolve very little from $z \sim 9$ to $z \sim$ 11. We also find that the abundance (surface density [arcmin^{-2}]) of our candidates exceeds nearly all theoretical predictions. We explore potential implications, including that at $z > 10$ star formation may

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JWST galaxies at z=15

Pre-JWST-launch predictions from GALFORM

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **474**, 2352–2372 (2018)
Advance Access publication 2017 November 13

doi:10.1093/mnras/stx2897

2018

Predictions for deep galaxy surveys with *JWST* from ΛCDM

William I. Cowley,[1,2★] Carlton M. Baugh,[1] Shaun Cole,[1] Carlos S. Frenk[1] and Cedric G. Lacey[1]

[1] *Institute for Computational Cosmology, Department of Physics, University of Durham, South Road, Durham DH1 3LE, UK*
[2] *Kapteyn Astronomical Institute, University of Groningen, PO Box 800, NL-9700 AV Groningen, the Netherlands*

GALFORM applied to Milennium XXL N-body simulation

→ Has enough resolution and volume!

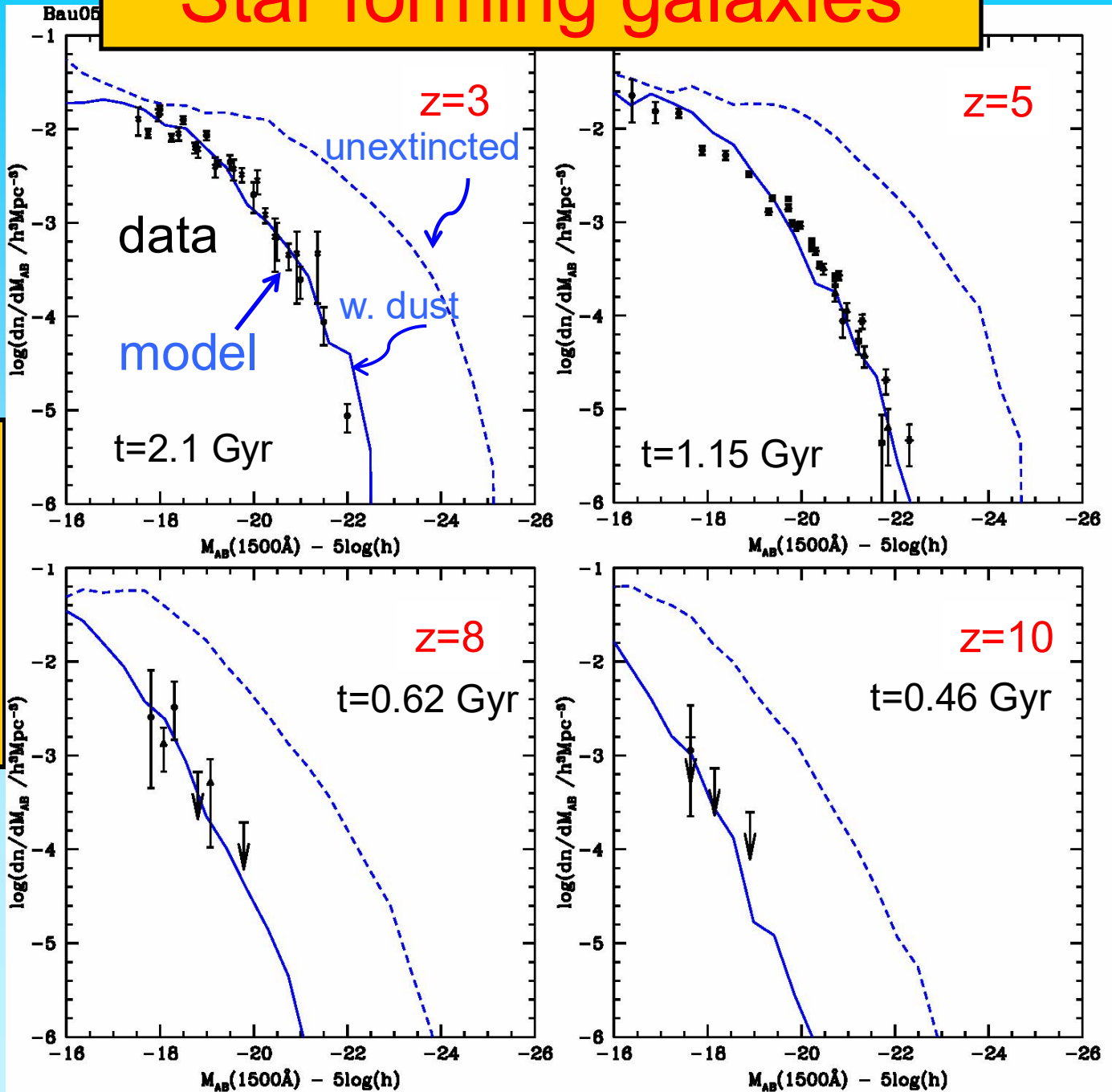
Star forming galaxies

University of Durham

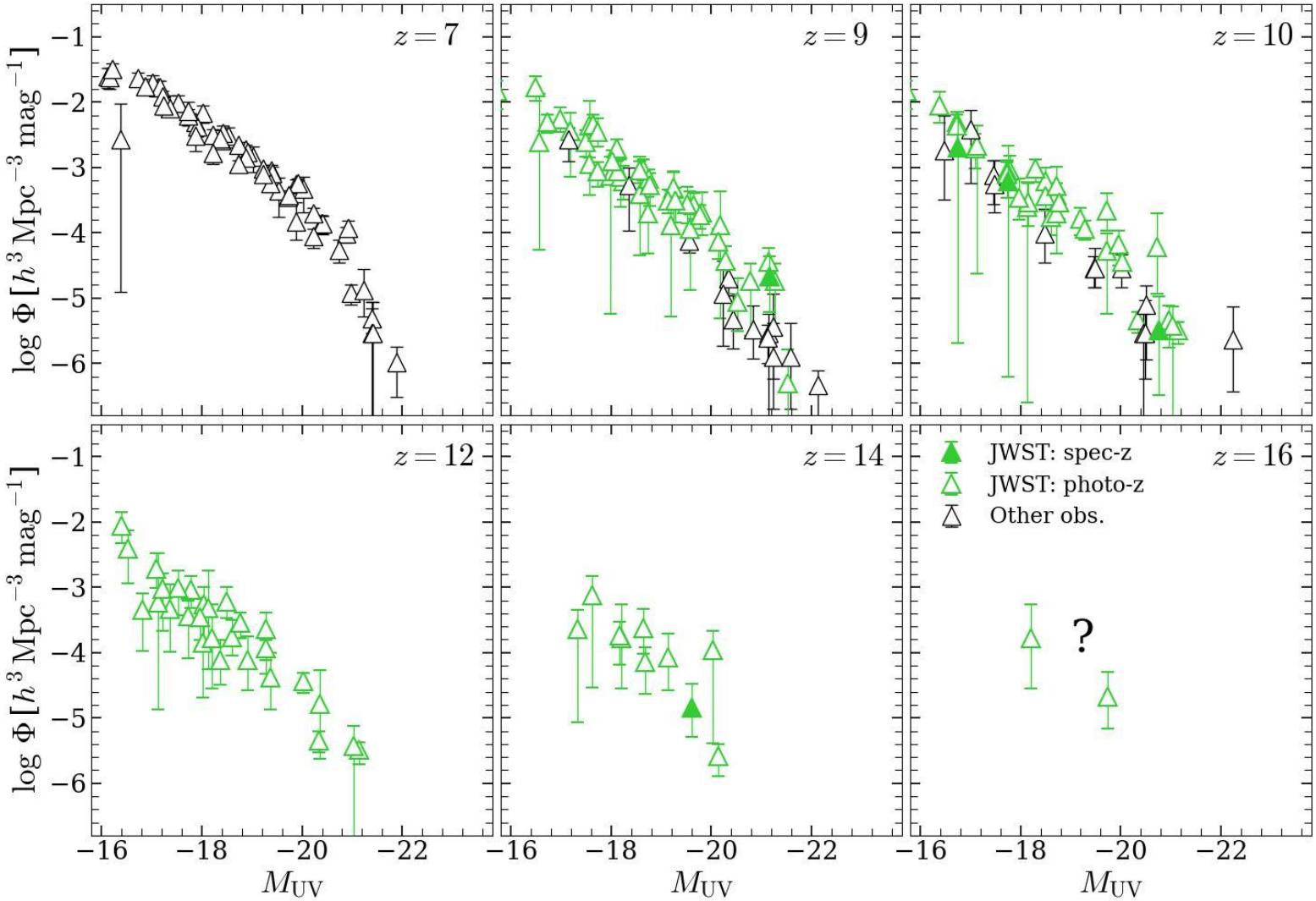
GALFORM

Evolution of Lyman-break galaxy lum. function

Lacey, Baugh, Frenk, Benson '12



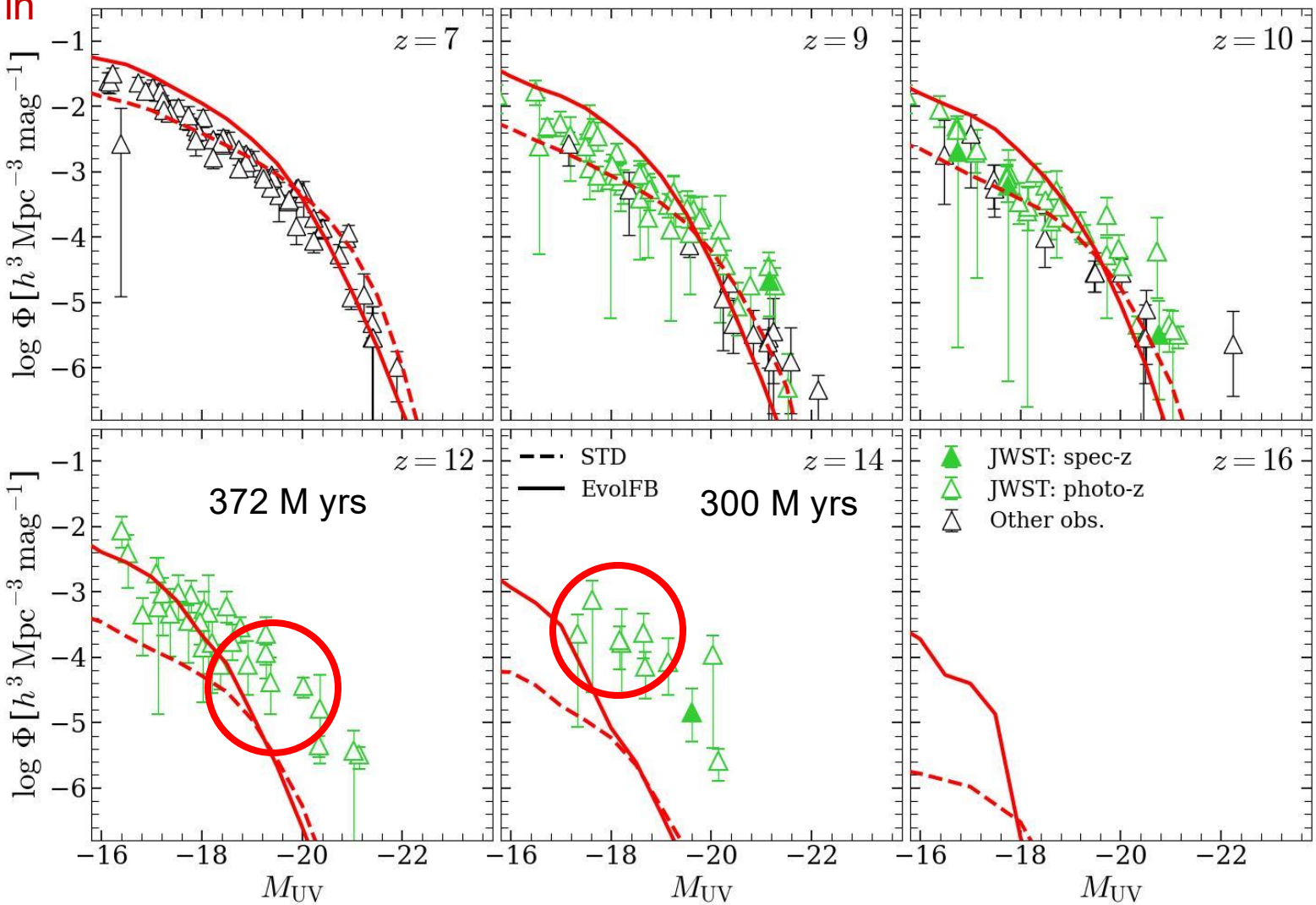
JWST galaxies at z=7-16



JWST galaxies at z=7-16

Key – top heavy IMF in bursts

Theoretical predictions precede data (Cowley + '18)



Lu, CSF, Bose, Lacey, Cole, Baugh, Helly '24

JWST galaxies at z=7-16

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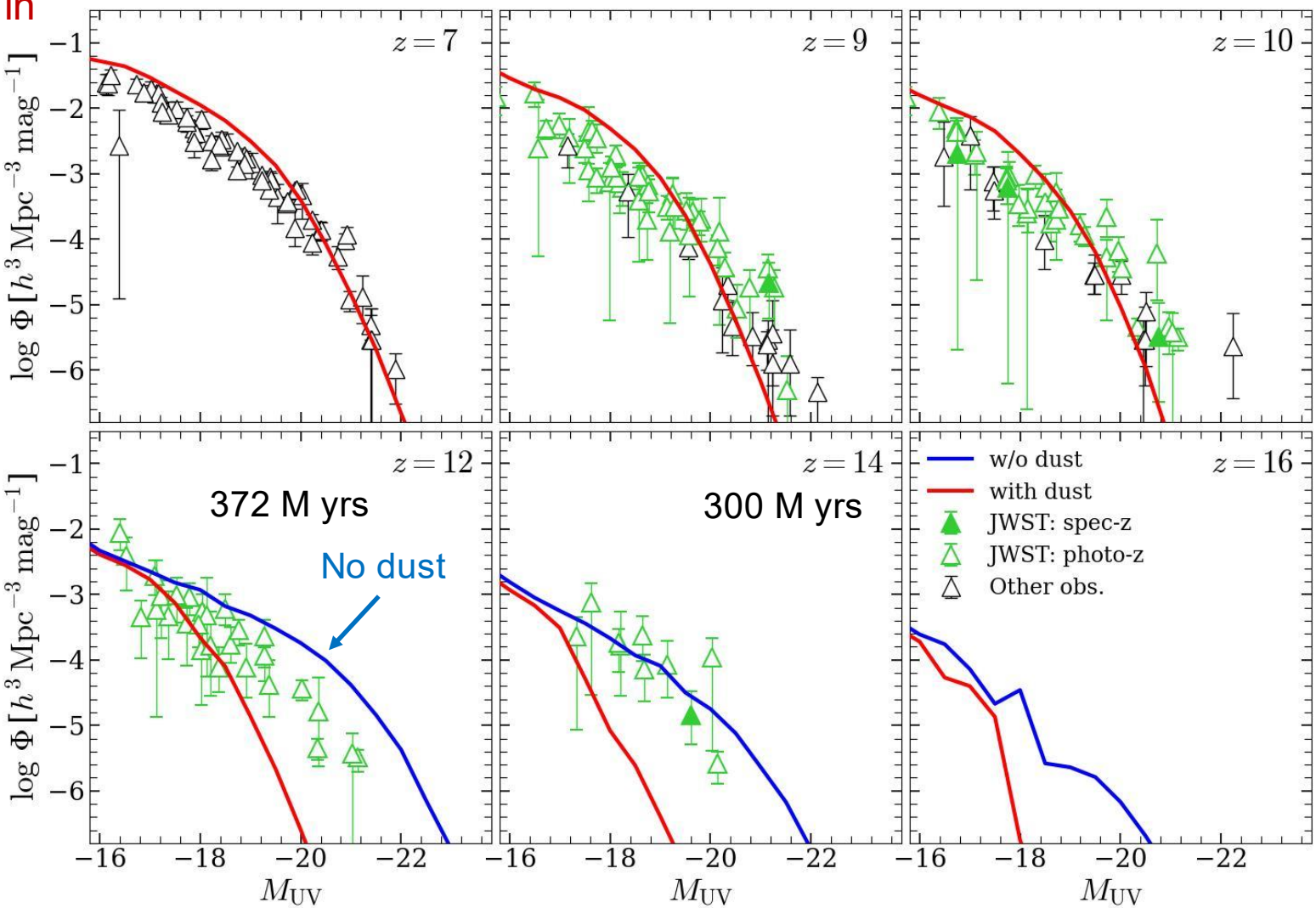

Shengdong Lu, CSF + 24

JWST galaxies at z=7-16

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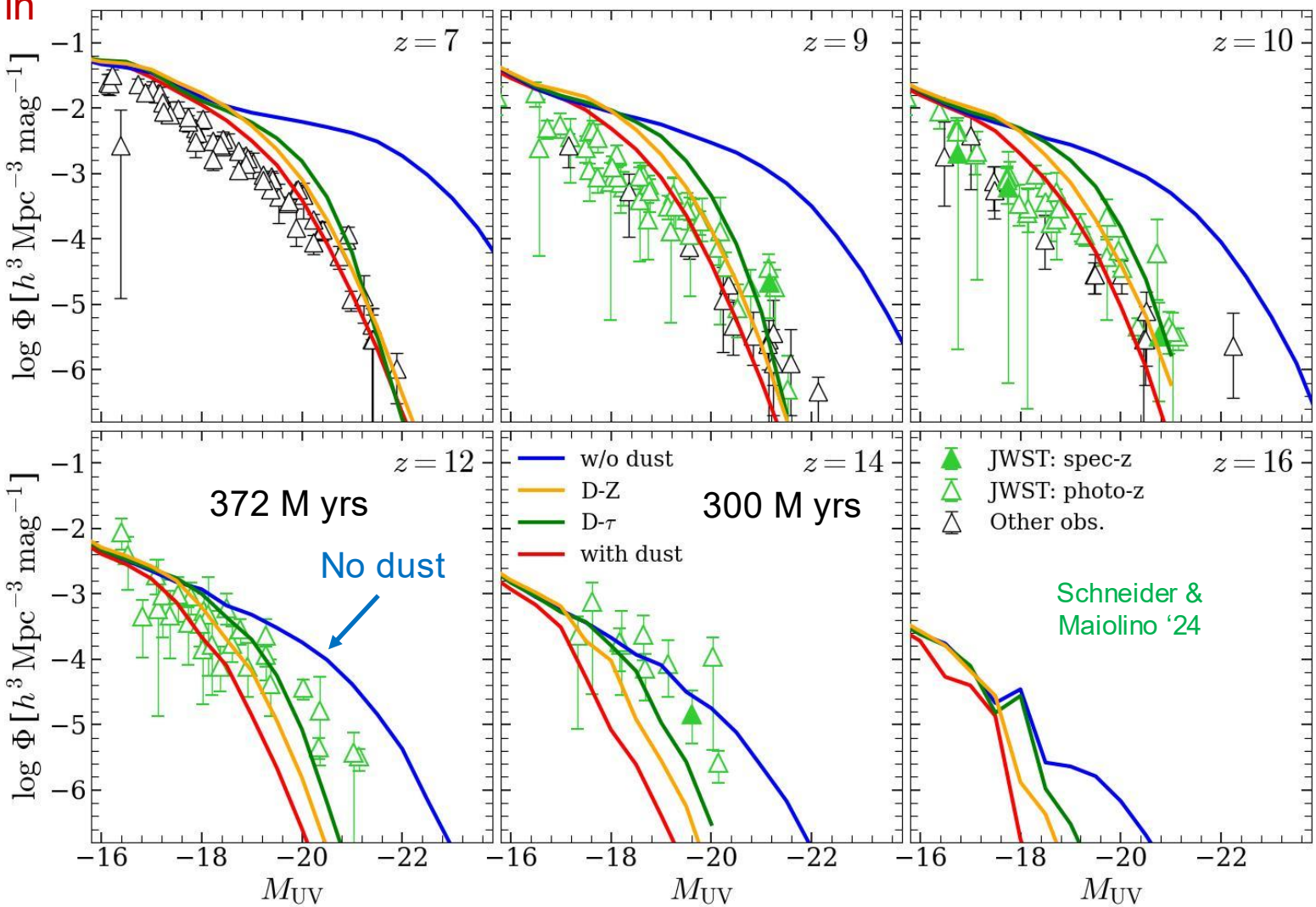


Shengdong Lu, CSF + 24

Tests of CDM on small scales/early times

UV luminosity function of JWST galaxies at z = 7 – 14 → just as predicted in ΛCDM in 2018 (with dust grains forming gradually at z>12)!

Lu, CSF+ '24

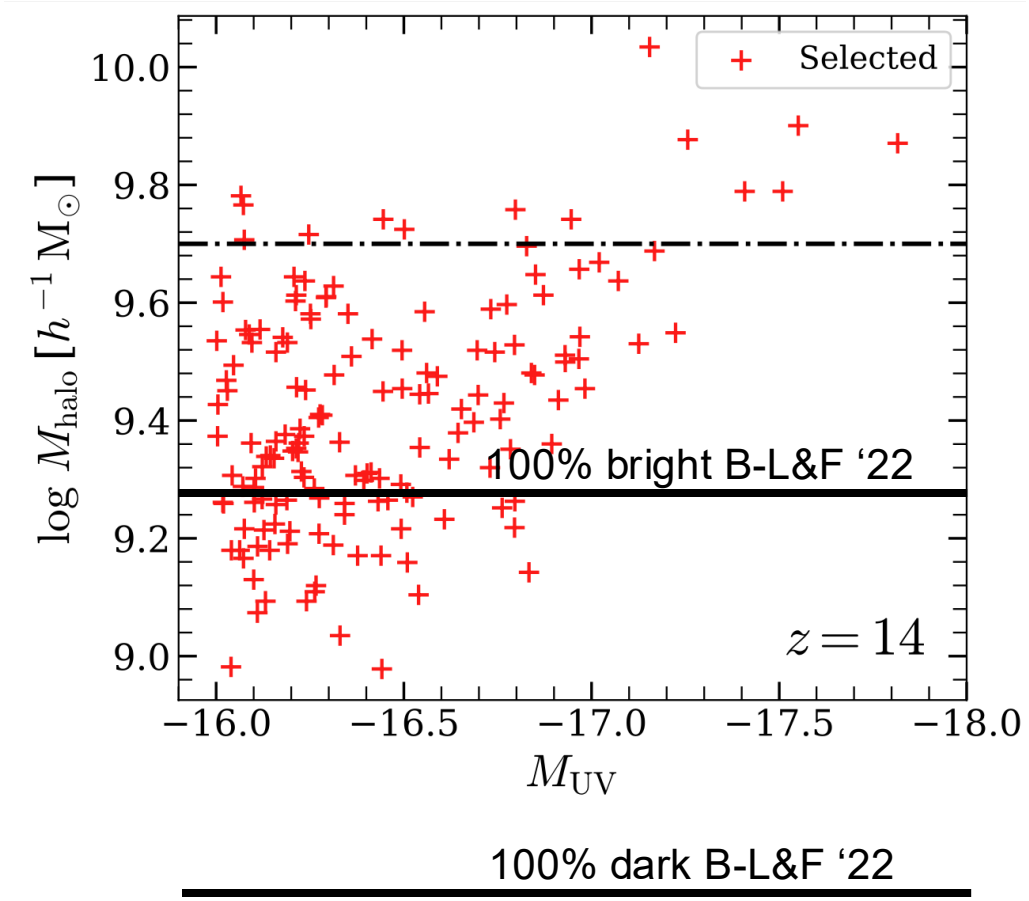
Key to this success

1. Top-heavy IMF in starbursts
2. Proper modelling of dust

Properties of z=14 galaxies

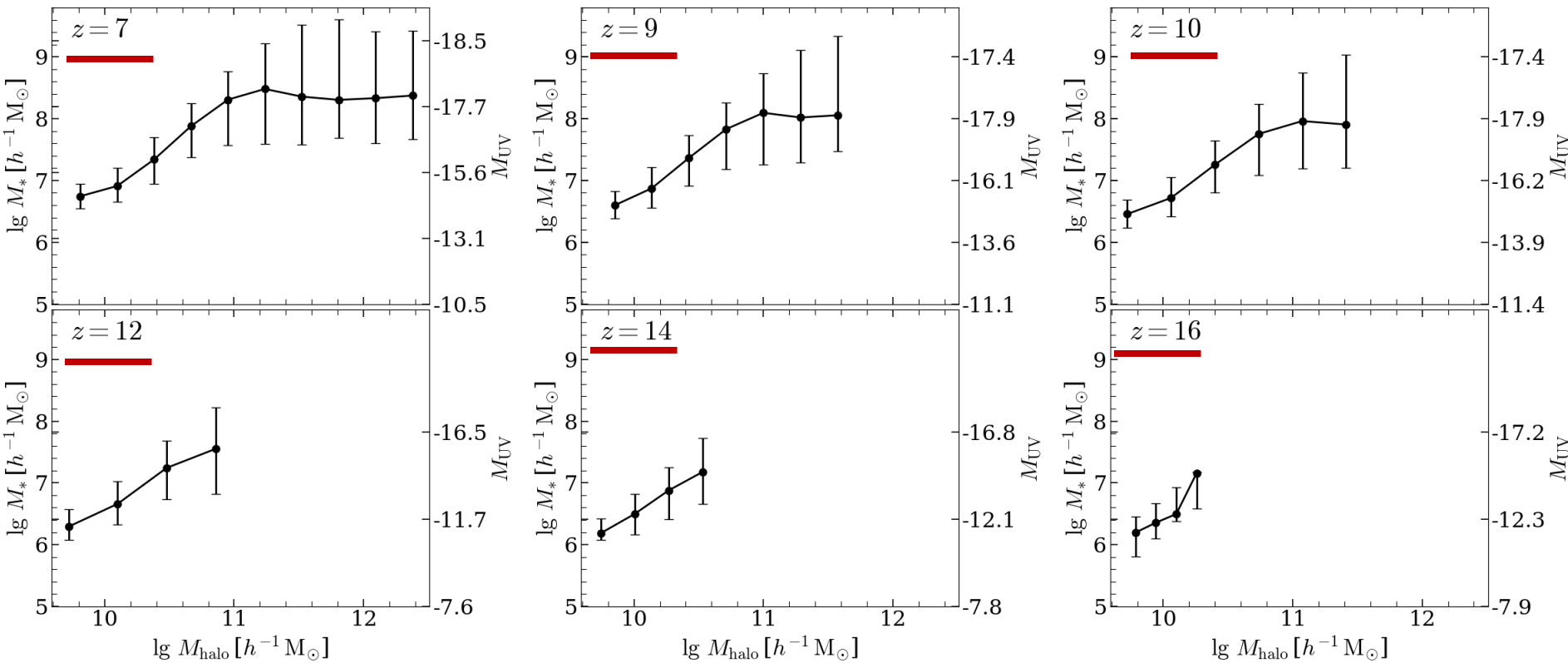
Lu, CSF + '24

JWST z=14 galaxies in narrow range of halo mass



JWST galaxies at z=7-16

Predicted halo-stellar mass relation



	z	Stellar mass	Halo mass
brightest galaxy:	12	2×10^8 M_o (~Sagittarius)	6×10^{10} M_o (~Sagittarius)
	16	10^7 M_o	2×10^{10} M_o

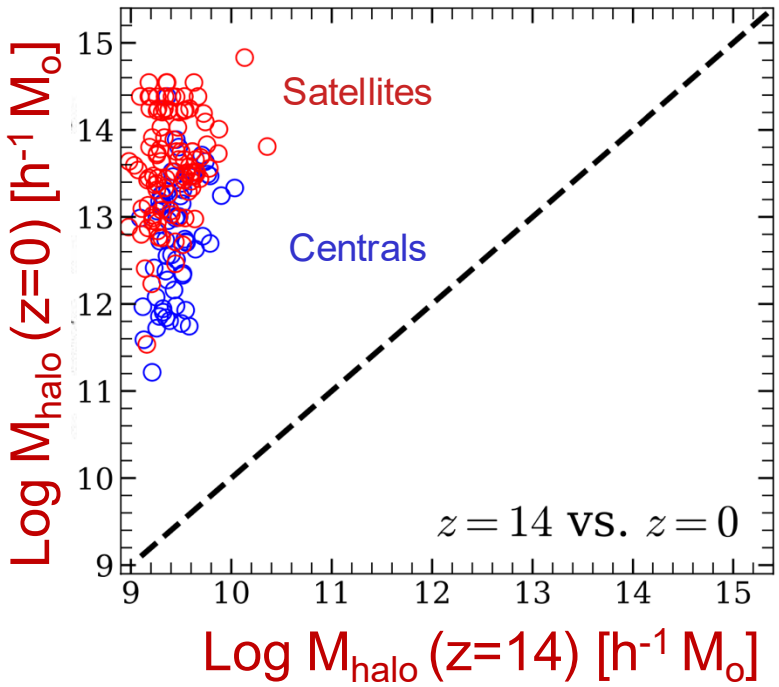
LMC: $M_* = 3 \times 10^9 M_{0;}$ $M_{halo} = 2 \times 10^{11} M_o$

Descendants of z=14 bright gals

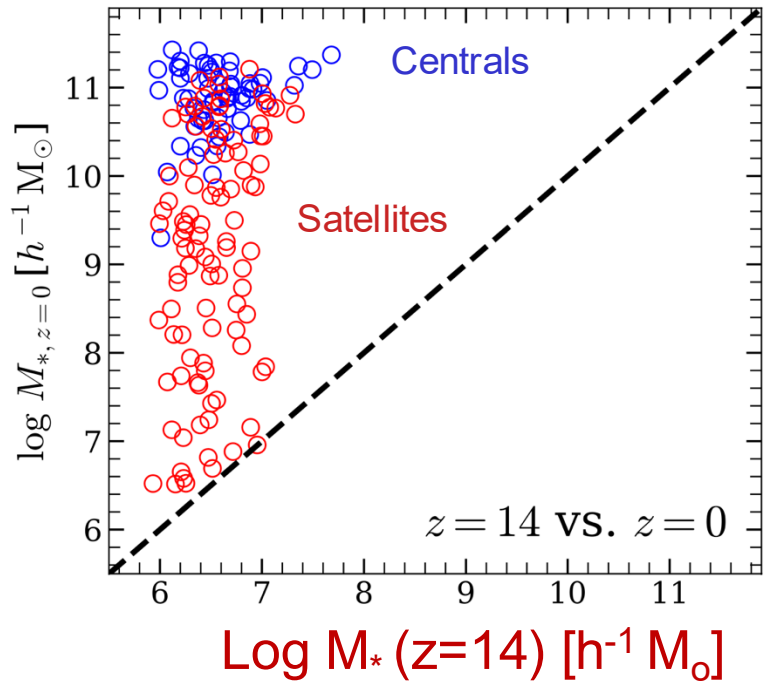
z=14 vs z=0

Lu, CSF + '24

Halo mass



Stellar mass



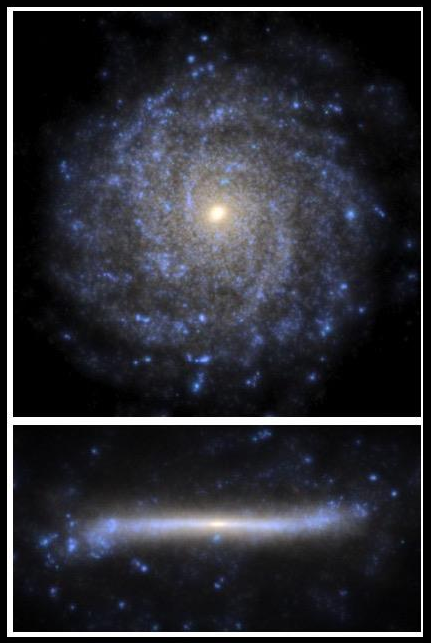
JWST galaxies: dwarfs at z=14, progenitors of bright centrals today

The COLIBRE simulations

COLIBRE: COLd Ism and Better REsolution

Builders:
- Chaikin
- Ploeckinger
- Schaller
- Schaye (PI)

Core members:
- Benitez-Llambay
- Correa
- Frenk
- Huško
- McGibbon
- Richings
- Trayford



Members:
- Bahe
- Borrow
- Crain
- Forouhar Moreno
- Helly
- Jenkins
- Lacey
- Ludlow
- Nobels
- Pfeffer
- Theuns

A new generation of cosmological simulations of galaxy formation

VIRG

Institute for Computational Cosmology

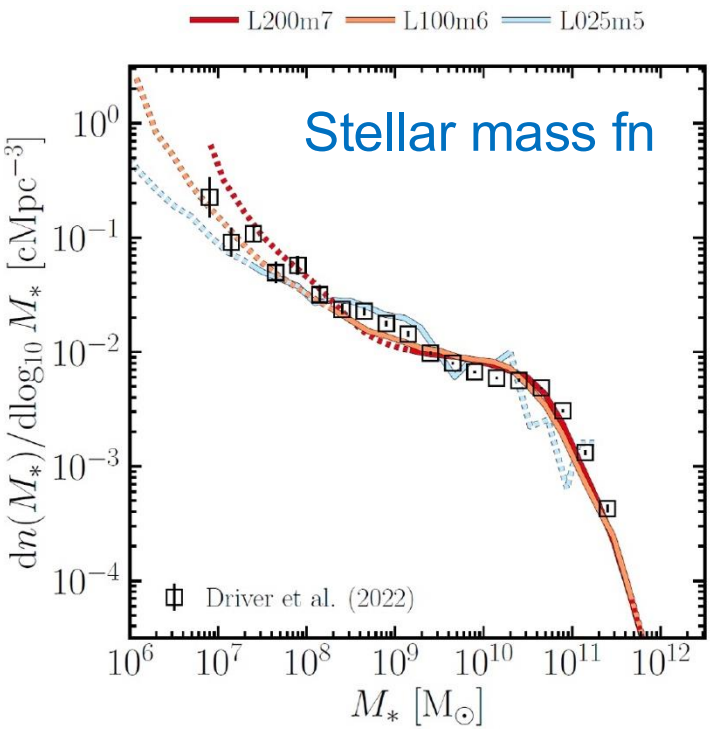
University of Durham

The COLIBRE simulations

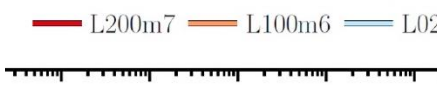
COLd Ism and Better Resolution (COLIBRE)

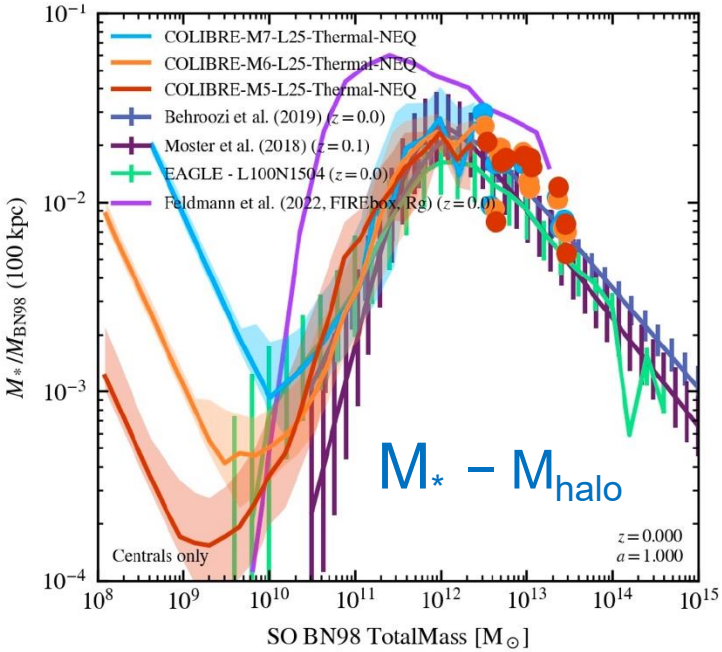
- Includes
  - Cold ($T << 10^4$ K) interstellar gas
  - New cooling (non-equil. H, He, e^-; self-shielding, UVB and interstellar radiation)
  - Dust (3 grain species, 2 grain sizes; coupled to cooling)
  - New 'chemistry' (new yields, diffusion, new SNIa, s- and r-process elements)
  - New stellar feedback (HII regions, winds, turbulence, improved stochastic SN feedback)
  - Improved BH and AGN physics (also runs with BH spin and jet feedback)
  - New star formation (Schmidt law with instability criterion)
  - Model for globular clusters (m5 only)
- Suppresses spurious energy transfer from DM to baryons by using 4x more DM than baryonic particles
- Very large simulations, 3008^3 baryonic and 4768^3 DM particles (20 times more than EAGLE)
- Wedding cake strategy:
  - Box sizes ranging from 400 Mpc to 25 Mpc
  - Particle masses ranging from ~10^7 to 10^5 $M_\odot$

The COLIBRE simulations

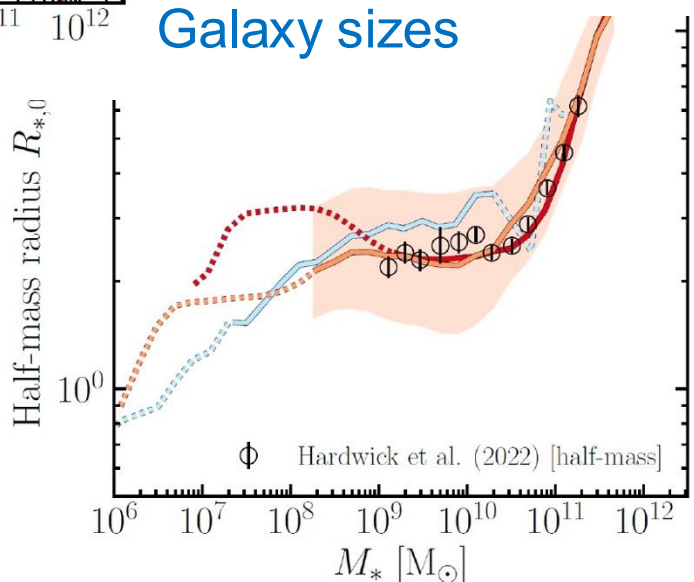


Calibration of subgrid parameters





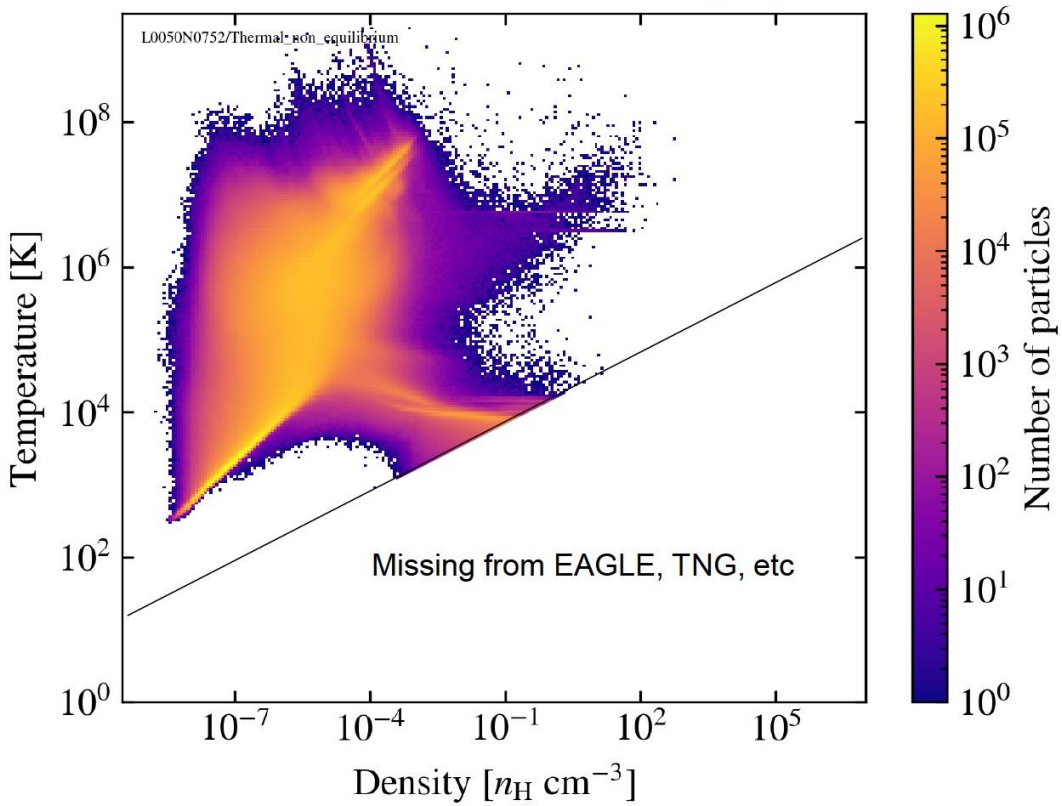
Galaxy sizes



Schaye+ ’25
Chaikin+ 25

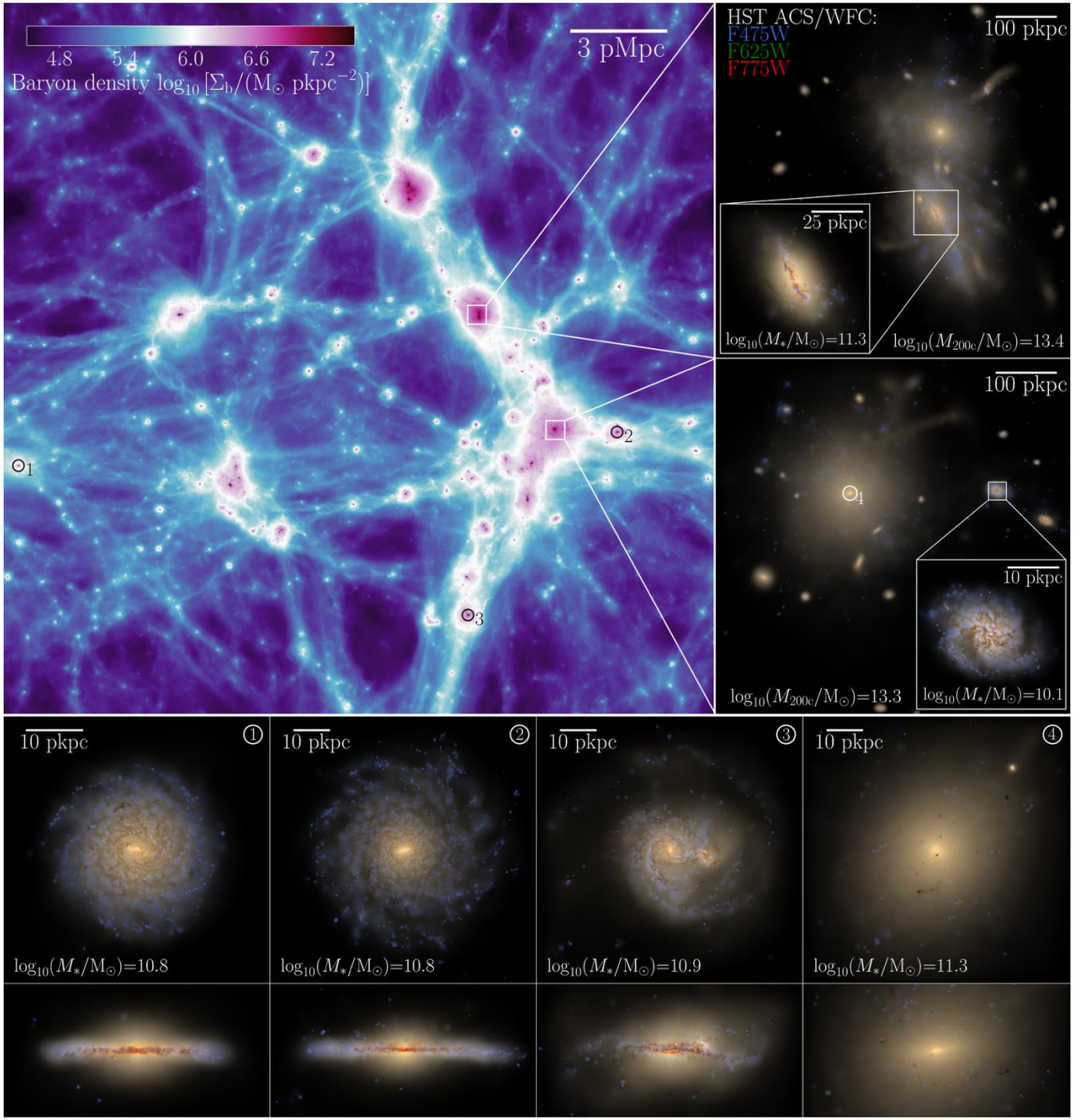
The COLIBRE simulations

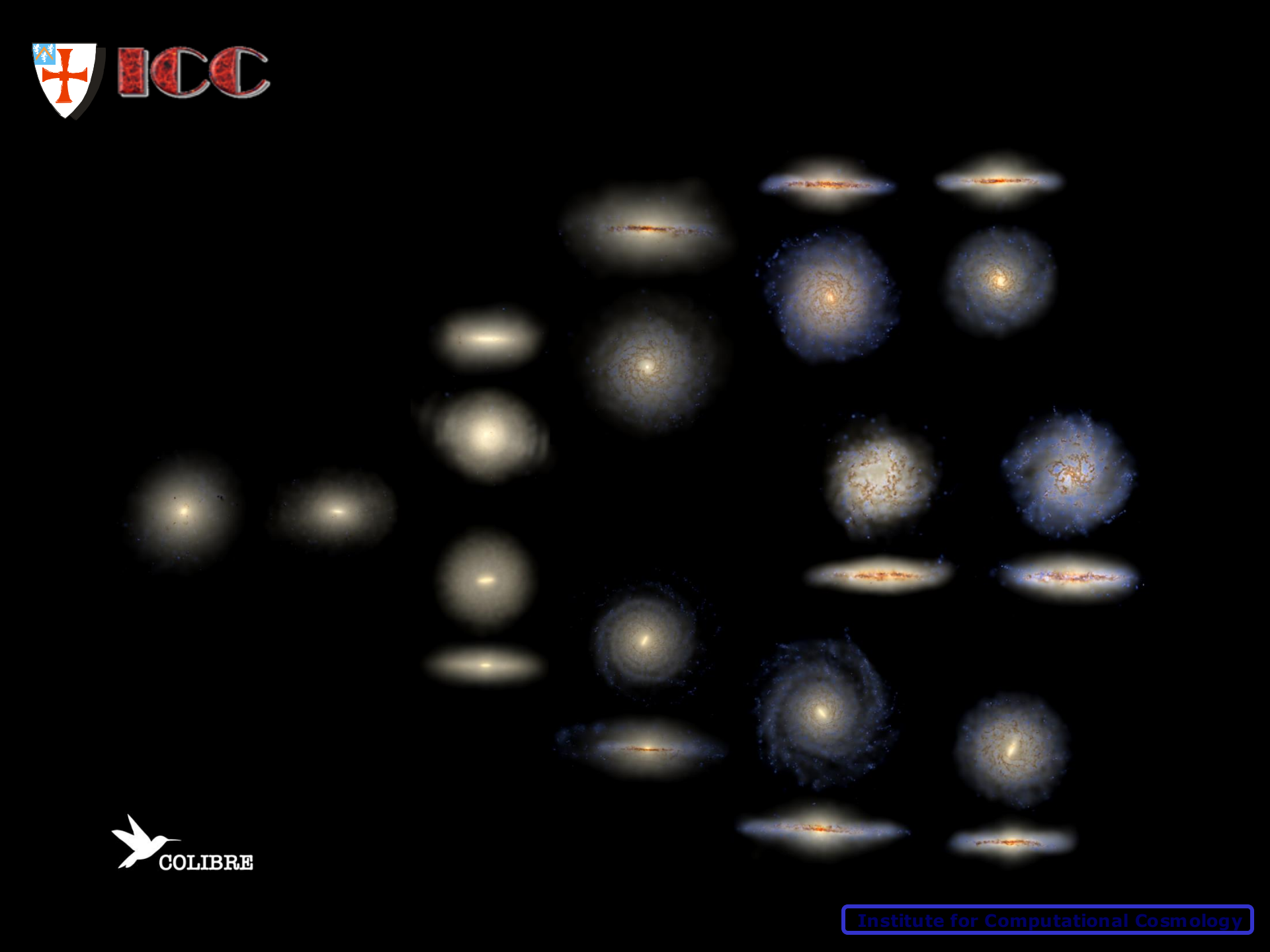
Mass distribution in temperature-density space



z = 0
L50m6

Schaye+ ’25
Chaikin+ 25

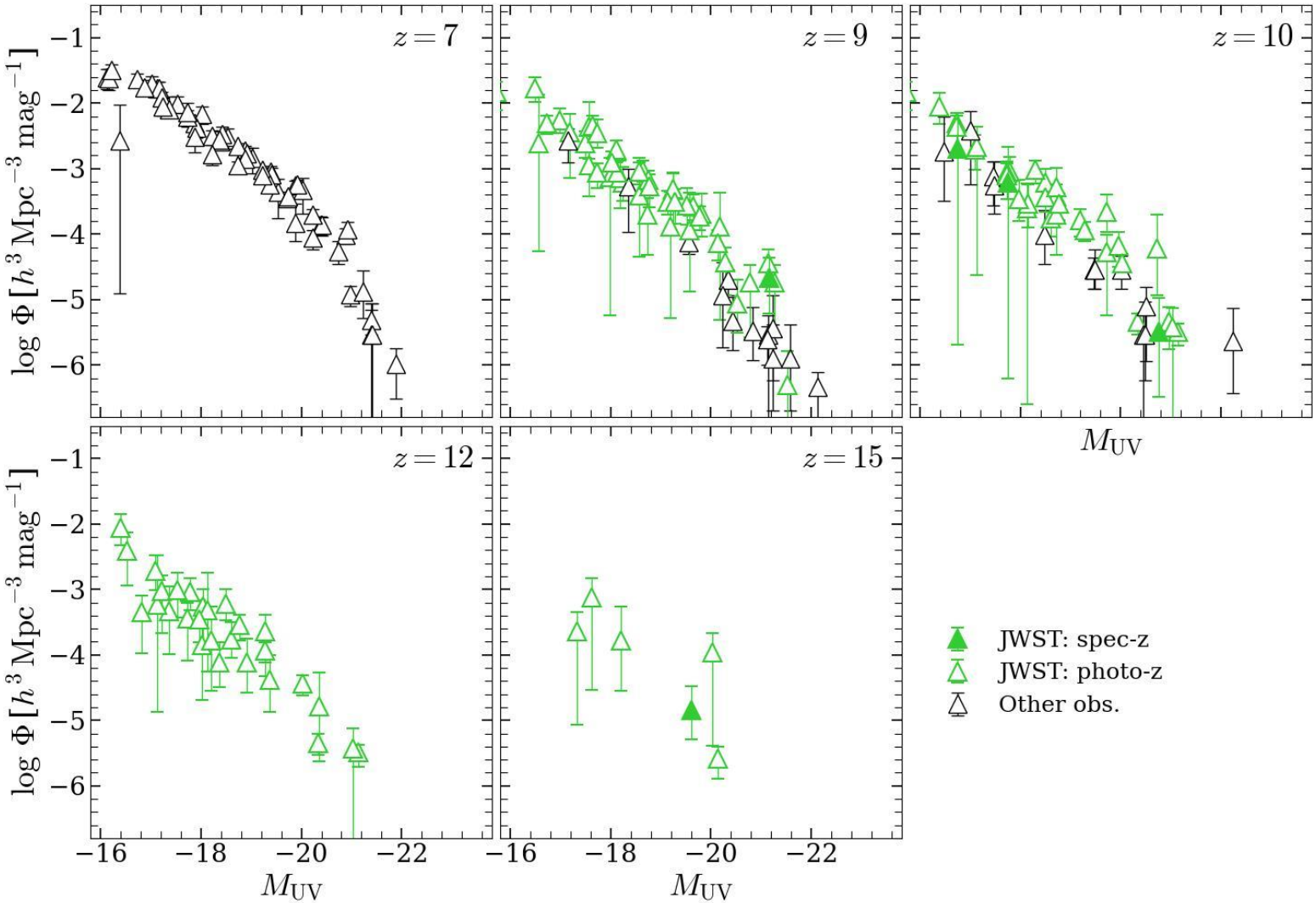

4.8
5.4
6.0
6.6
7.2
Baryon density $\log_{10}[\Sigma_b/(M_\odot\ \mathrm{pkpc}^{-2})]$
3 pMpc
1
2
3
HST ACS/WFC:
F475W
F625W
F775W
100 pkpc
25 pkpc
$\log_{10}(M_*/M_\odot)$=11.3
$\log_{10}(M_{200c}/M_\odot)$=13.4
100 pkpc
4
10 pkpc
$\log_{10}(M_{200c}/M_\odot)$=13.3
$\log_{10}(M_*/M_\odot)$=10.1
10 pkpc
1
$\log_{10}(M_*/M_\odot)$=10.8
10 pkpc
2
$\log_{10}(M_*/M_\odot)$=10.8
10 pkpc
3
$\log_{10}(M_*/M_\odot)$=10.9
10 pkpc
4
$\log_{10}(M_*/M_\odot)$=11.3


ICC
COLIBRE
Institute for Computational Cosmology

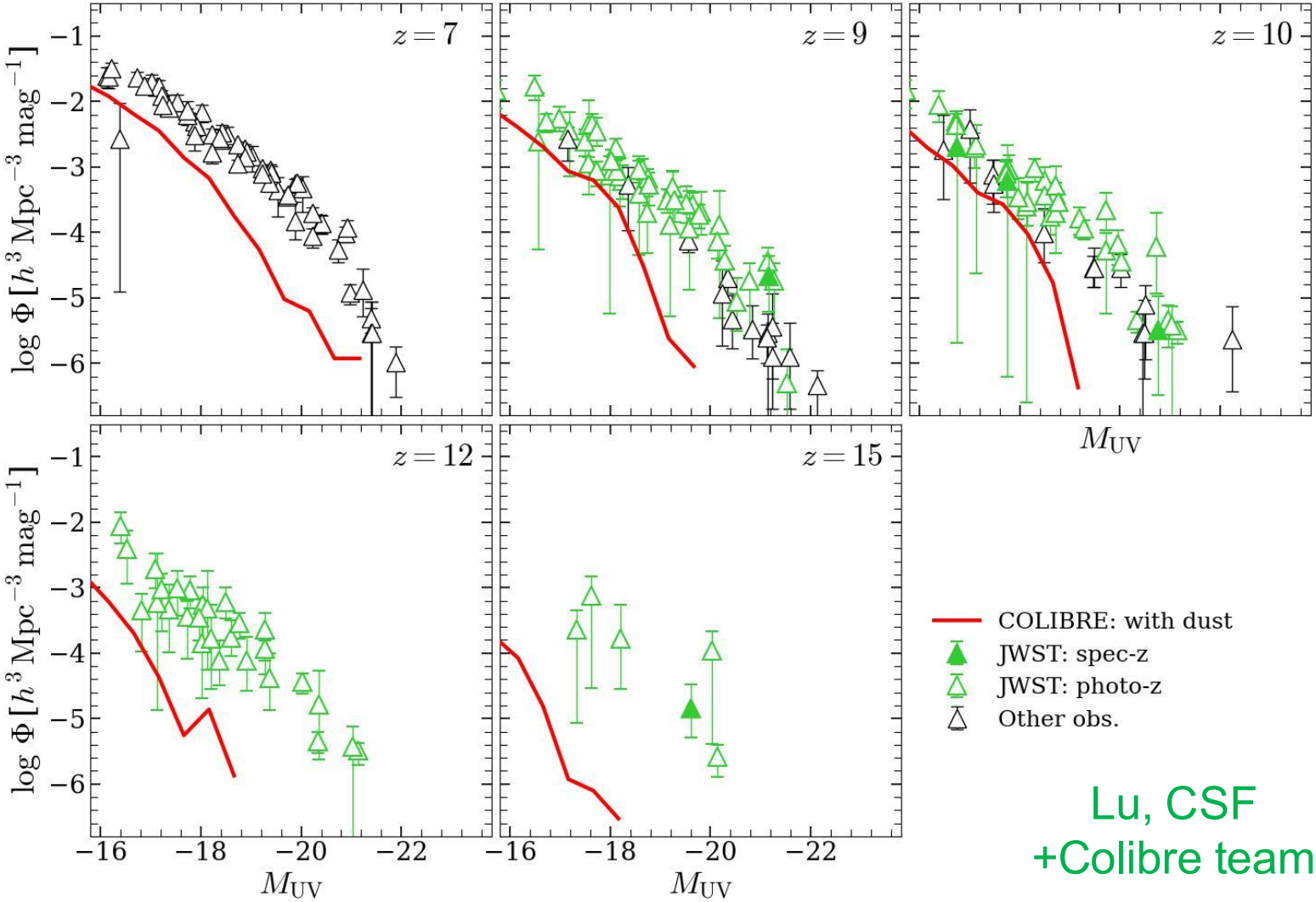
The COLIBRE simulations

Colibre assumes a Chabrier initial stellar mass function

UVLFs in COLIBRE

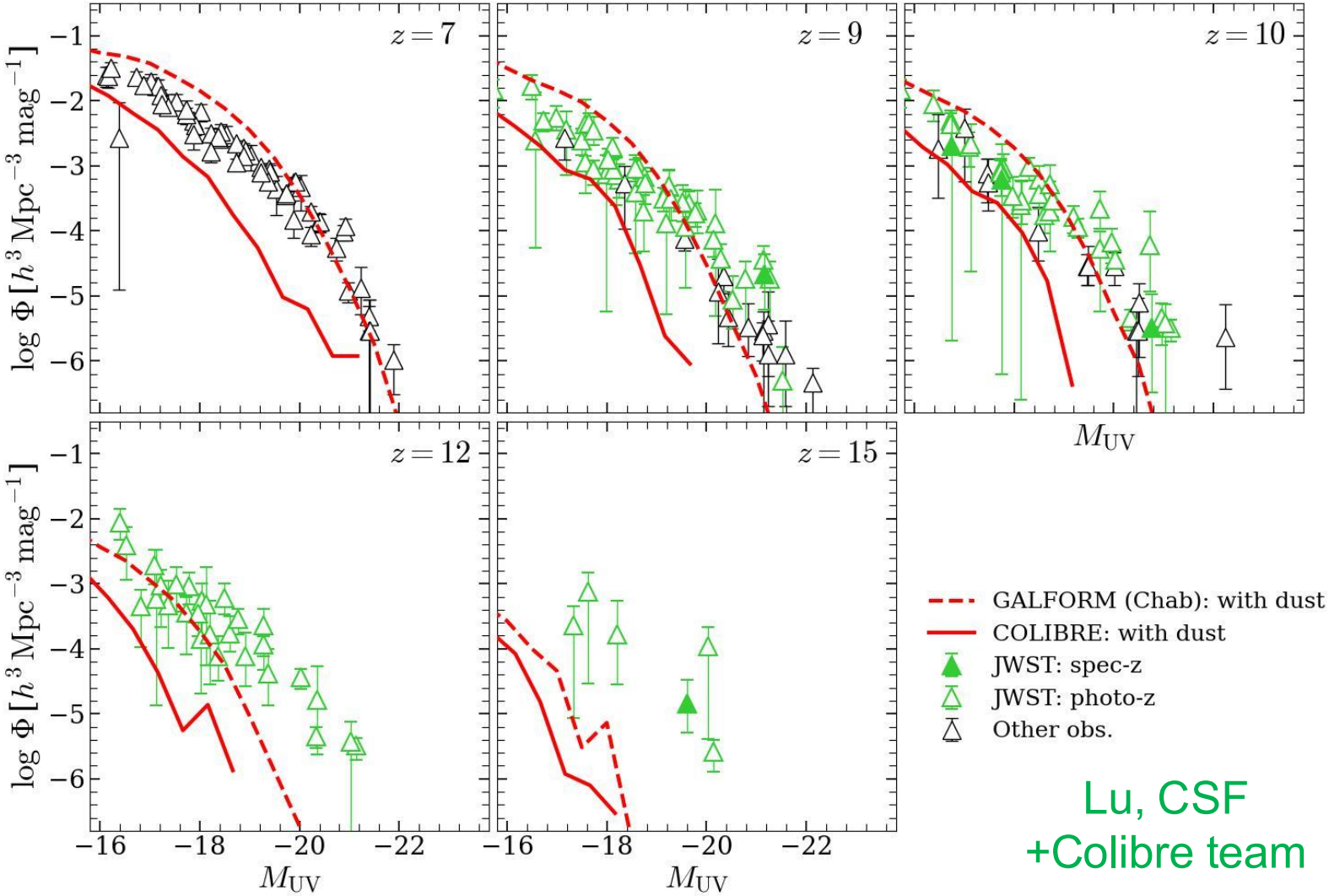


UVLFs in COLIBRE



Lu, CSF
+Colibre team

UVLFs in COLIBRE



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JWST galaxies at high-z: a new challenge to ΛCDM? → NO!

1. The UV LF of JWST galaxies at z=8-14 is as predicted by GALFORM in 2018, once dust formation timescale is included
2. A top-heavy IMF in starbursts is required (also for submm gals)
3. COLIBRE underpredicts the UVLF at z > 7 by > 2 orders of magnitude because it assumes a standard (Chabier) IMF
4. The brightest galaxies at z>10 have mass ~dwarfs today
5. They live in halos in a narrow range of masses: $10^8 - 10\ M_o$
6. Some are the progenitors of galaxies like the MW and above; most satellites in groups and clusters