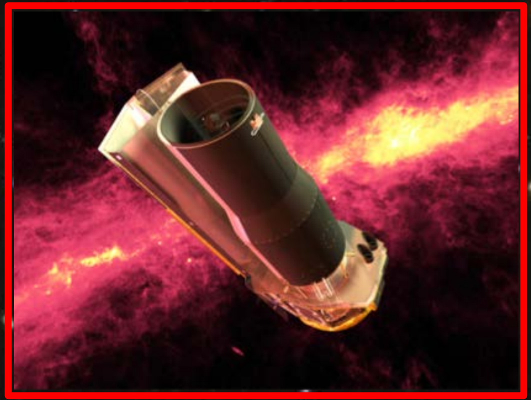
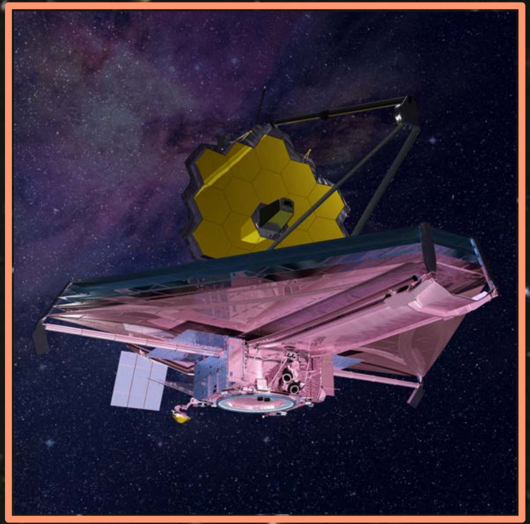
Melbourne
Colloquium
August 02 2017



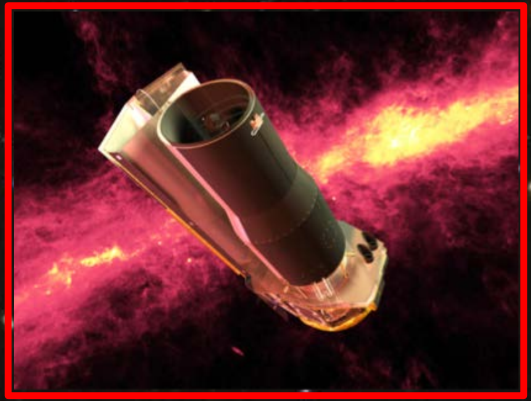
Galaxies at Cosmic Dawn: Exploring the First Billion Years with Hubble and Spitzer – Implications for JWST



Garth Illingworth
UCSC

firstgalaxies.org

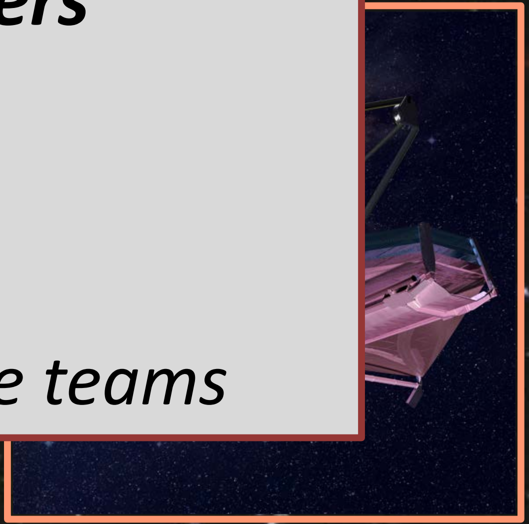
Melbourne
Colloquium
August 02 2017



science collaborators & science team members

Rychard Bouwens, Pascal Oesch

Ivo Labbé, Mauro Stefanon, Renske Smit,
Pieter van Dokkum, Marijn Franx, Dan Magee,
& the HUDF09/XDF/HLF, 3D-HST and ACS GTO science teams



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UCSC

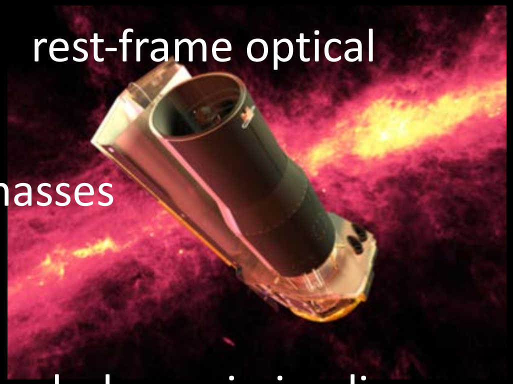
firstgalaxies.org

Hubble's partners in revealing the properties of high-redshift galaxies

IGM

AGN

rest-frame optical



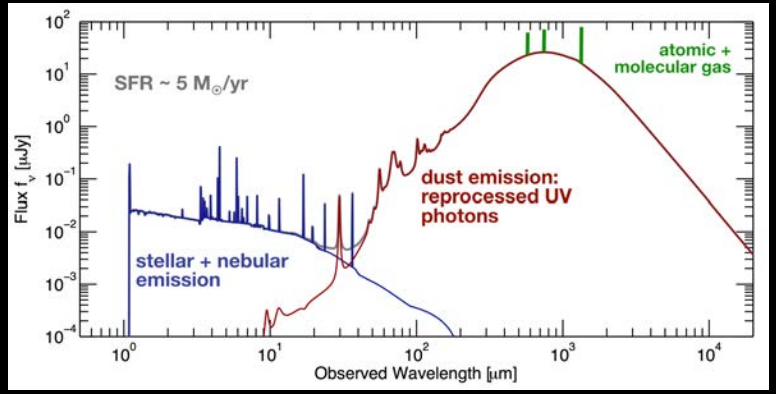
stellar masses

nebular emission lines

high-redshift galaxy samples

rest-frame UV

spectral energy distributions



star formation rates

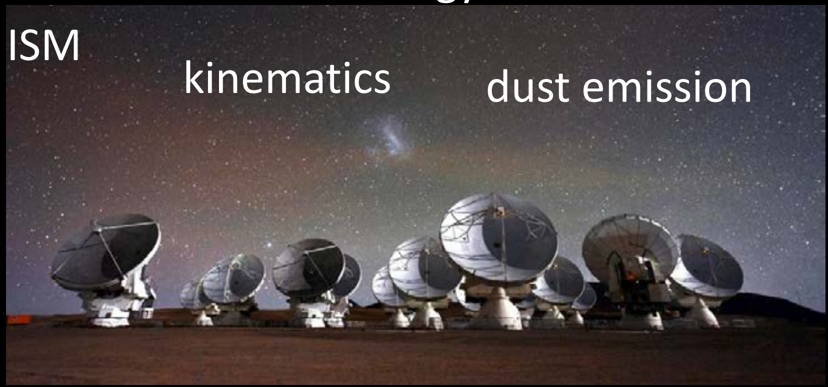
optical & near-IR spectroscopy – redshifts & kinematics

energy balance – FIR

ISM

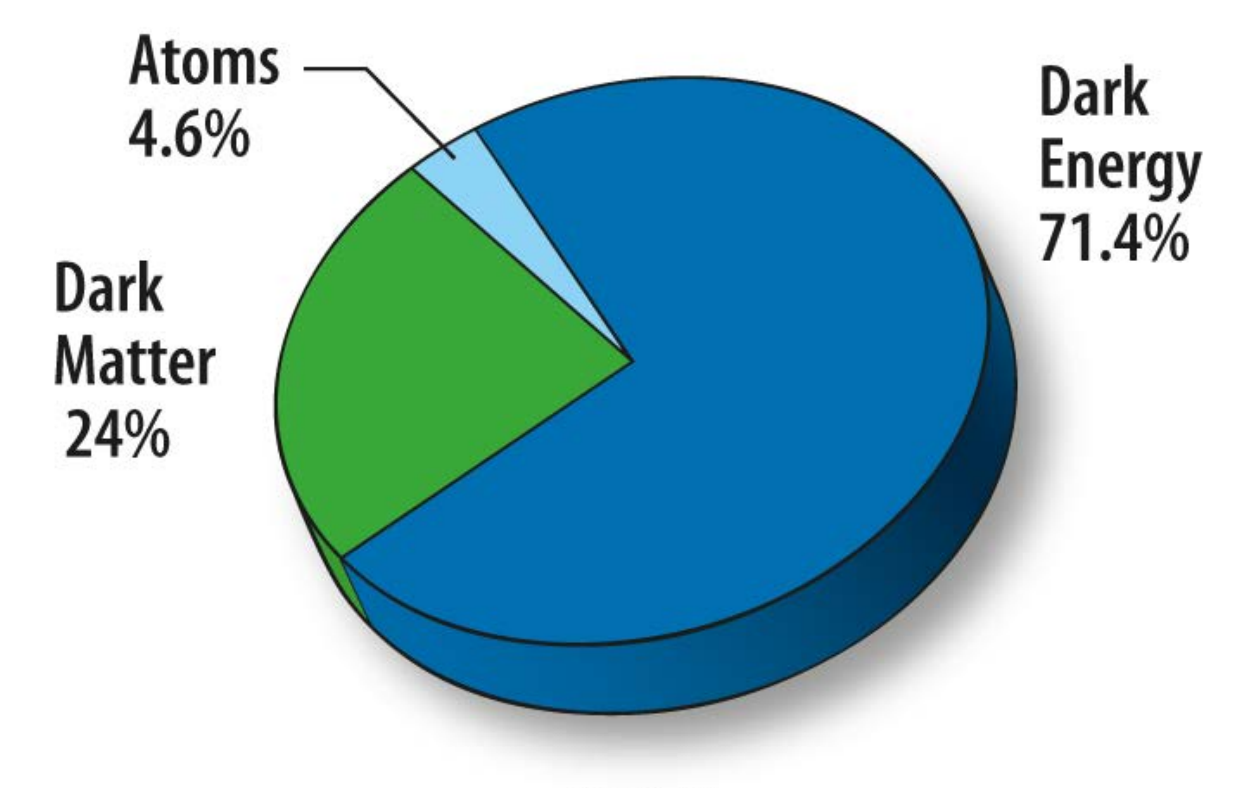
kinematics

dust emission



our strange universe

its all dark matter & dark energy –
and a little bit of "ordinary matter"



from WMAP and Planck telescopes

our strange universe

its all dark matter & dark energy –
and a little bit of “ordinary matter”

ordinary matter is, by
comparison, a bit mousey…

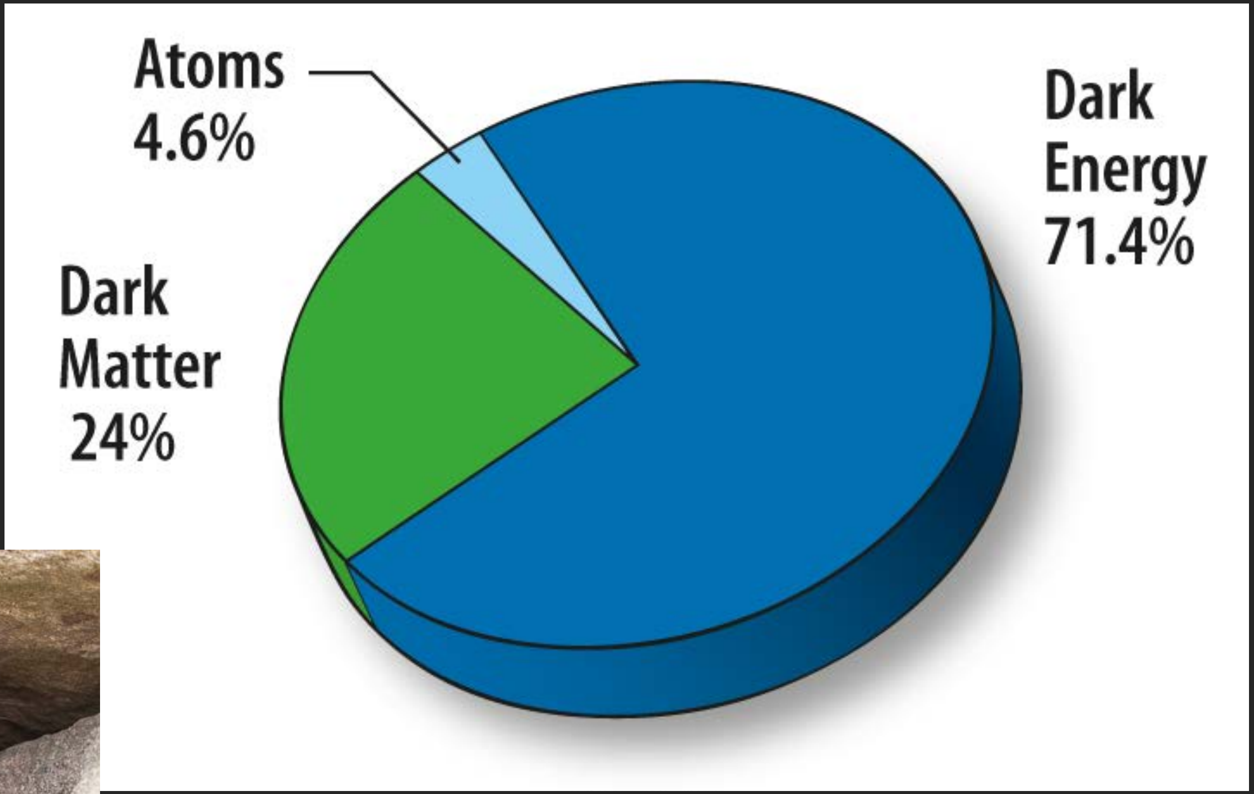


figure from WMAP and Planck telescopes

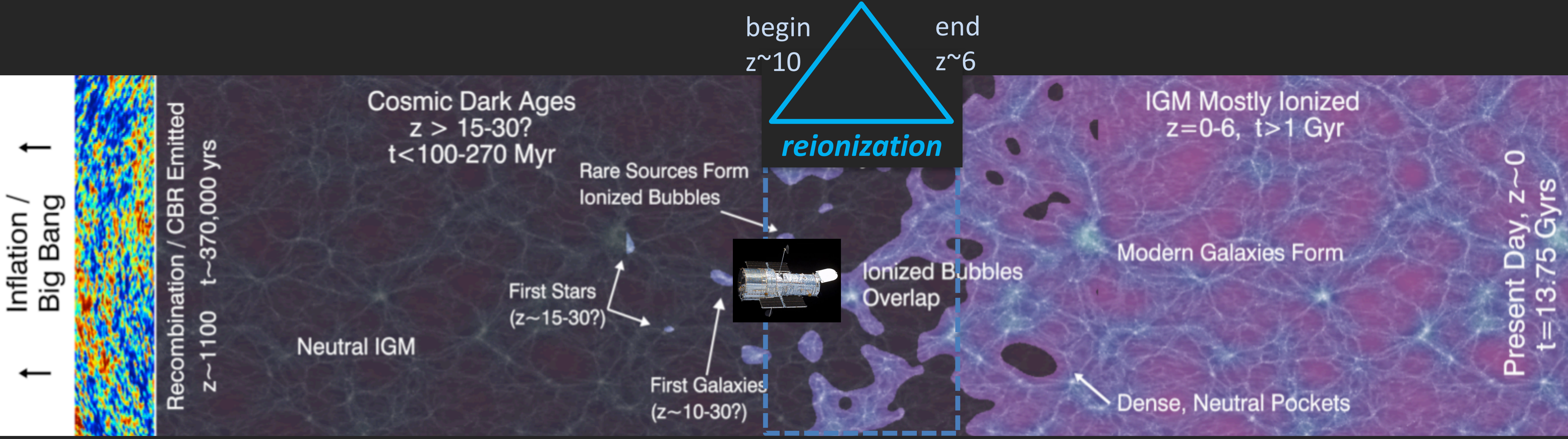
history of everything

reionization peak
z~7.8-8.8

Planck Collaboration: 2016

begin
z~10

end
z~6



Time	0.5 Gyr z~10	1 Gyr z~6	3 Gyr z~2-3	Now z=0

first galaxies

peak of star formation

Figure insert from Robertson et al. 2010

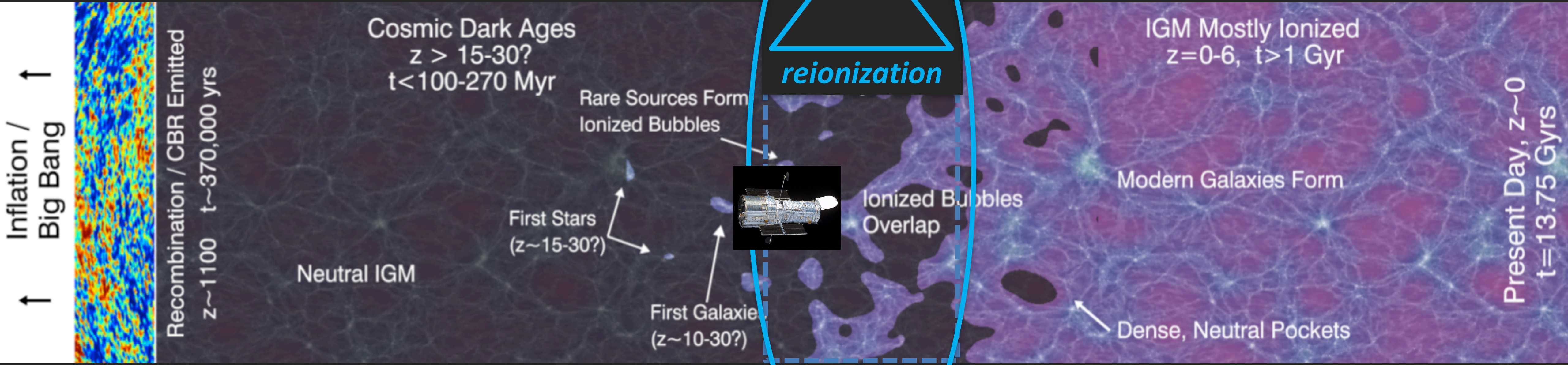
history of everything

reionization peak
z~7.8-8.8

Planck Collaboration: 2016

begin
z~10

end
z~6



0.5 Gyr
z~10

1 Gyr
z~6

3 Gyr
z~2-3

Now
z=0

Time

first galaxies

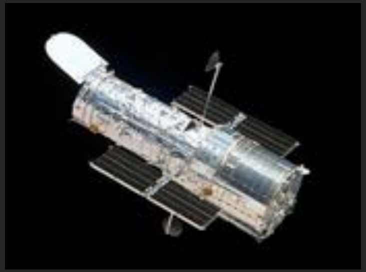
first 2% of stellar mass build-up

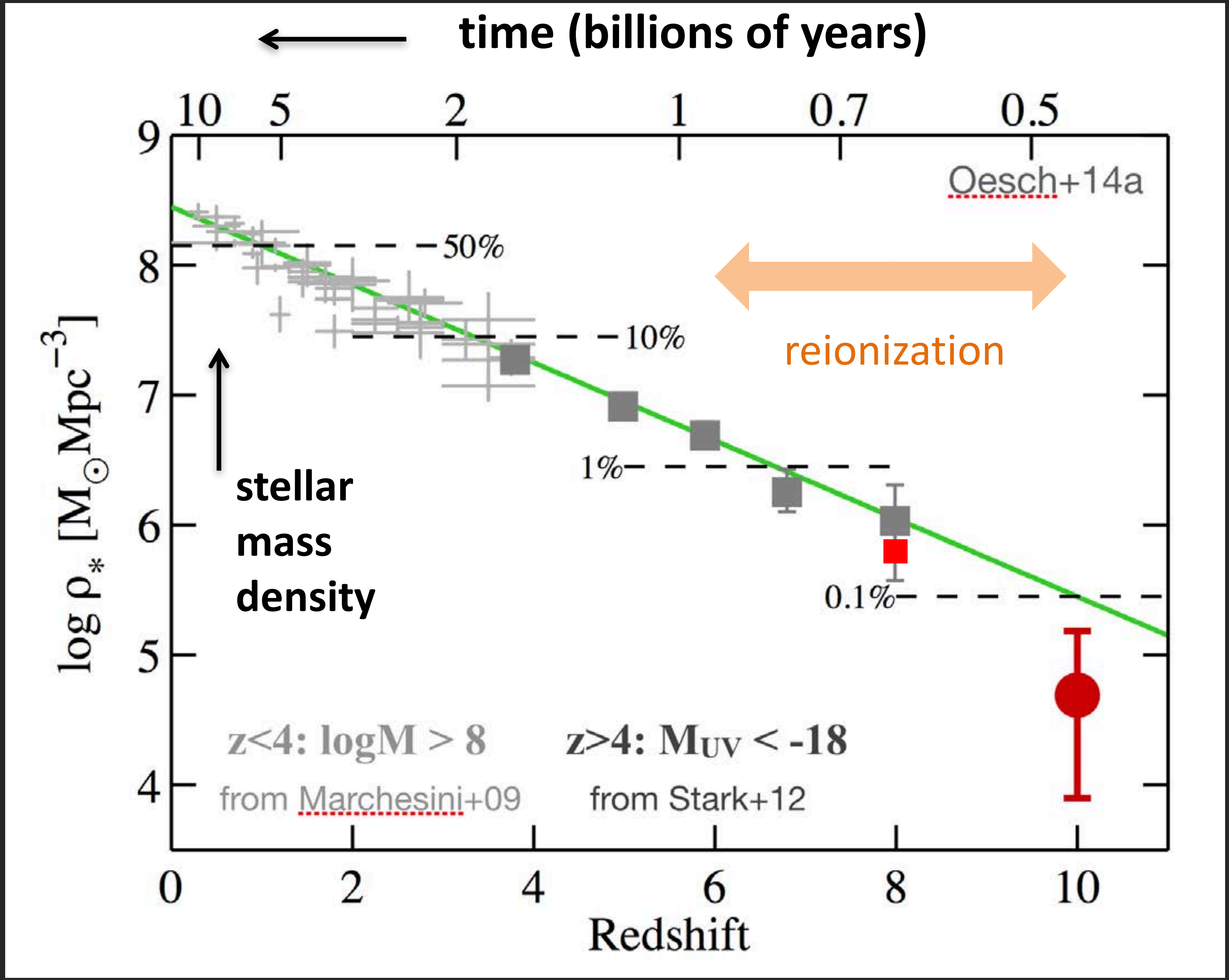
peak of star formation

Figure insert from Robertson et al. 2010

gdi

stellar mass density evolution





Oesch+2014

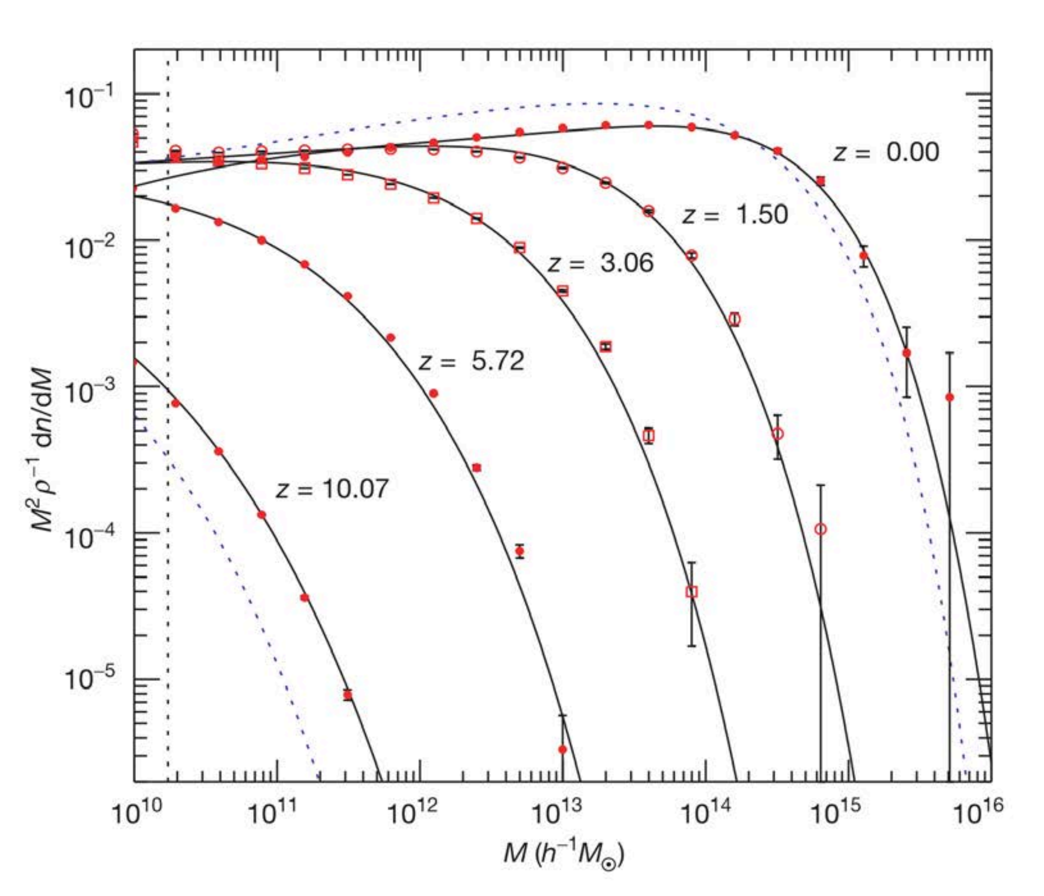
only ~2% of stellar mass density built up by the end of reionization

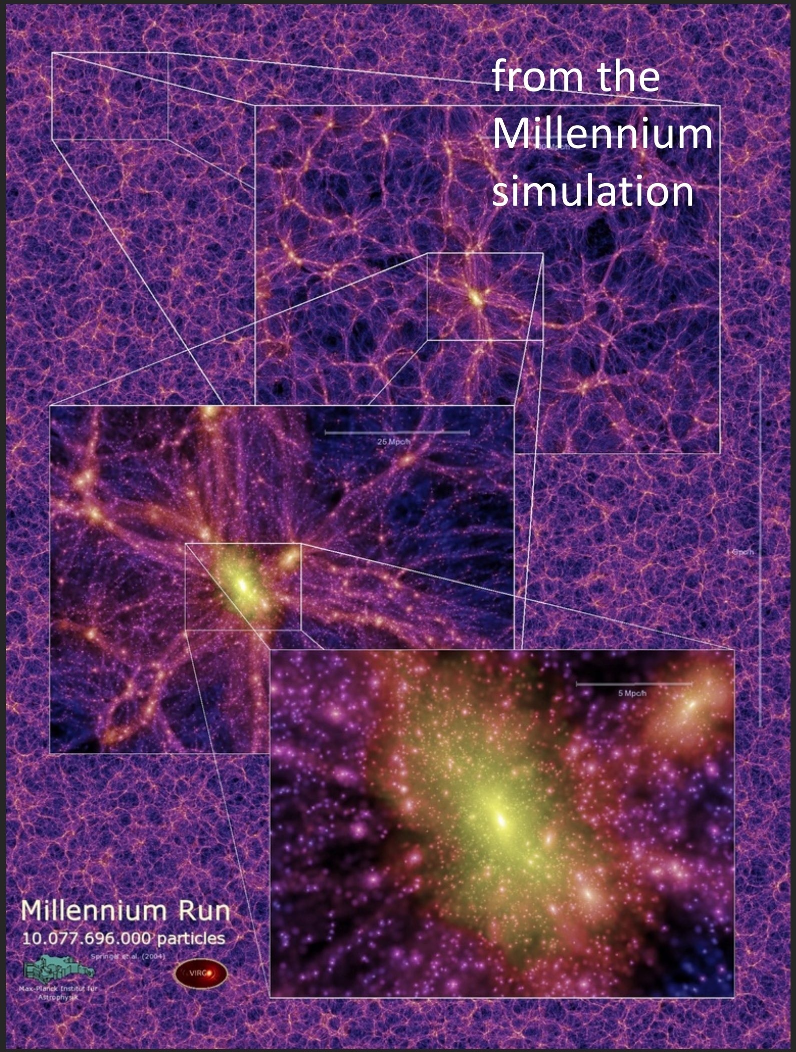
only ~0.3% at the peak of reionization

Cosmic Dawn – the time when galaxies were born and began to grow

the first Gyr → when halos of L* galaxies first form...
when significant metals first form...
when the universe was reionized...

rapid growth of galaxy-scale halos from z~10 to z~6



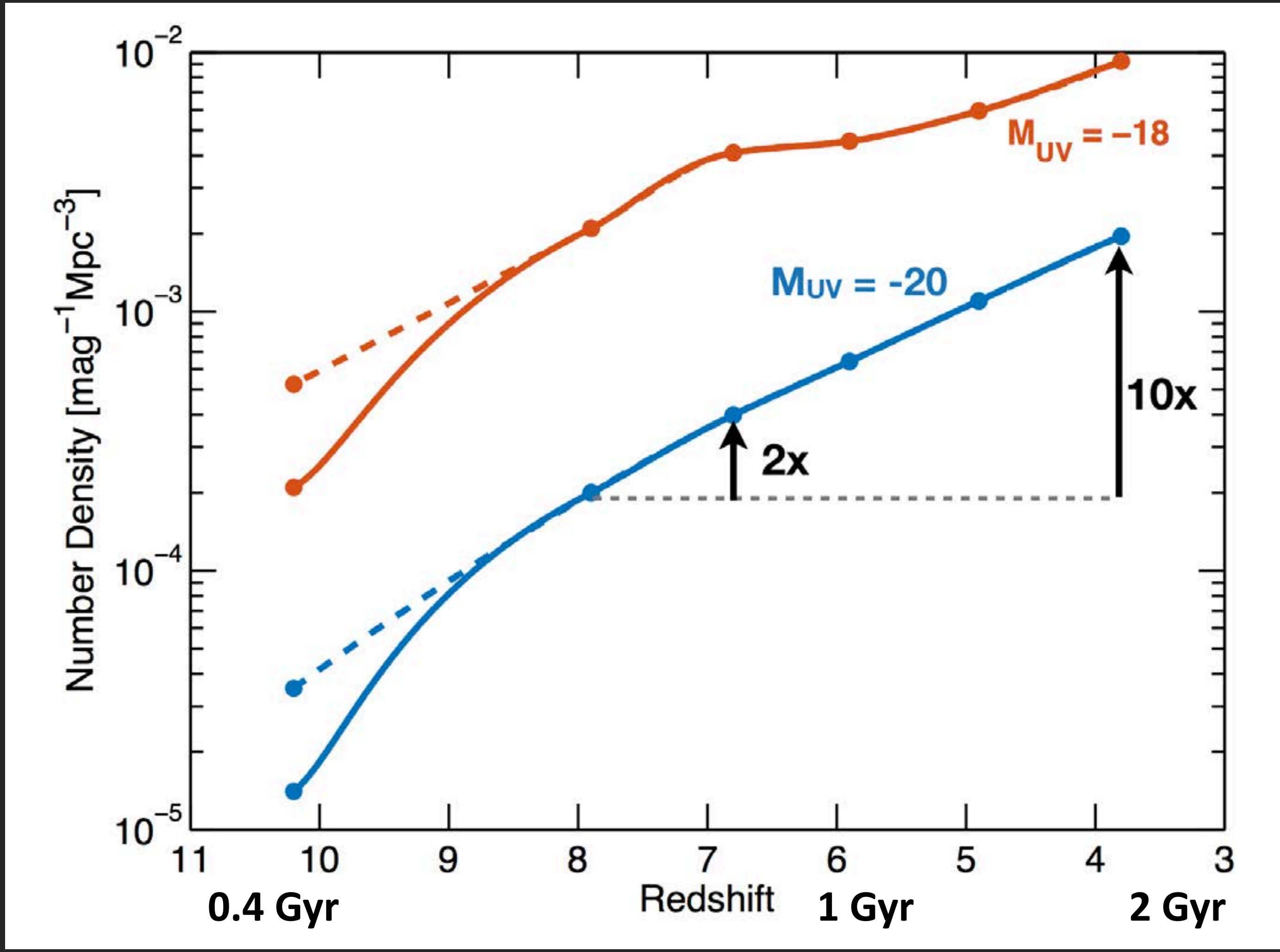


Springel+2005

gdi

Cosmic Dawn – the time when galaxies were born and began to grow

buildup in the
first 1-2 Gyrs



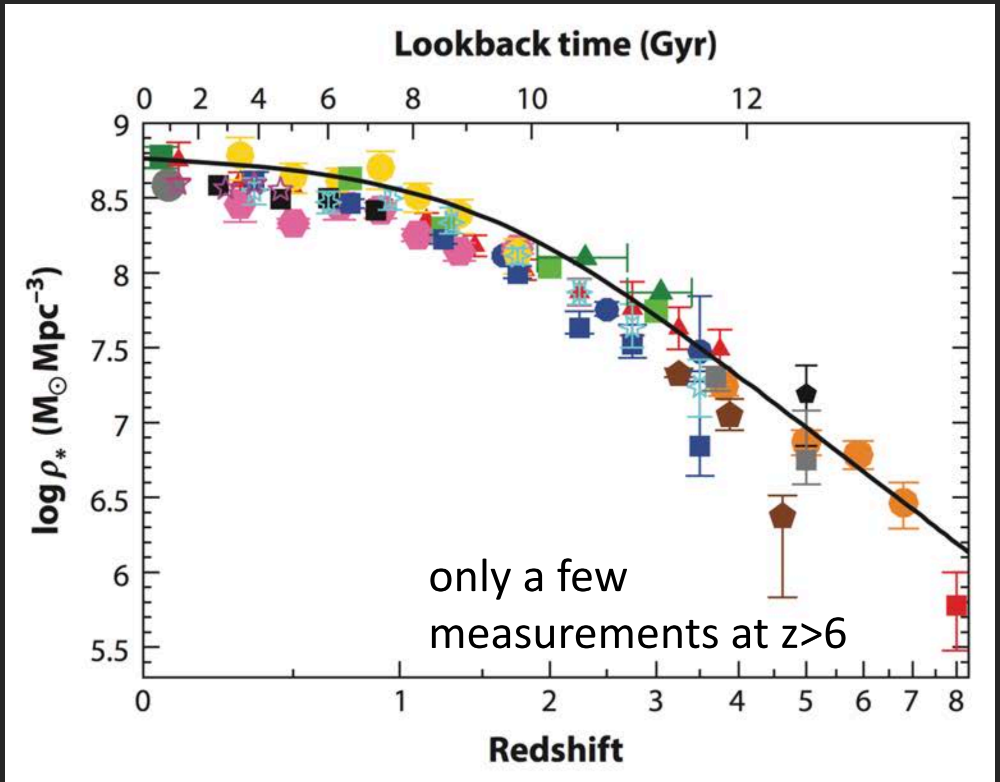
Galaxies are building up extremely rapidly across z~8 to z~4 (even faster at z~10 to z~8)

With HST, we are already approaching cosmic dawn

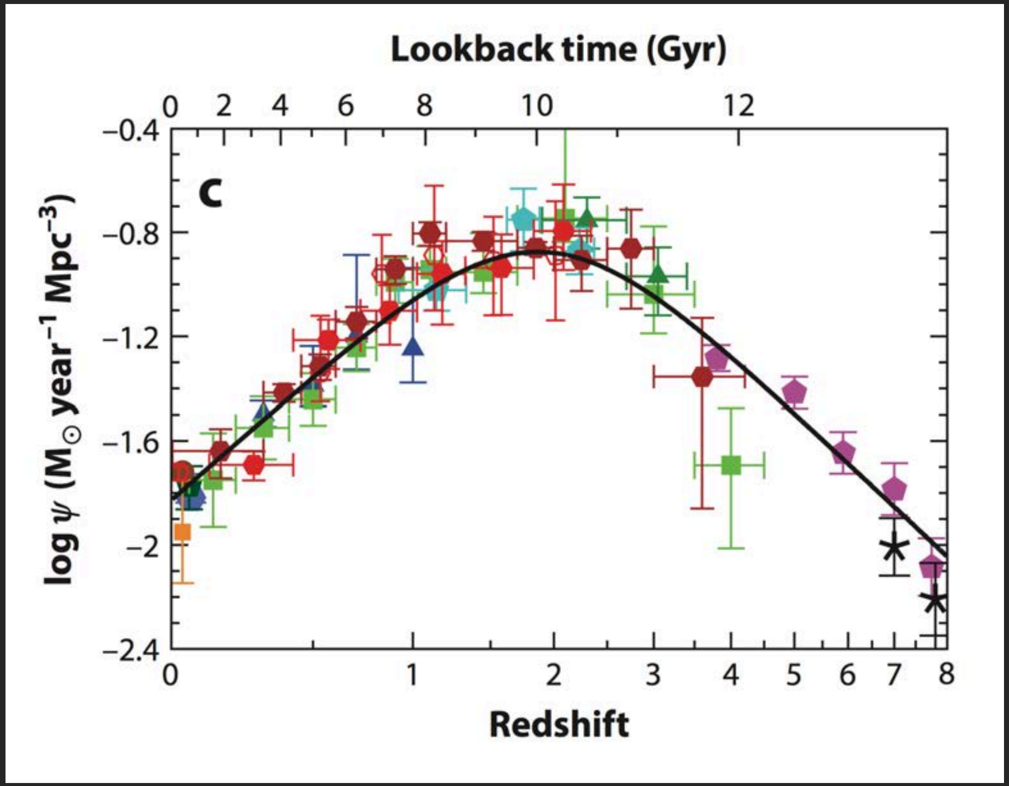
Oesch+2017

gdi

the global stellar mass and cosmic SFR density evolution



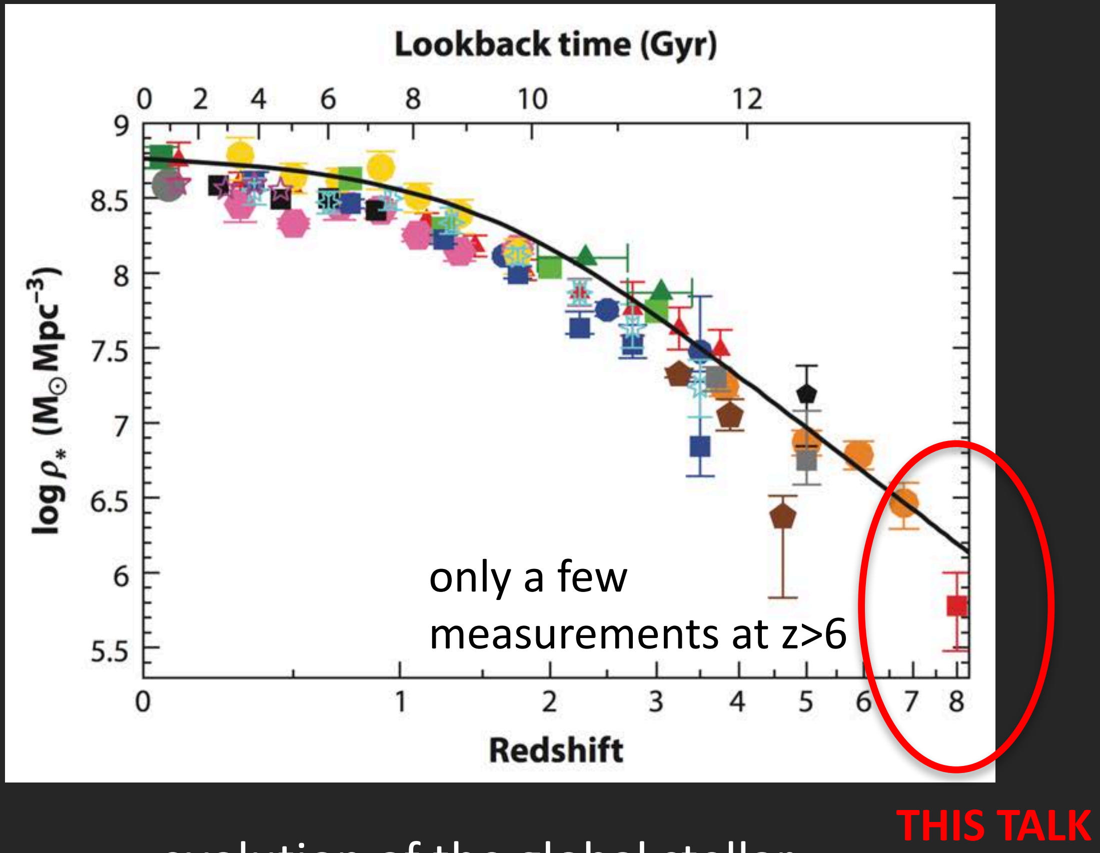
evolution of the global stellar mass density over 13 billion years



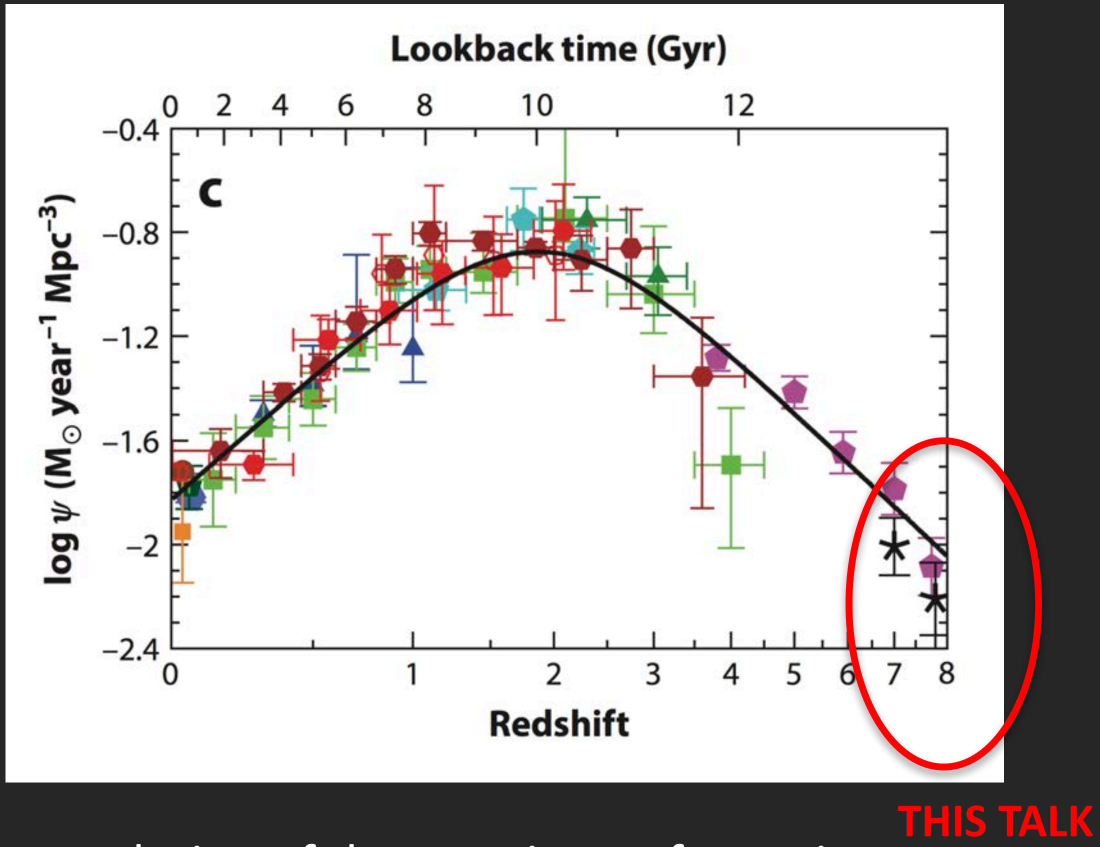
evolution of the cosmic star formation rate density over 13 billion years

Madau & Dickinson 2014

the global stellar mass and cosmic SFR density evolution



evolution of the global stellar mass density over 13 billion years



evolution of the cosmic star formation rate density over 13 billion years

Madau & Dickinson 2014

galaxies in the first Gyr

how do we find them?

what are their sizes (and colors?)

what is their distribution over luminosity?

(what are their stellar masses?)

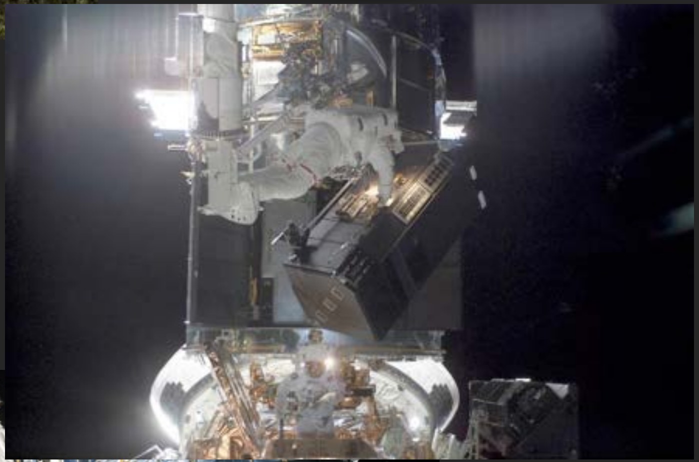
what role do they play in reionization?

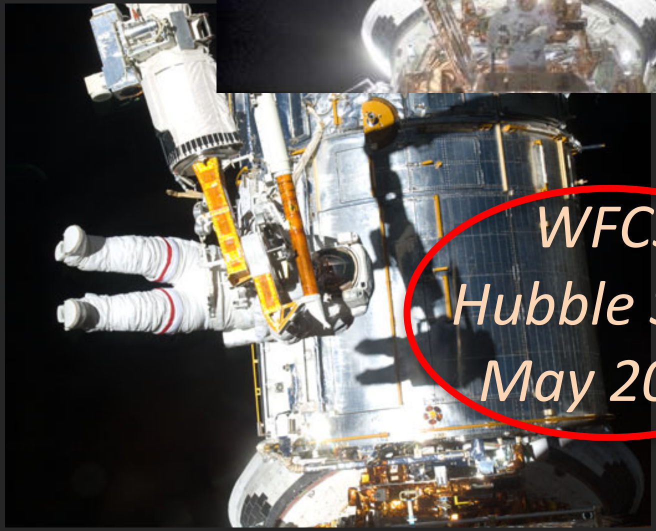
what are the earliest known galaxies?

where do we go from here (JWST)?

upgrading Hubble – ACS in 2002, WFC3 in 2009 – Spitzer in 2003

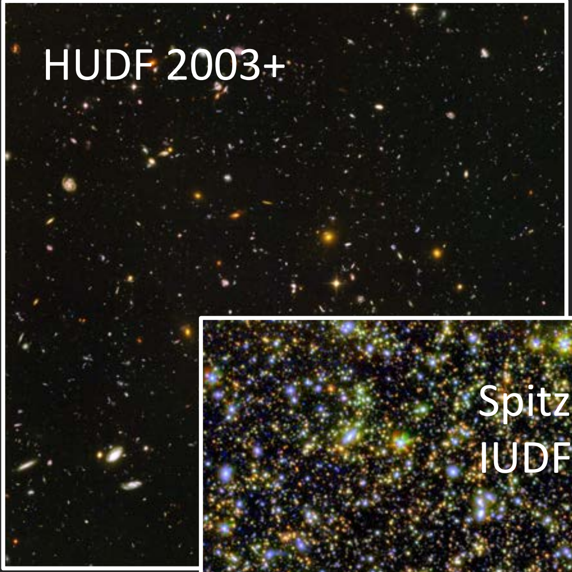
ACS
Hubble SM3b
Mar 2002

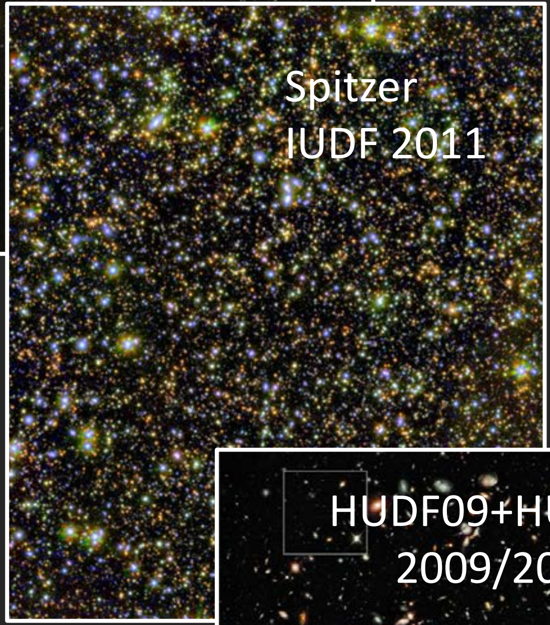


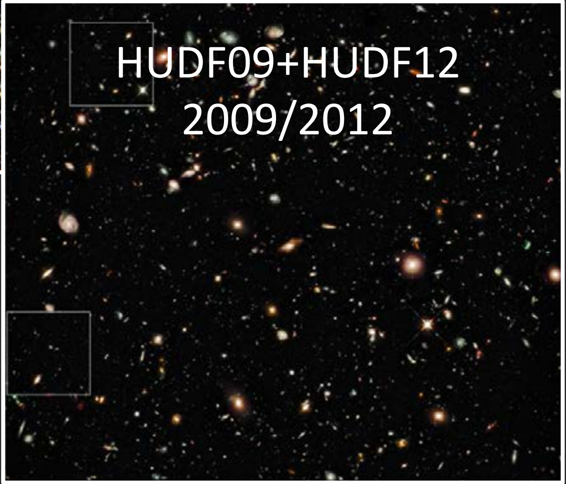


WFC3
Hubble SM4
May 2009

Spitzer
Aug 2003

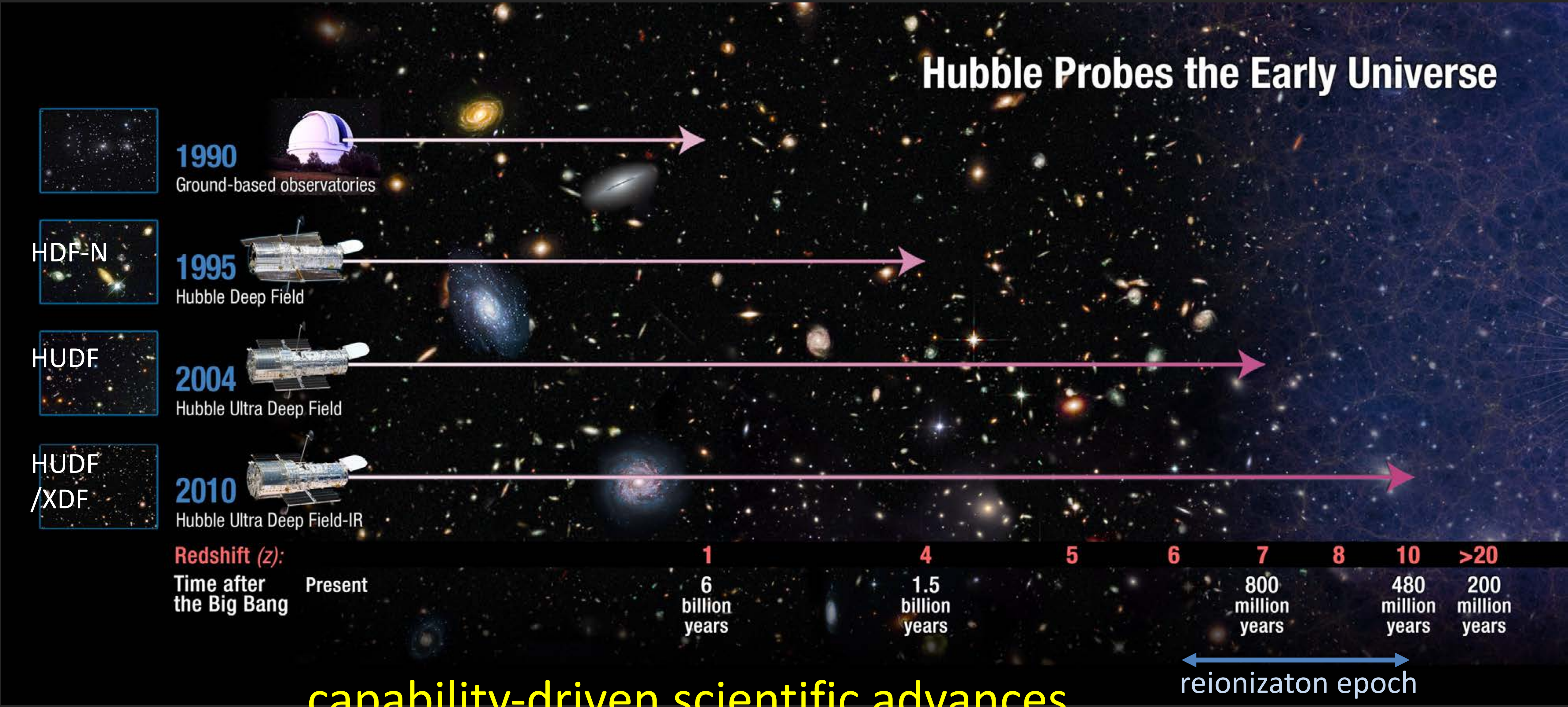






each new servicing mission resulted in a dramatic change in our ability to explore the early universe

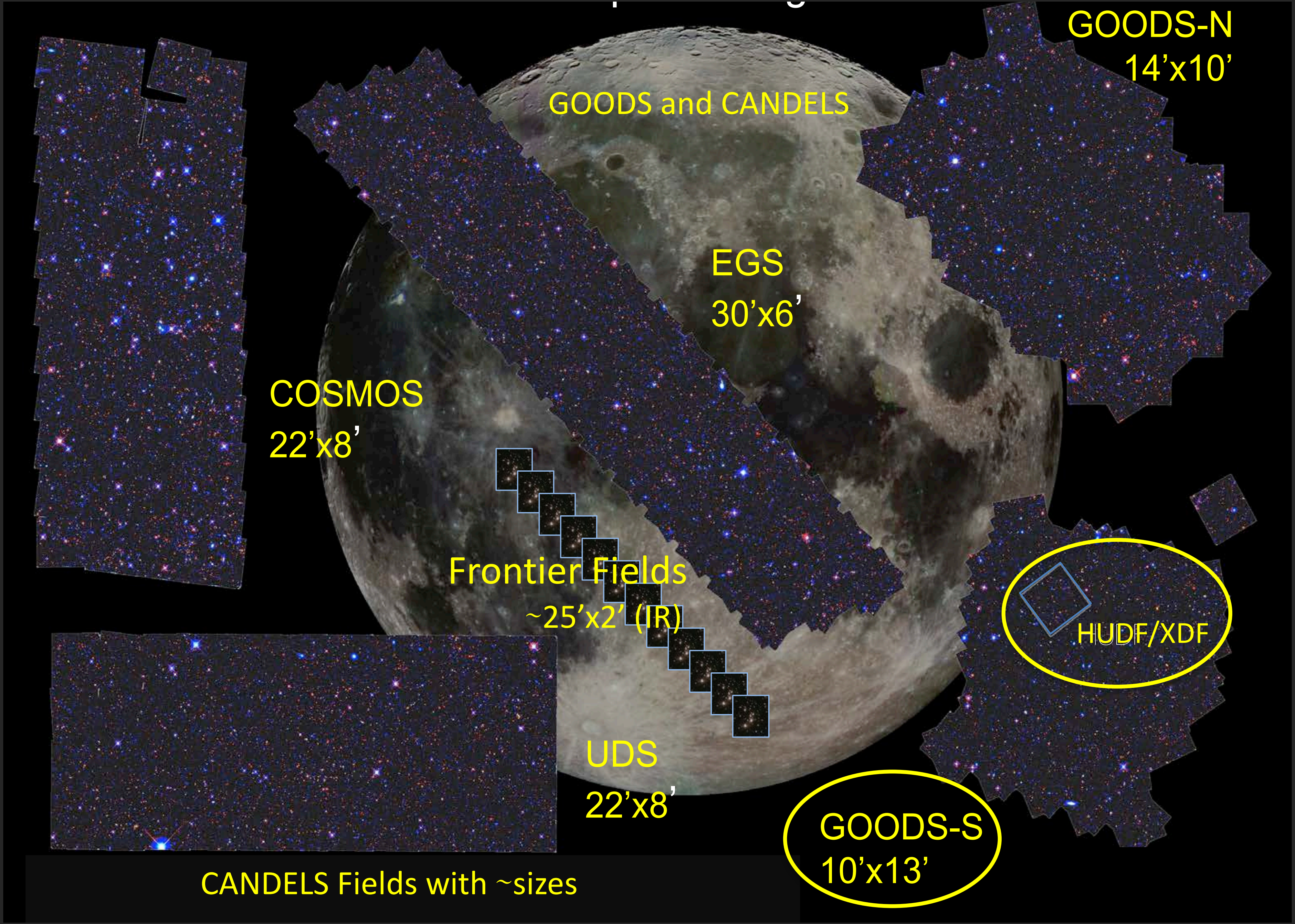
redshift limits with new capability



capability-driven scientific advances

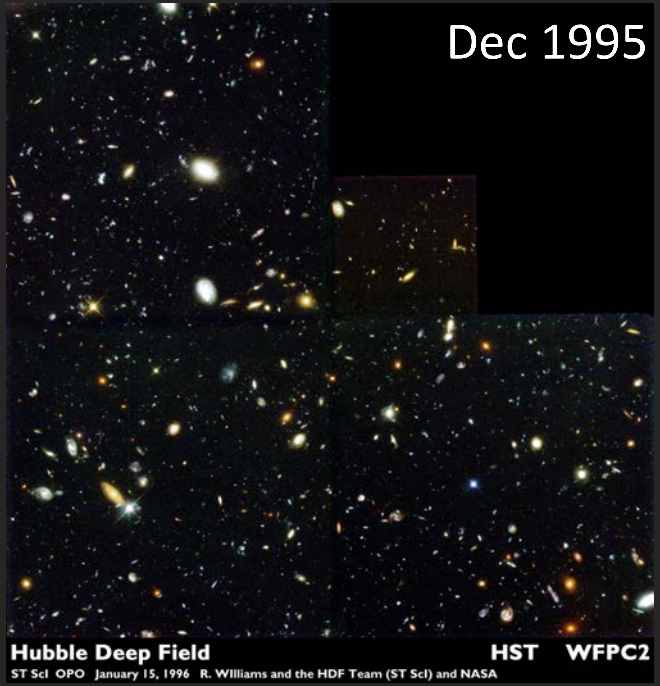

the survey datasets that are central to high-z galaxy studies

Hubble and Spitzer survey fields for high-redshift galaxies

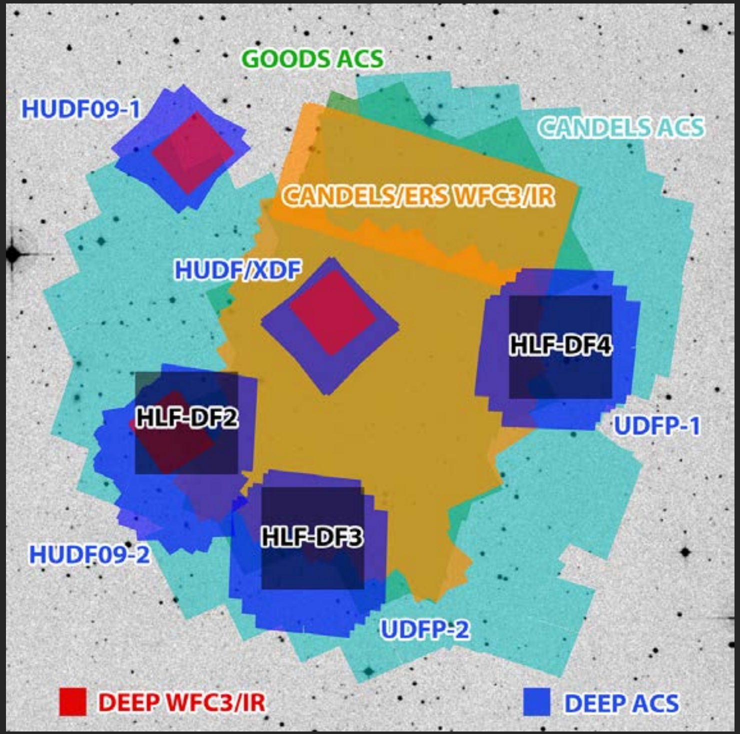


surveys with both wide and deep imaging are the lifeblood of distant galaxy research

started with HDF-N in Dec 1995



now over 15 million seconds of open datasets from HST, Spitzer, Chandra on the CDF-S/HUDF/GOODS-S area

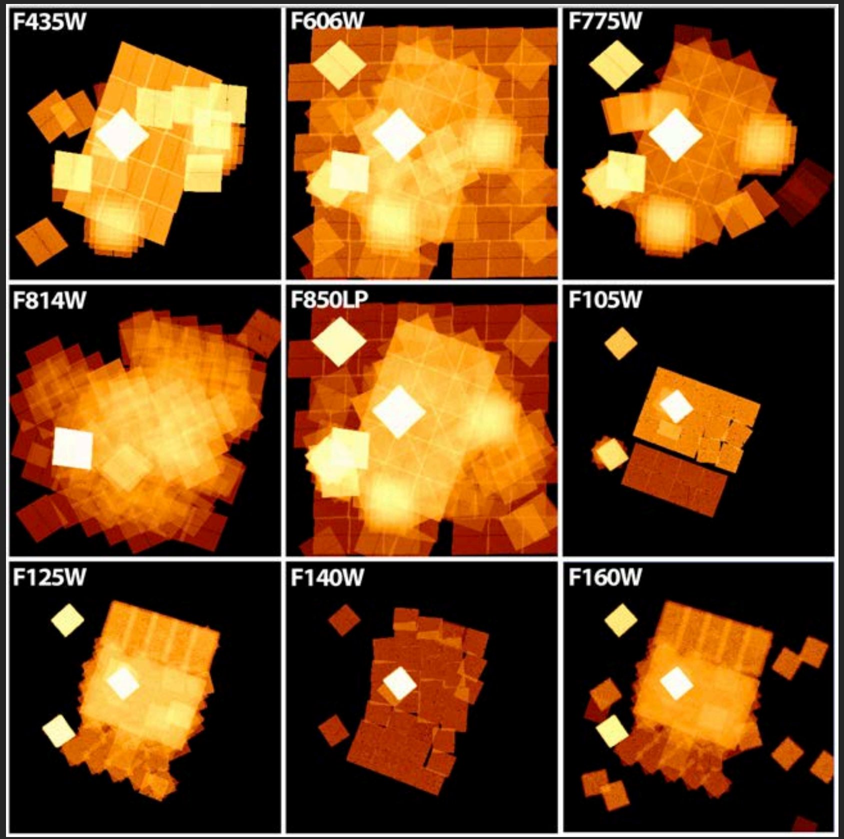


1999-2000	Chandra 1Ms
2002-2003	ACS GOODS
2003	ACS HUDF
2003	NICMOS HUDF
2004	Spitzer GOODS
2003-2007	NICMOS
2004	GRAPES
2005	HUDF05
2009	ERS
2009-2010	HUDF09
2009-2010	Spitzer SEDS
2010-2011	Chandra 3Ms
2010-2012	CANDELS
2010-2012	3D-HST
2010-2011	Spitzer IUDF10
2011-2012	Spitzer S-CANDELS
2011-2012	HUDF UVUDF
2012	HUDF12
2013	Spitzer IGOODS
2013-2016	Frontier Fields
2014	HDUV
2014	FIGS
2015	Spitzer GREATS

Hubble Legacy Field South (HLF-GOODS-S) V1.5 release

GOODS-S/CANDELS-S region – a unique region

The HLF-GOODS-S V1.5 release combines 7211 exposures from 2442 orbits over the GOODS-S/CANDELS-S region

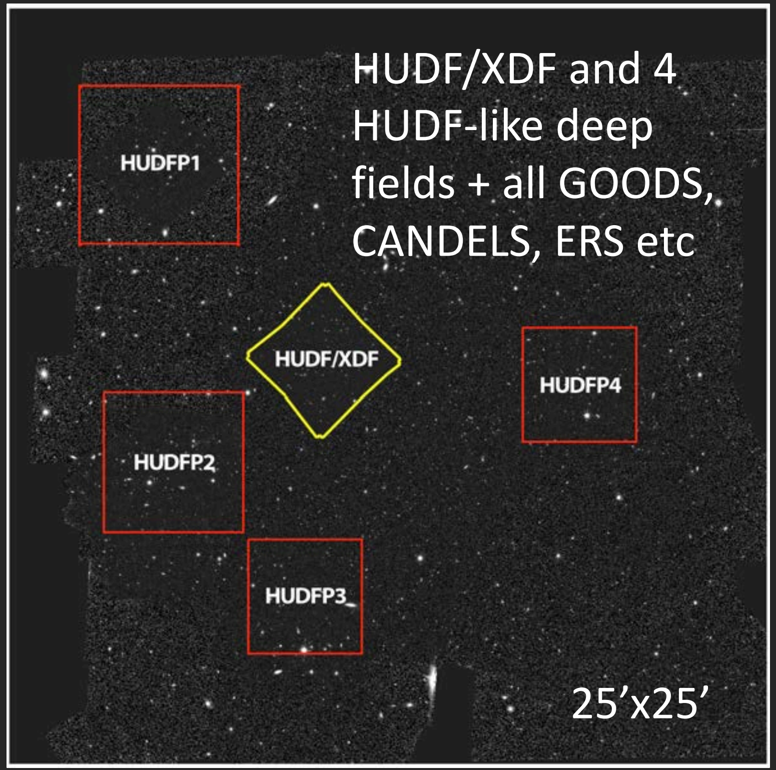


ACS + WFC3/IR – 9 filters (10 for V1.5 release with 098M)

firstgalaxies.org/hlf & *archive.stsci.edu/prepds/hlf/*

GDI Magee Bouwens Oesch Labbe+2016

5.8 Msec or ~70% of a Hubble Cycle



HUDF/XDF is Hubble's deepest image: ~32.5 AB mag 1σ

152 GB of aligned astrometric HST images

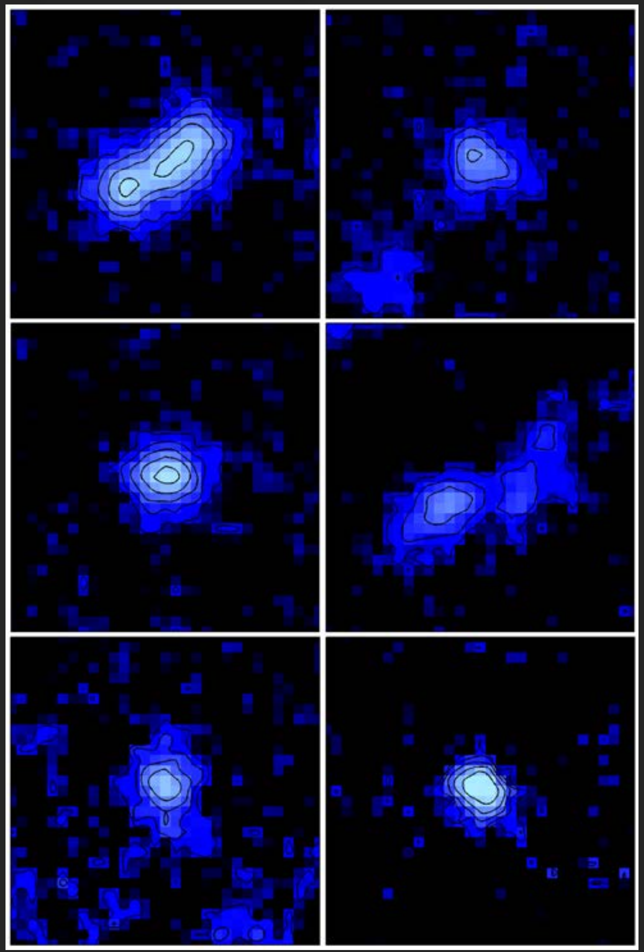

what we find and how we determine redshifts

Hubble images of galaxies in the first billion years

this is what the largest and brightest high-redshift galaxies typically look like at z>~6

luminous young star forming galaxies are a kpc or two in size (r_e <~ 1 kpc) – lower luminosity galaxies are much smaller

1.8” (~10 kpc)

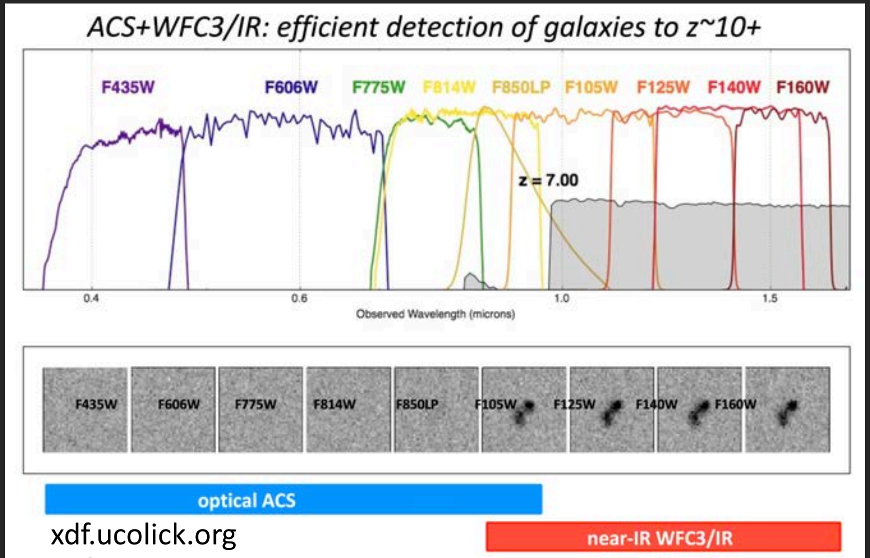


this is the size of the smallest high-redshift galaxies on the same scale

most galaxies in the first billion years are really small!

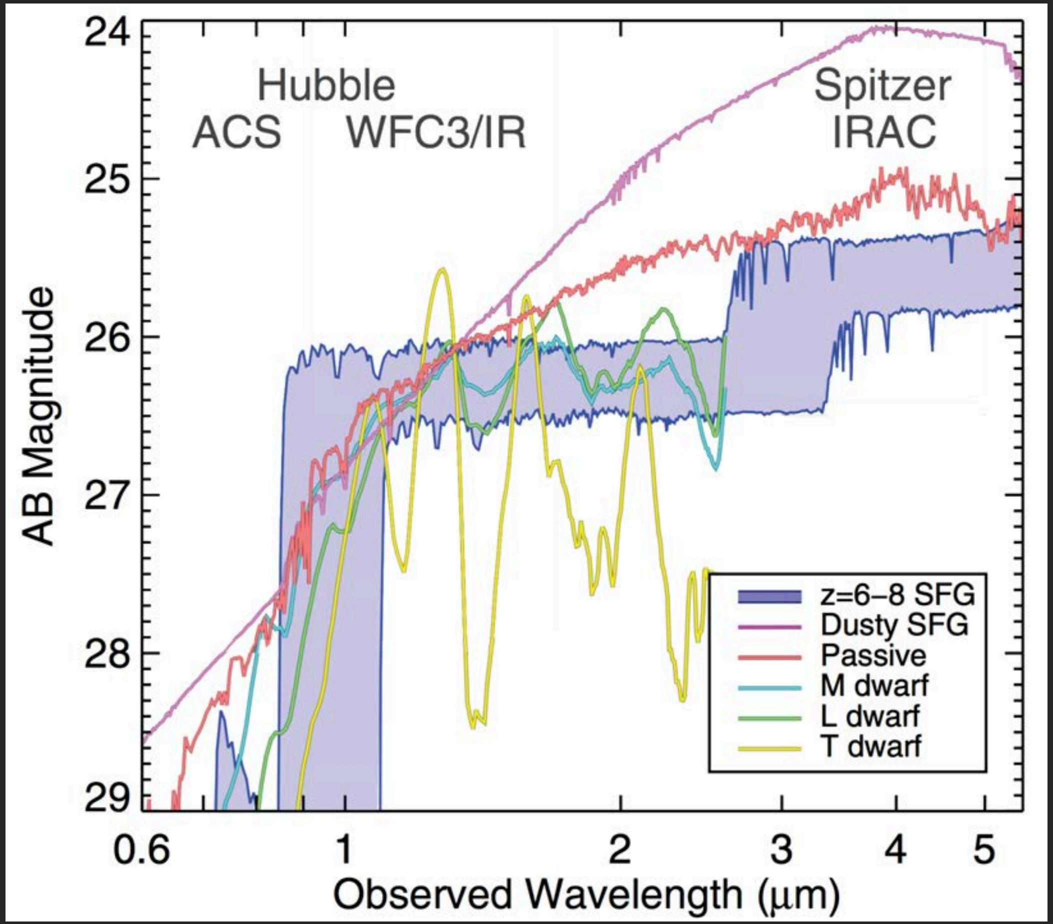
~size of Hubble PSF

photometric redshifts



GDI+2013

enable large, statistically-robust samples



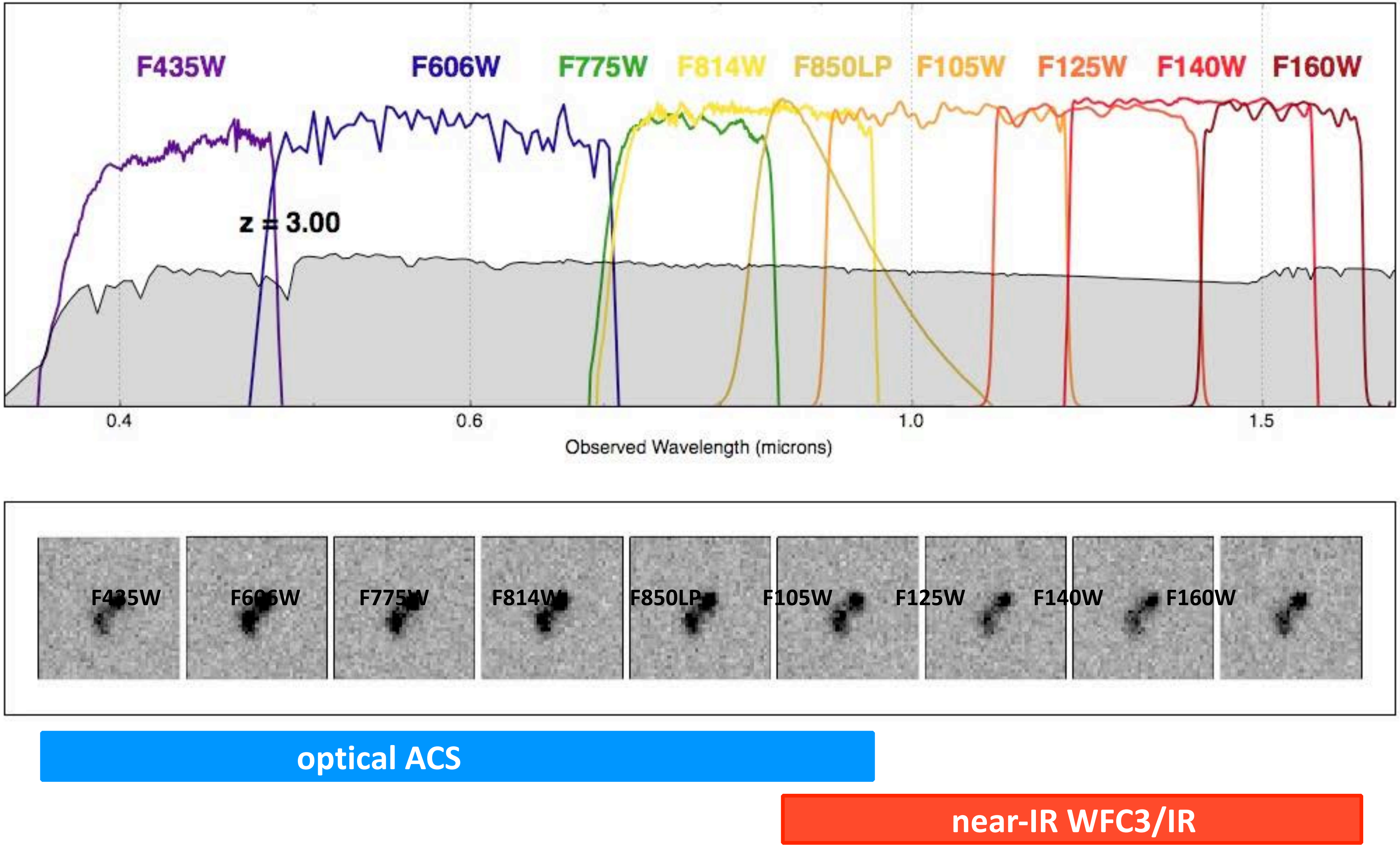
Finkelstein 2016

Lyman break galaxies – LBGs (“dropouts”)

LBGs have a distinctly different shape of the spectral energy distribution (SED)

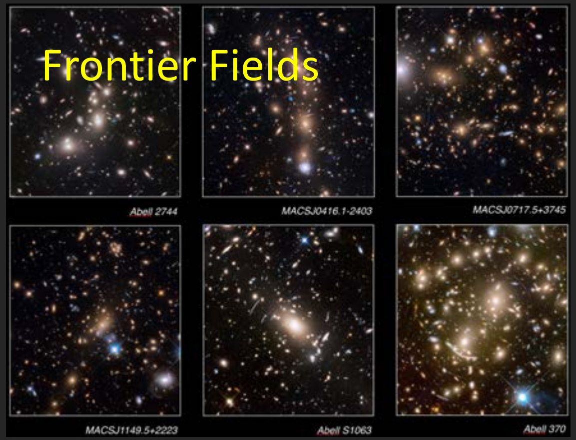
☞ reliable photometric redshift selection

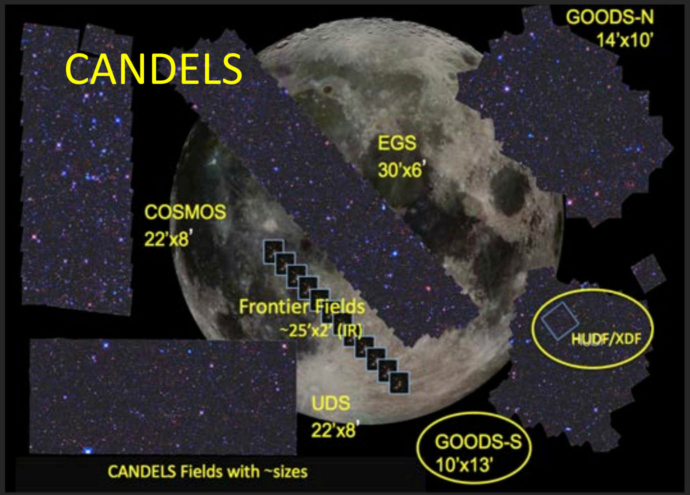
ACS+WFC3/IR: efficient detection of galaxies to z~10+



xdf.ucolick.org/

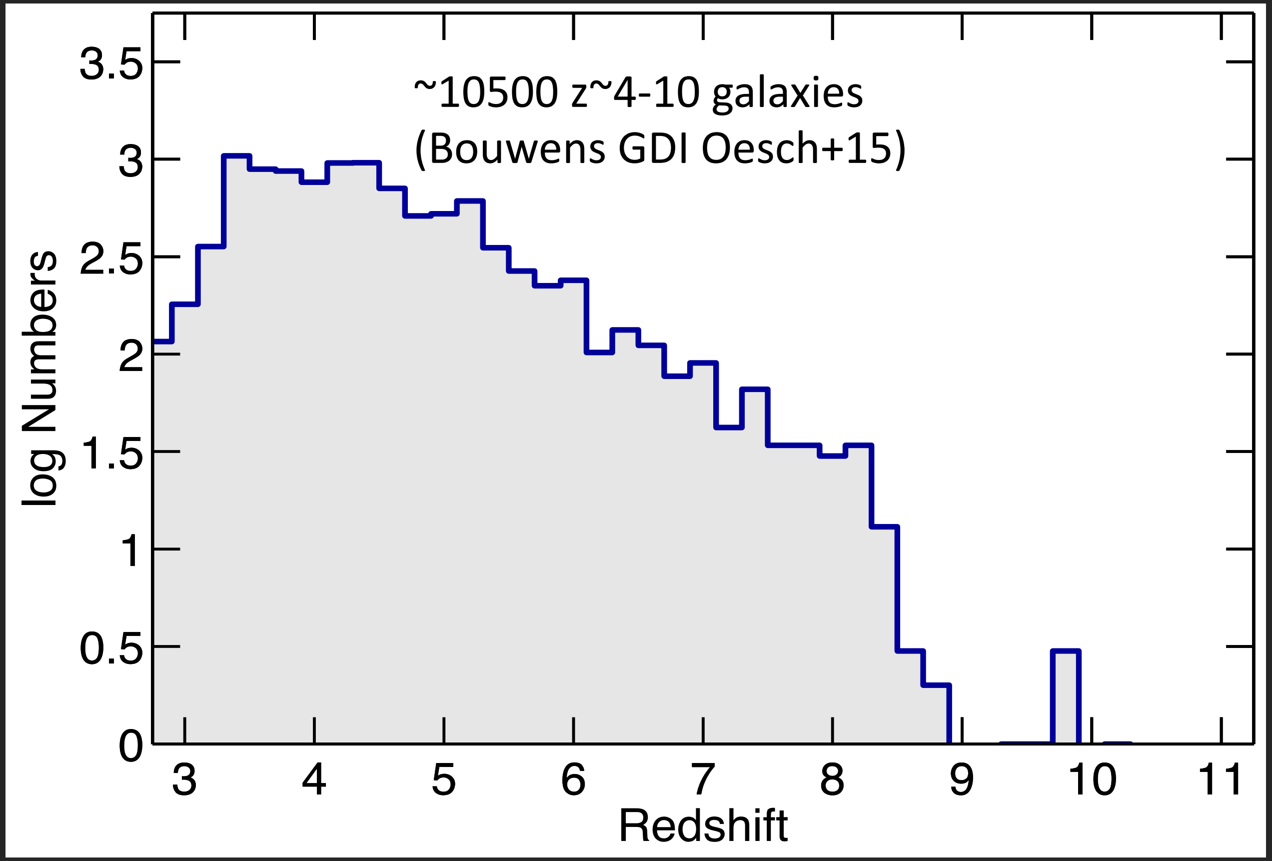
lots of early galaxies have been found by Hubble





by 2015 over 10000 galaxies found ➠
but finding galaxies in the first 500-600 Myr at z>8 is really hard!

many early galaxies found in these Hubble fields



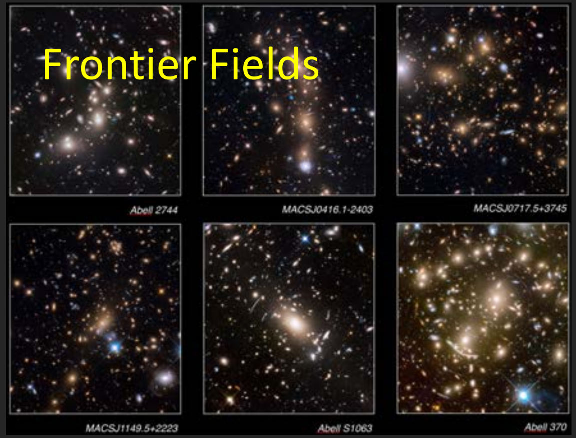
Bouwens GDI Oesch+ 2015, 2017

ground surveys also now have very large samples but largely z<5 – and so not shown

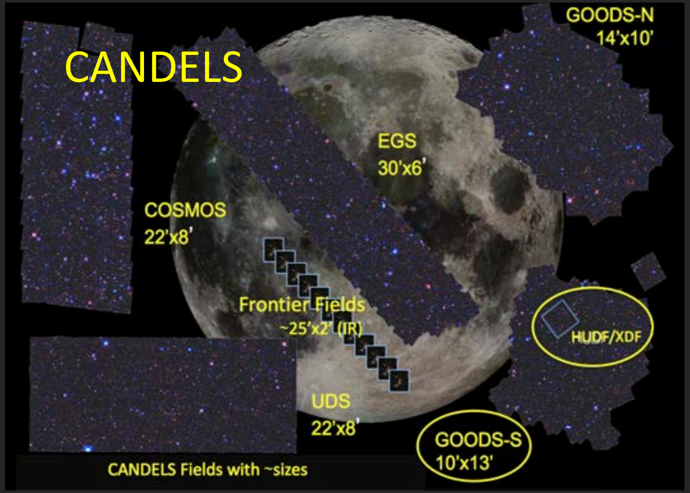
lots of early galaxies have been found by Hubble

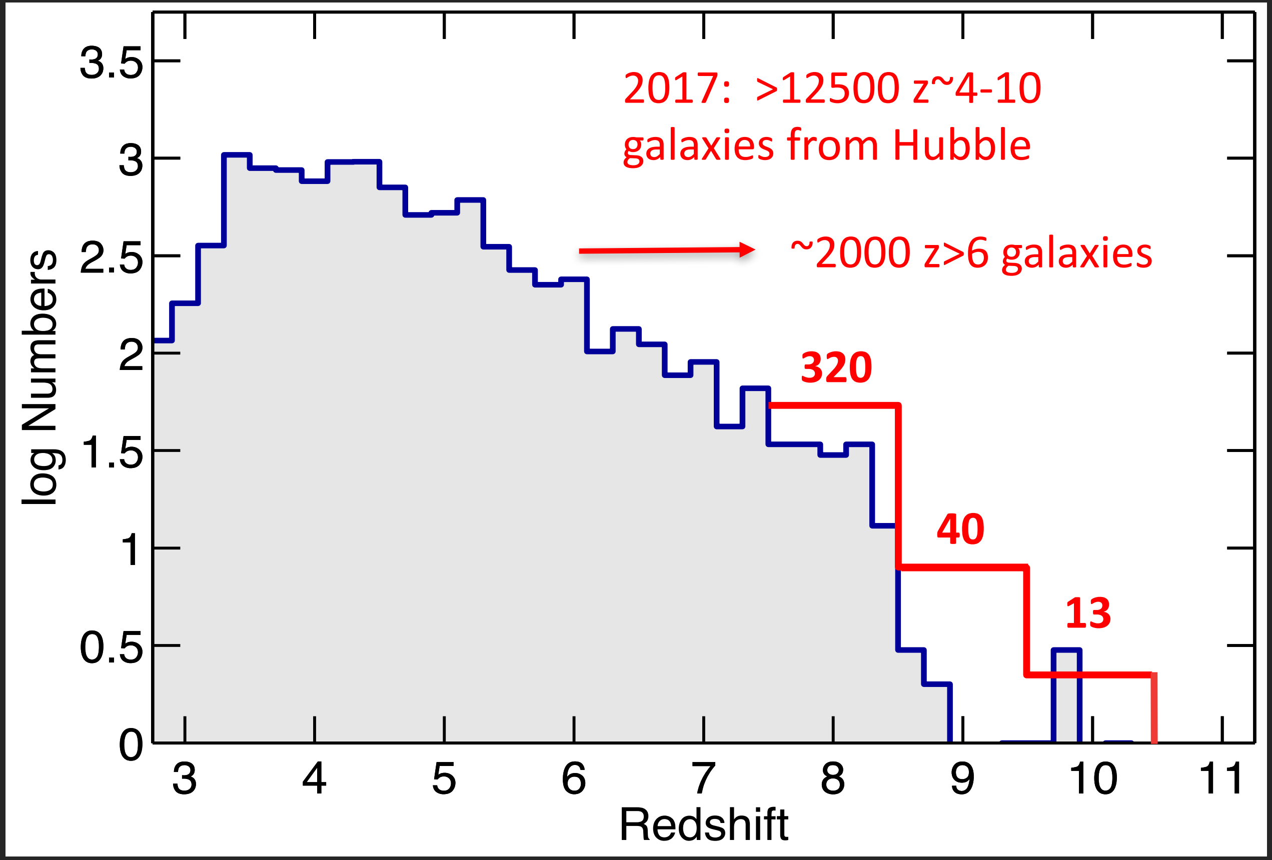
by 2017 the number went from ~10500 galaxies to over 12500

➠ but until JWST finding galaxies in the first 500-600 Myr at z>8 will be really hard!



many early galaxies found in these Hubble fields

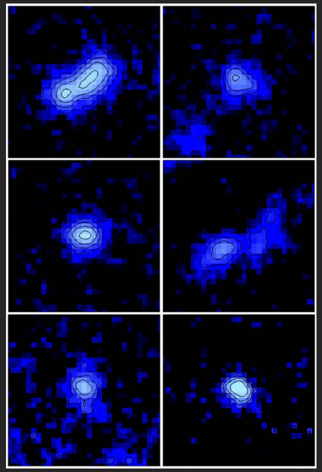




Bouwens GDI Oesch+ 2015, 2017

ground surveys also now have very large samples but largely z<5 – and so not shown

luminosity functions – the census of galaxies:
a key input for understanding galaxy build-up and reionization



over 12,000 high redshift Hubble-selected galaxies from z~4 to z~10!

HUDF/XDF *eXtreme Deep Field*

HUDF + HUDF09 + HUDF12 + everything else!

all optical ACS data and all WFC3/IR data on the HUDF from 2003-2013 from 19 programs combined into the XDF: eXtreme Deep Field

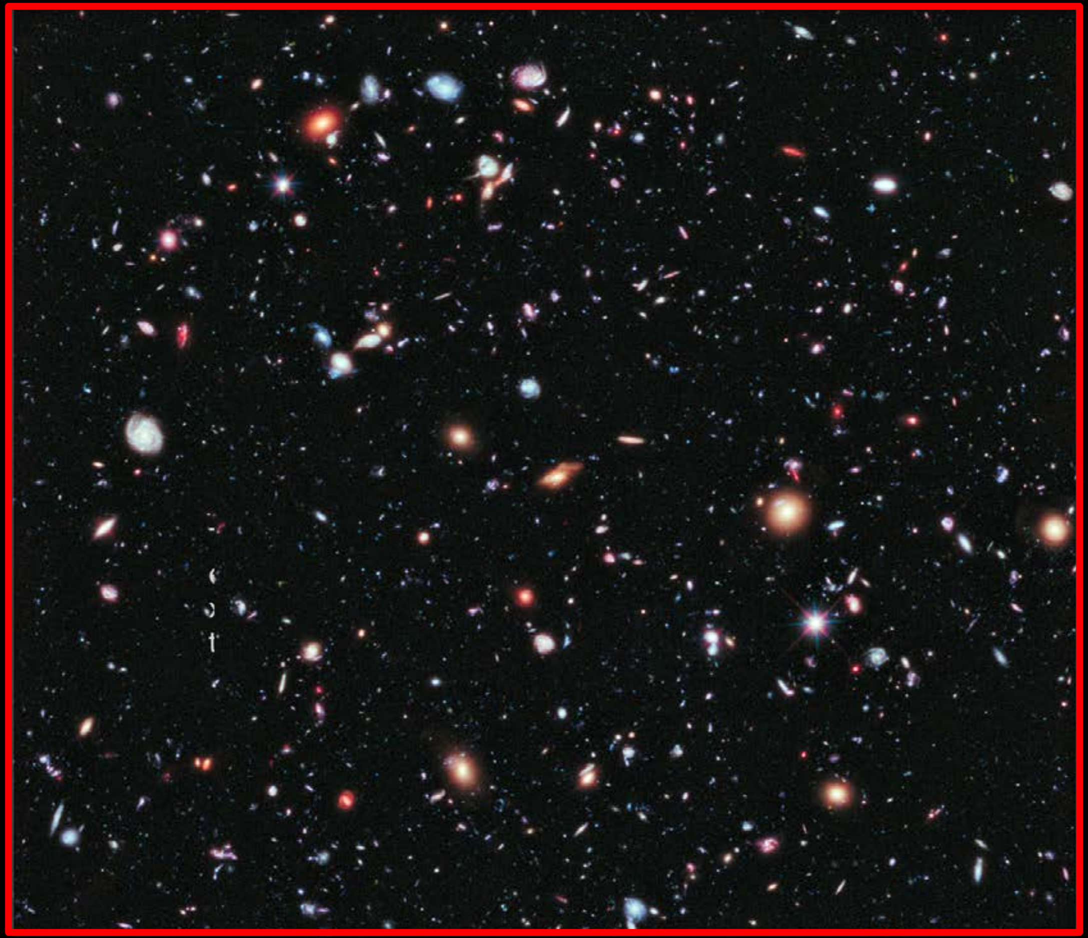
2 Msec of data from 2963 HST images (over 800 orbits in total)

matched dataset is deepest Hubble image

reaches ~31 AB mag 5σ or >32.5 AB mag 1σ

HUBBLE SPACE TELESCOPE

XDF • EXTREME DEEP FIELD



A decade of imaging on the Hubble Ultra Deep Field
The deepest image of the Universe

GDI+2013

xdf.ucolick.org

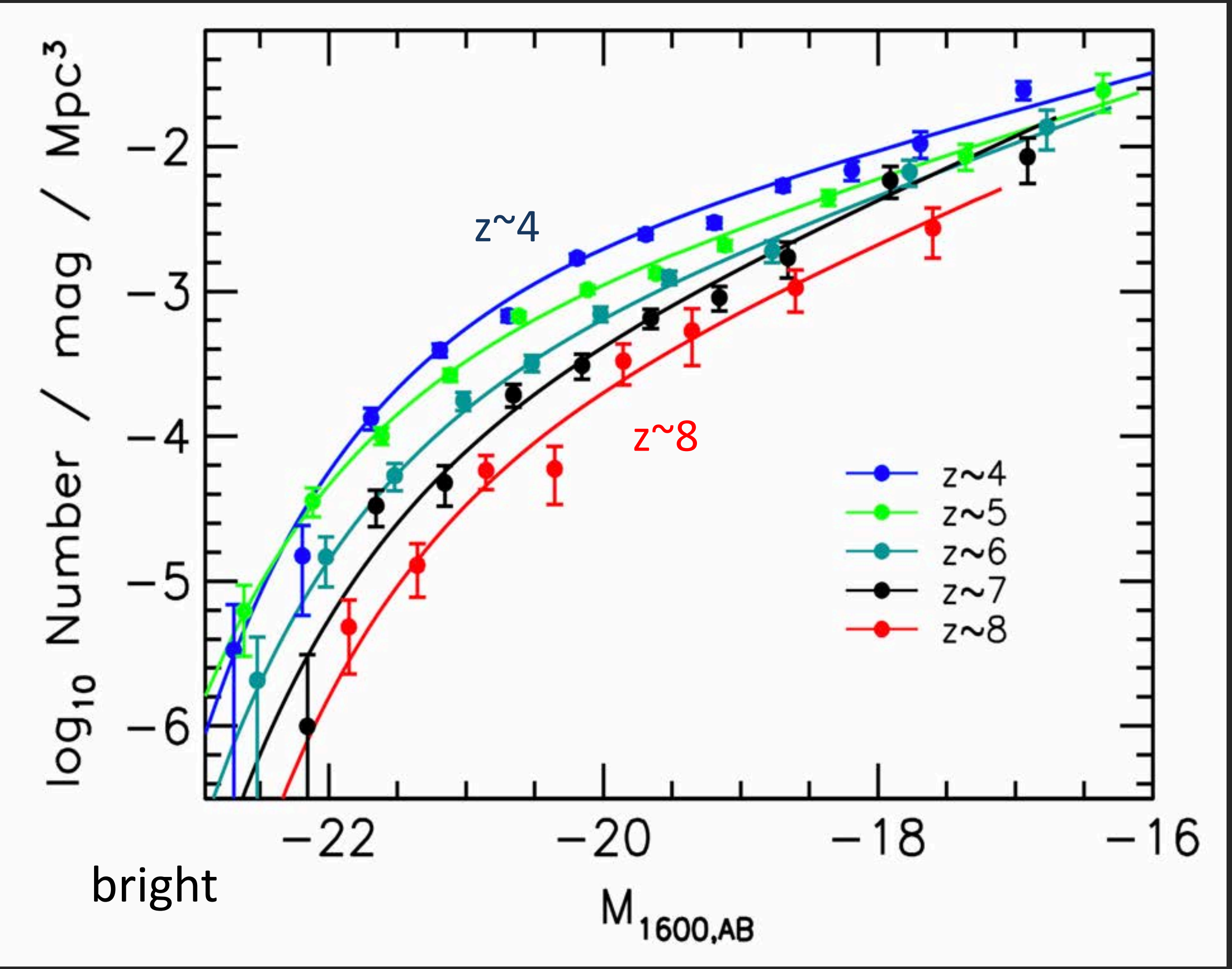
2012
NASA, ESA,
G. Illingworth, D. Magee, and P. Oesch (University of California, Santa Cruz),
R. Bouwens (Leiden University), and the XDF Team

luminosity functions for >10,000 z~4-8 galaxies from all HST deep & wide fields

two independent determinations (STY and stepwise maximum likelihood – SWML)

Schechter function:
luminosity L* (M*)
normalization φ*
faint-end slope α

#/mag/Mpc³



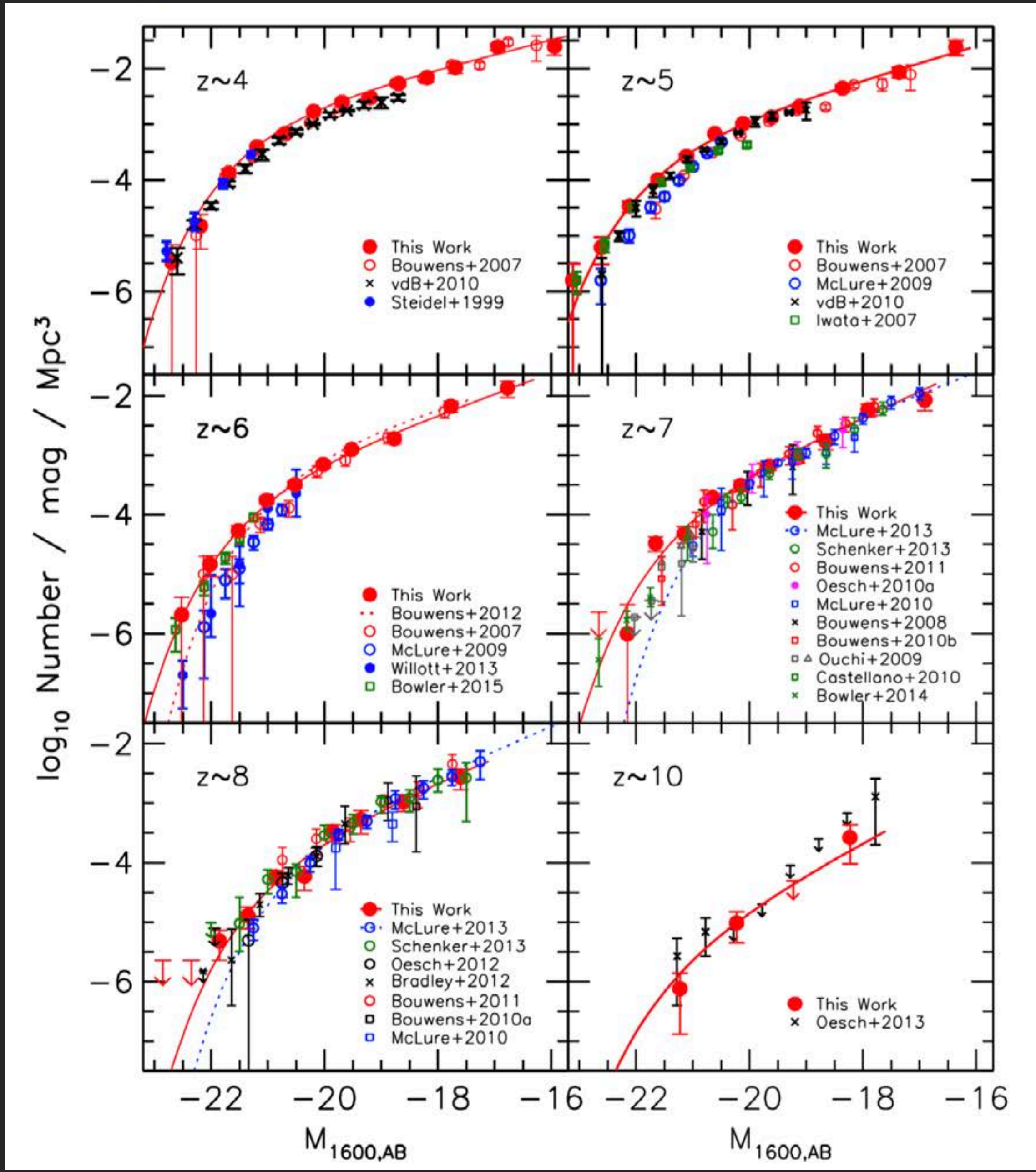
Bouwens GDI Oesch+2015

see also McLure+2013, Finkelstein+2015, Bowler+2015, Parsa+2016, Alavi+2016

luminosity functions for >10,000 z~4-8 galaxies from all HST deep & wide fields

encouraging consistency!

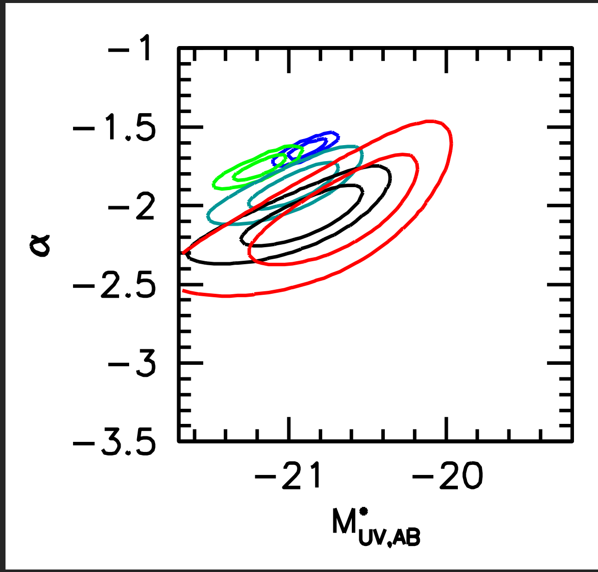
deviations from Schechter are not significant to z~7-8



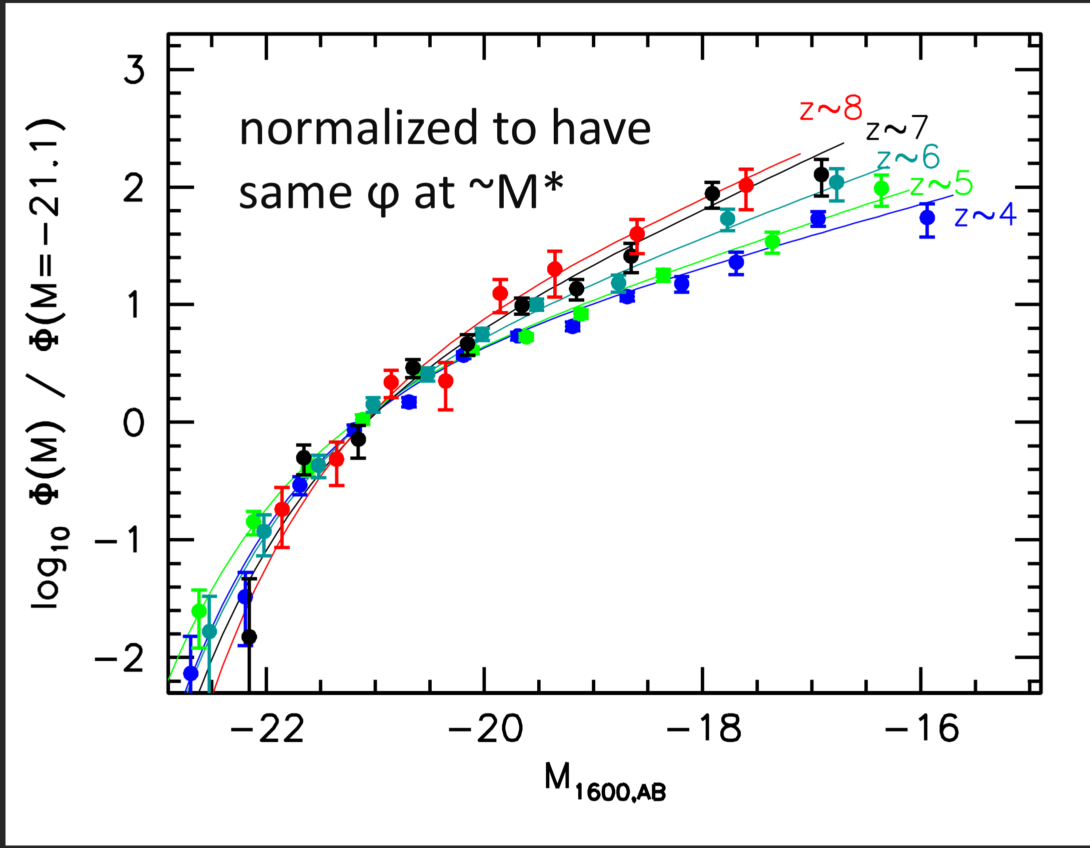
Bouwens GDI Oesch+2015

luminosity functions: steep faint end slope α

trend in α



68% and 95% confidence intervals



steeper slope α
at early times
(higher redshift)

clear steepening of LF at earlier times ⇨ more UV flux – makes a large difference to integrated flux since divergent at α<-2

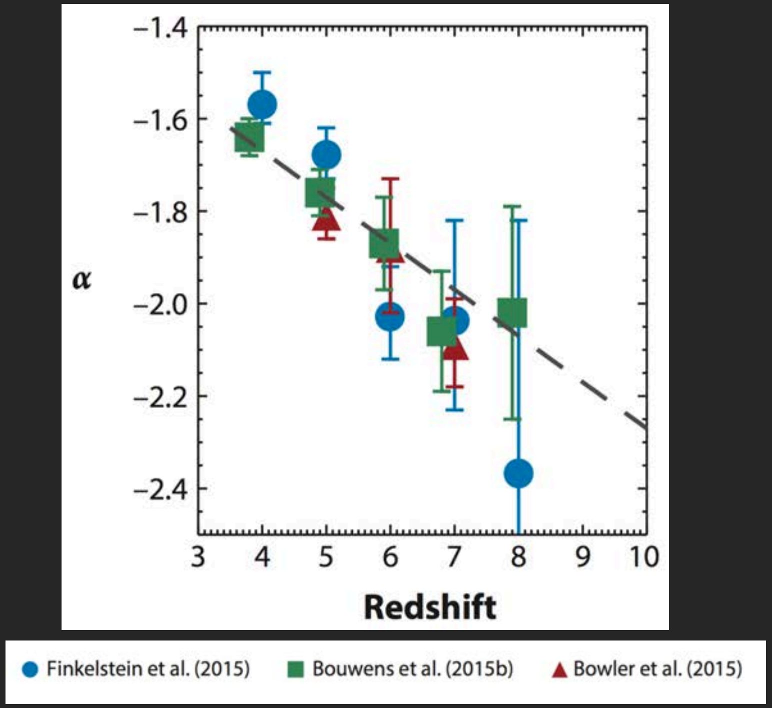
Bouwens GDI Oesch+2015

luminosity functions: steep faint end slope α

divergent at α<-2

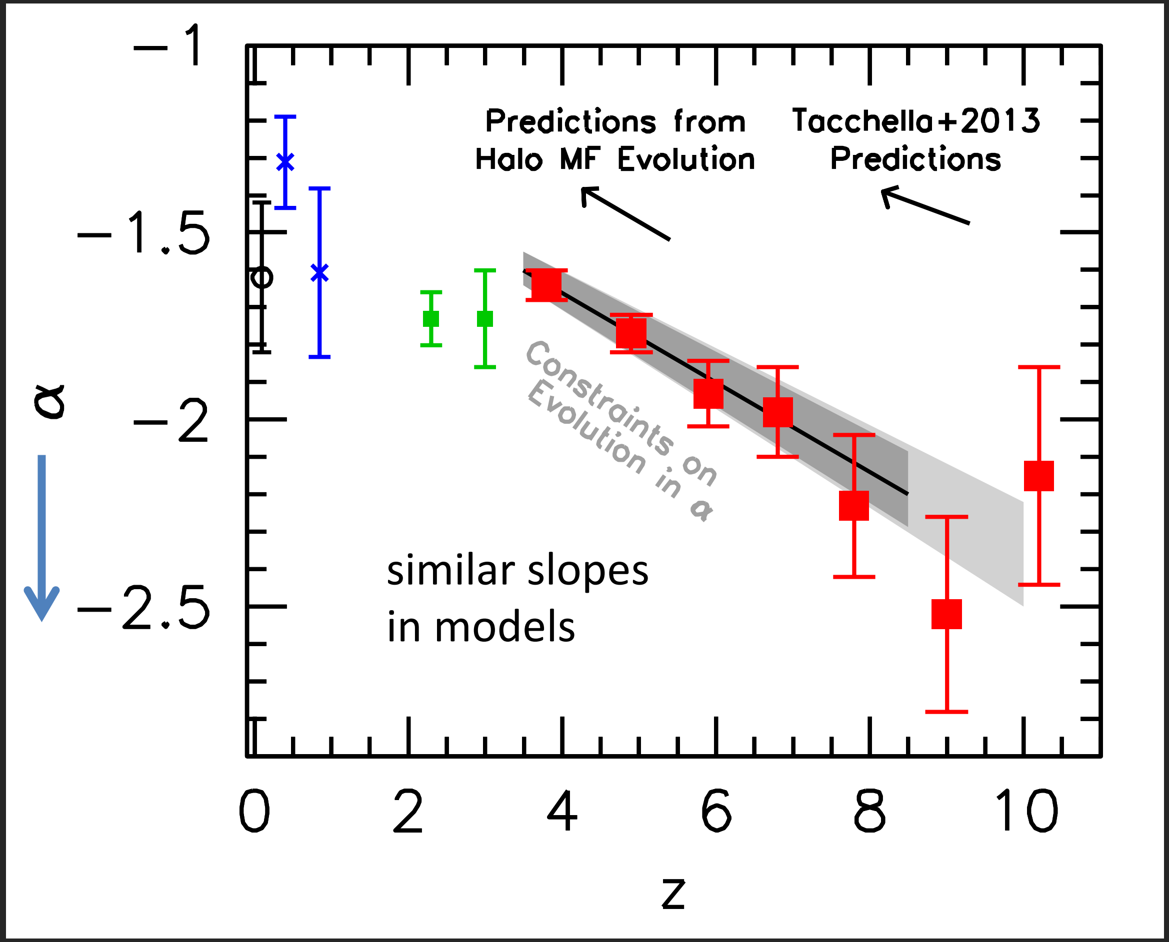
steeper slope α at early times – important for the reionization of the universe by galaxies

similar trends found by several groups



Stark 2016

steeper faint end slope α

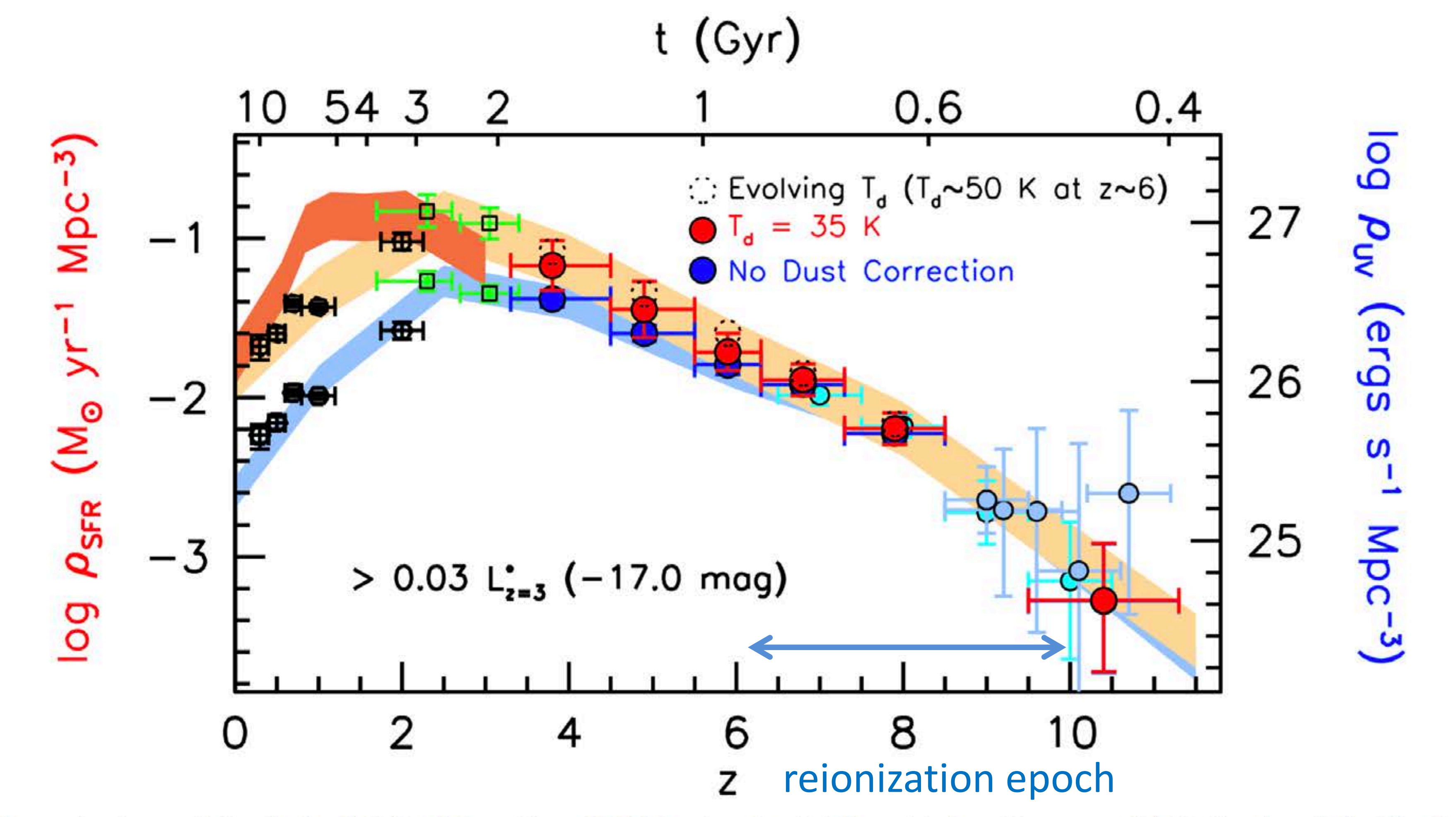


Bouwens GDI Oesch+2015

UV luminosity density and star formation rate density build-up

LFs + colors can be used to give us:

luminosity density(t) and star formation rate density(t)



see later for an update at z~9-10

from Bouwens GDI and Oesch+2015 (UV) and Bouwens+2016 (ALMA)
see also Bouwens GDI+ 2007, 2010, 2011, 2012

Frontier Fields

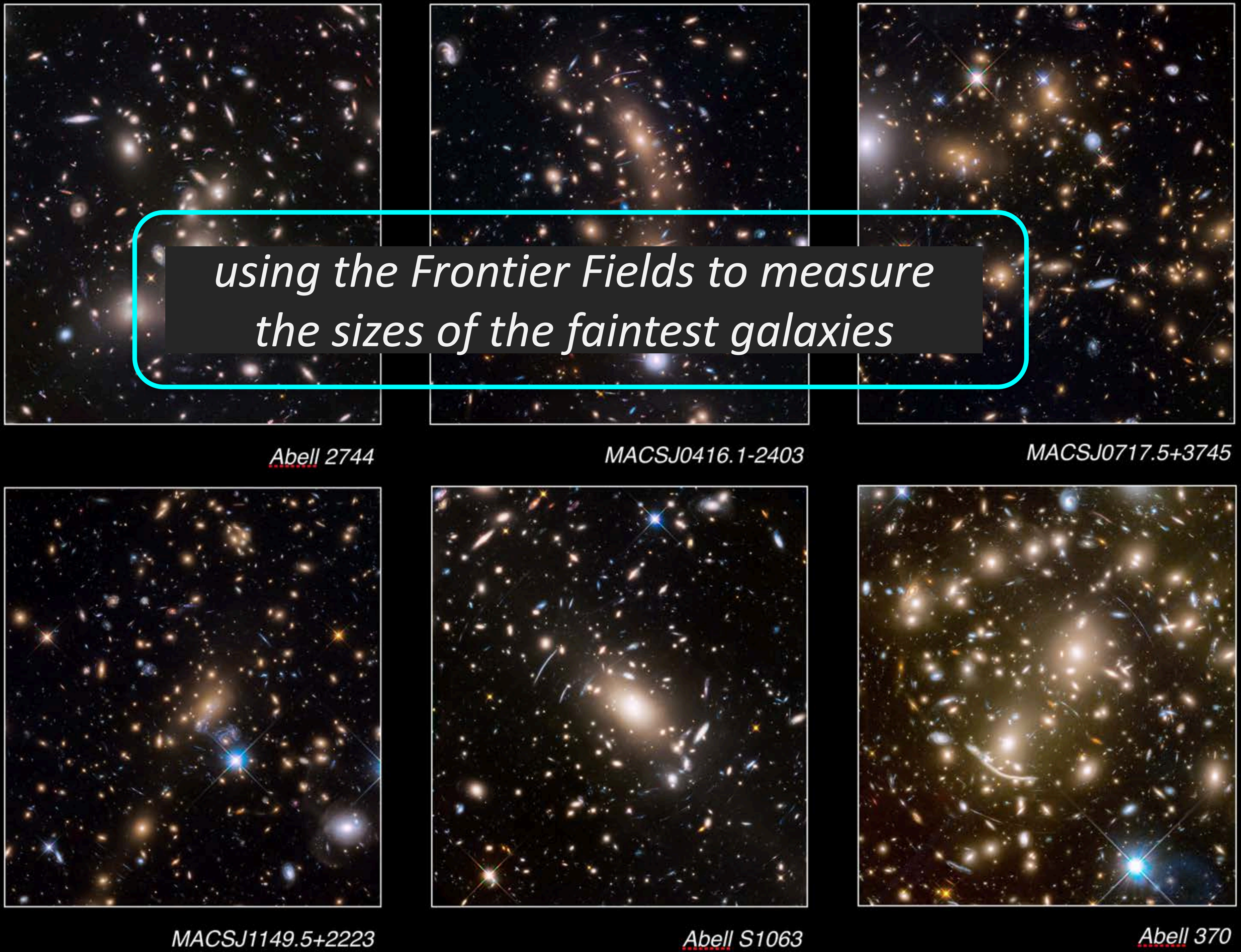
long history of galaxy cluster imaging programs with HST:

- ACS GTO Team
- CLASH
- HFF + others

6 clusters + 6 parallel fields:

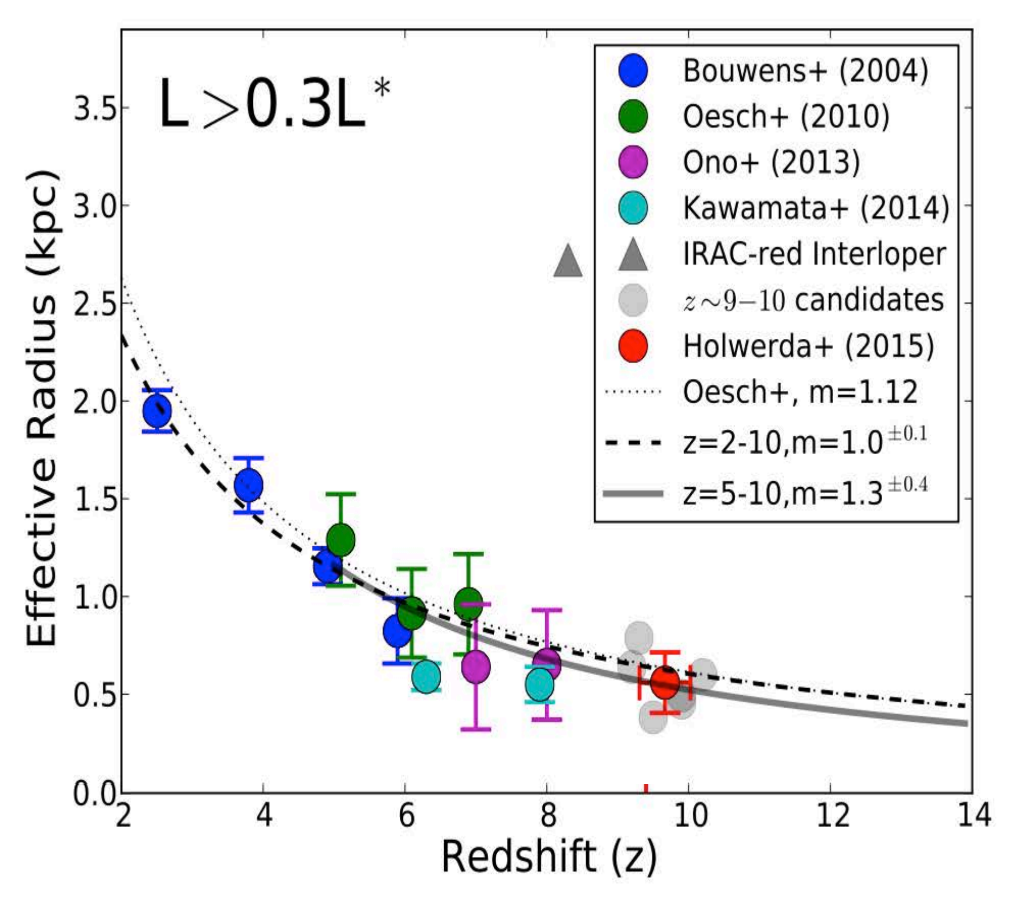
840 orbits of truly remarkable ACS and WFC3/IR data

1000 hours of Spitzer IRAC



galaxy sizes out to z~9

typical trends in size go as $r_{1/2} \sim (1+z)^{-1}$



from deep fields

Holwerda et al 2015

Cottage industry! see also Ferguson+2004, Bouwens+2004, Hathi+2008, Oesch+2010, Ono+2013, Kawamata+2014,Curtis-Lake+2014; Shibuyu+2015

trend consistent with constant L at a given halo mass

a remarkable fold arc in CL1358 – sizes of star-forming regions

a strongly lensed fold arc discovered in WFPC2 imaging of CL1358
followed up with Keck LRIS for redshift and kinematics + NIRSPEC imaging

galaxy CL1358-G1 at z= 4.92 – 1.3 Gyr after Big Bang:
lensed by a rich cluster of galaxies at z~0.3

distorted fold image of a magnified galaxy after nearby elliptical removed

recover source plane image – magnified 10-20X

- most star formation (>50%) in the brightest "blob"
- just 100-200pc in size (r_e ~130pc)

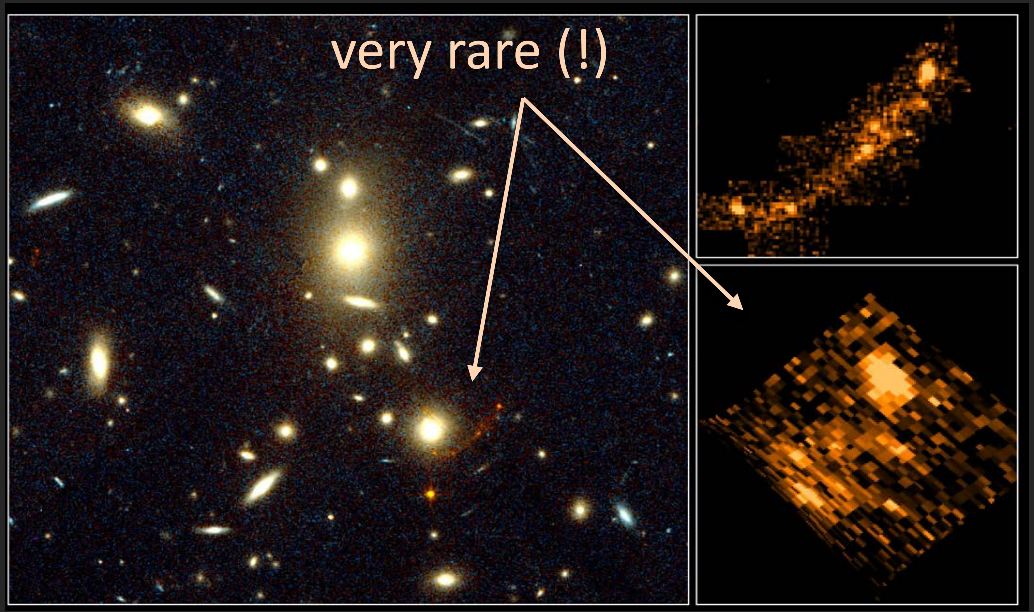
SFR around 40 $M_\odot$/yr

Franx Illingworth+1997

a remarkable fold arc in CL1358

lensed resolutions of ~100 pc or less
like 30-40 m telescope with AO

WFPC2 images

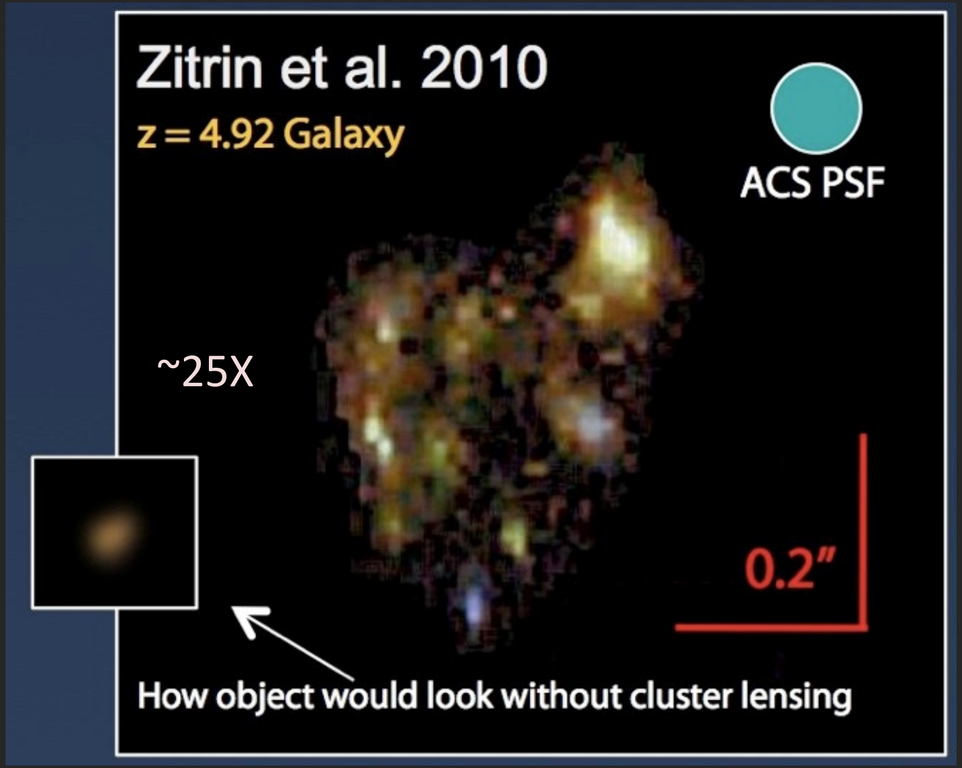


Franx, GDI+1997

z_{arc} = 4.92

Zitrin+2011

ACS images

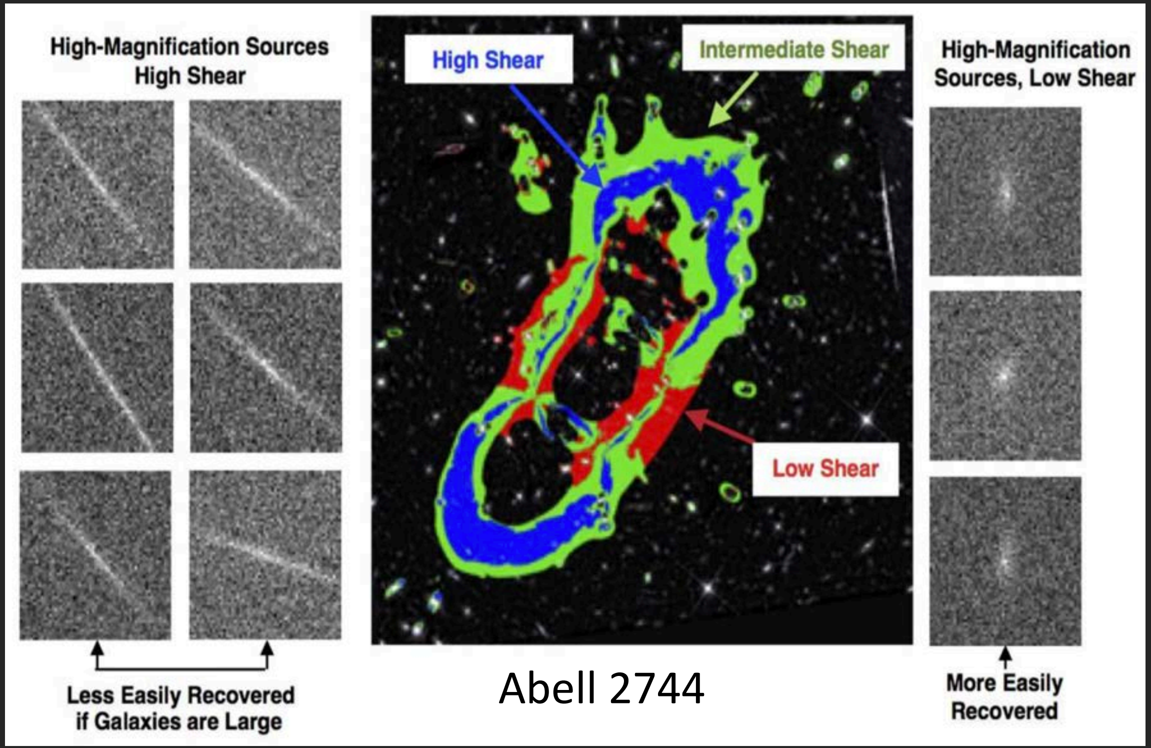


- very rare example showing such details in an early galaxy
- indicates star-forming regions at high z are very small

see also Swinbank+2009 for more kinematics

the remarkably small sizes of high redshift galaxies

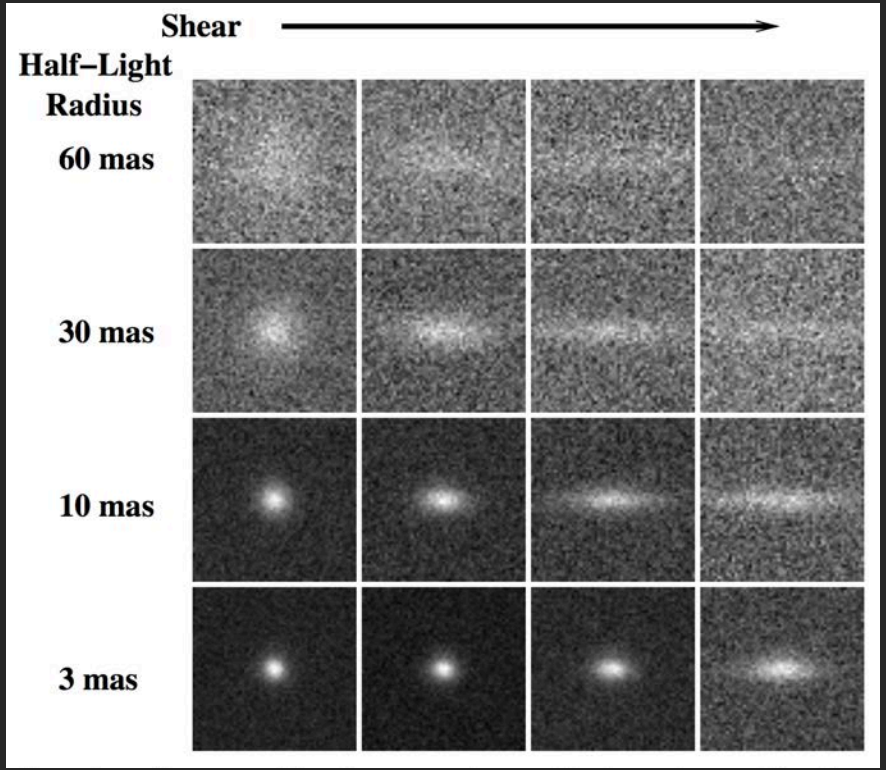
the Frontier Fields enable some very interesting constraints to be set on sizes



high shear, high magnification regions provide an opportunity to check sizes of galaxies

simulations with varying size at magnification μ = 20 & fixed total magnitude

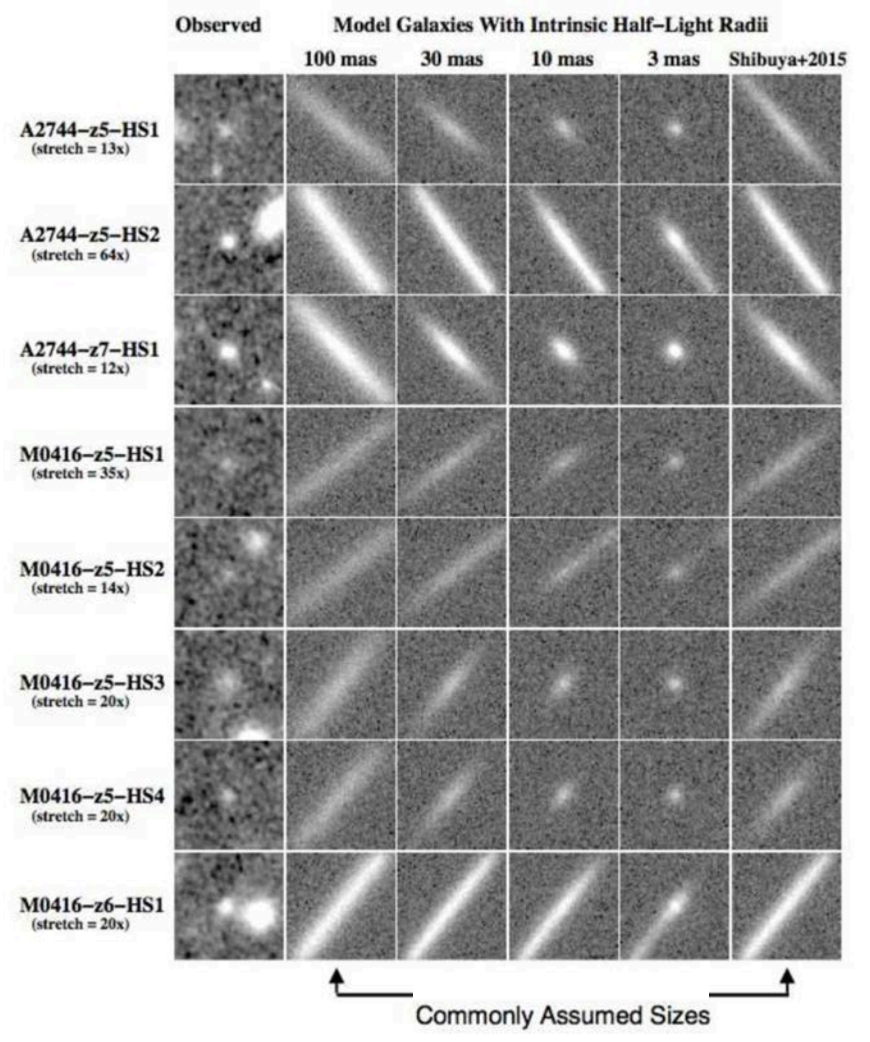
clearly if galaxies are small they will be detected more uniformly regardless of the shear



Bouwens GDI Oesch+2016

see also Oesch+ 2015

the remarkably small sizes of high redshift galaxies



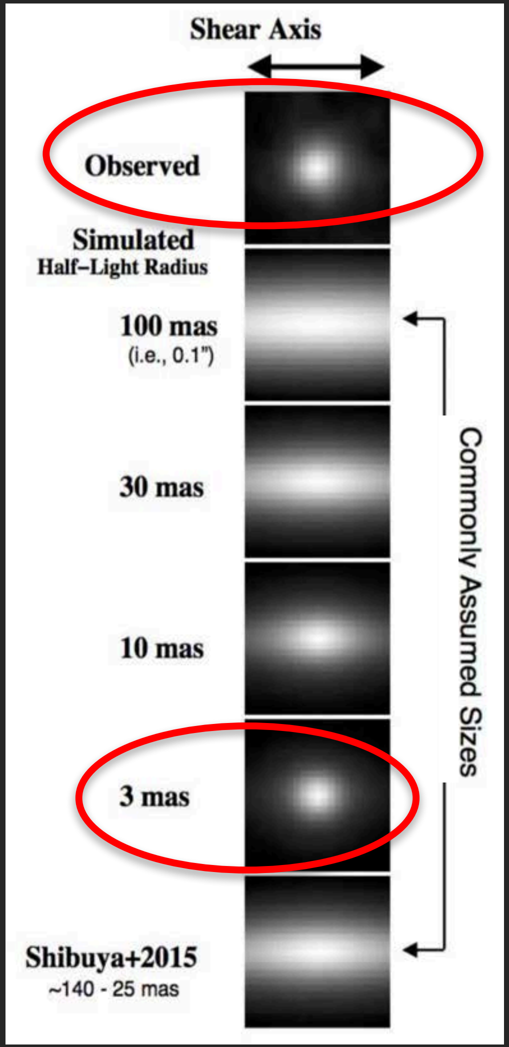
shear factors *S* from 12X to 64X

sizes of z~6 galaxies

stacked very faint $M_{UV,AB}$>-16 galaxies

galaxies that are expected to be highly sheared show no signs of extension!

very low luminosity high-z galaxies (z~6) are small: <10 mas!

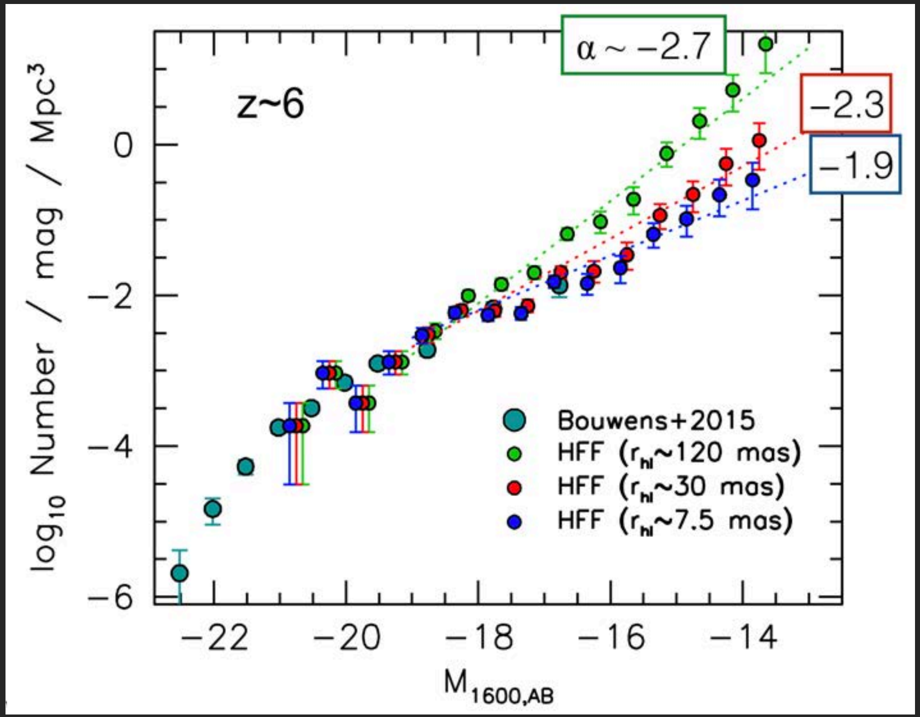


Bouwens+2016, 2017

see also Kawamata + 2015, Vanzella + 2016

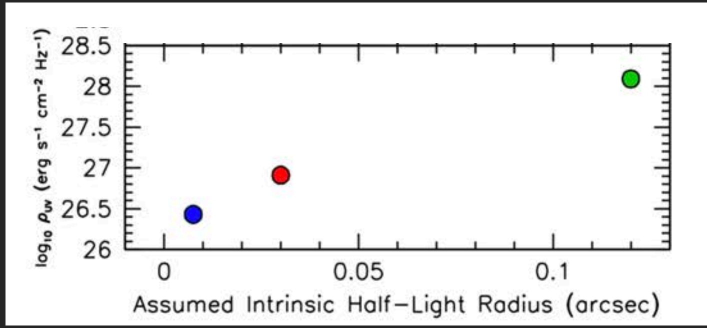
the impact on the UV luminosity density of size assumptions

☞ need to take great care to use the correct size of faint galaxies when deriving LF results from lensing clusters



completeness corrections are strongly size dependent – assuming the wrong size can lead to dramatic impacts on the derived slope

for example, differences in the derived luminosity density can be overstated by >10X if 120 mas is used instead of the actual 30 mas, or by >30X if the actual size is <10 mas



** using the correct size of galaxies is crucial if an accurate luminosity density or SFR density is to be derived **

Bouwens GDI Oesch+2016

the impact on the UV luminosity density of size assumptions

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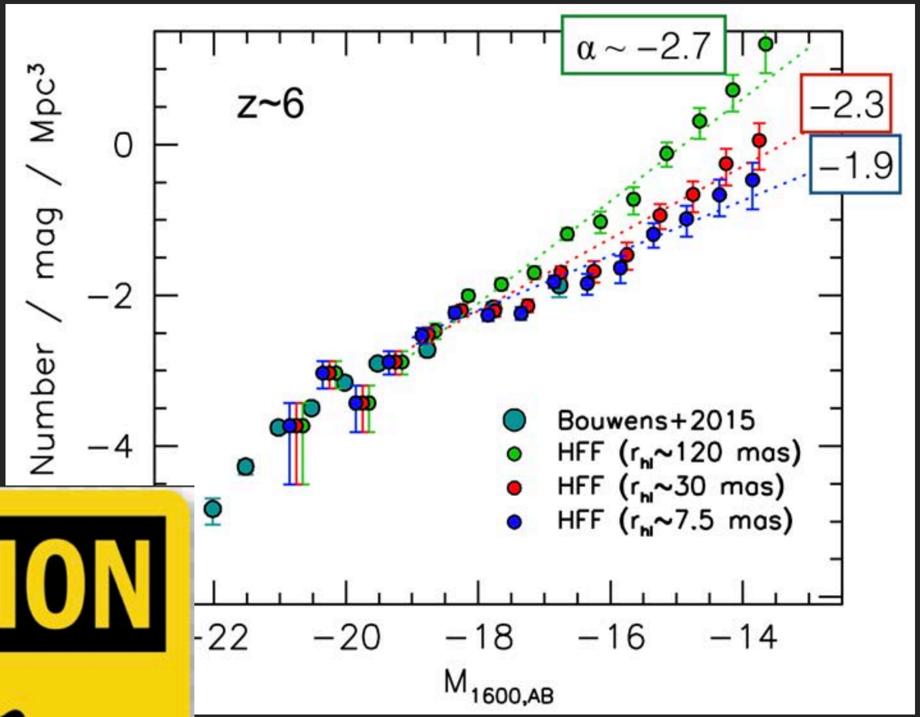
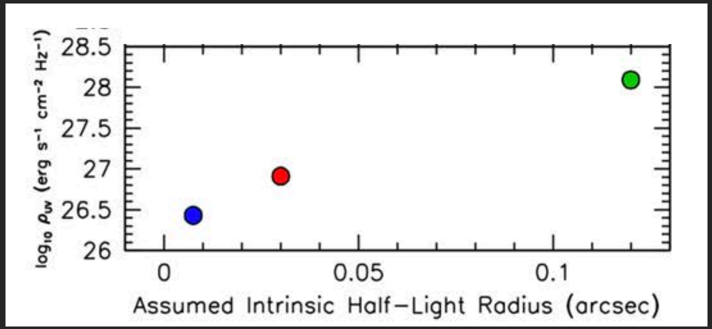




Bouwens GDI Oesch+2016

the remarkably small sizes of high redshift galaxies

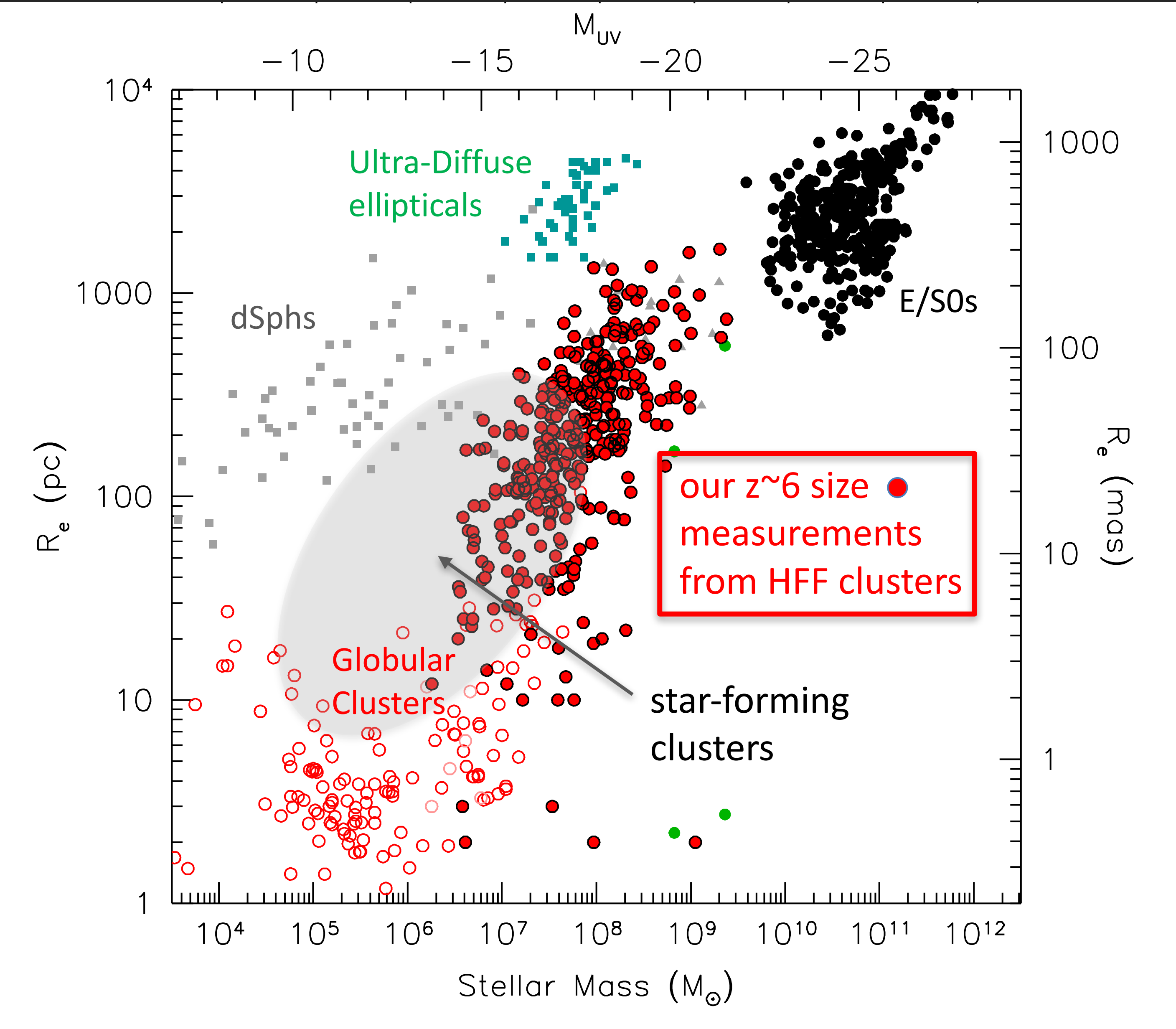
sizes of z~6 galaxies compared to star forming, clusters, globular clusters, dwarf spheroidals, E/S0s

local objects from Norris+2014

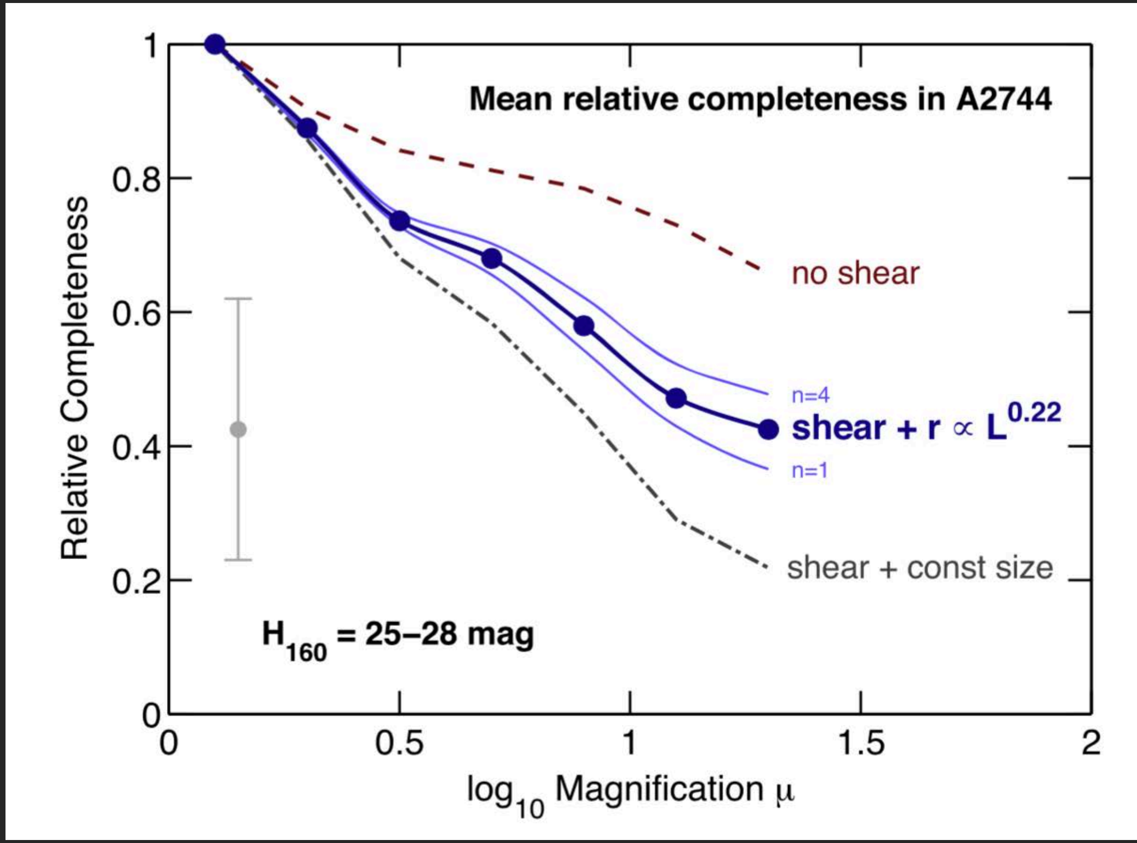
☞ could well be seeing some globular clusters forming at very high redshift….

Bouwens GDI Oesch+2016, 2017

see also Kawamata + 2015, Vanzella + 2016



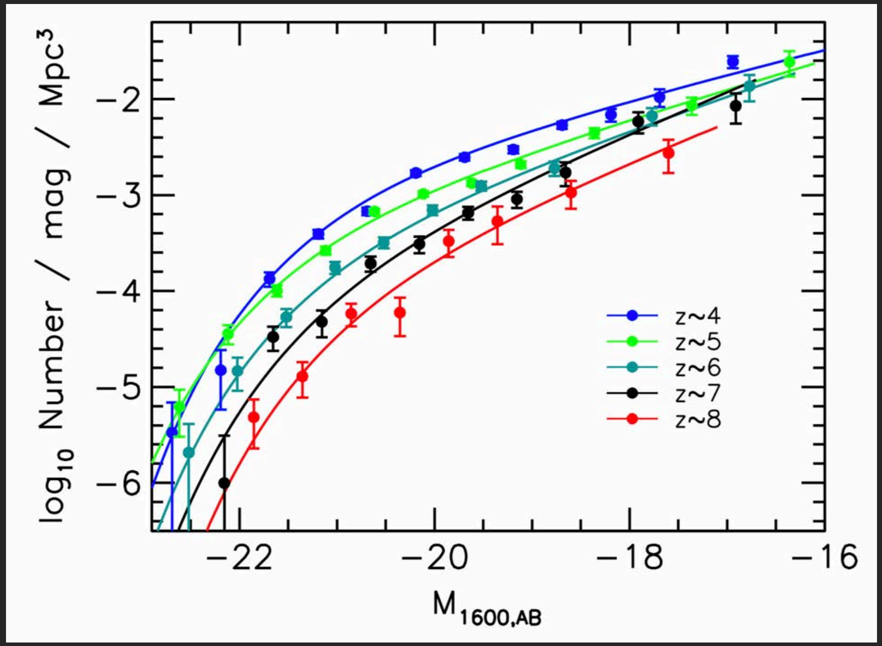
the challenges of using lensing clusters to extend the luminosity function to very faint sources – constraints on reionization



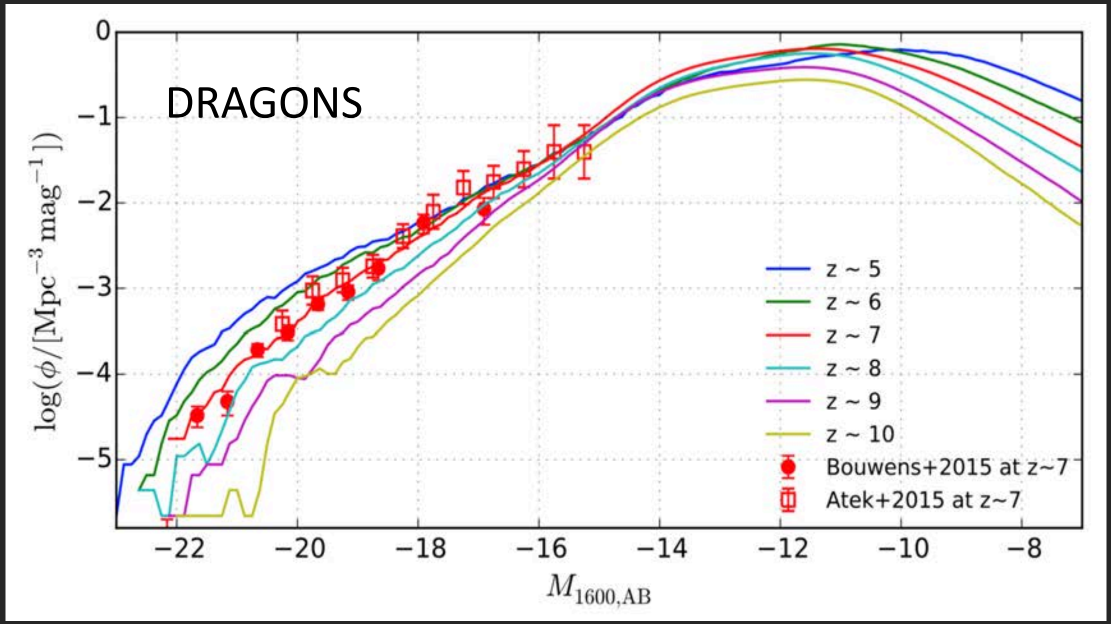
We showed in 2015 that shear in higher magnification regions in lensing clusters had a major impact on the completeness corrections and hence on the slope/shape of the LF (depending on size as per previous discussion)

Oesch Bouwens GDI+2015

pushing LFs to fainter limits to derive UV luminosity densities



Bouwens GDI Oesch+ 2015



theoretical LFs

Liu+2016

expect flattening or turn-over in the UV LF at low luminosities

need to go faint to very low luminosities since majority of UV luminosity density with α~-2 comes from very faint galaxies

strongly lensing clusters provide the opportunity to go much fainter than deep fields, but how faint can we reliably push?

the high magnification uncertainty

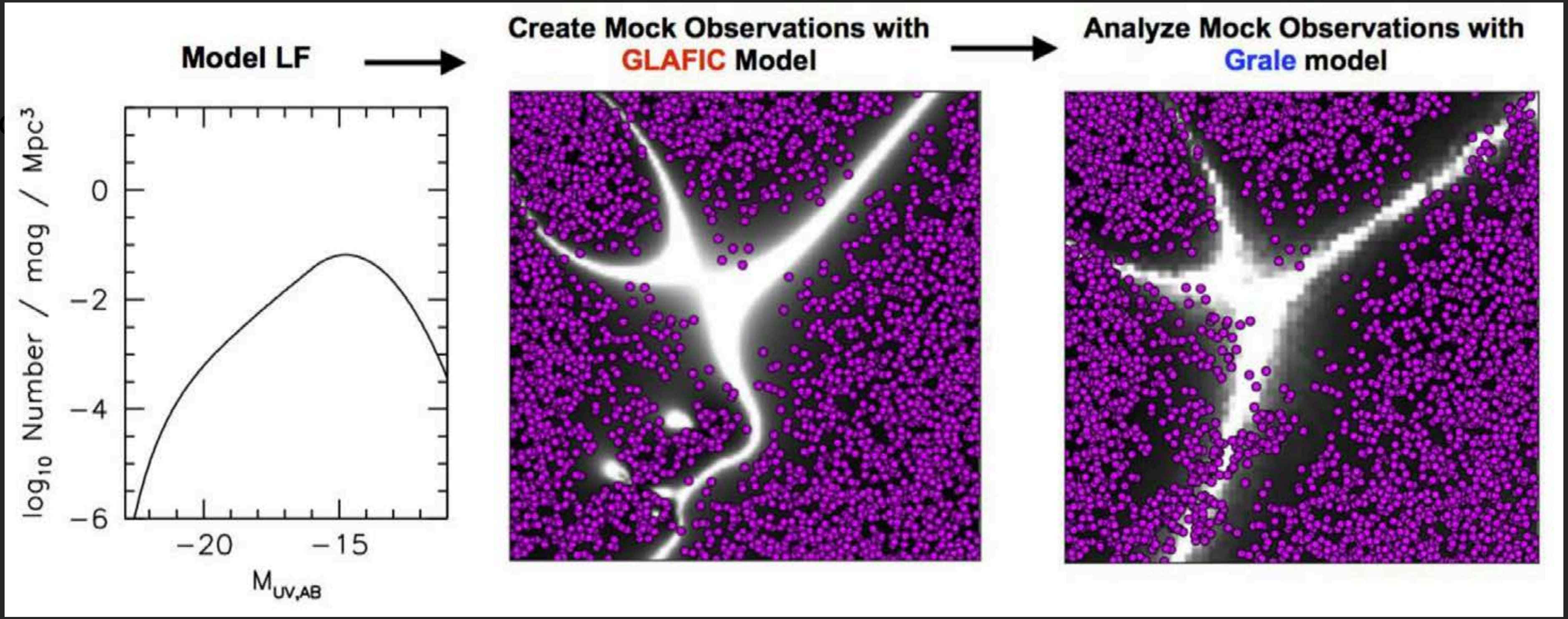
☞ very high magnifications are required to go fainter than -14

but comparisons and simulations have shown the magnification uncertainties are large at high magnifications

☞ quantify

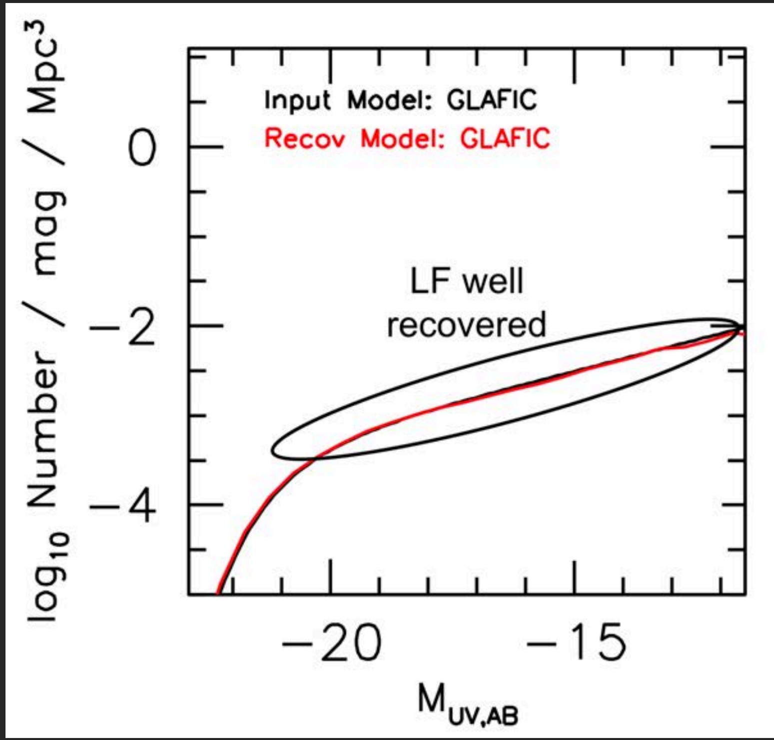
simulate using one model and try and recover sources using the other models
– repeat with wide range of input parameters (simulated for z~6 galaxies)

mo

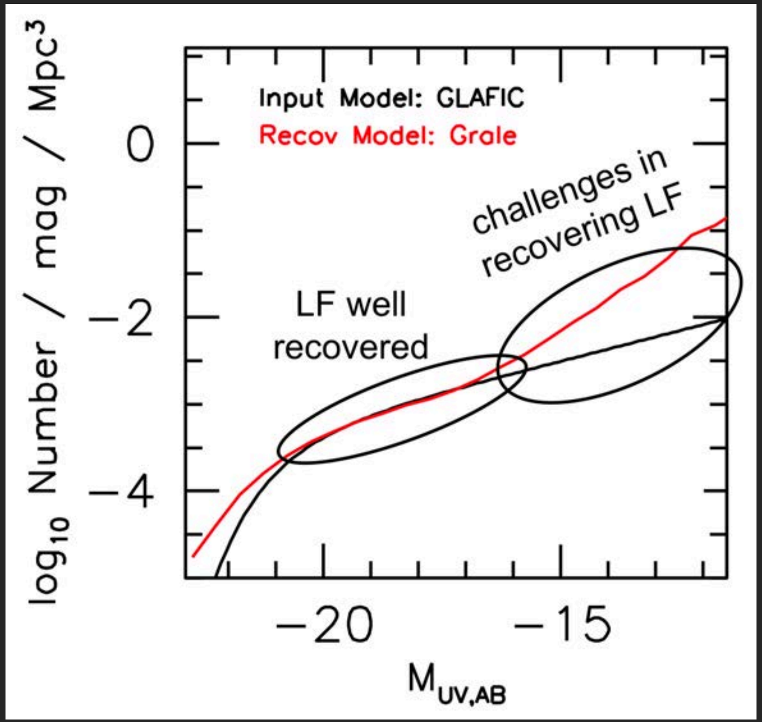


Bouwens Oesch GDI+2016

same high magnification region in both models *demonstration of impact on LFs from the HFF of systematic effects at high magnifications*



LF well-recovered with same model



LF not recovered – very large systemic offset at high magnifications

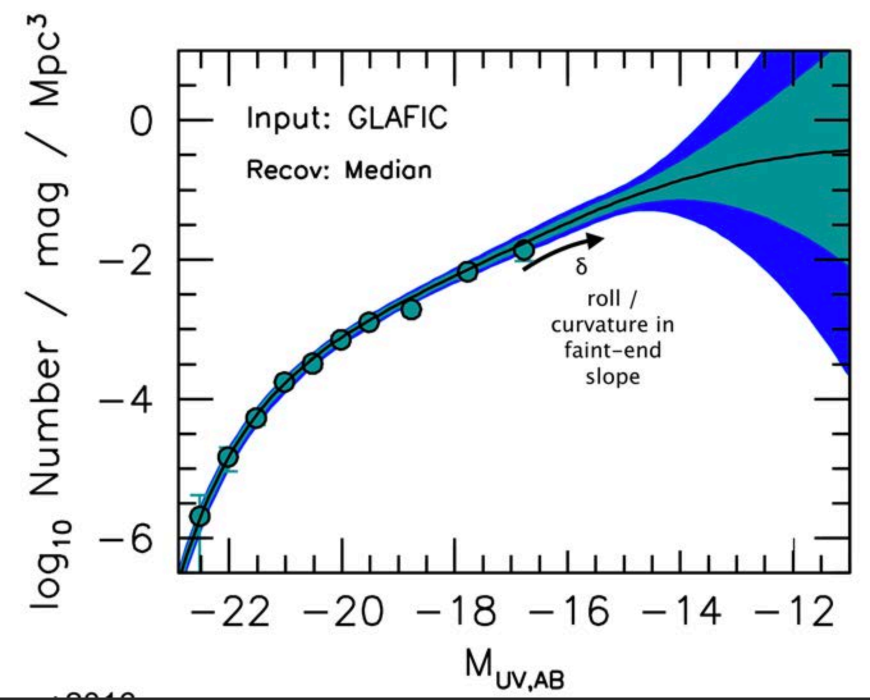
systematics are the limiting factor below $M_{UV,AB}$ ~ -15

Bouwens+2016

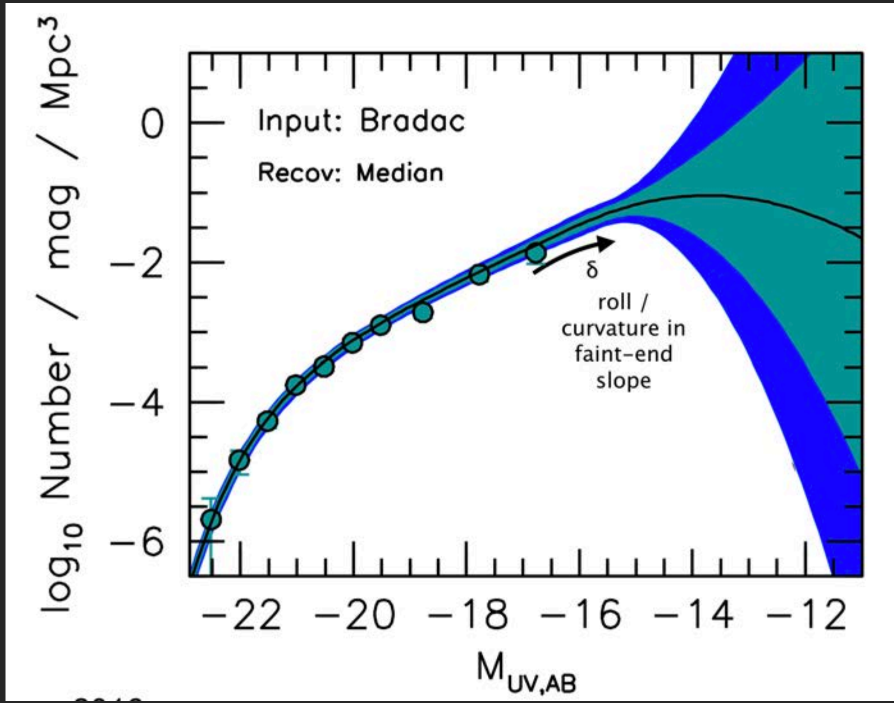
the high magnification uncertainty

☞ very high magnifications are required to go faint

when simulating using one model and recovering sources using the other (6) models, substantial differences are found for very large magnifications >~40



these results suggest that pushing fainter than ~-14 will not provide robust results

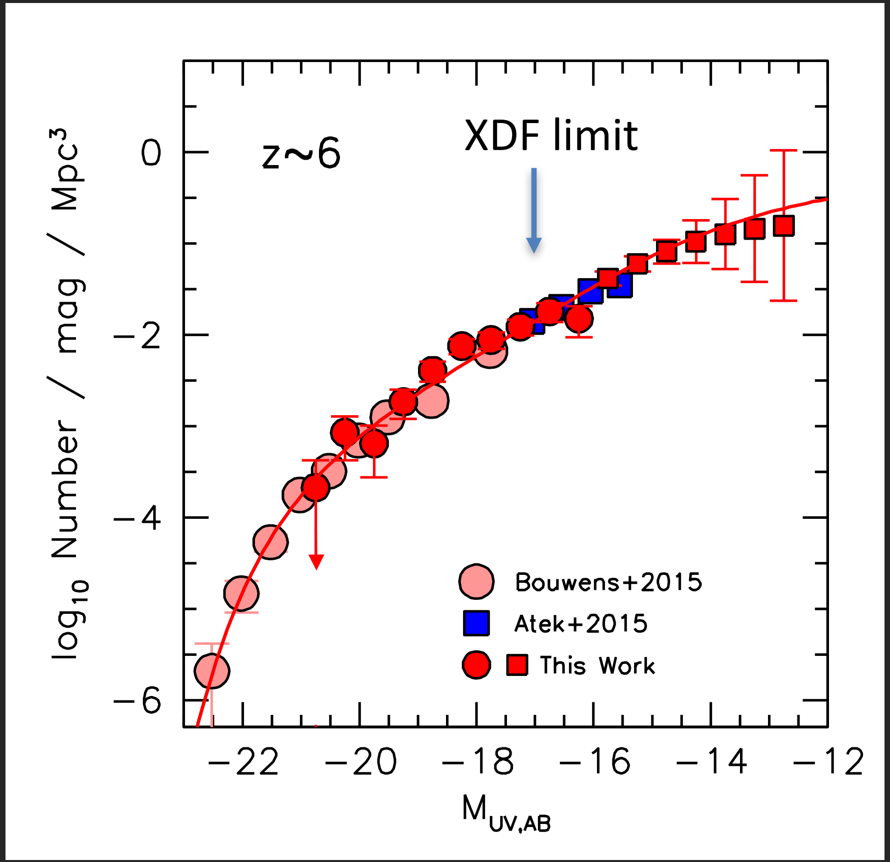


Bouwens Oesch GDI+2016

systematics are the limiting factor

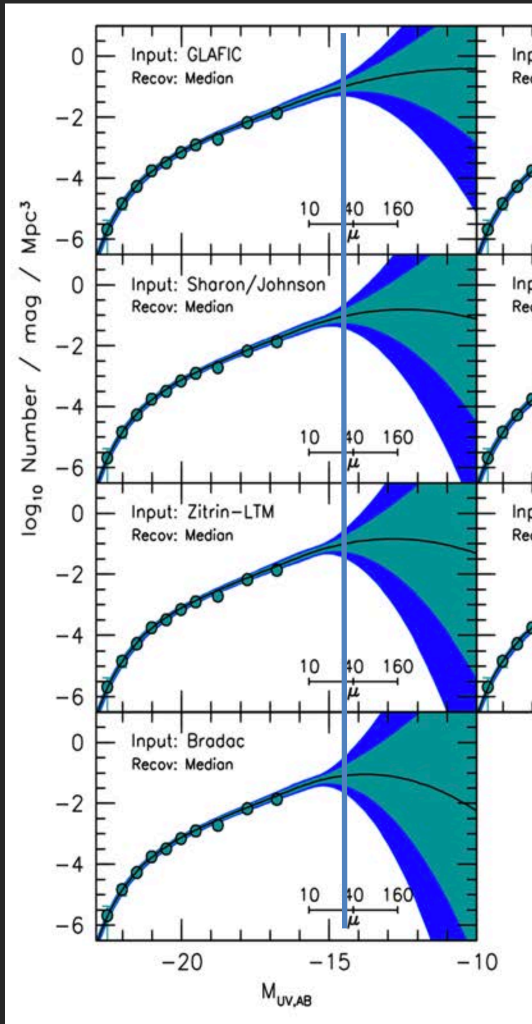
bottom line: the models agree well up to magnifications of ~30-40 but do not produce consistent results for faint sources at higher magnifications (as other comparison tests have shown also)

current limits on reliable LFs from the HFF



the systematic uncertainty fainter than $M_{UV,AB}$ ~-14.5 "blows-up"

the errors in the LF become so large as to make estimates of the LF from the HFF *not credible* below $M_{UV,AB}$ ~-14



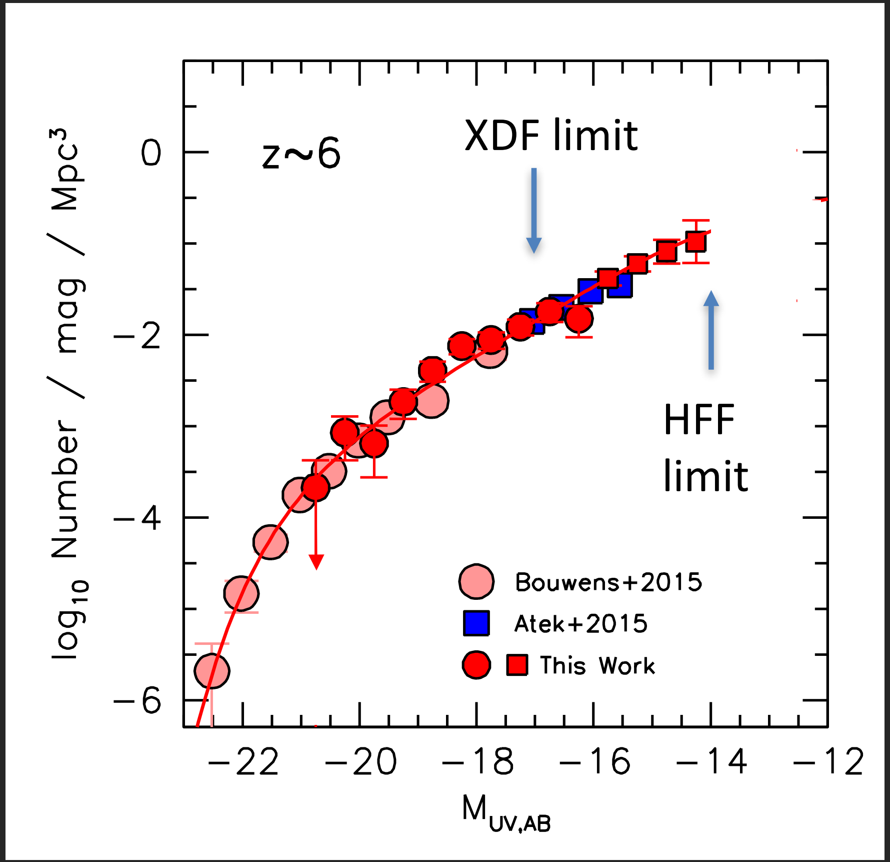
the uncertainty "blows up" fainter than -14.5

systematics are the limiting factor

Bouwens+2016

see Castellano+2015, Atek+2016, Livermore+2017

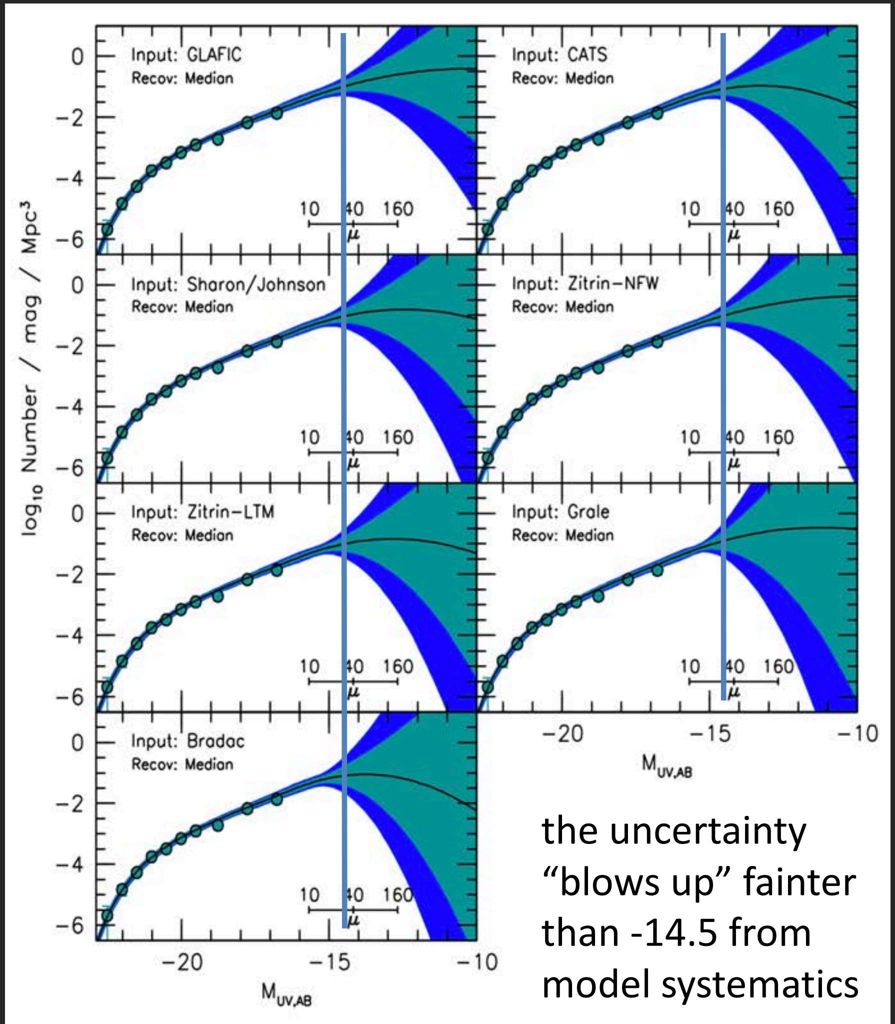
current limits on reliable LFs from the HFF



the Frontier Fields provide a reliable and robust gain of ~3 mags fainter than the HUDF/XDF, but no fainter than about $M_{UV,AB}$ ~-14

JWST will go to ~-13

Bouwens+2016

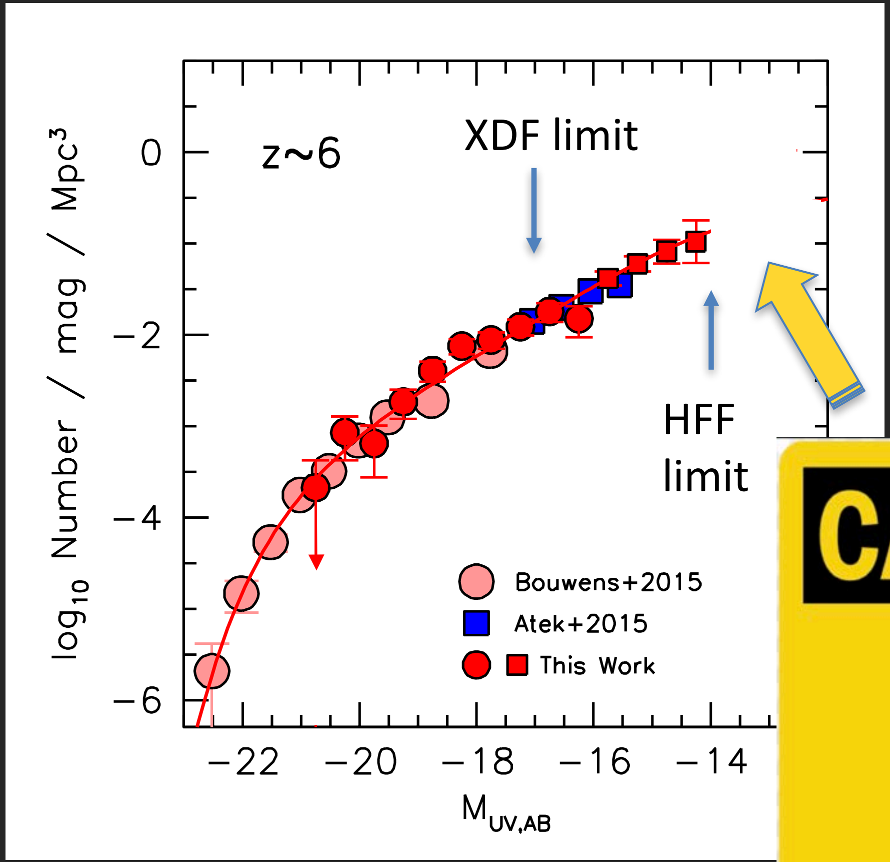


the uncertainty "blows up" fainter than -14.5 from model systematics

bottom line: with the current state of the art for lensing models and with current Hubble data one cannot set useful constraints fainter than about $M_{UV,AB}$ ~ -14

see Castellano+2015, Atek+2016, Livermore+2017

current limits on reliable LFs from the HFF



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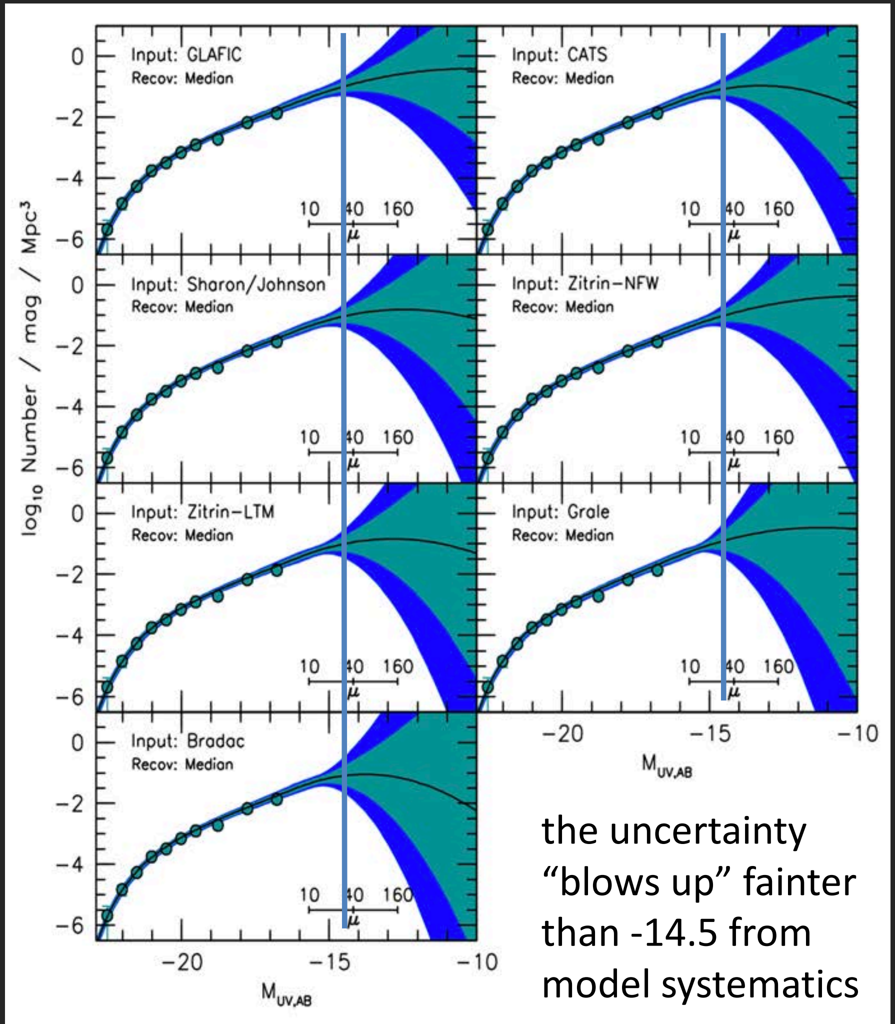

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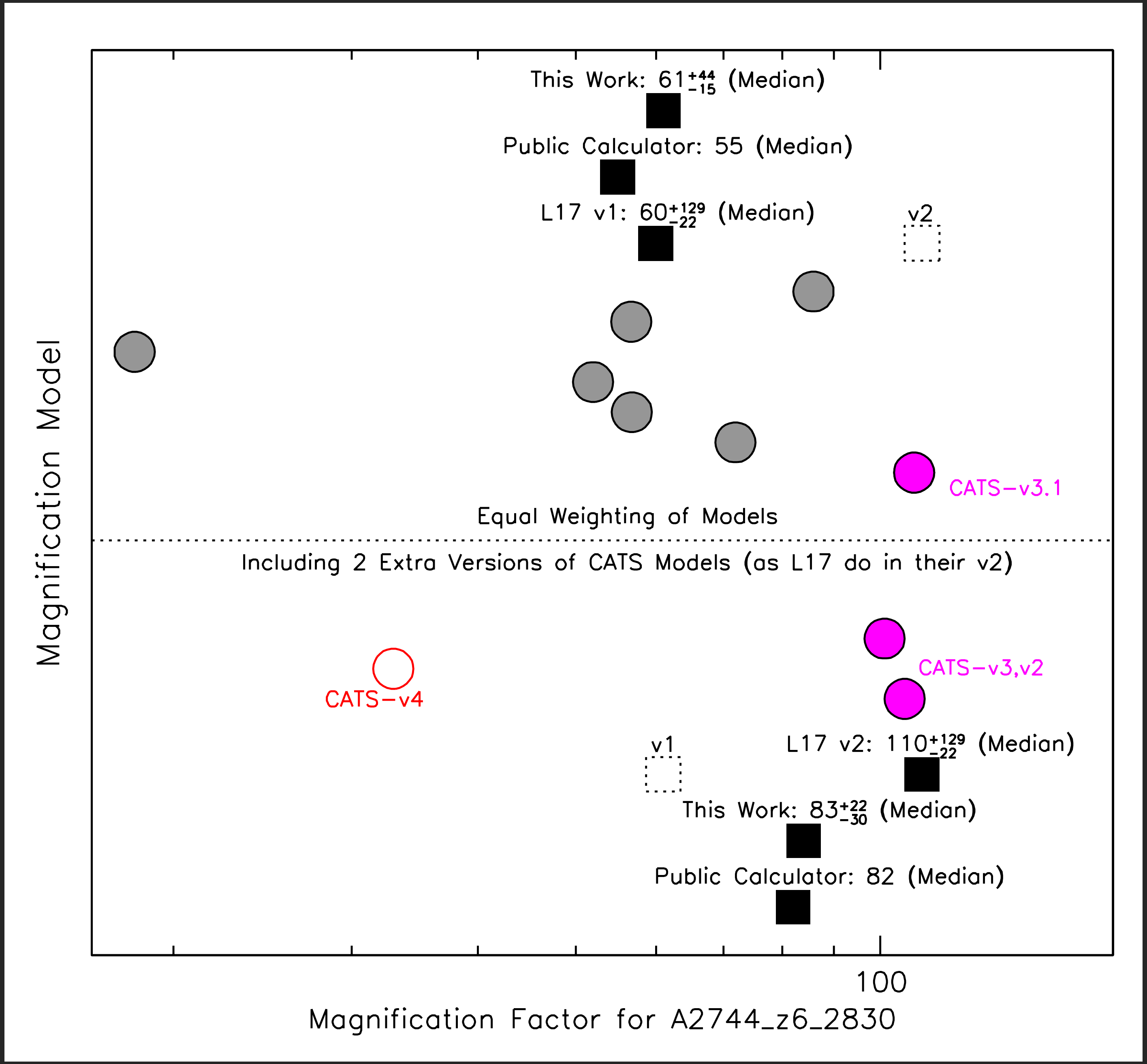
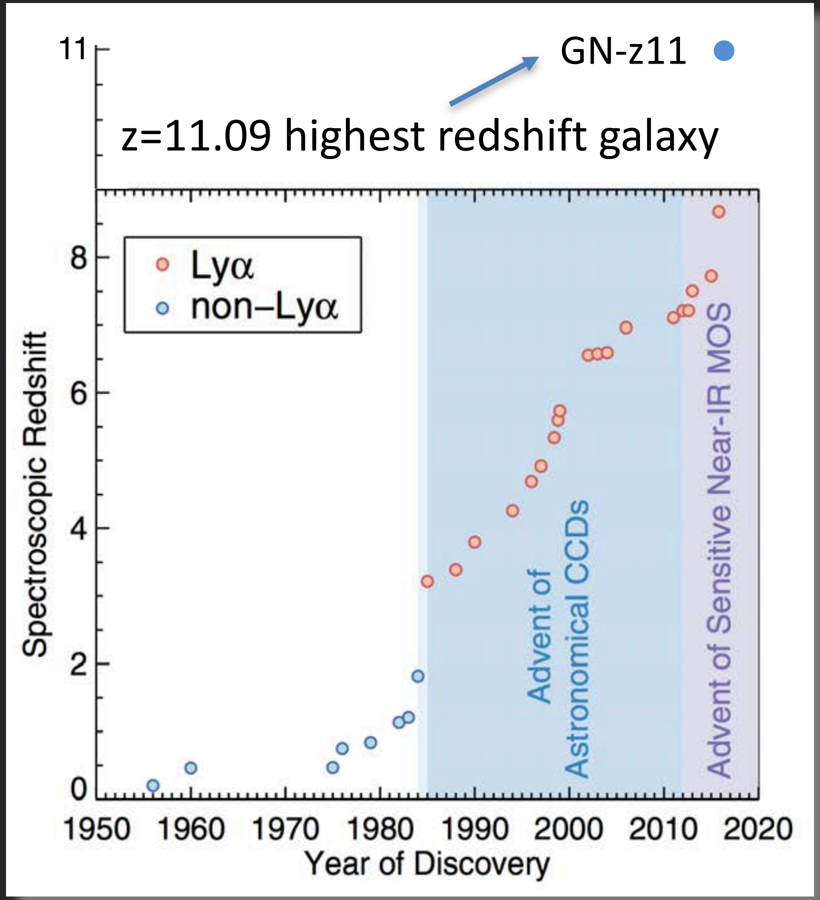


example of the range of model magnifications for a very highly magnified galaxy in HFF cluster A2744

different models return a wide range of magnifications from ~20 to ~110X

measuring the highest redshifts:
galaxies at the cosmic dawn



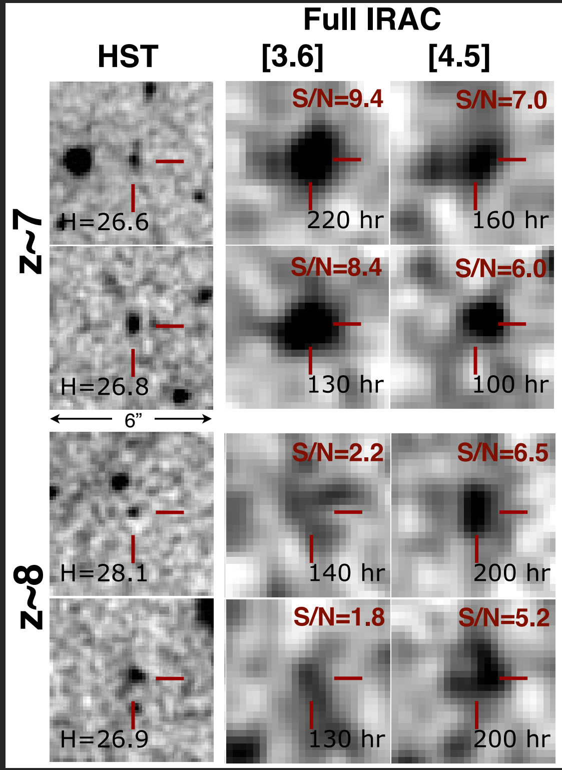
Finkelstein 2016

Spitzer observations of up to 200 hrs per IRAC filter

☞ Spitzer has revealed remarkably strong emission lines at z~7-8!

brightness changes in images due to [OIII] + Hβ moving from the 3.6μm band at z~7 to the 4.5μm band at z~8

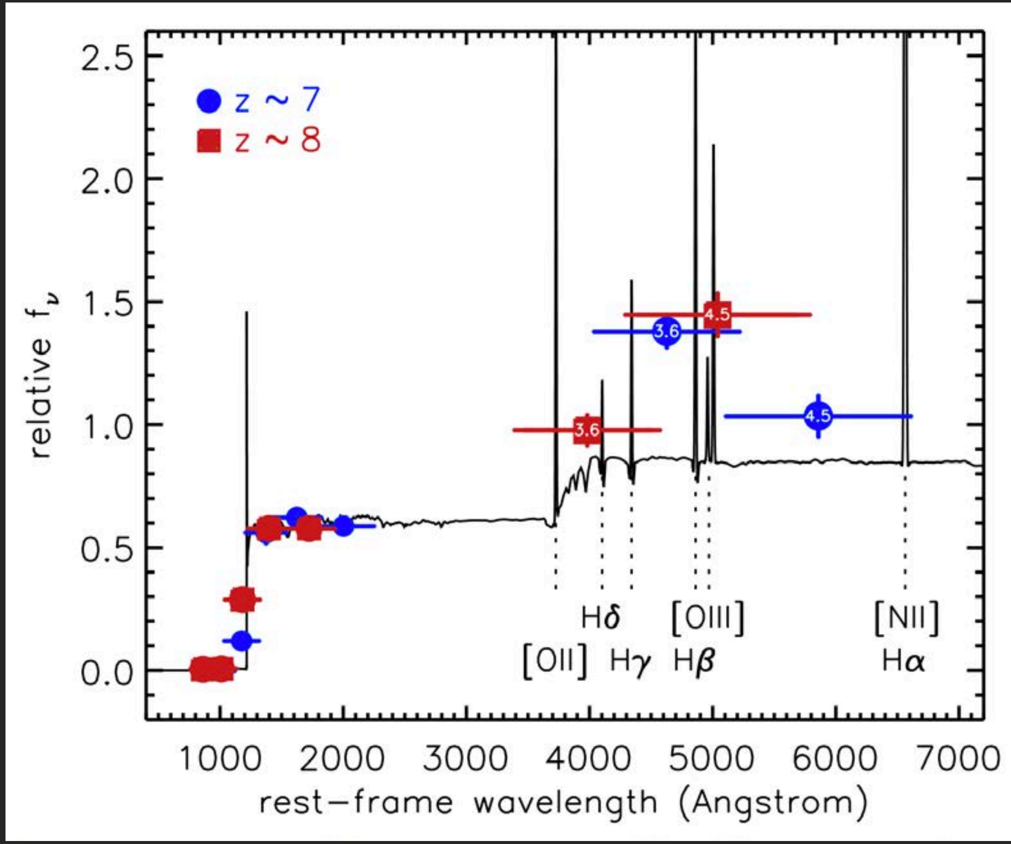
100-200 hrs
IUDF/IGOODS



the IRAC color flips from blue to red between z~7 and z~8

z~7

z~8



Spitzer/IRAC revealed: z~7-8 galaxies have extreme OIII+Hβ line emission

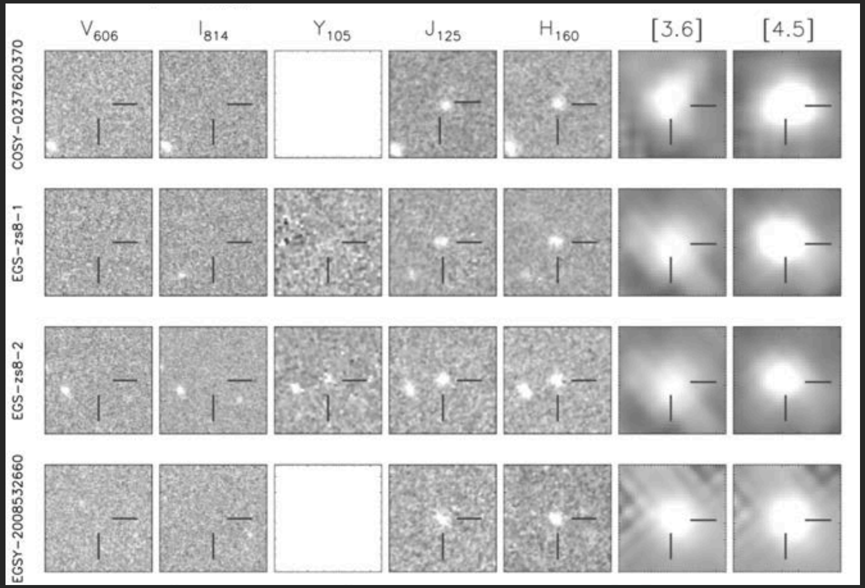
Labbé+2013, 2015, 2017 (in prep)

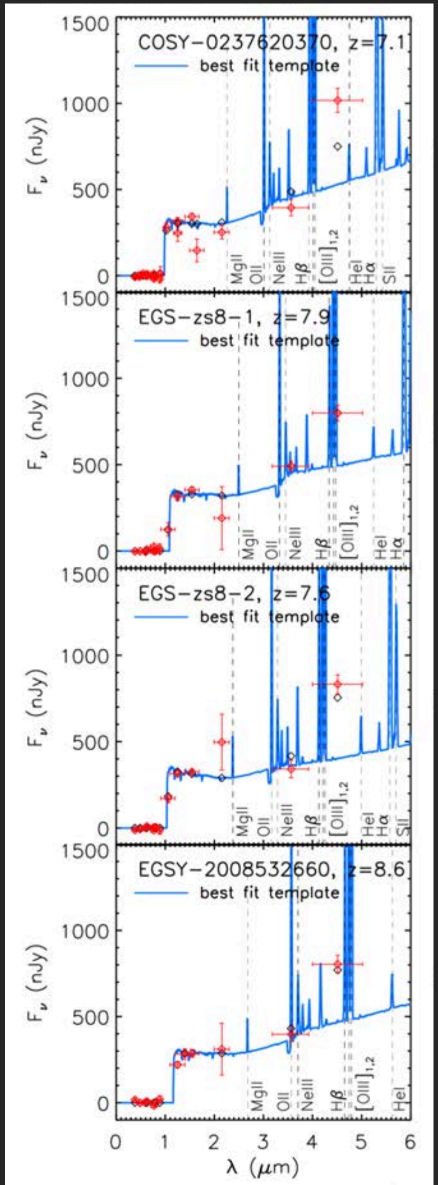
spectroscopy of the highest redshift galaxies

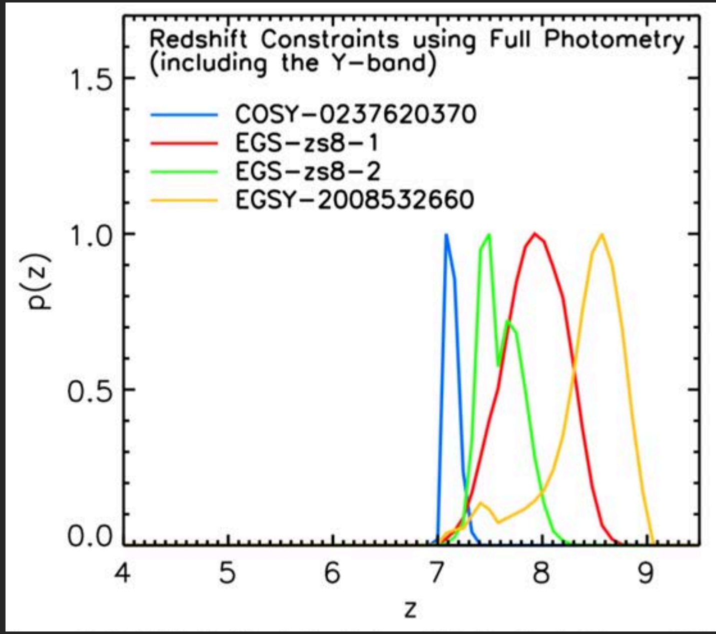
bright z~7-8 galaxies found recently from Hubble and Spitzer – ideal for spectroscopy

set of four from CANDELS-EGS

HST Spitzer





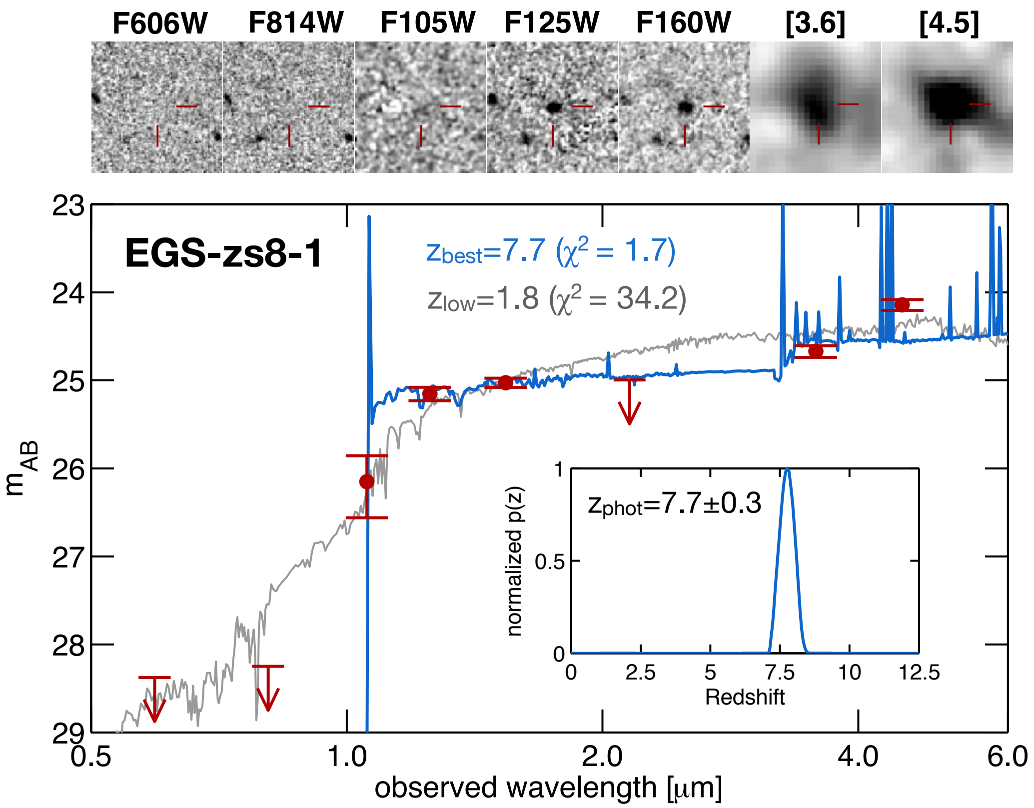


photometric redshifts
from Hubble+Spitzer

SED fits incl. emission
lines to get redshifts

Roberts-Borsani+2016

Lyα detection at z=7-8



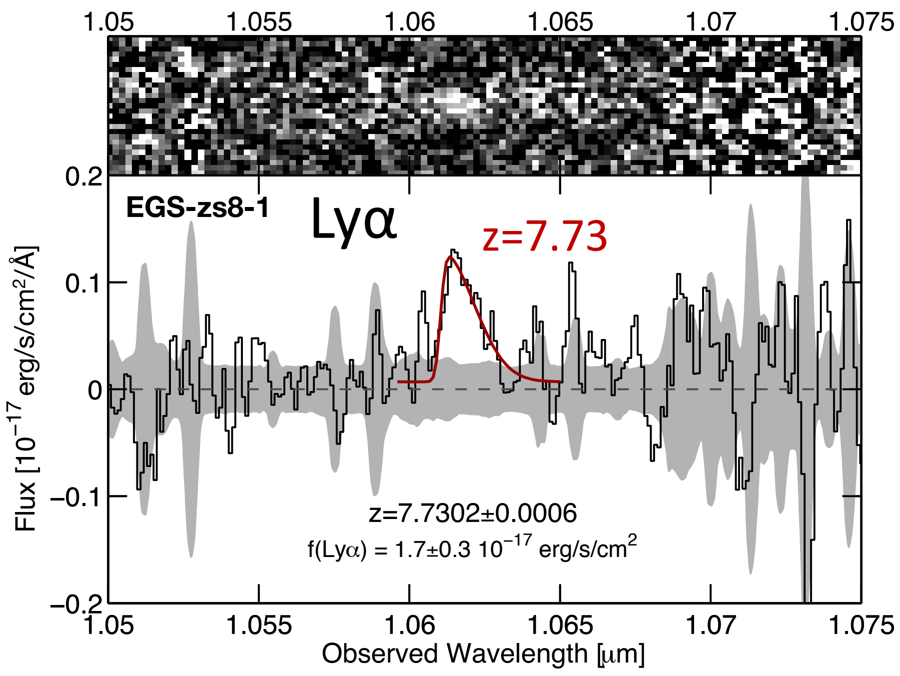
photometric z=7.7±0.3 from Hubble and Spitzer

MOSFIRE
Multi-Object Spectrometer for Infra-Red Exploration

Oesch+2015

images from Hubble and Spitzer ➔ spectra from Keck

use SED fits to verify that this is a Lyα detection
– and not a low redshift contaminant



Lyα z=7.7302±0.0006 from Keck MOSFIRE spectrum

highest confirmed redshift ever – for 4 months!

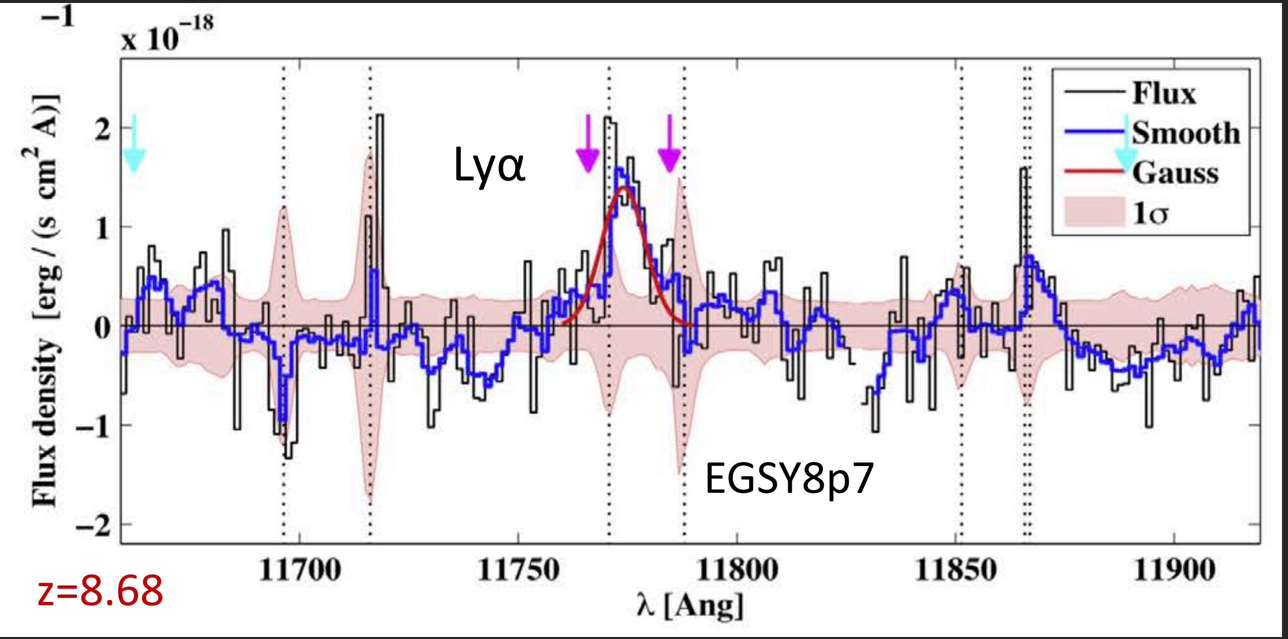
see also Ono+2012 and Finkelstein+2013 for other z~7 Lyα detections

highest redshift Lyα detection at z=8.68

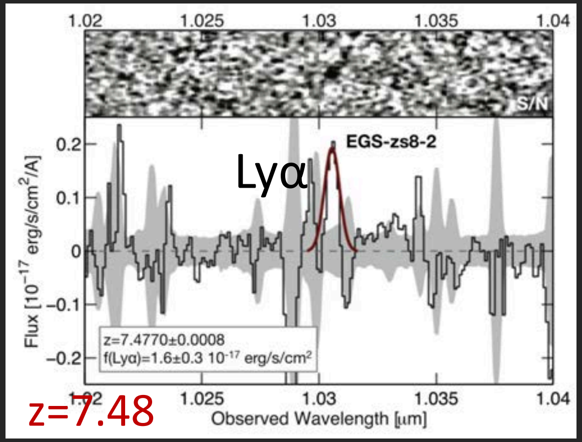
luminous galaxies in the heart of the reionization epoch:

note ☛ 100% spectroscopic success rate from Lyα detection!

the universe is substantially neutral at these redshifts – each of these very luminous galaxies probably resides in its own ionized bubble

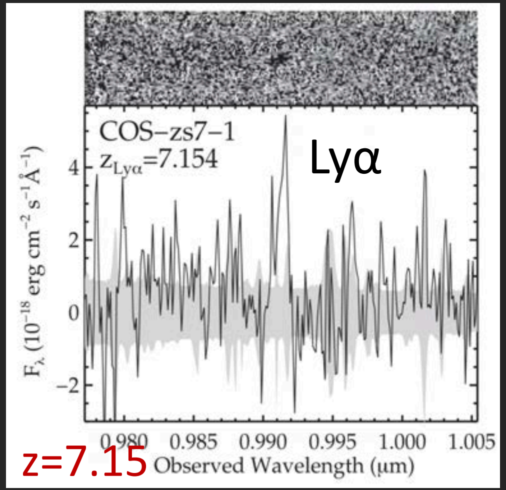


Zitrin+2015



Roberts-Borsani+2016

+ the other two



Stark+2017

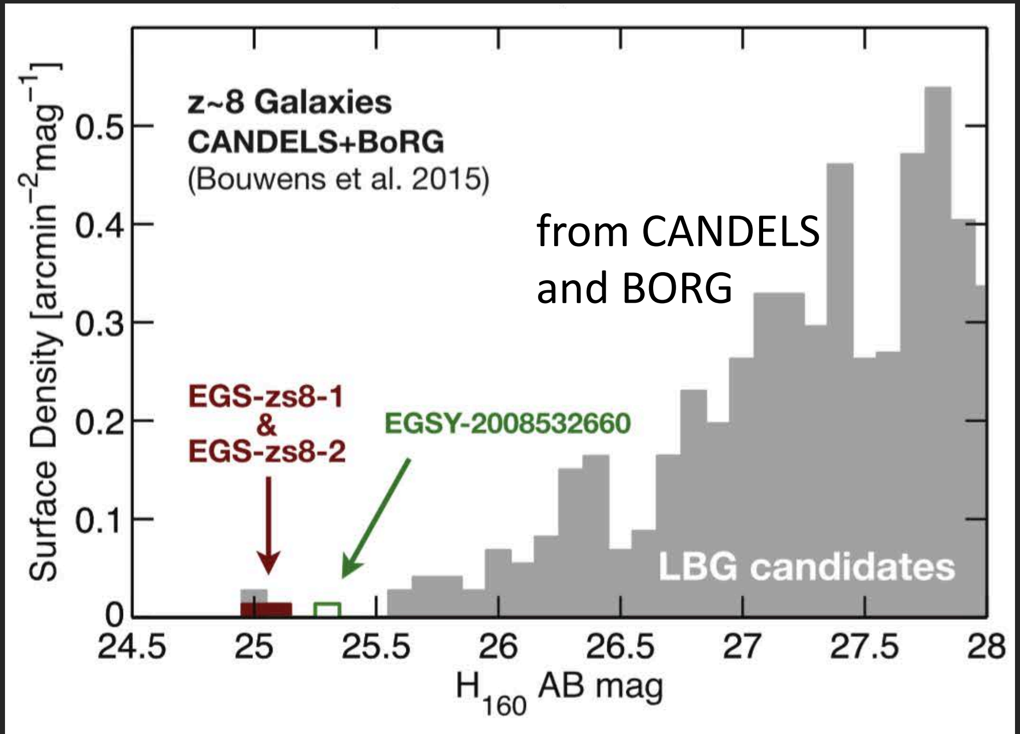
MOSFIRE
Multi-Object Spectrometer for Infra-Red Exploration

EGSY8p7 has highest Lyα redshift to date

so all four z~7-8 from Roberts-Borsani now have Keck Ly*α* redshifts

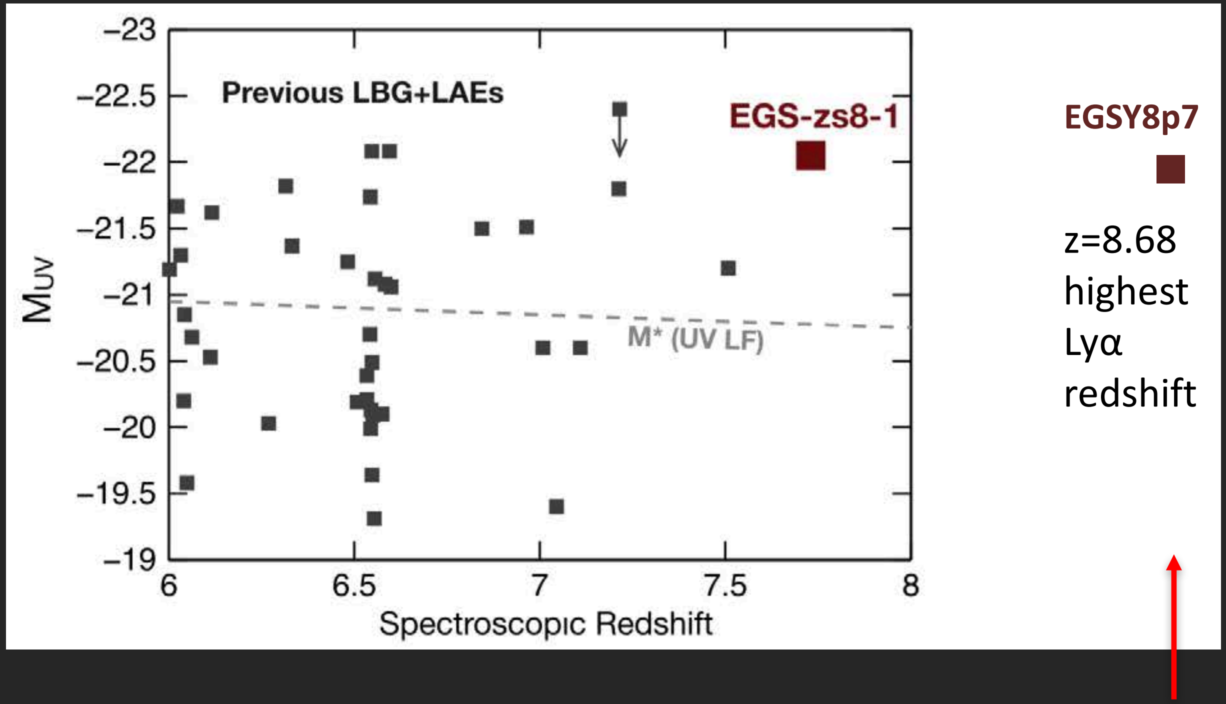
Lyα detections at z=7-8

surprisingly bright galaxies!



three of these four bright z~7-8 galaxies are located in CANDELS EGS – cosmic variance strikes again!

Roberts-Borsani+2016



still just a small number of spectroscopic redshifts at z>7.0

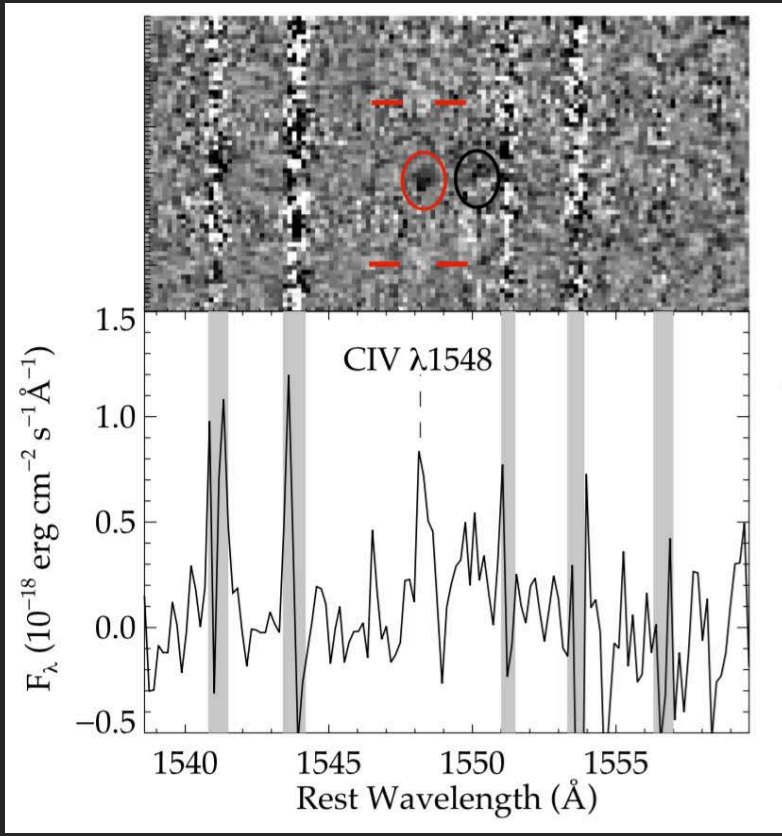
well over 1000 photometric redshifts from z~6.5-10

Oesch+2015

[CIII] & CIV detections at z=7-8

spectra from Keck MOSFIRE

extreme radiation fields in galaxies at z~7+

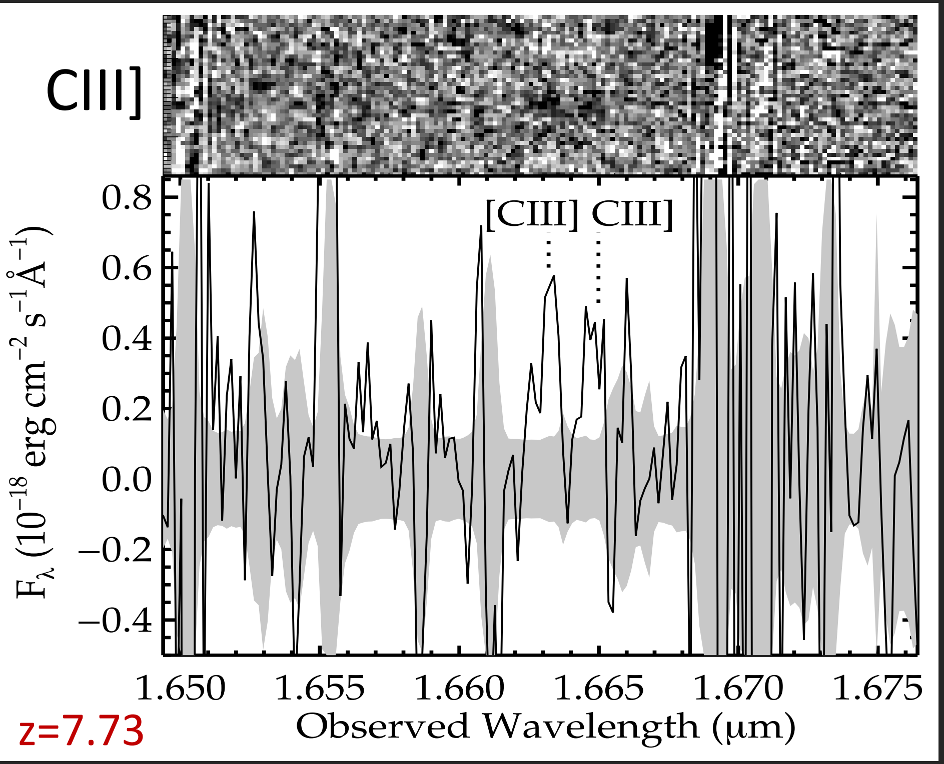


CIV from lensed galaxy A1703_zD6

high EW [CIII] emission (W_0=22+-2 Å)

☞ strong radiation field and low metallicity

CIV ☞ AGN? or hot metal-poor young population?



[CIII] at z=7.73 in EGS-zs8-1 from Keck MOSFIRE

Stark+2015

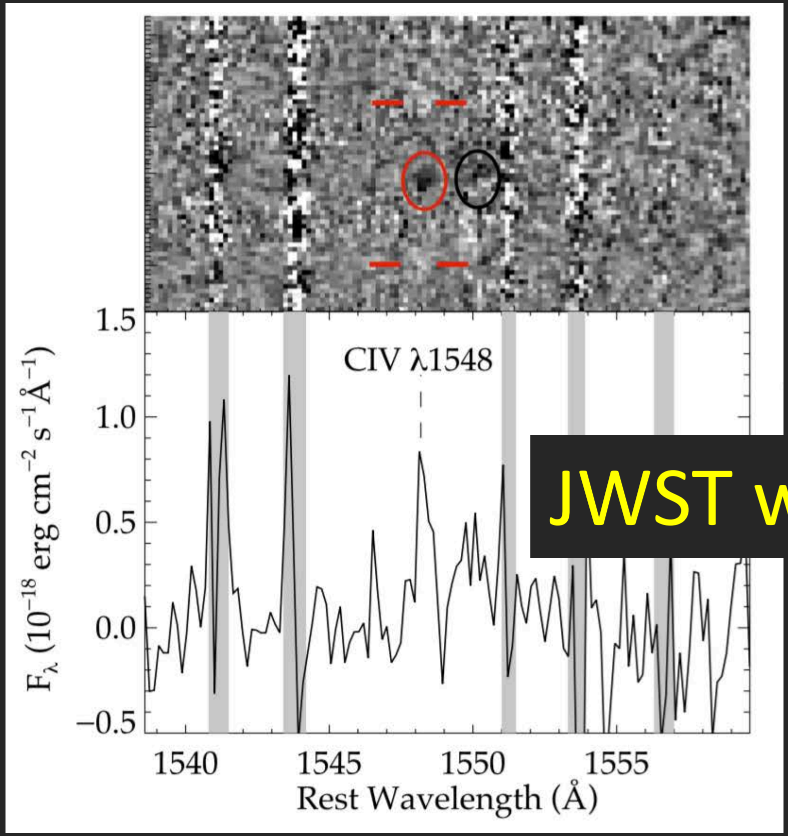
redshift same as Lyα for EGS-zs8-1 by Oesch+2015

Stark+2017

[CIII] & CIV detections at z=7-8

spectra from Keck MOSFIRE

extreme radiation fields in galaxies at z~7+



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JWST will do these really easily!

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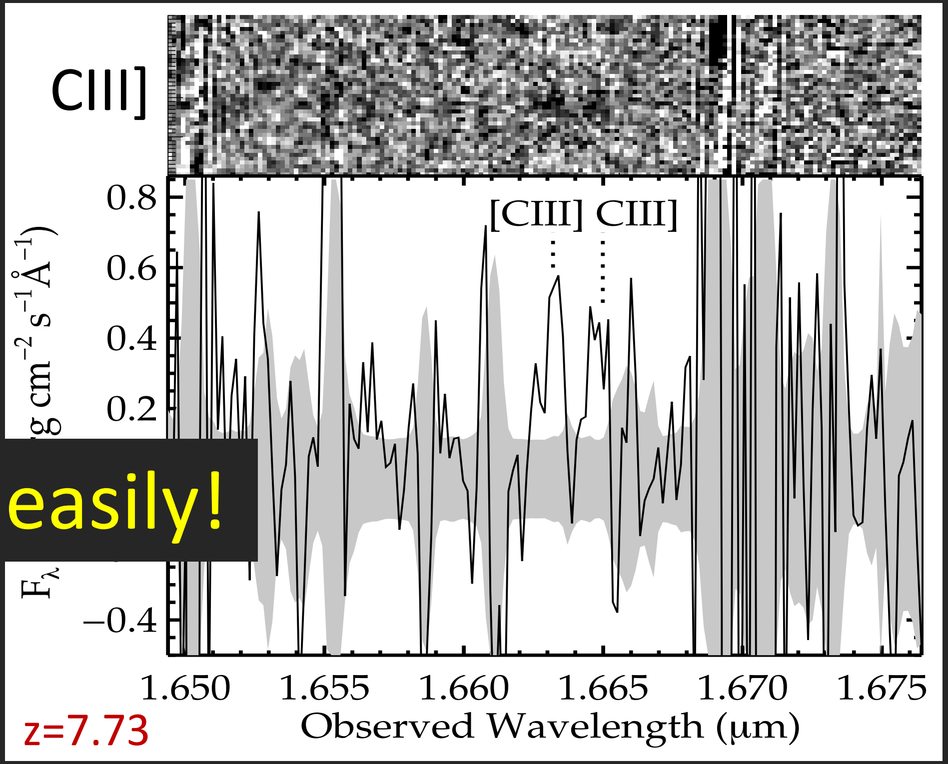


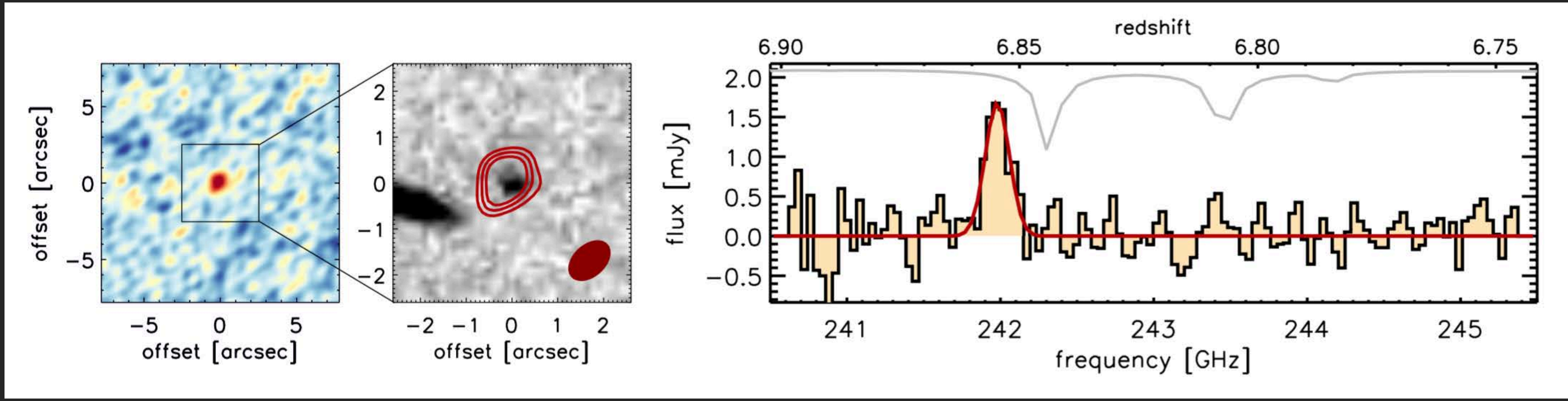
[CIII] at z=7.73 in EGS-zs8-1 from Keck MOSFIRE

Stark+2015

redshift same as Lyα for EGS-zs8-1 by Oesch+2015

Stark+2017

ALMA [C II] 157.74μm redshifts and velocity structure in two z~6.8 galaxies



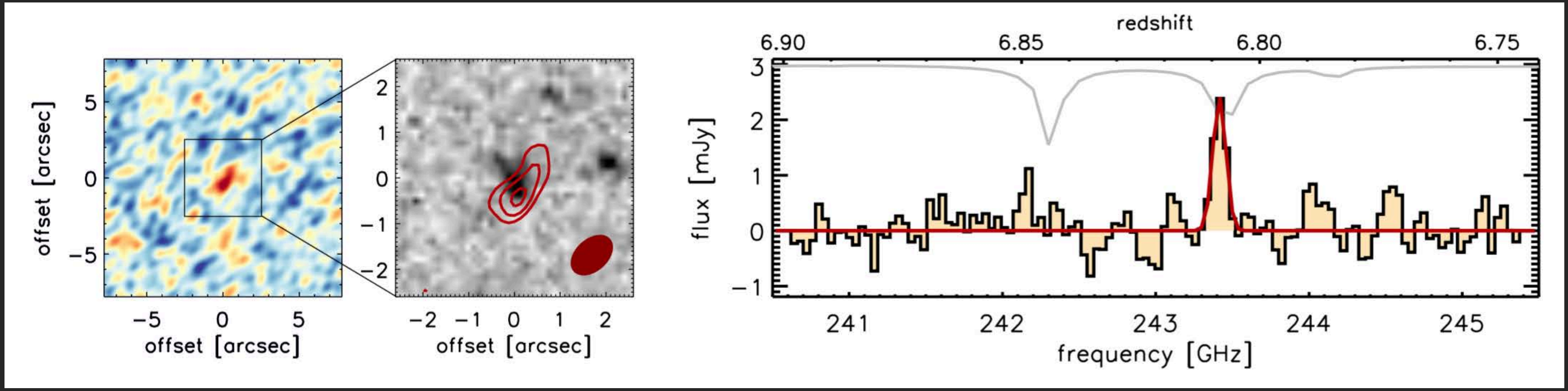
COS-3018555981

ALMA narrowband

HST image + ALMA (+ ALMA beam)

$z_{[CII]}$ = 6.8540±0.0003

$z_{[CII]}$ = 6.8076±0.0002

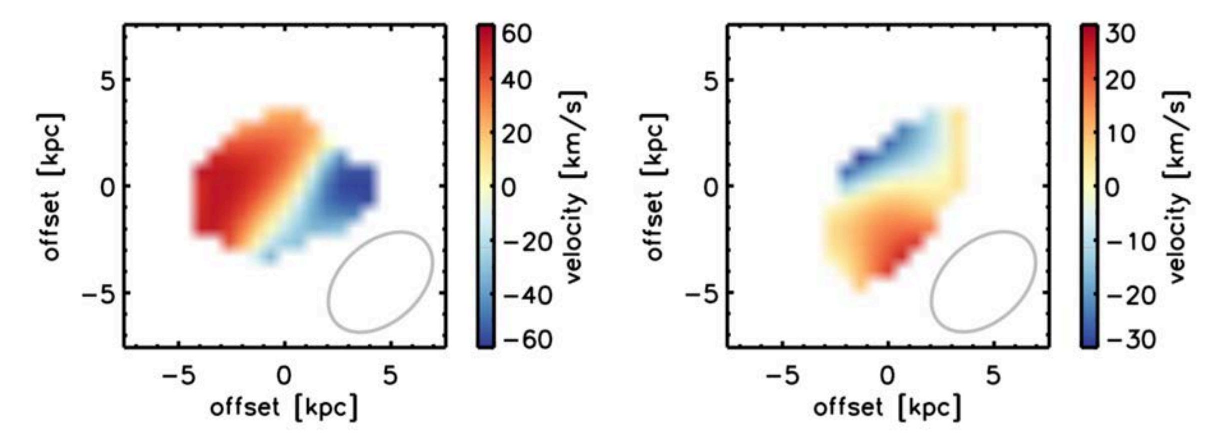


COS-2987030247

Smit + 2017

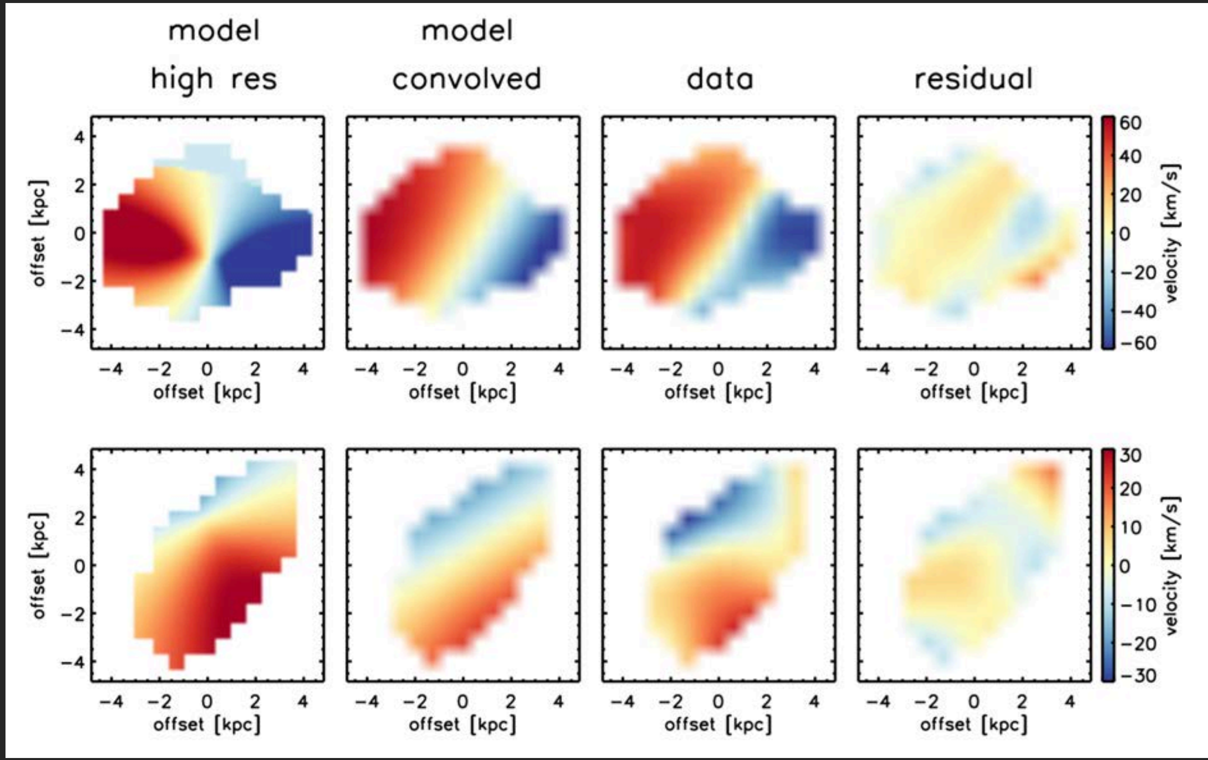
ALMA [C II] 157.74μm redshifts and velocity structure in two z~6.8 galaxies

consistent with rotation but could be more complex (merging?; gas flows?)



velocity structure in the two galaxies

models compared to data



Smit + 2017

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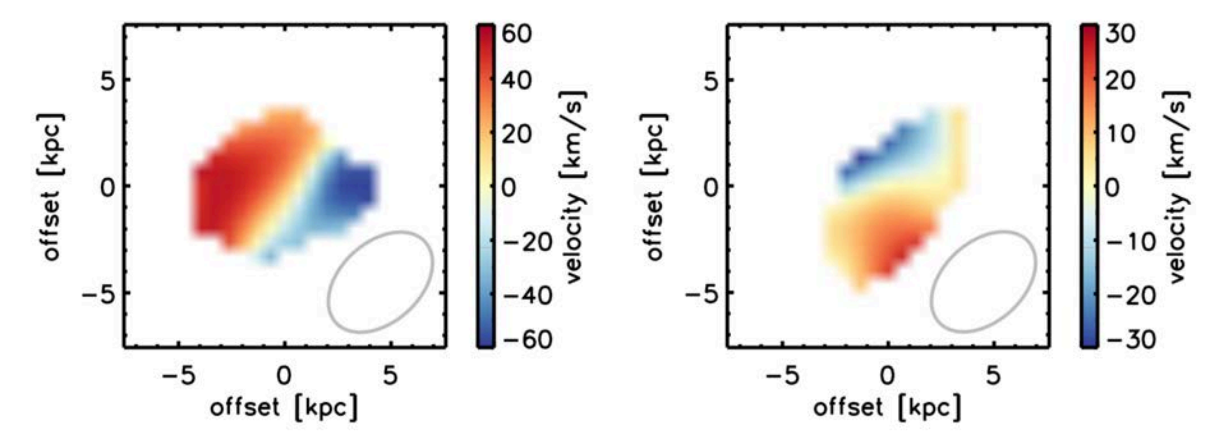
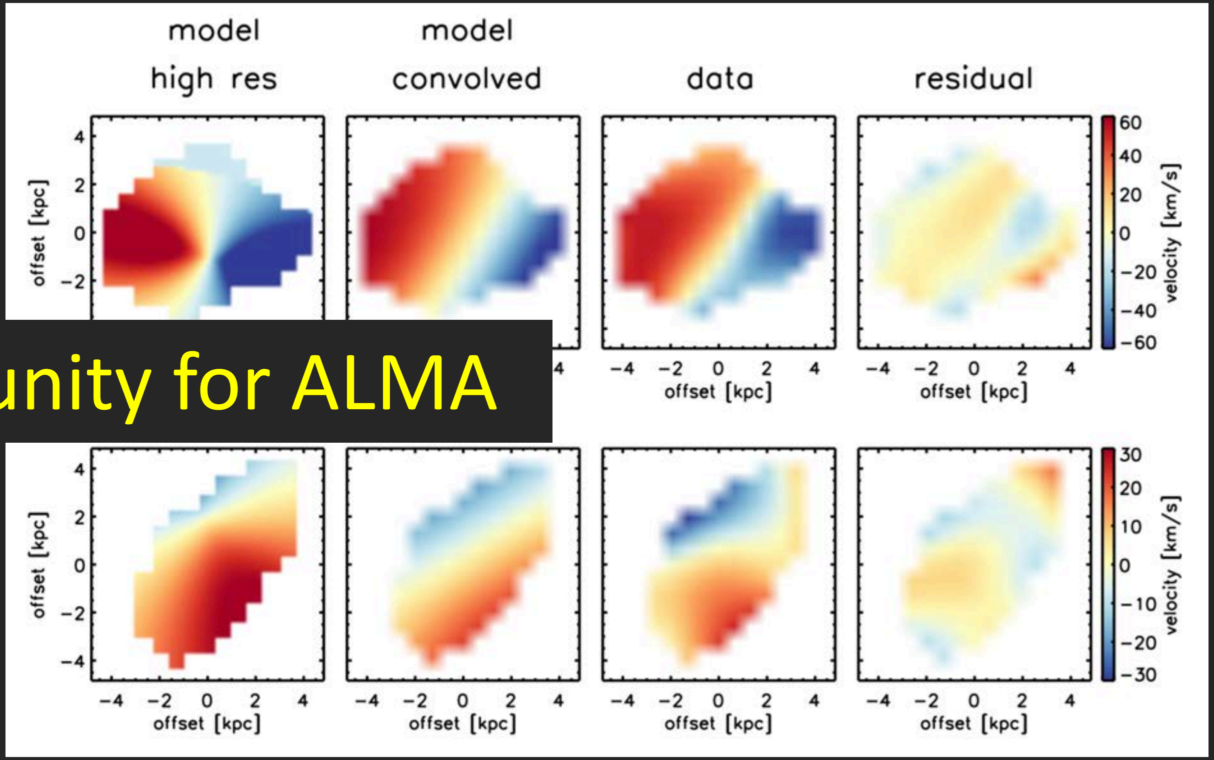


velocity structure in the two galaxies

models compared to data

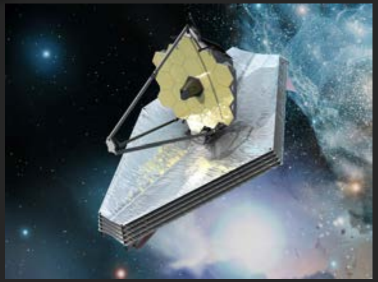


this suggests a major opportunity for ALMA

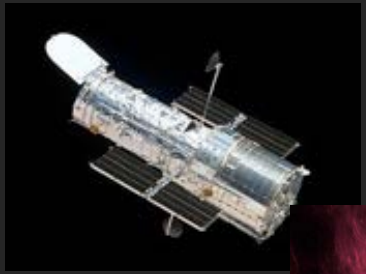
Smit + 2017

measuring the highest redshifts:

GN-z11

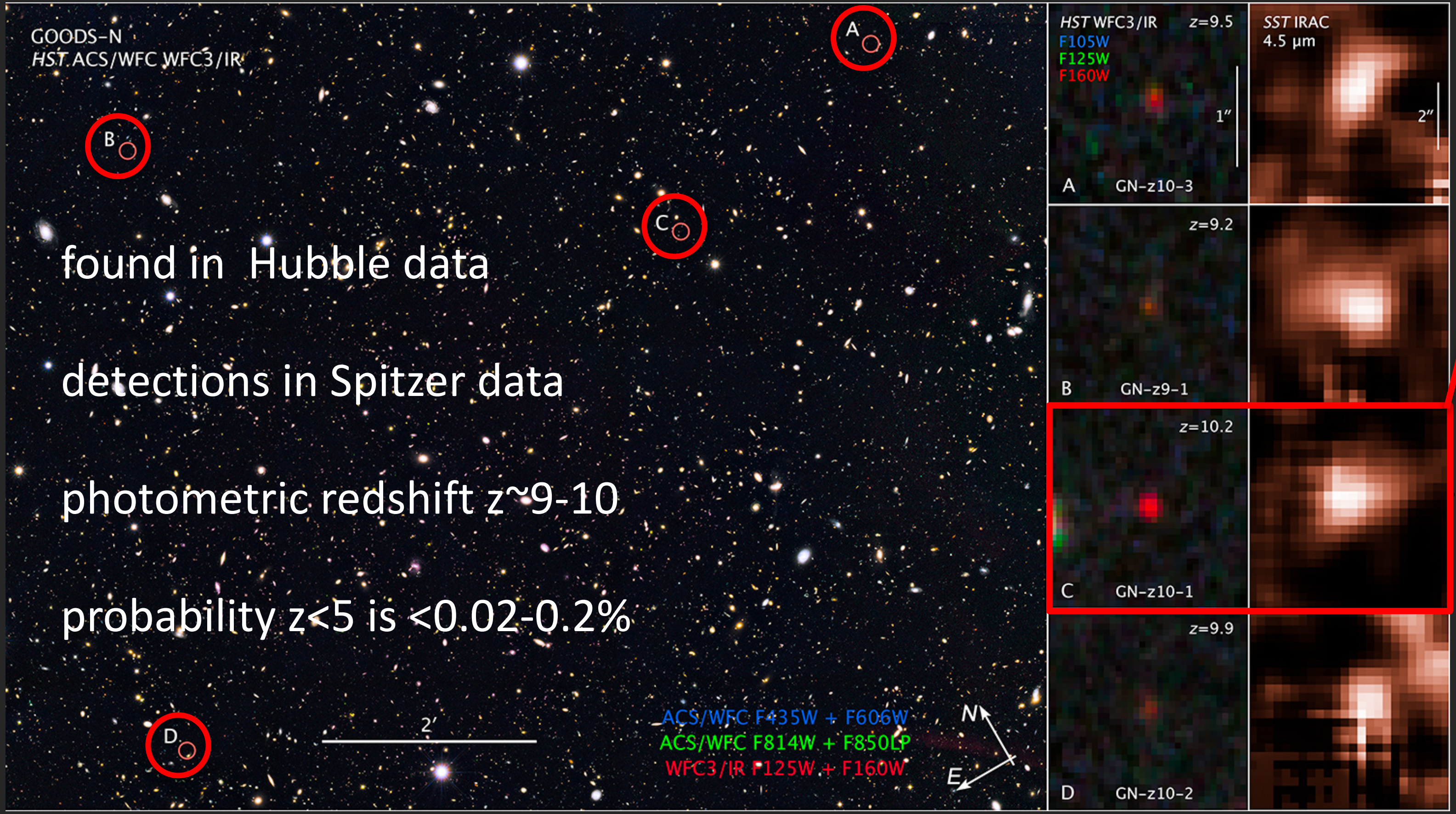


Hubble and Spitzer reach out into JWST territory with the determination of the z~ 11.1 redshift of GN-z11



very luminous galaxy candidates at redshift z~9-10

10-20X more luminous than previous galaxies found at 500 Myr



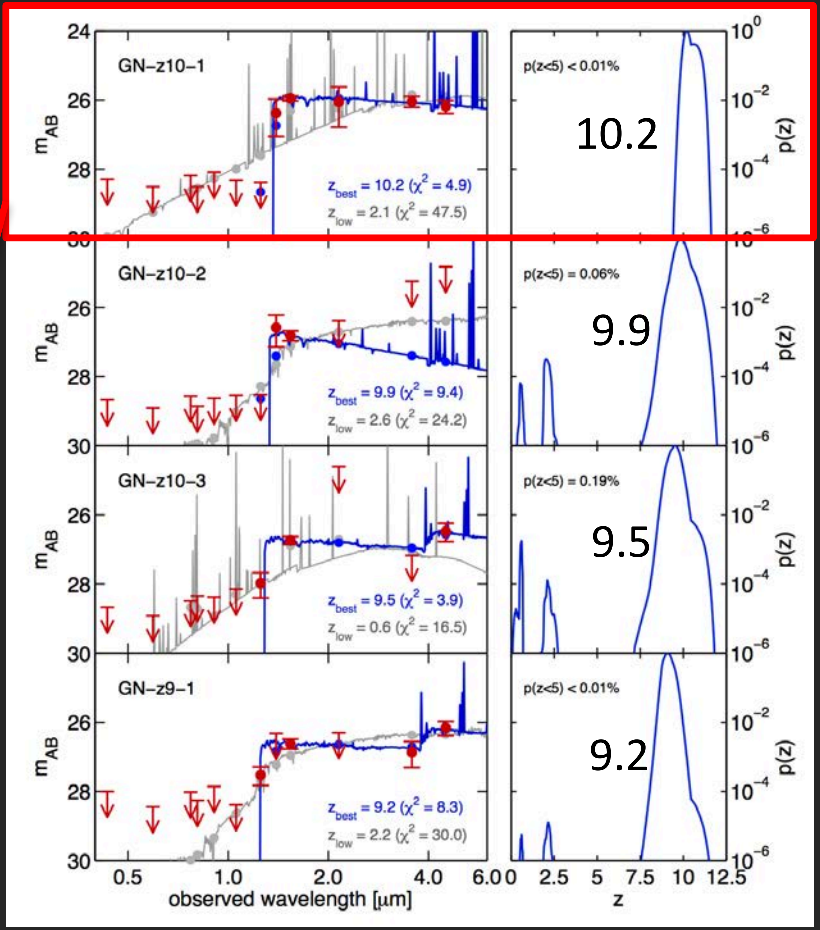
found in Hubble data

detections in Spitzer data

photometric redshift z~9-10

probability z<5 is <0.02-0.2%

Hubble Spitzer

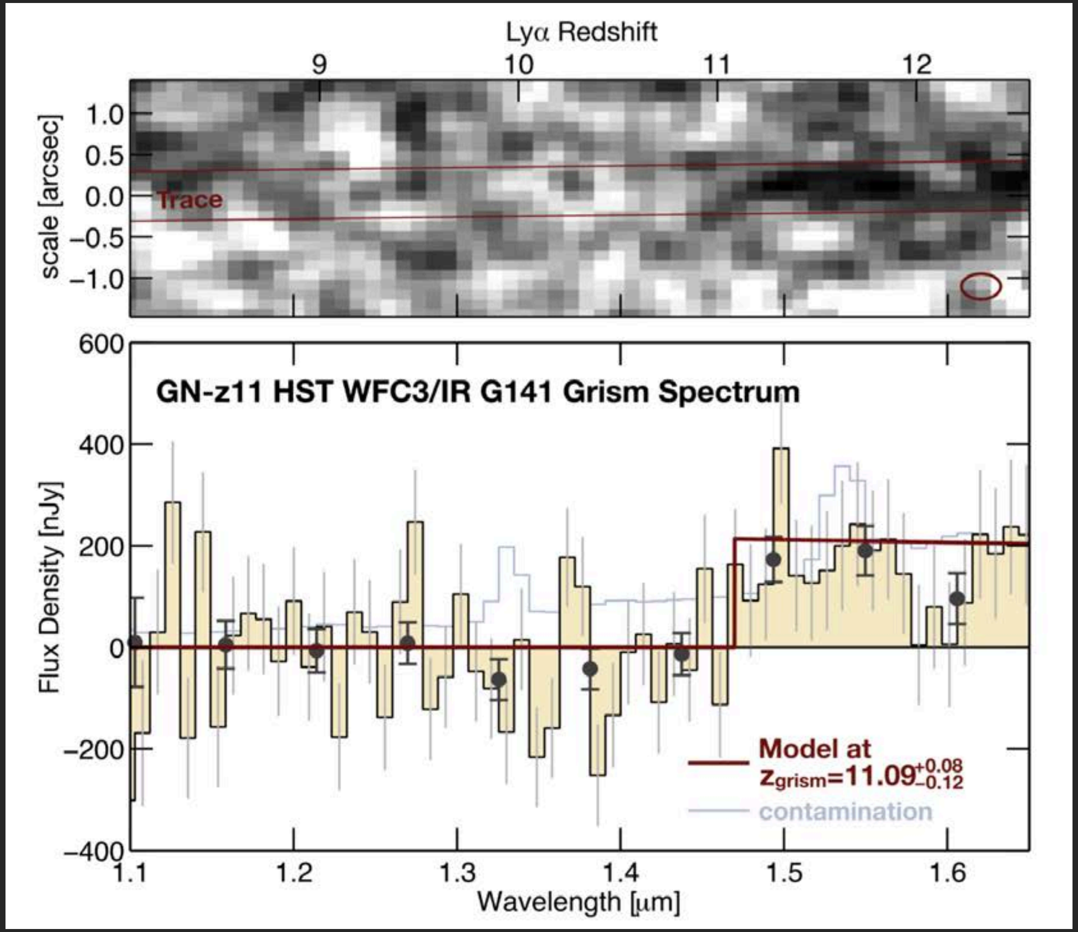


constraints on masses and ages:
~10^9 $M_\odot$ and 100-300 Myr

Oesch Bouwens GDI+2014

GN-z10-1 will be discussed below

GN-z11

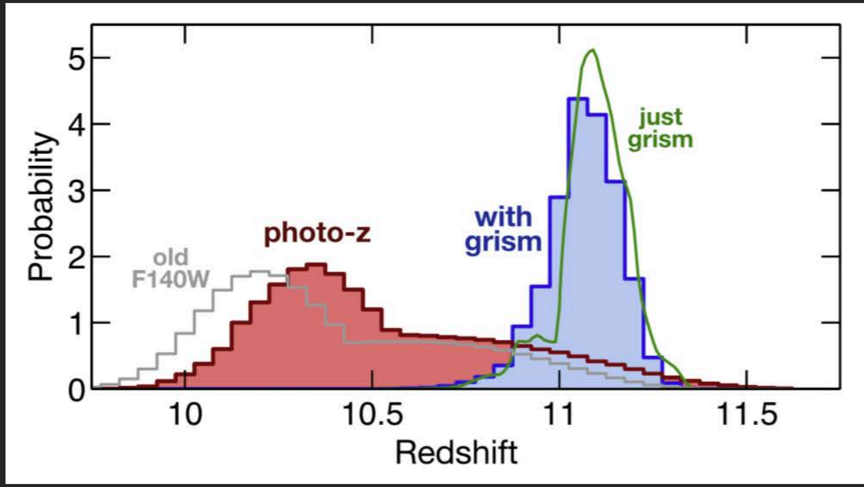


first detected as a very luminous z~10 galaxy in GOODS-N as GN-z10-1

GN-z10-1 => GN-z11

WFC3/IR grism detected break & confirmed redshift to be $11.09^{+0.08}_{-0.12}$

age of universe is 400 Myr at z~11

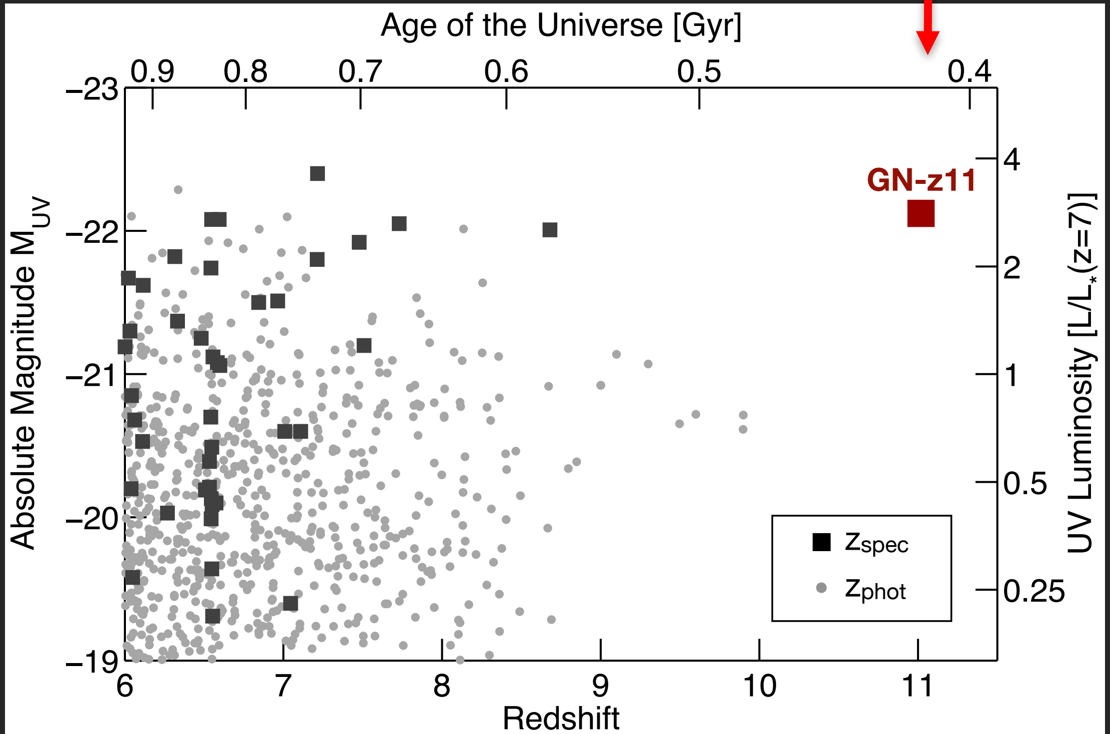


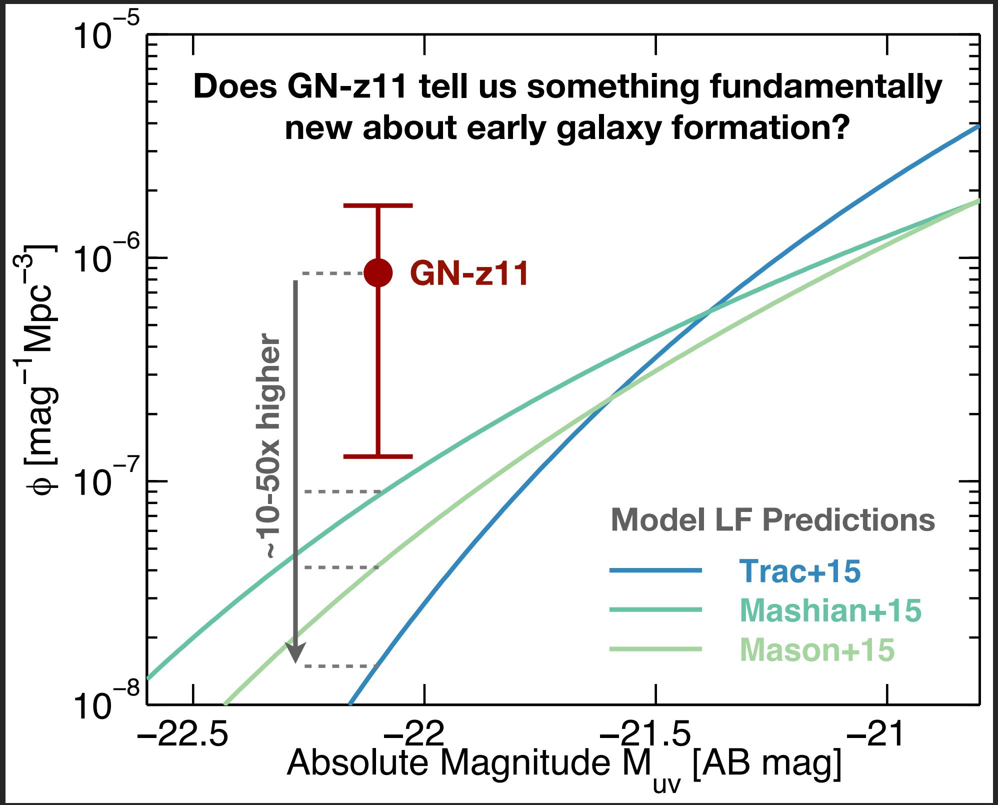
combination of HST grism + WFC3/IR + Spitzer IRAC gives high degree of confidence to redshift determination

Oesch+2014, 2016

GN-z11 – the most distant galaxy found to date

surprising discovery of GN-z11:
HST+Spitzer are reaching into JWST territory

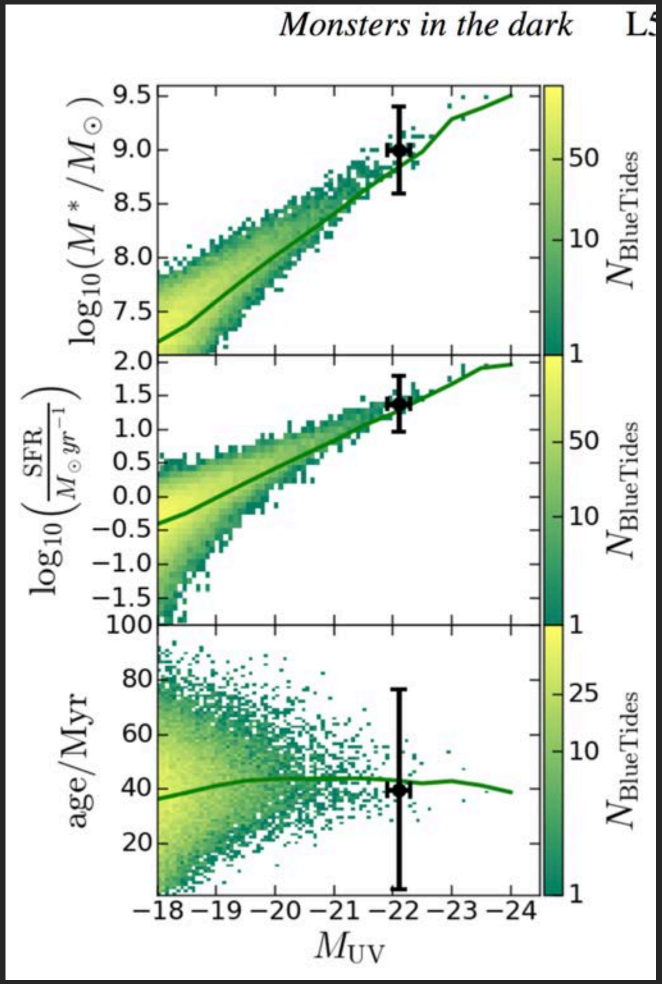




- Detection of GN-z11 in *existing data* is unexpected, given current models
- Expected to require 10-100x larger areas to find one z~11 galaxy as bright as GN-z11
- Difficult though to draw conclusions based on one source

Oesch+2016

GN-z11



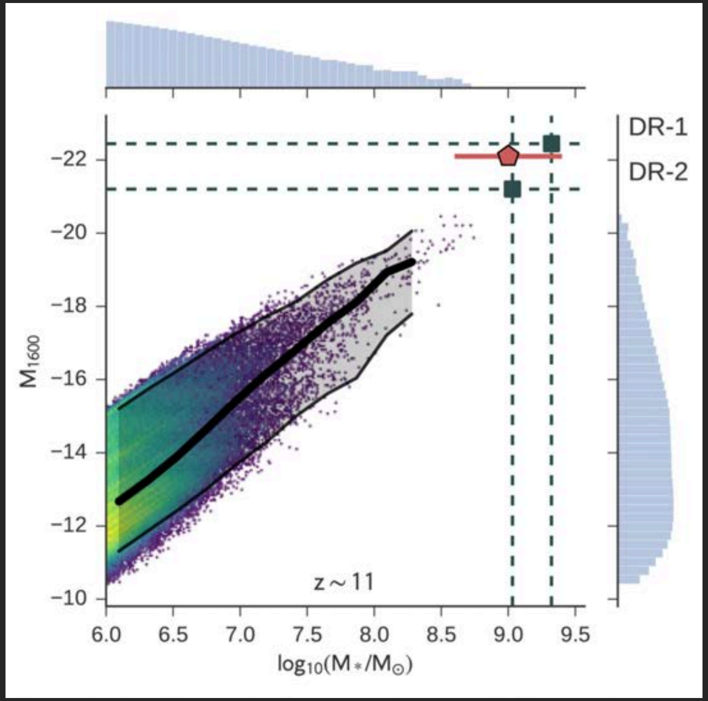
BlueTides Waters+2016

simulations show that galaxies as massive as GNz-11 at z~11 are rare but not unexpected per se

mass 10^9 $M_\odot$ SFR 24 $M_\odot$/yr
A_{UV} <0.2 mag β -2.5 age 40 Myr

physical properties of GN-z11 are consistent with large-volume simulations

unexpected to find GN-z11 in such small search volumes/areas (by factor 10-100)?



Mutch+2016 DRAGONS

What does GN-z11 really look like?

GN-z11 will be blue from its numerous hot young stars, and very irregular in shape – with compact regions bursting with forming stars

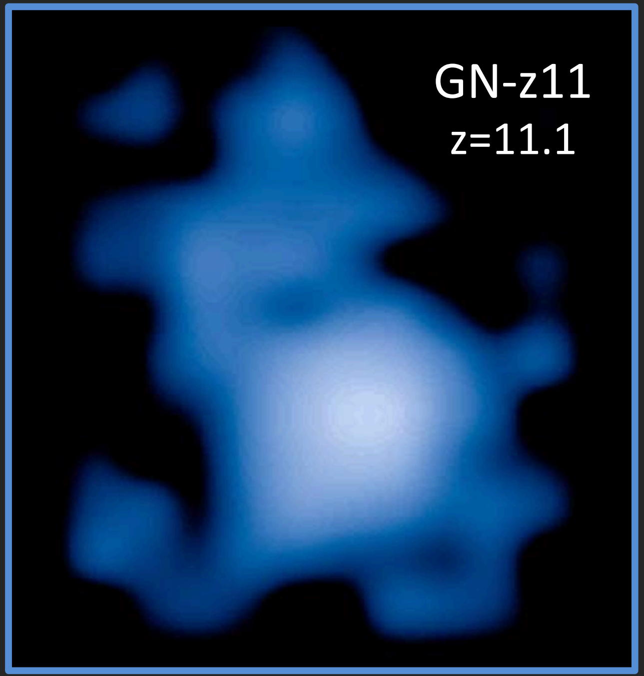


Image Credit:
NASA, ESA, P. Oesch, G. Brammer, P. van Dokkum, G. Illingworth

this is about the best we can do on GN-z11

but is GN-z11 actually like this?

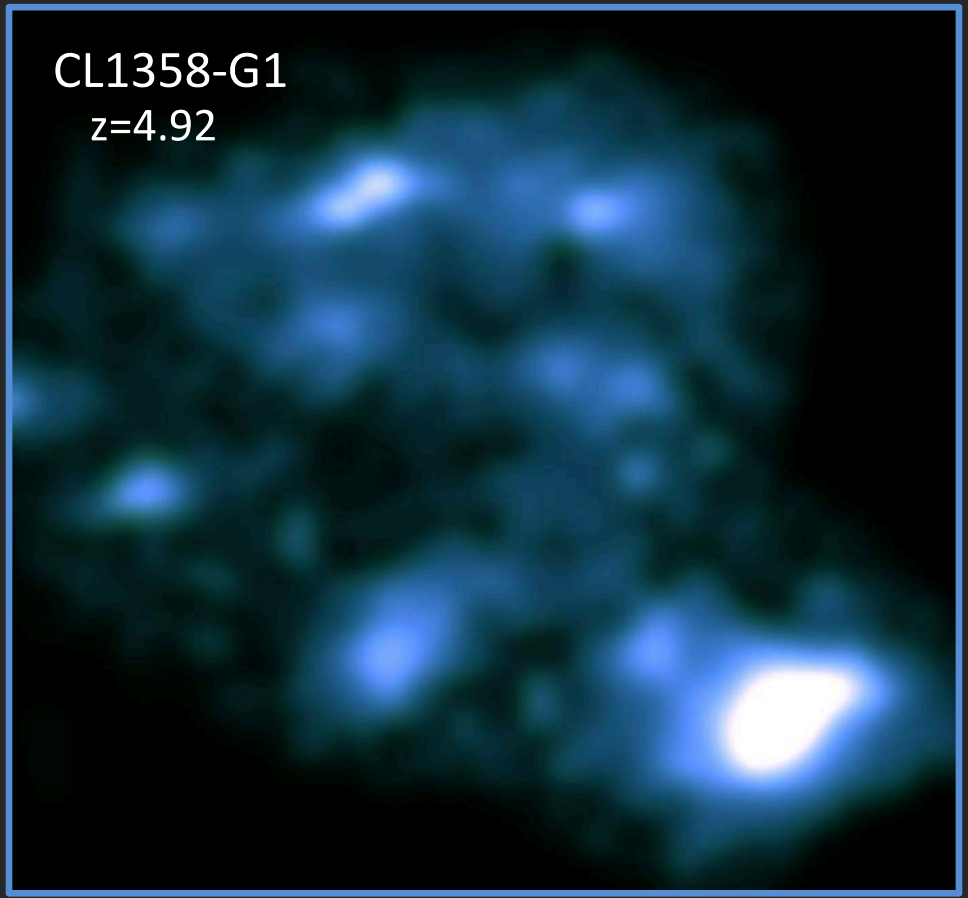
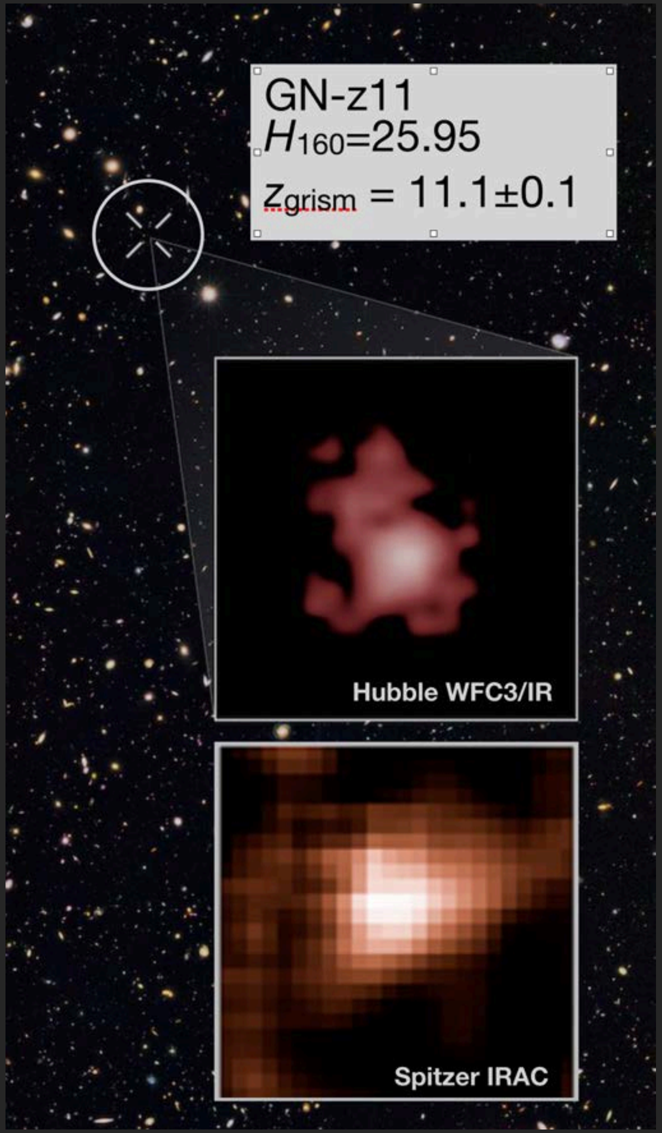


Image Credit: D. Magee, G. Illingworth, A. Zitrin, M. Franx

CL1358-G1 is very rare high-redshift galaxy that has been magnified over 25X by a galaxy cluster gravitational lens

GN-z11 – the most distant galaxy found to date



Oesch+2016

just 400 million years after the Big Bang
– looking back through 97% of all time

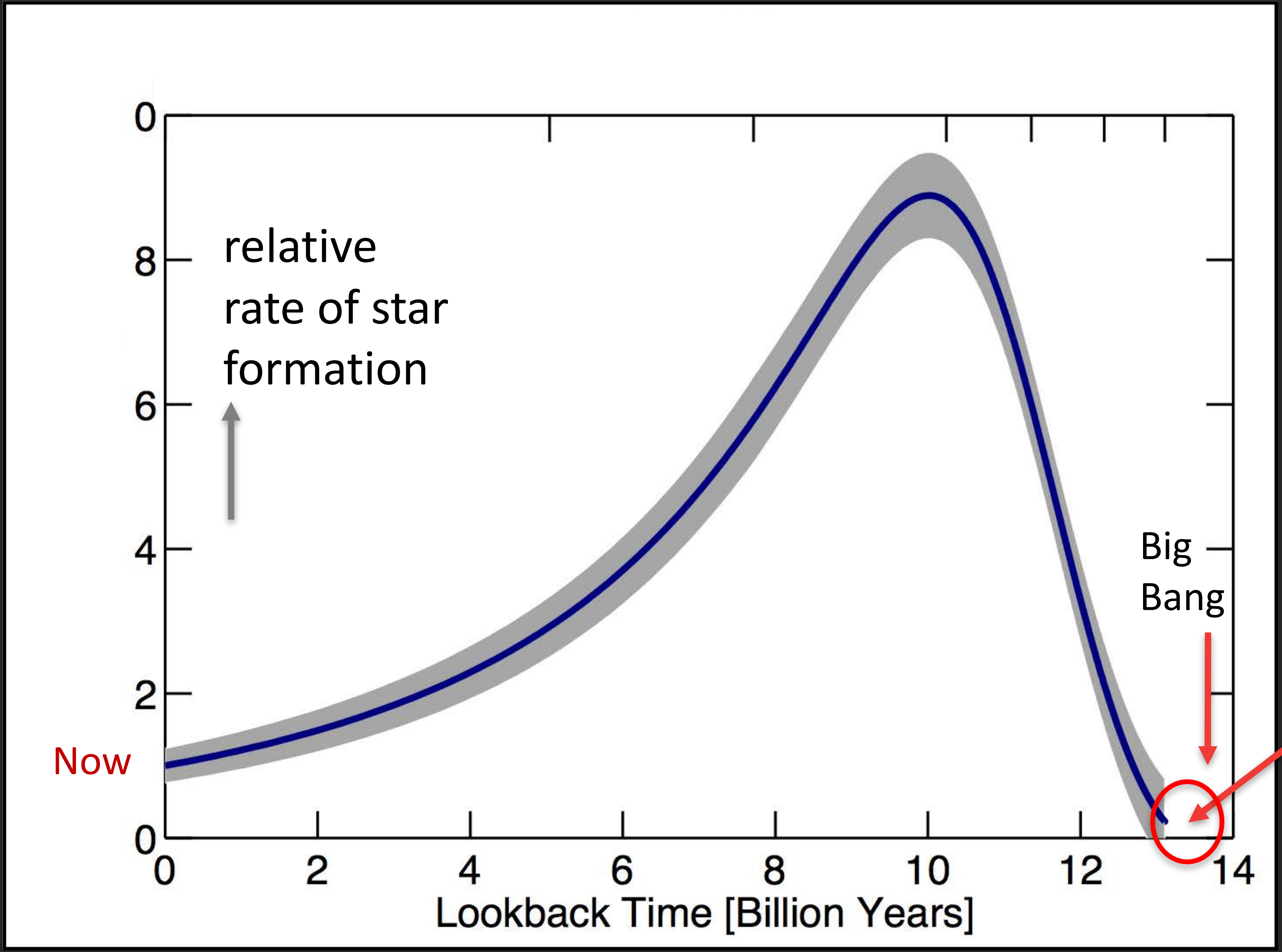
this shatters all other records for “most distant”
– previous record holder from Keck is at z~8.68

probably the most distant confirmed galaxy until JWST flies

measuring the highest redshifts
galaxies at z~10
implications for the cosmic star formation rate density

z~10-11 is the current frontier in the Cosmic Dawn

cosmic star formation rate density over all time



the star formation rate density over 96% of time

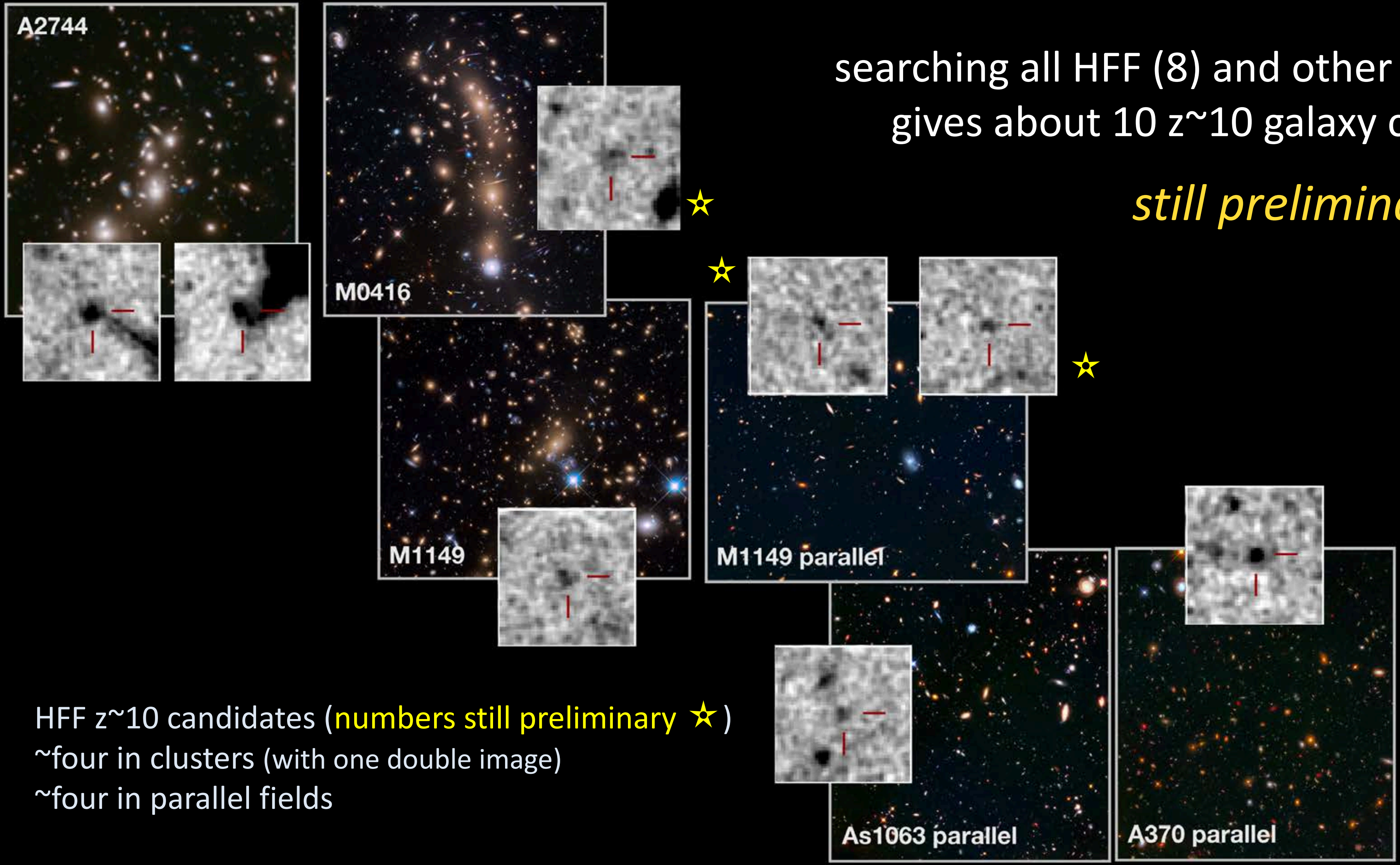
"terra incognita" – where the first galaxies form

figure credit Pascal Oesch

galaxies at z~10 in HFF and field

searching all HFF (8) and other HST fields (5)
gives about 10 z~10 galaxy candidates

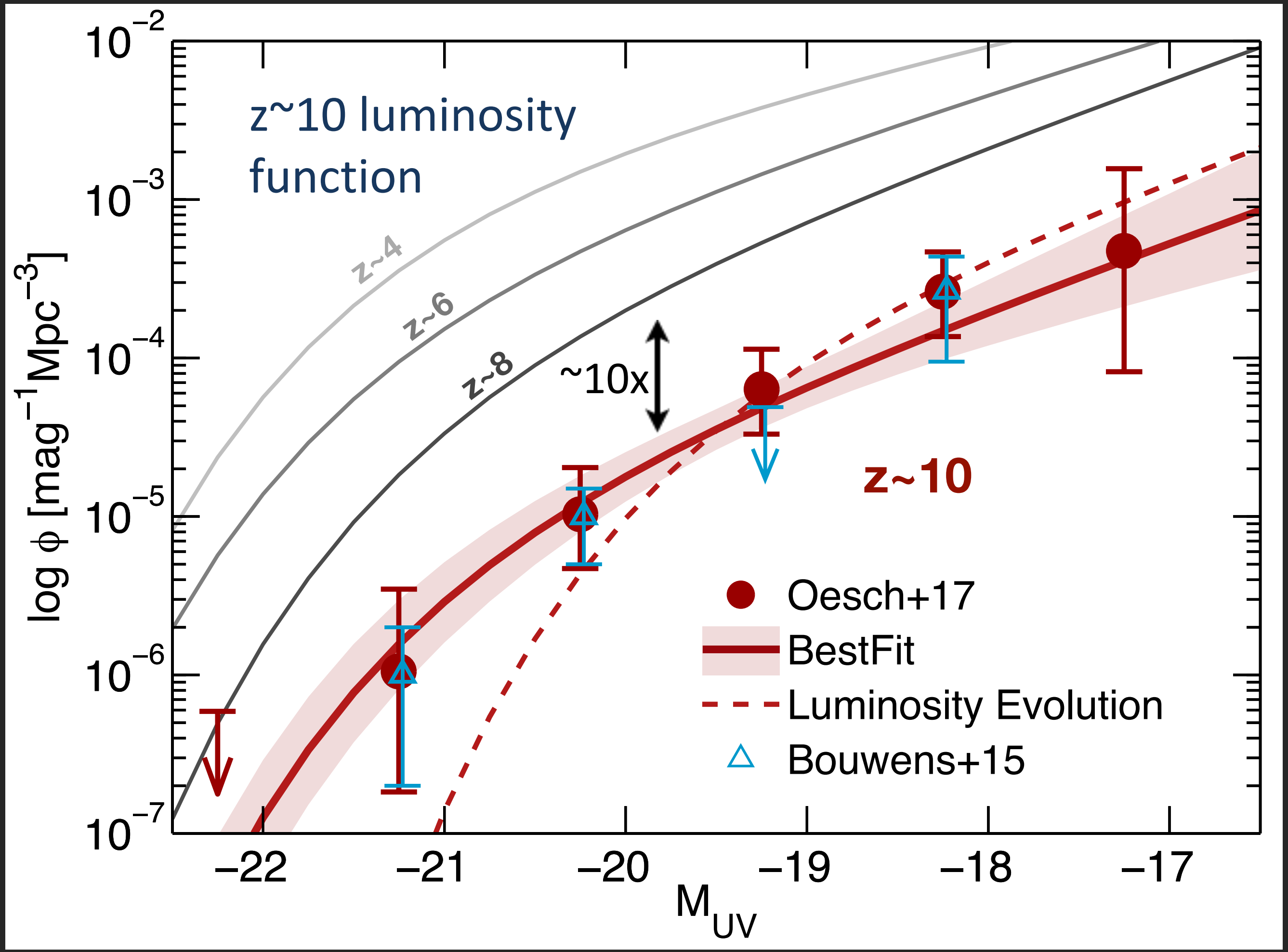
still preliminary search



HFF z~10 candidates (numbers still preliminary ☆)
~four in clusters (with one double image)
~four in parallel fields

Oesch+2017
in prep

the luminosity function at z~10 galaxies



best fit LF: density evolution from z~8 LF by 10x

the age of the universe at z~10 is ~500 Myr

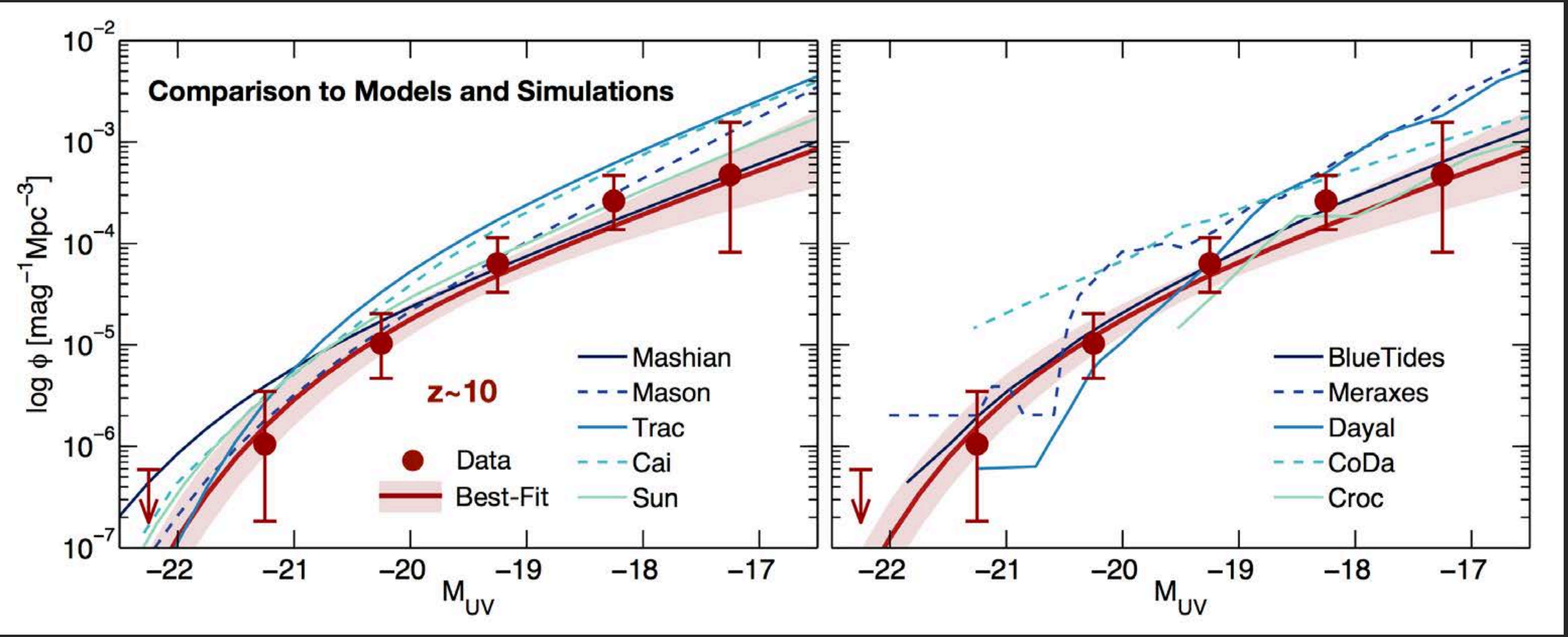
the fields searched include all with WFC3/IR data (e.g., HUDF/XDF, CANDELS, ERS, HUDF-Parallels, 6 HFFs + 6 HFF-Parallels)

z~10 galaxies are hard to find! – seven years of WFC3/IR have only turned only ~10 after we have searched essentially every suitable Hubble field including all 6 Frontier Fields

details are preliminary

Oesch+2017 in prep

the luminosity function at z~10 galaxies

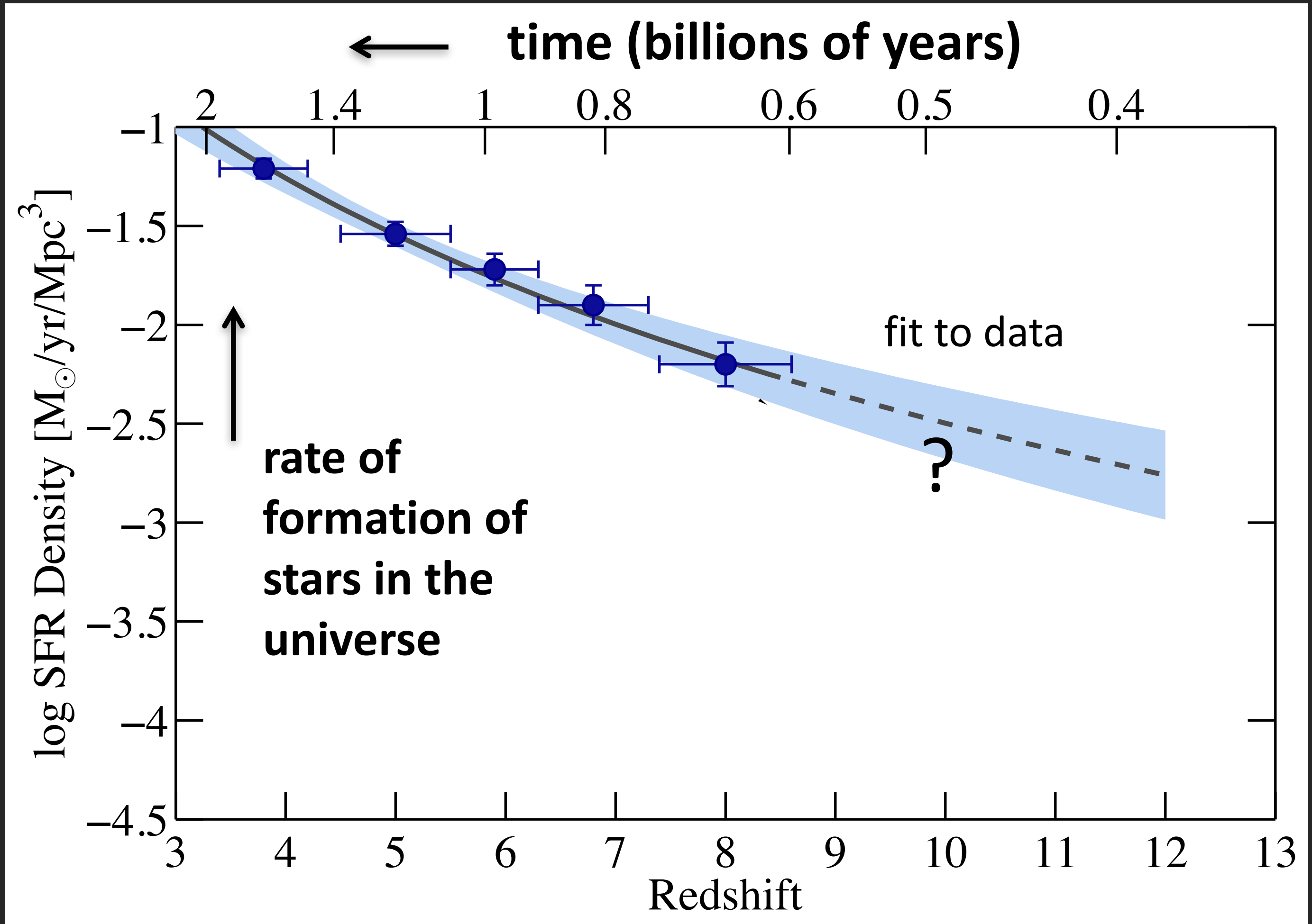


considerable spread but shape matches (broadly) – but models are consistently high

Oesch+2017 in prep

what is the star formation rate density at z~10

derive luminosity density and star formation rate density from luminosity functions



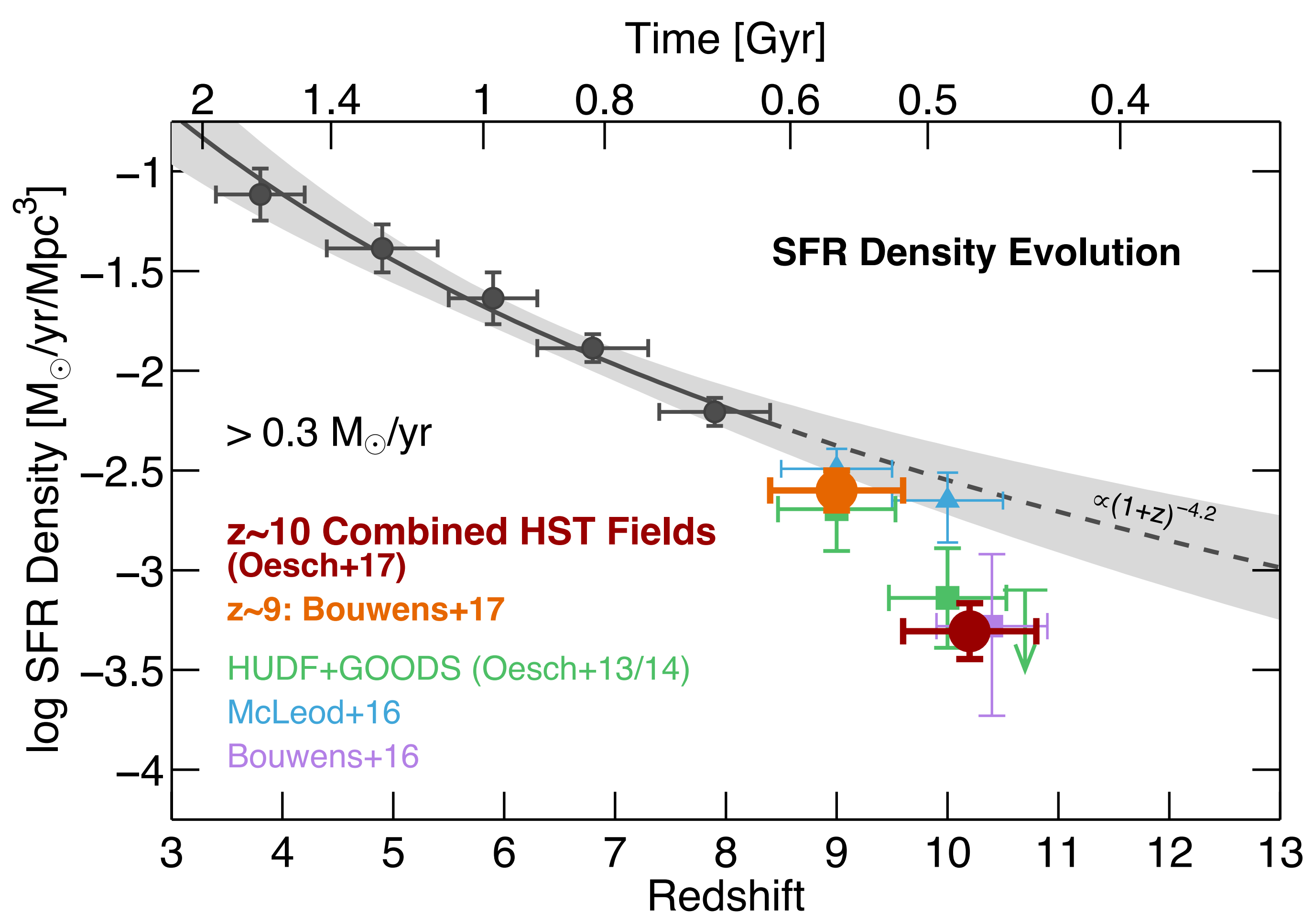
the star formation rate density at z~9-10

the latest results are fascinating!

they indicate clearly a trend to lower SFRD at z>8

"accelerated evolution"

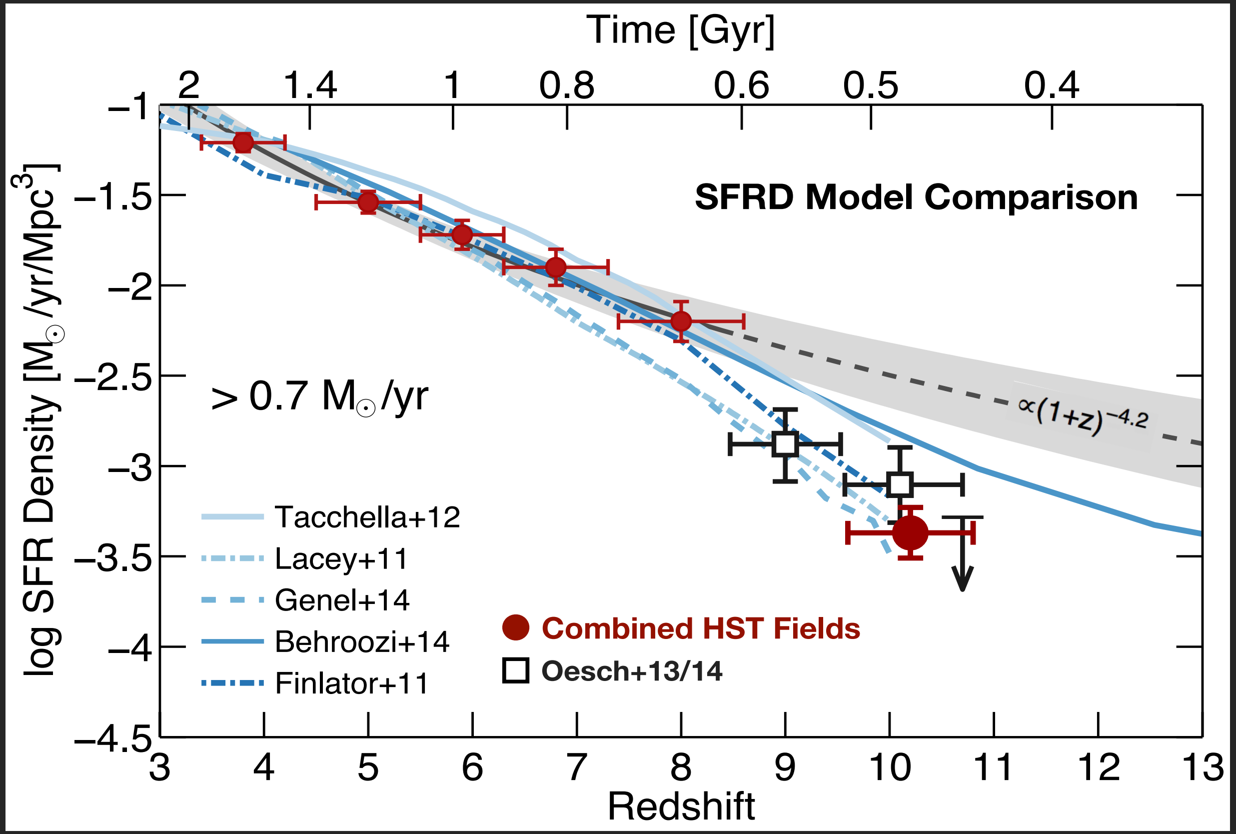
"Combined HST fields" is the SFRD value at z~10 from the latest z~10 luminosity function

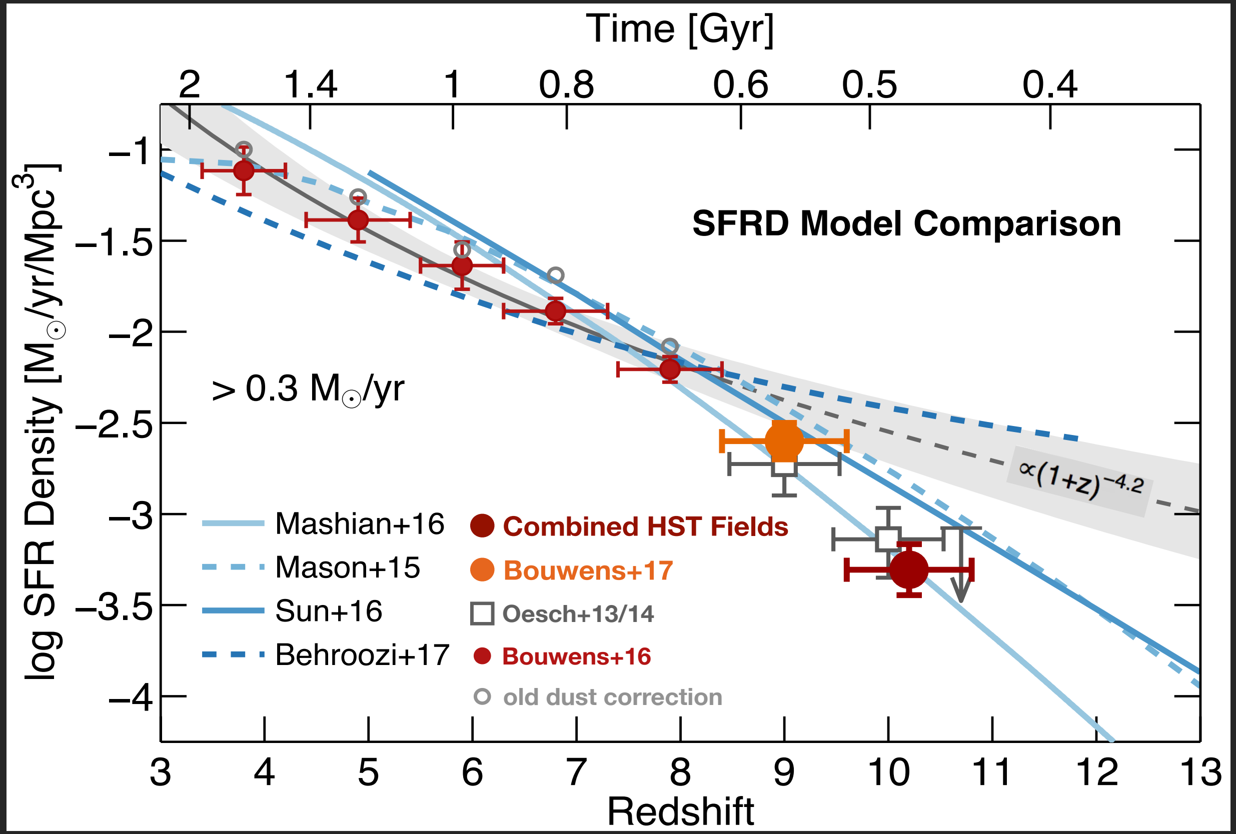


Oesch+2017 in prep

see also Bouwens+2017

the star formation rate density at z~9-10





note that "accelerated evolution" is seen in nearly all models,
but this topic has been the rather controversial in the field....

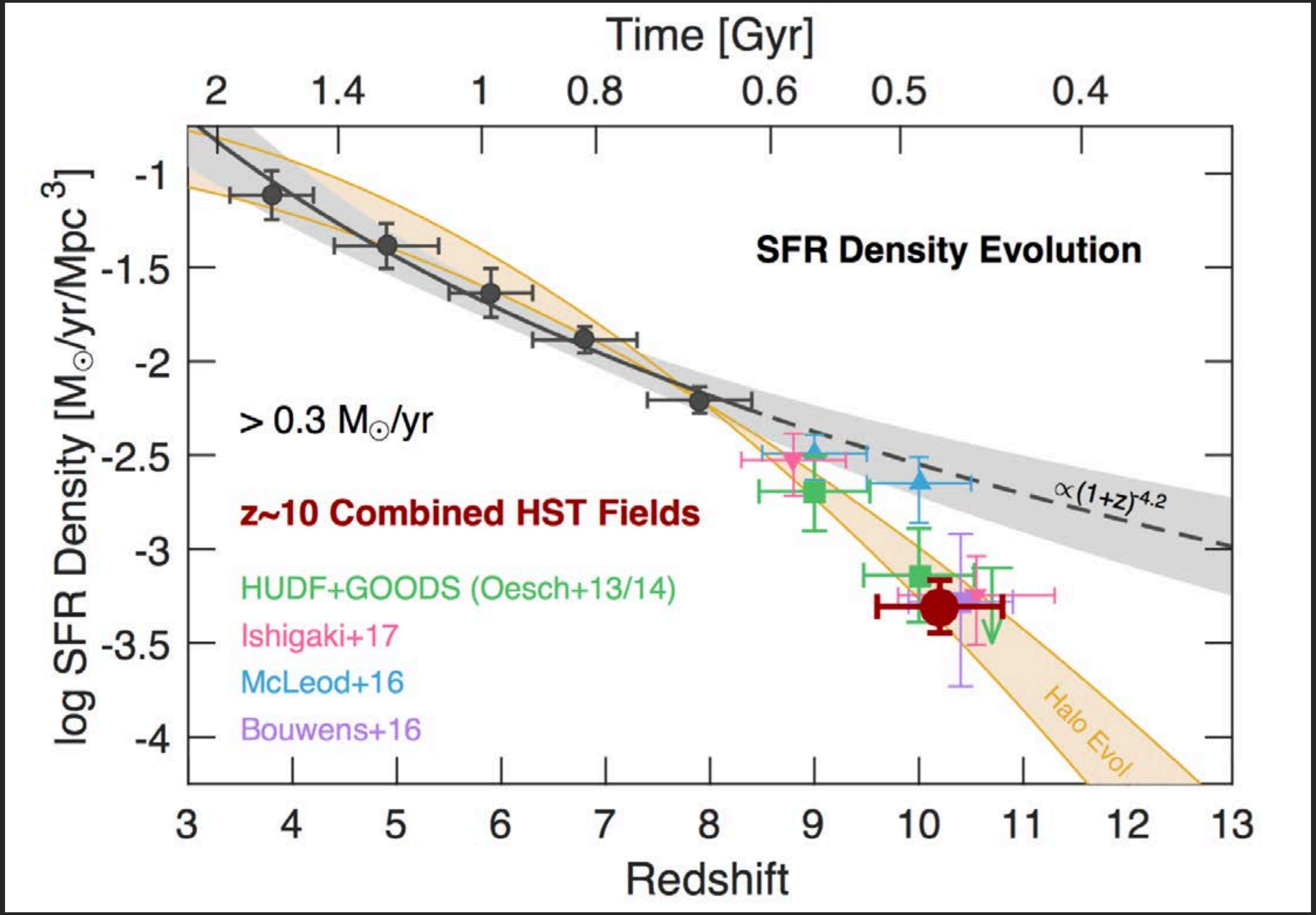
Oesch+2017 in prep

the star formation rate density at z~9-10

they indicate clearly a trend to lower SFRD at z>8

"accelerated evolution" is actually consistent with the expected buildup* of dark matter halos over that time

*dark matter halo cumulative growth to ~10^{10} $M_{\odot}$ from HMFcalc – Murray+2013

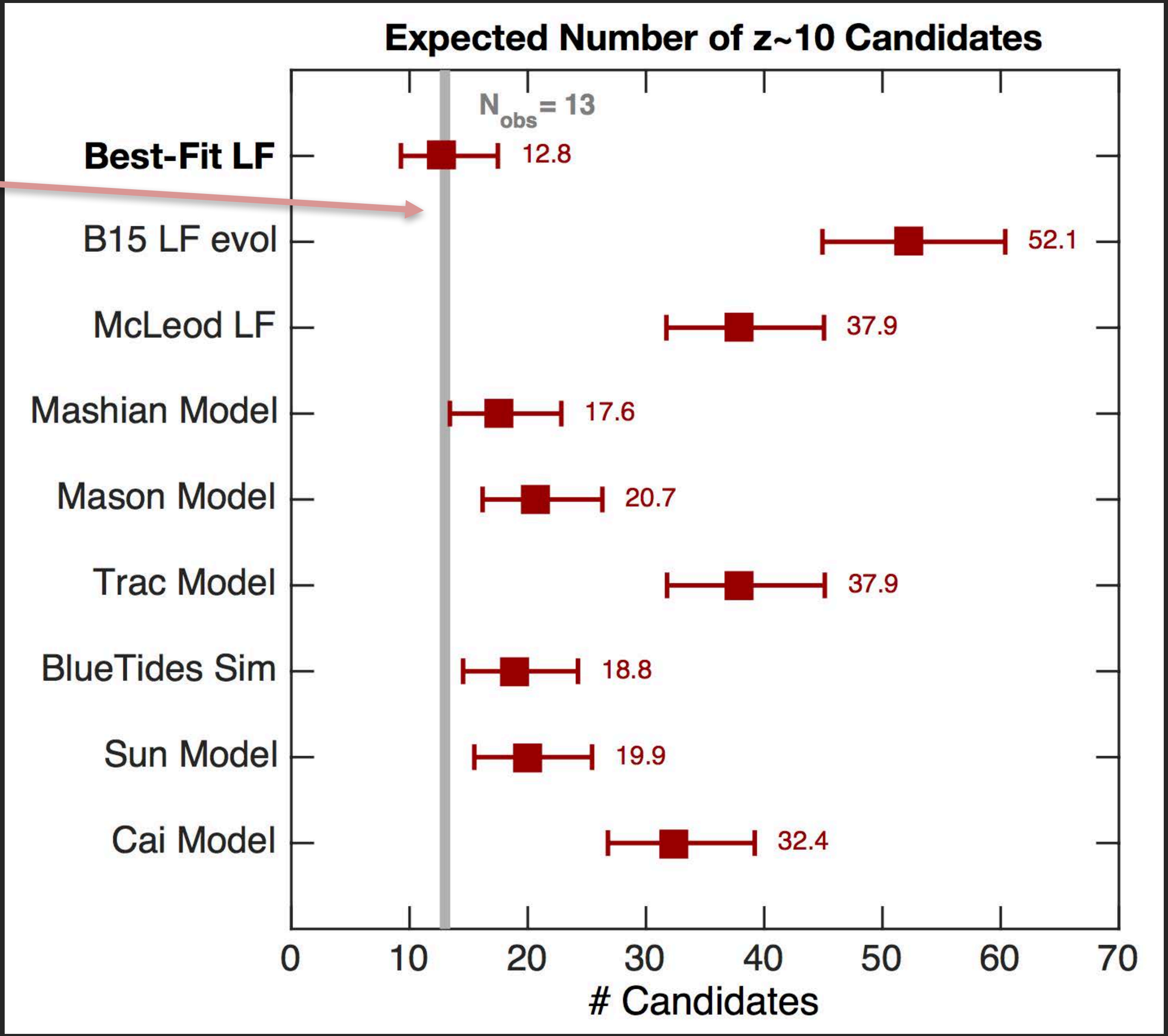


Oesch+2017 in prep

the case of the missing z~10 galaxies

numbers are preliminary

observed number
of z~10 galaxies

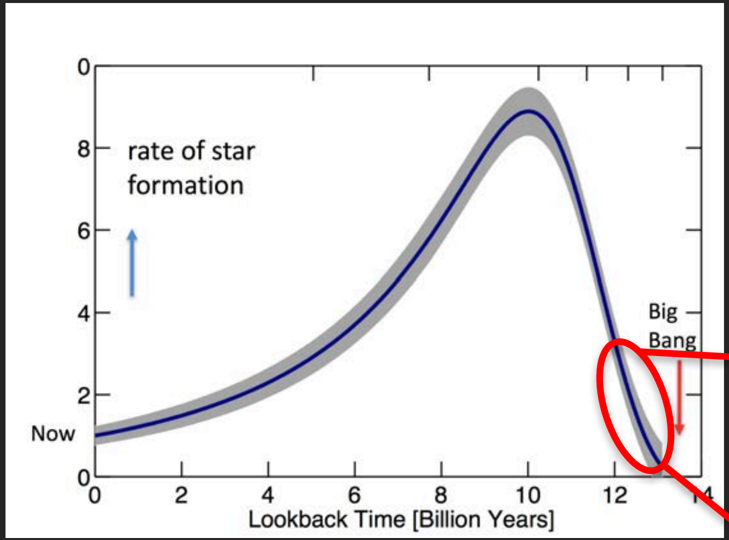


indication that the situation at z~10 is unusual

the numbers of objects that we have found is not consistent with the models

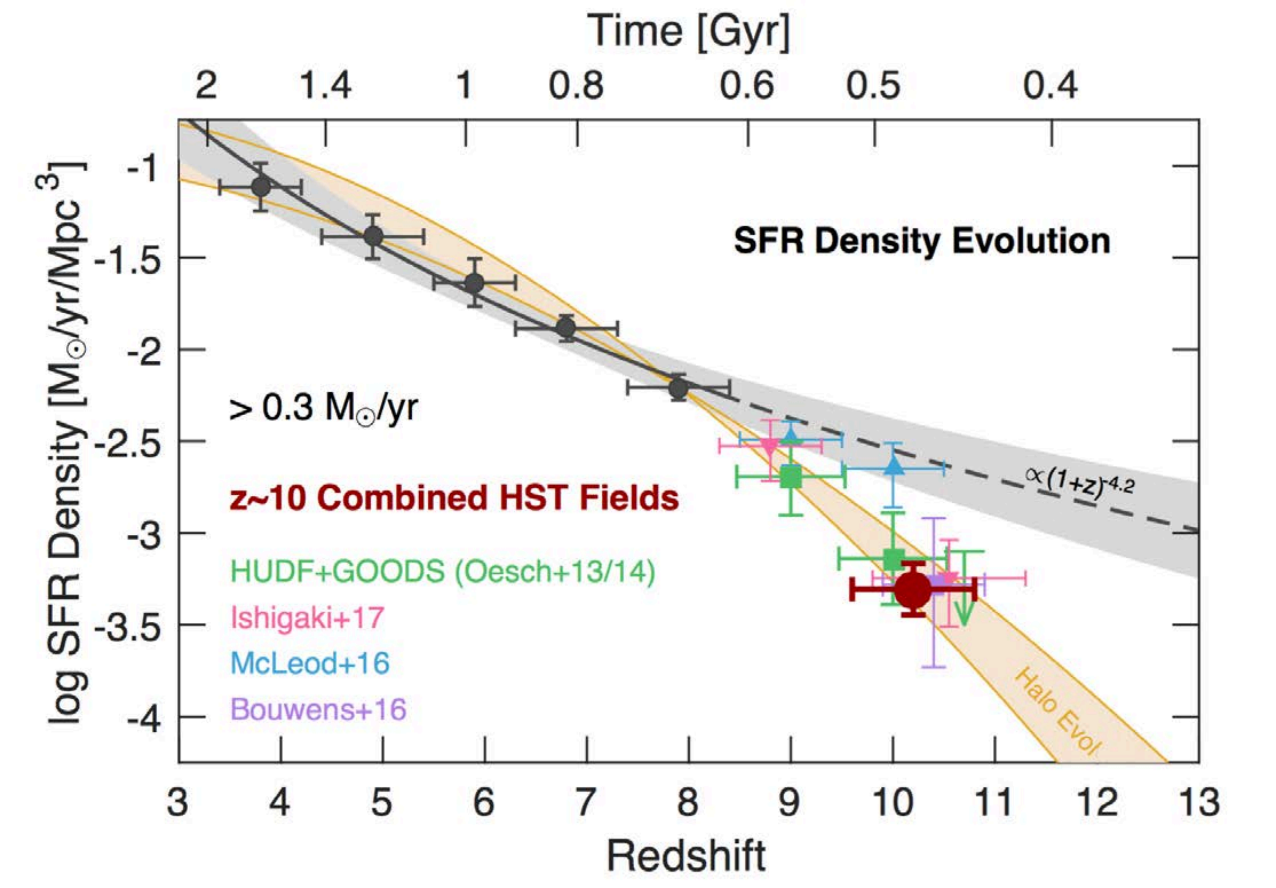
Oesch+2017 in prep

cosmic star formation in the first 1.5 billion years



there are far fewer galaxies than we (naively) expected at early times

this is an important result for JWST

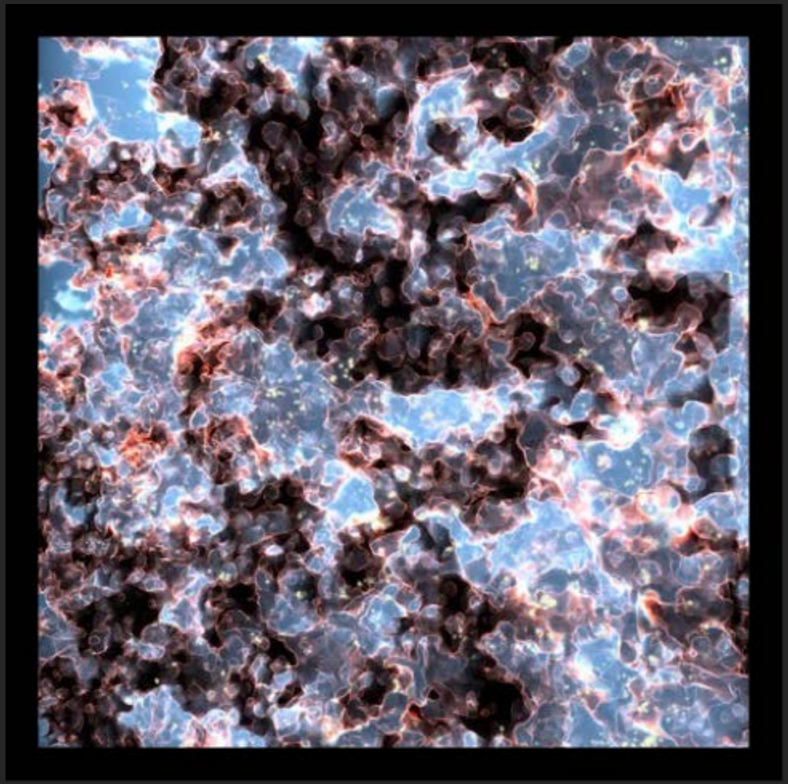


"accelerated evolution" is actually consistent with the expected buildup of dark matter halos over that time

galaxies are evolving rapidly in the first ~600 million years

Oesch Bouwens GDI+ 2017 in prep

reionization epoch – latest Planck 2016 results



simulation: Alvarez et al. 2009

striking concordance between latest Planck results and galaxy constraints

implications of onset of reionization at z~10

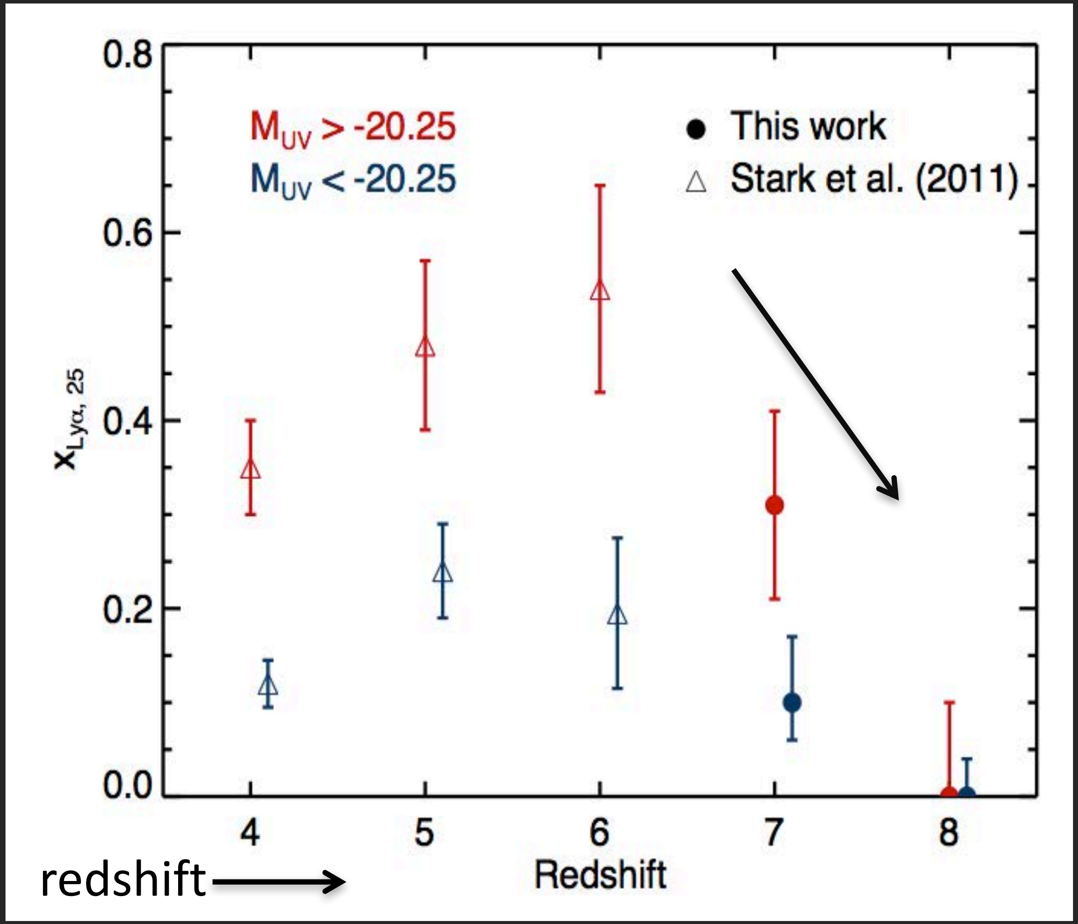
increasing neutral fraction at z>6

large fraction of these Lyα measurements made at Keck with DEIMOS and MOSFIRE

~100 galaxies at z>~ 6

fraction of galaxies with Lyα EW > 25 Å

Schenker+2014



universe is increasingly neutral at z>6

Stark+2011, 2017

also Stark+2011, Schenker+2012, Treu+2013

contributions from Fontana+2010, Pentericci+2011, 2014; Stark+2011, Ono+2012, Caruana+2012, 2014, Schenker+2012, ; Treu+2013, Tilvi+2014, +

the galaxy luminosity density in the reionization epoch

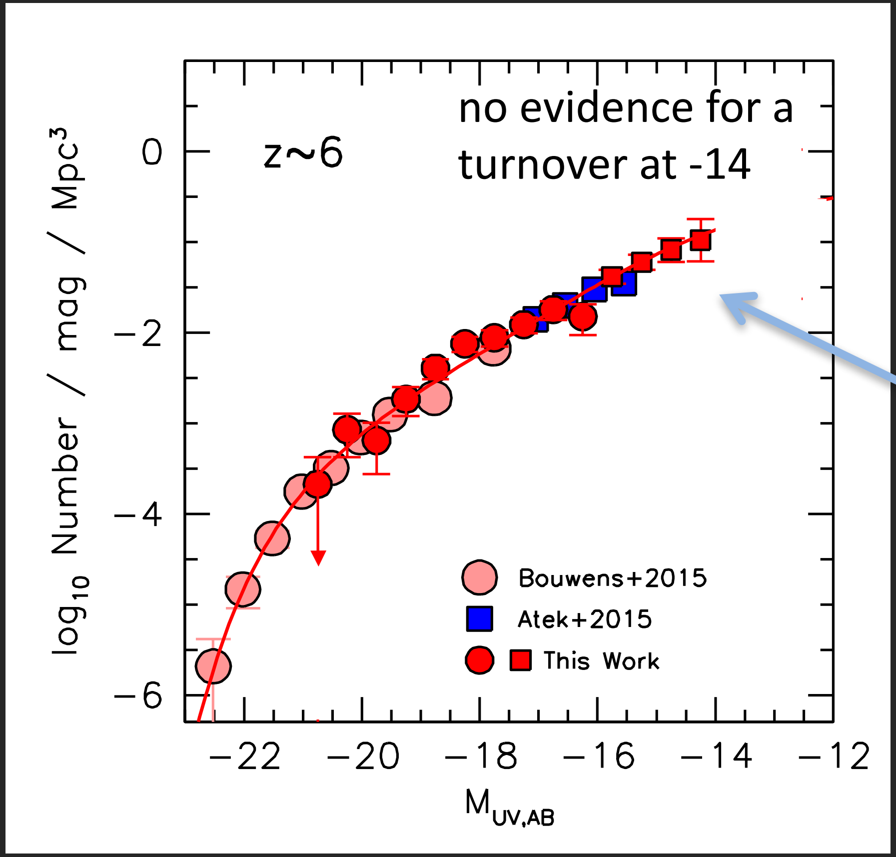
can galaxies reionize the universe?

most likely: steep LF to -14 and plausible f_{esc} around 10-20% needed

☞ see new work by Naidu+2016 on f_{esc} (the escape of the UV photons from galaxies)

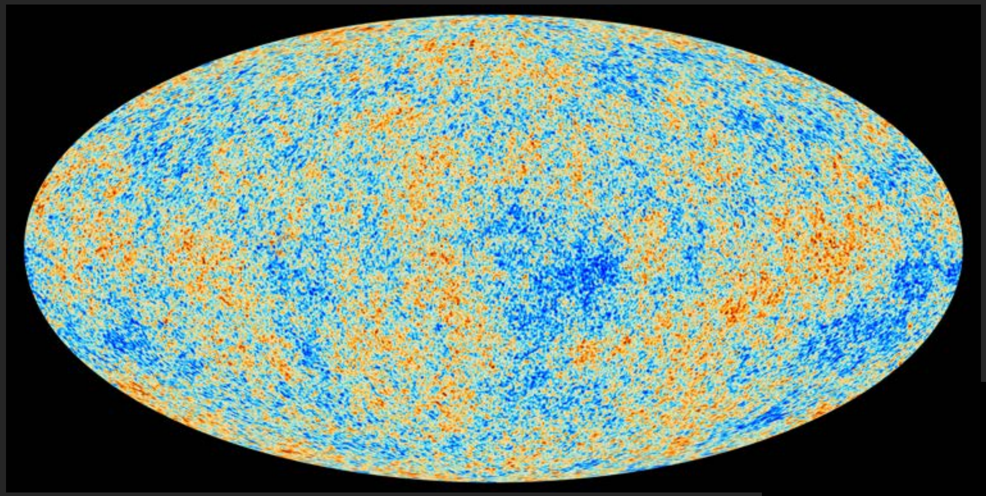
consensus view is that galaxies can do the job!

see latest Planck results below that add weight to galaxies doing the job



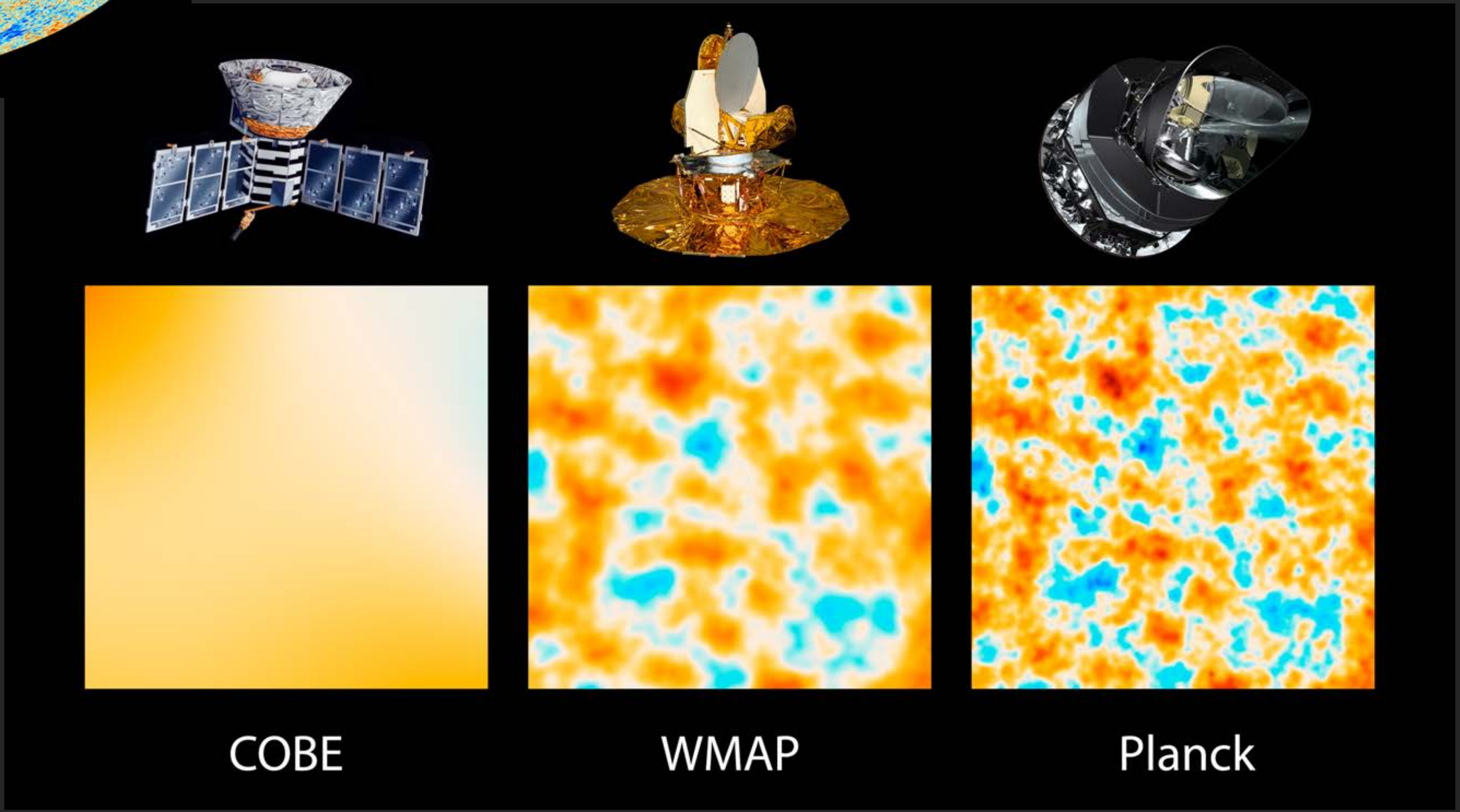
plenty of UV photons

measuring the fluctuations in the 3°K microwave background across the whole sky



Planck all-sky map of the microwave 3°K background

three amazing missions



1989 2001 2009

constraints on the reionization history

Planck 2016

remarkable mission

- …Thomson optical depth τ = 0.058±0.012….
- …average redshift at which reionization occurs is found to lie between *z* = 7.8 and 8.8…
- …upper limit to the width of the reionization period of Δ*z* < 2.8.
- …the Universe is ionized at less than the 10% level at redshifts above *z* ≃ 10…
- …an early onset of reionization is strongly disfavored by the *Planck* data.

Planck intermediate results

XLVII. *Planck* constraints on reionization history

Planck Collaboration: R. Adam[67], N. Aghanim[53], M. Ashdown[63,7], J. Aumont[53], C. Baccigalupi[75], M. Ballardini[29,45,48], A. J. Banday[85,10], R. B. Barreiro[58], N. Bartolo[28,59], S. Basak[75], R. Battye[61], K. Benabed[54,84], J.-P. Bernard[85,10], M. Bersanelli[32,46], P. Bielewicz[72,10,75], J. J. Bock[60,11], A. Bonaldi[61], L. Bonavera[16], J. R. Bond[9], J. Borrill[12,81], F. R. Bouchet[54,79], F. Boulanger[53], M. Bucher[1], C. Burigana[45,30,48], E. Calabrese[82], J.-F. Cardoso[66,1,54], J. Carron[21], H. C. Chiang[23,8], L. P. L. Colombo[19,60], C. Combet[67], B. Comis[67], F. Couchot[64], A. Coulais[65], B. P. Crill[60,11], A. Curto[58,7,63], F. Cuttaia[45], R. J. Davis[61], P. de Bernardis[31], A. de Rosa[45], G. de Zotti[42,75], J. Delabrouille[1], E. Di Valentino[54,79], C. Dickinson[61], J. M. Diego[58], O. Doré[60,11], M. Douspis[53], A. Ducout[54,52], X. Dupac[36], F. Elsner[20,54,84], T. A. Enßlin[70], H. K. Eriksen[56], E. Falgarone[65], Y. Fantaye[34,3], F. Finelli[45,48], F. Forastieri[30,49], M. Frailis[44], A. A. Fraisse[23], E. Franceschi[45], A. Frolov[78], S. Galeotta[44], S. Galli[62], K. Ganga[1], R. T. Génova-Santos[57,15], M. Gerbino[83,74,31], T. Ghosh[53], J. González-Nuevo[16,58], K. M. Górski[60,87], A. Gruppuso[45,48], J. E. Gudmundsson[83,74,23], F. K. Hansen[56], G. Helou[11], S. Henrot-Versillé[64], D. Herranz[58], E. Hivon[54,84], Z. Huang[9], S. Ilić[85,10,6], A. H. Jaffe[52], W. C. Jones[23], E. Keihänen[22], R. Keskitalo[12], T. S. Kisner[69], L. Knox[25], N. Krachmalnicoff[32], M. Kunz[14,53,3], H. Kurki-Suonio[22,41], G. Lagache[5,53], A. Lähteenmäki[2,41], J.-M. Lamarre[65], M. Langer[53], A. Lasenby[7,63], M. Lattanzi[30,49], C. R. Lawrence[60], M. Le Jeune[1], F. Levrier[65], A. Lewis[21], M. Liguori[28,59], P. B. Lilje[56], M. López-Caniego[36], Y.-Z. Ma[61,76], J. F. Macías-Pérez[67], G. Maggio[44], A. Mangilli[53,64], M. Maris[44], P. G. Martin[9], E. Martínez-González[58], S. Matarrese[28,59,38], N. Mauri[48], J. D. McEwen[71], P. R. Meinhold[26], A. Melchiorri[31,50], A. Mennella[32,46], M. Migliaccio[55,63], M.-A. Miville-Deschênes[53,9], D. Molinari[30,45,49], A. Moneti[54], L. Montier[85,10], G. Morgante[45], A. Moss[77], P. Naselsky[73,35], P. Natoli[30,4,49], C. A. Oxborrow[13], L. Pagano[31,50], D. Paoletti[45,48], B. Partridge[40], G. Patanchon[1], L. Patrizii[48], O. Perdereau[64], L. Perotto[67], V. Pettorino[39], F. Piacentini[31], S. Plaszczynski[64], L. Polastri[30,49], G. Polenta[4,43], J.-L. Puget[53], J. P. Rachen[17,70], B. Racine[56], M. Reinecke[70], M. Remazeilles[61,53,1], A. Renzi[34,51], G. Rocha[60,11], M. Rossetti[32,46], G. Roudier[1,65,60], J. A. Rubiño-Martín[57,15], B. Ruiz-Granados[86], L. Salvati[31], M. Sandri[45], M. Savelainen[22,41], D. Scott[18], G. Sirri[48], R. Sunyaev[70,80], A.-S. Suur-Uski[22,41], J. A. Tauber[37], M. Tenti[47], L. Toffolatti[16,58,45], M. Tomasi[32,46], M. Tristram[64,⋆], T. Trombetti[45,30], J. Valiviita[22,41], F. Van Tent[68], P. Vielva[58], F. Villa[45], N. Vittorio[33], B. D. Wandelt[54,84,27], I. K. Wehus[60,56], M. White[24], A. Zacchei[44], and A. Zonca[26]

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ABSTRACT

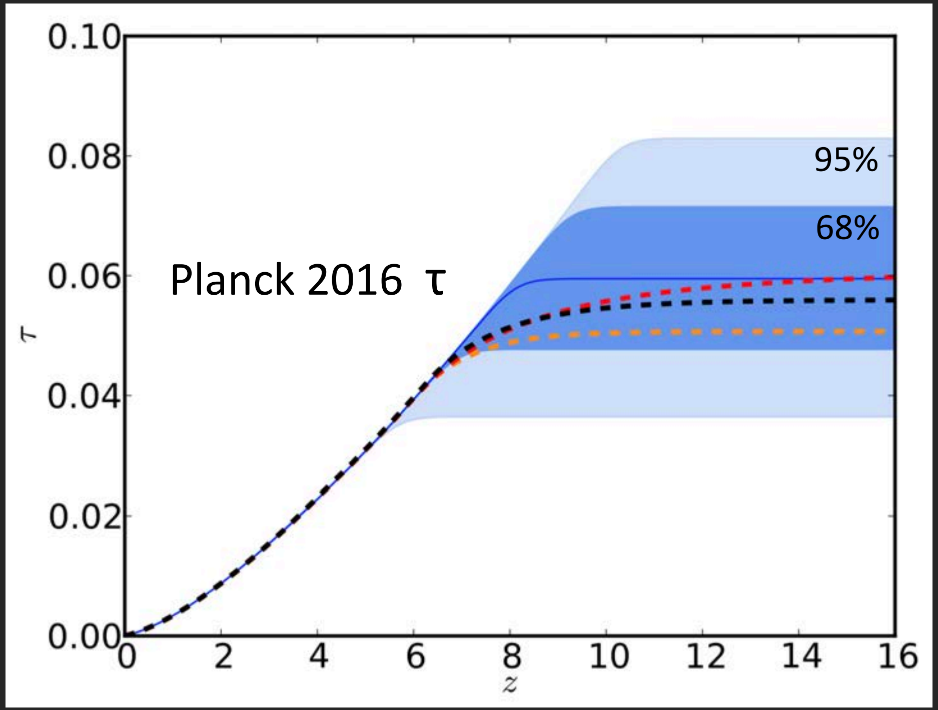
We investigate constraints on cosmic reionization extracted from the *Planck* cosmic microwave background (CMB) data. We combine the *Planck* CMB anisotropy data in temperature with the low-multipole polarization data to fit ΛCDM models with various parameterizations of the reionization history. We obtain a Thomson optical depth $\tau = 0.058 \pm 0.012$ for the commonly adopted instantaneous reionization model. This confirms, with data solely from CMB anisotropies, the low value suggested by combining *Planck* 2015 results with other data sets, and also reduces the uncertainties. We reconstruct the history of the ionization fraction using either a symmetric or an asymmetric model for the transition between the neutral and ionized phases. To determine better constraints on the duration of the reionization process, we also make use of measurements of the amplitude of the kinetic Sunyaev-Zeldovich (kSZ) effect using additional information from the high-resolution Atacama Cosmology Telescope and South Pole Telescope experiments. The average redshift at which reionization occurs is found to lie between $z = 7.8$ and 8.8, depending on the model of reionization adopted. Using kSZ constraints and a redshift-symmetric reionization model, we find an upper limit to the width of the reionization period of $\Delta z < 2.8$. In all cases, we find that the Universe is ionized at less than the 10% level at redshifts above $z \simeq 10$. This suggests that an early onset of reionization is strongly disfavoured by the *Planck* data. We show that this result also reduces the tension between CMB-based analyses and constraints from other astrophysical sources.

Key words. cosmic background radiation – dark ages, reionization, first stars – polarization

Plank Collaboration XLVII + 2016

reionization constraints from Planck 2016

striking consistency with galaxy results

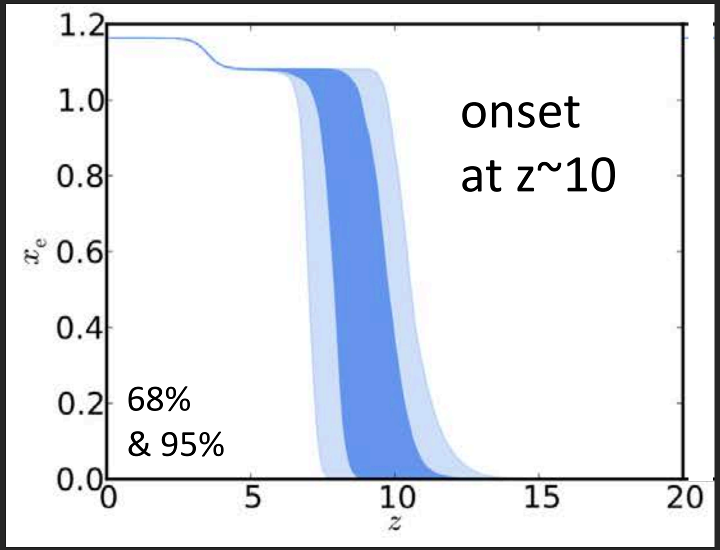


Bouwens+2015
Robertson+2015
Ishigaki+2015

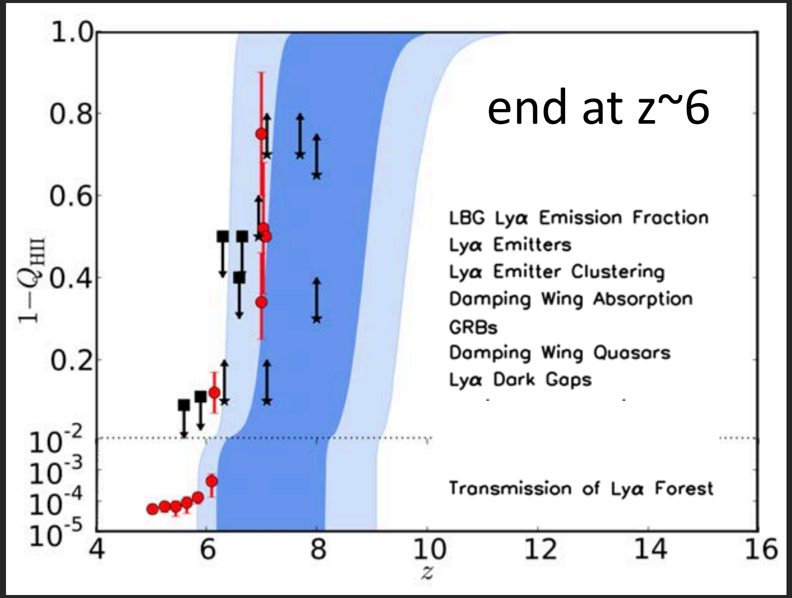
evolution of the integrated optical depth compared to galaxy results

Plank Collaboration XLVII + 2016

constraints on ionization fraction from onset during reionization

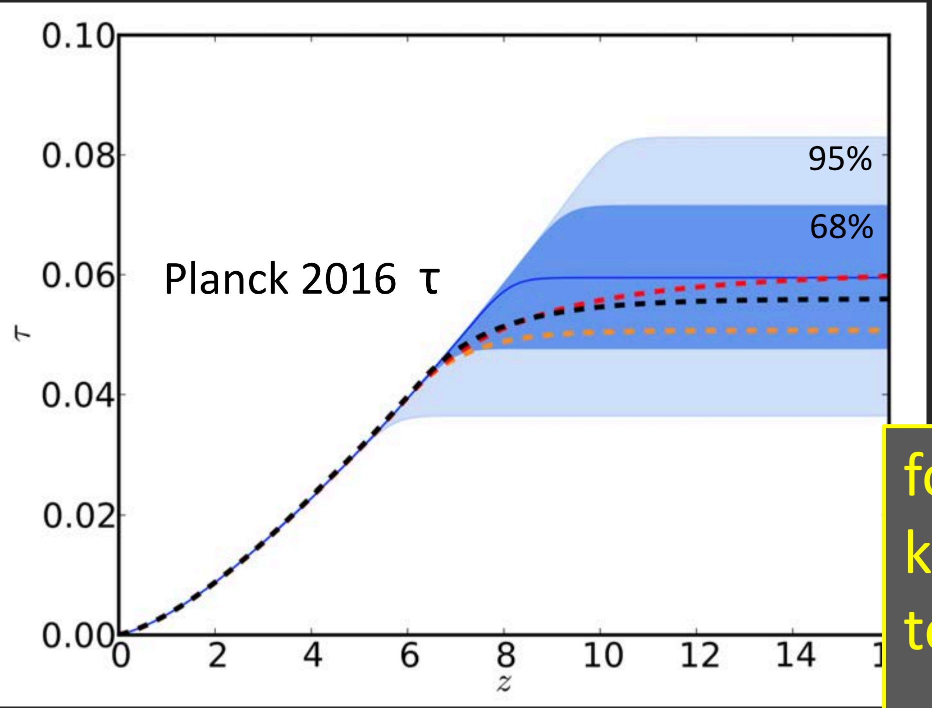


reionization history compared with observational constraints



reionization constraints from Planck 2016

striking consistency with galaxy results



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evolution of the integrated optical depth compared to galaxy results

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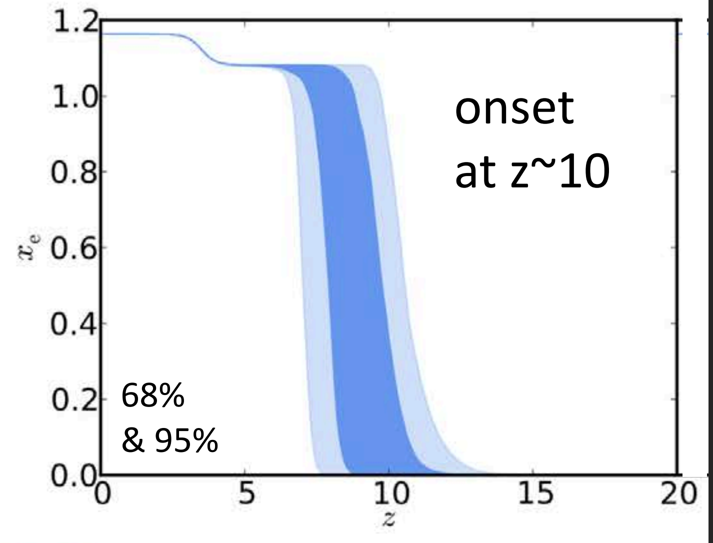
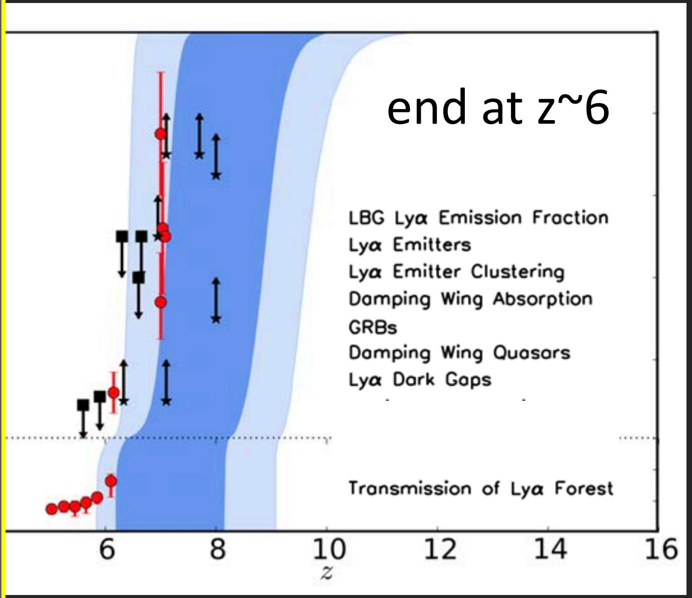


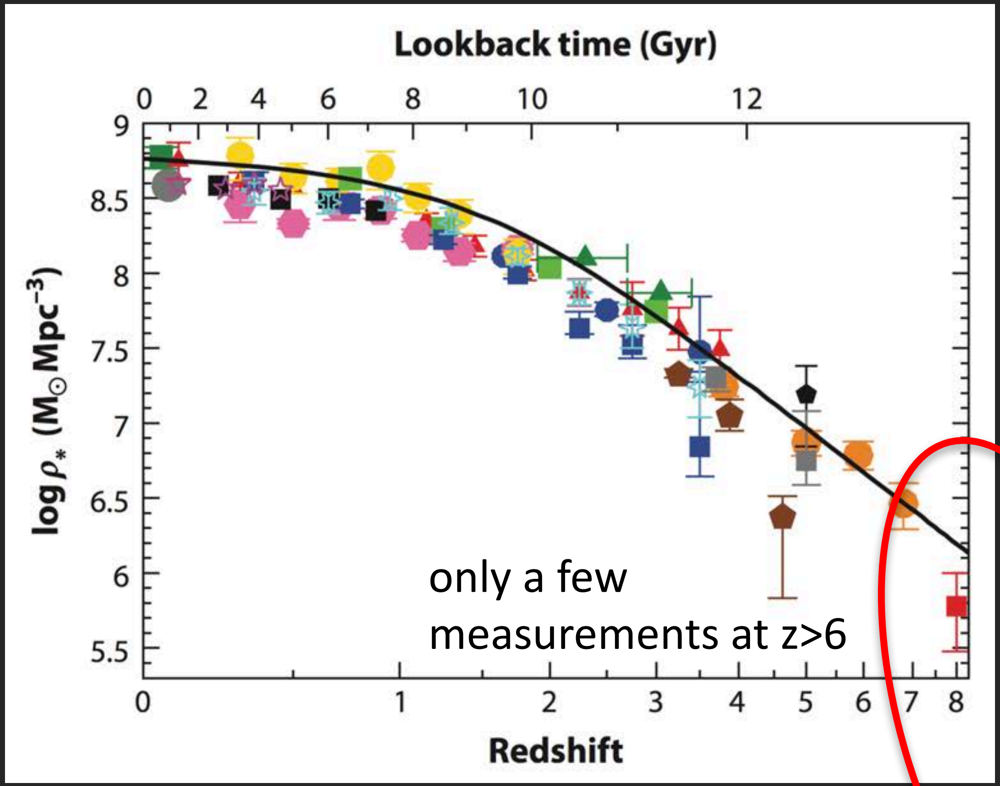
for the first time we now know when galaxies started to reionize the universe

this is a crucial piece of information for how far back we might have to look to find "first galaxies"



what’s needed for further exploration of the first billion years for distant galaxies?

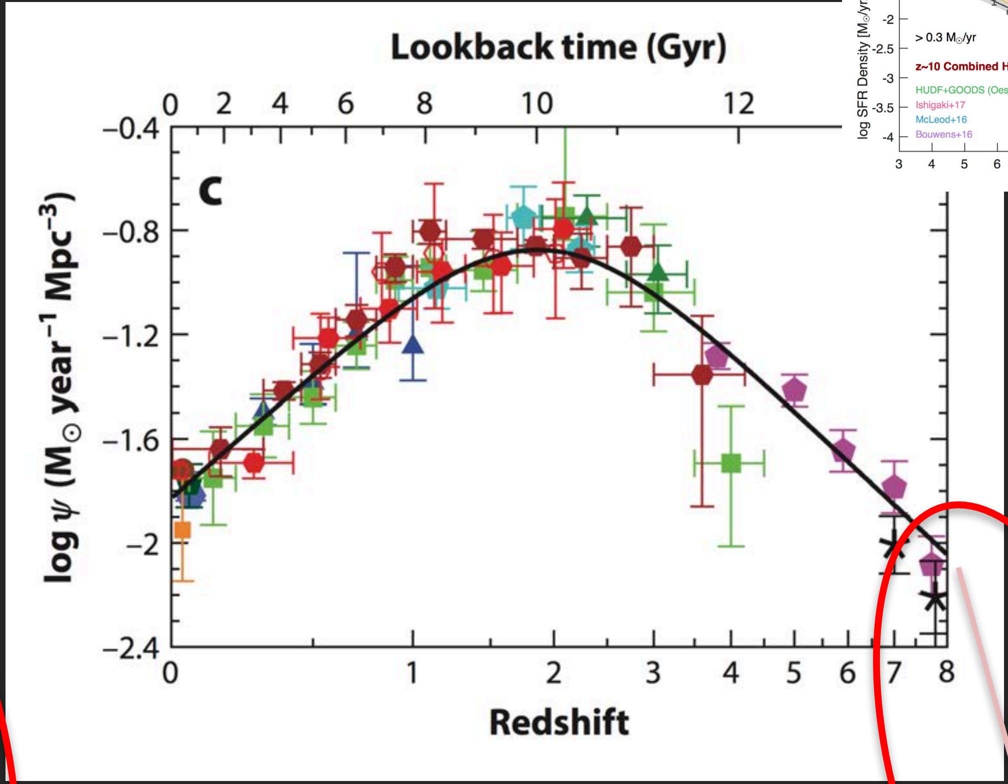
the global stellar mass and cosmic SFR density evolution

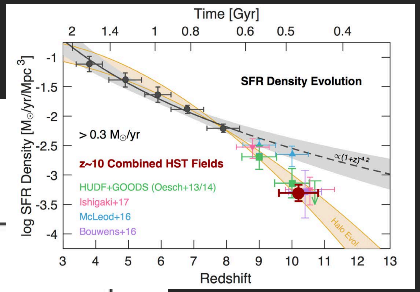


only a few measurements at z>6

z~10-15

evolution of the global stellar mass density over 13 billion years





new results at z>8

evolution of the cosmic star formation rate density over 13 billion years

z~10

Madau & Dickinson 2014

☛ *into the JWST era* ☚

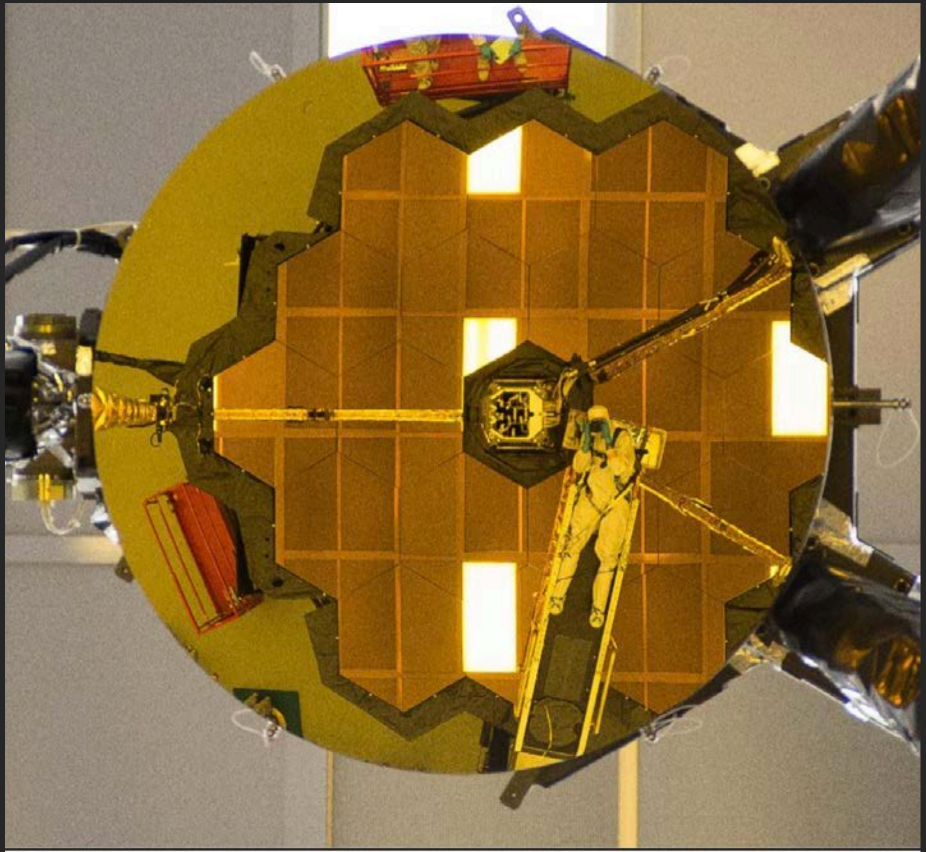
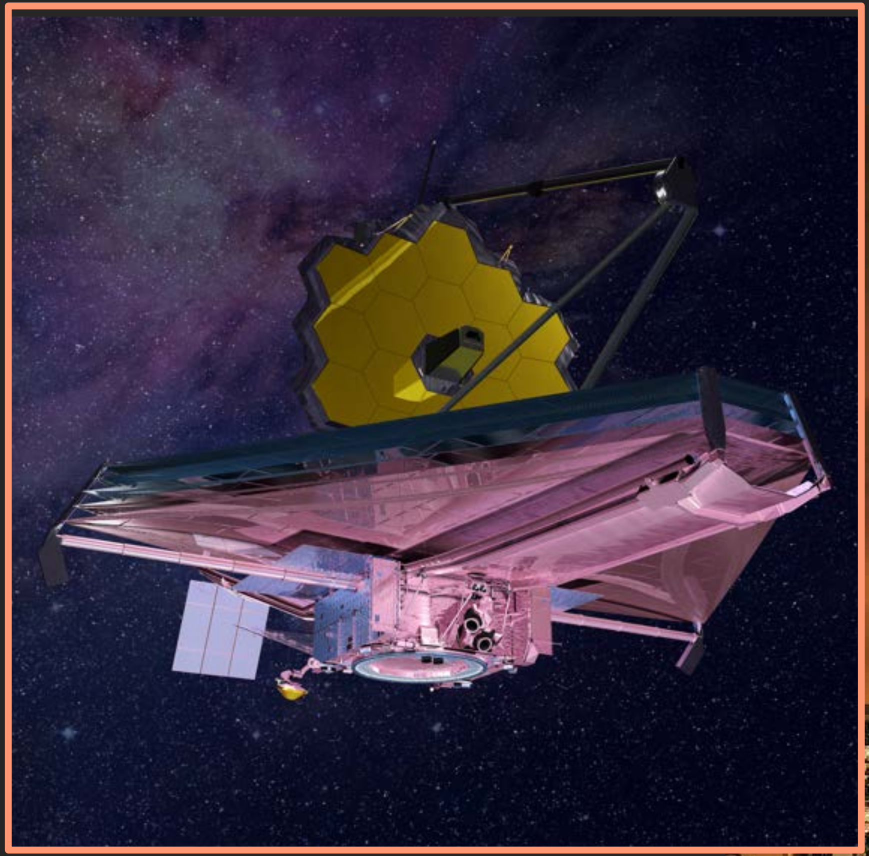


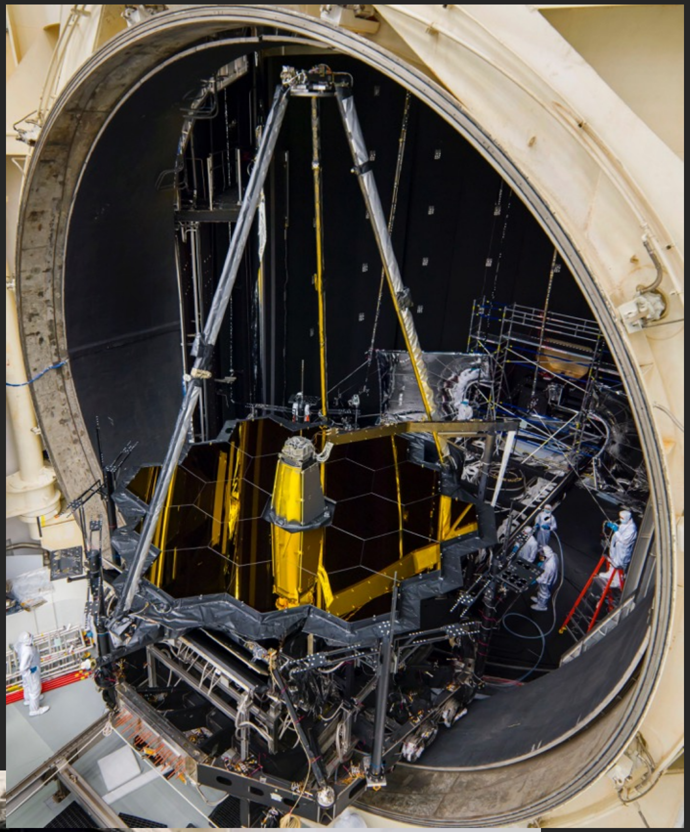
Image Credit: Larkin Carey (seen on diving board

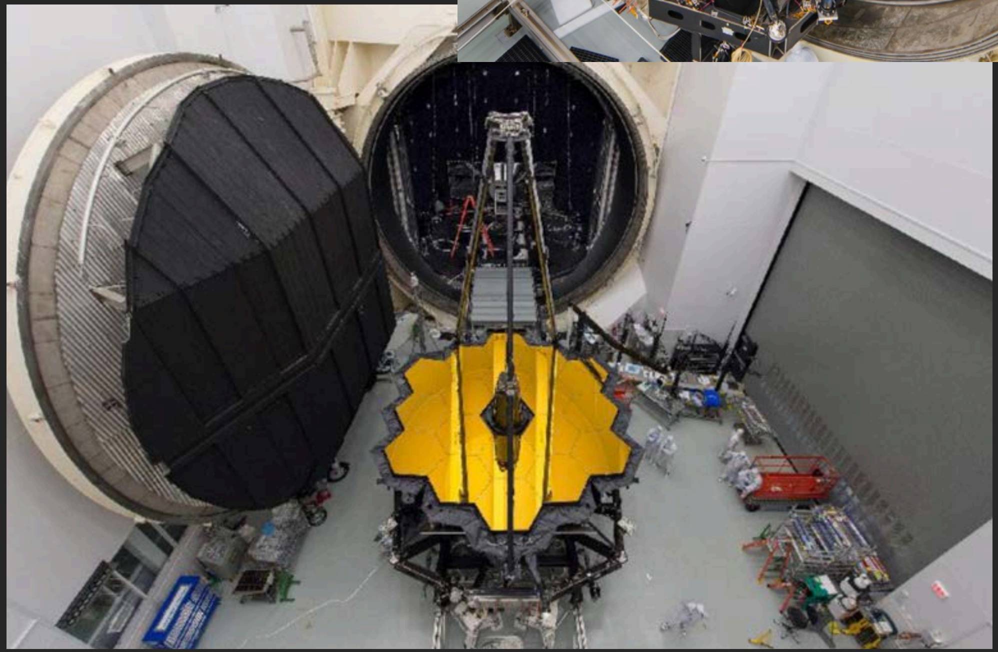
JWST is the "what's next" for the earliest galaxies

JWST launches Oct 2018



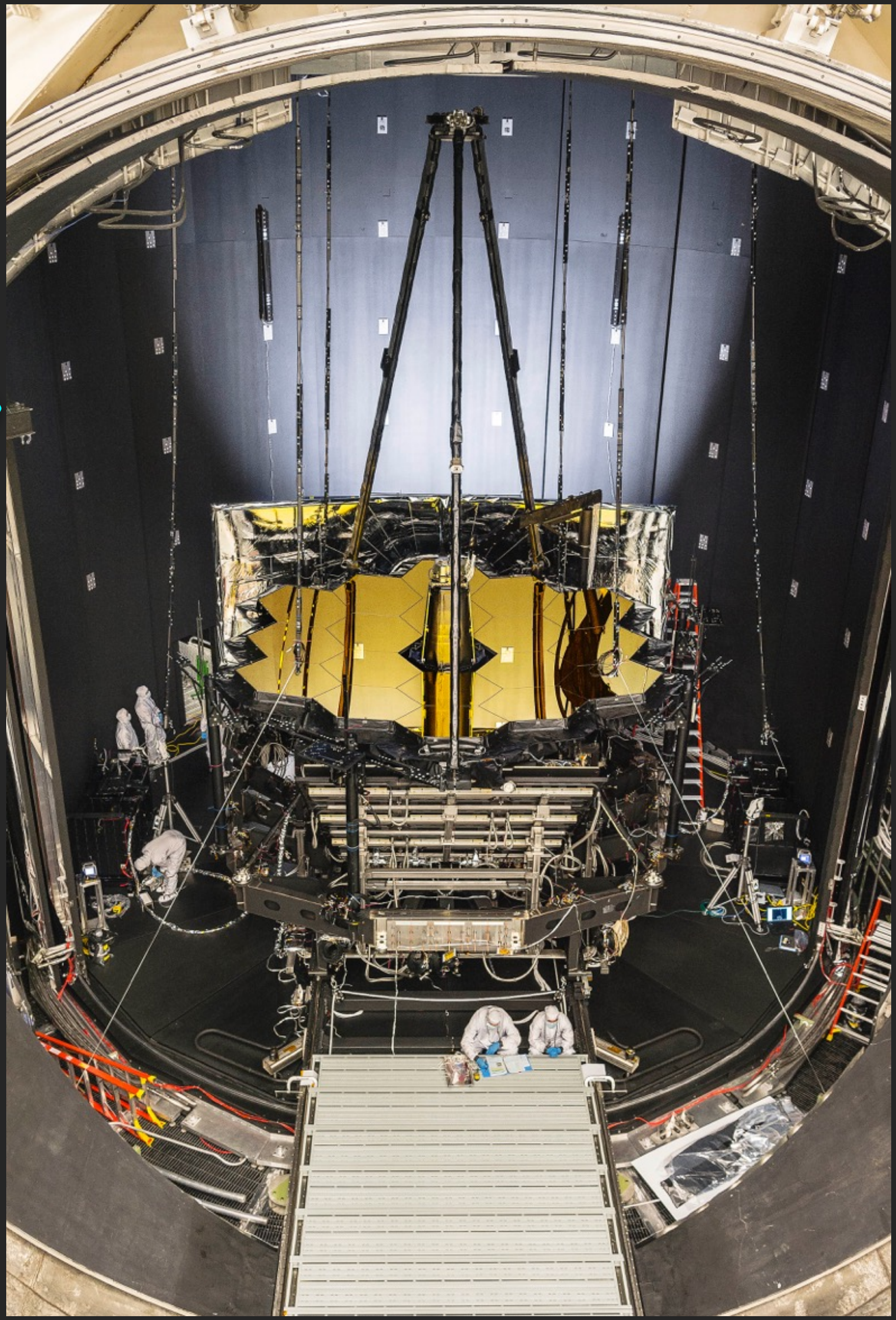
note people





JWST OTIS CV test at JSC

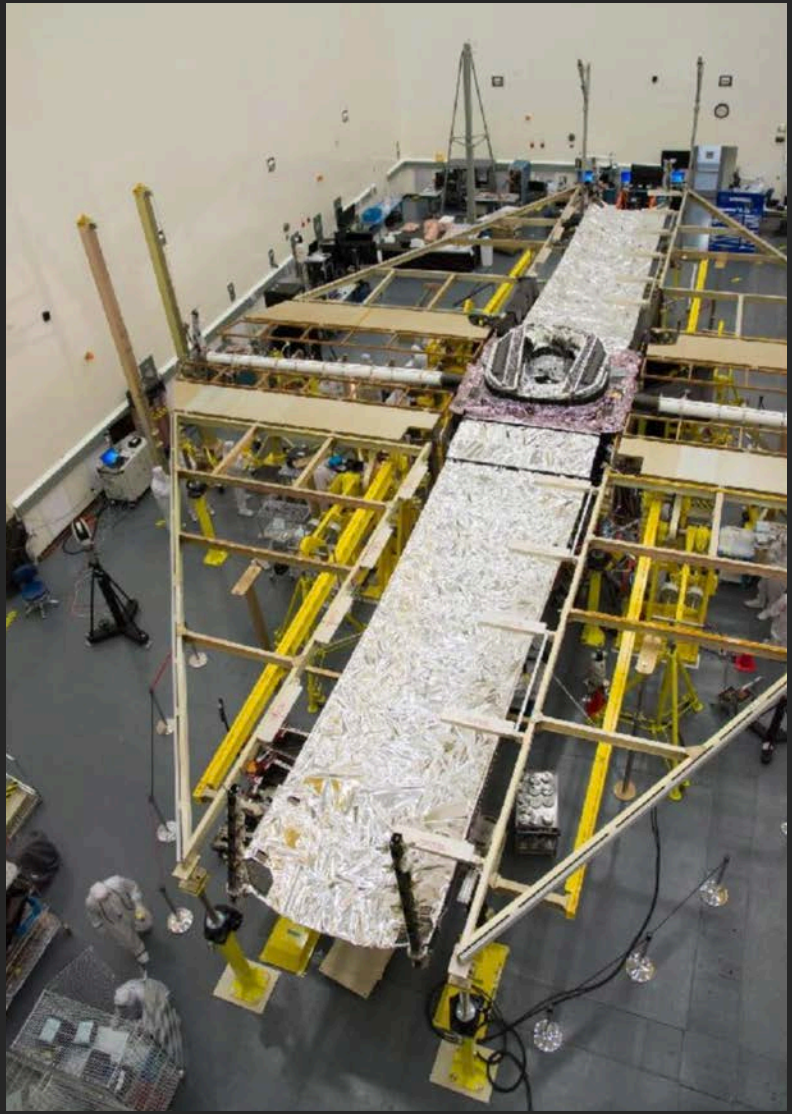
moving OTIS in through the chamber door and OTIS in the chamber



JWST Spacecraft assembly in the clean room at NGAS

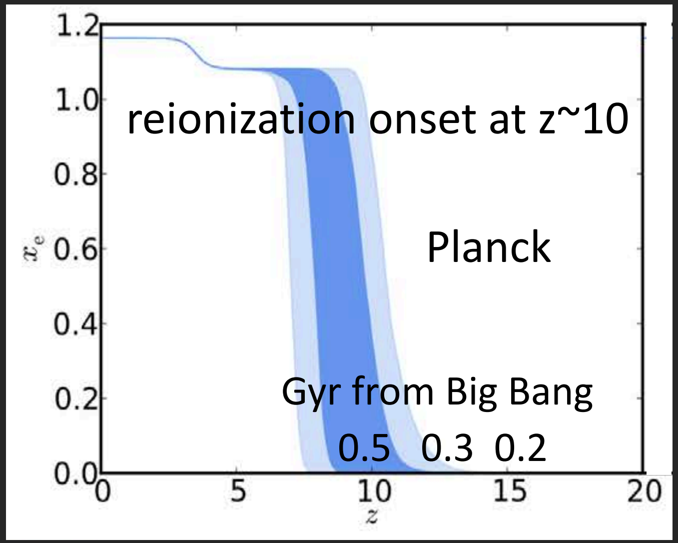
the spacecraft plus sunshield pallets plus the OTIS simulator

the sunshield pallets deployed with (folded) sunshields installed

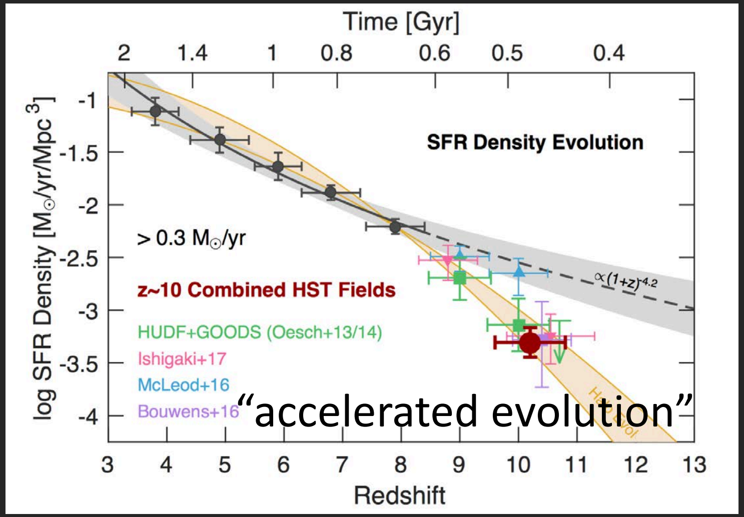


JWST is very large!

implications for JWST and "first light" from the z~9-10 LFs and the latest Planck 2016 results



what does all this tell us about JWST and the "first" galaxies?



First Light and Reionization

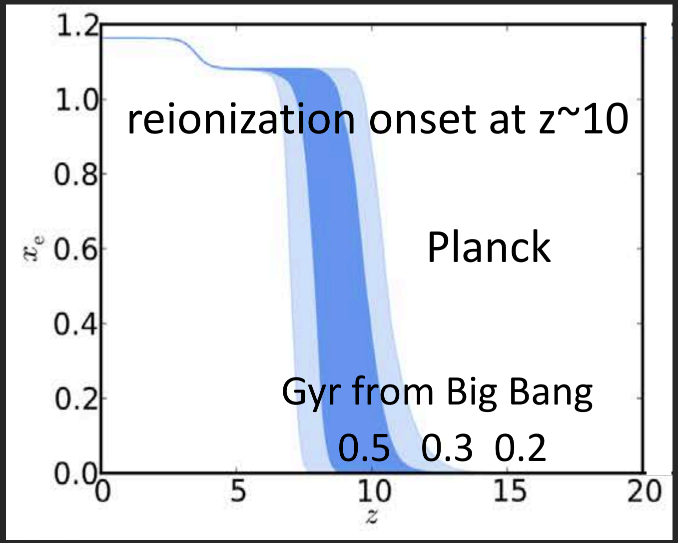
one of JWST's four science themes

what is "first light" and what are "first galaxies"?

?? first stars ⇨ first star clusters ⇨ larger star clusters ⇨ multiple star clusters of various ages ??

much discussion about what JWST can see in this progression

very challenging if "first galaxies" were very early (z~15-20? – z>15 is very difficult for JWST)



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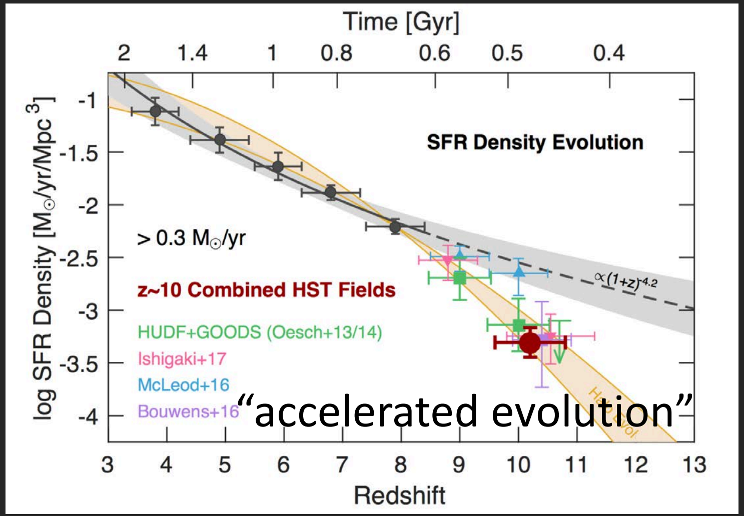
First Light and Reionization

one of JWST's four science themes



New results: "accelerated evolution" from z~9-10 LFs and reionization turn-on at z~10-11 from Planck

=> suggest major changes in the nature of the galaxy population at redshifts more like z~12-15

I think these results point to substantial build-up of the earliest galaxies at z~12-15 – very accessible for JWST's "first light" goal

☞ exciting times ahead at "Cosmic Sunrise"! ☜

summary thoughts:

onset of reionization at z~10-11 (Planck), small sizes and "accelerated evolution" at z>8 suggest great opportunities for JWST to see major changes in galaxy build-up to z~15 as part of its "first light" goal

☞ "Cosmic Sunrise" may well be within reach of JWST?

remarkable concordance on Planck 2016 results and galaxy LF measurements make it highly likely that galaxies are responsible for reionization – modulo escape fraction uncertainty at z>6

very faint galaxies are extremely small – HFF results suggest <10 mas for faintest galaxies:

☛ are we seeing globular cluster formation at very early times?

the HFF lensing clusters have allowed luminosity functions to reach substantially fainter limits but are subject to very large systematic uncertainties at magnifications higher than ~40X – this limits current LFs to ~-14.5 – JWST will reach to ~-13, and further possible as models improve, but challenging

detection of bright z~10 candidates is surprising – more numerous than expected by a large factor?