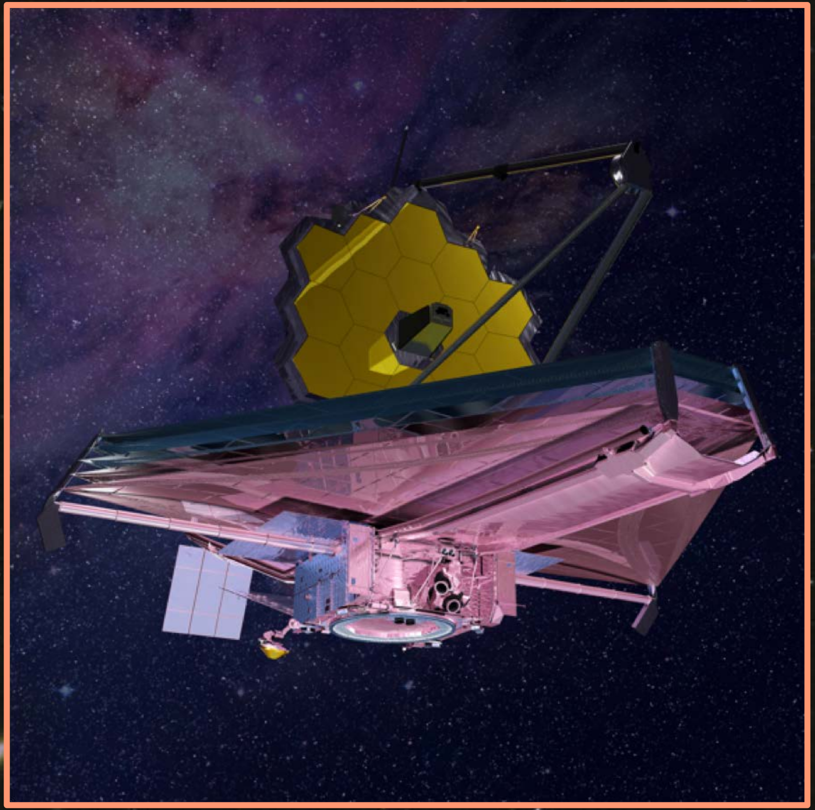
John N. Bahcall Lecture
Space Telescope Science Institute
March 12 2018



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

Garth Illingworth
University of California Santa Cruz

firstgalaxies.org

figure credit: Adolf Schaller

John Bahcall

2000 SIRTF (Spitzer) Legacy Science TAC.
John was TAC Chair. Garth was Panel Chair

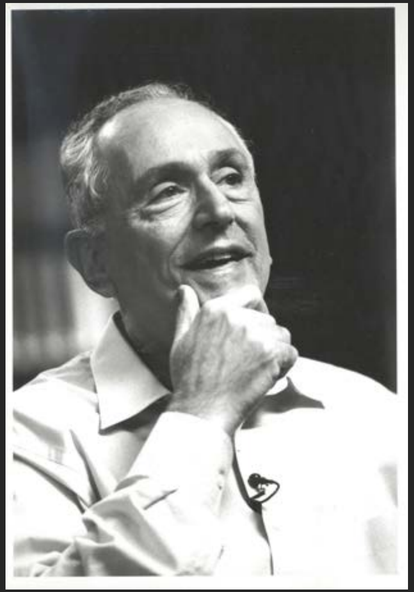
1970s and on: John's continuing efforts to support Hubble were crucial and inspiring (and a model for what was needed for a major mission to be realized)

"What is at stake here is not only a piece of stellar technology but our commitment to the most fundamental human quest: understanding the cosmos." – John N. Bahcall

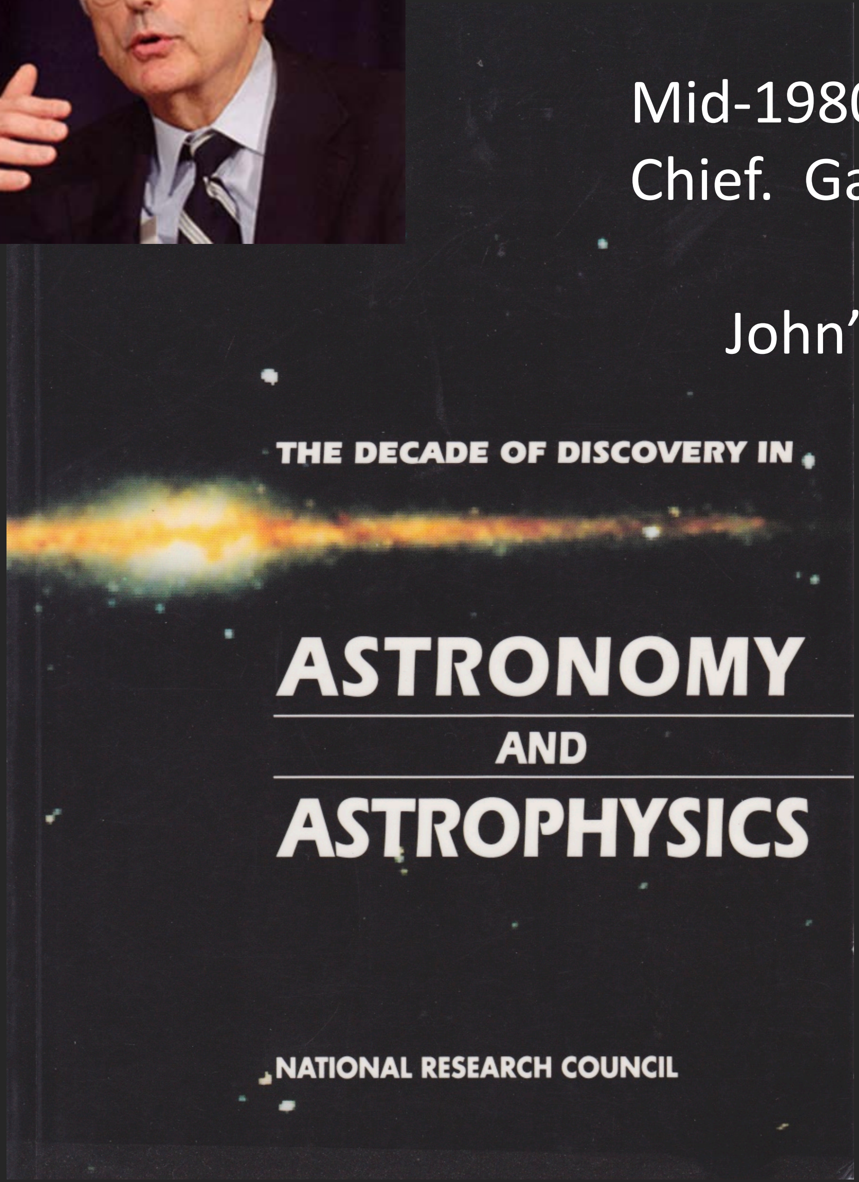
gdi

John Bahcall

Mid-1980s – John's visits to STScI. Neta was Branch Chief. Garth was Deputy Director under Riccardo



John's introductory remarks and participation in the NGST 1989 workshop

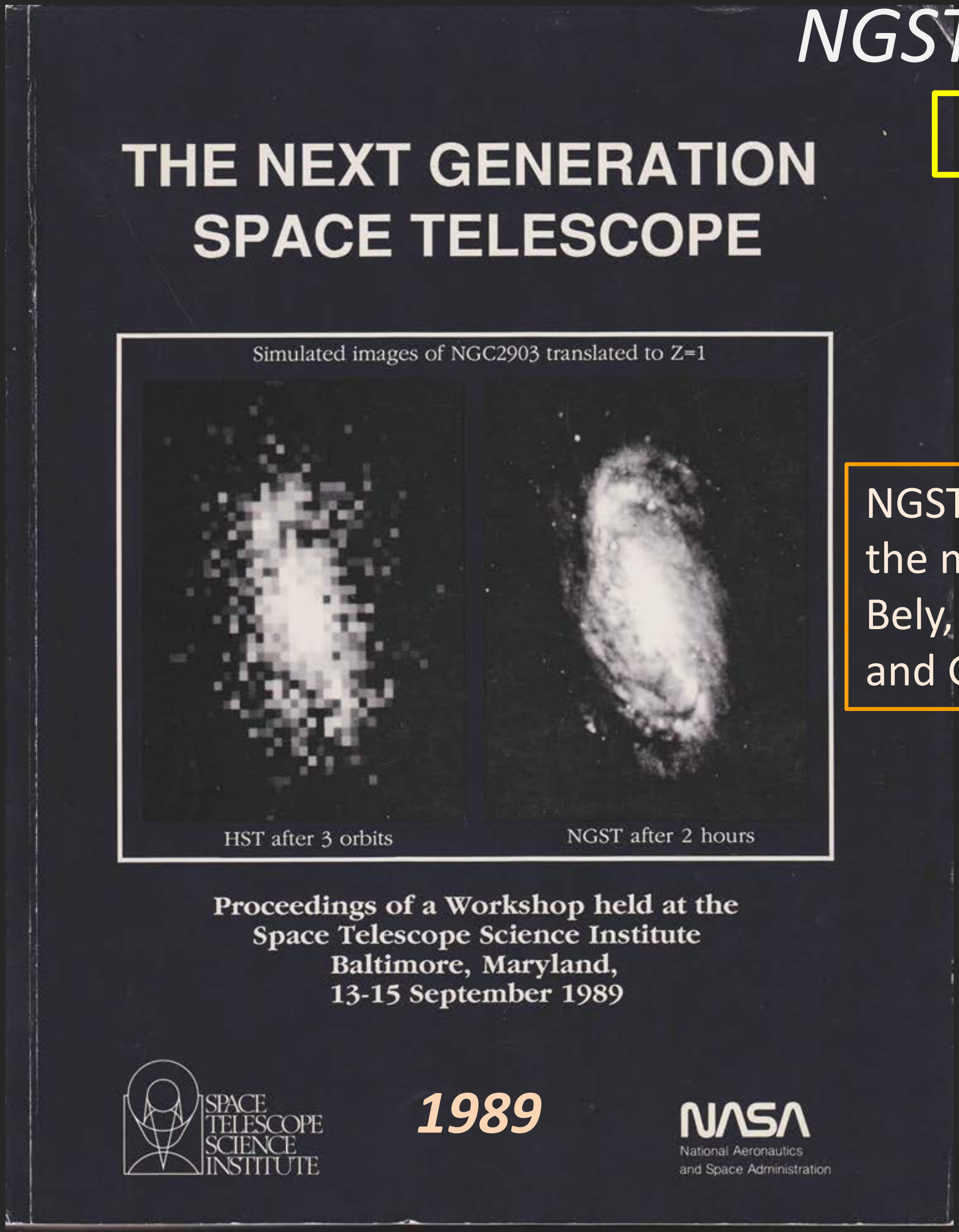


1990: John was Chair, 1990/91 Astronomy Decadal Survey. Garth was Chair, UV-Optical in Space Panel

gdi

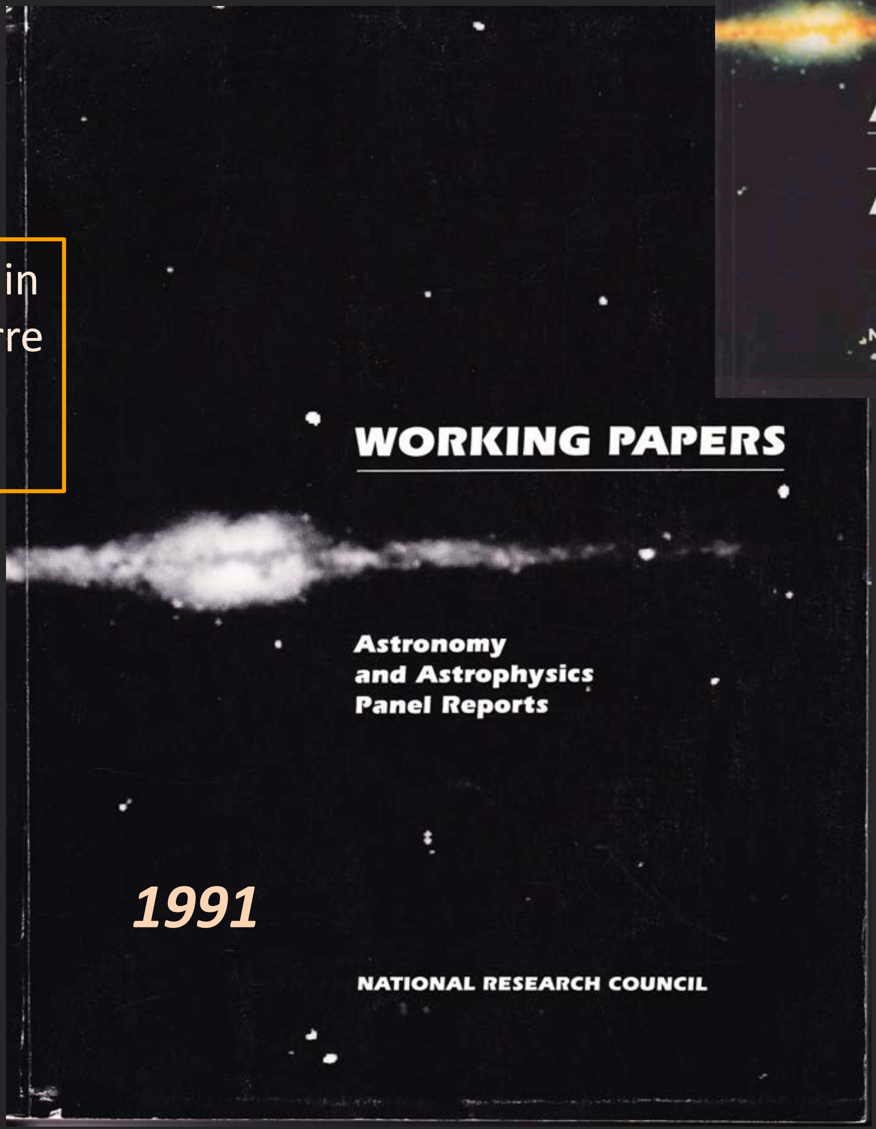
NGST (JWST) – key early events

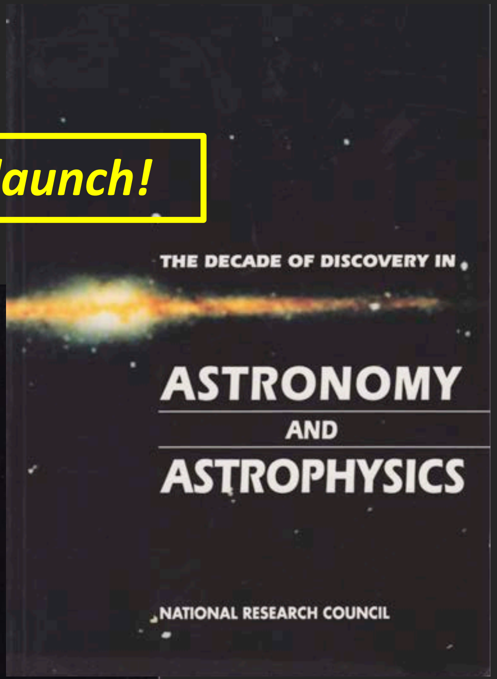
30 years from NGST mission concept to JWST launch!



1989

NGST started at STScI in the mid-1980s by Pierre Bely, Peter Stockman and Garth Illingworth





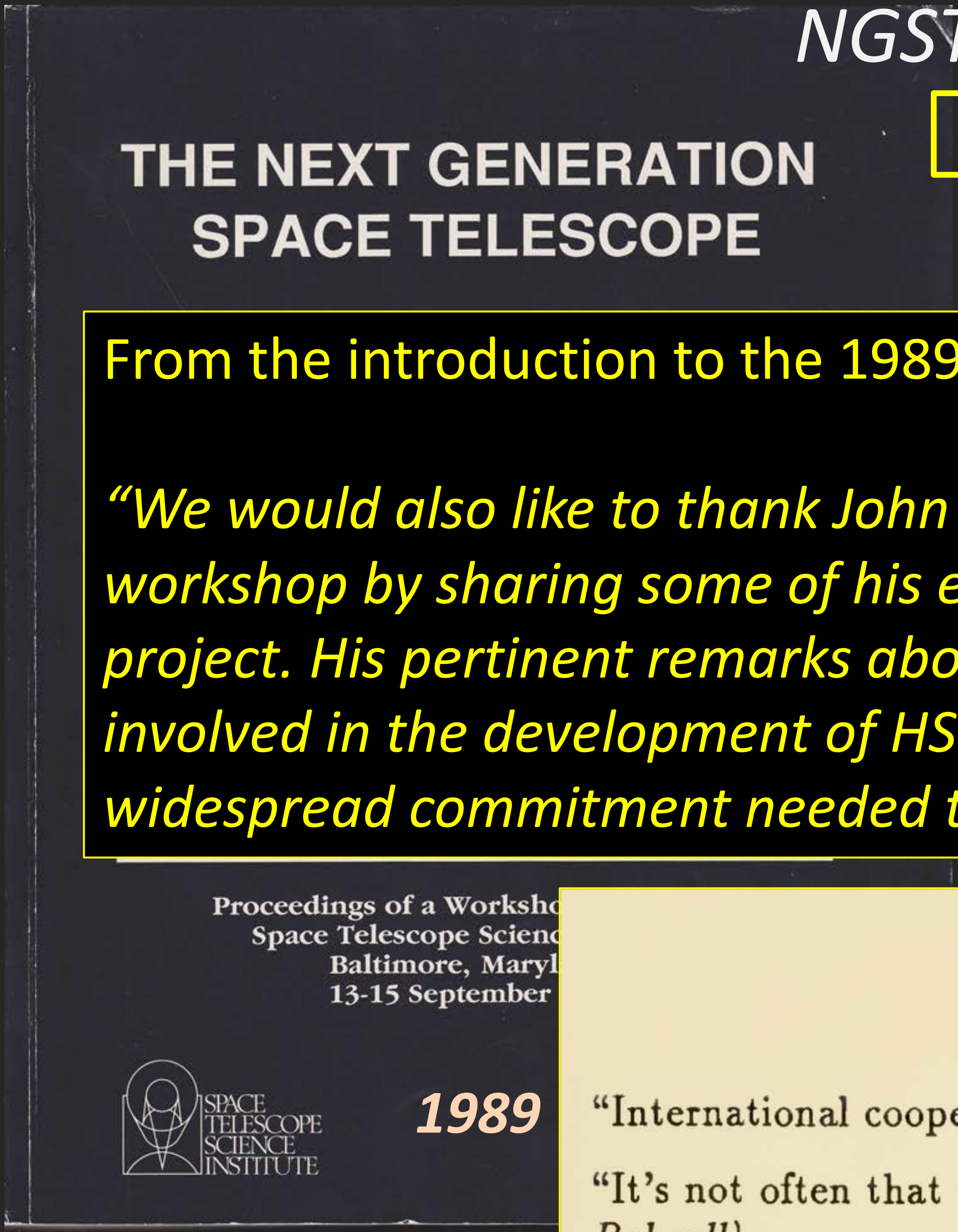
1991

www.ucolick.org/~gdi/early_jwst/

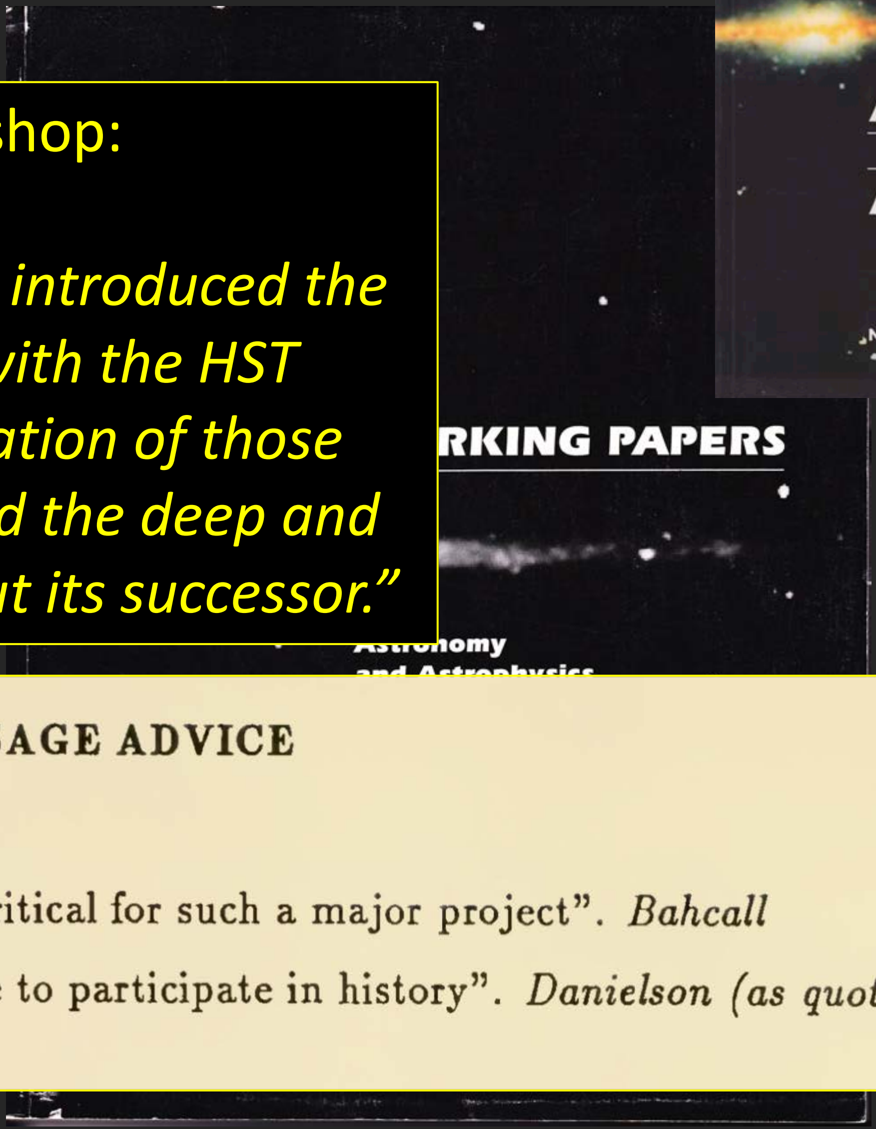
gdi

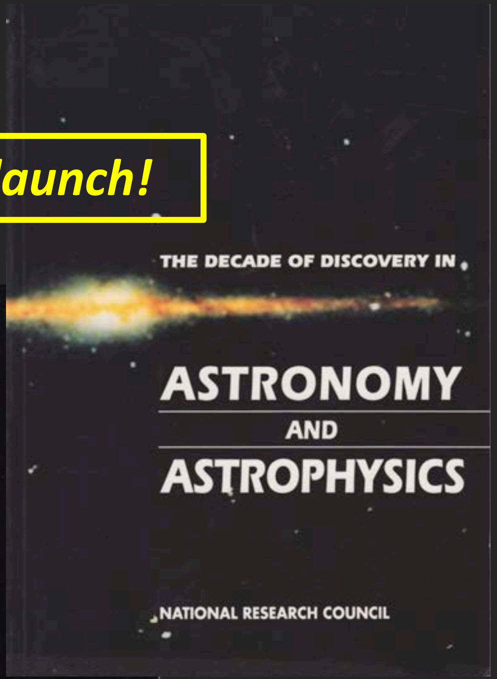
NGST (JWST) – key early events

30 years from NGST mission concept to JWST launch!



1989





From the introduction to the 1989 NGST workshop:

"We would also like to thank John Bahcall who introduced the workshop by sharing some of his experiences with the HST project. His pertinent remarks about the dedication of those involved in the development of HST emphasized the deep and widespread commitment needed to bring about its successor."

SAGE ADVICE

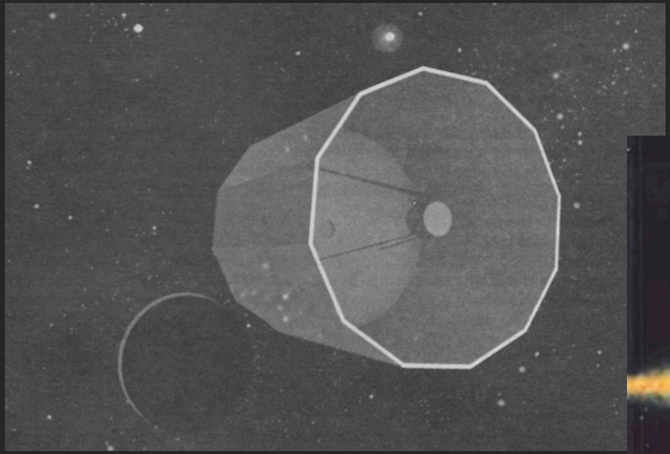
"International cooperation may be critical for such a major project". *Bahcall*

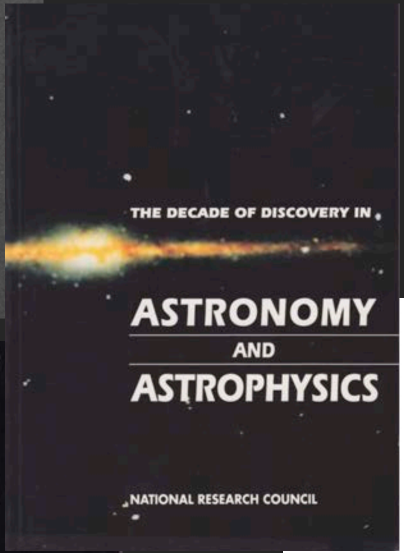
"It's not often that we have a chance to participate in history". *Danielson (as quoted by Bahcall)*

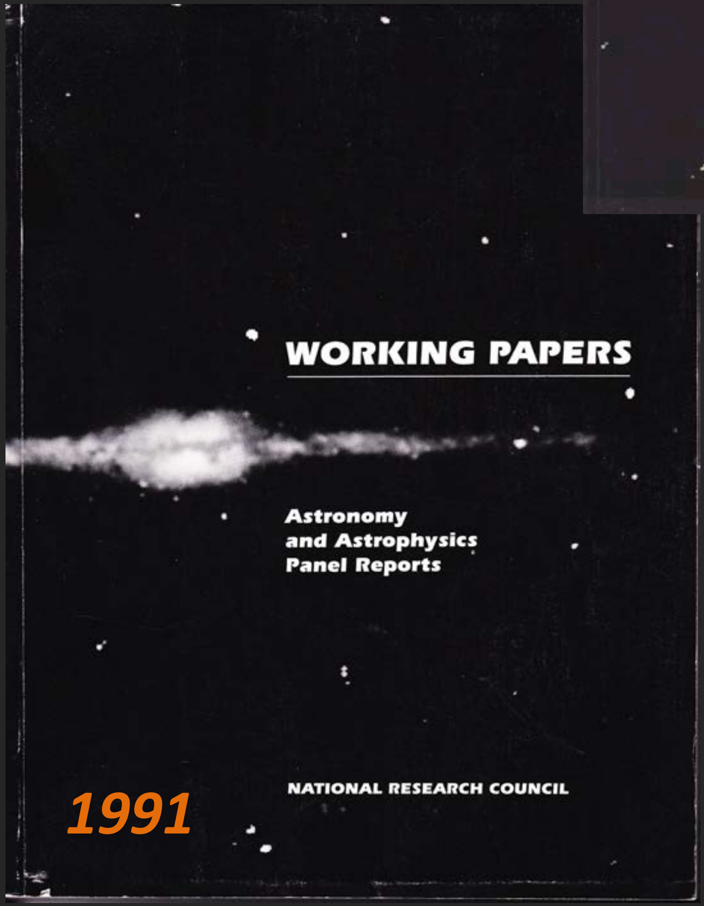
www.ucolick.org/~gdi/early_jwst/

gdi

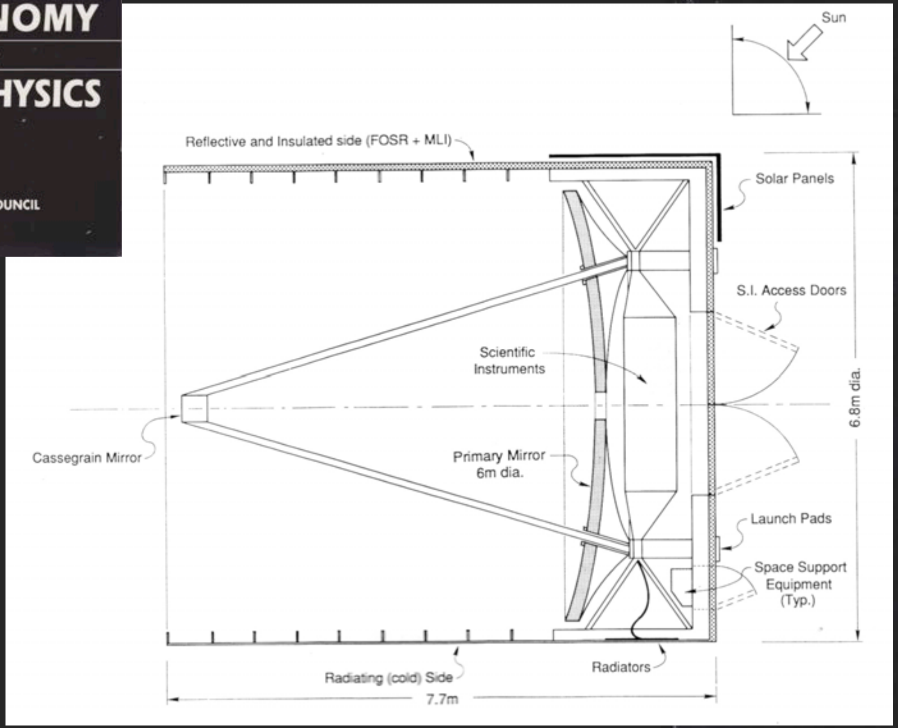
NGST & the 1990 Decadal

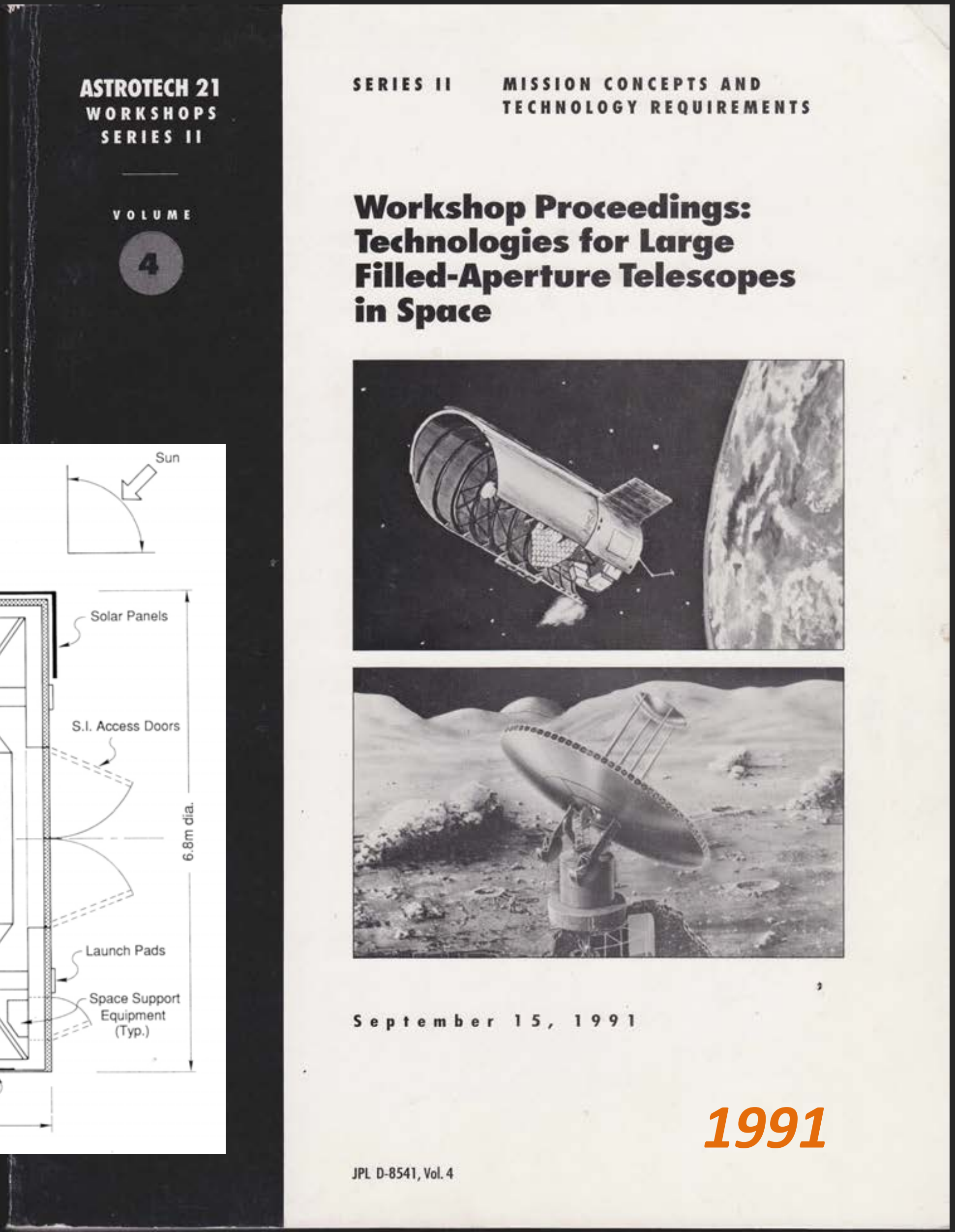






1991



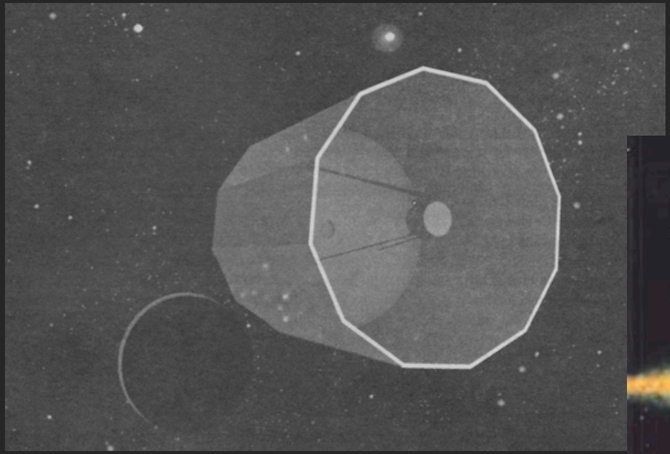


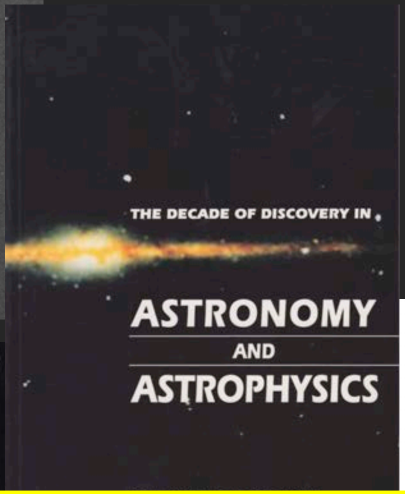
1991

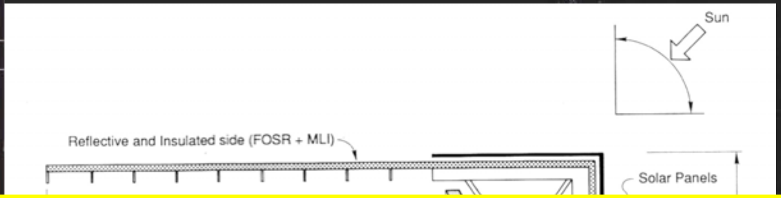
see 2016 STScI Newsletter article
NGST: The Early Days of JWST
newsletter.stsci.edu/early-webb-history

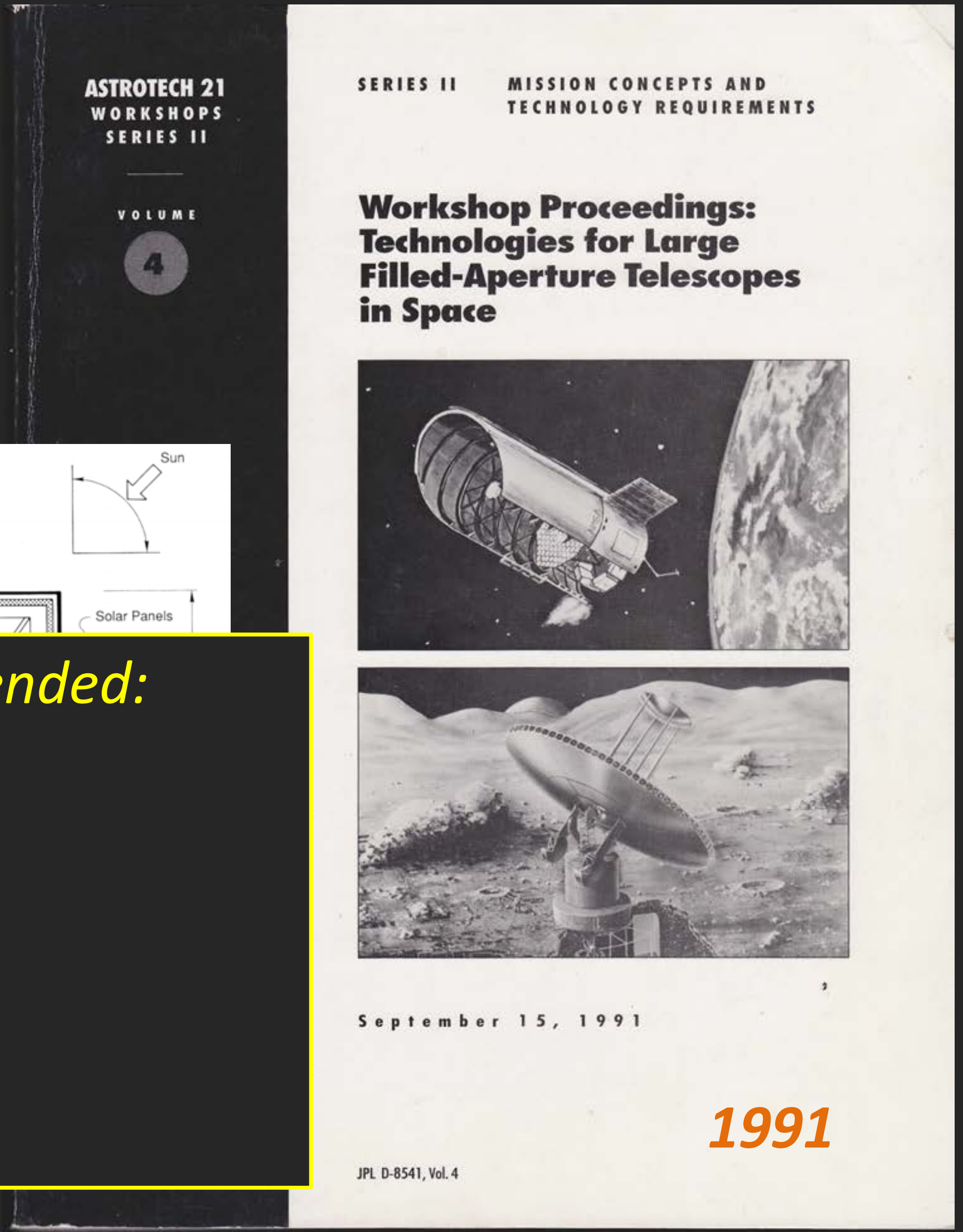
gdi

NGST & the 1990 Decadal









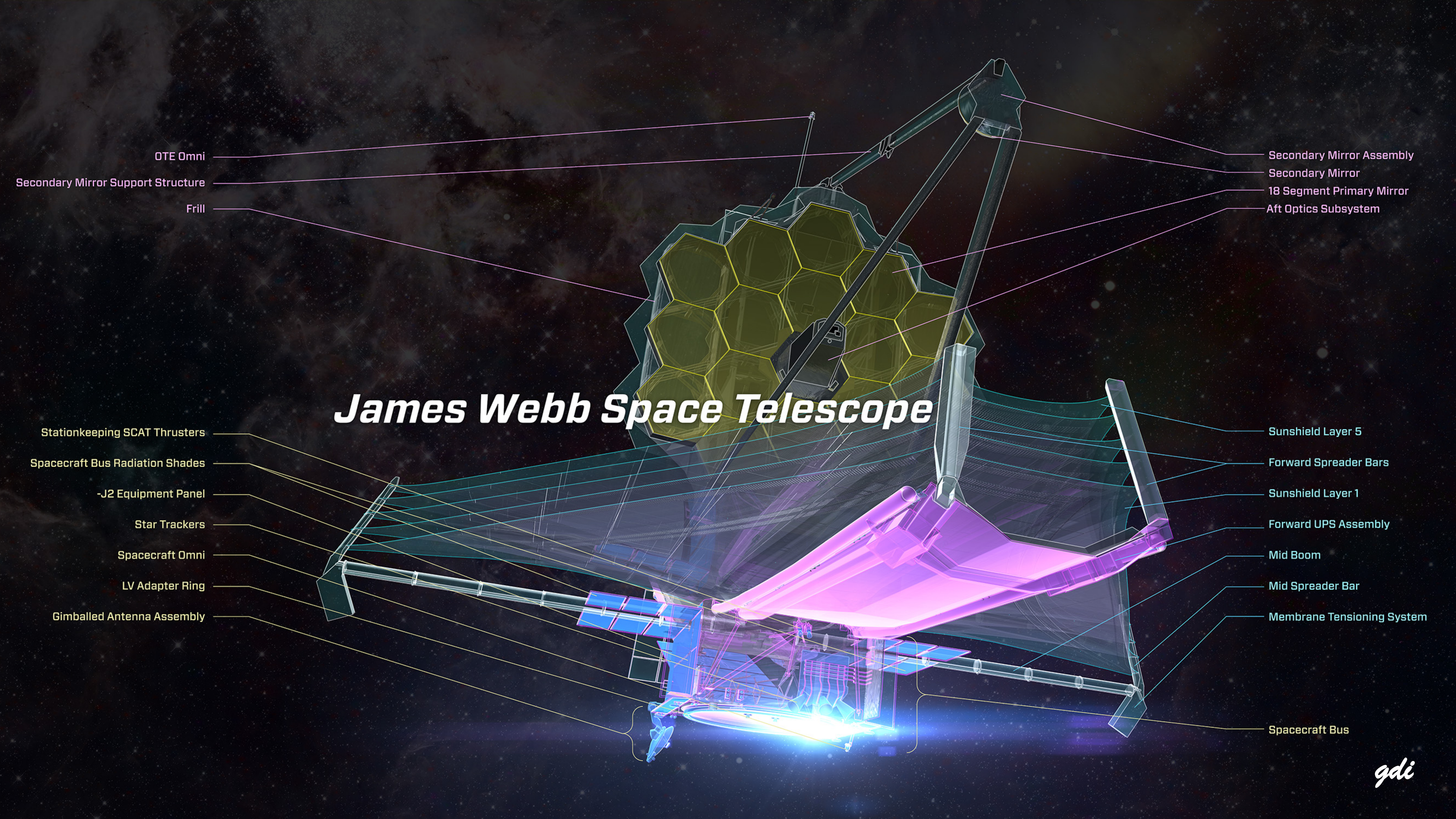
1990 Decadal Survey: UV-Optical in Space Panel recommended:

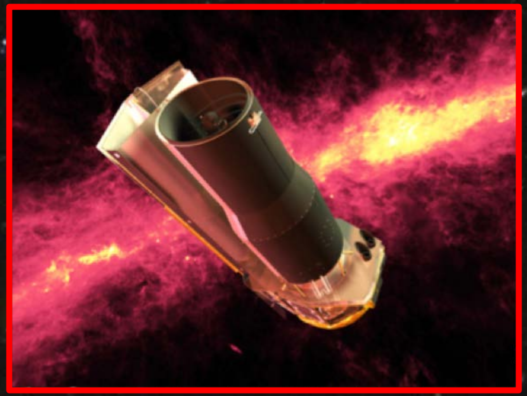
- *6-m passively-cooled infrared telescope*
- *derived a cost of $2B in FY90$ (~$4B in 2018$)*
- *for launch in 2009 to a high orbit*

1991

see 2016 STScI Newsletter article
NGST: The Early Days of JWST
newsletter.stsci.edu/early-webb-history

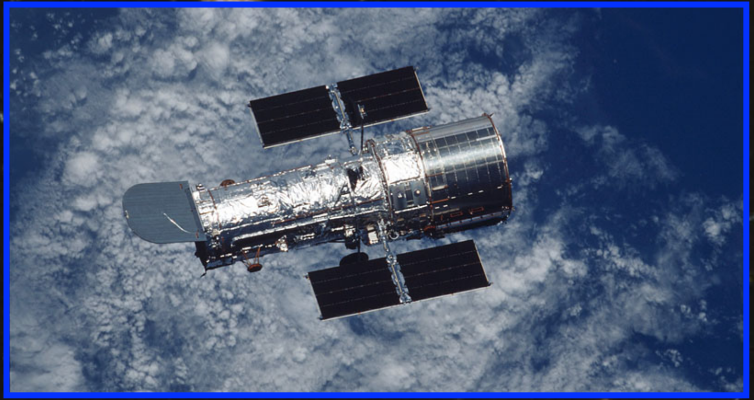
gdi

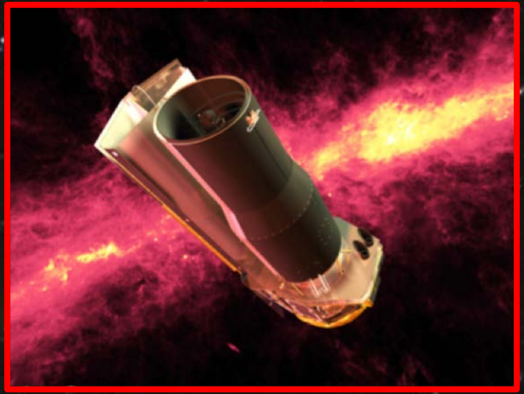

James Webb Space Telescope
OTE Omni
Secondary Mirror Support Structure
Frill
Secondary Mirror Assembly
Secondary Mirror
18 Segment Primary Mirror
Aft Optics Subsystem
Stationkeeping SCAT Thrusters
Spacecraft Bus Radiation Shades
-J2 Equipment Panel
Star Trackers
Spacecraft Omni
LV Adapter Ring
Gimballed Antenna Assembly
Sunshield Layer 5
Forward Spreader Bars
Sunshield Layer 1
Forward UPS Assembly
Mid Boom
Mid Spreader Bar
Membrane Tensioning System
Spacecraft Bus
gdi



galaxies at cosmic dawn

gdi





galaxies at cosmic dawn

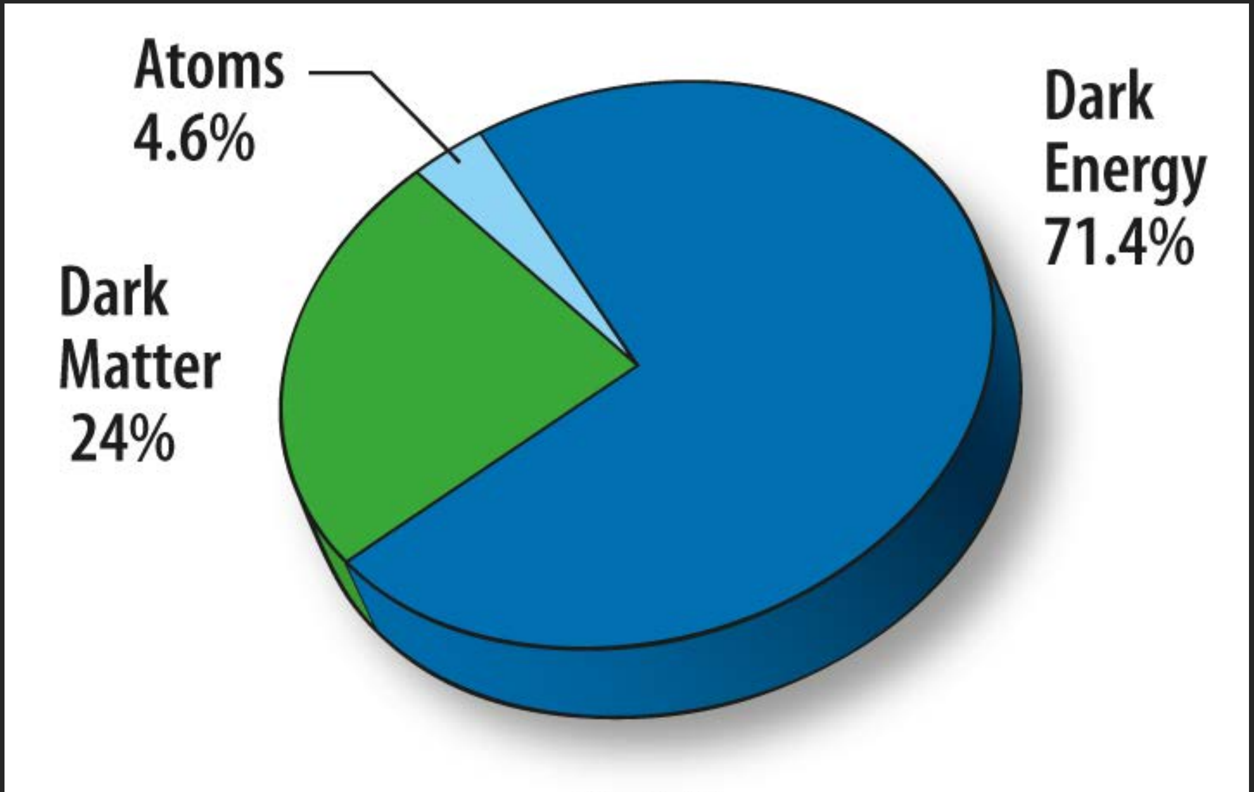
science collaborators & science team members

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

gdi

our strange universe

it is all dark matter & dark energy – and a little bit of ordinary matter "icing on the cake"

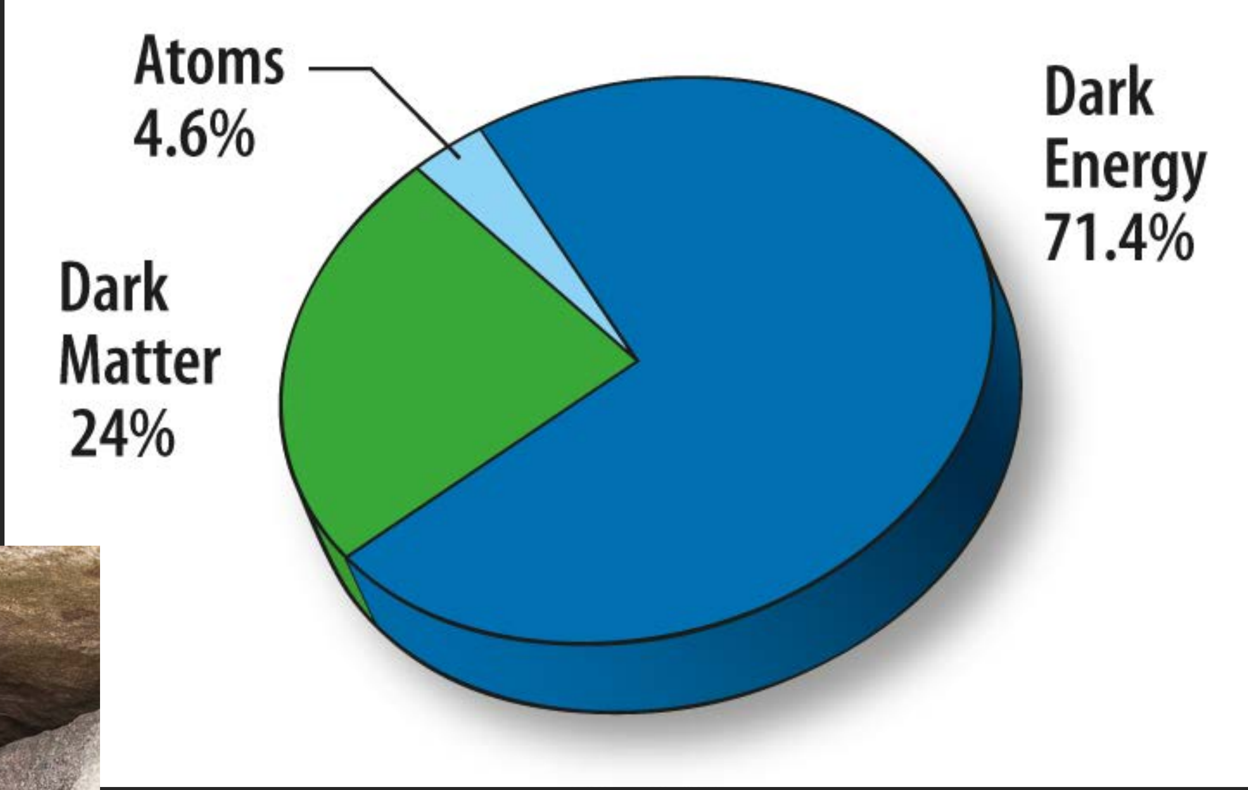


from WMAP and Planck telescopes

gdi

our strange universe

it is all dark matter & dark energy – and a little bit of ordinary matter “icing on the cake”



ordinary matter is, by comparison, a bit mousey…

from WMAP and Planck telescopes

gdi

history of everything

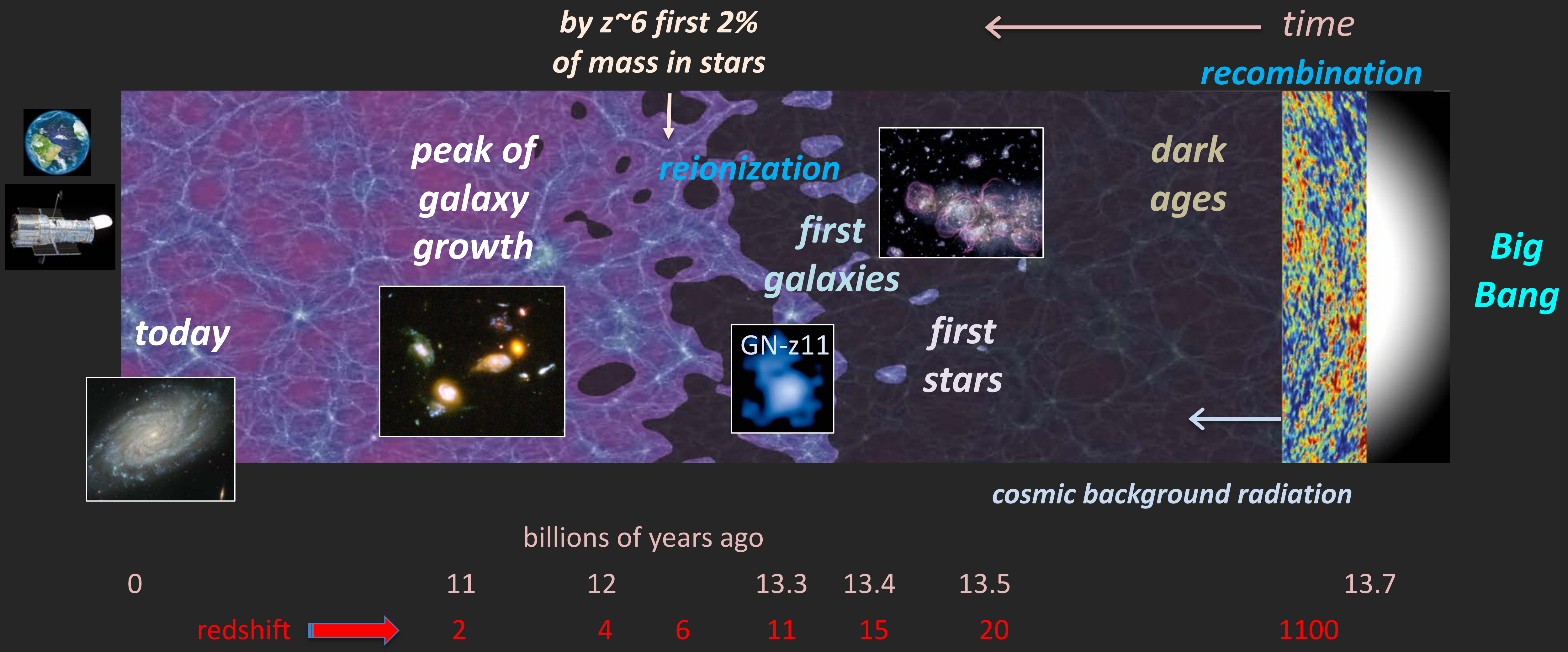


figure credit: insert adapted from Brant Robertson UCSC

gdi

history of everything

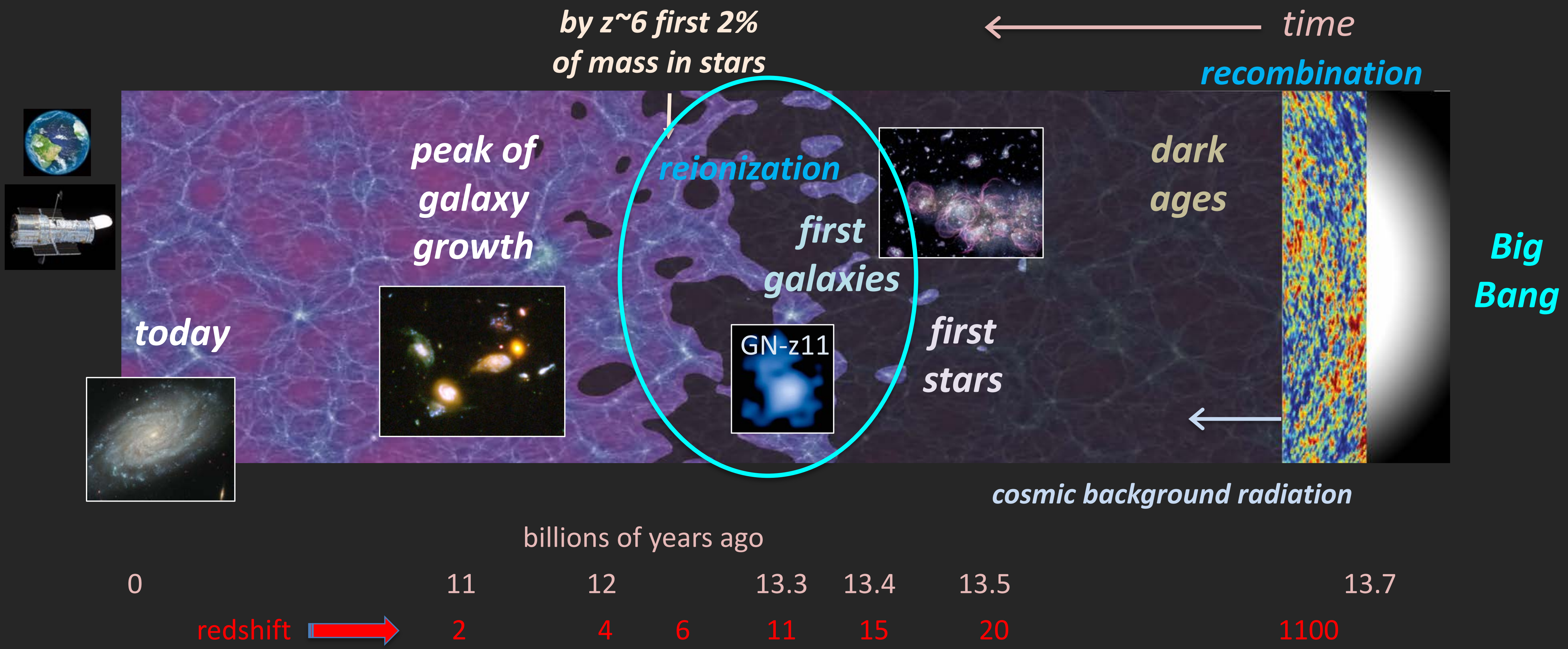
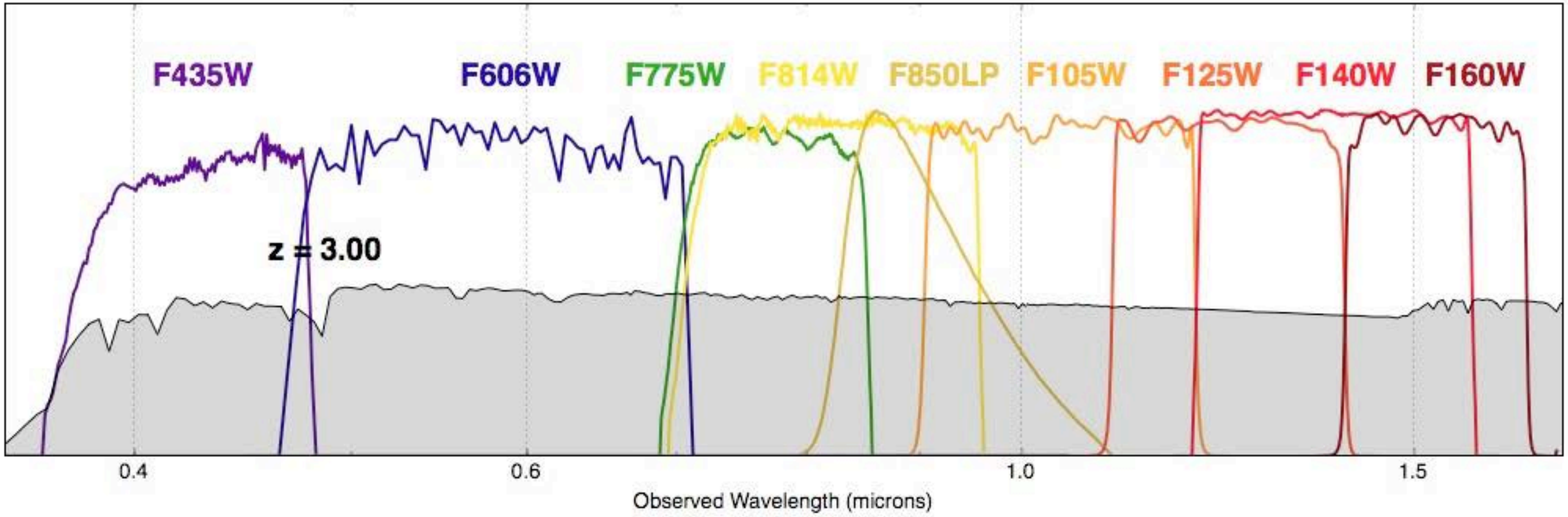
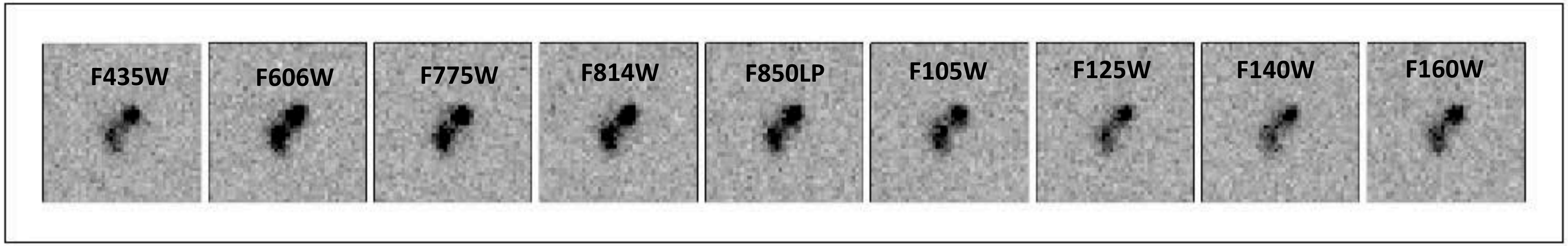


figure credit: insert adapted from Brant Robertson UCSC

gdi

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





optical ACS

near-IR WFC3/IR

xdf.ucolick.org/

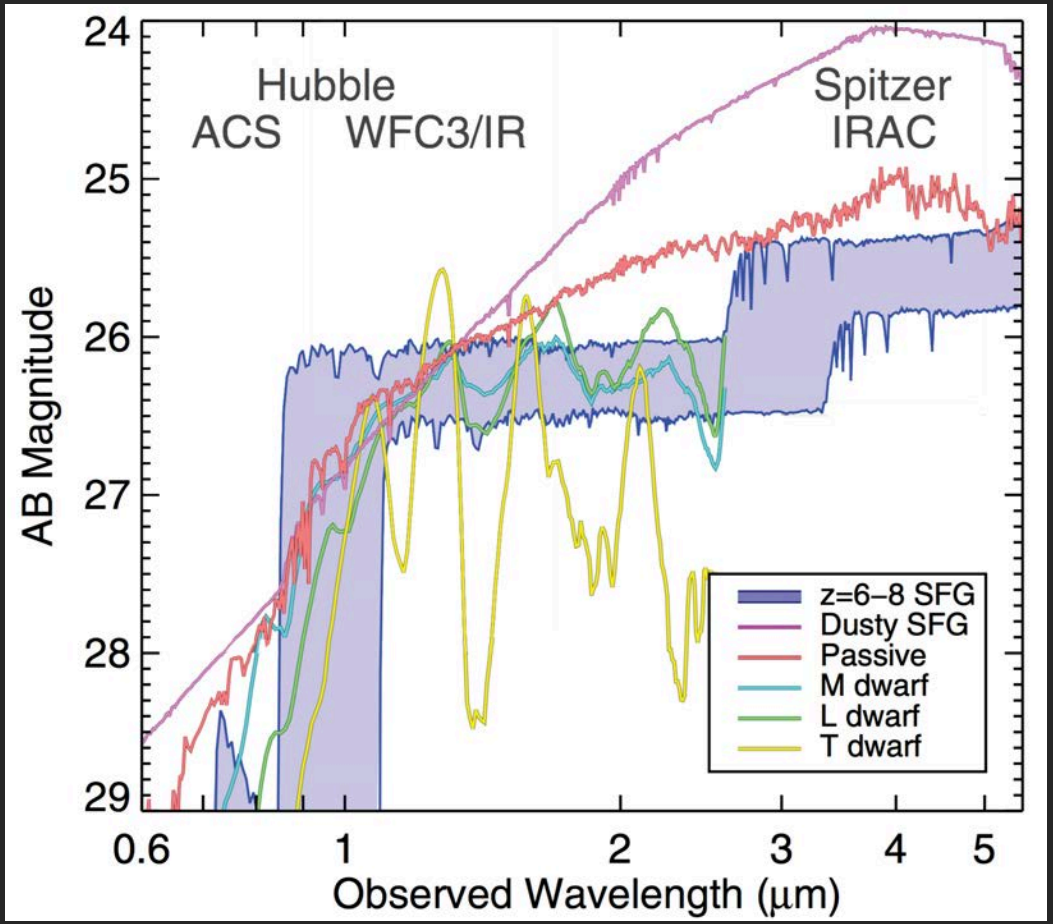
photometric redshifts

enable large, statistically-robust samples

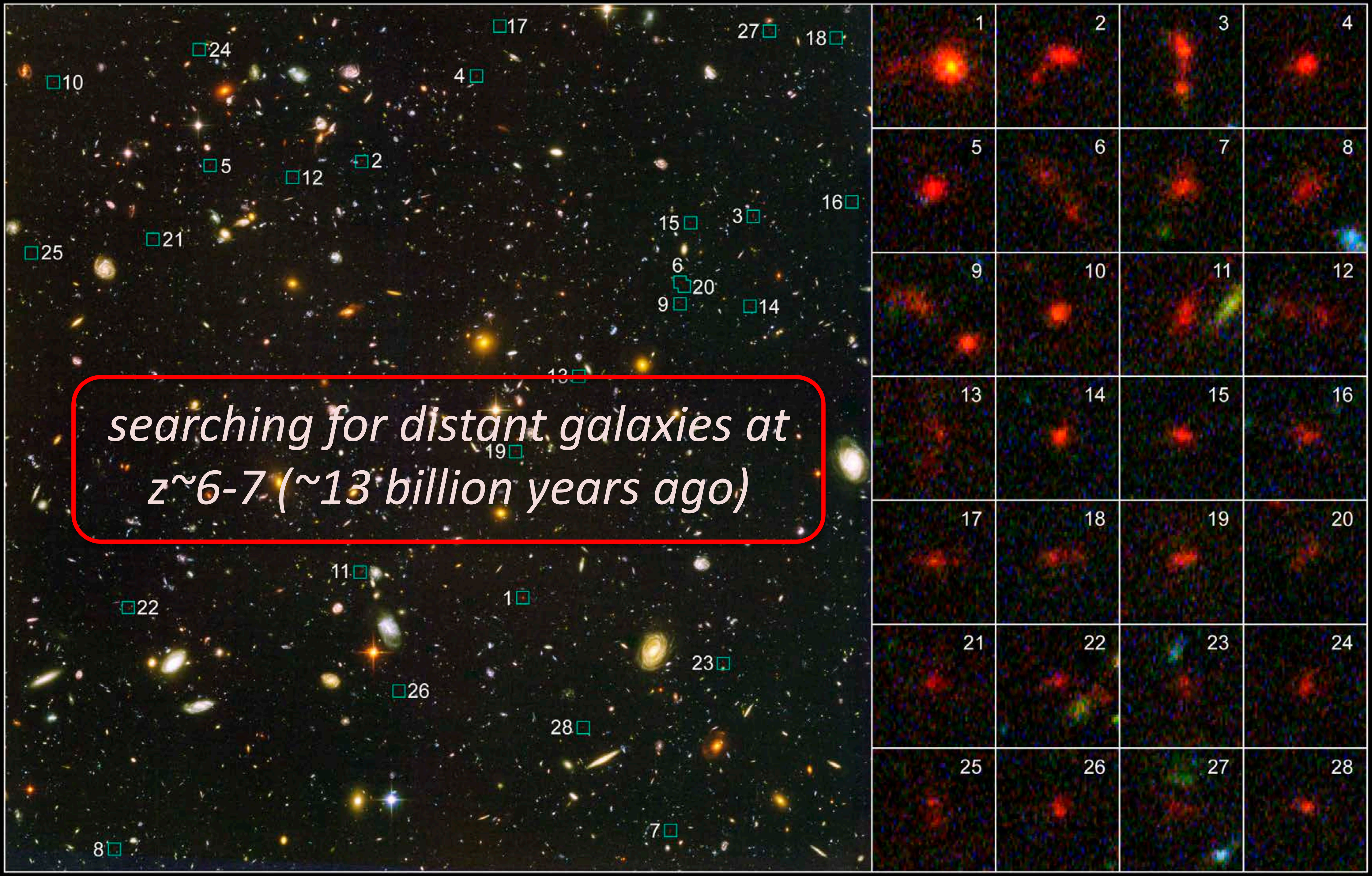
Lyman break galaxies – LBGs (“dropouts”)

LBGs have a distinctly different shape for their spectral energy distribution (SED) leading to

☞ reliable photometric redshift selection



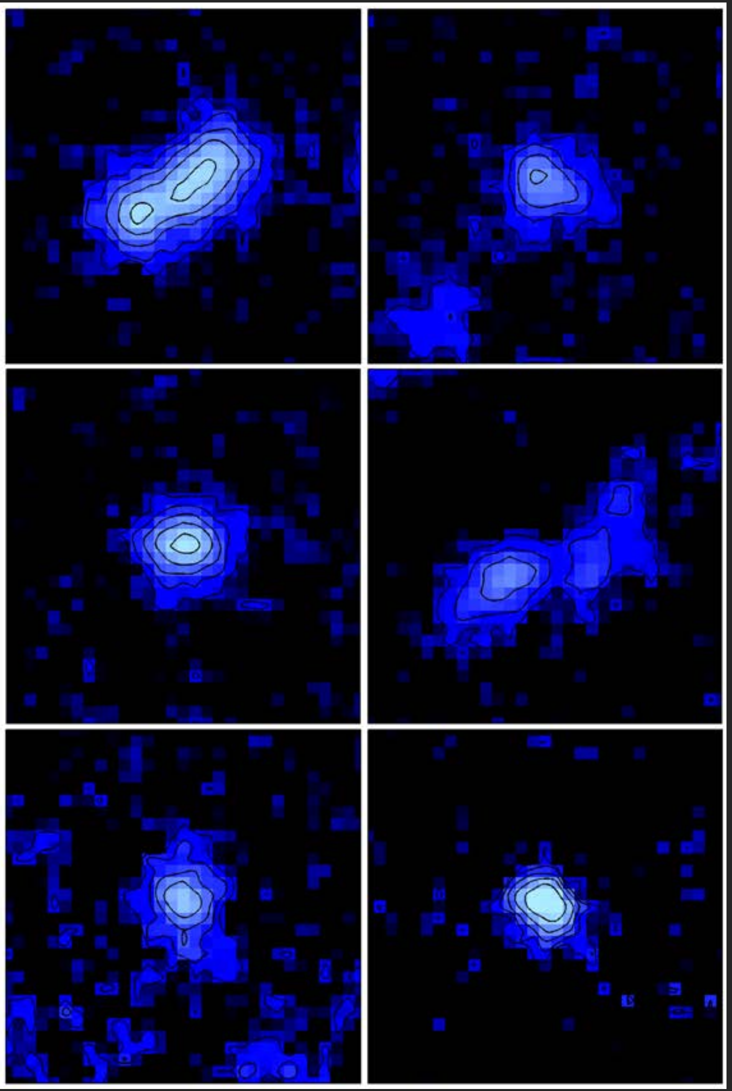
Finkelstein 2016



very distant galaxies look red in our images

gdi

1.8” (~10 kpc)



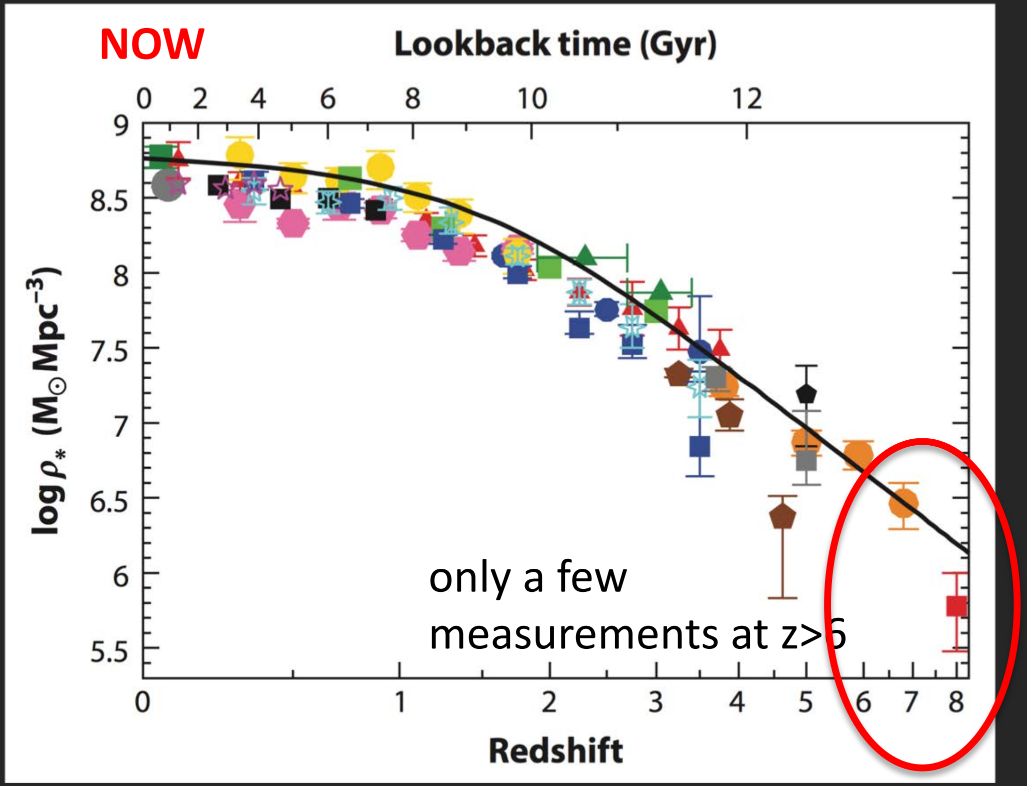
what have we learned about galaxies in the first several billion years

a sample of bright galaxies
about 900 million years
after the Big Bang

have been represented in blue
to better convey what they
really look like

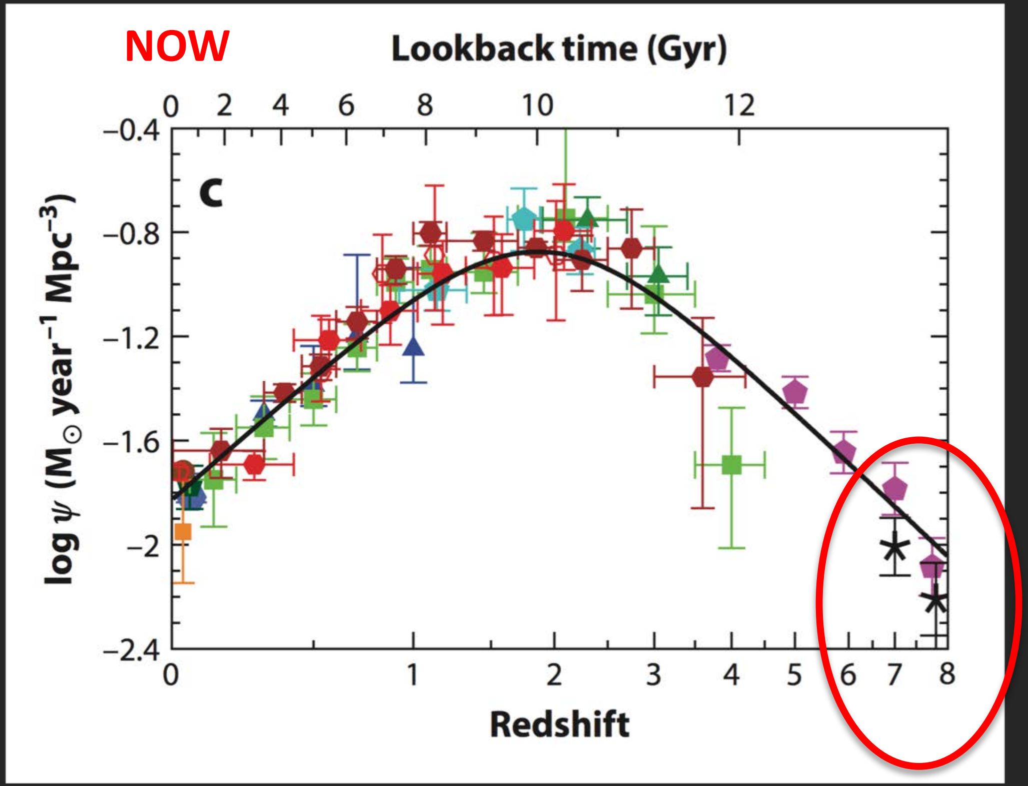
gdi

evolution of stellar mass and star formation over 13 billion years



First Gyr

evolution of the mass density in stars



First Gyr

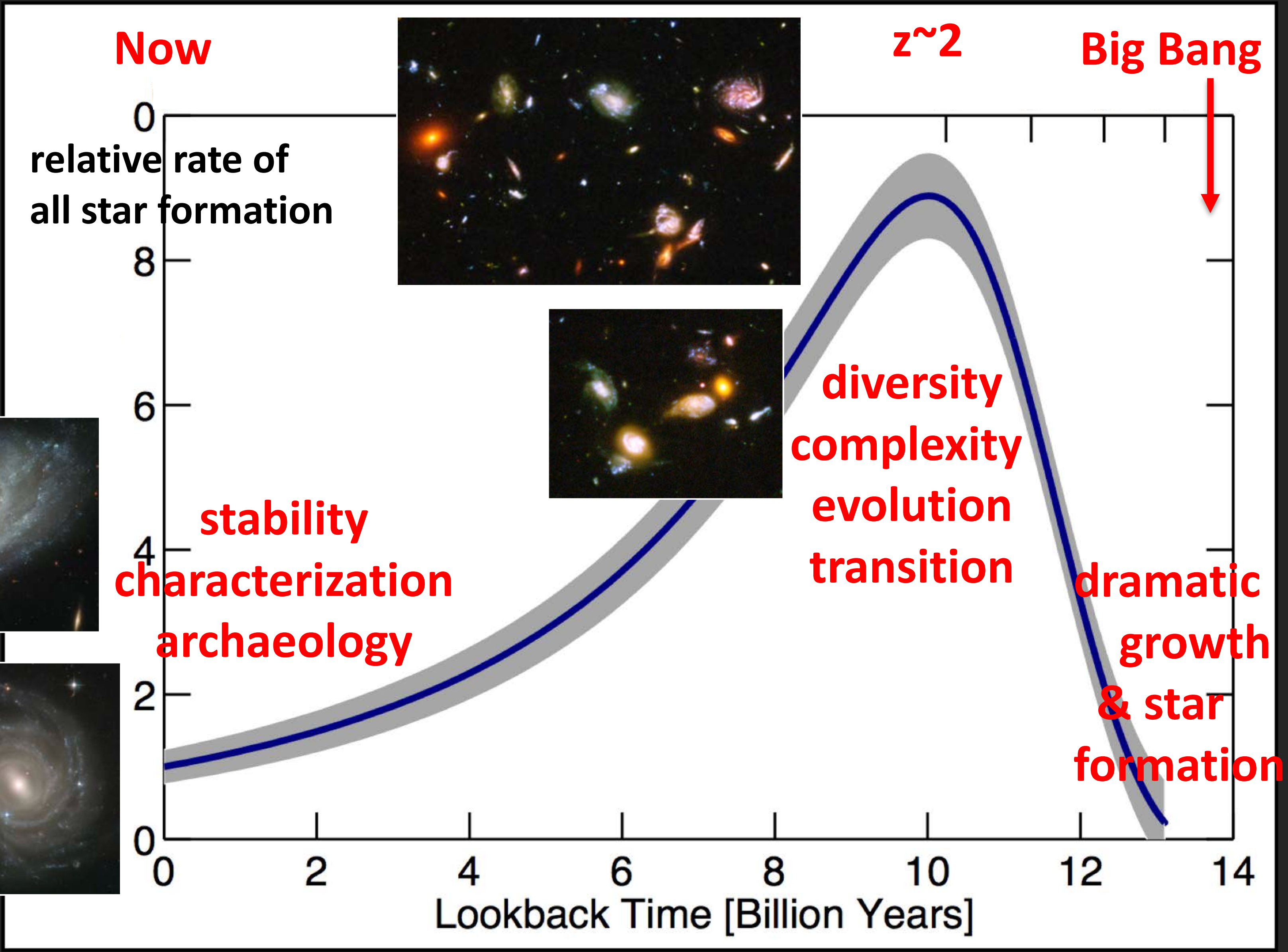
evolution of the star formation rate density

note that at z~8 (650 Myr) – just 0.3% of stellar mass built-up

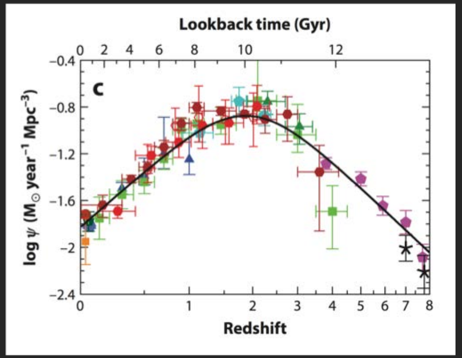
Madau & Dickinson 2014

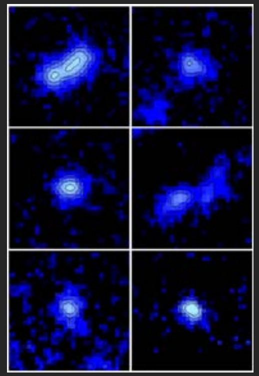
gdi

cosmic star formation over all time



revealing the star formation rate density over 96% of time

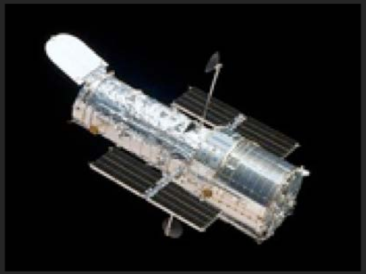


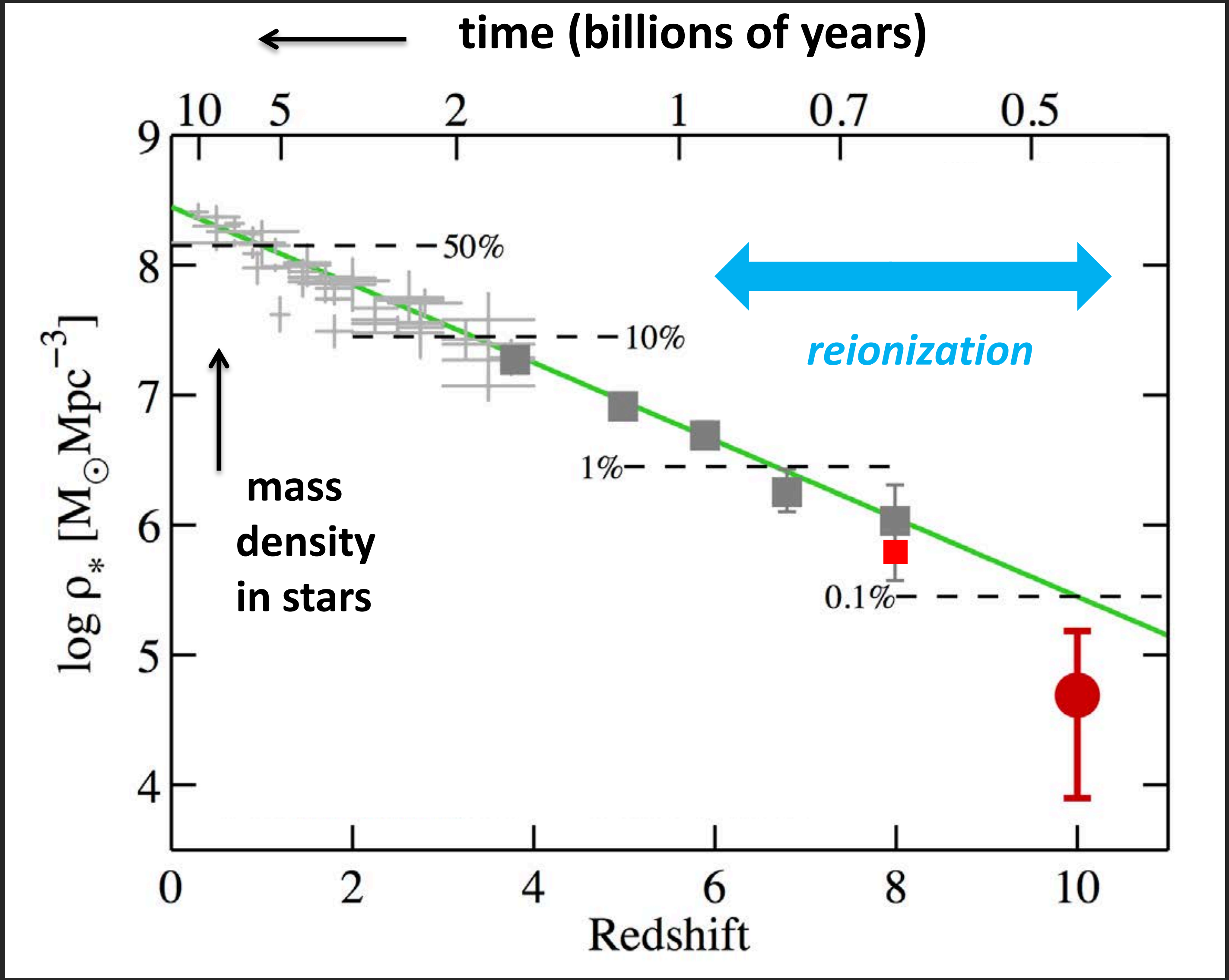


linear figure credit:
Pascal Oesch

gdi

buildup of mass in the universe in stars





Oesch+2014

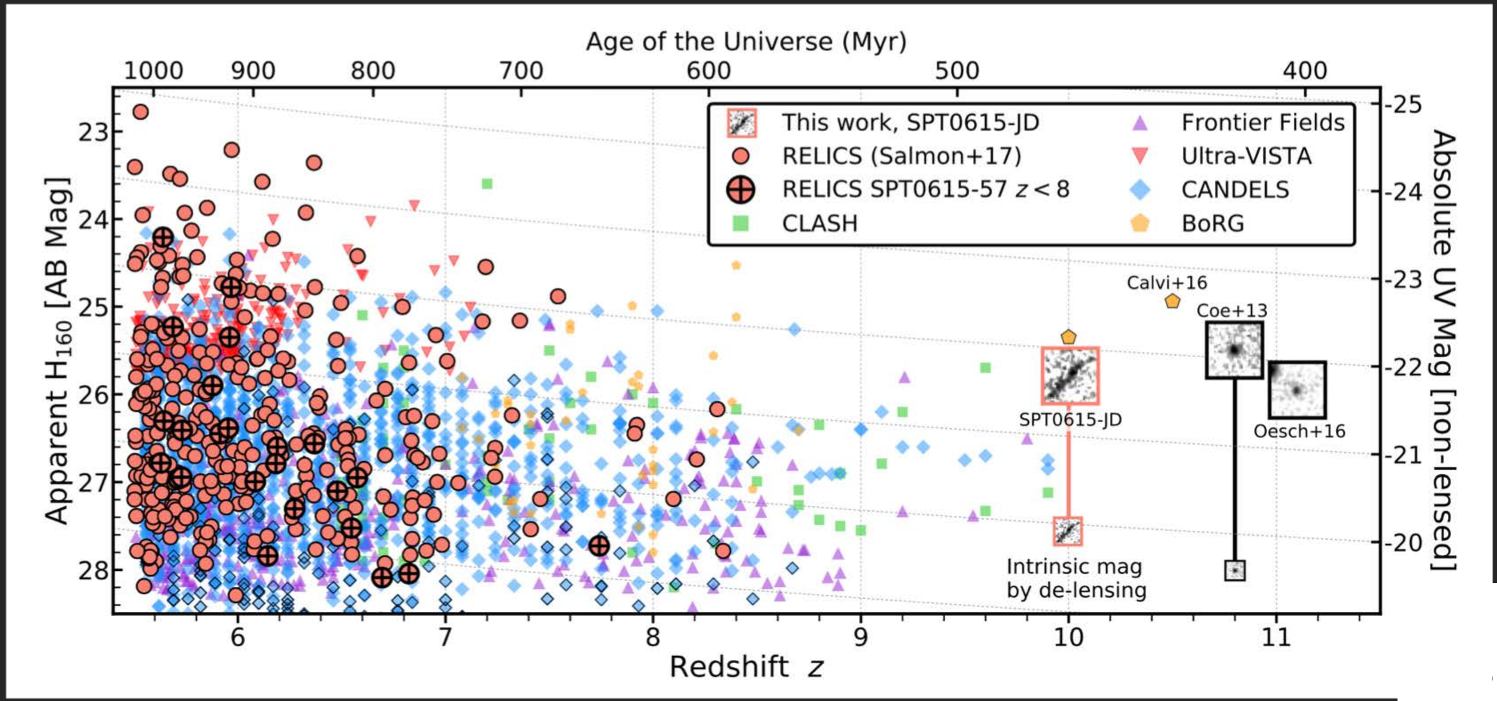
only ~2% of stellar mass density built up by the end of reionization

only ~0.1% at the start of reionization at z~10 (see later)

gdi

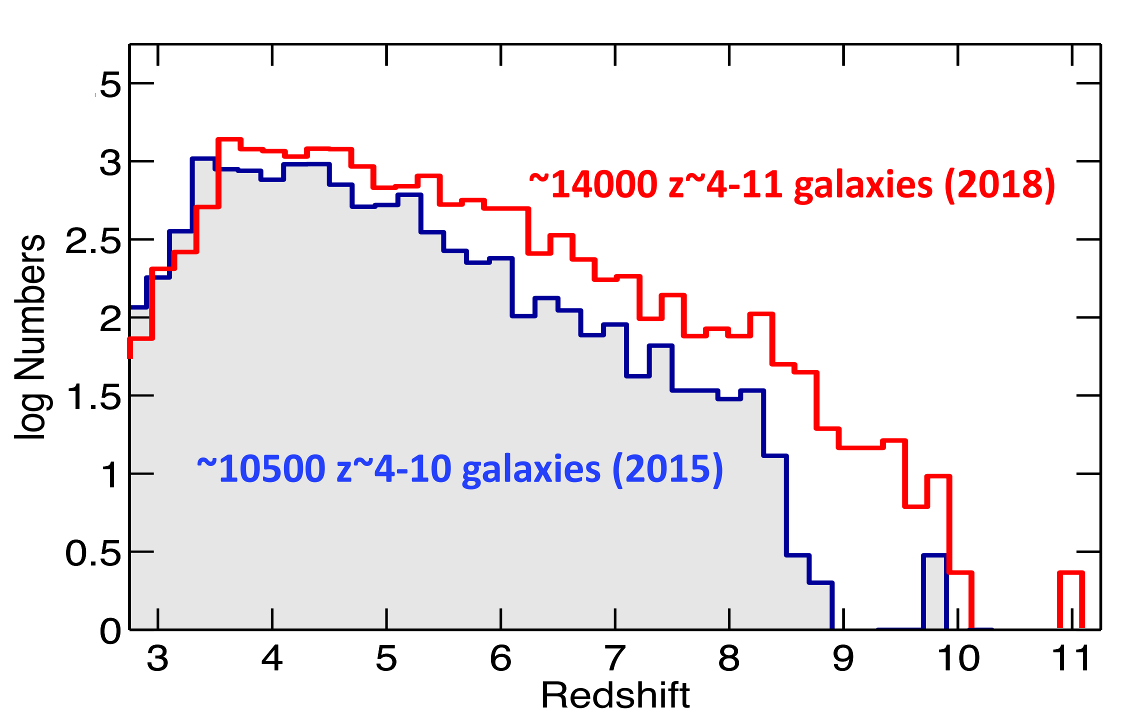
high-redshift galaxies

WFC3/IR opened up the reionization epoch at z>6



Salmon+2017

Hubble Frontier Fields have now added many more galaxies



Bouwens GDI Oesch+15

very large samples of z>4 galaxies from Hubble

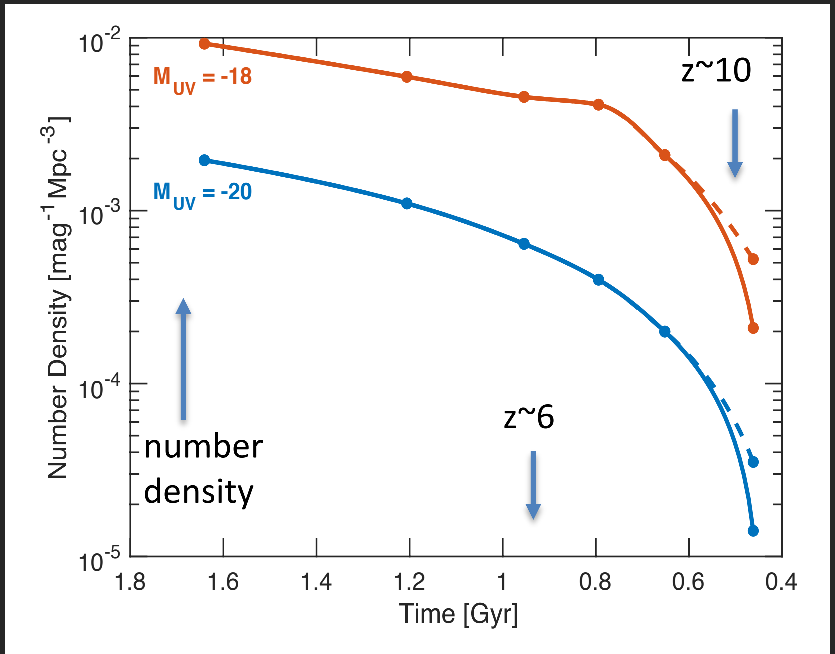
ground surveys also now have resulted in very large samples but largely at z<5-6 – (and are not shown)

gdi

Cosmic Dawn – the time of the first stars and galaxies

the first billion years → we see galaxies building up extremely rapidly from redshift z~10 to z~6 (480 million years to 1 billion years)

a time of rapid growth of the dark matter halos within which galaxies form

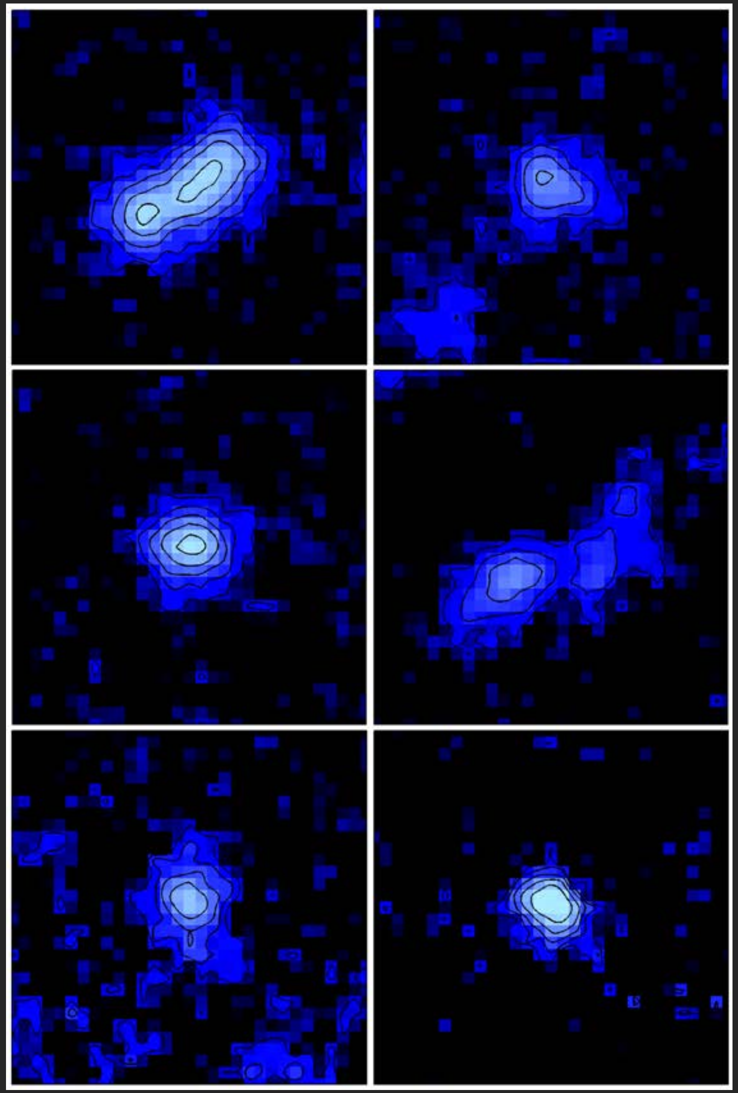


a time when significant quantities of heavier elements were produced in stars and ejected into the gas in galaxies

a time when the universe was reionized...

HST and Spitzer have let us explore in this fascinating period

gdi

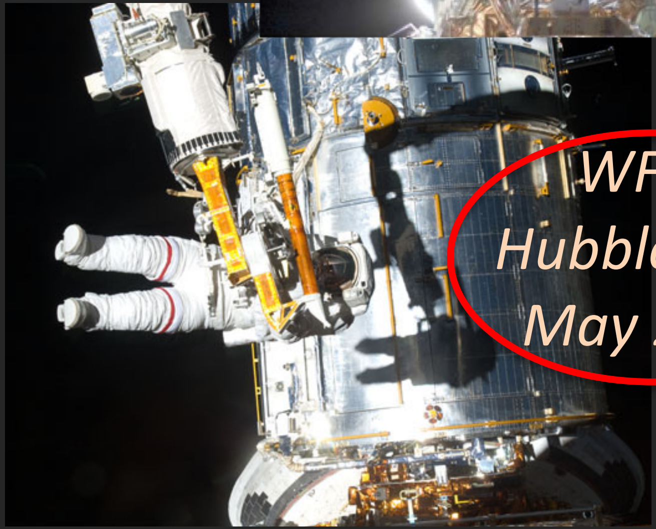


how have we learned about galaxies in the first billion years

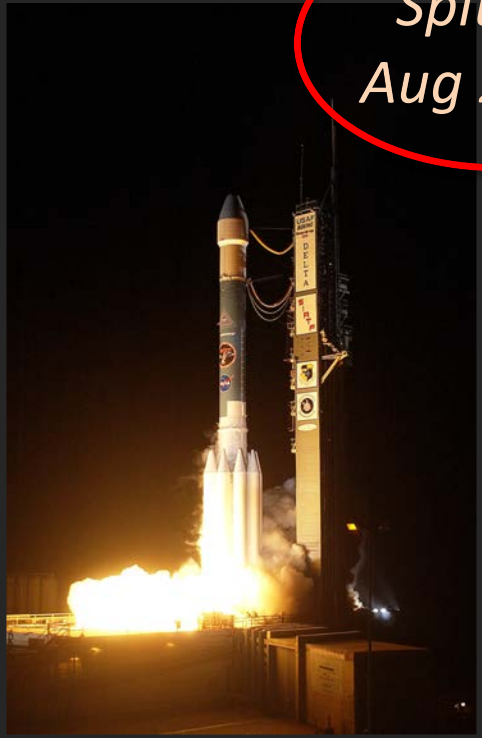
gdi

the telescopes and cameras that enabled the exploration of the early universe

ACS
Hubble SM3B
Mar 2002



WFC3
Hubble SM4
May 2009



Spitzer
Aug 2003

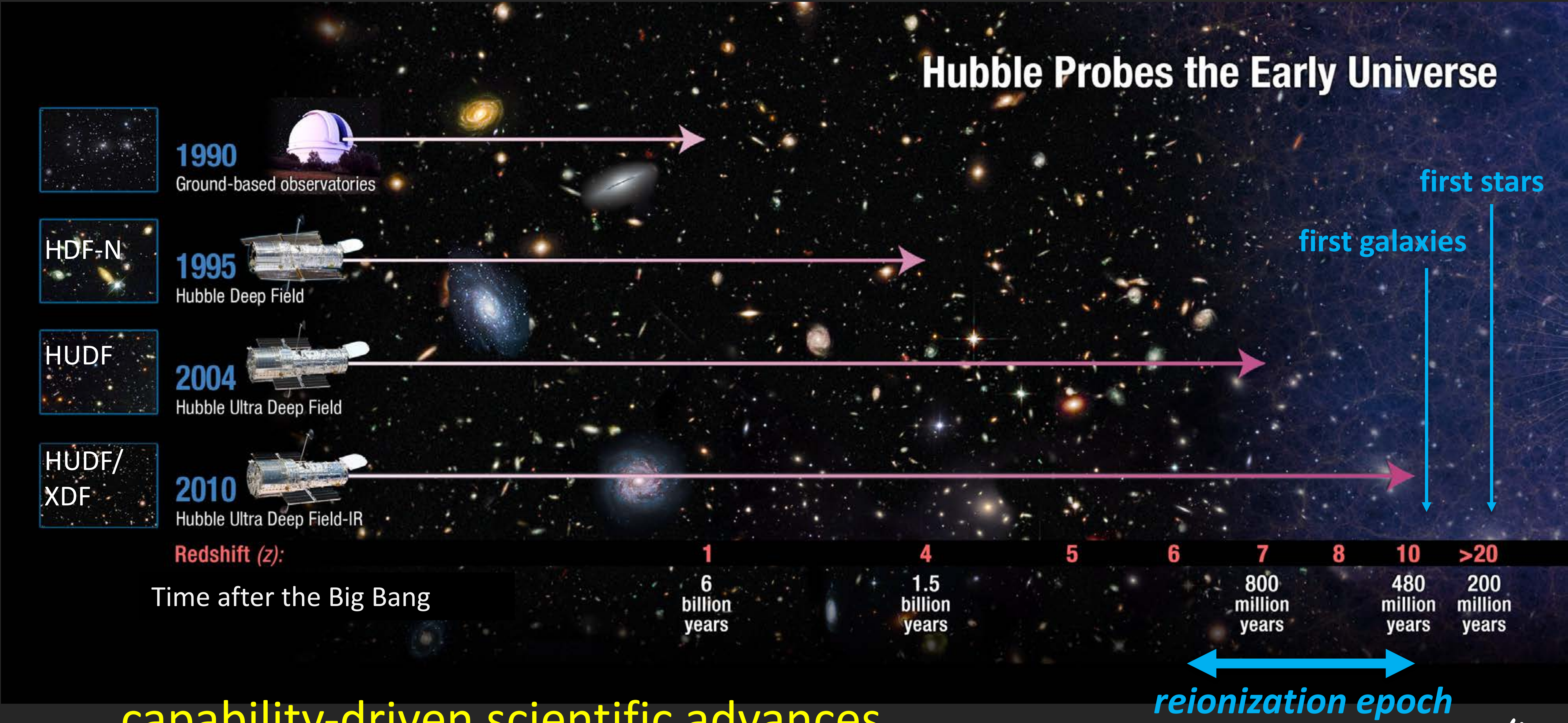
upgraded Hubble
ACS in 2002
WFC3 in 2009

launched Spitzer in 2003

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

gdi

redshift limits increase with new capability



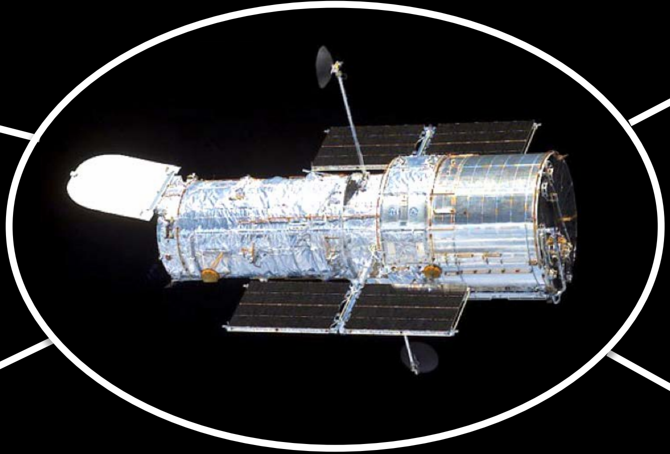
capability-driven scientific advances

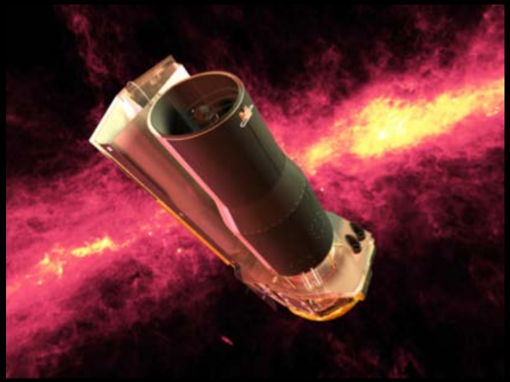
gdi

Hubble’s partners for distant galaxies

Chandra
Great Observatory

Hubble
Great Observatory

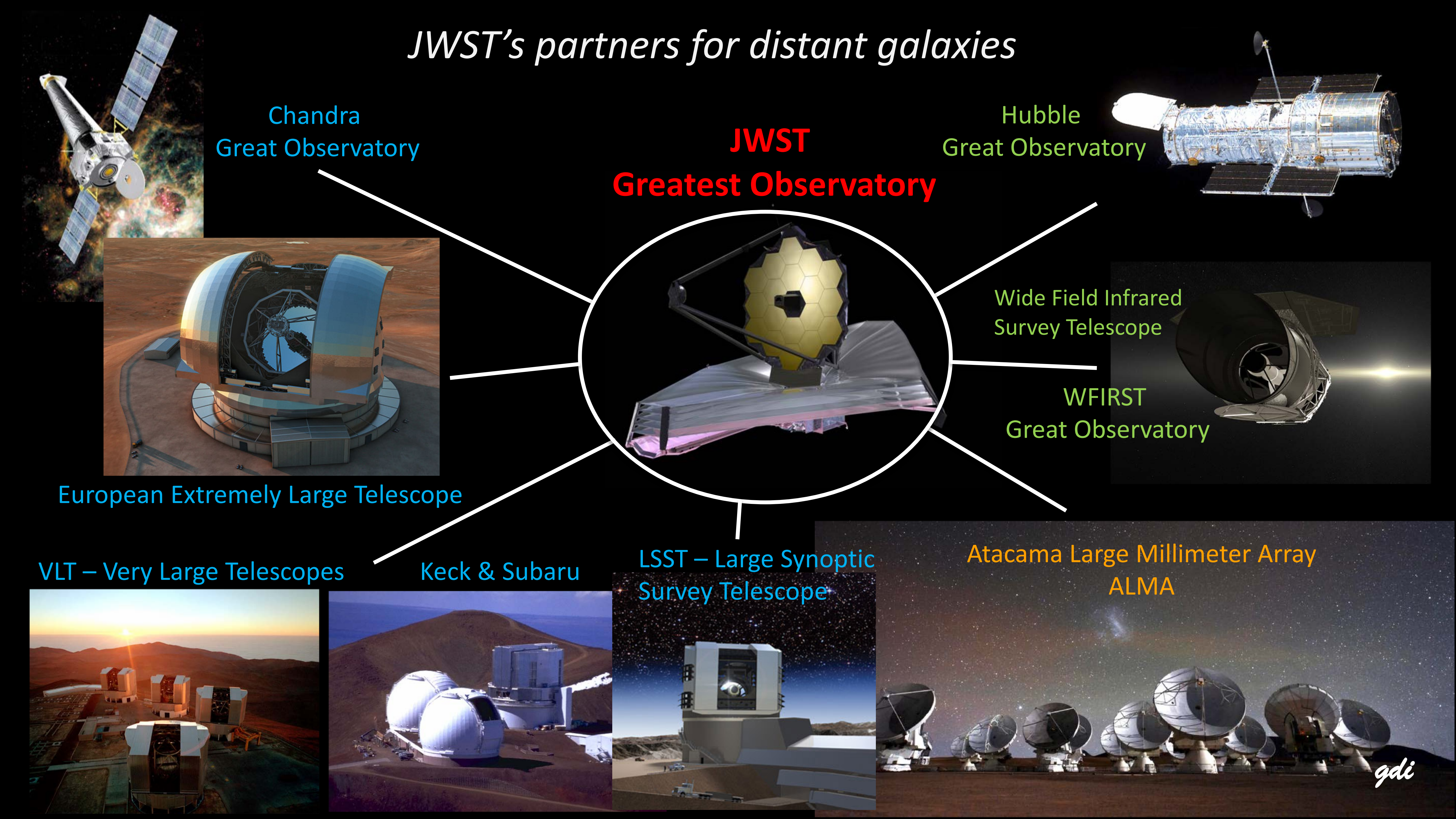


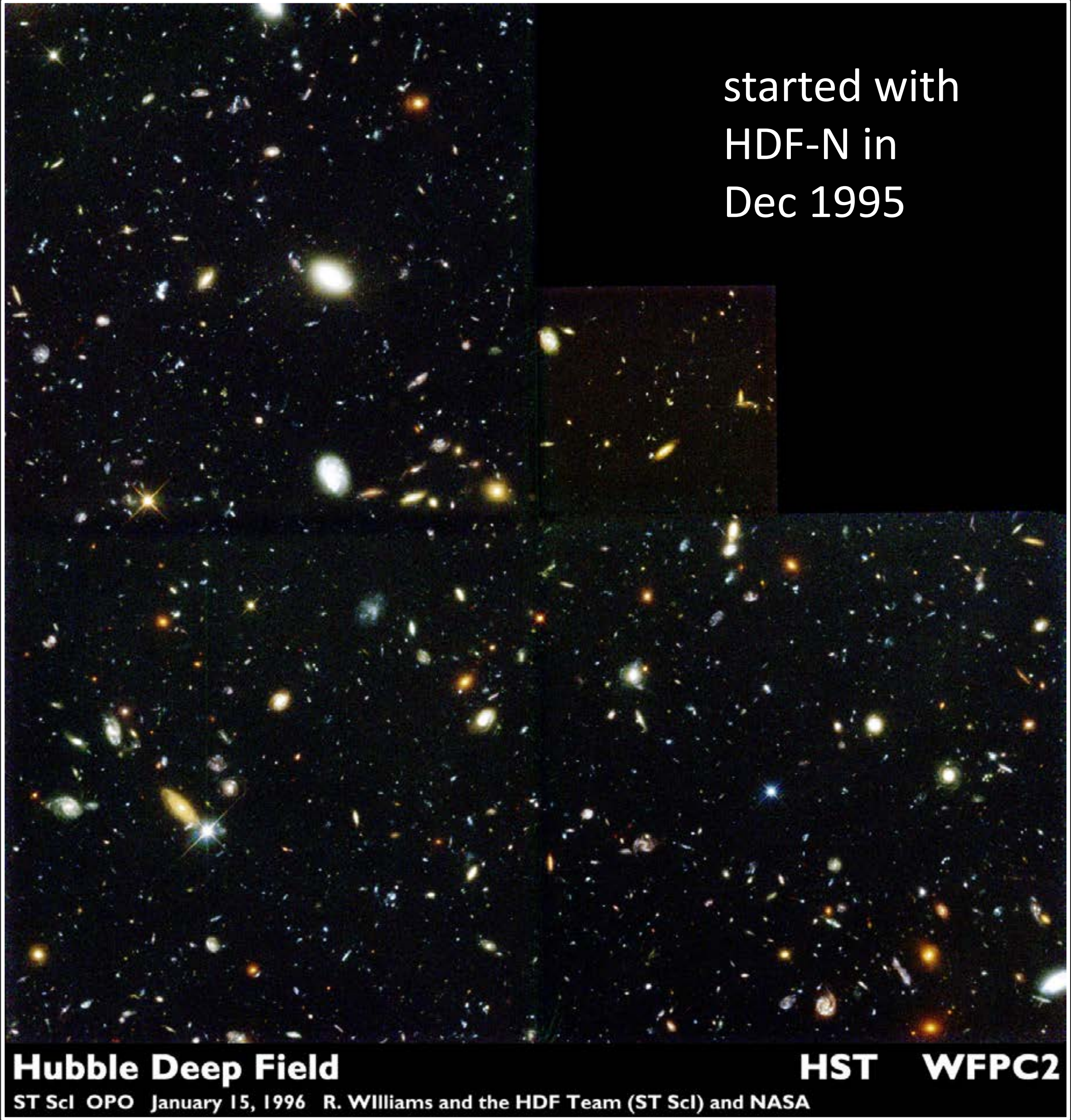


Spitzer
Great Observatory

VLT – Very Large telescope

Keck & Subaru telescopes


JWST's partners for distant galaxies
Chandra
Great Observatory
JWST
Greatest Observatory
Hubble
Great Observatory
Wide Field Infrared
Survey Telescope
WFIRST
Great Observatory
European Extremely Large Telescope
VLT – Very Large Telescopes
Keck & Subaru
LSST – Large Synoptic
Survey Telescope
Atacama Large Millimeter Array
ALMA
gdi



the survey datasets used for high-redshift galaxy studies

gdi

Hubble and Spitzer survey fields for high-redshift galaxies

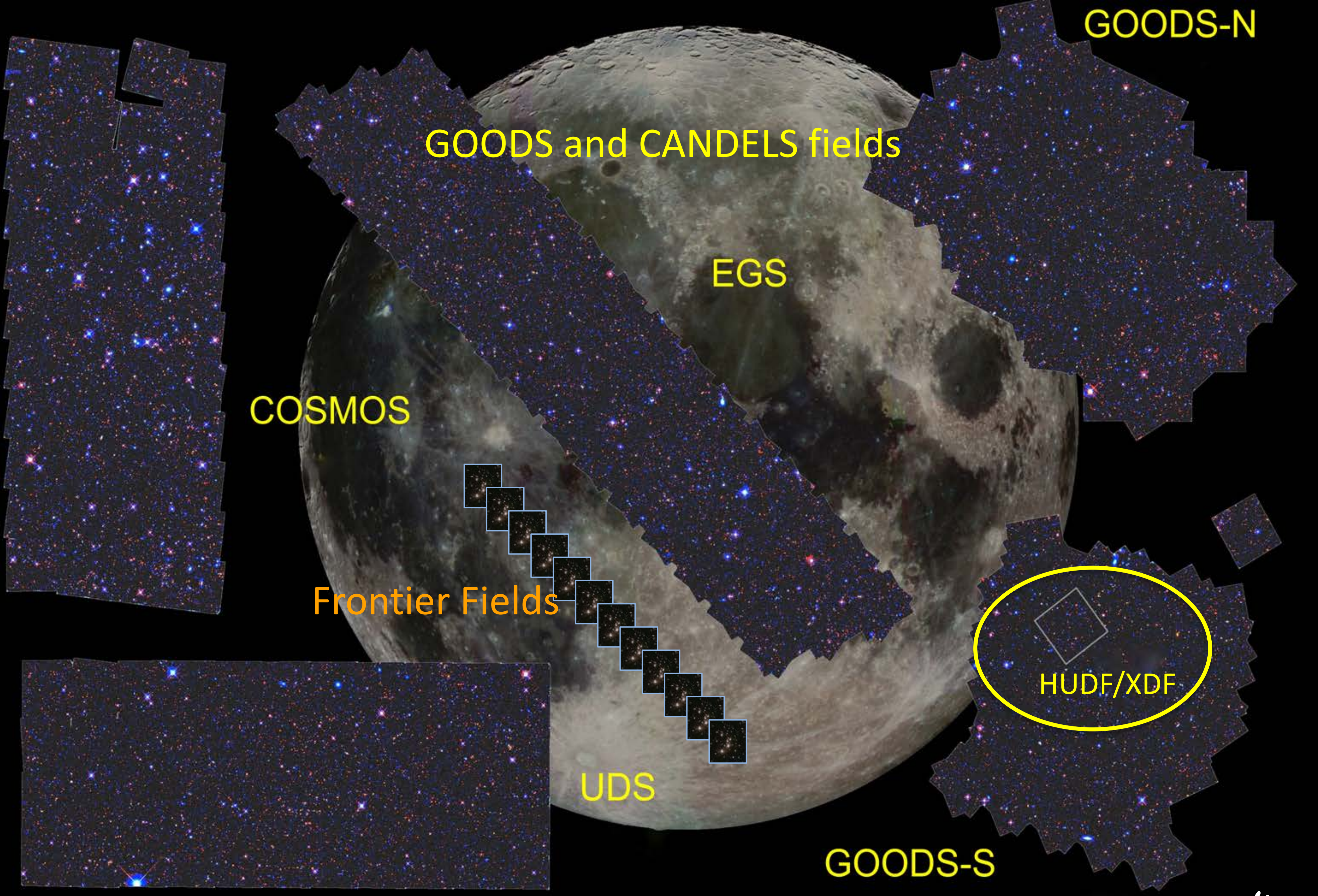


figure credit: Harry Ferguson and the CANDELS team

XDF/HUDF (*eXtreme Deep Field)*

deepest ever Hubble image

2963 HST images

from 800 orbits of Hubble

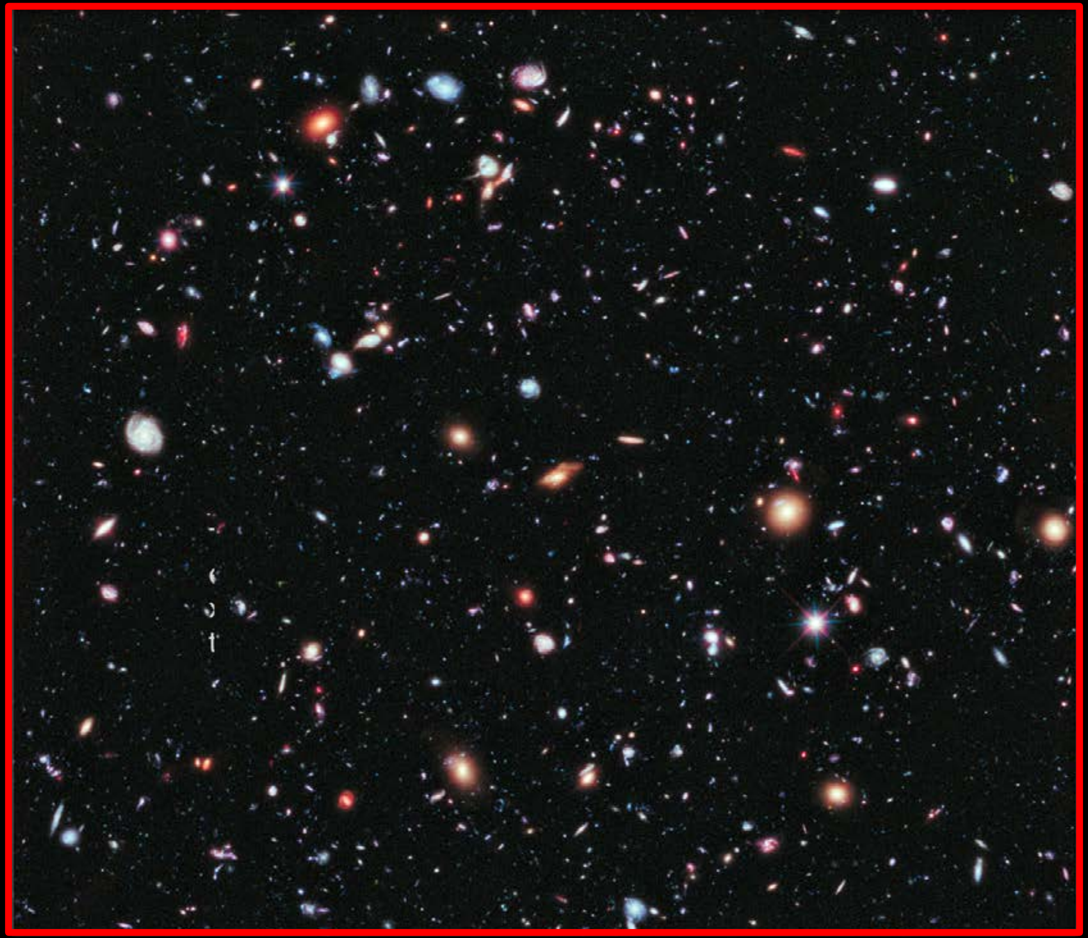
for a 23 day total exposure on the HUDF!

all optical ACS data and all infrared WFC3/IR data on the HUDF from 2003-2013 from 19 programs

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

xdf.ucolick.org

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

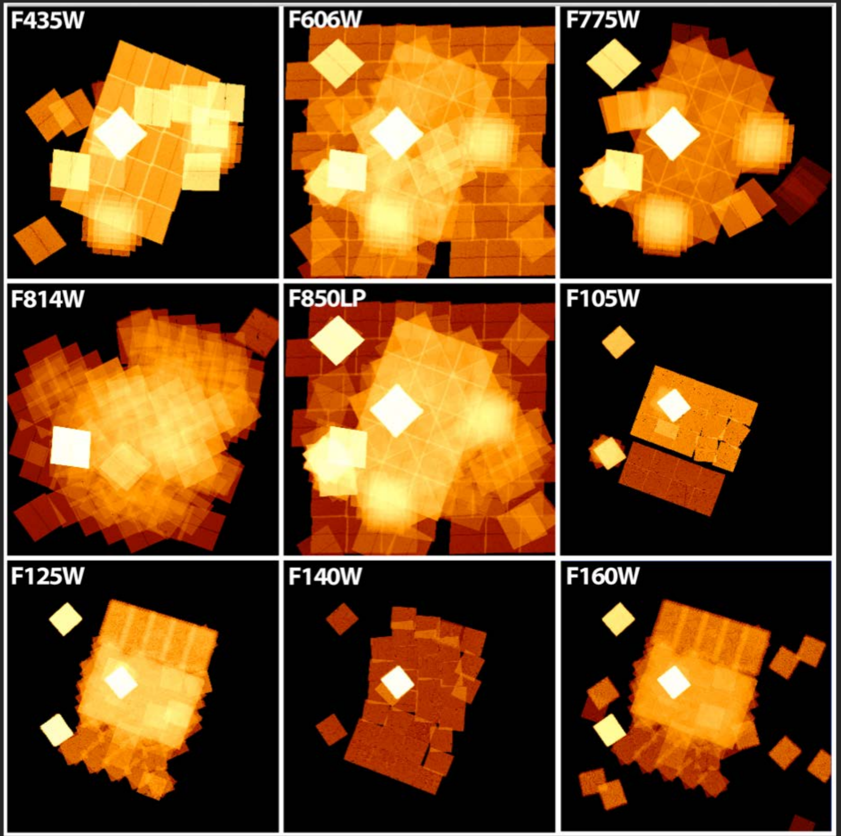
2012
NASA, ESA,
G. Illingworth, D. Magee, and P. Oesch (University of California, Santa Cruz),
R. Bouwens (Leiden University), and the XDF Team

gdi

CDF-S/GOODS-S/CANDELS-S – a remarkable and unique region

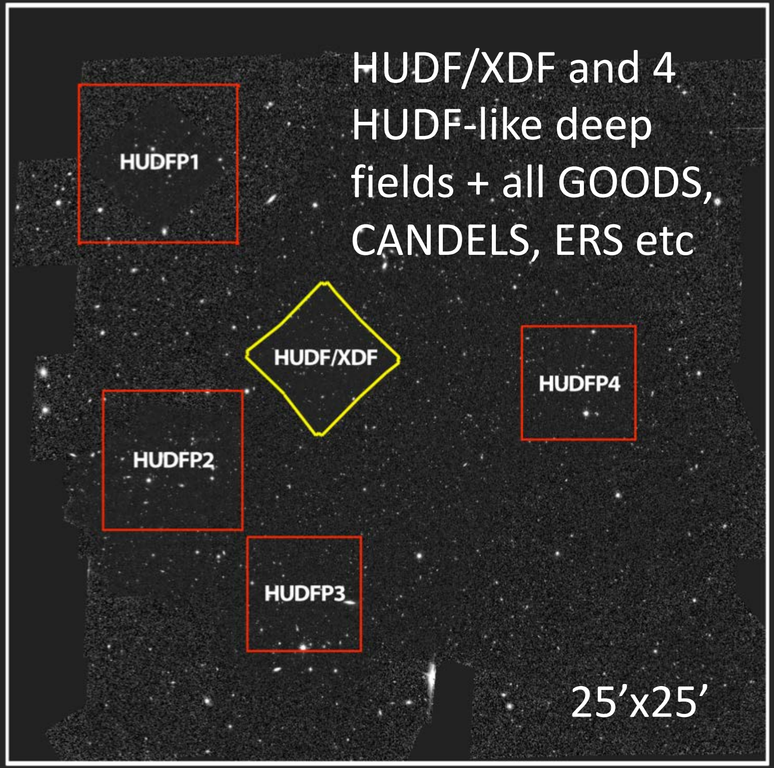
Hubble Legacy Field South (HLF-GOODS-S)

7211 exposures from 2442 orbits



ACS + WFC3/IR – 10 filters in the V1.5 release (+098M)

5.8 Msec or ~70% of a Hubble Cycle



152 GB of aligned astrometric HST images

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

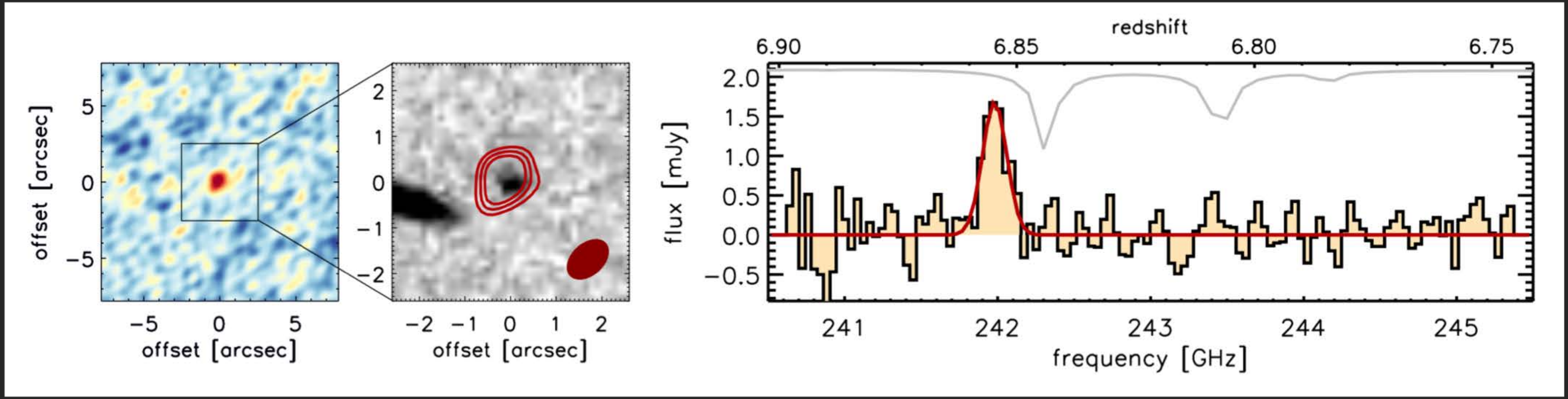
GDI Magee+2016, 2017

gdi

another remarkable new measurement from ALMA

gdi

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



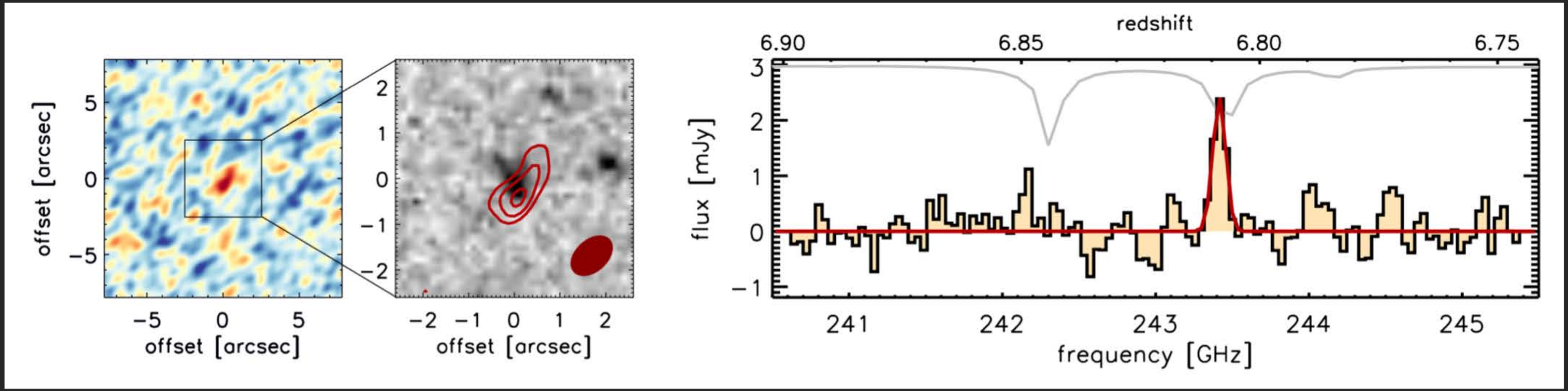
COS-3018555981

ALMA narrowband

HST image + ALMA (+ ALMA beam)

$z_{[CII]}$ = 6.8540±0.0003

$z_{[CII]}$ = 6.8076±0.0002



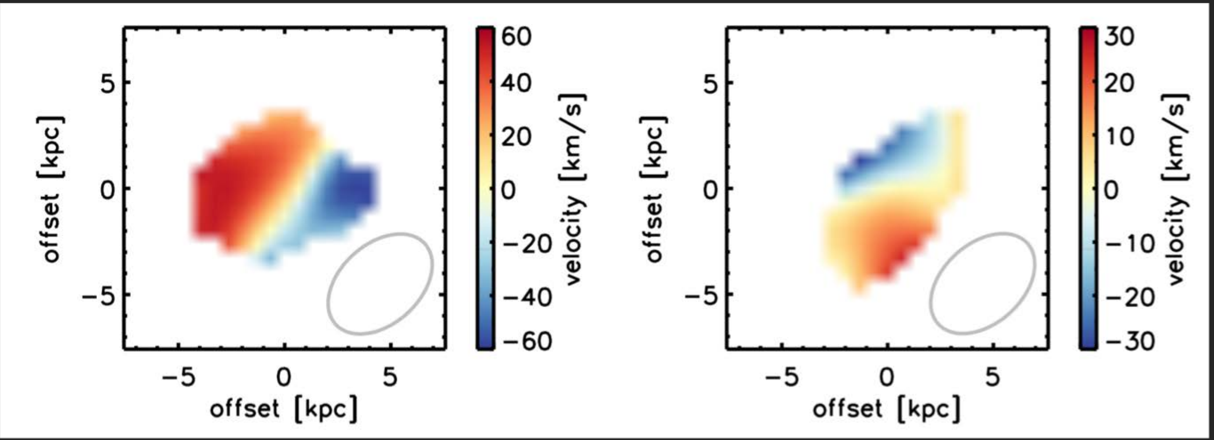
COS-2987030247

Smit + 2017

gdi

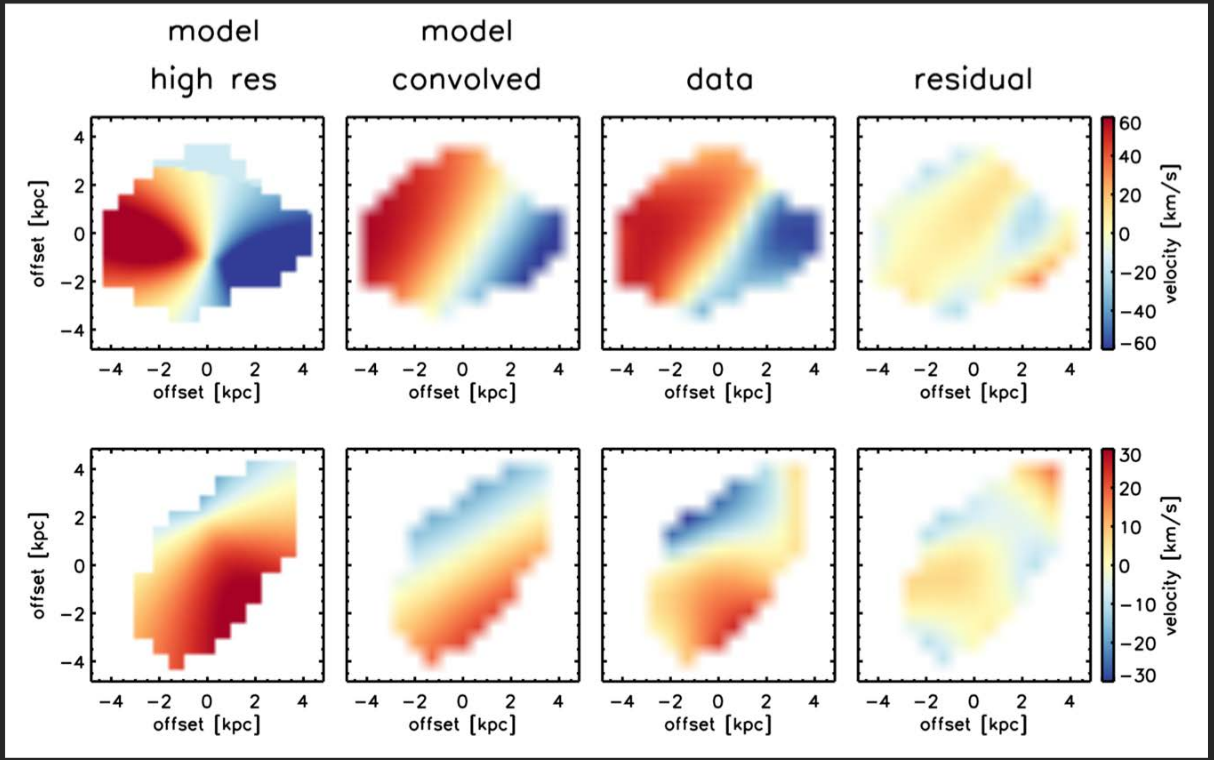
ALMA [C II] 157.74μm redshifts and velocity structure in two z~6.8 galaxies

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



velocity structure in the two galaxies

rotation models compared to data

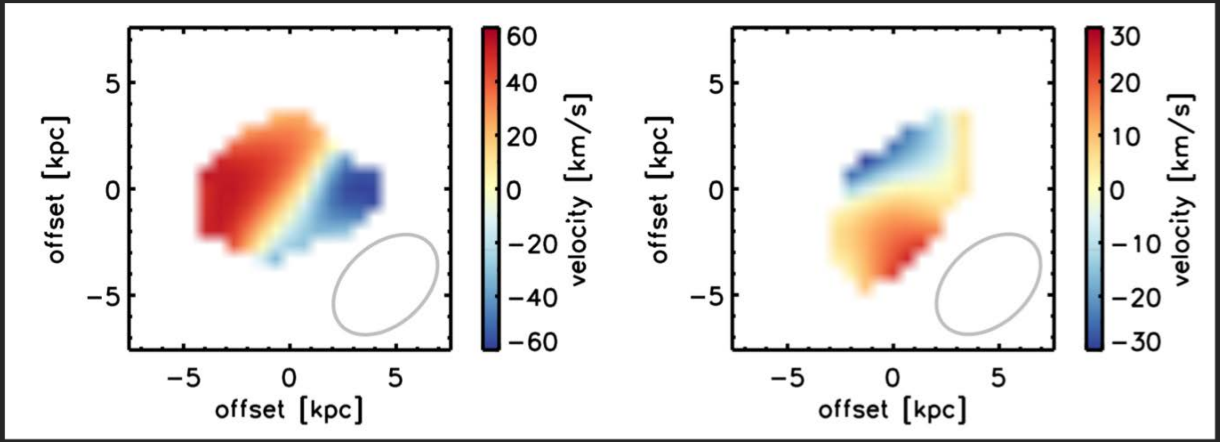


Smit + 2017

gdi

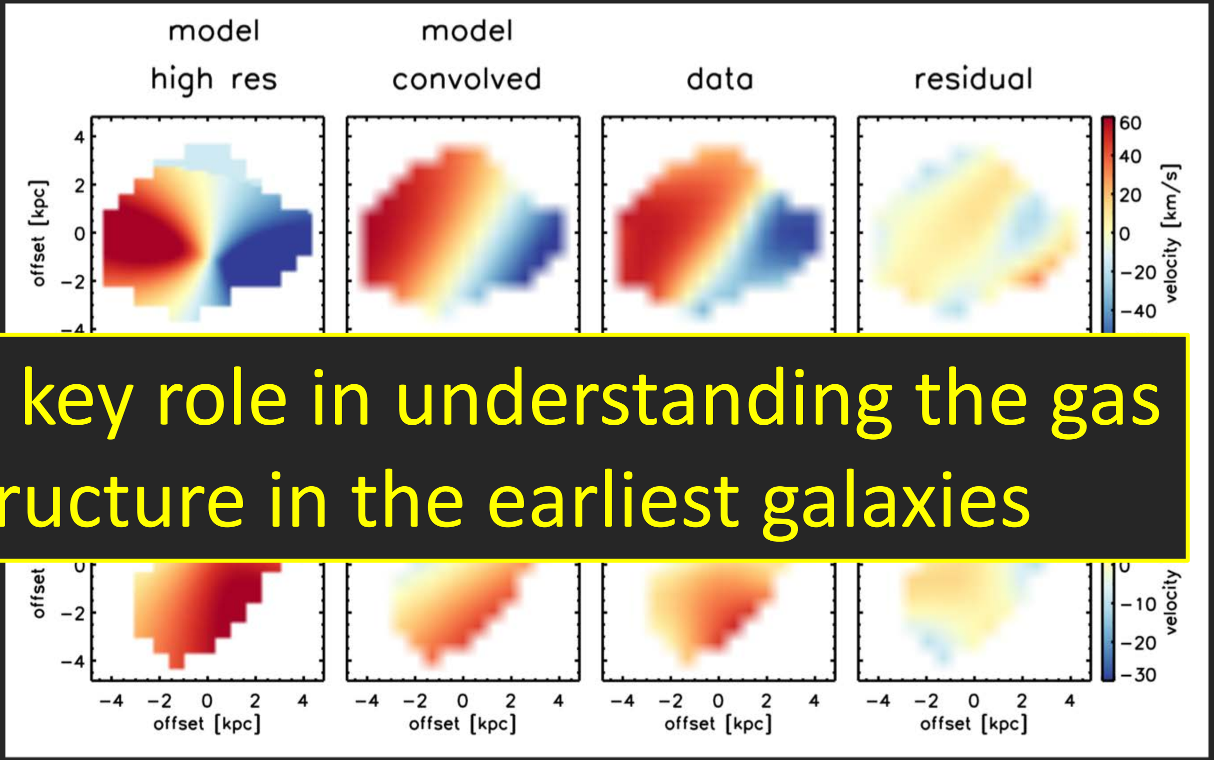
ALMA [C II] 157.74μm redshifts and velocity structure in two z~6.8 galaxies

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

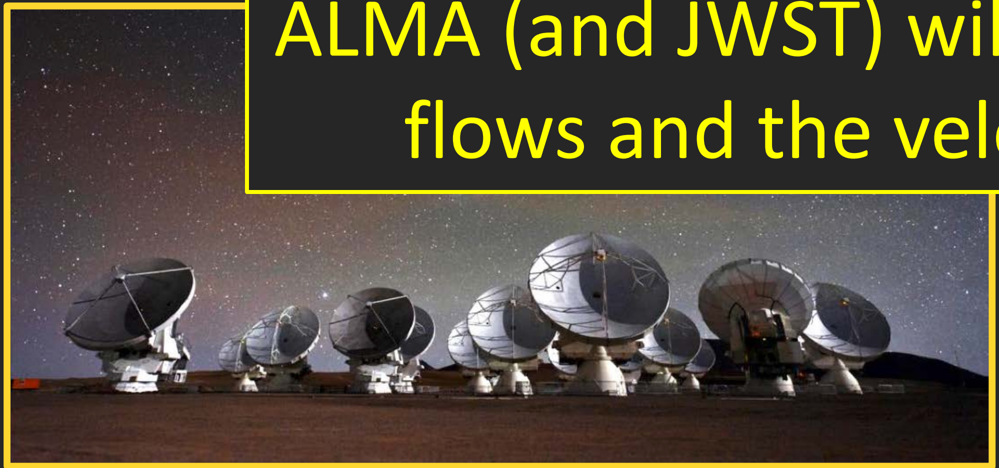


velocity structure in the two galaxies

rotation models compared to data



ALMA (and JWST) will play a key role in understanding the gas flows and the velocity structure in the earliest galaxies



Smit + 2017

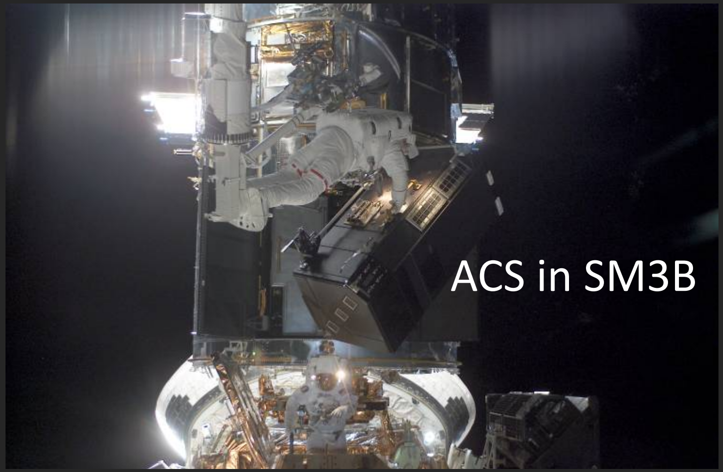
gdi

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

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

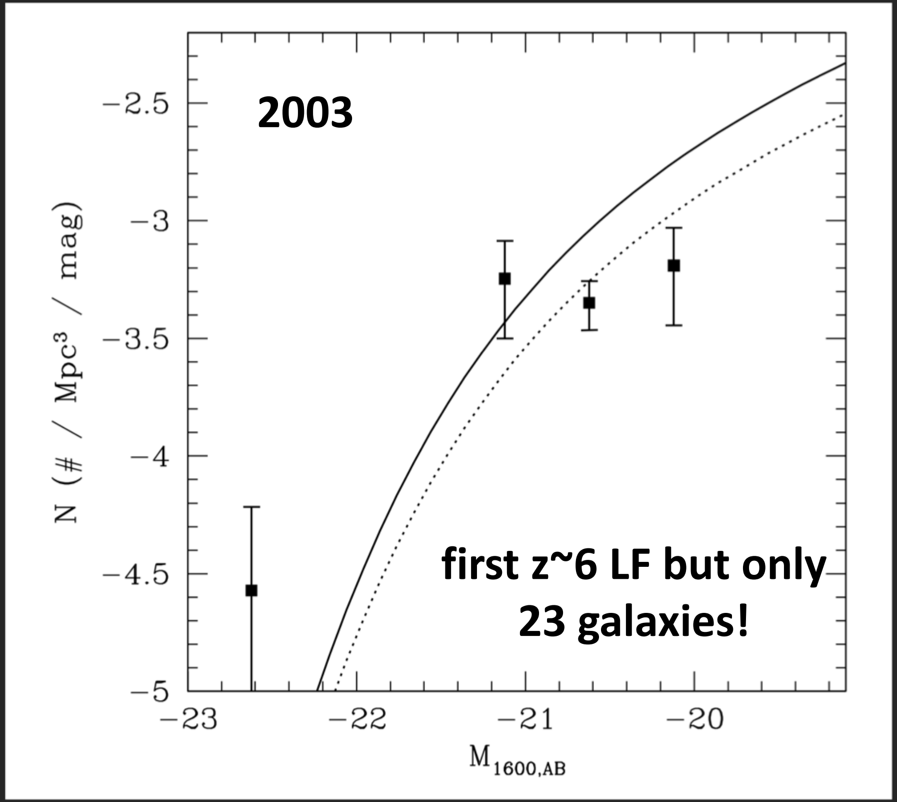
gdi

ACS enabled the first redshift z~6 sample



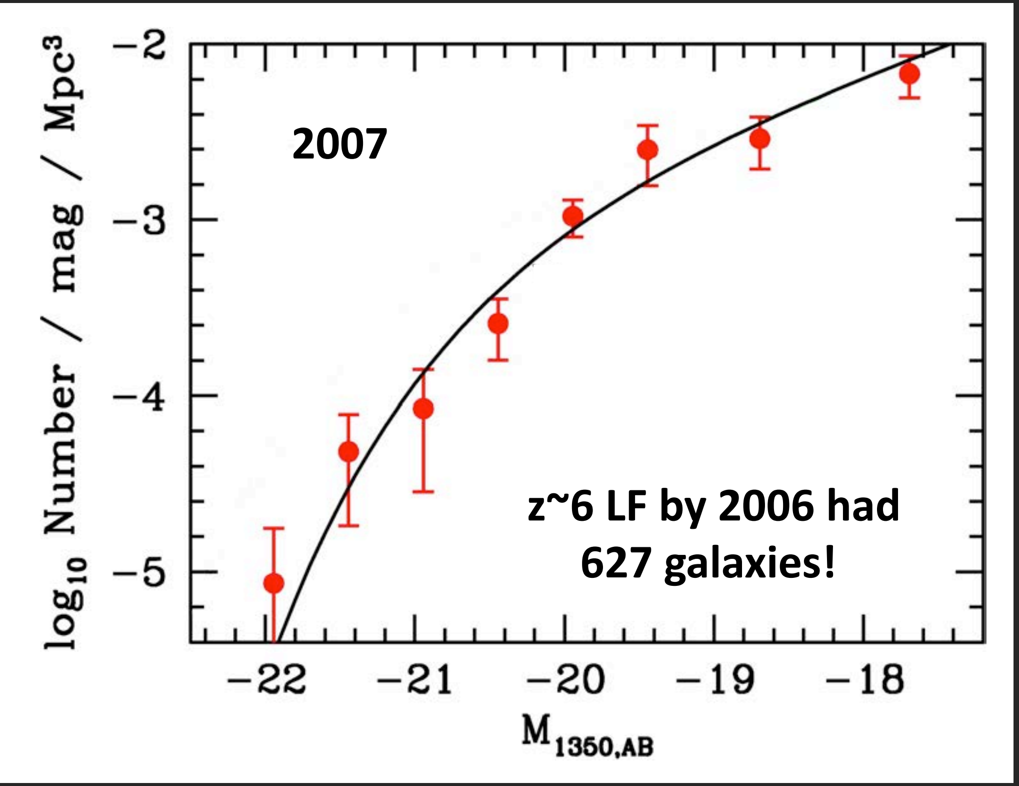
- ACS: 10-20X “discovery efficiency” of WFPC2 (more galaxies)
- enhanced wavelength coverage (higher redshift galaxies)

first luminosity function at 1 Gyr (z~6)



Bouwens GDI+2003

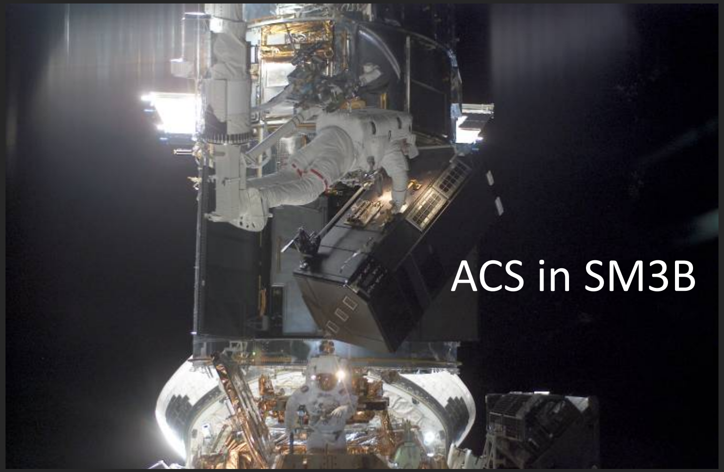
3 years later: 27X (627) as many z~6 galaxies



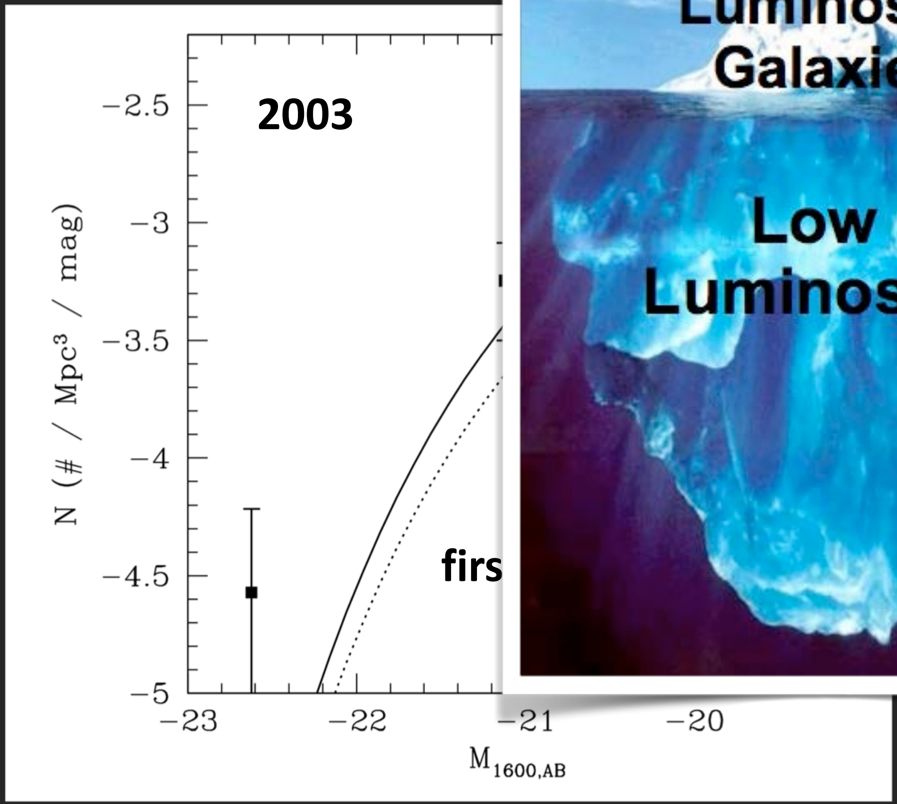
Bouwens GDI+2007

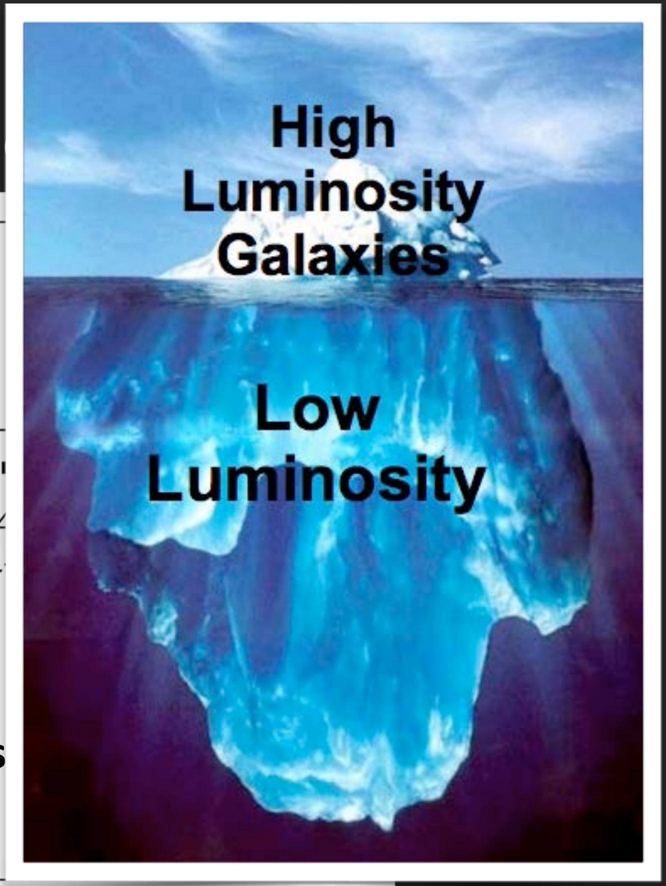
ACS enabled the first redshift z~6 sample

- ACS: 10-20X “discovery efficiency” of WFPC2 (more galaxies)
- enhanced wavelength coverage (higher redshift galaxies)

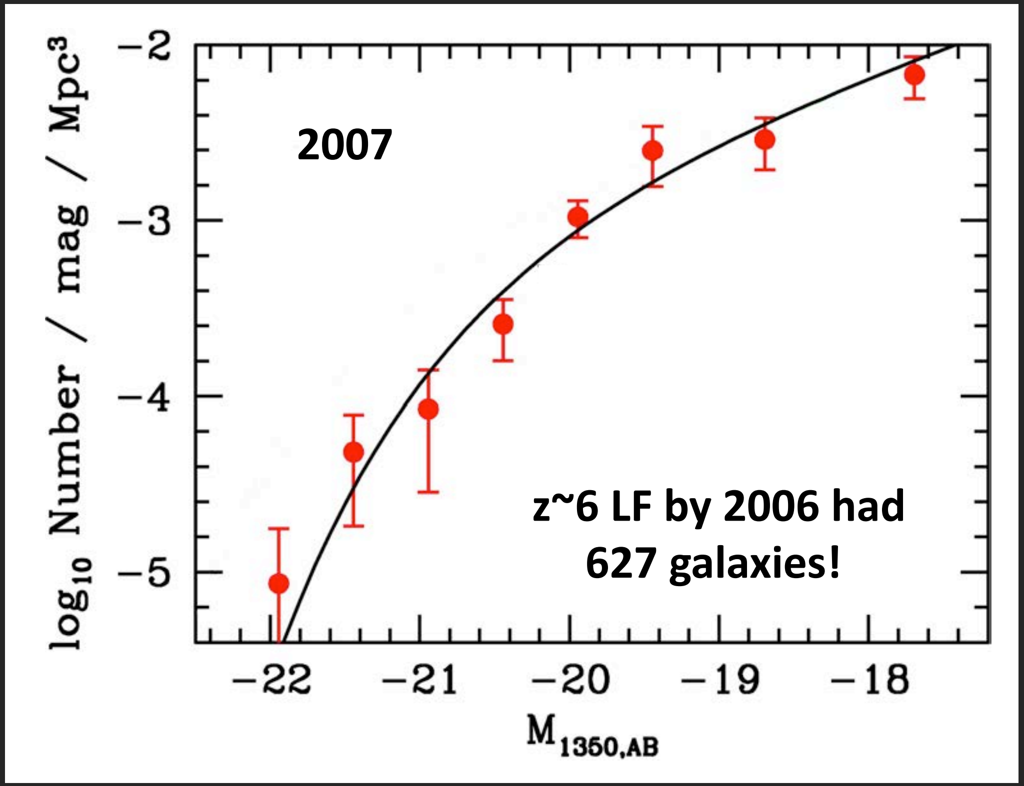


first luminosity functi





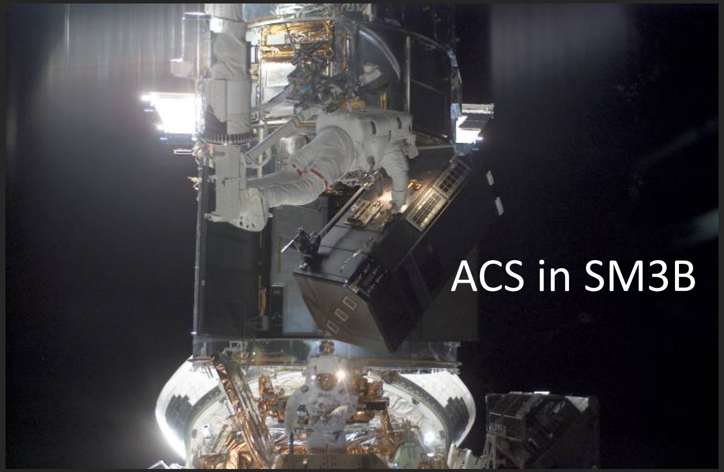
3 years later: 27X (627) as many z~6 galaxies



Bouwens GDI+2003

Bouwens GDI+2007

gdi

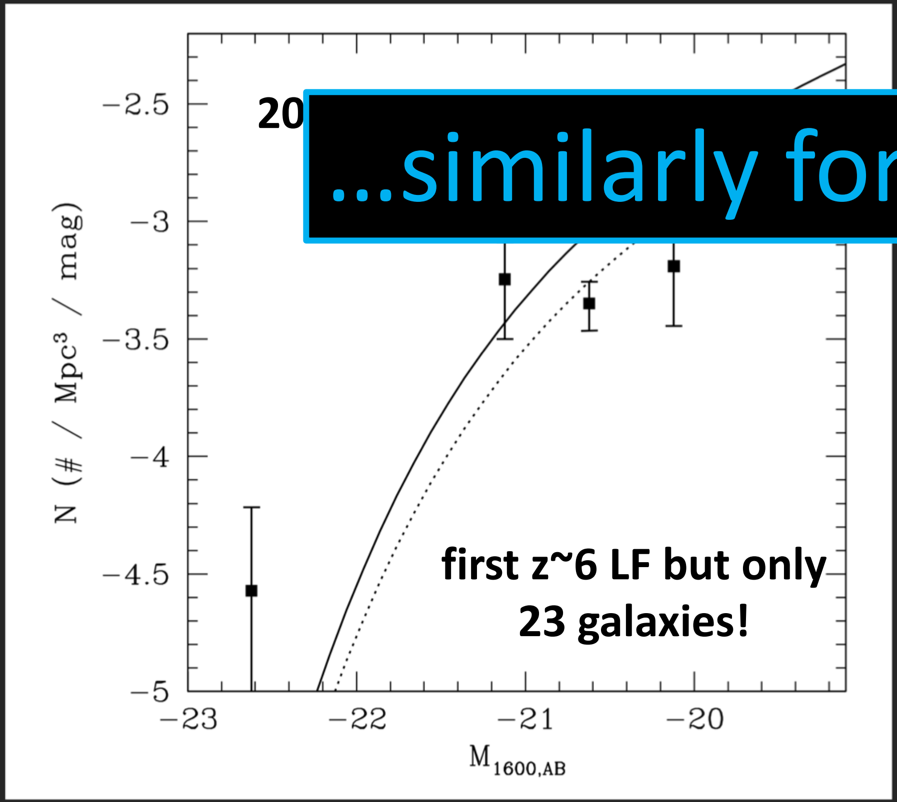


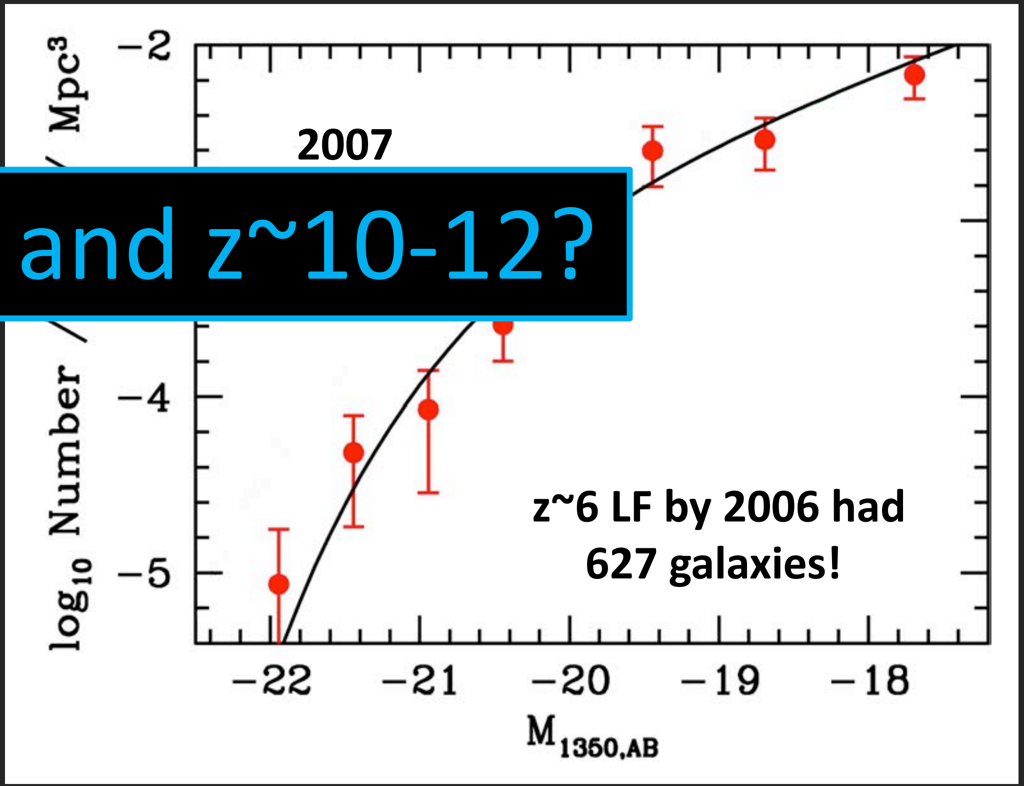
ACS enabled the first redshift z~6 sample

- ACS: 10-20X "discovery efficiency" of WFPC2 (more galaxies)
- enhanced wavelength coverage (higher redshift galaxies)

3 years later: 27X (627) as many z~6 galaxies

first luminosity function at 1 Gyr (z~6)





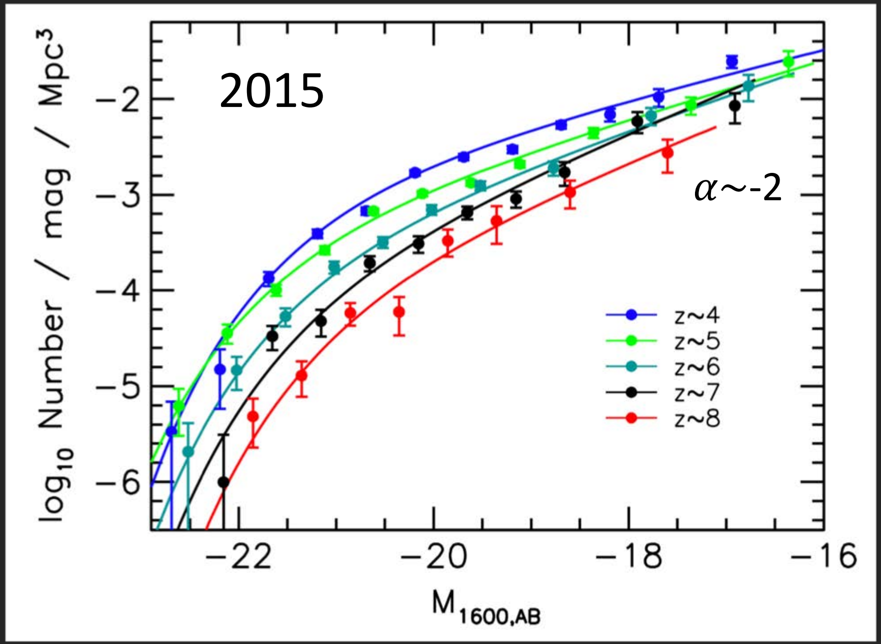
...similarly for JWST and z~10-12?

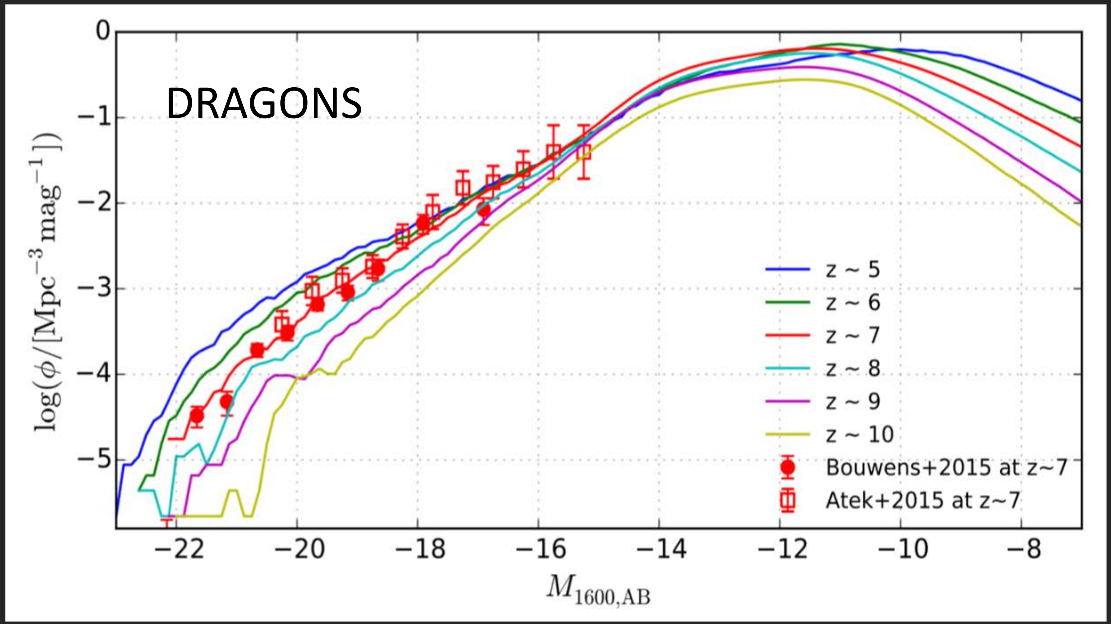
Bouwens GDI+2003

Bouwens GDI+2007

gdi

pushing LFs to fainter limits to derive UV luminosity densities





theoretical LFs

Liu+2016

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

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

but how do we go fainter than XDF?

Bouwens GDI Oesch+2015

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

gdi

Frontier Fields HFF

long history of galaxy cluster imaging programs with HST from WFPC2 to ACS to WFC3:

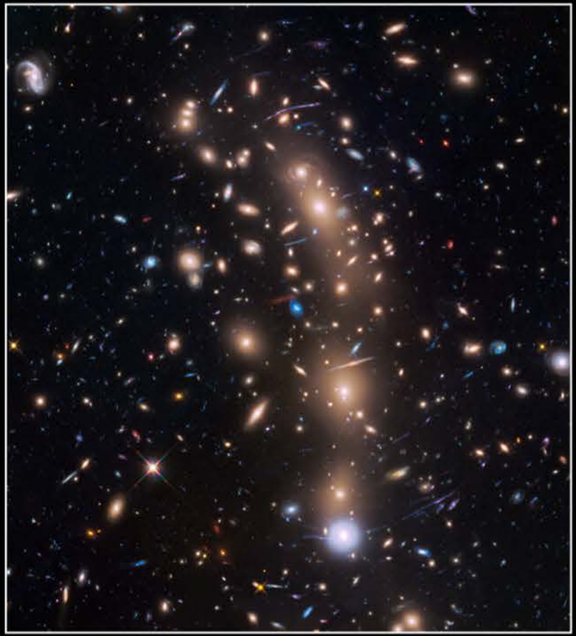
- ACS GTO Team
- CLASH
- HFF
- RELICS
- + others

6 clusters + 6 parallel fields

840 orbits of ACS and WFC3/IR images

1000 hours of Spitzer IRAC

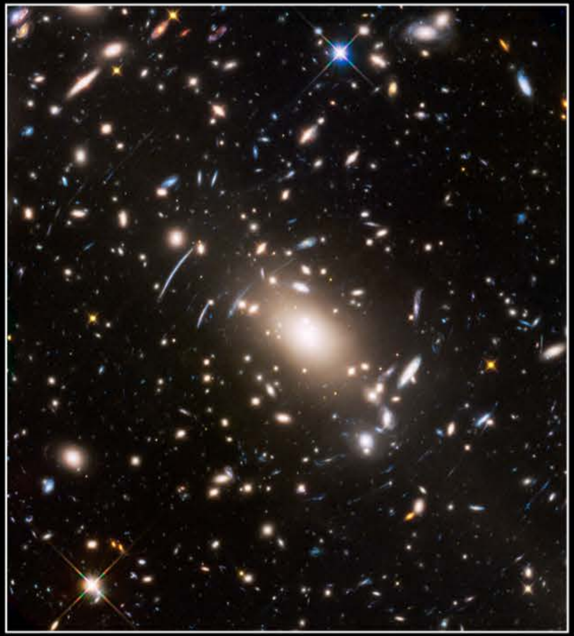
Abell 2744



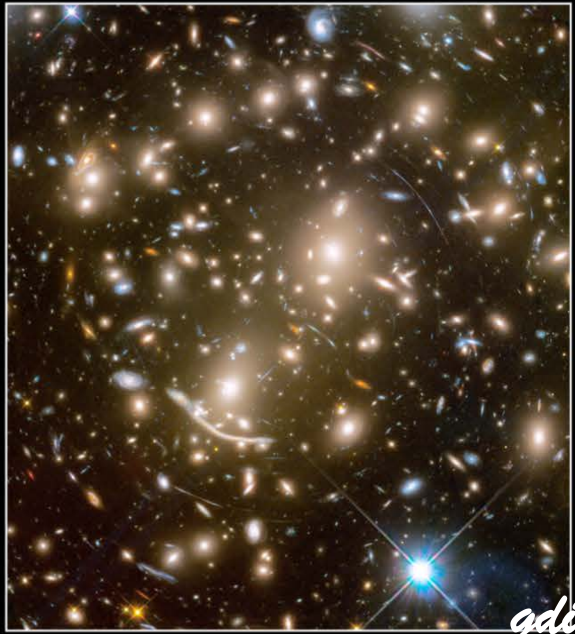
MACSJ0416.1-2403

MACSJ0717.5+3745

MACSJ1149.5+2223



Abell S1063



Abell 370

figure credit: Jennifer Lotz

Frontier Fields
HFF

long history of galaxy cluster imaging programs with HST from WFPC2 to ACS to WFC3:

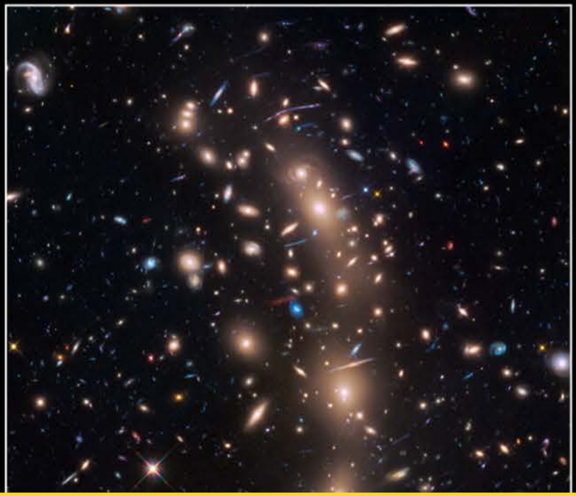
- ACS GTO Team
- CLASH
- HFF
- RELICS
- + others

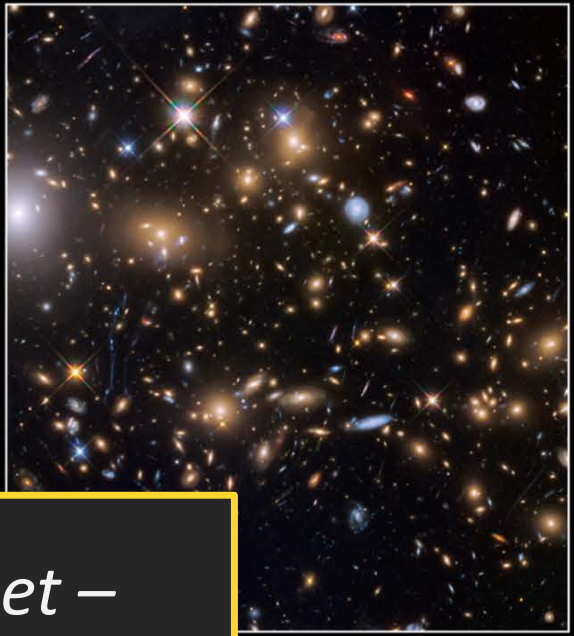
6 clusters + 6 parallel fields

840 orbits of ACS and WFC3/IR images

1000 hours of Spitzer IRAC

figure credit: Jennifer Lotz

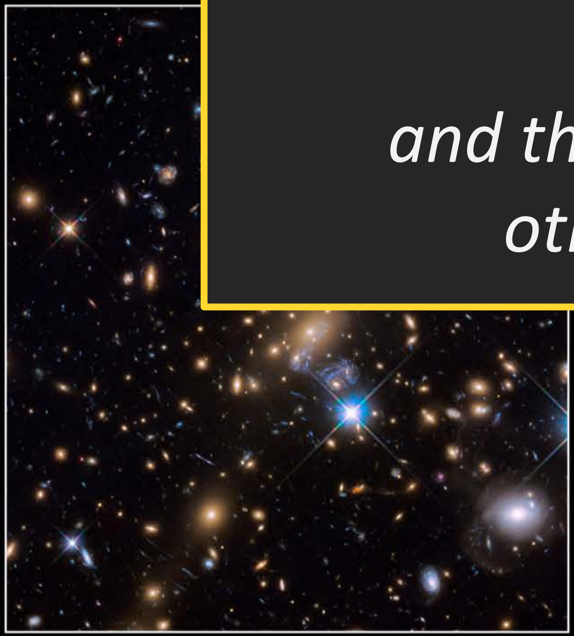




MACSJ0717.5+3745

– the HFF is a remarkable dataset –
thanks to Matt Mountain

and thanks to Jennifer Lotz and others on the HFF team



MACSJ1149.5+2223

Abell S1063

Abell 370

gdi

the challenges of luminosity functions using lensing clusters

☛ model uncertainties at high magnifications ☚

different models yield substantially
different results at high magnification

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

gdi

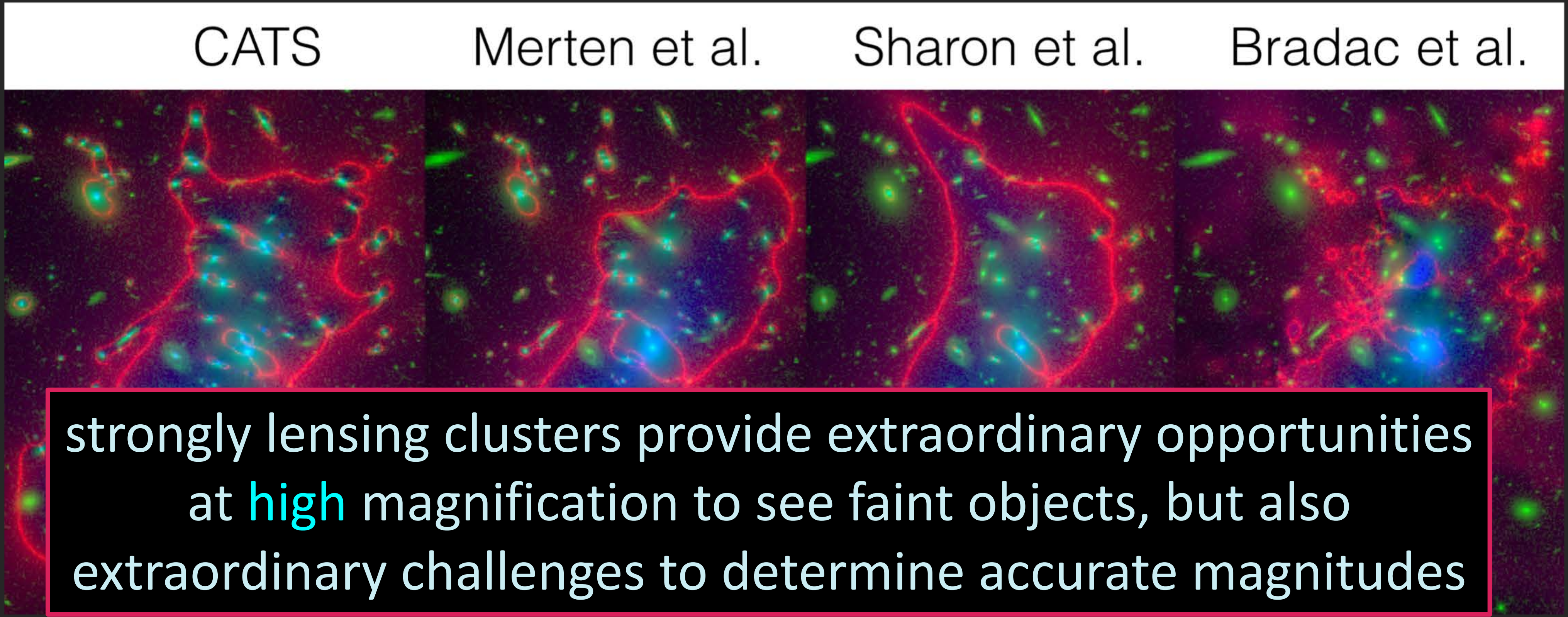
modelling challenging at high magnifications

critical curves for four different models for the HFF cluster Abell 2744 and sources at z~9

from Atek 2017 – adapted from www.stsci.edu/hst/campaigns/frontier-fields/Lensing-Models

gdi

modelling challenging at high magnifications



strongly lensing clusters provide extraordinary opportunities at high magnification to see faint objects, but also extraordinary challenges to determine accurate magnitudes

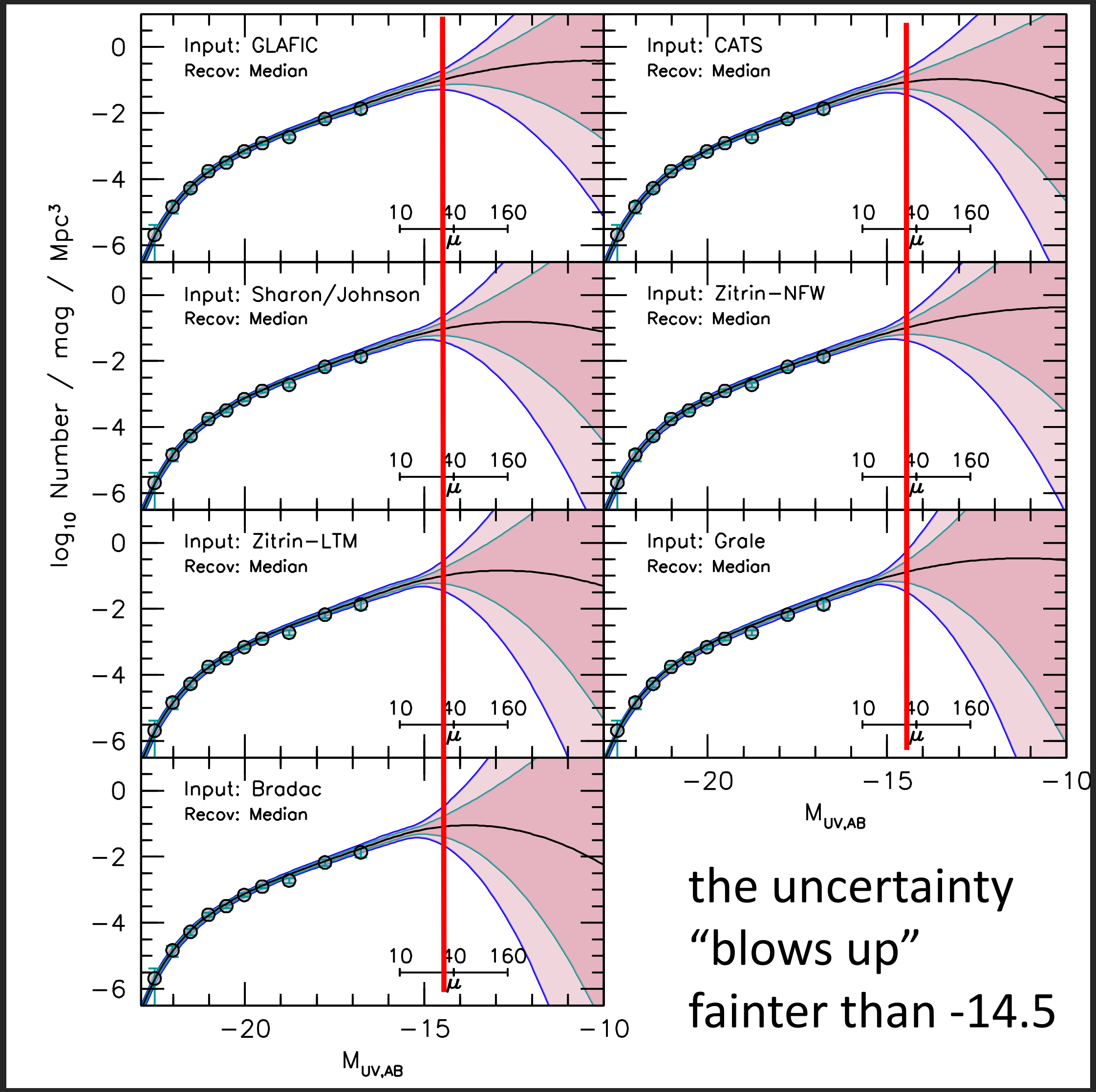
critical curves for four different models for the HFF cluster Abell 2744 and sources at z~9

from Atek 2017 – adapted from www.stsci.edu/hst/campaigns/frontier-fields/Lensing-Models

gdi

limit for reliable LFs from the HFFs

(Hubble Frontier Fields)



forward modelling simulations

the errors in the LF become so large as to make estimates of the LF from the HFF *of limited value* below $M_{UV,AB}$ ~-14.5

model systematics are the limiting factor

Bouwens+2017b

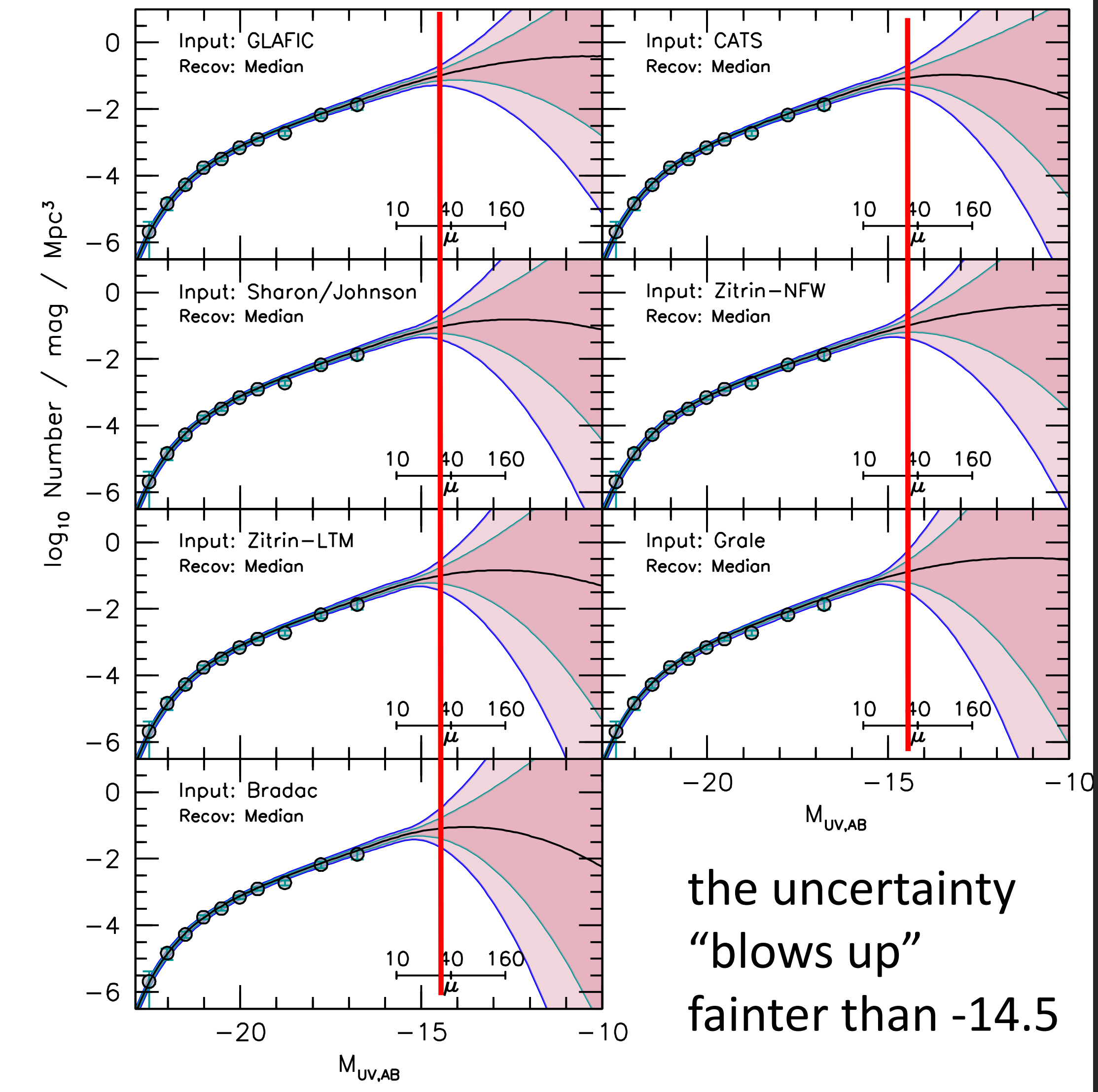
see also Castellano+2015, Atek+2016, 2018, Laporte+2016; Livermore+2017; Ishigaki+2017; Yue+2018

gdi

limit for reliable LFs from the HFFs

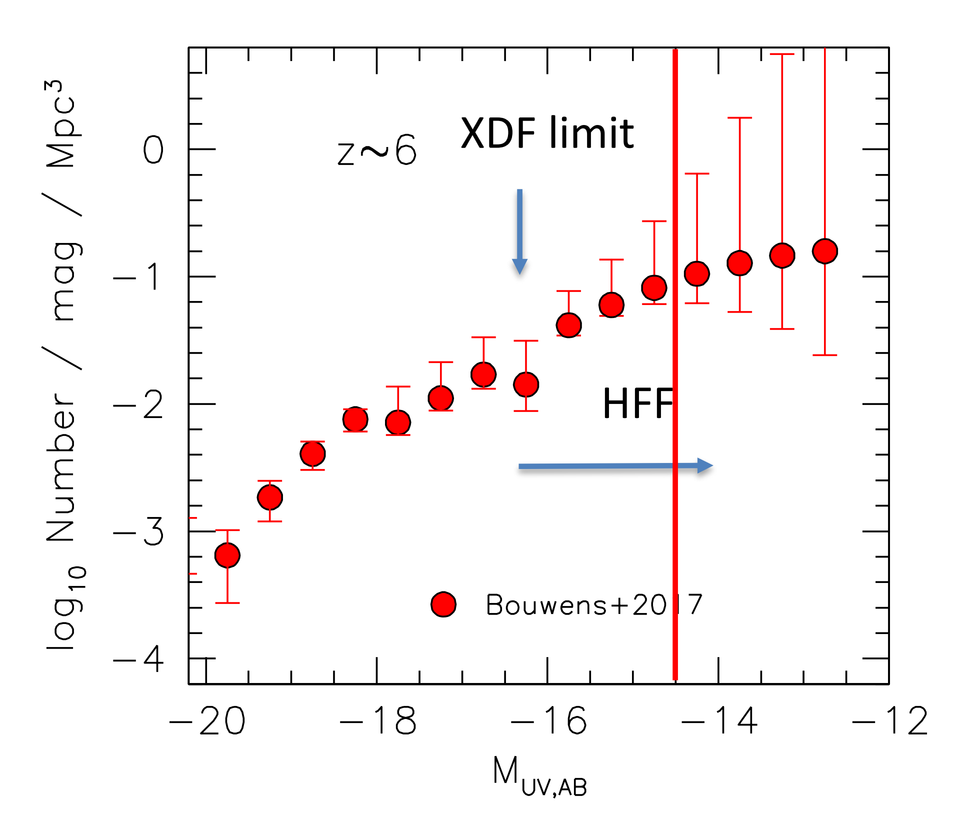
(Hubble Frontier Fields)

HFF gained us ~2 mags



forward modelling simulations

the errors in the LF become so large as to make estimates of the LF from the HFF *of limited value* below $M_{UV,AB}$ ~-14.5



model systematics are the limiting factor

Bouwens+2017b

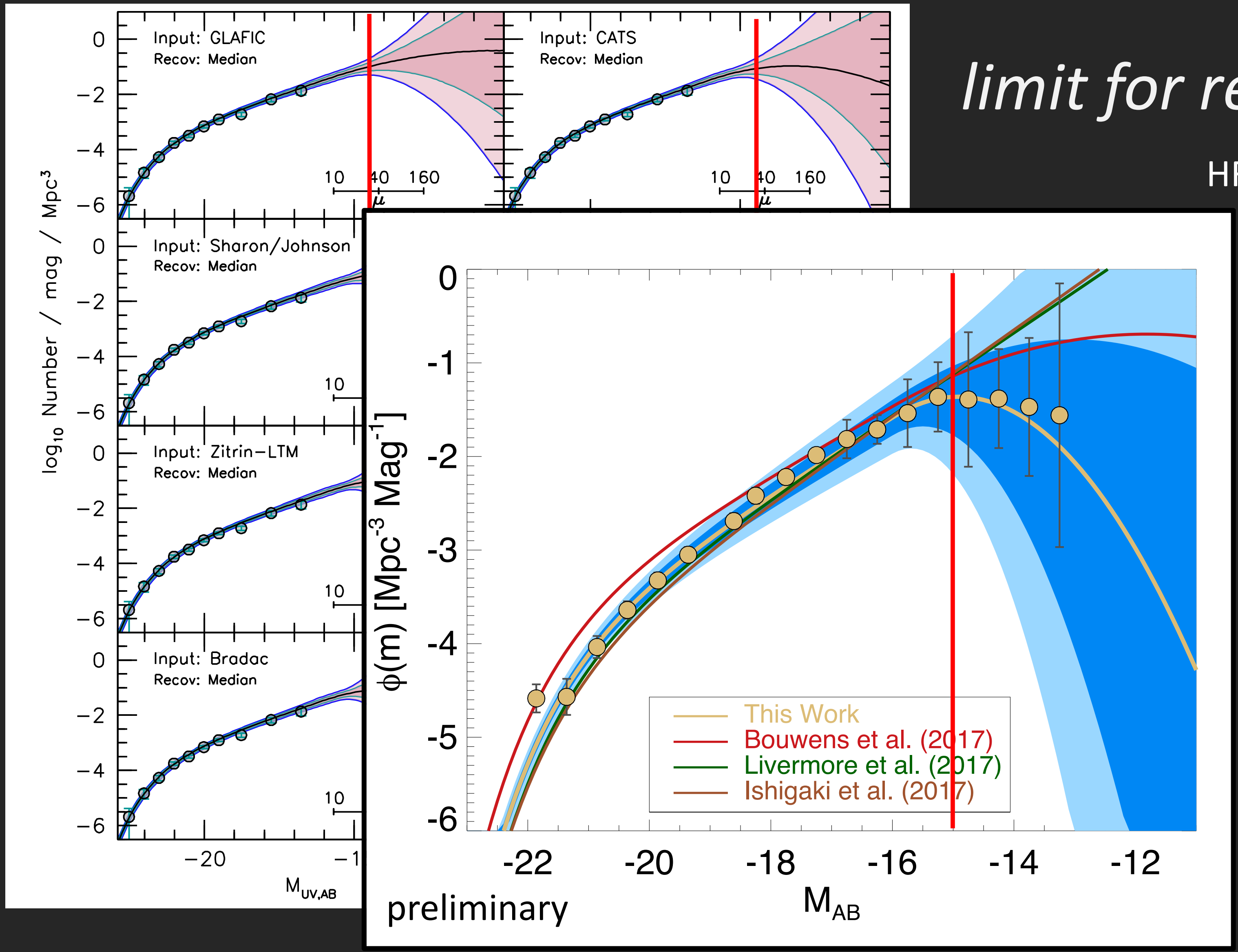
see also Castellano+2015; Bouwens+2015; Atek+2016, 2018; Laporte+2016; Livermore+2017; Ishigaki+2017; Yue+2018

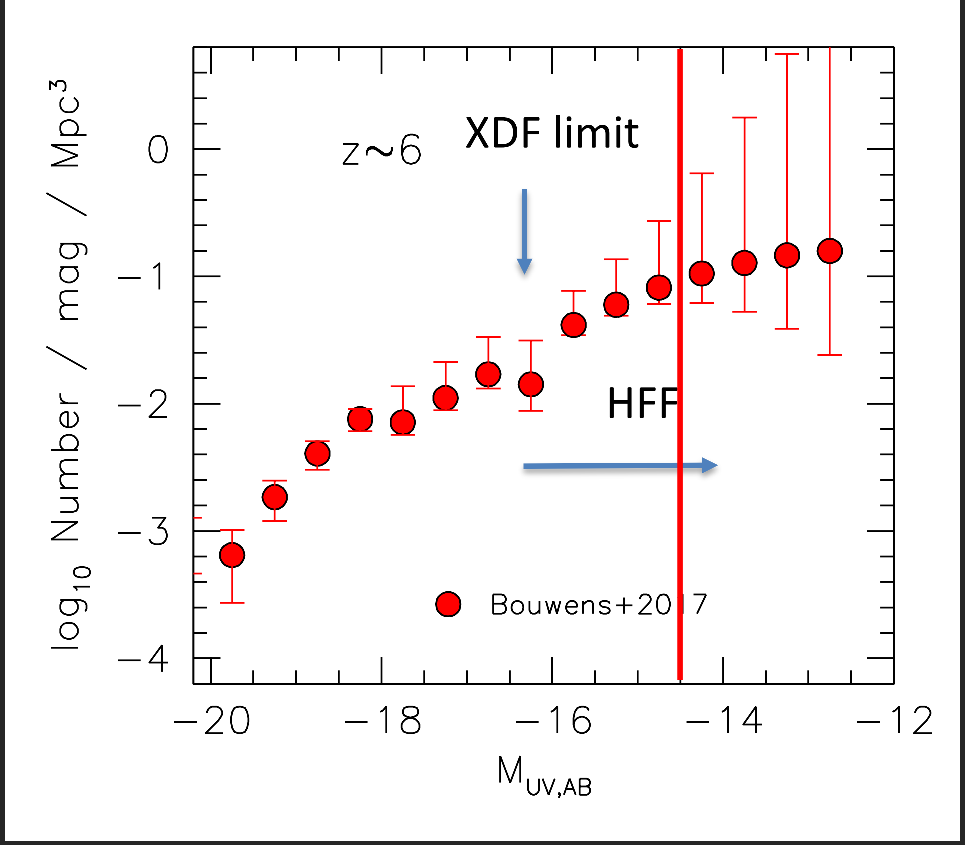
gdi

limit for reliable LFs from the HFFs

(Hubble Frontier Fields)

HFF gained us ~2 mags





Atek+2018

Bouwens+2017b

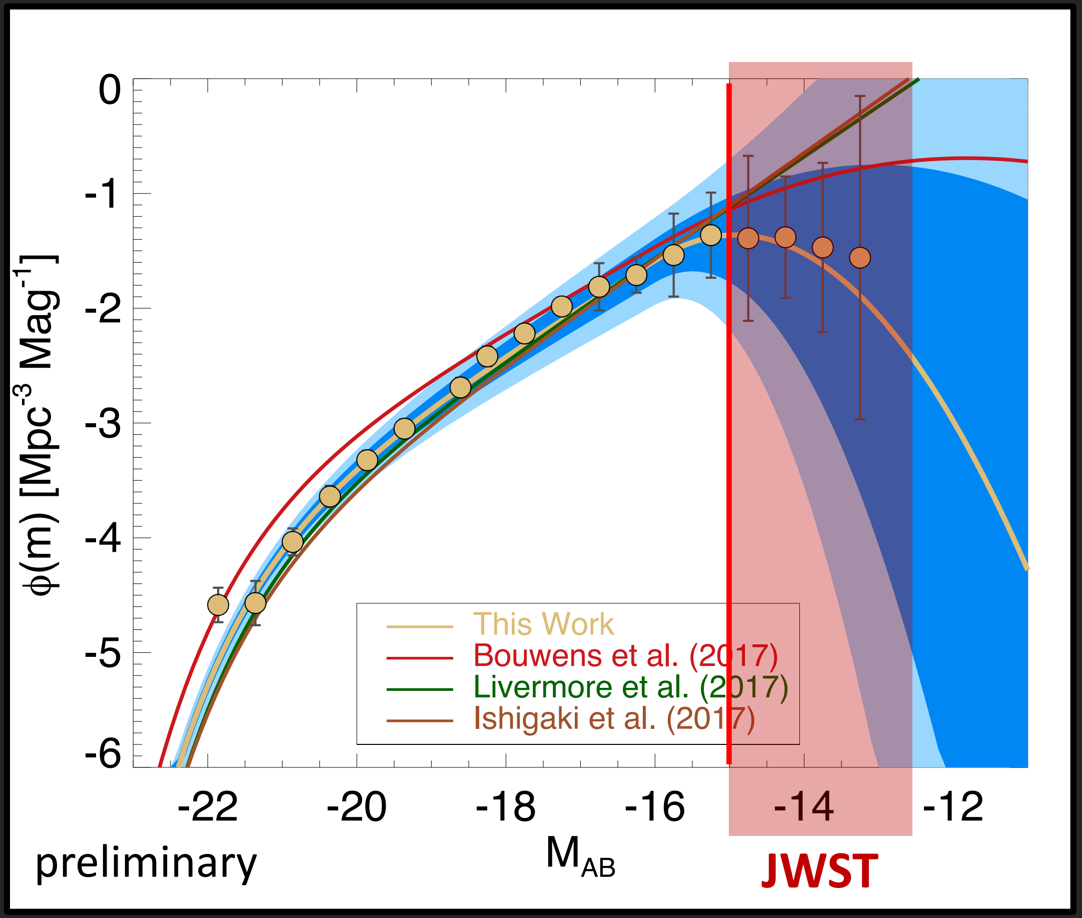
large systematic errors and large uncertainties below ~-14.5 to -15 mag – confirmed by Atek+2018

gdi

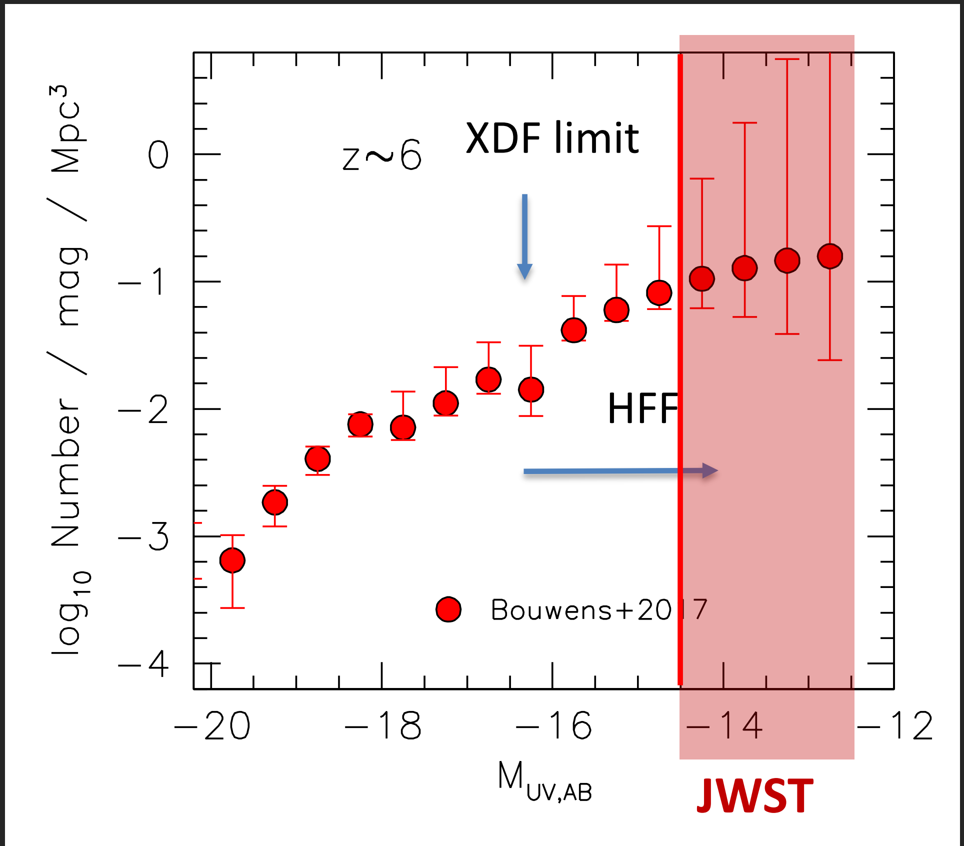
see also Castellano+2015; Bouwens+2015; Atek+2016, 2018; Laporte+2016; Livermore+2017; Ishigaki+2017; Yue+2018

limit for reliable LFs from the HFFs

(Hubble Frontier Fields)



Atek+2018



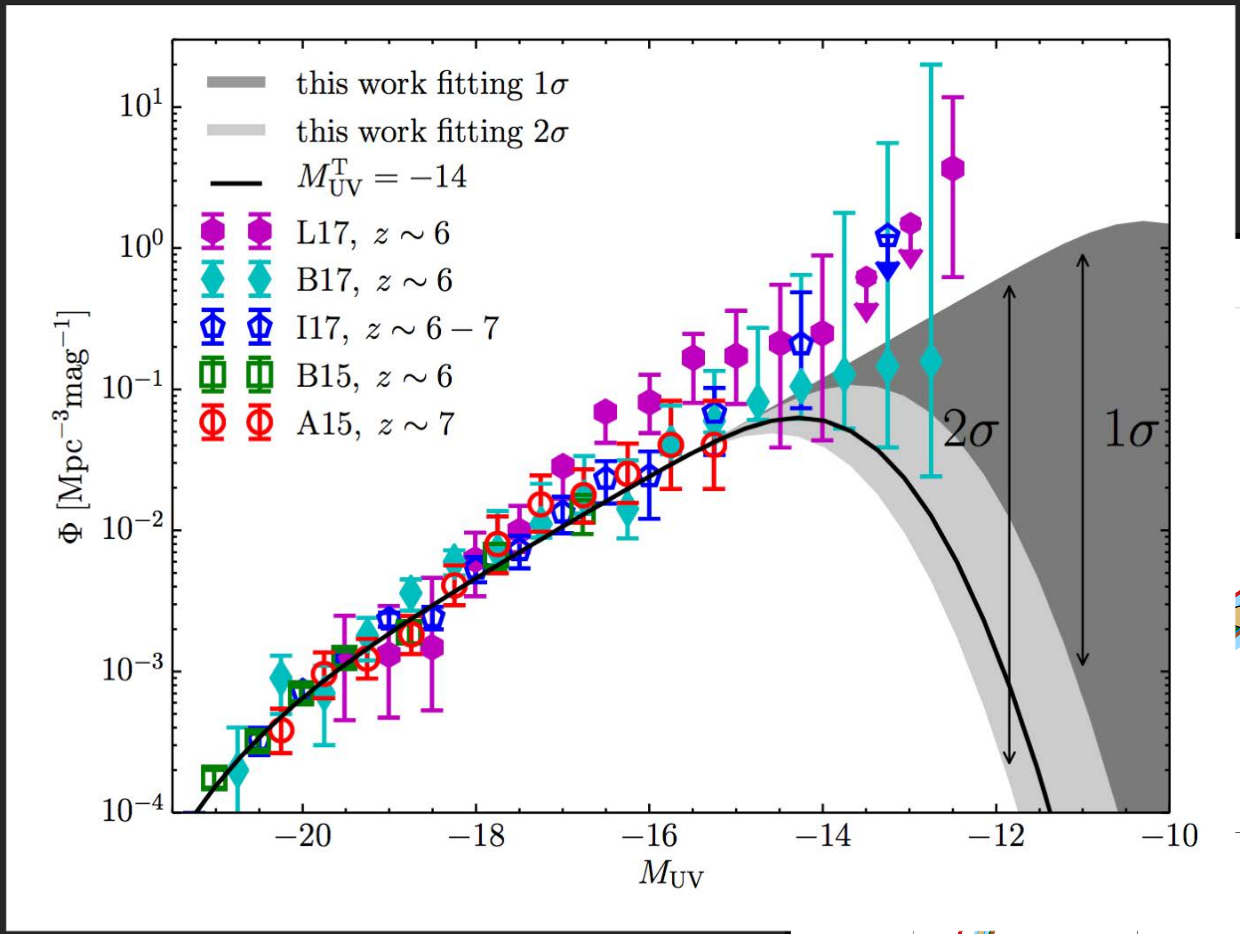
Bouwens+2017b

JWST imaging should allow us to measure the turnover

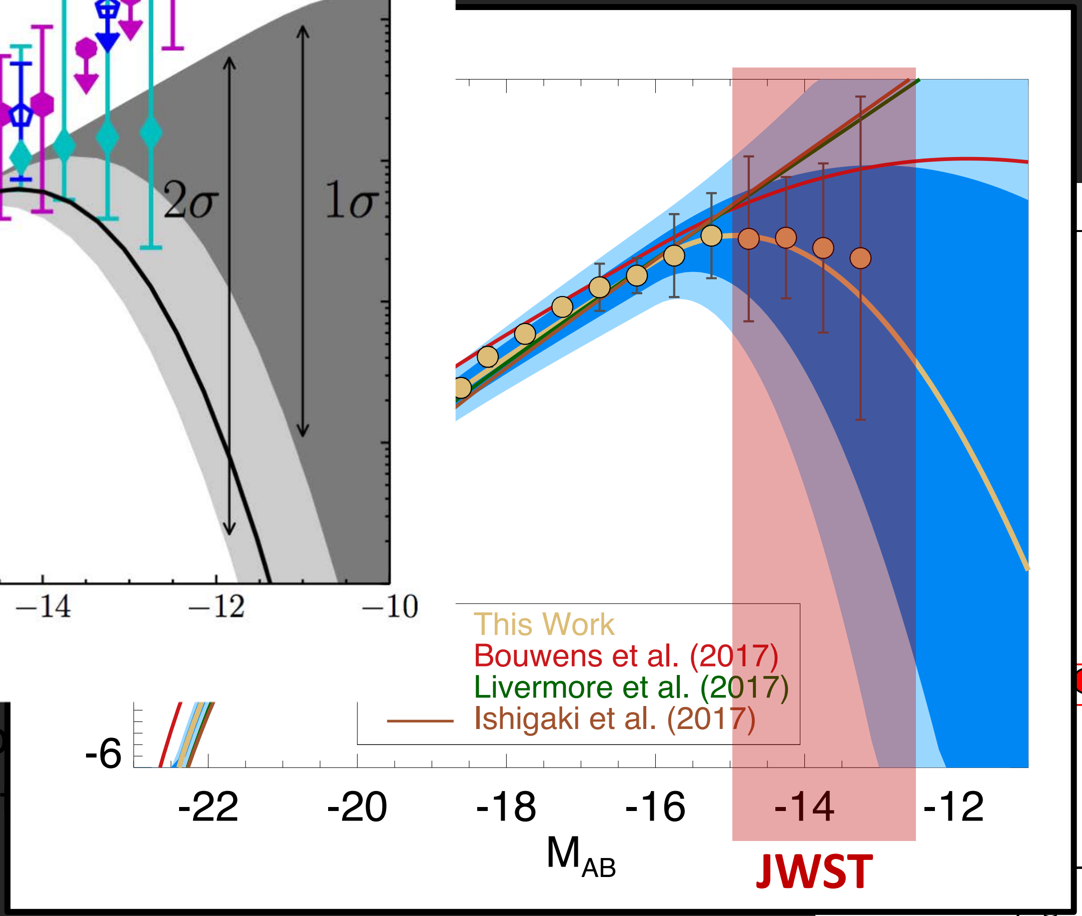
see also Castellano+2015; Bouwens+2015; Atek+2016, 2018; Laporte+2016; Livermore+2017; Ishigaki+2017; Yue+2018

gdi

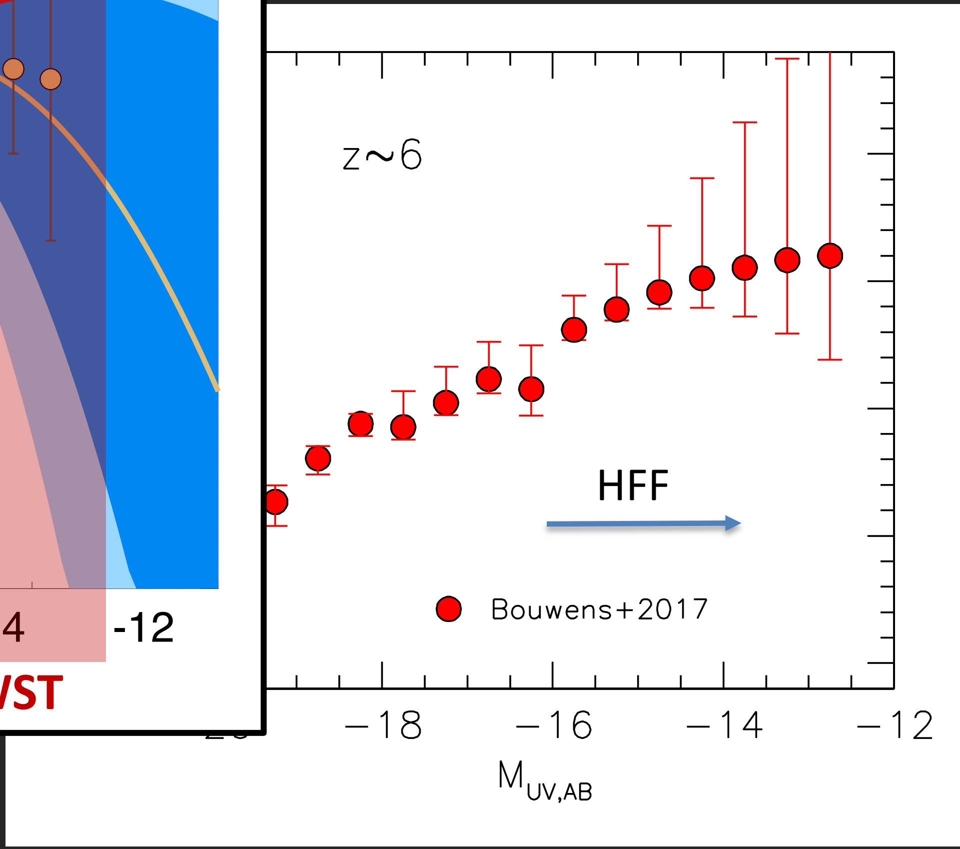
many groups getting LFs on HFFs



Yue+2017



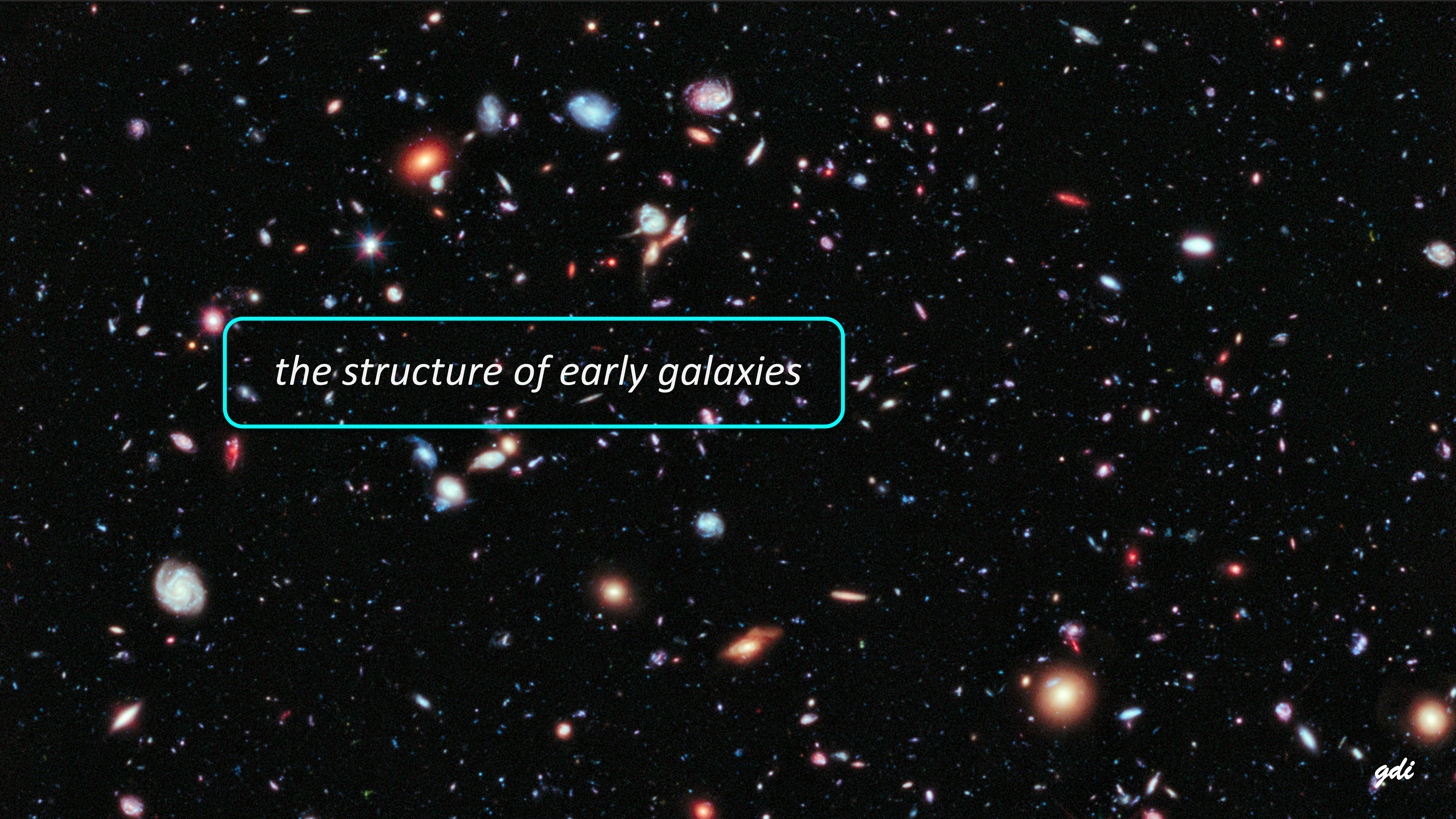
Atek+2018



Bouwens+2017b

see also Castellano+2015; Bouwens+2015; Atek+2016, 2018; Laporte+2016; Livermore+2017; Ishigaki+2017; Yue+2018

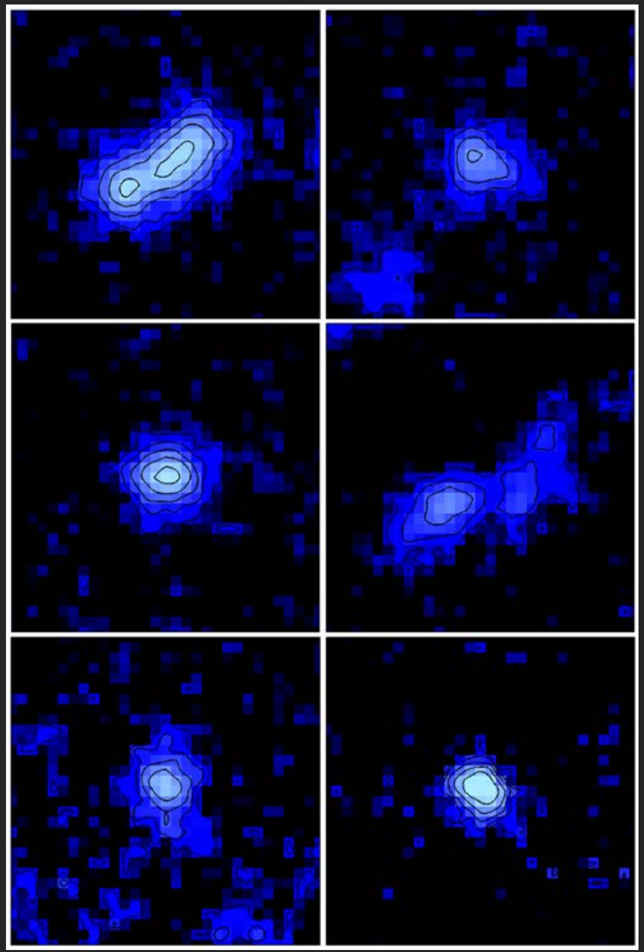
gdi


the structure of early galaxies
gdi

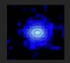
galaxies in the first billion years

large bright z~6-7 galaxies

1.8” (~10 kpc)



small faint distant galaxies



really tiny!

most galaxies in the first billion years have been measured to be very small!

~size of the Hubble point spread function

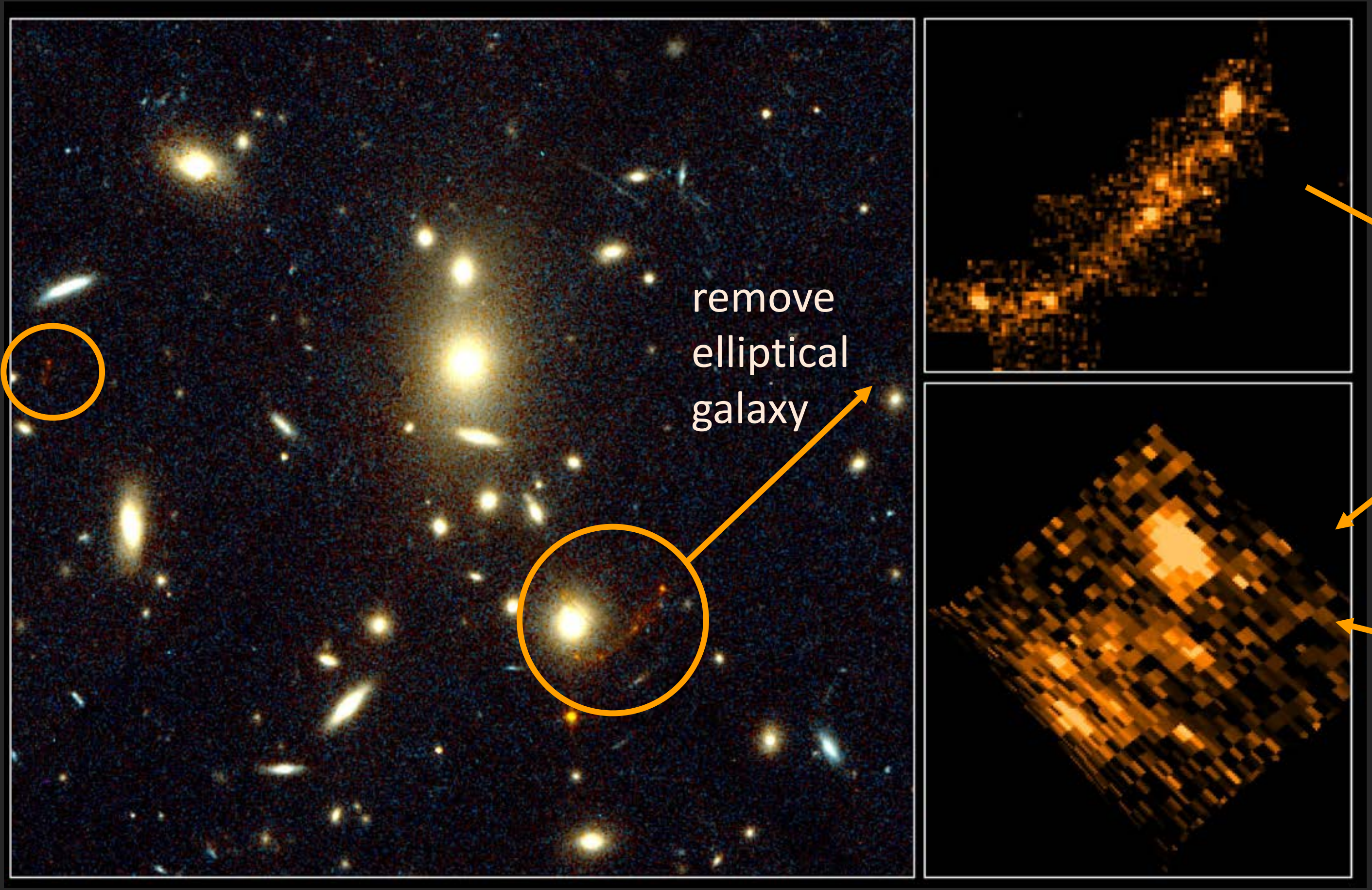
a large galaxy now

gdi

a remarkable fold arc in CL1358

cluster of galaxies CL1358 at z=0.33
magnifies faint z=4.92 background galaxy

1996: get ~20X magnified image of distant galaxy 12.5 million years ago



WFPC2 image

CL1358-G1 at z=4.92

model gravity in cluster
remove distortions
recover source plane image

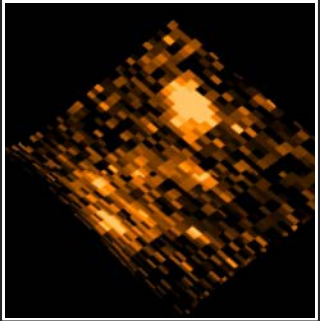
50% of star formation (>50%) in the bright “blob” r_e ~130pc

SFR around 40 $M_\odot$/yr

Franx GDI+1997

gdi

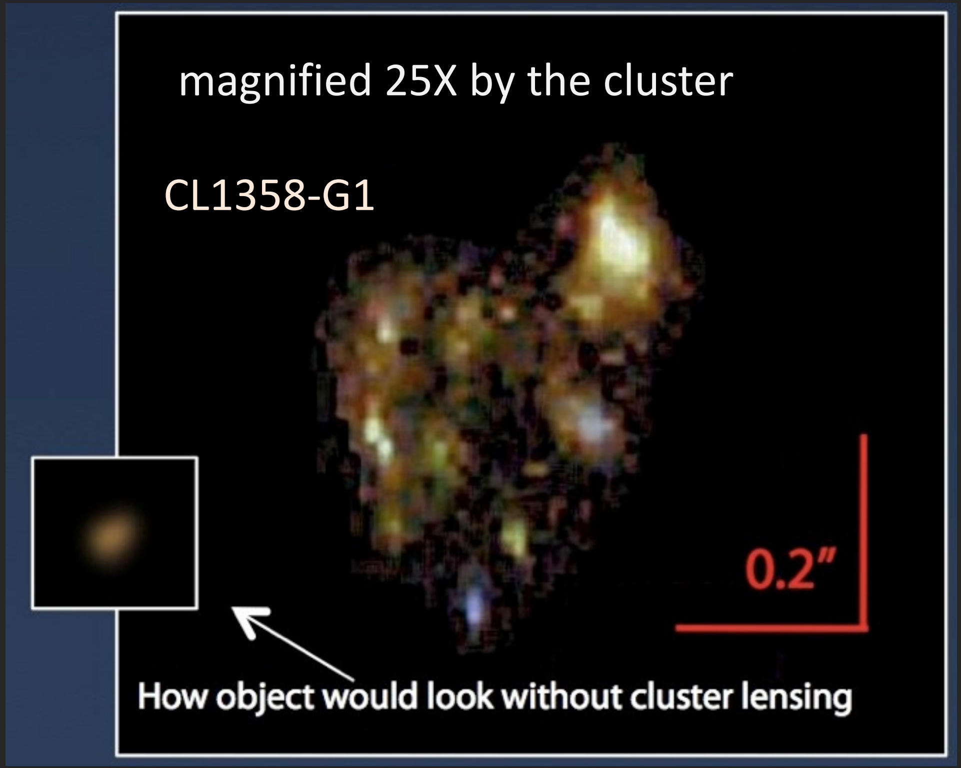
unique insight into the structure of a high redshift galaxy

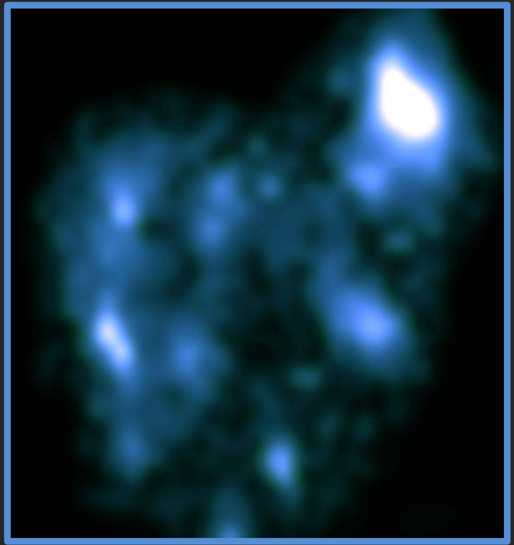


1996 WFPC2 image

found in 1996 – still the best magnified image we have for a galaxy in the first 2 billion years

2004 image from Hubble's Advanced Camera ACS





CL1358-G1 probably looks more like this!

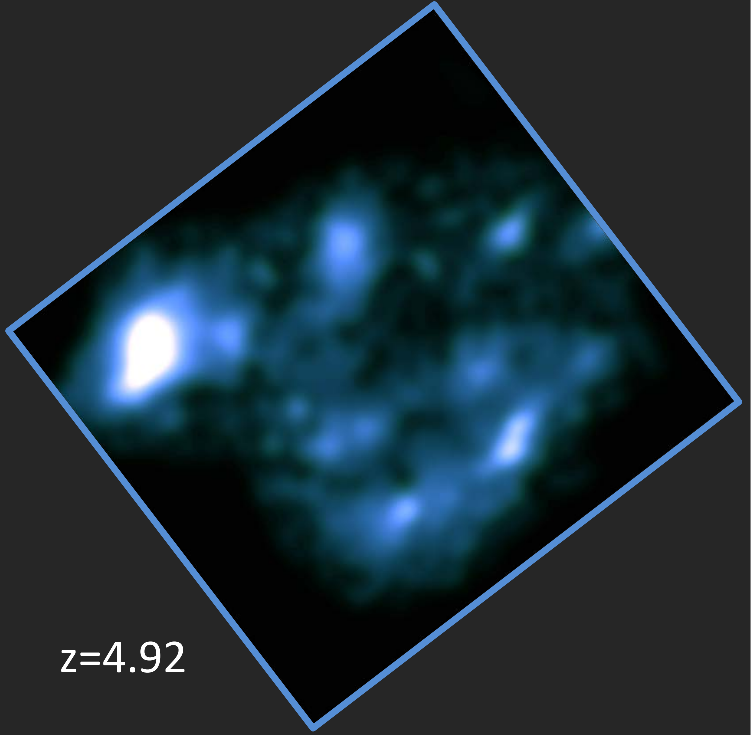
- very rare to see such details
- star-forming regions at high redshift are very small

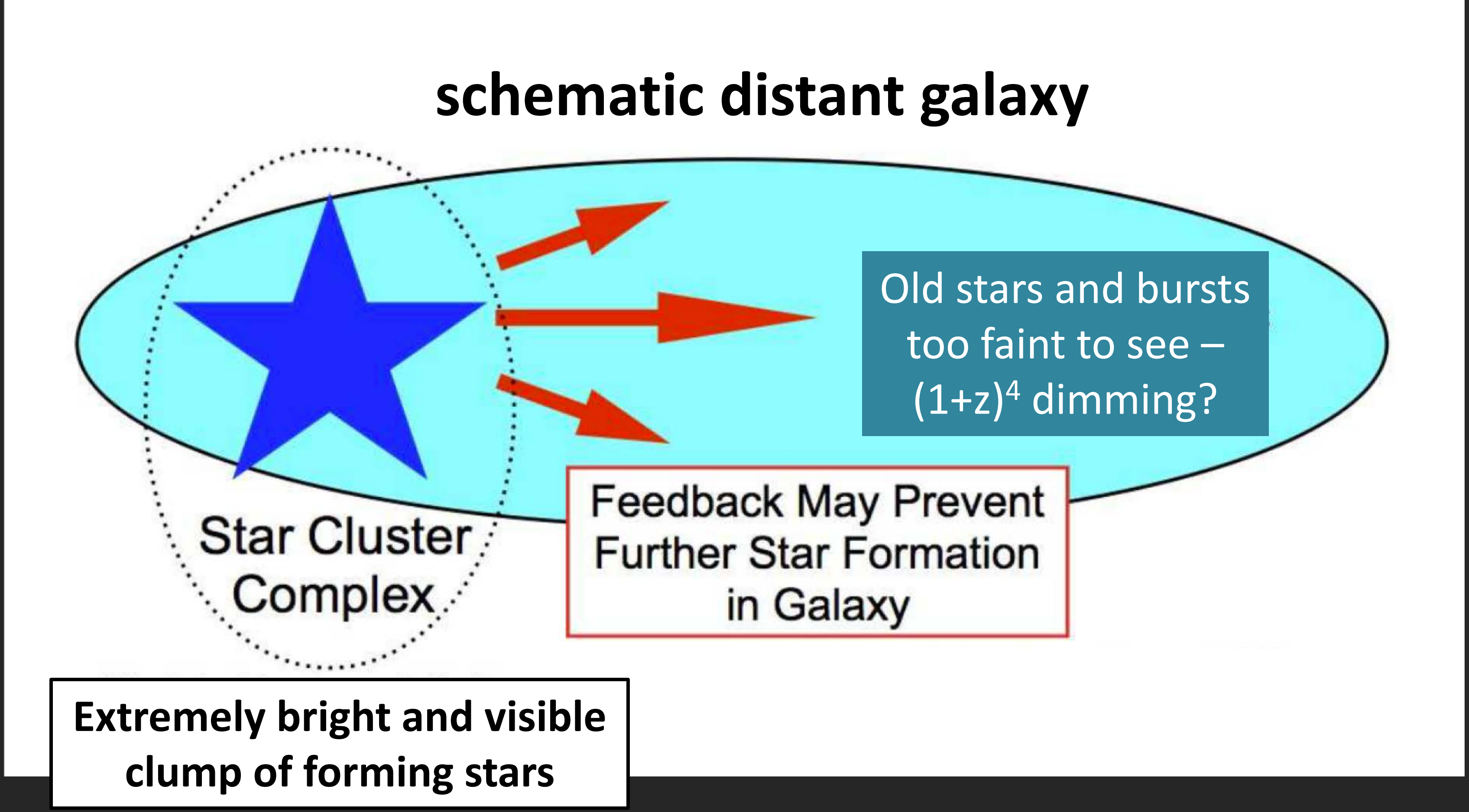
Zitrin+2011

gdi

are high redshift galaxies really so small?

cf. CL1358-G1





☞ we could well be seeing a compact bright region (or regions) in a larger object in most z>6-7 galaxies

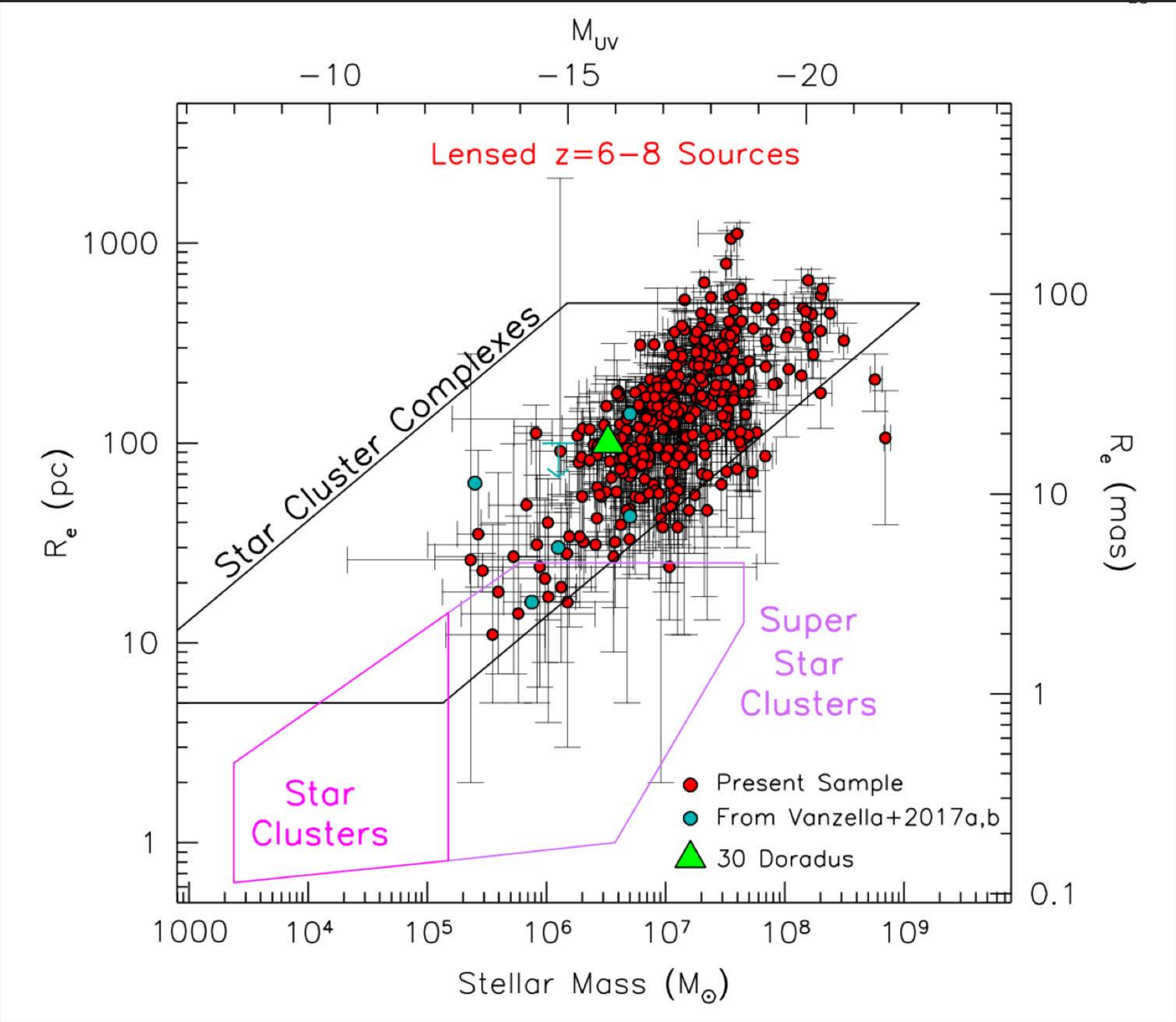
gdi

z~6-8 galaxy size comparison to star-forming regions

sizes of 307 z~6-8 galaxies in HFFs

compared to star-forming clusters or complexes and super star clusters

☞ observed sizes of z~6-8 galaxies are similar to lower redshift z~0-3 star-forming complexes – note 30 Doradus



Bouwens+2017c

see also Vanzella+2017a,b; Laporte+2016; Kawamata+2015,2017

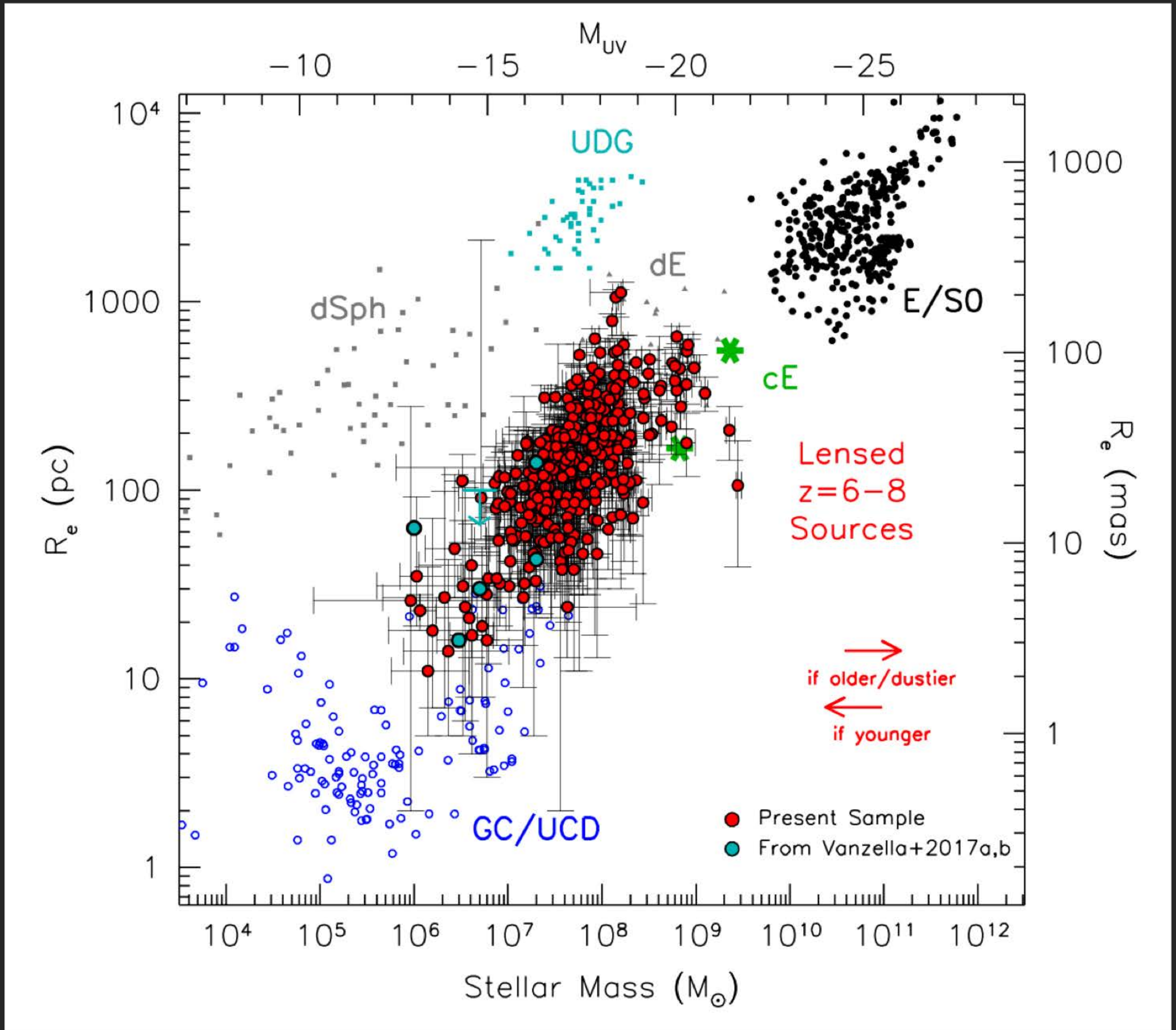
gdi

z~6-8 galaxy size comparison to nearby evolved objects

sizes of z~6-8 galaxies in HFFs compared to nearby evolved objects

local objects from Norris+2014
(see also Brodie+2011)

☞ could we be seeing some globular clusters forming at very high redshift?



Bouwens+2017c

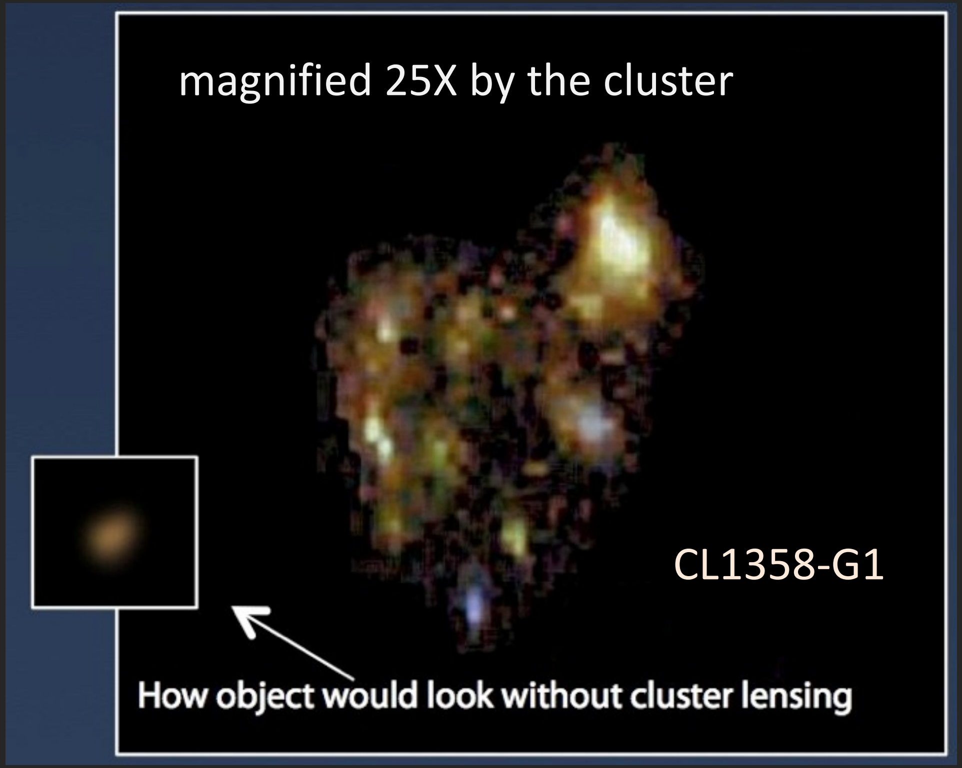
see also Vanzella+2017a,b; Laporte+2016; Kawamata+2015,2017

gdi

how will we find more like CL1358-G1?

>100 clusters have been searched – CL1358-G1 is still the best and only one at high redshift

30-40 m telescopes will give <100 pc resolution from lasers and adaptive optics



30-40 m ELT with adaptive optics needed to measure the sizes of star-forming regions in a large sample of early galaxies

ELT – Extremely Large Telescope

gdi

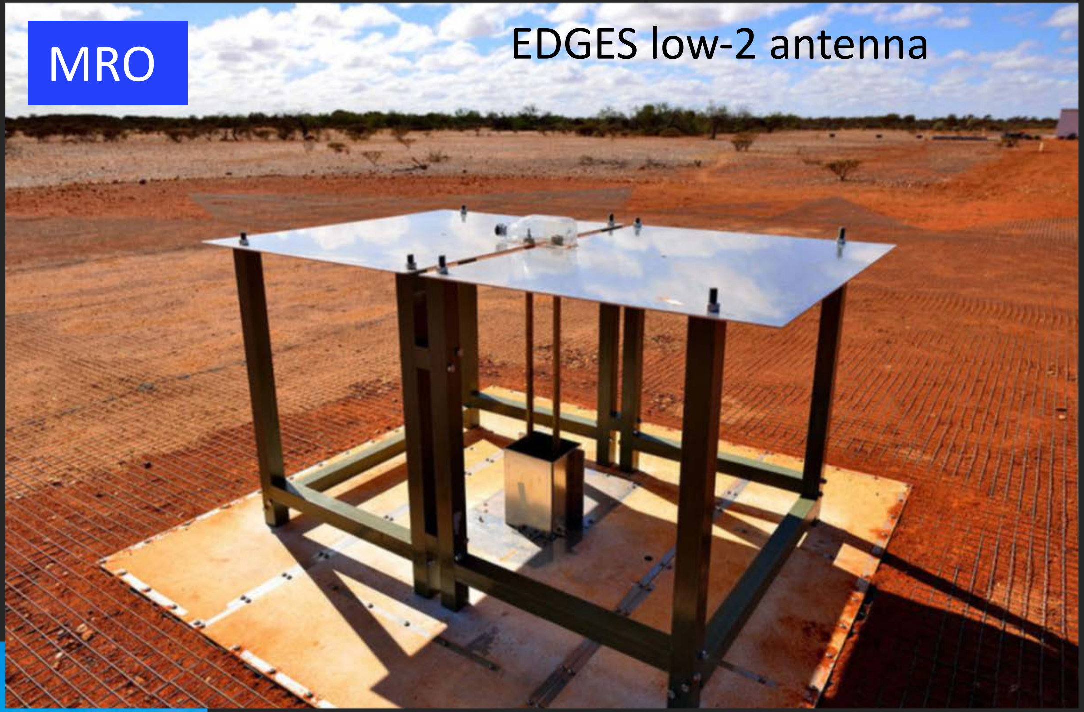
our first indication of when the “first stars” appeared

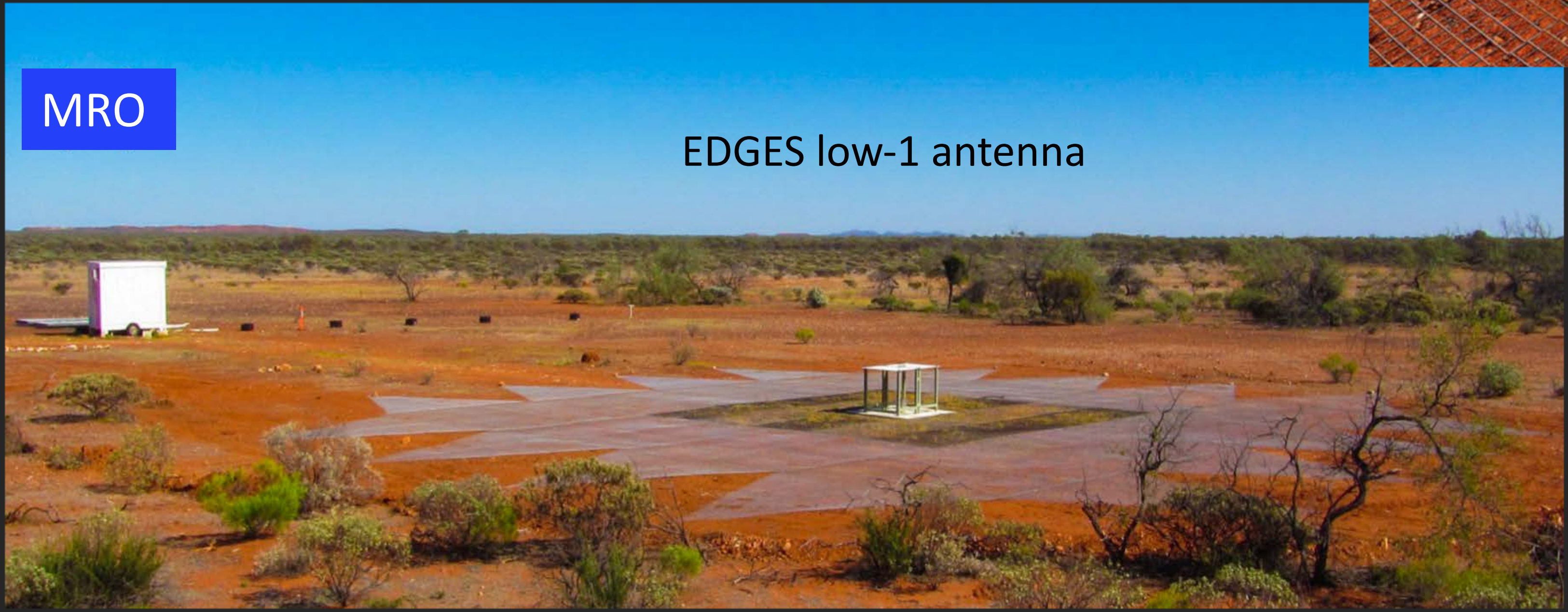
gdi

first evidence for when the "first stars" started to shine brightly

found by these funny-looking (and small) radio antennae in the desert of Western Australia….

Experiment to Detect the Global Epoch of Reionization Signature





Murchison Radio-astronomy Observatory (MRO) in Western Australia

NEW RESULT

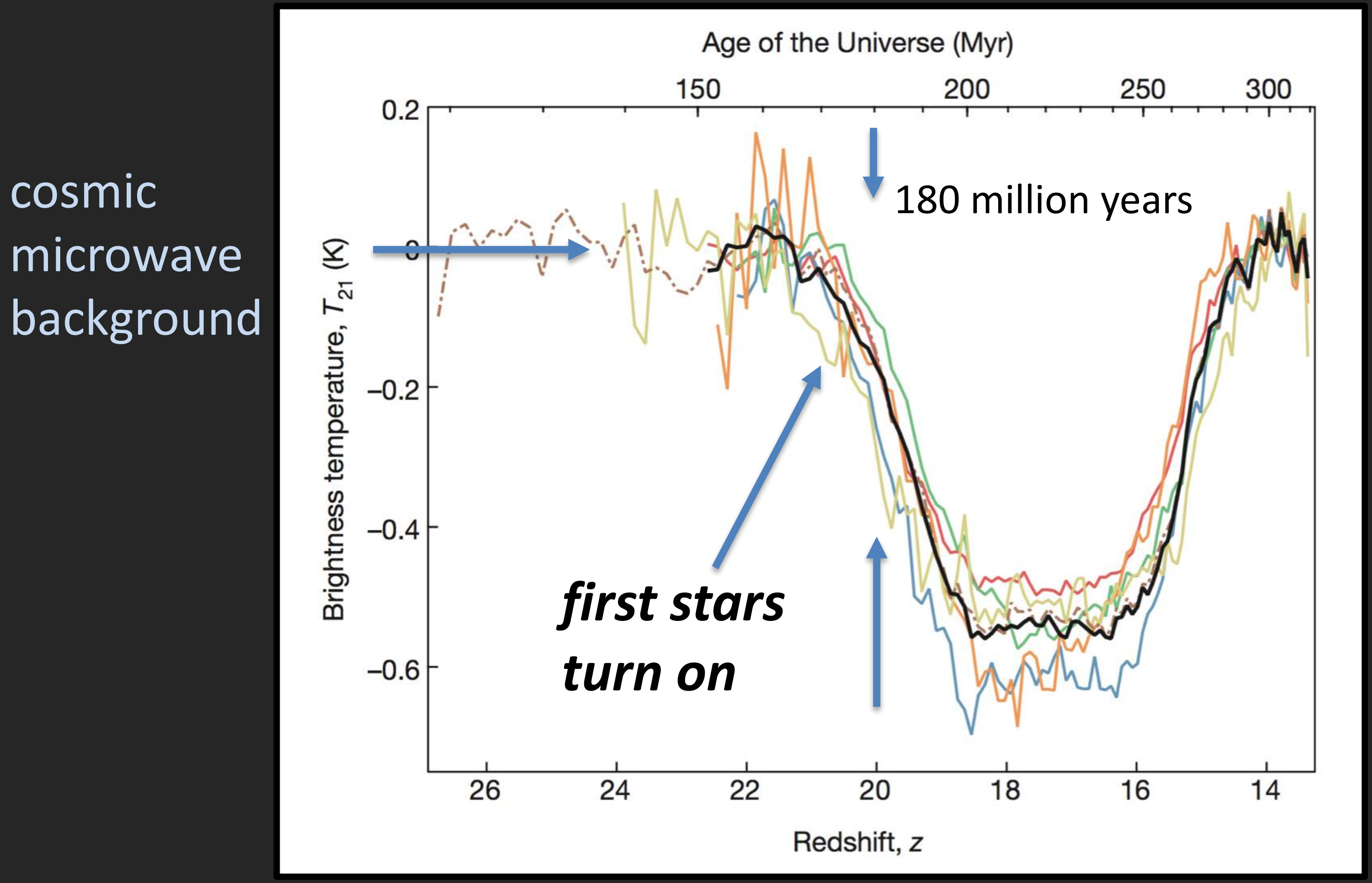
published March 01
Nature

Bowman, Rogers, Monsalve, Mozdzen & Mahesh

National Science Foundation

gdi

first evidence for when the "first stars" started to shine brightly



NEW RESULT

published March 01
Nature

is this correct?

confirmation?

first stars become prominent at redshift z~20 (~180 million years)

Bowman+2018

gdi

first evidence for when the "first stars" started to shine brightly

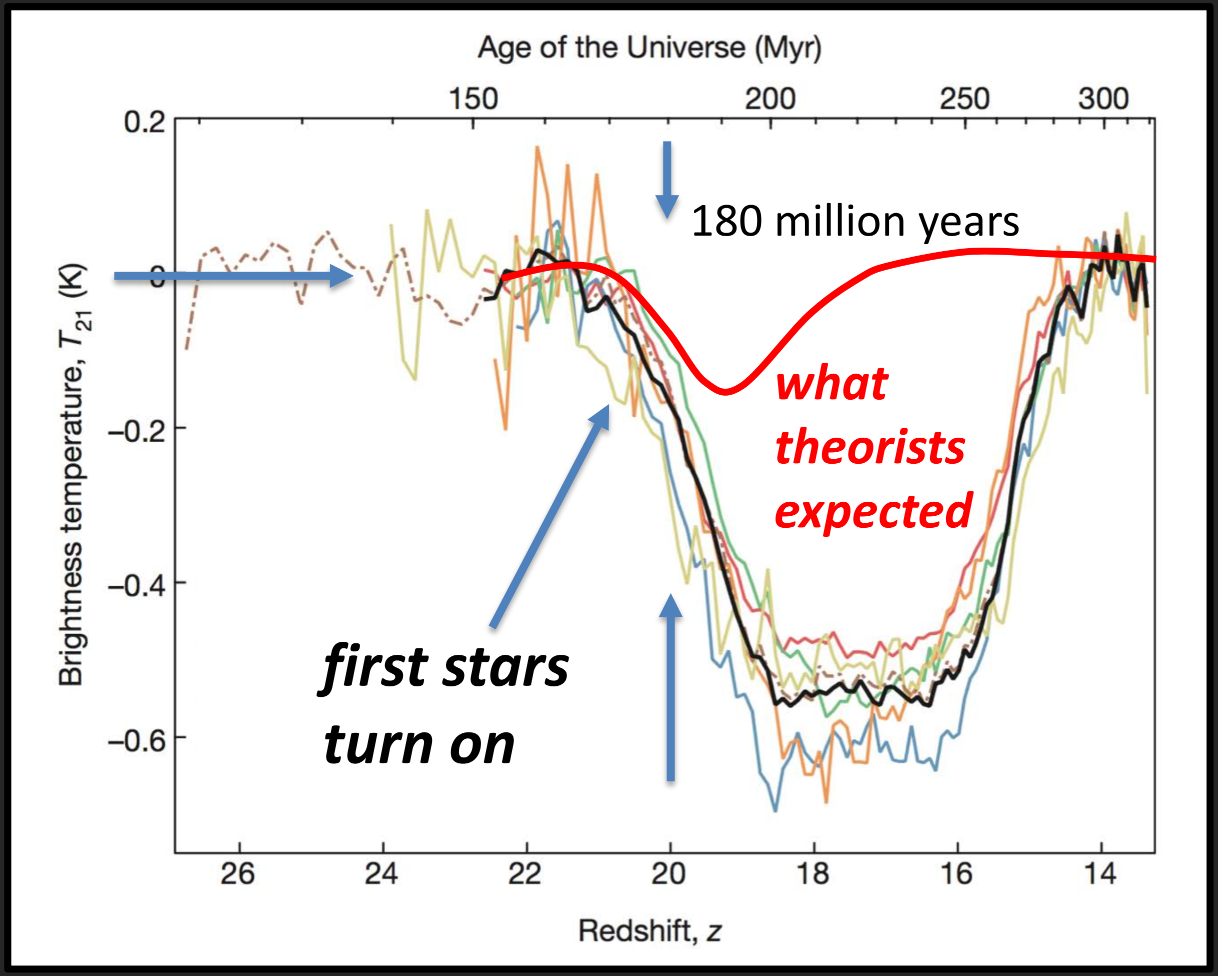
cosmic microwave background

NEW RESULT

published March 01
Nature

is this correct?

confirmation?



?

first stars become prominent at redshift z~20 (~180 million years)

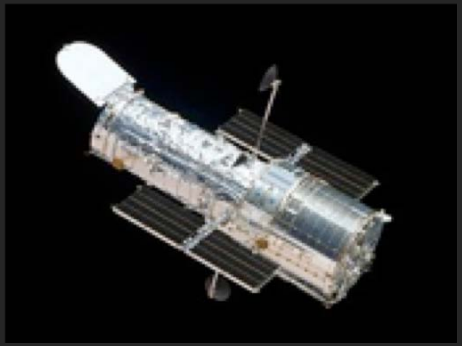
Bowman+2018

gdi

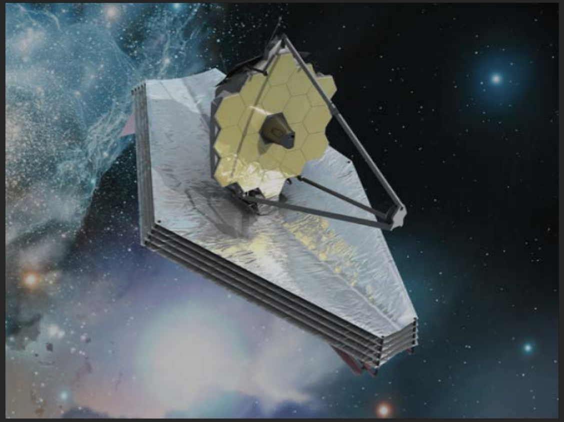
what do we know about the first galaxies?

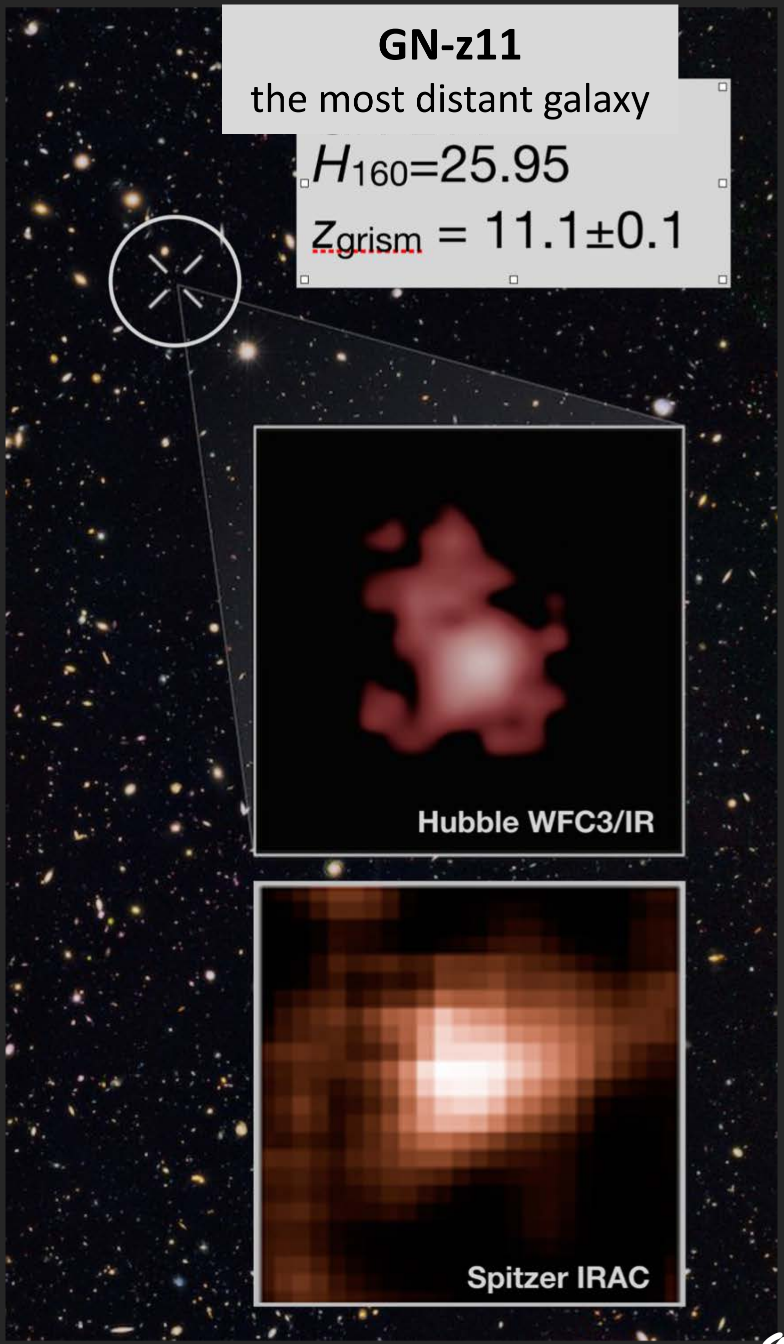
the first galaxies must be earlier than GN-z11

i.e., earlier than 400 million years
but probably not by much – maybe 100-200 million years?



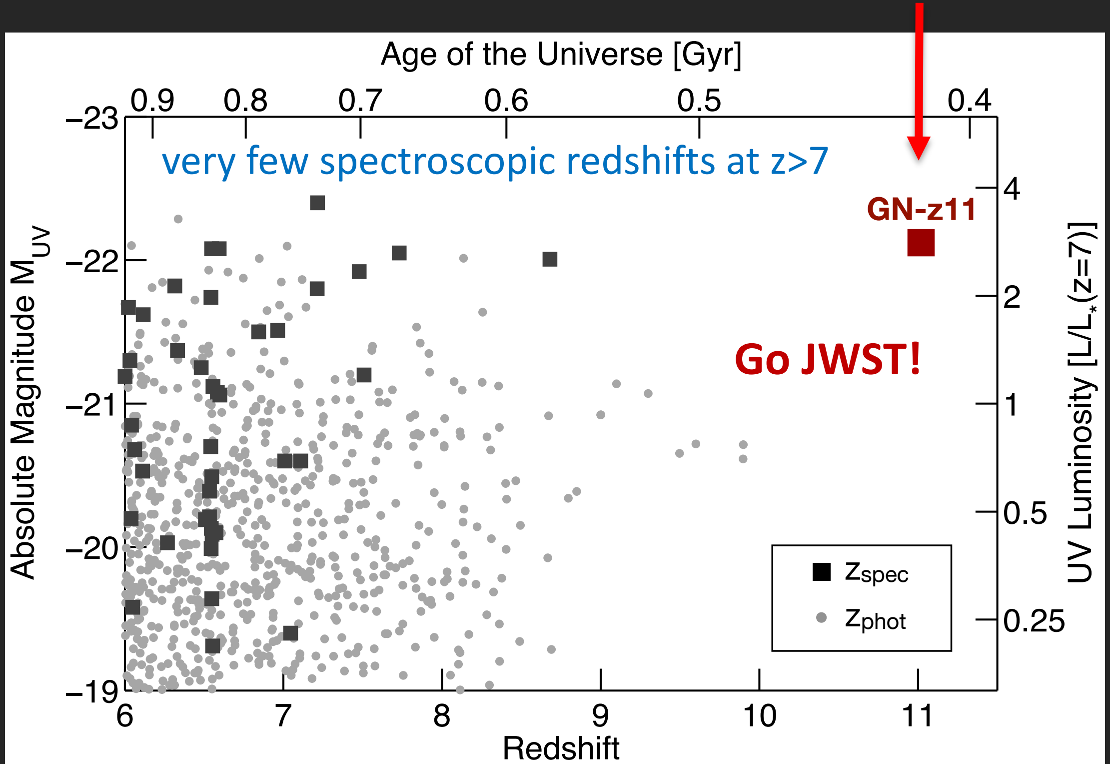
Hubble and Spitzer have been reaching into JWST territory!

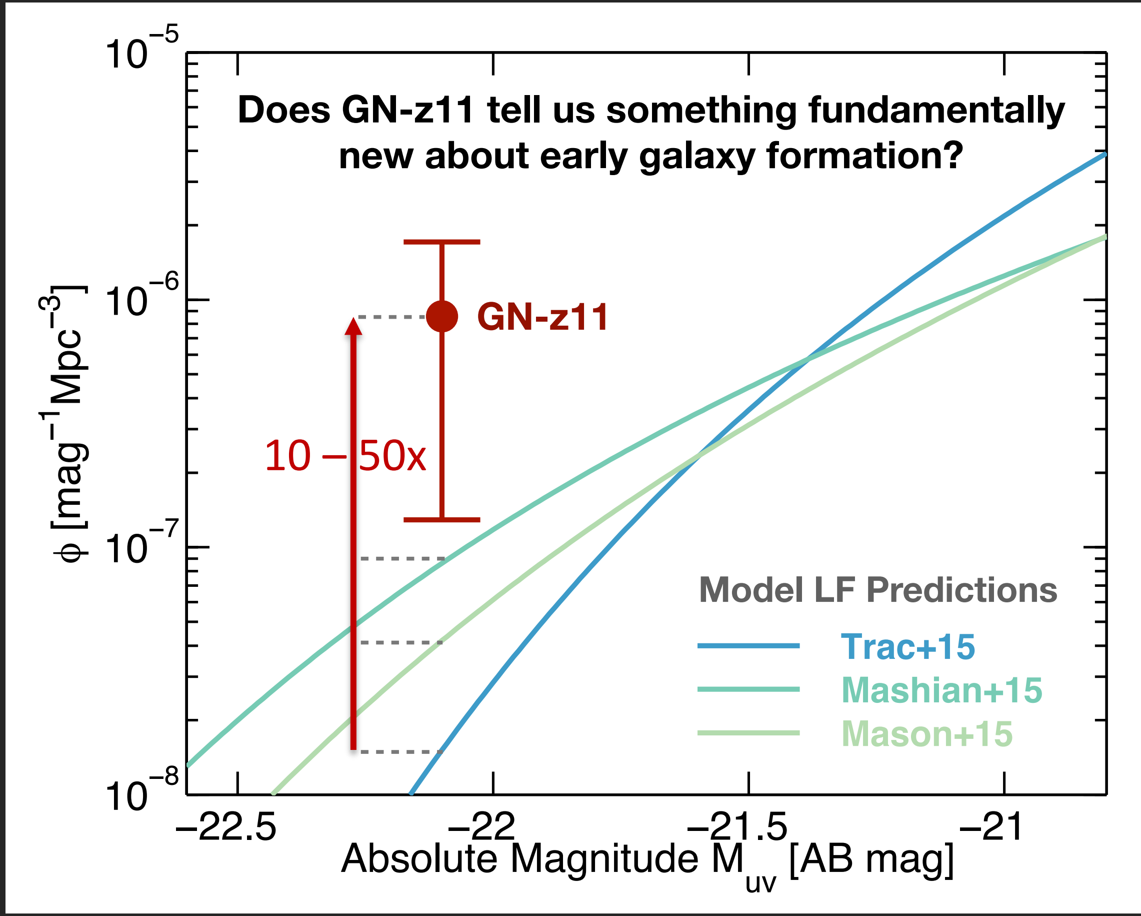




GN-z11 – the most distant galaxy found to date

surprising discovery of GN-z11





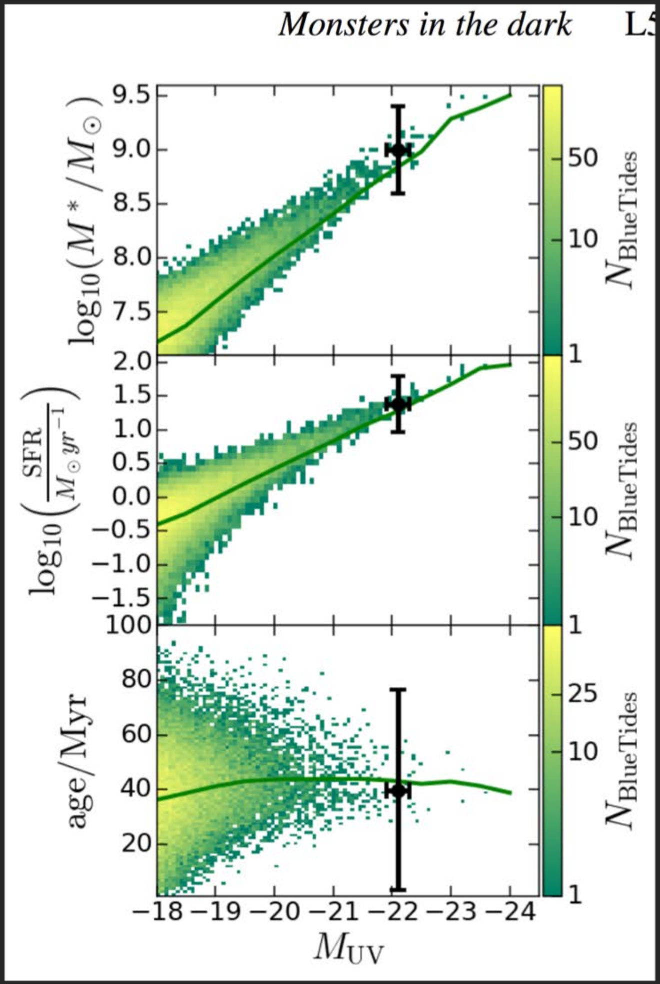
- detection of GN-z11 in *existing data* is unexpected, given current models

Oesch+2016

gdi

GN-z11

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

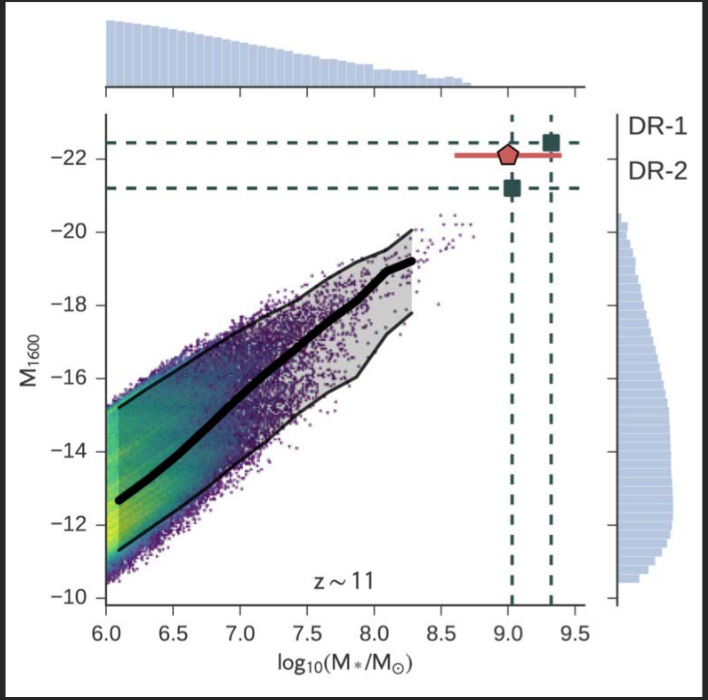


BlueTides Waters+2016

mass 10^9 $M_\odot$ SFR 24 $M_\odot$/yr

β -2.5 A_{UV} <0.2 mag age 40 Myr

the derived physical properties of GN-z11
are consistent with expectations from
large-volume simulations



Mutch+2016 DRAGONS

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

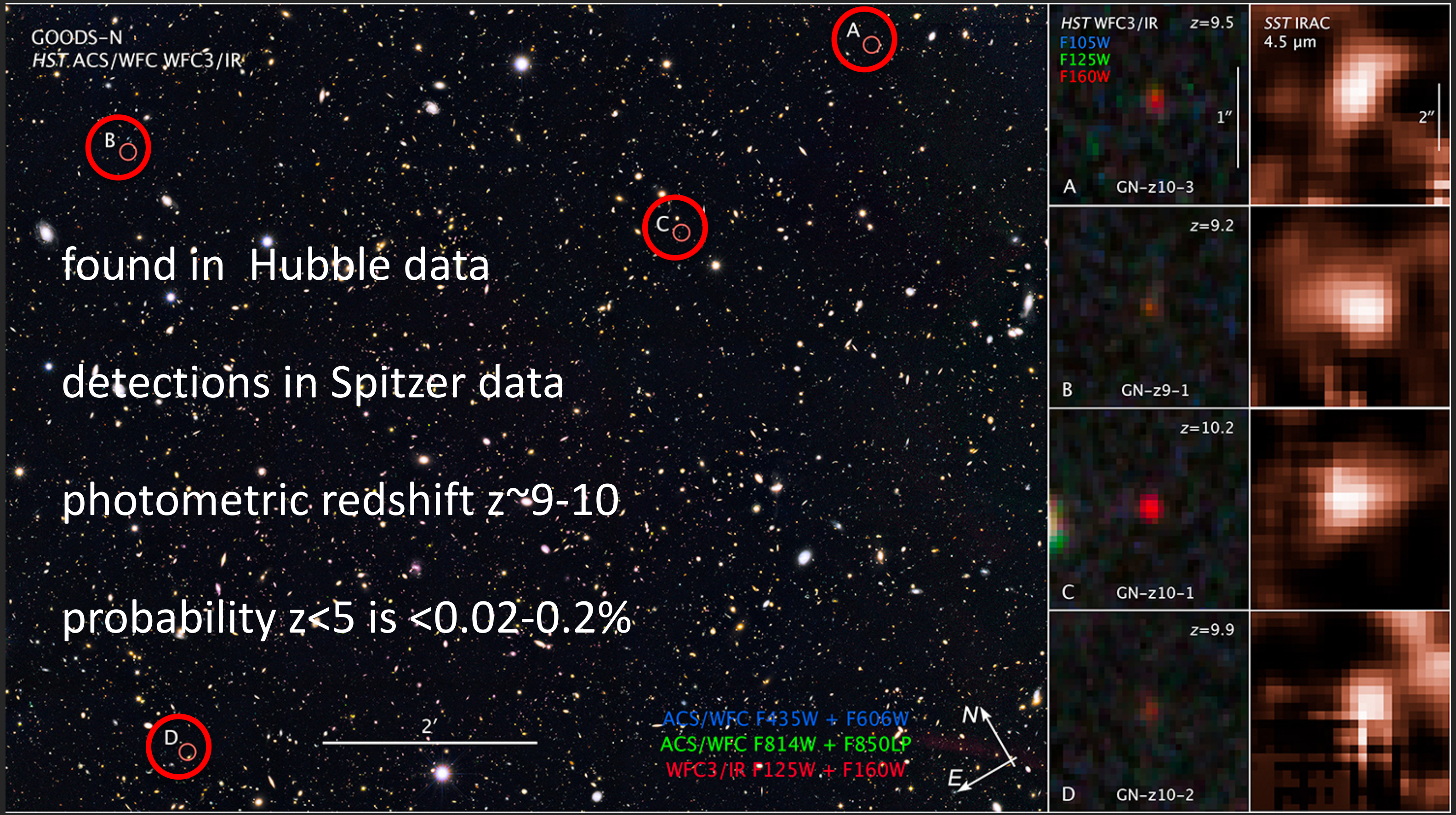
gdi

the highest redshift galaxies

galaxies at z~10 (480 Myr)

gdi

some very luminous galaxy candidates at redshift z~9-10



found in Hubble data

detections in Spitzer data

photometric redshift z~9-10

probability z<5 is <0.02-0.2%

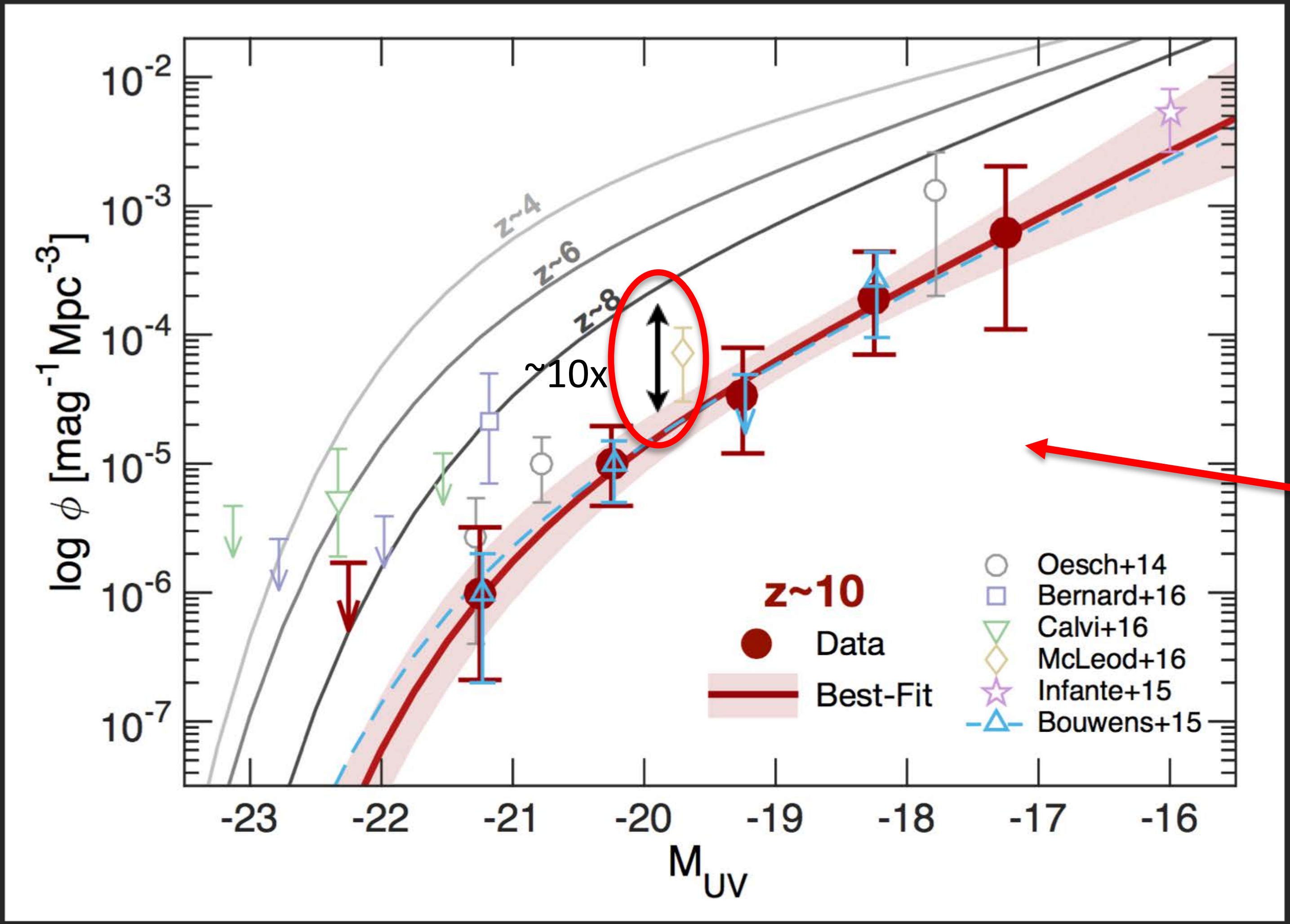
GN-z11

Hubble Spitzer

Oesch Bouwens GDI+2014

gdi

the luminosity function at z~10



z~10 galaxies are hard to find!

8 years of WFC3/IR imaging

only 9 galaxies in the major Legacy fields: HUDF/XDF + CANDELS/GOODS + HFF

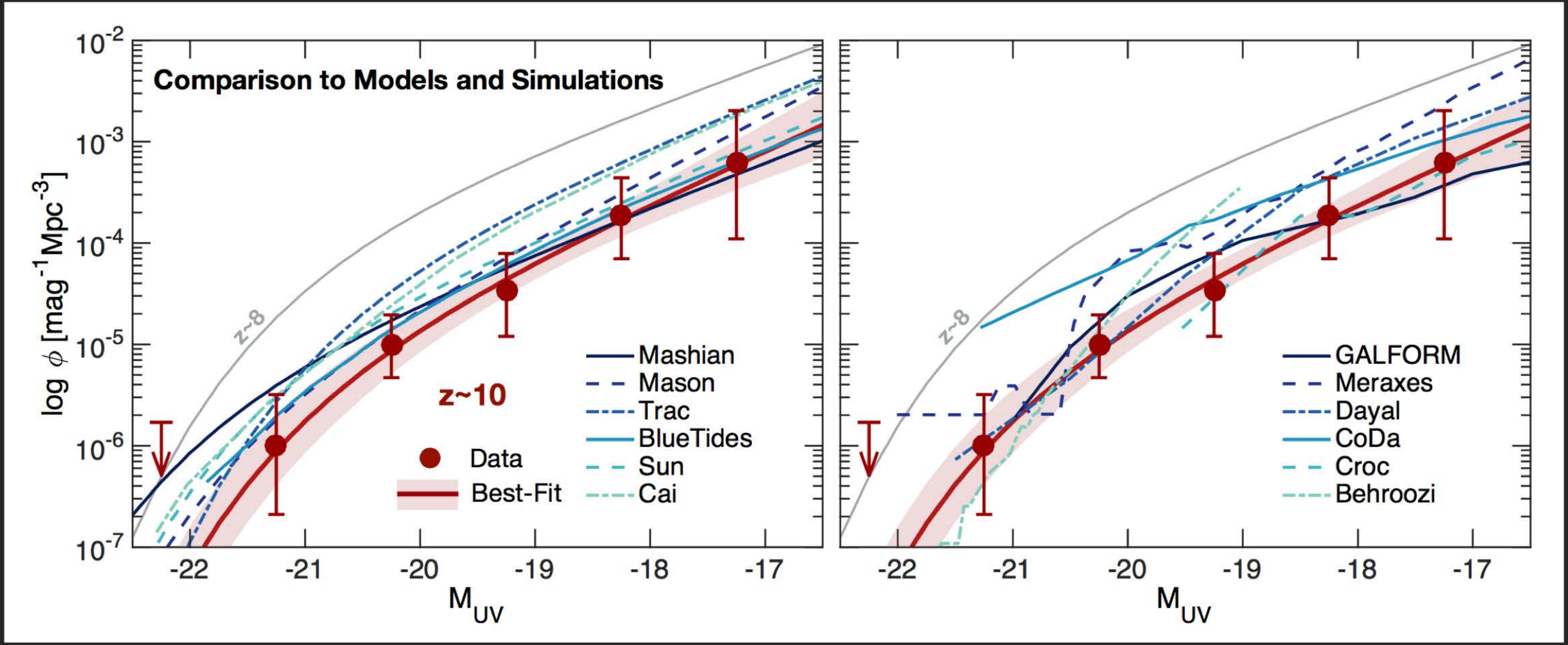
note the change of an order of magnitude between z~8 and z~10

Oesch+2017

gdi

see also: Zheng+2012; Coe+2013; Bouwens+2013,15,16; Ellis+2013; McLure+2013; Ishigaki+2014,17; Infante+2015; Bernard+2016; Calvi+2016; McLeod+2016

model comparisons – the luminosity function at z~10



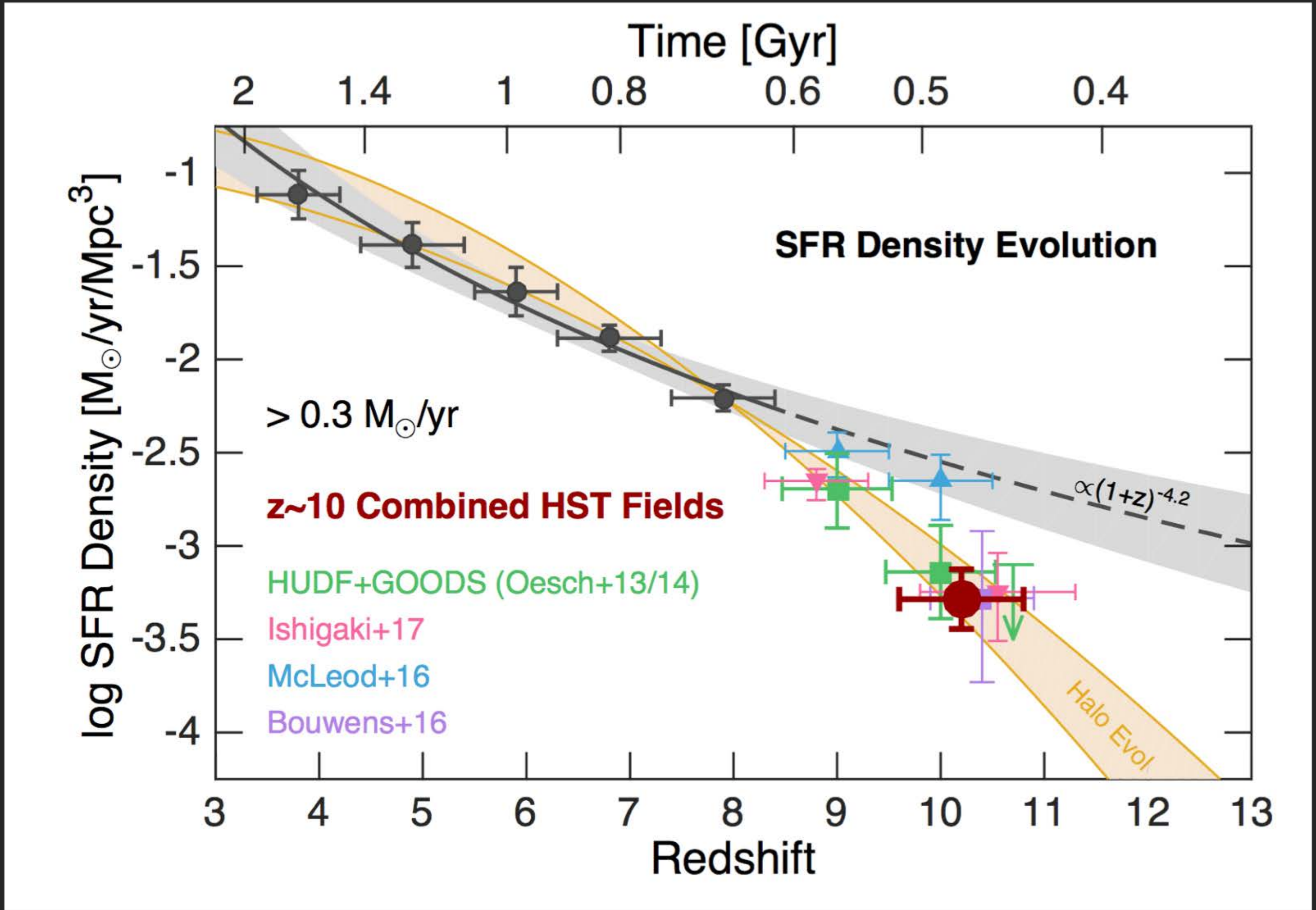
considerable spread but shape matches (broadly) to models –
but models are consistently high

Oesch+2017

gdi

"accelerated evolution" – the star formation rate density at z~9-10

clearly a trend to lower SFRD at z>8



Oesch+2013,2014,2017

gdi

see also: Zheng+2012; Coe+2013; Bouwens+2013,15,16; Ellis+2013; McLure+2013; Ishigaki+2014,17; Infante+2015; Bernard+2016; Calvi+2016; McLeod+2016

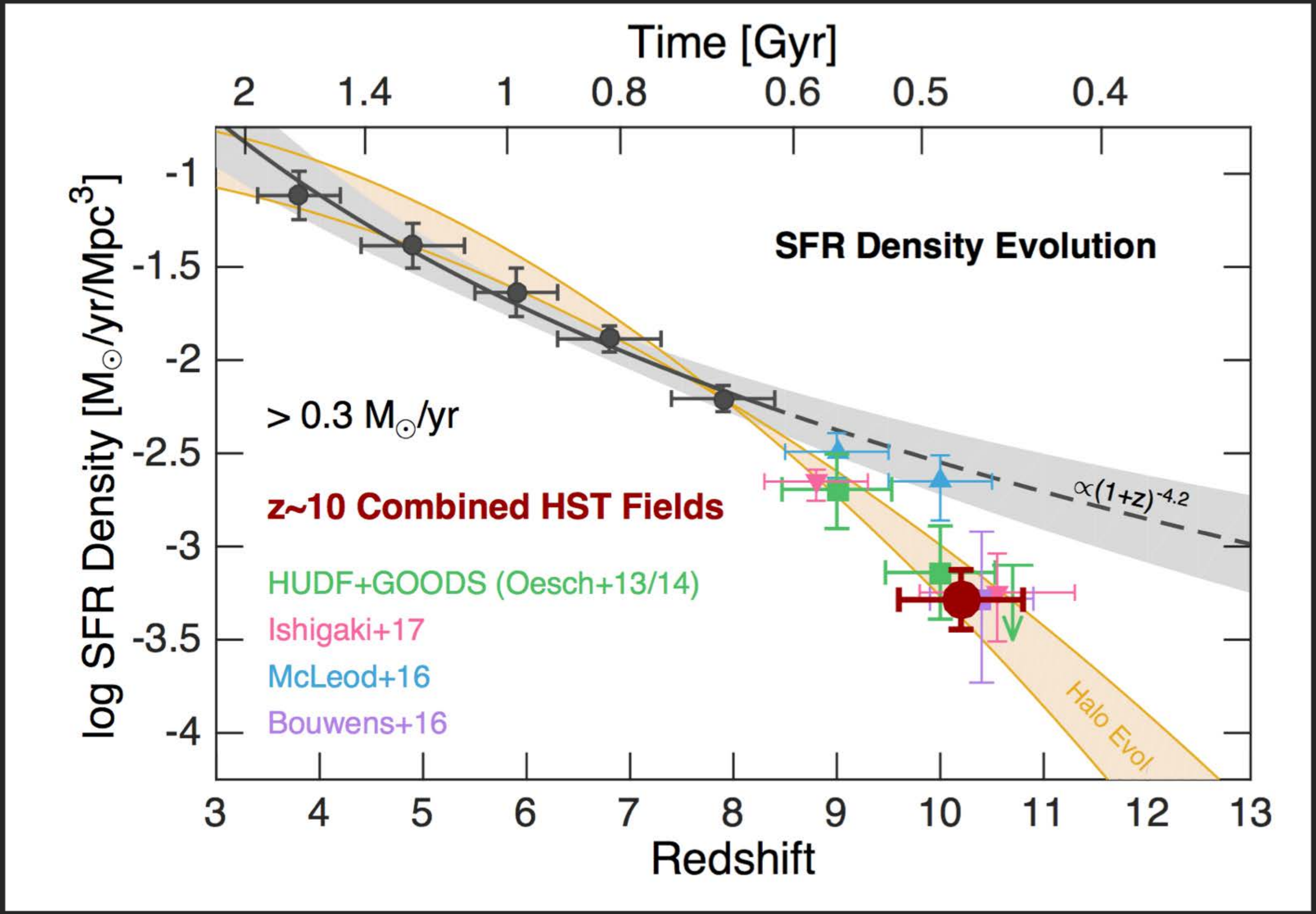
"accelerated evolution" – the star formation rate density at z~9-10

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

Note: this result also indicates that there is no evolution in Star Formation Efficiency (SFE) with cosmic time

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



Oesch+2013,2014,2017

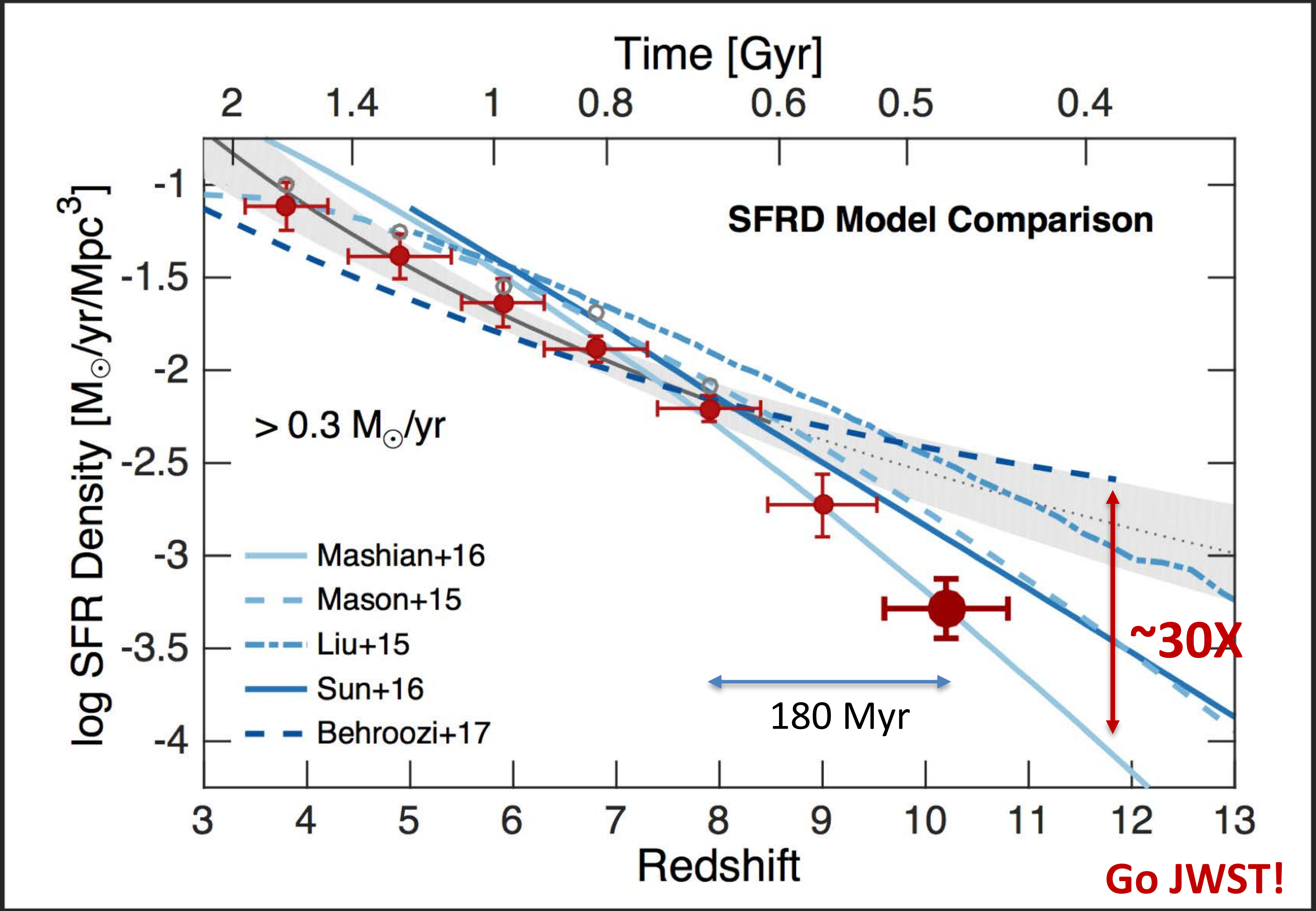
gdi

see also: Zheng+2012; Coe+2013; Bouwens+2013,15,16; Ellis+2013; McLure+2013; Ishigaki+2014,17; Infante+2015; Bernard+2016; Calvi+2016; McLeod+2016

model comparisons – the star formation rate density at z>6

note that "accelerated evolution" is seen in some models, but there is a large range of shapes/slopes

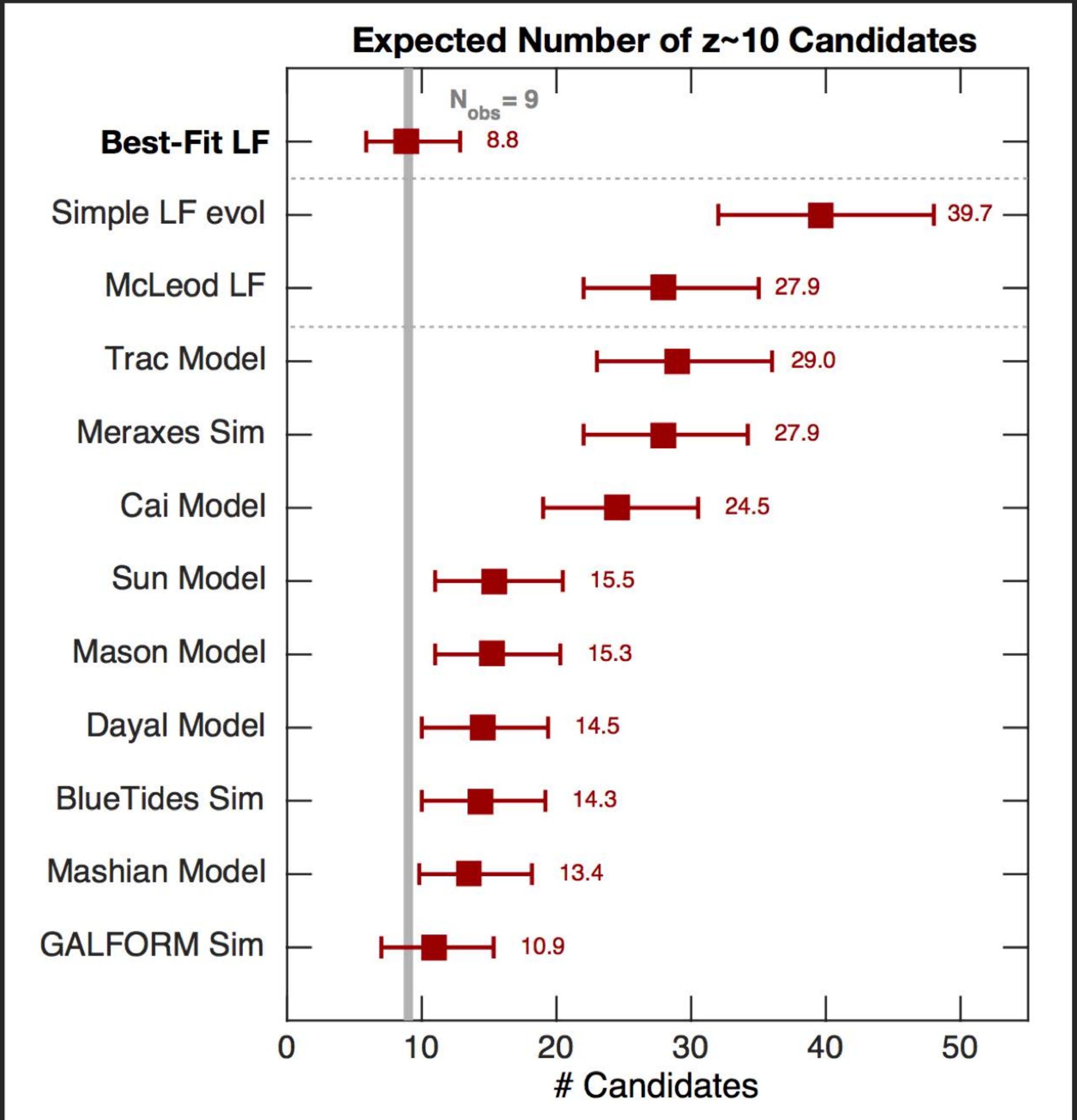
Oesch+2017



gdi

the case of the missing z~10 galaxies

number of z~10 galaxies from
“observed luminosity function” →



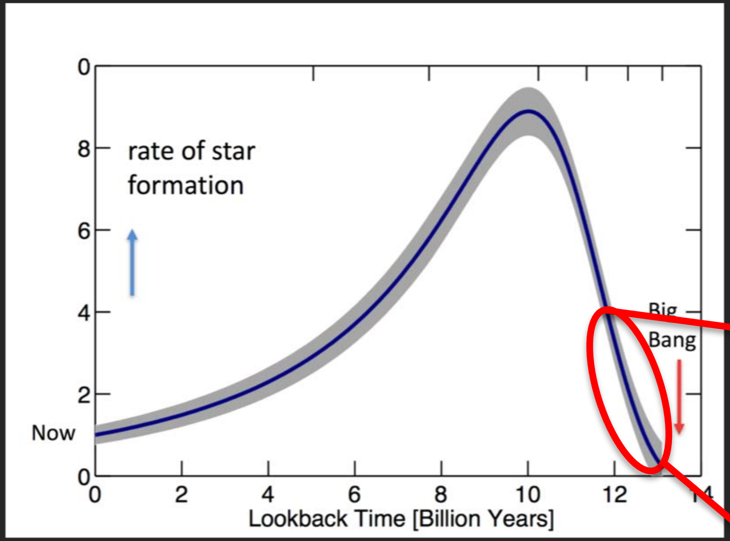
the situation at z~10 is unexpected

the numbers of objects is smaller than predicted by models – the offsets are quite systematic

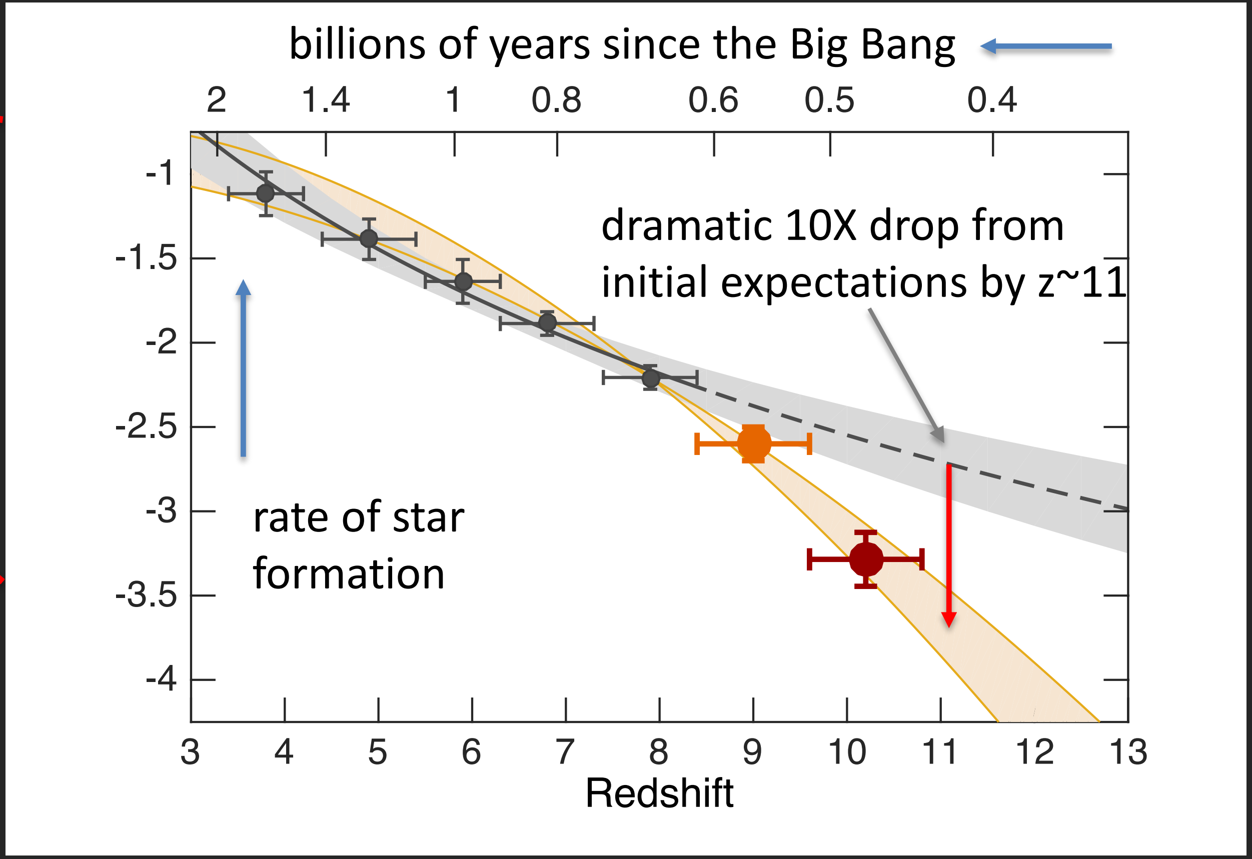
Oesch+2017

gdi

way fewer galaxies than expected at redshift 10!



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



galaxies are evolving rapidly earlier than 650 million years

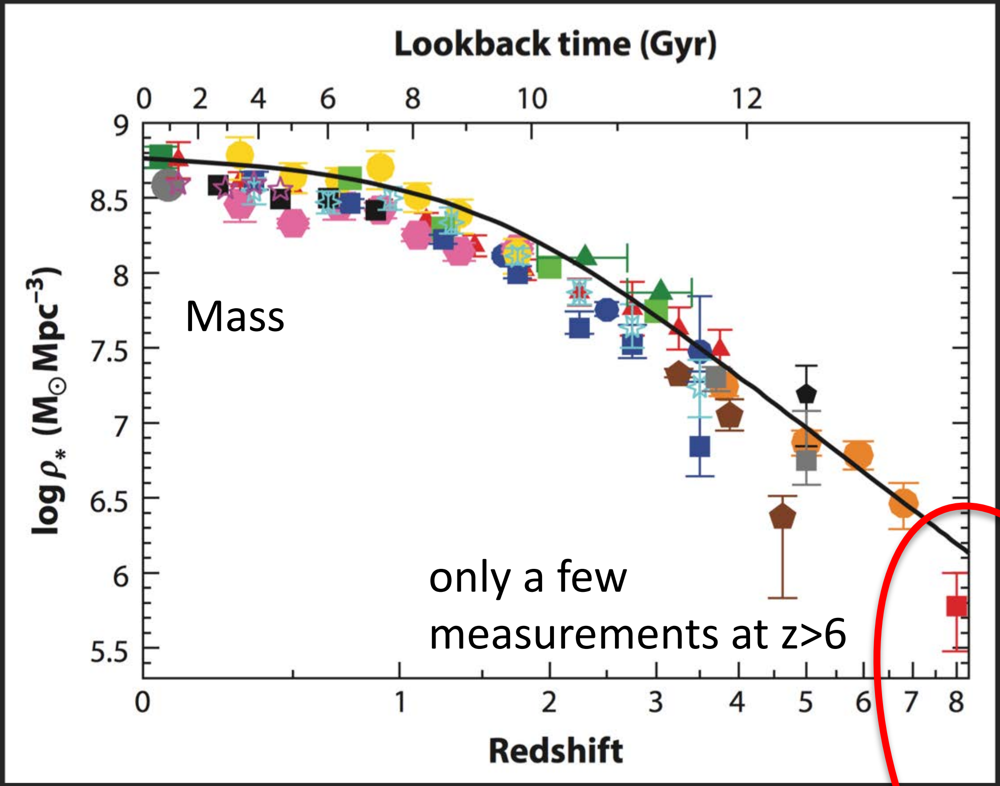
"accelerated evolution" is a very important result for JWST

Oesch+2017

Bouwens+2018

gdi

the global stellar mass and cosmic SFR density evolution

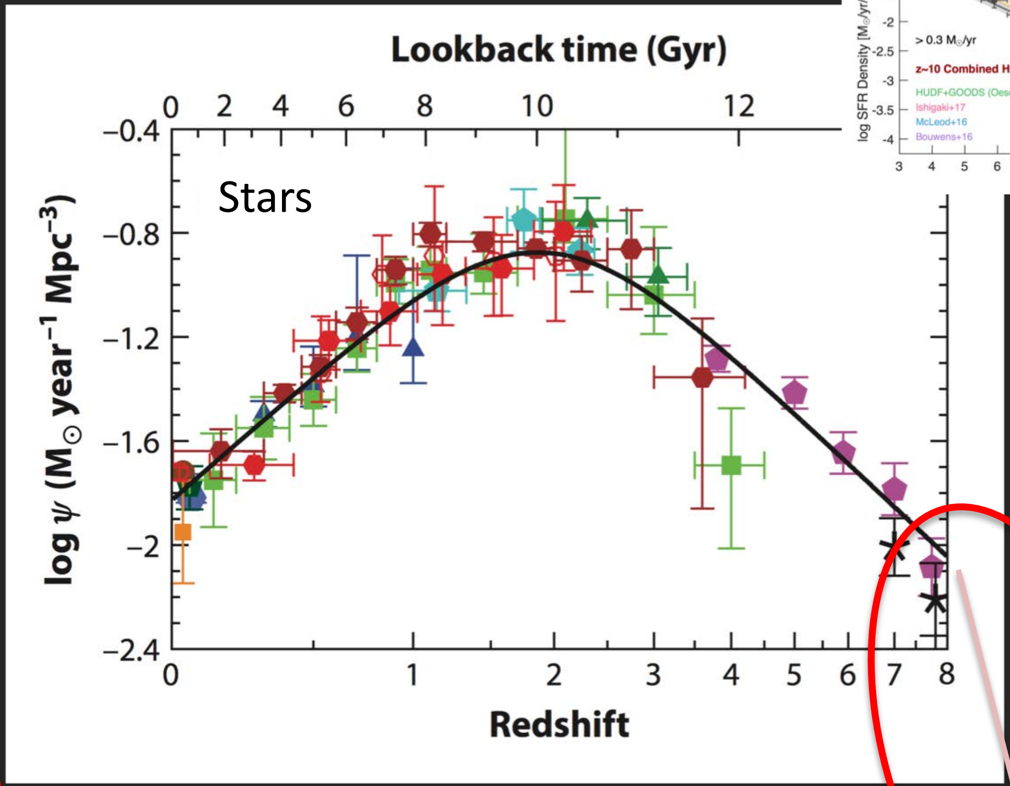


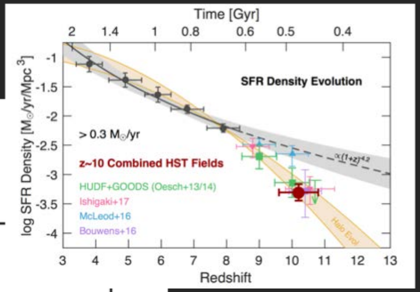
z~10

?

evolution of the global stellar mass density over 13 billion years

Madau & Dickinson 2014





new results at z>8

z~10

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

gdi

☛ *what does this mean for JWST and our search for the "first galaxies"?* ☚

gdi

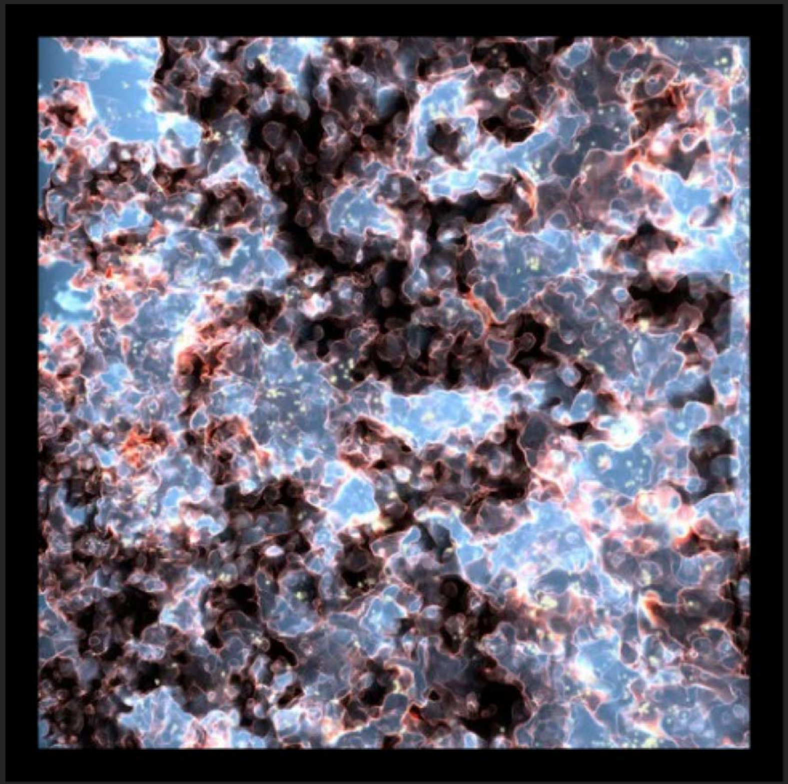
can JWST find the first galaxies?

will they be so rare that they will be hard to find?

will they occur at such high redshifts that they will be hard for JWST to see?

gdi

reionization epoch – 2016 Planck results

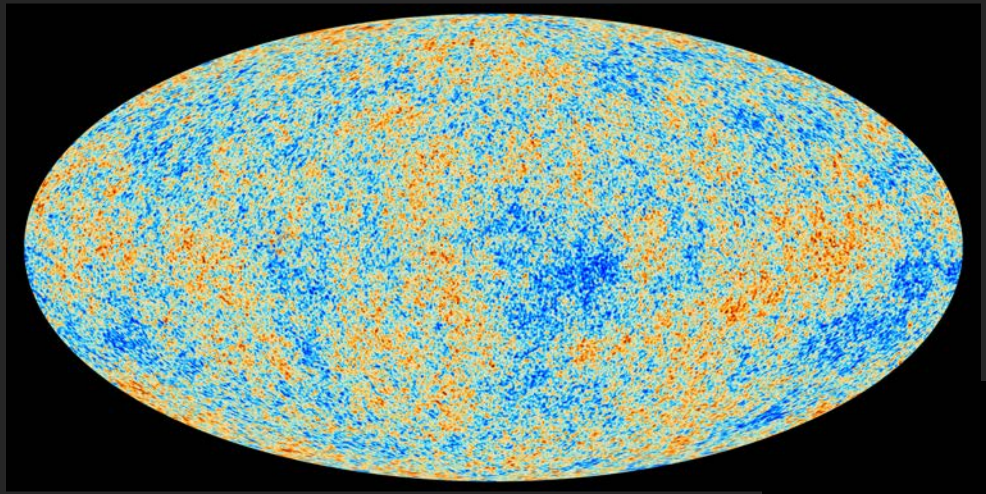


simulation: Alvarez et al. 2009

striking concordance between 2016 Planck results and galaxy constraints

implications of onset of reionization at z~10

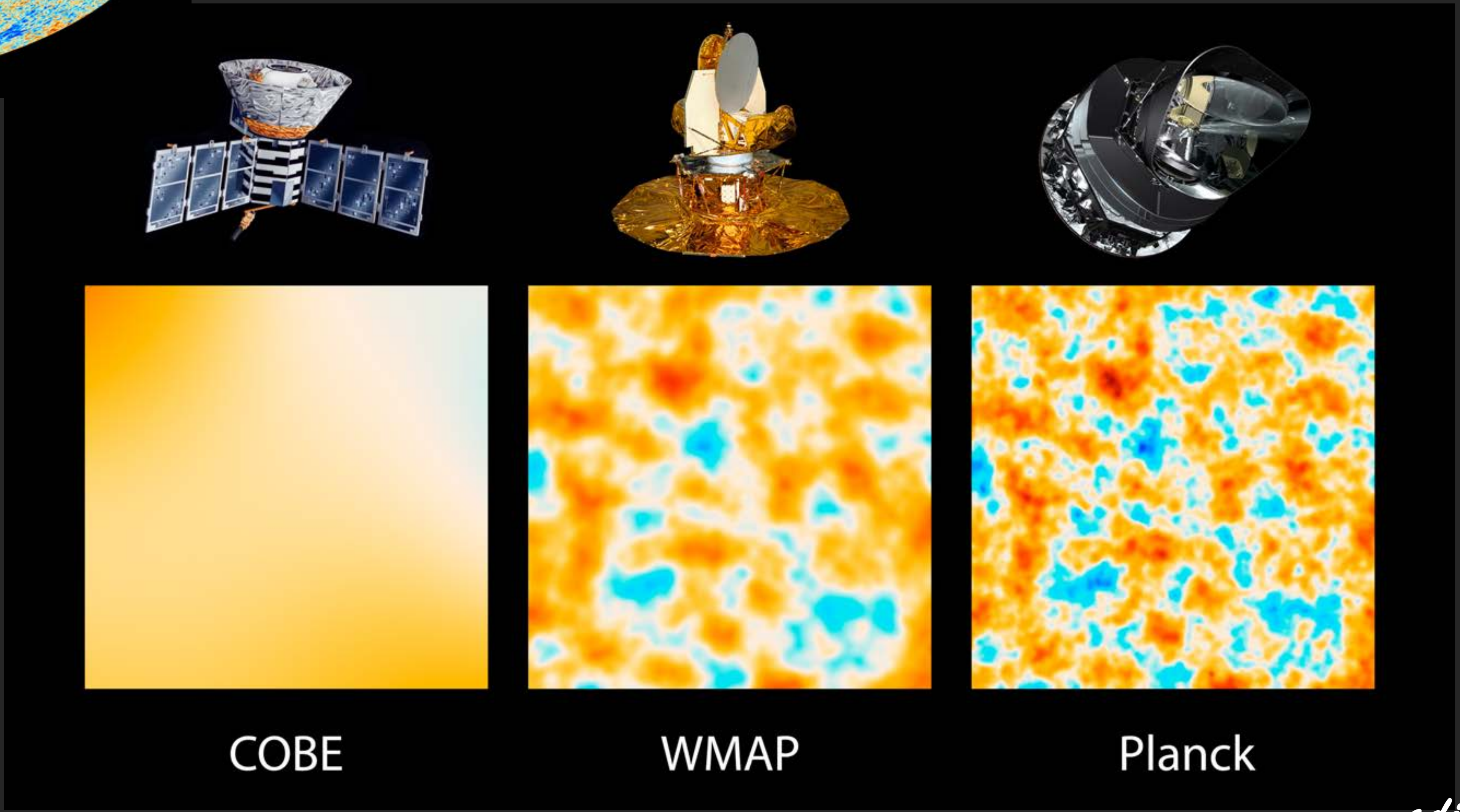
gdi



measuring the fluctuations in the 3ºK microwave background across the whole sky

Planck all-sky map of the microwave 3ºK background

three amazing missions



1989 2001 2009

gdi

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]

Received 11 May 2016 / Accepted 23 July 2016

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

gdi

constraints on the reionization history

Planck 2016

remarkable mission

- …Thomson optical depth $\tau = 0.058 \pm 0.012$….
- …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 $\Delta z < 2.8$.
- …the Universe is ionized at less than the 10% level at redshifts above $z \simeq 10$…
- …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]

Received 11 May 2016 / Accepted 23 July 2016

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.

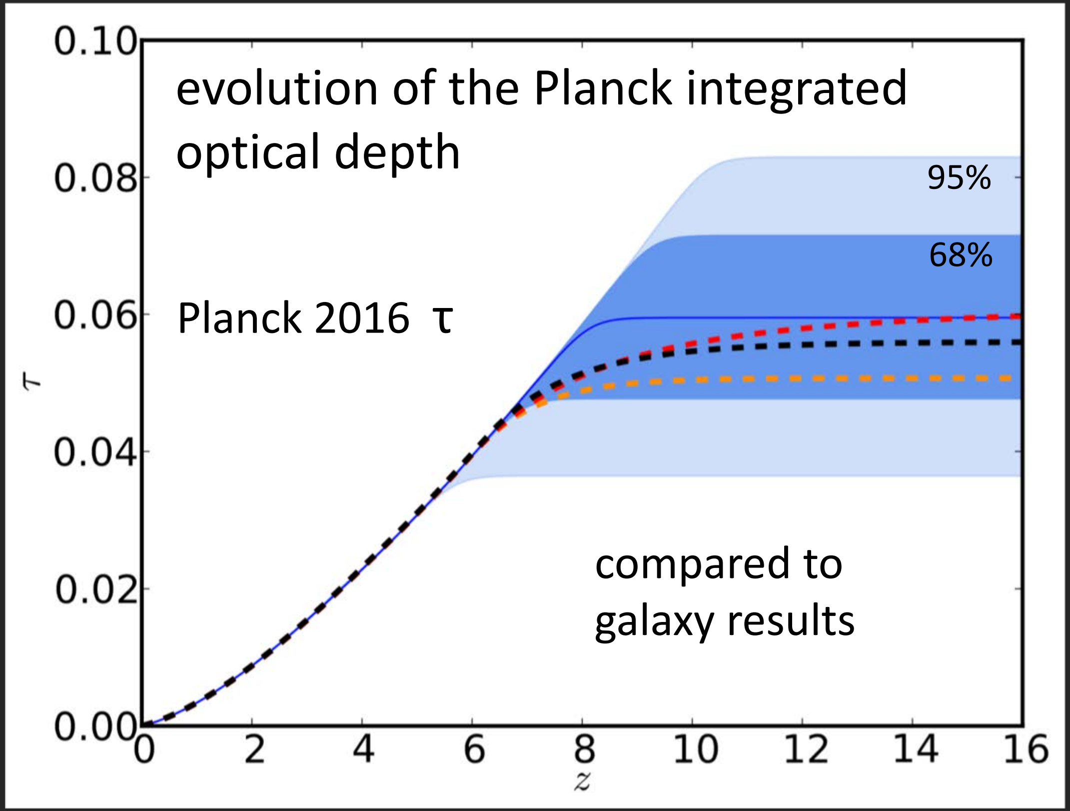
Key words. cosmic background radiation – dark ages, reionization, first stars – polarization

Plank Collaboration XLVII + 2016

gdi

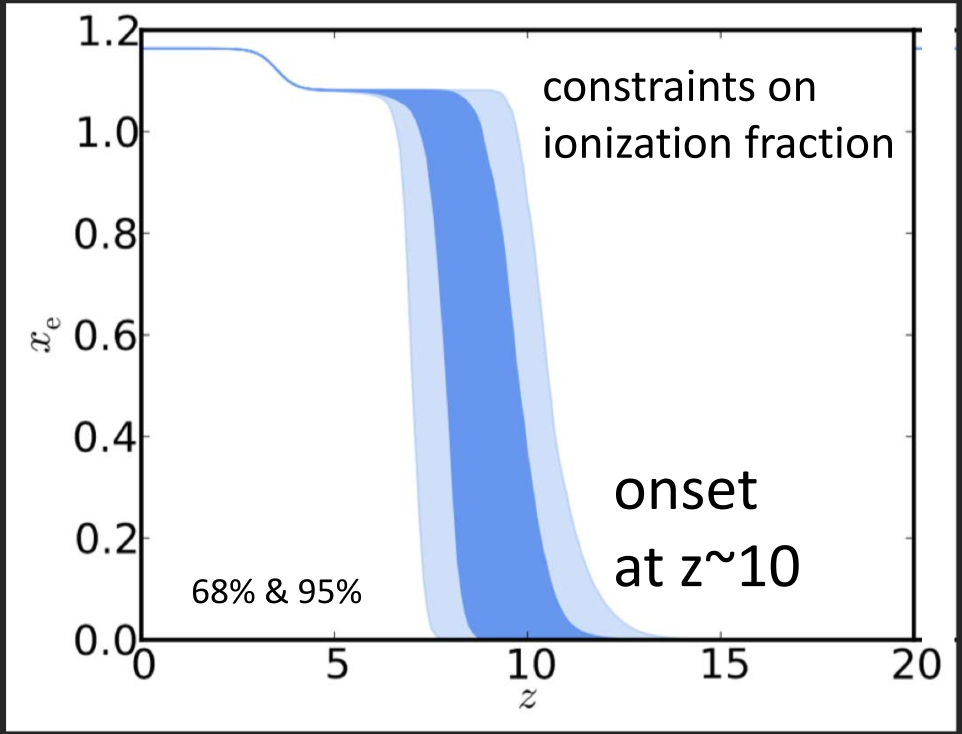
reionization constraints from Planck 2016

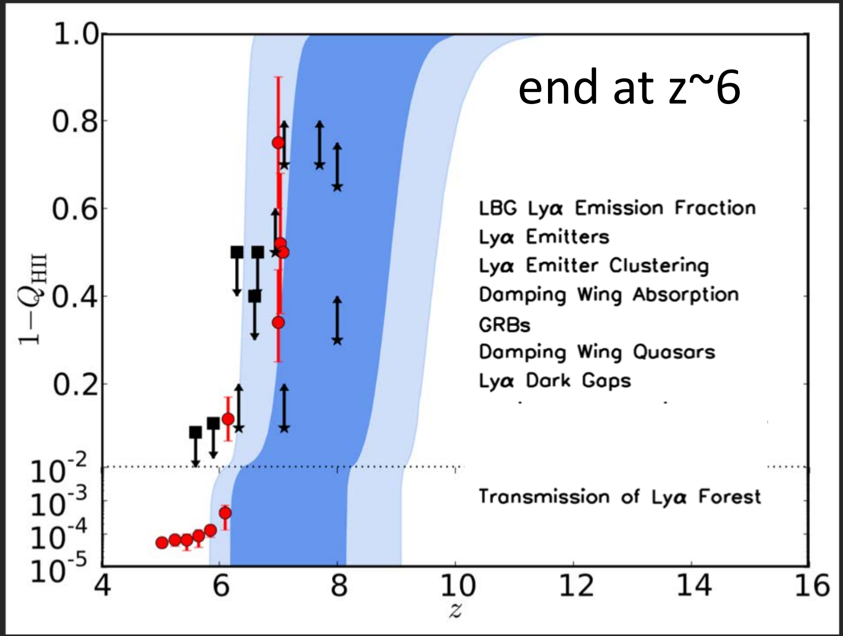
striking consistency with galaxy results



Bouwens+2015
Robertson+2015
Ishigaki+2015

Plank Collaboration XLVII + 2016



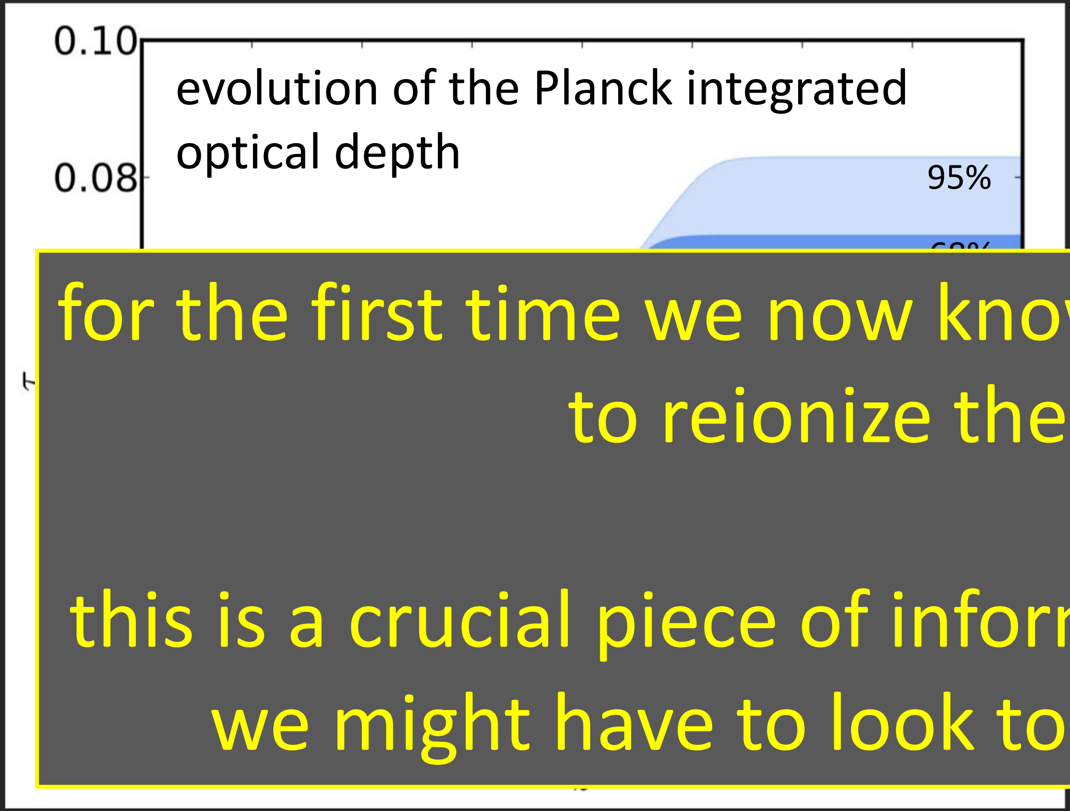


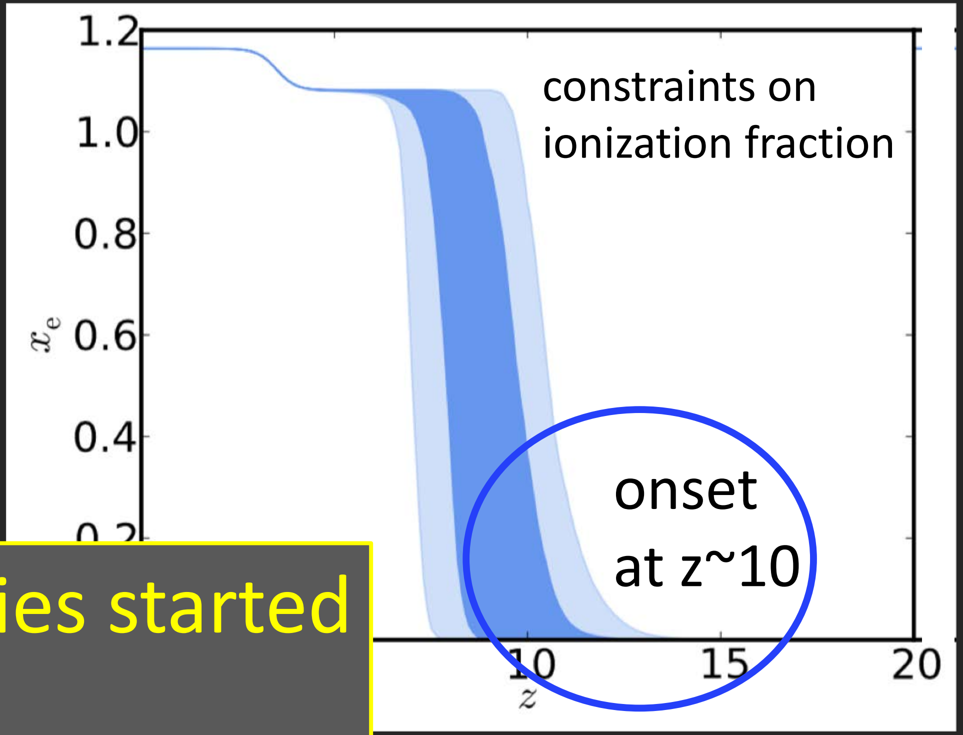
reionization history compared with observational constraints

gdi

reionization constraints from Planck 2016

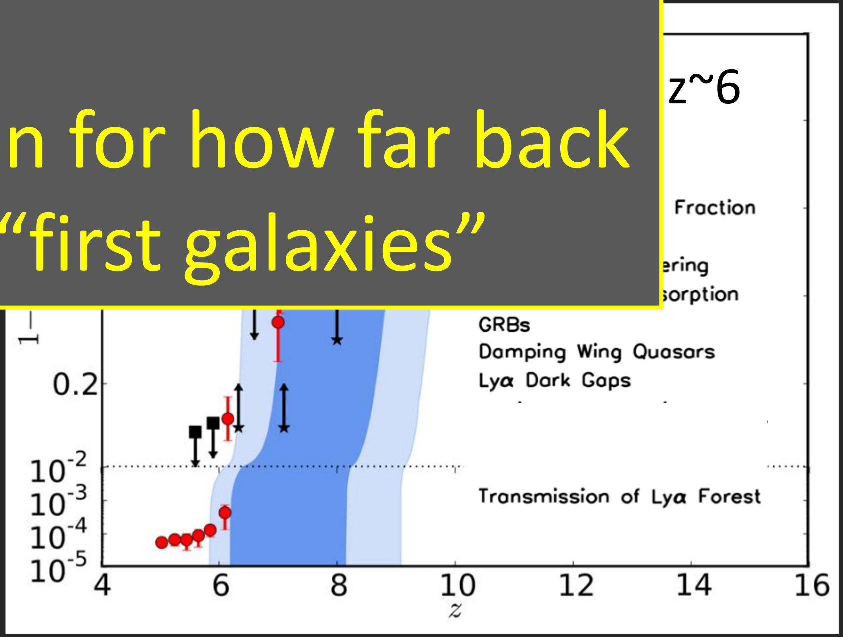
striking consistency with galaxy results





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"



reionization history compared with observational constraints

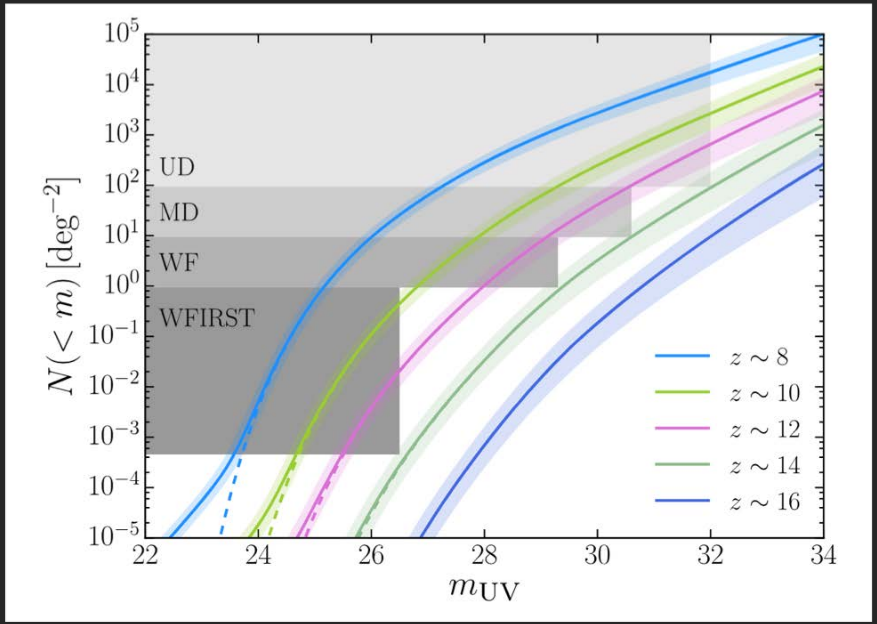
Plank Collaboration XLVII + 2016

gdi

“First Light and Reionization”

one of JWST’s four science themes

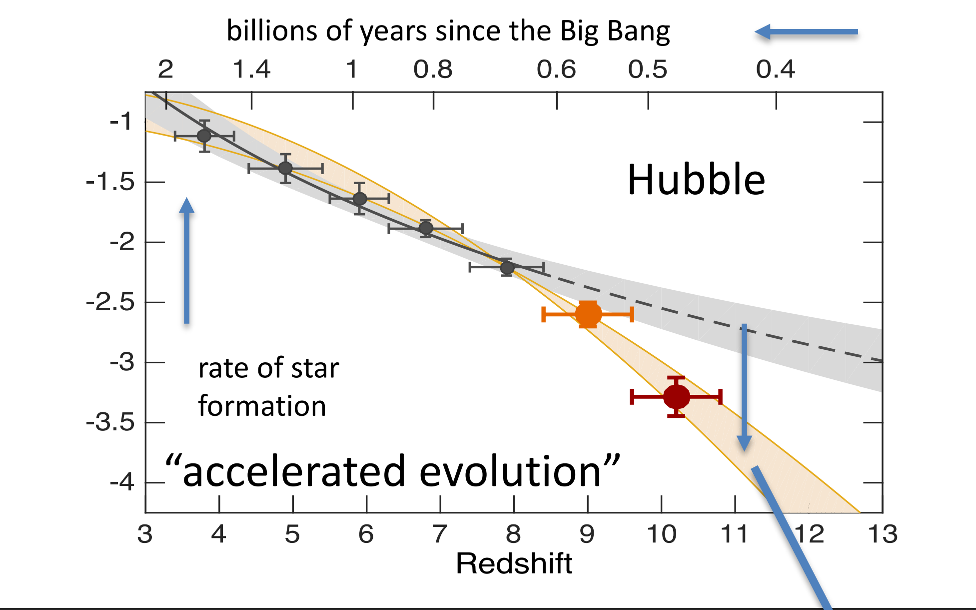
can JWST see the “first galaxies”?



recent studies suggest that JWST will reach to redshift z~ 14-15 in the deepest studies.

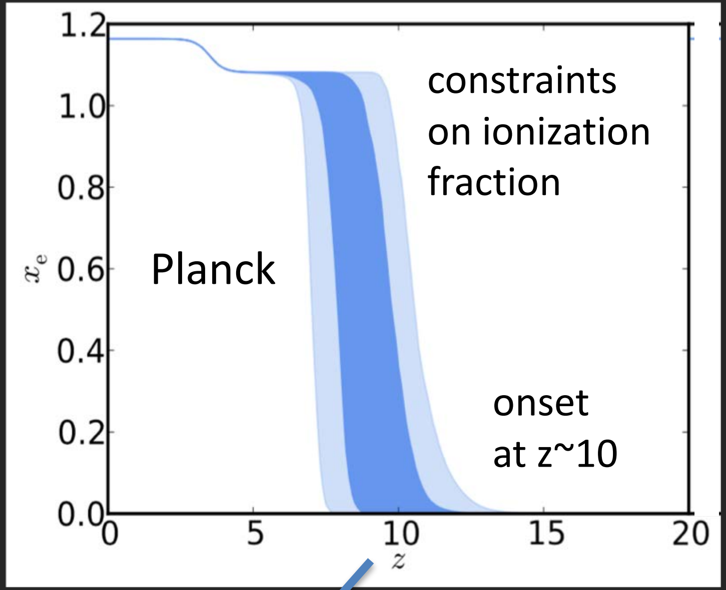
Mason+2015

gdi



*can JWST see the "first galaxies"?***

**depends on what one means by "first galaxies" but probably yes...



large 10X drop from expected at z~11 + galaxy turn-on at z~10-11

☛ suggest major changes in galaxy population at z~10-12 ☚

great for JWST's "first light" goal since galaxies are evolving rapidly at z~10-12

likely major changes over z~10-15 – where JWST can see them!

☞ exciting times ahead at "Cosmic Sunrise"! ☜

gdi

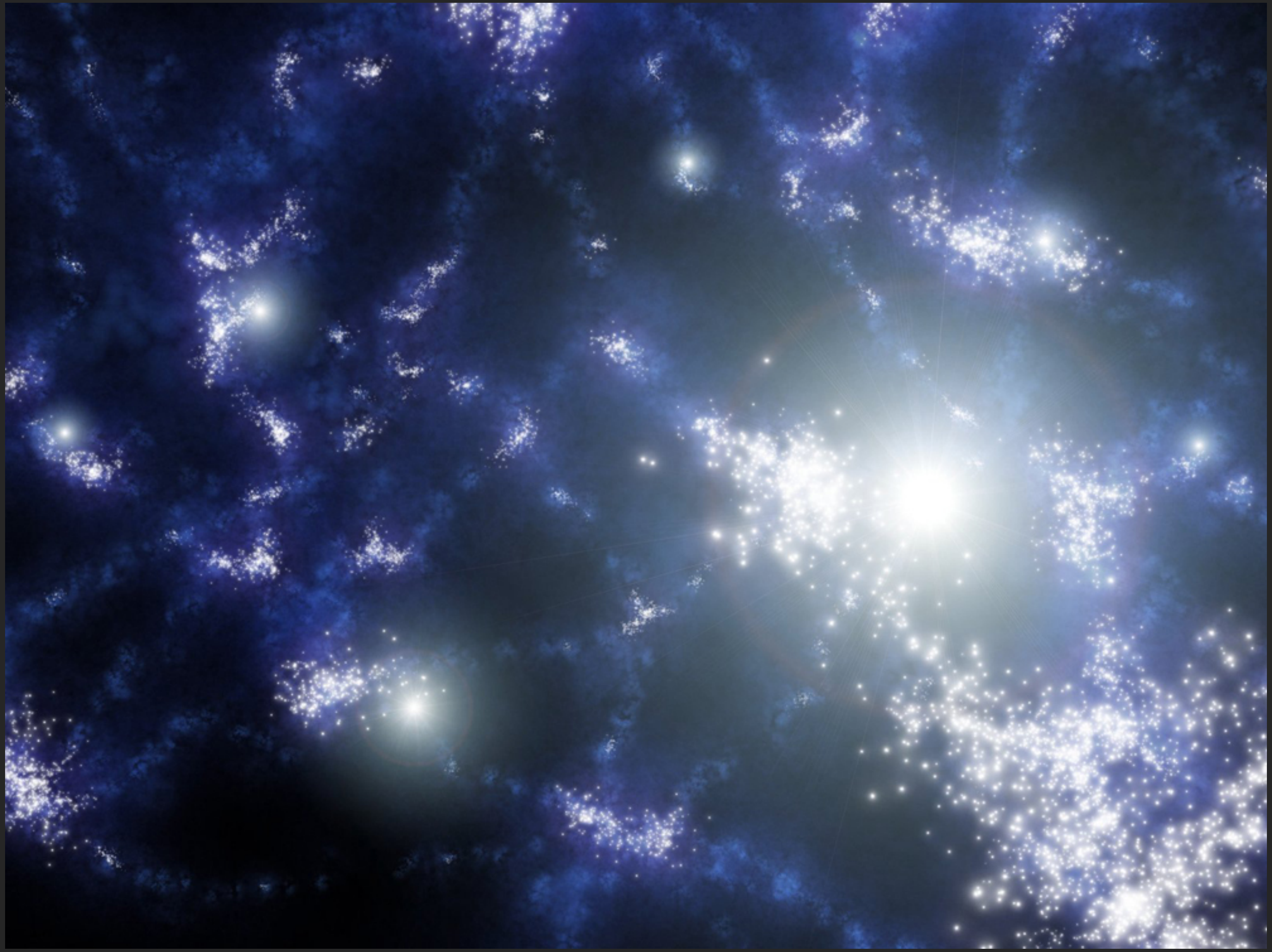
the dramatic brightening after dawn

desert sunrise

gdi

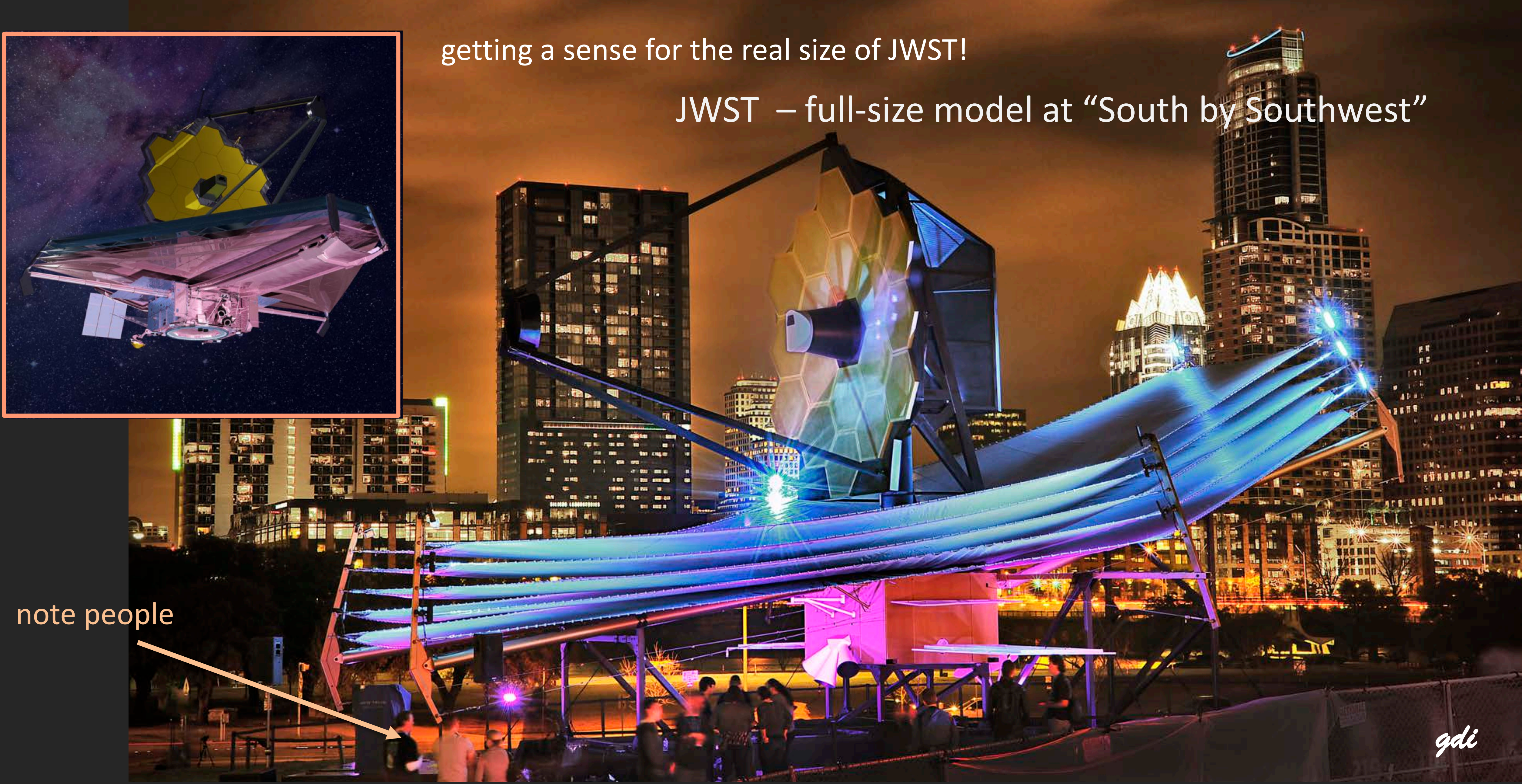
the dramatic brightening after cosmic dawn

"Cosmic Sunrise" as the first galaxies burst forth at z~12-15



gdi

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



getting a sense for the real size of JWST!

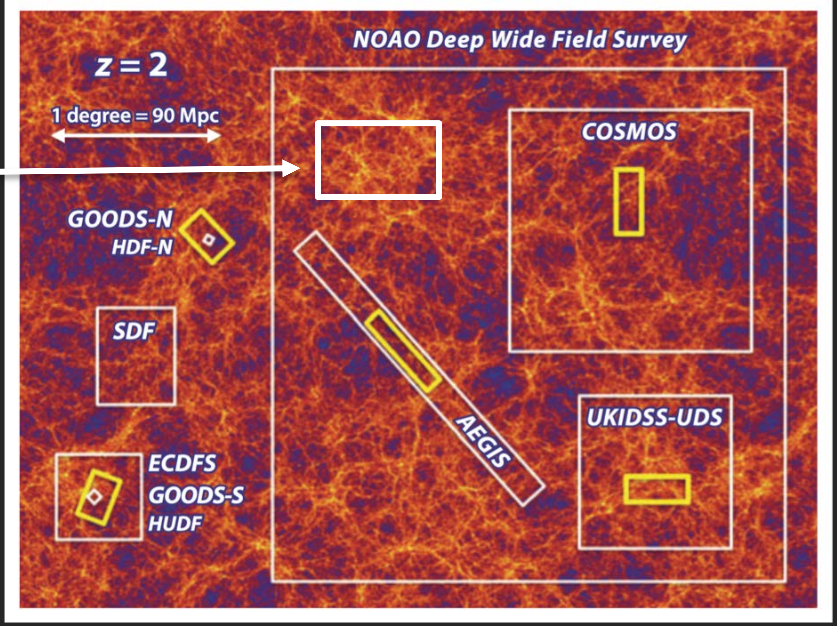
JWST – full-size model at "South by Southwest"

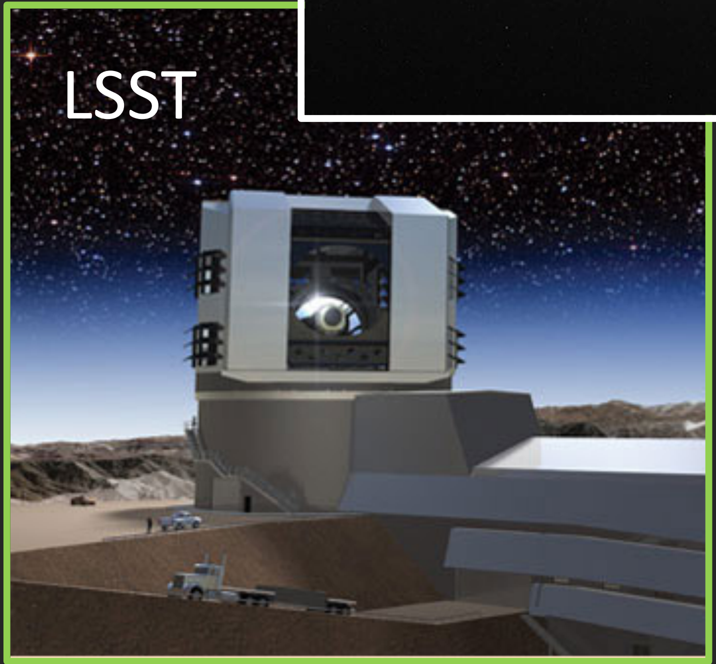
note people

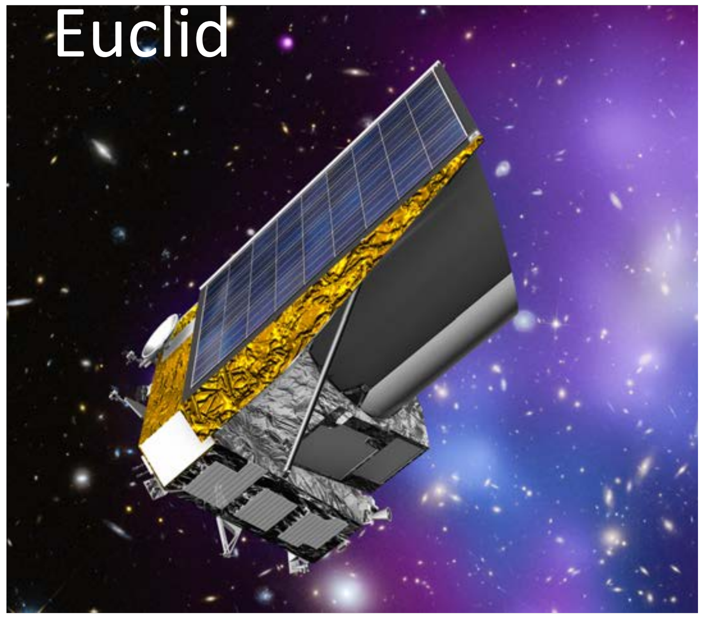
surveys to minimize cosmic variance

wide-area imaging >>Hubble or JWST

WFIRST →







gdi

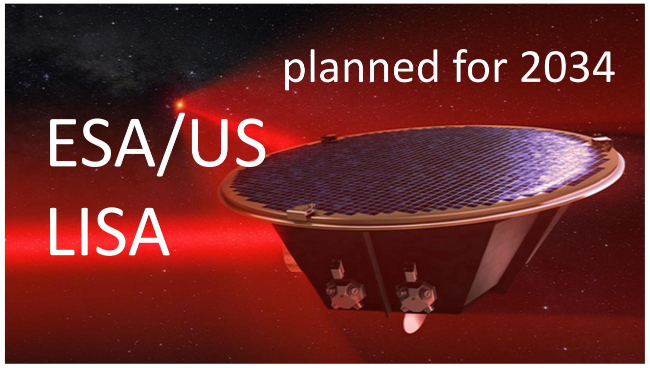
☛ *the long-term future – after JWST* ☚

great opportunities, but great challenges…..

gdi

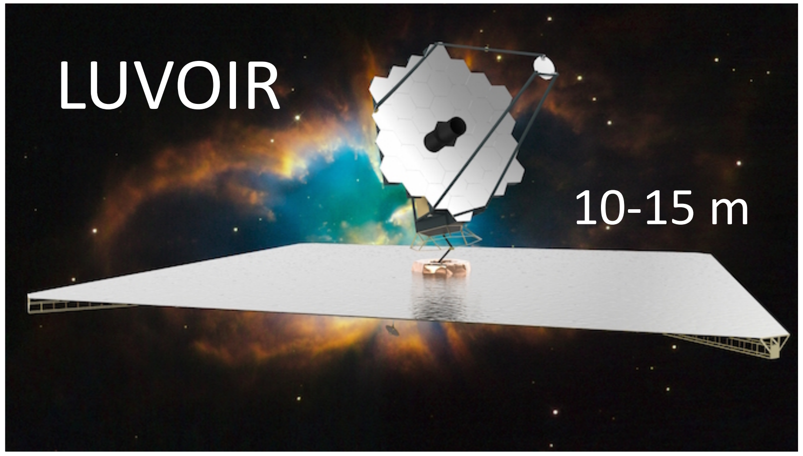
☛ *the flagships of the 2030s (?)* ☚

✓

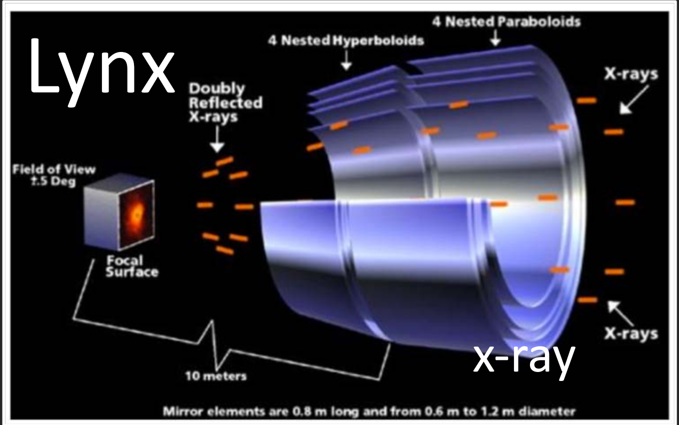


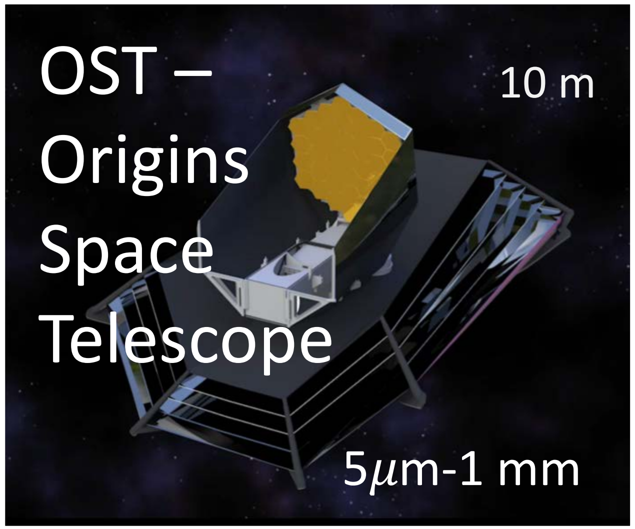
✓

NASA strategic missions under study for the 2020 Decadal



?

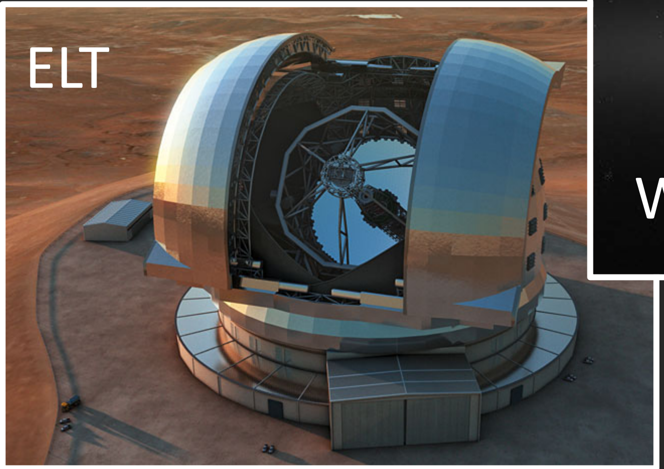


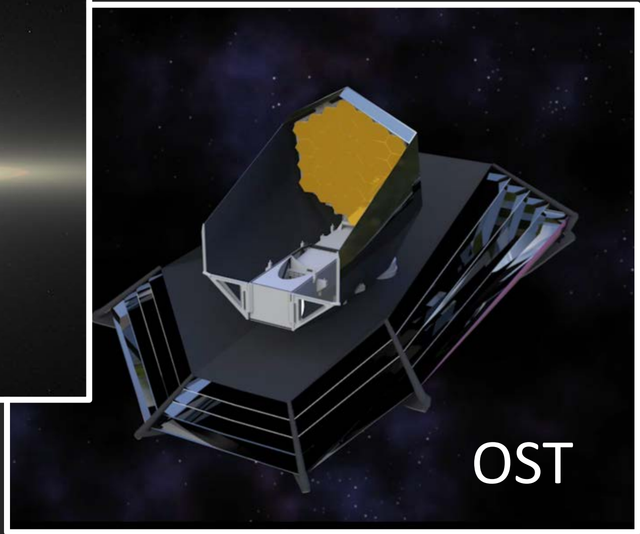


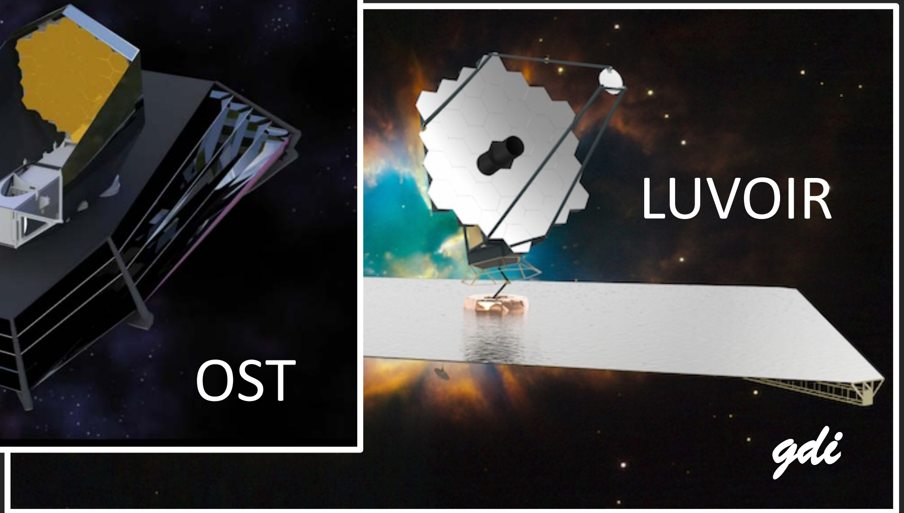
only 0-1 of these!

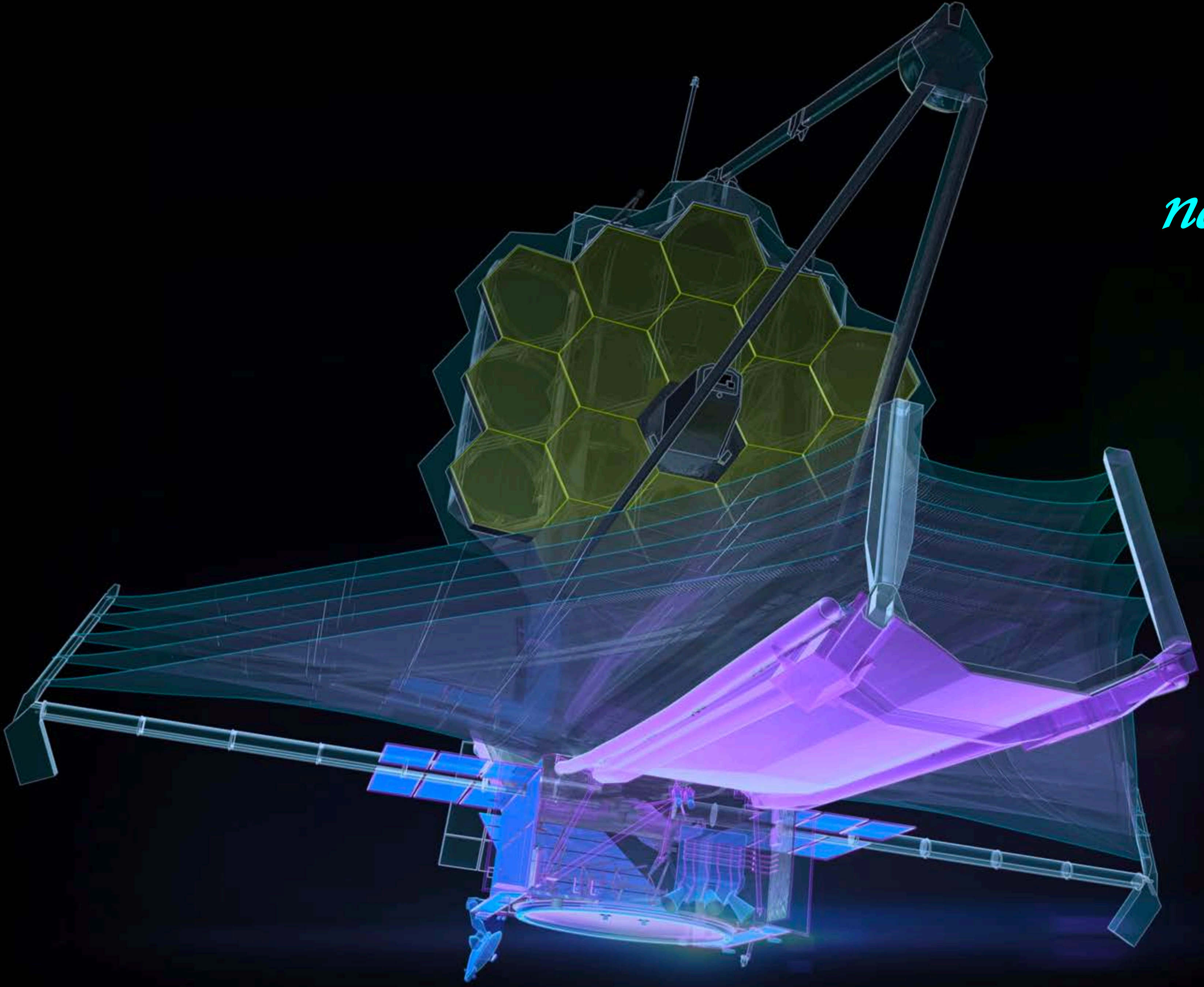
gdi

☛ JWST, along with WFIRST (and similar telescopes) and the ELT, will transform our understanding of distant galaxies in the next decade, but, for distant galaxies, another "next generation telescope" will be needed in the decade beyond ☚



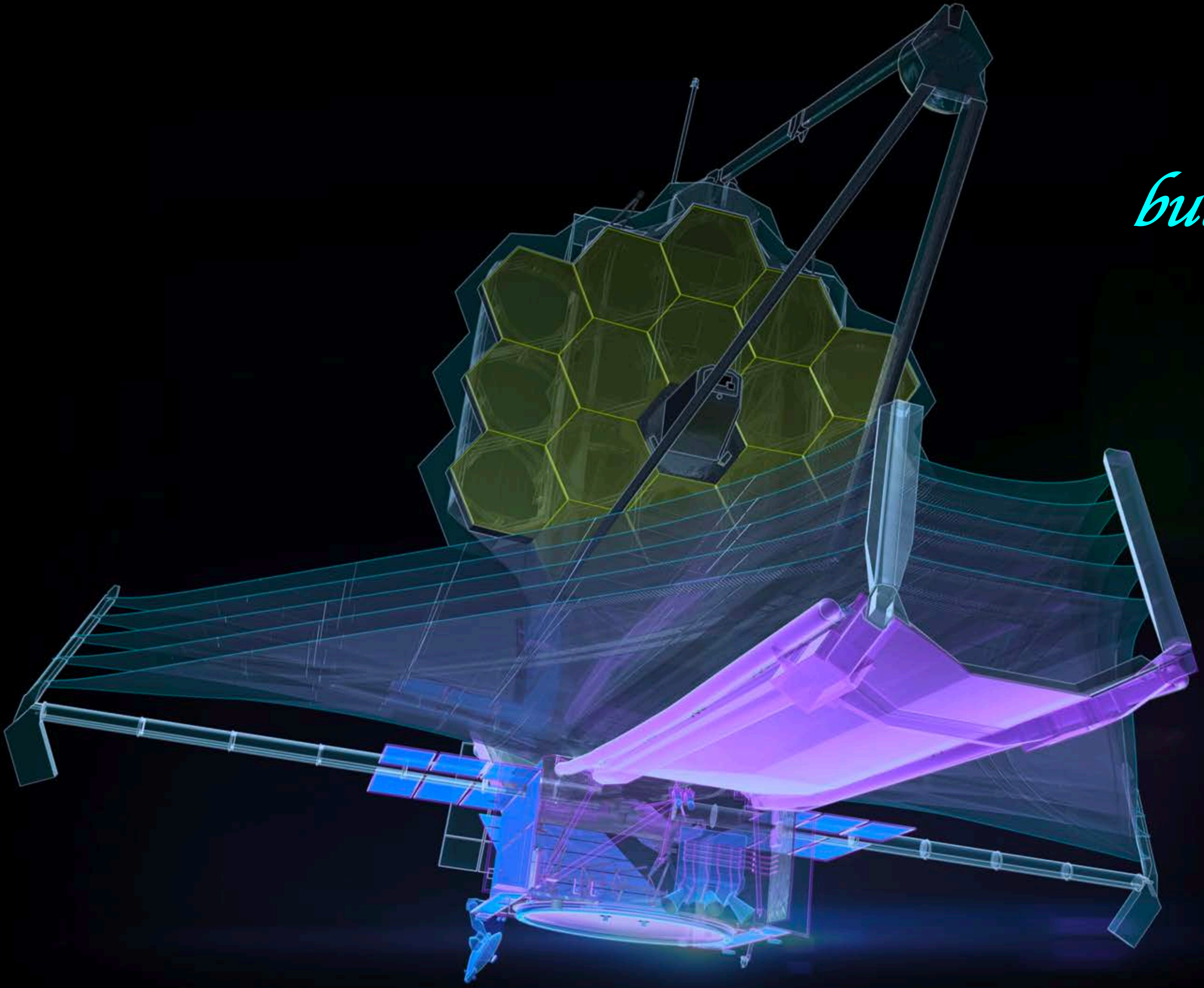






not the end...

gdi



but the beginning...

gdi