23RD AUSTRALIAN INSTITUTE OF PHYSICS CONGRESS
JOINT WITH
AUSTRALIAN OPTICAL SOCIETY (AOS) CONFERENCE;
43RD AUSTRALIAN CONFERENCE ON OPTICAL FIBRE TECHNOLOGY (ACOFT);
2018 CONFERENCE ON OPTOELECTRONIC AND MICROELECTRONIC MATERIALS AND DEVICES (COMMAD 2018)
9-13 December 2018 • Perth, Western Australia

Plenary 5
December 13, 2018

Galaxies at Cosmic Dawn: Exploring the First Billion Years with the Hubble Space Telescope

Garth Illingworth
University of California Santa Cruz

figure credit: Adolf Schaller

firstgalaxies.org

23RD AUSTRALIAN INSTITUTE OF PHYSICS CONGRESS

JOINT WITH
AUSTRALIAN OPTICAL SOCIETY (AOS) CONFERENCE;
43RD AUSTRALIAN CONFERENCE ON OPTICAL FIBRE TECHNOLOGY (ACOFT);
2018 CONFERENCE ON OPTOELECTRONIC AND MICROELECTRONIC MATERIALS AND DEVICES (COMMAD 2018)

9-13 December 2018 • Perth, Western Australia

Plenary 5
December 13, 2018

Cosmic Sunrise

Galaxies at ~~Cosmic Dawn~~: Exploring the First Billion Years with the Hubble Space Telescope

Garth Illingworth
University of California Santa Cruz

figure credit: Adolf Schaller

firstgalaxies.org

galaxies in the first billion years

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

history of everything

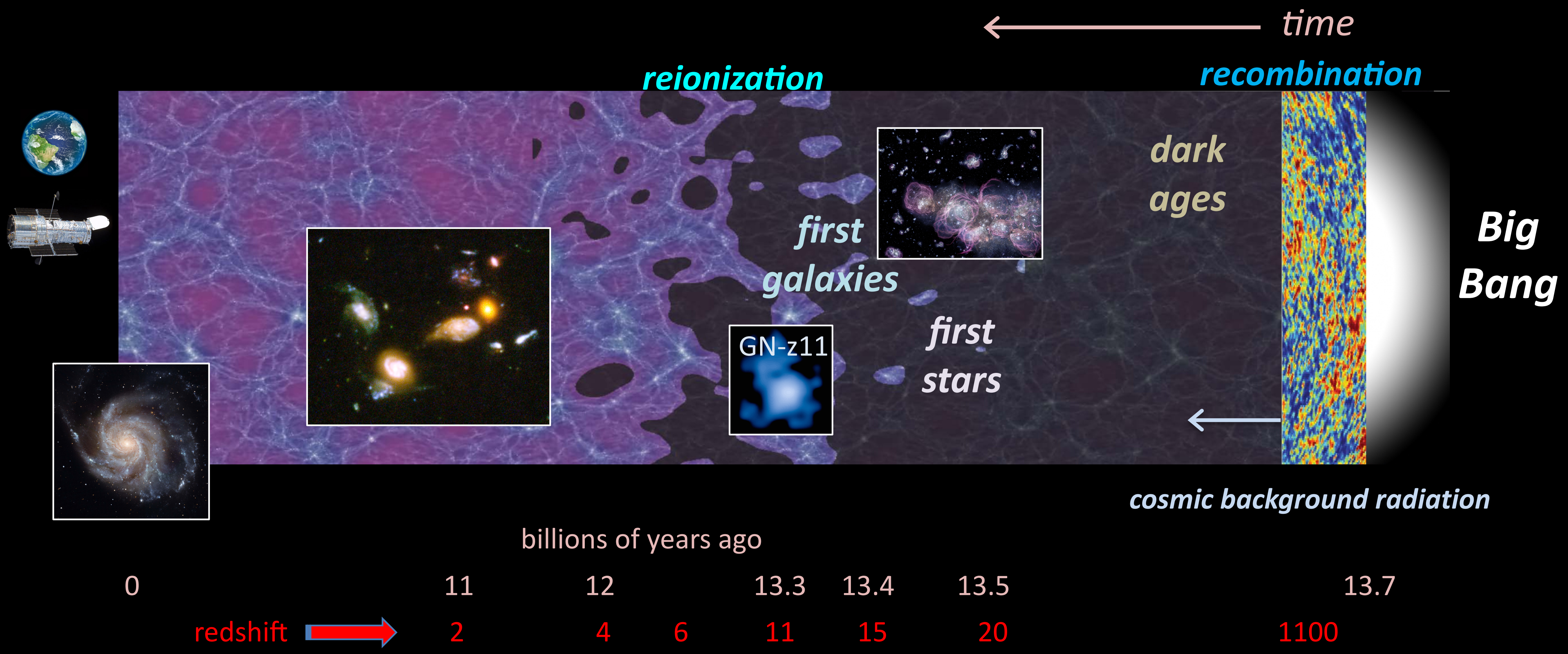
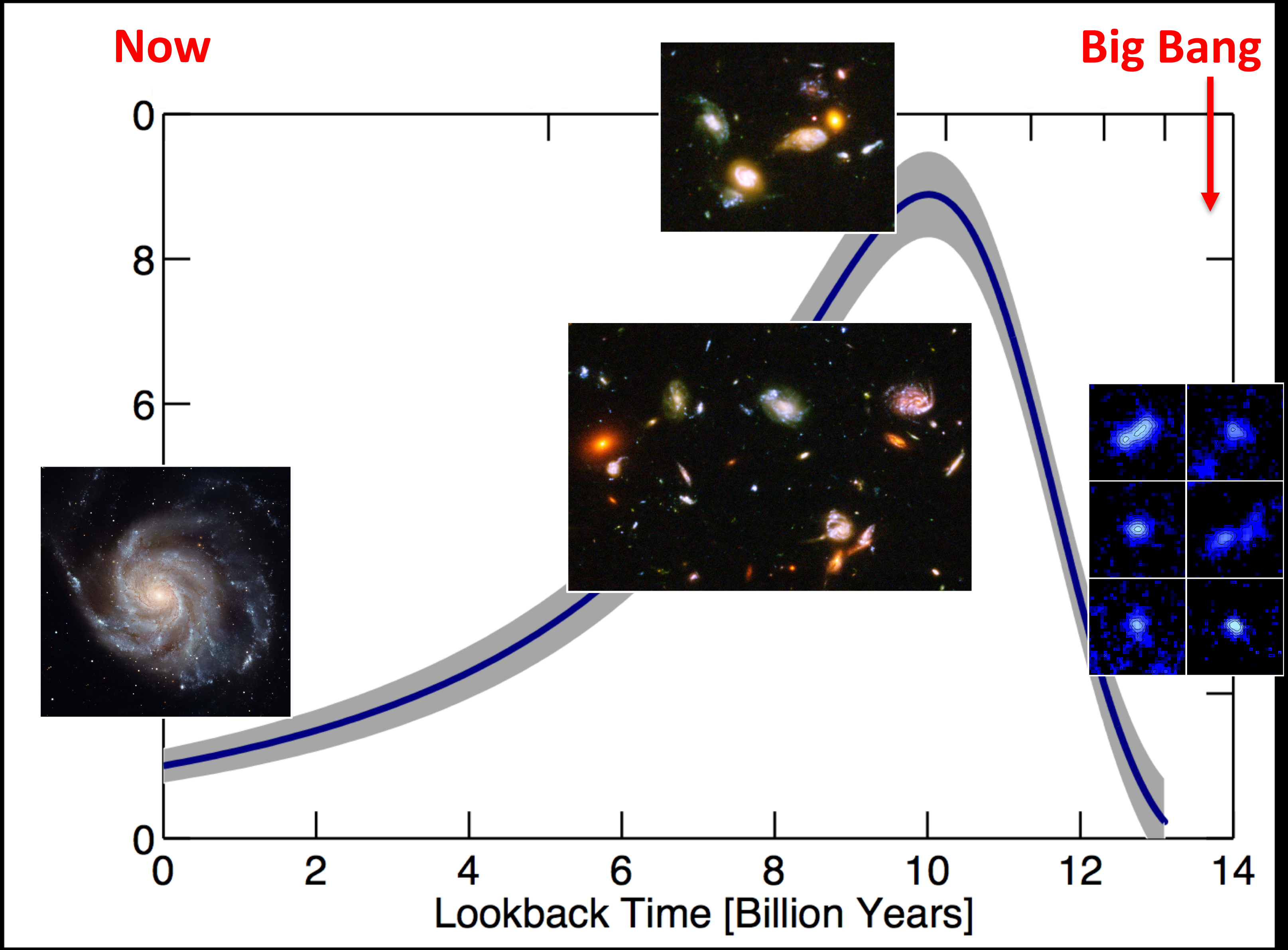


figure credit: insert adapted from Brant Robertson UCSC

gdi

rate of cosmic star formation



linear figure credit:
Pascal Oesch

gdi

history of everything

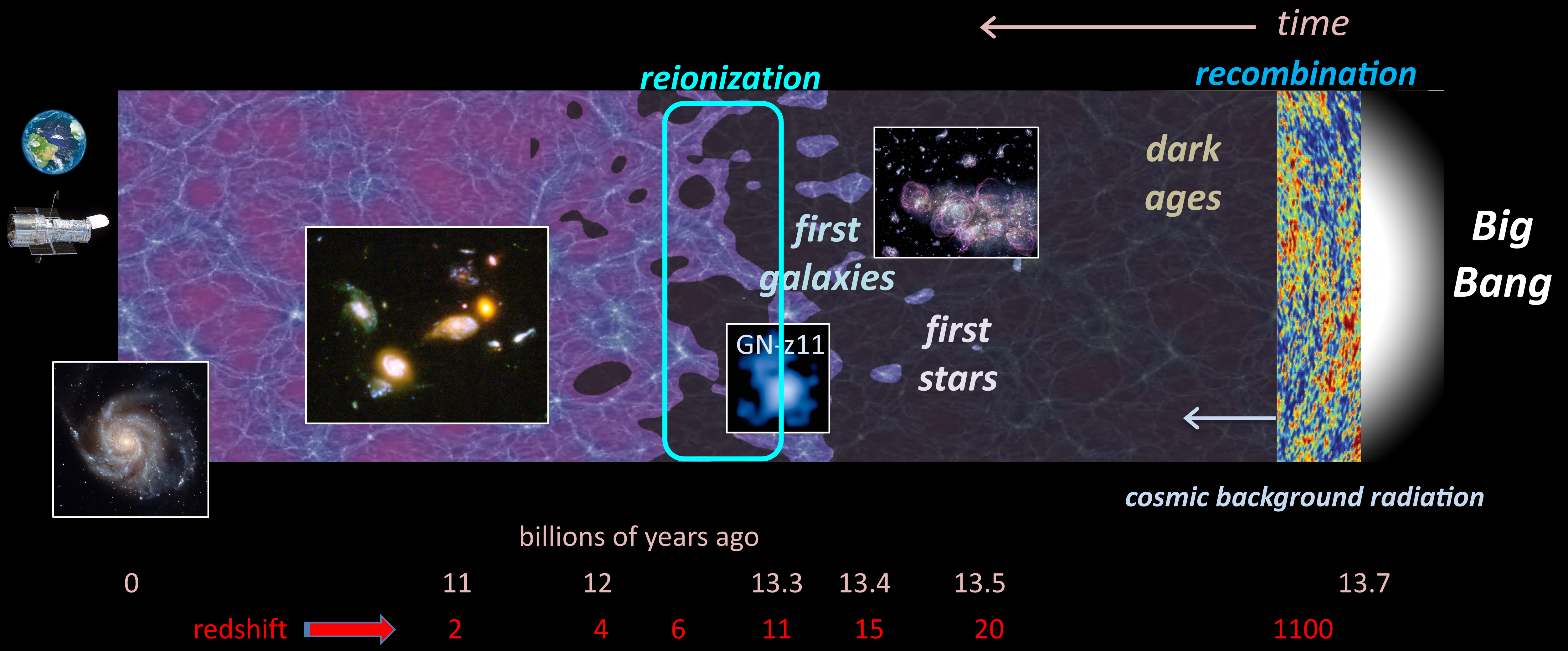


figure credit: insert adapted from Brant Robertson UCSC

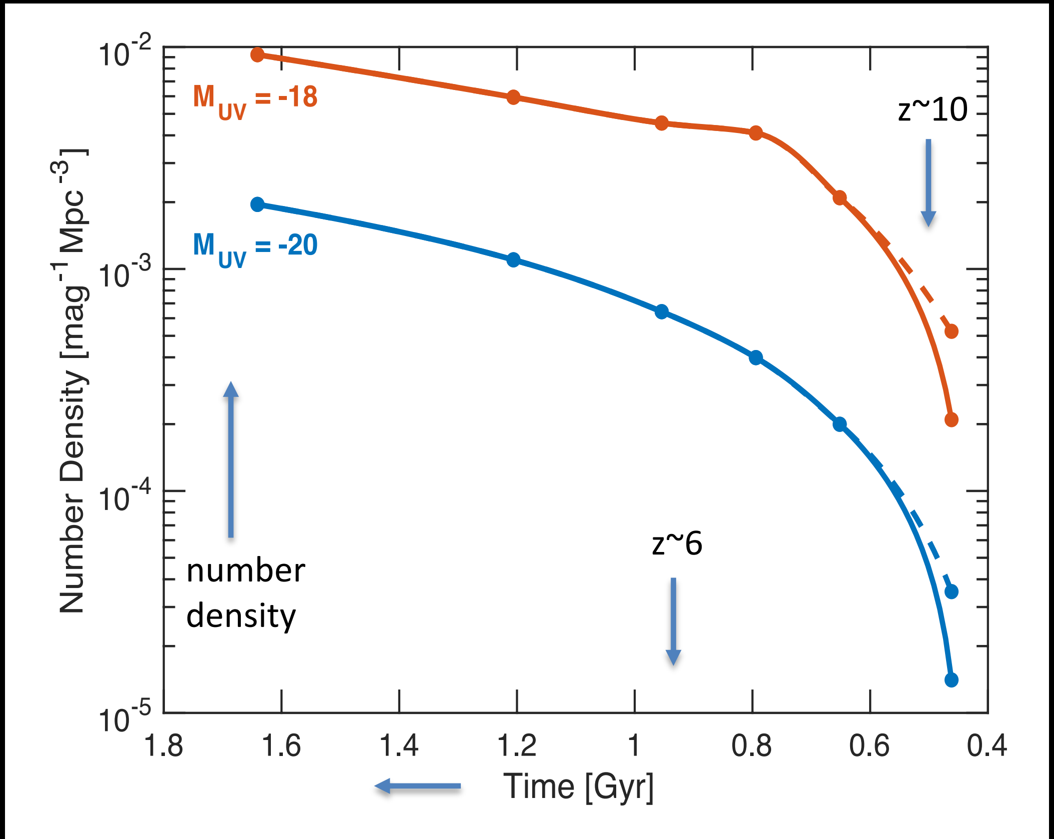
gdi

exploring the first billion years

gdi

Cosmic ~~Dawn~~ Morning – the time of rapid buildup of galaxies

during the first billion years → we know that galaxies built up extremely rapidly from 500 million years to 1 billion years



rapid growth of the dark matter halos within which galaxies form

significant quantities of heavier elements were produced in stars and ejected

the universe was reionized (Planck 2018)

HST and Spitzer have let us explore galaxies in this fascinating period

gdi


1990
Canada

Riccardo Giacconi

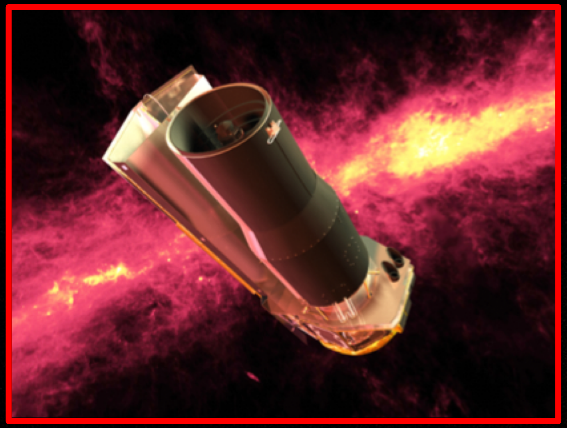
1931-2018

X-Ray astronomy pioneer

Nobel Prize 2002

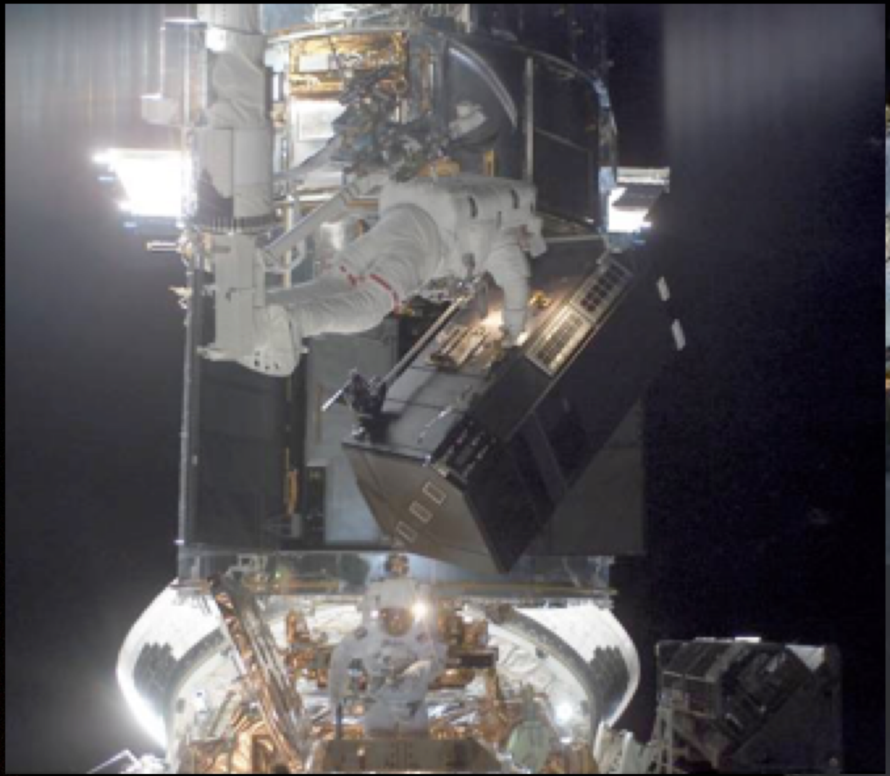
Hubble Space Telescope; European VLT; ALMA

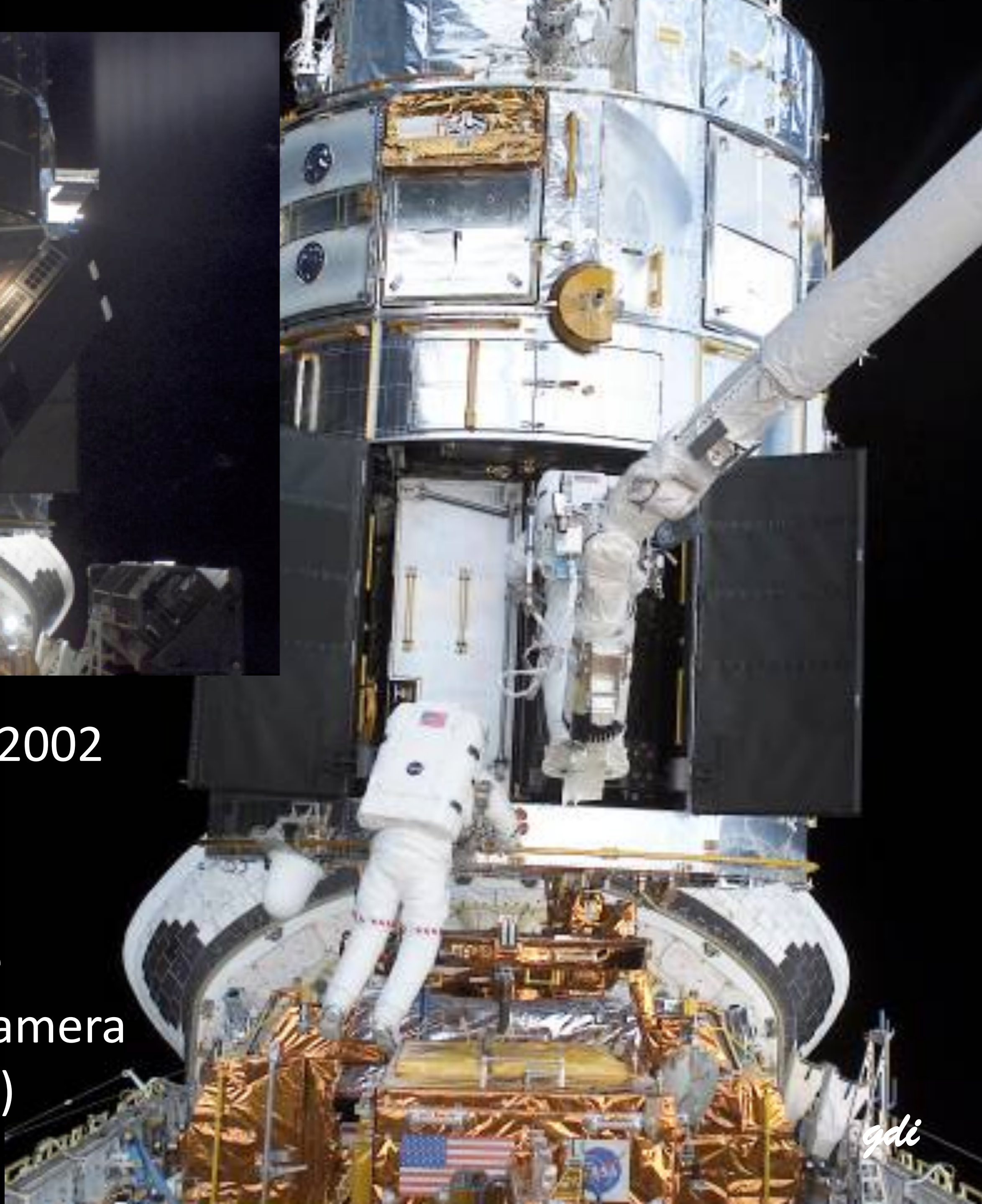
"ruthless intellectual honesty"



Spitzer
(mid-infrared)

2003

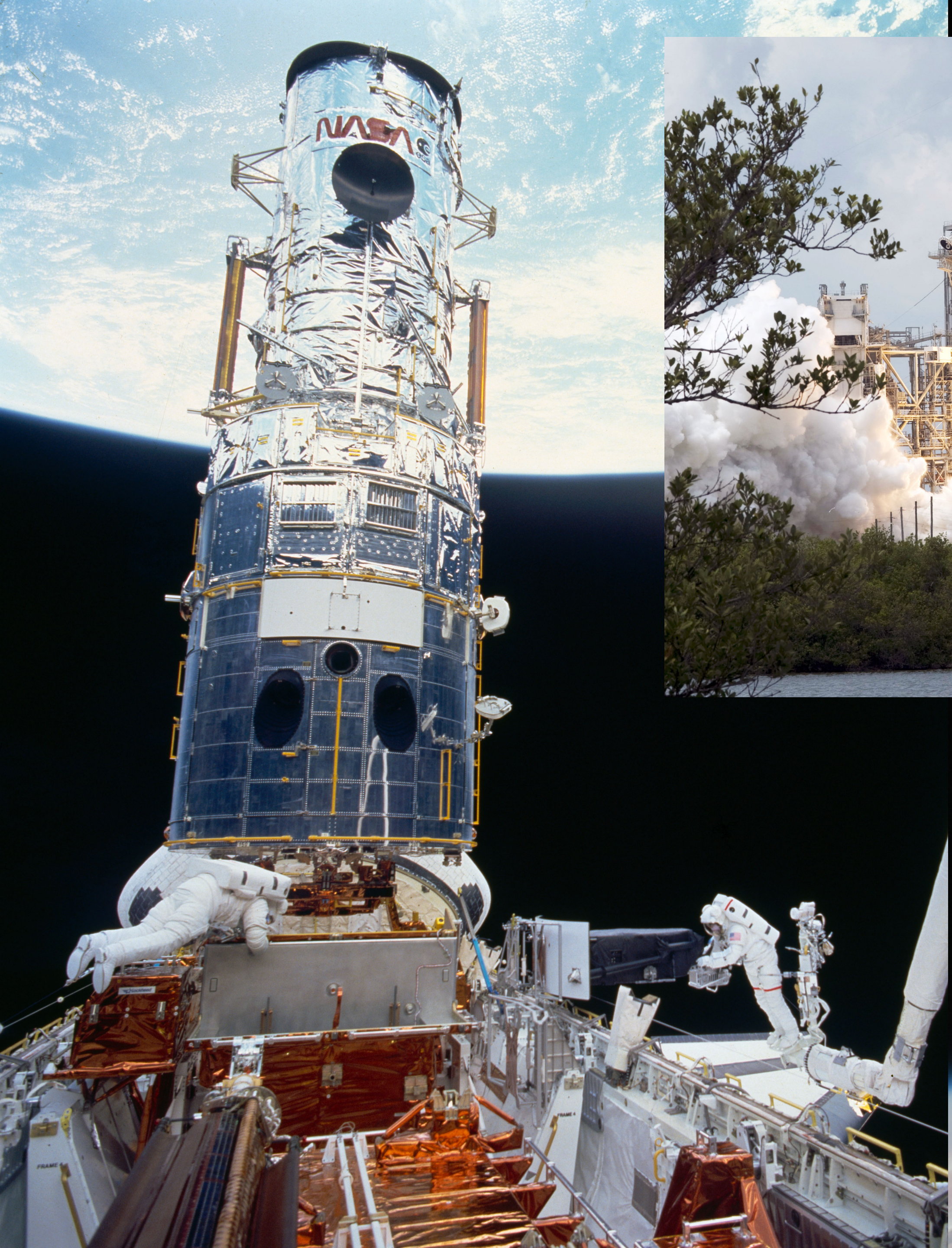


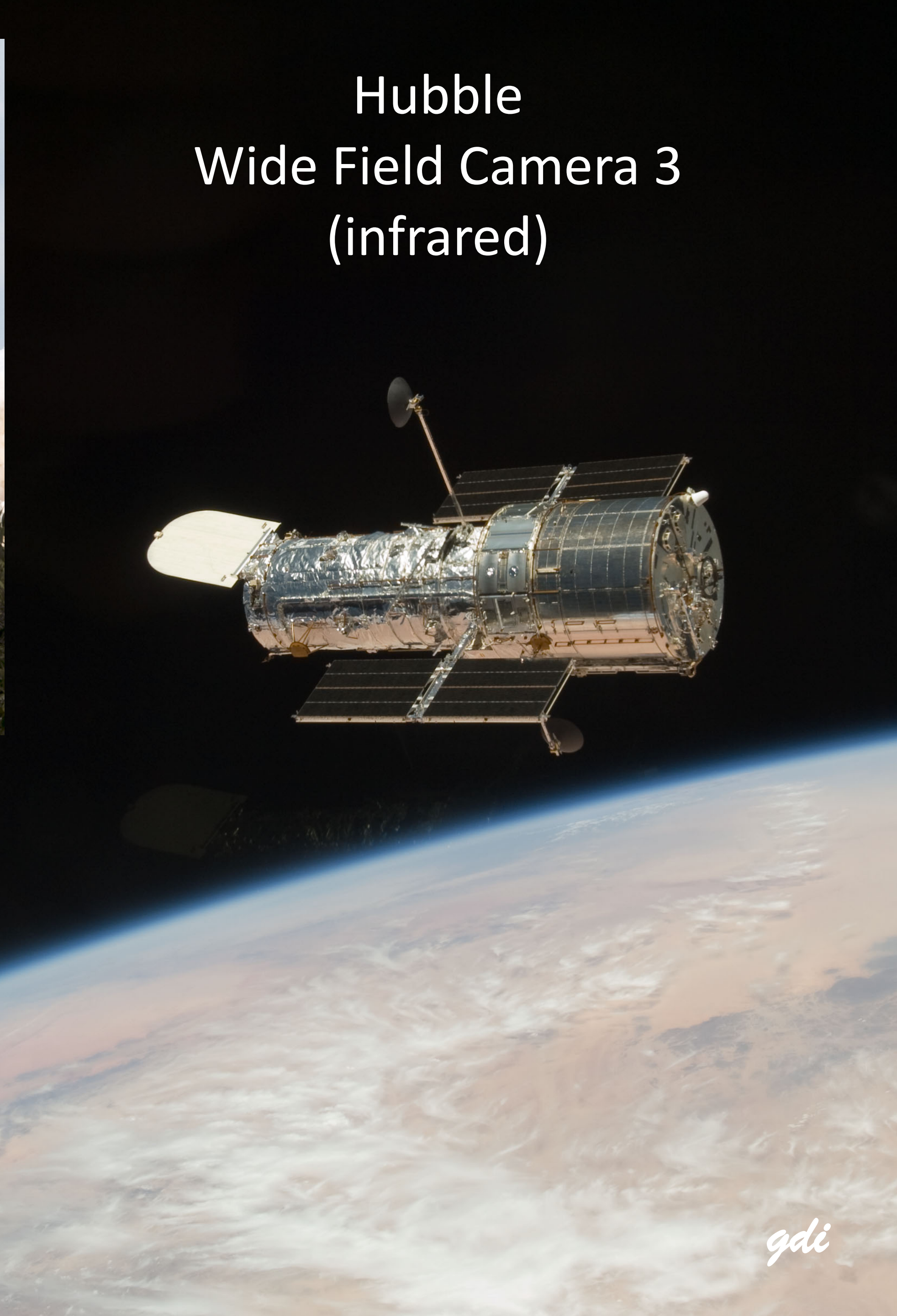


2002

Hubble
Advanced Camera
(visible)

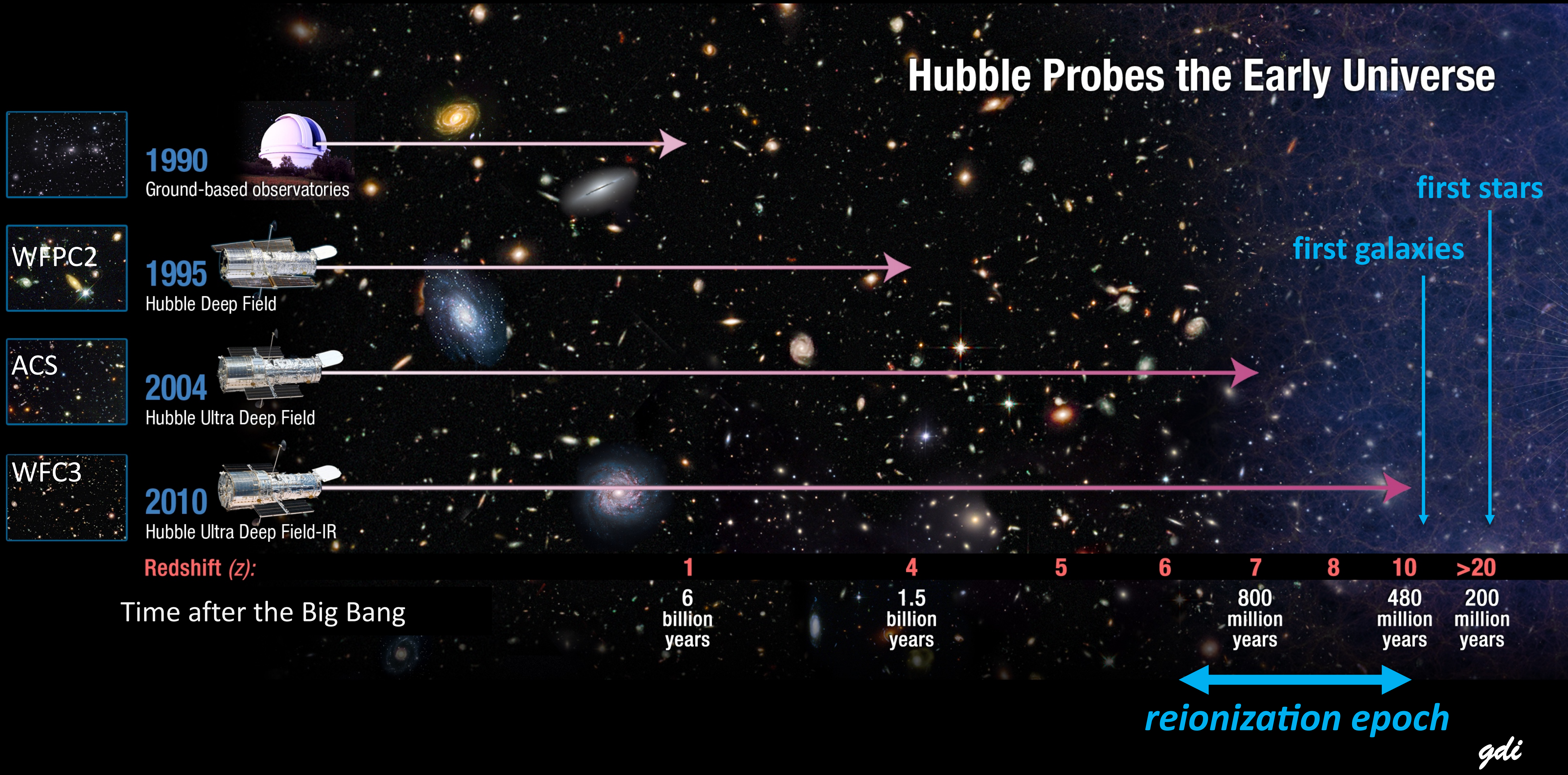
Hubble
Wide Field Camera 3
(infrared)



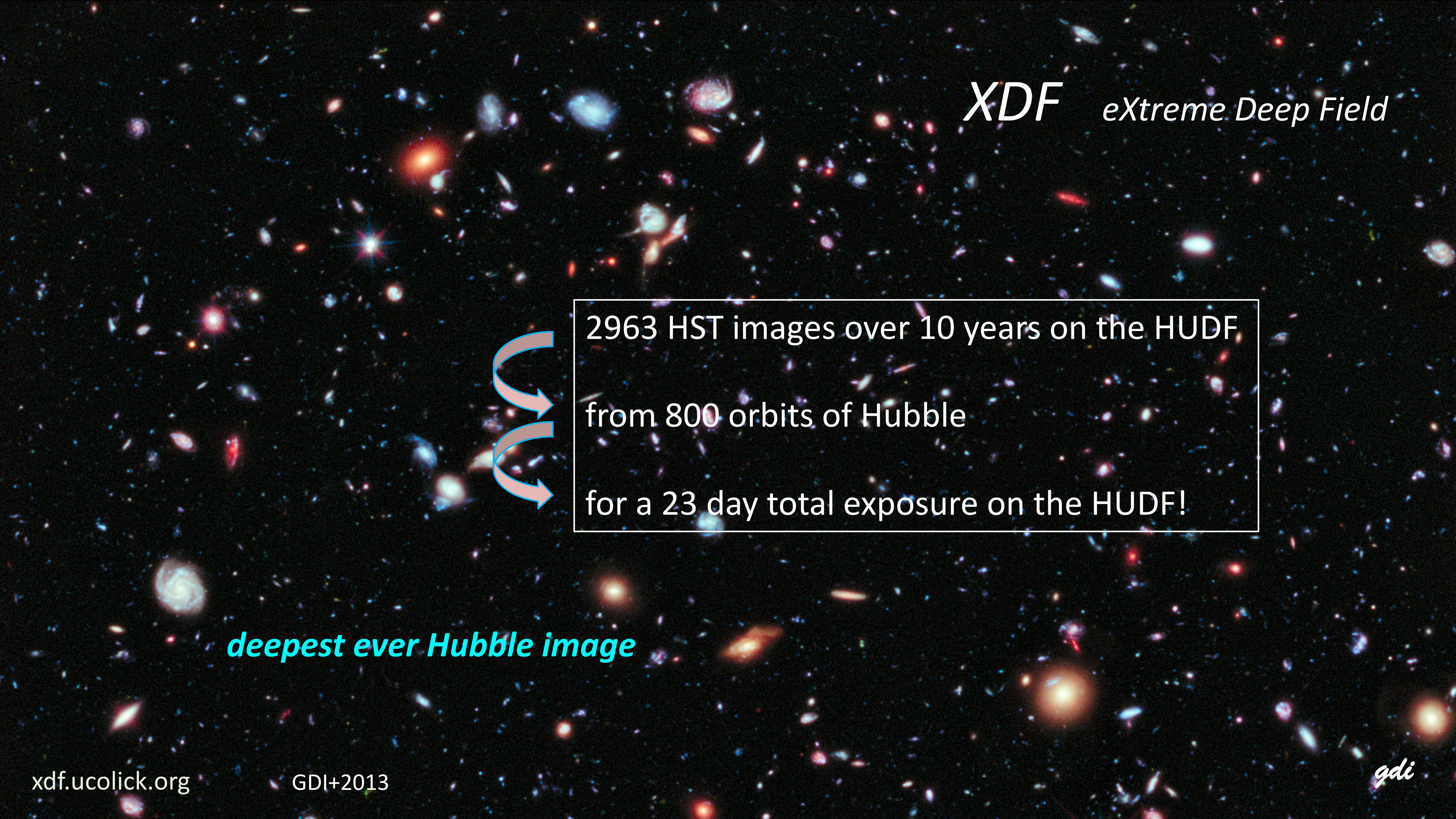


2009

look back time increases with each new camera




XDF eXtreme Deep Field
2012
gdi


XDF eXtreme Deep Field
2963 HST images over 10 years on the HUDF
from 800 orbits of Hubble
for a 23 day total exposure on the HUDF!
deepest ever Hubble image
xdf.ucolick.org
GDI+2013
gdi

Hubble and Spitzer survey fields for high-redshift galaxies

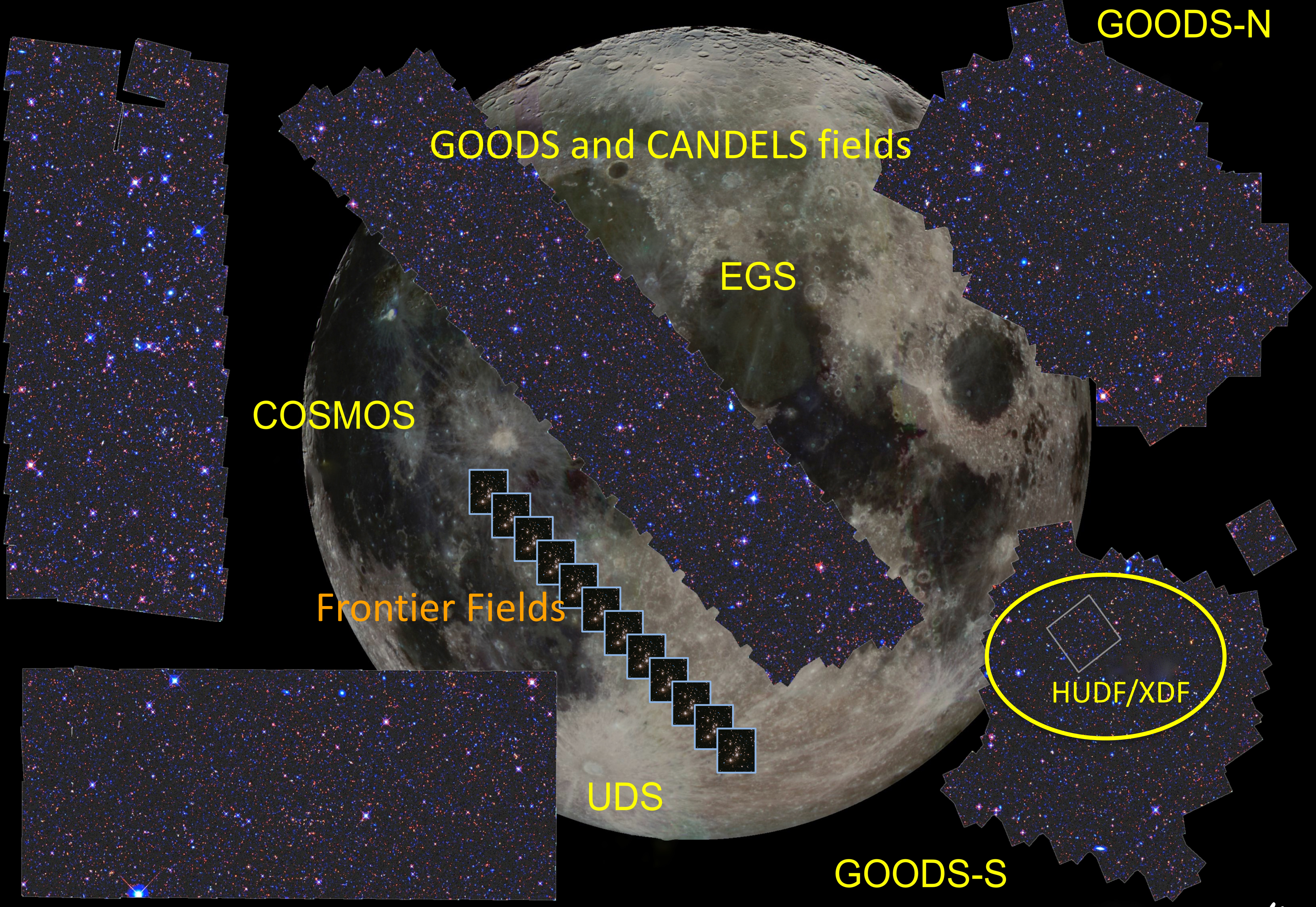


figure credit: Harry Ferguson and the CANDELS team

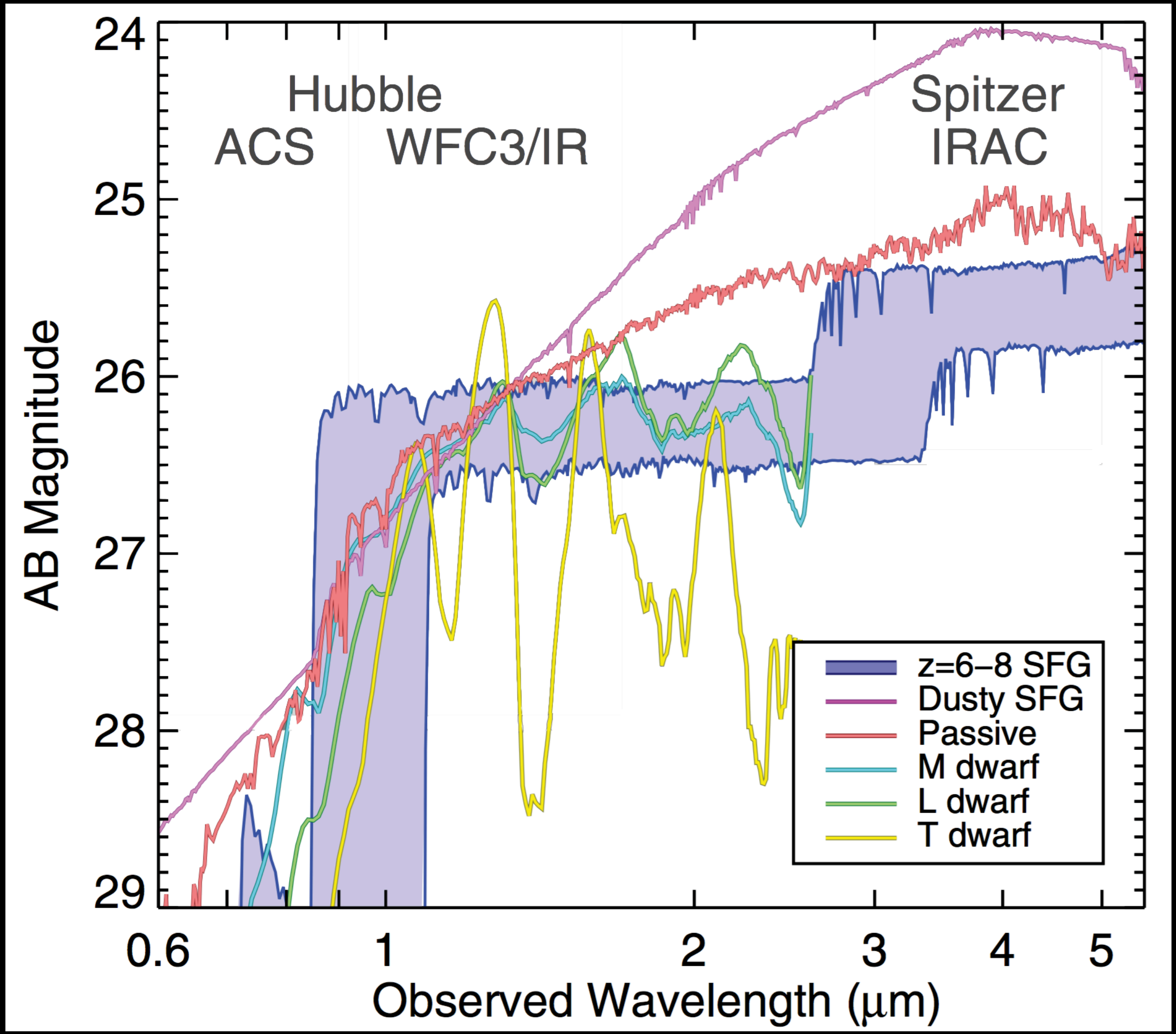
photometric redshifts

enable large, statistically-robust samples

Lyman break galaxies – LBGs (“dropouts”)

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

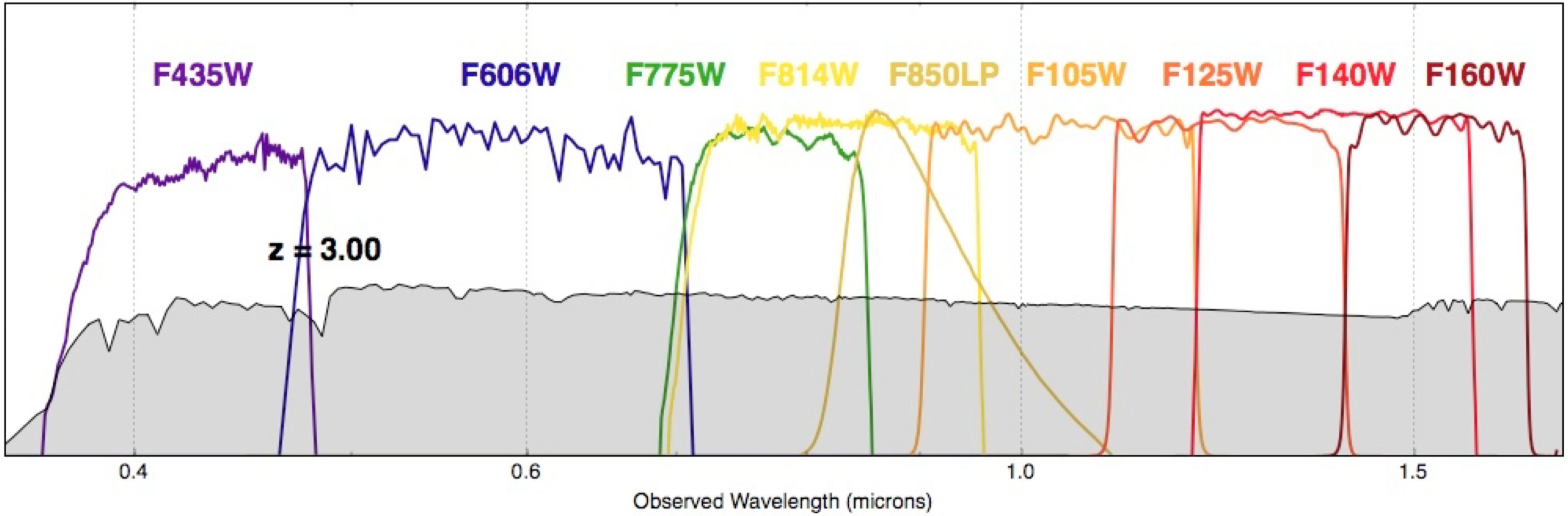
☞ reliable photometric redshift selection

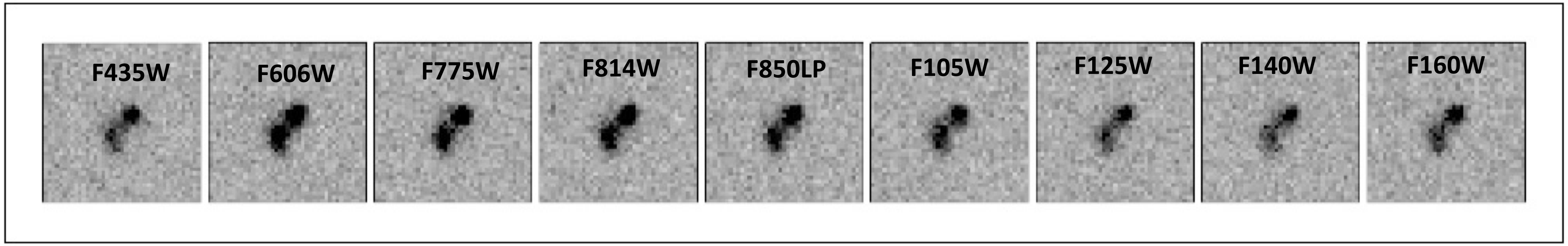


Finkelstein 2016

gdi

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

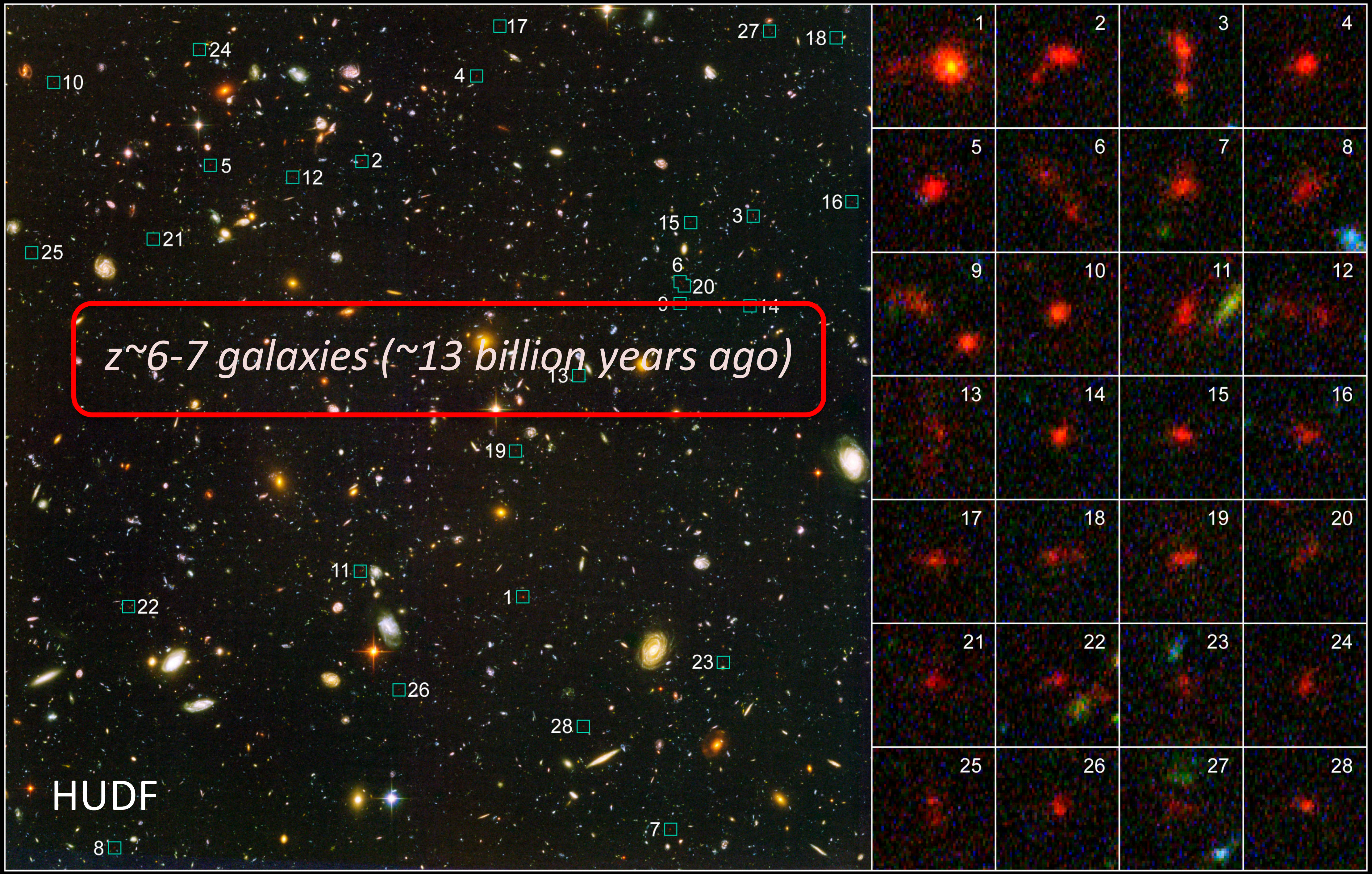




optical ACS

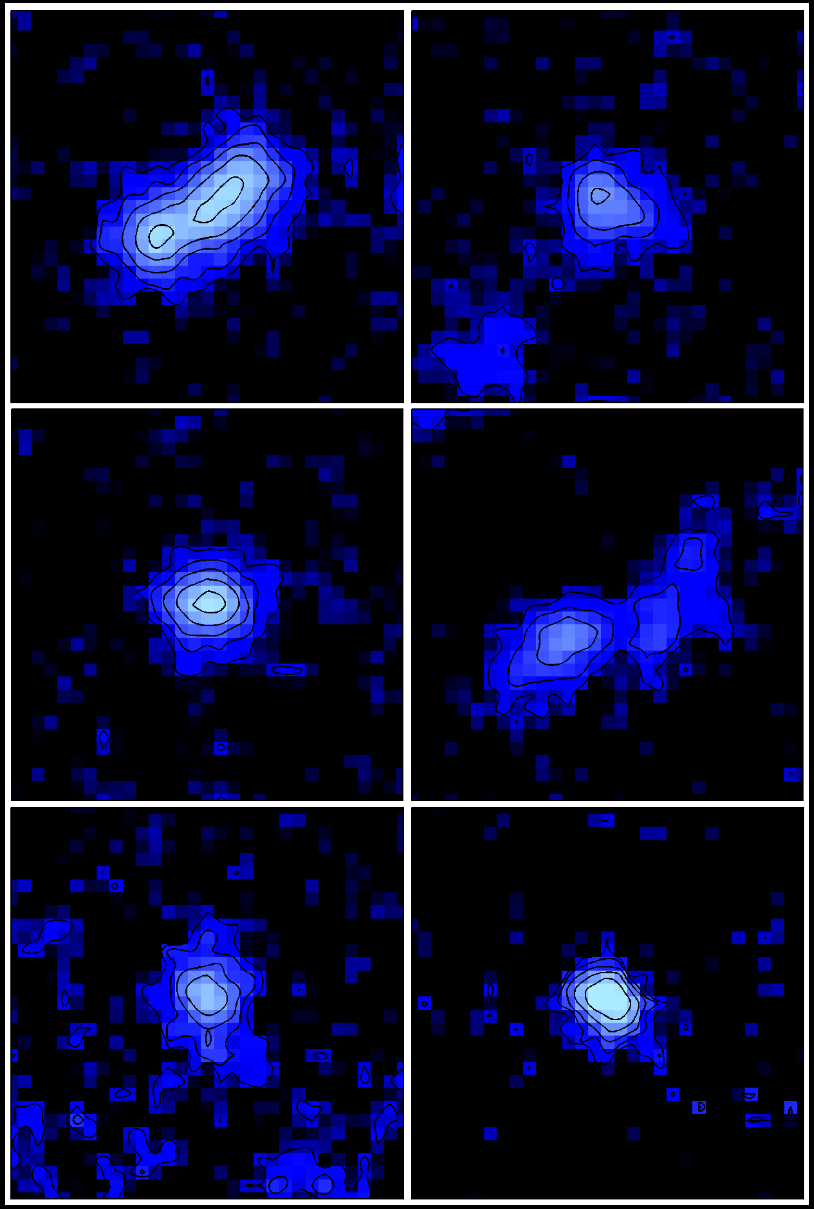
near-IR WFC3/IR

xdf.ucolick.org/



gdi

1.8” (~10 kpc)



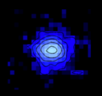
a sample of bright galaxies at z~6
about 900 million years after the Big Bang

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

~size of the Hubble
point spread function

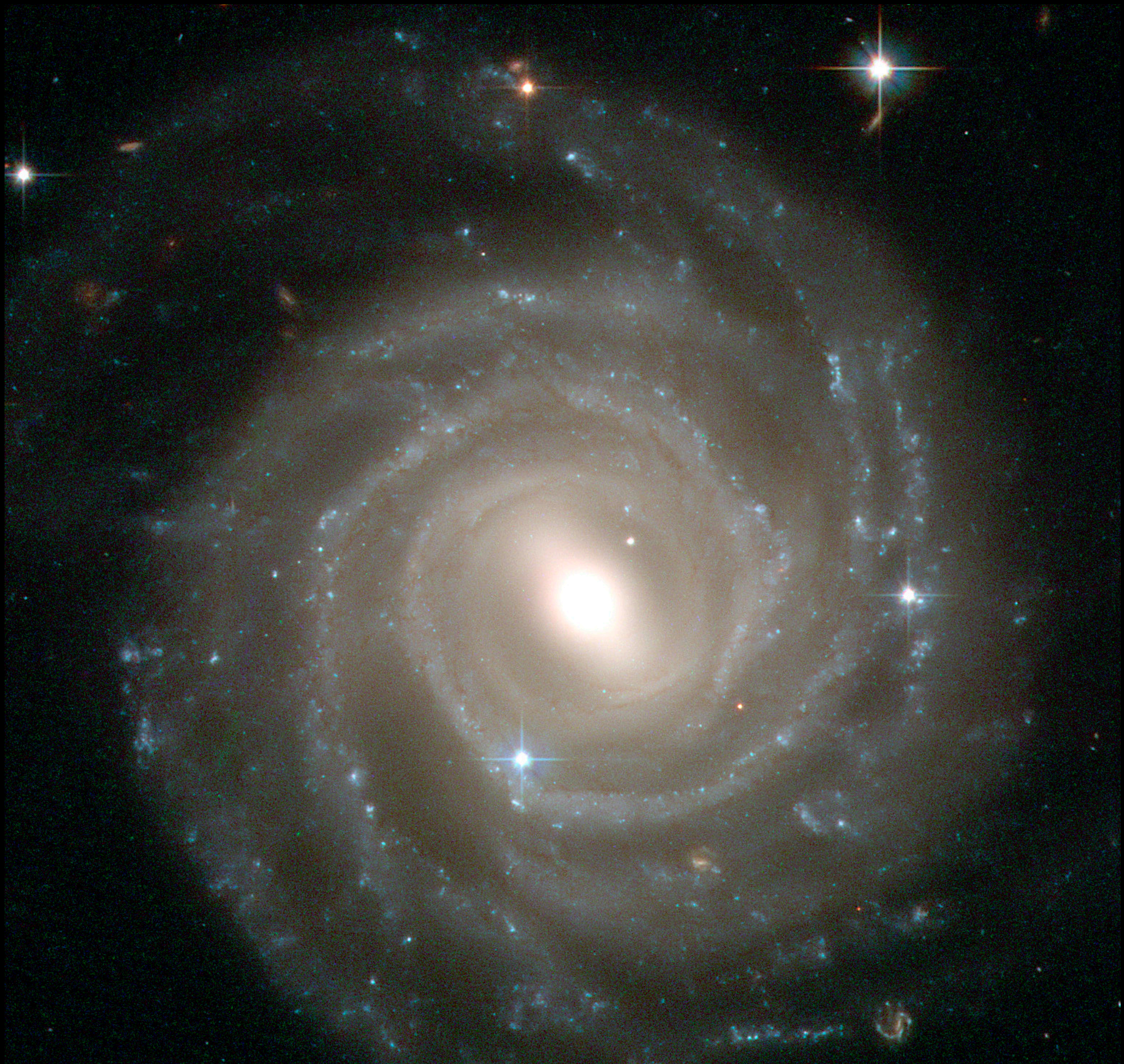
gdi

galaxies at ~1 Gyr (z~6) are small

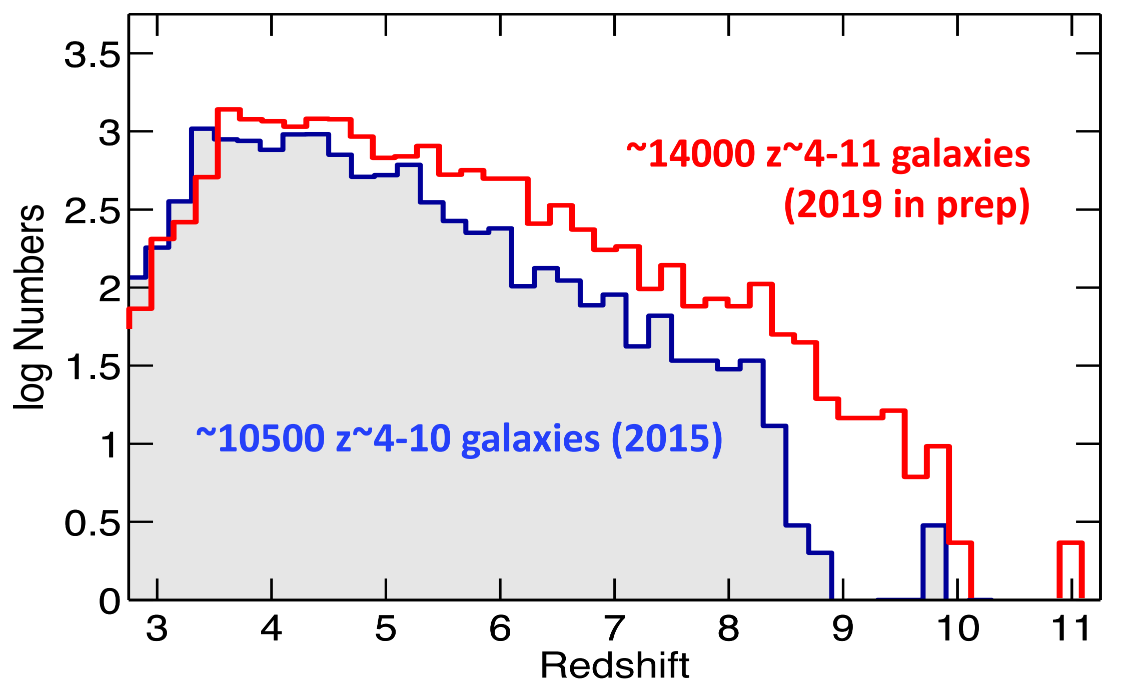


a typical z~6 galaxy

~same scale



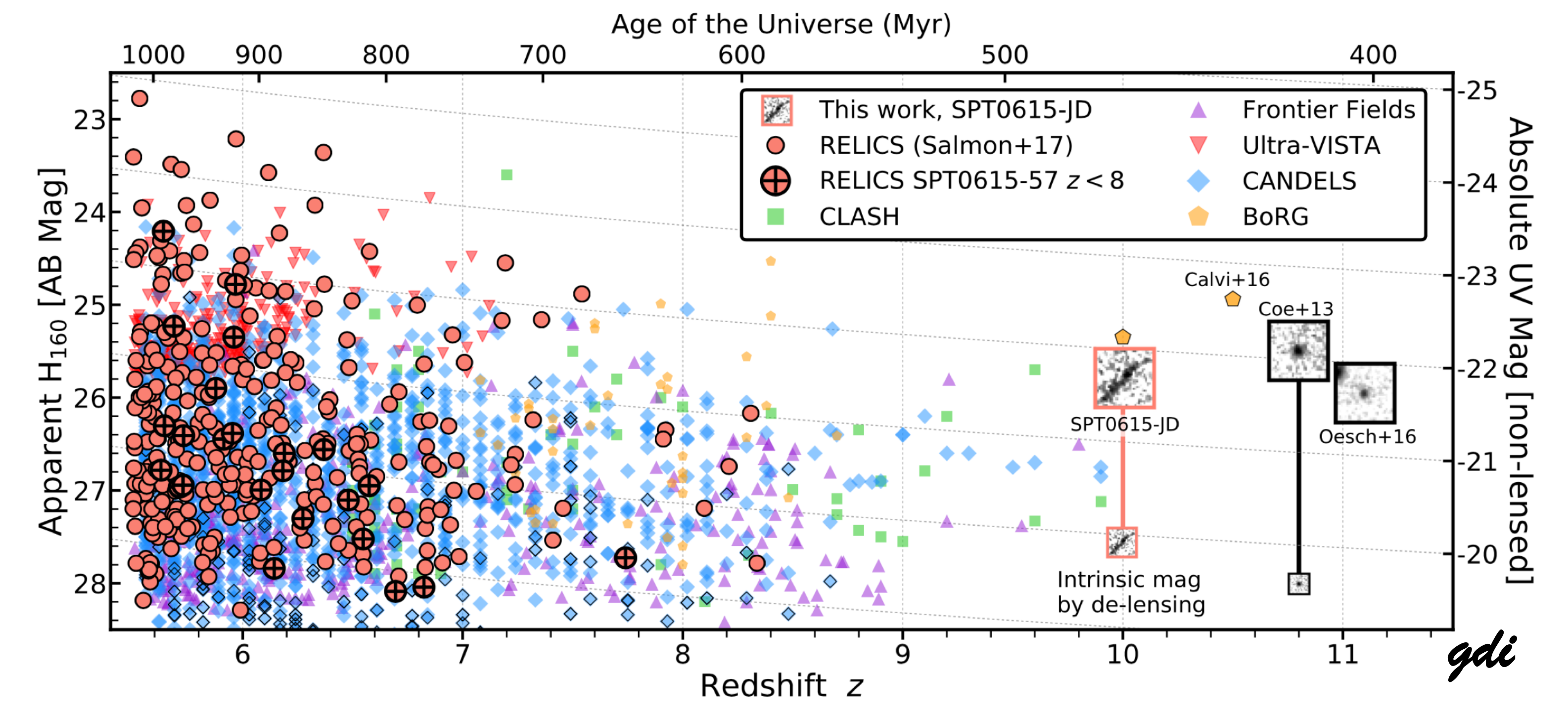
UGC-12158 – similar to the Milky Way



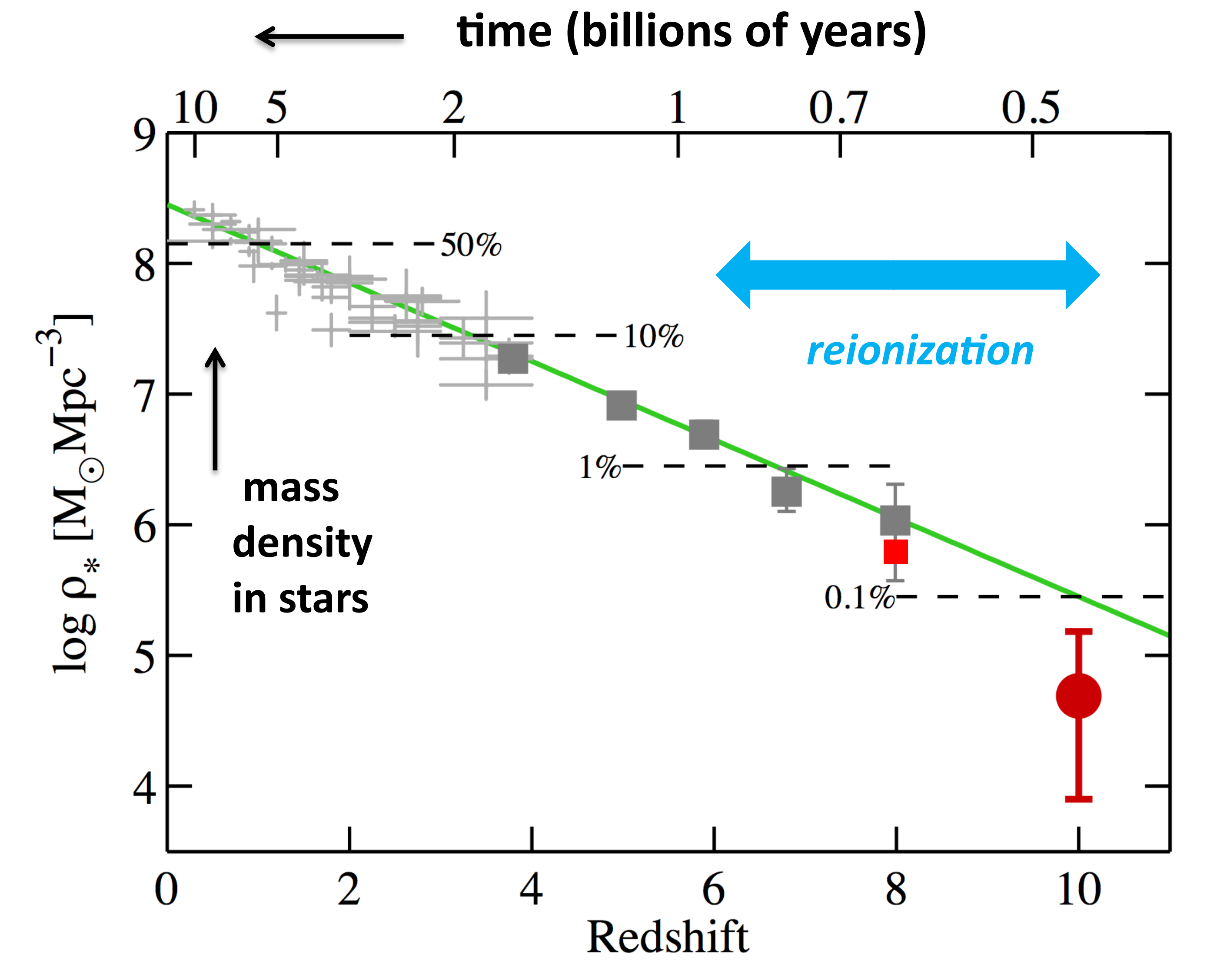
very large samples of galaxies in the first 2 billion years from Hubble

Bouwens GDI Oesch+15

Salmon+2017



buildup of mass in the universe in stars



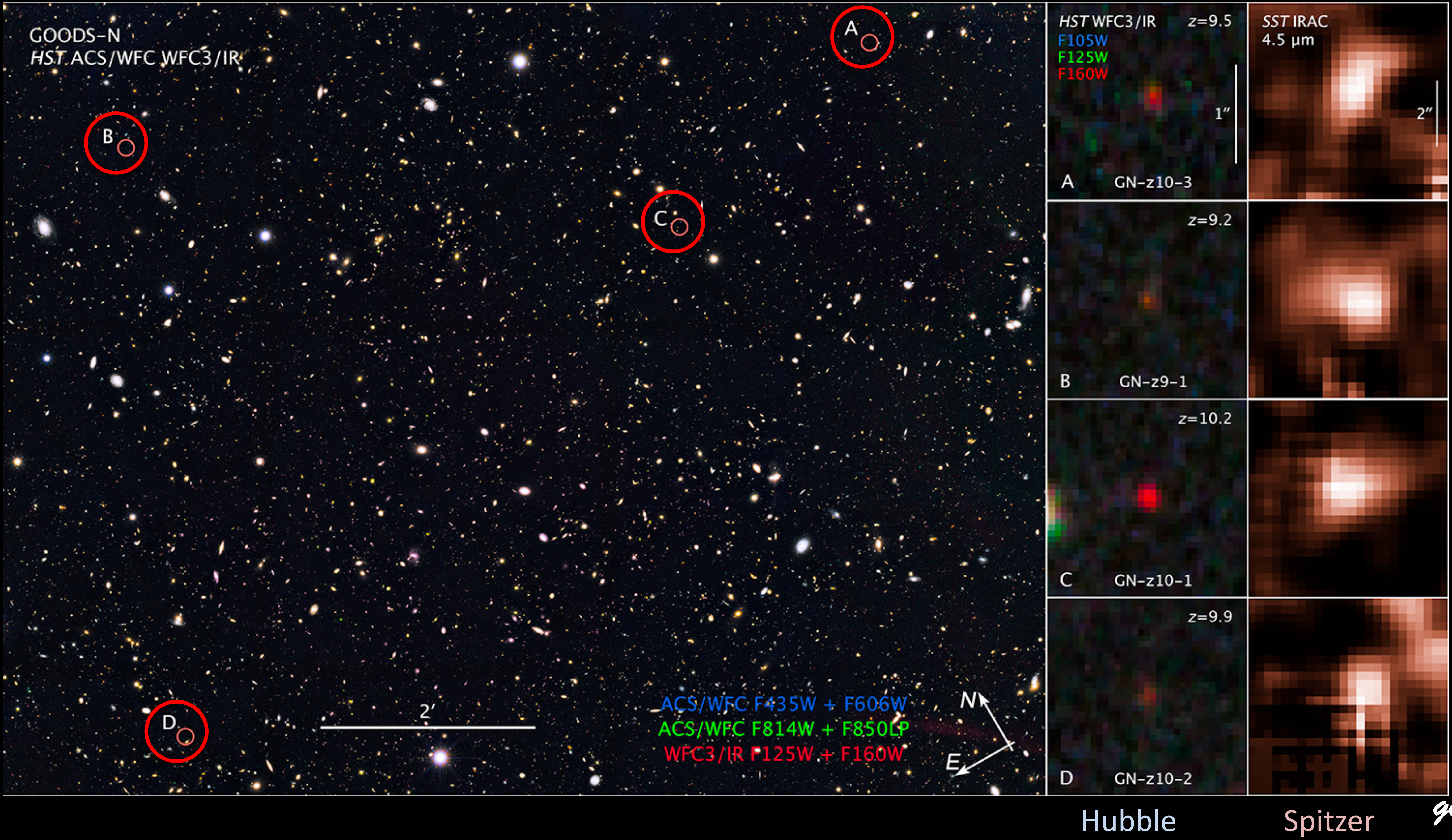
Oesch+2014

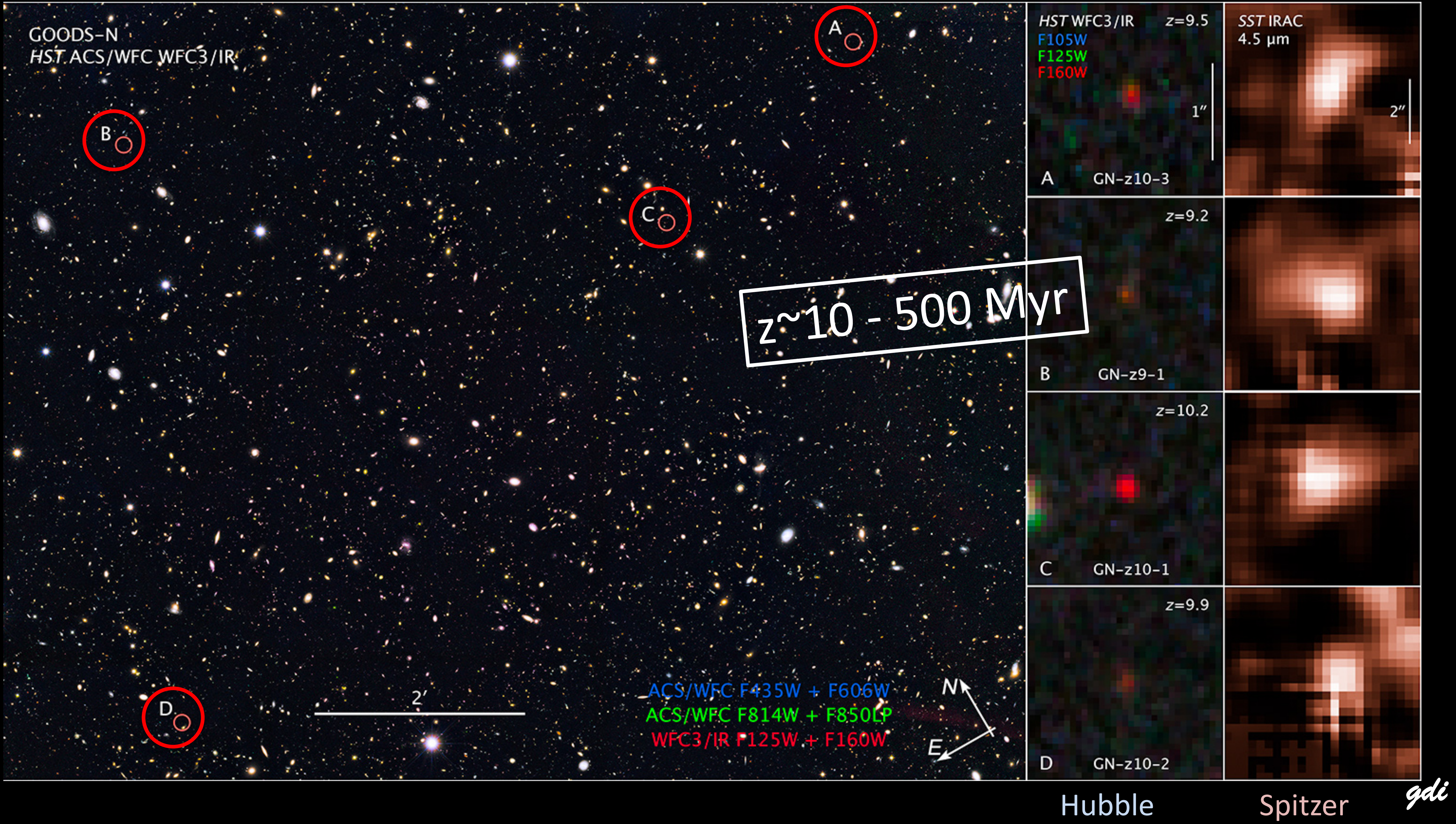
gdi

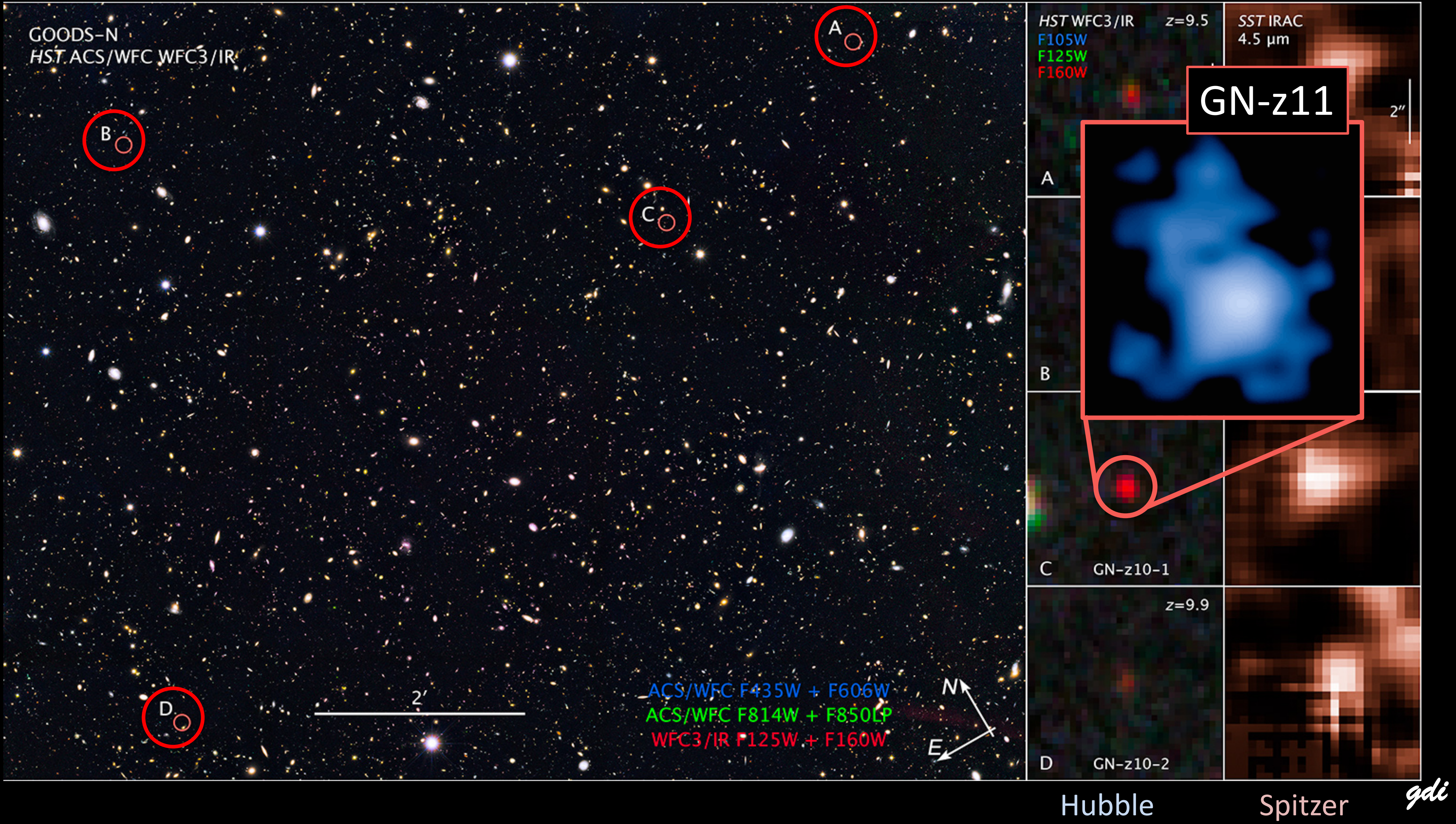
what constraints do we have on the first galaxies?

searching for the earliest galaxies

gdi


GOODS-N
HST ACS/WFC WFC3/IR
A
B
C
D
2′
ACS/WFC F435W + F606W
ACS/WFC F814W + F850LP
WFC3/IR F125W + F160W
N
E
HST WFC3/IR
F105W
F125W
F160W
z=9.5
1″
A GN-z10-3
SST IRAC
4.5 μm
2″
z=9.2
B GN-z9-1
z=10.2
C GN-z10-1
z=9.9
D GN-z10-2
Hubble
Spitzer

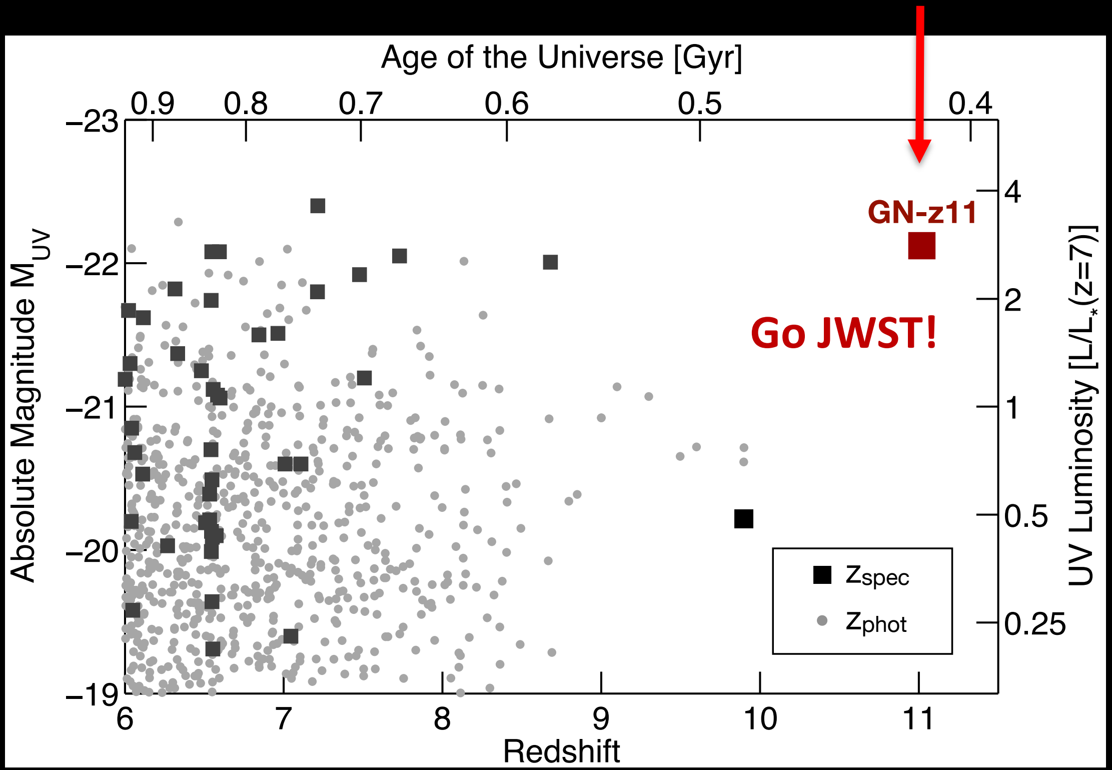

GOODS-N
HST ACS/WFC WFC3/IR
A
B
C
D
2′
ACS/WFC F435W + F606W
ACS/WFC F814W + F850LP
WFC3/IR F125W + F160W
N
E
HST WFC3/IR z=9.5
F105W
F125W
F160W
1″
A GN-z10-3
SST IRAC
4.5 μm
2″
z=9.2
B GN-z9-1
z=10.2
C GN-z10-1
z=9.9
D GN-z10-2
z~10 - 500 Myr
Hubble
Spitzer
gdi

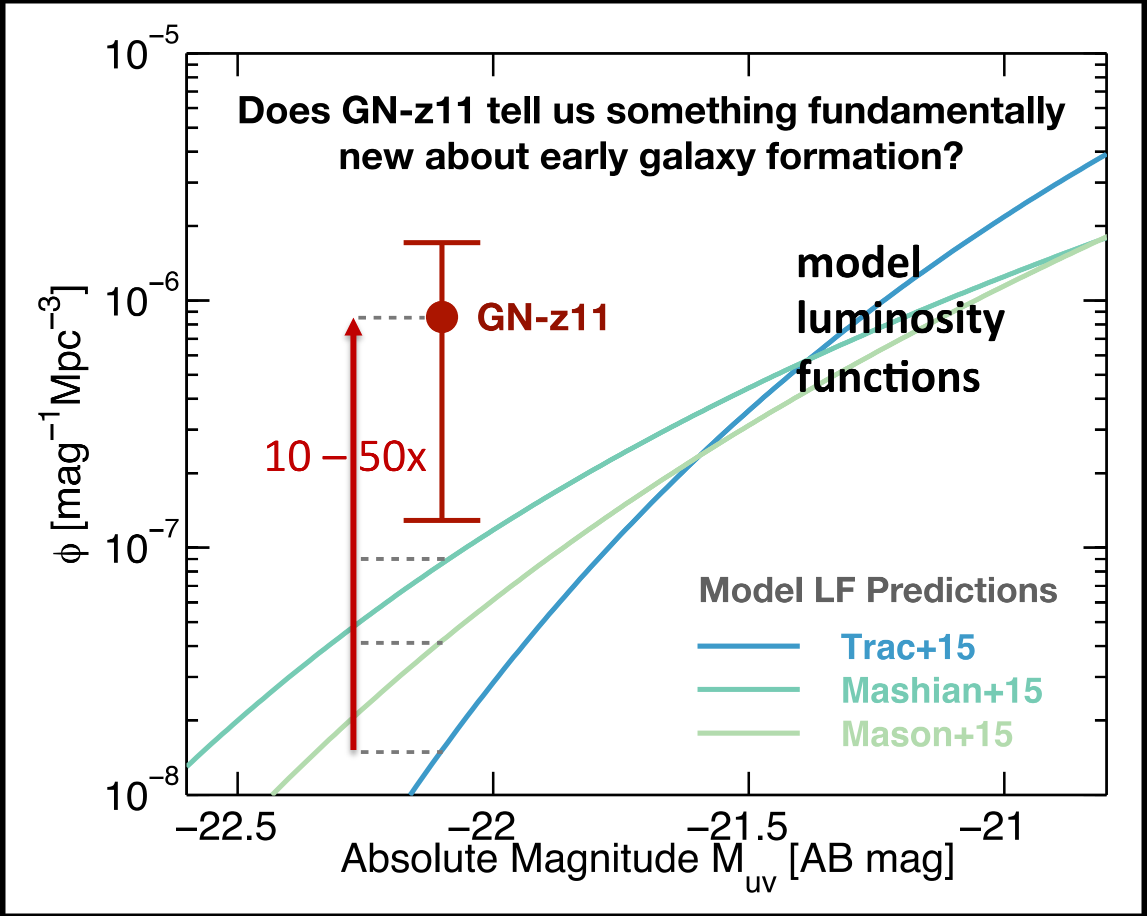

GOODS-N
HST ACS/WFC WFC3/IR
A
B
C
D
2′
ACS/WFC F435W + F606W
ACS/WFC F814W + F850LP
WFC3/IR F125W + F160W
N
E
HST WFC3/IR
z=9.5
F105W
F125W
F160W
SST IRAC
4.5 μm
2″
GN-z11
GN-z10-1
z=9.9
GN-z10-2
Hubble
Spitzer
gdi

the most distant galaxy found to date

surprising discovery of GN-z11

very few spectroscopic redshifts at z>7





Oesch+2016

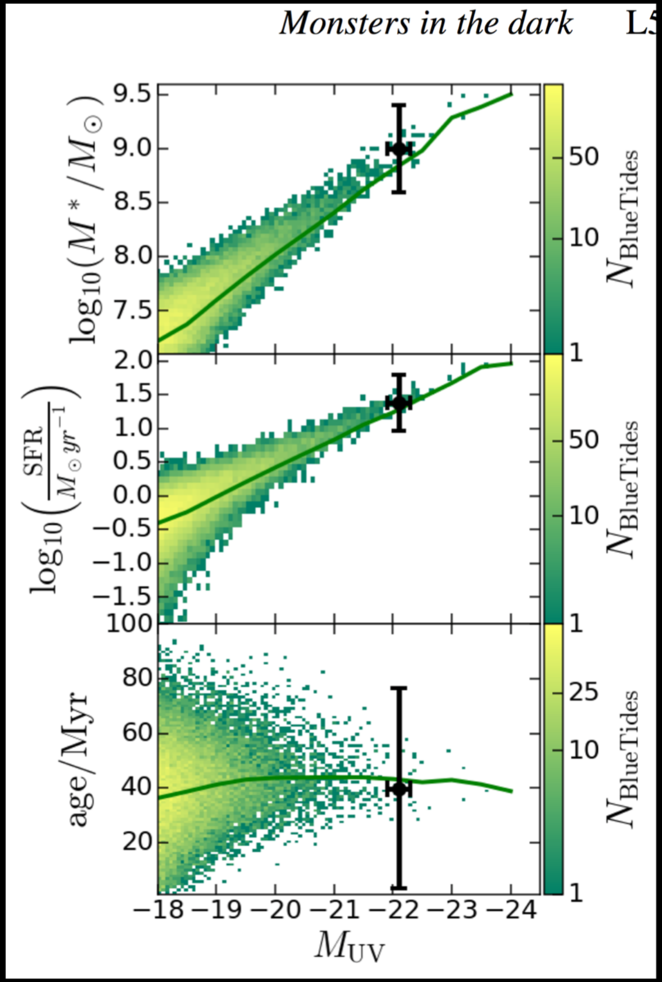
detection of GN-z11 in *existing data* is unexpected, given current models

gdi

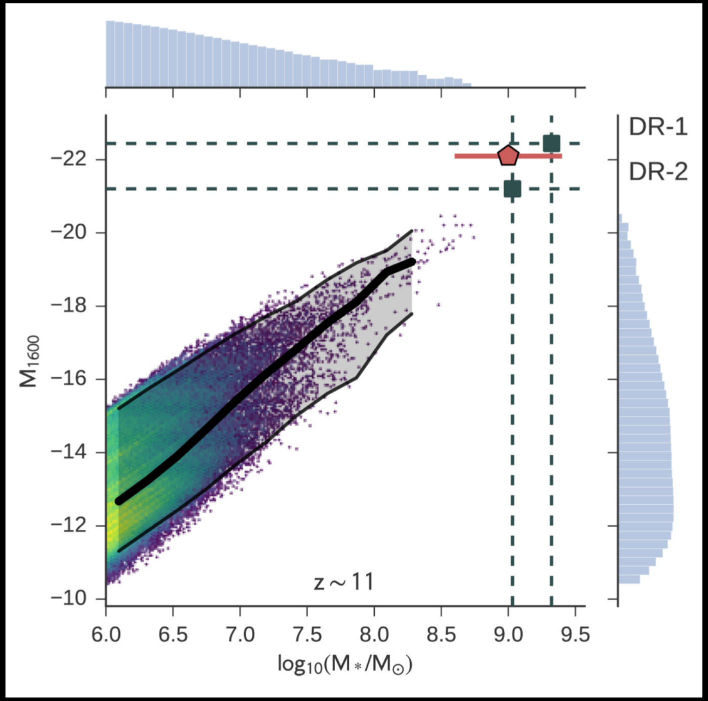
GN-z11

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
β -2.5 A_{UV} <0.2 mag age 40 Myr



BlueTides Waters+2016

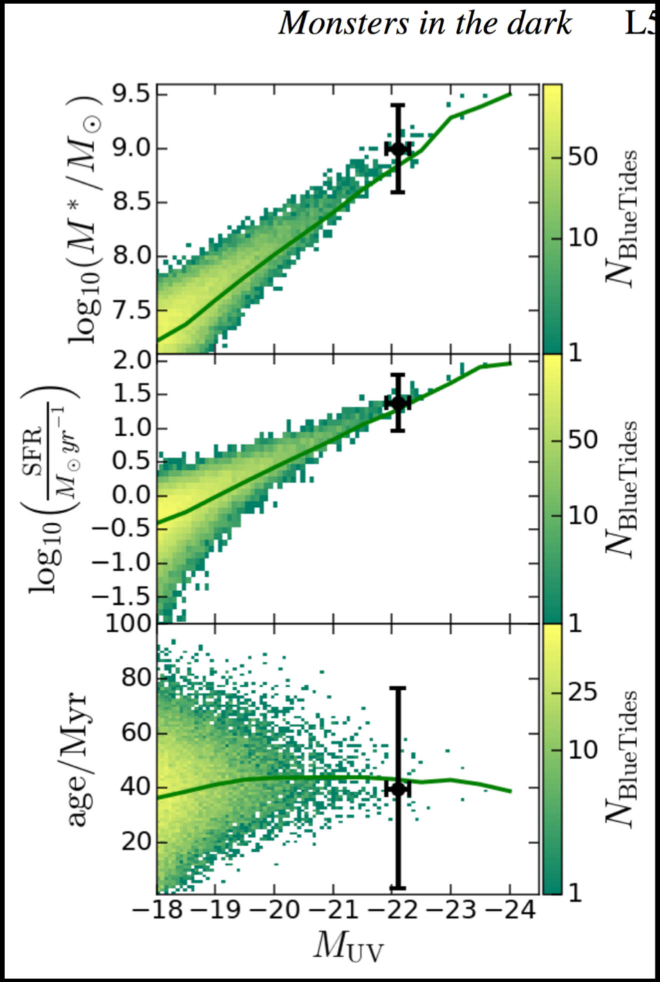


Mutch+2016 DRAGONS

gdi

GN-z11

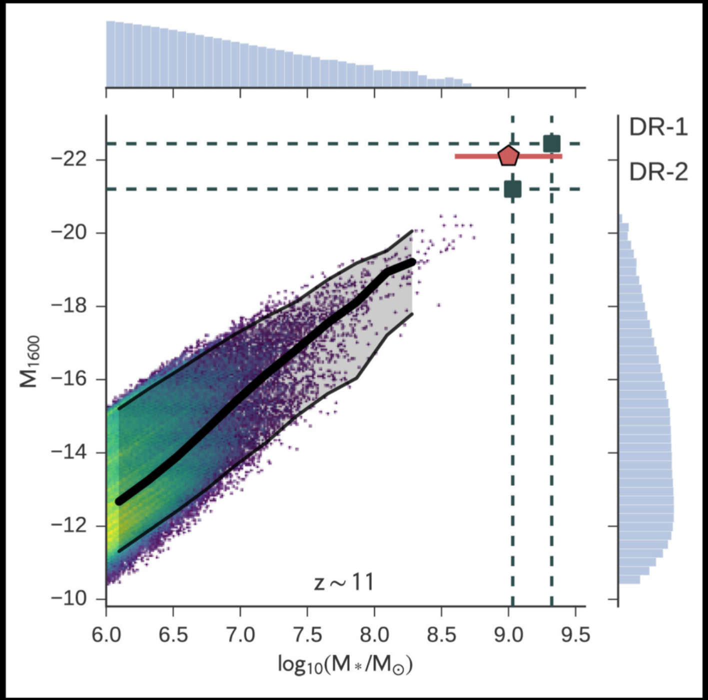
simulations show that galaxies as massive as GNz-11
at z~11 are rare but not unexpected *per se*



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

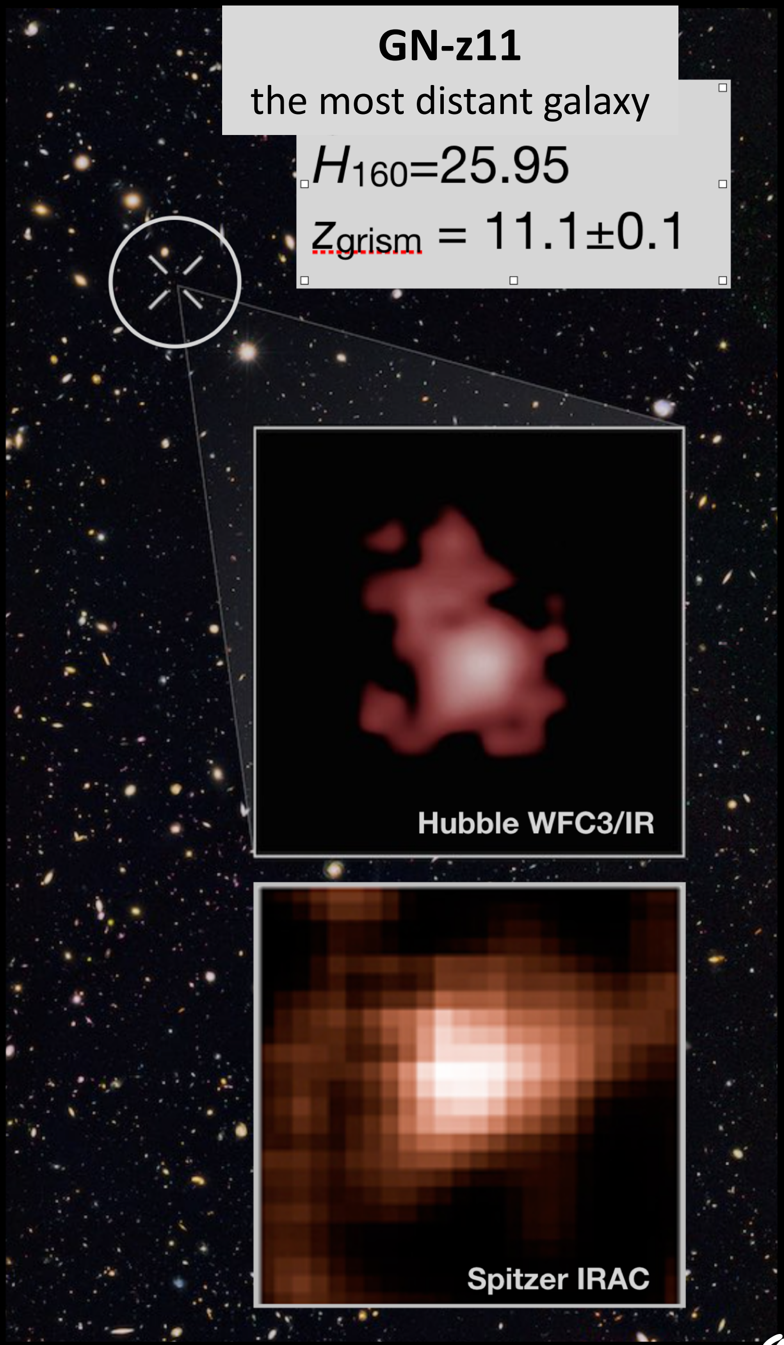
but it is unexpected to find GN-z11
in such small search
volumes/areas (by factor 10-100)?

gdi

GN-z11 is not a "first galaxy"

the "first galaxies" occurred earlier than 400 million years

but probably not by much – maybe 100-200 million years?



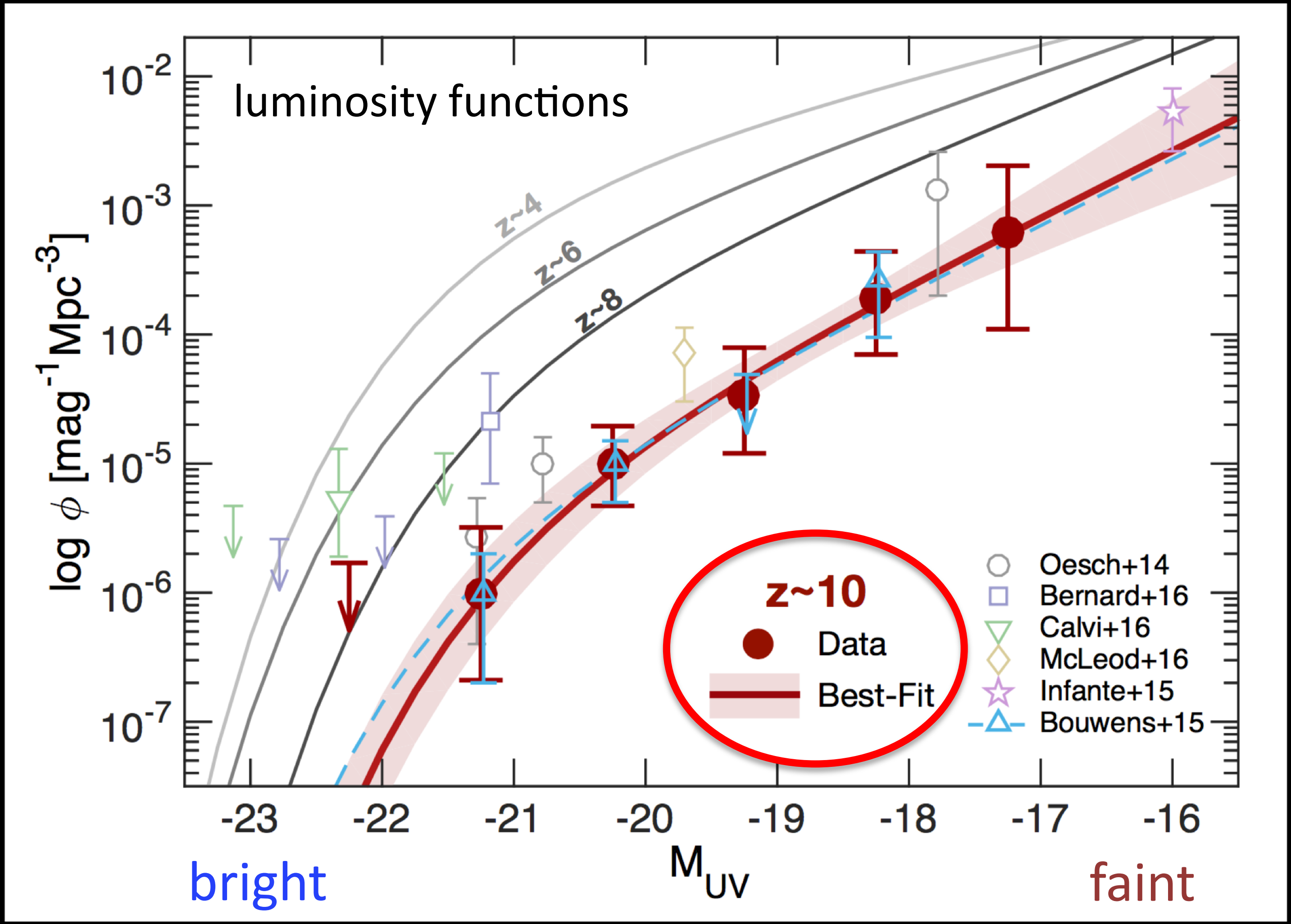
gdi

what constraints can Hubble and Spitzer put on the "first galaxies"

what do the highest redshift galaxies at z~10 (480 Myr) tell us

gdi

z~10 (500 Myr) galaxies are hard to find!



8 years of WFC3/IR imaging

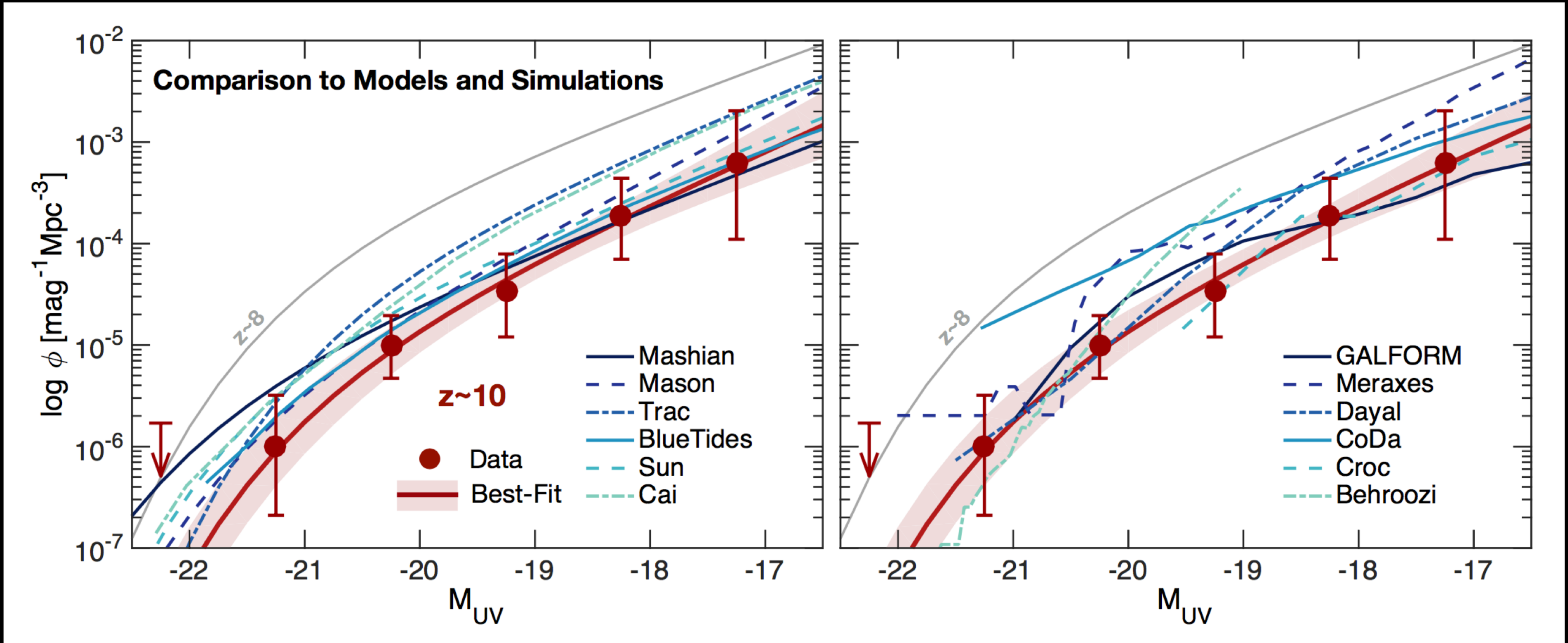
searched every WFC3/IR dataset but we find only 9 galaxies at ~500 Myr

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



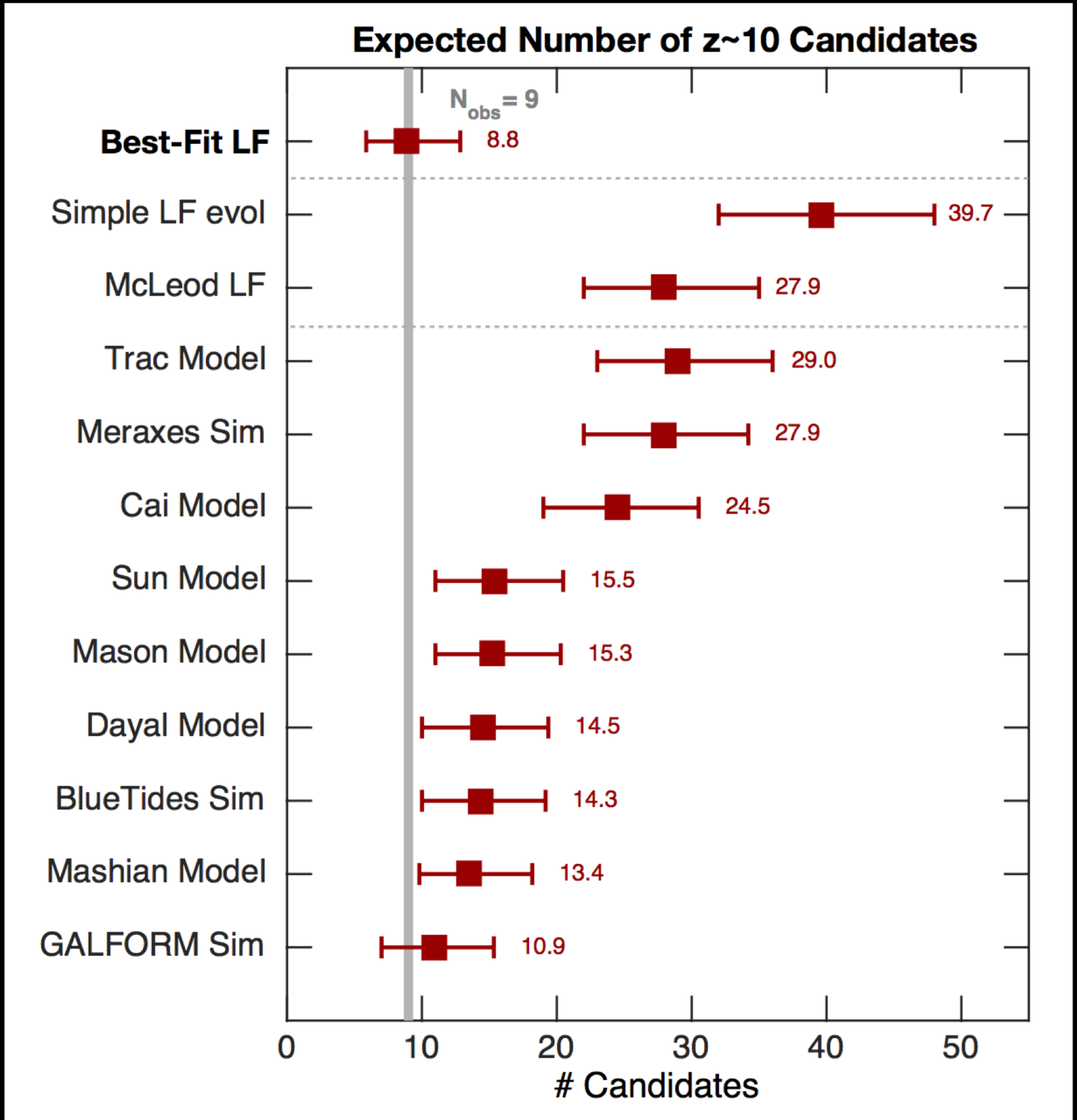
considerable spread
shape matches (broadly) to models –
but models are consistently high

Oesch+2017

gdi

the case of the missing z~10 galaxies

number of z~10 galaxies from
"observed luminosity function"



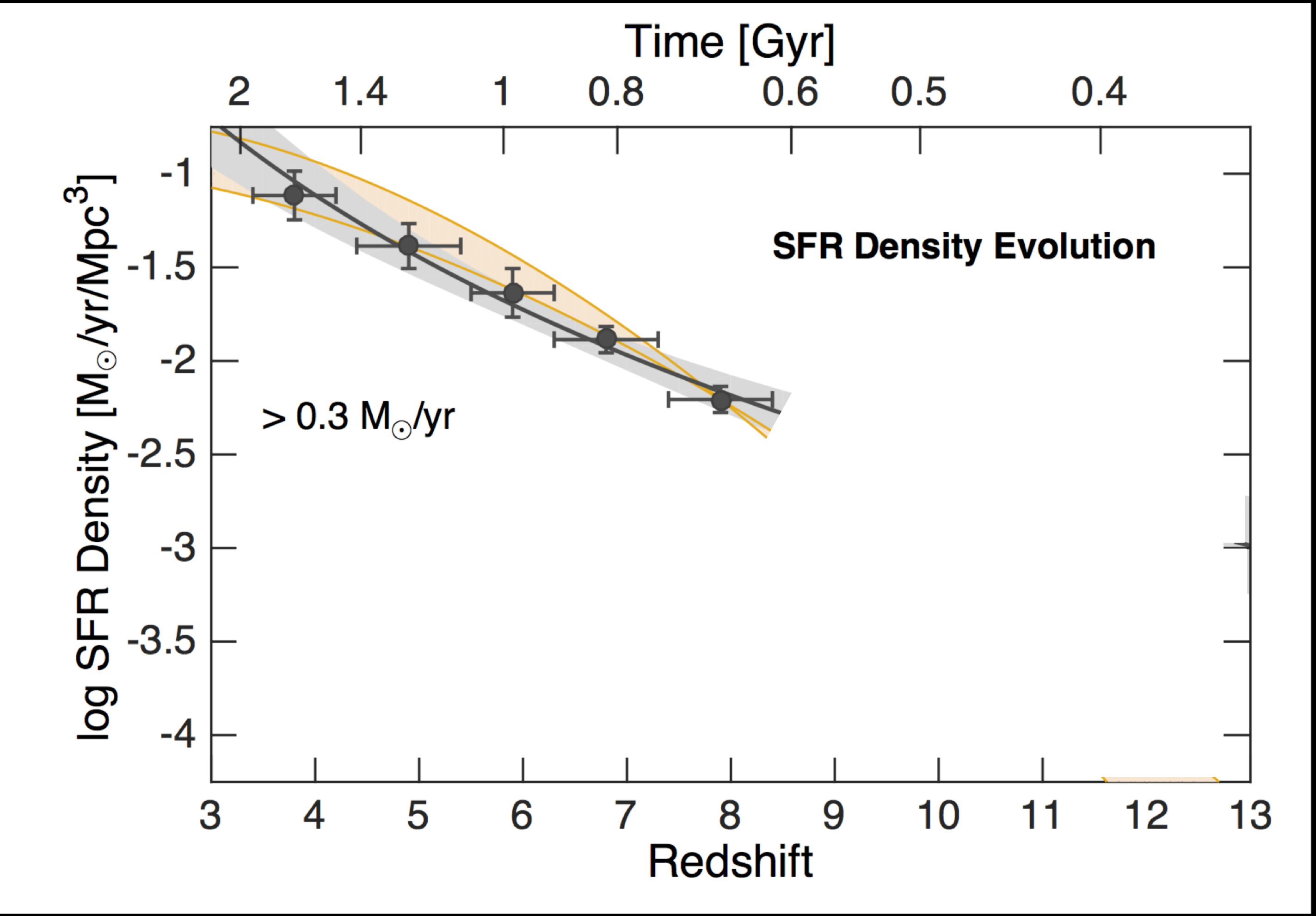
the situation at z~10 is unexpected

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

Oesch+2017

gdi

the star formation rate density to z~8 (650 Myr)



Oesch+2013,2014,2017

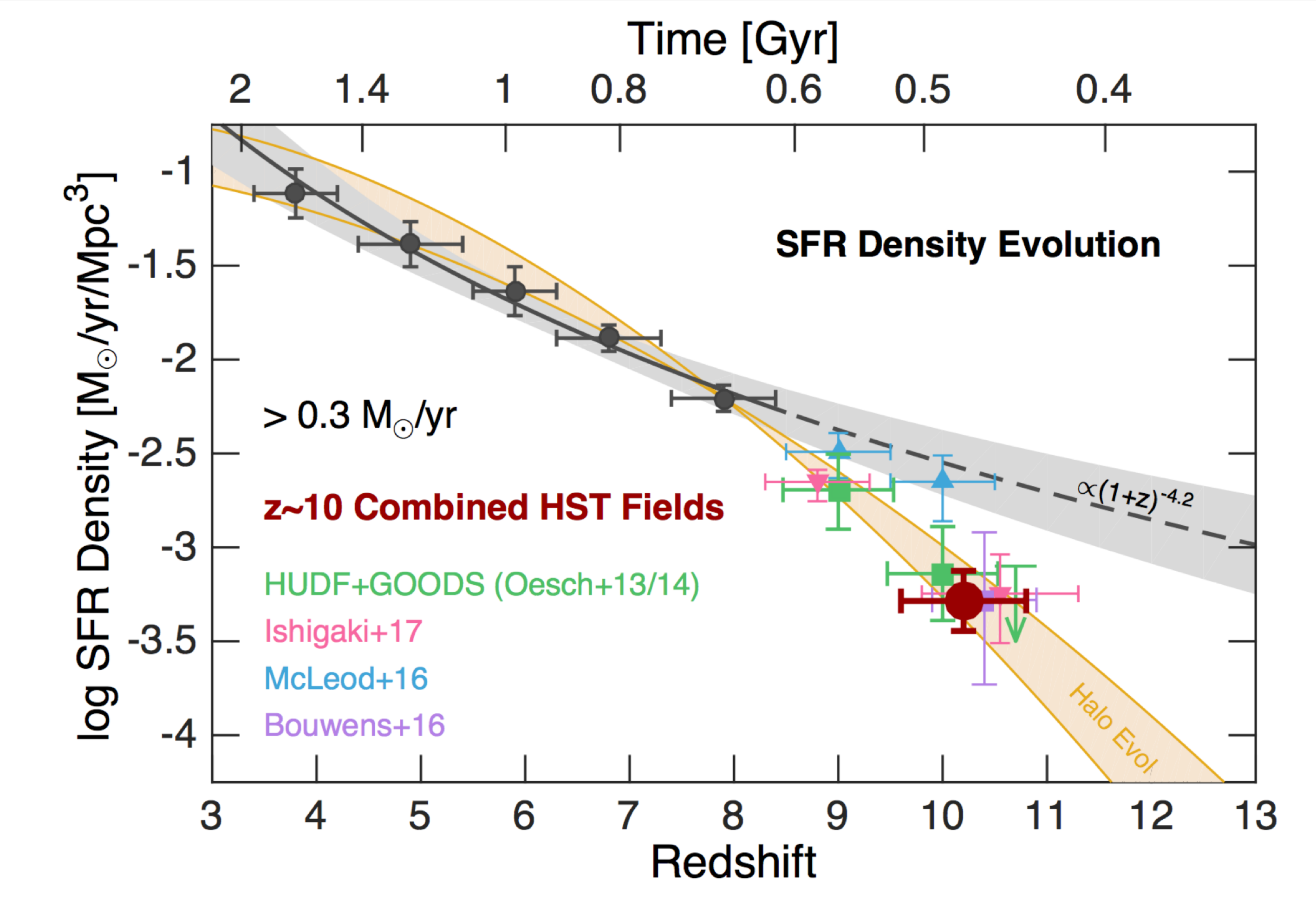
gdi

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”



Oesch+2013,2014,2017

gdi

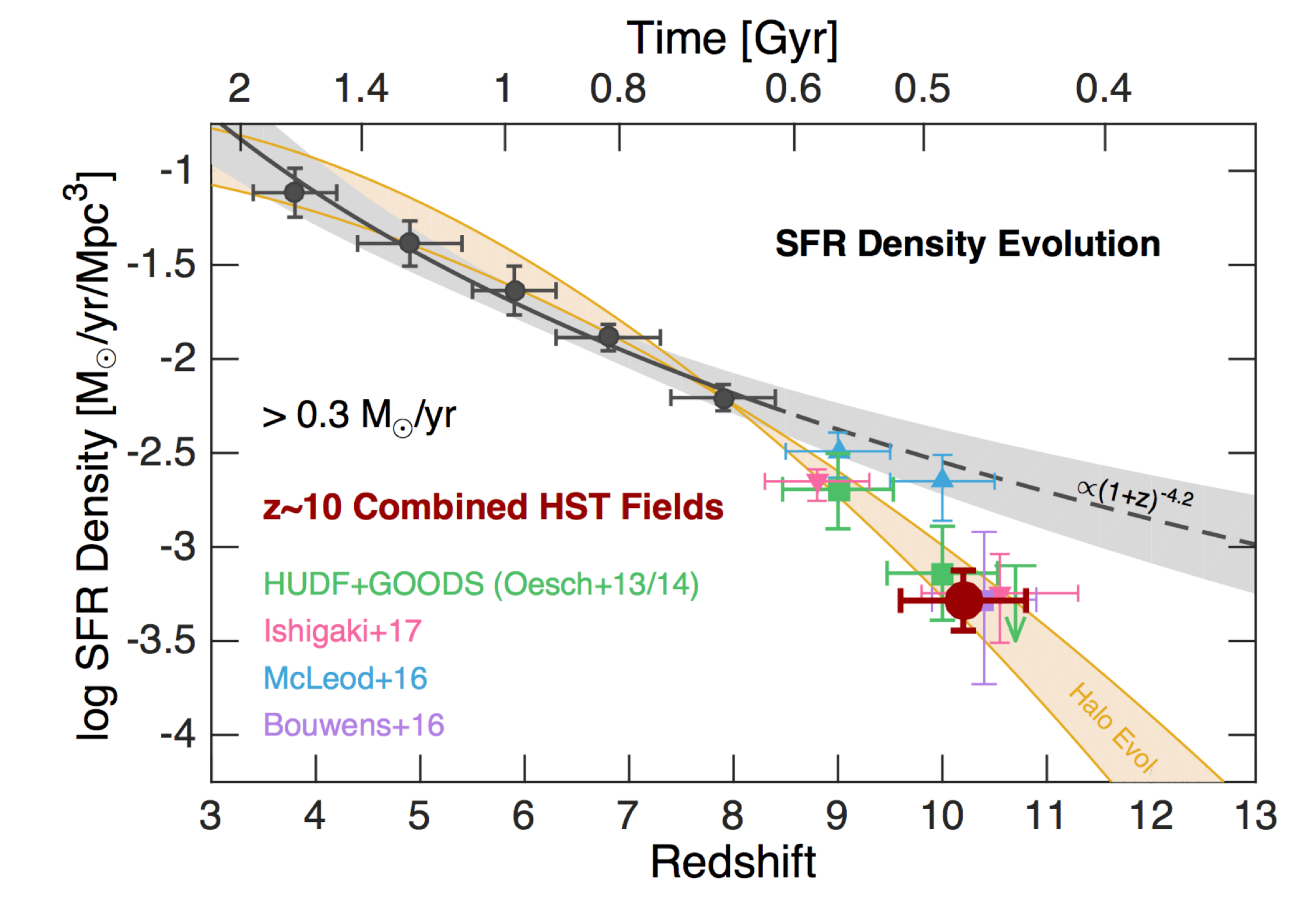
see also: Zheng+2012; Coe+2013; Bouwens+2013,15,16; Ellis+2013; McLure+2013; Ishigaki+2014,17; Infante+2015; Bernard+2016; Calvi+2016; McLeod+2016

“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

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



Oesch+2013,2014,2017

gdi

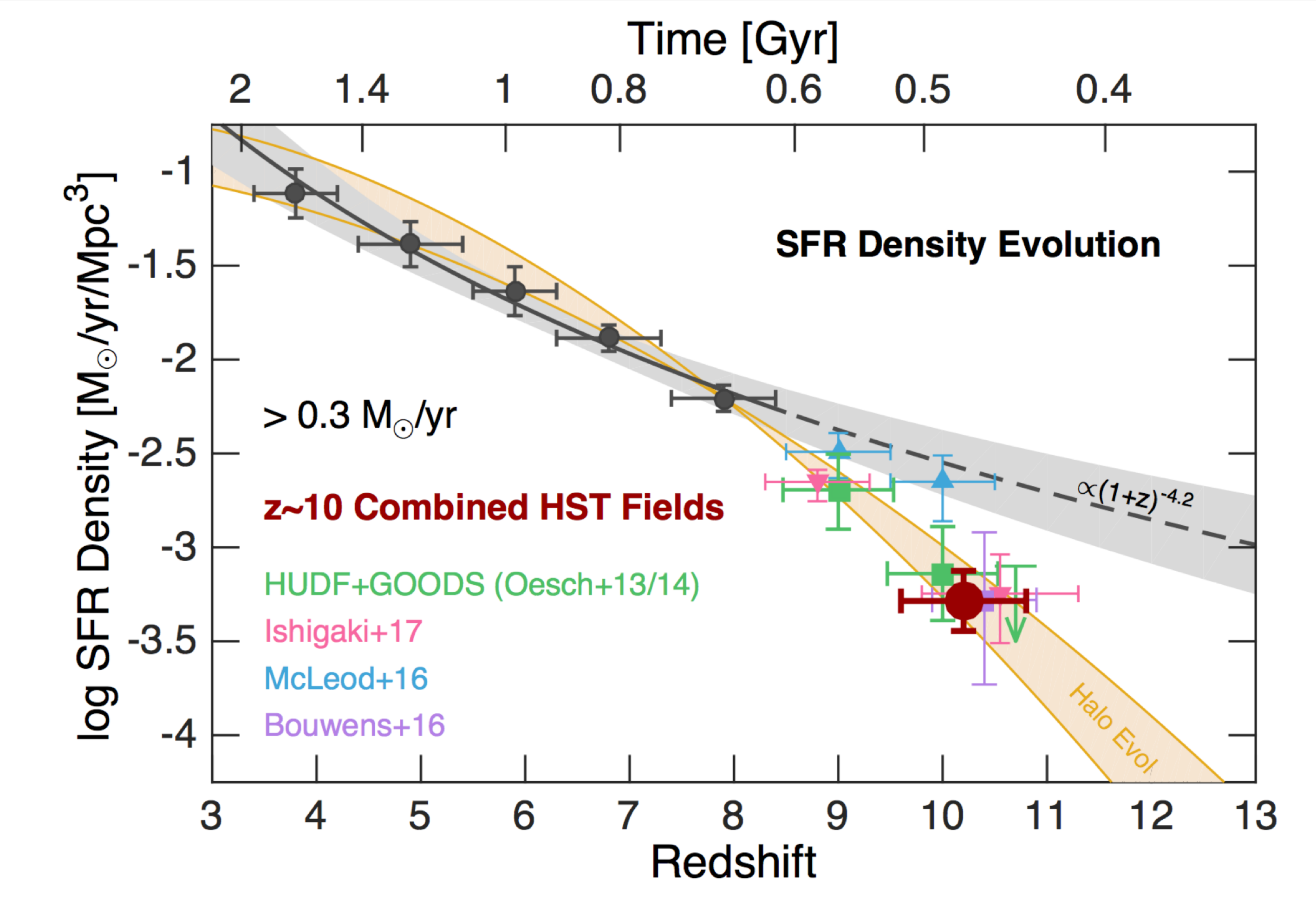
see also: Zheng+2012; Coe+2013; Bouwens+2013,15,16; Ellis+2013; McLure+2013; Ishigaki+2014,17; Infante+2015; Bernard+2016; Calvi+2016; McLeod+2016

"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



Oesch+2013,2014,2017

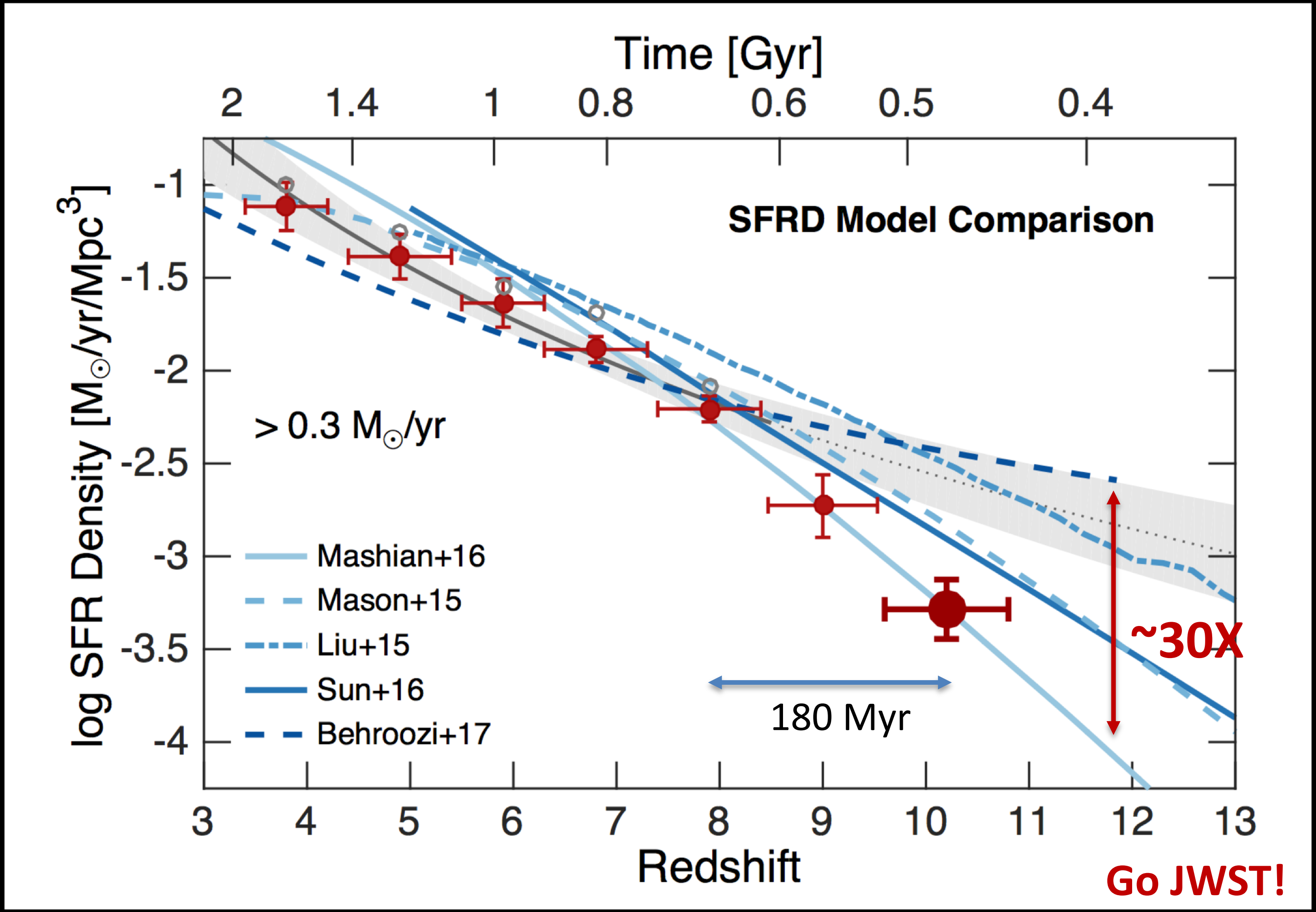
gdi

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

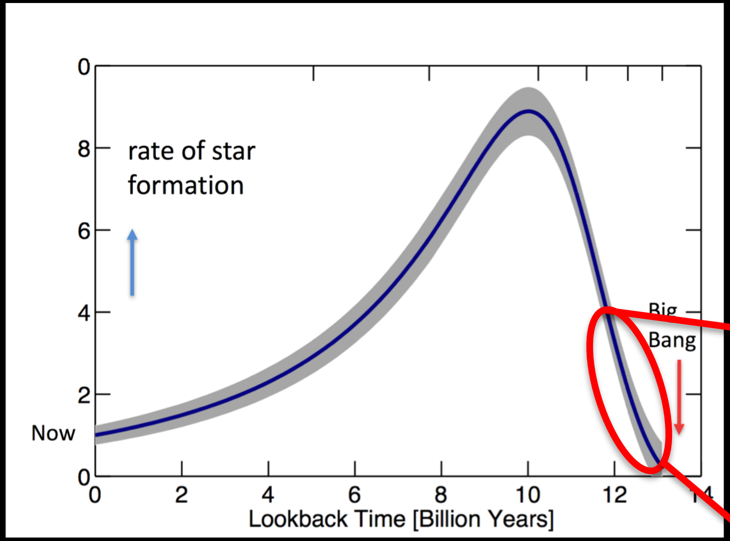
note that there is a large range of shapes/slopes!

Oesch+2017

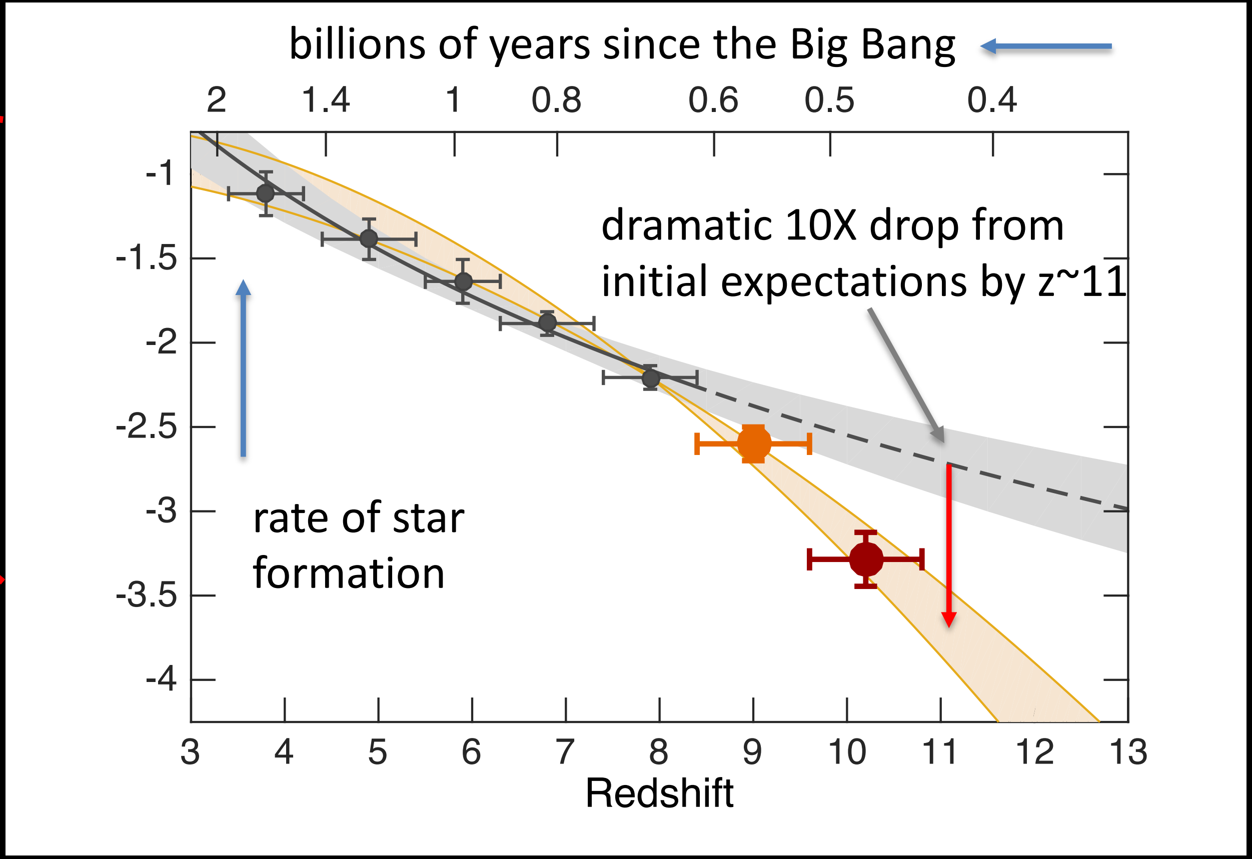


gdi

way fewer galaxies than expected at redshift 10!



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



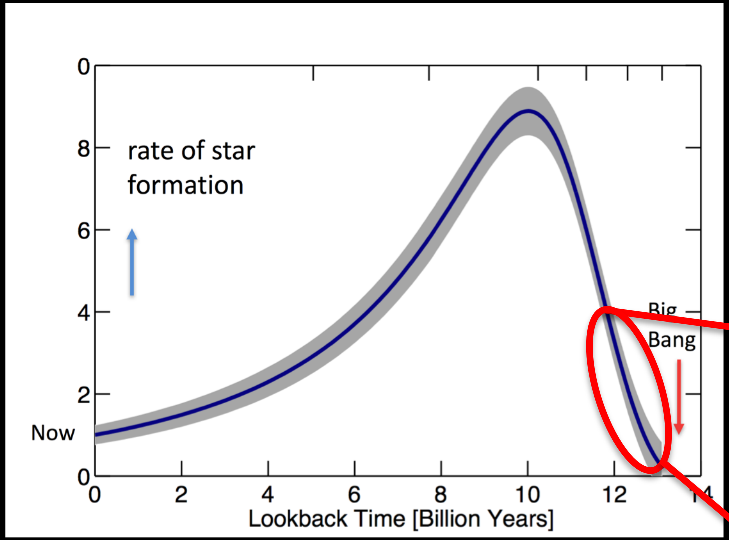
galaxies are evolving rapidly earlier than 650 million years

Oesch+2017

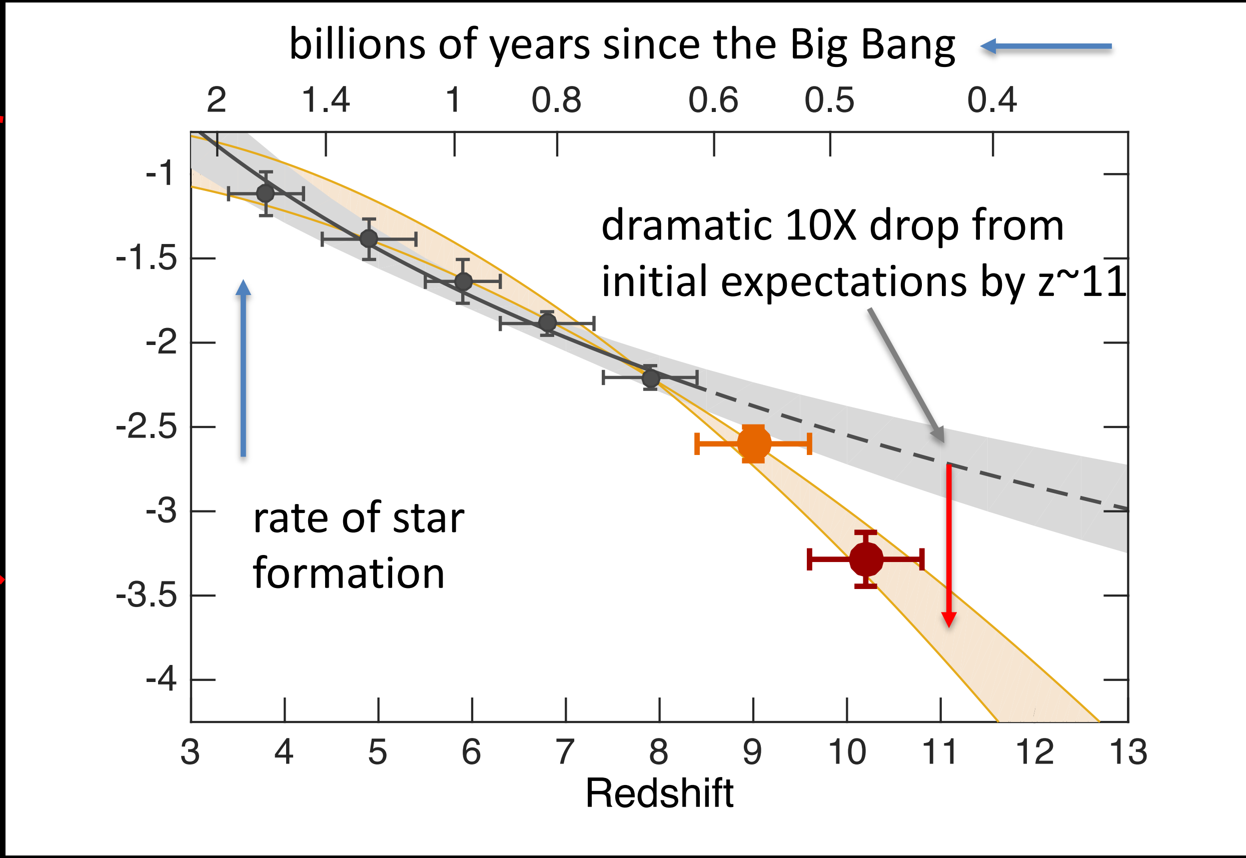
Bouwens+2018

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

Oesch+2017

"accelerated evolution" is a very important result in the search for the "first galaxies"

Bouwens+2018

gdi

when did the “first stars” appear?

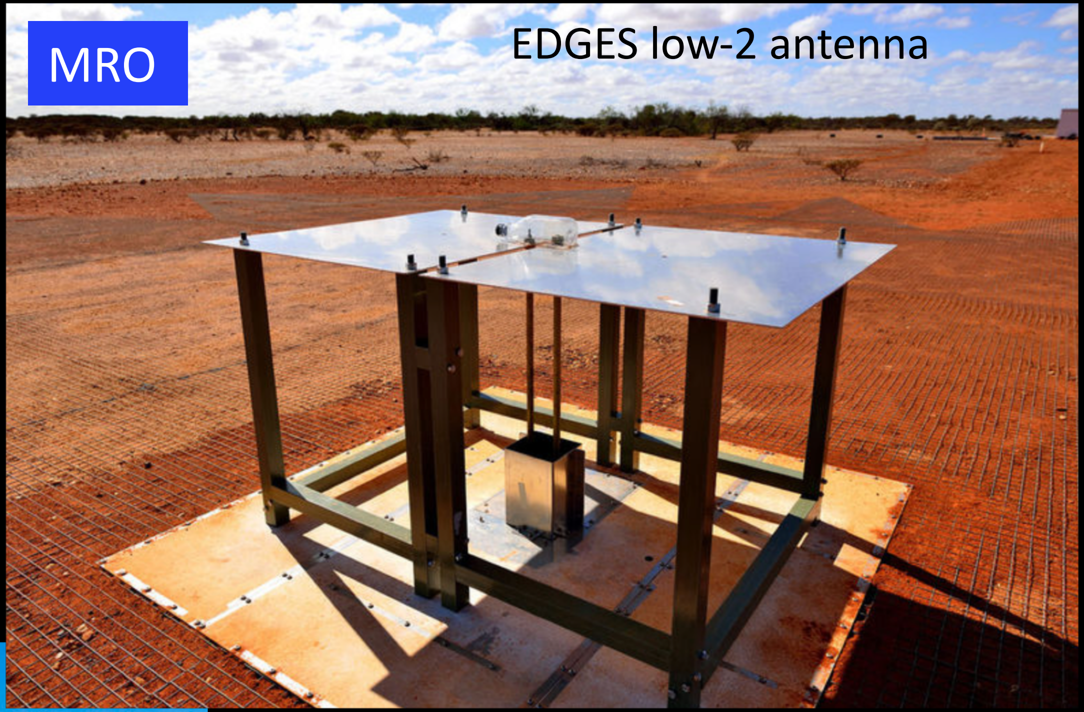
gdi

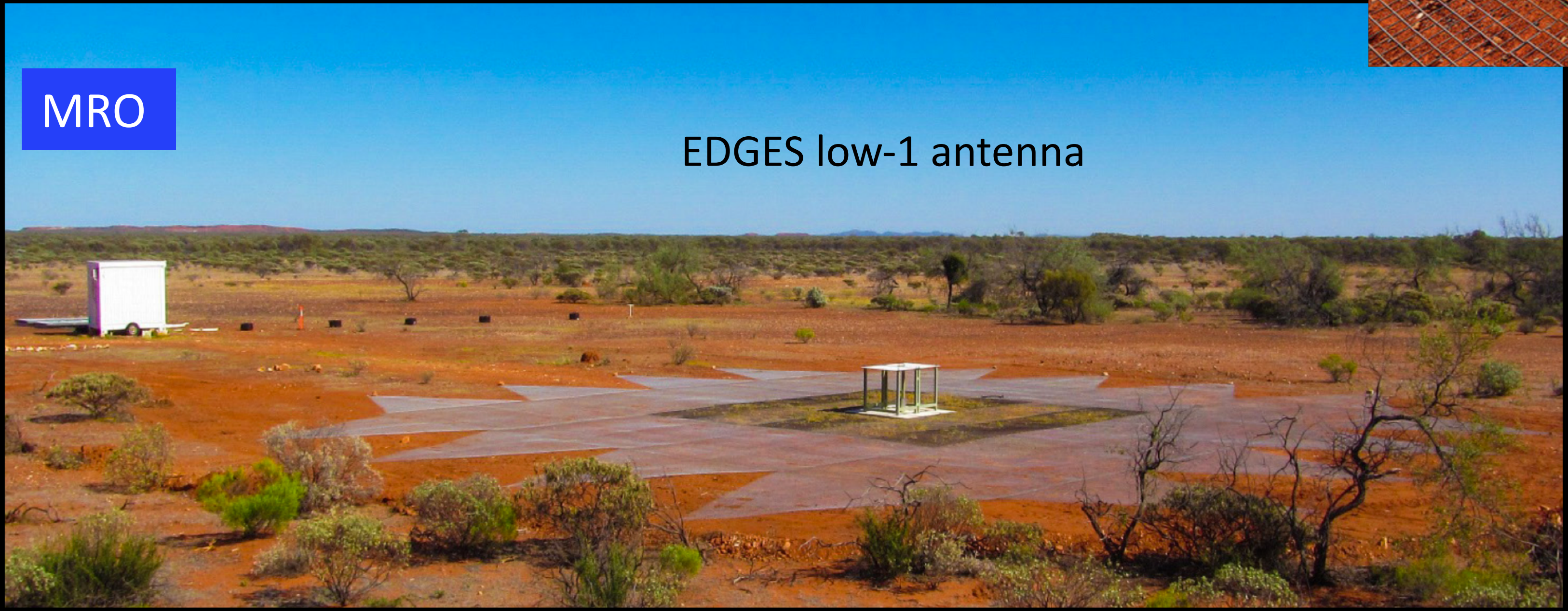

Murchison Radio-Astronomy Observatory (MRO)
gdi

detection of when first stars “turned on”

EDGES:

Experiment to Detect the Global Epoch of Reionization Signature





Murchison Radio-astronomy Observatory (MRO) in Western Australia

Recent RESULT

published March 2018
Nature

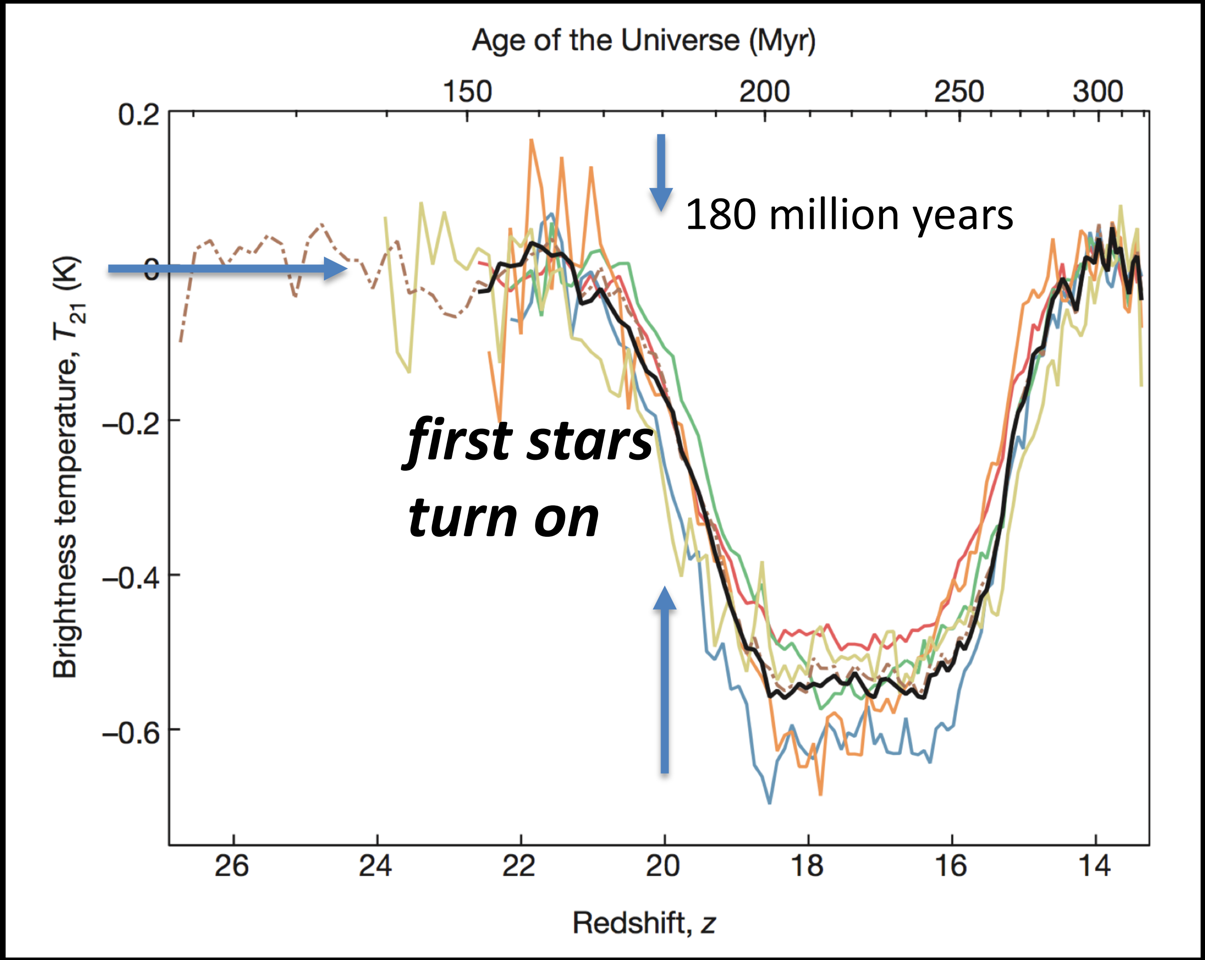
Bowman, Rogers,
Monsalve, Mozdzen
& Mahesh

gdi

the "first stars"

when the "first stars" started to produce UV Lα photons

cosmic microwave background



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

Bowman+2018

gdi

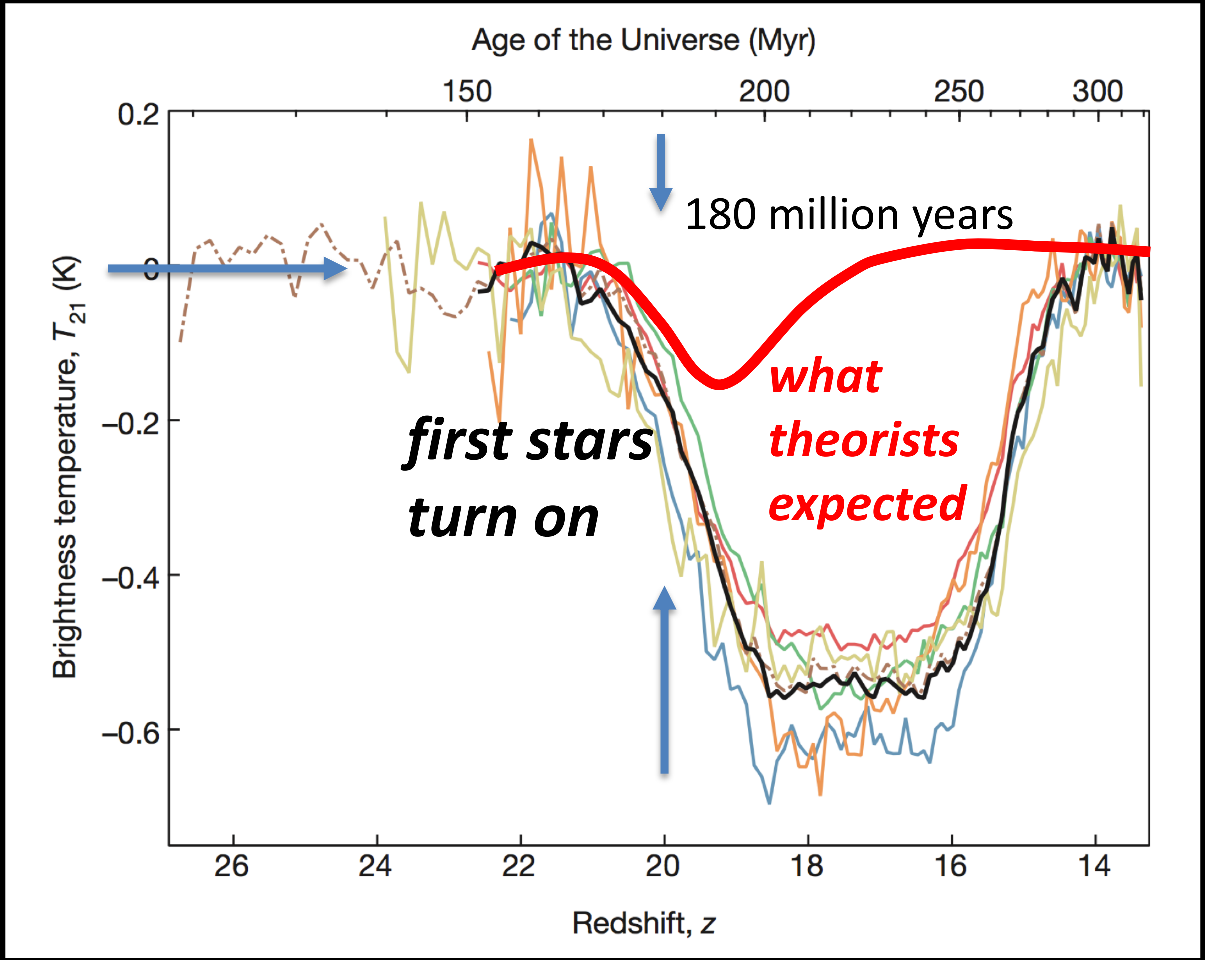
the "first stars"

when the "first stars" started to produce UV Lα photons

is this result correct?

confirmation?

implications:
(dark matter interactions)?



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

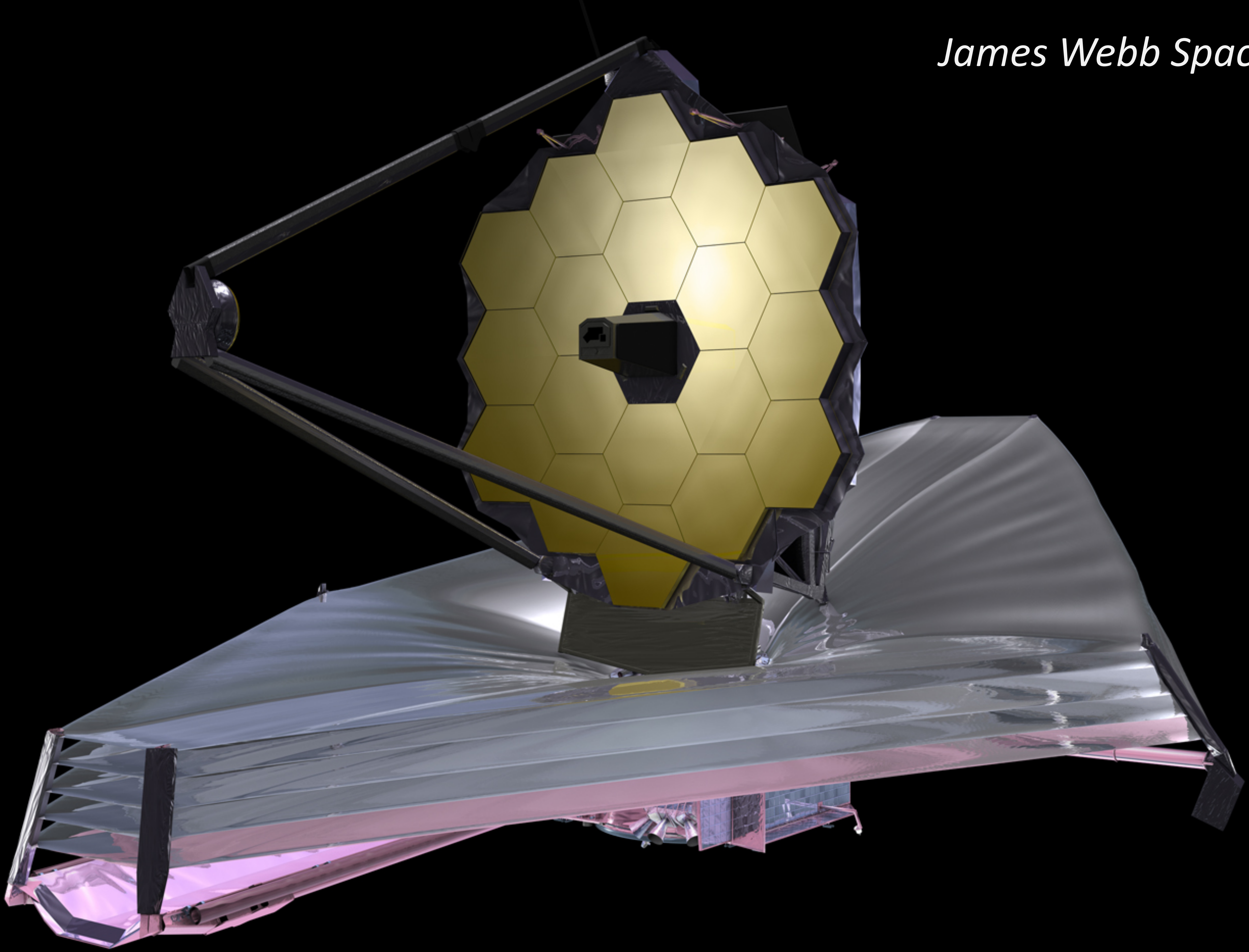
Bowman+2018

gdi

☛ *what comes next in our search for the "first galaxies"?* ☚

gdi

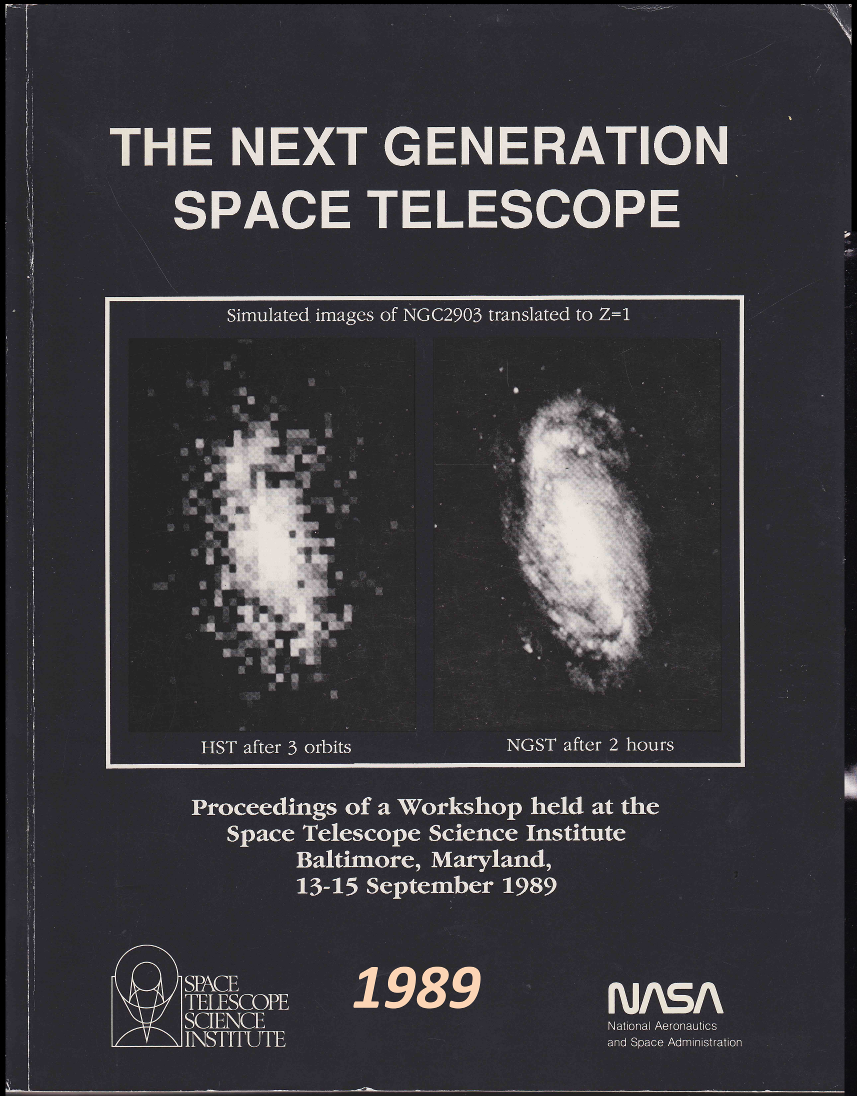
James Webb Space Telescope

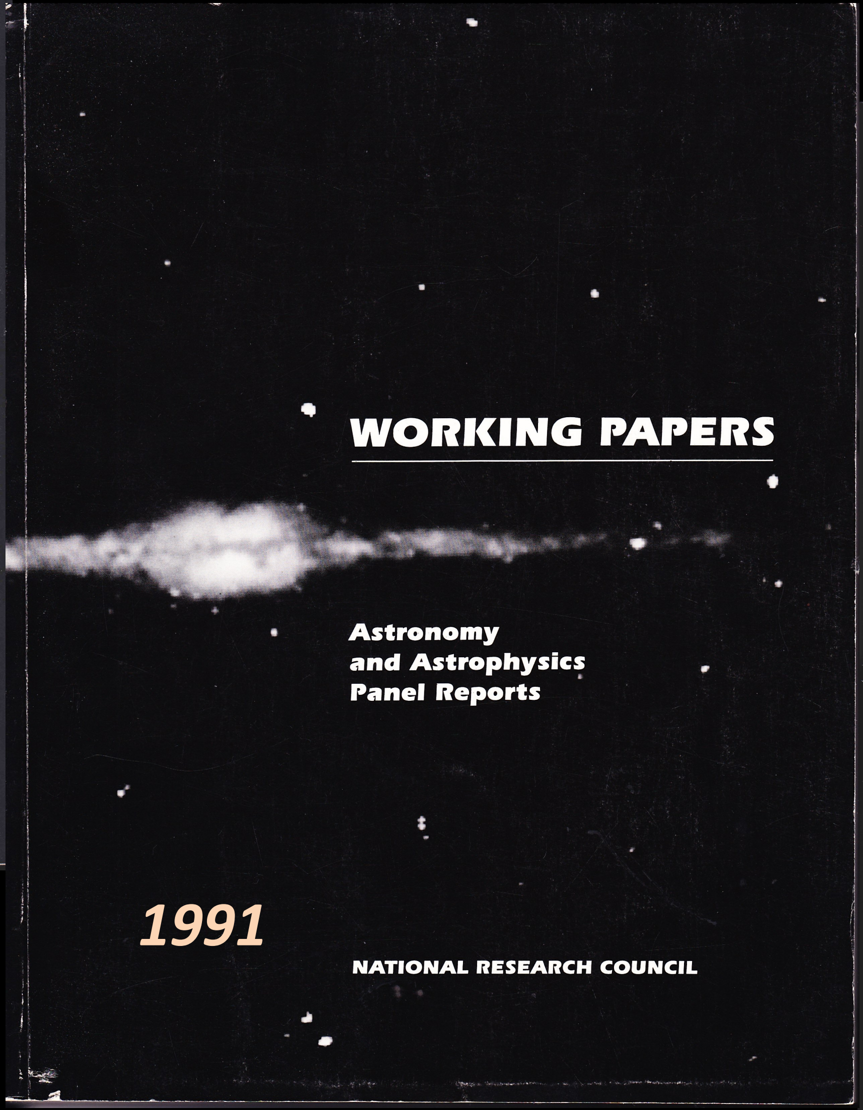


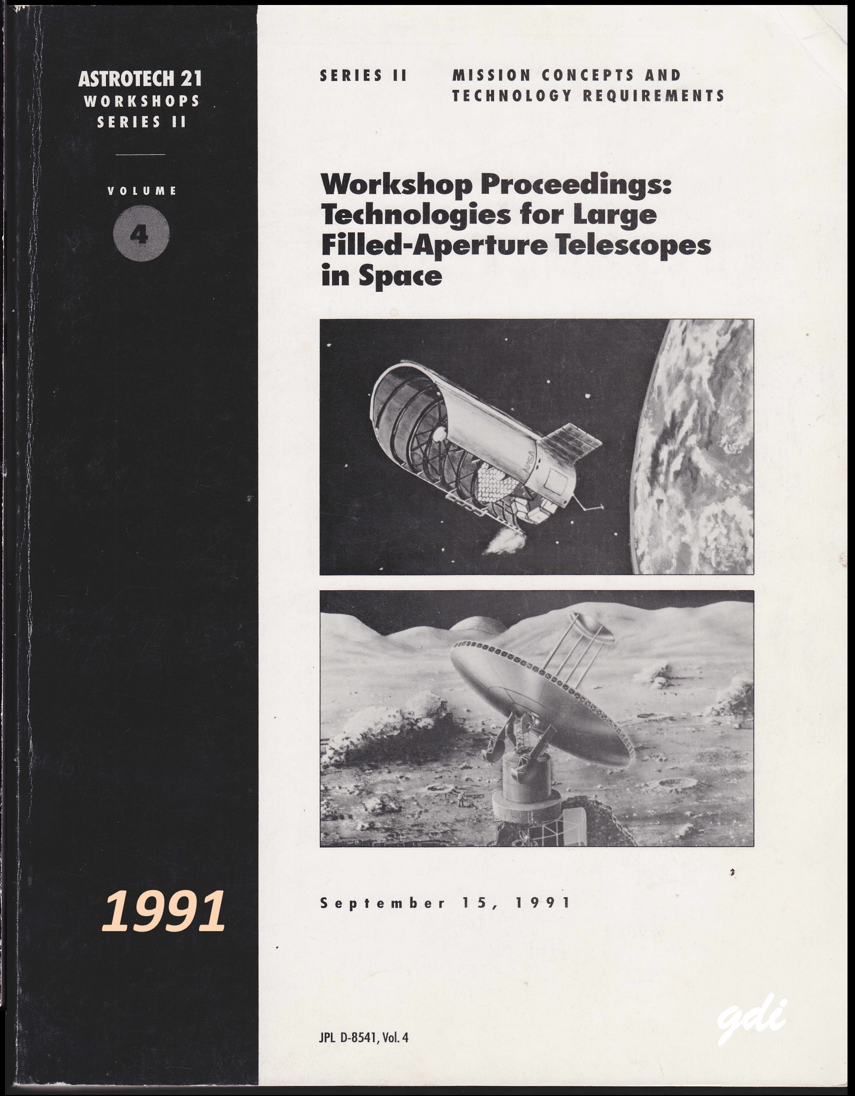
gdi


full-size JWST model at "South by Southwest"
people
gdi

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



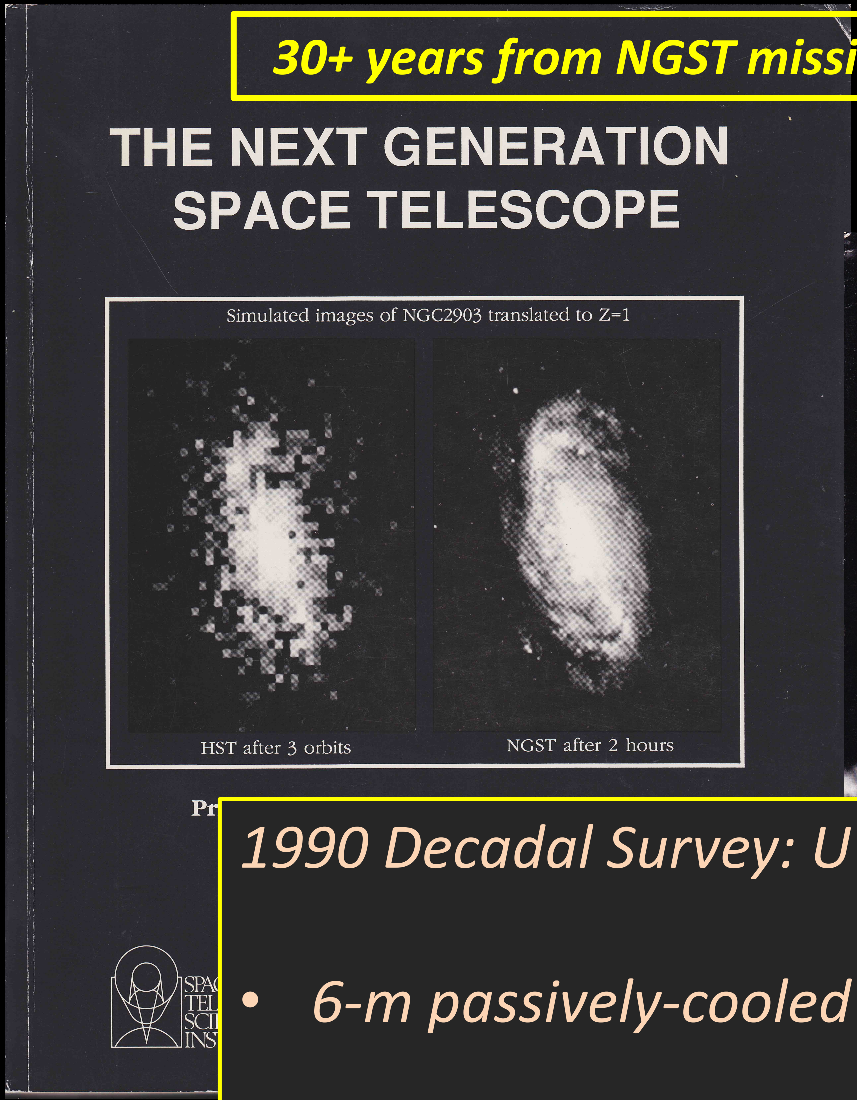


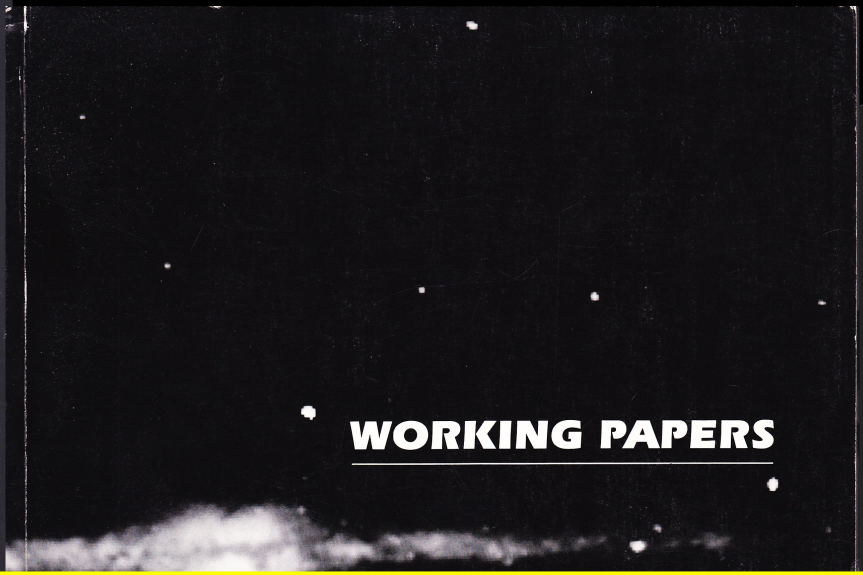


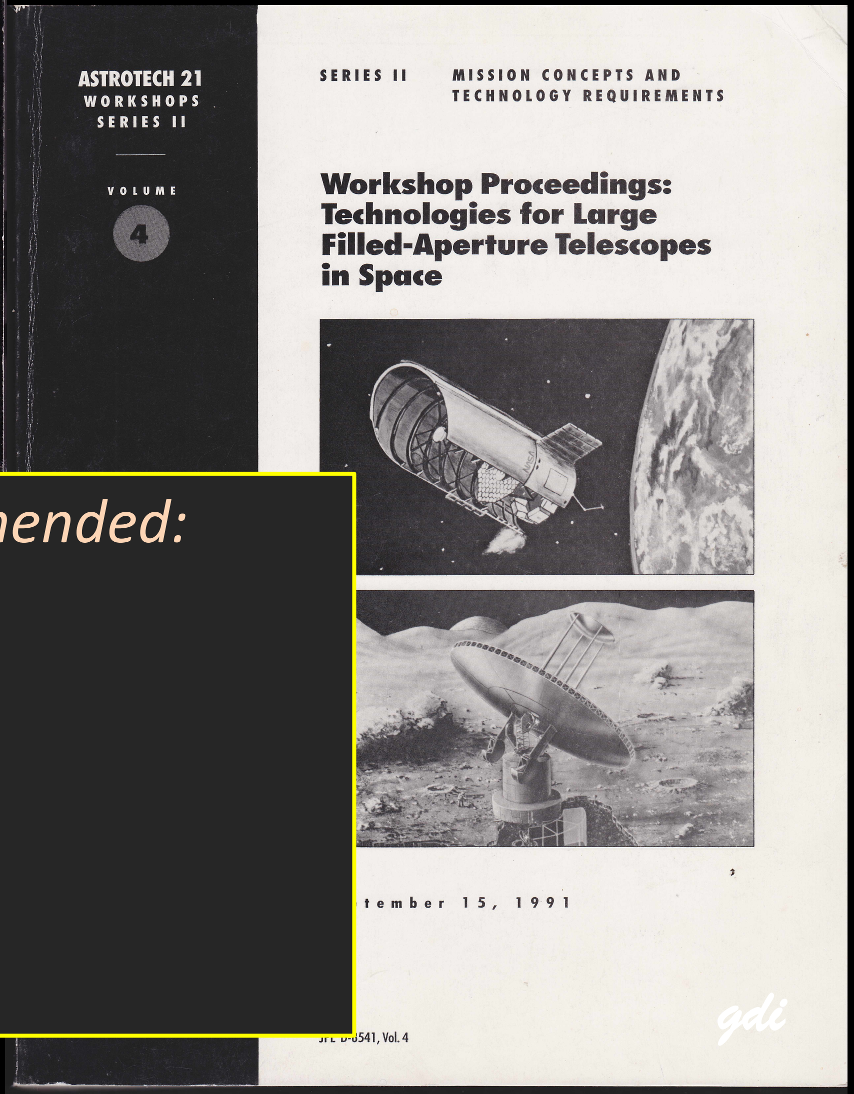
Riccardo Giacconi told us that it would take a long time – “start early”

30+ years from NGST mission concept to JWST launch!

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

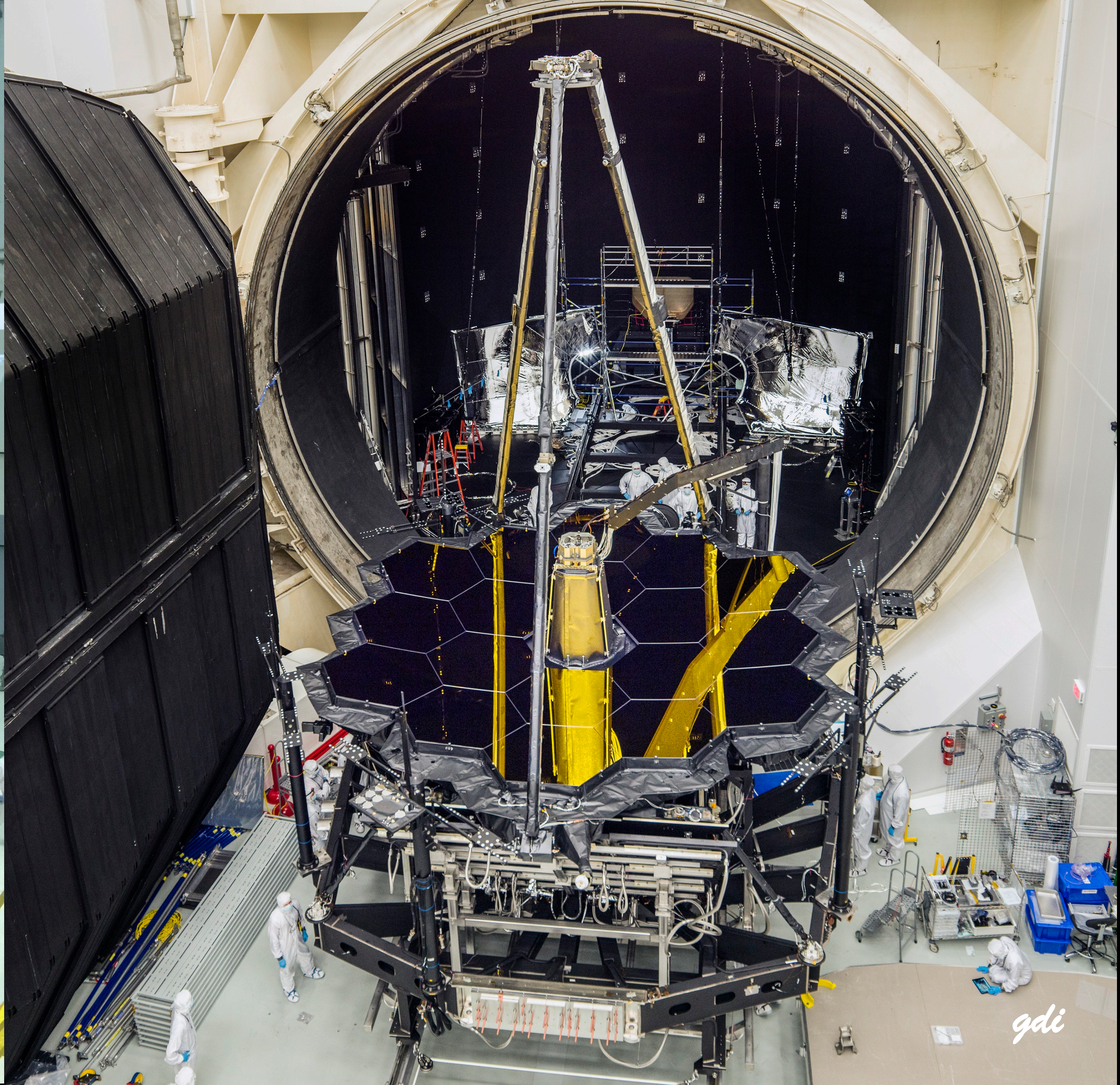






1990 Decadal Survey: UV-Optical in Space Panel recommended:

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


gdi


NORTHROP GRUMMAN
JLG 2630ES
www.jlg.com
7334
JLG
EXIT
gdi

recent issues shifted launch date out by ~2 years

current launch date: late 2020

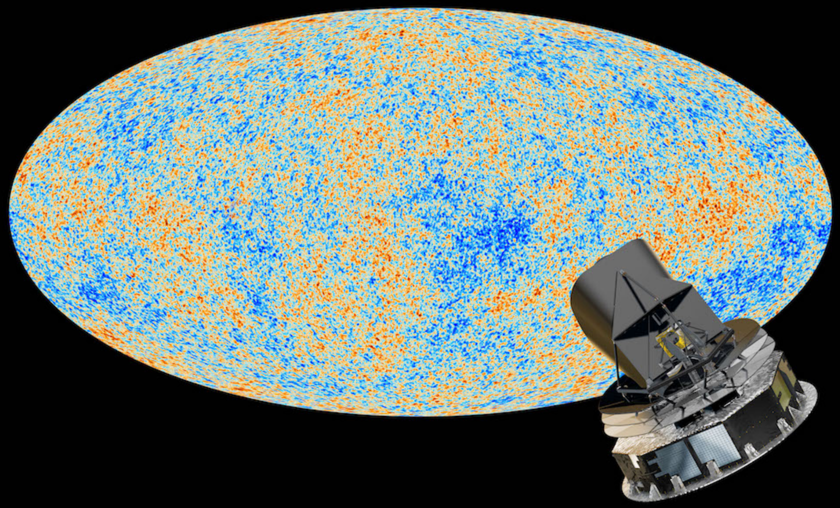
gdi

can JWST find the first galaxies?

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

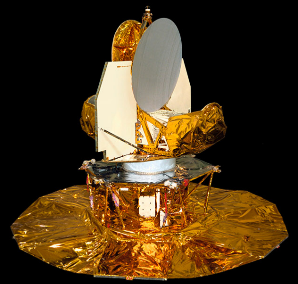
will they occur at such high redshifts that they will be hard for JWST to see?

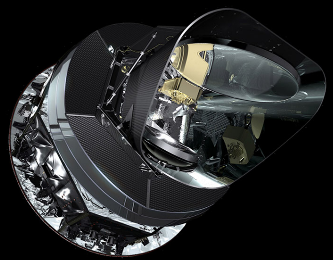
gdi

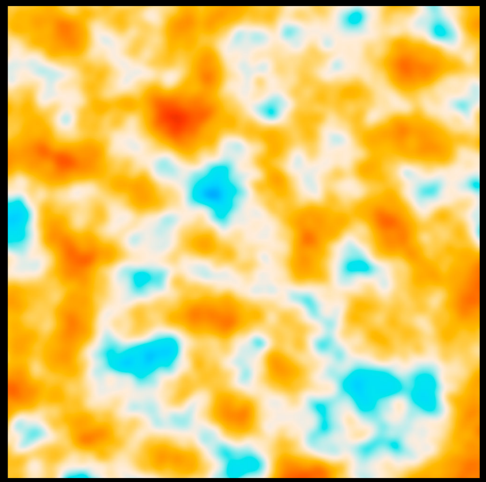


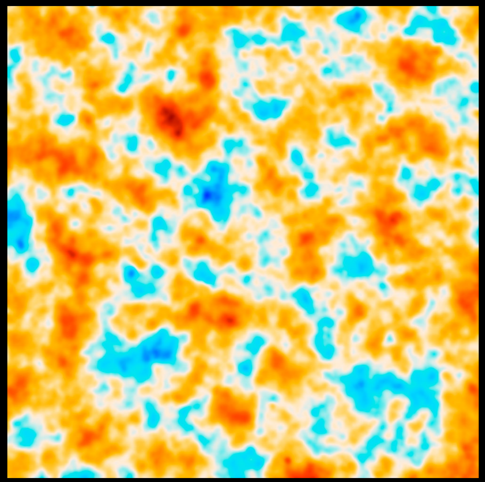
measuring the fluctuations in the 3°K microwave background across the whole sky

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









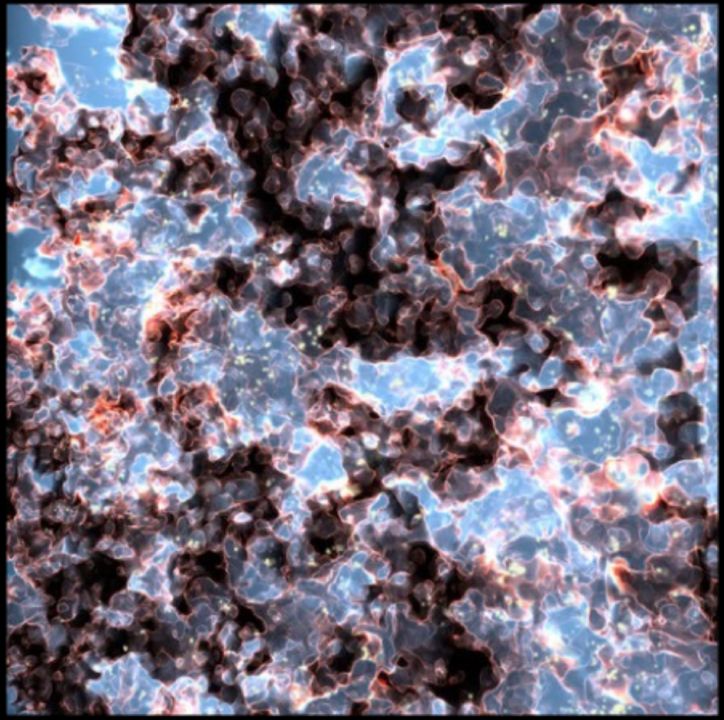
three amazing missions

COBE	WMAP	Planck
1989	2001	2009

gdi

reionization epoch – Planck 2016/2018 results

remarkable mission



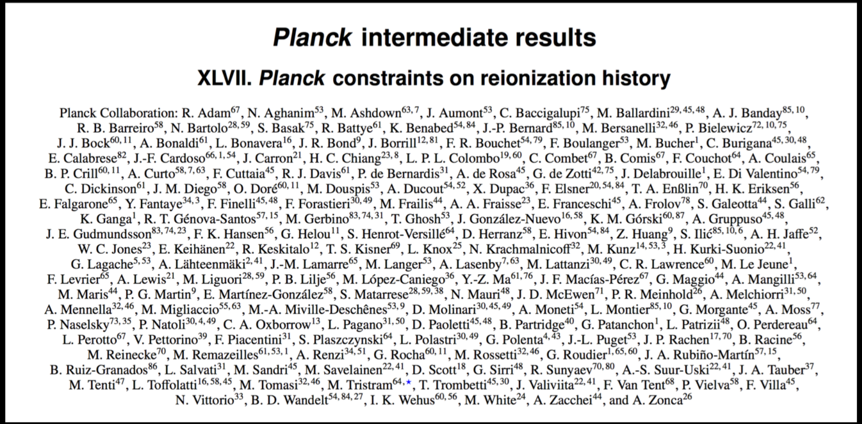
reionization simulation: Alvarez et al. 2009

gdi

Planck 2016/2018

constraints on the reionization history

Plank Collaboration XLVII + 2016
Plank Results VI Cosmological Parameters + 2018
Plank Results I Overview and Legacy + 2018



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]

…Thomson optical depth: $\tau = 0.054 \pm 0.007$

…mid-point redshift at which reionization occurs is found to lie at $z = 7.7 \pm 0.7$

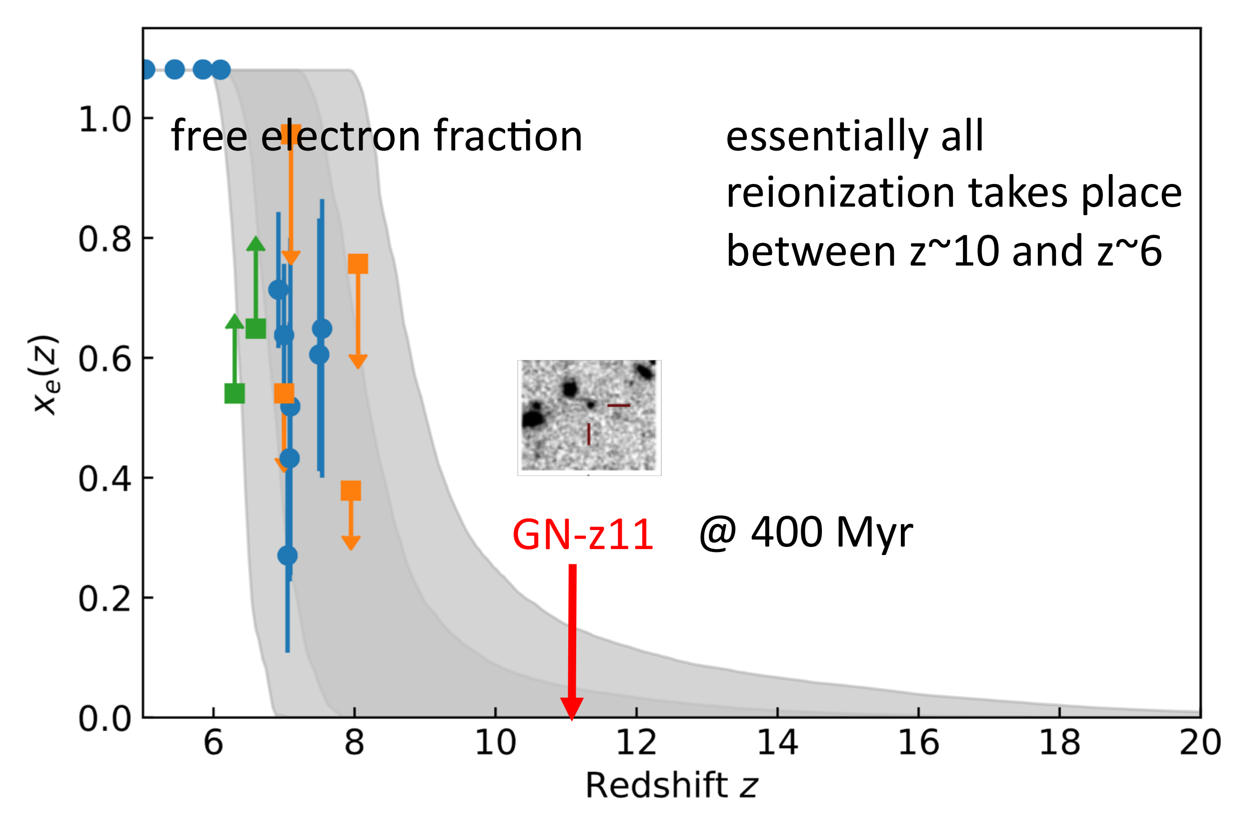
…upper limit to the width of the reionization period of $\Delta z < 2.8$.

…the Universe is ionized at much less than the 10% level at redshifts above $z \simeq 10$…
(<1% above $z \simeq 15$)

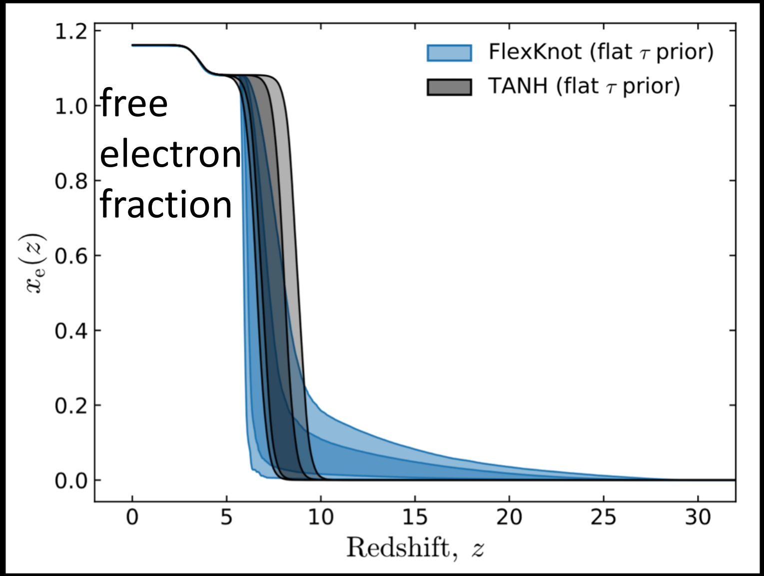
…an early onset of reionization is strongly disfavored by *Planck* data

gdi

reionization constraints from Planck 2018



Plank Collaboration Results I + 2018



Planck Collaboration VI+2018

GN-z11 is a pathfinder into the epoch of the earliest galaxies

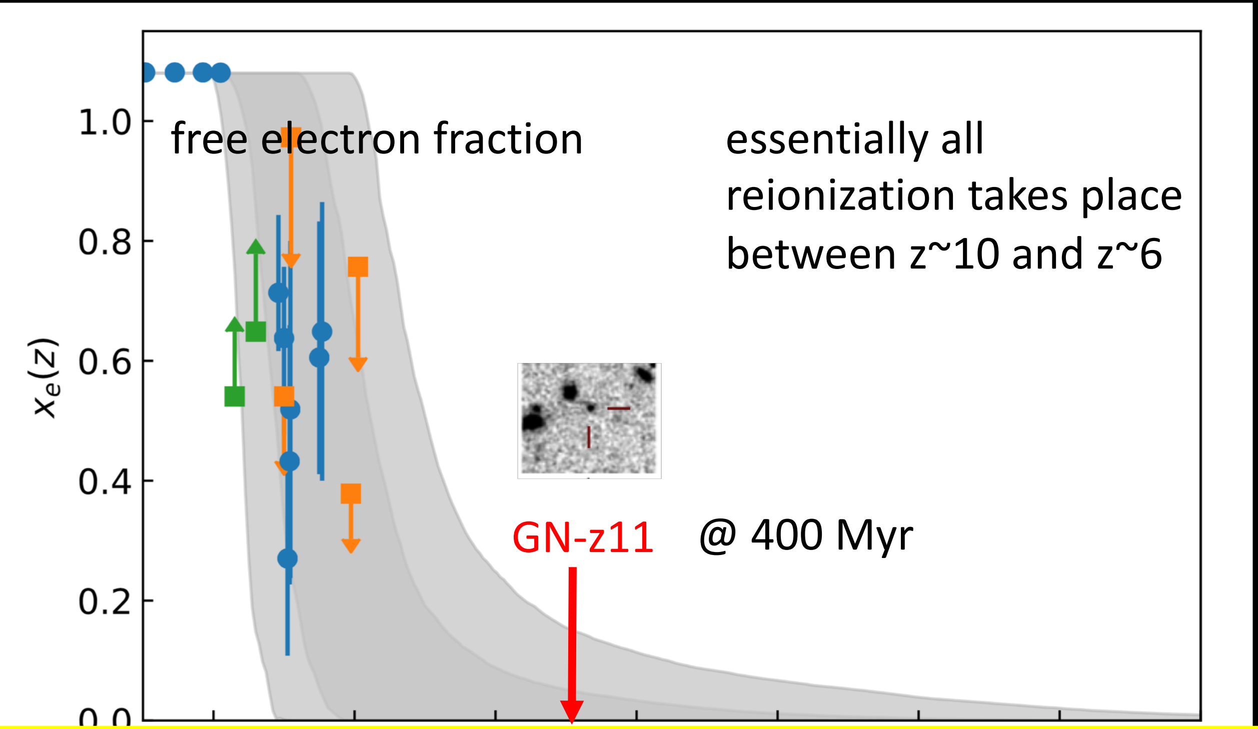
….*Planck* data prefer a late and fast transition from a neutral to an ionized universe….

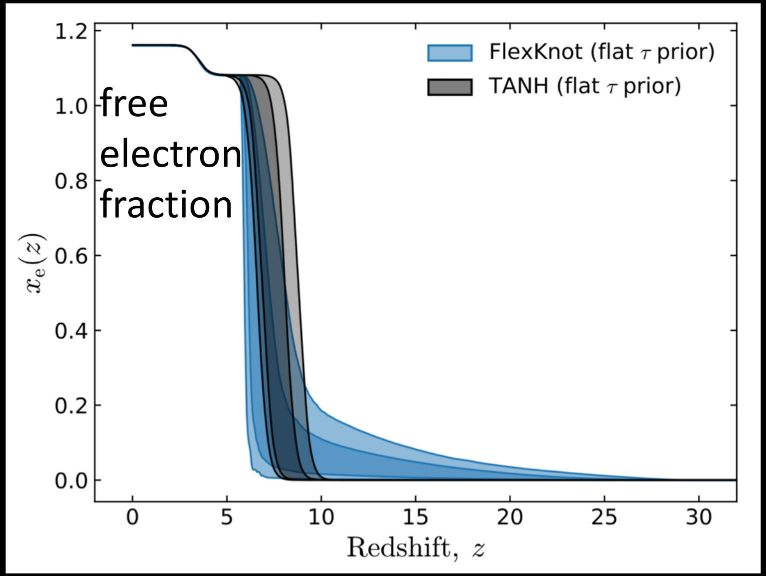
….non-standard early galaxies or significantly evolving escape and clumping factors are no longer required

….nor do the *Planck* results require any emission from high-redshift (z = 10–15) galaxies

gdi

reionization constraints from Planck 2018





Planck Collaboration VI+2018

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

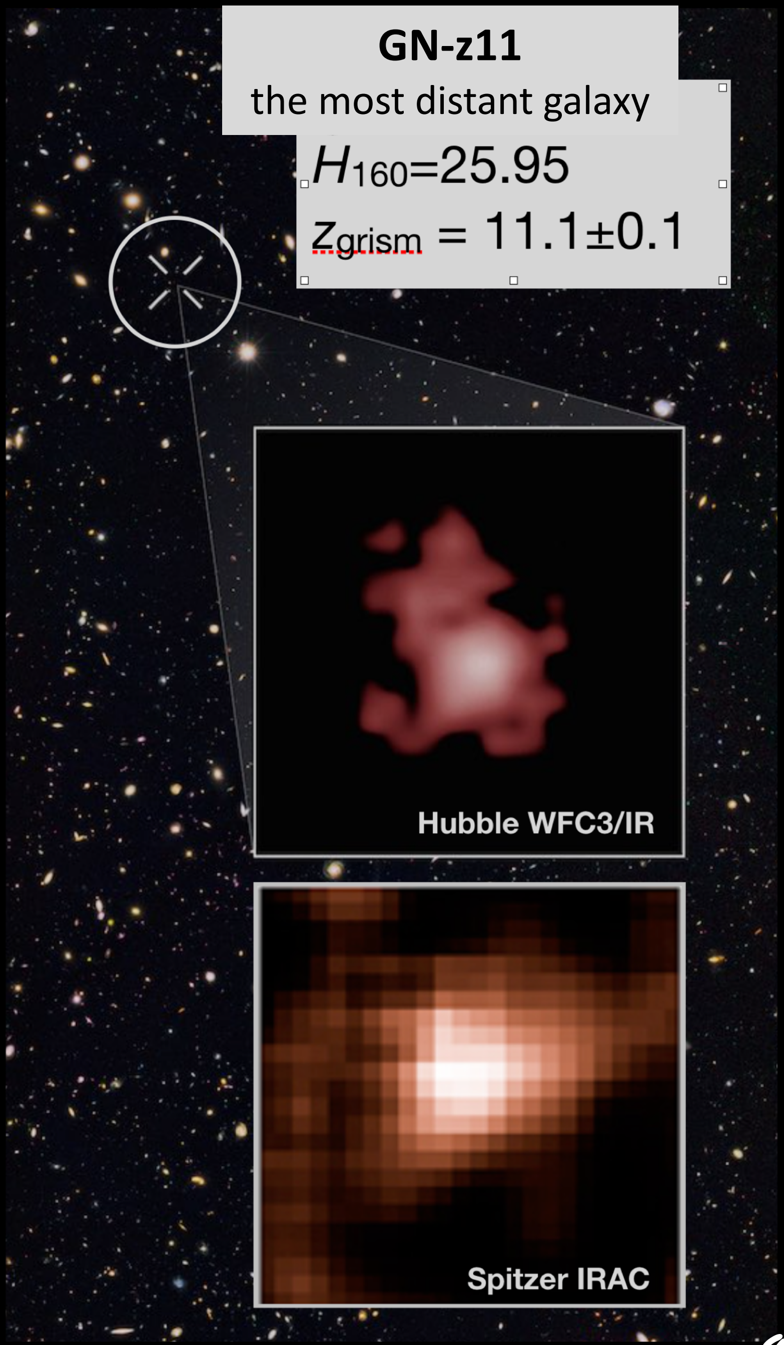
this is a crucial piece of information for how far back we might have to look to find "first galaxies"

gdi

while GN-z11 is not a "first galaxy", but GN-z11 is a pathfinder

the new 2018 Planck results show that reionization occurs almost entirely at $z<10$

GN-z11 thus provides a window into cosmic sunrise, before reionization occurs — an epoch we thought was inaccessible without JWST!



gdi

reionization history compared with observational astrophysical constraints

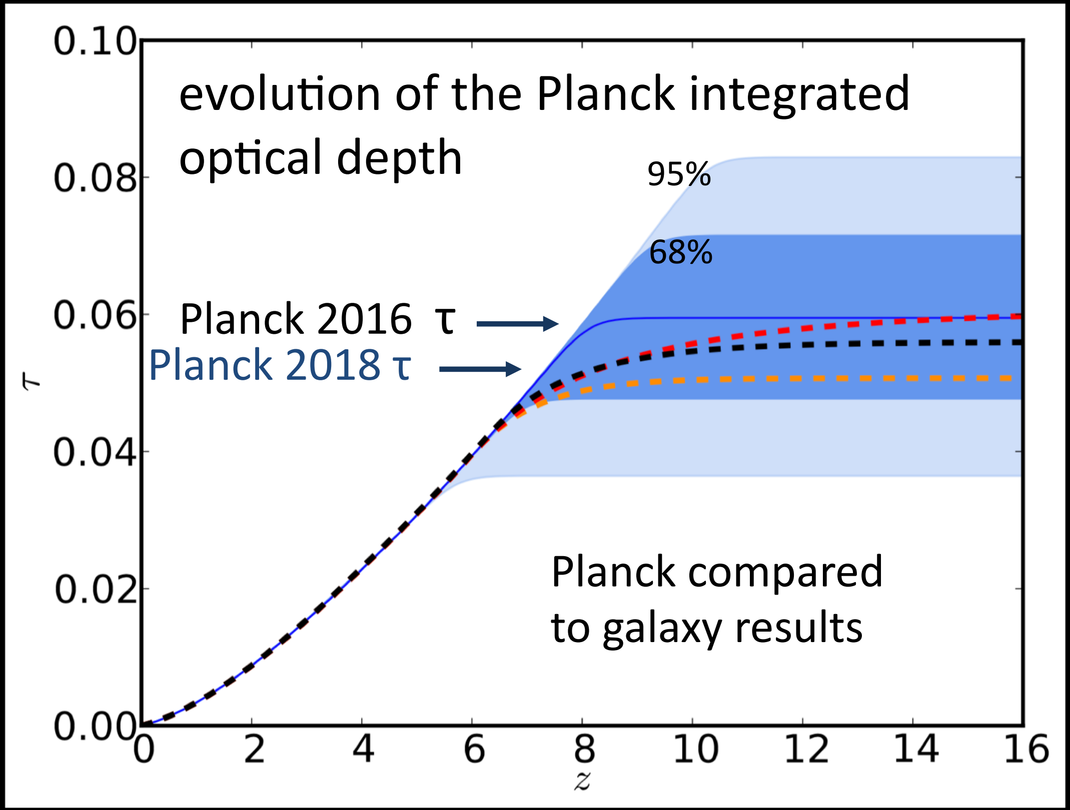
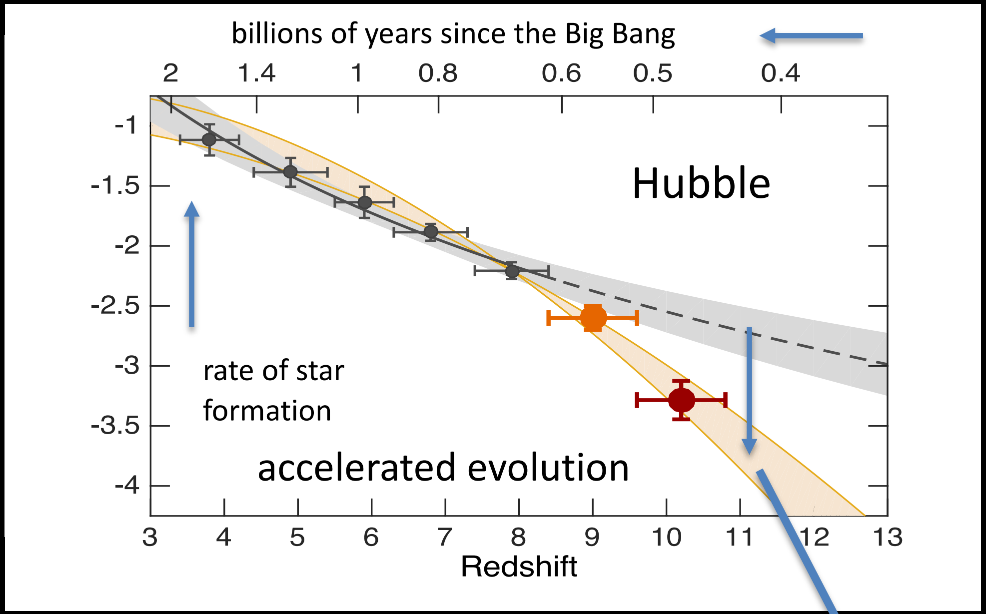


figure from Plank Collaboration XLVII + 2016

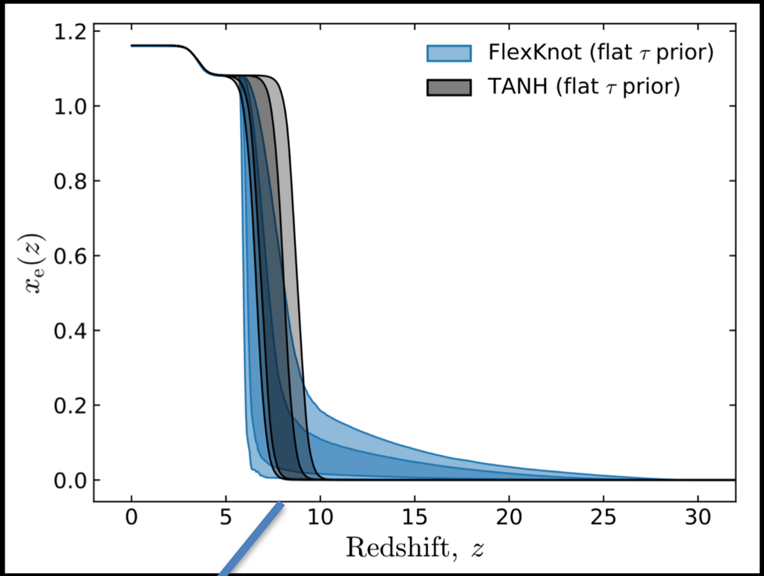
Bouwens+2015
Robertson+2015
Ishigaki+2015

striking consistency with Hubble results indicating that galaxies were responsible for reionization

gdi



can JWST see the "first galaxies"?



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

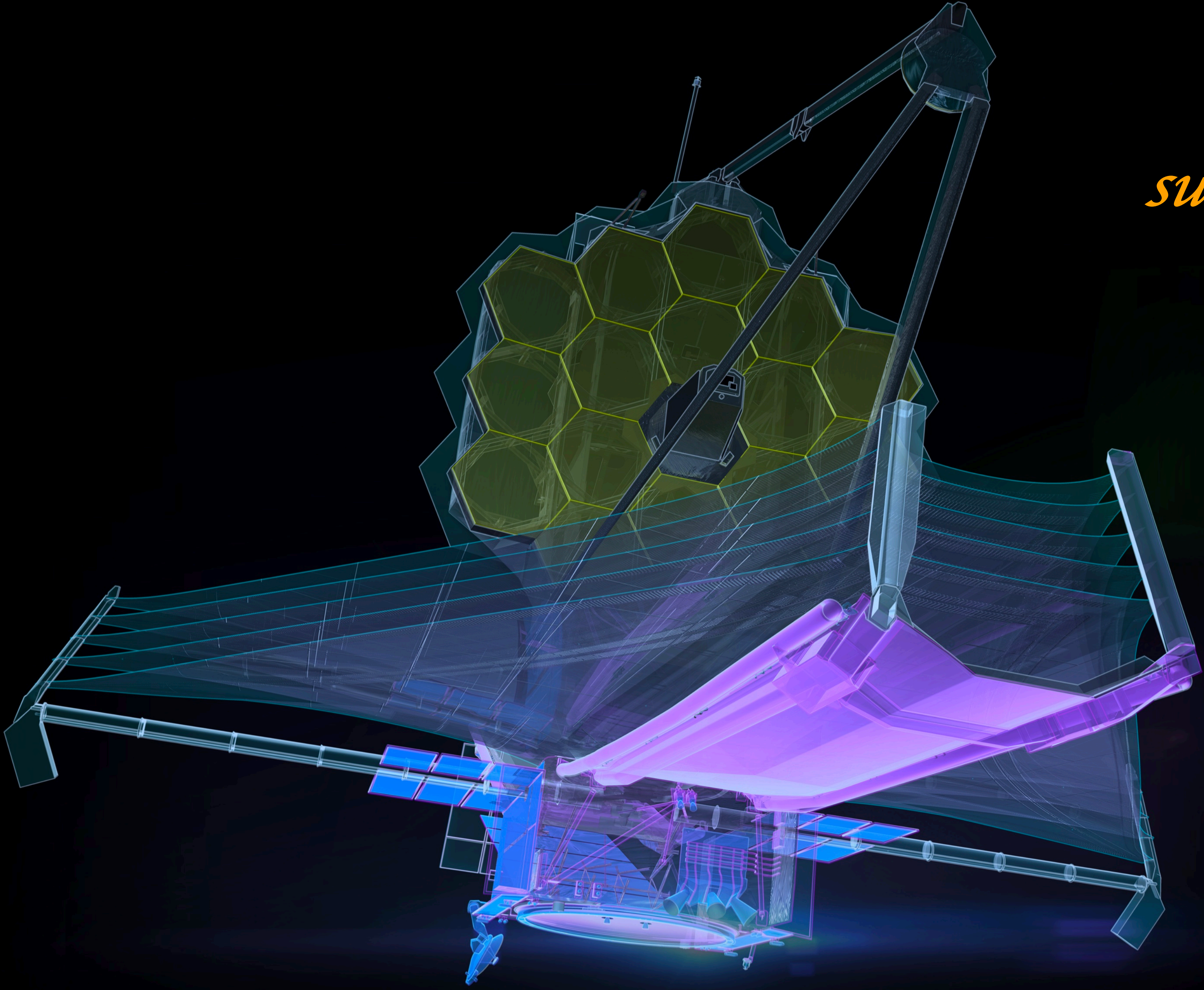
☛ suggest major changes in galaxy population at z~10-12-15 ☚

great for JWST's "first light" goal since galaxies are evolving rapidly at z~10-12-15
and JWST will be able to detect galaxies out to z~15

☞ JWST should reveal much about "Cosmic Sunrise"! ☜

gdi

our cosmic sunrise telescope



gdi

Cosmic Sunrise: Revealing the First Galaxies with JWST

figure credit: Adolf Schaller

firstgalaxies.org