INTO THE STARLIGHT:
The End of the Cosmic Dark Ages
March 3rd — 9th, 2019

Aspen Center for Physics
March 05 2019

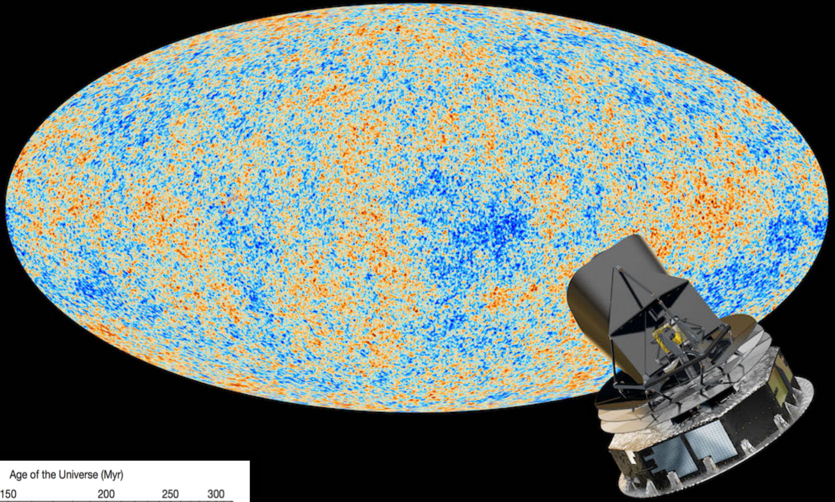
Revealing Cosmic Sunrise: Galaxy Build-up in the First 600 Myr

Garth Illingworth
University of California Santa Cruz

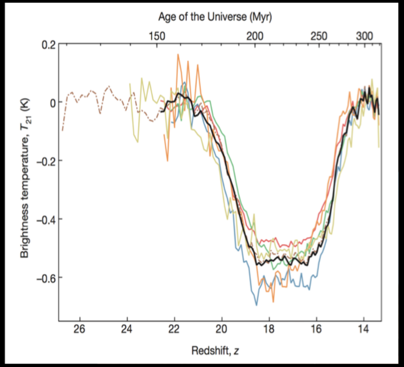
figure credit: Adolf Schaller

firstgalaxies.org

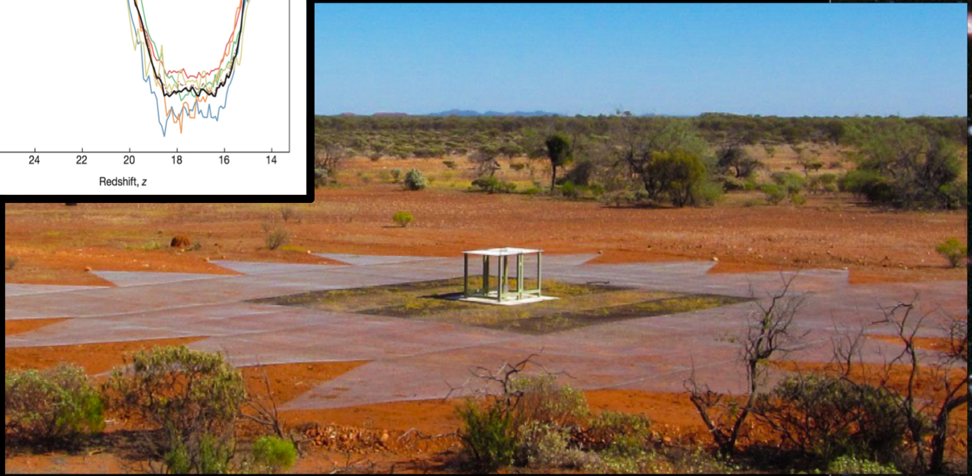
insight into the epoch of the first galaxies
– inspired by JWST "first light" goal

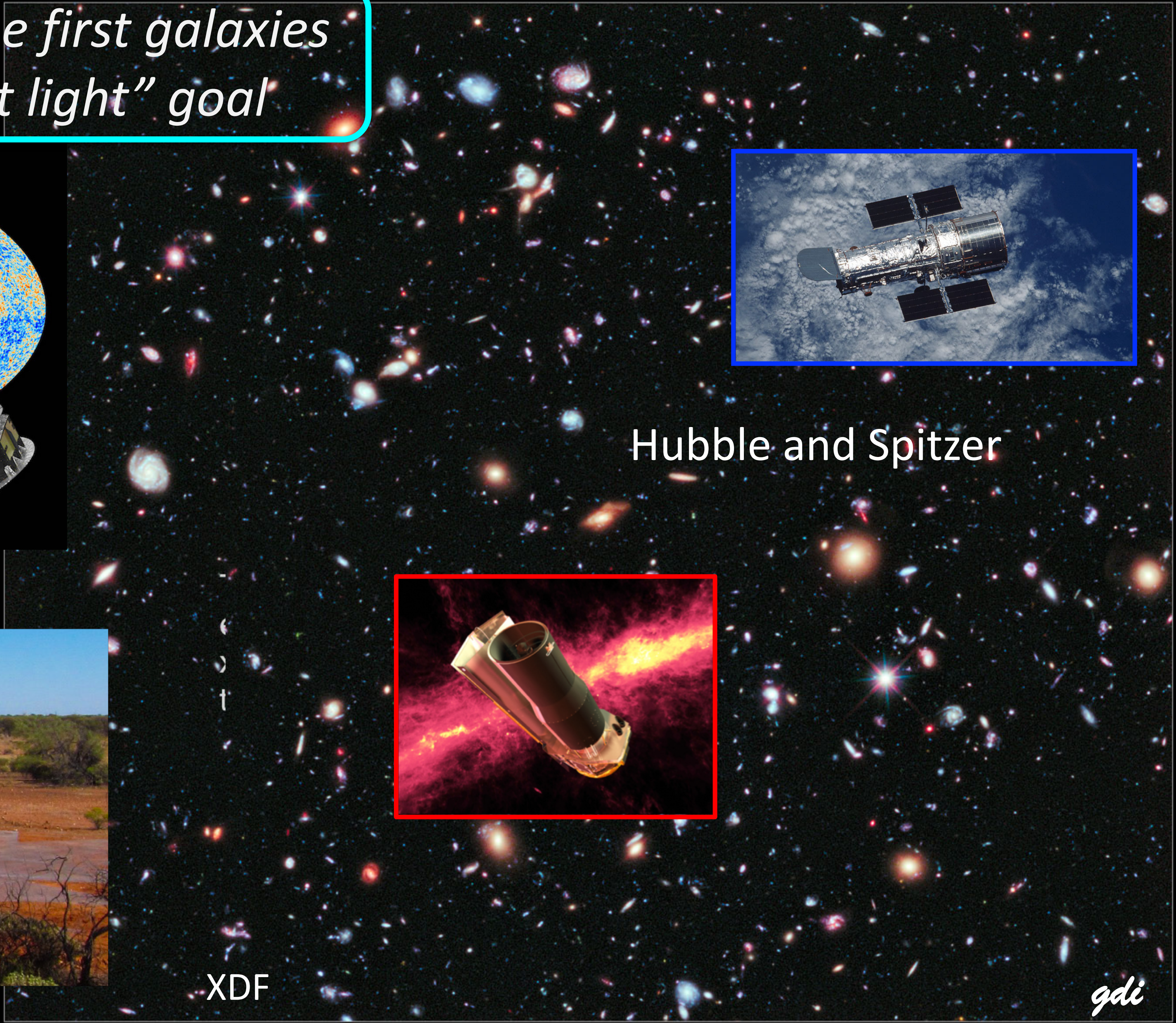


Planck



EDGES



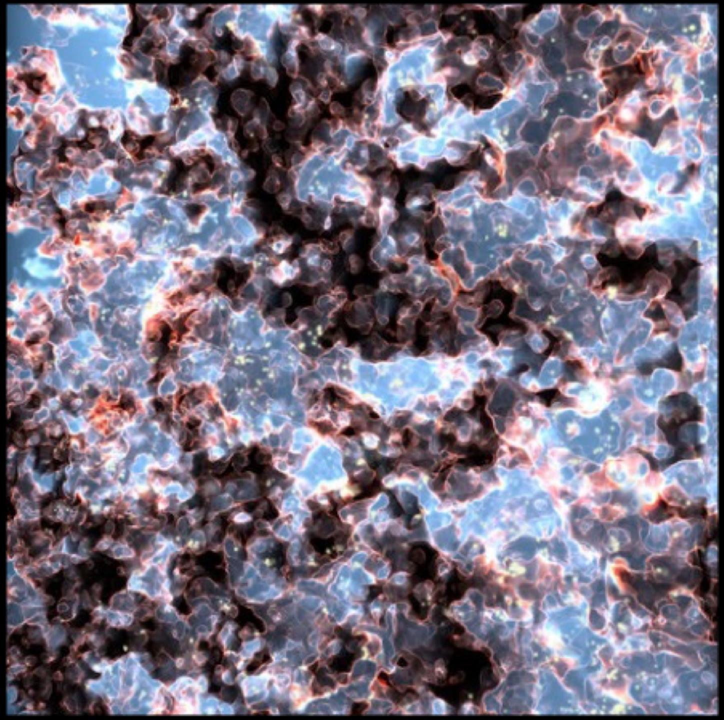


Hubble and Spitzer

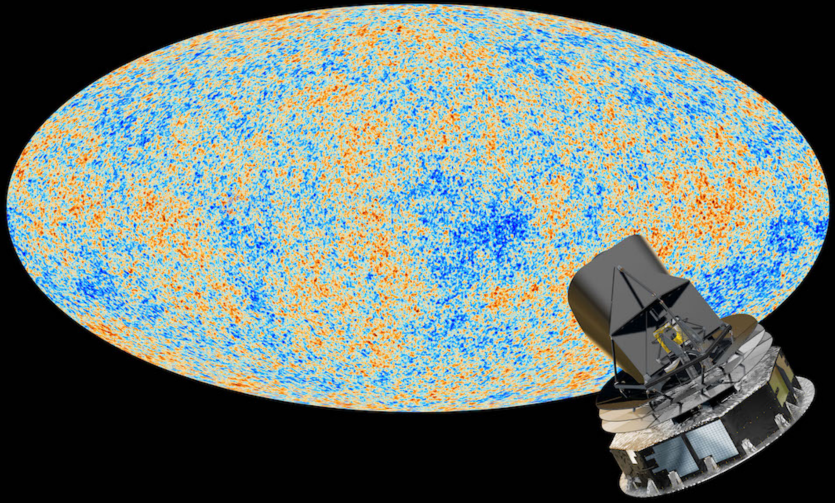
XDF

gdi

reionization epoch – Planck 2016/2018 results



reionization simulation: Alvarez et al. 2009



remarkable mission

gdi

Planck 2016/2018

constraints on the reionization history

…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 $\Delta z < 2.8$.

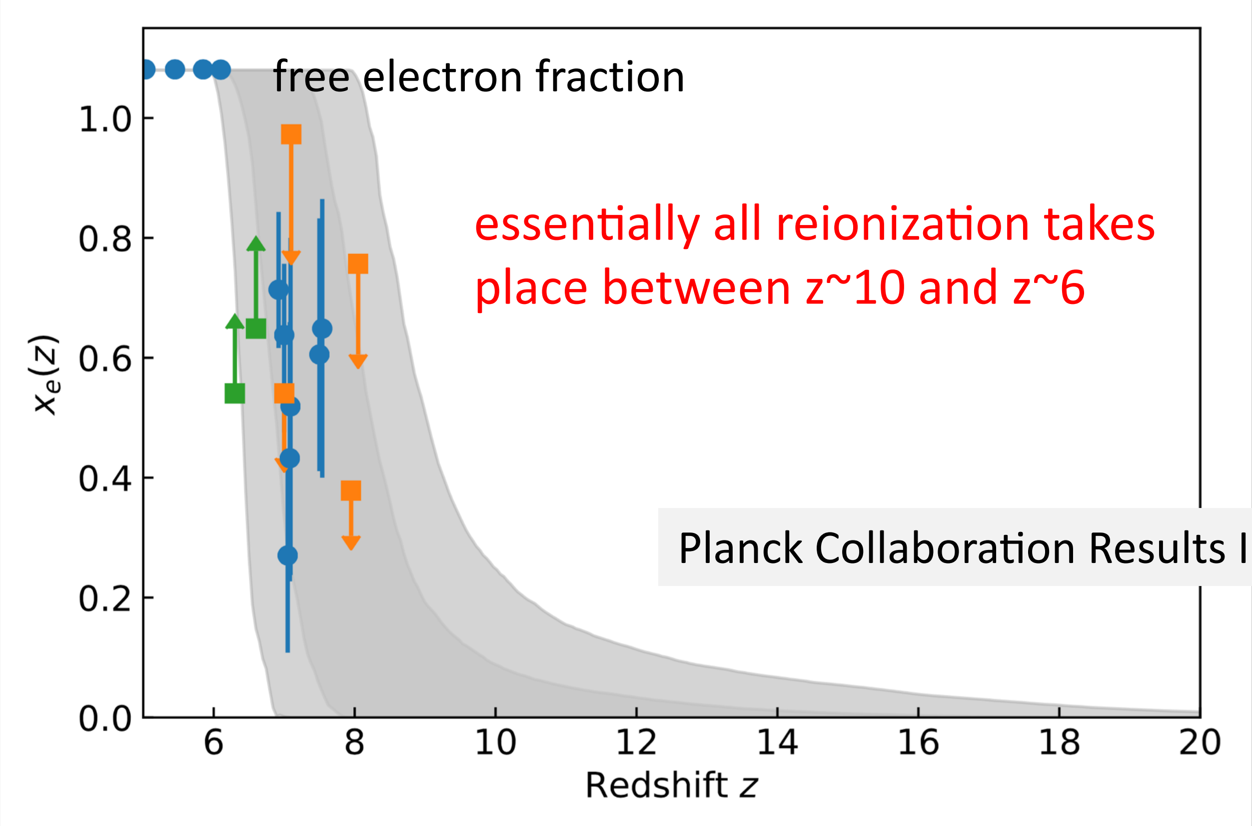
…the Universe is ionized at much less than the 10% level at redshifts above $z \simeq 10$…
(<1% above $z \simeq 15$)

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

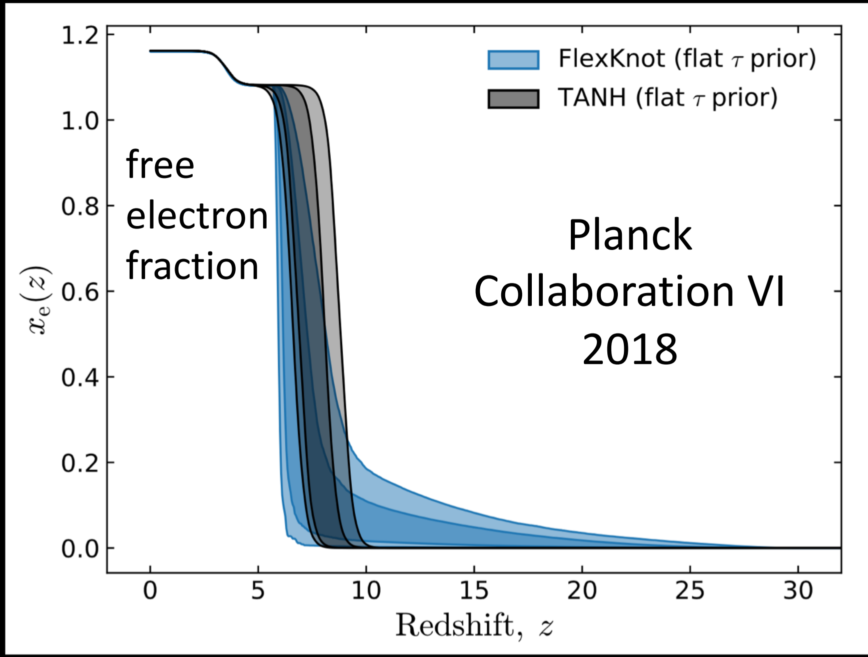
Planck Collaboration XLVII + 2016
Planck Results VI Cosmological Parameters + 2018
Planck Results I Overview and Legacy + 2018

gdi

reionization constraints from Planck 2018



Planck Collaboration Results I + 2018



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

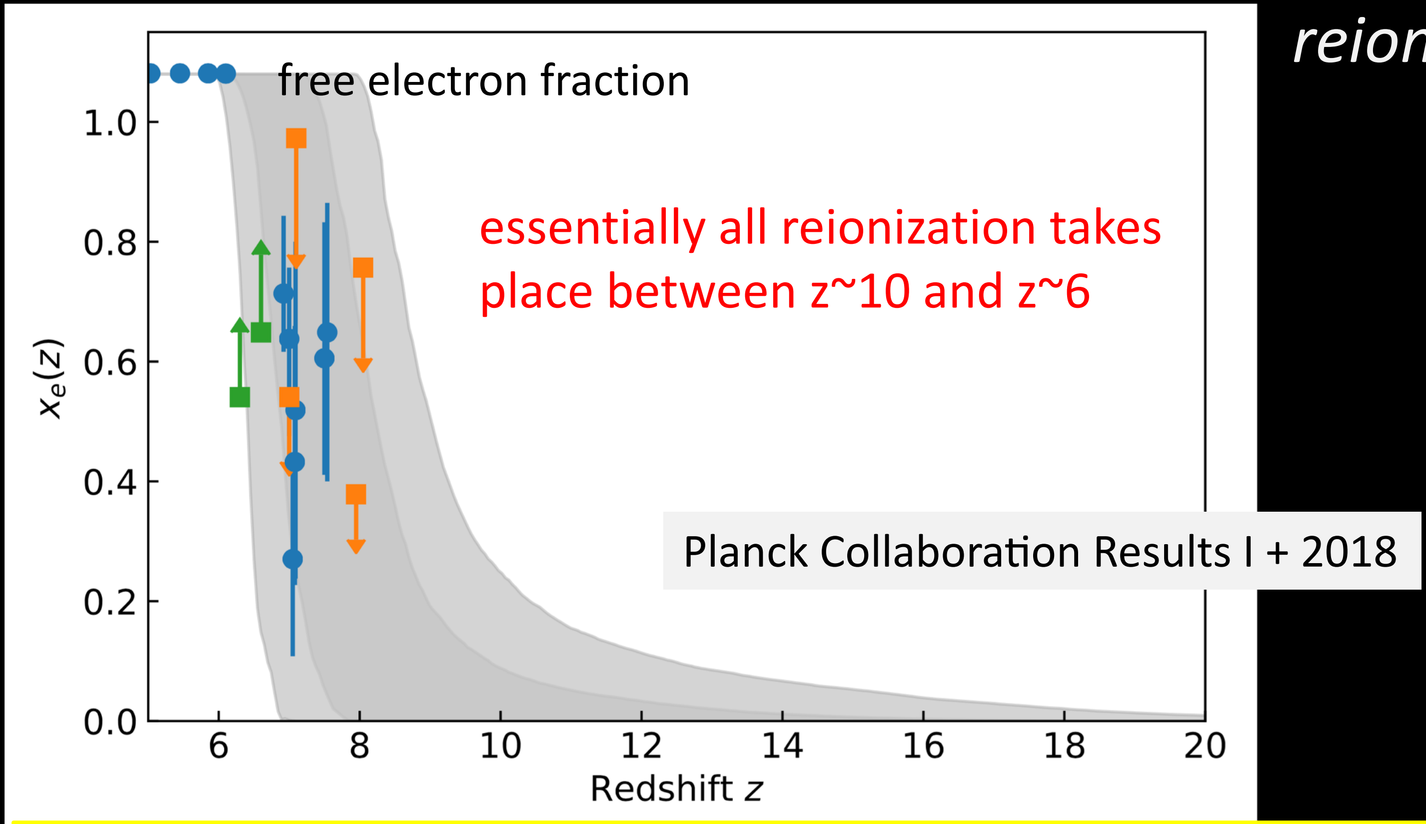
…the Universe is ionized at much less than the 10% level at redshifts above $z \simeq 10$… (<1% above $z \simeq 15$).

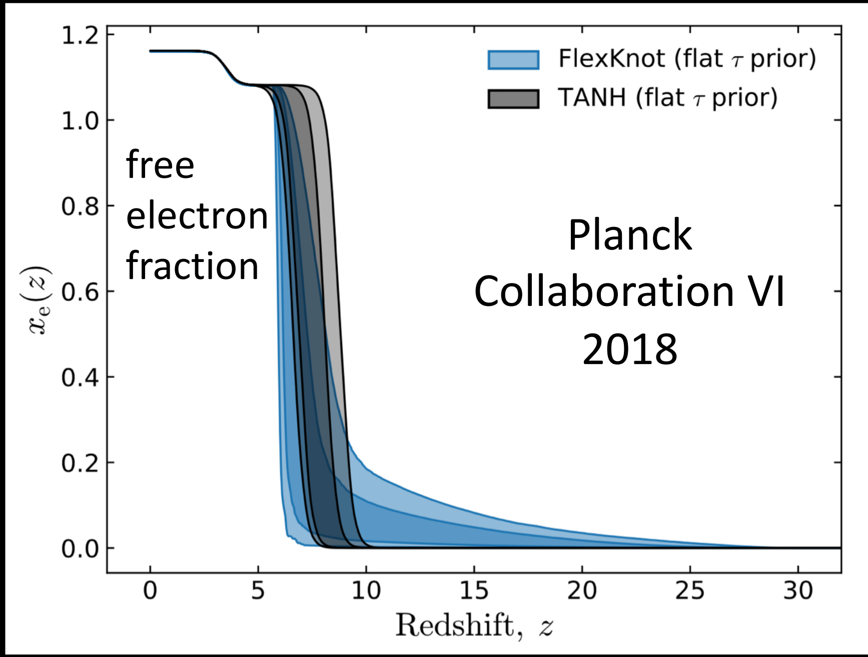
….non-standard early galaxies or significantly evolving escape and clumping factors are no longer required.

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

gdi

reionization constraints from Planck 2018





we now know when
galaxies really began to reionize the universe (at z<10)

this is a crucial piece of information re the epoch of the first galaxies

gdi

reionization history compared with observational astrophysical constraints

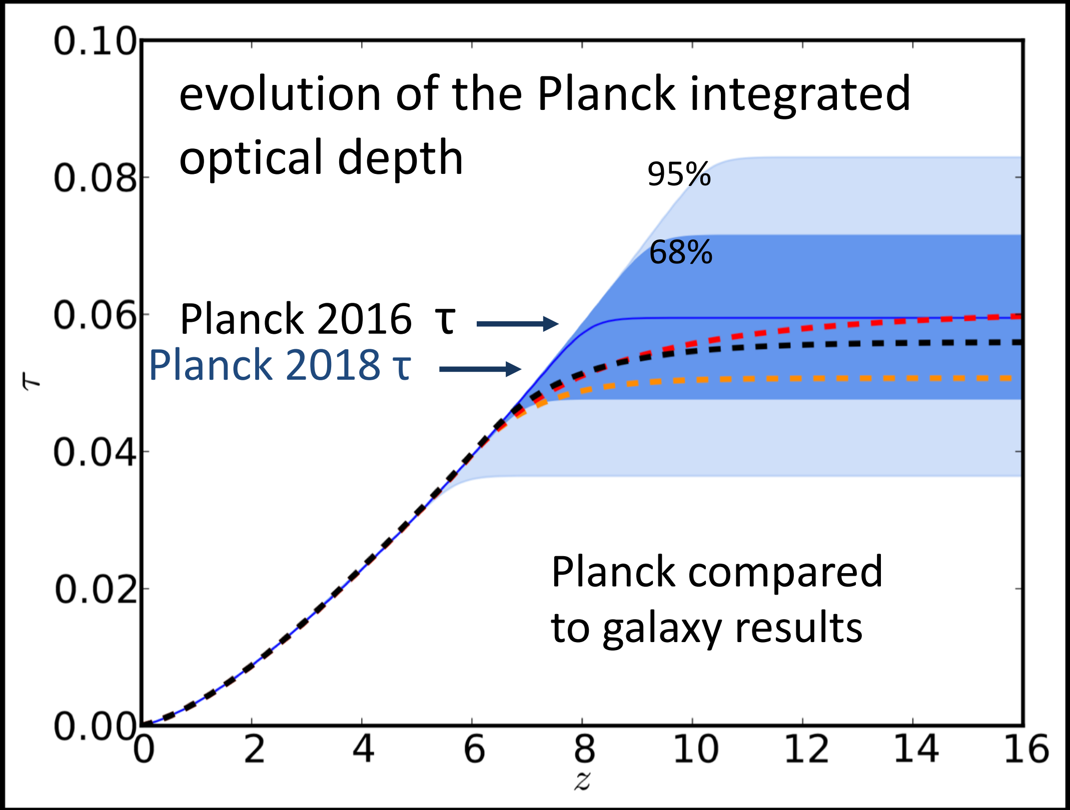


figure from Planck Collaboration XLVII + 2016

Bouwens+2015

Robertson+2015

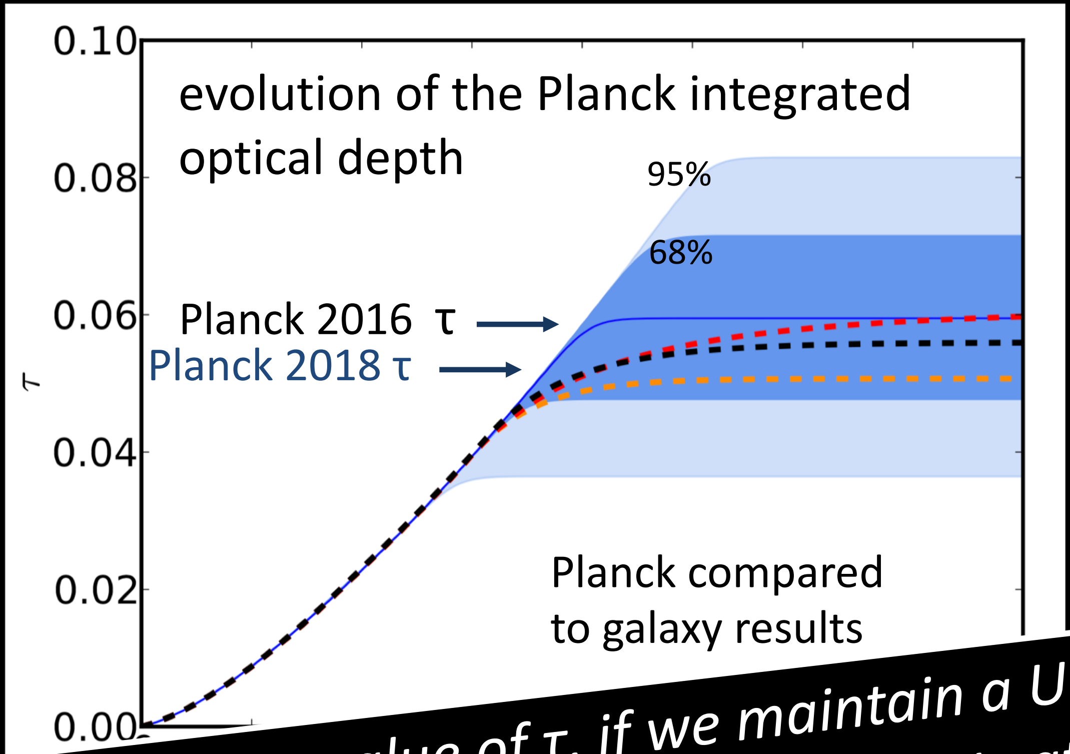
Ishigaki+2015

striking consistency with Hubble results

indicates that galaxies were responsible for reionization

gdi

reionization history compared with observational astrophysical constraints



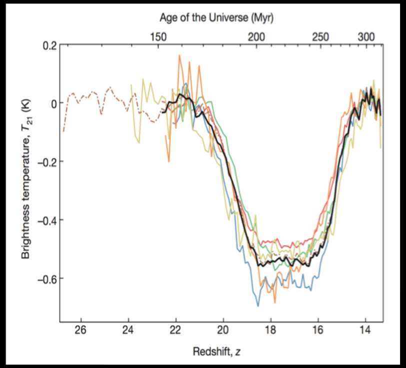
Bouwens+2015
Robertson+2015
Ishigaki+2015

"With the present value of τ, if we maintain a UV-luminosity density at the maximum level allowed by the luminosity density constraints at redshifts z < 9, then the currently observed galaxy population at $M_{UV} < -17$ seems to be sufficient to comply with all the observational constraints without the need for high-redshift (z = 10–15) galaxies."

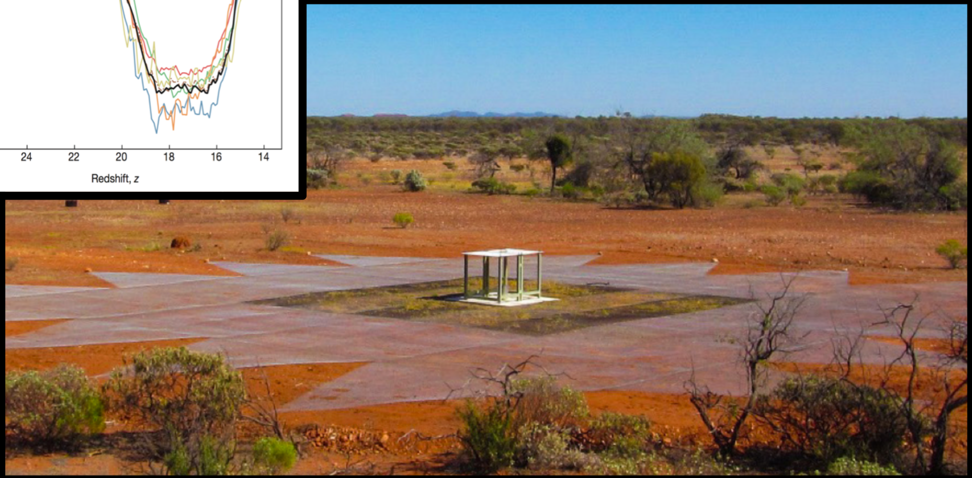
Planck intermediate results XLVII. Planck constraints on reionization history 2016

gdi

when did the “first stars” appear?



EDGES



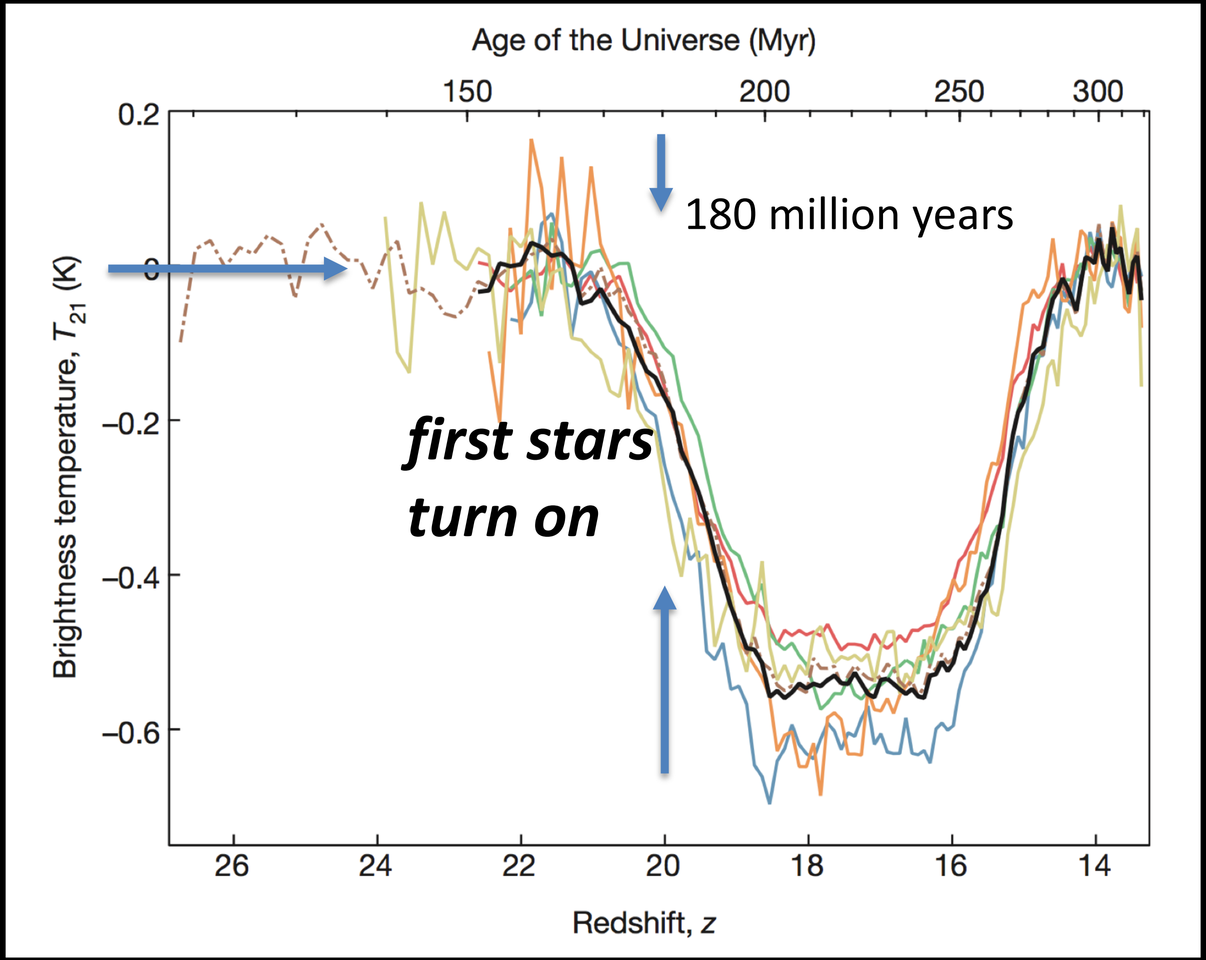
gdi


EDGES:
Experiment to Detect the Global Epoch of Reionization Signature
EDGES low-1 antenna
Murchison Radio-Astronomy Observatory (MRO)
gdi

timing 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

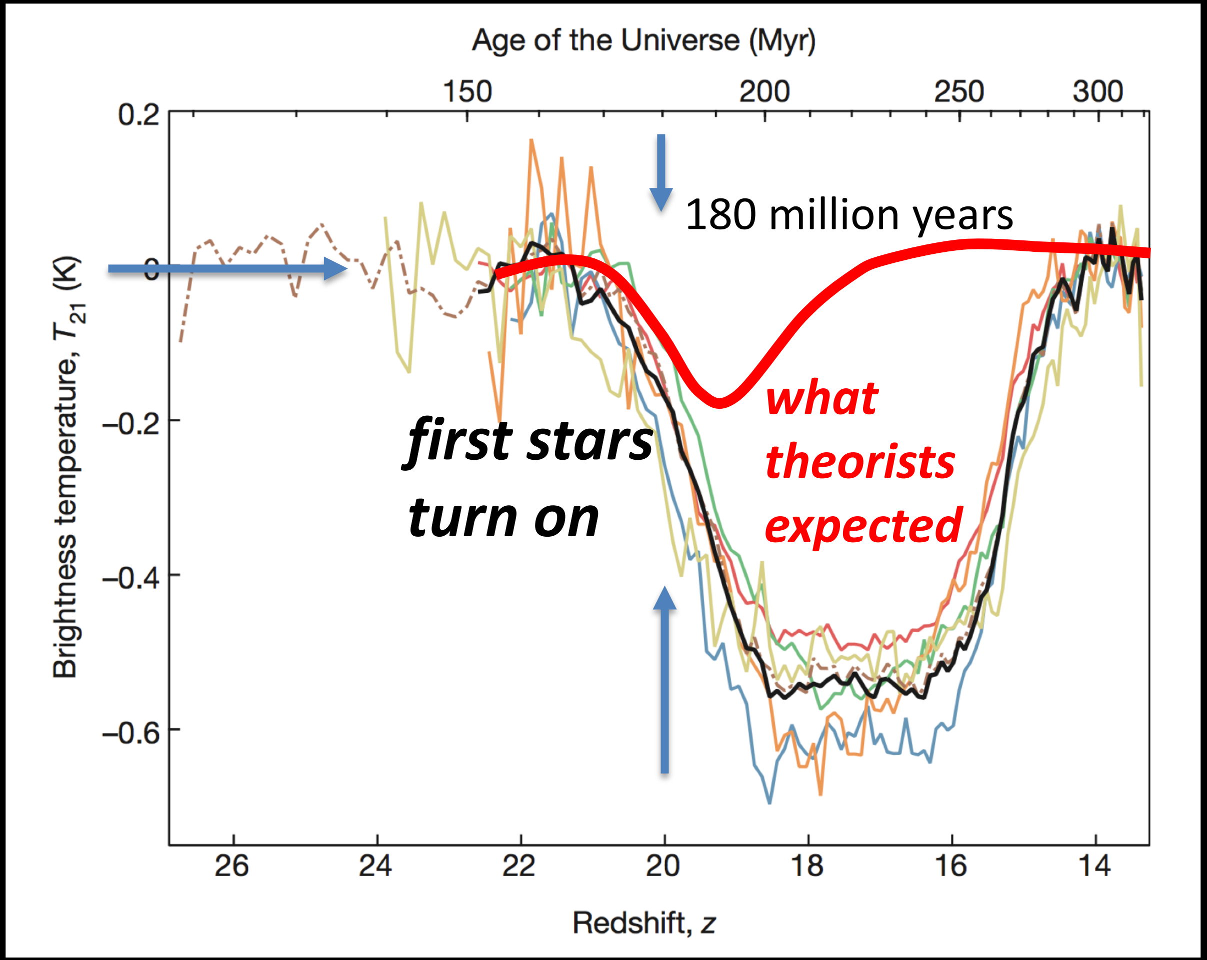
timing the "first stars"

is this result correct?

confirmation?
extraordinary impact
=> needs extraordinary confirmation efforts

implications:
(new physics – dark matter interactions; early radio sources)?

cosmic microwave background



?

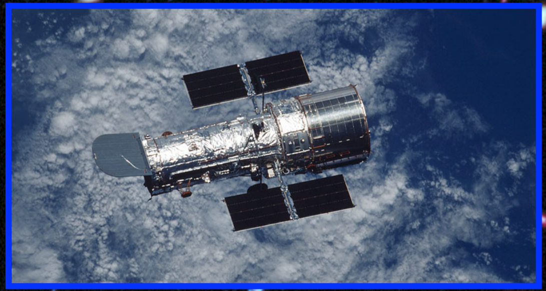
EDGES: first stars become prominent at redshift z~20 (~180 million years)

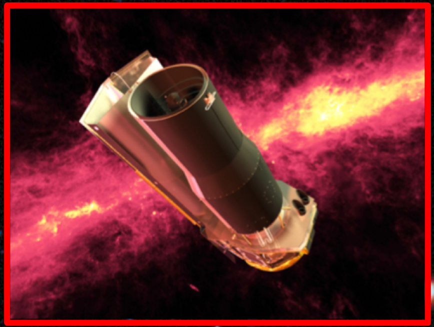
Bowman+2018

gdi

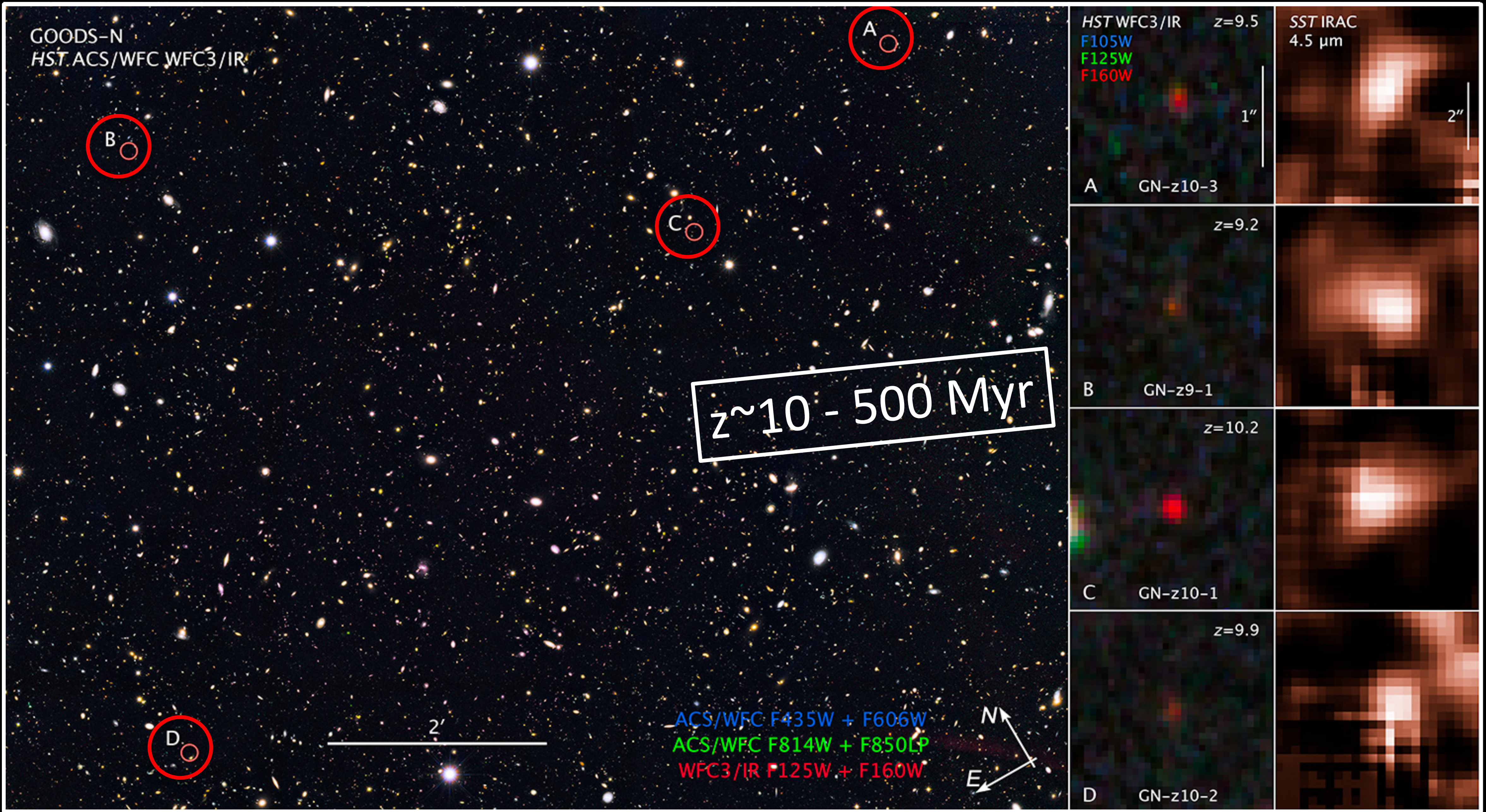
what constraints do we have on the first galaxies?

searching for the earliest galaxies





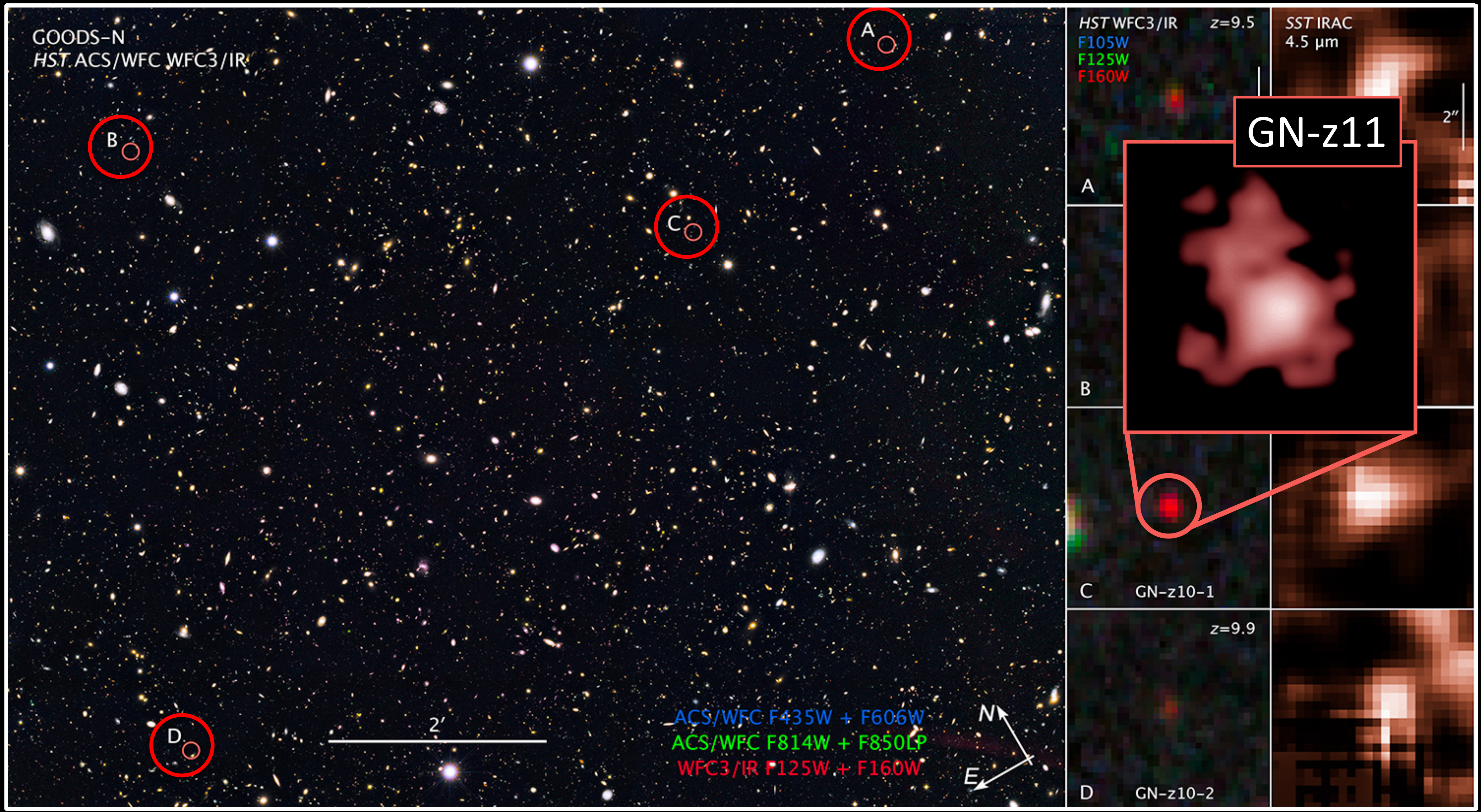
gdi



Oesch + 2014

Hubble Spitzer

gdi



Oesch + 2014, 2016

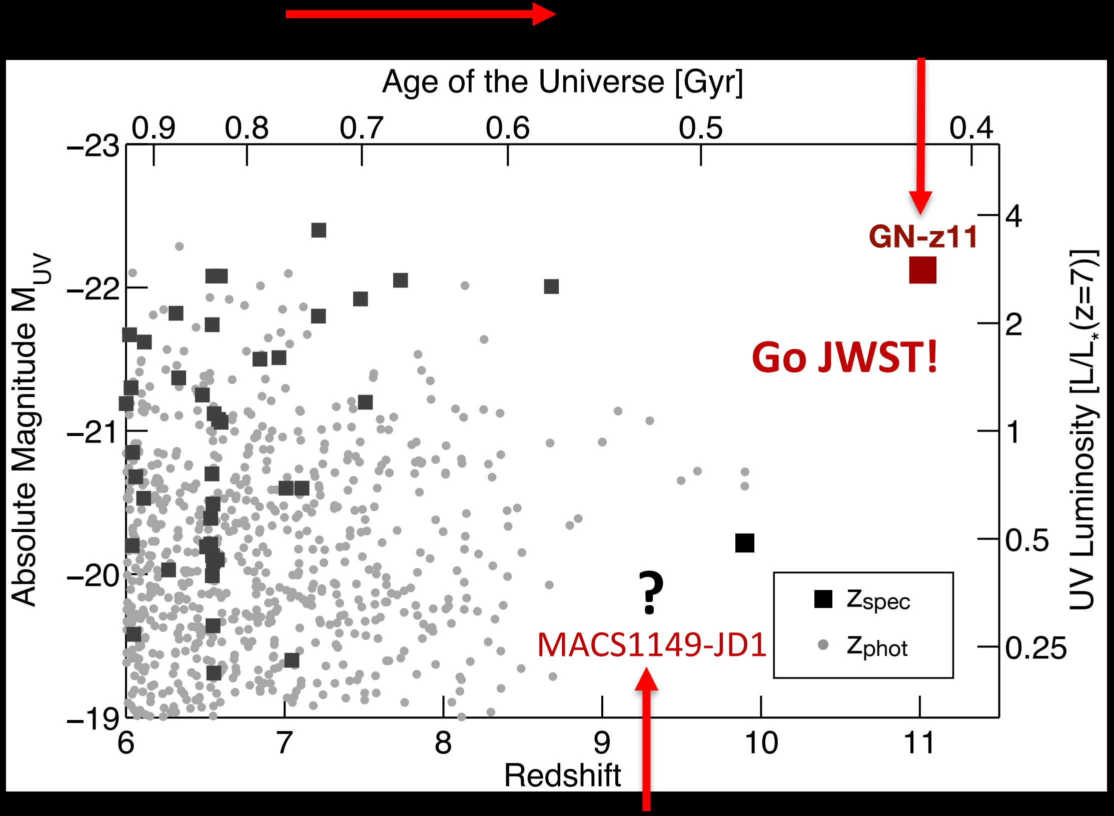
Hubble Spitzer

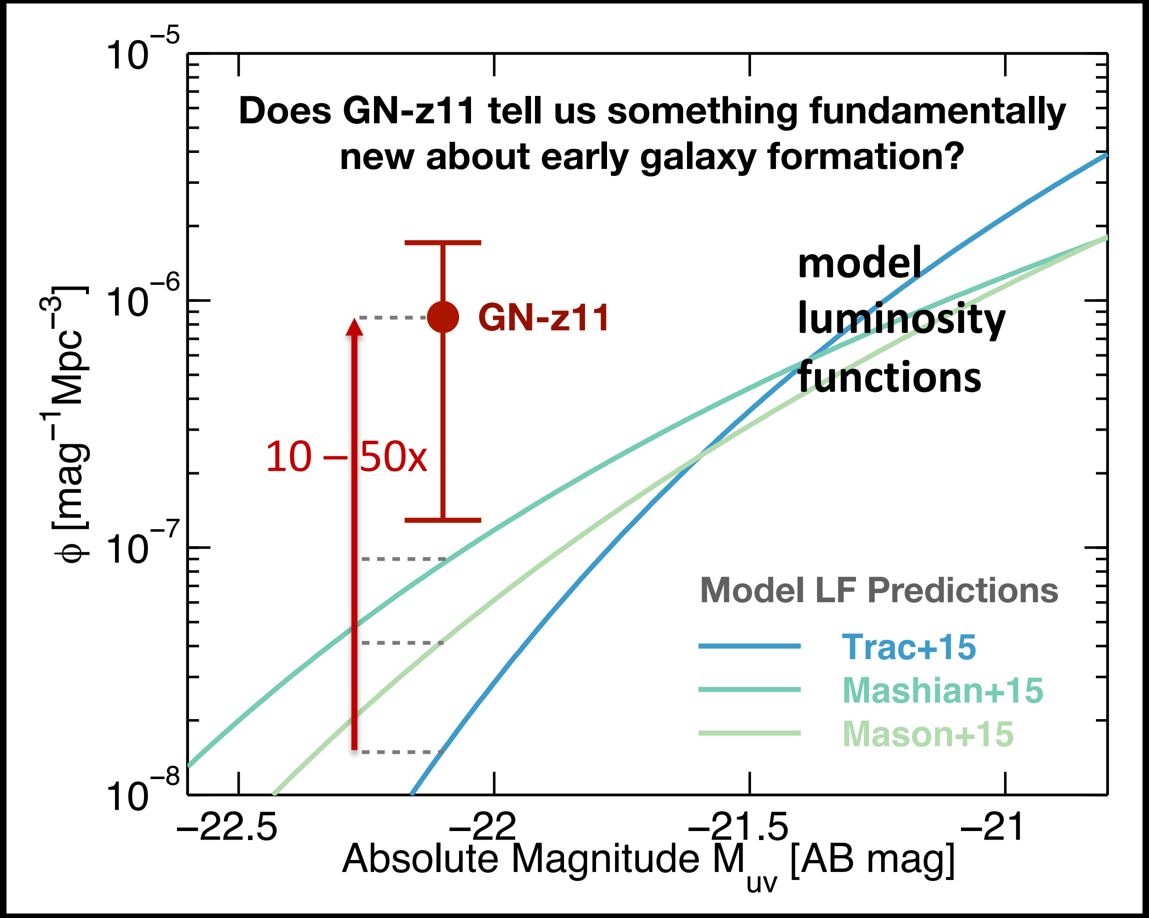
gdi

the most distant galaxy found to date

surprising discovery of GN-z11

sample of spectroscopic redshifts at z>7 still <20 galaxies





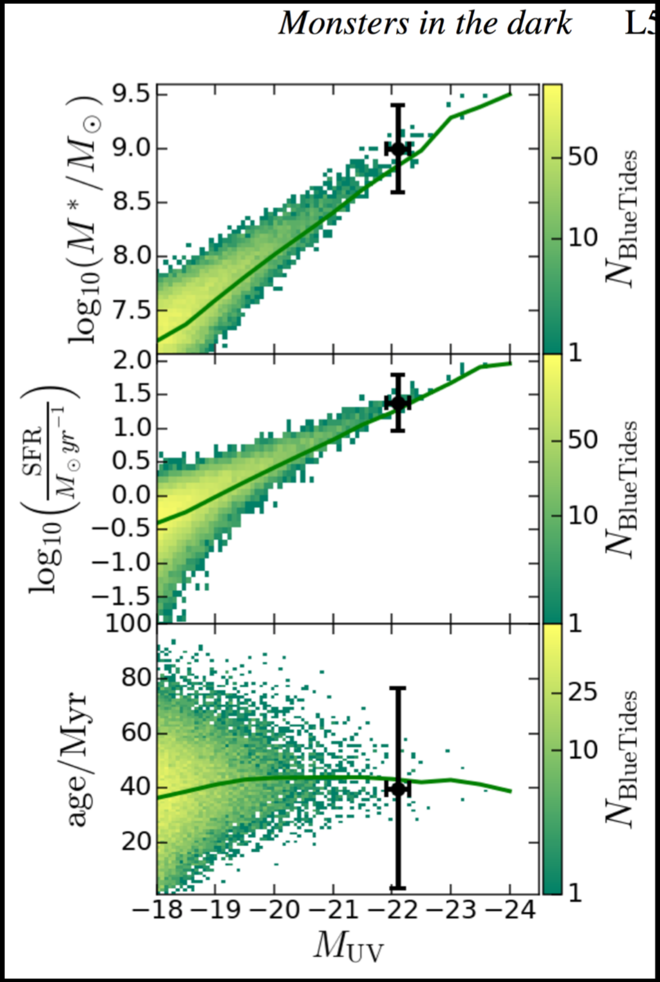
Oesch+2016

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*

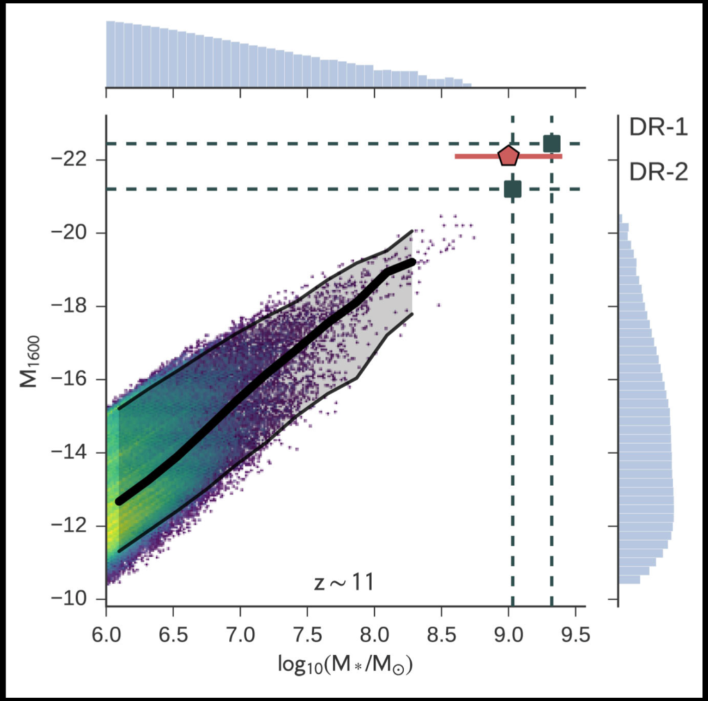


BlueTides Waters+2016

GN-z11 observed properties

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

β -2.5 A_{UV} <0.2 mag age 40 Myr

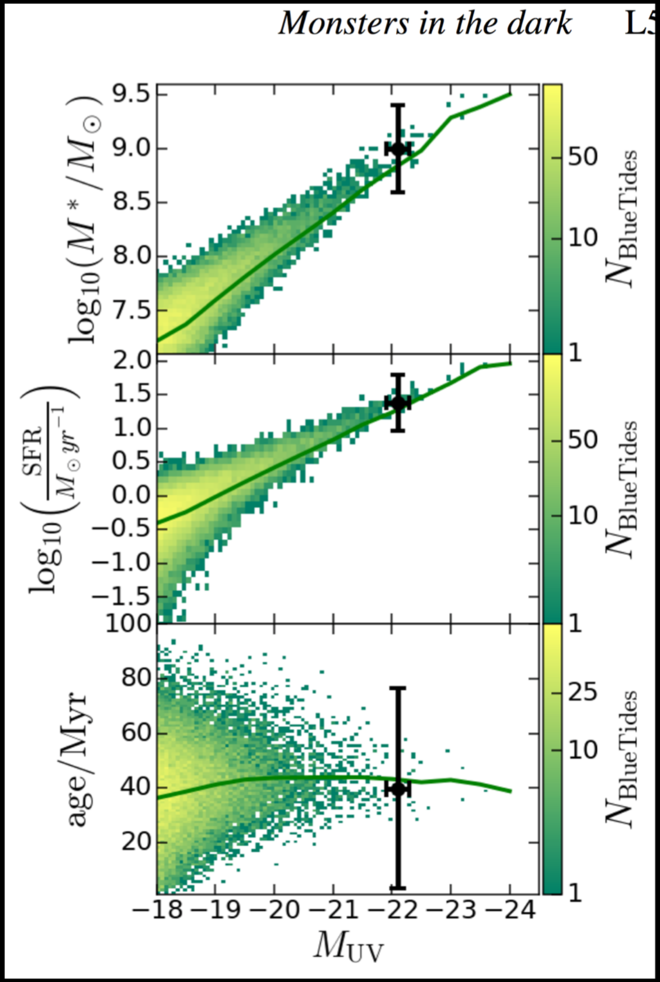


Mutch+2016 DRAGONS

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

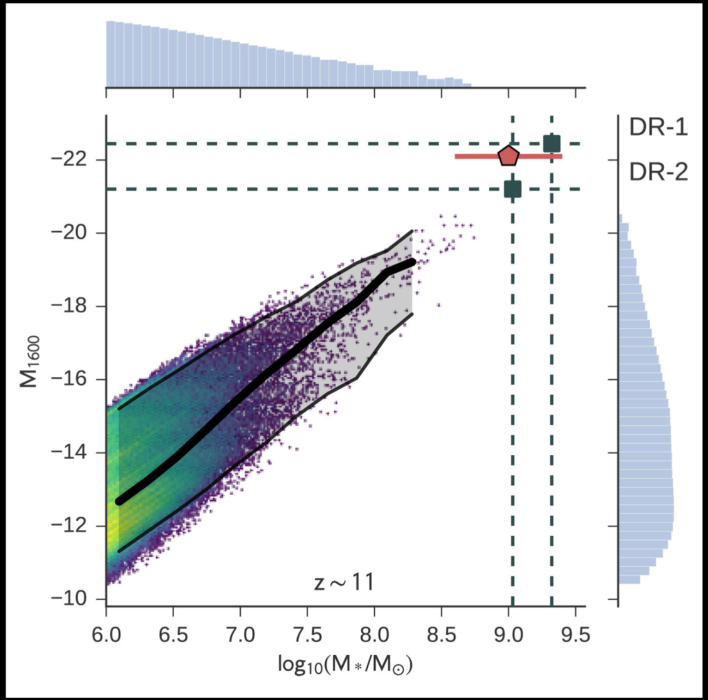
GN-z11 observed properties

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

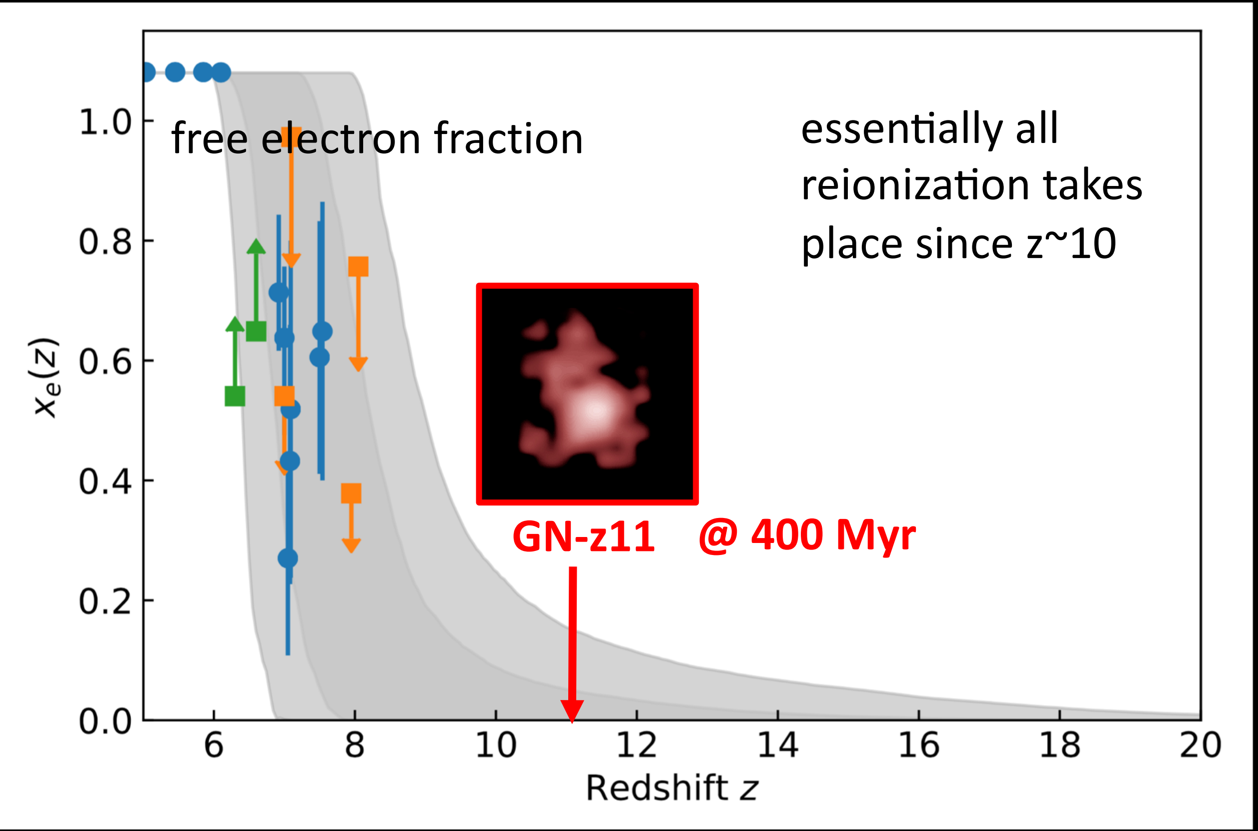
but it is unexpected to find GN-z11 in such small search volumes/areas (by factor 10-100)?



Mutch+2016 DRAGONS

gdi

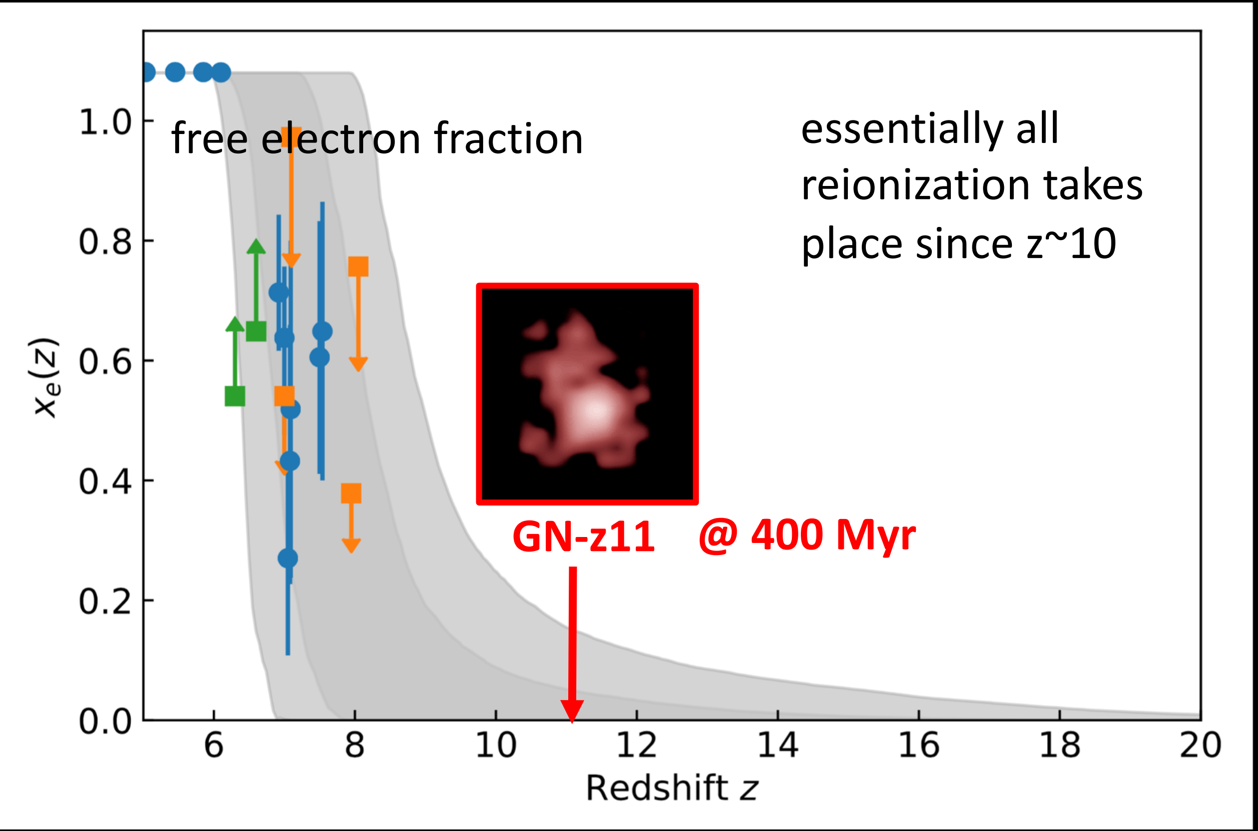
GN-z11 is a galaxy essentially in the pre-reionization epoch — an epoch we thought was inaccessible without JWST!



GN-z11 is a pathfinder for the earliest galaxies

Planck Collaboration Results I + 2018

GN-z11 is a galaxy essentially in the pre-reionization epoch — an epoch we thought was inaccessible without JWST!



Planck Collaboration Results I + 2018

GN-z11 is a pathfinder for the earliest galaxies

WFIRST

gdi

what constraints do we have on the first galaxies?

searching for evidence of early star formation

gdi

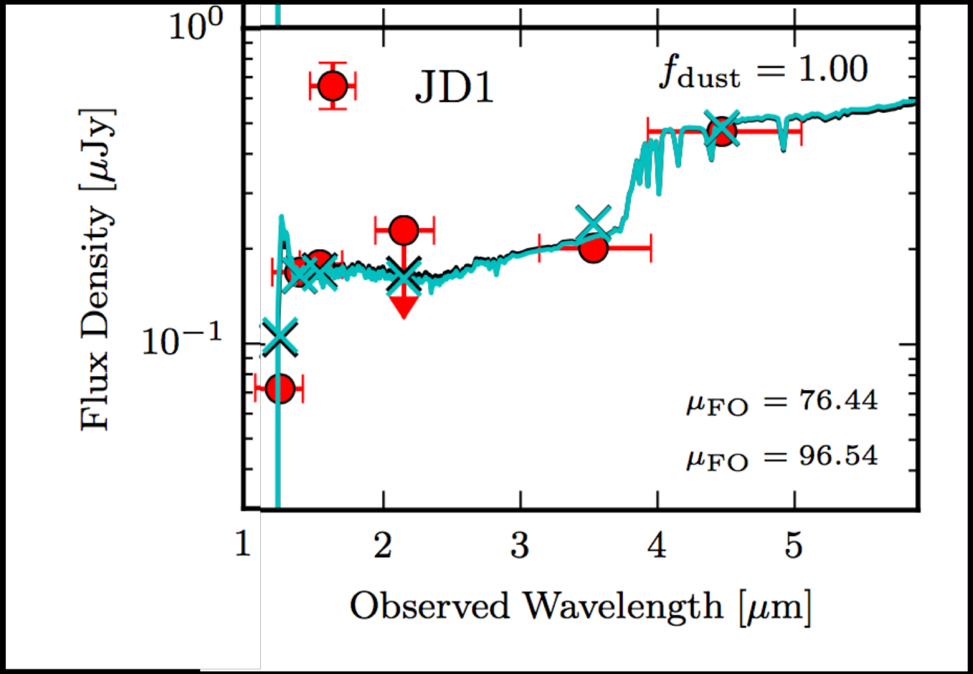
MACS1149–JD1

z=9.11 from ALMA [OIII]

Hashimoto et al (and Katz et al) show large IRAC break in JD1 SED
interpreted as a Balmer break, indicating
old population that formed 300 Myr earlier at z~15

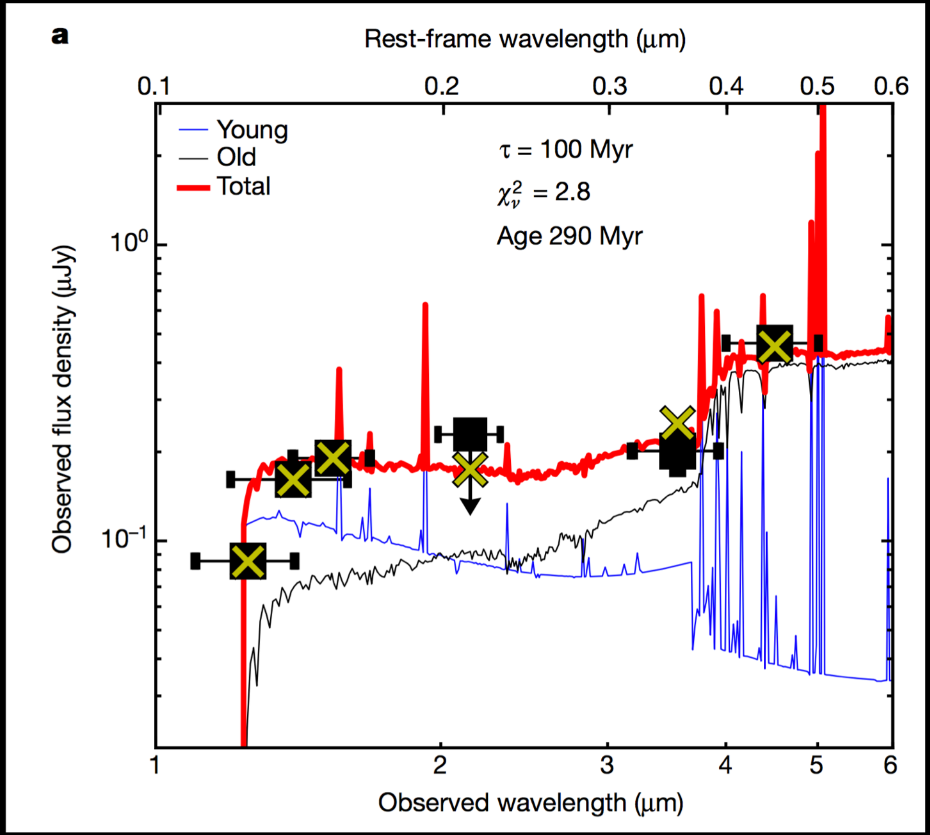
very puzzling since Balmer breaks are quite rare at somewhat lower redshifts – where samples are large

errors on the IRAC photometry are surprisingly small



single panel from Fig 9 – Katz+2019

IRAC color
3.6-4.5 = 0.91±0.18
from
Zheng et al 2017



Hashimoto+2018

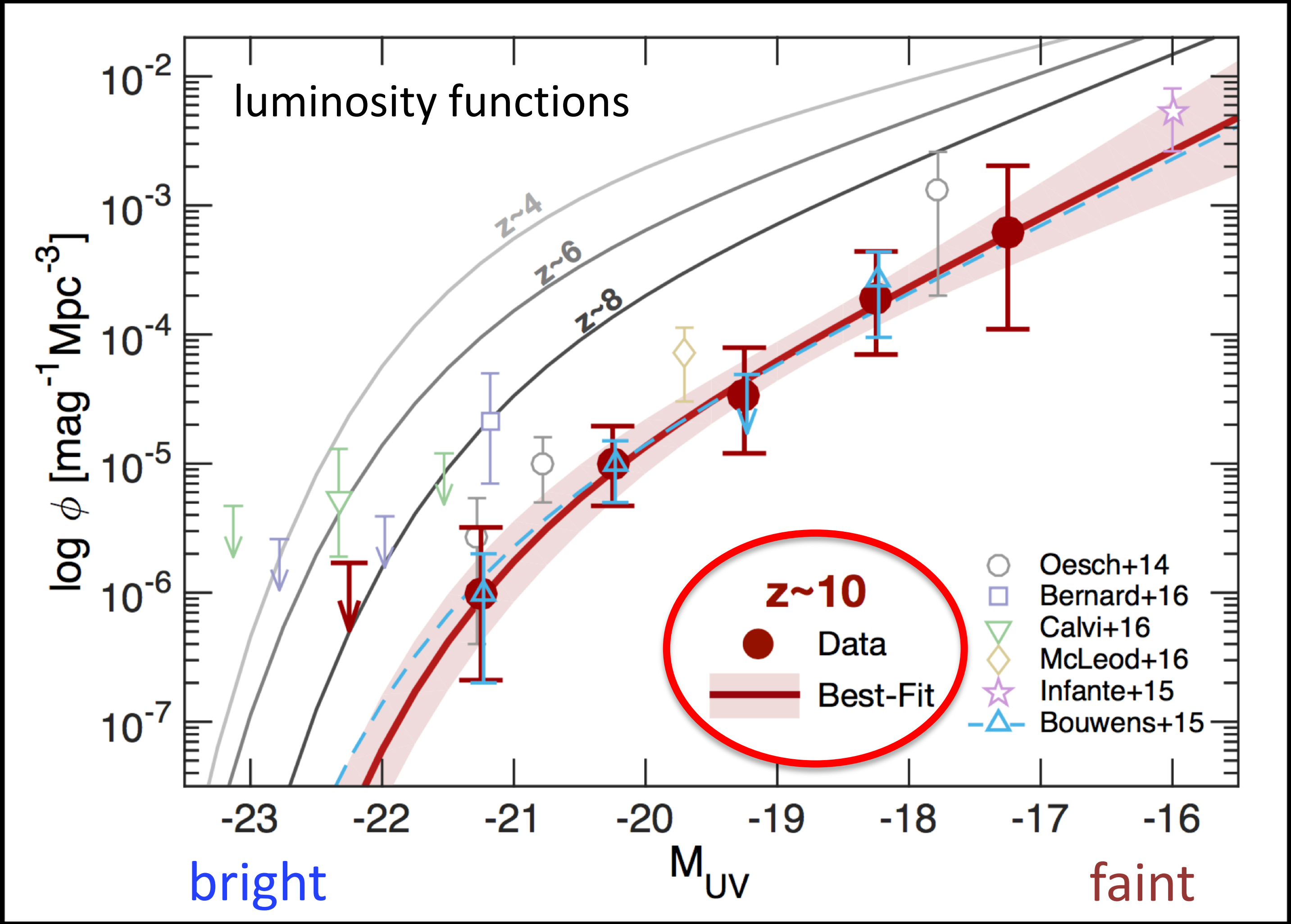
gdi

what constraints can Hubble and Spitzer put on the first galaxy epoch?

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

gdi

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



from 8 years of WFC3/IR imaging

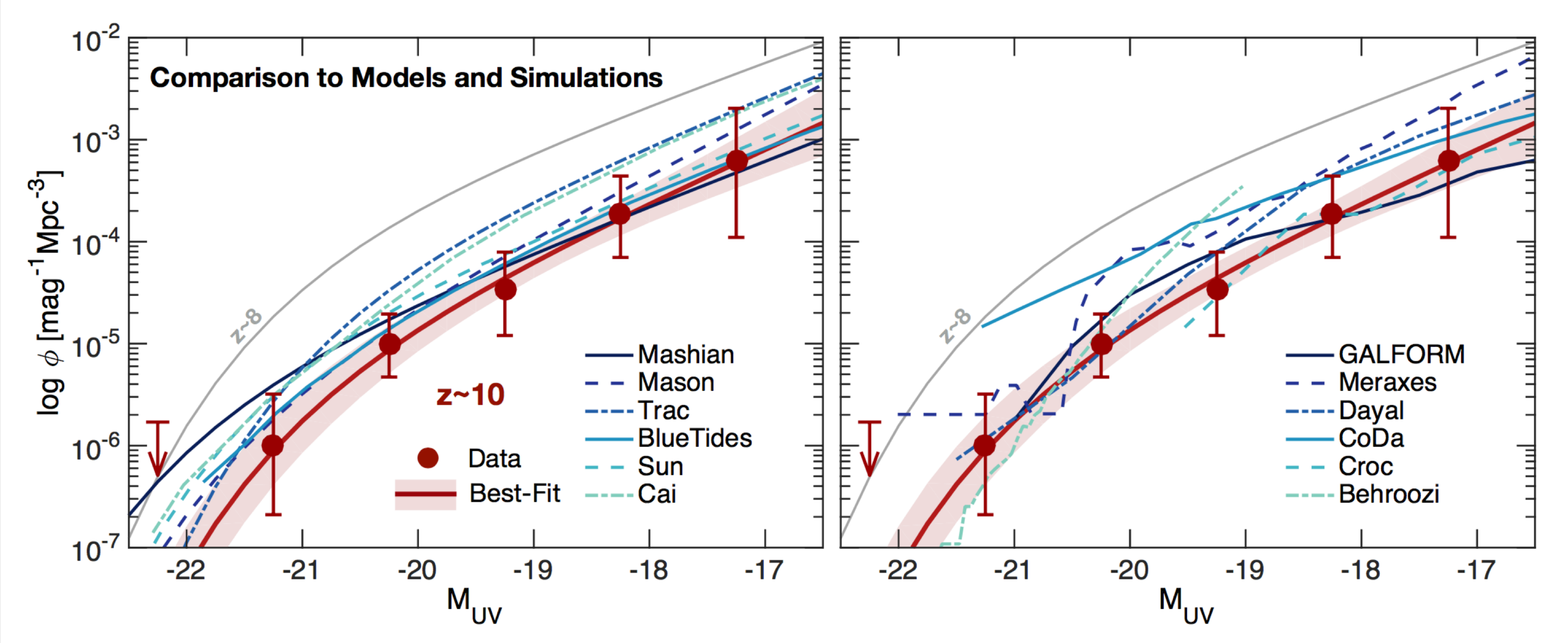
searched every WFC3/IR dataset but we find only 9 z~10 galaxies (at ~500 Myr)

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

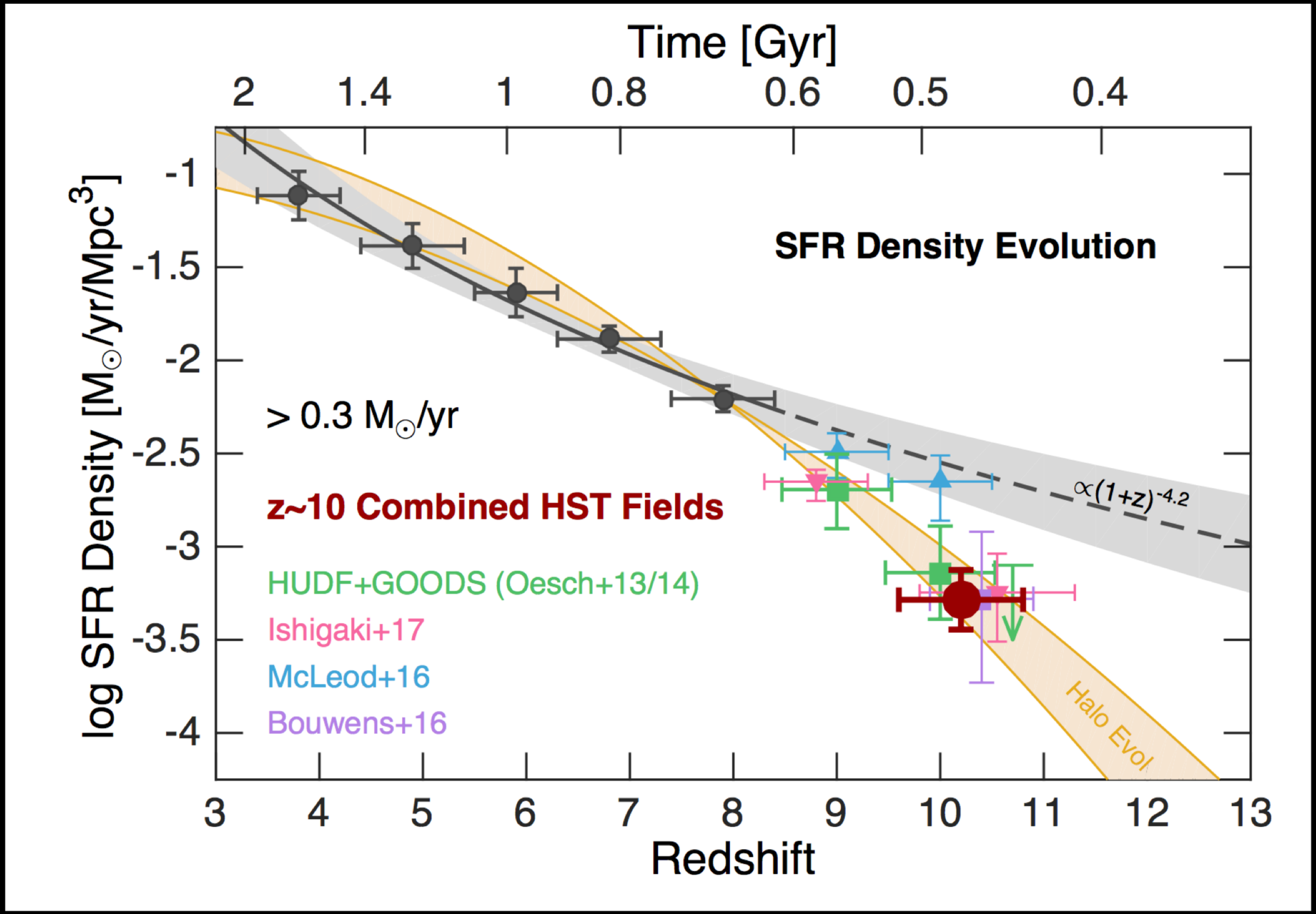
gdi

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

clearly a trend to lower SFRD at z>8 than initially expected

“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

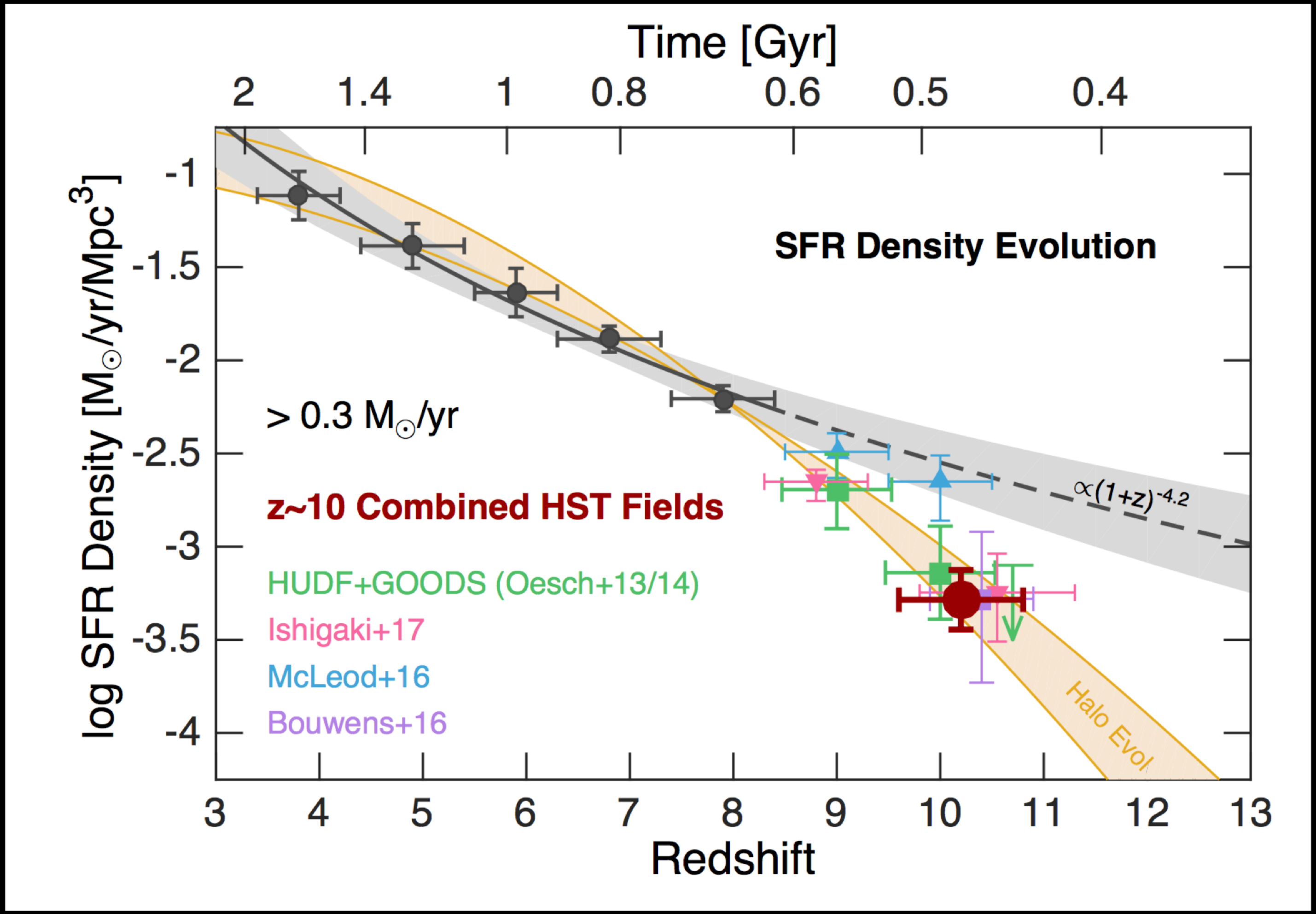
see also: Zheng+2012; Coe+2013; Bouwens+2013,15,16; Ellis+2013; McLure+2013; Ishigaki+2014,17; Infante+2015; Bernard+2016; Calvi+2016; McLeod+2016

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

clearly a trend to lower SFRD at z>8 than initially expected

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

Note: this result also indicates that the star formation efficiency (SFE) does not evolve significantly with cosmic time at z>6



Oesch+2013,2014,2017

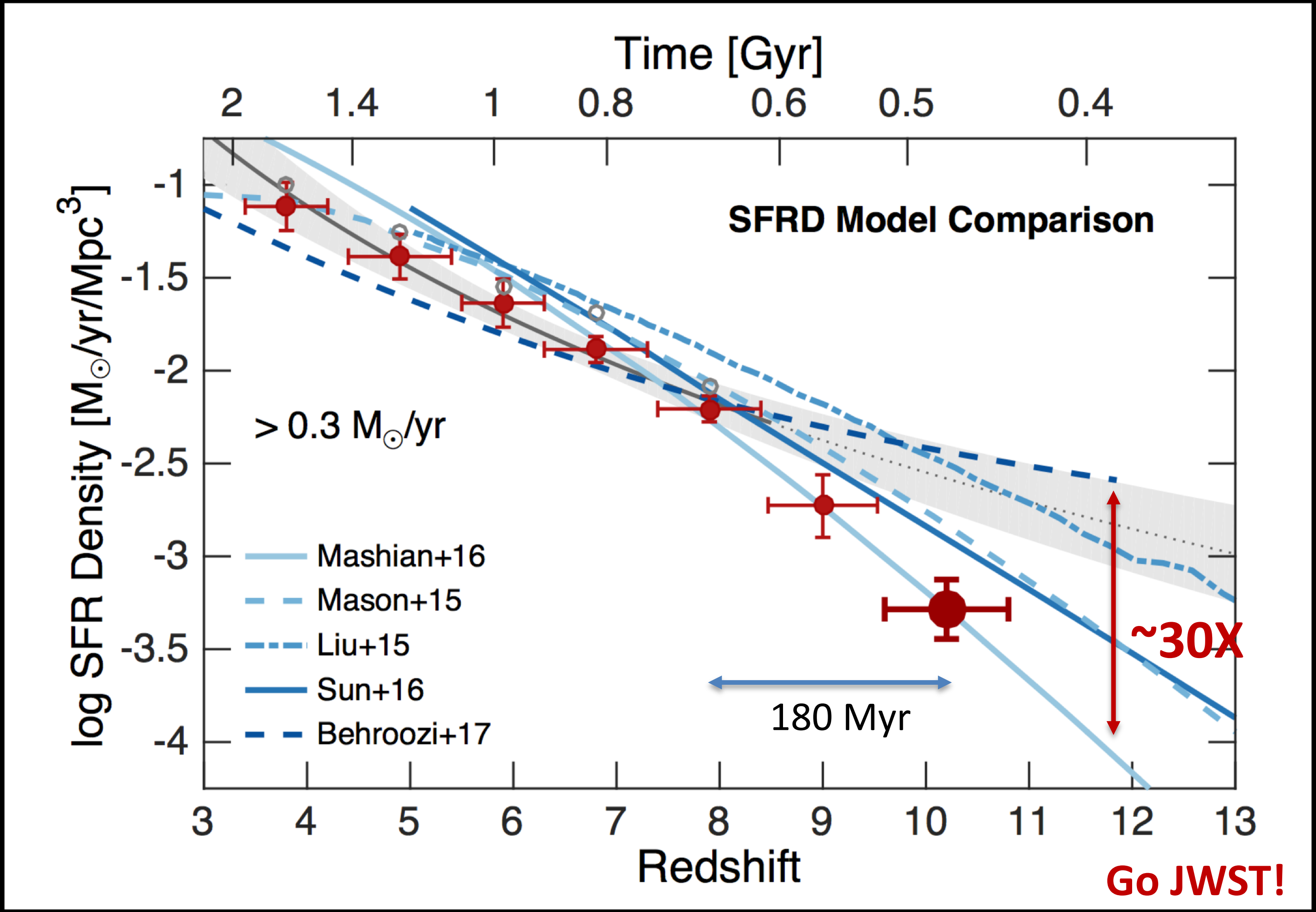
gdi

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!

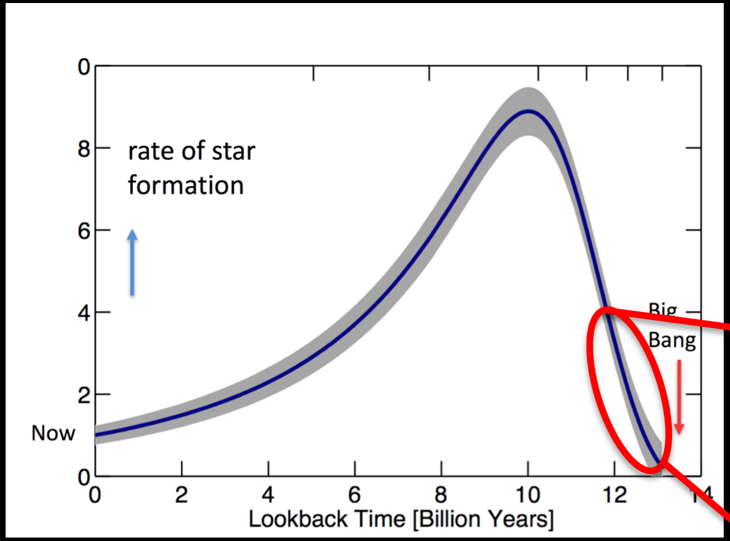
Oesch+2017



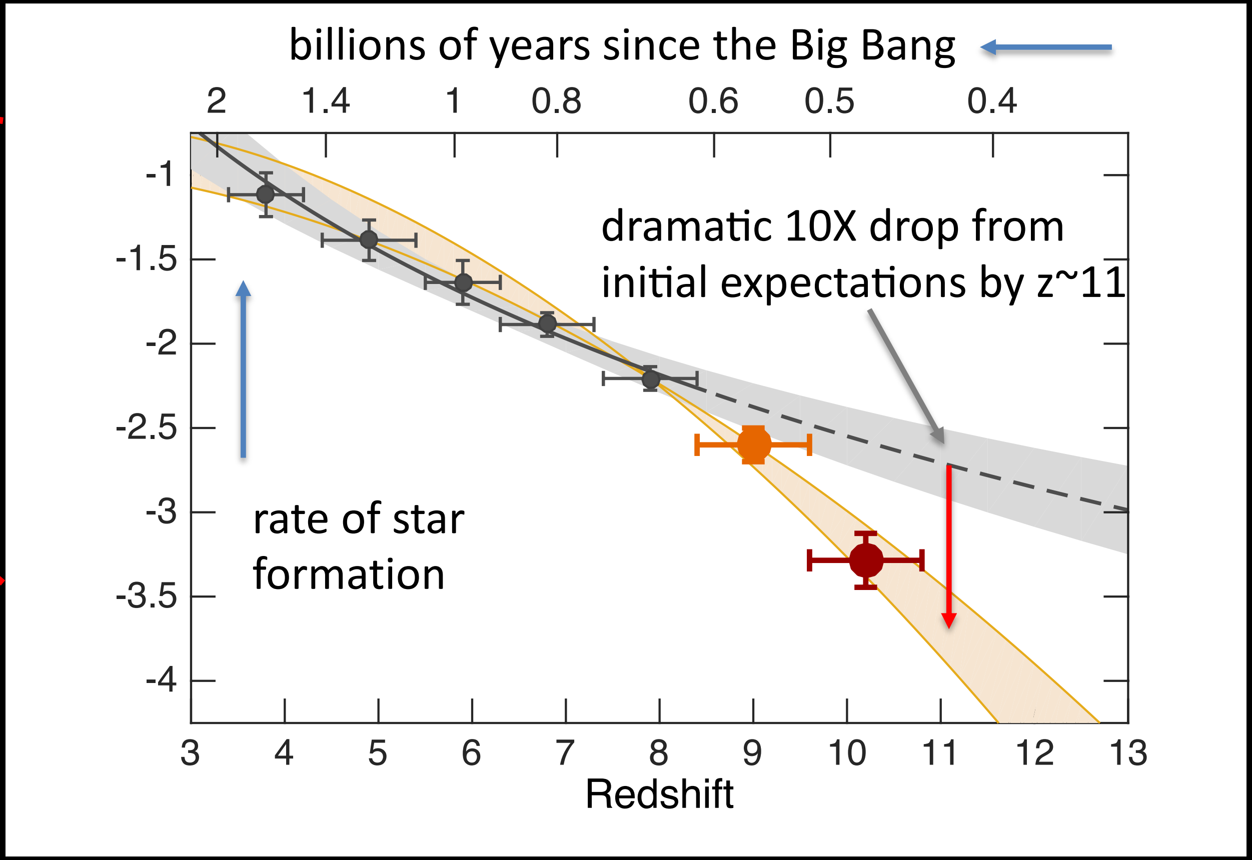
Bouwens+2019

gdi

way fewer galaxies than expected at redshift 10!



galaxies are evolving rapidly earlier than 650 million years

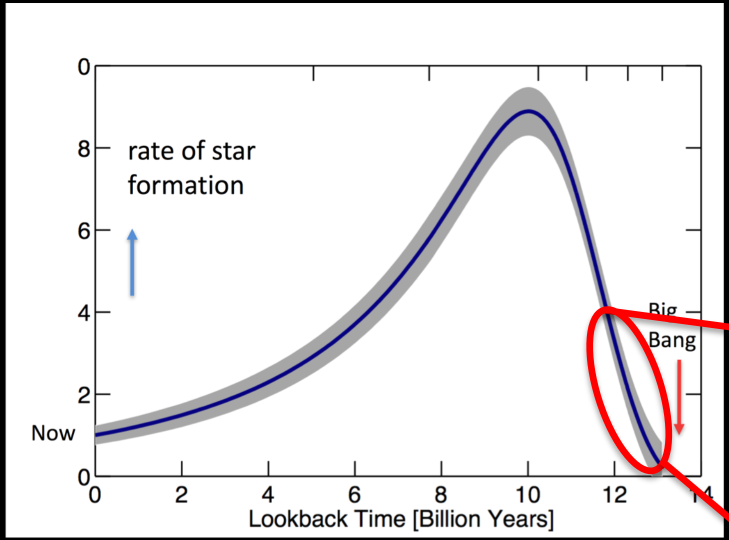


Oesch+2017

Bouwens+2019

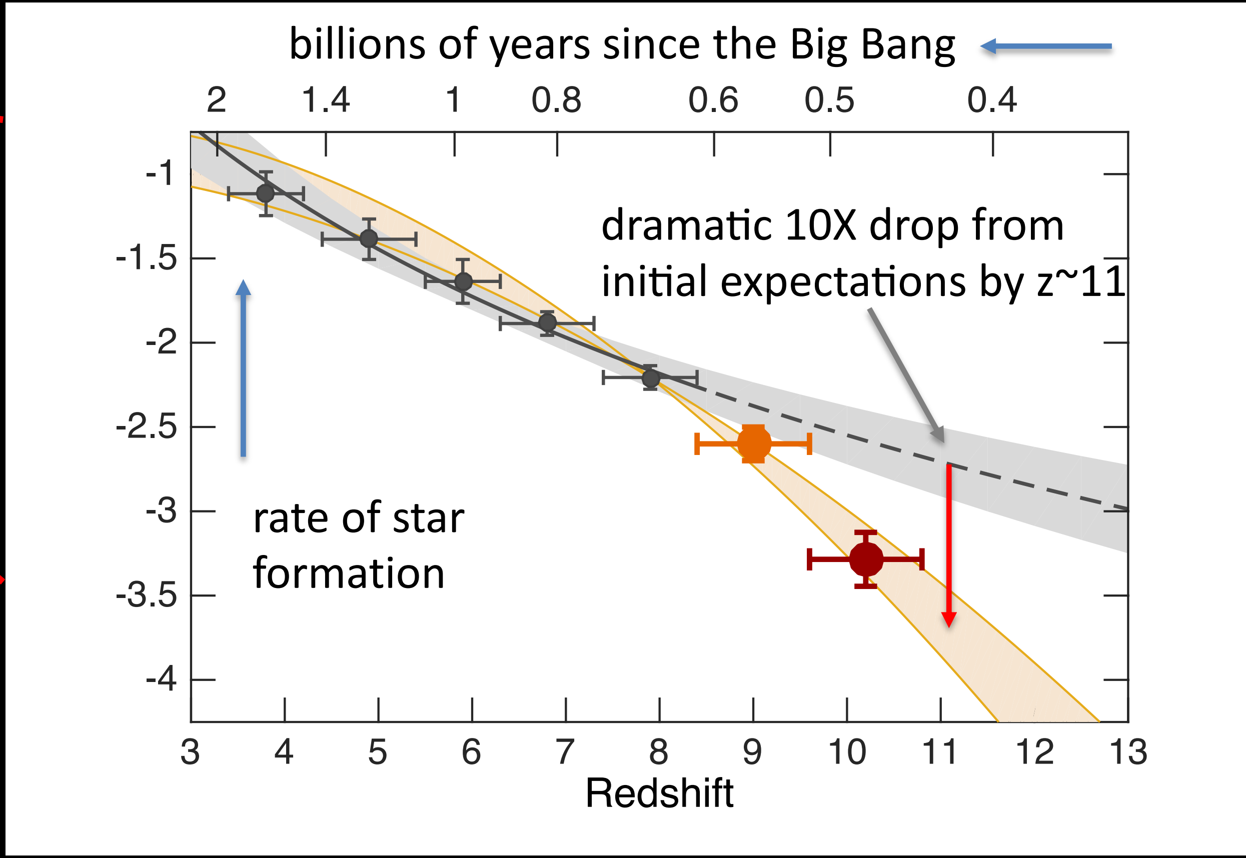
gdi

way fewer galaxies than expected at redshift 10!



galaxies are evolving rapidly earlier than 650 million years

"accelerated evolution" clearly has implications for the search for the earliest galaxies



Oesch+2017

Bouwens+2019

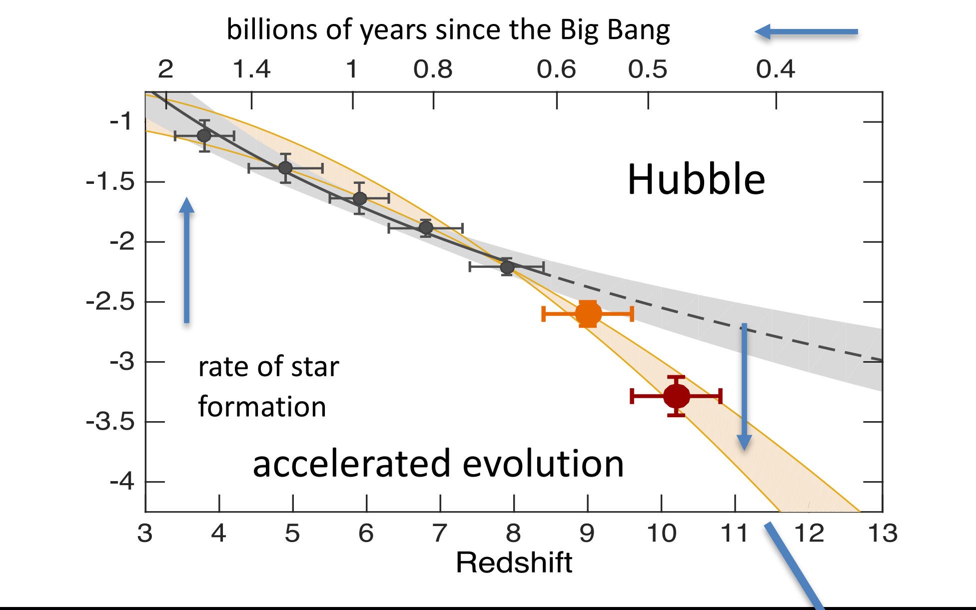
gdi

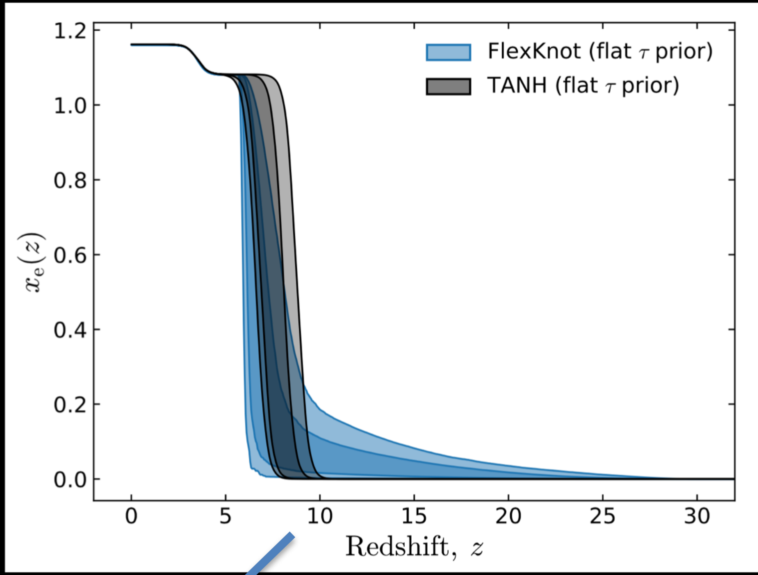
can JWST find the first galaxies?

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





can JWST see first epoch galaxies?

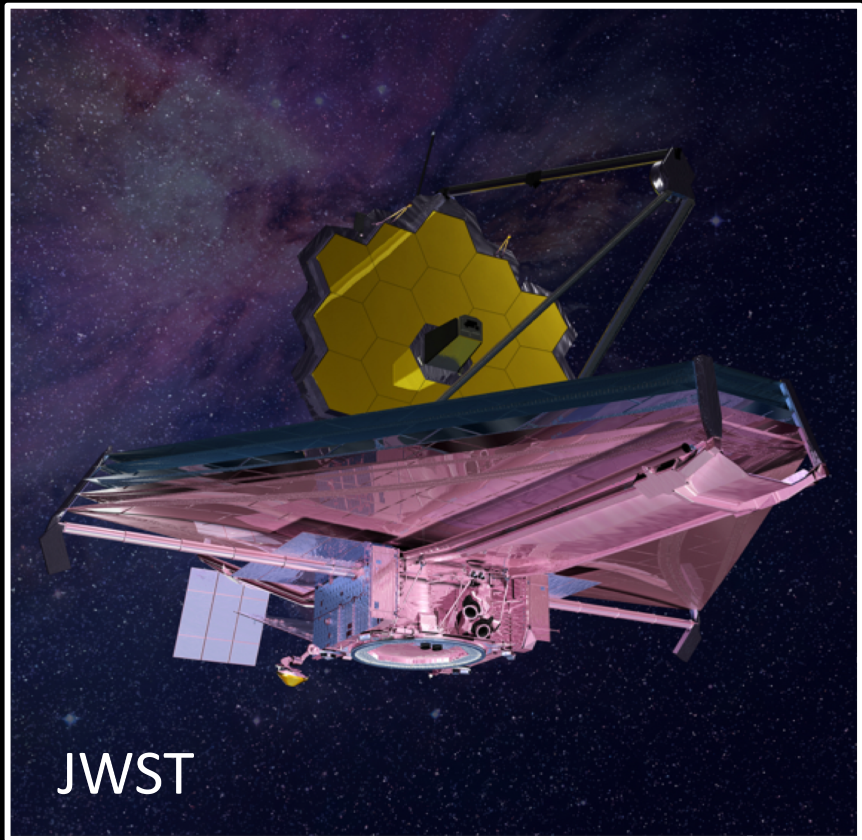
galaxies evolving rapidly at z>9 + reionization turn-on at z~10 (<1% at z~15)

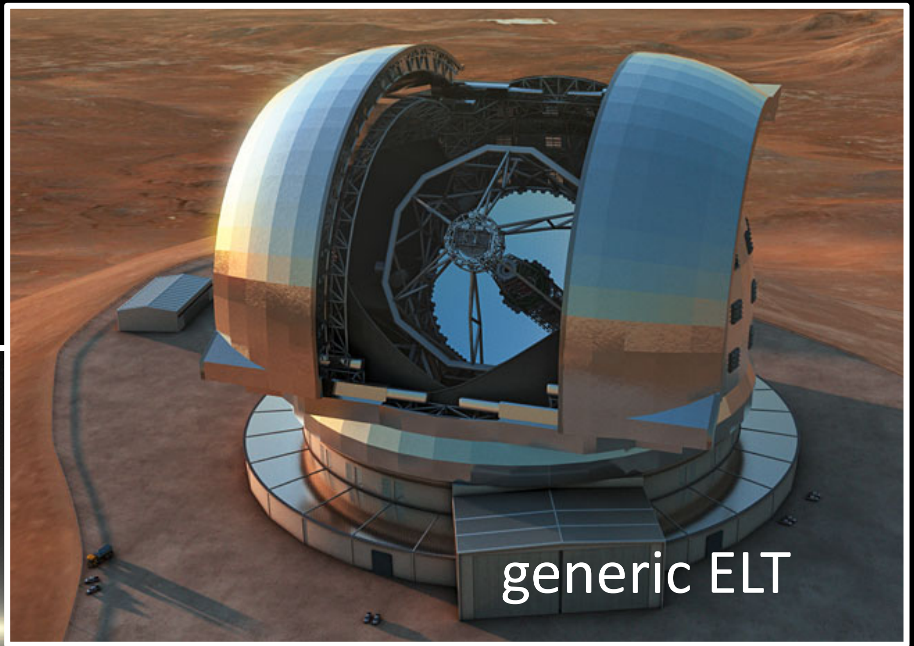
☛ suggest major changes in galaxy population at z~10-12-15 ☚

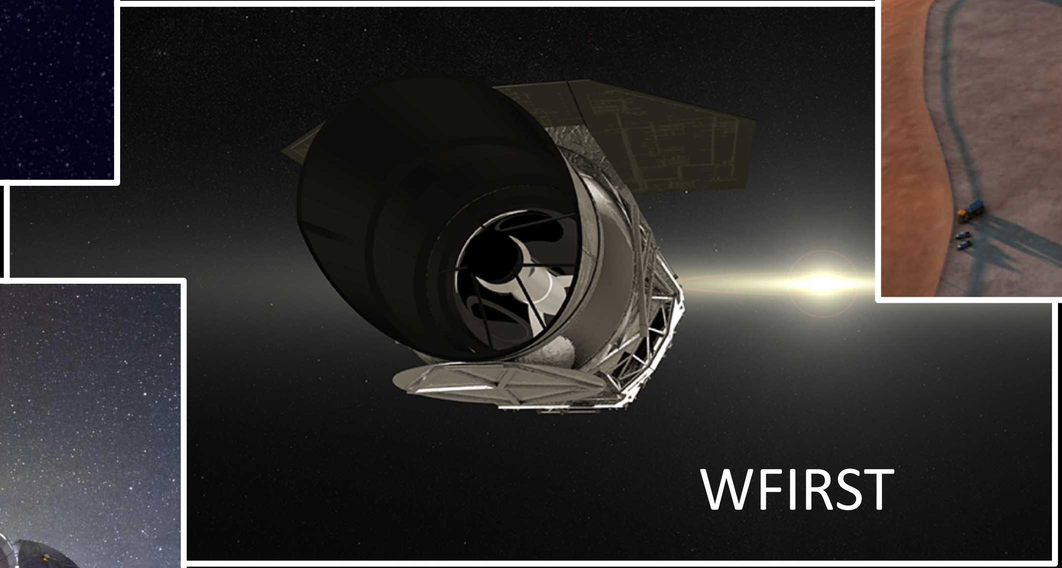
great for JWST's "first light" goal since galaxies likely evolving rapidly at z~10-12-15
and JWST will be able to detect galaxies out to z~15

gdi

our "first galaxy epoch" telescopes

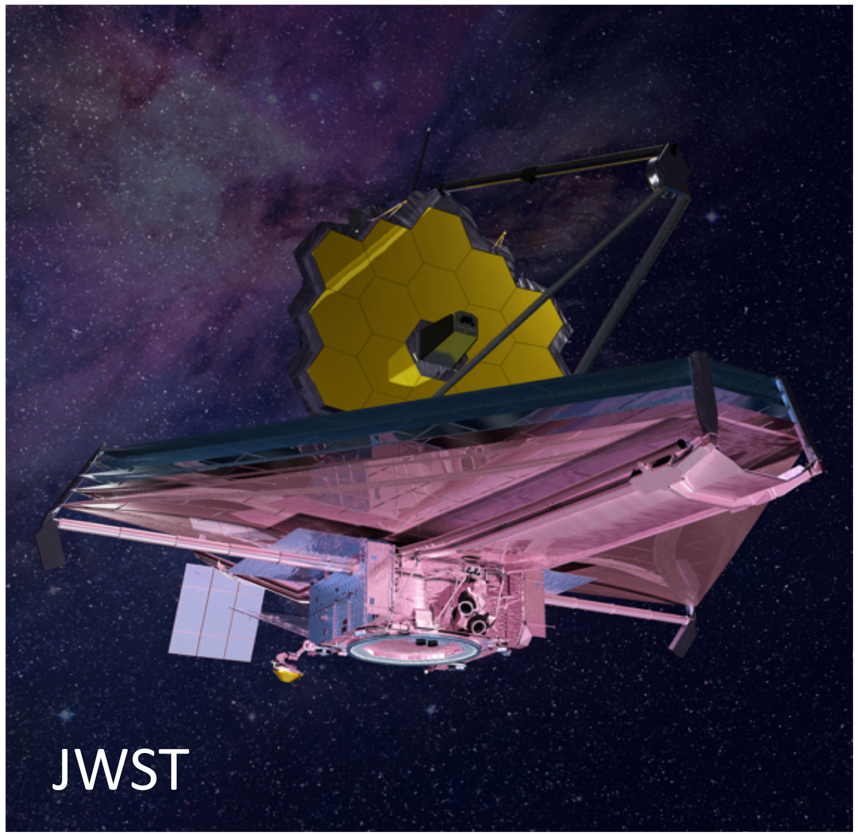




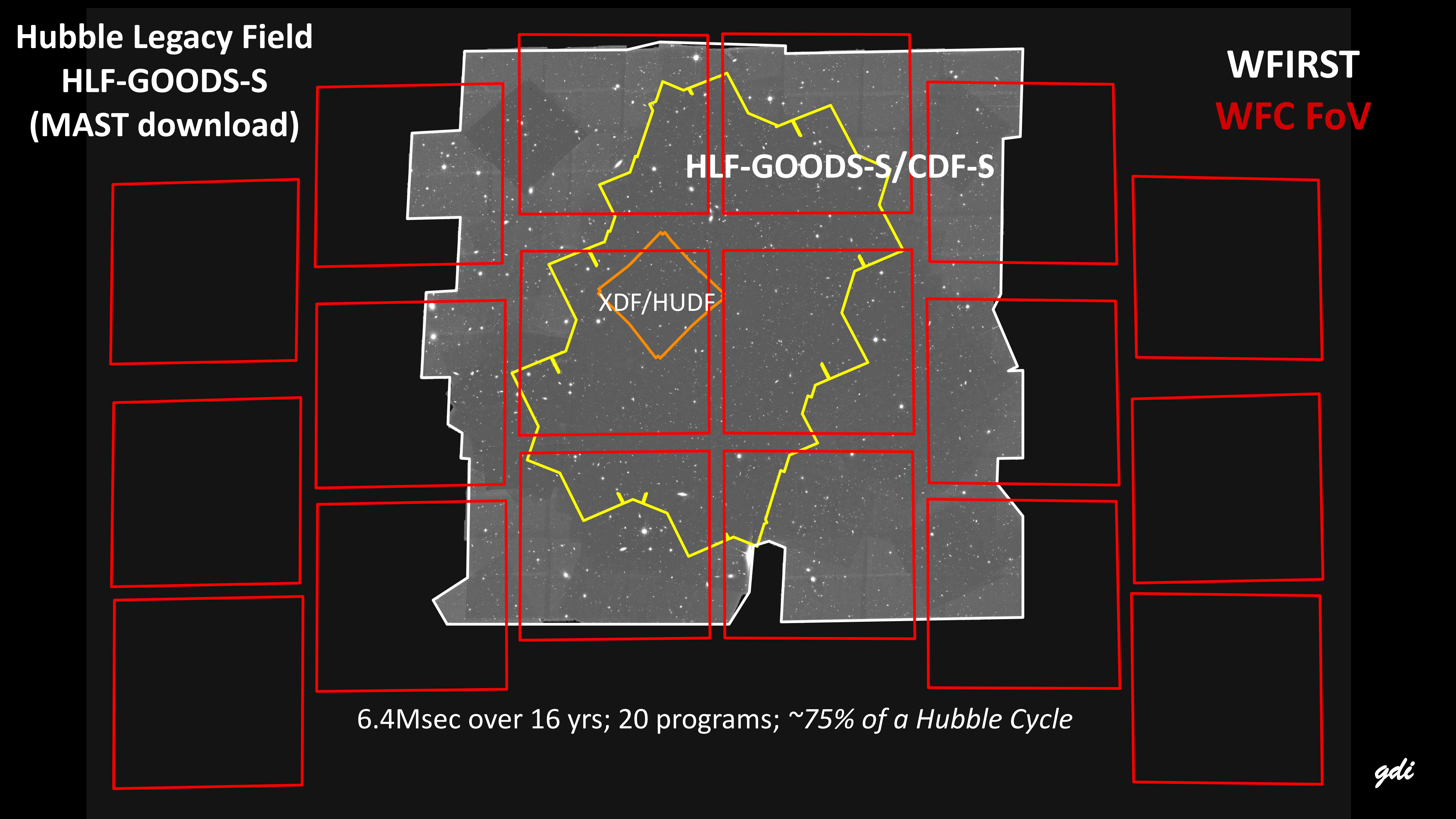


gdi

our "first galaxy epoch" telescopes

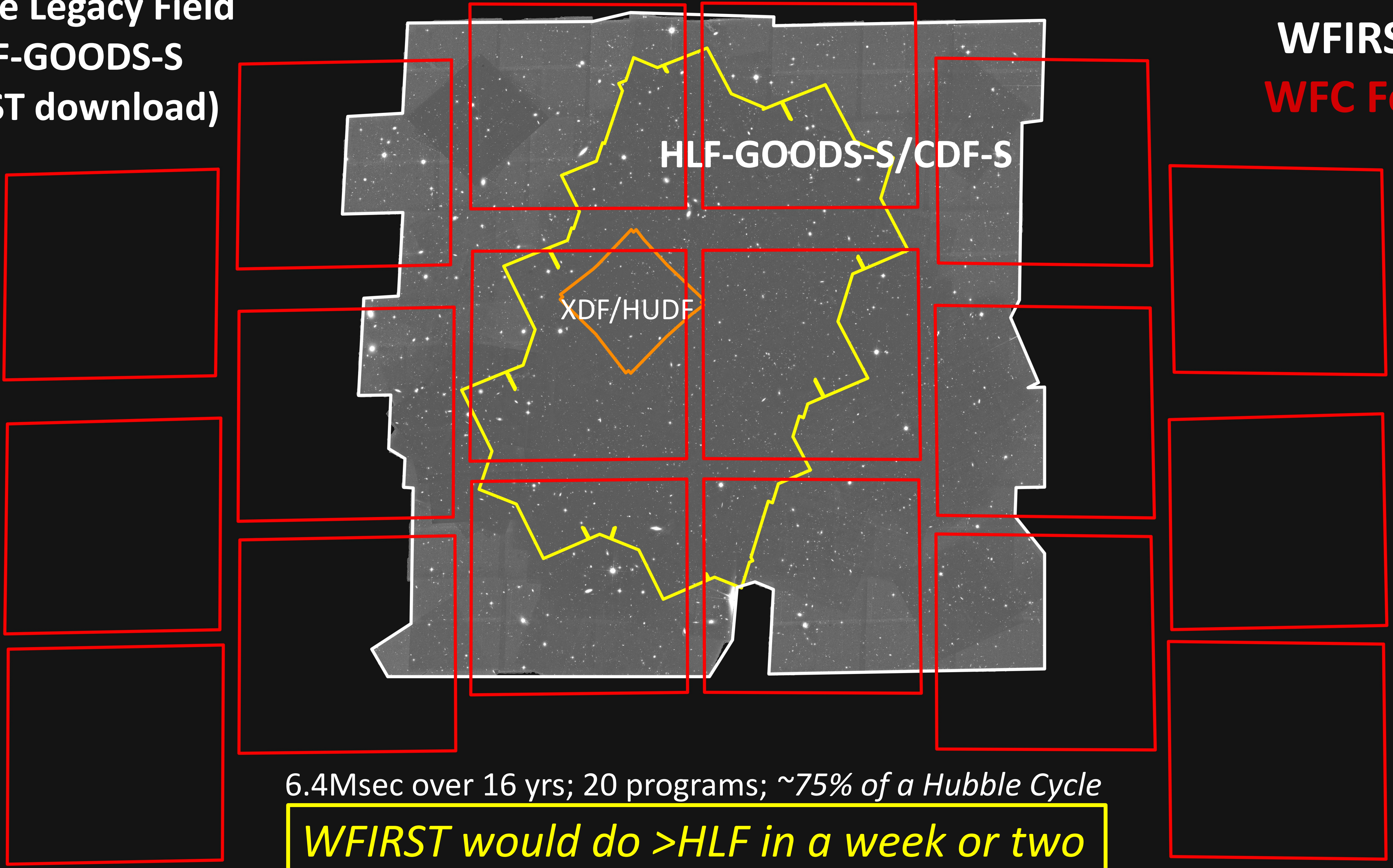


gdi


Hubble Legacy Field
HLF-GOODS-S
(MAST download)
WFIRST
WFC FoV
HLF-GOODS-S/CDF-S
XDF/HUDF
6.4Msec over 16 yrs; 20 programs; ~75% of a Hubble Cycle
gdi

Hubble Legacy Field
HLF-GOODS-S
(MAST download)

WFIRST
WFC FoV



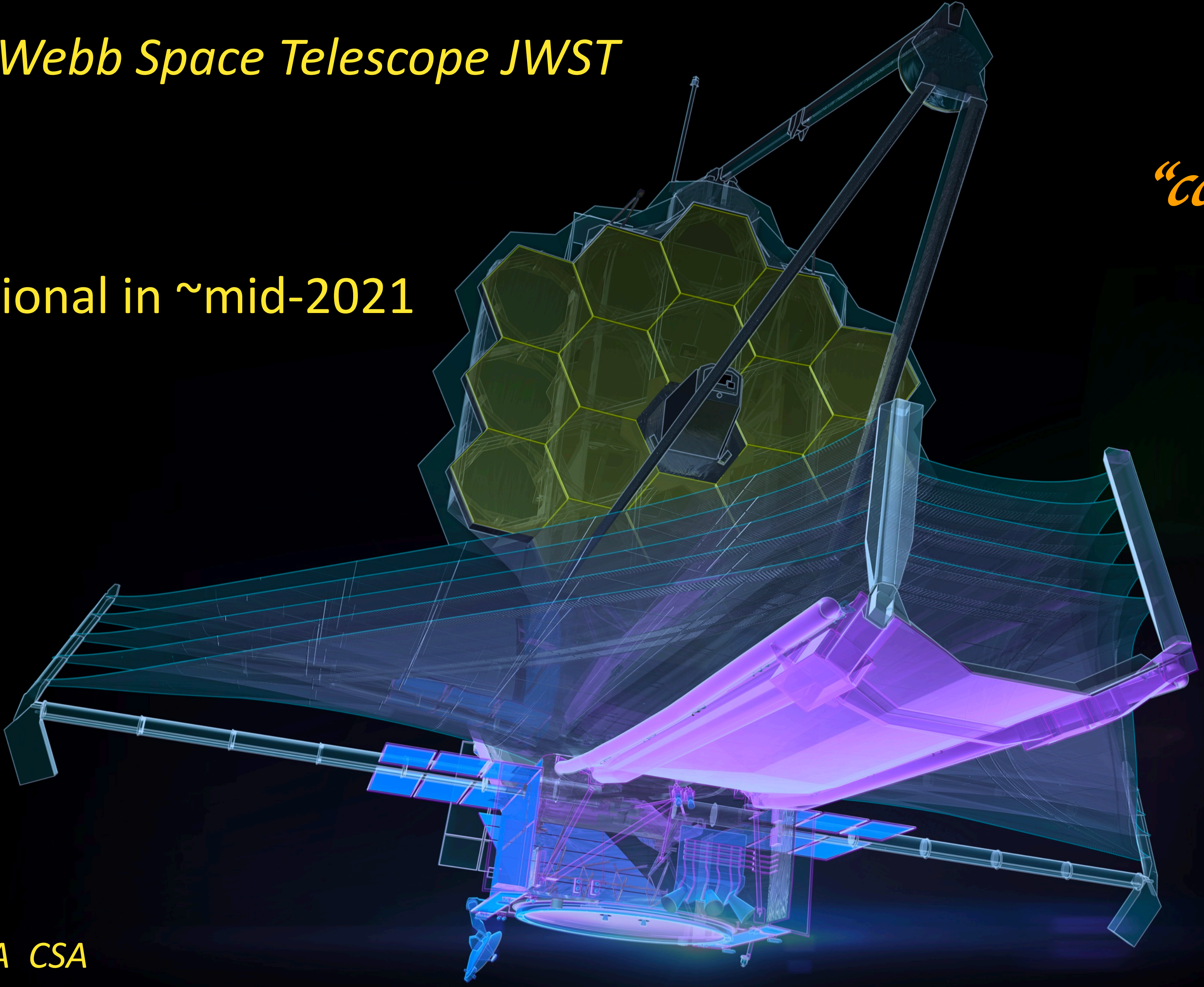
6.4Msec over 16 yrs; 20 programs; *~75% of a Hubble Cycle*

WFIRST would do >HLF in a week or two

gdi

James Webb Space Telescope JWST

operational in ~mid-2021



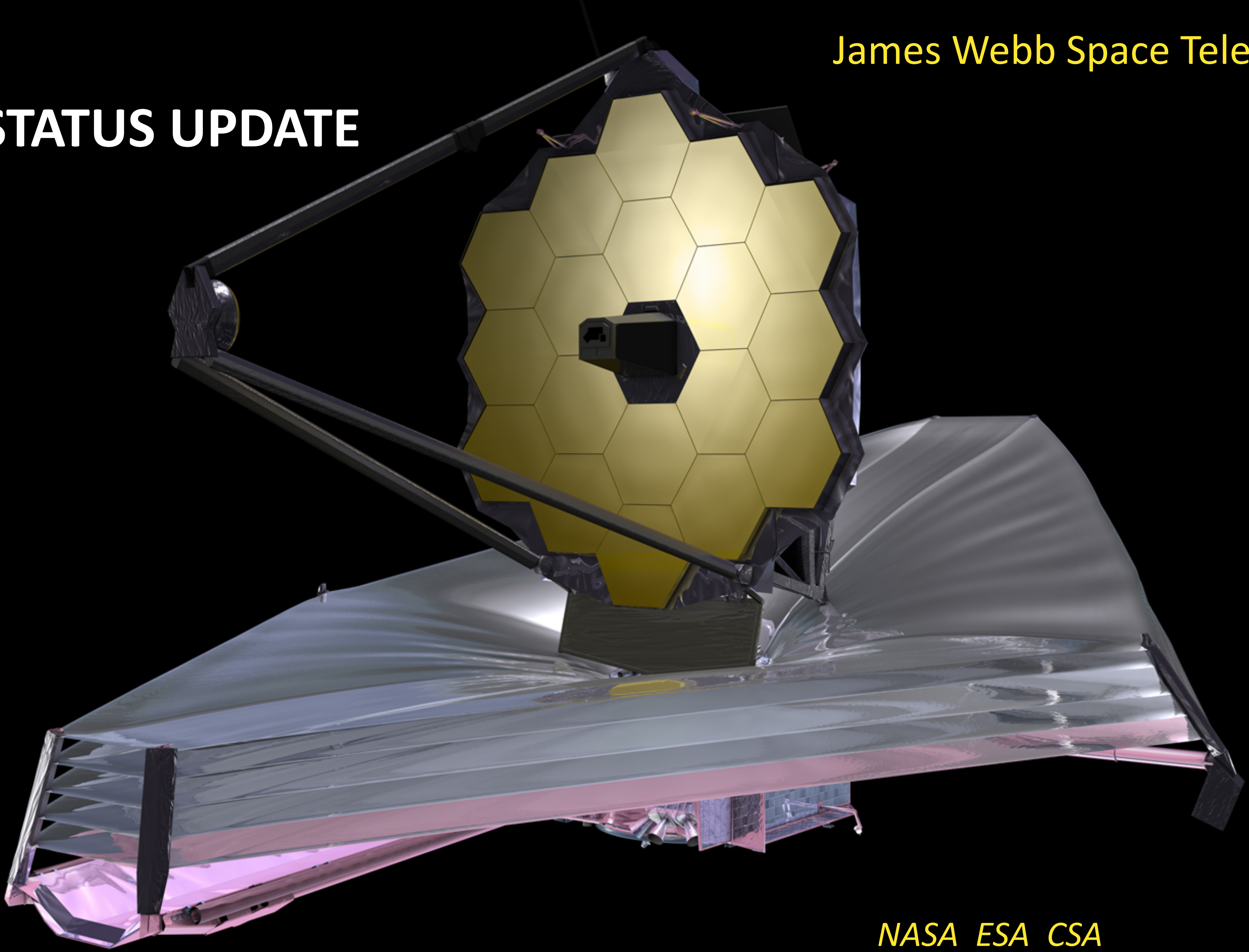
our first "cosmic sunrise" telescope

NASA ESA CSA

gdi

JWST STATUS UPDATE

James Webb Space Telescope JWST

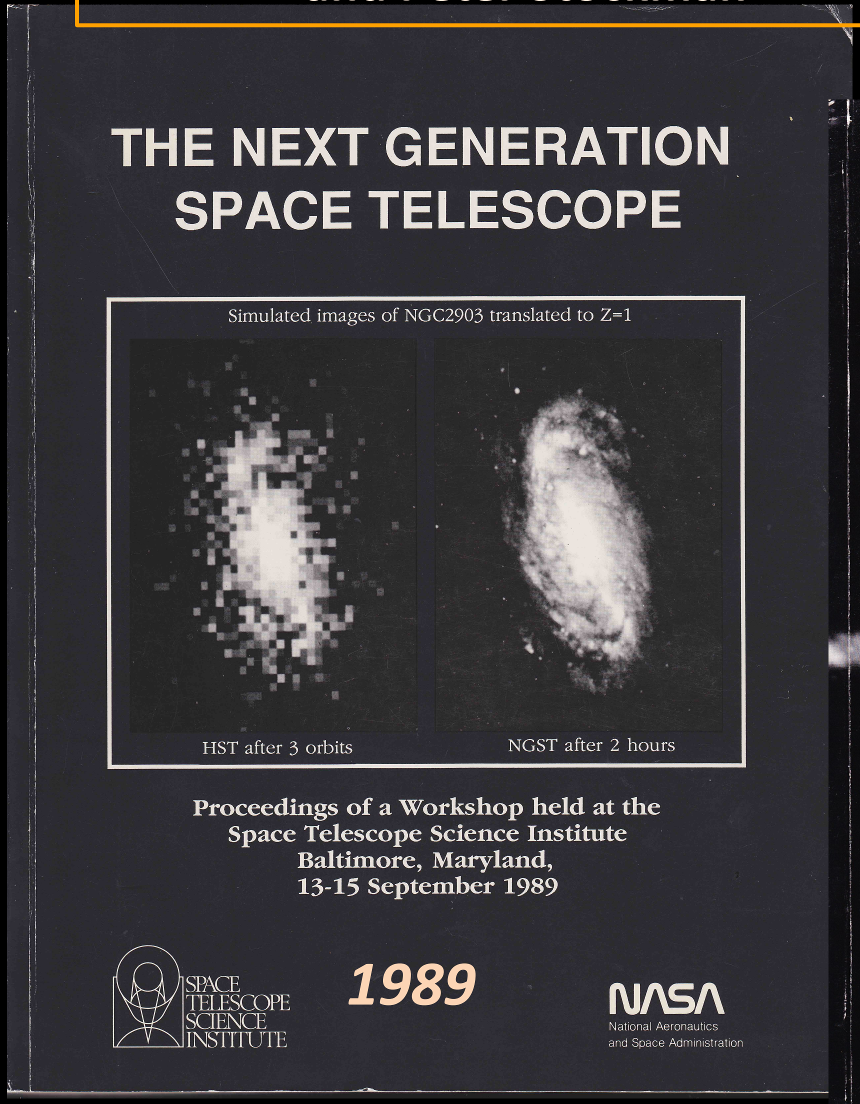


NASA ESA CSA

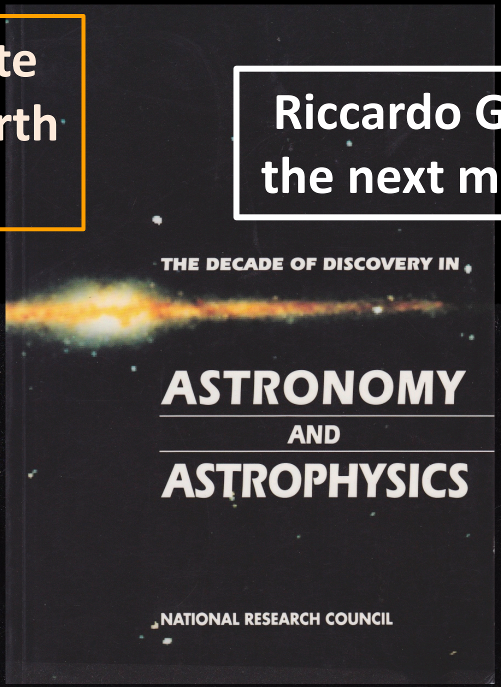
gdi

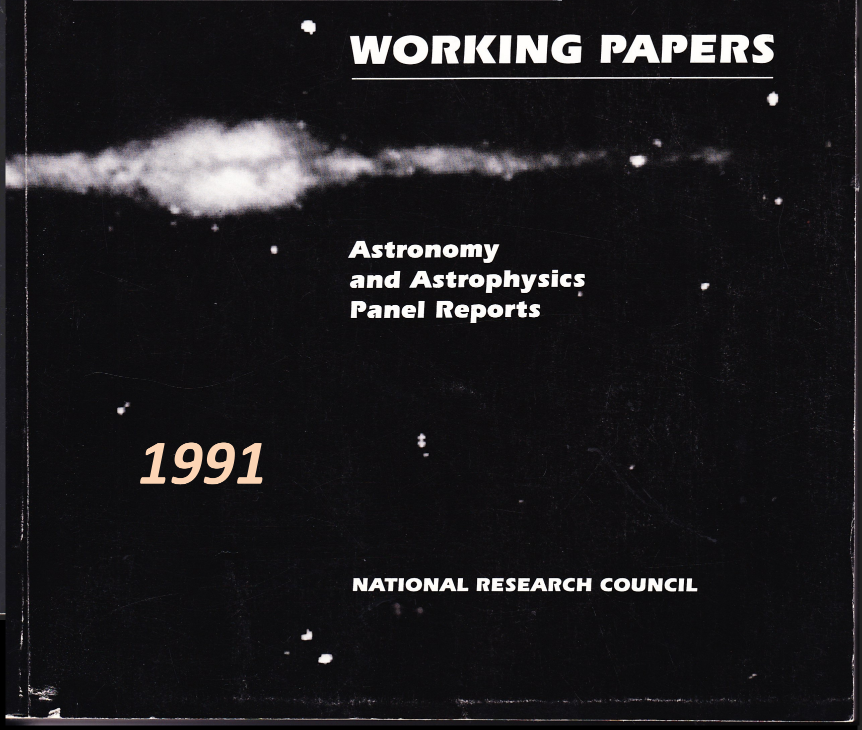
NGST started at STScI in the mid-late 1980s by Pierre Bely, Garth Illingworth and Peter Stockman

Riccardo Giacconi encouraged us in 1986/7 – "start early on the next mission" – he told us that it would take a long time!

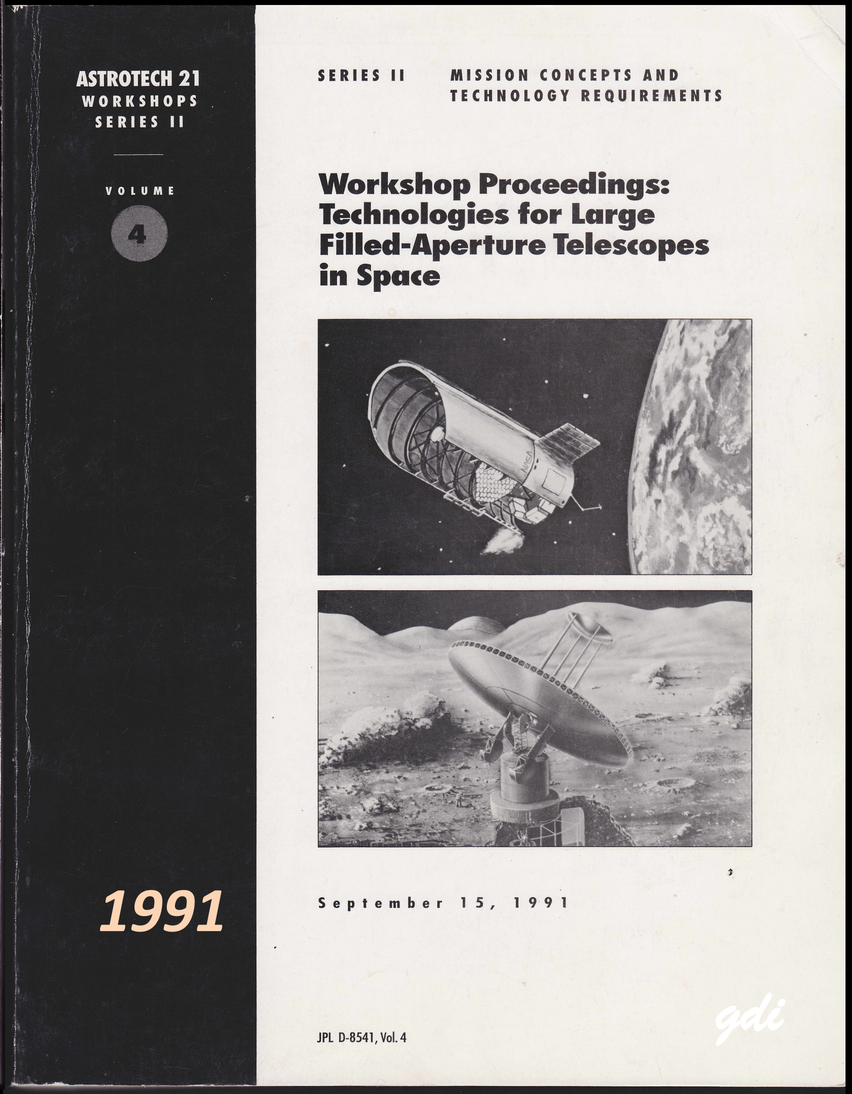


1989





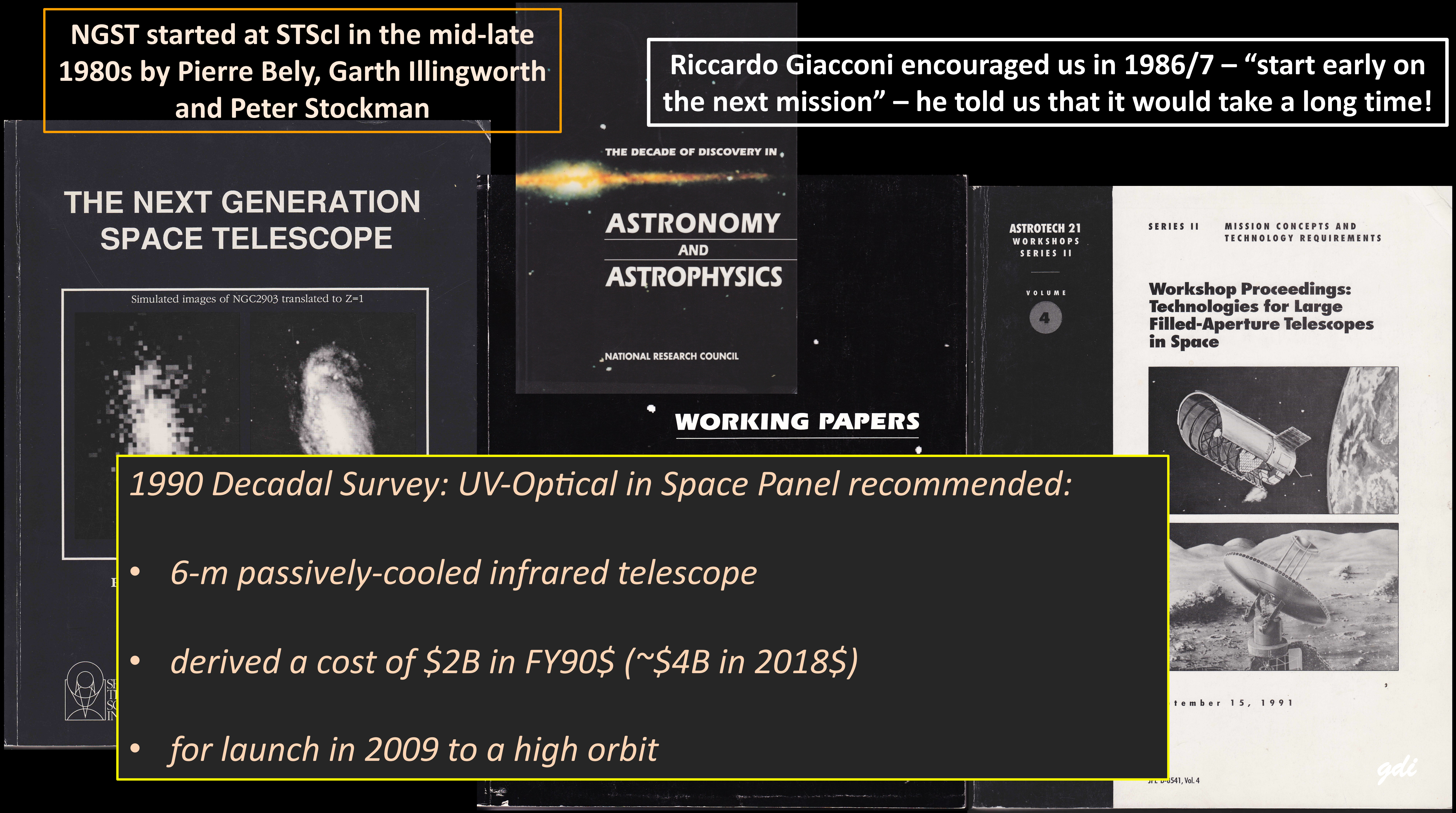
1991



1991

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

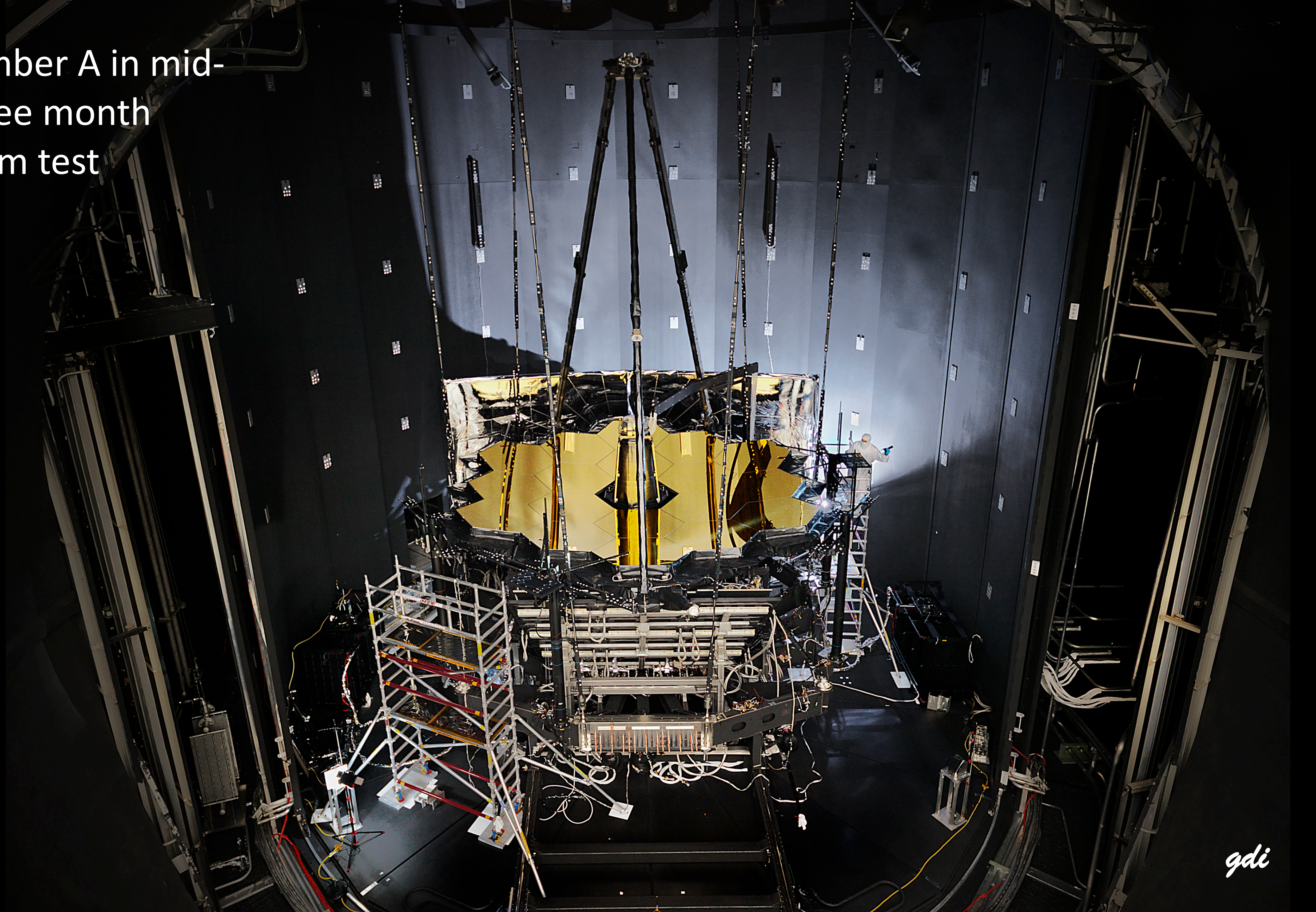
Riccardo Giacconi encouraged us in 1986/7 – “start early on the next mission” – he told us that it would take a long time!



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

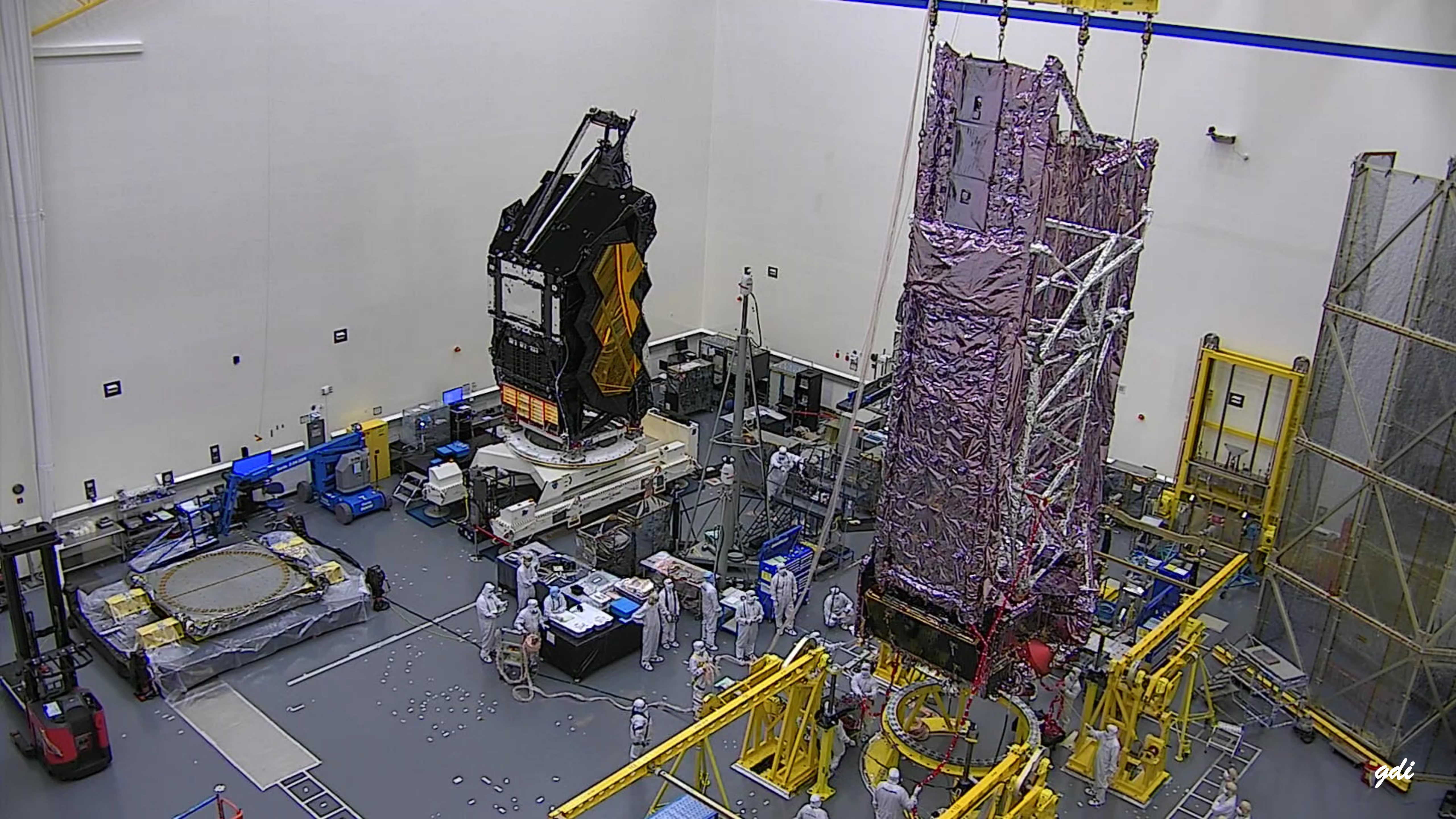
- *6-m passively-cooled infrared telescope*
- *derived a cost of $2B in FY90$ (~$4B in 2018$)*
- *for launch in 2009 to a high orbit*

OTIS in JSC Chamber A in mid-2017 for the three month cryogenic vacuum test

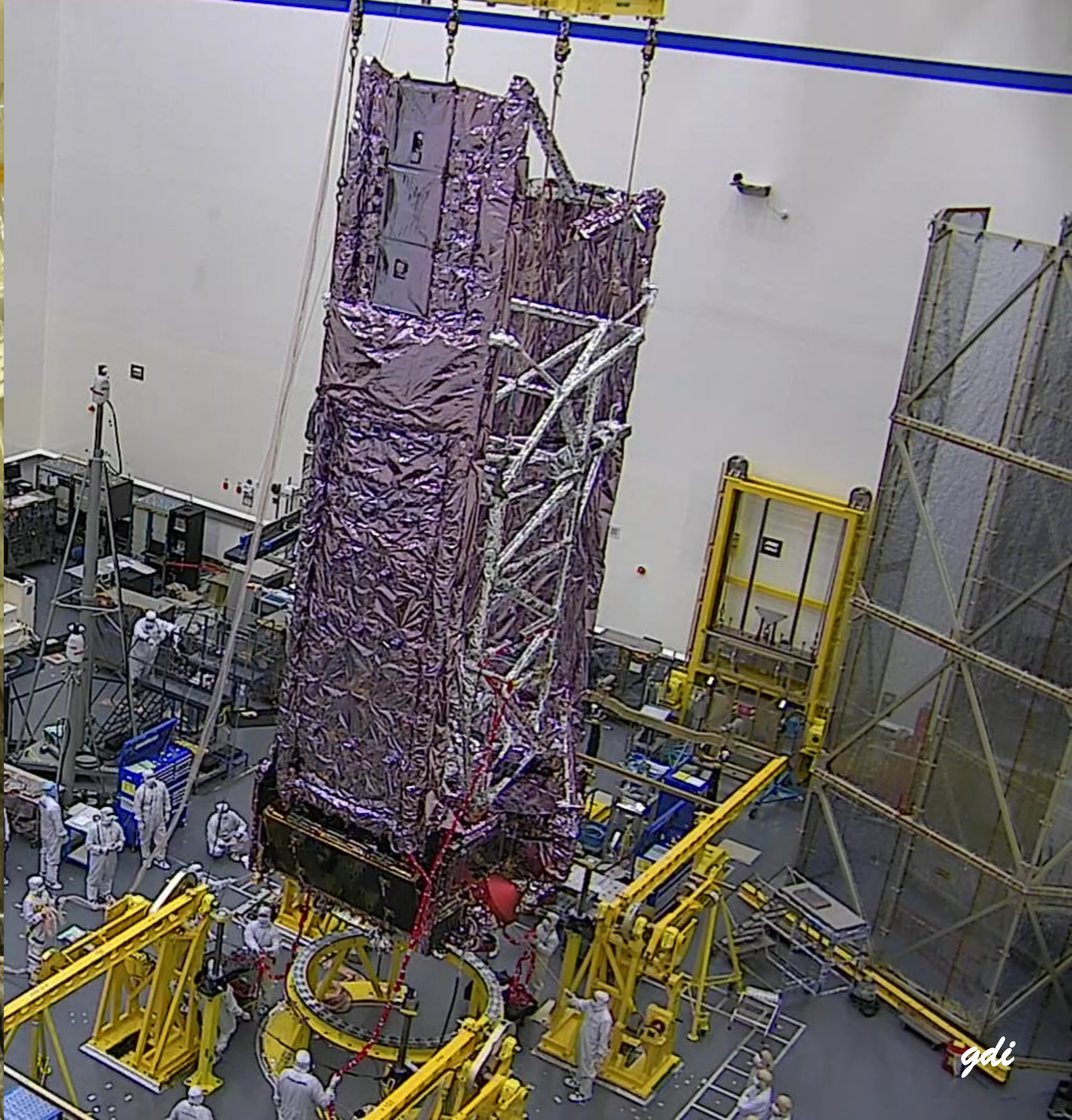



JWST flight sunshield
in Northrop Grumman
clean room
gdi

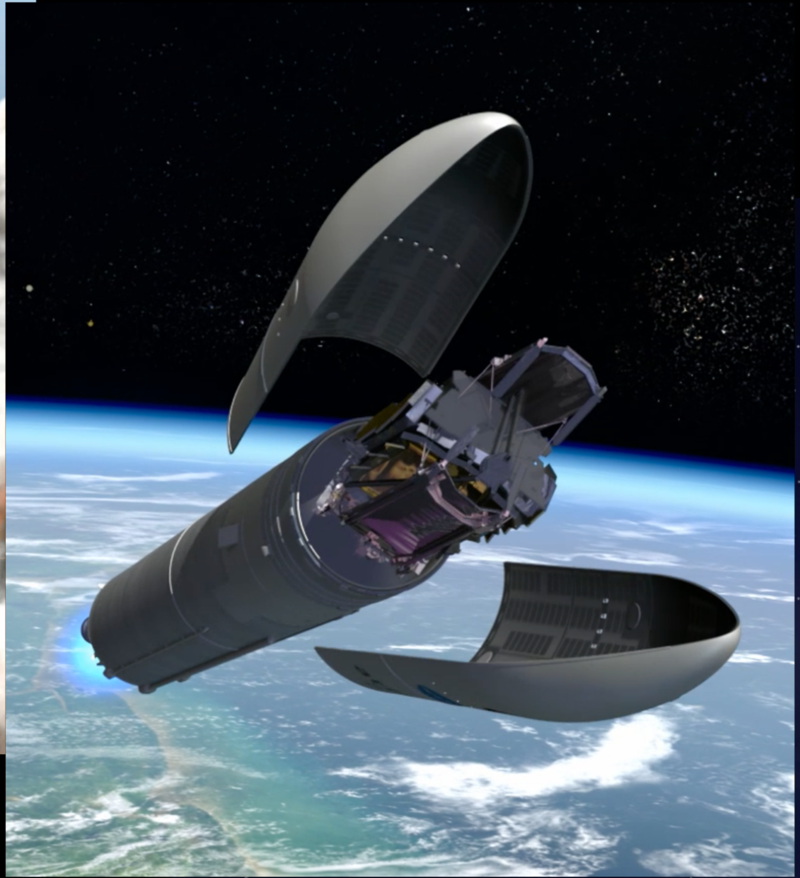

SCE
OTIS
NORTHROP GRUMMAN
JLG 2630ES
7334
JLG
EXIT
gdi

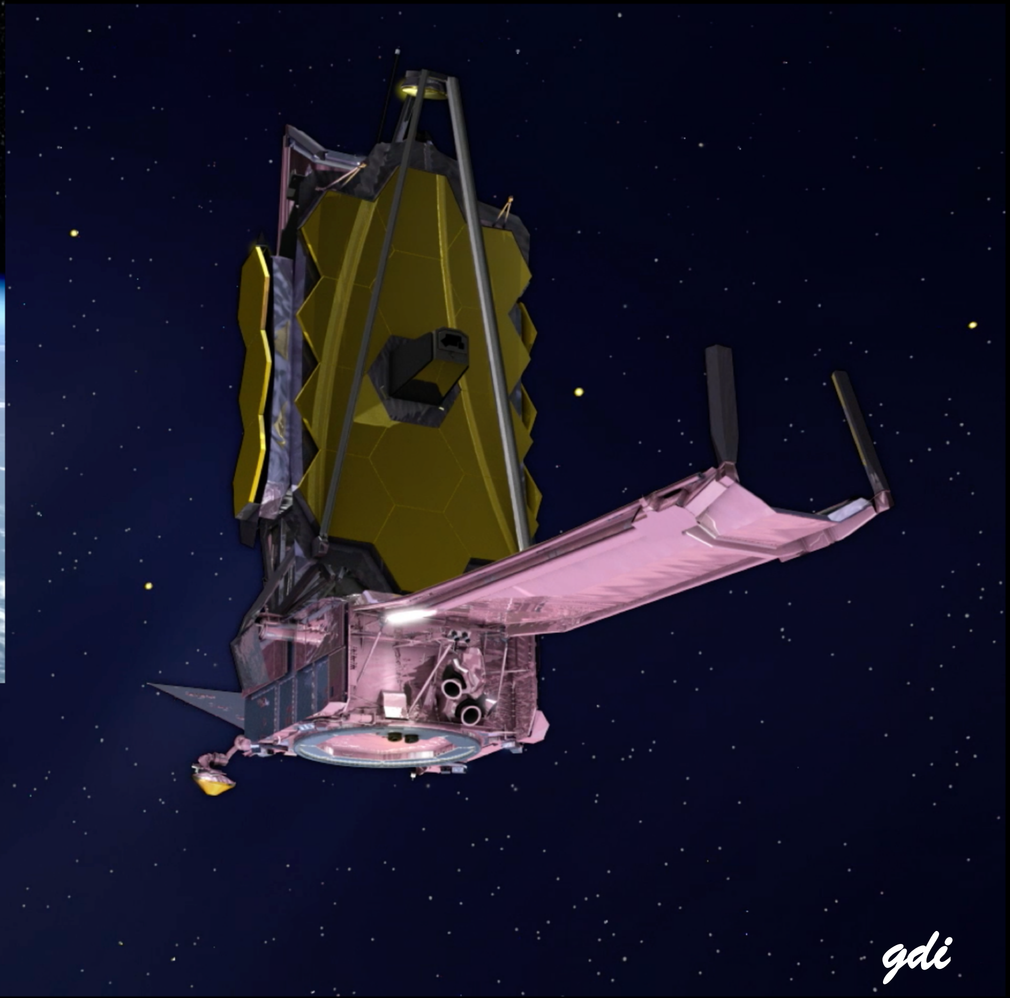

gdi




gdi

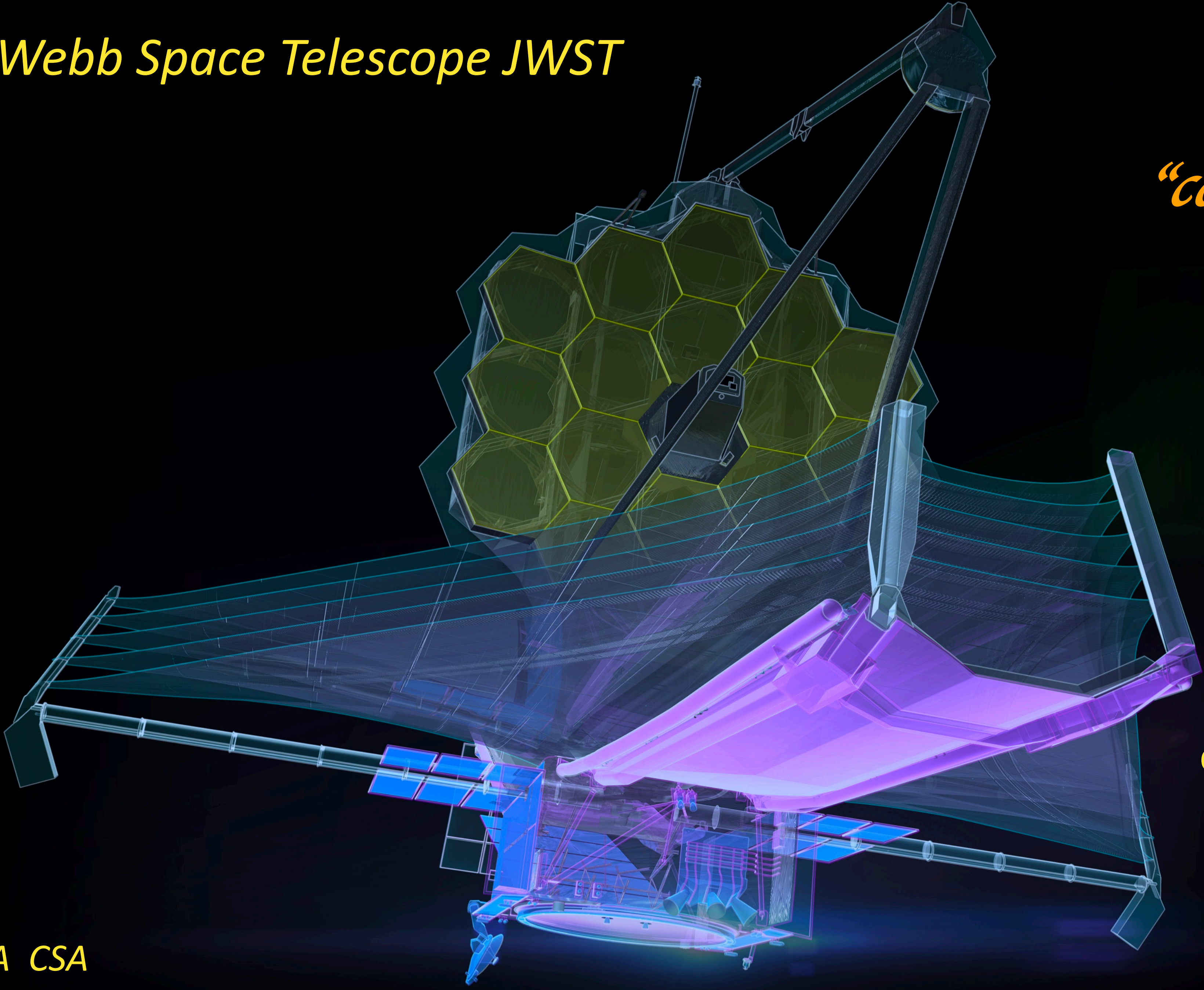
JWST launching on the European Ariane 5 in about 2 years





James Webb Space Telescope JWST

our first “cosmic sunrise” telescope

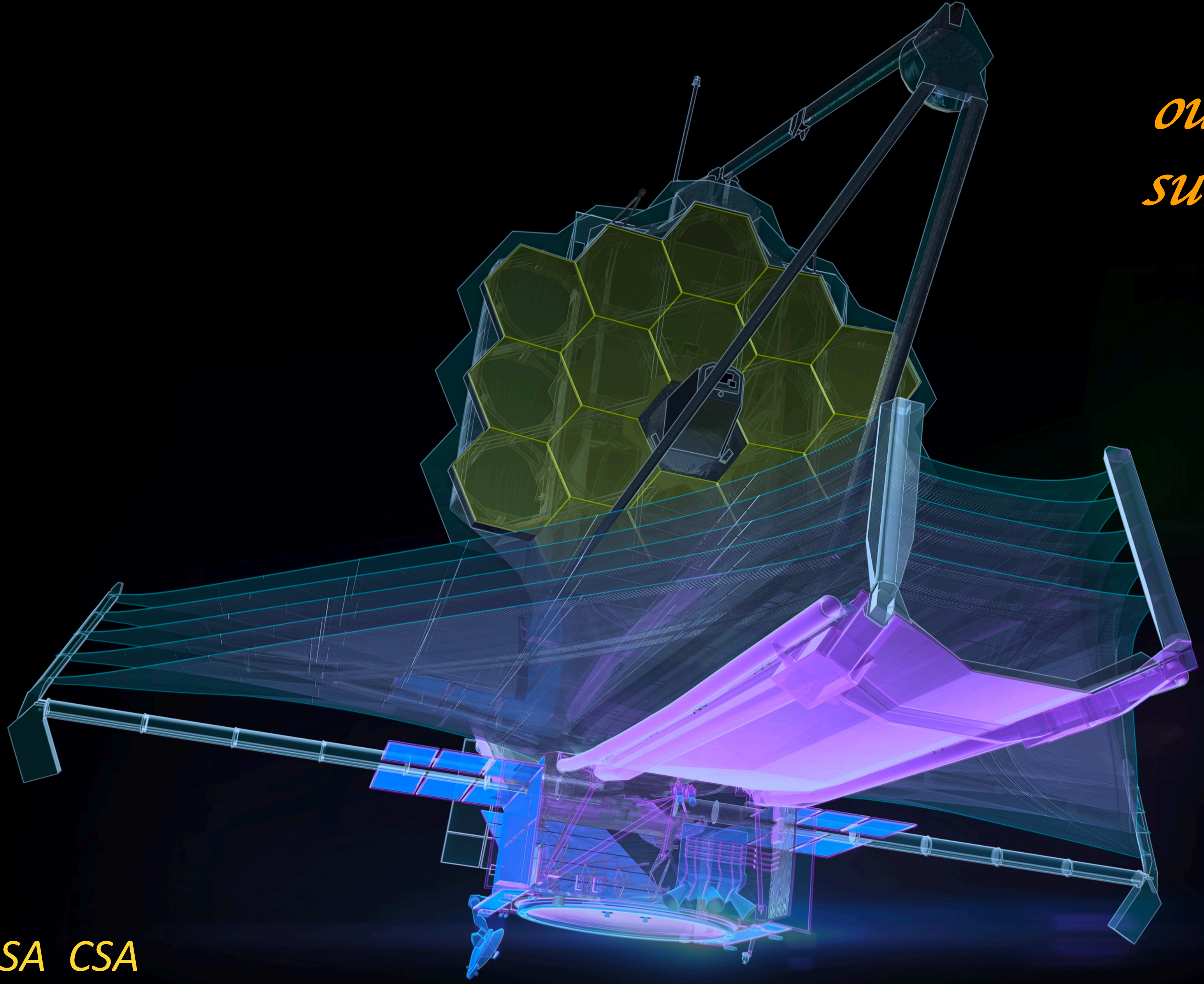


operational in 2021

NASA ESA CSA

gdi

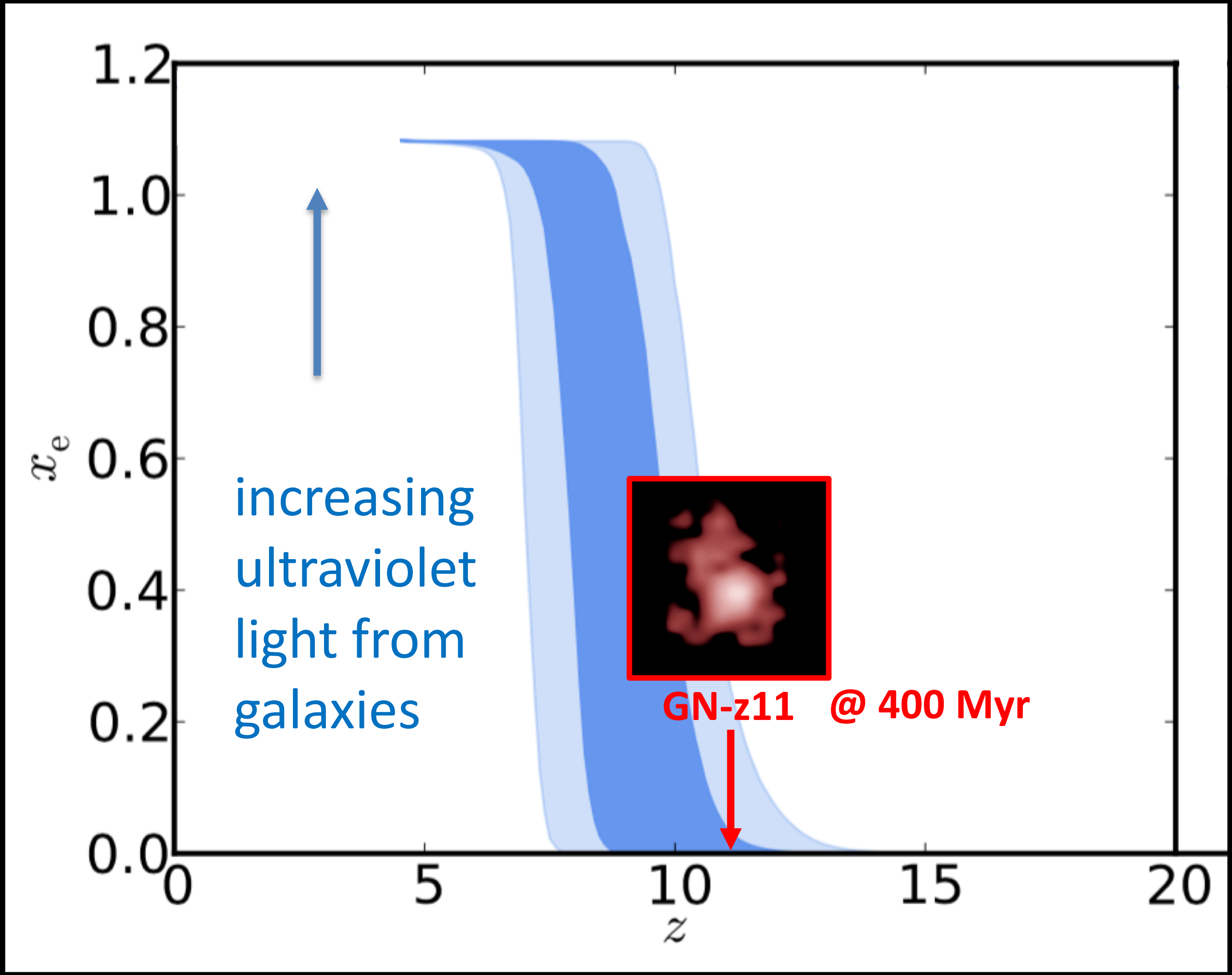
our first cosmic sunrise telescope



NASA ESA CSA

gdi

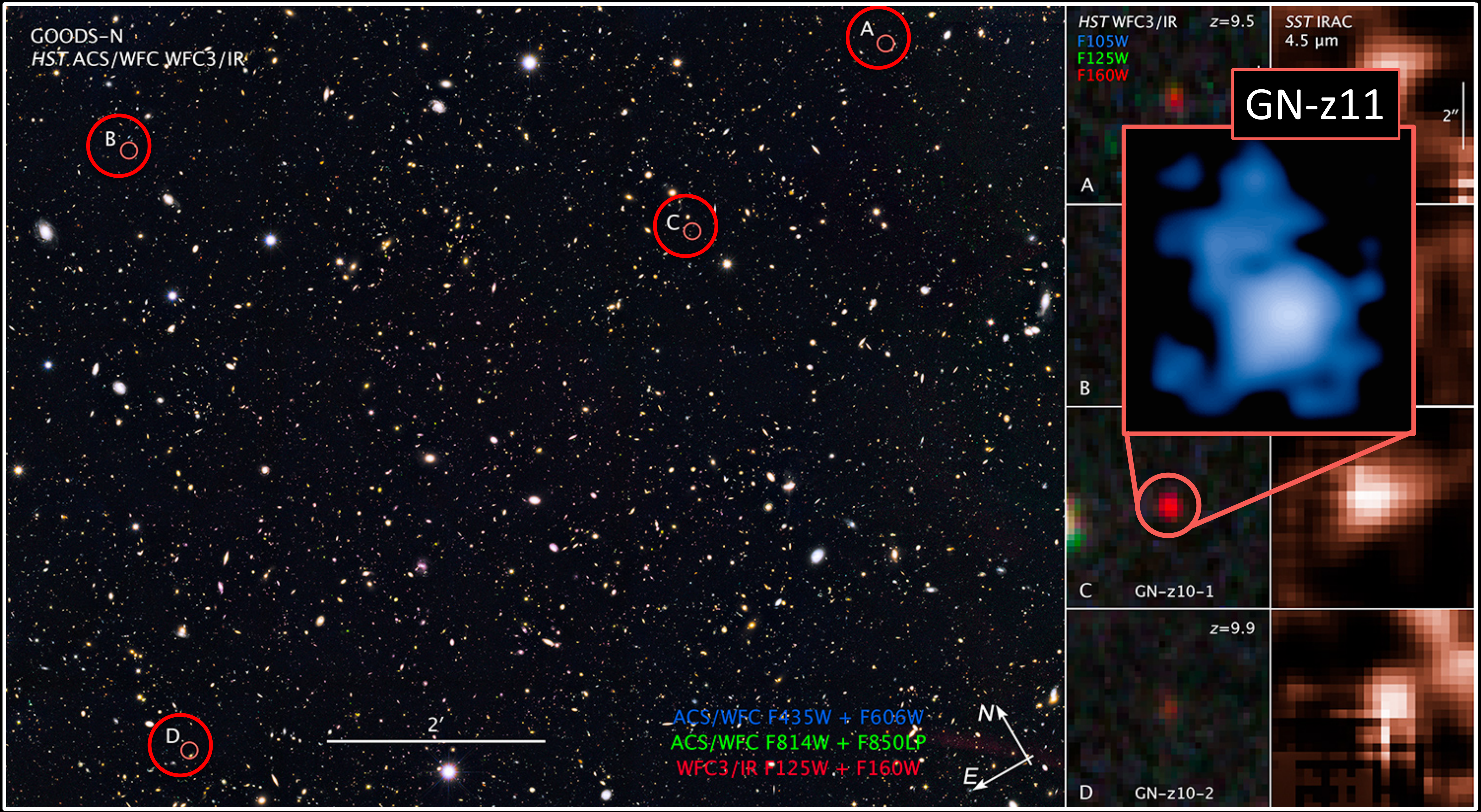
reionization constraints from Planck 2018



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

Planck Collaboration

gdi



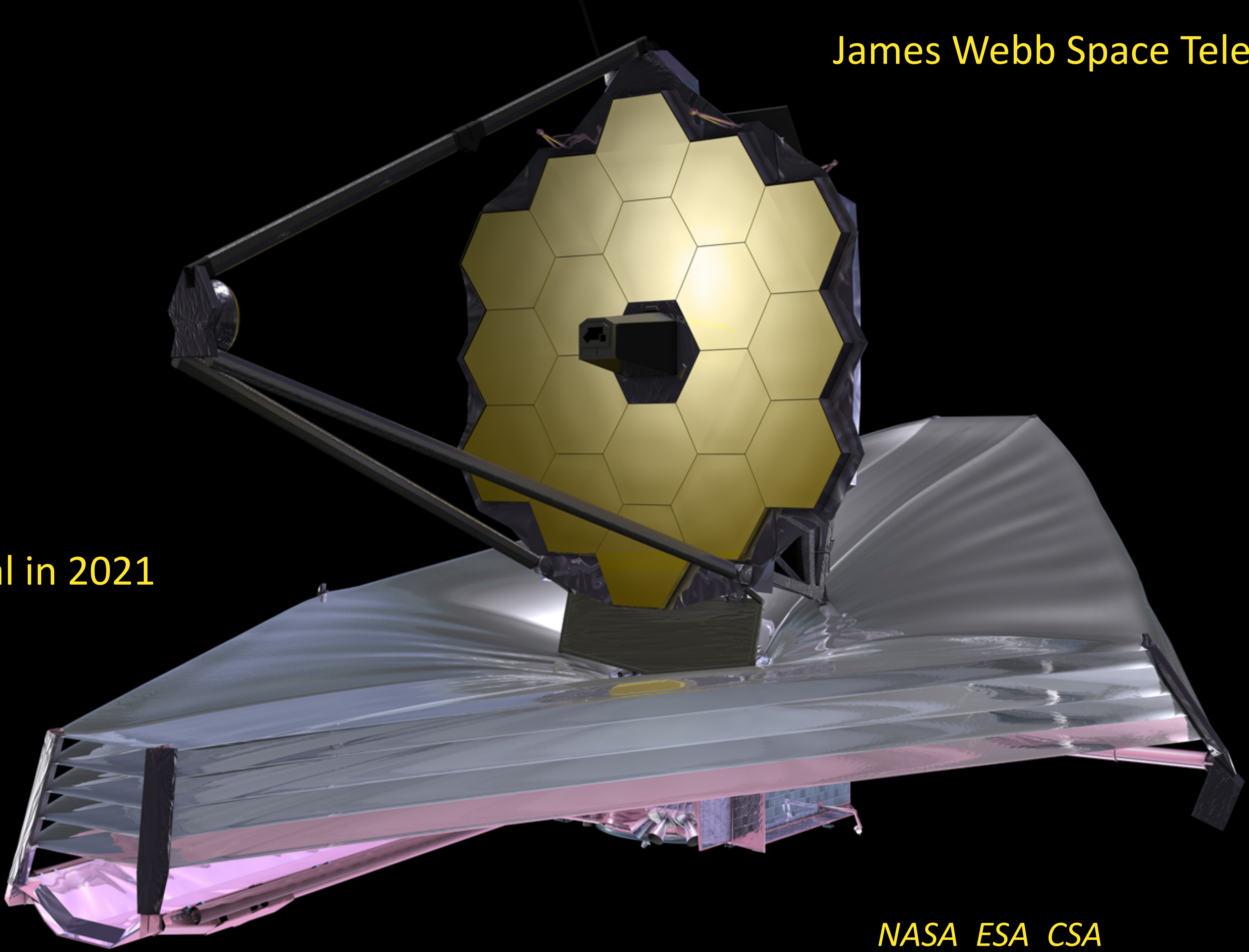
Oesch + 2014, 2016

Hubble Spitzer

gdi

JWST sunshield in Northrop Grumman clean room

James Webb Space Telescope JWST

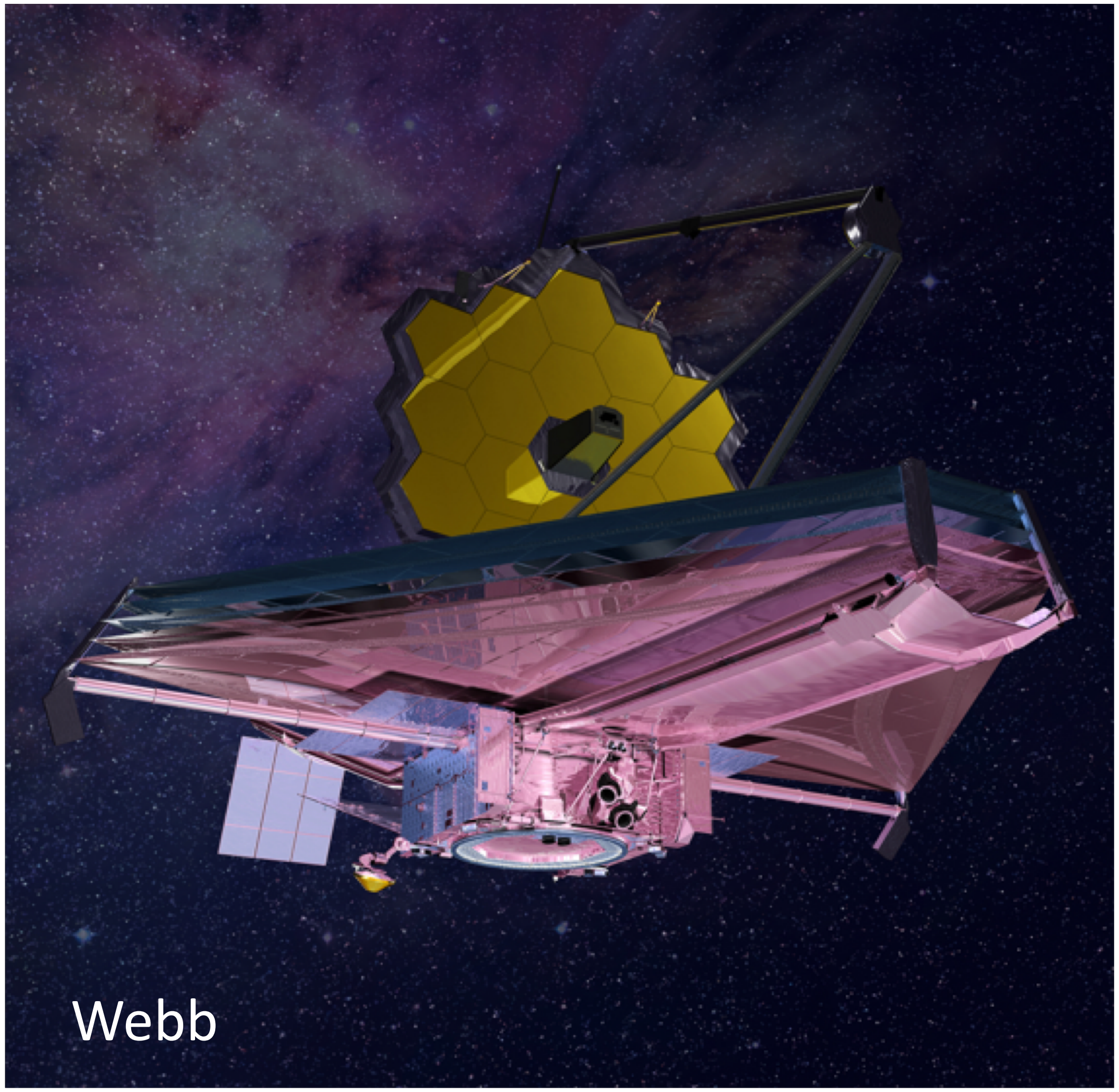


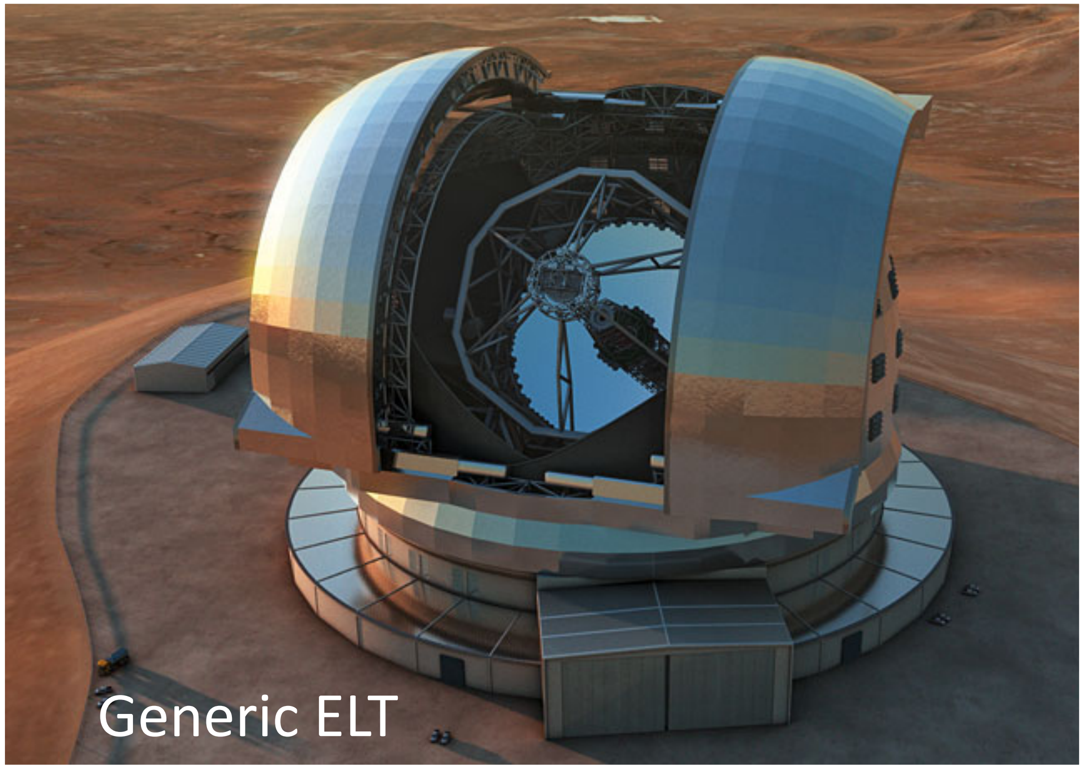
operational in 2021

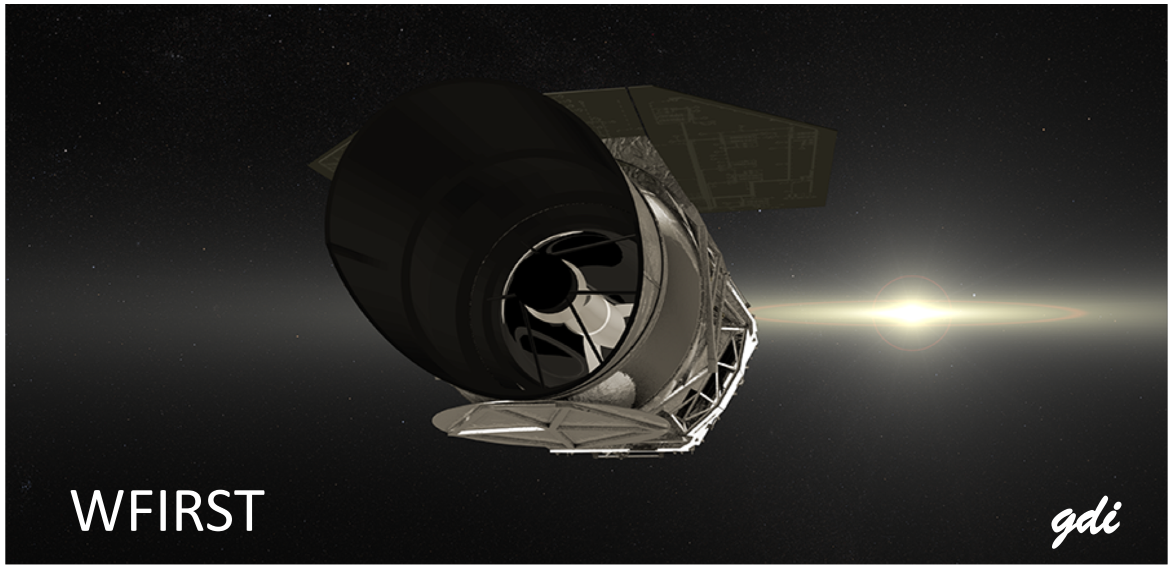
NASA ESA CSA

gdi

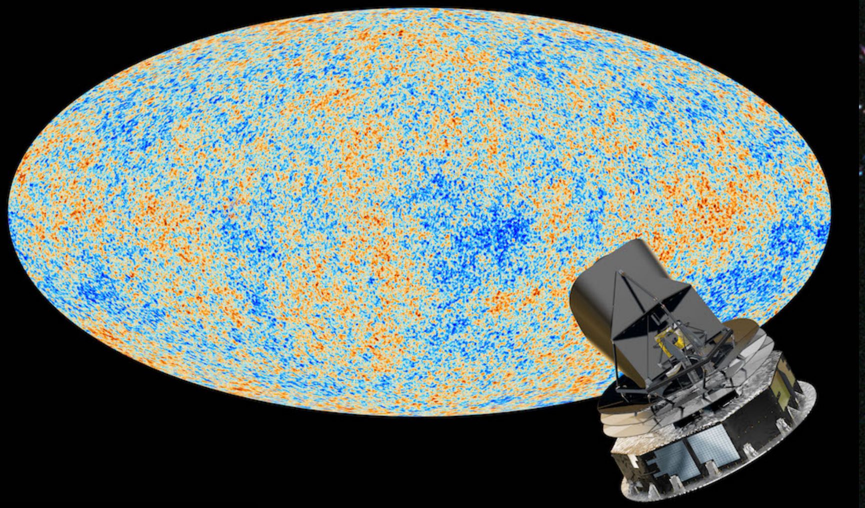
our "first galaxy epoch" telescopes



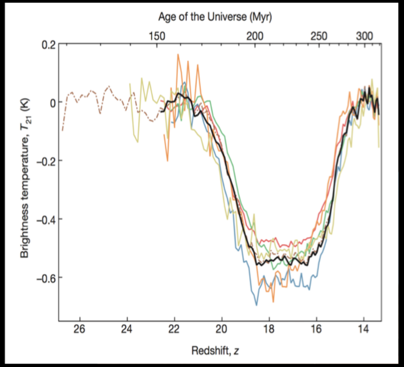




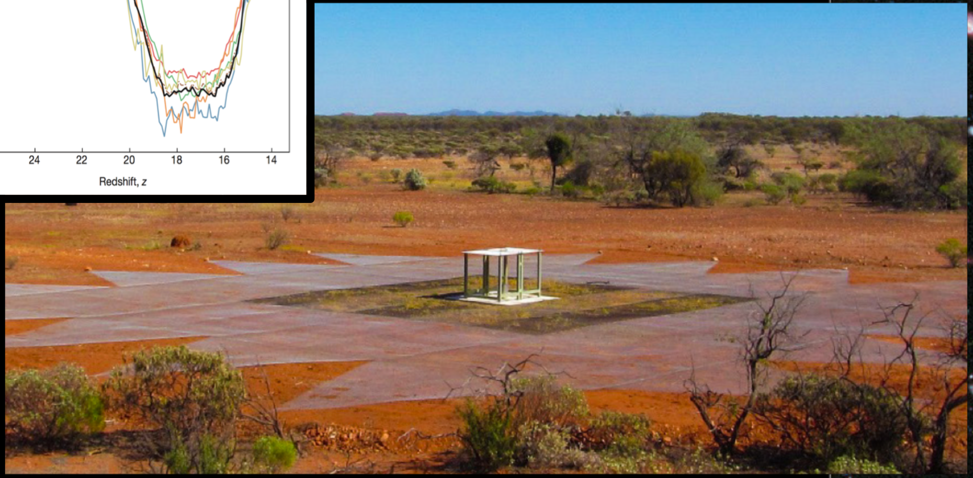
insight into the epoch of the first galaxies

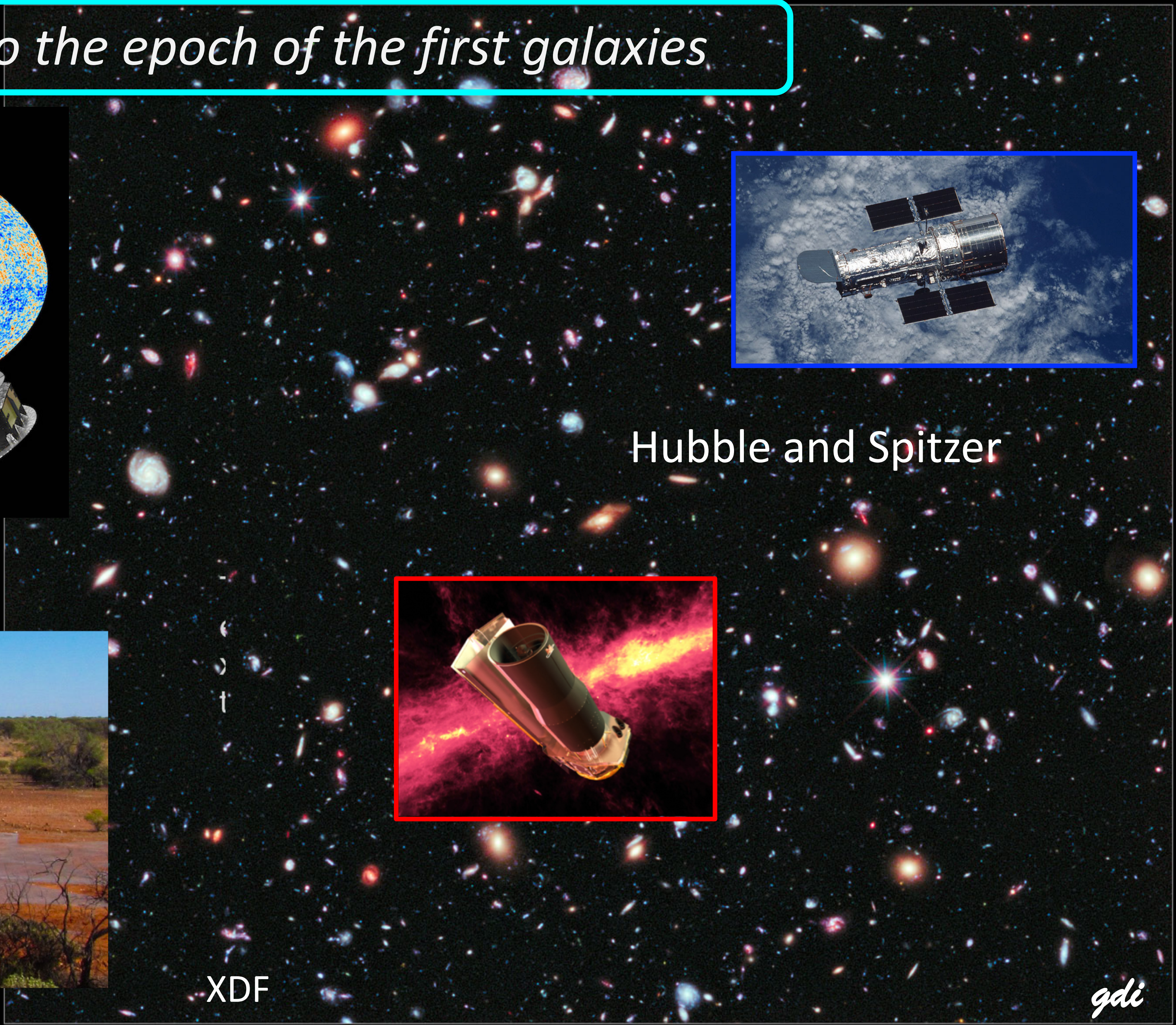


Planck



EDGES





what constraints do we have on the first galaxies?

searching for the earliest galaxies

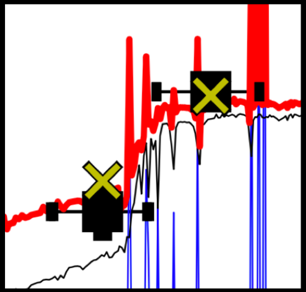
gdi

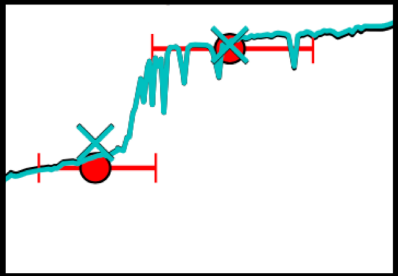
MACS1149–JD1

z=9.11 from ALMA [OIII]

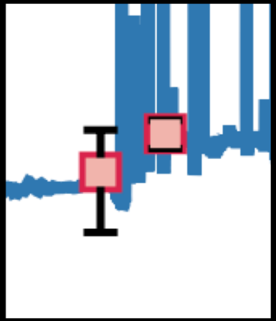
comparison of IRAC measurements from three different groups

Hashimoto+ & Katz+ IRAC color
3.6-4.5 = 0.91±0.18
** this is ~5σ **

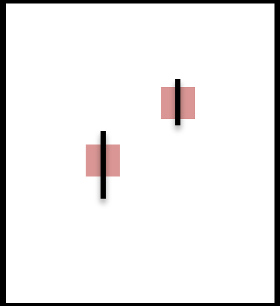




Shipley+ IRAC color
3.6-4.5 ~ 0.3±0.?
** this is ~1σ **



our recent IRAC color
3.6-4.5 = 0.51±0.26
** this is ~2σ **



the inconsistencies in the IRAC photometry need to be resolved

vertical scales are ~same – horizontal differ

gdi