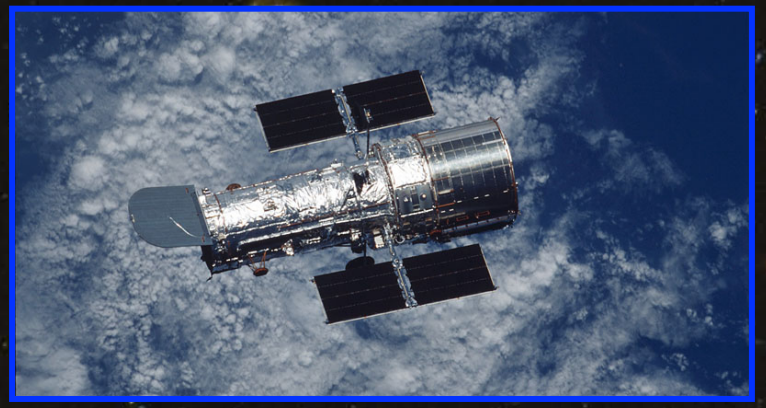
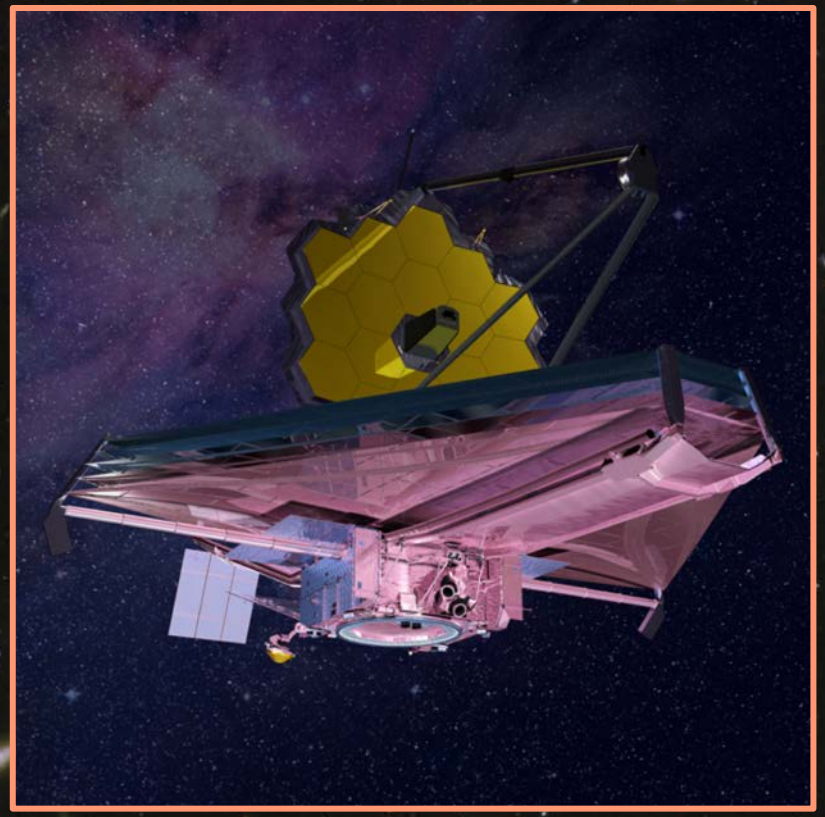


John N. Bahcall Lecture
National Air and Space Museum
March 14 2018



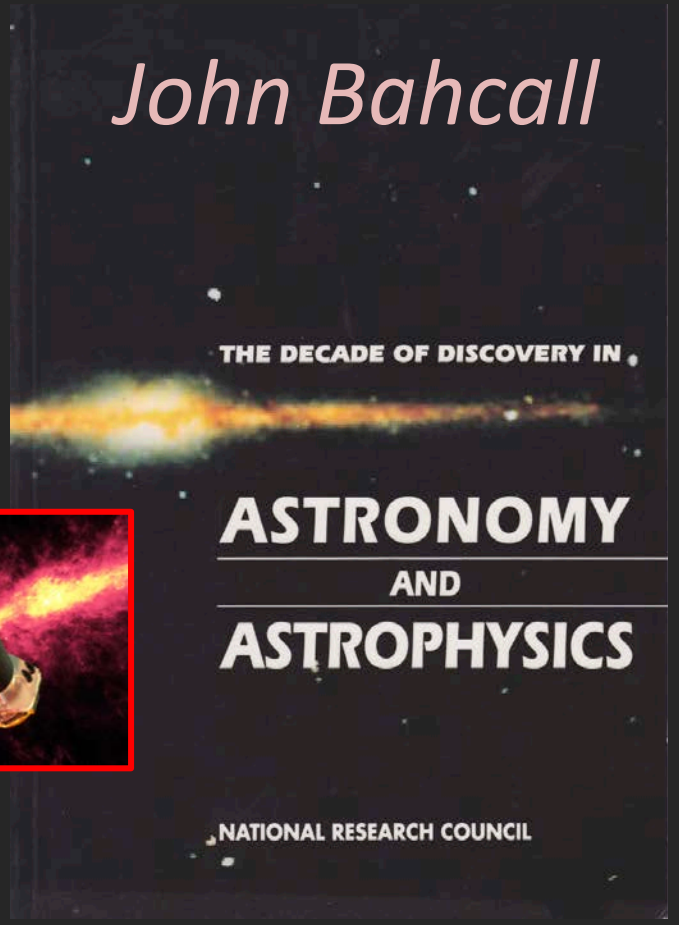
The Earliest Galaxies: Exploring Cosmic Sunrise with Hubble, Spitzer, and JWST

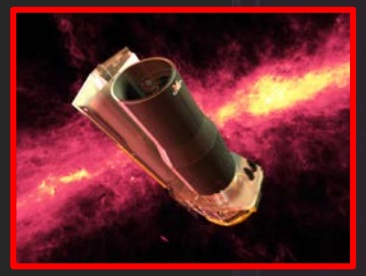
Garth Illingworth
University of California Santa Cruz

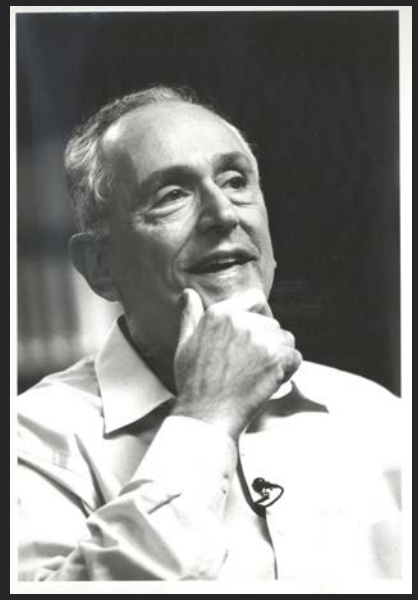
firstgalaxies.org

figure credit: Adolf Schaller

John Bahcall







1970s—1980s John's continuing efforts to support Hubble were crucial and inspiring – and a model for what was needed from scientists for a major mission to be successful

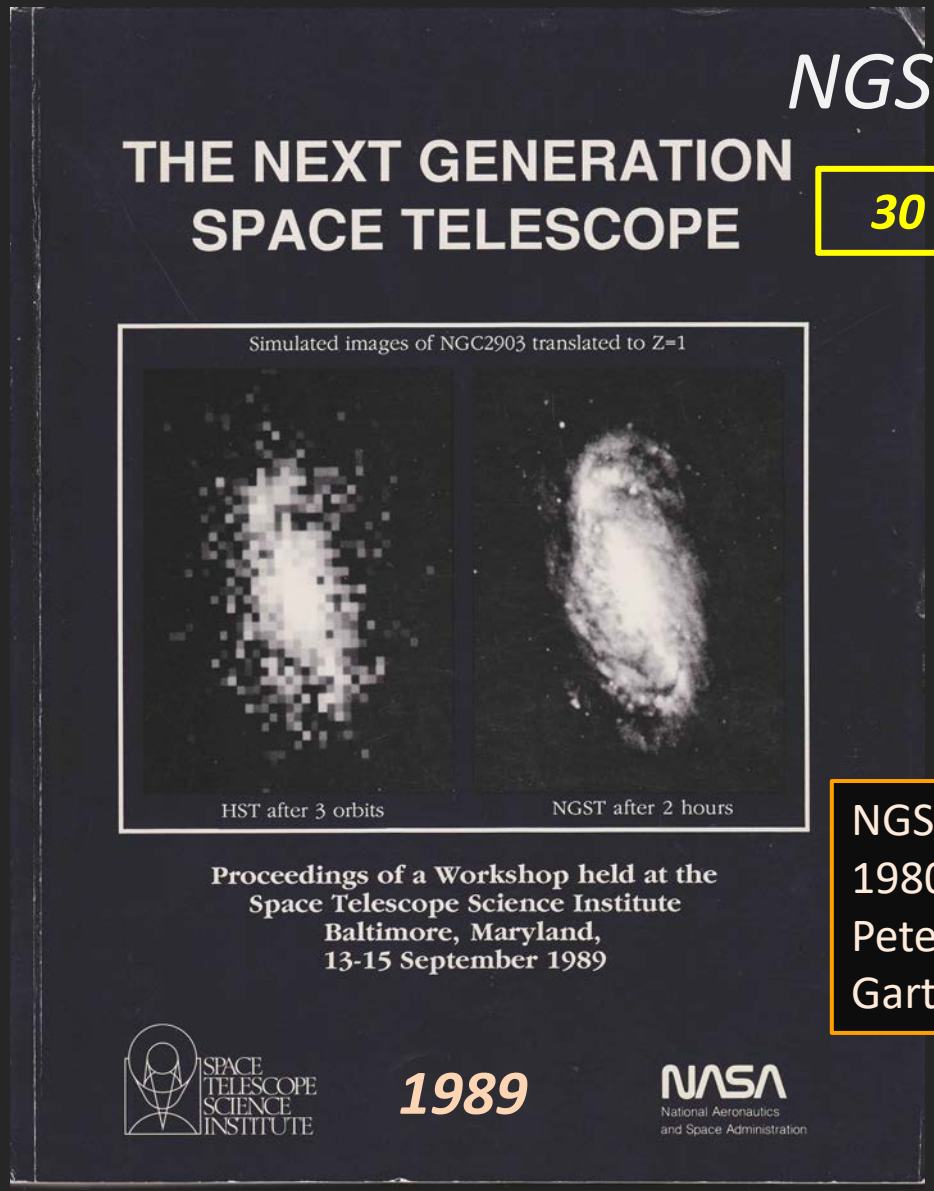
1989 – John's introductory remarks and participation in the Next Generation Space Telescope workshop

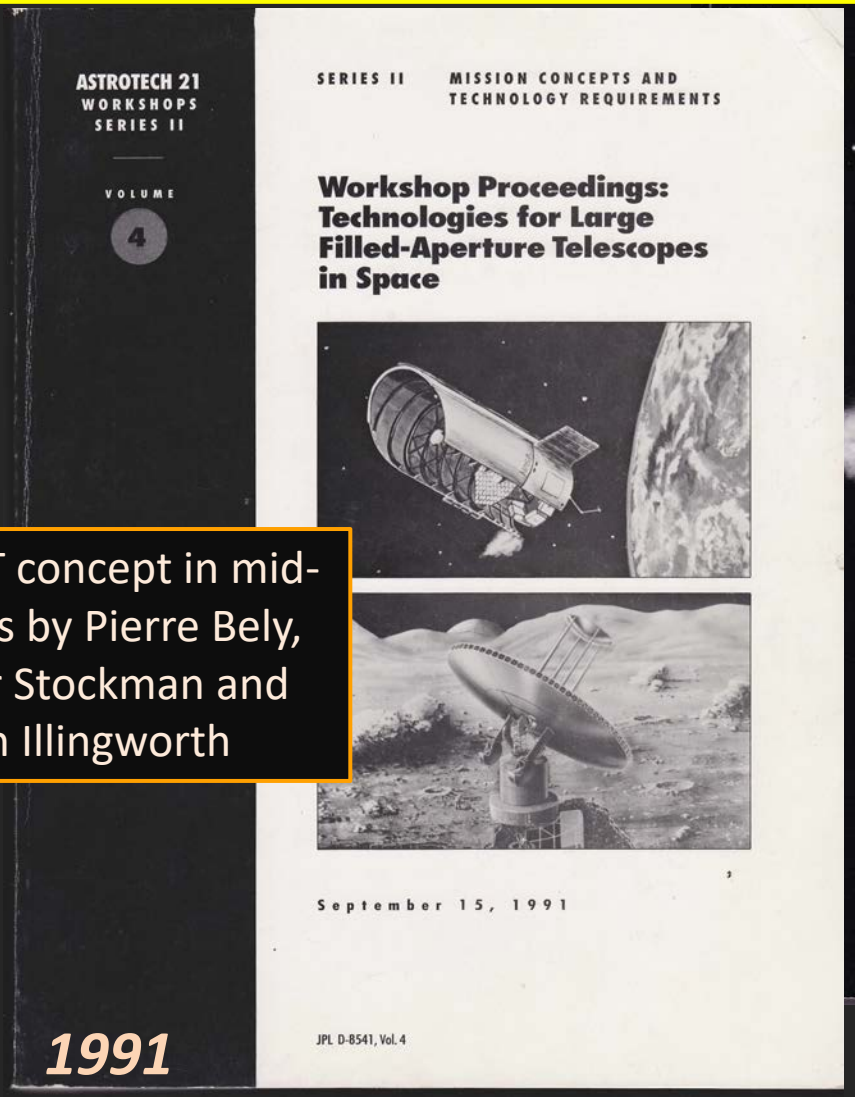
1991 – John was Chair, Astronomy Decadal Survey. I was Chair of UV-Optical in Space Panel.

gdi

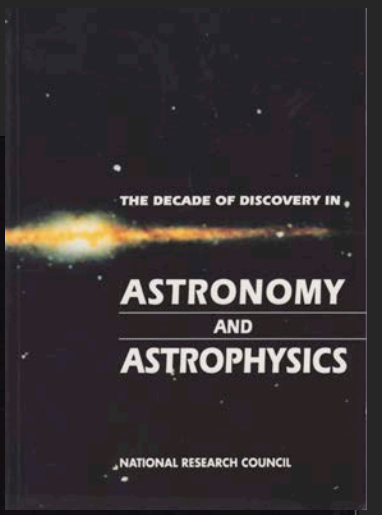
NGST ⇨ JWST – key early events

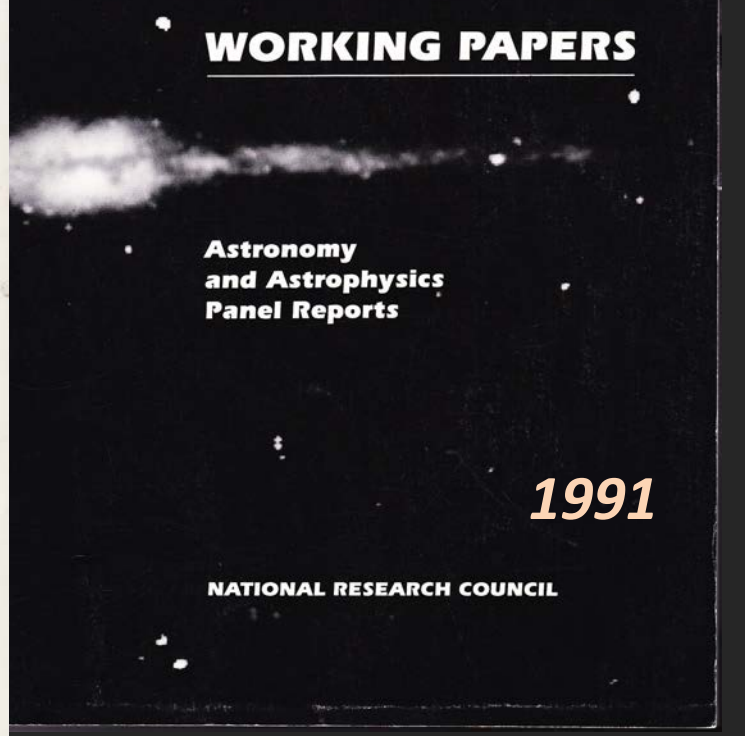
30 years from NGST mission concept to JWST launch!





NGST concept in mid-1980s by Pierre Bely, Peter Stockman and Garth Illingworth





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

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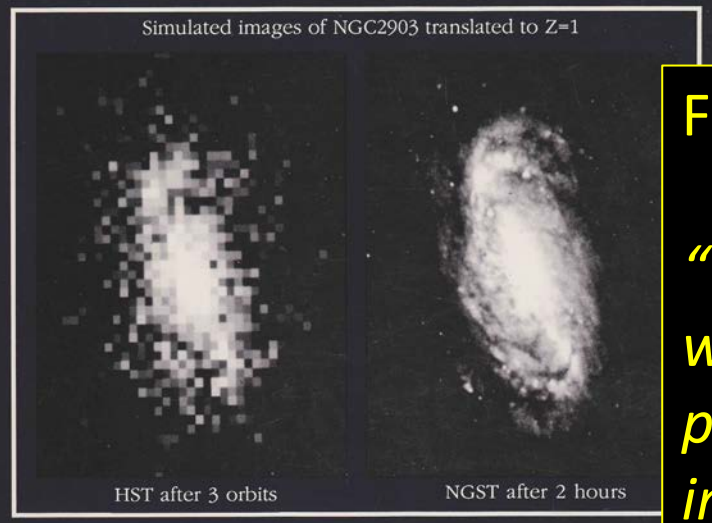
NGST ⇨ JWST – key early events

30 years from NGST mission concept to JWST launch!

THE NEXT GENERATION SPACE TELESCOPE



Proceedings of a Workshop held at the Space Telescope Science Institute Baltimore, Maryland, 13-15 September 1989

SPACE TELESCOPE SCIENCE INSTITUTE

1989

ASTROTECH 21 WORKSHOPS SERIES II

SERIES II MISSION CONCEPTS AND TECHNOLOGY REQUIREMENTS

THE DECADE OF DISCOVERY IN ASTRONOMY AND ASTROPHYSICS

1991

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)*

see 2016 STScI Newsletter ar
NGST: The Early Days of JWS
newsletter.stsci.edu/early-w

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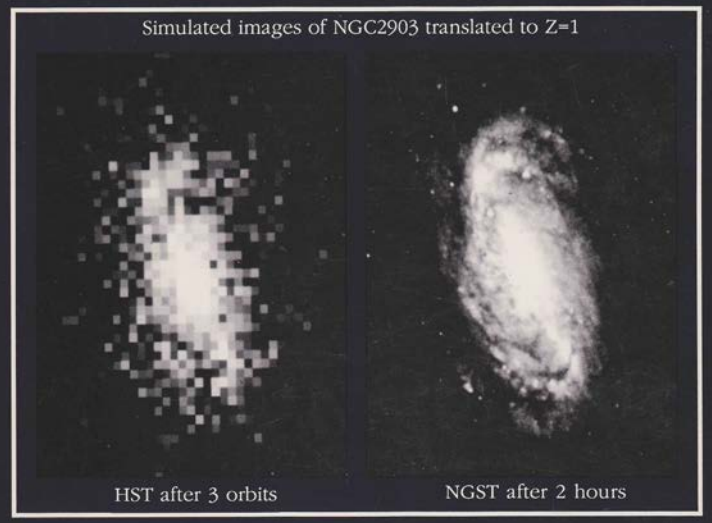
NGST ⇨ JWST – key early events

30 years from NGST mission concept to JWST launch!

THE NEXT GENERATION SPACE TELESCOPE



Proceedings of a
Space Telesco
Baltimo
13-15 Se

SPACE TELESCOPE SCIENCE INSTITUTE

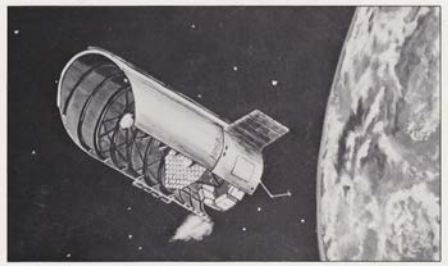
1

ASTROTECH 21
WORKSHOPS
SERIES II

VOLUME 4

SERIES II MISSION CONCEPTS AND TECHNOLOGY REQUIREMENTS

Workshop Proceedings: Technologies for Large Filled-Aperture Telescopes in Space



THE DECADE OF DISCOVERY IN

ASTRONOMY AND ASTROPHYSICS

NATIONAL RESEARCH COUNCIL

WORKING PAPERS

Astronomy and Astrophysics Panel Reports

1991

COUNCIL

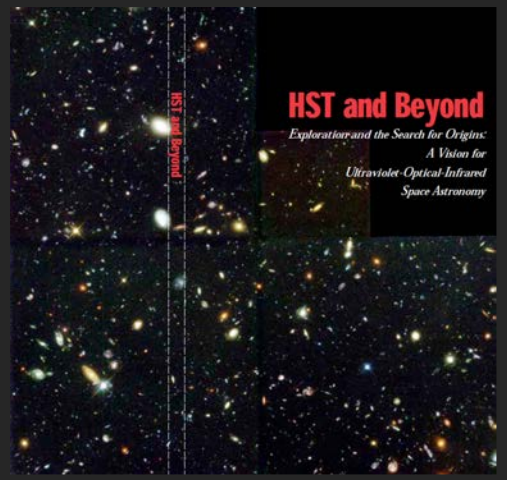
1990 Decadal Survey: UV-Optical in Space Panel recommended:

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

see 2016 STScI News
NGST: The Early Days
newsletter.stsci.edu/

gdi

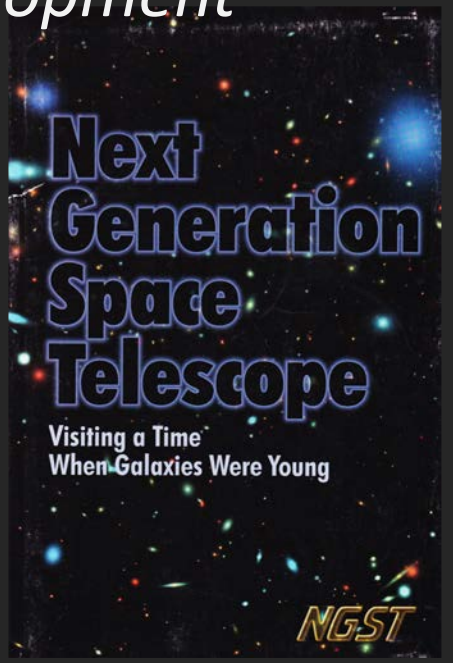
NGST ⇨ JWST – key steps in the 1990s leading to development



1996: *HST and Beyond* study (chair Alan Dressler) has 3 recommendations including an IR telescope "….of aperture 4 m or larger, optimized for imaging and spectroscopy over .... 1-5 μm."

1996: key step at American Astronomical Society meeting:

NASA Administrator Dan Goldin says: "I see Alan Dressler here. All he wants is a four meter optic that goes from a half micron to 20 microns. And I said to him, "Why do you ask for such a modest thing? Why not go after six or seven meters?"'"

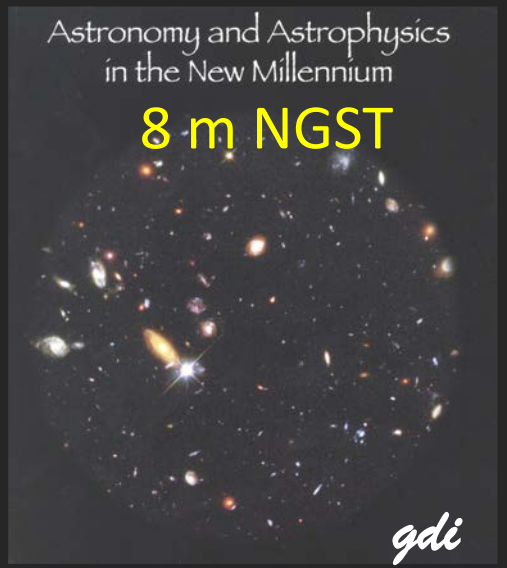


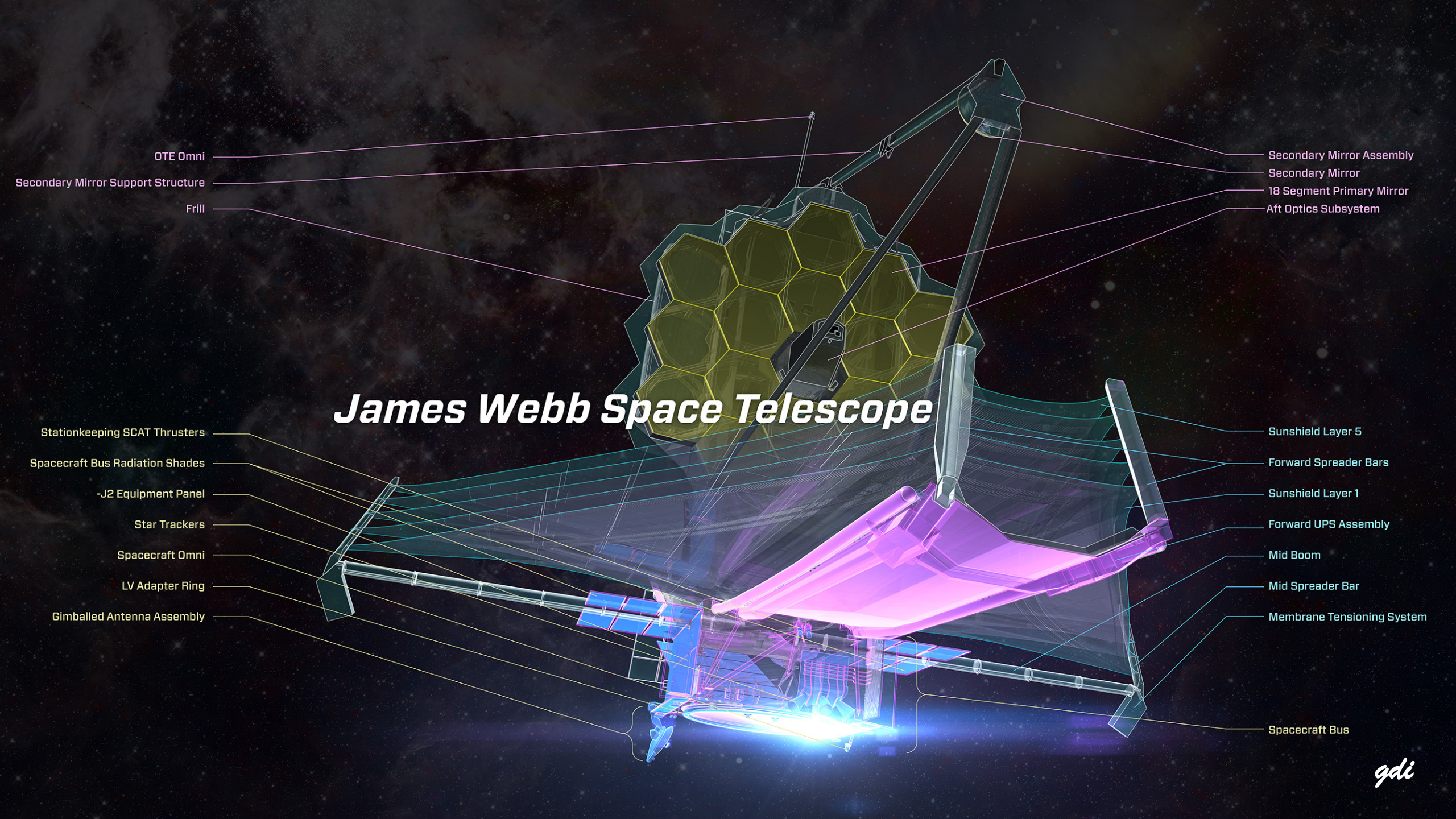
✓ Dan Goldin later says "go for 8 m" ✓

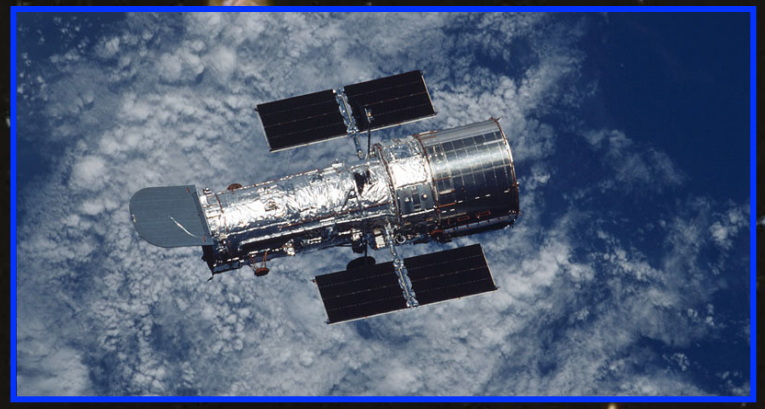
NASA Office of Space Science AA Ed Weiler requests that Goddard Space Flight Center (GSFC) study NGST
John Mather, and many others at GSFC, take NGST forward

1999: SMD AA Weiler signs Formulation Authorization
NASA initiates NGST

2000: Astronomy Decadal survey makes 8 m NGST top space project




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

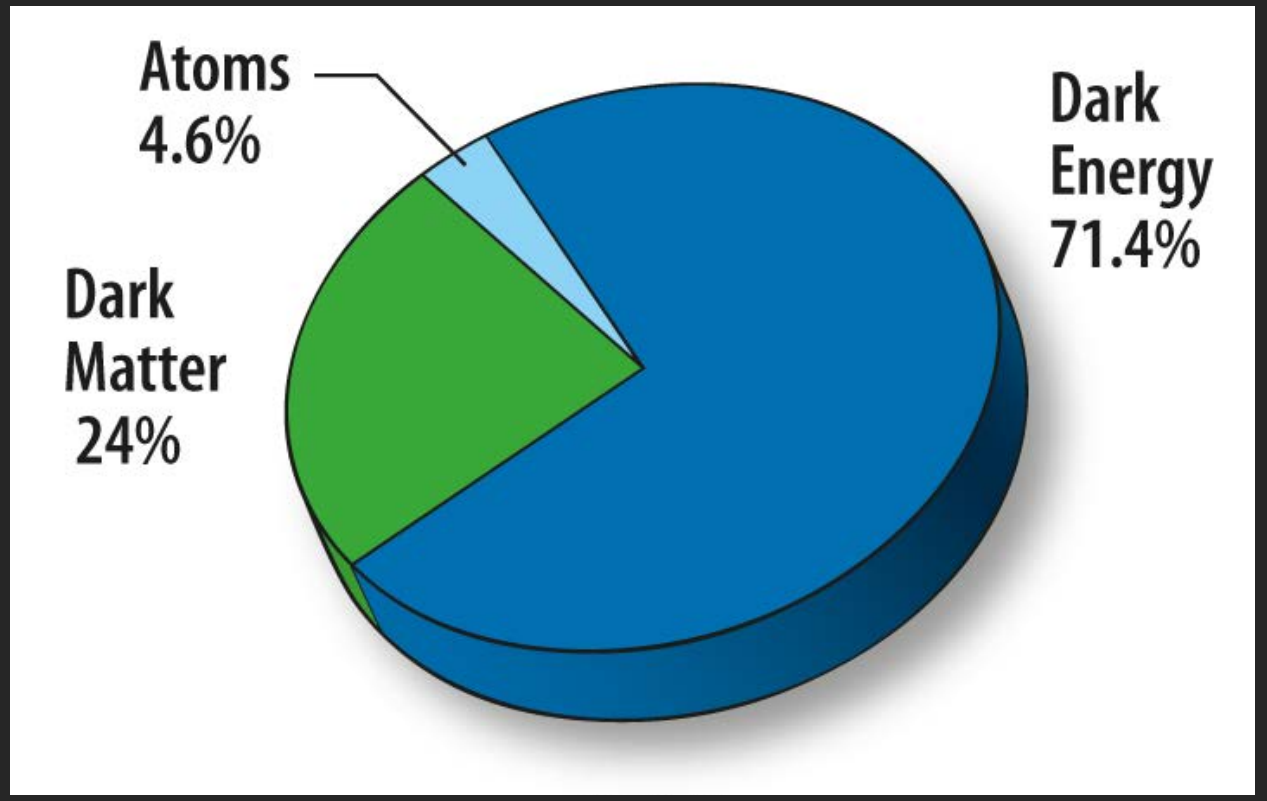


galaxies at cosmic dawn

gdi

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

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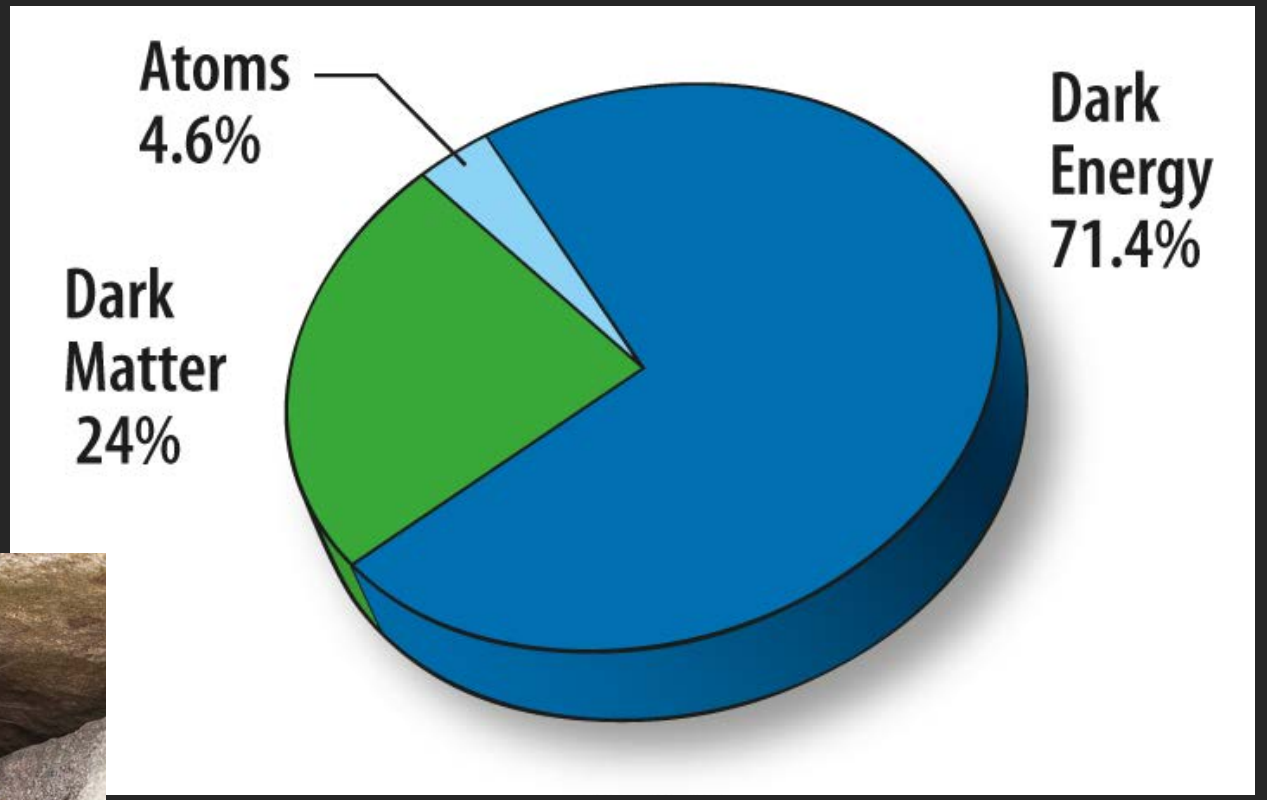

from WMAP and Planck telescopes

ordinary matter is, by comparison, a bit mousey…

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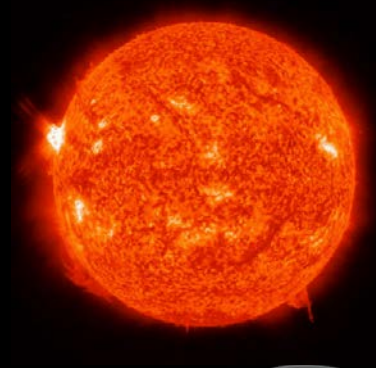
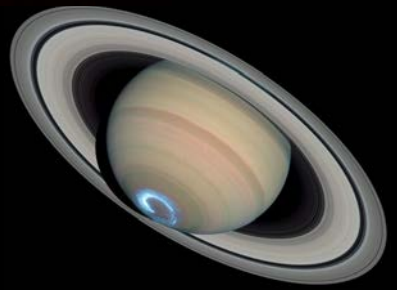
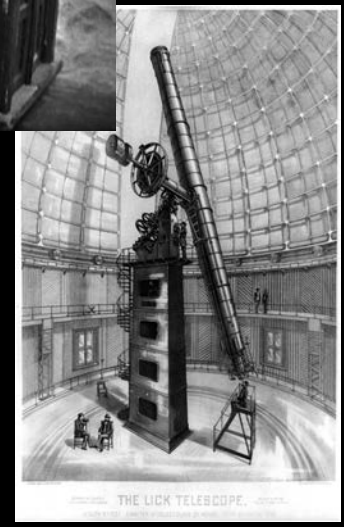
telescopes are “time machines”

8.3 min



71-88 min





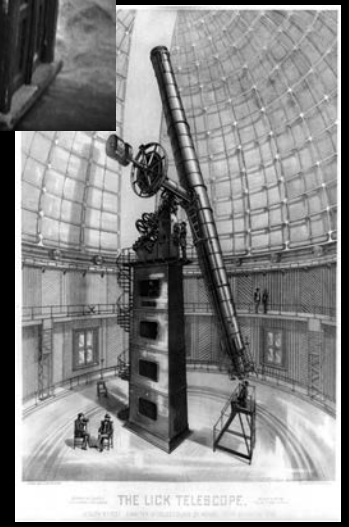
4.24 yrs

about 26,000 yrs

telescopes are “time machines”

2.54 million years

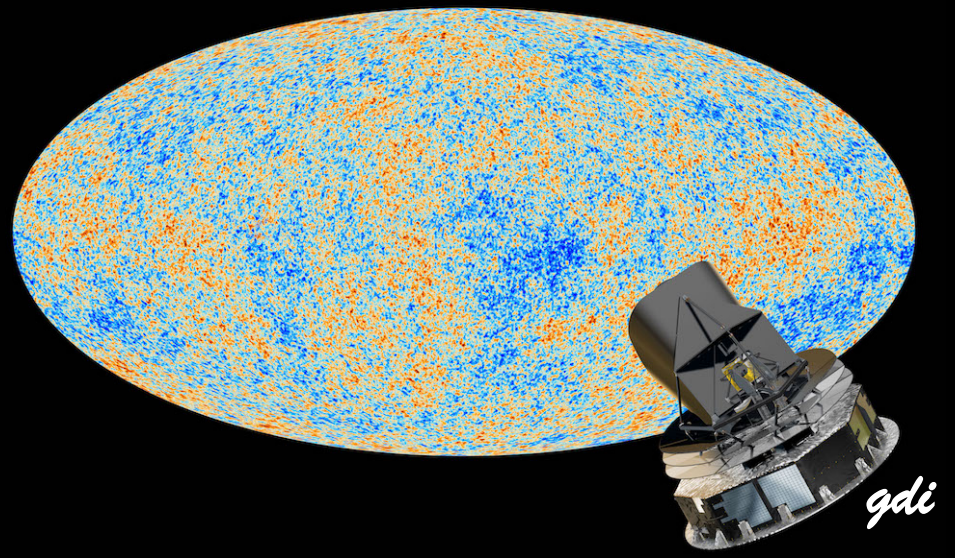
2.27 billion years



13.31 billion years

Gn-z11

13.72 billion years



gdi

GN-z11

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from the Big Dipper close by in our Milky Way to the most distance galaxy known (GN-z11)

history of everything

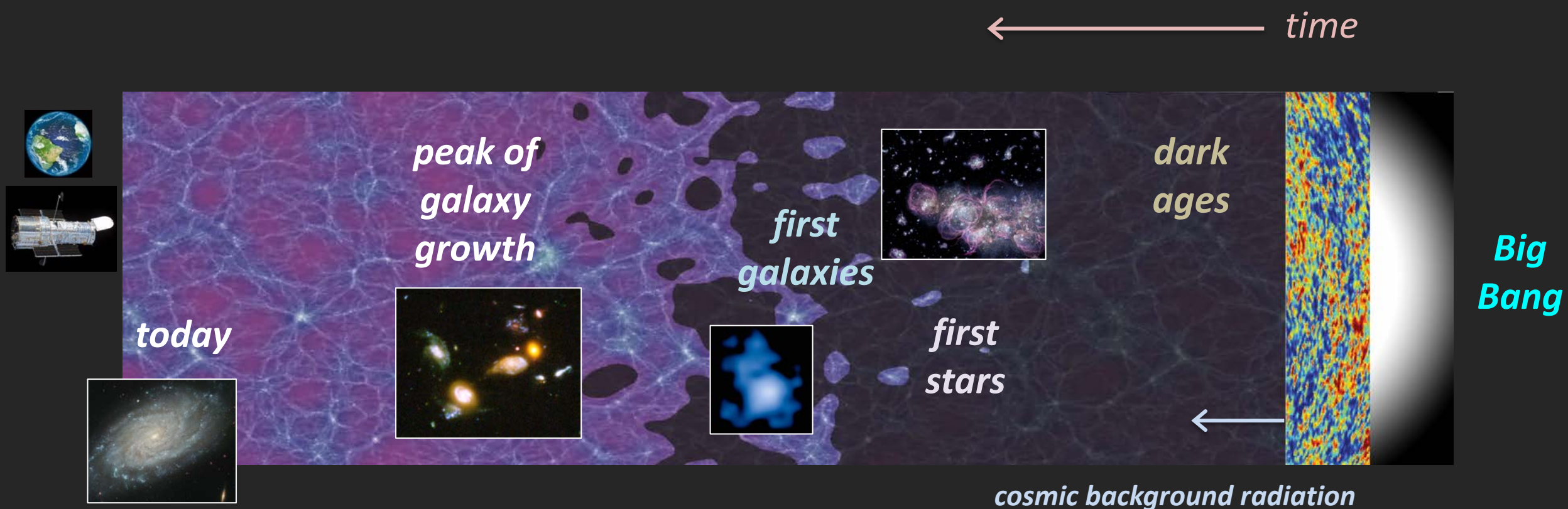

figure credit: insert adapted from Brant Robertson UCSC

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history of everything

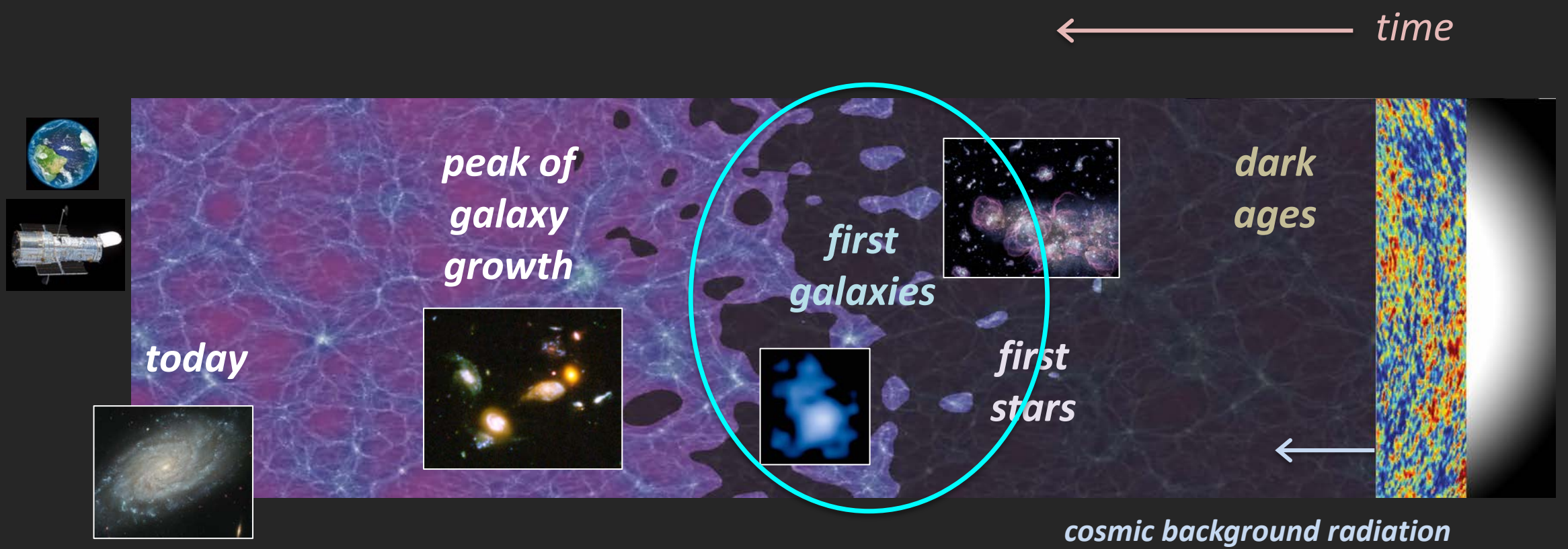

figure credit: insert adapted from Brant Robertson UCSC

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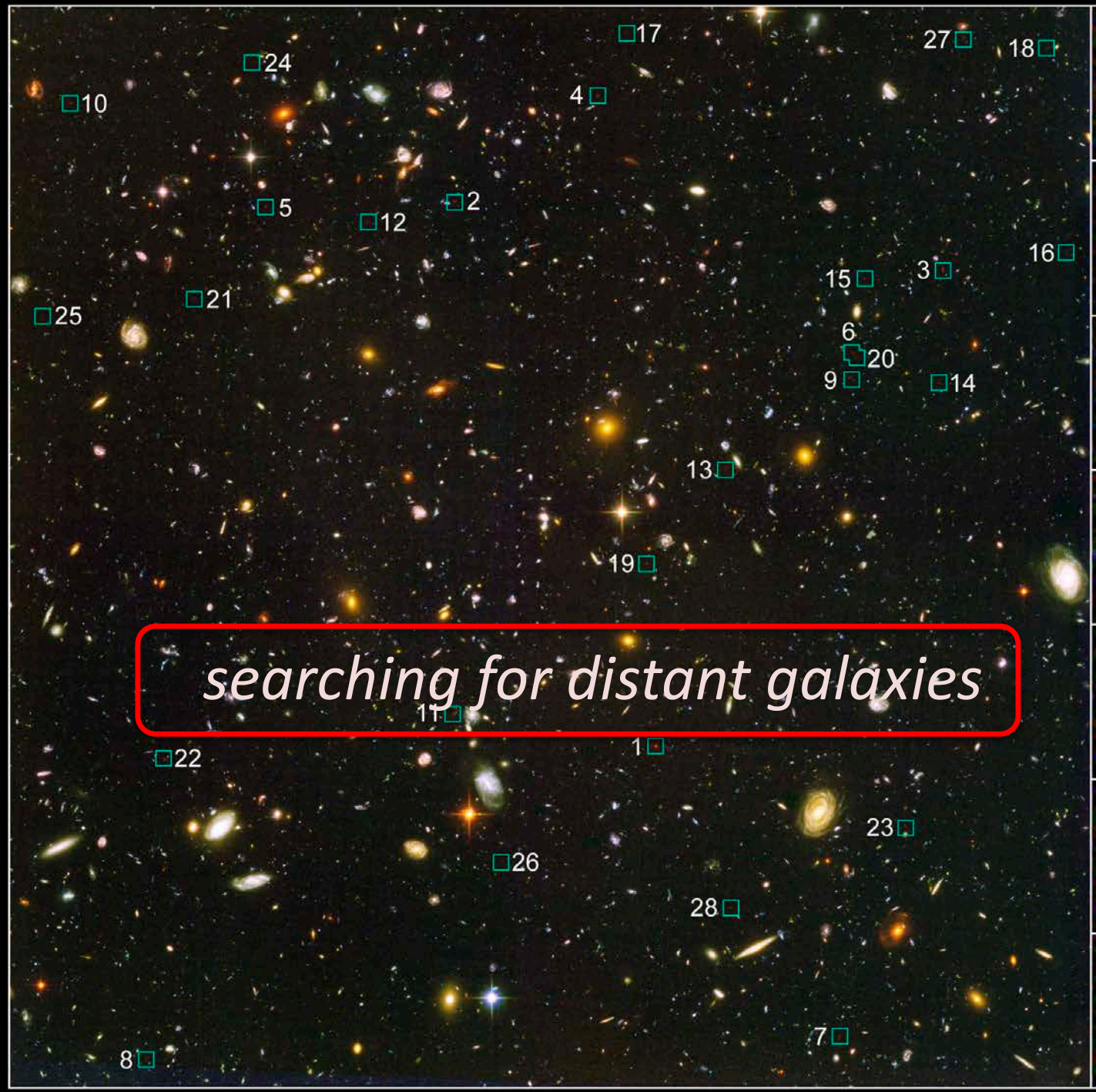

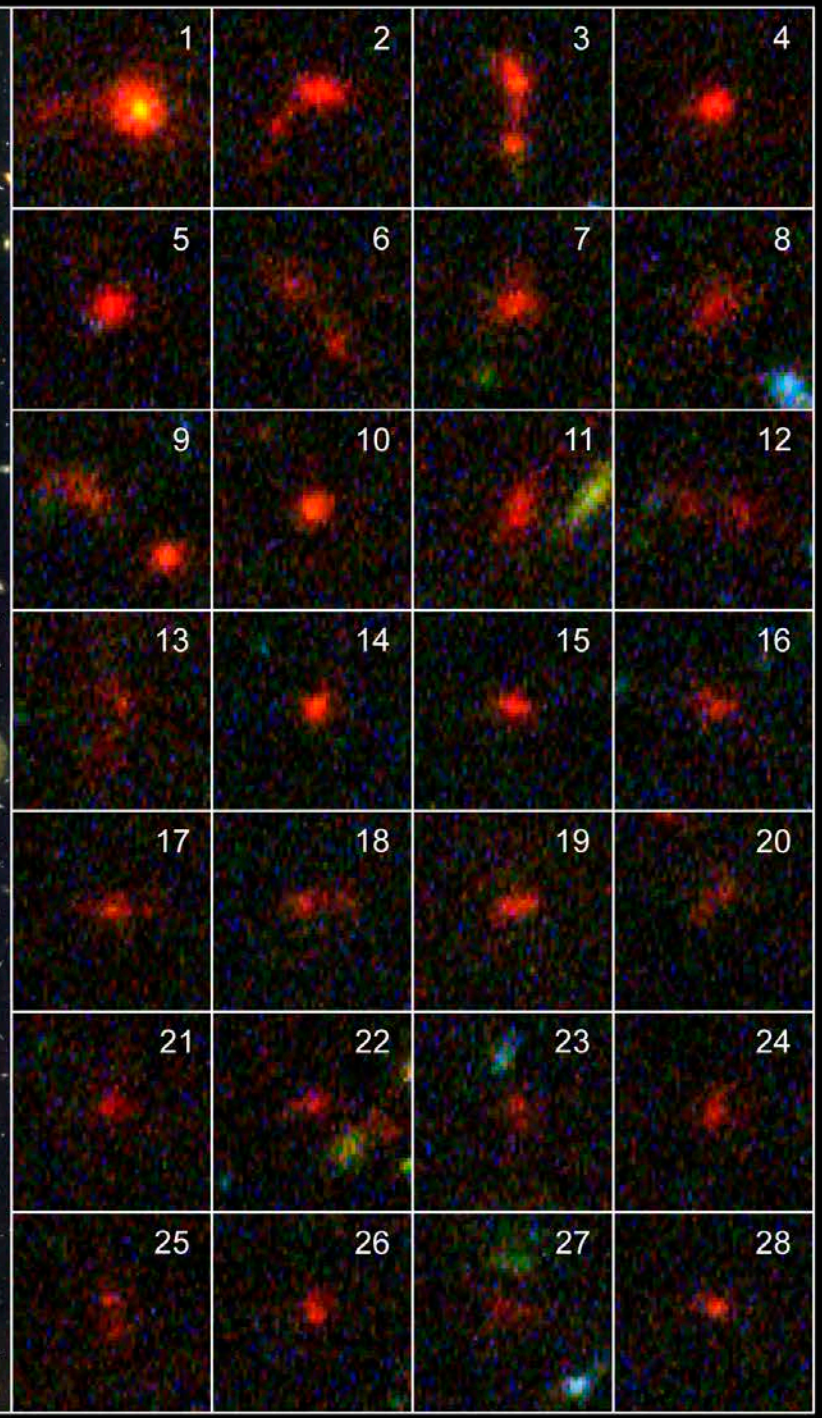

very distant galaxies look very red in our images

galaxies seen 12.9 billion years ago

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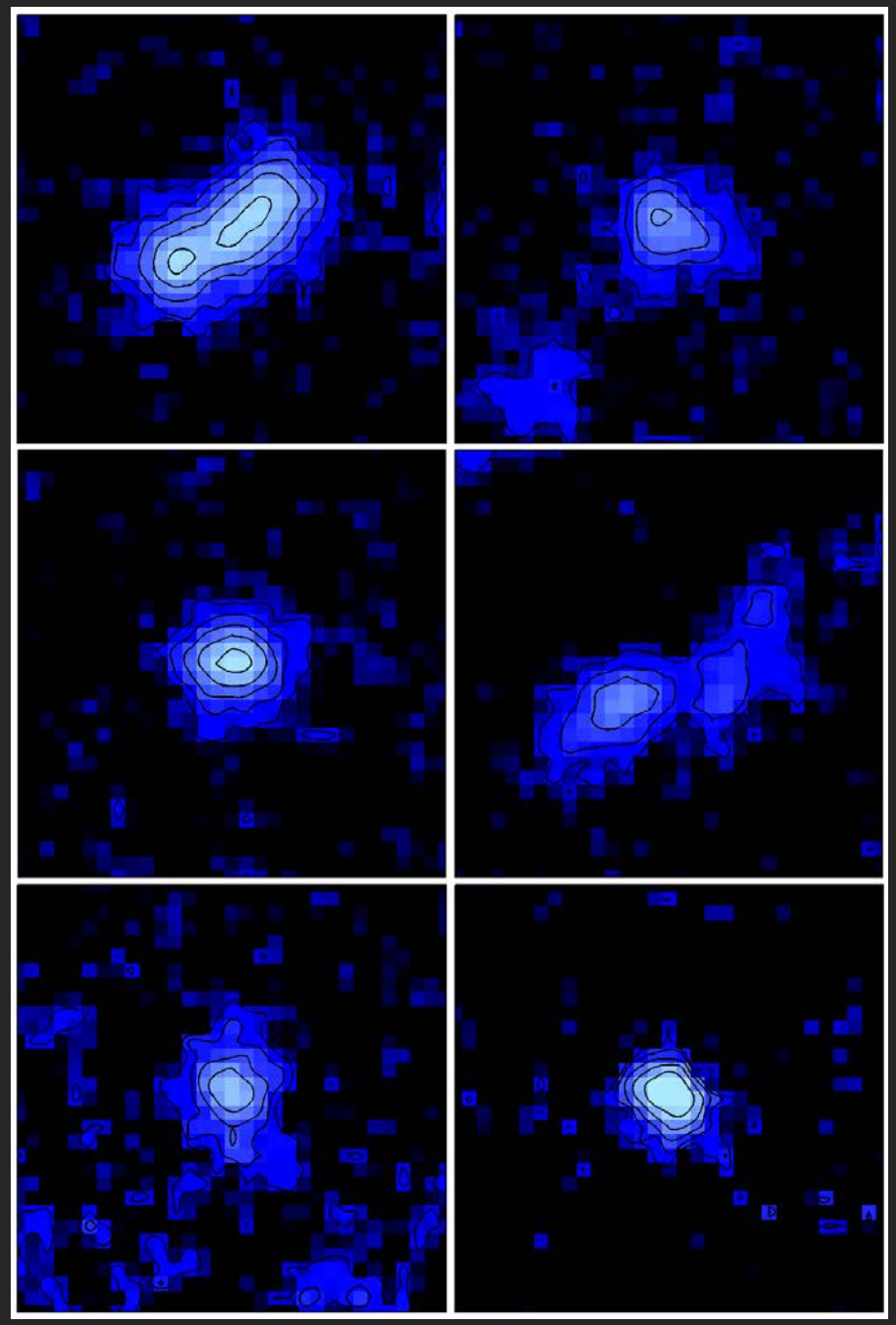


what some bright galaxies actually looked like 13 billion years ago!

they are not really red

they are actually very blue!

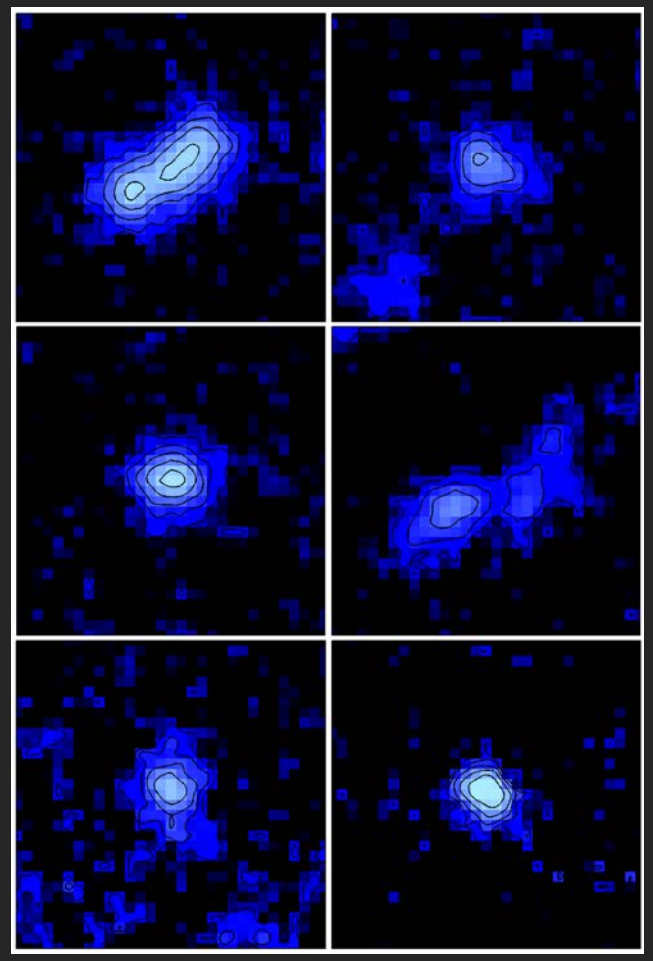
lots of hot young blue stars

gdi

galaxies in the first billion years

bright distant galaxies

5-10,000 light years



faint distant galaxies

100-500 light years

really tiny!

faint galaxies in the first billion years are measured to be very small

the "Milky Way" now

100,000 light years

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how we determine redshifts

for redshifts astronomers use "z"

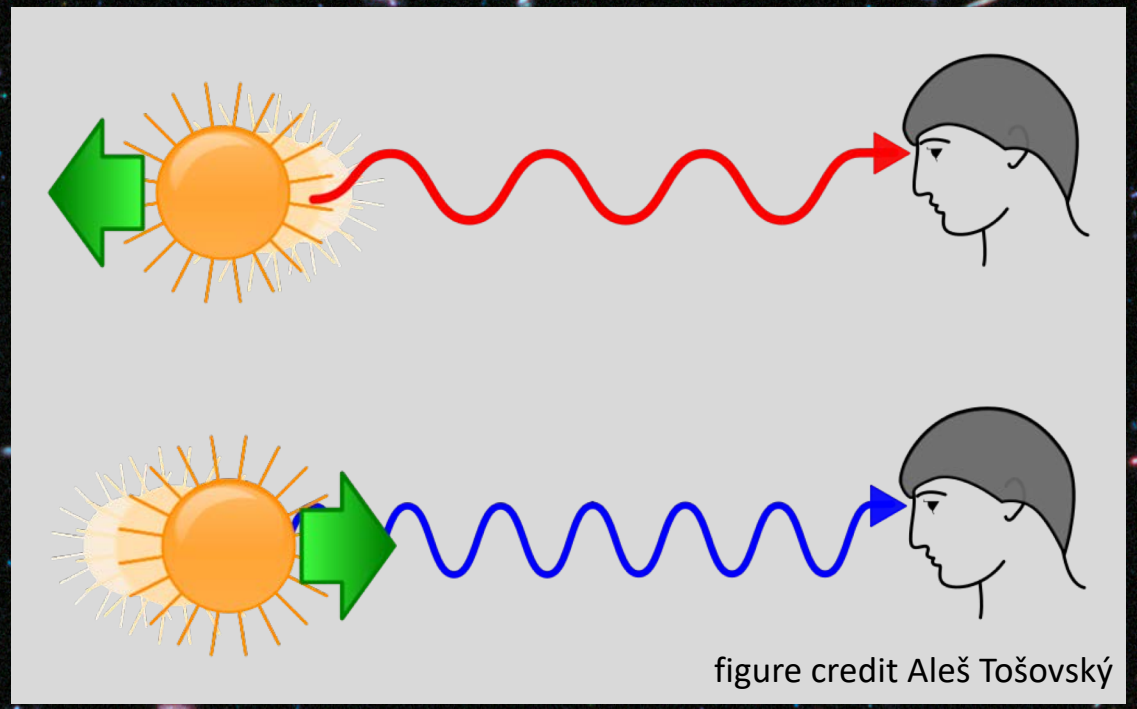
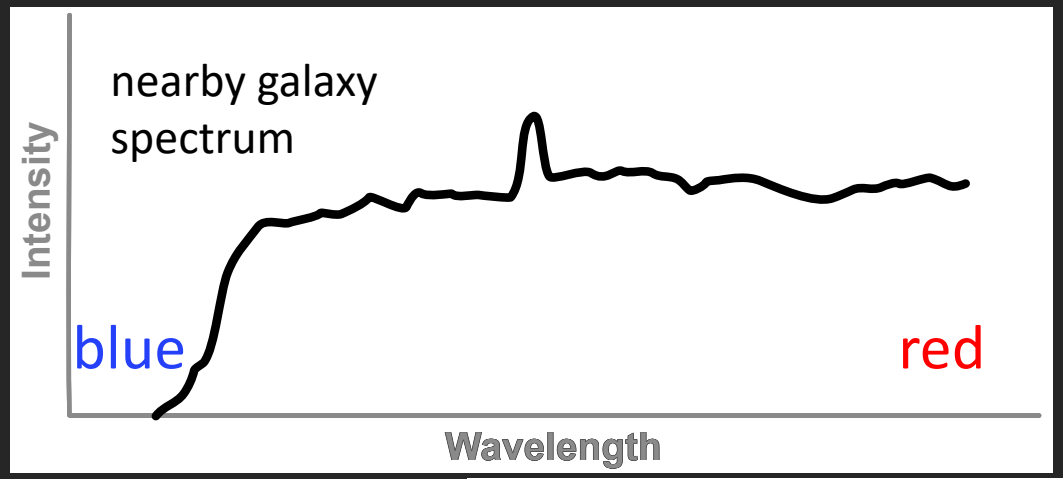
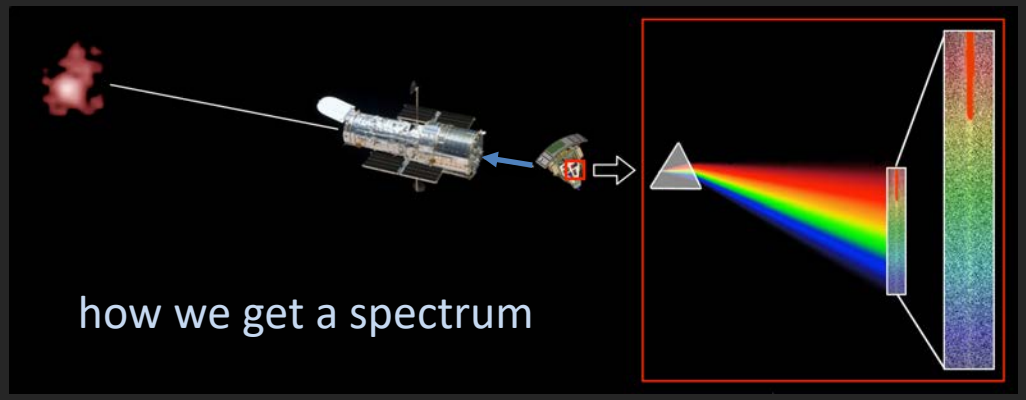


figure credit Aleš Tošovský

gdi



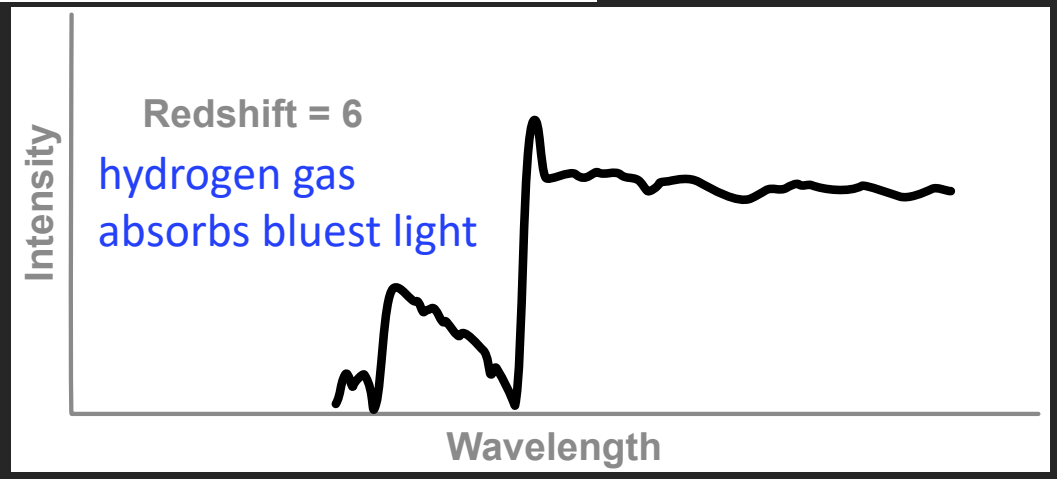
redshifts ("z")



hydrogen gas in the universe absorbs the bluest light (ultraviolet) light from galaxies

☞ find the break and it tells how fast the galaxy is moving

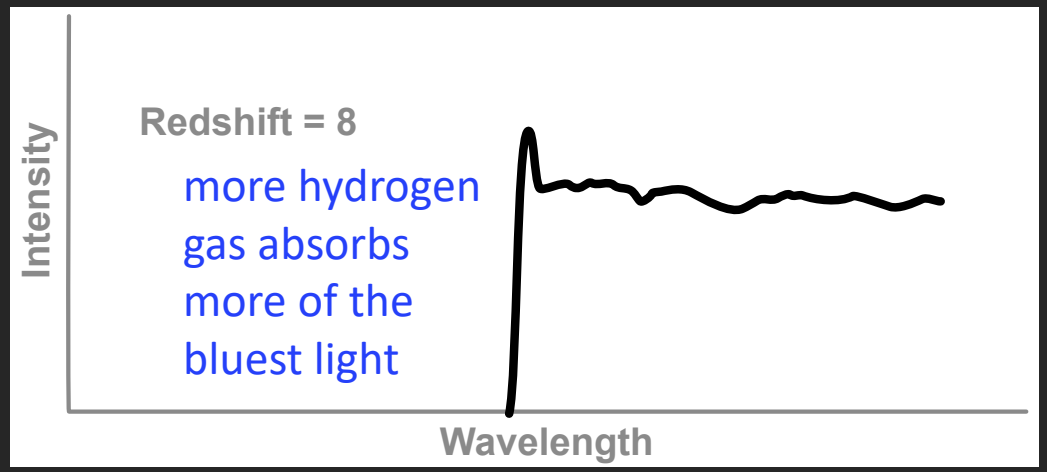
z=6 spectrum shifted to red



☞ change in wavelength gives redshift

at z=6 galaxy is moving away at 96% of the speed of light!

z=8 spectrum shifted even more to red



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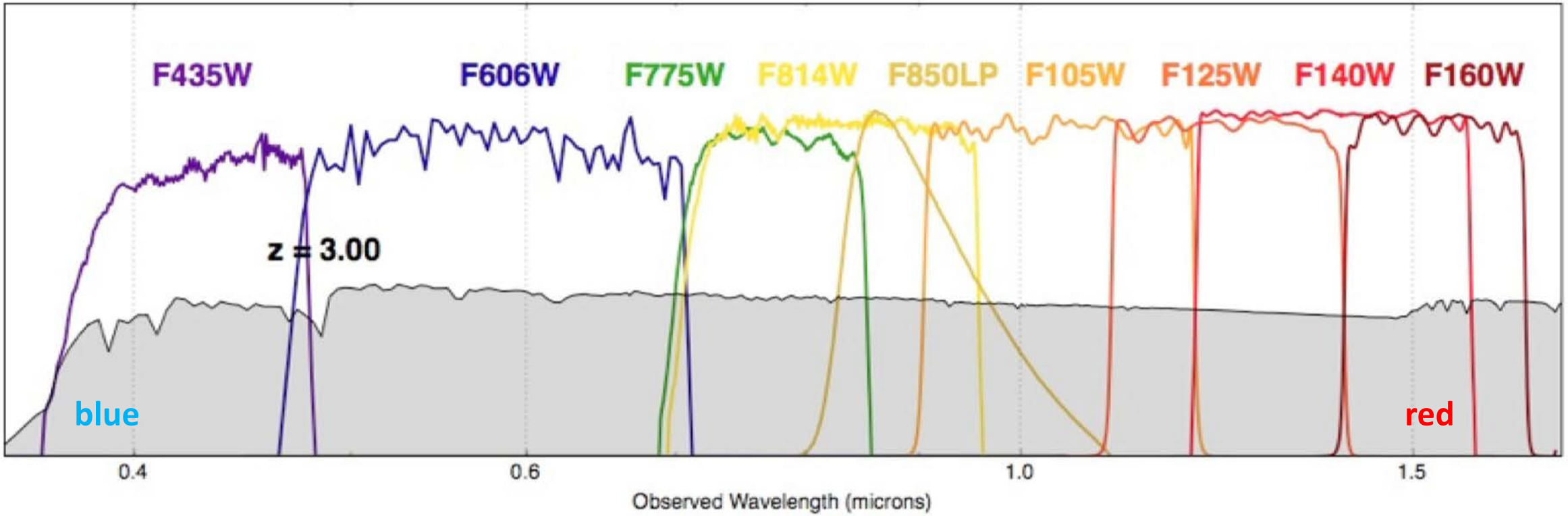

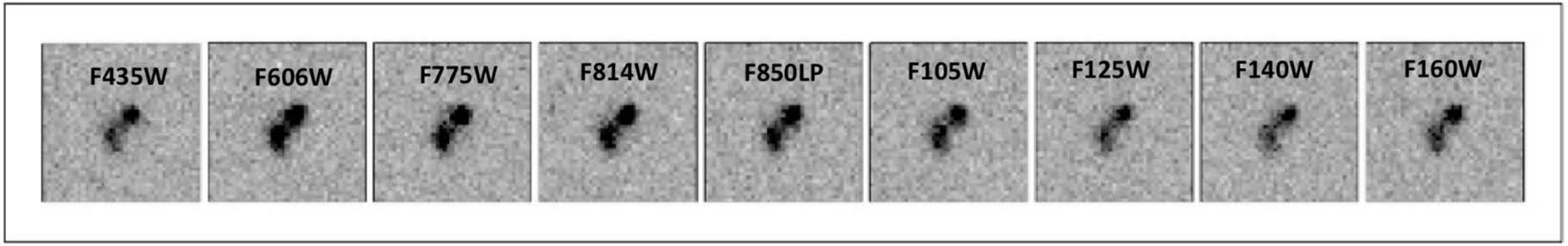

optical ACS

near-IR WFC3/IR

xdf.ucolick.org/

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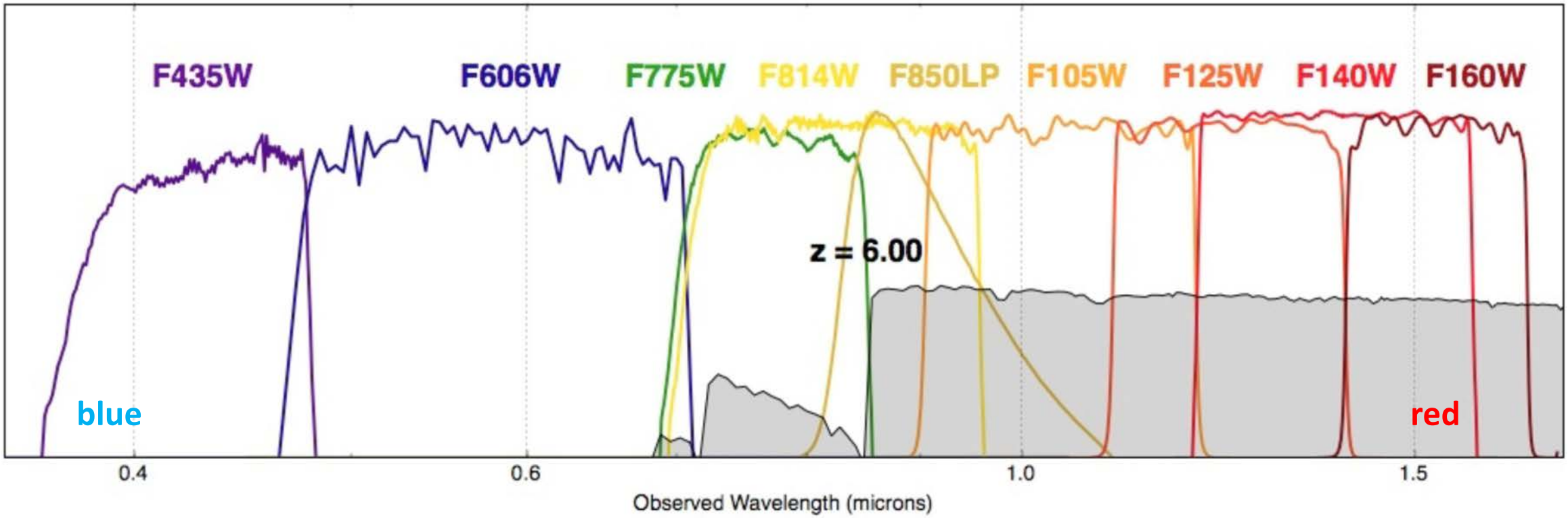
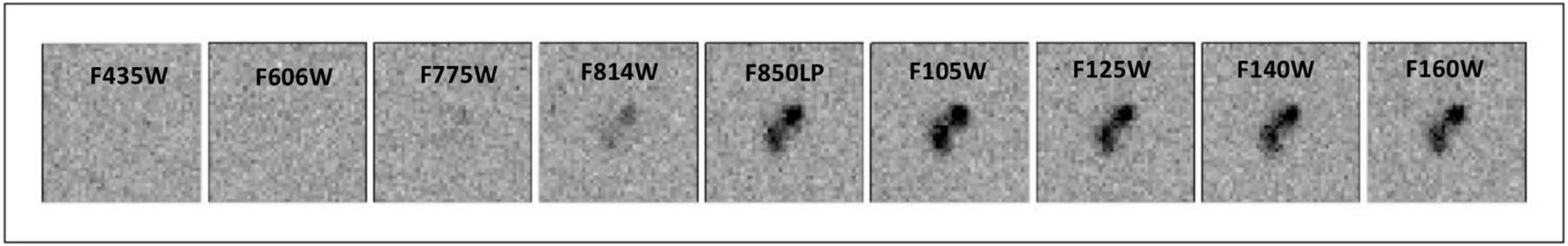
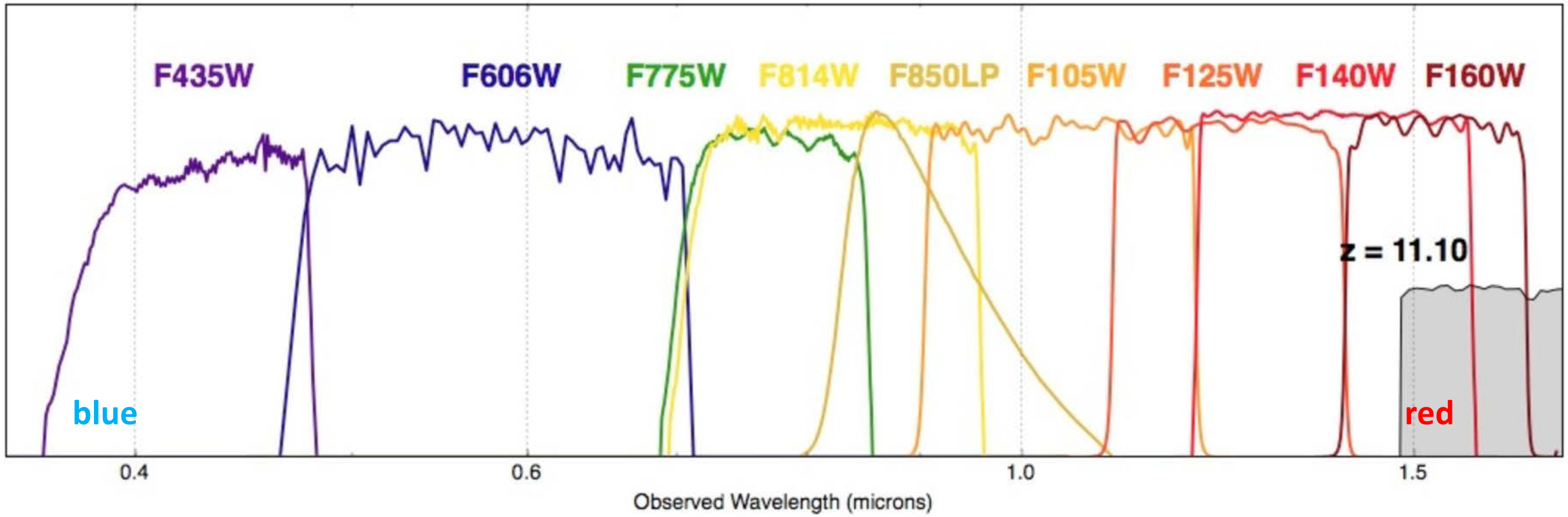


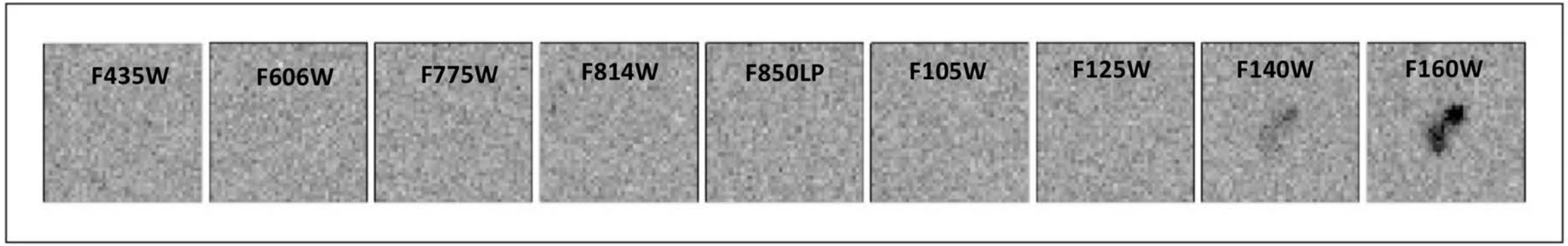


optical ACS

near-IR WFC3/IR

gdi



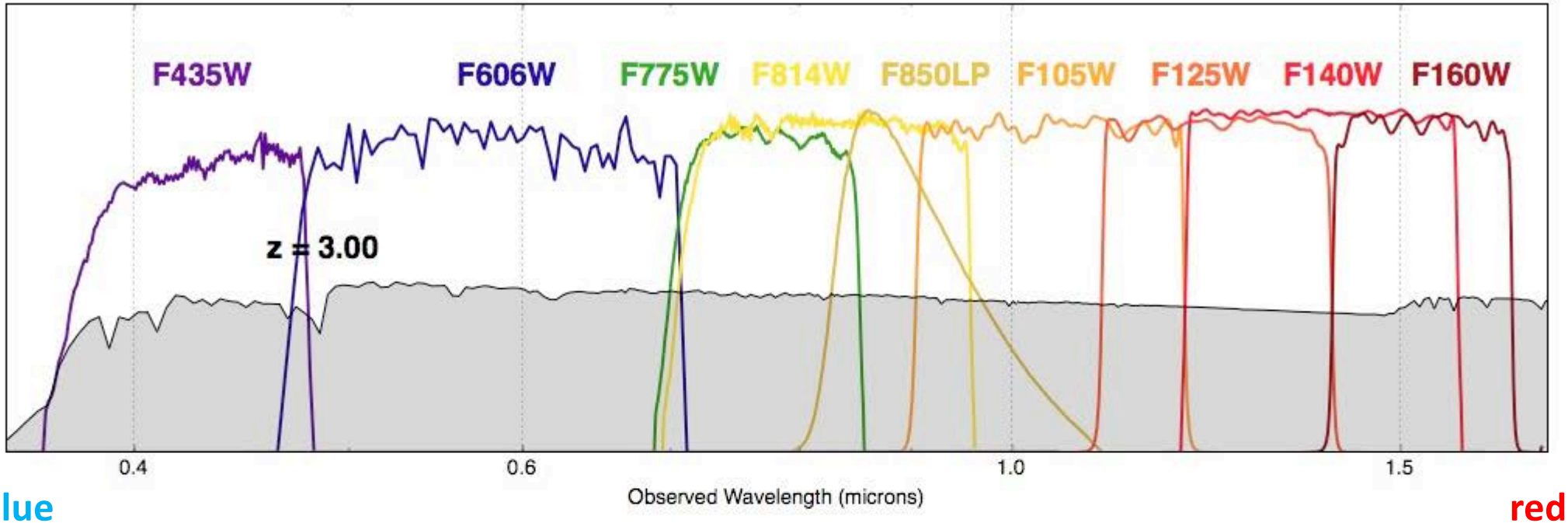


optical ACS

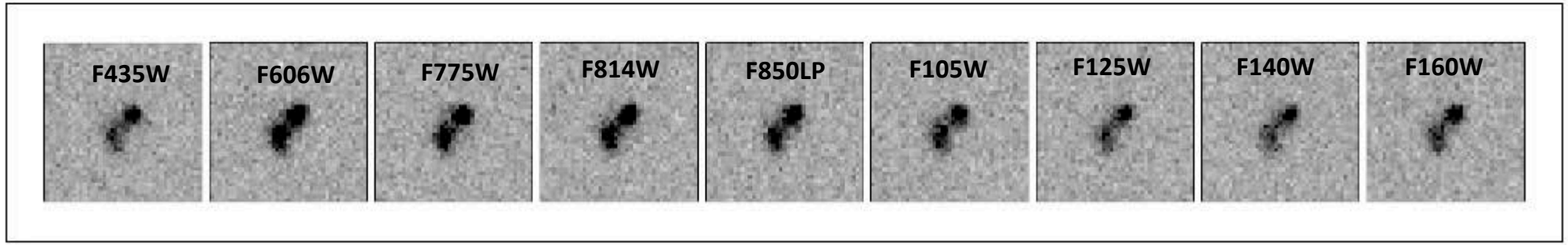
near-IR WFC3/IR

gdi

ACS+WFC3/IR: efficient redshifts to z~11



blue red



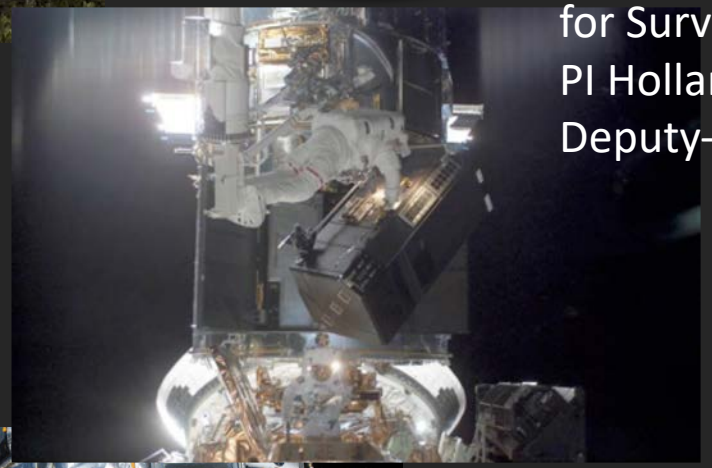
optical ACS

near-IR WFC3/IR

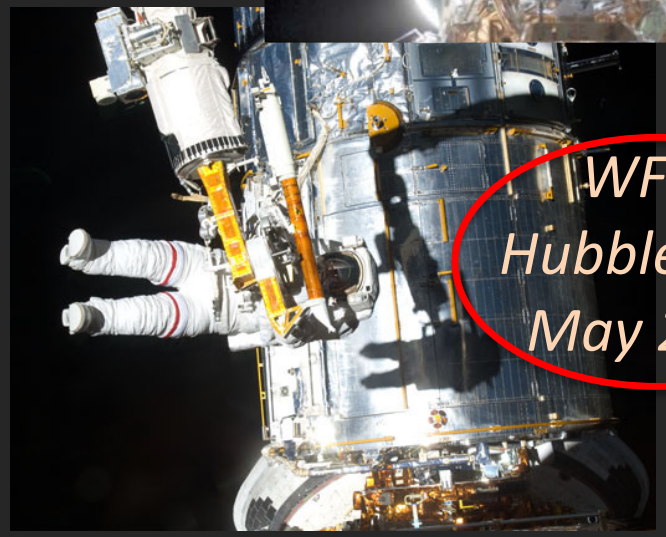
xdf.ucolick.org/

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

ACS
Hubble SM3B
Mar 2002

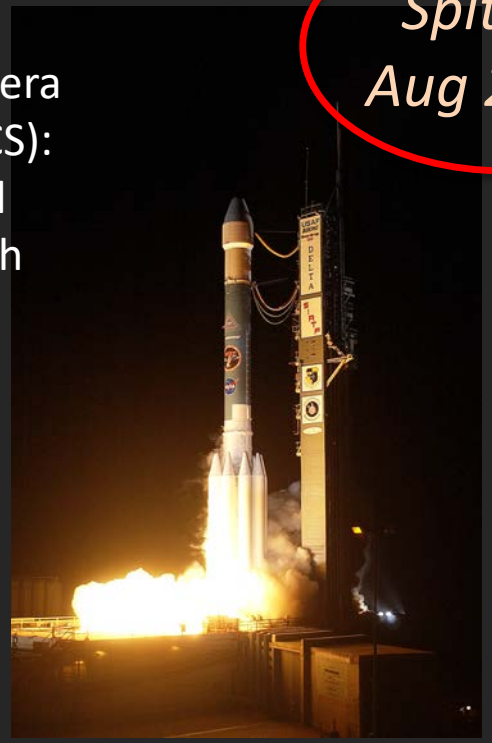


Advanced Camera for Surveys (ACS):
PI Holland Ford
Deputy-PI Garth



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

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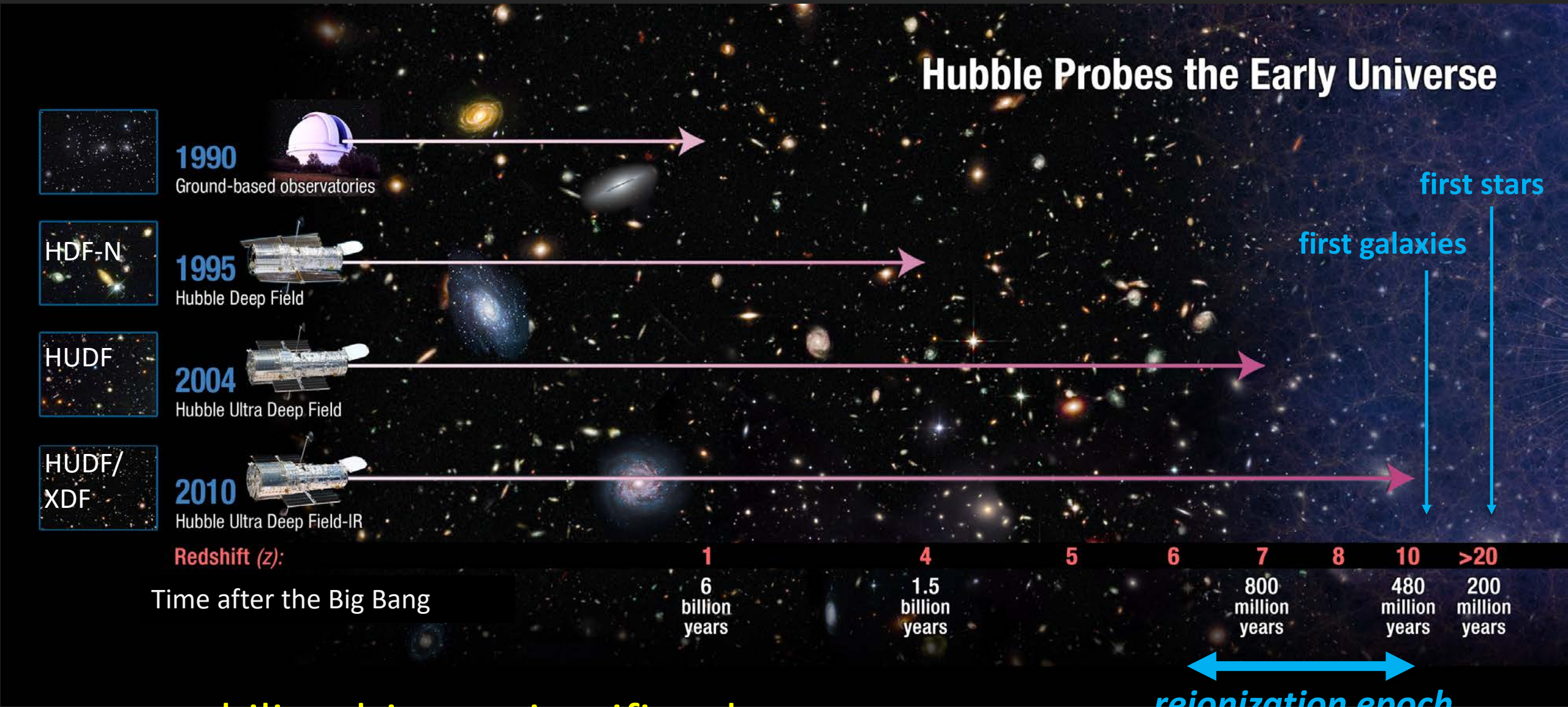
redshift limits increase with new capability



capability-driven scientific advances

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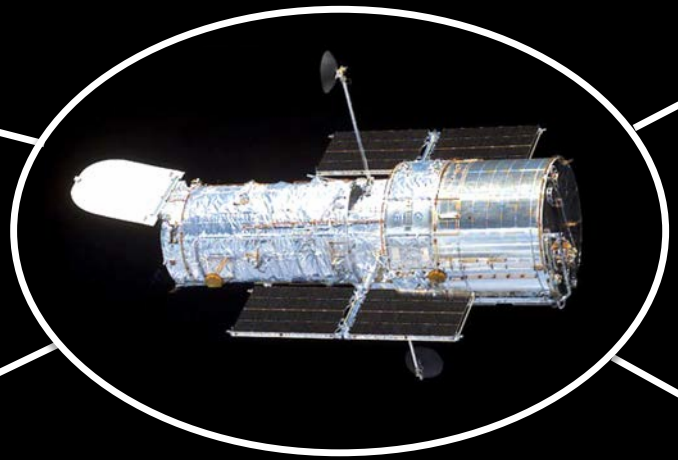
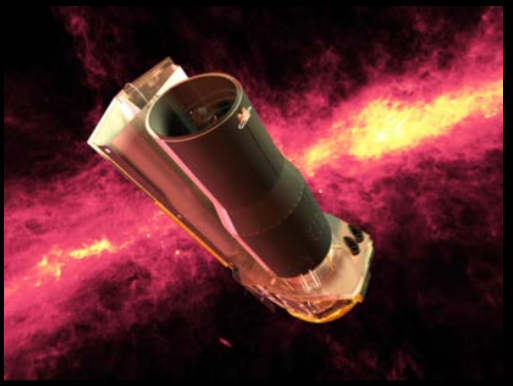
Hubble's partners for distant galaxies

Chandra
Great Observatory

Hubble
Great Observatory





Spitzer
Great Observatory

VLT – Very Large telescope

Keck & Subaru telescopes

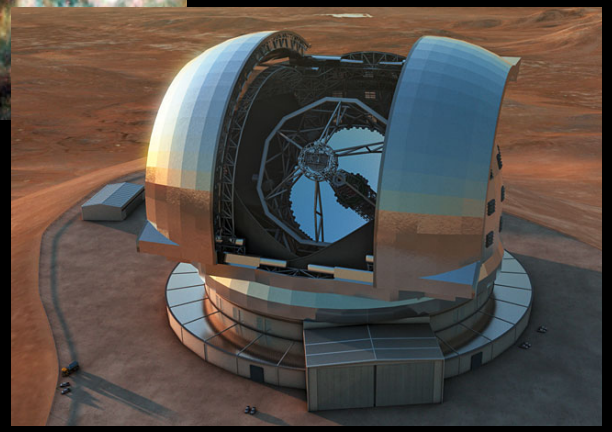
Atacama Large Millimeter Array
ALMA

JWST's partners for distant galaxies

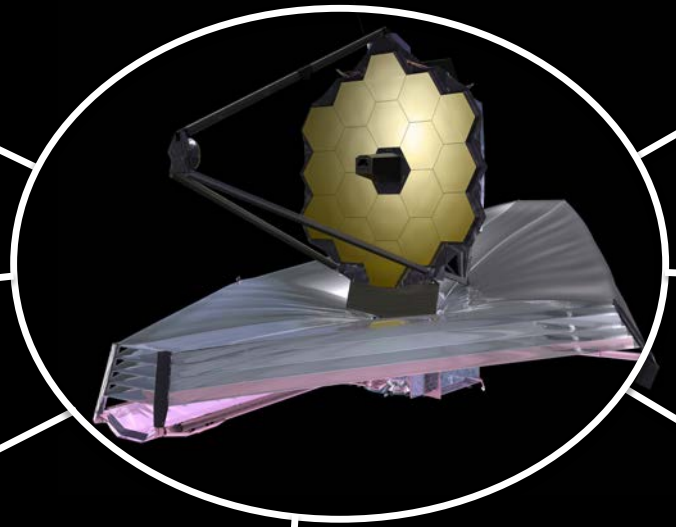
Chandra
Great Observatory

JWST
Greatest Observatory

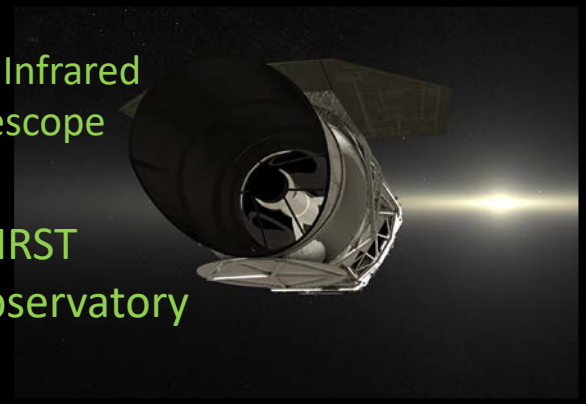
Hubble
Great Observatory



European Extremely Large Telescope



Wide Field Infrared
Survey Telescope

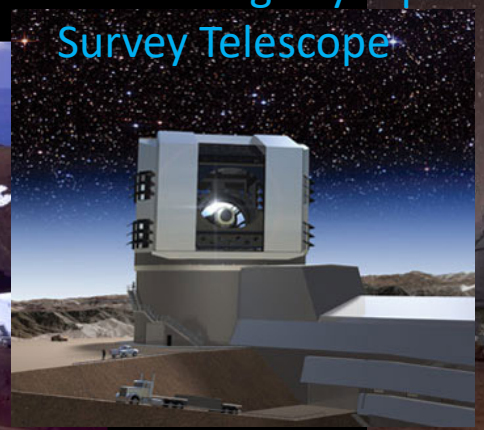


WFIRST
Great Observatory

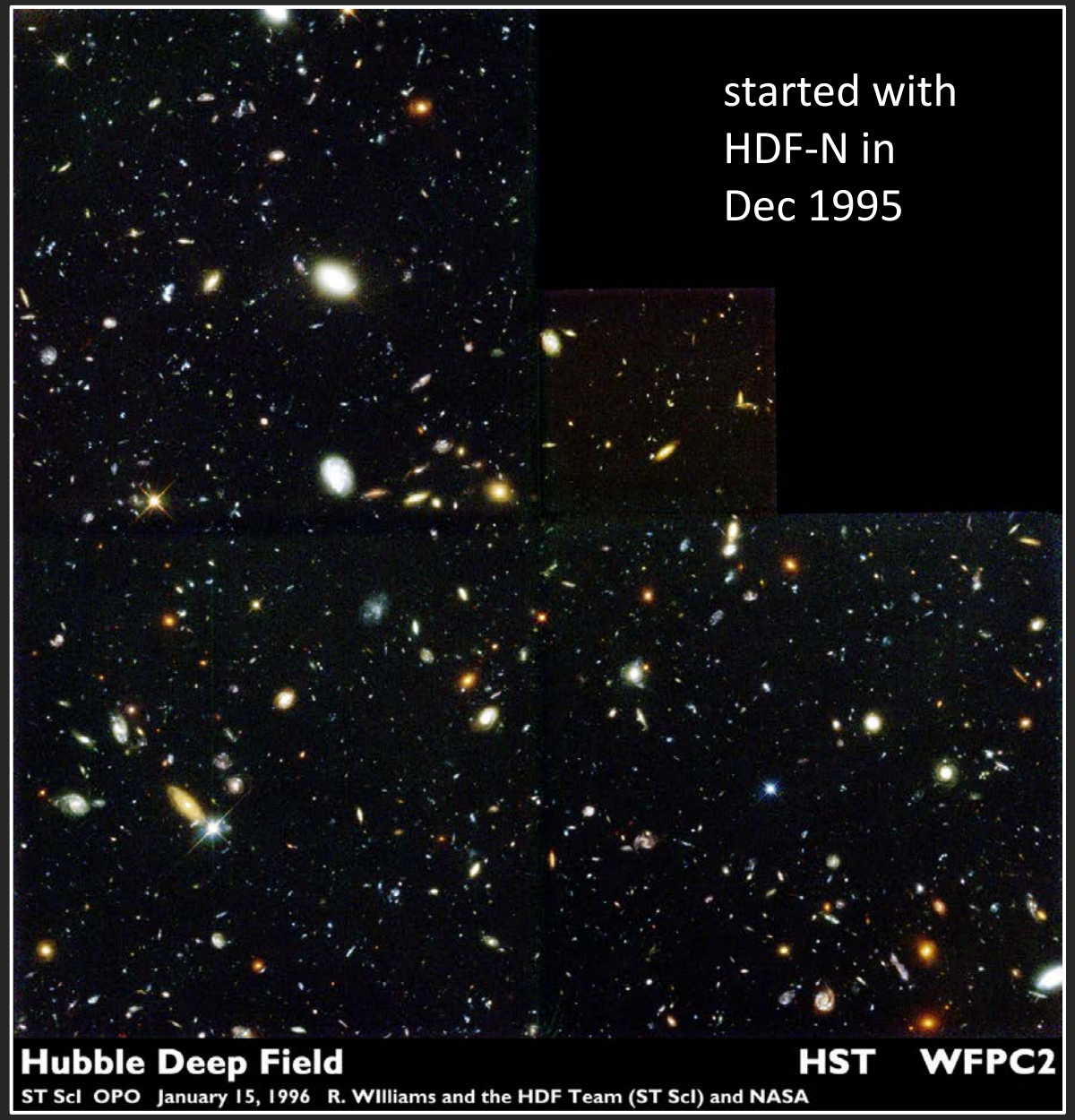
VLT – Very Large Telescopes

Keck & Subaru

LSST – Large Synoptic
Survey Telescope



Atacama Large Millimeter Array
ALMA



the survey images used for high-redshift galaxy studies

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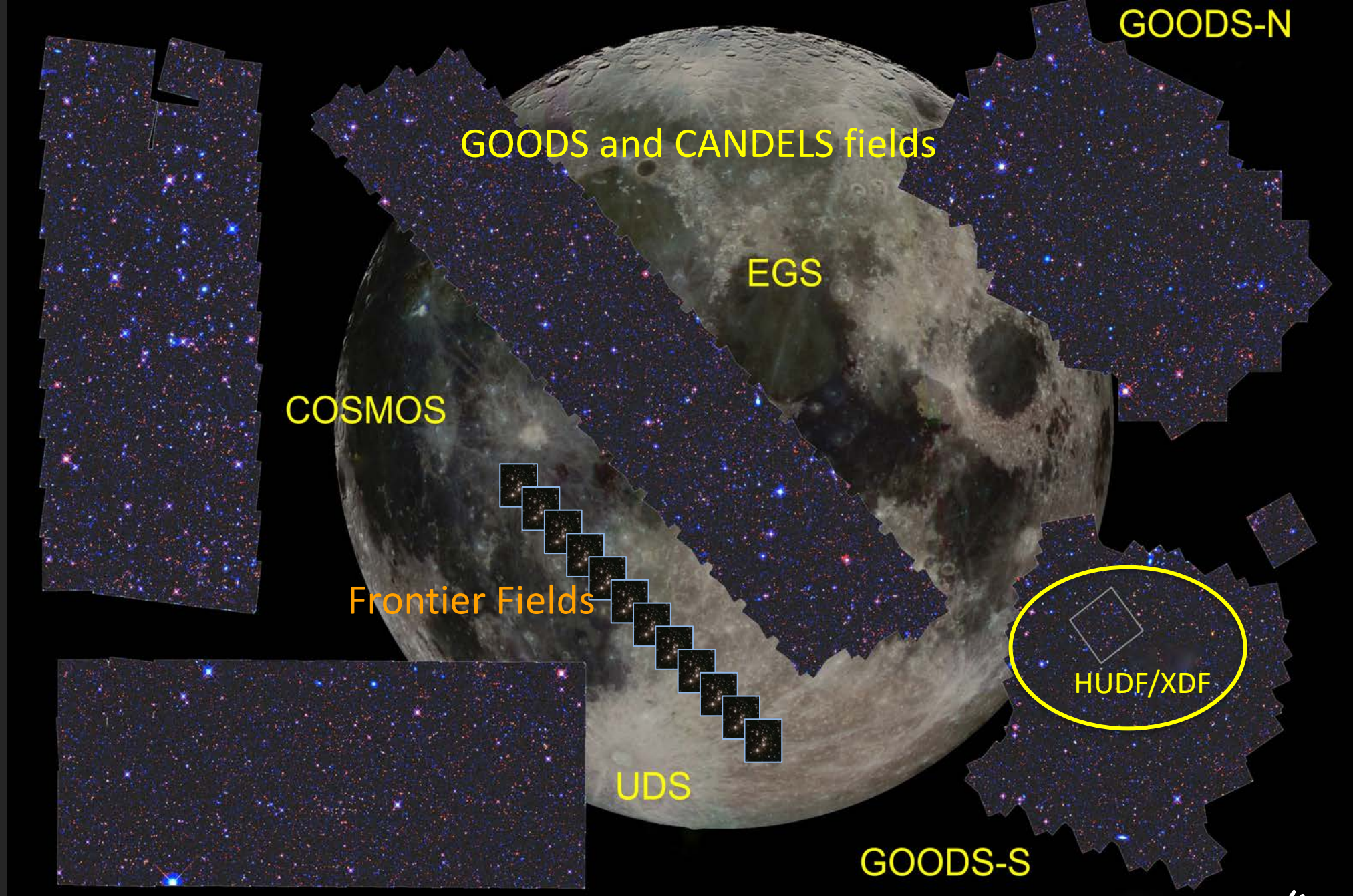
Hubble and Spitzer survey fields for high-redshift galaxies



HUDF: Hubble Ultra-Deep Field

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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

xdf.ucolick.org

HUDF: Hubble Ultra-Deep Field

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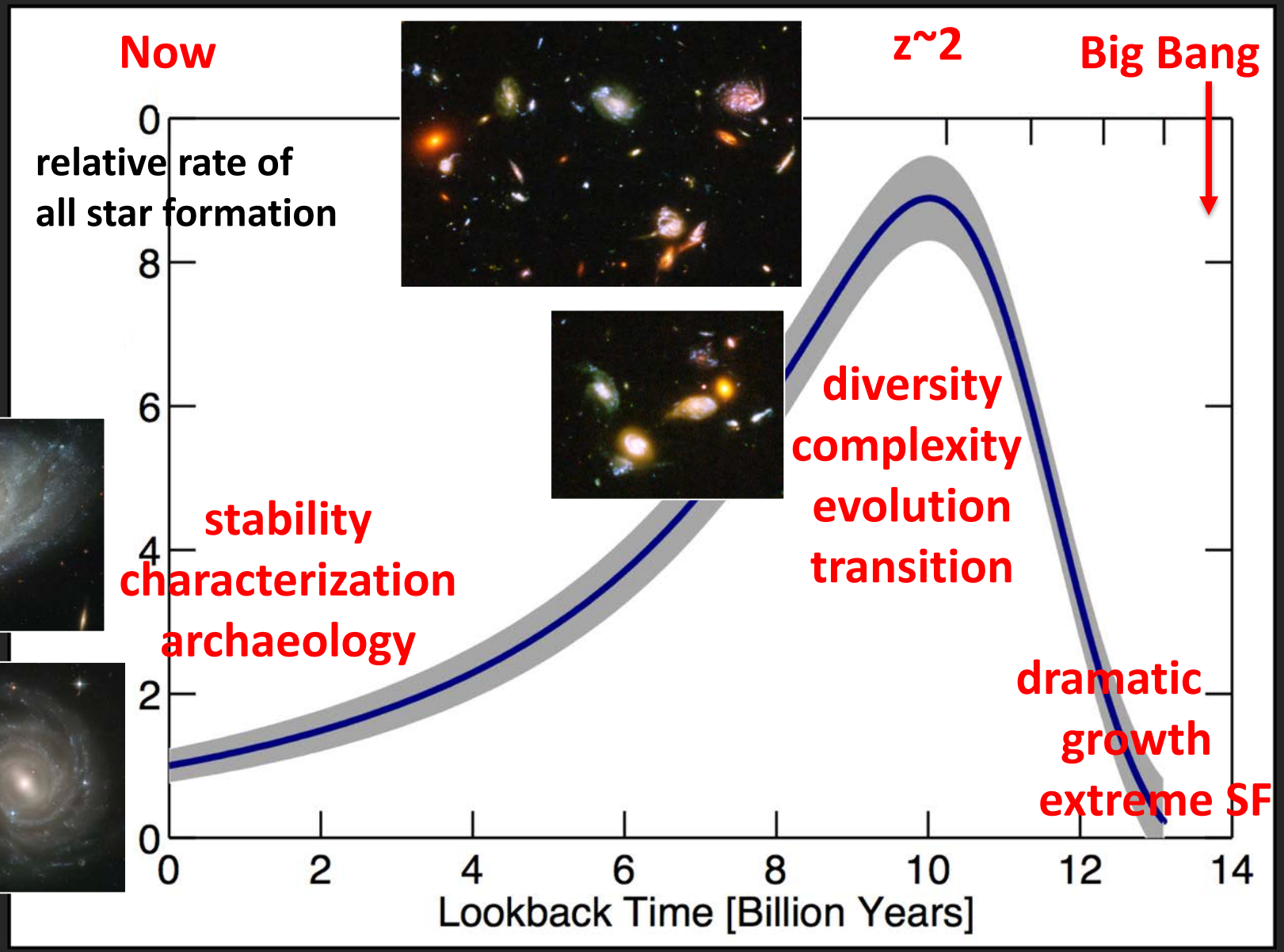
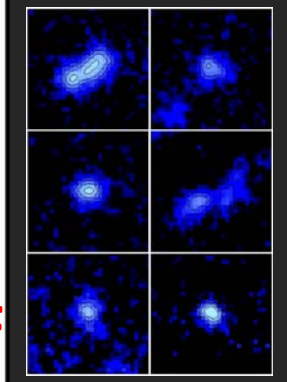
cosmic star formation over all time





dramatic change over time of how many stars are forming in the universe

linear figure credit:
Pascal Oesch

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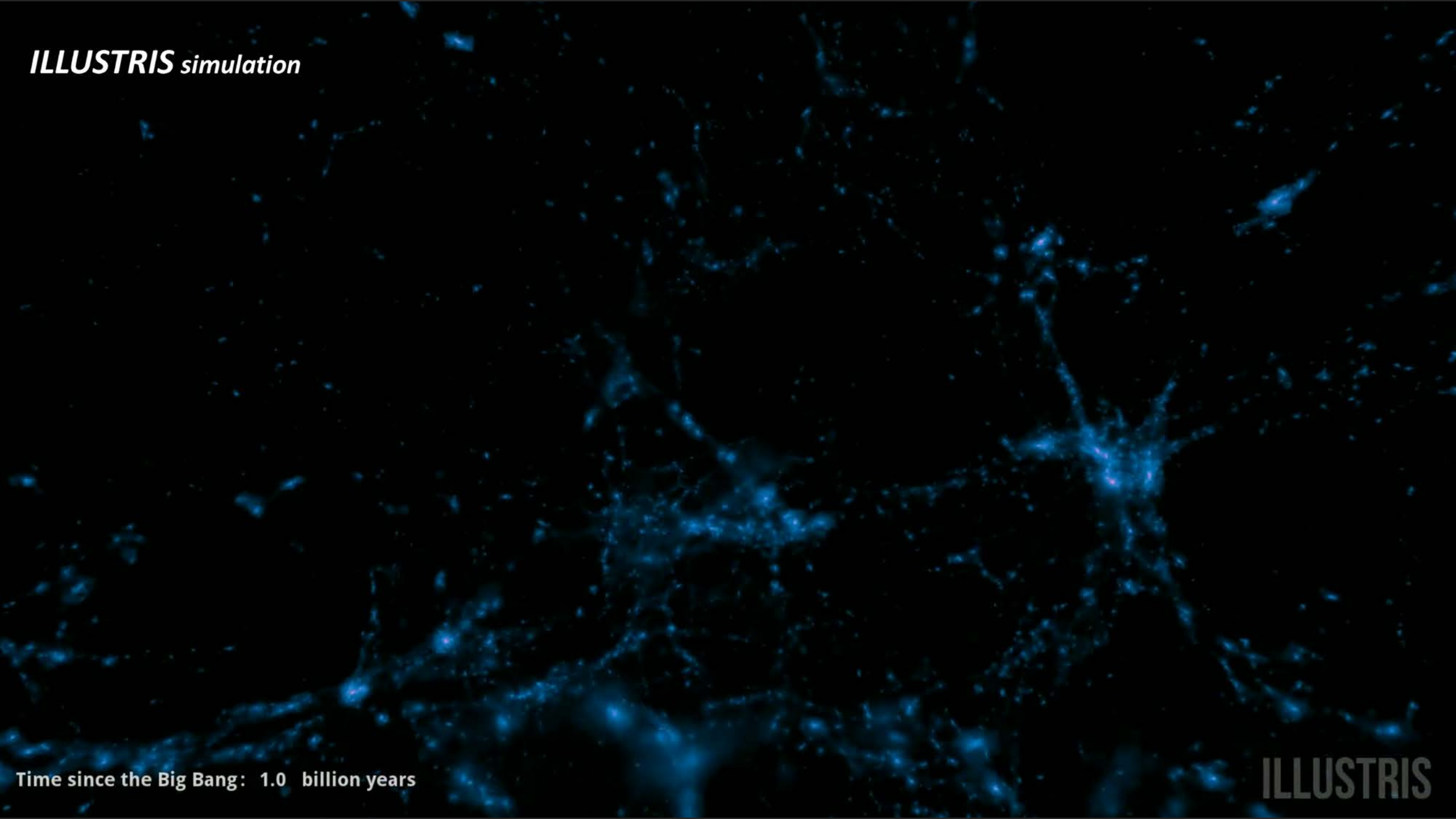
ILLUSTRIS simulation
Time since the Big Bang: 1.0 billion years
ILLUSTRIS

JWST is mainly infrared

Hubble is mainly optical

why are we going to the infrared?

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why we go to the infrared

"Pillars of Creation"

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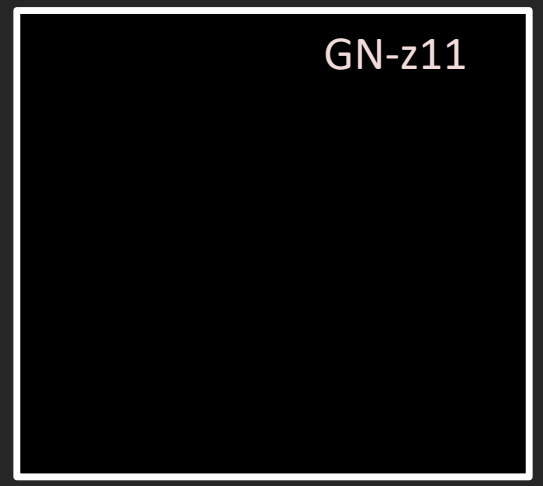
why we
must
go to
the
infrared

to reach the "first galaxies"



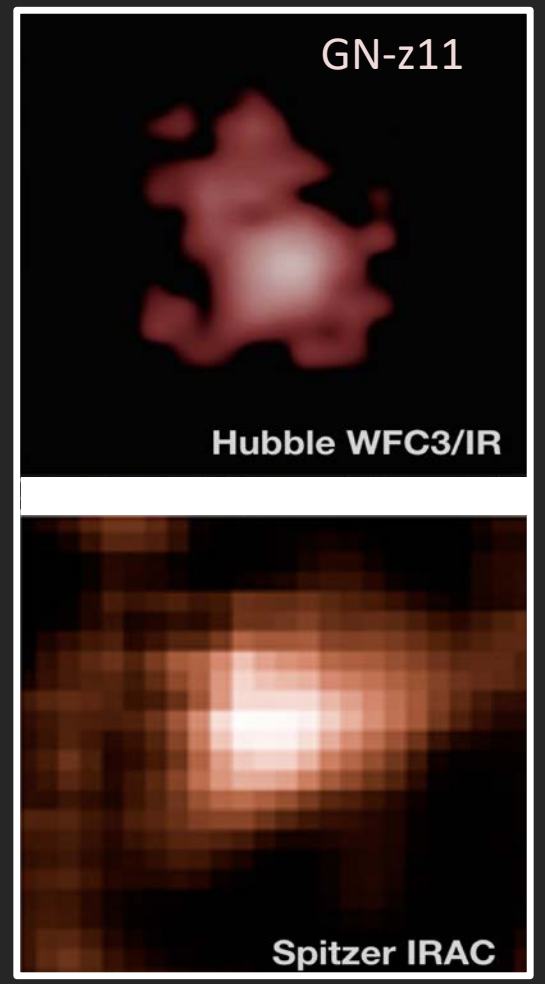
this is the most distant galaxy that we know

and this is what it looks like a visible image

gdi

why we
must
go to
the
infrared

to reach the "first galaxies"



this is the most distant galaxy that we know

and it can only be seen in infrared images

the even more distant "first galaxies" can only be seen in the infrared

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history of everything

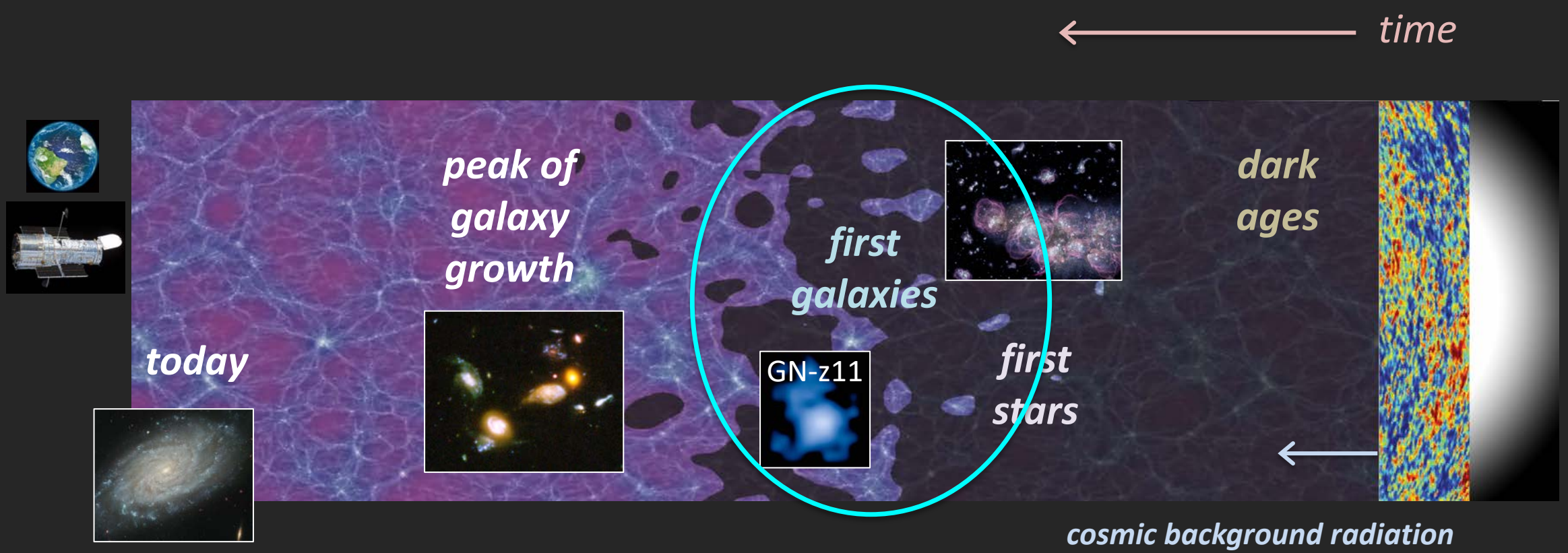

figure credit: insert adapted from Brant Robertson UCSC

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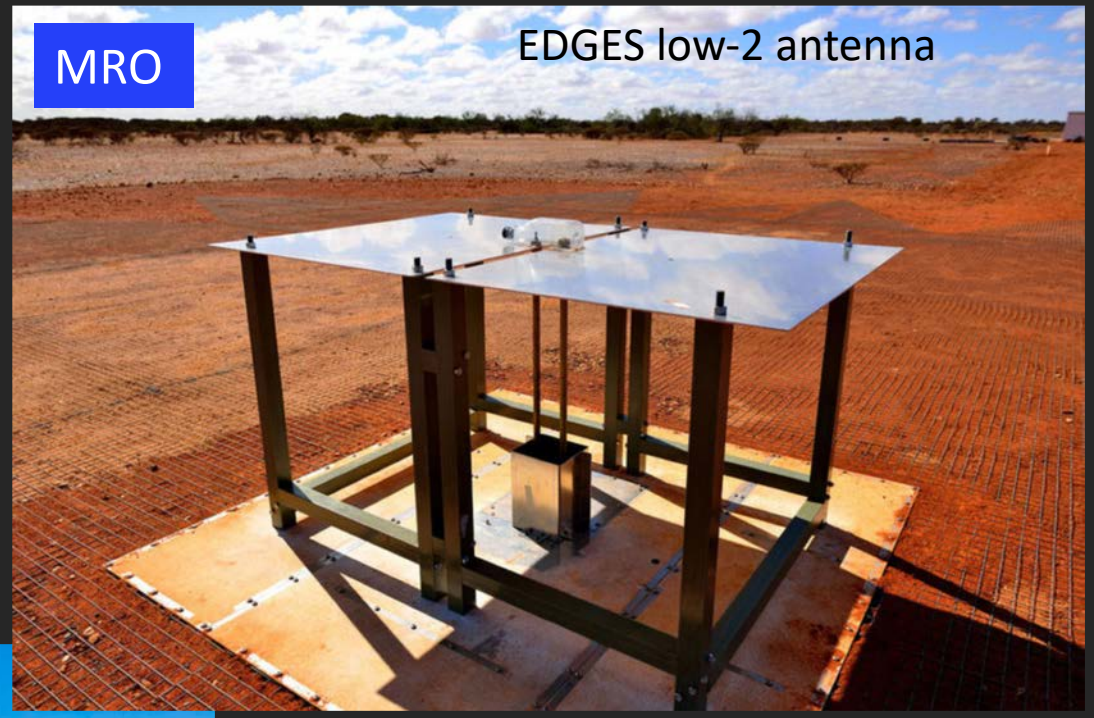
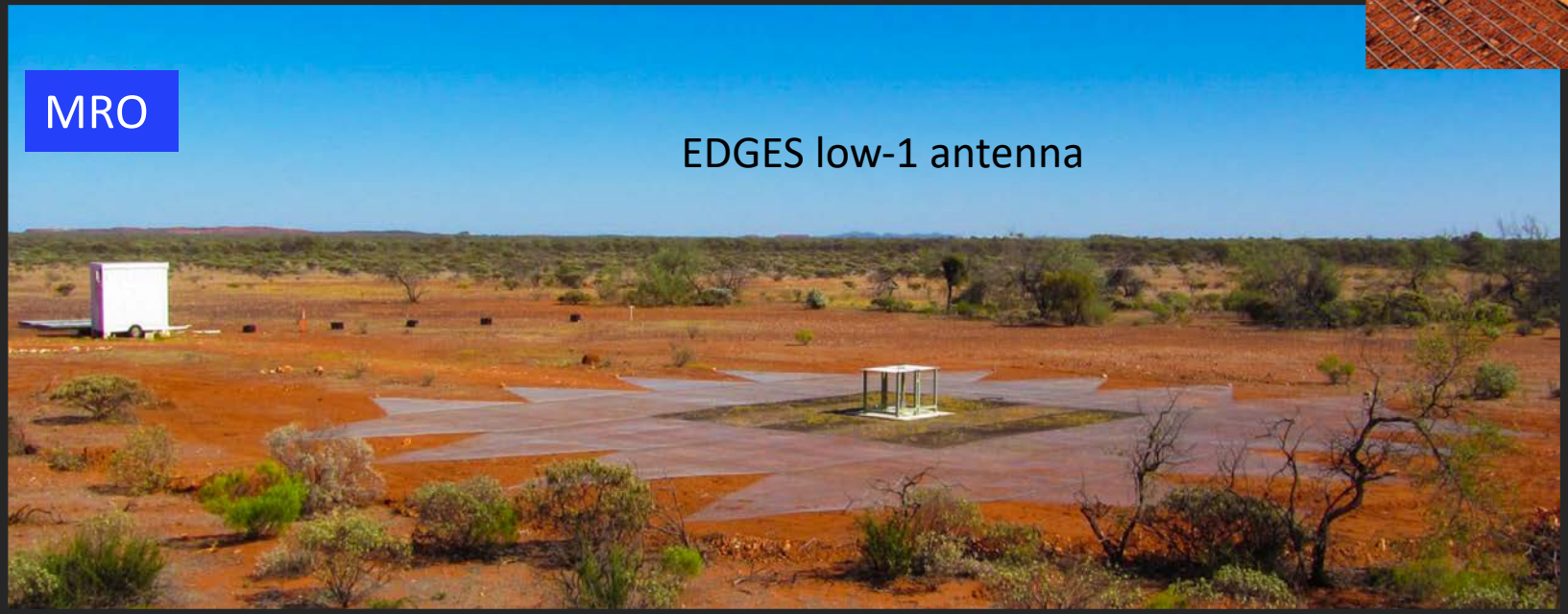
first evidence for when the "first stars" started to shine brightly

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

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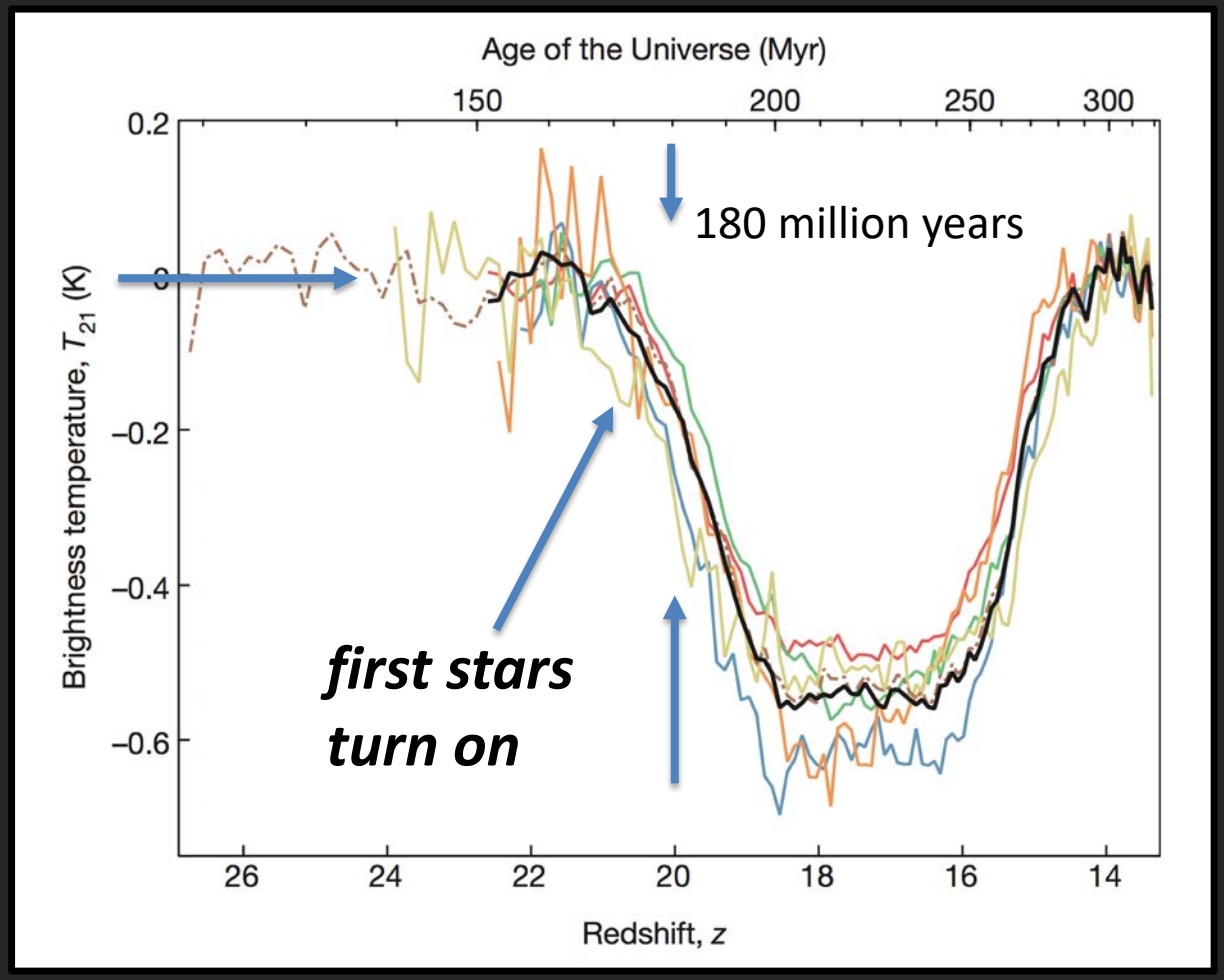
first evidence for when the "first stars" started to shine brightly

cosmic microwave background



NEW RESULT

published March 01 Nature

is this correct?

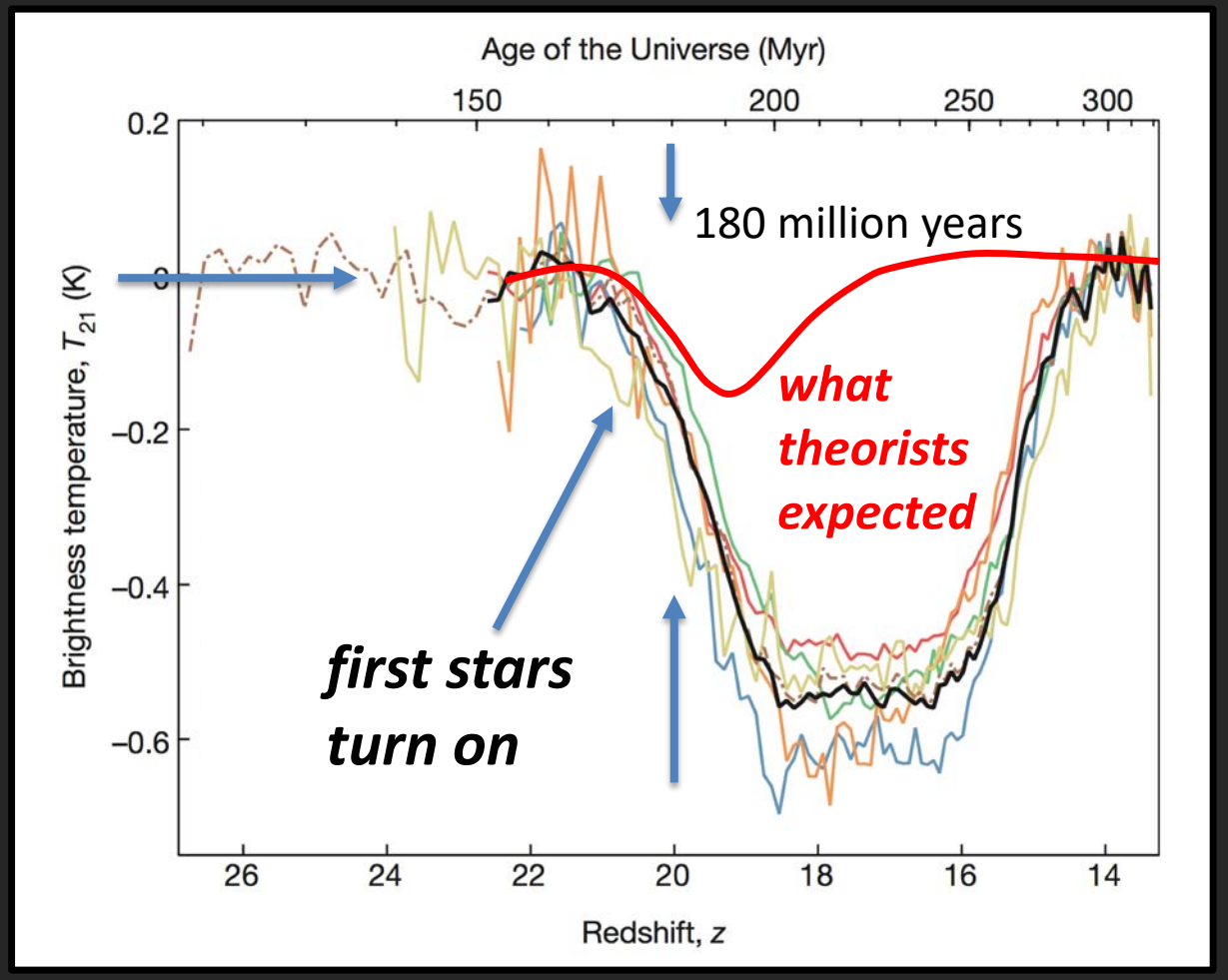
confirmation?

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

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)

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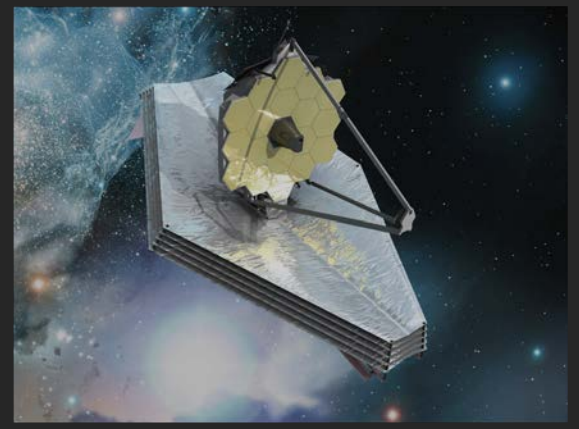
what do we know about the first galaxies?

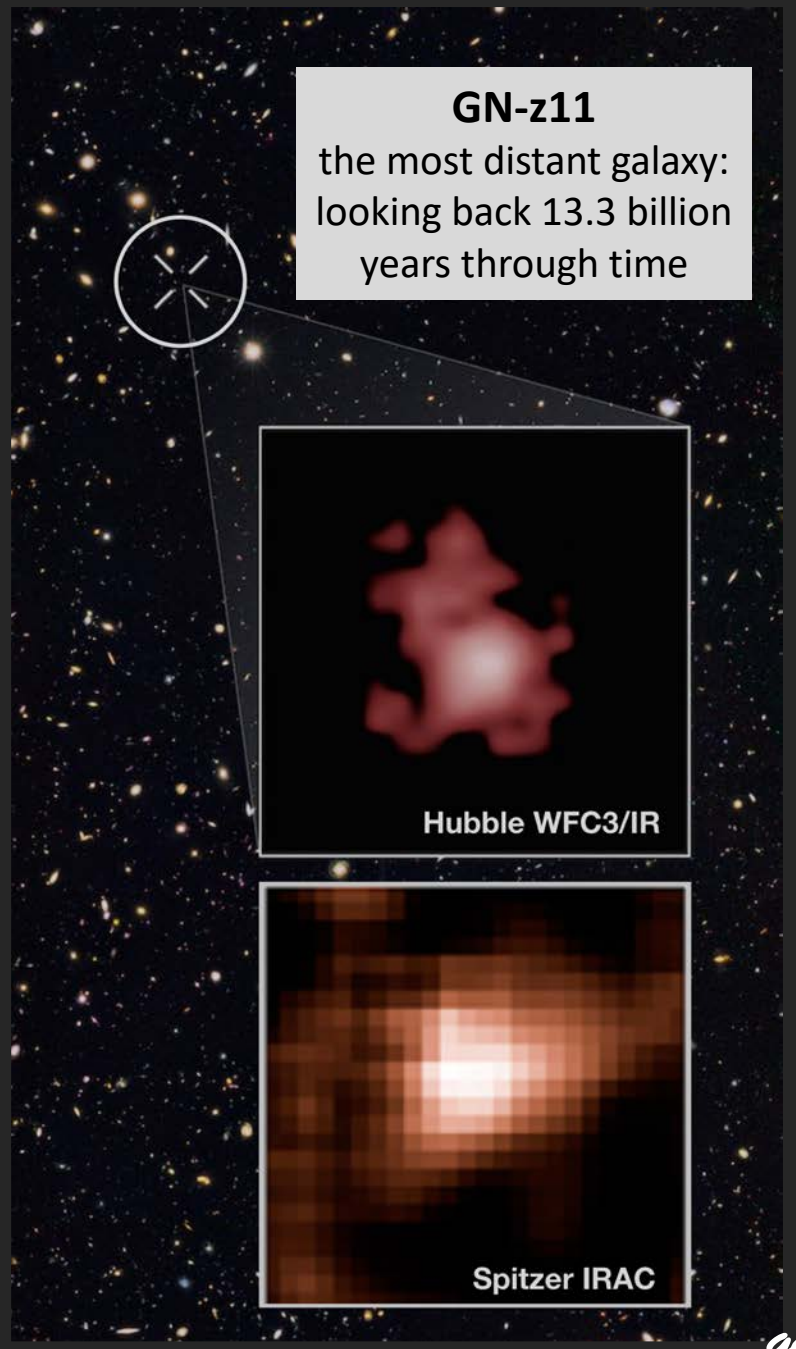
the first galaxies must be earlier than GN-z11

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

Hubble and Spitzer have been reaching into JWST territory!

☛ close to "Cosmic Sunrise" ☚





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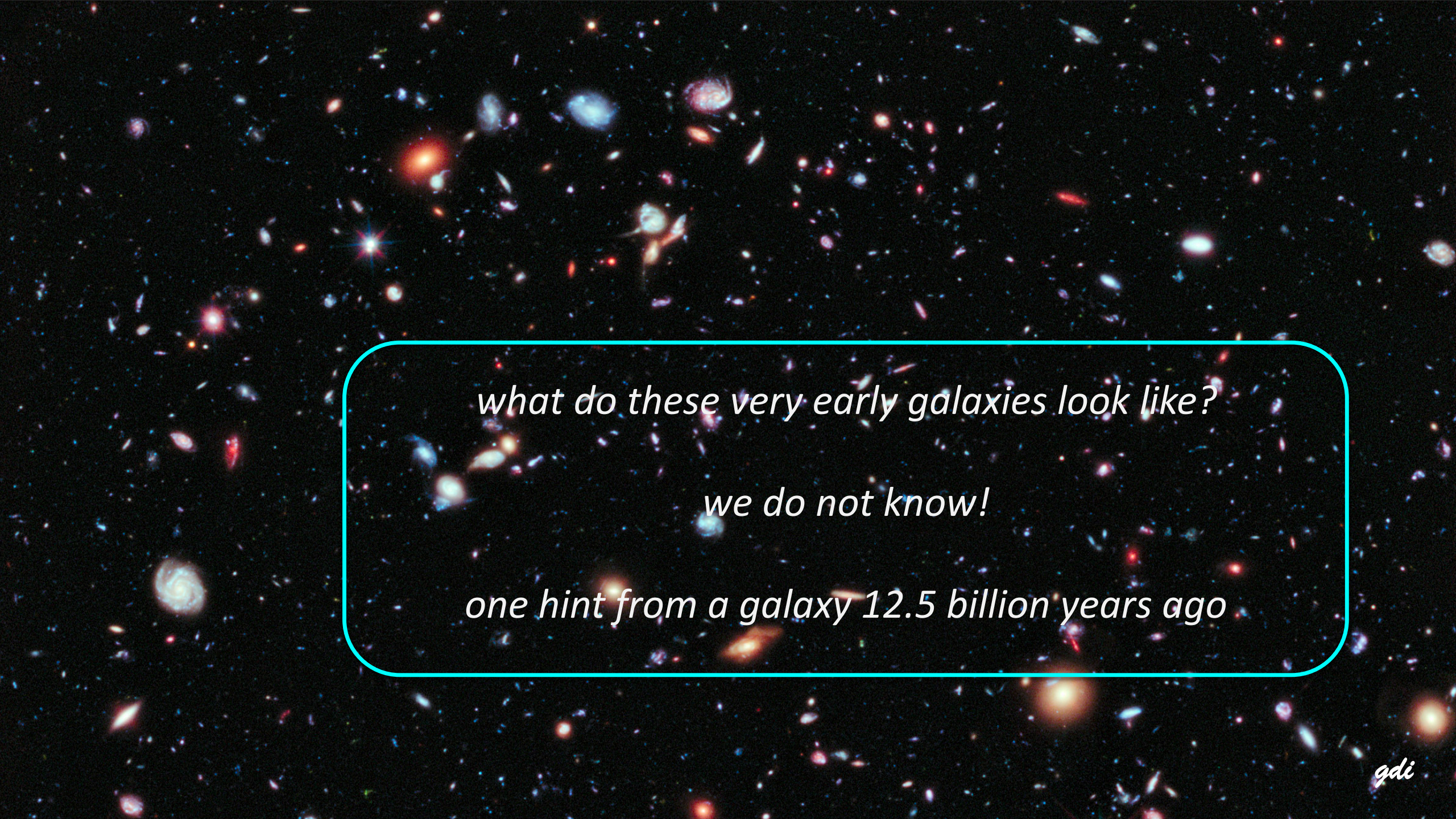
what do these very early galaxies look like?
we do not know!
one hint from a galaxy 12.5 billion years ago
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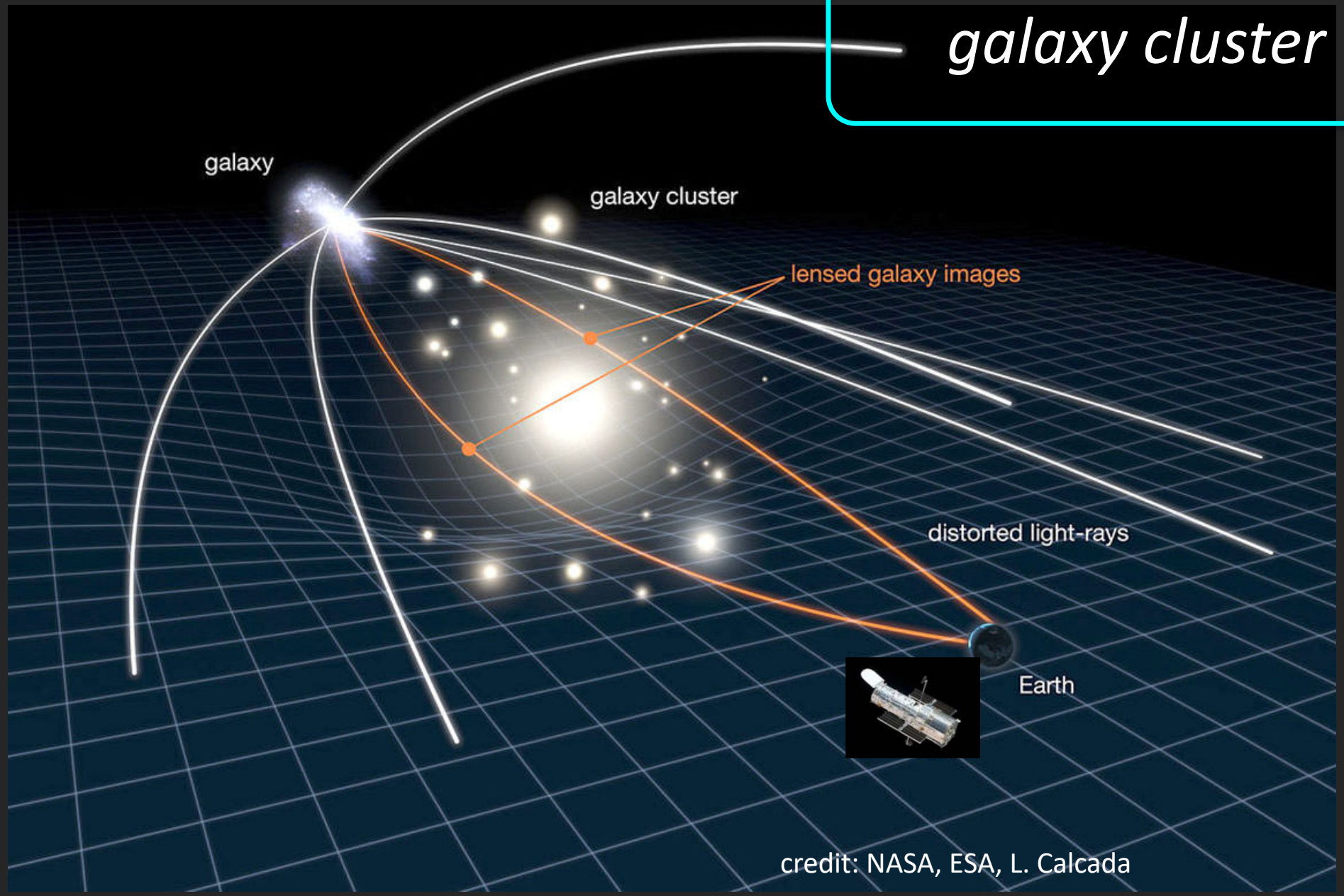
galaxy cluster "lenses"



credit: NASA, ESA, L. Calcada

the way to see what faint galaxies really look like…

by combining Hubble with a "cosmic telescope"

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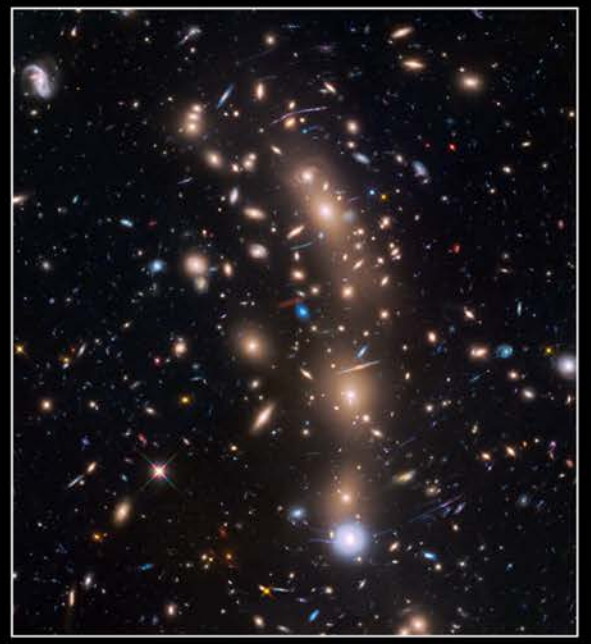
Hubble Frontier Fields

6 galaxy clusters

Hubble and Spitzer imaging

Abell 2744



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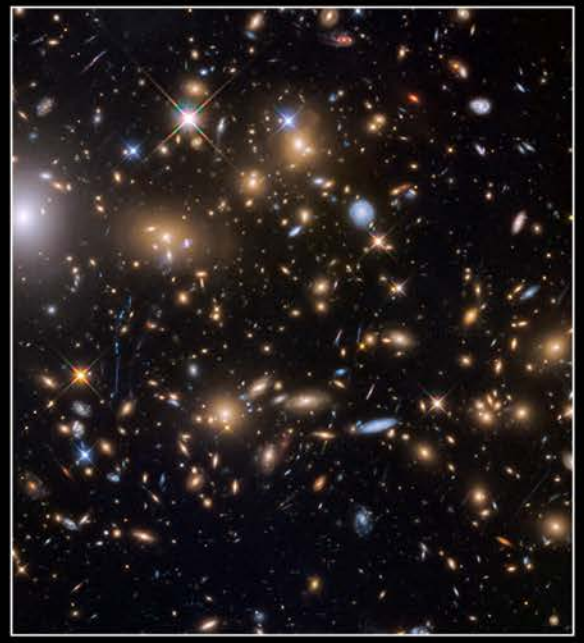

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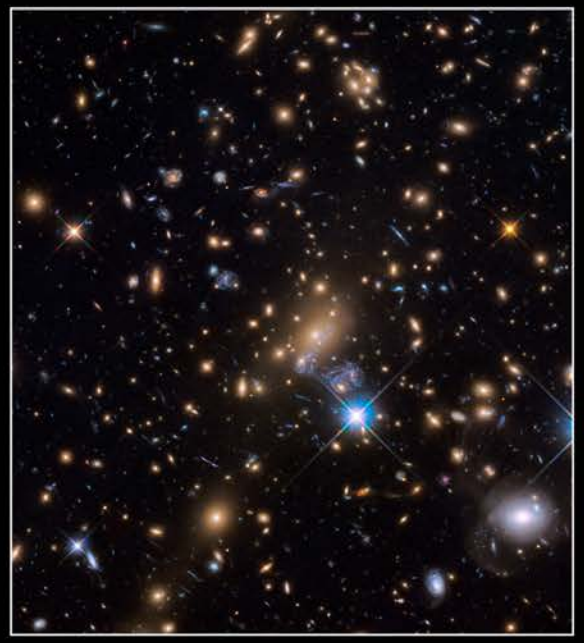
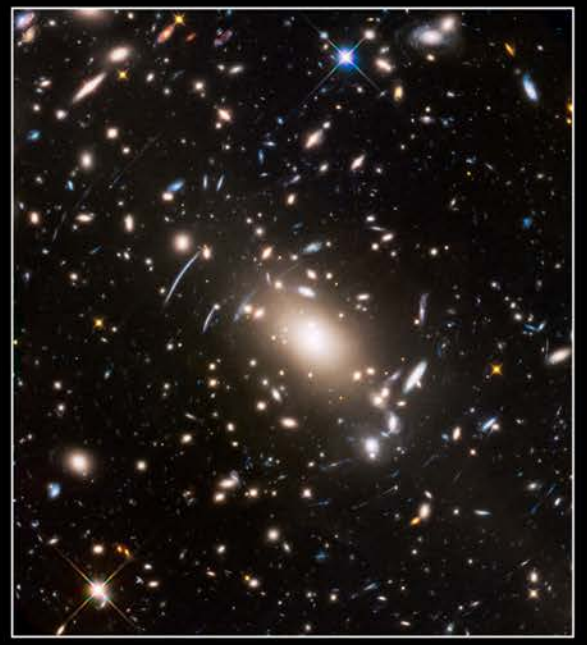
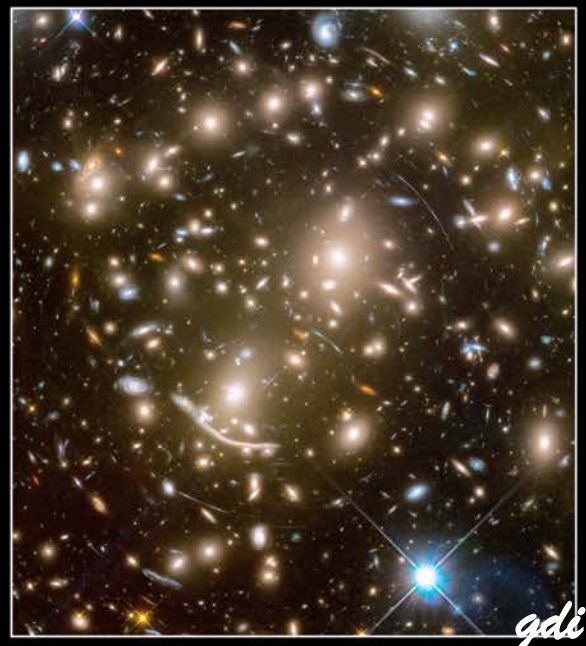


MACSJ1149.5+2223



Abell S1063



Abell 370

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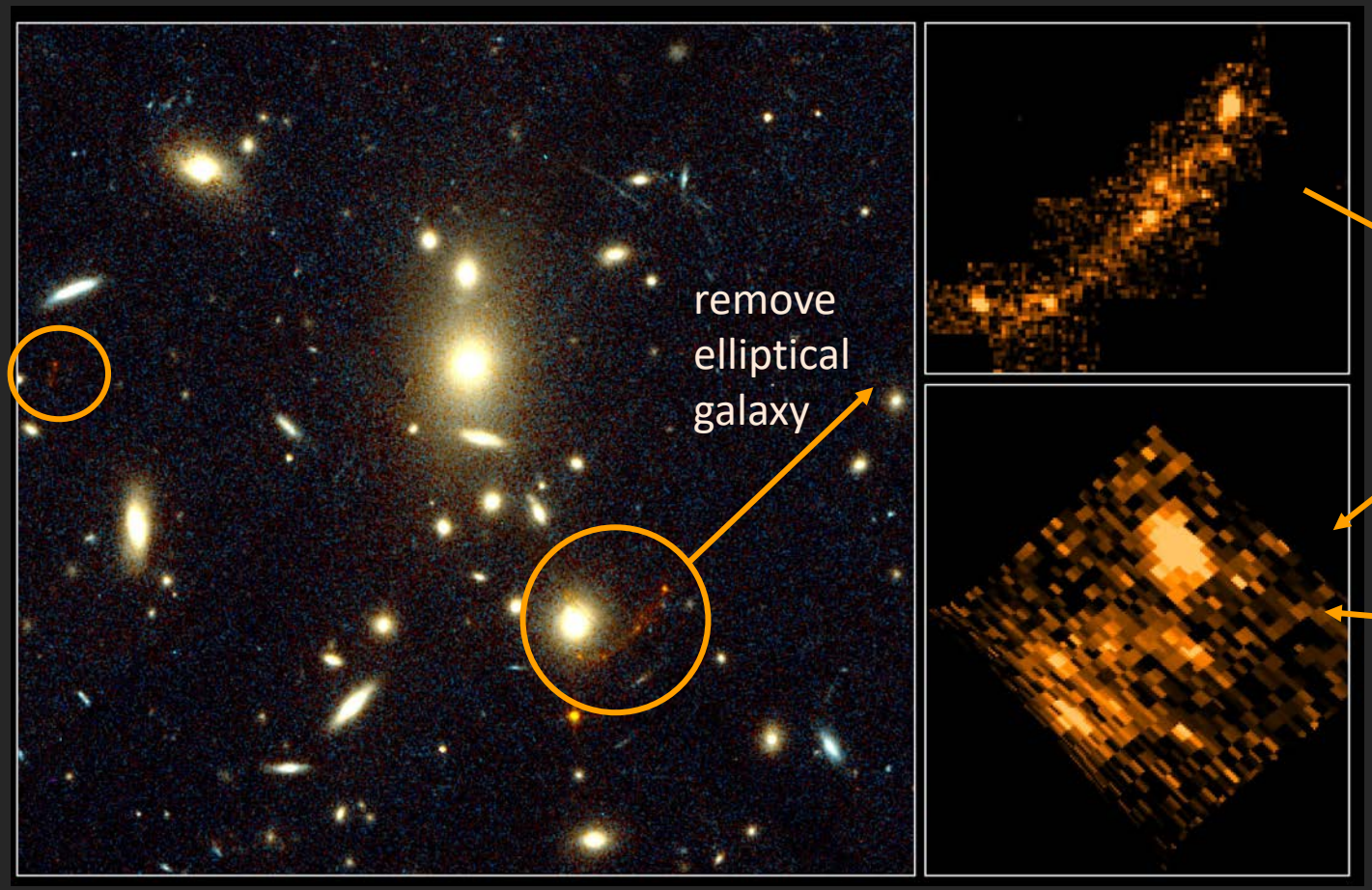
a remarkable fold arc in CL1358

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

cluster of galaxies CL1358 magnifies faint galaxy that lies far beyond



CL1358-G1 at z=4.92

model gravity in cluster
remove distortions

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

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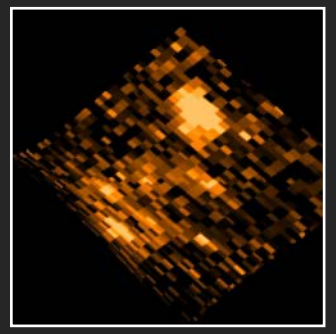
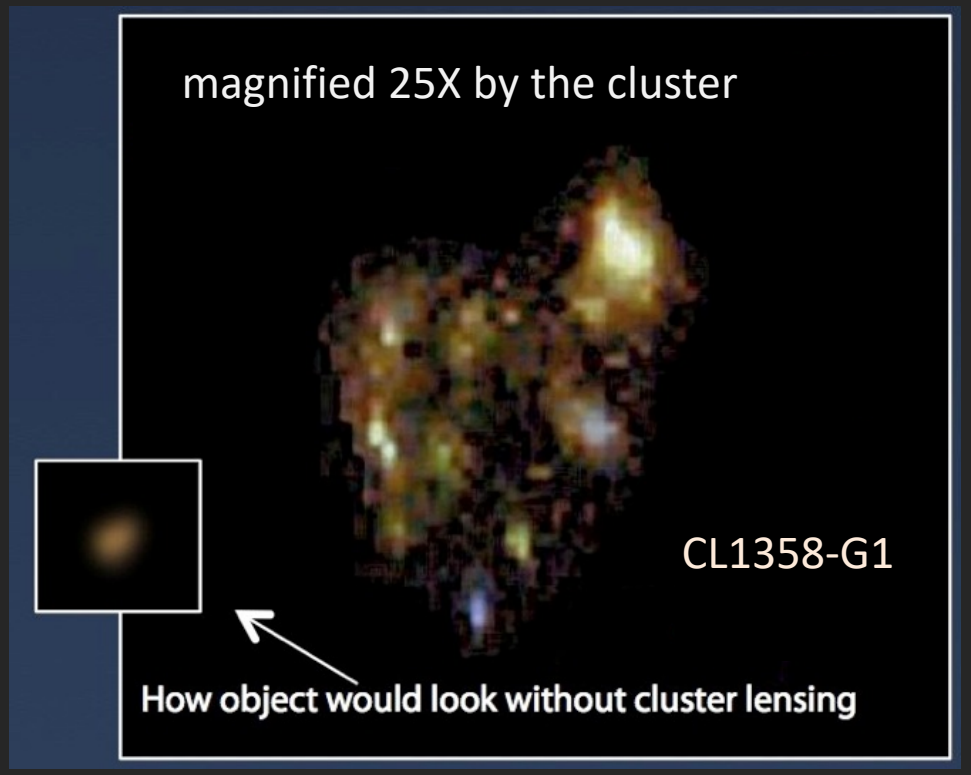
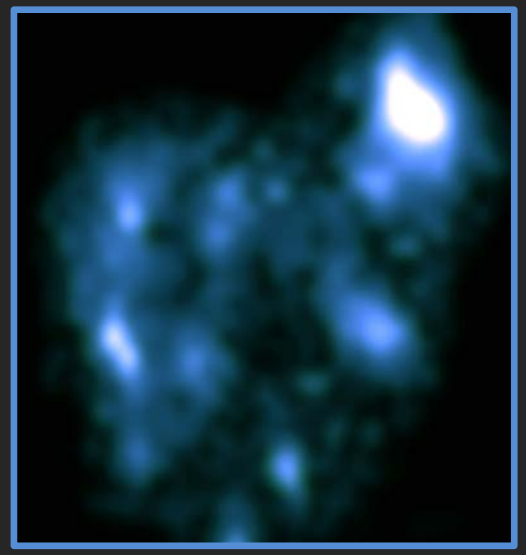
unique insight into the structure of a high redshift galaxy



1996 image

2004 image from Hubble's Advanced Camera





CL1358-G1 probably looks more like this!

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

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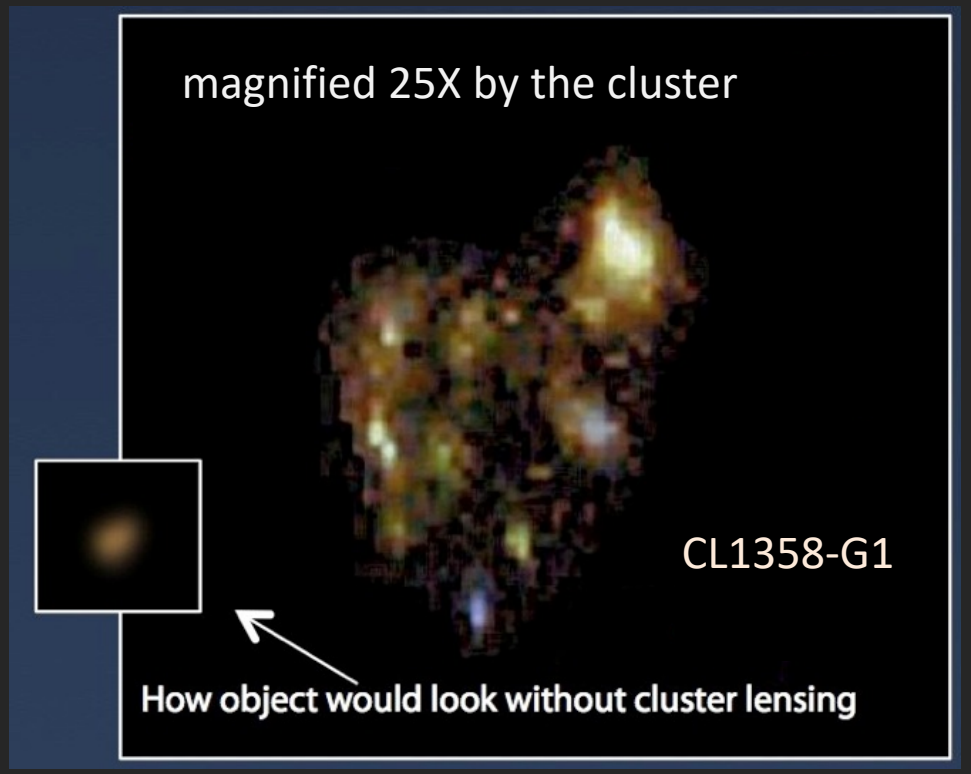
how will we find more?

>100 clusters have been searched – CL1358G1 is still the best and only one at high redshift

we need a really big telescope and lasers and adaptive optics



30-40 m ELT with adaptive optics needed to see what early galaxies really look like

ELT – Extremely Large Telescope

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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?

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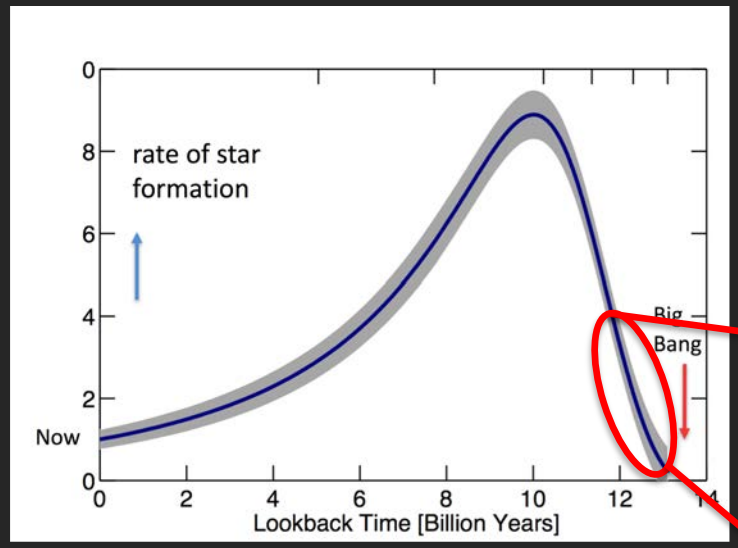
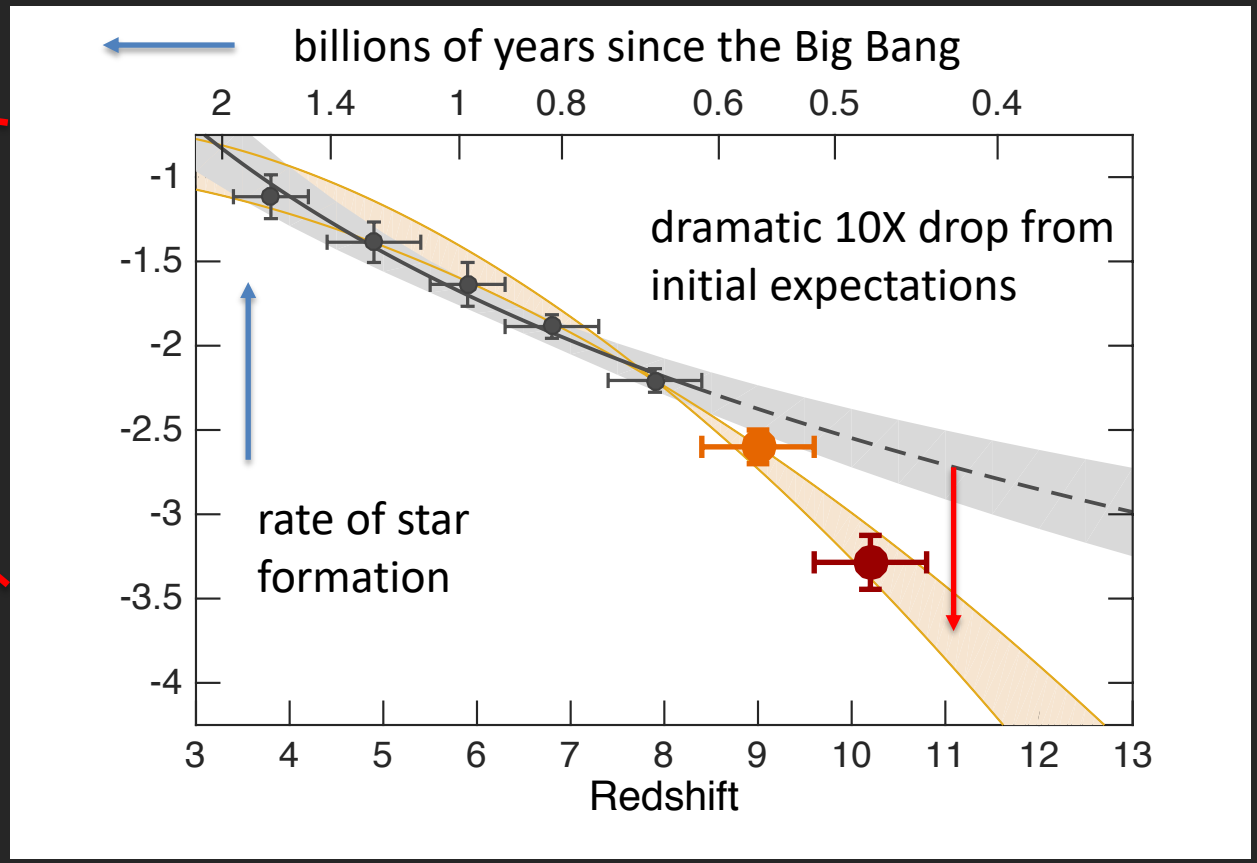
way fewer galaxies than expected at redshift 10



galaxies are evolving rapidly earlier than 650 million years



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

this is a very important result for JWST

2018 publication

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galaxies are evolving rapidly earlier than 650 million years

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

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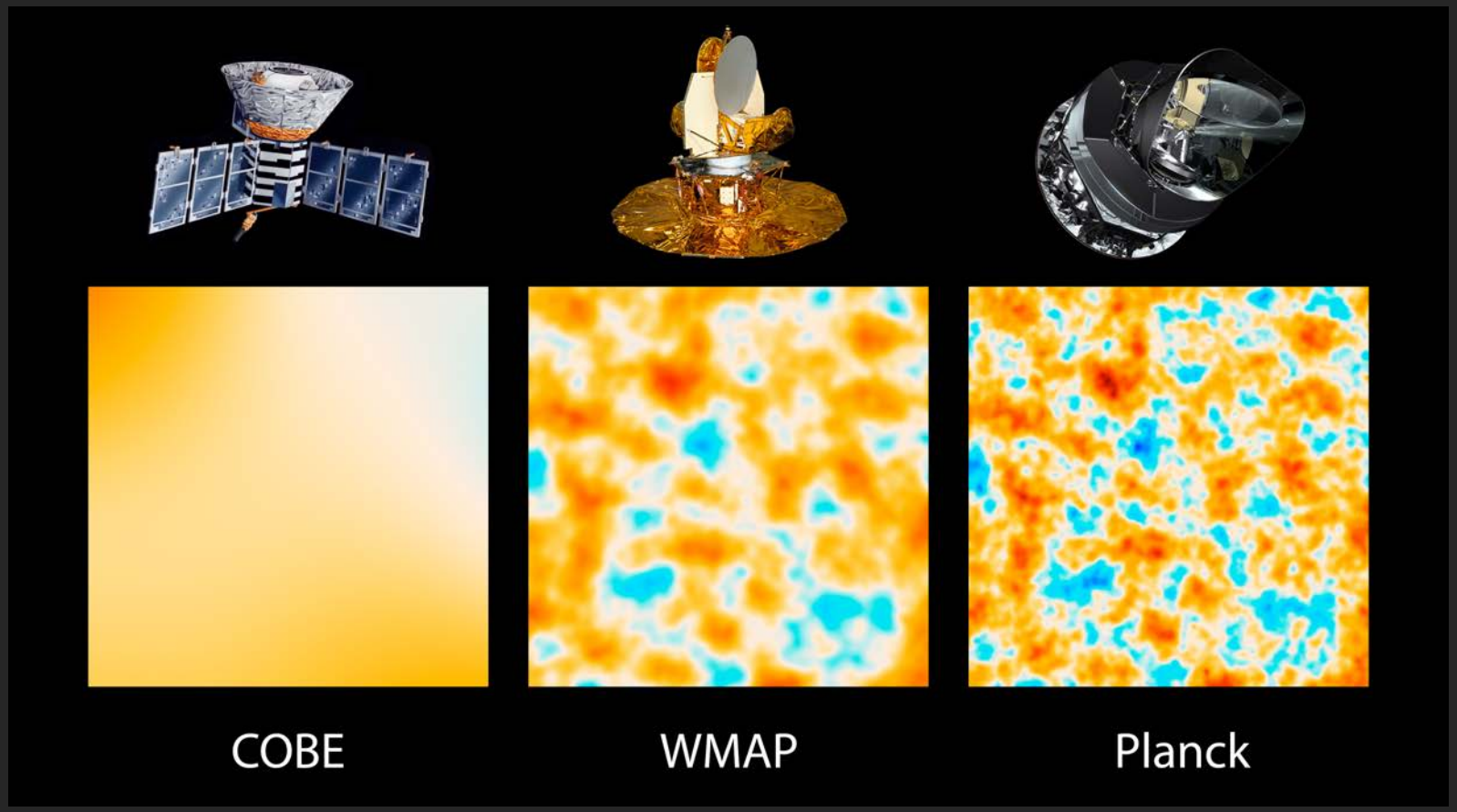
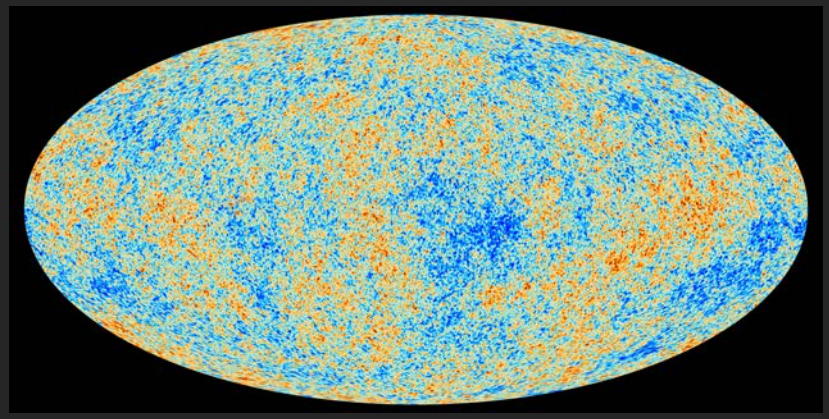
measuring the fluctuations in the 3°K cosmic microwave background

three amazing missions





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

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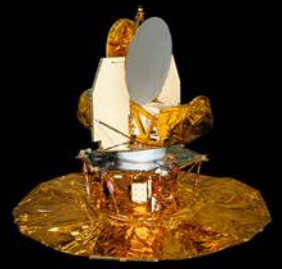
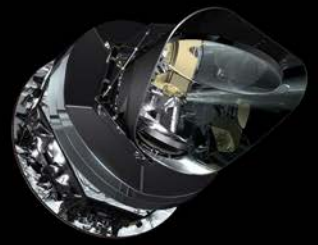
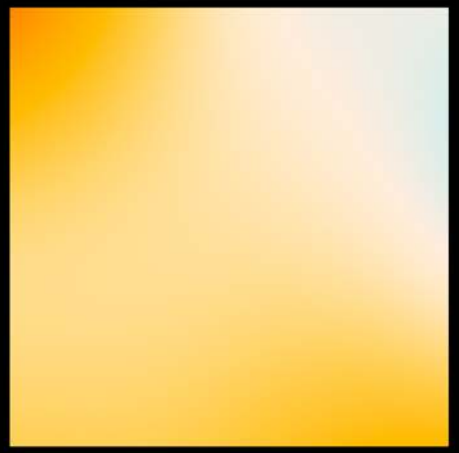
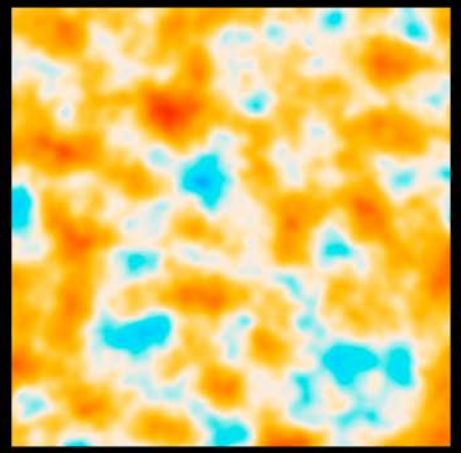
measuring the fluctuations in the 3°K cosmic microwave background

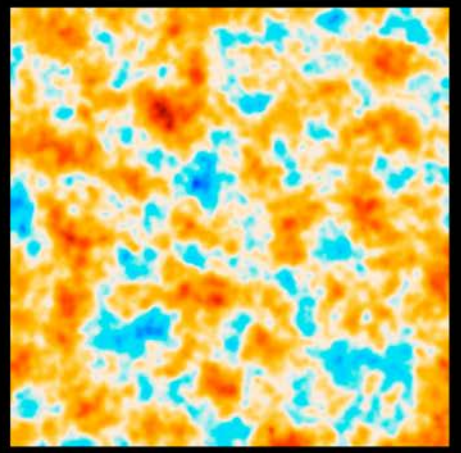
three amazing missions









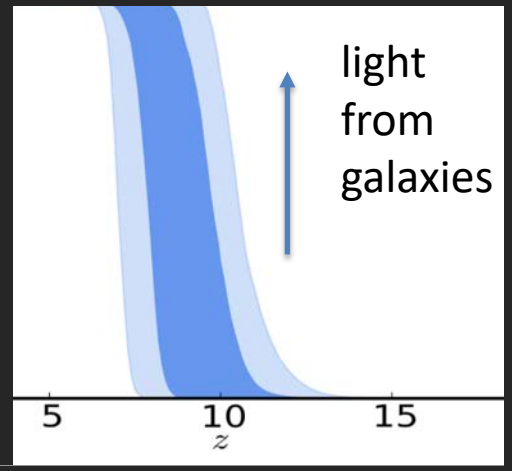


COBE 1989

WMAP 2001

Planck 2009

Planck tells us that galaxies started to put out a lot of light at z~10



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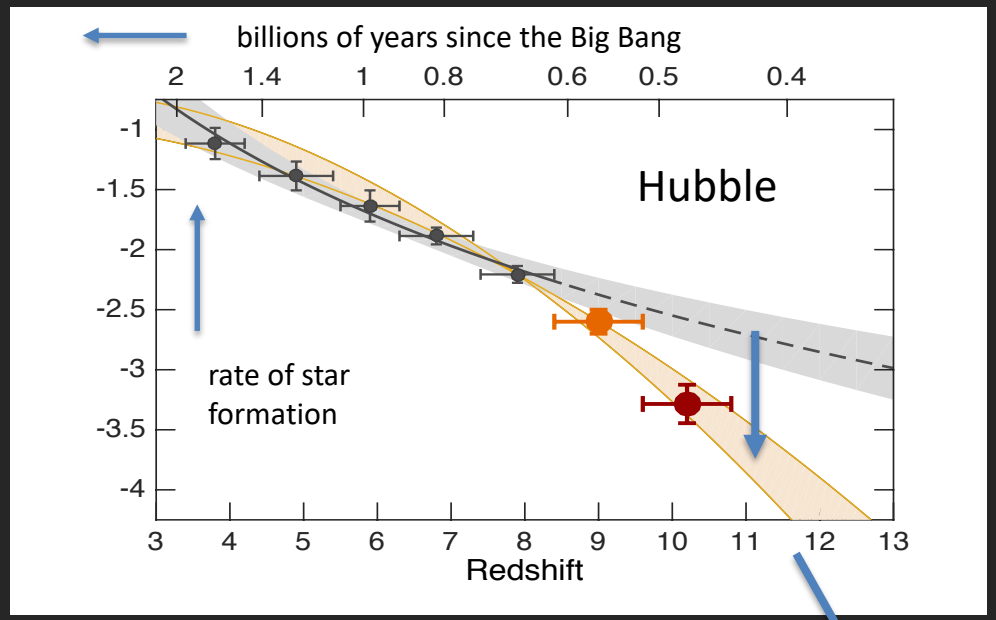
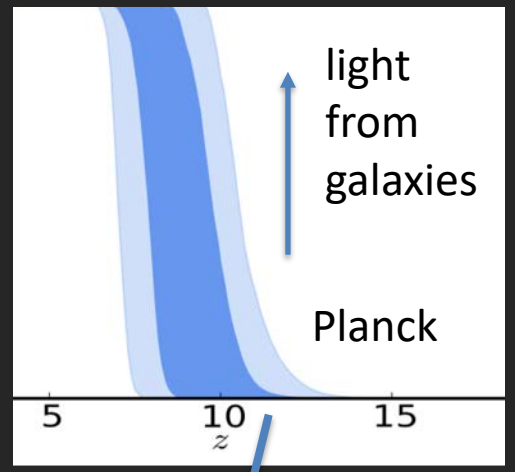


will JWST see the "first galaxies"?



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

☛ suggest dramatic changes in galaxies at z~10-12 ☚

great for JWST's "first light" goal since galaxies are turning on at z~10-12
likely major changes from z~10-15 – where JWST can see them

☞ exciting times ahead at "Cosmic Sunrise" for JWST! ☜

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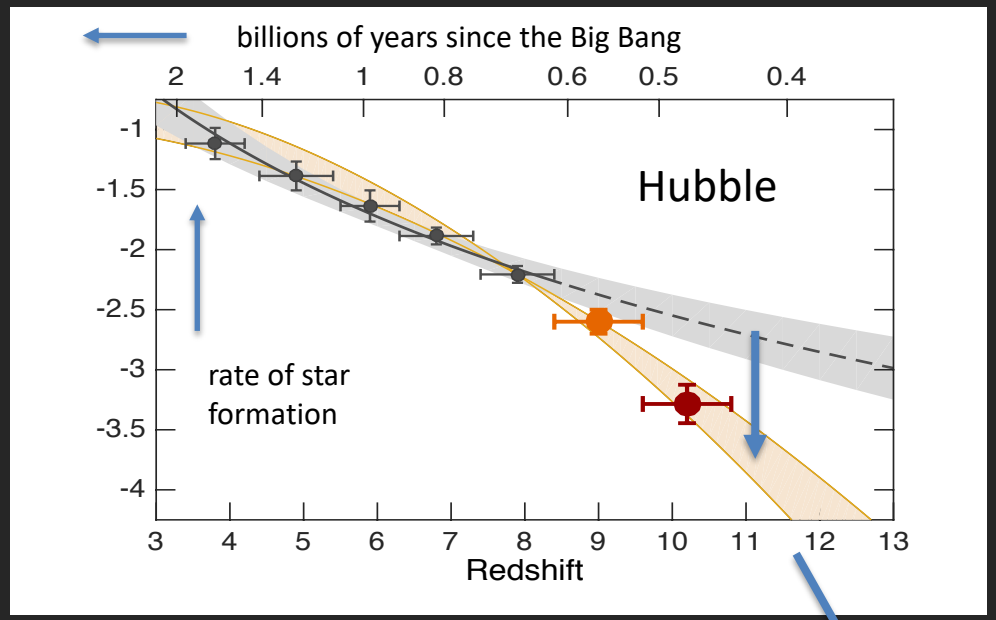
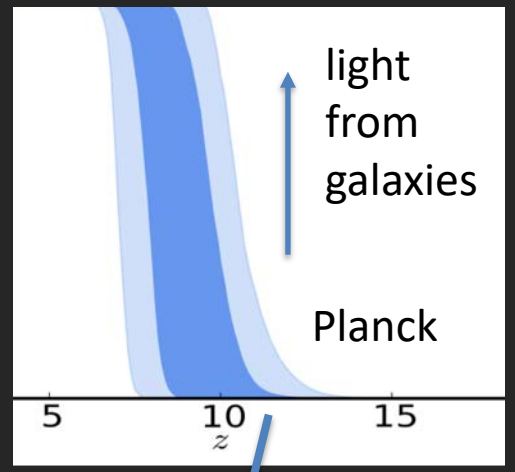


will JWST see the "first galaxies"?

yes, I think that there is a really good chance that we will



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☞ exciting times ahead at "Cosmic Sunrise" for JWST! ☜

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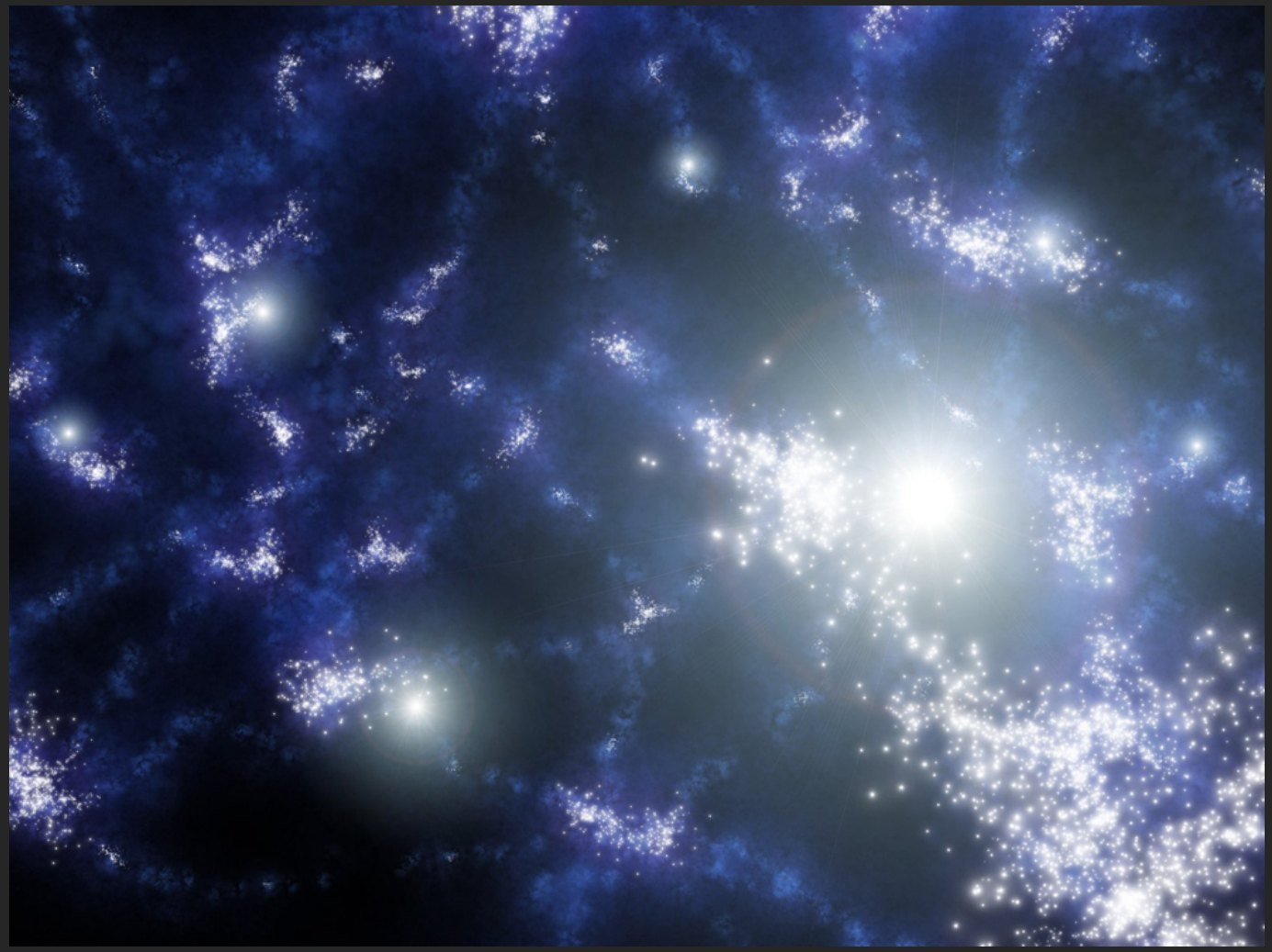
the dramatic brightening after dawn

desert sunrise

gdi

the dramatic brightening after cosmic dawn

“Cosmic Sunrise” – as the first galaxies burst forth around 300 million years after the Big Bang



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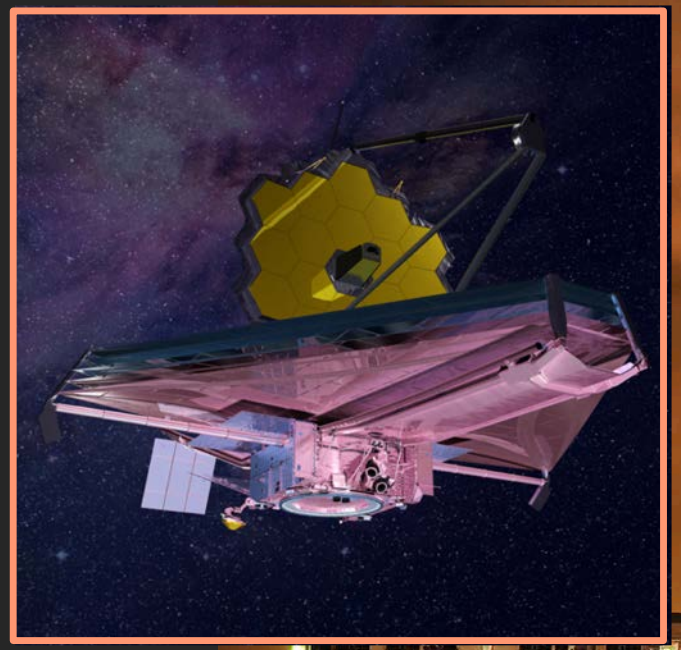
JWST is the "what's next" for the earliest galaxies



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

note people

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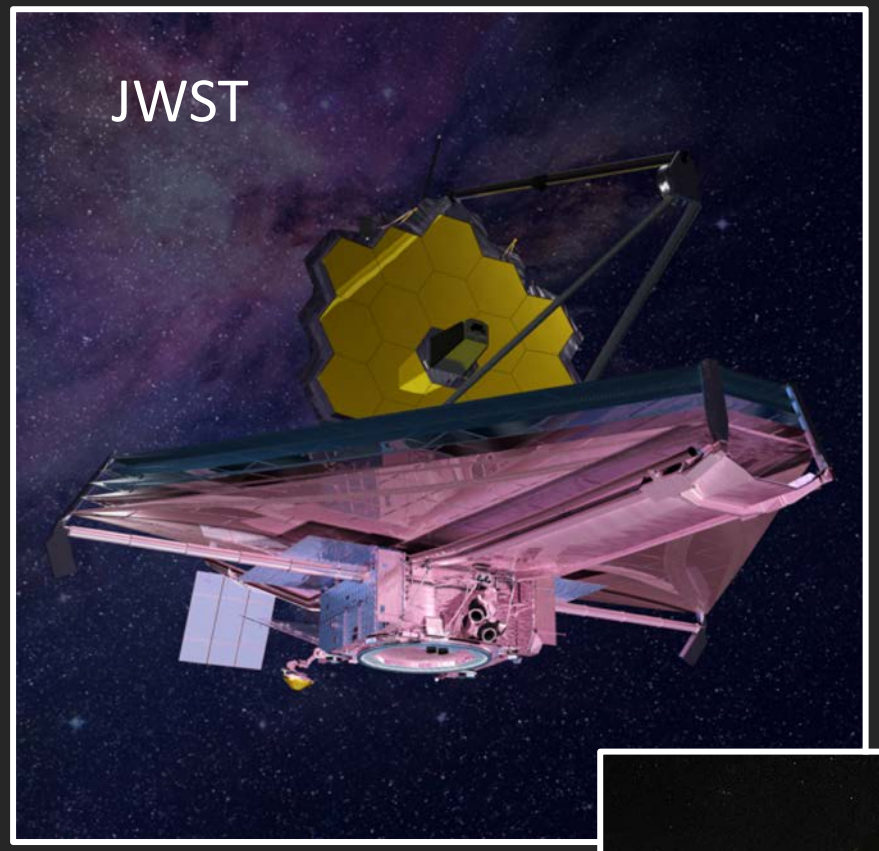
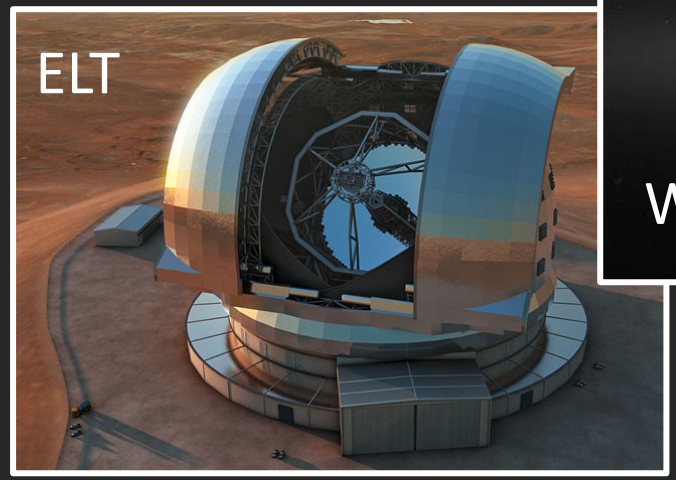
JWST will be launched on an Ariane 5

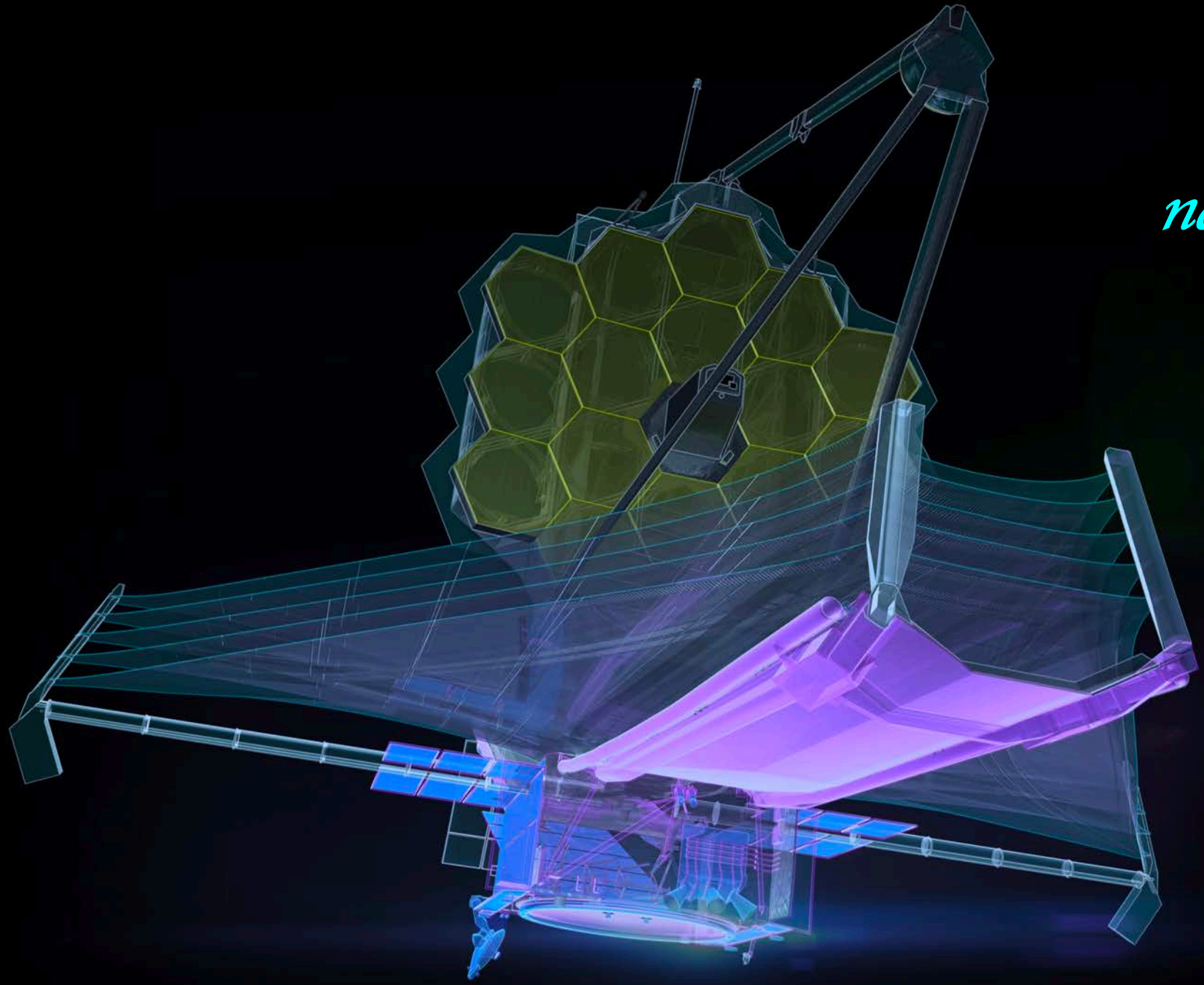
simulated images

gdi



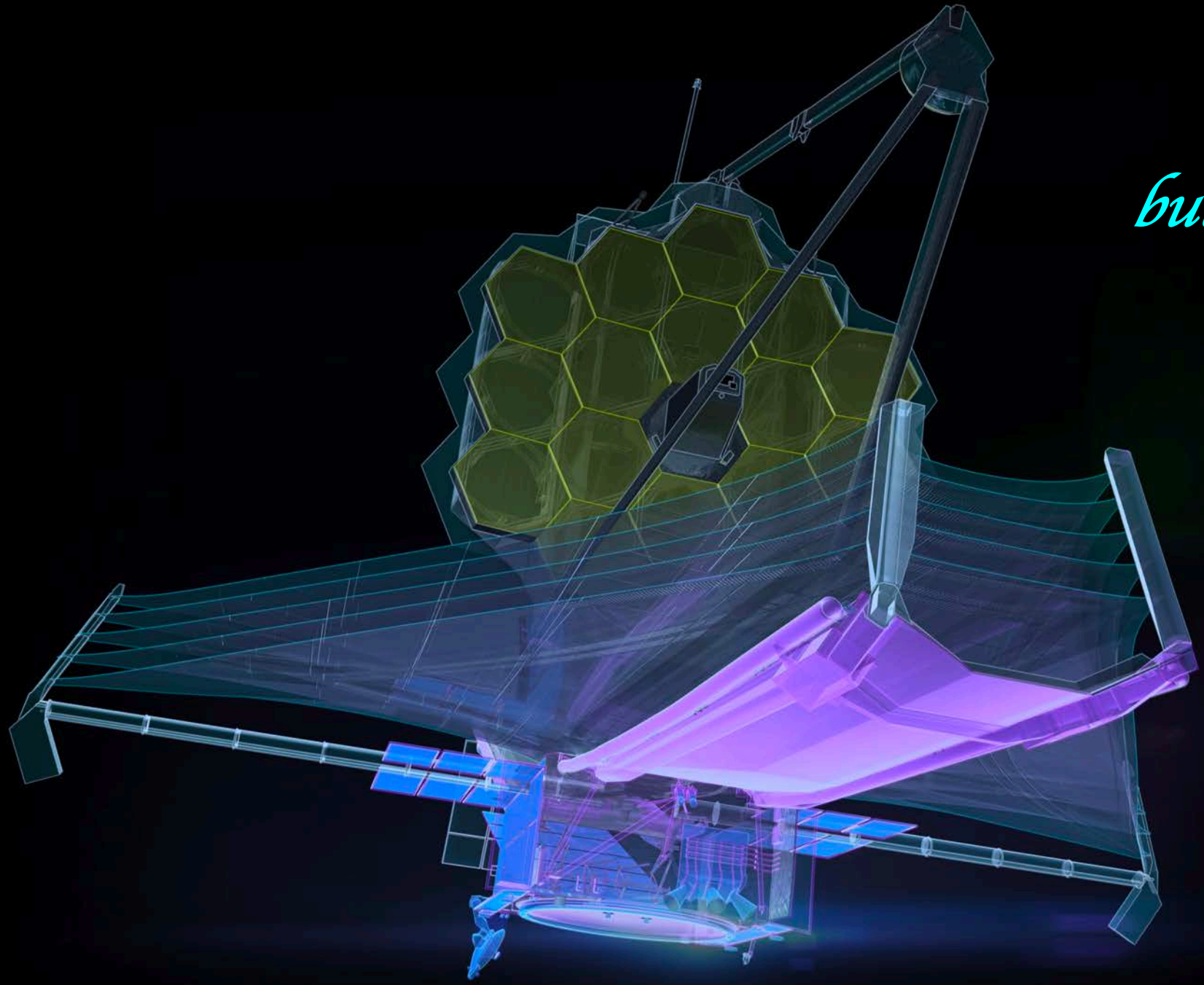
☛ *JWST, along with WFIRST (and similar telescopes) and the ELT, will transform our understanding of distant galaxies in the next decade, but, for distant galaxies, another "next generation telescope" will be needed in the decade beyond* ☚





not the end...

gdi



but the beginning...

gdi