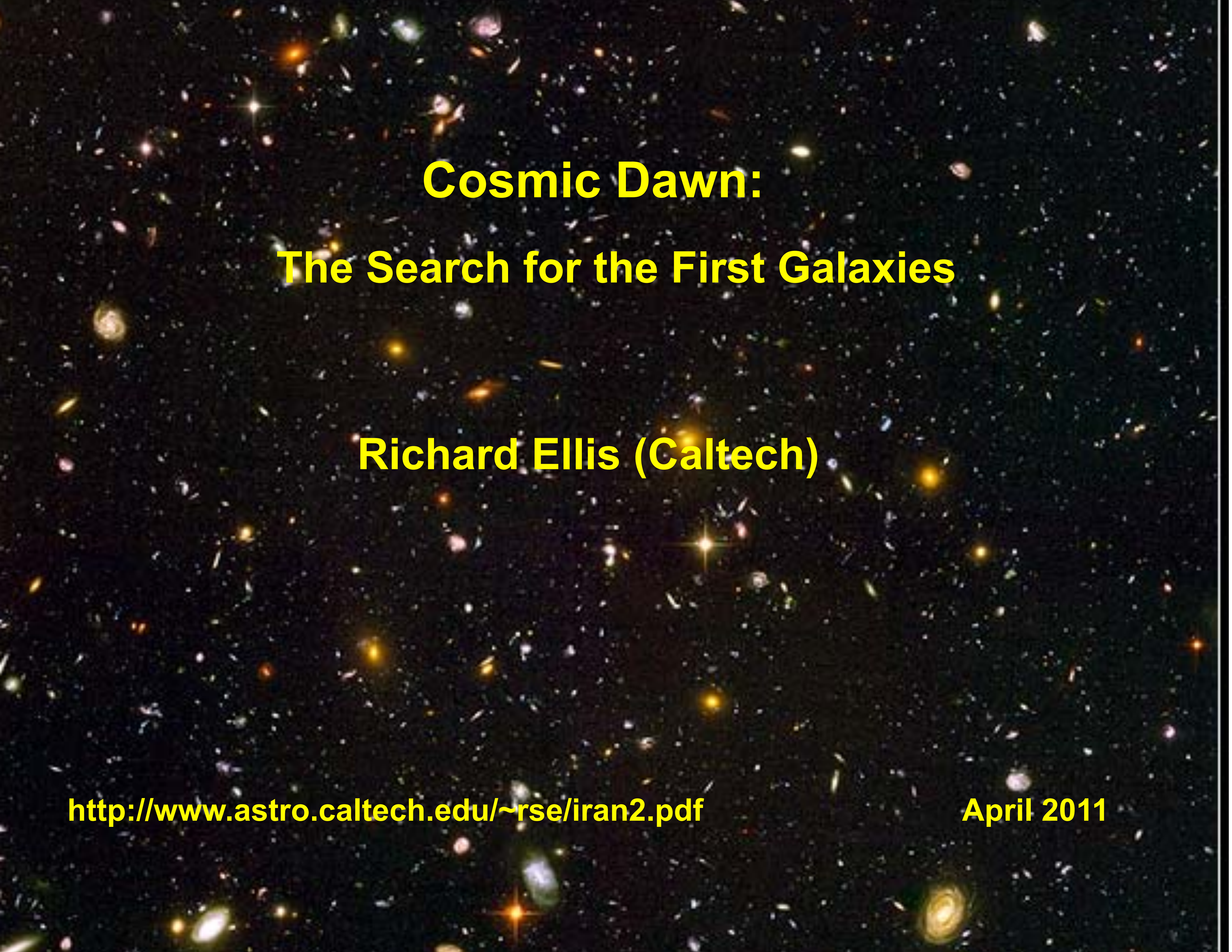


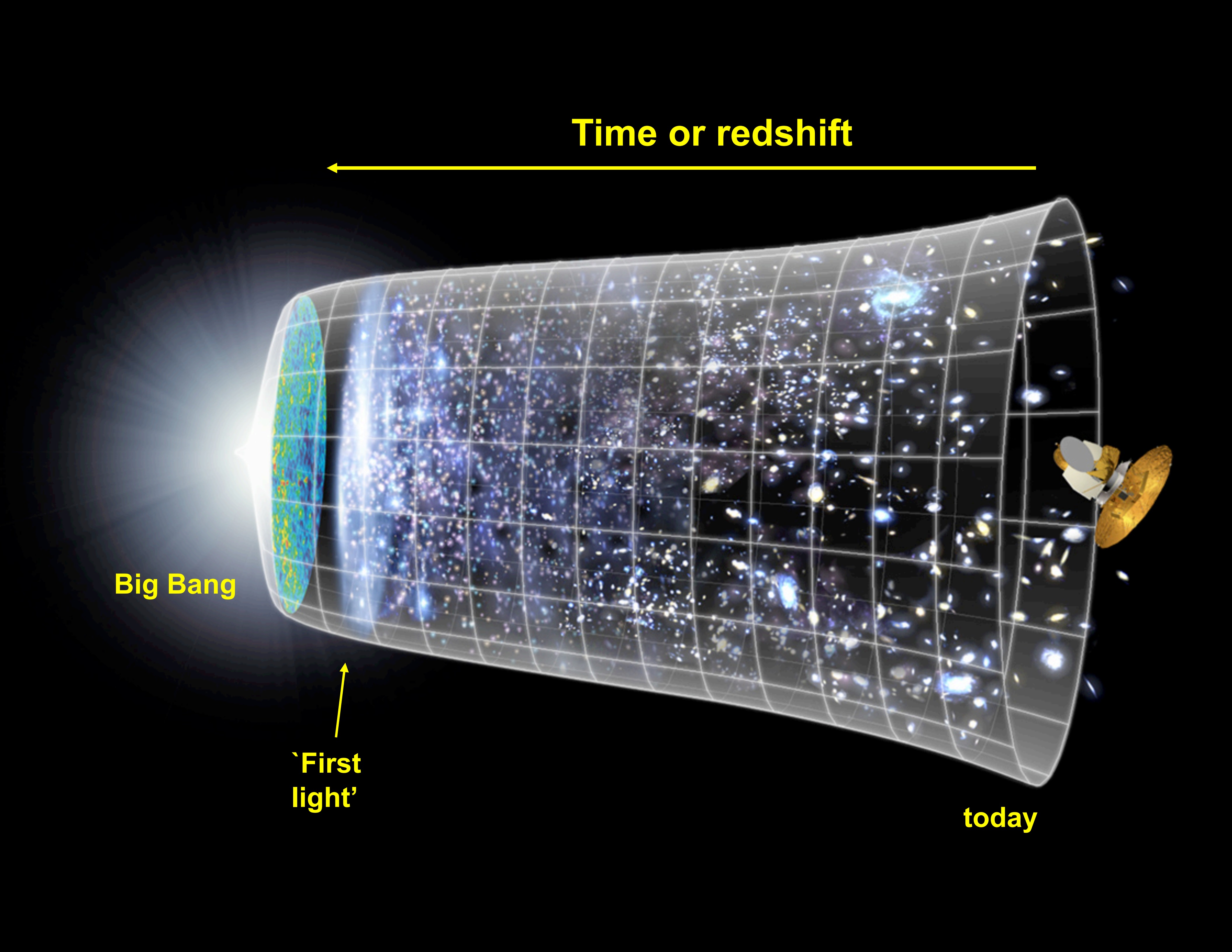
Cosmic Dawn:

The Search for the First Galaxies

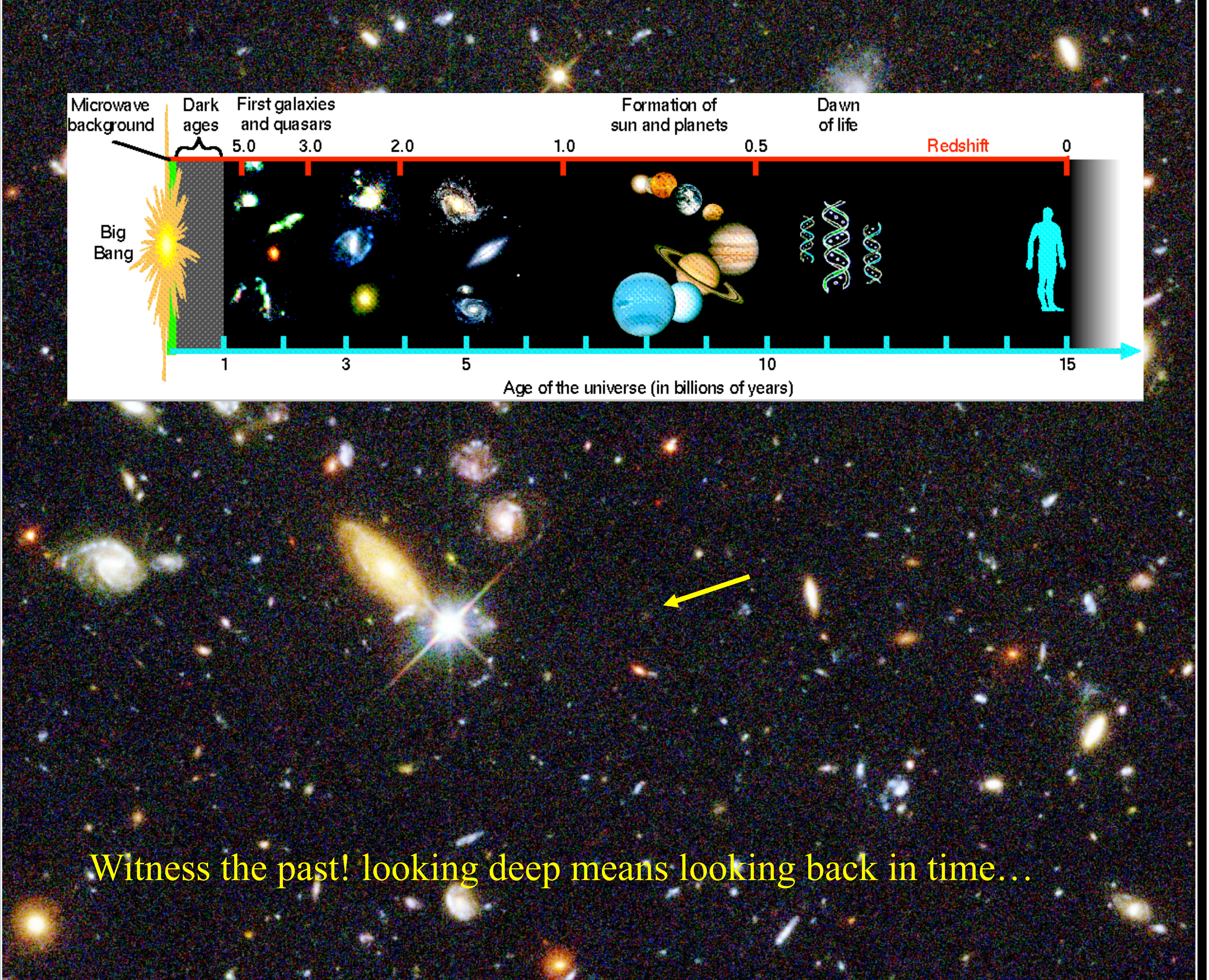
Richard Ellis (Caltech)

http://www.astro.caltech.edu/~rse/iran2.pdf

April 2011



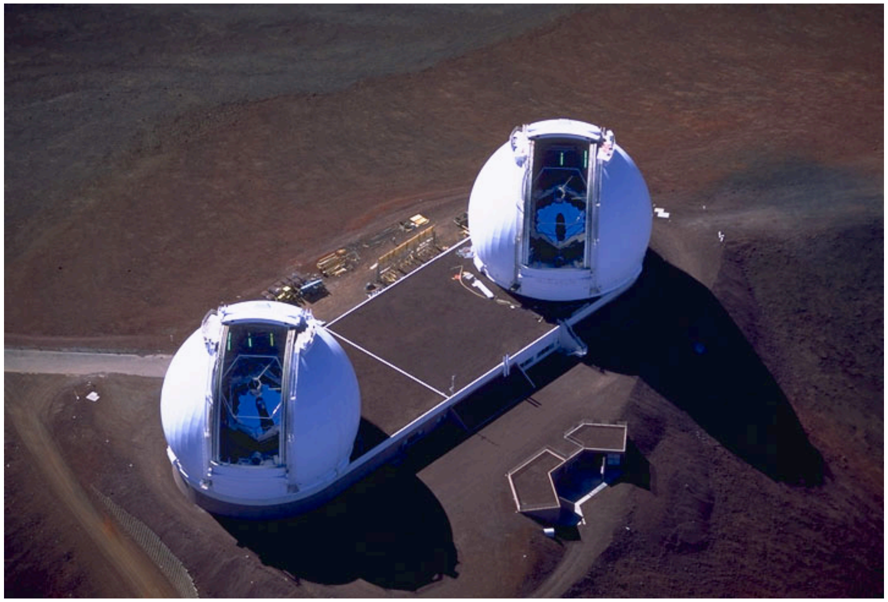
Time or redshift
Big Bang
`First light'
today

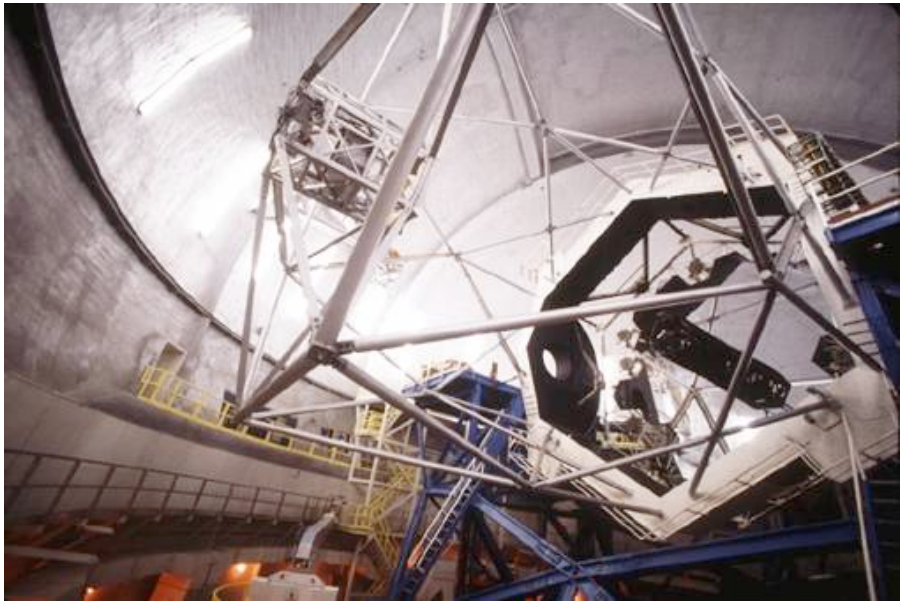


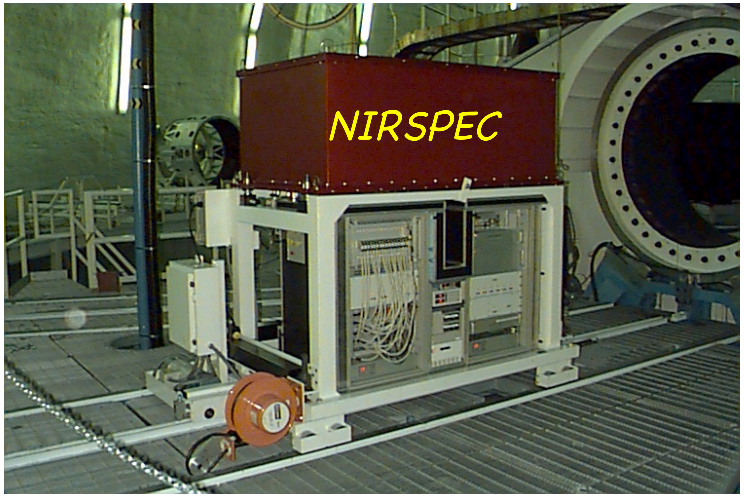
Microwave background
Dark ages
First galaxies and quasars
Formation of sun and planets
Dawn of life
Big Bang
5.0
3.0
2.0
1.0
0.5
Redshift
0
1
3
5
10
15
Age of the universe (in billions of years)
Witness the past! looking deep means looking back in time…

An Observational Adventure Starring..

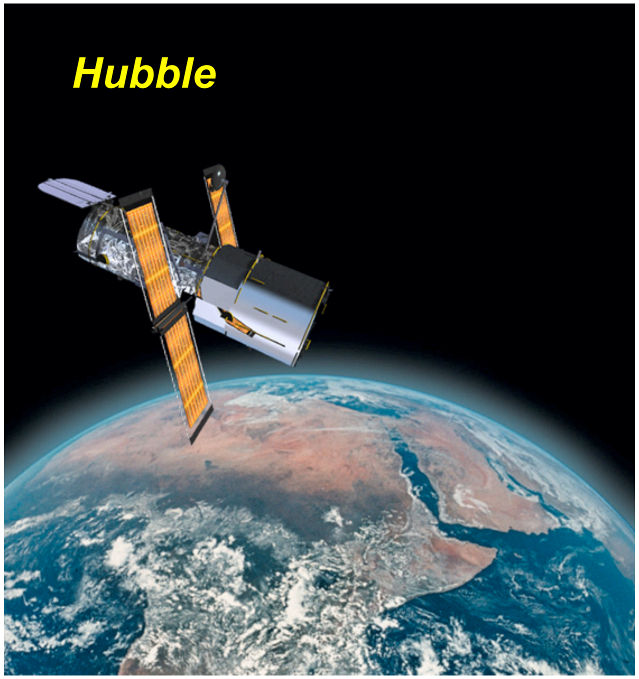
- the two Keck 10-meter reflectors & their spectrographs

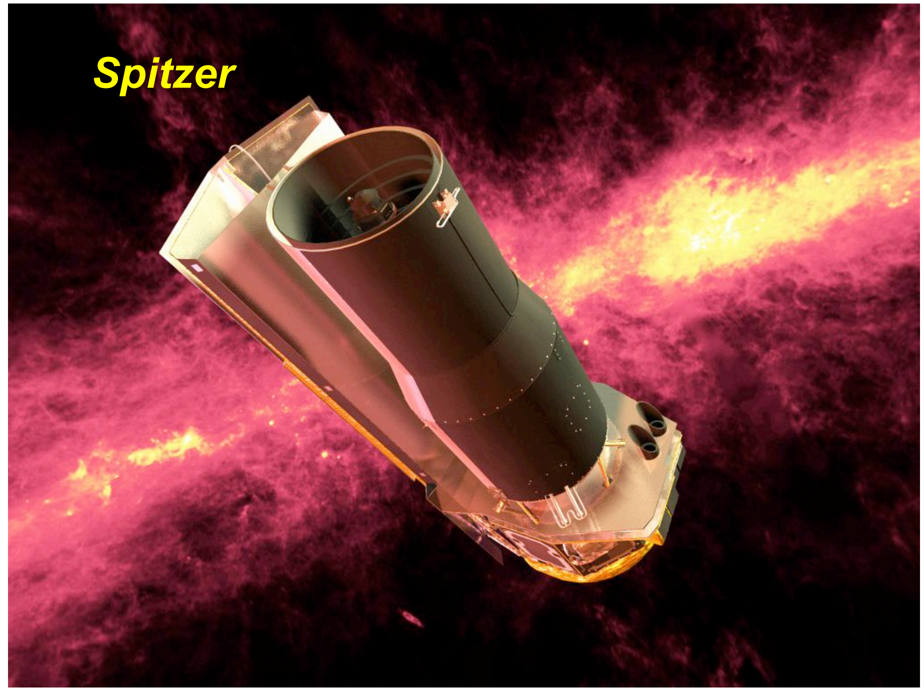


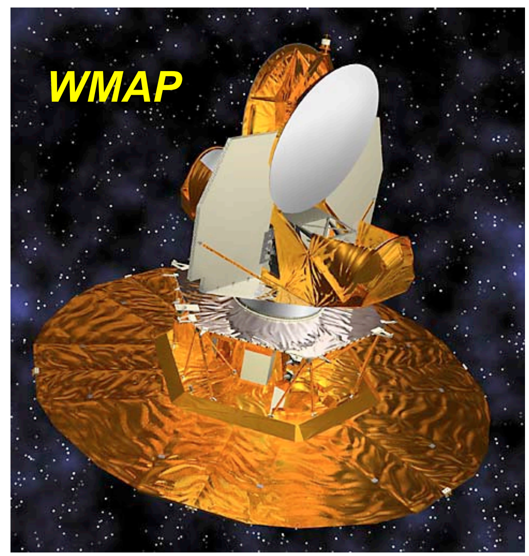




… and three unique space telescopes







Hubble: exquisite deep imaging

Spitzer: sensitive to older stars

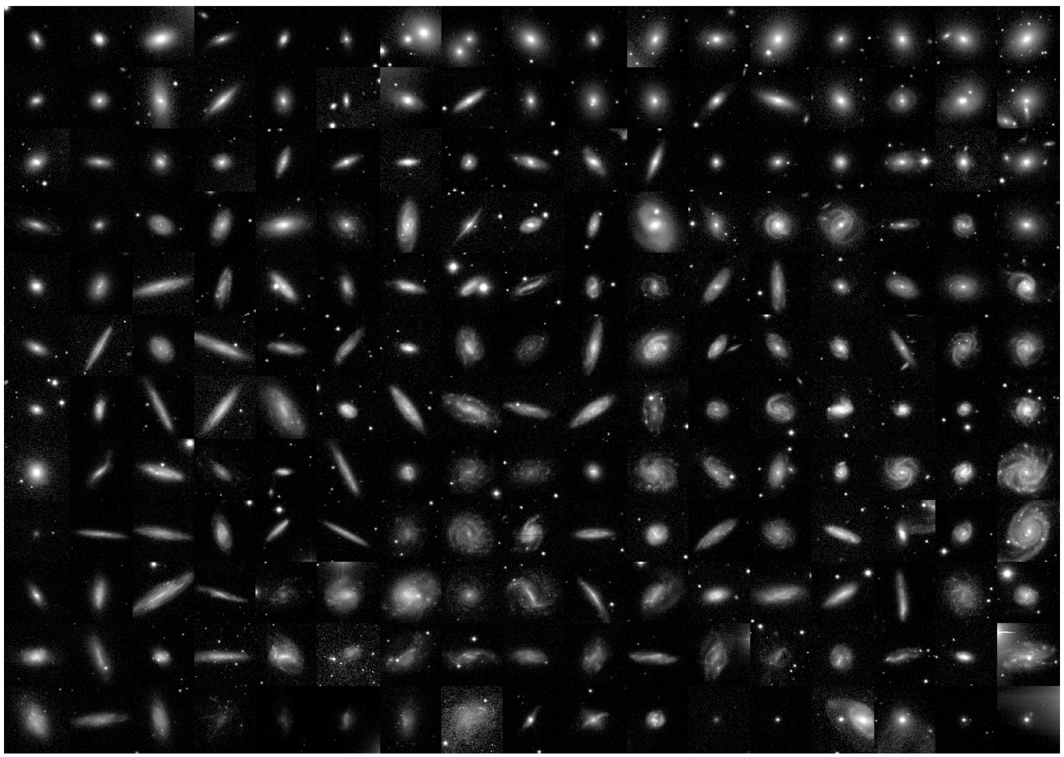
WMAP: studies of microwave background radiation and its scattering by foreground material

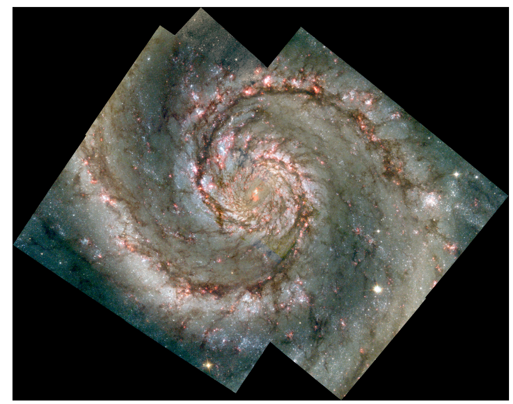
Tracing the History of Starlight

Our quest is to find and understand the earliest cosmic systems containing the first stars which formed barely 100-500 million years after the Big Bang - when the Universe was only 3% of its present age. Some of these stars long since died but many are still shining.

Galaxies represent the giant systems where these stars now reside.

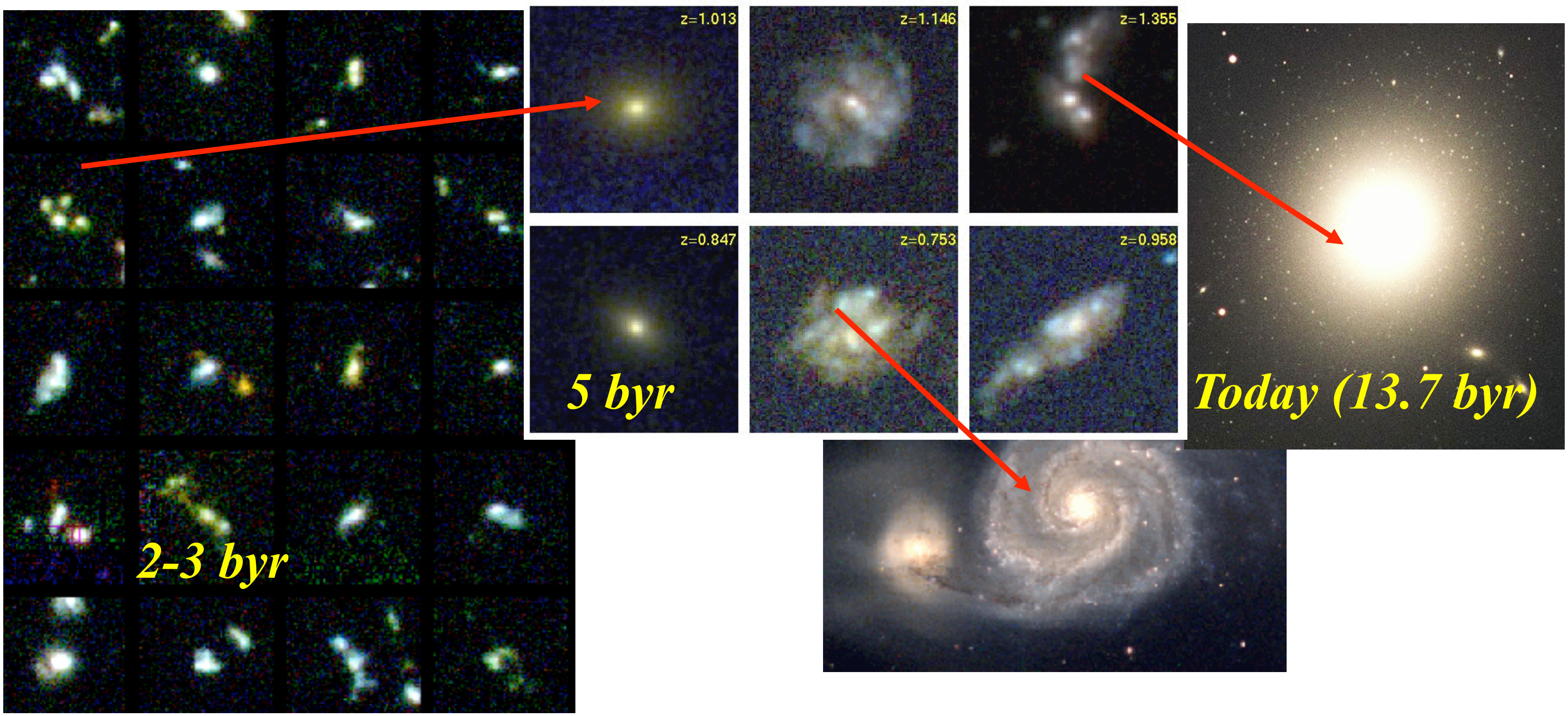
To trace the history of starlight we must trace the history of galaxies





Unraveling Cosmic History

Keck and Palomar, aided by remarkable Hubble Space Telescope images have enabled us to explore the history of the rich variety of present-day galaxies. We have pieced together the story of galaxy formation and evolution back to 2 billion years after the Big Bang (85% of cosmic history)



Finding Distant Galaxies using `Dropouts'

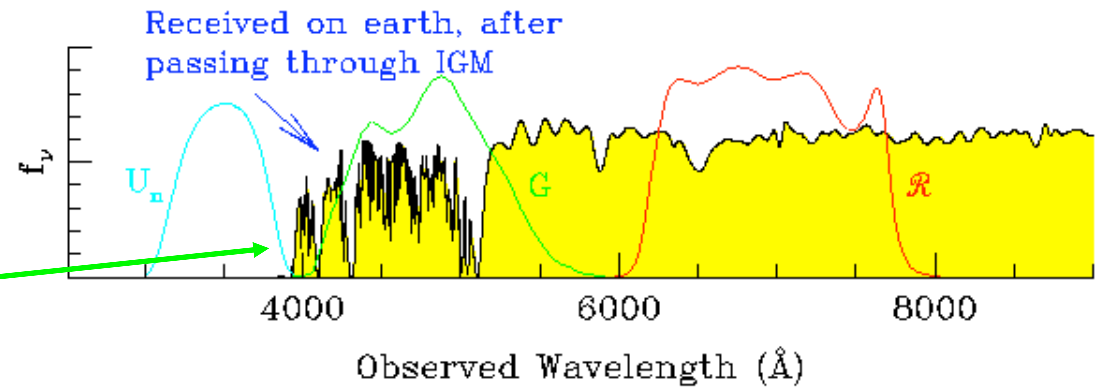
How to find the most distant galaxies seen at early times?

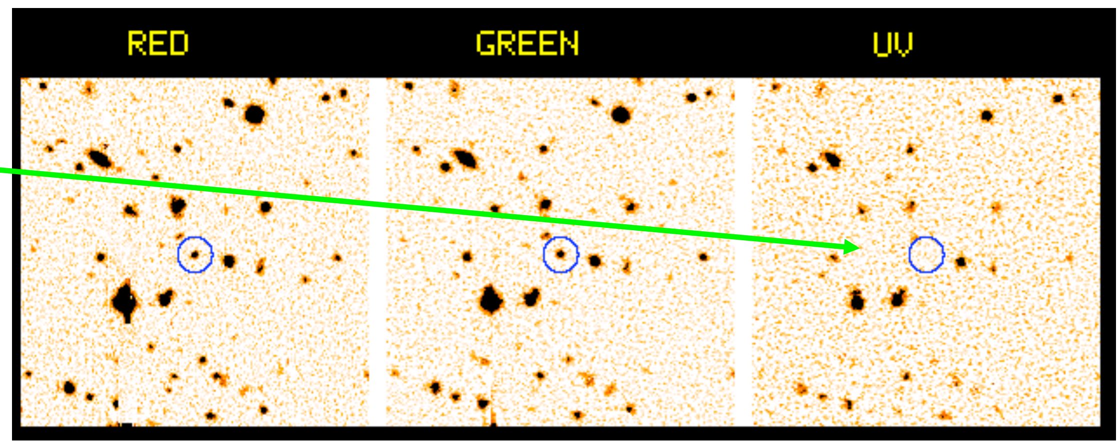
• At large redshift, the signal from a remote galaxy declines due to hydrogen absorption at a particular frequency which enters the range of optical telescopes

• Search for tell-tale 'drop' in signal in ultraviolet signal:

• Palomar does the searching

• Keck verifies the distance via a spectrum

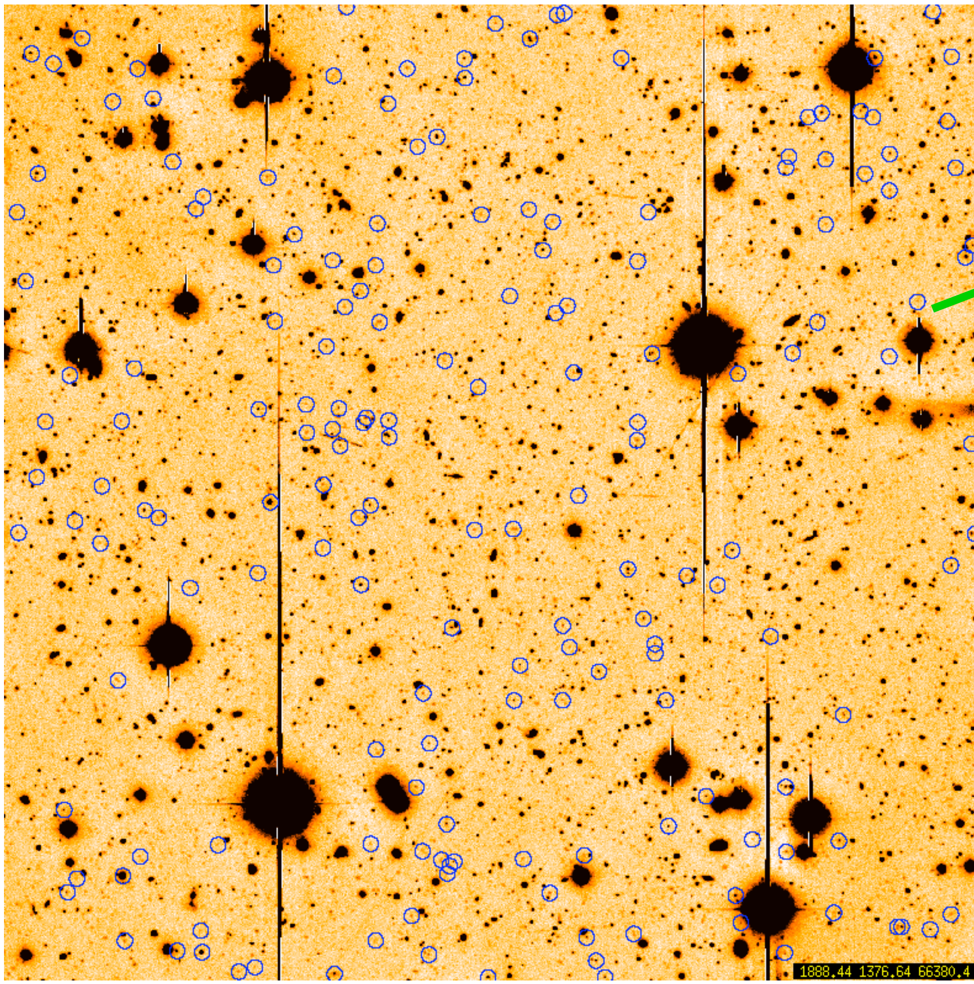


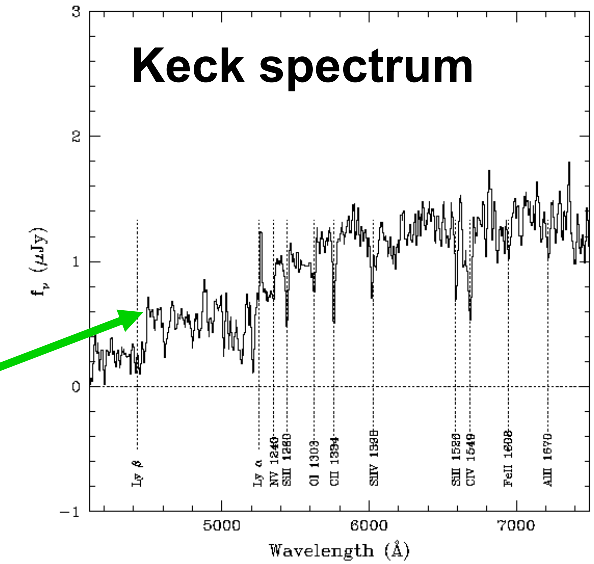


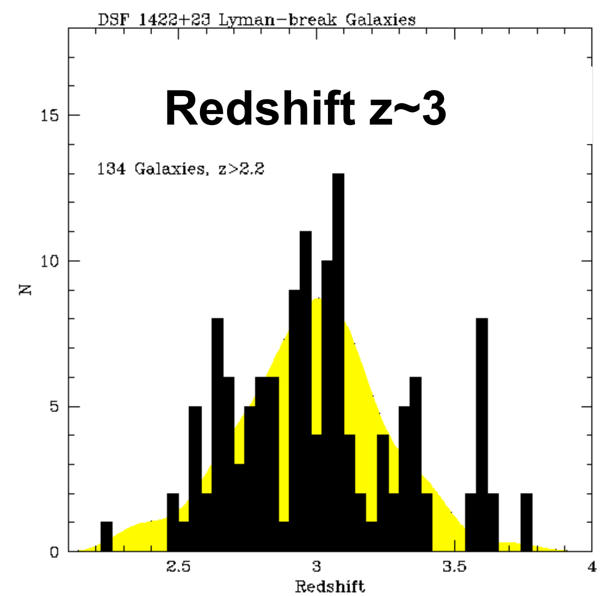
Pioneering work done at Caltech by Chuck Steidel and co-workers

Spectroscopic Confirmation at Keck

Deep Palomar image

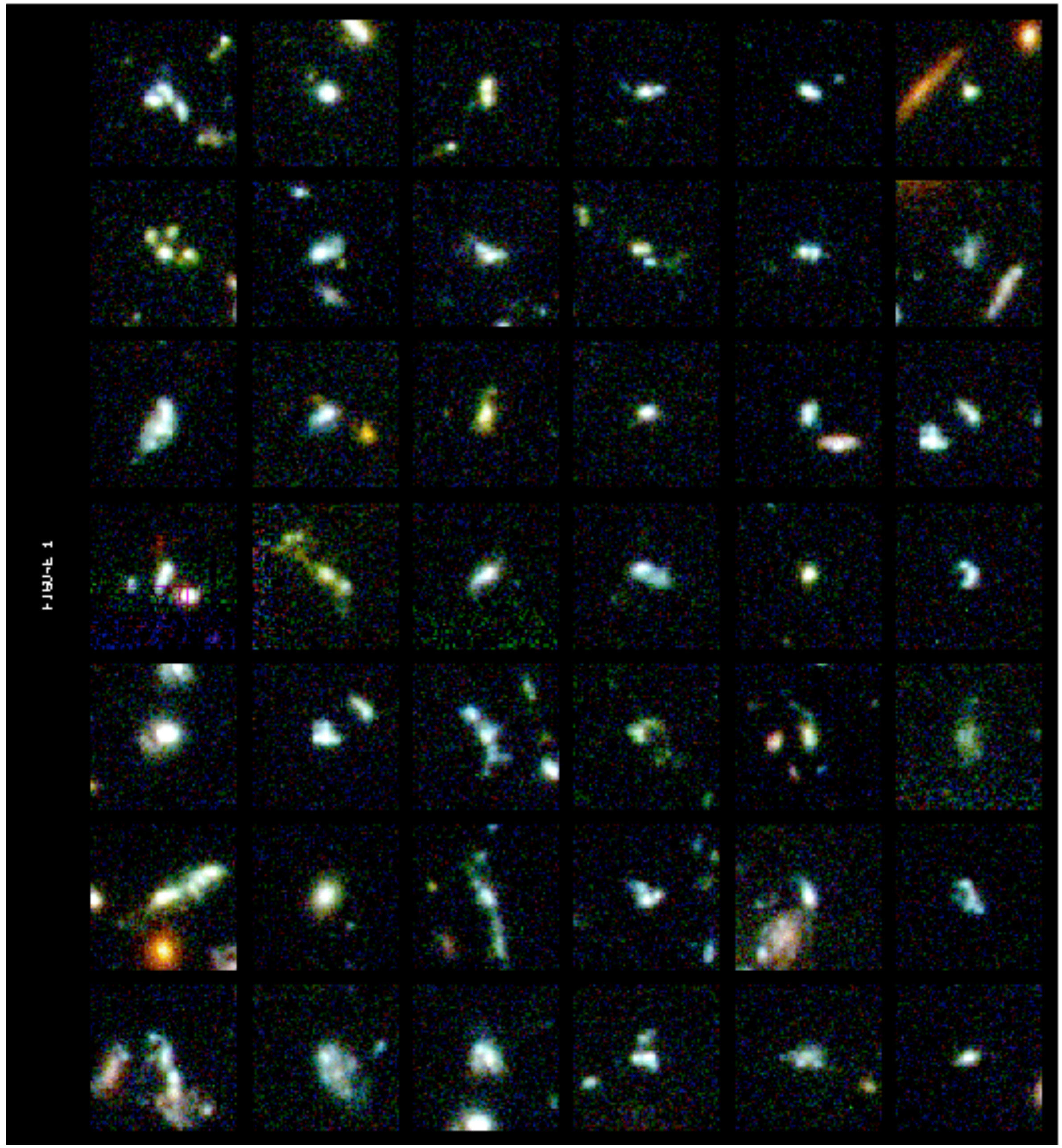


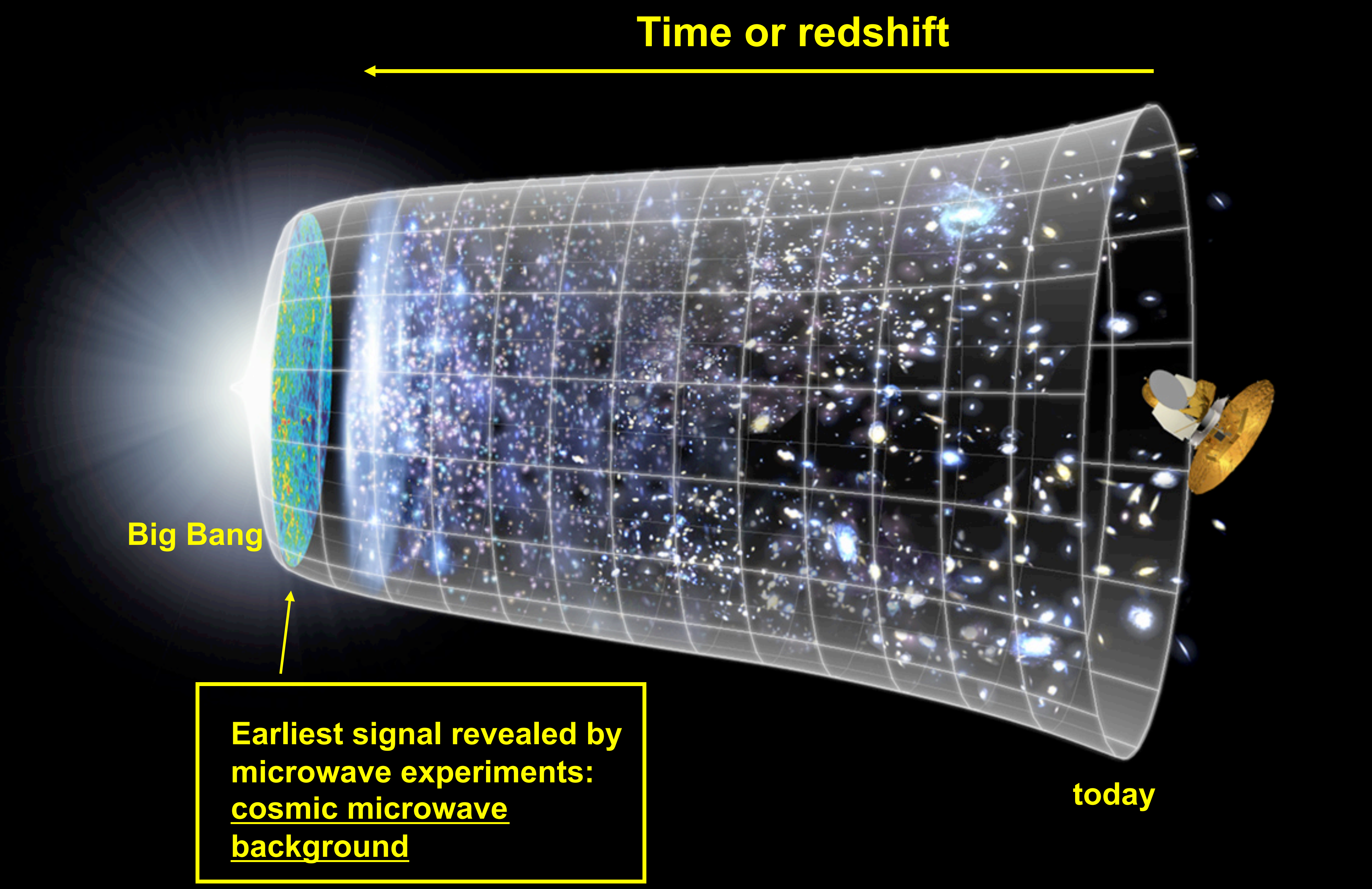




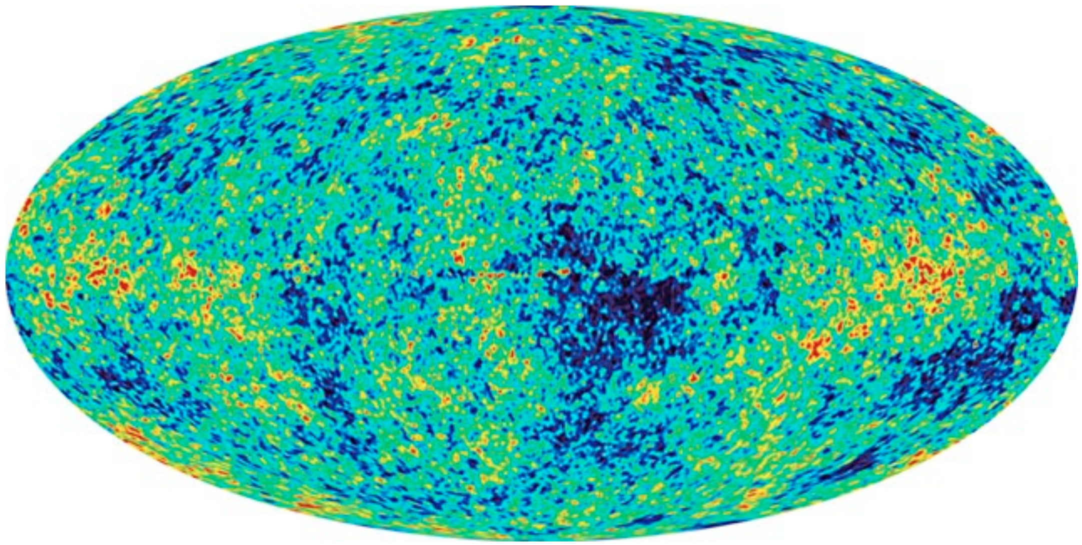
What do these early galaxies look like?

Hubble images of these spectroscopically-confirmed galaxies with redshifts z ~ 3 reveal small physical scale-lengths and irregular morphologies: many appear to be merging or assembling from smaller units - <u>immature systems</u>




Time or redshift
Big Bang
today
Earliest signal revealed by microwave experiments: cosmic microwave background

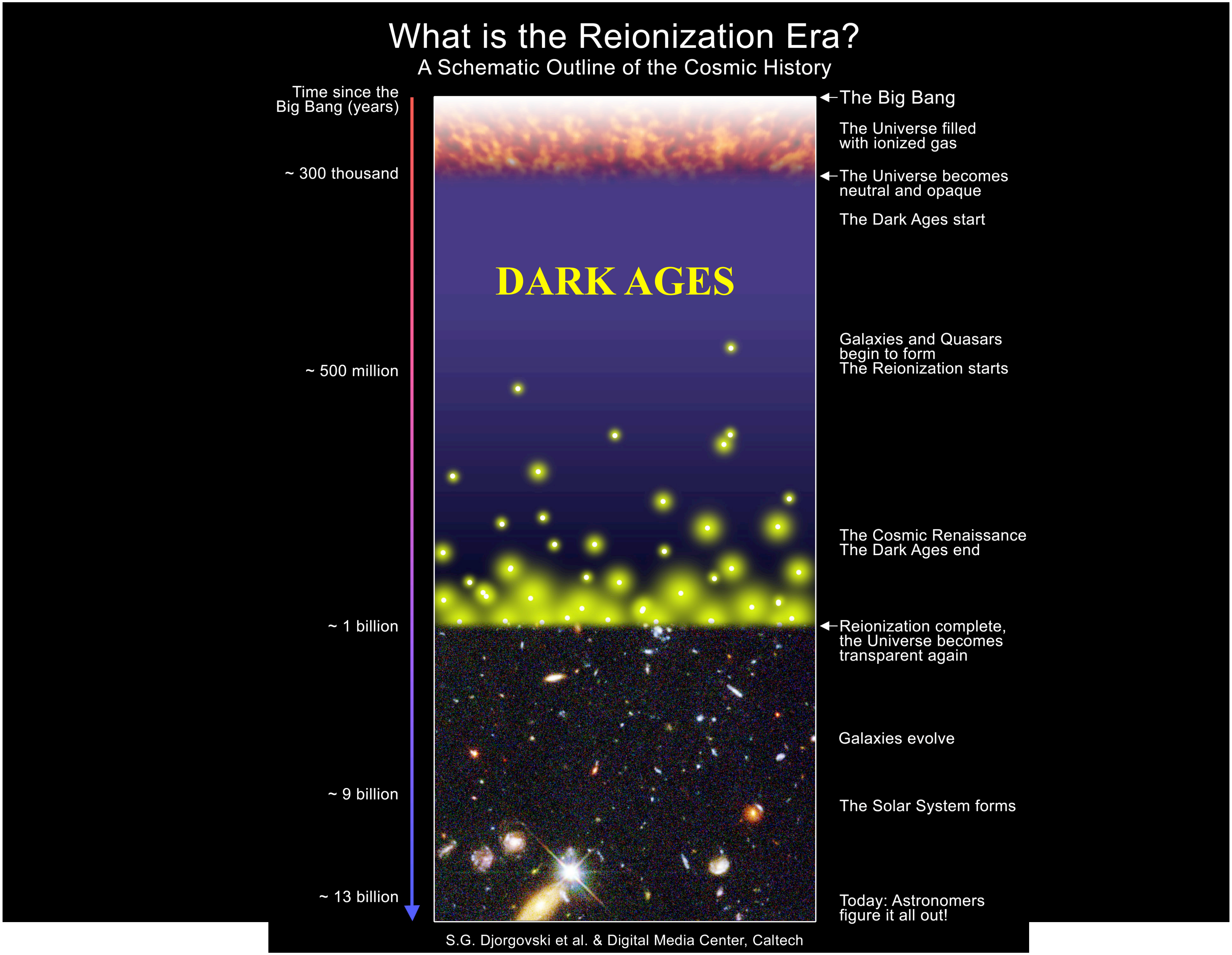
What happened next?



Microwave background radiation is seen 372,000 yrs after creation representing the time when hydrogen atoms form for the first time

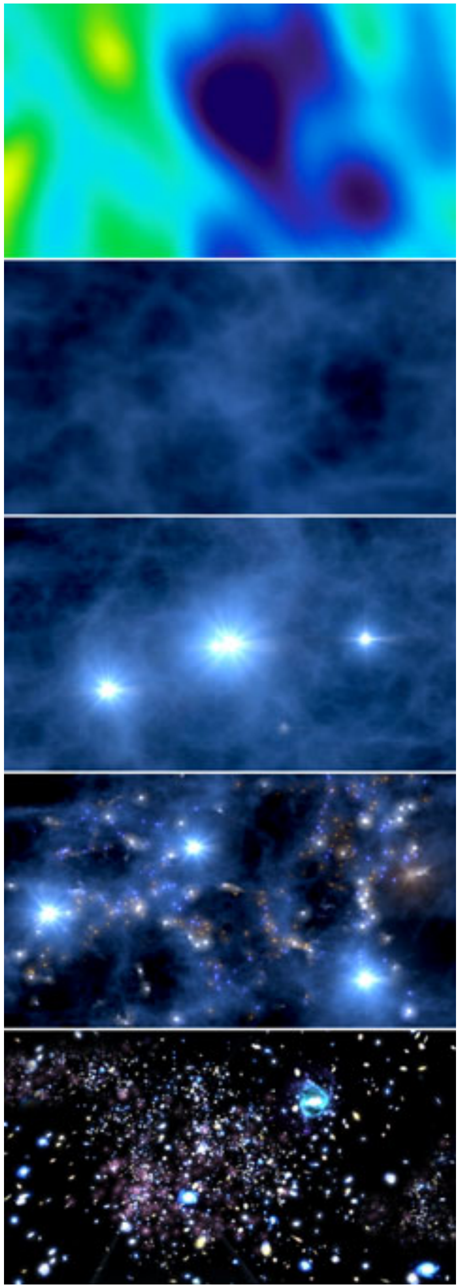
Universe then enters a period called the `**dark ages**': cold hydrogen clouds clump and eventually collapse to form stars

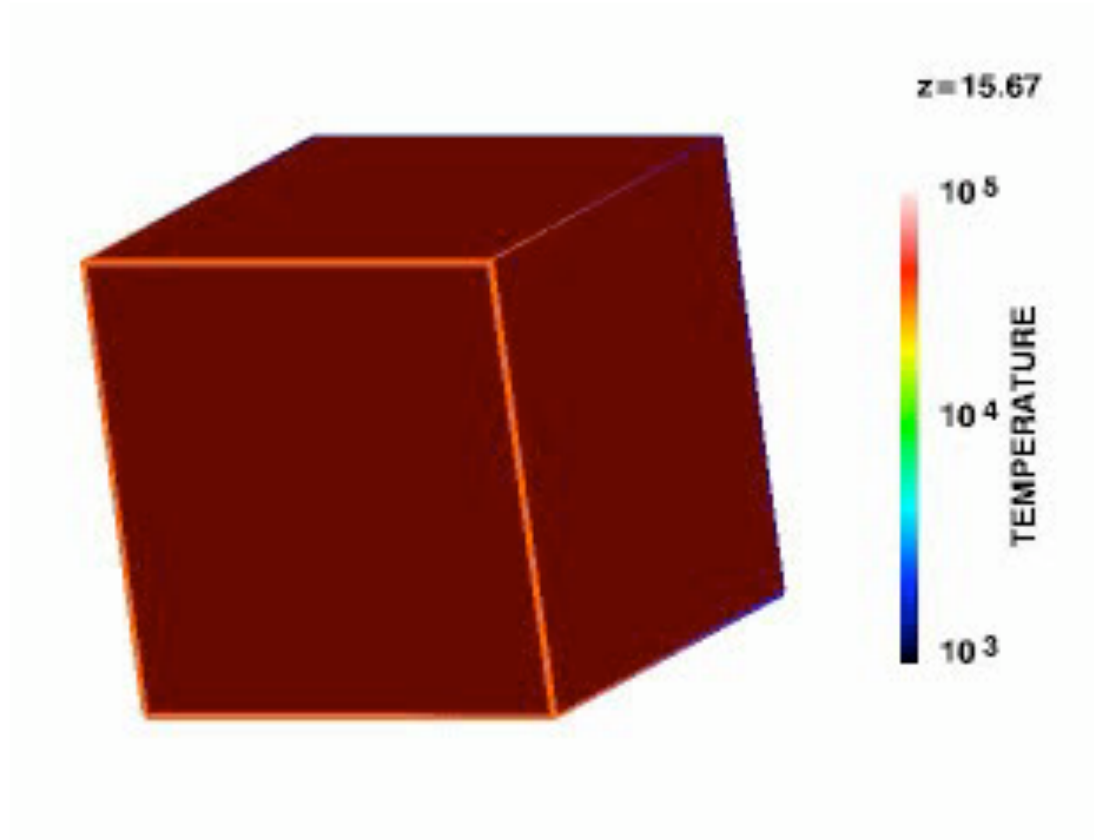
Stars eventually energize hydrogen in deep space breaking it into electrons and protons (process called `**reionization**')


What is the Reionization Era?
A Schematic Outline of the Cosmic History
Time since the Big Bang (years)
~ 300 thousand
~ 500 million
~ 1 billion
~ 9 billion
~ 13 billion
DARK AGES
The Big Bang
The Universe filled with ionized gas
The Universe becomes neutral and opaque
The Dark Ages start
Galaxies and Quasars begin to form
The Reionization starts
The Cosmic Renaissance
The Dark Ages end
Reionization complete, the Universe becomes transparent again
Galaxies evolve
The Solar System forms
Today: Astronomers figure it all out!
S.G. Djorgovski et al. & Digital Media Center, Caltech

End of the Dark Ages:

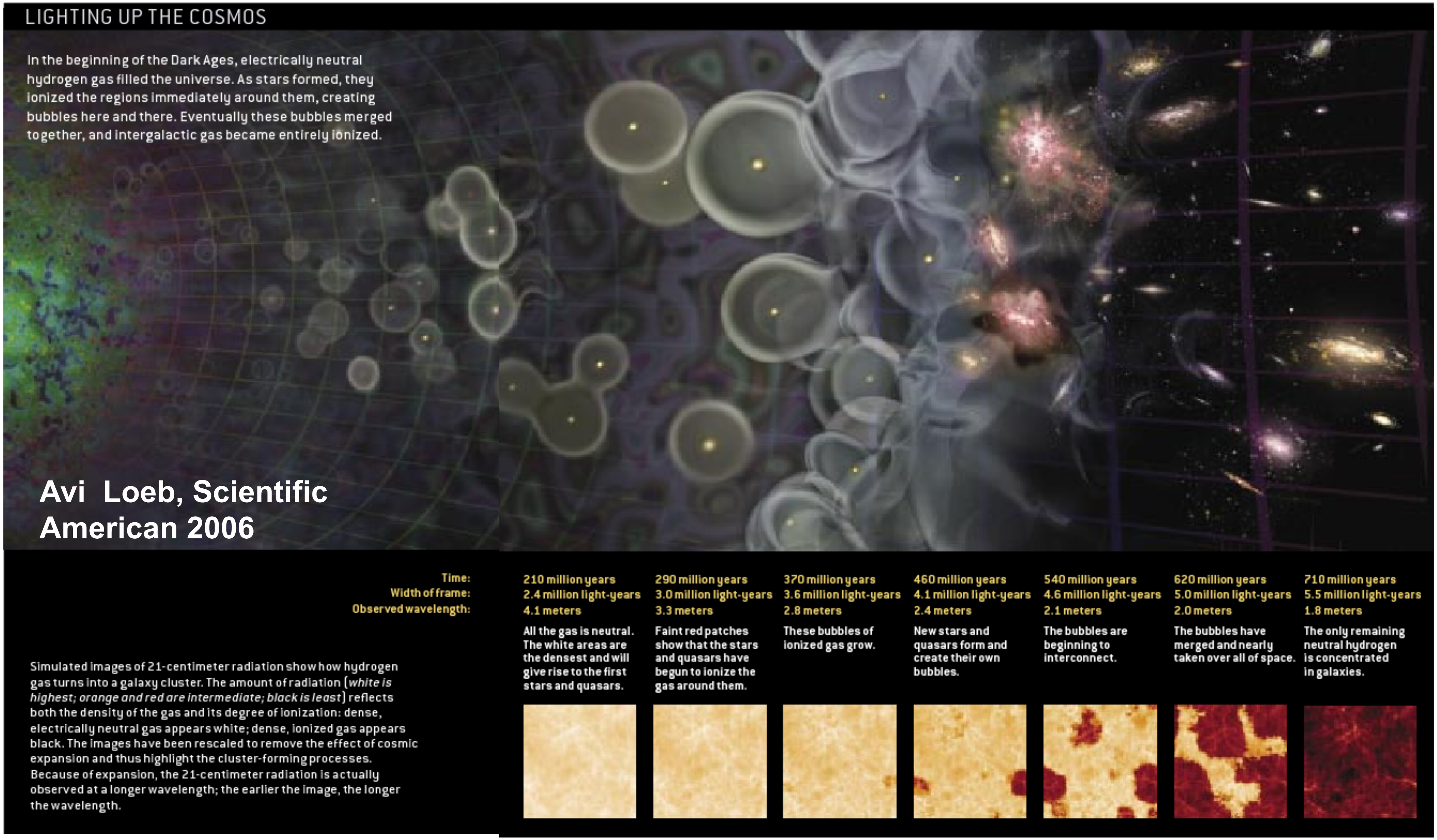
Reionization of Hydrogen by First Star-forming Galaxies





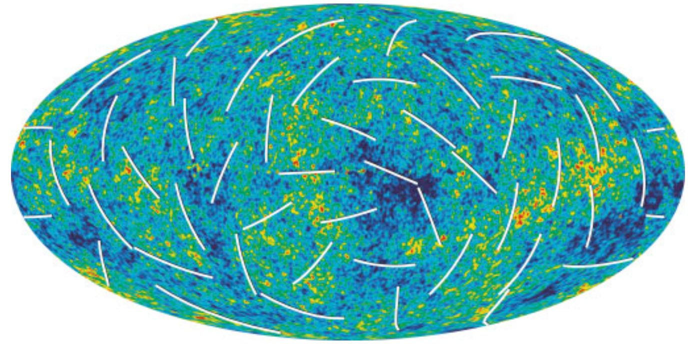
time

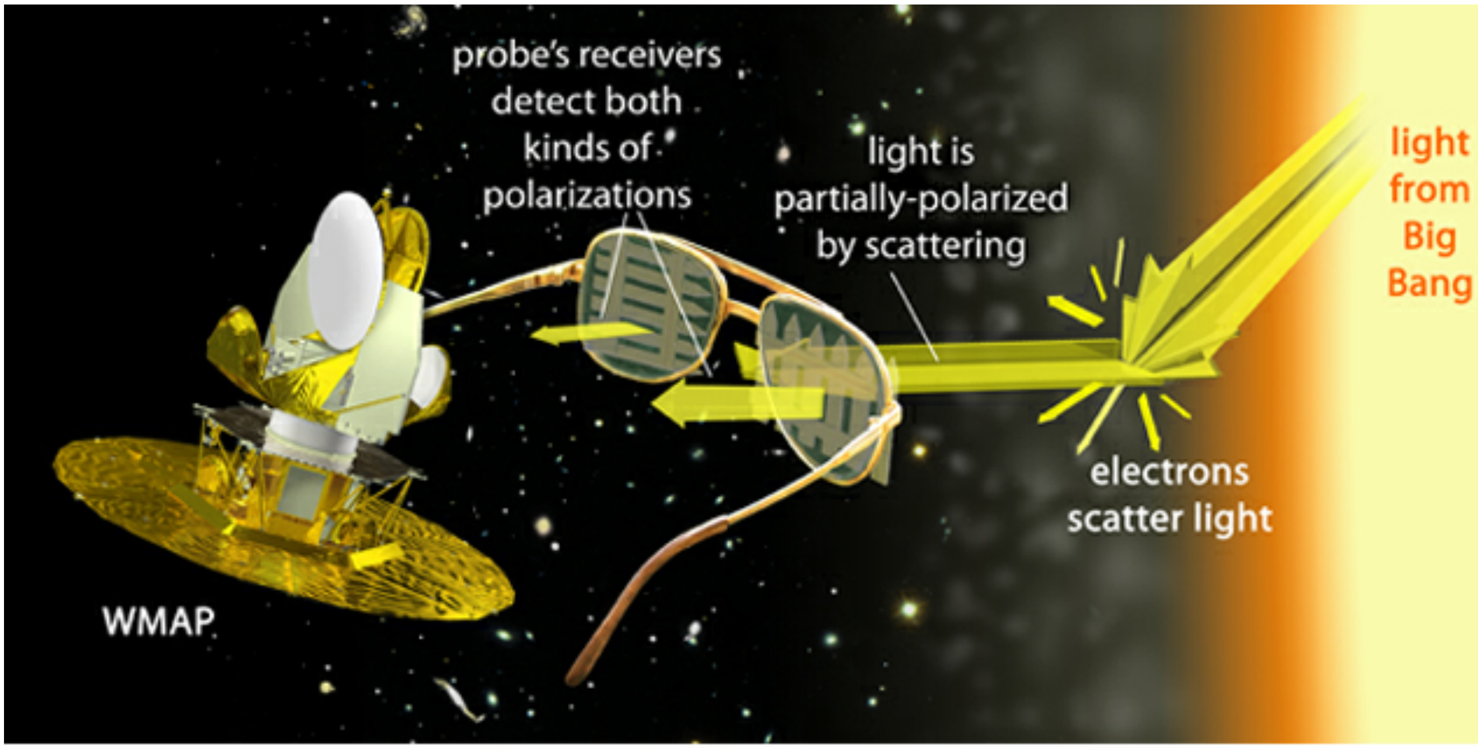
Theorists' View of Cosmic Dawn



Wonderful..but did it really happen like this..?

Polarization of Microwave Background



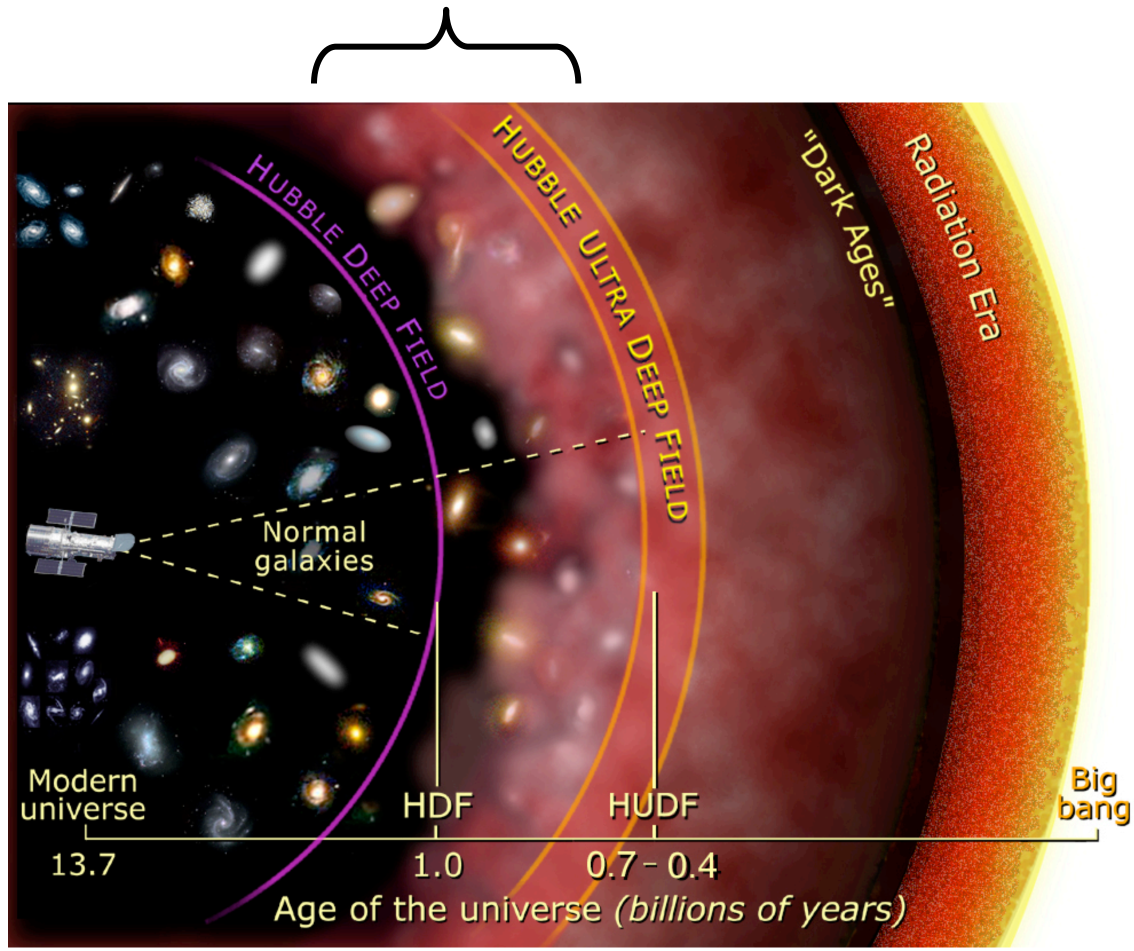


Polarization in microwave background probes electron scattering in the foreground i.e. electrons from the time of reionization

WMAP signal suggests reionization occurred at $6<z<15$ corresponding to 300 - 900 million years after Big Bang

The Holy Grail: Finding the Earliest Galaxies

End of the dark ages

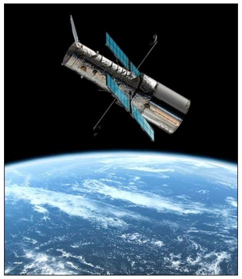


Summary:

Indirect evidence from polarization of the microwave background suggests there was a sharp transition in deep space sometime between z=6 and 15, corresponding to 300-900 million years after the Big Bang

Most likely this was the blaze of light from the first luminous systems:

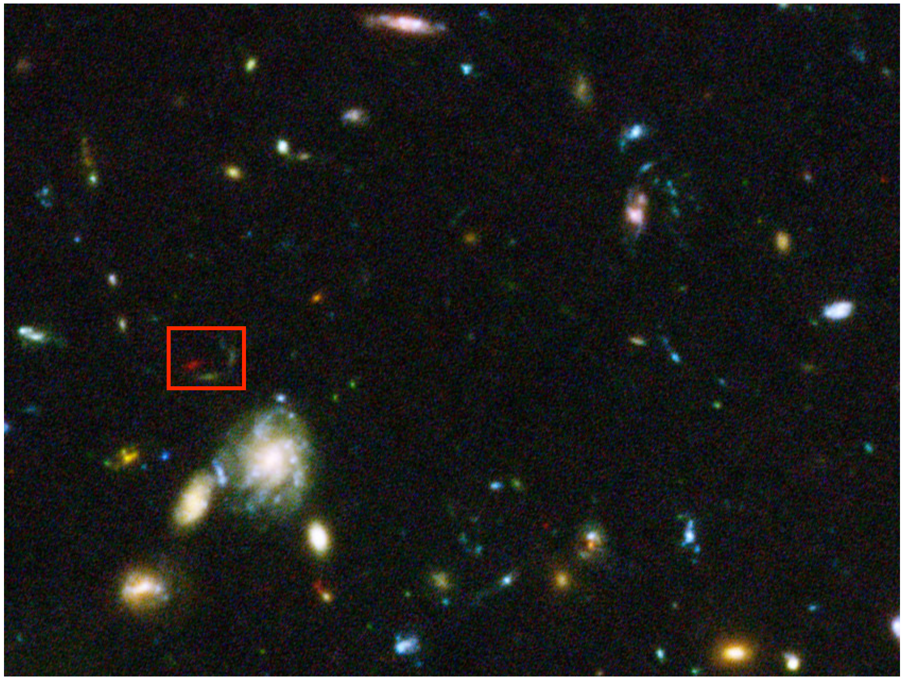
Can we detect them?



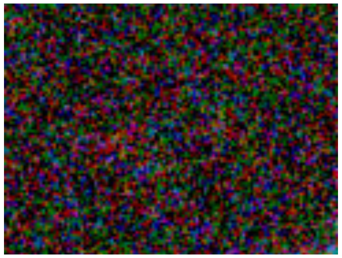
The Hubble Ultra Deep Field

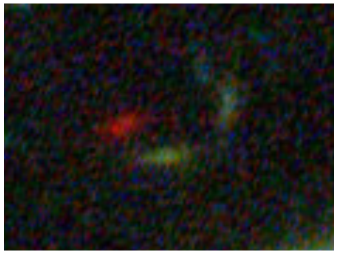
The HUDF remains the deepest optical image

GOODS field – 13 orbits

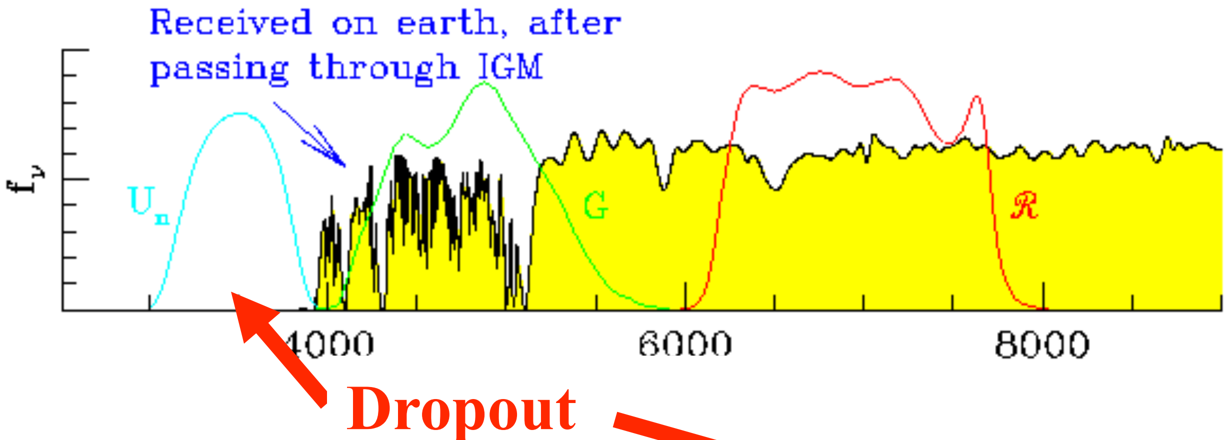


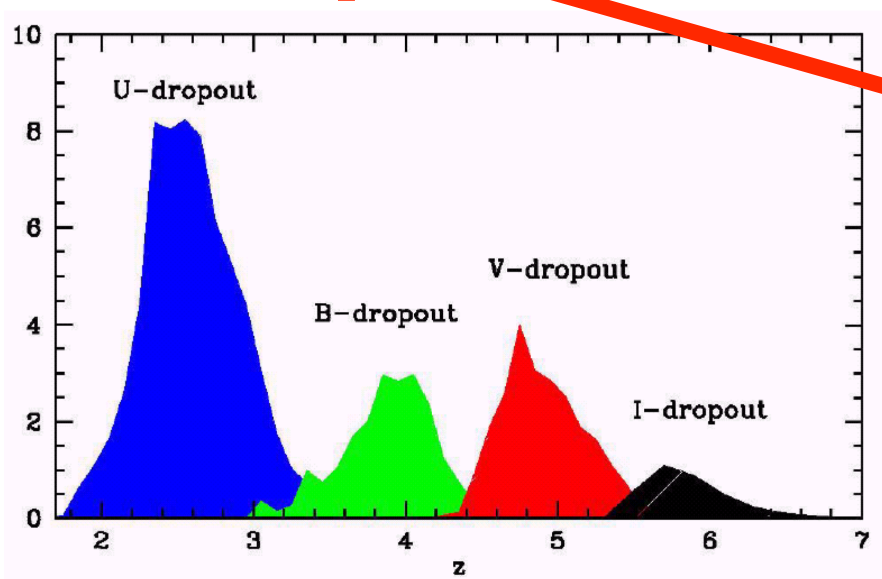
HUDF – 400 orbits



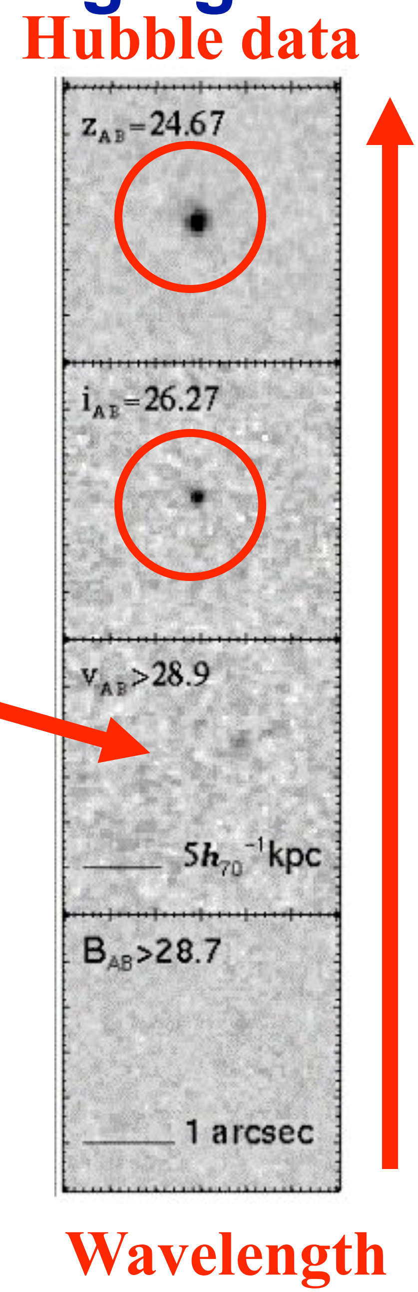


Very distant sources in deep Hubble imaging

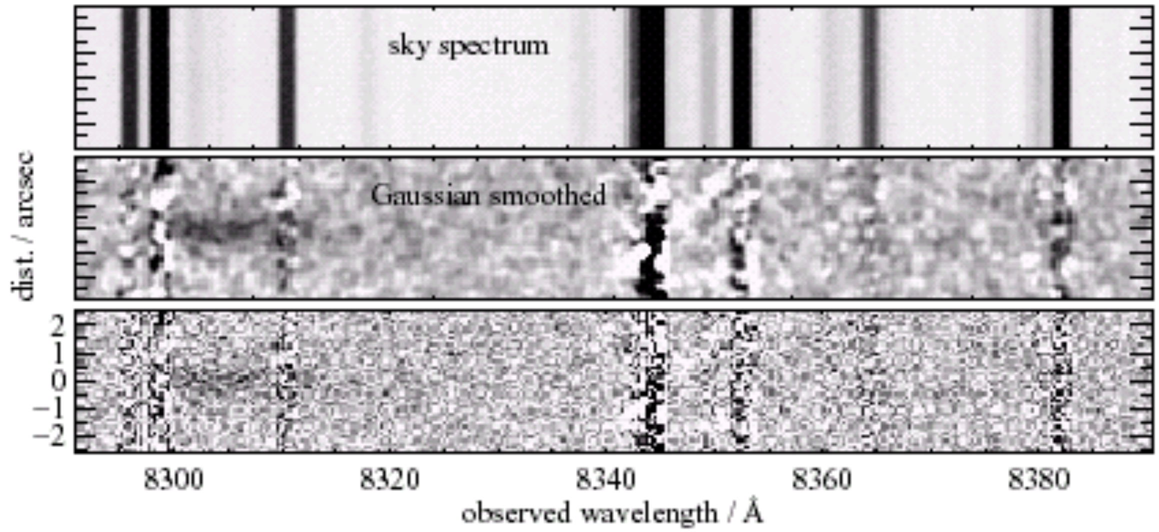


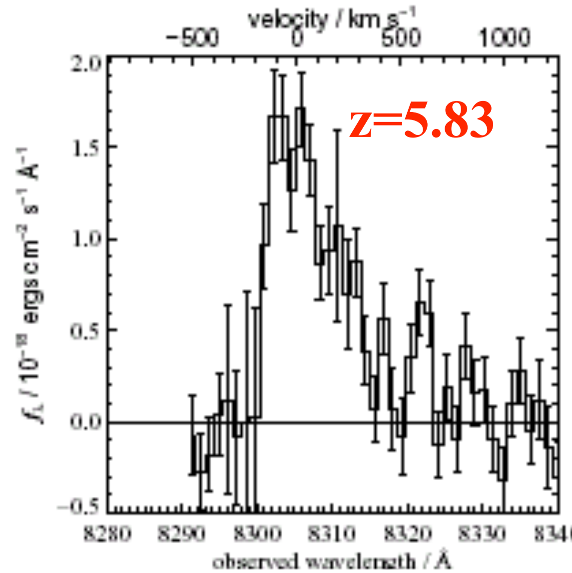


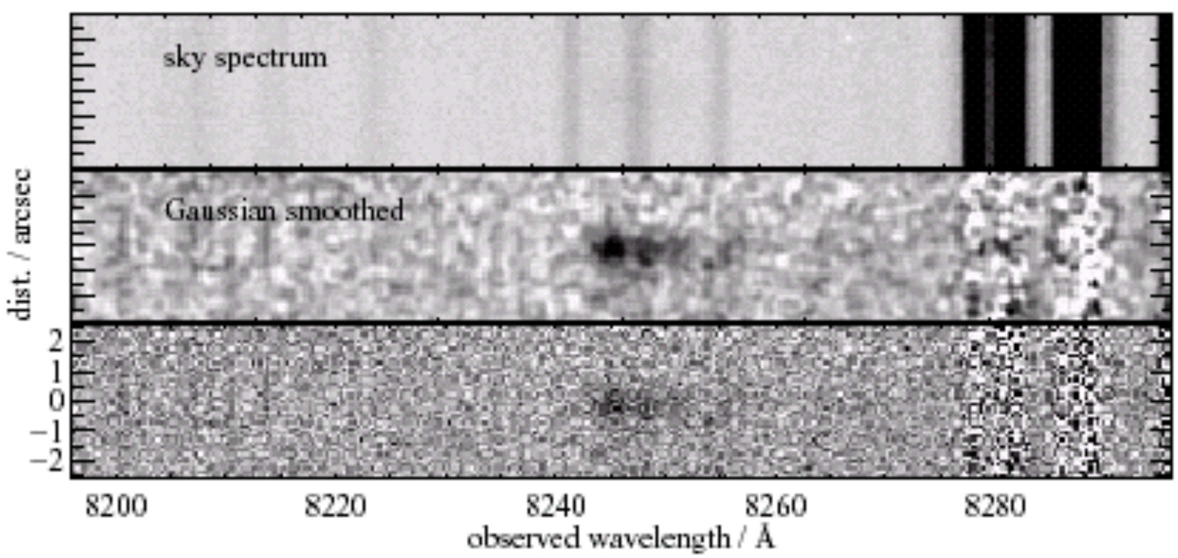
We can extend the `dropout' technique used successfully at z=3 to find examples of star-forming galaxies beyond z=5 by looking for dropouts in redder bands

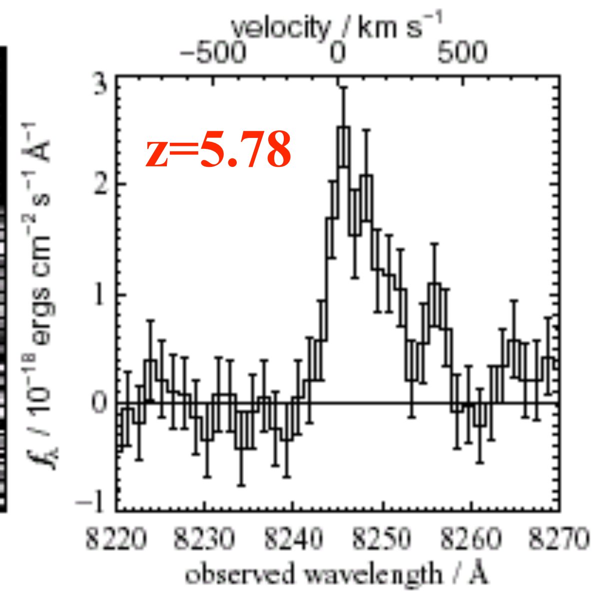


Keck spectroscopy of distant dropouts



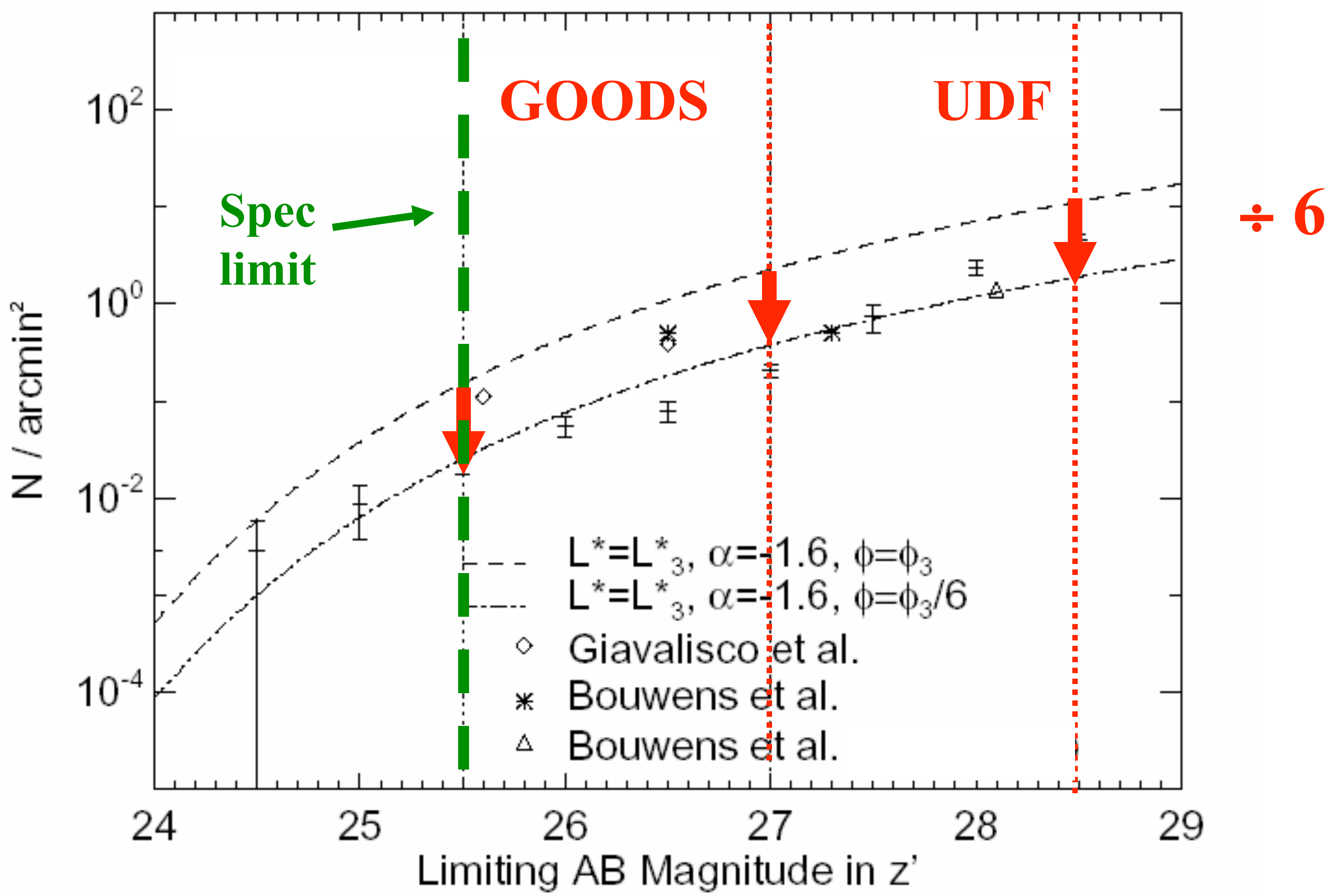






Bunker, RSE et al (2004)

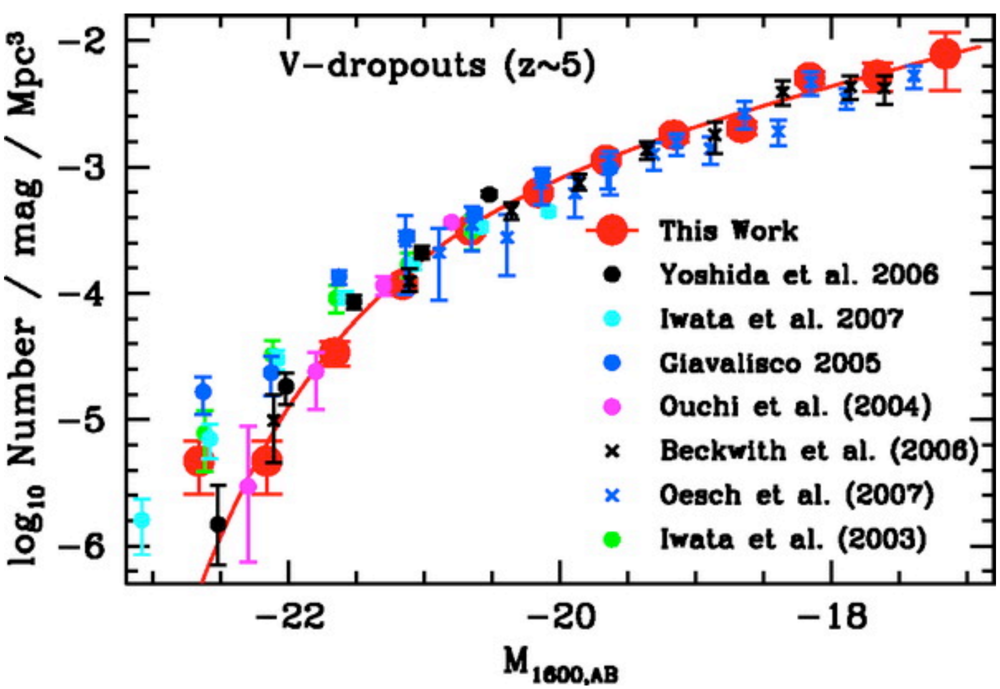
Upshot: luminosity distribution at z~6

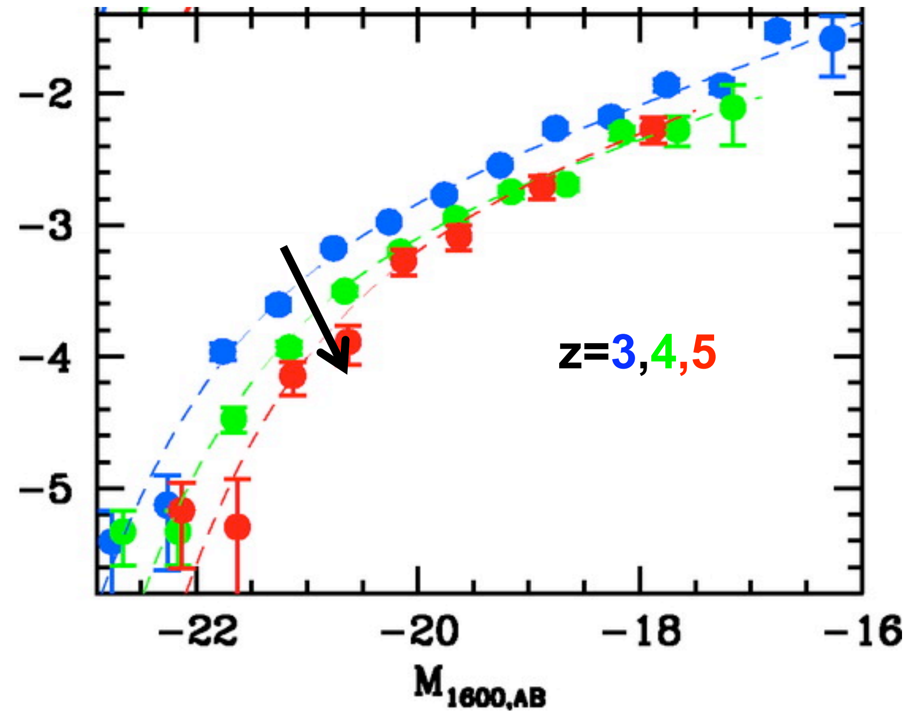


GOODS/UDF data to z_{AB}'=28.5 consistent with z=3 LF but ÷ 6

Bunker, Stanway, Ellis & McMahon MNRAS 355, 374 (2004)

And With Larger Samples from Hubble…

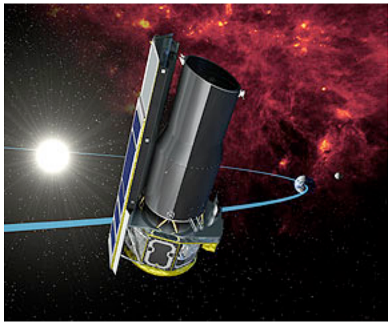




- Many groups analyzing the public data (& fortunately agree!)
- Confirmation of decline in abundance with redshift

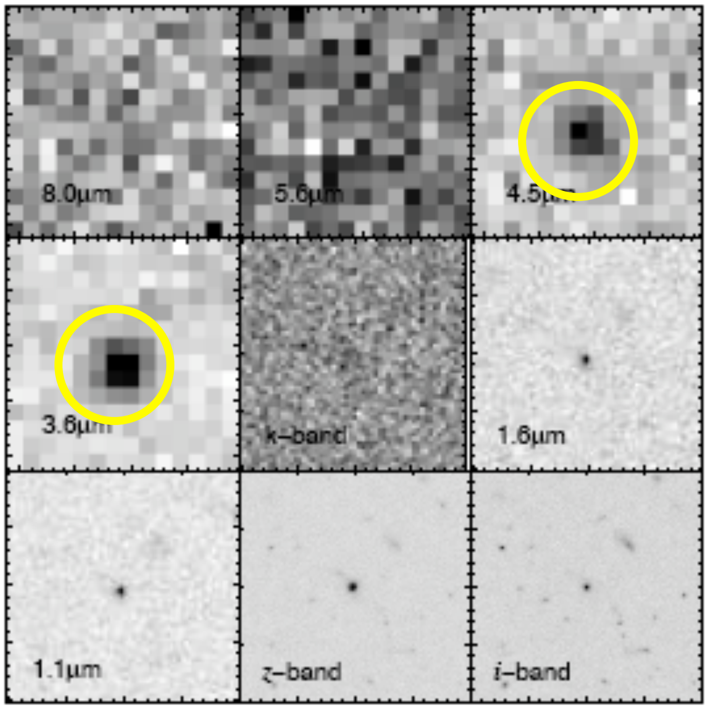
Bouwens, Illingworth, Franx & Ford (2007) Ap J 670, 928

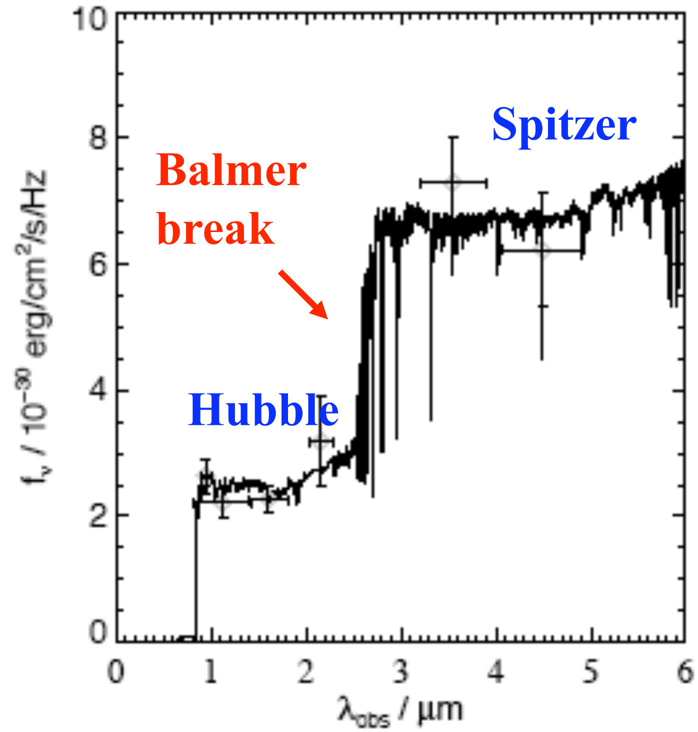
Spitzer Space Telescope: Stellar Masses & Ages



A modest 85cm cooled telescope can see the most distant known objects and provide crucial data on their <u>**assembled mass in stars and their ages**</u>

$z_{spec}=5.83$ age > 100 Myr; mass ~$3.10^{10}\ M_\odot$

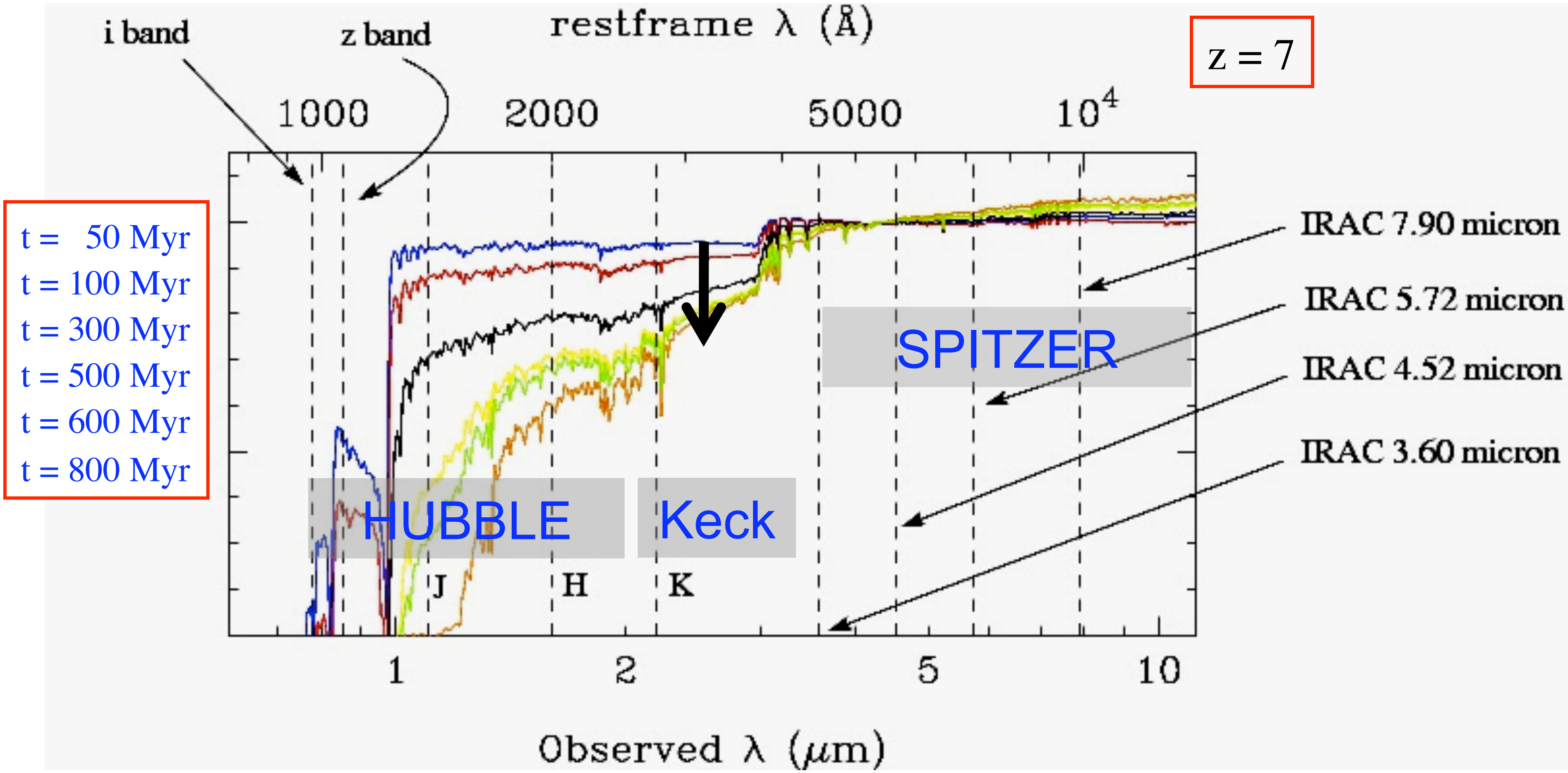




Eyles, RSE et al (2005): Old Stars at z~6 !

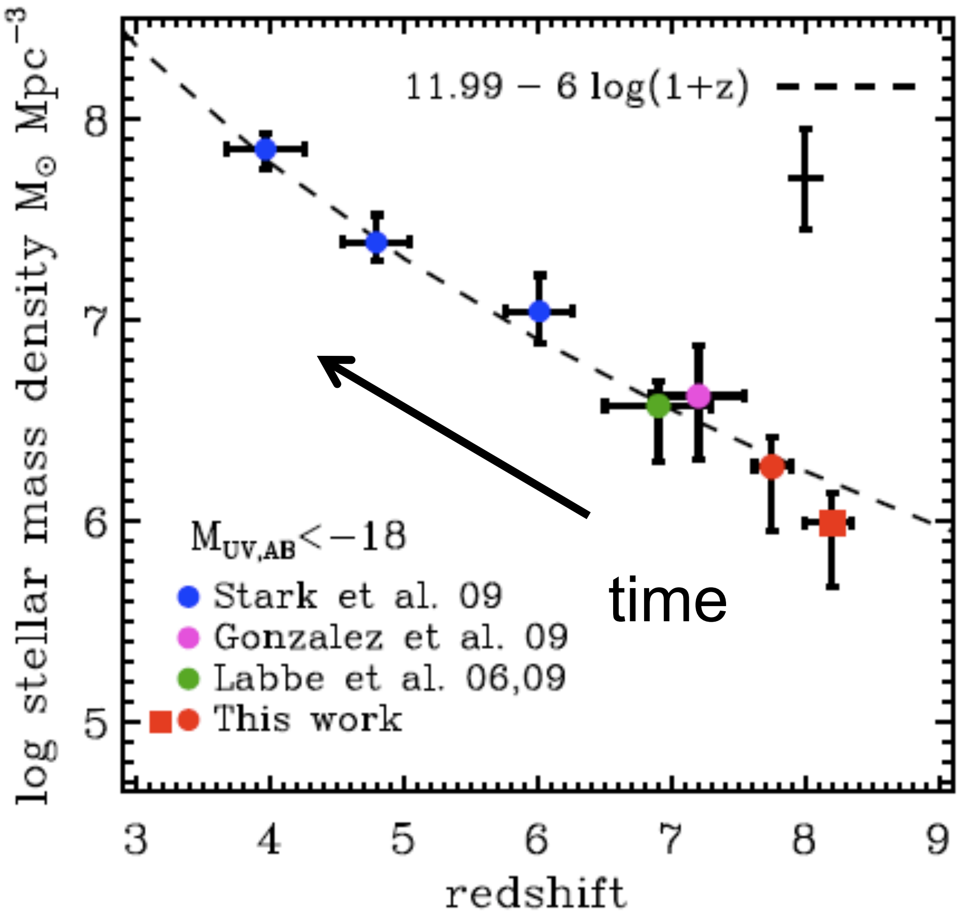
This means star formation occurred even earlier – so we should see star forming systems at even greater distances in the past

Spitzer and Hubble Combine as `Age Indicator'



Hubble measures on-going star formation rate
Spitzer measures assembled mass in older stars
Combination gives the age

Density of Stellar Mass with Time



HERE
LIETH
THE
DARK
AGES

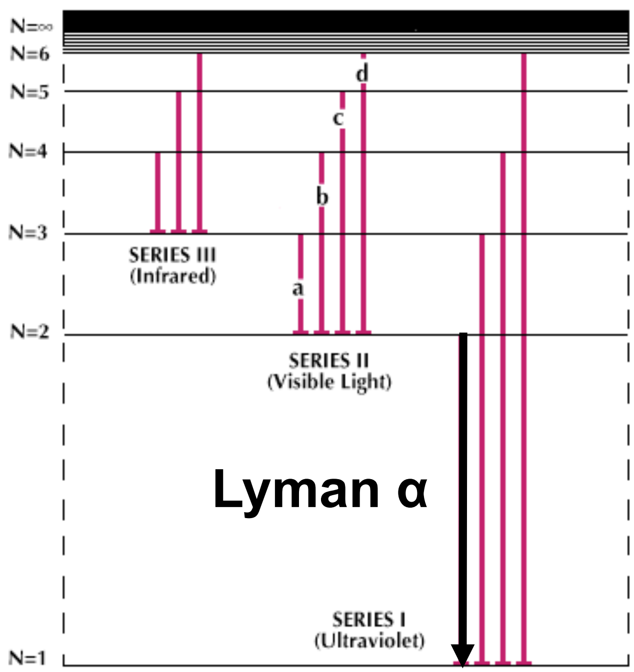
Spitzer allows us to do a census of how the mass in stars per unit volume grows with time – this encodes the past history of star formation

Stark, RSE et al 2007,2009; Labbé et al 2009ab

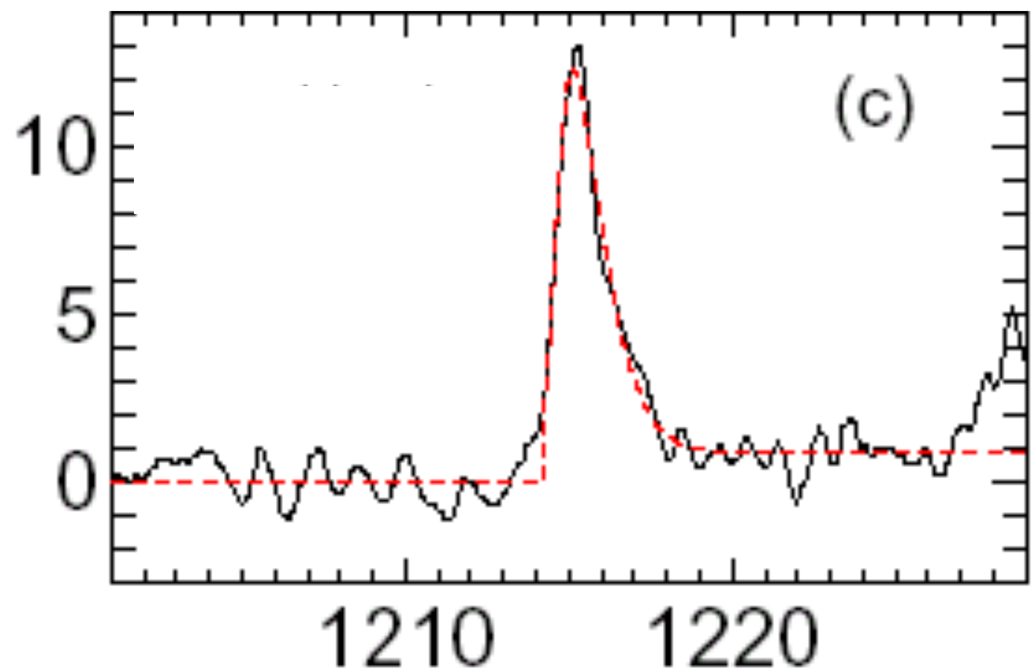
Lyman α Surveys

Another effective way to find early star-forming galaxies utilizes the fact they will contain <u>hot gas</u> emitting the Lyman alpha spectrum line of hydrogen redshifted from the <u>ultraviolet</u>

6-7% of a young galaxy light may emerge in this single line!

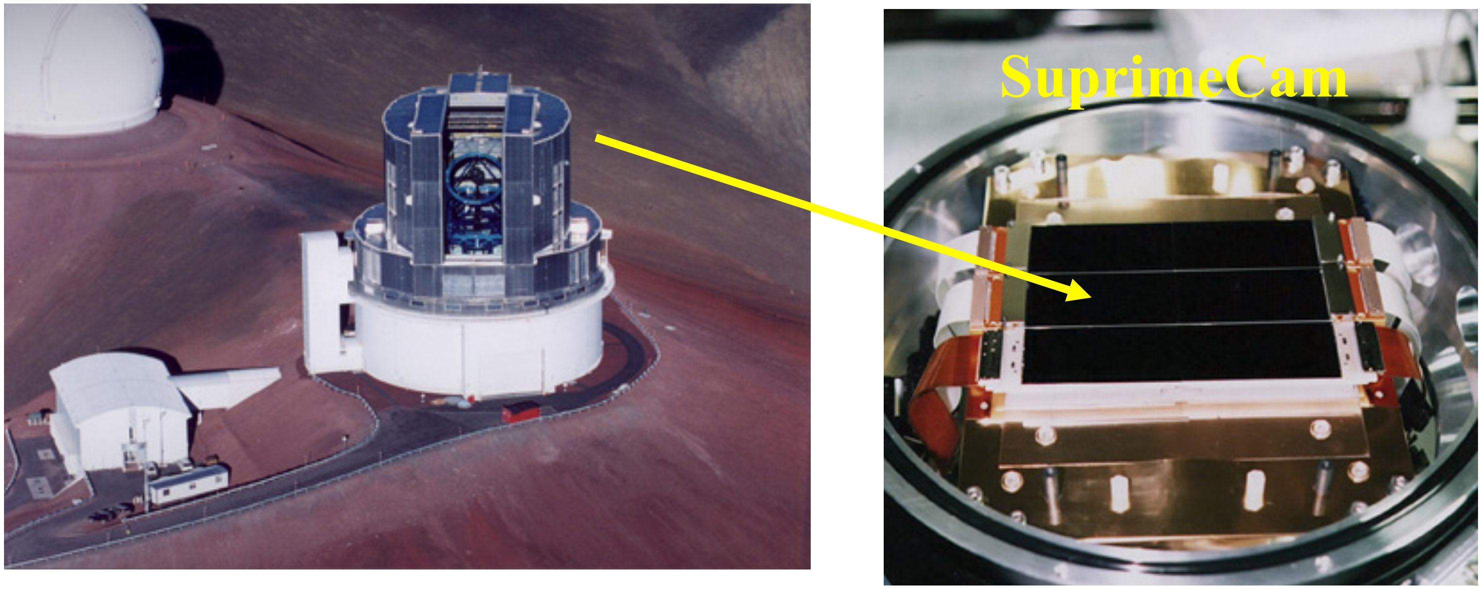


Energy Levels of Hydrogen



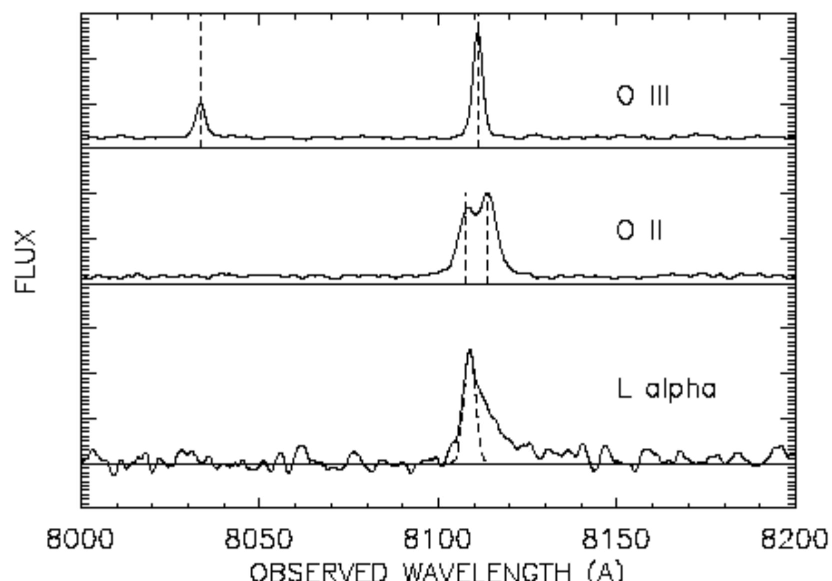
Wavelength (Å) →

Wide Field Imaging from Subaru



<u>Mauna Kea `Ohana'</u>:

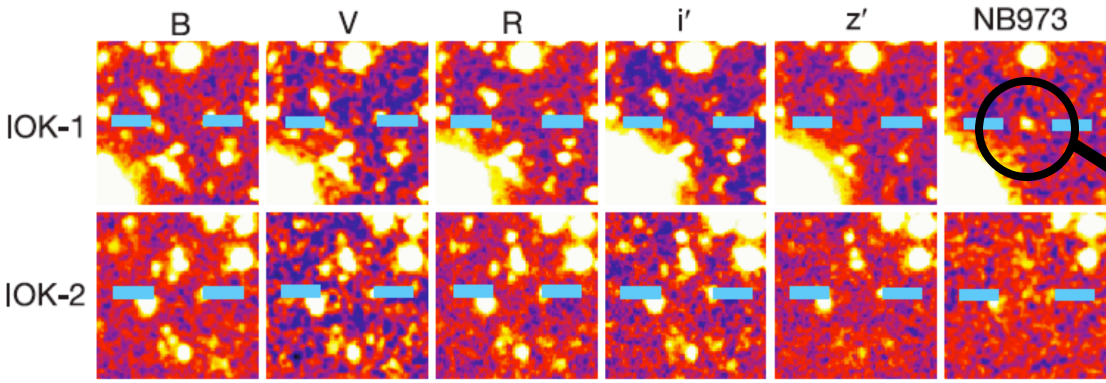
Panoramic imaging with Subaru with Keck spectroscopic verification to ensure narrow line is high redshift Lyman α

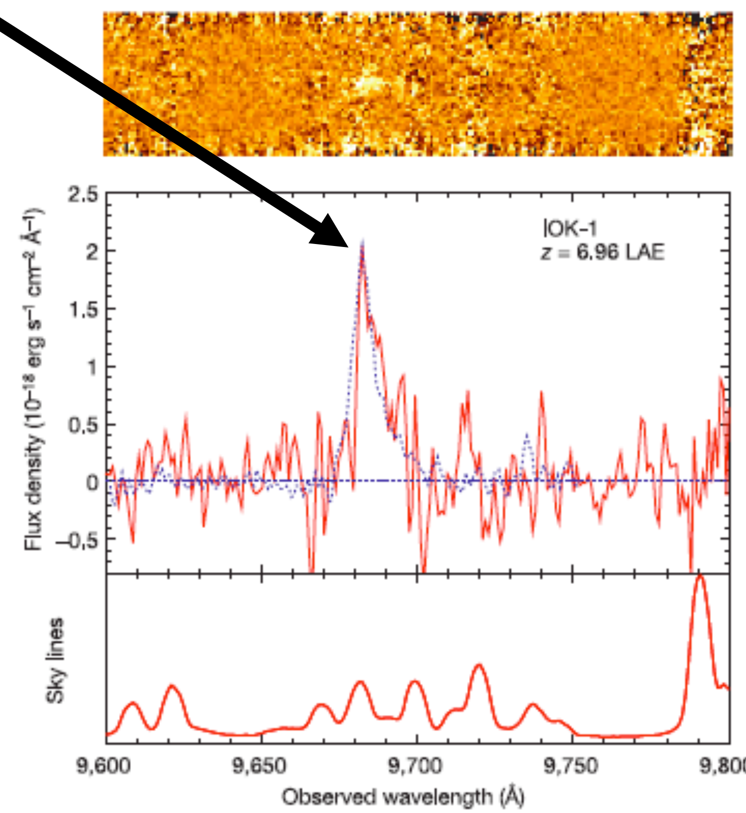


E. Hu (U Hawaii), M. Ouchi (Carnegie)

A galaxy at a redshift z = 6.96

Masanori Iye[1,2,3], Kazuaki Ota[2], Nobunari Kashikawa[1], Hisanori Furusawa[4], Tetsuya Hashimoto[2], Takashi Hattori[4], Yuichi Matsuda[5], Tomoki Morokuma[6], Masami Ouchi[7] & Kazuhiro Shimasaku[2]



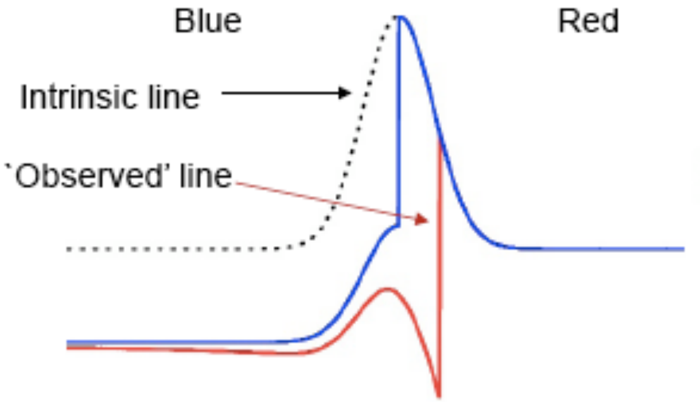


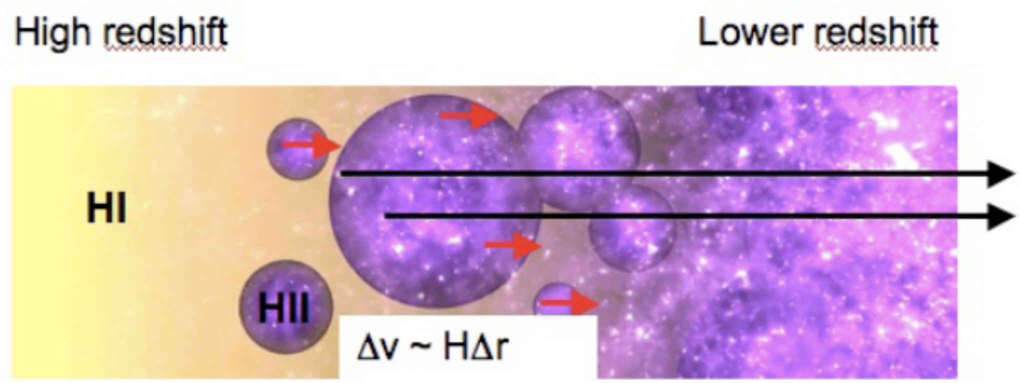
Direct imaging through a narrow band filter with Subaru found 2 candidate z~7 galaxies

One was spectroscopically confirmed at z=6.96

Nature 443, 186 (2006)

Lyman α as a probe of the Dark Ages

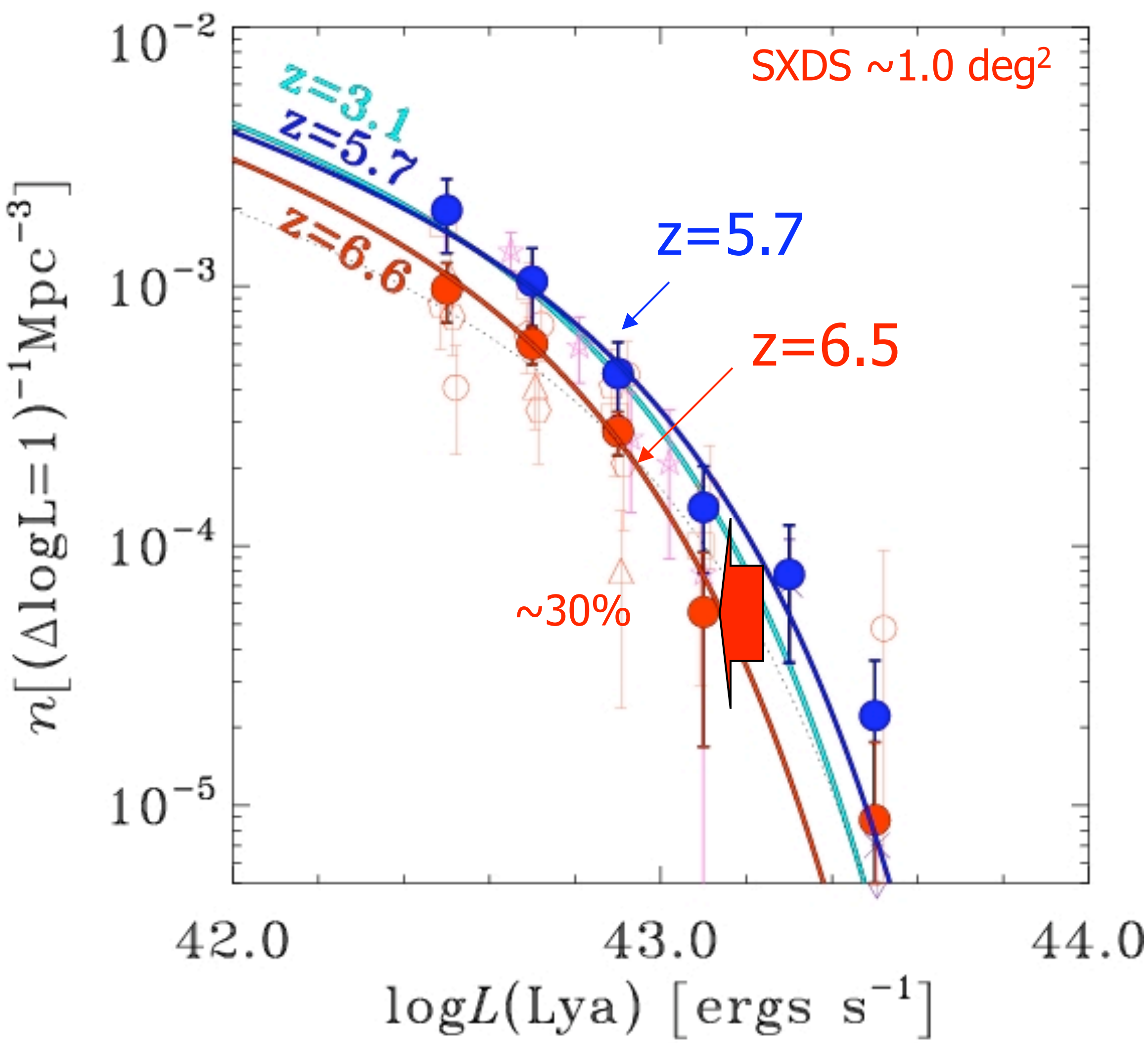




- Lyman α line is weakened by neutral hydrogen and thus a valuable tracer of its presence
- Neutral hydrogen in `Dark Ages' acts as fog obscuring the line emission from young galaxies
- A sudden drop in the visibility of line emitting galaxies may indicate we are entering the Dark Ages!

A Rapid Drop in Lyman α Emitters 5.7<z<6.6?

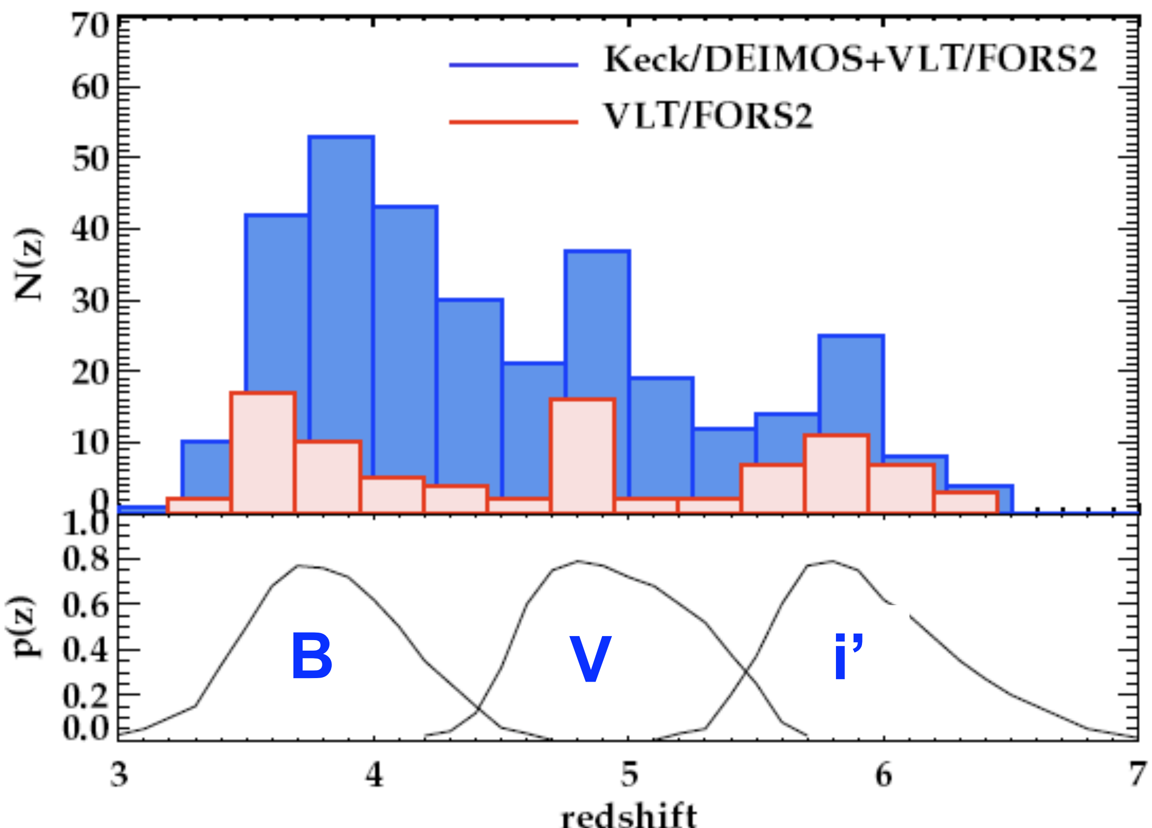
- Our Subaru colleagues have an interesting result!
- They see a tantalizing drop in the number of Lyman α emitters over a small redshift interval 5.7< z< 6.6 (150 Myr)
- Would seem surprising for the galaxy population to coordinate itself so well over such a short time interval
- Are we entering the Dark Ages at z~6.5?



Ouchi et al (2010)

New Keck Spectroscopic Survey of 4 < z < 7 Galaxies

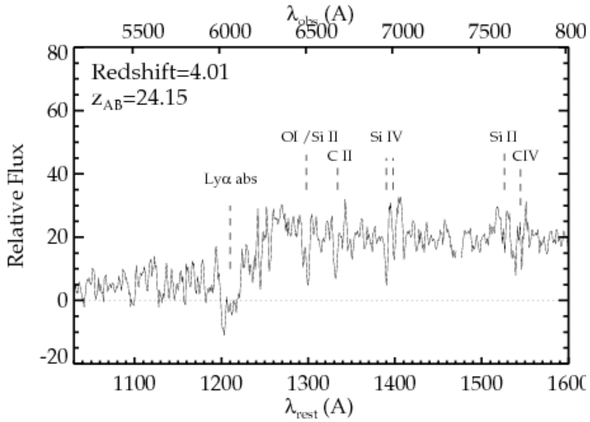
- Most ambitious redshift survey so far with Keck
- 8-16 hr exposures with DEIMOS to m_{AB}=26.5 (emission lines to m_{AB}~27.5)
- Keck/DEIMOS: 361 B + 141 V + 45 I + 17 z-drops = 564 spectra
- VLT/FORS2 retro-selected + same criteria: 195 spectra (Vanzella et al)



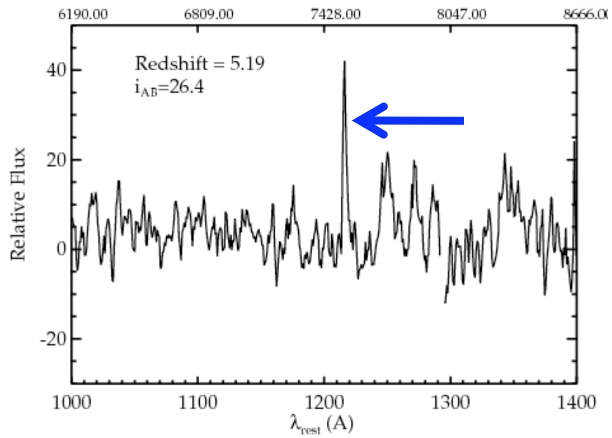
Stark et al (2010) MN submitted

Some Keck Spectra

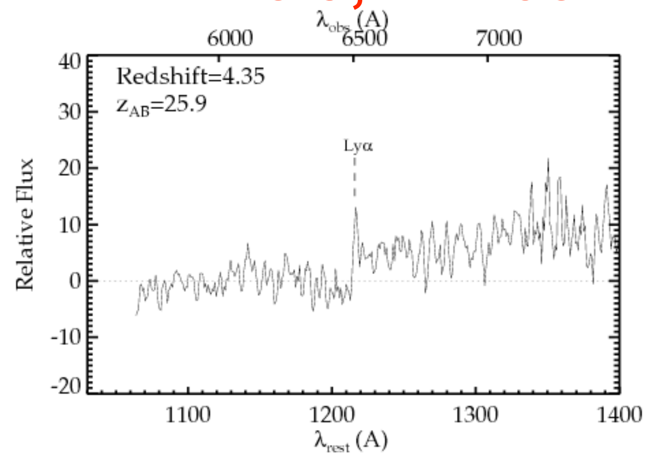
m=24.15, z=4.01



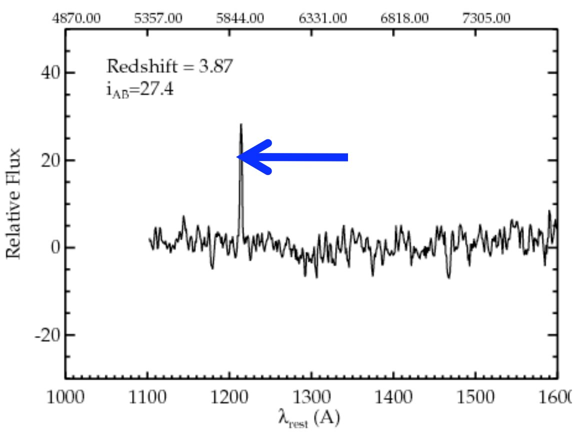
m=26.4, z=5.19



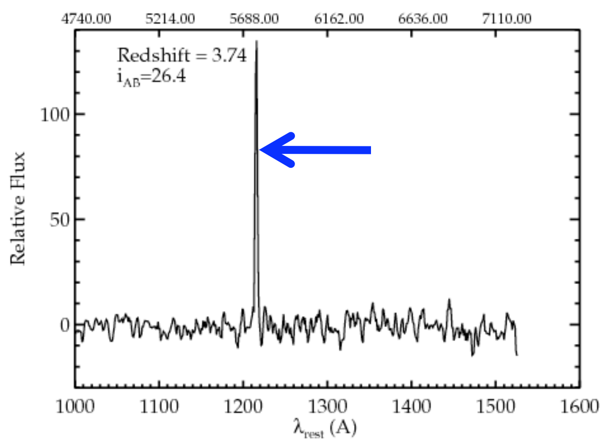
m=25.9, z=4.35



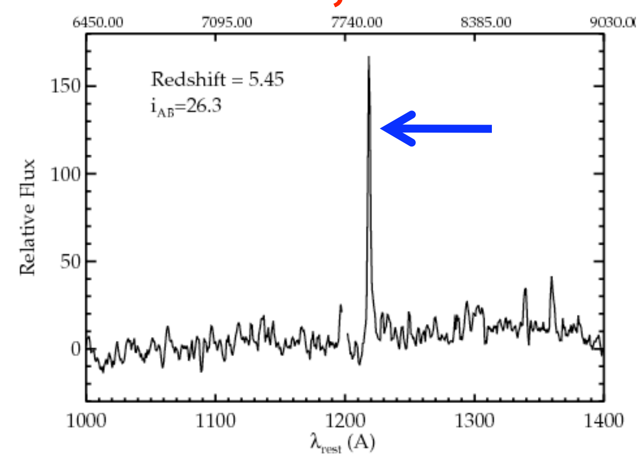
m=27.4, z=3.87



m=26.4, z=3.74

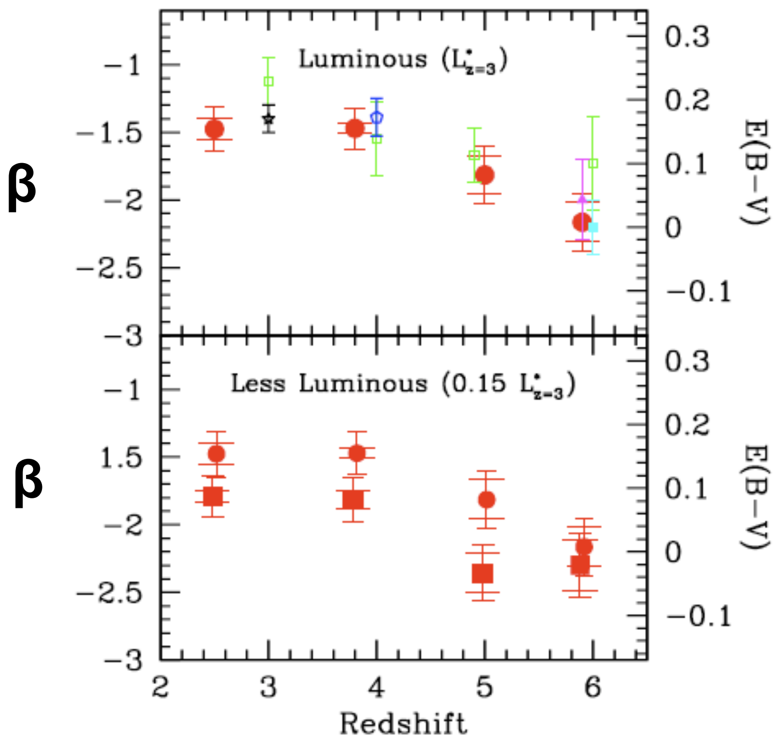


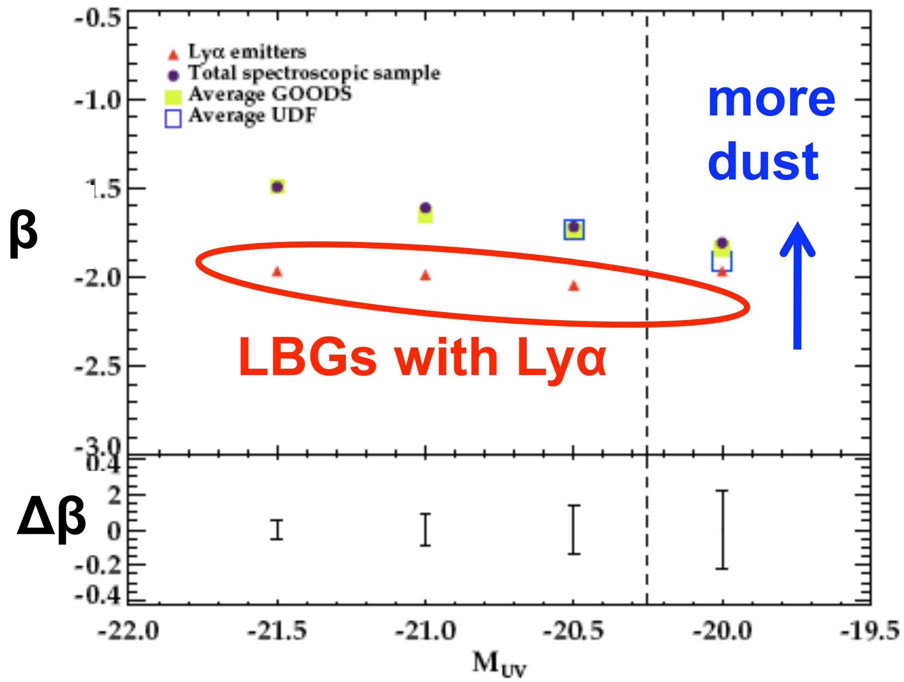
m=26.3,z=5.45



Survey demonstrates Lyα line is more prominent in *feeble* galaxies free from dust, and at *earlier times*; therefore a valuable tracer of the Dark Ages

Reduced Dust Extinction in High z Galaxies

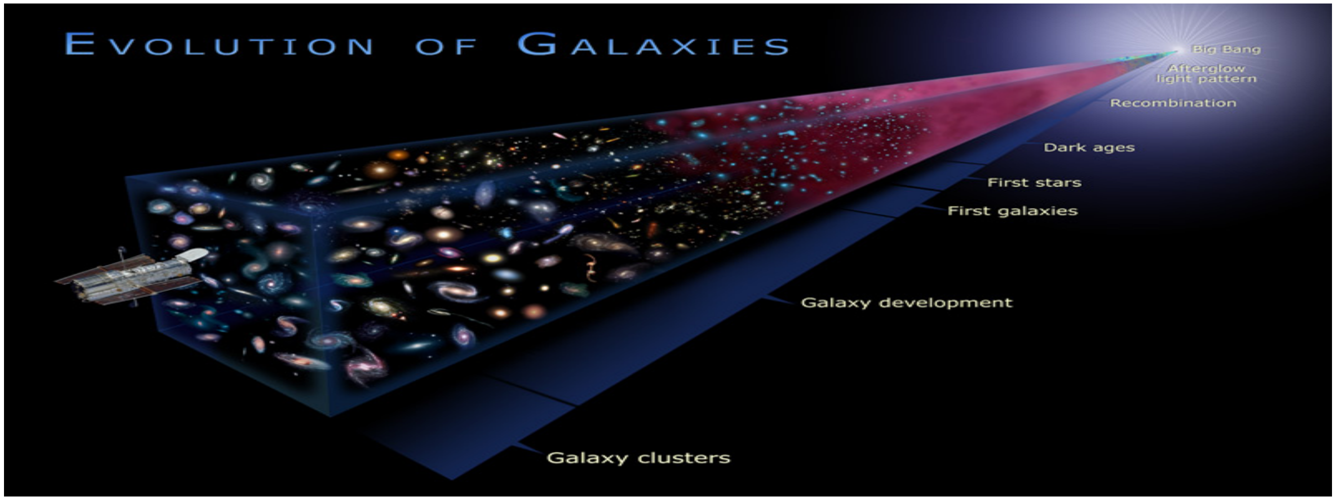




- High redshift and low luminosity galaxies are less dusty: as inferred from UV continuum slope β (flux ~ λ^{β})
- UV slope β also correlates with presence of Lyα in LBG spectra

Bouwens et al (2009); Stark et al (2010)

Summary (z < 7)

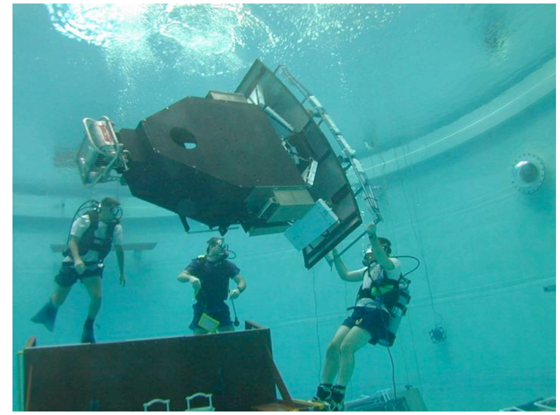


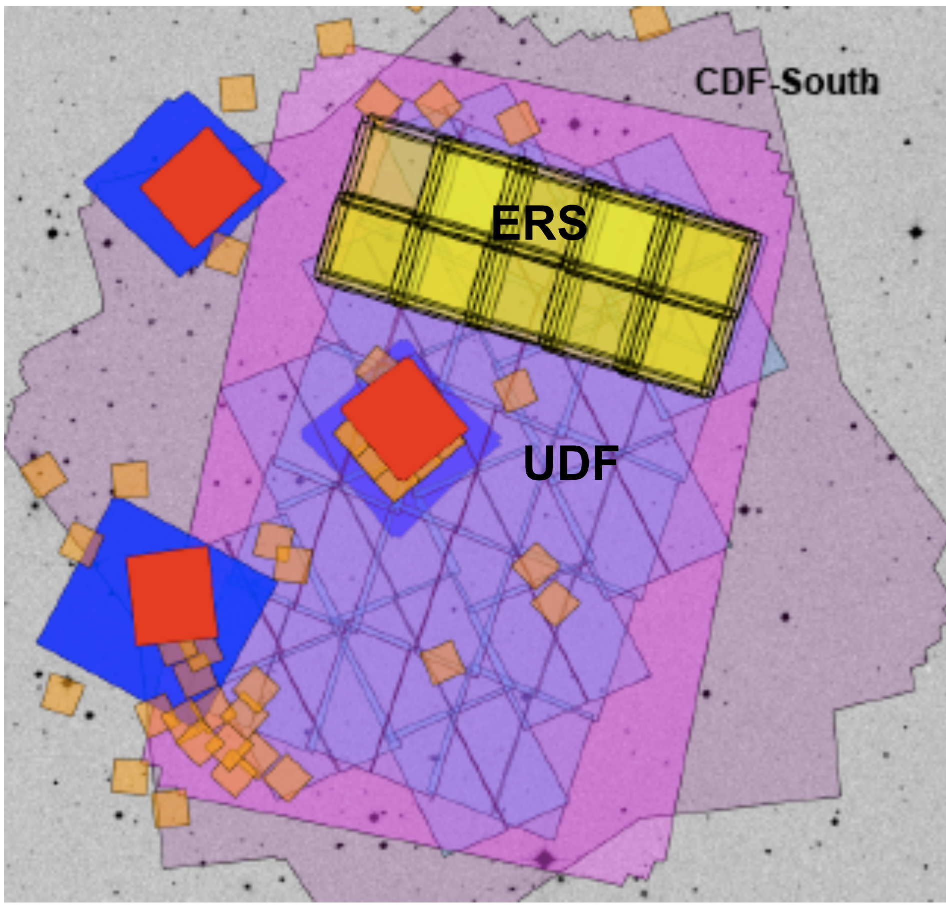
- Microwave background polarization from WMAP satellite demonstrates cosmic dawn was extended in time over $6<z<15$
- Assembled stellar mass from Spitzer at $z\sim5$ indicative of much earlier SF
- Drop in Lyman α fraction over $5.7<z<7$ may indicate increase in neutral gas

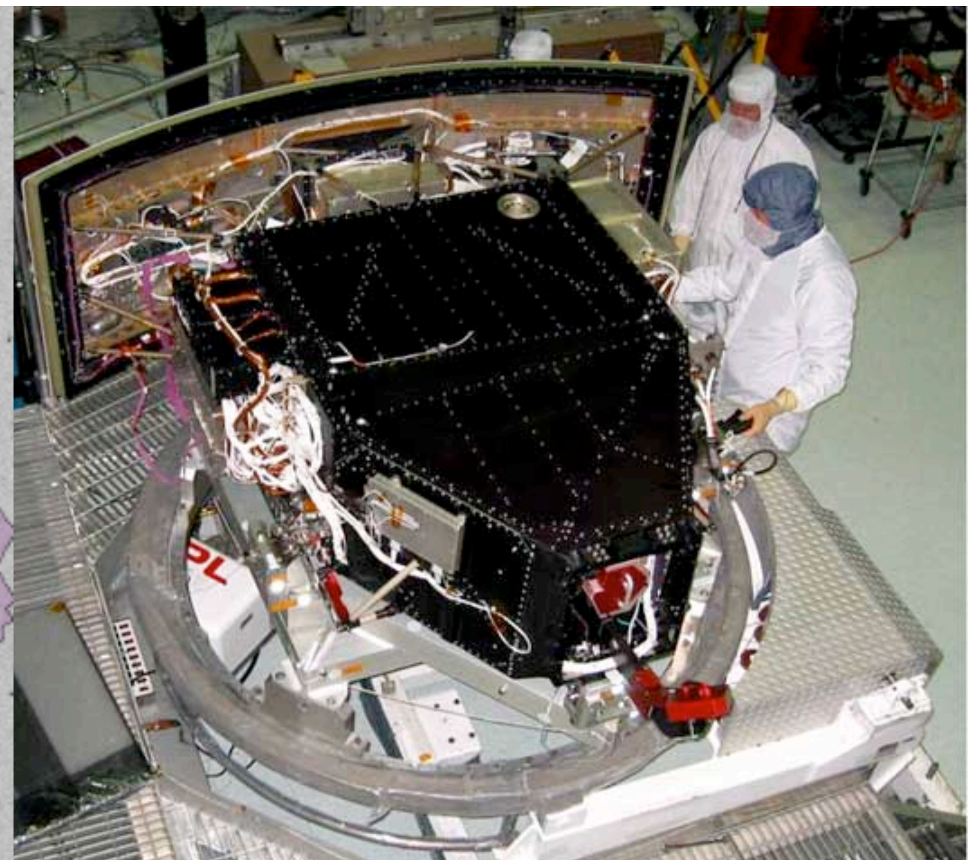
Expect abundant population of star forming sources $z > 7$
Use $z > 7$ sources to extend/confirm the Lyman α `visibility test'

Wide Field Camera 3

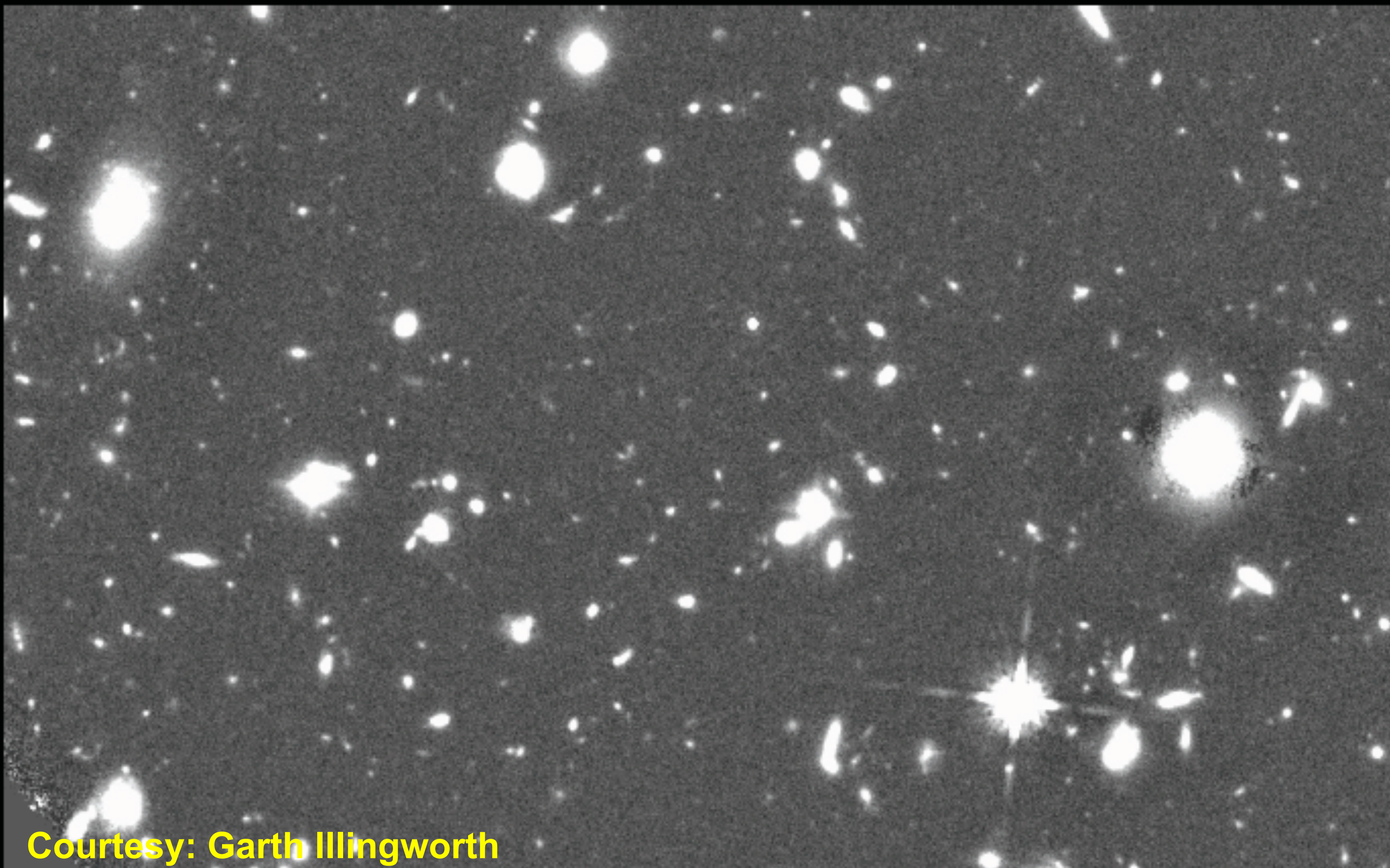
WFC3/IR: 850 - 1170nm
2.1 × 2.3 arcmin field of view
0.13 arcsec pixel^{-1}

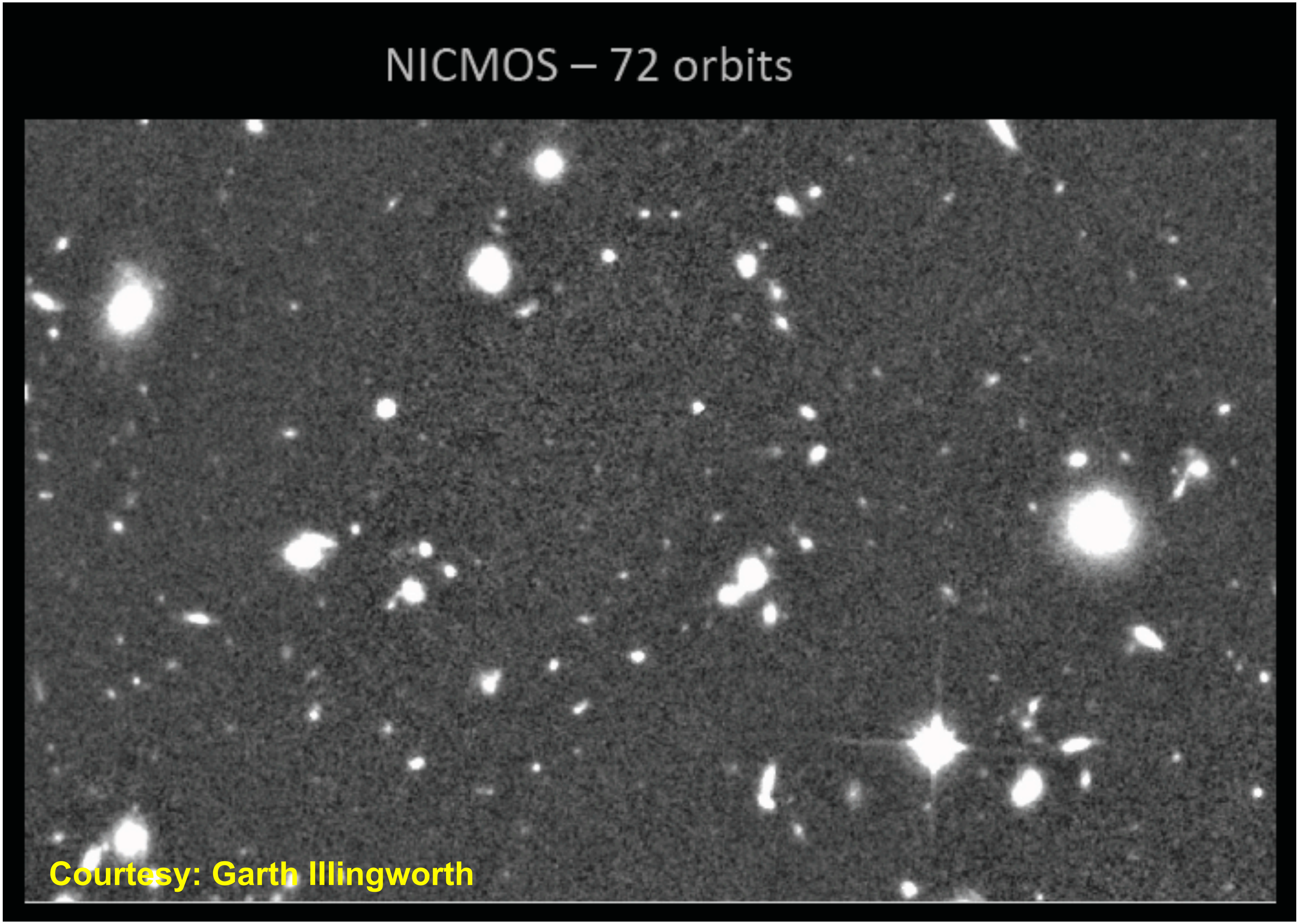






WFC3/IR – 16 orbits




NICMOS – 72 orbits
Courtesy: Garth Illingworth

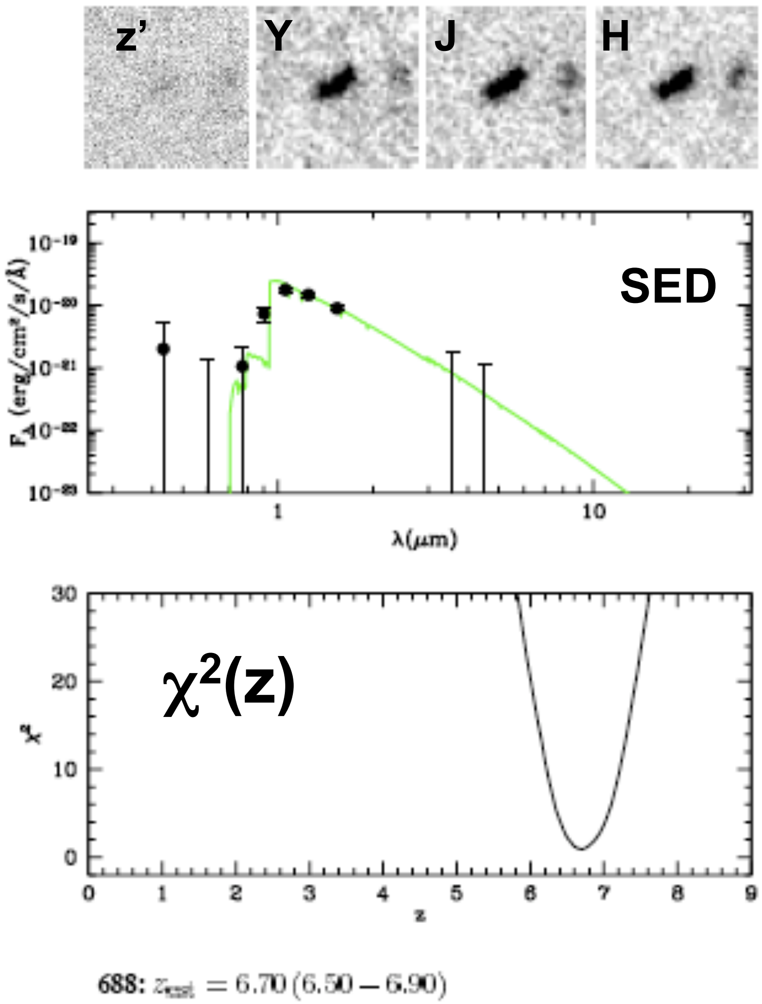
Hubble Ultra Deep Field • Infrared
Hubble Space Telescope • WFC3/IR

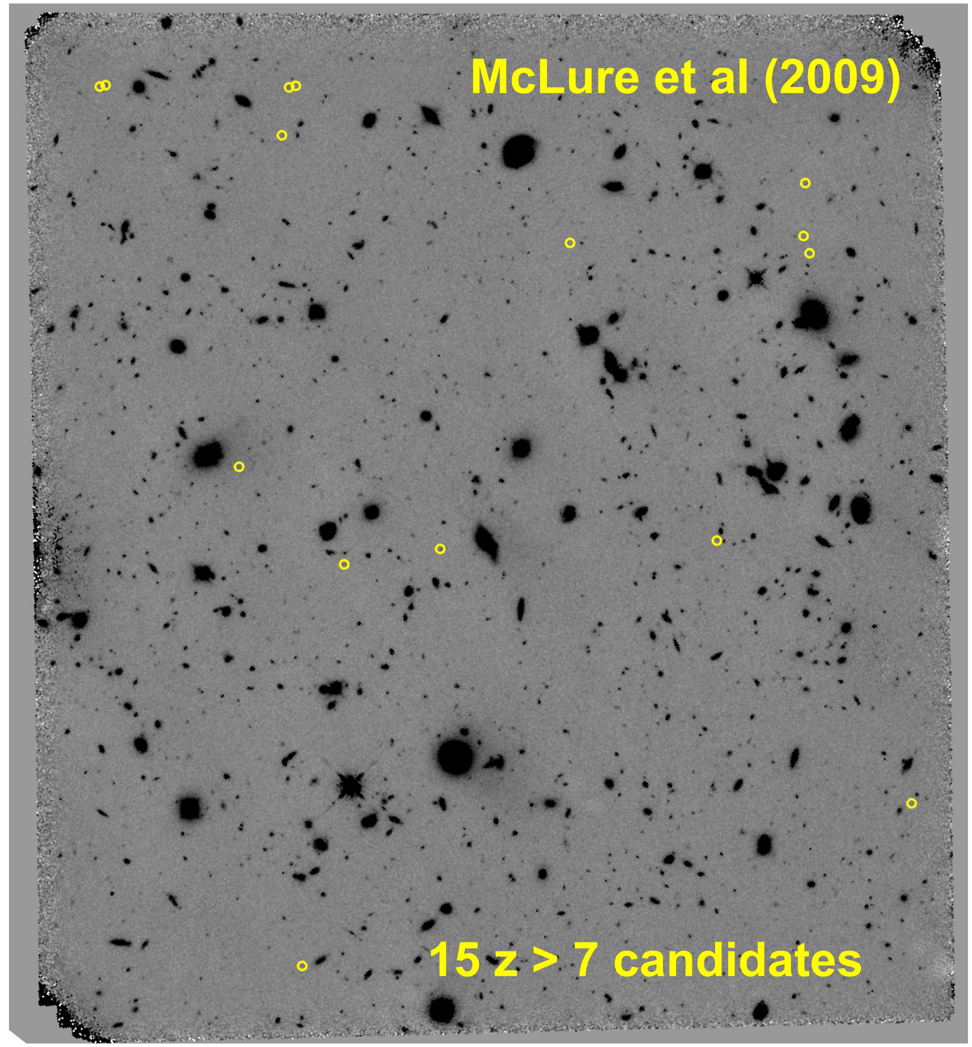
Astronomers Love the New Hubble Camera!

Upon release of public data from UDF and GOODS-ERS field, 12 scientific articles in 4 months from 4 international teams – 4 of these papers within 10 days!

Bouwens et al 0909.1803
Oesch et al 0909.1806
Bunker et al 0909.2255
McLure et al 0909.2437
Bouwens et al 0910.0001
Yan et al 0910.0077
Labbé et al 0910.0838
Wilkins et al 0910.1098
Labbé et al 0911.1365
Finkelstein et al 0912.1338
Bunker & Wilkins 0912.1351
Wilkins et al 1002.4866

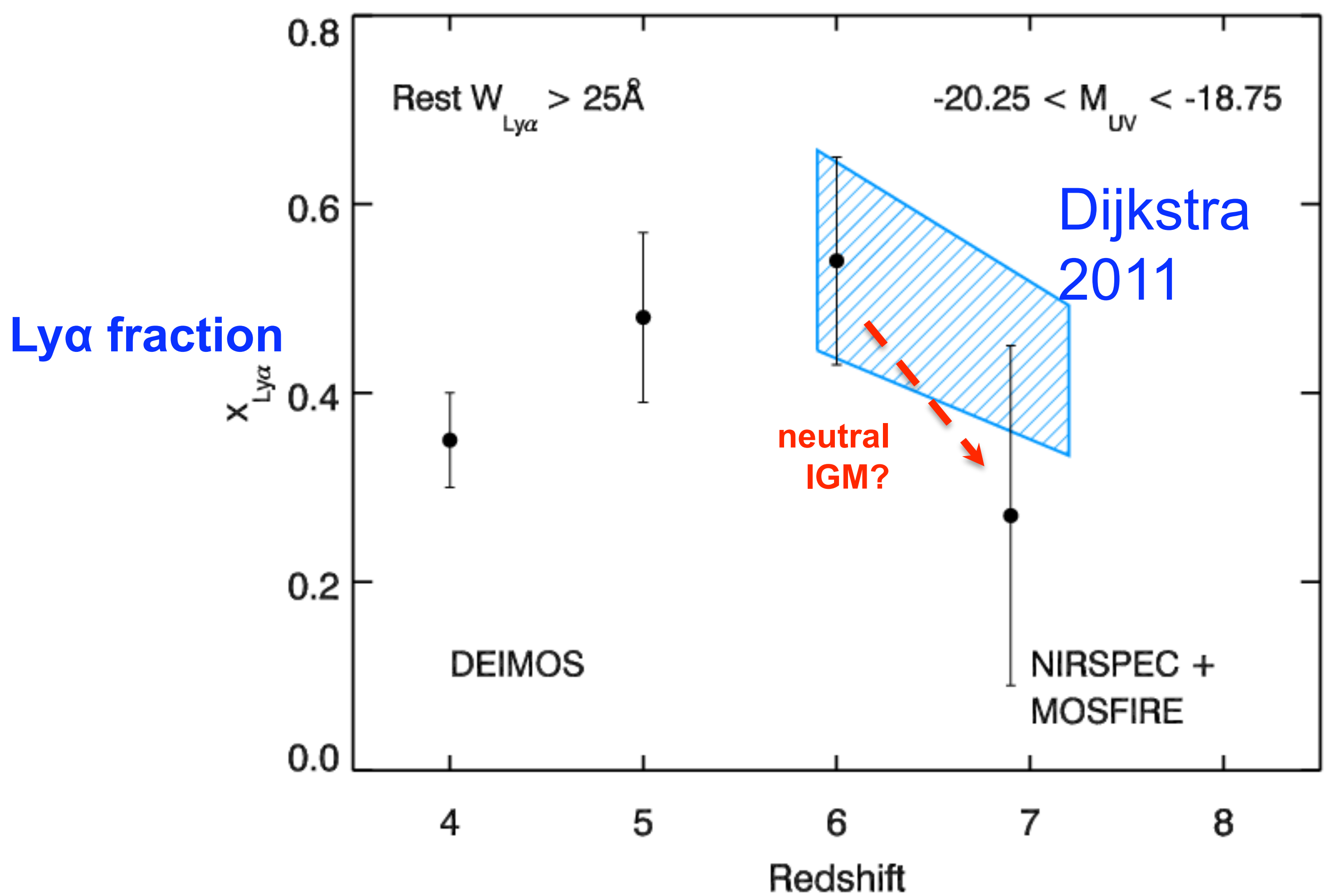
z >7 candidates from WFC3 UDF campaign





3 infrared filters (c.f. 2 with earlier camera) leads to more secure distance estimates and reliable UV continuum slopes

Lyman α as a Tracer of Reionization: The Latest



Faint near-IR spectra required to extend reionization test over all luminosities

Keck limits (cgs): MOSFIRE (3hr, 5σ) 3 10^{-18}

Schenker et al (2011)

Did Galaxies Reionize the Universe?

Are the abundances and properties of star forming galaxies over $7 < z < 10$ sufficient to account for cosmic reionization?

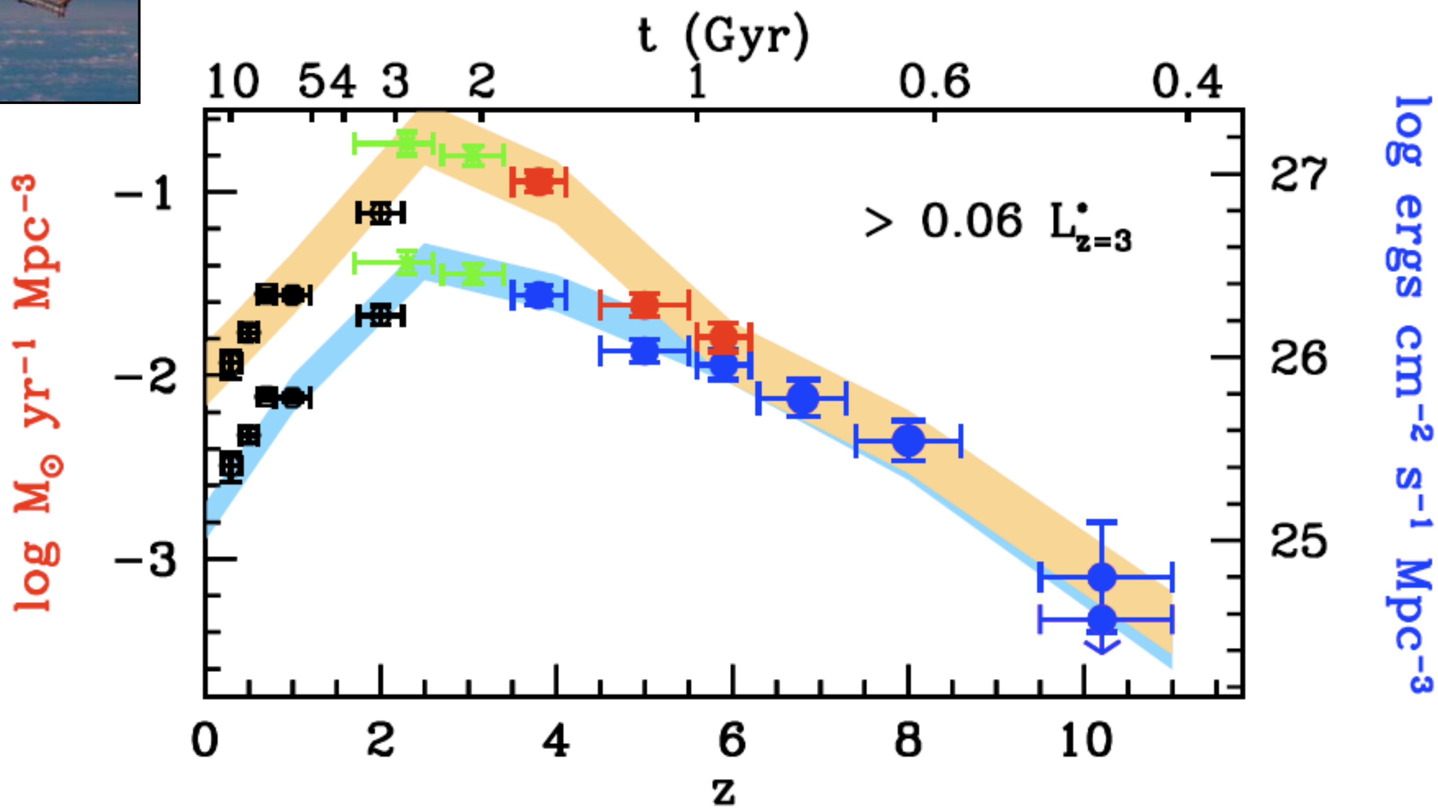
There are only 3 basic requirements:

- A sustained output from star-forming galaxies over $7<z<10$ (continuity in trends over $\Delta t \sim 300$ Myr)
- A steep faint end slope ensuring high fraction of UV photons arises from abundant sub-luminous sources ($\alpha < -1.8$), i.e. ρ_{SFR}
- A high escape fraction of ionizing photons ($f_{esc}>0.2$) via improved understanding of UV slope β

Prospects for resolving ambiguities in next 2-3 years is promising via

- current UDF campaign (Illingworth 105W, 125W, 160W)
- shallower GOODS MCT campaign (Faber/Ferguson)
- proposed deeper targeted UDF campaign (105W, 140W, 160W)

Sustained Population: LBGs 6 < z < 8+

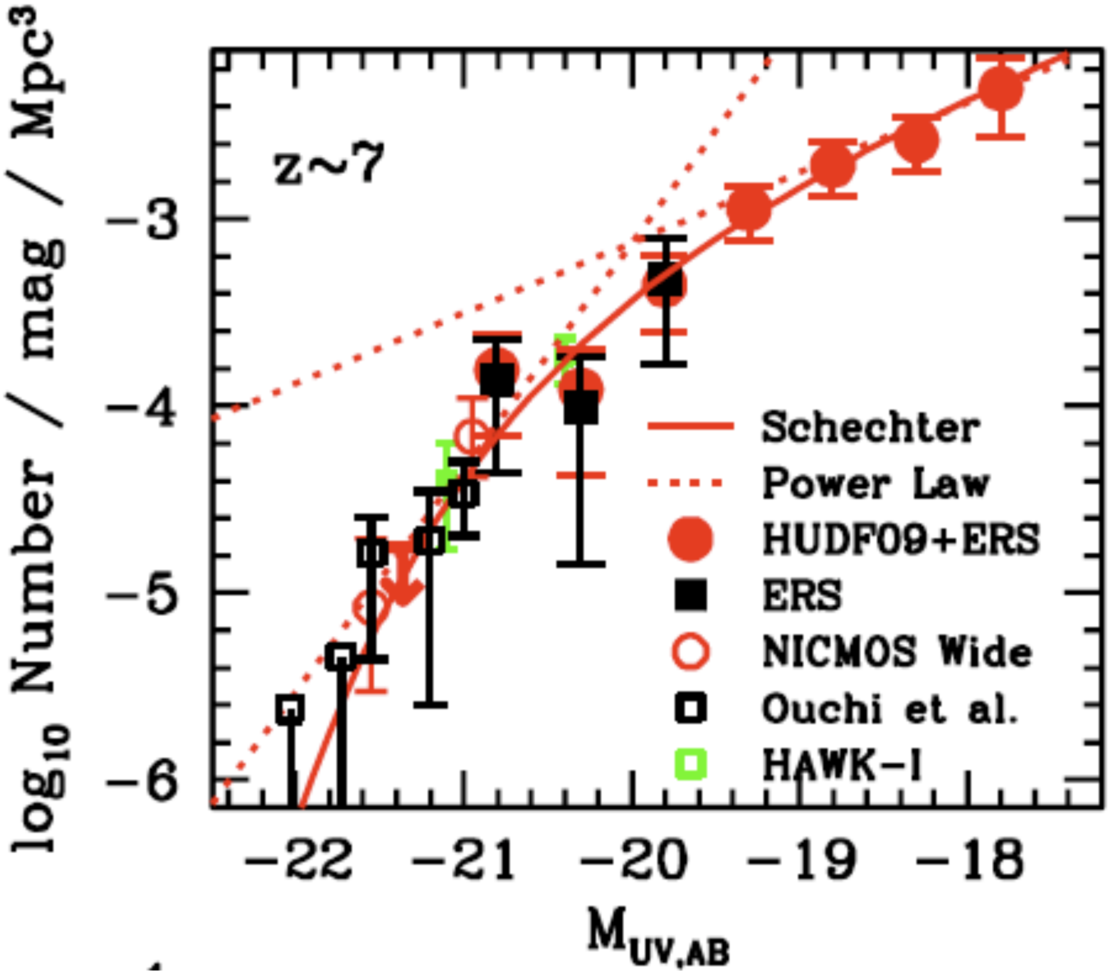


HUDF + parallel fields (AB~29, 4 arcmin^2) + ERS area (AB~27.5, 40 arcmin^2)

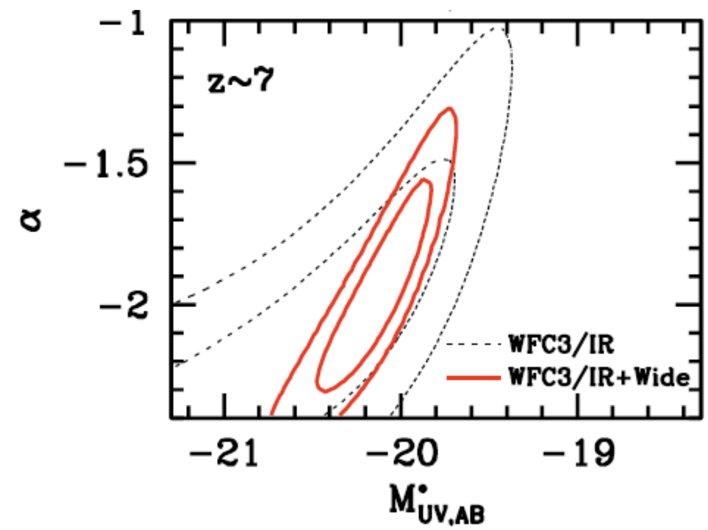
Bouwens et al astro-ph/1006.4360: 66 z~7 and 47 z~8 candidates

McLure et al astro-ph/1102.4881: 70 6 < z < 8.7 candidates with more rigorous photo-z criteria

LF@ z~7: Large Contribution from Faint LBGs



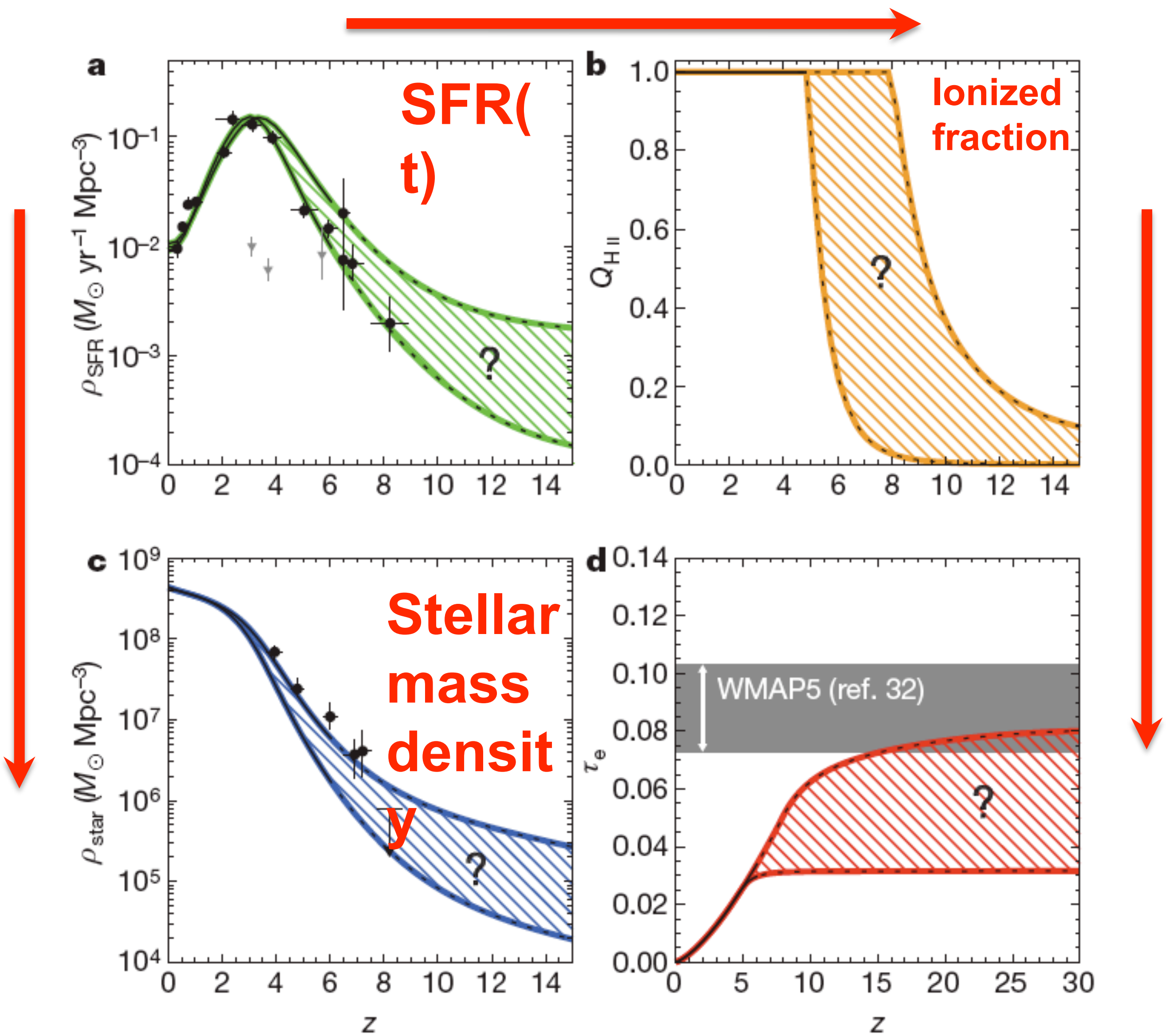
Utilizing deep + shallow WFC3/IR plus Subaru



Steep faint end slope: low star formers ~1 $M_\odot$ yr^{-1} dominant

Ouchi et al 2009 Ap J 706, 1136; Bouwens et al astro-ph/1006.4360 plus many earlier papers (Oesch, Bunker, McLure…)

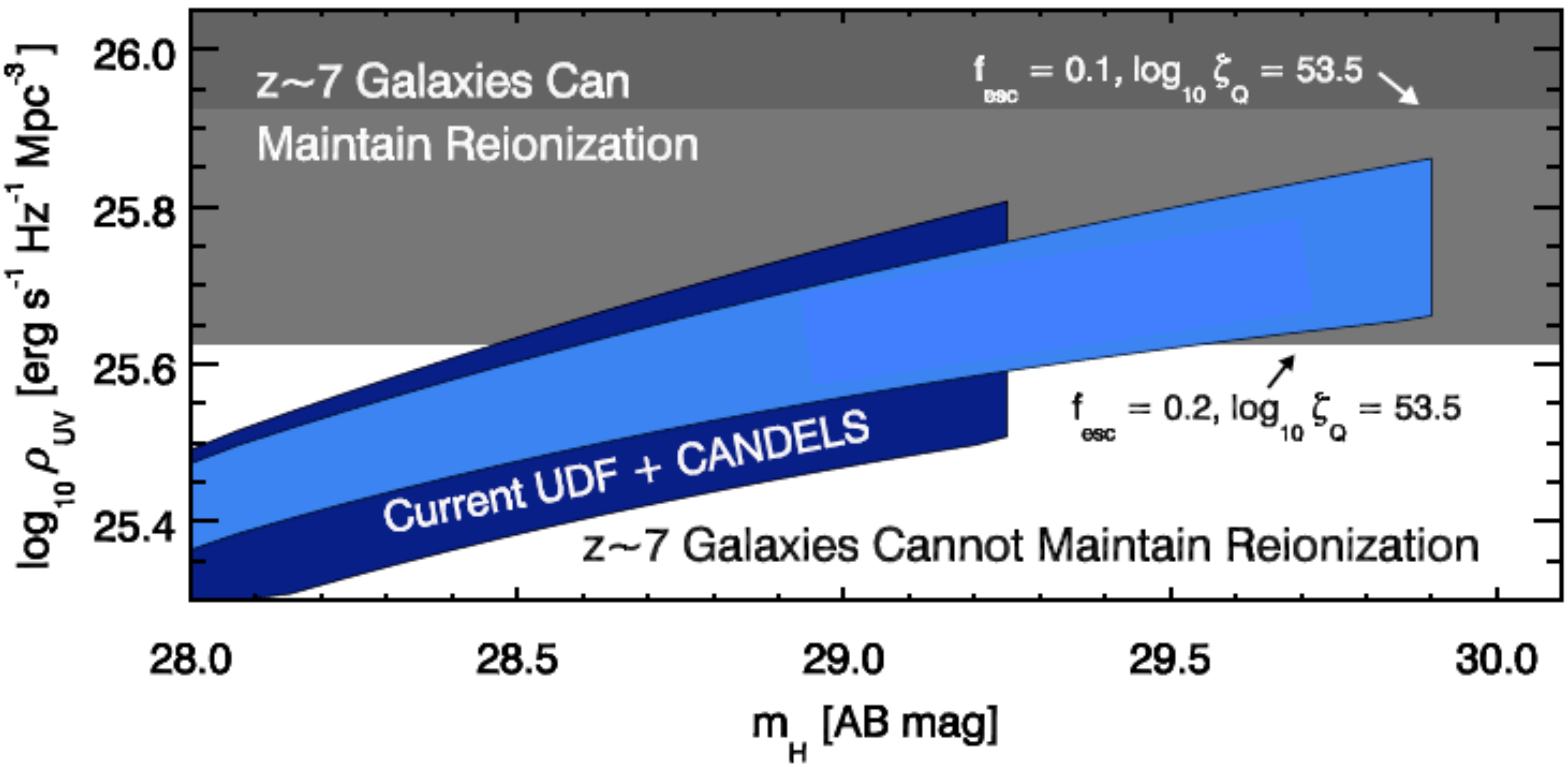
Did Galaxies Reionize Universe?



Robertson et al (2010) : some tensions even given the significant uncertainties

Projected Situation pre-TMT/JWST

Emission rate of ionizing photons Mpc^{-3} compared to abundance of star-forming galaxies



Two astrophysical variables: escape fraction of ionizing photons f_{esc}
ionizing photons per unit star formation rate ζ_Q

Robertson et al (2010)

Where Next?

In addition to continued imaging with WFC3 on Hubble Space Telescope…

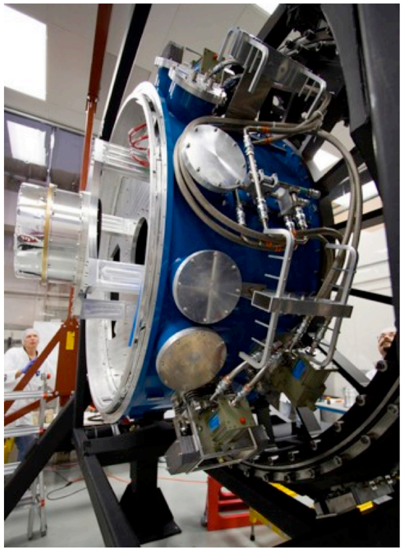
Improved performance from our existing telescopes will extend present work

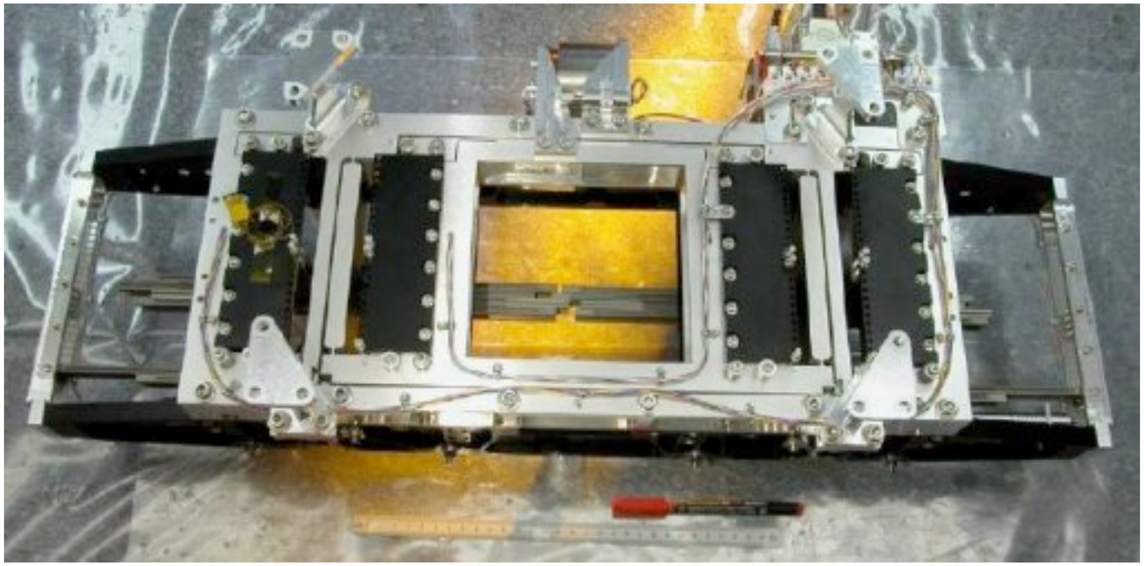
- Keck MoSFIRE: - multi-object infrared spectra for $z > 7$ sources

2017+: James Webb Space Telescope and a 30m ground-based telescope (TMT)

- a new partnership, similar to the successful one between Hubble and Keck
- more detailed surveys beyond z~10 and fainter sources z~7-10

MOSFIRE (Keck I) – May 2011





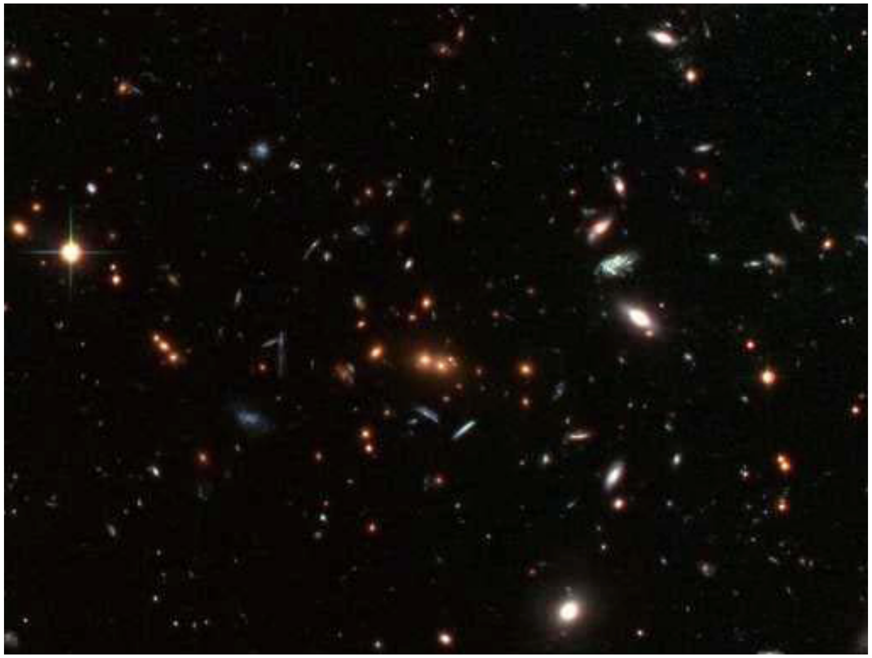
Cryogenic Multi-slit IR spectrograph

6.1 x 3.1 arcmin spectroscopic field

λλ0.97 - 2.45 microns

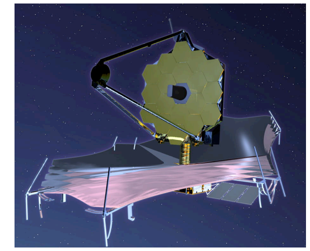
45 slits via configurable slit unit (<5mins)

Ideal for measuring Lyman α in Hubble sources



James Webb Space Telescope: 2017

...

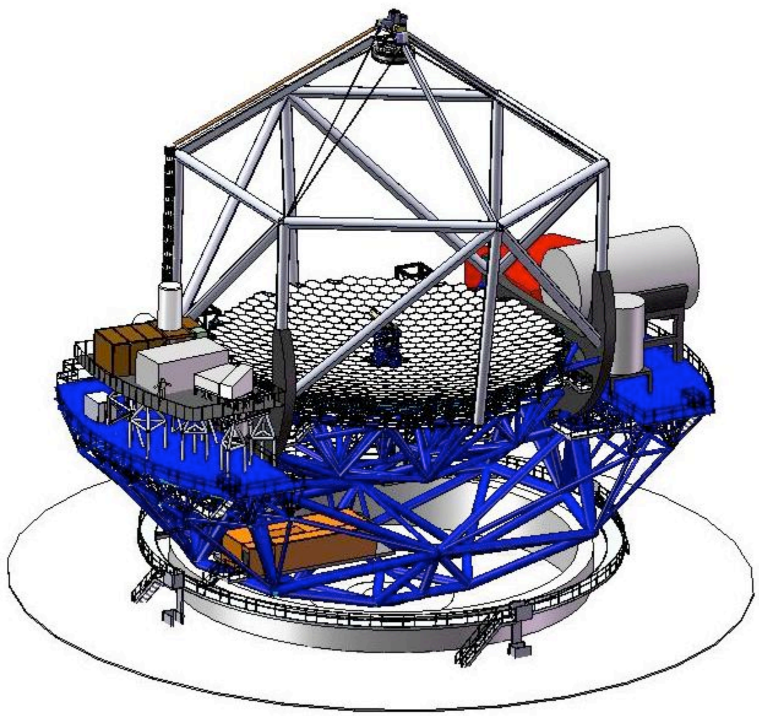


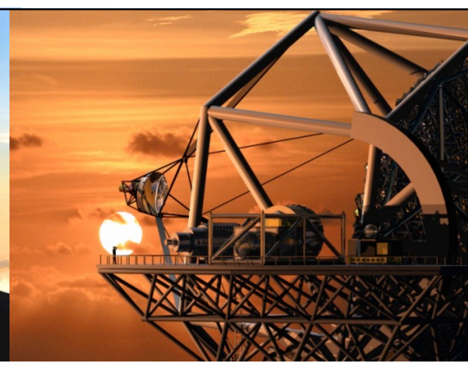

TMT
THIRTY METER TELESCOPE
Partners are: Caltech, U. California, Canada, Japan, China & India

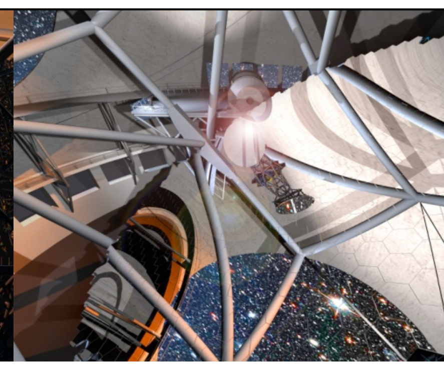
TMT
THIRTY METER TELESCOPE

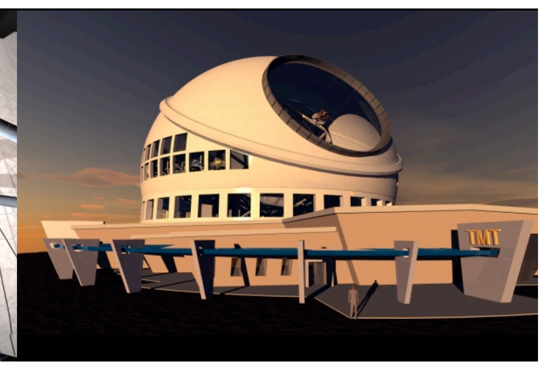
TMT: Fast Facts

30 meter, filled aperture, 492-segment
primary mirror
Three-mirror telescope
f/1 primary
Field of view 20 arcminute
Wavelength 0.31 – 28 μm
Fully integrated adaptive optics
Seeing-limited mode
Partners: Caltech, UC, Canada
Japan, China, India

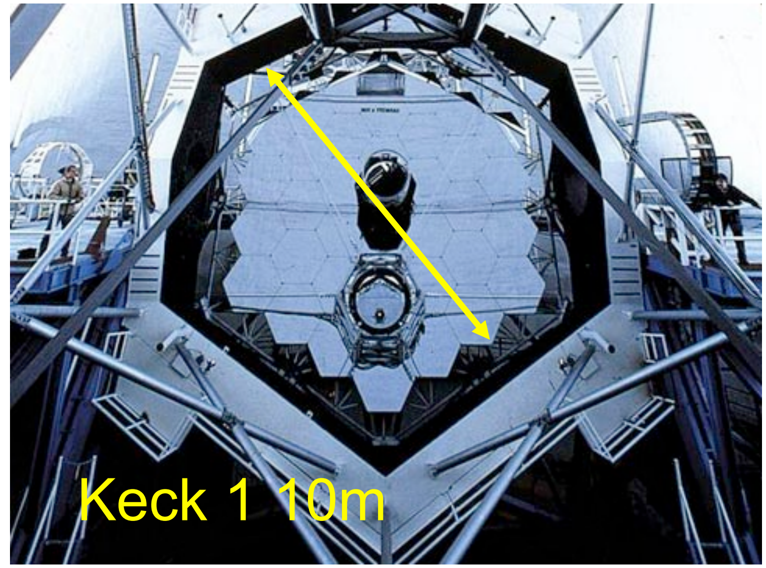


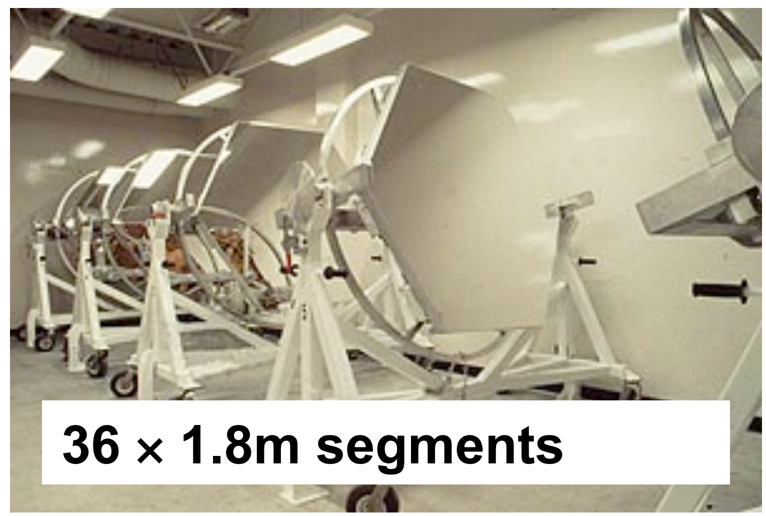






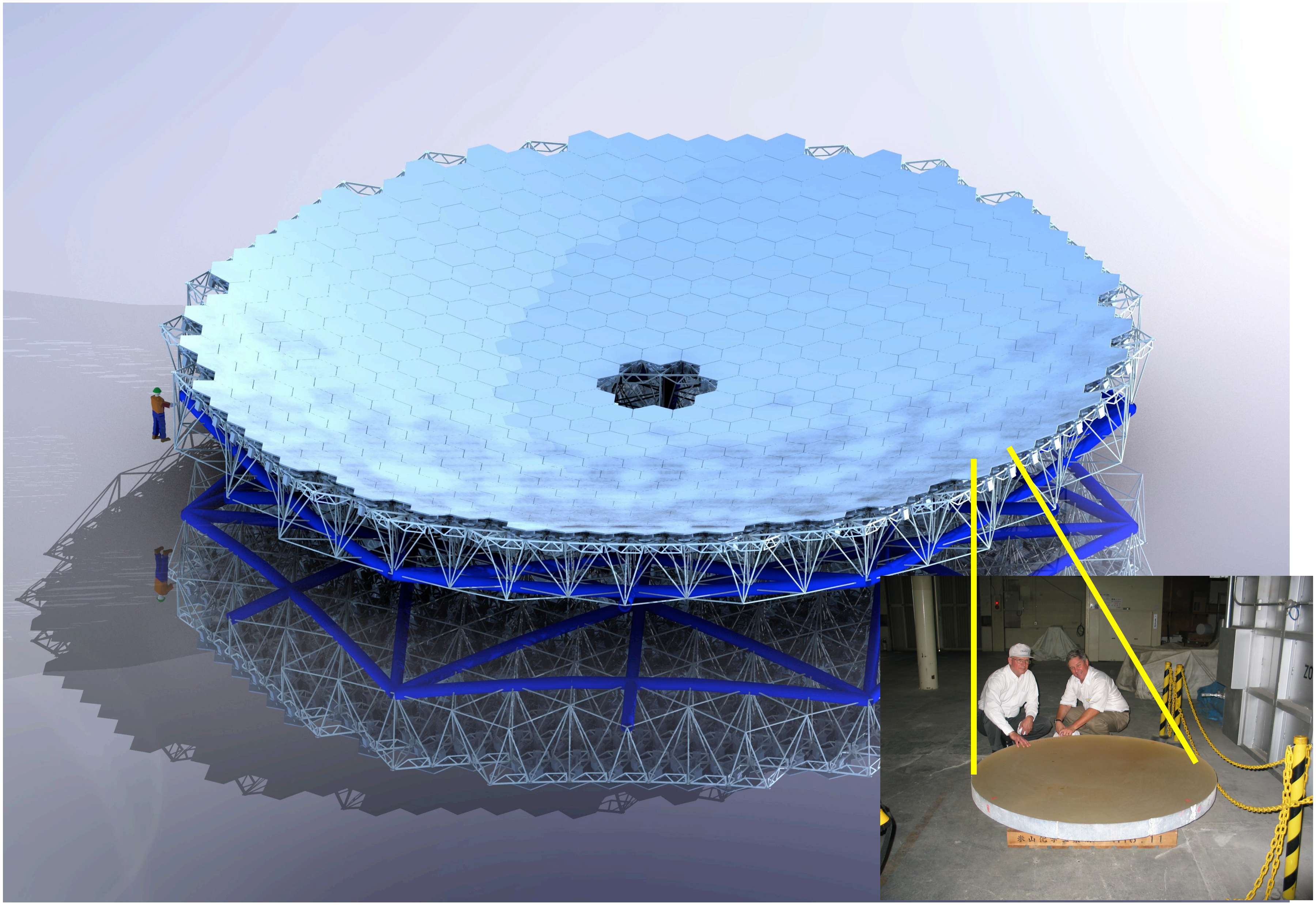
Segmented Primaries – Keck Shows the Way





Enables larger, actively-controlled 30m class primaries

Primary Mirror: 492 × 1.4m segments



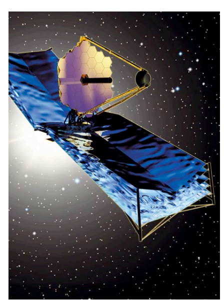
Adaptive Optics Changes Ground-Space Synergy

TMT with AO will have <u>better resolution</u> than JWST (*not a dream: Keck AO has better resolution than HST*)

– together with large aperture significantly changes space-ground synergy

First galaxies:

- TMT is key to locating more abundant, fainter, smaller sources (AO gives ×10-100 gain over JWST depending on angular size).
- JWST probes to higher z in mid-IR



Lensed galaxies at z ~6
Unlensed sizes ~ 150pc or < 30mas!

Conclusions: Is it Worth it?

"At the last dim horizon, we search among ghostly errors of observations for landmarks that are scarcely more substantial. *The search will continue. The urge is older than history. It is not satisfied and it will not be oppressed.*"

Edwin Hubble (Realm of the Nebulae)