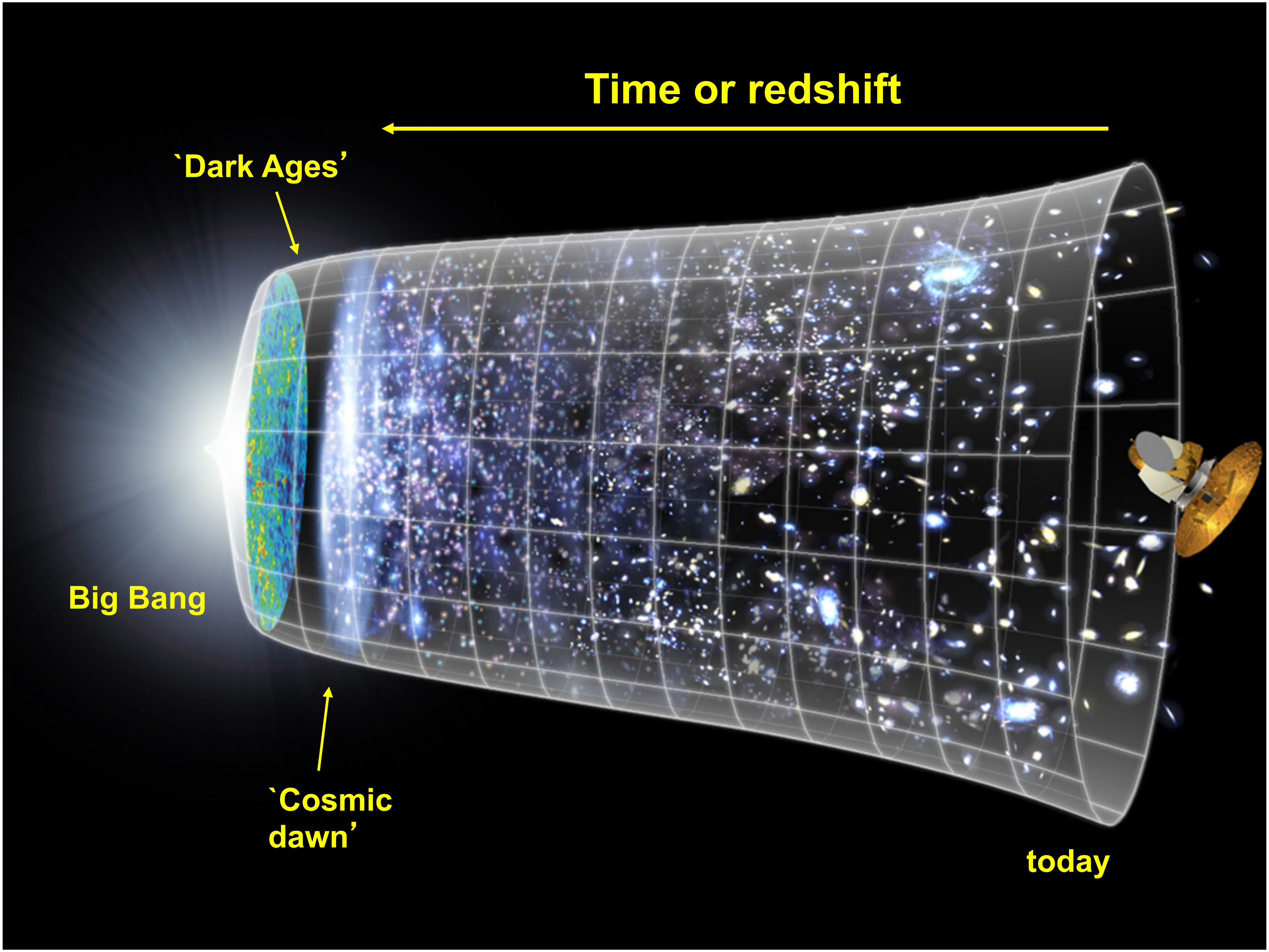
Cosmic Dawn:

The Quest for the First Galaxies

Richard Ellis (Caltech)

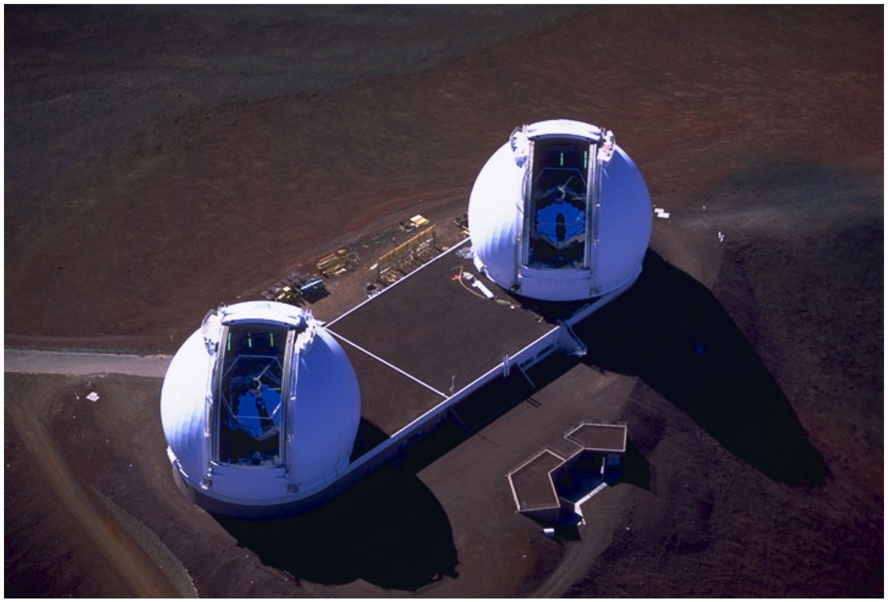
SPECC-2012

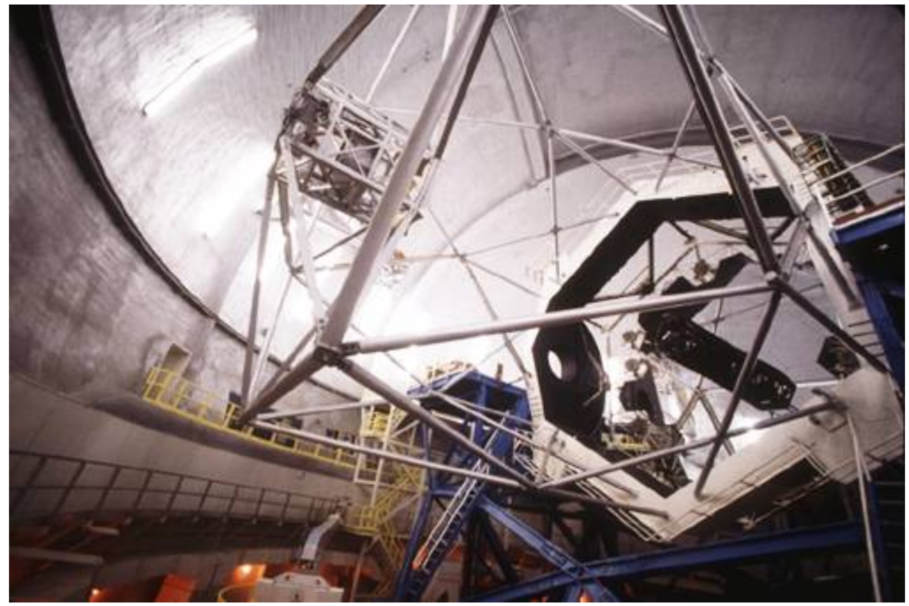
December 17th 2012

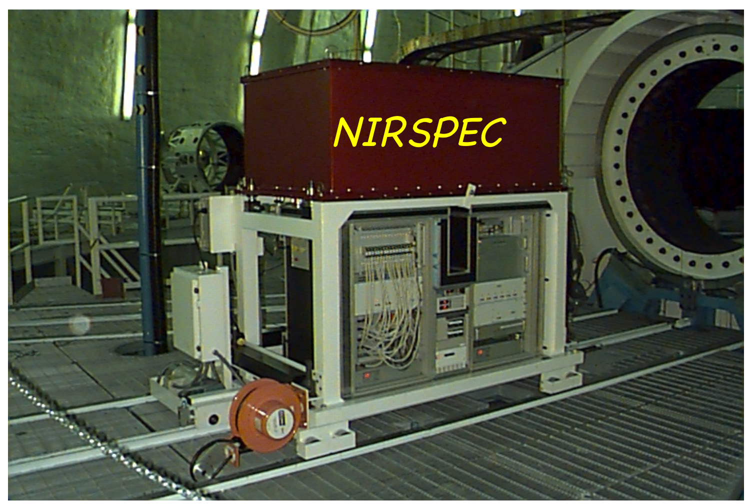

Time or redshift
`Dark Ages'
Big Bang
`Cosmic
dawn'
today

An Observational Adventure Starring..

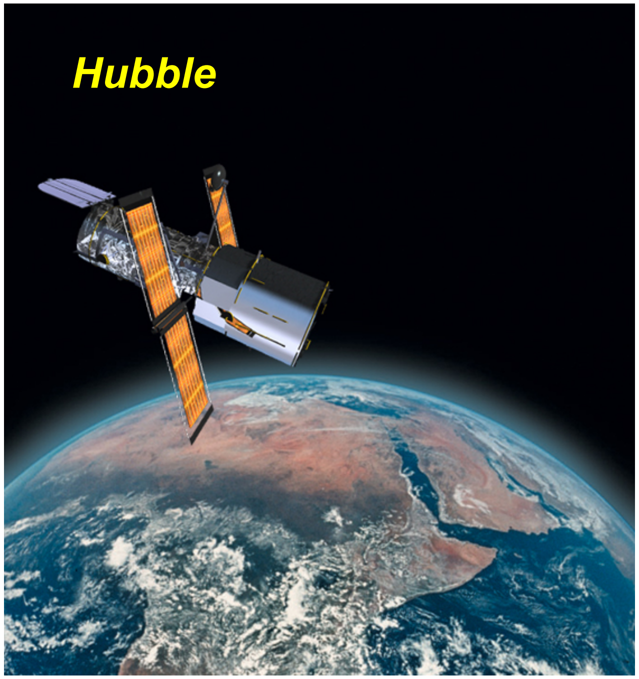
- the two Keck 10-meter reflectors & their spectrographs

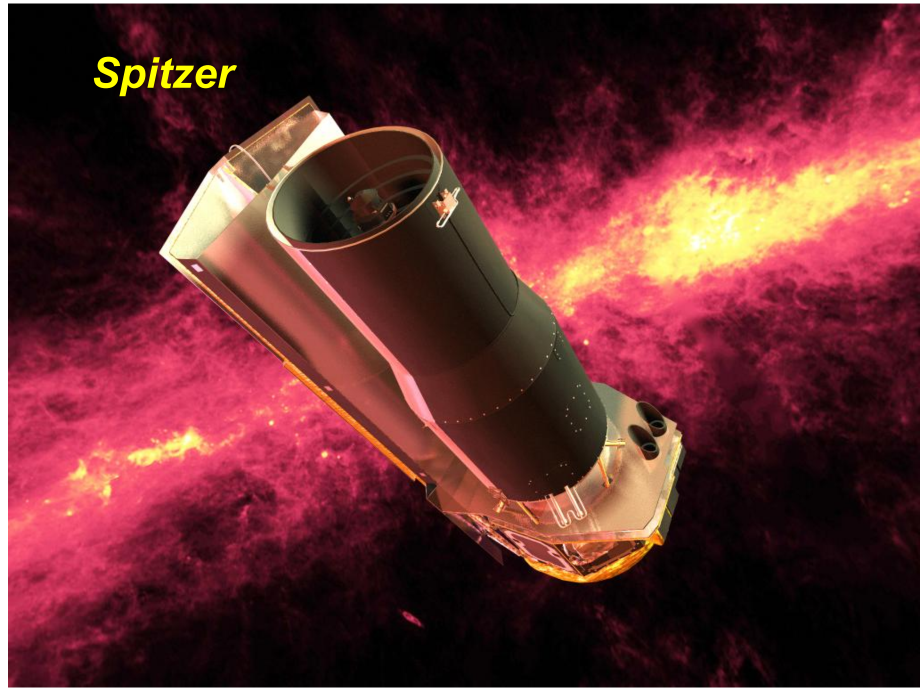


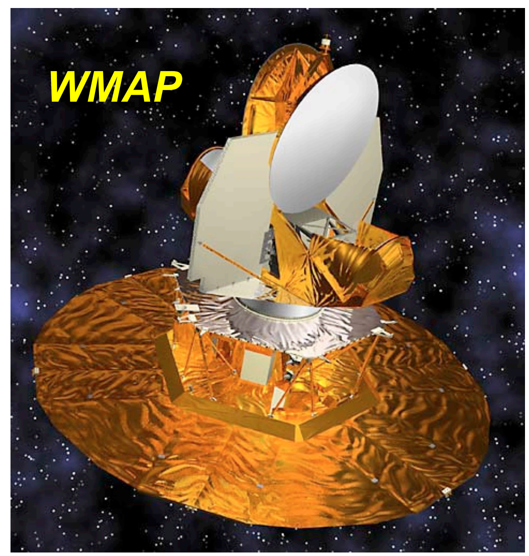




… and three unique space telescopes







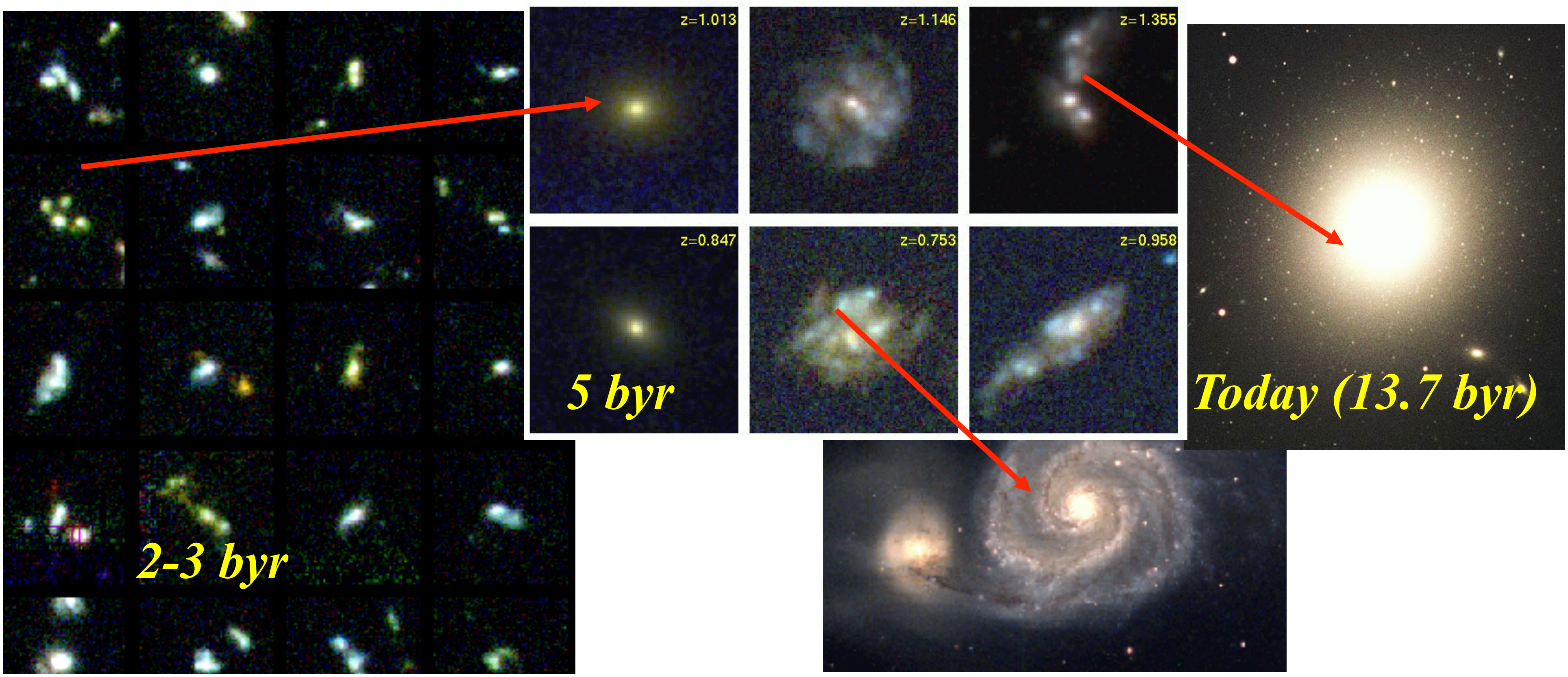
Hubble: exquisite deep imaging

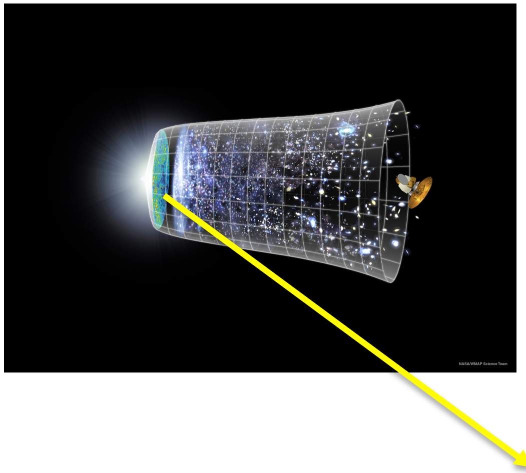
Spitzer: sensitive to older stars

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

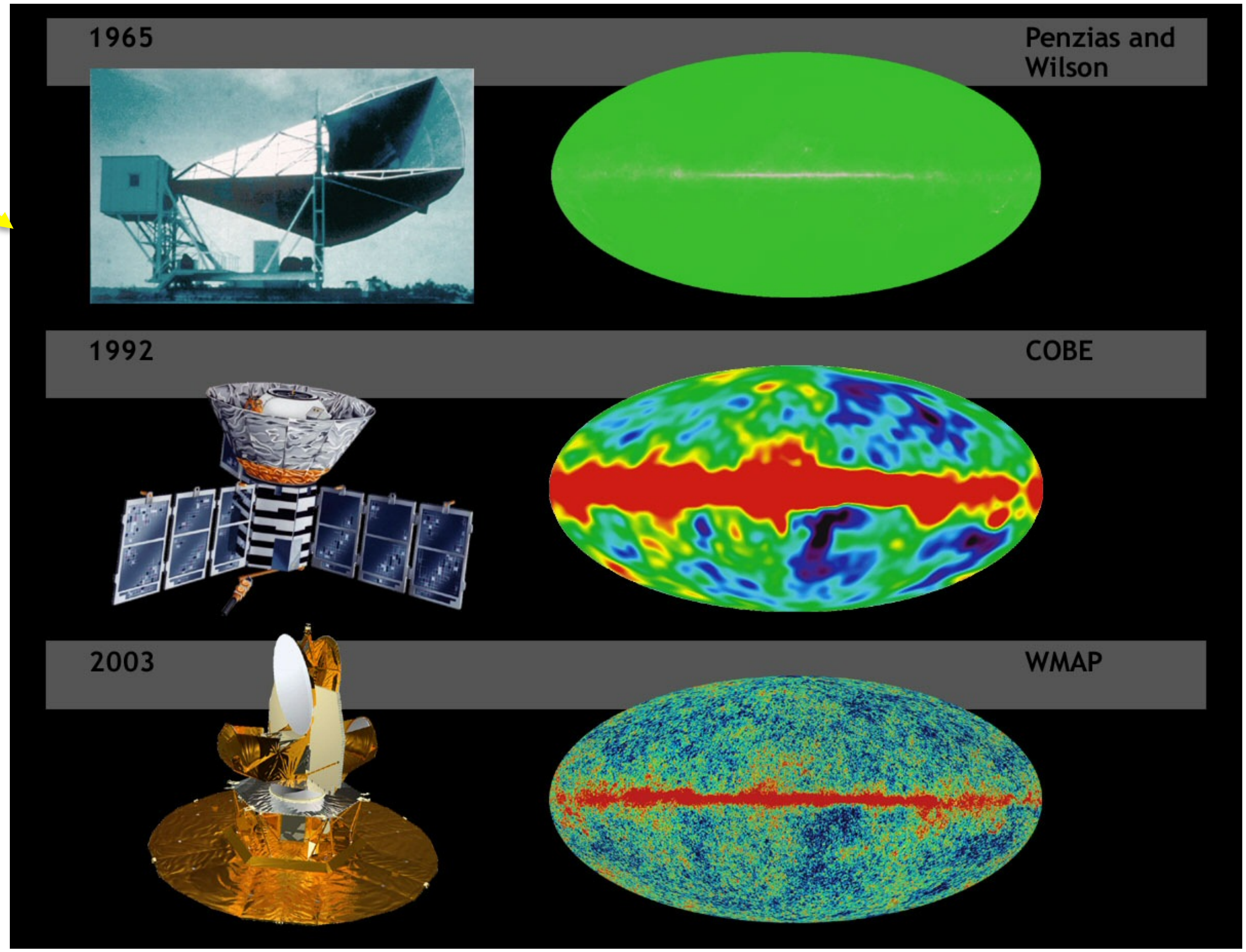
Unraveling Cosmic History

Keck and Palomar, aided by 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)



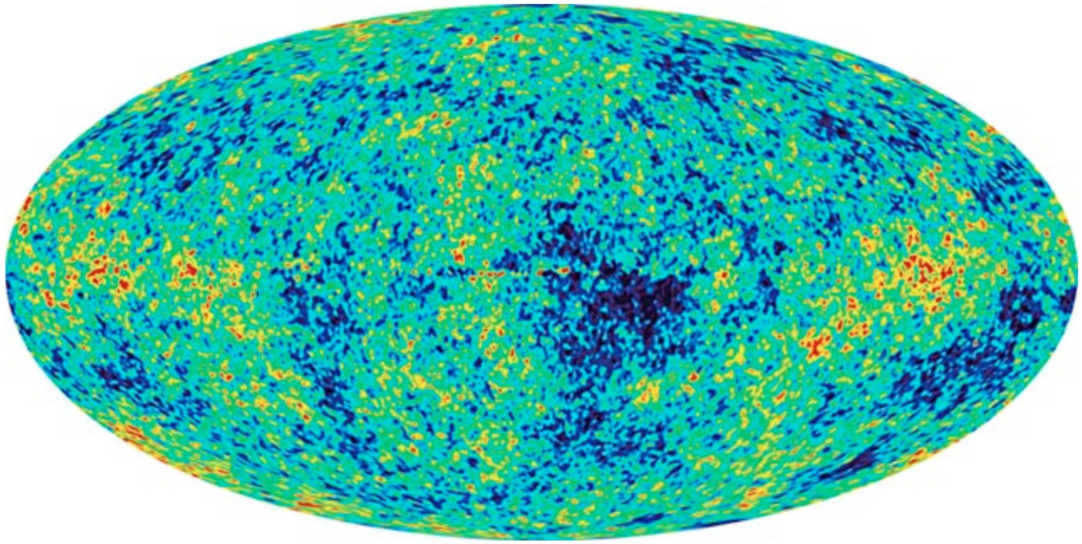


Cosmic Microwave Background



Microwave background corresponds to separation of matter & radiation at redshift z =1088 ±1 when age = 372,000 years

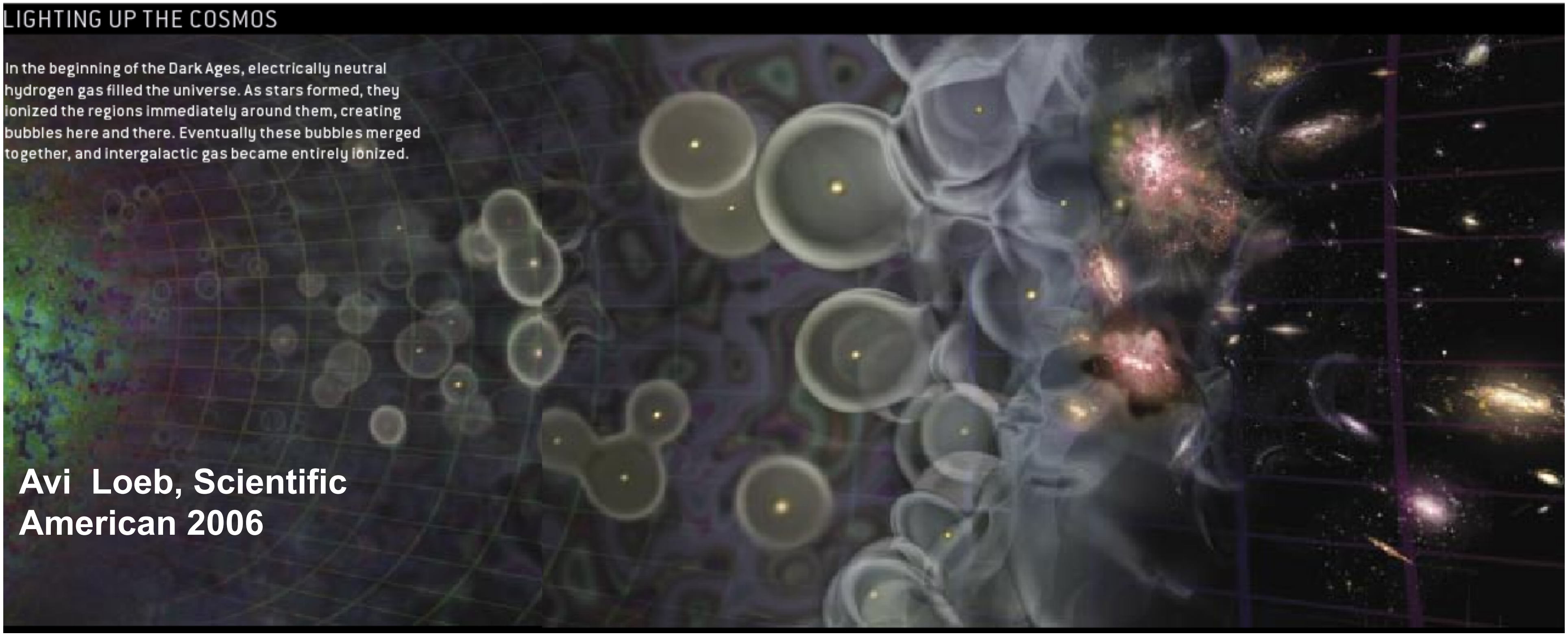
What happened next?



Universe then enters a period called the `**Dark Ages**' : cold hydrogen clouds clump under gravity and collapse to form stars

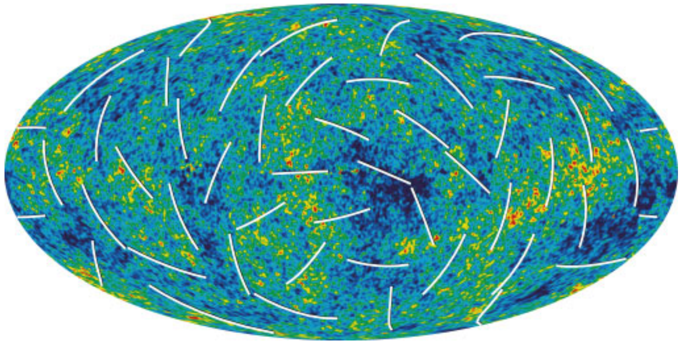
Stars eventually energize hydrogen in deep space breaking it into electrons and protons (process called `**reionization**')

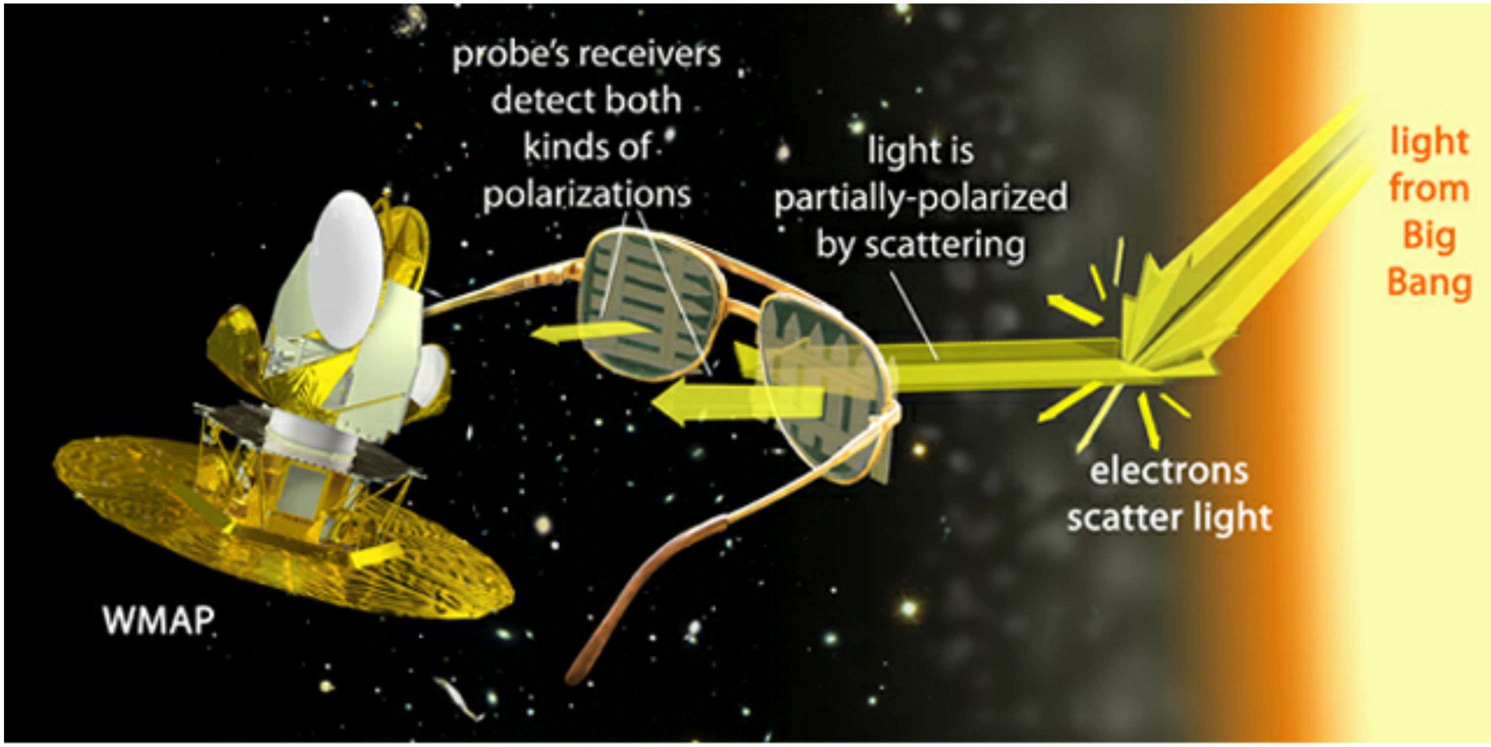
Theorists' View of Cosmic Dawn



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

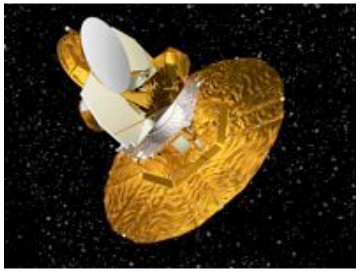
Polarization of Microwave Background



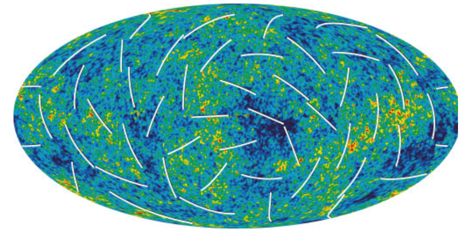


Polarization arises from foreground electrons at the time of reionization

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

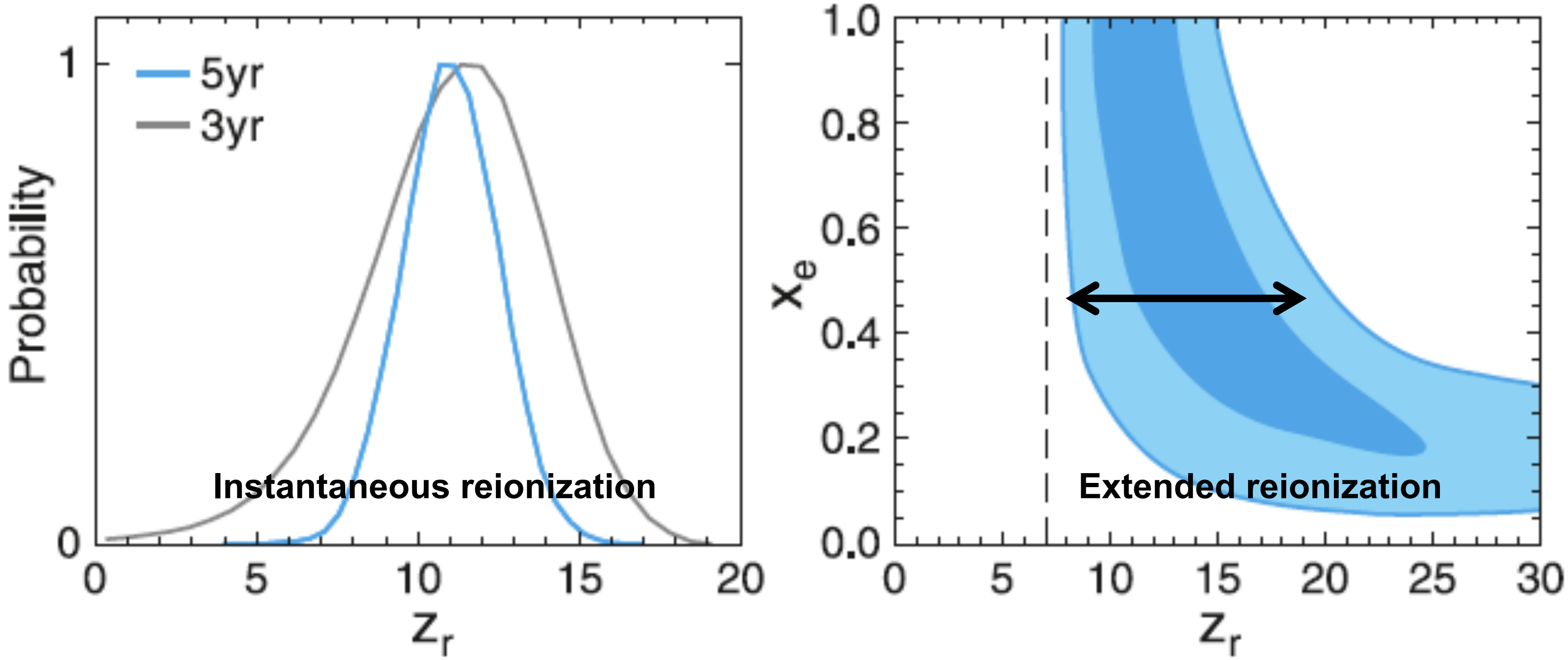


WMAP Polarization



WMAP measures optical depth of electron scattering

τ = 0.088± 0.015 (2010)



Reionization peaks at redshift z~11 (400 Myr) or could extend from z~20 to z~6 (200 Myr to 1 billion yrs)

Can reject instantaneous reionization at z~6-7 (1 billion ys)

CMB does <u>not</u> pinpoint the responsible cosmic sources

The Big Questions

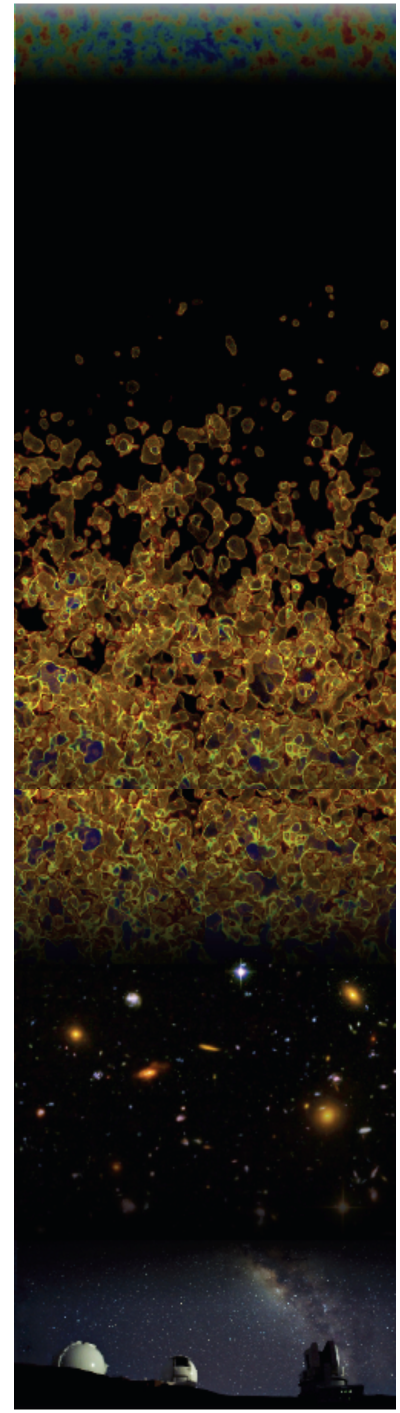
1. When was Cosmic Dawn?

   Was it a dramatic event in a narrow period of time or did the birth of galaxies happen gradually?

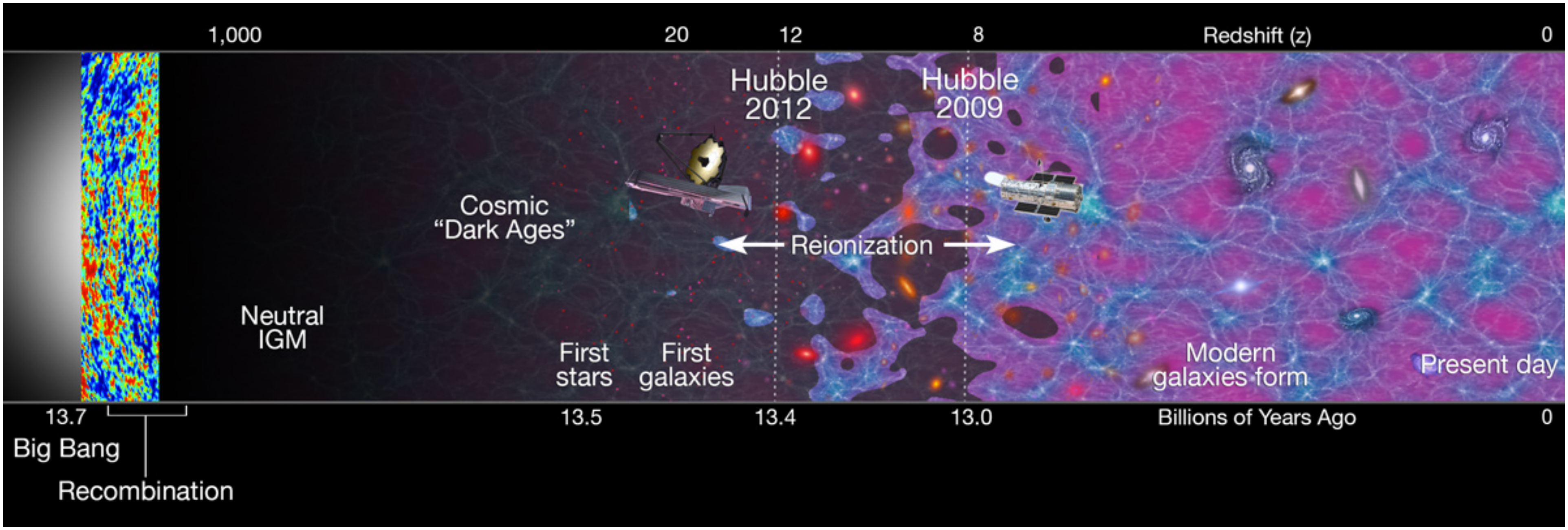
2. Can we be sure light from early galaxies caused cosmic reionization?

   We have some guide on when reionization occurred from studies of the microwave background

We must search for early galaxies to answer these questions in the time interval 200-800 million years after the Big Bang



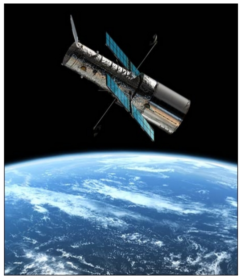
Deep Imaging & Spectroscopy with Hubble & Keck



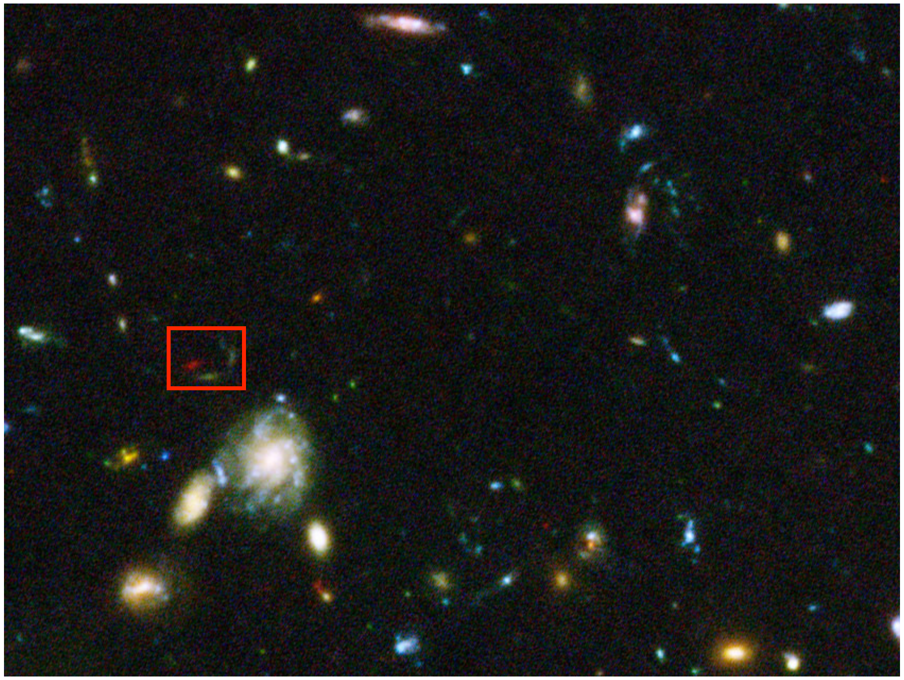
In a series of deep images, Hubble has penetrated deep into the heart of the reionization era; this has enabled:

- a census of early galaxies which addresses their role in reionization
- spectroscopy from Keck which determines how reionization progressed

The Hubble Ultra Deep Field (2004)

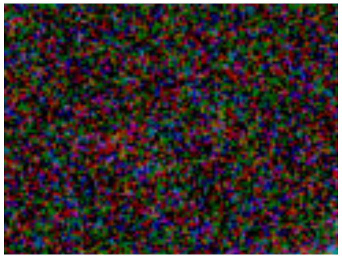


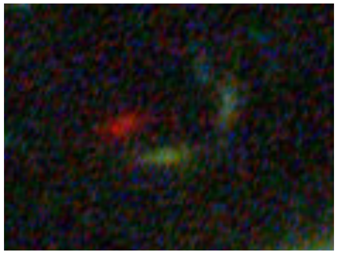
The deepest optical image



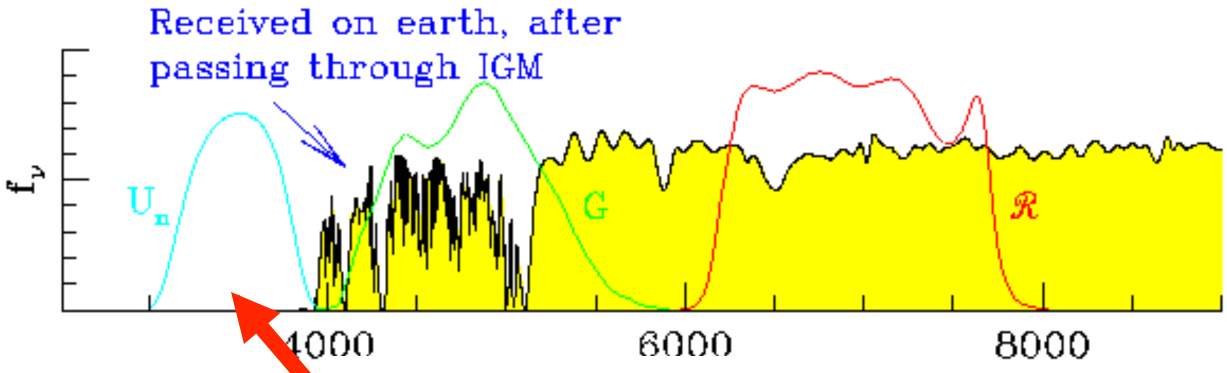
GOODS field – 13 orbits

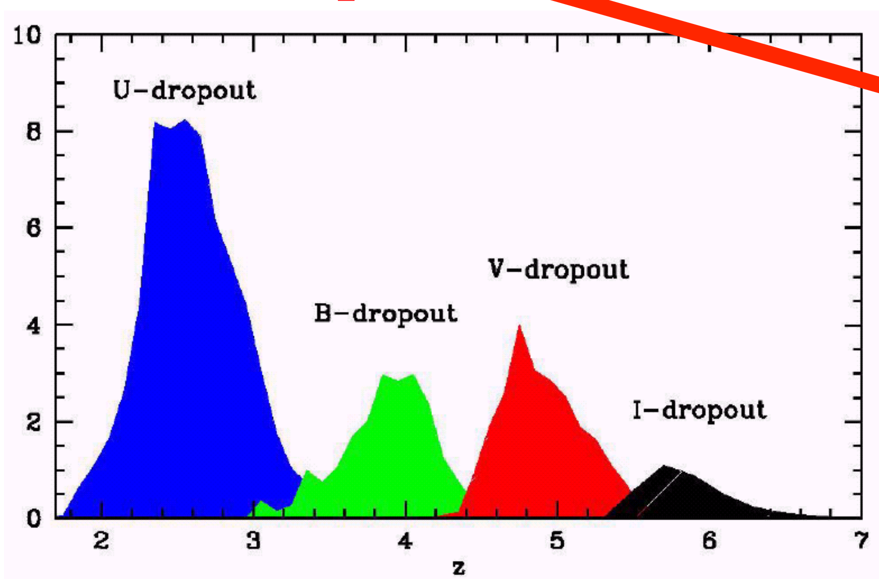
HUDF – 400 orbits

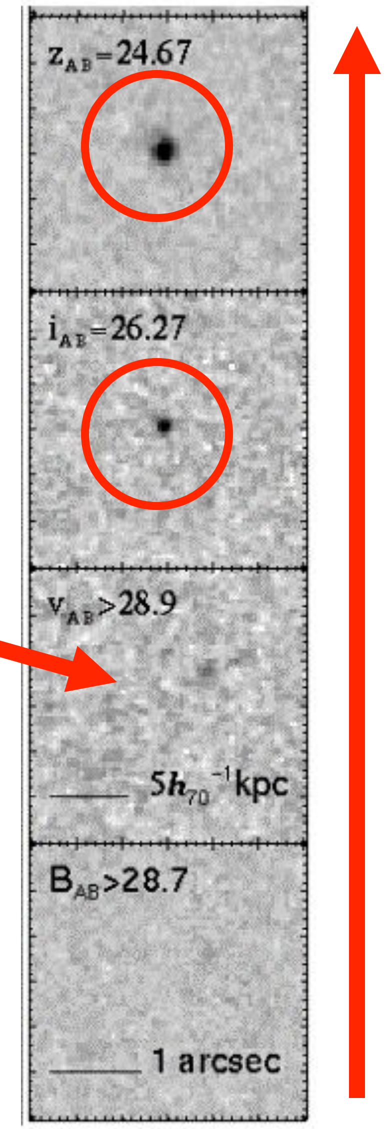




Selecting early galaxies in deep Hubble images



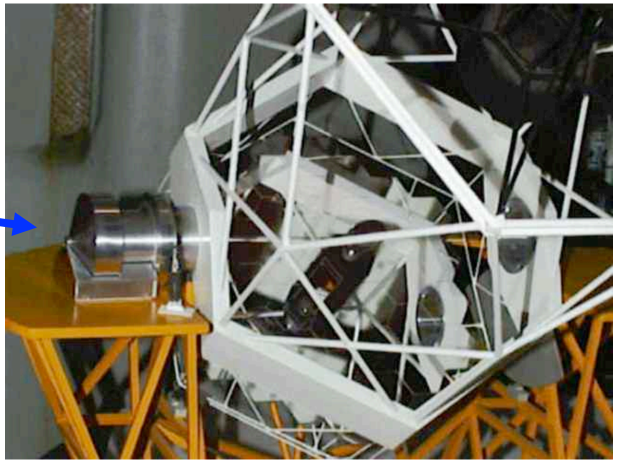


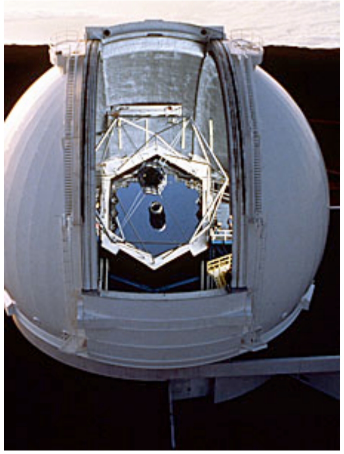


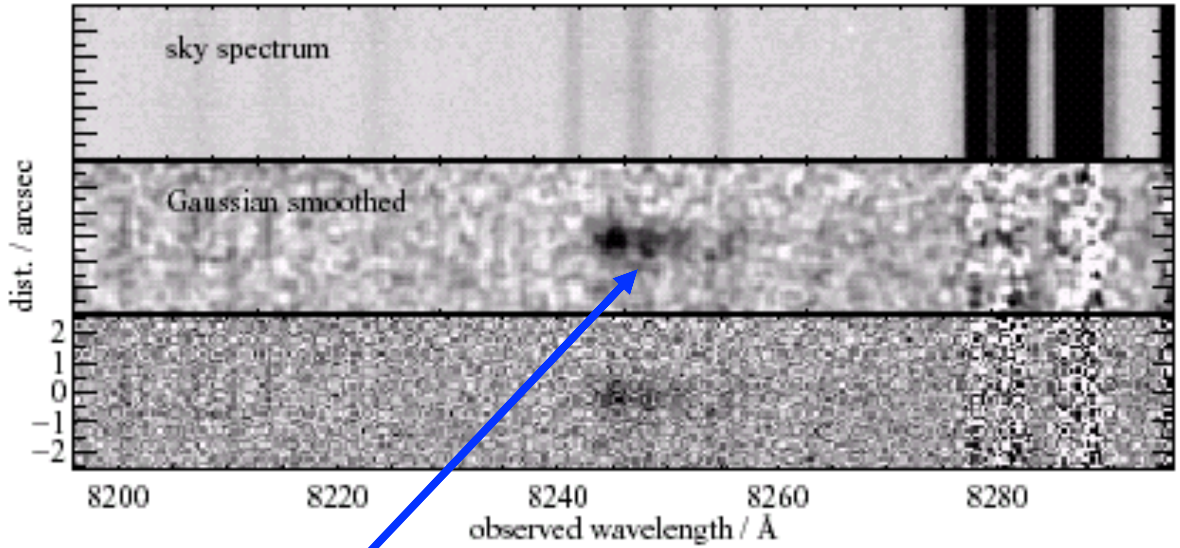
We extend the `dropout' technique used successfully at redshifts z=3 to find galaxies at higher redshifts by looking for `dropouts' in bands at longer (redder) wavelengths

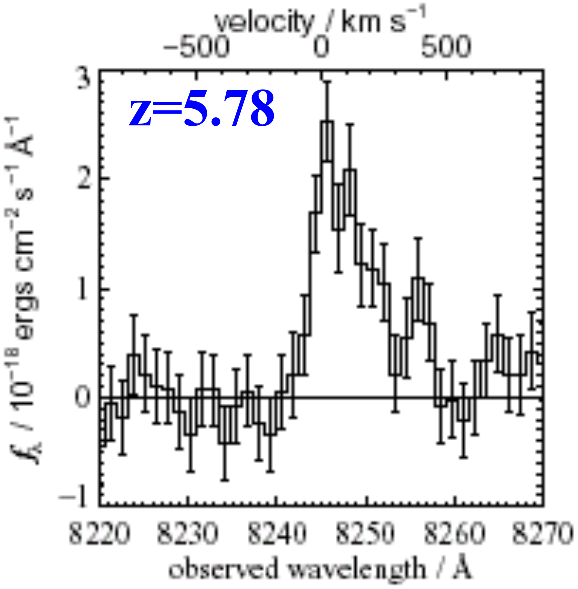
Keck spectroscopy of `dropout' galaxies

Spectrum of very faint i-band dropout with DEIMOS verifies technique









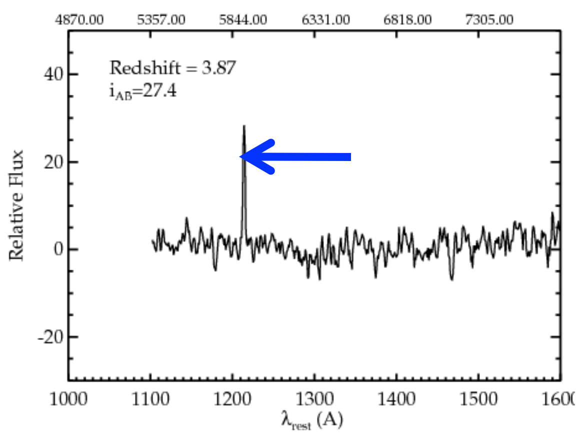
Spectrum line of hydrogen (***Lyman alpha***) in galaxy confirms redshift is z=5.78

Bunker, Ellis et al (2004)

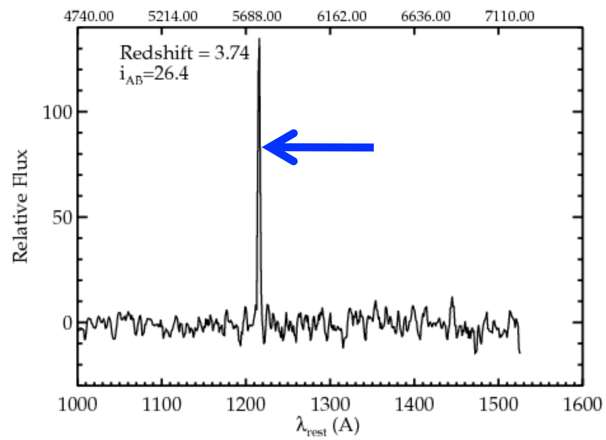
Keck Spectroscopic Survey of 3 < z < 8 LBGs

- Statistics so far: 351 B + 151 V + 89 I + 21 z + 5 Y drops = 617 spectra
- European VLT survey + same criteria: 195 spectra (Vanzella et al)

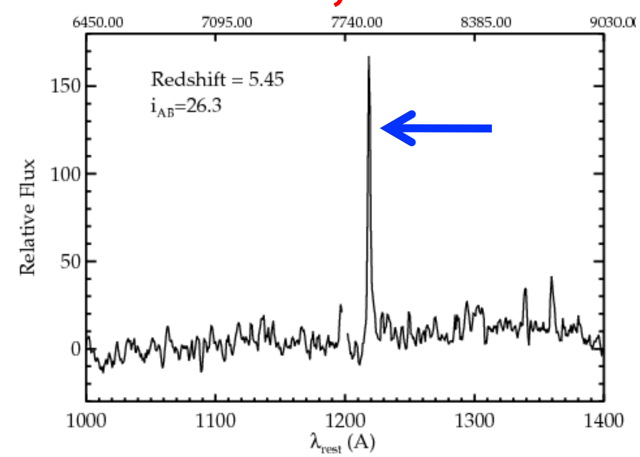
m=27.4, z=3.87



m=26.4, z=3.74



m=26.3,z=5.45



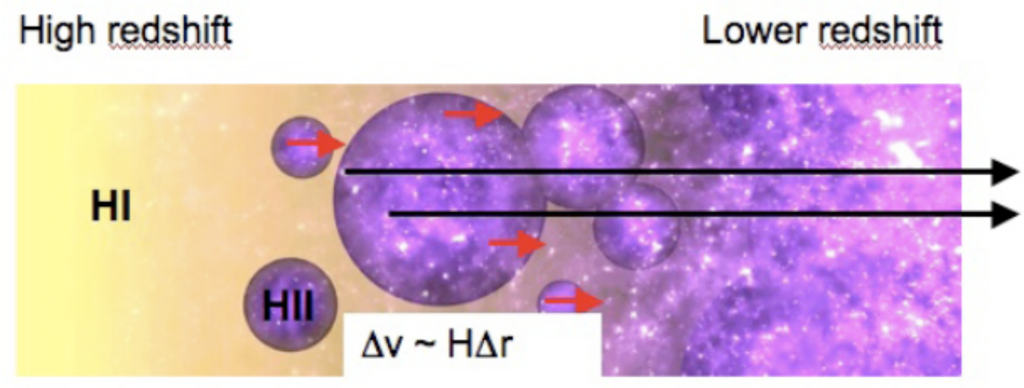
We measures the rate of occurrence of the Lyman alpha emission line

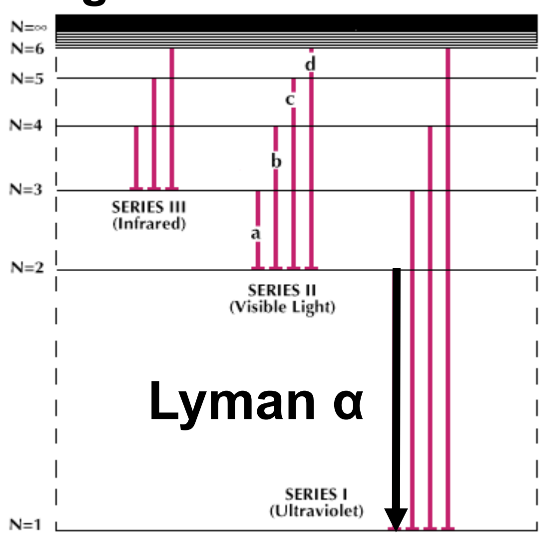
When we enter the Dark Ages we expect the fraction to suddenly drop

Stark, Ellis et al (2010, 2011)

When did Dark Ages End?

- Lyman alpha line is <u>scattered by hydrogen along the sight line</u> and thus can trace its presence
- `Dark Ages' acts as <u>fog</u> obscuring line emission from young galaxies
- A drop in the visibility of Lyman alpha line suggests entering the Dark Ages!





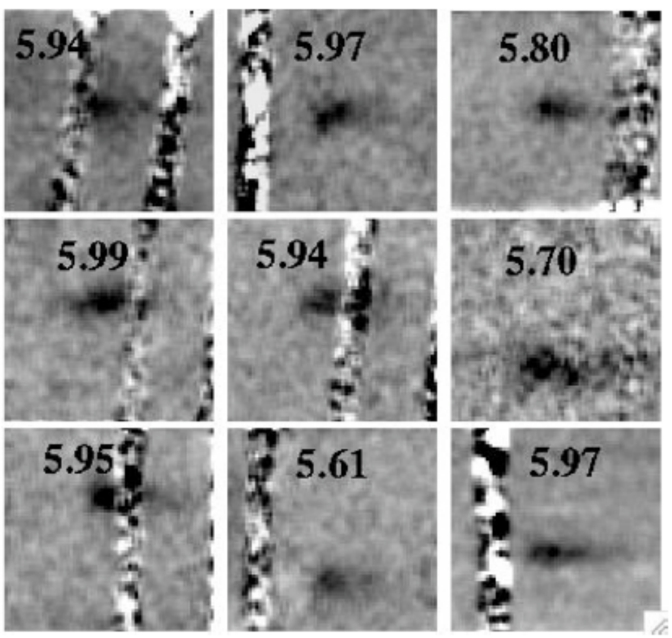
Energy Levels of Hydrogen

Line detections in Hubble galaxies 6.3 < z < 8

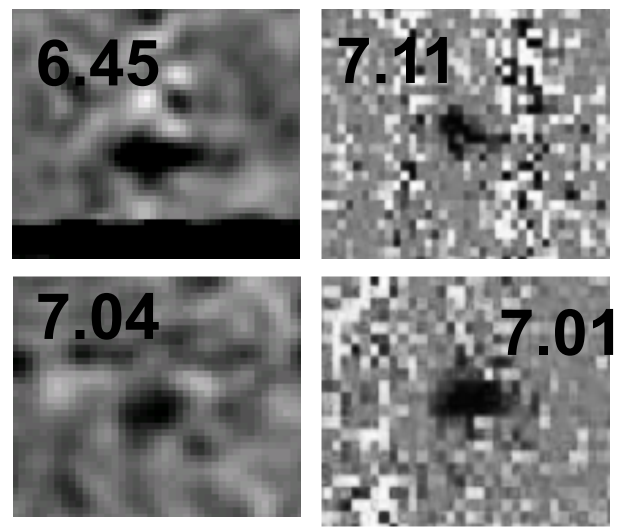
Keck spectra of 19 z > 6.3 HST-selected galaxies

Plus 7 spectra from European VLT (Fontana et al 2010)

z~6 emitters

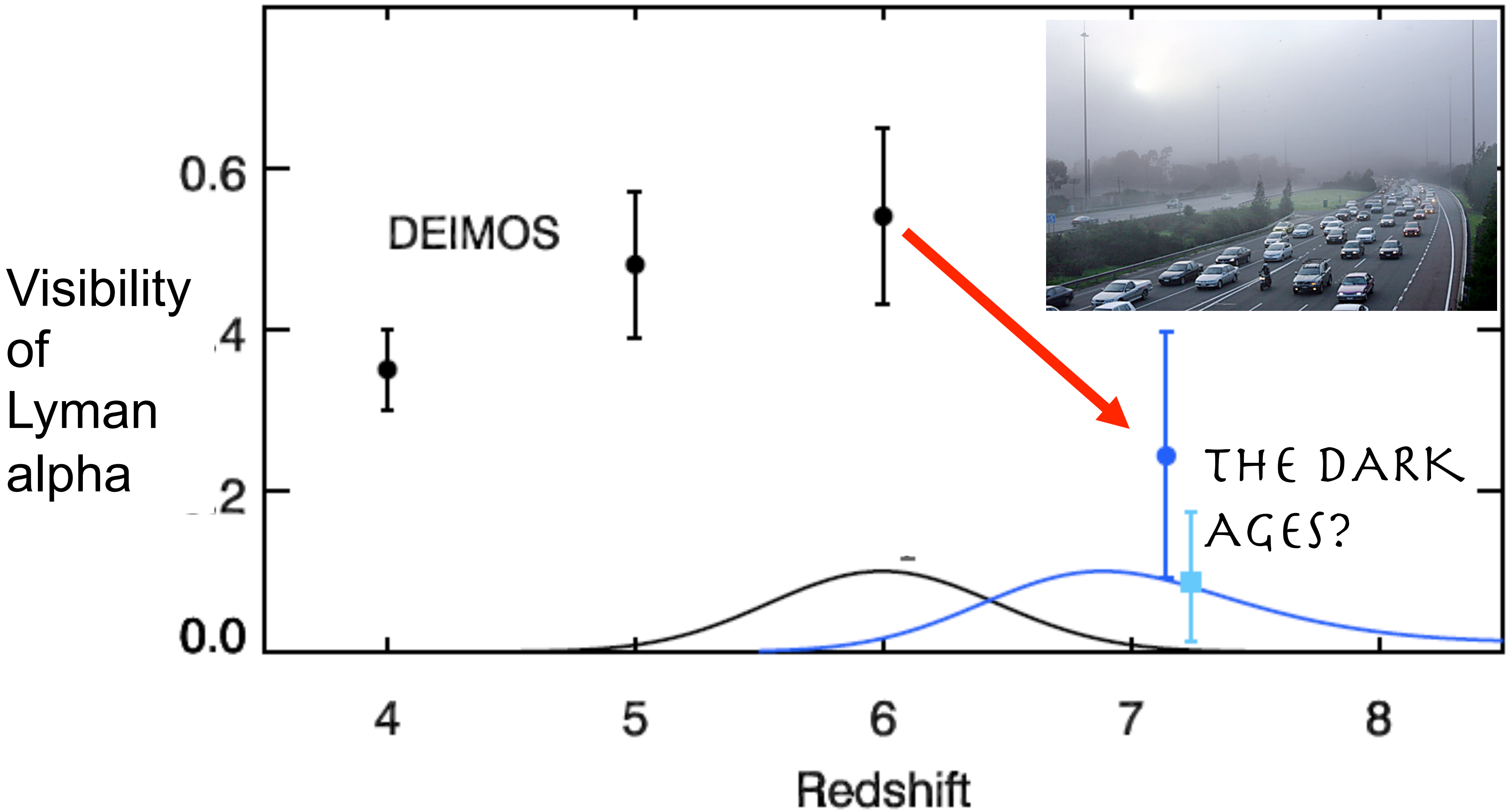


New z ~6.5-7.1 emitters



Schenker, Ellis et al (2012)

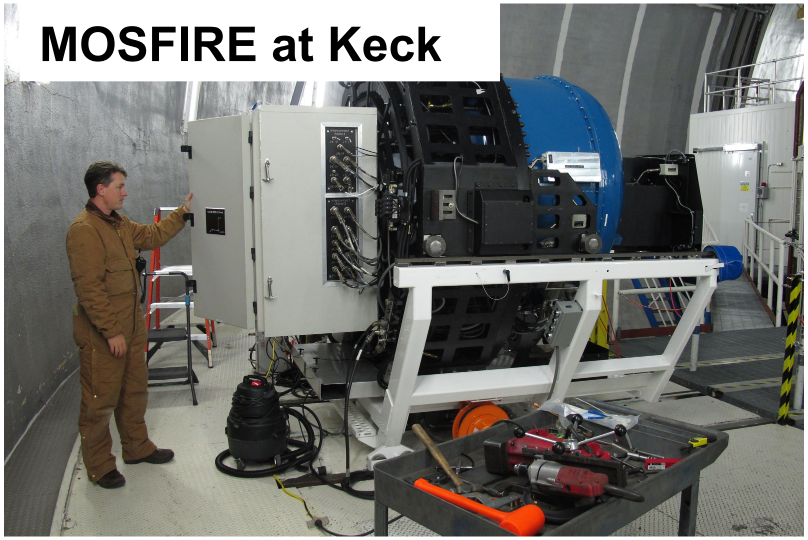
When Did the Dark Ages End?

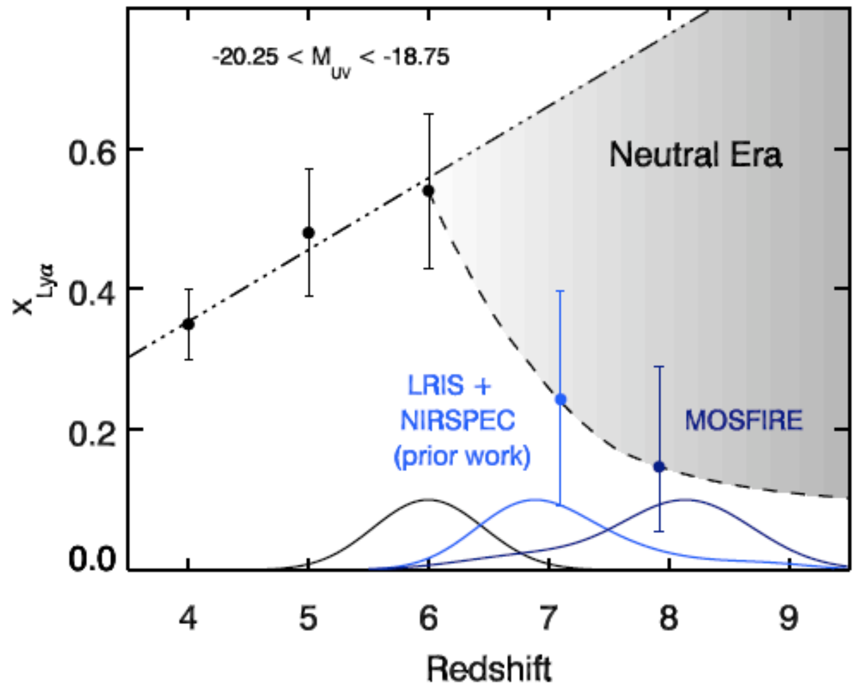


The sudden decline in the visibility of Lyman alpha emission beyond redshift 7 suggests we have detected the Dark Ages

Schenker, Ellis et al (2012)

MOSFIRE Keck Spectrograph



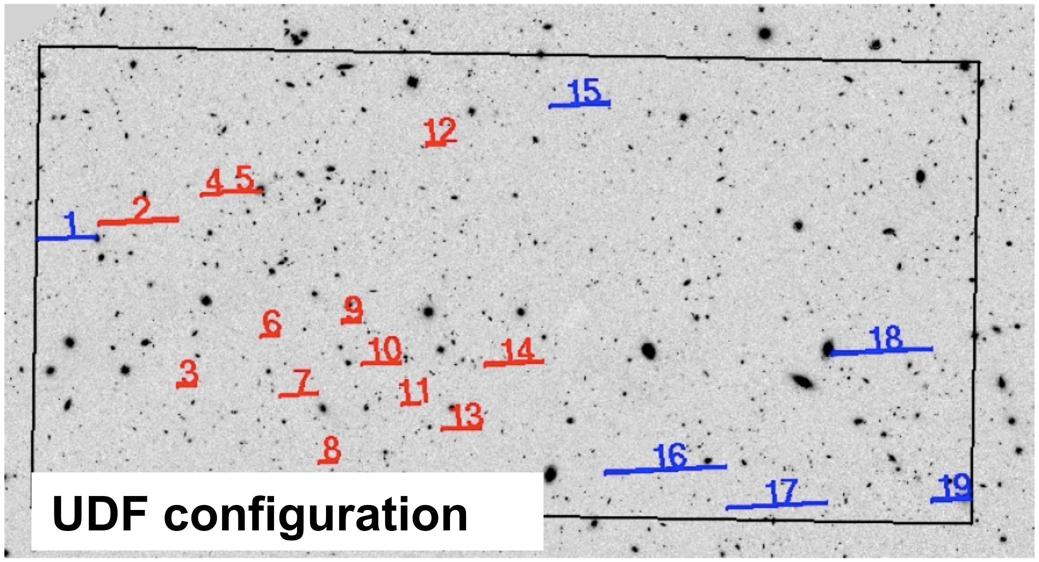


Multi-slit infrared spectrograph

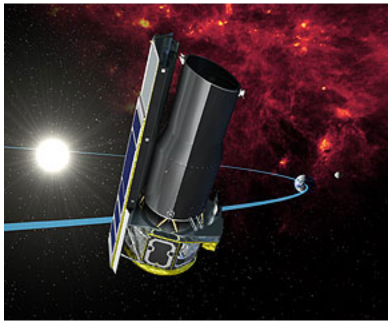
6.1 x 3.1 arcmin field of view

Wavelength range: 0.97 - 2.45 microns

45 objects at a time!

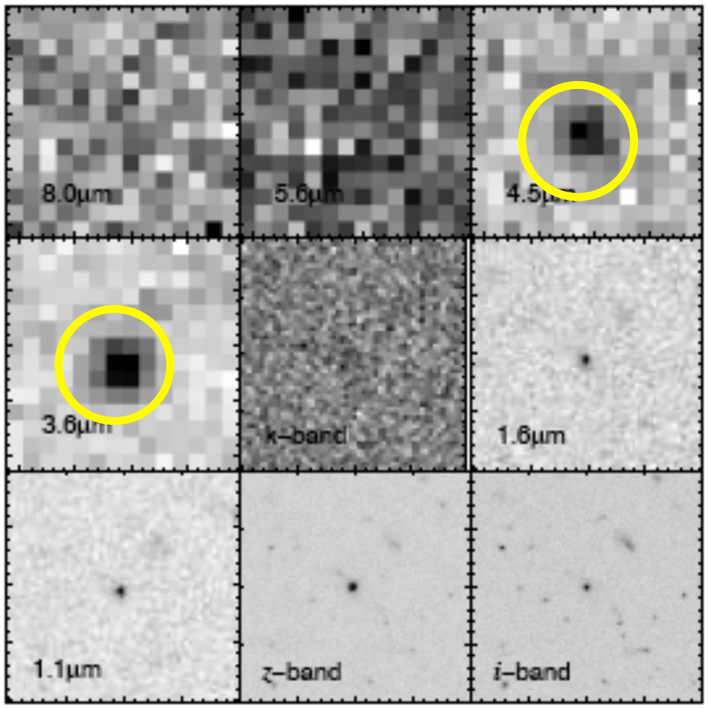


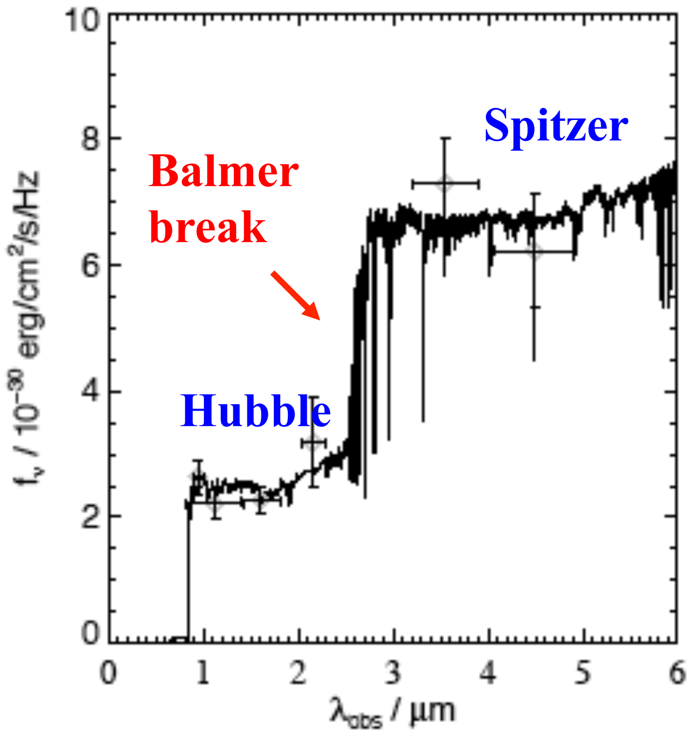
Spitzer Space Telescope: Old Stars at Redshift 6



85cm telescope can see the most distant known objects and measure their **assembled mass in stars and ages**

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

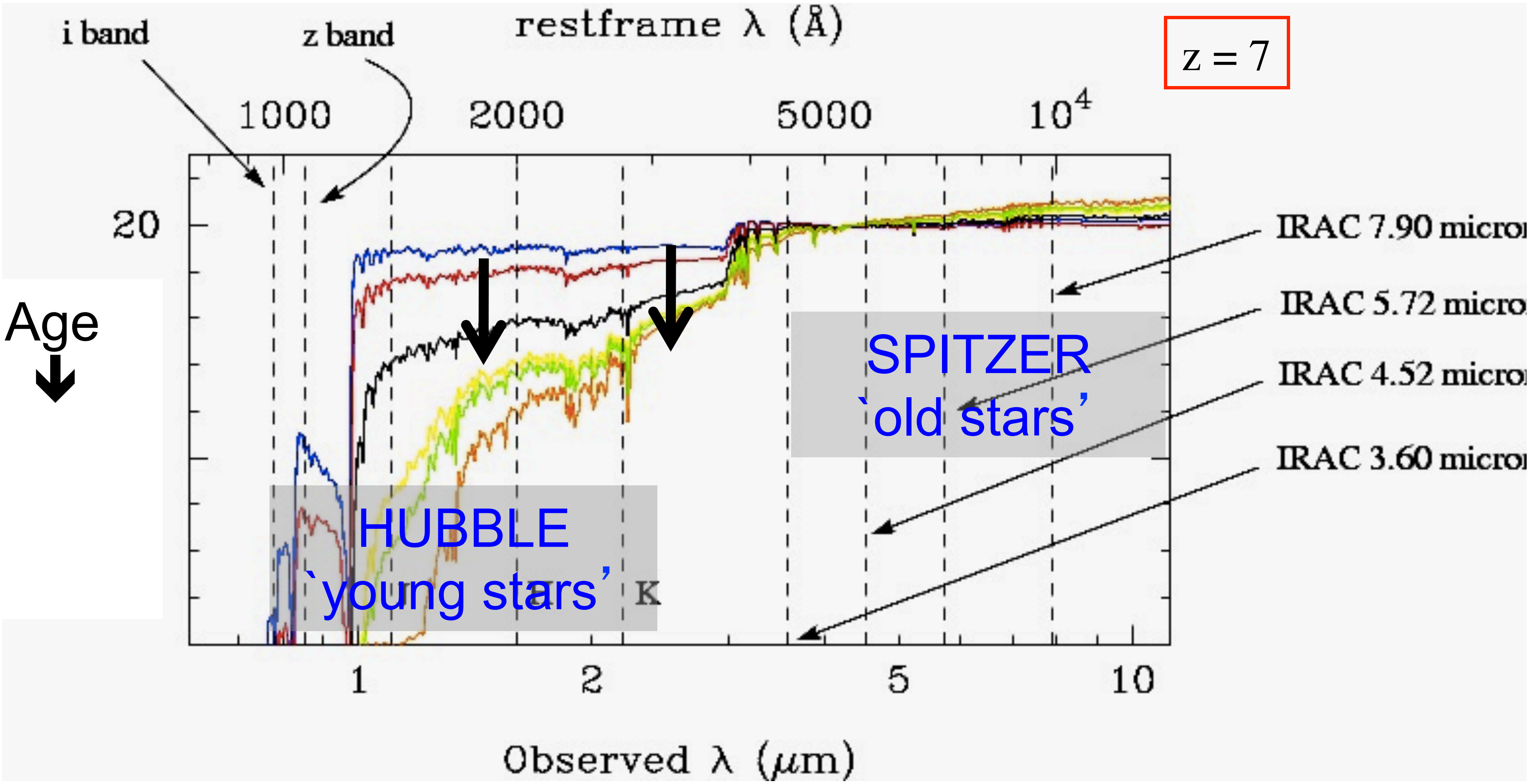




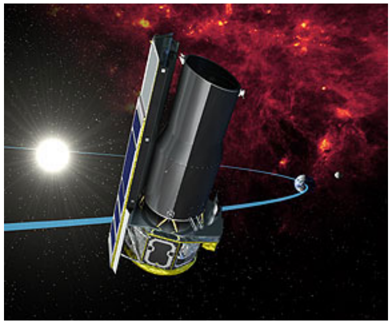
Prior star formation implies presence of systems at even earlier times!

Eyles, Ellis et al (2005)

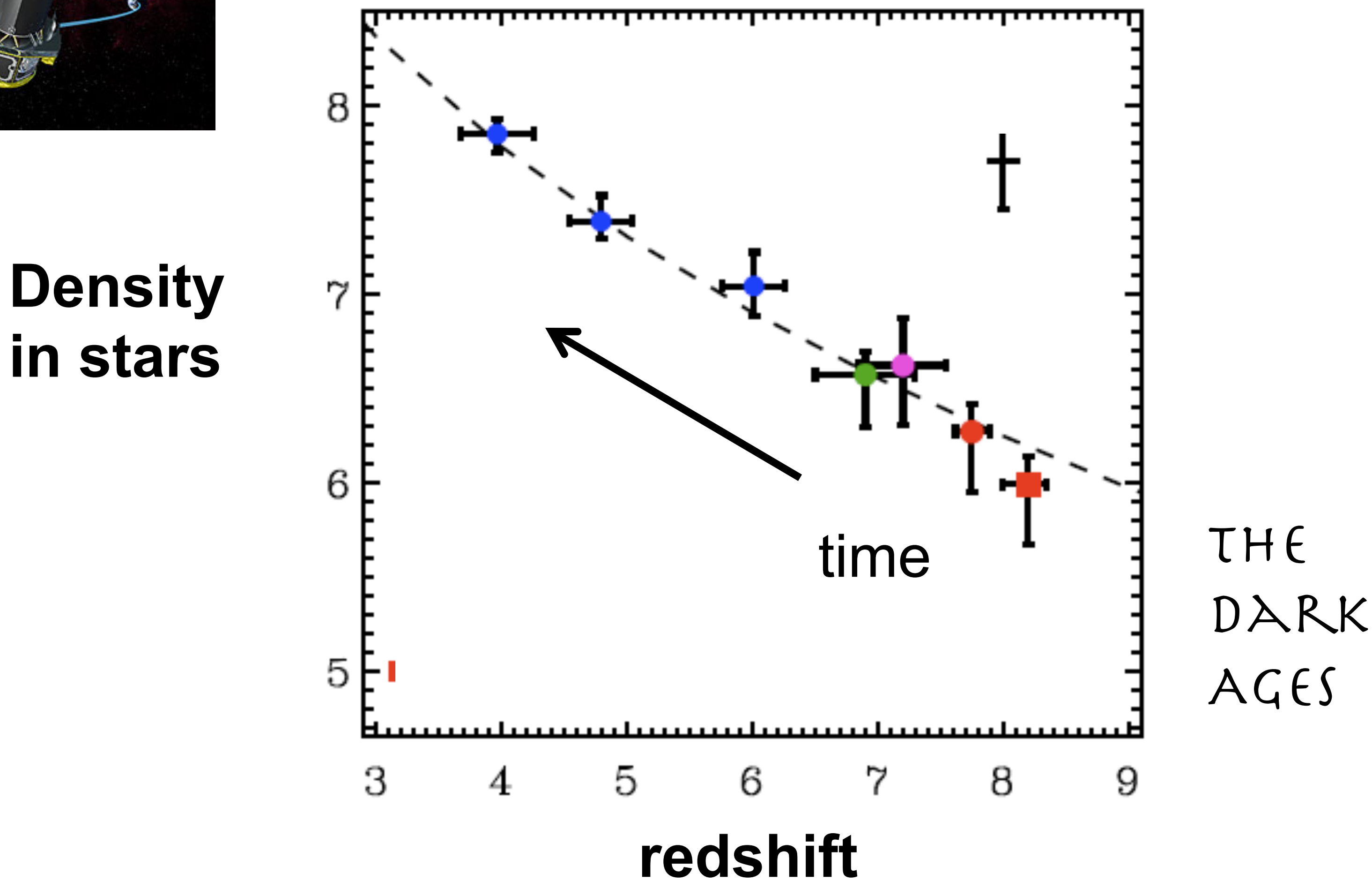
Spitzer and Hubble Combine as `Age Indicator'



Hubble measures current rate of star formation
Spitzer measures mass in older stars
Combination gives the age



Growth of Stellar Mass with Time

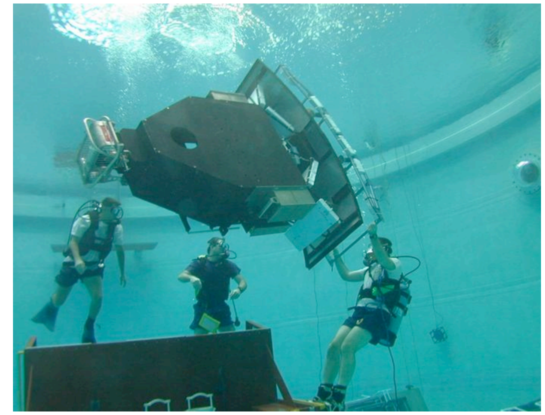


Spitzer gives a census of how the mass in stars grows with time

It predicts there is more early star formation than Hubble has so far seen!

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

Wide Field Camera 3 installed on Hubble (2009)

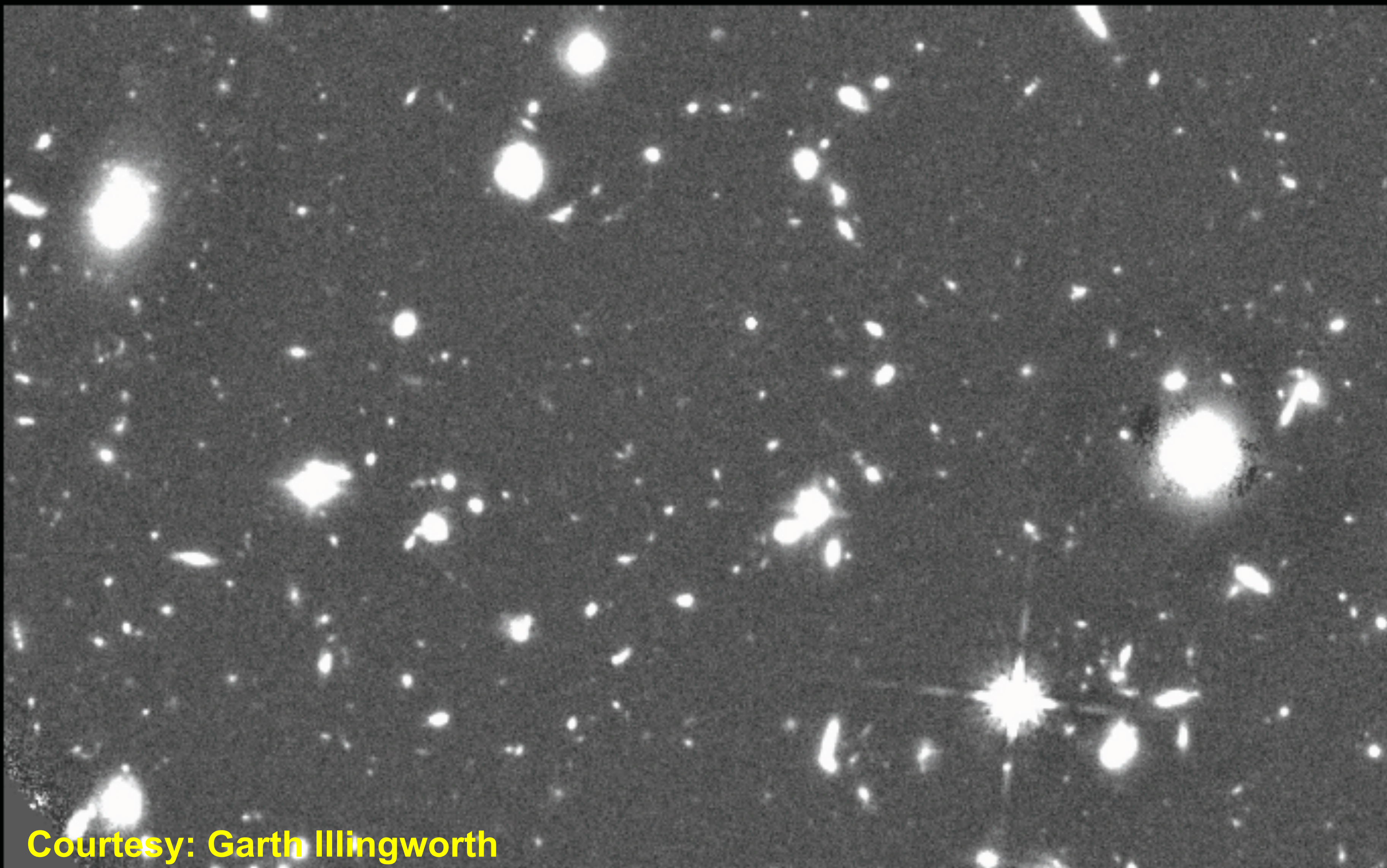


Dramatic progress following new infrared camera on Hubble Space Telescope in May 2009

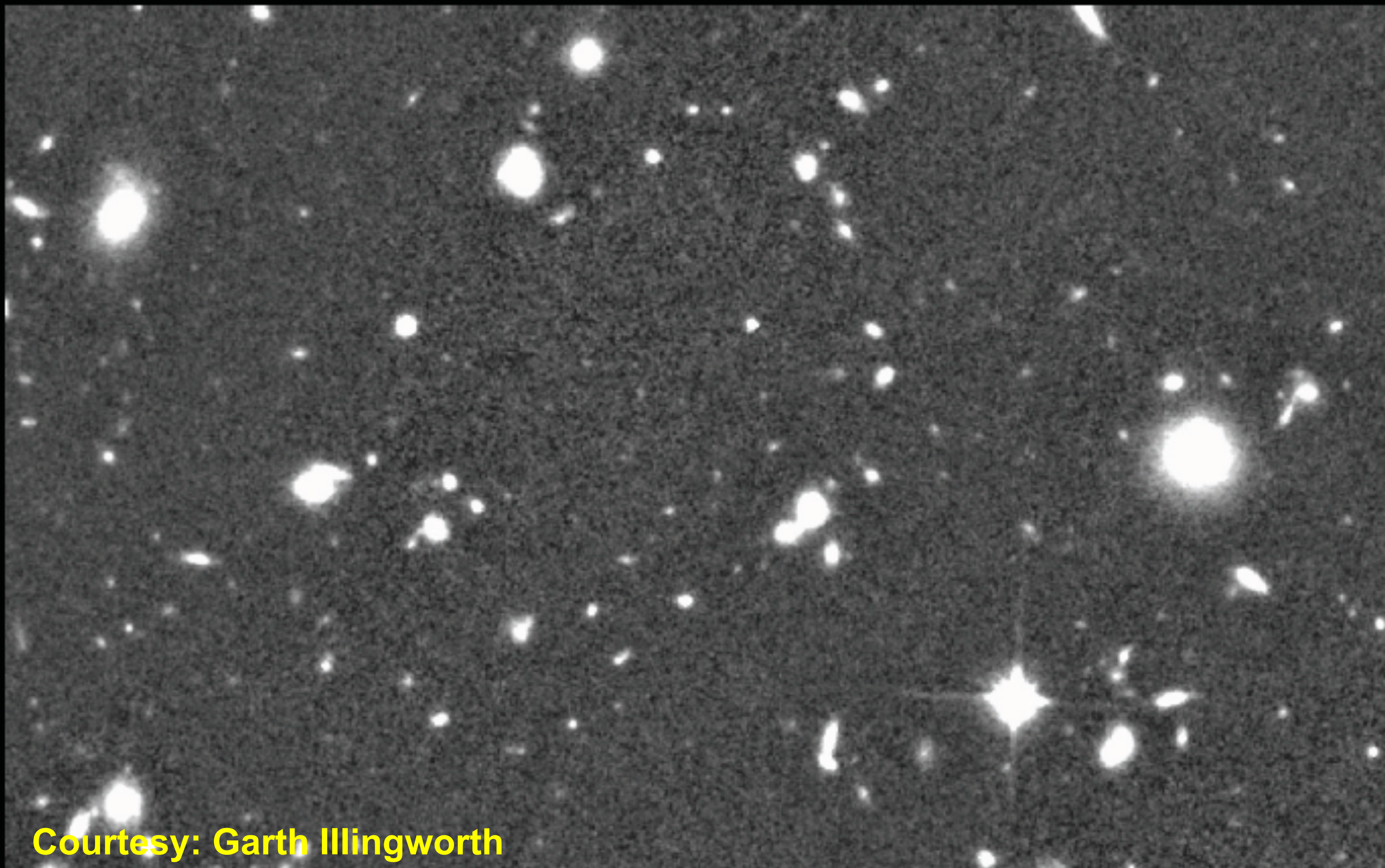
- better sensitivity
- smaller pixels
- bigger field of view

40-fold improvement over earlier camera!

WFC3/IR – 16 orbits



NICMOS – 72 orbits



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

Hubble Ultra Deep Field 2012
Hubble Space Telescope WFC3/IR

NASA and ESA
STScI-PRC12-48a

Hubble Ultra Deep Field 2012

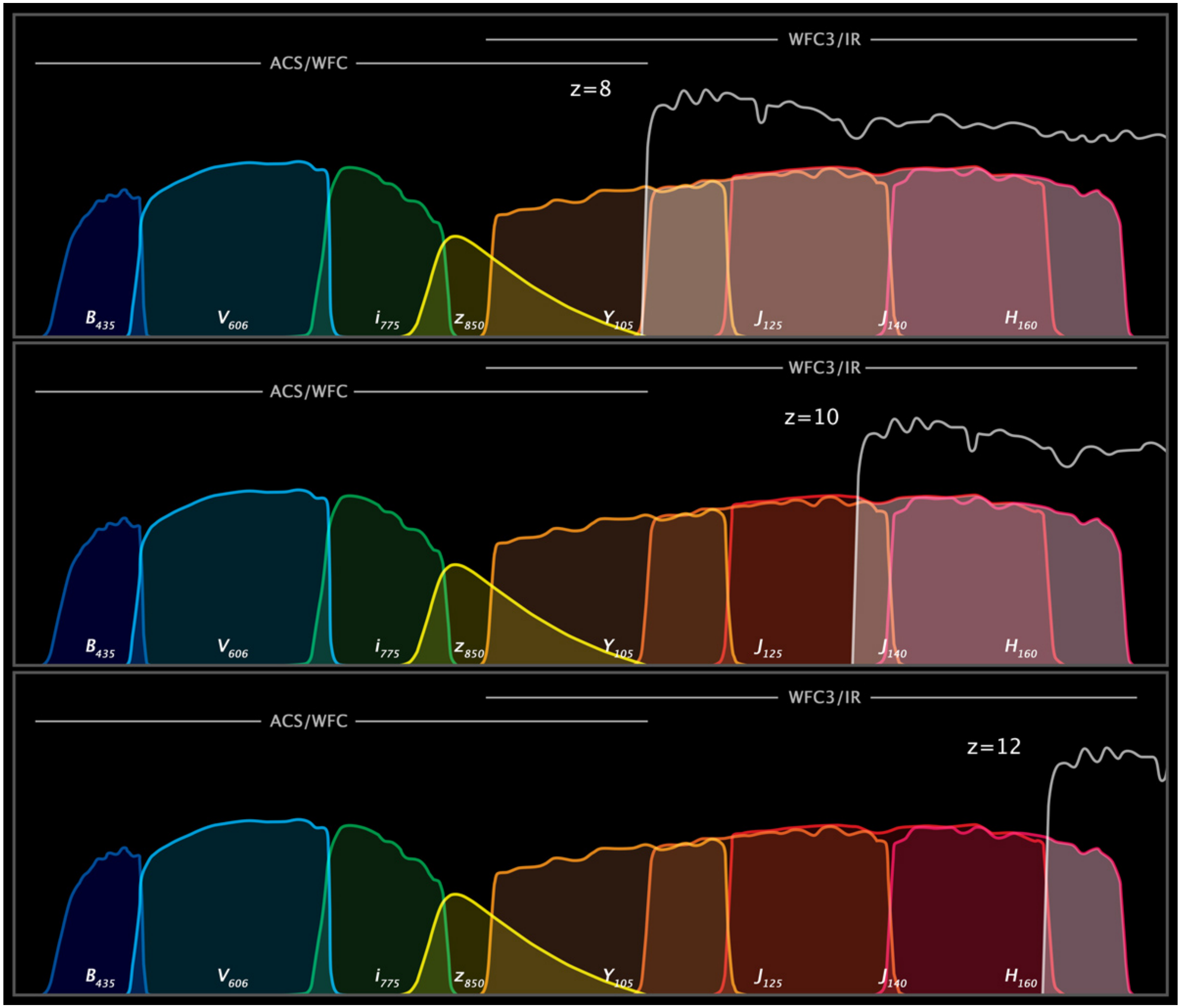
100 orbit HST campaign with infrared camera

Twice the depth of 2009 campaign

Four times deeper in key filter used to isolate z>8.5 early galaxies

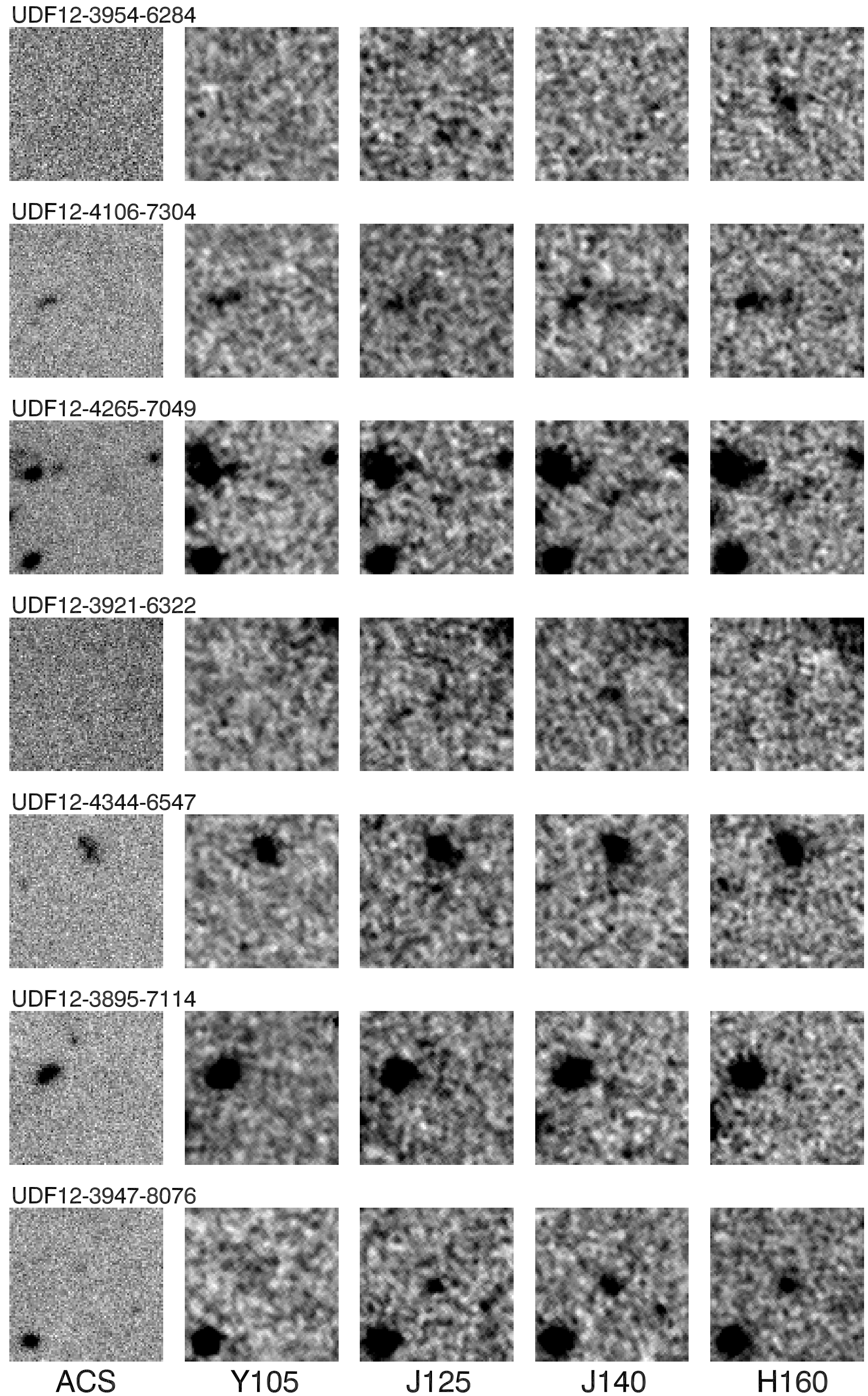
Additional infrared filters to improve redshift fidelity

UDF12 team: RSE (PI), Caltech, Arizona, UCLA, STScI, Edinburgh, Tokyo



UDF 2012 Census

7 star-forming galaxies located in time period 350 to 600 Million years after Big Bang



z=11.9 350 Myr

z=9.5 520 Myr

z=9.5 520 Myr

z=8.8 570 Myr

z=8.7 580 Myr

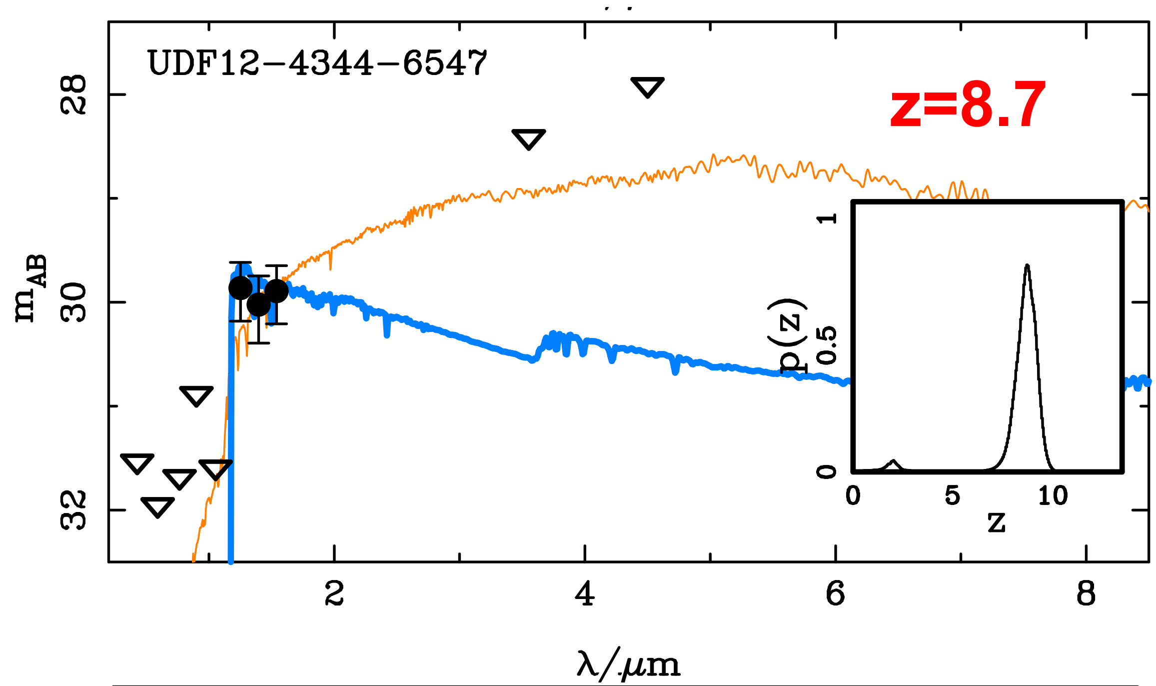
z=8.6 590 Myr

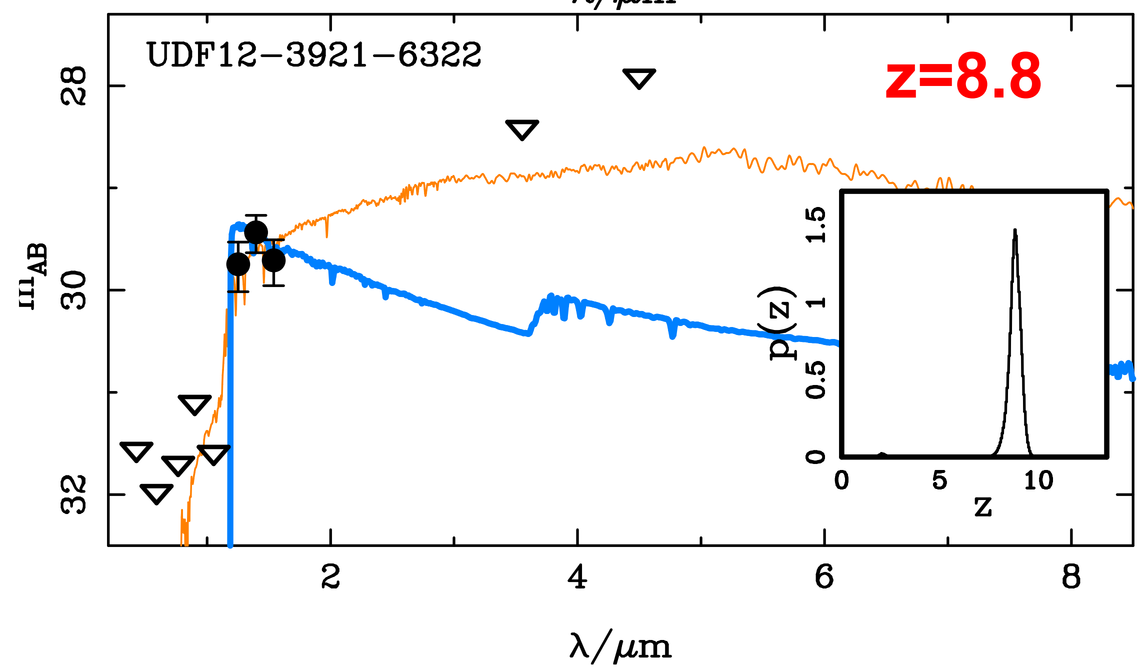
z=8.6 590 Myr

Ellis et al (in press)

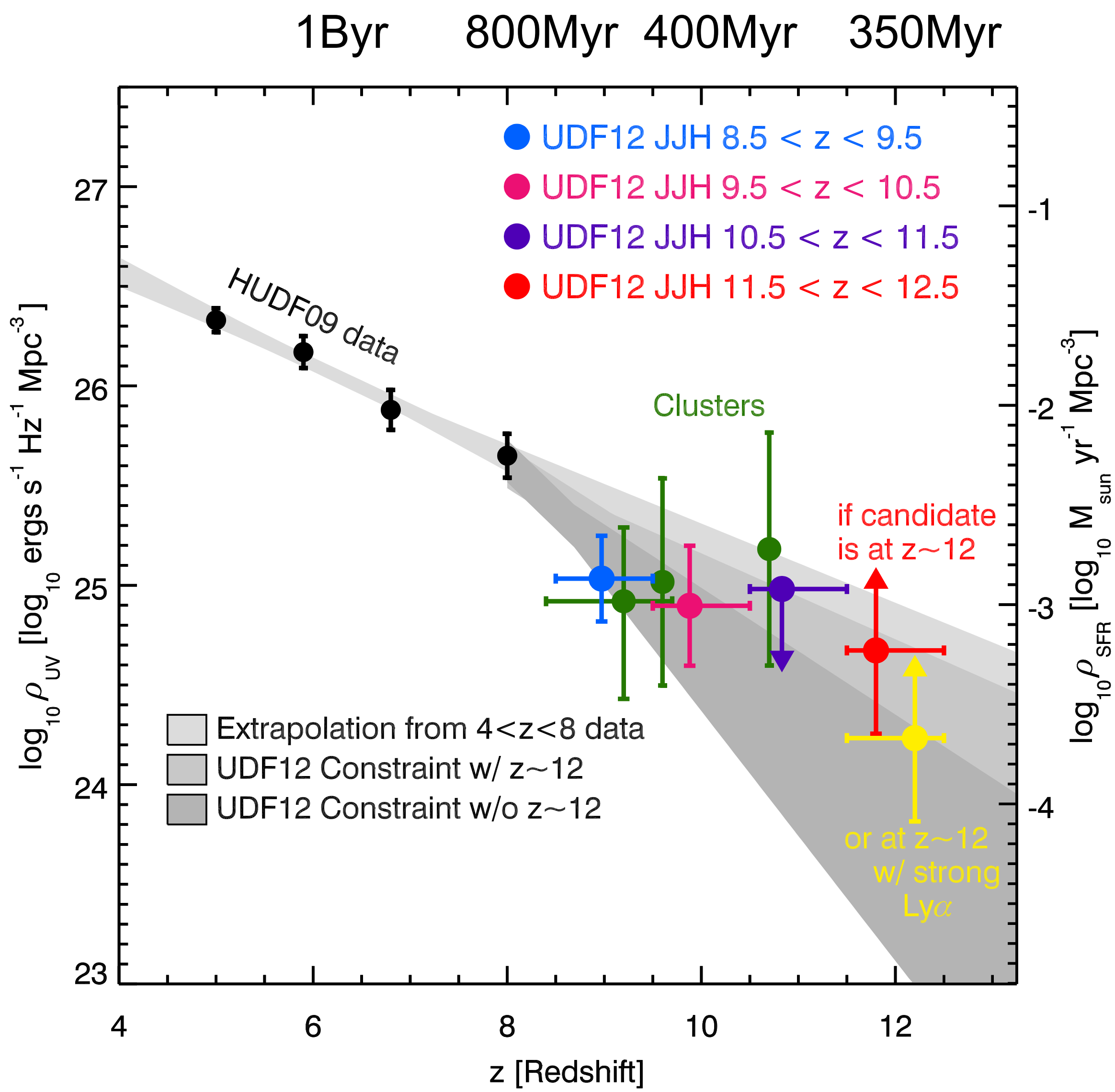
Photometric Redshifts

Using the combination of 4 optical and 4 infrared filters, the redshifts of individual galaxies can be determined for systems well beyond current spectroscopic reach



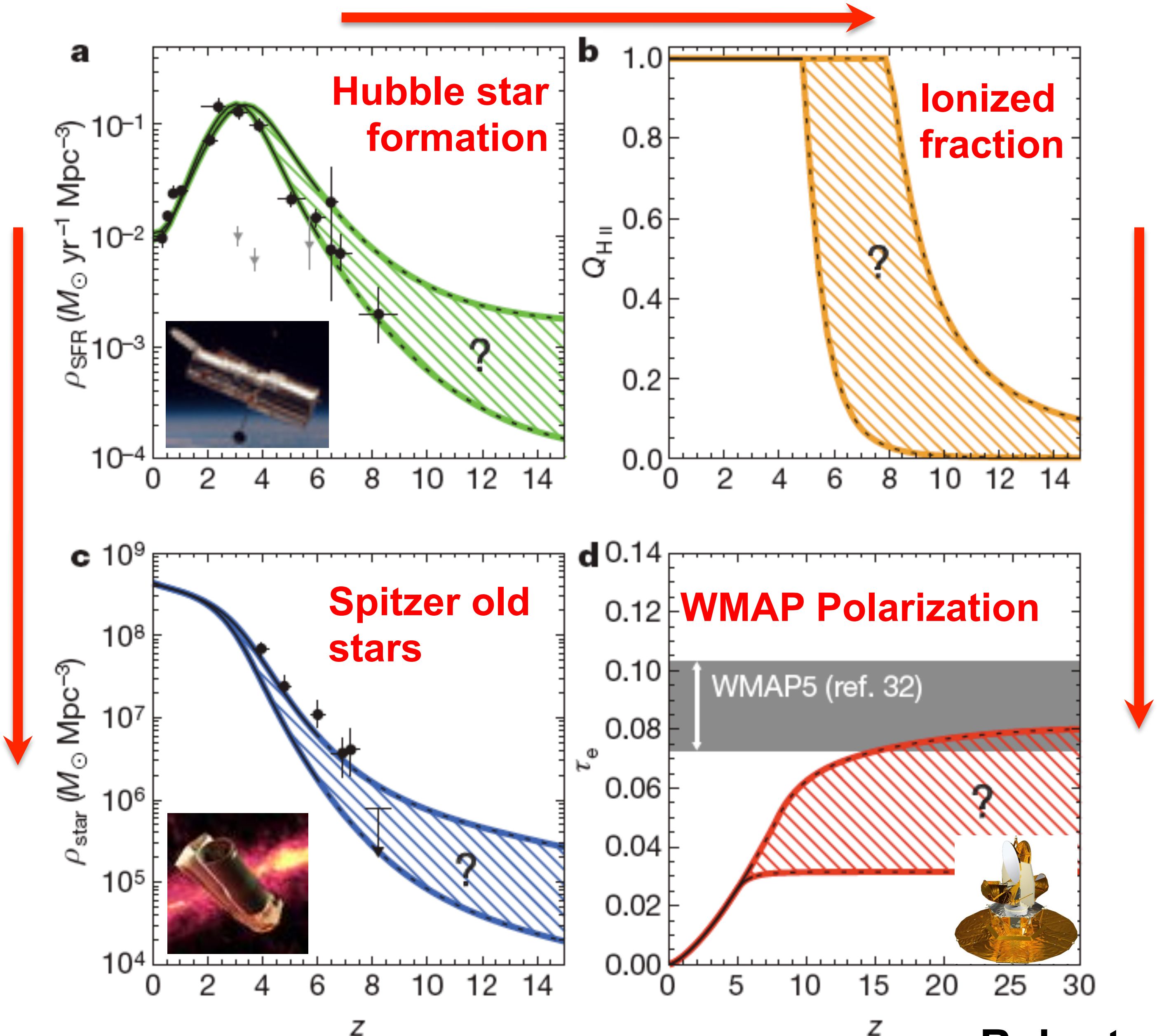


Cosmic Star Formation History



See smooth decline in number of galaxies out to z~12 (350 Myr)

Did Early Galaxies End the Dark Ages?



Robertson, Ellis et al

Where Next?

We have made great progress in last 2 years through combination of Hubble, Spitzer in space and Keck on the ground.

In next two years:

- new multi-object infrared spectrograph on Keck; verify `Lyα visibility' test to z~8 with greater significance

In next decade:

- Thirty Meter Telescope (TMT)
- James Webb Space Telescope (infrared space telescope)

All promises great progress in exploring this final frontier

Working at the frontier…

A warning from an independent commentator…

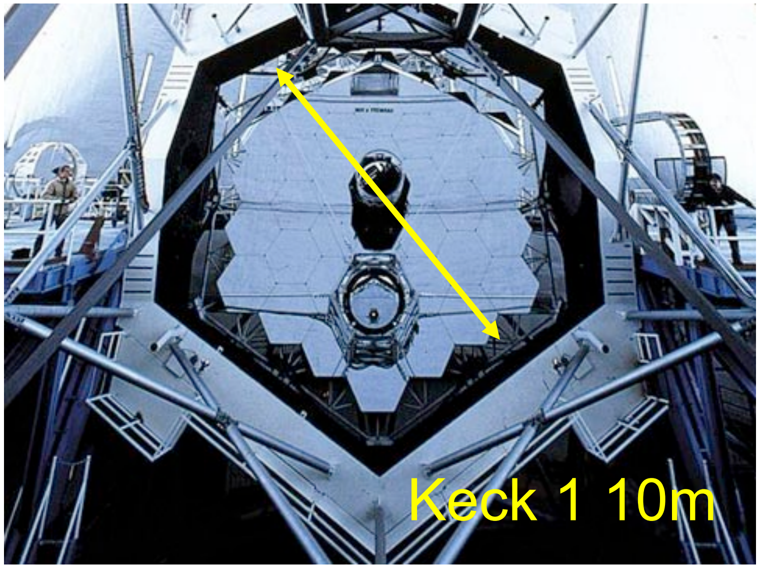
DAVE BARRY

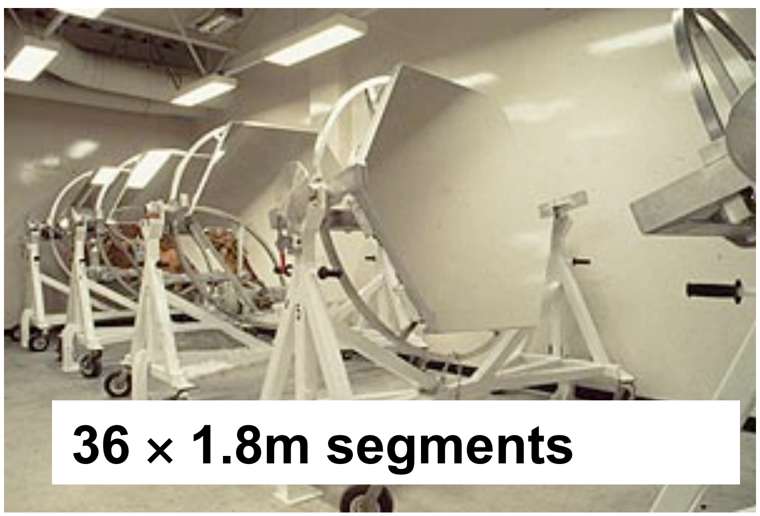
Over the years I have been harshly critical of the scientific community for wasting time researching things nobody cares about, such as the universe. I don't know about you, but I'm tired of reading newspaper stories like this:

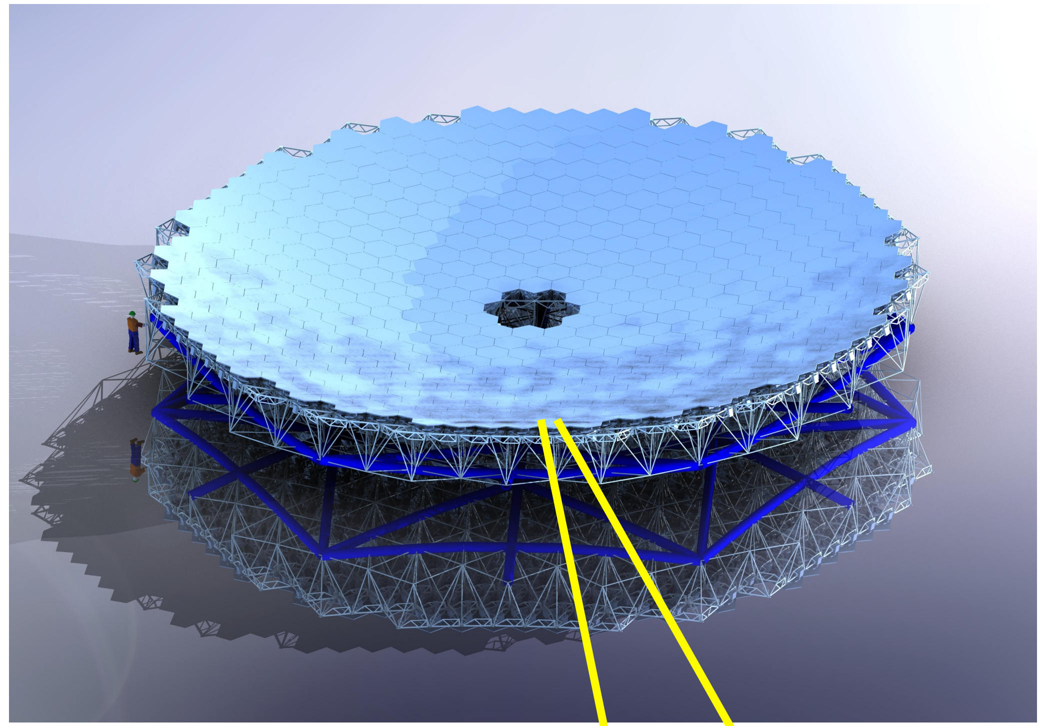
"Using a giant telescope, astronomers at the prestigious Crudwinkle Observatory have observed a teensy light smudge that they say is a humongous galaxy cluster 17 jillion light years away, which would make it the farthest-away thing that astronomers have discovered this week. However, astronomers at the rival Fendleman Observatory charged that what the Crudwinkle scientists discovered is actually mayonnaise on the lens. Both groups of astronomers say they plan to use these new findings to obtain even larger telescopes."


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

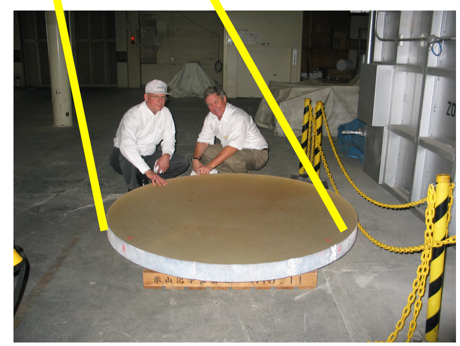
Segmented Mirrors – Keck Shows the Way



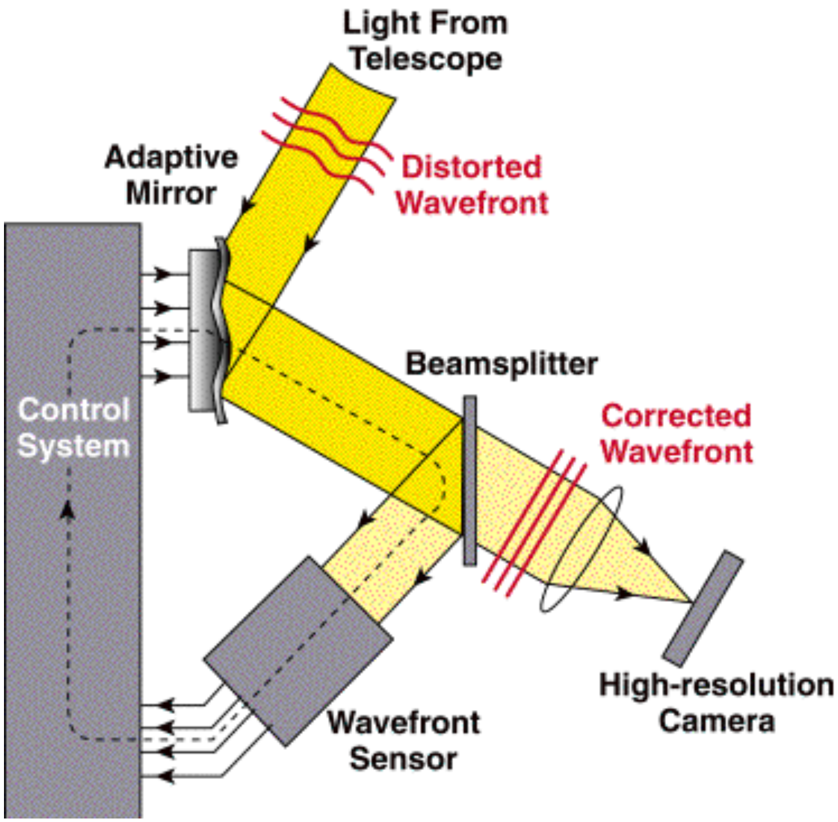


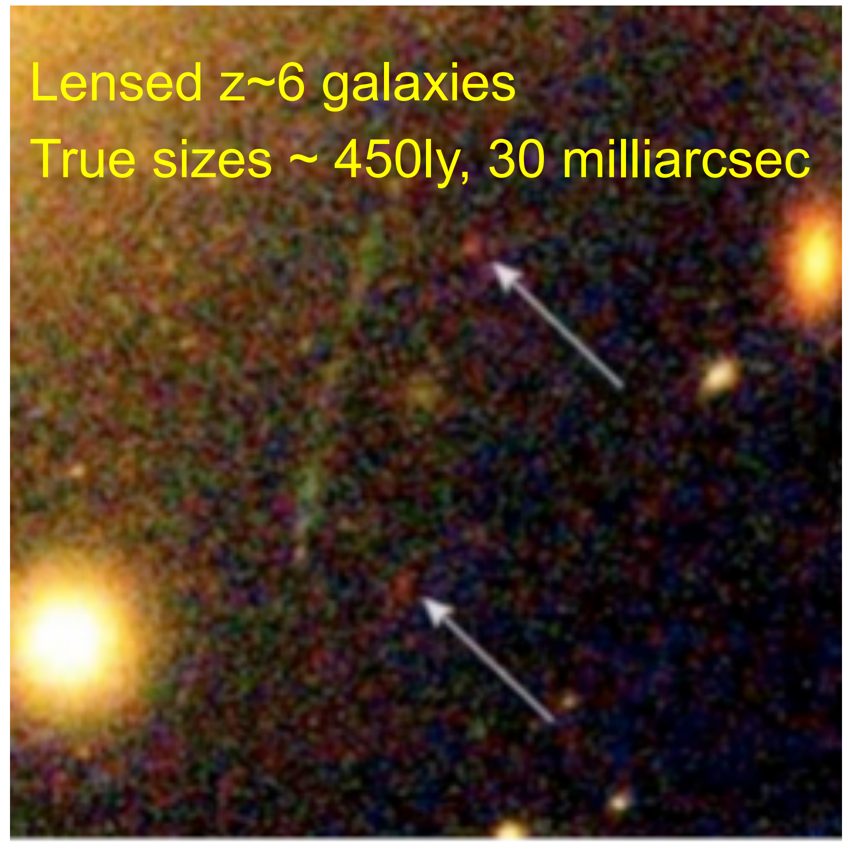


TMT: 492 × 1.4m segments



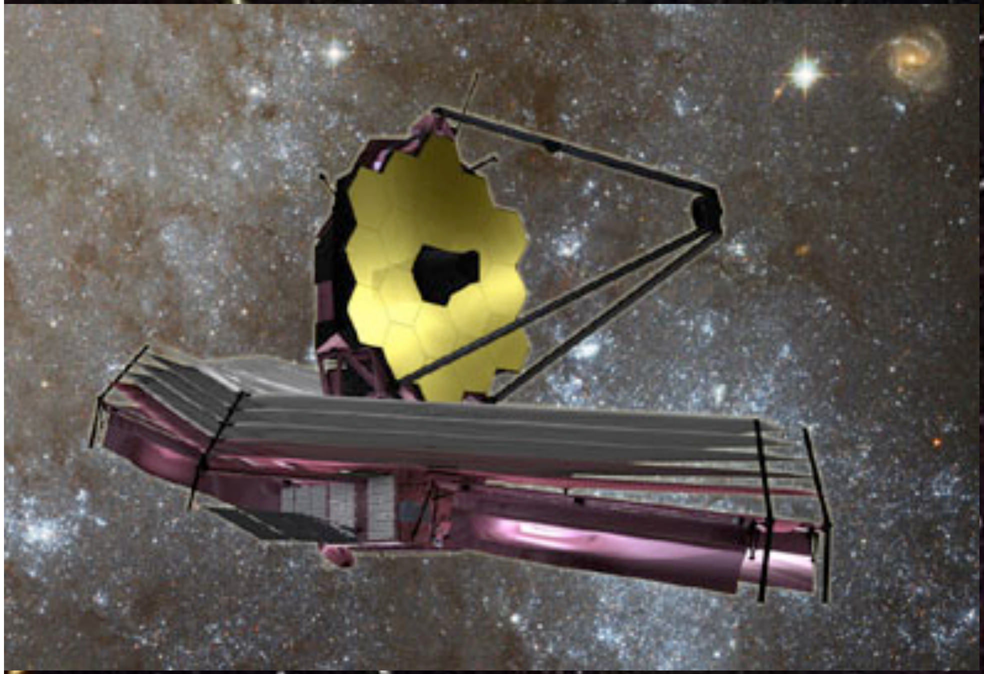
The Importance of Adaptive Optics

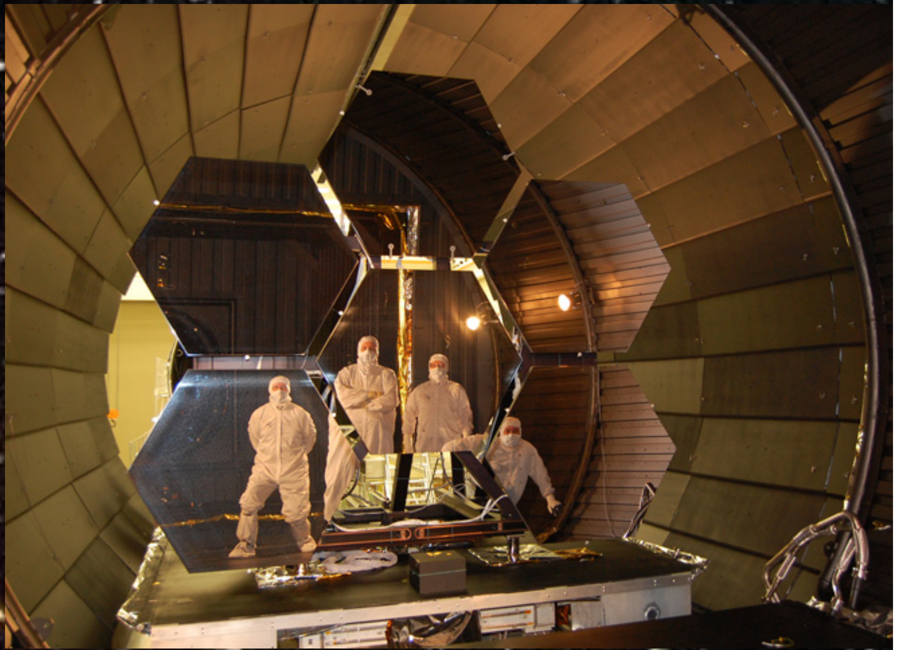




Adaptive optics will enable TMT to outperform James Webb in image quality
An unique advantage in searching for physically-small distant galaxies

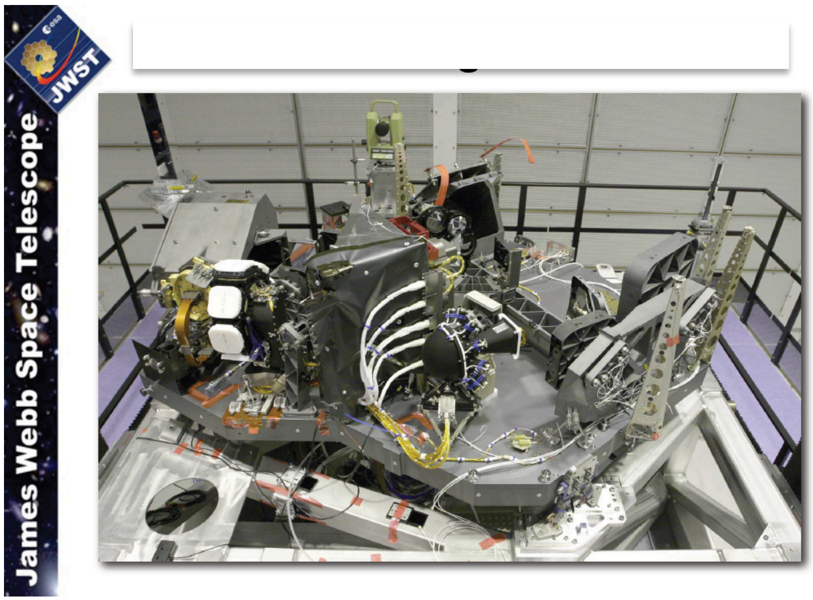
James Webb Space Telescope



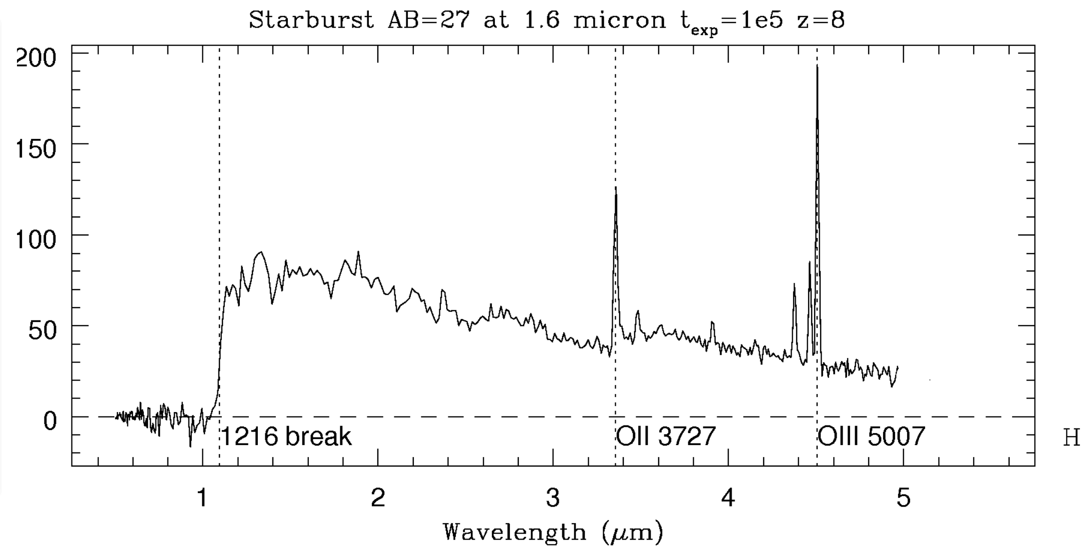


Mid-infrared Spectroscopy with James Webb

NIRSpec Instrument



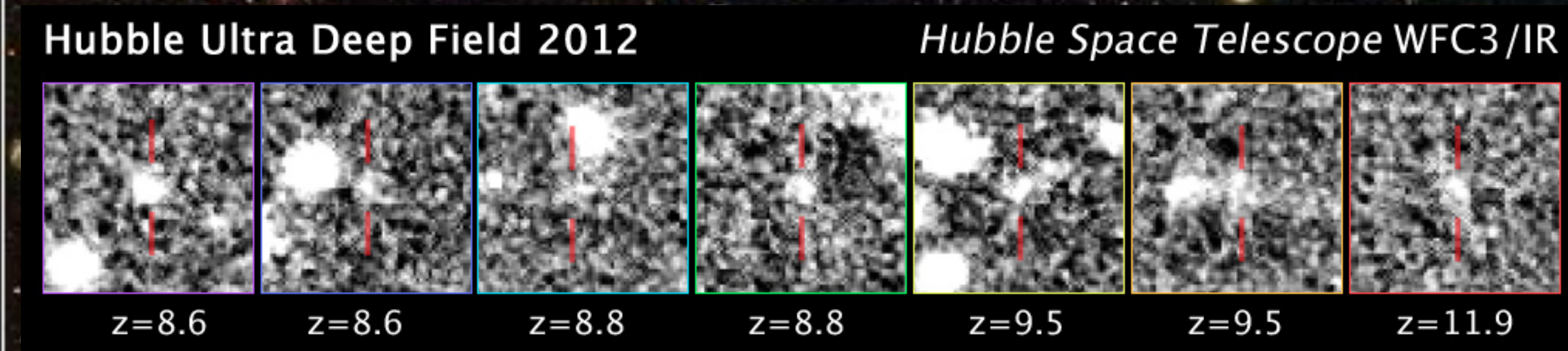
z=8 galaxy; 25 hour exposure



JWST provides access beyond 2 microns enabling us to detect starlight and measure composition of gas in redshift 8-20 galaxies.

Ultimate test for first generation systems – no heavy elements!

Fin



Happy Birthday Steve!