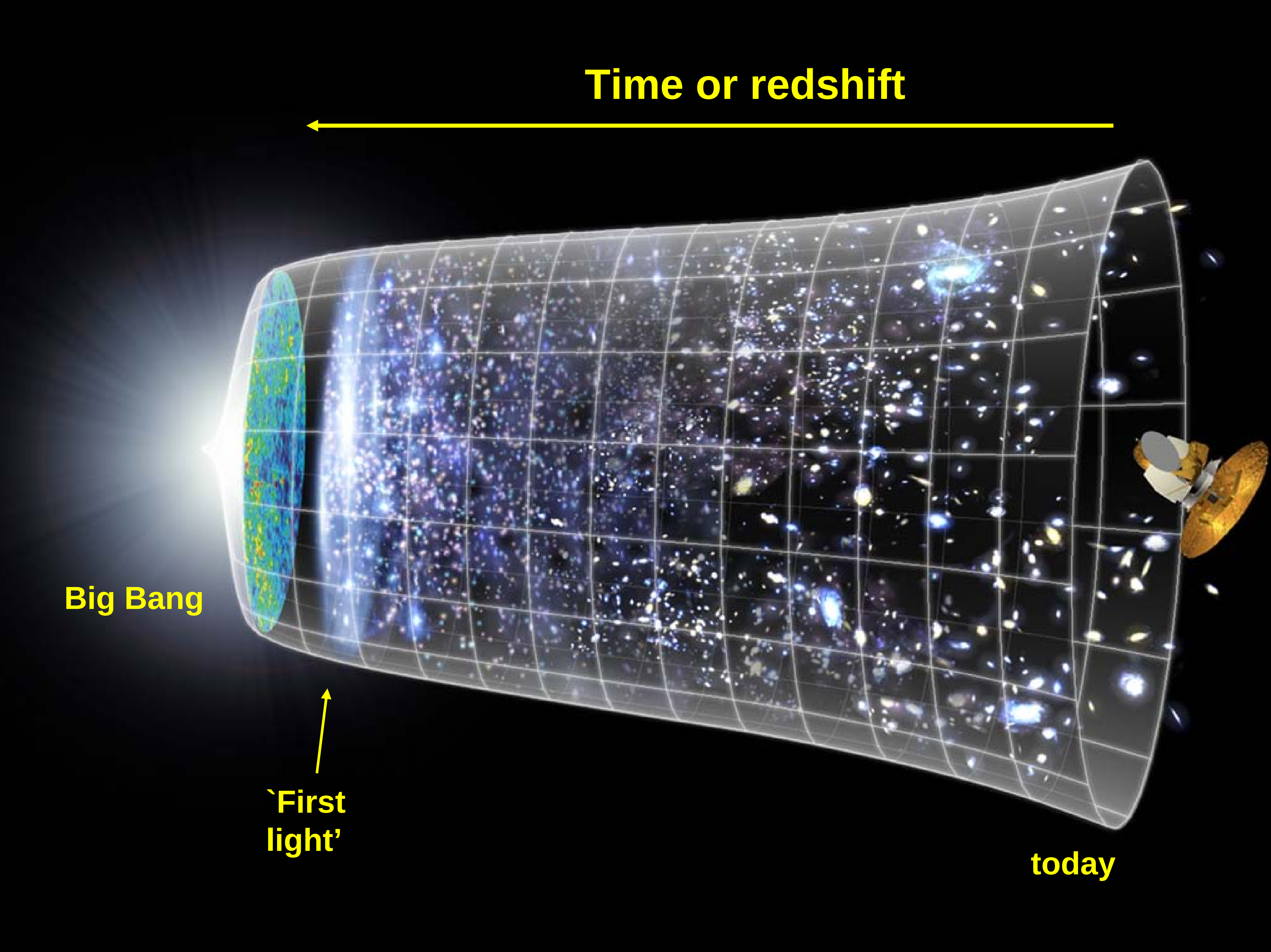
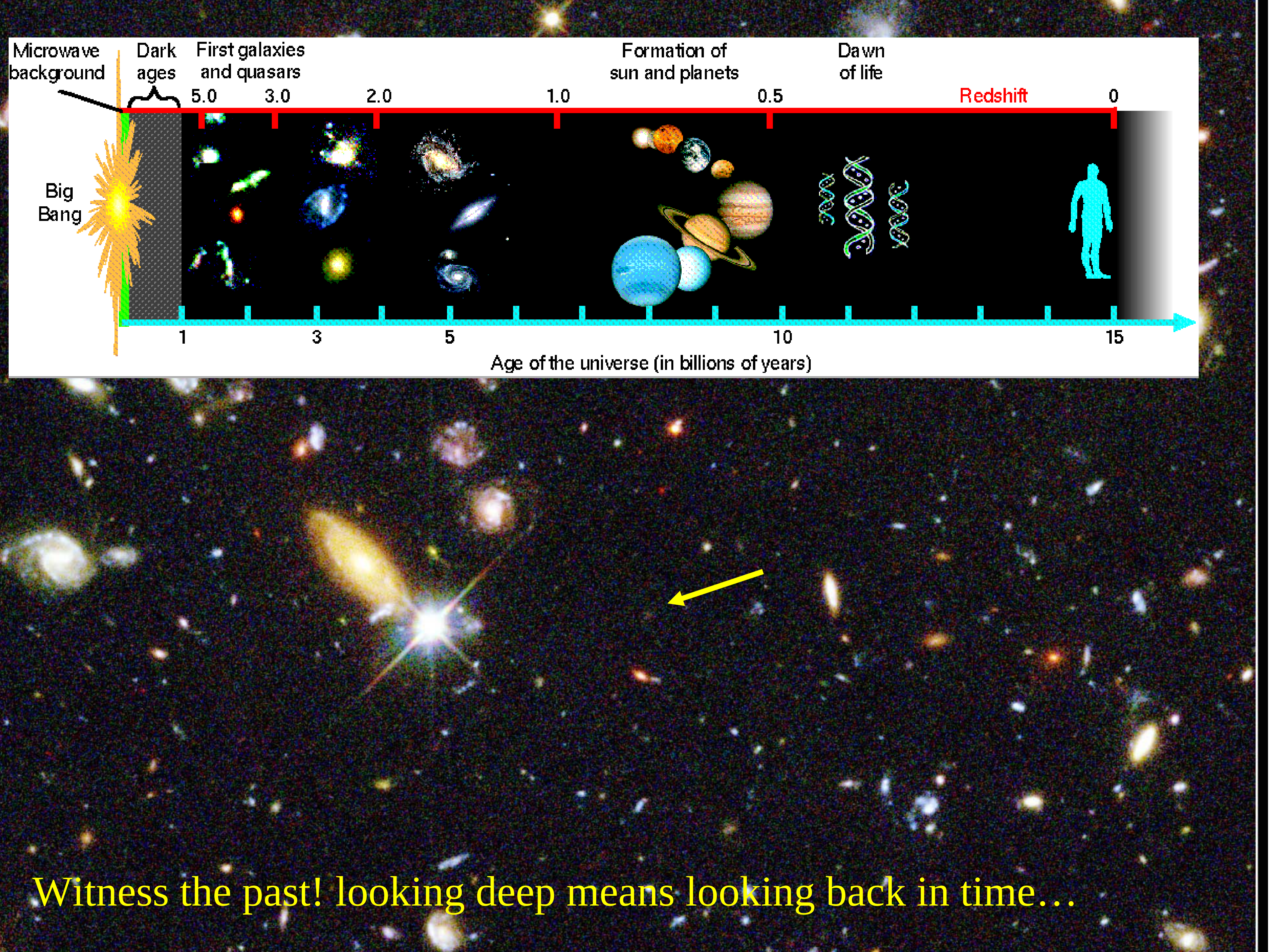
Cosmic Dawn
Pursuit of the First Galaxies

Richard Ellis (Caltech)

Keck Advancement Lecture

January 16th 2008

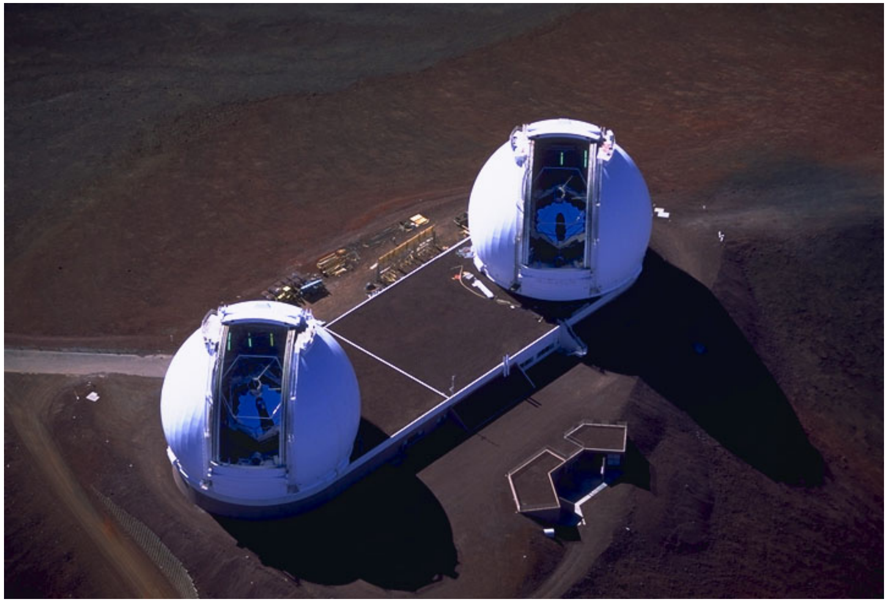

Time or redshift
Big Bang
`First light'
today

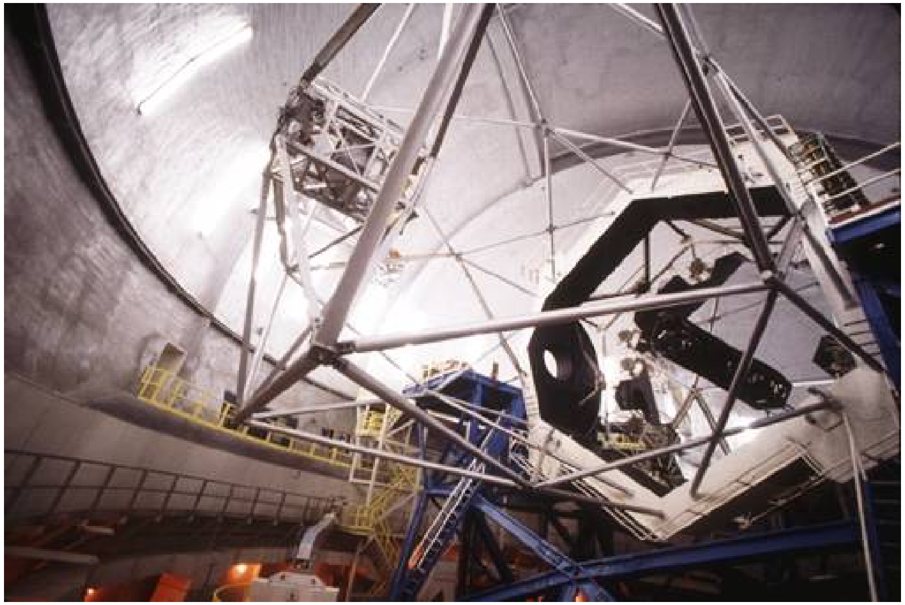


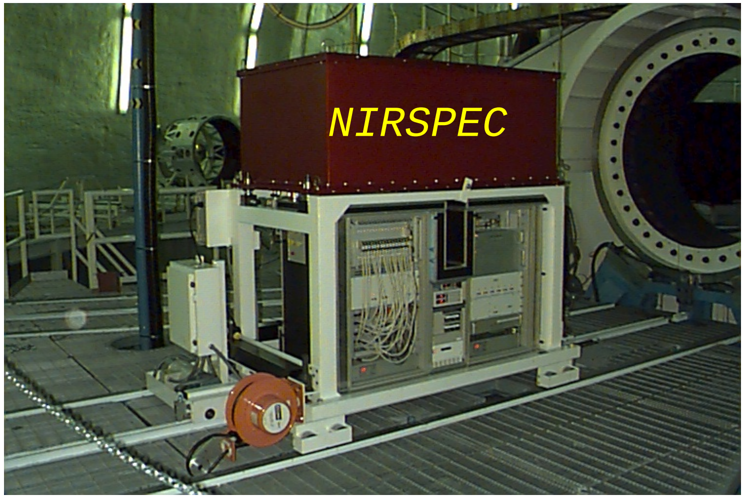
Witness the past! looking deep means looking back in time…

An Observational Adventure Starring..

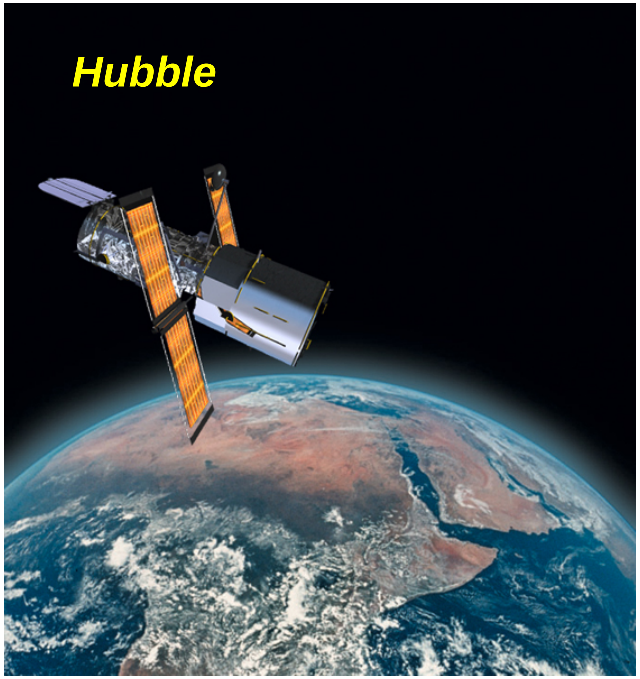
- the two Keck 10-meter reflectors & their spectrographs

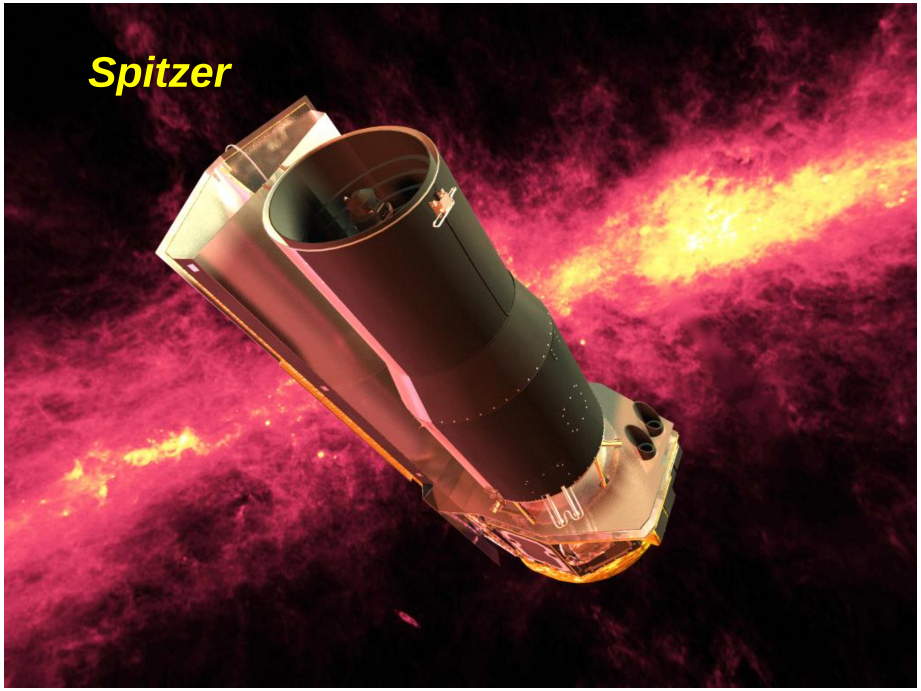






… and three unique space telescopes

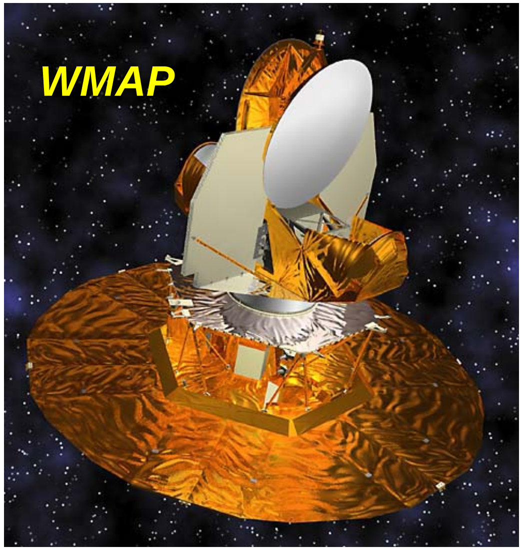




Hubble: exquisite deep imaging

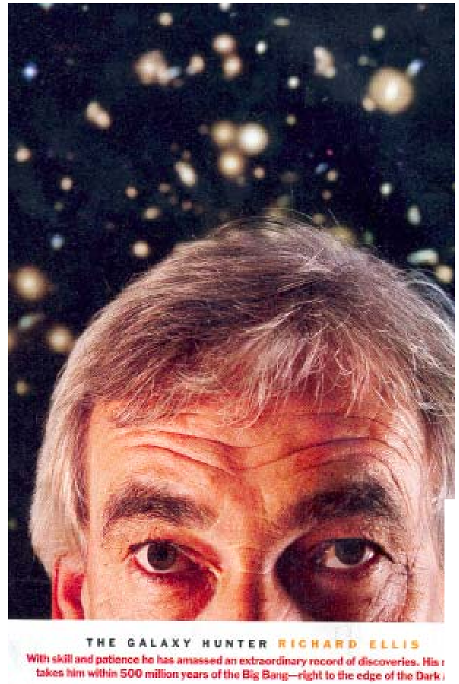
Spitzer: sensitive to older stars

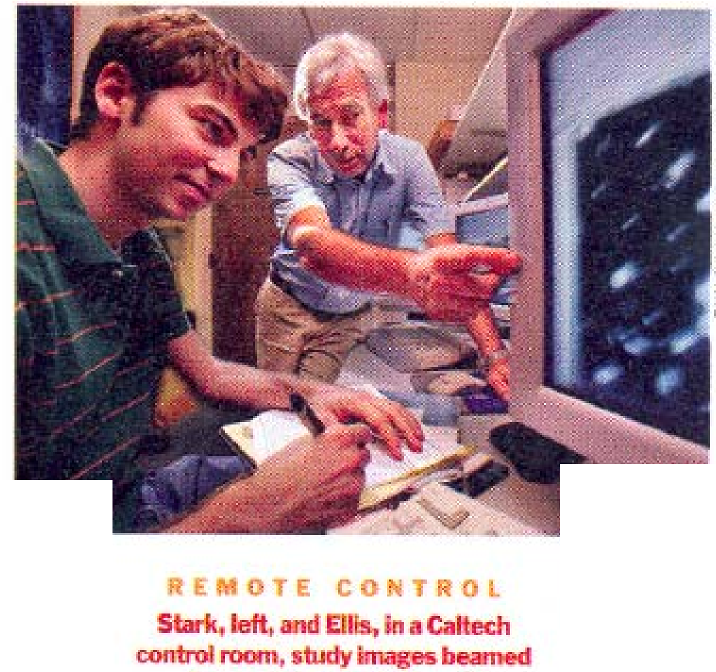
WMAP: studies of microwave background radiation and its scattering by foreground material



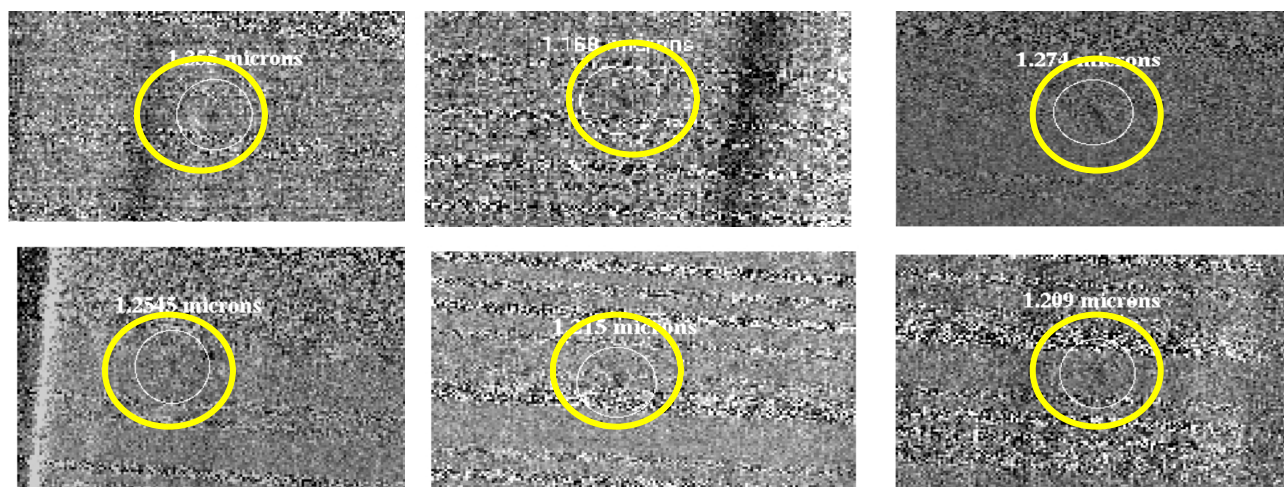
Finding the Earliest Sources

Sep 4 2006





8.6 < z < 10.2



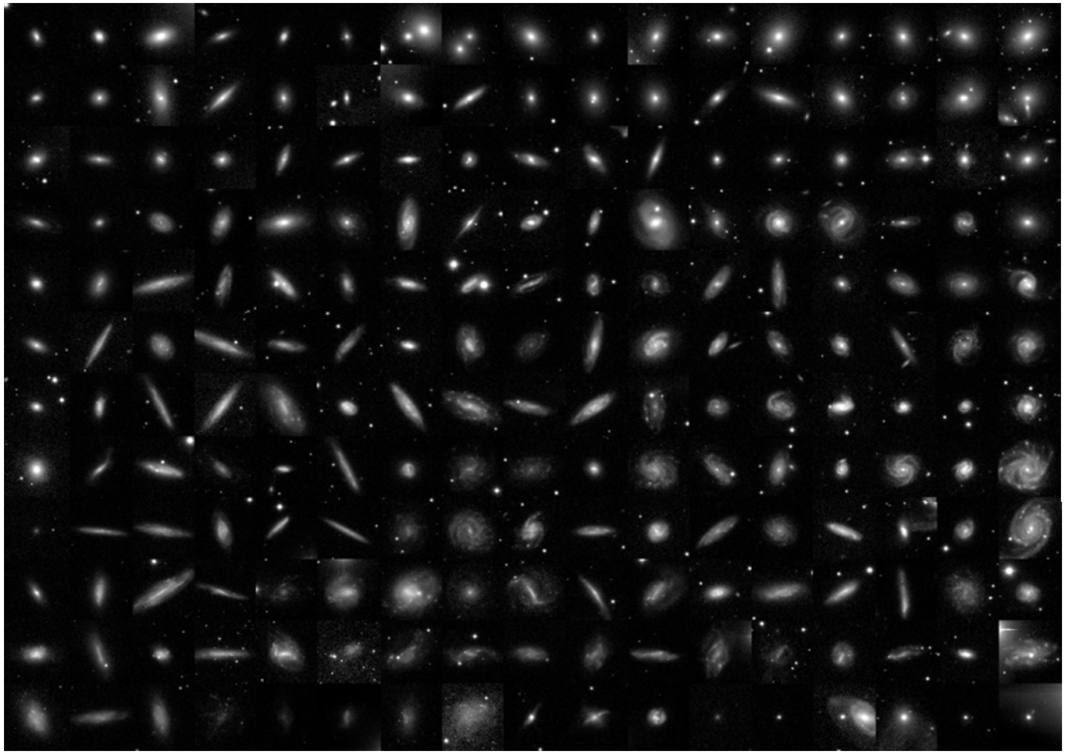
Sources seen when the Universe was 4% of present age

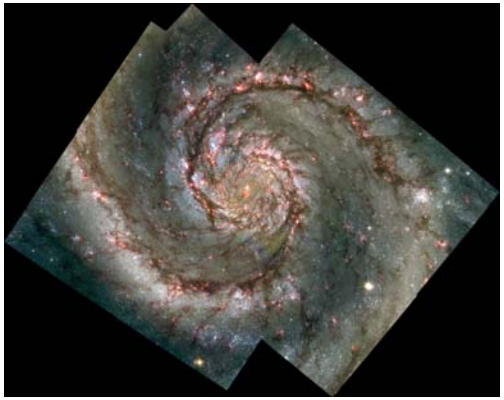
Tracing the History of Starlight

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.

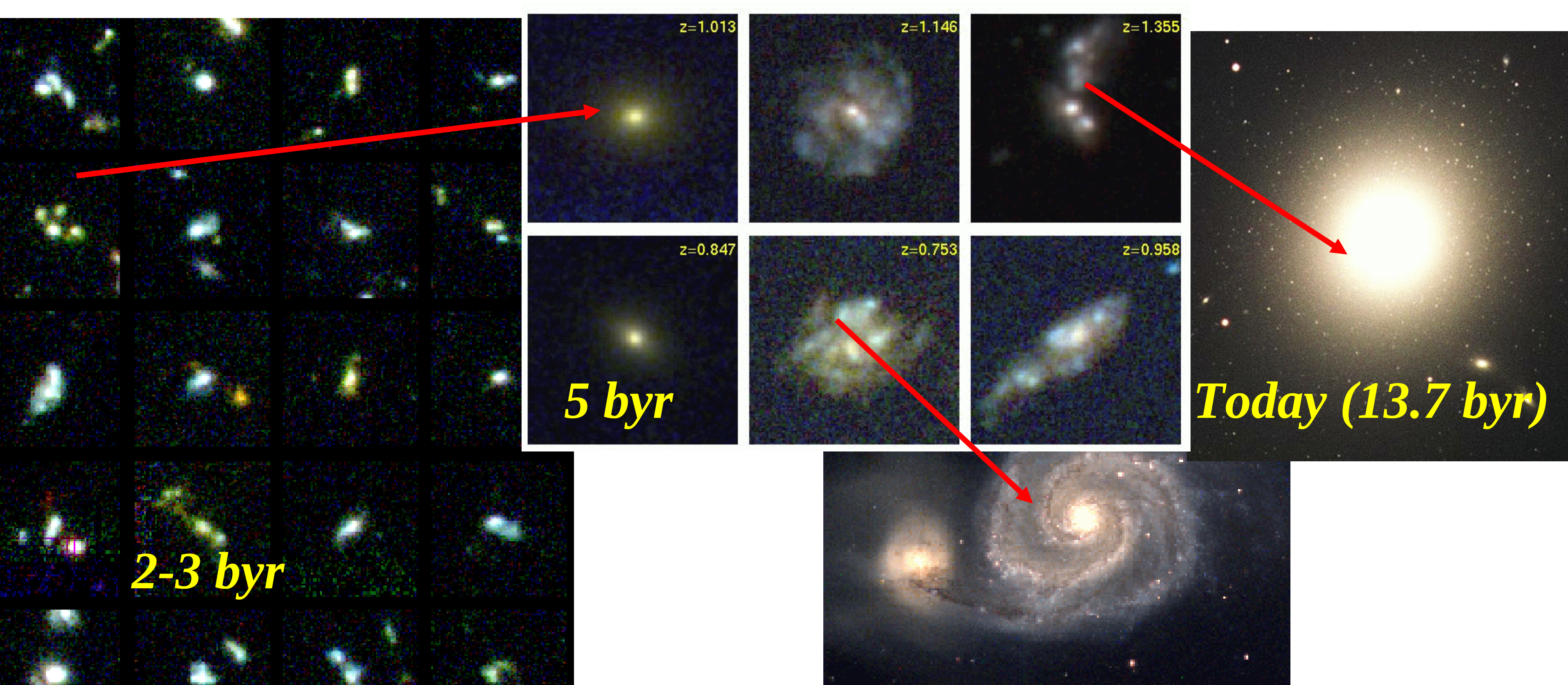
To trace the history of starlight we must trace the history of galaxies





Unraveling Cosmic History

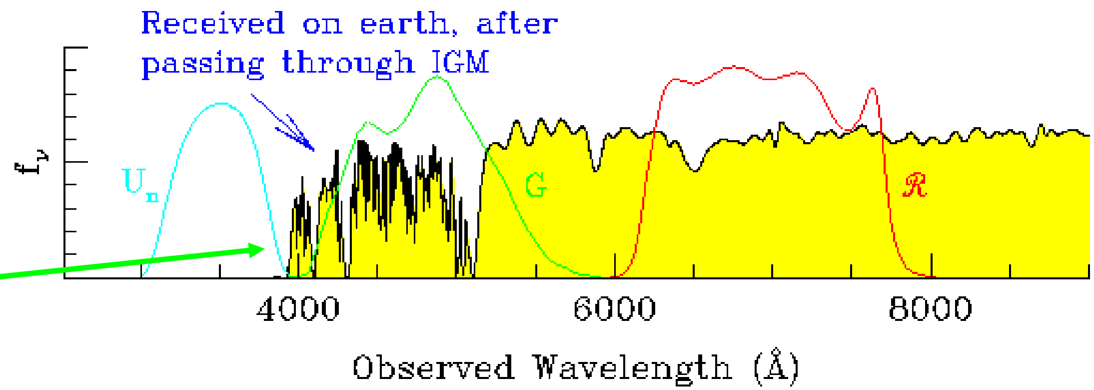
Keck and Palomar, aided by remarkable Hubble Space Telescope images have enabled us to explore the history of the rich variety of present-day galaxies. We have pieced together the story of galaxy formation and evolution back to 2 billion years after the Big Bang (85% of cosmic history)



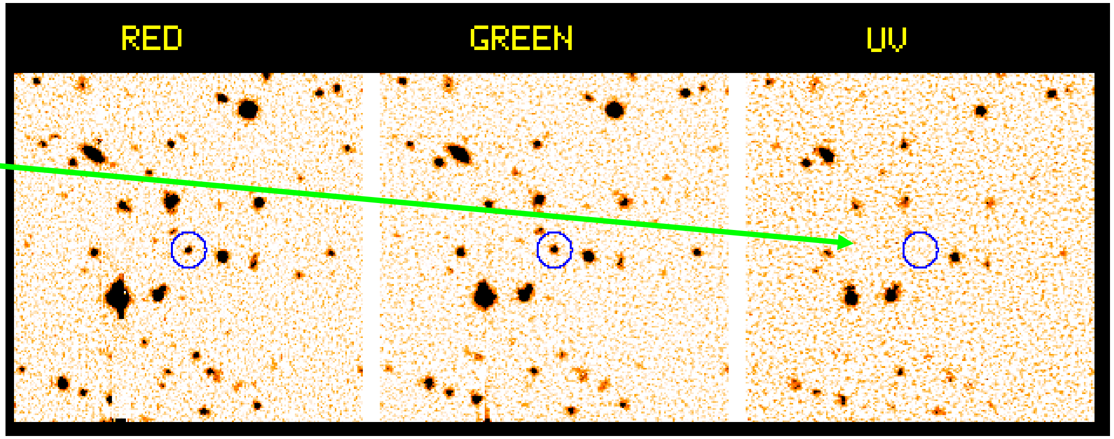
Finding Distant Galaxies using `Dropouts'

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:



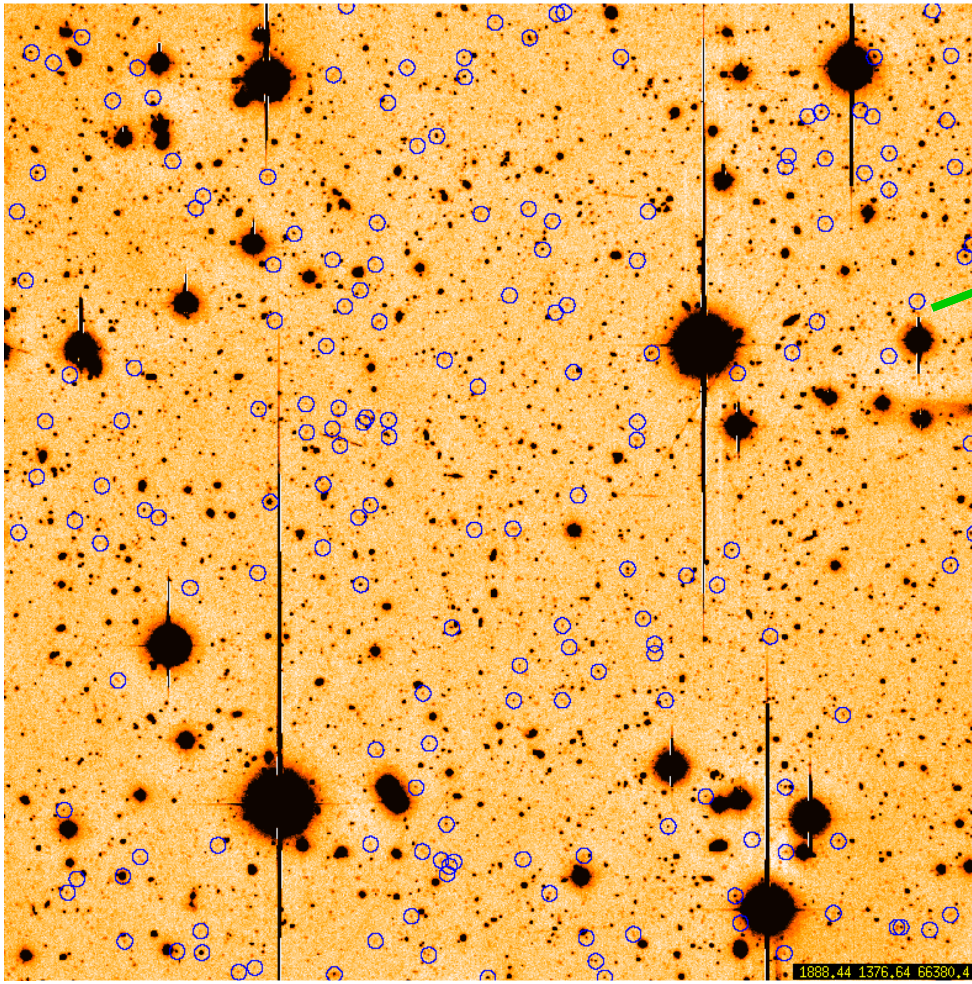
• Palomar does the searching

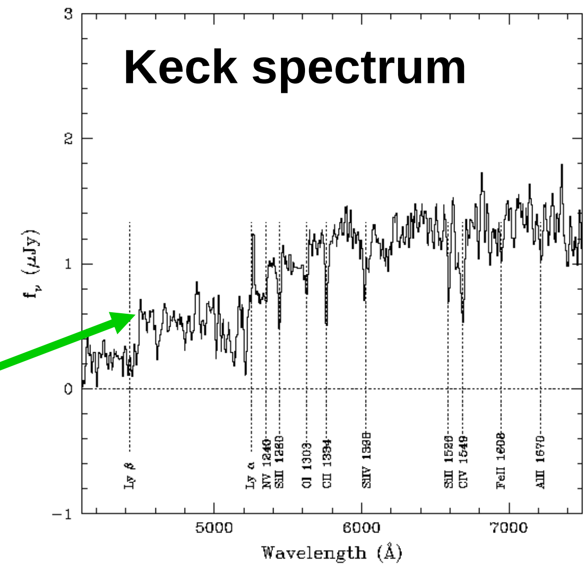
• Keck verifies the distance via a spectrum

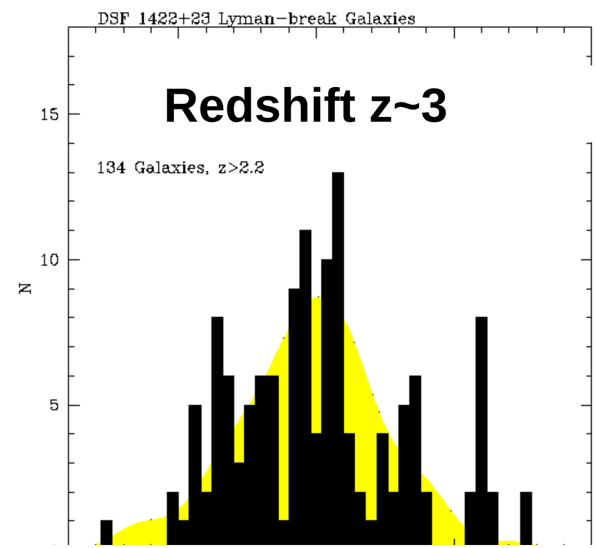
C. Steidel and co-workers at Caltech have found hundreds of distant galaxies successfully via this remarkable technique

Spectroscopic Confirmation at Keck

Deep Palomar image



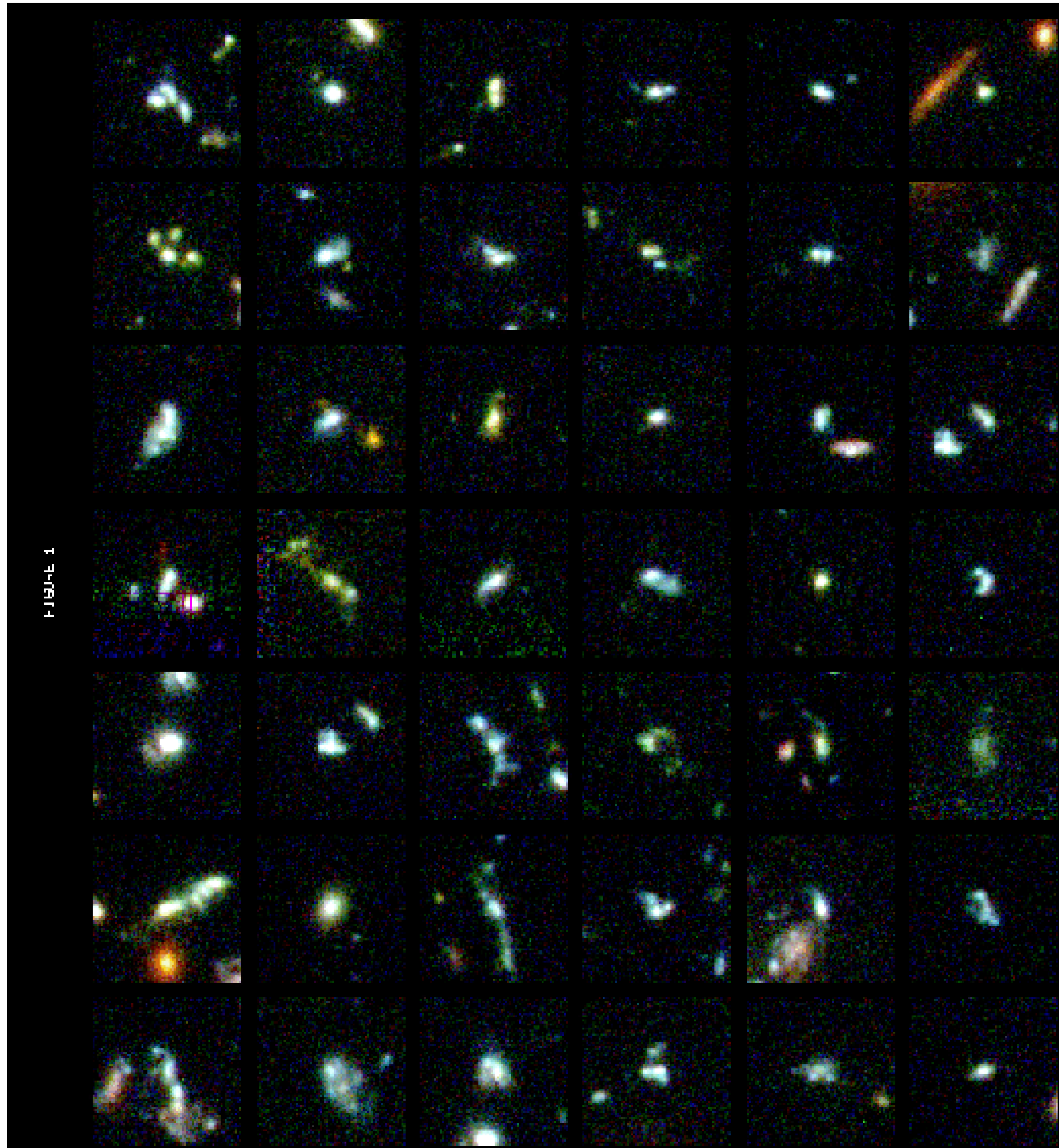


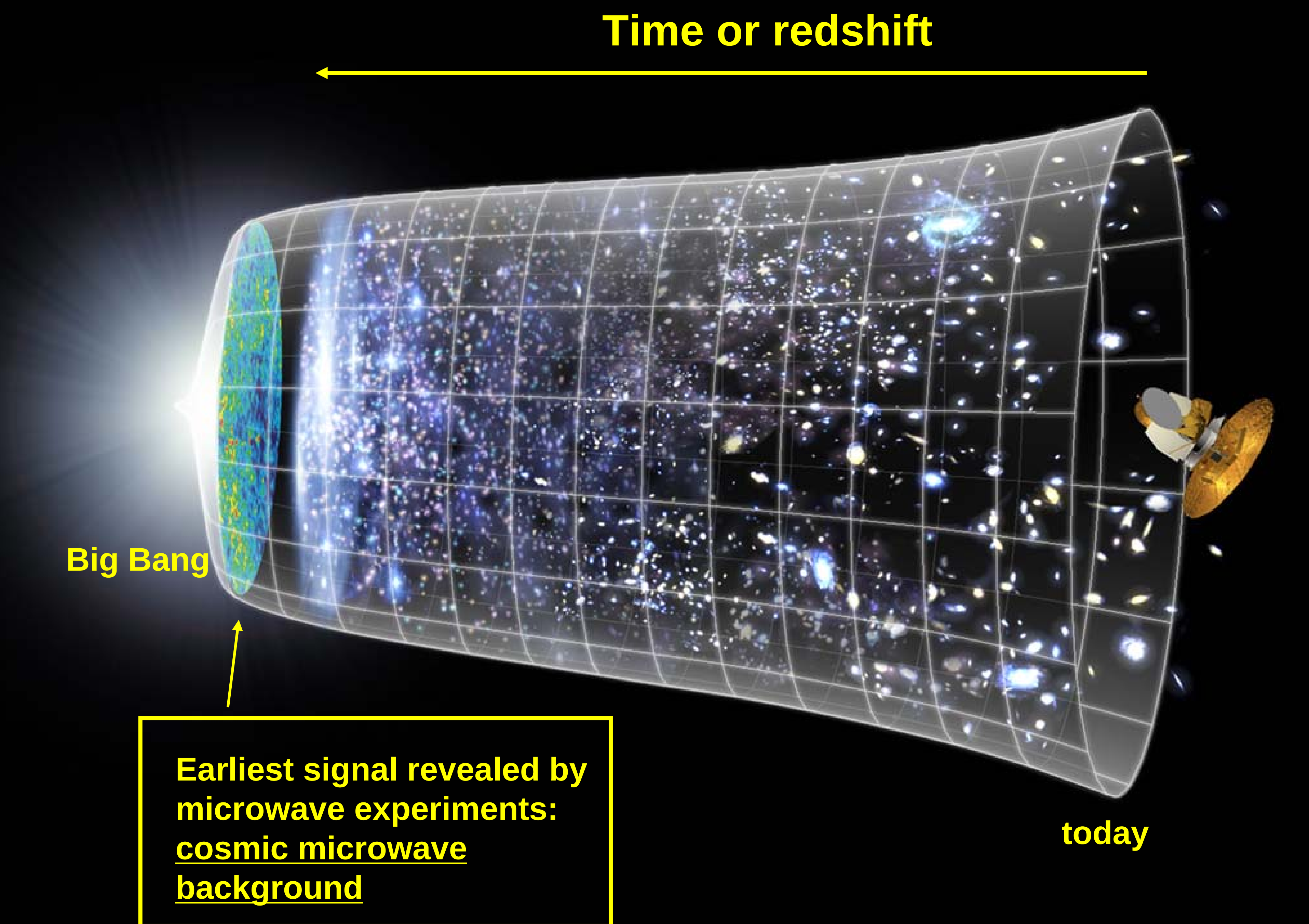


NB: The technique selects only <u>star-forming systems</u> whose strong ultraviolet signal is redshifted into the optical region

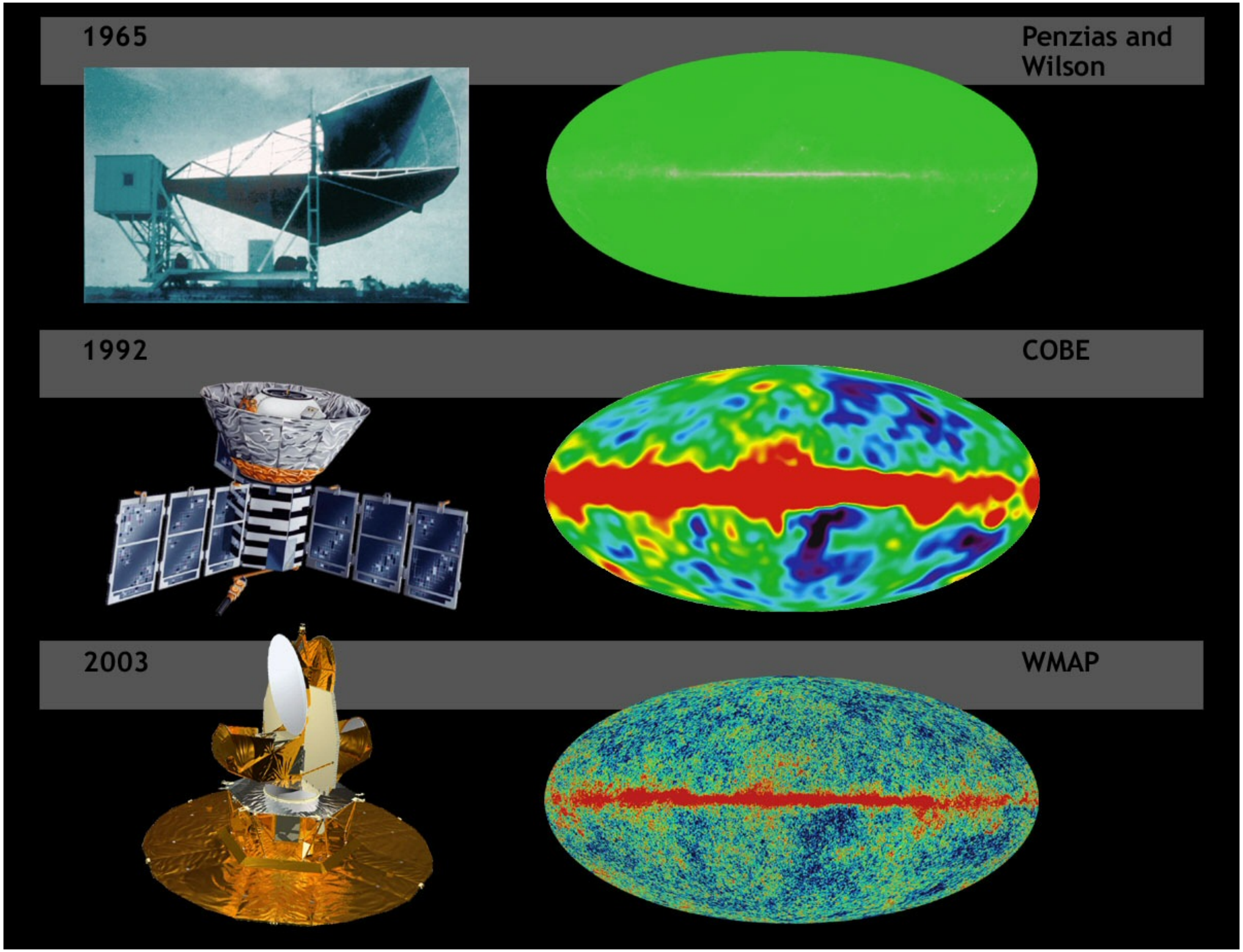
What do these early galaxies look like?

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>



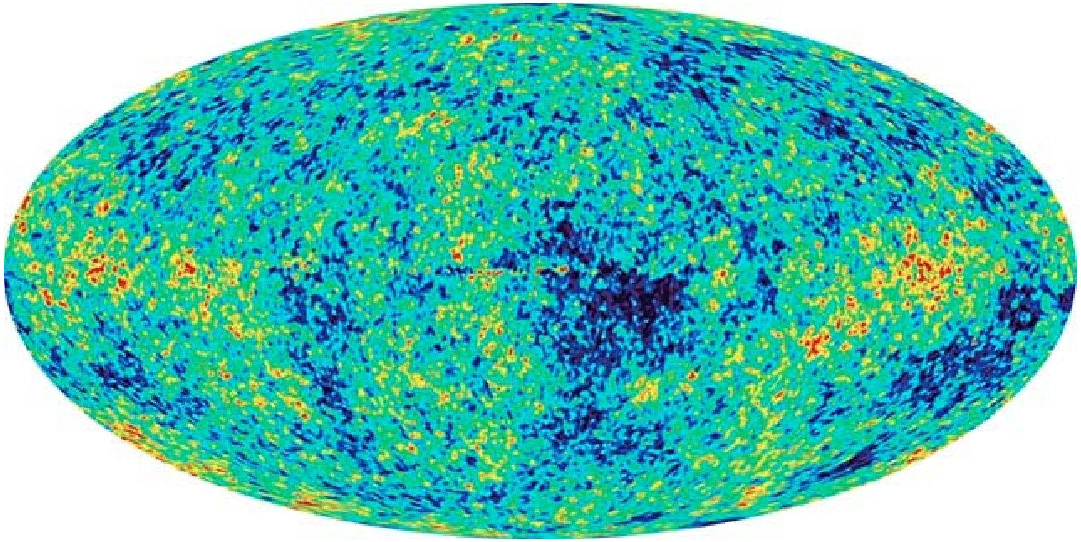

Time or redshift
Big Bang
Earliest signal revealed by microwave experiments: cosmic microwave background
today

Progress in Microwave Background Studies



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

What happened next?



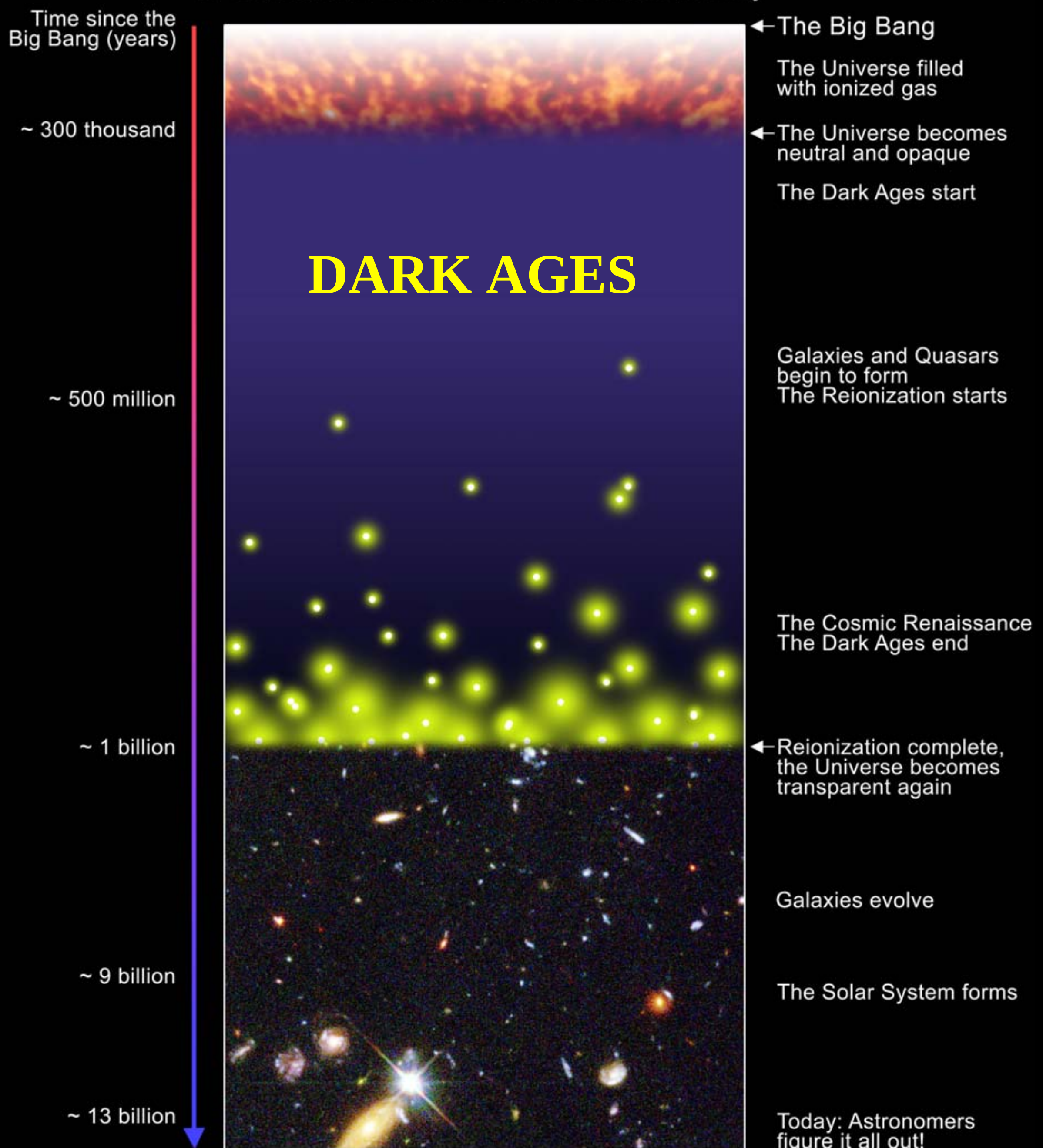
Microwave background radiation is seen 372,000 yrs after creation representing the time when hydrogen atoms form for the first time

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'**)

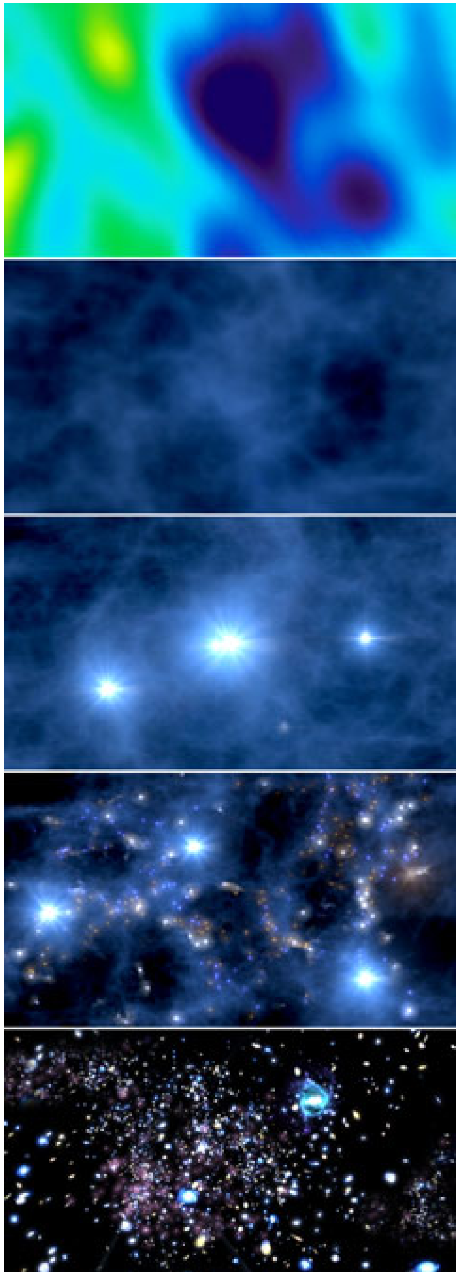
What is the Reionization Era?

A Schematic Outline of the Cosmic History



End of the Dark Ages:

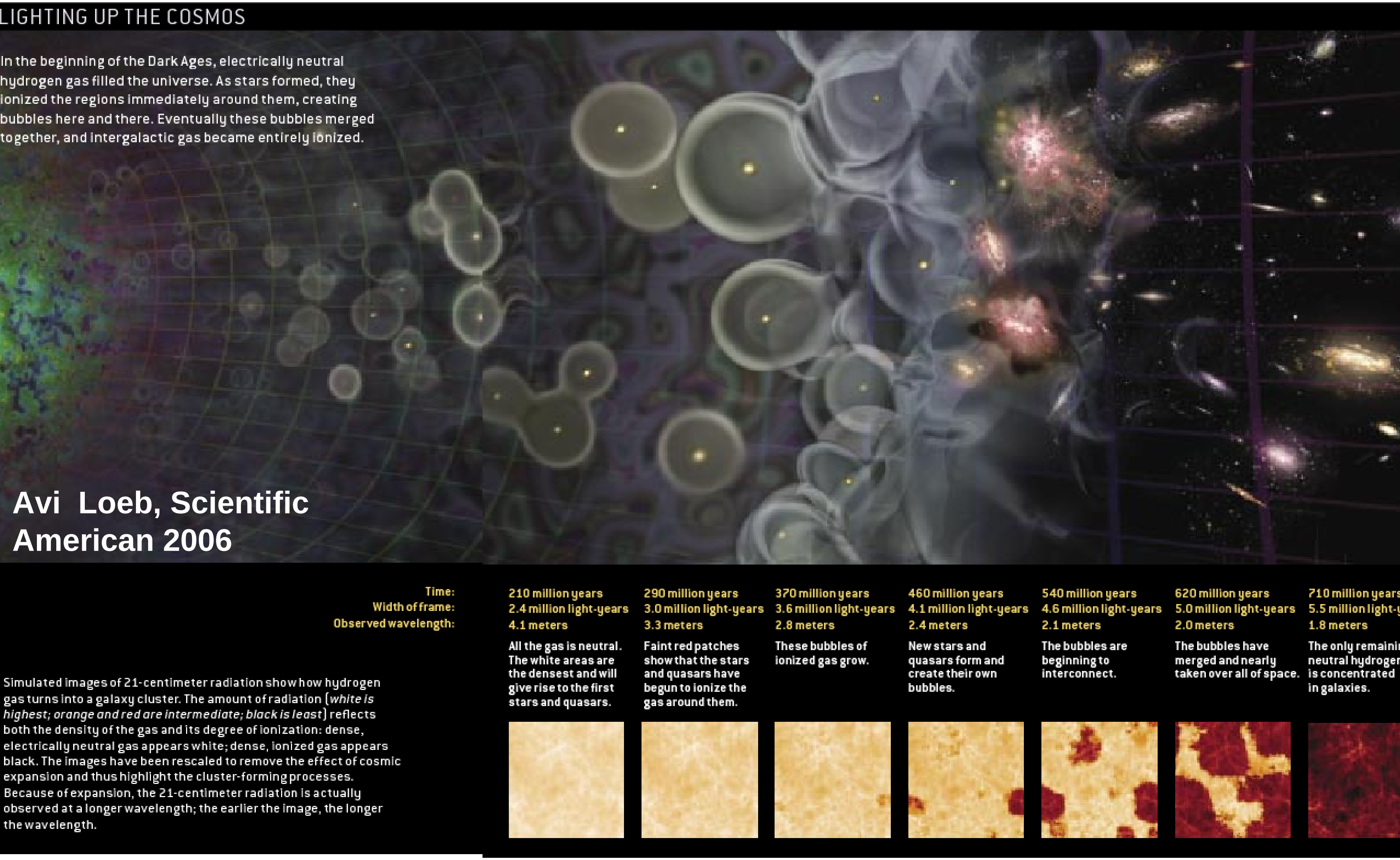
Reionization of Hydrogen by First Star-forming Galaxies



QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

time

Theorists' View of Cosmic Reionization

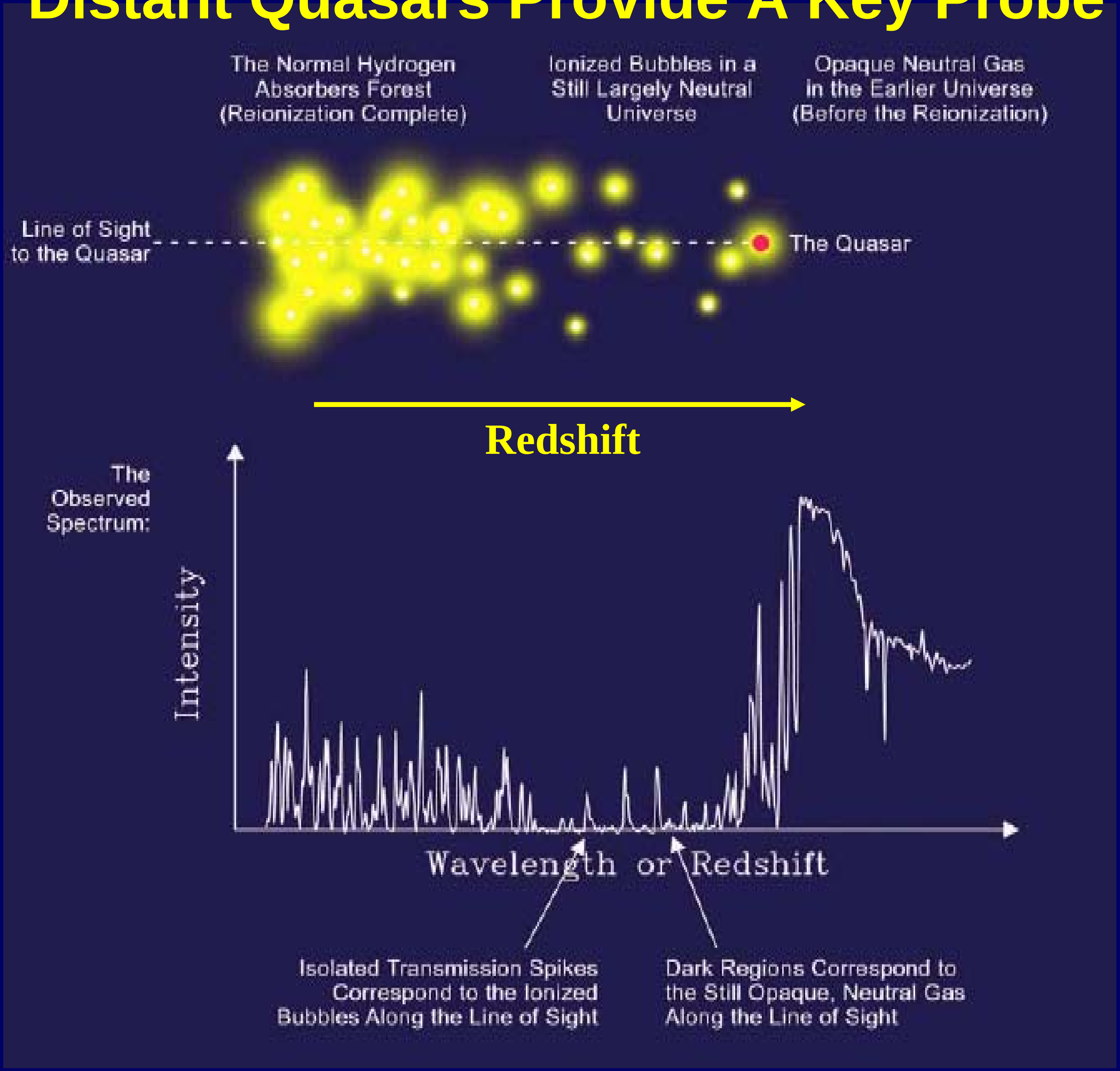


Avi Loeb, Scientific American 2006

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

Distant Quasars Provide A Key Probe

Observer

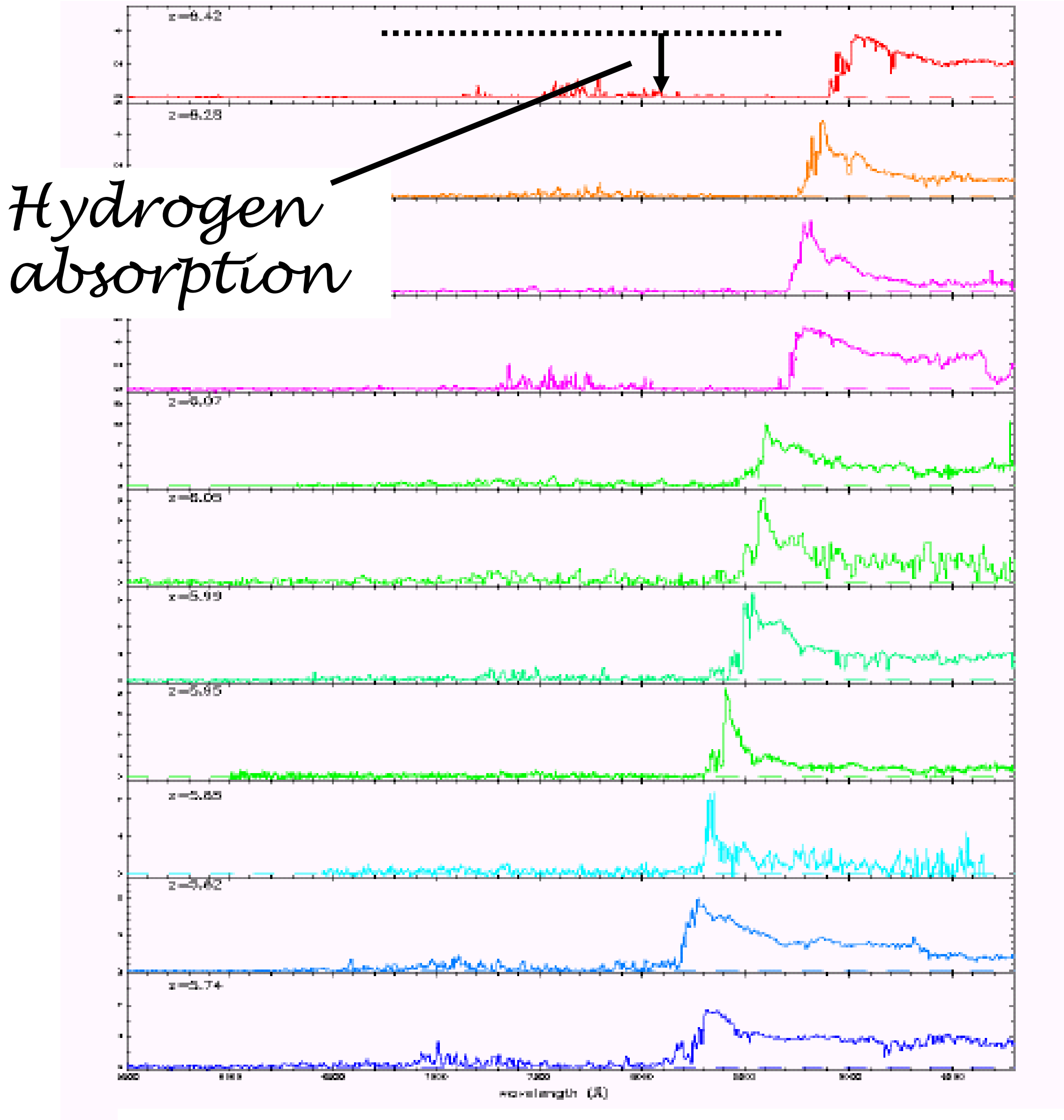


Keck ESI Spectra of the Most Distant Quasars

Quasars are intense beacons lighting up intervening clouds of hydrogen gas.

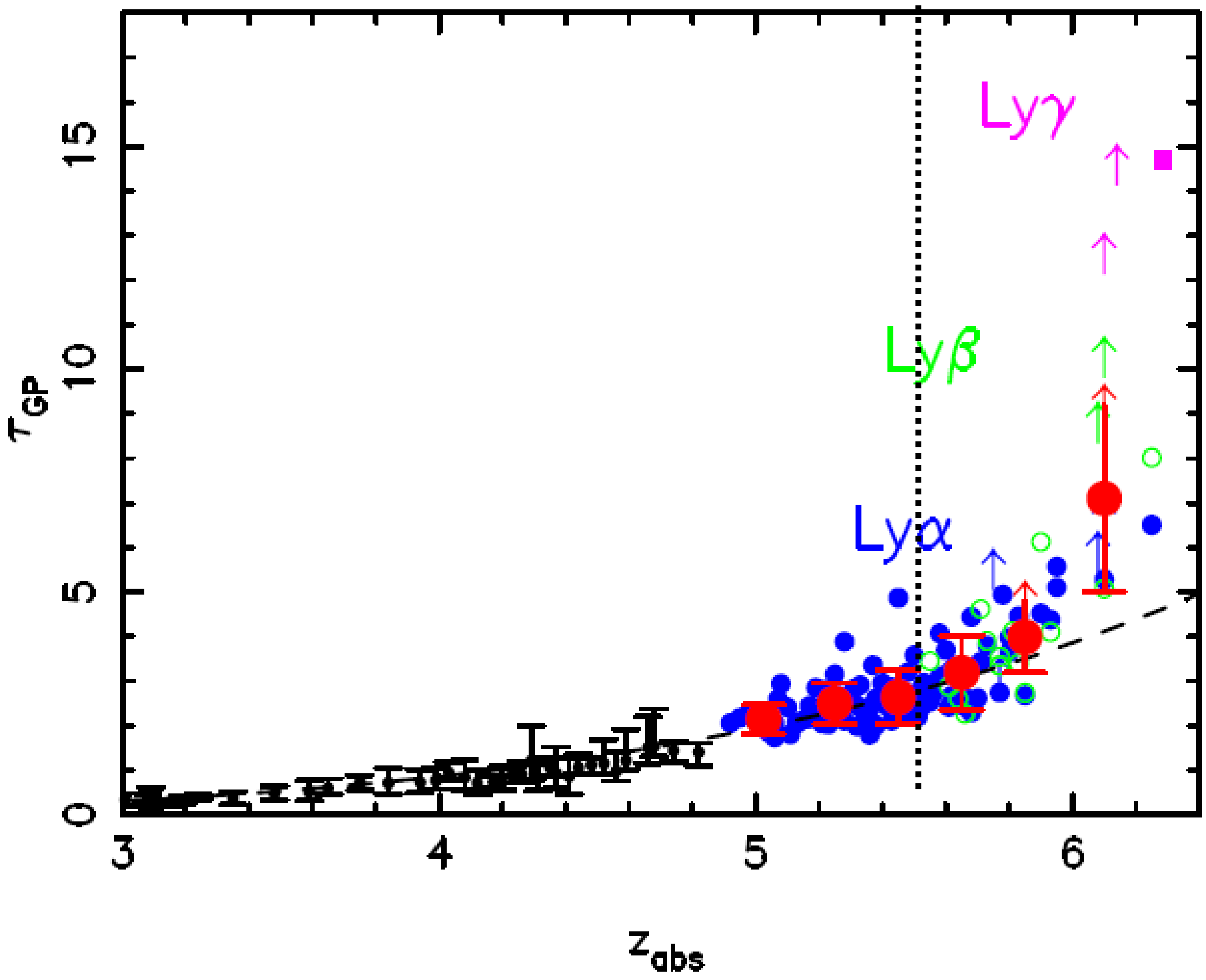
As we approach the end of reionization we would expect an abrupt change in the amount of hydrogen absorption

Is it seen?



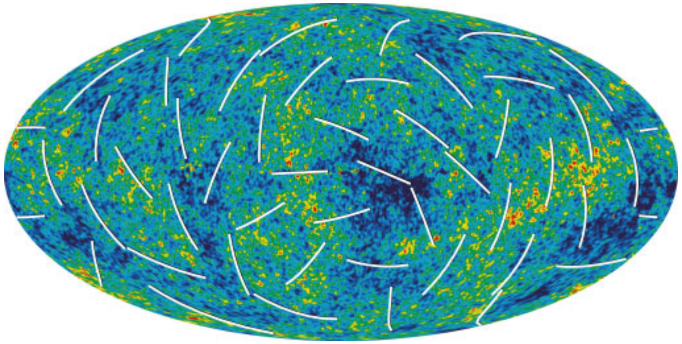
X. Fan (U. Arizona)

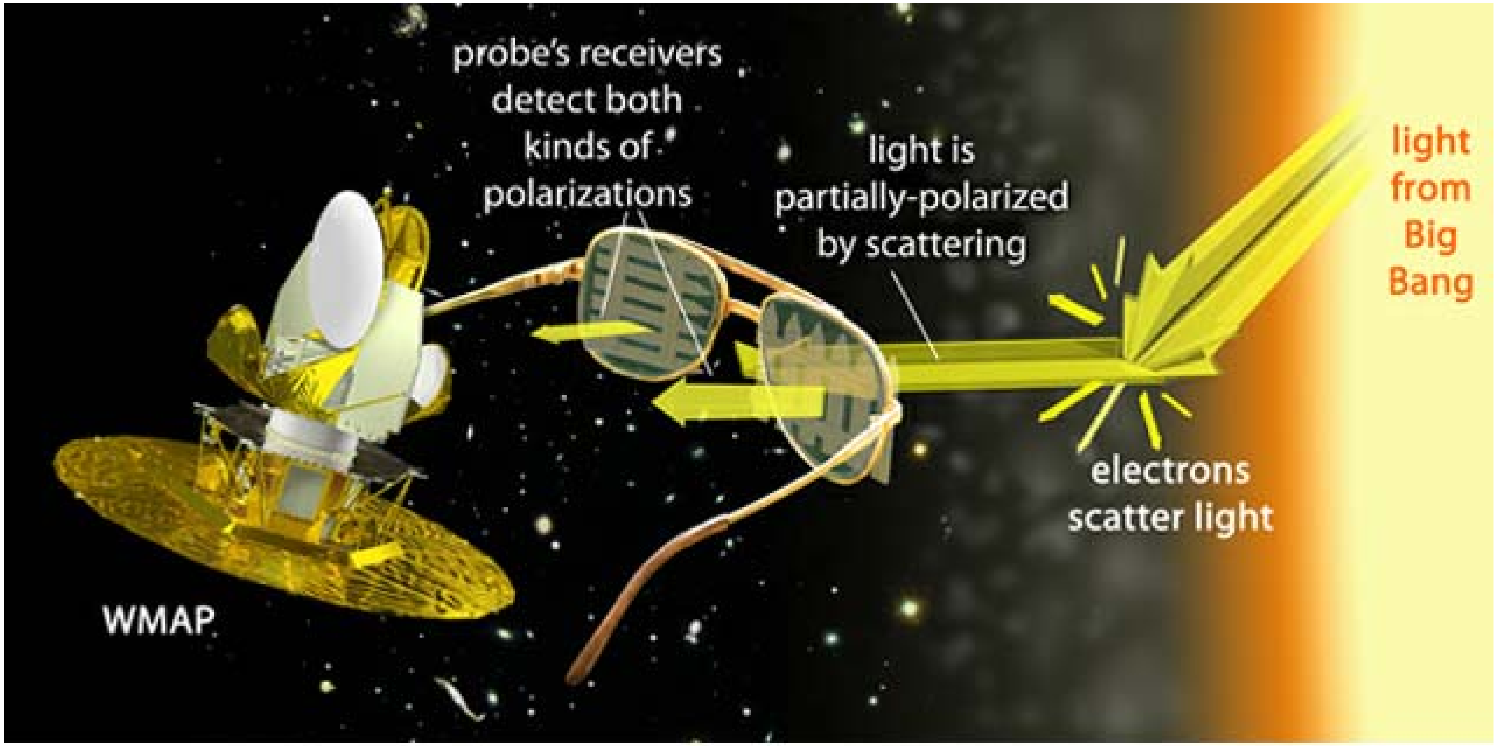
Depth of Hydrogen Absorption in Quasar Spectra



Beyond redshift 5.5, there is a tantalizing upturn in the amount of hydrogen absorption - we may be approaching the end of the dark ages!

Polarization in WMAP Data





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

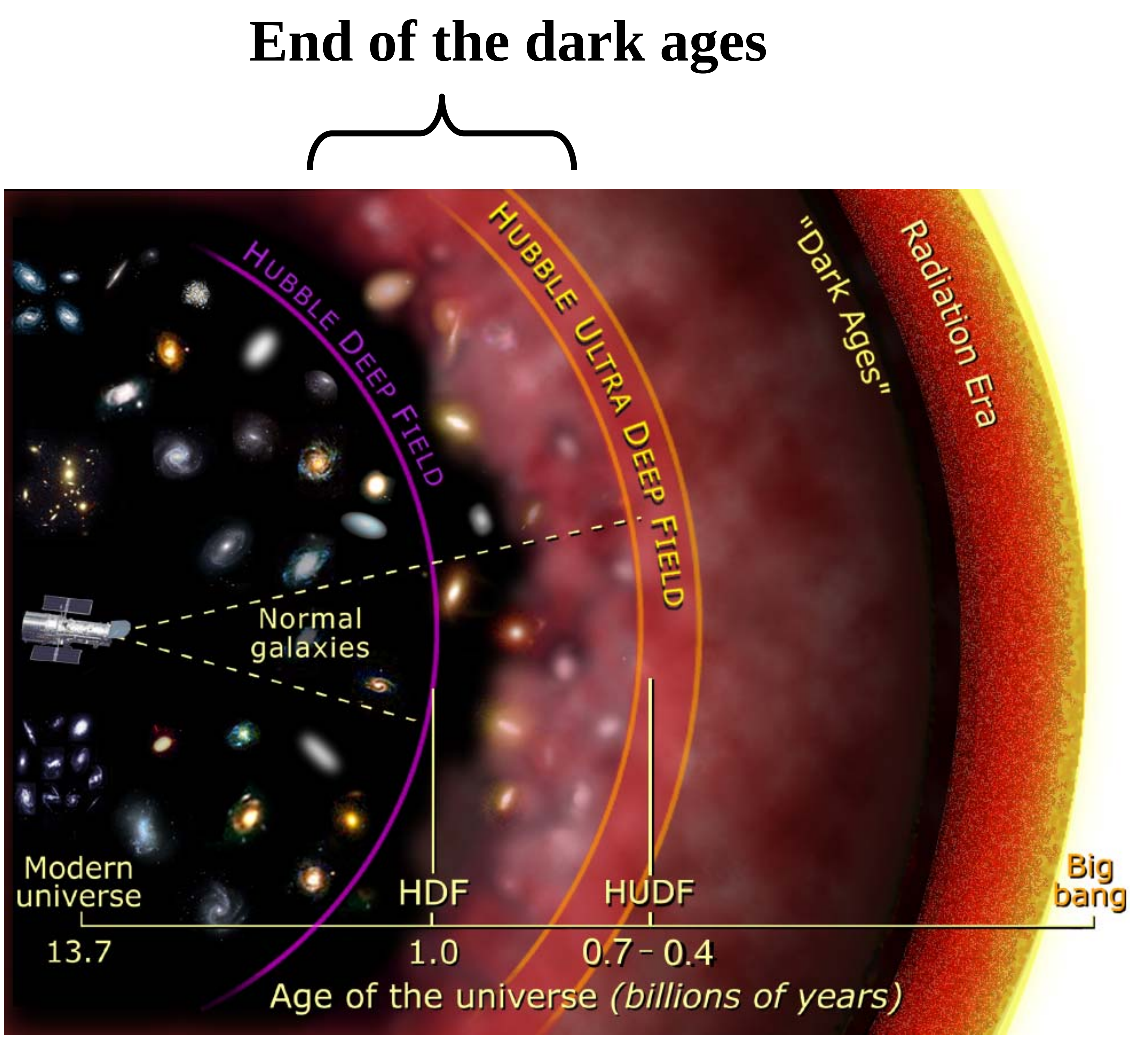
Finding the Earliest Galaxies

Summary:

Indirect evidence from high redshift quasars and 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:

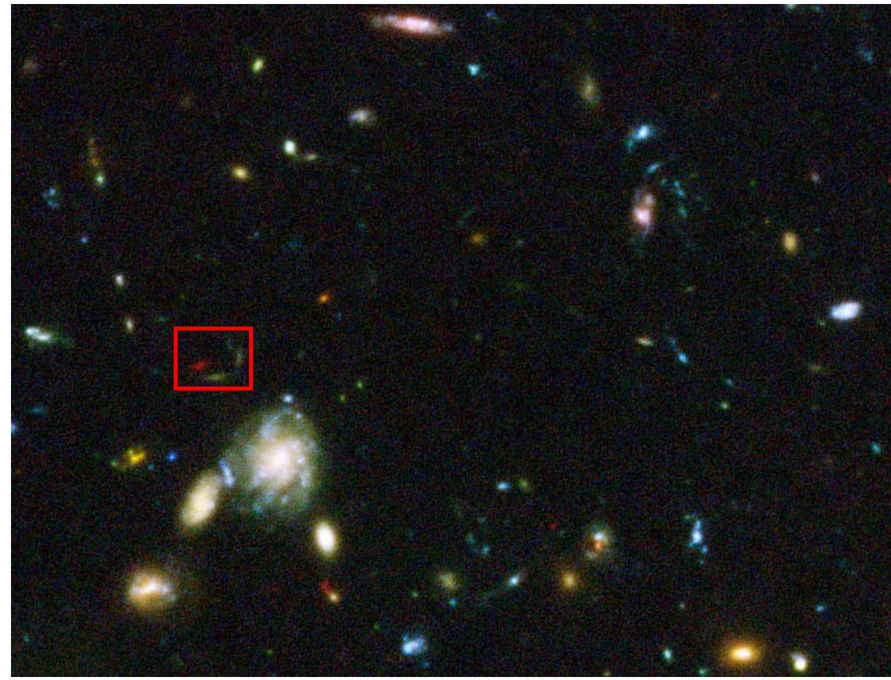
Can we detect them?



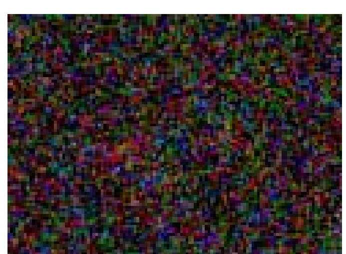
The Hubble Ultra Deep Field

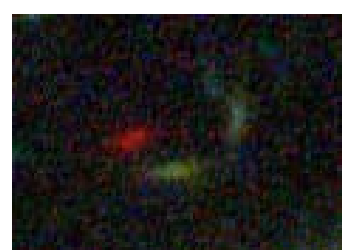
The HUDF remains the deepest ever optical image

GOODS field – 13 orbits

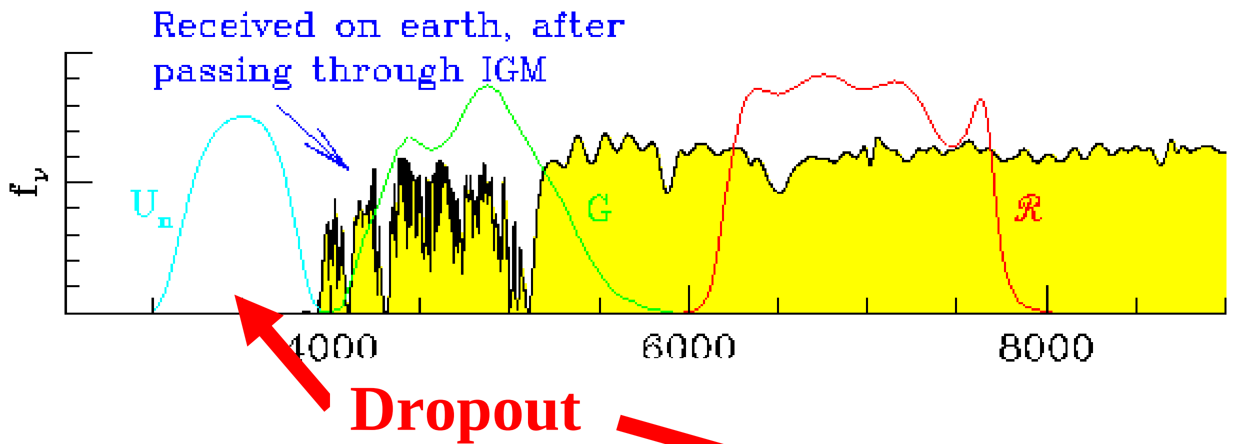


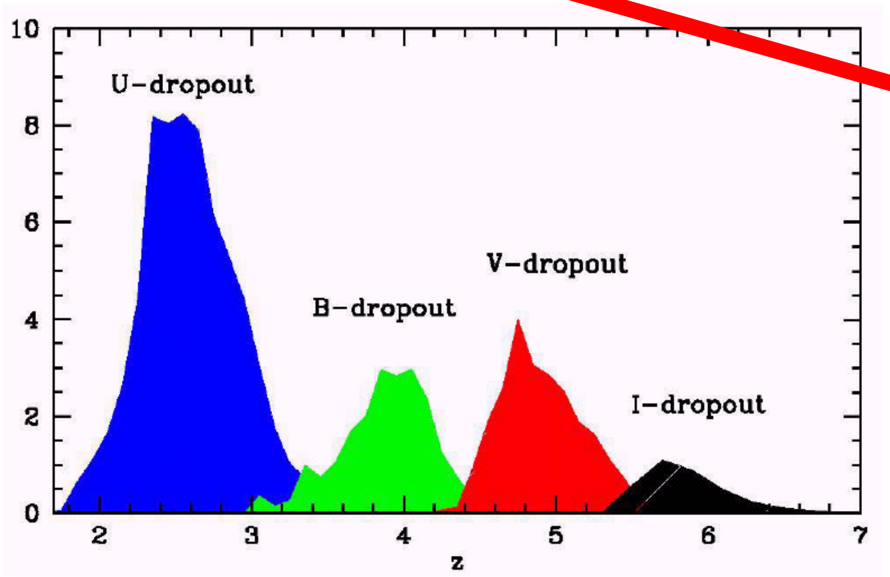
HUDF – 400 orbits

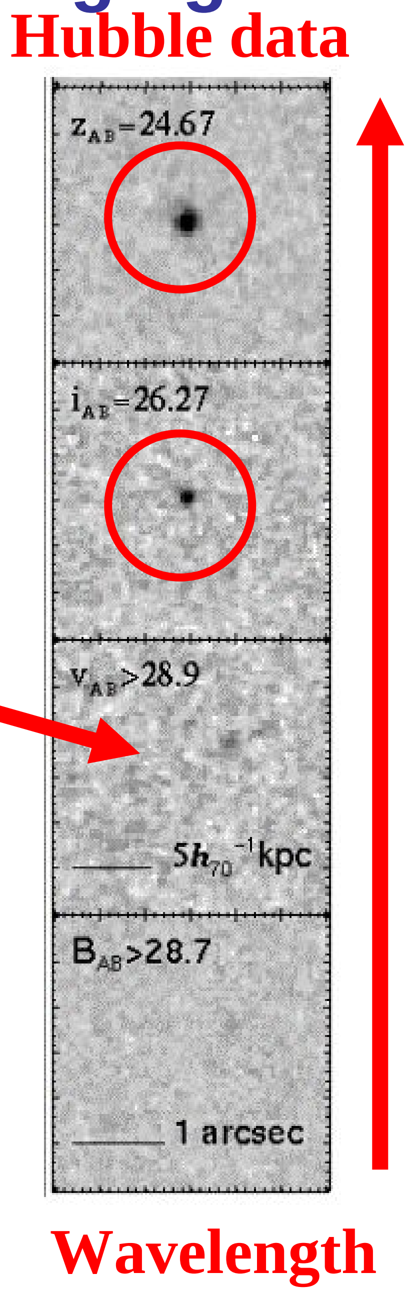




Very distant sources in deep Hubble imaging

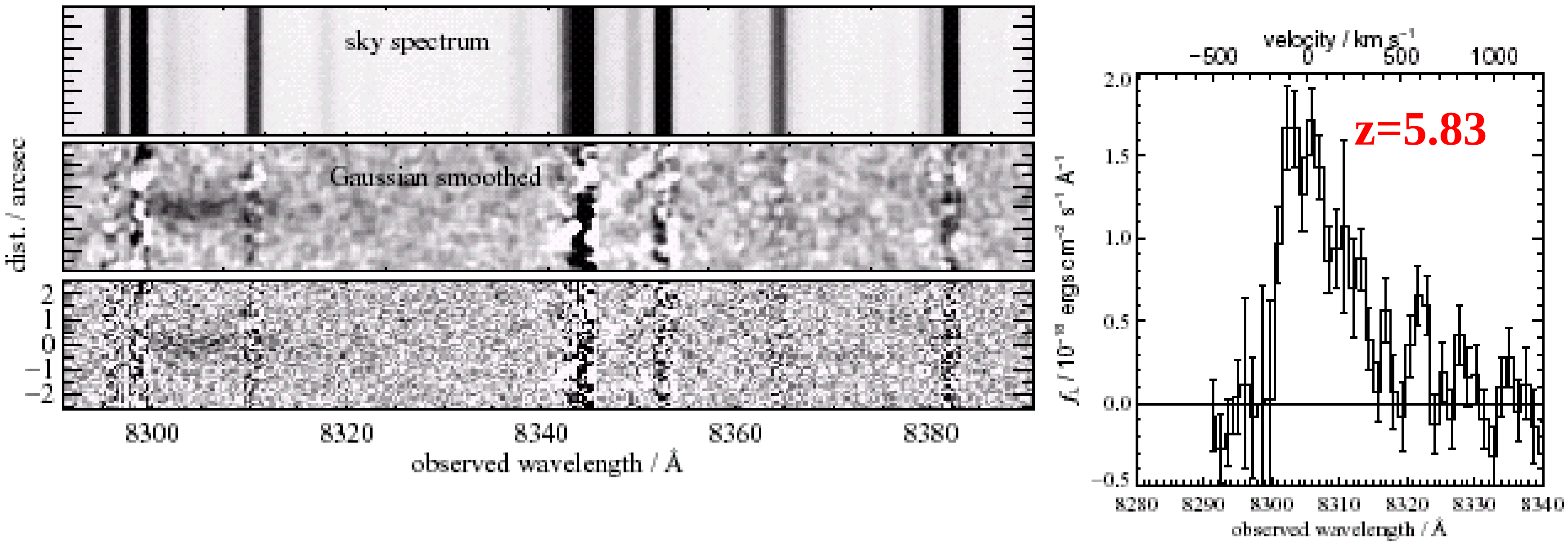


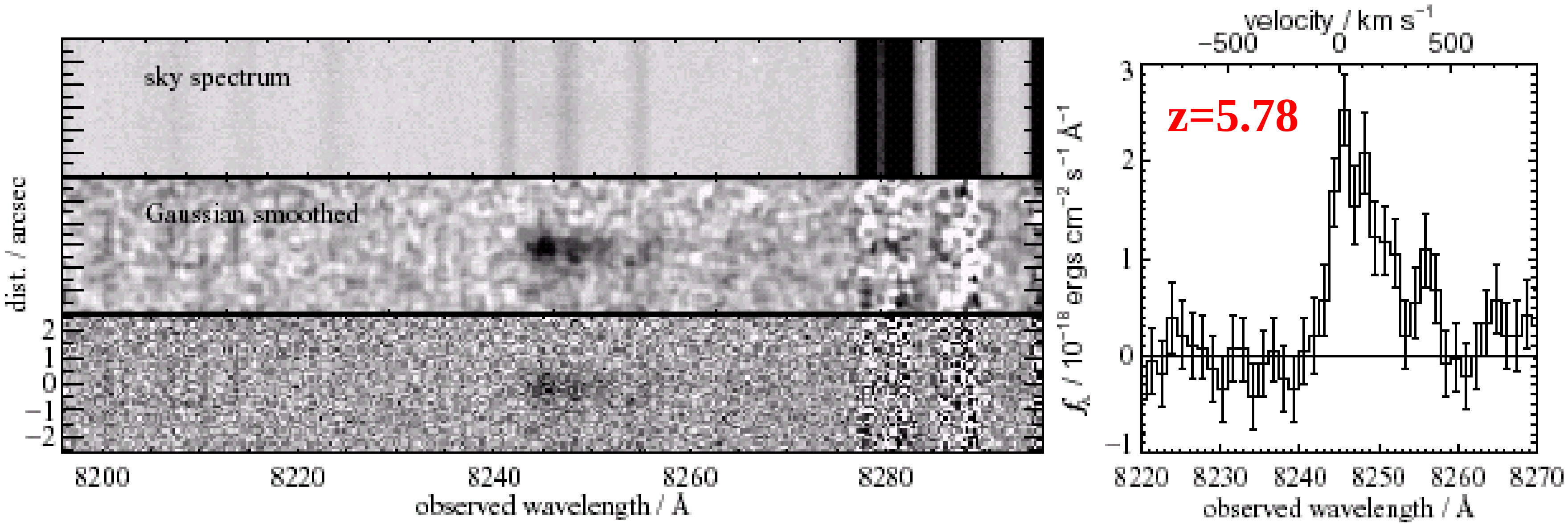




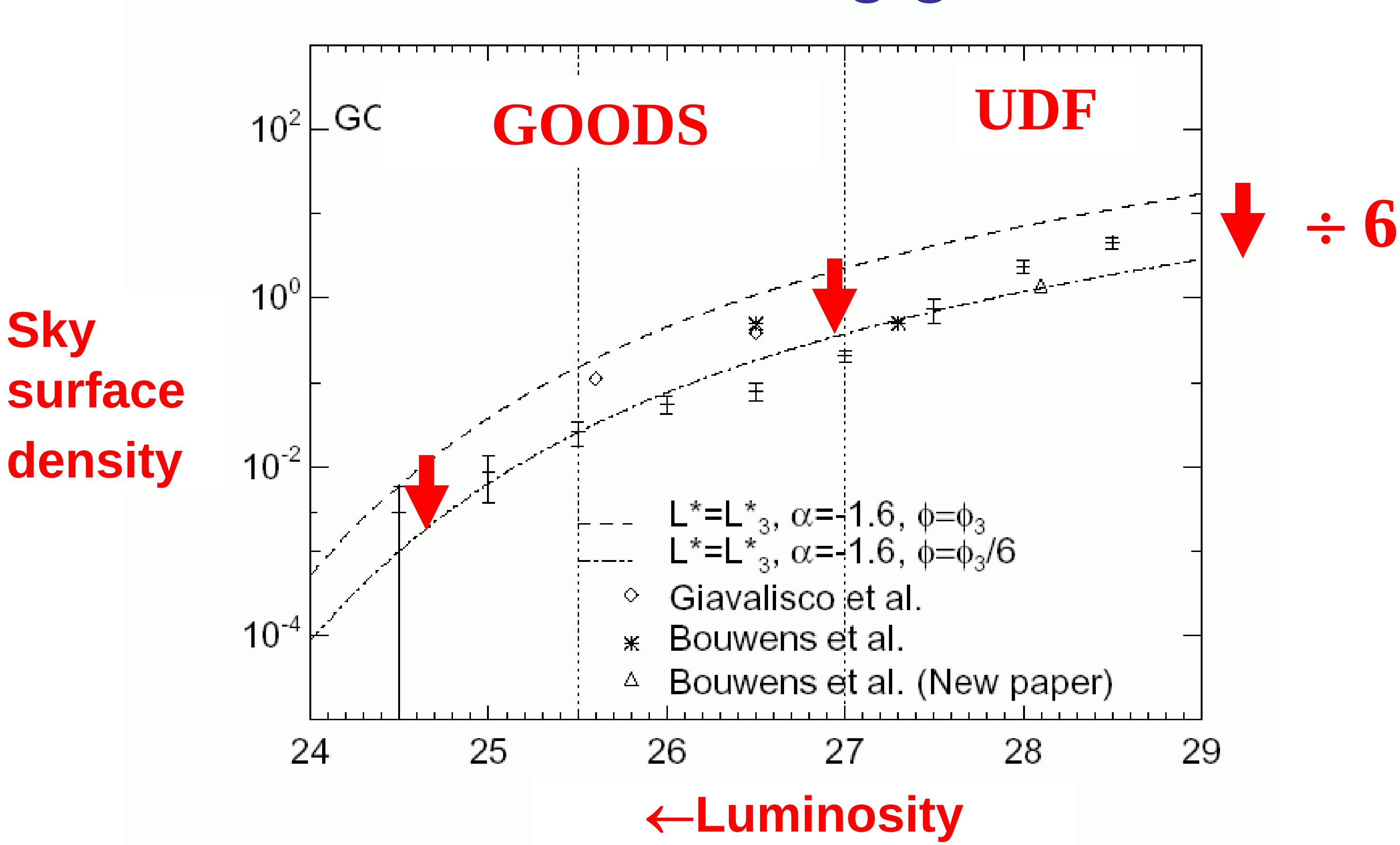
We can extend the `dropout' technique used successfully at z=3 to find examples of star-forming galaxies beyond z=5 by looking for dropouts in redder bands

Keck DEIMOS spectroscopy of i-band dropouts





Census of star-forming galaxies at z=6



Combining wide field GOODS survey with narrower Ultra Deep Field reveals the luminosity distribution of z~6 galaxies

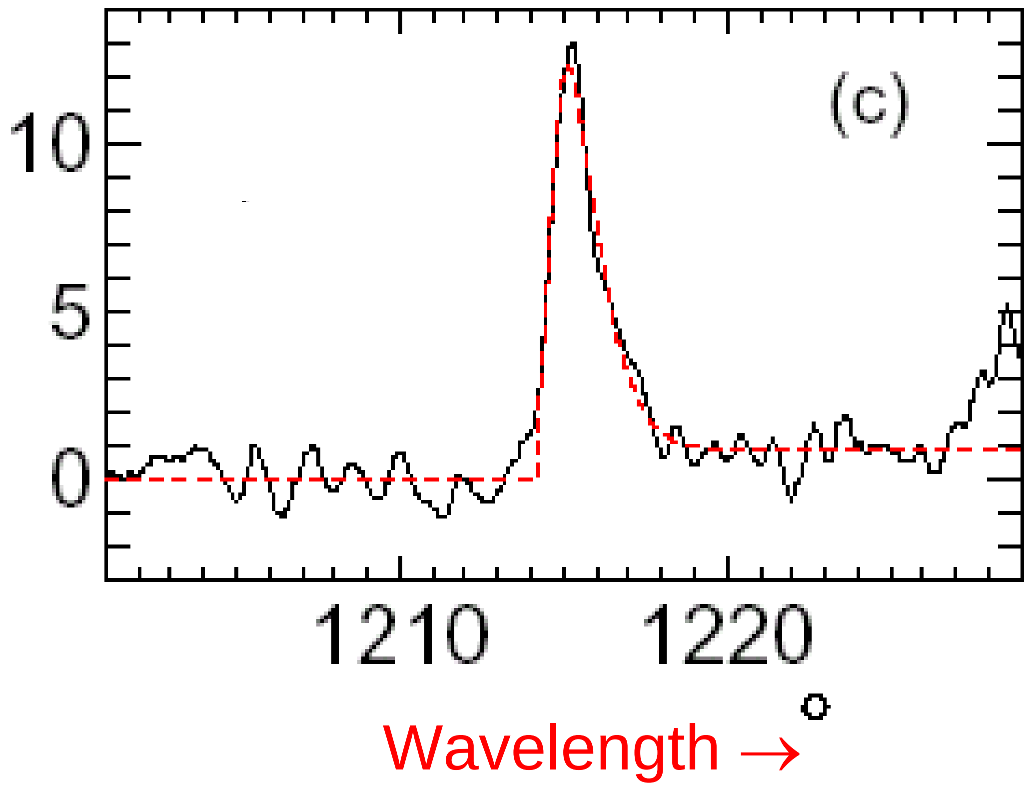
Counts are consistent with those at z=3 with a <u>decline in abundance</u> of ×6

We are approaching the beginning of the star-forming era!

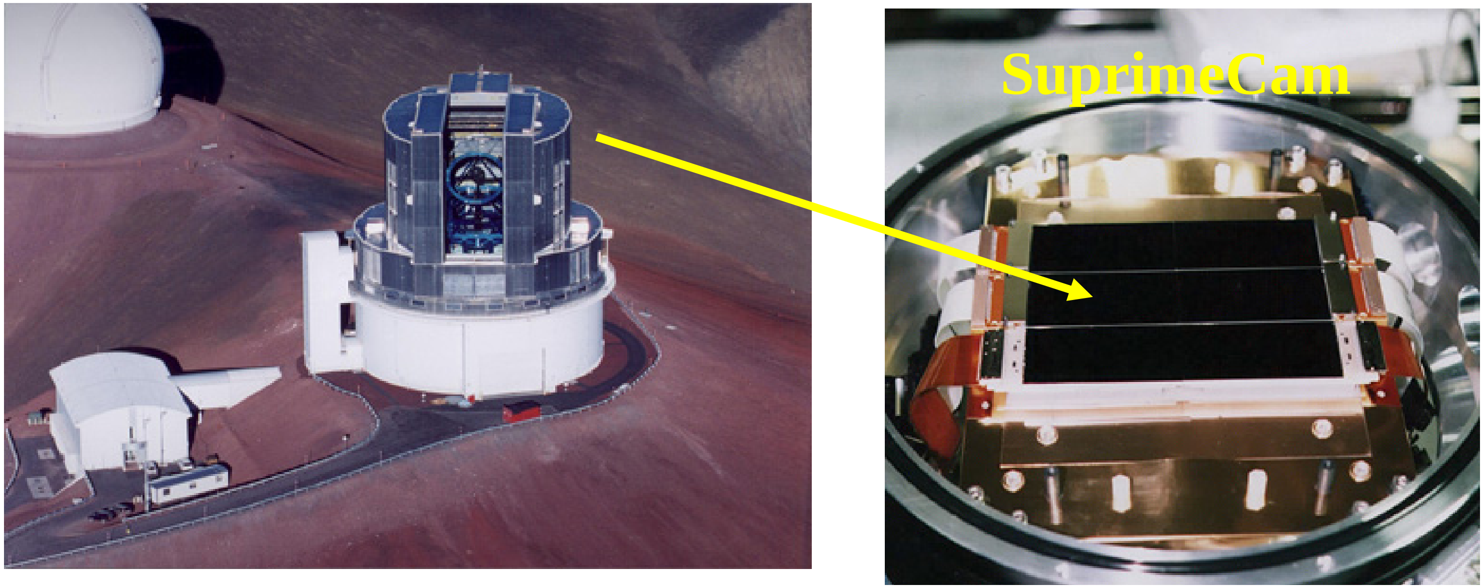
Lyman α Surveys

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

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

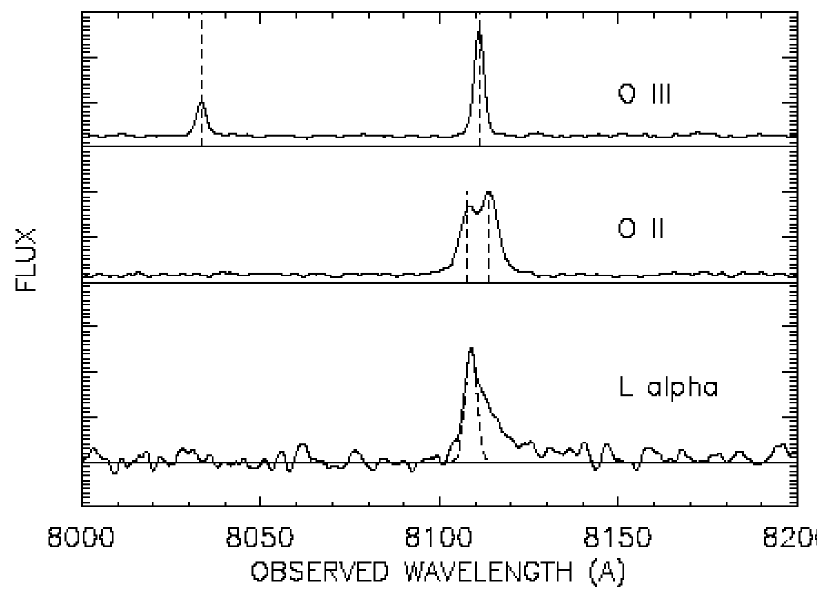


Wide Field Imaging from Subaru



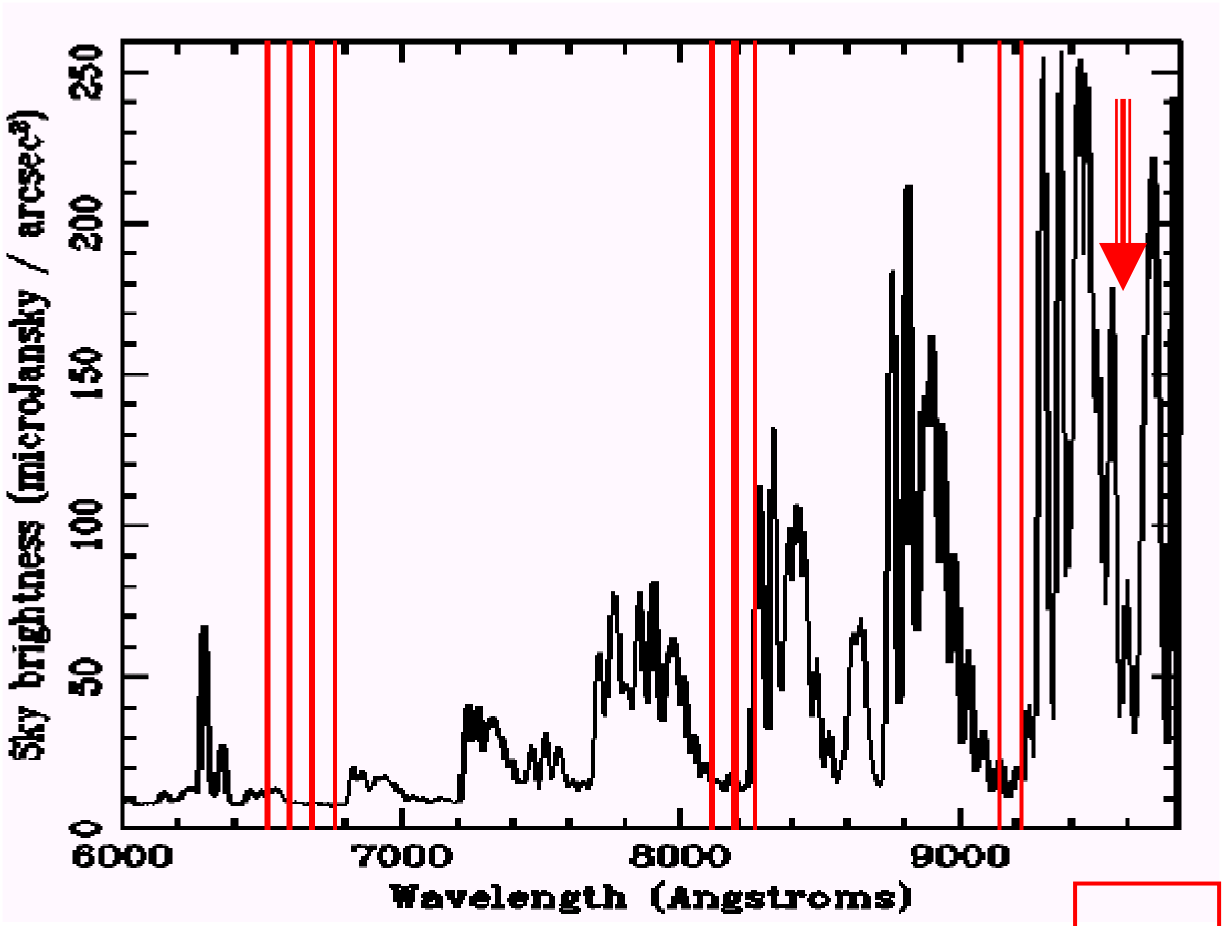
<u>Mauna Kea `Ohana'</u>:

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



E. Hu (U Hawaii)

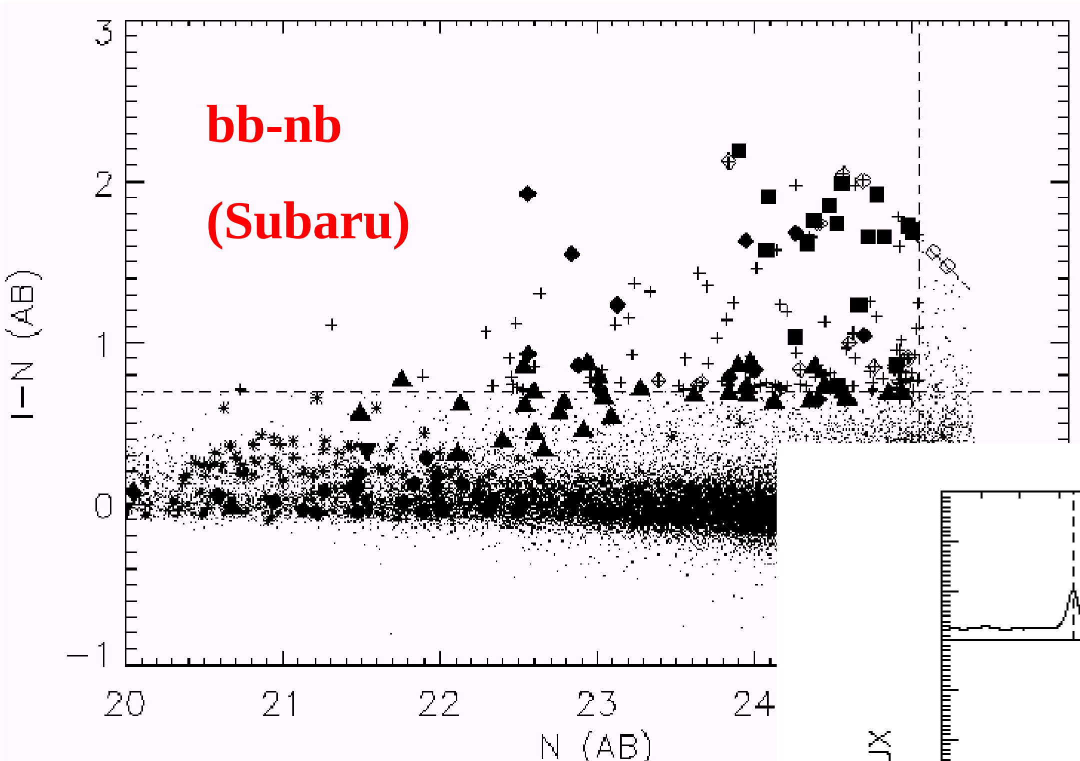
Narrow band filters & z=7 barrier



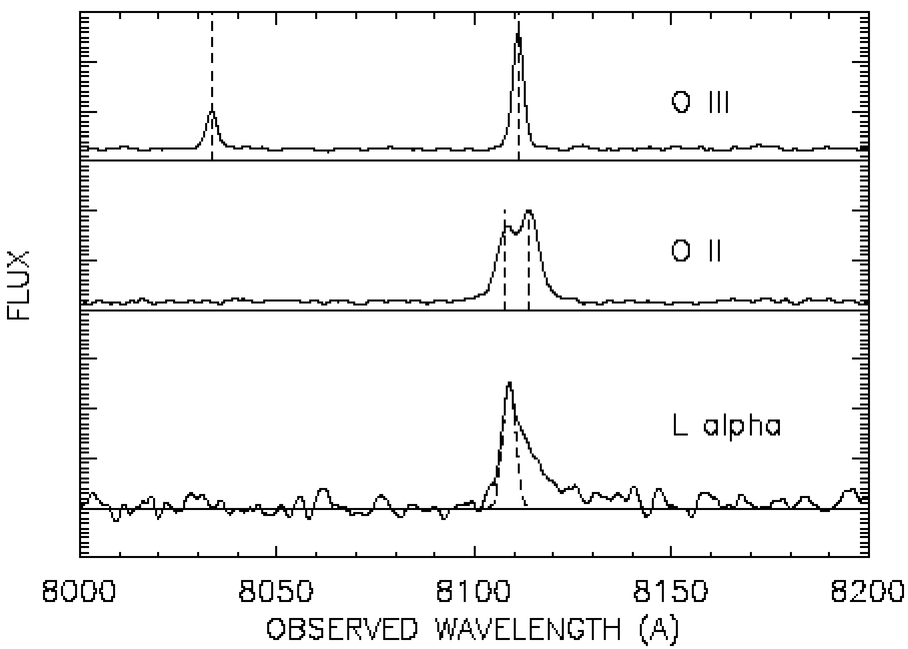
z(Lα) = 4.7 5.7 6.6 6.9

Requires panoramic imaging as Δz range is small: restricted to z<7

Candidate Selection & Removal of Interlopers



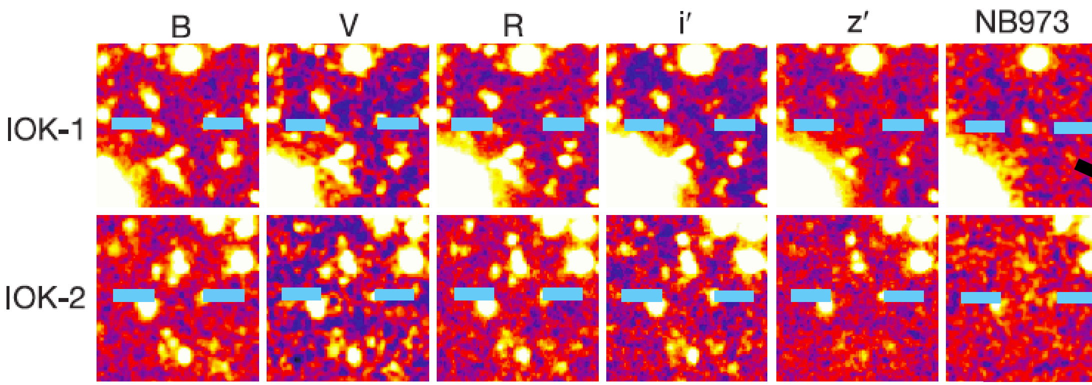
Keck spectra

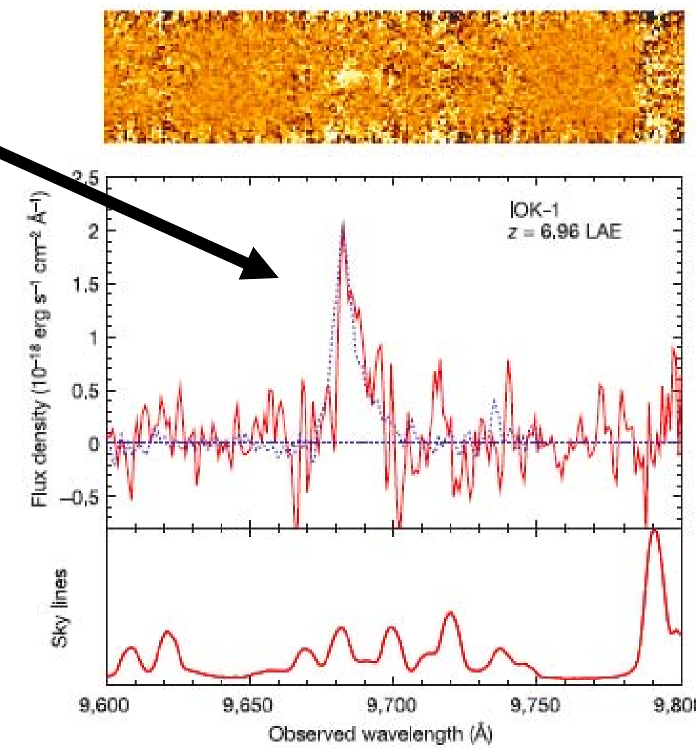


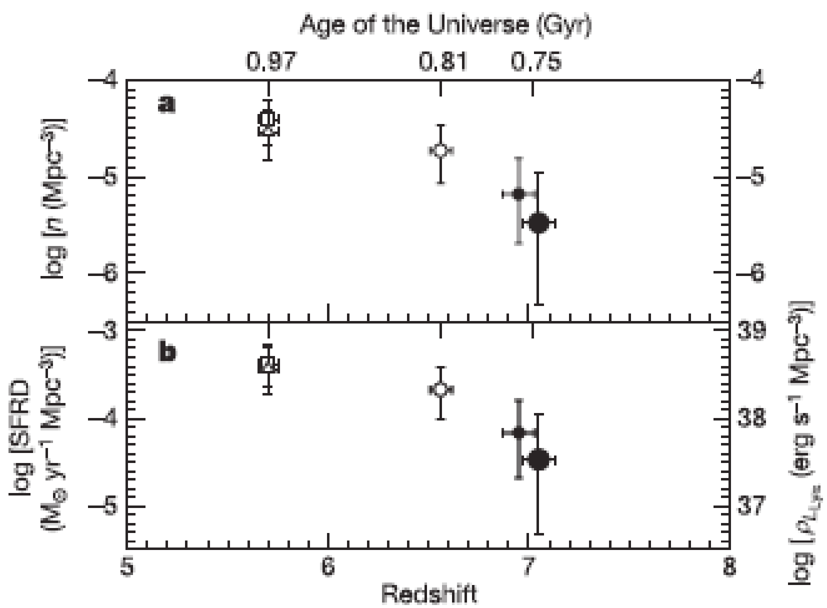
Hu et al (2003) z=5.7 survey

A galaxy at a redshift z = 6.96 *Nature 443, 186 (2006)*

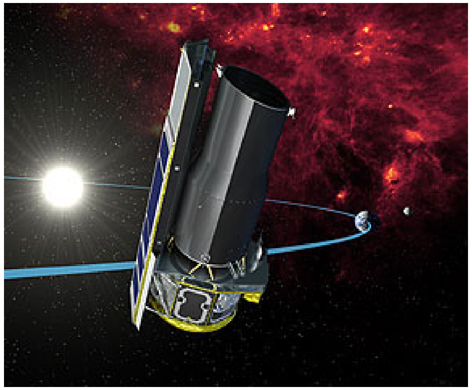
Masanori Iye[1,2,3], Kazuaki Ota[2], Nobunari Kashikawa[1], Hisanori Furusawa[4], Tetsuya Hashimoto[2], Takashi Hattori[4], Yuichi Matsuda[5], Tomoki Morokuma[6], Masami Ouchi[7] & Kazuhiro Shimasaku[2]







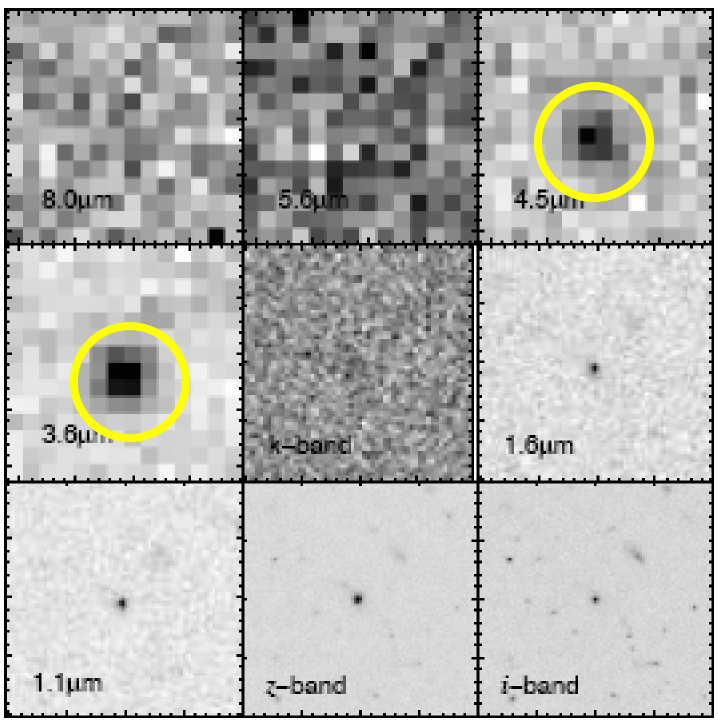
The Spitzer Space Telescope Revolution



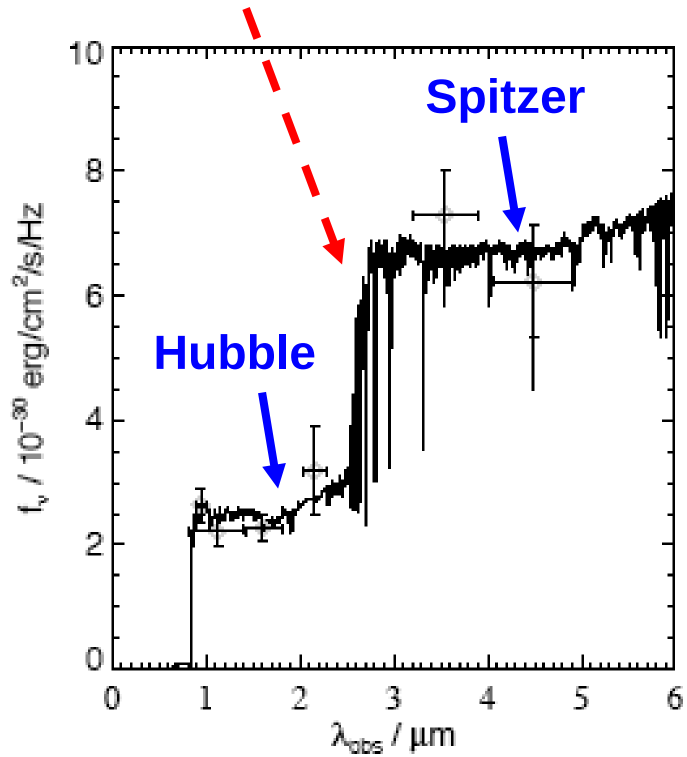
A modest 60cm cooled telescope detects most distant known objects & provides crucial data on their ages and assembled stellar masses

Data points to a lot of earlier activity!

z=5.83 galaxy detected by Hubble

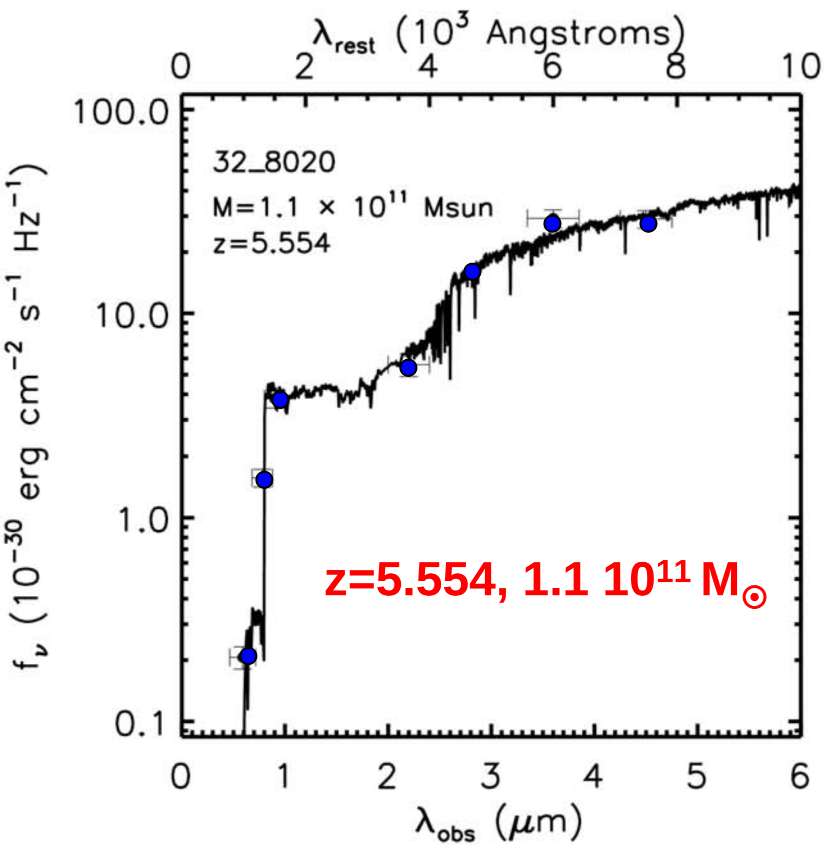


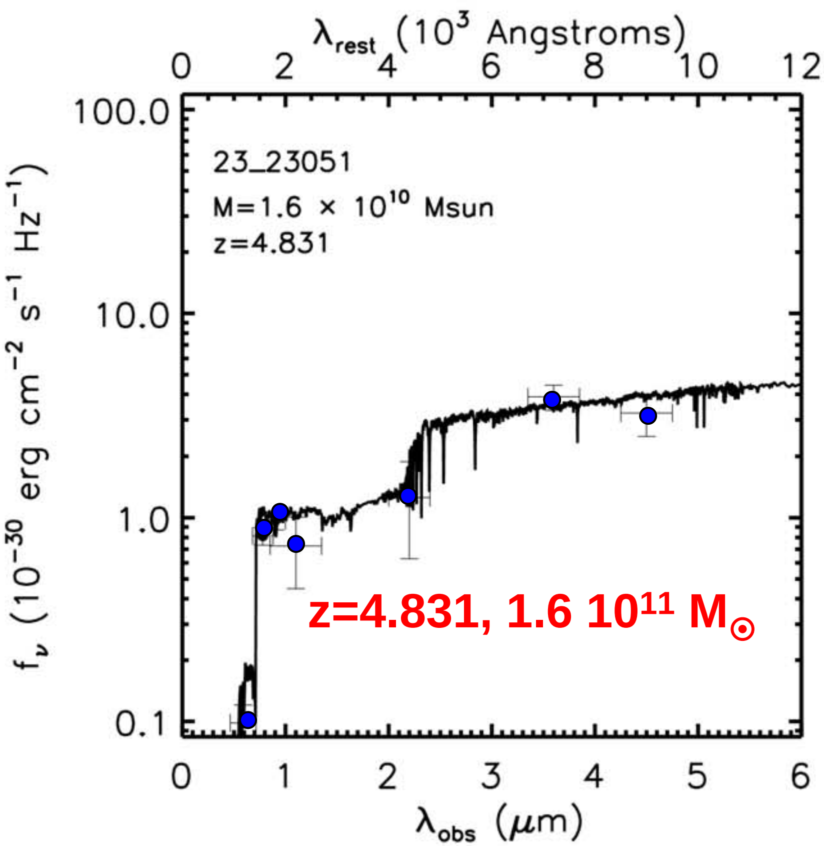
Spectral Evidence of Old Stars



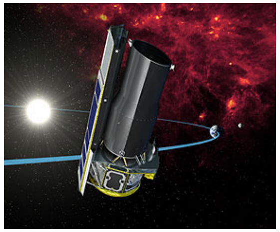
Census of Old Stars at Redshift 5

The amount of mass in old stars already in place at z=5 provides an `accounting record' of all the past star formation, i.e. that which occurred before z=5

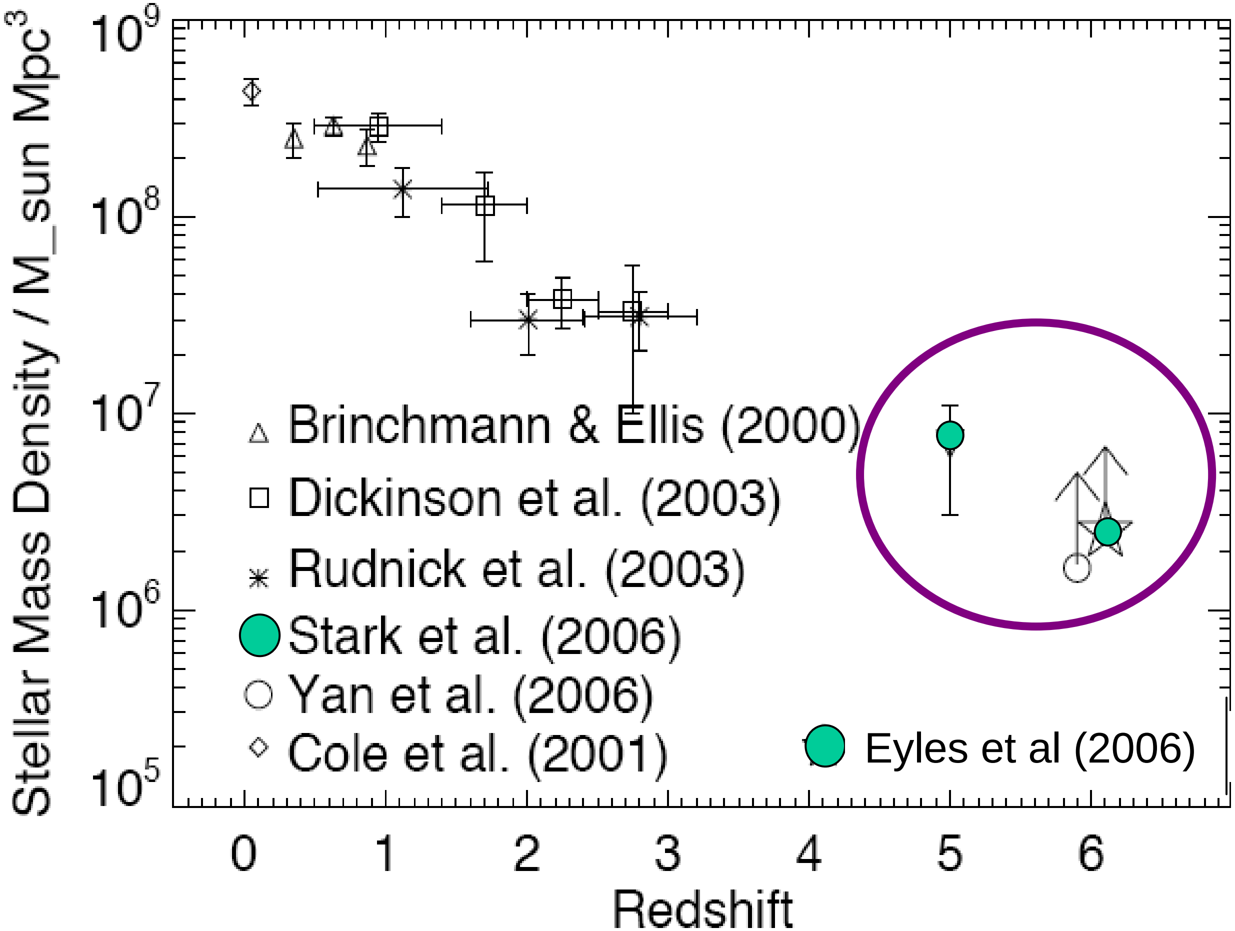




D. Stark et al



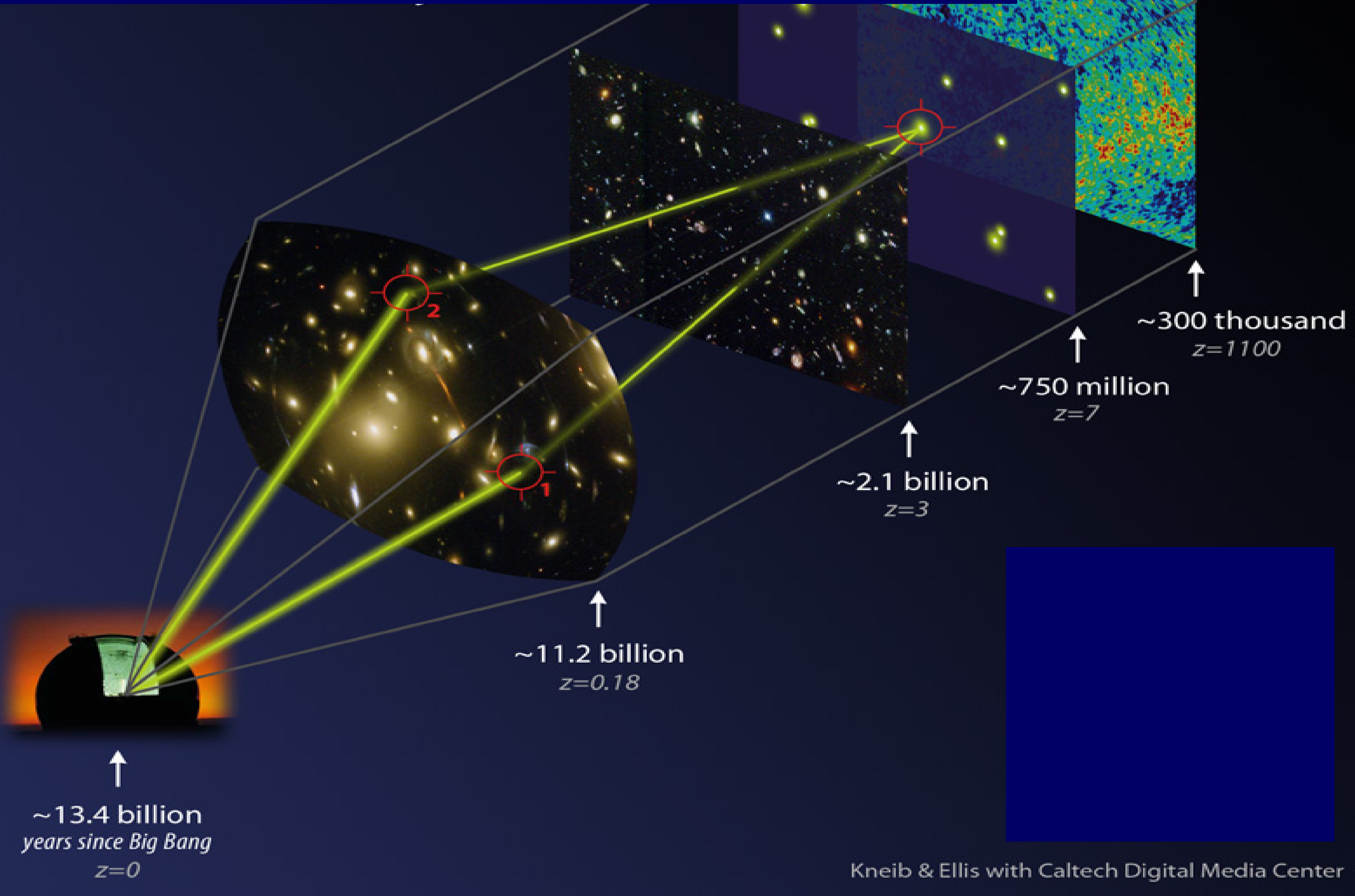
Assembled Stellar Mass by z~5-6



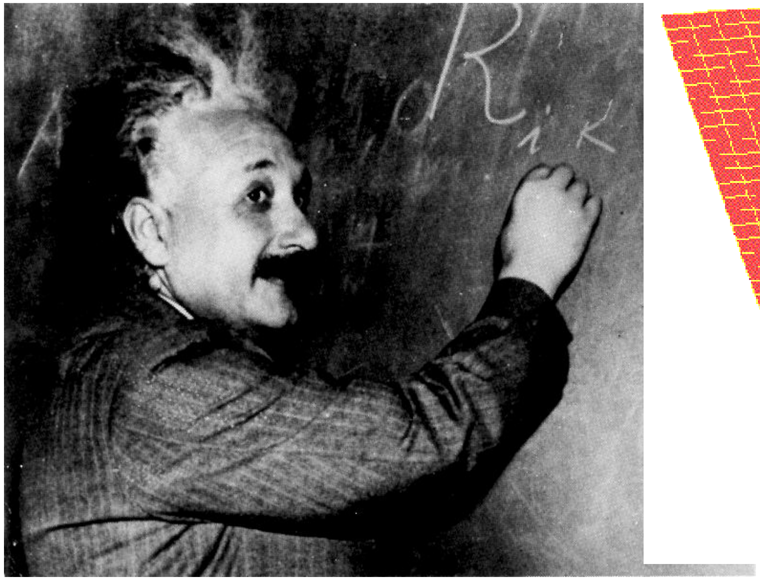
Assembled stellar mass density at z~5-6 is surprisingly high

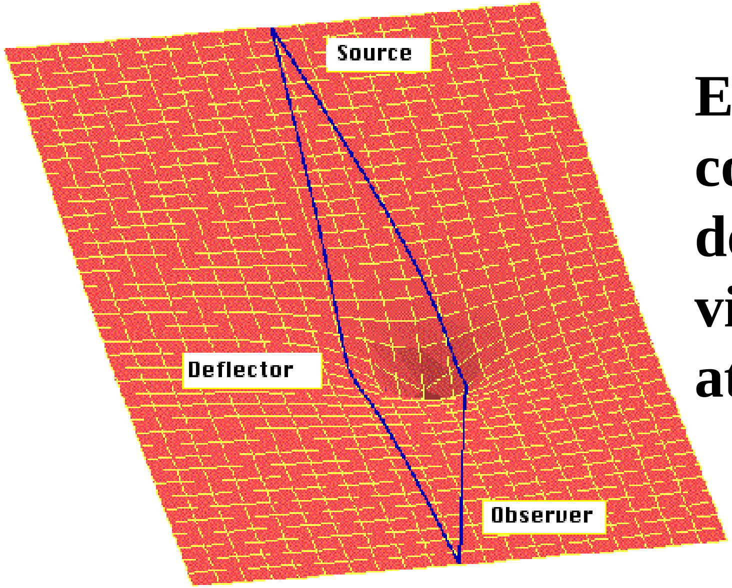
Suggests a lot of earlier activity must be present! Can we find it??

Boosting the signal with gravitational lenses

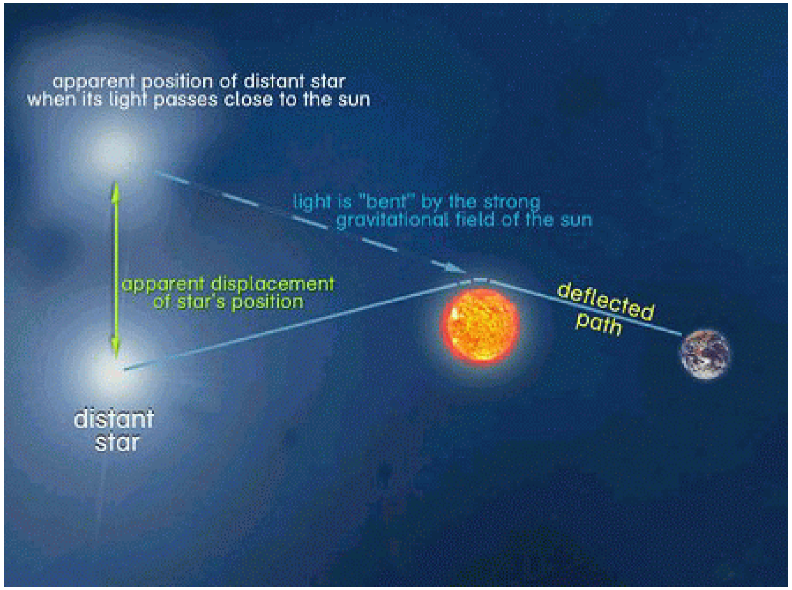


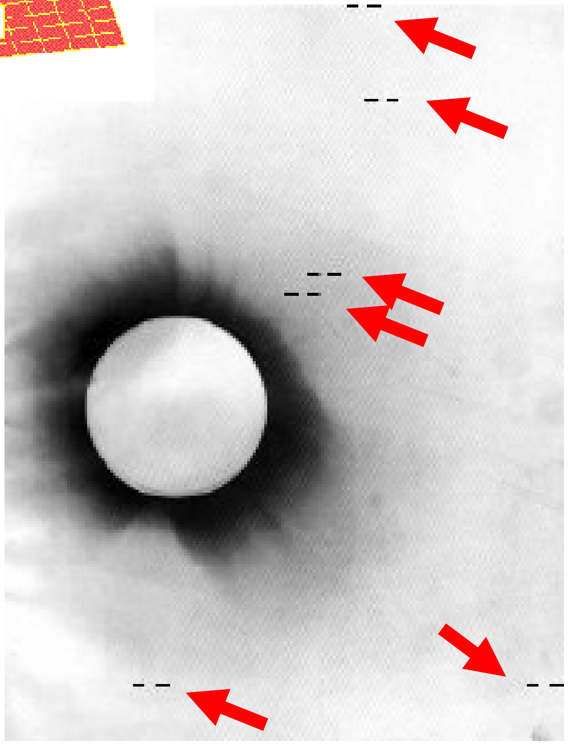
Gravitational Lensing





Eddington (1919) confirms the sun deflects starlight via measurements at a total eclipse

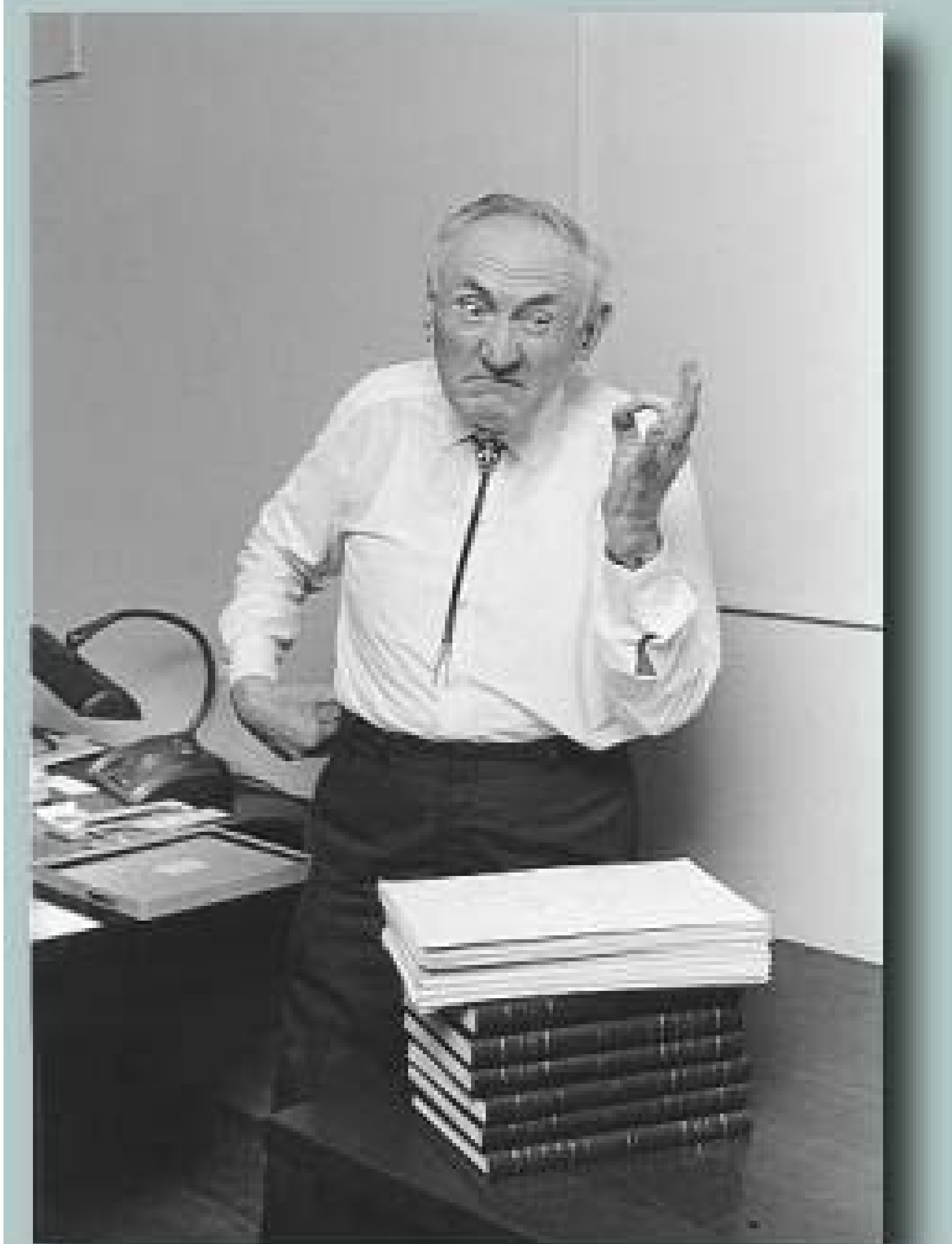




Fritz Zwicky
(Caltech)

First to deduce the presence of copious amounts of dark matter.

Suggested use of gravitational lensing in clusters of galaxies would extend the power of a telescope ..a point overlooked by Einstein and which lay dormant for a further 50 years!



Simulated view through transparent dark lens

QuickTime™ and a
Sorenson Video decompressor
are needed to see this picture.

Courtesy: Lars Christensen (ESA)

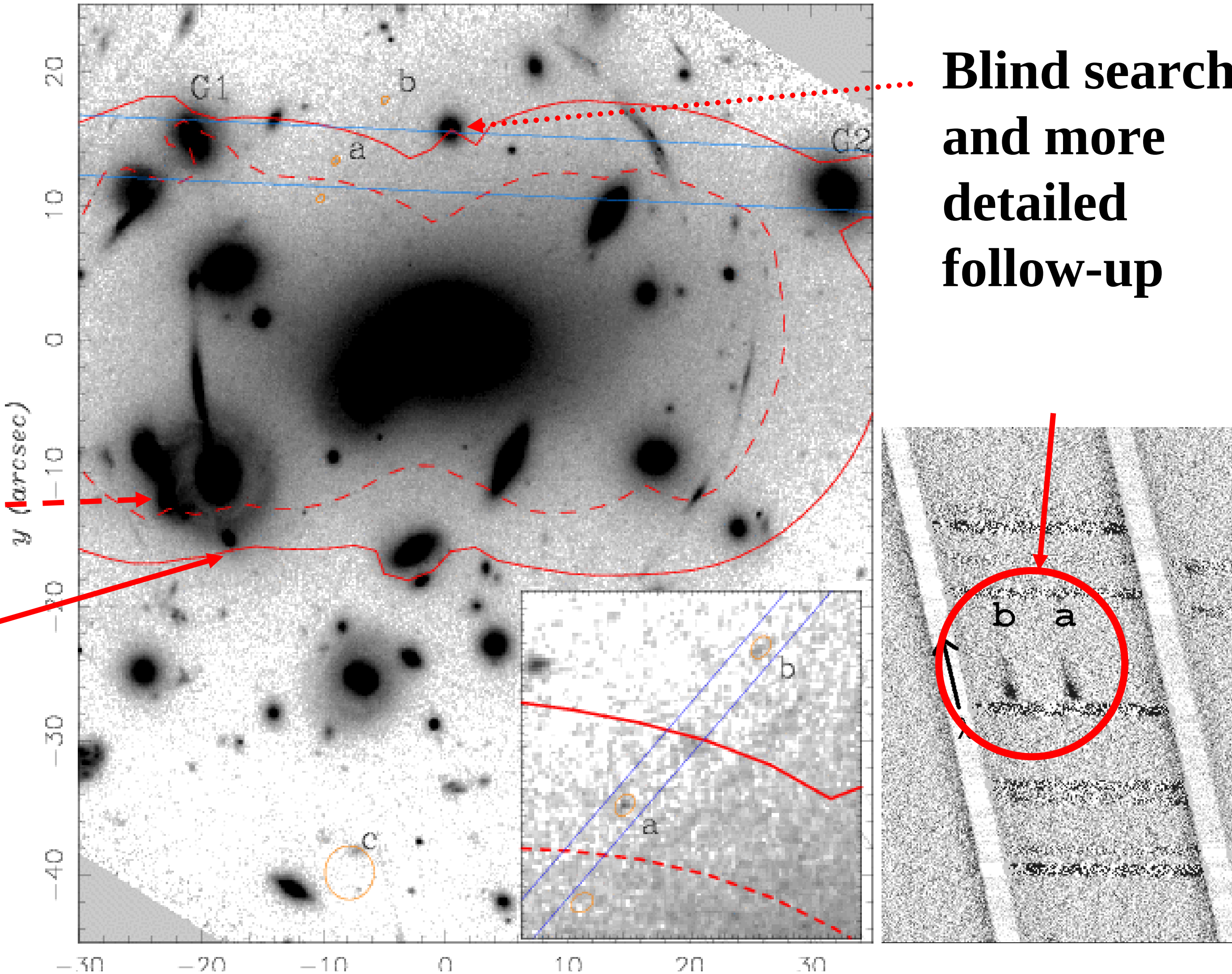
Combining Keck and a `Gravitational' Telescope

Critical lines (points of high magnification) for background sources at

z=1

and for

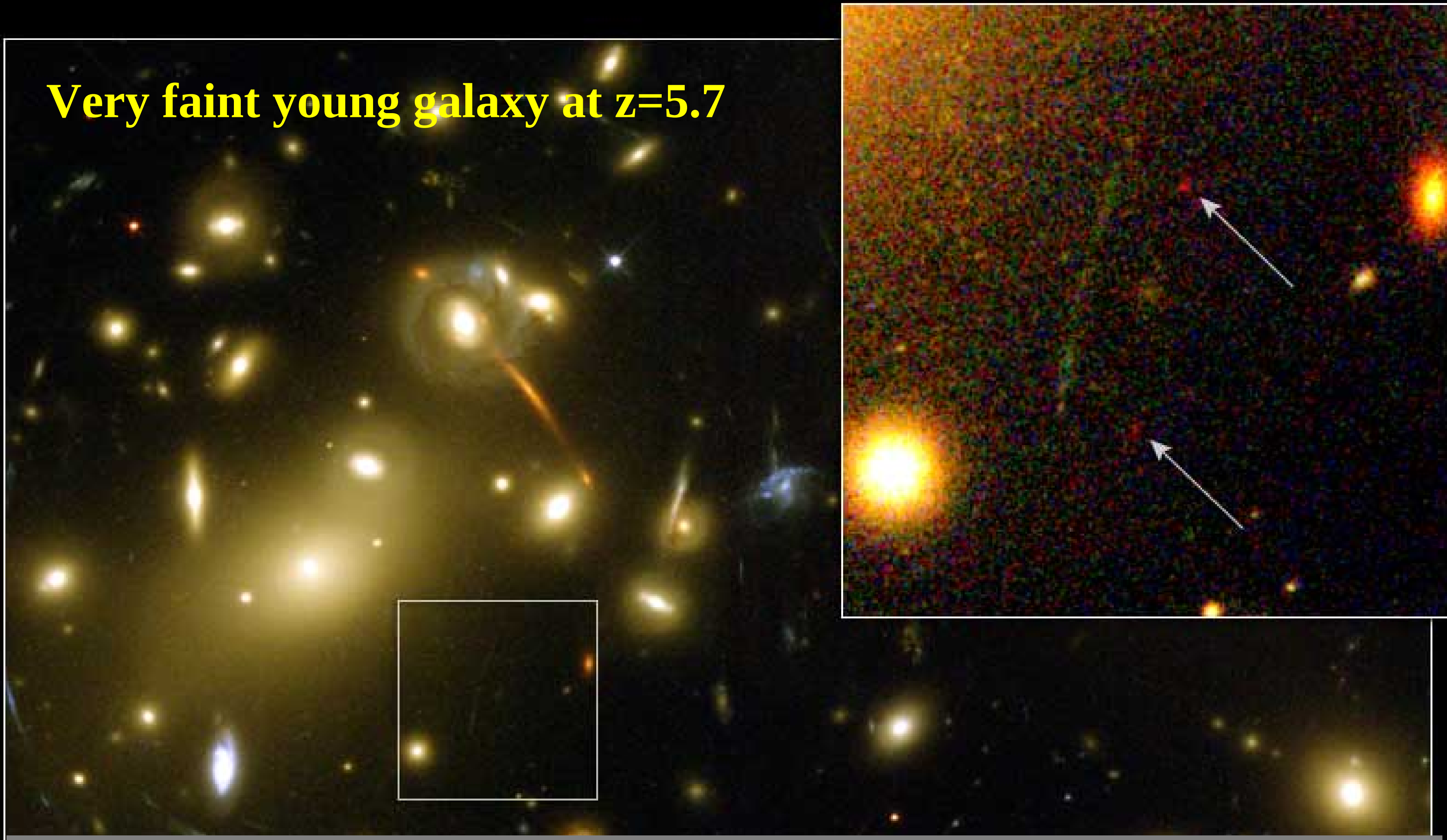
z=5



Blind search and more detailed follow-up

Utilizing strong magnification (×10-30) of clusters, probe much fainter than other methods but in small areas

Very faint young galaxy at z=5.7

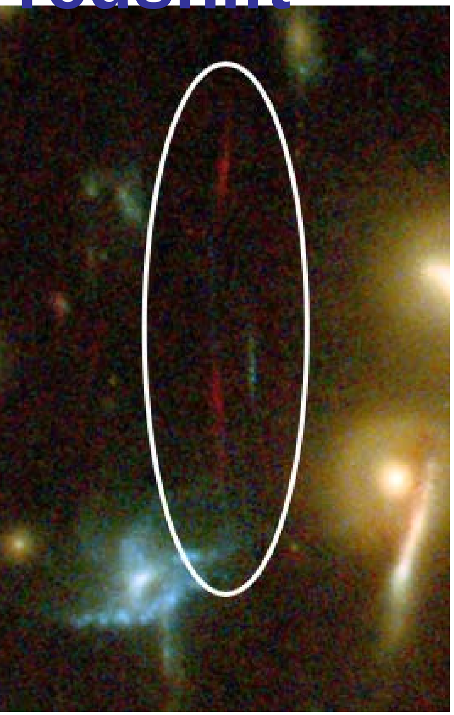


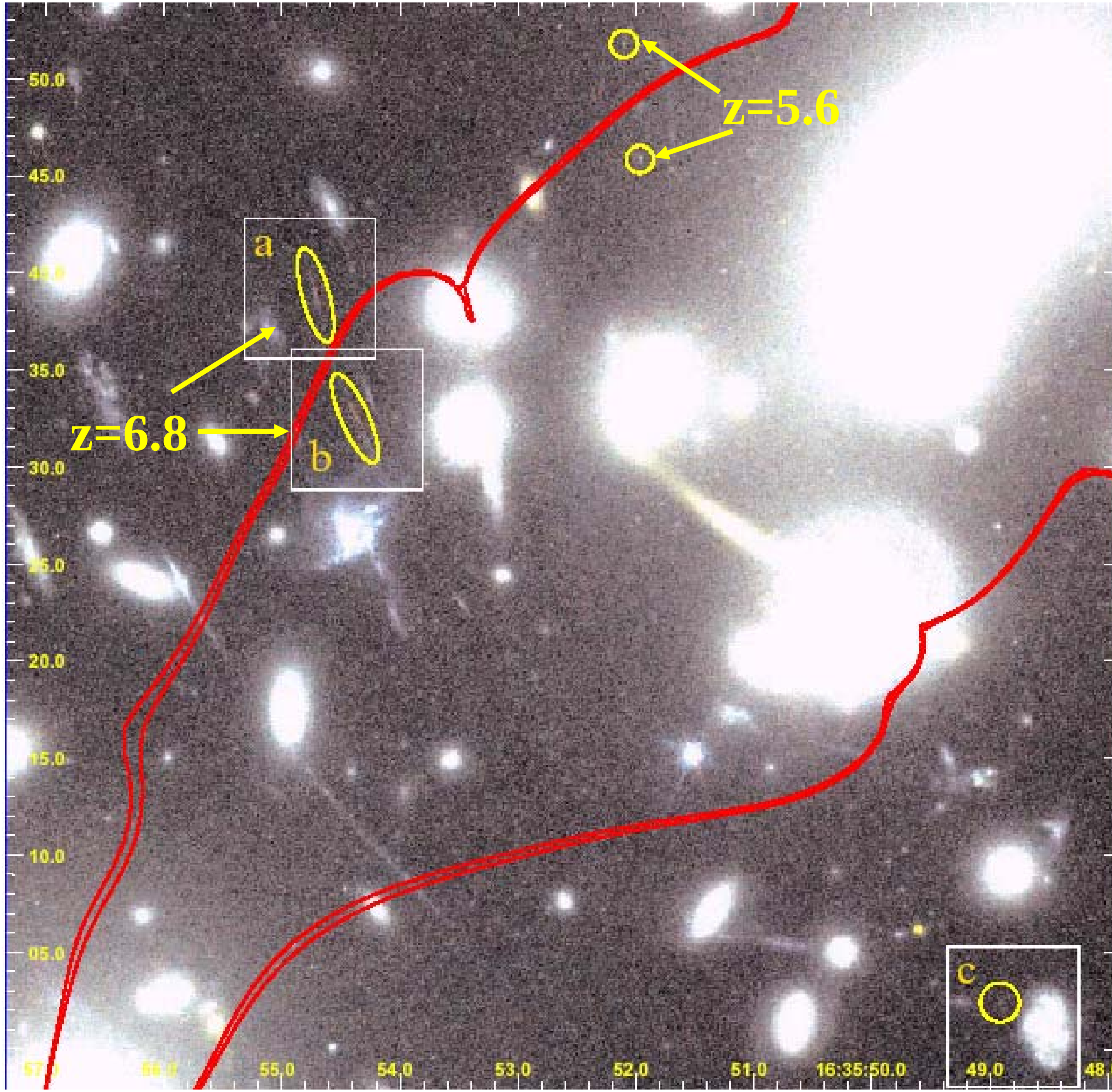
- Magnification = ×30 → 20 × fainter than unlensed searches
- Very low mass (10 million solar masses) and age < 1-2 million yrs

Distant Object Gravitationally Lensed by Galaxy Cluster Abell 2218 **HST • WFPC2**

NASA, ESA, R. Ellis (Caltech) and J.-P. Kneib (Observatoire Midi-Pyrenees) • STScI-PRC01-32

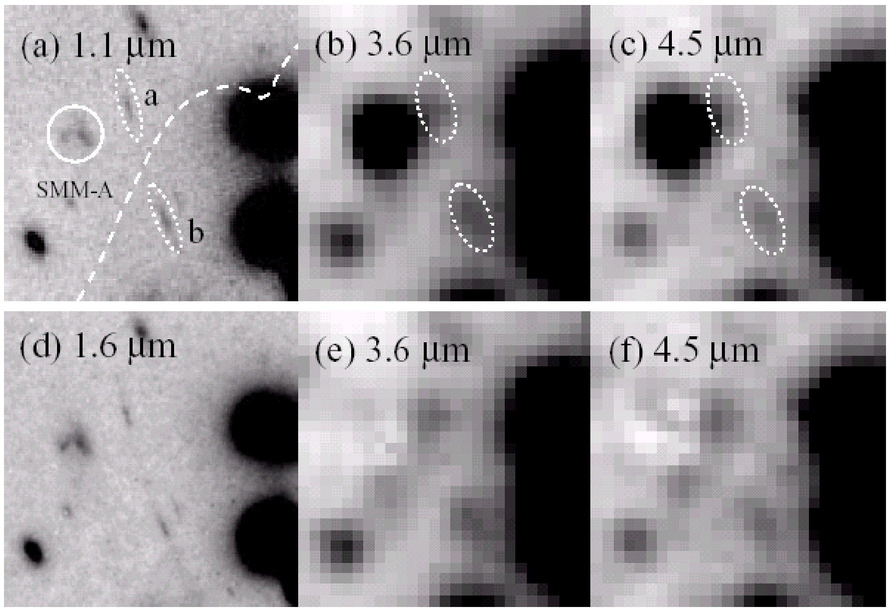
Extension to higher redshift



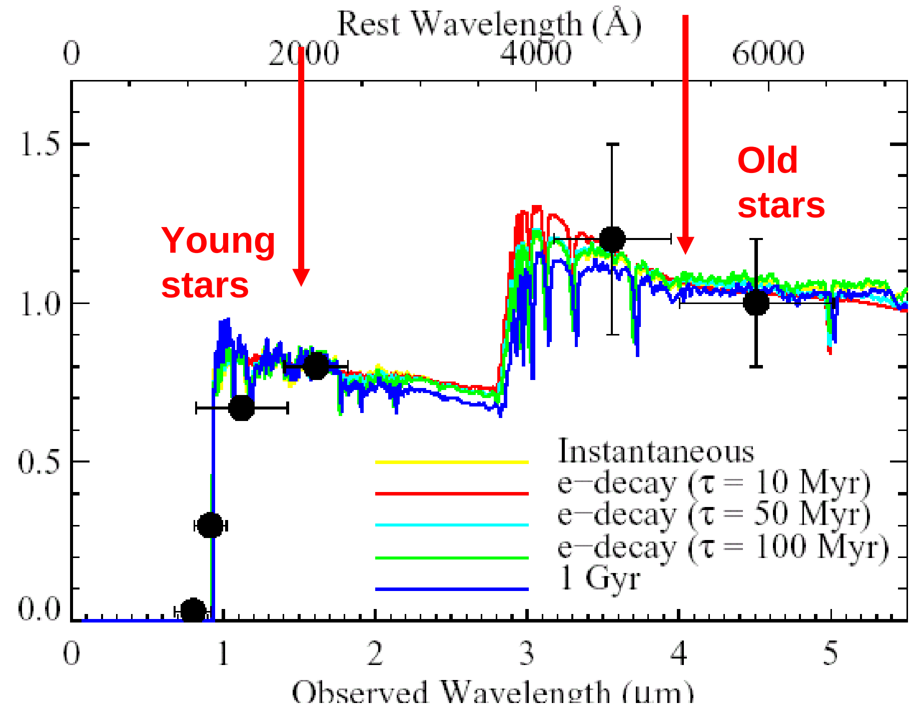


Deciphering past history of z~6.8 system

Hubble Spitzer



Hubble Spitzer

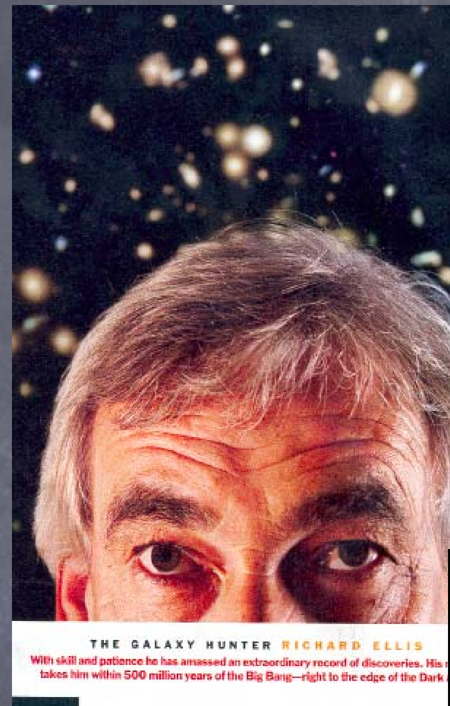


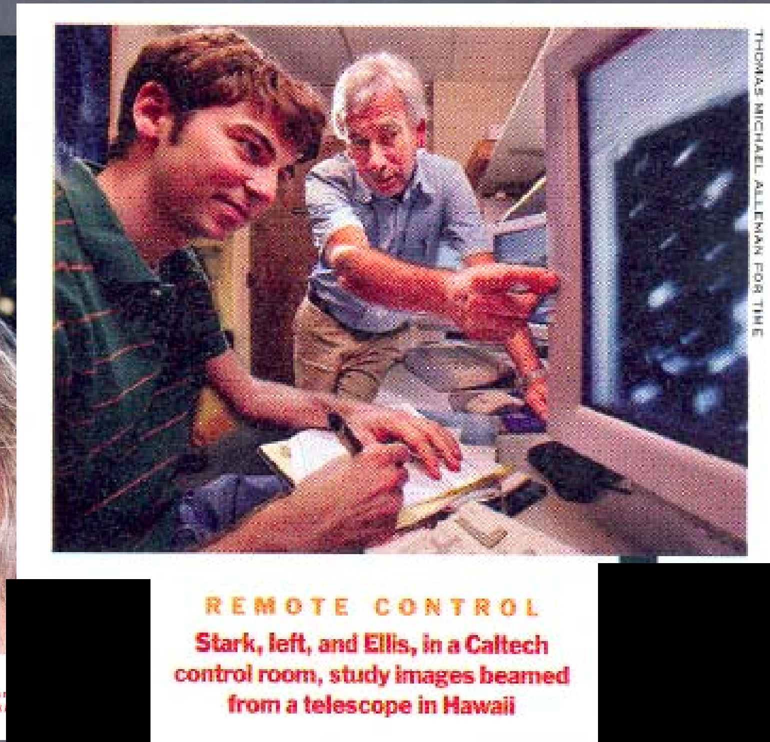
Spitzer → this is already a well-established system 800 Myrs after Big Bang

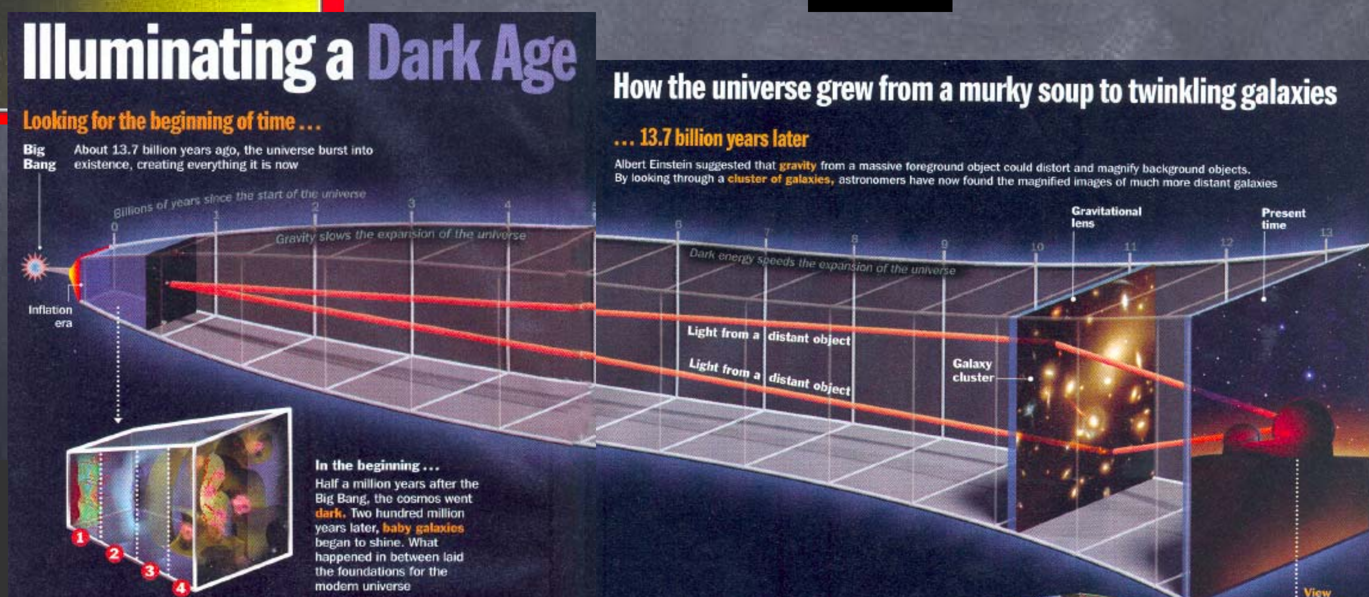
Star formation rate = 2.6 solar masses/yr; stellar mass ~ 0.5% Milky Way

Age at this epoch: 100 – 450 million yrs, so formed at $9 < z_F < 12$

If representative, this is an object in decline after `first light'!







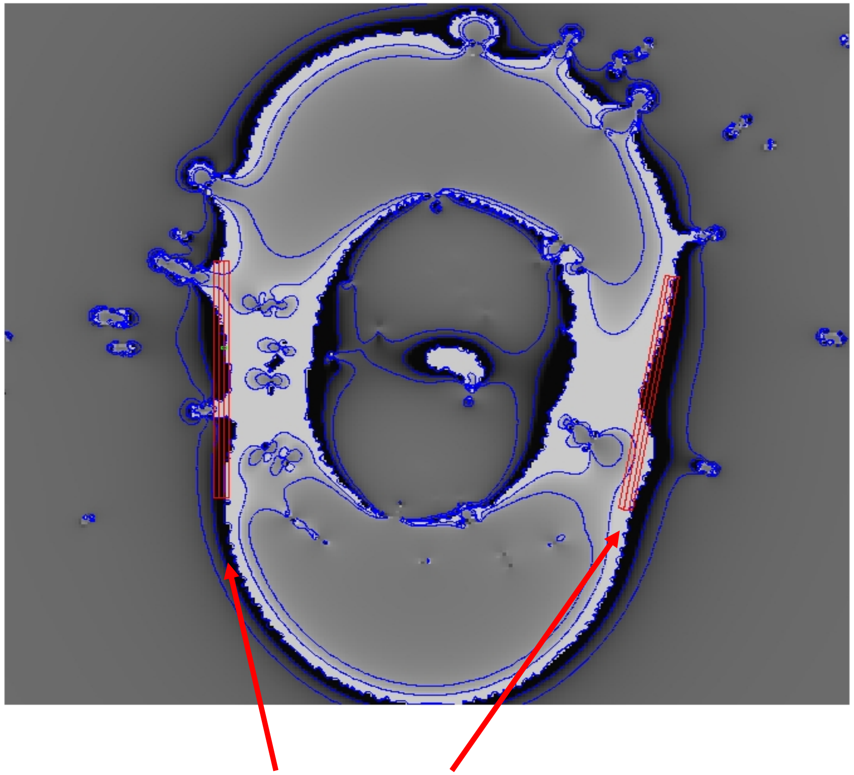
Sep 4 2006

eting,

Pushing Further Back - I: Keck Lyman α mapping

We have extended the successful optical survey for magnified Lyman alpha emitters into the near-infrared where we are sensitive to sources with redshift z~8-10

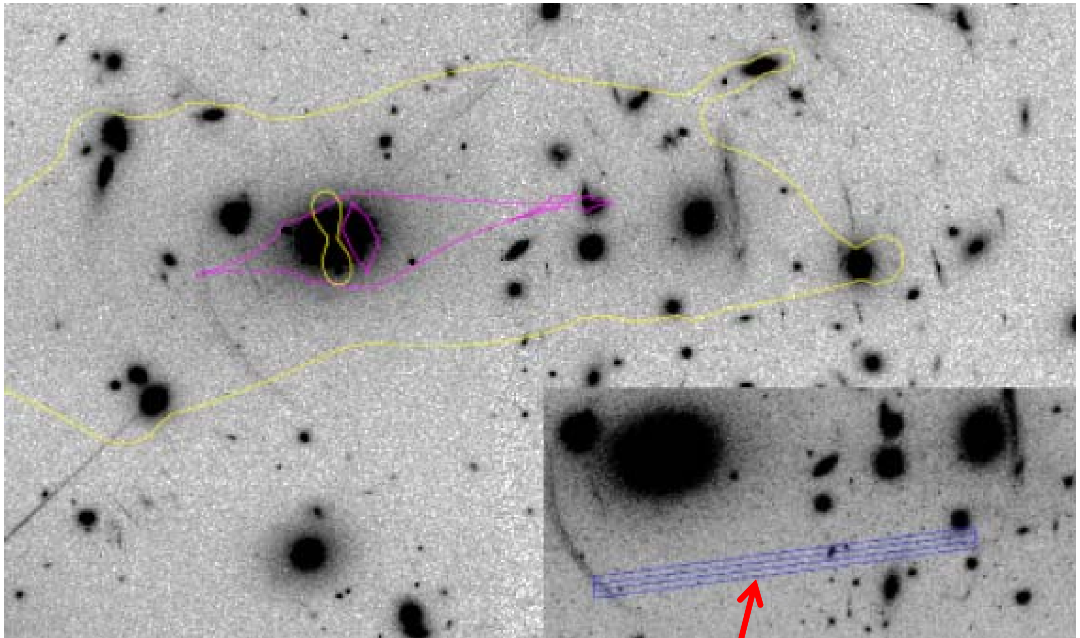
Using Keck's NIRSPEC, the goal is to provide the first constraints on whether there are sufficient feeble sources to contribute to reionization and hence to end the `dark ages'



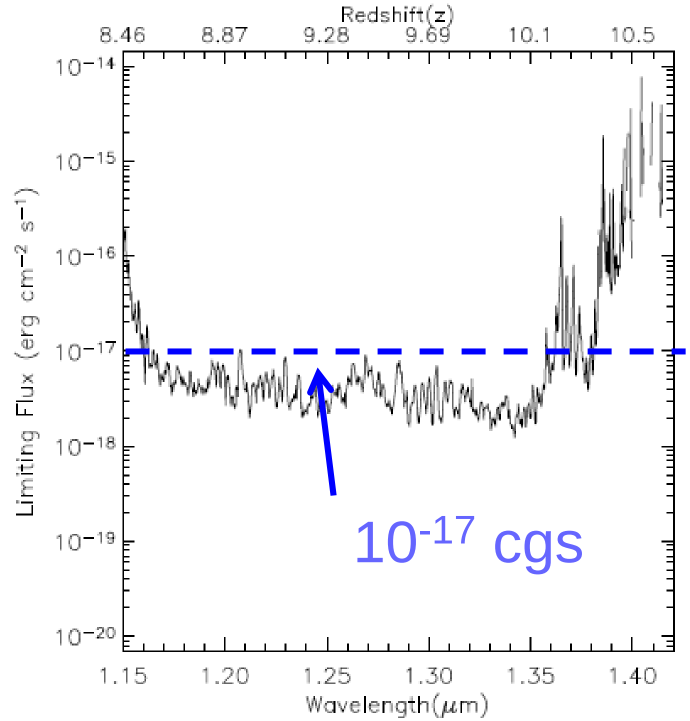
NIRSPEC (infrared) Slits arranged to lie on the critical lines of very high magnification

Example: Abell 2390

Cluster critical line for $z_S > 7$



Wavelength sensitivity (1.5hr)

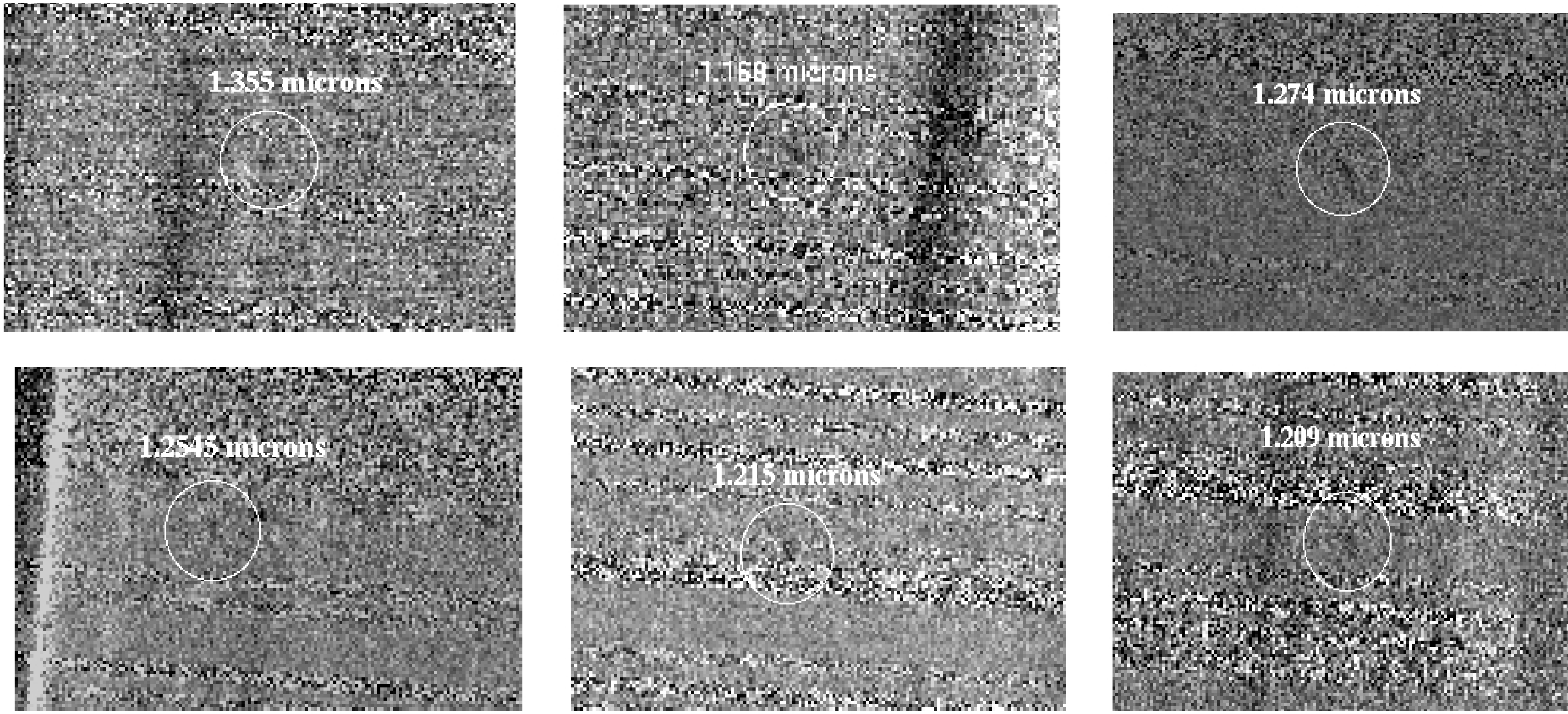


NIRSPEC slit positions

- 9 clusters completed to October 2005
- Clusters have well-defined mass models & deep ACS imaging
- Obs. sensitivity ~ 3-9.10^{-18} cgs; magn. > ×15-20 throughout
- Sky area observed: 0.3 arcmin^2; V(comoving)~50 Mpc^3
- 6 promising lensed emitter candidates (>5σ)
- $8.6 < z < 10.1$; L ~ 2 - 10. 10^{41} cgs; SFR ~ 0.2 -1 $M_\odot$ yr^{-1}

Candidate Lyα Emitters

$8.6 < z < 10.2$; L ~ 2 - 10. 10^{41} cgs; SFR ~ 0.2 - 1 $M_{\odot}$ yr^{-1}



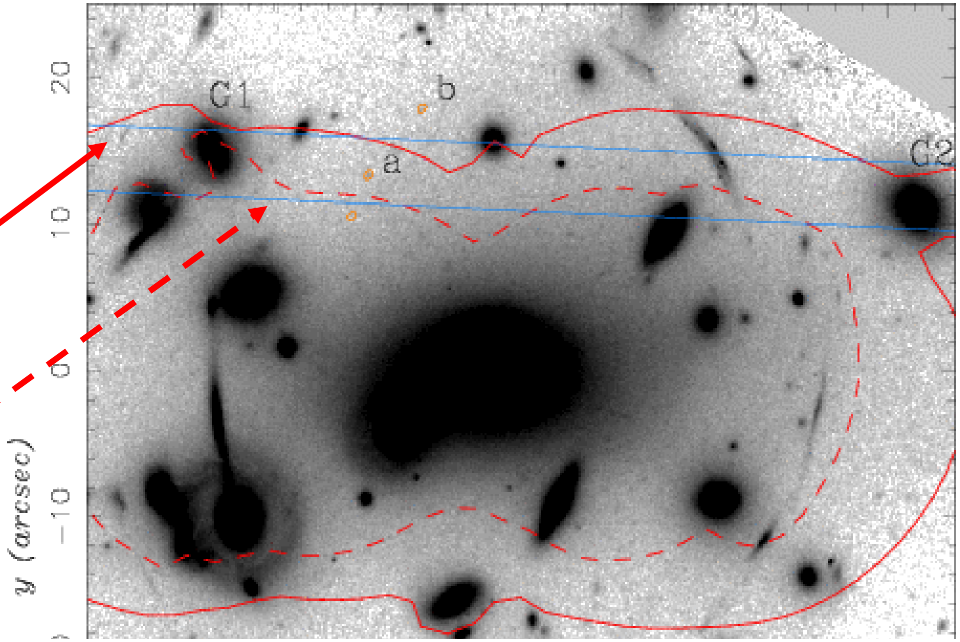
Recognize burden of proof that these are z~10 emitters is high

Each detection is seen in independent exposures/visits

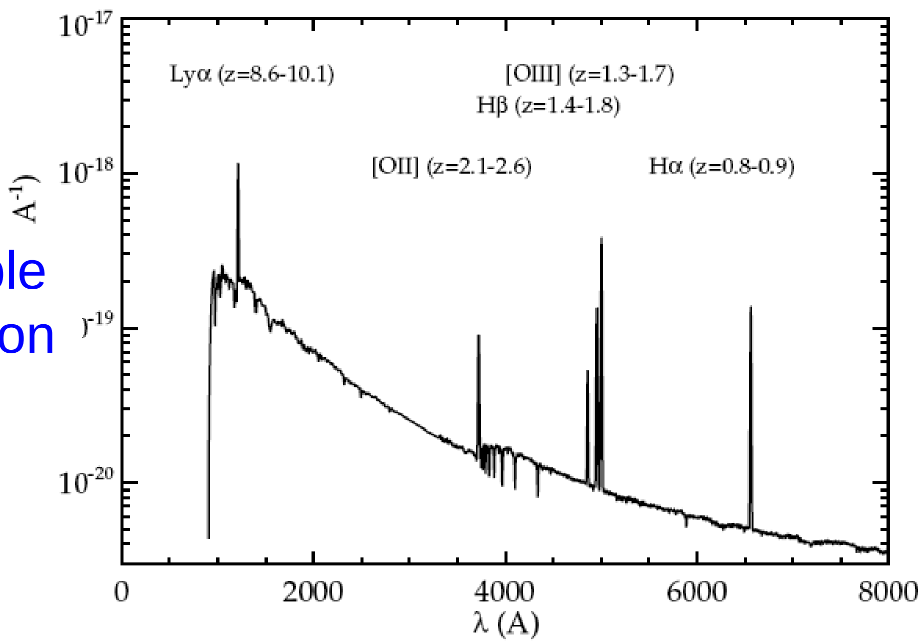
Interlopers? Critical Line Location Depends on z

z=5

z=1



Possible emission lines



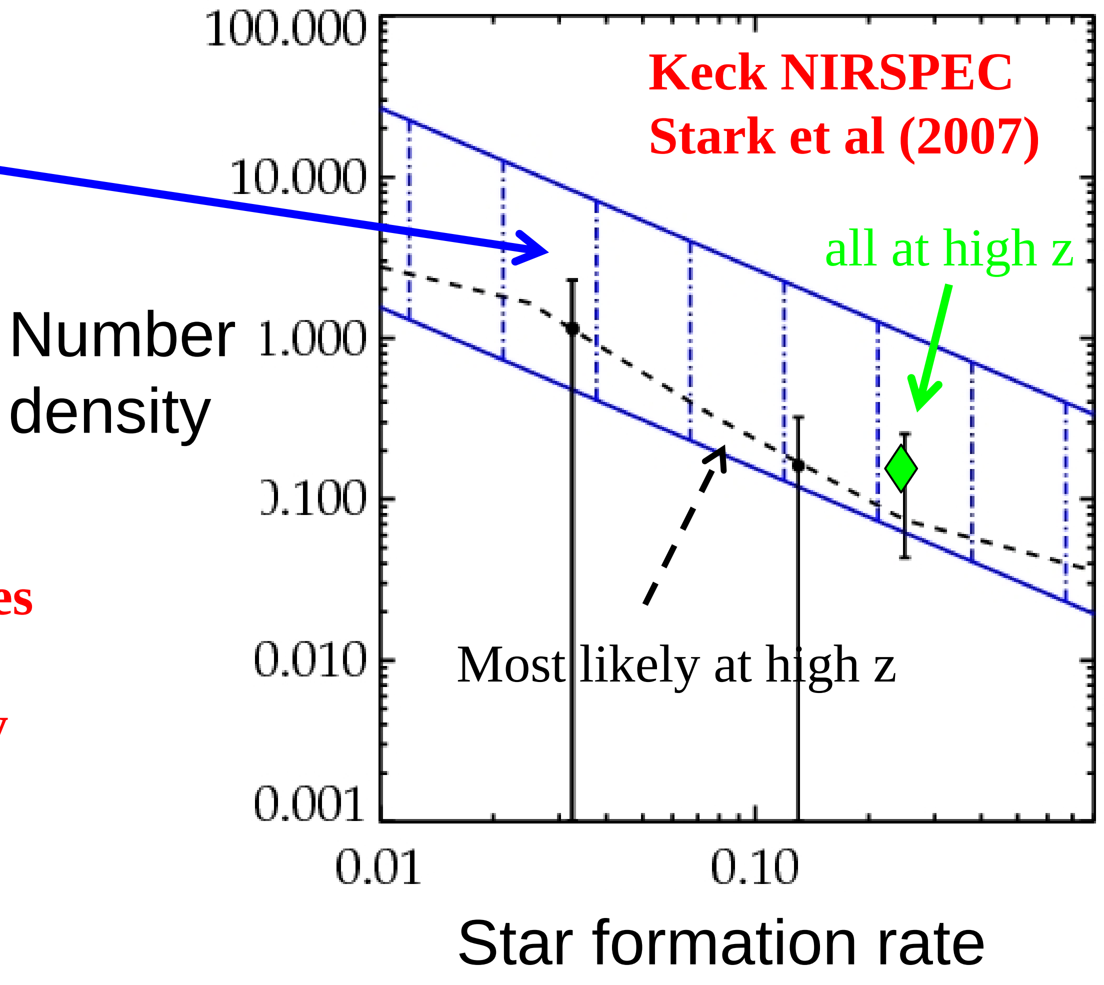
Bonus of strong lensing:

By only searching the z>5 critical line, we minimize contamination from magnified interlopers at 1<z<3 which would lie elsewhere in the image plane.

So contamination is less likely than in non-lensed searches

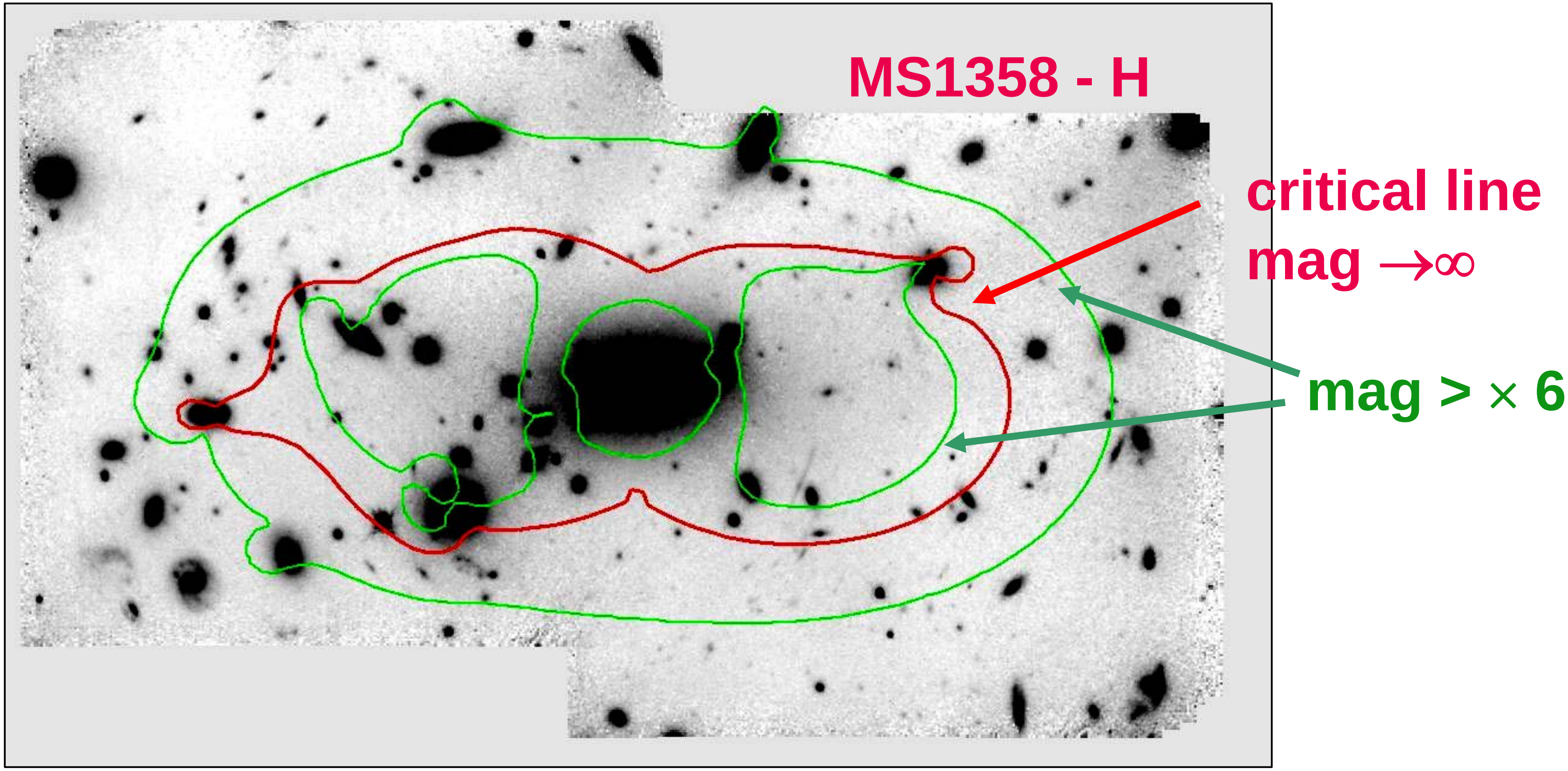
Did our faint galaxies at z~10 cause reionization?

Zone for a significant contribution of ionizing radiation

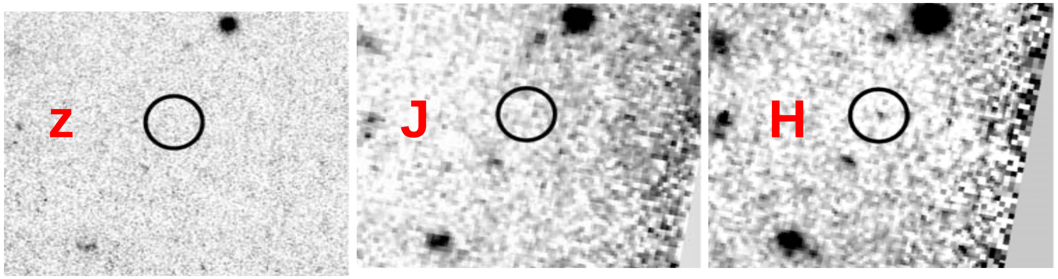


If >3 of our 6 candidates are at high z, low luminosity galaxies may play a dominant role in cosmic reionization

Pushing Further Back - II: Keck, Hubble & Spitzer



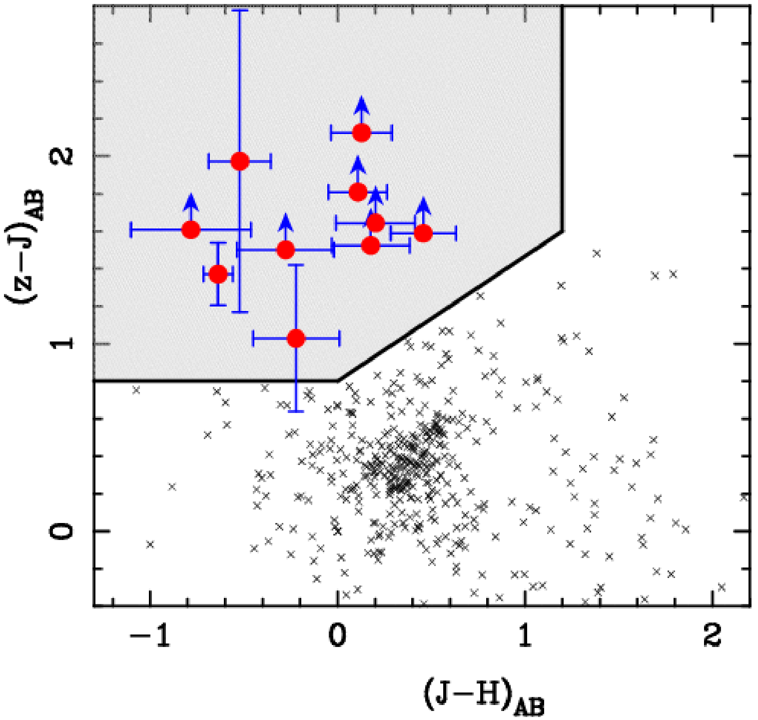
- Imaging 8 clusters with Hubble/Spitzer
- Finding lensed drop outs with z~7-12

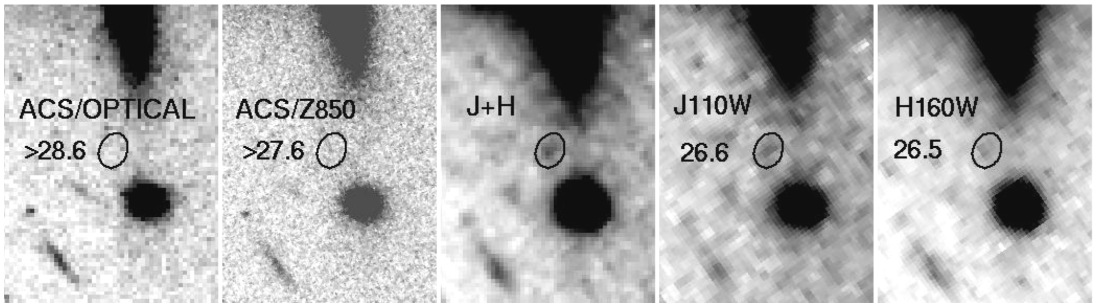


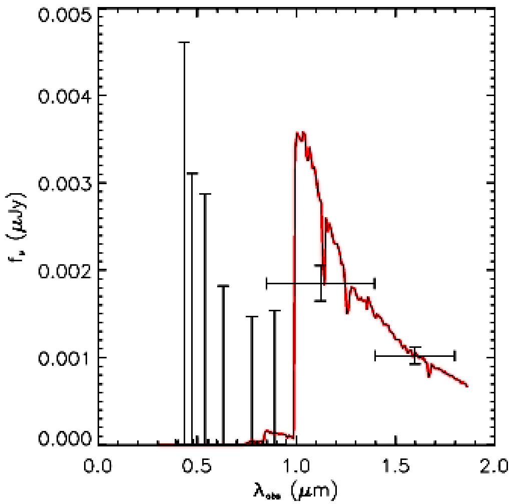
Candidate with z~11

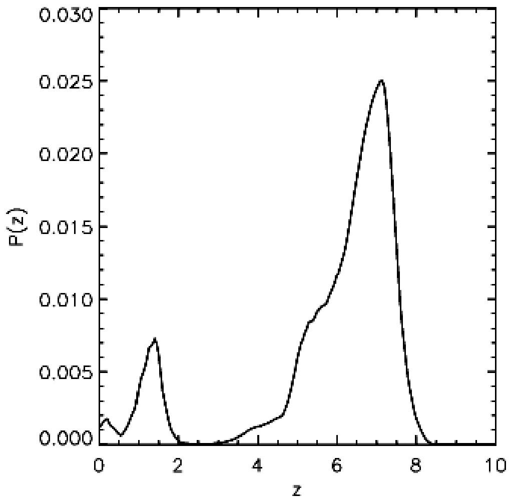
Richard et al (2008)

Lensed z-band dropouts (z~7-8)









- 10 candidate z-drops in the 6 clusters surveyed to H_{AB} ~ 26 - 26.8
- Implied SFR ~ 0.1 - 2 $M_\odot$ yr^{-1} (unlensed)
- Spectroscopic follow-up with NIRSPEC (v difficult)
- z~1-2 red galaxies expected to be main contaminants

Summary: What We Have Learned?

• The accumulated stellar mass at z~5 (1.2 billion years after the Big Bang) points to a lot of early star formation which is probably enough to have ended the `dark ages'.

• We cannot directly see this earlier population of star forming galaxies via conventional surveys so we guess the sources responsible must be intrinsically very faint

• Via the magnification of gravitational lensing we have secured the first glimpse of an early population of sub-luminous sources. Their abundance is sufficiently high that they may dominate the reionization process

• We are finding further candidates supporting this deduction. We will need to study all these in more detail with improved techniques

Where Next?

Improved performance from our existing telescopes will extend present work

- adaptive optics on Keck: - detailed studies of selected z~5 systems
- Keck MoSFIRE: - multi-object infrared spectra for z > 7 sources
- new infrared camera WF3 on Hubble (Servicing Mission 9/08):
  panoramic imaging for z > 7 sources

2014+: 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

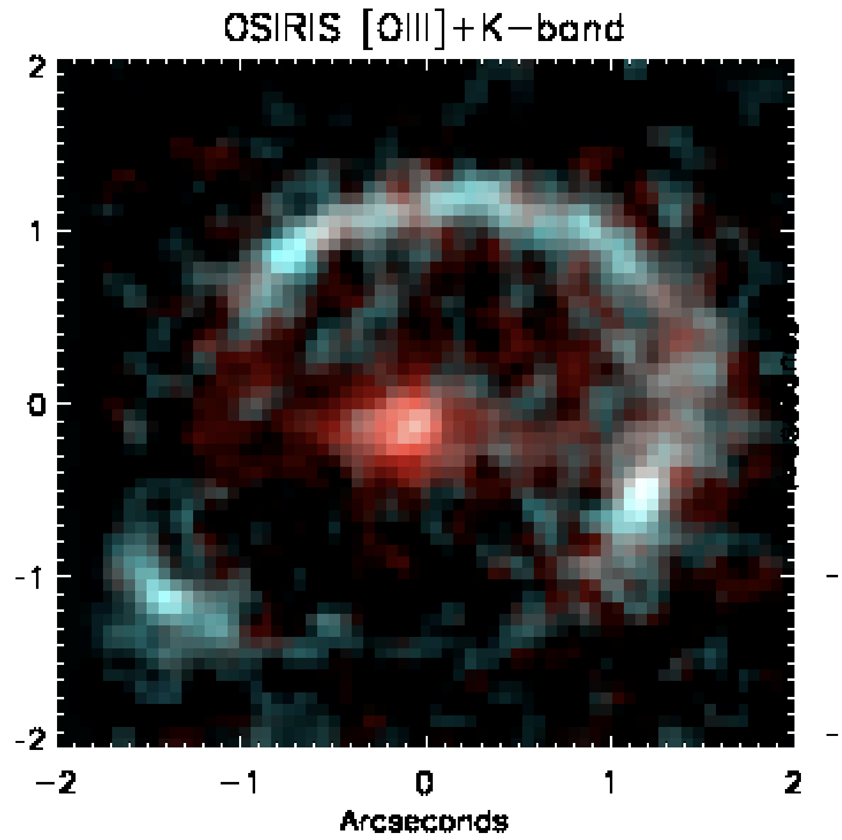

All-Sky Adaptive Optics is Here!
Keck Laser Guide Star

Gravitational Lensing + Adaptive Optics!

A highly magnified z=3.1 galaxy

How and when do these early galaxies `mature' into the more familiar rotating spirals we see today?

Distant galaxies are very small and faint - Keck + adaptive optics is blazing the trail!



Keck/OSIRIS laser (Sept 2007)

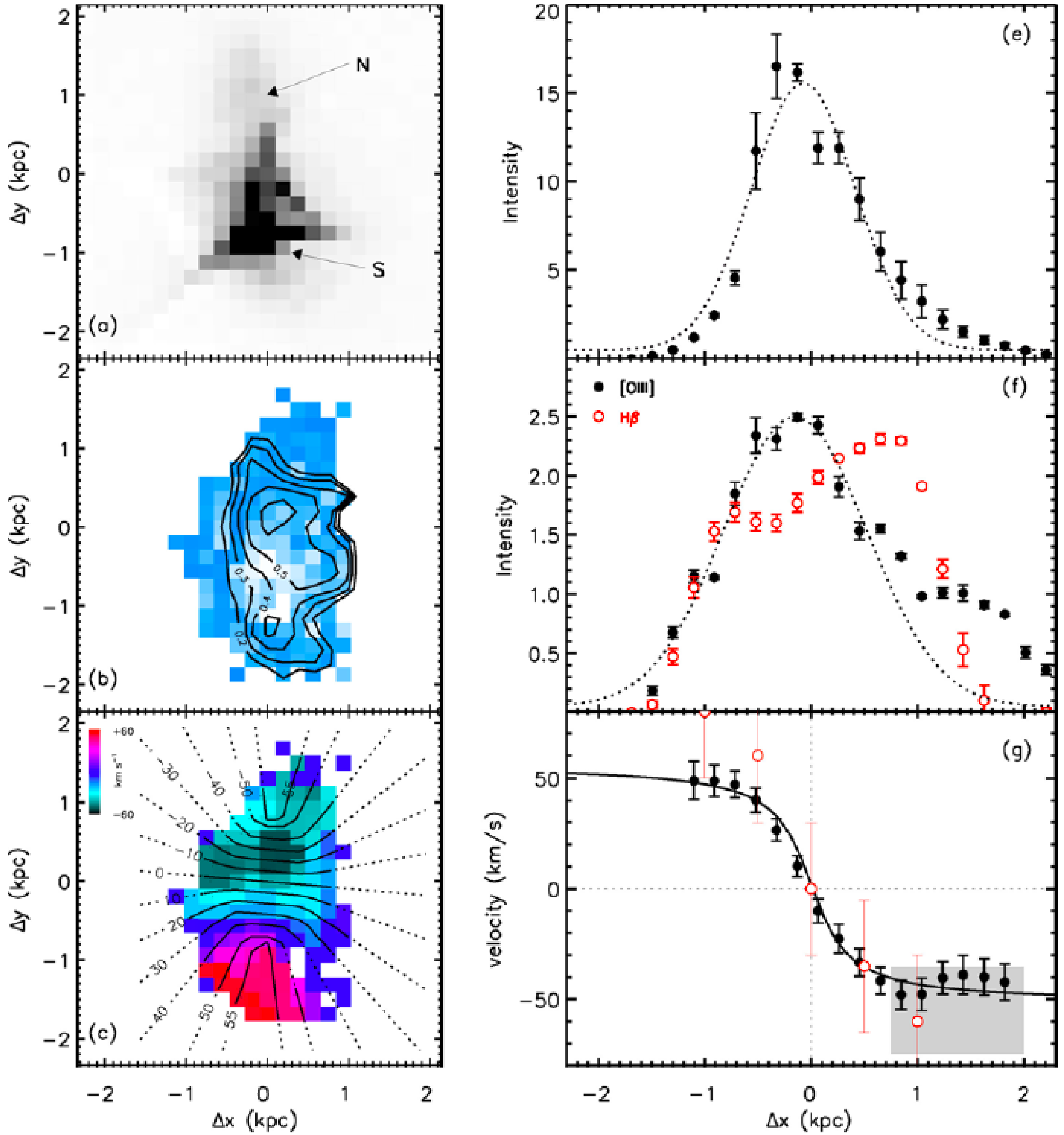
Laser adaptive optics delivers 75 milli arcsec resolution

BUT: x28 magnification means ~8 milliarcsec (100 pc) in source plane!!

Rotation in a young galaxy seen 3 billion years after the Big Bang

Intensity →

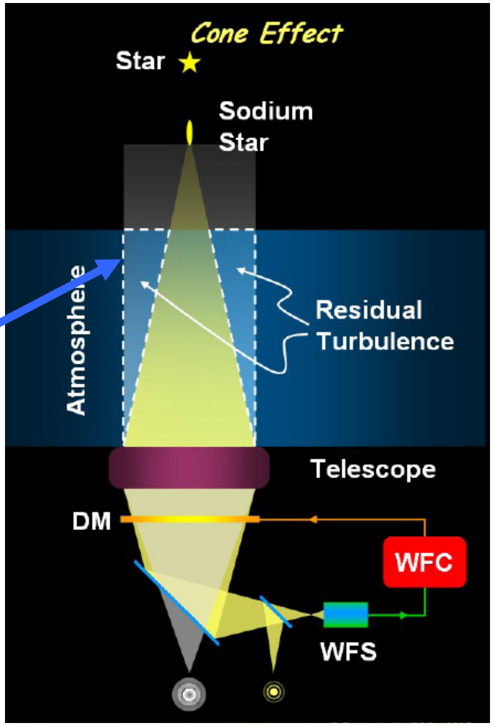
Rotation →



Keck LGSAO + OSIRIS

Stark et al, Nature (submitted)

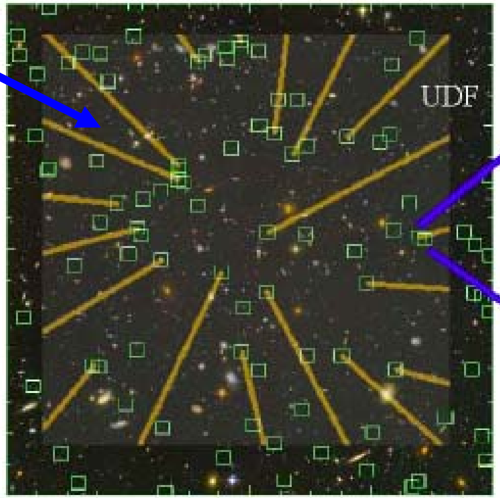
Next Generation Adaptive Optics



- Single laser - definitely exciting but performance limited by `cone effect'!

"We can see enough to know what we're missing!"

- Next Steps:
  - Multiple lasers to defeat `cone effect'
  - Multi-deformable mirrors widen field with uniform correction
  - Independent correction of multi-objects in a larger field



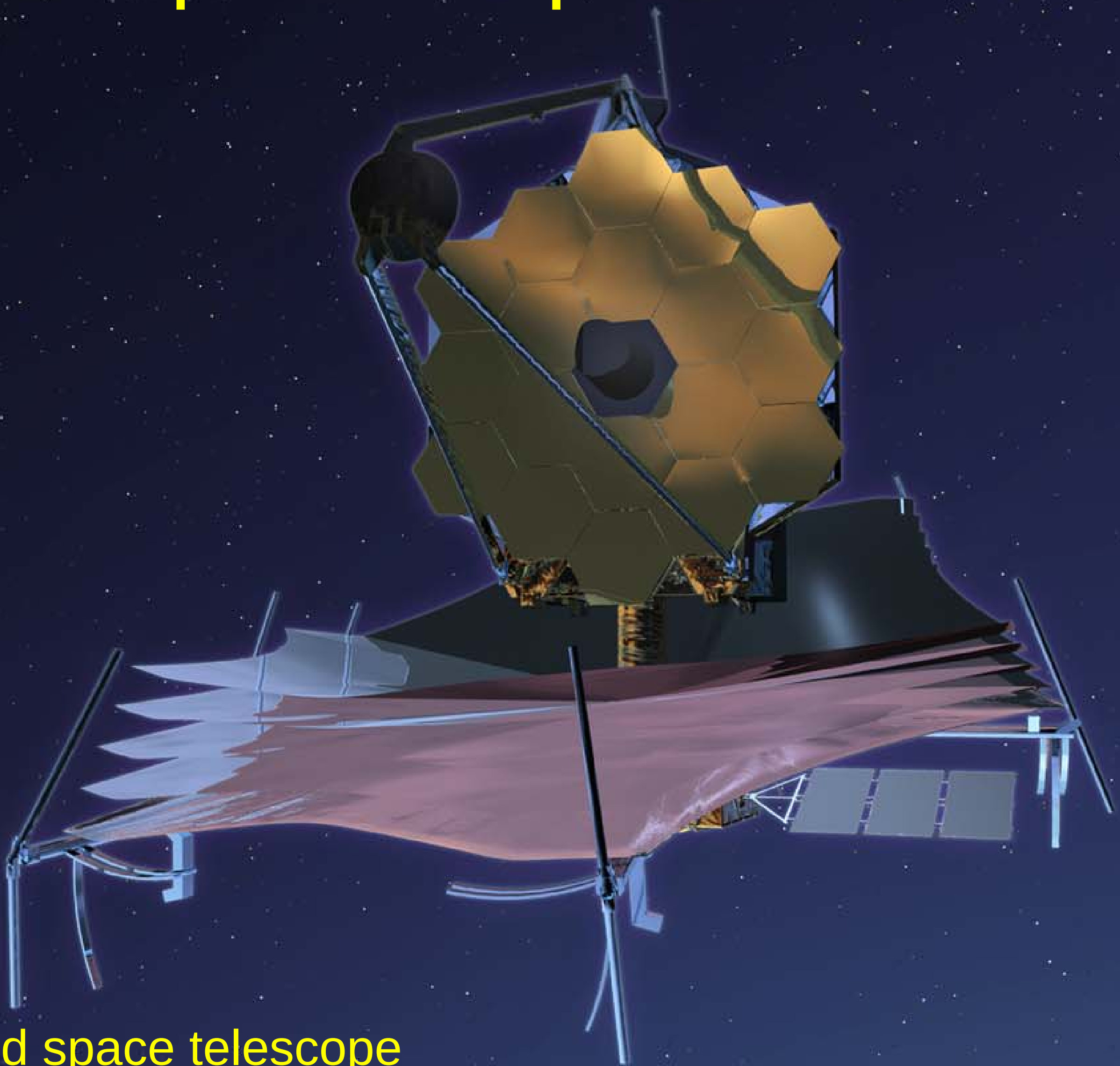
Next generation adaptive optics will allow us to study large numbers of early (small) objects in far greater detail to take our story to the next level of detail

HST Wide Field Camera 3

WF3 properties: (IR channel 850 - 1170nm):
2.1 × 2.3 arcmin field of view
0.13 arcsec pixel^{-1}
2 grisms, several nb filters

WFC3/IR can cover the same area as NICMOS Cam3 to the same depth in one tenth of the time. This would allow us in principle to extend to the near-IR surveys like GOODS and the UDF.

James Webb Space Telescope

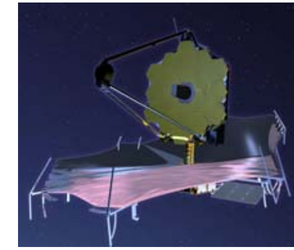


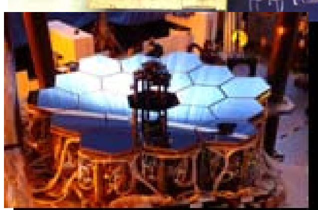
6.5m infrared space telescope

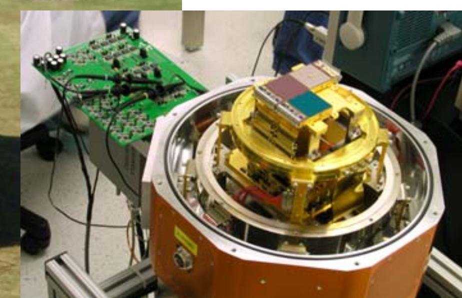
Under construction & due for launch ~2013

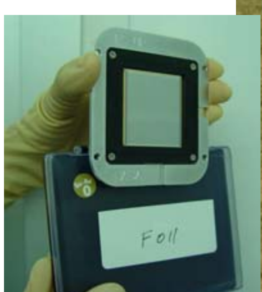
JWST is on track

..if the $$’s continue to flow..





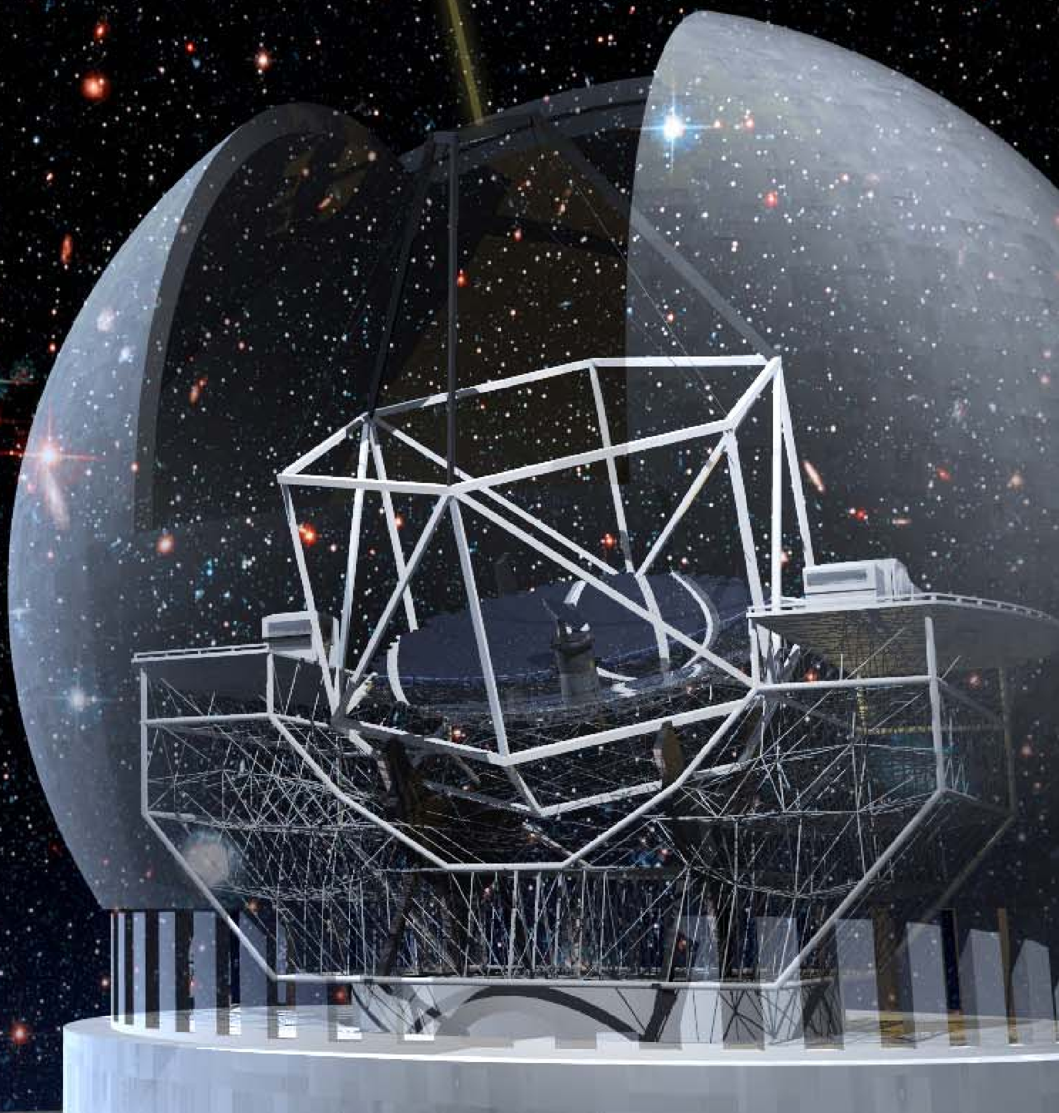




Thirty Meter Telescope Project

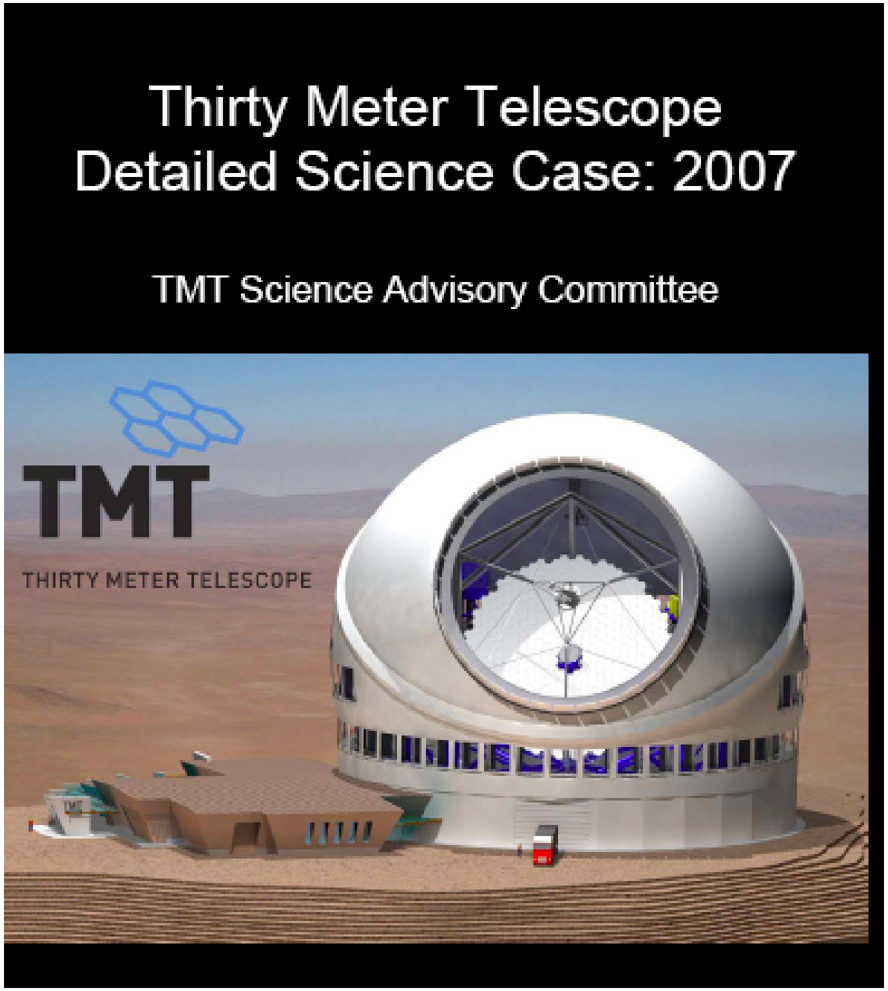
A partnership of Caltech, U California,Canada (& hopefully Japan)

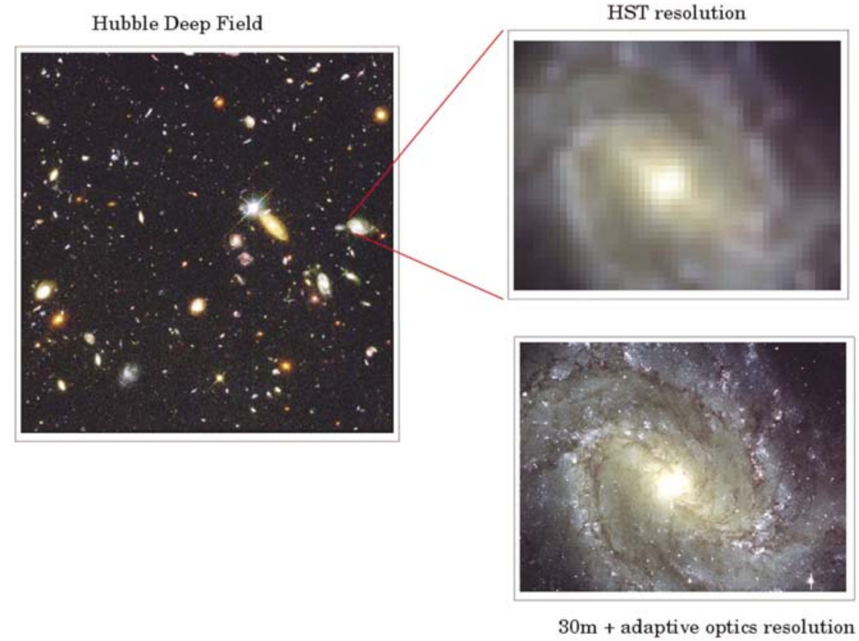
- Completing detailed design
- Builds on successful Keck technologies
- Operational ~2016



http://www.tmt.org

Ground-based Synergy (2015-2025): TMT/JWST





TMT will offer the combination of the gains discussed earlier plus that of increased aperture and resolution

See http://www.tmt.org/foundation-docs/index.html

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)

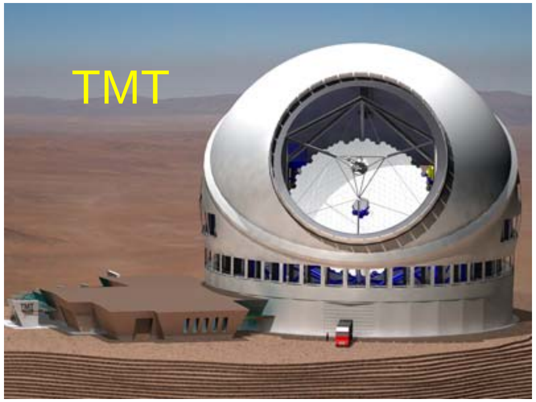
Era of ELTs (2016 -)

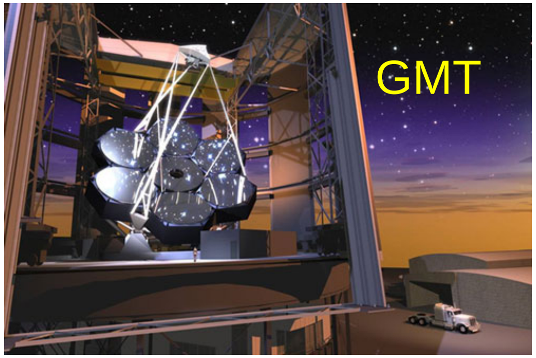
A new generation of 20-42m ELTs is being designed:

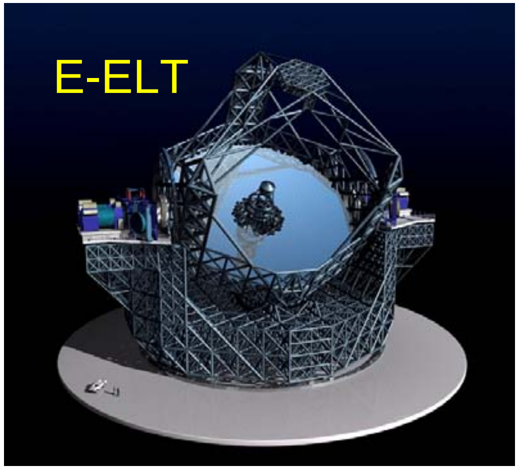
• Thirty Meter Telescope (www.tmt.org)
- Caltech, UC, Canada + poss. Japan
- 30m f/1 primary via 492 × 1.4m segments
- $80M design underway (2004-2009)
- $760M construction cost (FY2006)
- major fund-raising already underway

• Giant Magellan Telescope (www.gmto.org)
- Carnegie, Harvard, Arizona, Texas, Australia + others
- 21m f/0.7 primary via 6 × 8.2m segments
- funds for $50M design study being raised

• European ELT (www.eso.org/projects/e-elt)
- 42m f/1 primary with 900+ ×1.4m segments
- 5 mirror design
- 57M Euros design underway (2007-)

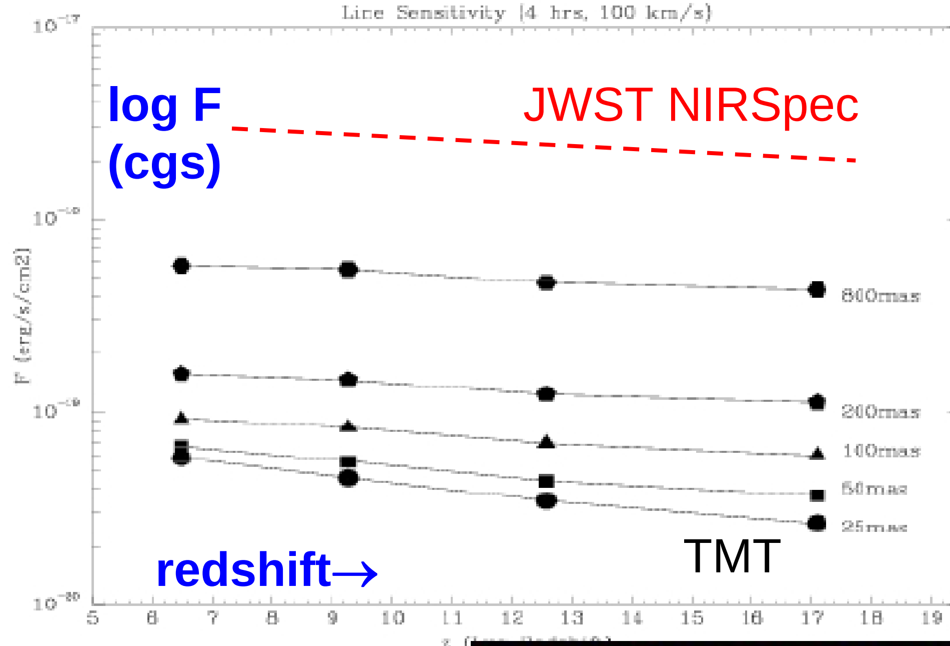




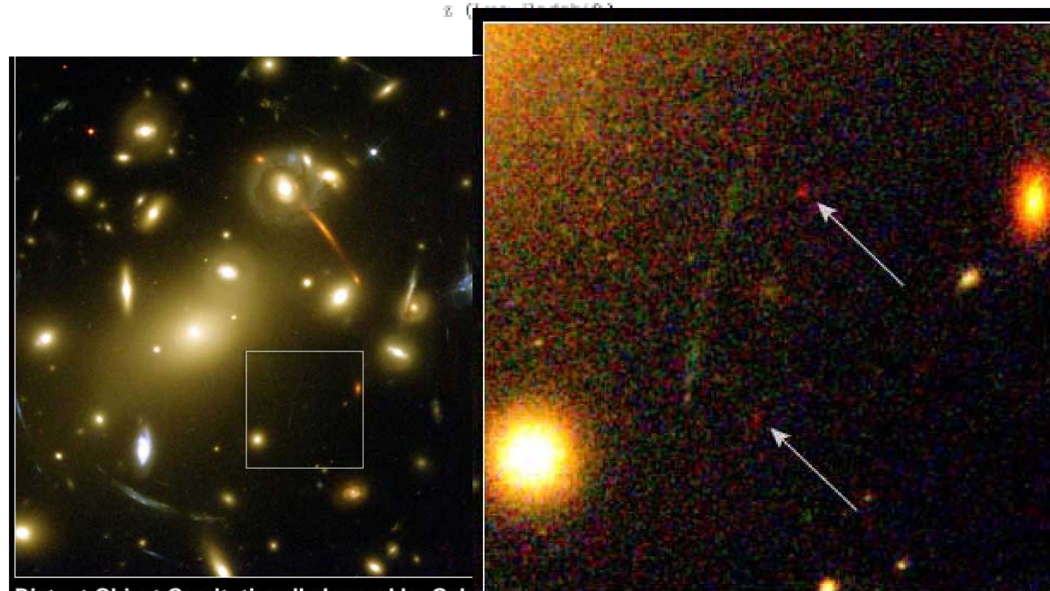


Probing Early Galaxies: Effect of Source Size

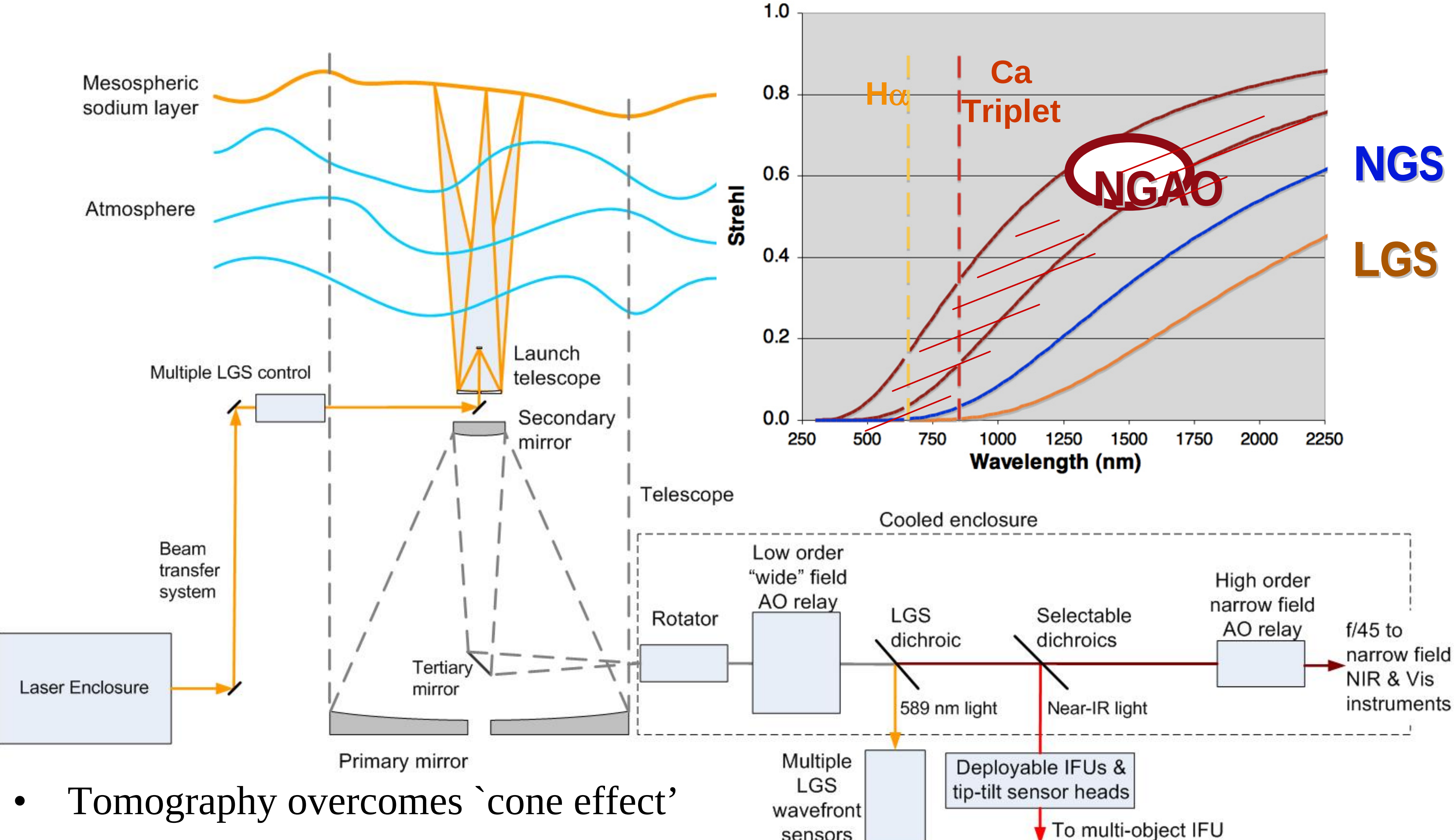
- How small are z~10 sources?
- Strongly-lensed examples have intrinsic sizes ~30mas!
- Gain of TMT+AO over JWST in detection very significant



- Abell 2218 z~5.7 Lyα emitter
- Magnification ×30
- HST size 0.23 × <0.15 arcsec
- Unlensed source is 30 mas
- Source is < 150pc in size!


Distant Object Gravitationally Lensed by Gala
NASA, ESA, R. Ellis (Caltech) and J.-P. Kneib (Observatoire Midi-Pyrenees) • STScI-PRC01-32

Keck Next Generation AO



- Tomography overcomes `cone effect'
- AO-corrected, IR tip-tilt improves sky coverage
- Closed-loop for 1st relay; open-loop for deployable IFUs & 2nd relay

Courtesy: Wizinowich & Keck AO team