Galaxy Formation/Evolution and Cosmic Reionization Probed with Multi-wavelength Observations of Distant Galaxies

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Outline of the Talk

1. Background
2. Research
   - Study of Early Galaxy Formation/Evolution
     (Quest for the Farthest Galaxies)
   - Study of Cosmic Reionization
   - Study of Early Structure Formation
     (Protocluster of Galaxies)
3. Conclusion

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     (Protocluster of Galaxies)
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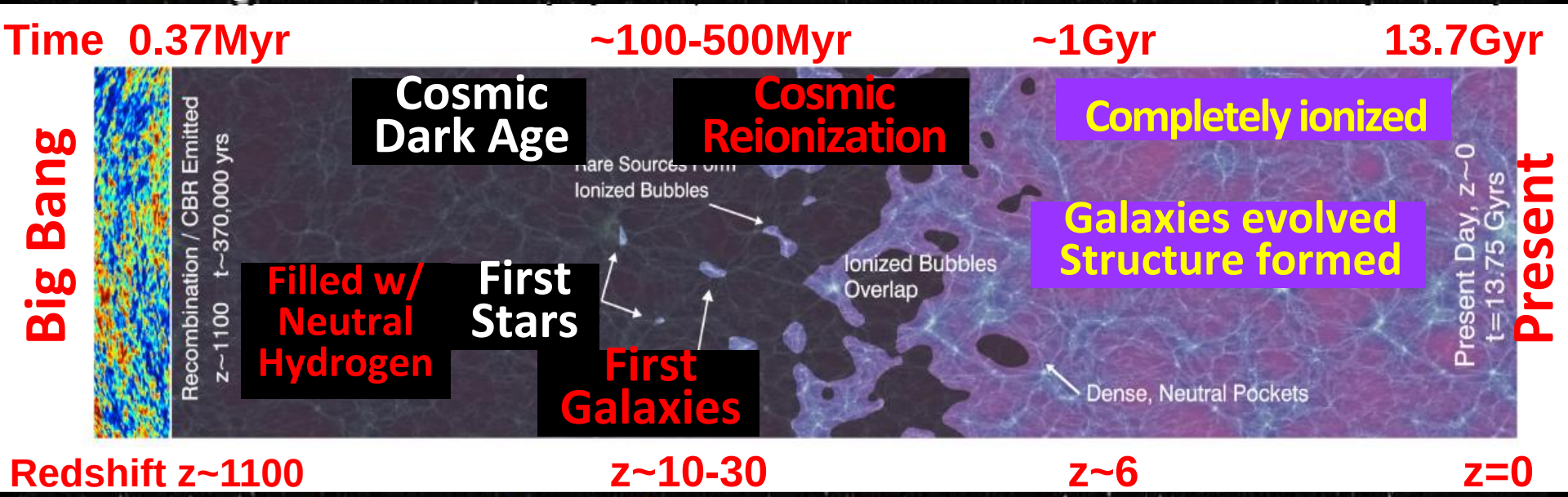
History of the Universe

Fig: Robertson et al.(2010)



1. Studying Galaxy/Structure Formation/Evolution

- When and how did the first generations of galaxies form?
- How have galaxies and structures evolved from the past to present?

2. Studying Reionization of the Universe

- When did cosmic reionization start and end?
- How had reionization progressed in time and space?

Final Goal:

To understand relation between Galaxy Evolution and Reionization

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2. Research
   - Study of Early Galaxy Formation/Evolution
     (Quest for the Farthest Galaxies)
   - Study of Cosmic Reionization
   - Study of Early Structure Formation
     (Protocluster of Galaxies)
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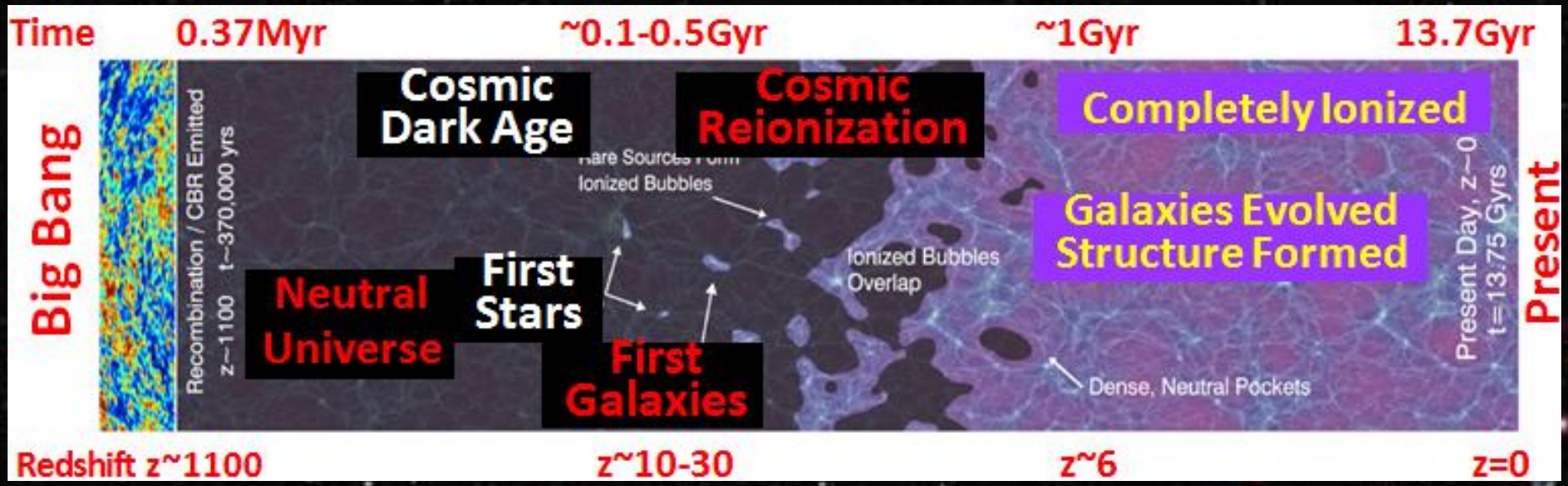
Fig: History of the Universe (Robertson+10)



1. Study of Galaxy Formation/Evolution in the Early Universe

1. When and how did the first generations of galaxies form?
2. How have galaxies evolved from the past to present?

↓

Observing distant galaxies = Observing the past galaxies

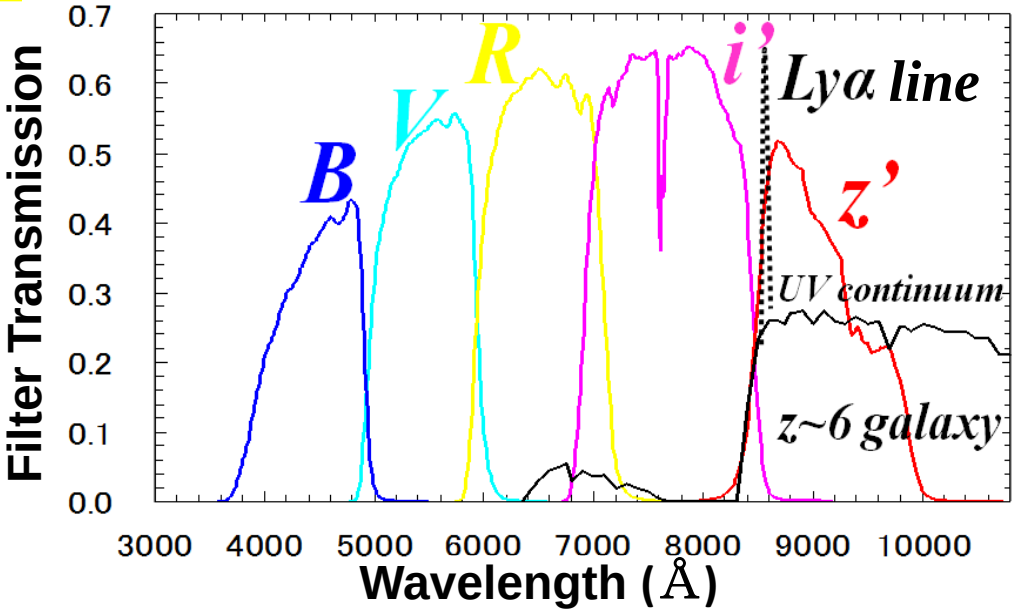
↓

1: first galaxies ⇒ oldest galaxies ⇒ detecting most distant galaxies

2: Tracing galaxy evolution ⇒ Comparing galaxies at different redshifts

Method to detect distant galaxies ①

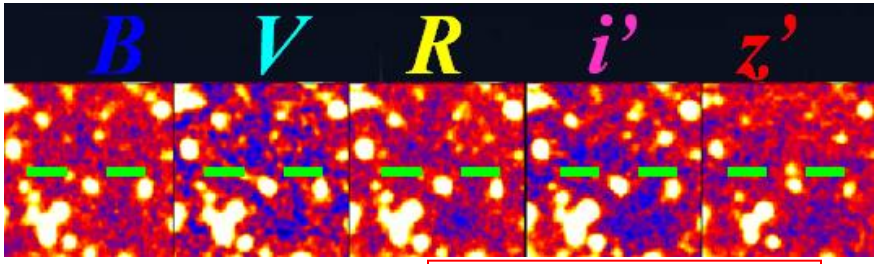
Detecting UV continuum with Broadband Filters (Δz ~ 1)



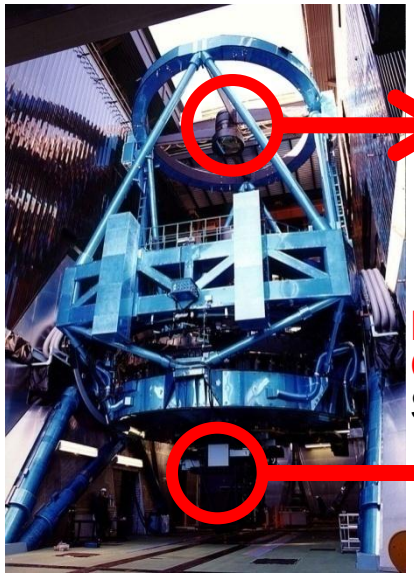
Imaging

Blank Night Sky Field

z ~ 6 **Galaxy Candidates**



Spectroscopy



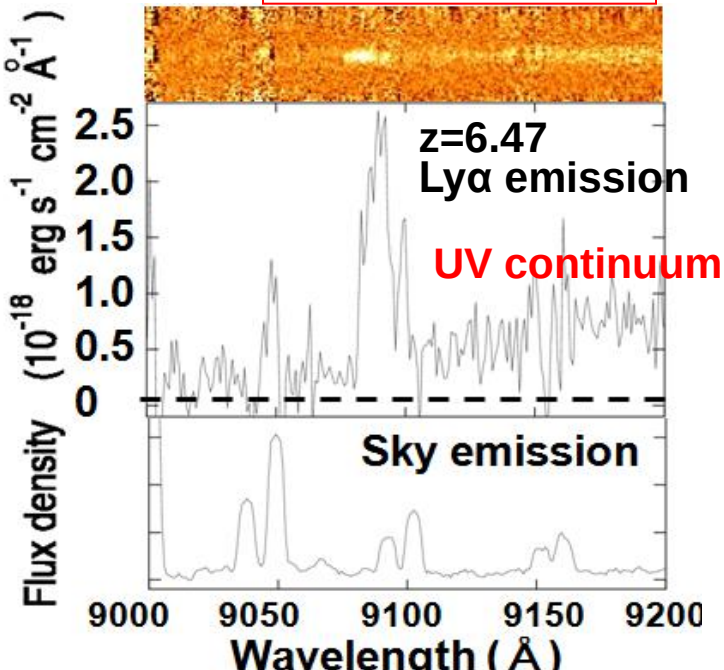
Imaging

Prime Focus Camera
Suprime-Cam

Spectroscopy

8m Subaru Telescope

FOCAS Spectrograph



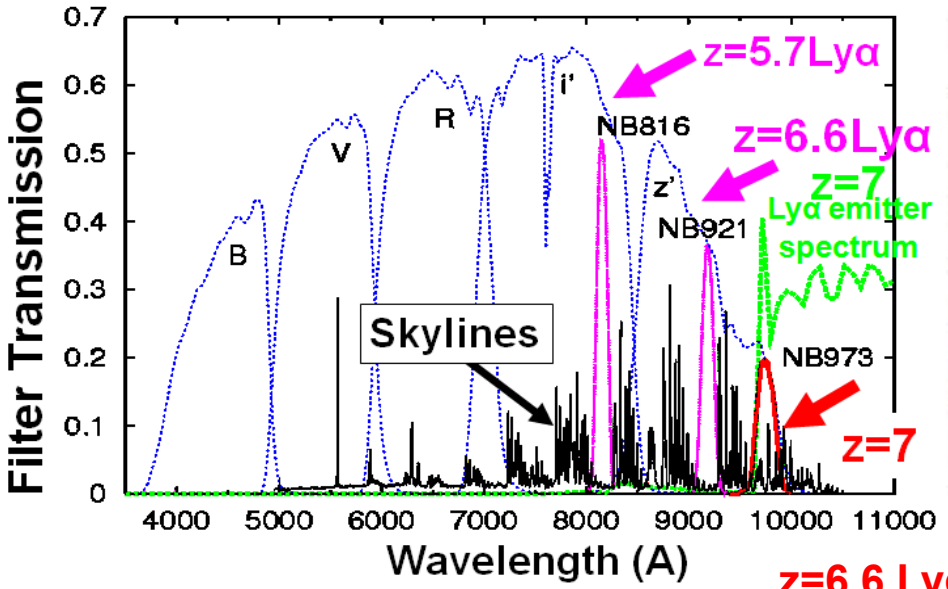
Method to detect distant galaxies ②

Detecting Lyα line with Narrowband Filters (Δz ~ 0.1-0.2)

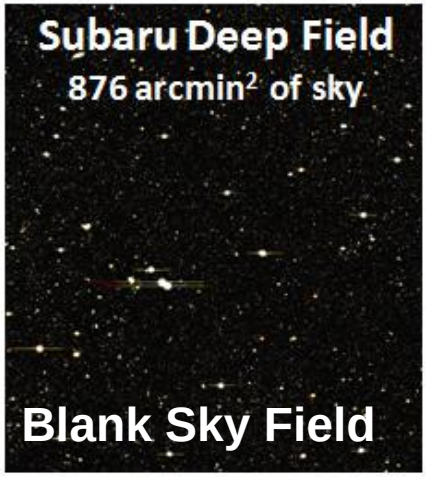
Subaru Telescope
Prime Focus
Camera
Suprime-Cam

FOCAS Spectrograph

Broadband (BB) filters: B, V, R, i', z'
Narrowband (NB) filters: z=5.7, 6.6, 7 Lyα

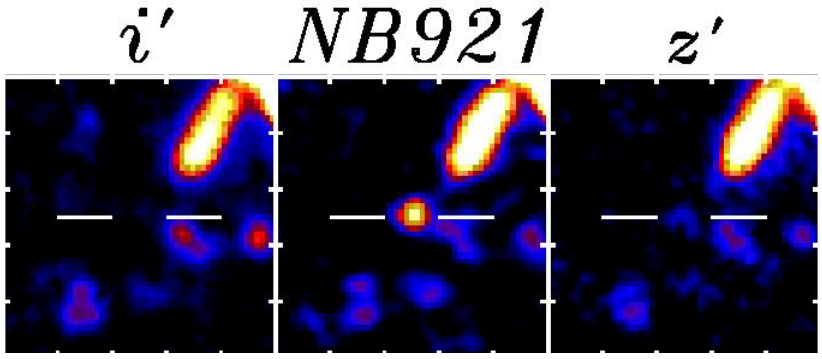


Imaging

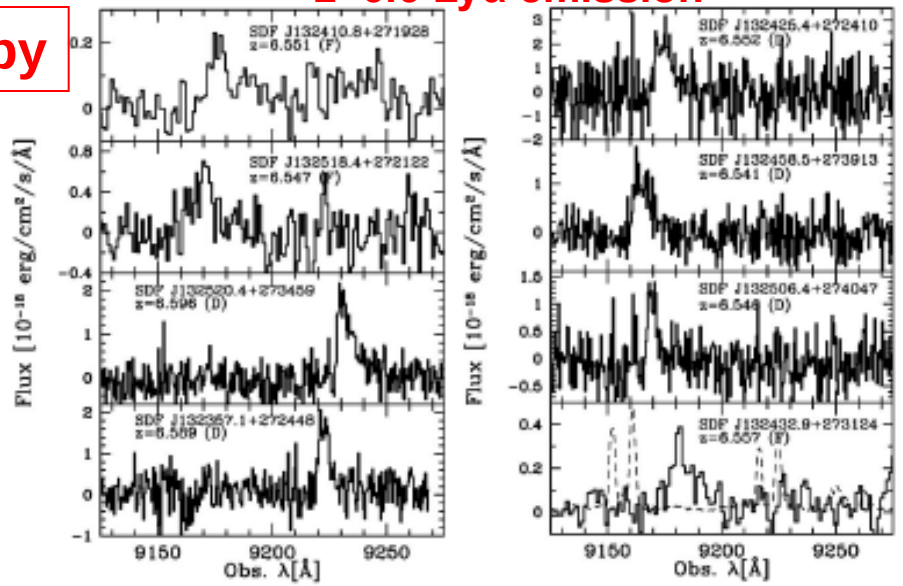


Spectroscopy

z=6.6 Galaxy Candidates

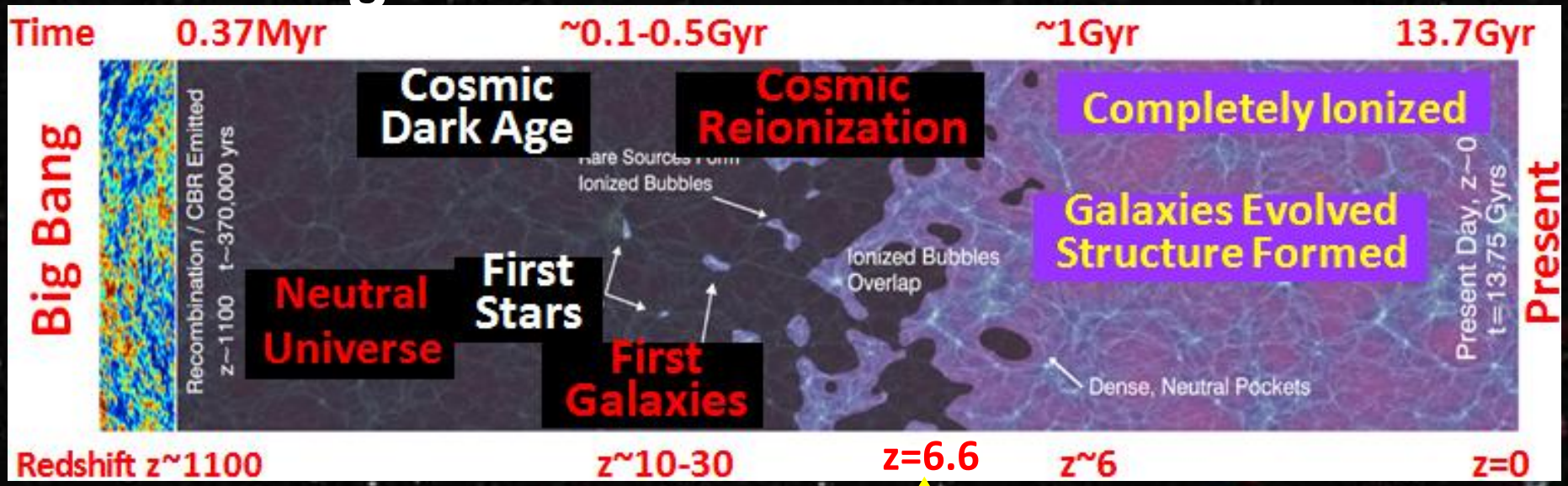


z=6.6 Lyα emission



Recent Progress

Fig: History of the Universe (Robertson+10)



Trend:

Detecting more and more distant galaxies

- Approaching epoch of 1st galaxies
- Probing galaxy evolution
- Studying reionization from the properties of galaxies

z=6.6 galaxies
A few years age …
The most distant galaxies ever observed

Discovery of z=7.0 galaxy
z=7.2 galaxy
(I and collaborators)

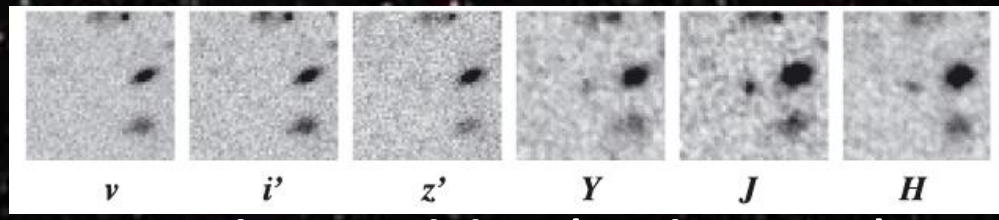
Detections of z=8-12 galaxy candidates

Detecting UV continuum with Broadband Filters

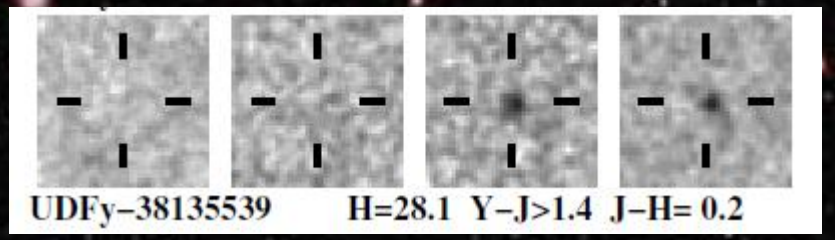
Hubble Space Telescope/WFC3 Camera revolutionized detections of candidates for z~7-12 galaxies

Hubble Ultra Deep Field ©STScI

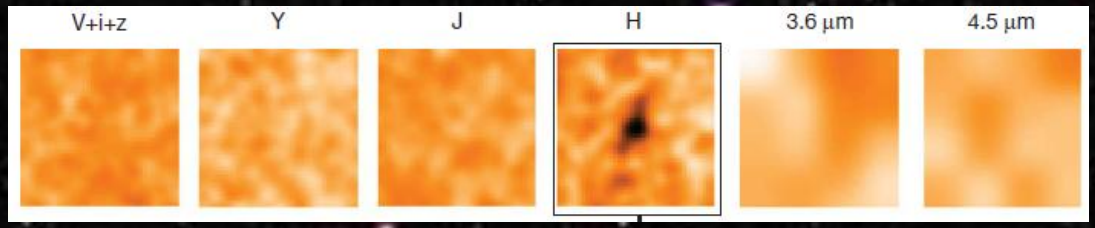
Installation of WFC3 Camera to Hubble Space Telescope



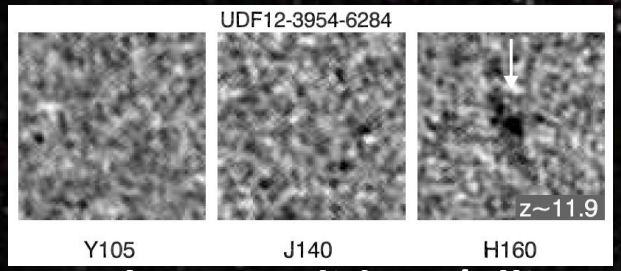
z ~ 7 galaxy candidate (Bunker+2010)



z ~ 8 galaxy candidate (Bouwens+2010)



z ~ 10 galaxy candidates (Bouwens+2011)



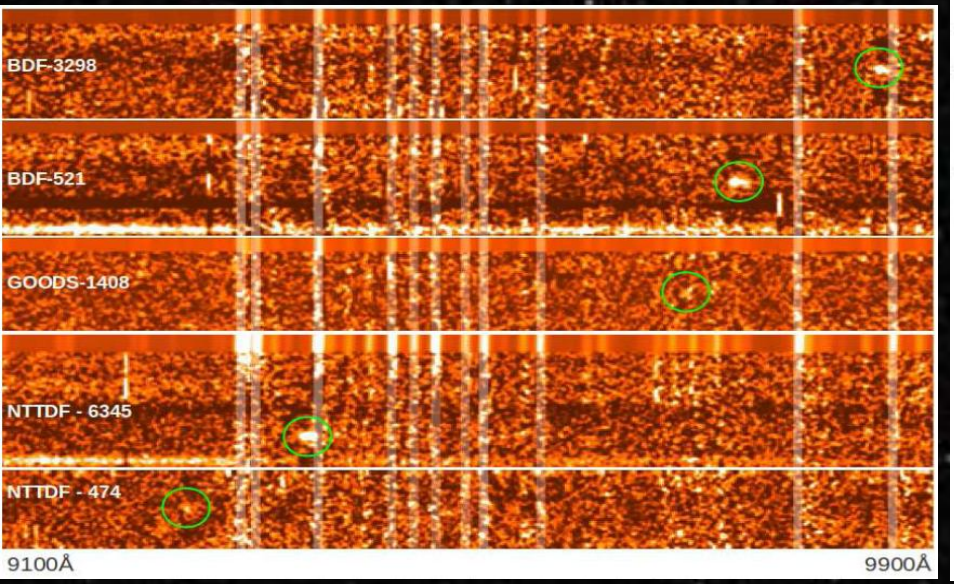
z ~ 12 galaxy candidate (Ellis+2012)

Spectroscopy has been successful to confirm real galaxies up to z ~ 7

8m Very Large Telescope (VLT)

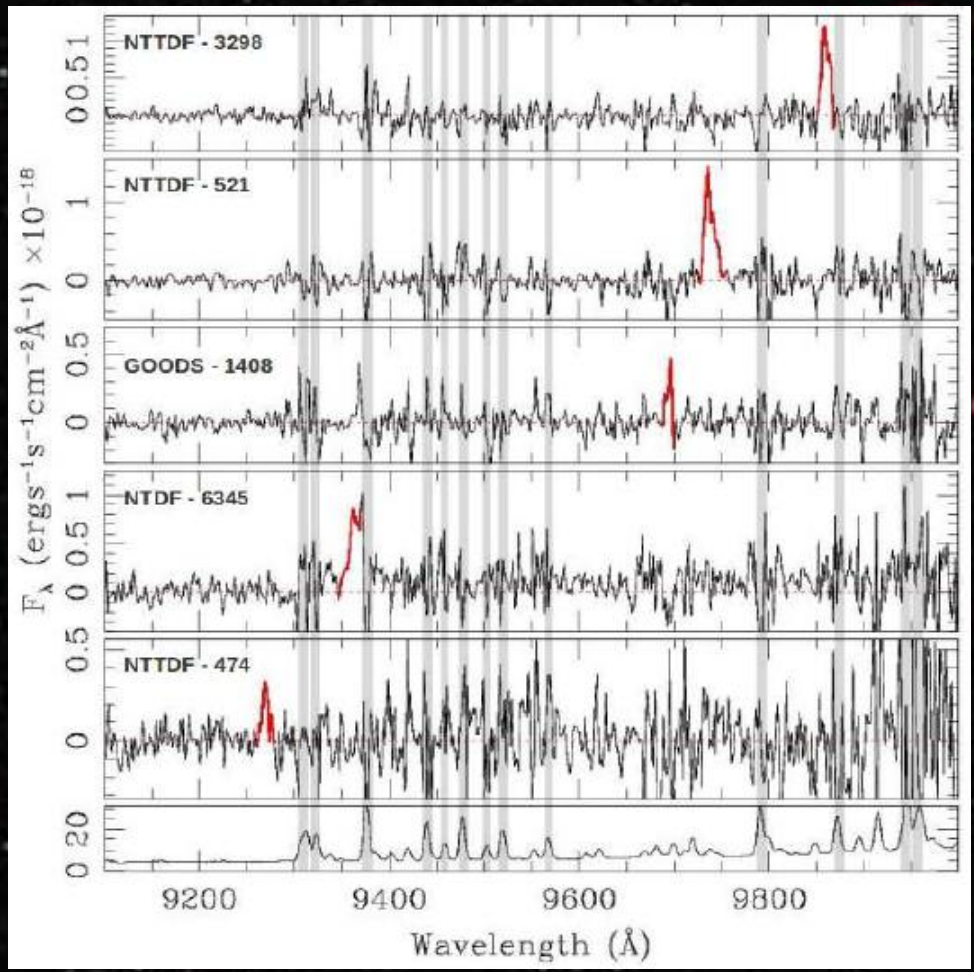
FORS2 Spectrograph

2D spectra of z~7 galaxies



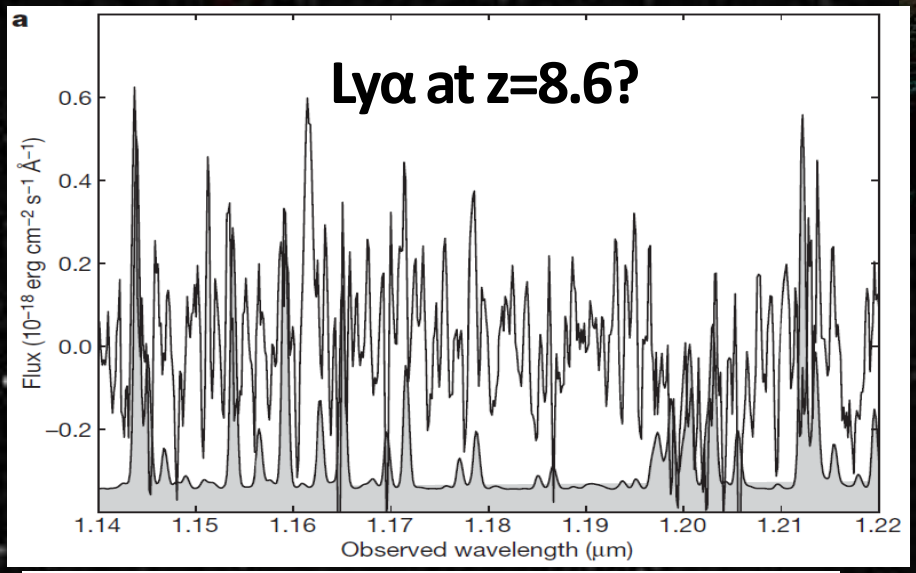
Pentericci et al.2011

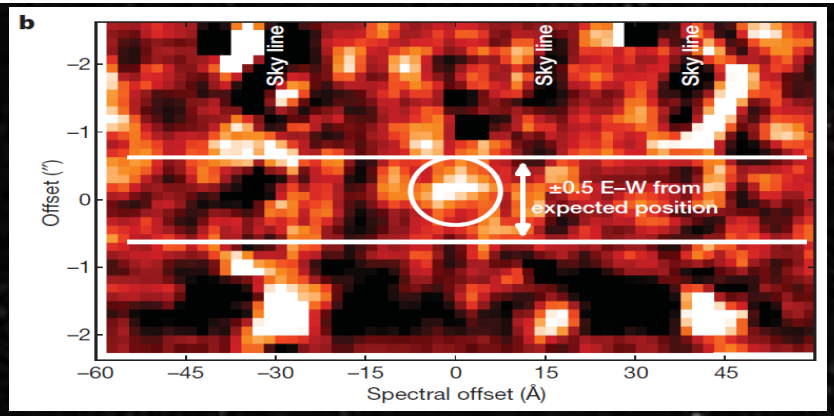
1D spectra of z~7 galaxies



One claim to have confirmed a z ~ 8.6 galaxy, but it was refuted later

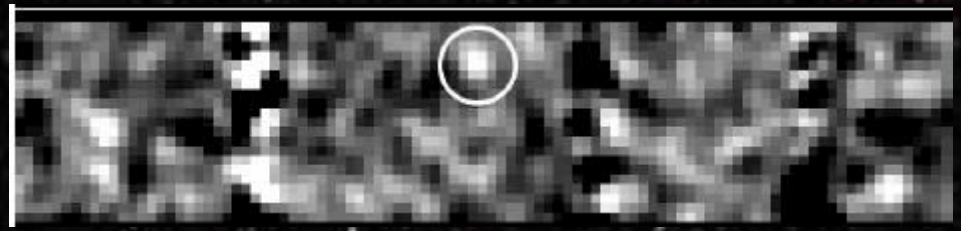
Lehnert et al.2010 claimed confirmation of a z ~ 8.6 galaxy.





Bunker et al.2012 refuted this.

No detection of Lyα line at z ~ 8.6



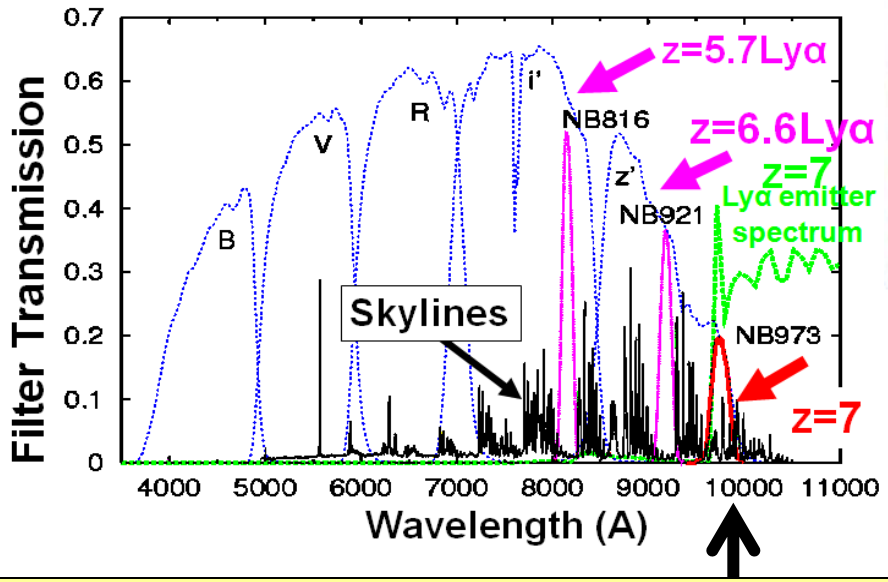
Simulation (Fake source added): Should be detected like this.

Detecting Lyα line with Narrowband Filters (I and collaborator's approach)

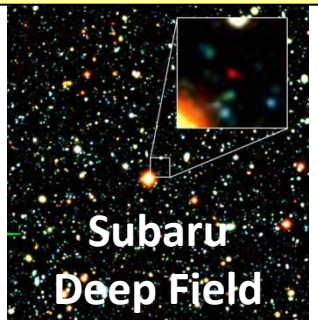
Discovery of the MOST DISTANT (as of 2006-2011) galaxy at z=6.96
Galaxy Formation was already under way just 750 Myr after the Bing Bang (only 6% of the present age of the Universe)

Iye, Ota & Kashikawa et al. 2006, Nature, 443, 186

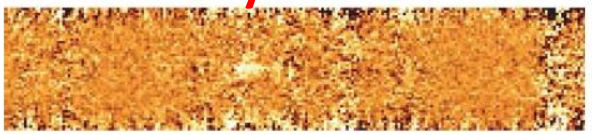
Broadband (BB) filters: B, V, R, i', z'
Narrowband (NB) filters: z=5.7, 6.6, 7 Lyα

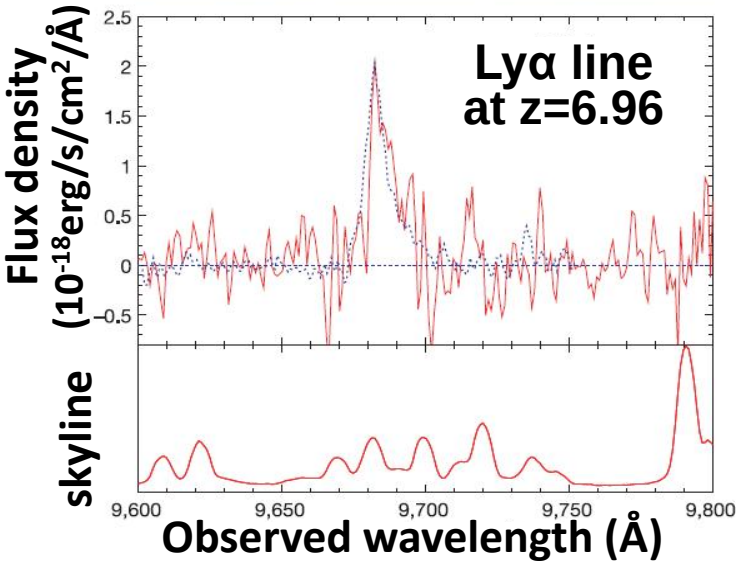


8m Subaru Telescope
Suprim-Cam (Prime Focus Camema)

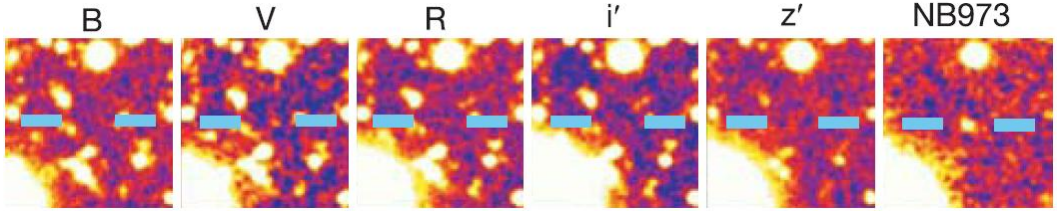


Spectroscopic confirmation of z=6.96 Lyα emission





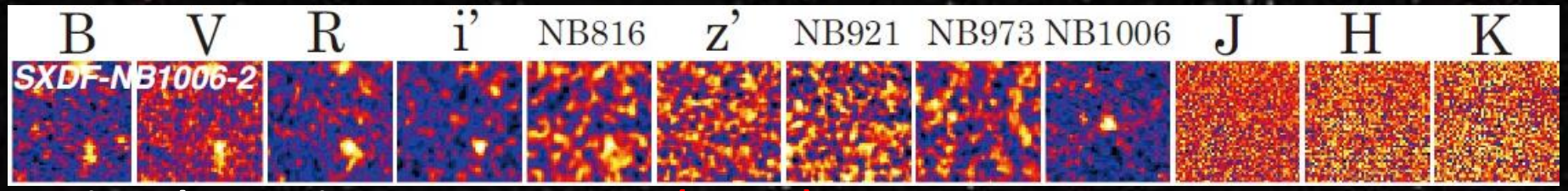
Imaging & spectroscopy of z=7 Lyα was very difficult due to a sharp drop in CCD sensitivity & dense night skylines.



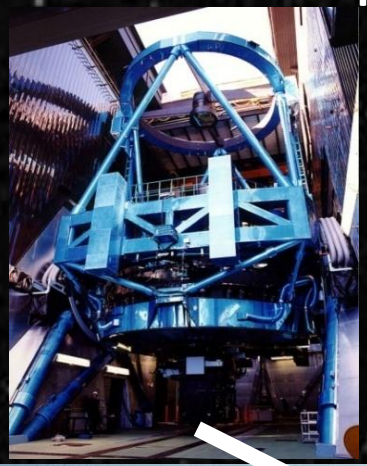
BB and NB filter images of a z=7 galaxy candidate

Discovery of a z=7.215 galaxy (current redshift record!)

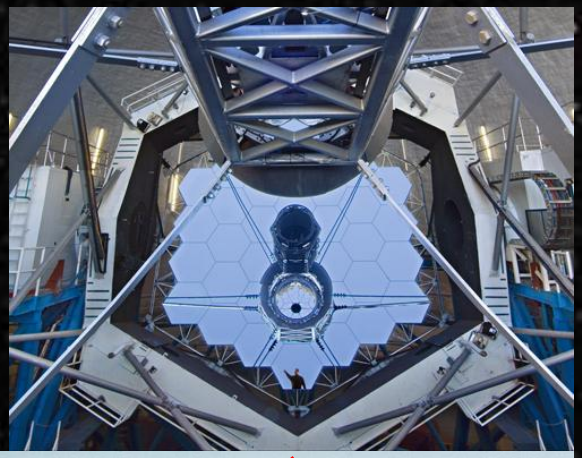
Shibuya, Kashikawa, Ota et al. 2012



Imaging observation
8m Subaru Telescope



Spectroscopy (PI Ota)
10m Keck Telescope



~4200m Mt. Mauna Kea Hawaii

A spectrum of a z=7.215 Lyα emitting galaxy

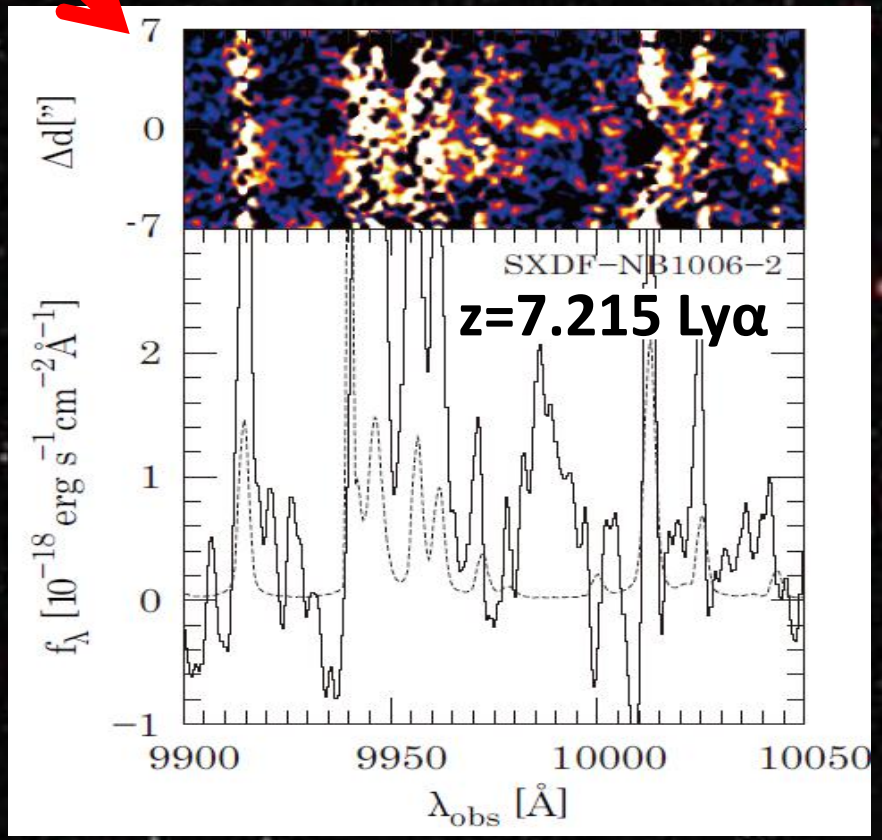


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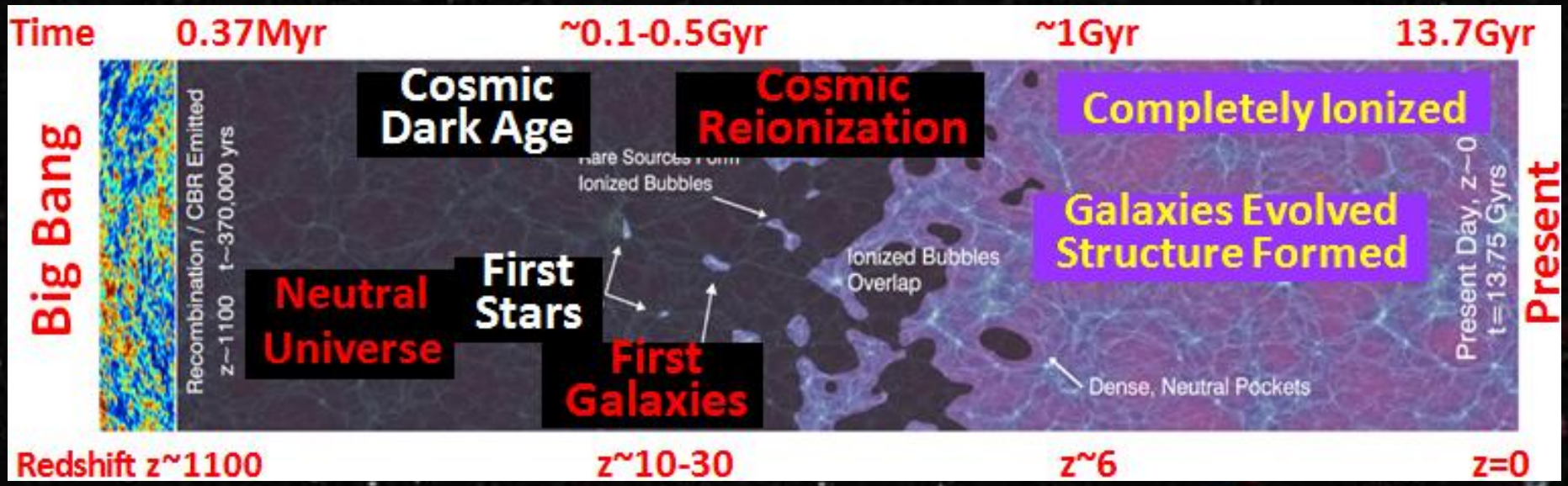
Fig: History of the Universe (Robertson+10)



- Observing distant galaxies
  - Galaxy Formation and Evolution
  - State of Cosmic Reionization

2. Study of Cosmic Reionization

3. When did reionization start and end?

4. How had reionization progressed in time and space?

↓

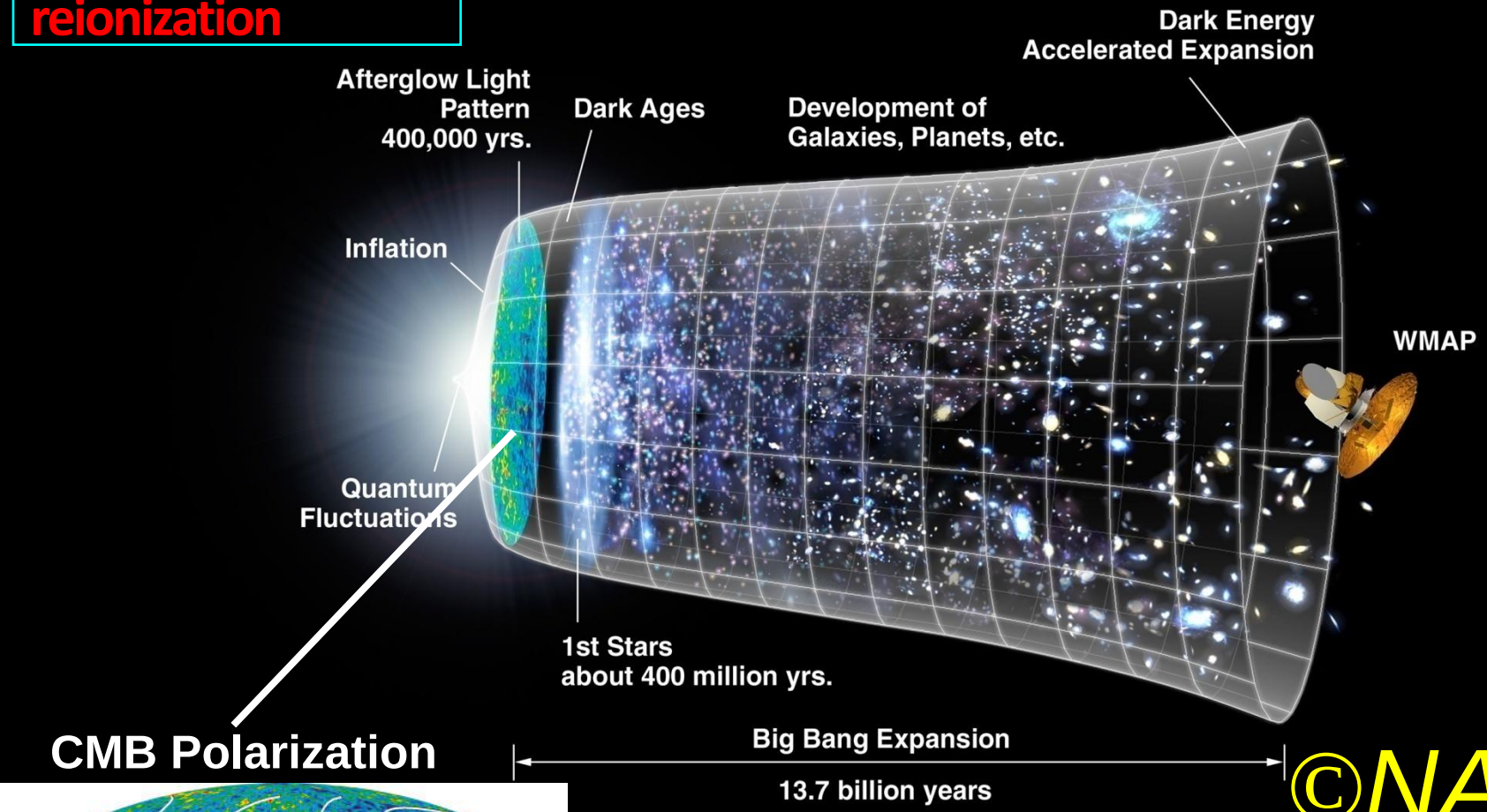
3: Finding epoch where neutral hydrogen fraction ≥ 0% and ~ 100%

4: Tracing how neutral hydrogen fraction changes with redshift and space

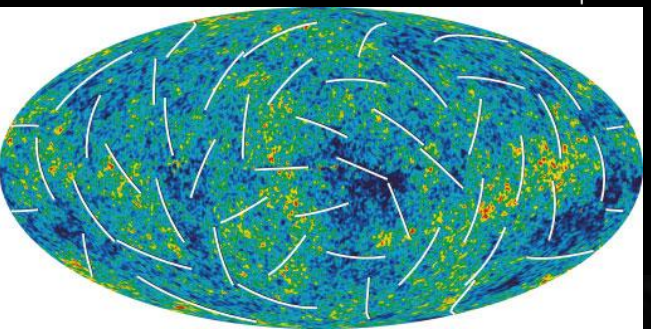
WMAP satellite constrained the epoch of cosmic reionization

Free electrons ionized from neutral hydrogen scatters photons of Cosmic Microwave Background (CMB)

⇒ Polarization of CMB



CMB Polarization



©NASA

Cosmic reionization took place at $z_{reion}=10.6\pm1.2$

NASA/WMAP Science Team

Komatsu et al. 2011

Spectral absorption of distant Quasars can constrain when cosmic reionization ended

Ionized H (After reion.) | Neutral H & Ionized H (Reion. in prgress) | Neutral H (Before reion.)

Observer
Line of sight

Quasar

Ionized H bubbles

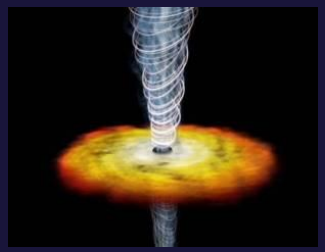
flux

Lyα

Spectrum of distant quasar

Wavelength or Redshift

Wavelength（Å）



Quasar

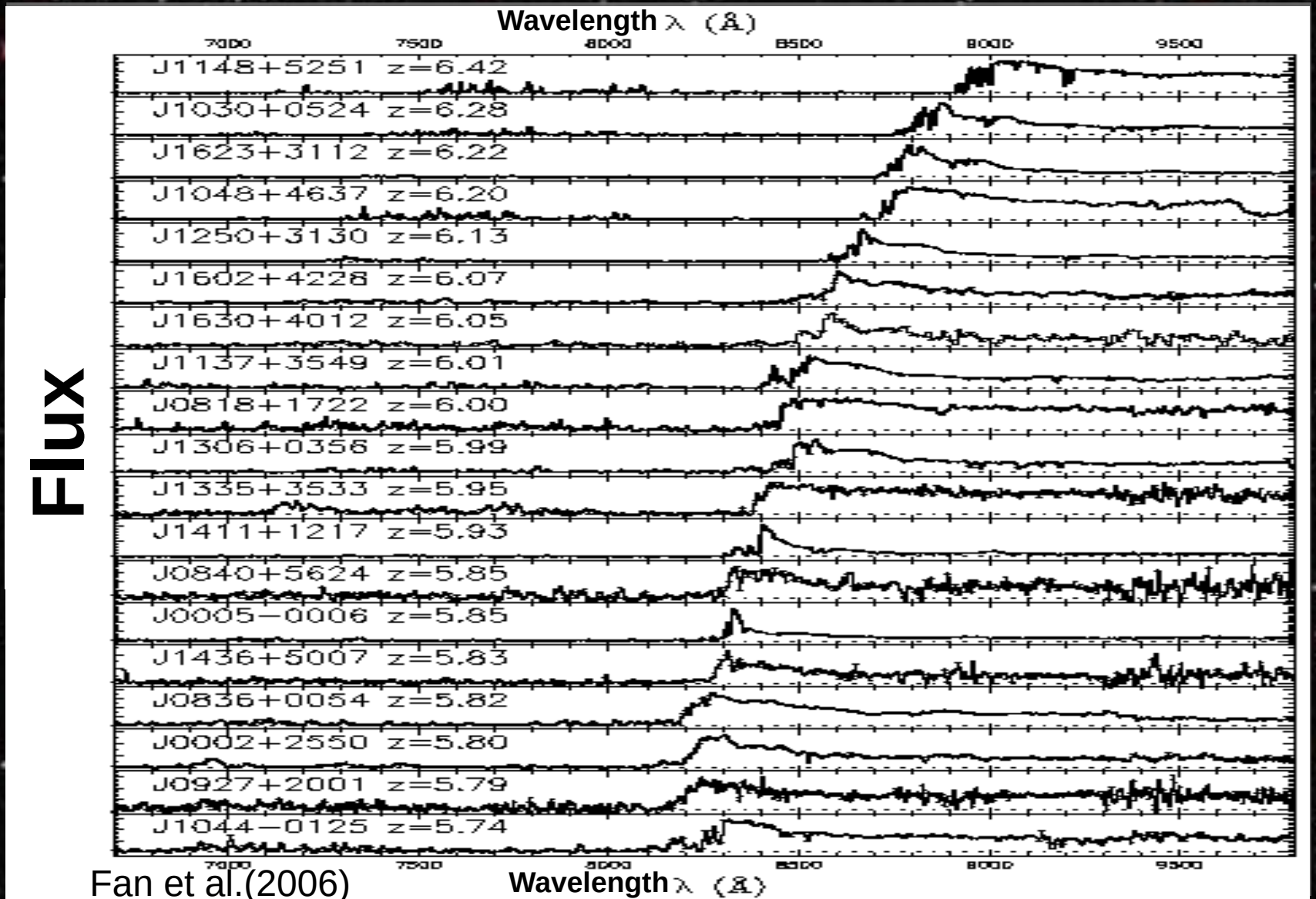
Isolated Transmission
= Ionized H bubble

Dark Regions
= still opaque neutral H

Strong absorption was observed at $z \geq 6$

Volume averaged neutral H fraction of the z~6 Universe ~1 – 4 %

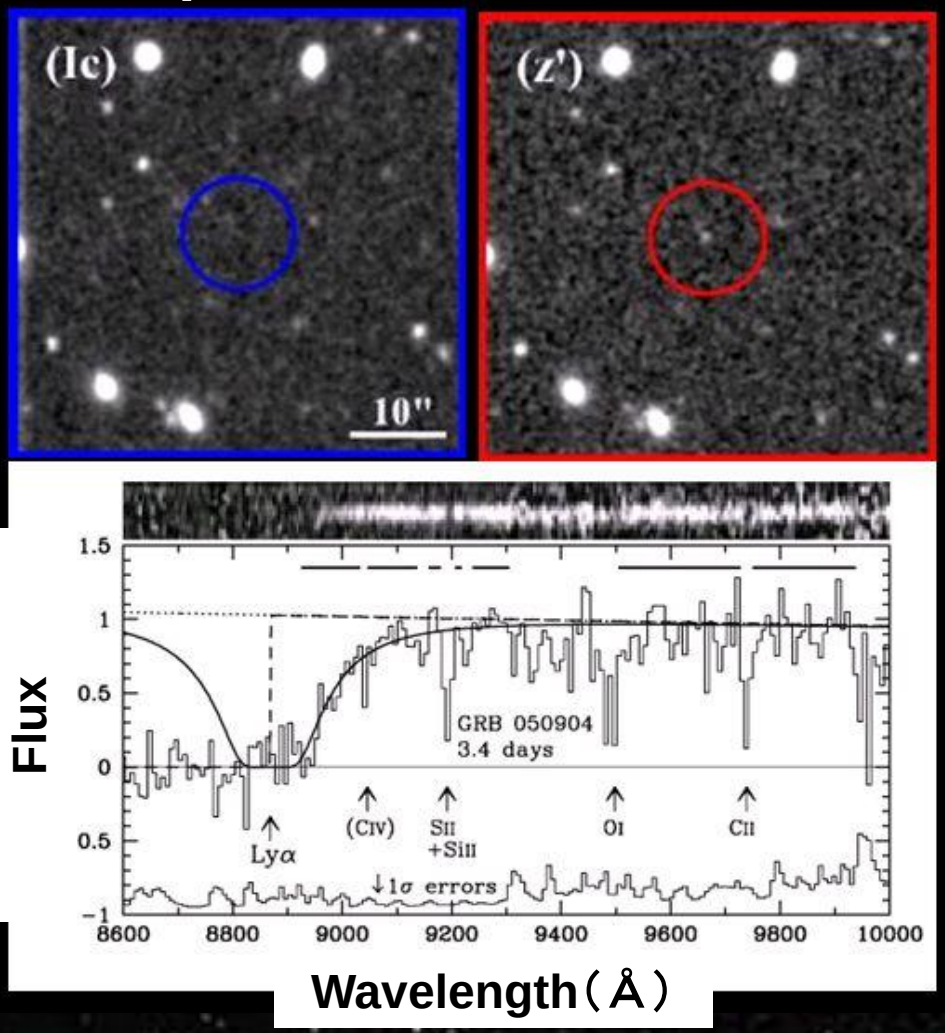
Reinozation seems to have ended at z~6 (1 Gyr after Big Bang)



Fan et al.(2006)

z=6.3 Gamma Ray Burst (GRB)

Totani et al.(2006)



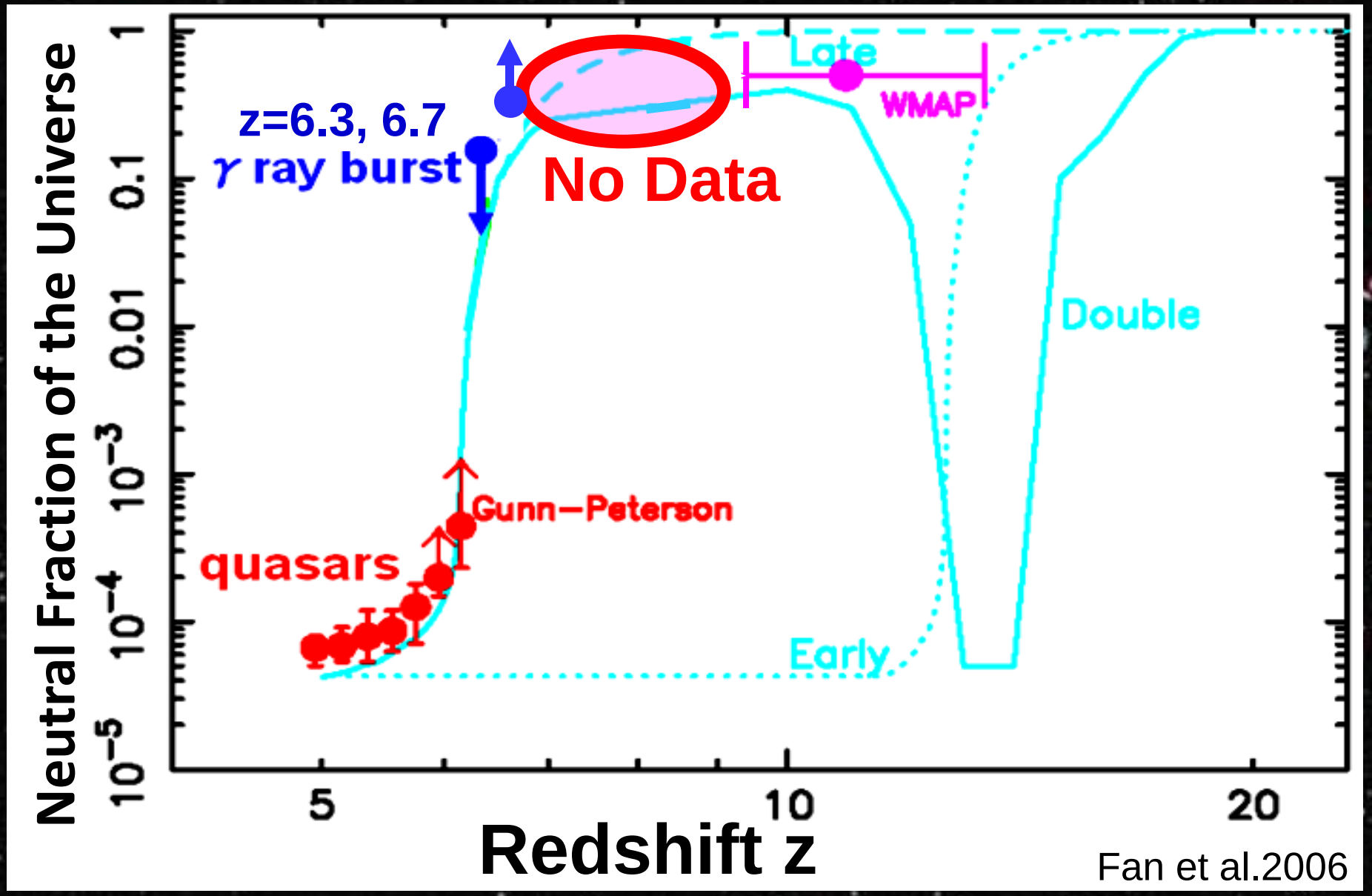
Explosion at the end of lifetime of massive stars

Observable up to z~10 due to its extreme brightness

©NASA

Neutral H fraction of the Universe at z=6.3 ≤ 17%

Cosmic Reionization History: Early vs. Late



Lyα emitting galaxies can be a probe of cosmic reionization

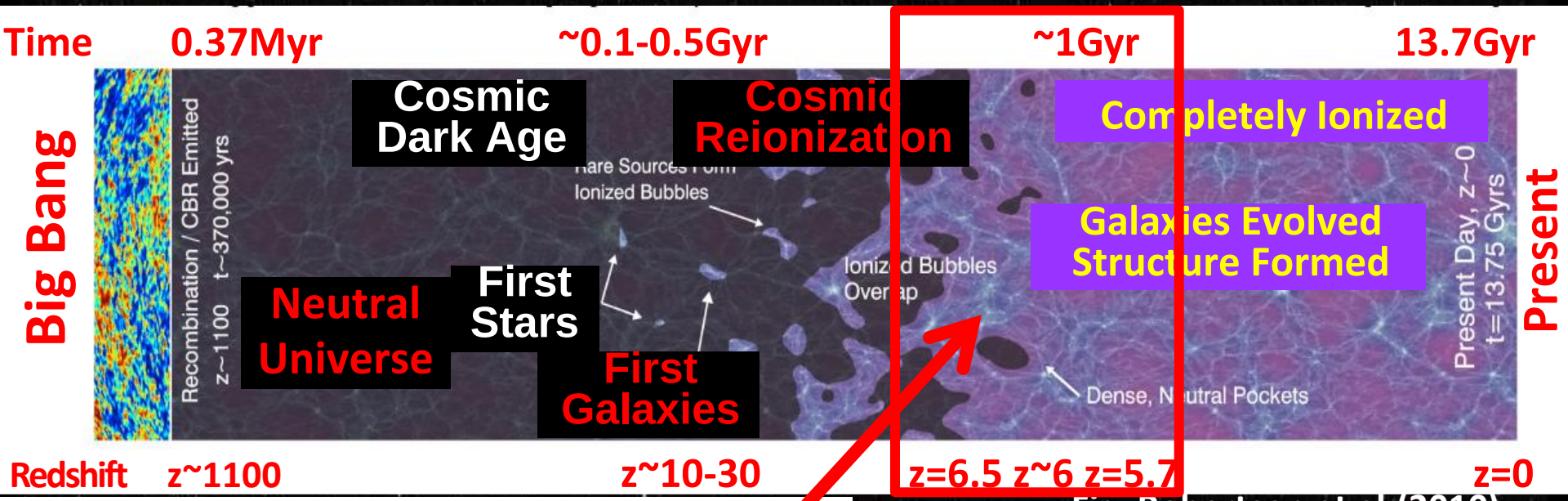
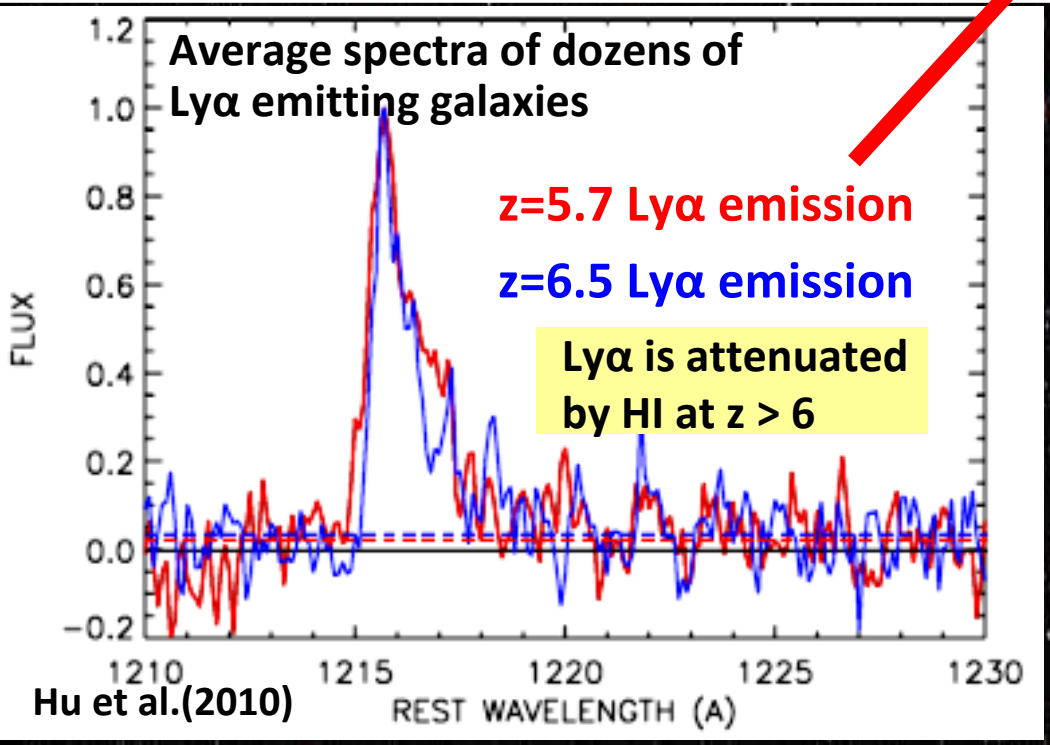


Fig: Robertson et al.(2010)



Hu et al.(2010)

Neutral hydrogen absorbs or scatters Lyα photons.

↓

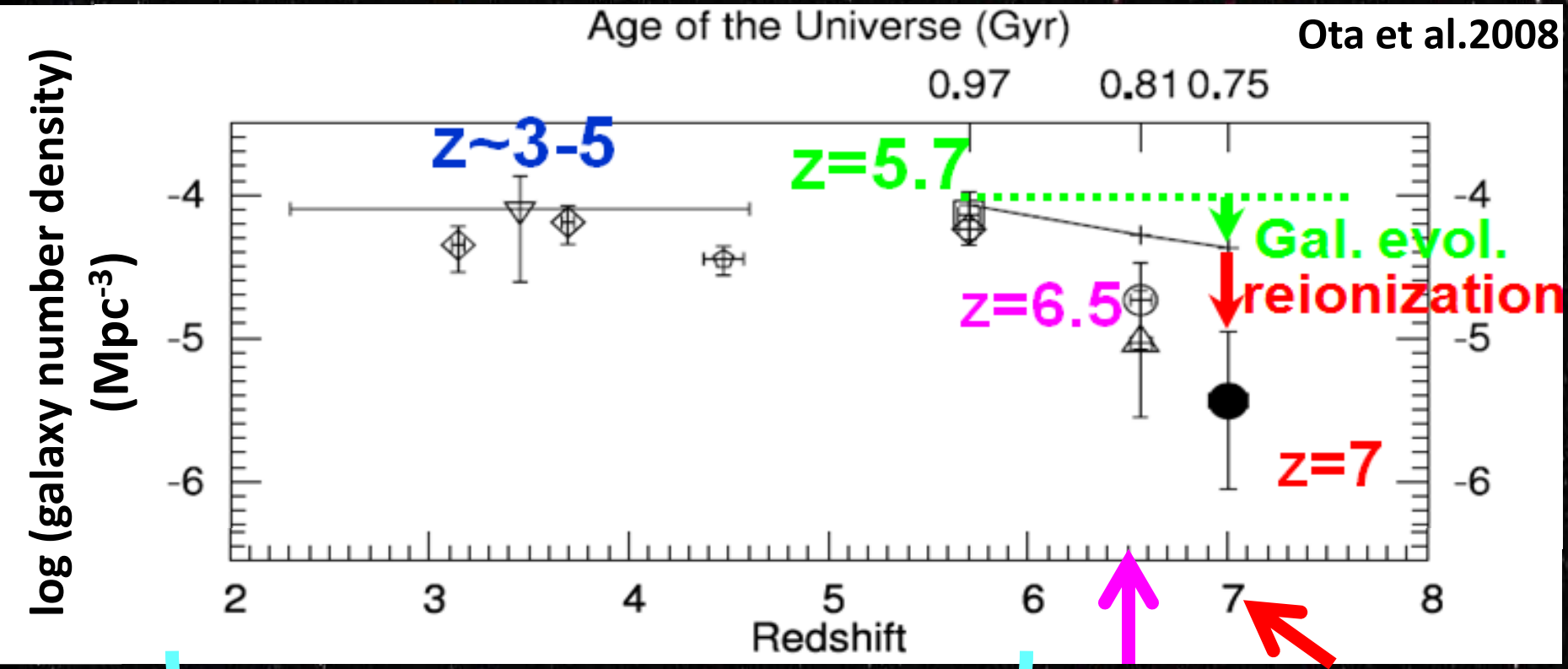
If the Universe is partly neutral, Lyα fluxes of galaxies are attenuated.

↓

The detected number of Lyα emitting galaxies decreases as neutral fraction increases.

Constraint on Cosmic Reionization from Galaxies

I found that the observed number density of Lyα emitting galaxies decreases with redshift at z > 6.



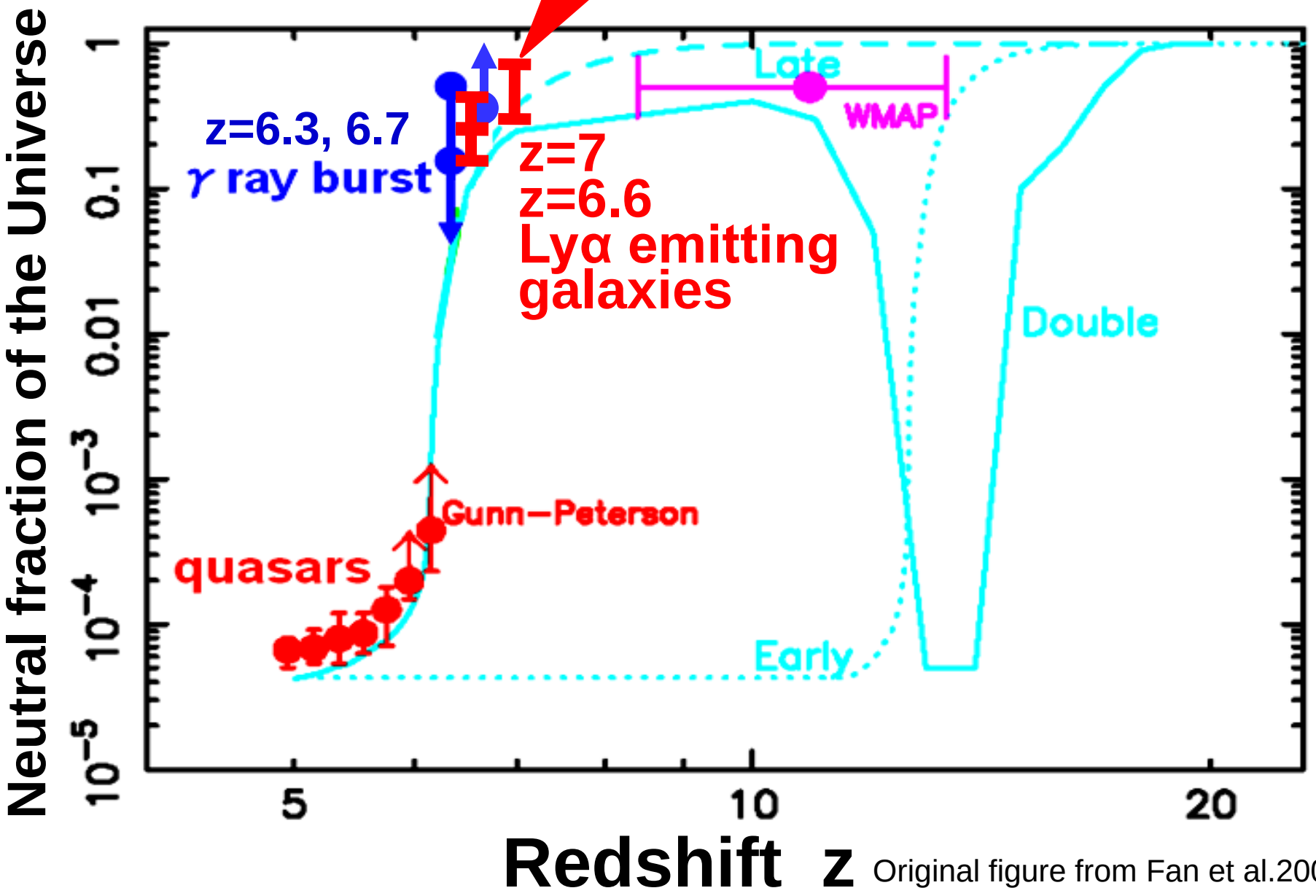
The Universe is fully reionized

20-40% neutral

30-60% neutral

This support the idea that cosmic reionization completed at z ~ 6.

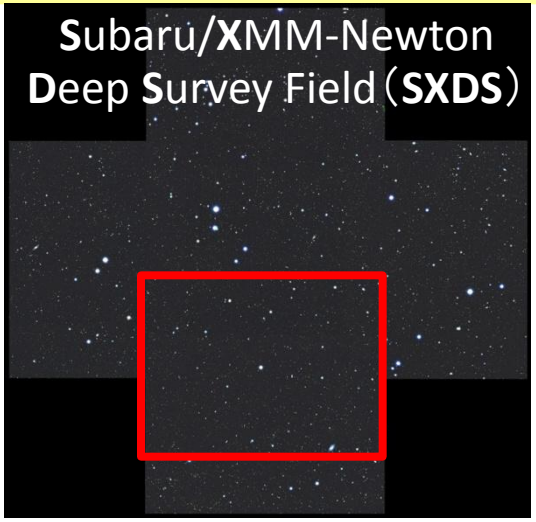
First constraint on reionization state at z = 7

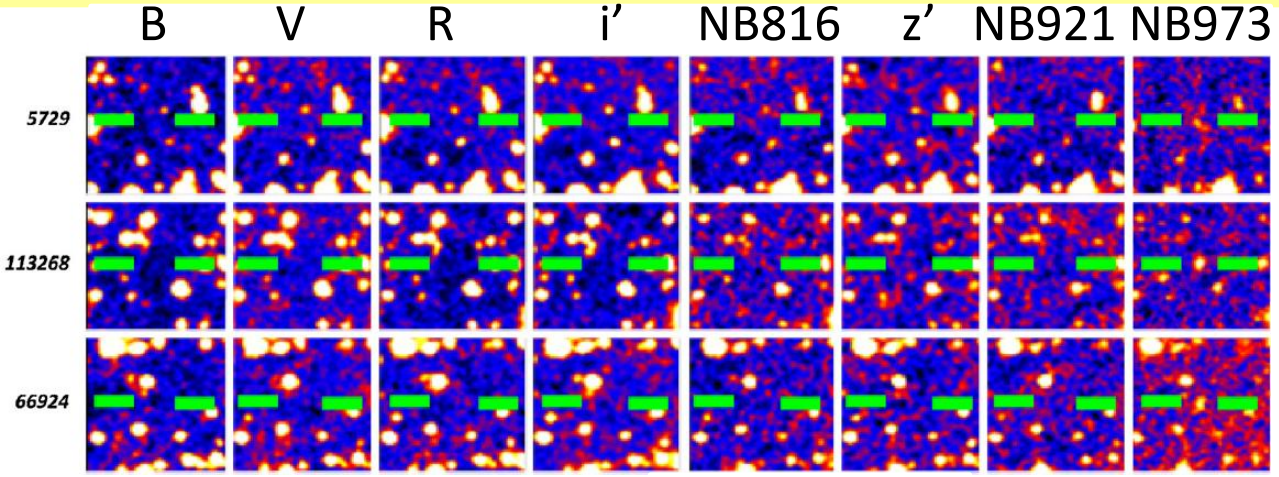


Original figure from Fan et al.2006

Another Independent Survey to confirm the result

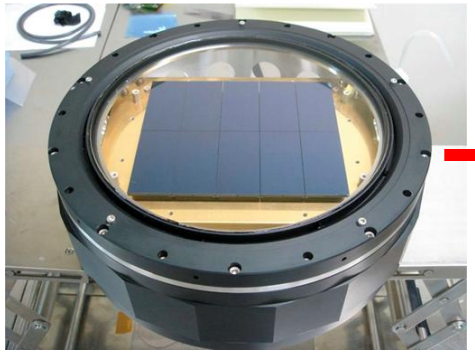
Independent observation of z=7 Lyα emitting galaxies in a different sky field to the deeper detection limit => I again confirmed that *the Universe is partly neutral at z =7.*



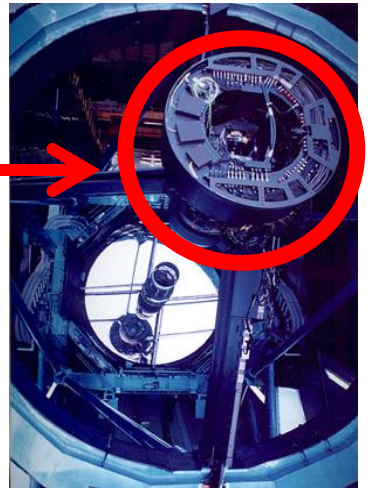


BB and NB filter images of z=7 galaxy candidates

Ota et al. 2010a, ApJ, 722, 803

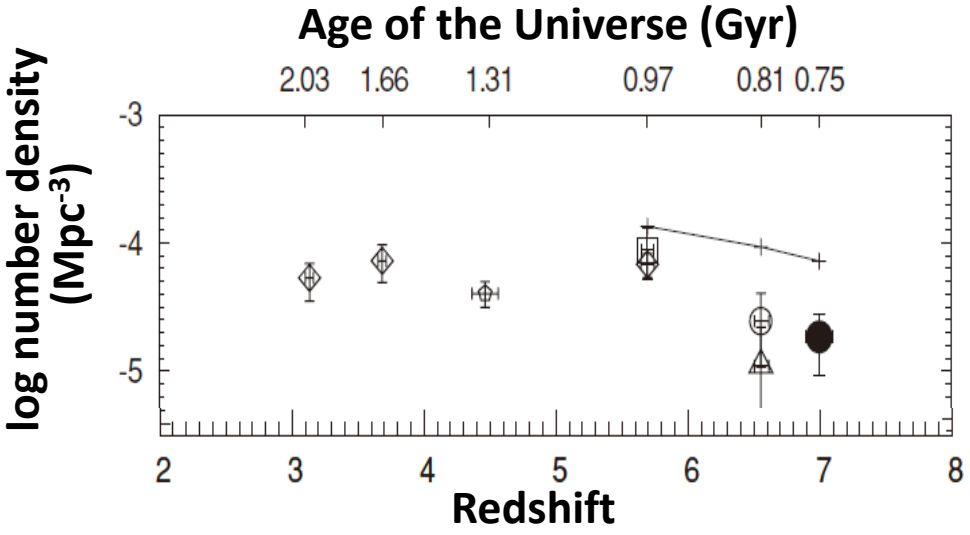


Fully depleted CCDs



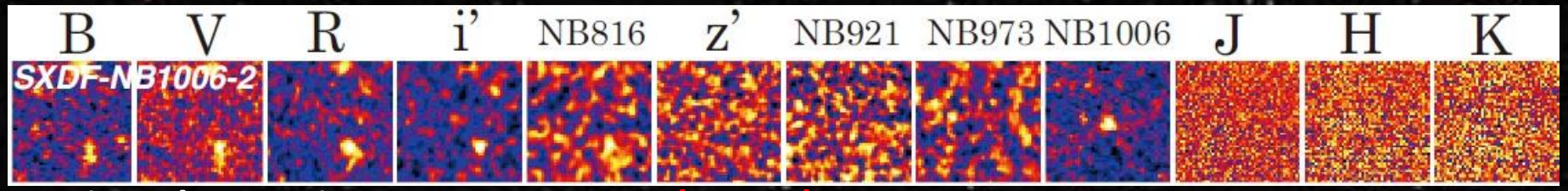
8m Subaru Telescope Suprime-Cam

x2 more sensitive to z ~ 7 Lyα (~1μm)

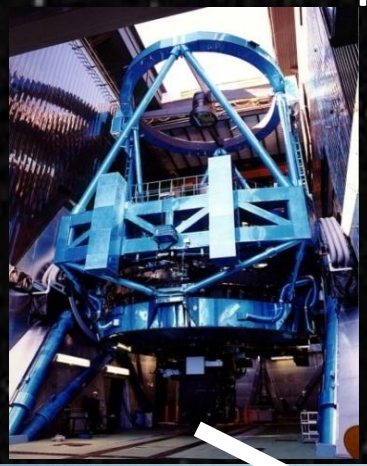


Discovery of a z=7.215 galaxy (current redshift record!)

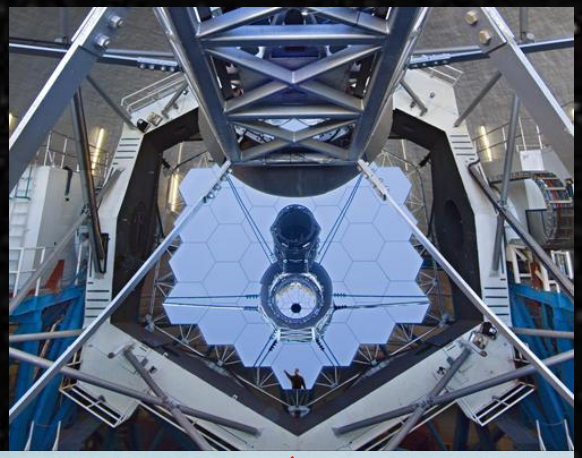
Shibuya, Kashikawa, Ota et al. 2012



Imaging observation
8m Subaru Telescope

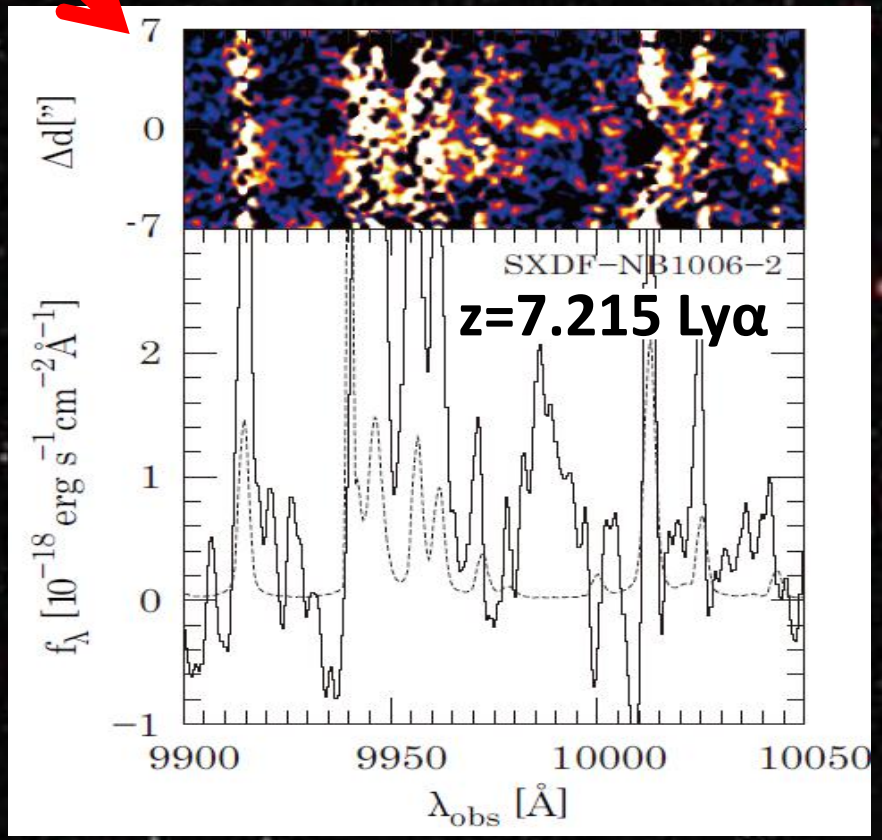


Spectroscopy (PI Ota)
10m Keck Telescope

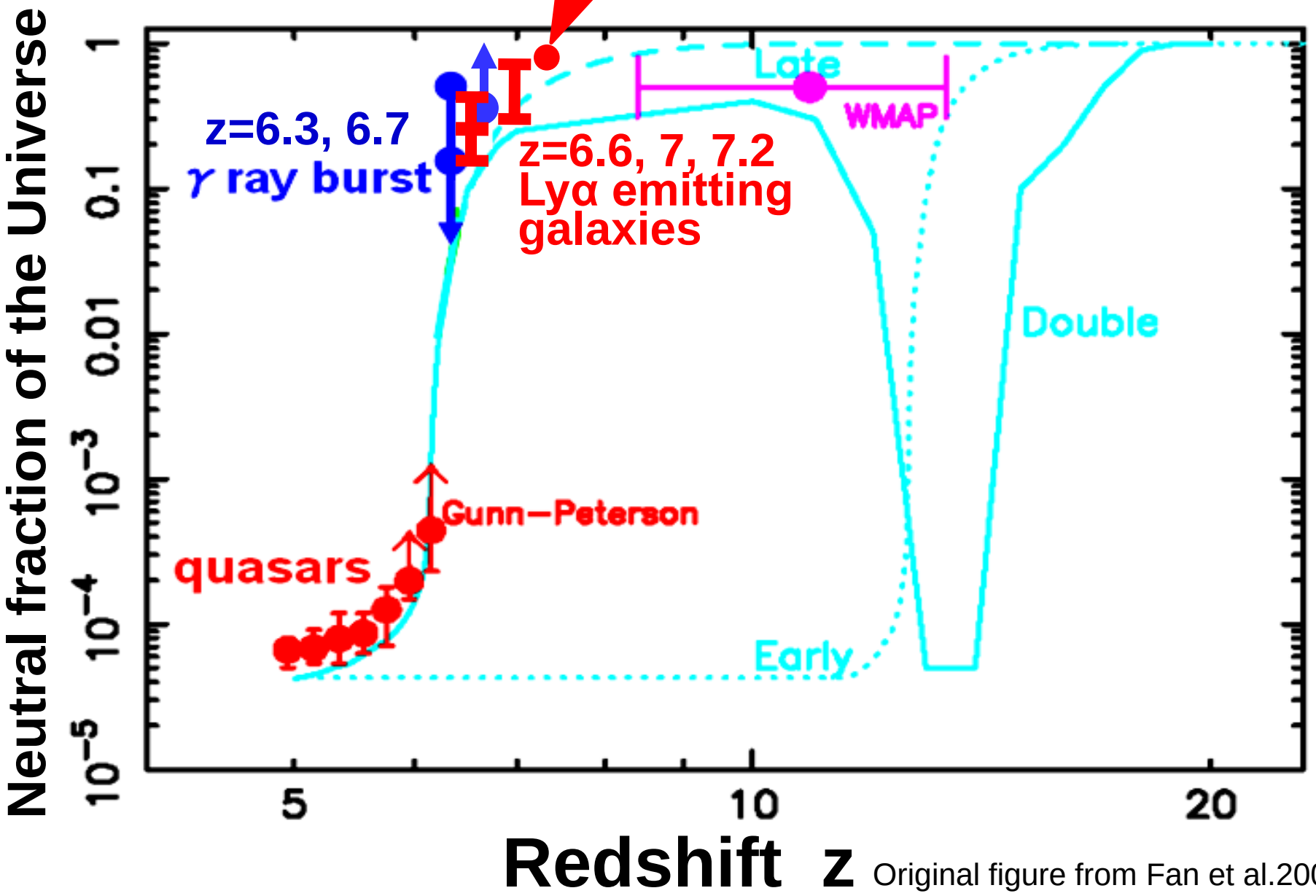


~4200m Mt. Mauna Kea Hawaii

A spectrum of a z=7.215 Lyα emitting galaxy



Constraint on reionization state at z = 7.2



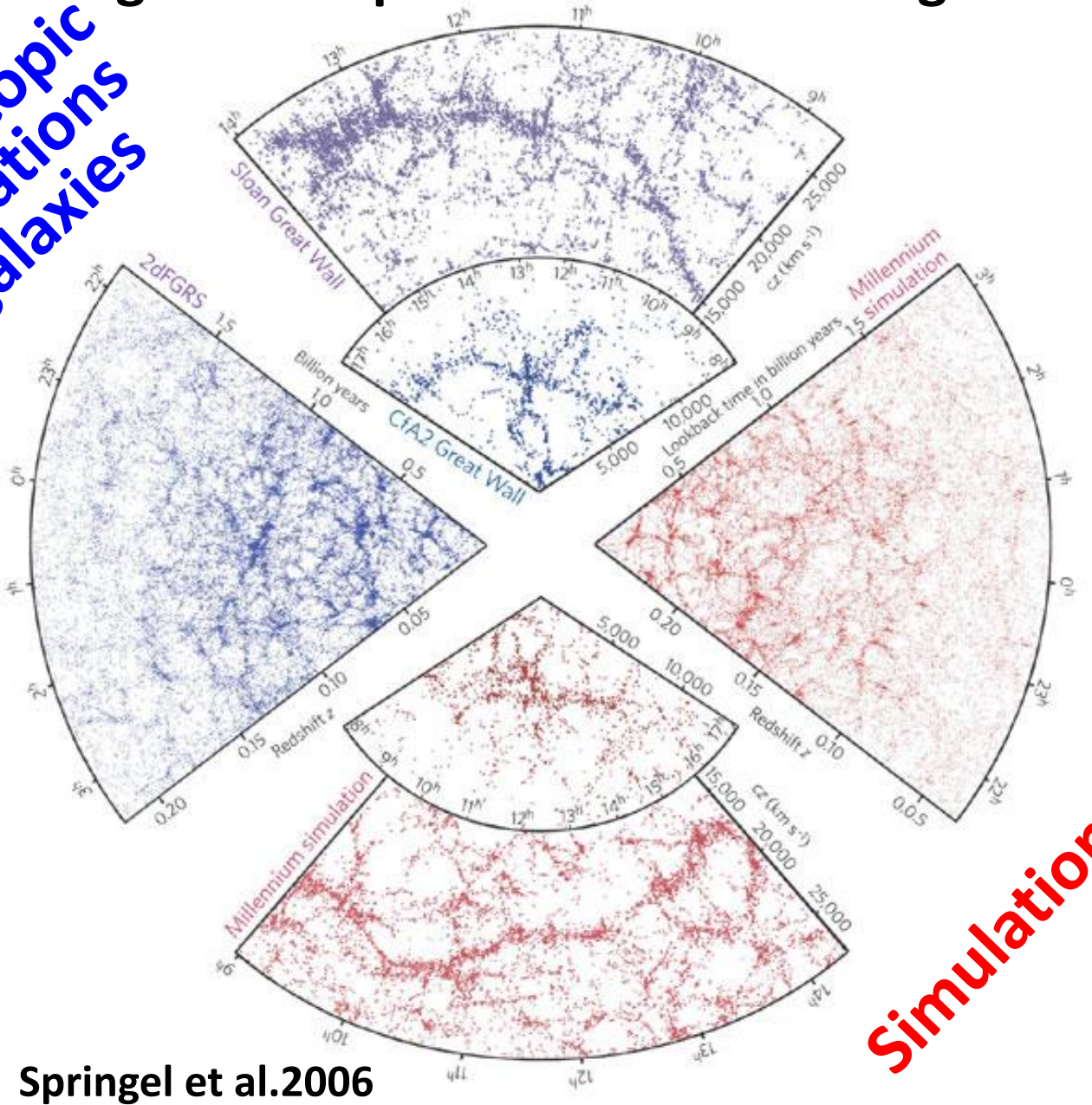
Original figure from Fan et al.2006

1. Background
2. Research
   - Study of Early Galaxy Formation/Evolution
     (Quest for the Farthest Galaxies)
   - Study of Cosmic Reionization
   - Study of Early Structure Formation
     (Protocluster of Galaxies)
3. Conclusion

Large Scale Structure of the Universe

inhomogeneous spatial distribution of galaxies

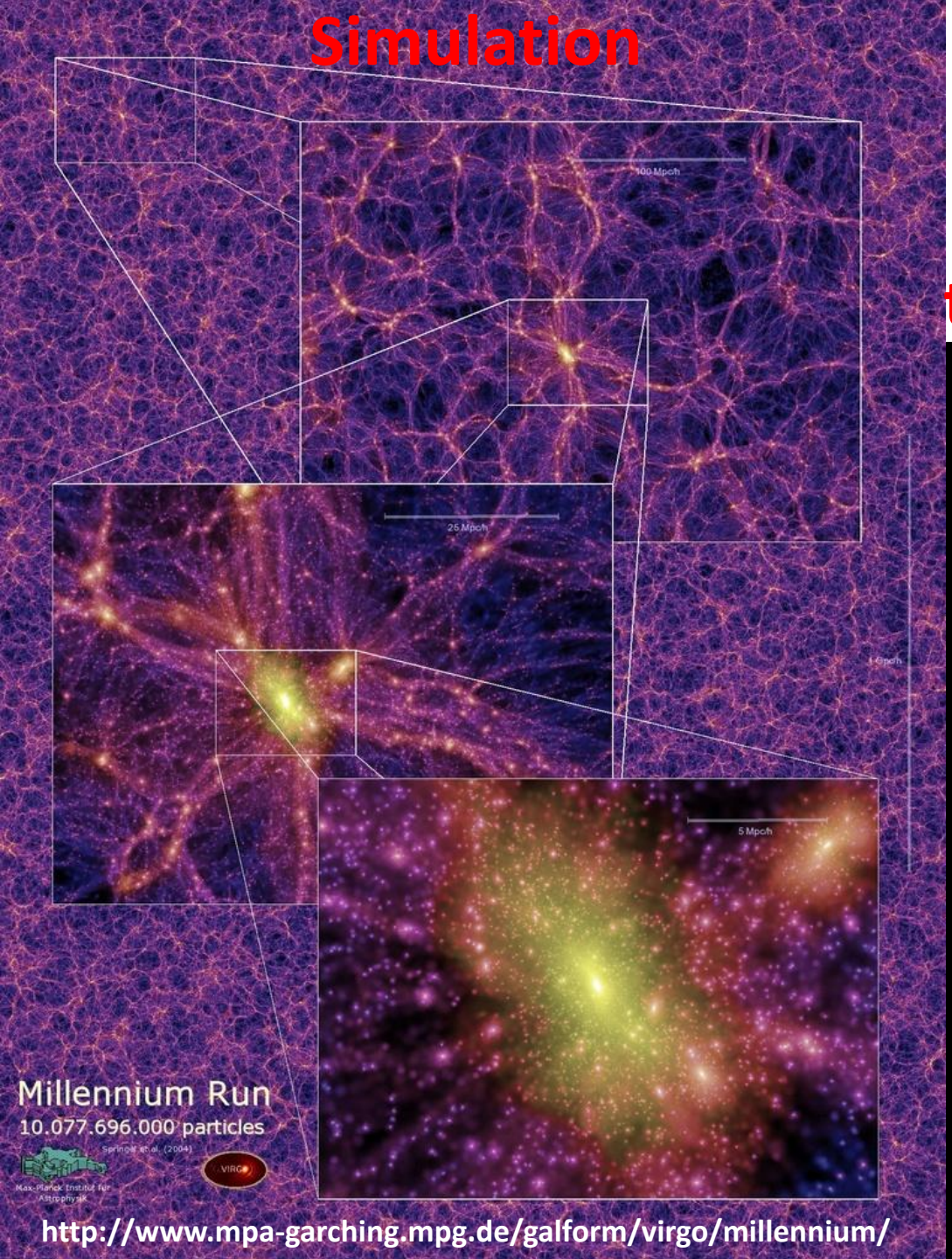
Spectroscopic observations of galaxies



Simulation

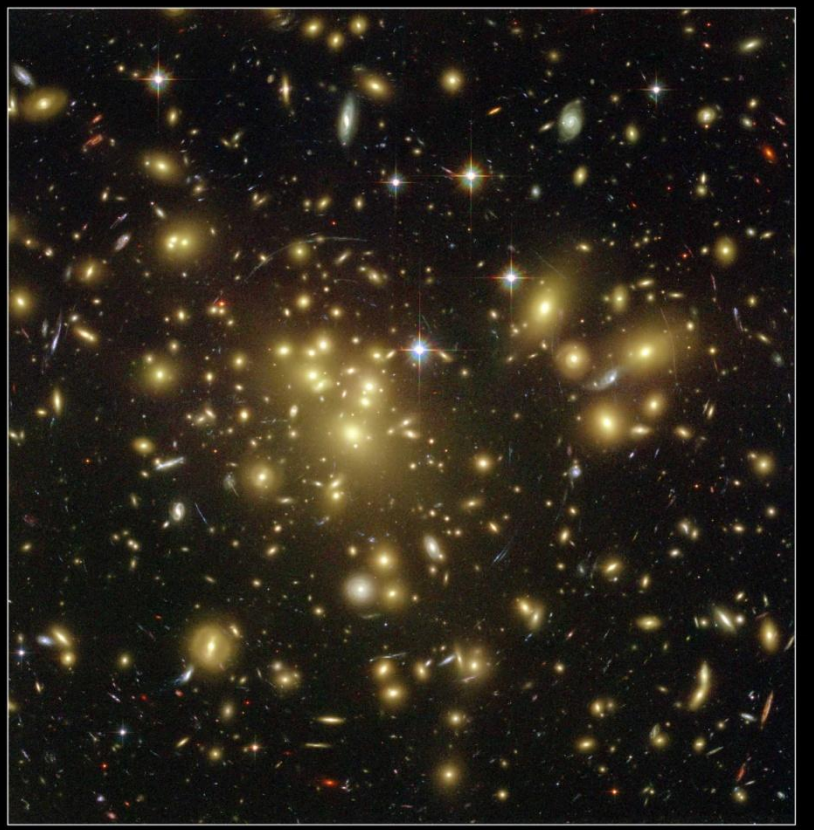
Springel et al.2006

Simulation



http://www.mpa-garching.mpg.de/galform/virgo/millennium/

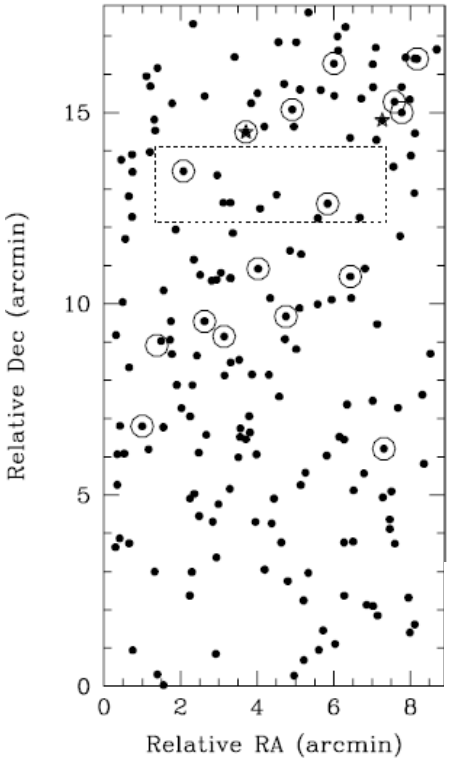
Cluster of Galaxies
seen in
the present-day Universe



Galaxy Cluster Abell 1689
Hubble Space Telescope • Advanced Camera for Surveys

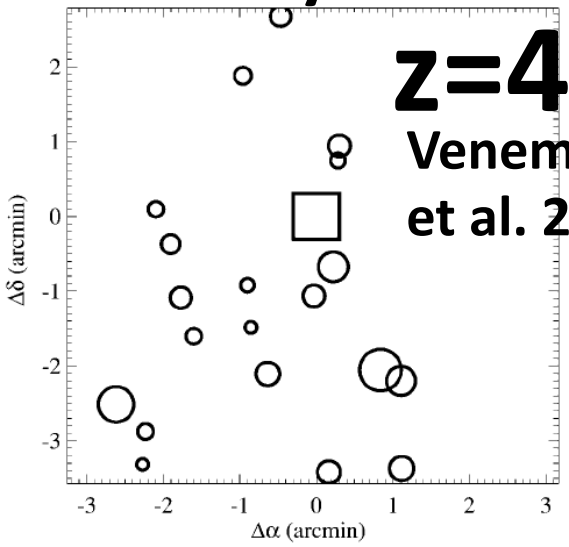
NASA, N. Benitez (JHU), T. Broadhurst (The Hebrew University), H. Ford (JHU), M. Clampin(STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA
STScI-PRC03-01a

Progenitor of cluster of galaxies = Protocluster in the early Universe



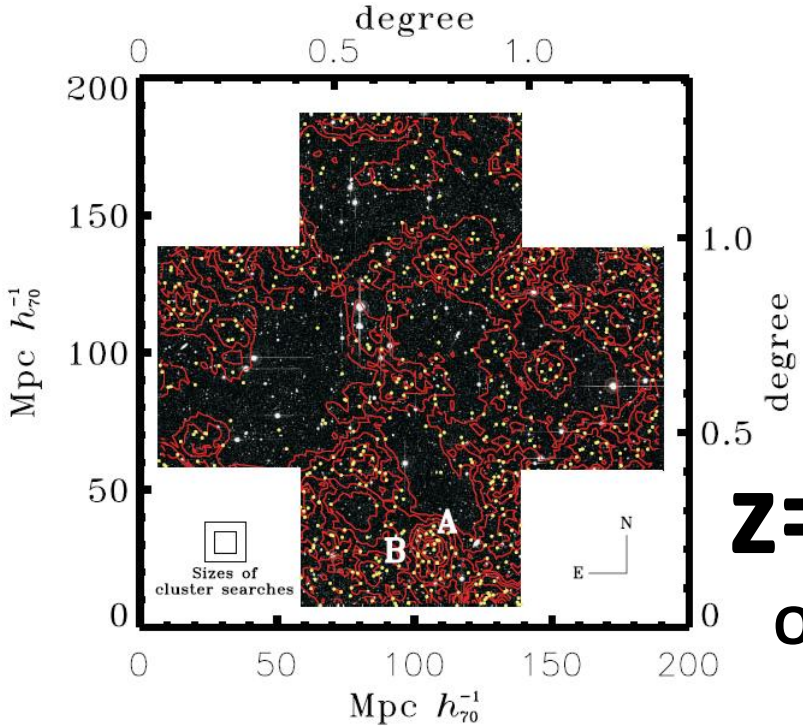
z=3

Steidel et al.1998



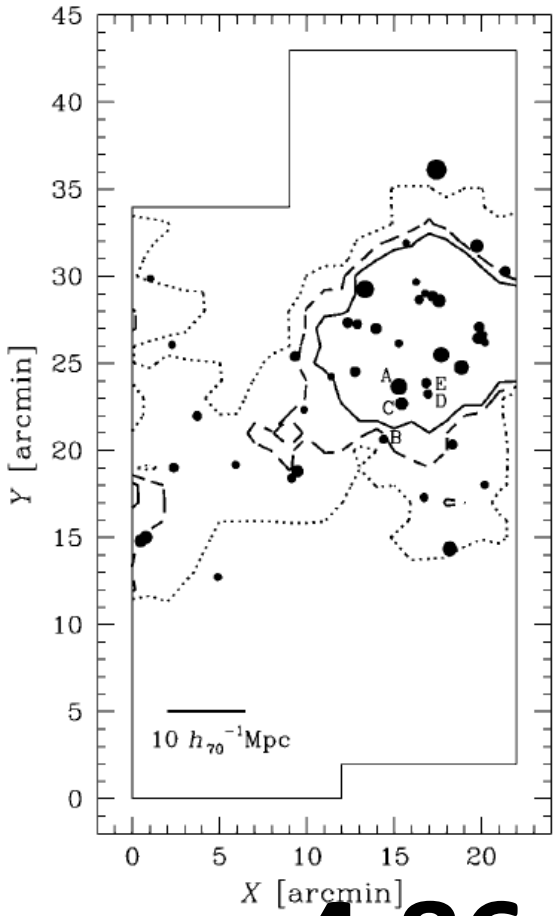
z=4.1

Venemans et al. 2002



z=5.7

Ouchi et al. 2005



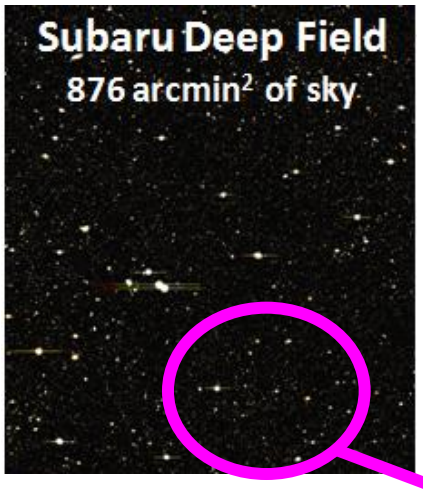
z=4.86

Shimasaku et al. 2003

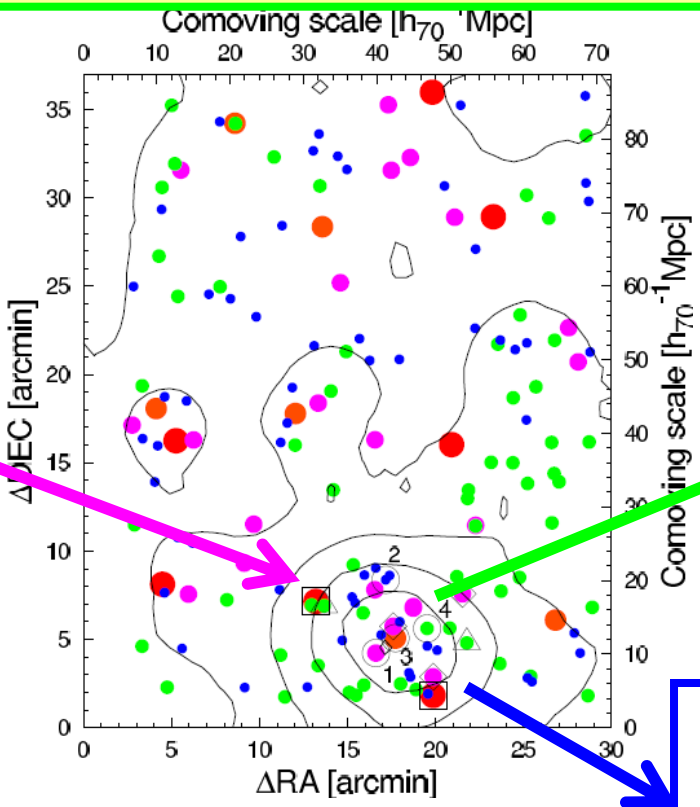
We discovered the most distant protocluster of galaxies at z~6

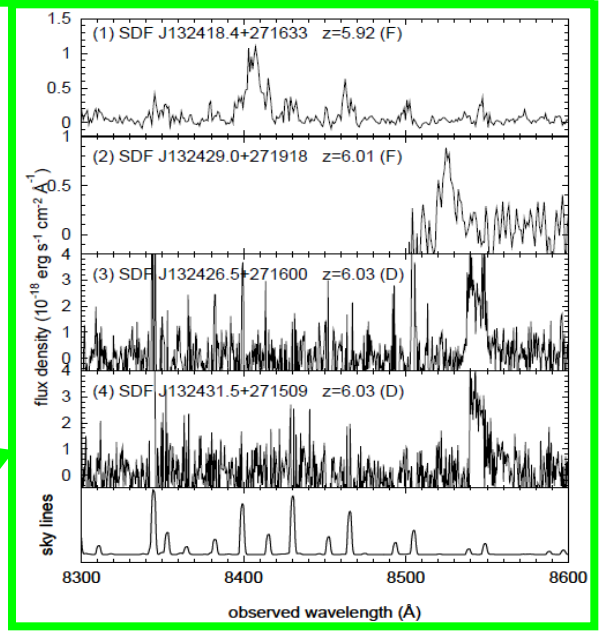
- Large Scale structure was forming just 1Gyr after the Big Bang
- Cosmic reionization might have progressed inhomogeneously

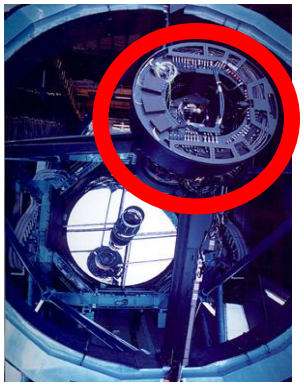
(1) Ota et al.(2008) identified the overdensity region and spectroscopically confirmed four z~6 Lyα emitting galaxies.



Subaru Telescope
Suprime-Cam
1 pointing image
= Subaru Deep Field

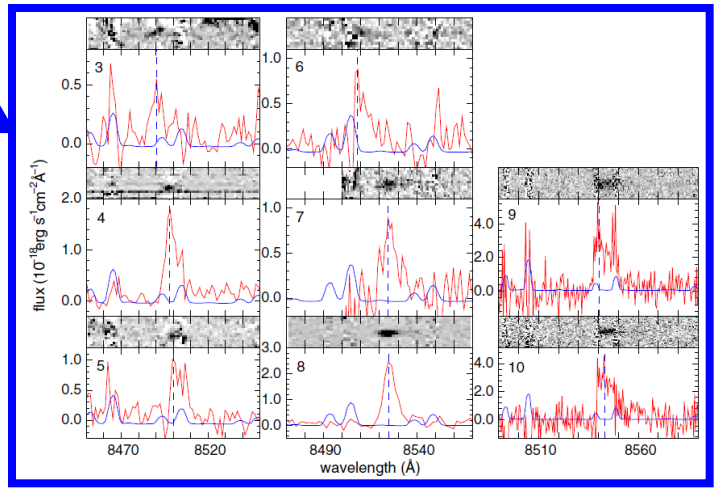






(2)

Toshikawa, Kashikawa, Ota et al.(2012) confirmed four more z~6 Lyα emitting galaxies => definitive identification of z~6 protocluster of galaxies



Conclusion / Summary

Science Objectives

(1) Study galaxy/structure formation/evolution
(2) Study cosmic reionization

Recent Progress in the Fields

(1) Galaxy candidates have been detected up to z ~ 7-12, but real ones have been confirmed up to z ~ 7
(2) WMAP, quasars & γ-ray bursts imply reionization started at z ~ 10 and ended at z ~ 6, but this idea lacked the data at $6.5 < z < 10$
(3) Protoclusters were observed up to z ~ 5.7

Our Results

(1) We confirmed galaxy formation at z ~ 7 and 7.2 Universe
(2) Neutral fraction at z ~ 7 and 7.2 connects WMAP, quasars & γ-ray bursts results about reionization.
(3) We found protocluster at z ~ 6, implying structure formation just 1 Gyr after the Big bang and spatially inhomogeneous reionization.