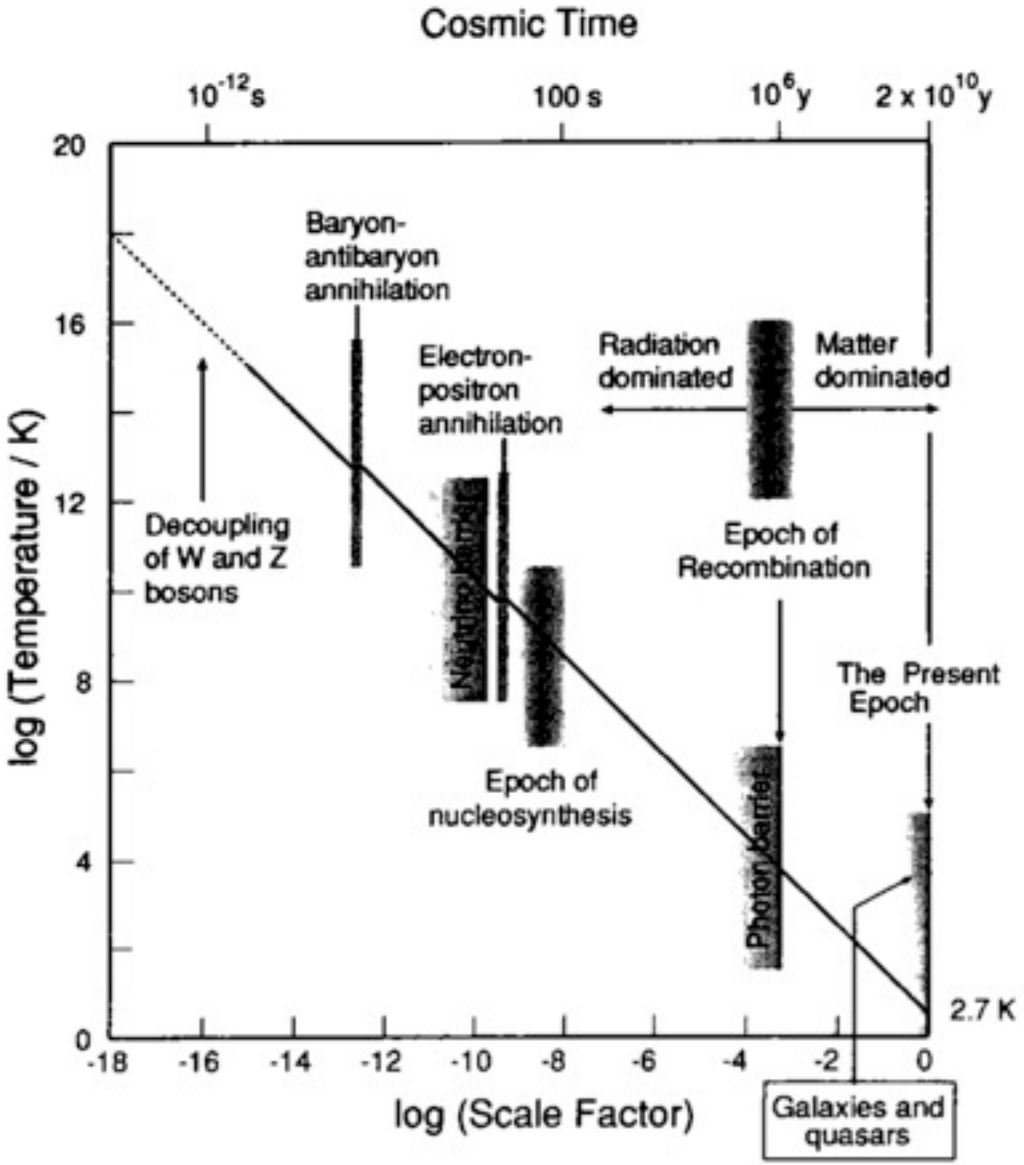
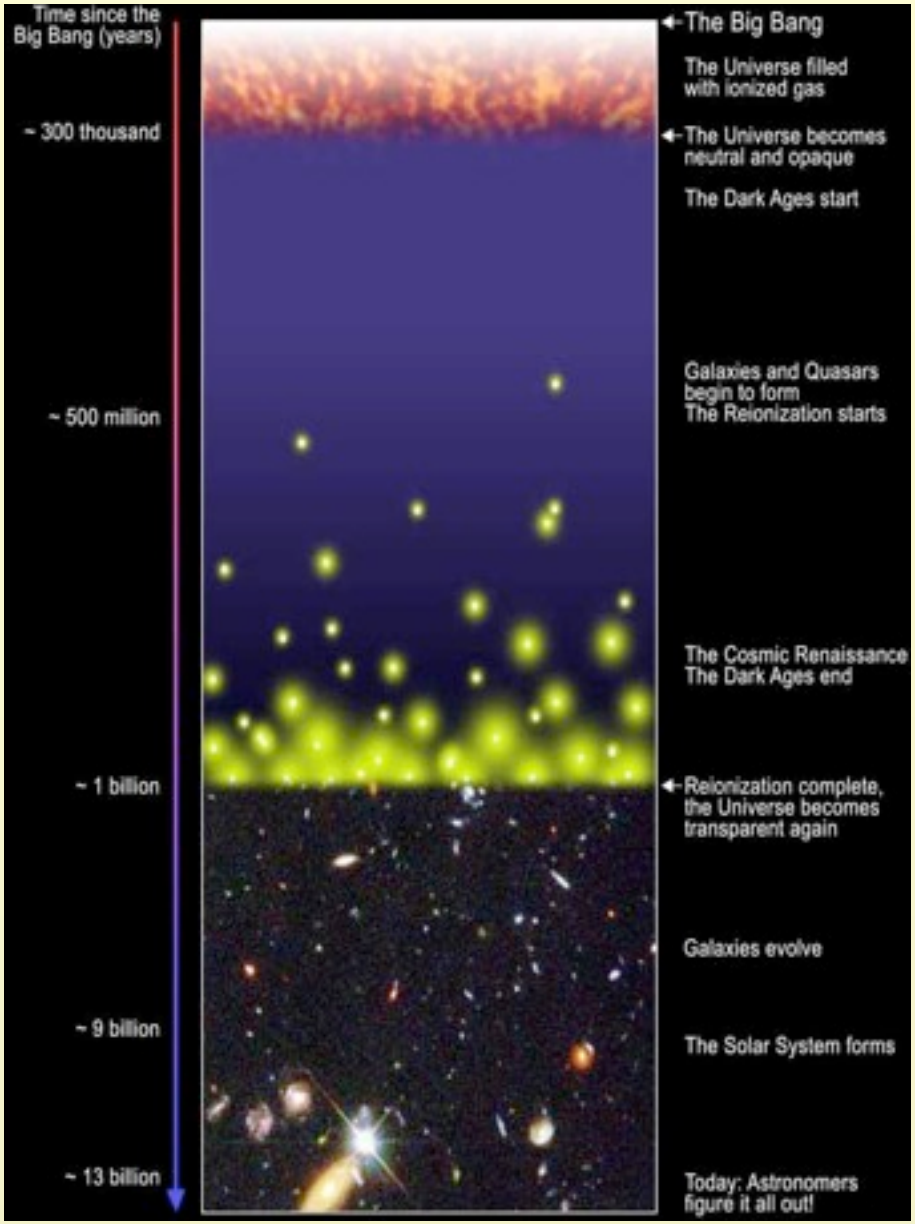

Cosmic Time
10^{-12}s
100 s
10^{6}y
2×10^{10}y
20
16
12
8
4
0
log (Temperature / K)
Baryon-antibaryon annihilation
Electron-positron annihilation
Radiation dominated
Matter dominated
Decoupling of W and Z bosons
Neutrino barrier
Epoch of Recombination
The Present Epoch
Epoch of nucleosynthesis
Photon barrier
2.7 K
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
log (Scale Factor)
Galaxies and quasars

A brief cosmic history



←Big Bang: the universe filled with hot gas

←Cosmic Dark Age: no light no star, no quasar

←First light: the first galaxies and quasars in the universe

←Cosmic Renaissance: universe lit up by young galaxies and quasars

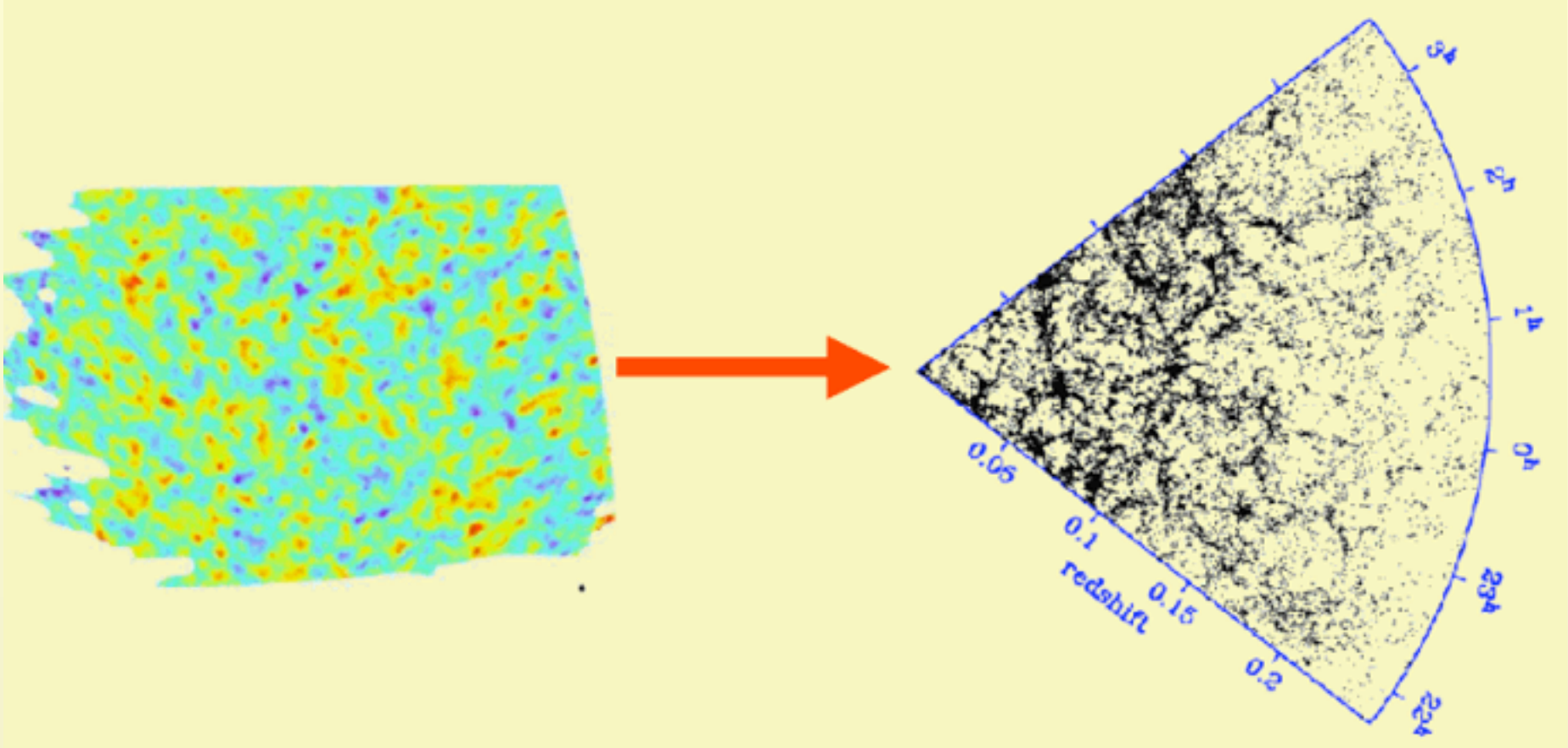
←"reionization" completed, the universe is transpartent and the dark ages ended

← today

Galaxy Formation

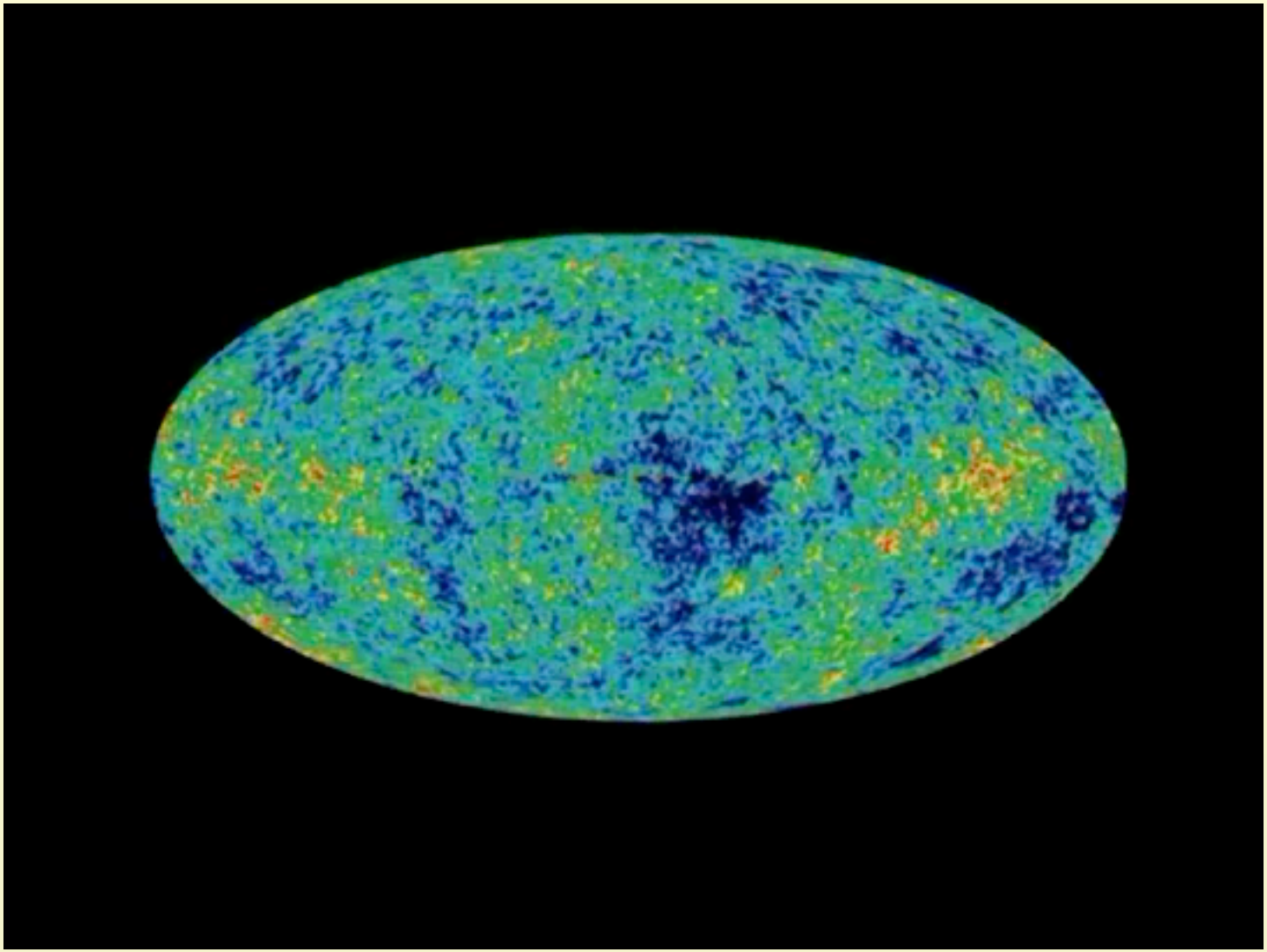
Apr 29/May 1, 2014

Goal of a galaxy formation theory: from CMB fluctuation to current day galaxy large scale structure



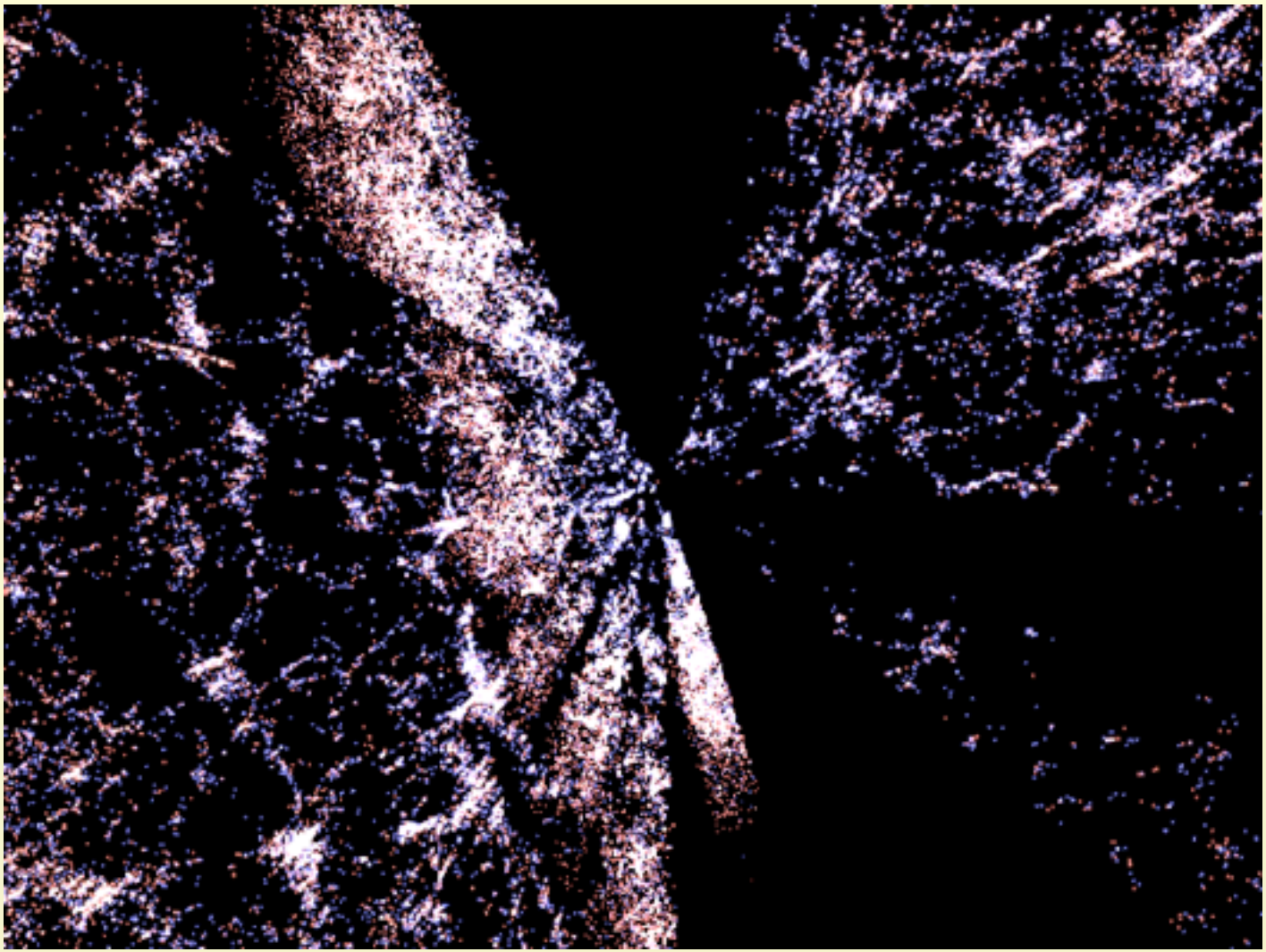
WMAP to local galaxies

WMAP to local galaxies



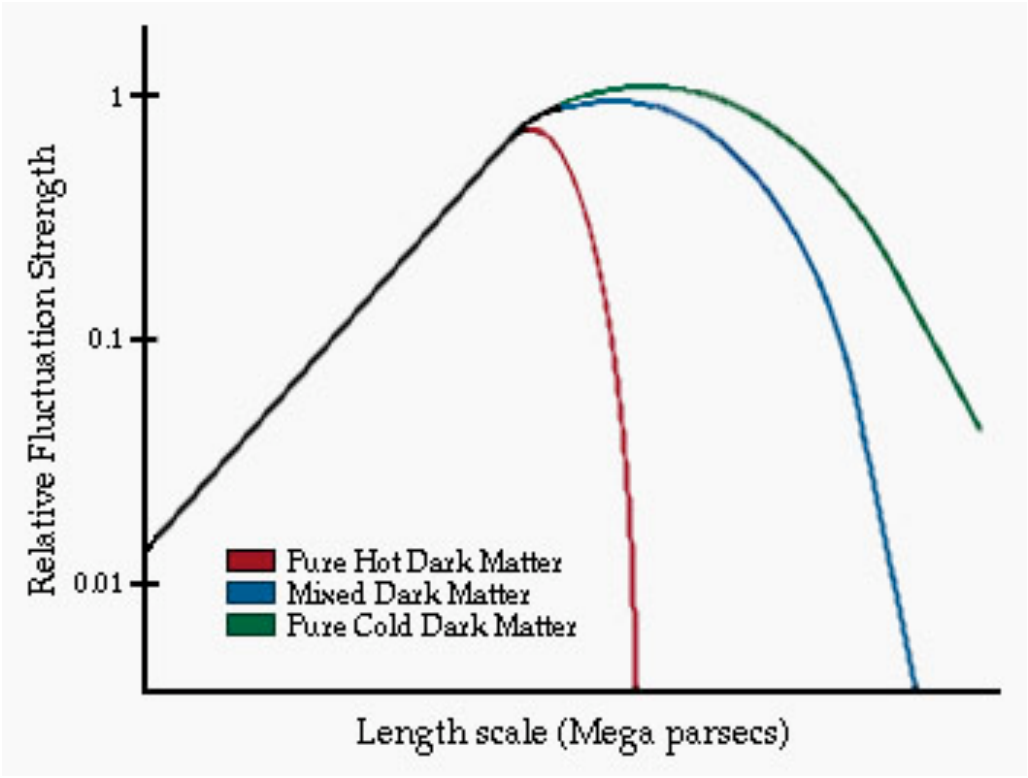
From SDSS to WMAP

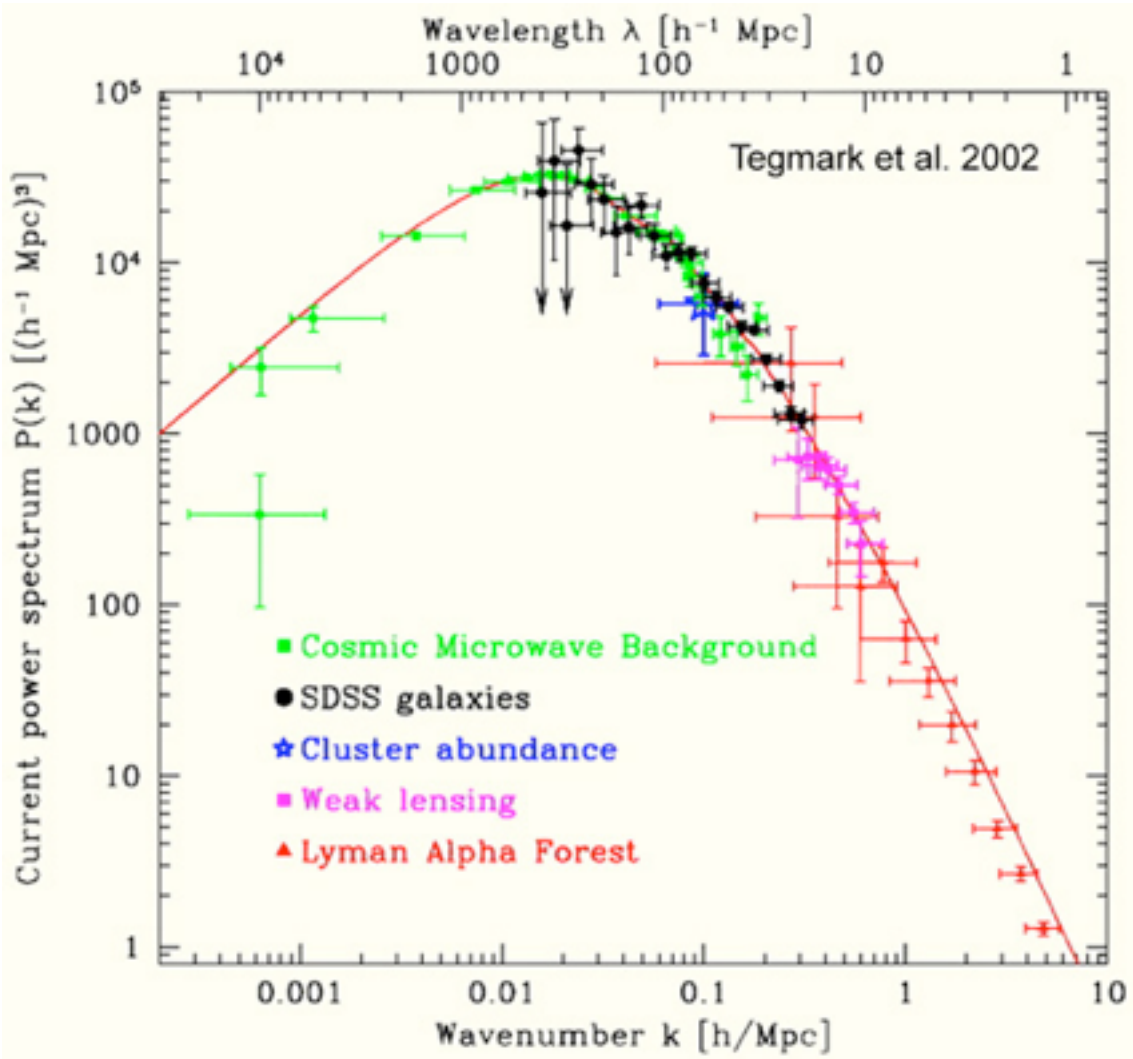
From SDSS to WMAP



Ingredients of a Galaxy Formation Theory

- Cosmological model
  - Set the time scale, determine the growth of gravitational instability
- Density fluctuation power spectrum
  - Seeds of gravitational instability
  - Evolution of dark matter power spectrum
  - Structure formation
- Star formation and evolution of star/gas
  - Heating and cooling of baryons
  - Radiation output
  - Feedback of galaxy formation process
  - Impact on intergalactic medium


Relative Fluctuation Strength
1
0.1
0.01
Pure Hot Dark Matter
Mixed Dark Matter
Pure Cold Dark Matter
Length scale (Mega parsecs)


Wavelength λ [h⁻¹ Mpc]
10⁴
1000
100
10
1
Tegmark et al. 2002
Current power spectrum P(k) [(h⁻¹ Mpc)³]
10⁵
10⁴
1000
100
10
1
Cosmic Microwave Background
SDSS galaxies
Cluster abundance
Weak lensing
Lyman Alpha Forest
0.001
0.01
0.1
1
10
Wavenumber k [h/Mpc]

Growth of structure

- Evolution of density field

$$\rho(t) = \overline{\rho}(t)[1 + \delta(t)].$$

- Growth of small perturbation

$$\delta(t) = D_1(t) + BD_2(t)$$

$$D_1(t) = \frac{\dot{R}}{R}\int_0^R \dot{R}^{-3} dR.$$

- In critical universe

$$\delta(t) = At^{2/3} + Bt^{-1}.$$

Growth of structure

- In different cosmology

$$D_1(t) \sim t^{2/3}, \text{when } 1 + \mathrm{z} >> 1/\Omega_0 - 1, \text{at high redshift.}$$

$$D_1(t) \sim \text{constant}, \text{when } 1 + \mathrm{z} << 1/\Omega_0 - 1, \text{at low redshift.}$$

Ingredients of a Galaxy Formation Theory

- Cosmological model
  - Set the time scale, determine the growth of gravitational instability
- Density fluctuation power spectrum
  - Seeds of gravitational instability
  - Evolution of dark matter power spectrum
  - Structure formation
- Star formation and evolution of star/gas
  - Heating and cooling of baryons
  - Radiation output
  - Feedback of galaxy formation process
  - Impact on intergalactic medium

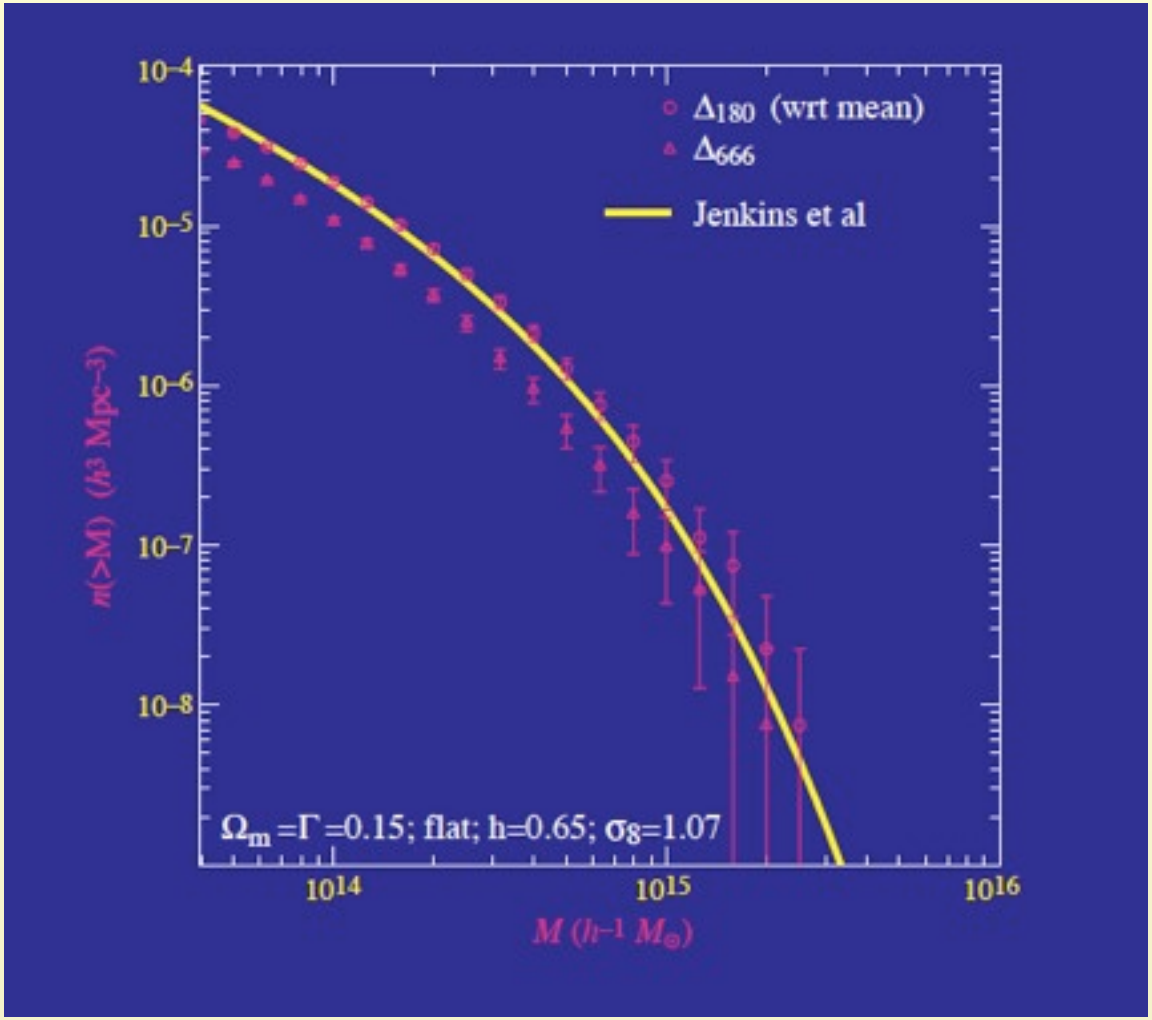
Studies of non-linear structure formation

- Analytical approximation
- Simulations:
  - N-body simulation
  - Hydrodynamical simulation
  - Semi-analytic models
    - Dark matter evolution from N-body
    - Baryonic physics from empirical laws

Gravitational collapse

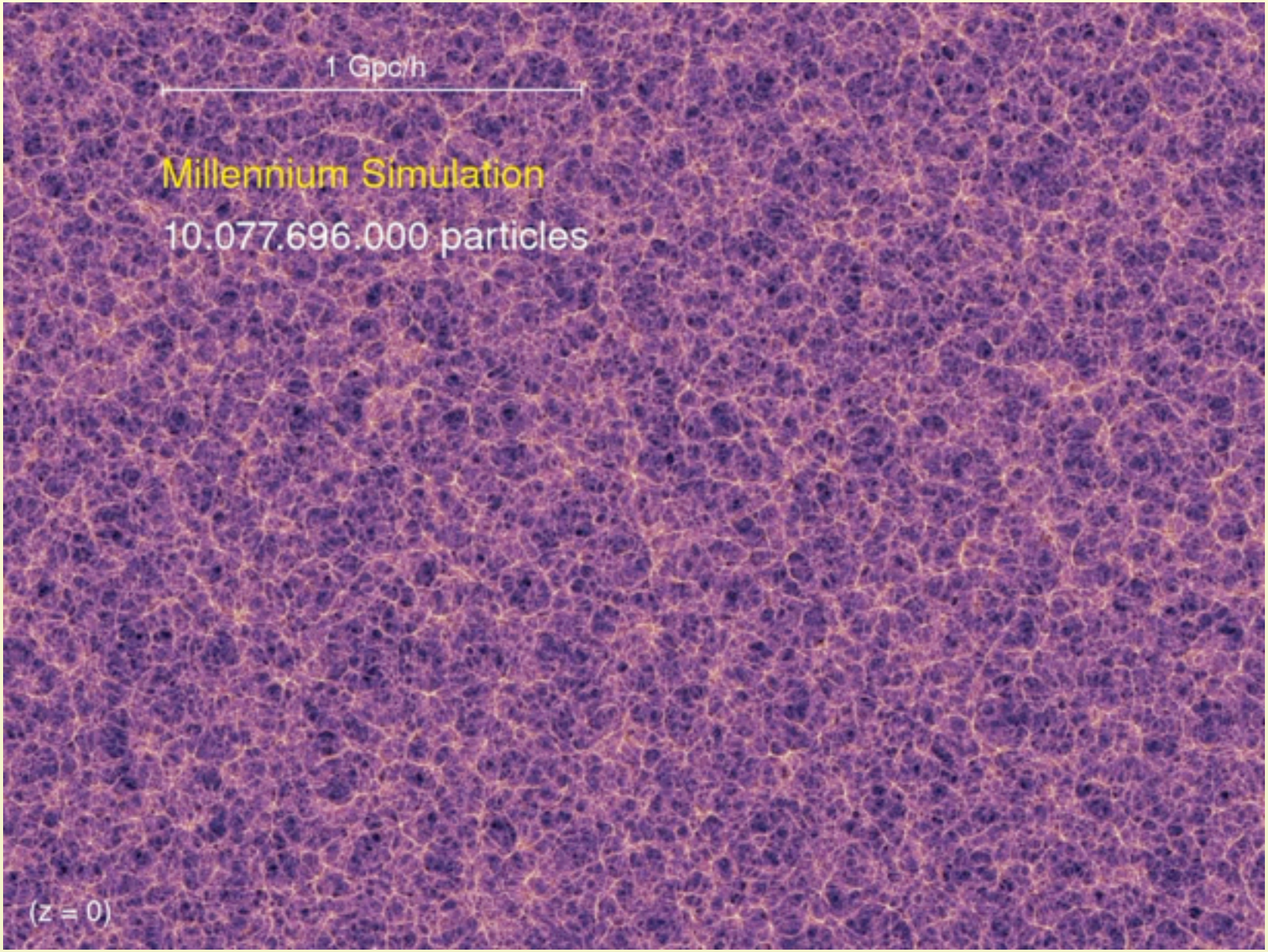
- In E-dS universe
  - First, perturbation grows linearly with scale factor
  - Subsequent non-linear growth can be treated as an over-critical universe
  - Highly non-linear growth: using simulation
- Spherical collapse theory
  - Perturbation reaches maximum expansion at t_max
  - The perturbation will virialize after 2t_max, when it reaches an overdensity of ~200: dark matter halo
  - Press-Schechter approximation predict number of dark matter halos as a function of mass and redshift

$$N(M)dM = \frac{1}{2\sqrt{\pi}}\left(1+\frac{n}{3}\right)\frac{\bar{\rho}}{M^2}\left(\frac{M}{M^*}\right)^{(3+n)/6}\exp\left(-\left(\frac{M}{M^*}\right)^{(3+n)/3}\right)$$



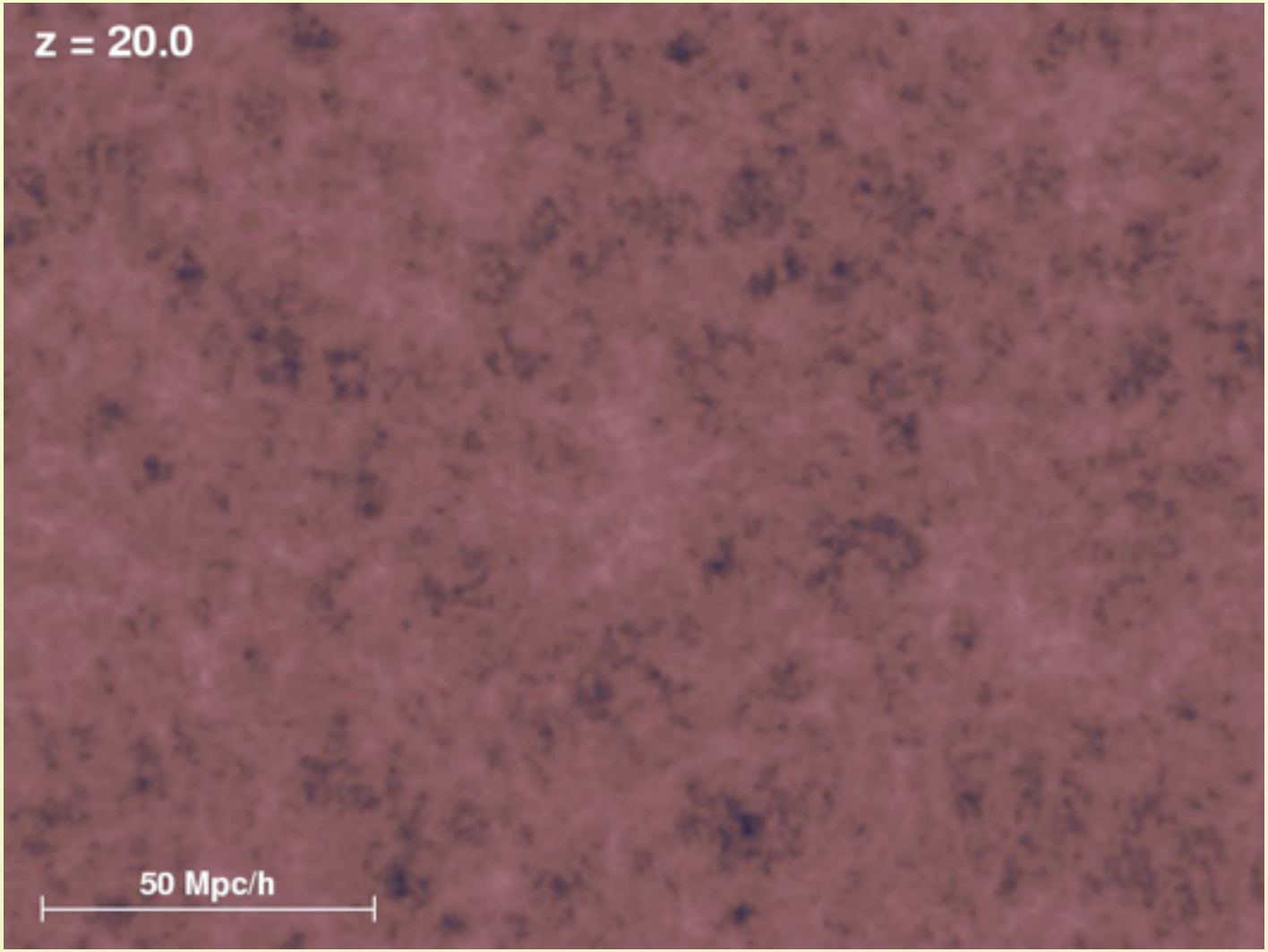
The largest N-body Simulation

The largest N-body Simulation



Evolution of structures

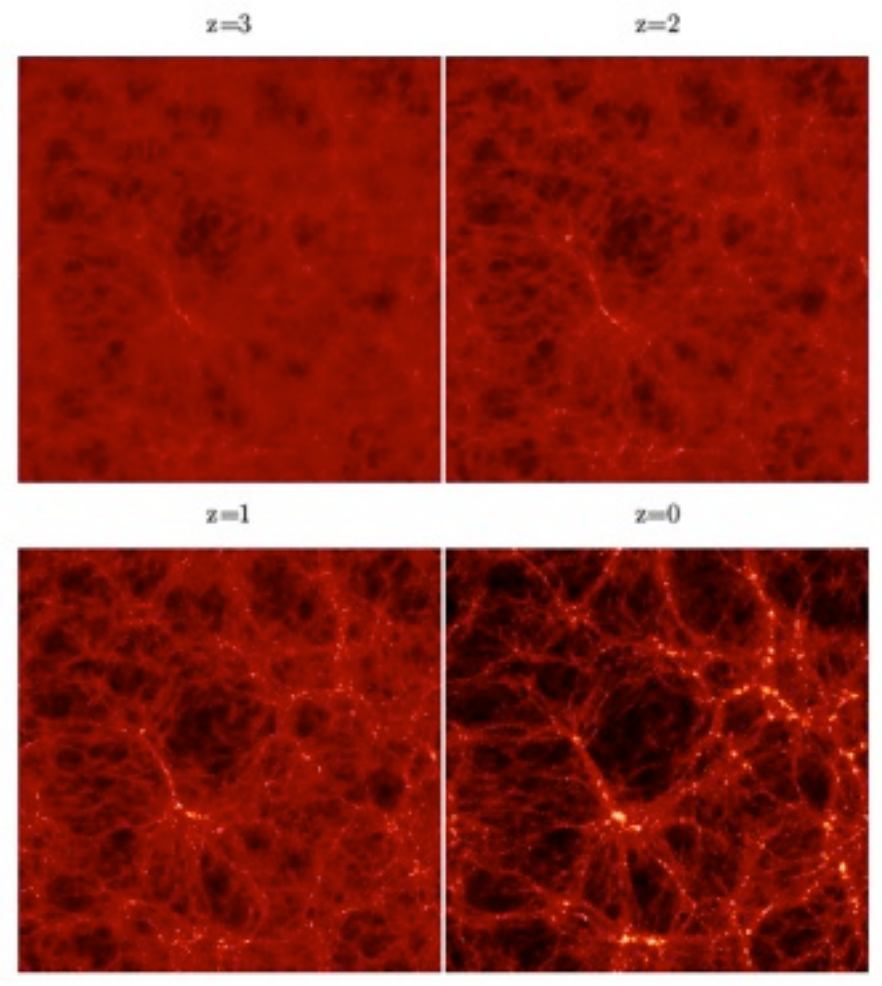
Evolution of structures



Biased Galaxy Formation

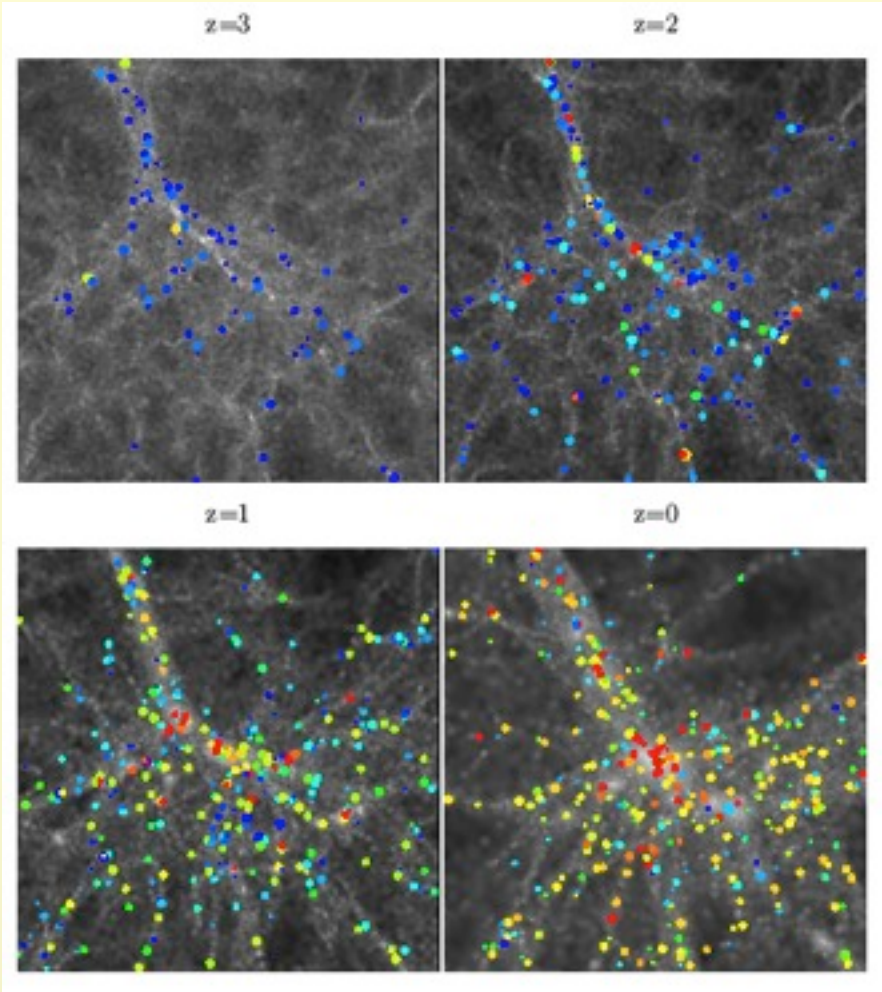
- Key questions:
  - How are galaxy formation and galaxy large scale structure related to dark matter distribution?
  - How do galaxies form from dark matter density fluctuation?
  - Where did the first galaxies form?
  - Do galaxies trace dark matter at large scale?
- Basic idea:
  - Galaxies do not trace exact dark matter distribution
  - Galaxies form only at high density fluctuation peaks
  - The earliest galaxies formed at the highest, rarest peaks in the early universe

What simulation shows?
Dark matter distribution



What simulation shows: Galaxy distribution

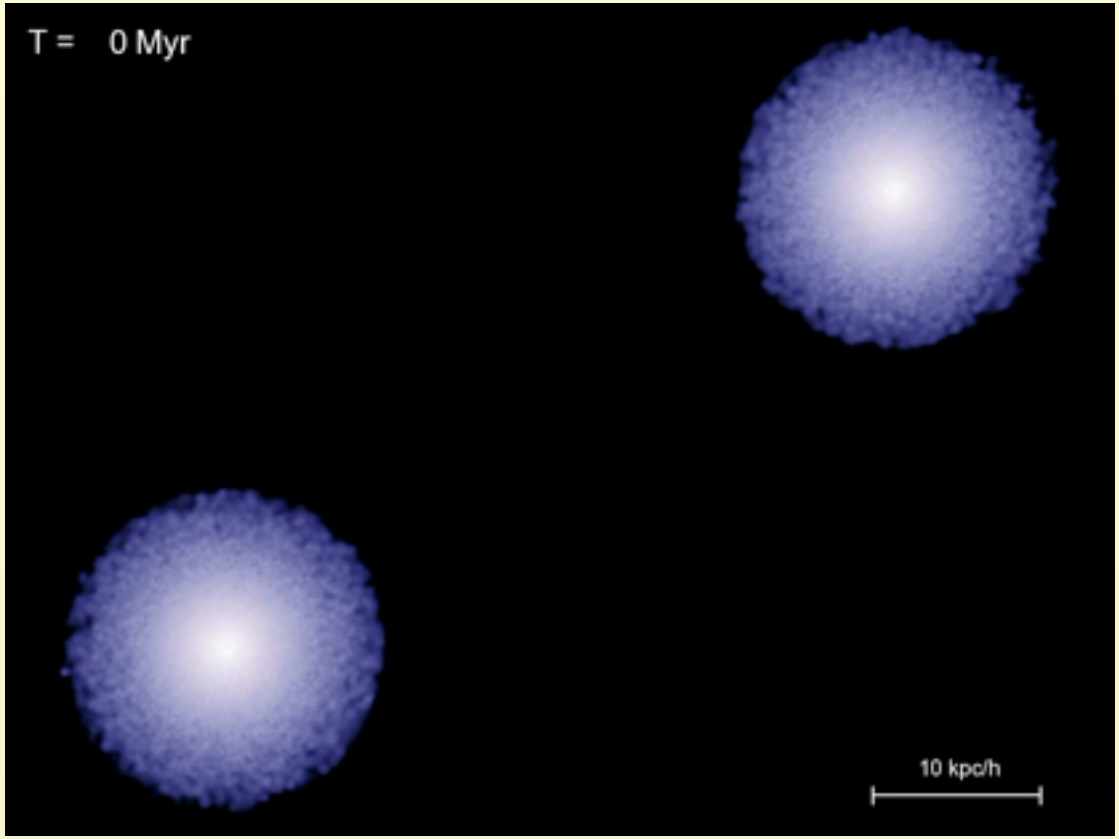
Colors:
Rest-frame color
Of the galaxy
Blue: young;
Red: old



Biased Galaxy Formation

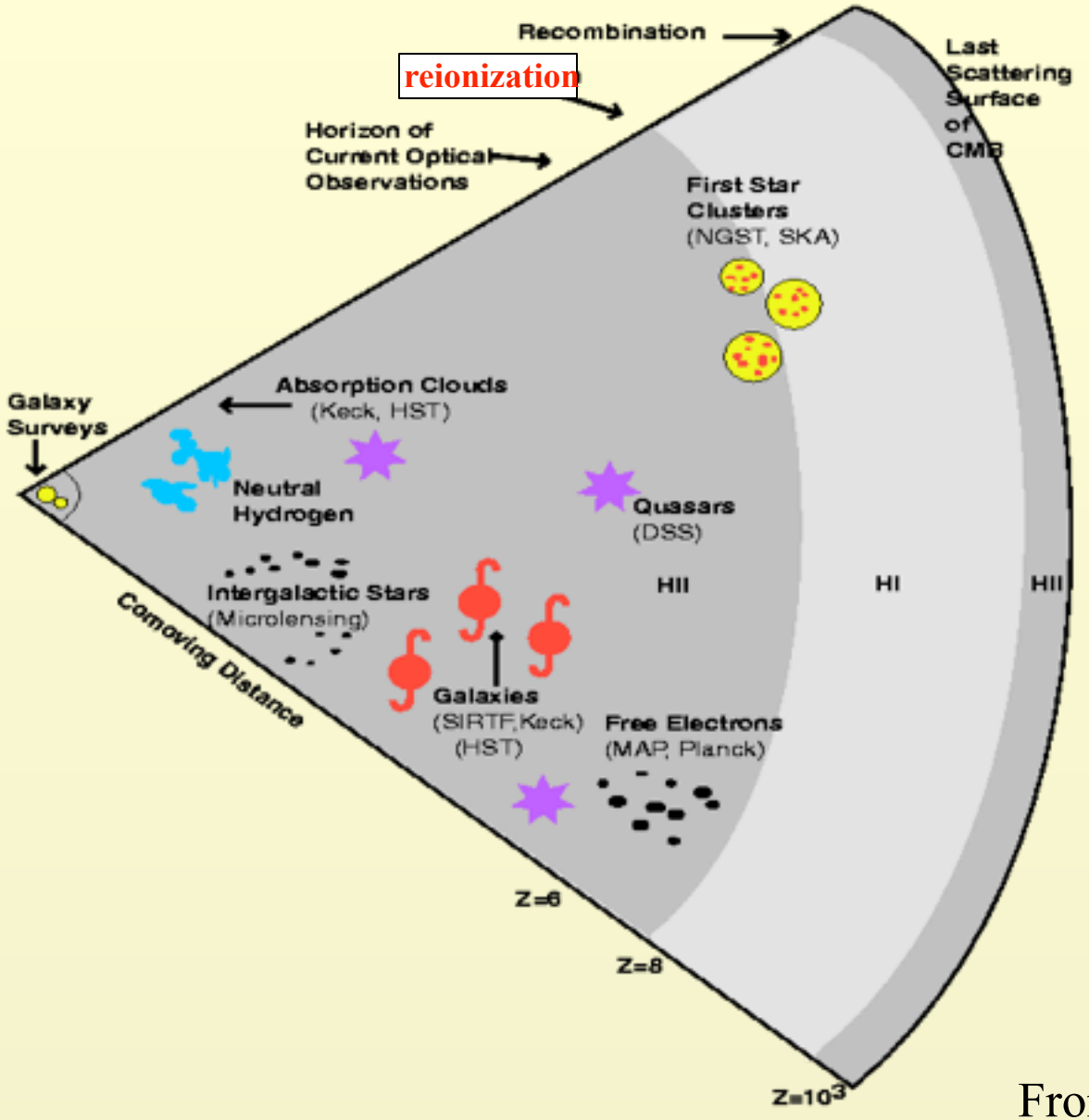
Galaxy merger and feedback

Galaxy merger and feedback



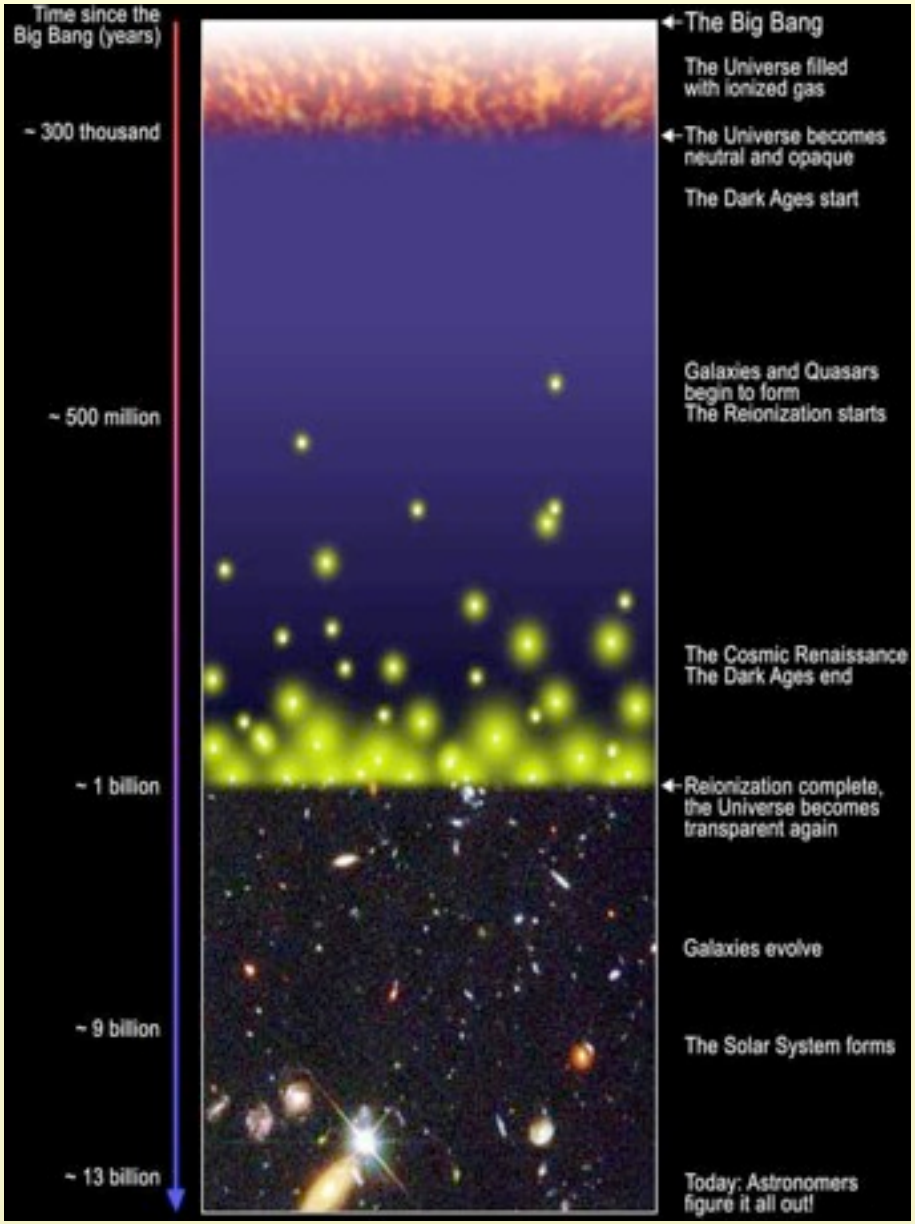
Epoch of Reionization

May 1, 2014

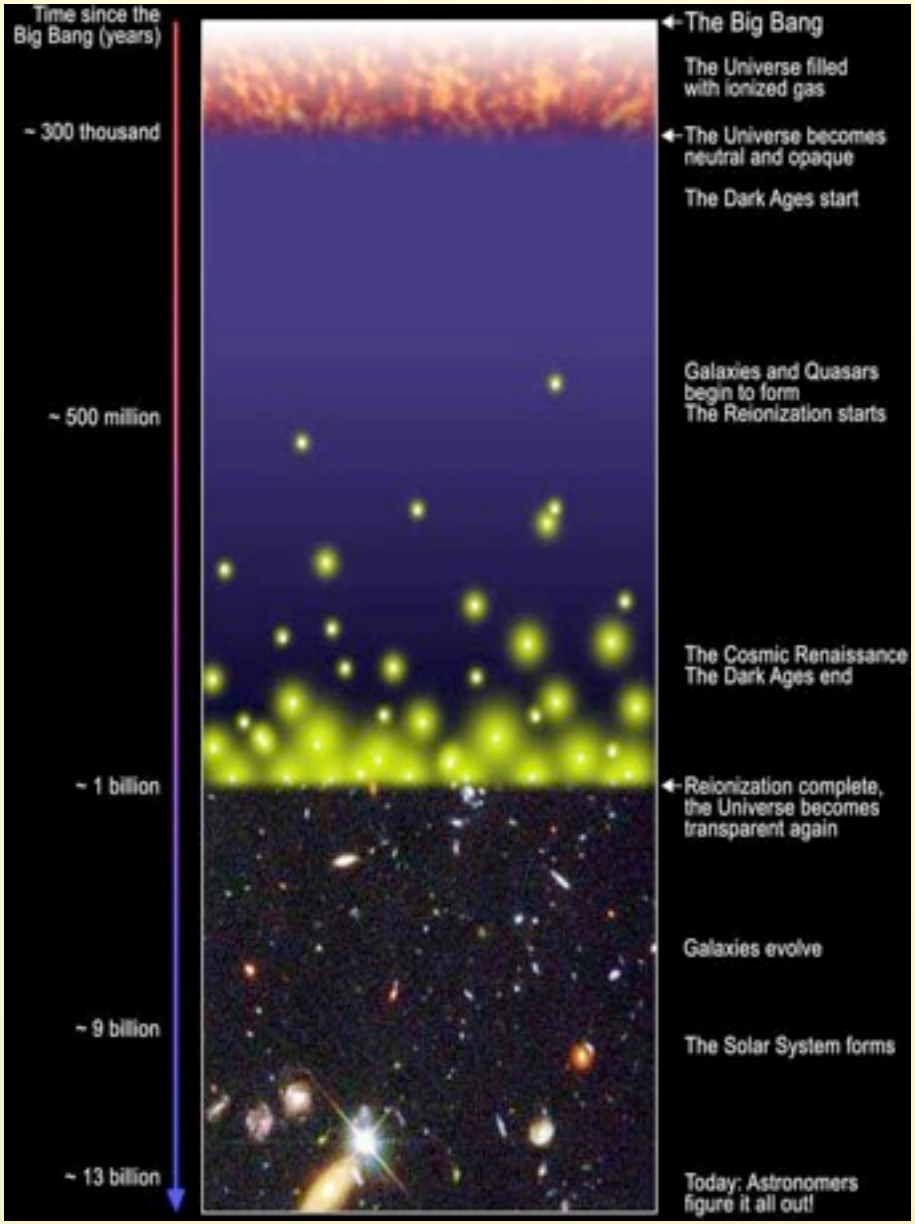


From Avi Loeb

A brief cosmic history

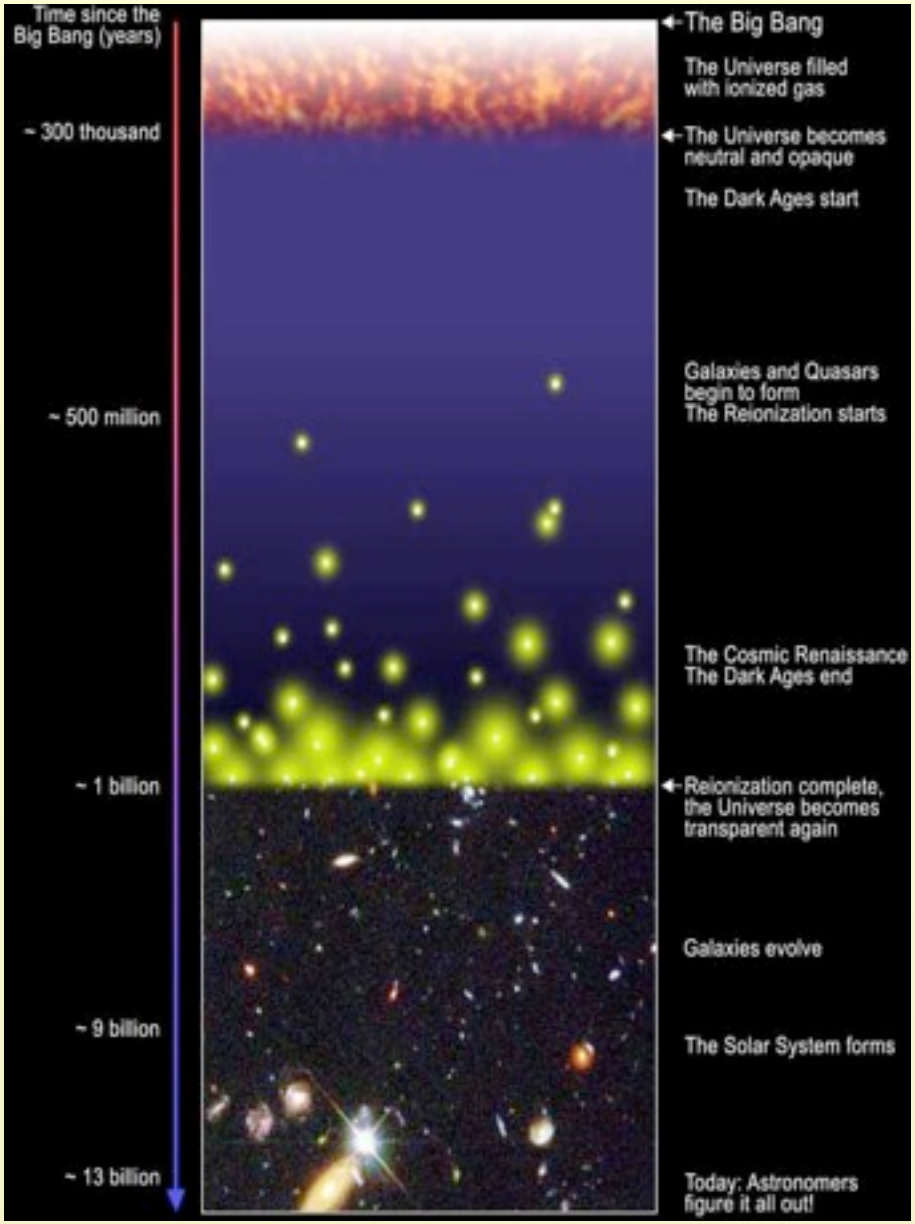


A brief cosmic history

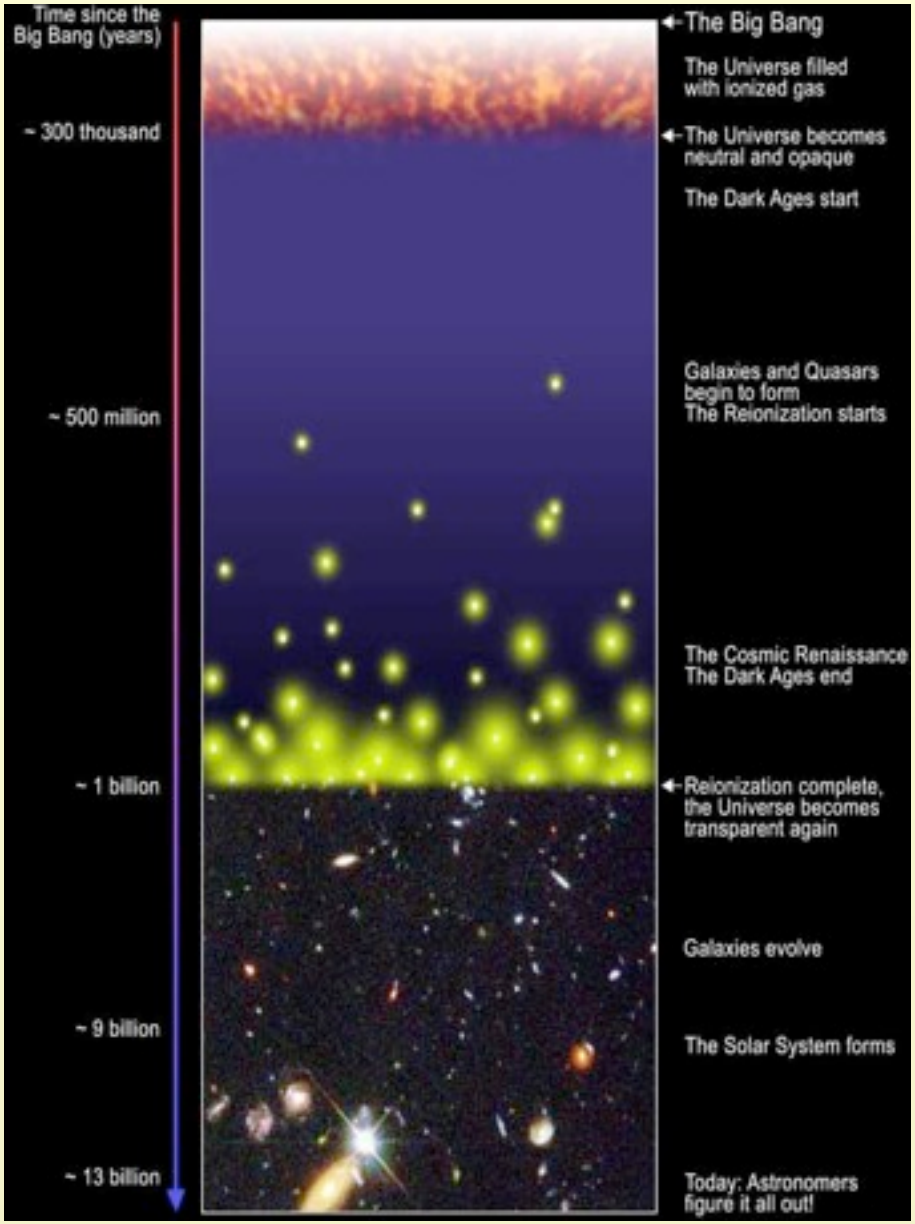


←Big Bang: the universe filled with hot gas

A brief cosmic history

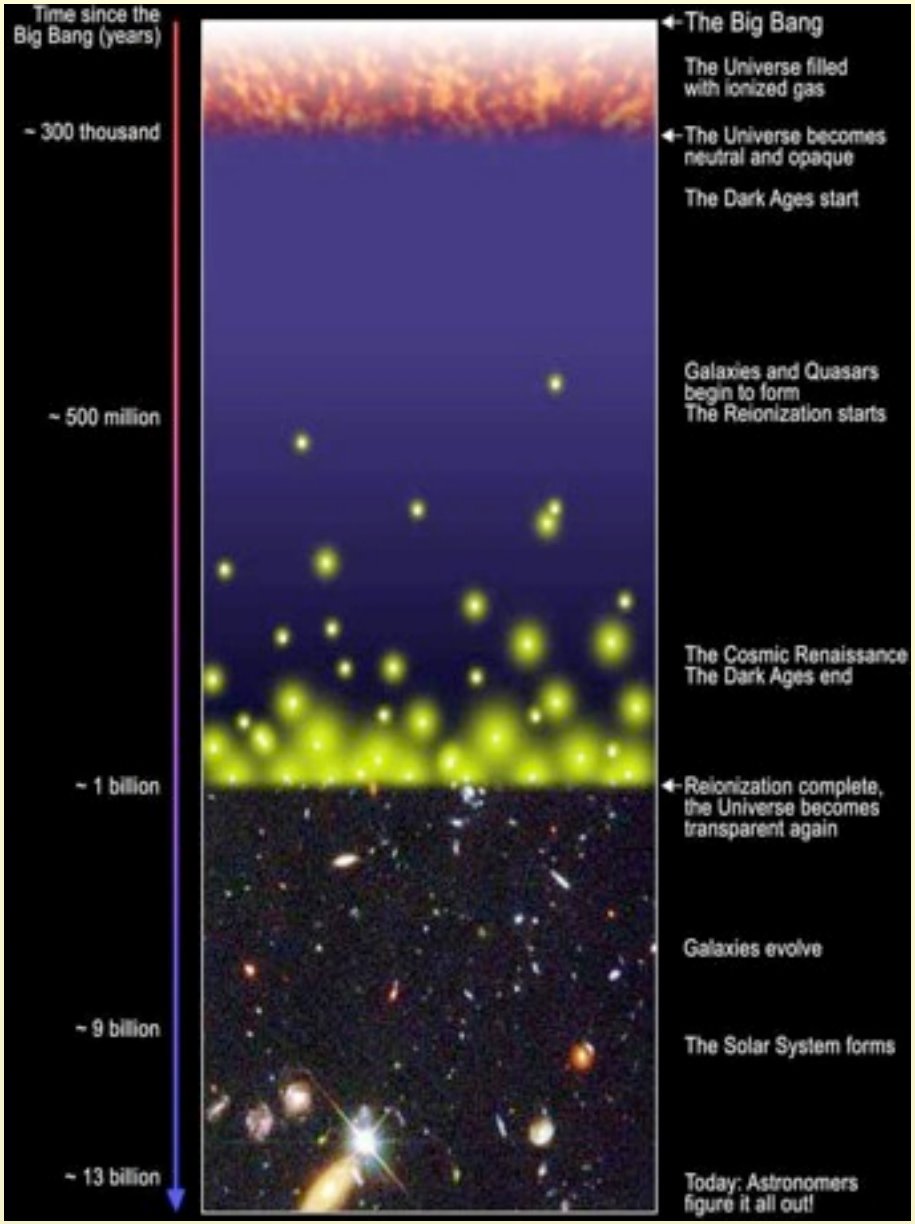


A brief cosmic history

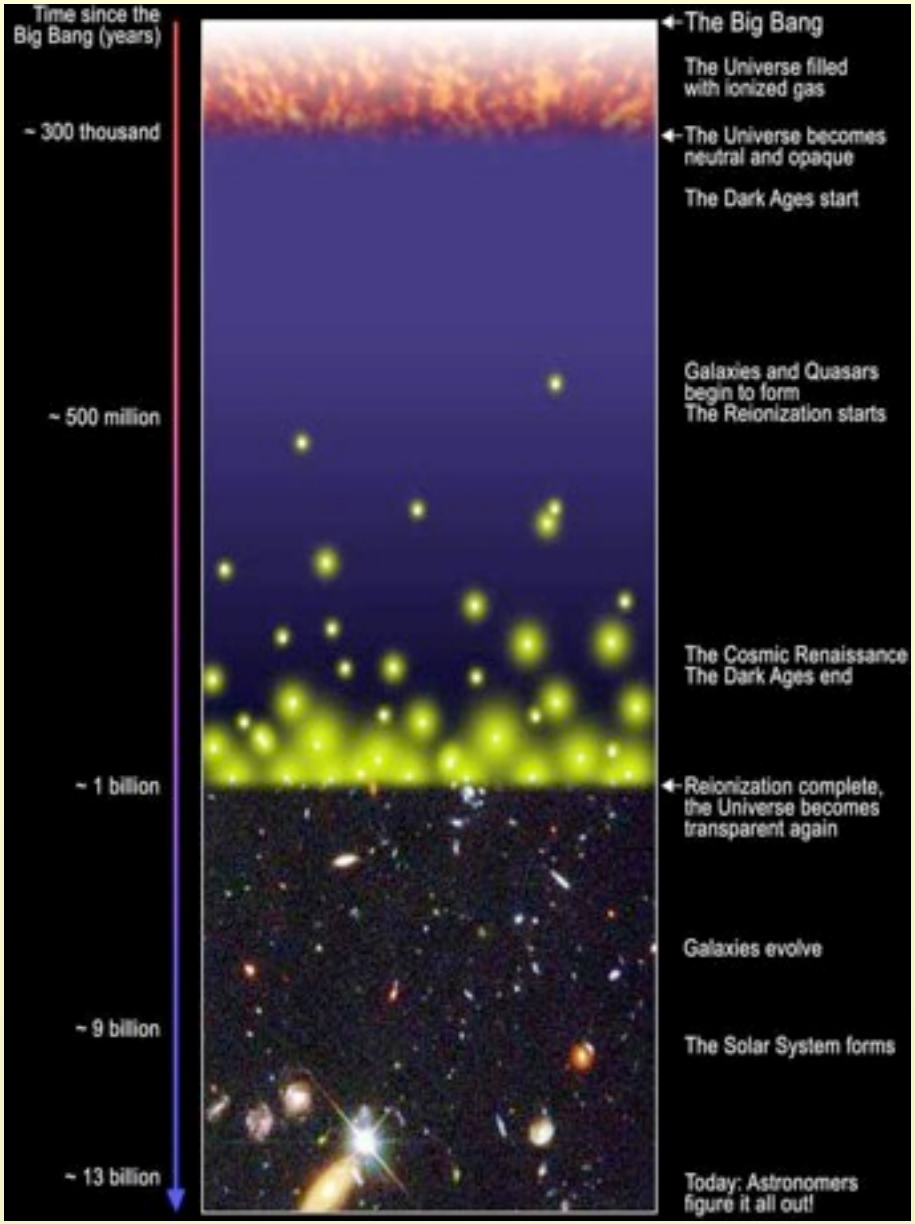


←Cosmic Dark Age: no light
no star, no quasar

A brief cosmic history

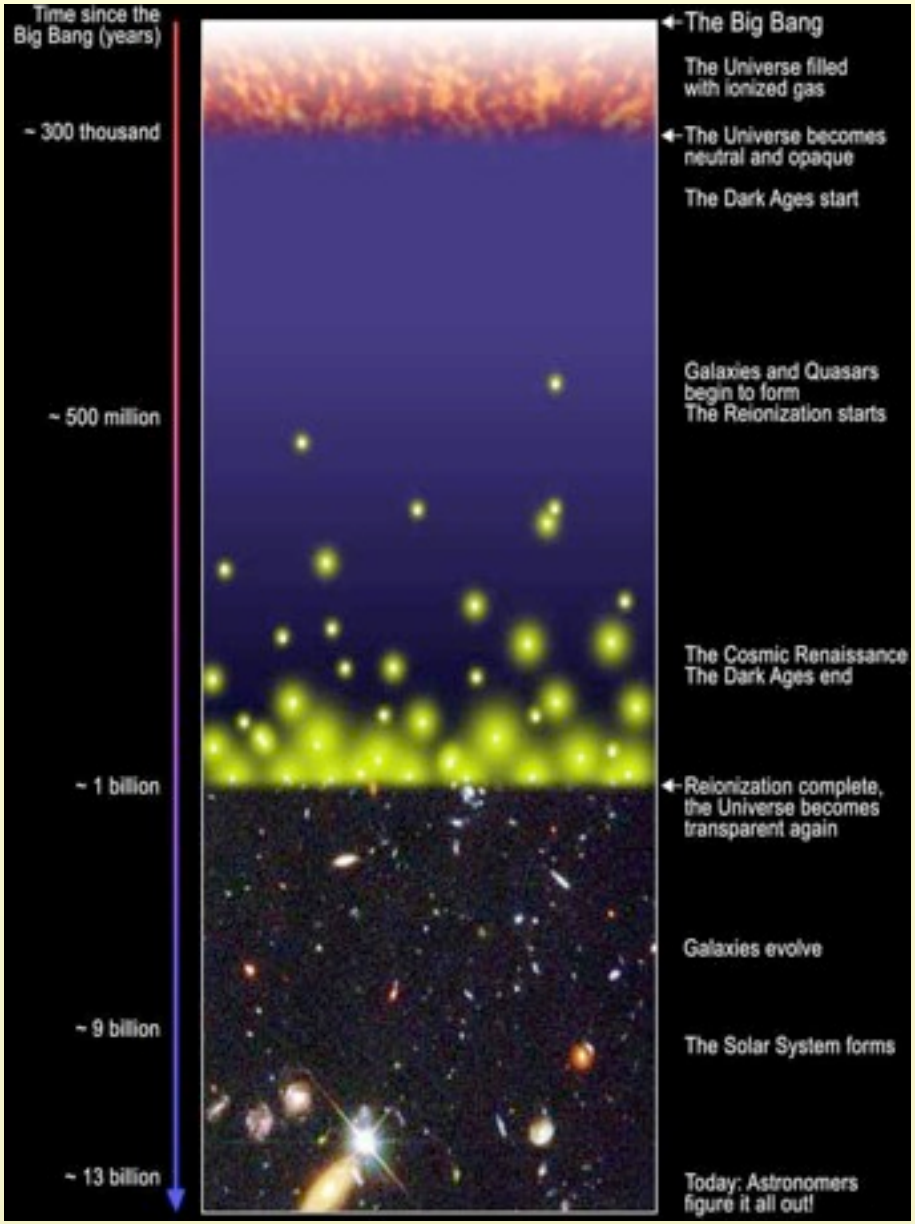


A brief cosmic history

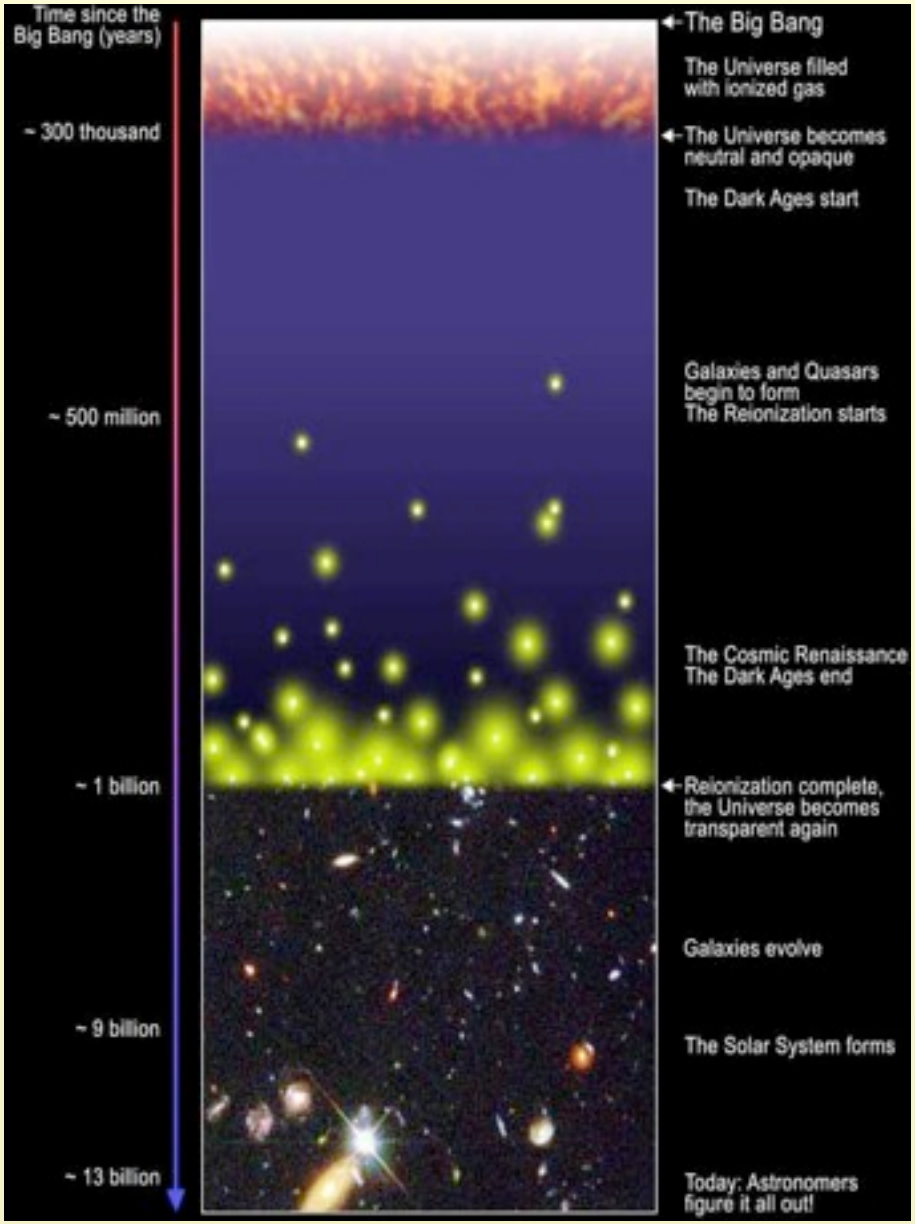


←First light: the first galaxies and quasars in the universe

A brief cosmic history

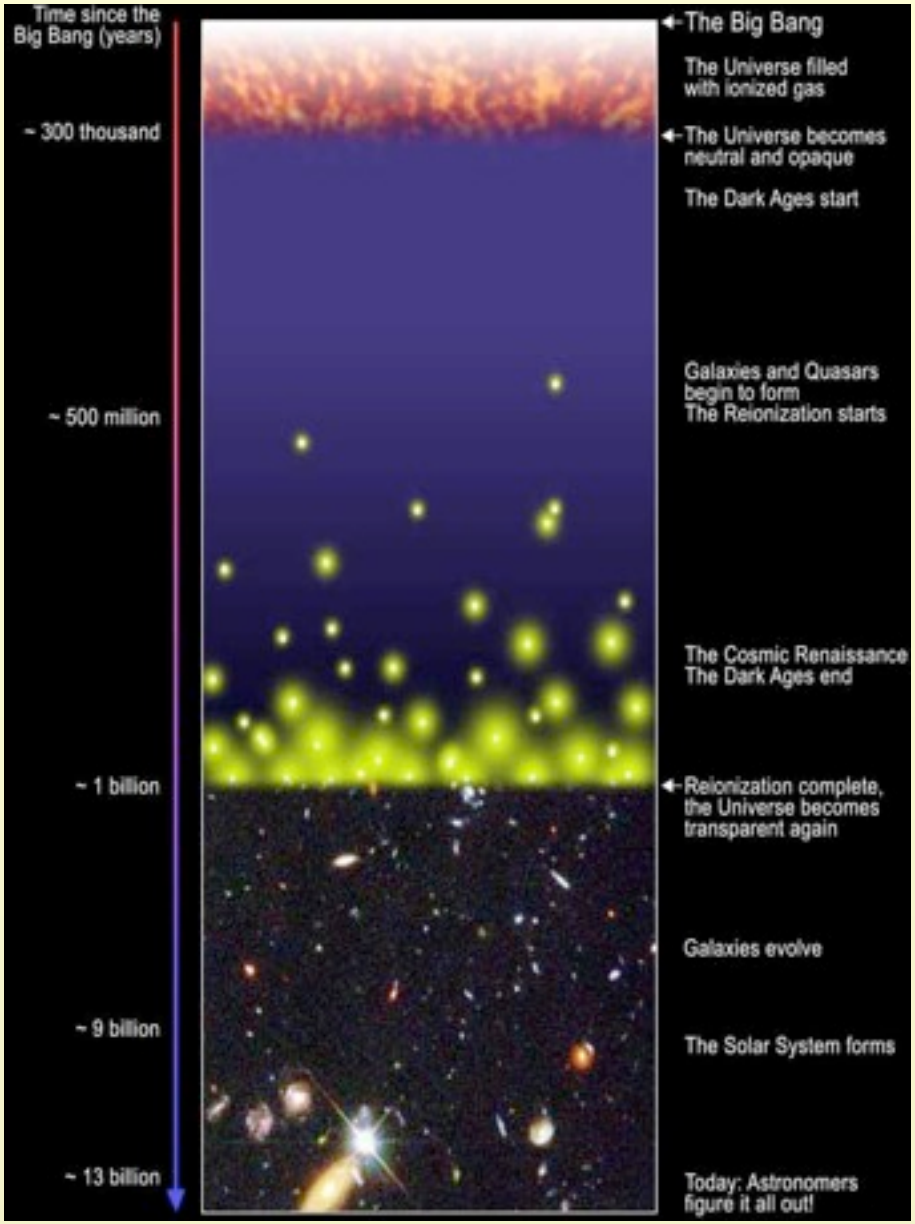


A brief cosmic history

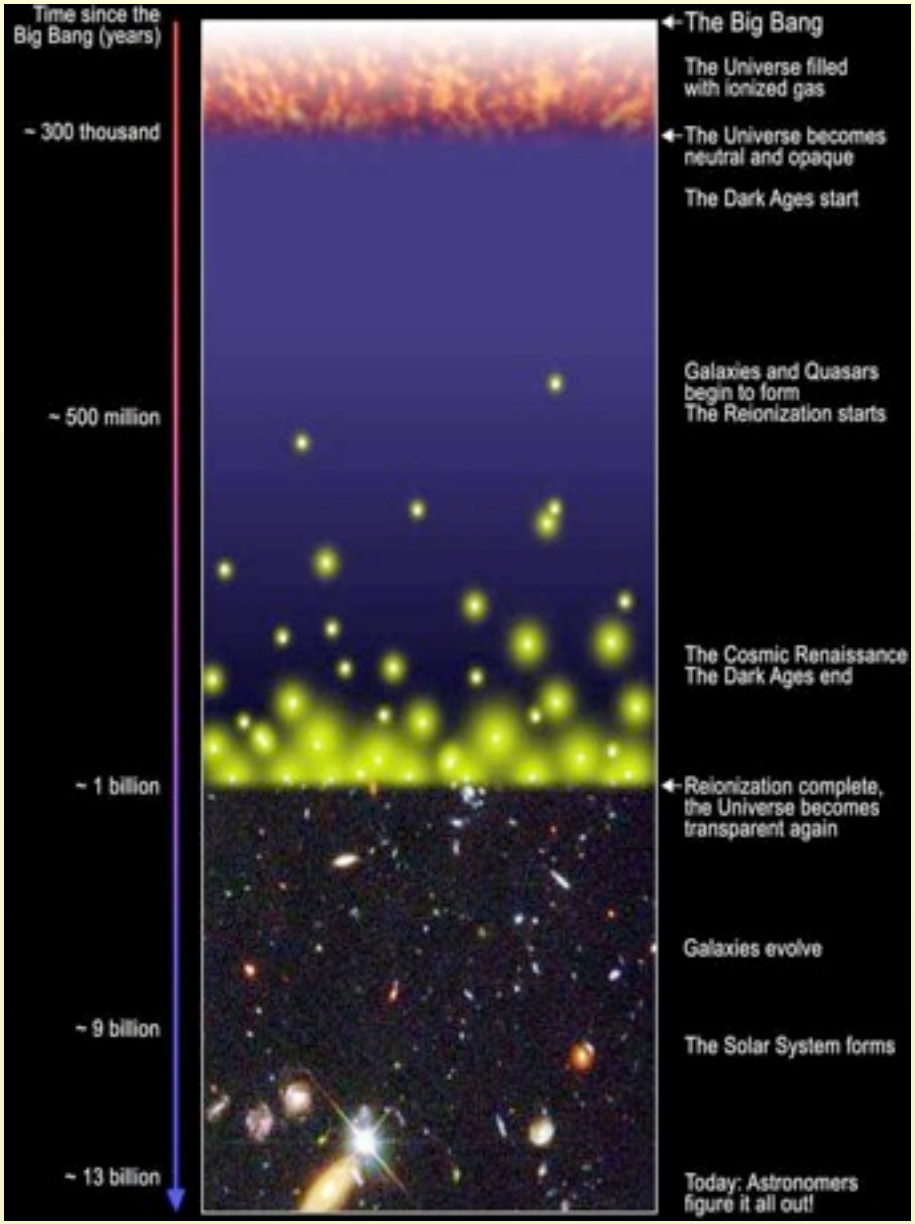


←Cosmic Renaissance: universe lit up by young galaxies and quasars

A brief cosmic history

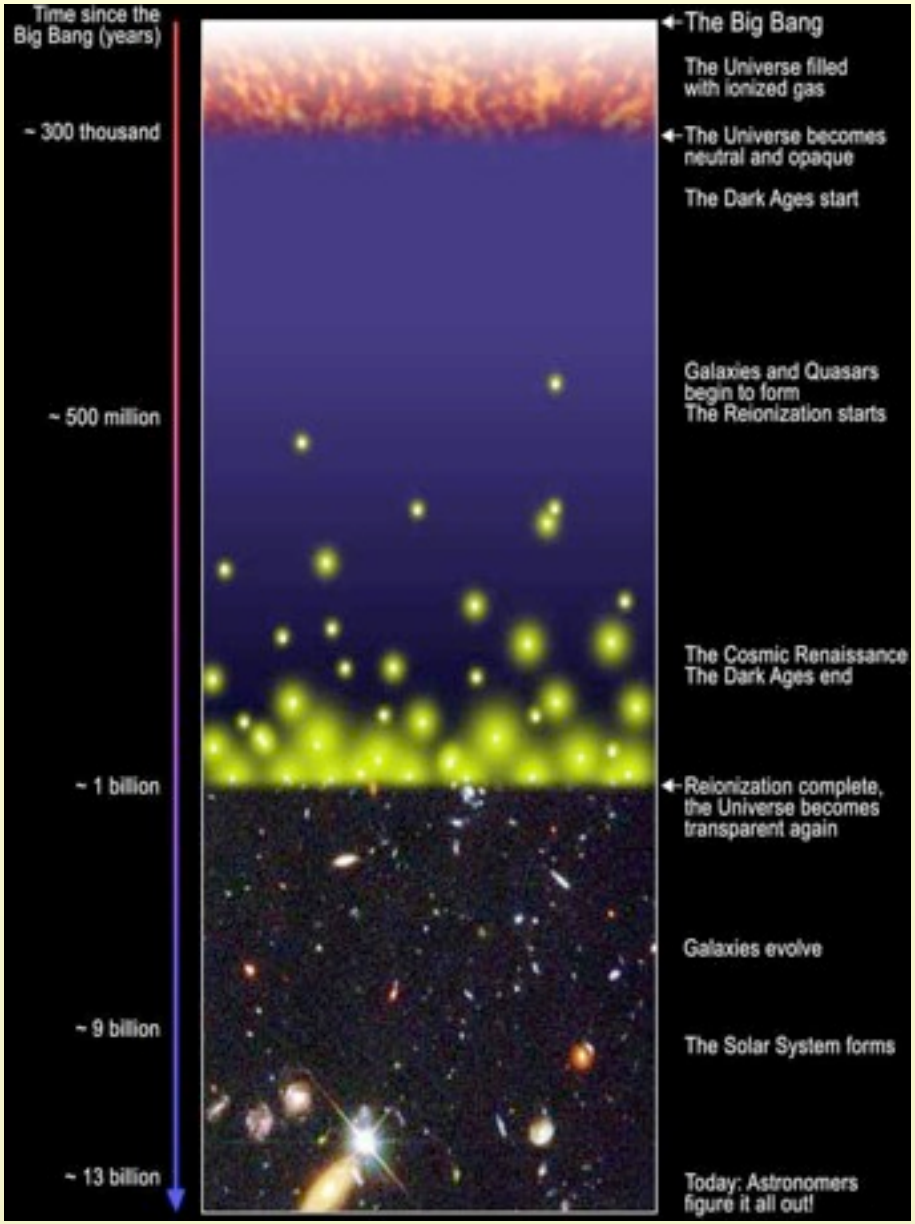


A brief cosmic history

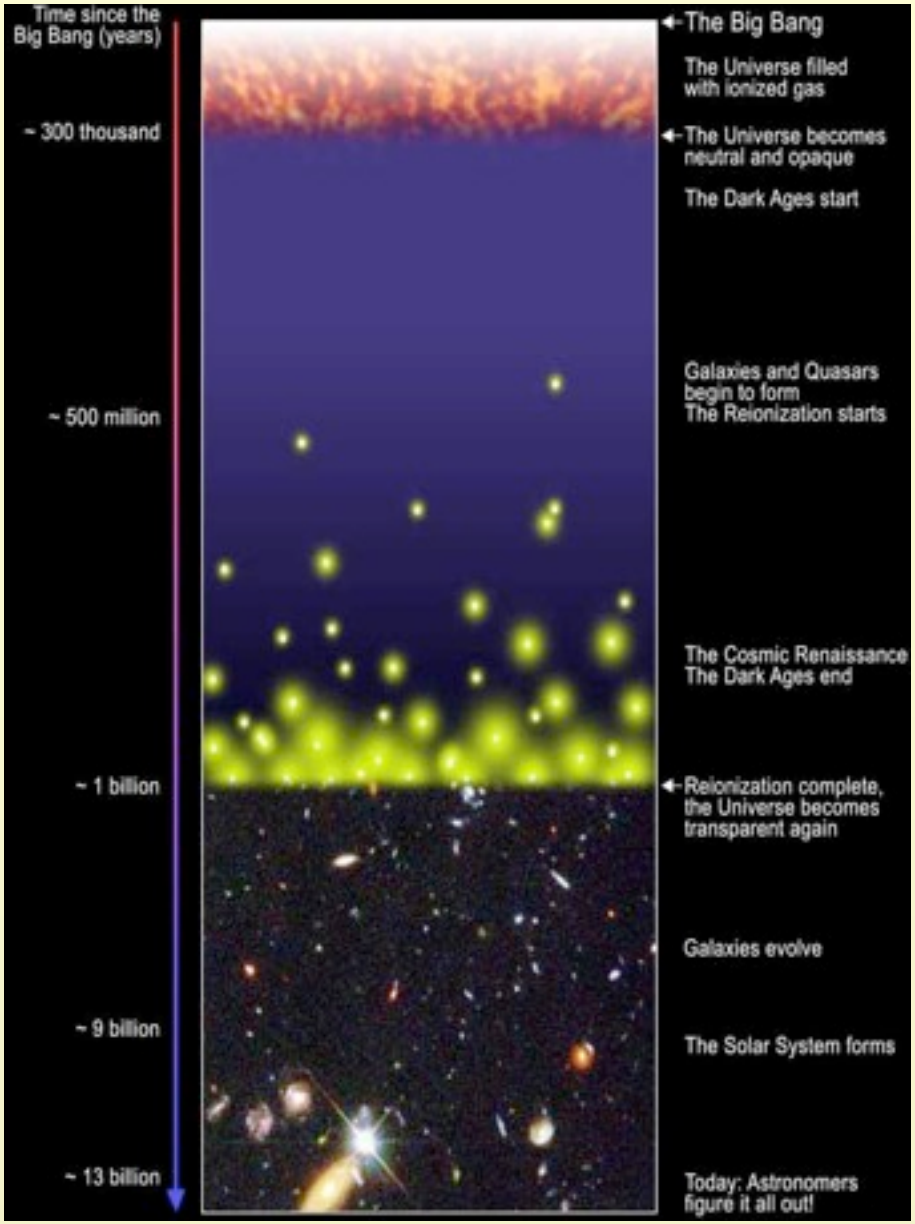


←"reionization" completed, the universe is transparent and the dark ages ended

A brief cosmic history

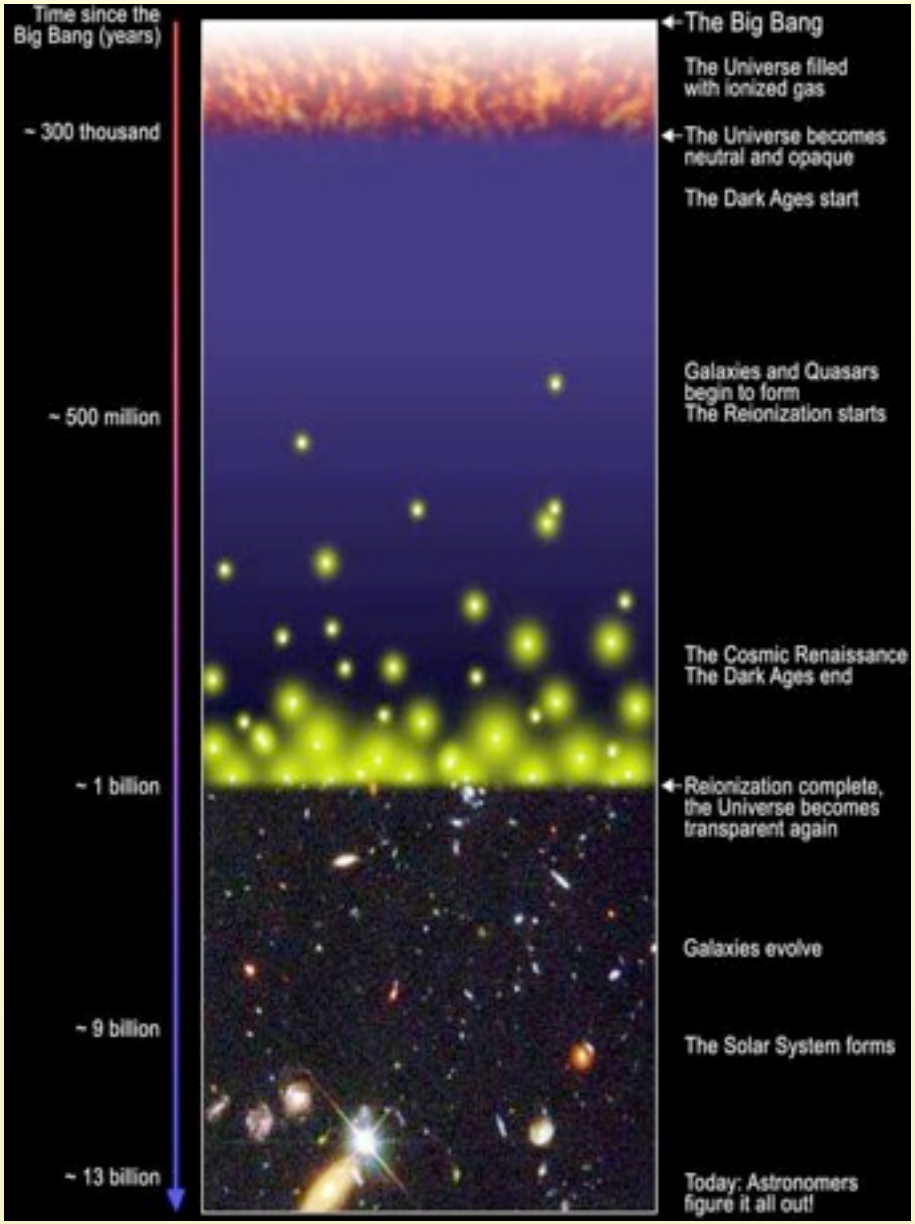


A brief cosmic history

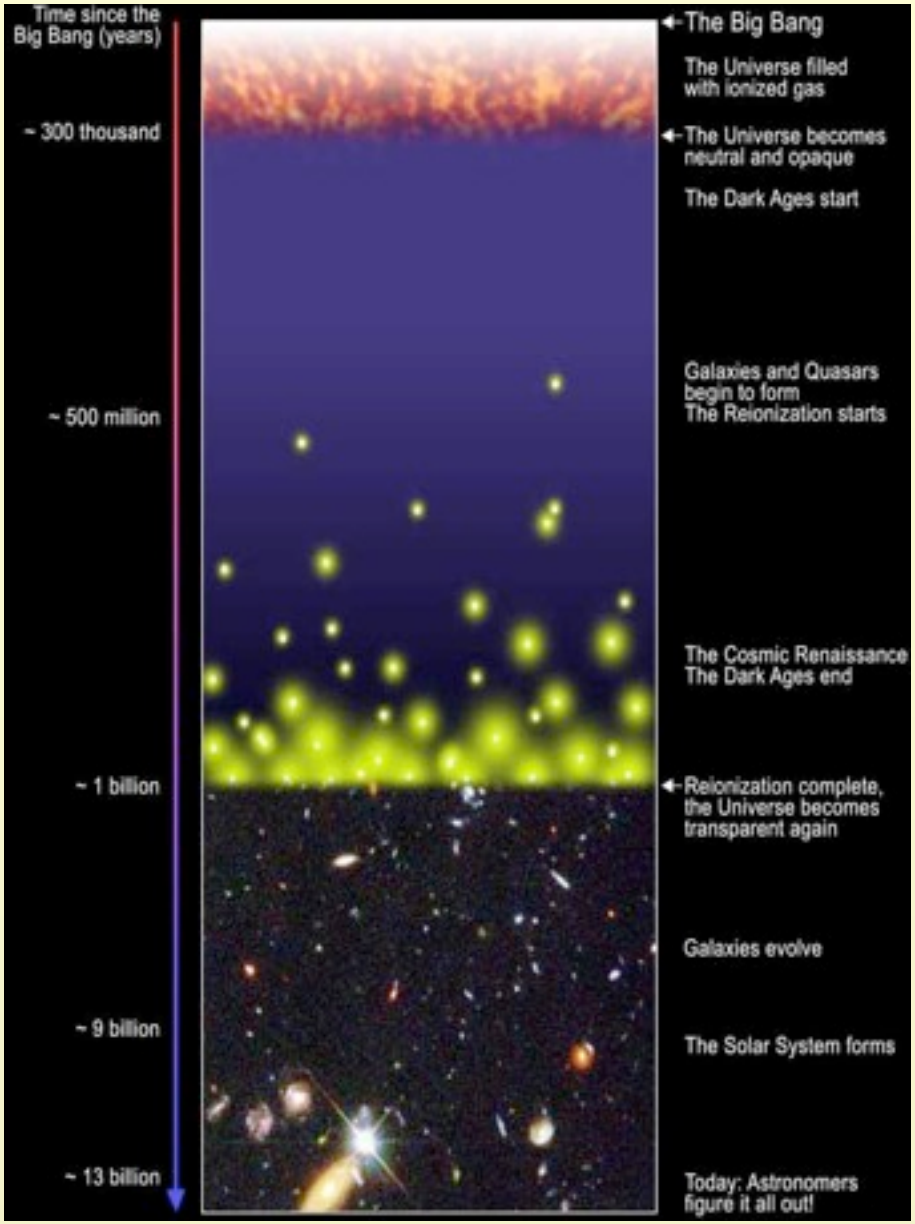


← today

A brief cosmic history



A brief cosmic history



←Big Bang: the universe filled with hot gas

←Cosmic Dark Age: no light no star, no quasar

←First light: the first galaxies and quasars in the universe

←Cosmic Renaissance: universe lit up by young galaxies and quasars

←"reionization" completed, the universe is transparent and the dark ages ended

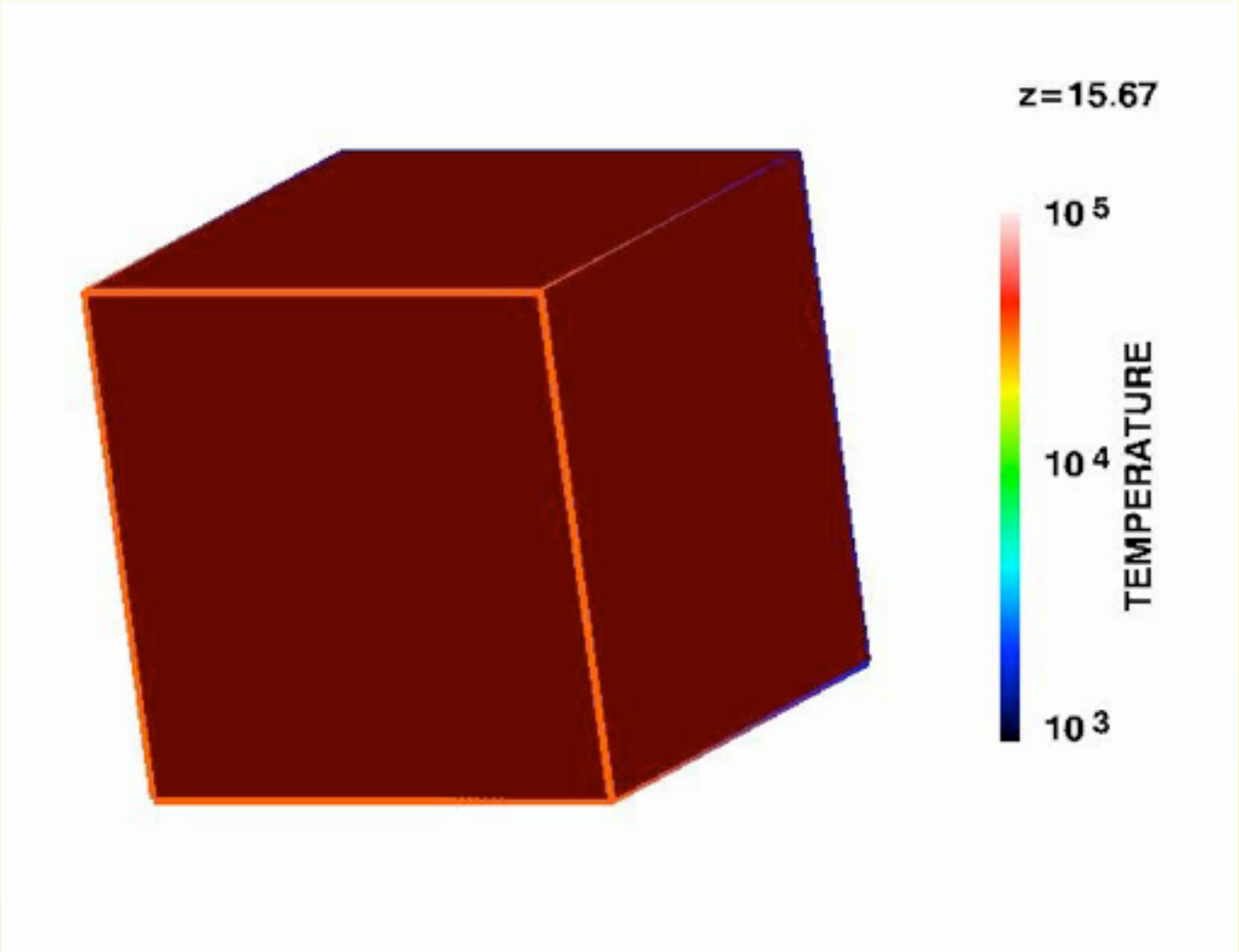
← today

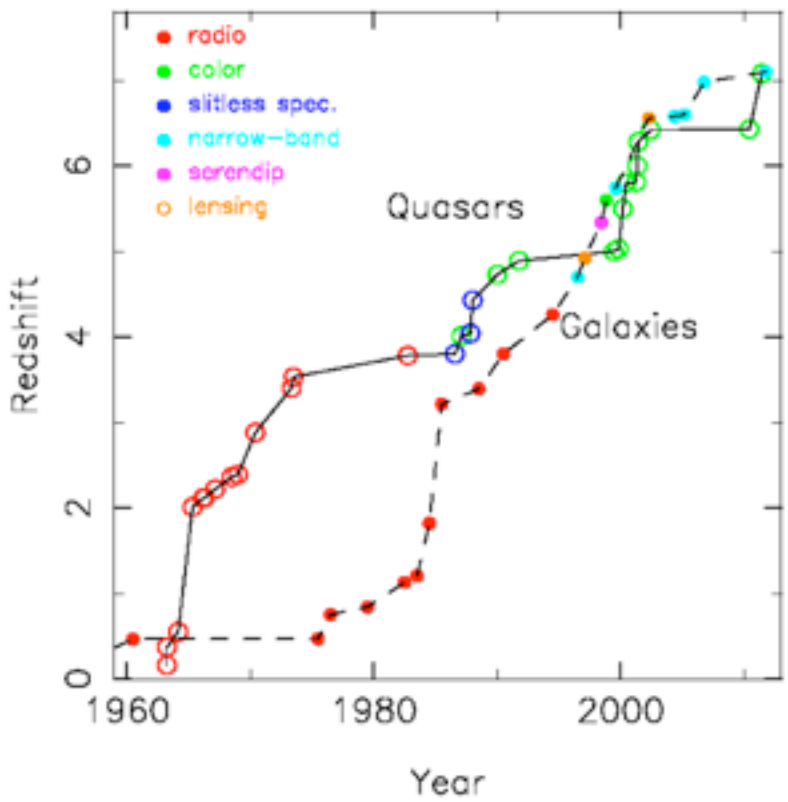
Reionization

- After recombination, the universe was neutral
- At z~20 – 30, the first generation galaxies and mini quasars formed
- At z~6 – 15, the UV radiation from the first generation objects ionized most of the HI in the universe
  - The neutral fraction of the universe changed from 1 to 10^-5 (phase transition in ionization state)
  - The temperature of the intergalactic medium (IGM) electrons changed from CMB temperature to 10^4 (phase transition accompanied by temperature change)
  - IGM becomes transparent to UV radiation, the universe is like a giant HII region (temperature change accompanied by opacity change)

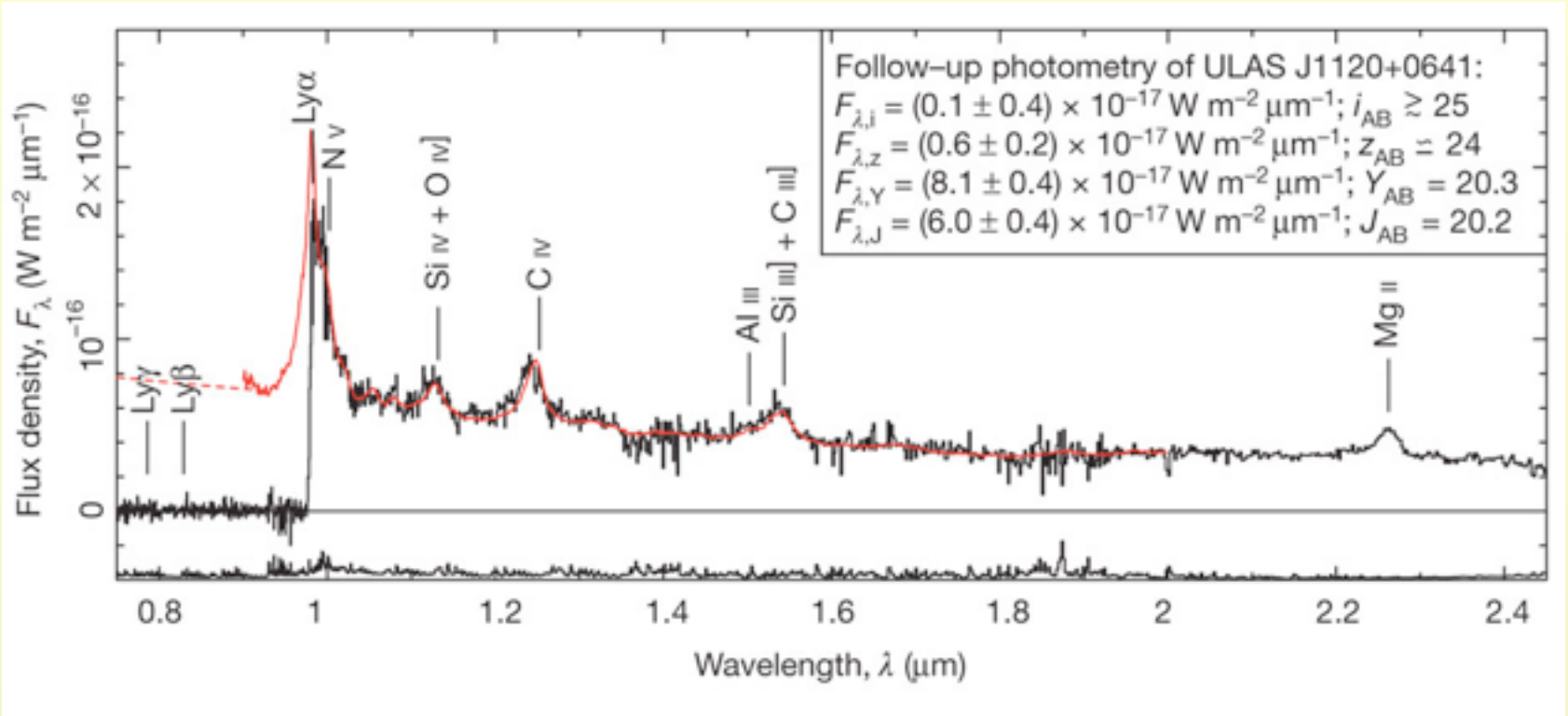
The end of dark ages: Movie

The end of dark ages: Movie

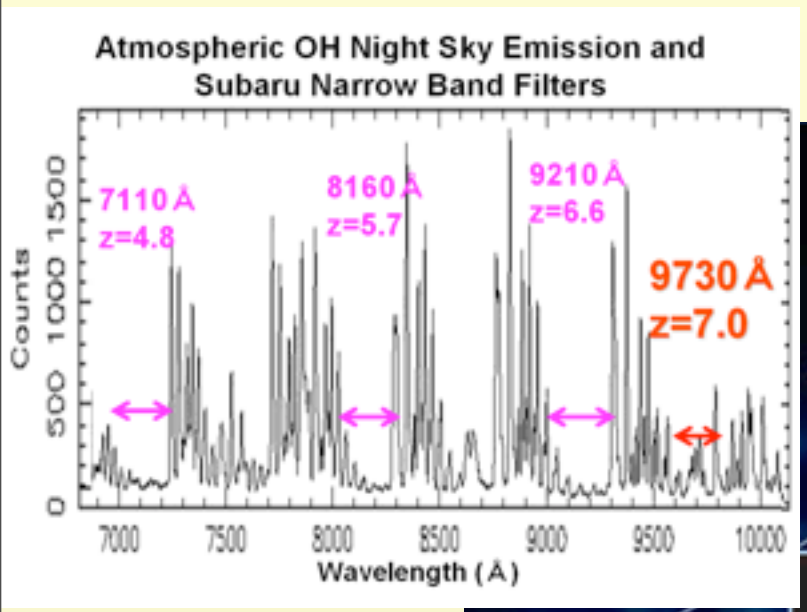


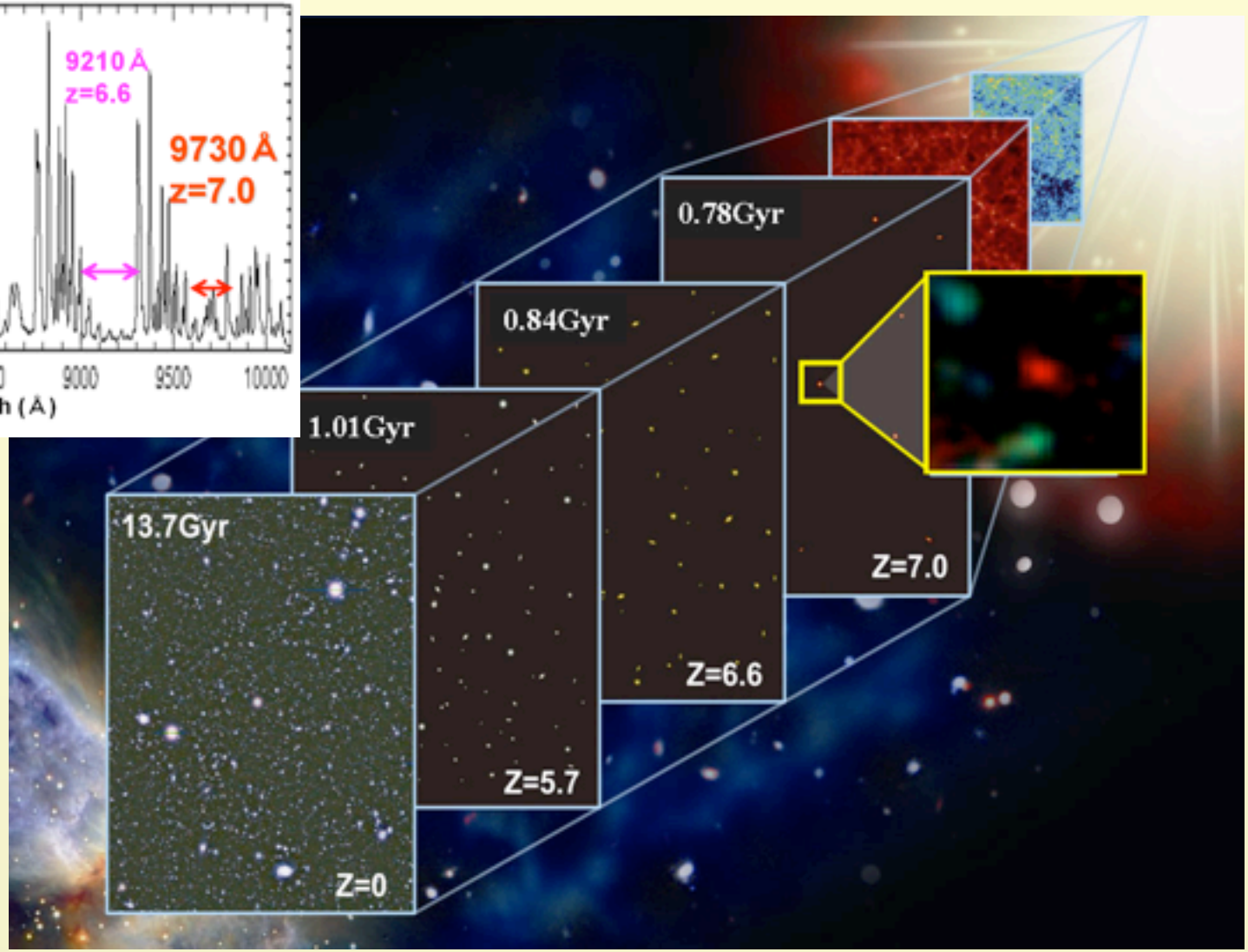

radio
color
slitless spec.
narrow-band
serendip
lensing
Quasars
Galaxies
Redshift
0
2
4
6
1960
1980
2000
Year

The Highest Redshift Quasar
z=7.085

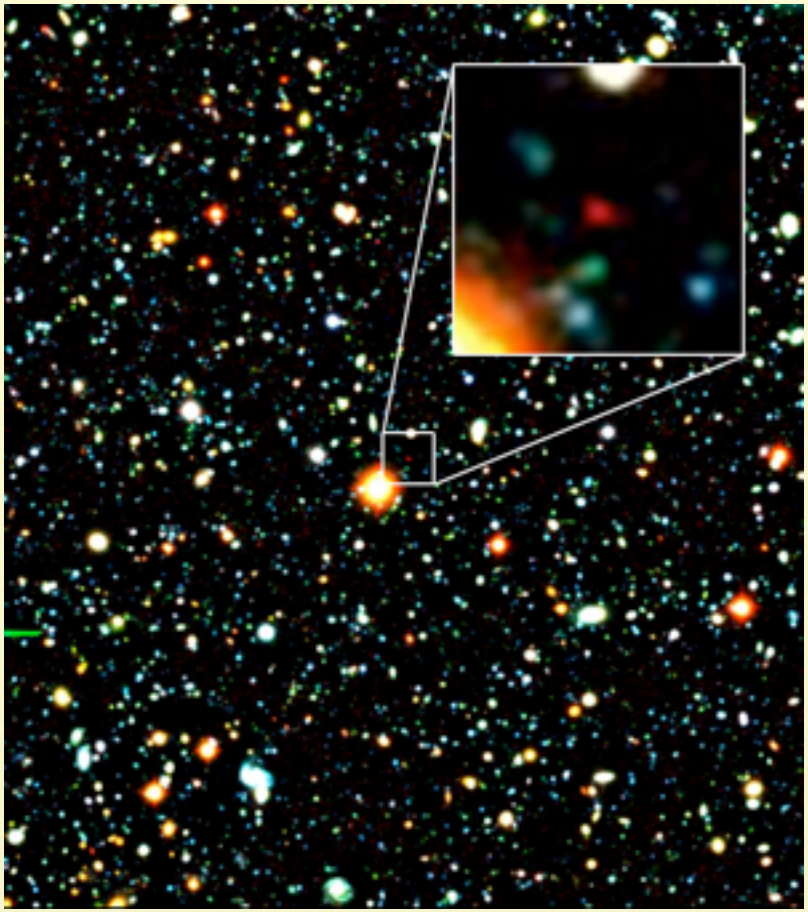


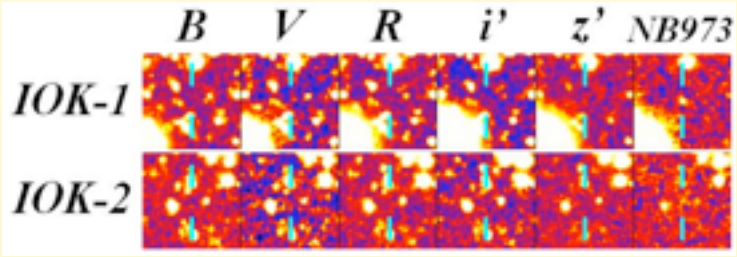
Matching towards high-z

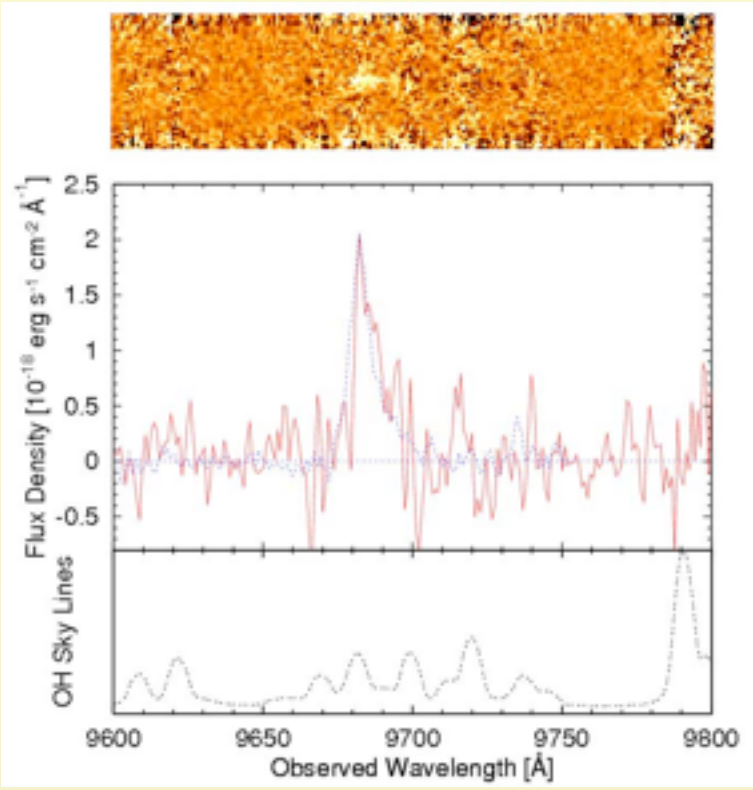




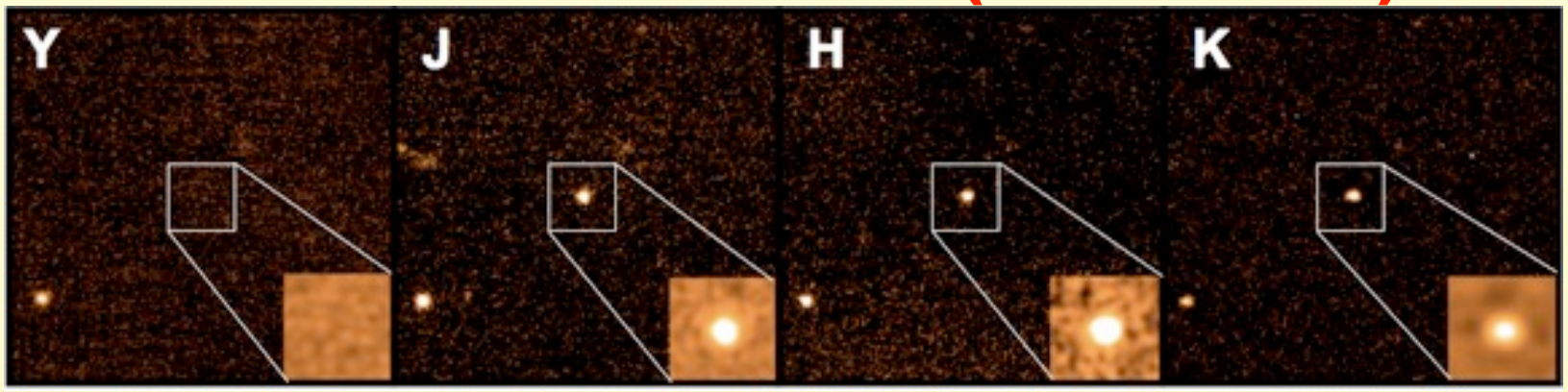
z=6.98

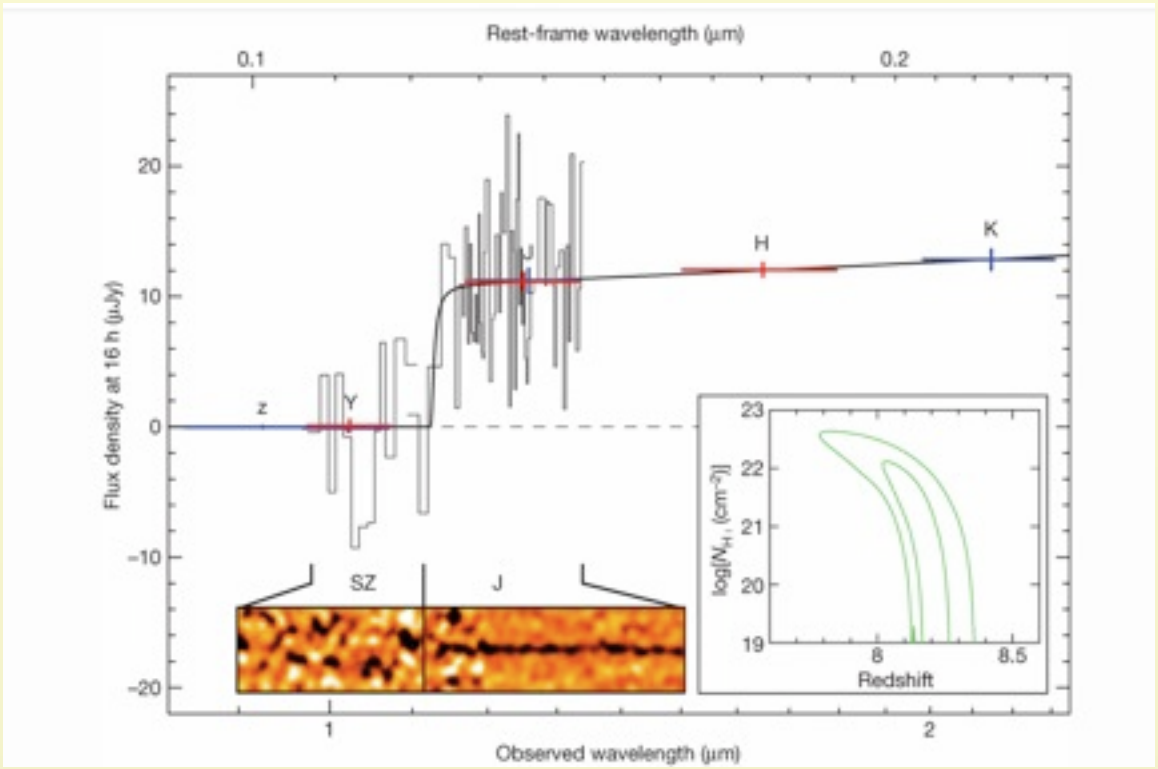



B
V
R
i'
z'
NB973
IOK-1
IOK-2

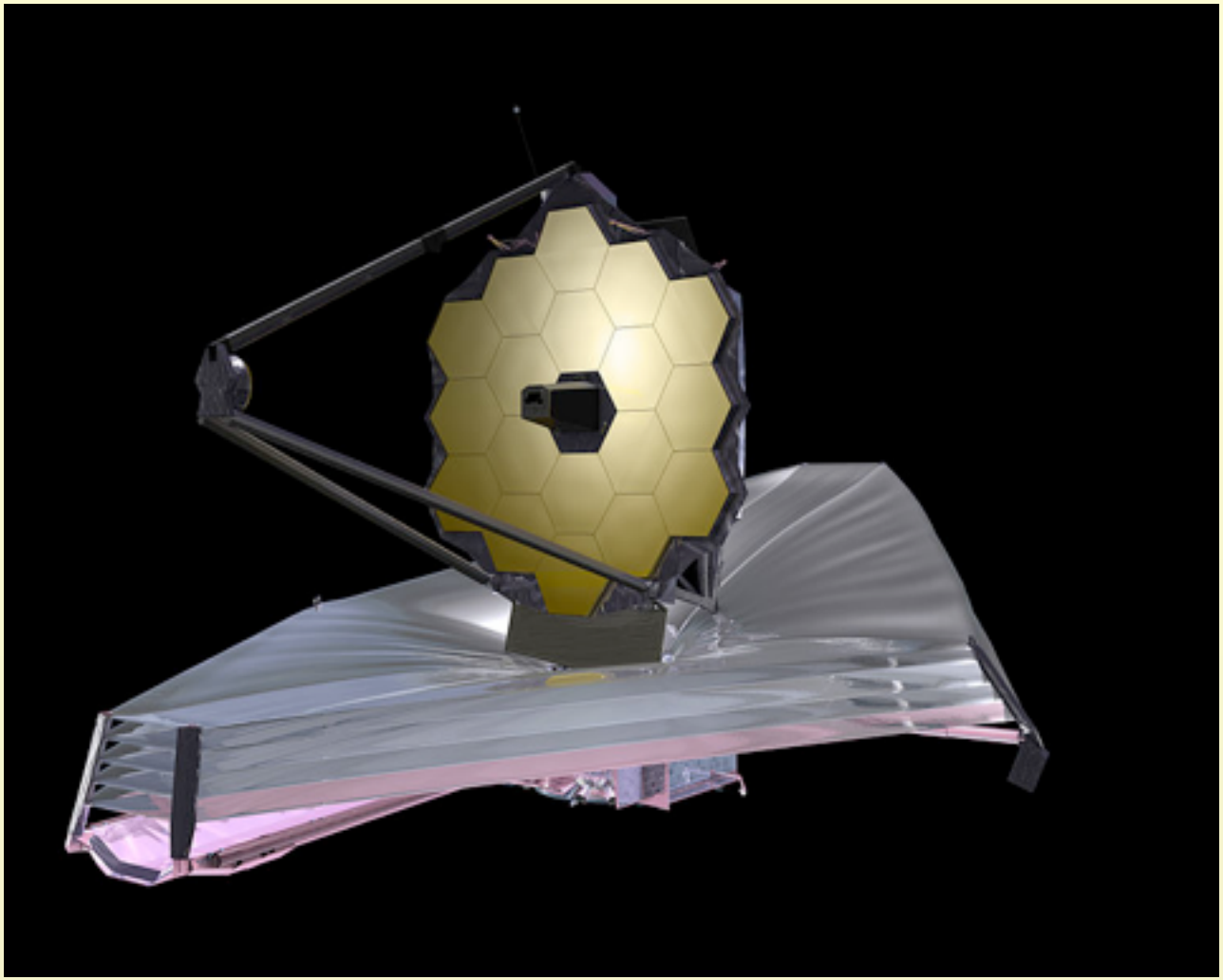

Flux Density [10^-18 erg s^-1 cm^-2 Å^-1]
2.5
2
1.5
1
0.5
0
-0.5
OH Sky Lines
9600
9650
9700
9750
9800
Observed Wavelength [Å]

The Most Distant Object in the Known Universe (z=8.2 GRB)

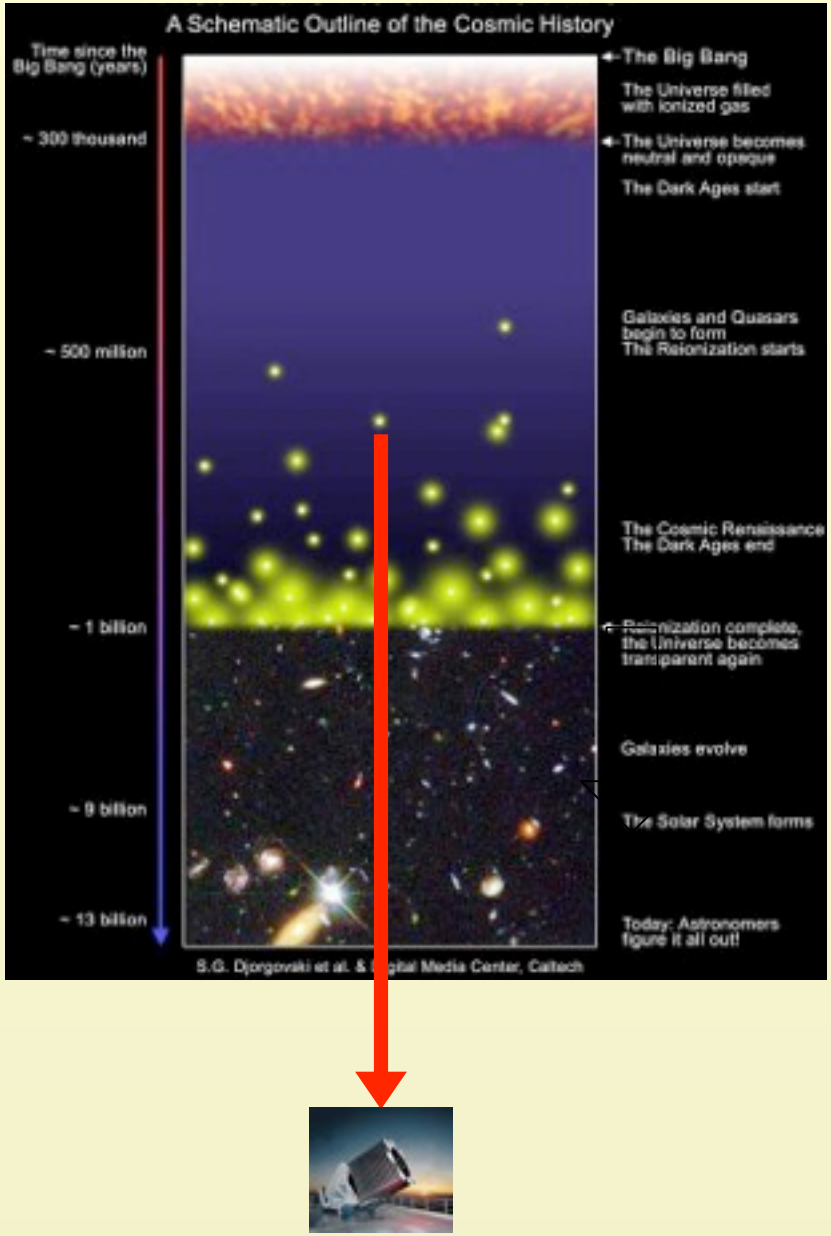




James-Webb Space Telescope



Using Quasar to Probe the End of Dark Ages



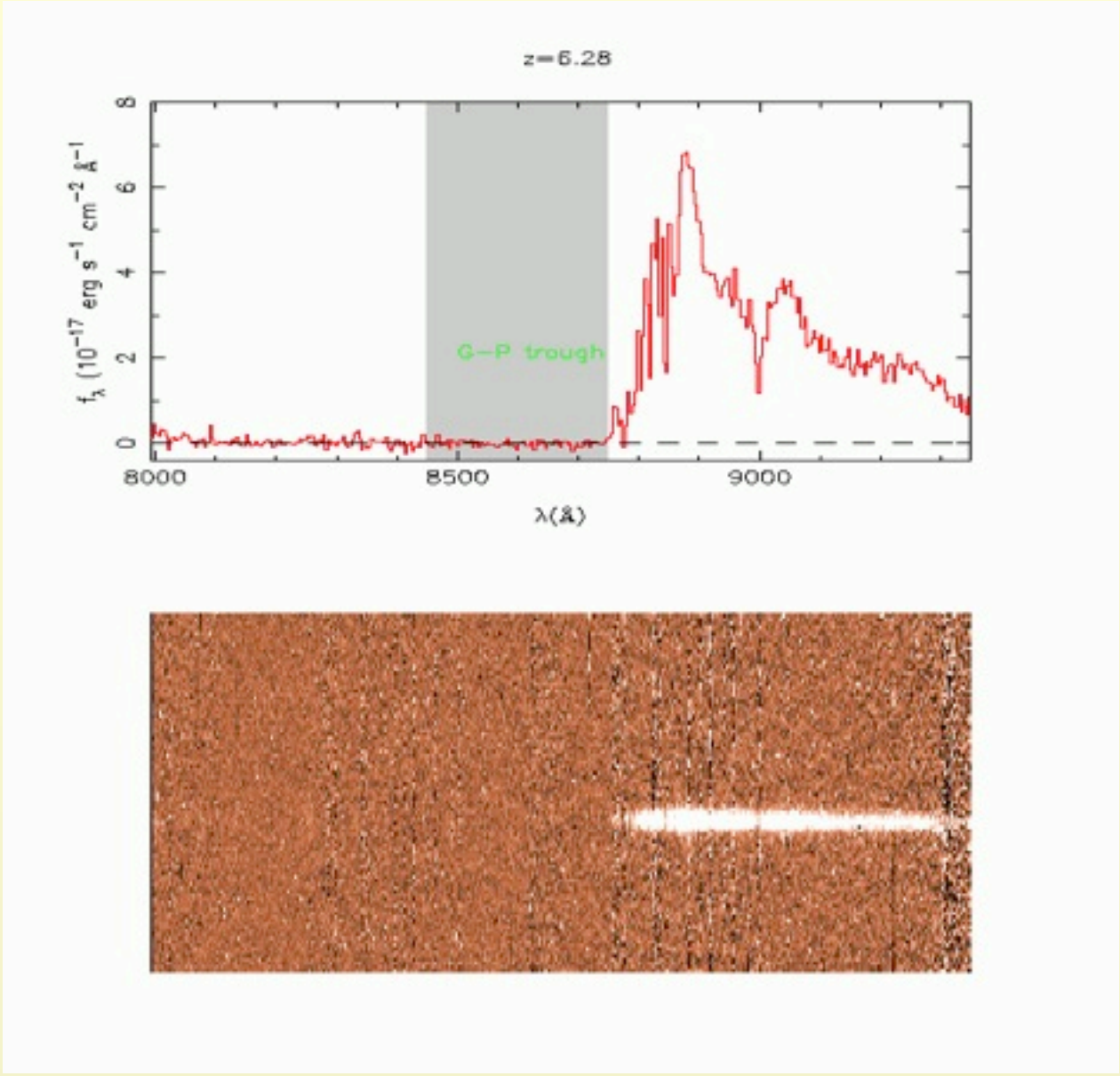
- Diffuse gas in the universe between quasar and observer will leave signature on the quasar spectrum
- Prior to the end of dark ages:
  - Universe was full of cold, atomic gas
  - It was opaque to ultraviolet photons and would create deep absorption troughs in quasar spectra
  - ***Gunn-Peterson (1965) effect***

  → detection of cosmic dark ages
- After reionization:
  - The universe is transparent to UV photons

Searching for Gunn-Peterson Trough

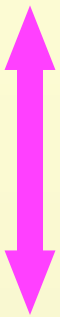
- Gunn and Peterson (1965)
  - "It is observed that the continuum of the source continues to the blue of Ly-α (in quasar 3C9, z=2.01)"
  - "only about one part of 5×10^6 of the total mass at that time could have been in the form of intergalactic neutral hydrogen "
- Absence of G-P trough → ***the universe is still highly ionized***
- ***First detection of complete G-P trough: SDSS J1030 (z=6.28, Becker et al. 2001)***
- G-P optical depth → evolution of ionizing background and neutral fraction of the IGM

First detection of Gunn-Peterson Effect



Evolution of Lyman Absorptions at

transparent

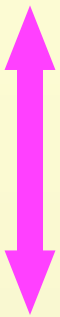


opaque

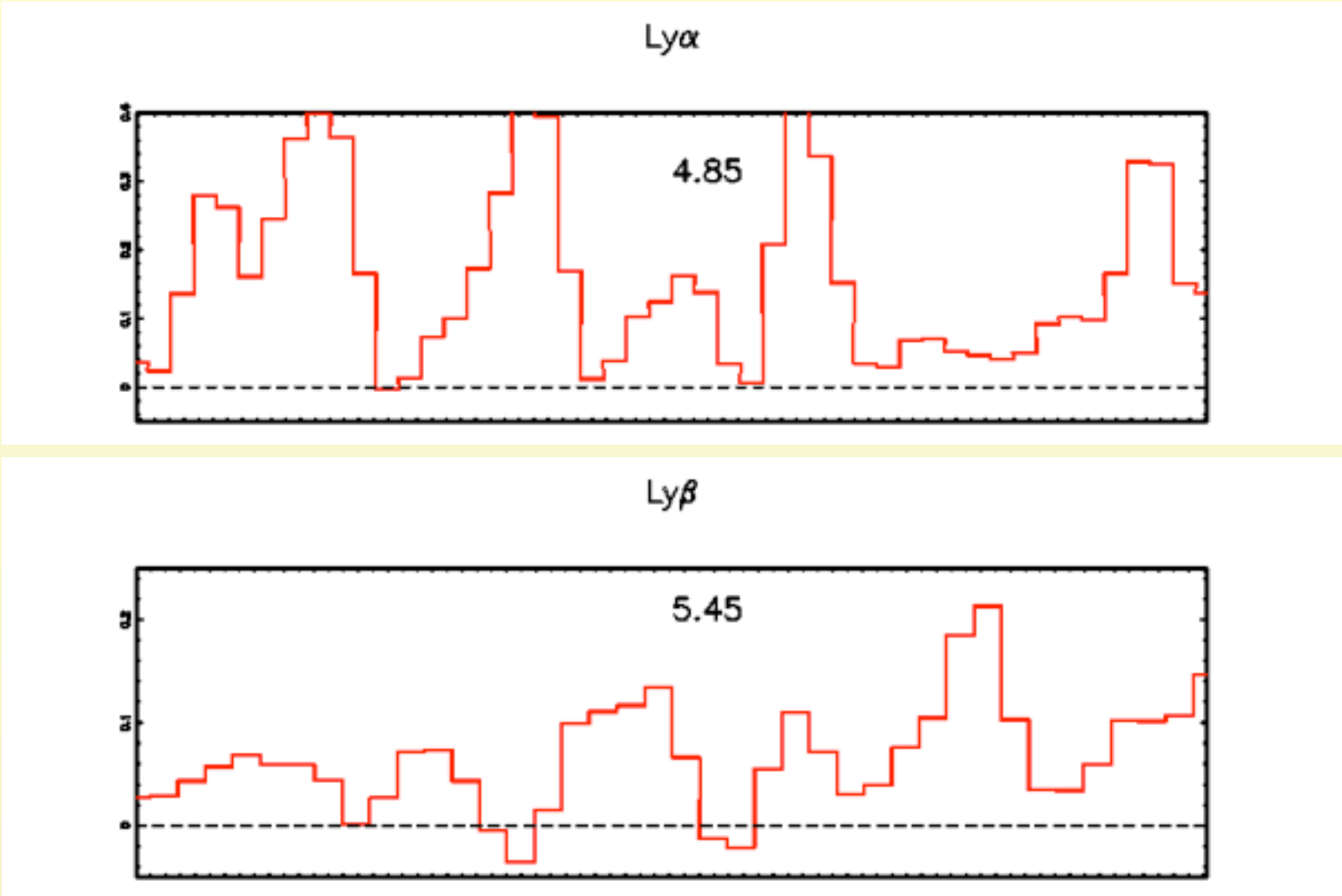
$\Delta z = 0.15$

Evolution of Lyman Absorptions at

transparent



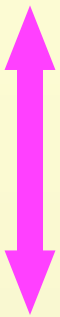
opaque



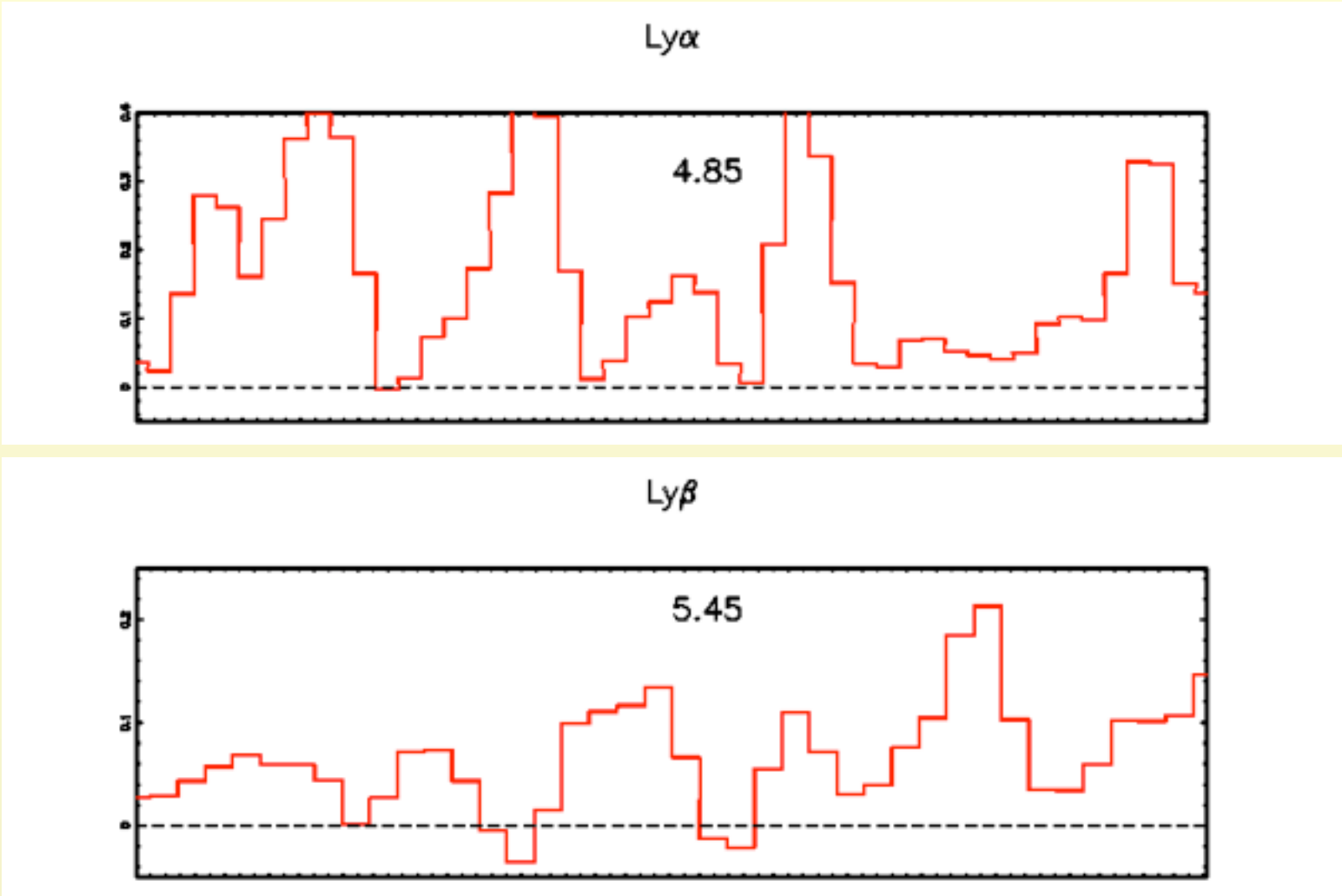
$\Delta z = 0.15$

Evolution of Lyman Absorptions at

transparent

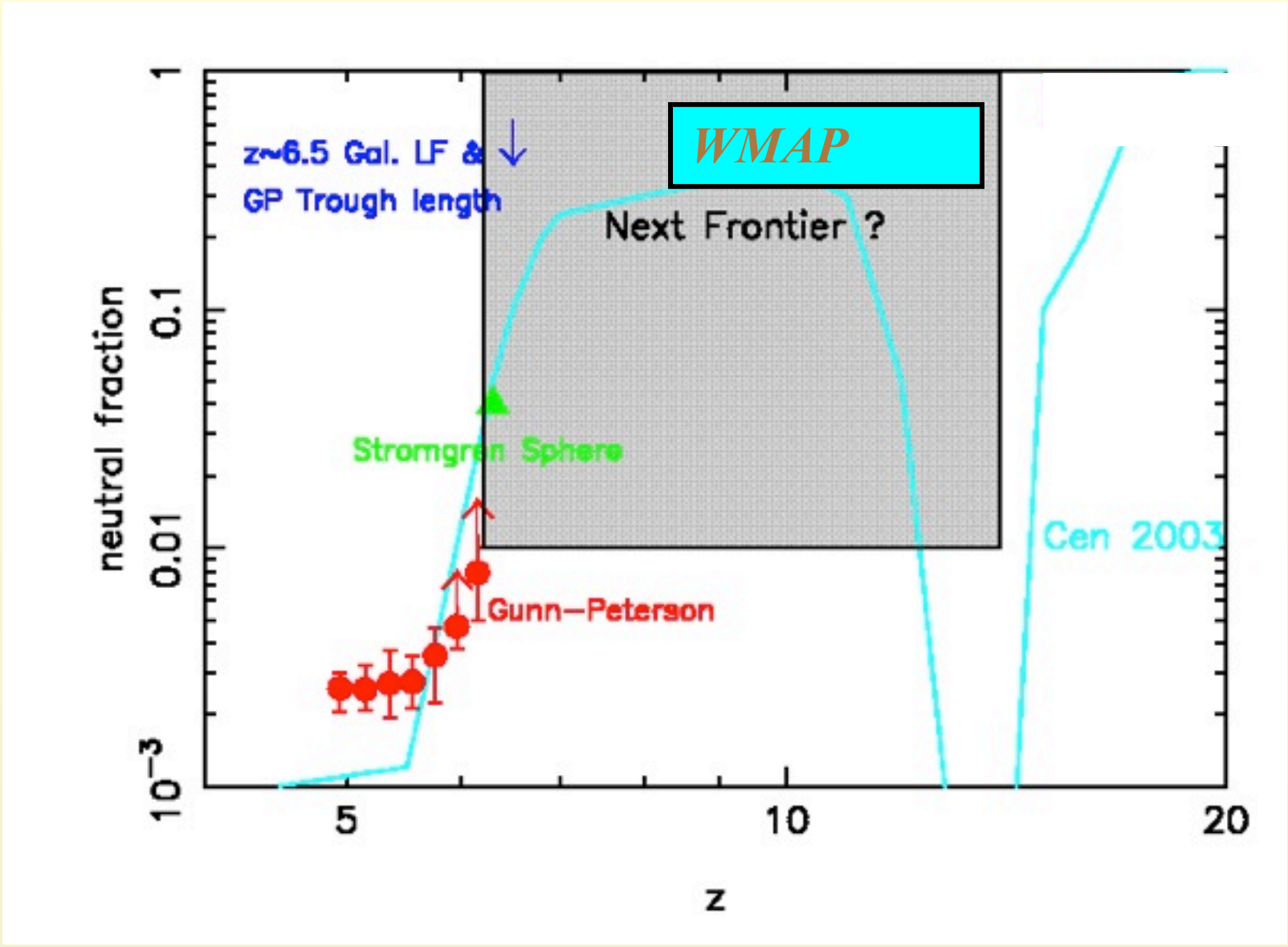


opaque



$\Delta z = 0.15$

Probing Reionization History




New Worlds,
New Horizons
in Astronomy and Astrophysics
NATIONAL RESEARCH COUNCIL

Looking ahead

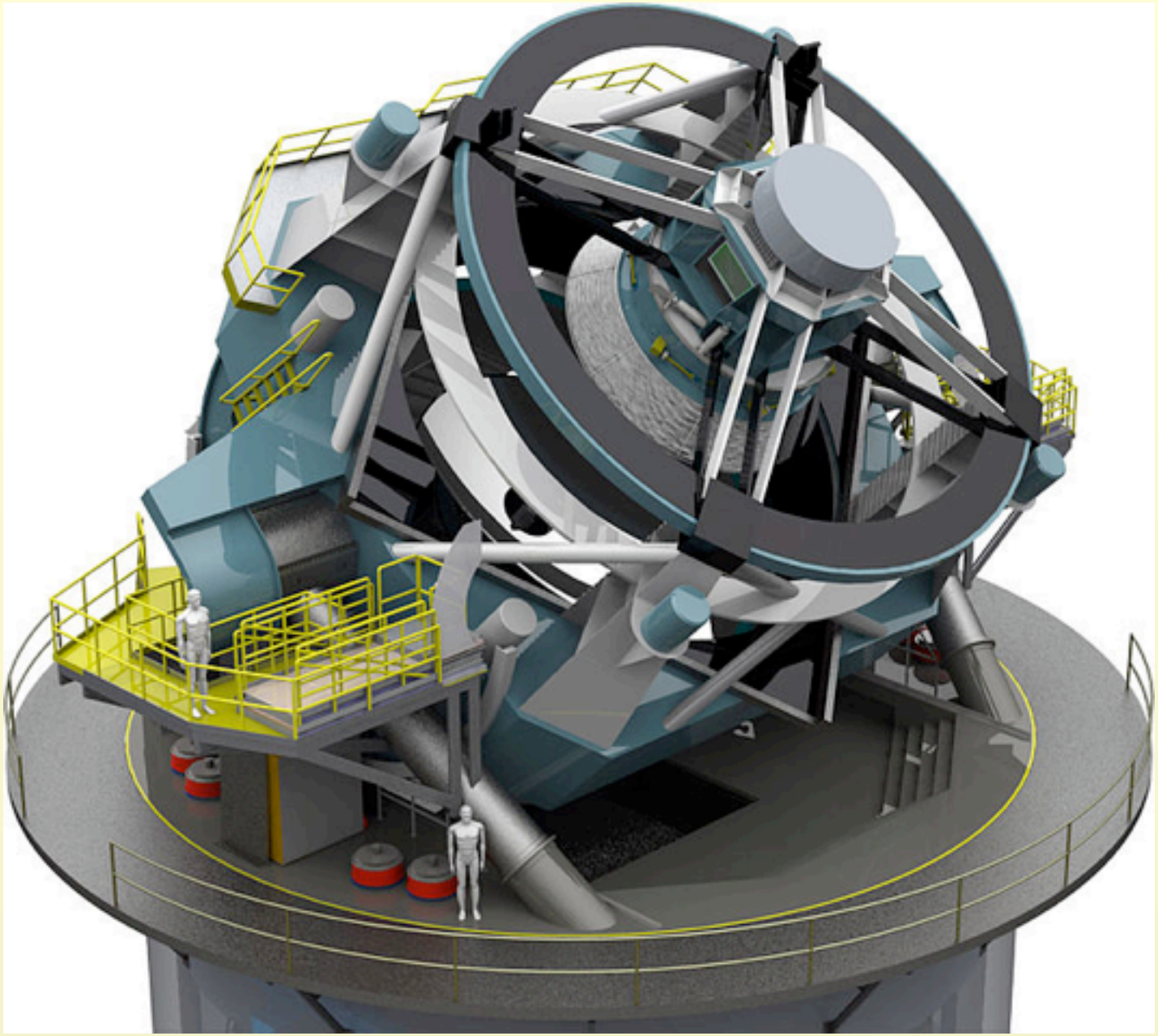
- Astro2010 Decadel Survey
  - Identify the most important questions and opportunities
  - Make detailed recommendations of missions and initiatives
  - Roadmap for astronomy community and funding agency

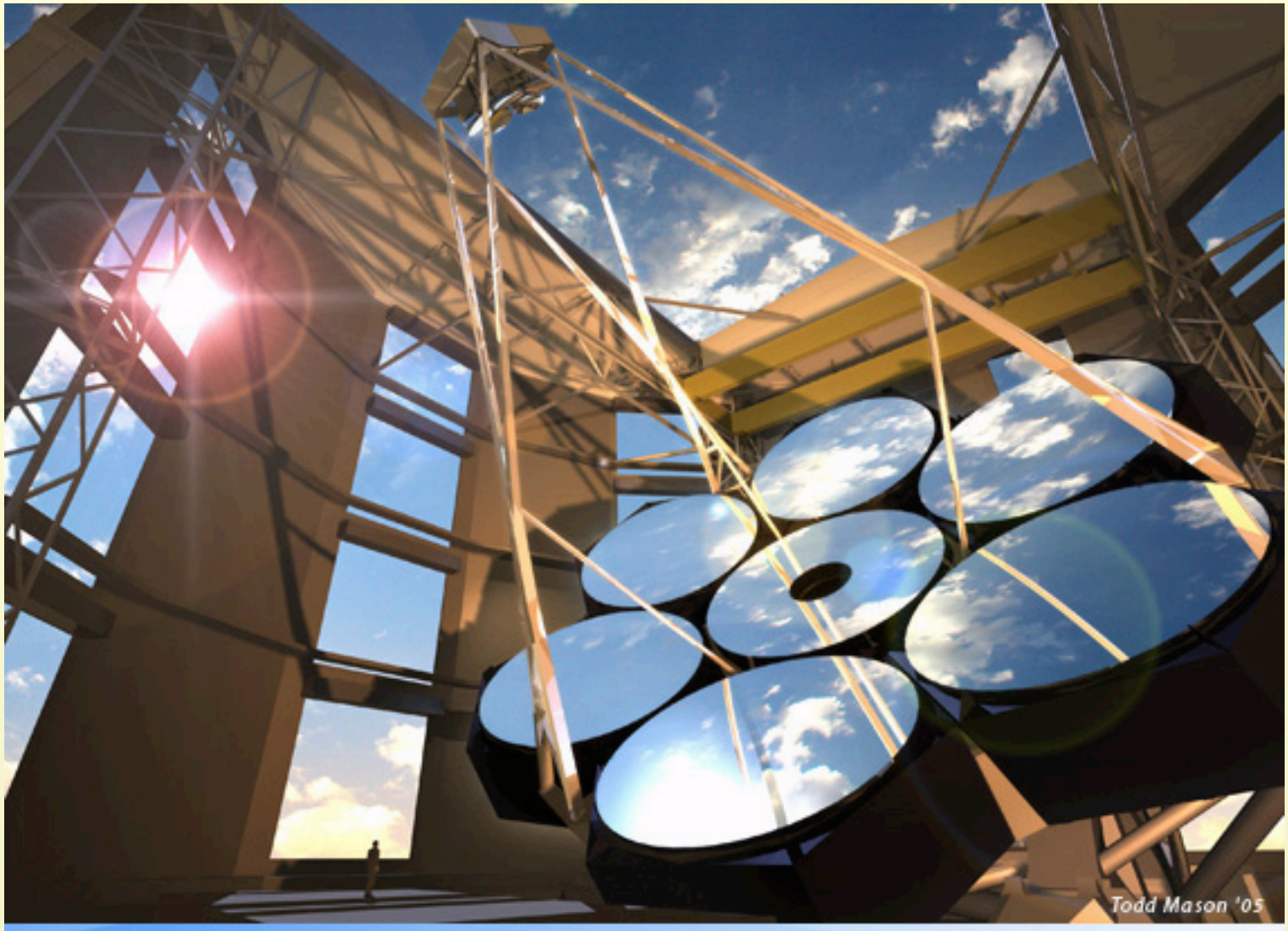
Main science objectives

- Cosmic Dawn
  - First stars, galaxies and black holes
- New Worlds
  - Seeking nearby, habitable planets
- Physics of the Universe
  - Dark matter, dark energy, inflation, general relativity etc.

Large-scale Ground-based Program - Prioritized

1. Large Synoptic Survey Telescope (LSST)
2. Mid-Scale Innovations Program
3. Giant Segmented Mirror Telescope (GSMT)
4. Atmospheric Cerenkov Telescope Array (ACTA)





Giant Magellan Telescope Organization

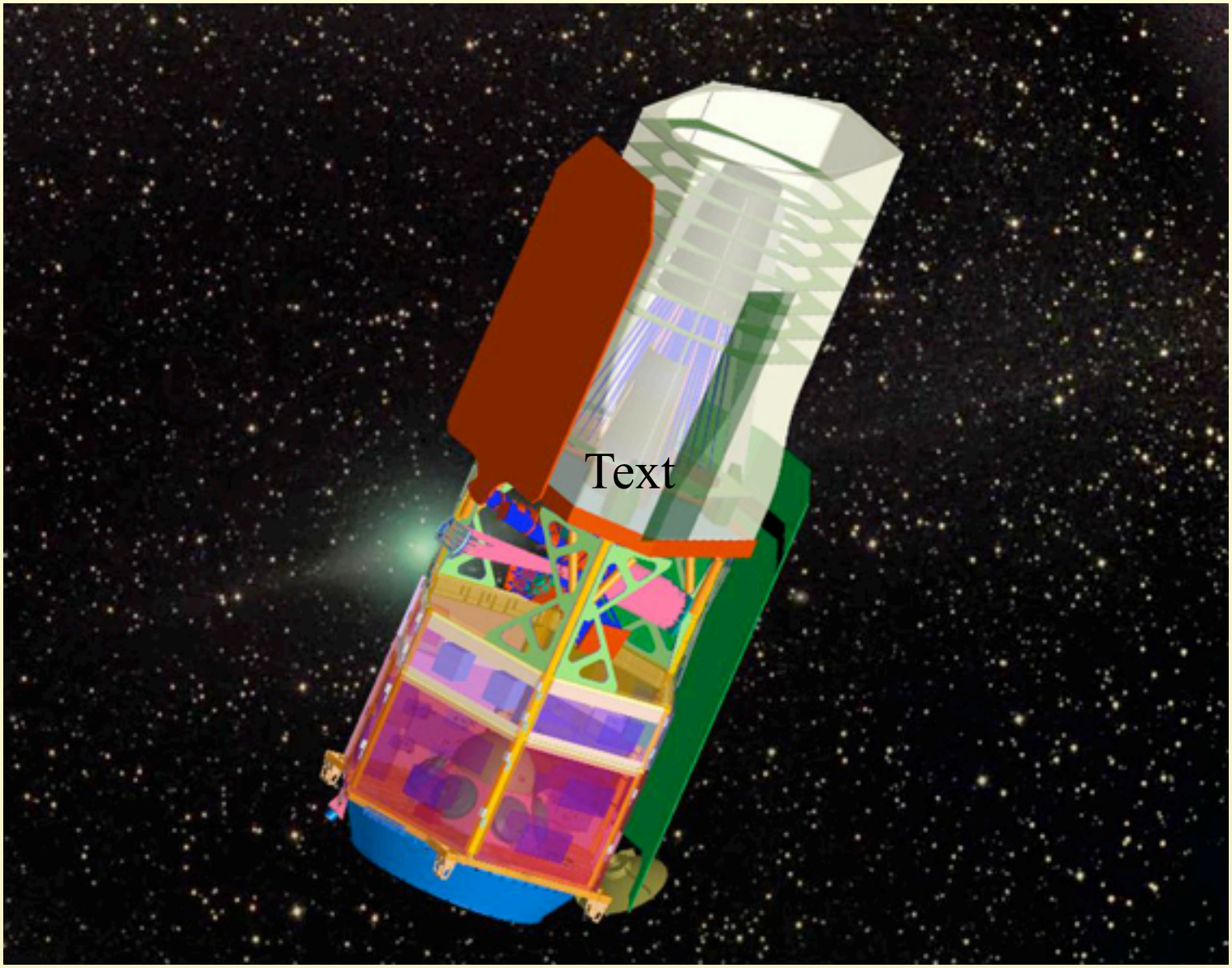
Large Scale Space Program - Prioritized

1. Wide Field InfraRed Survey Telescope (WFIRST)

1. Explorer Program Augmentation

2. Laser Interferometer Space Antenna (LISA)

3. International X-ray Observatory (IXO)


Text