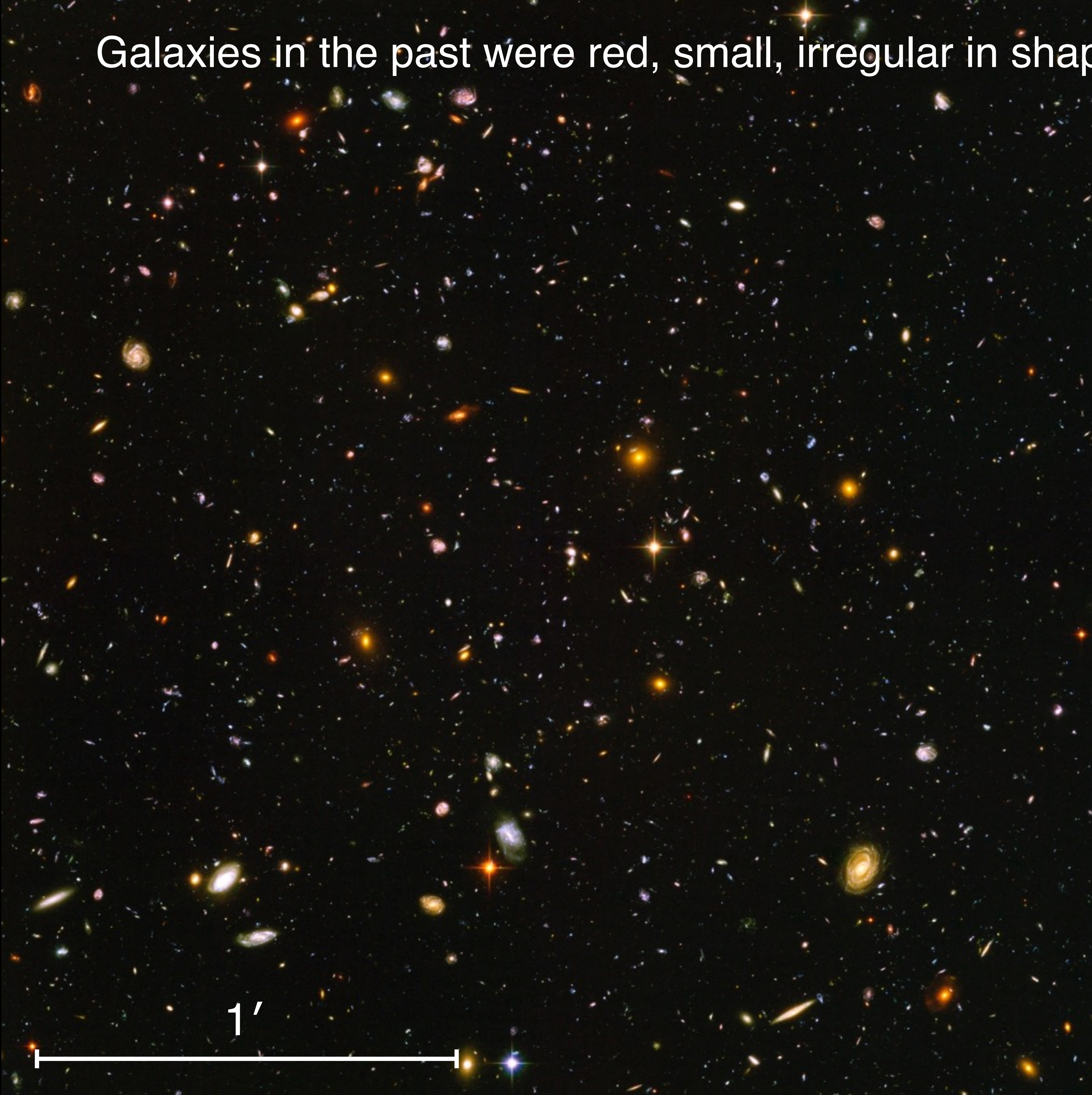
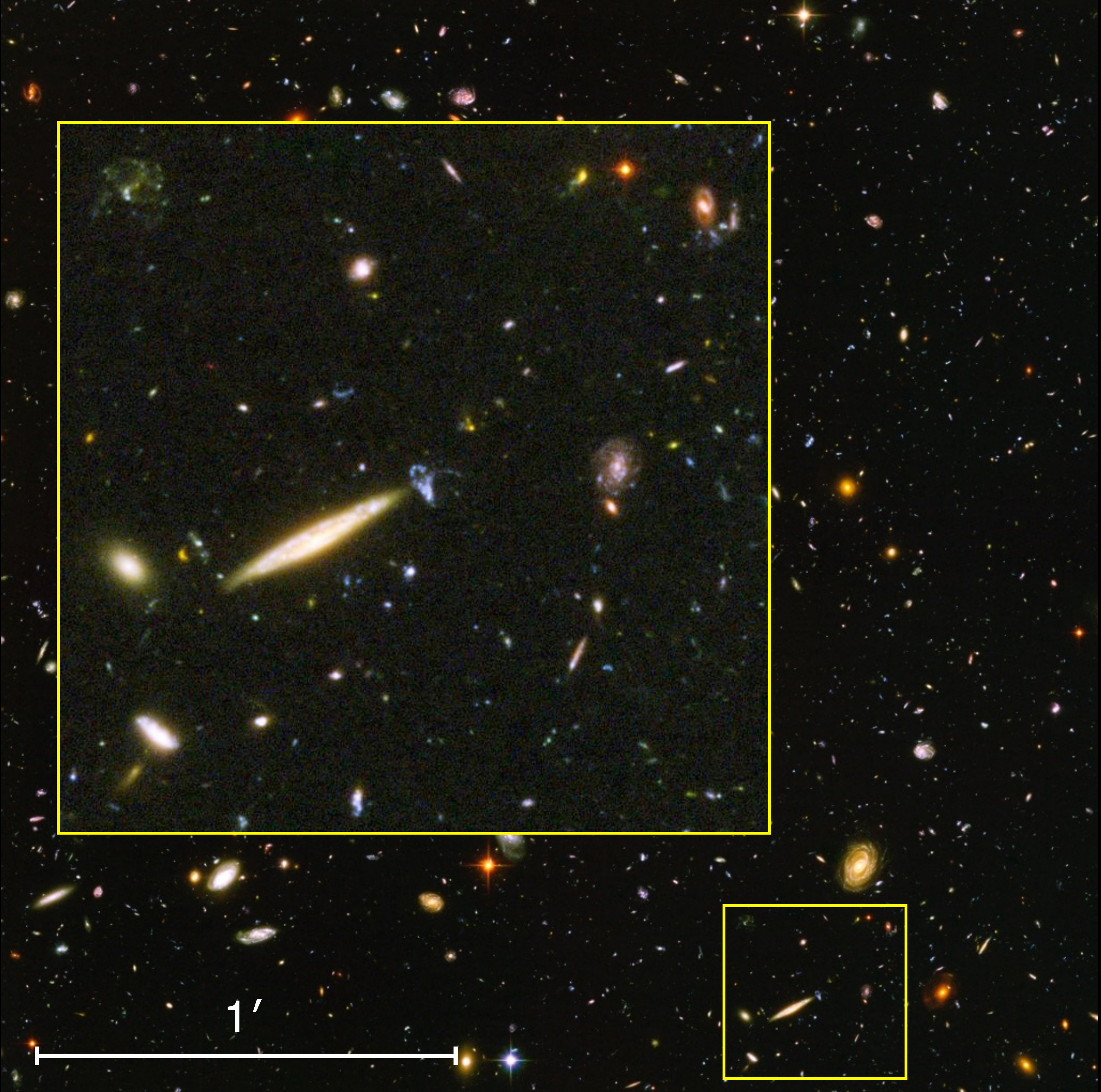
Formation and evolution of galaxies

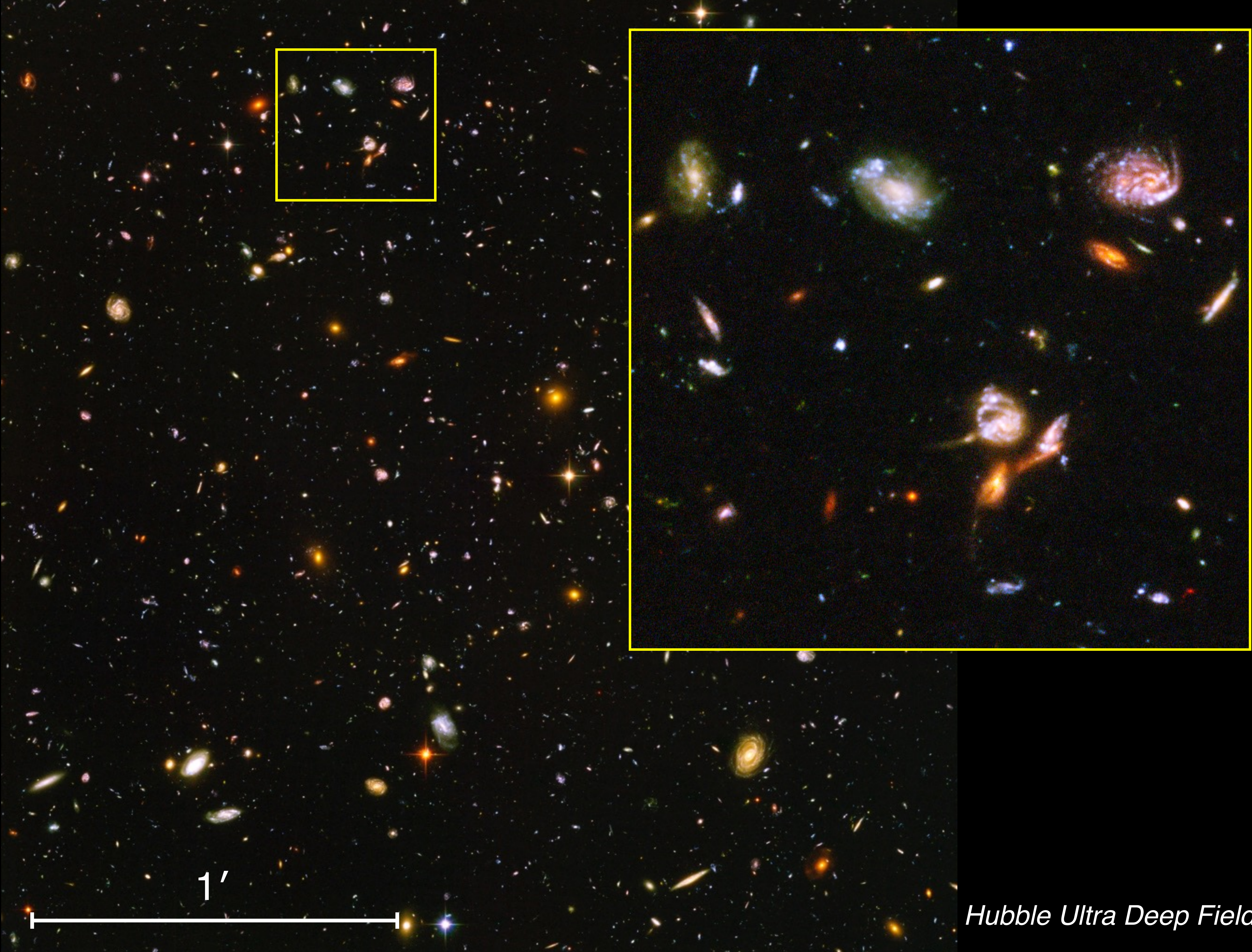
Galaxies in the past were red, small, irregular in shape & interacting



Hubble Ultra Deep Field



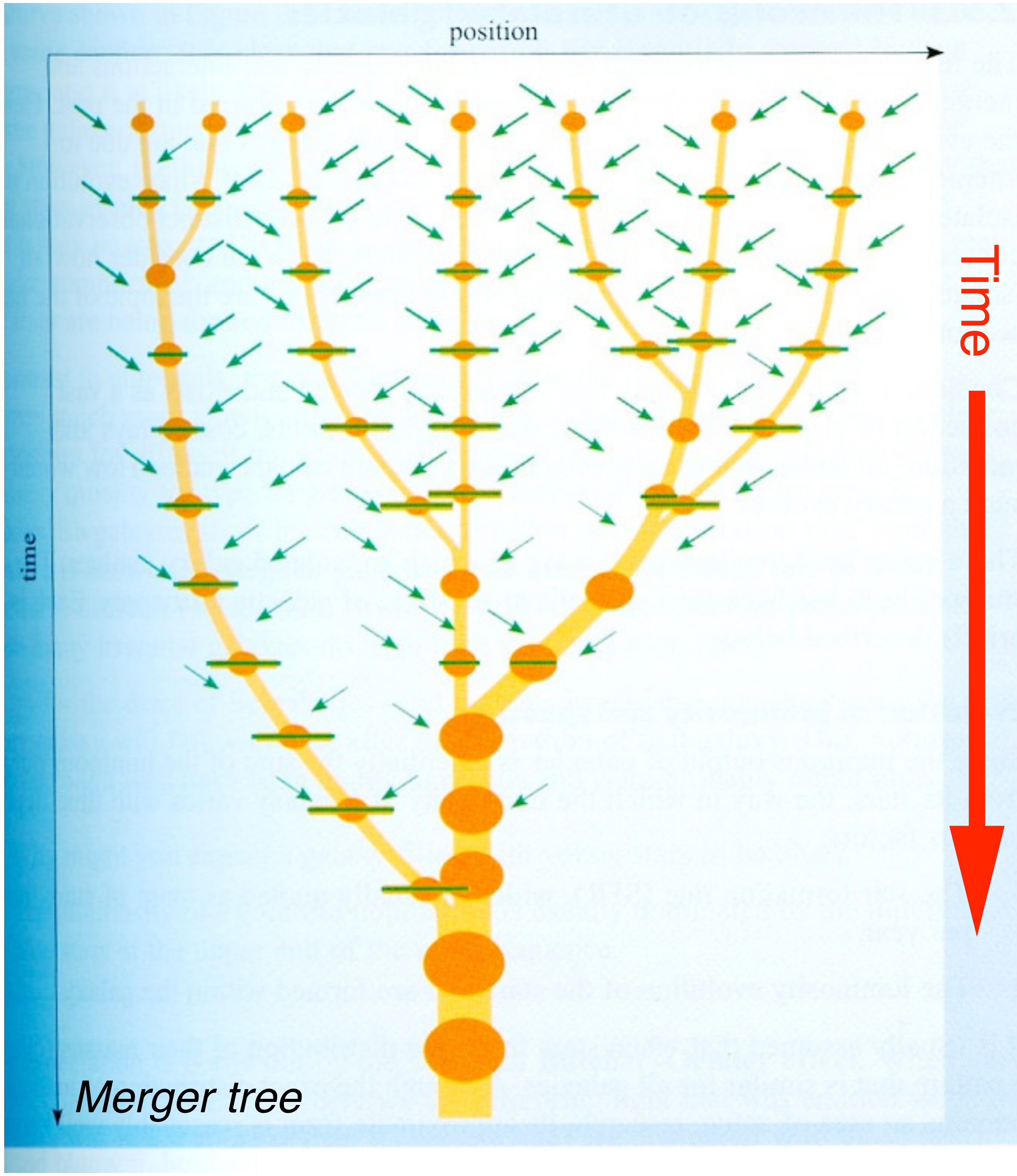
Hubble Ultra Deep Field



Hubble Ultra Deep Field

Cold Dark Matter (CDM) model for galaxy formation and evolution

(**hierarchical scenario**, different from *Hot Dark Matter* model)



In **CDM** model, first formed structures have total mass $M \sim 10^6\, M_\odot$

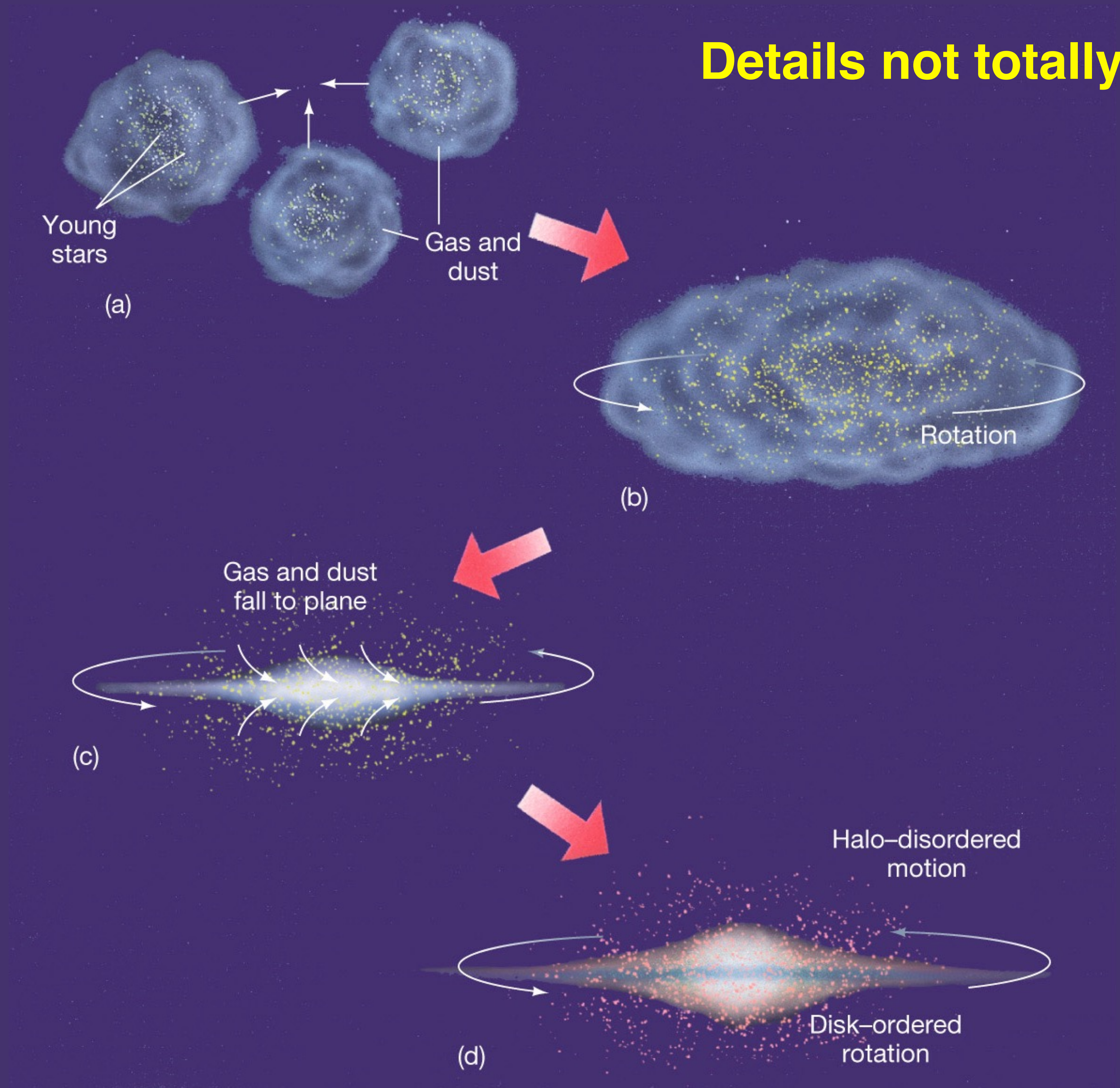
Figure 2.32 A 'merger tree' that shows the schematic history of the formation of a single giant elliptical galaxy by the merger of many smaller galaxies. The stellar content of galaxies is shown in dark orange and neutral gas is indicated in green. The result of every merger event is an elliptical galaxy. The longer an individual galaxy goes without a merger (those on the longest 'branches') the more substantial is the disc that develops by in-fall of intergalactic gas. Note also that as time passes, the density of intergalactic gas decreases, so discs grow more slowly at later times. (M. Merrifield (University of Nottingham))

Cold: non-relativistic dark-matter particles (they explain better observed galaxies over time)

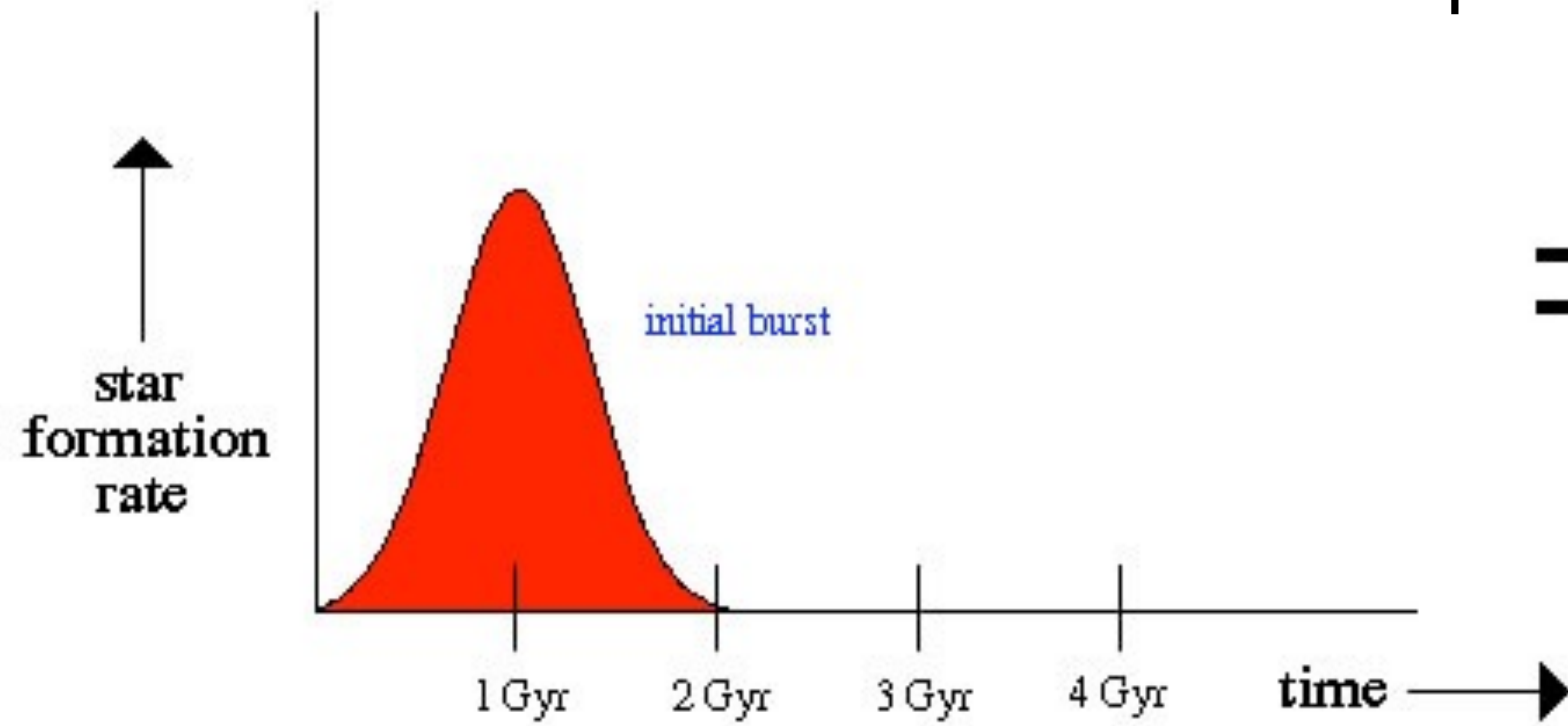
Hot: relativistic dark-matter particles (not favoured scenario by observations)

Formation of disk in spiral galaxies

Details not totally known



Schematic representation of *star formation history* in galaxies with different morphology

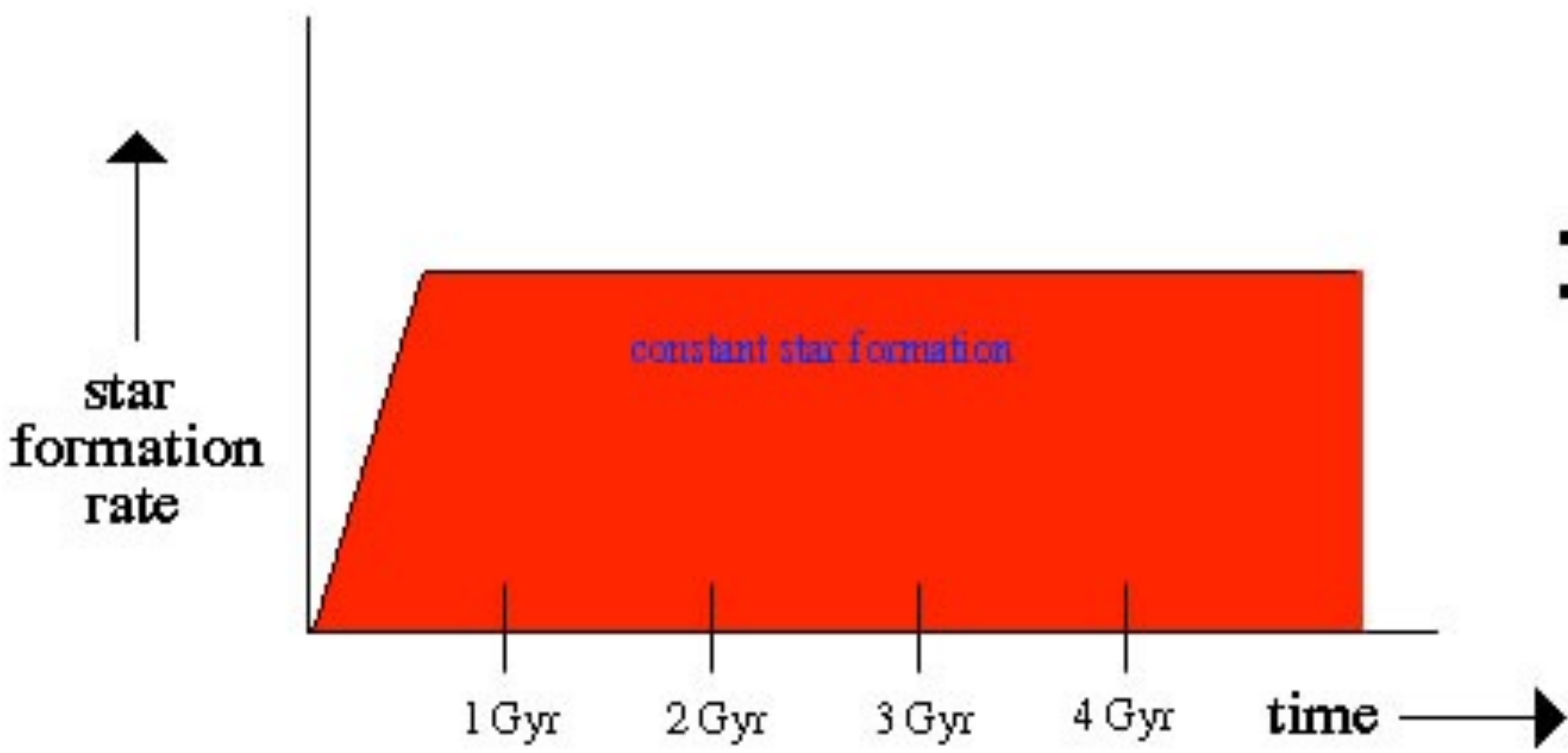


=

elliptical galaxy

(red core and envelope
= old stellar population)

- **Are elliptical galaxies formed from mergers?**
- **Are different stars coming from different galaxies?**

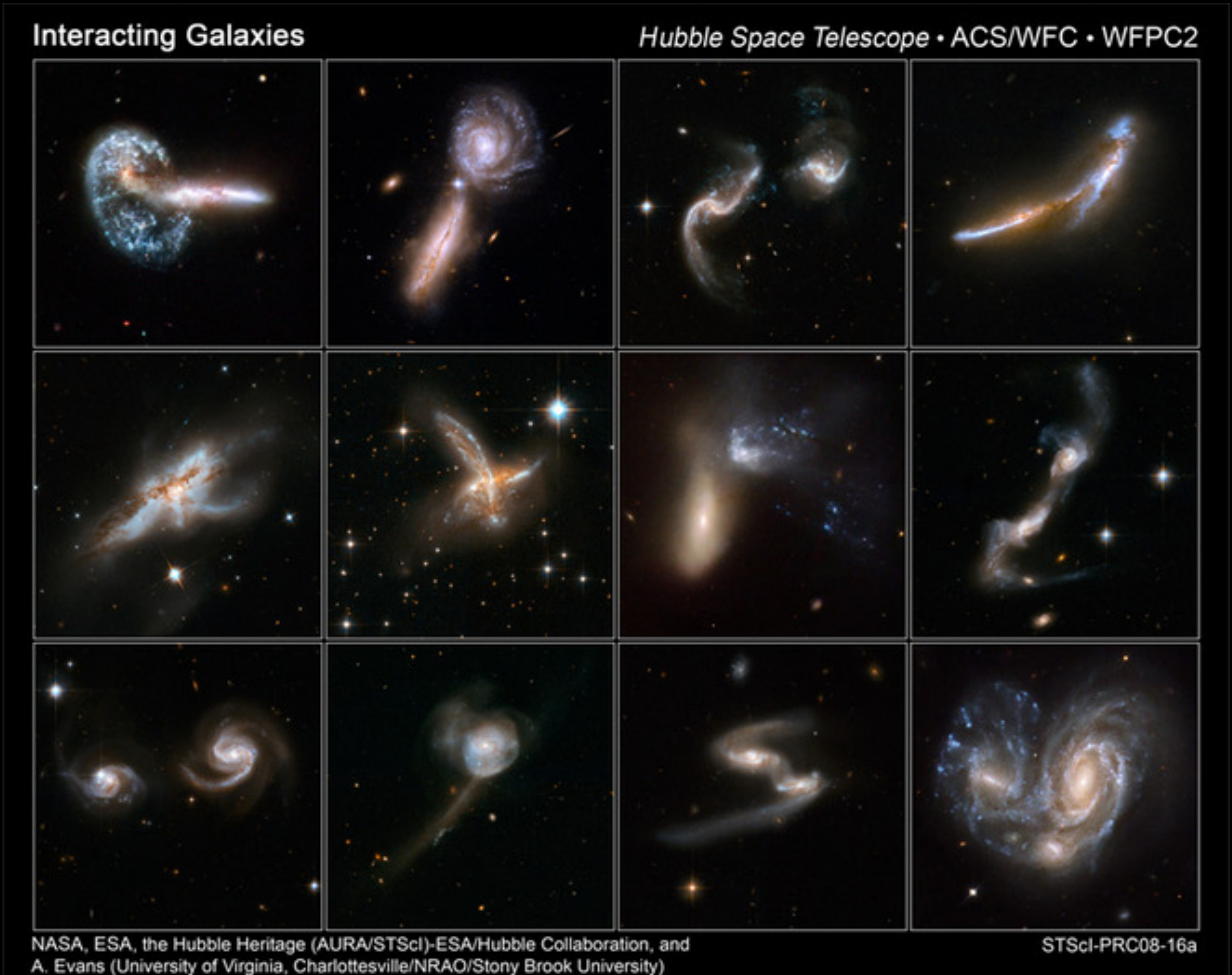


=

spiral galaxy

(red bulge = old
blue disk = young)

Interactions and mergers of galaxies important mechanism for galaxy formation and evolution



Interaction triggers star formation

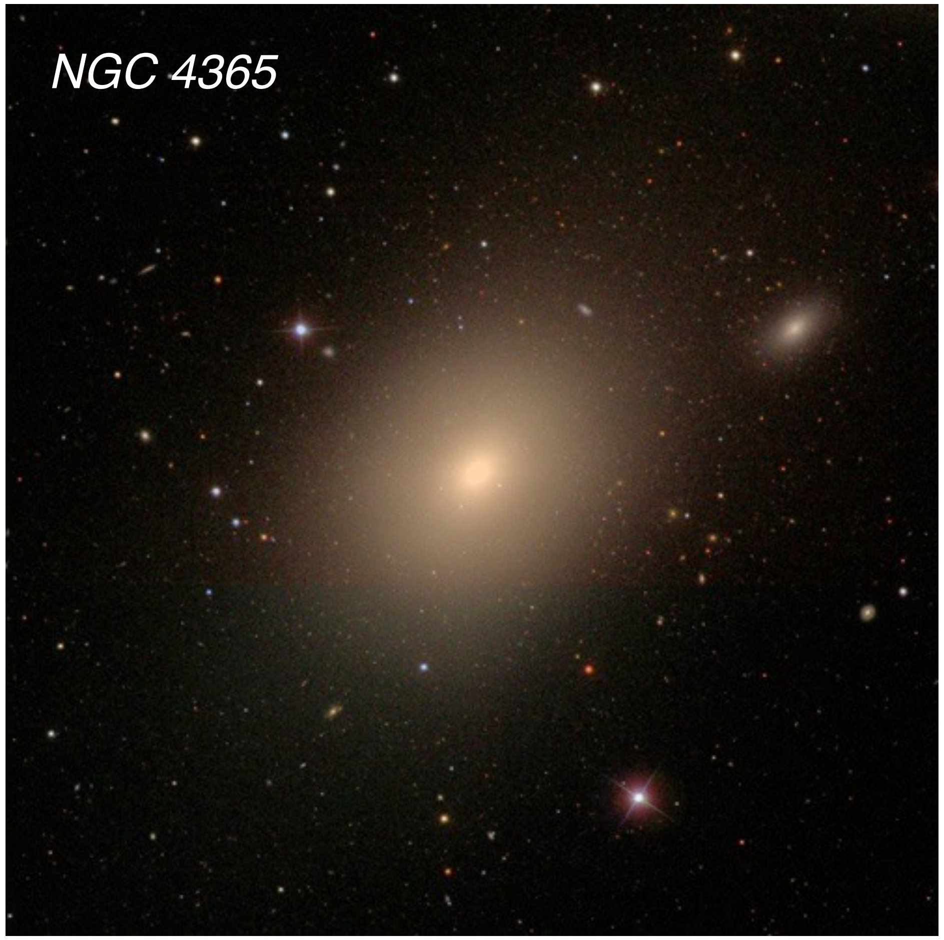
(*star-burst galaxies* seen in near infrared)

Antennae Galaxies
Distance: 14 Mpc

Interaction triggers star formation

(*star-burst galaxies* seen in near infrared)

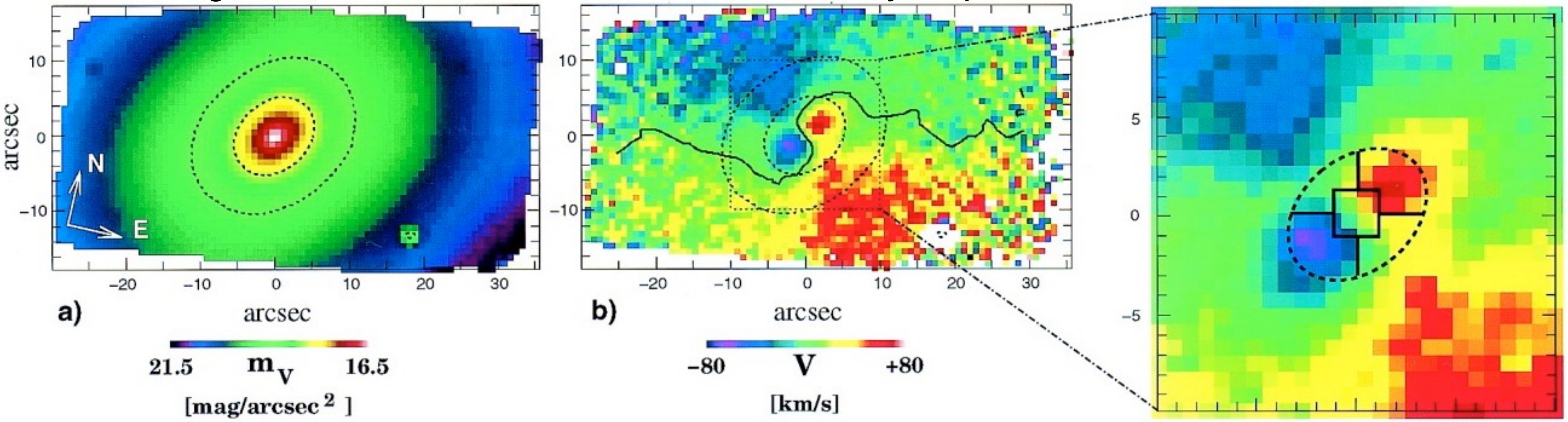
Example of *E3* elliptical galaxy with **decoupled core**



Core of the galaxy **counter-rotating** with respect to the main body of the galaxy probably the **result of merging of 2 galaxies** with, initially, perpendicular rotating axis

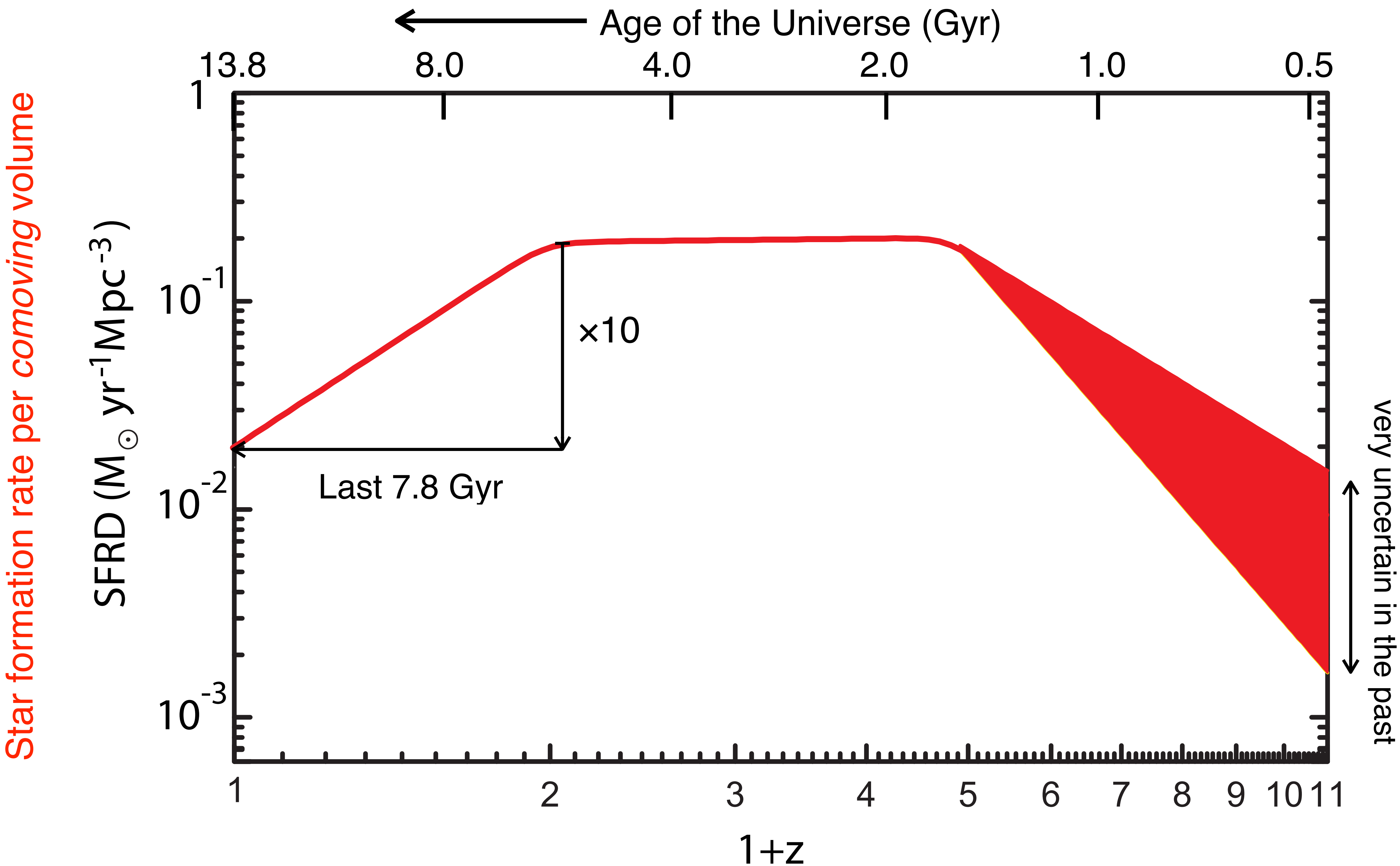
Surface brightness

Stellar velocity map



History of the star formation rate density (**SFRD**) in the universe

The universe is less active now than in the past, it is ageing!



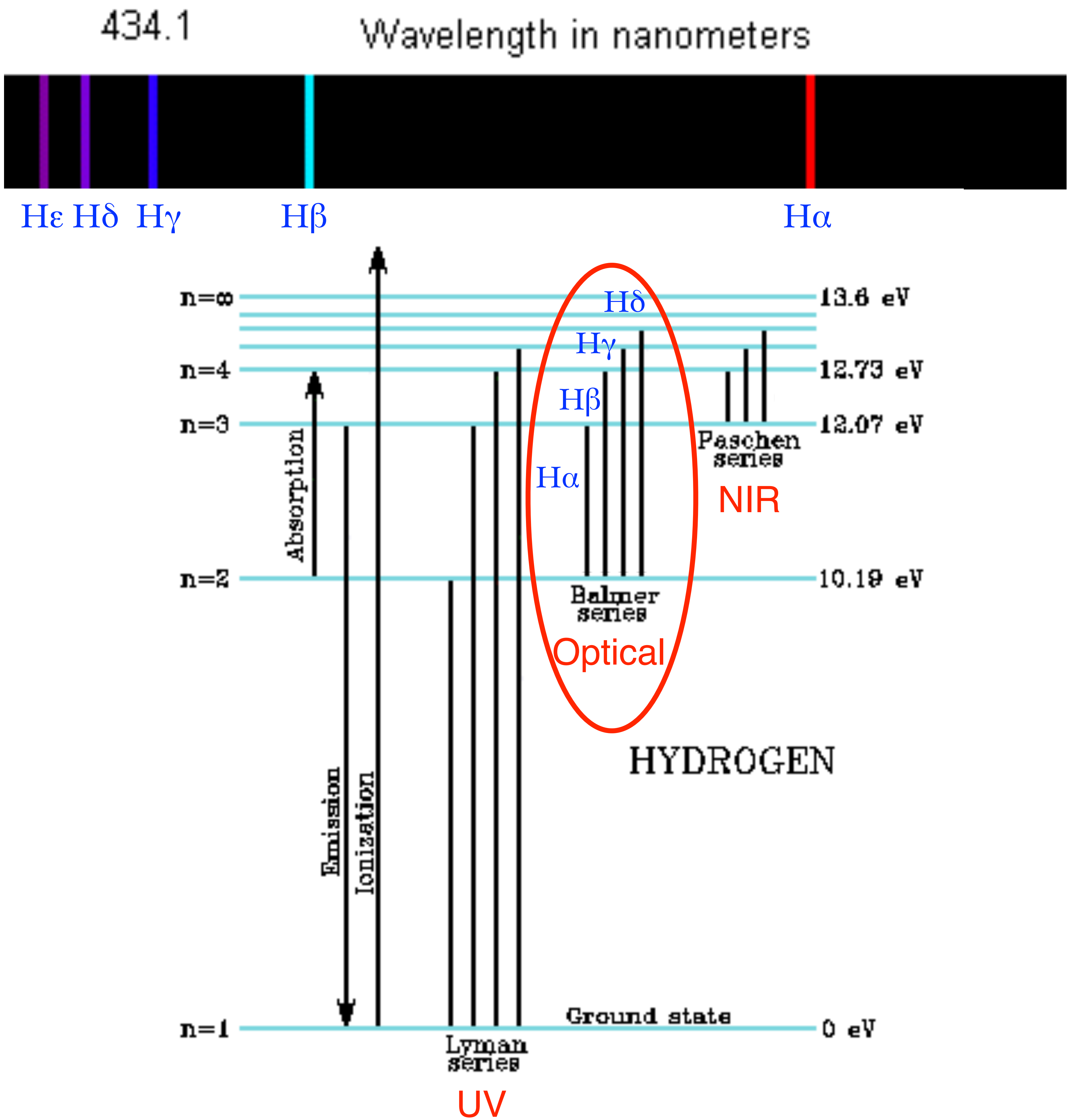
Physical distance (called ***proper distance***) between two points is ℓ

Then, ***comoving distance*** is $\ell_C = \ell/(1+z)$ factors out expansion of universe and does not change with time

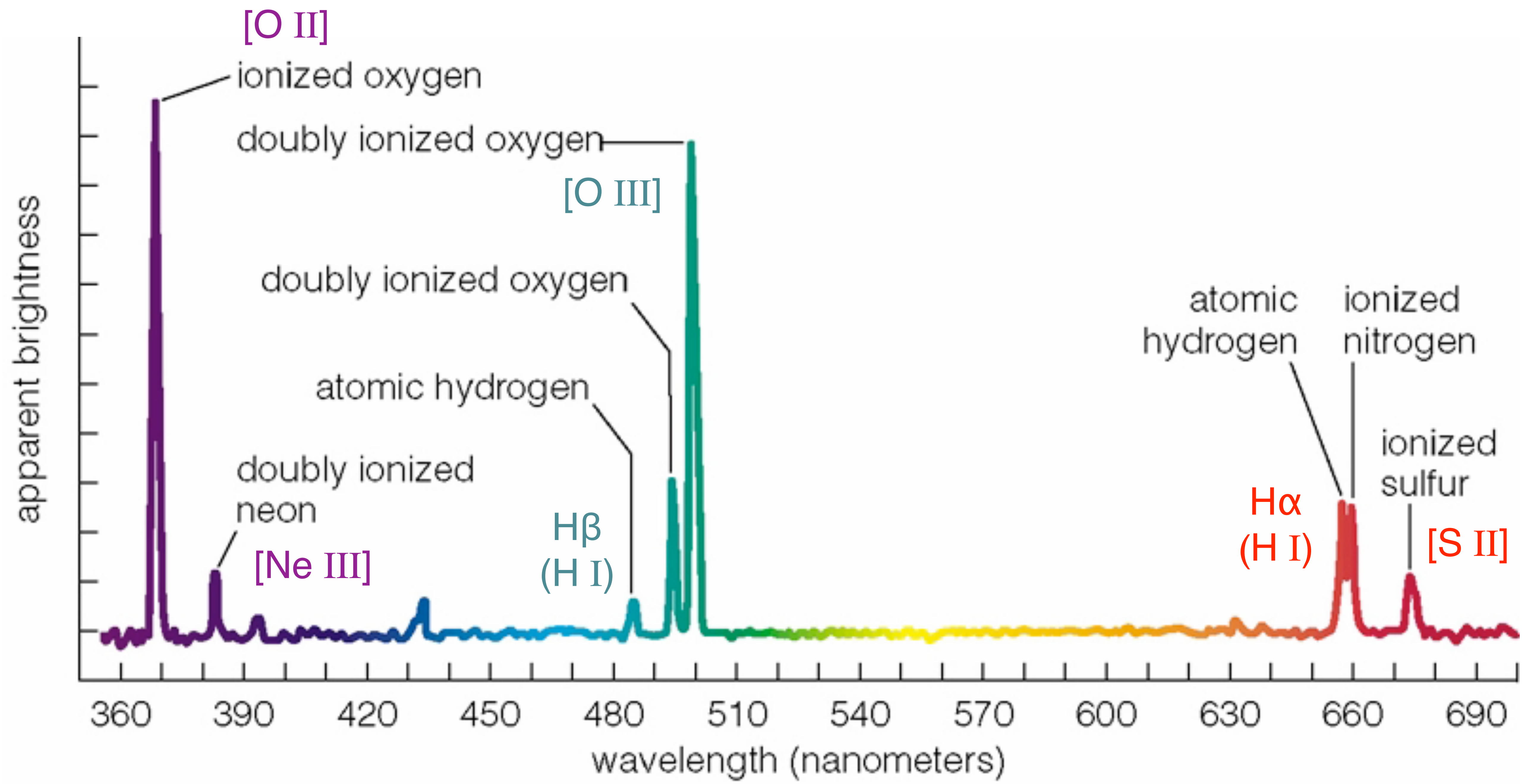
Spectra of galaxies

An H II region is a star-forming region

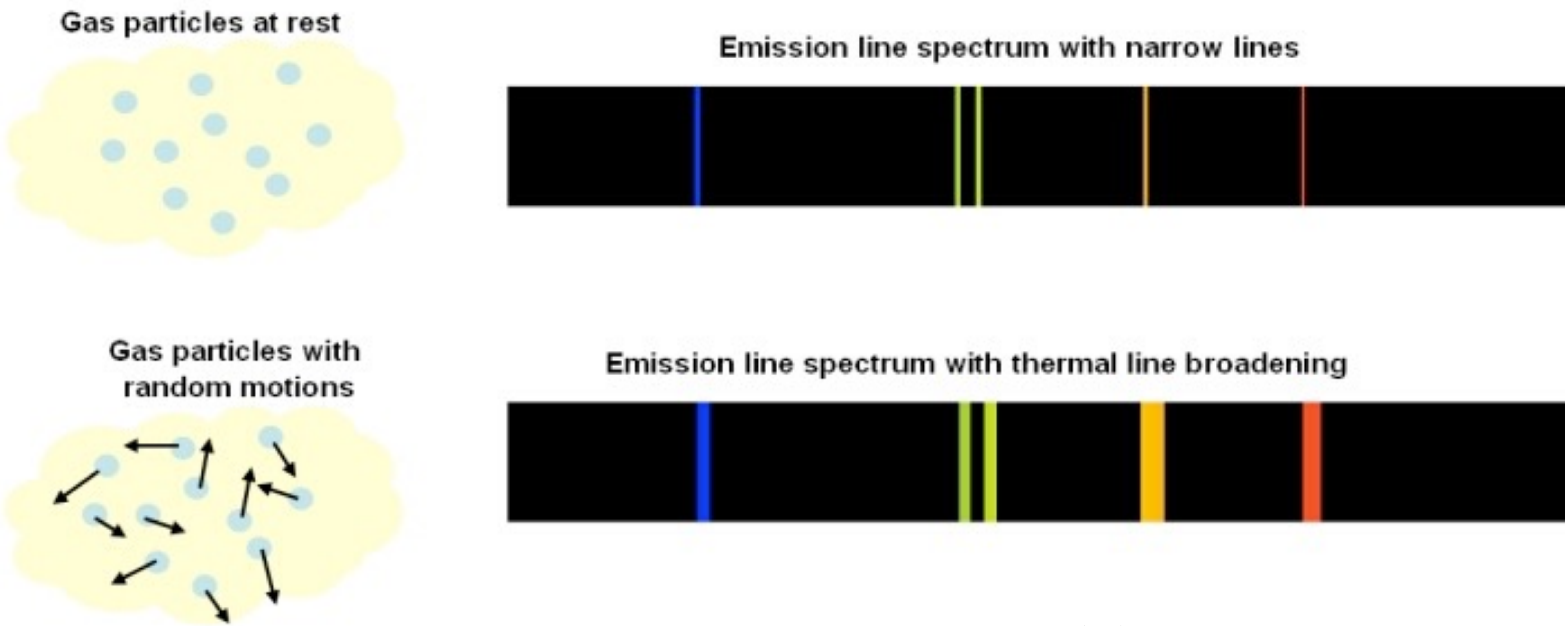
Energy levels and Balmer lines in hydrogen atom



Emission lines in H II regions



Thermal broadening of emission lines in gas



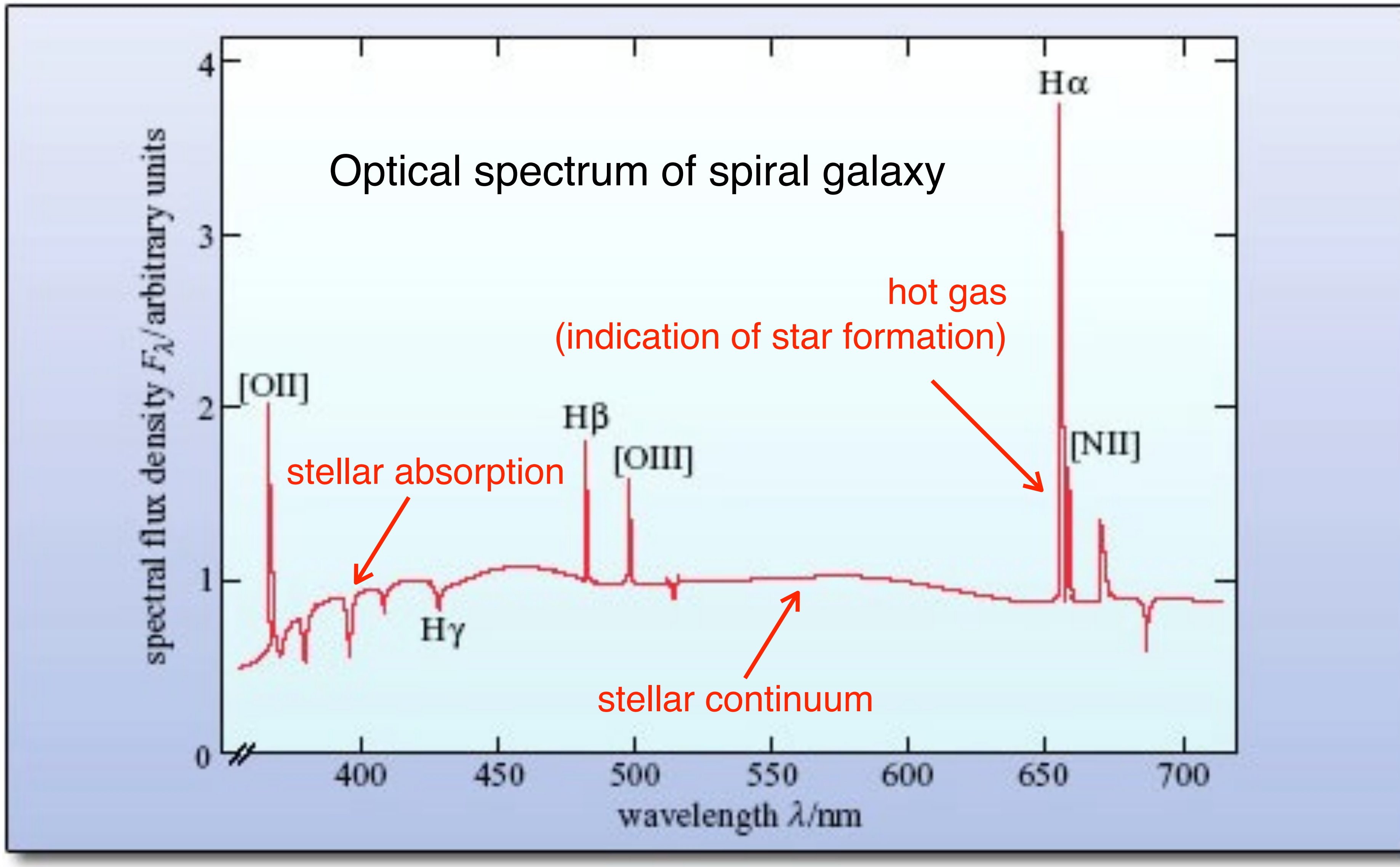
Doppler broadening: $\Delta\lambda/\lambda = \Delta\upsilon/c$

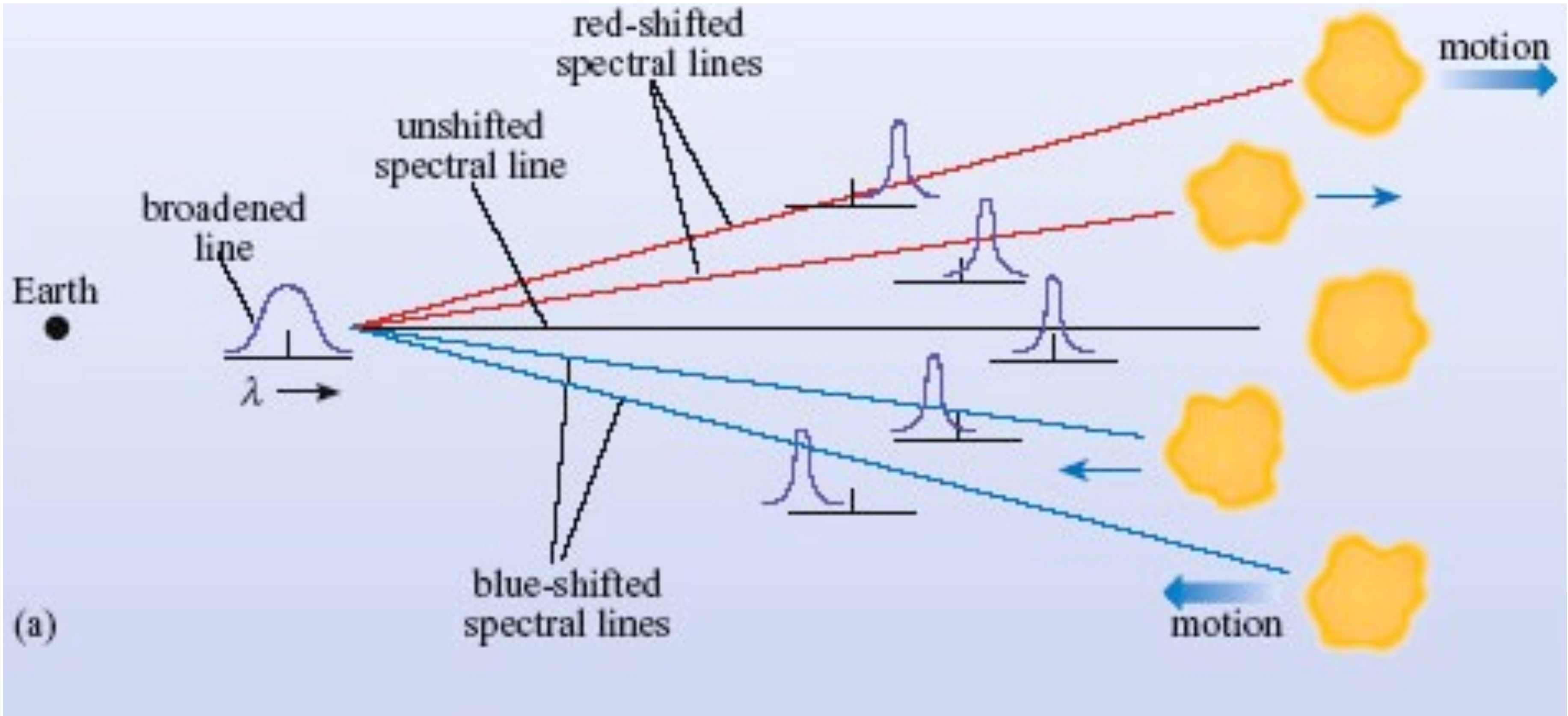
Gas temperature from: $\Delta\upsilon \approx (2kT/m)^{1/2}$

m: particle mass

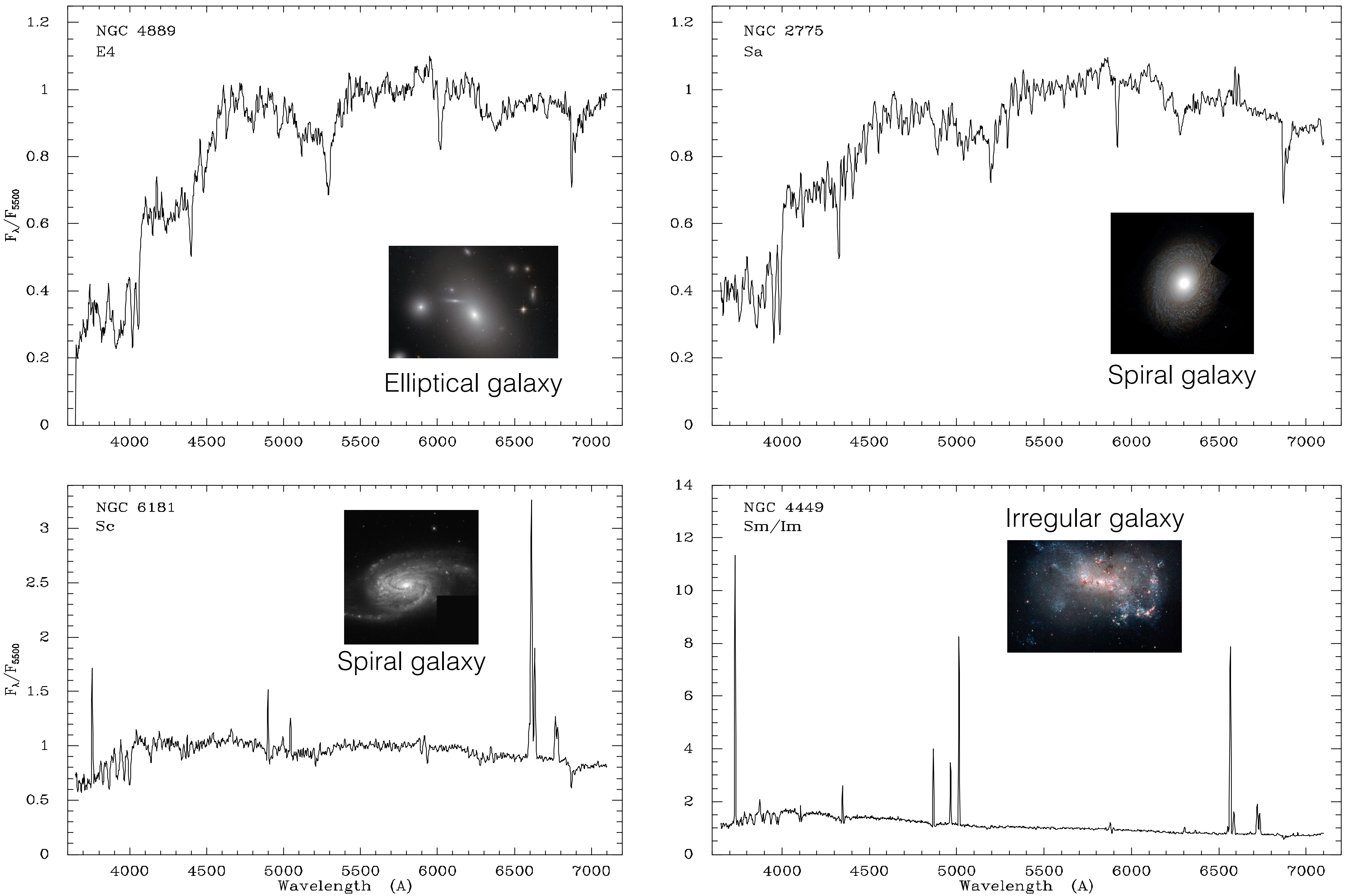
T: gas temperature

k: Boltzman constant

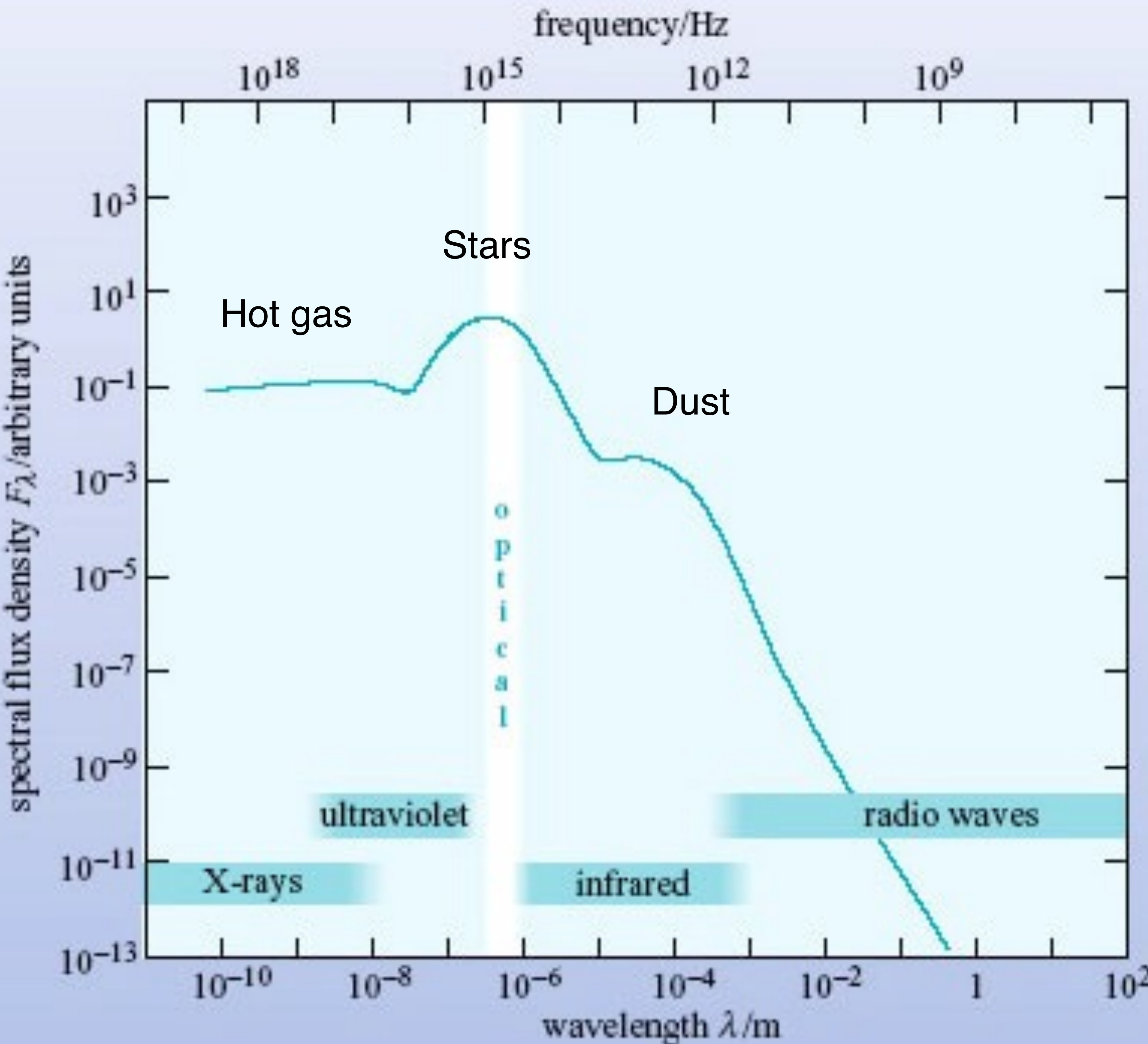

Optical spectrum of spiral galaxy
spectral flux density F_λ / arbitrary units
wavelength λ/nm
[OII]
Hβ
[OIII]
Hγ
Hα
[NII]
stellar absorption
hot gas
(indication of star formation)
stellar continuum
0
1
2
3
4
400
450
500
550
600
650
700


red-shifted
spectral lines
motion
unshifted
spectral line
broadened
line
Earth
λ
blue-shifted
spectral lines
motion
(a)

Integrated spectra of elliptical, spiral, & irregular galaxies

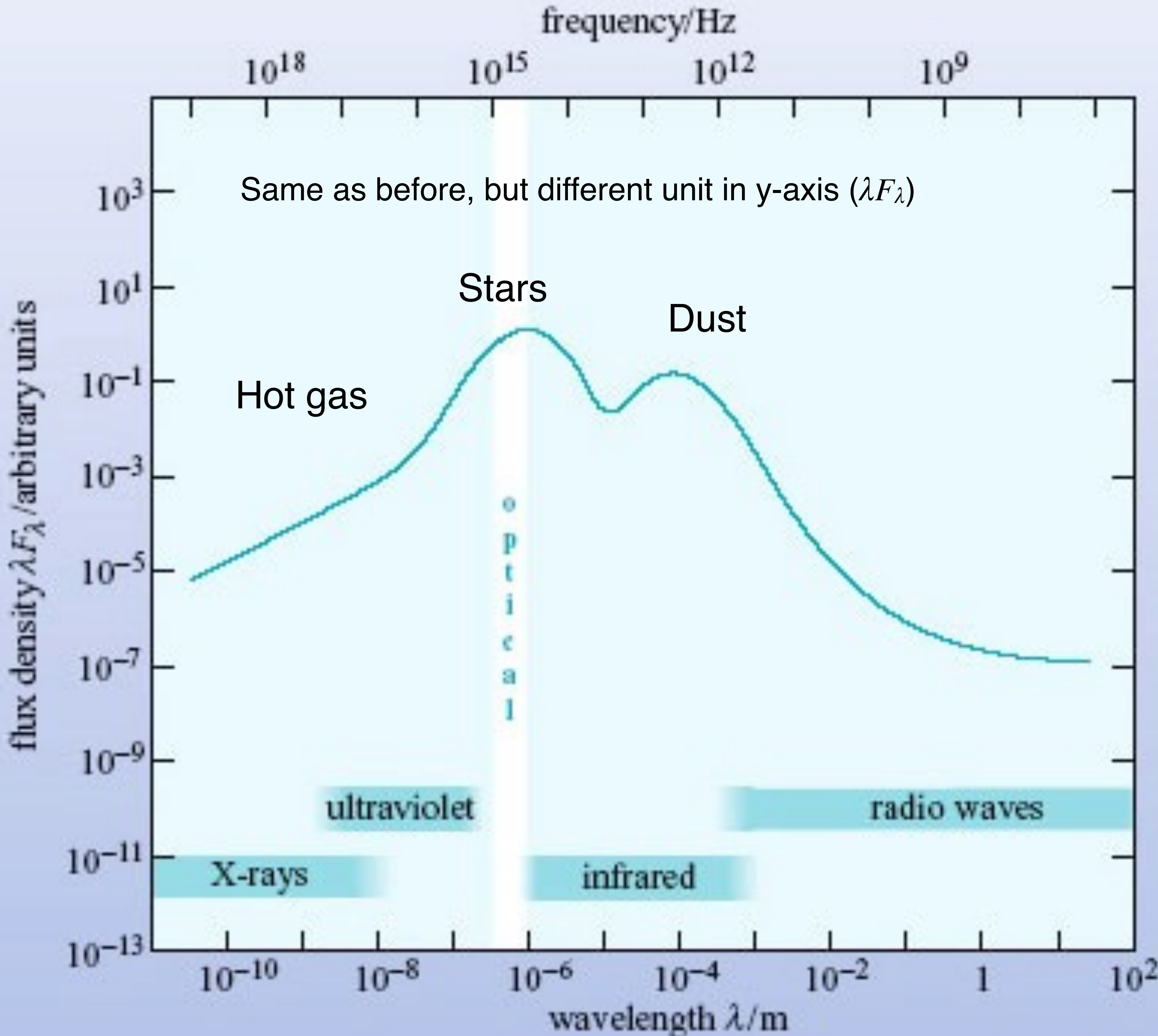


Broad-band spectrum of normal spiral galaxy

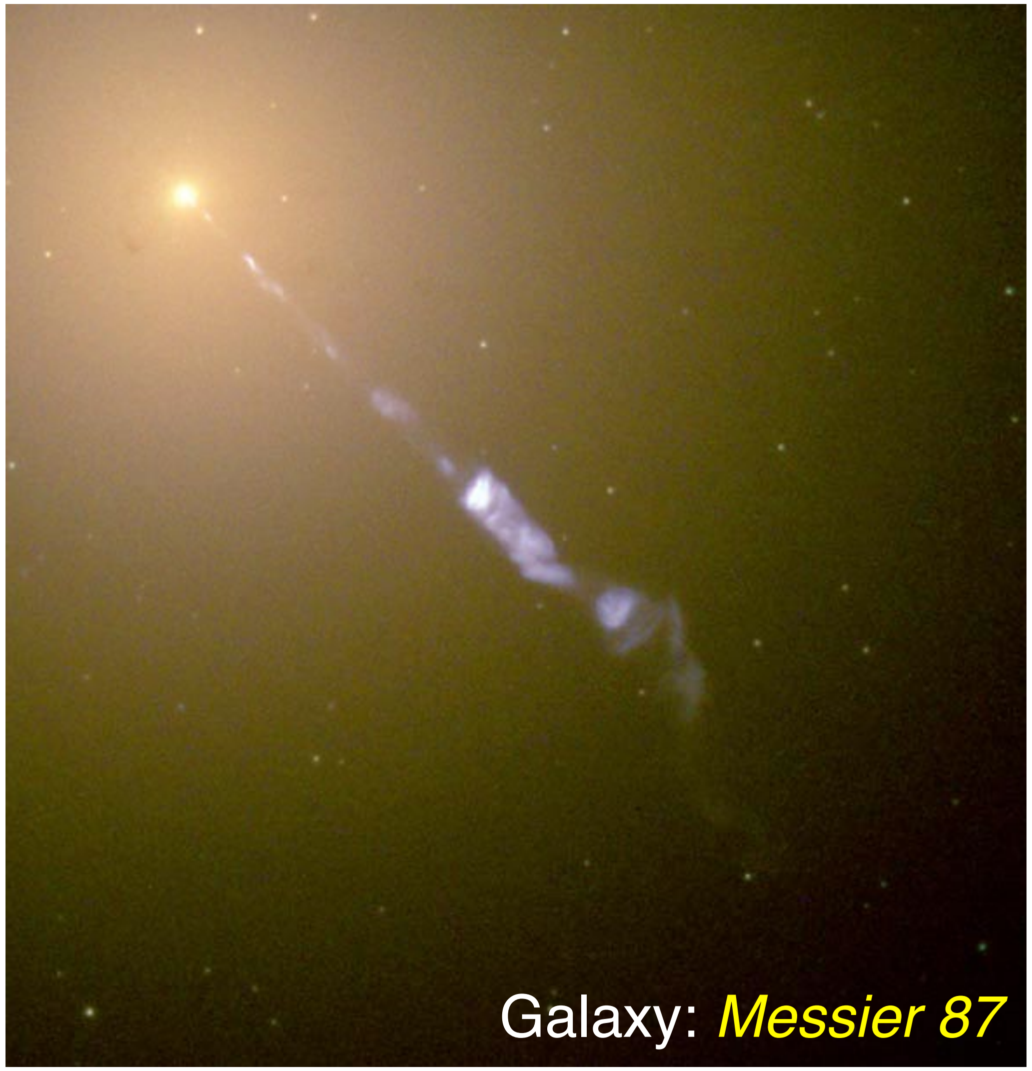


Spectral Energy Distribution (SED) of galaxy

This is *wavelength* × *flux density* : λF_λ (in W m^{-2} units) related to emitted energy



Galaxies with very bright (***active***) massive black hole at center



Galaxies with nucleus emitting high luminosity due to presence massive black hole at center

Different names for common origin

- Active Galactic Nuclei (AGN)
- Quasi Steller Objects (QSO)
- Quasi-Stellar Radio Sources (quasar)
- Seyfert galaxies
- Radio galaxies
- Blazars
- BL Lac

Bright emission ($L > 10^{11}\, L_{\odot}$) from small region around **massive black hole (MBH)**

Accreting disk around MBH with size typically **a little larger than solar system**

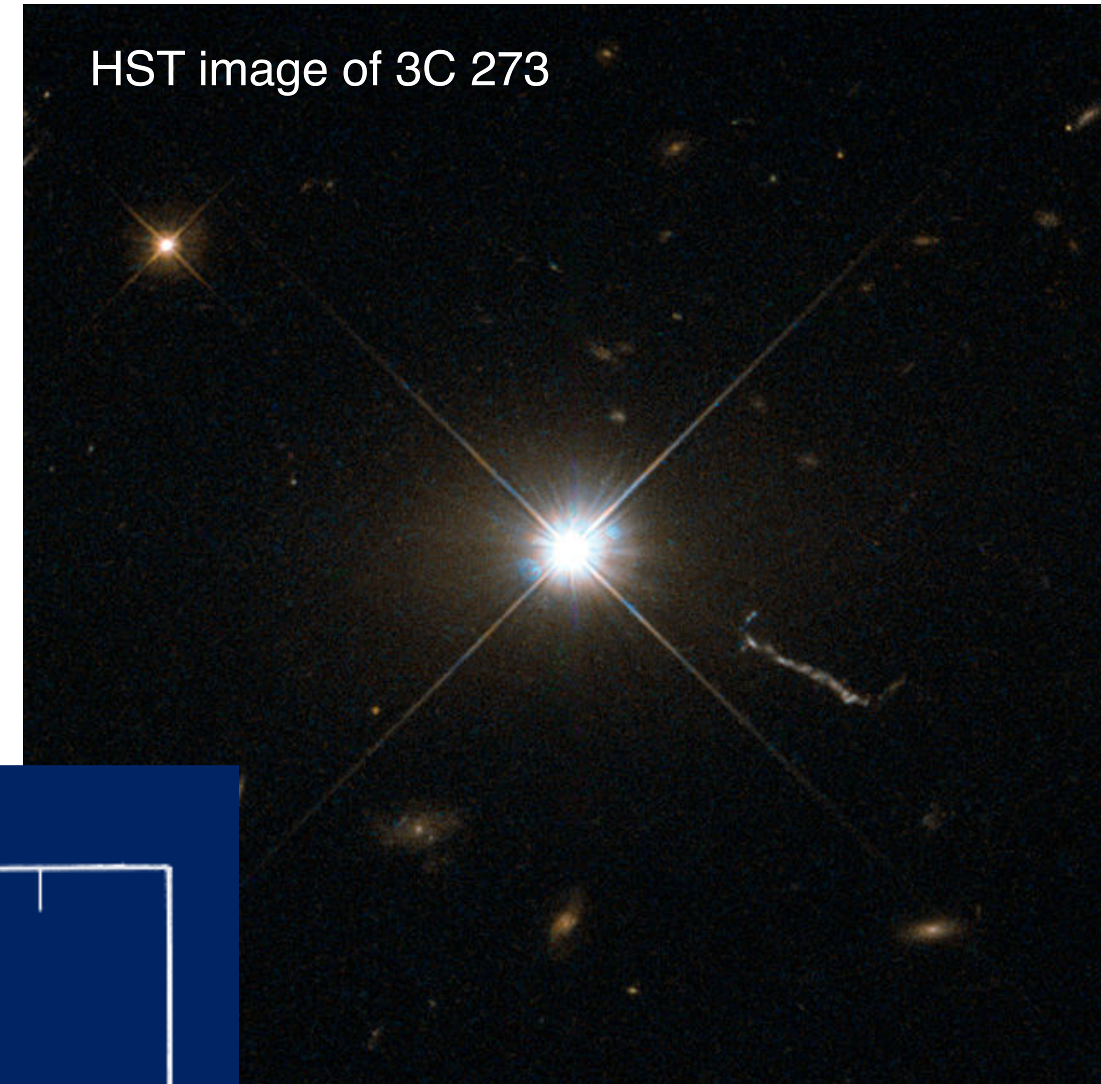
Accretion disk $\Longrightarrow$ power from gravitational energy converted to radiation

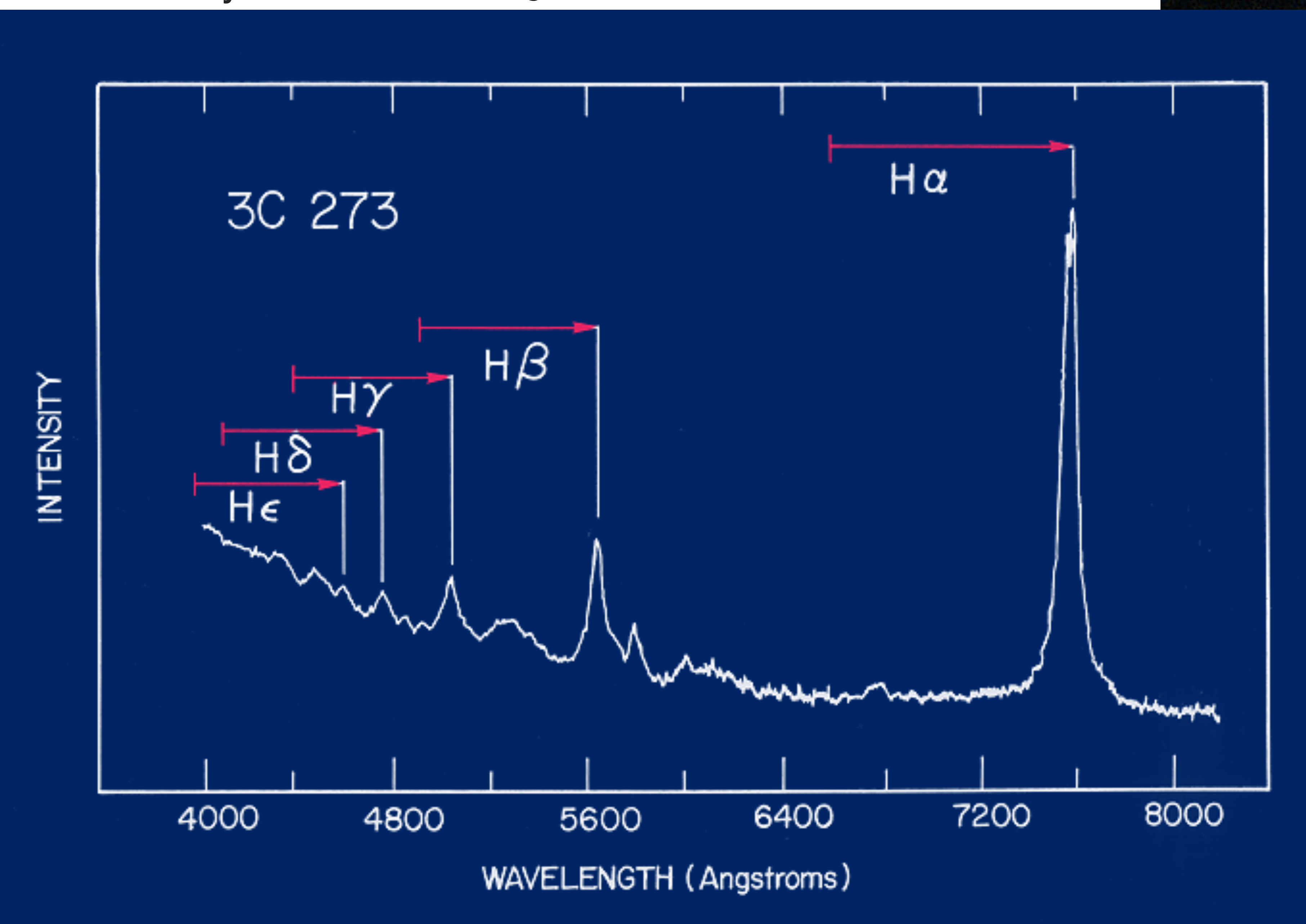
Different properties due to different orientation of the source with respect to Earth

The **first quasar** ever detected (1963)

3C 273 quasi-star in appearance
Observed magnitude: $m = 12.9$

Redshift: $z = 0.158$
Distance: 749 Mpc
Absolute magnitude: $M = -26.7$
Luminosity: $L = 4 \times 10^{12}\ L_\odot$



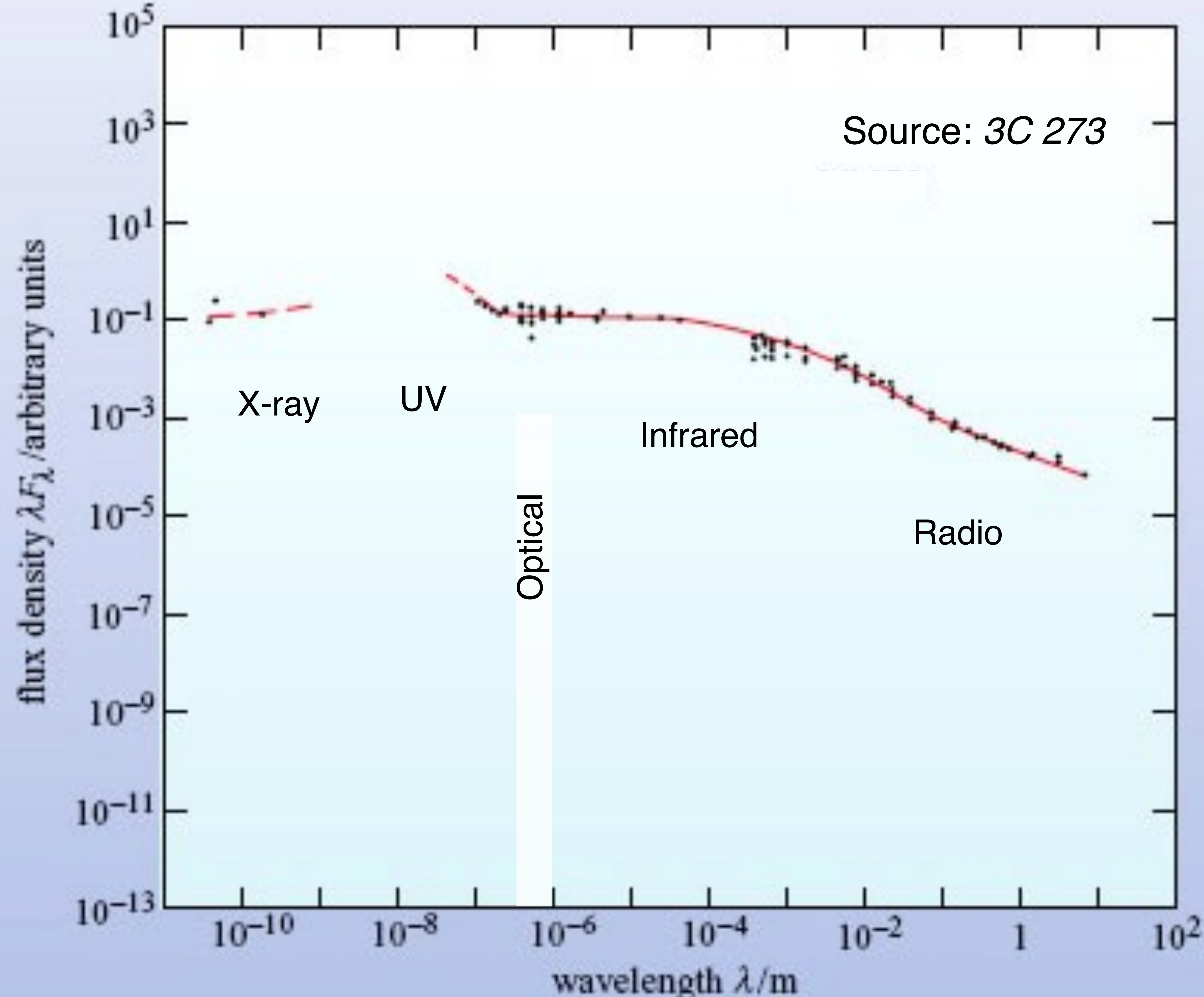


Doppler shift of wavelength λ to the red:

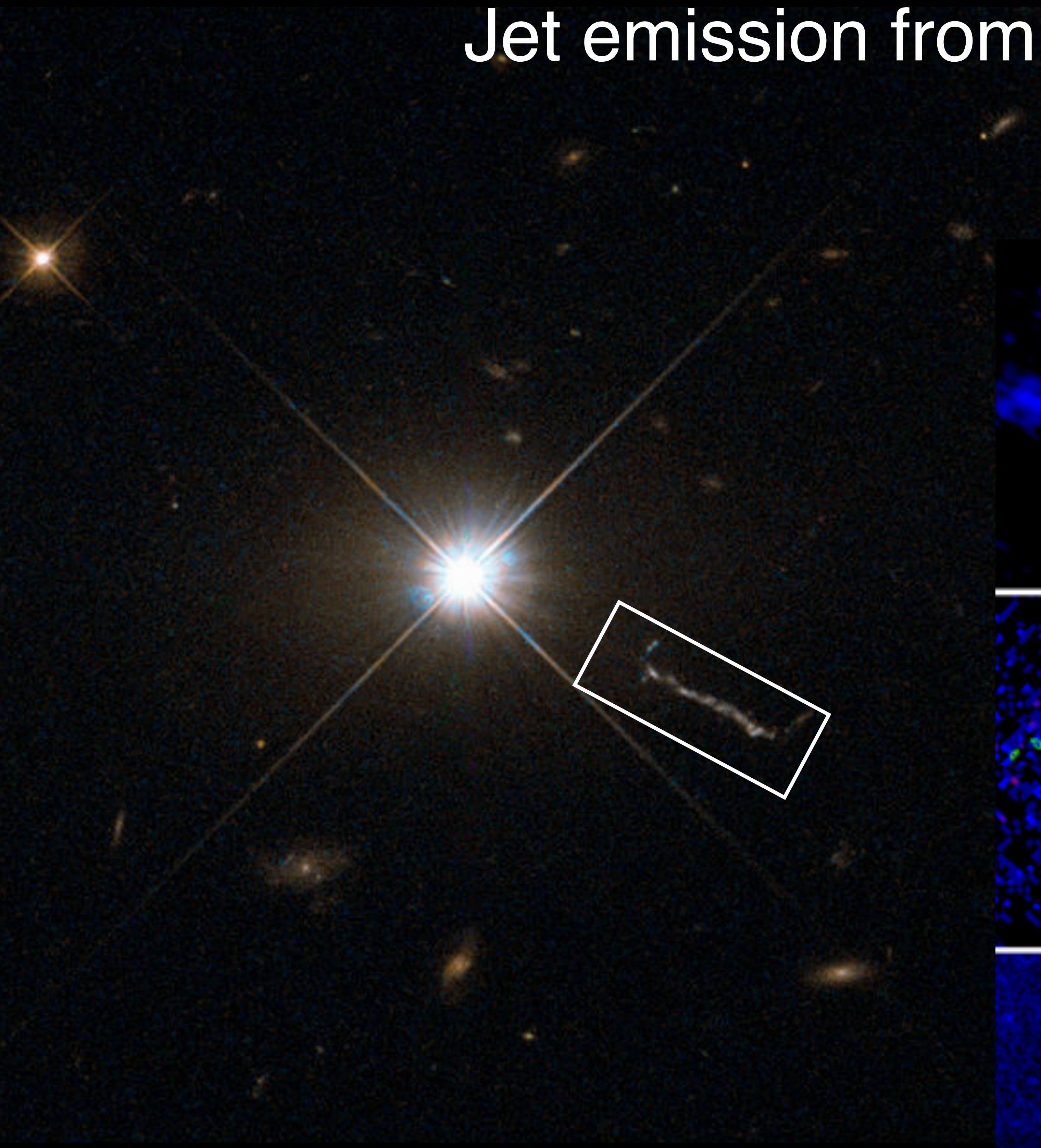
$$\frac{\lambda_o - \lambda_r}{\lambda_r} \equiv z \longleftarrow \text{redshift}$$

Spectral Energy Distribution of a quasar

(very flat, thus much brighter in **radio** and **X-ray** than galaxies)

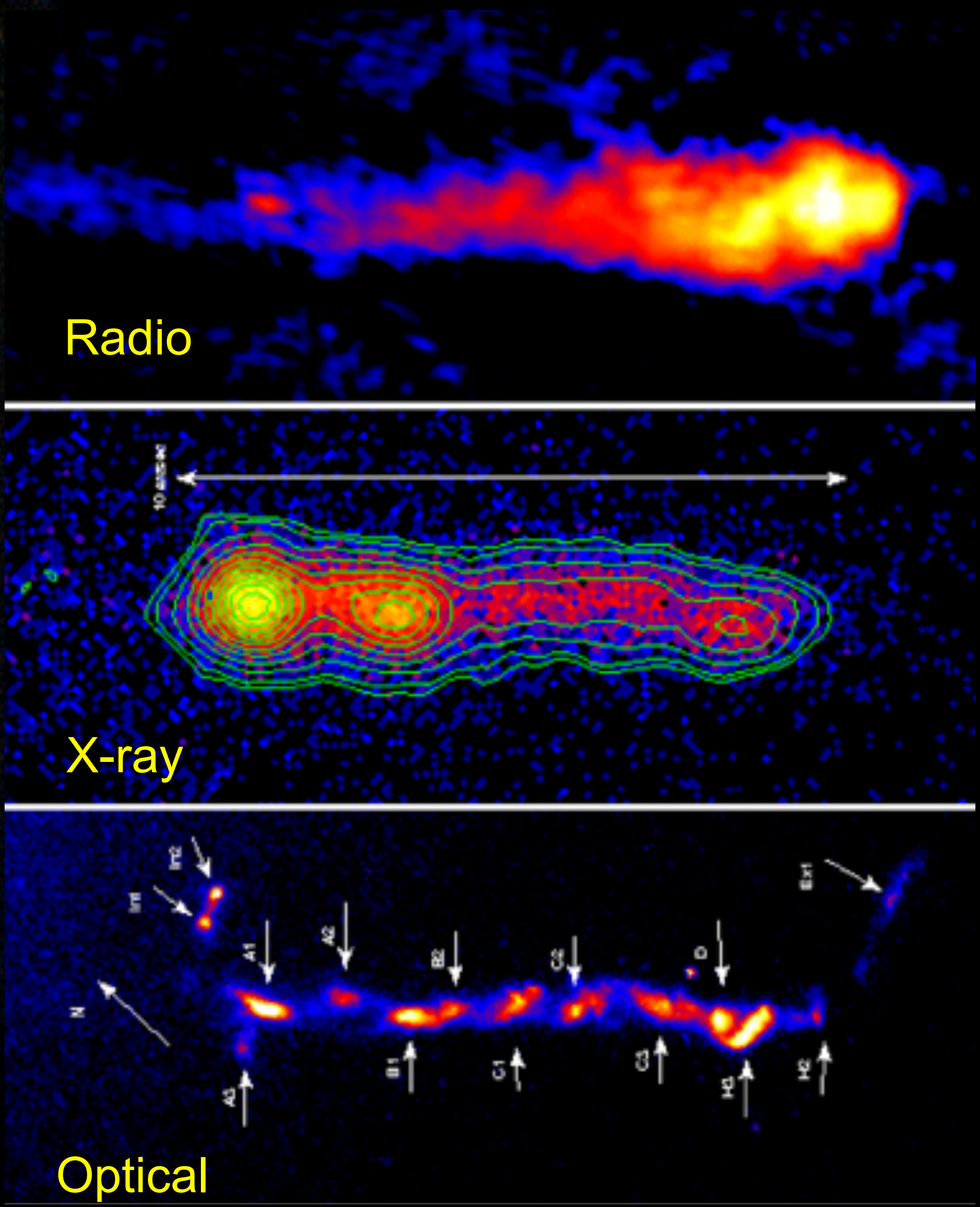


Jet emission from a quasar



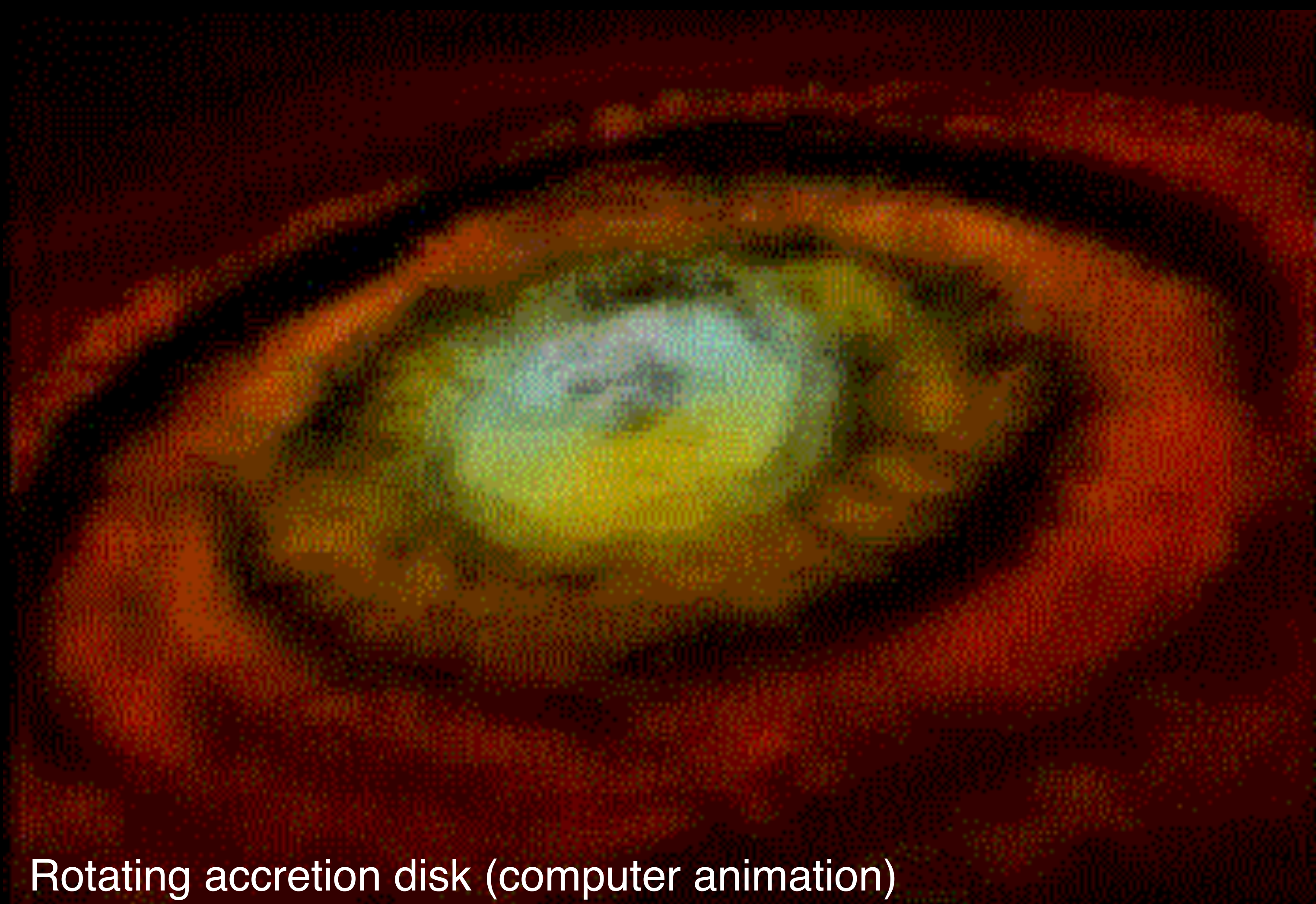
The jet in *3C 273* originating from quasar at center powered by strong magnetic fields

Relativistic motion of particles



Origin of the bright emission: *active galactic nucleus* has accretion disk around massive black hole

- Typical luminosity very high: $L_{AGN} \sim 3\times10^{11}\ L_{\odot} \sim 10^{38}$ W = 10^{45} ergs/s
- Emitting region very small
- Small volume and large radiation power $\Longrightarrow$ central engine is supermassive BH



Rotating accretion disk (computer animation)

Schwarzschild radius: $R_S = 2GM_{BH}/c^2$

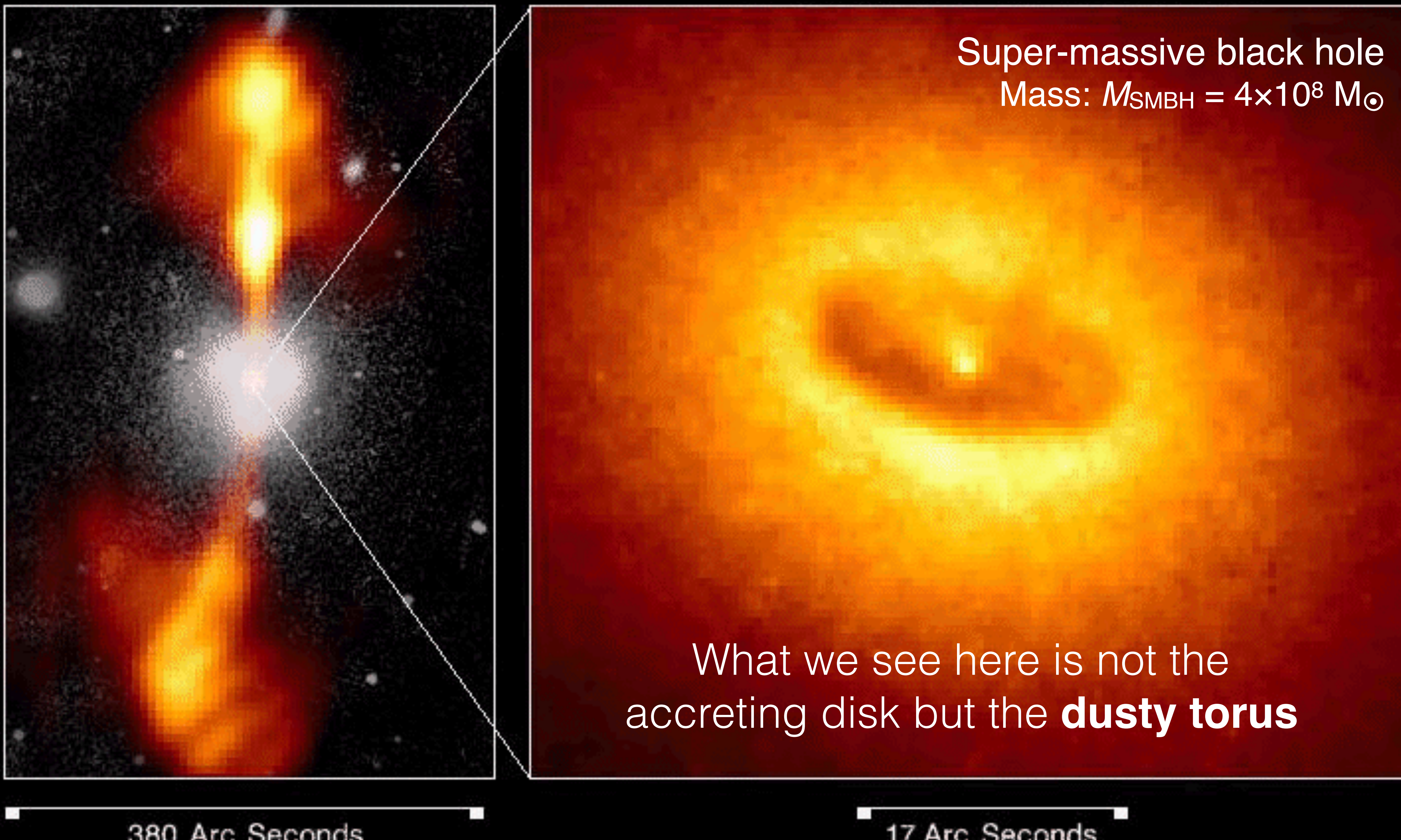
Most radiation coming from $\boldsymbol{R}$ **= few ×** $\boldsymbol{R_S}$ due to potential gravitational energy converted into energy

Images indicate presence of disk around massive black hole

Giant radio elliptical galaxy: *NGC 4261*
Apparent magnitude: $m_V = 11.4$
Distance: 29.4 ± 2.6 Mpc (redshift: $z = 0.007465$)

Optical and radio image

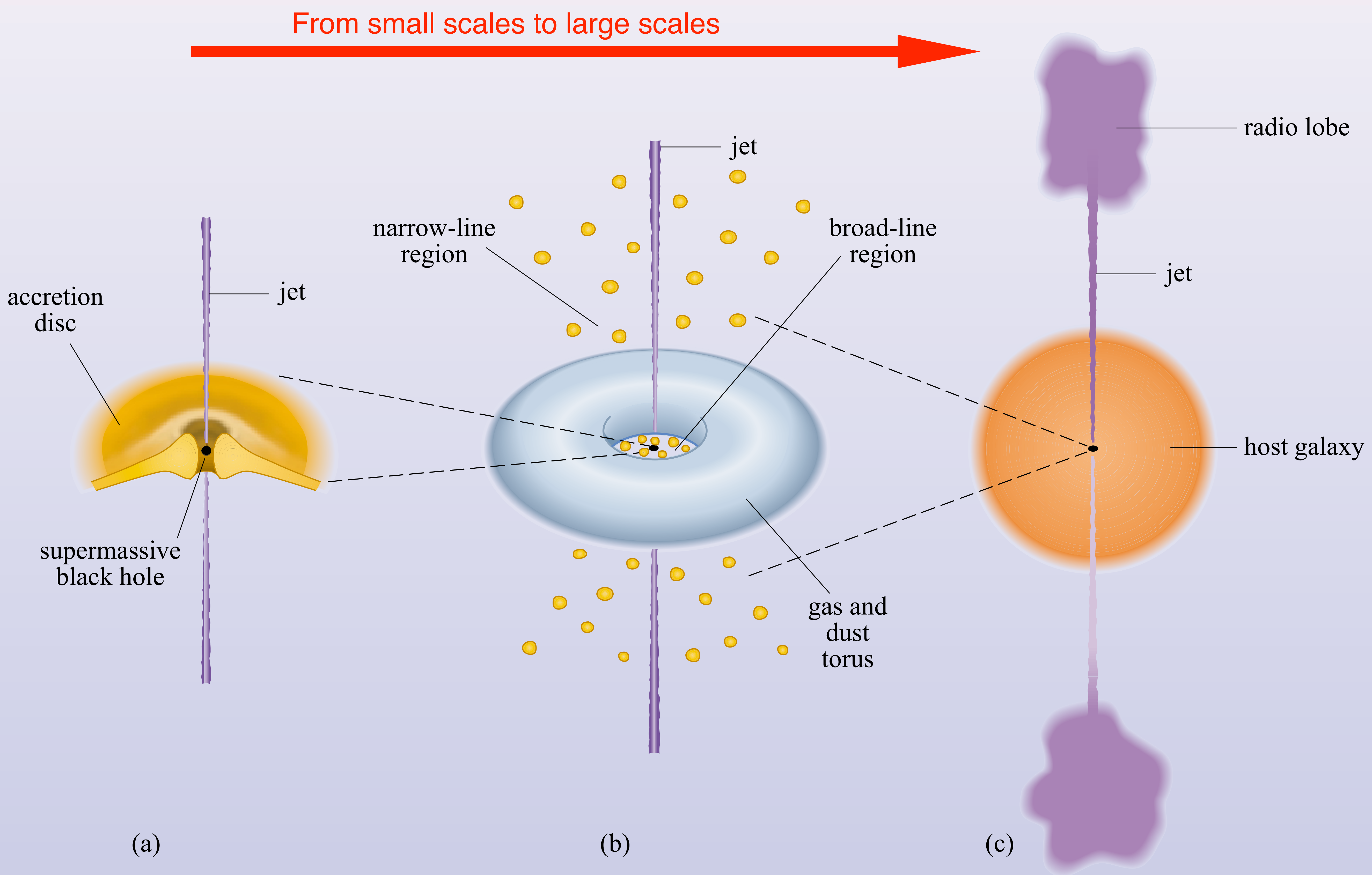
HST image of gas and dust

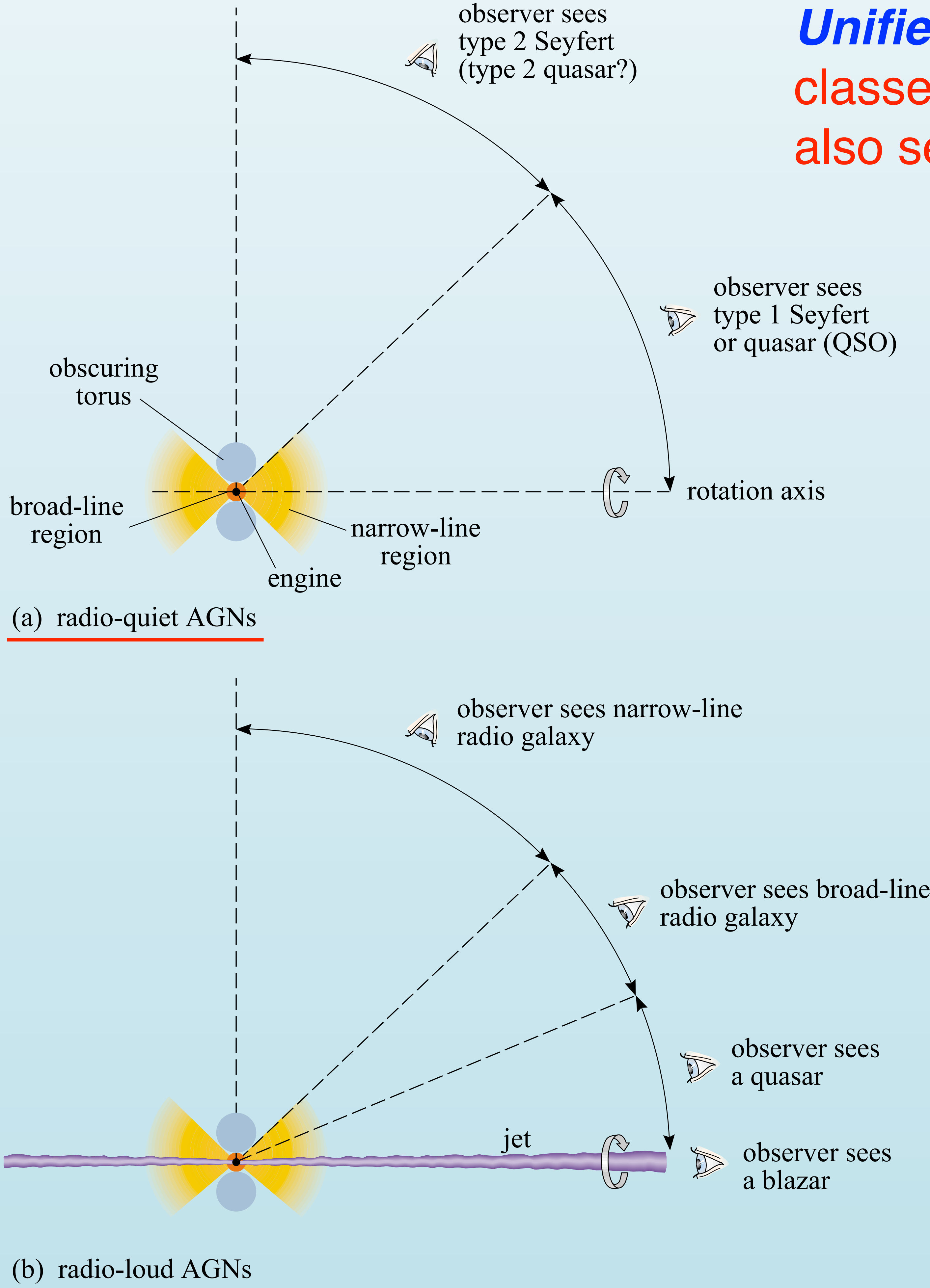


58.5 kpc

2.6 kpc

Generic model of galaxy with active nucleus



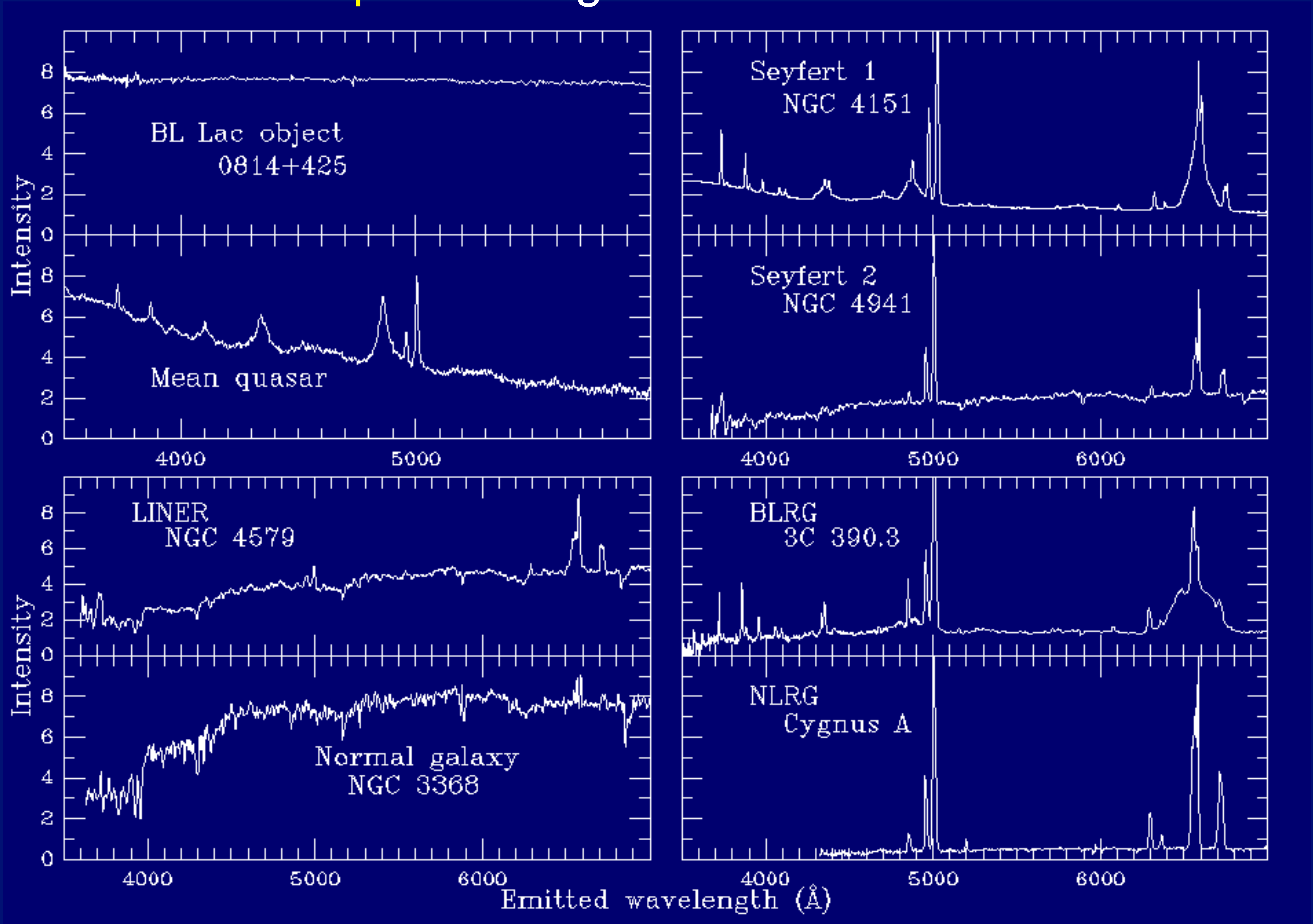


Unified Model describes all different classes of Active Galactic Nuclei (AGN) also seen at **different orientation**

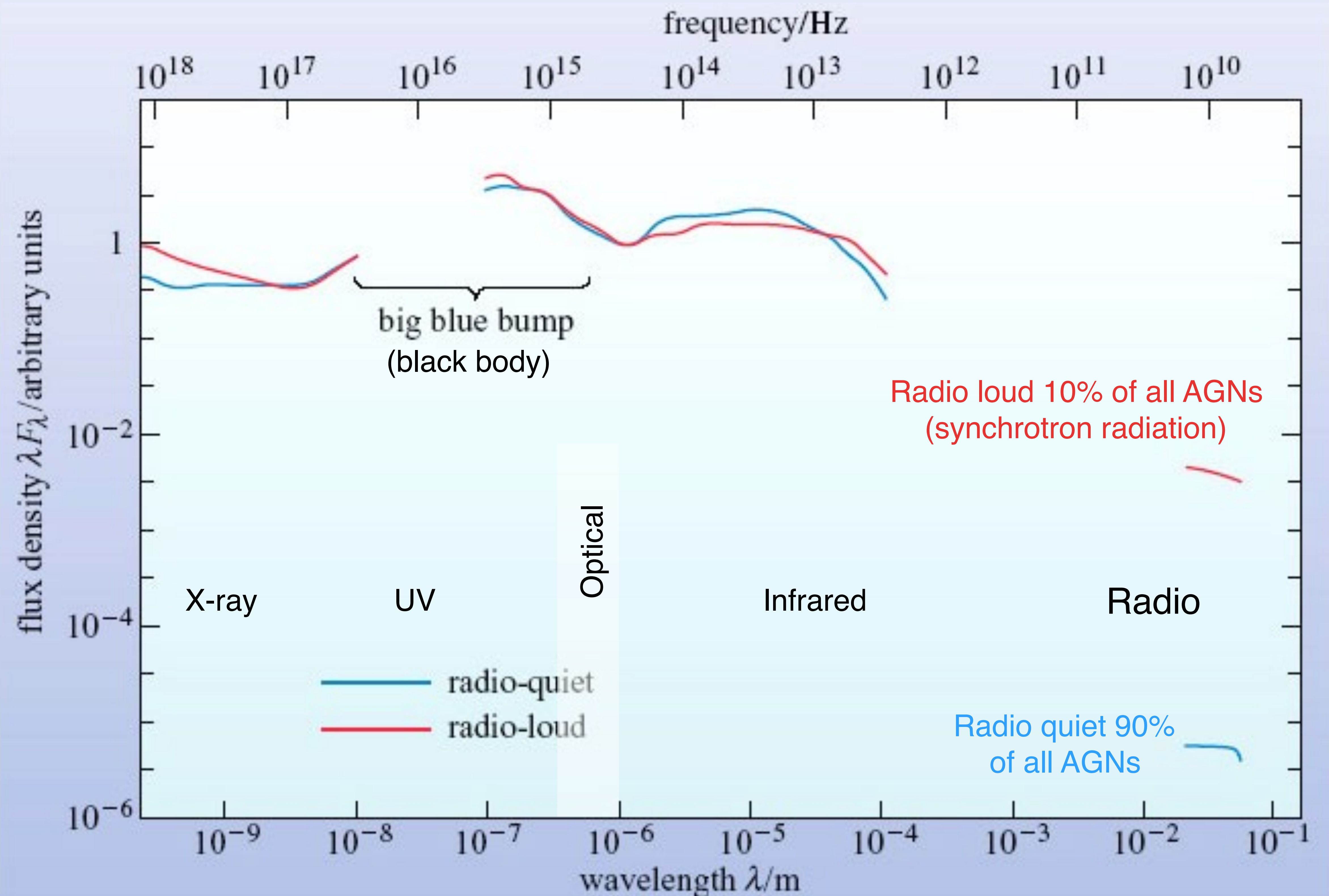
- Different orientation of active region with respect to view from Earth
- ***QSOs*** or ***quasars*** are most distant and brightest **AGNs**
- ***Seyfert*** are mostly spiral galaxies with bright nucleus (in 10/% all galaxies in nearby universe) closer and fainter than *quasars*
- ***Type 1 Seyfert*** have narrow and broad emission lines
- ***Type 2 Seyfert*** are obscured by dusty torus

- **Jet** is a strong radio source
- 10% of all **QSOs** are radio loud
- When **AGN** totally obscured by dust $\Longrightarrow$ ***radio galaxy*** can be observed
- **AGN** seen as a ***Blazer*** when relativistic jet pointing towards the Earth
- Among the most energetic phenomena in the universe
- Also called ***BL Lac object***

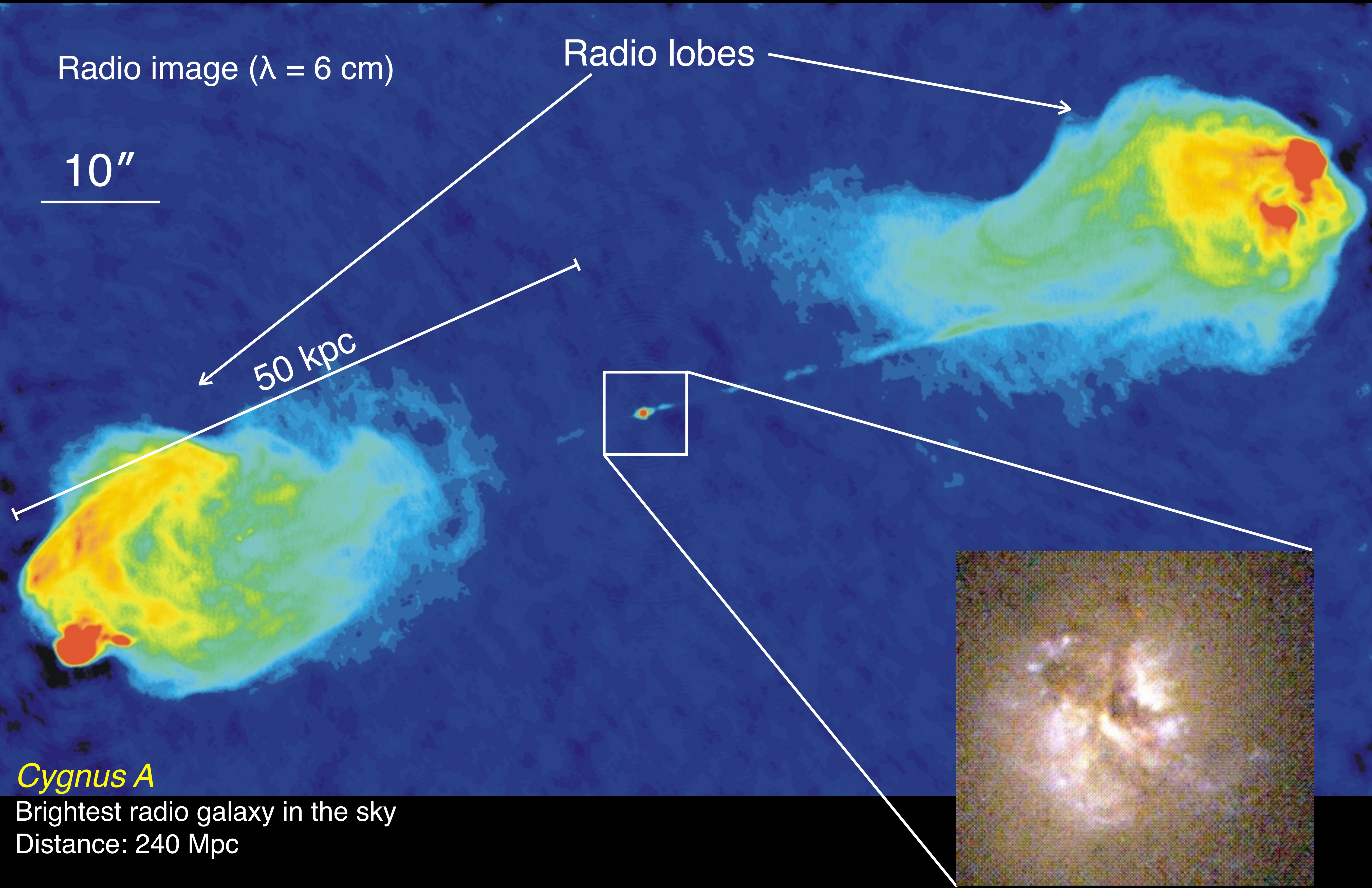
Different spectra for galaxies with active nucleus



Spectral energy distribution of ***radio-loud*** & ***radio-quiet*** **quasar**



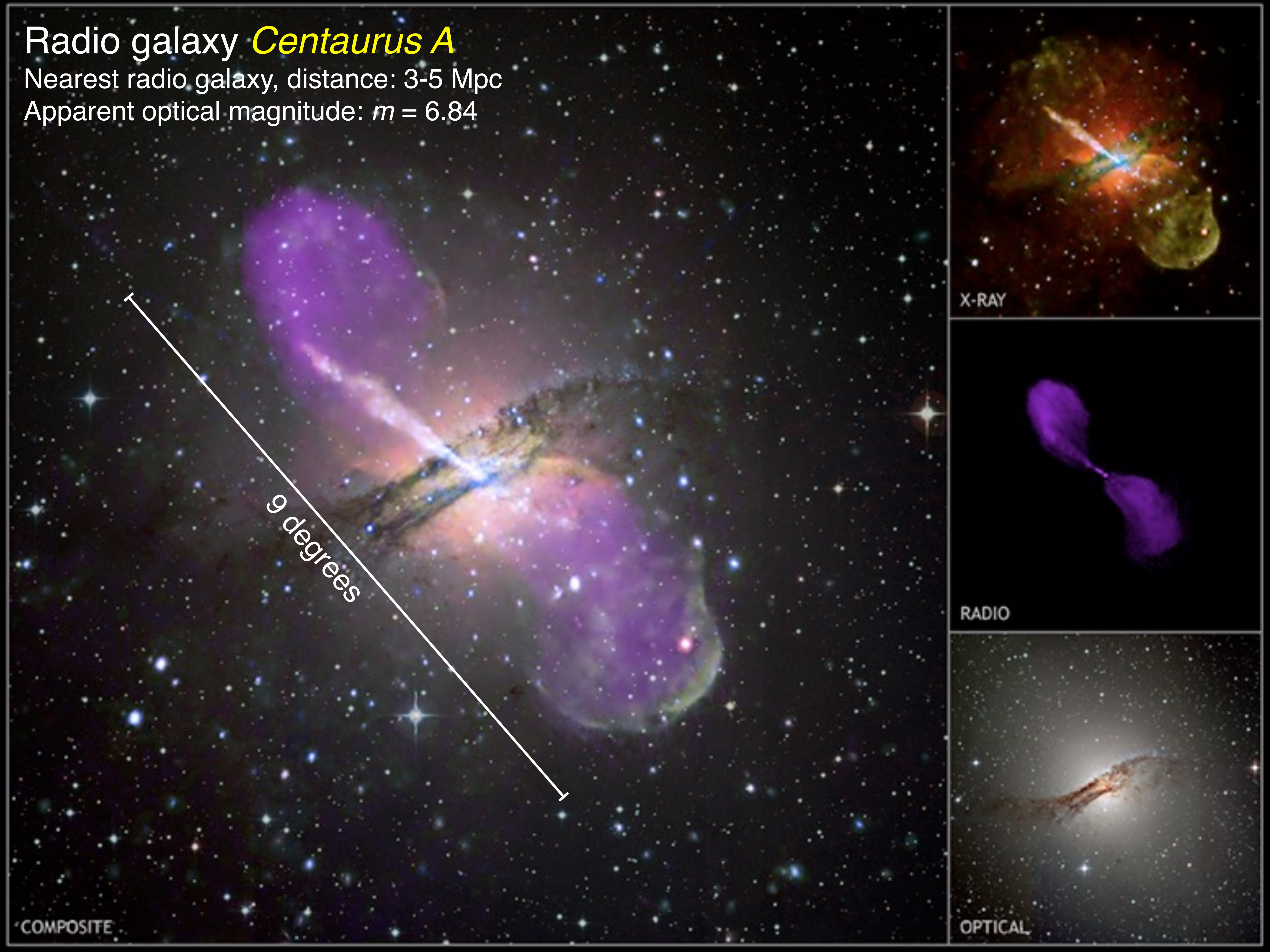
Radio galaxy with dust-obscured active galactic nucleus



Brightest radio galaxy in the sky
Distance: 240 Mpc

Optical emission of
elliptical galaxy absorbed by dust

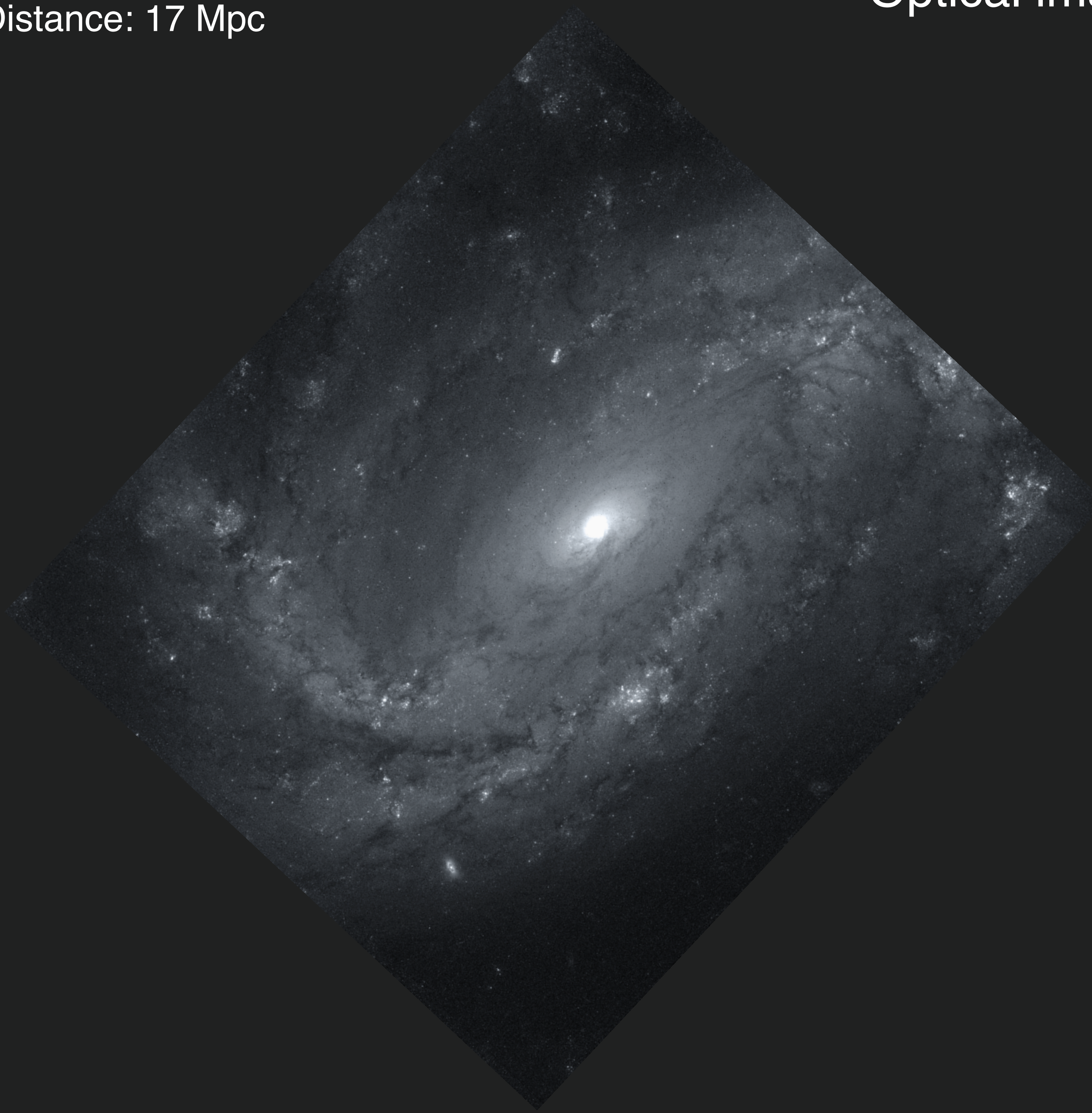
Radio galaxies dominate the sky in radio wavelength


Radio galaxy *Centaurus A*
Nearest radio galaxy, distance: 3-5 Mpc
Apparent optical magnitude: $m = 6.84$
9 degrees
COMPOSITE
X-RAY
RADIO
OPTICAL

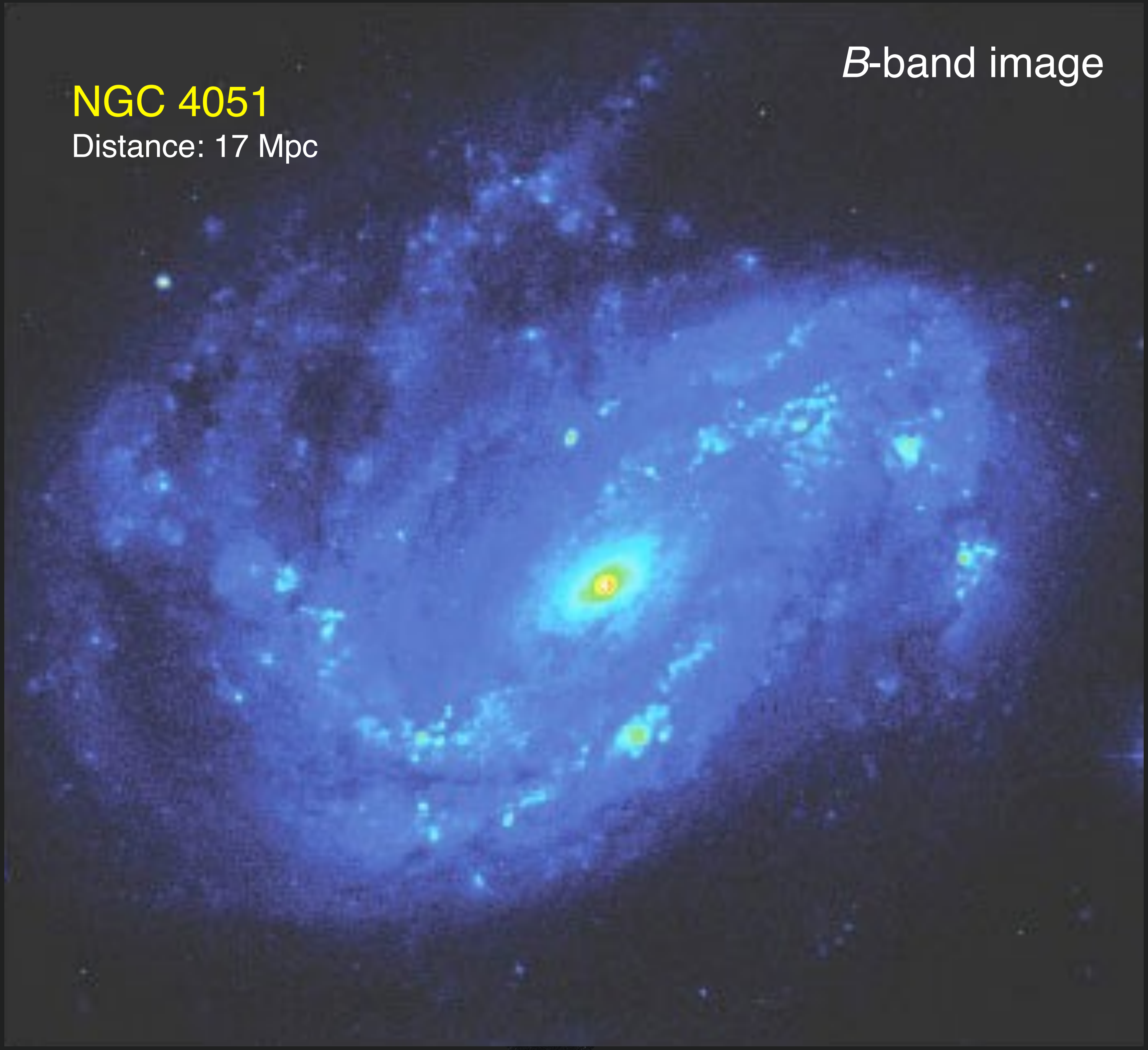
Seyfert galaxies are spiral galaxies with bright nucleus (AGN)
(generally nearby objects)

NGC 4051
Distance: 17 Mpc

Optical image

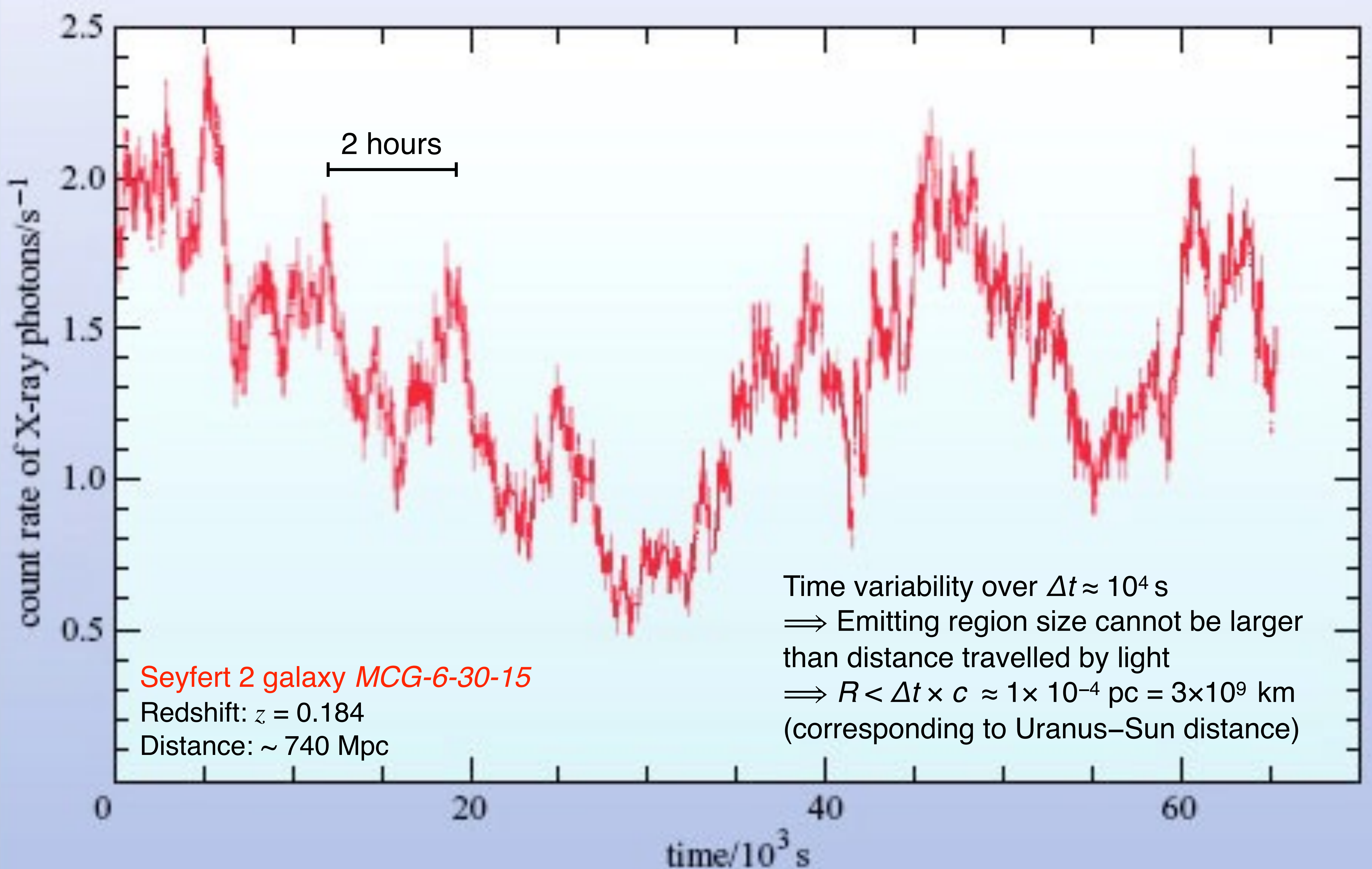


Seyfert galaxies are spiral galaxies with bright nucleus (AGN)
(generally nearby objects)



Time variability (in X-ray) of a Seyfert galaxy

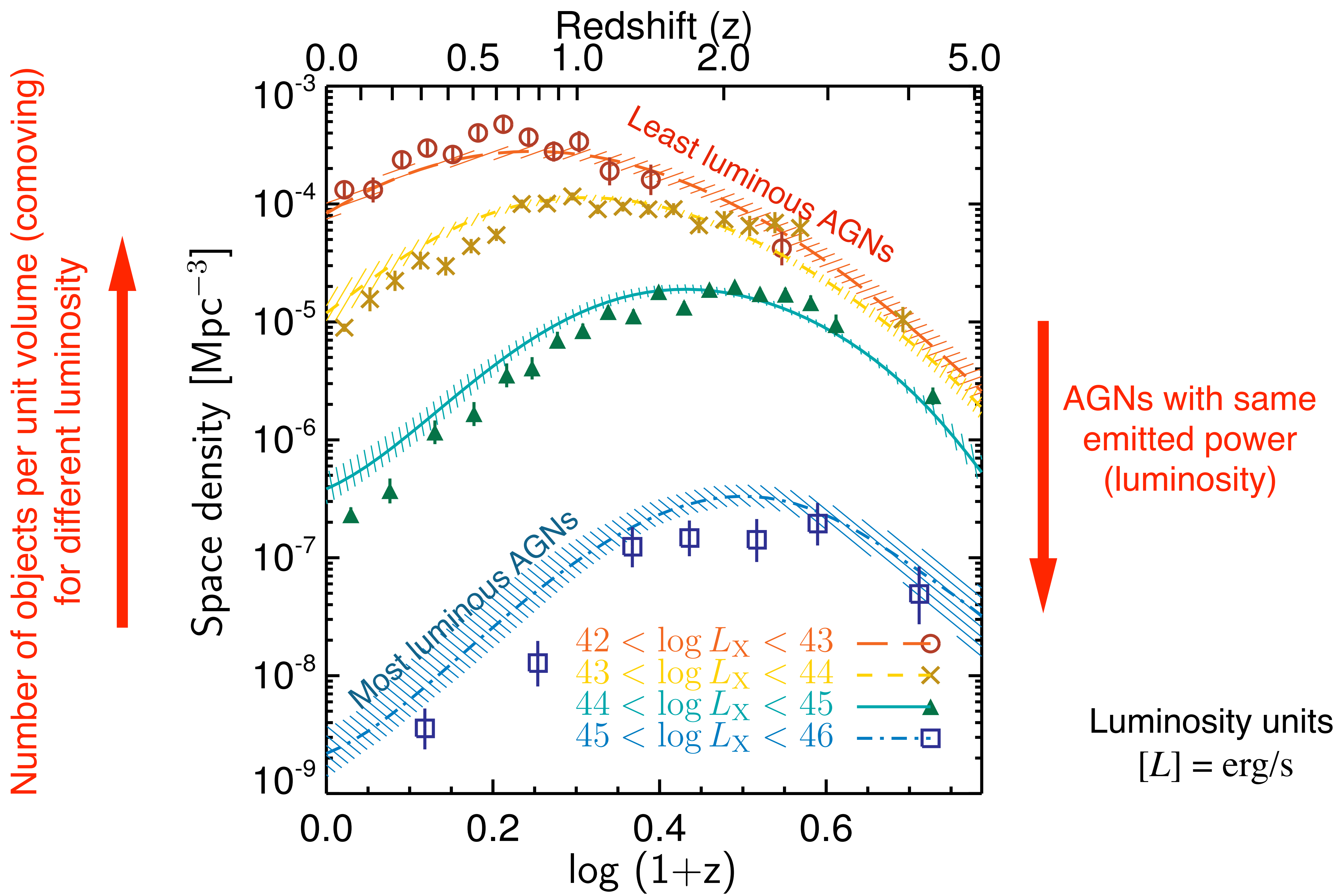
Used to constrain the size of AGN



Seyfert 2 galaxy *MCG-6-30-15*
Redshift: z = 0.184
Distance: ~ 740 Mpc

Time variability over $\Delta t \approx 10^4$ s
$\Longrightarrow$ Emitting region size cannot be larger than distance travelled by light
$\Longrightarrow$ $R < \Delta t \times c \approx 1 \times 10^{-4}$ pc $= 3 \times 10^9$ km
(corresponding to Uranus–Sun distance)

Time evolution of number density of quasars (or AGN)



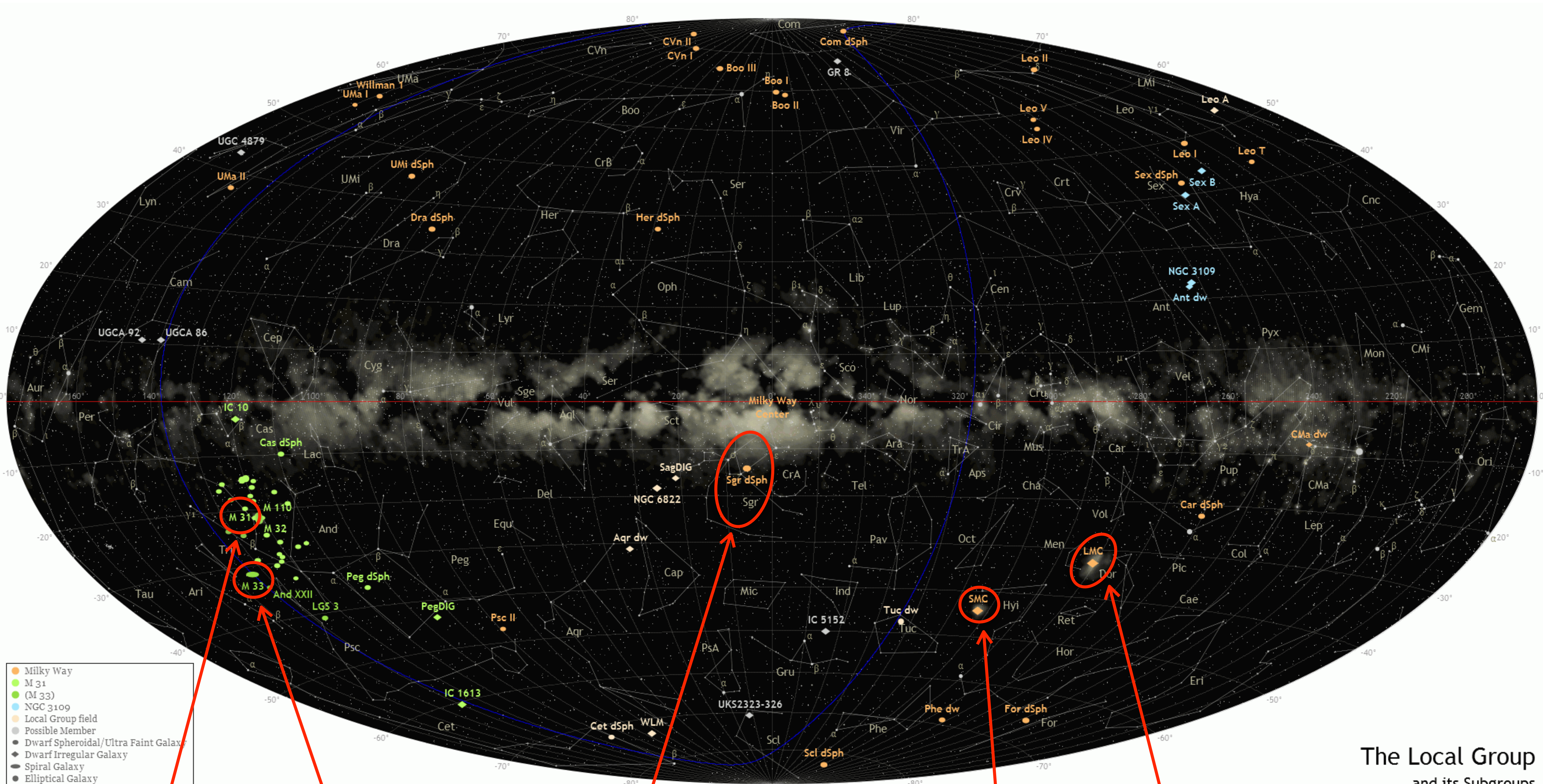
Luminosity units: $[L]$ = erg/s

Time evolution: quasars (or AGN) are **turning off**

The most distant QSO ever discovered is seen when the universe was ~ 699 Myr old (z = 7.54)

Group of galaxies
&
Clusters of galaxies

Galaxies close to the Milky Way form the *Local Group*



Triangulum Galaxy (Messier 33)
Distance: 730–940 kpc

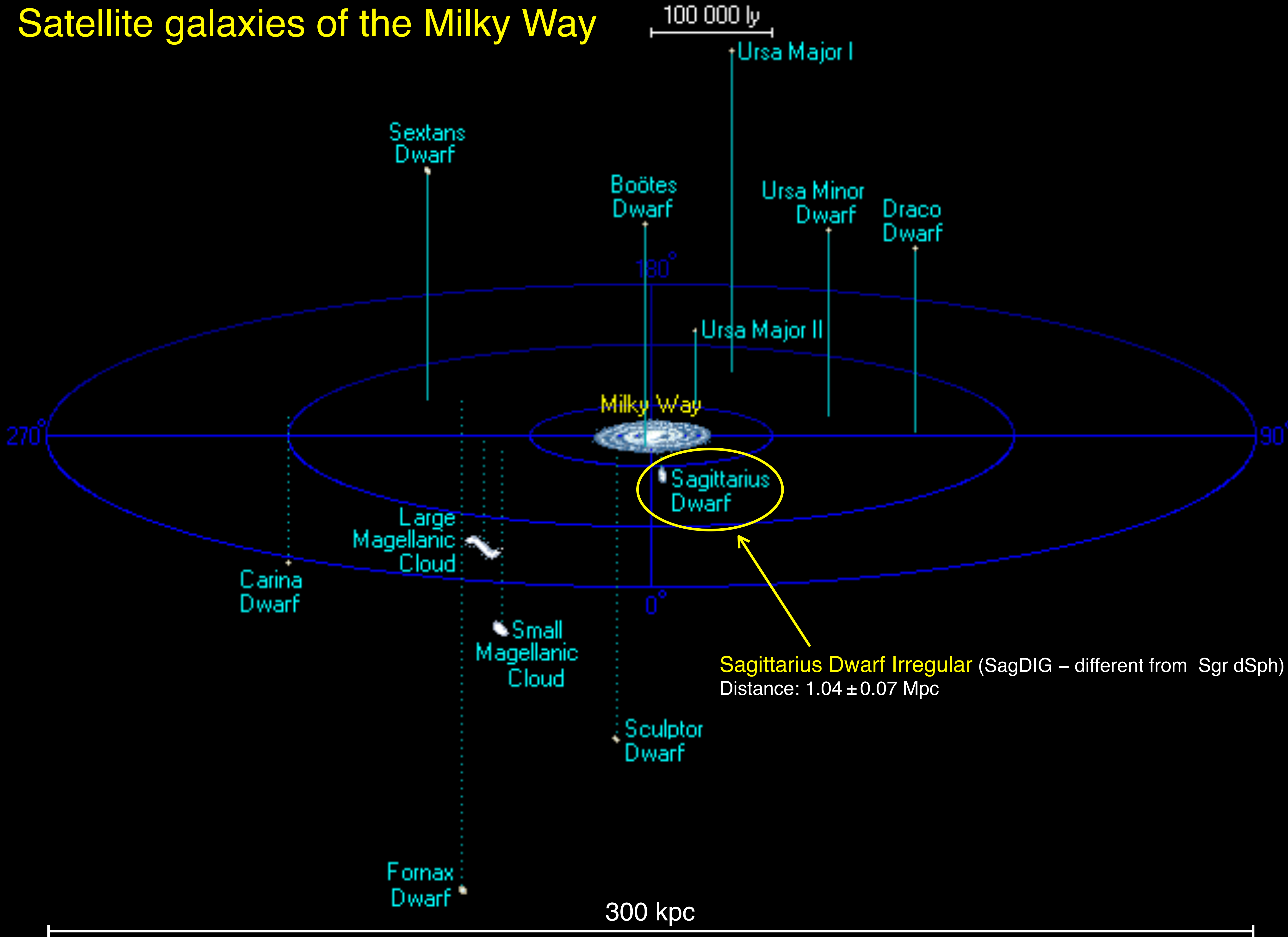
Andromeda (Messier 31)
Most massive galaxy in the *Local Group*
Distance: 778 ± 33 kpc

Sagittarius Dwarf Elliptical Galaxy (Sgr dSph)
Distance: 15 ± 2 kpc
Closest galaxy to the Milky Way

Small Magellanic Cloud (SMC)
Distance: 61 ± 1 kpc

Large Magellanic Cloud (LMC)
Distance: 50.0 ± 1.1 kpc

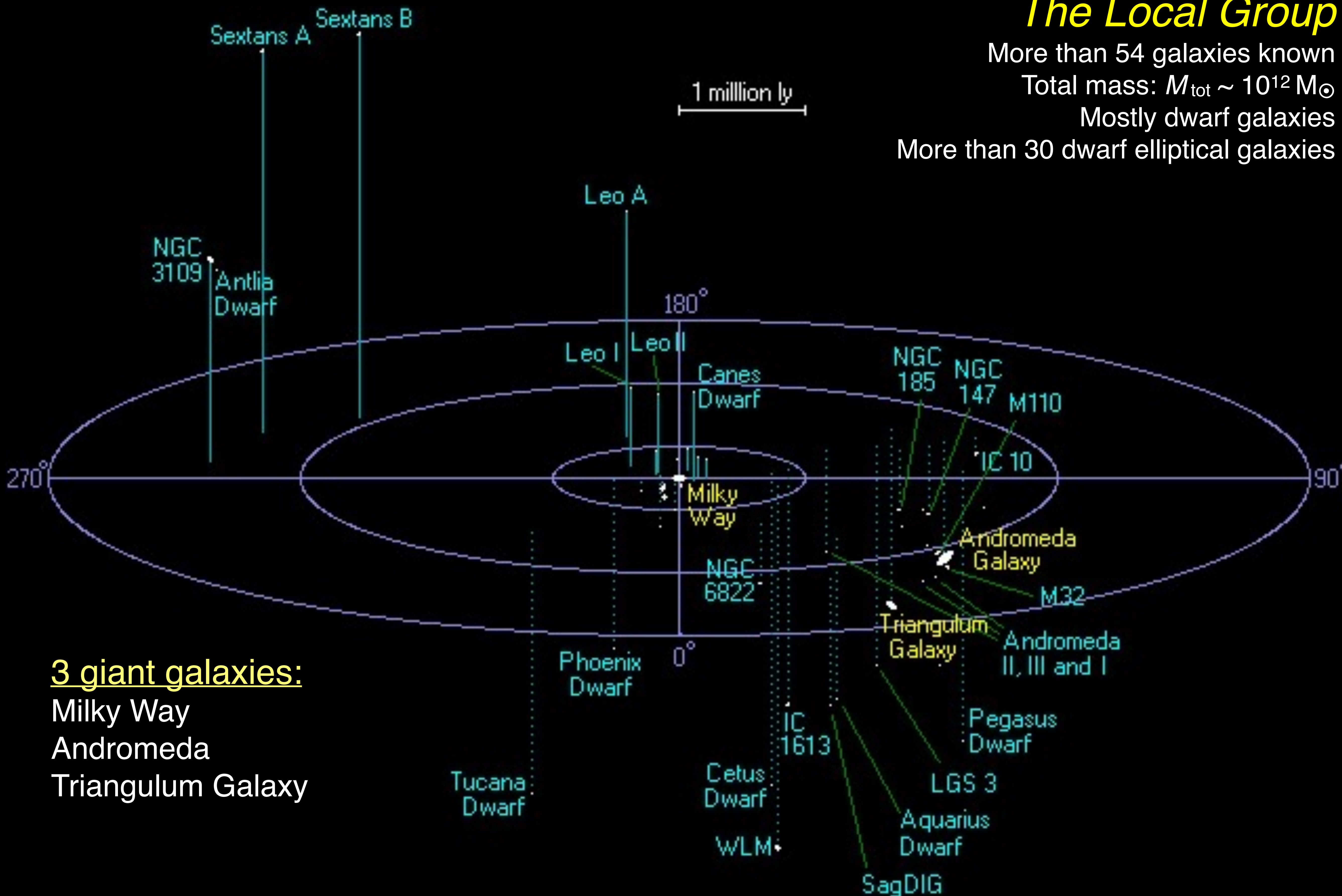
Satellite galaxies of the Milky Way



Sagittarius Dwarf Irregular (SagDIG – different from Sgr dSph)
Distance: 1.04 ± 0.07 Mpc

The Local Group

More than 54 galaxies known
Total mass: $M_{tot} \sim 10^{12}\ M_{\odot}$
Mostly dwarf galaxies
More than 30 dwarf elliptical galaxies



<u>3 giant galaxies:</u>

Milky Way
Andromeda
Triangulum Galaxy

3 Mpc

Beyond the *Local Group*

The cluster of galaxies closest to the Milky Way

The Virgo Cluster

Distance: $d = 20$ Mpc

Binding mass: $M \sim 1.2\times10^{15}\ M_\odot$

Size: ~ 3 Mpc

About 1500 galaxies (mix of elliptical, S0 & spiral galaxies)

The cluster of galaxies closest to the Milky Way

The Virgo Cluster

Distance: $d = 20$ Mpc

Binding mass: $M \sim 1.2\times10^{15}\ M_\odot$

Size: ~ 3 Mpc

About 1500 galaxies (mix of elliptical, S0 & spiral galaxies)

Radio galaxy *M87* with jet

Apparent magnitude: $m_V = 9.59$

Distance: 16.40 ± 0.50 Mpc

Total mass: $M_{tot} = 6\times10^{12}\ M_\odot$

Mass central black hole: $M_{BH} = 7\times10^{9}\ M_\odot$

Messier 87: one of the most massive galaxies in the *Local Universe*

Messier 87: one of the most massive galaxies in the *Local Universe*

Messier 87: radio galaxy with jet

Distance: 16.4 ± 0.5 Mpc

Total mass: $M_{tot} = 6 \times 10^{12}\ M_{\odot}$

Mass central black hole: $M_{BH} = 7 \times 10^{9}\ M_{\odot}$

(one of the highest mass known for a black hole)

Optical image

Messier 87: radio galaxy with jet

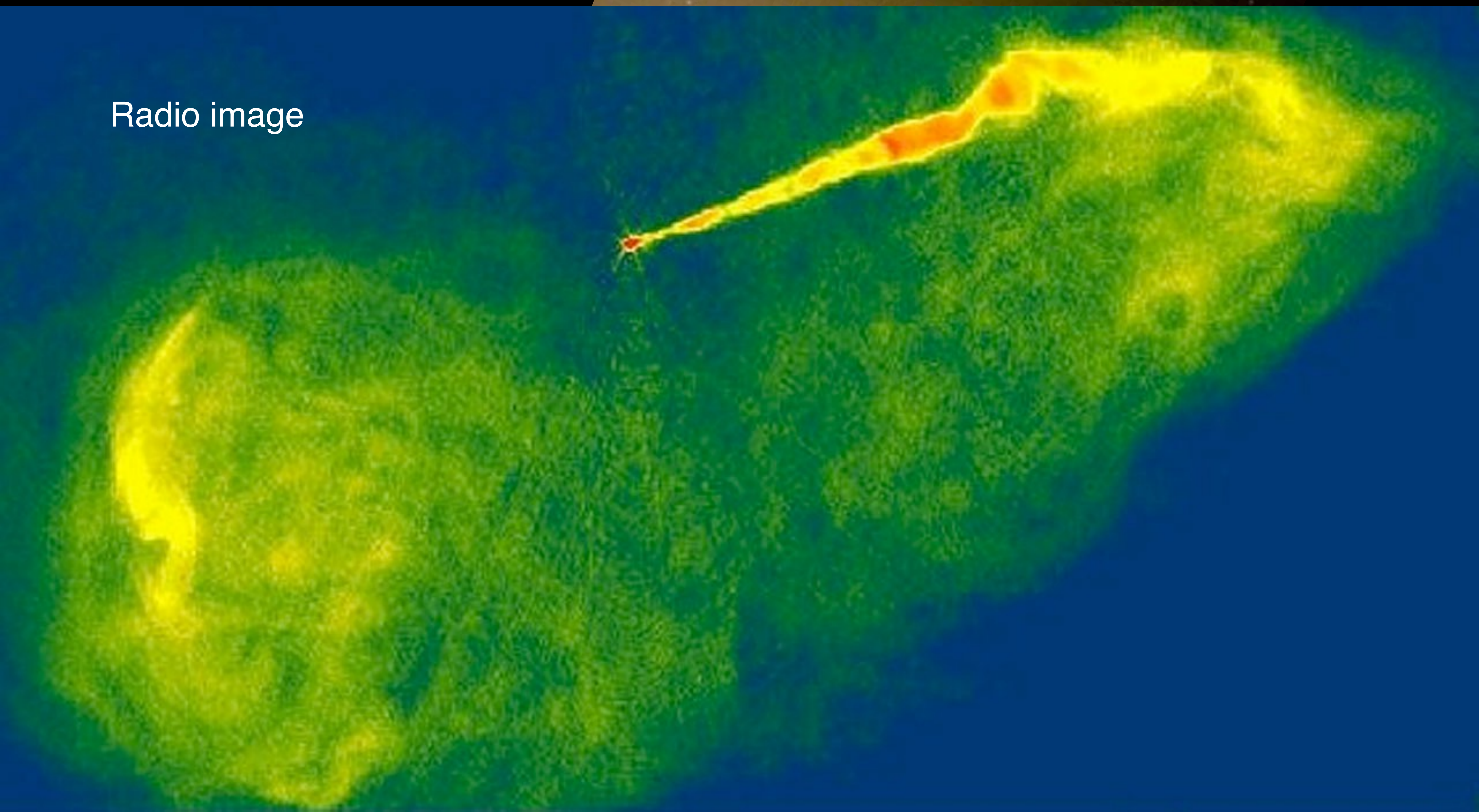
Distance: 16.4 ± 0.5 Mpc

Total mass: $M_{tot} = 6 \times 10^{12}\ M_\odot$

Mass central black hole: $M_{BH} = 7 \times 10^{9}\ M_\odot$

(one of the highest mass known for a black hole)

Optical image



Messier 87

&

Most detailed image of a Black Hole ever obtained with

Event Horizon Telescope (EHT)

Messier 87: radio galaxy with jet

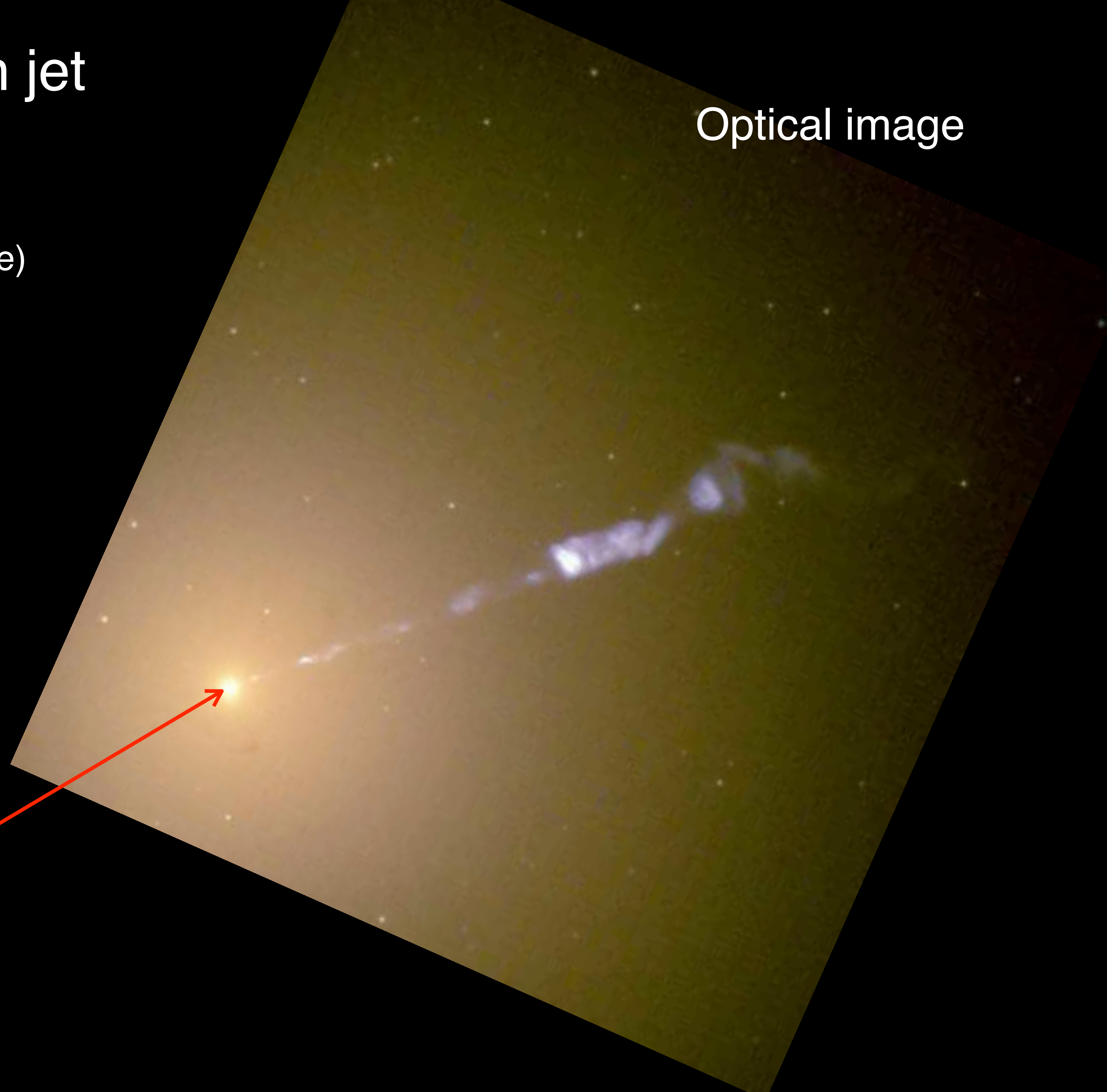
Distance: 16.4 ± 0.5 Mpc

Total mass: $M_{tot} = 6\times10^{12}\ M_\odot$

Mass central black hole: $M_{BH} = 7\times10^{9}\ M_\odot$

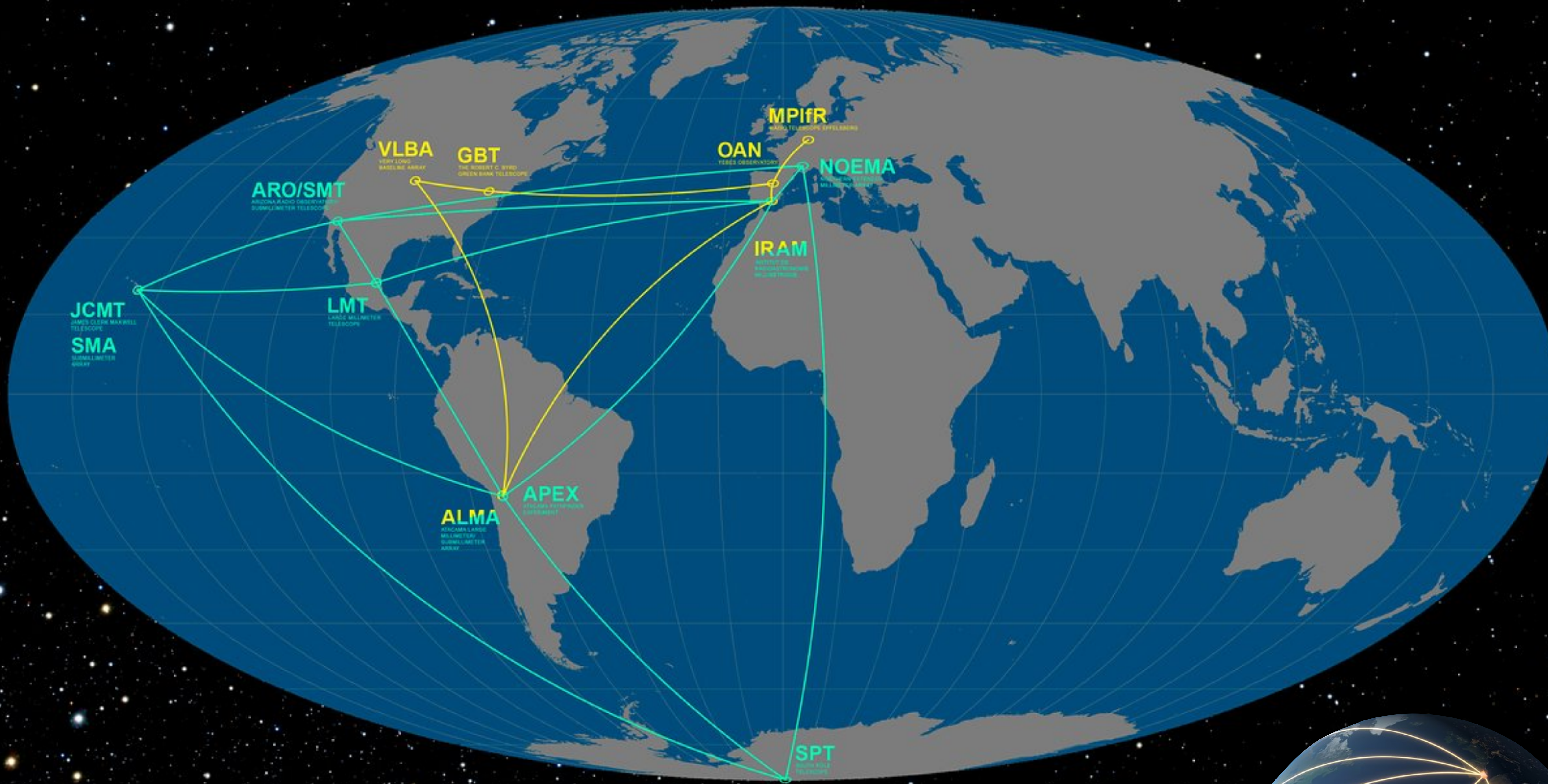
(one of the highest mass known for a black hole)

Optical image



Black hole at center

Event Horizon Telescopes (EHT) to "observe" a black hole



EHT uses technique called *very-long-baseline interferometry* (VLBI)

8 radio observatories used on the entire Earth

Total data volume collected in 2017: 5 petabytes (350 terabytes/day)

Resolution achieved: 20 micro-arcseconds (20 μas)

Wavelength observed: λ = 1.3 mm

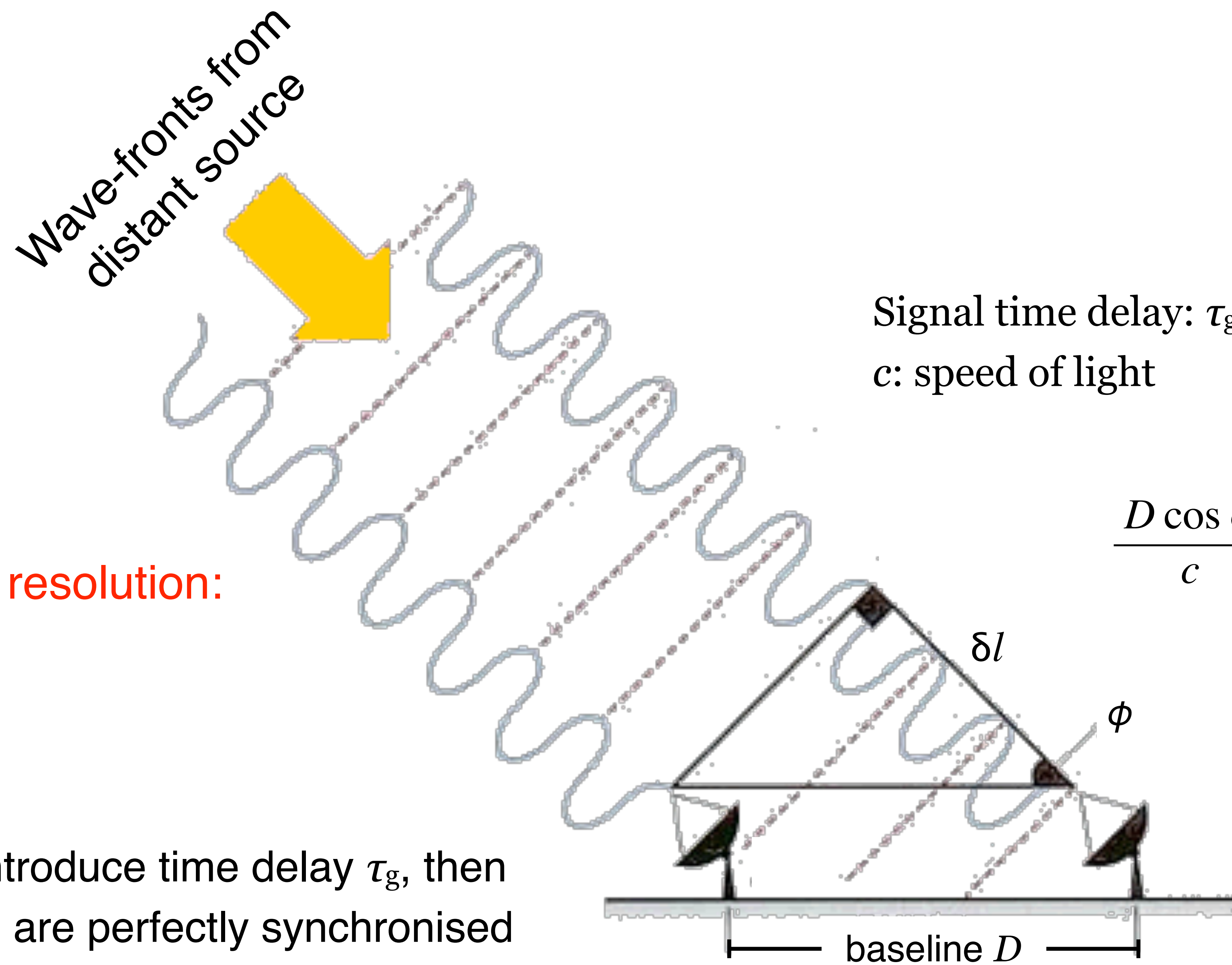
Interferometry with relatively small radio antennas
to get resolution of giant telescope

ALMA - Atacama Large Millimeter Array
66 12/7-meter diameter antennas
Movable antennas covering area from 150 metres to 16 kilometres

Interferometry for radio telescopes

Interferometer: signal is combined from two or more telescopes to produce a sharper image to obtain **higher angular resolution**

Same source $\Longrightarrow$ signal perfectly in phase & same frequency



Signal time delay: $\tau_g = \delta l / c$
c: speed of light

$$\frac{D \cos \phi}{c} = \tau_g$$

Effective angolar resolution:

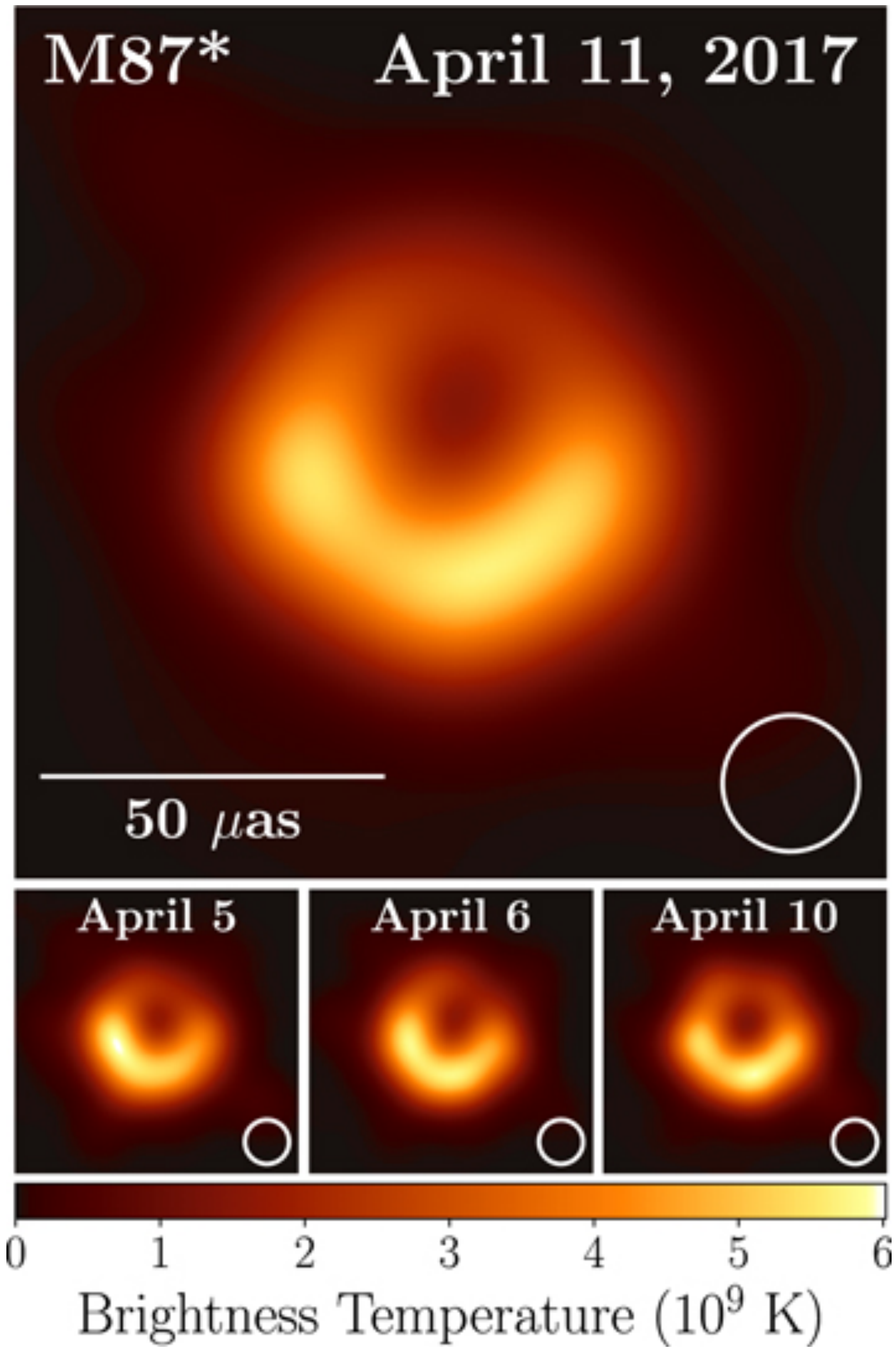
$$\theta = 1.220 \frac{\lambda}{D}$$

Atomic clock to introduce time delay τ_g, then combined signals are perfectly synchronised

Effective diameter

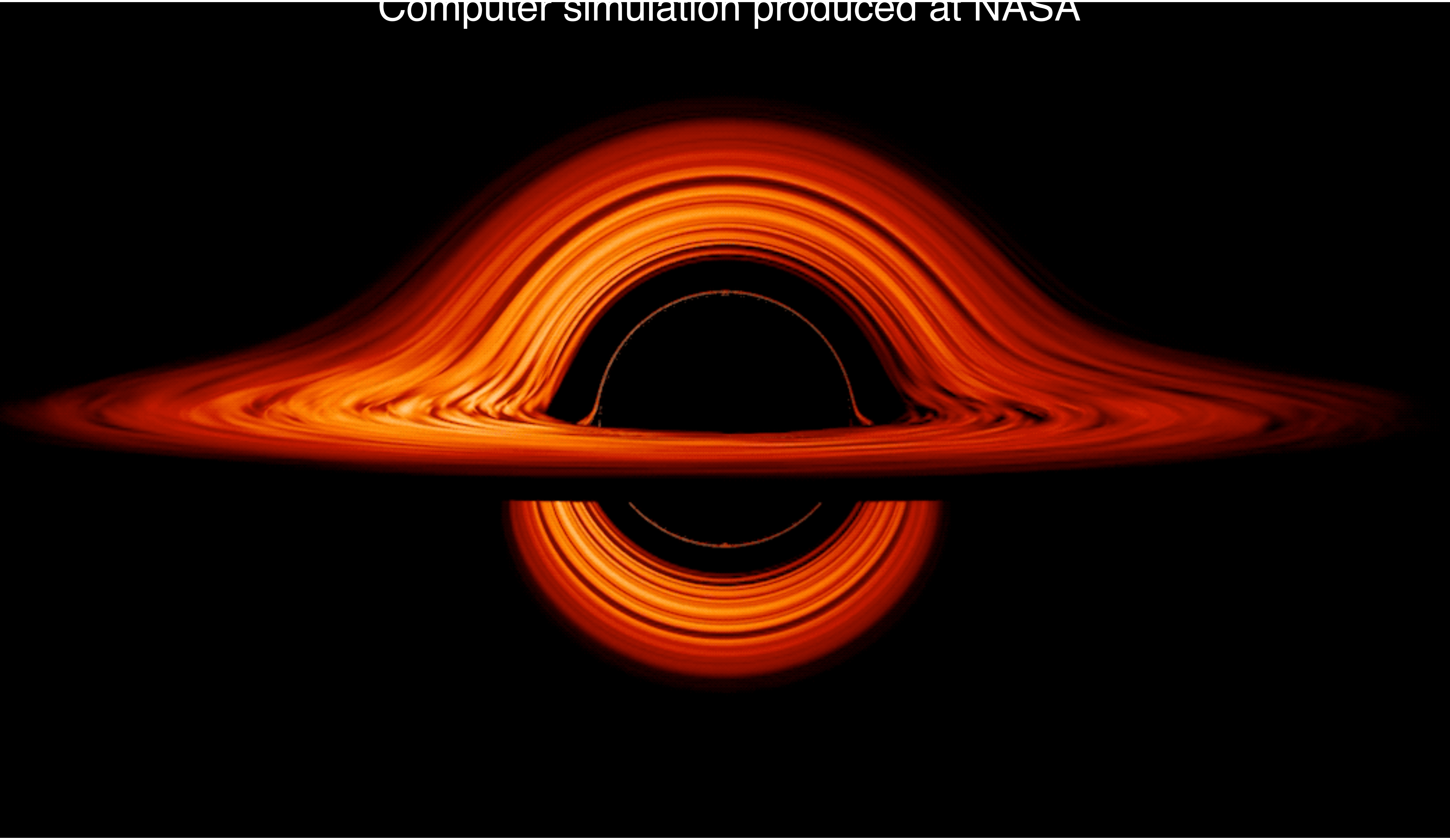
Most detailed image of a Black Hole ever obtained

Direct studies of event horizon now possible via astronomical observations



- Image resolution: 20 micro arc-seconds (μas)
- Equivalent to a **2 cents coin seen from Earth on the Moon**
- Completely dark region is where light cannot escape
- Luminous ring diameter: **42 ± 3 μas**, brighter in the south
- Inclination angle of the orbiting disk with respect to Earth: 17°
- **Event horizon** around **2.5 times smaller than dark region**
- Size of event horizon is just under **40 billion km**
- Equivalent to the **orbit of Pluto around the Sun**
- Measured mass of black hole: $\boldsymbol{M_{BH} = (6.5 \pm 0.7) \times 10^9 M_\odot}$

Visualization of region around black hole

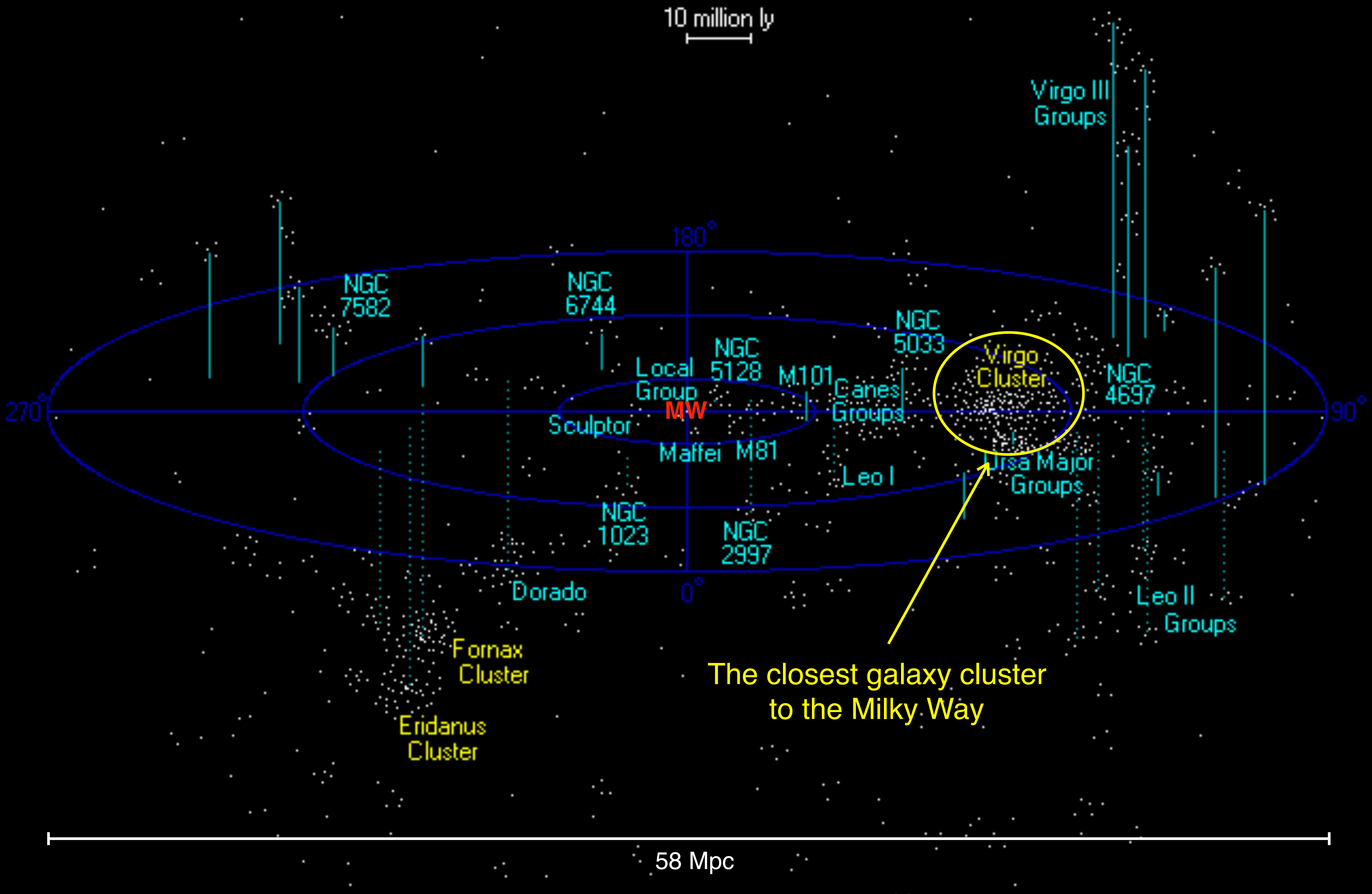


Super clusters of galaxies

The largest structures gravitational bound
in the universe

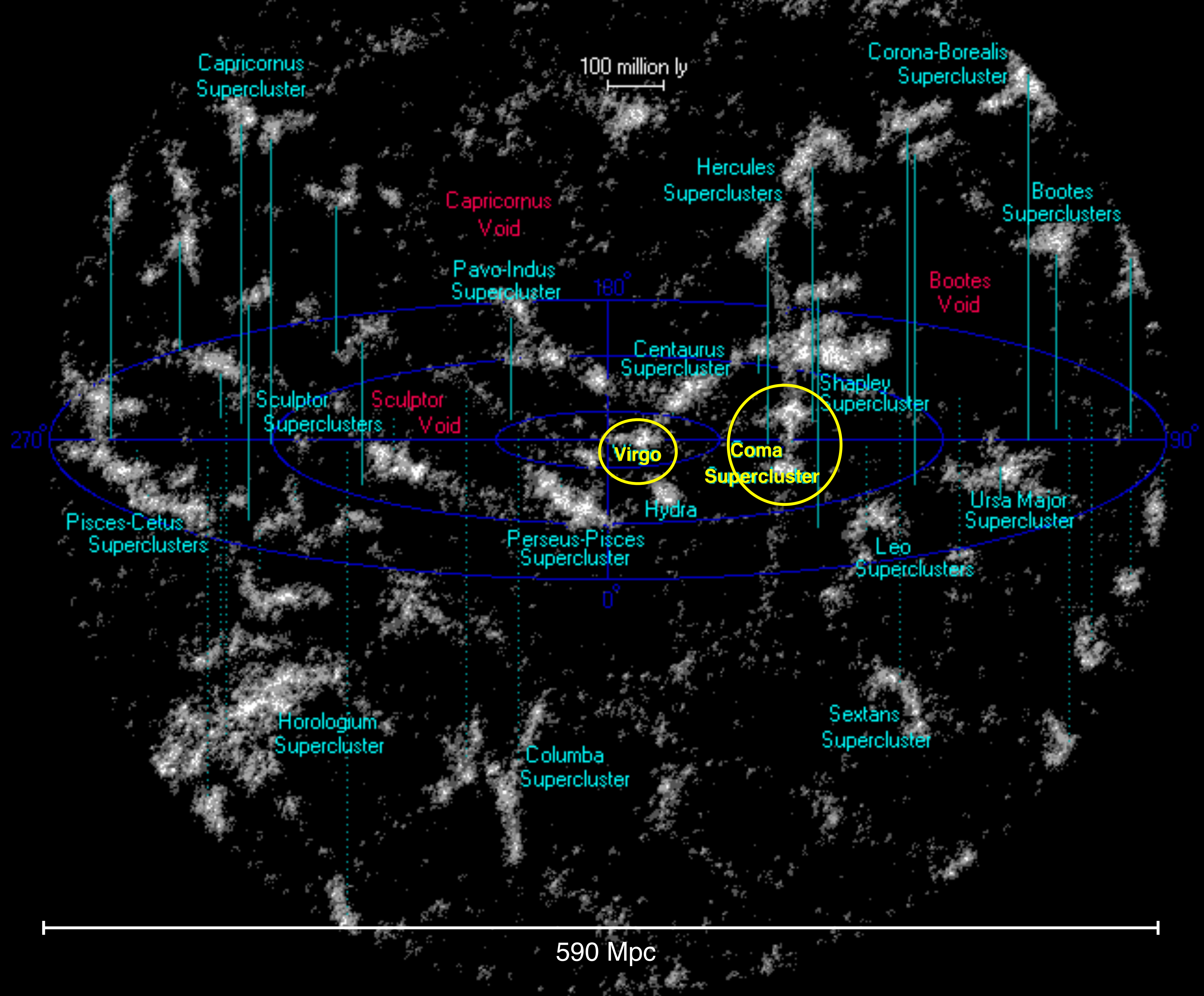
Virgo Supercluster

At least 100 galaxy groups & clusters



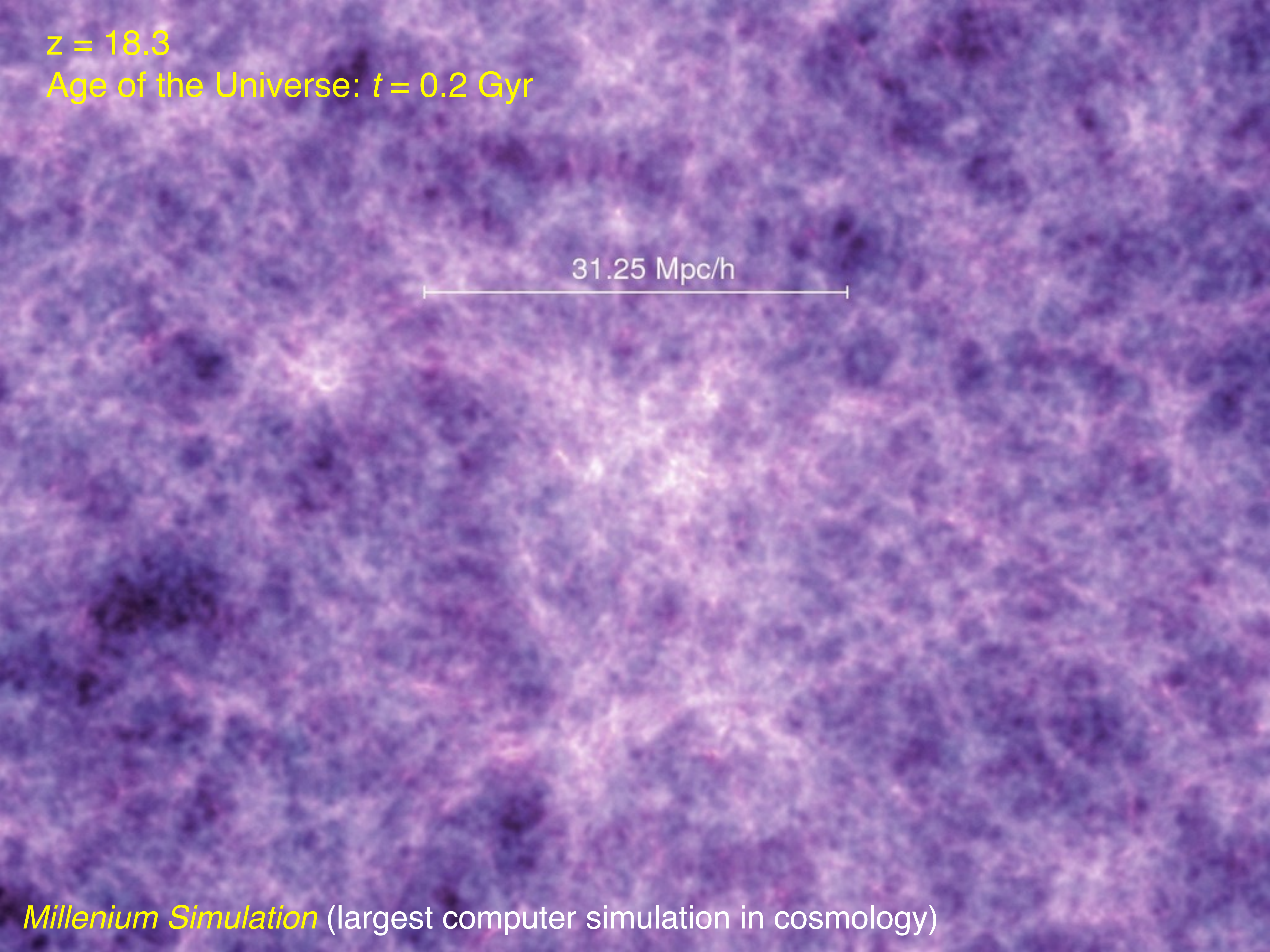
The Neighbouring Superclusters

Superclusters are the largest structures in the universe

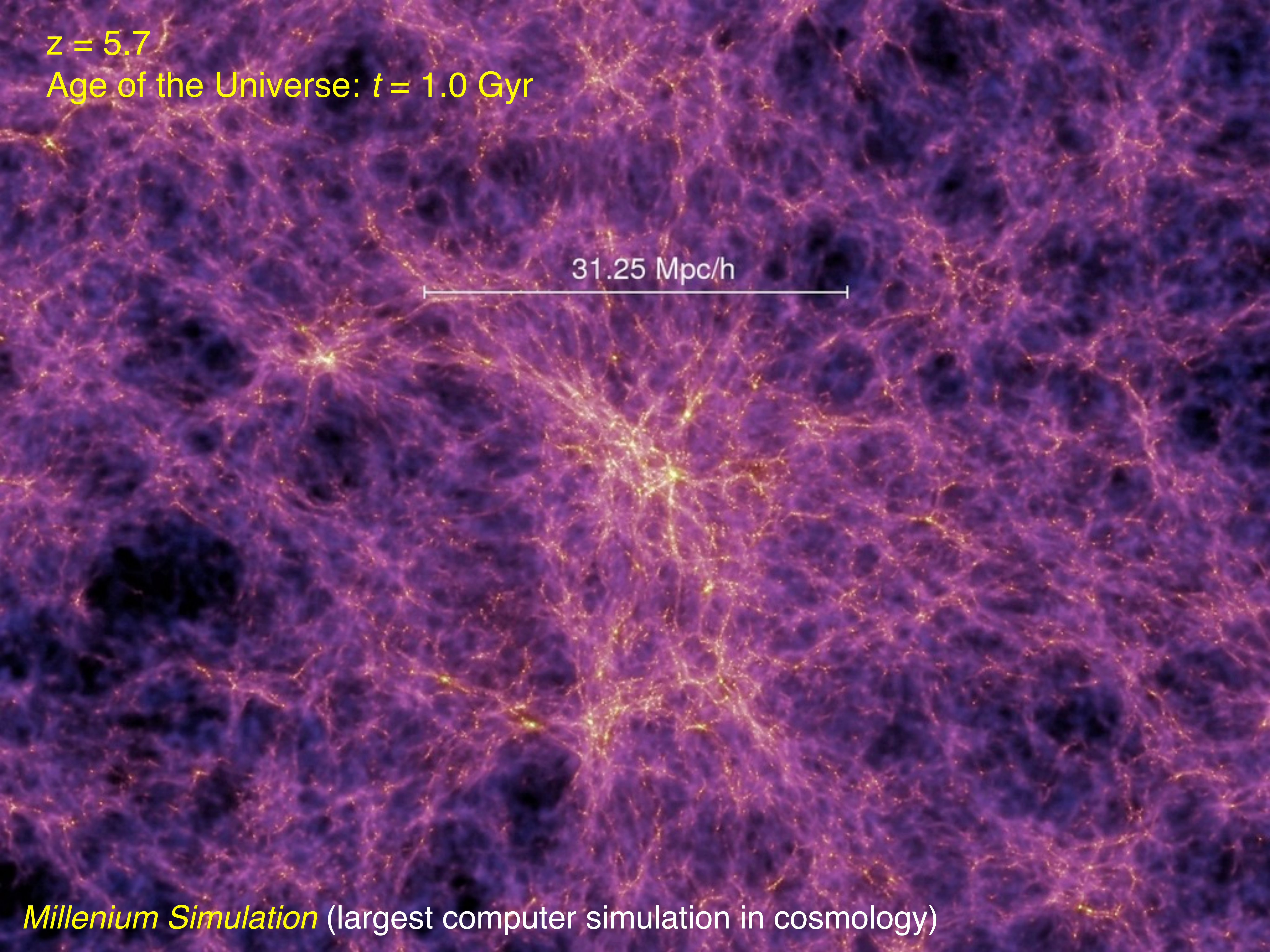


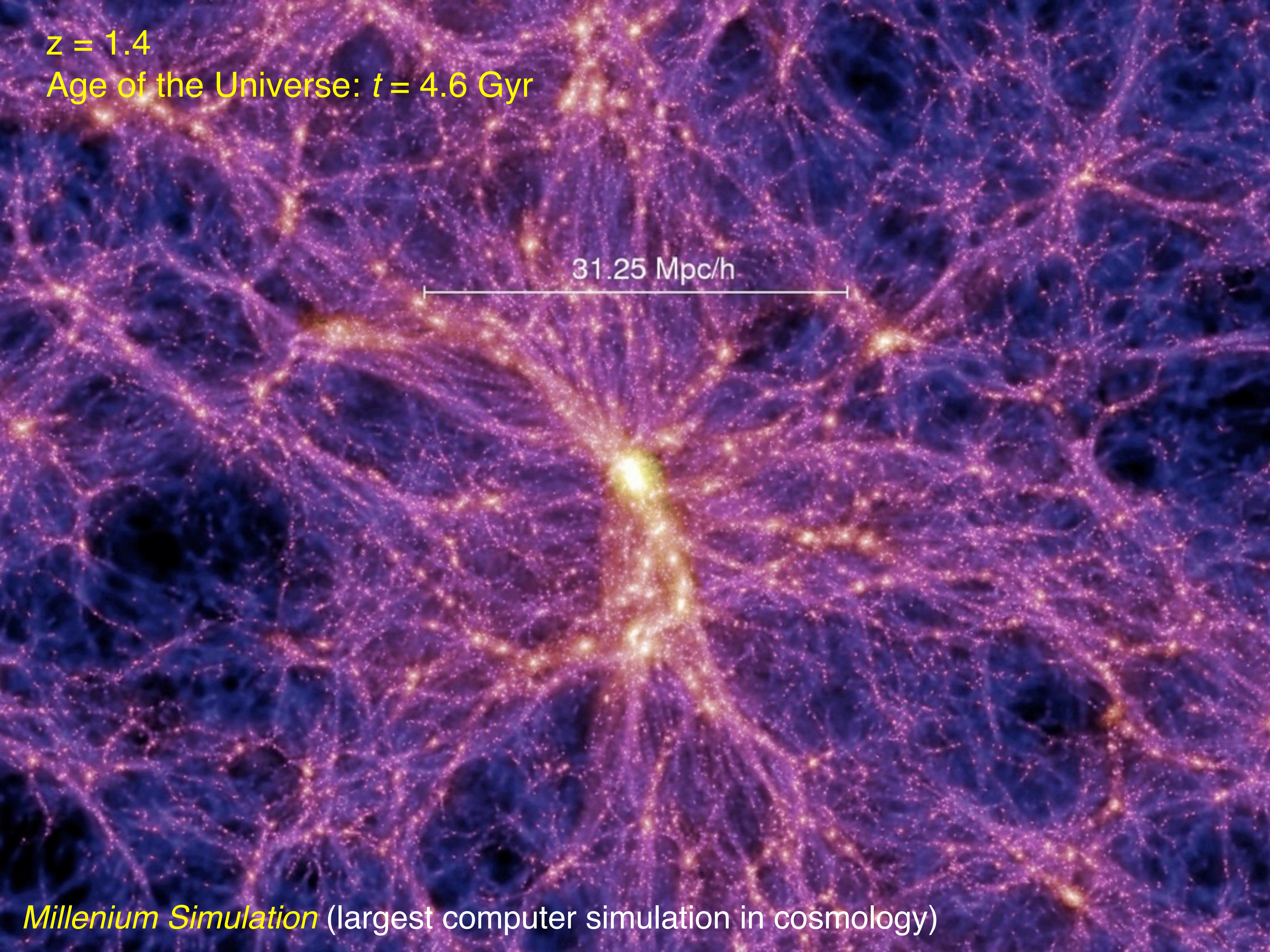
$z = 18.3$

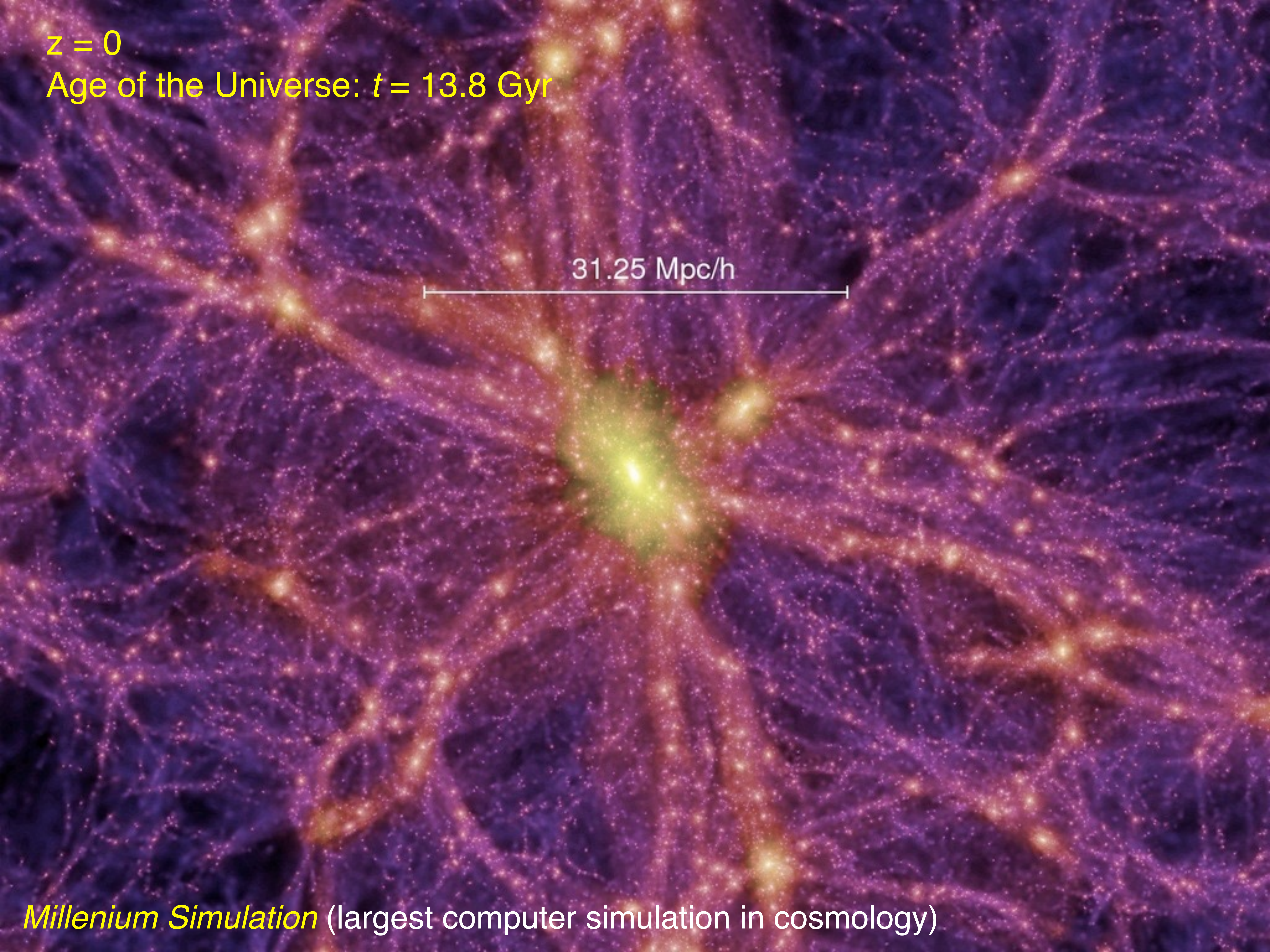
Age of the Universe: $t = 0.2$ Gyr



Millenium Simulation (largest computer simulation in cosmology)


z = 5.7
Age of the Universe: t = 1.0 Gyr
31.25 Mpc/h
Millenium Simulation (largest computer simulation in cosmology)


z = 1.4
Age of the Universe: t = 4.6 Gyr
31.25 Mpc/h
Millenium Simulation (largest computer simulation in cosmology)



Millenium Simulation (largest computer simulation in cosmology)

Mass of galaxy clusters

- All methods confirm that mass dominated by dark matter
- Baryonic mass in galaxies less than 10% of the total
- Methods are also used for mass of elliptical galaxies

Method 1: *Virial Theorem*, uses velocity dispersion of galaxies Δv

For *Virial Theorem*, motion of galaxies related to gravitational potential:

$$E_k = -E_g/2$$

$$\text{large } \Delta v \implies \text{large } M$$

$$M = (\Delta v)^2 R/G$$

M & R: mass & radius of cluster

- Attention: system has to be *virialized*
- First evidence that 70%-90% dark matter

Coma Cluster

Binding mass: $M \sim 7\times10^{14}\ M_\odot$

Distance: d = 102 Mpc

Redshift: z = 0.0231 (6925 km/s)

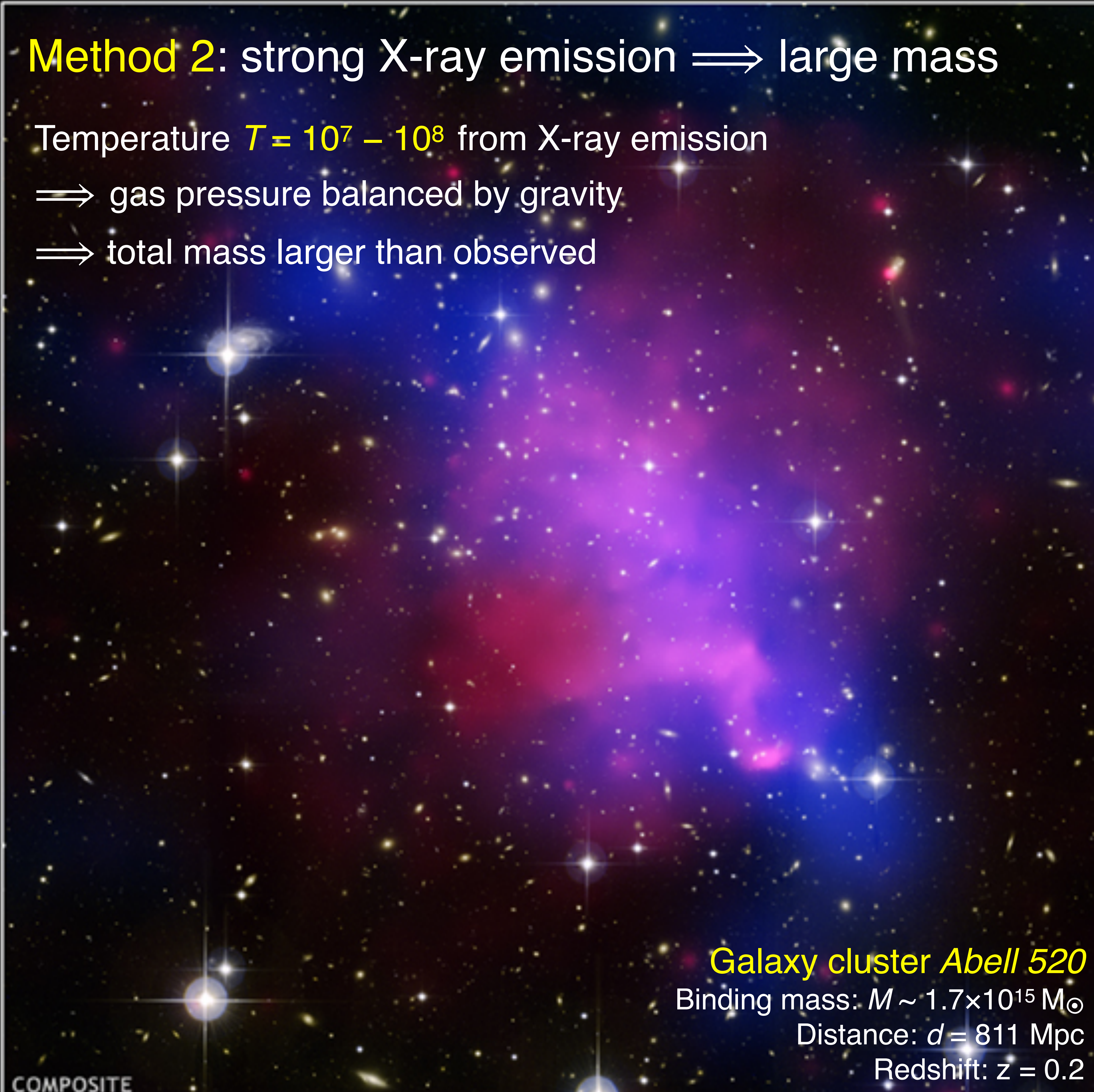
More than 1000 galaxies (mainly ellipticals)

Method 2: strong X-ray emission $\Longrightarrow$ large mass

Temperature $T = 10^7 - 10^8$ from X-ray emission

$\Longrightarrow$ gas pressure balanced by gravity

$\Longrightarrow$ total mass larger than observed

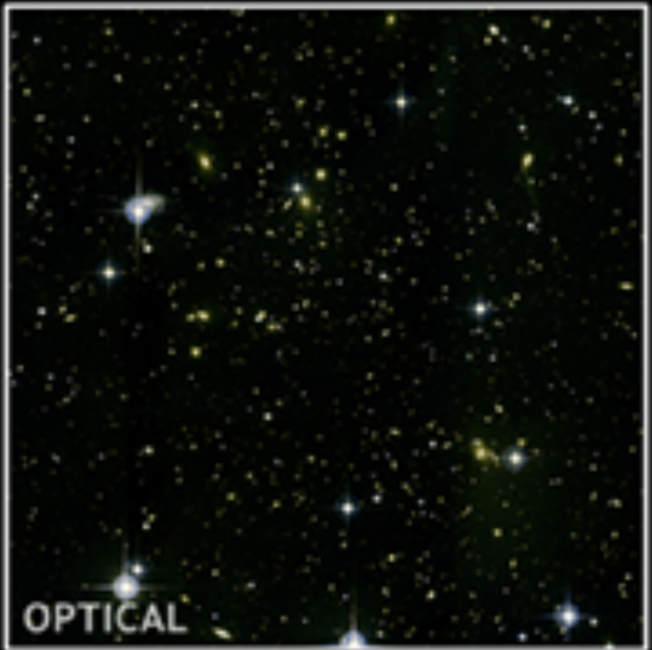


Galaxy cluster *Abell 520*

Binding mass: $M \sim 1.7 \times 10^{15}\ M_\odot$

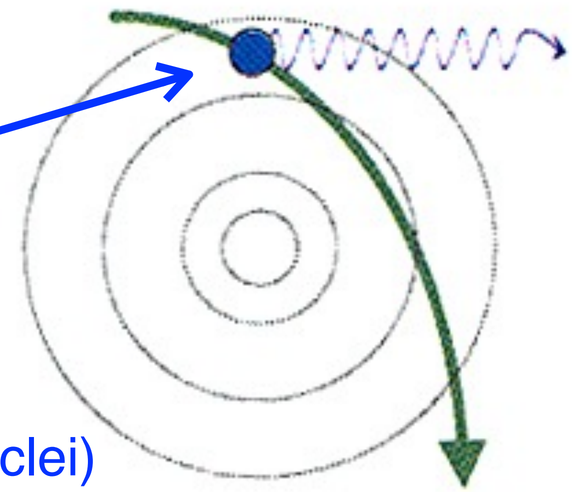
Distance: $d = 811$ Mpc

Redshift: $z = 0.2$

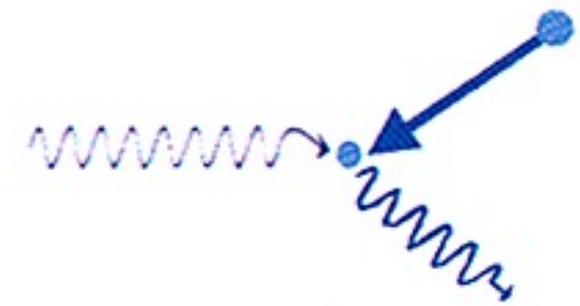


High energy emission in clusters of galaxies due to *Bremsstrahlung*

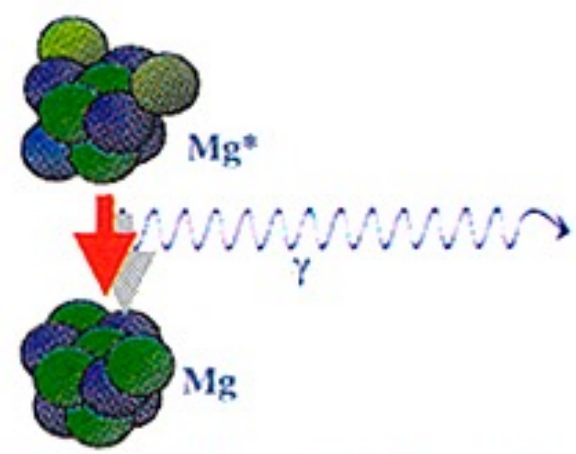
Thermal Bremsstrahlung emission
in galaxy clusters
(free electrons decelerated by atomic nuclei)



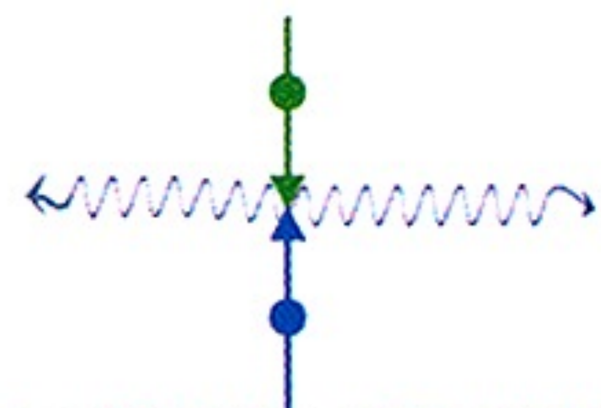
Accelerated Charged Particles



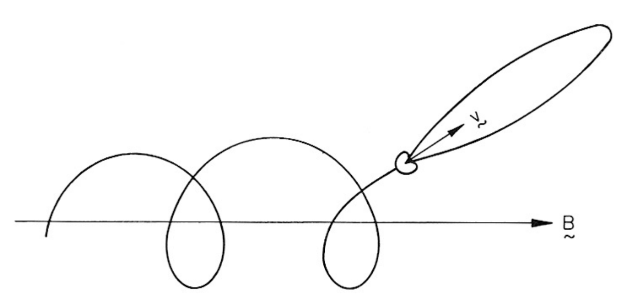
Inverse Compton Scattering



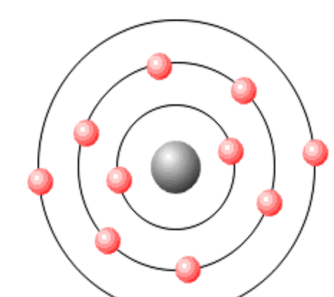
De-Excitation of Atomic Nuclei



Annihilation of Particle-Antiparticle Pairs

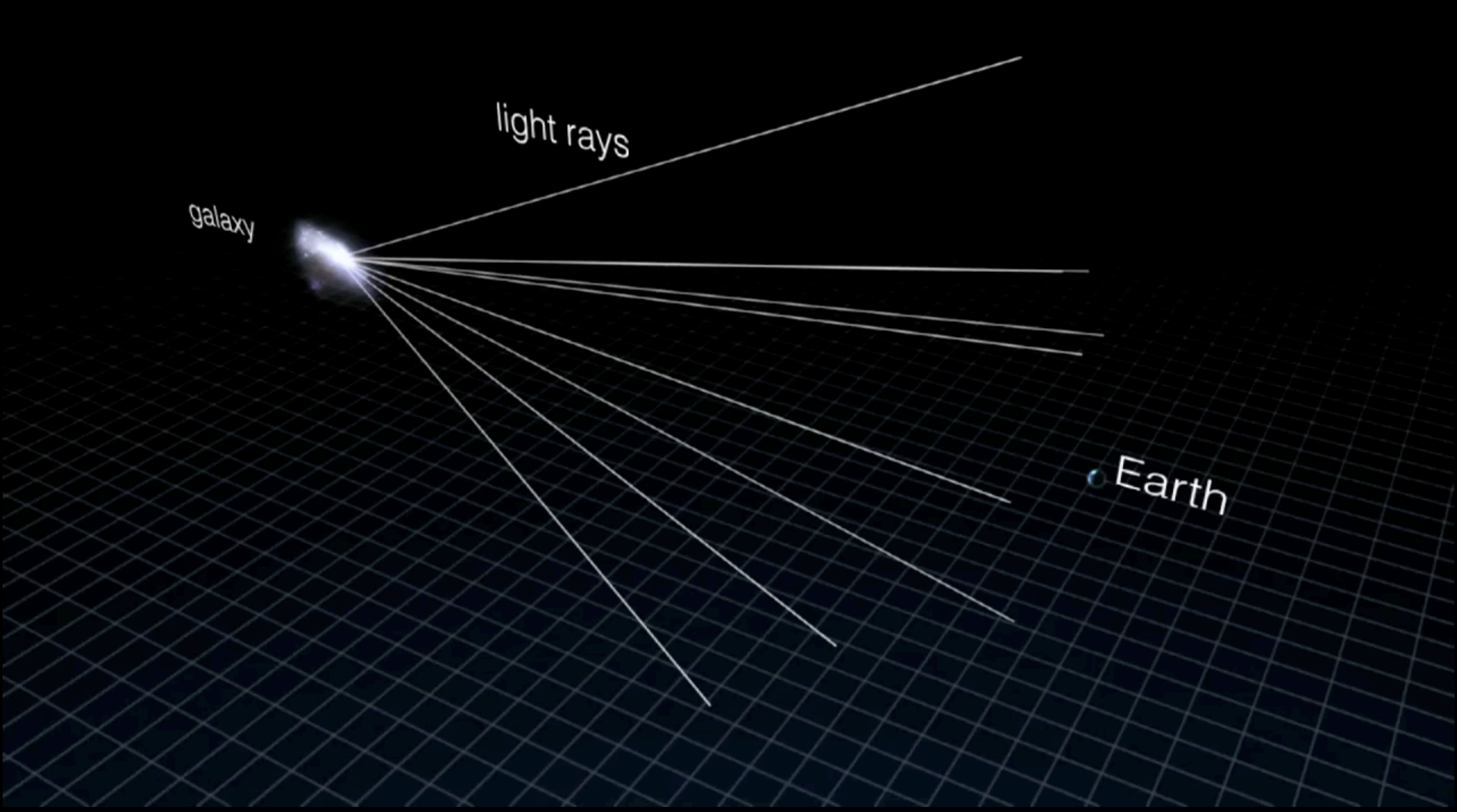


Synchrotron



Characteristic X-rays

Method 3: gravitational lensing in galaxy clusters



Amount of distortion depends on **total cluster mass** (lens)

Video: https://www.youtube.com/watch?v=QByYDIQezg8

Method 3: gravitational lensing in galaxy clusters

Group of galaxies: *Cheshire Cat*

Lens redshift: $z = 0.431$

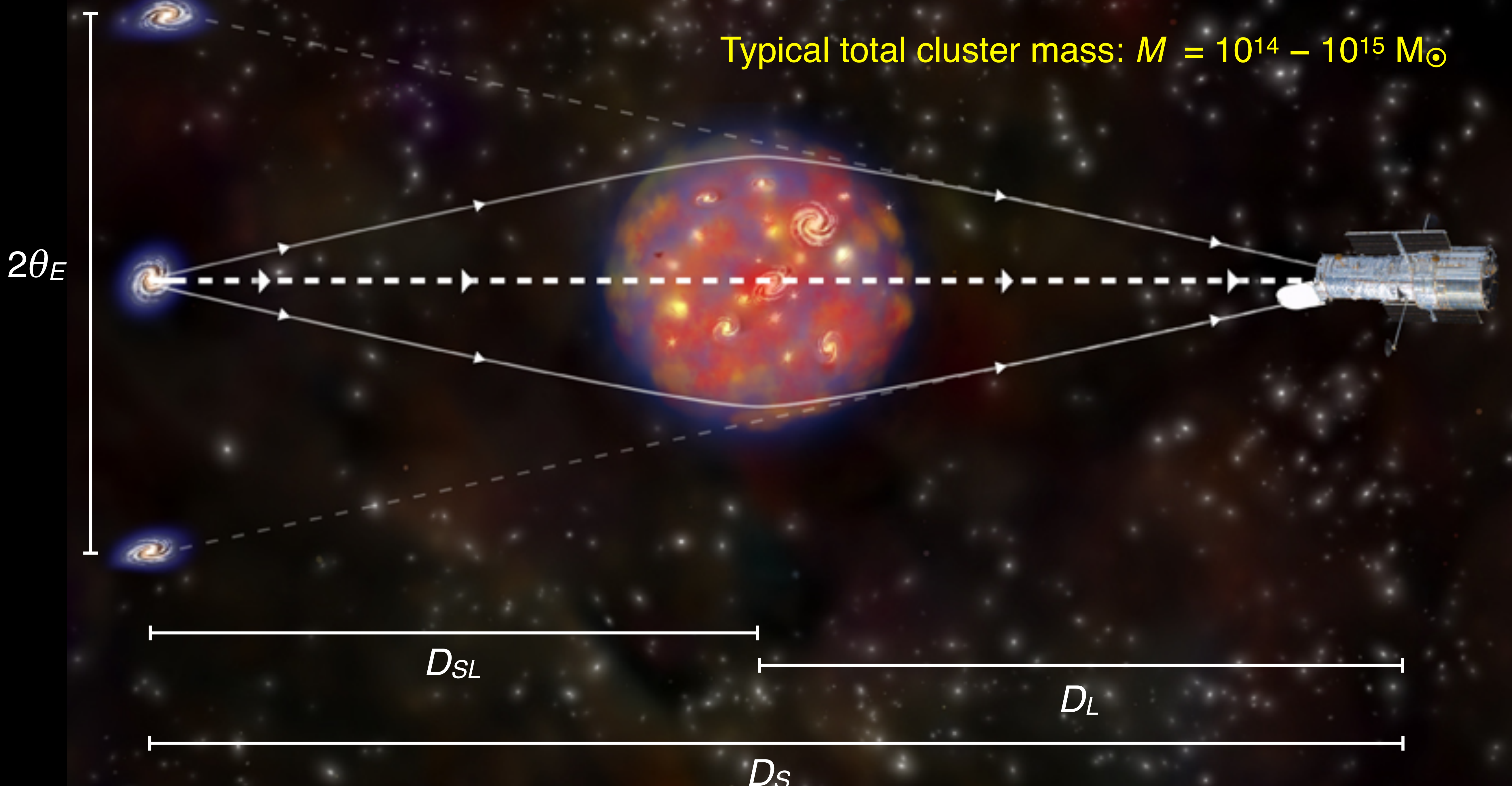
Redshift of lensed galaxies: $z = 0.80 – 2.78$

Optical and X-ray images

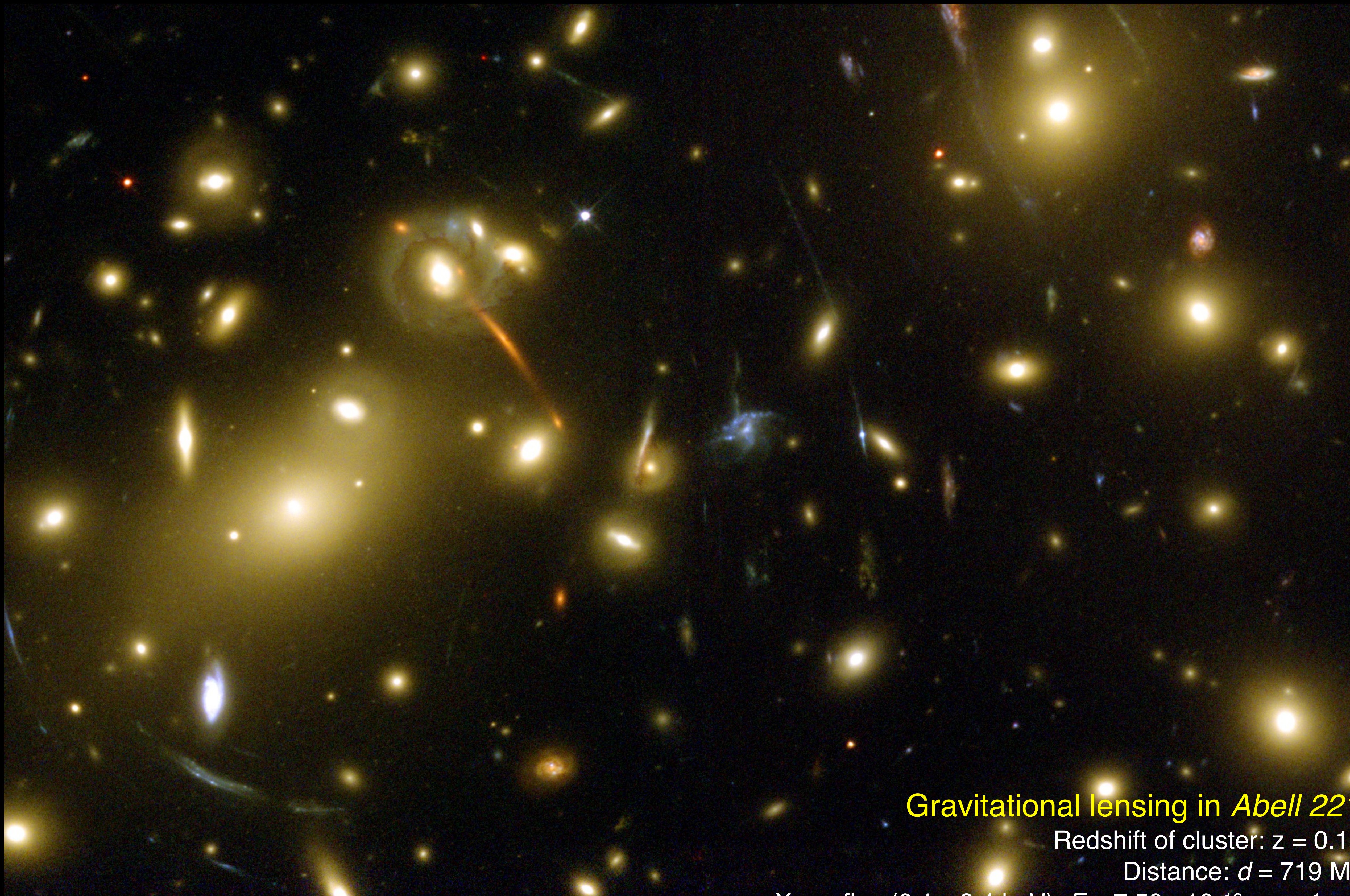
Method 3: gravitational lensing in galaxy clusters

D_S: distance source (background galaxy)
D_L: distance lens (foreground galaxy cluster)
D_{SL}: distance source-lens
θ_E : apparent radius of Einstein ring

Typical total cluster mass: $M = 10^{14} - 10^{15}\ M_\odot$



Gravitational lensing in galaxy clusters to find most distant galaxies



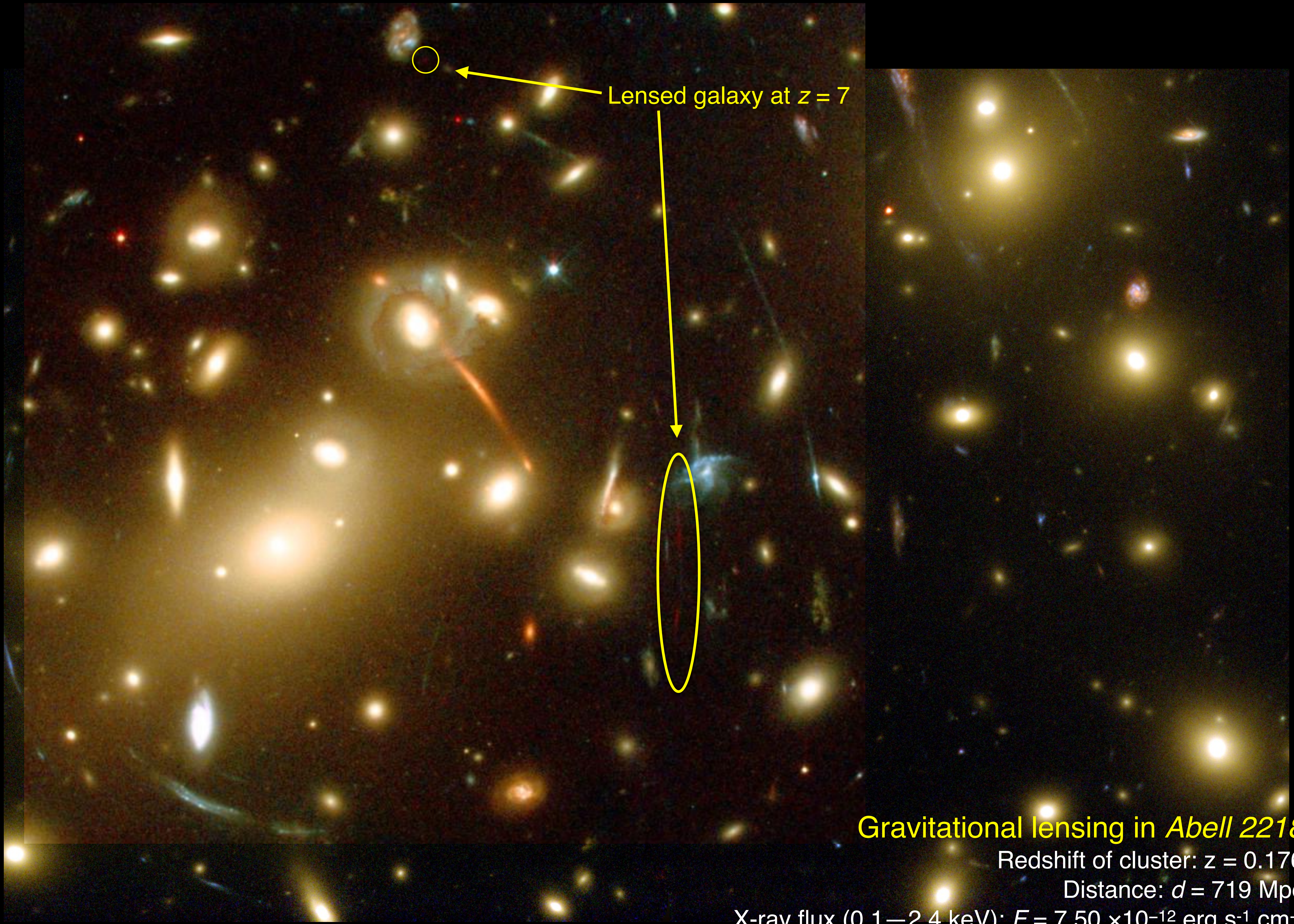
Gravitational lensing in *Abell 2218*

Redshift of cluster: $z = 0.176$

Distance: $d = 719$ Mpc

X-ray flux (0.1—2.4 keV): $F = 7.50 \times 10^{-12}$ erg s^{-1} cm^{-2}

Gravitational lensing in galaxy clusters to find most distant galaxies



The Large scale structure:

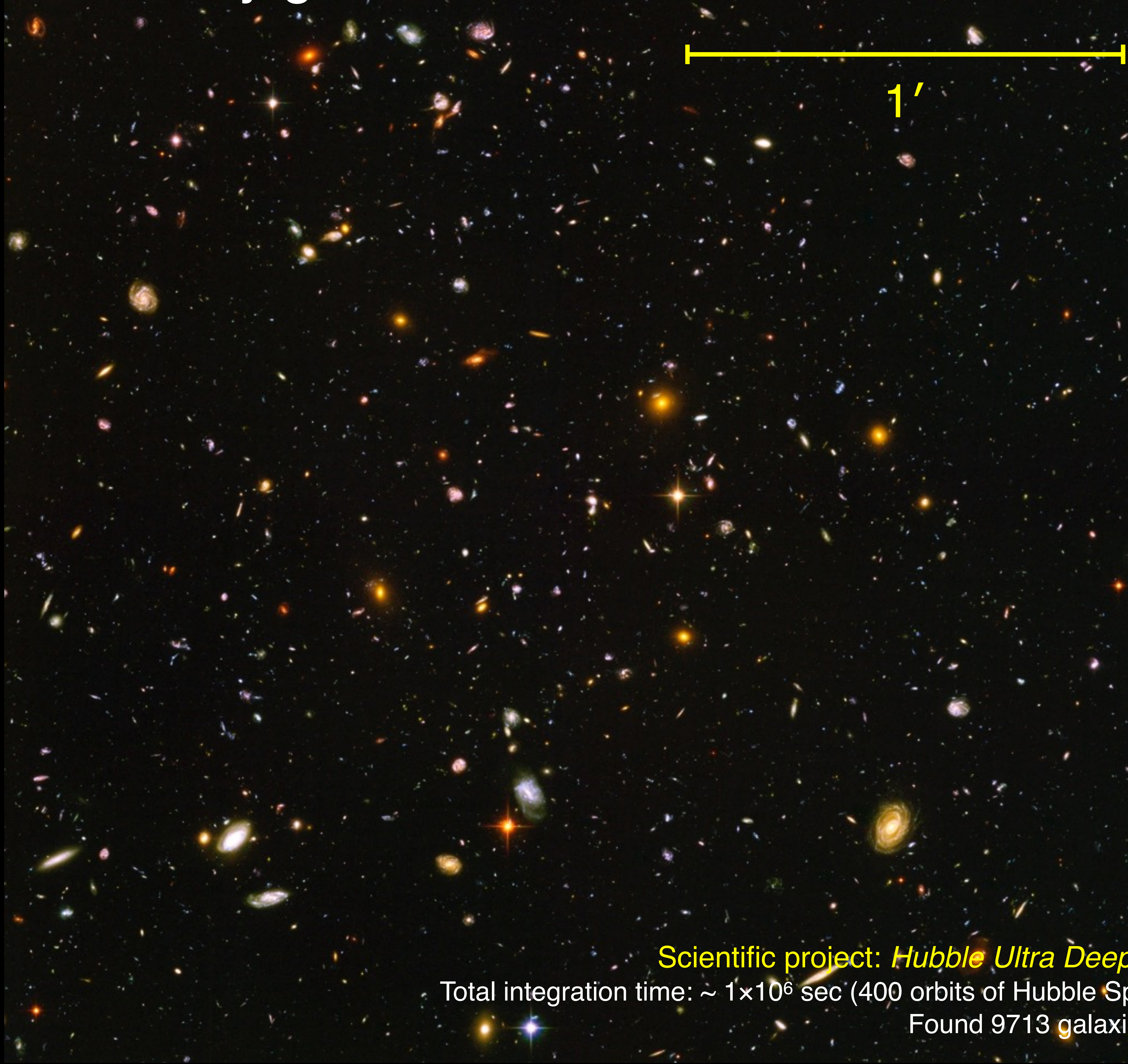
distribution of galaxies on large scale

and

The intergalactic medium (IGM):

gas in space between galaxies

How many galaxies are there in the universe?

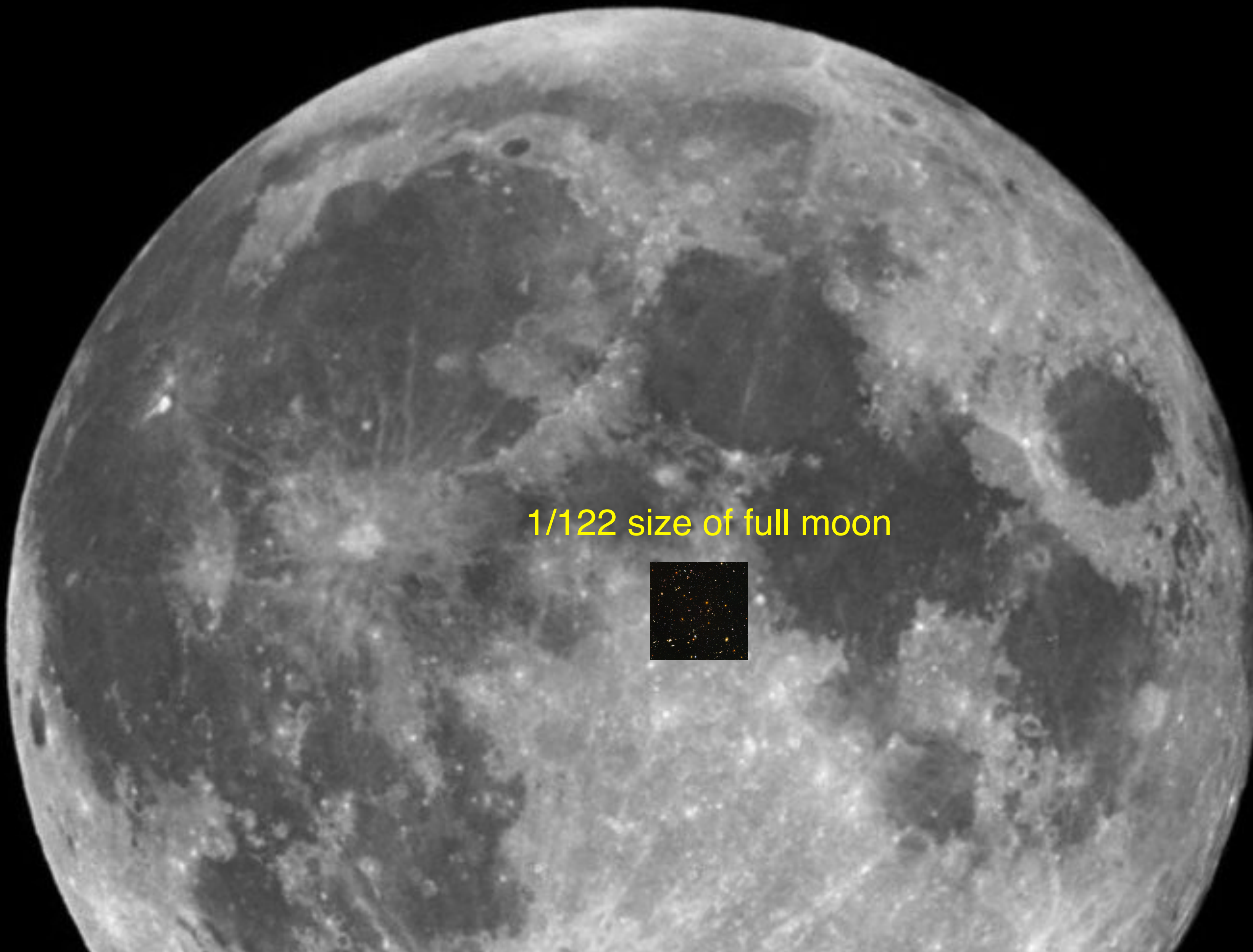


Scientific project: *Hubble Ultra Deep Field (HUDF)*

Total integration time: ~ 1×10^6 sec (400 orbits of Hubble Space Telescope)

Found 9713 galaxies in one image

The full Moon



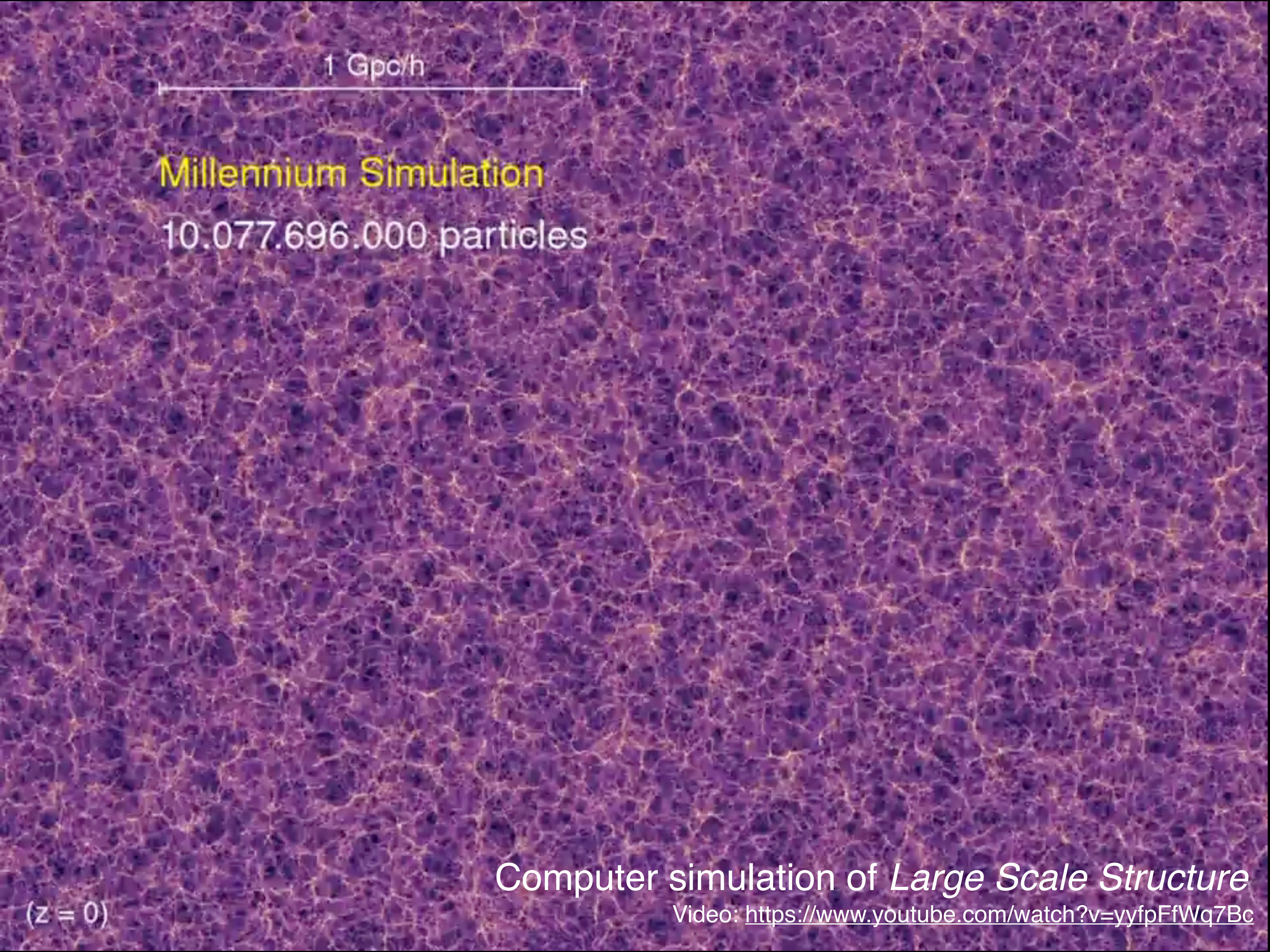
The whole sky: more than 41253 square degrees (26 million times larger than *HUDF*)

Therefore AT LEAST 250 billion galaxies in the whole sky

Corrections for what we don't see, because:

- Too far
- Too small
- Obscured

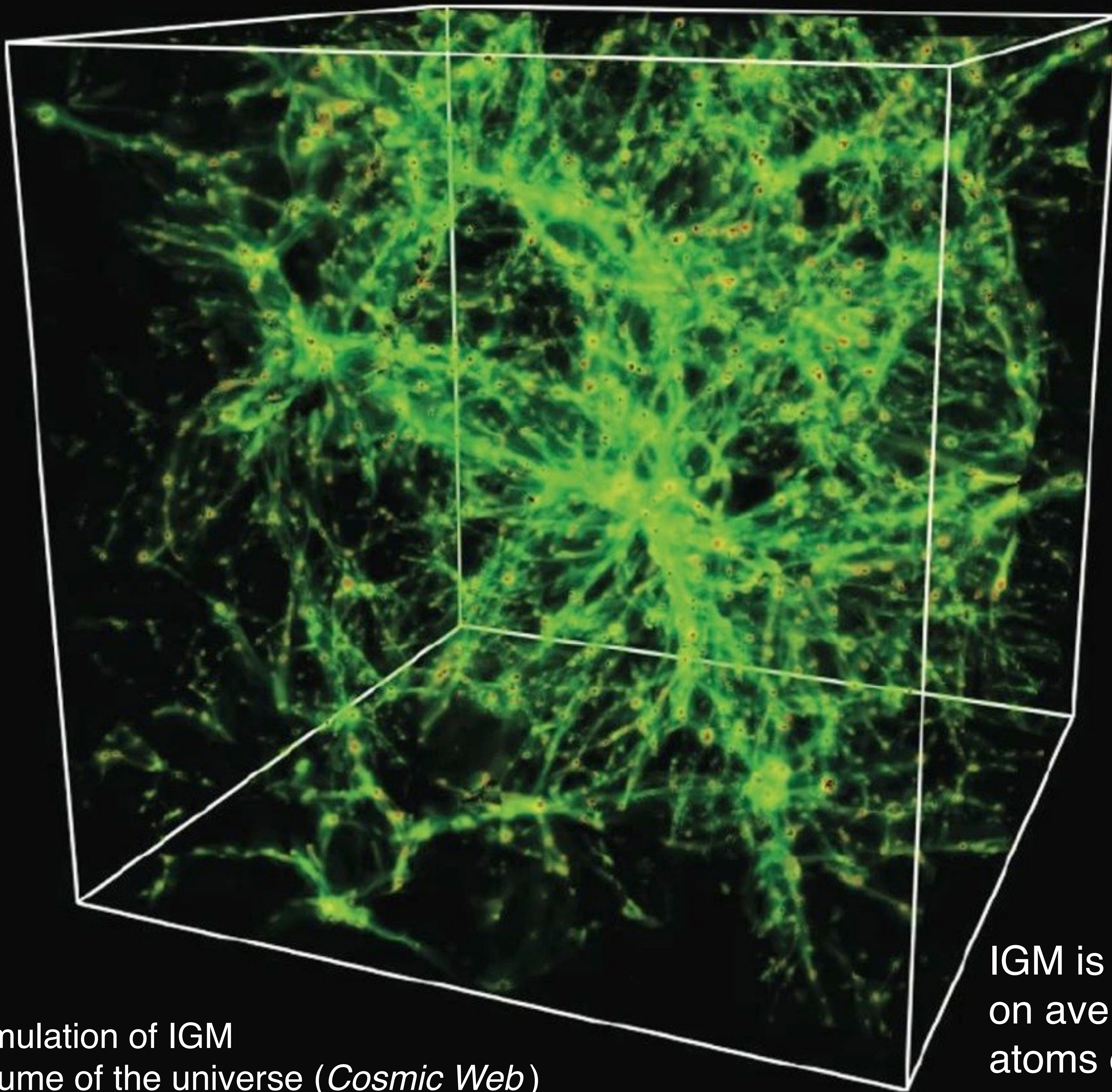
Thus, total number of galaxies: $N_{galaxies}$ ~ 2×10^{12} (30% uncertainty)



Computer simulation of *Large Scale Structure*

Video: https://www.youtube.com/watch?v=yyfpFfWq7Bc

The space between galaxies is not empty: the *Intergalactic Medium* and the *Cosmic Web*

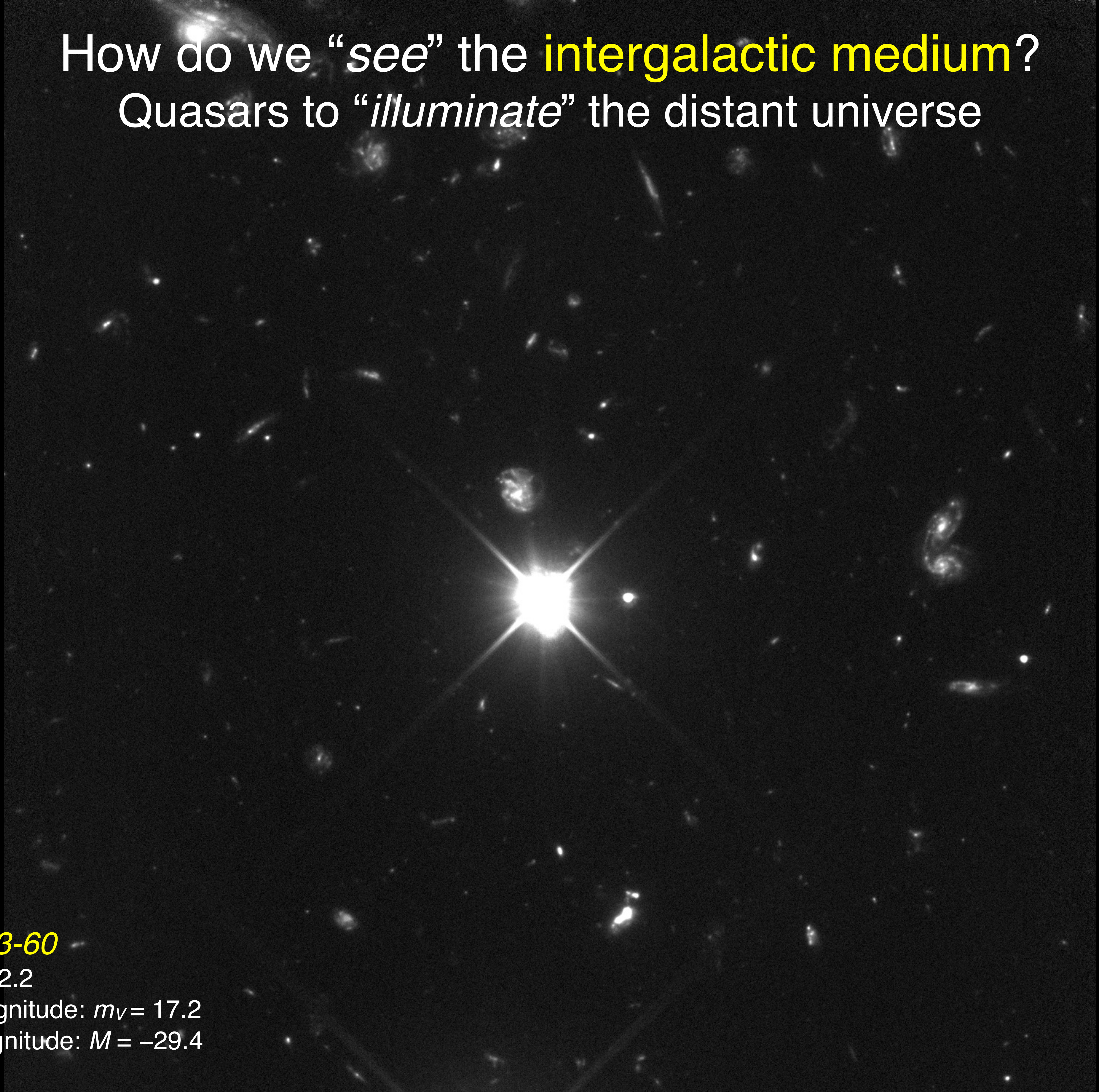


Computer simulation of IGM
in a large volume of the universe (*Cosmic Web*)

IGM is almost fully ionized gas
on average with about $1/10^4$
atoms of neutral hydrogen

How do we “*see*” the intergalactic medium?

Quasars to “*illuminate*” the distant universe



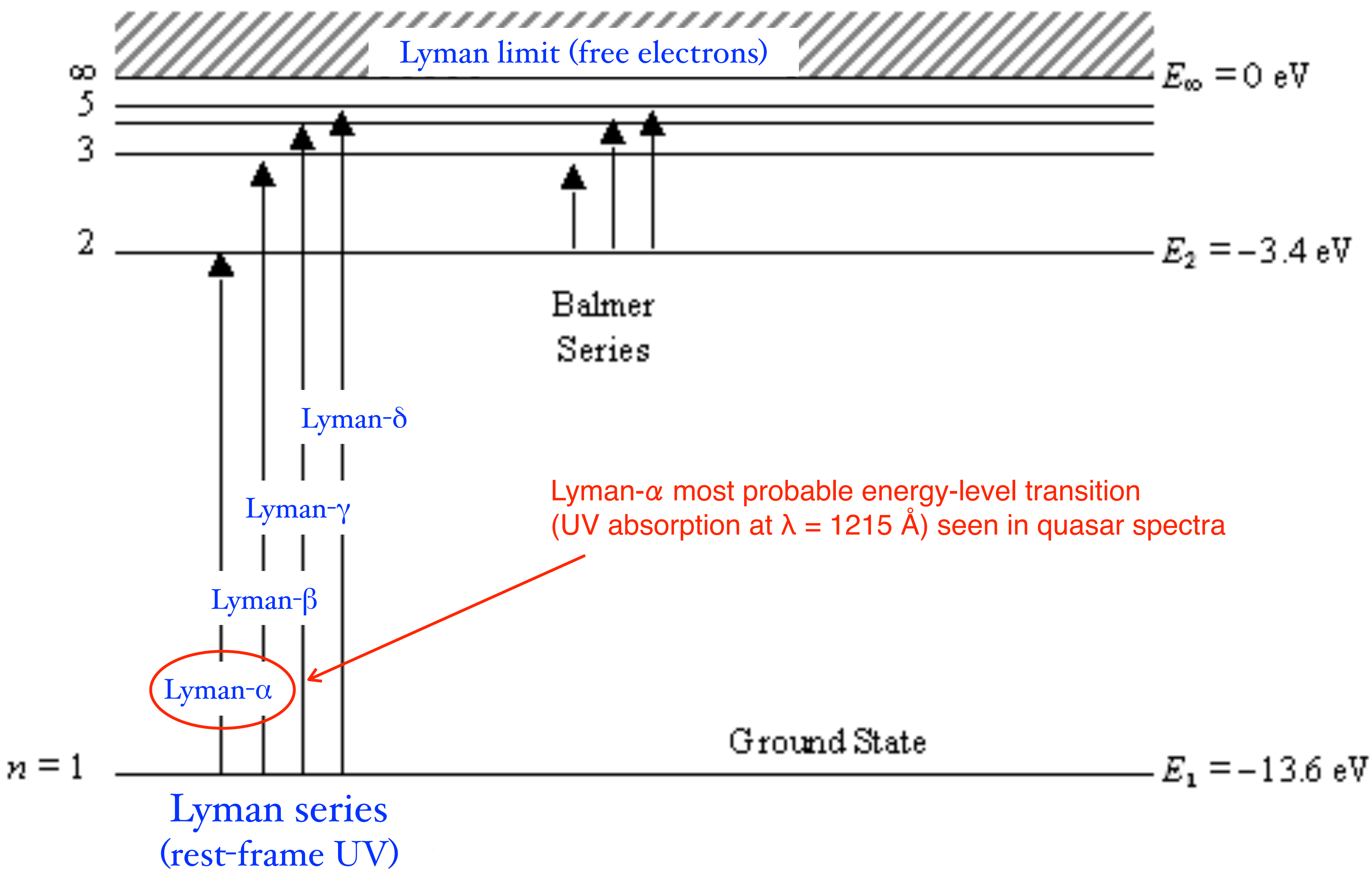
QSO J2233-60

Redshift: $z = 2.2$

Apparent magnitude: $m_V = 17.2$

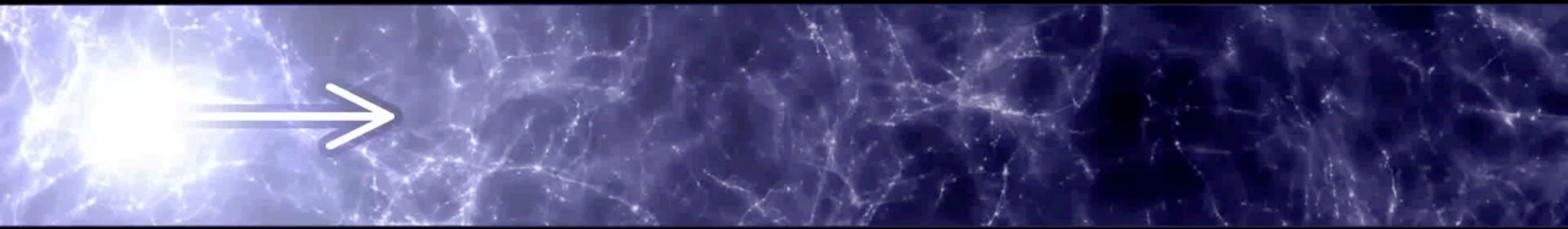
Absolute magnitude: $M = -29.4$

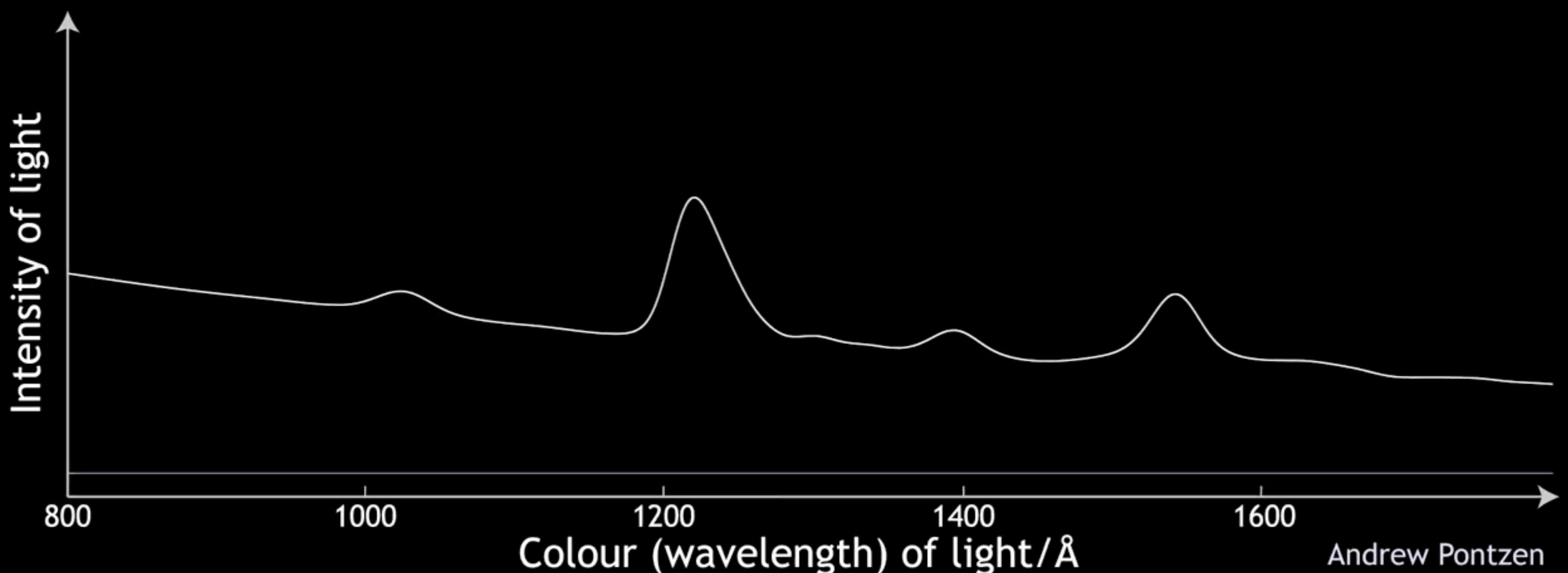
Energy levels of the hydrogen atom



Quasar light to "*see*" the intergalactic medium

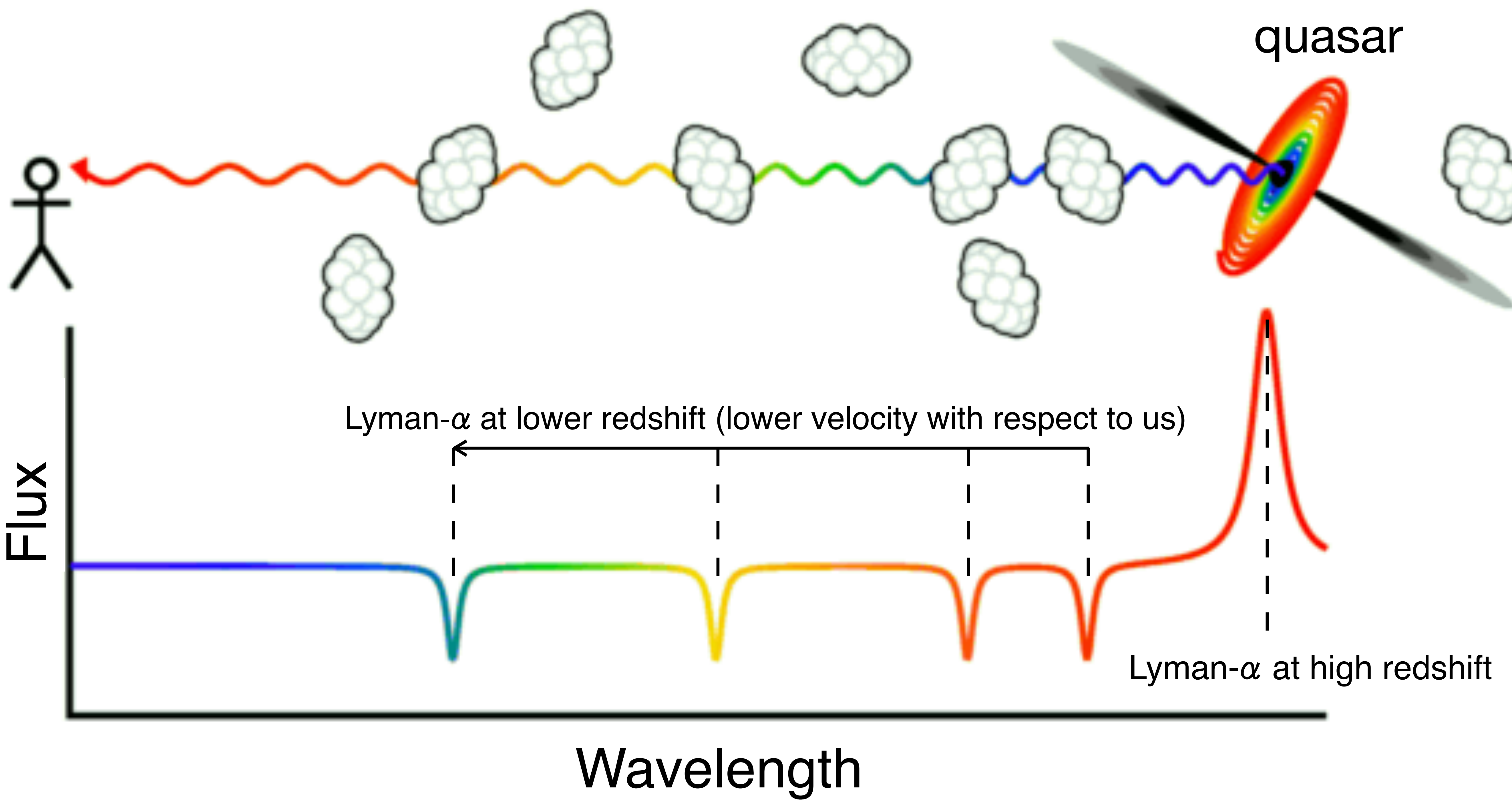
The Lyman-α forest



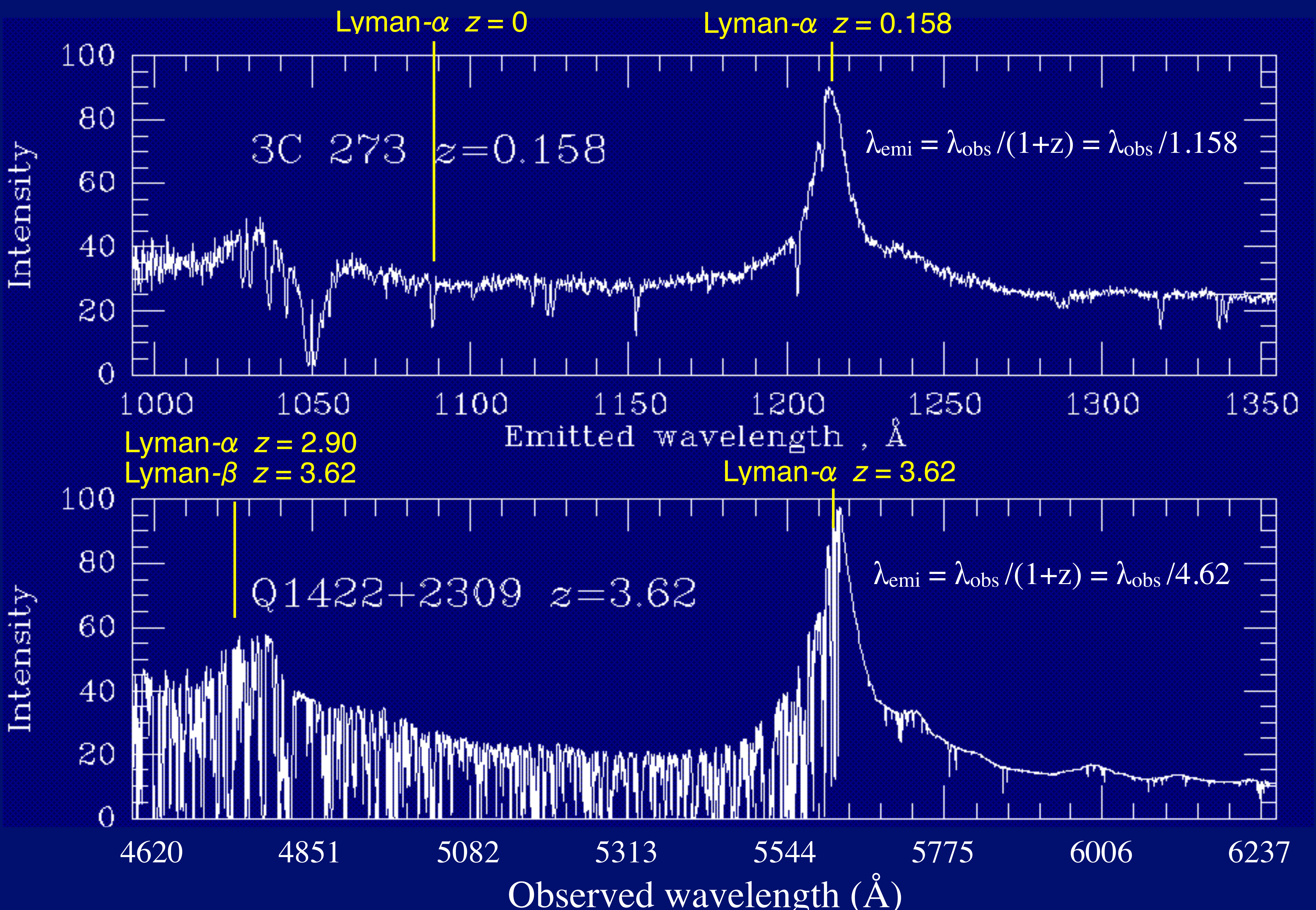


Video: https://www.youtube.com/watch?v=6Bn7Ka0Tjjw

The intergalactic medium and the Lyman-α forest



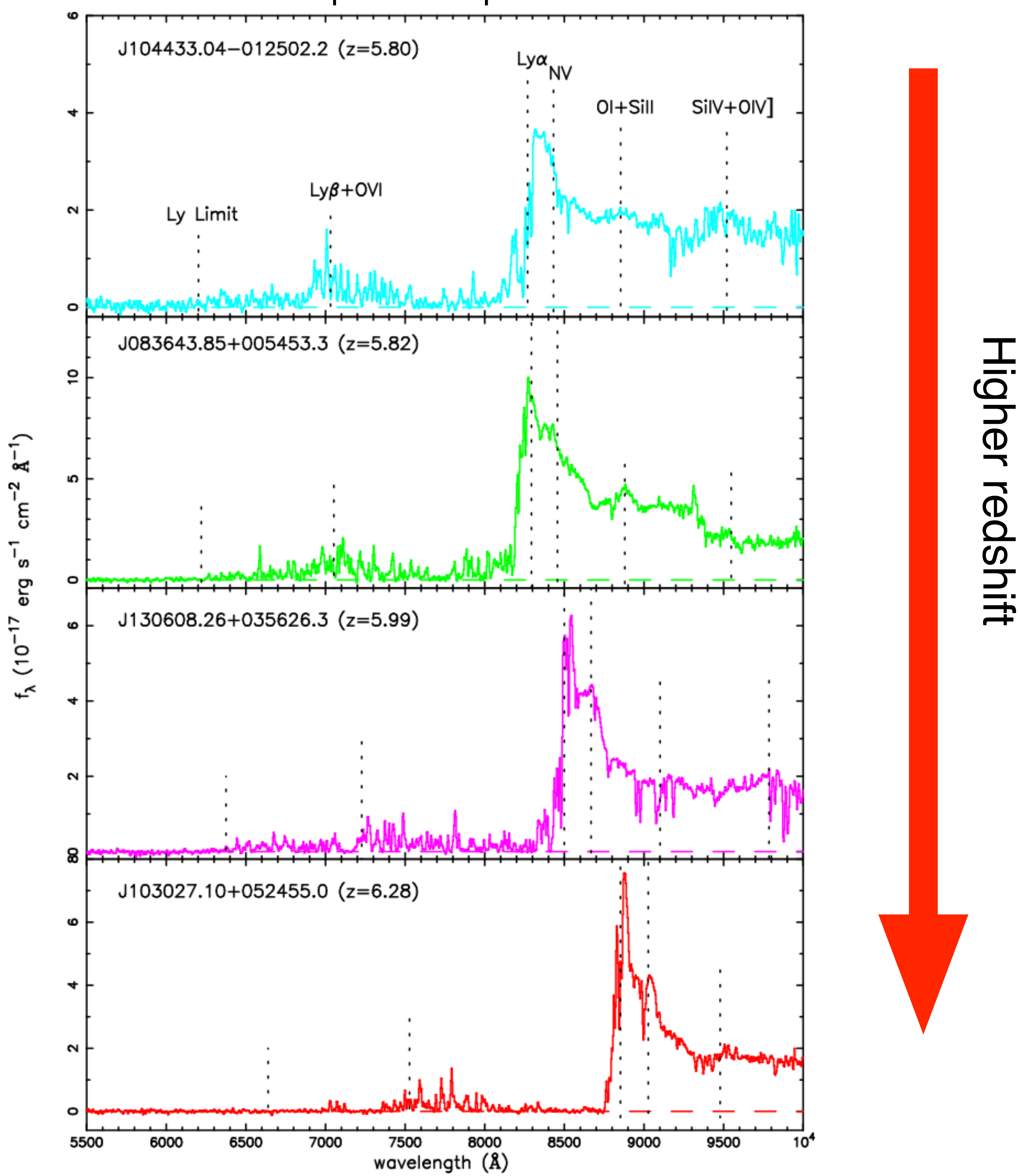
A low-redshift and high-redshift quasar with the forest



Redshift evolution of "*redness*" of quasars

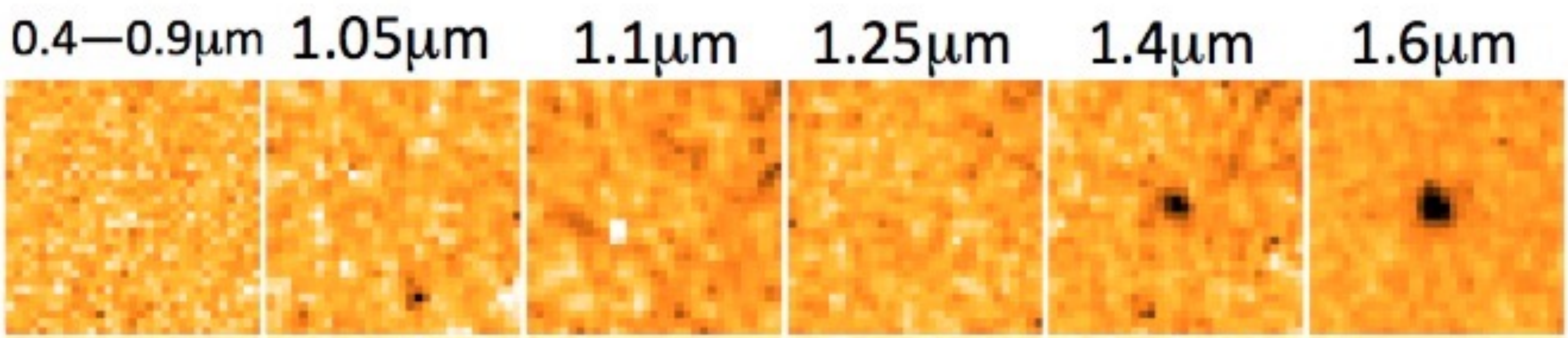
1. The universe was initially dominated by neutral gas (electrically neutral)
2. With time, it gets:
   a. more ionized
   b. larger (expansion)
3. Then, initially, Lyman-α forest very crowded
4. With time, Lyman-α clouds disappear (ionized by UV photons from quasars and young stars in galaxies)
5. Today, more than 99% of atoms are ionized (plasmas everywhere)

Spectra of quasars



Consequences of IGM absorption: higher redshift galaxies are redder

Increasing wavelength

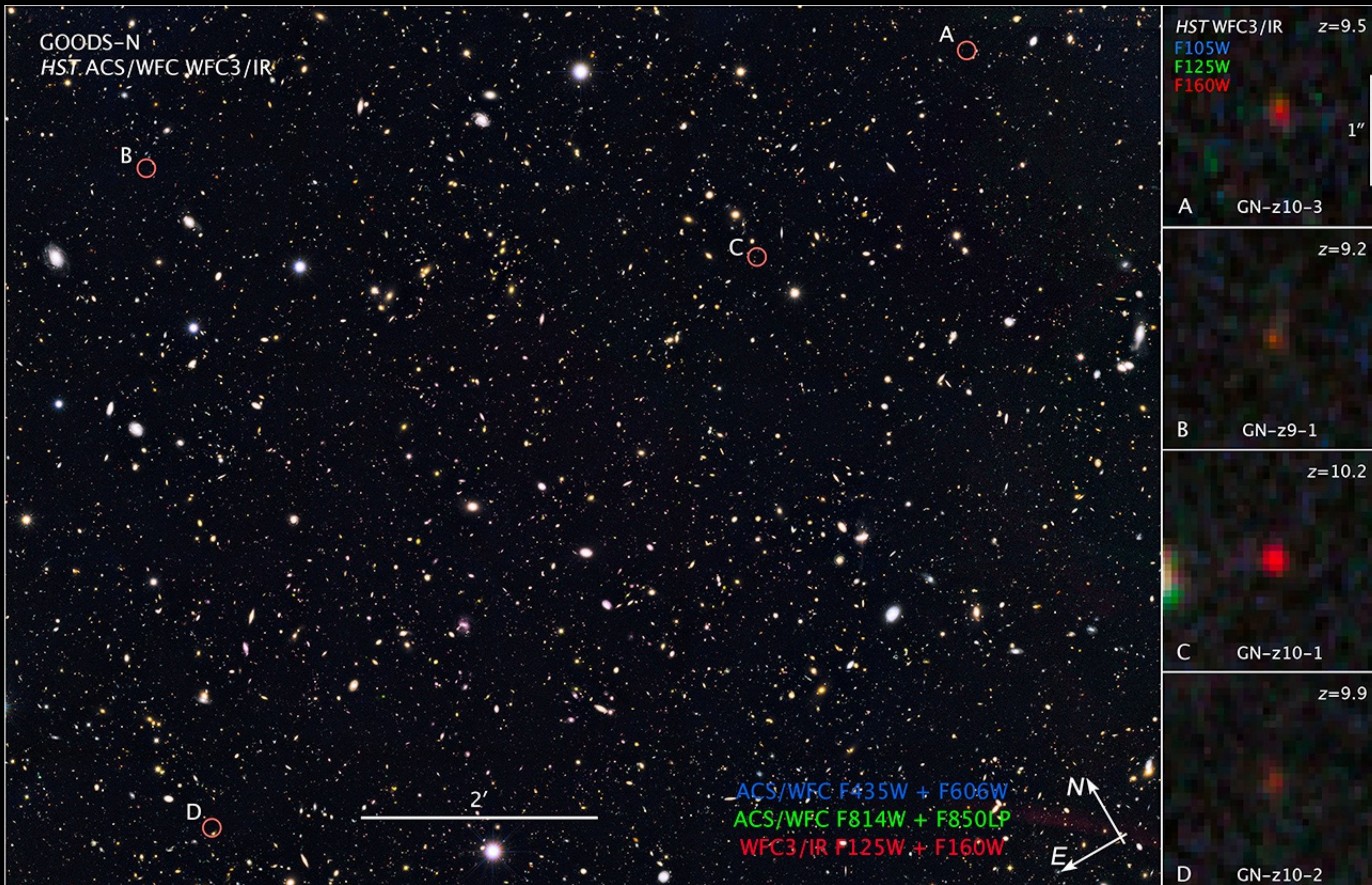


Images with different filters of gravitationally-lensed galaxy
(from blue band to the near infrared band)

Galaxy detected only in the near infrared $\Longrightarrow$ high redshift

$$z = 1.42\ \mu\text{m} / 1215.67\ \text{Å} \times 10^4 - 1 = 10.7$$

Consequences of IGM absorption: higher redshift galaxies are redder



Matter density in different objects of the universe *TODAY*

Summary

Object	Density (kg/m³)
Black hole of stellar origin	10^{19}
Neutron star	10^{18}
White dwarf star	10^{9}
The Sun	1000
Gas cloud in the Galaxy	10^{-18}
The Galaxy	10^{-21}
Cluster of galaxy	10^{-24}
The Universe as a whole	10^{-27}

More precisely, mean mass density of universe: $\rho_m = 2.6\times10^{-27}$ kg/m³ (85% dark matter)
Considering that one proton is 1.67×10^{-27} kg
On average, a volume of the universe $V = 4$ m³ are necessary to get one proton
THE UNIVERSE **TODAY** IS EMPTY