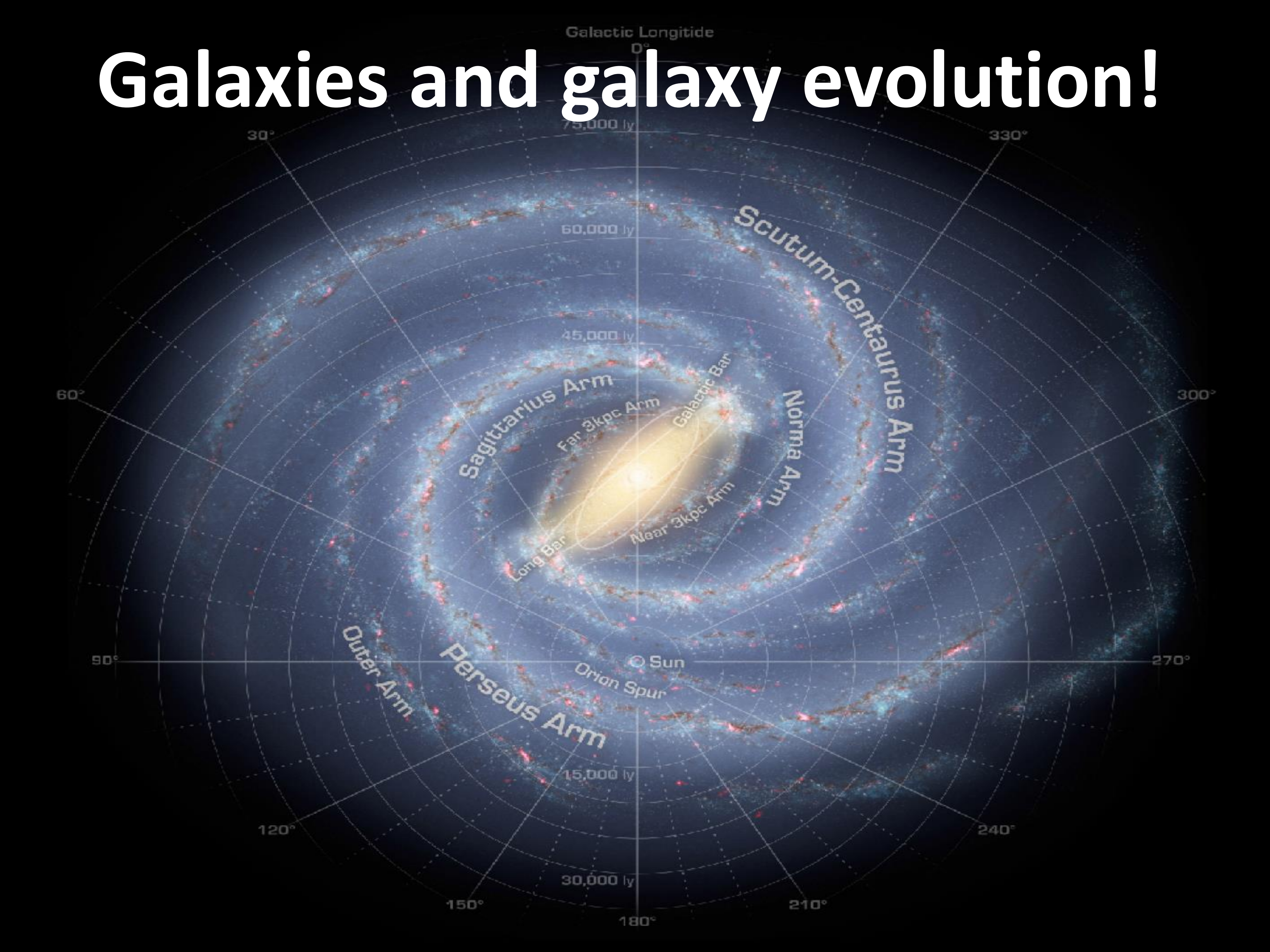
Galaxies and galaxy evolution!

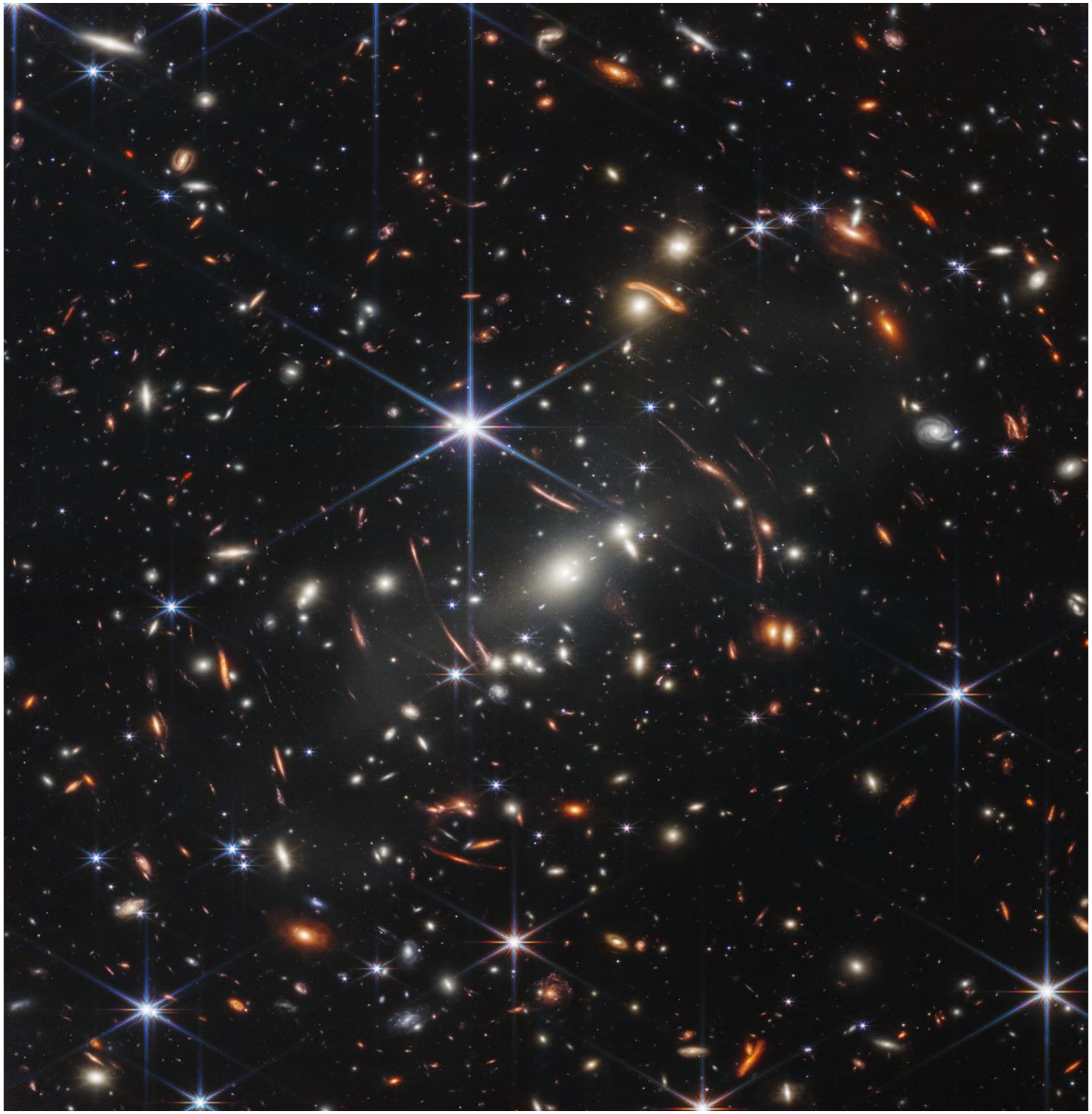


Future classes

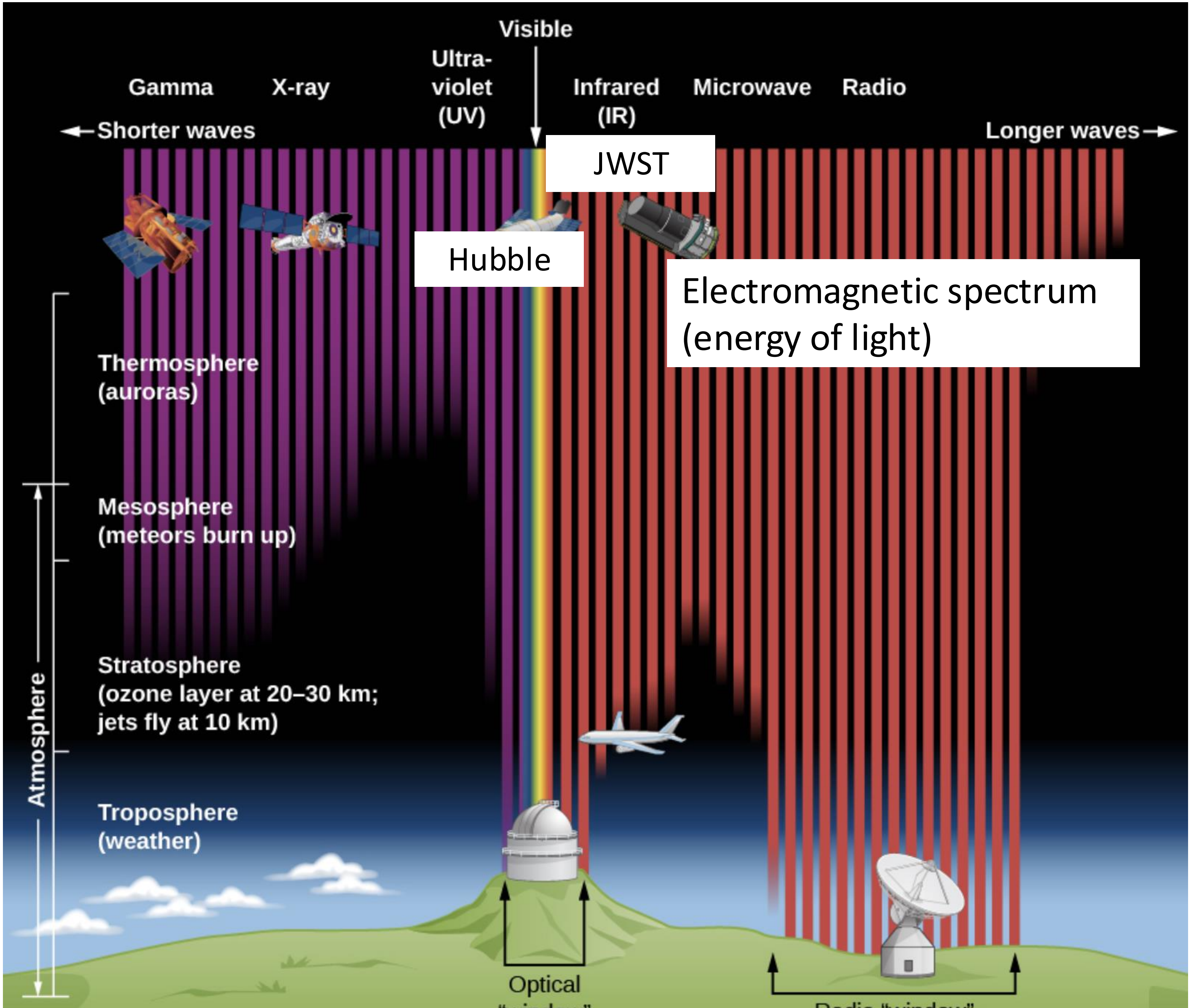
- Next week: Big Bang and Cosmology
- Nov 7: Black holes!
- Nov 14-Dec 5: Our solar system
- Dec 12-26:
  - The Scientific Method, History/Philosophy of Science/Telescopes
  - Life in the solar system

- Two more homeworks, one project
  - To be circulated tonight/tomorrow (also at github)
  - Remember to take photos of sunsets (or sunrises)
    - Need at least 4 through the semester

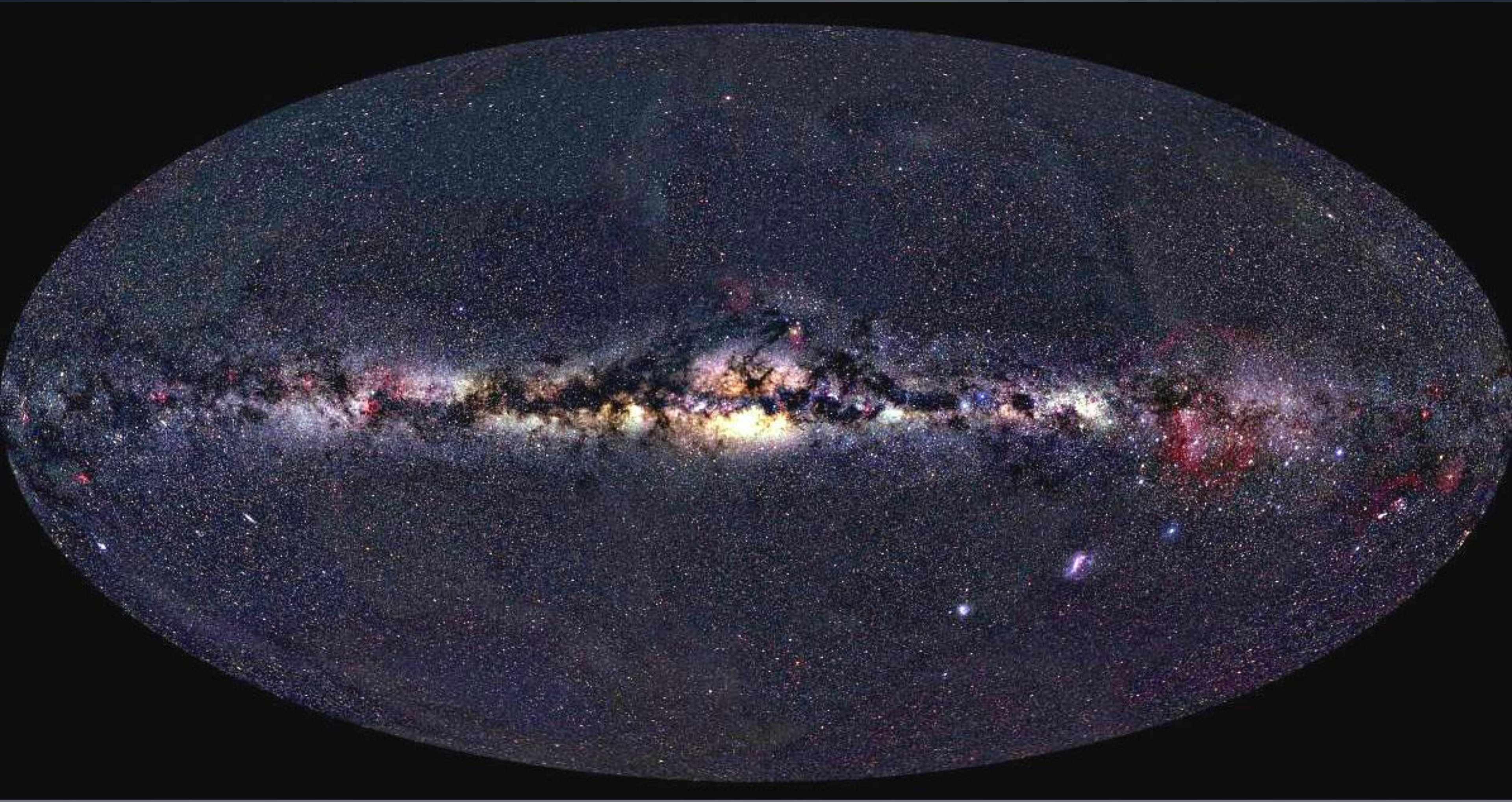
- Did I receive your oral report?
  - I have no idea!
  - Don't throw your report in the trash, save it in case your email didn't go through!



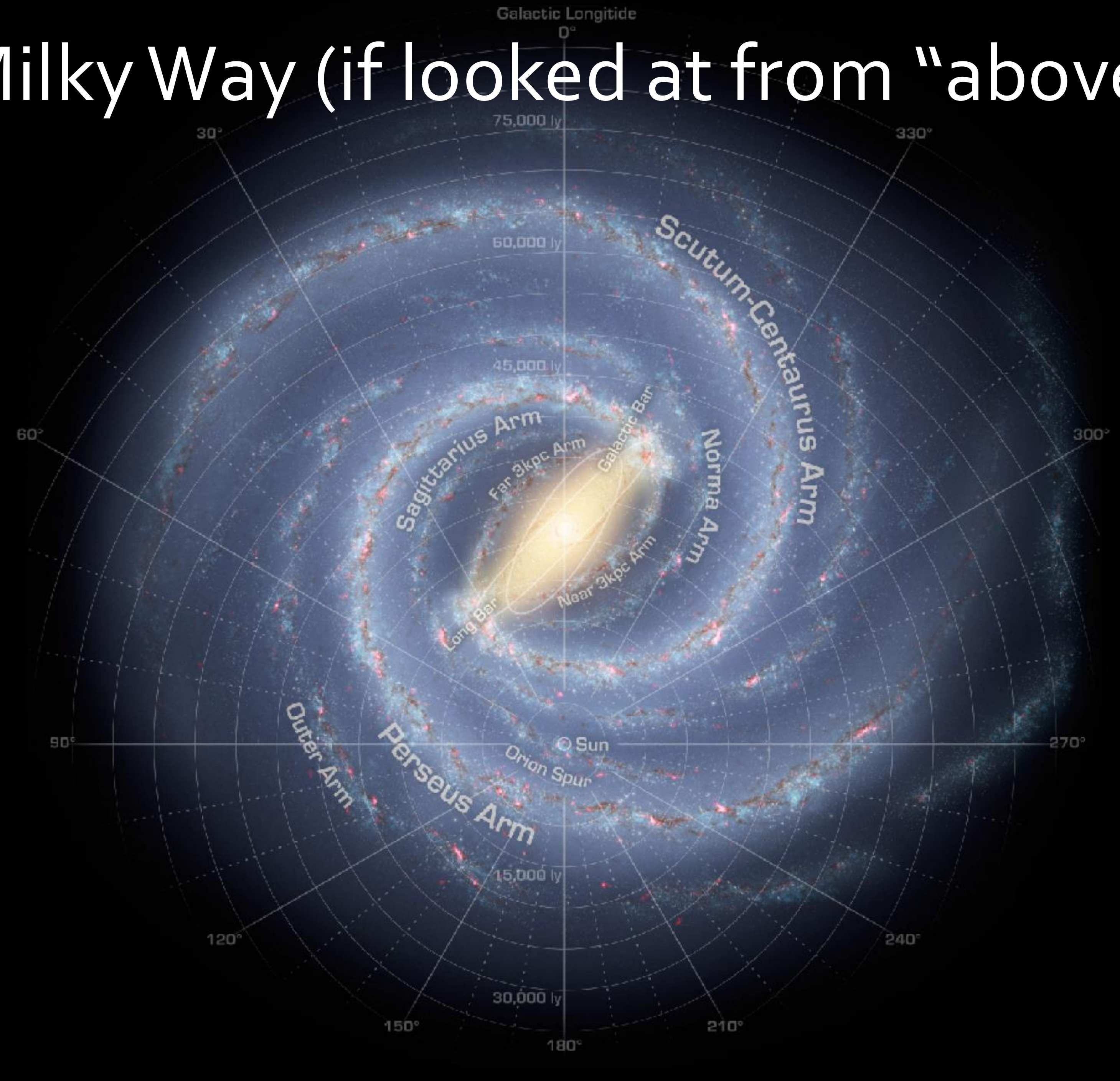
- James Webb Space Telescope
- New infrared telescope

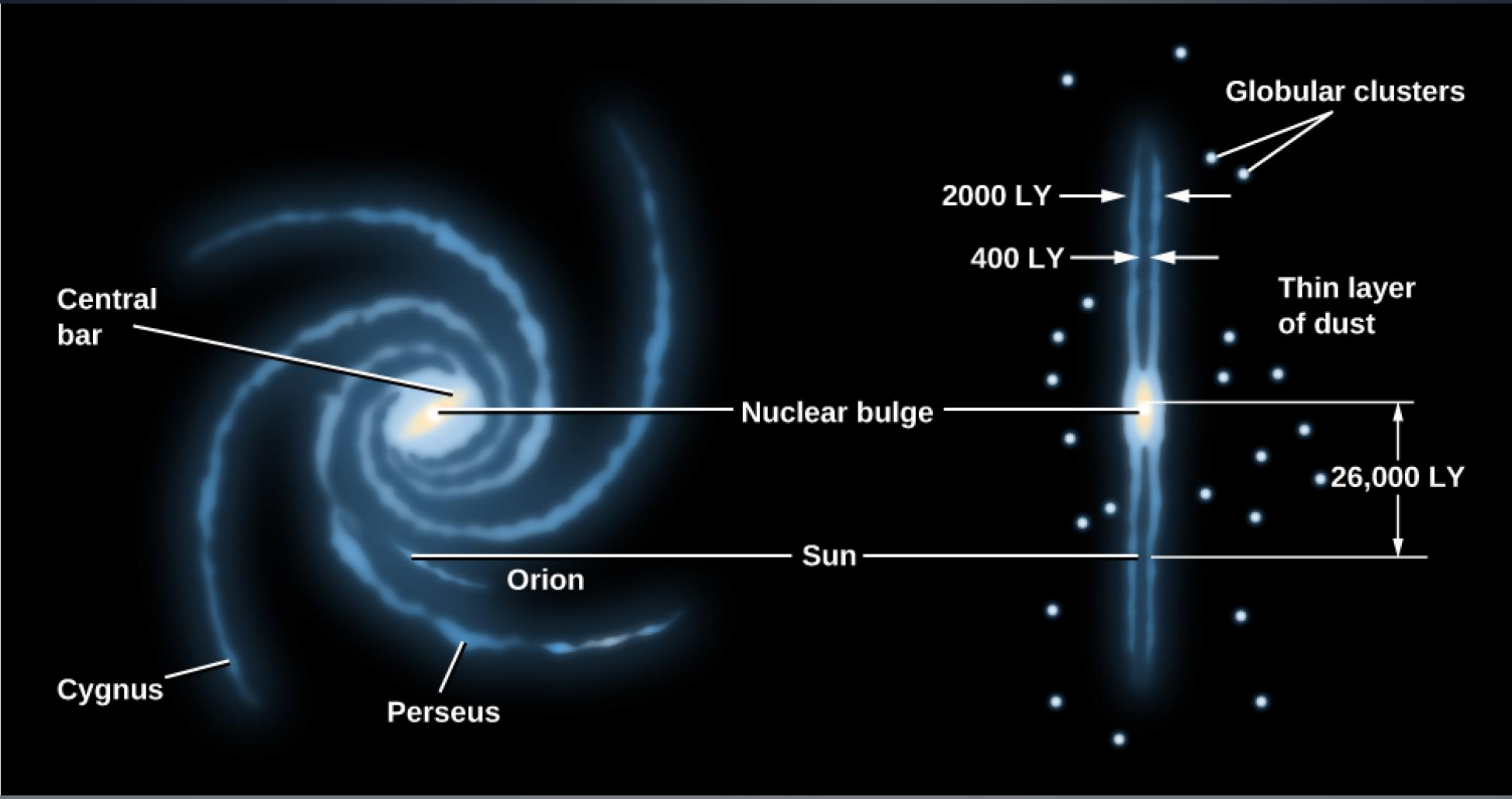

Visible
Gamma
X-ray
Ultra-
violet
(UV)
Infrared
(IR)
Microwave
Radio
Shorter waves
Longer waves
JWST
Hubble
Electromagnetic spectrum
(energy of light)
Thermosphere
(auroras)
Mesosphere
(meteors burn up)
Stratosphere
(ozone layer at 20–30 km;
jets fly at 10 km)
Troposphere
(weather)
Atmosphere
Optical

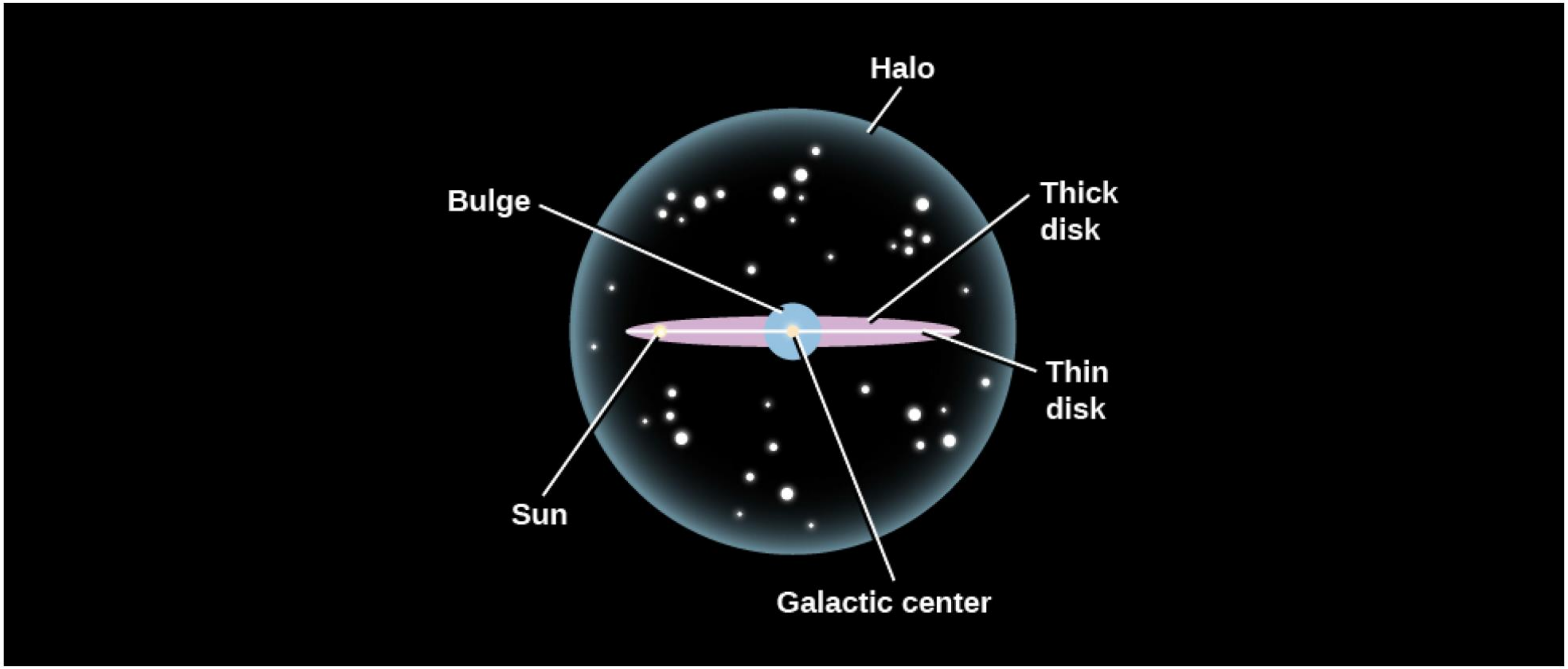
All-sky optical map

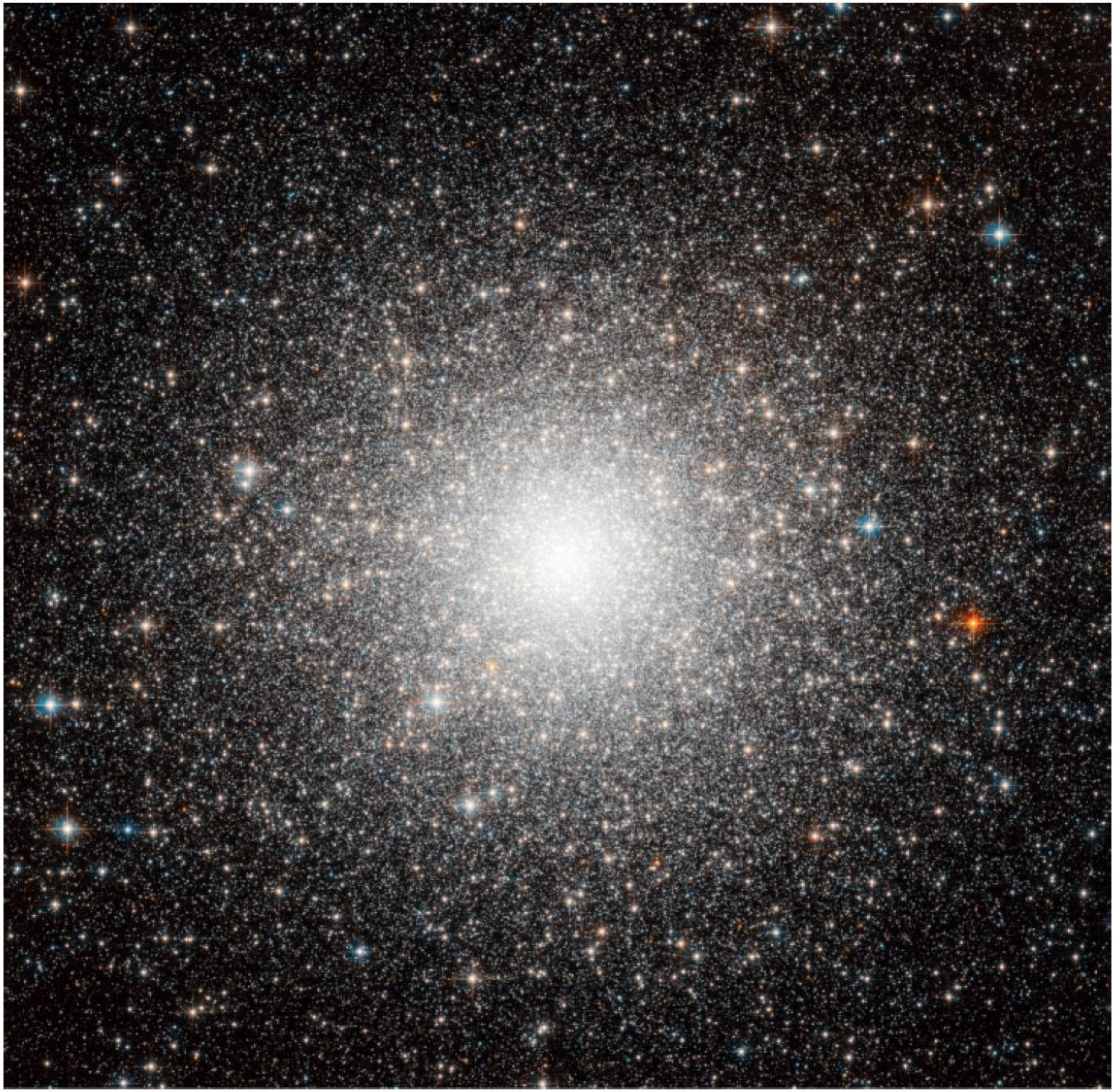


Milky Way (if looked at from "above"



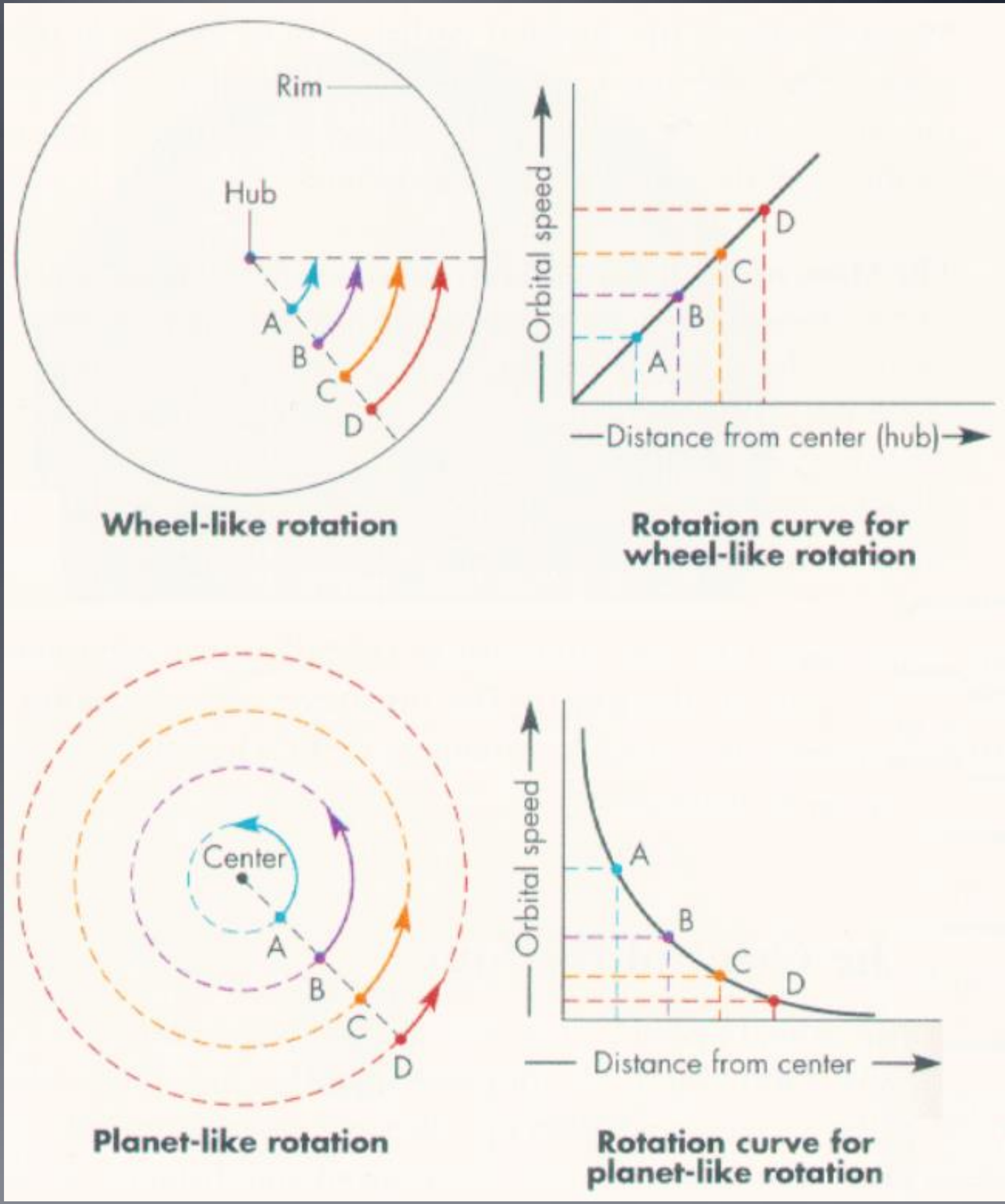

Globular clusters
2000 LY
400 LY
Thin layer
of dust
Central
bar
Nuclear bulge
26,000 LY
Sun
Orion
Cygnus
Perseus

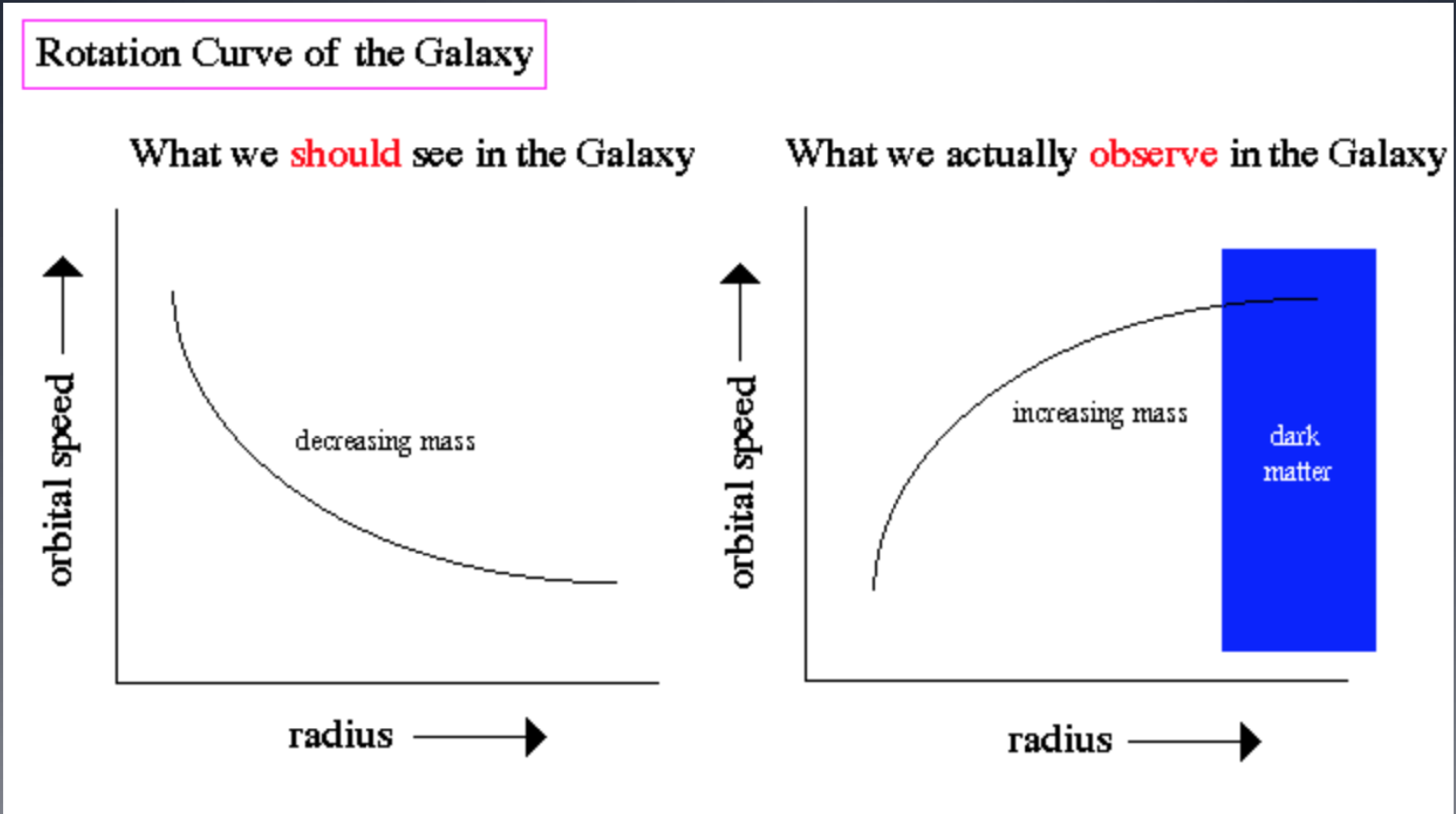

Halo
Bulge
Thick disk
Thin disk
Sun
Galactic center



- How to measure the mass of the galaxy?

  Kepler's laws!





Rotation Curve of the Galaxy
What we should see in the Galaxy
What we actually observe in the Galaxy
orbital speed
decreasing mass
radius
orbital speed
increasing mass
dark
matter
radius

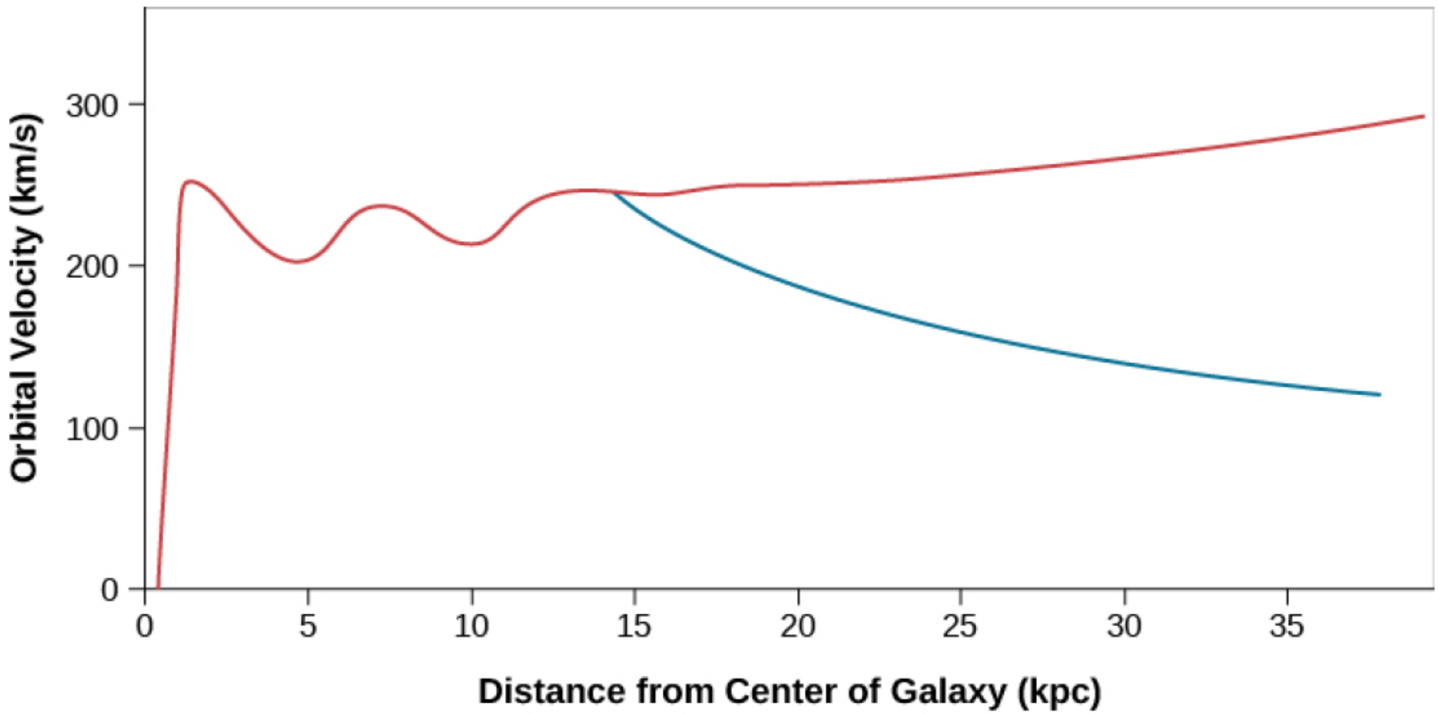
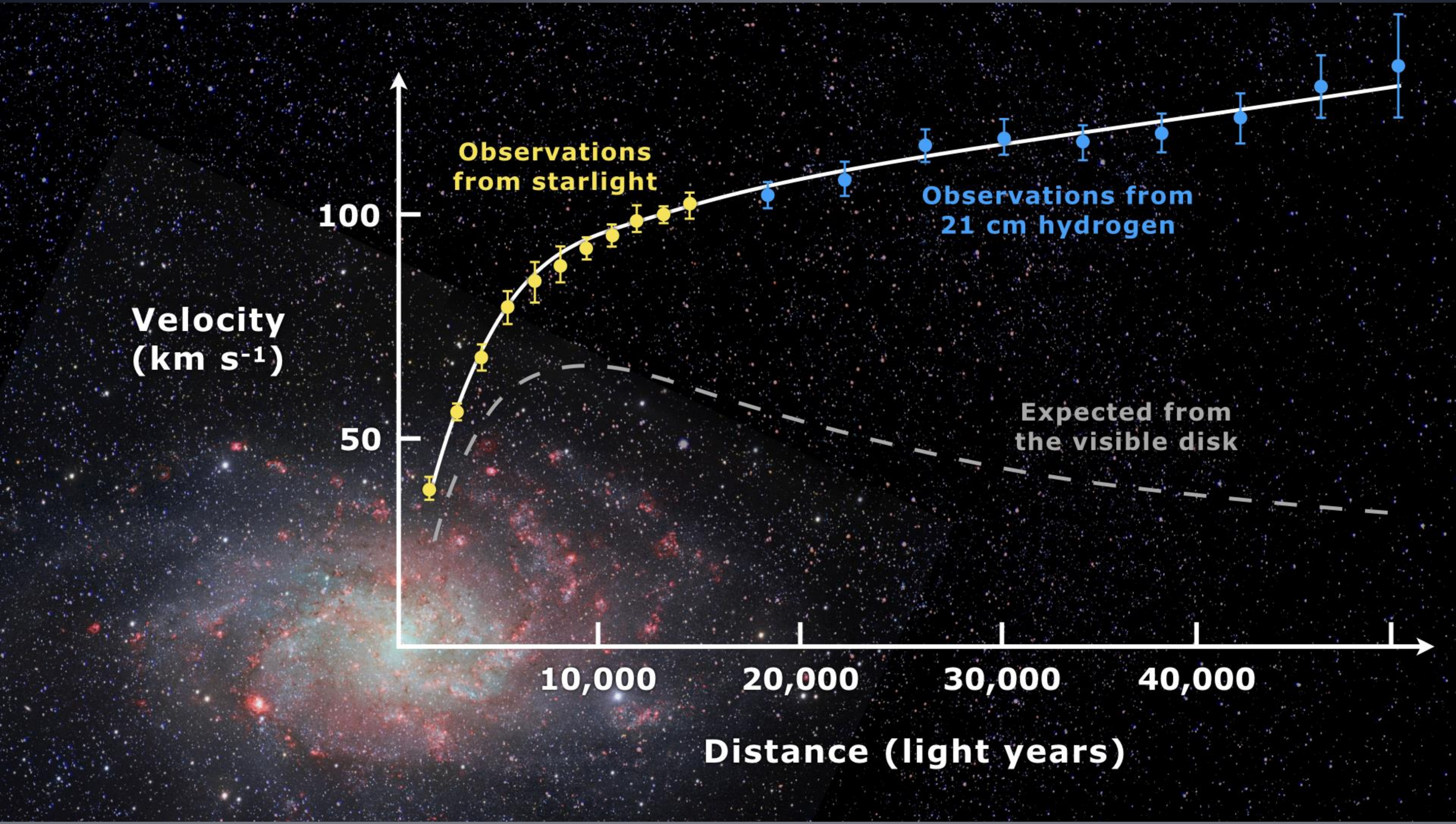


Figure 25.13 Rotation Curve of the Galaxy. The orbital speed of carbon monoxide (CO) and hydrogen (H) gas at different distances from the center of the Milky Way Galaxy is shown in red. The blue curve shows what the rotation curve would look like if all the matter in the Galaxy were located inside a radius of 50,000 light-years. Instead of going down, the speed of gas clouds farther out remains high, indicating a great deal of mass beyond the Sun’s orbit. The horizontal axis shows the distance from the galactic center in kiloparsecs (where a kiloparsec equals 3,260 light-years).


Observations
from starlight
Observations from
21 cm hydrogen
Velocity
(km s-1)
100
50
Expected from
the visible disk
10,000
20,000
30,000
40,000
Distance (light years)

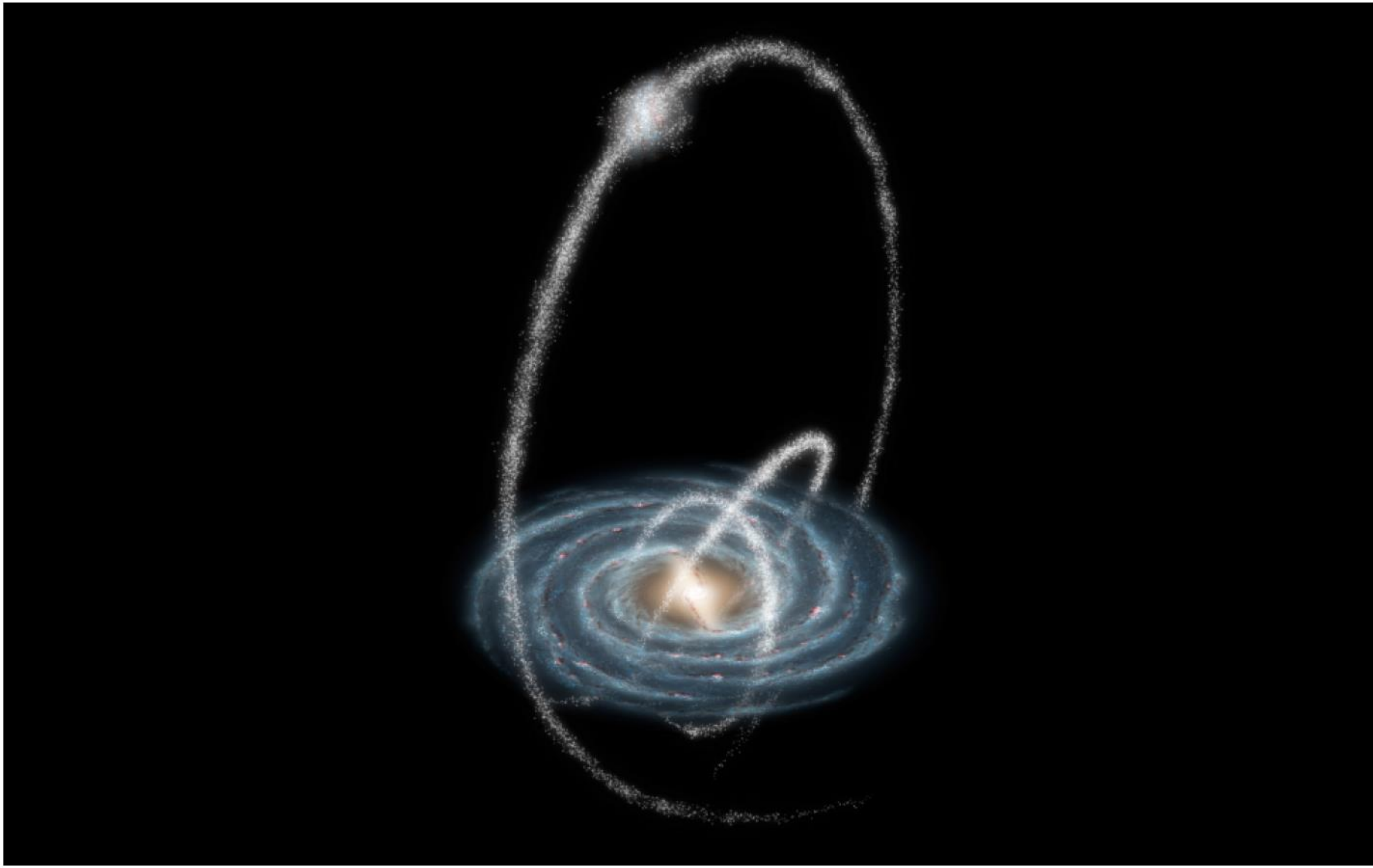
Dark Matter!

- We can measure accurately the mass of the galaxy through Kepler's Laws/gravity
- We can measure the mass of stars+gas
- Mass of stars = 0.2 x mass of galaxy

Rule out: black holes, brown dwarfs/planets, interstellar gas

Dark matter: exotic, non-interacting particle

Dark=not interacting; 80% of mass!

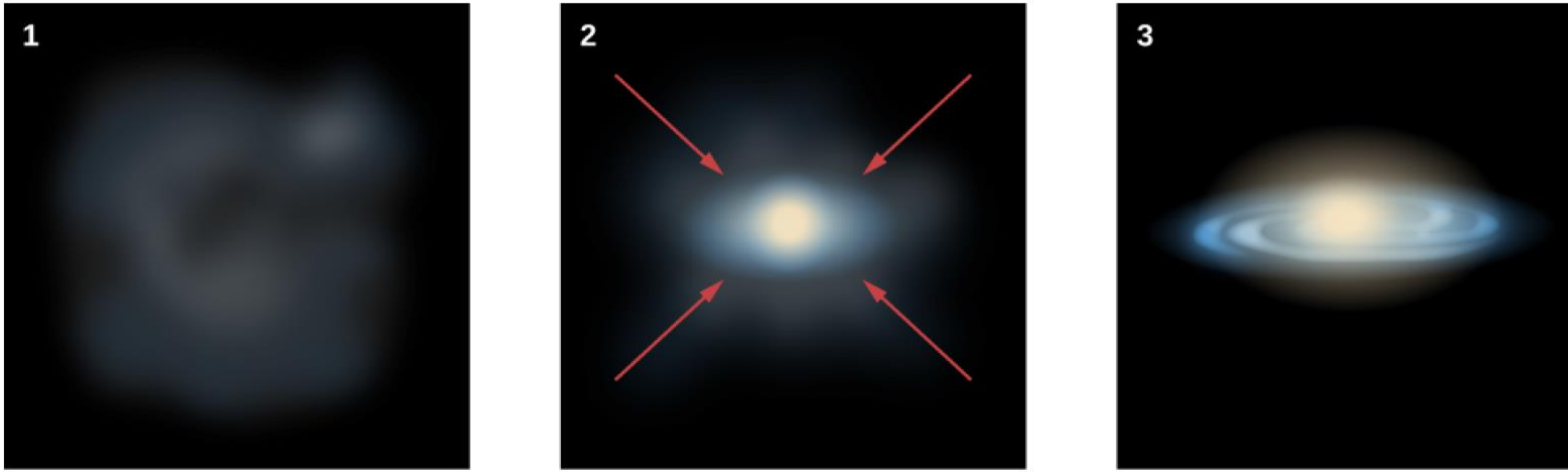


Simulations of Milky Way Formation

Evolution of the Sagittarius Dwarf Spheroidal Galaxy in the Halo of the Milky Way

David R. Law
(Dunlap Institute, Univ. of Toronto)

Rapid Collapse

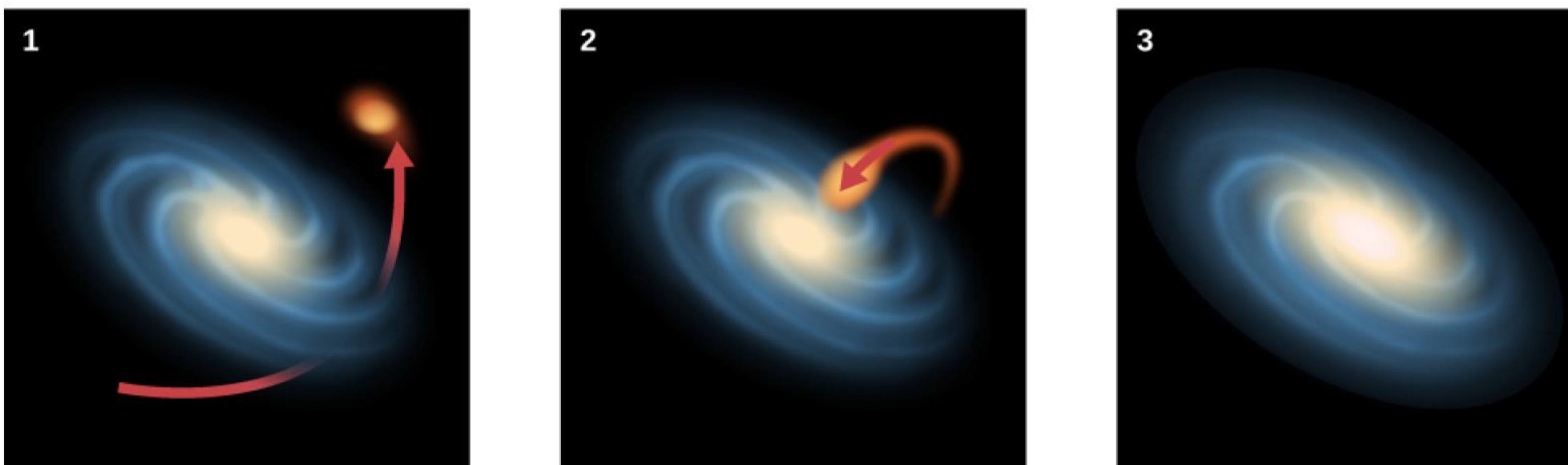


Primordial hydrogen cloud.

Cloud collapses under gravity.

Large bulge of ancient stars dominates galaxy.

Environmental Effects



Disk galaxy and companion.

Smaller galaxy falls into disk galaxy.

Bulge inflates with addition of young stars and gas.

Galaxy keywords

- Galaxy: gravitationally bound system of stars, gas, dust, and dark matter.
  - 1000-100,000 light years in radius
  - Many kinds of shapes and sizes
- Range: 10^8-10^{14} stars
  - Milky Way: 10^{11} stars (a large galaxy)
- Supermassive black hole
  - Milky Way: $4\ 10^6$ Msun (small central black hole)

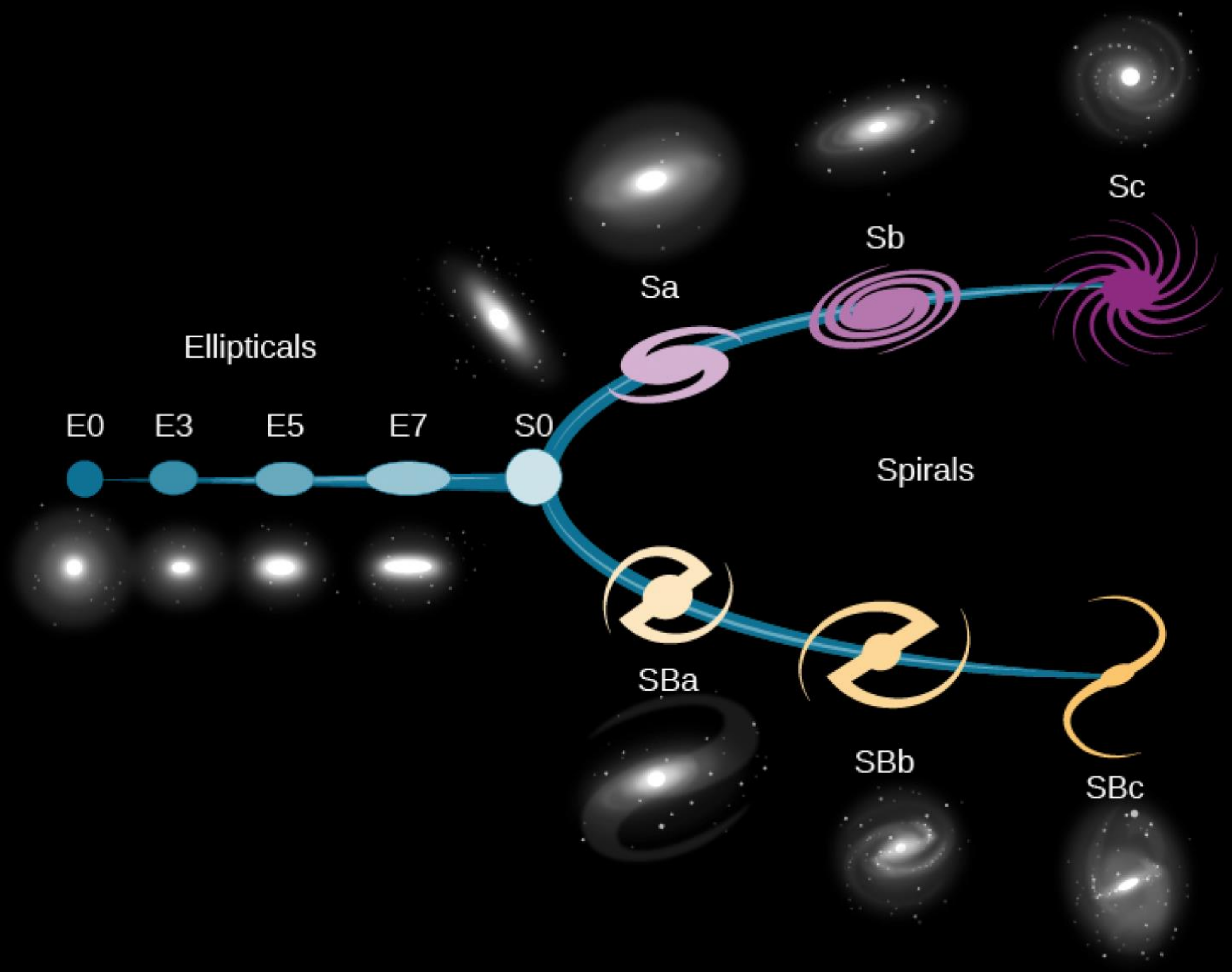
Galaxy: keywords

- **Spiral arms:** "shape" of young stars/dense gas in some galaxies
- **Supermassive black hole:** massive black hole at center of galaxy
- **Dark Matter halo:** spherical halo of dark matter around the galaxy
- **Galactic rotation:** rotation of stars/gas around galaxy
- **Central bulge:** bulge around nucleus of galaxy

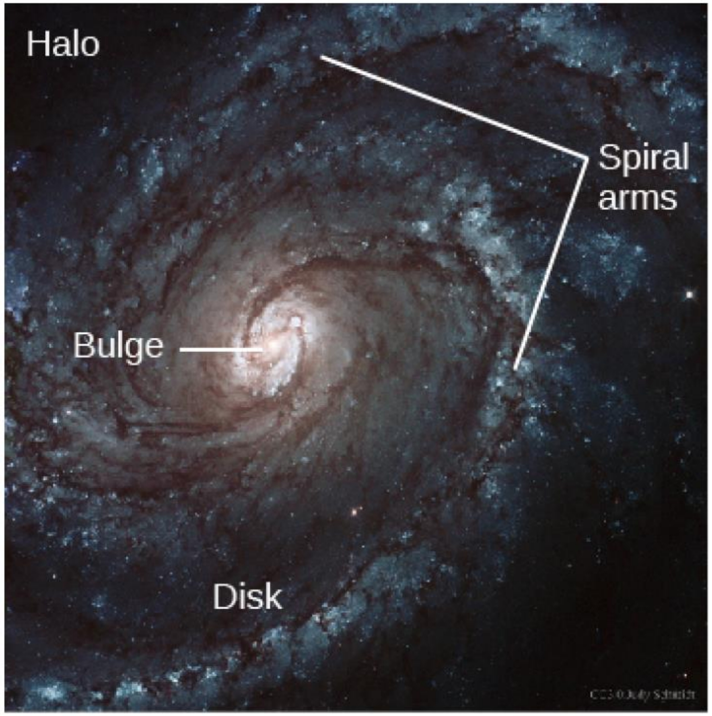
Galaxy keywords

- Elliptical galaxy: ellipse, no star formation
- Irregular galaxy: no pattern, merger
- Spiral galaxy:
- Redshift: lines shifted to longer wavelength from expansion of universe
- Distance ladder: steps to calculate distance
- Galaxy evolution: changes in galaxies over cosmic time
- Local group: small cluster of galaxies, including Milky Way
- Starburst: galaxy with a burst of star formation, often a result of collisions
- Quasar and AGN: accreting supermassive black holes

Galaxies and their supermassive black holes



Spiral galaxies



Spirals: dense gas gets clustered
Gas forms stars: young, blue, bright

Elliptical galaxy (no more star formation)

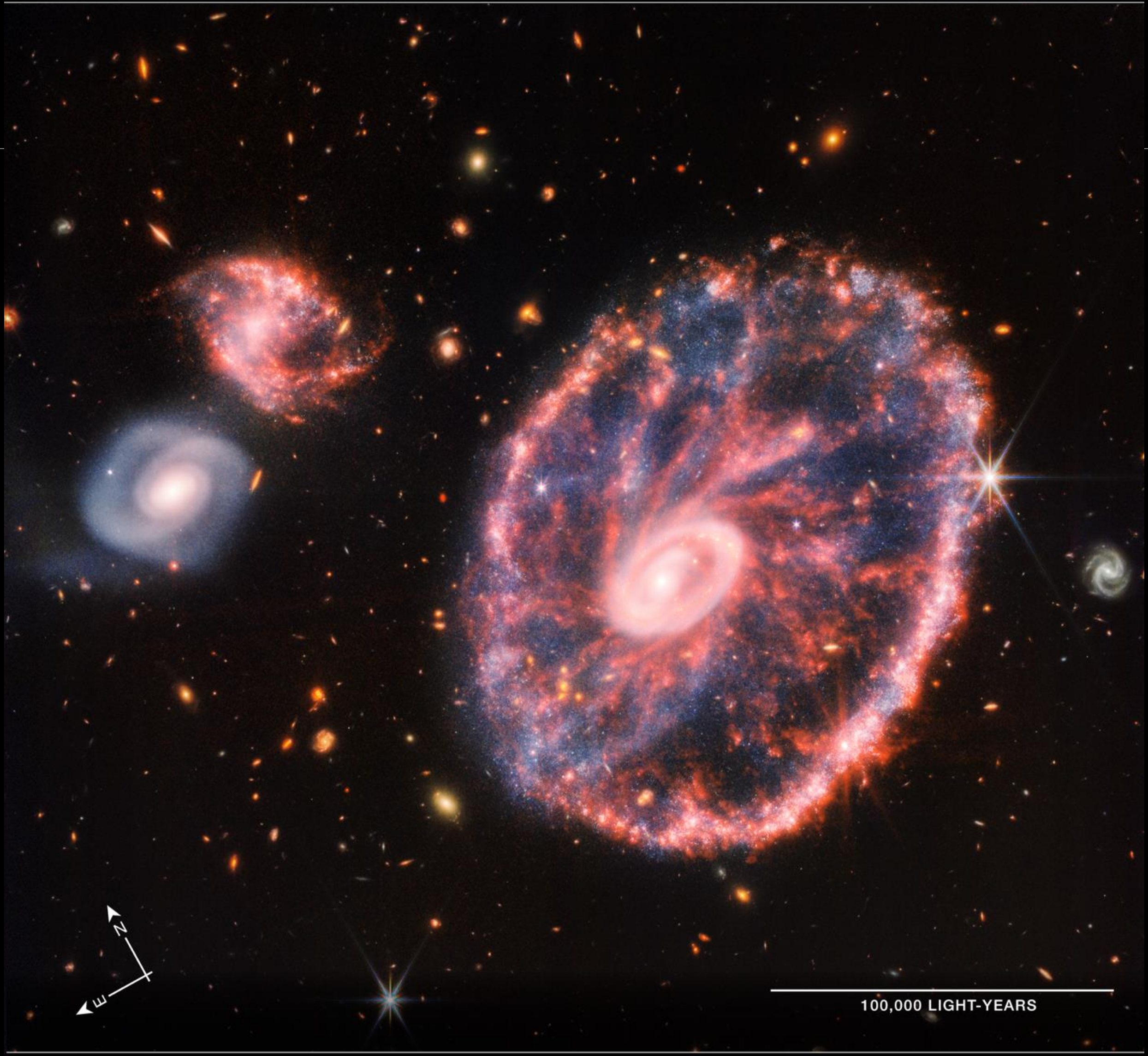
Irregular galaxy (merger)

Elliptical: red and dead
No dust/gas, no star formation

Mergers: starbursts
Lots of young stars and dust, gas

JAMES WEBB SPACE TELESCOPE

CARTWHEEL GALAXY | ESO 350-40

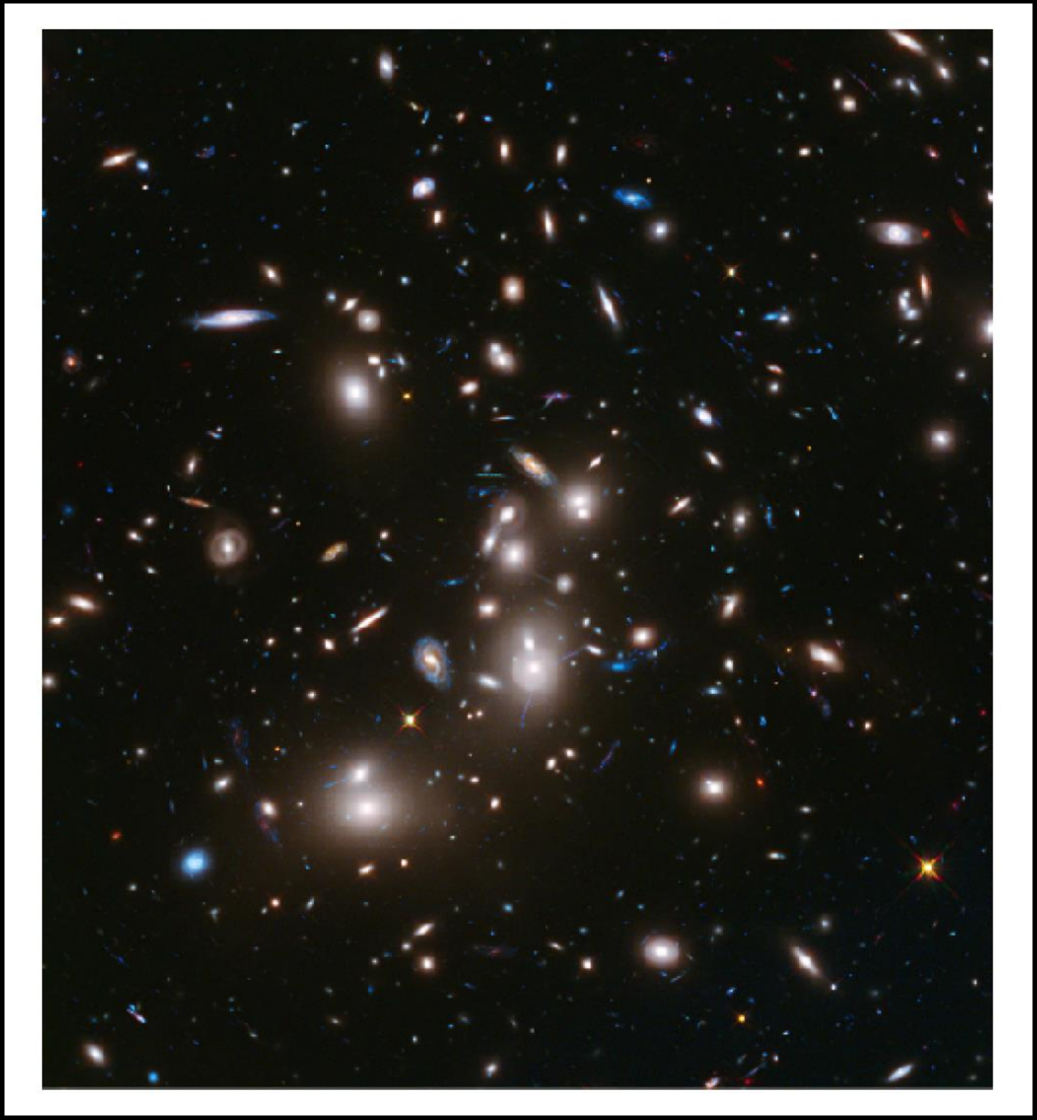


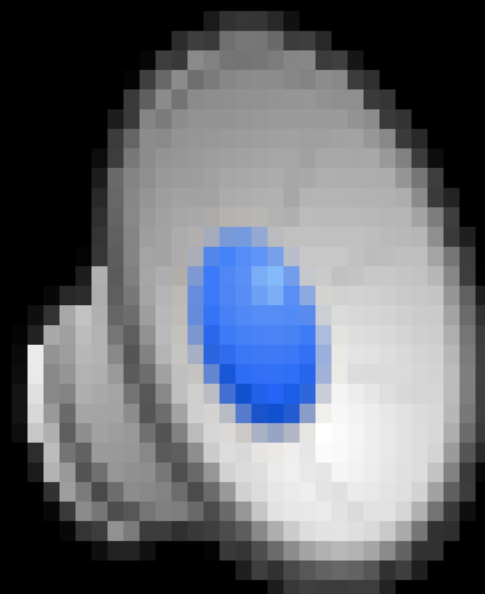
NIRCam Filters | F090W F150W F200W F277W F356W F444W

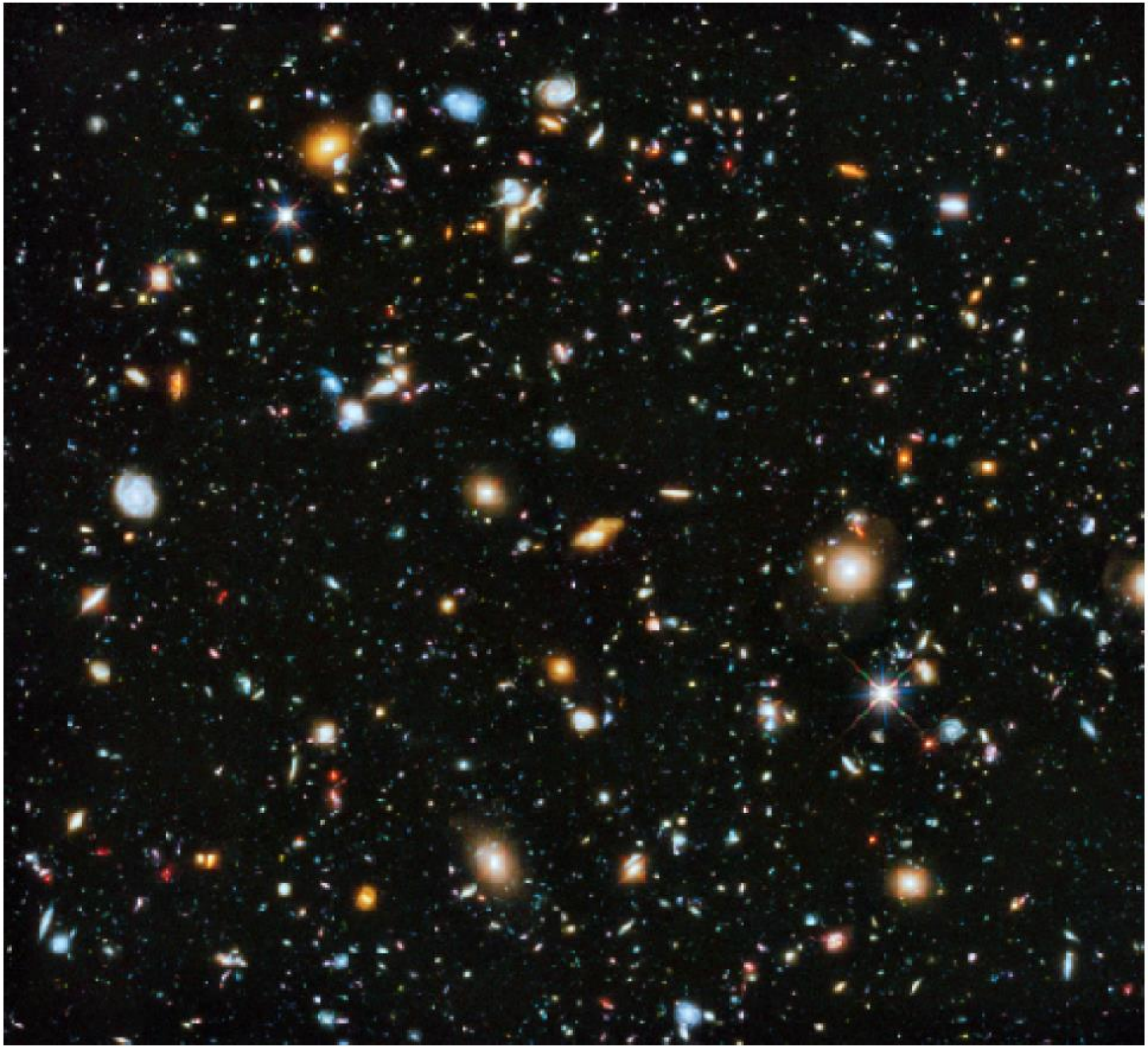
MIRI Filters | F770W F1000W F1280W F1800W

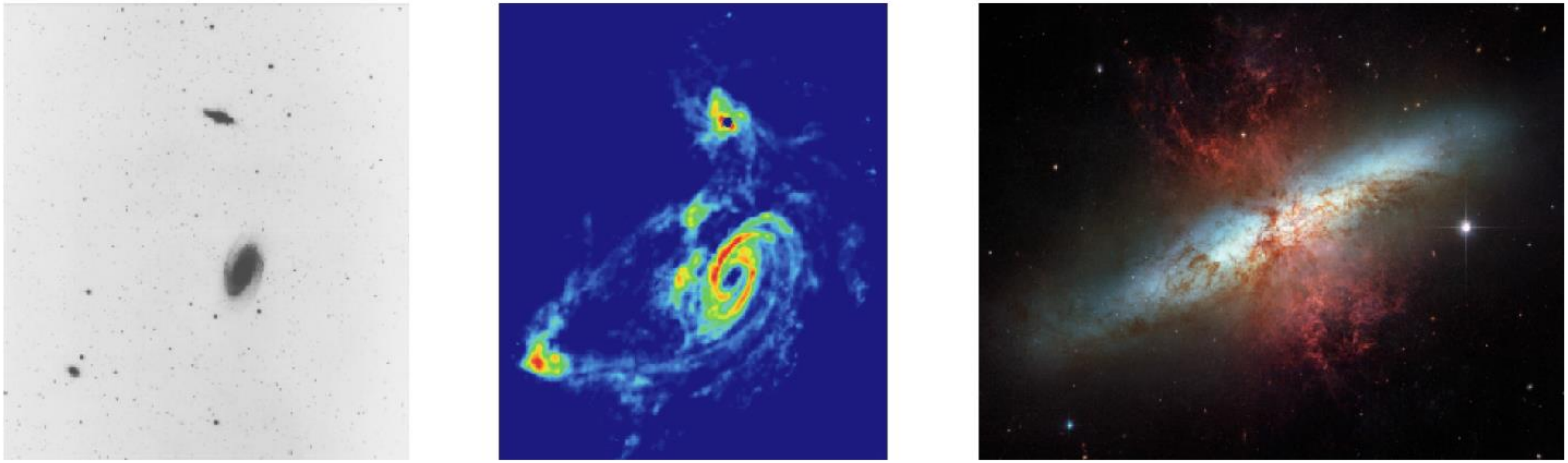

Hubble

Hubble (Space Telescope) Deep Field

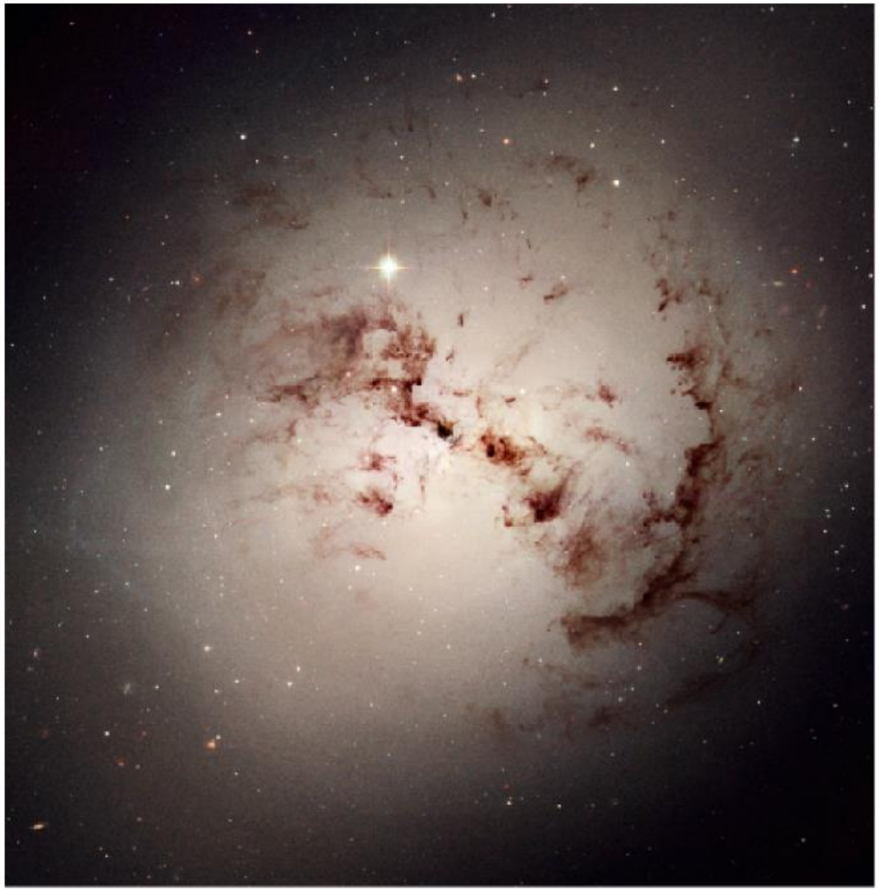


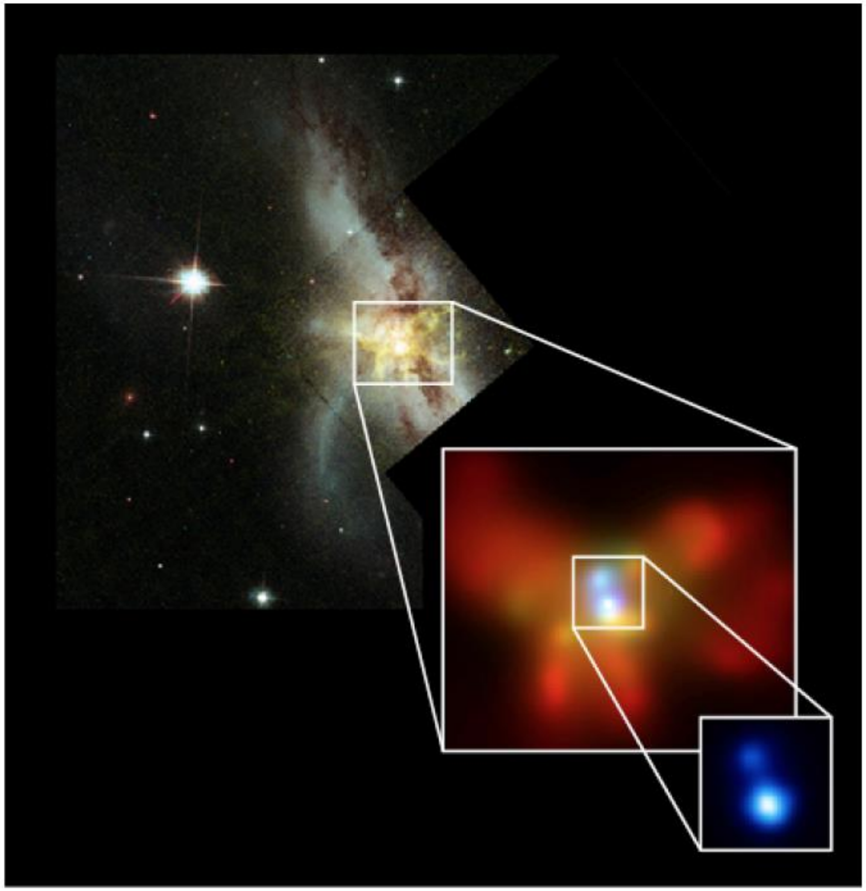


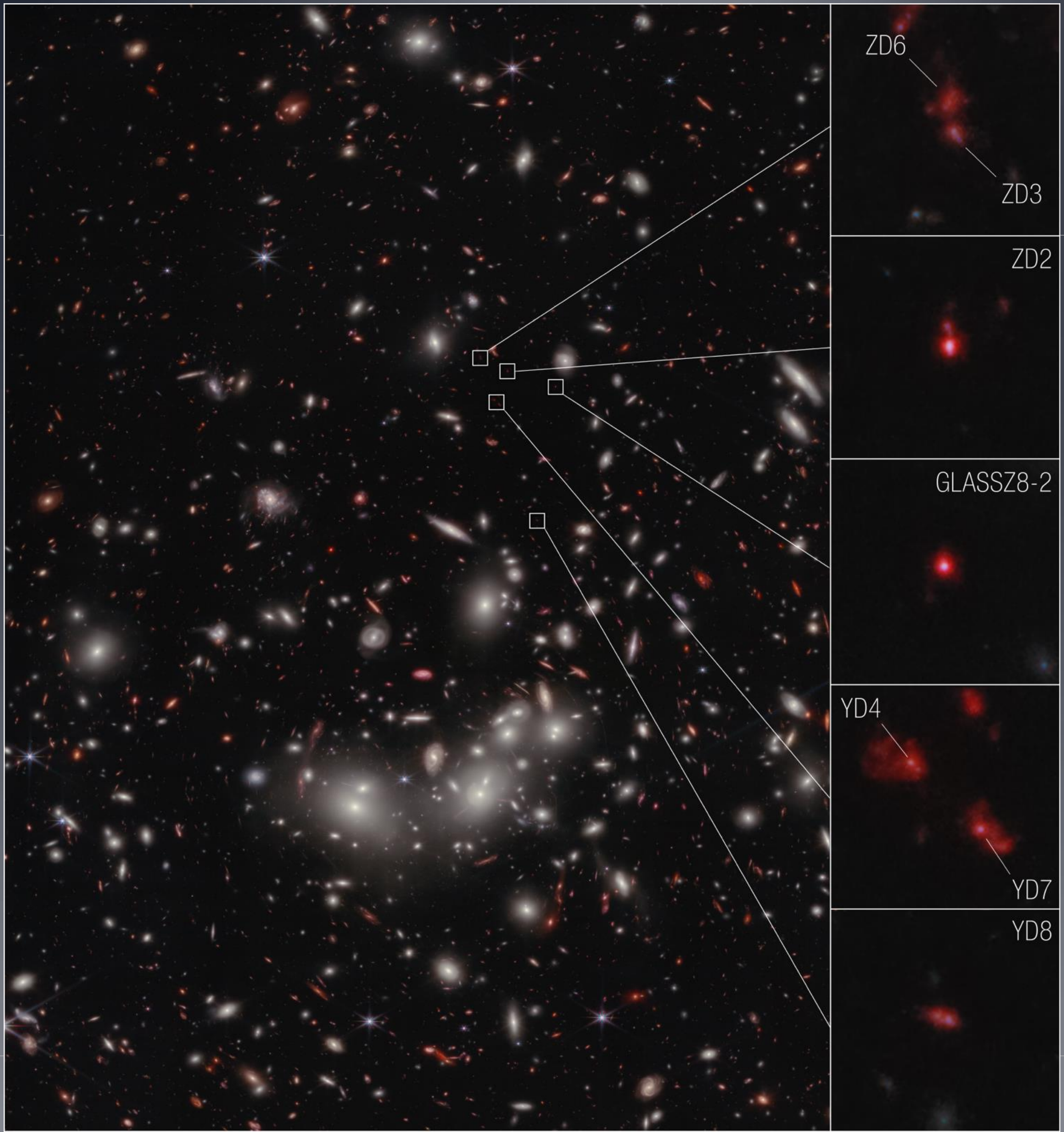


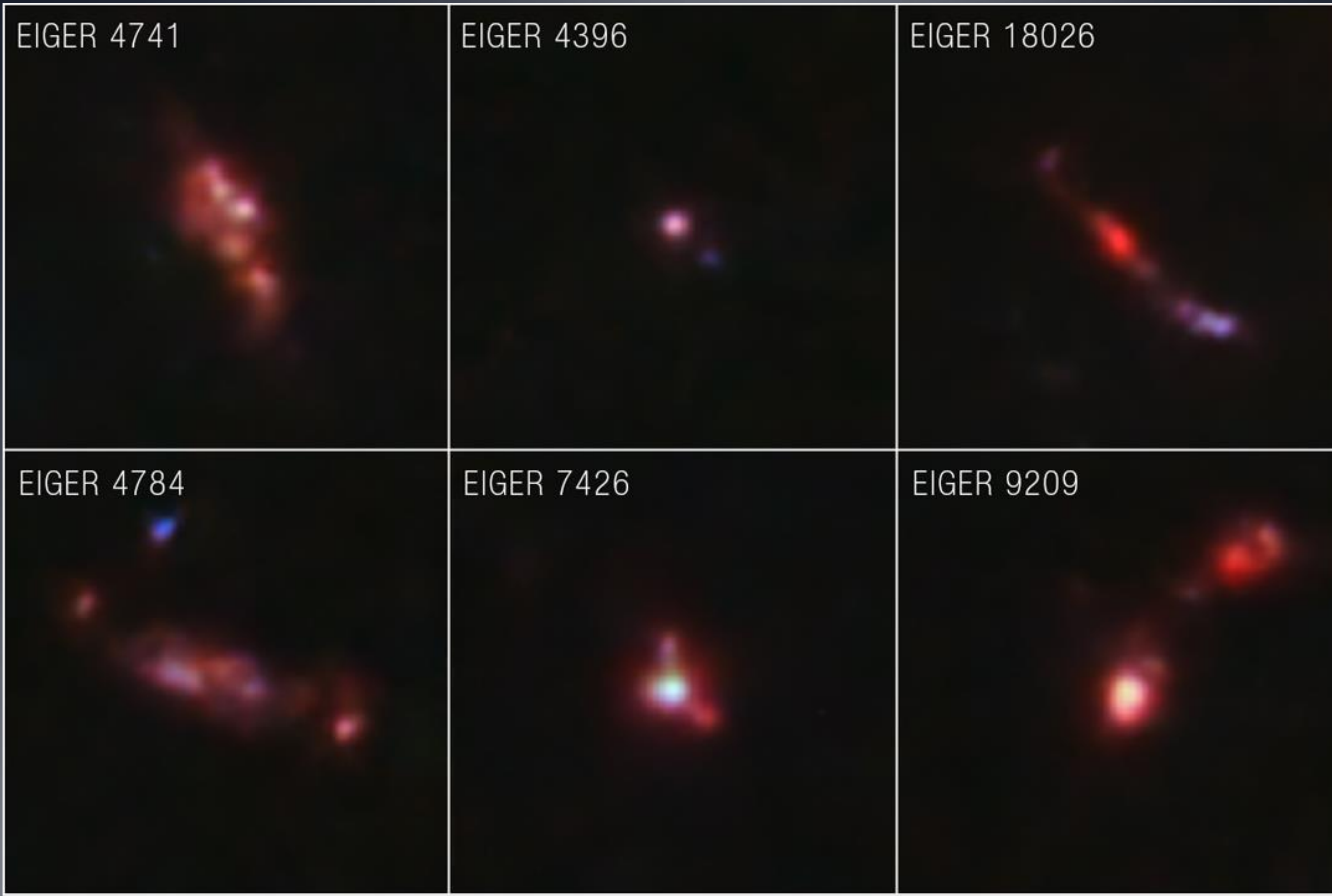


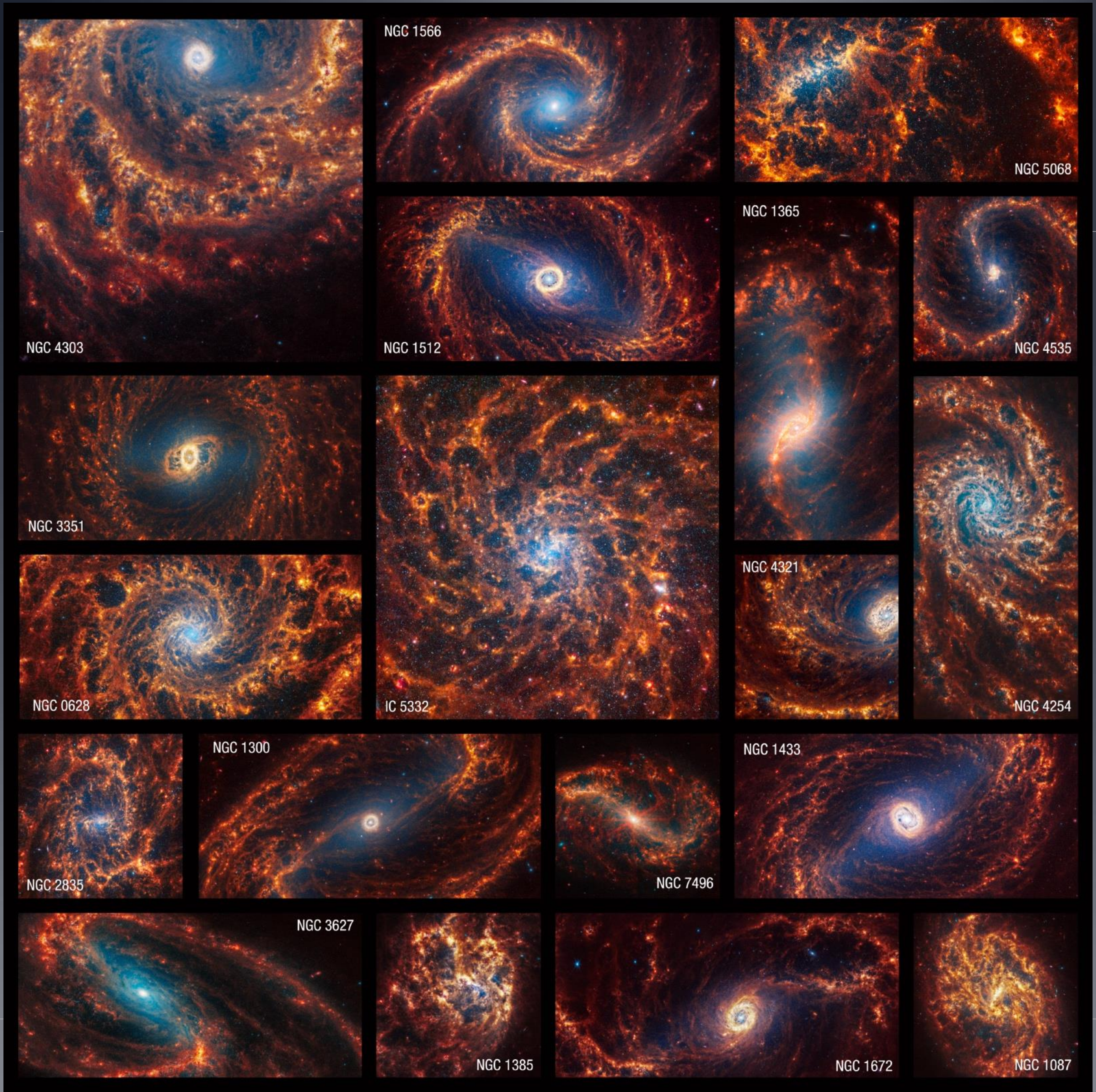
(a) (b) (c)







ZD6
ZD3
ZD2
GLASSZ8-2
YD4
YD7
YD8


EIGER 4741
EIGER 4396
EIGER 18026
EIGER 4784
EIGER 7426
EIGER 9209


NGC 4303
NGC 1566
NGC 5068
NGC 1512
NGC 1365
NGC 4535
NGC 3351
IC 5332
NGC 4321
NGC 4254
NGC 0628
NGC 2835
NGC 1300
NGC 7496
NGC 1433
NGC 3627
NGC 1385
NGC 1672
NGC 1087

Characteristics of the Different Types of Galaxies

Characteristic	Spirals	Ellipticals	Irregulars
Mass (M_{Sun})	10^9 to 10^{12}	10^5 to 10^{13}	10^8 to 10^{11}
Diameter (thousands of light-years)	15 to 150	3 to >700	3 to 30
Luminosity (L_{Sun})	10^8 to 10^{11}	10^6 to 10^{11}	10^7 to 2×10^9
Populations of stars	Old and young	Old	Old and young
Interstellar matter	Gas and dust	Almost no dust; little gas	Much gas; some have little dust, some much dust
Mass-to-light ratio in the visible part	2 to 10	10 to 20	1 to 10
Mass-to-light ratio for total galaxy	100	100	?

Mass-to-light ratio: why different?

Characteristics of the Different Types of Galaxies

Characteristic	Spirals	Ellipticals	Irregulars
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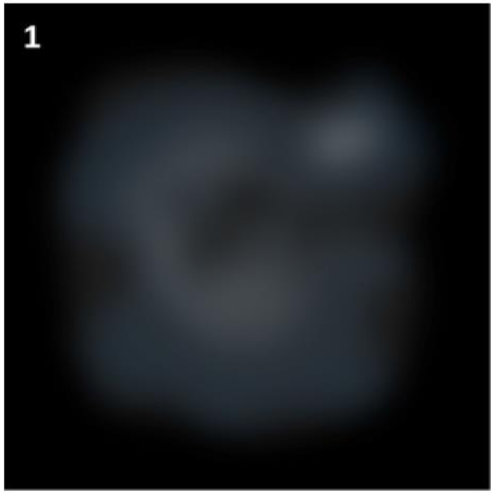
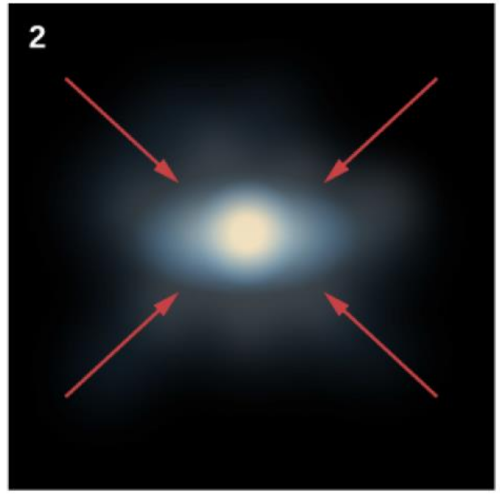
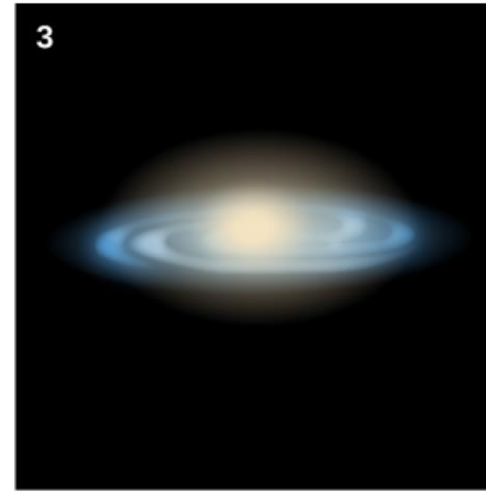
Rapid Collapse



Primordial hydrogen cloud.

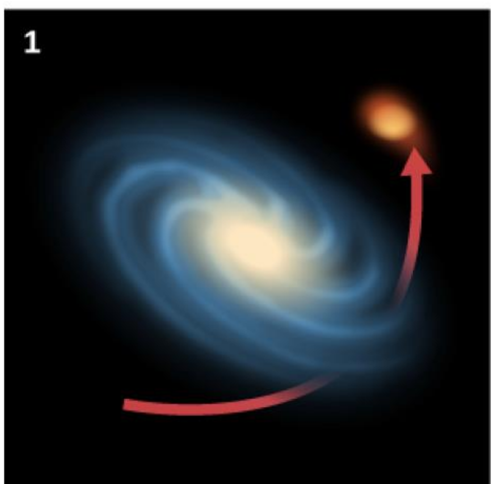


Cloud collapses under gravity.

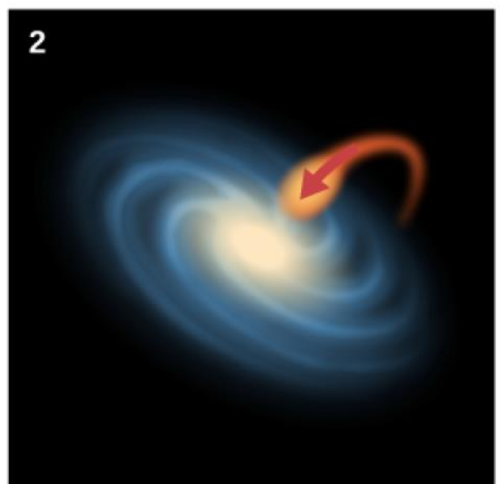


Large bulge of ancient stars dominates galaxy.

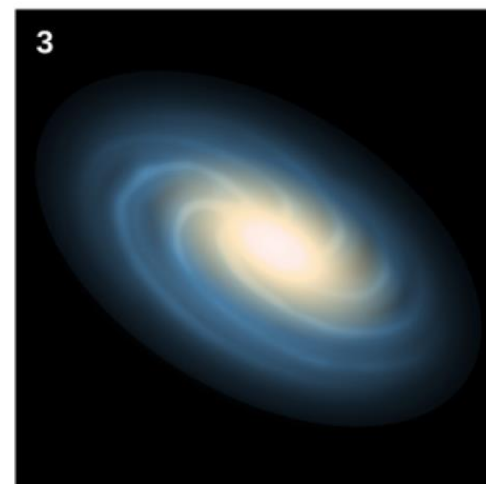
Environmental Effects



Disk galaxy and companion.



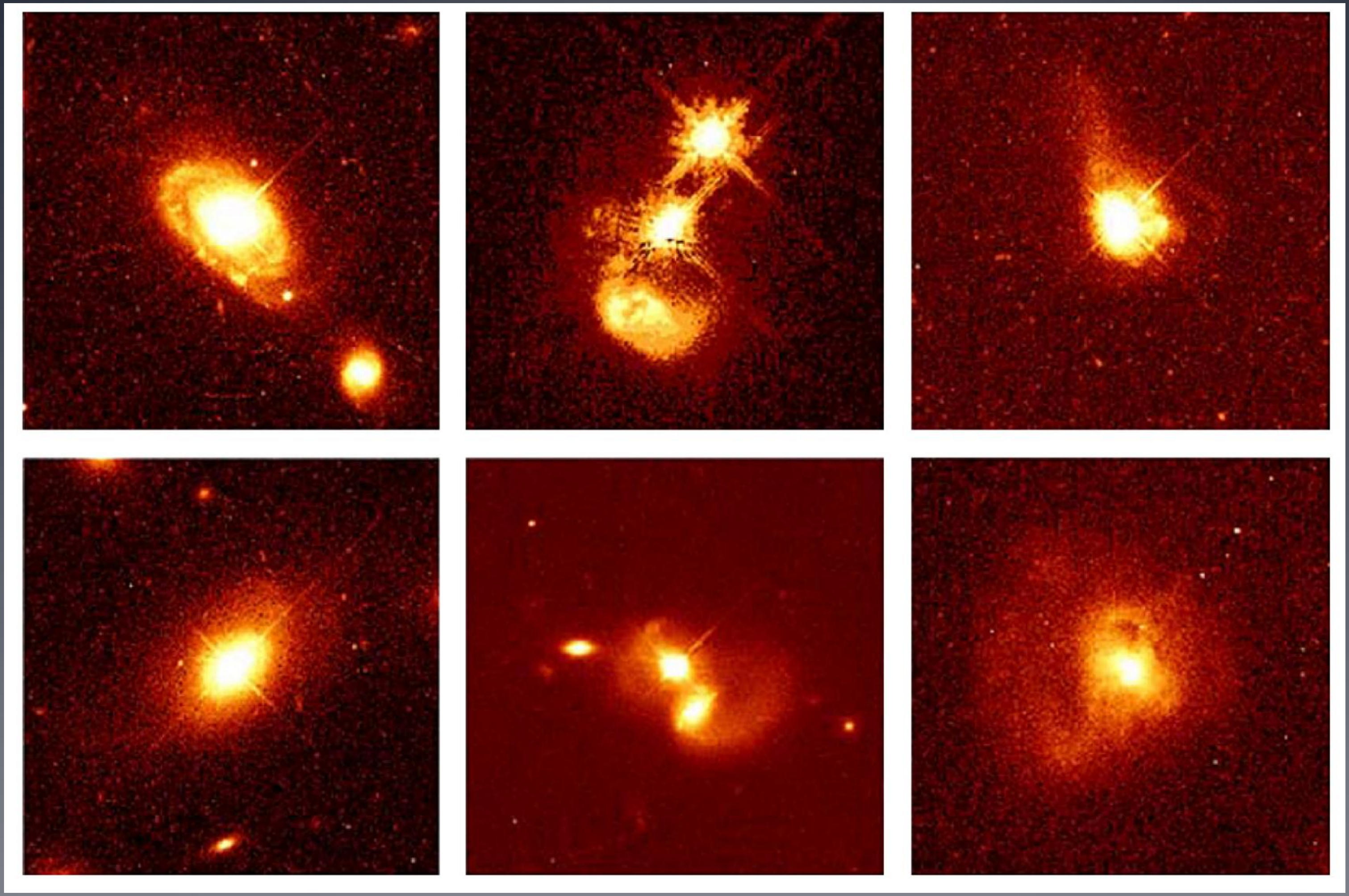
Smaller galaxy falls into disk galaxy.



Bulge inflates with addition of young stars and gas.

Supermassive black holes!
Quasars: quasi-stellar objects

Quasars: accreting gas, outshines their host galaxies (but they do have host galaxies)

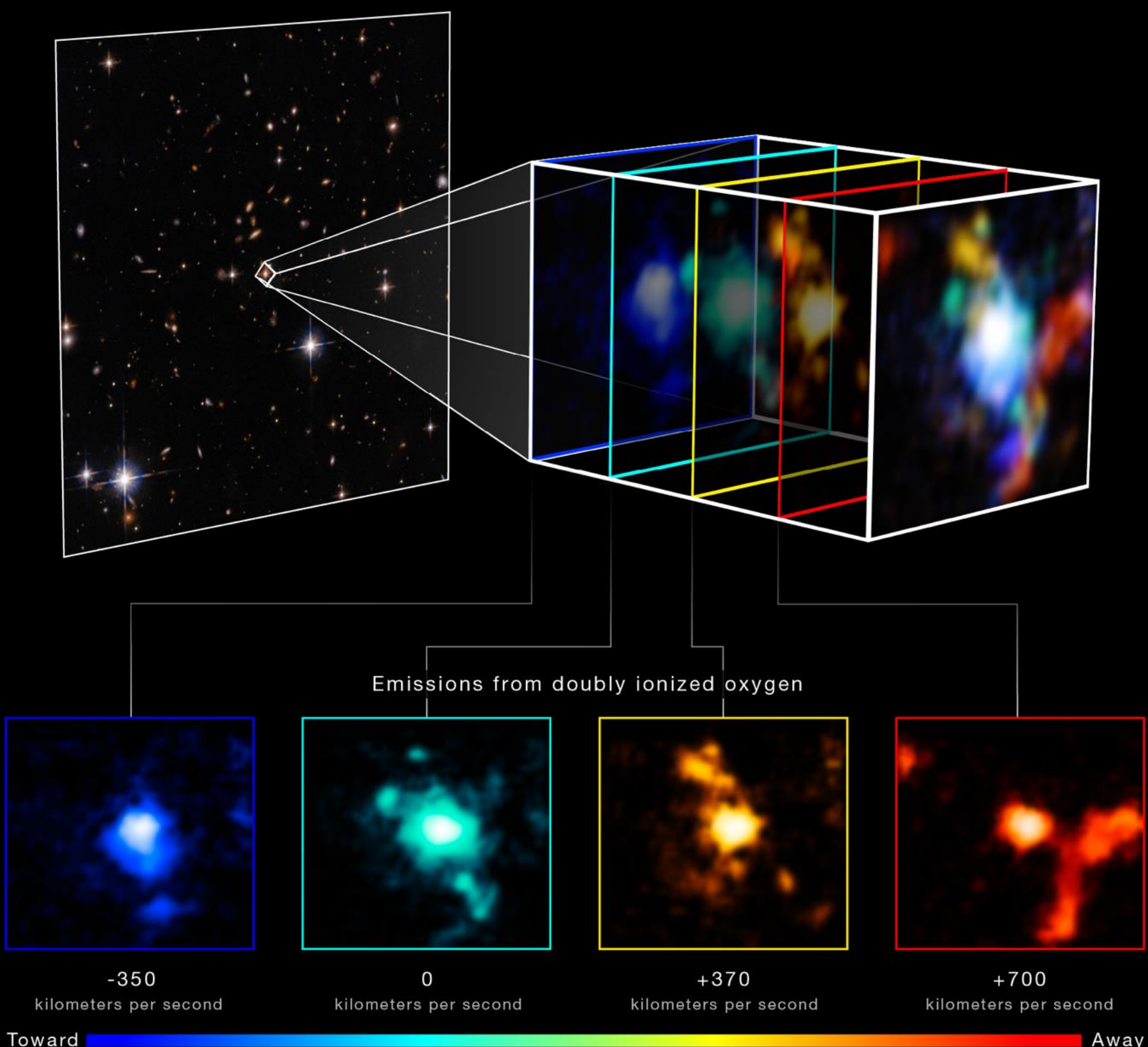


SDSS J165202.64+172852.3

MOTIONS OF GAS AROUND AN EXTREMELY RED QUASAR

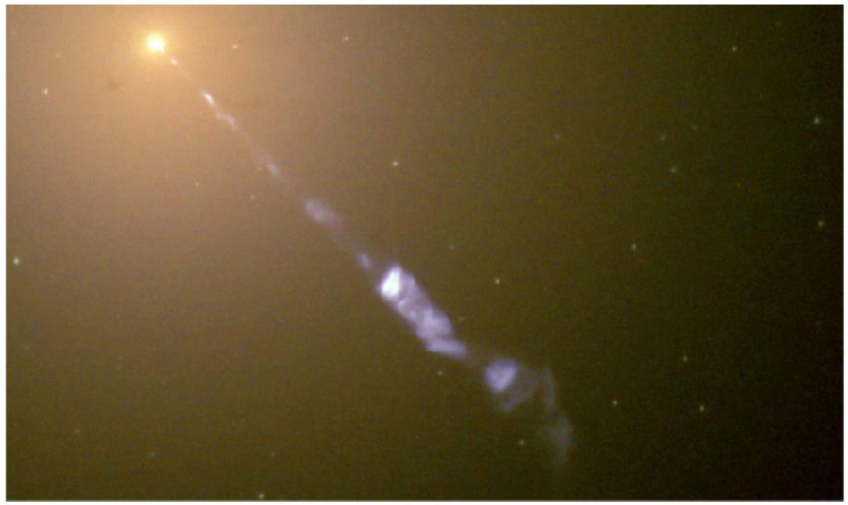
Hubble ACS + WFC3 Imaging

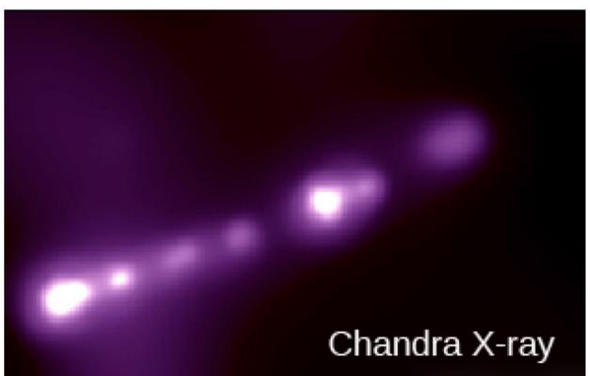
Webb NIRSpec IFU Spectroscopy

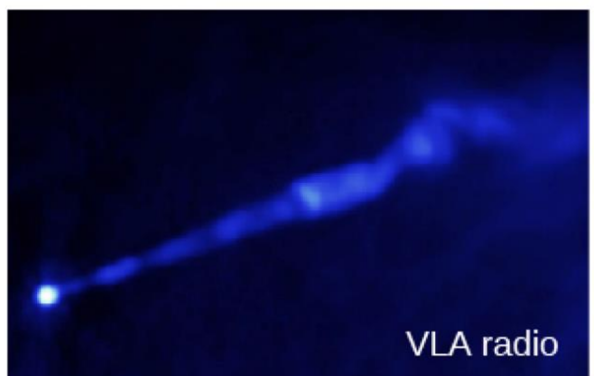


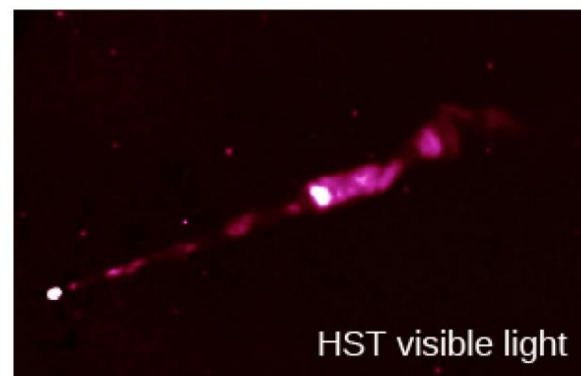
WEBB
SPACE TELESCOPE

Jets from the central black hole

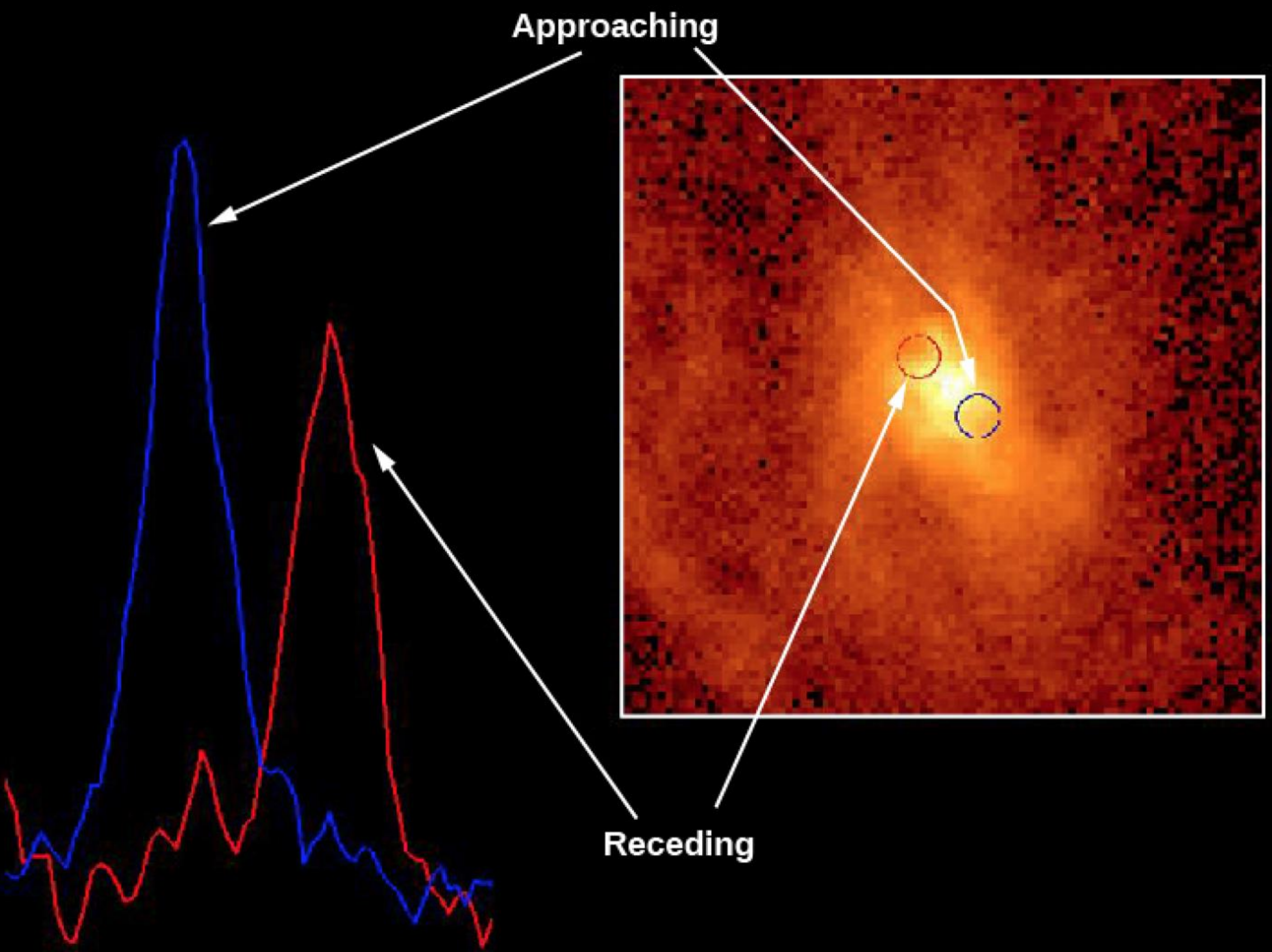


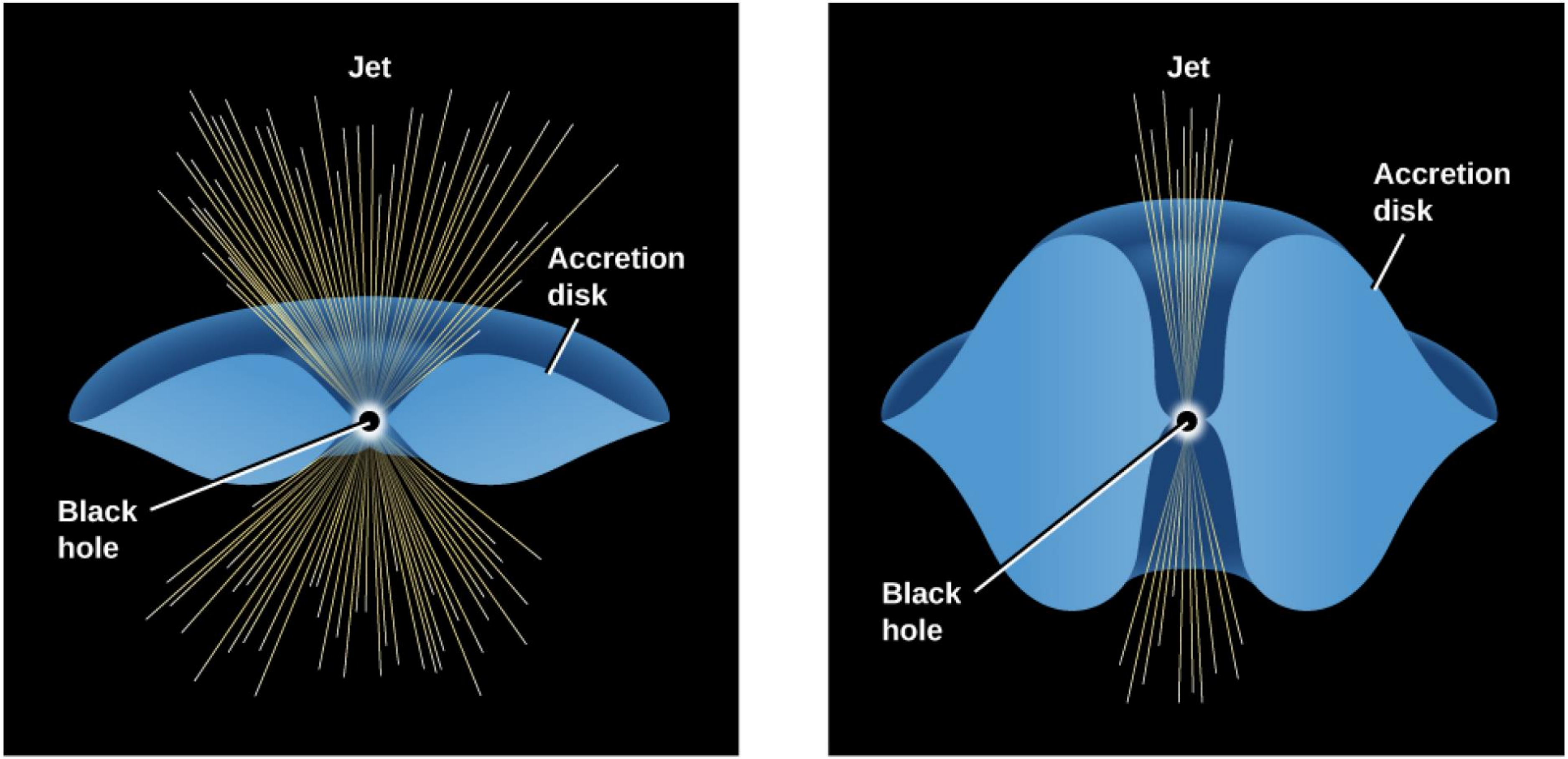


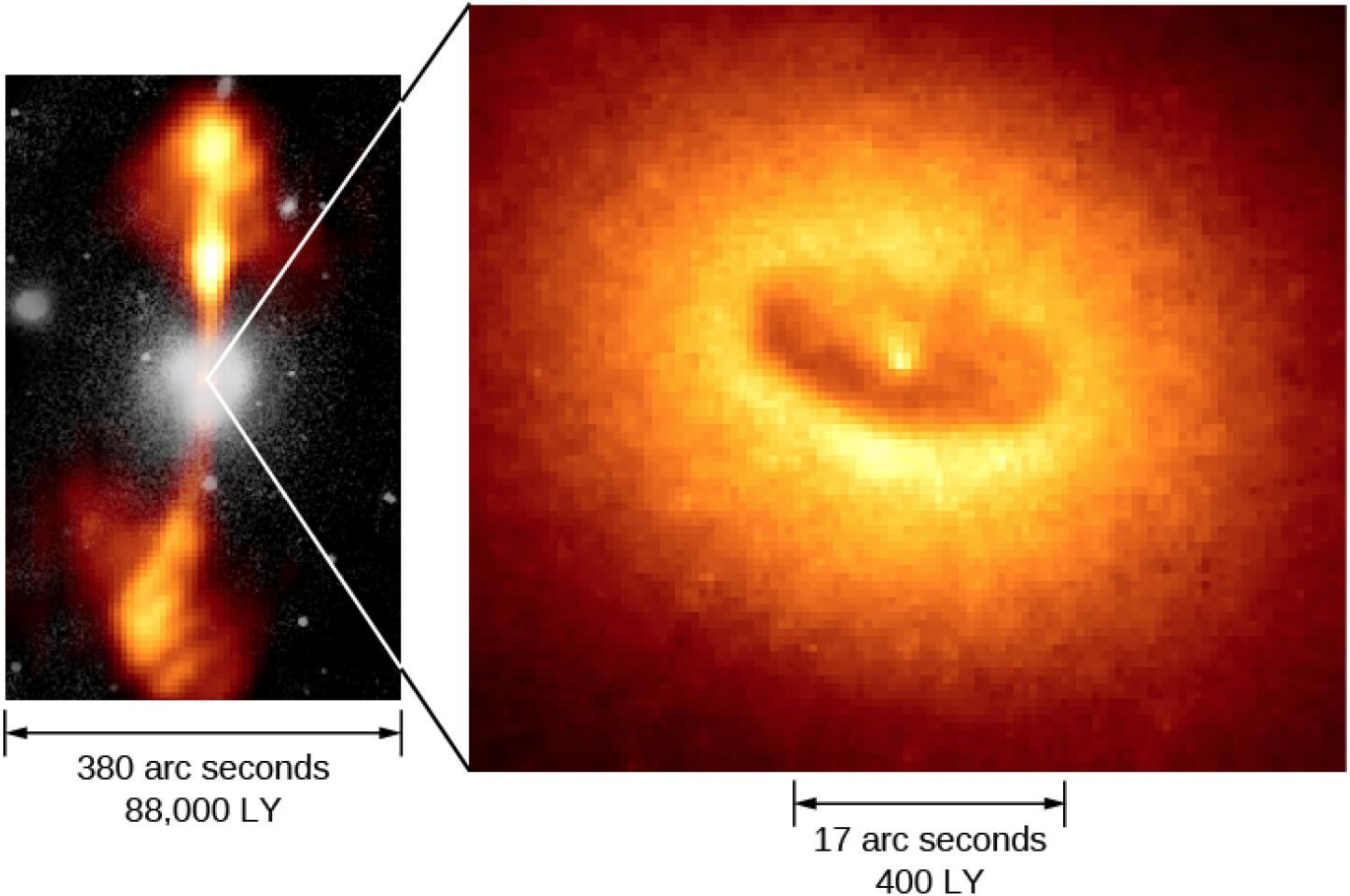




Mass of black hole from velocity shifts

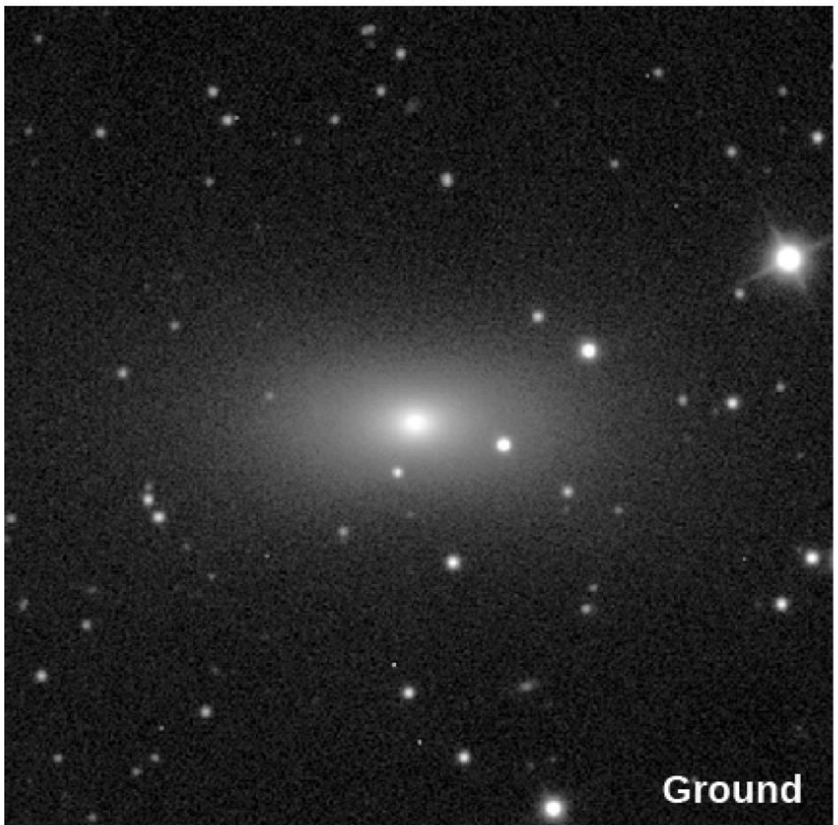


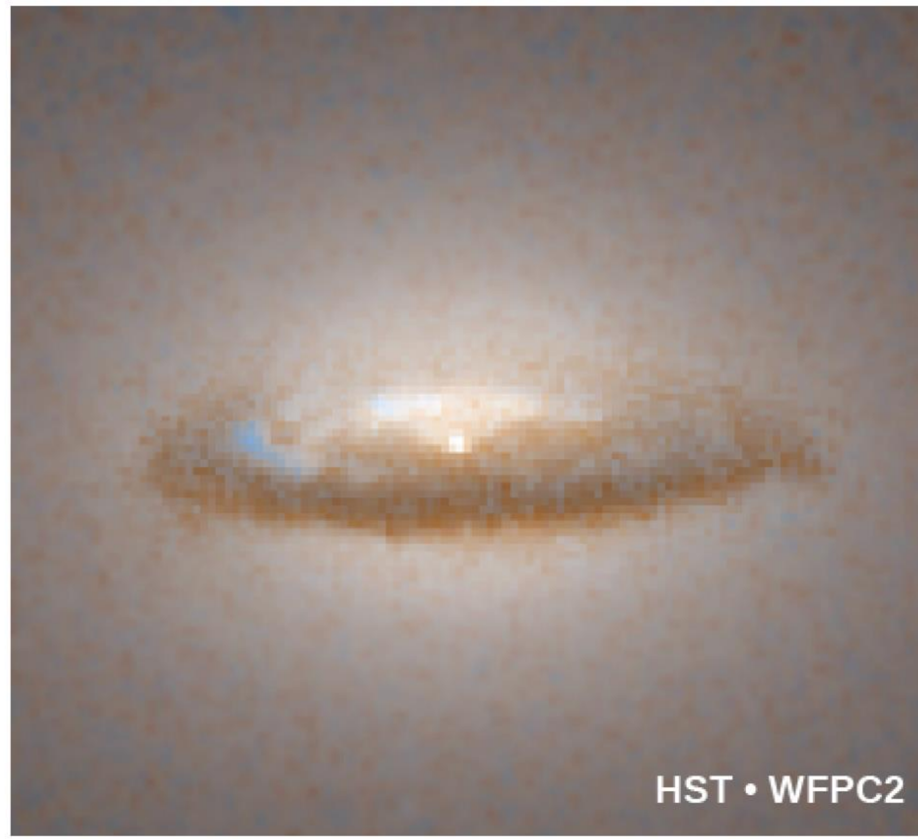

Jet
Accretion disk
Black hole
Jet
Accretion disk
Black hole



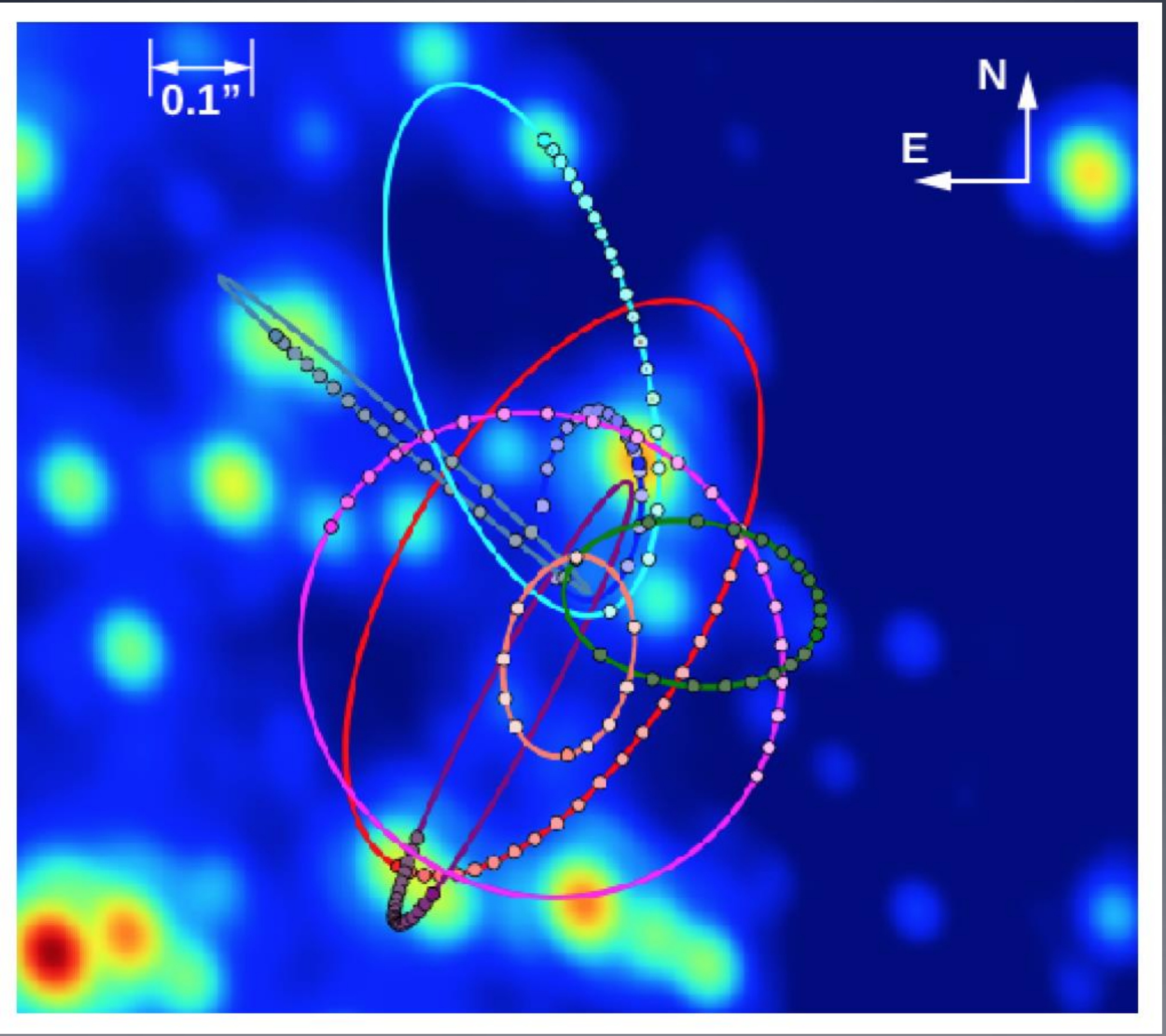
380 arc seconds
88,000 LY
17 arc seconds
400 LY

Imaging: can't get close enough to resolve the black hole

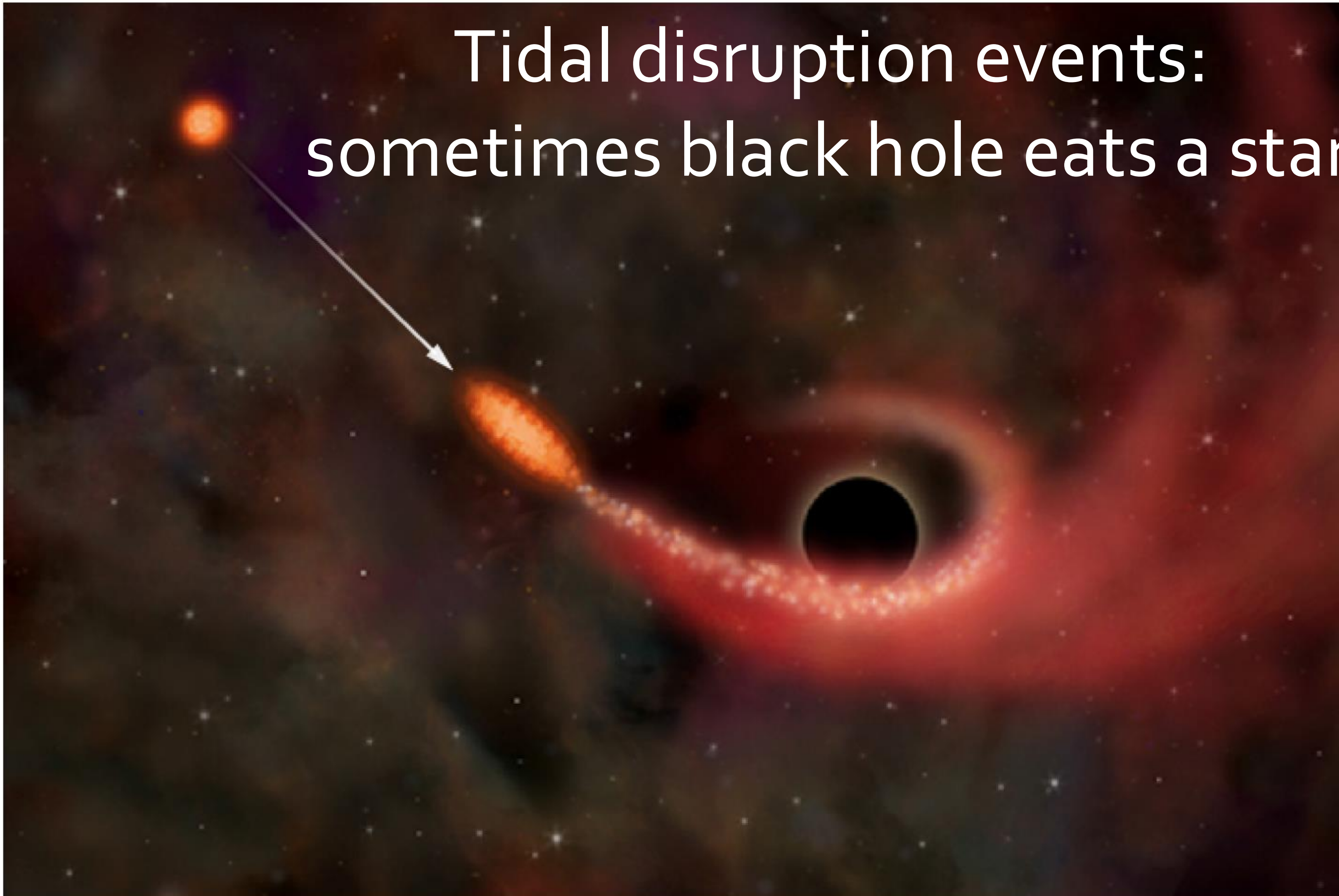




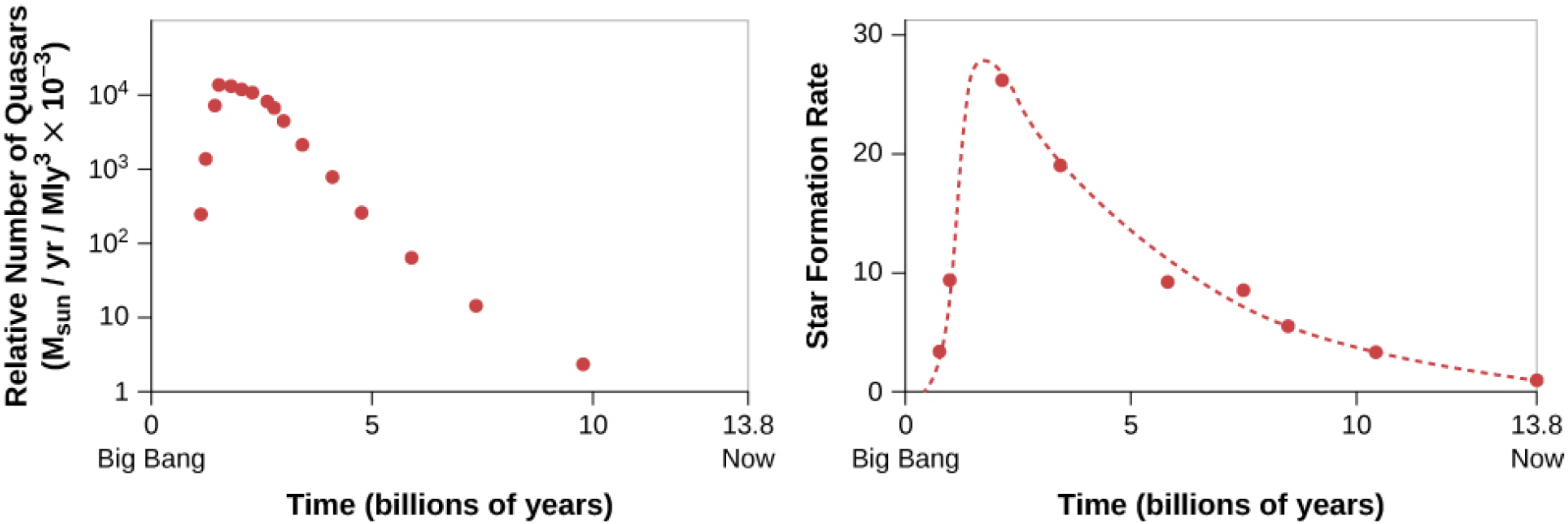
Galactic center orbits



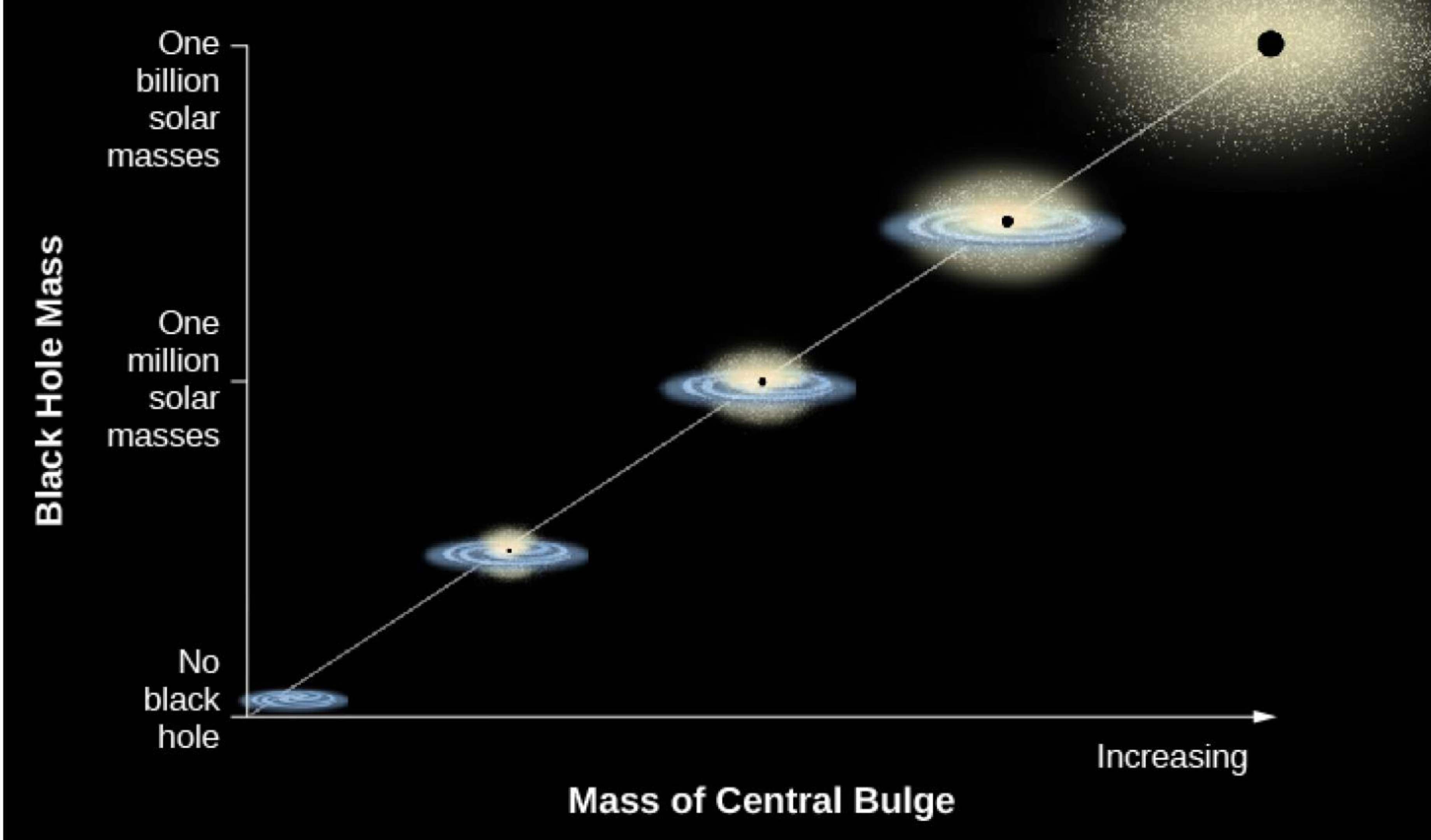
Tidal disruption events: sometimes black hole eats a star



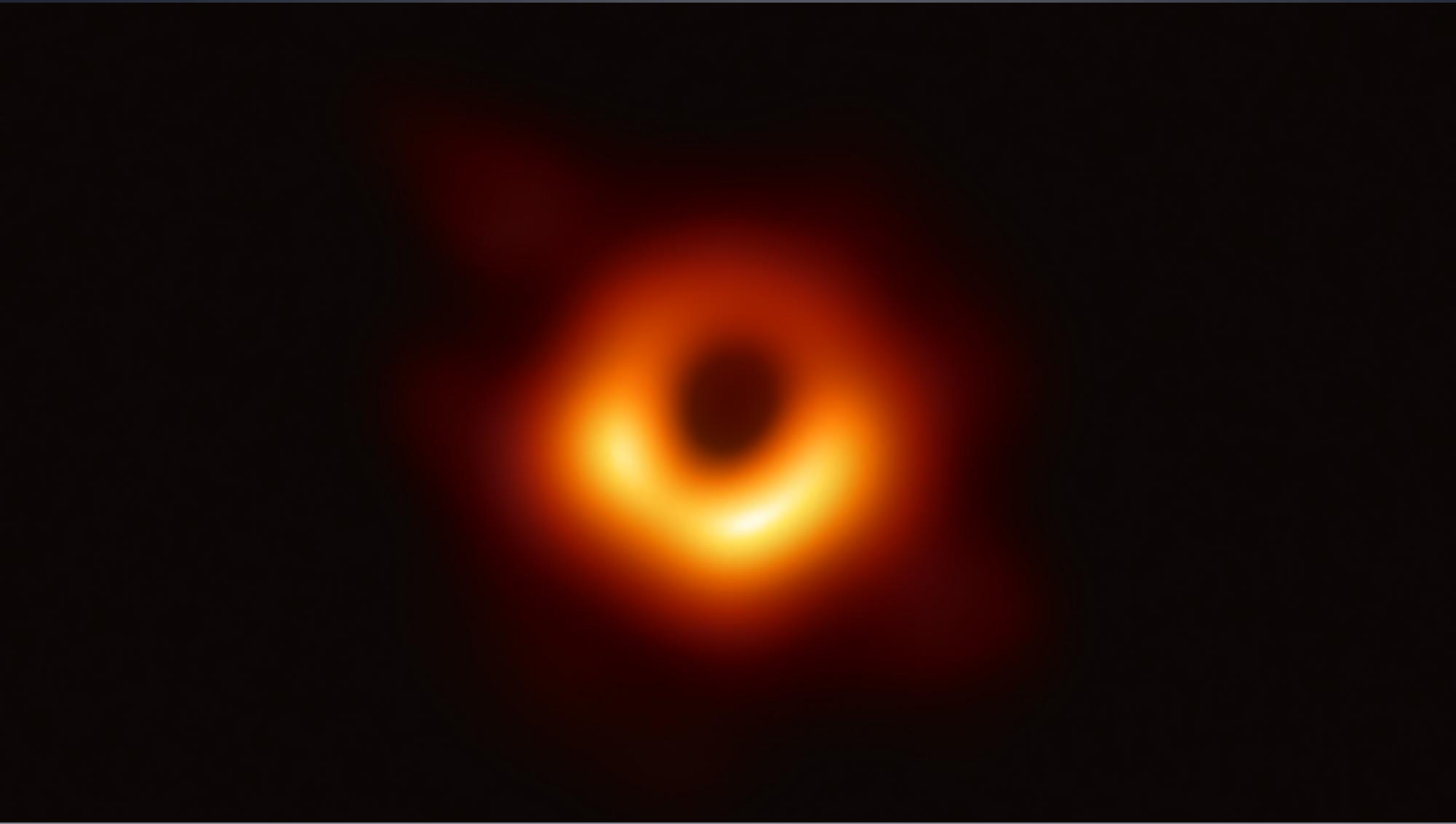
More quasars early in the universe

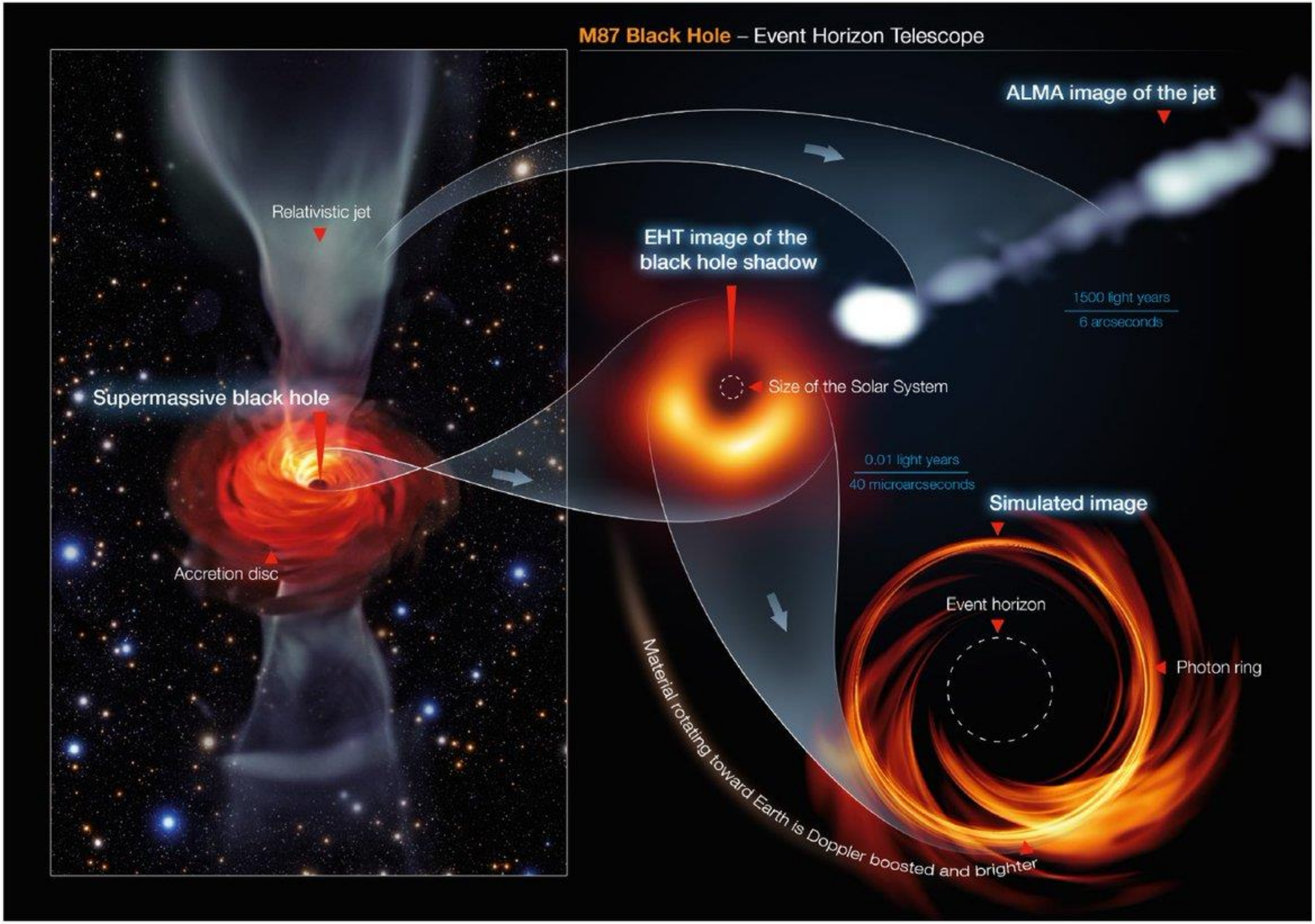


Quasars and galaxies grow together



First "image" of a black hole
Supermassive black hole of M87

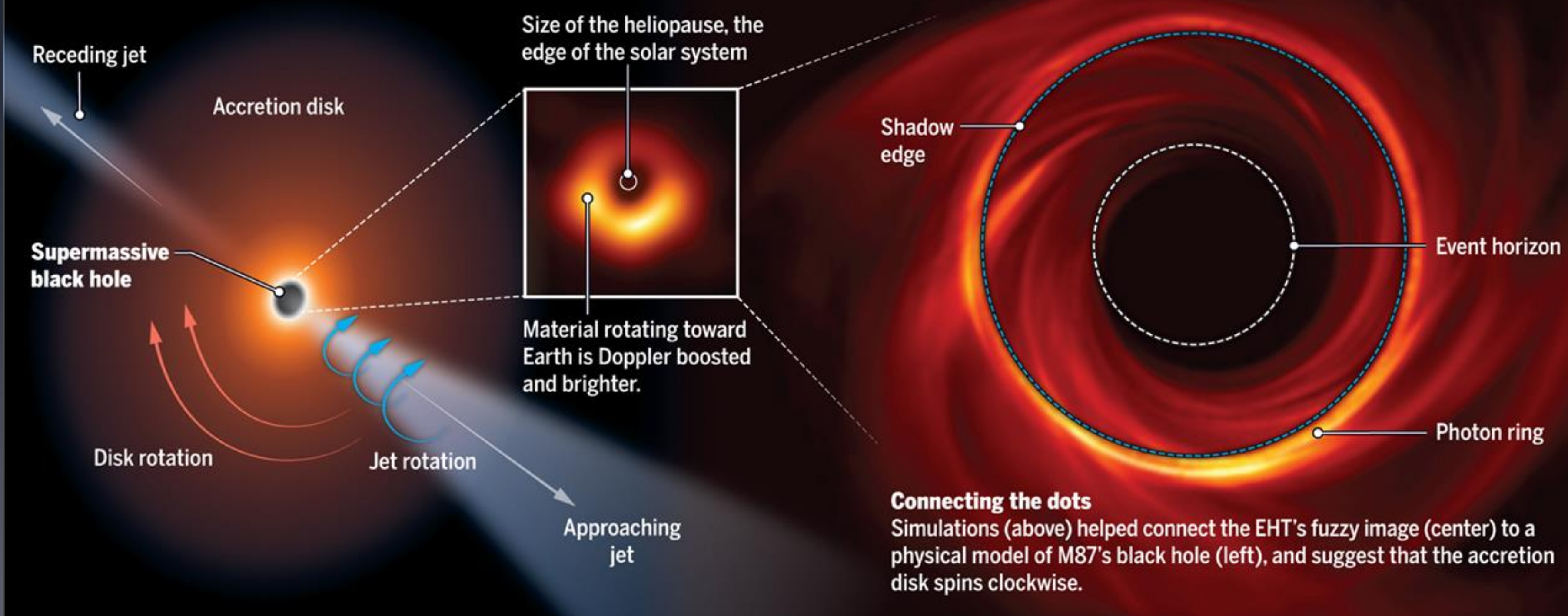




M87 Black Hole – Event Horizon Telescope
ALMA image of the jet
Relativistic jet
EHT image of the black hole shadow
1500 light years
6 arcseconds
Size of the Solar System
Supermassive black hole
0.01 light years
40 microarcseconds
Simulated image
Accretion disc
Event horizon
Photon ring
Material rotating toward Earth is Doppler boosted and brighter
C. Goddi, Z. Younsi, J. Davelaar/M.Kornmesser/ESO

Strange beast

The Event Horizon Telescope (EHT) team took 2 years to produce an image of the black hole at the center of nearby galaxy Messier 87 (M87), which feeds on a swirling disk of bright matter. Its gravity is so strong that photons orbit it, creating a bright ring. Gravitational lensing magnifies the black hole's event horizon into a larger dark shadow, which may be partially filled by material in front of the hole.



Hubble (Space Telescope) Deep Field:

A lot of galaxies

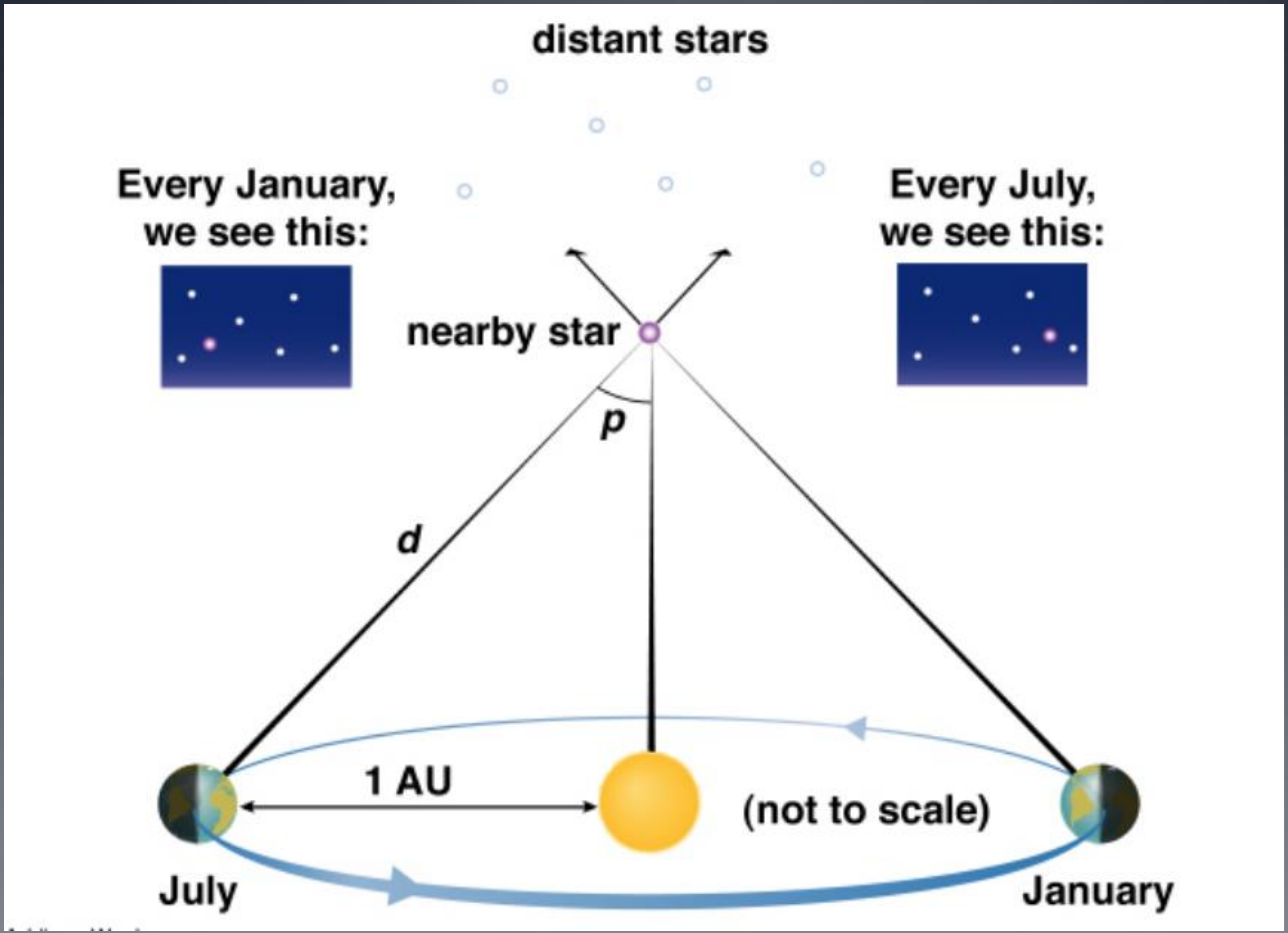
How far away are they?

The distance ladder!
How to measure distances?

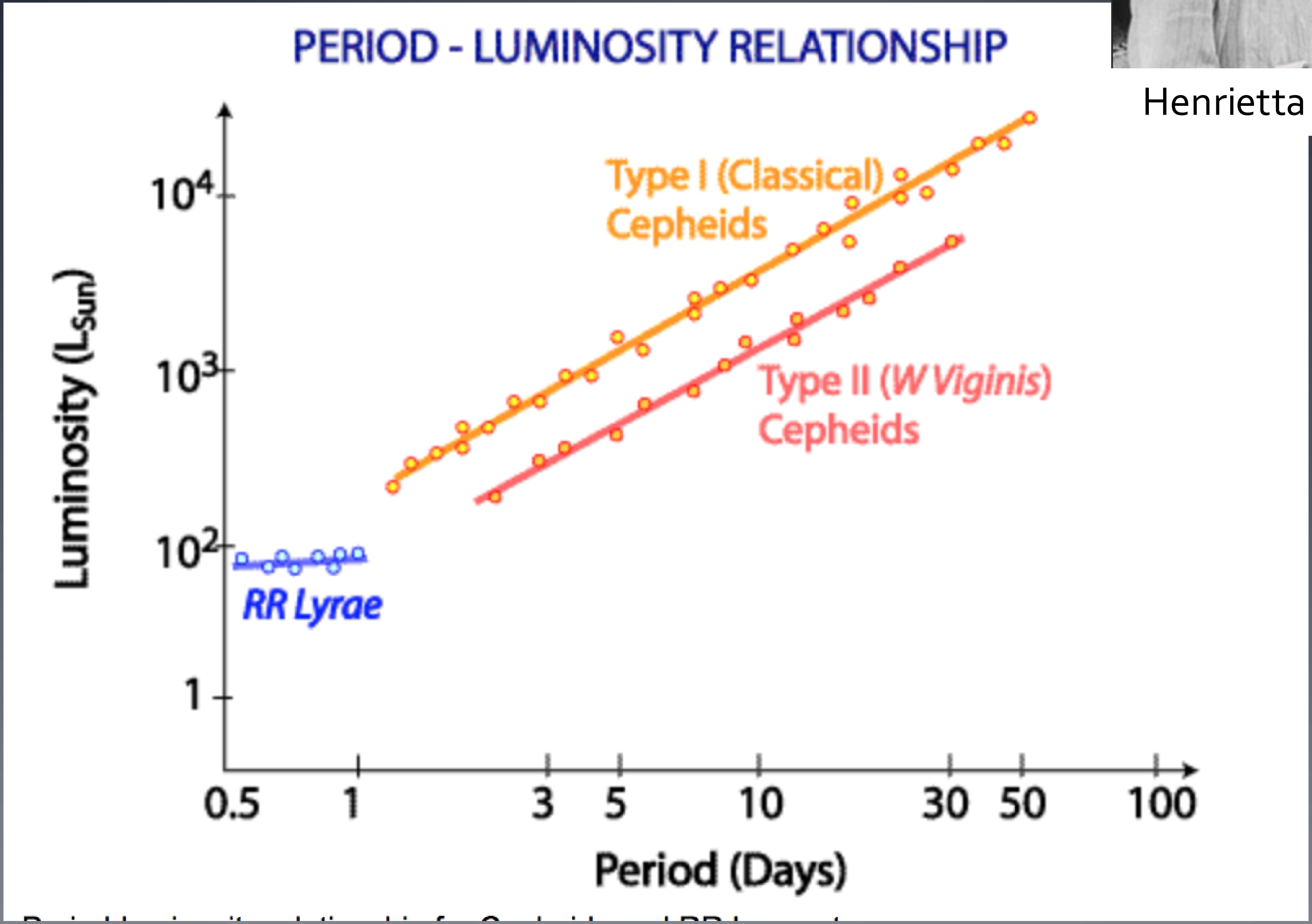
Some Methods for Estimating Distance to Galaxies

Method	Galaxy Type	Approximate Distance Range (millions of light-years)
Planetary nebulae	All	0–70
Cepheid variables	Spiral, irregulars	0–110
Tully-Fisher relation	Spiral	0–300
Type Ia supernovae	All	0–11,000
Redshifts (Hubble's law)	All	300–13,000

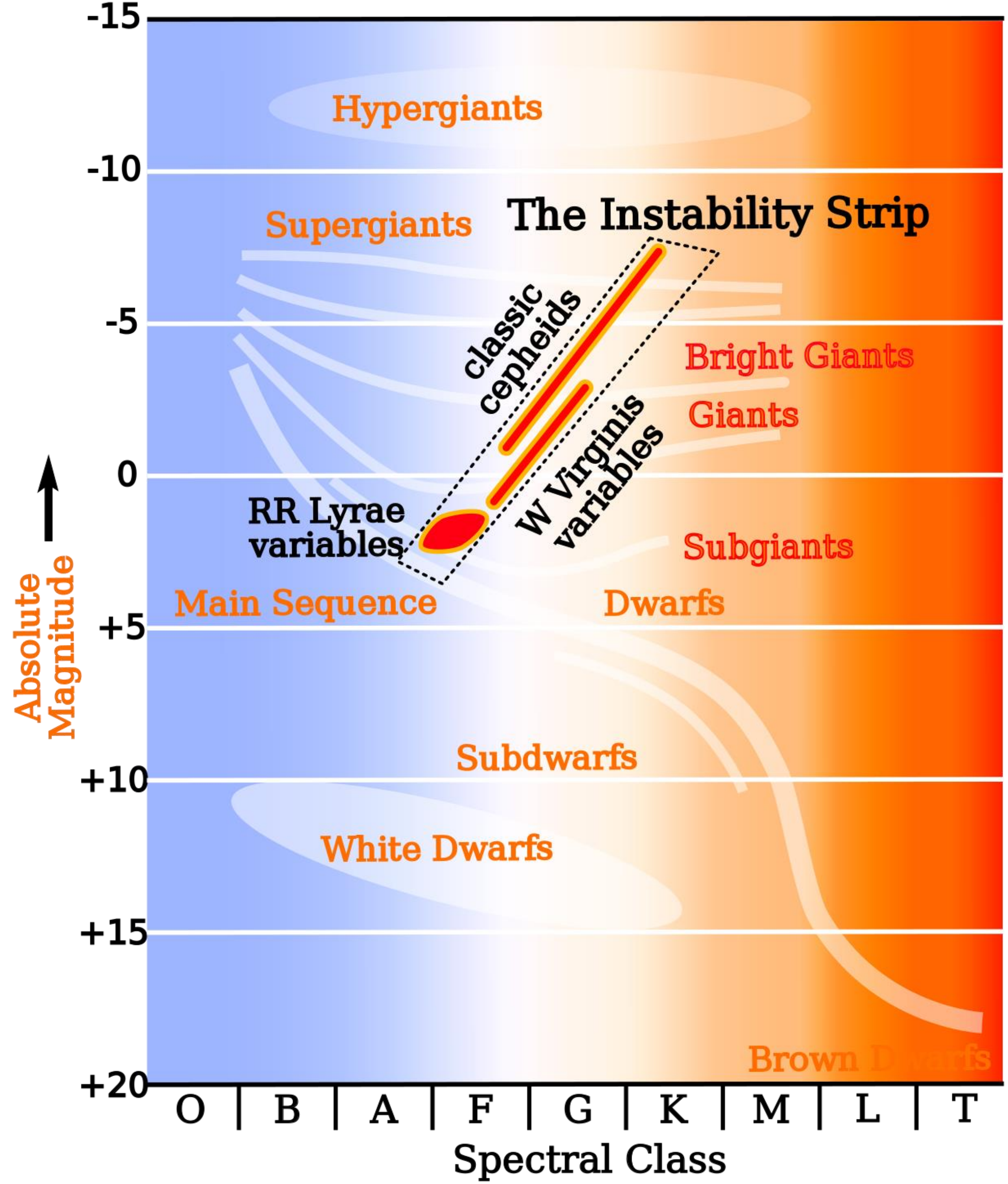
Parallax: galaxies are way too far away



Nearby galaxies: use variable stars!

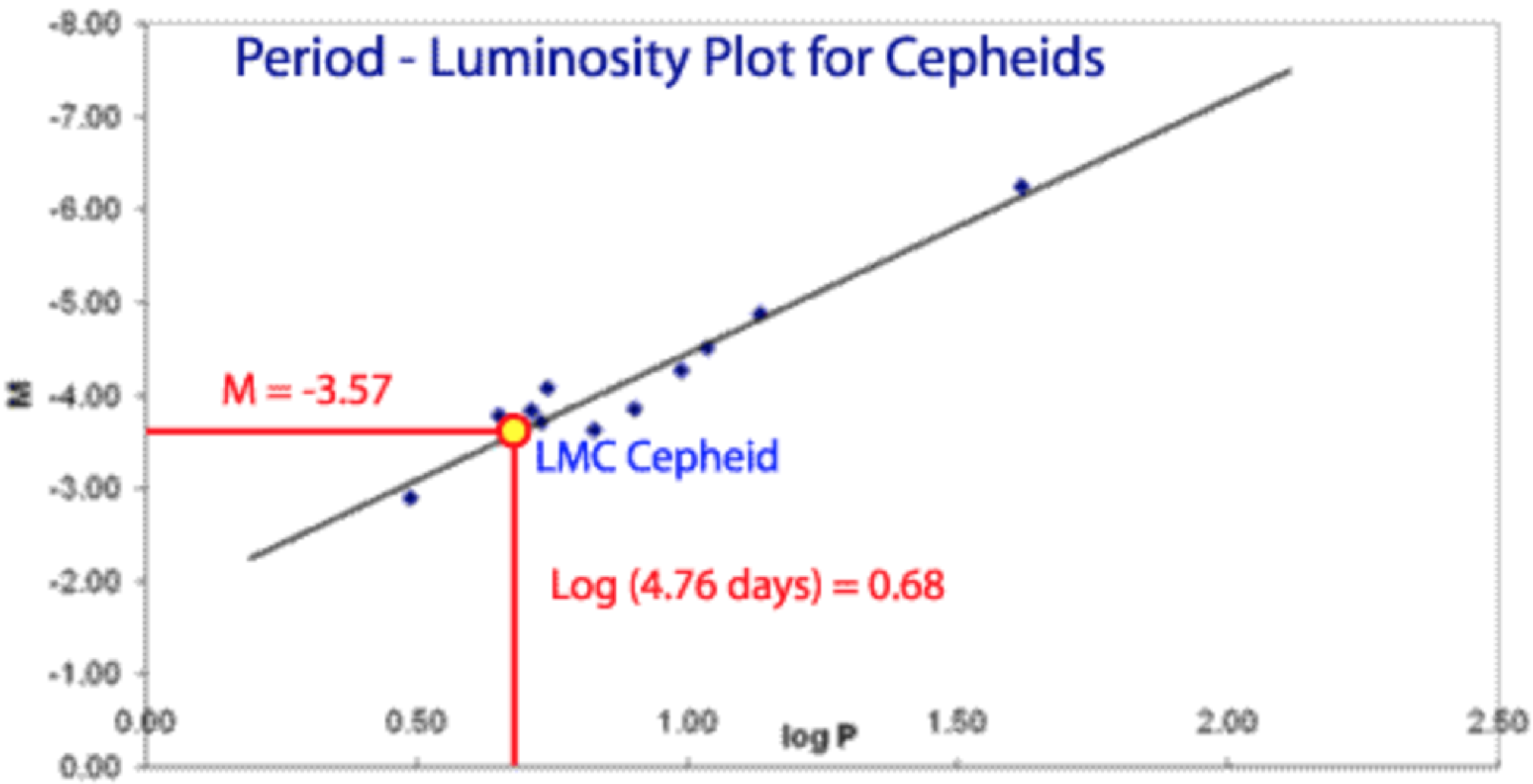


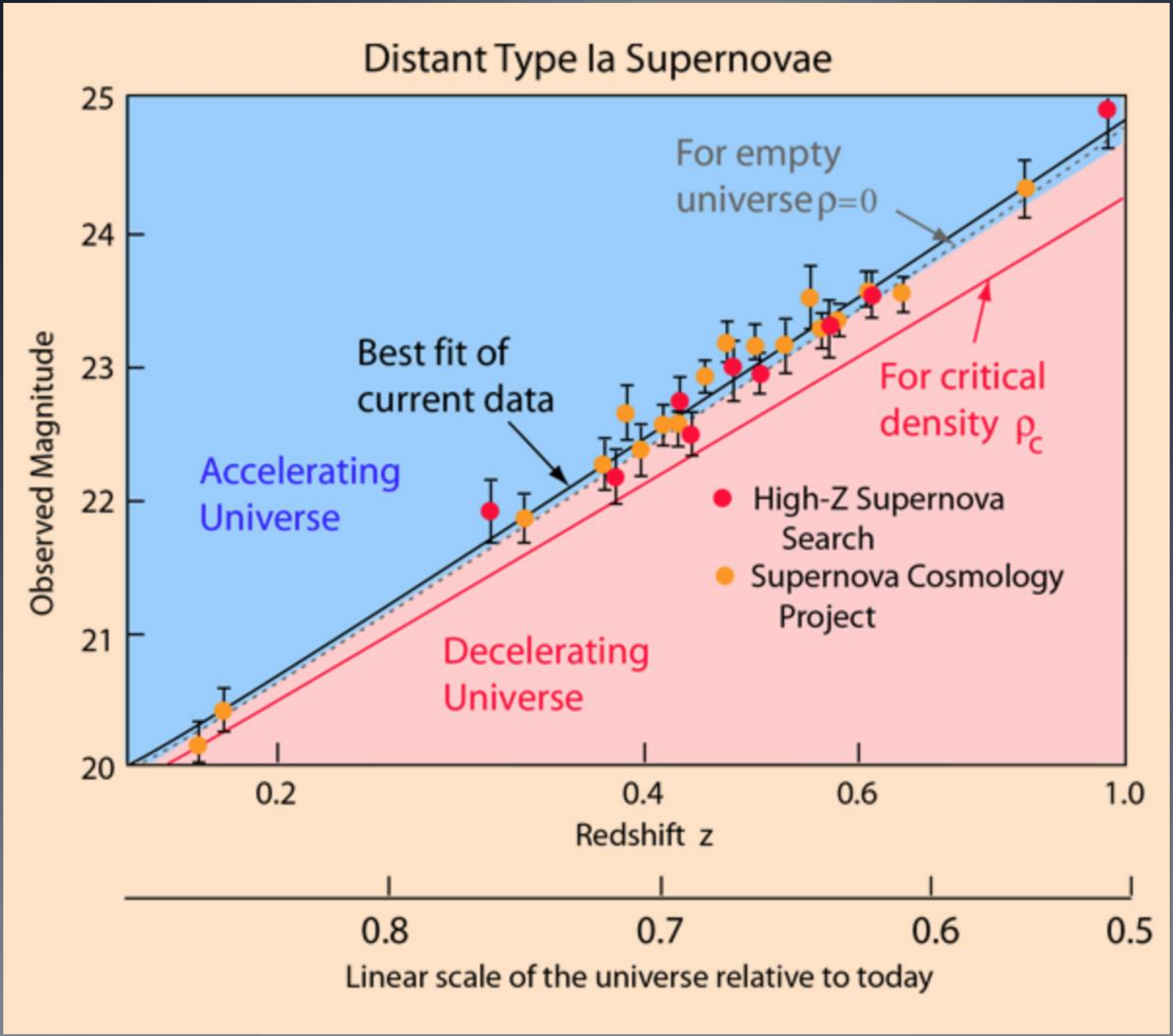
Henrietta Leavitt



The Instability Strip
Hypergiants
Supergiants
classic cepheids
W Virginis variables
Bright Giants
Giants
RR Lyrae variables
Subgiants
Main Sequence
Dwarfs
Subdwarfs
White Dwarfs
Brown Dwarfs
Absolute Magnitude
-15
-10
-5
0
+5
+10
+15
+20
O
B
A
F
G
K
M
L
T
Spectral Class

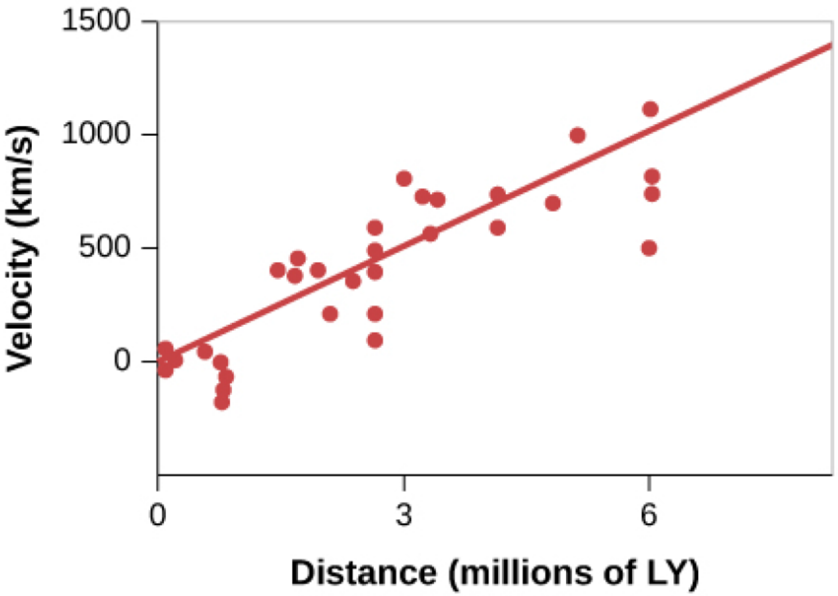
Period => absolute magnitude => distance



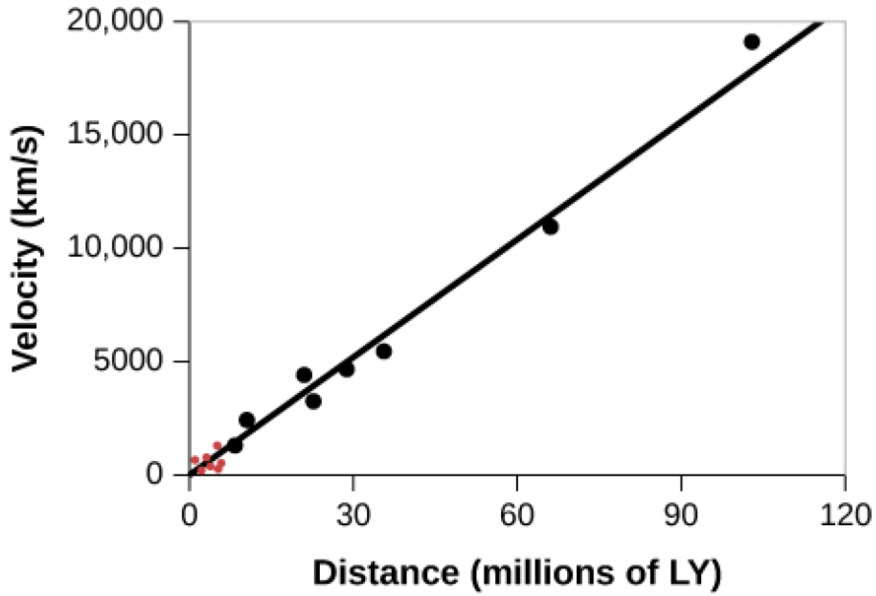

Distant Type Ia Supernovae
25
24
23
22
21
20
Observed Magnitude
For empty universe ρ=0
Best fit of current data
Accelerating Universe
For critical density ρc
High-Z Supernova Search
Supernova Cosmology Project
Decelerating Universe
0.2
0.4
0.6
1.0
Redshift z
0.8
0.7
0.6
0.5
Linear scale of the universe relative to today

Hubble's Law: distance proportional to redshift
Redshift: spectrum of light shifted to red
(going away from us)

Hubble's Data (1929)

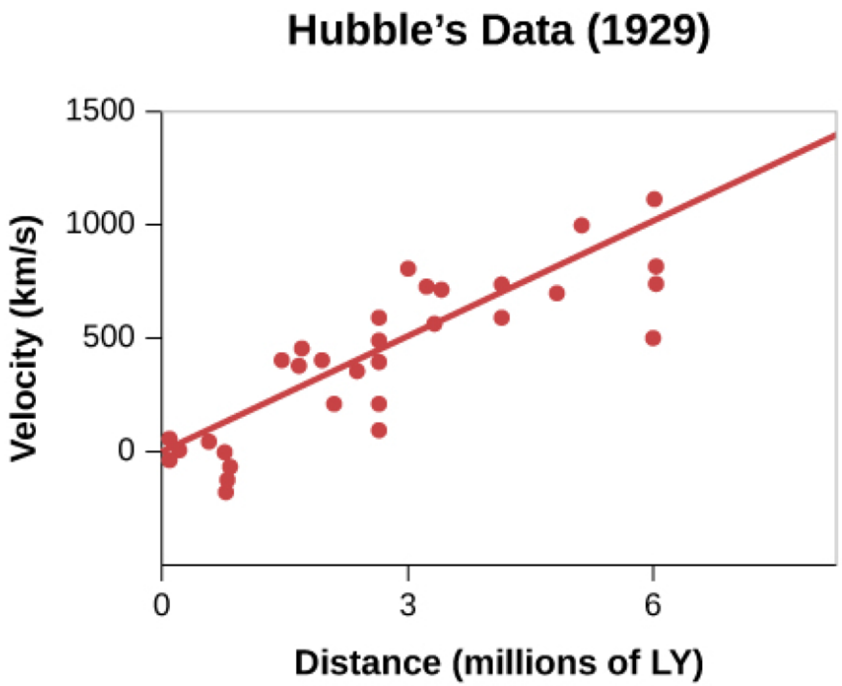


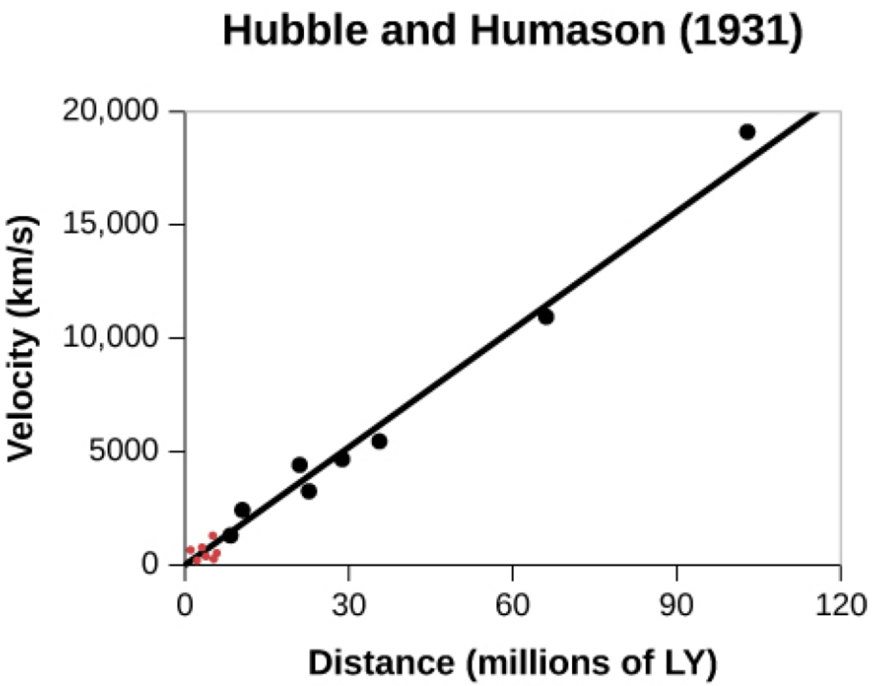
Hubble and Humason (1931)



$$V = H \times d$$

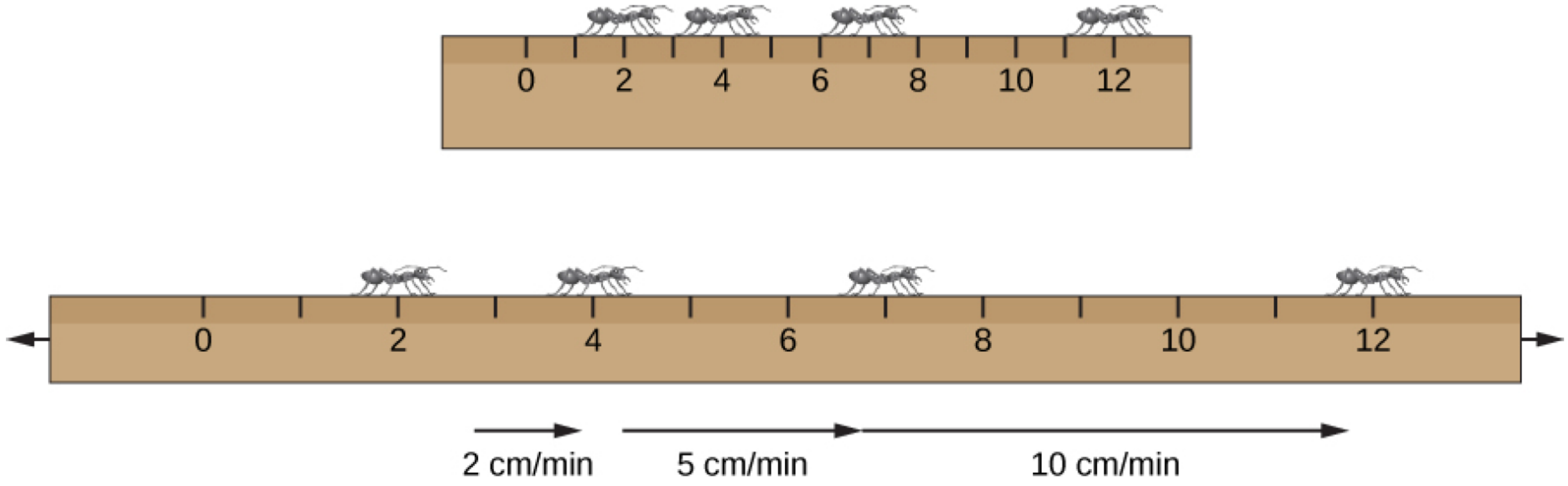
When we look at larger distances, we are looking into the past!





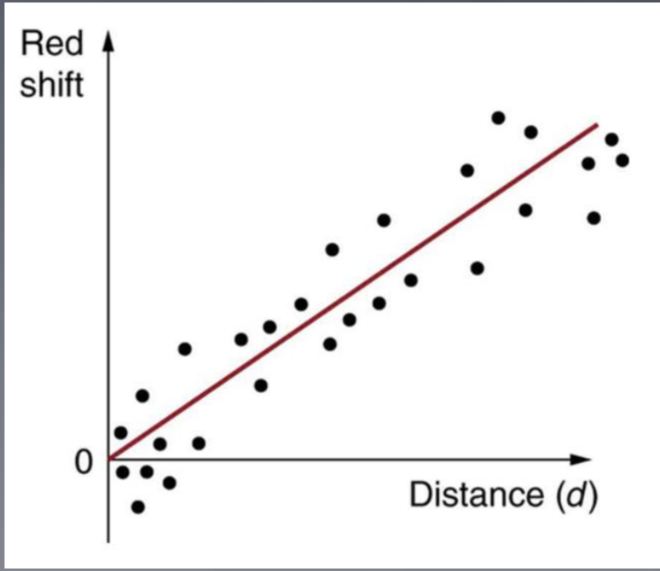
$$V = H \times d$$

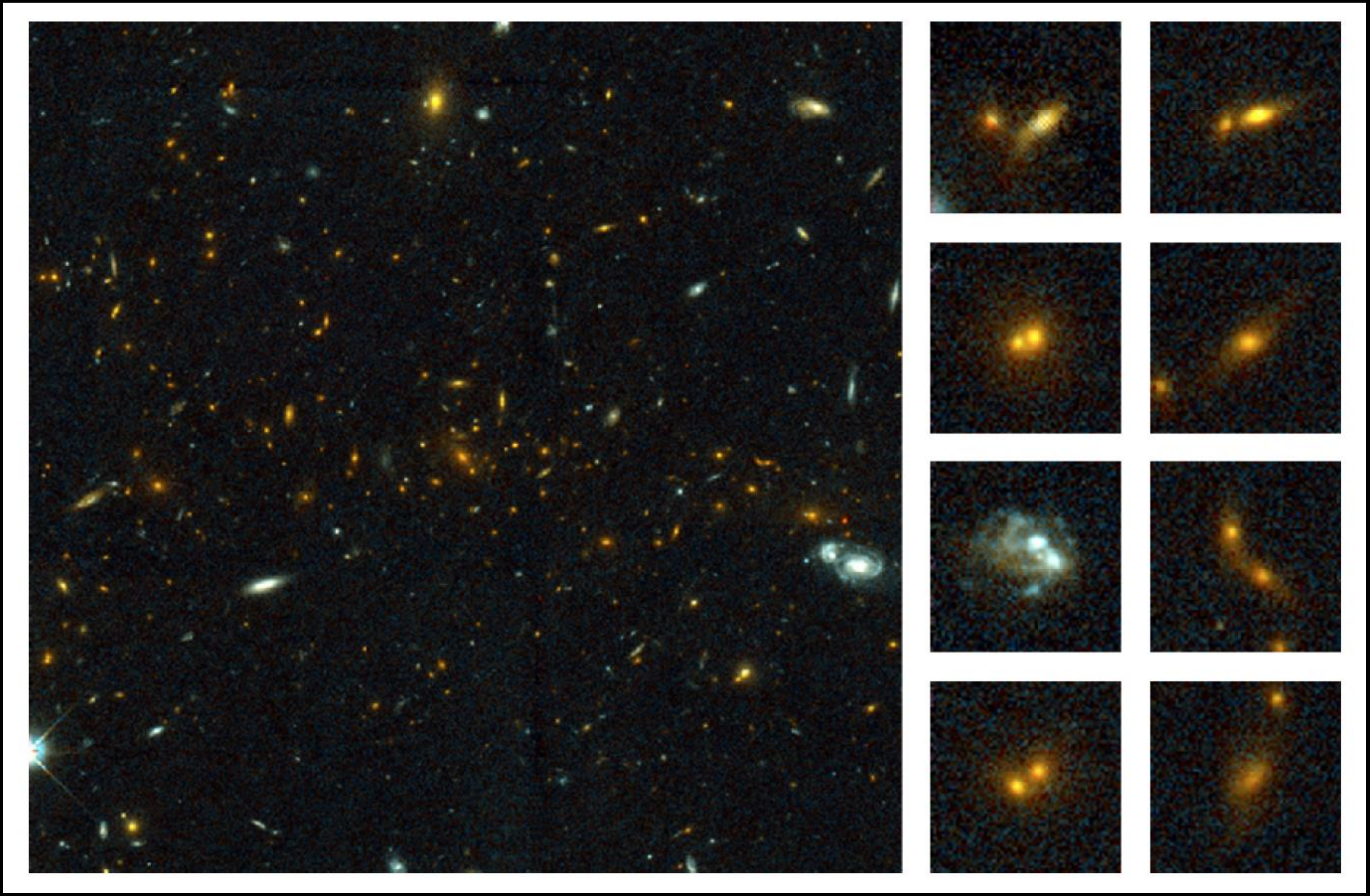
Expansion of universe and redshift



Redshift: 3D maps of a 2D sky

(More next week for cosmology)

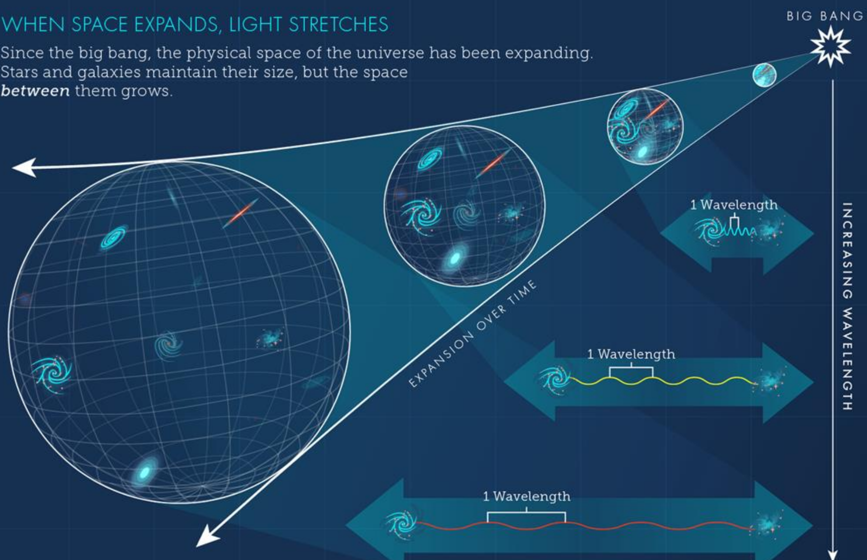




WHAT IS
COSMOLOGICAL REDSHIFT?

WHEN SPACE EXPANDS, LIGHT STRETCHES

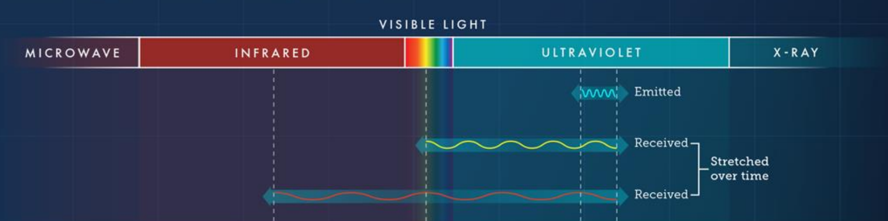
Since the big bang, the physical space of the universe has been expanding. Stars and galaxies maintain their size, but the space ***between*** them grows.



As light travels through expanding space, it is stretched to longer wavelengths.

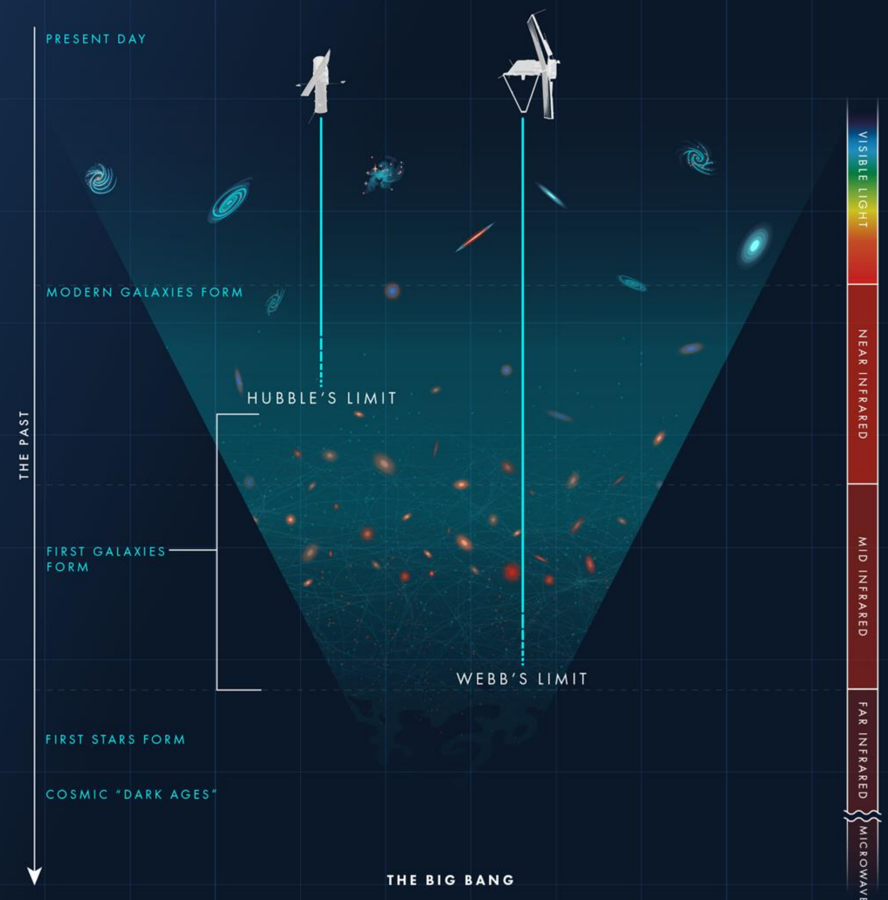
REDDER THAN RED

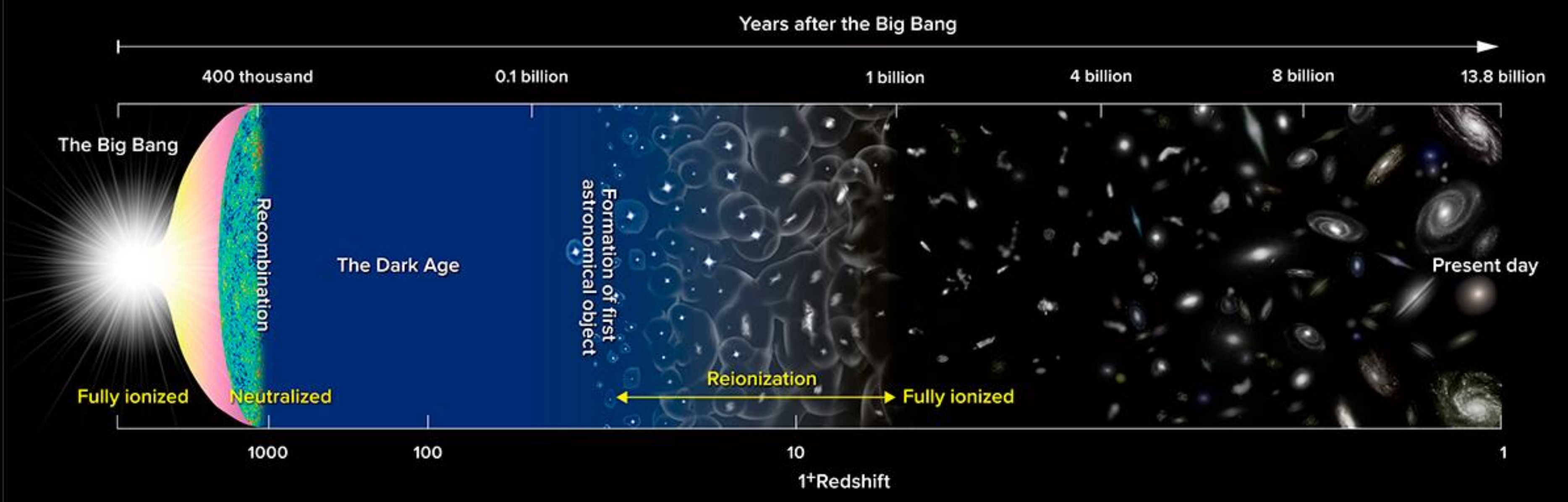
The longest visible wavelength is red.
Beyond red are longer wavelengths that we can't see, starting with infrared.
When light is stretched by the expansion of space, we say that it is **redshifted**—from its original wavelength to a longer, redder one.



SEEING THE PAST

Telescopes with **infrared** detectors allow us to see the ancient light of the first galaxies, which has been redshifted over space and time.





Years after the Big Bang
400 thousand
0.1 billion
1 billion
4 billion
8 billion
13.8 billion
The Big Bang
Recombination
The Dark Age
Formation of first astronomical object
Present day
Reionization
Fully ionized
Neutralized
Fully ionized
1000
100
10
1
1+Redshift

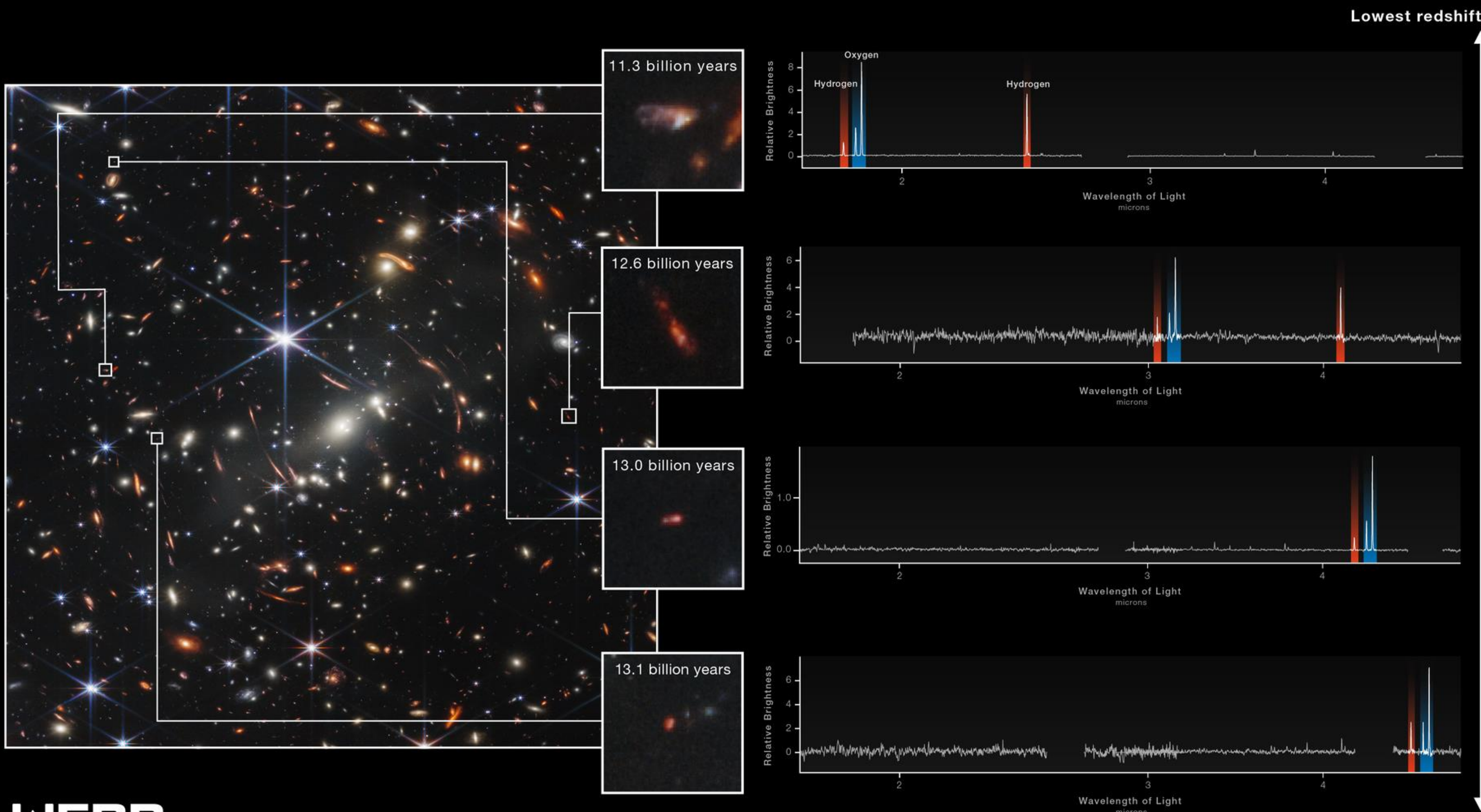
Searching for galaxies: redshift and wavelength

GALAXY CLUSTER SMACS 0723

WEBB SPECTRA IDENTIFY GALAXIES IN THE VERY EARLY UNIVERSE

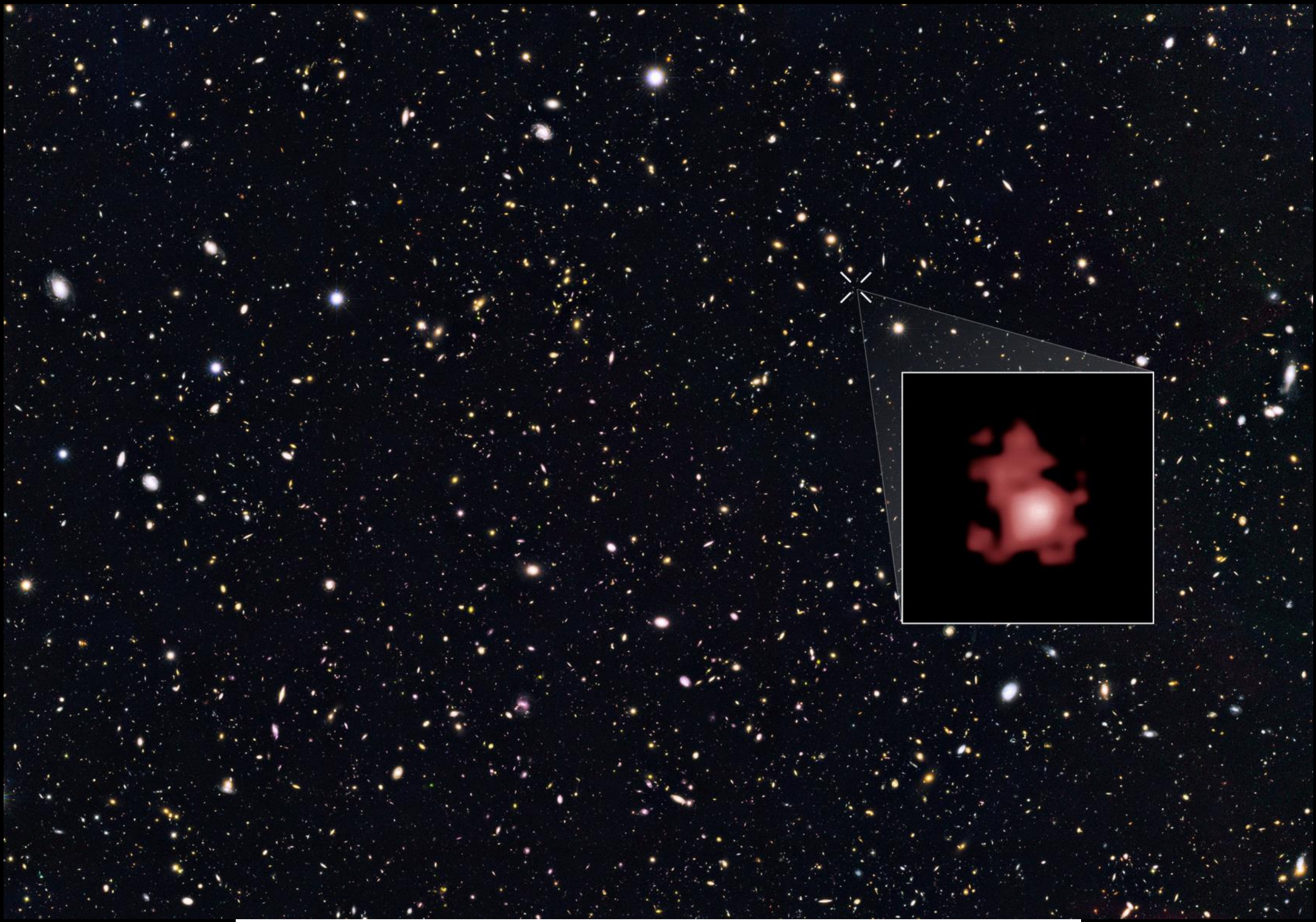
NIRCam Imaging

NIRSpec Microshutter Array Spectroscopy

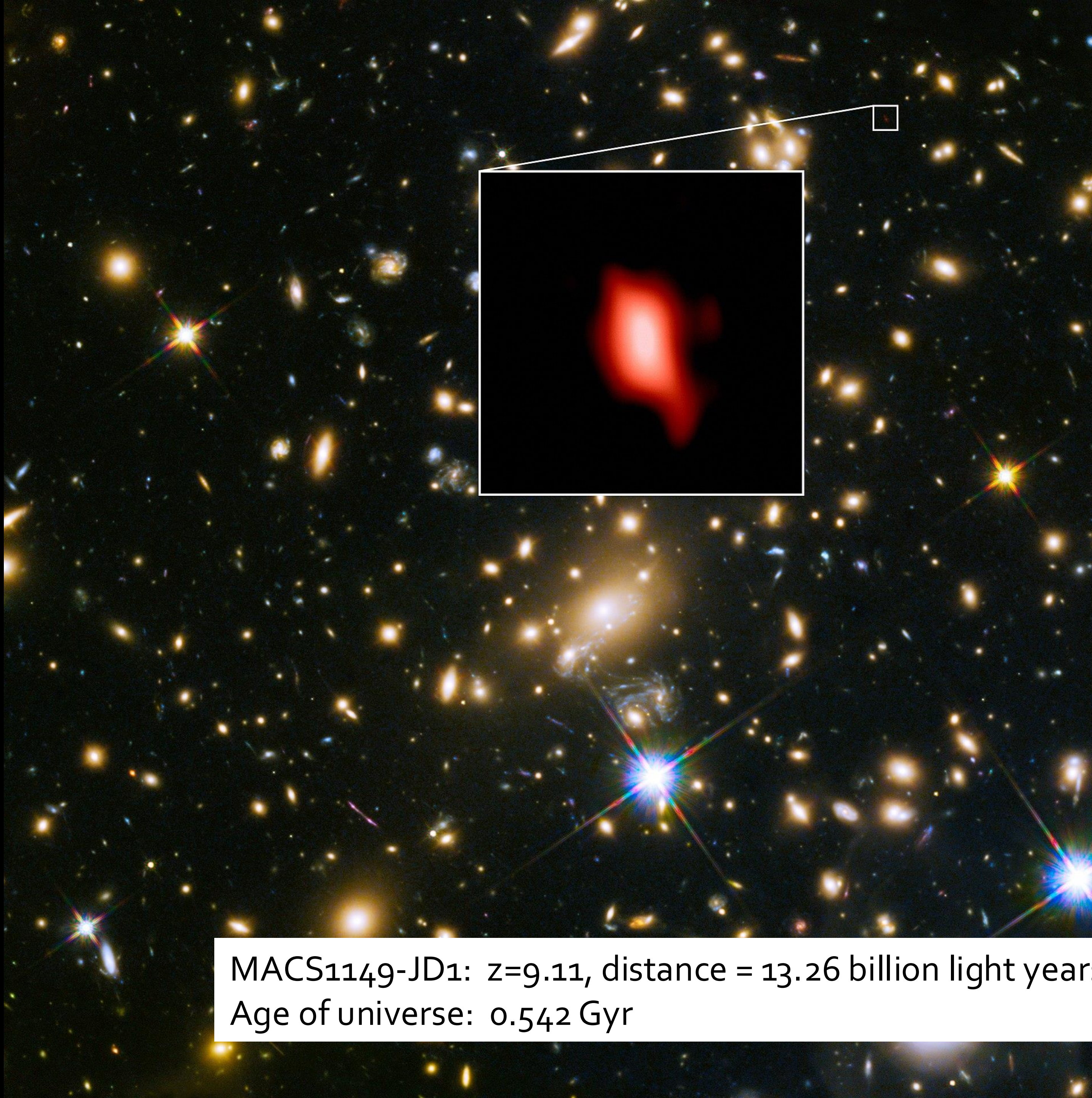


WEBB
SPACE TELESCOPE


a
b
c
a
b
c

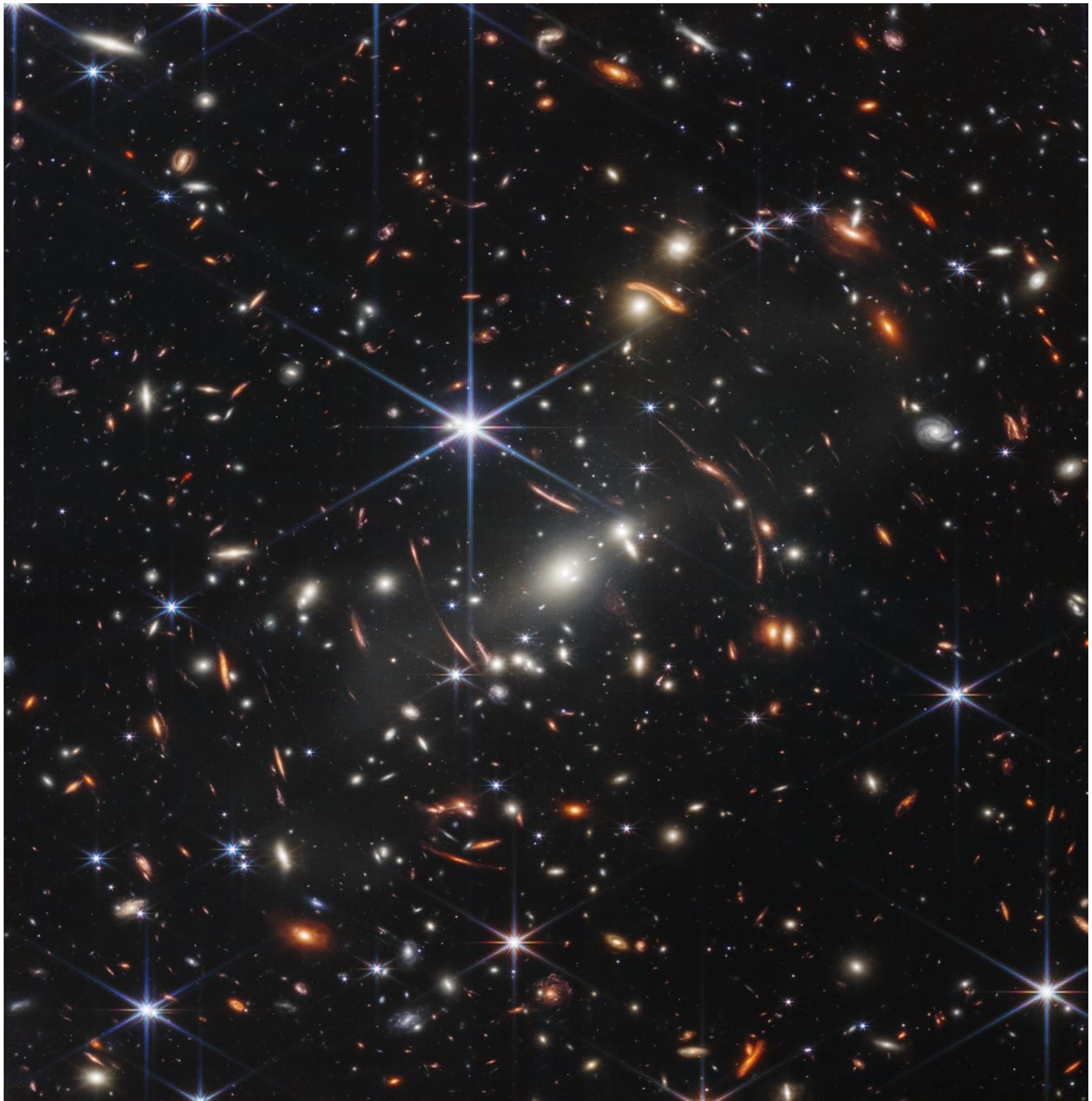


Most distant known object (before JWST)
GN-z11: z=11.09, distance = 13.39 billion light years
Age of universe: 0.414 Gyr



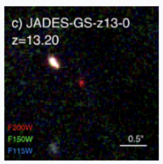
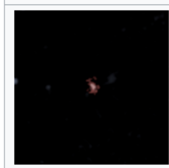
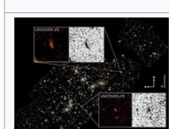
MACS1149-JD1: z=9.11, distance = 13.26 billion light years
Age of universe: 0.542 Gyr

JWST Early Images

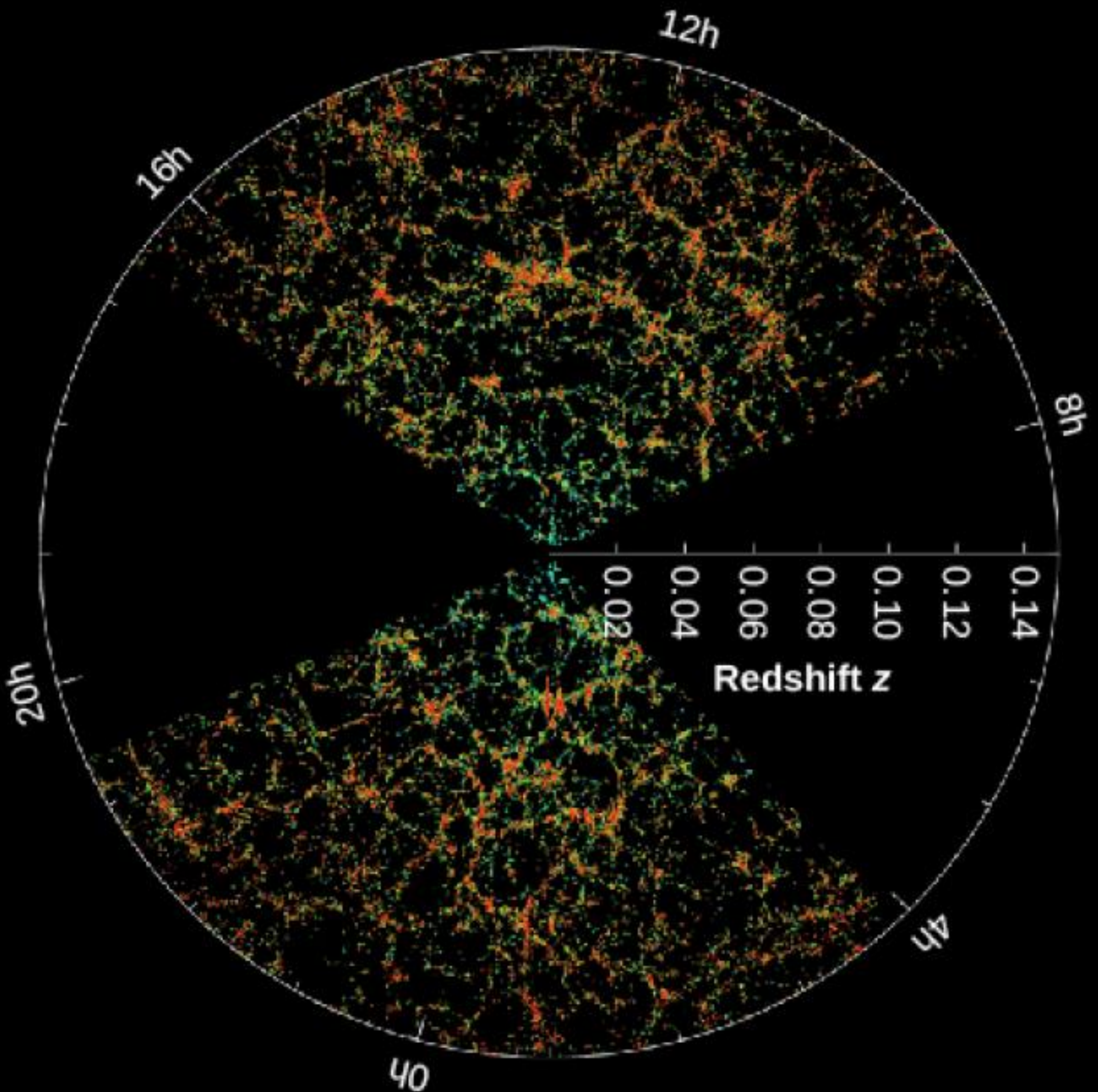


- James Webb Space Telescope
- New infrared telescope

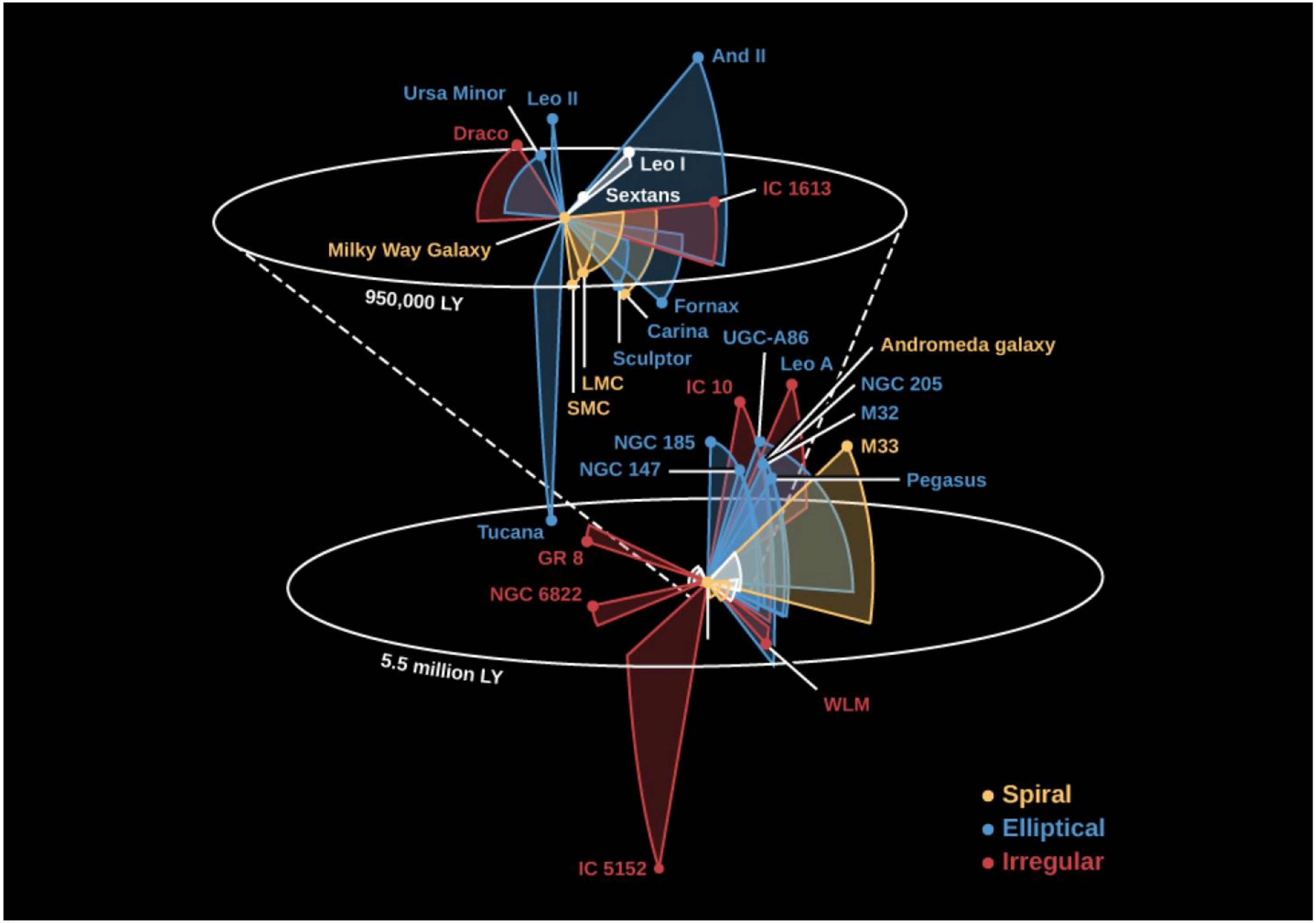
Most distant astronomical objects with spectroscopic redshift determinations

Image	Name	Redshift (z)	Light travel distance§ (Gly)[4][5][6][7]	Proper distance (Gly)	Type	Notes
	JADES-GS-z14-0	$z = 14.32^{+0.08}_{-0.20}$			Galaxy	Lyman-break galaxy, detection of the Lyman break with JWST/NIRSpec.[8]
	JADES-GS-z14-1	$z = 13.90^{+0.17}_{-0.17}$			Galaxy	Lyman-break galaxy, detection of the Lyman break with JWST/NIRSpec.[9]
	JADES-GS-z13-0	$z = 13.20^{+0.04}_{-0.07}$	13.576[4] / 13.596[5] / 13.474[6] / 13.473[7]	33.6	Galaxy	Lyman-break galaxy, detection of the Lyman break with JWST/NIRSpec.[10]
	UNCOVER-z13	$z = 13.079^{+0.014}_{-0.001}$	13.51	32.56†	Galaxy	Lyman-break galaxy, detection of the Lyman break with JWST/NIRSpec.[11]
	JADES-GS-z12-0	$z = 12.63^{+0.24}_{-0.08}$	13.556[4] / 13.576[5] / 13.454[6] / 13.453[7]	32.34†	Galaxy	Lyman-break galaxy, detection of the Lyman break with JWST/NIRCam [10] and JWST/NIRSpec,[12] and CIII] line emission with JWST/NIRSpec.[12] Most distant spectroscopic redshift from emission lines; most distant detection of non-primordial elements (C, O, Ne).
	UNCOVER-z12	$z = 12.393^{+0.004}_{-0.001}$	13.48	32.21†	Galaxy	Lyman-break galaxy, detection of the Lyman break with JWST/NIRSpec.[11]

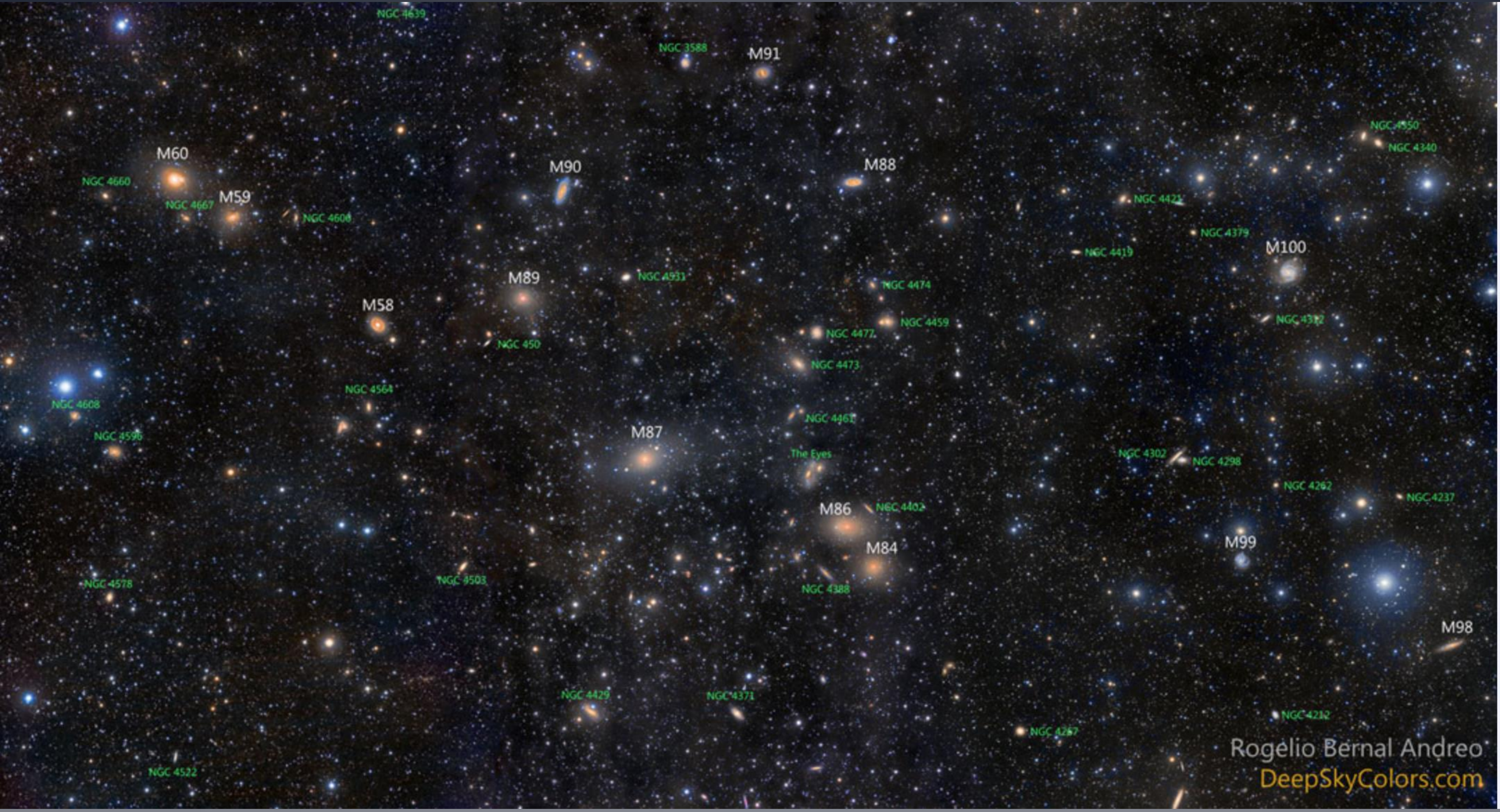
3D map of the universe: clusters and voids



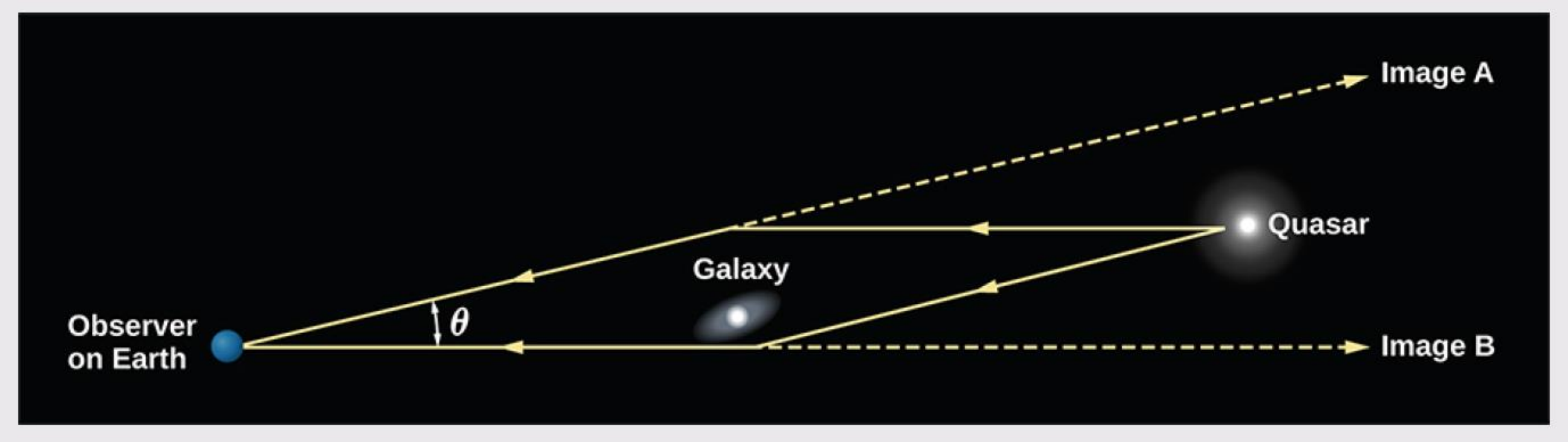
Galaxies cluster together: Local Group

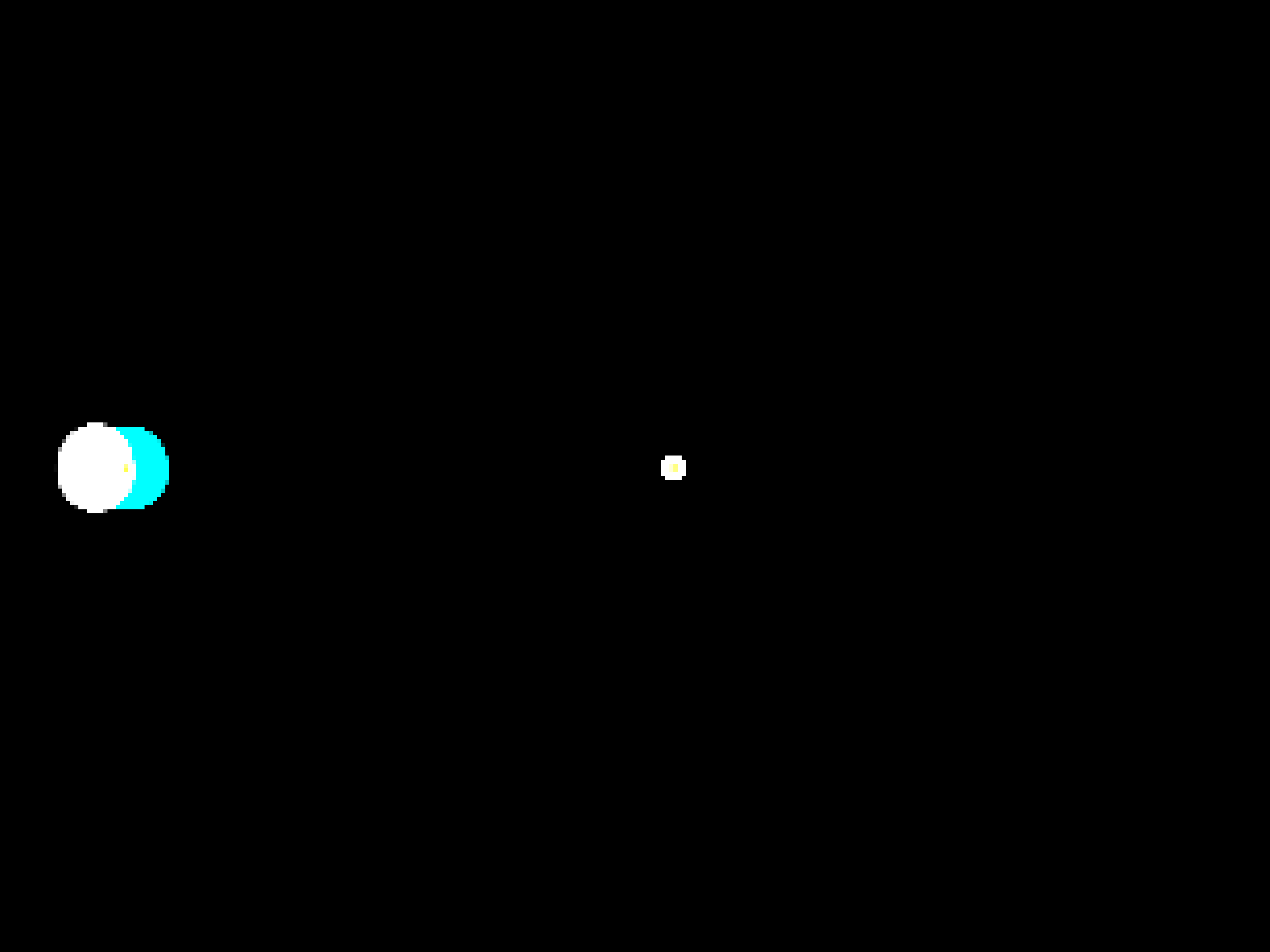


Virgo Cluster

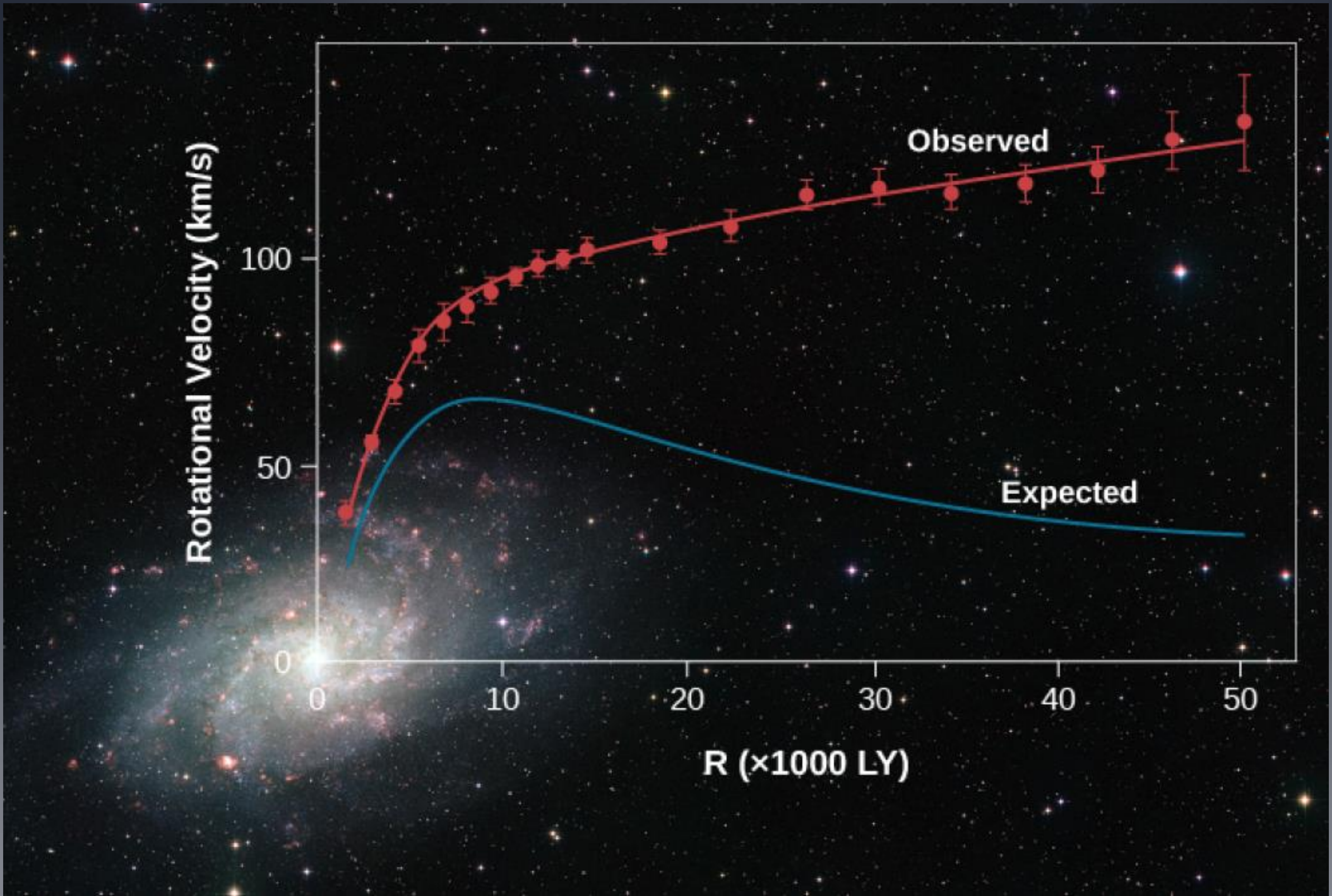


Masses and dark matter: gravitational lensing

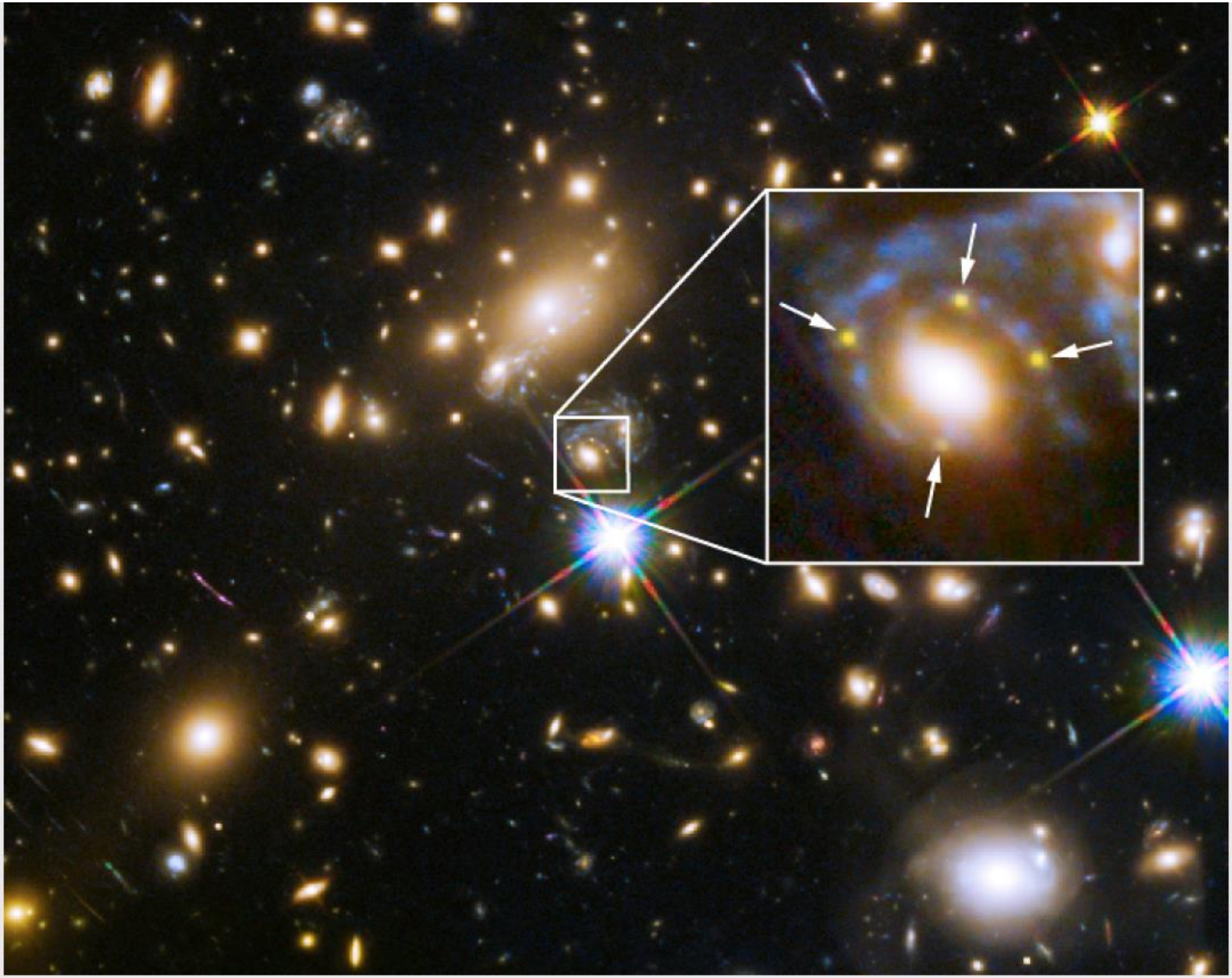


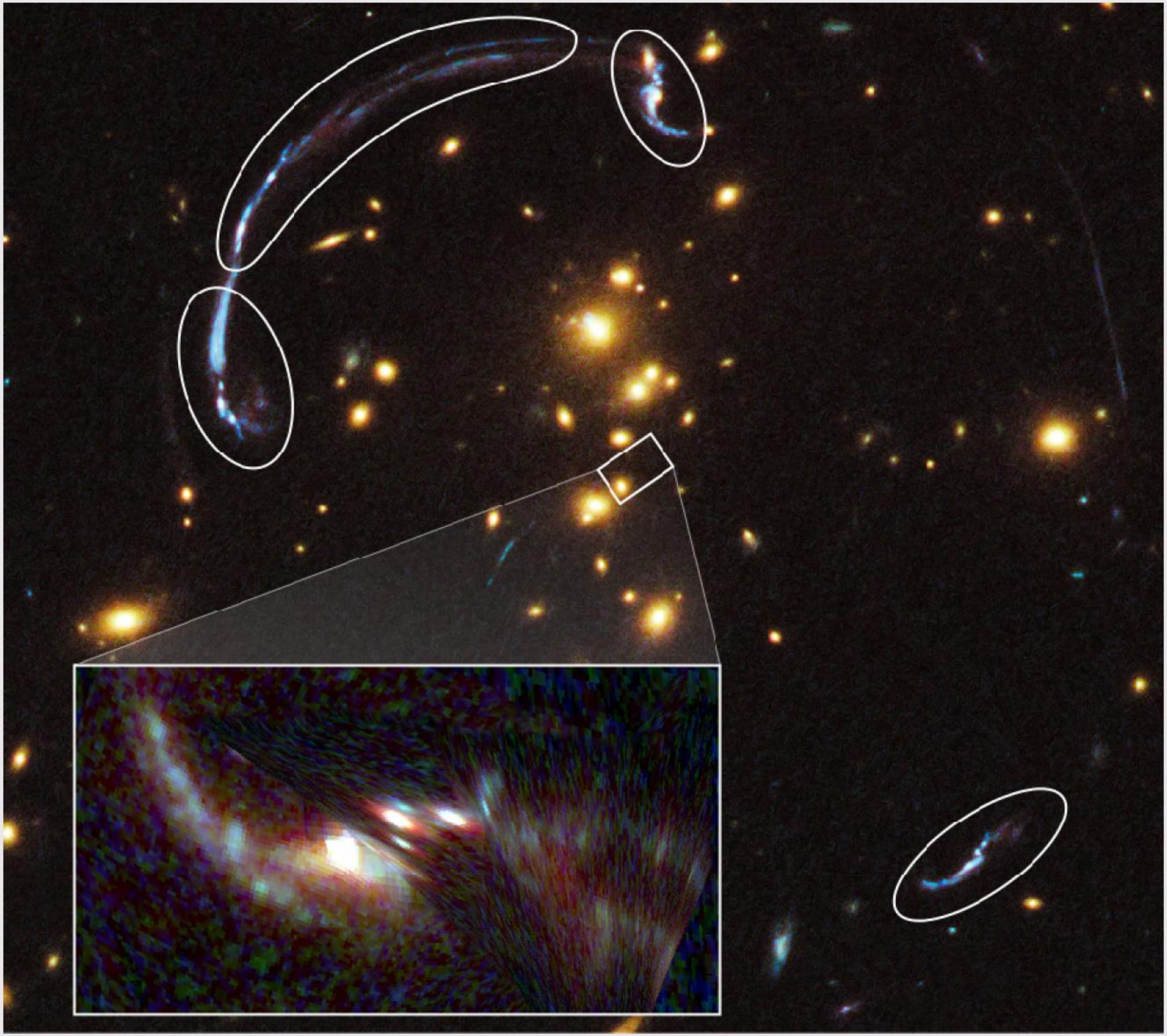


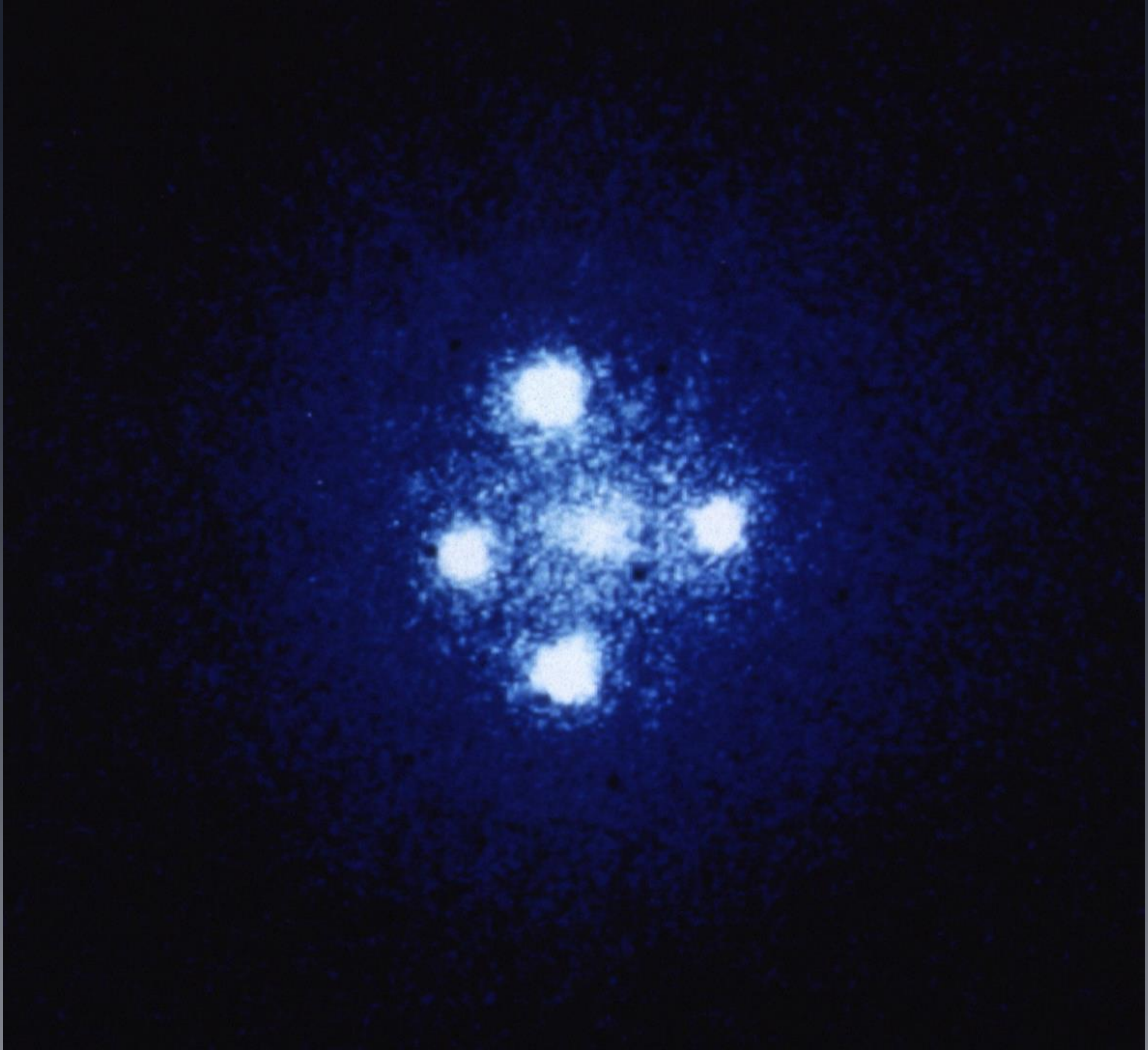
Galaxy rotation curve: evidence for dark matter

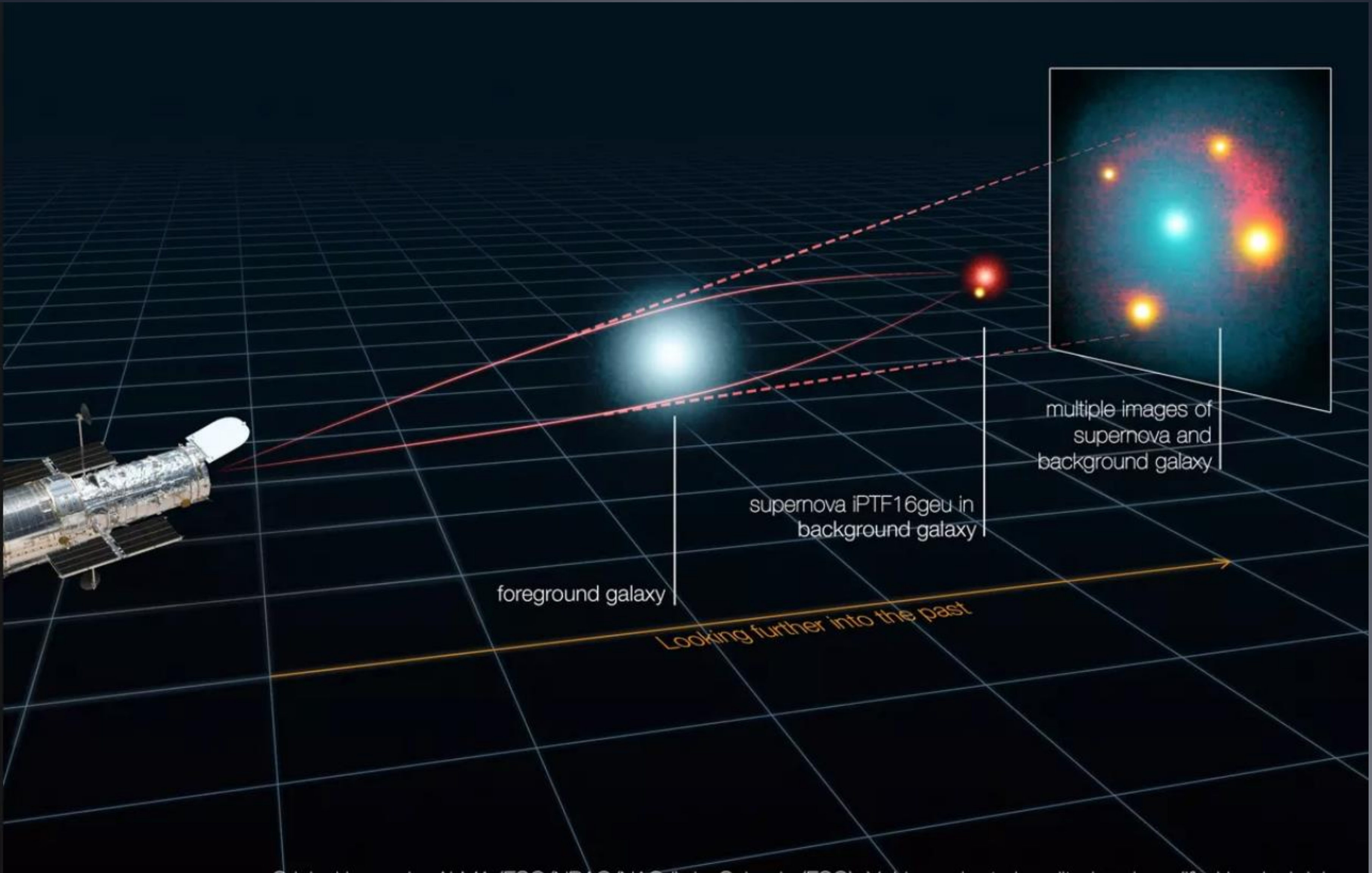


Gravitational lensing

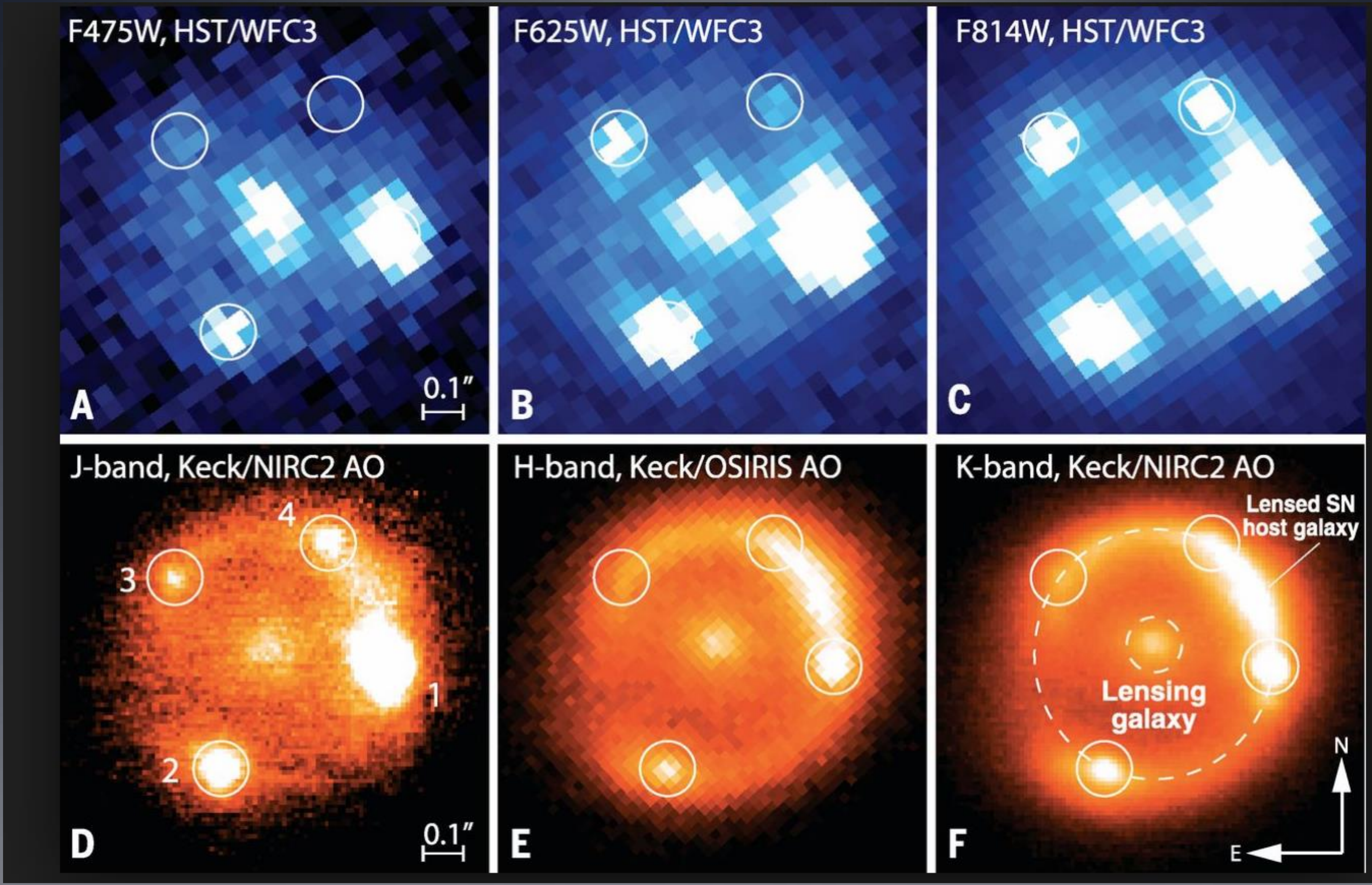




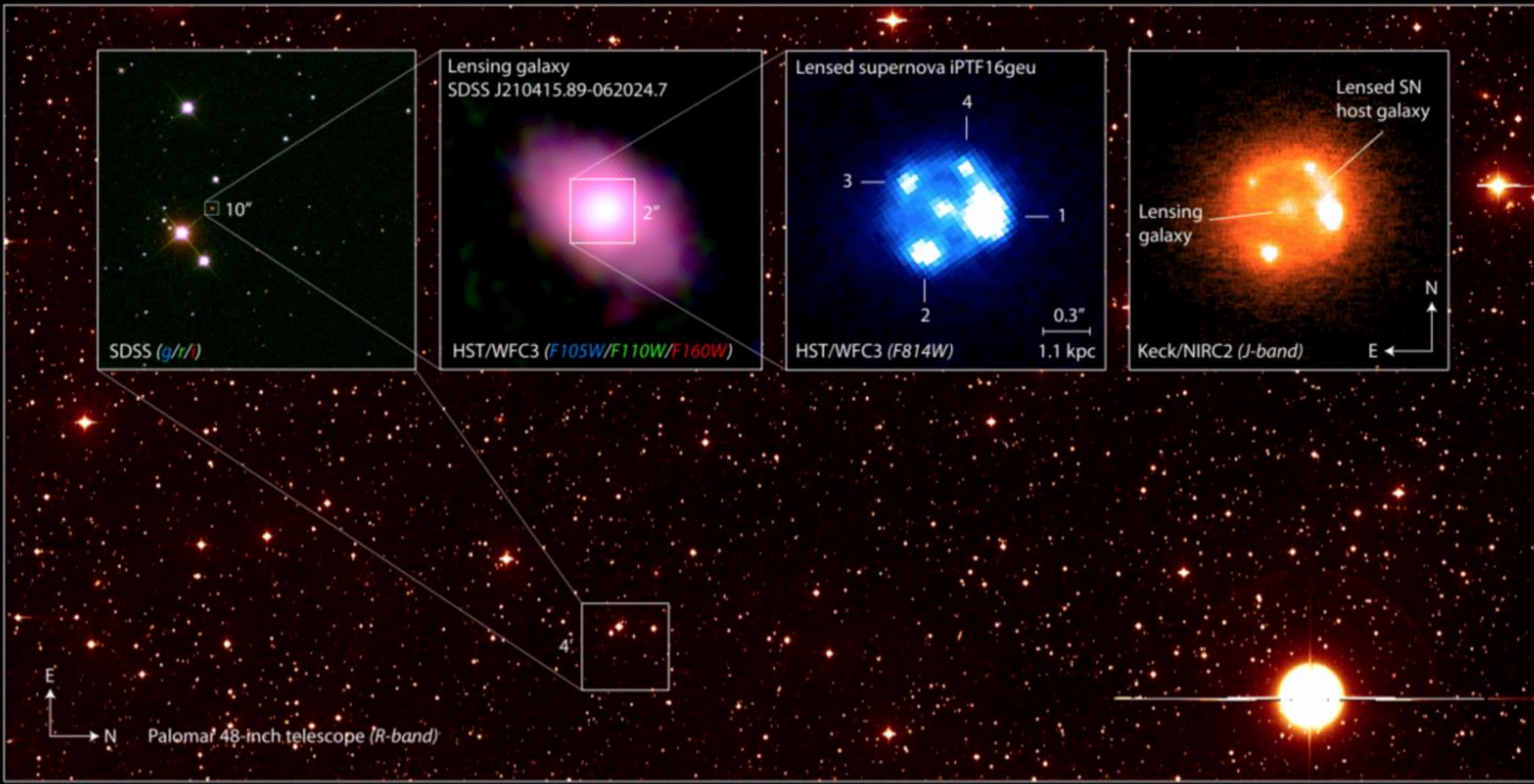




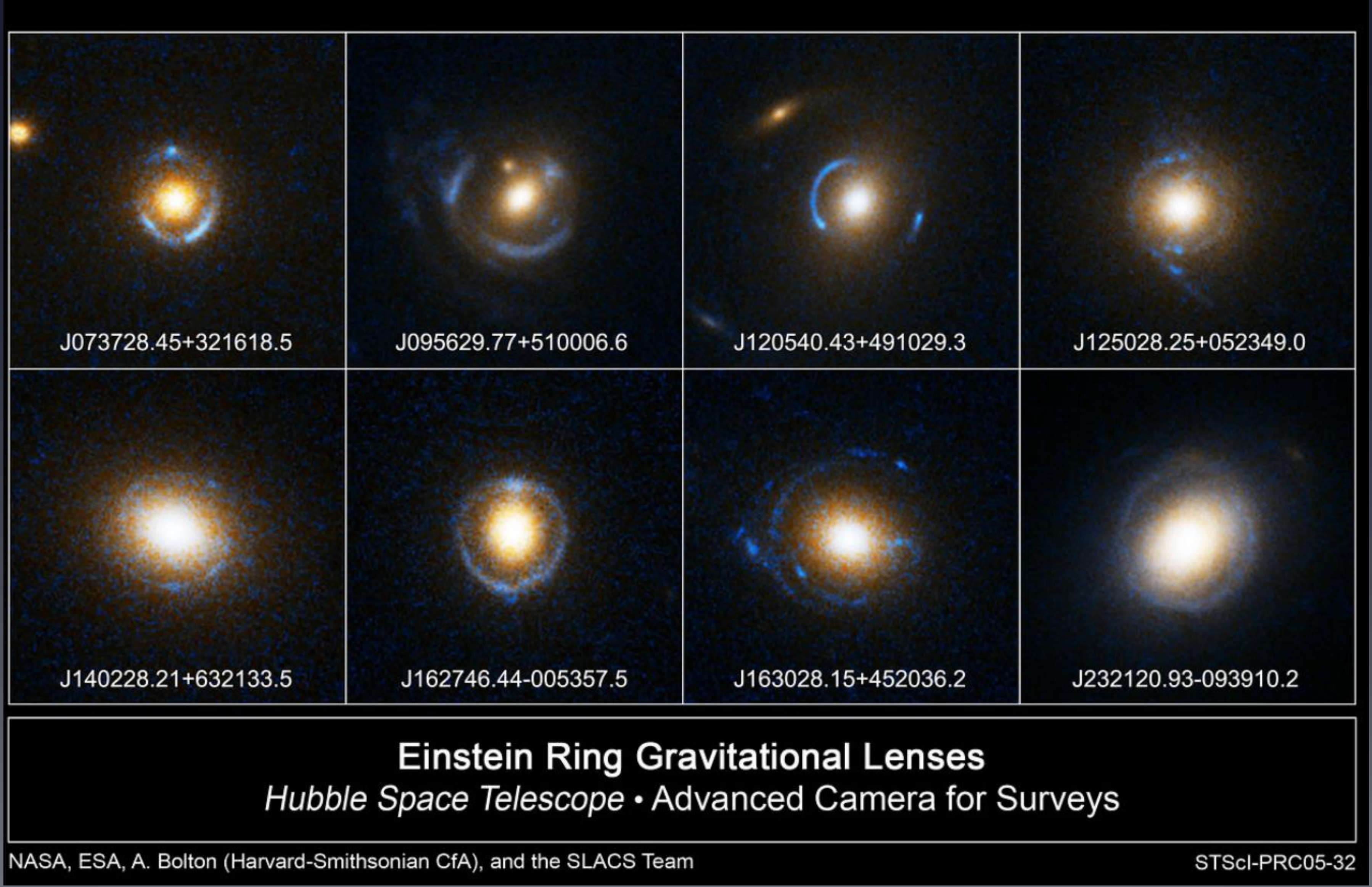
Original image by ALMA (ESO/NRAO/NAOJ), L. Calçada (ESO), Y. Hezaveh et al., edited and modified by Joel Johans



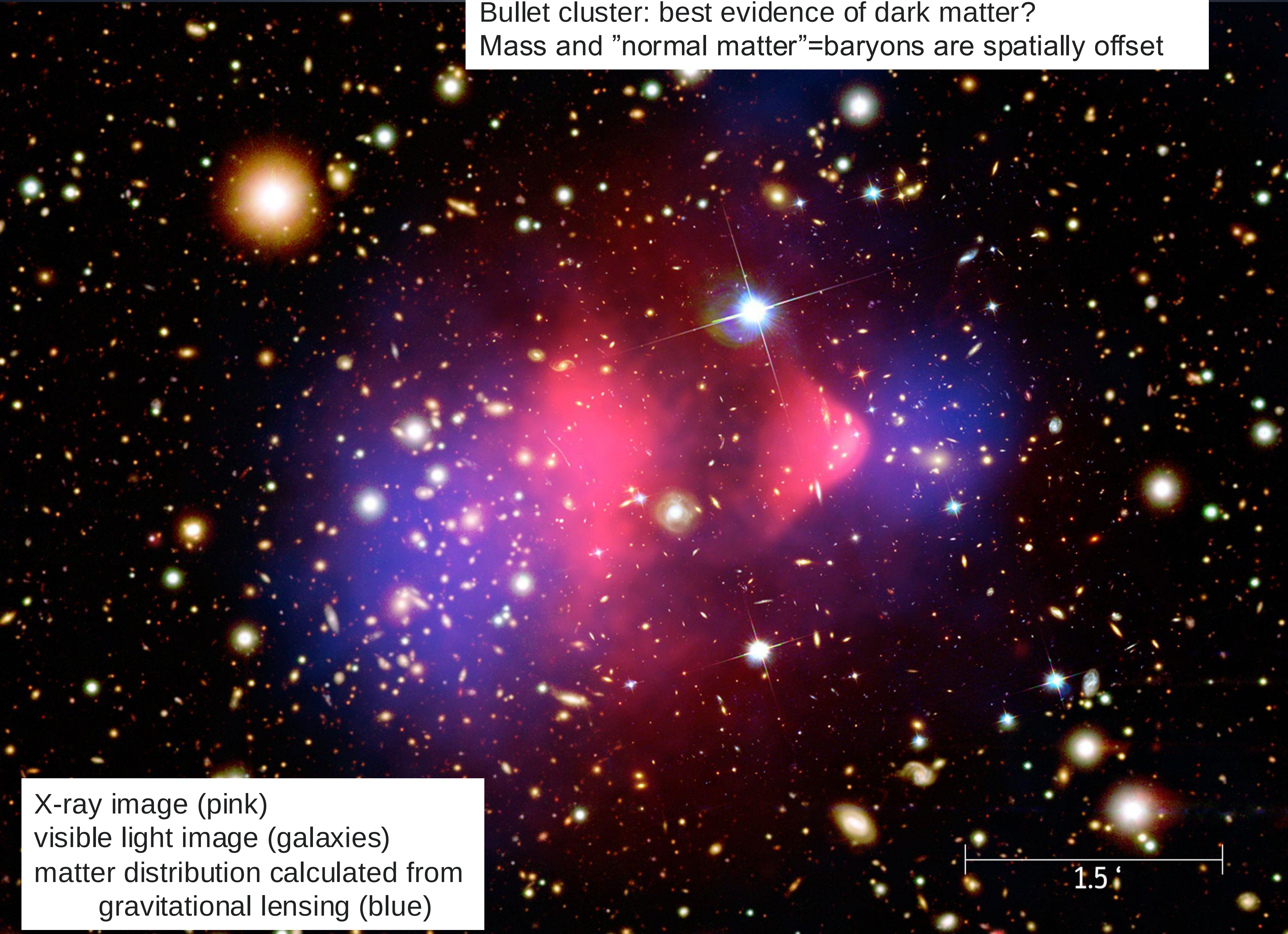
F475W, HST/WFC3
0.1″
A
F625W, HST/WFC3
B
F814W, HST/WFC3
C
J-band, Keck/NIRC2 AO
4
3
1
2
0.1″
D
H-band, Keck/OSIRIS AO
E
K-band, Keck/NIRC2 AO
Lensed SN host galaxy
Lensing galaxy
N
E
F



Lensing galaxy
SDSS J210415.89-062024.7
Lensed supernova iPTF16geu
4
3
1
2
0.3″
1.1 kpc
Lensed SN
host galaxy
Lensing
galaxy
10″
2″
SDSS (g/r/i)
HST/WFC3 (F105W/F110W/F160W)
HST/WFC3 (F814W)
Keck/NIRC2 (J-band)
N
E
4′
E
N
Palomar 48-inch telescope (R-band)


J073728.45+321618.5
J095629.77+510006.6
J120540.43+491029.3
J125028.25+052349.0
J140228.21+632133.5
J162746.44-005357.5
J163028.15+452036.2
J232120.93-093910.2
Einstein Ring Gravitational Lenses
Hubble Space Telescope • Advanced Camera for Surveys
NASA, ESA, A. Bolton (Harvard-Smithsonian CfA), and the SLACS Team
STScI-PRC05-32

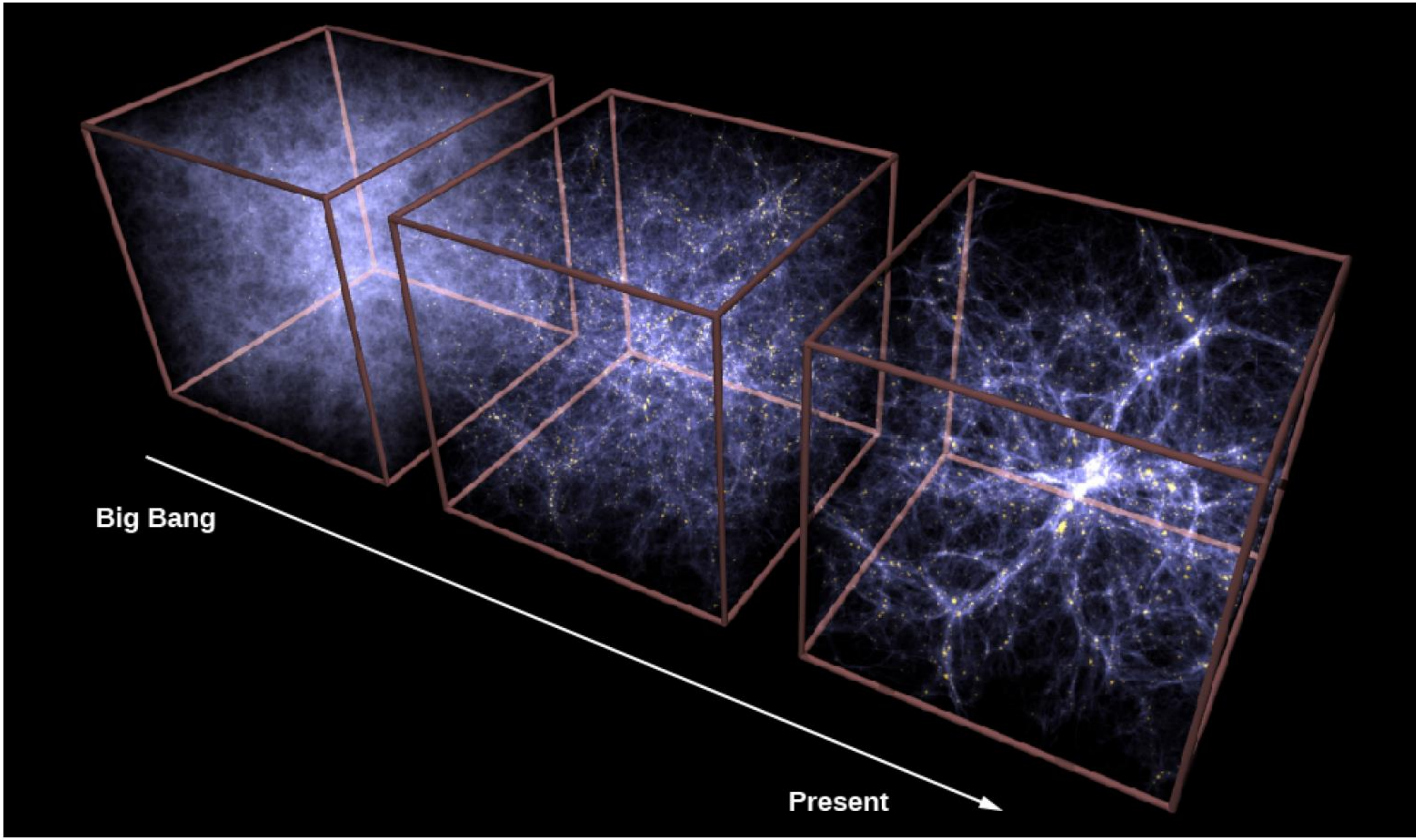
Bullet cluster: best evidence of dark matter?
Mass and ”normal matter”=baryons are spatially offset



X-ray image (pink)
visible light image (galaxies)
matter distribution calculated from
gravitational lensing (blue)

Galaxy keywords

- **Elliptical galaxy: ellipse, no star formation**
- **Irregular galaxy: no pattern, merger**
- **Spiral galaxy:**
- **Redshift: lines shifted to longer wavelength from expansion of universe**
- **Distance ladder: steps to calculate distance**
- **Galaxy evolution: changes in galaxies over cosmic time**
- **Local group: small cluster of galaxies, including Milky Way**
- **Starburst: galaxy with a burst of star formation, often a result of collisions**
- **Quasar and AGN: accreting supermassive black holes**


Big Bang
Present