



# Galaxies across the Universe

Debra Elmegreen

Emerita Professor of Astronomy

Vassar LLI Science Sampler – March 27, 2026

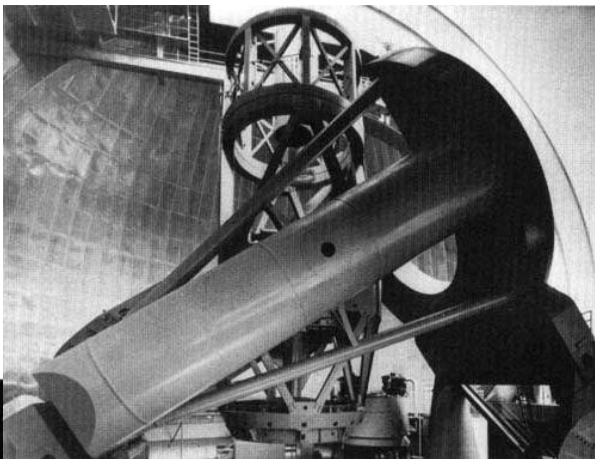
Astronomy is the oldest science...

...it inspires and unites us

Vassar LLI Science Sampler – March 27, 2026

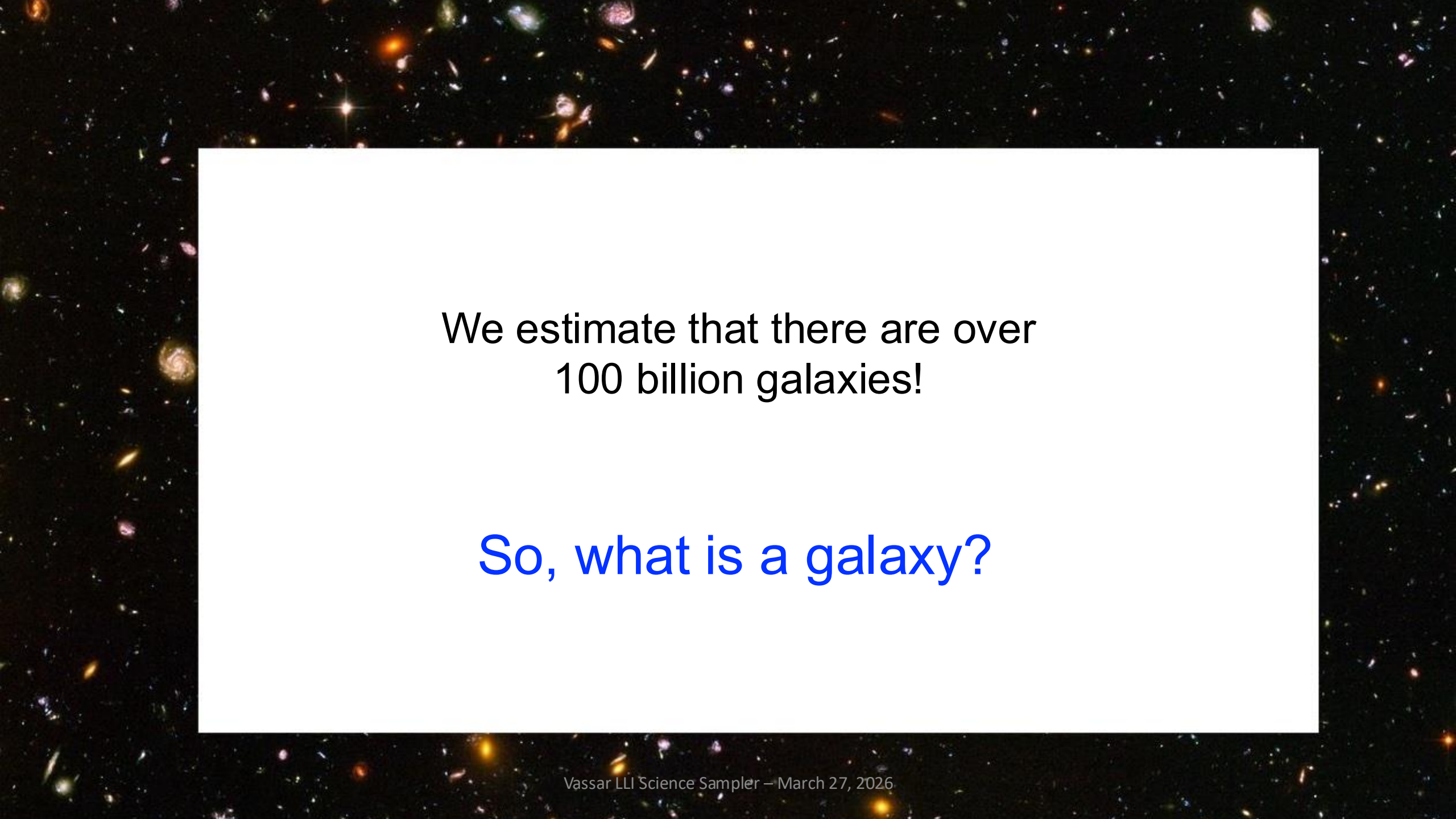
Vera Rubin

Yet it has only been **100 years** since astronomers have had telescopes big enough and techniques clever enough to figure out that there are other **galaxies**



Maria Mitchell





We estimate that there are over  
100 billion galaxies!

So, what is a galaxy?

**Galaxies** are objects that contain <1 billion to >1 trillion stars plus gas, dust, and dark matter, bound by gravity

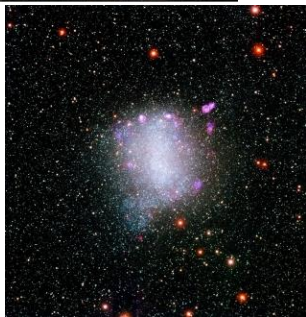


In the nearby universe, 3 types dominate:

**Ellipticals** have 3-D shapes and are red



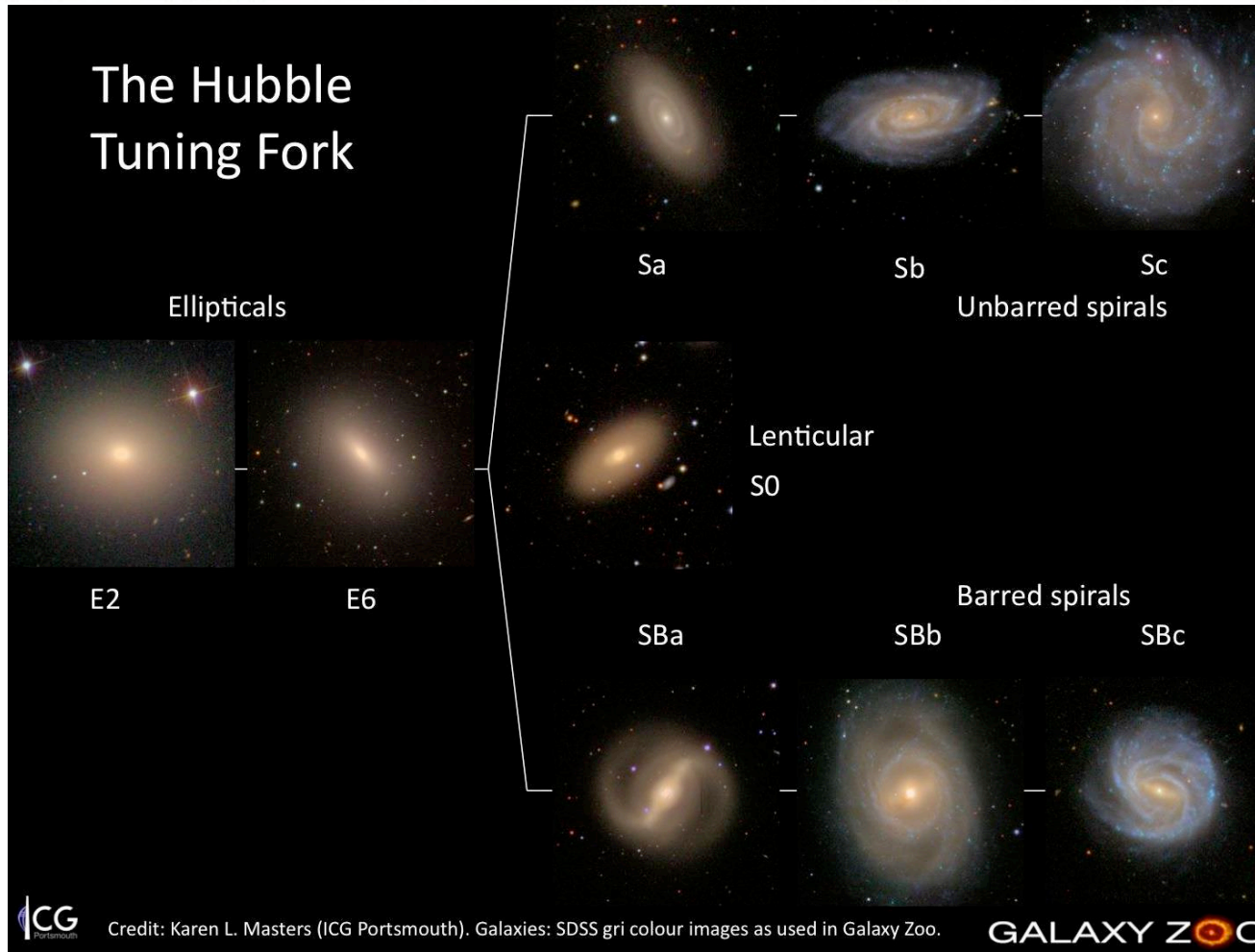
**Spirals** are flattened with a central bulge and arms are bluer



**Irregulars** are chaotic and are blue

SDSS

# The Hubble Tuning Fork



Galaxy **shapes** reflect their underlying **physics** (e.g., their rotations and star motions)

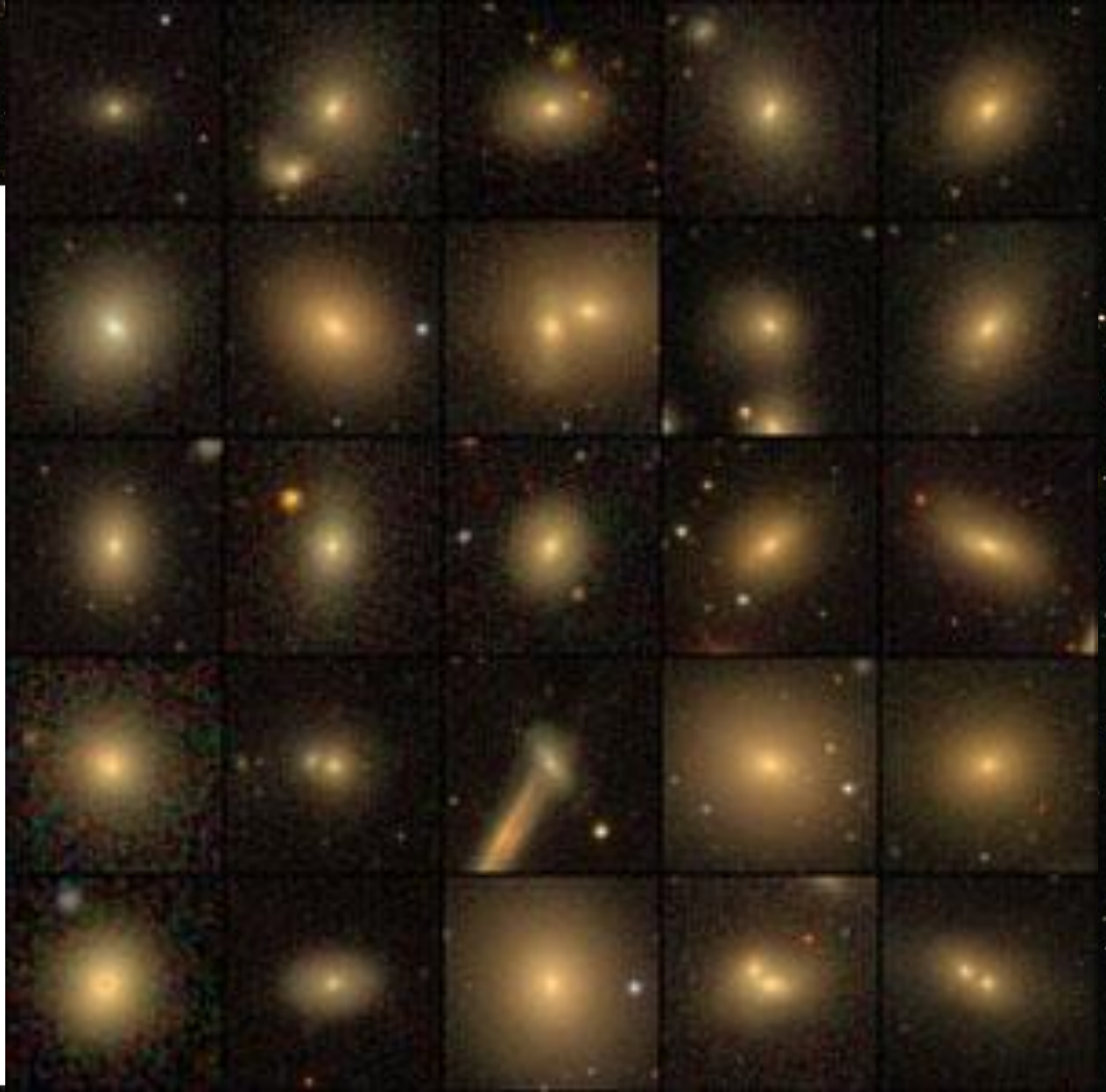
Their **colors** reflect their **star formation histories** (bluer = younger, hotter, more massive stars)

## Elliptical galaxies

They have little ordered rotation so maintain their spherical shape

Little gas means no new star formation

Blanton and Moustakas ARAA 2009



## Spiral galaxies

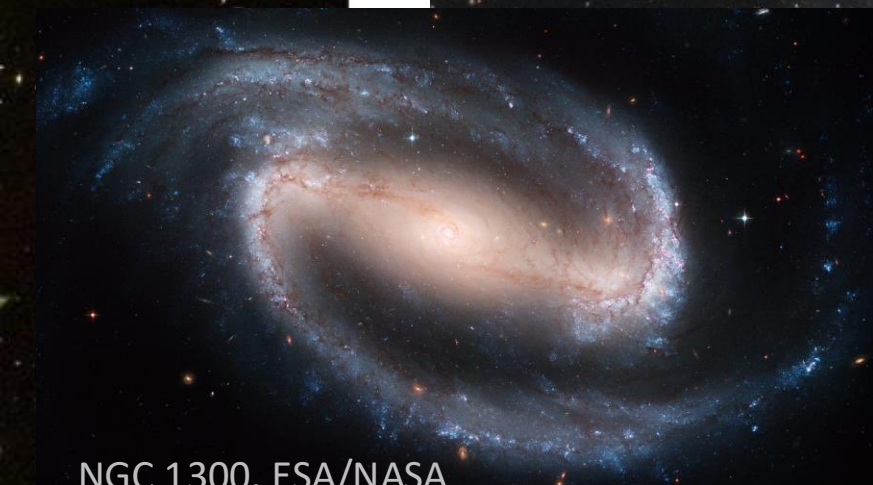
rotate in a plane  
(100-300 km/s)

Waves rippling through  
the disk generate spiral  
structure

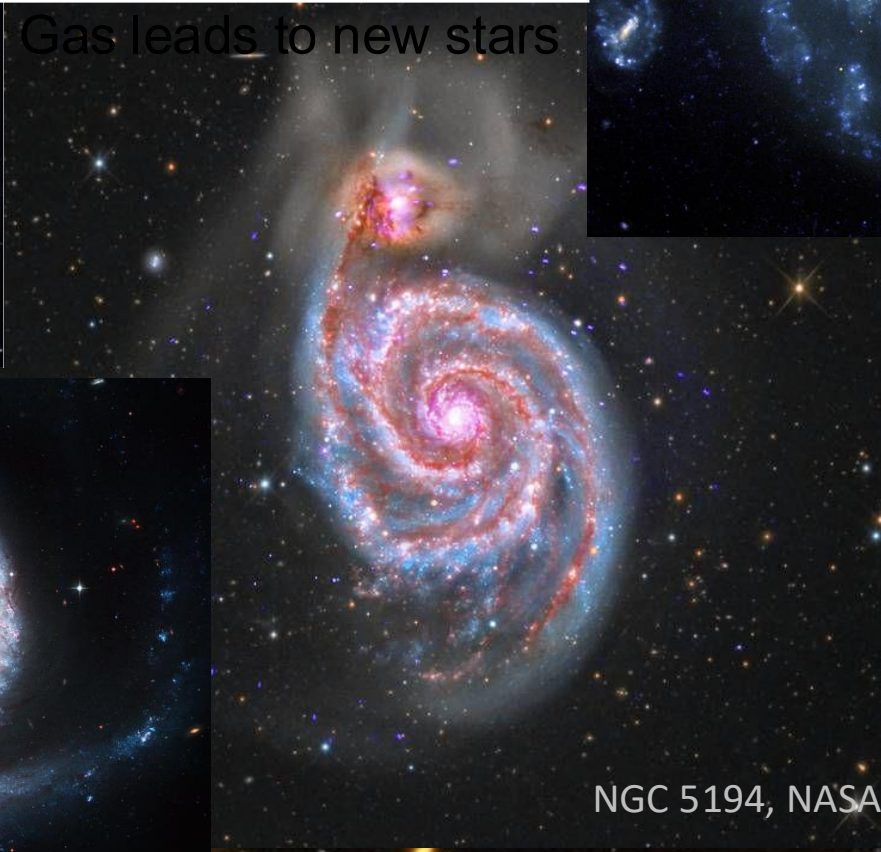
Gas leads to new stars



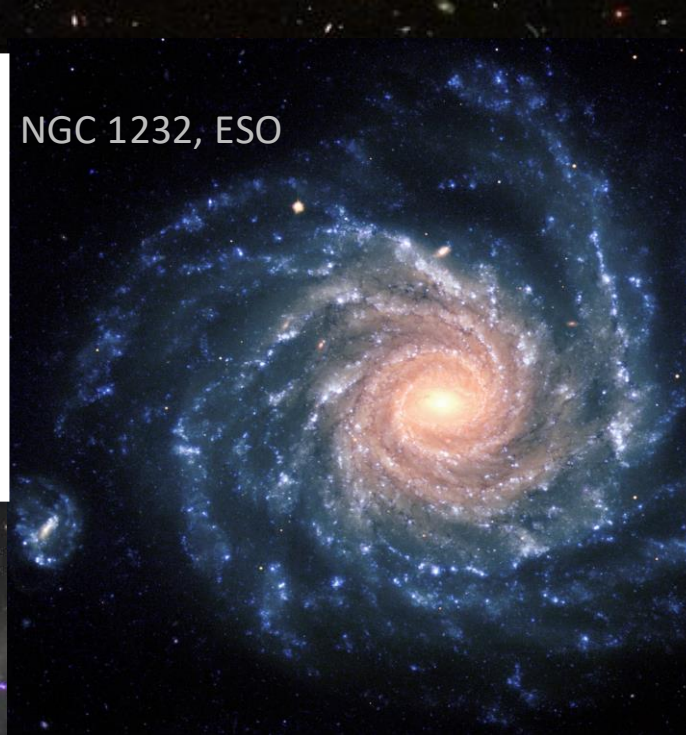
NGC 1365; SSRO/PROMPT



NGC 1300; ESA/NASA



NGC 5194; NASA



NGC 1232; ESO



NGC 3521; ESO/O. Malin

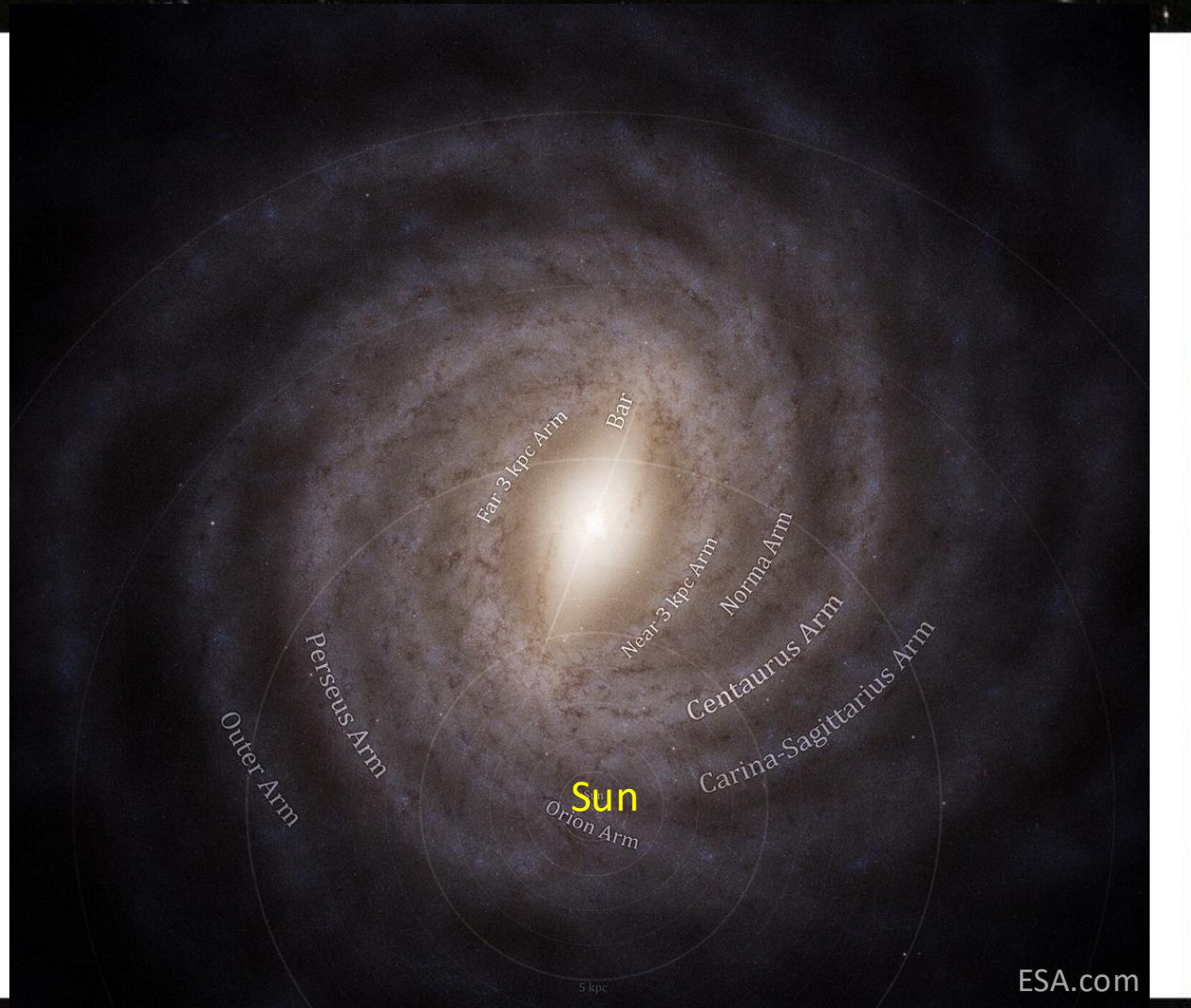


IC 342; ESA

Our Milky Way galaxy  
is a (barred) spiral

Its total stellar mass is  
about 200 billion times  
the mass of the Sun

Visualization based on  
Gaia satellite data of 2  
billion stars (Sept. 2025)



The band we call the Milky Way is the plane (disk) of our galaxy

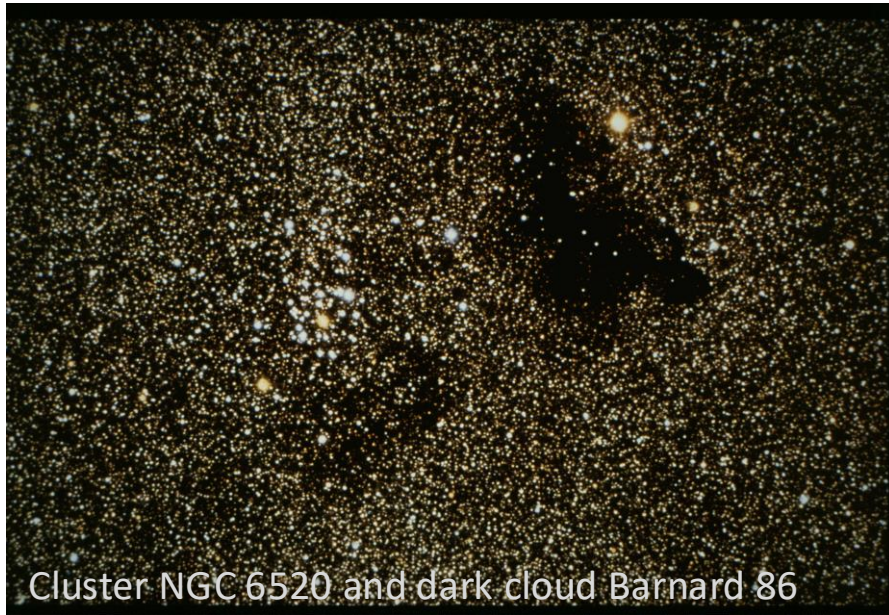


NGC 4013 – edge-on galaxy  
("New General Catalog" number)



Our galaxy - Milky Way

The dark areas are molecular clouds, which can form new stars

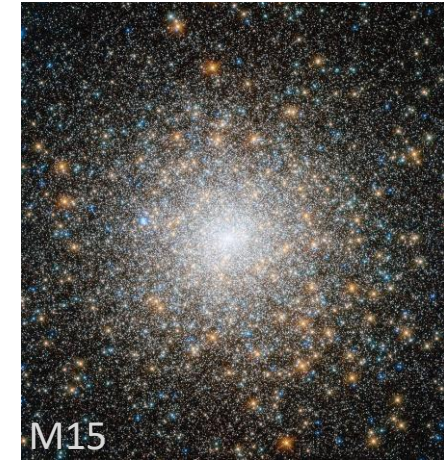


Cluster NGC 6520 and dark cloud Barnard 86

ESO



(messier-objects.com)



M15

Young open clusters  
have 1000s of stars

Old globular clusters  
have 100,000s of stars

Young cluster, clearing cloud around it



The Tarantula Nebula, as seen by JWST. [NASA, ESA, CSA, STScI, Webb ERO Production Team]

**Irregular galaxies** are fluffy disks (30-50 km/s rotation)

Lots of gas leads to new star formation

(hot stars are blue, ionized gas is red)



## Galaxies provide insights into conditions in the early Universe

- How and when do they form?
- How do they evolve?

## The clues we have to study them are from:

- electromagnetic radiation (*look at them!*)
- gravitational effects (*see how they interact!*)
- computer simulations (*compare with observations*)



NGC 3314 (STScI)

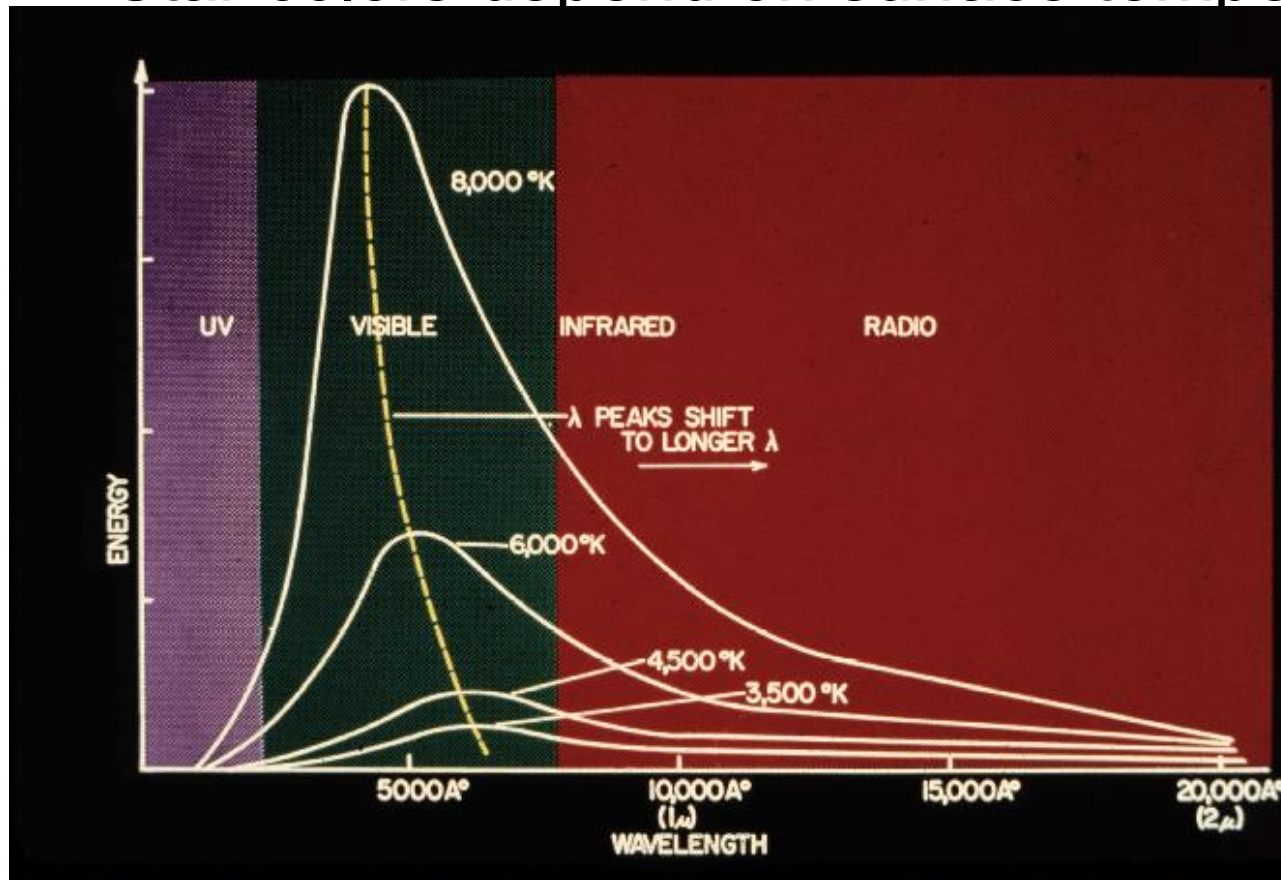
## Galaxy light is composite light from billions of stars of different types

To interpret galaxy light, we need to know:

- The color and brightness of a star as a function of its age and mass
- The lifetime of a star of a given mass
- The relative proportion of stars of different masses

Then, a galaxy's color and brightness can be modeled to determine its star formation history and mass

## Star colors depend on surface temperatures



Blackbody radiation

$$\lambda_{peak}(\text{\AA}) = \frac{3 \times 10^7}{T(K)}$$



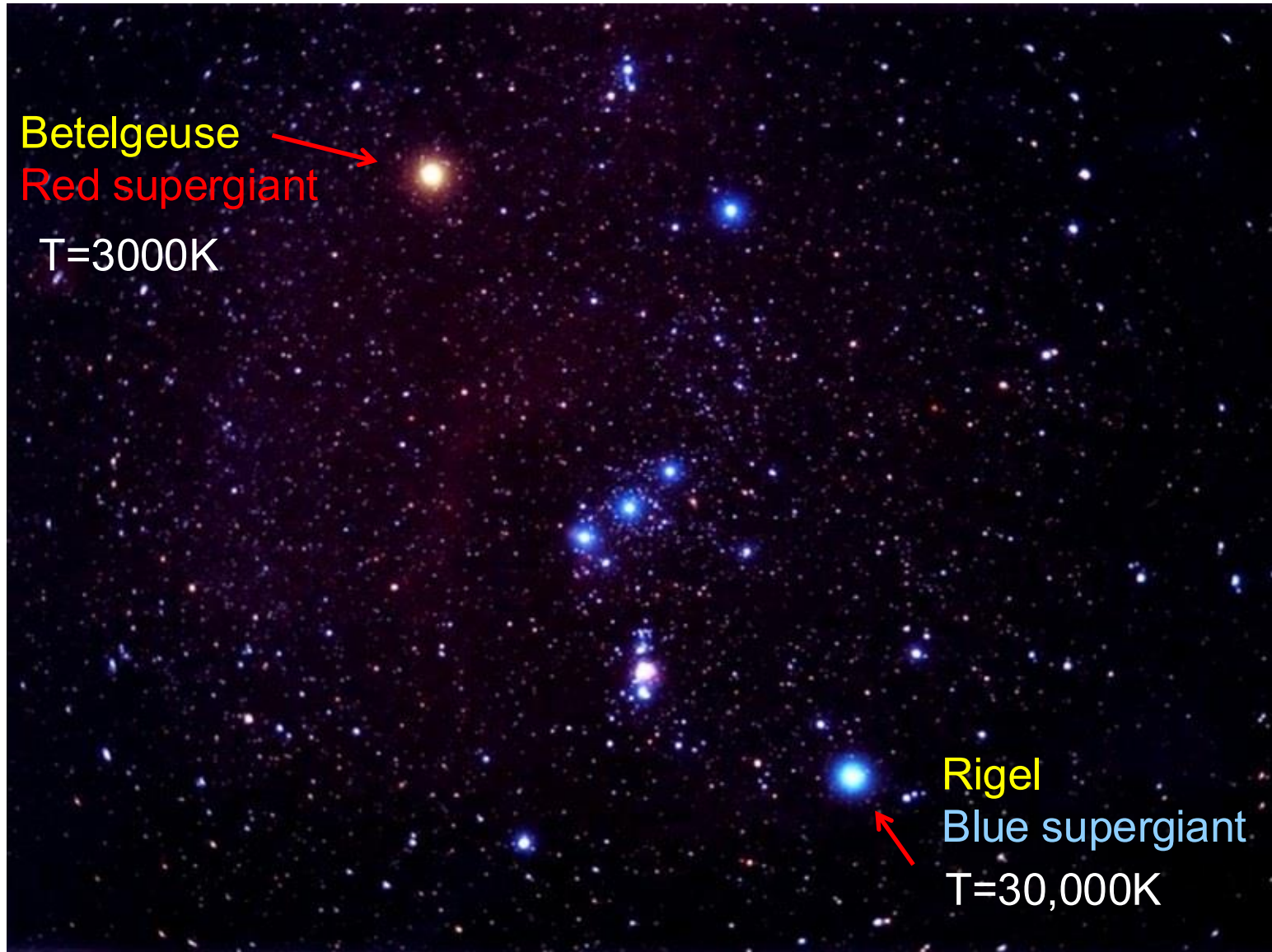
Sun

6000K

hotter stars are bluer than cooler stars

# Orion

Betelgeuse  
Red supergiant  
T=3000K



Rigel  
Blue supergiant  
T=30,000K

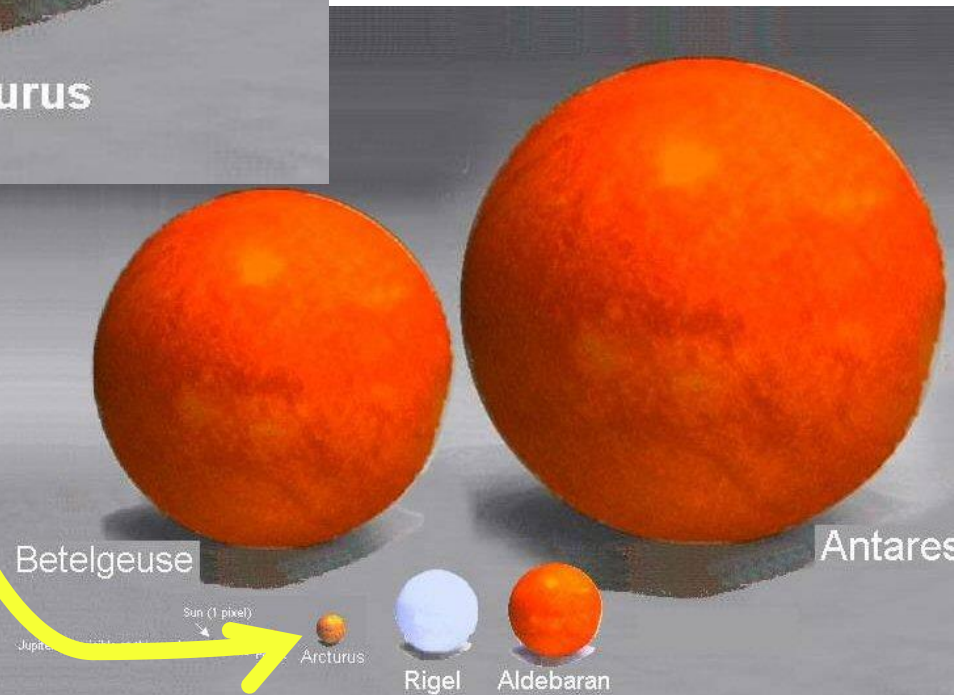
Sun



Star luminosity depends on size and temperature

Our Sun is a middle-size star; there are also giants and supergiants

Arcturus



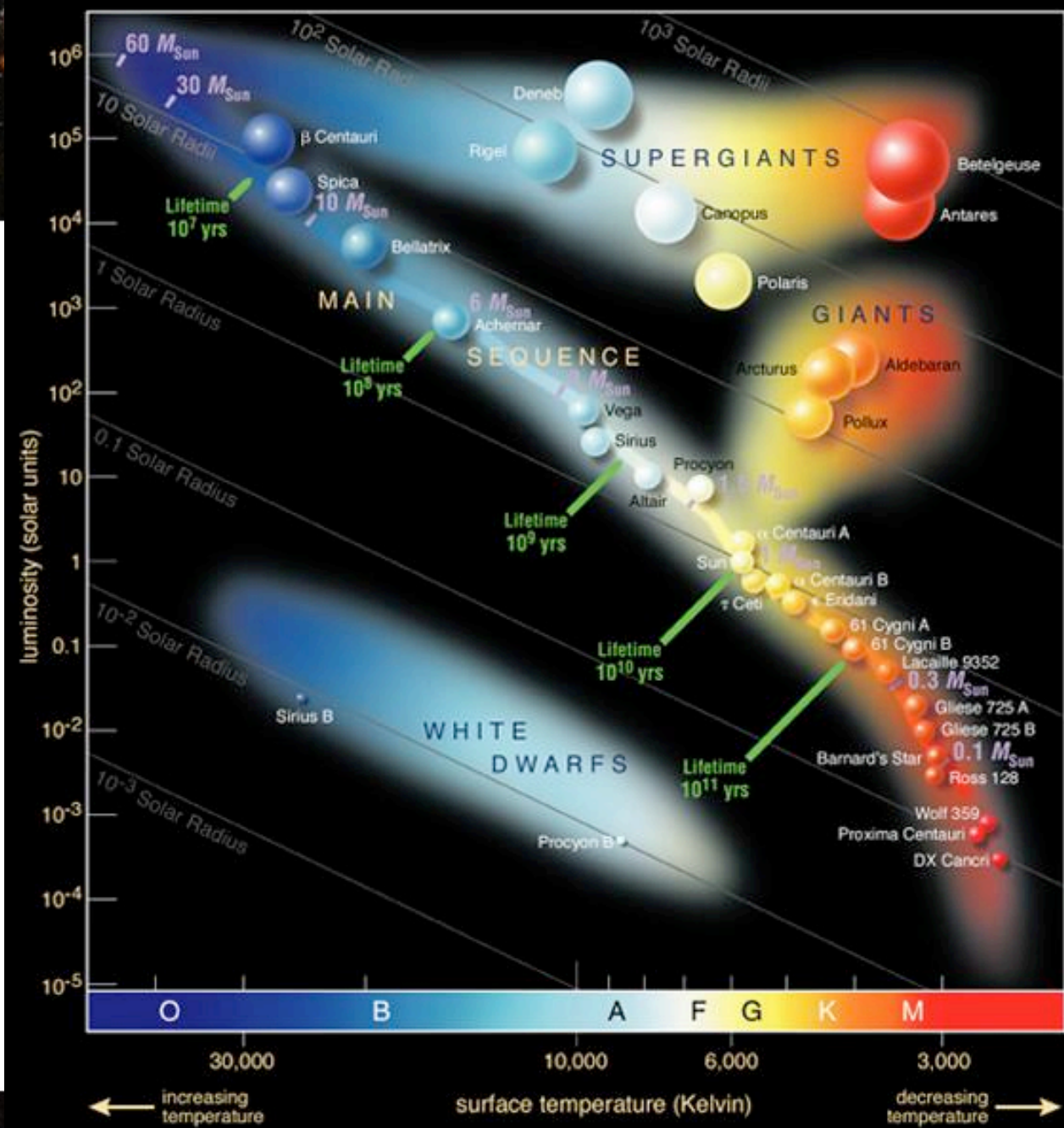
# Hertzsprung-Russell diagram

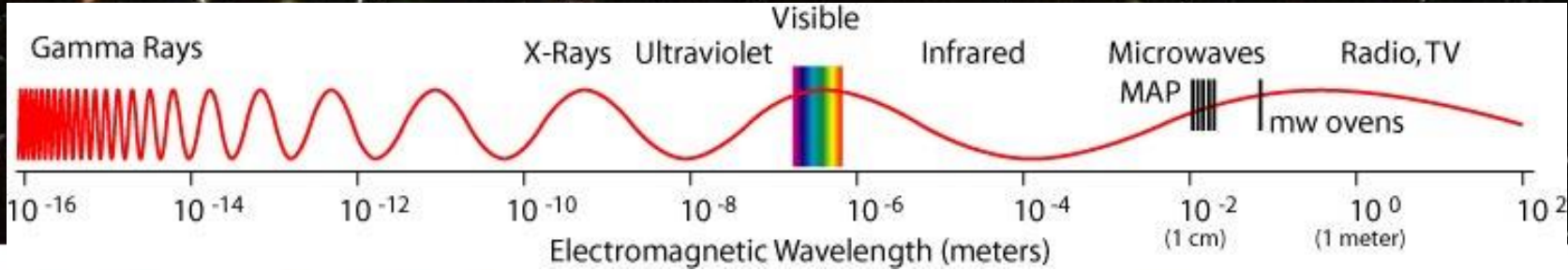
Stars fuse H  $\rightarrow$  He on the Main Sequence ( $10^7\text{K}$  core)

High mass stars are hotter (bluer) and have shorter lives

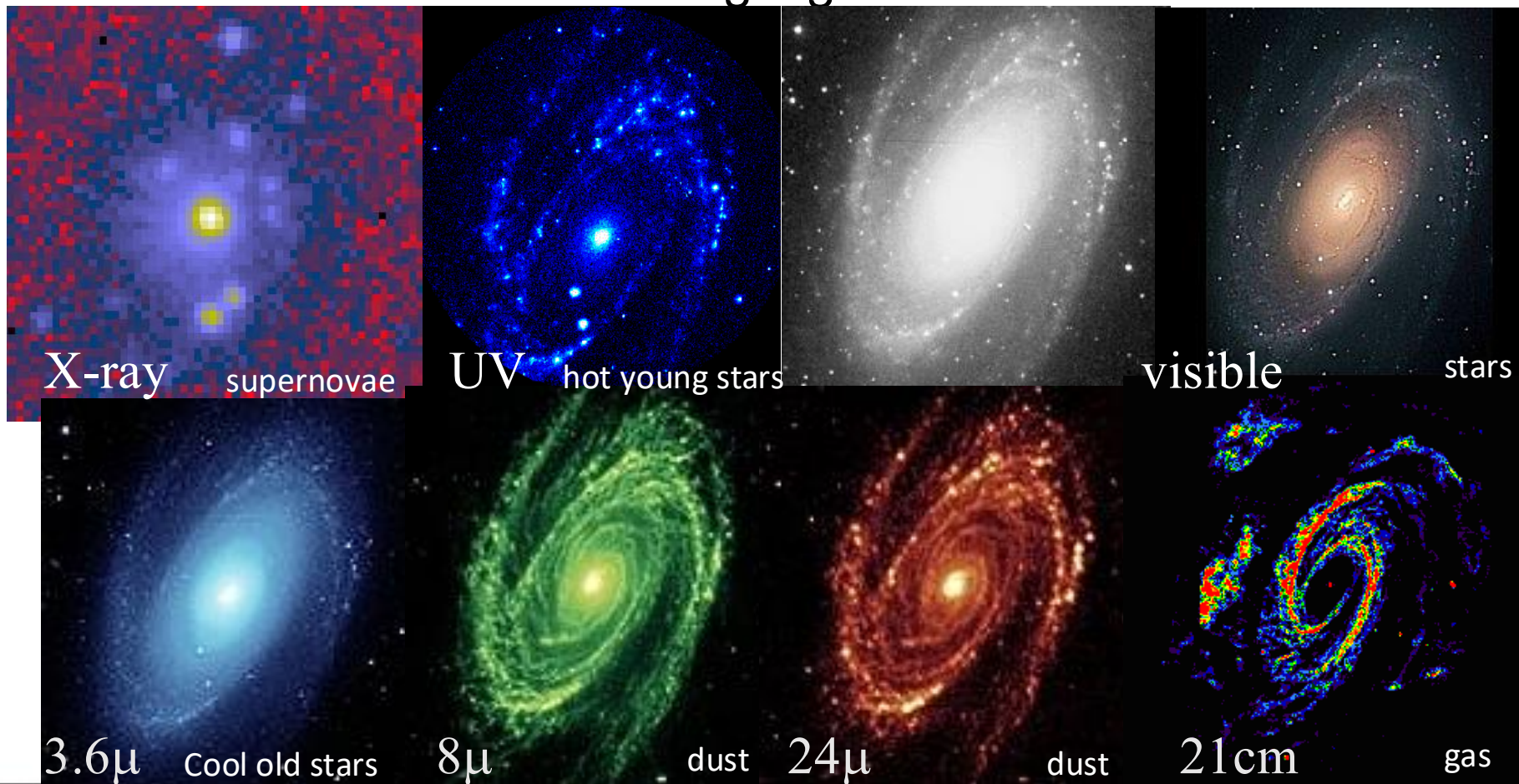
Low mass stars are cooler (redder) and live longer

That is why ellipticals are red (no new stars) and spirals and irregulars are blue



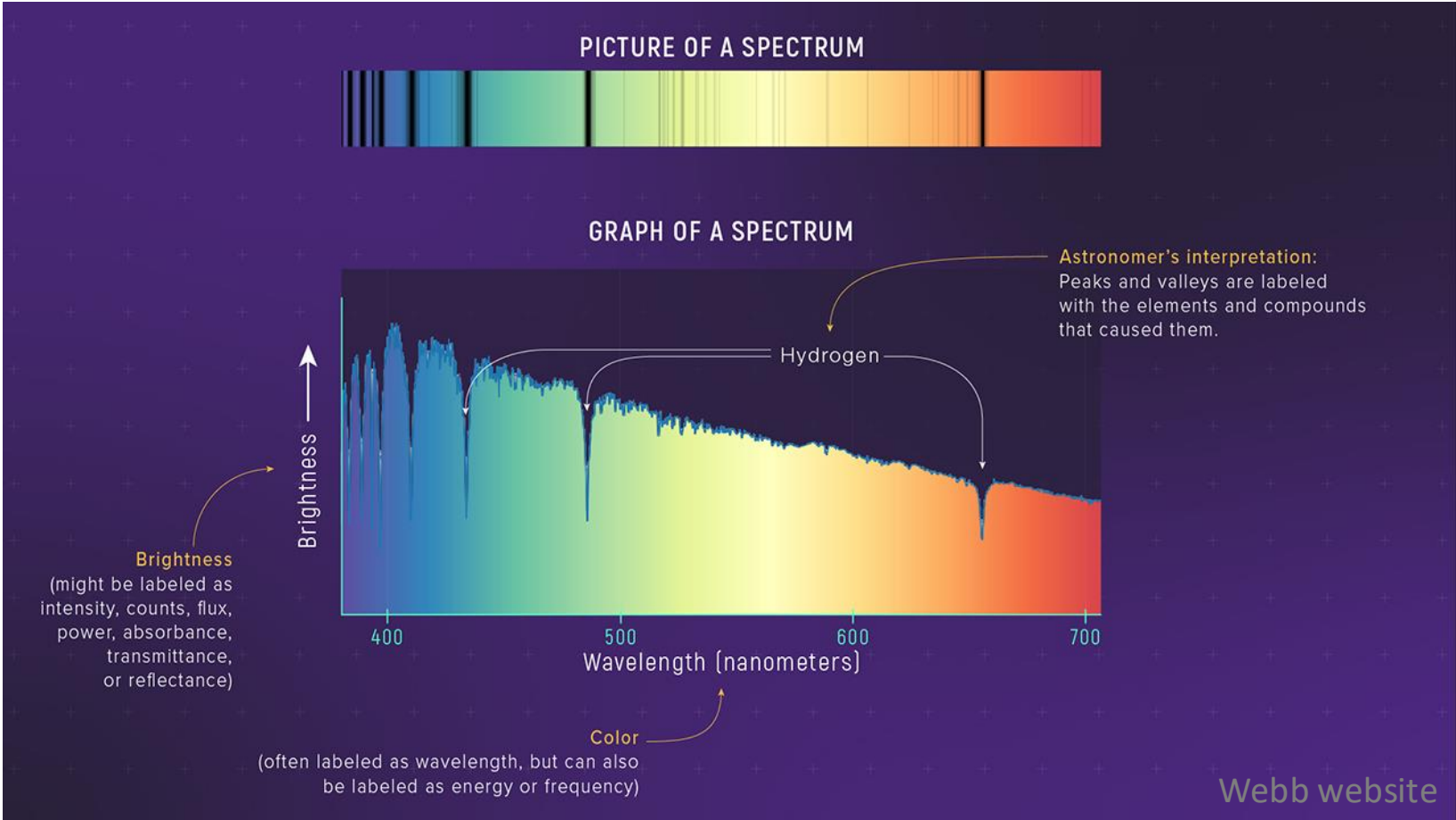


We can use **filters** to highlight different features: M81

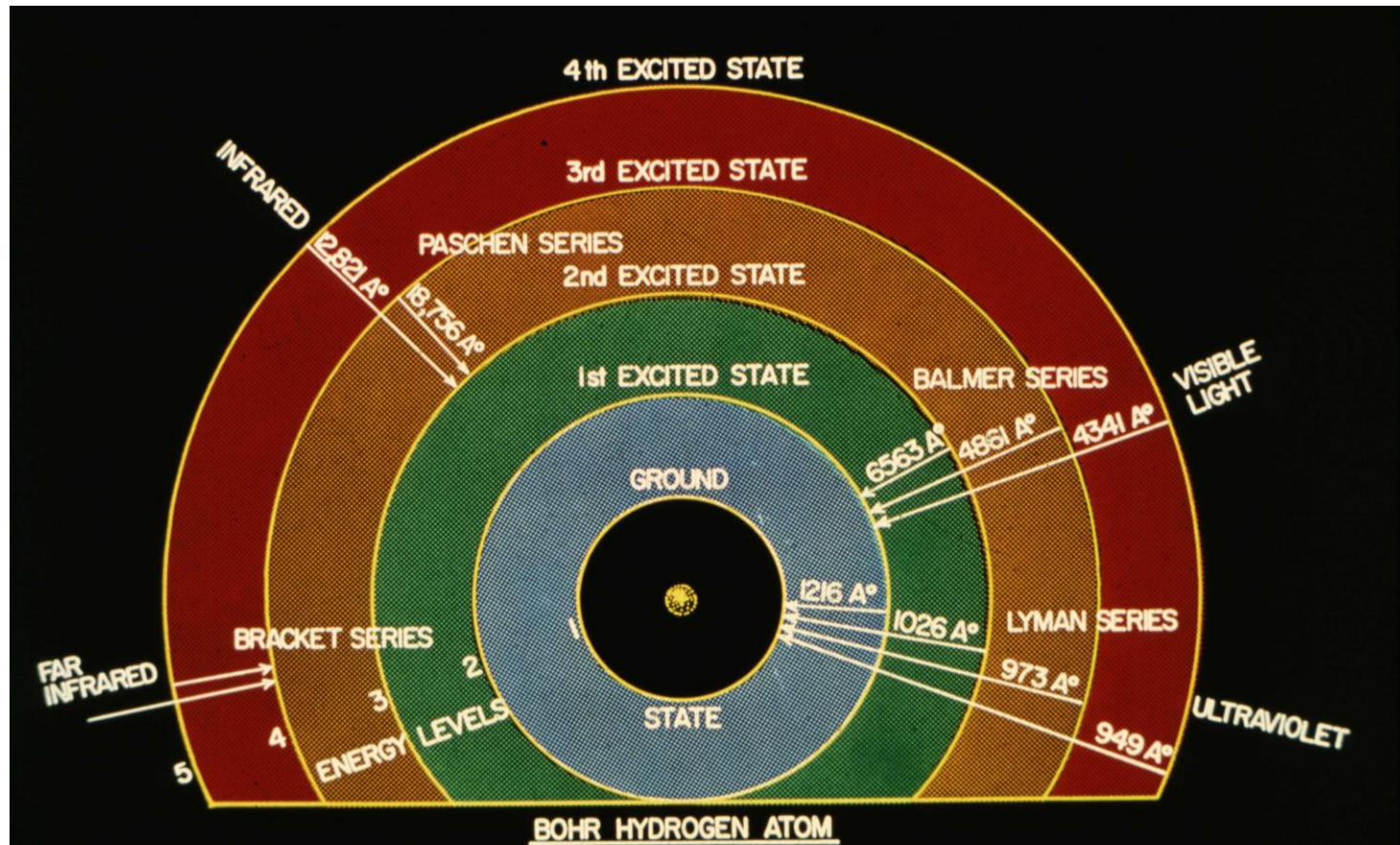


SSC site

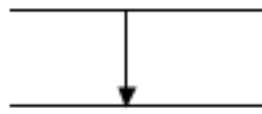
# We can also use **spectroscopy** to dissect light



# Why we get spectral lines: Bohr model of hydrogen

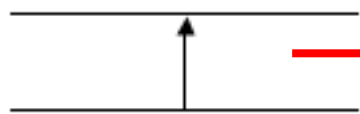


Jump down = **emission**



(gives up energy)

Jump up = **absorption**

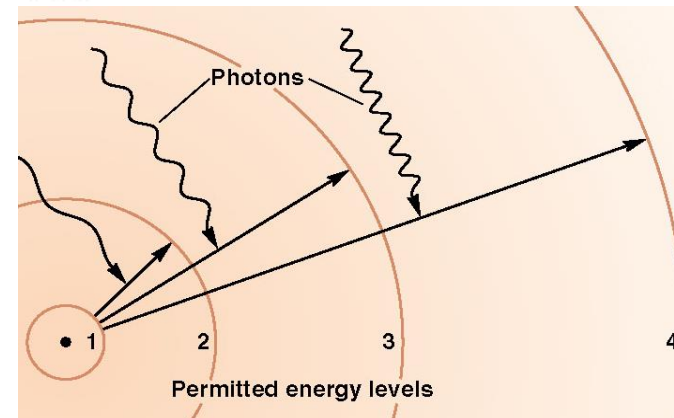


(requires energy)

## Emission and absorption for H

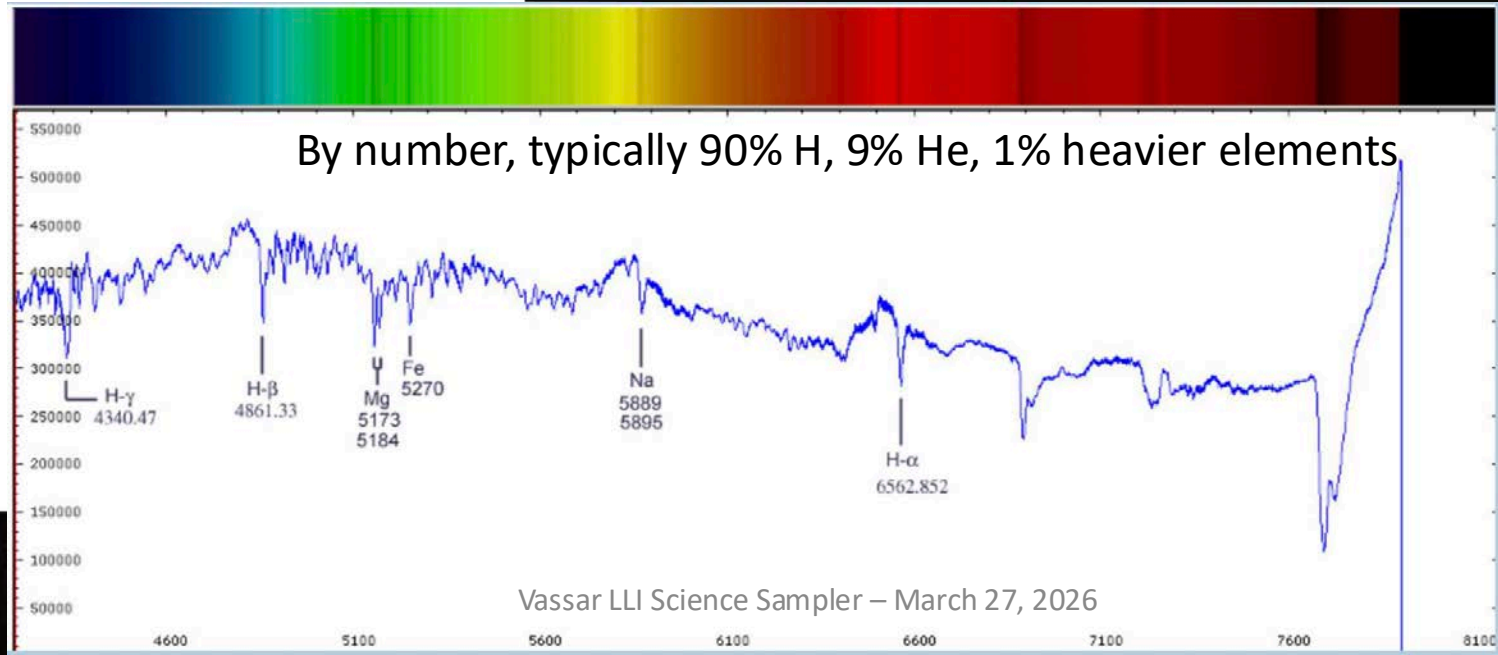
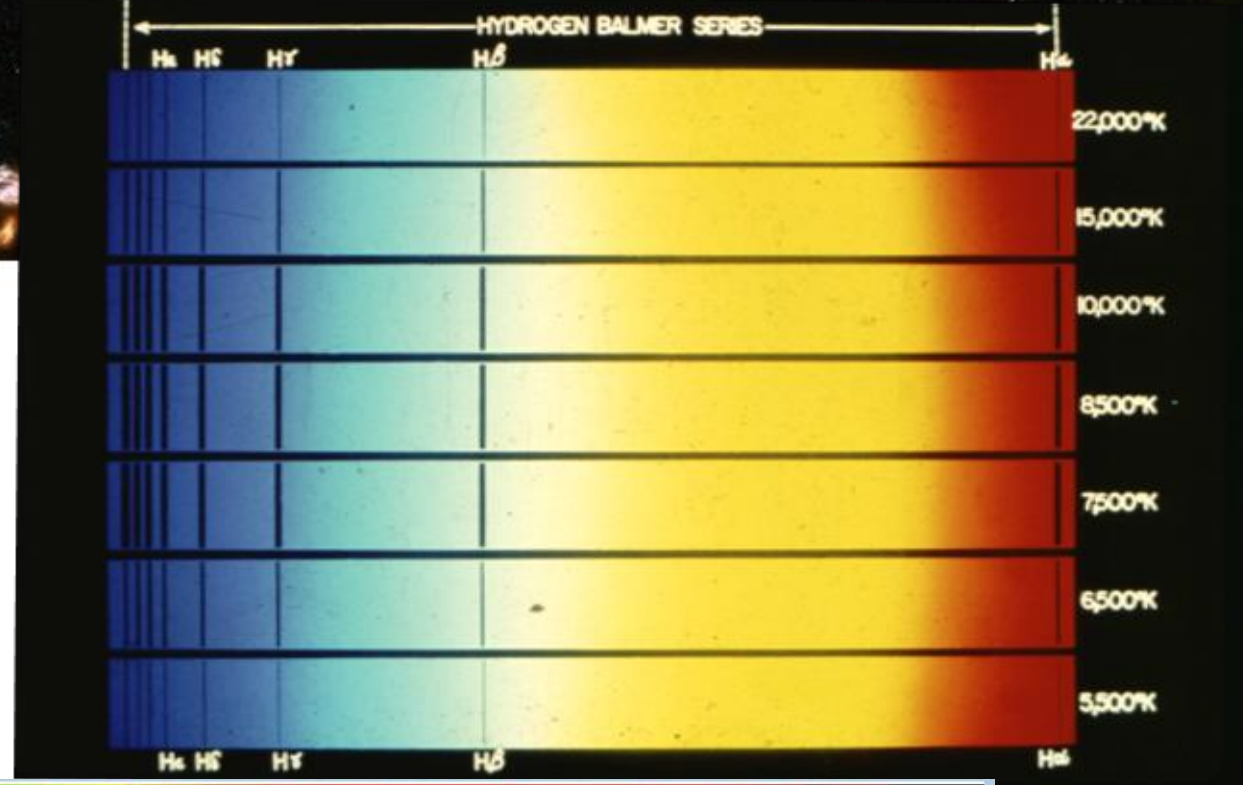


Copyright © Addison Wesley



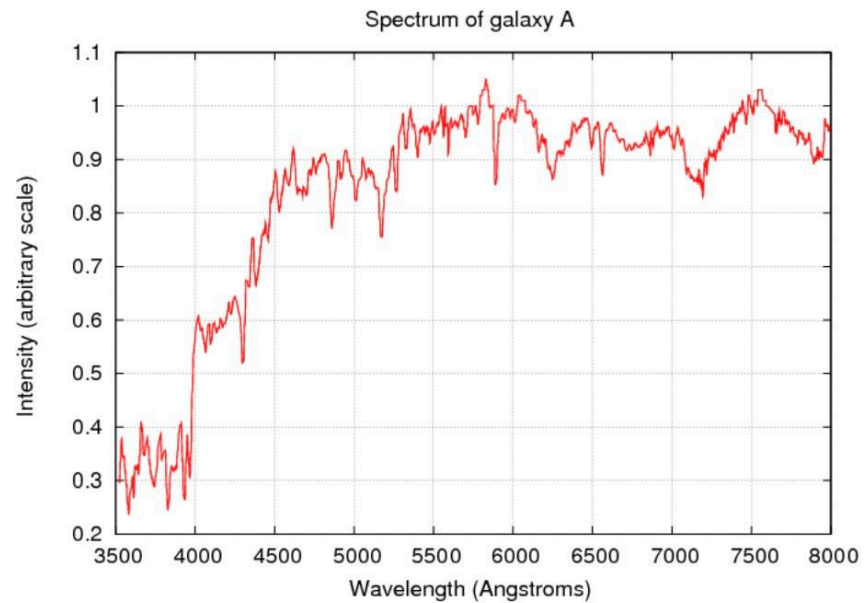
For individual stars,  
absorption lines tell  
temperature and  
composition

(but stars all have about  
the same composition)



H lines  
strongest at  
10,000K  
surface  
temperature

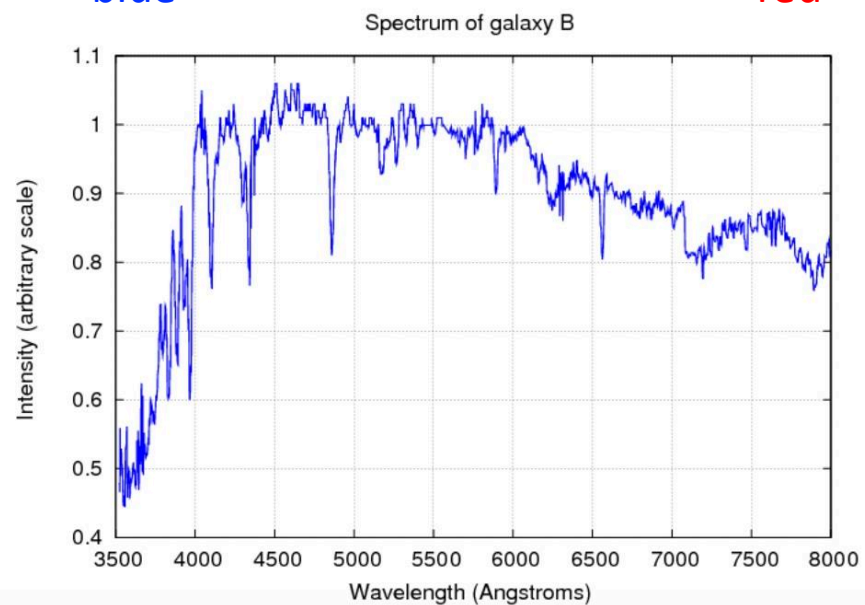
A galaxy's spectrum shows **composite** starlight



blue

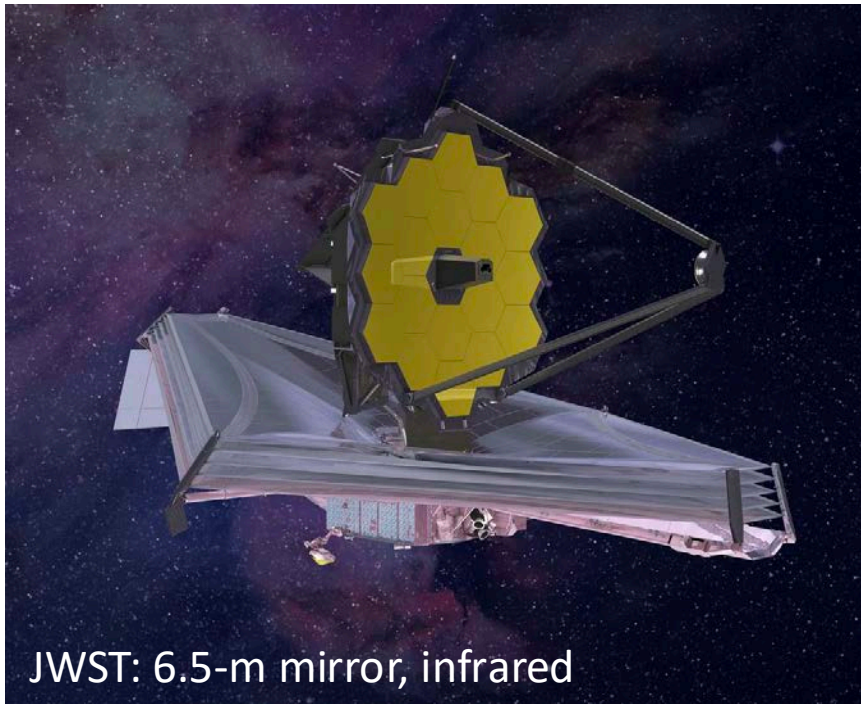
red

Elliptical



Spiral

To analyze starlight from faint distant galaxies, we use satellites such as the Hubble Space Telescope, **HST** (launched 1990)...



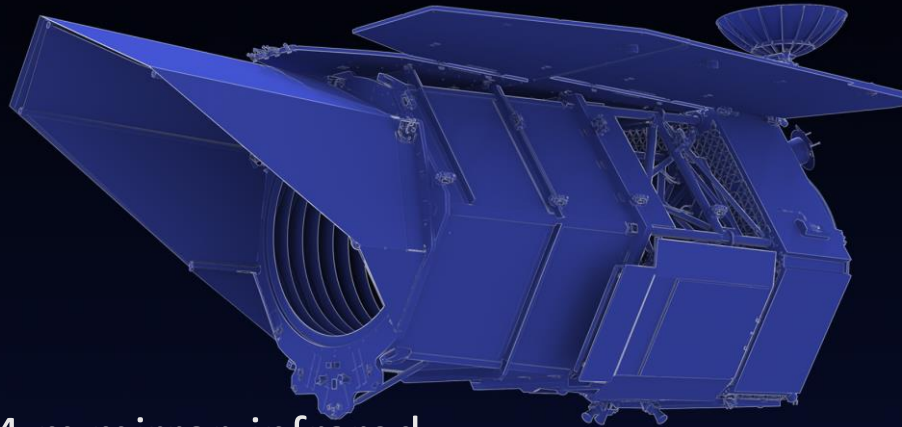
JWST: 6.5-m mirror, infrared



HST: 2.4-m mirror, ultraviolet and optical

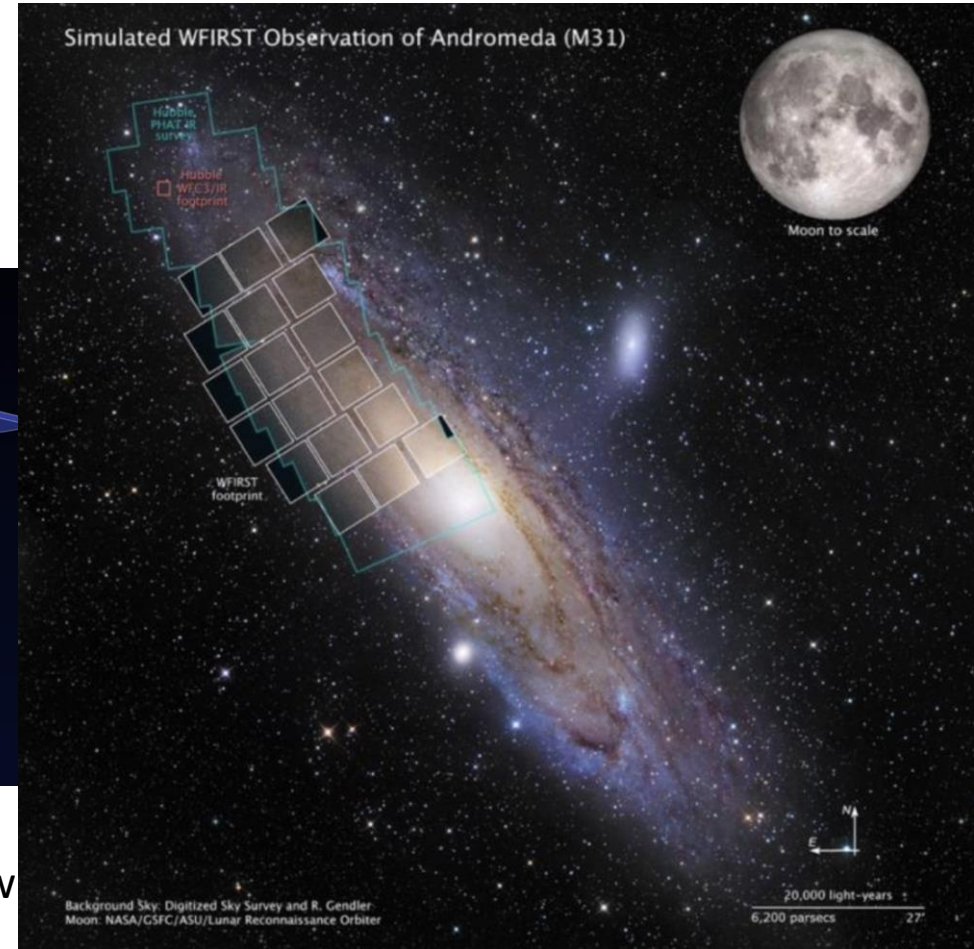
...and the James Webb Space Telescope, **JWST** (2021)

# And soon the Nancy G. Roman Space Telescope (scheduled 2027)

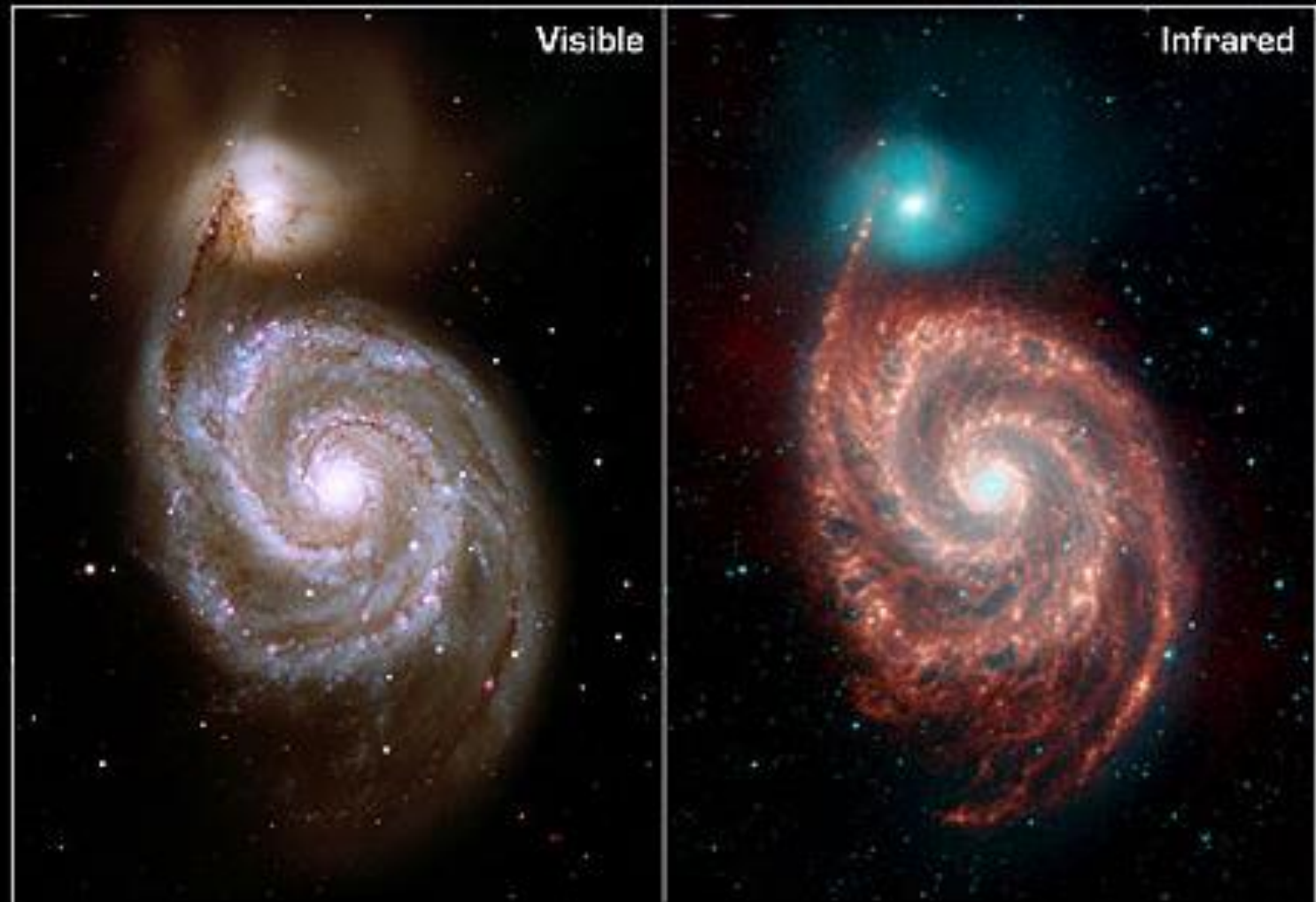


2.4-m mirror, infrared

Very wide field of view  
(100x Hubble)



Spiral M51  
in visible  
and infrared



**Spiral Galaxy M51 ("Whirlpool Galaxy")**

NASA / JPL-Caltech / R. Kennicutt (Univ. of Arizona)

**Spitzer Space Telescope • IRAC**

ssc2004-19a

## JWST images of M51

Near-infrared  
(6563 Angstroms,  
ionized gas heated  
by new star  
formation)

Mid-infrared  
(5-28 microns;  
cool dust)



Adamo, Elmegreen, et al. FEAST 2023; ESO

Spiral  
galaxy  
M74



Hubble / Optical



Hubble & Webb



Webb / Infrared

HST

combined

JWST

## Spiral galaxy NGC 1068

It contains a central black hole and strong wind, lighting up in X-rays

- X-rays from Chandra (blue)
- radio data from NSF's VLA (pink)
- optical data from Hubble and JWST (yellow, gray and gold)

Chandra website



Ground-based telescopes complement space-based telescopes. Besides existing 5- to 10-meter telescopes, new ones are underway



Artistic rendering of European Extremely Large Telescope (E-ELT) in Chile, 39m, to be completed ~2027



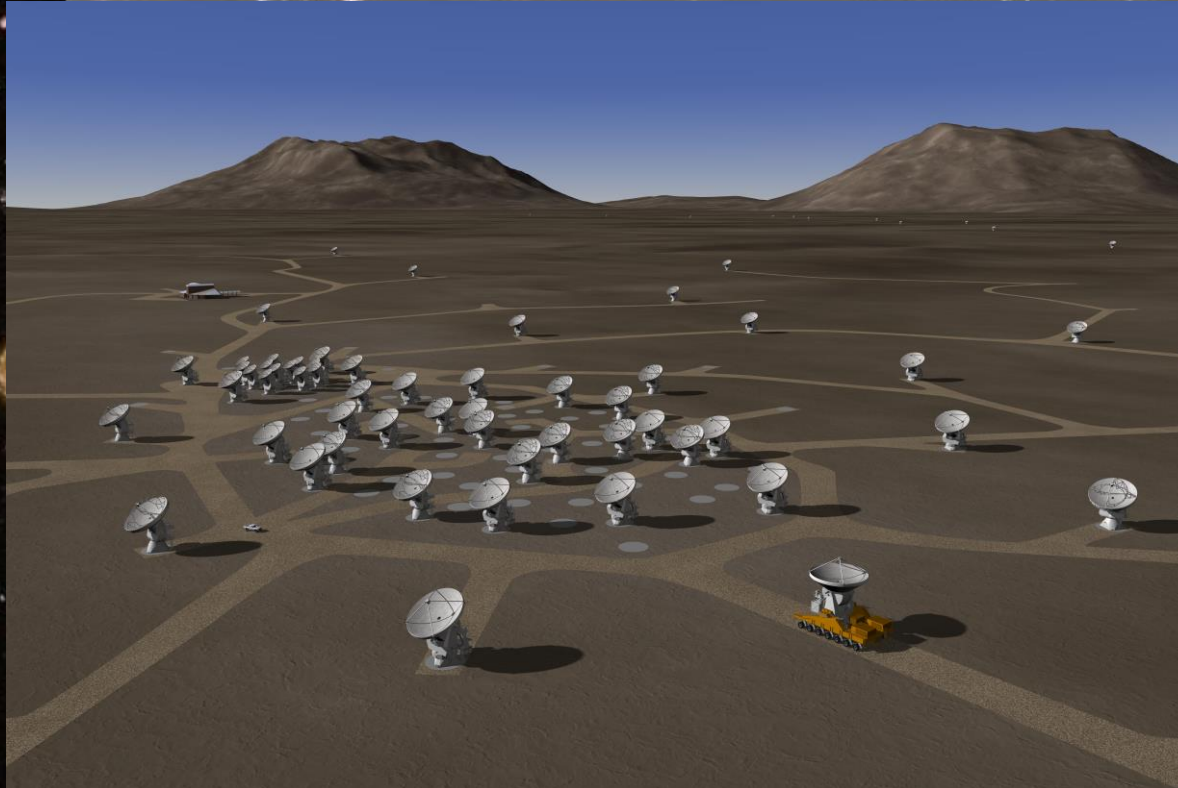
Vera Rubin Observatory in Chile, 8.4m wide field, first light June 2025

First Rubin  
Observatory  
image

10-yr survey  
will repeatedly  
image 20  
billion galaxies  
(plus stars and  
solar system  
objects)

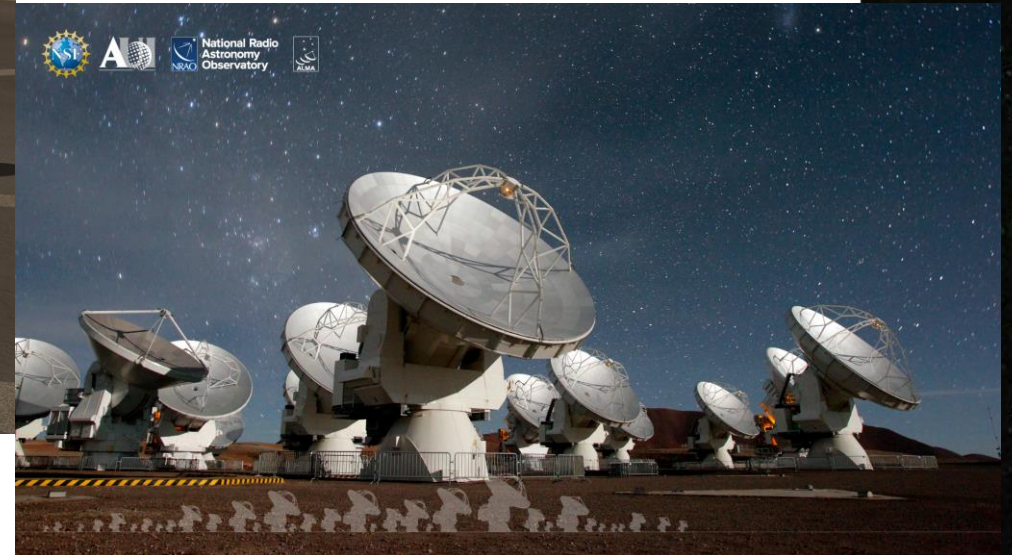


Rubin website; June 2025



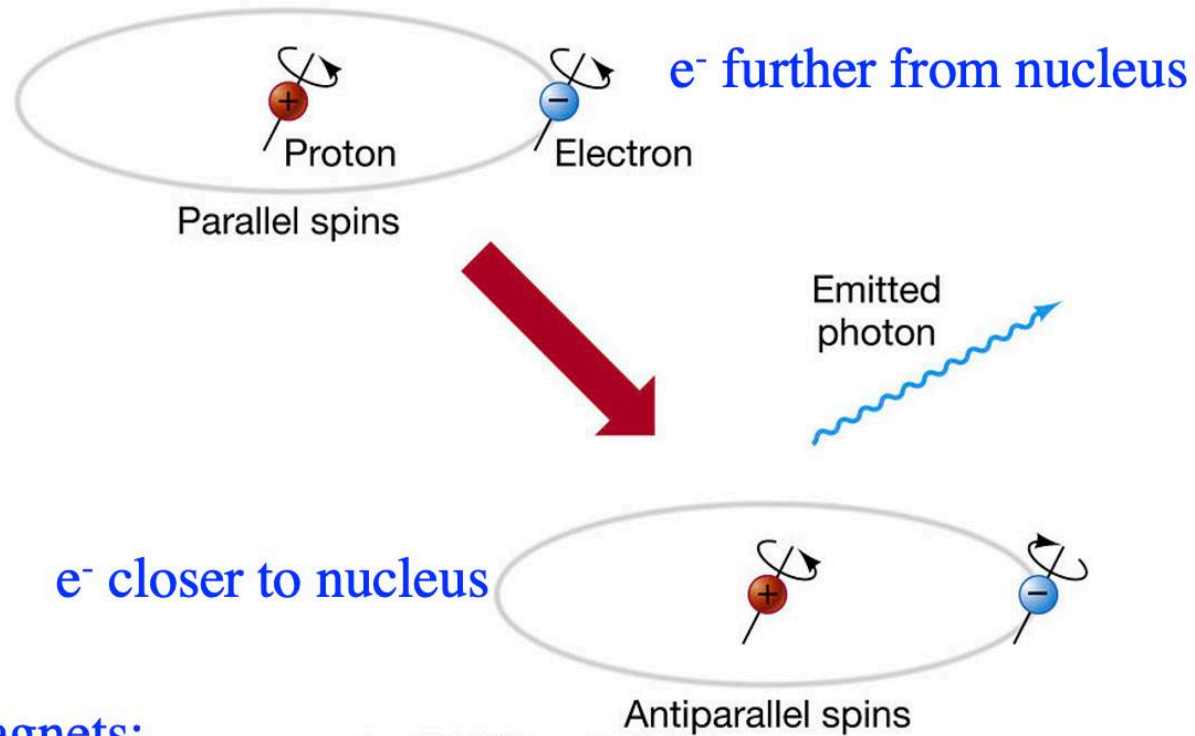
Atacama Large Millimeter Array (ALMA) in Chile  
(molecules; besides  $H_2$ , CO is most abundant of 100 molecules)

We use radio arrays to study gas atoms and molecules

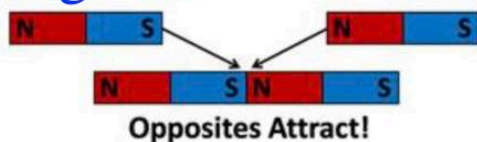


Very Large Array (VLA) in U.S. ( $H$  atoms)

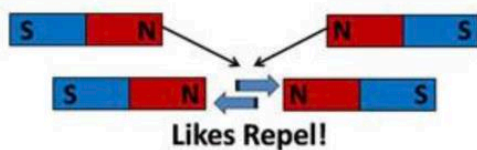
# Neutral hydrogen (HI) radiates at 21 cm from “spin-flip”; 100K gas



Like bar magnets:

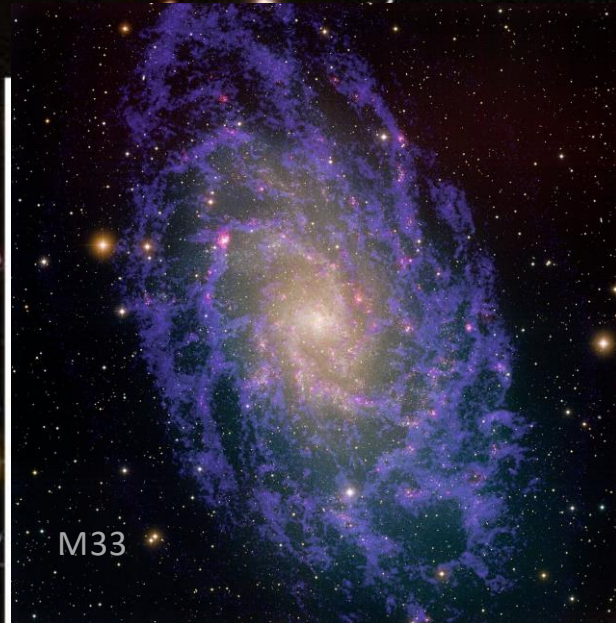


(Like antiparallel state - closer)



(Like parallel state – further apart)

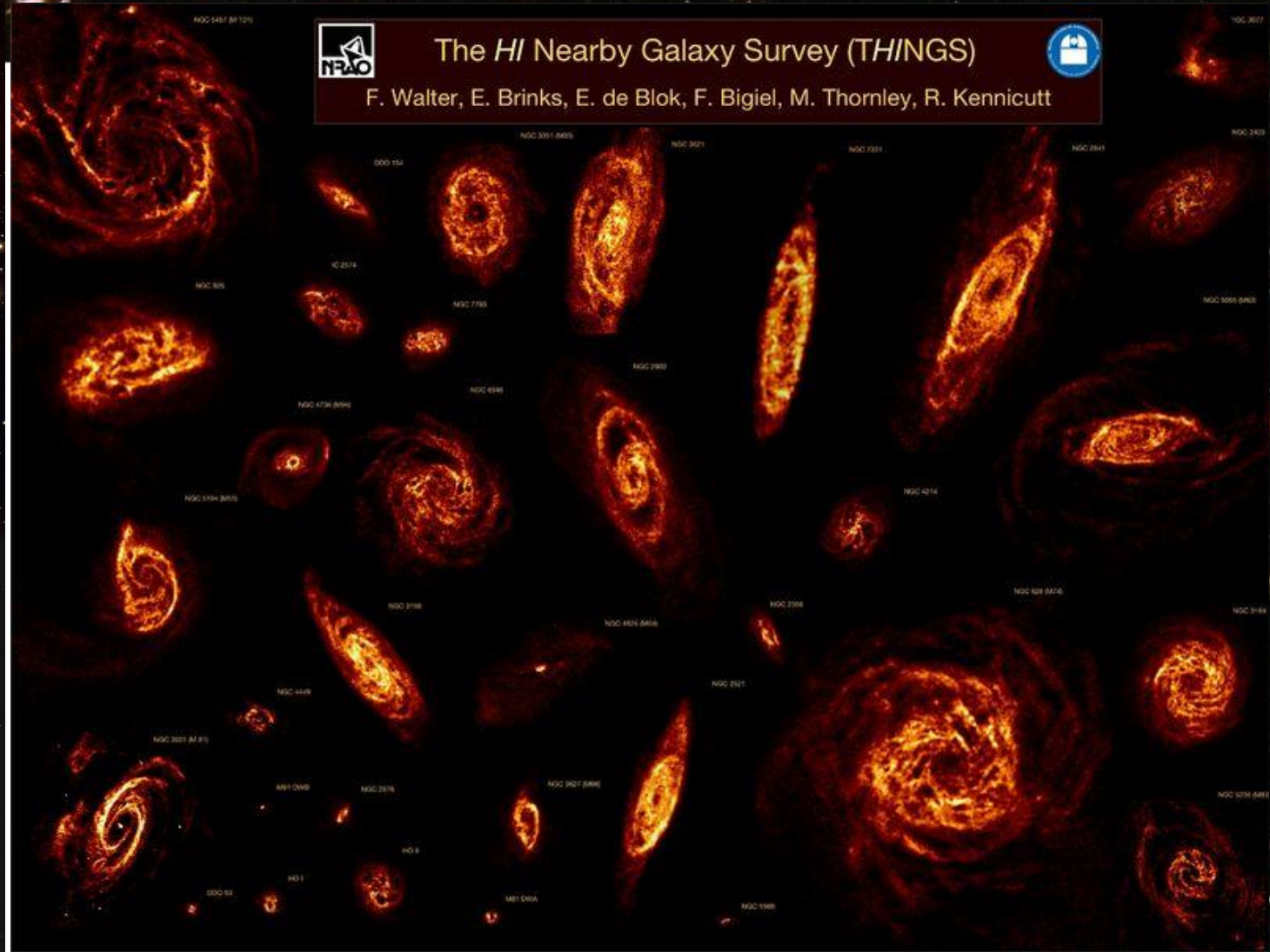
# Atomic gas (hydrogen) in galaxies



M33

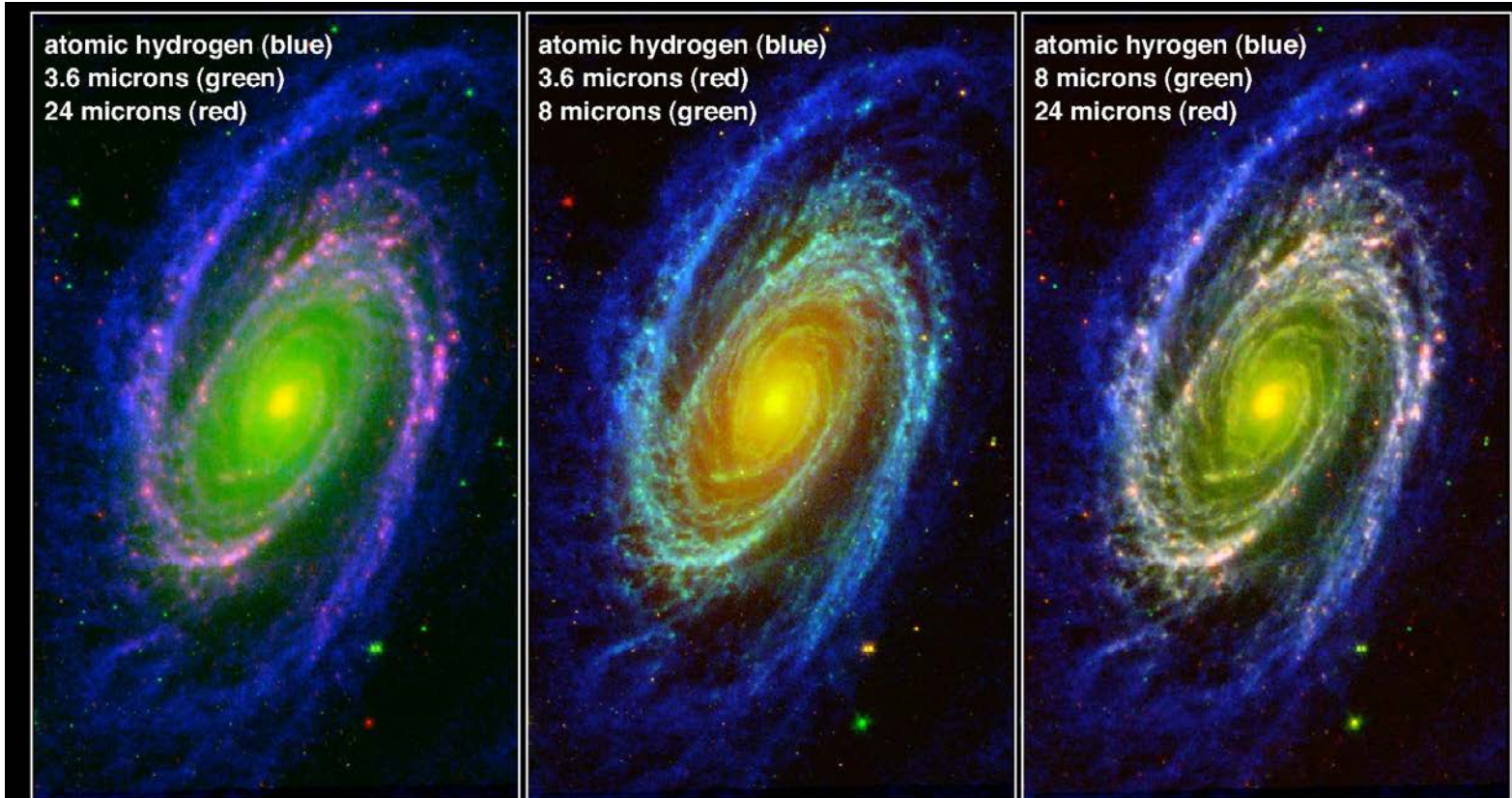


M51



NRAO

# Appearance of stars, gas, dust in galaxy M81



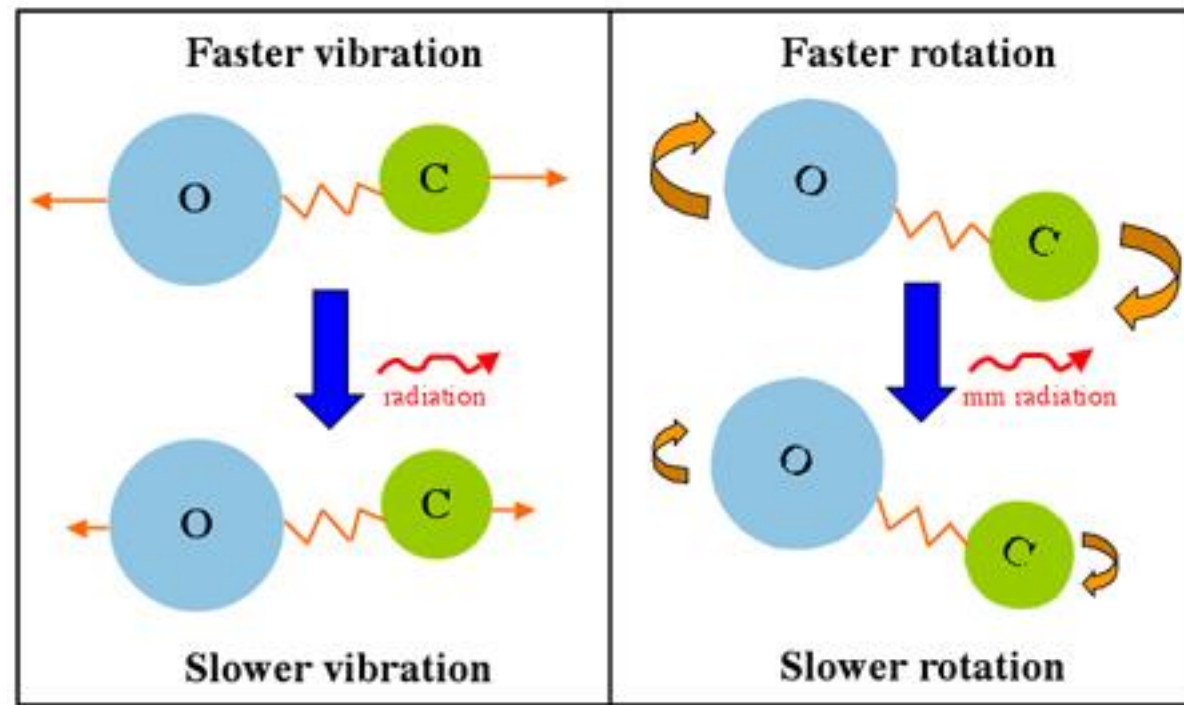
**Spiral Galaxy Messier 81**

**NASA Spitzer Space Telescope and NRAO VLA**

Molecules radiate when they change their rotation or vibration (generally through collisions with other molecules)

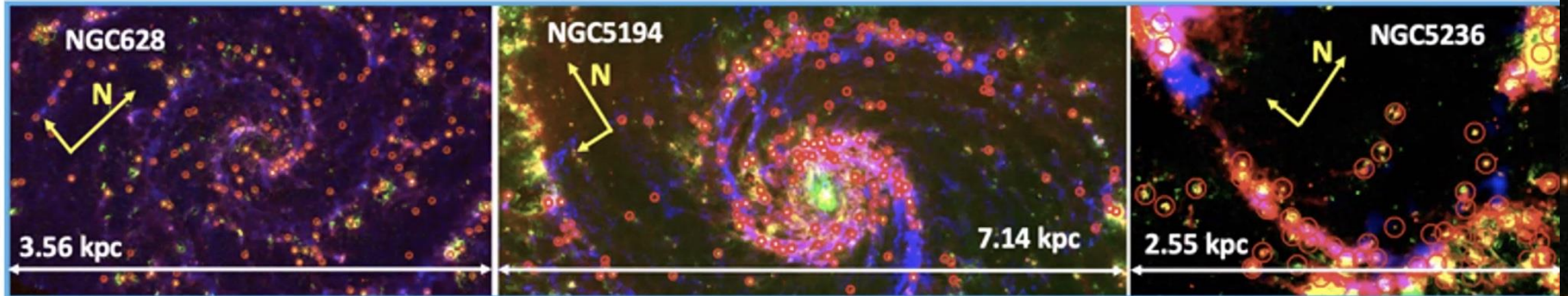
H<sub>2</sub> emission is very weak. Use other molecules as “tracers”.

CO is good tracer; only 1 in 10<sup>4</sup> compared to H<sub>2</sub>, but strong radiation (10K gas)



mm-wave  
emission

## Molecular data combined with HST, JWST



Color composites of: PdBI/ALMA CO (blue), HST/H $\alpha$  (green), JWST/21  $\mu$ m (red)  
- Red circles identify HII regions/complexes ( $\sim$ 60 pc radius) -- **353 regions in total**

Can derive star formation rates and gas densities

Calzetti, Elmegreen et al. 2026 in prep

Galaxies often have neighbors, which affect their evolution

Mergers can create elliptical galaxies



HST

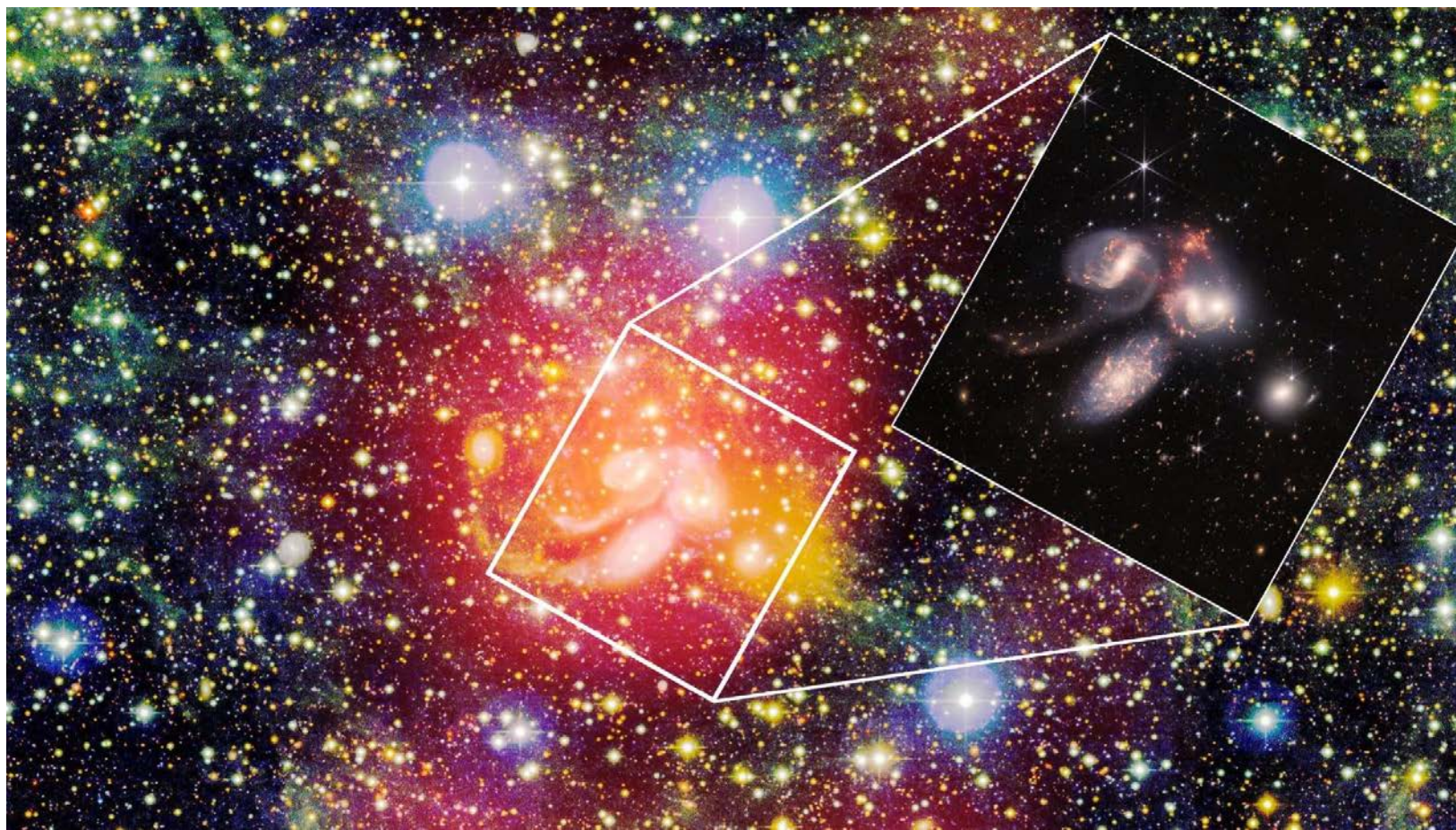
Stephan's  
Quintet



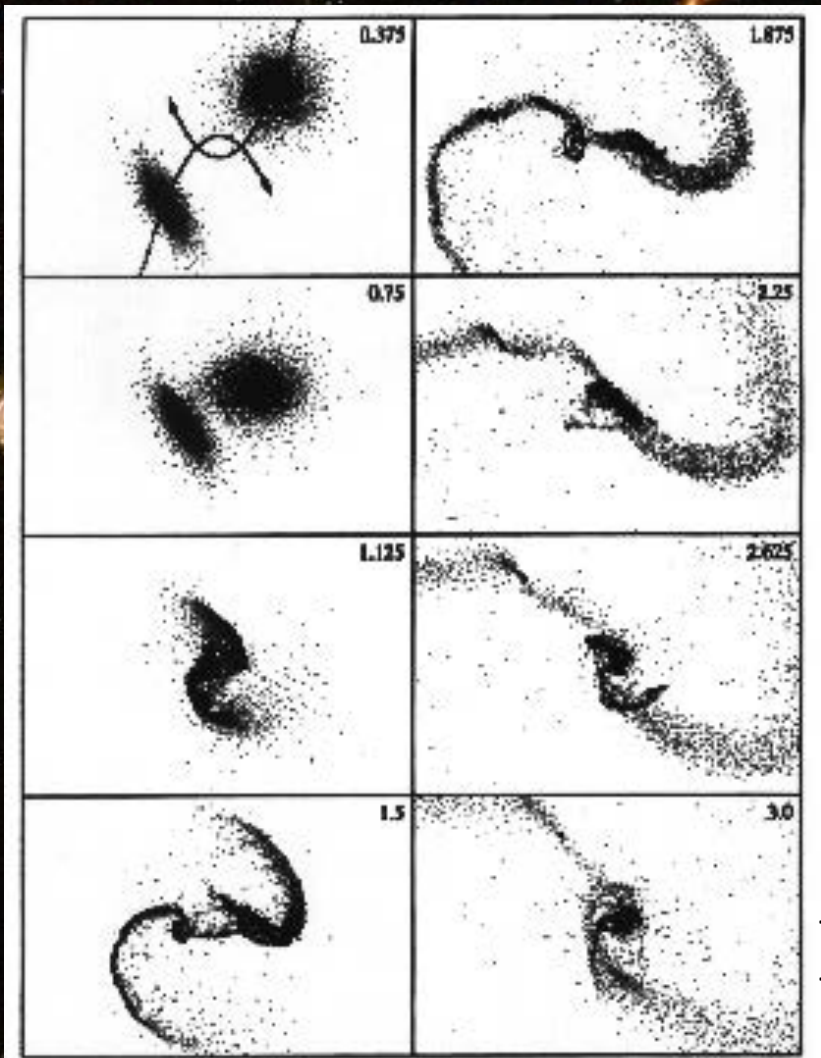
JWST

## Groups of galaxies have extended gas envelopes

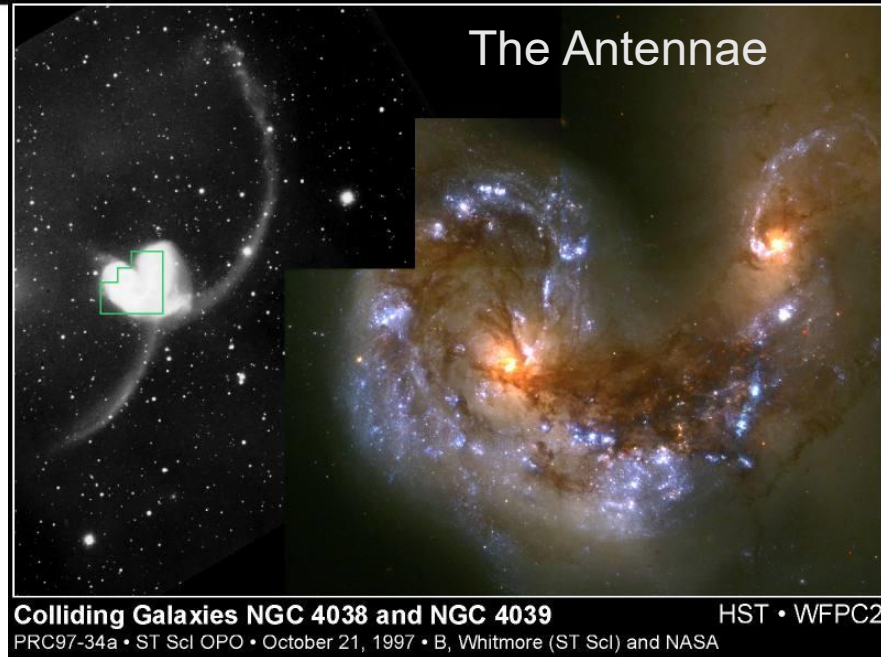
Atomic gas in red, observed with China's FAST radio telescope



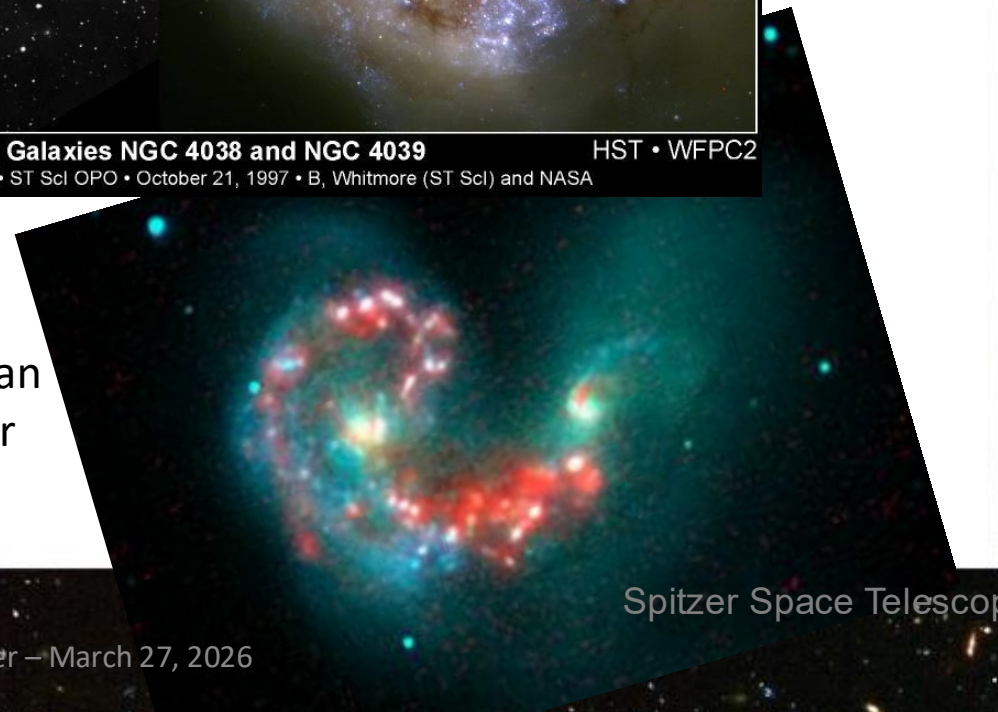
Computer simulations help show how tidal forces act on galaxies as they collide



Toomre & Toomre 1970



Mergers can trigger star formation



Spitzer Space Telescope

Spiral galaxies  
IC 2163 and  
NGC 2207 are  
merging

Optical  
(stars)

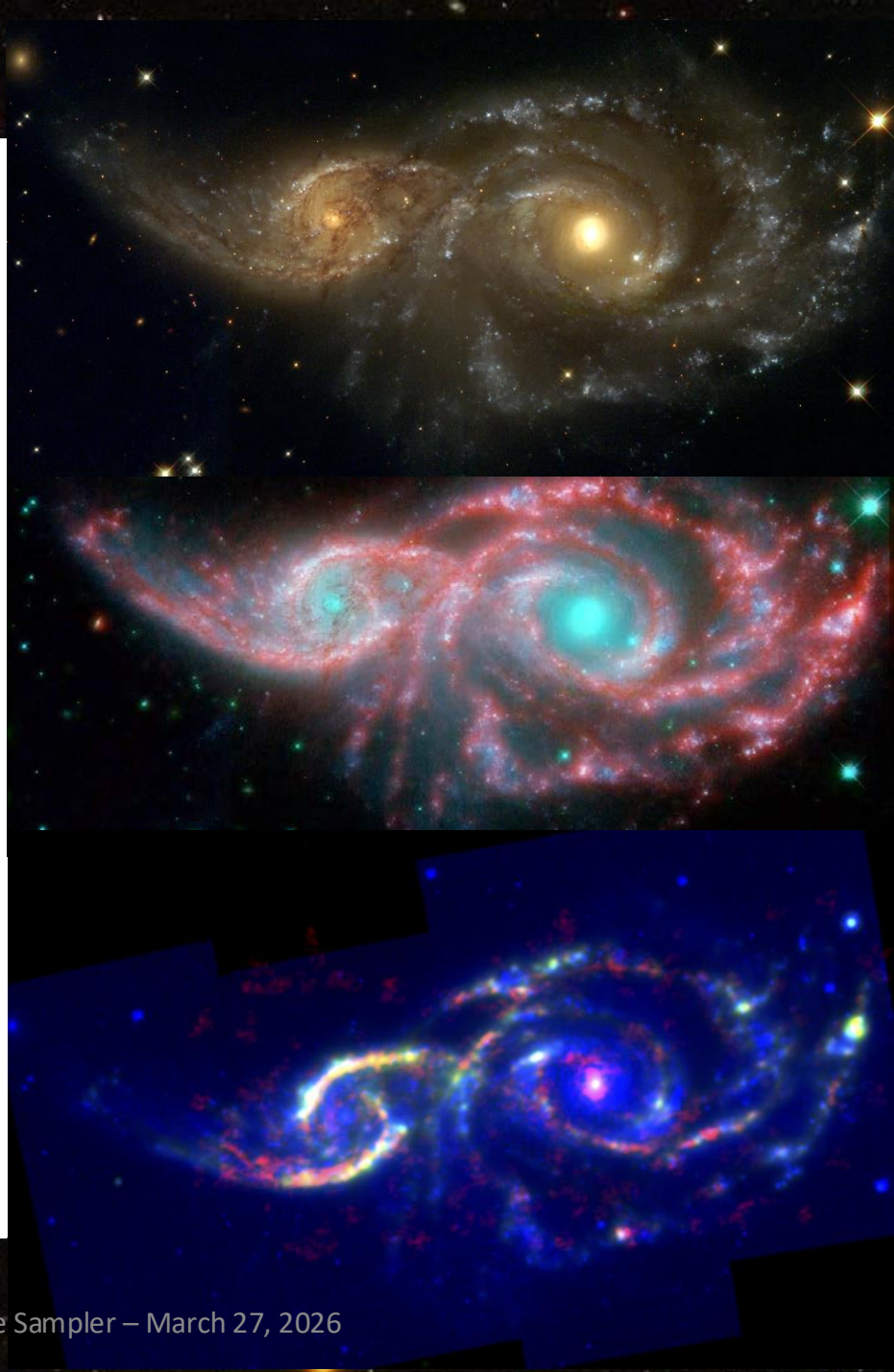
Infrared  
(dust)

120 million light years away

(1 light year is the distance  
light travels in a year  
= 6 trillion miles)

Radio  
(gas)

Elmegreen et al. 2001, 2006, 2017



Hubble

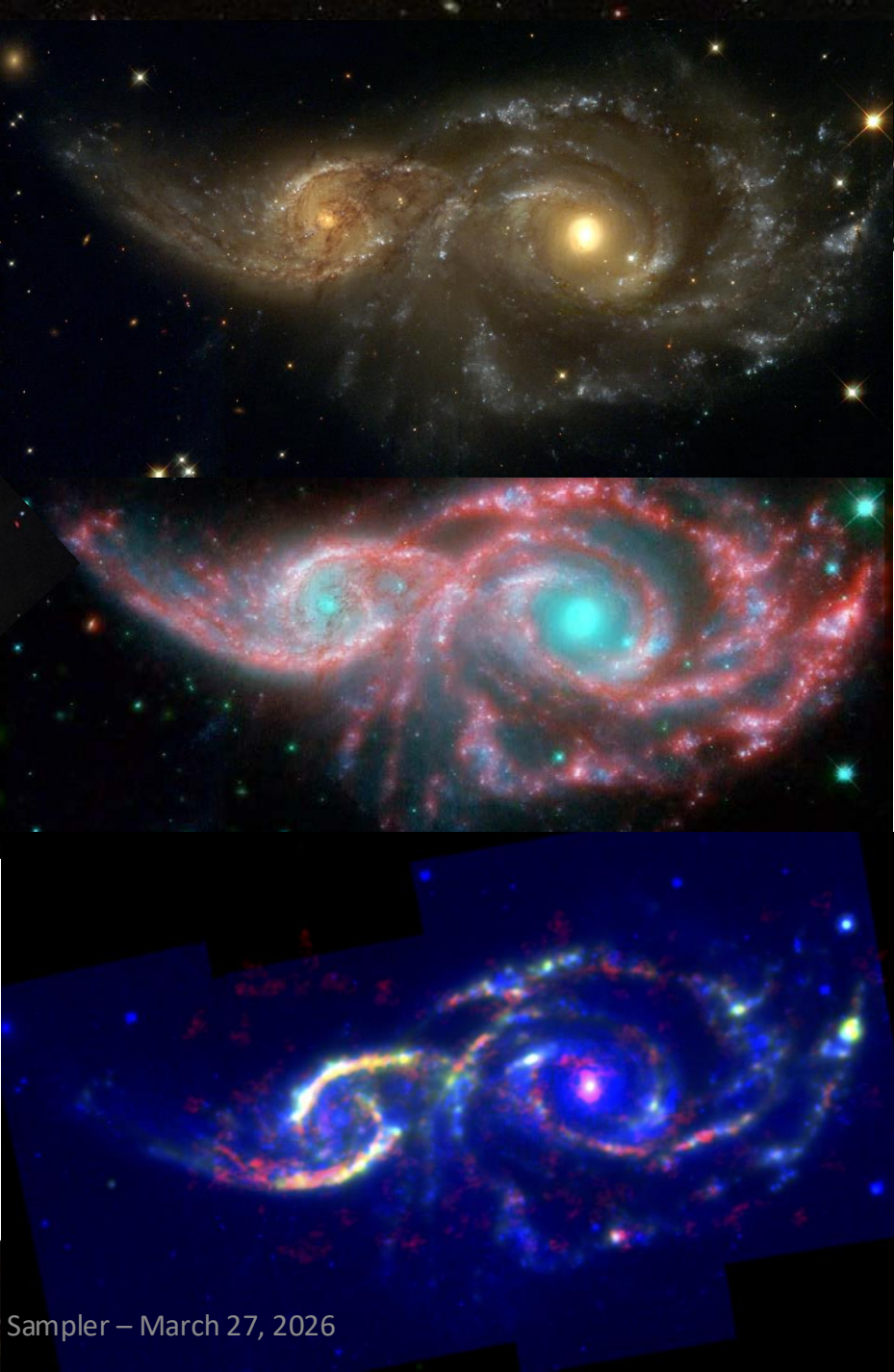
Spitzer

VLA



JWST (dust)  
+ Chandra (X-ray)

NASA, 2025

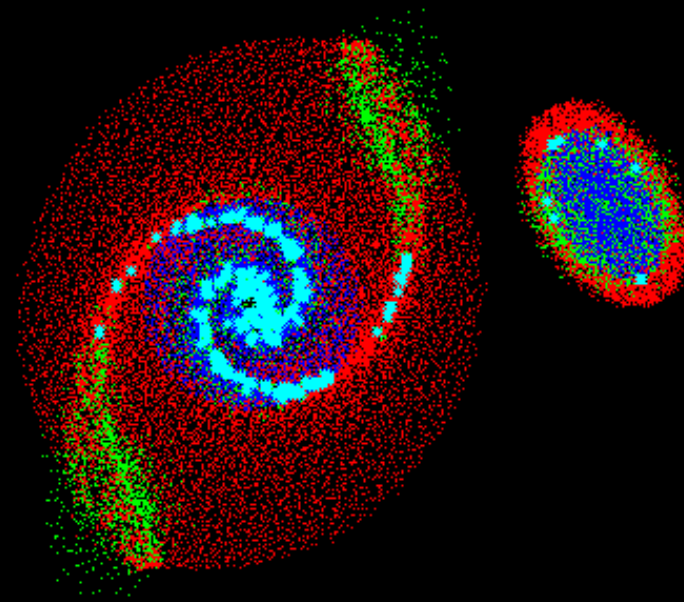


Hubble

Spitzer

VLA

Simulation of  
IC 2163 and  
NGC 2207  
interaction



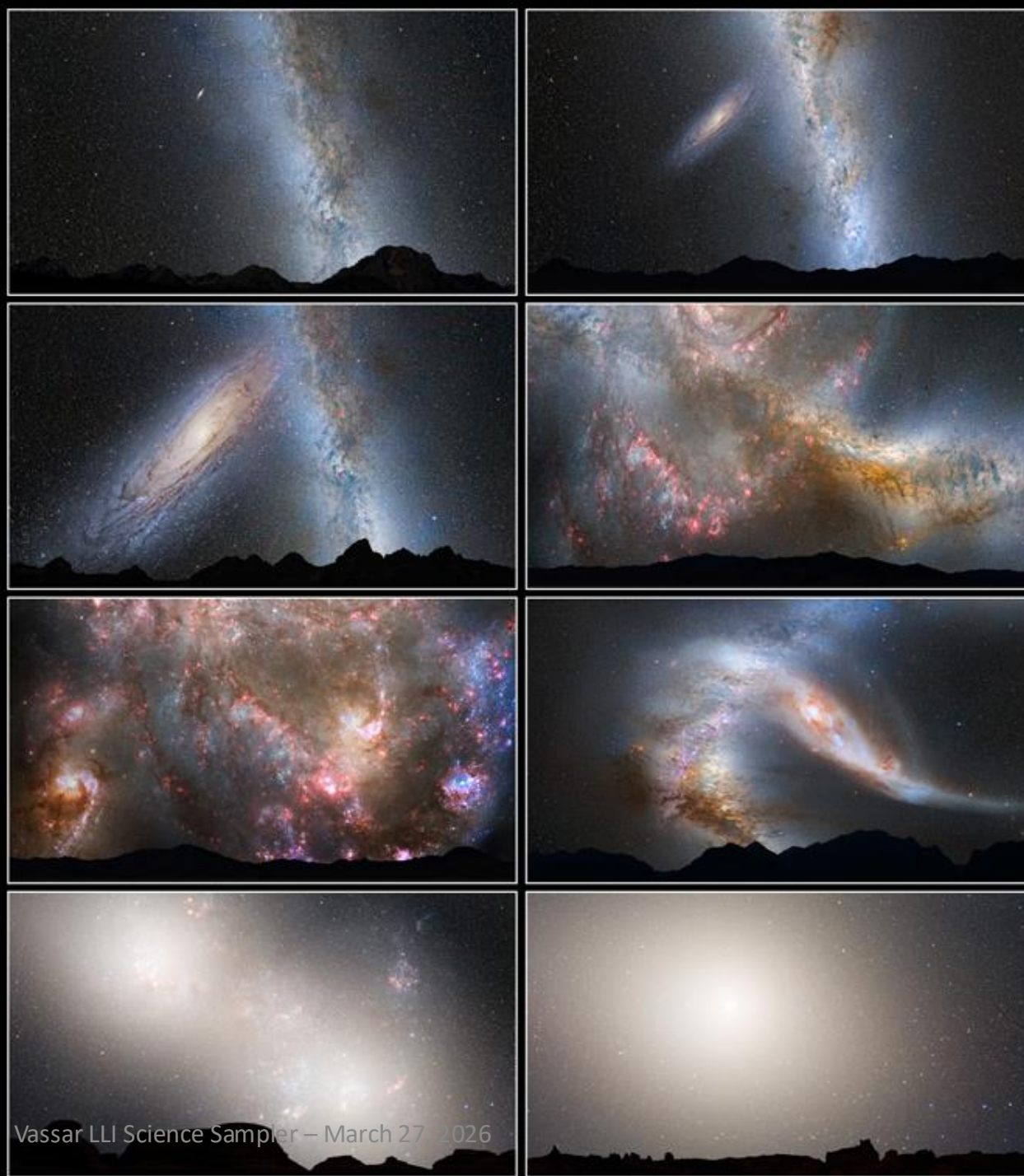
Andromeda is our  
nearest big galaxy,  
2.5 million light  
years away



Our galaxy may merge with Andromeda in 3-4 billion years

# Simulated merger sequence

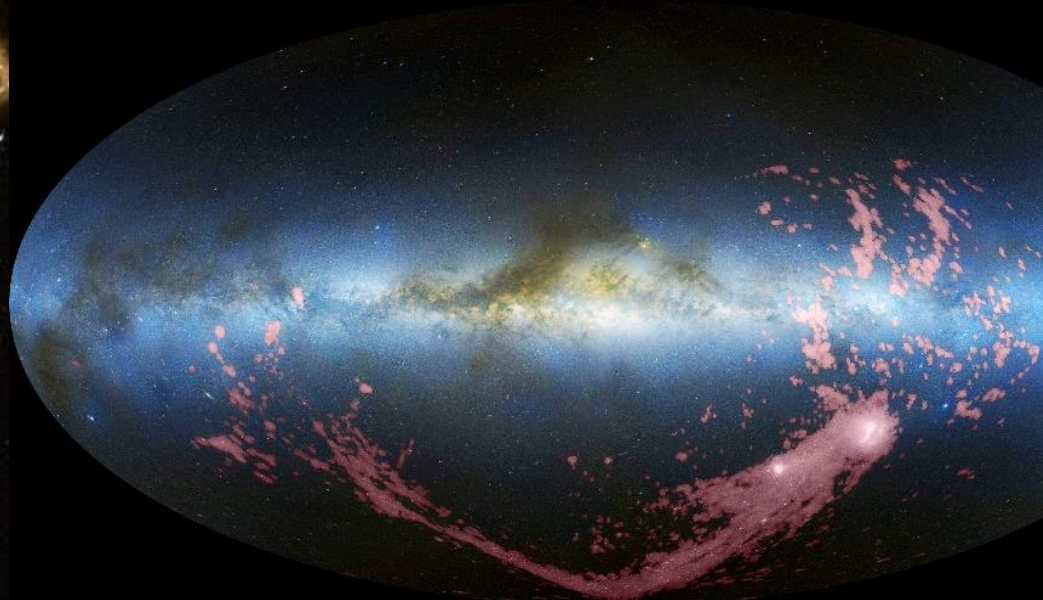
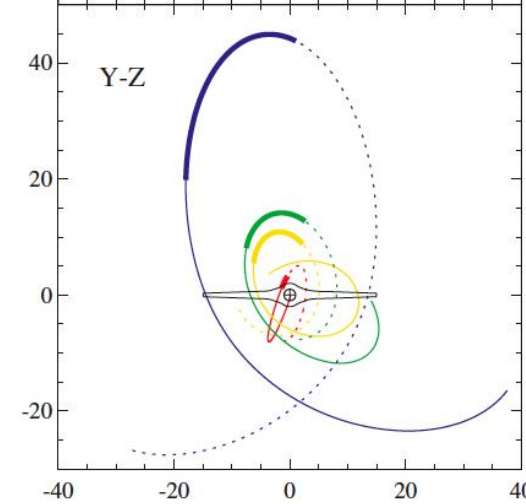
Levay et al. 2012, NASA site



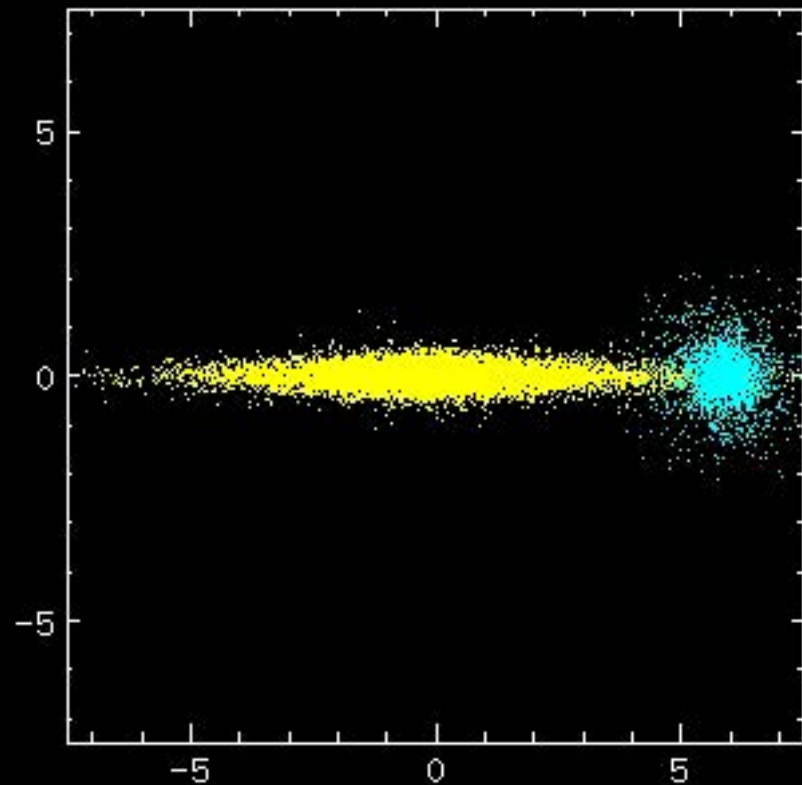
The Large and Small Magellanic Clouds are nearby irregular galaxies, 150,000 light years away – they are being shredded



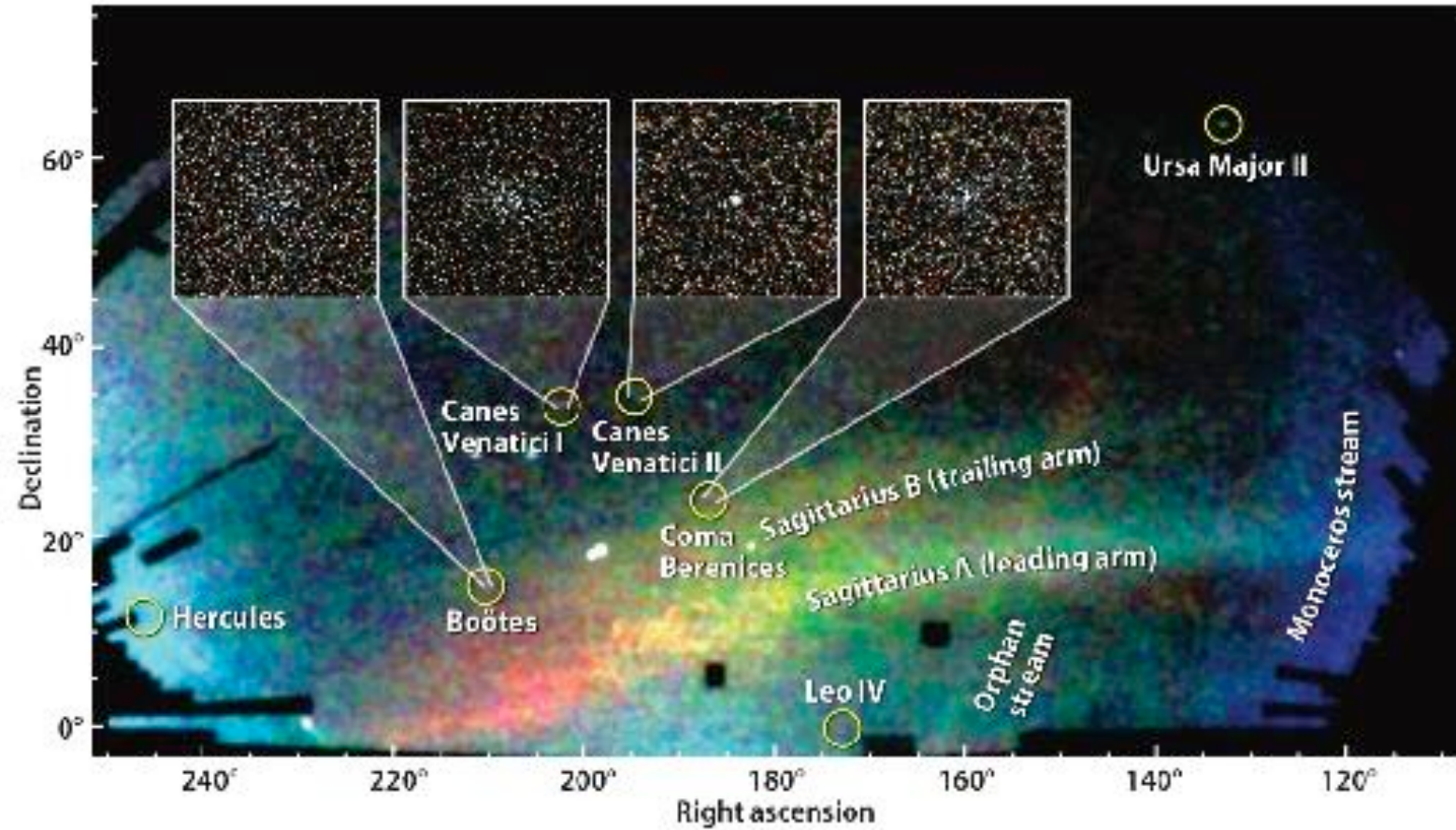
Tidally shredded dwarfs add to our halo – computer simulation of observed star streams coming from different dwarfs

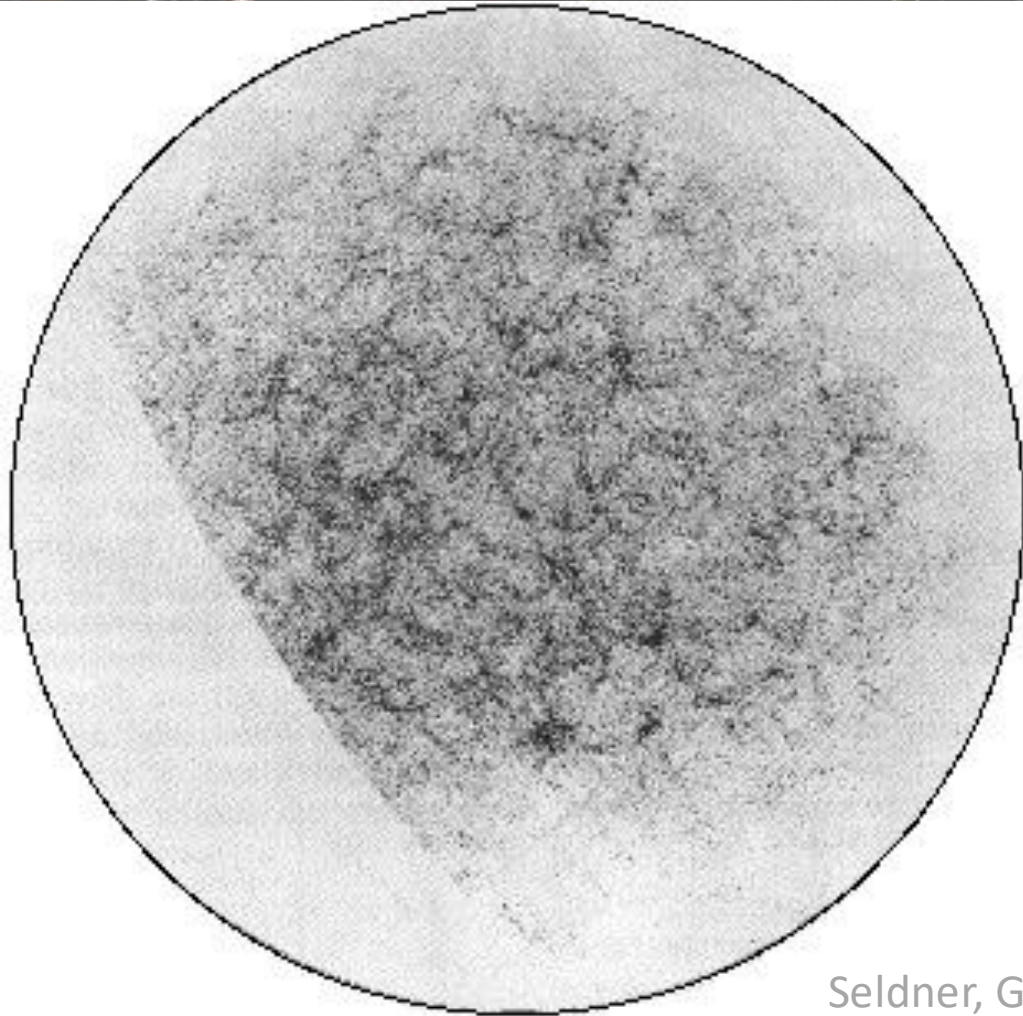


The Magellanic Stream in HI from LMC, SMC debris



Observations  
of star streams  
from the Sloan  
Digital Sky  
Survey





One million galaxies are shown here

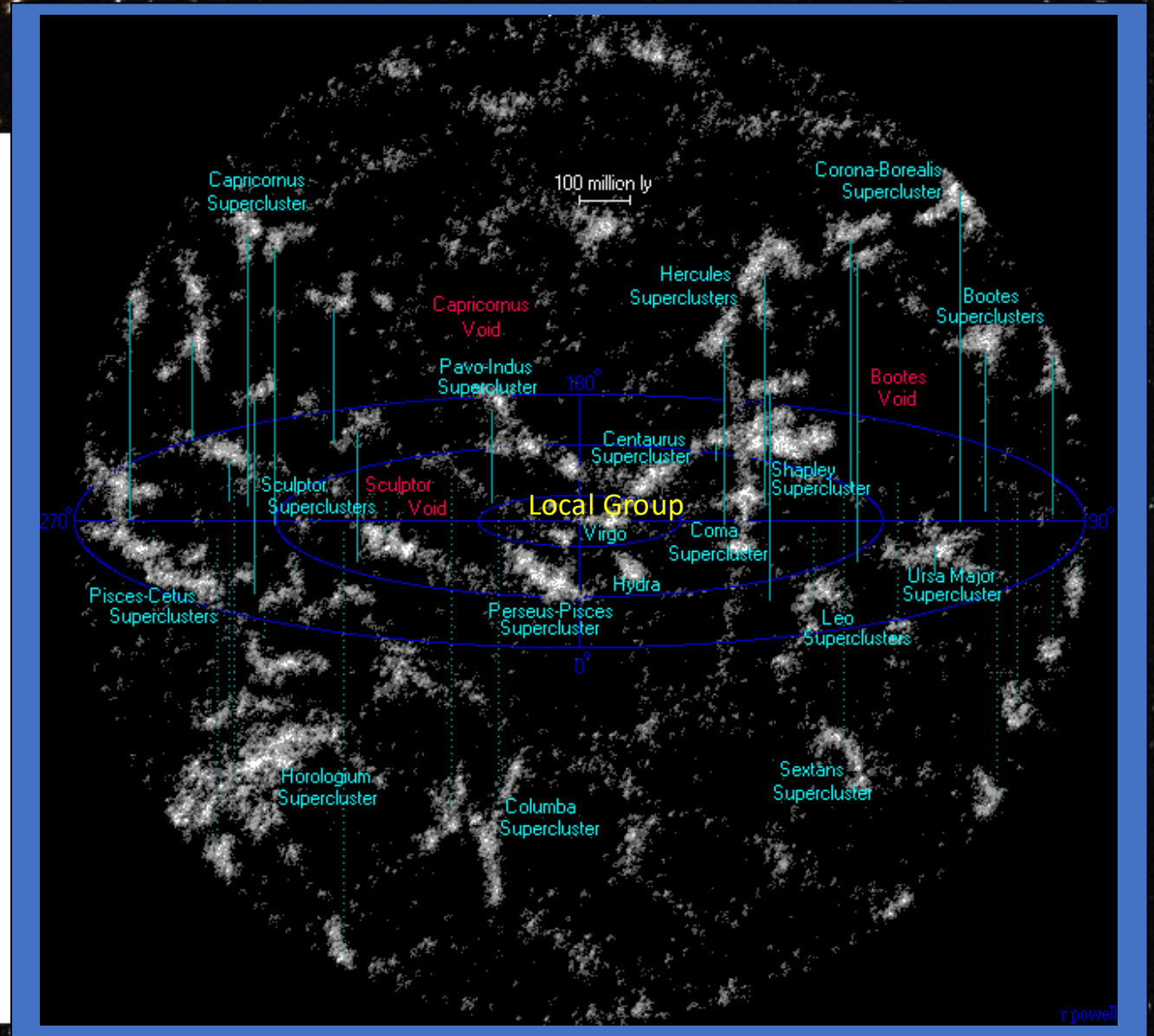
The “bubble-void” structure gives clues to how rapidly the Universe expanded

Seldner, Groth & Peebles 1977

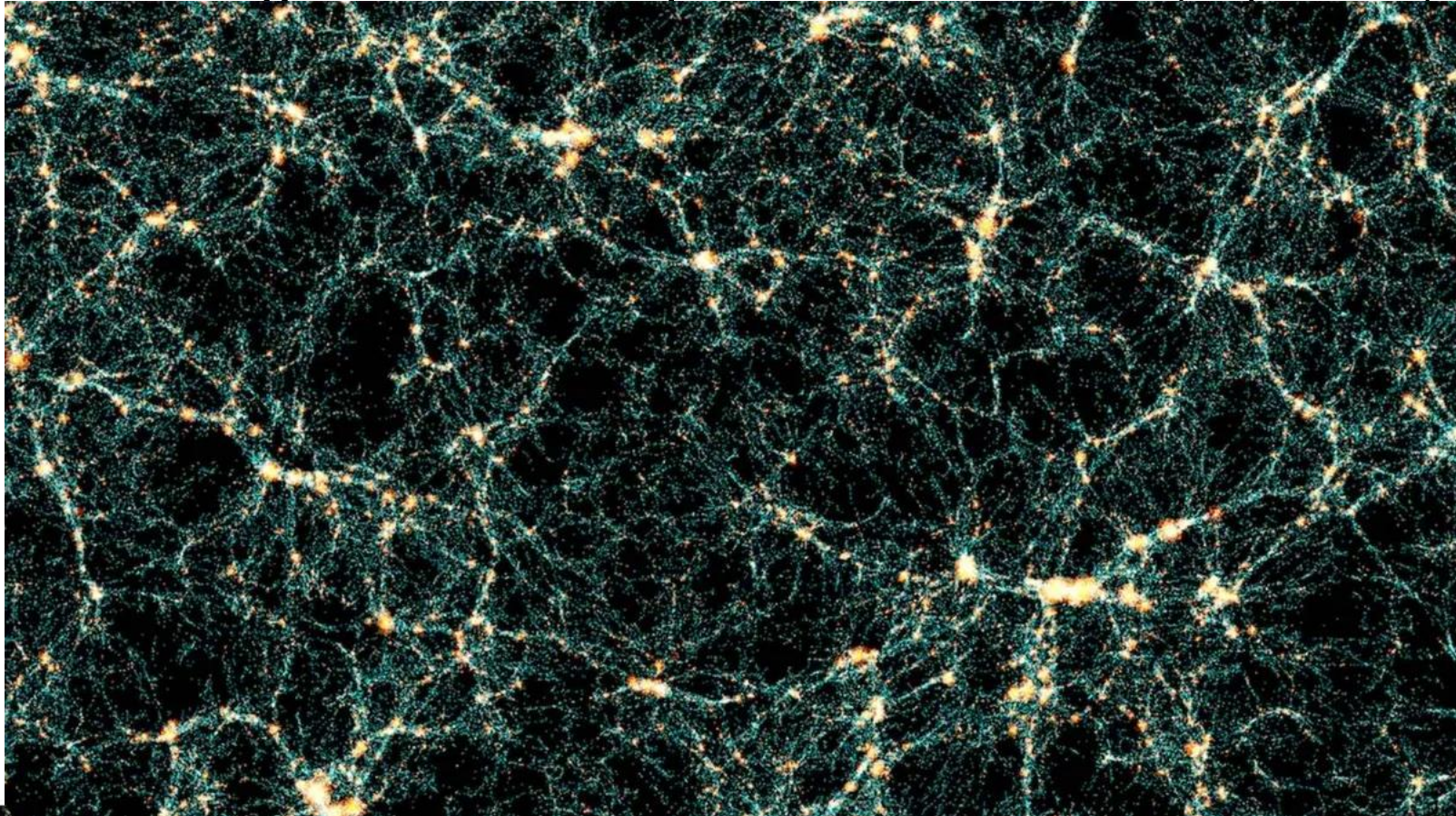
## Large-scale 3-D distribution of galaxies

Galaxies are clumped into clusters and superclusters

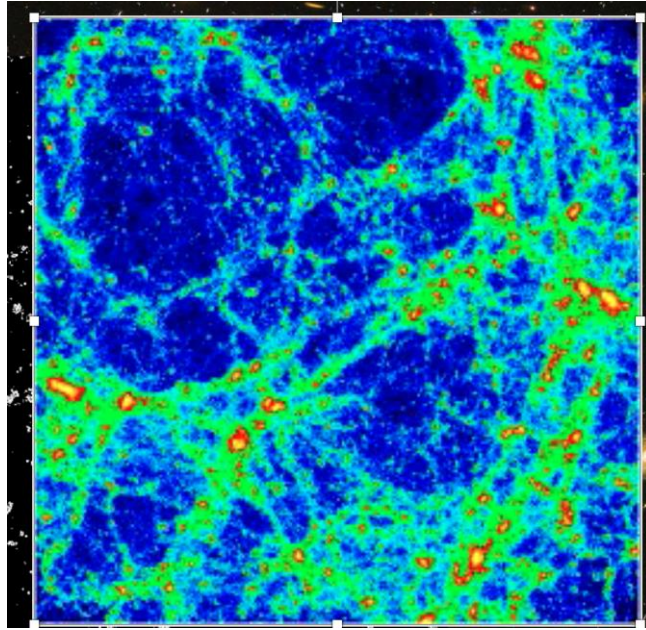
(Our Local Group has ~ 2 dozen members)



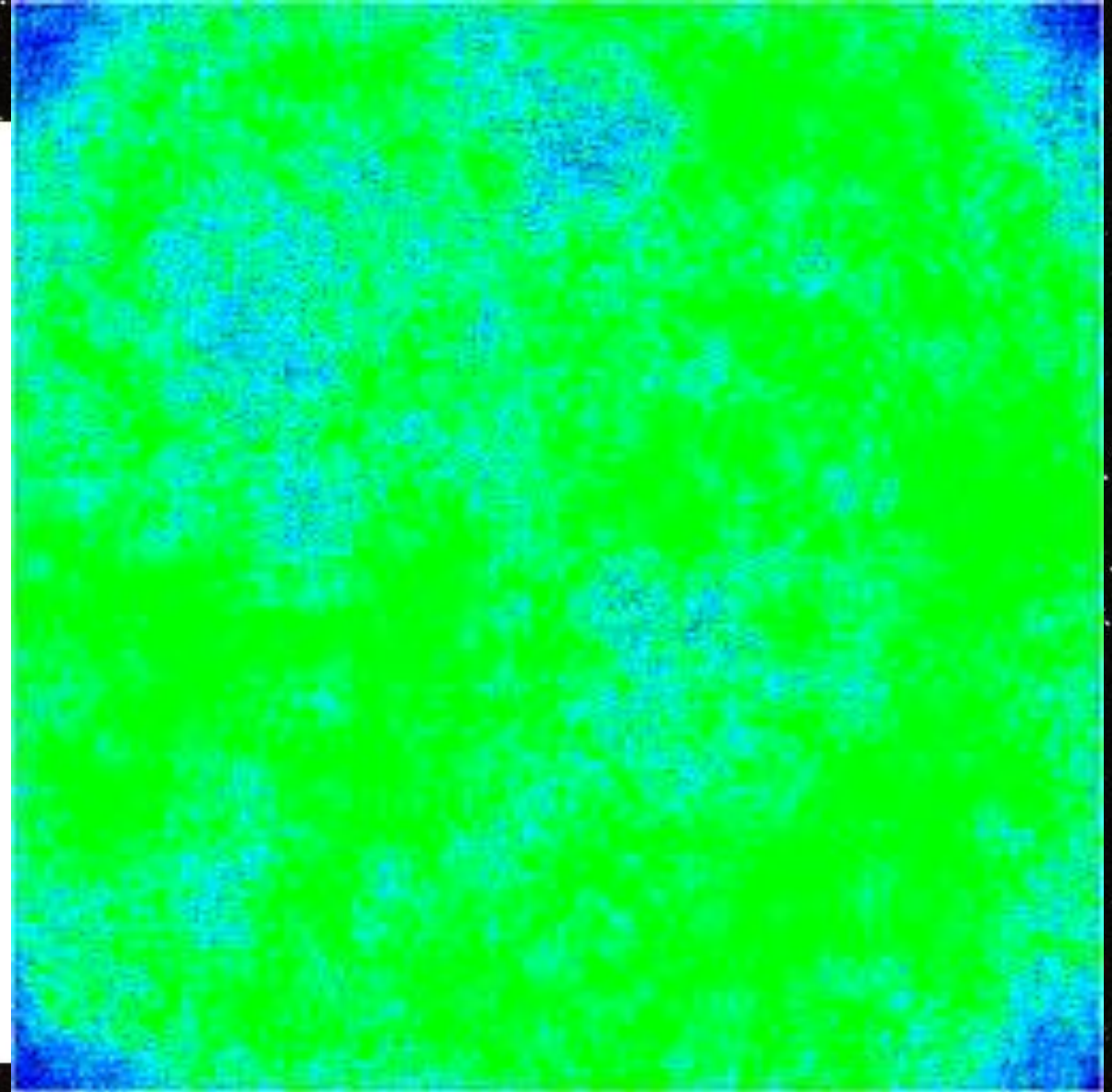
The Euclid consortium just released its simulation of 3.4 billion galaxies to compare with new data (Sept. 2025)



Computer simulations help us understand how structure first formed from the cosmic web of matter



NASA

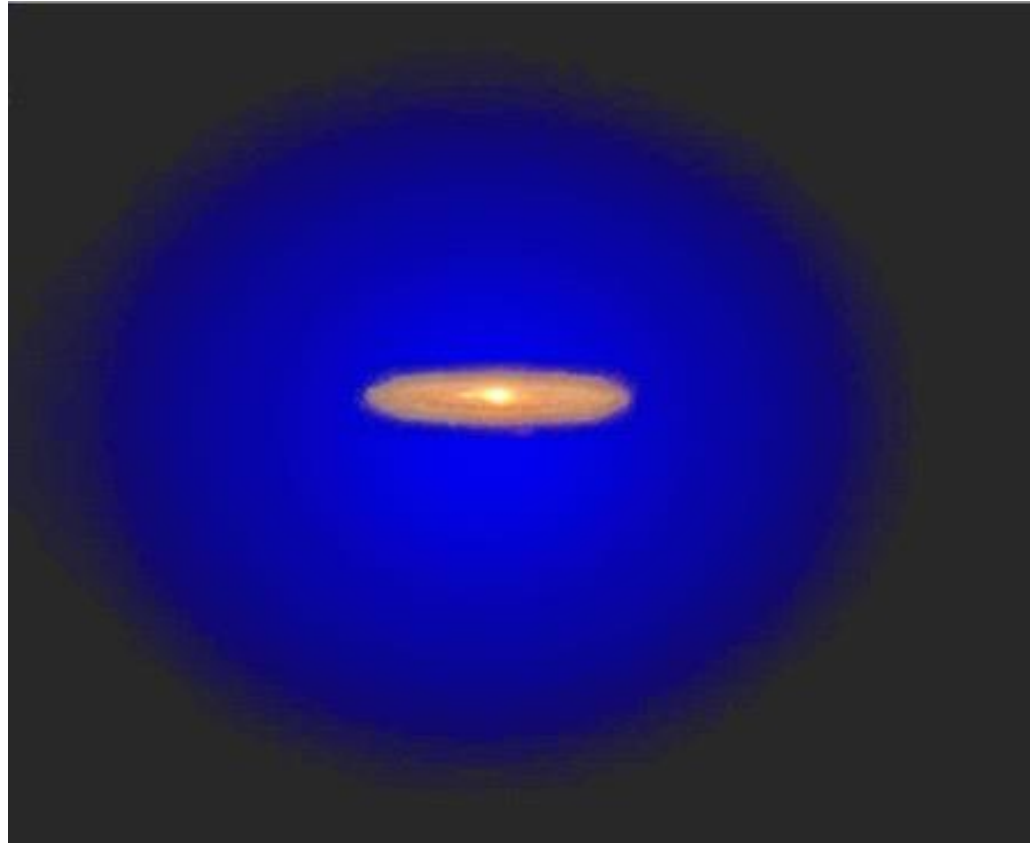


Dark matter (not made of protons) randomly clumped together in the early Universe and attracted gas to make galaxies

A dark matter halo surrounds each galaxy

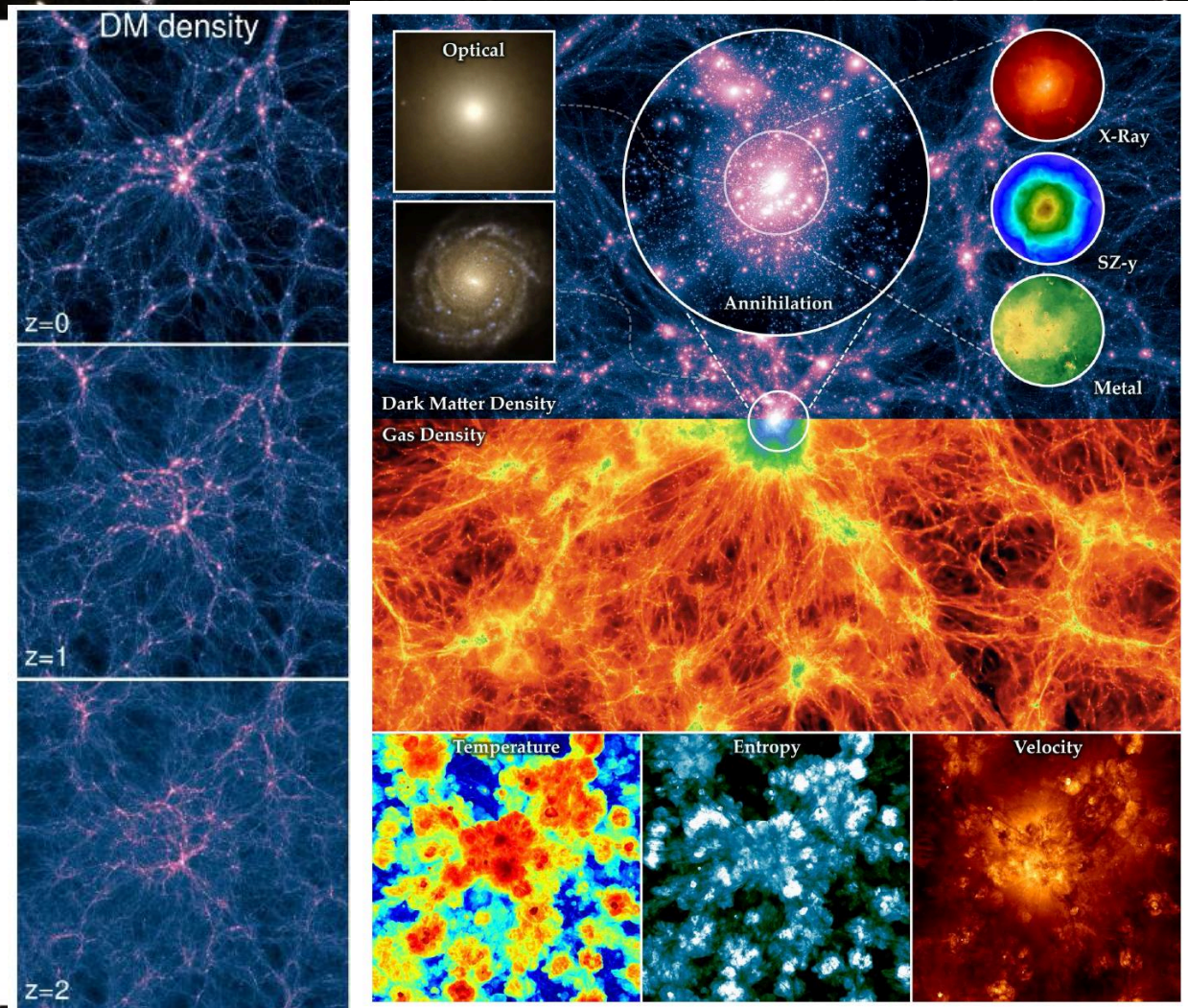
(confirmed by Vera Rubin)

and exists throughout space



Galaxies and clusters of galaxies formed along filaments of dark matter in the first billion years

Illustris simulation,  
<https://www.illustris-project.org/explorer/>



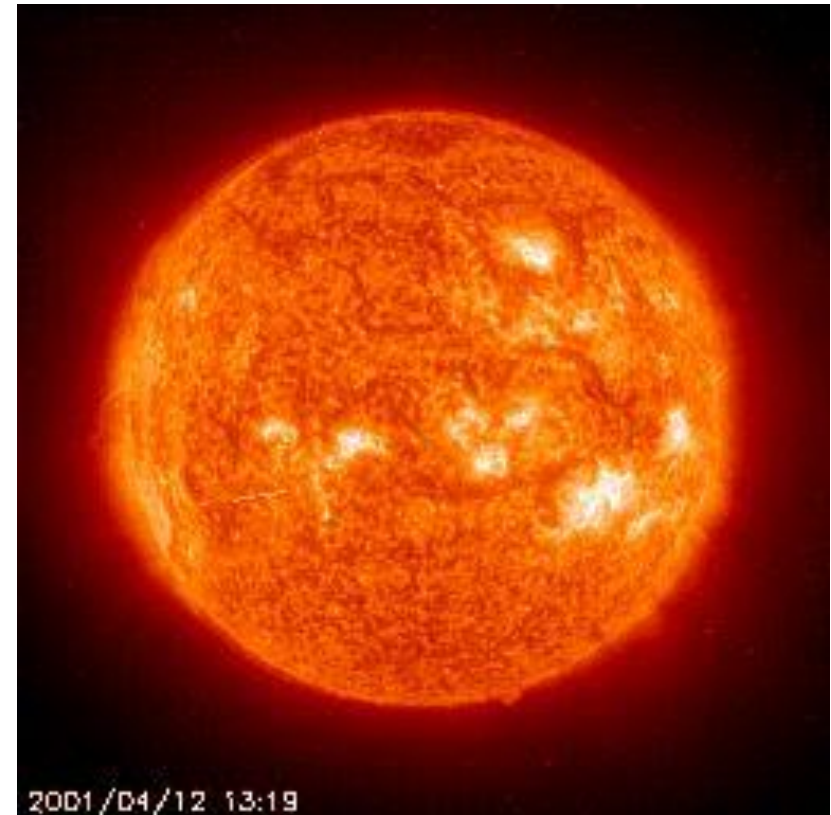
To understand how galaxies change over time, we need to look to the early Universe.

The Universe is like a **time machine**:  
as we look **out** in space, we look **back** in time

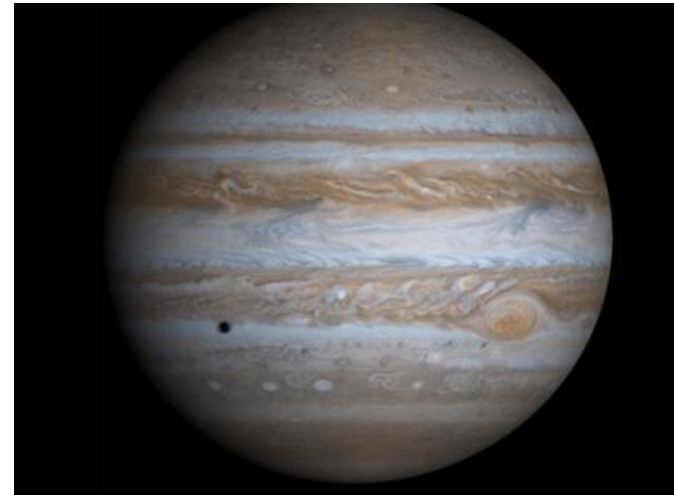
Light travels at a velocity of  $3 \times 10^8$  km/s

Our sun is 93 million miles away, so its light takes 8 minutes to reach us

(**time = distance/velocity**)



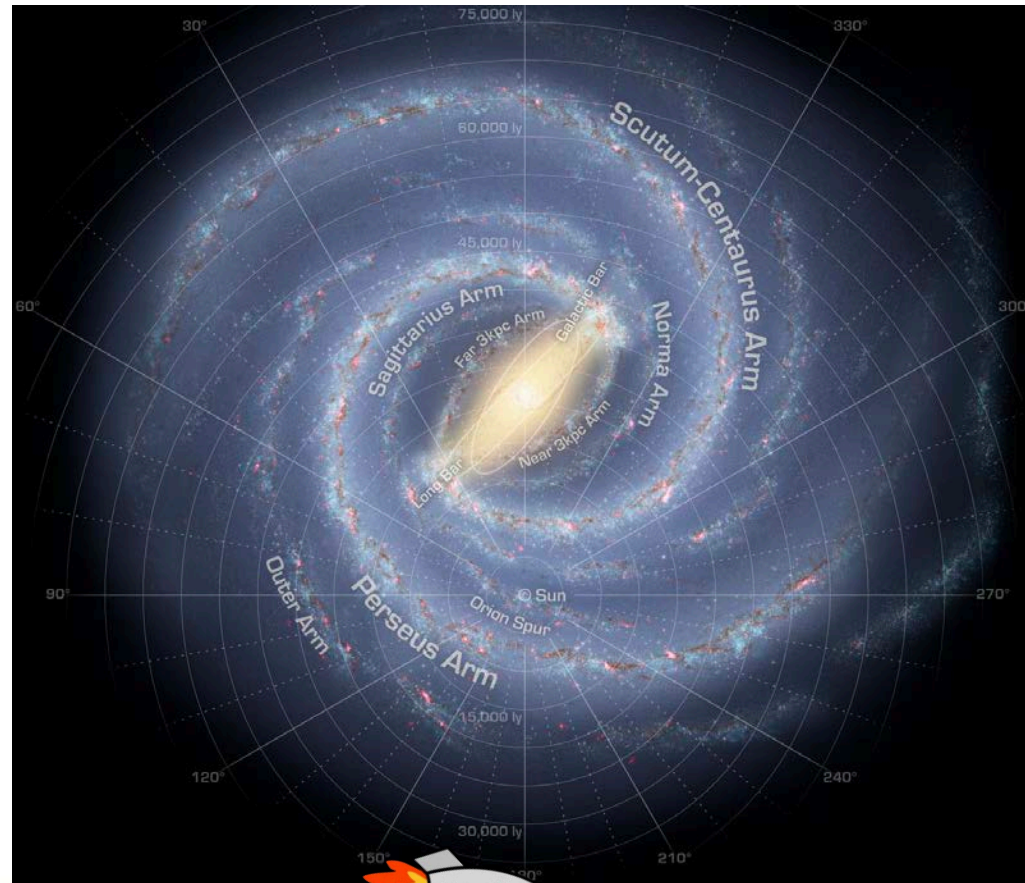
Light from Jupiter takes about 1/2 hour  
to reach us



Light from Proxima Centauri, our  
nearest star, takes 4.25 years to  
reach us  
(i.e., it is 4.25 light years away)



It takes light about 100,000 years to cross our galaxy



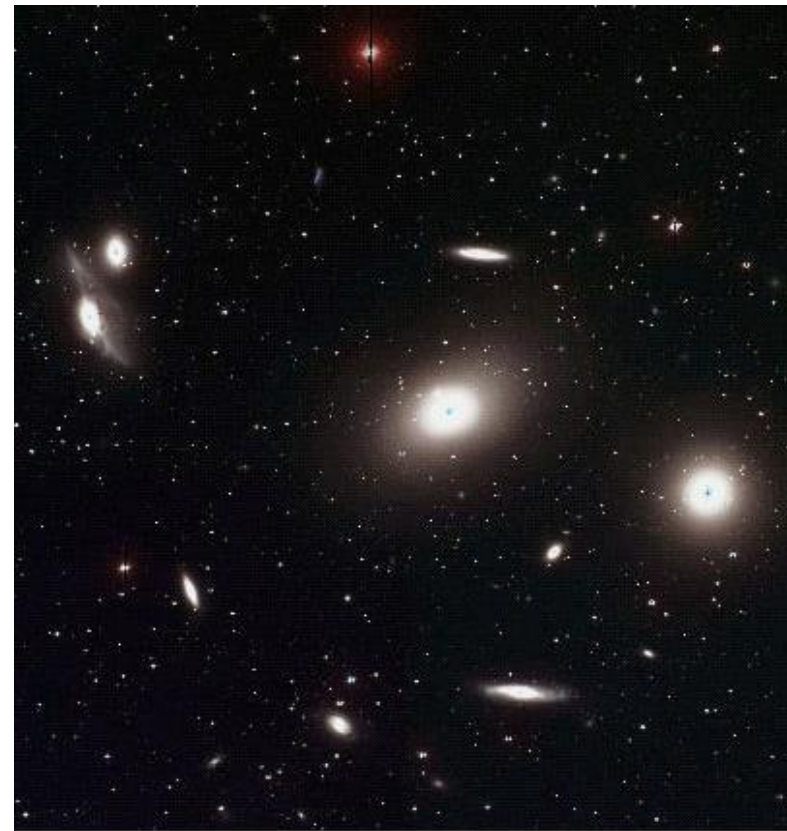
NASA



Virgo Cluster (our nearest cluster of galaxies) is 65 million light years away, so we see it as it was when dinosaurs walked the Earth!



POSS

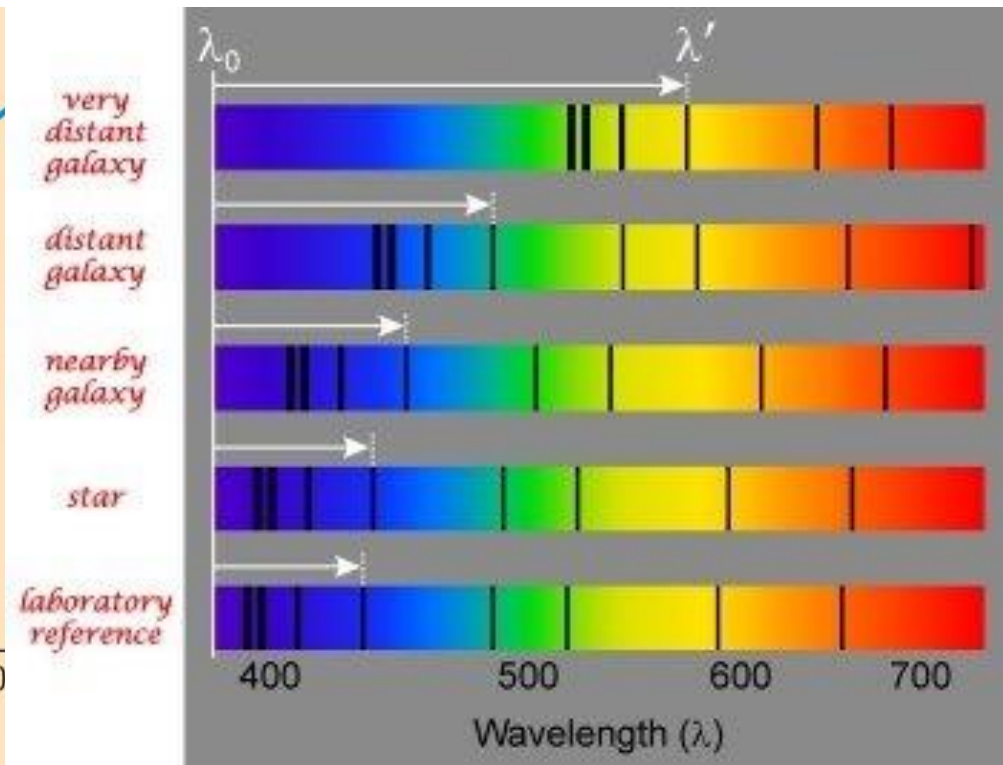
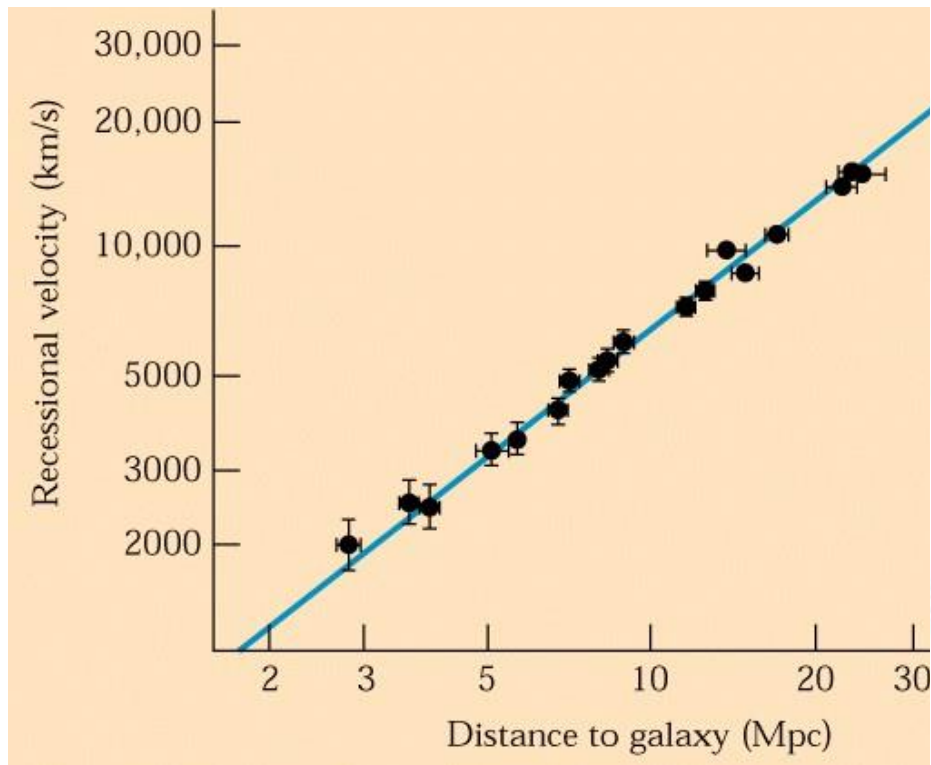




We can now observe galaxies billions of light years away!

By looking at lots of images of galaxies when they were young and comparing with galaxies near us today, we can piece together how galaxies evolve.

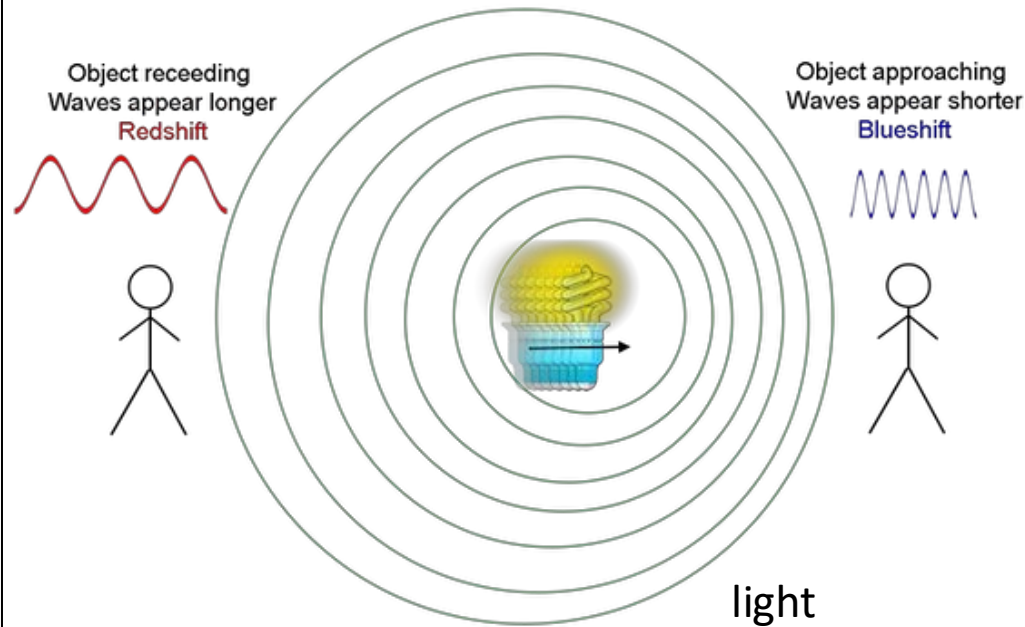
The universe is expanding, so light from distant galaxies is **redshifted**



Hubble & Humason; Lemaitre

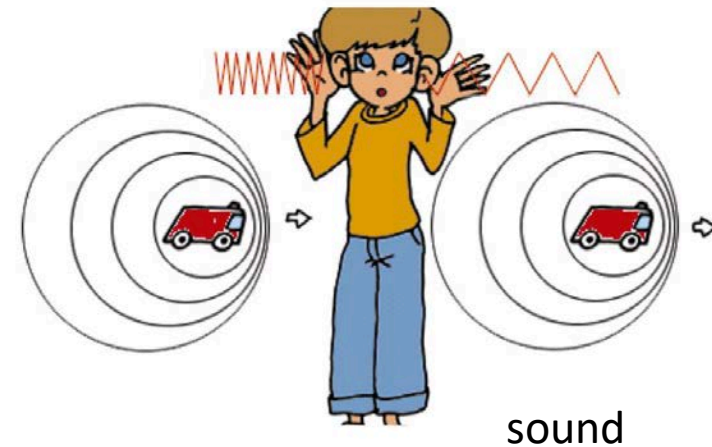
We can measure velocities from the Doppler shift:  
there's a change in wavelength observed if there is motion

For small velocities, 
$$\frac{v}{c} = \frac{\Delta\lambda}{\lambda}$$



(There's a relativistic correction for high velocities)

Doppler effect:  
blueshift=towards, redshift=away

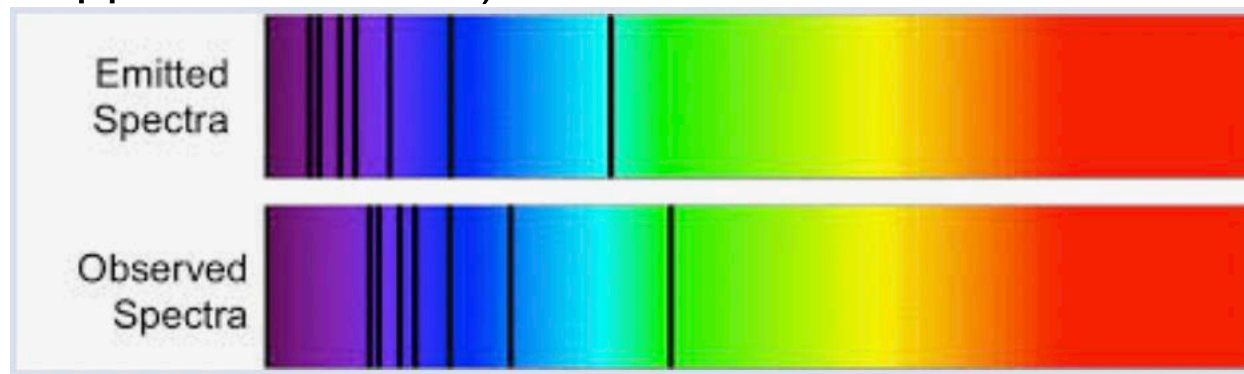


Similarly, we measure velocities (and therefore distances) to galaxies from redshifted lines caused by the Universe's expansion

The **redshift**,  $z$ , is defined in terms of relative shifted wavelength,  $\lambda$

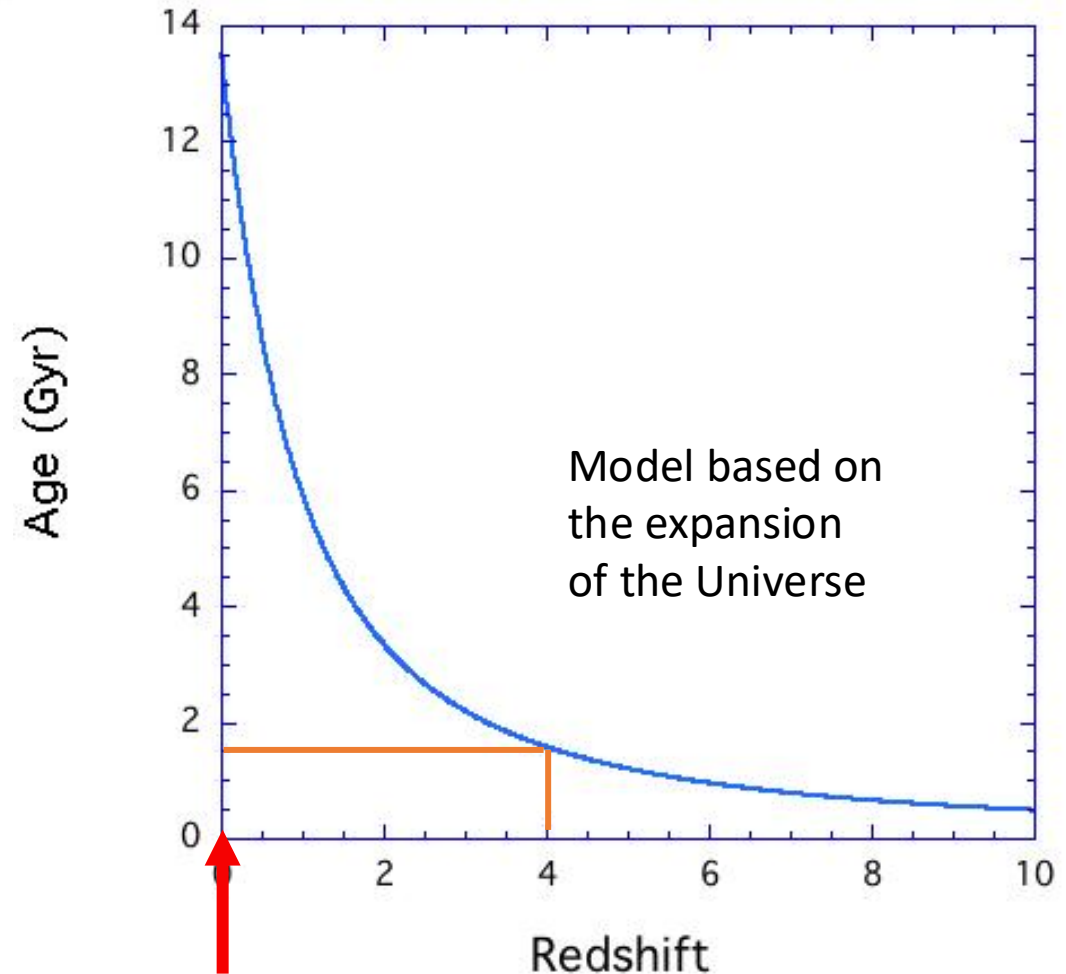
$$\lambda_{\text{observed}} / \lambda_{\text{rest}} = z + 1$$

e.g., a galaxy at  $z = 4$  will have emission at  $1500\text{\AA}$  shifted to  $7500\text{\AA}$  (so **UV** appears as far **red**)



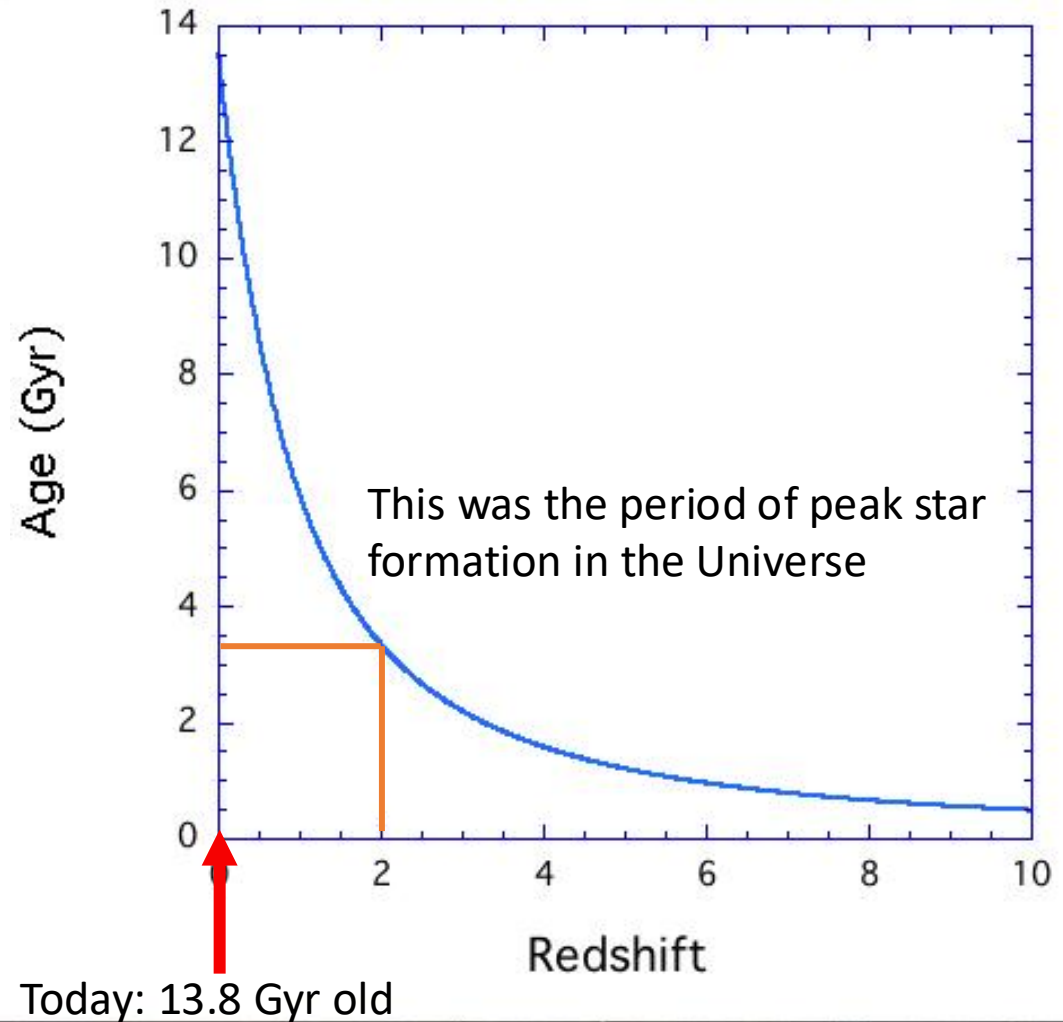
At  $z = 4$ , we see objects as they were less than 2 billion years after the Big Bang

(greater than 11 billion light years from us!)

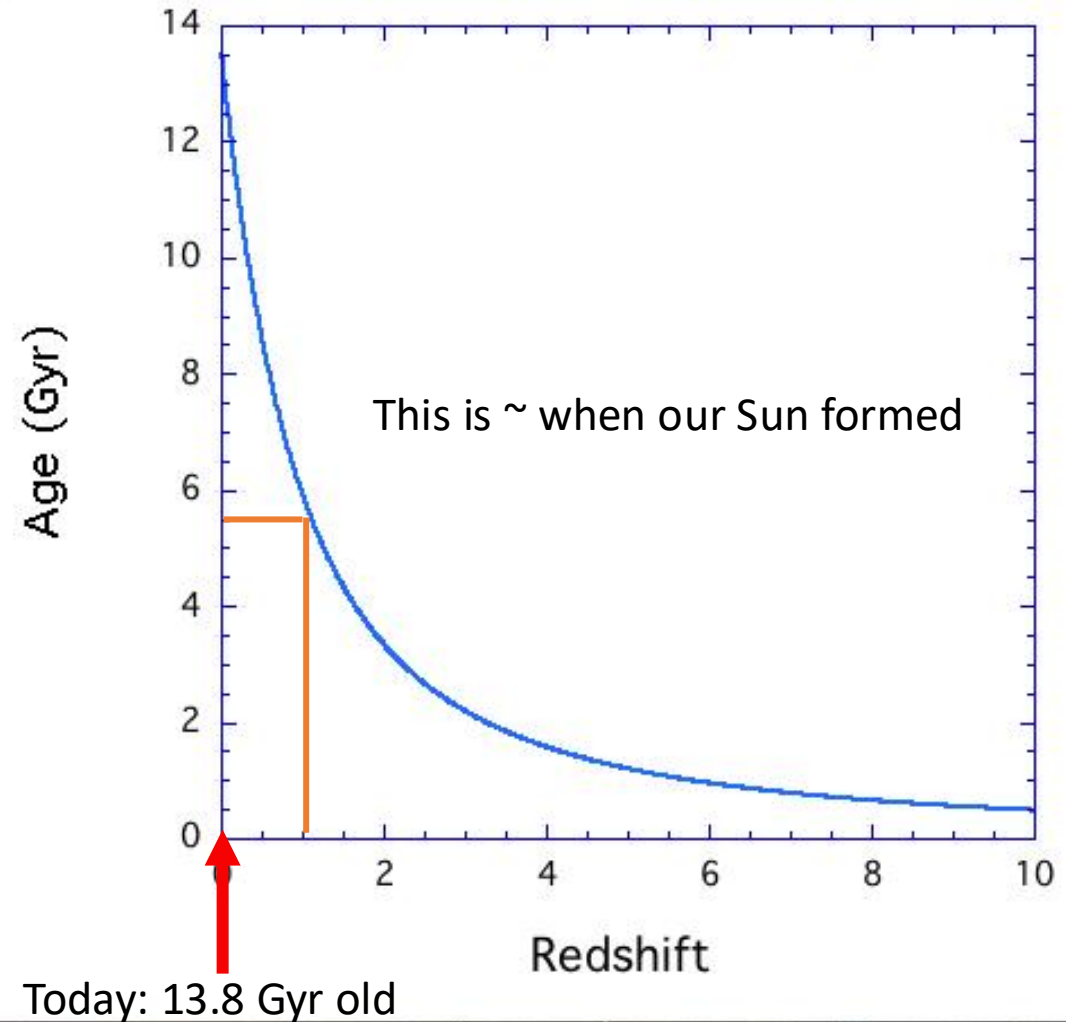


Today: 13.8 Gyr old

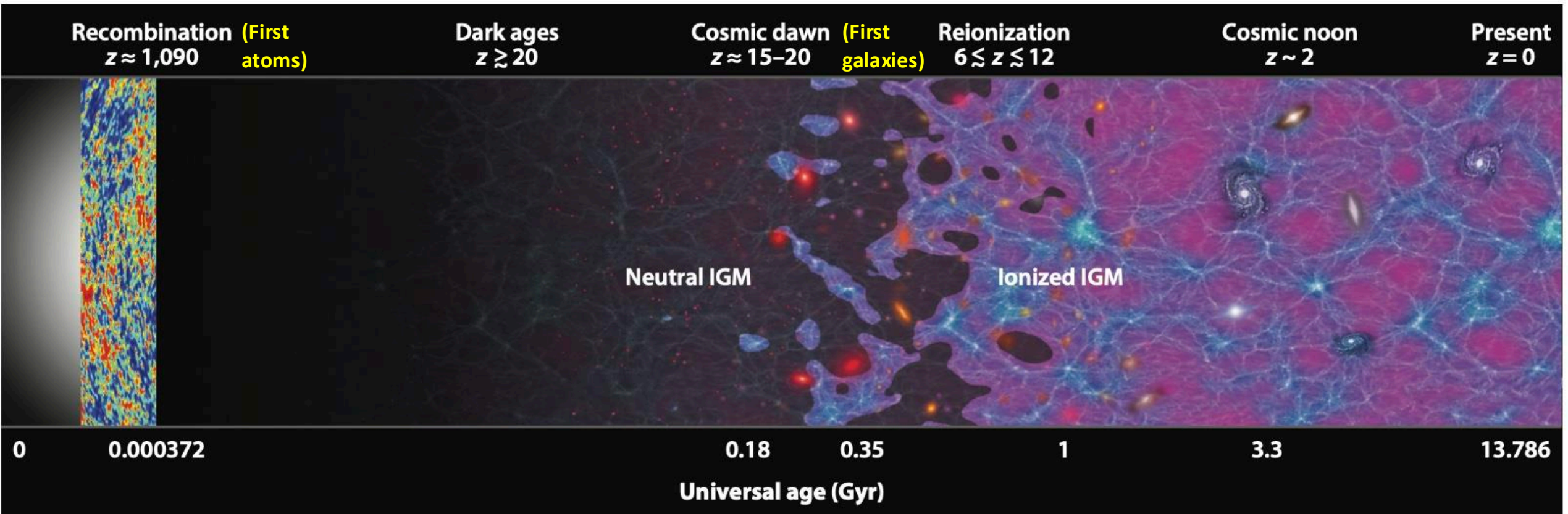
At  $z = 2$ , we see objects when the Universe was about 1/3 its current age



At  $z = 1$ , we see objects when the Universe was about 1/2 its current age

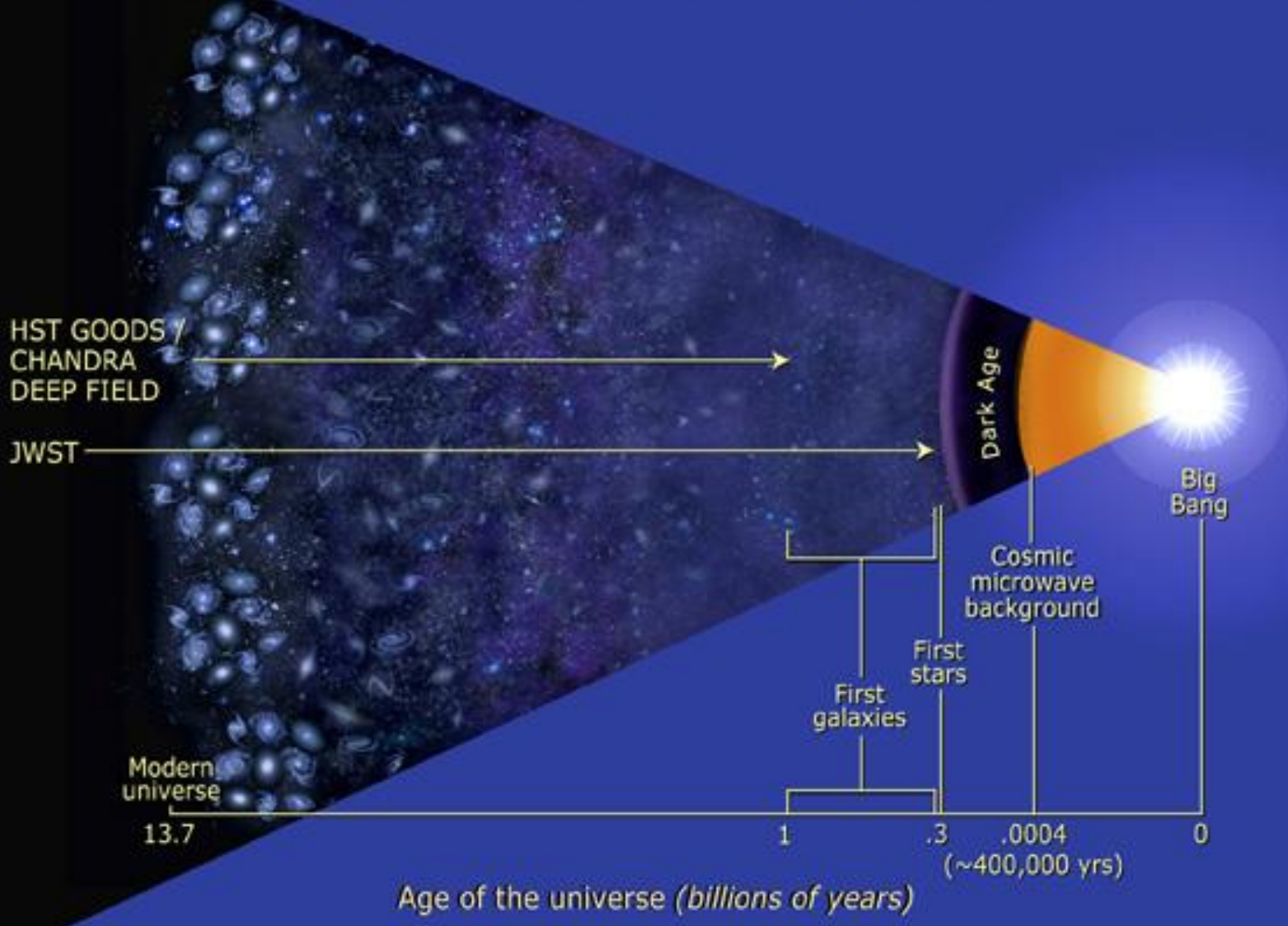


## Timescale with ages and redshifts



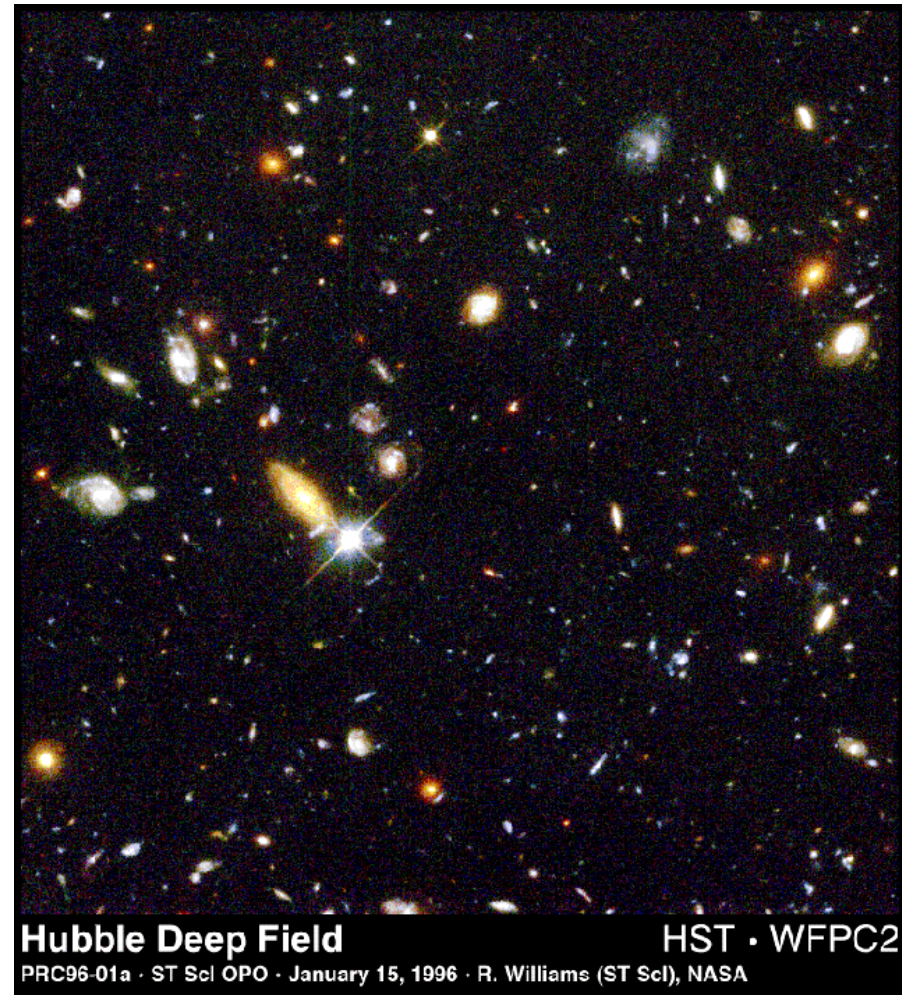
Robertson 2022

# Seeing back into the cosmos



The Hubble Deep Fields (north and south) were imaged in 1996

Thousands of distant galaxies are seen in “blank” regions of the sky out to  $z=1-2$  (when our Universe was about half its current age)



**Hubble Deep Field**

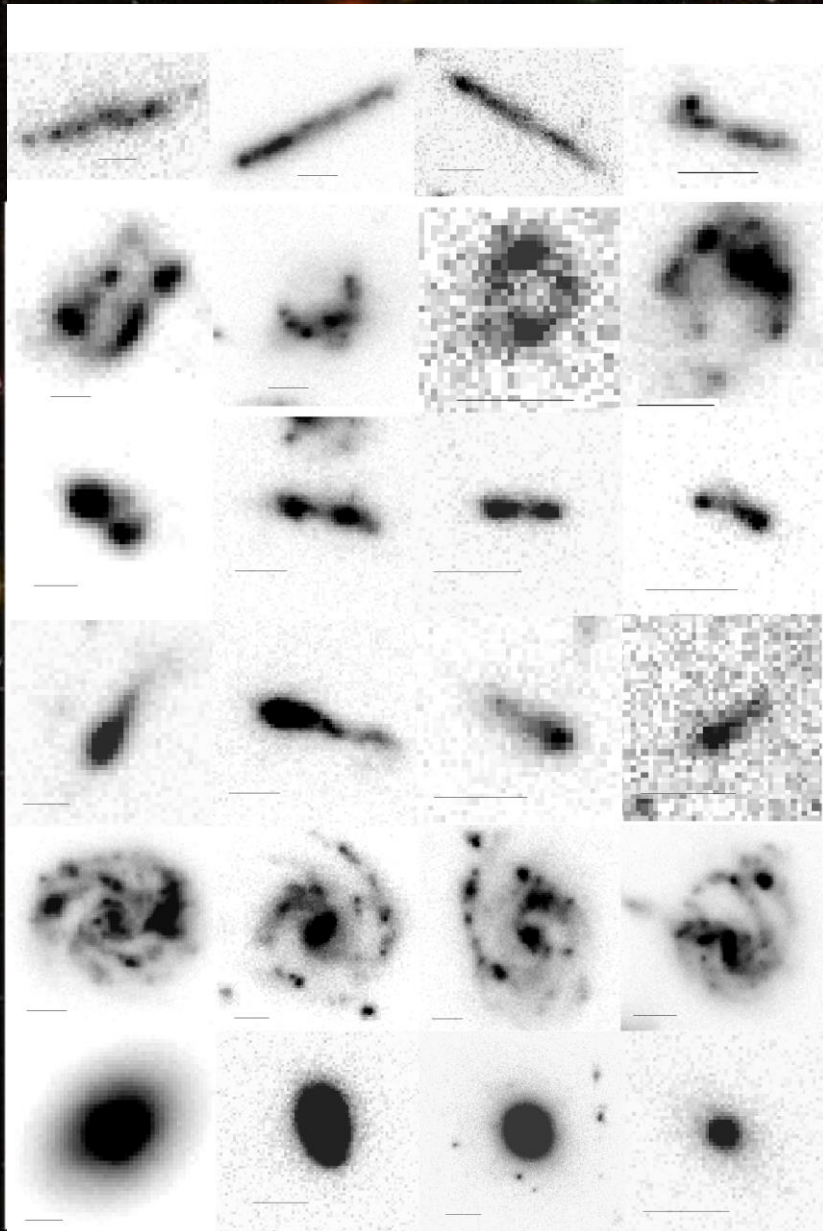
**HST · WFPC2**

PRC96-01a · ST ScI OPO · January 15, 1996 · R. Williams (ST ScI), NASA

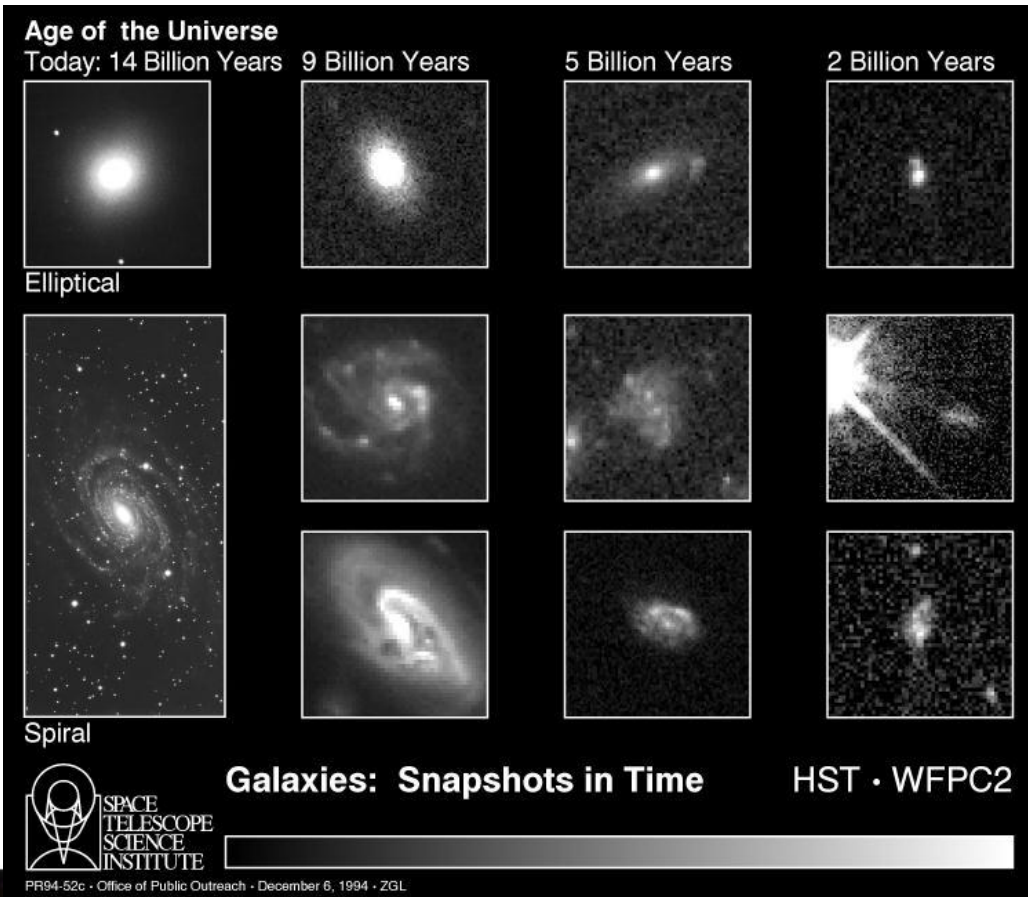
Clumpy

Spiral

Elliptical



Galaxies at high redshift often look peculiar and clumpy, not like most of today's galaxies



Elmegreen et al. 2005

The Ultra Deep Field (UDF, 2003-2012) reaches distances on average more than twice as far as the HDFs.

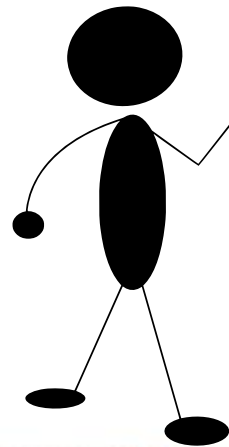
10,000 galaxies are seen at  $z = 2$  to 11!



STScI

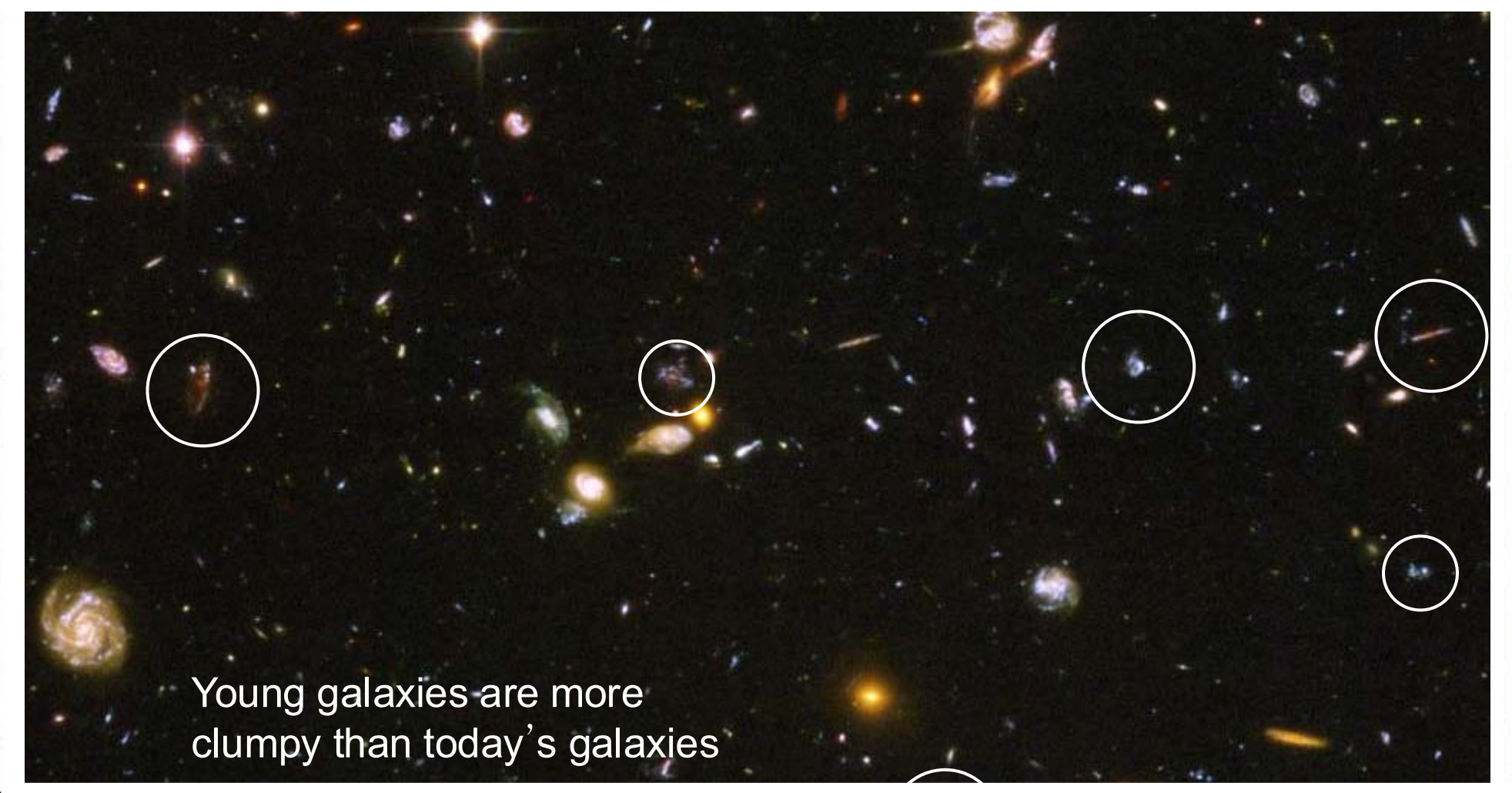
# This is the UDF!

Hold a needle at arm's length and look through its hole. That's the tiny piece of sky the Ultra Deep Field covers!

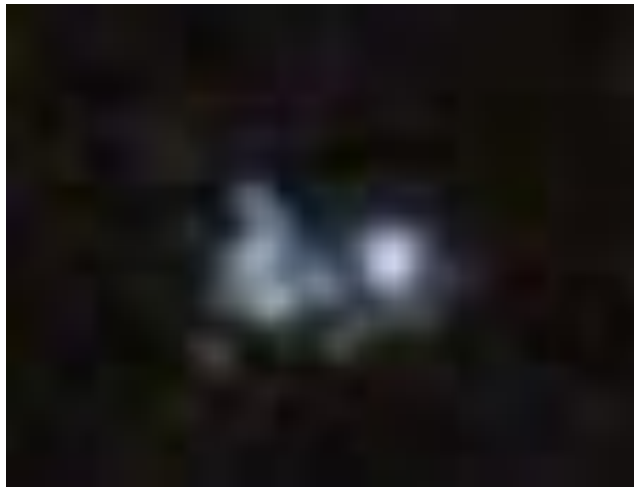


Part of the UDF

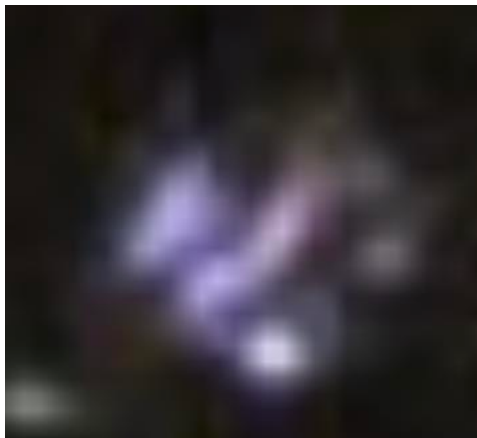




Young galaxies are more  
clumpy than today's galaxies

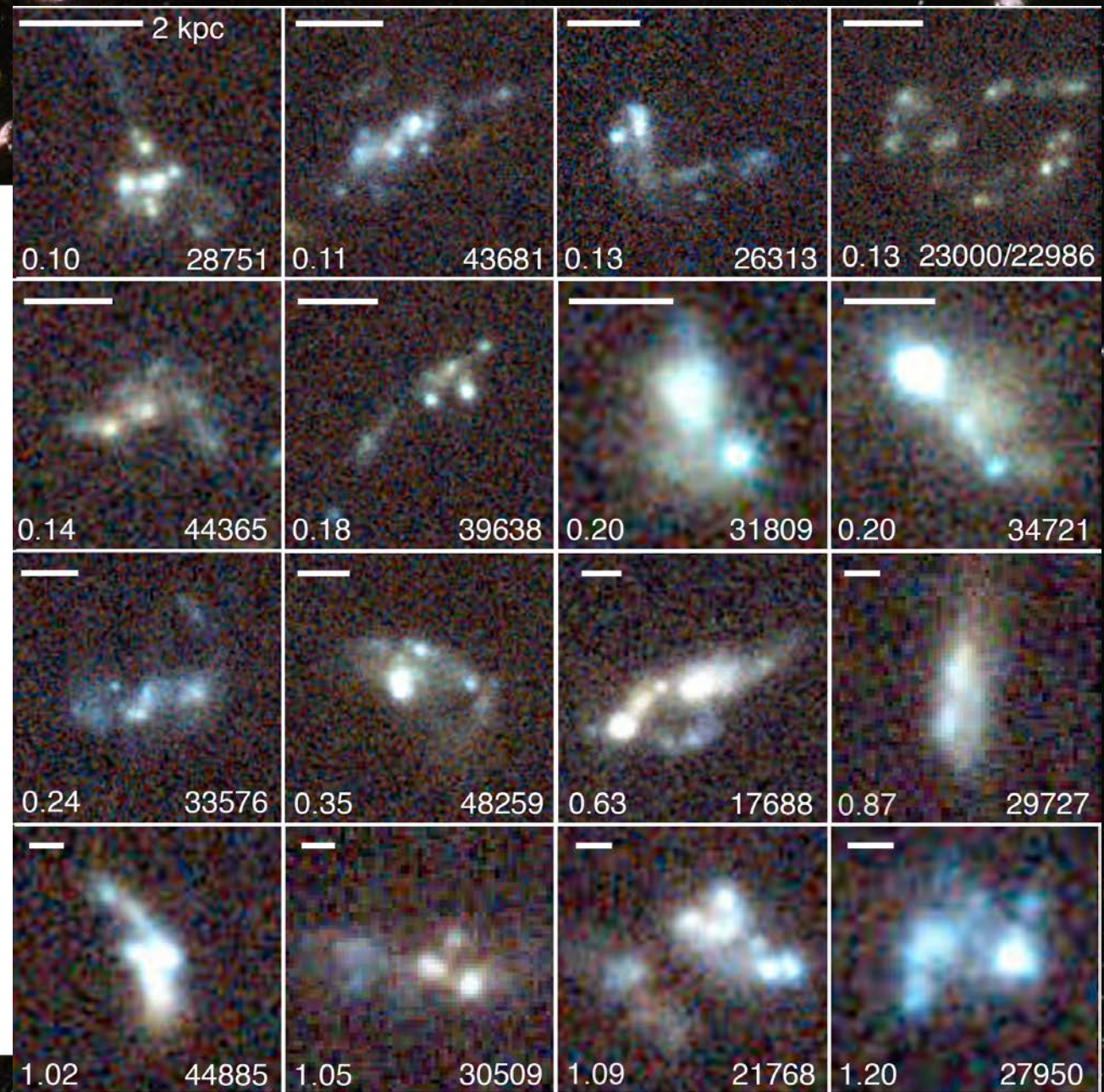


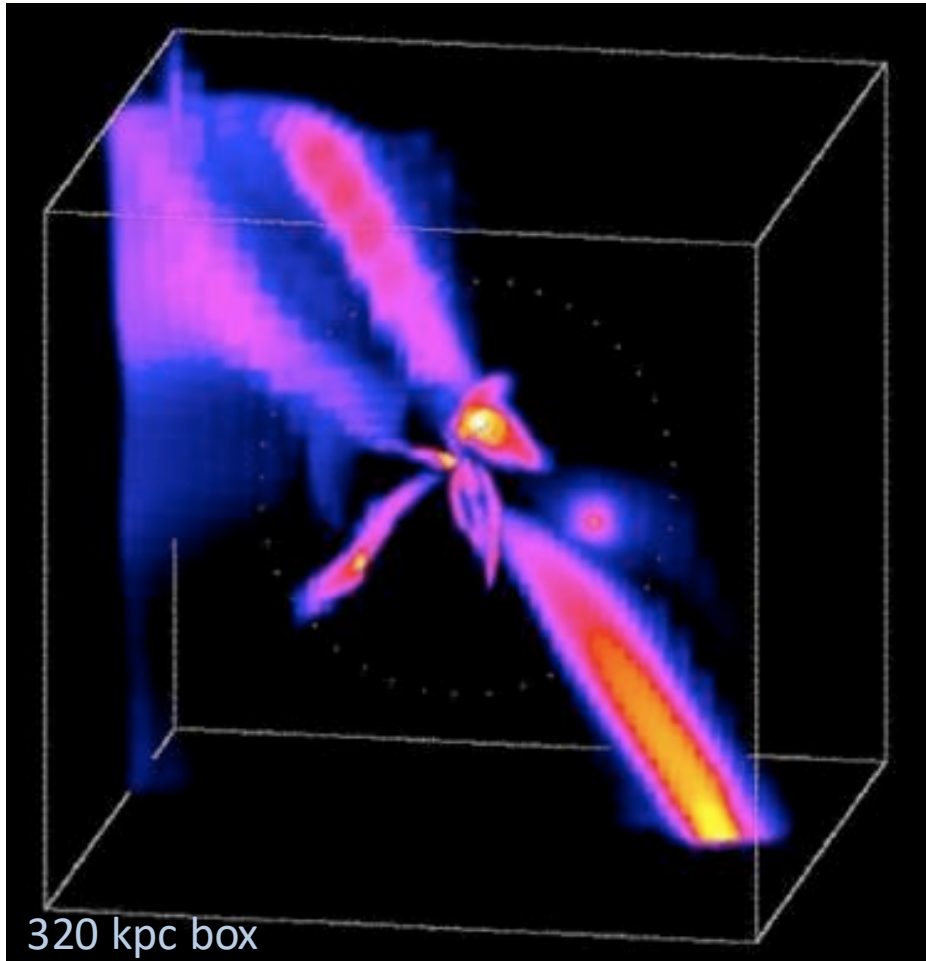
Zoom-in



Clumpy galaxies in the early universe have big knots of star formation (gas motions 100 km/s must be overcome) and grow through gas accretion from the cosmic web

Elmegreen et al. 2009

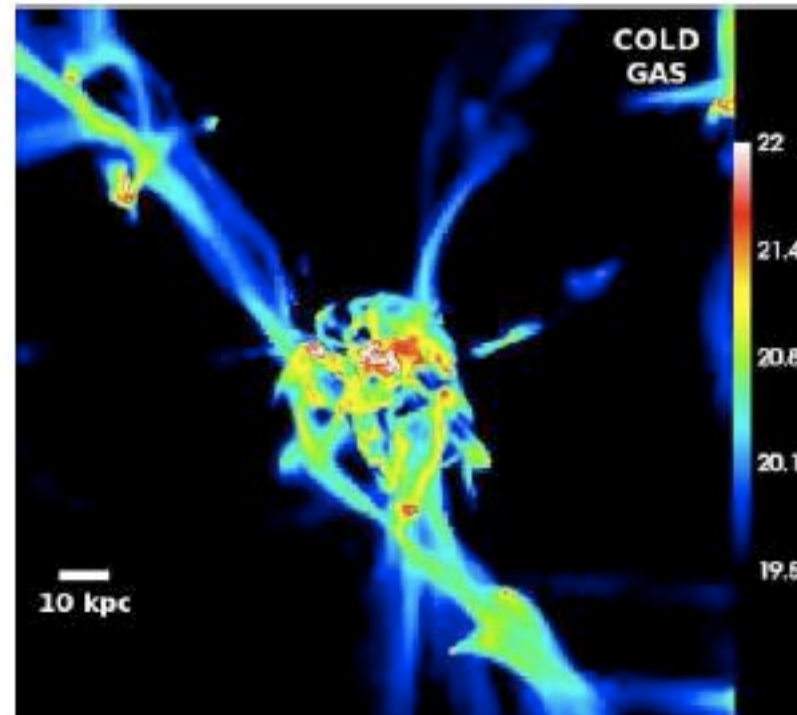




320 kpc box

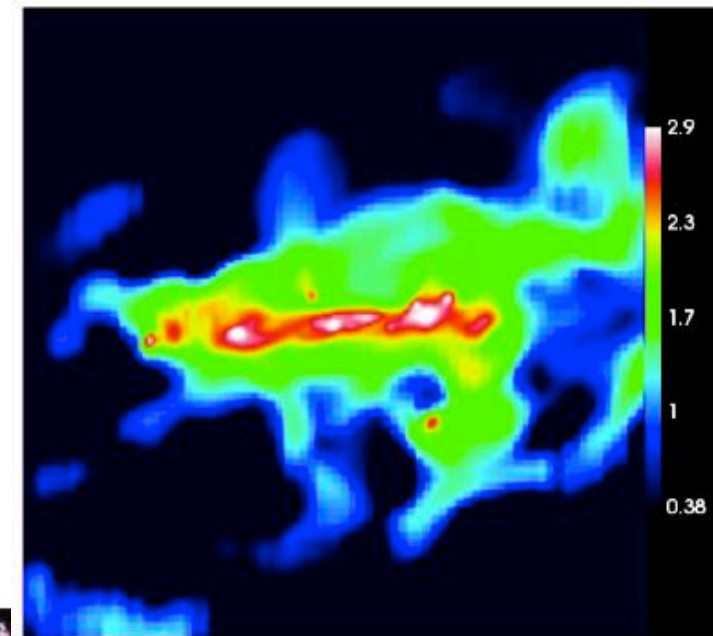
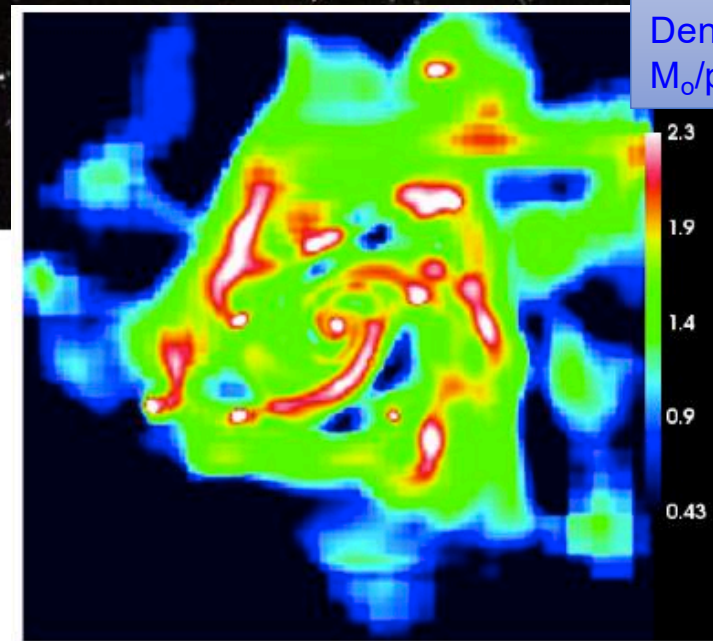
Dekel et al. 2008

Zooming in on young  
( $z=2$ ) galaxies in  
simulations

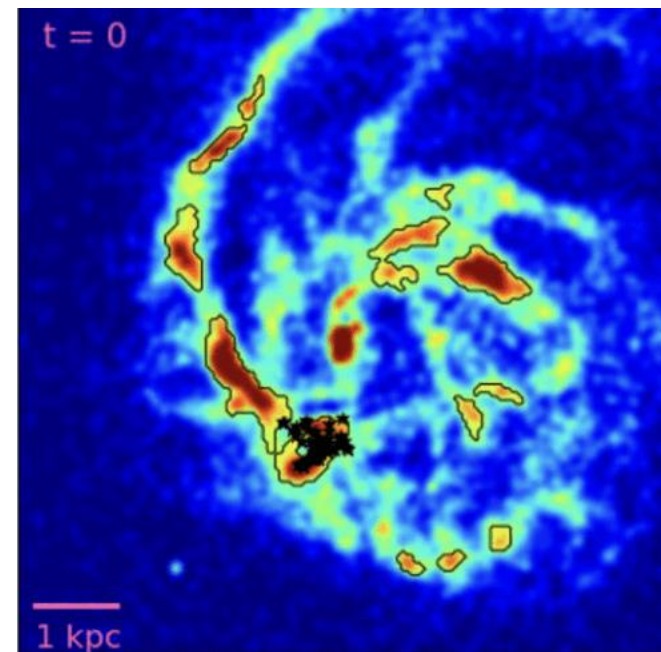
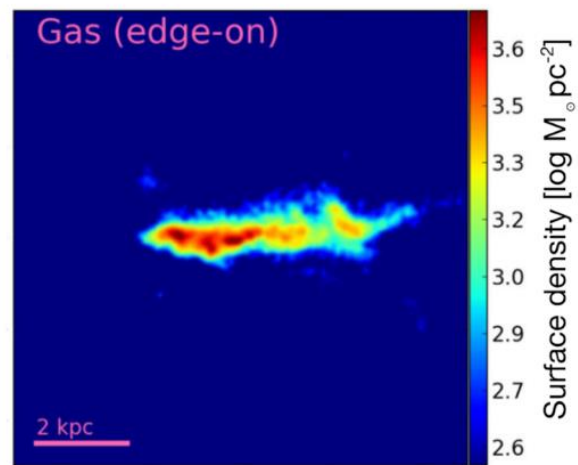
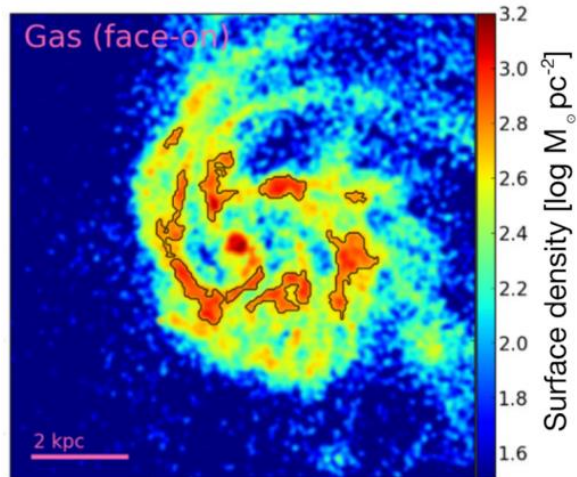


Ceverino, Dekel, Bournaud 09

Top and side view of gas for  $z=2.3$  galaxy from cosmological gas streams forming giant clumps in disks



Dekel et al. 2009

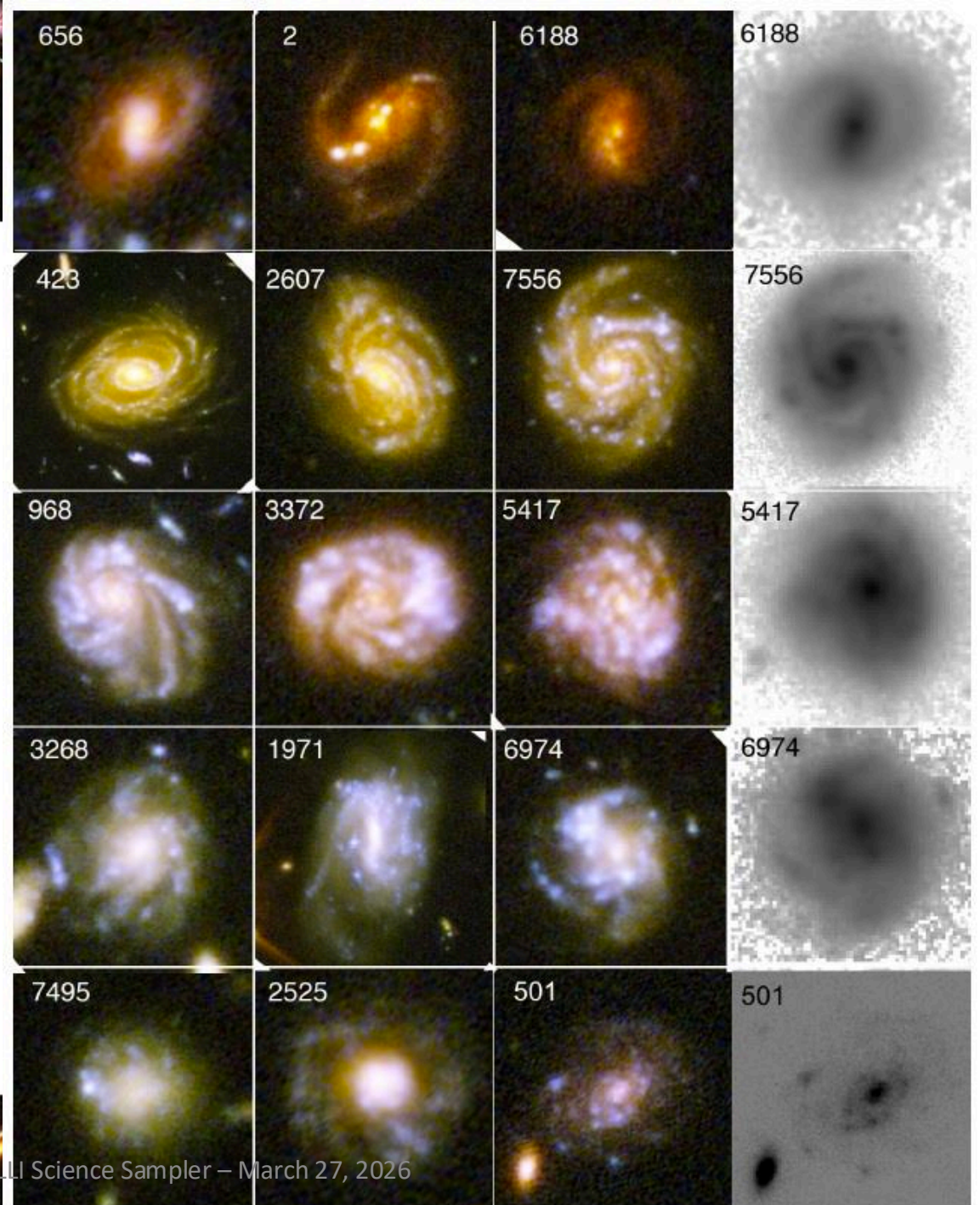


Pannekoek et al. 2017

FIRE cosmological simulation of clumpy galaxy at  $z \sim 2$  showing clump dispersal

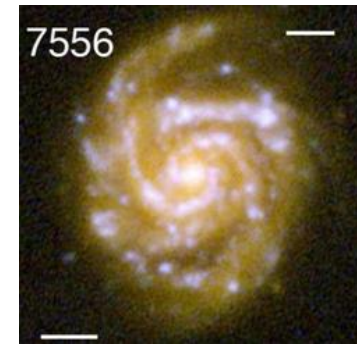
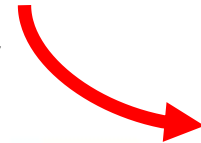
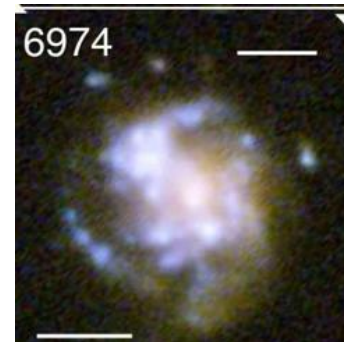
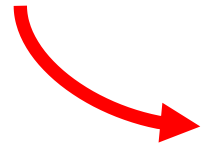
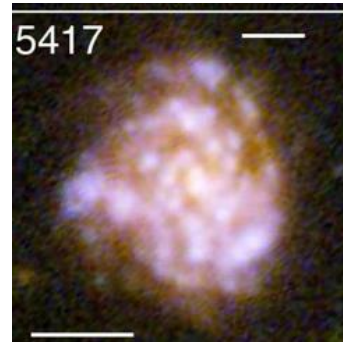
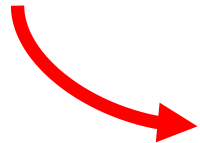
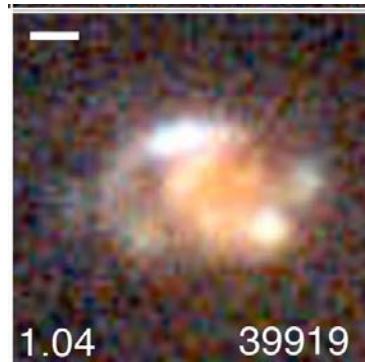
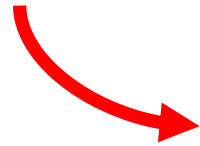
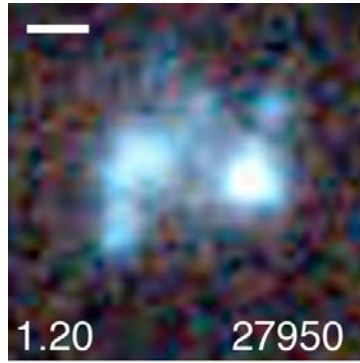
**Spiral structure** in most galaxies first appeared when the universe was about 1/3 its current age ( $z < 2$ )

This is when disks became less turbulent, so waves could ripple through the disk to create pinwheel patterns



Elmegreen et al. 2014

Proposed evolutionary sequence as clumps dissolve or migrate to center:



The transition

Decreasing gas accretion + more stars in disk  $\rightarrow$  disk thinner and less turbulent over time (losing energy through radiation)

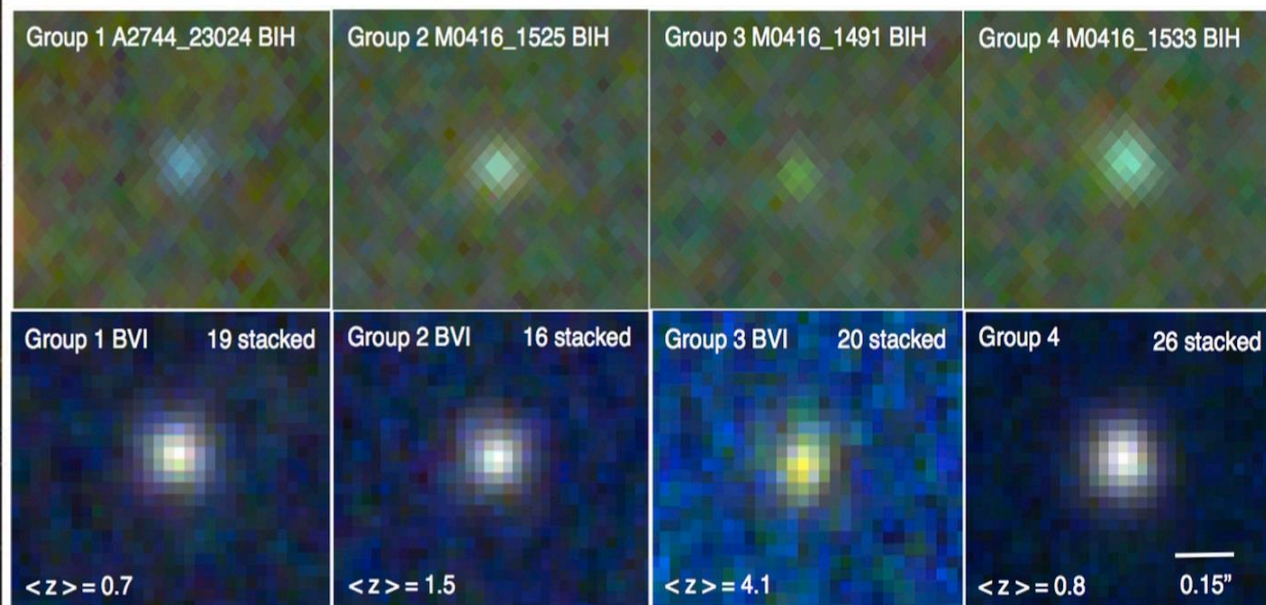
Elmegreen et al. 2014

HST Frontier Fields are galaxy clusters out to  $z=1-2$





Sometimes even tinier galaxies are seen far away, like these **Little Blue Dots**



Elmegreen<sup>2</sup> 2018

These  $z=1-4$  galaxies are 1 million solar masses and may be precursors of the globular clusters that are now in the halos of big galaxies

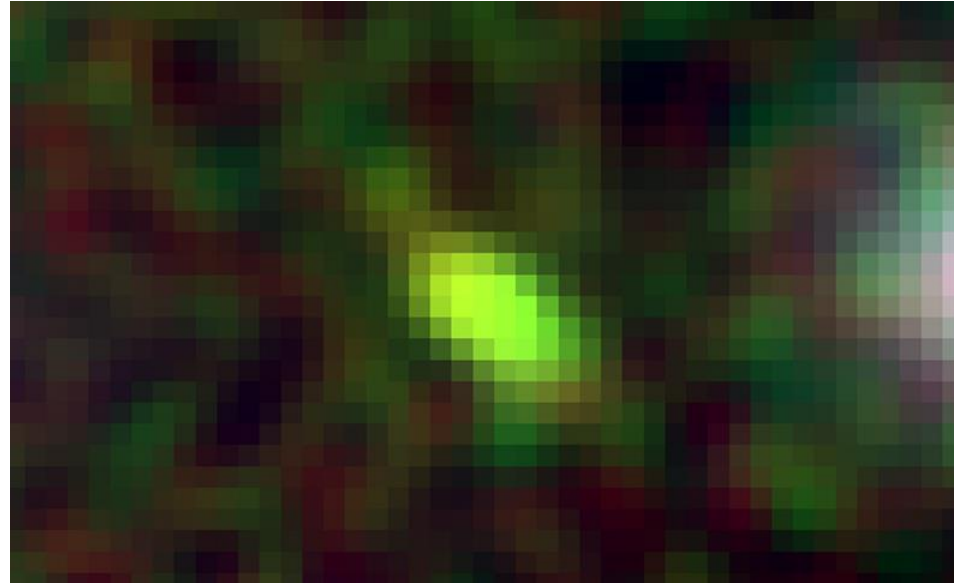


Globular cluster M13

JWST observed this foreground galaxy cluster, which acts as a lens to magnify distant galaxies

(highlighted by squares)





These distant galaxies at  $z=7$  have an estimated mass of 2 million solar masses, like the Little Blue Dots only more distant.

Their starlight may provide much of the ionization in the early Universe.

Credit: NASA/ESA/CSA/Bezanson et al. 2024 and Wold et al. 2025

## Little Red Dots

(less than 1/100<sup>th</sup> the size of the Milky Way)  
at  $z=4-9$  (within 1.5 billion years after the Big Bang)

They may be supermassive growing black holes, or extreme star formation, or a black hole in a cocoon  
(Nature Oct. 2025)

CEERS 14448  
 $z=4.75$



NGDEEP 4321  
 $z=8.92$



PRIMER-COS 10539  
 $z=7.48$



CEERS 20320  
 $z=5.27$



JADES 9186  
 $z=4.99$



PRIMER-UDS 17818  
 $z=6.40$



JWST; Kocevski 2022

One Little Red Dot, formed just 500 million years after the Big Bang ( $z=9.3$ ), contains the earliest confirmed black hole (radiation from the disk around it is different than starlight)



Artist rendition; Zumalt, mcdonaldobservatory.com  
(Taylor et al. 2025)

It is 300 million times  
the mass of the Sun

Note that all elliptical and spiral galaxies may have supermassive black holes; the Milky Way's is about 4 million solar masses

A distant  
cluster of  
galaxies  
from  
JWST

(The arcs  
are from  
lensing of  
background  
objects)

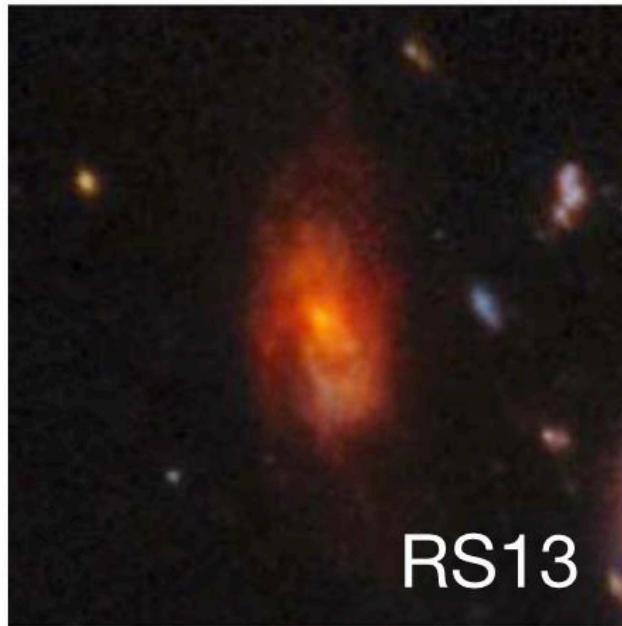
1<sup>st</sup> image,  
July 2022



Mid-Infrared

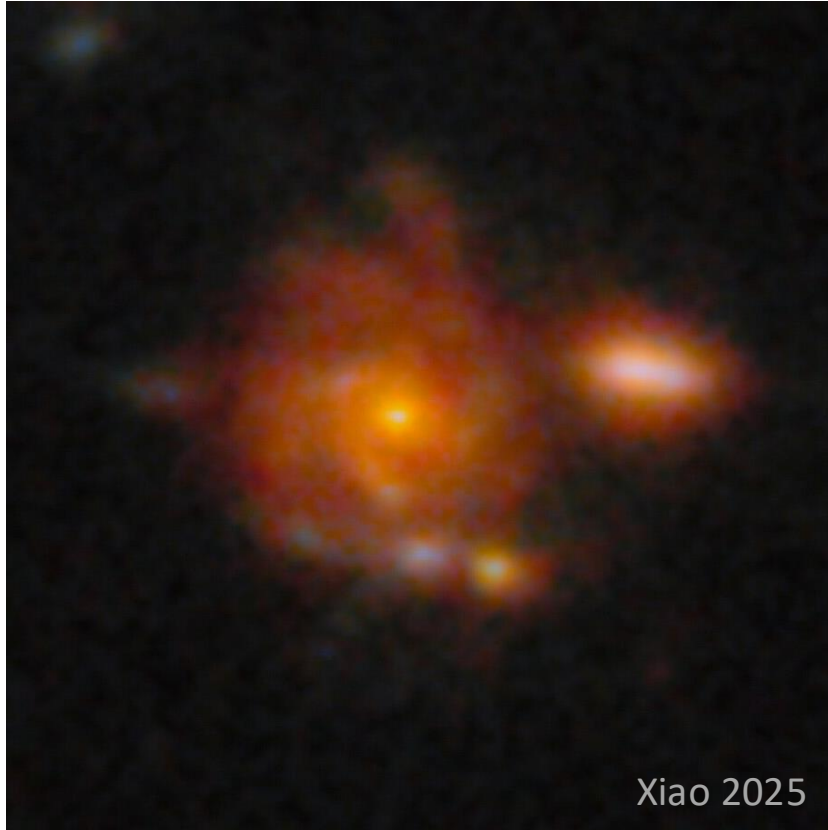
Near-Infrared

This first image from JWST revealed “spiral” galaxies at  $z=1-3$  that are intrinsically red because of heavy dust obscuration



Fudamoto et al. 2022

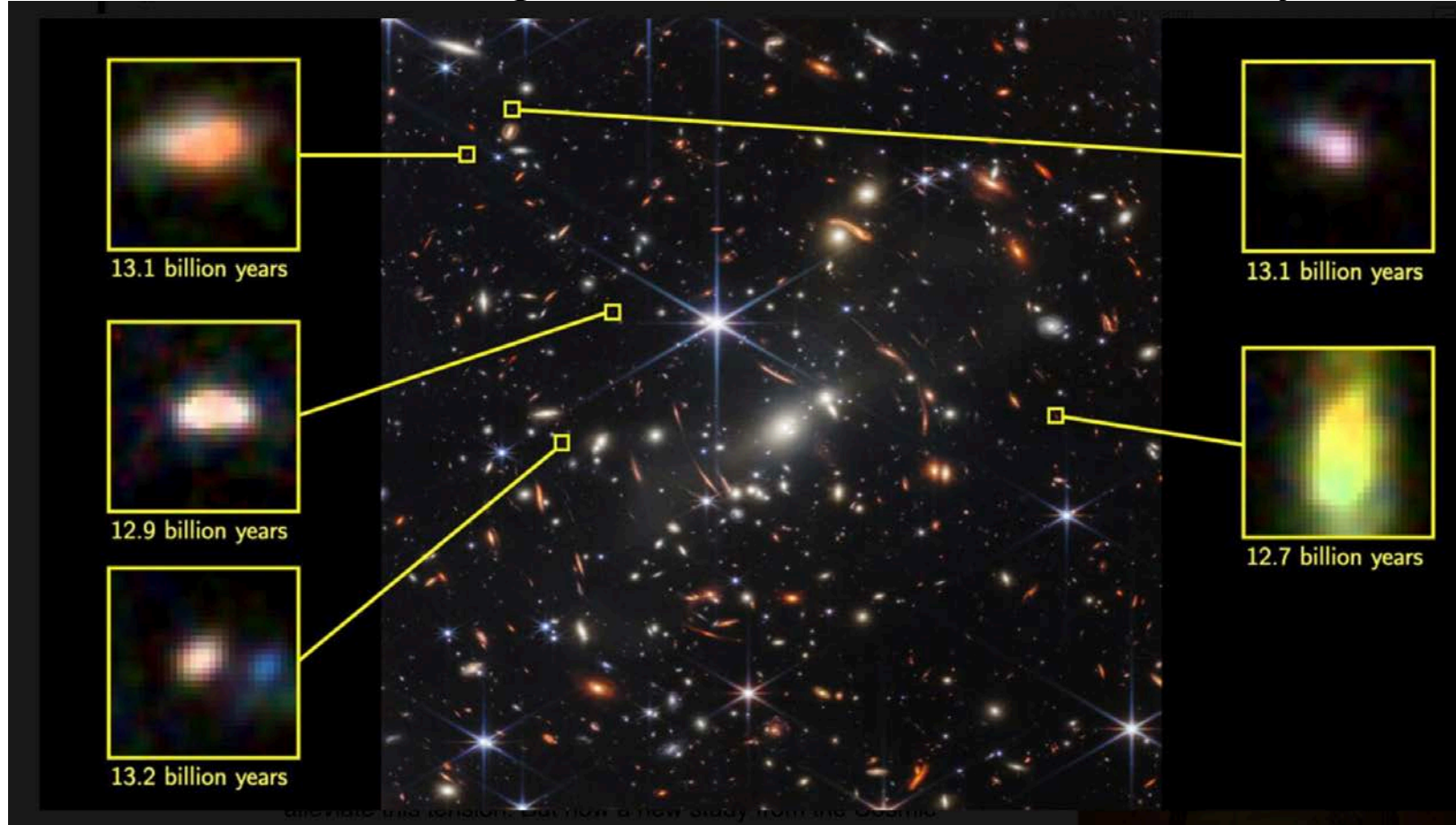
A JWST surprise: a massive spiral at higher redshift,  $z=5.2$



Zhúlóng

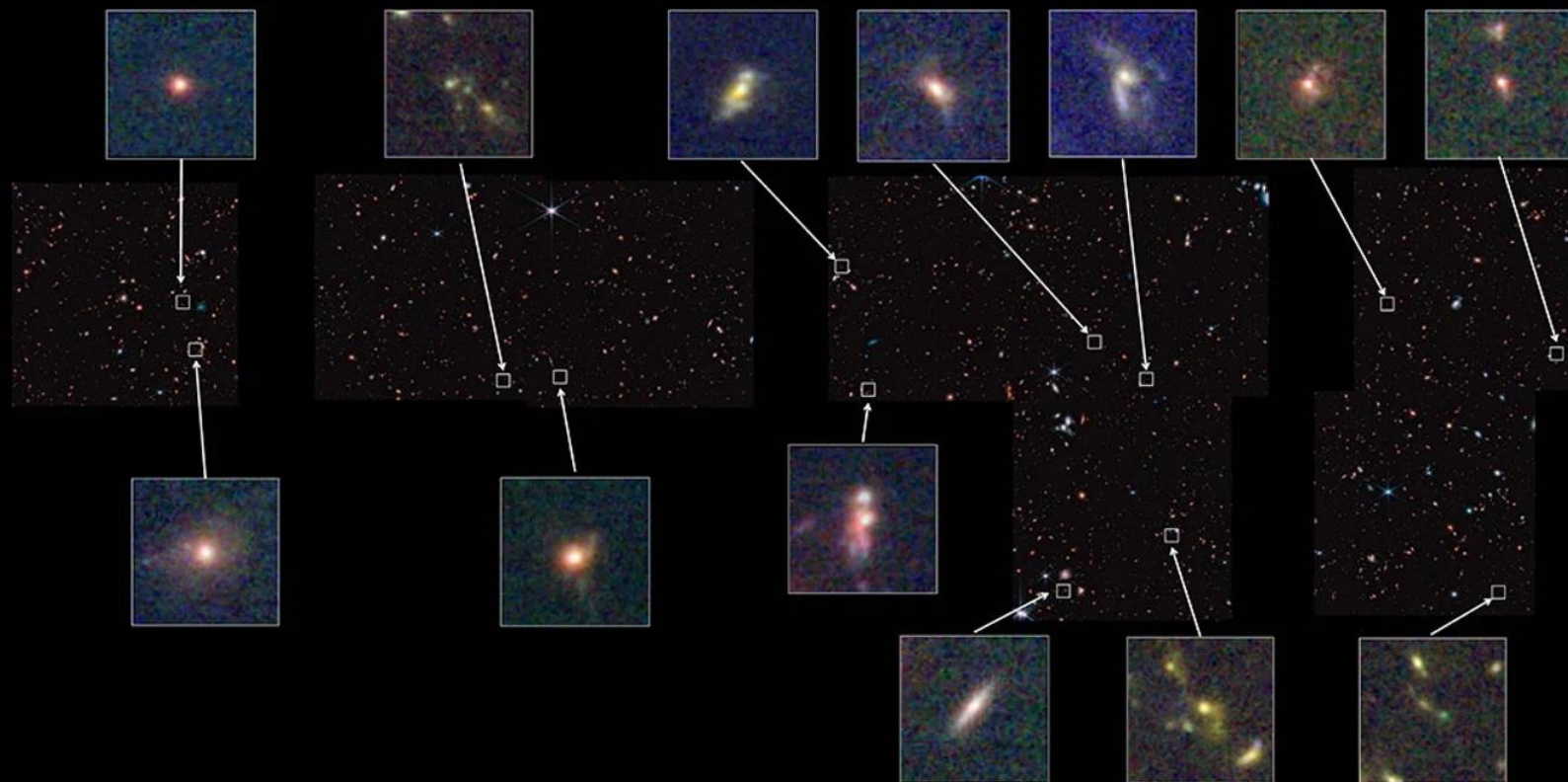
This galaxy, the size of the Milky Way, would have formed in the first billion years after the Big Bang

The five zoom-ins are galaxies seen some 13 billion years ago



NASA, ESA, CSA, STScI / Giménez-Arteaga et al. (2023)

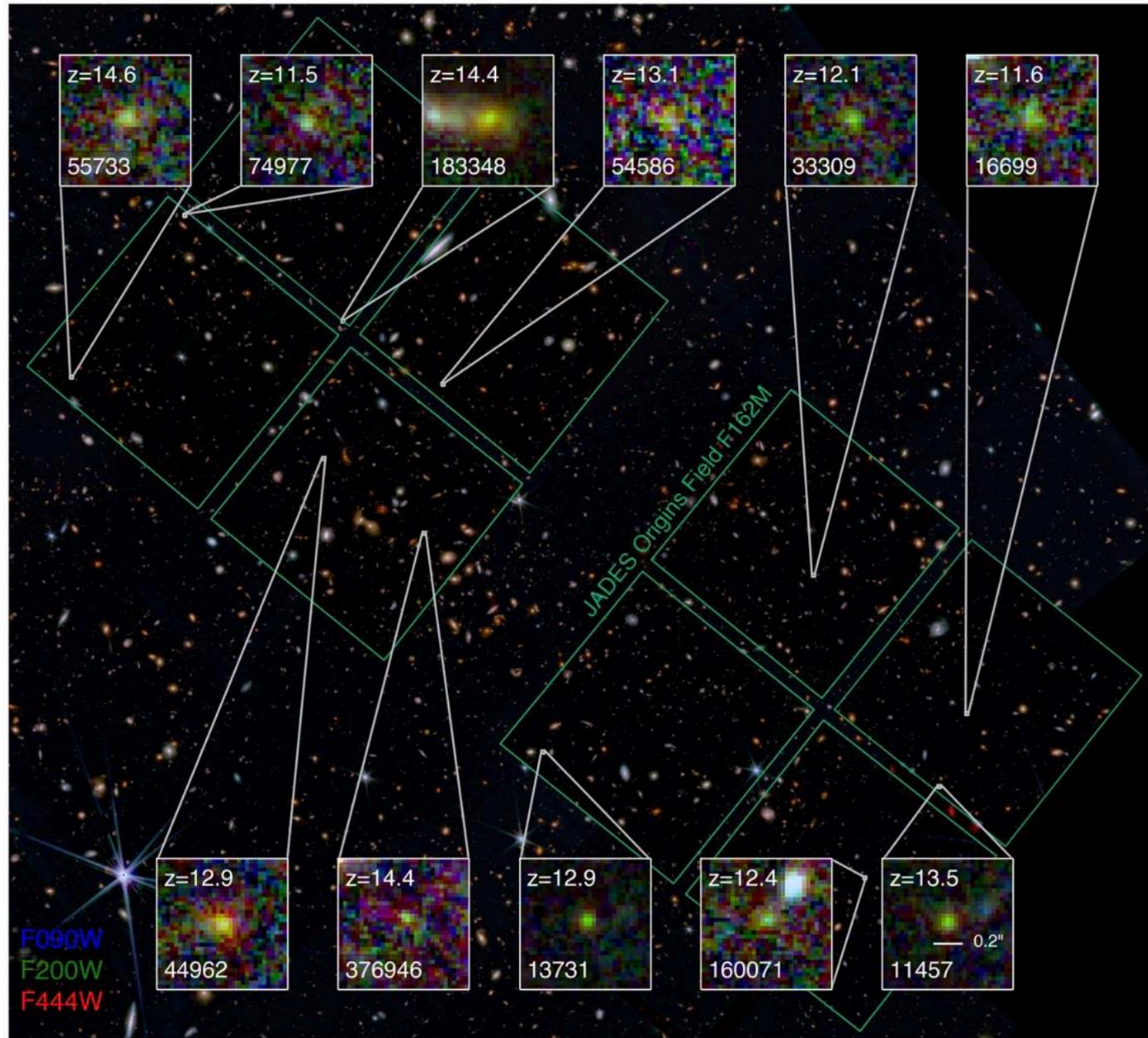
More distant  
galaxies  
observed  
with JWST



NASA/STScI/CEERS/TACC/S. Finkelstein/M. Bagley/J. Kartaltepe

# Candidate high z galaxies

Robertson et al. 2024



GALAXY CLUSTER SMACS 0723

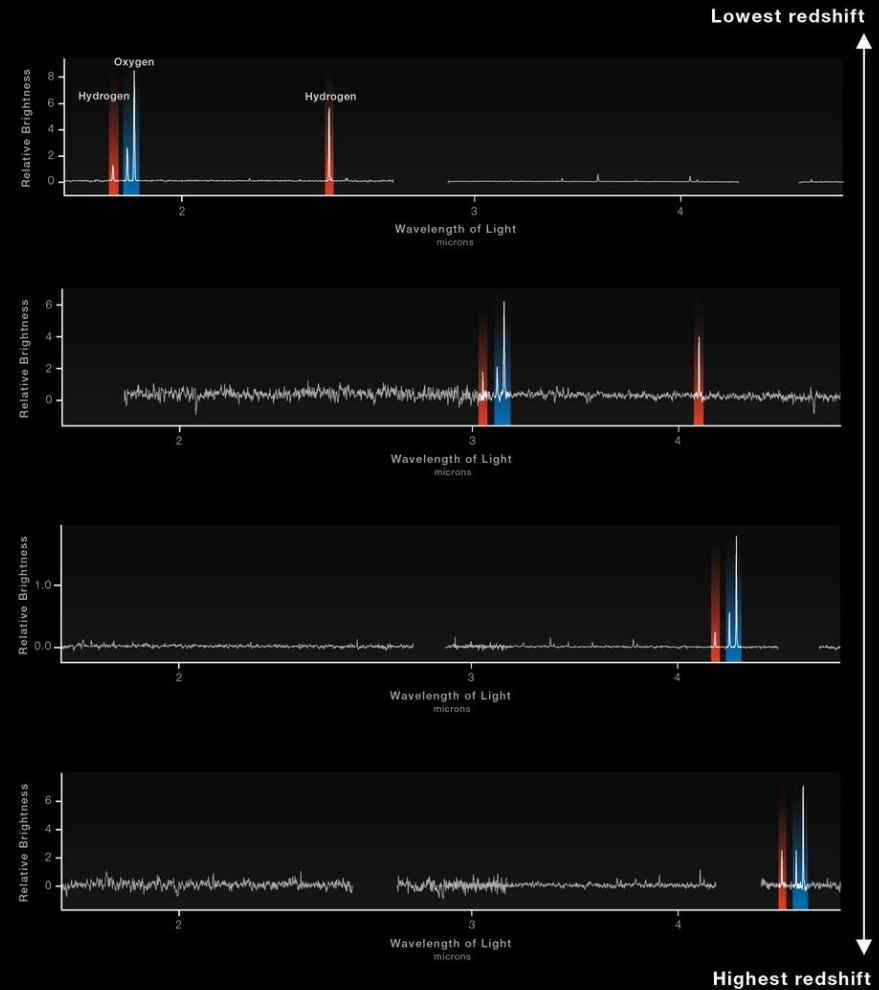
# WEBB SPECTRA IDENTIFY GALAXIES IN THE VERY EARLY UNIVERSE

NIRCam Imaging

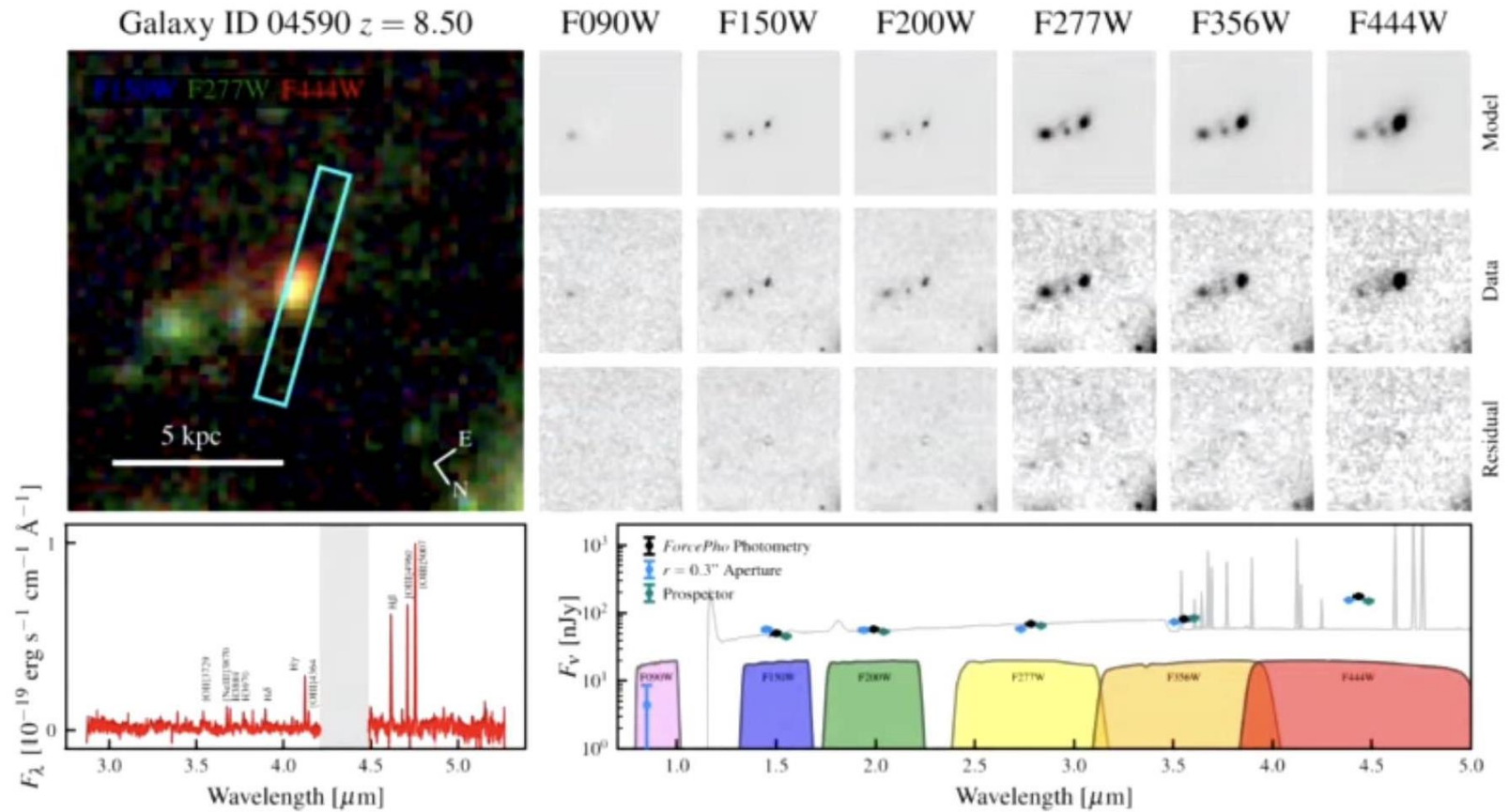


**WEBB**  
SPACE TELESCOPE

NIRSpec Microshutter Array Spectroscopy



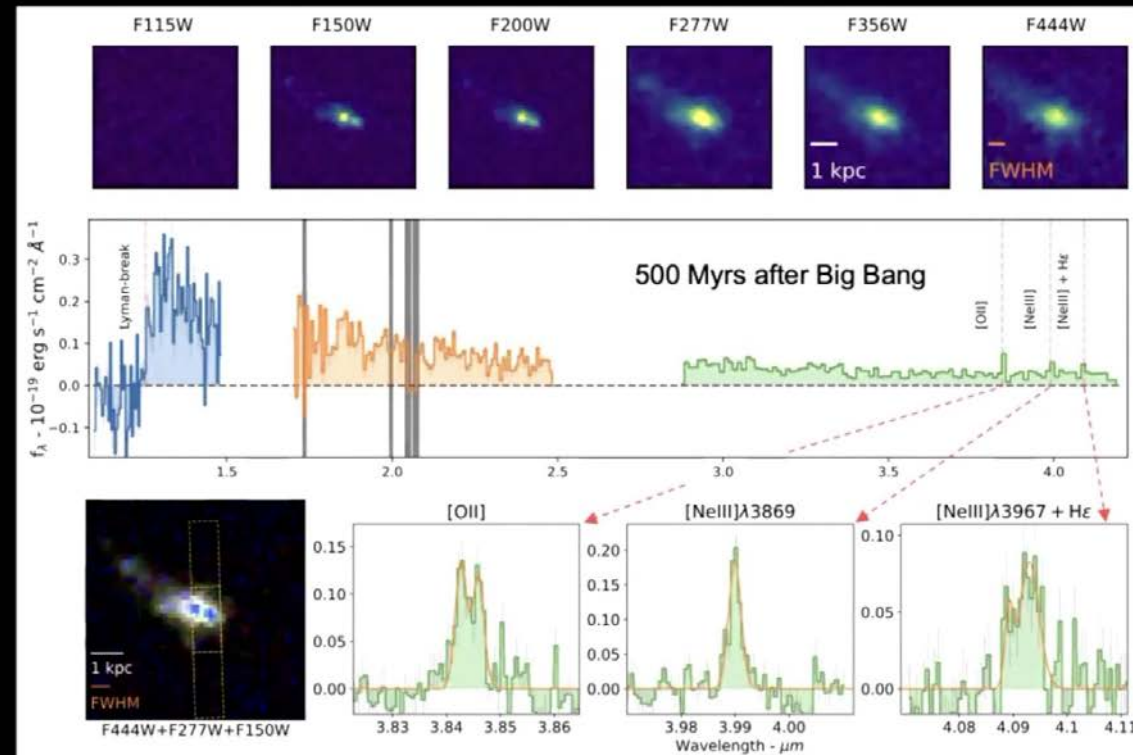
# A high z galaxy's spectrum and images in different filters



Tacchella, Johnson, Robertson + arXiv:2208.03281

Spectroscopy with Webb confirmed a distant galaxy

A massive galaxy at  $z=9.3$  ( $10^9 M_{\text{sun}}$ )



Boyett et al. 2023

DISTANT GALAXY BEHIND SMACS 0723

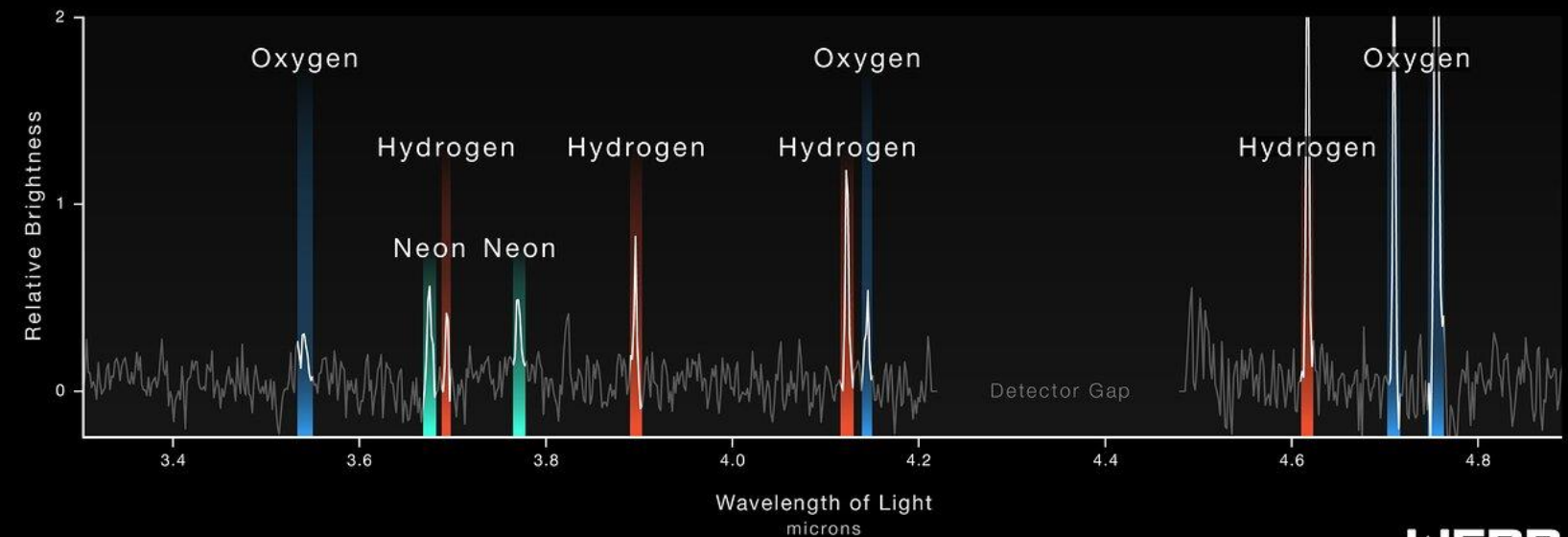
# WEBB SPECTRUM SHOWCASES GALAXY'S COMPOSITION

Lines other than hydrogen reveal details of the star formation history since these elements can **only** come from previous supernovae


NIRCam Imaging



NIRSpec Microshutter Array Spectroscopy




**WEBB**  
SPACE TELESCOPE



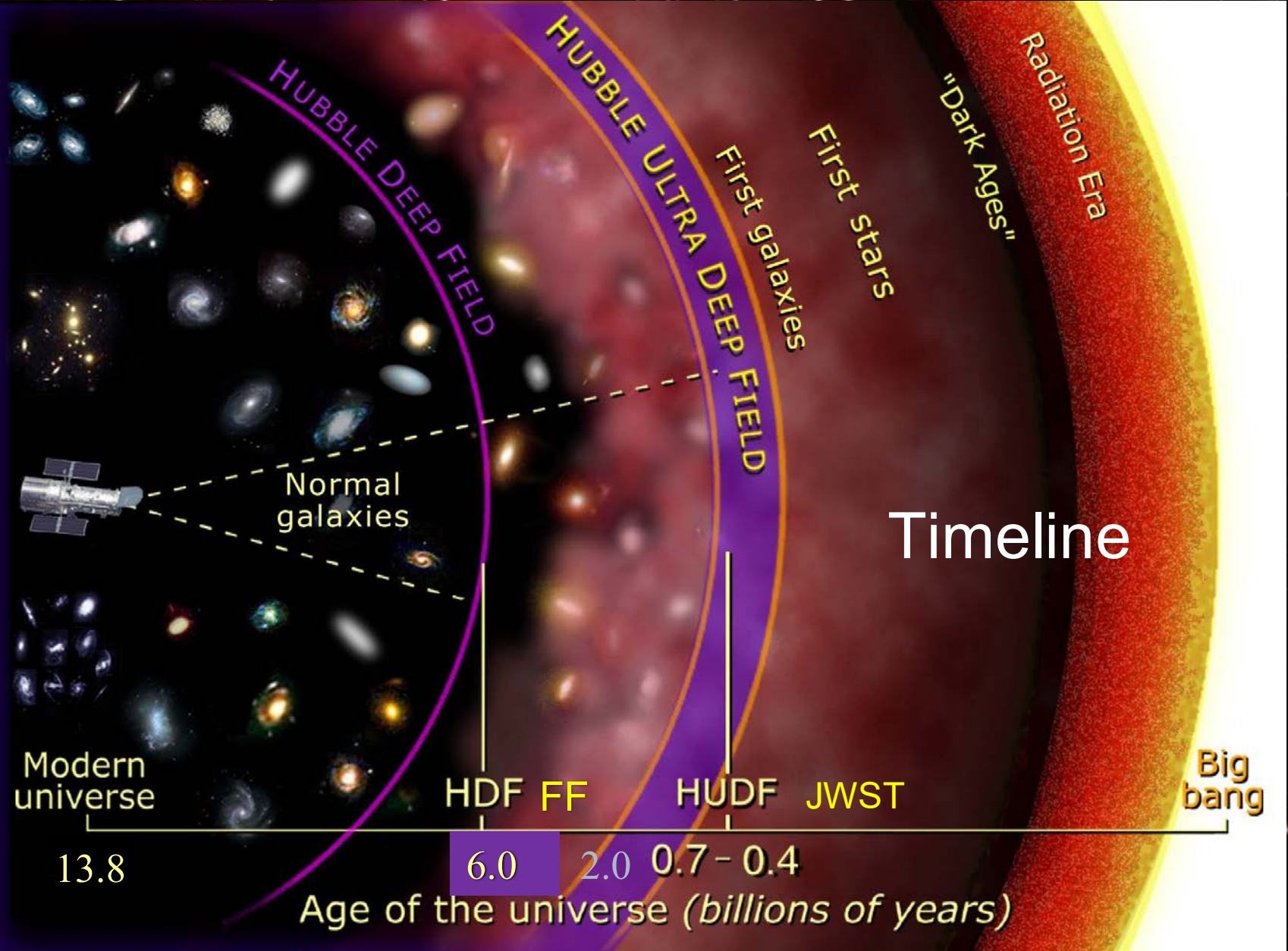
The most distant galaxy confirmed so far is at  $z=14.32$ , less than 300 million years after the Big Bang

JWST, Carniani et al.  
2024 ([webbtelescope.org](https://www.webbtelescope.org))



JADES-GS-z14-0

So, the formation and evolution of galaxies is becoming more clear as we continue to push the boundaries of observation and theory



As we continue to explore, remember: we are all together...



apod.nasa.gov

...under one sky!

© Michael Goh

*Thank you!*