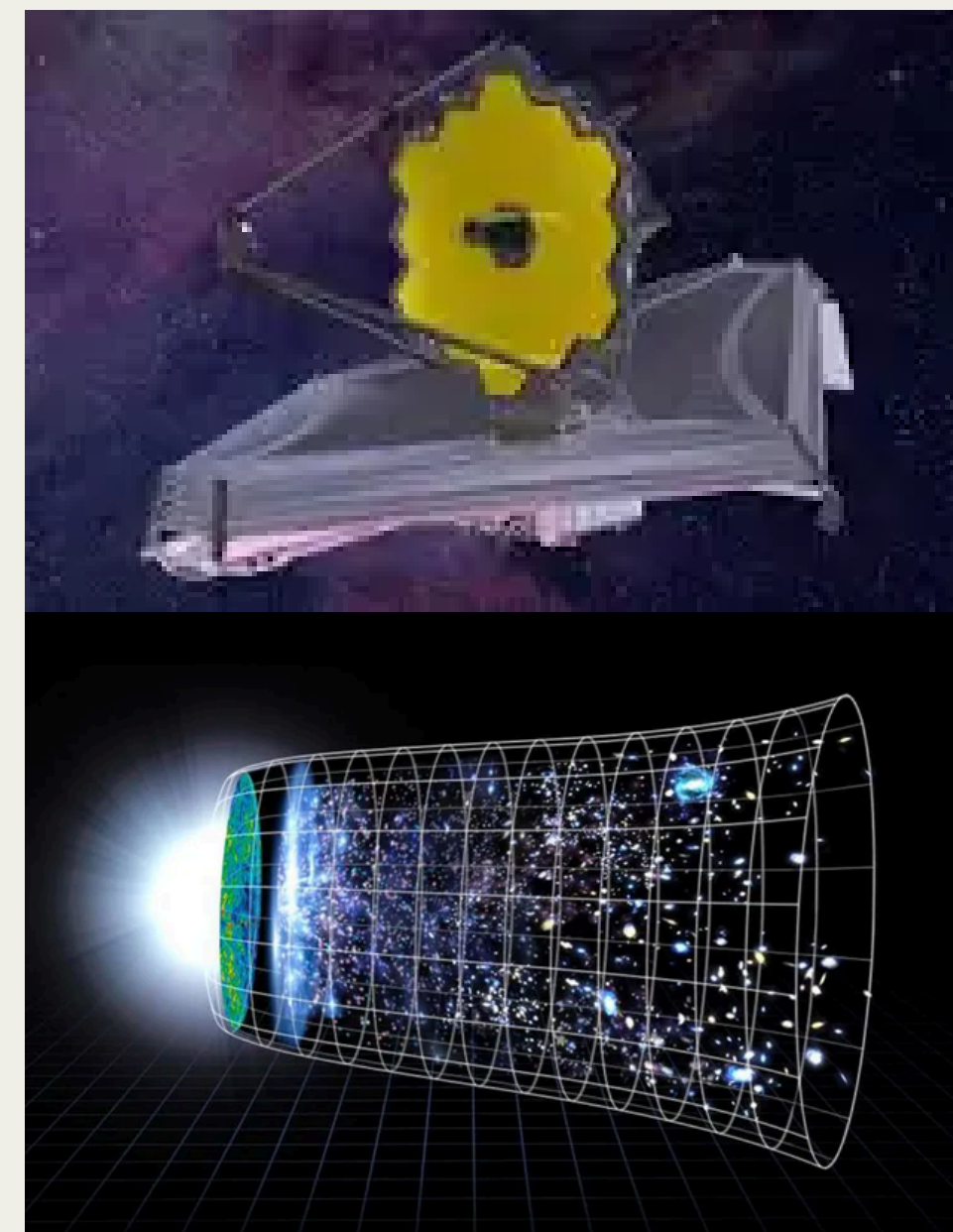


Expansion of the Universe and Spectroscopic Identification of Z-Shifted Lines Observed by JWST



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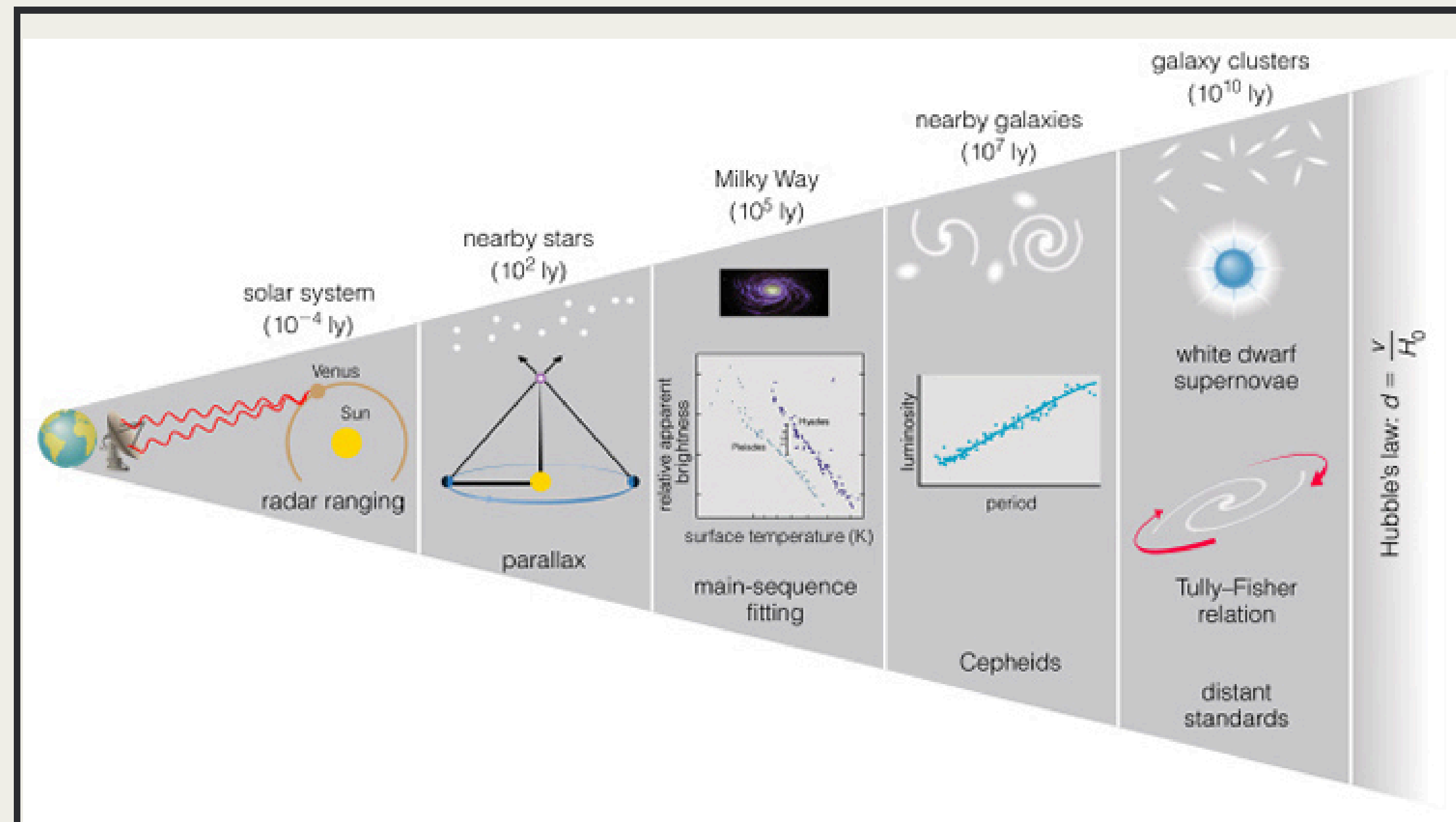
RESEARCH ADVISER: PROF. SULTANA N. NAHAR

**RESEARCH LOCATION: ASTRONOMY DEPARTMENT,
THE OHIO STATE UNIVERSITY, COLUMBUS, USA**

SPRING—SUMMER 2025

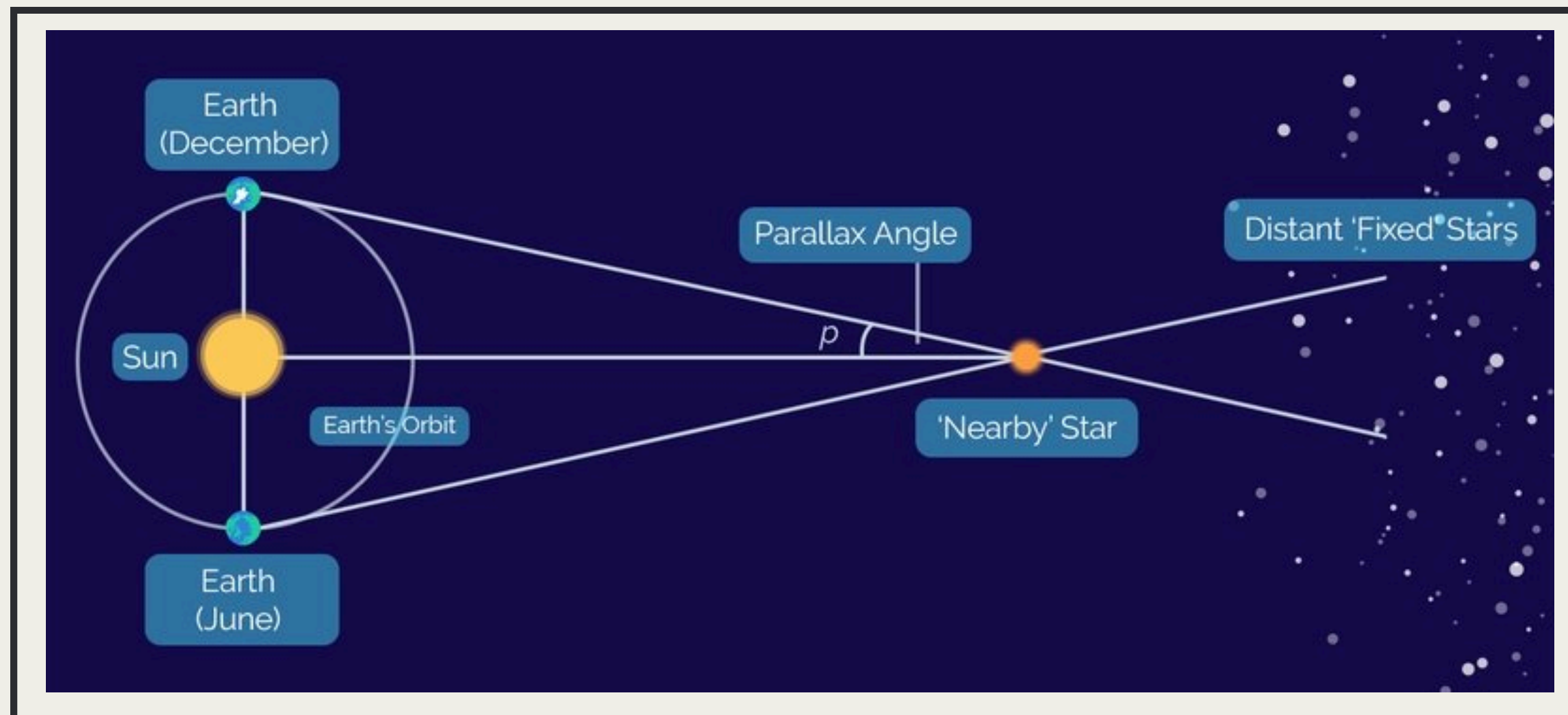
INTRODUCTION: MEASURING DISTANCES IN SPACE

- Astronomers use a cosmic distance ladder to measure distances across the universe.
- Methods vary by scale: from nearby stars to galaxies billions of light-years away.
- Techniques build on each other for more accurate measurements.



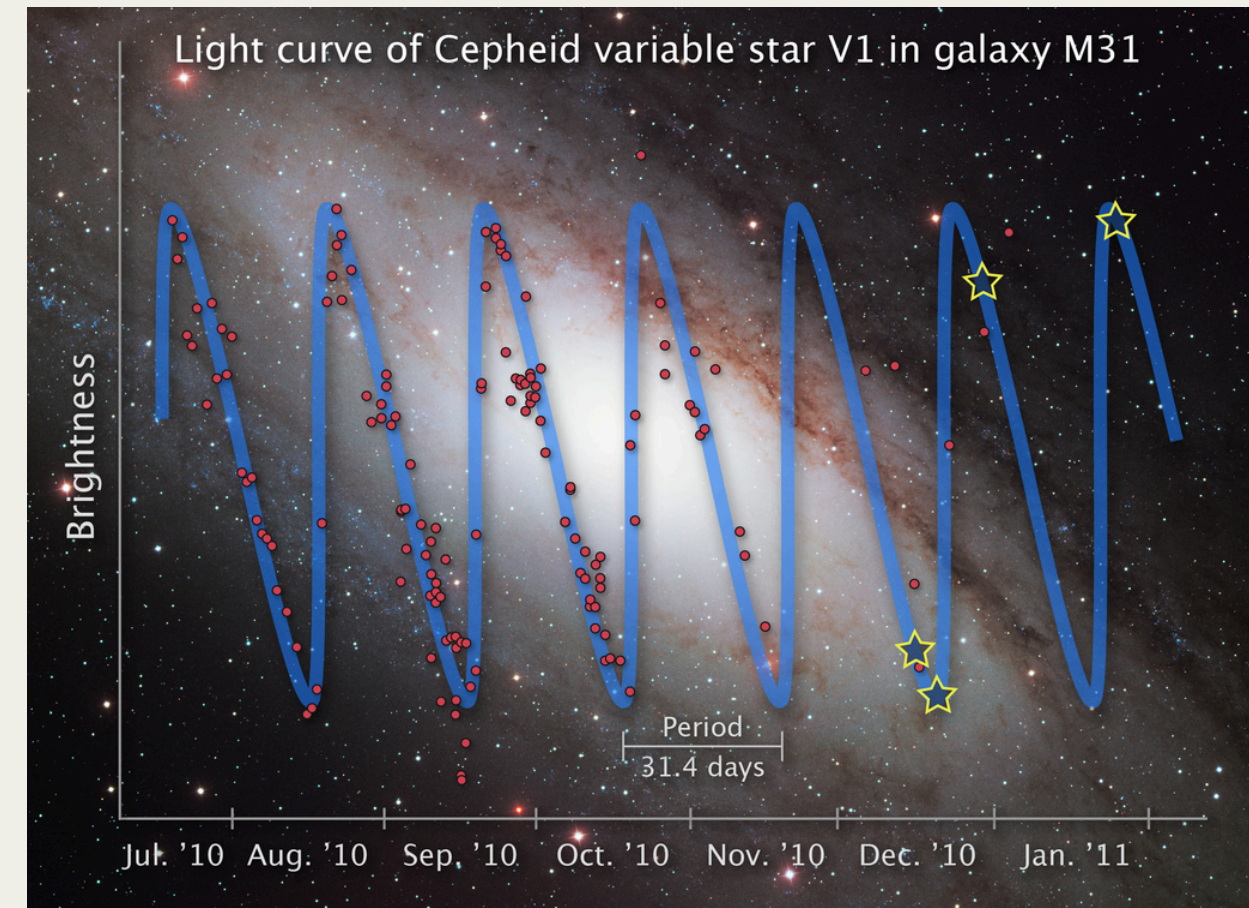
MEASURING NEARBY DISTANCES – STELLAR PARALLAX

- Measures distances to stars within 100 light-years.
- Based on Earth's orbit around the Sun, using trigonometry.
- Works for nearby stars; less effective beyond a few hundred light-years.



STANDARD CANDLES – CEPHEID VARIABLES

- Cepheid Variables pulse in brightness at regular intervals.
- The longer the pulse, the brighter the star.
- Used to measure distances up to 80 million light-years.



SUPERNOVAE – TYPE 1A SUPERNOVAE

- Supernovae explode with a known energy release.
- Serve as "standard candles" for measuring galaxies up to 10 billion light-years away.
- Crucial for measuring large-scale distances.
- Provide consistent luminosity that allows astronomers to compare their brightness and calculate precise distances.

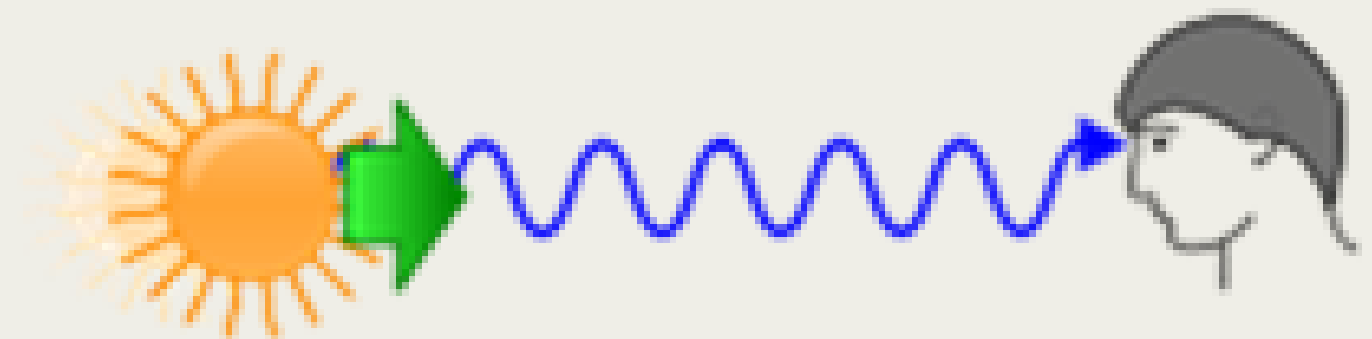


Supernova Remnant
Cassiopeia A

CHANGE IN WAVELENGTH DUE TO THE MOTION OF THE OBJECT



redshift: wavelength longer



blueshift: wavelength shorter

REDSHIFT AND THE EXPANDING UNIVERSE

$$z = \frac{\lambda_{\text{obs}} - \lambda_{\text{rest}}}{\lambda_{\text{rest}}}$$

where z = redshift

and λ_{obs} = observed wavelength

and λ_{rest} = rest wavelength

(and λ is the lower case Greek letter lambda)

$$v = H_0 d$$

v = recessional velocity of galaxy

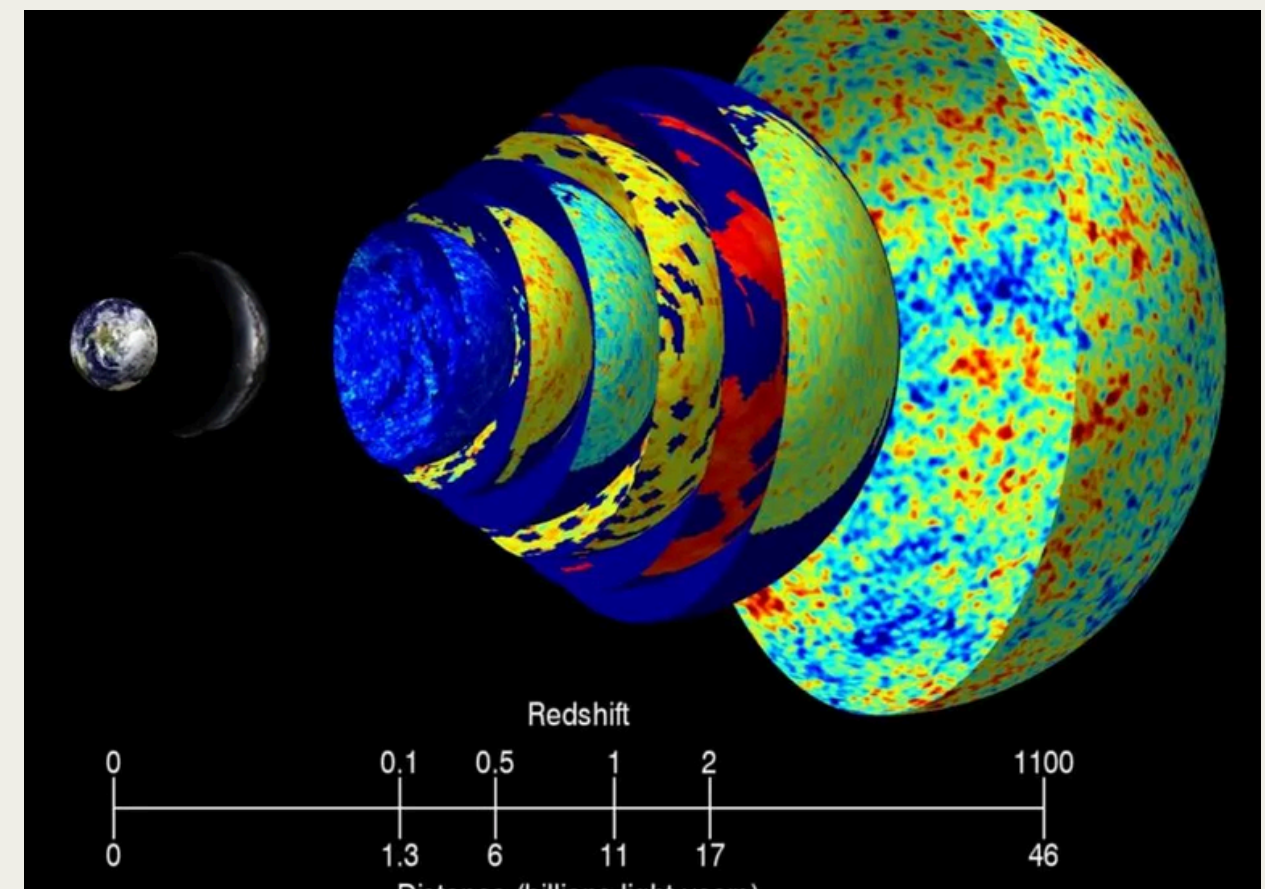
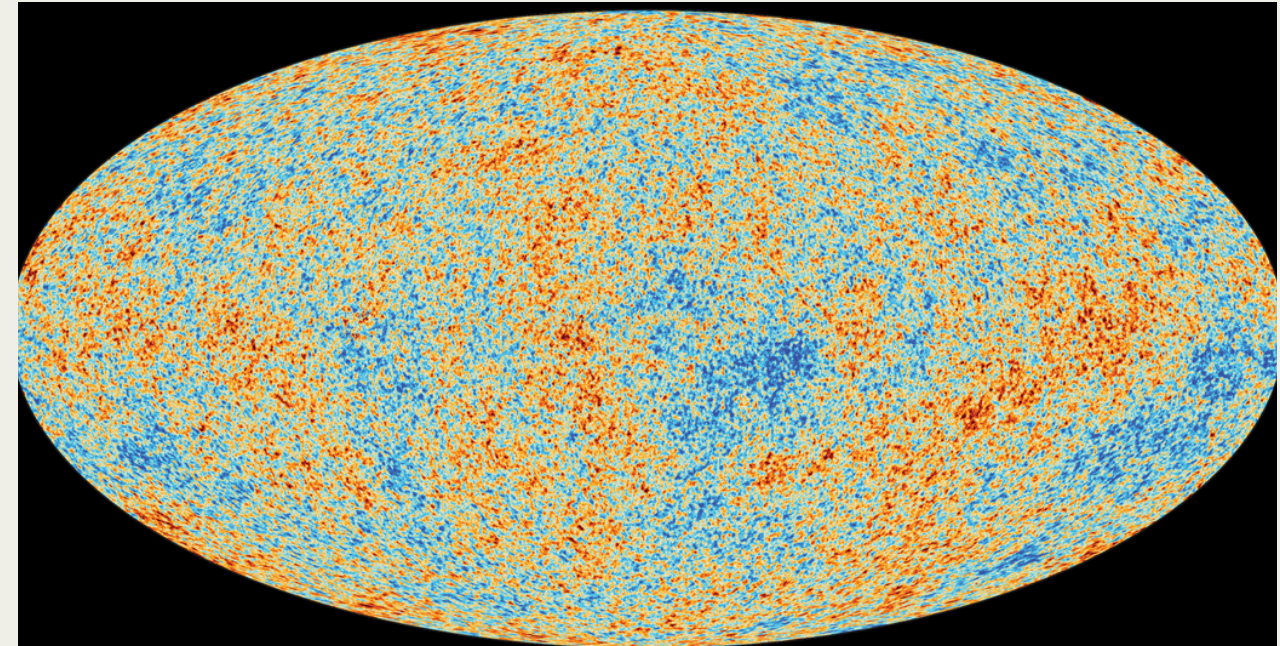
H_0 = Hubble constant

d = distance to galaxy

- Galaxies move away, causing redshift in their light.
- Redshift shows the velocity of galaxies, helping calculate their distance.
- Hubble's Law relates redshift to distance for galaxies billions of light-years away.

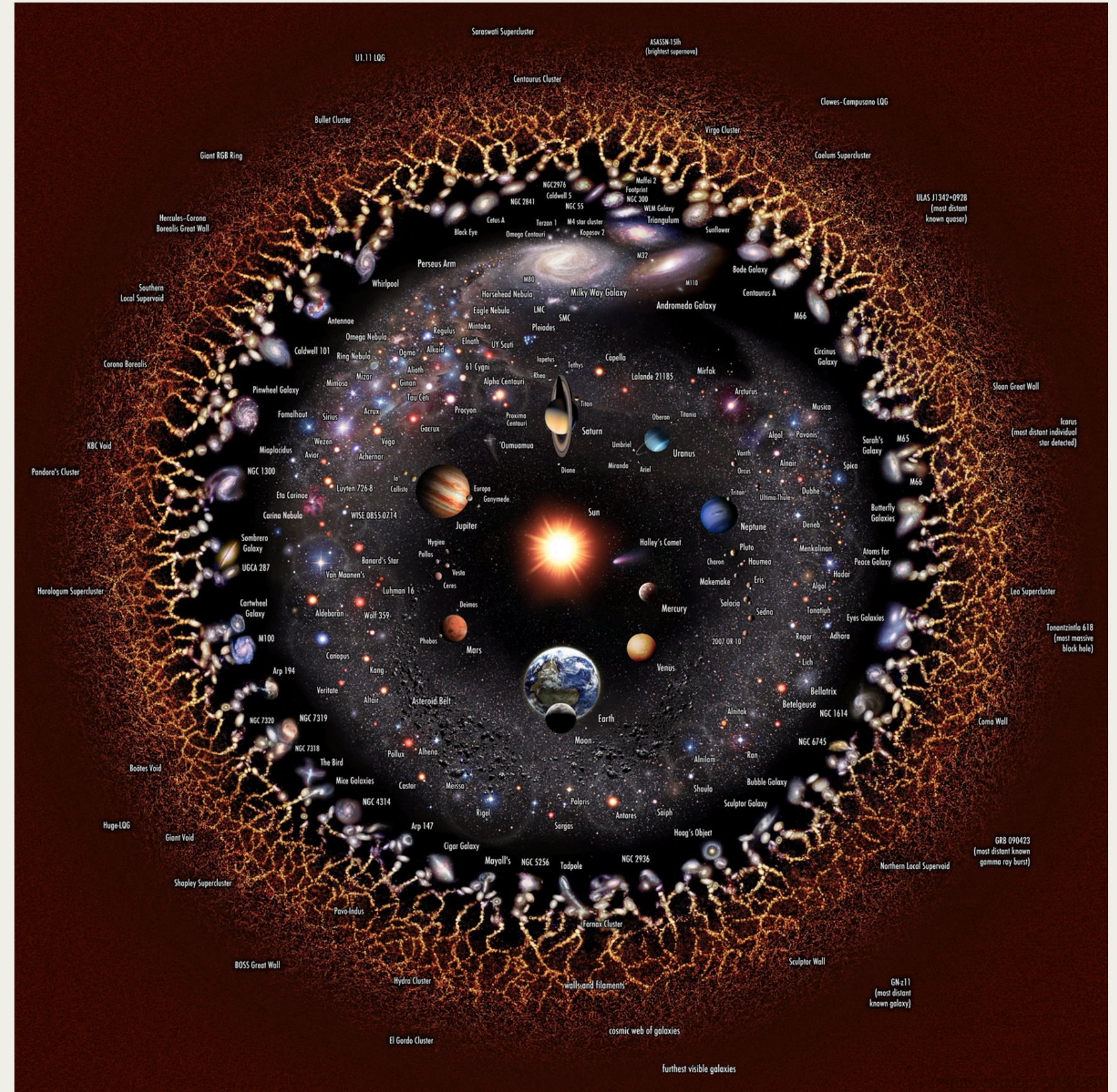
COSMIC MICROWAVE BACKGROUND (CMB)

- Radiation from the Big Bang, sets a baseline for the universe's size.
- Age of the universe: 13.8 Billion years.
- Provides insight into the observable universe, extending to 46 billion light-years.
- The CMB helps us understand the scale and structure of the universe.



SCALING TO THE UNIVERSE

- Methods scale from solar system (parallax) to the edge of the observable universe (CMB).
- Parallax measures nearby objects, Cepheids and supernovae extend to millions of light-years.
- Redshift and CMB cover distances up to the edge of the observable universe (46 billion light-years).



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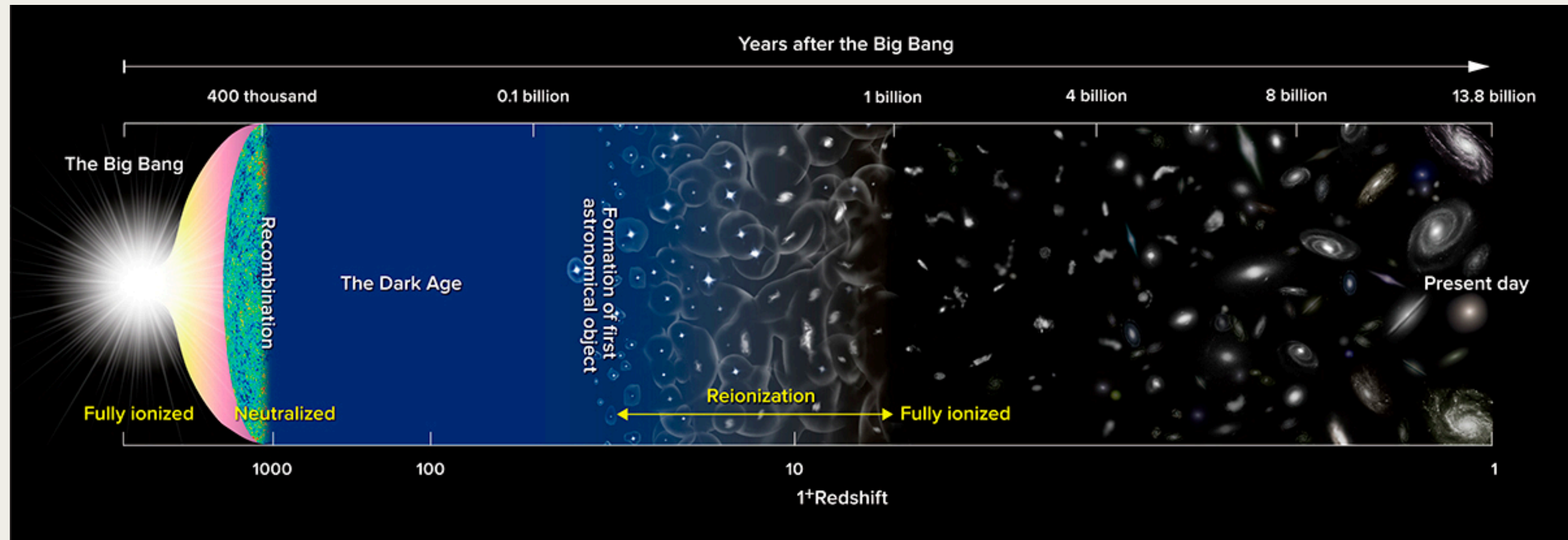
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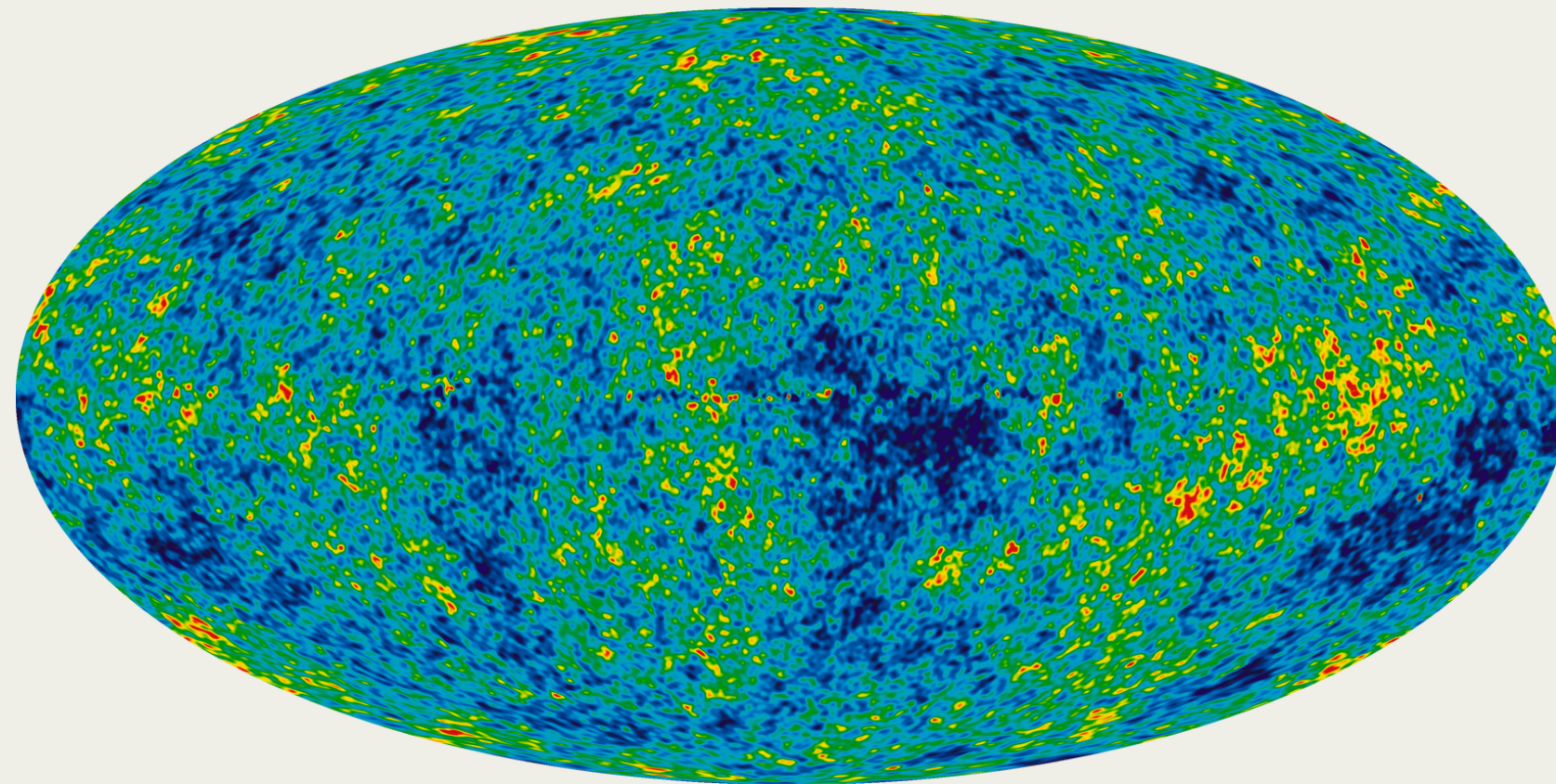
The Age of the Universe and the James Webb Space Telescope

AGE OF THE UNIVERSE – OVERVIEW

- Estimated at 13.8 billion years based on multiple lines of evidence.
- Determined through cosmic observations and mathematical models.
- Key methods include studying the cosmic microwave background (CMB) and the universe's expansion.



COSMIC MICROWAVE BACKGROUND (CMB)



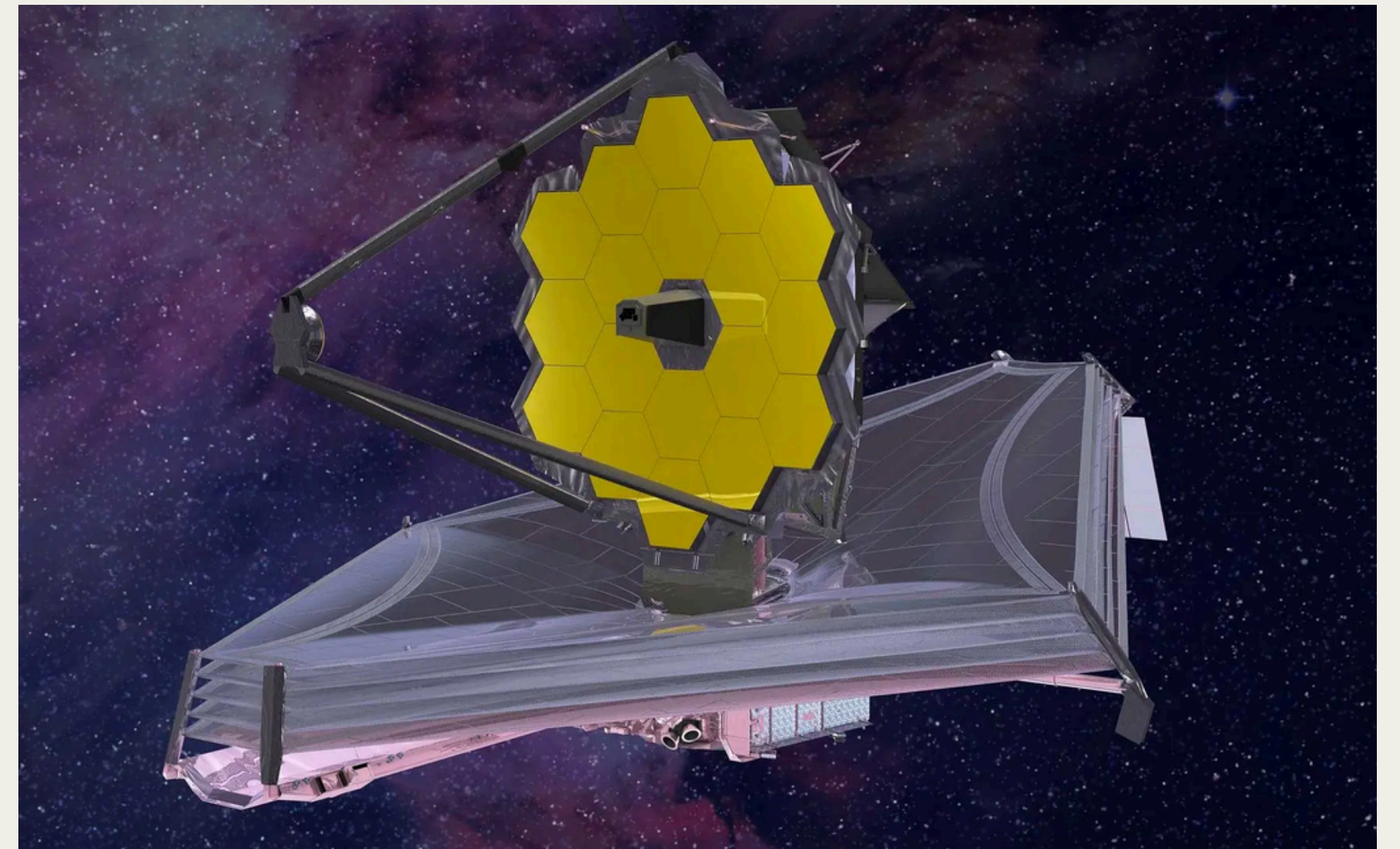
- The CMB is the oldest light in the universe, a remnant of the Big Bang.
- Detailed mapping of CMB temperature variations helps estimate cosmic age.
- Data from missions like WMAP and Planck confirm the 13.8-billion-year figure.

HUBBLE'S LAW & UNIVERSAL EXPANSION

- The Hubble constant measures how fast galaxies move away from us.
- Extrapolating backward suggests a singular origin: the Big Bang.
- JWST refines this by observing early galaxies and testing expansion models.

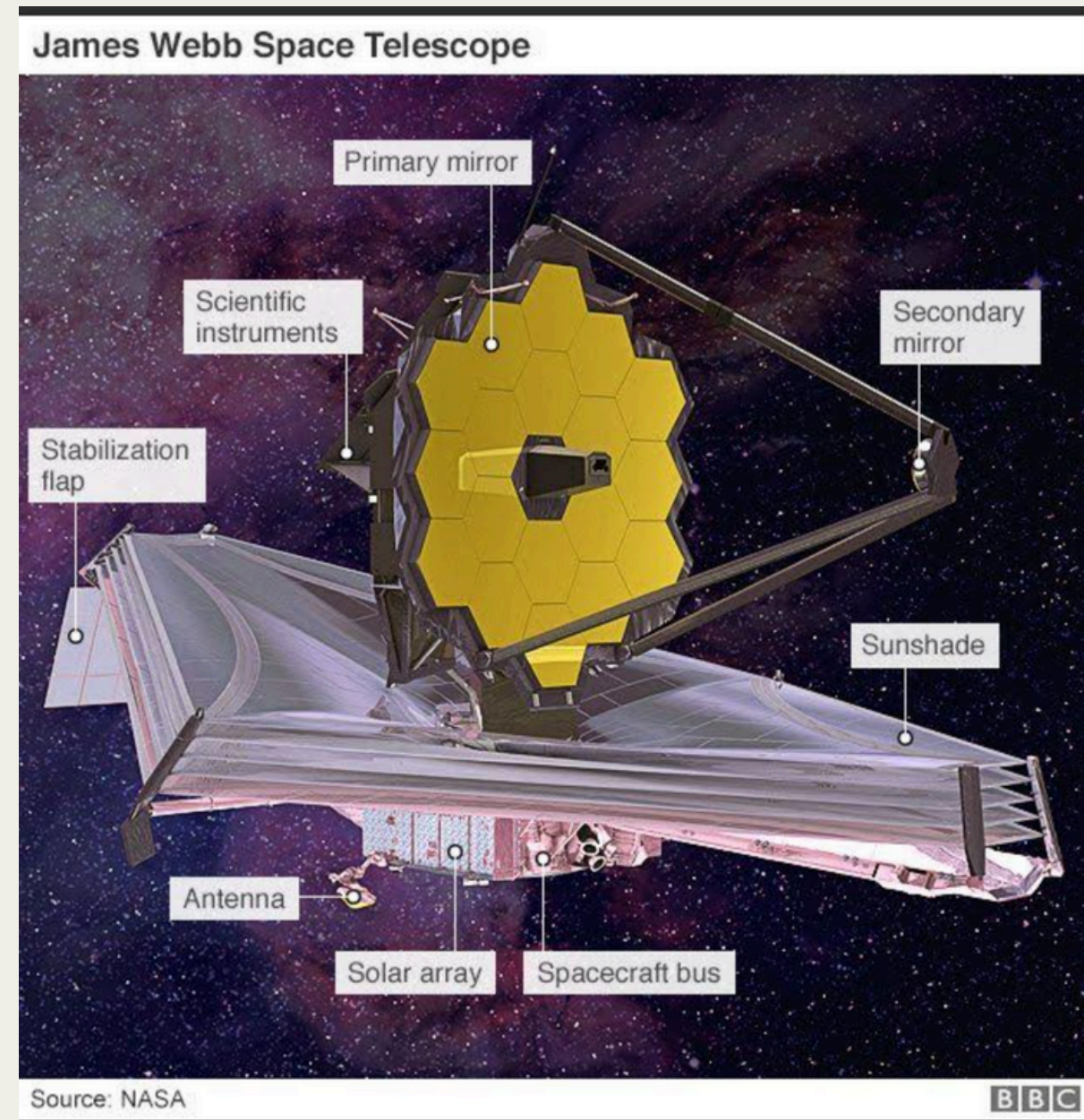
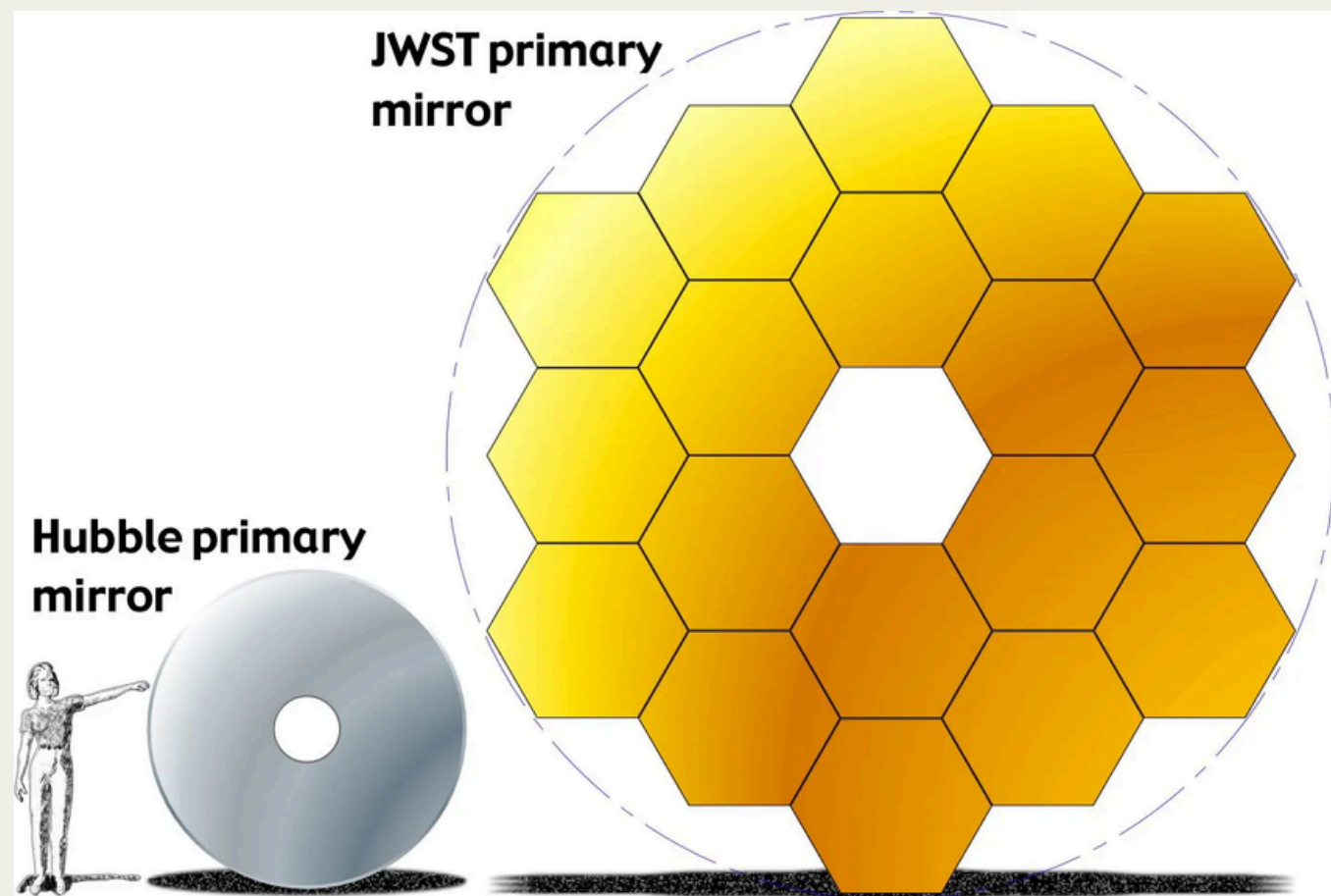
INTRODUCTION TO JWST

- Launched December 25, 2021, as the successor to Hubble.
- Largest and most powerful space telescope ever built.
- Focuses on infrared astronomy to study the universe's earliest light, detecting weaker forms of photons, detecting infrared photons.
- Gold is utilized due to its extremely reflective properties.



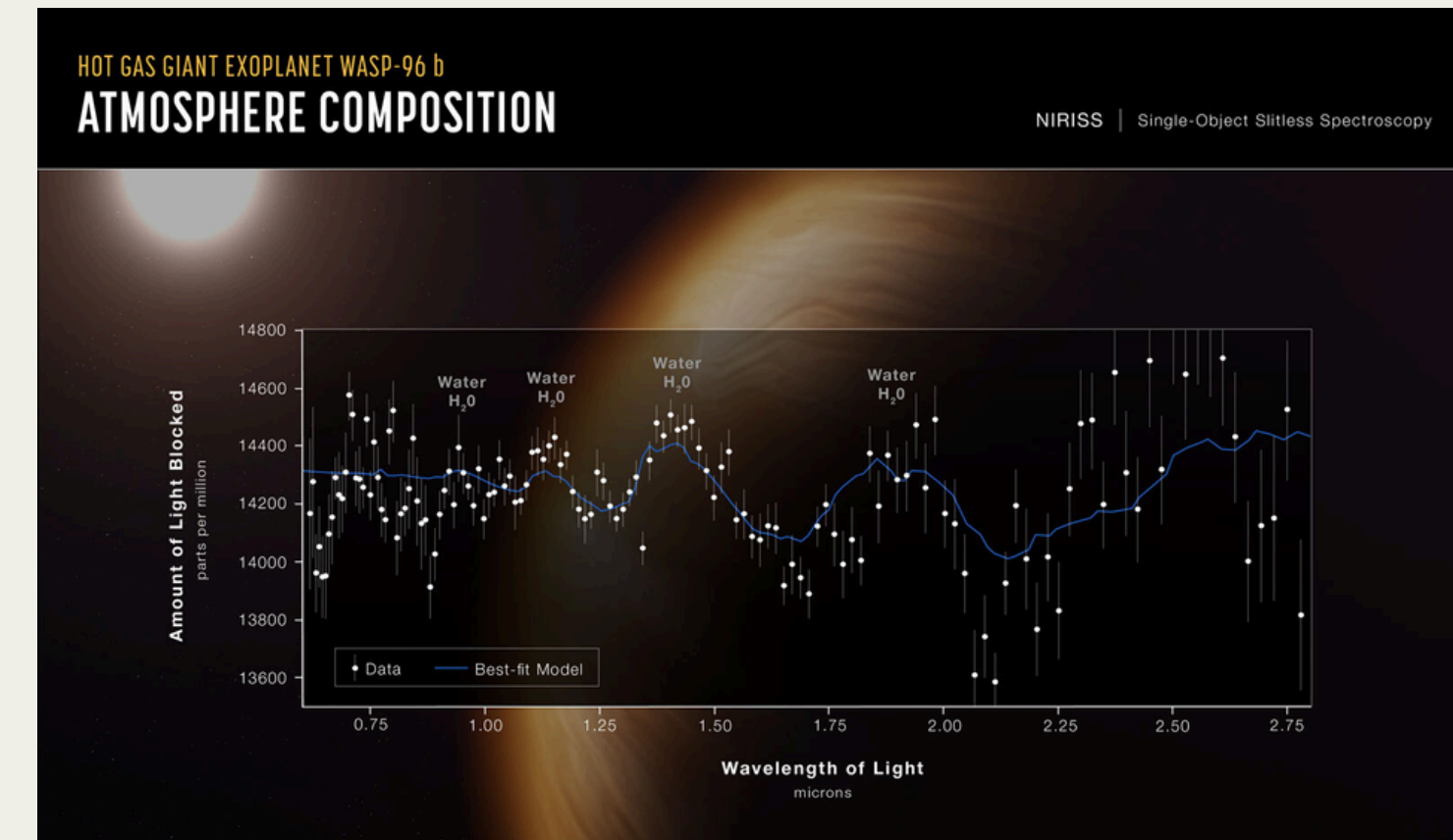
JWST'S PRIMARY MIRROR & INSTRUMENTS

- 6.5-meter gold-coated mirror captures faint and distant light.
- Equipped with four major scientific instruments: NIRCam, NIRSpec, MIRI, and NIRISS.
- Designed for studying galaxies, exoplanets, and star formation.



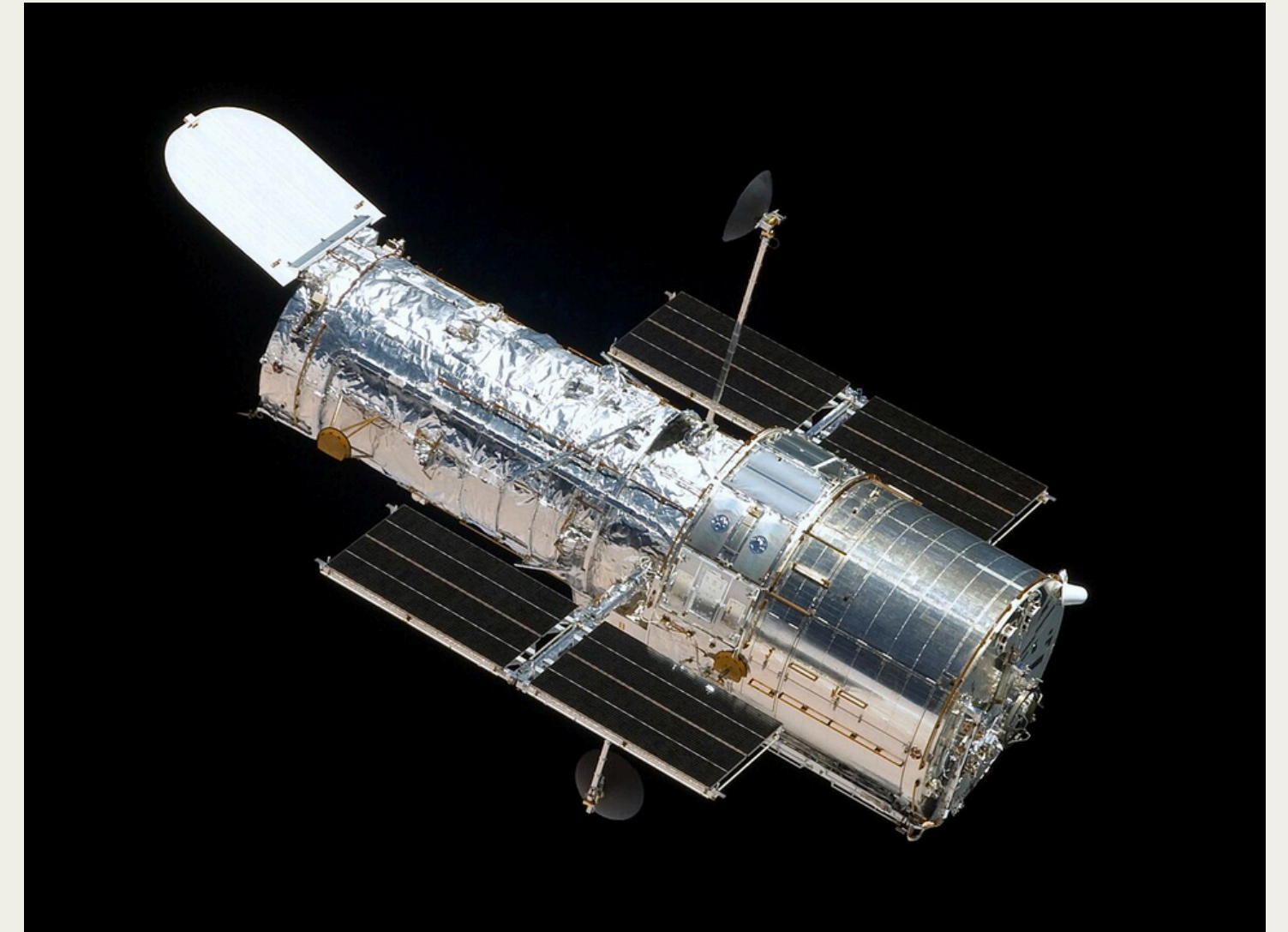
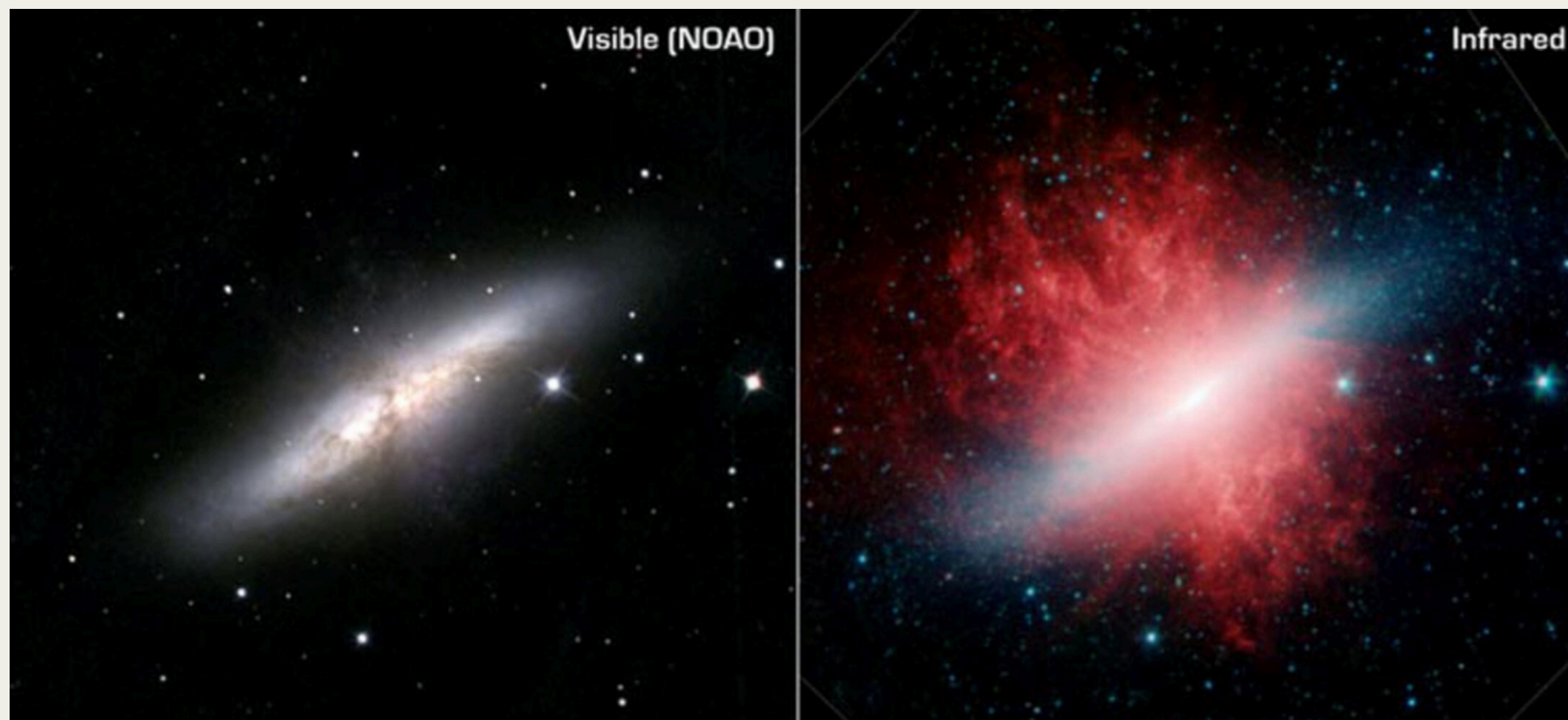
JWST'S MISSION OBJECTIVES

- Observing the first galaxies formed after the Big Bang.
- Investigating how galaxies and stars evolve over time.
- Studying exoplanets' atmospheres to assess potential habitability.
- Detecting new galaxies that have not been detected.



INFRARED ASTRONOMY & JWST'S ADVANTAGE

- Infrared light penetrates cosmic dust to reveal hidden structures.
- Allows observation of distant galaxies, exoplanets, and forming stars.
- Expands beyond Hubble's capabilities by detecting much older cosmic events.



JWST'S EARLY DISCOVERIES

- Identified galaxies from 300 million years after the Big Bang.
- Detected water vapor and methane in exoplanet atmospheres.
- Observed star formation in unprecedented detail.

CONNECTING JWST TO THE AGE OF THE UNIVERSE

- JWST provides direct evidence of early galaxies, confirming the 13.8-billion-year estimate.
- Helps refine the Hubble constant by studying distant cosmic structures.
- Expands our understanding of the universe's evolution by tracing its earliest light.

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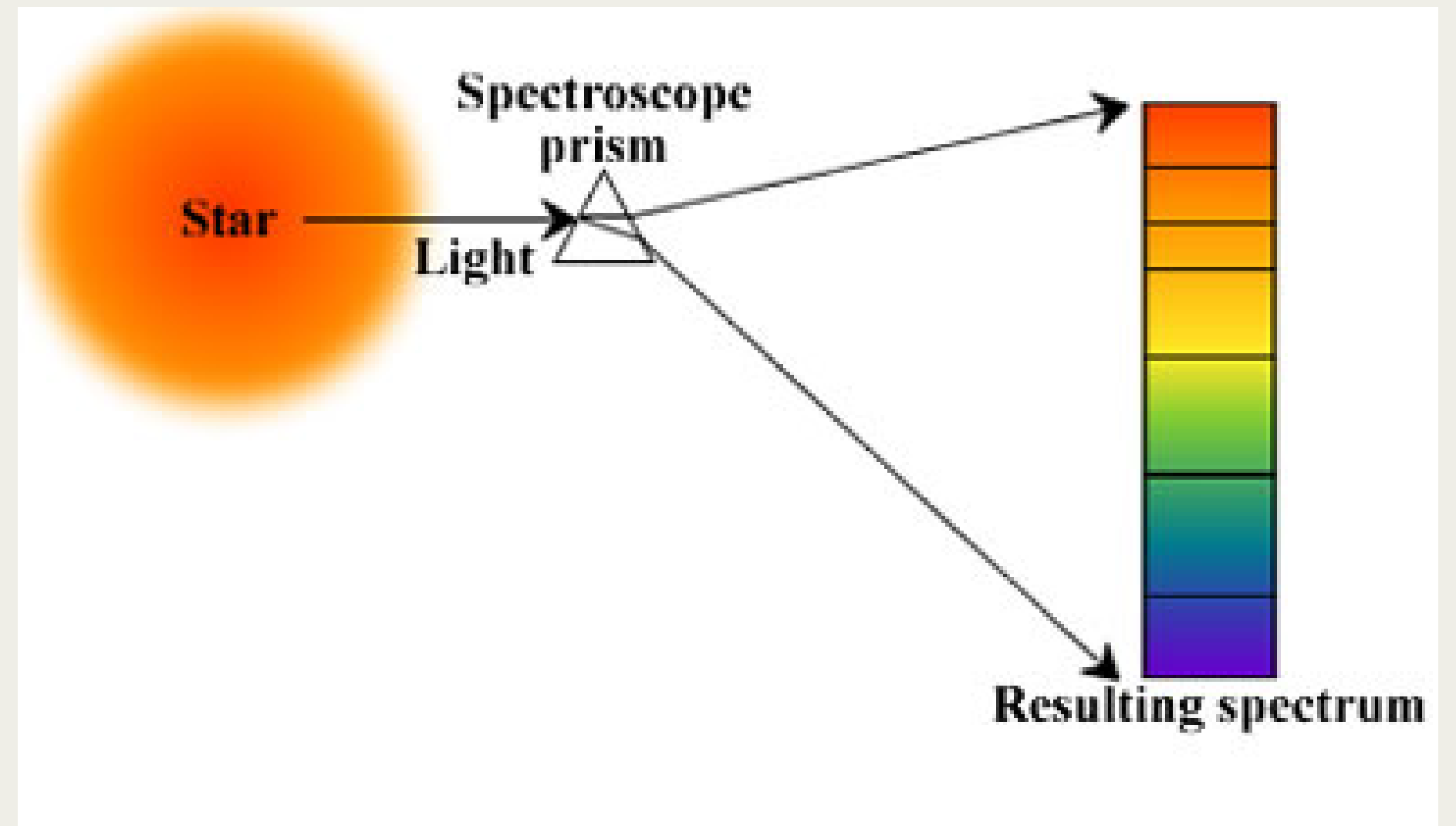
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Atomic Spectroscopy and the James Webb Space Telescope

THE ROLE OF SPECTROSCOPY IN ASTRONOMY

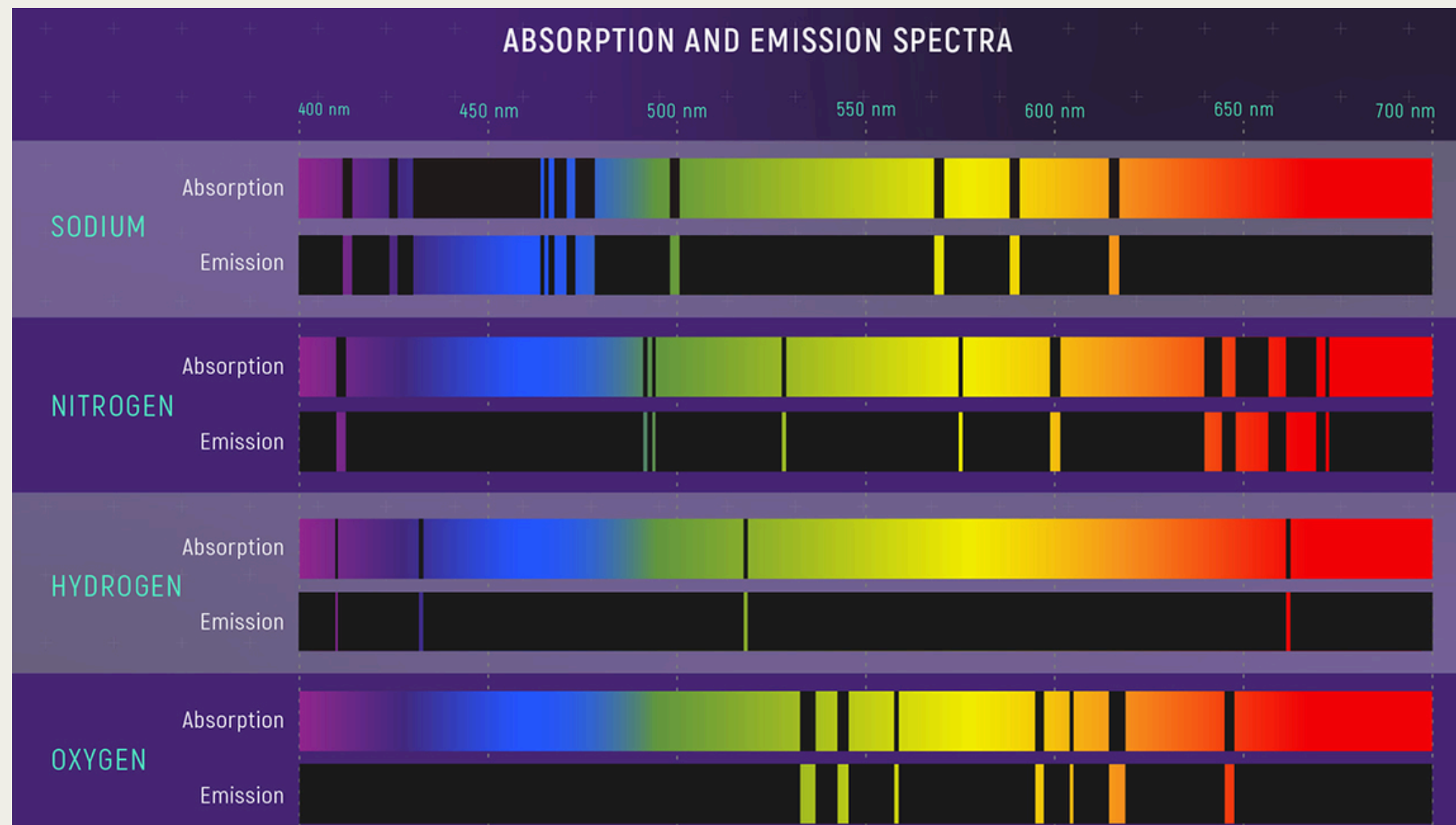
- Spectroscopy analyzes light from celestial objects to determine their chemical compositions.
- Elements emit/absorb light at unique wavelengths, creating identifiable spectral lines.
- Helps astronomers study stellar evolution, galaxy formation, and cosmic chemistry.



ALLOWED LINES

- Allowed lines are spectral lines that result from electron transitions between energy levels that obey quantum mechanical selection rules.
- These transitions occur quickly and produce strong, easily detectable emission or absorption lines in spectra.
- Common in high-density environments like stars, allowed lines help identify abundant elements such as hydrogen and helium.

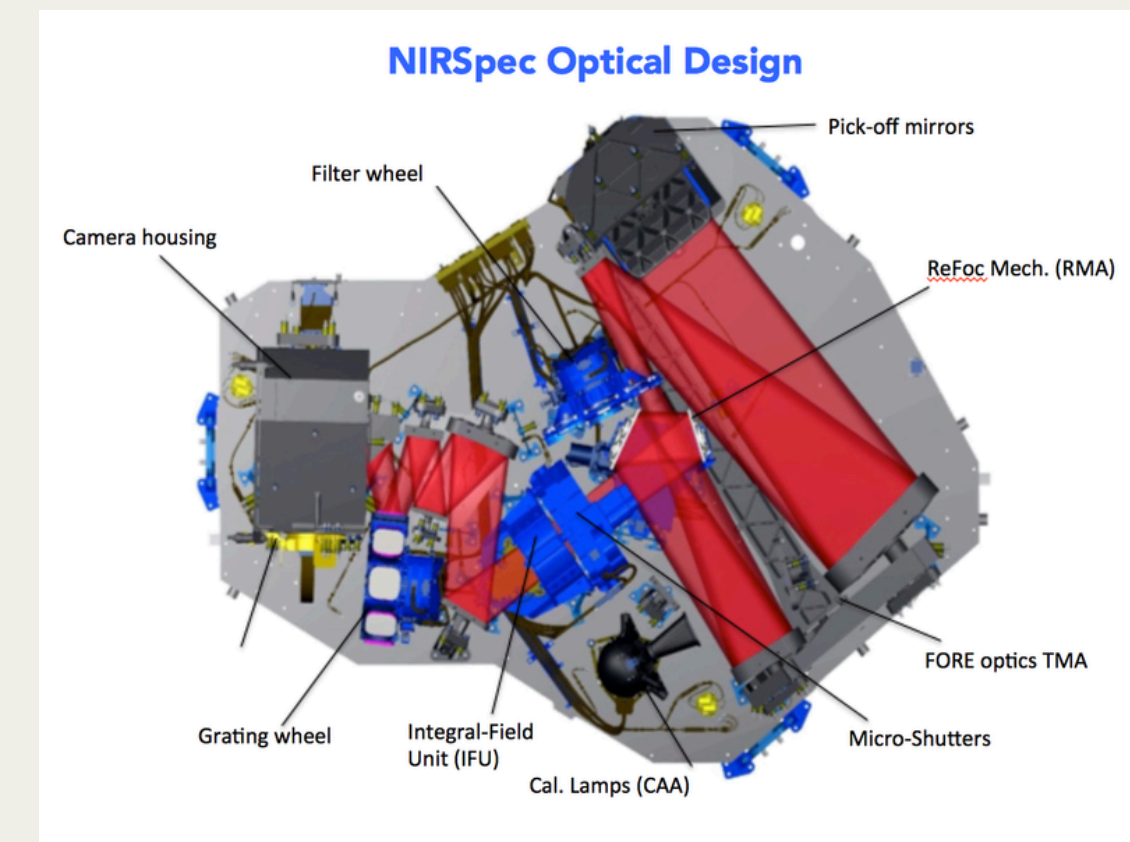
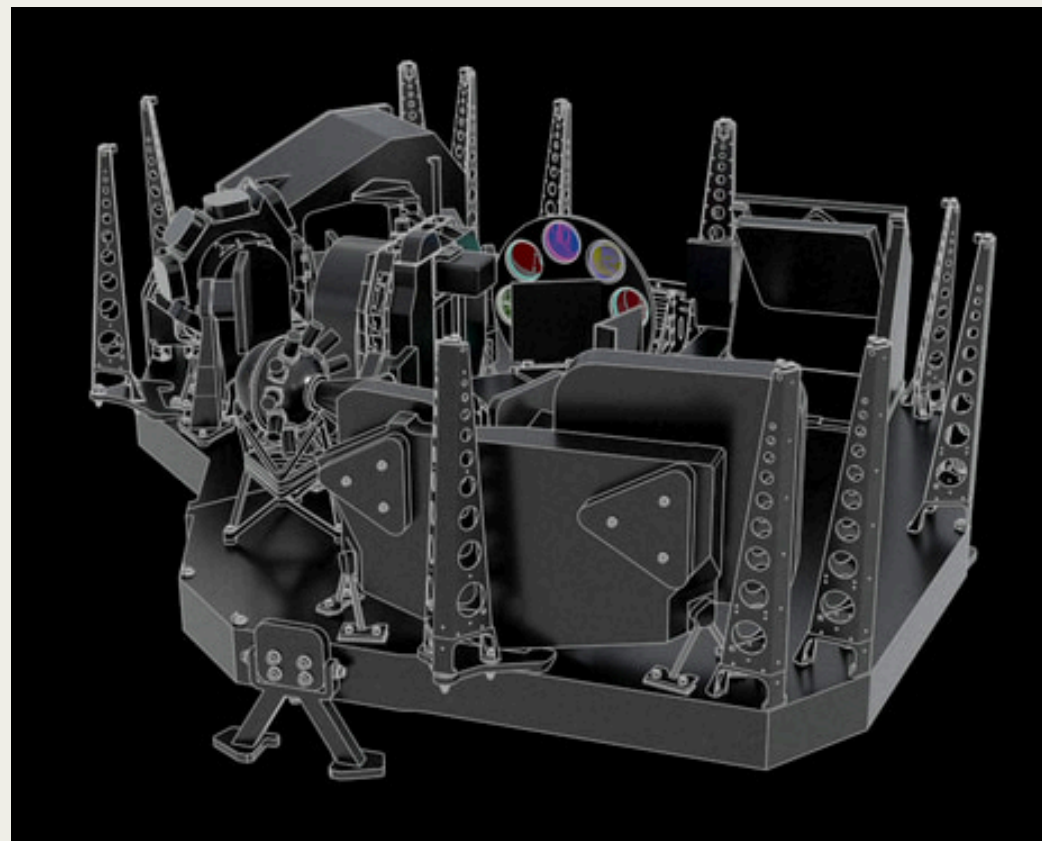
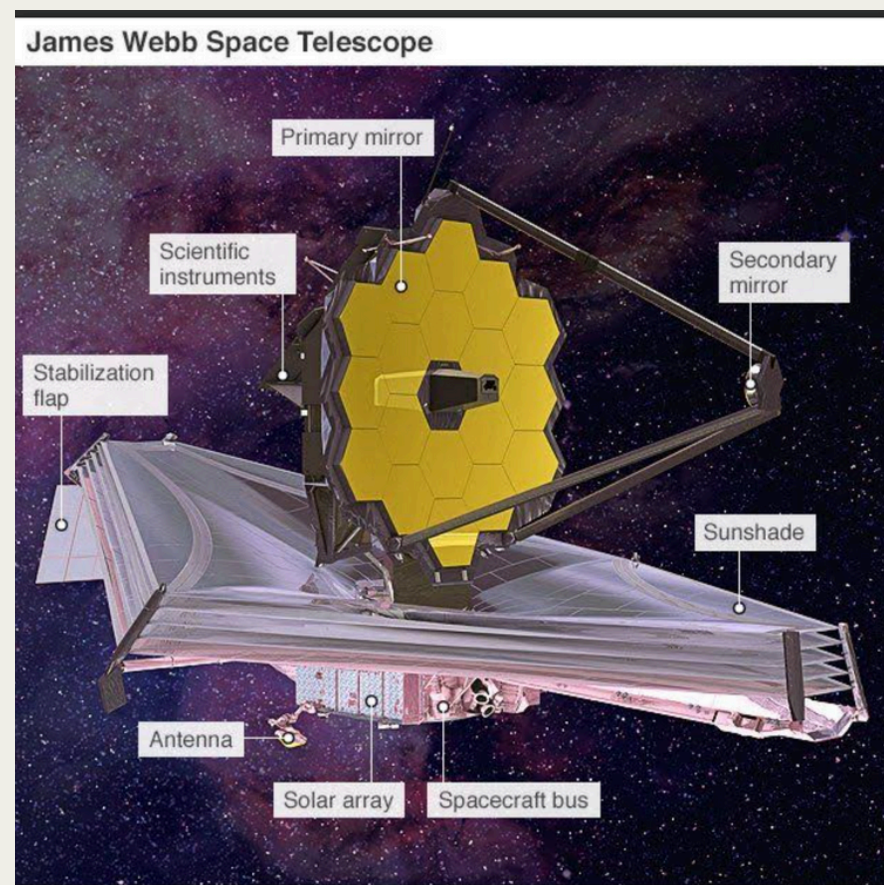
FORBIDDEN EMISSION LINES & THEIR IMPORTANCE



- Emission lines from elements like nitrogen, sodium, and oxygen appear under low-density conditions in space.
- These lines help identify the composition and temperature of nebulae and distant galaxies.
- They provide crucial data on star formation regions and black hole surroundings.

JWST'S SPECTROSCOPIC CAPABILITIES & NIRSPEC

- JWST's Near-Infrared Spectrograph (NIRSpec) observes light from 0.6 to 5.0 micrometers.
- Can analyze up to 100 objects at once, ideal for studying distant galaxies and exoplanets.
- Enables scientists to examine the atmosphere of exoplanets and the early universe.



JWST'S KEY DISCOVERIES USING SPECTROSCOPY



- Identified JADES-GS-z14-0, the most distant galaxy, from 290 million years after the Big Bang, compared to what HST found ~700 millions years after Big Bang.
- Detected frozen CO₂ and hydrogen peroxide on Pluto's moon Charon, revealing surface chemistry.
- Found “rogue planets” (planetary-mass objects without stars), providing insights into planet formation.

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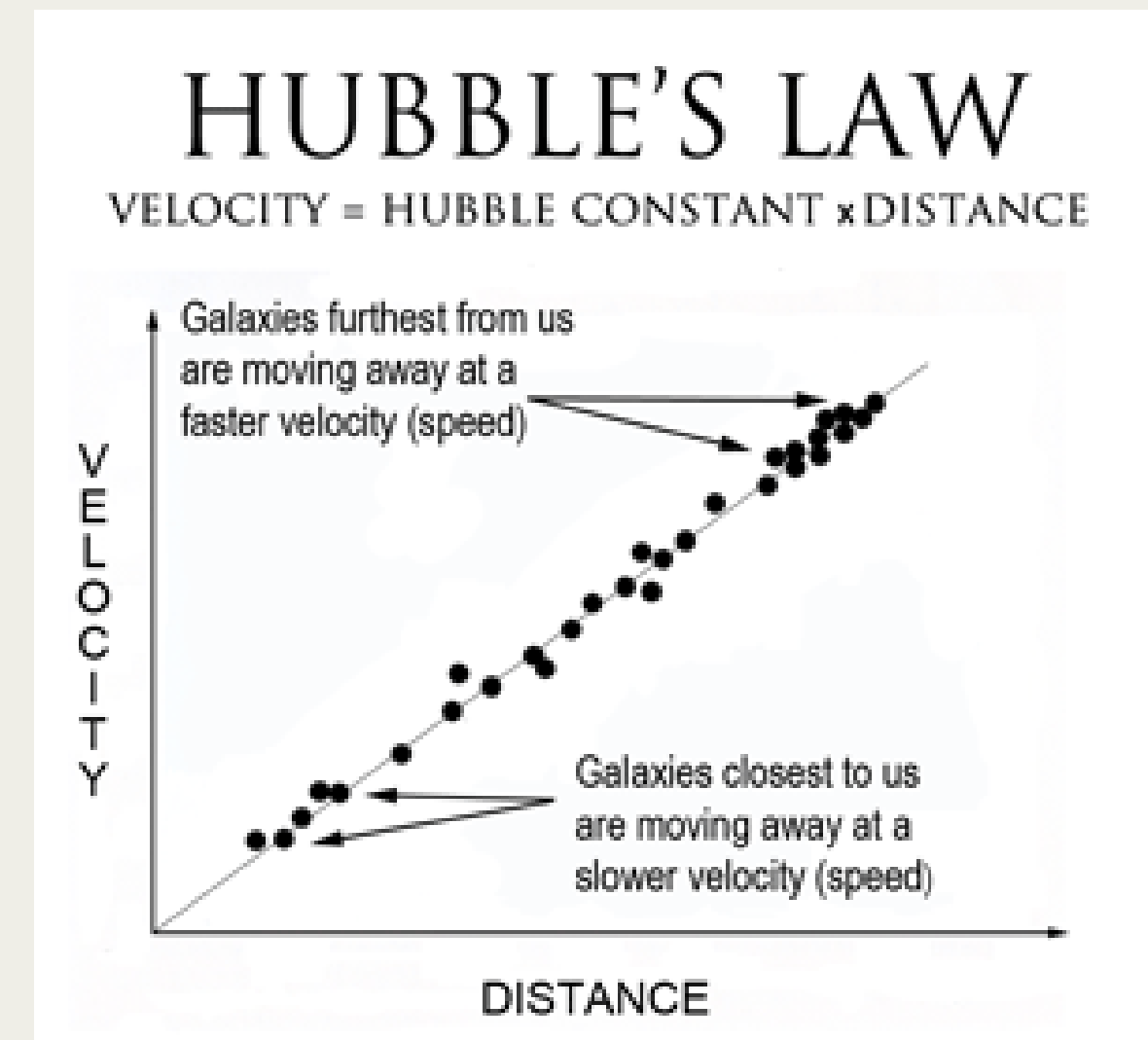
OBJECTIVES OF THIS STUDY

- To identify spectral lines in JWST data from a distant galaxy using observed wavelengths.
- To calculate the redshift of these lines from an astronomical object.
- (1) Use the redshift to gain information regarding to age and distance from Earth of the object.
- (2) To match the rest-frame wavelengths with known transitions using the NIST database. Along with identifying and confirming the presence of certain elements.

THEORETICAL BACKGROUND

i. Expansion of the Universe

- Edwin Powell Hubble found that the universe is expanding from observation; He introduced a constant, known as Hubble's constant, H_0
- Hubble's constant is related to the distance and age of the object.
- Hubble's constant is no longer a constant however as the universe is expanding at an accelerating rate. Hubble's law is estimated to be 73 km per second per megaparsec
- Velocity and redshift relation: $v \approx c \times z$ (for small redshifts)
- Higher redshift means greater distance from Earth
- Redshift helps determine both composition and look-back time



THEORETICAL BACKGROUND

i. Expansion of the Universe

$$v = H_0 d$$

v = recessional velocity of galaxy

H_0 = Hubble constant

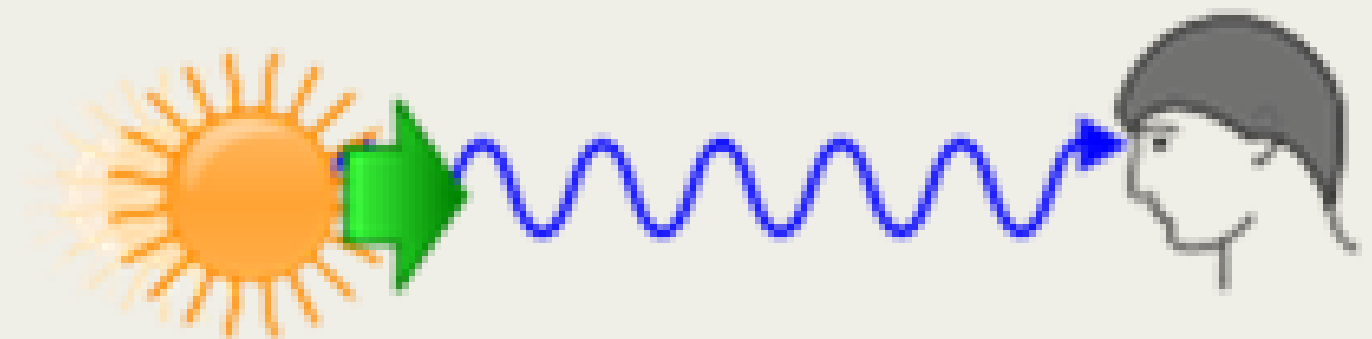
d = distance to galaxy

THEORETICAL BACKGROUND

i. Expansion of the Universe

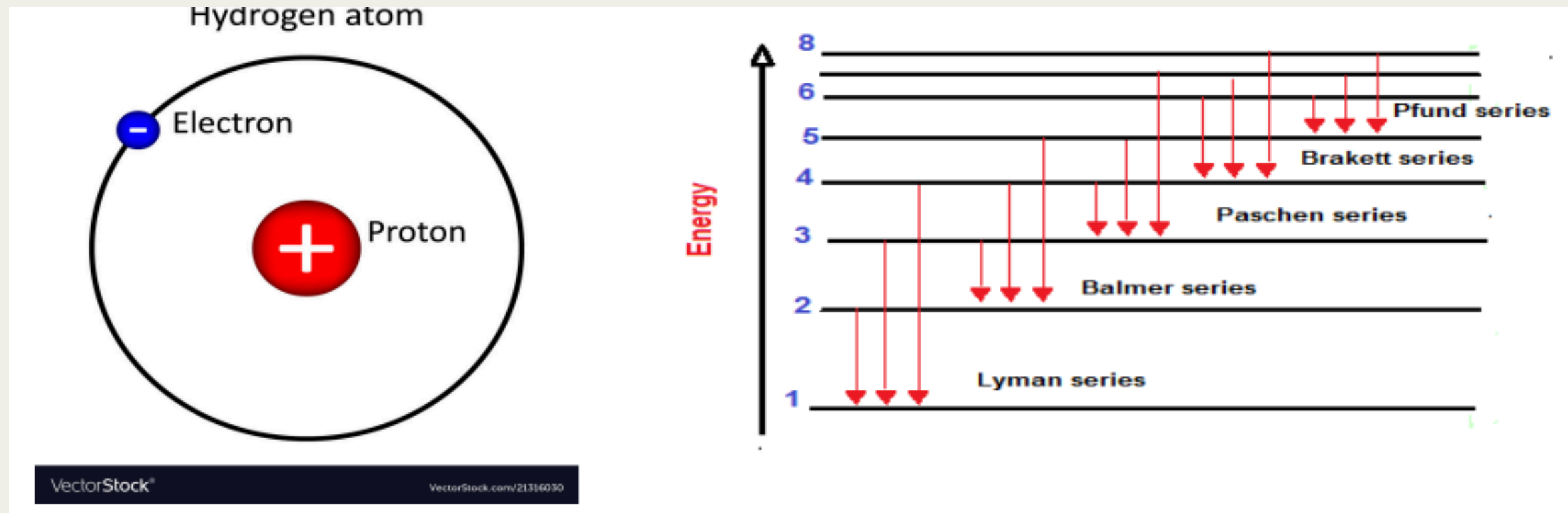


redshift: wavelength longer



blueshift: wavelength shorter

ii. Atomic Transitions and the Rydberg Formula



- Atoms emit light at specific wavelengths when electrons transition between energy levels
- These energy levels are quantized, meaning they can only occupy specific states.
- The Rydberg Formula helps predict the wavelengths of hydrogen spectral lines based on these energy transitions.
- For hydrogen, we can have various series of transitions — Lyman series and Balmer Series (shown in the top-right side of the figure above).

ii. Atomic Transitions and the Rydberg Formula

Rydberg Formula:

$$\frac{1}{\lambda} = (R_H)(Z)^2 \left(\frac{1}{n_1^2} - \frac{1}{n_2^2} \right)$$

- Explains how electrons falling between energy levels emit light.
- Focus on hydrogen's Balmer series (transitions to $n_1 = 2$).
- Variables explained: λ = wavelength of emitted light, R = Rydberg constant, Z = atomic number (for hydrogen, $Z=1$)
- n_1, n_2 = lower and higher energy levels respectively

METHODOLOGY

MATCHING SPECTRAL LINES TO ELEMENTS

- Used JWST's publicly available near-infrared spectral data from a distant lensed galaxy
- Visually estimated emission line positions based on the spectrum's micron scale
- Converted observed wavelengths to rest-frame values using the redshift equation
- Compared rest-frame wavelengths to NIST Atomic Spectra Database for atomic transition matches

VERIFYING LINES AND REDSHIFT VALUES

- Rest-frame wavelengths were calculated by dividing observed values by $(1 + z)$
- These wavelengths were converted from microns to angstroms ($\times 10,000$)
- Rest values were compared to NIST database entries to identify atomic transitions
- This process verified the redshift and supported consistent element identification across all lines

RESULTS & DISCUSSION

INITIAL DATA AND VISUAL ANALYSIS

- Started with JWST spectral image of a galaxy lensed by SMACS 0723.
- Emission lines visible in near-infrared range.
- Wavelengths estimated by eye, matching lines to micron (μm) scale on spectrum.
- One prominent line observed at $3.7 \mu\text{m}$ chosen for redshift estimation.



JWST SPECTRUM

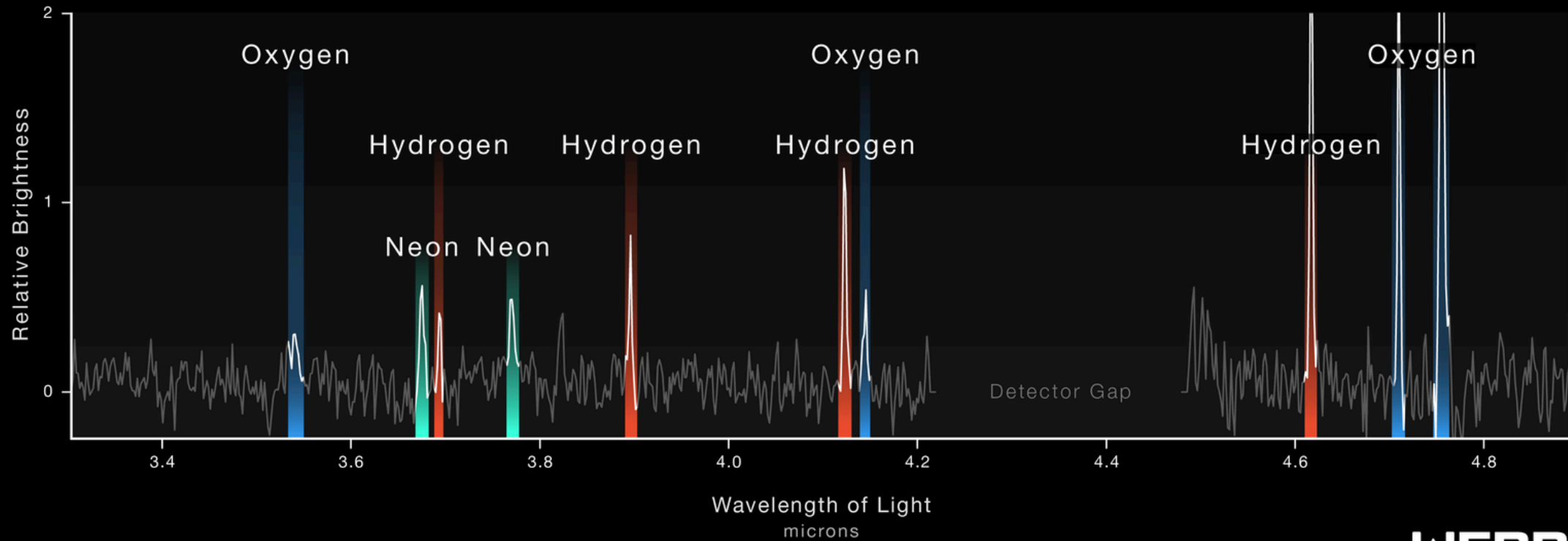
DISTANT GALAXY BEHIND SMACS 0723

WEBB SPECTRUM SHOWCASES GALAXY'S COMPOSITION

NIRCam Imaging



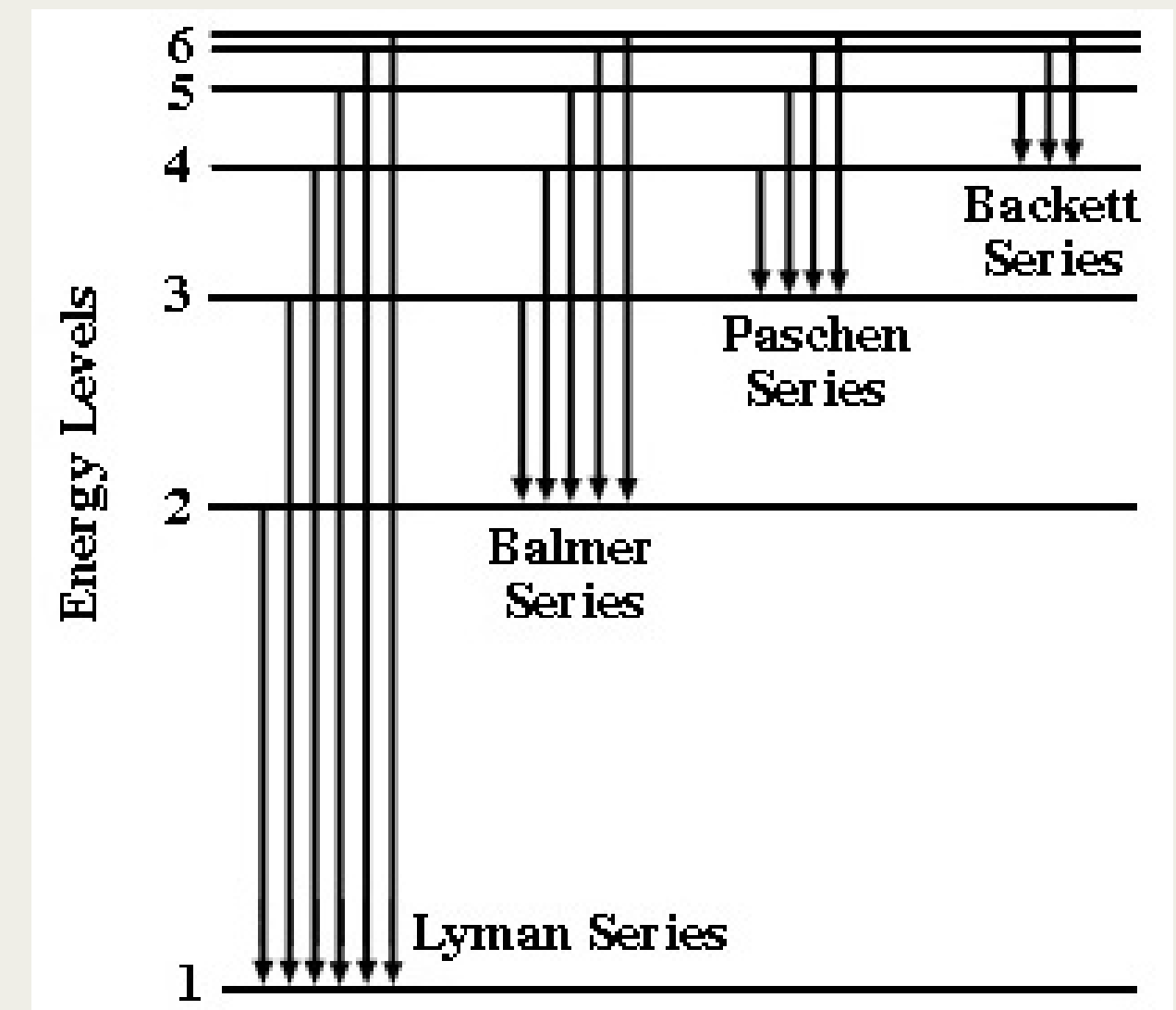
NIRSpec Microshutter Array Spectroscopy



WEBB
SPACE TELESCOPE

IDENTIFYING THE REDSHIFTED LINE

- Initially, the 3.7 micron line was thought to come from hydrogen's Lyman series, but the wavelength was too long.
- Attention shifted to the Balmer series, where electrons fall to the $n=2$ level, producing visible and near-infrared light.
- The Rydberg formula was used to test energy level transitions by trial and error.
- The $n=9$ to $n=2$ transition matched a rest wavelength of 0.434 microns, leading to a calculated redshift of about 8.65.



APPLYING REDSHIFT AND IDENTIFYING ELEMENTS

- Applied redshift uniformly to all observed emission lines.
- Calculated rest wavelengths by dividing observed wavelengths by $(1 + z)$.
- Converted rest wavelengths from microns to angstroms ($\times 10,000$).
- Compared results to NIST Atomic Spectra Database for elemental identification

IDENTIFICATION OF THE SPECTROSCOPIC LINES OBSERVED BY JWST

Element	Observed JWST Wavelengths (microns)	Identified Wavelengths of JWST lines with Z = 8.65 (Å)	Closest Wavelengths from the NIST table	Identified Transition
Oxygen	3.54	3668	3,855.0139	$2s^2 2p^3(^2D^\circ) 3s\ ^1D^\circ_2 - 2s^2 2p^3(^2P^\circ) 3p\ ^1D_2$
Neon	3.64	3772	3,769.654	$2s^2 2p^5(^2P^\circ_{1/2}) 3s\ ^2[1/2]^\circ_1 - 2s^2 2p^5(^2P^\circ_{1/2}) 3d\ ^2[5/2]^\circ_2$
Hydrogen	3.7	3836	3,835.397	$2p\ ^2P^\circ_{3/2} - 9d\ ^2D_{5/2}$
Neon	3.79	3927	3,943.540	$2s^2 2p^5(^2P^\circ_{3/2}) 3p\ ^2[1/2]_1 - 2s^2 2p^5(^2P^\circ_{1/2}) 10d\ ^2[3/2]^\circ_2$
Hydrogen	3.85	3984	3,970.075	$2p\ ^2P^\circ_{3/2} - 7d\ ^2D_{5/2}$
Hydrogen	4.07	4214	4,101.734	$2p\ ^2P^\circ_{3/2} - 6d\ ^2D_{5/2}$
Oxygen	4.08	4226	4,233.27	$2s^2 2p^3(^4S^\circ) 4p\ ^3P_2 - 2s^2 2p^3(^2D^\circ_{3/2}) 3d\ ^3P^\circ_2$
Hydrogen	4.61	4777	4,861.283	$2s\ ^2S_{1/2} - 4d\ ^2D_{5/2}$
Oxygen	4.77	4944	5,329.10	$2s^2 2p^3(^4S^\circ) 3p\ ^5P_1 - 2s^2 2p^3(^4S^\circ) 5d\ ^5D^\circ_1$
Oxygen	4.78	4954	5,329.10	$2s^2 2p^3(^4S^\circ) 3p\ ^5P_1 - 2s^2 2p^3(^4S^\circ) 5d\ ^5D^\circ_1$

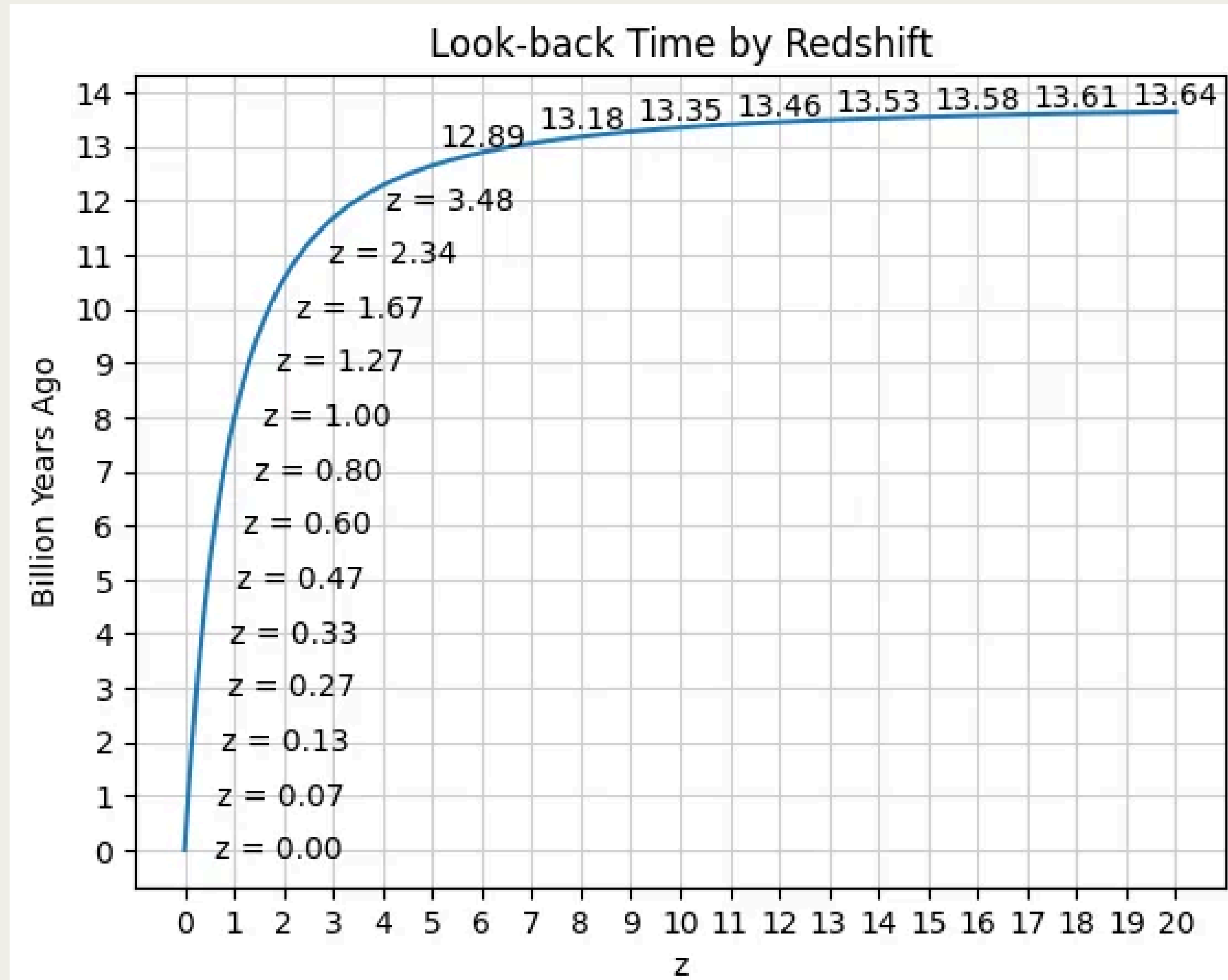
CONCLUSIONS OF REDSHIFT AND ELEMENTAL MATCHES

- Redshift ($z = 8.65$) was calculated using a hydrogen Balmer line at 3.7 microns.
- Rydberg formula and trial-and-error were used to find the correct transition ($n=9 \rightarrow n=2$).
- This redshift allowed the rest of the spectral lines to be matched across the galaxy's emission.
- Elements like hydrogen, oxygen, and neon were identified by comparing to NIST reference wavelengths.

INTERPRETING THE DETECTED ELEMENTS

- Hydrogen Balmer lines suggest active star formation and young, hot stars.
- Oxygen detections point to chemical enrichment from past star formation cycles.
- Neon indicates the presence of massive stars and rapid evolution in early galaxies.
- These results show that this galaxy had already undergone significant chemical development.

INTERPRETING THE DETECTED ELEMENTS



LIMITATIONS AND OVERALL SIGNIFICANCE

- Wavelengths were estimated by eye, which introduces uncertainty.
- Redshift was based on a single hydrogen line using trial and error.
- Manual matching reduces precision compared to automated or statistical methods.
- Despite limitations, consistency across data supports the findings.

FUTURE PLANS AND CONCLUSIONS

- This study confirmed redshift ($z = 8.65$) and identified elements using JWST spectral data and Balmer line analysis.
- Future work will use software to extract spectral lines more precisely and reduce human error.
- Statistical fitting tools can improve redshift accuracy and help confirm more elemental matches.
- Applying this method to additional galaxies and using lensing models can reveal how early galaxies evolved across the universe.

THANK YOU!

I would like to thank The Ohio State University and
Professor Sultana N. Nahar for carrying out my
research project.

I can take questions now.