THE JAMES WEBB SPACE TELESCOPE

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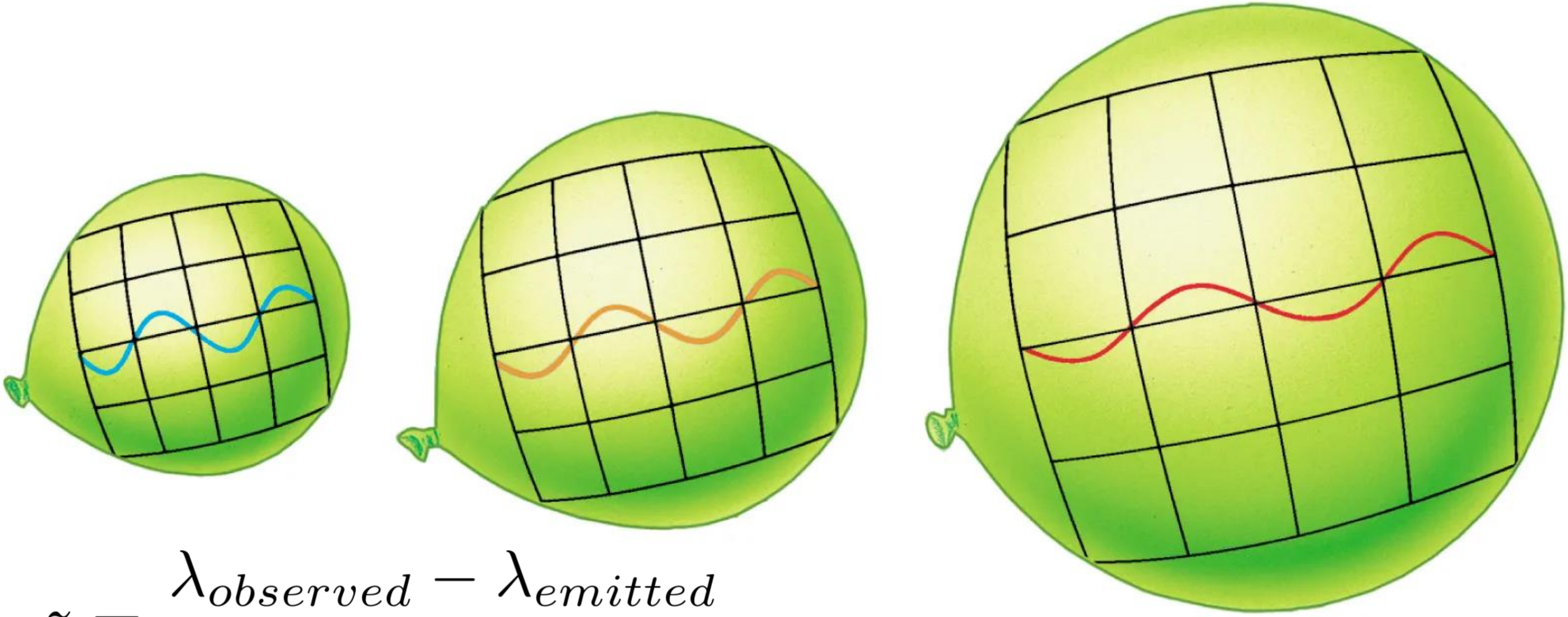
Plan

- Day 1:
  - Introduction – motivation
  - Modern astronomical telescopes
  - JWST – history, design and deployment

- Day 2:
  - Star & planet formation – the background
  - JWST – new results

- **Day 3:**
  - **Galaxy formation & cosmology – the background**
  - **JWST – new results**

Redshift (z), Distance, Age



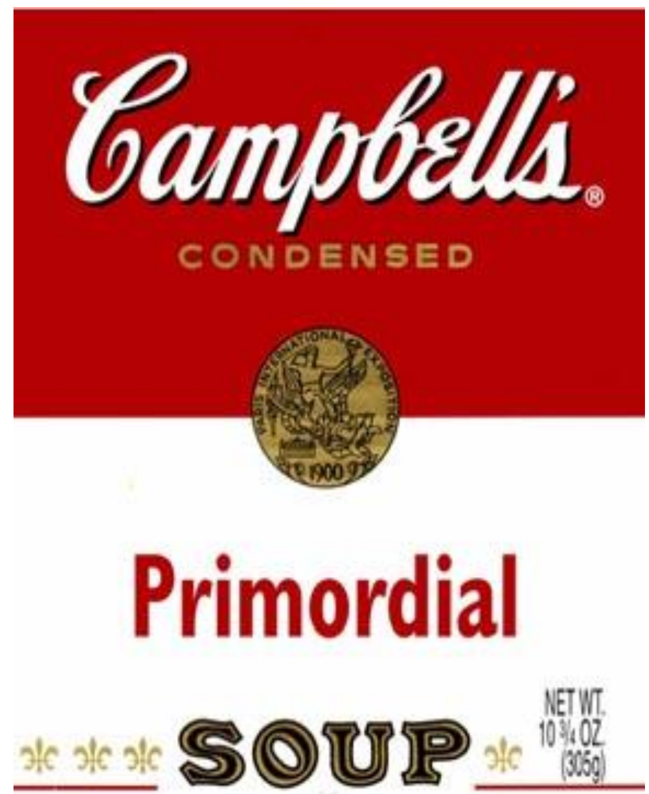
$$z = \frac{\lambda_{observed} - \lambda_{emitted}}{\lambda_{emitted}}$$

$$z + 1 = \frac{\lambda_{observed}}{\lambda_{emitted}}$$

$$\frac{S(z)}{S(now)} = \frac{1}{z+1}$$

Ten Seconds After The Big Bang

- The Universe was a hot (billion K) soup of matter and radiation, with small random variations in density
- Components:
  - **Baryons** (protons & neutrons – n & p)
  - Electrons (e)
  - Neutrinos (ν)
  -
  - Photons (γ) – 10^9 for every particle
  - Dark matter particles

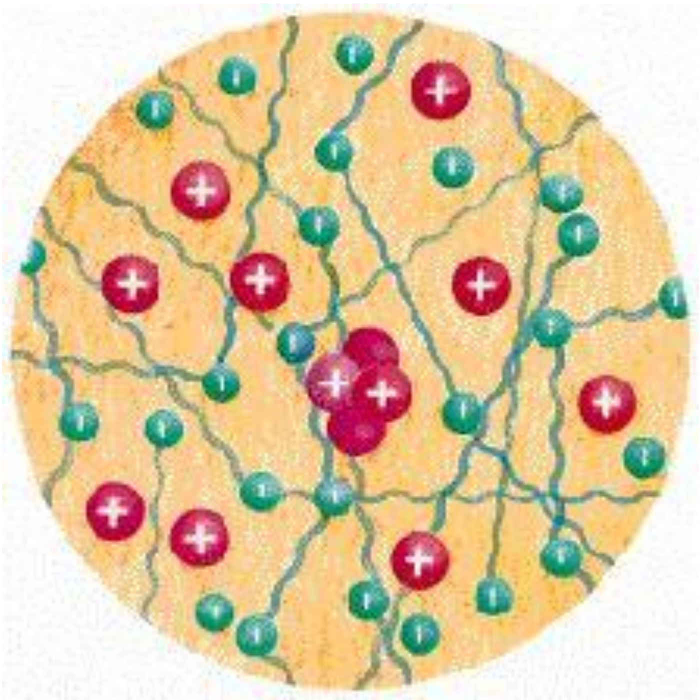


Before Stars & Galaxies

- By 20 min. after the Big Bang H had undergone fusion to form some light elements: the Universe was a soup of matter and radiation, with small random variations in density
- Components:
  - Hydrogen (^1H), Helium (^4He) and trace amounts of their isotopes (eg, deuterium) and Lithium (^7Li)
  - Electrons (e)
  - Neutrinos (ν)
  - Photons (γ) – 10^9 for every particle
  - Dark matter

Formation of Structure

- How do we go from this:

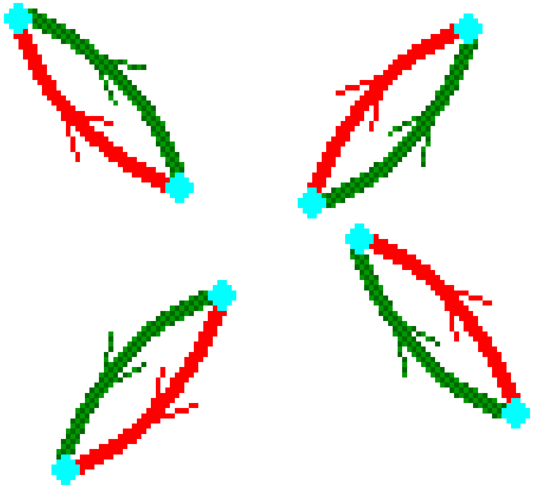


- to this?

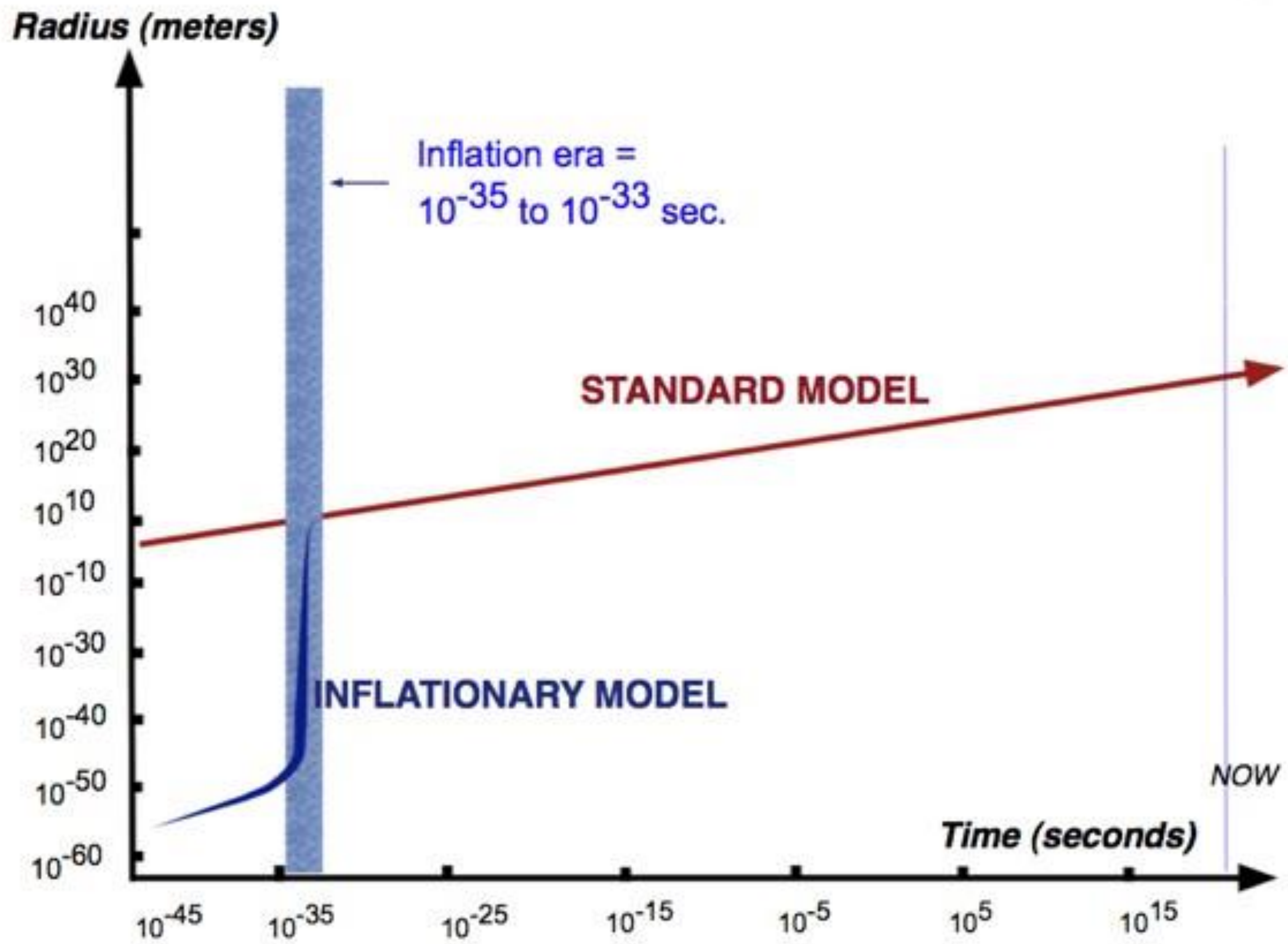
Quantum Fluctuations

- Space is a sea of virtual particles popping into and out of existence
- Pairs can appear for a short time determined by the Heisenberg Uncertainty Principle

- **Random fluctuations are inevitable in the quantum world**



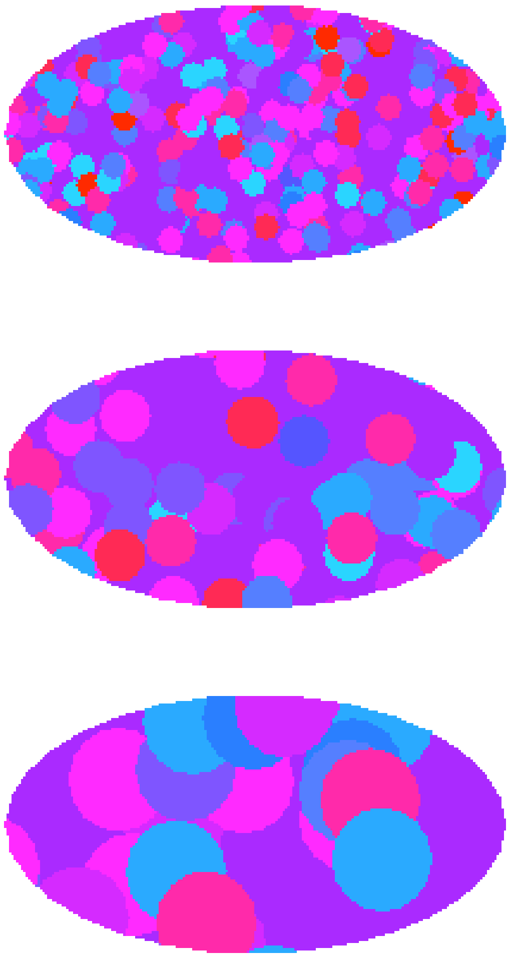
Inflation



Radius (meters)
Inflation era = 10^{-35} to 10^{-33} sec.
10^{40}
10^{30}
10^{20}
10^{10}
10^{-10}
10^{-30}
10^{-40}
10^{-50}
10^{-60}
STANDARD MODEL
INFLATIONARY MODEL
NOW
Time (seconds)
10^{-45}
10^{-35}
10^{-25}
10^{-15}
10^{-5}
10^{5}
10^{15}

Quantum Fluctuations + Inflation

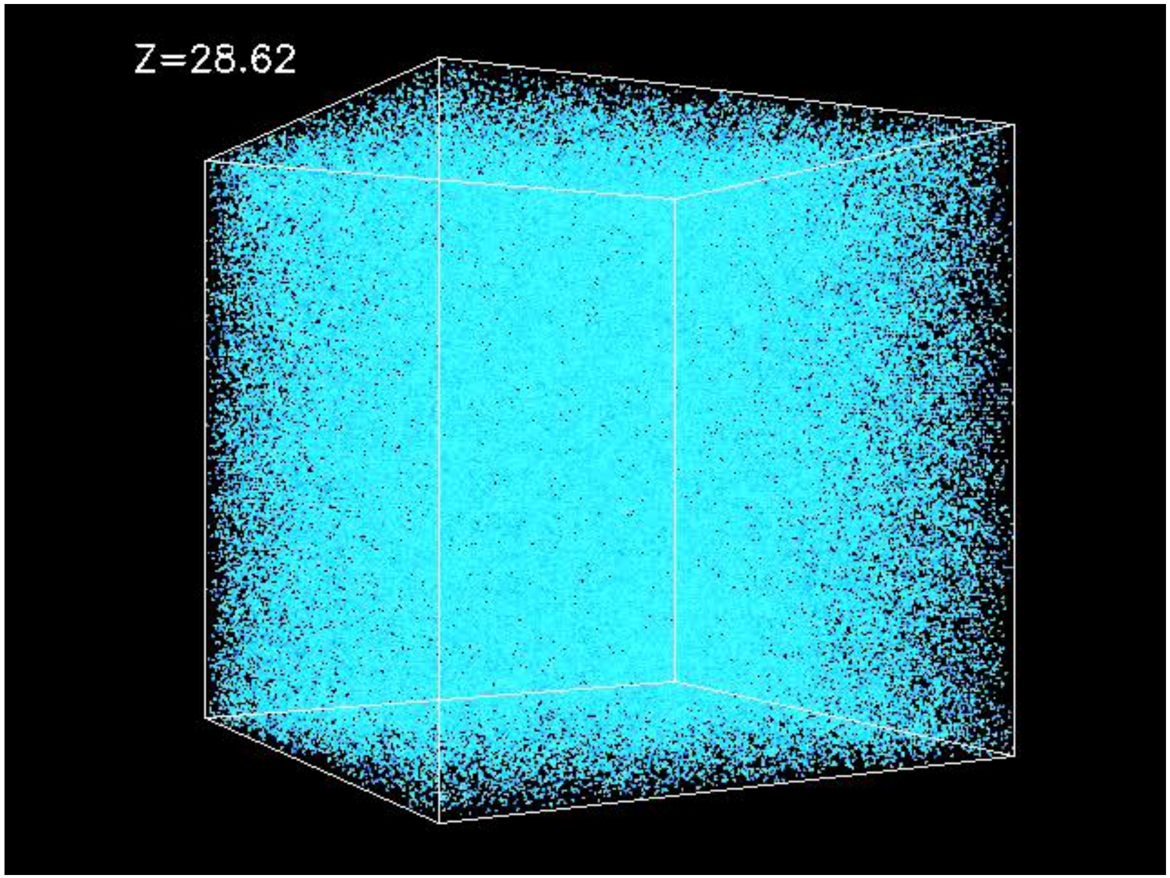
- The Universe was a sea of quantum fluctuations at the start of inflation
- Inflation stretches these – no "sloshing" because inflation is so fast the fluctuations are effectively frozen into the flow
- Each successive generation of fluctuations is inflated less
- After inflation, the Universe expands, encompassing a hierarchy of structure

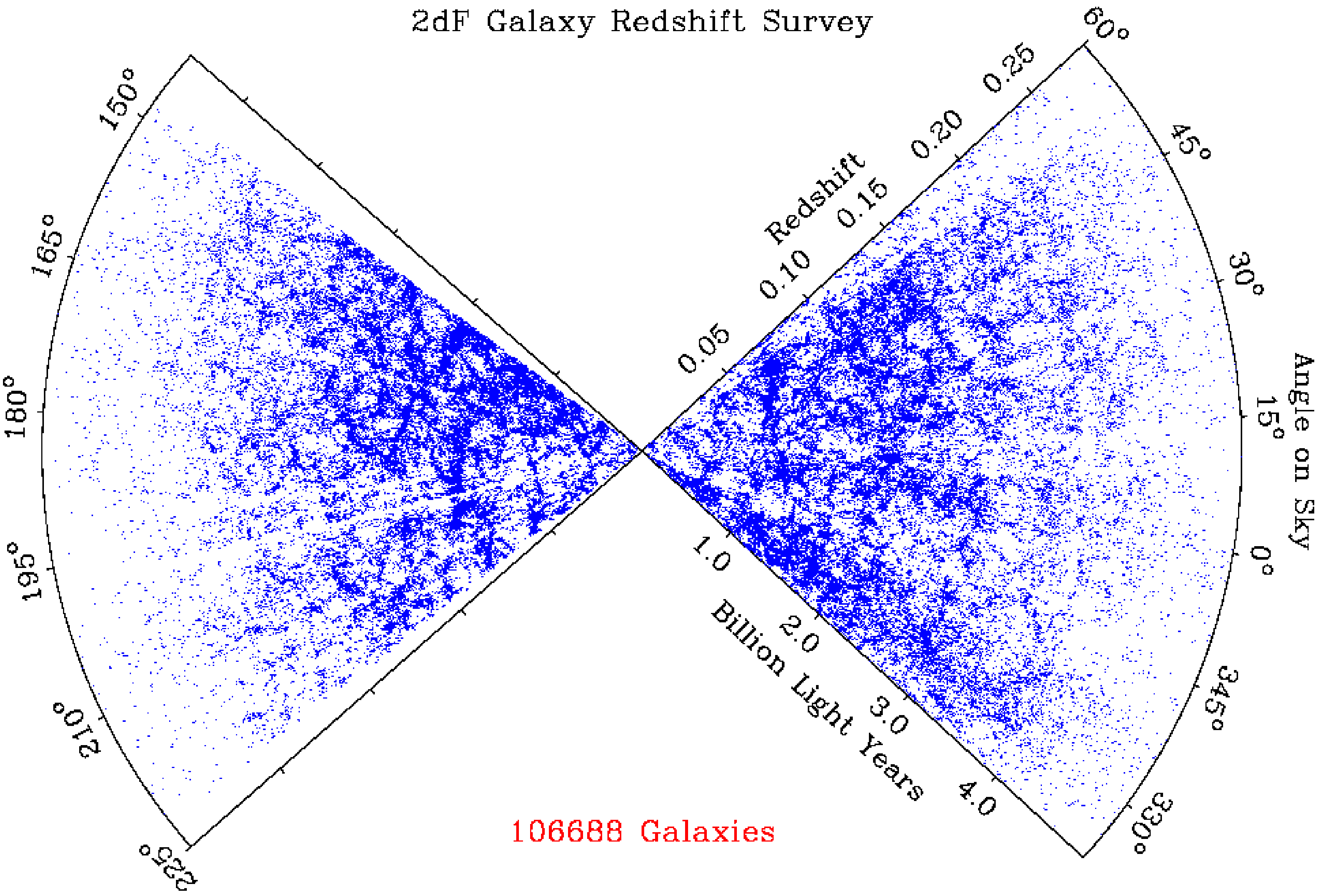


Growth Of Structure

- The dark matter fluctuations started growing soon after the Big Bang – by the time baryonic matter follows they are at the 1 in 1000 level
- Baryon fluctuations can't grow until after radiation can stream through matter (380,000 years after Big Bang) and then begin to "fall" into dark matter halos
- *We would not have the structure we have today without dark matter*
- *Gravity alone explains the large-scale structure of sheets & filaments!*

Evolution To The Present Day





2dF Galaxy Redshift Survey
Redshift
0.05
0.10
0.15
0.20
0.25
Billion Light Years
1.0
2.0
3.0
4.0
Angle on Sky
150°
165°
180°
195°
210°
225°
60°
45°
30°
15°
0°
345°
330°
106688 Galaxies

A Star Is Born

- Simulations suggest that stars with masses 300 – 1000 $M_{\odot}$ formed in the densest parts of protogalaxies some millions of years after the Big Bang

- They needed to be massive for gravity to overcome pressure – there would have been few options for cooling, as the heavy elements do not exist yet

Bright Stars

- These stars are massive, so hot; but also….

- In stars today C, N, and O catalyze fusion reactions
- These early stars had none of these elements
- Energy production was less efficient – they needed to be more compact and hotter

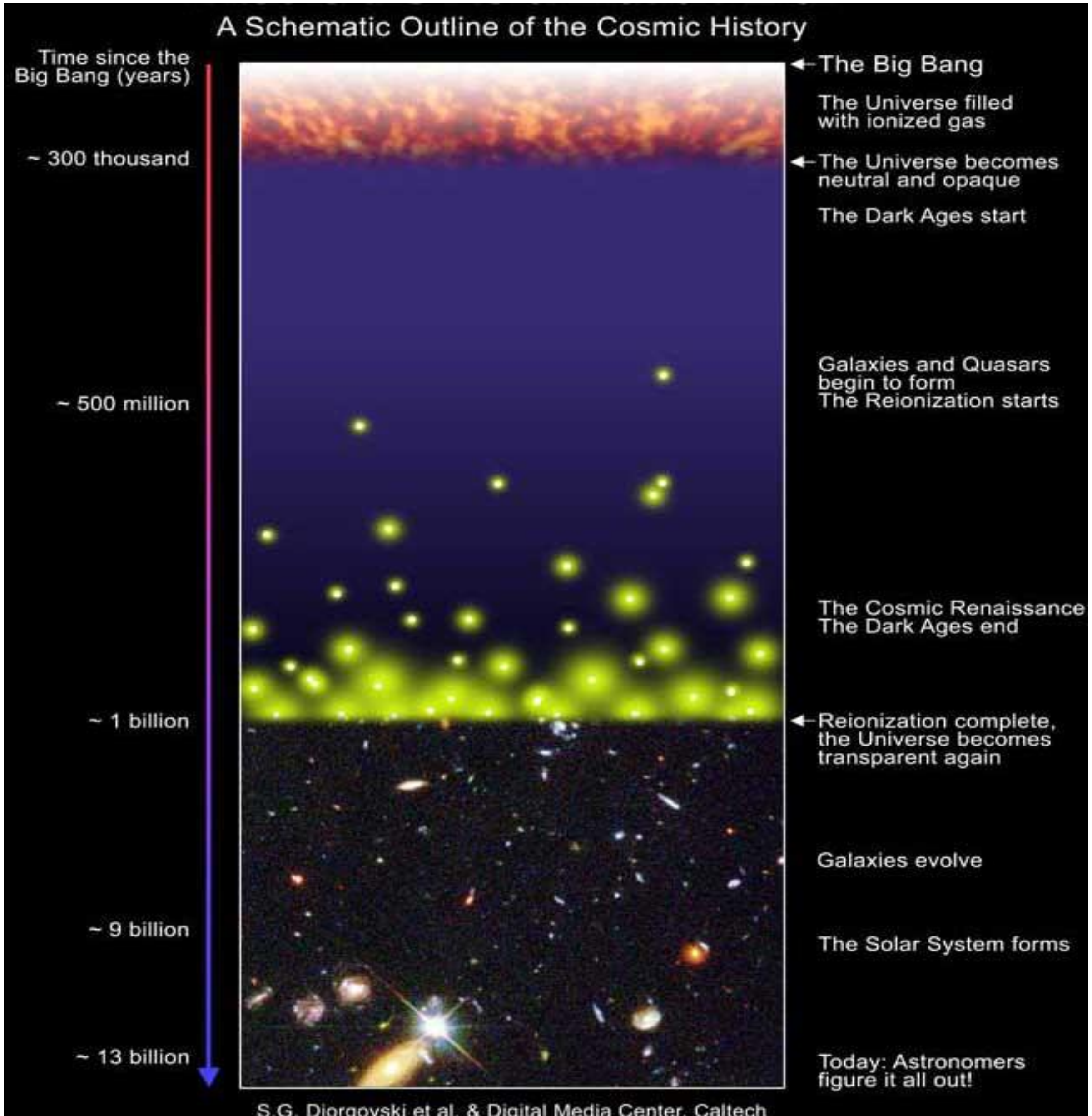
- These first stars had $T_{surface}$ ~ 100,000 K

Cosmic Renaissance

- These stars shone **ultraviolet hot**
- Even if only 1 part in 100,000 of all the baryons formed early stars, the UV from these would have re-ionized the whole Universe: bubbles of ionized gas growing and merging to fill space

- **But did they? Did the 1st stars or the 1st galaxies make the Universe transparent?**

End Of The Dark Ages



Galaxy & SMBH Growth I

There is currently no true consensus

- Pure accretion? This is really problematic:
  - Inflow is limited by outflow of radiation arising from energy released by inflow
  - If the radiation pushes with an efficiency of 10%, and we start with a 100 solar mass object, it will take <u>at least</u> 0.5 billion years to make a billion solar mass SMBH
  - But such SMBHs must have been in place when the Universe was only 0.8 billion years old, because we see luminous active galaxies back then
  - Accretion at levels way above that expected???

SMBH = Supermassive Black Hole

Fragmentation

- Which sounds more plausible?
  - A. Denser gas radiates more energy, gets colder, and thus has less pressure, so gets even denser, radiates more, etc…
  - B. Less dense gas radiates more energy, gets colder and thus has less pressure, so gets even less dense, radiates less, etc…
  - C. Gas density can’t influence how much energy a gas radiates; end of story

Galaxy & SMBH Growth II

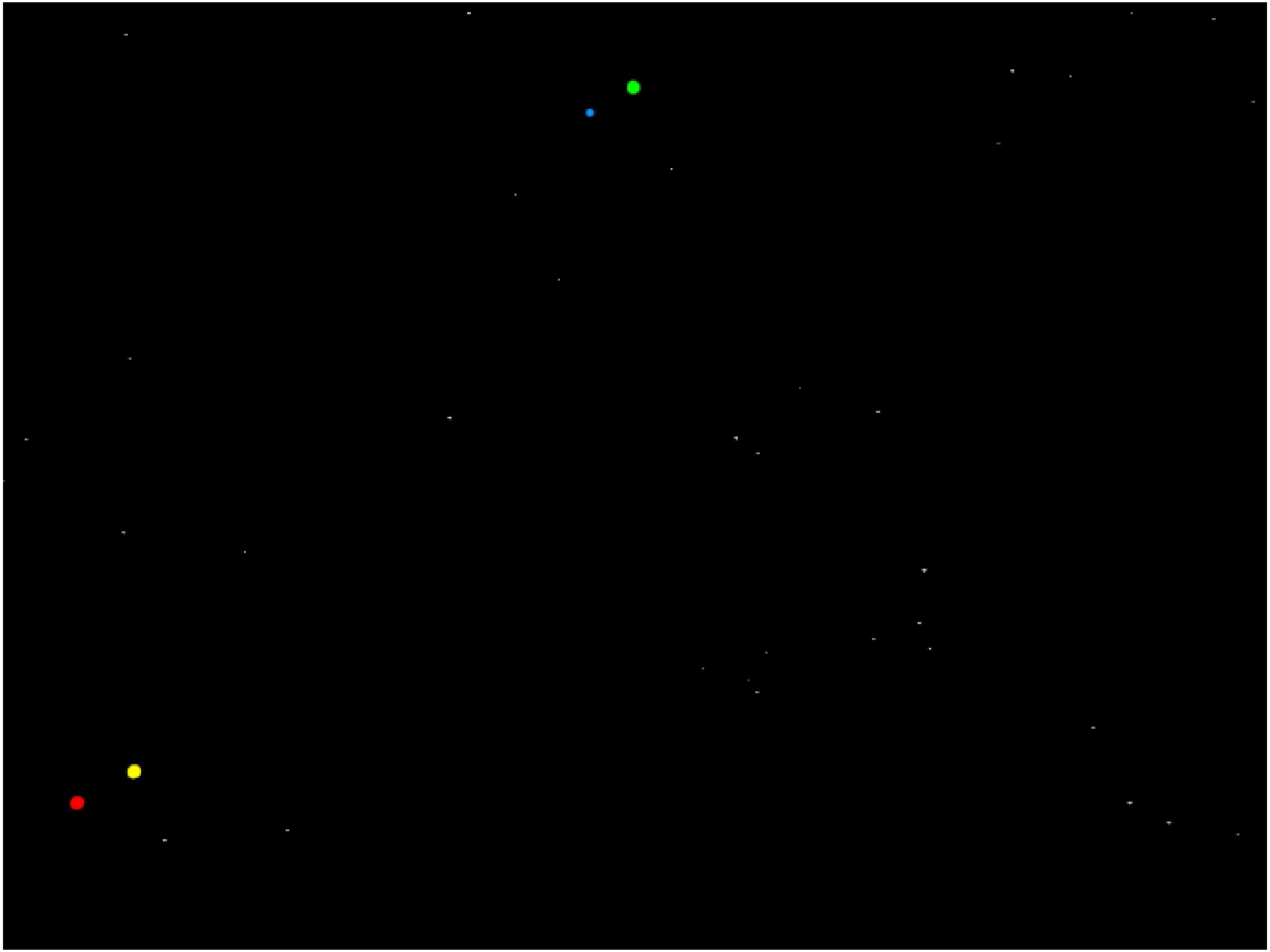
- Monolithic collapse of 10,000-million solar mass gas cloud to a SMBH – followed by accretion? This is also a bit problematic:
  - Efficient cooling of gas tends to lead to fragmentation of gas clouds – multiple small objects, as with star clusters today
  - But early in Universe, cooling would have been inefficient
    - no heavy elements due to prior generations of stars
    - not even H_2 – destroyed by UV from 1^{st} stars, etc.
  - **Might** have prevented fragmentation, allowing single, big objects to form, but the argument is not water-tight

Interactions

- Stars are tiny compared with the distance between them
- So, can stars in a cluster interact with each other?
  - A. No, if the stars are in a cluster their gravitational pulls have cancelled out
  - B. Yes, through their gravitational attractions
  - C. No, they all orbit the cluster center
  - D. Yes, clusters are old, so there will always be chance interactions

Interactions contd.

- A single star just “sits there”
- Two stars can only orbit their center of mass
- Three or more stars can interact gravitationally , with one or more ejected (the cluster of stars is “evaporating”), leaving the others more tightly bound (stars in the cluster are “merging”)
- Evaporation or Merging? Only the details on a case by case basis tells us which process wins

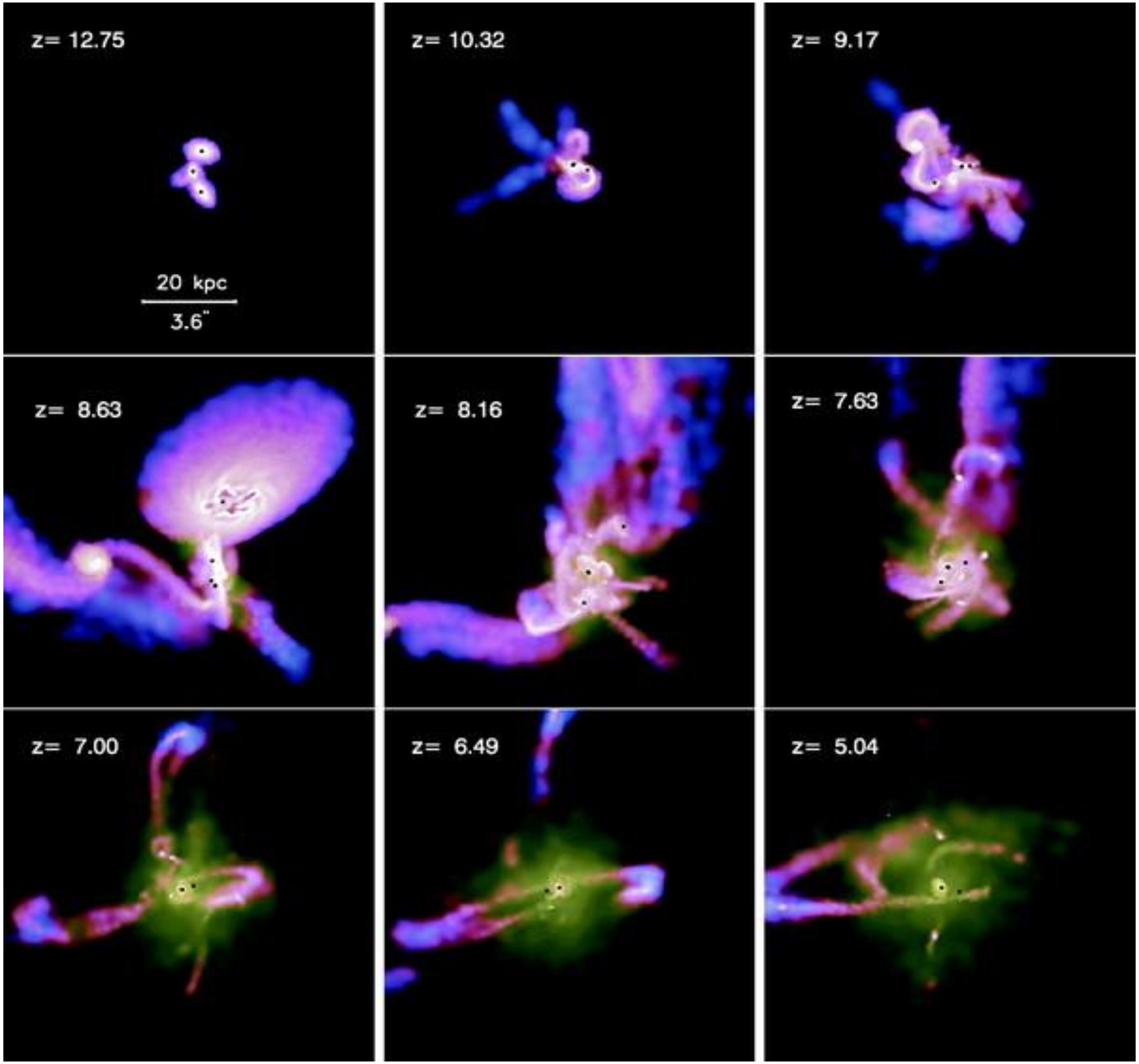


Galaxy & SMBH Growth III

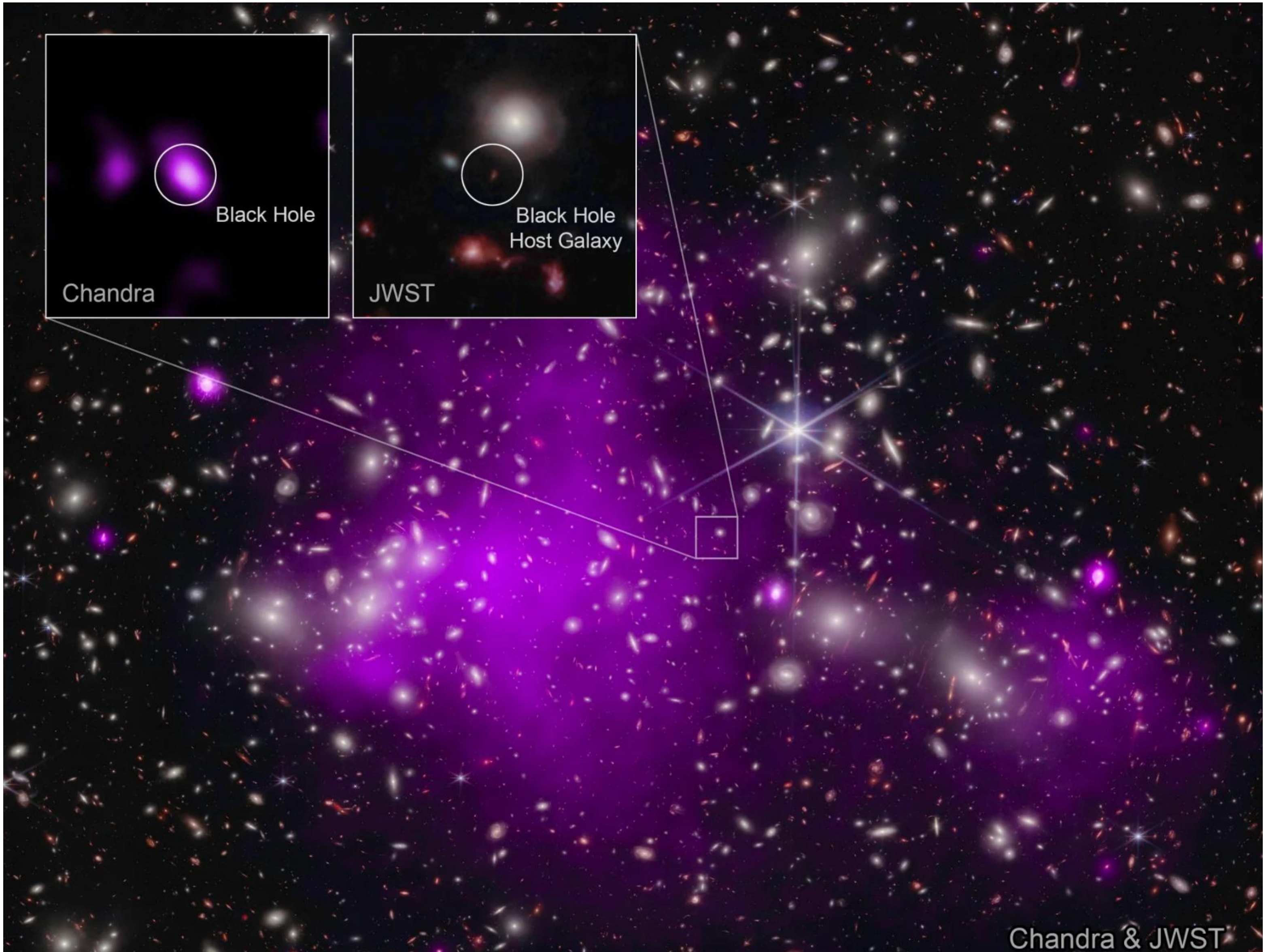
- Merger of dense star cluster – maybe with 100,000 solar masses of stars/remnants within a region a few light years in diameter? Possible, but there are great uncertainties, and it might not lead to very massive BHs
- Cluster could collapse in a few million years – good
- But maybe produce a BH of only a few 1000-10,000 solar masses – not enough

Galaxy & SMBH Growth IV

- **Mergers followed by accretion, <u>with the remnants of the 1st massive stars as seeds</u>?**
- This looks more promising
- In the same way that we think the `cosmic web' arises in a bottom up scenario – small stuff first, building to bigger structures – it's suggested that protogalaxies with one or a few BHs from the 1st stars merge hierarchically
- Once a sufficiently massive BH exists, accretion can `finish the job'


z= 12.75
20 kpc
3.6"
z= 10.32
z= 9.17
z= 8.63
z= 8.16
z= 7.63
z= 7.00
z= 6.49
z= 5.04

UHZ1 – Black Hole



UHZ1 – Supermassive Black Hole

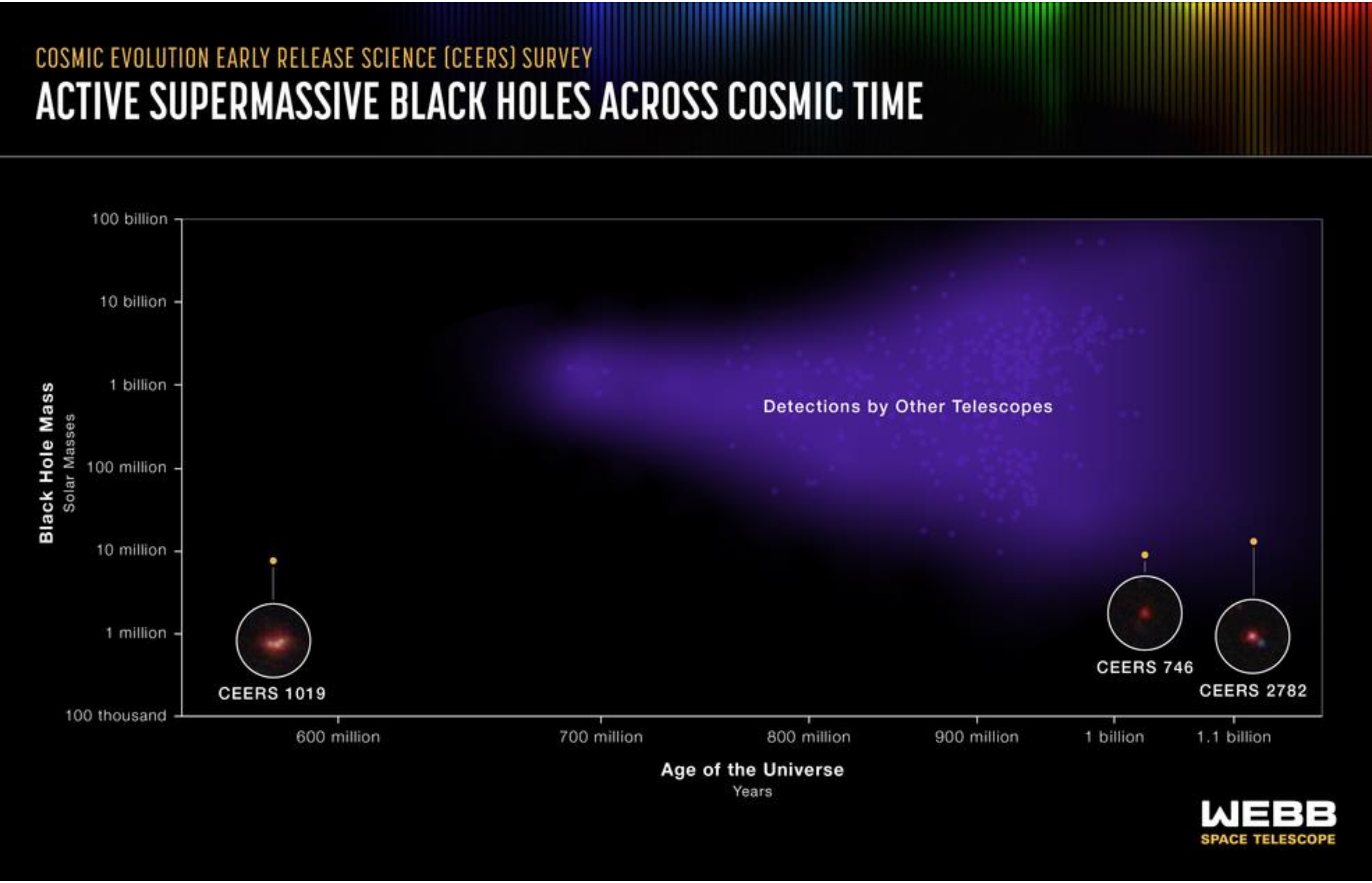
- Two is better than one! Black hole lies behind Abell 2744 which lenses it: magnified by x4 (see last week)
- JWST + Chandra (X-ray observations)
- Most distant black hole seen in X-rays, 470 million years after Big Bang
- Black hole and host galaxy have similar mass: 10-100 million solar masses (BH mass from intensity of X-rays, galaxy stellar mass from luminosity)
- **Suggests monolithic collapse of gas cloud as origin**

CEERS 1019 – Active SMBH

CEERS Mosaic of 100,000 galaxies

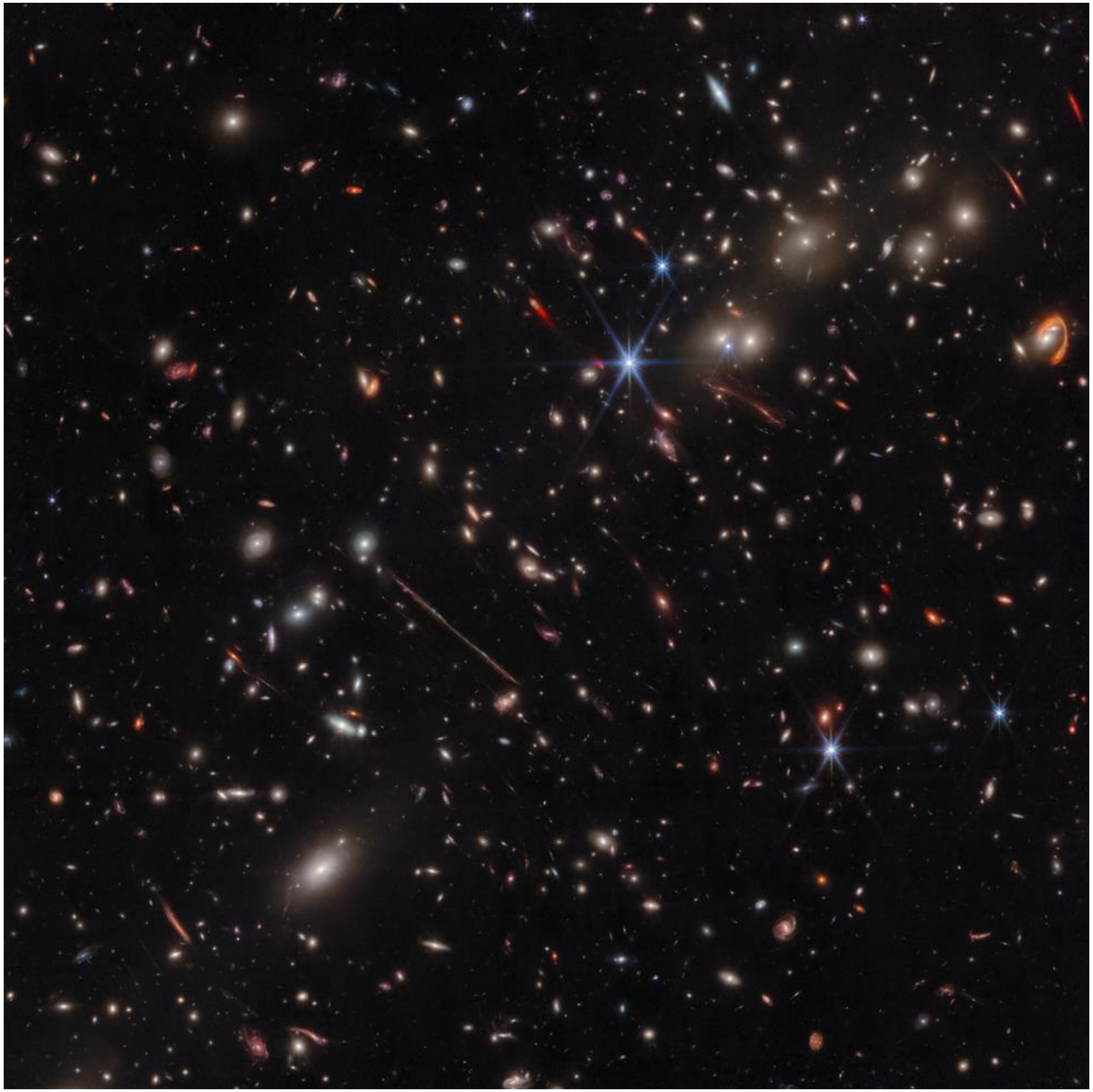
CEERS 1019 – Active SMBH

- Most distant (from 570 million years after the Big Bang), least massive active SMBH
- Cosmic Evolution Early Release Science Survey using NIRCam, MIRI, NIRSpec
- Mass is 9 million solar masses (cf. Sgr A*, M87, etc.)
- Spectra are the key: so many well measured lines that the accretion rate and galaxy star formation rate can be determined
- **Accretion important? Continues to challenge SMBH+galaxy growth models**



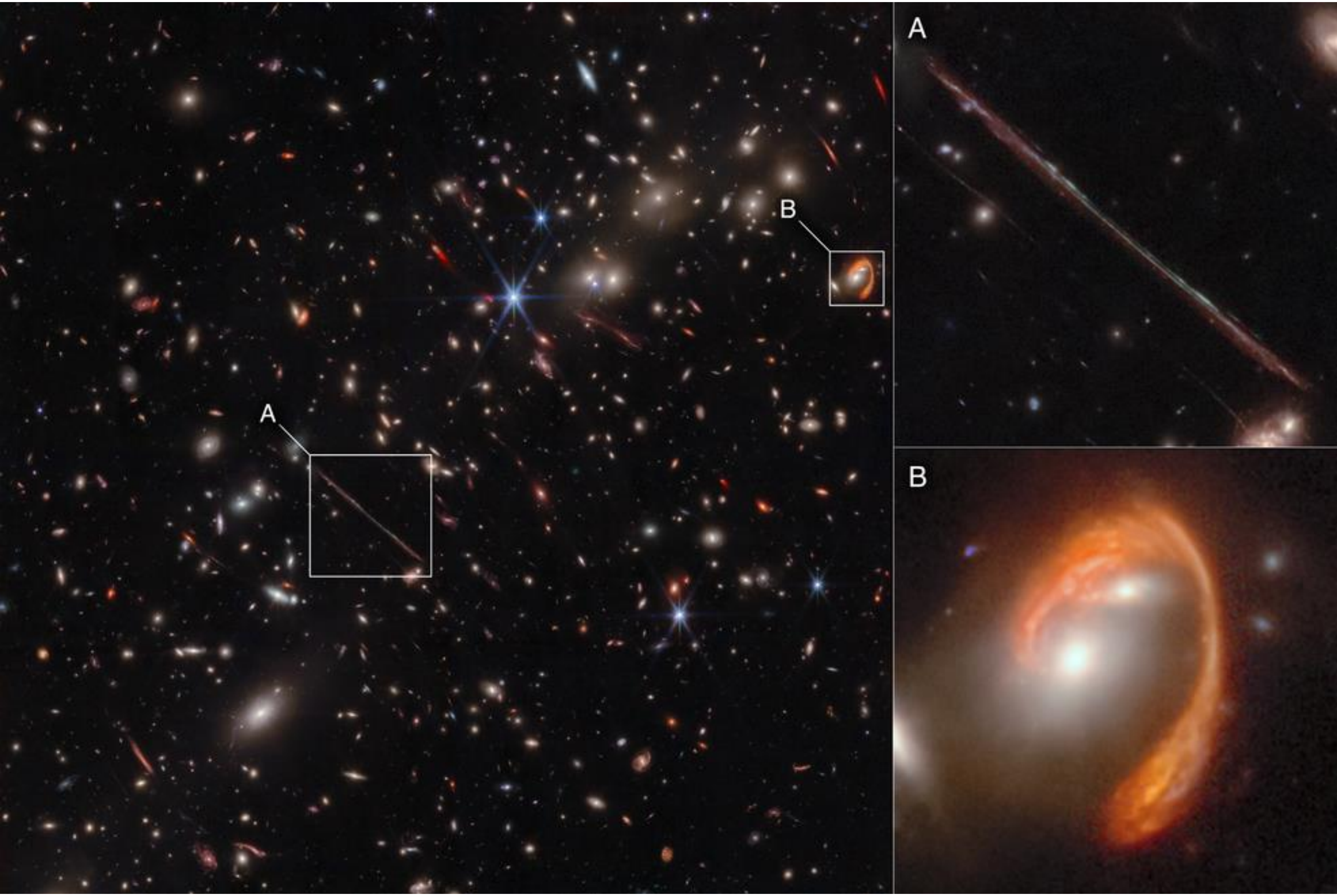
COSMIC EVOLUTION EARLY RELEASE SCIENCE (CEERS) SURVEY
ACTIVE SUPERMASSIVE BLACK HOLES ACROSS COSMIC TIME
Black Hole Mass
Solar Masses
100 billion
10 billion
1 billion
100 million
10 million
1 million
100 thousand
Detections by Other Telescopes
CEERS 1019
CEERS 746
CEERS 2782
600 million
700 million
800 million
900 million
1 billion
1.1 billion
Age of the Universe
Years
WEBB
SPACE TELESCOPE

El Gordo Cluster



El Gordo Cluster

- Most massive cluster known as far back as when the Universe was about 6 billion years old
- Magnifies many more distant objects
- A. *La Flaca* – The Thin One
- B. *El Anzuelo* – The Fish Hook
  - Red because of dust & cosmological redshift (light has taken 10.6 billion years to reach us)
  - Correction for distortion reveals a disk about ¼ size of Milky Way
  - Quenching of star formation evident near galaxy's center
- **Direct probe of the star forming history of a galaxy**

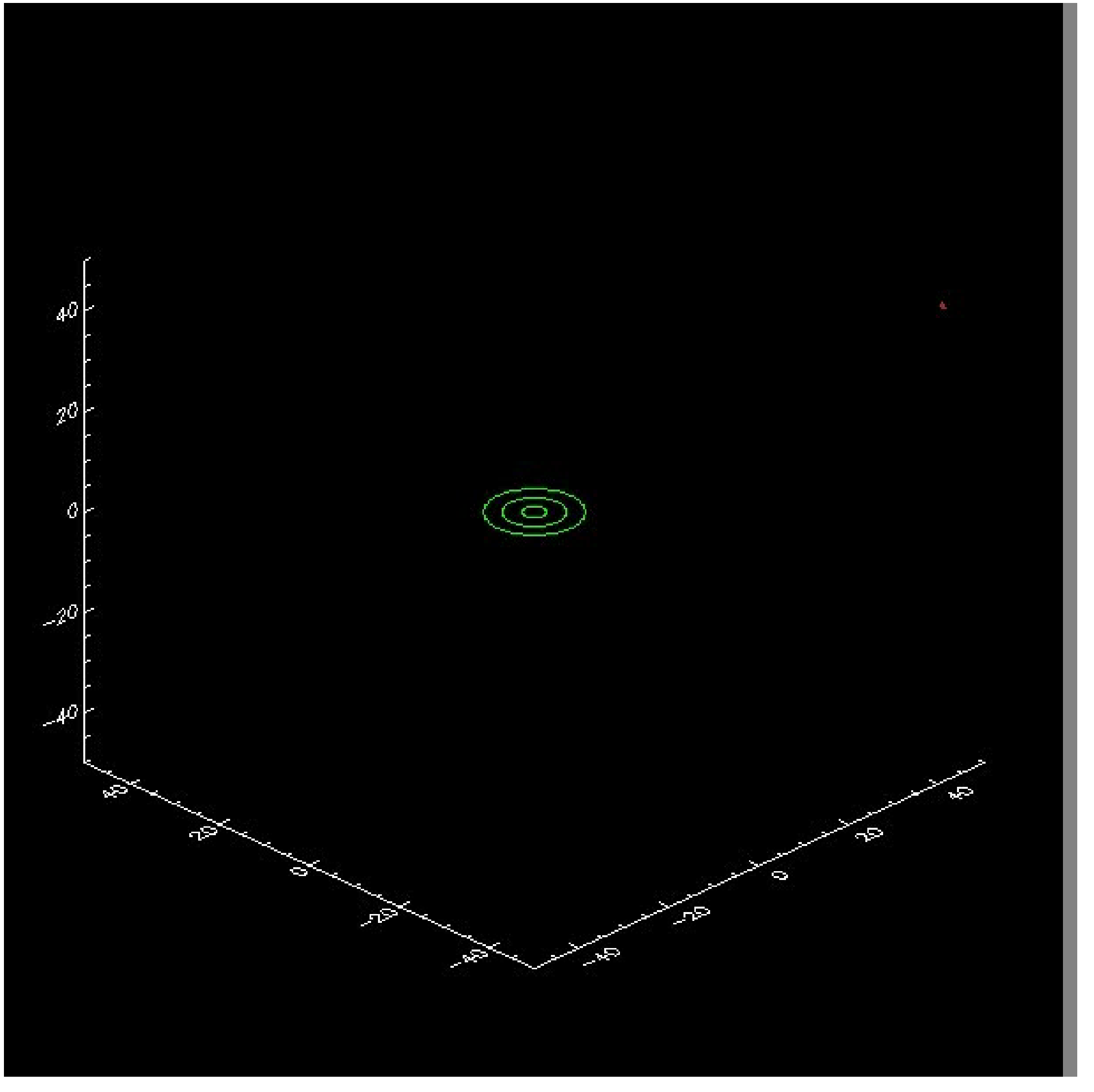

A
B
A
B

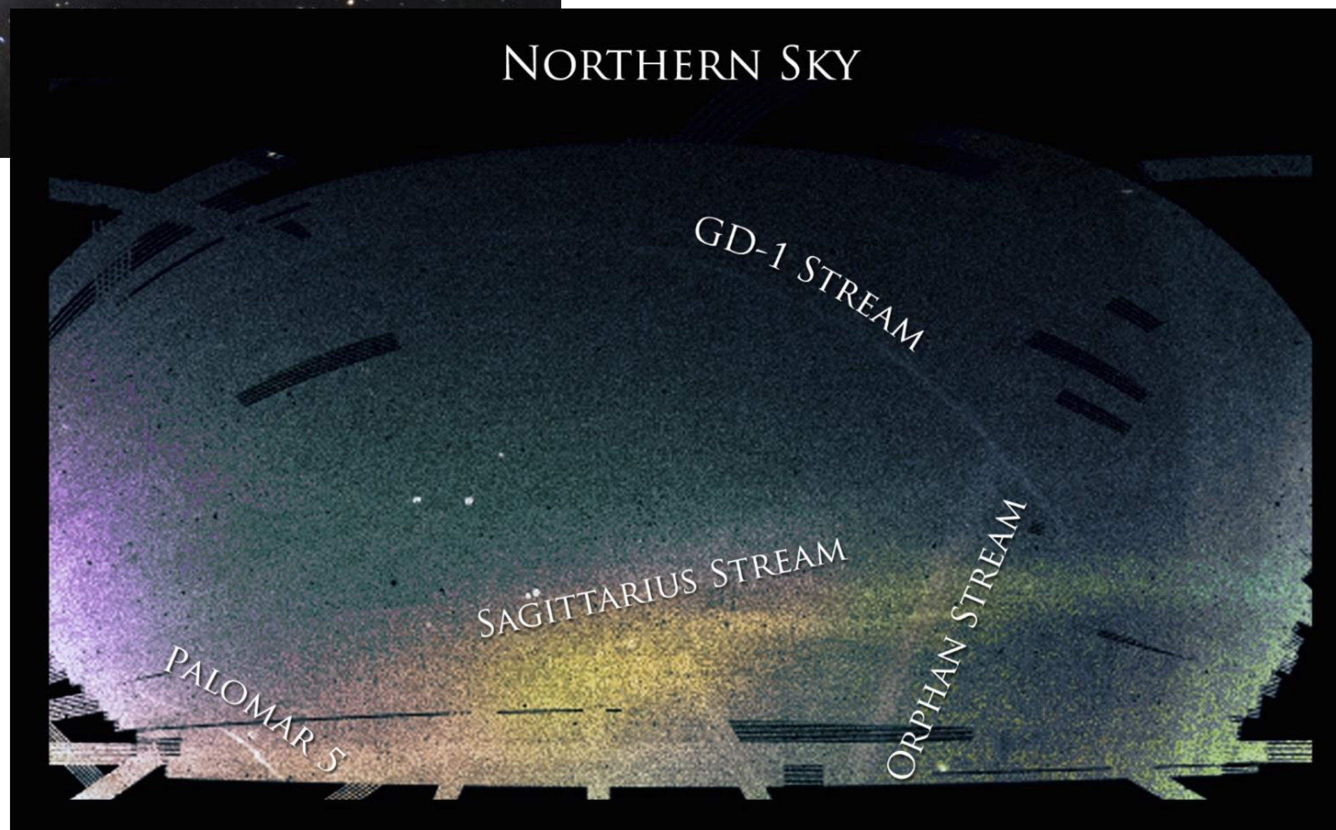
James Webb & Cosmic Web

James Webb & Cosmic Web

- NIRCam image of a thread-like arrangement of 10 galaxies (white circles; quasar in central galaxy of triple)
- 3 million light year long structure
- 830 million years after Big Bang
- Can be expected to have evolved into a rich cluster
- **Strong support for picture of a cosmic web that forms by gravitational collapse, galaxies forming along sheets and filaments by about 1 billion years after Big Bang**

Footnote: Evolution Continues!



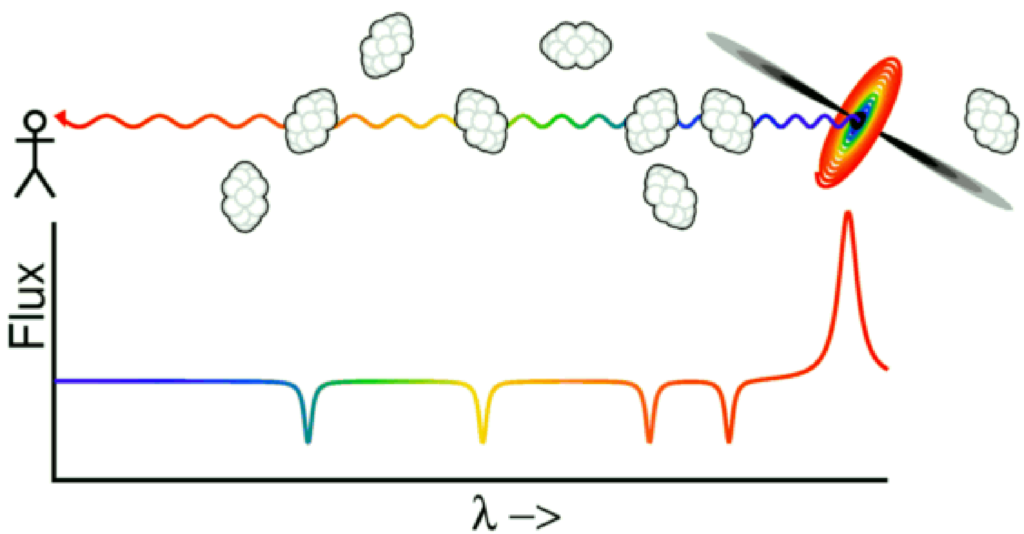


Northern Sky
GD-1 Stream
Sagittarius Stream
Orphan Stream
Palomar 5

End Of The Dark Ages

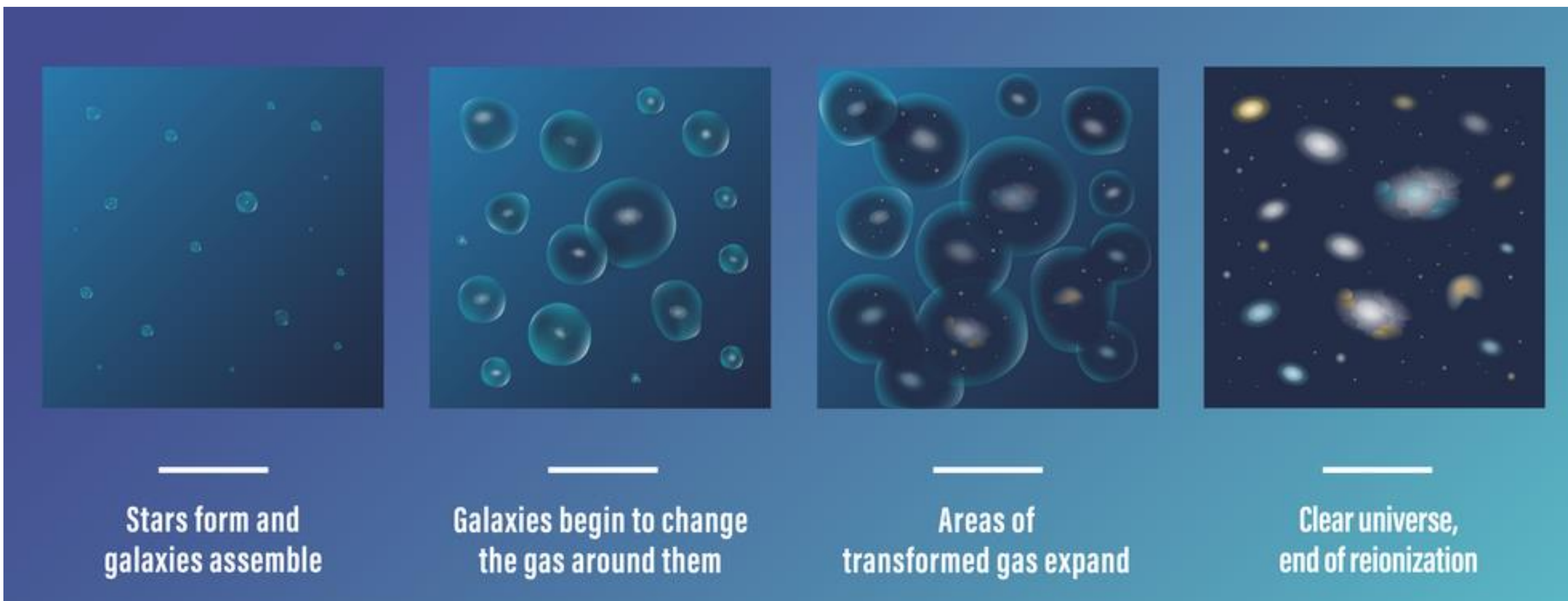
End Of The Dark Ages

- JWST, Keck & VLT observations: Emission-line galaxies and Intergalactic Gas in the Epoch of Reionization
- Galaxies are surrounded by transparent regions 2 million light years in radius
- Probed using a distant quasar as a backlight



End Of The Dark Ages

- JWST, Keck & VLT observations: Emission-line galaxies and Intergalactic Gas in the Epoch of Reionization
- **Was it the 1st stars or 1st galaxies that reionized the Universe? Starlight from the 1st galaxies!**

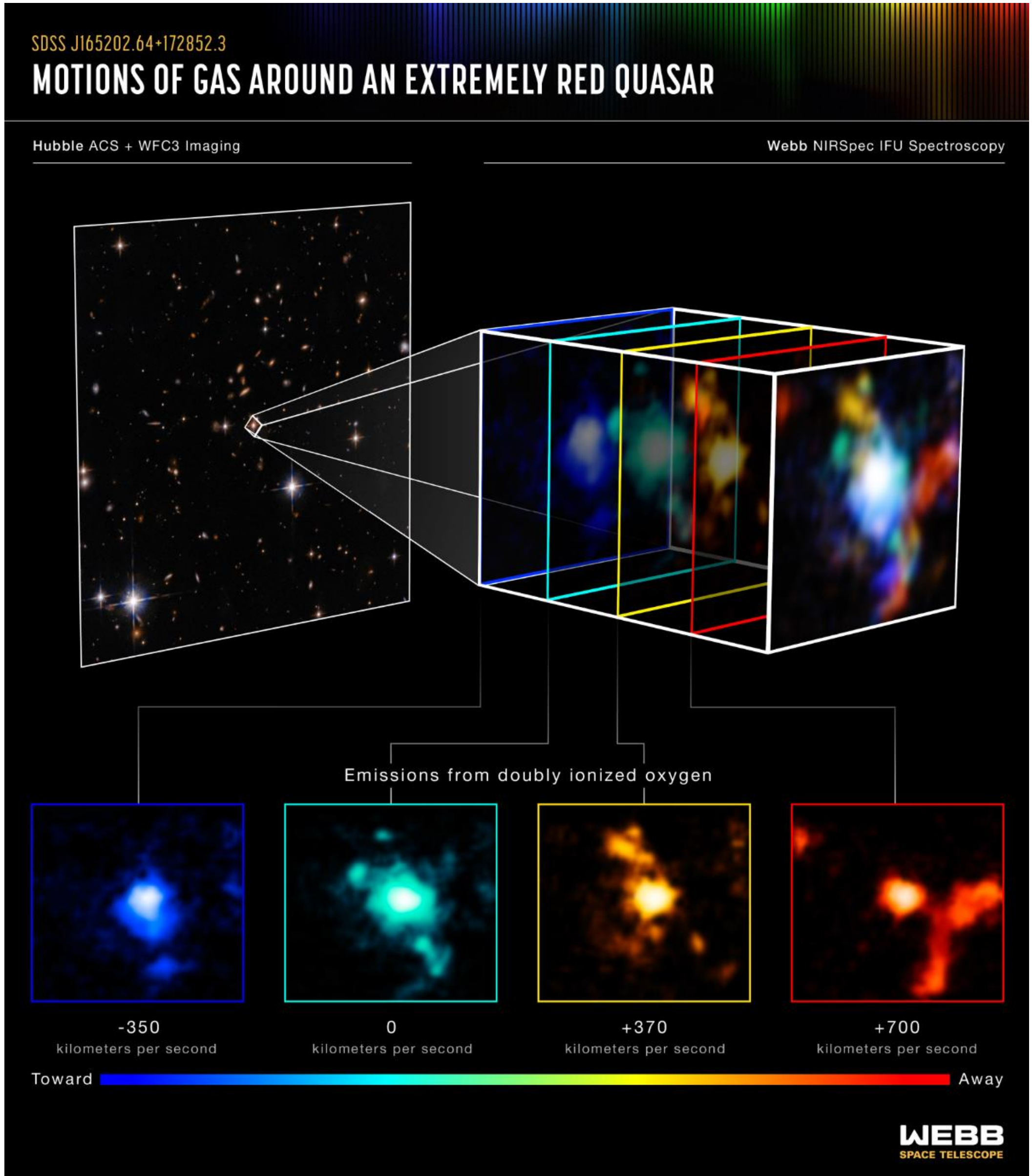


Pandora’s Cluster

Pandora’s Cluster

- NIRCam image of 3 massive clusters merging to form a megacluster
- Creates unusually powerful gravitational lens
- Note: over 50,000 sources in this field
- Had been observed by HST, but only the core of the cluster had been studied
- **JWST provides unprecedented breadth and depth, and is thus a powerful tool for cosmological studies**

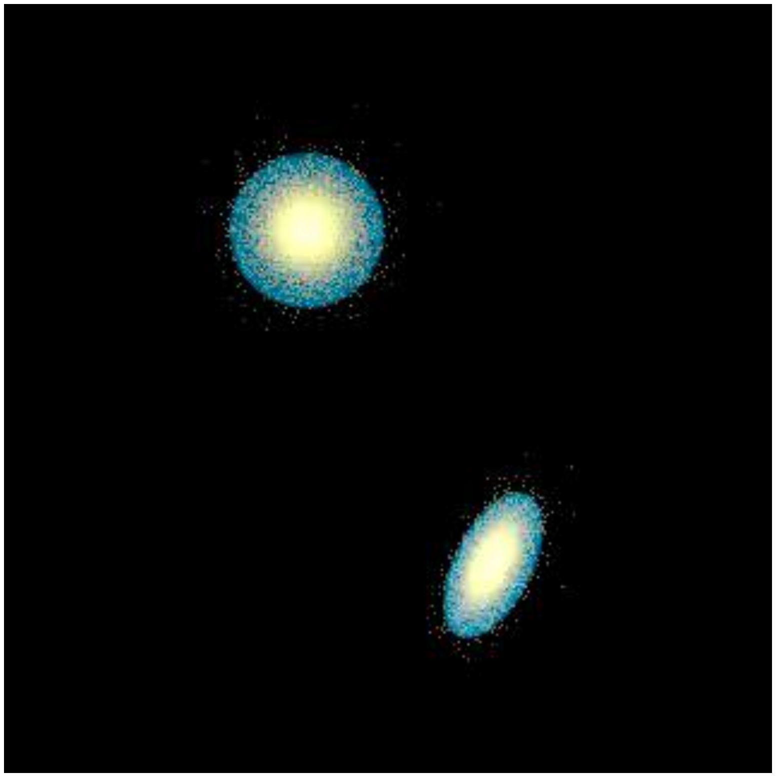
A Cosmic Knot

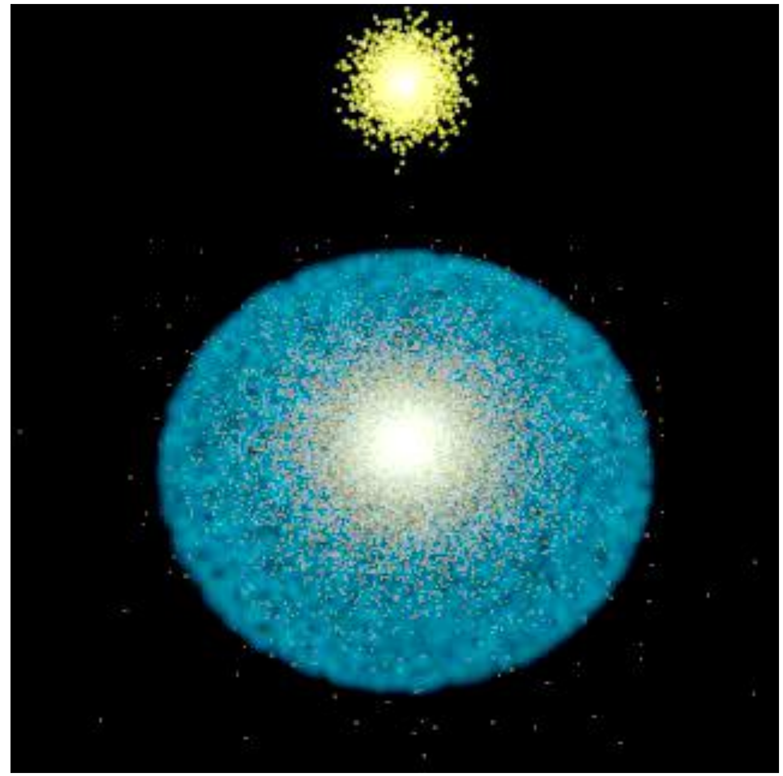


A Cosmic Knot

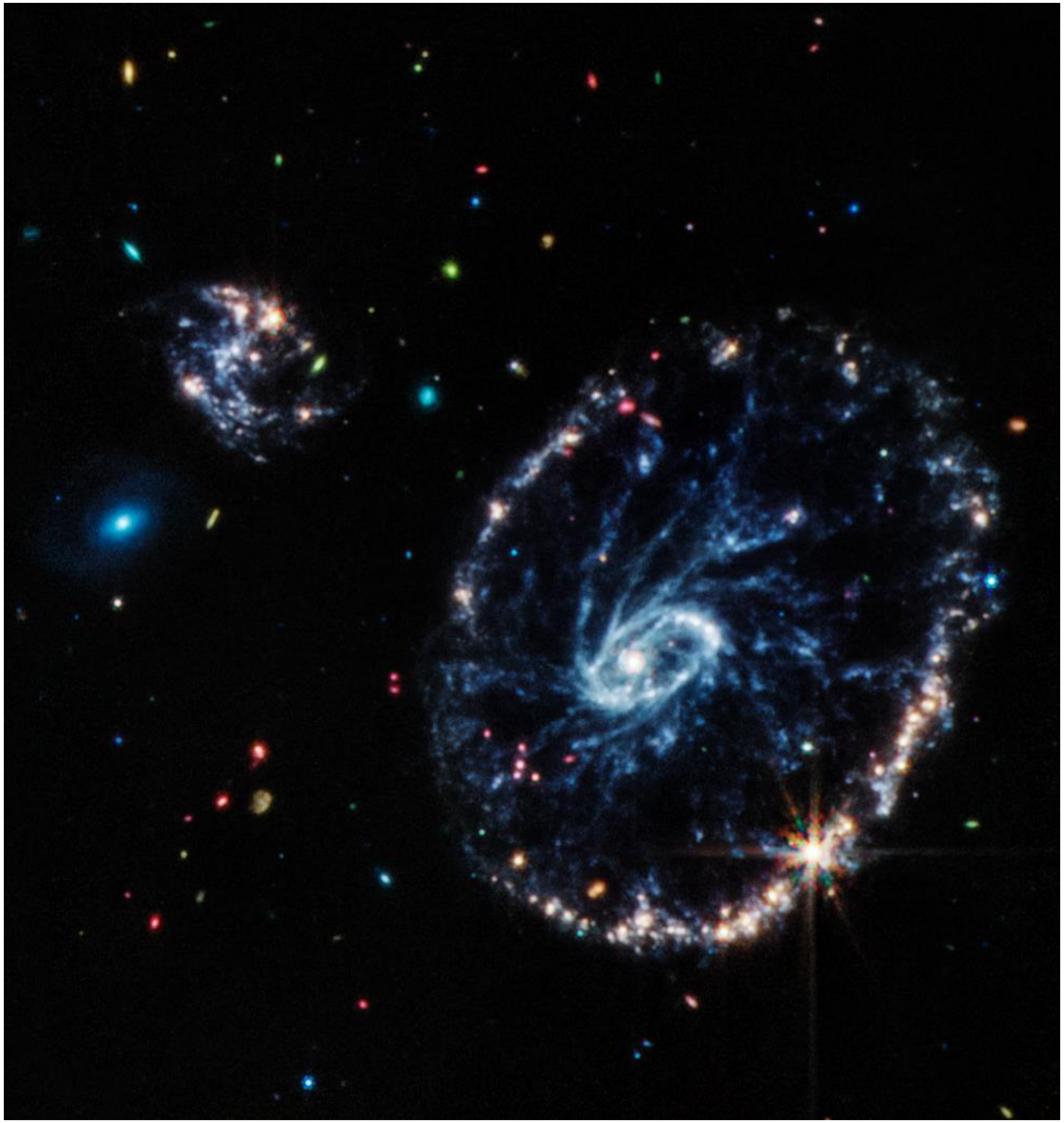
- NIRSpec + HST observations of a quasar (active galactic nucleus)
- Seen about 2 billion years after Big Bang
- Seems to be a dense knot of galaxy formation as 3 (or more) protogalaxies swirl around the quasar, maybe merging to form a final massive galaxy
- **Observed speeds of almost 1000 km/s are challenging to explain, as they require masses implying an incredible density of material**

Background: Galaxy Interactions





The Cartwheel Galaxy



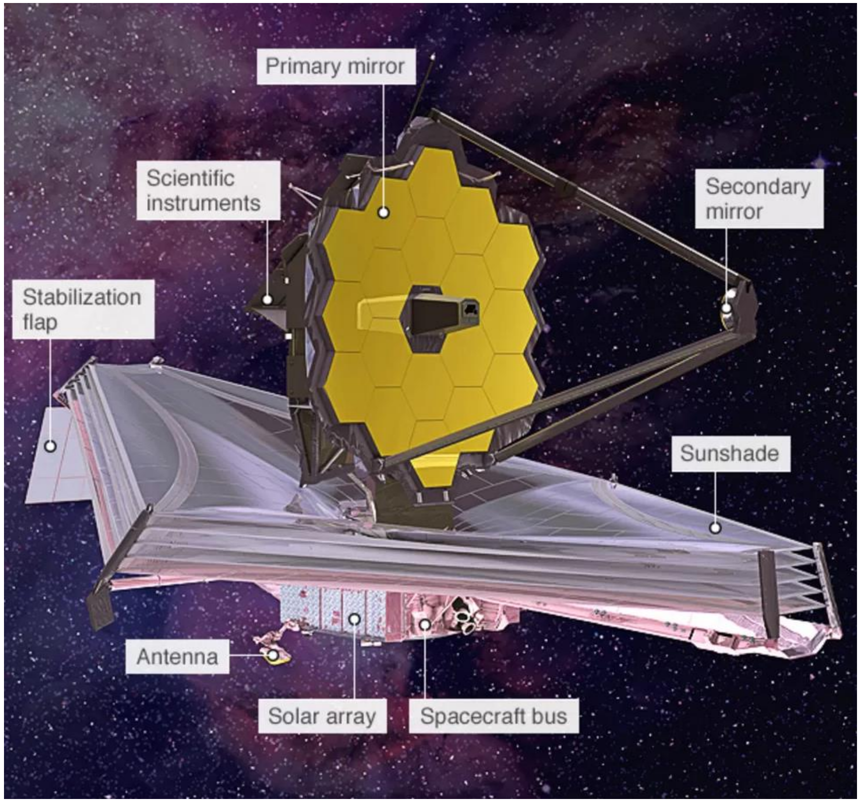
The Cartwheel Galaxy

The Cartwheel Galaxy

- 1st image: MIRI image of Cartwheel galaxy, and 2 small companions, at a distance of 500 million light years
- 2nd image: NIRCam & MIRI combined, helps reveal detail
- Inner ring has large amounts of hot dust, with gigantic young star clusters embedded
- Outer ring, which has expanded for over 400 million years, is dominated by star formation and supernovae
- **JWST explores a period of galactic evolution with amazing detail on structure, dynamics, stellar populations and dust/gas composition**

The James Webb Space Telescope

- We have just scratched to surface of JWST work
- Check out:
  - Your favorite (trusted) news sources
  - Astronomy Magazine (www.astronomy.com)
  - Sky & Telescope (skyandtelescope.org)
  - Space.com (www.space.com)



- **Thanks for coming!**