Galaxies: Structure, formation and evolution

Lecture 11

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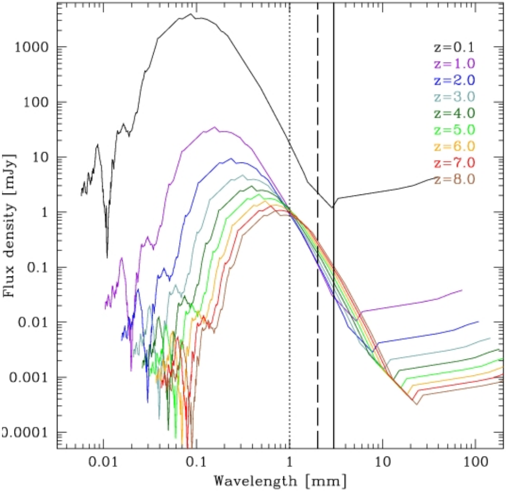
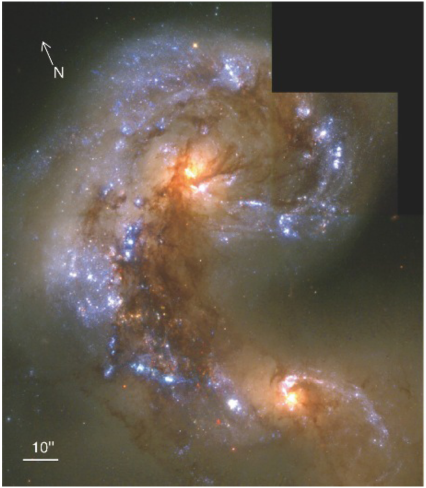
Starburst galaxies

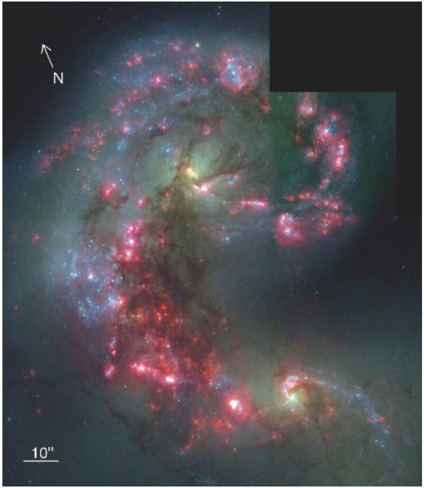
Milky Way is forming stars with a rate of $\sim 3M_{\odot}$/yr, the star formation rate in starburst galaxies can be larger by a factor of more than a hundred. Dust heated by hot stars radiates in the FIR, rendering starbursts very strong FIR emitters. Many of them were discovered by the IRAS satellite (IRAS galaxies”); they are also called ULIRGs (ultra-luminous infrared galaxies). Negative k-correction

Negative K correction- Arp 220



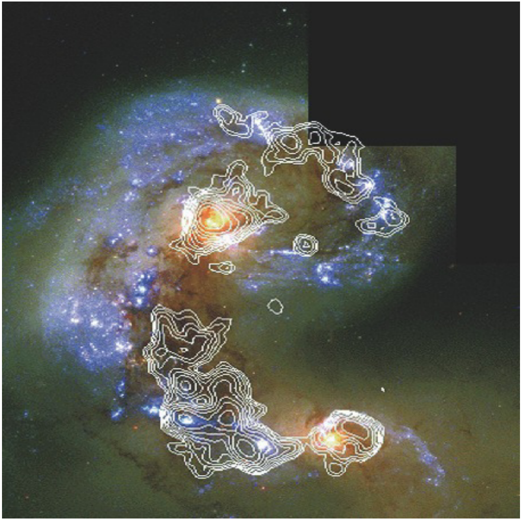
The Antennae- each knot $10^5 M_\odot$





Red and blue supergiants also seen.

The Antennae - IR emission



Extremely red objects - $R - K > 5$

Consist of almost equal numbers of

1. elliptical galaxies that already have, at $z \sim 1$, a luminosity similar to that of today's ellipticals, and are at that epoch already dominated by an old stellar population
2. Galaxies with active star formation which do not show a 4000Å break but which feature the emission line of [OII] at $\lambda = 3727$Å, a clear sign of star formation. These are red because they are heavily dust obscured. Radio-FIR observations show that these are ULIRGS.

Photometric redshifts - by product of stellar population synthesis

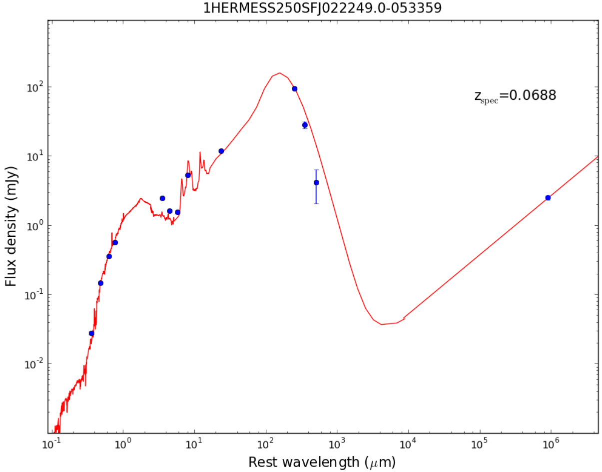
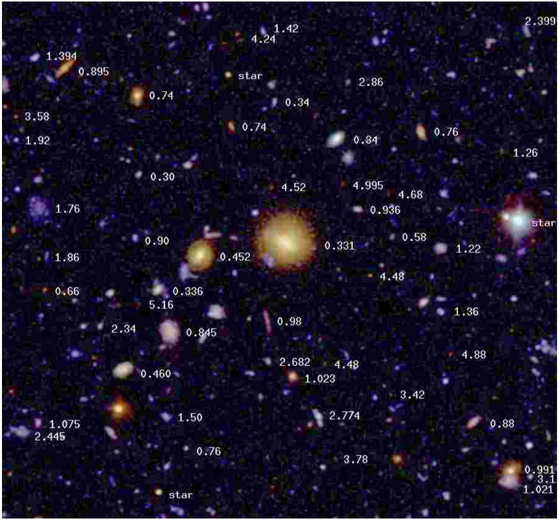
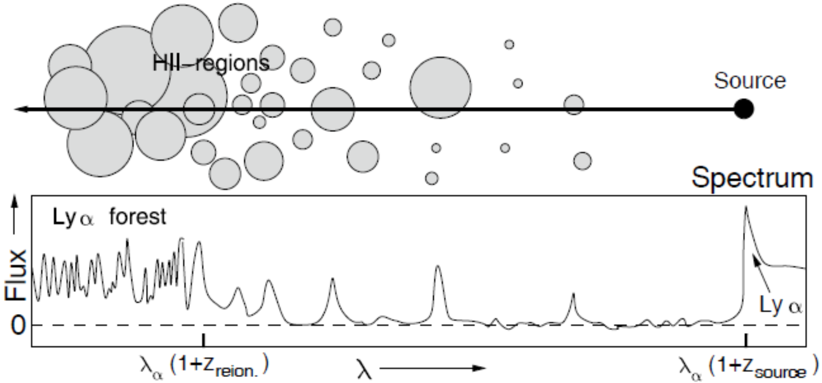


Photo z for thousands of objects



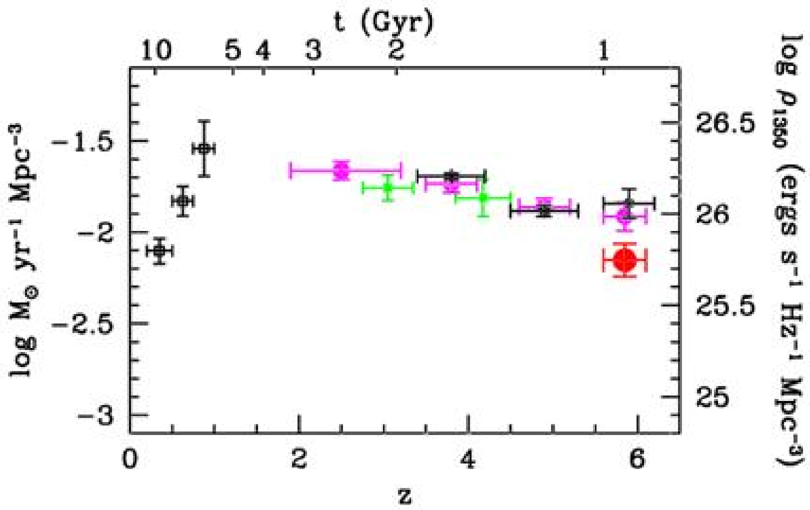
Reionisation spectrum



SFR over cosmic time

The density of star formation, $\rho_{\rm SFR}$, is defined as the mass of newly formed stars per year per unit (comoving) volume, typically measured in $M_\odot \mathrm{yr}^{-1}$ Mpc^{-3}. Therefore, $\rho_{\rm SFR}$ as a function of redshift specifies how many stars have formed at any time.
For details on how cosmic star formation rate evolved with redshift see ARAA article by Madau & Dickinson (2014).

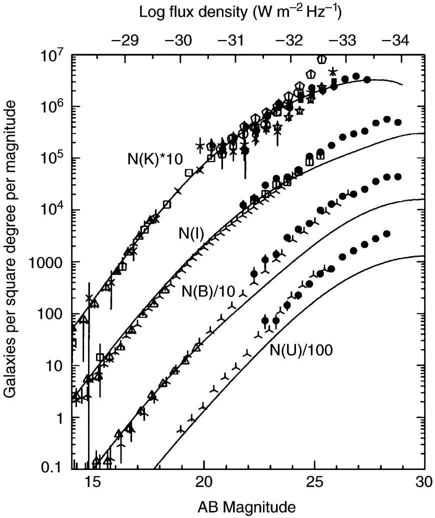
Lilly-Madau diagram



Hierarchical galaxy formation

(i) encounters and mergers of galaxies play a central role in their evolution, and in fact galaxies are formed by the mergers of smaller galaxies (ii) even apparently isolated galaxies are surrounded by much larger dark halos whose outermost tendrils are linked to the halos of neighboring galaxies and (iii) gas, stars, and dark matter are being accreted onto galaxies continuously up to the present time.

HDF number counts - evidence of evolution



Luminosity evolution versus density evolution

Luminosity evolution measured in terms of luminosity per comoving unit volume. Density evolution in terms of number of galaxies per comoving unit volume. Extremely difficult to disentangle at high redshift due to selection biases.
But luminosity functions can be compared at two redshifts to see which of these is dominant.

Topics not covered in the high redshift universe

- Lyman alpha absorber, damped DLAs and Lyman limit systems
- backgrounds: CMB (most important for cosmologists), CIB, CXB

Cosmic X-ray background

- the “soft” background(below 0.3 keV) caused by galactic X-ray emission, the “galactic” X-ray background. It is produced largely by emission from hot gas in the Local Bubble within 100 parsecs of the Sun.
- the “hard” background (above 0.3keV), from a combination of many unresolved X-ray sources outside of the Milky Way, the “cosmic” X-ray background. Deep surveys with the Chandra X-ray Observatory, have demonstrated that around 80% of the cosmic X-ray background is due to resolved extra-galactic X-ray sources, the bulk of which are unobscured and obscured AGN.

Cosmic infra-red background

diffuse radiation mainly caused by dust emission.

High supernova rates in starburst galaxies

Measuring star formation - IR

Emission in the far infrared (FIR). This is radiation emitted by warm dust which is heated by hot young stars. For the relation of FIR luminosity to the SFR, observation yields the approximate relation

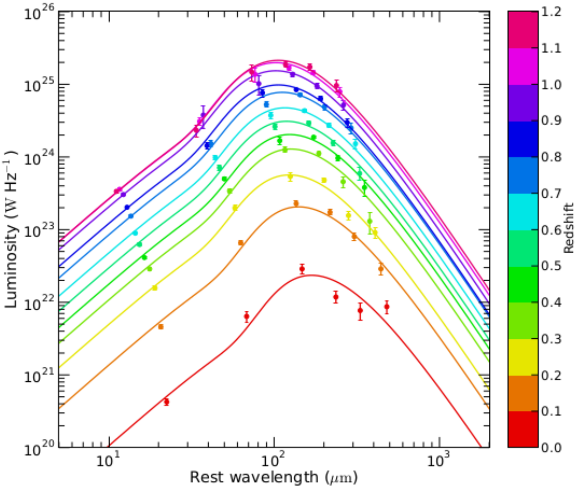
$$\frac{\mathrm{SFR}_{\mathrm{FIR}}}{M_\odot/\mathrm{yr}} \sim \frac{L_{\mathrm{FIR}}}{5.8 \times 10^9 L_\odot}$$

Measuring the SFR - Radio

A very tight correlation exists between the radio luminosity of galaxies and their luminosity in the FIR, over many orders of magnitude of the corresponding luminosities. Since $L_{\rm FIR}$ is a good indicator of the star-formation rate, this should apply for radiation in the radio as well.

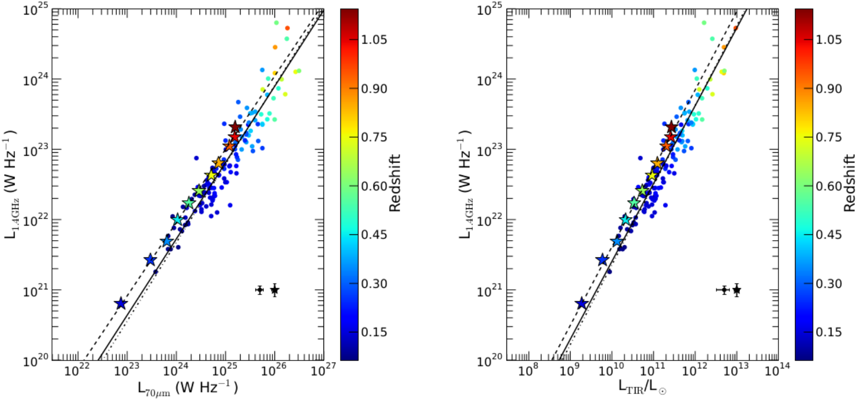
$$\frac{\rm SFR_{1.4GHz}}{M_\odot/\rm yr} \sim \frac{L_{\rm 1.4GHz}}{8.4 \times 10^{27} \rm erg\ s^{-1} Hz^{-1}}$$

FIR SED of stacked sources at different redshifts



Basu, Wadadekar et al. (2015)

The Radio FIR correlation



Basu, Wadadekar et al. (2015)

Measuring the SFR - H_α

This line emission comes mainly from the HII regions that form around young hot stars.

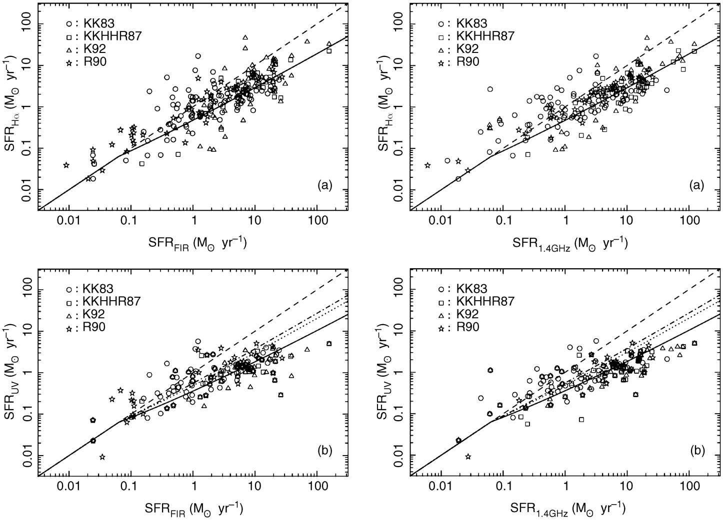
$$\frac{\mathrm{SFR}_{\mathrm{H}\alpha}}{M_\odot/\mathrm{yr}} \sim \frac{L_{\mathrm{H}\alpha}}{1.3 \times 10^{41} \mathrm{erg\ s}^{-1}}$$

Measuring the SFR - UV

This is only emitted by hot young stars, thus indicating the SFR in the most recent past - an *instantaneous* SFR

$$\frac{\mathrm{SFR_{UV}}}{M_\odot/\mathrm{yr}} \sim \frac{L_\mathrm{UV}}{7.2 \times 10^{27} \mathrm{erg\ s^{-1} Hz^{-1}}}$$

SFR estimators compared



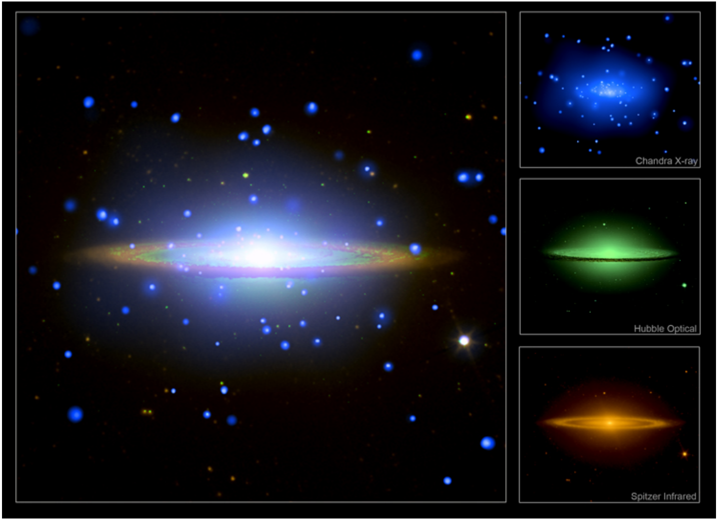
Other star formation indicators

The fine-structure line of singly ionized carbon at $\lambda = 157.7\mu$m is of particular importance as it is one of the brightest emission lines in galaxies, which can account for a fraction of a percent of their total luminosity. The emission is produced in regions which are subject to UV radiation from hot stars, and thus associated with star-formation activity. Due to its wavelength, this line is difficult to observe and has, until recently, been detected only in star-forming regions in our Galaxy and in other local galaxies. **All this has changed with ALMA.**

Measuring SFR from X-ray emission

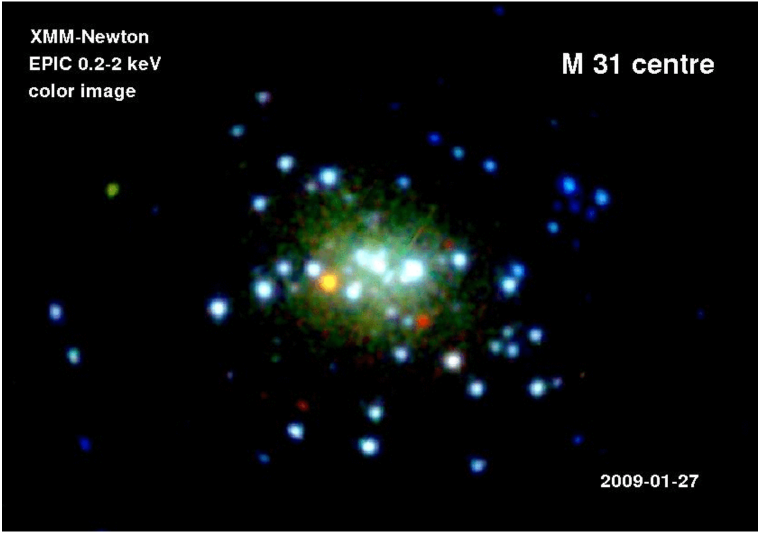
In star-forming galaxies, the X-ray luminosity is produced by high-mass X-ray binaries, massive stars, and supernovae, but non-negligible contributions from low-mass X-ray binaries are also present. The latter are not directly related to recent star formation, and represent a source of uncertainty in the calibration of SFR(X-ray).

ULX in star forming galaxies



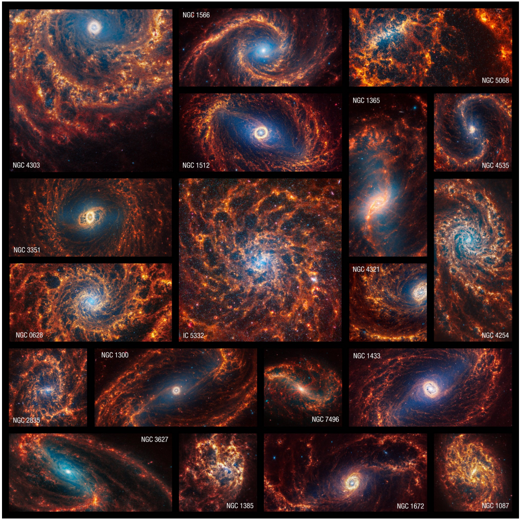
Why resolution is important?

ULX in center of M31

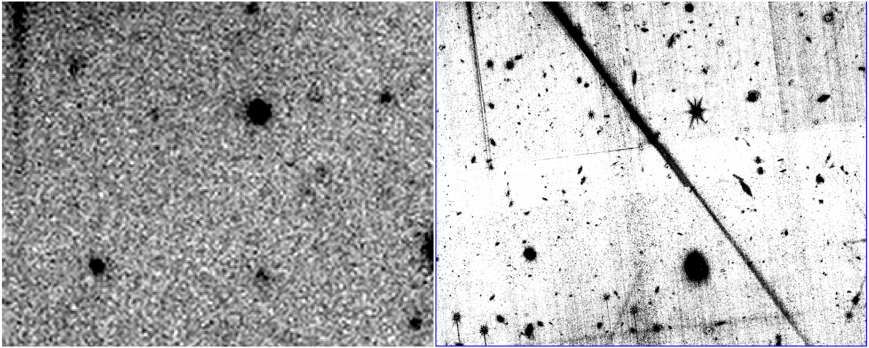


JWST

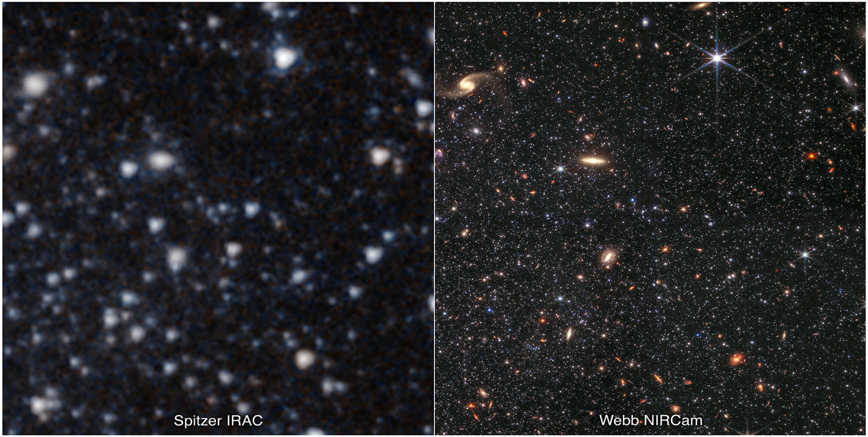
Exquisite details of nearby galaxies- MIRI magic



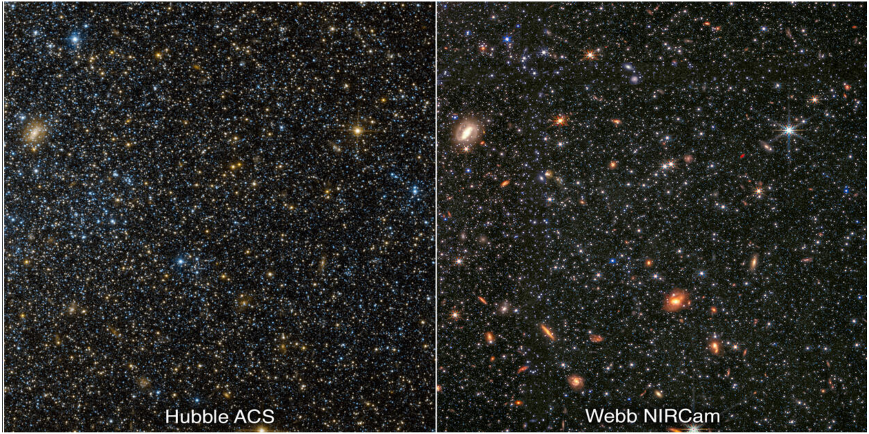
JWST imaging is much deeper than local large area surveys



Spitzer JWST comparison



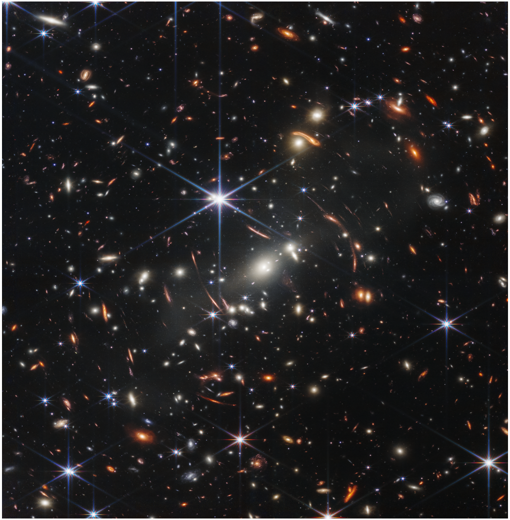
HST JWST comparison - resolution, sensitivity, what else?



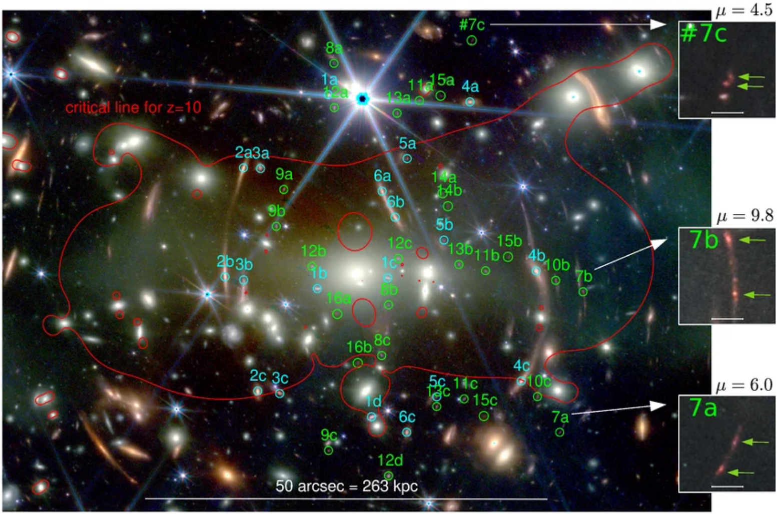
HST dark galaxies

What are the implications of this?

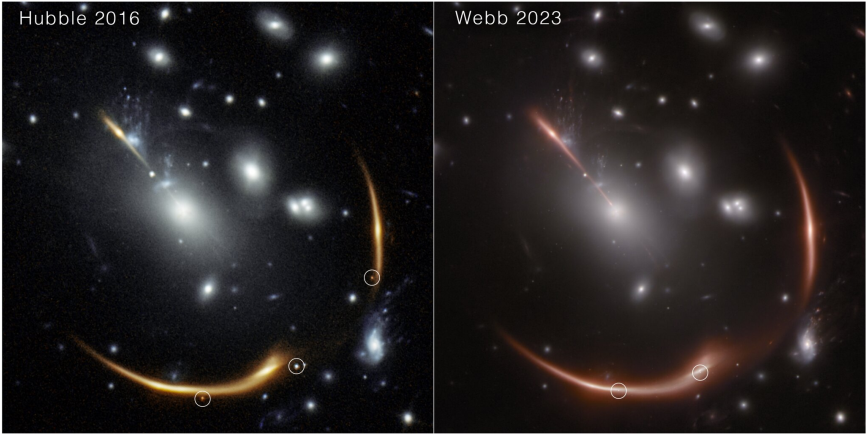
Lensing magnification allows for detection of high z galaxies



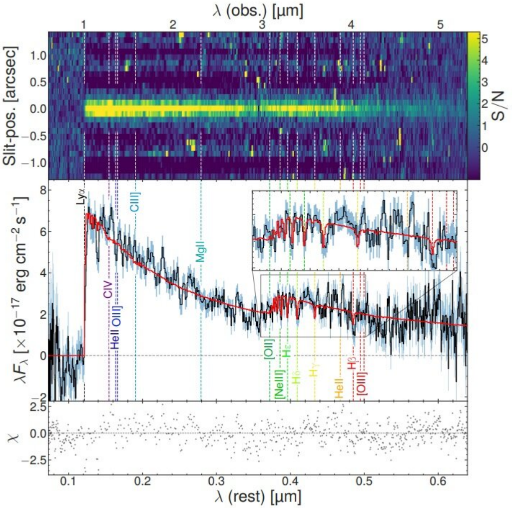
High z lensed galaxies with JWST



One multiply lensed supernova already found by JWST

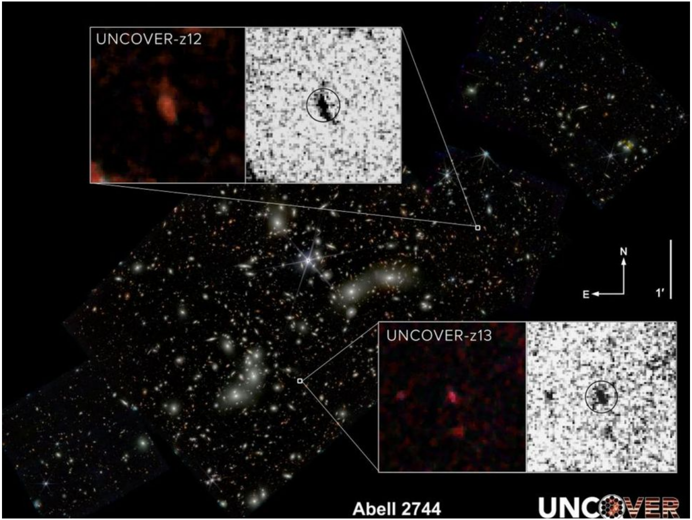


This galaxy is at redshift > 5

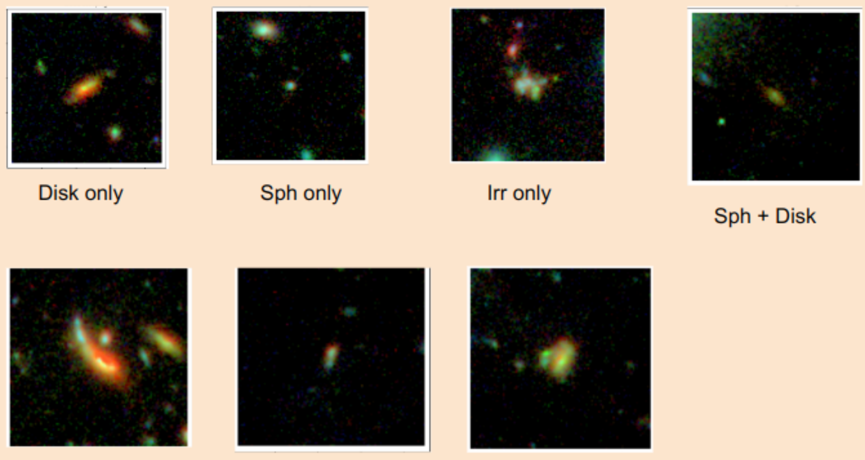


Looser et al. (2023)

Galaxies beyond redshift 10



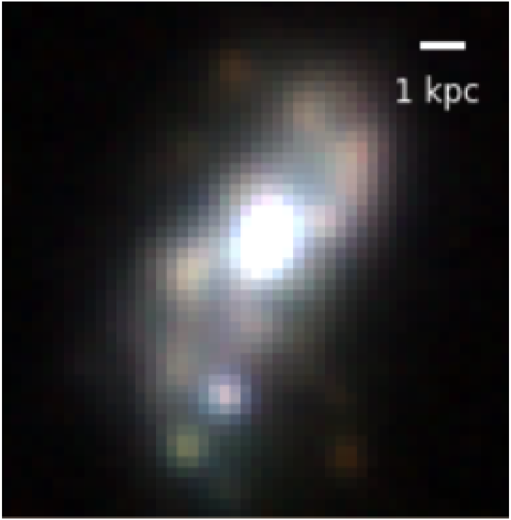
Galaxies with $3 < z < 6$



$\sim$ 50% of galaxies show disk-like morphology

Jain & Wadadekar (2024)

A spiral galaxy at $z \sim 4$, size 10 kpc, $M_* = 10^{10} M_\odot$



Jain & Wadadekar (2024)

Challenges posed by JWST observations to current theories

- too many galaxies at $z > 6$
- too many massive galaxies at $z > 6$
- too many massive,quiescent galaxies at $z > 5$
- too many large, massive disks at $3 < z < 6$
- too many massive spirals at $3 < z < 6$