



UNIVERSITY OF
COPENHAGEN

DAWN

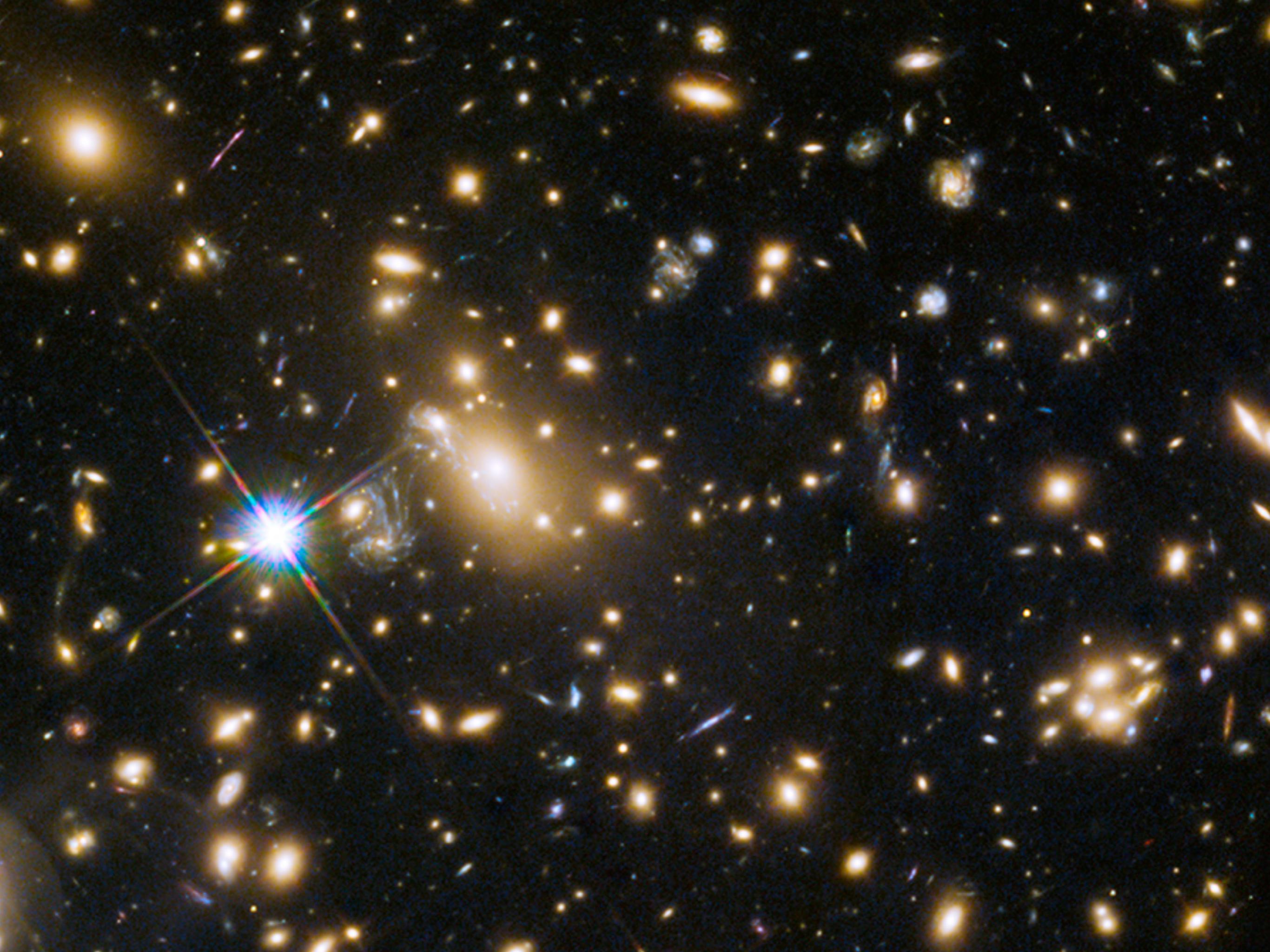


Danmarks
Grundforskningsfond
Danish National
Research Foundation

Applied Statistics: *Detection and characterization of the most distant galaxies*

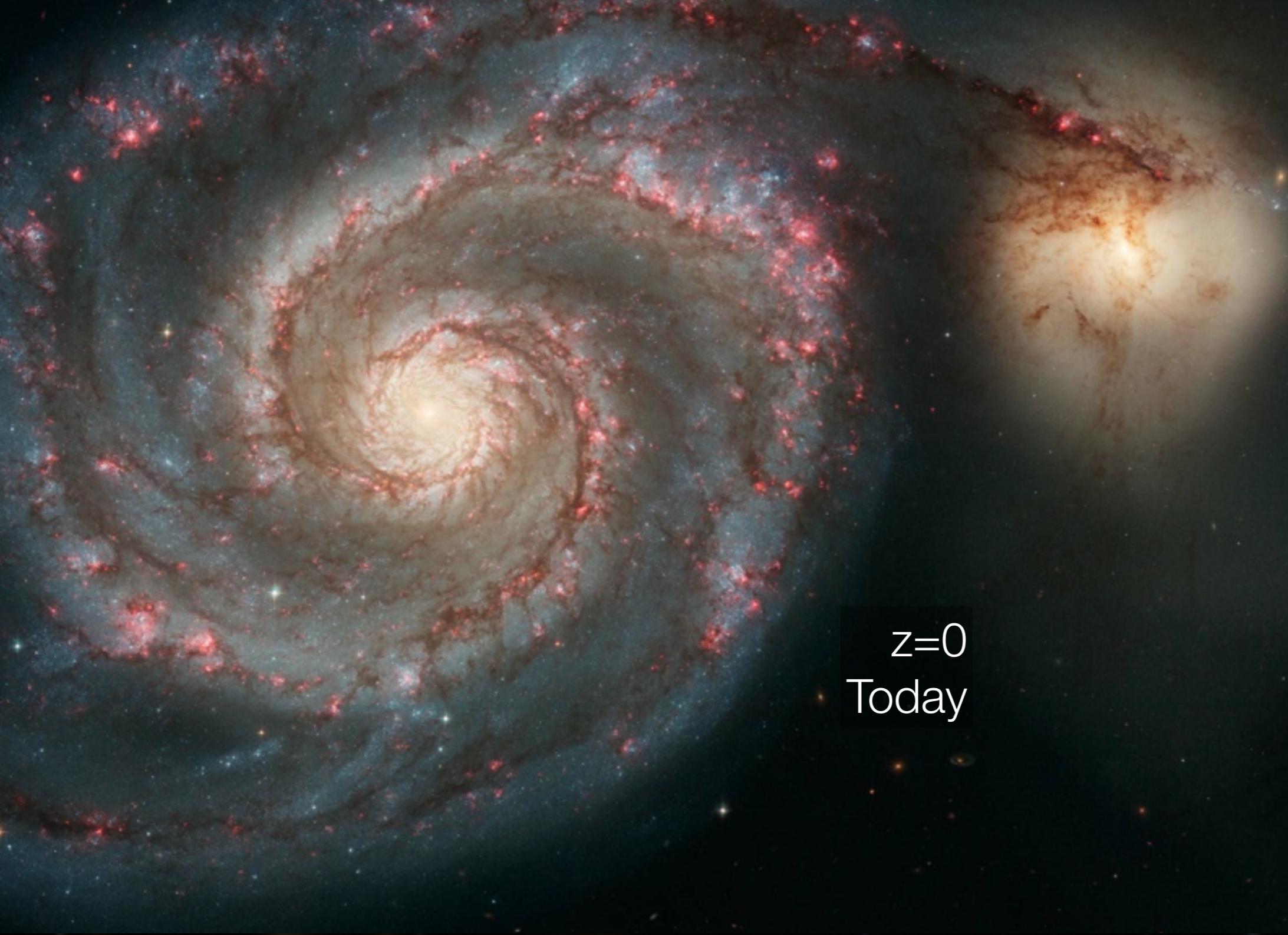
Gabriel Brammer







$z \sim 9.5$
12 Billion years ago

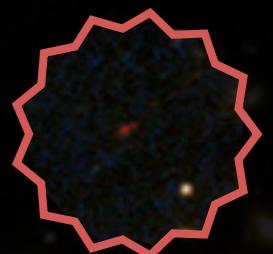


$z=0$
Today

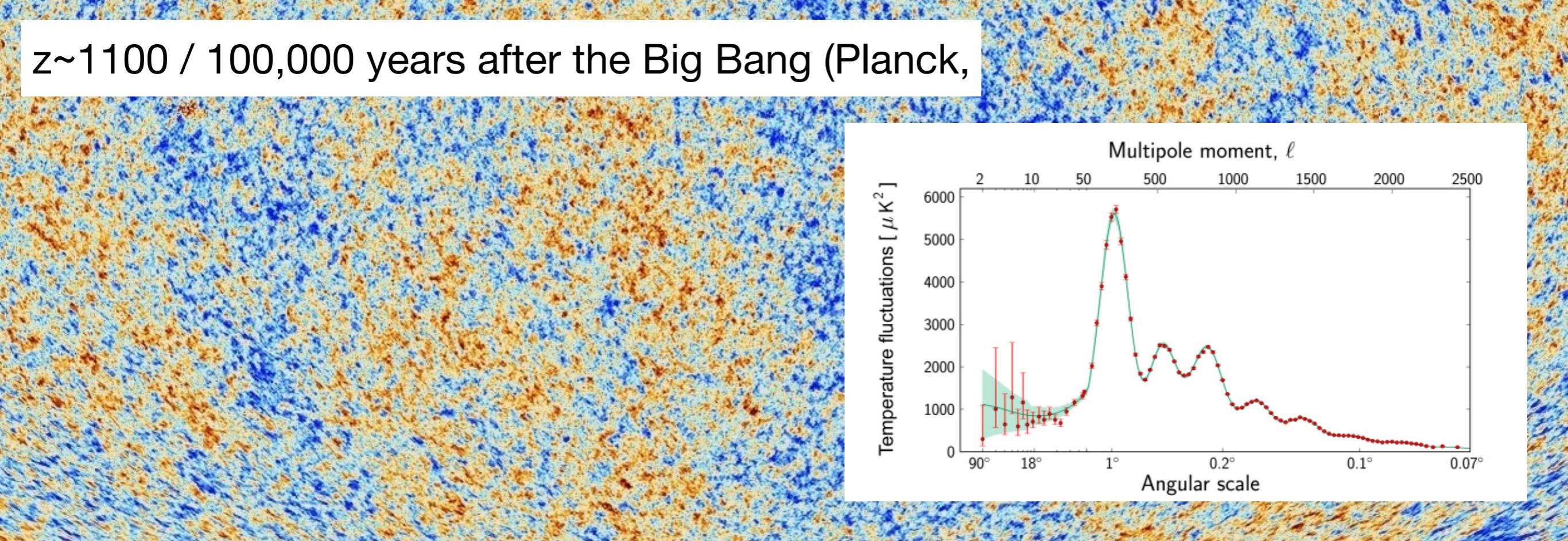


Expanding Universe:
 $"z"$ = "redshift" \approx distance
 \approx time in the past for finite c

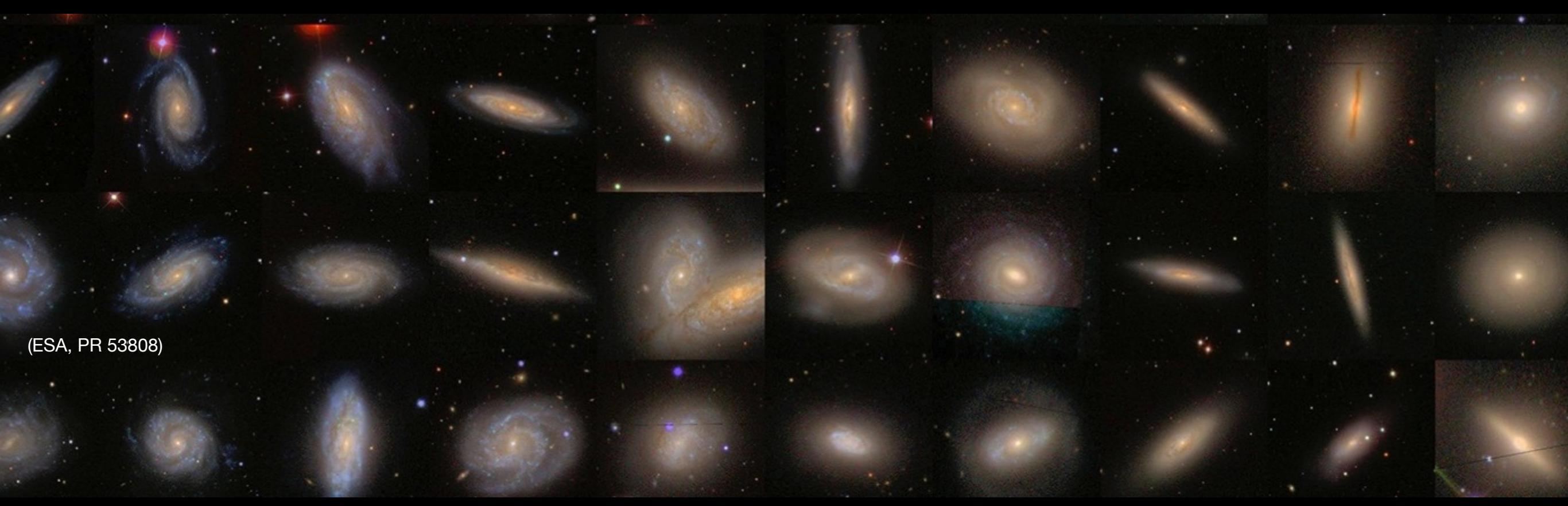
$z \sim 9.5$
12 Billion years ago

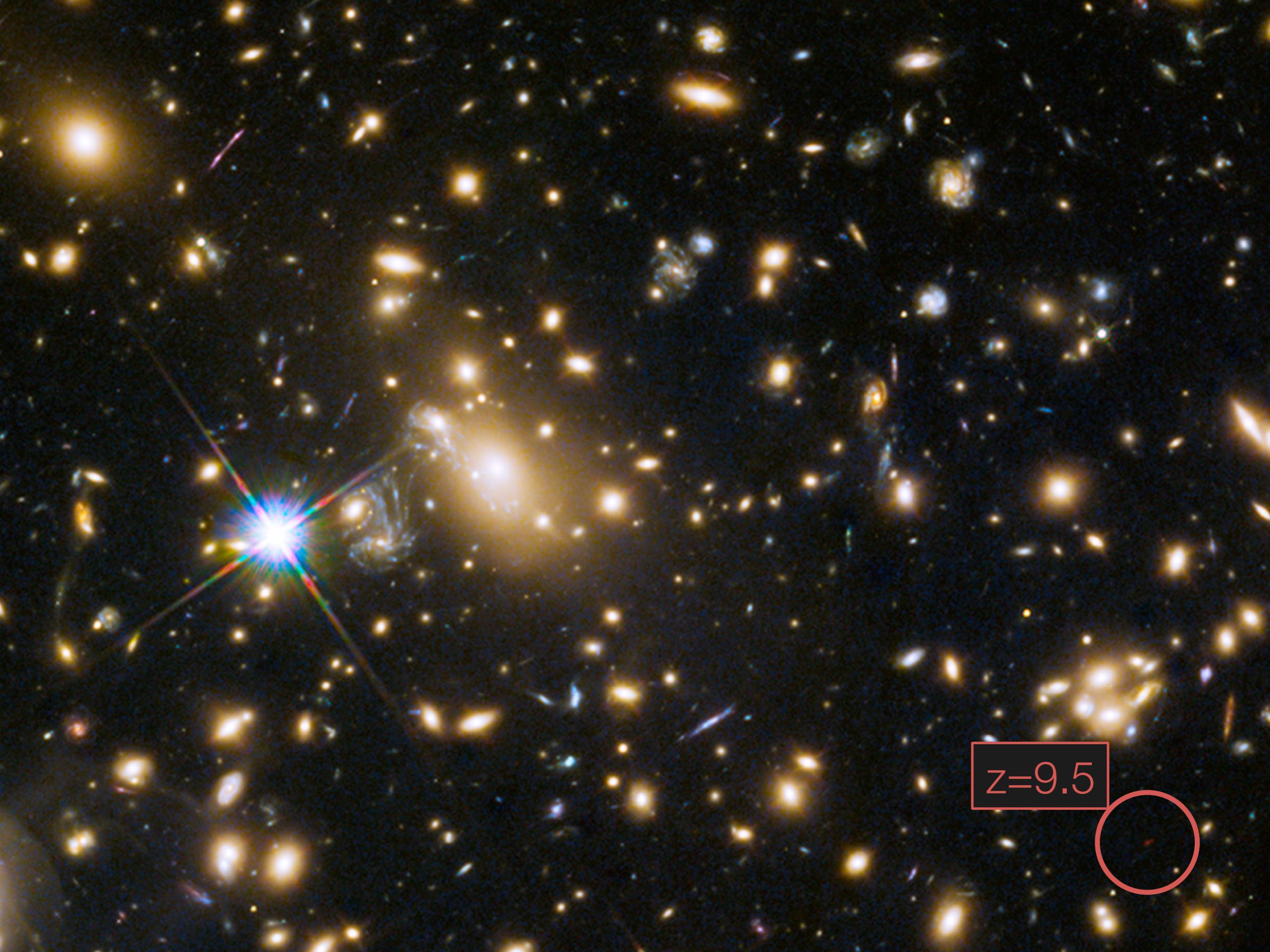


$z \sim 1100$ / 100,000 years after the Big Bang (Planck,

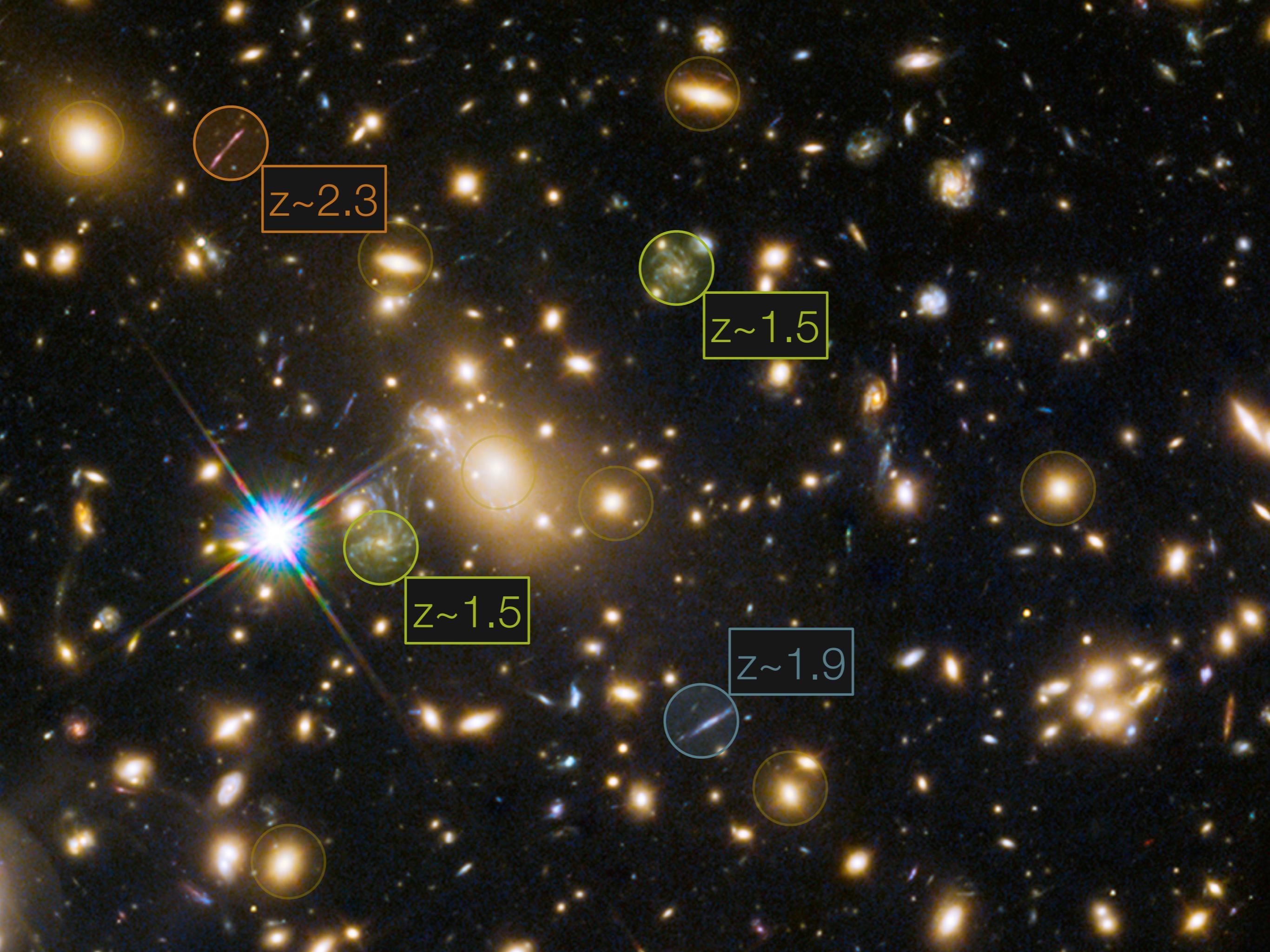


13.7 gigayears after the Big Bang (Sloan Digital Sky Survey)





$z=9.5$



$z \sim 2.3$

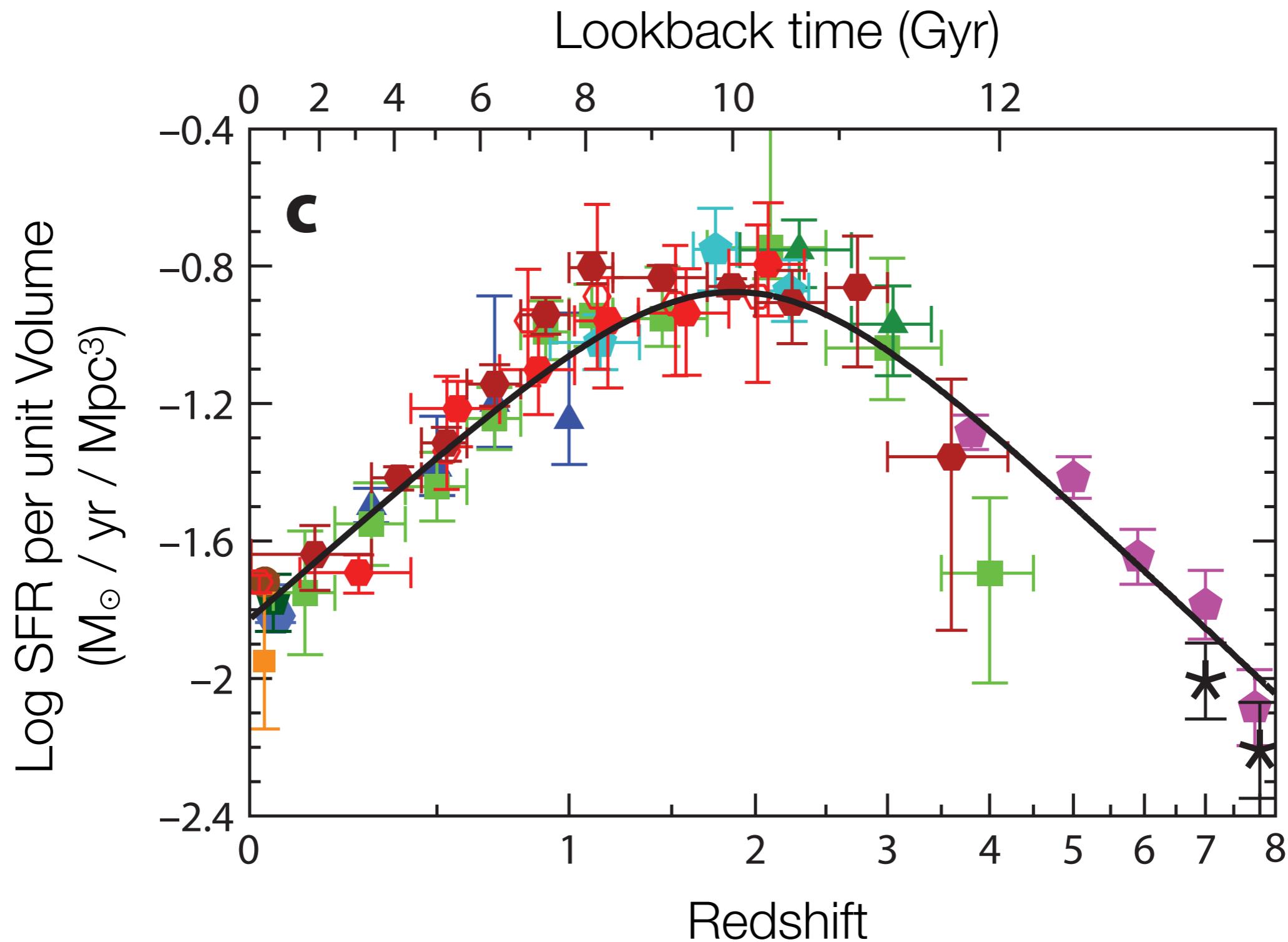
$z \sim 1.5$

$z \sim 1.5$

$z \sim 1.9$

Cosmic Star Formation History

Madau & Dickinson +14



Under the hood - standard imaging

- ♦ Images from a telescope sample the brightness distribution of the sky
- ♦ Calibration, background, noise model
- ♦ Typically sources of interest are much fainter than the background, so take many exposures and average them (**central limit theorem**)
 - * $\text{S/N} \sim \sqrt{t}$

Under the hood - standard imaging

- ♦ Basic "astronomy" done with 2D images that sample the (projected) brightness distribution of sources on the sky

1923
E. Hubble



Under the hood - standard imaging

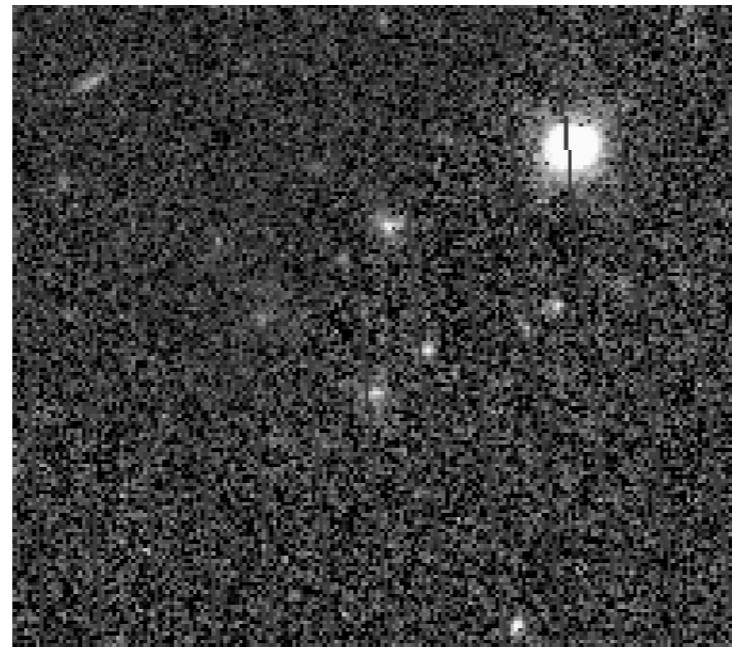
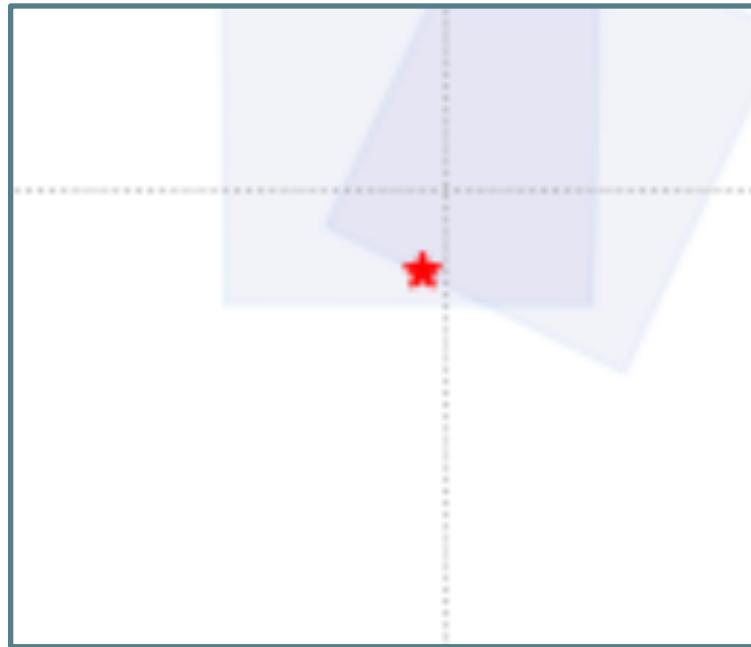
- ◆ Modern digital detectors are ~**linear** photon-counting devices that can be **calibrated** to an absolute scale (e.g. W / m²)

2004, Hubble Space Telescope

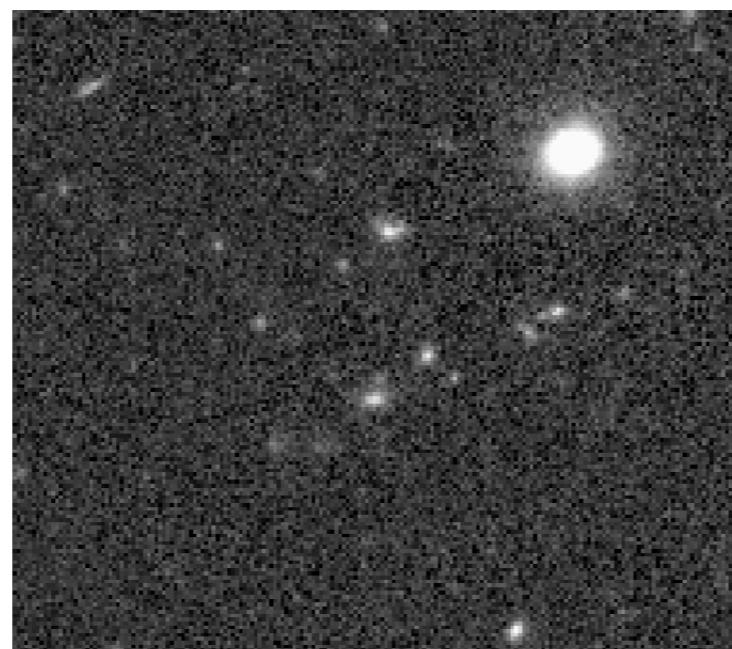
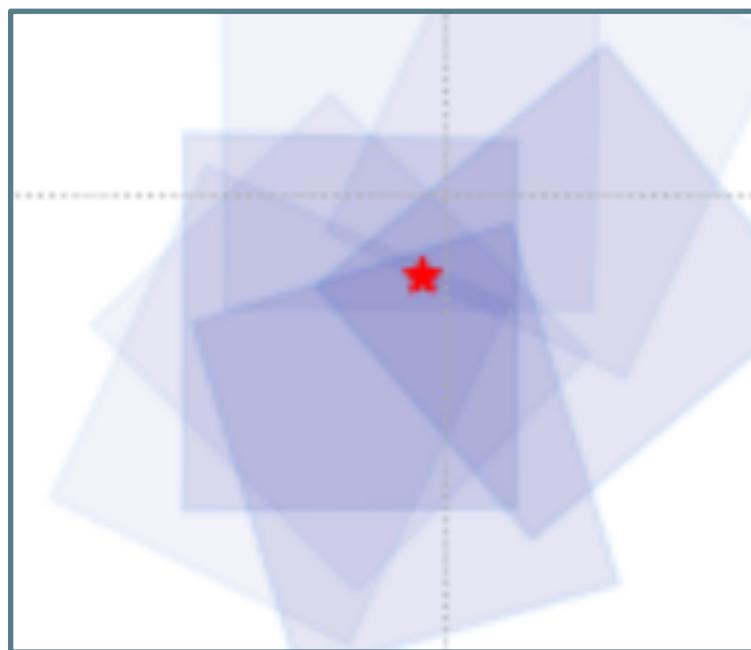


Imaging statistics

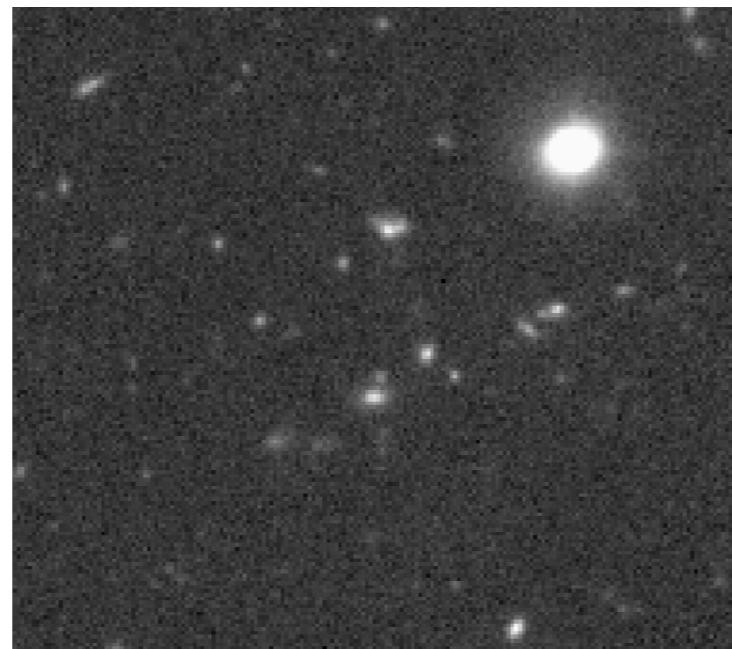
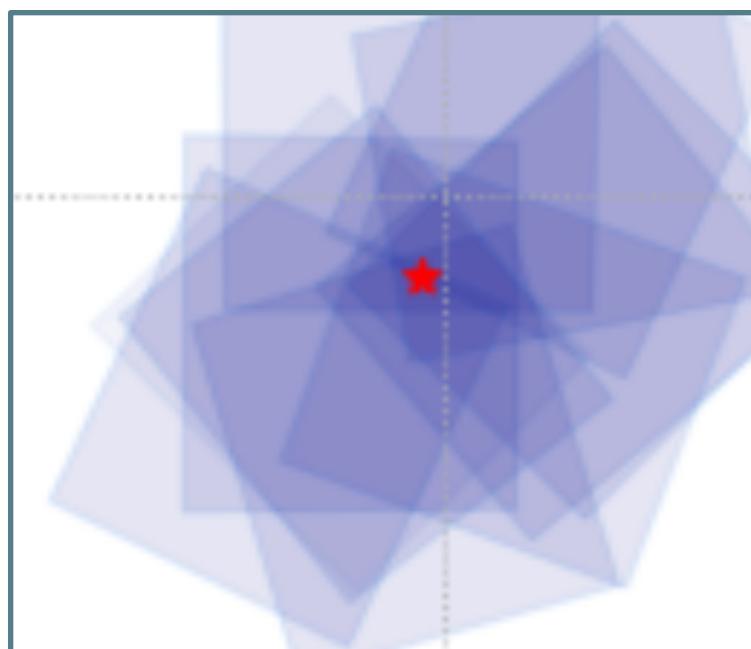
- ♦ \mathbf{S} - Signal rate from source of interest (e.g., photons / s)
- ♦ \mathbf{B} - "background" rate
- ♦ $N\epsilon^2$ - Random noise reading the charge on the detector N times
- ♦ t - "open shutter" integration time
- ♦ Variance $\mathbf{Var} = (\mathbf{S} + \mathbf{B}) t + N\epsilon^2$
- ♦ For $B \gg S$, $N\epsilon^2$ (faint sources, expensive detectors),
 $\text{Signal-to-noise} \approx t / t^{-1/2} \approx t^{1/2}$
 - ♦ Increasing signal-to-noise by a factor of **two** requires **four** times the integration time
- ♦ **Central limit theorem** provides approximately Gaussian statistics, but this should be verified and preserved!



$t \sim 10$ minutes



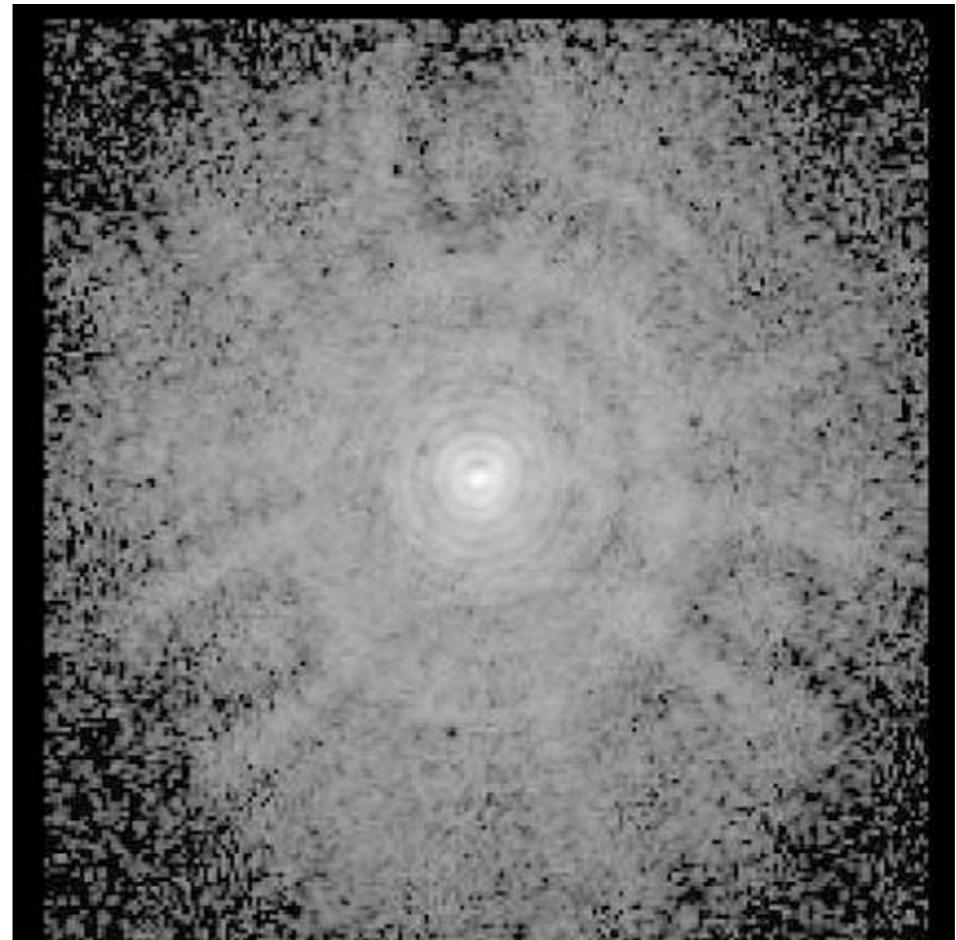
$t \sim 2$ hours



$t \sim 9$ hours

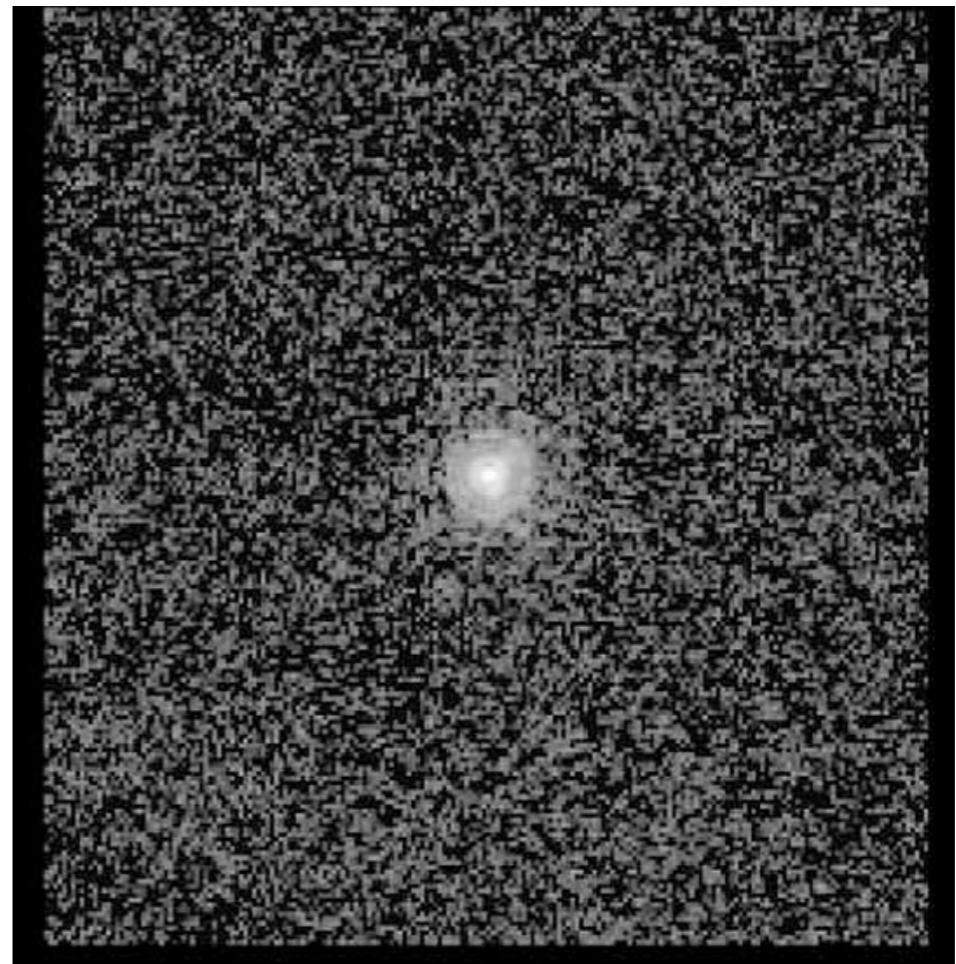
Source detection and characterization

- ♦ Point sources in an image (stars) have a finite size set by the telescope diameter and optics
 - * "Point spread function"



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Source detection and characterization

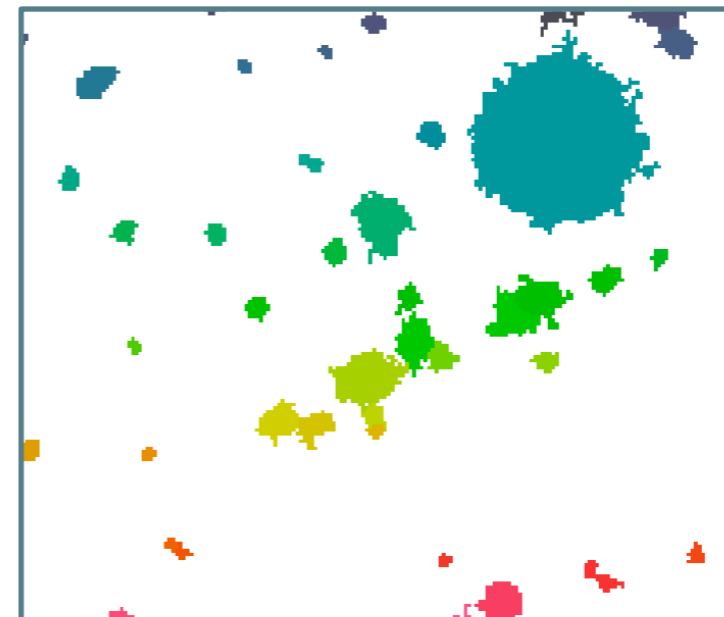
- ♦ Point sources in an image (stars) have a finite size set by the telescope diameter and optics
 - * "Point spread function"
- ♦ Basic weighted source detection
 - * $I = (S / Var * PSF) / (1 / Var * PSF^2)$
 - * $Var(I) = 1 / (1 / Var * PSF^2)$
- ♦ Essentially, a least squares fit for the intensity of a point source anywhere in an image

Source detection and characterization

- ♦ **But be careful!** Large images can provide many "trials" for detecting sources, so " 3σ " can be risky.
- ♦ E.g., relatively small HST images are 2400x2400 "PSFs" in size, so $p=0.01$ can still be a very big number.
- ♦ Worse still in presence of uncontrolled systematics.

Source detection and characterization

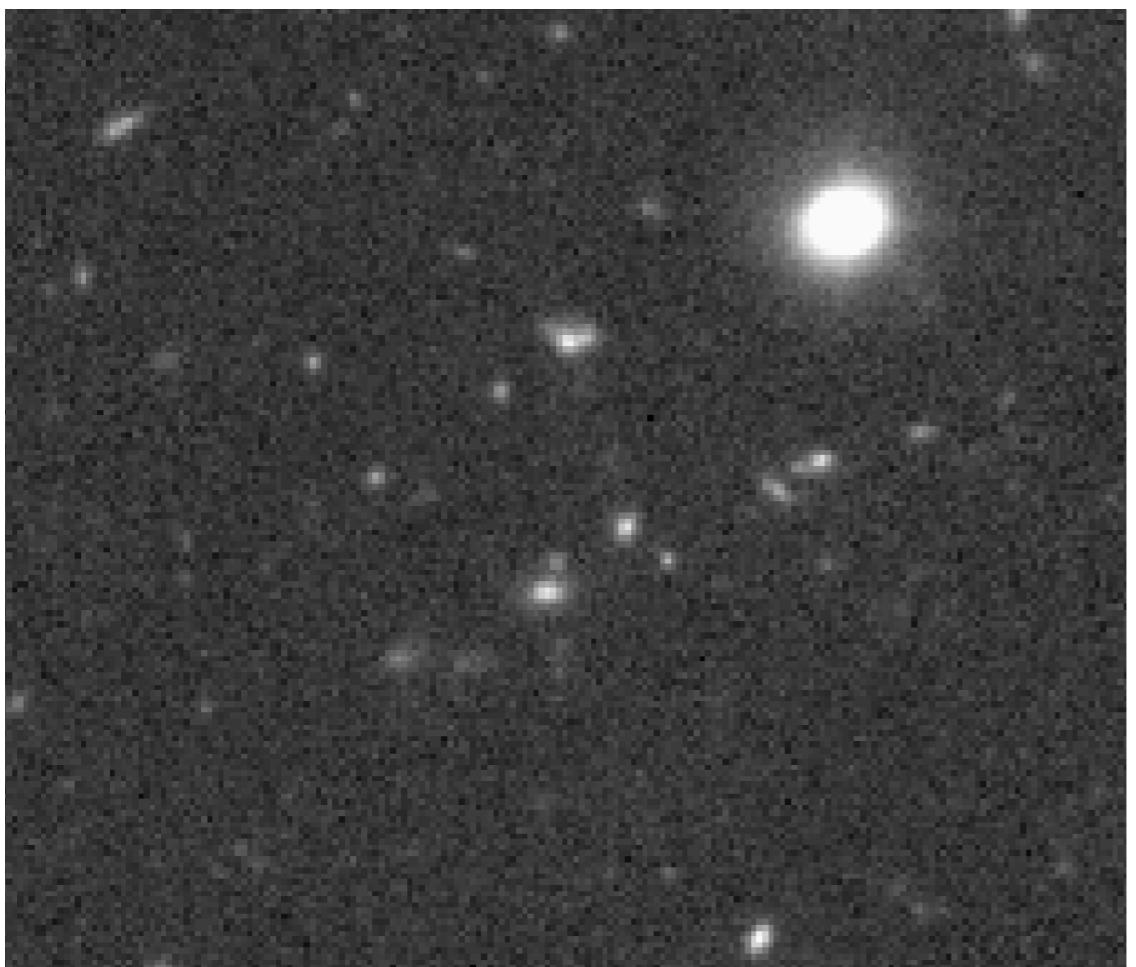
- ◆ Image **segmentation** assigns regions of the image to discrete sources (e.g., scikit-image)



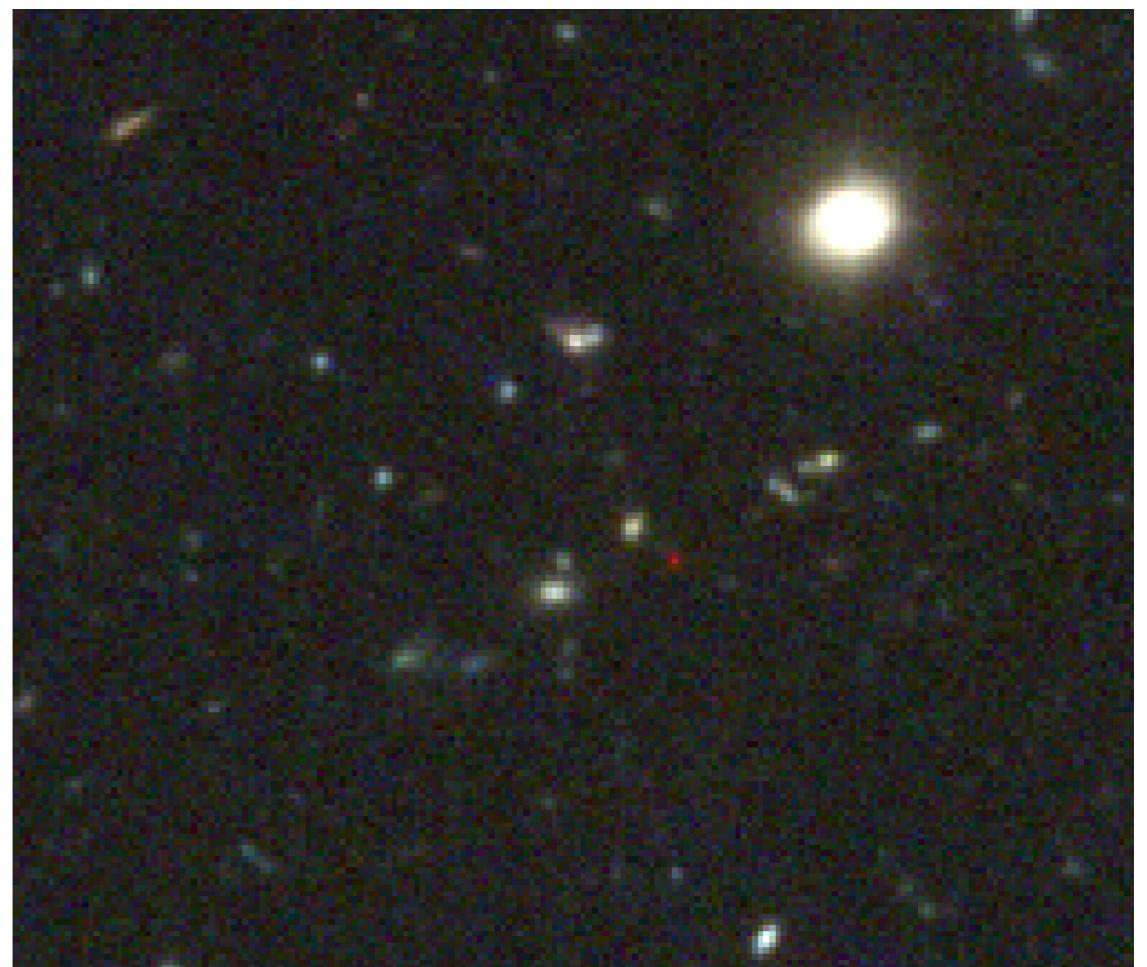
- ◆ Measure moments of the light distribution for discrete sources, e.g., sum, FWHM

A third dimension: spectral shape $I(\lambda)$

- ♦ Imaging: bandpass filters
- ♦ (Much more complicated optics can provide full spectra across the 2D spatial field)

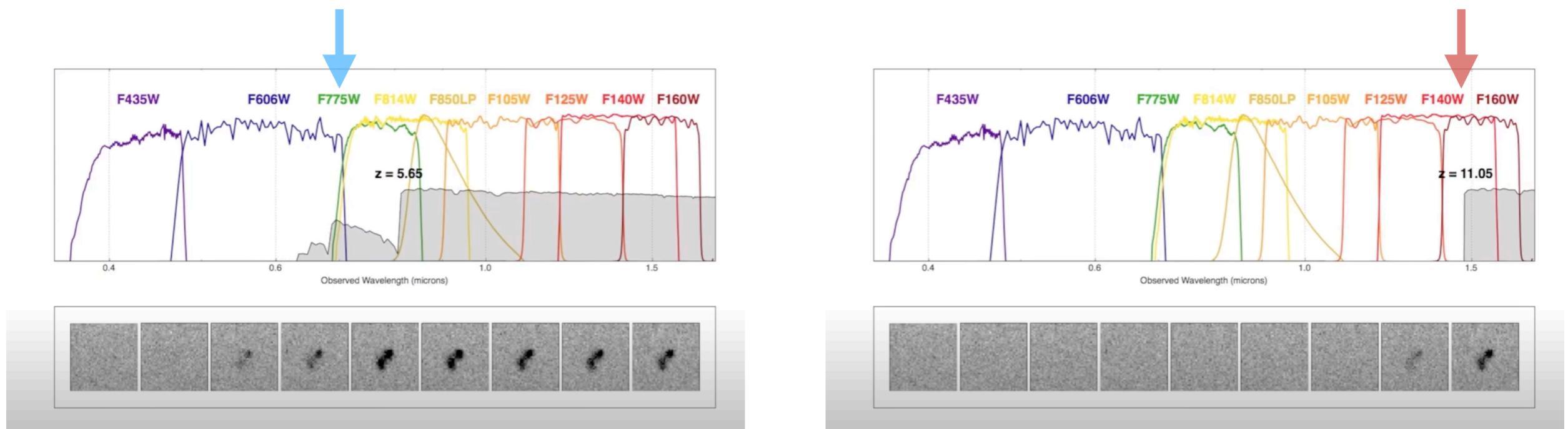


λ
1.0 μm
1.3 μm
1.6 μm



Crude distance estimates: "dropouts"

- Neutral Hydrogen along the line-of-sight to distant galaxies absorbs all light below 1216 Å
- Creates a step-function signal that can be an effective distance indicator ("Lyman break")
 - Simply observe an object in multiple filters and the bluest wavelength in which that object is detected $\sim 1216\text{\AA}$



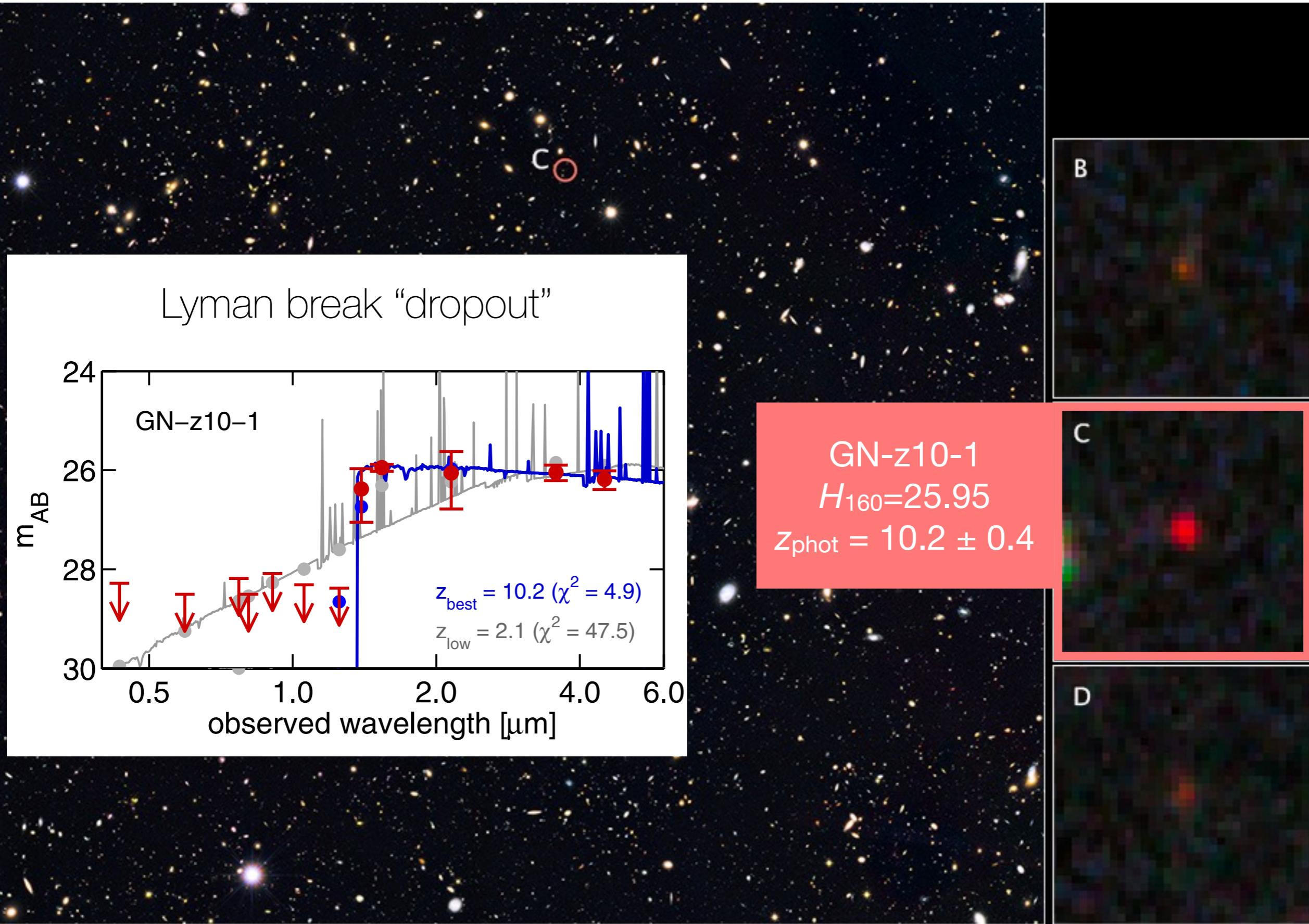
Candidate #2 (GN-z10): $z \sim 10$?

Oesch+15

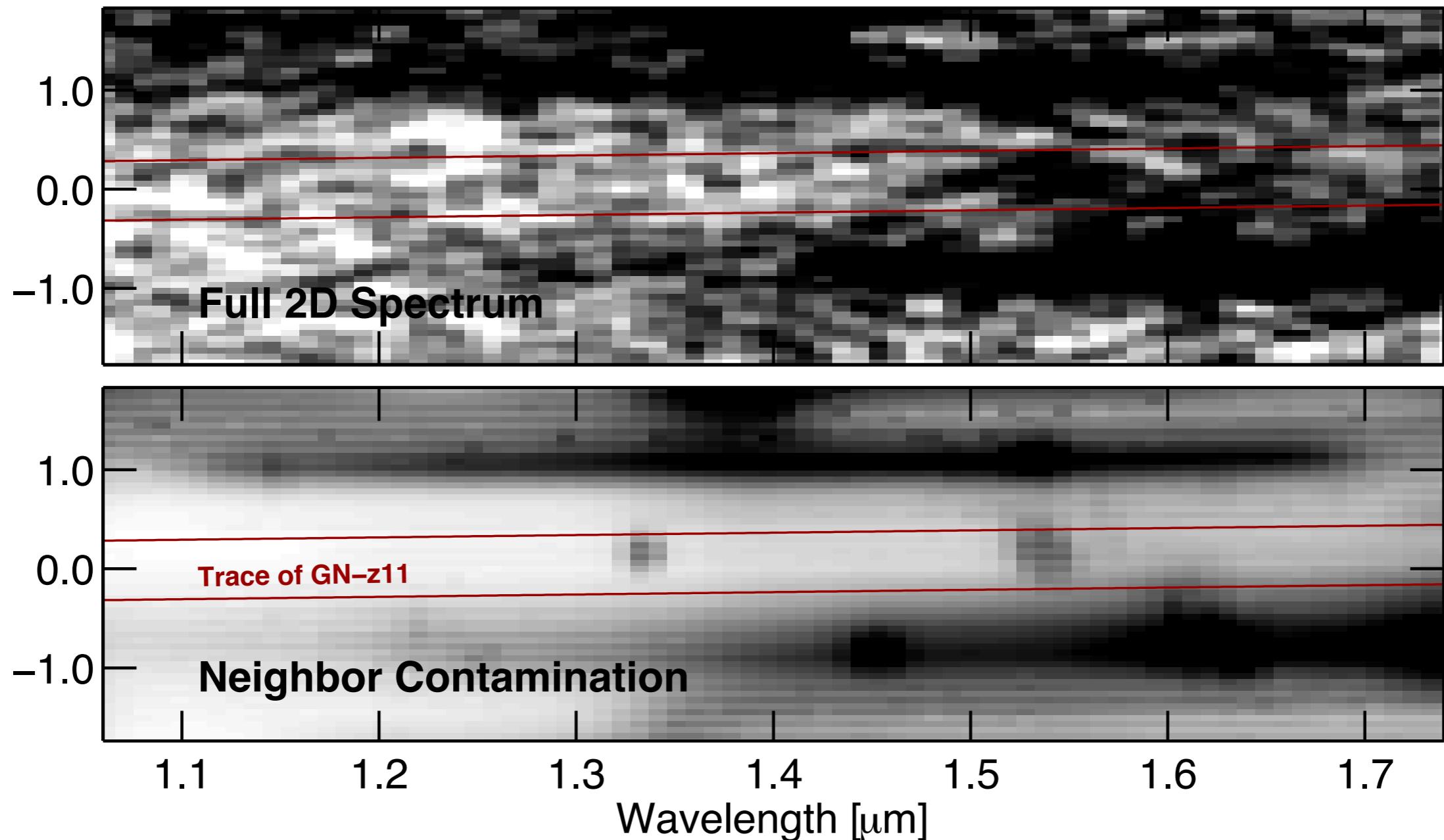


Candidate #2 (GN-z10): $z \sim 10$?

Oesch+15



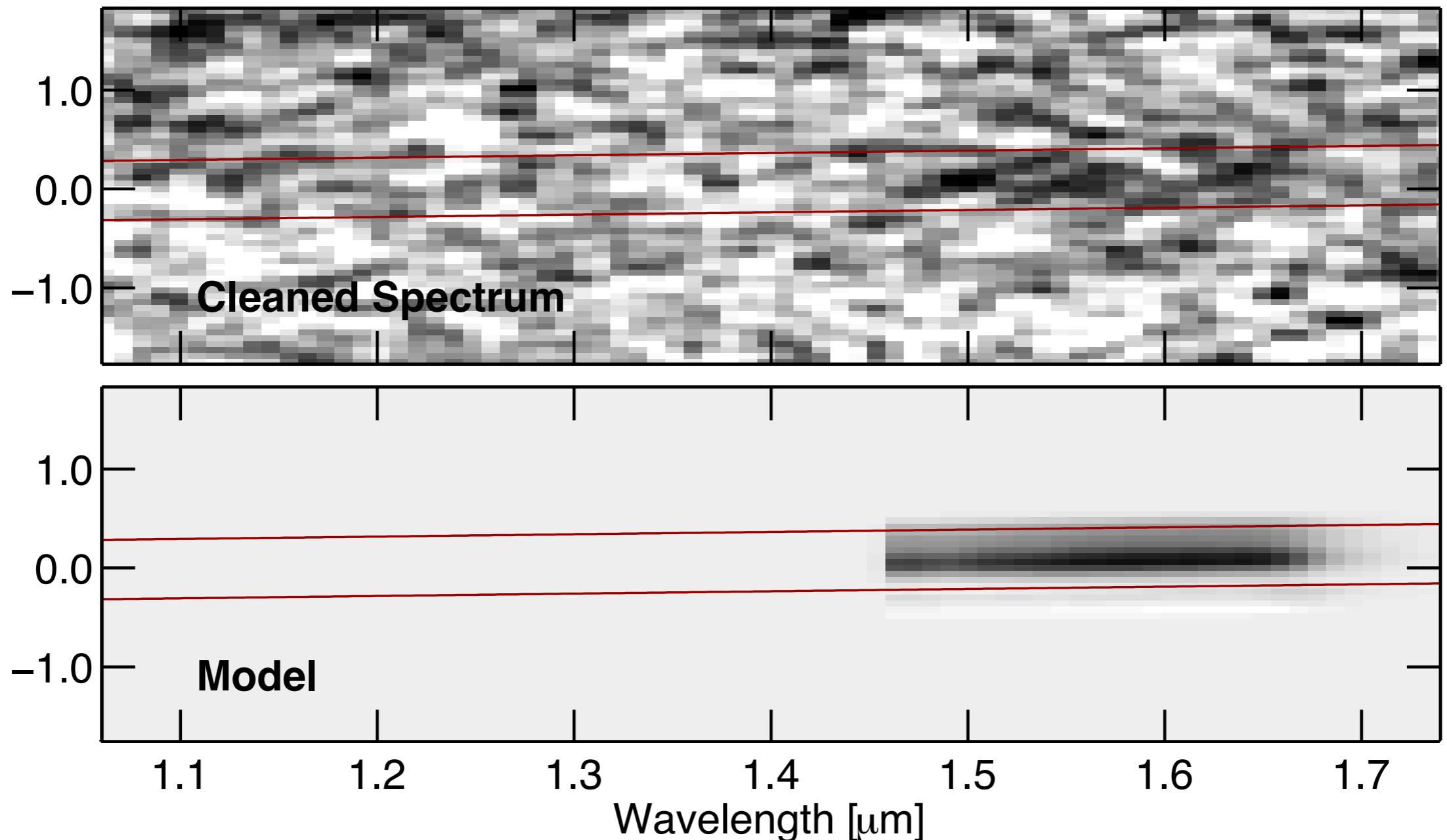
Candidate #2 (GN-z10): z~10?



Candidate #2 (GN-z11): $z \sim 10?$ $z = 11.1 \pm 0.1$

Oesch, Brammer+16

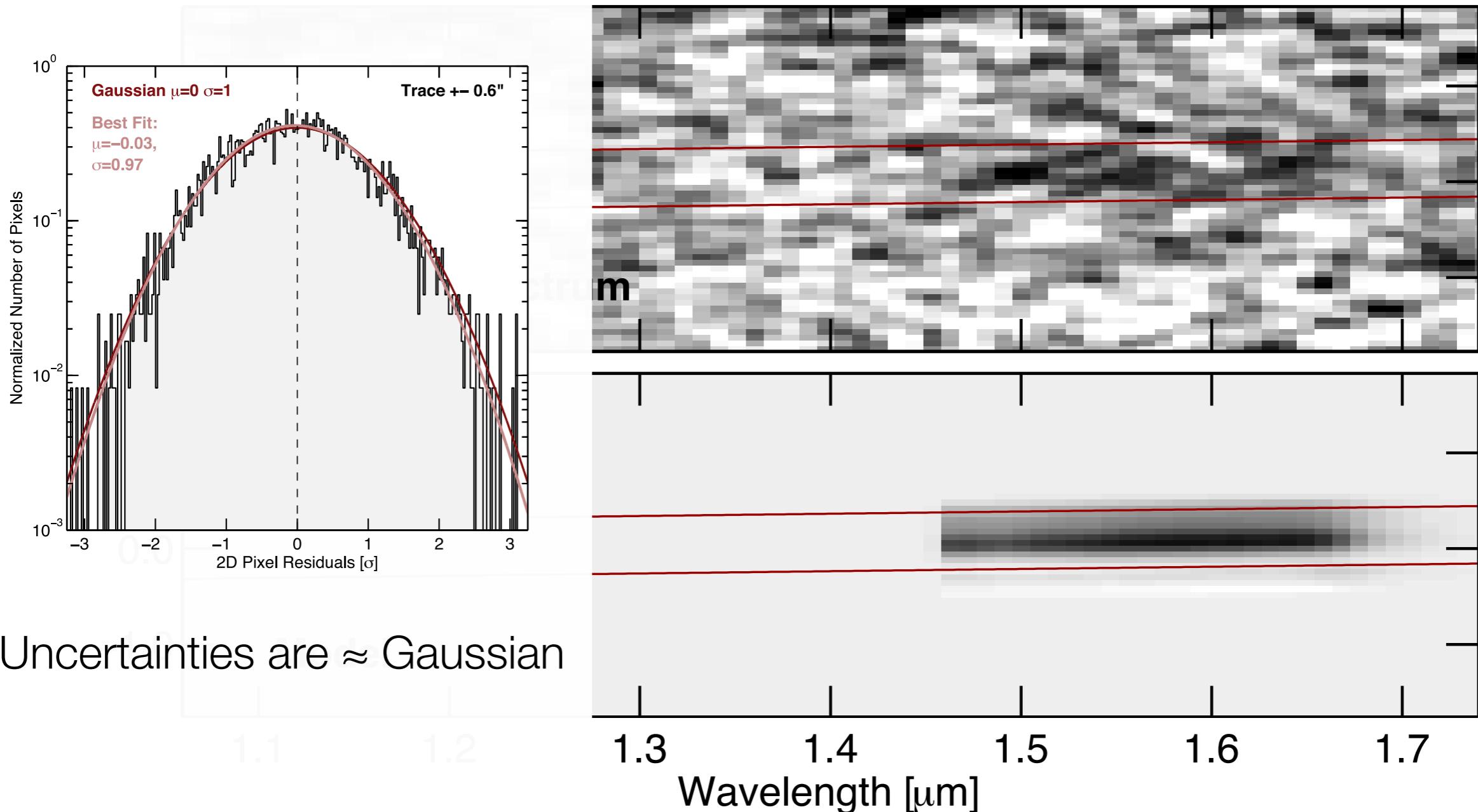
- ◆ Deep *HST* spectrum supports Lyman-break @ $z=11$



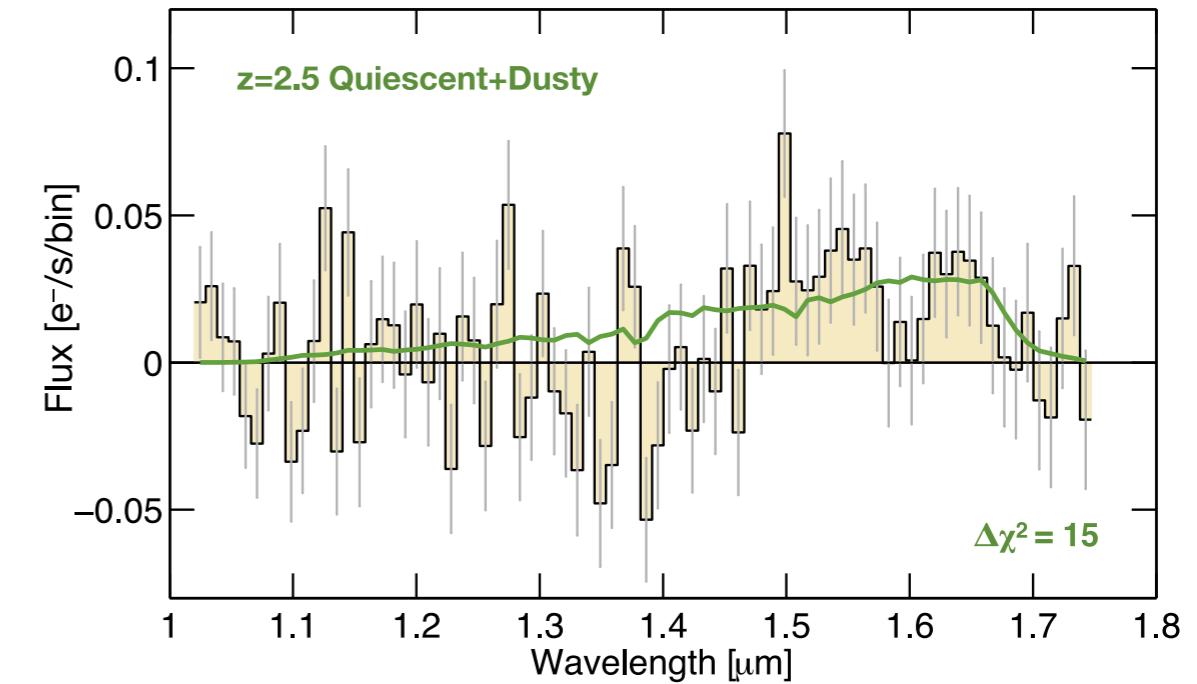
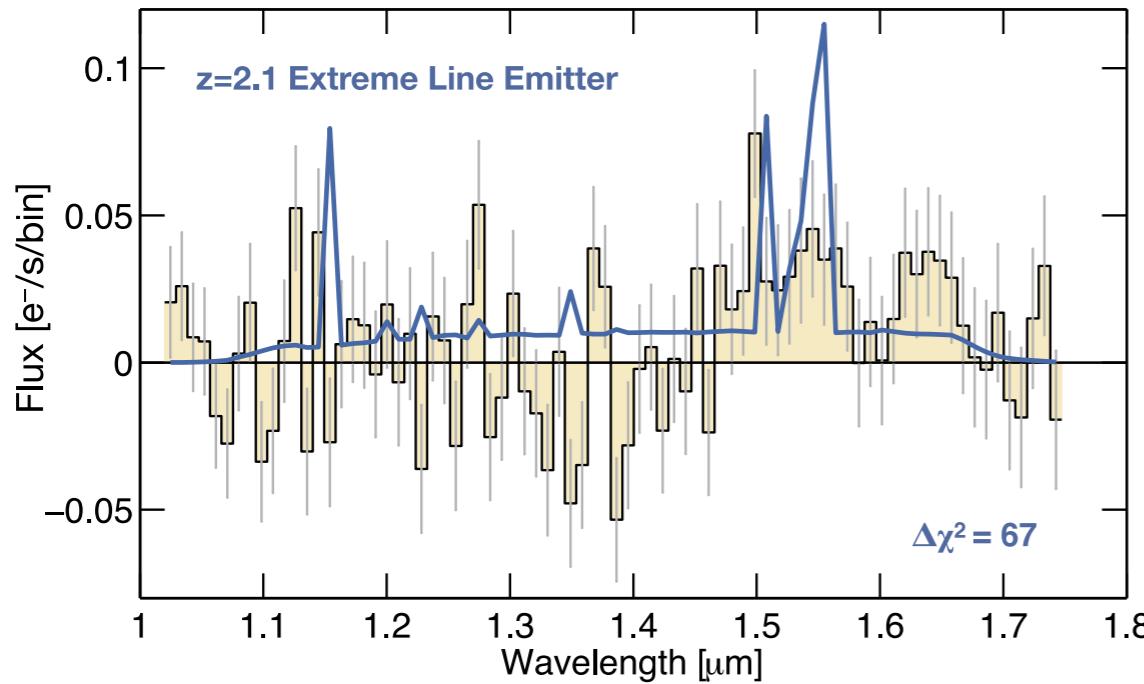
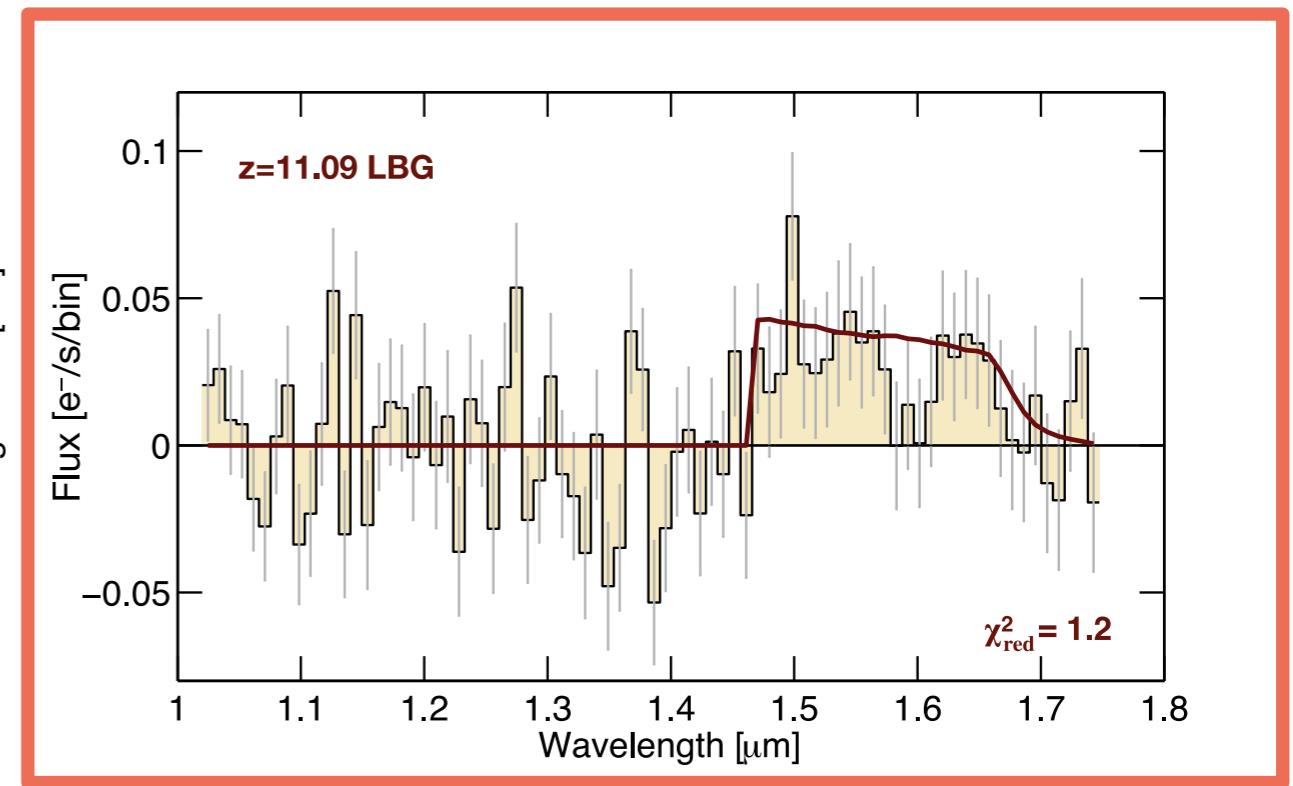
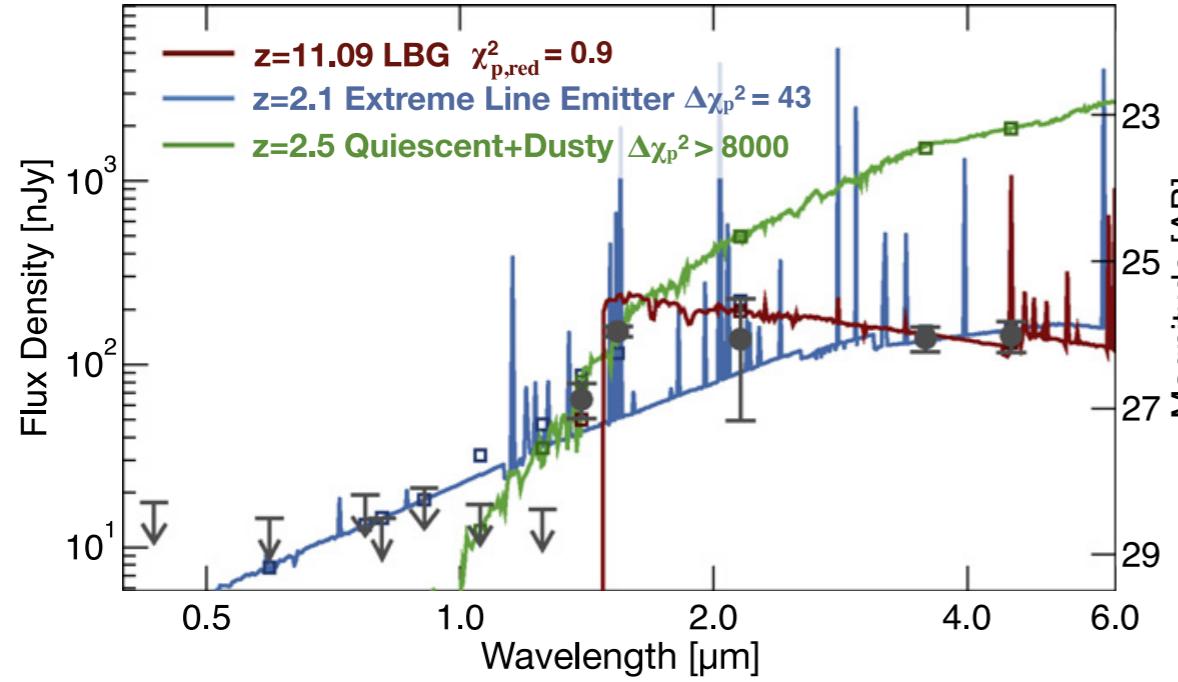
Candidate #2 (GN-z11): $z \sim 10?$ $z = 11.1 \pm 0.1$

Oesch, Brammer+16

- Deep *HST* spectrum supports Lyman-break @ $z=11$



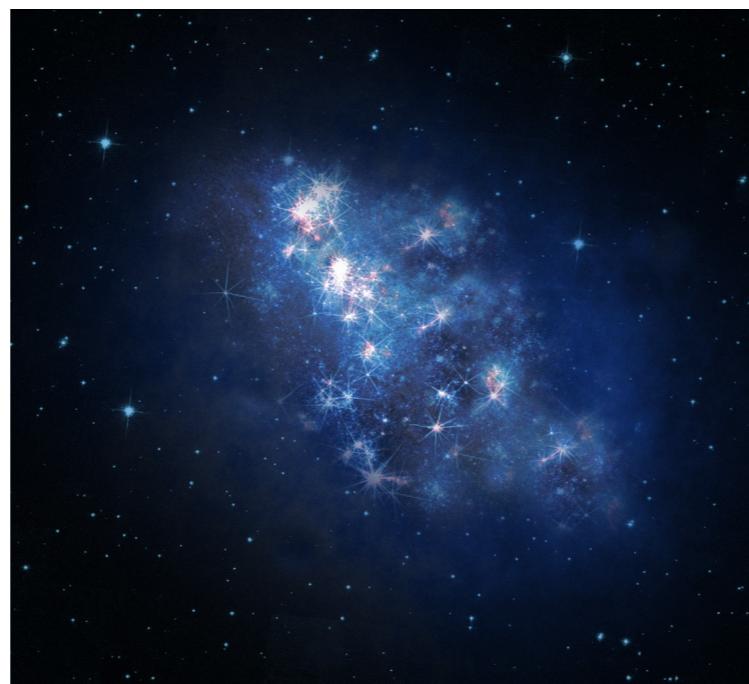
Favored interpretation



Potential contaminants inconsistent with the spectrum

Candidate #2 (GN-z11): $z \sim 10?$ $z = 11.1 \pm 0.1$

Oesch, Brammer+16



M51

GN-Z11

Distance: 13.4b light years

Radius: 2500 light years

Mass in stars: $10^9 M_\odot$

Star formation rate: $25 M_\odot / \text{yr}$

Milky Way

–

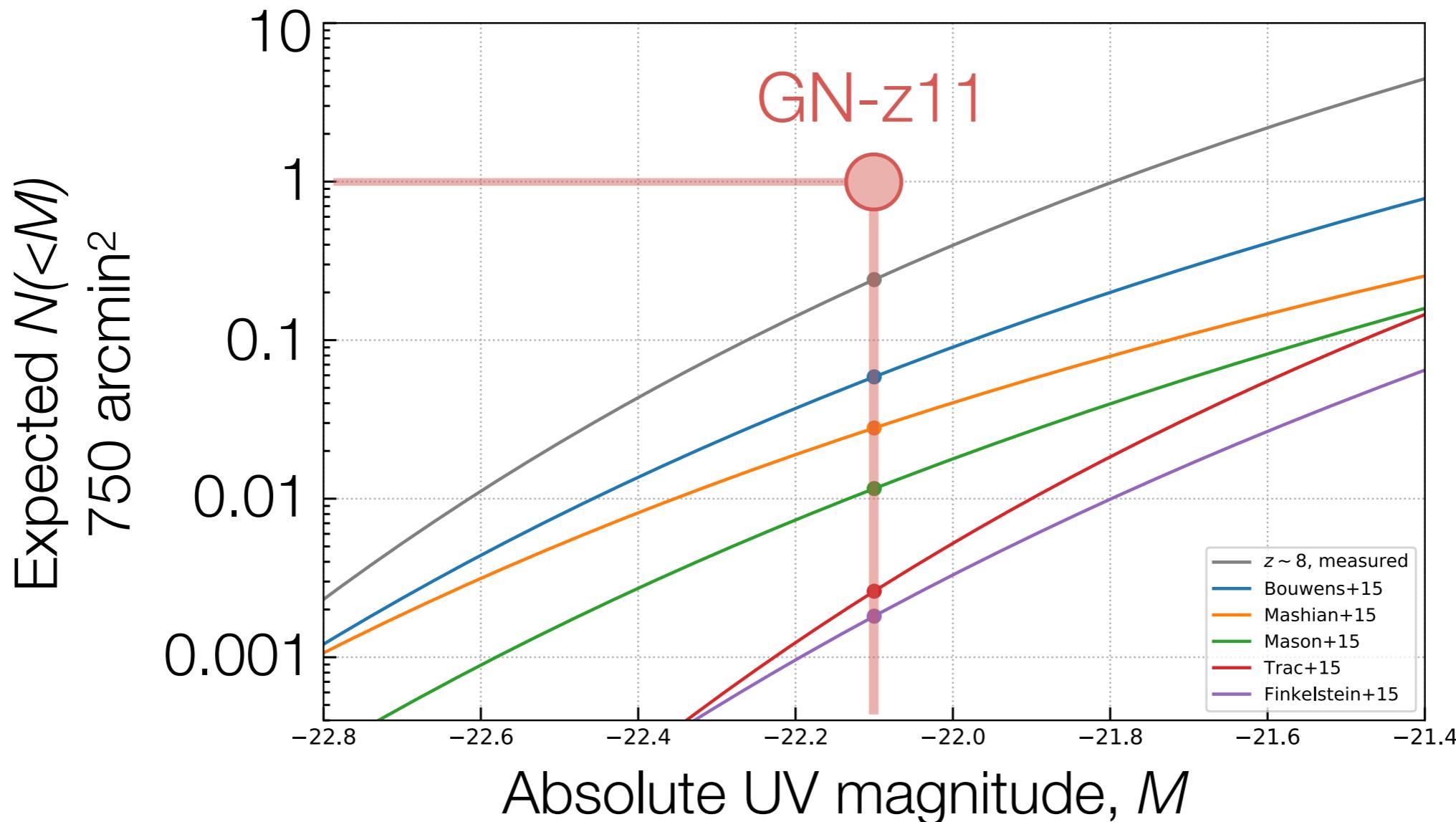
25 × larger

50 × larger

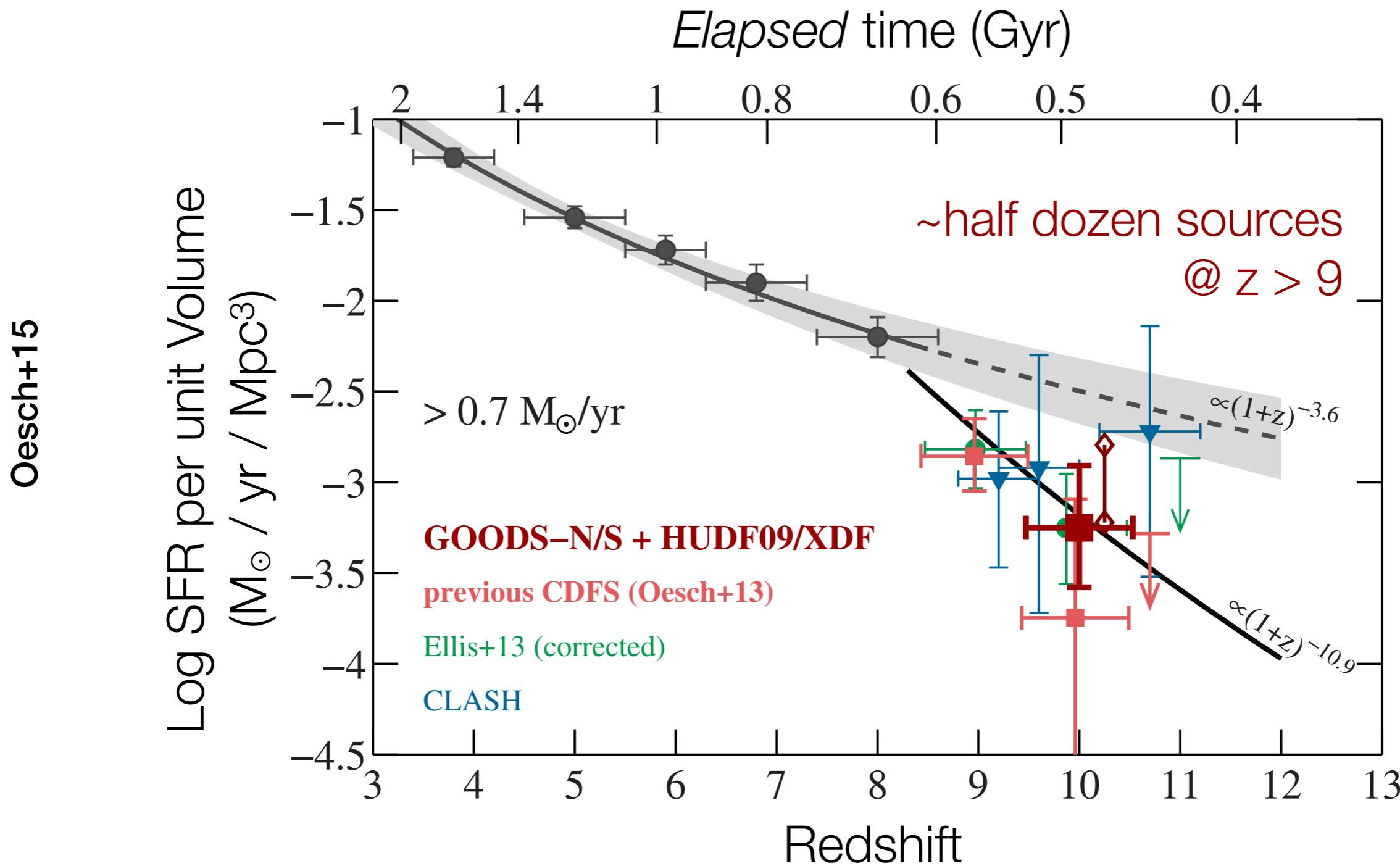
50 × lower

Expected counts at $z>10$

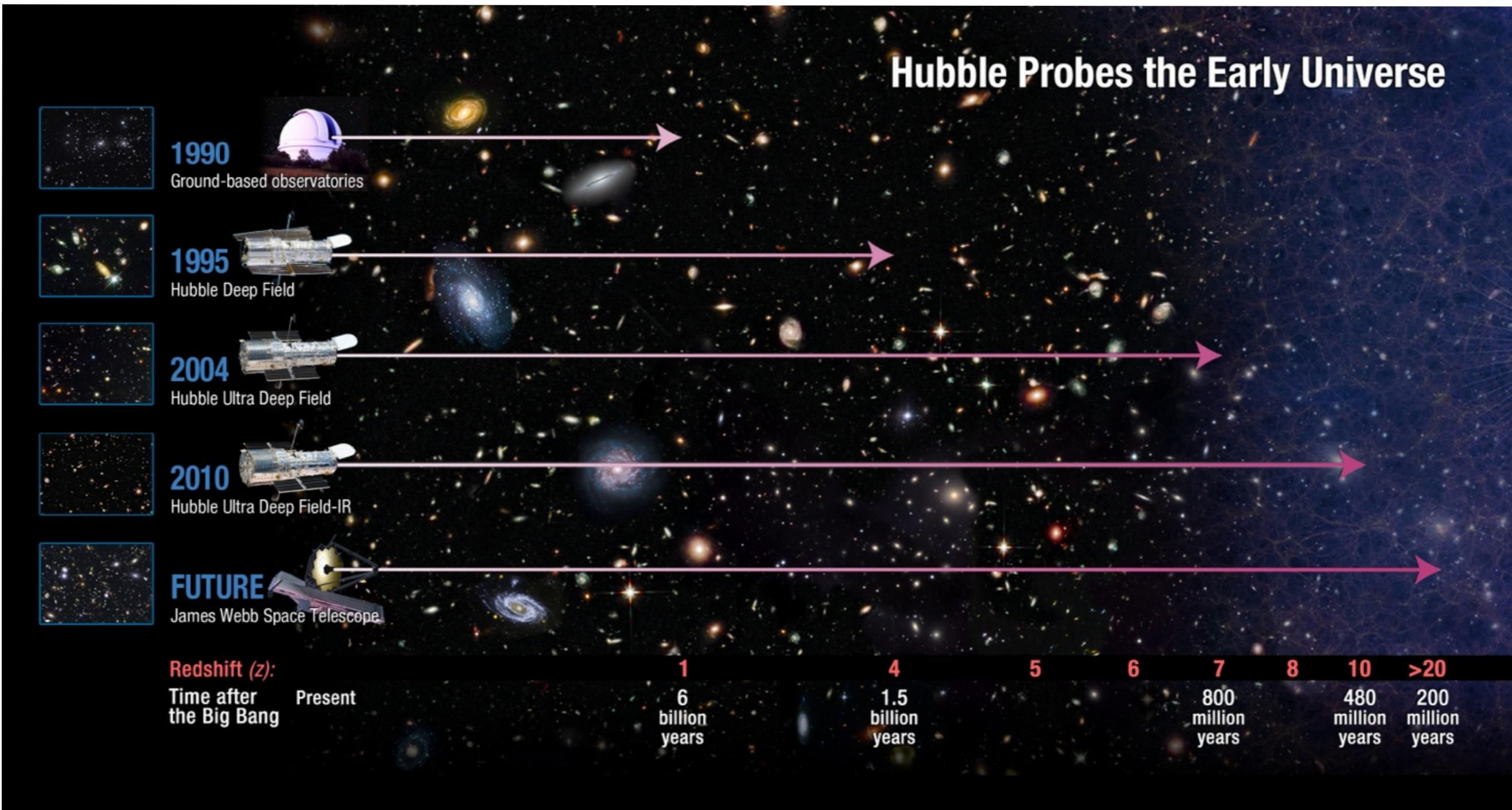
- Should have needed a survey $>15\times$ larger to find GN-z11 based on extrapolations from lower z !



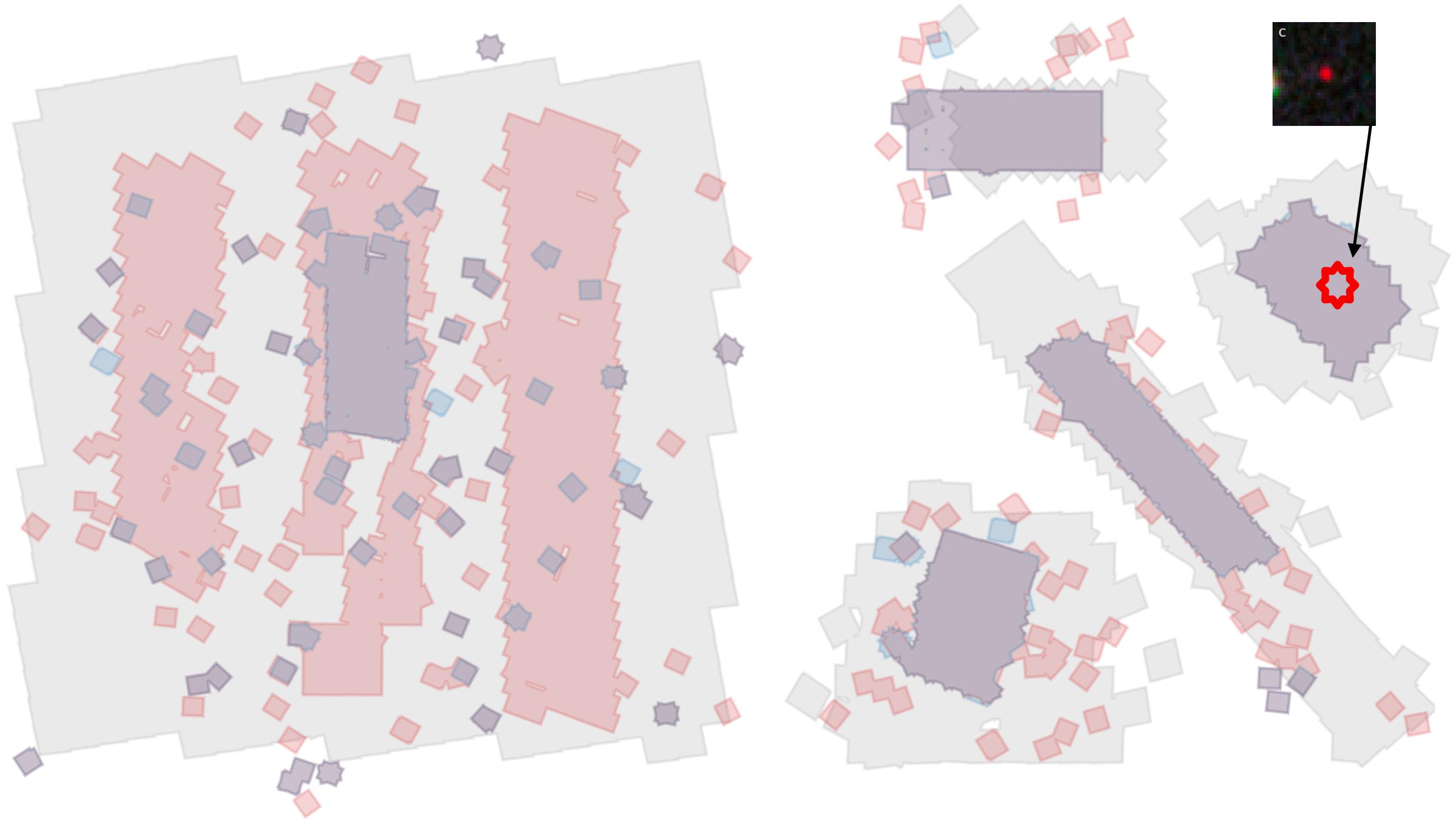
Cosmic Star Formation History: Cosmic Dawn



Cosmic Star Formation History: Cosmic Dawn



Automated "pipeline" processing for more comprehensive search.



Aside: a UV burst in GNz11?

- ♦ Jiang et al. (Nature Astronomy, Dec. 2020, <https://arxiv.org/abs/2012.06937>) reported detection of a **transient burst** while they were observing GN-z11 in 2017!

