Tracing Galaxy Evolution in the High-Redshift Universe with JWST

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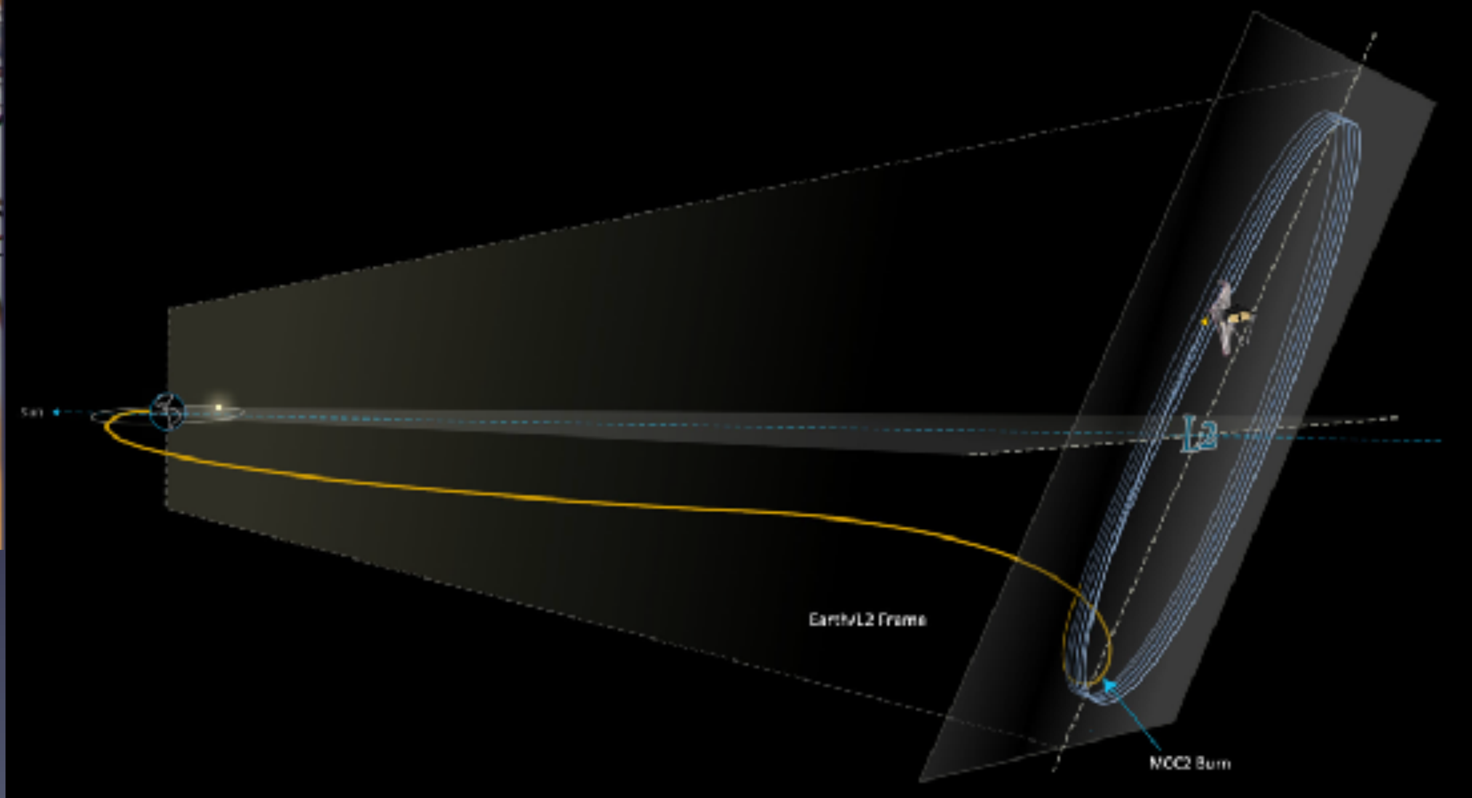
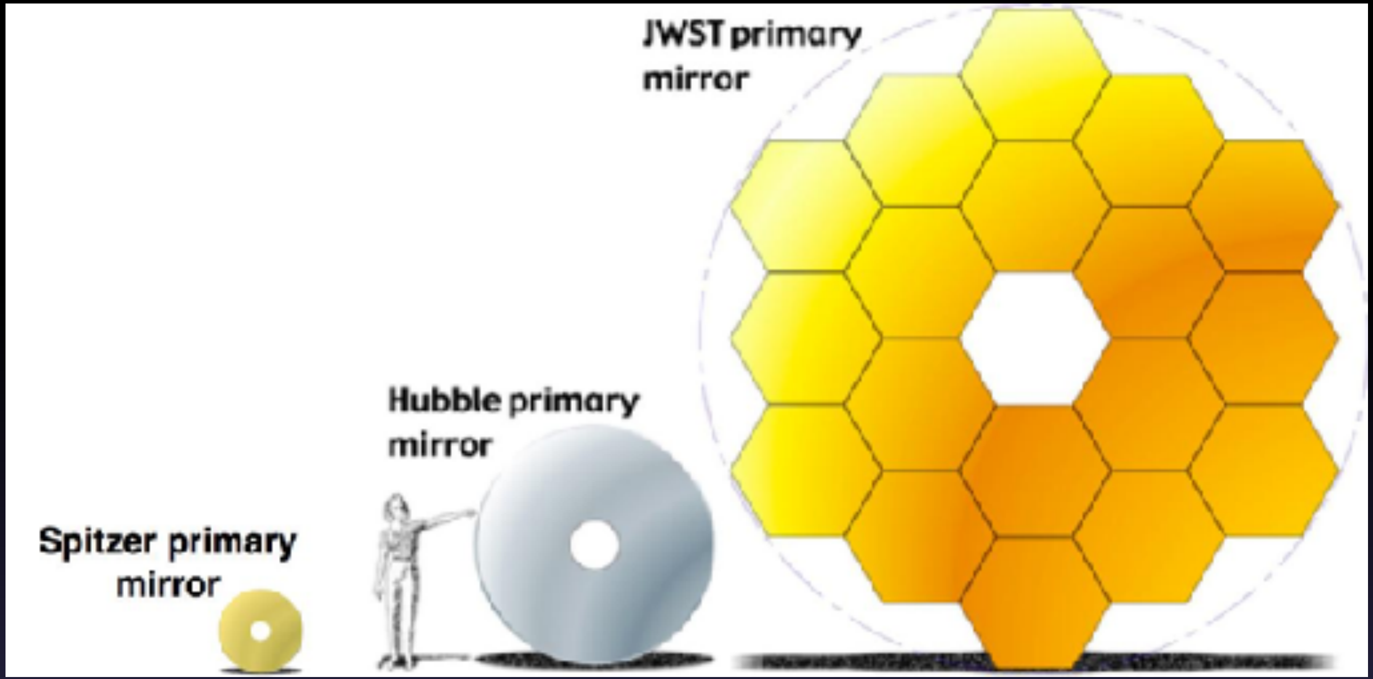
Content

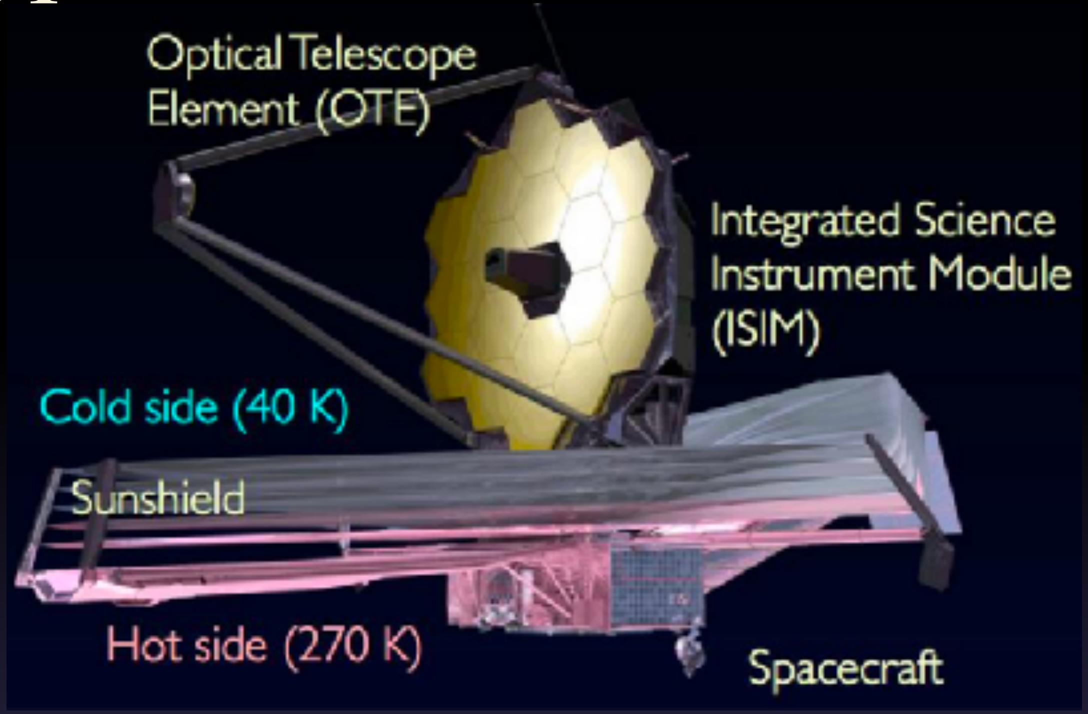
- A short introduction to JWST instruments and capabilities
- A (highly incomplete) overview of some recent discoveries from JWST high-redshift galaxy surveys
- Dissecting the details of galaxy evolution with 3D spectroscopy from JWST NIRSpec slit-stepping



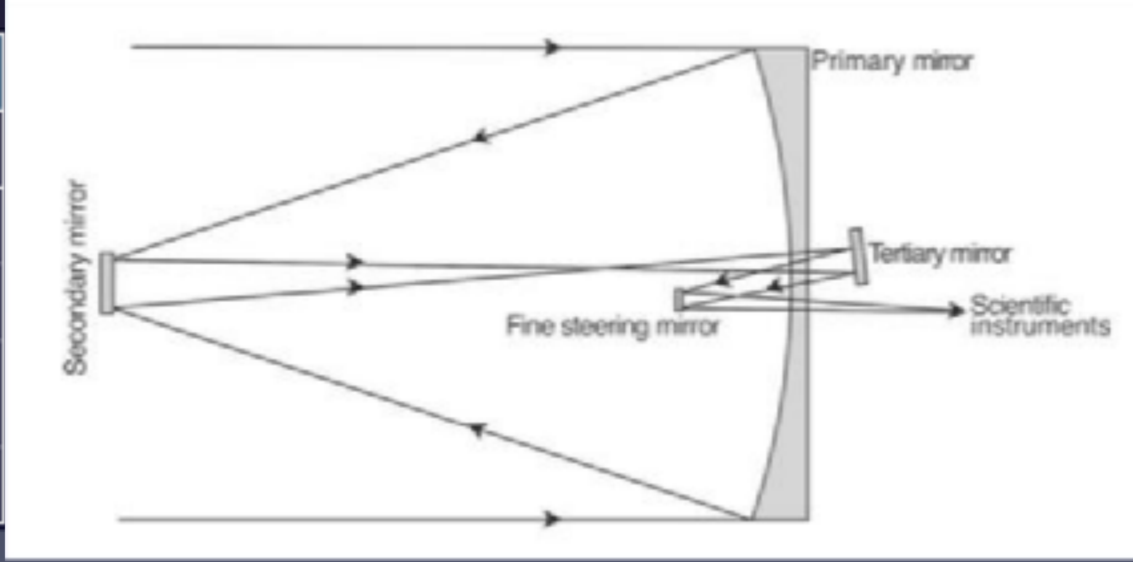
JWST launch: Christmas day 2021

JWST 101





	Hubble	Spitzer	JWST
Primary diameter	2.4	0.85	6.6
Collecting Area (m^2)	4.24	0.5	26.3
Observatory Mass (kg)	11,000	860	6,300
Observatory Volume, when stowed (m^3)	190	13	155
Orbit Location	LEO	Earth-trailing solar	Sun-Earth L2



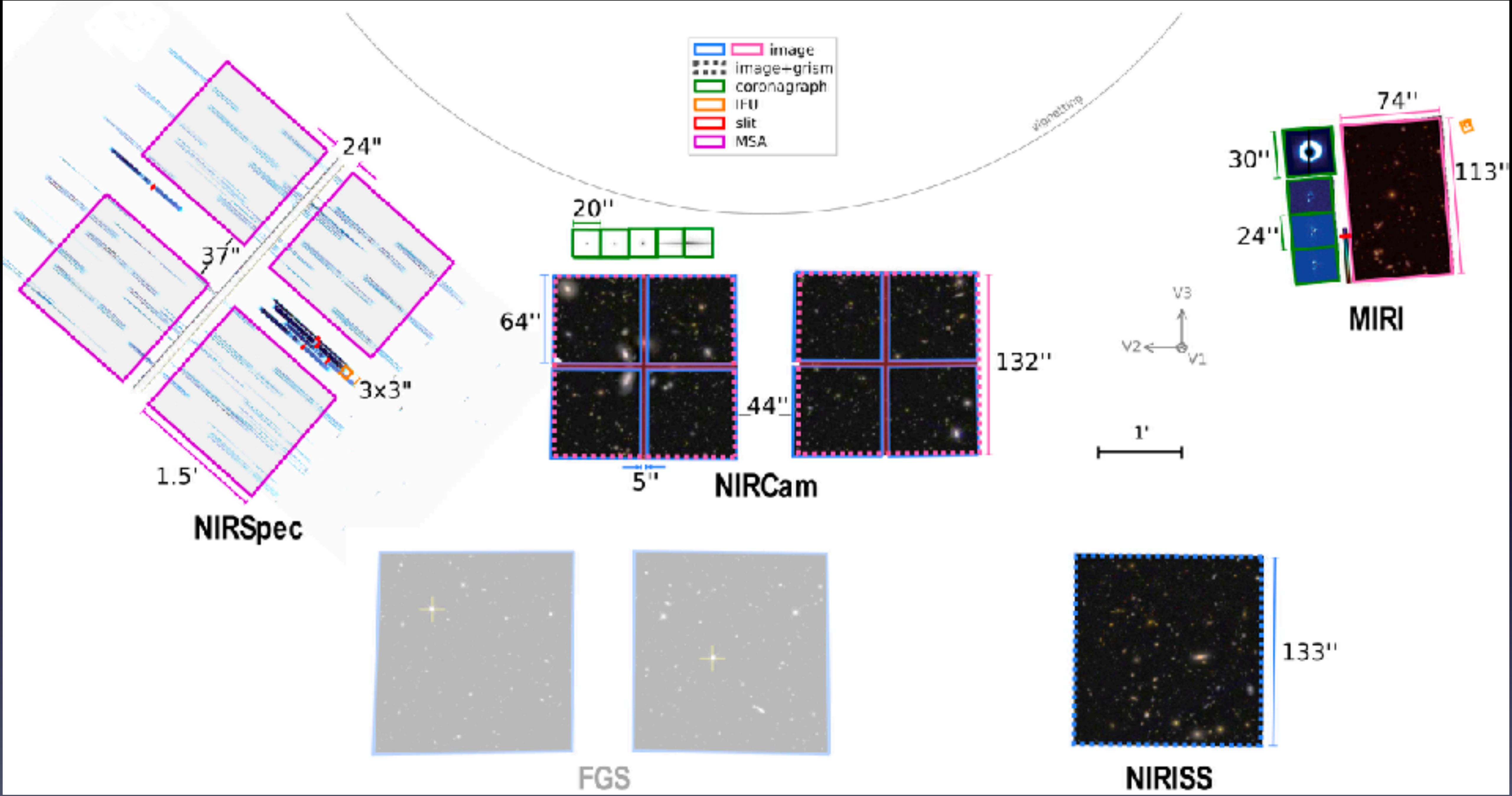
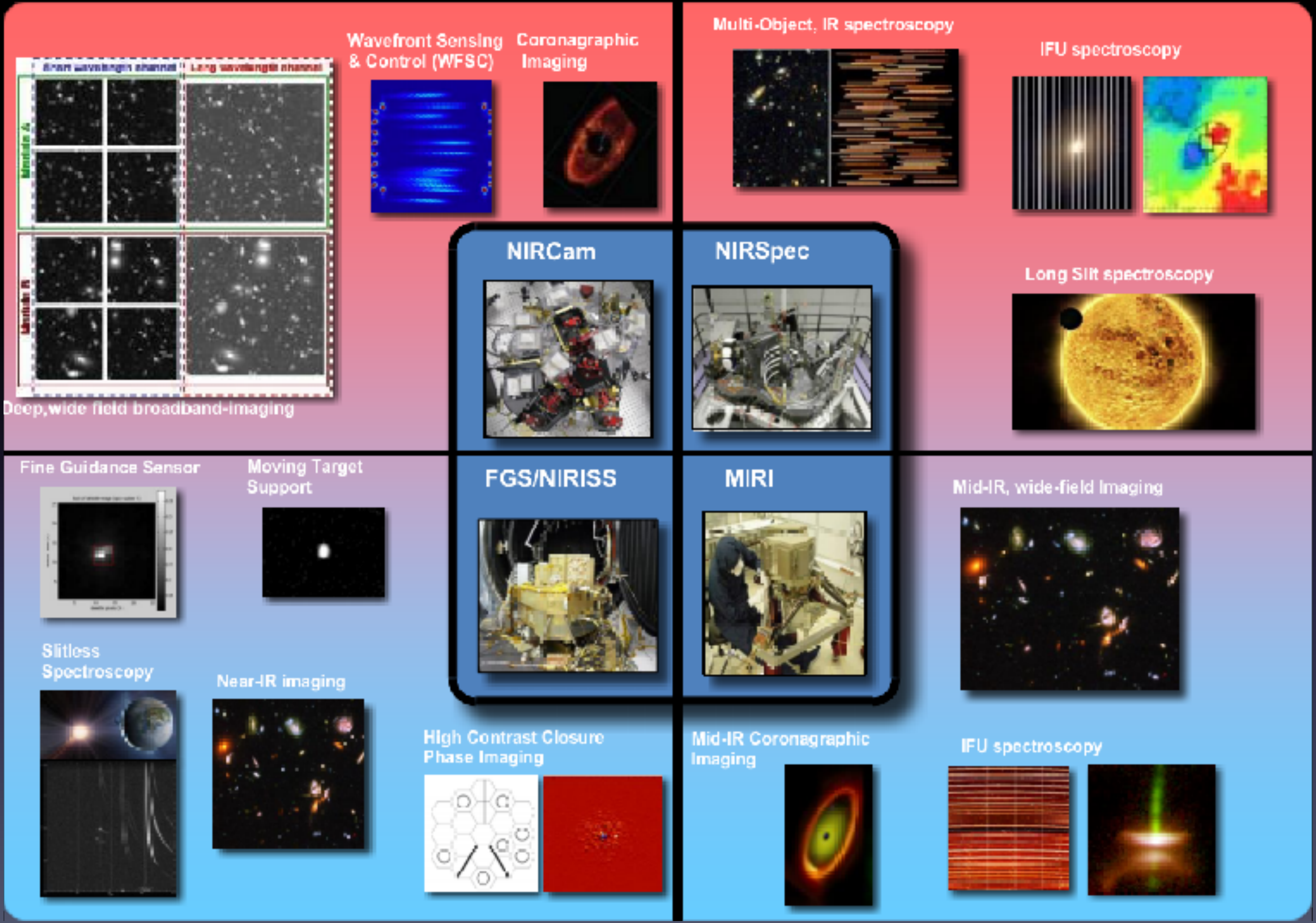
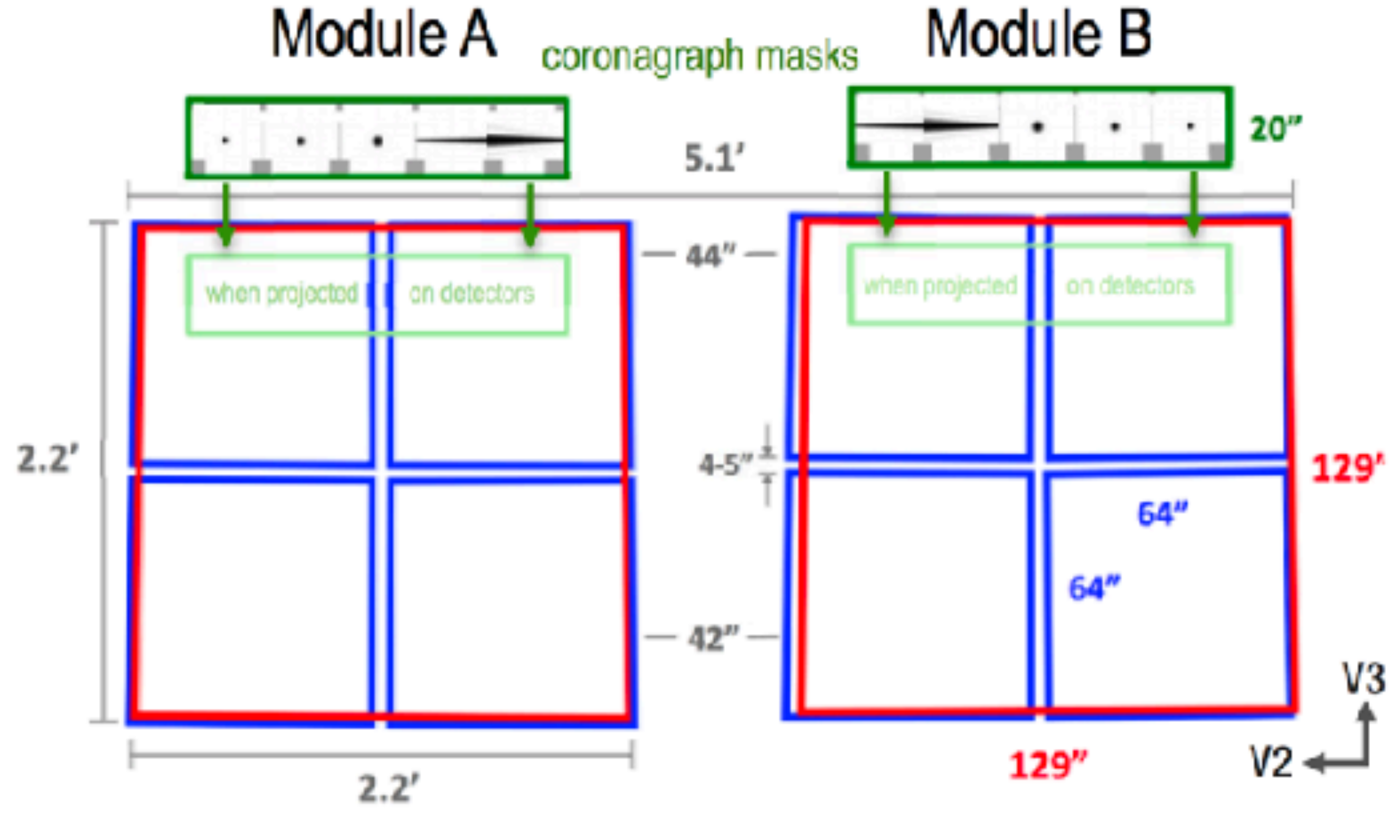


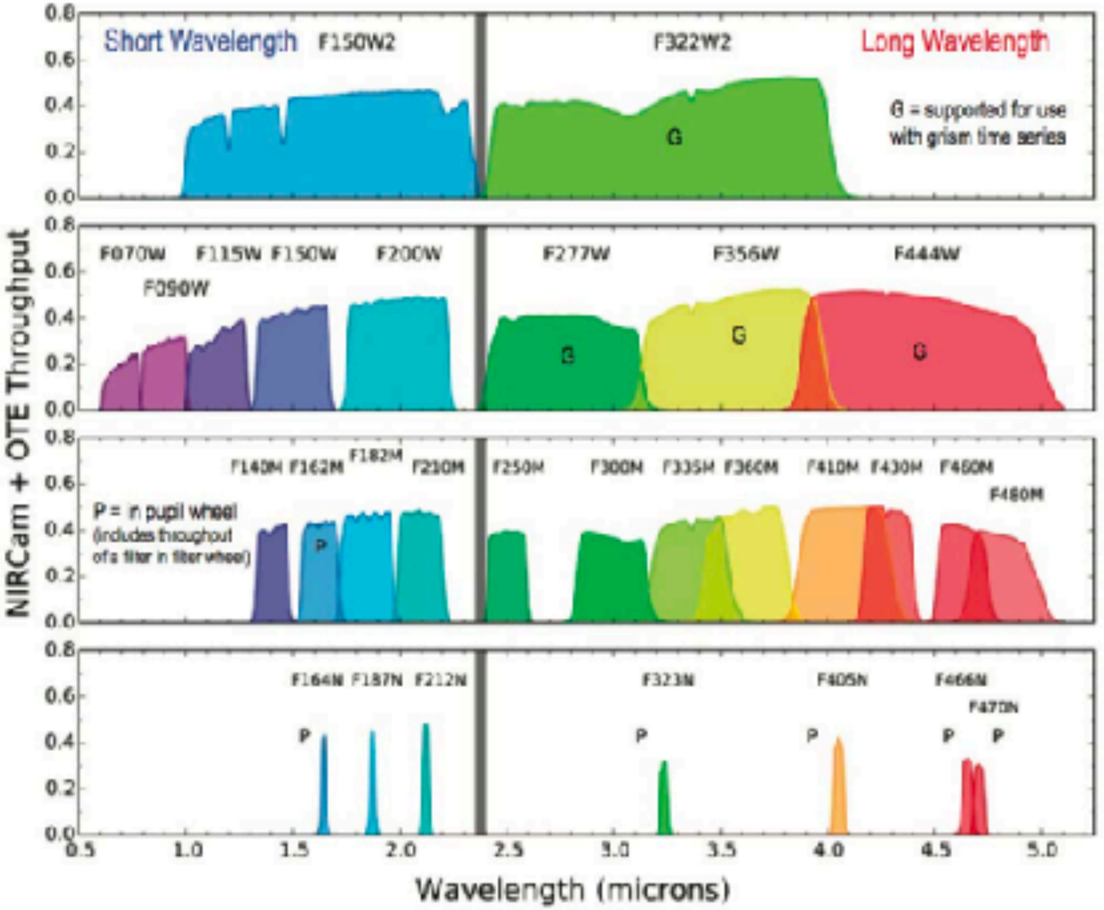
image
image+grism
coronagraph
IFU
slit
MSA
vignetting
24"
37"
3x3"
1.5'
NIRSpec
20"
64"
44"
132"
5"
NIRCam
V3
V2
V1
1'
74"
30"
113"
24"
MIRI
FGS
133"
NIRISS



Wavefront Sensing & Control (WFSC)
Coronagraphic Imaging
Multi-Object, IR spectroscopy
IFU spectroscopy
NIRCam
NIRSpec
Long Slit spectroscopy
Deep,wide field broadband-imaging
Fine Guidance Sensor
Moving Target Support
FGS/NIRISS
MIRI
Mid-IR, wide-field Imaging
Slitless Spectroscopy
Near-IR imaging
High Contrast Closure Phase Imaging
Mid-IR Coronagraphic Imaging
IFU spectroscopy

NIRCam



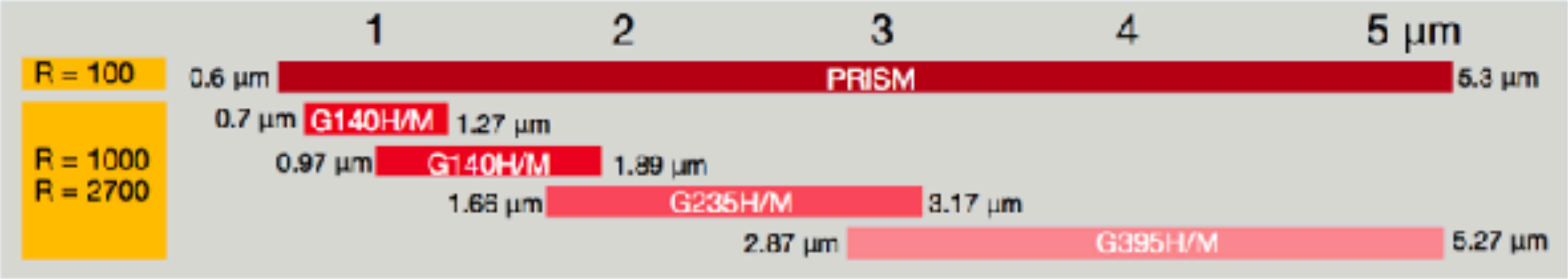


overlapping FOVs imaged simultaneously using a dichroic { short wavelength detectors / long wavelength detectors

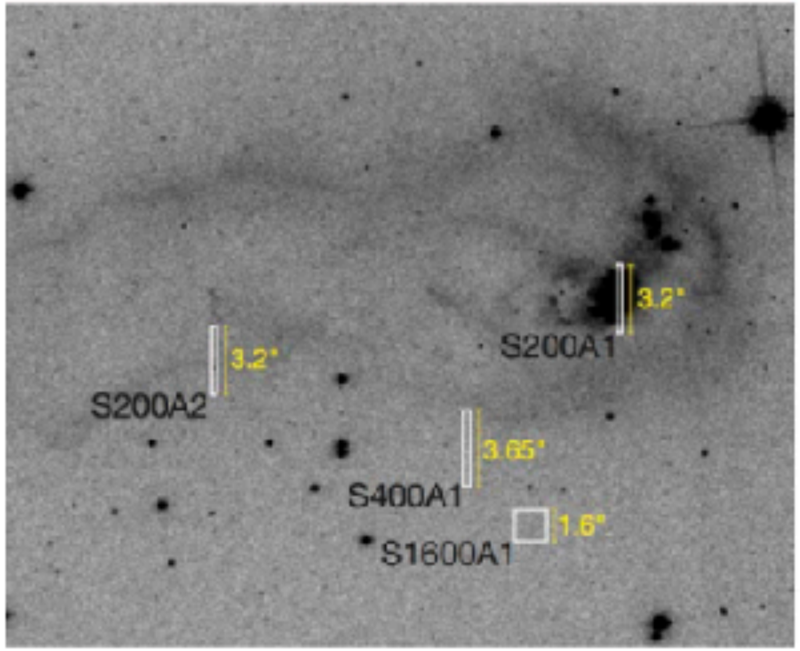
Teledyne HgCdTe H2RG detectors
2048 × 2048 pixels including reference rows and columns insensitive to light

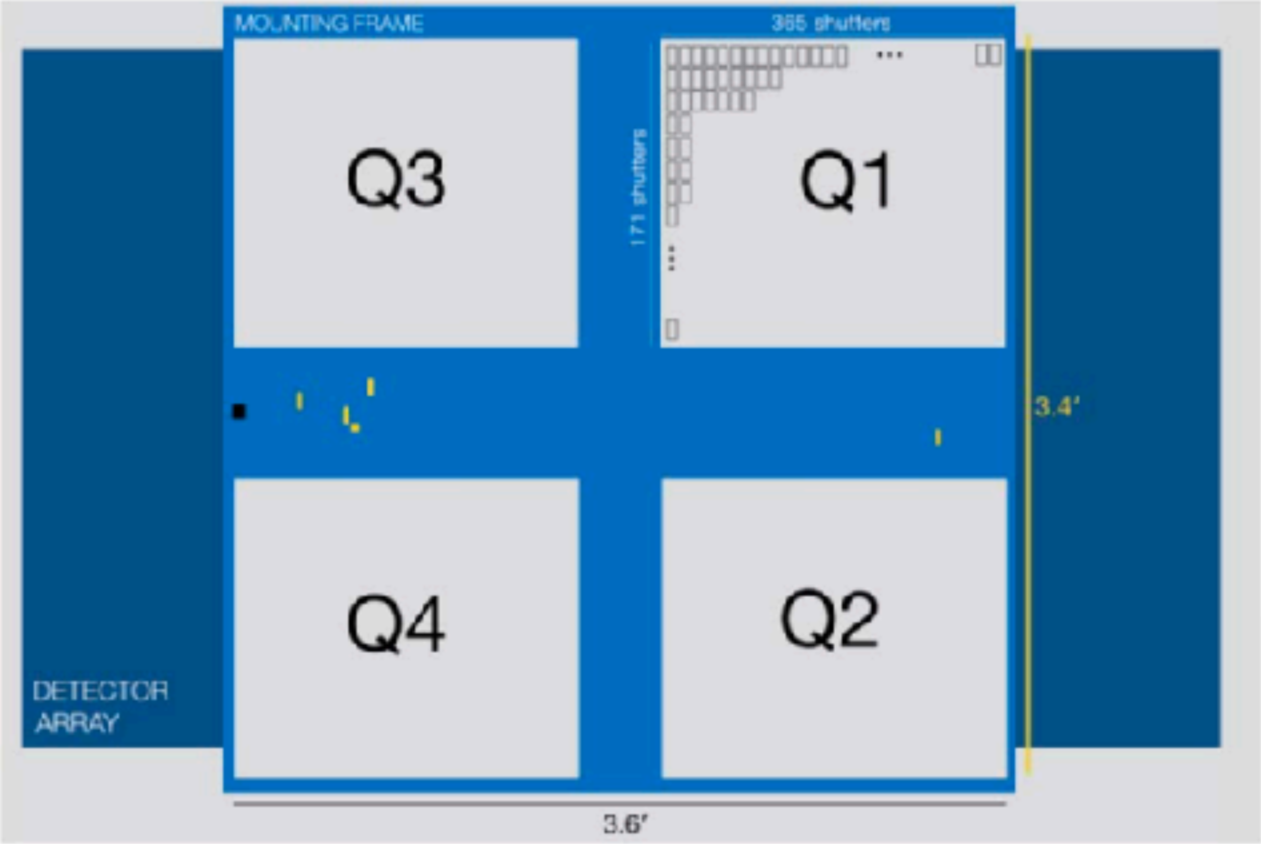
And 2.5-5 micron slitless spectroscopy

NIRSpec



Fixed Slits and BOTS Mode





NIRISS

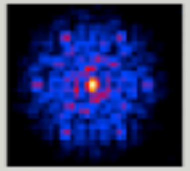
Aperture Masking Interferometry

Non-Redundant Mask (NRM)
+ Medium-Band "Red" Filters

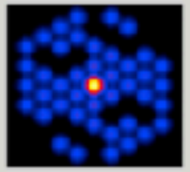
7-hole aperture mask with 21 distinct ("non-redundant") separations ("baselines")

Mask

Michelson:
$\delta\theta = 0.5\ \lambda / D$



NRM PSF (Interferogram)



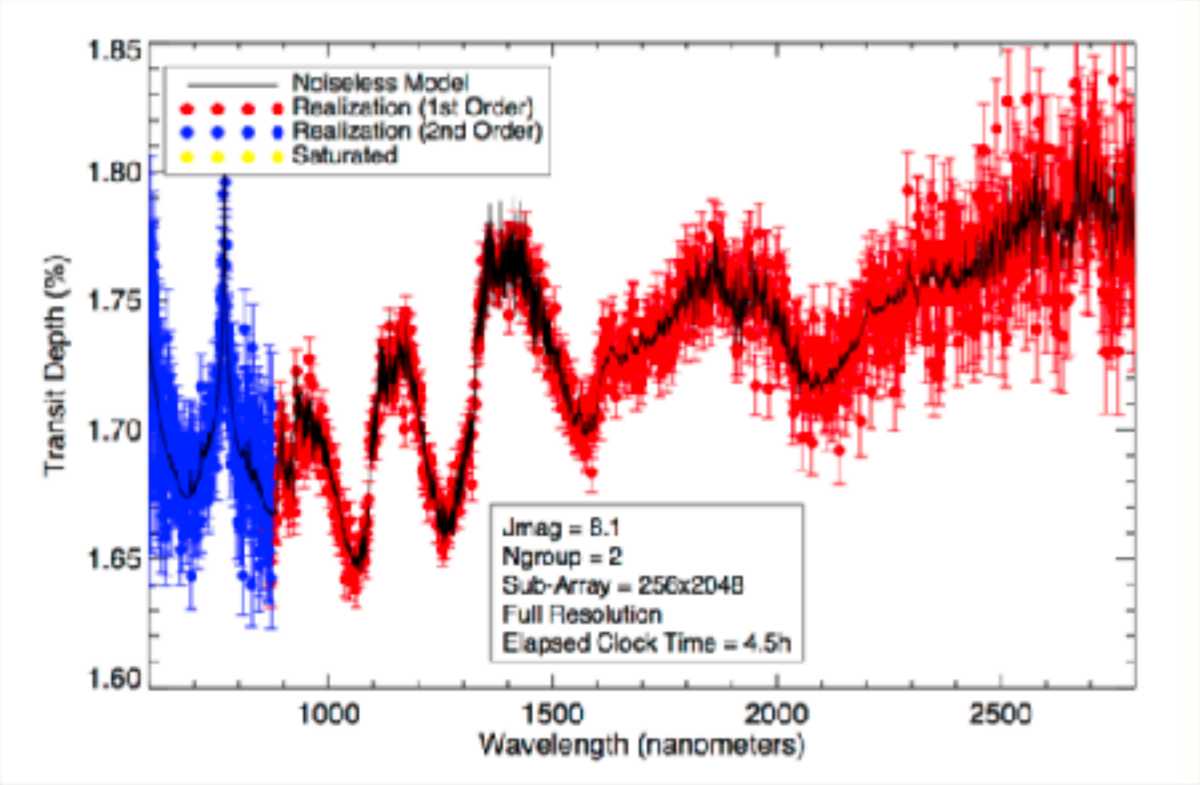
Fourier Transform

NIRISS AMI enables exoplanet detection at 3.8, 4.3, and 4.8 μm around stars as bright as M'~4, reaching 10^{-4} contrast at separations of 70–400 milli-arcseconds. It provides lower contrast at 2.8 μm with the F277W filter.

Image reconstruction is also enabled.

Single-Object Slitless Spectroscopy with NIRISS

Simulated NIRISS/SOSS spectrum of the atmosphere of WASP 69b
Model courtesy of Björn Benneke



Wide-Field Slitless Spectroscopy with NIRISS: Simulations of MACS J0416.1-2403

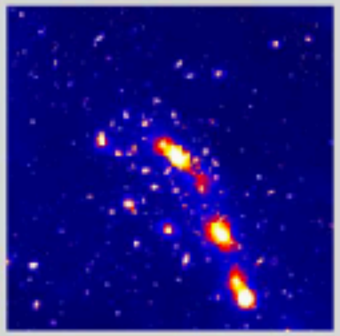
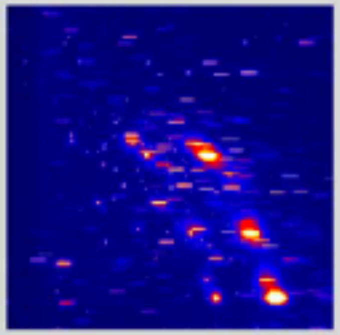
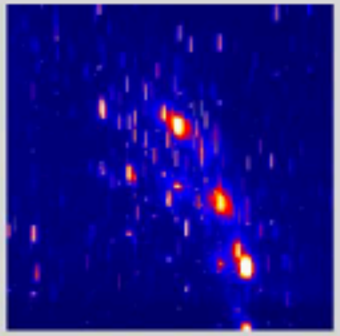


Image: F200W

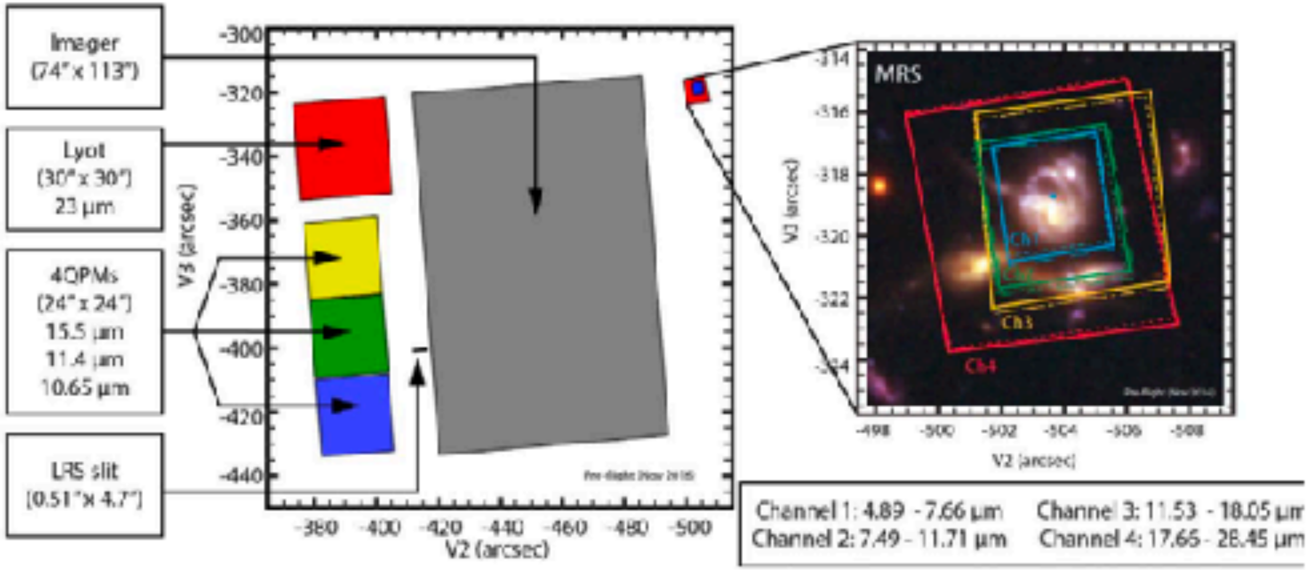


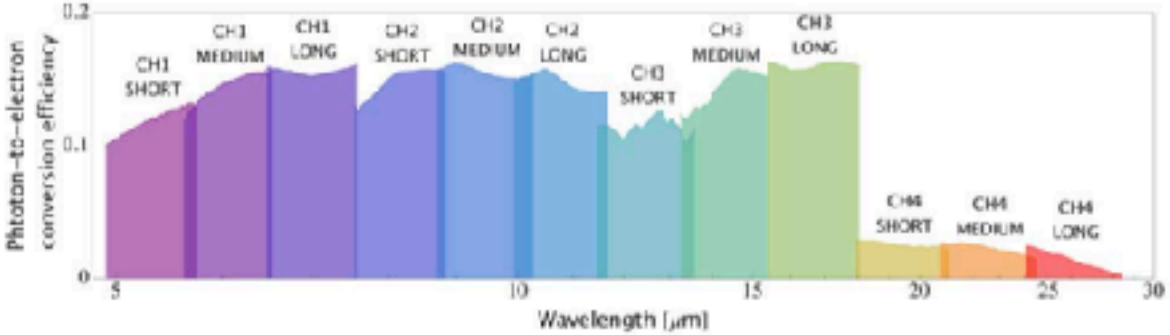
Spectra: GR150C, F200W

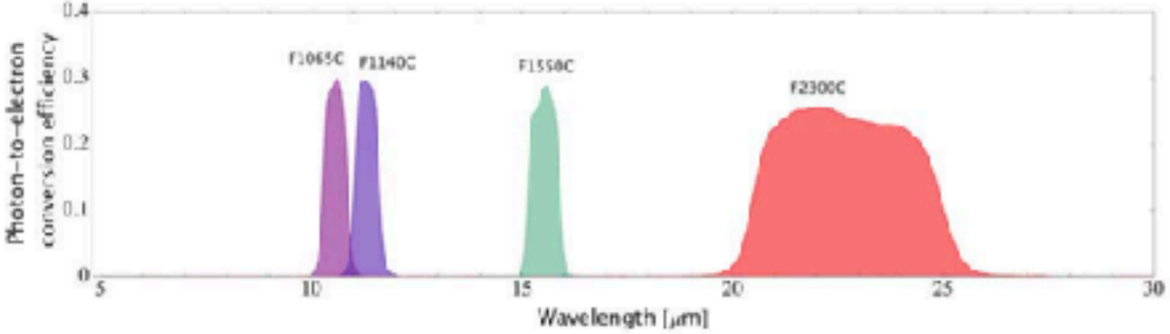


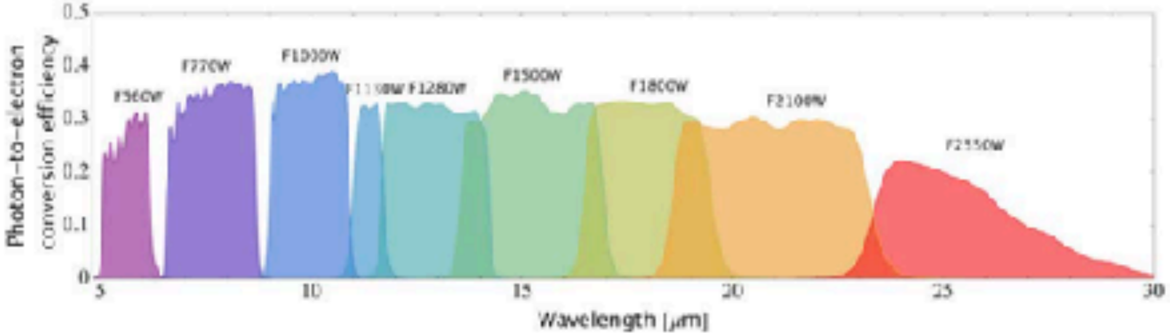
Spectra: GR150R, F200W

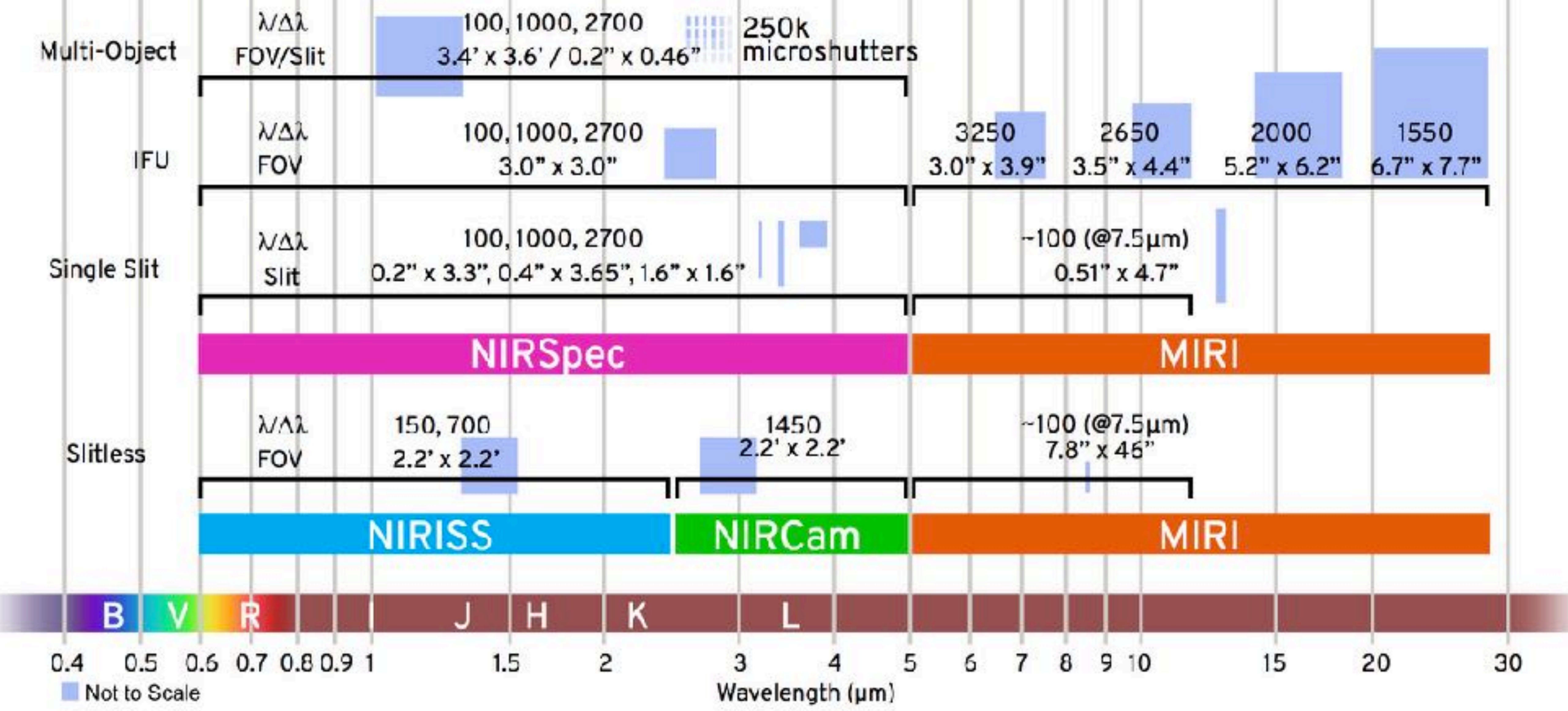
MIRI


Imager
(74" x 113")
Lyot
(30" x 30")
23 µm
4QPMs
(24" x 24")
15.5 µm
11.4 µm
10.65 µm
LRS slit
(0.51" x 4.7")
V3 (arcsec)
V2 (arcsec)
MRS
Ch1
Ch3
Ch4
V3 (arcsec)
V2 (arcsec)
Channel 1: 4.89 - 7.66 µm
Channel 2: 7.49 - 11.71 µm
Channel 3: 11.53 - 18.05 µm
Channel 4: 17.66 - 28.45 µm

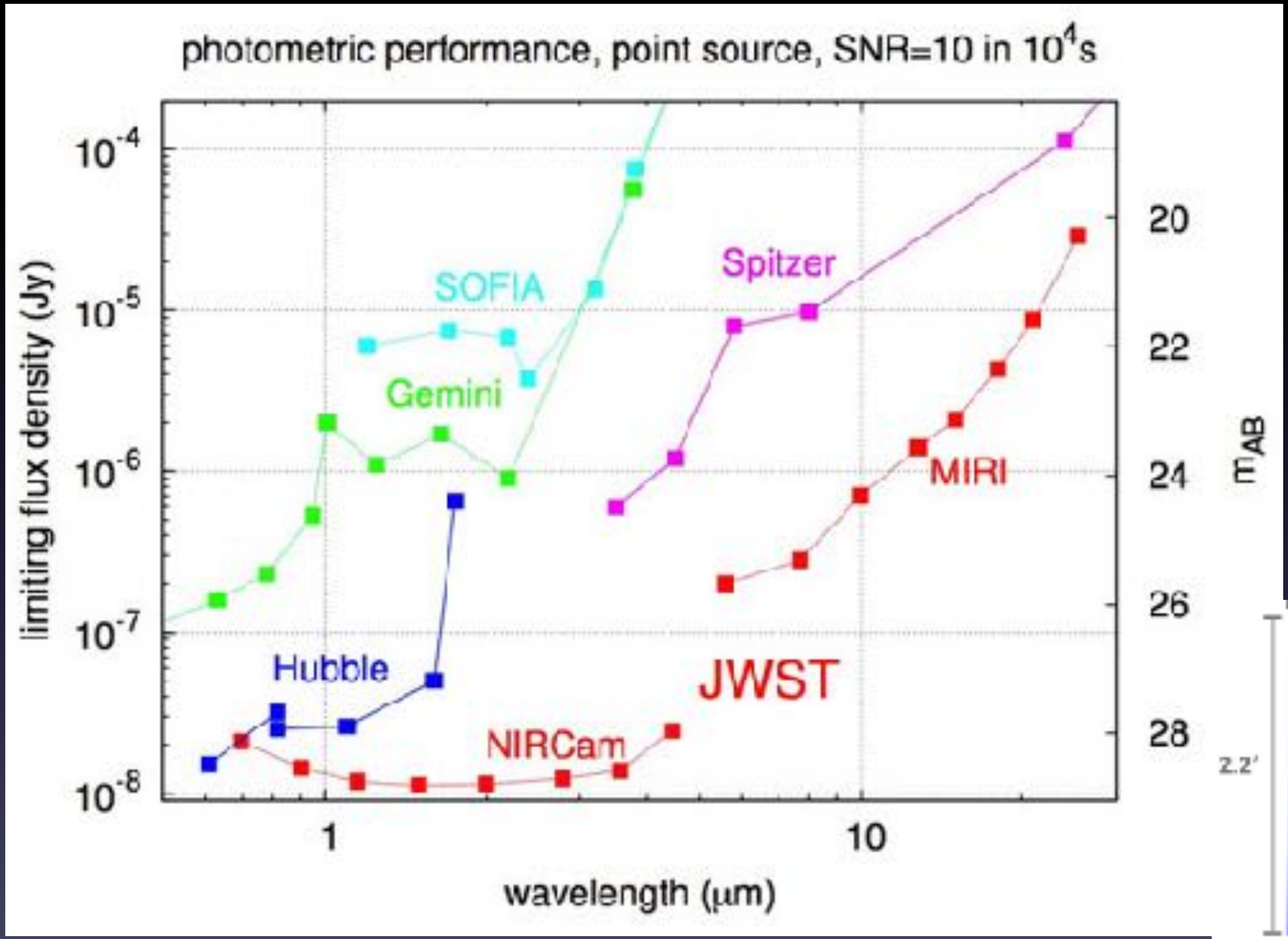

Photon-to-electron conversion efficiency
CH1 SHORT
CH1 MEDIUM
CH1 LONG
CH2 SHORT
CH2 MEDIUM
CH2 LONG
CH3 SHORT
CH3 MEDIUM
CH3 LONG
CH4 SHORT
CH4 MEDIUM
CH4 LONG
Wavelength [µm]


Photon-to-electron conversion efficiency
F1065C
F1140C
F1550C
F2300C
Wavelength [µm]


Photon-to-electron conversion efficiency
F560W
F770W
F1000W
F1280W
F1500W
F1800W
F2100W
F2550W
Wavelength [µm]

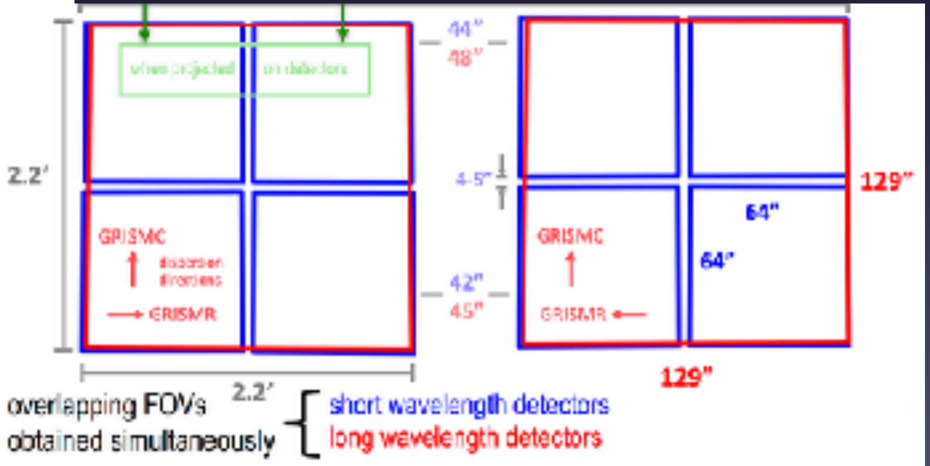

Multi-Object
λ/Δλ
FOV/Slit
100, 1000, 2700
3.4' x 3.6' / 0.2" x 0.46"
250k
microshutters
IFU
λ/Δλ
FOV
100, 1000, 2700
3.0" x 3.0"
3250
3.0" x 3.9"
2650
3.5" x 4.4"
2000
5.2" x 6.2"
1550
6.7" x 7.7"
Single Slit
λ/Δλ
Slit
100, 1000, 2700
0.2" x 3.3", 0.4" x 3.65", 1.6" x 1.6"
~100 (@7.5μm)
0.51" x 4.7"
NIRSpec
MIRI
Slitless
λ/Δλ
FOV
150, 700
2.2' x 2.2'
1450
2.2' x 2.2'
~100 (@7.5μm)
7.8" x 46"
NIRISS
NIRCam
MIRI
B V R I J H K L
0.4 0.5 0.6 0.7 0.8 0.9 1 1.5 2 3 4 5 6 7 8 9 10 15 20 30
Not to Scale
Wavelength (μm)

JWST's exquisite sensitivities: photometry

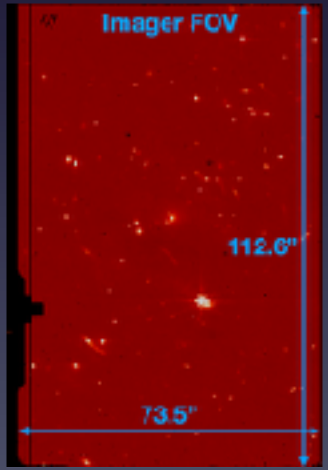


Instrument	Wavelength range	Mode of use
NIRCam	0.6 μm < λ < 5 μm	Primary or parallel
MIRI	5.6 μm < λ < 25.5 μm	Primary or parallel
NIRISS	0.8 μm < λ < 5 μm	Primary or parallel

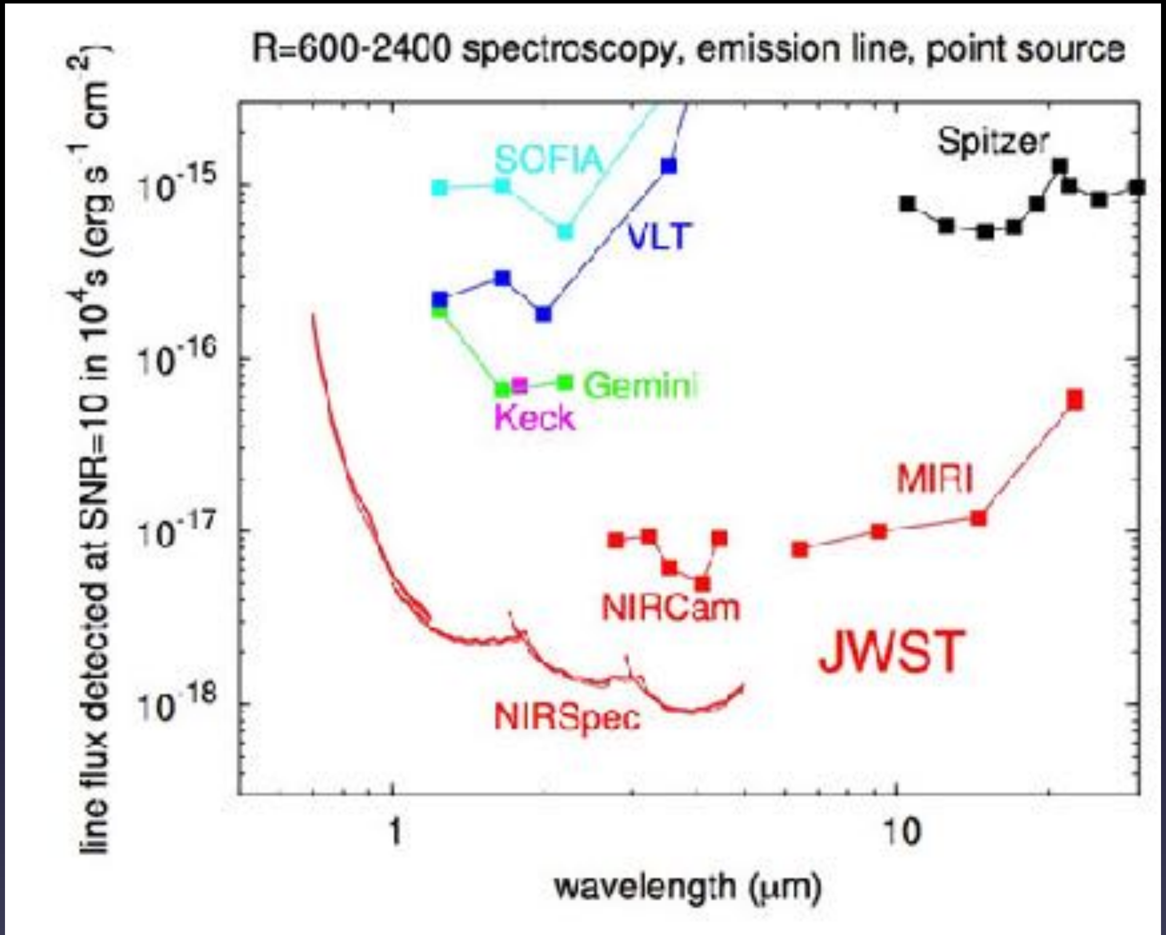
NIRCam

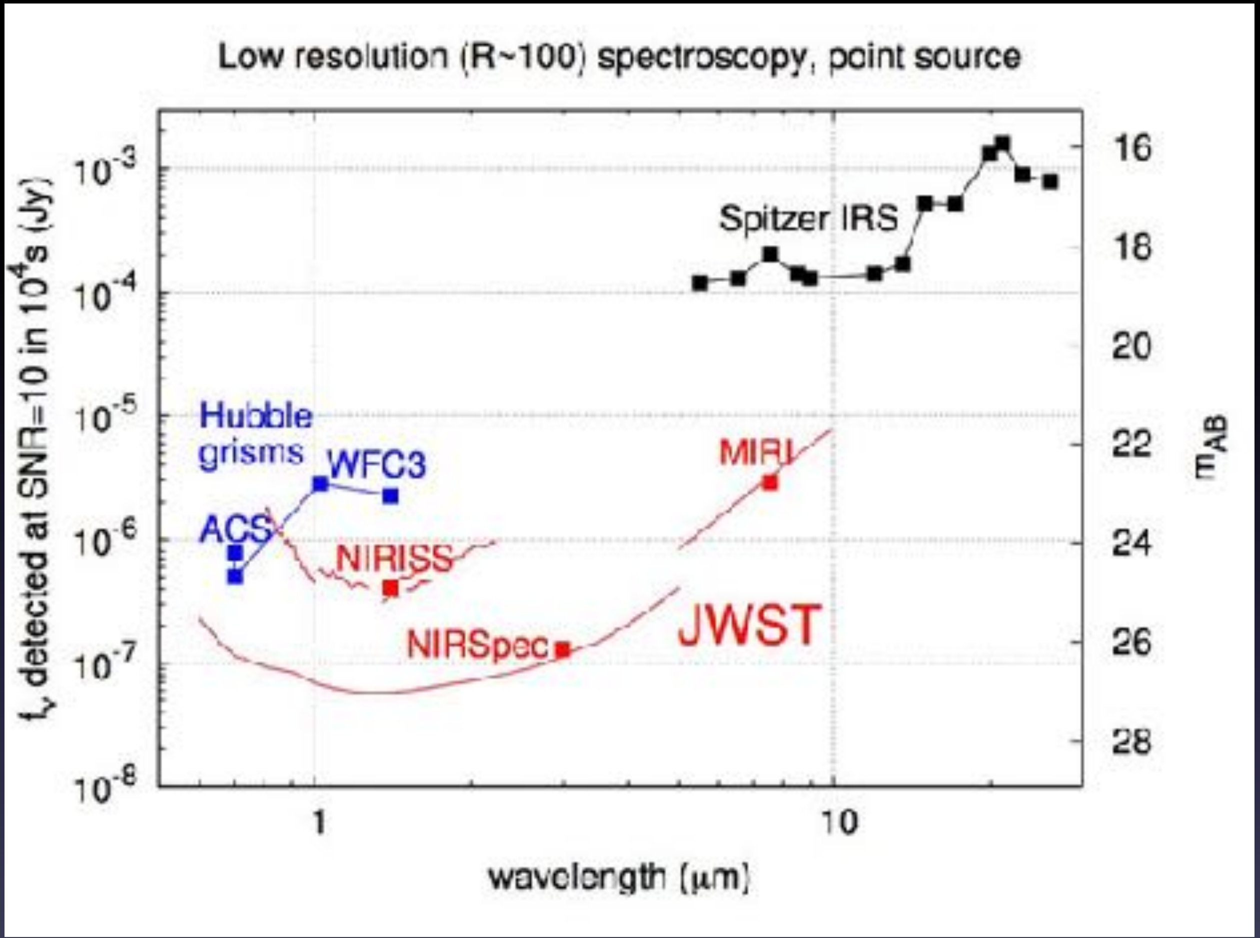


MIRI



JWST's exquisite sensitivities: spectroscopy

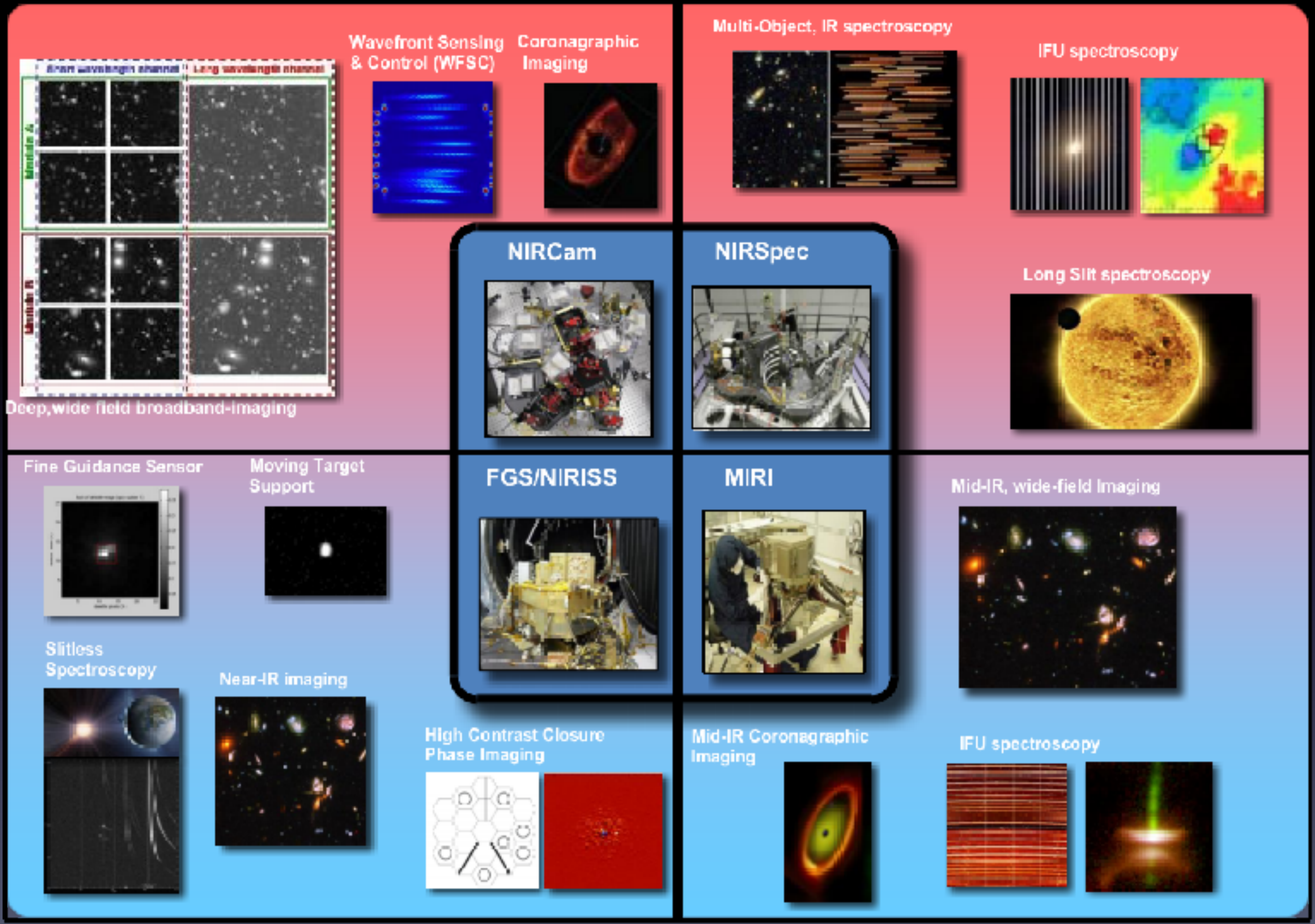




- 100x Gemini at 2 μm: low IR background in space
- 50x Spitzer at 8 μm: large aperture cryogenic telescope

Li, Cai, **WX** et al.
submitted to ApJS

WX et al. 2022
ApJL, 938, L16

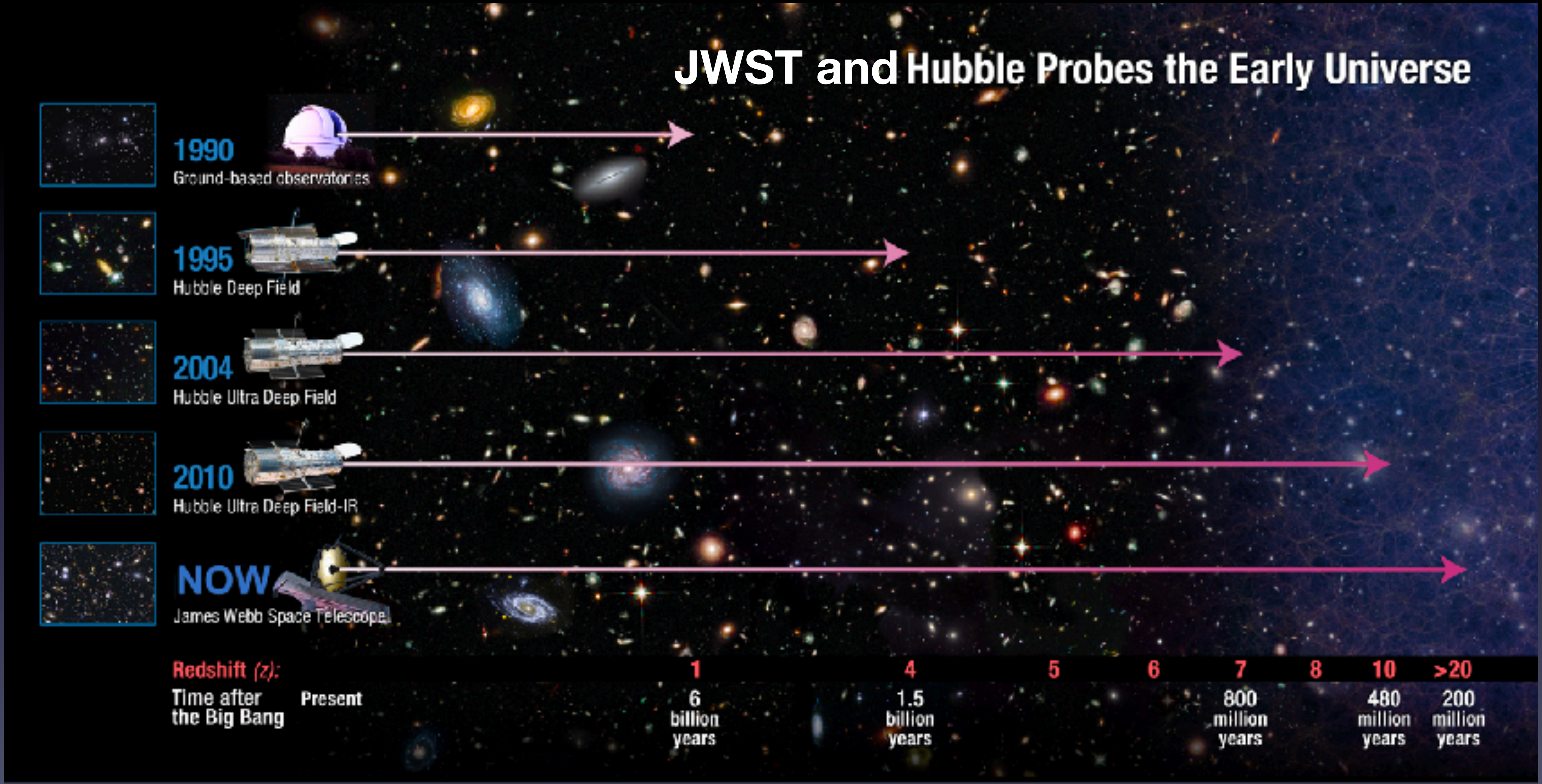


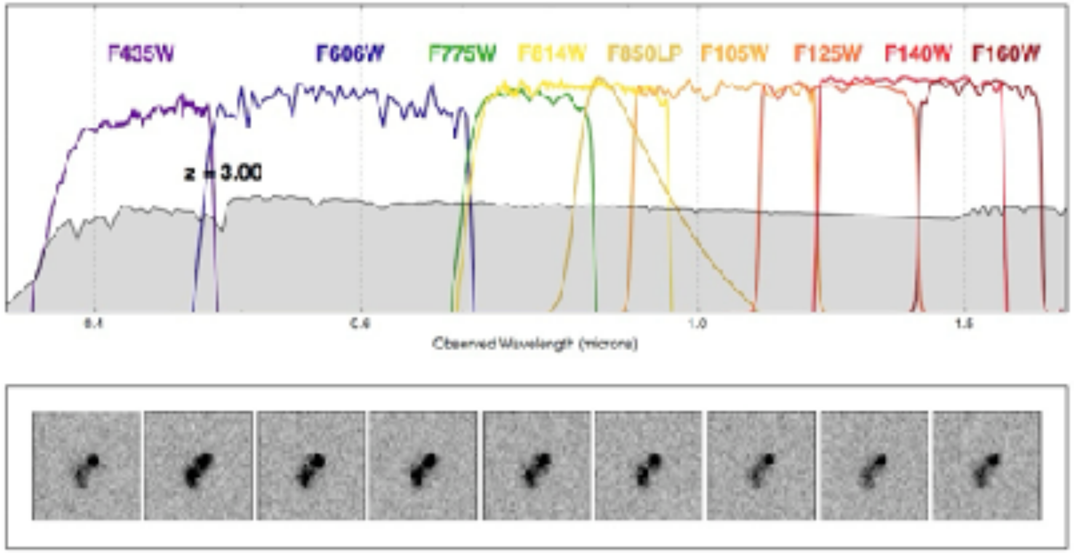
WX et al. 2024
ApJL, 967, L42

Goldsmith, Wang, **WX** et al. 2025, ApJL, 985, L4

The pursuit of the redshift frontier

Advancing the redshift frontier with HST and JWST

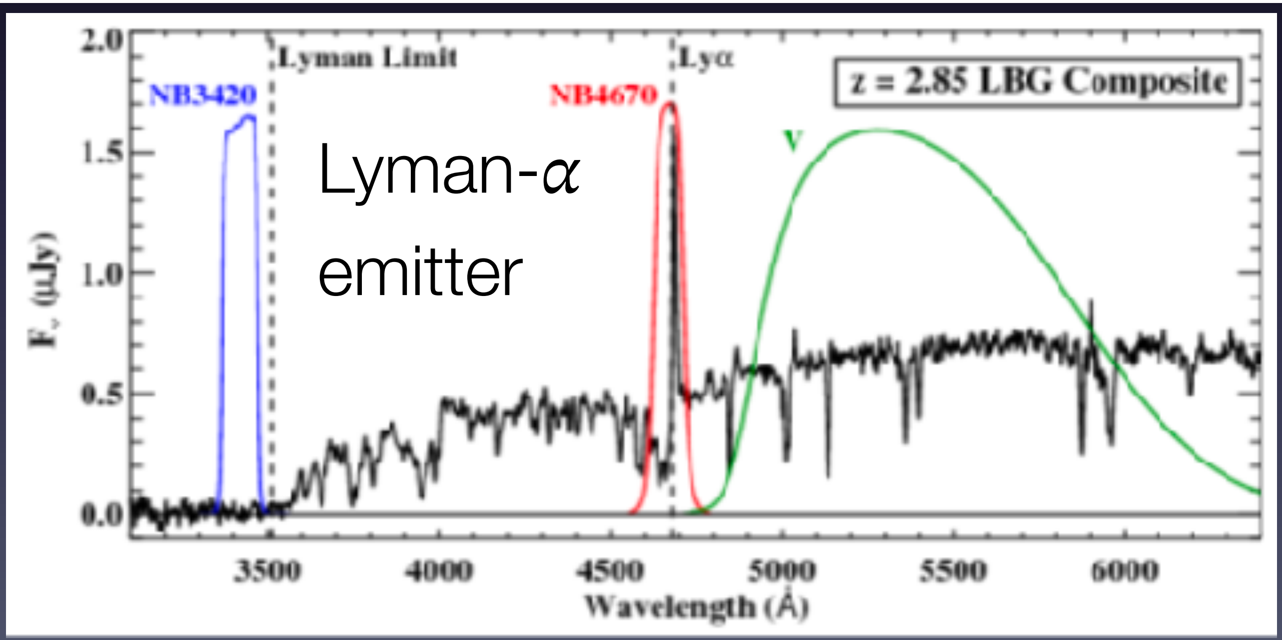




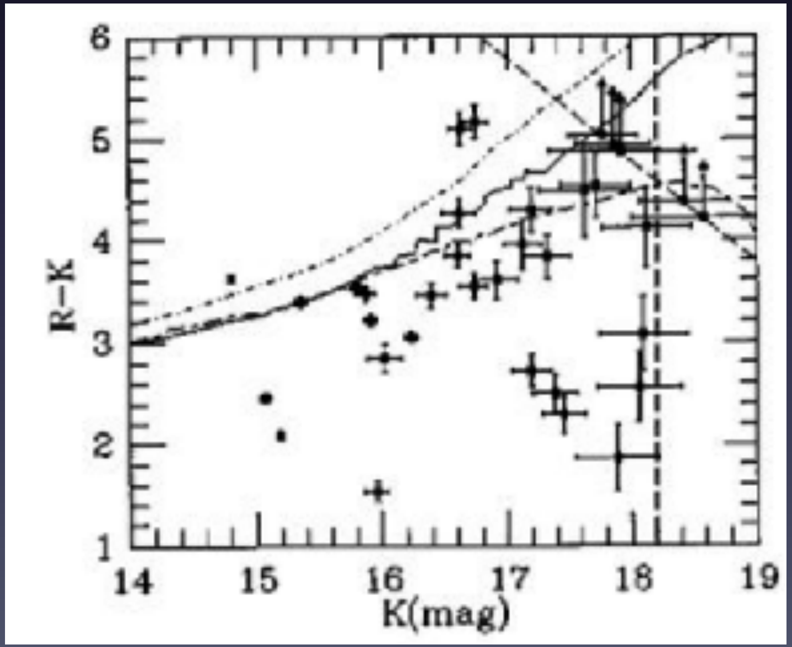
Lyman-break galaxies (LBGs)

sub-millimeter galaxies (SMGs)

Extremely Red Objects (EROs)



Lyman-α emitter

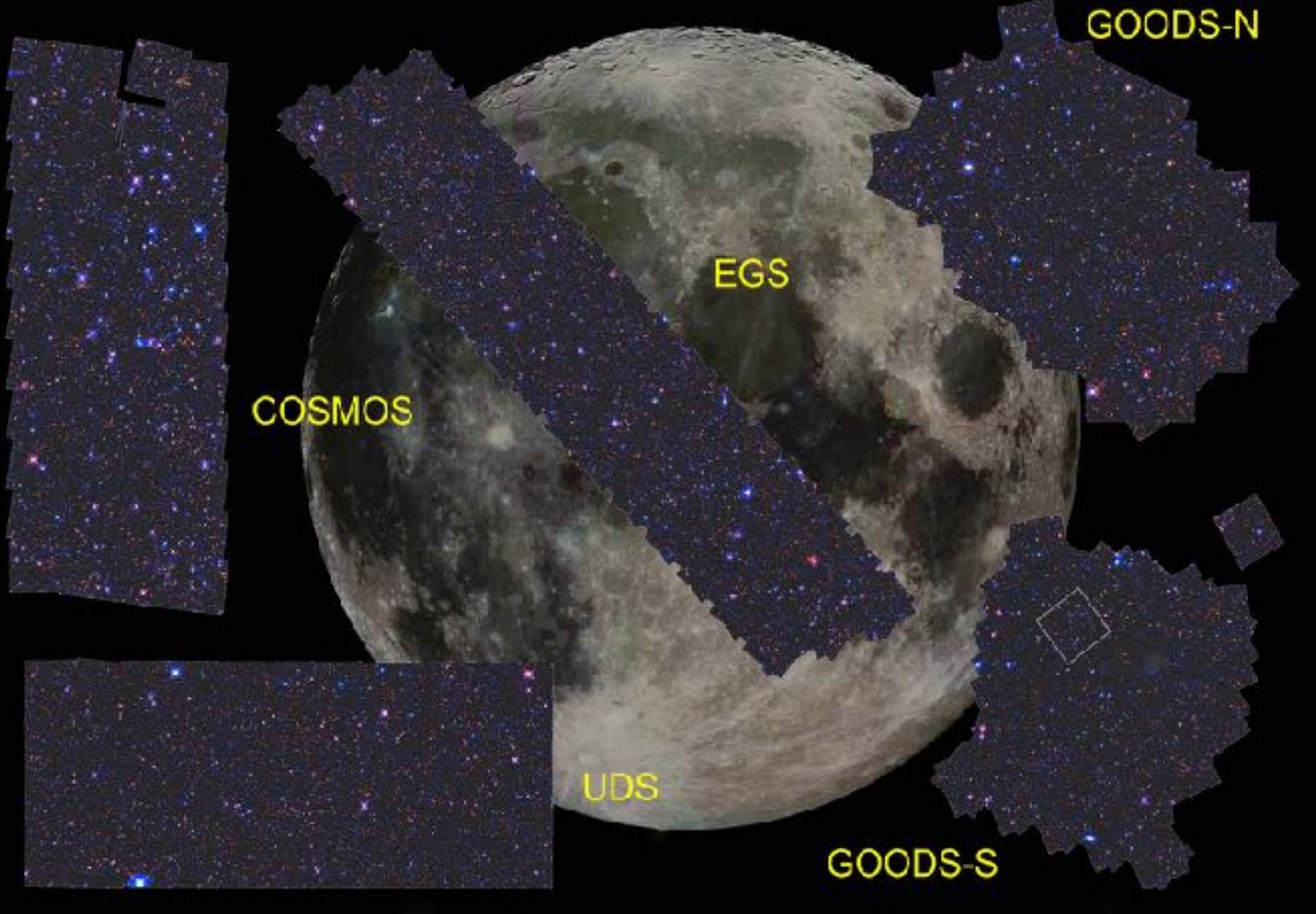


- LBGs
- LAEs
- BzK
- BX/BM
- LAEs
- SMGs
- DOGs

HST's legacy extragalactic fields: (UV)CANDELS

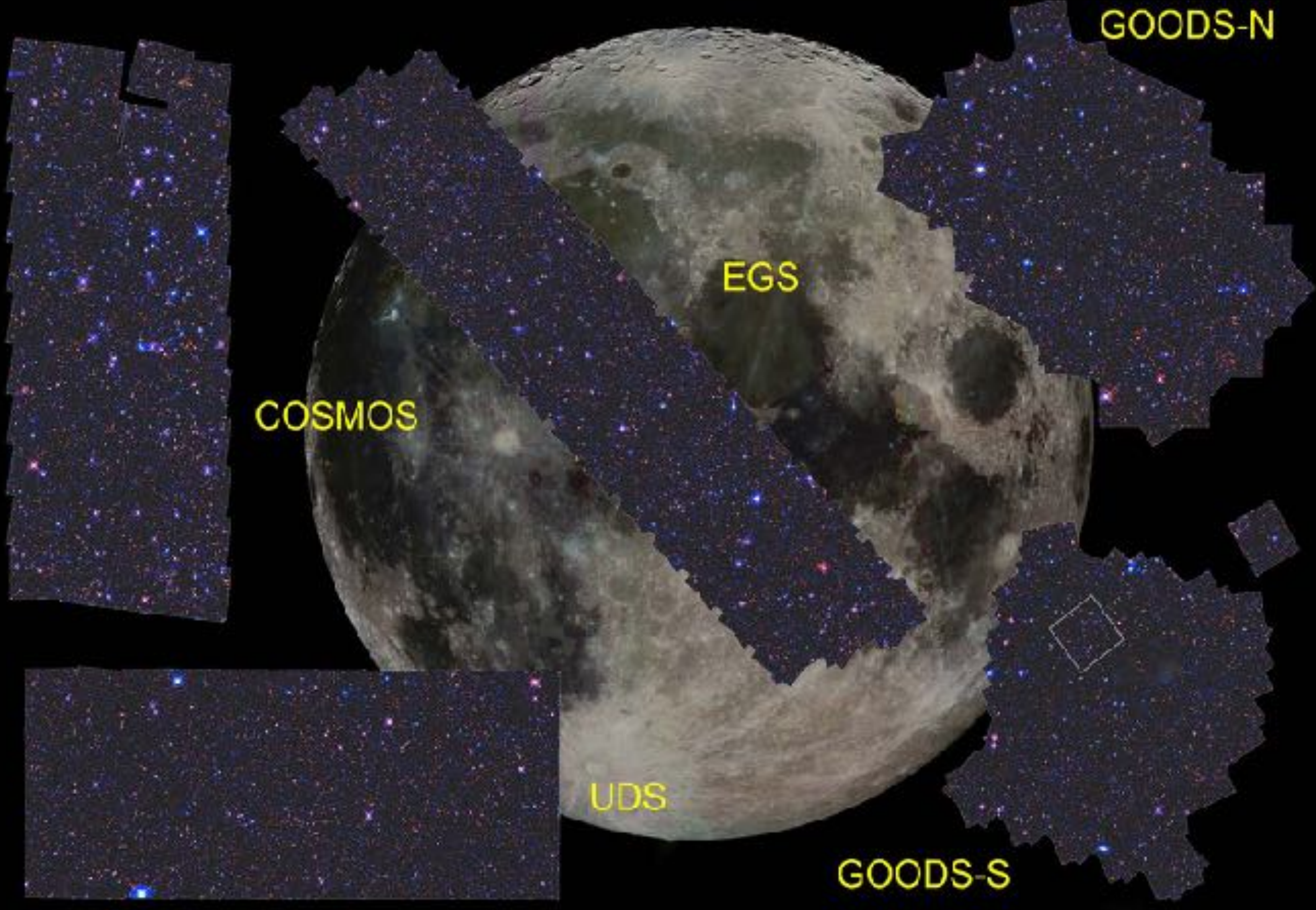
- CANDELS is *Hubble*'s largest survey of distant galaxies that observes five fields in separate parts of the sky in optical and near-infrared wavelengths.

Grogin+11; Koekemoer+11

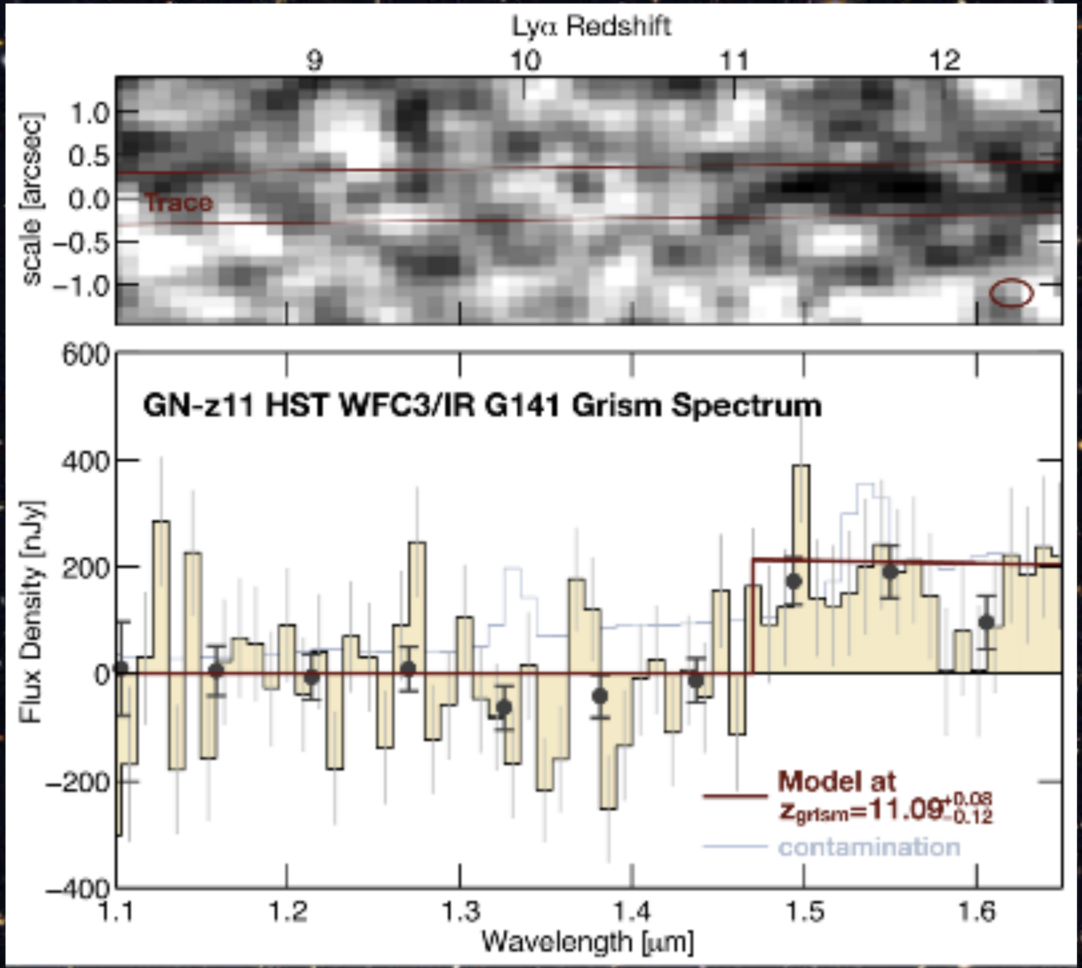


HST's legacy extragalactic fields: (UV)CANDELS

- CANDELS is *Hubble*'s largest survey of distant galaxies that observes five fields in separate parts of the sky in optical and near-infrared wavelengths.
- UVCANDELS adds the blue-optical and UV images to four of these CANDELS fields with total sky coverage about 60% of that by the full moon.

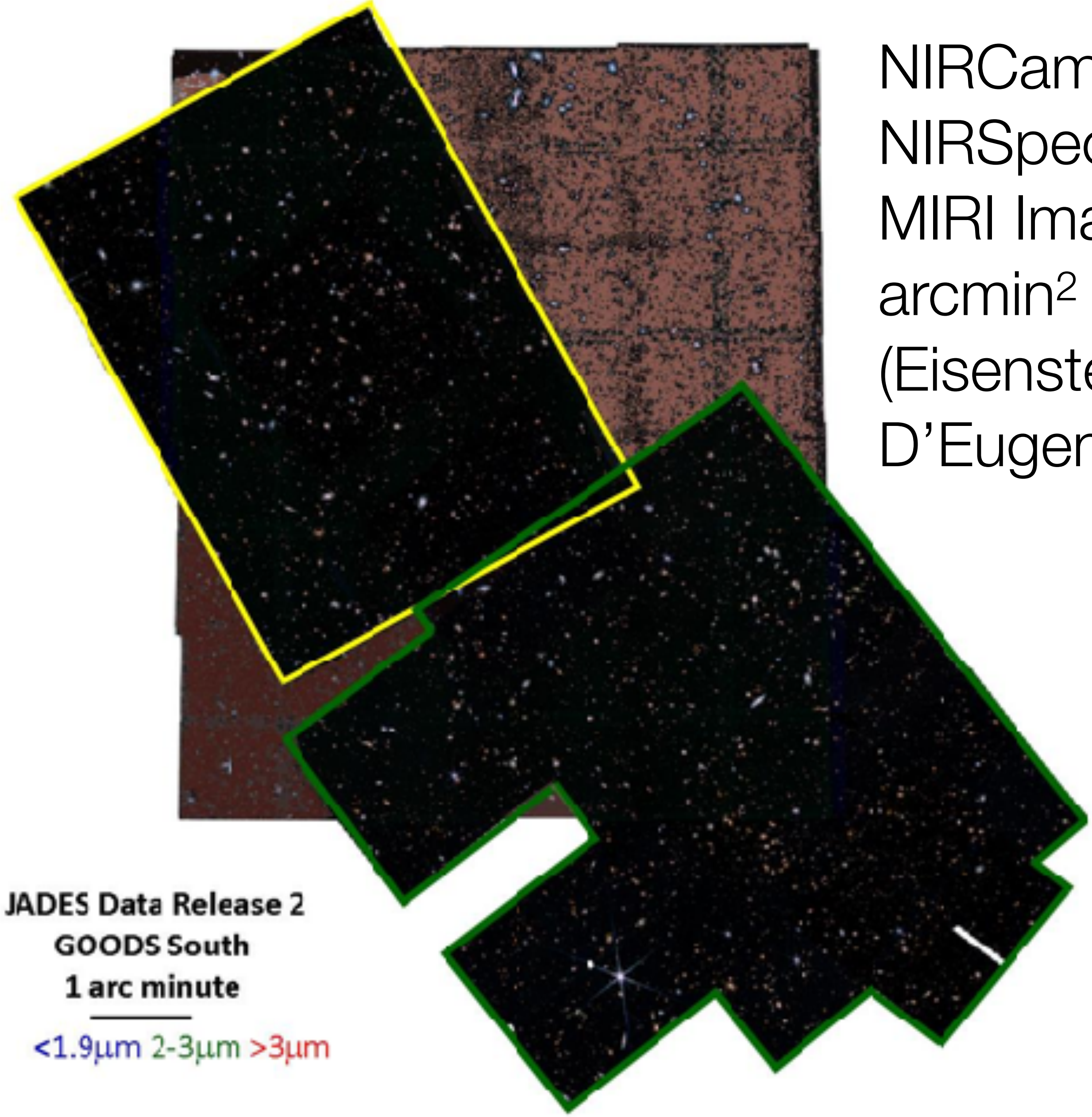


Sun, **WX**+24; **WX**+25

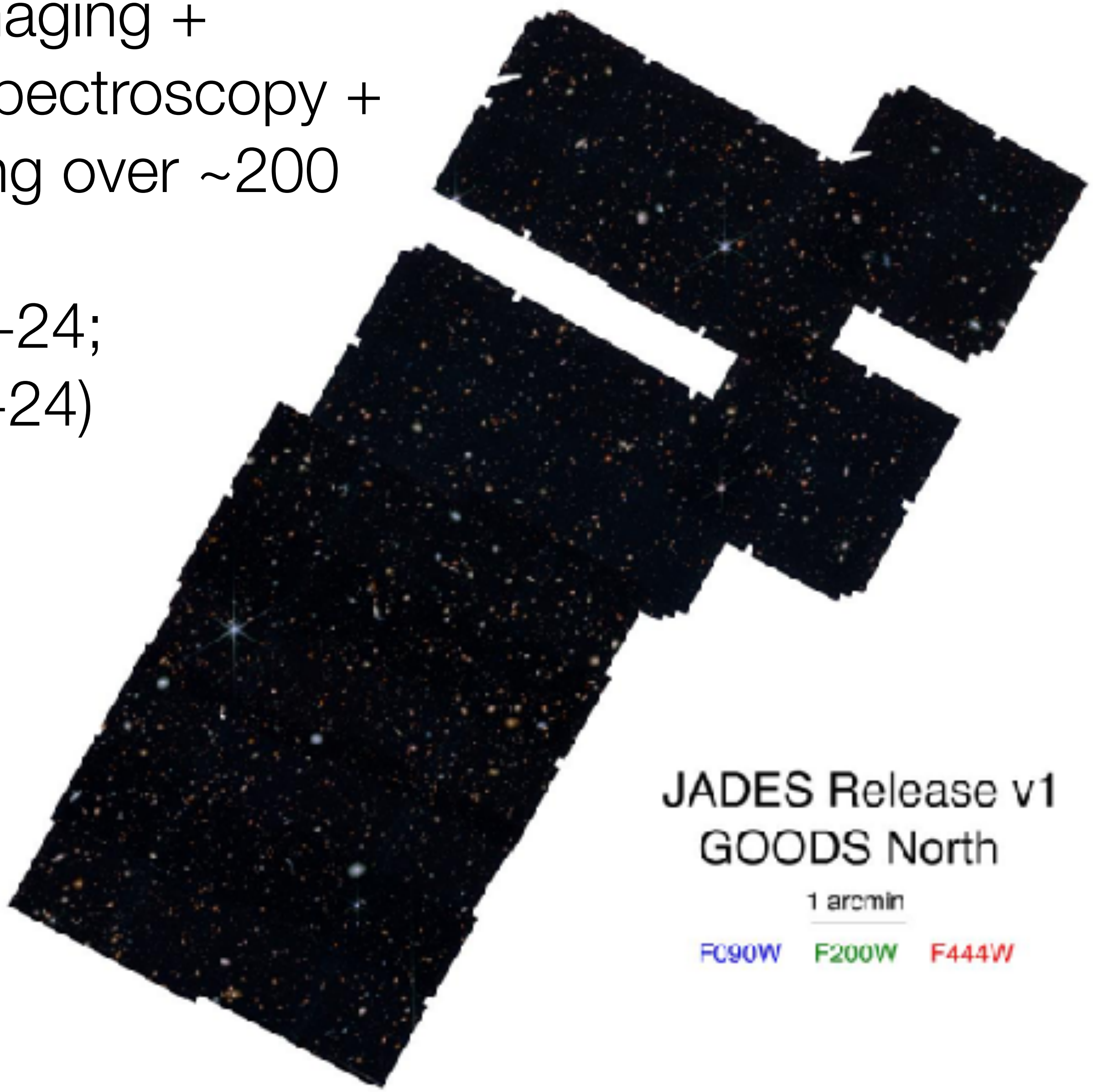


GN-z11 was the most distant and brightest among galaxy candidates during reionization observed with HST. Oesch+2016 measured its spec-z to be 11.09

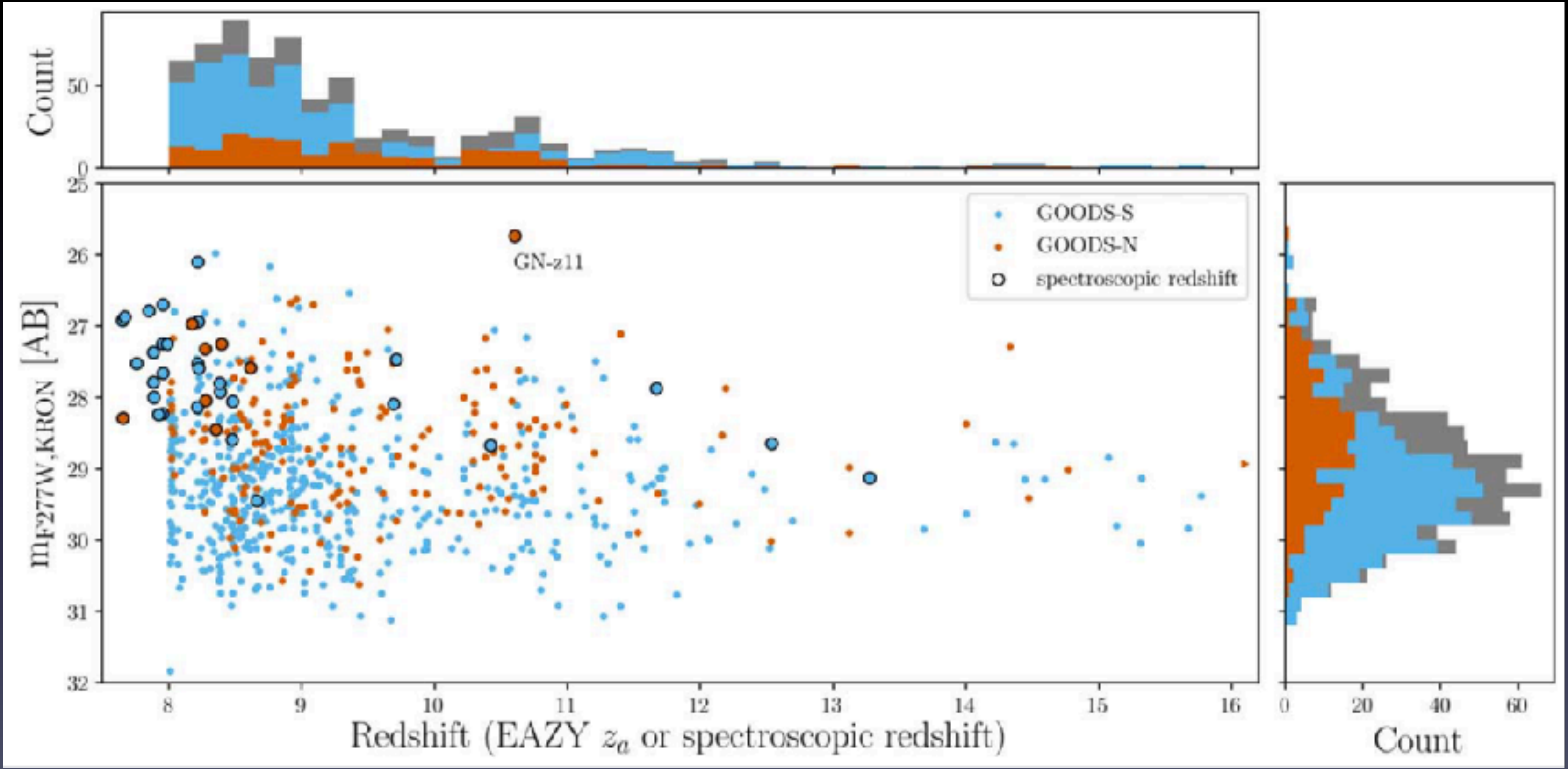
JWST Advanced Deep Extragalactic Survey



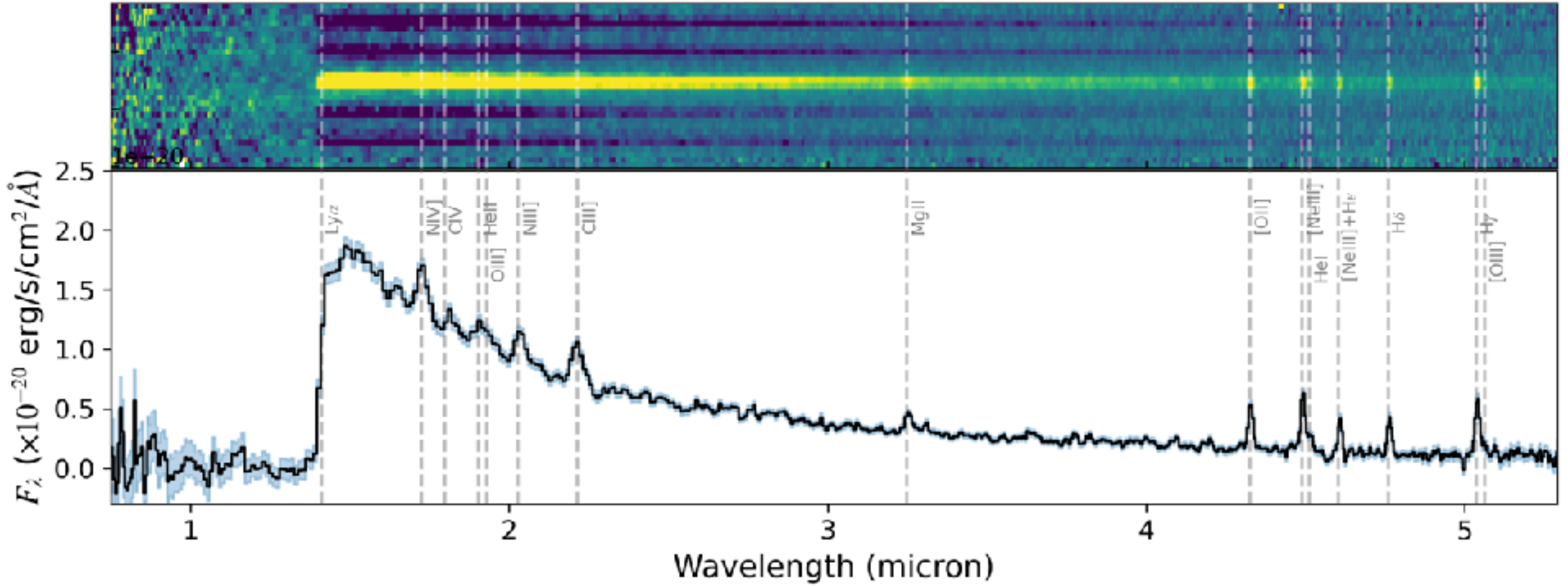
NIRCam Imaging +
NIRSpec Spectroscopy +
MIRI Imaging over ~200 arcmin^2
(Eisenstein+24;
D'Eugenio+24)



JADES high-z galaxy candidates: Hainline+23

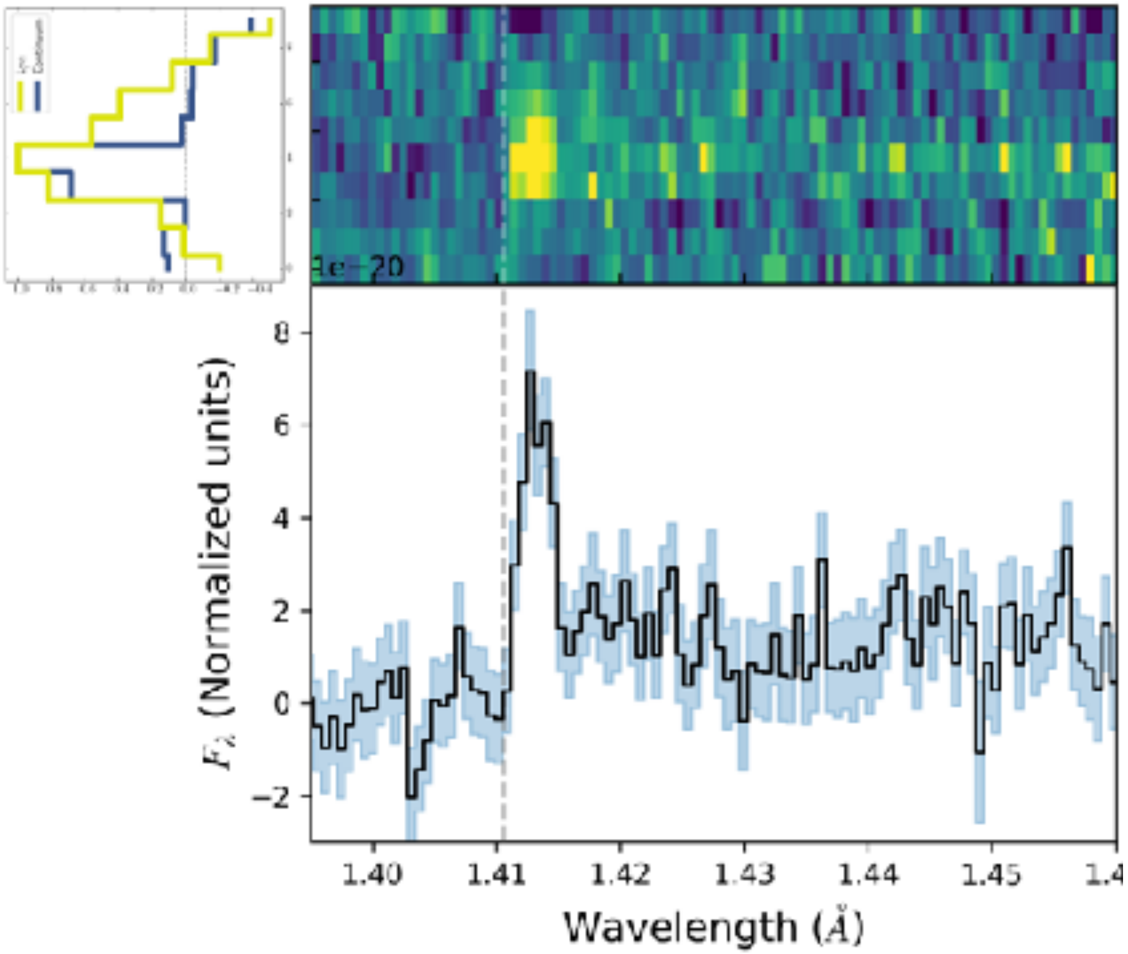


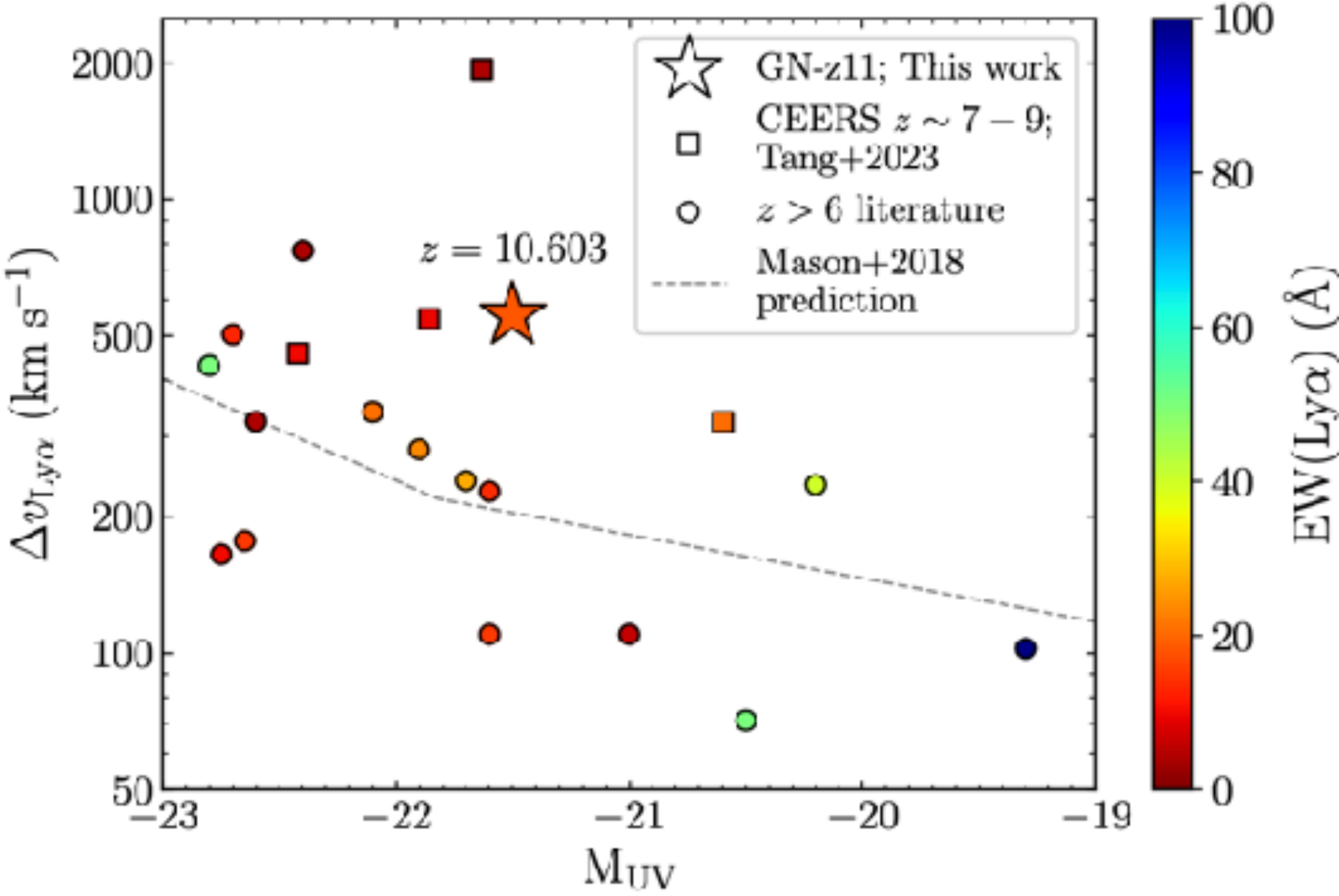
JADES spectroscopy of GN-z11: Bunker+23



We see a plethora of strong emission lines, pinpointing spec-z to be 10.603!

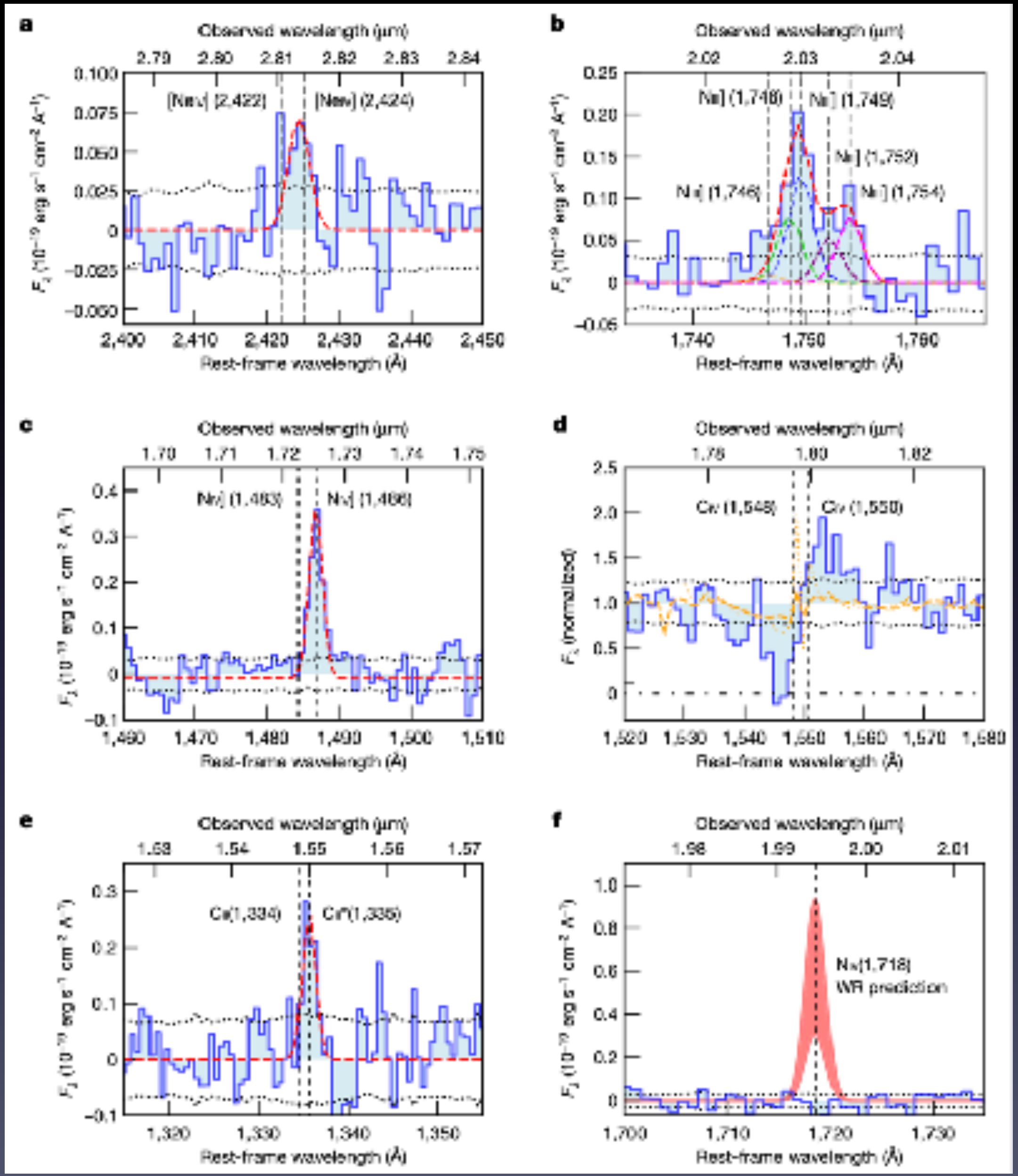
JADES spectroscopy of GN-z11: Bunker+23

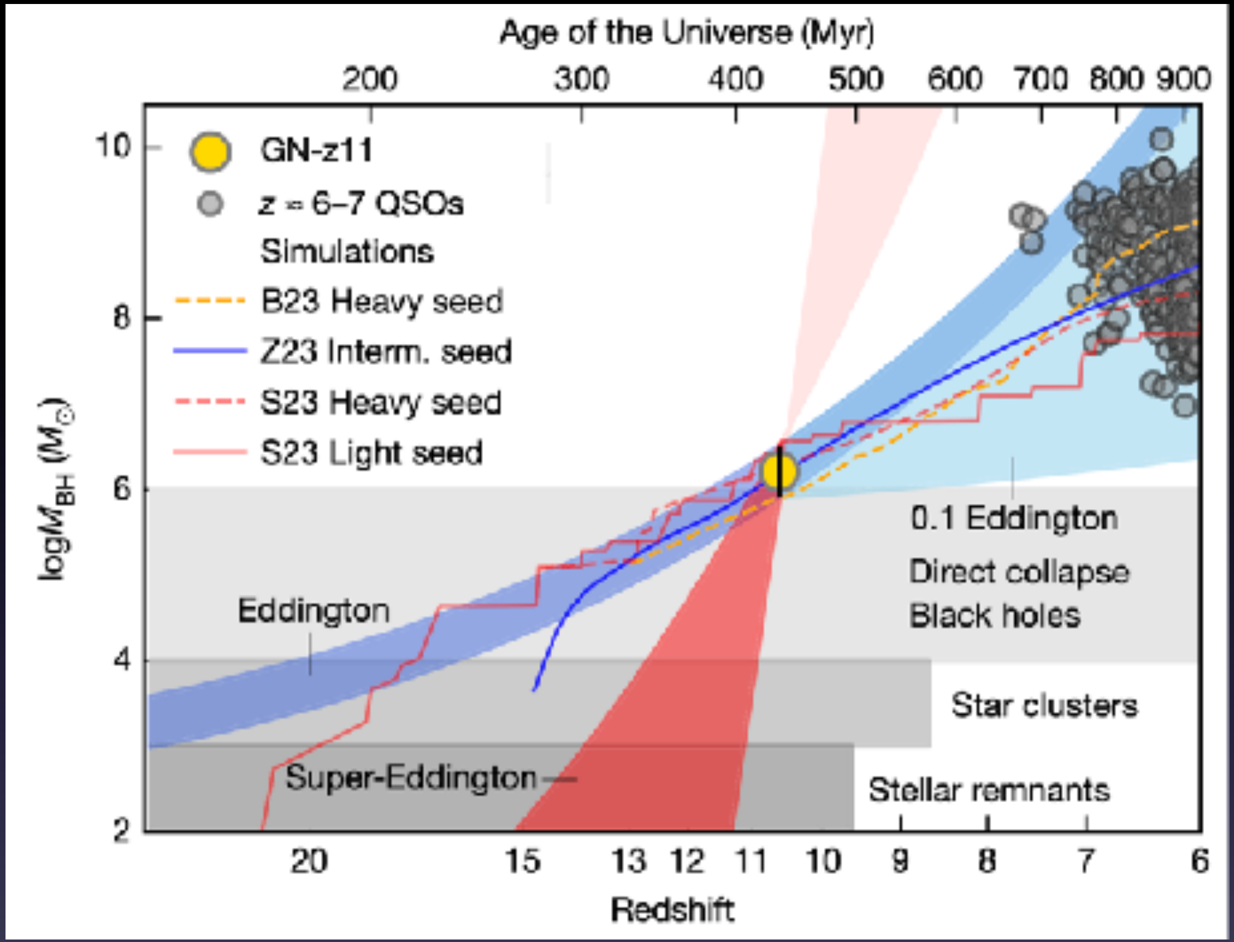




Lyα emission being offset from by 555 km/s from the systemic redshift, and can be explained by back-scattering from the far side of galactic-scale outflows.

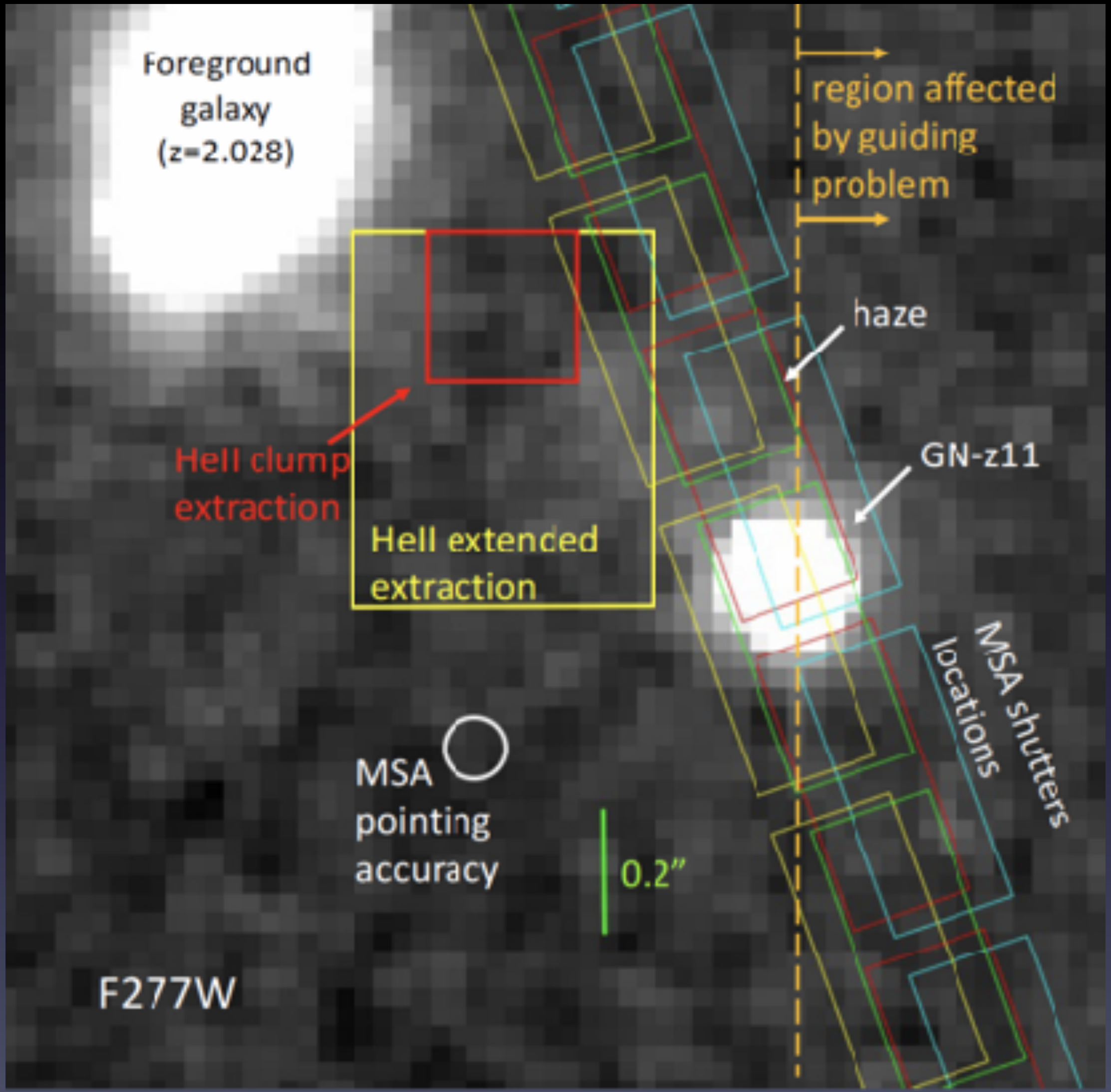
An accreting BH in the center of GN-z11

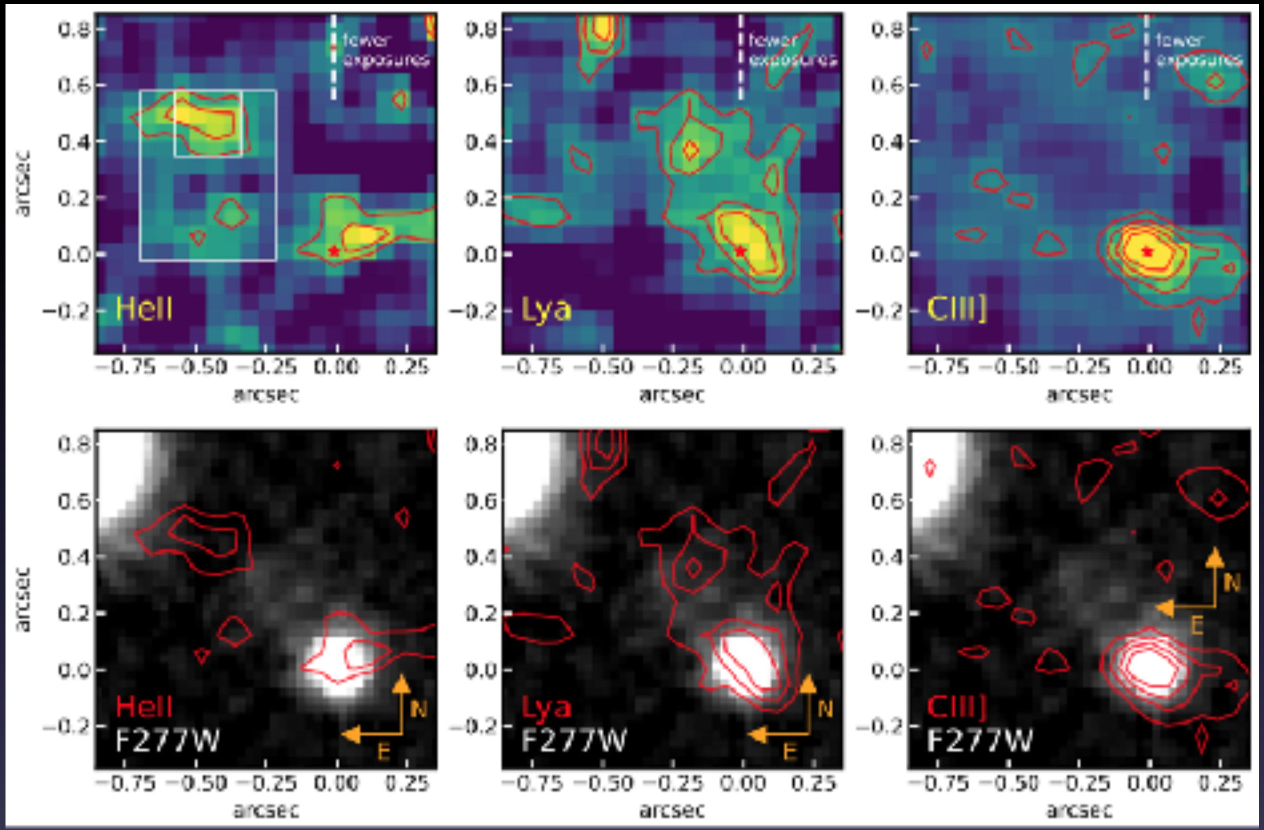




Strong [Ne IV] λλ2422,2424 doublet in medium-res NIRSpec spectra => signature of AGN ionization (Maiolino+24)

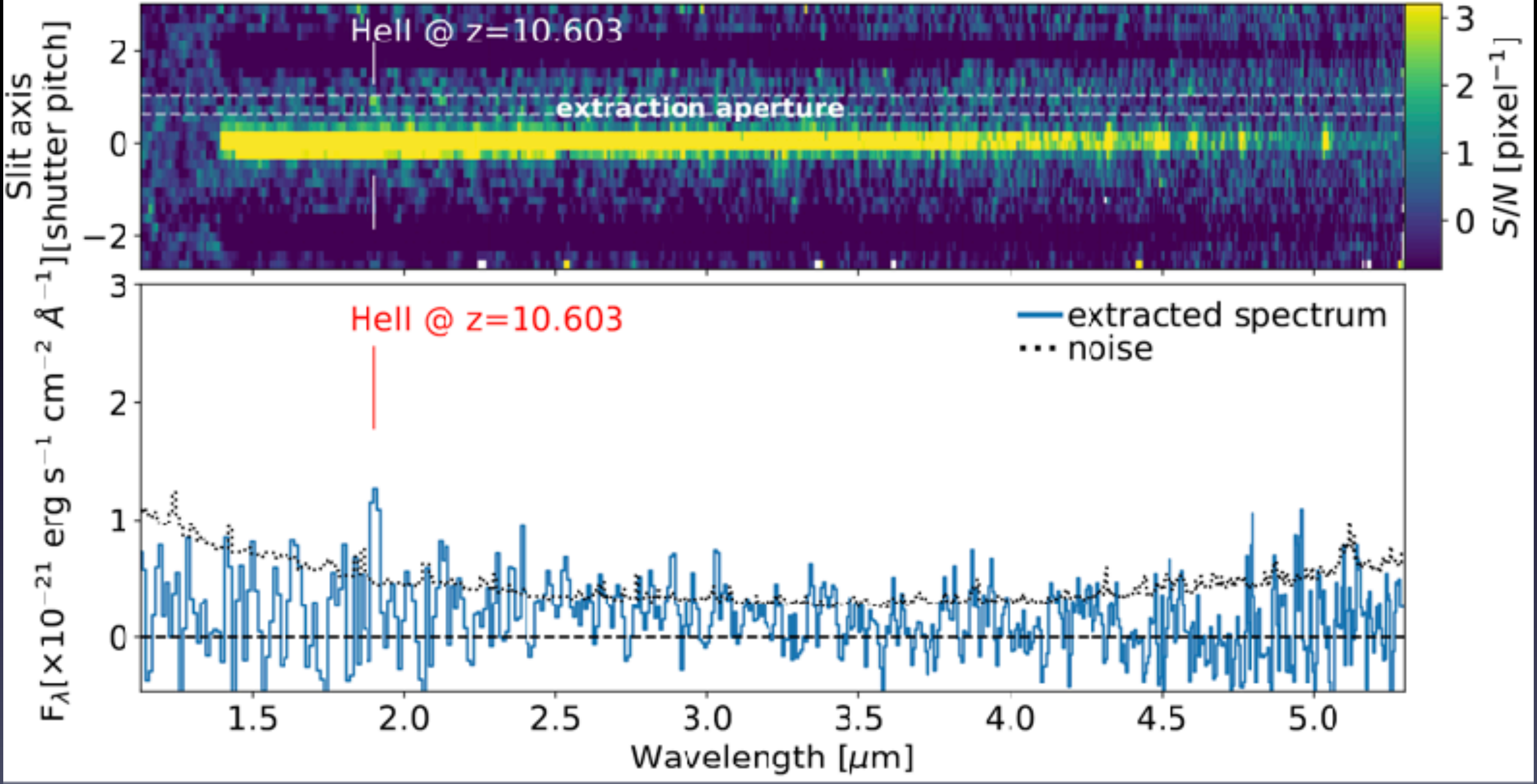
Possible Population III signatures in the halo of GN-z11





He II λ1640 detection in the outskirt of GN-z11 (Maiolino+23)

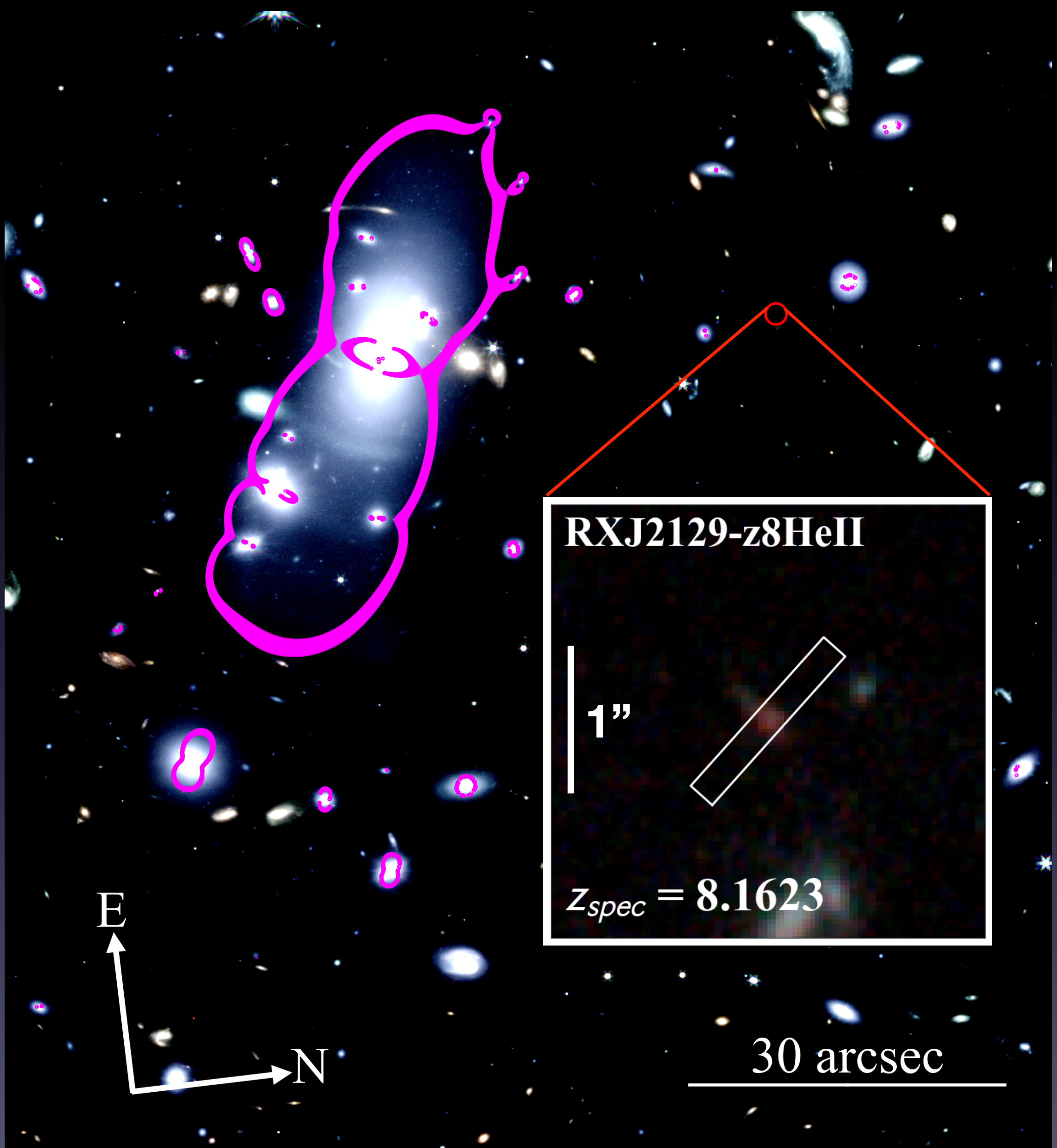
Possible Population III signatures in the halo of GN-z11

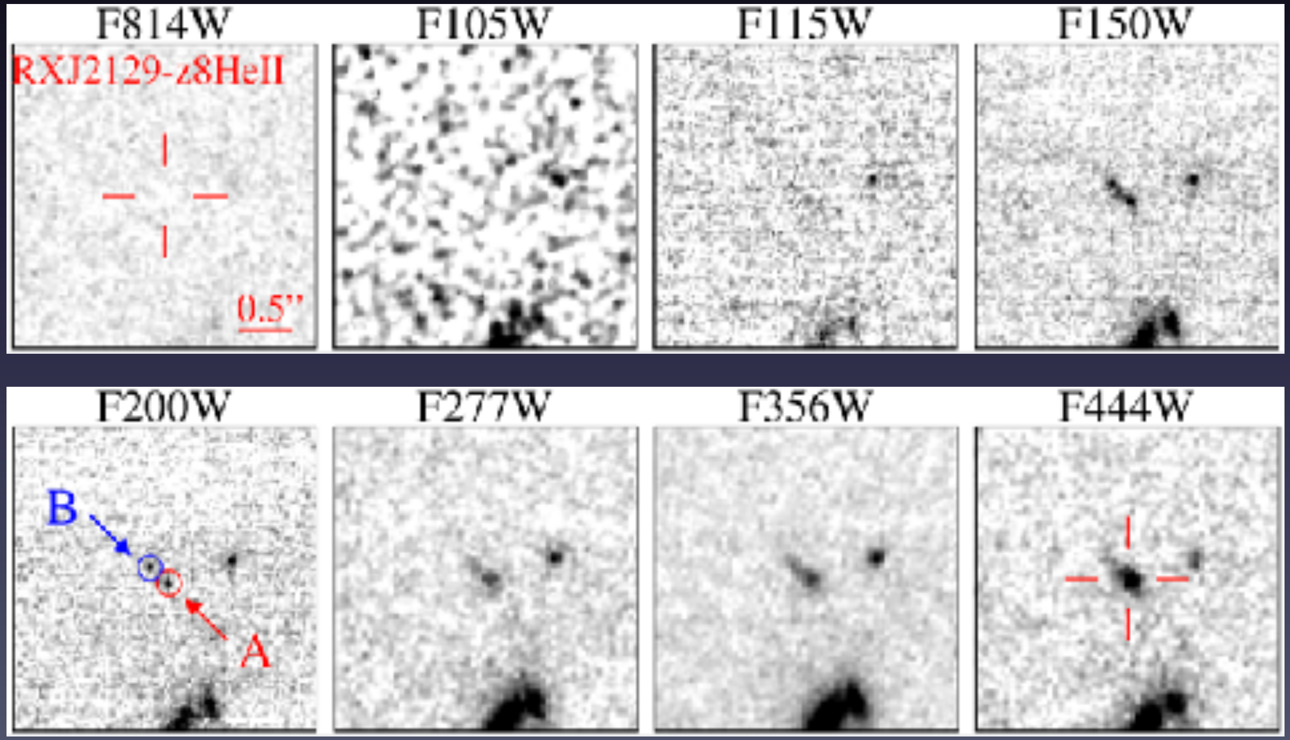


A He II λ1640 emitter with blue UV spectral slope at z=8.16

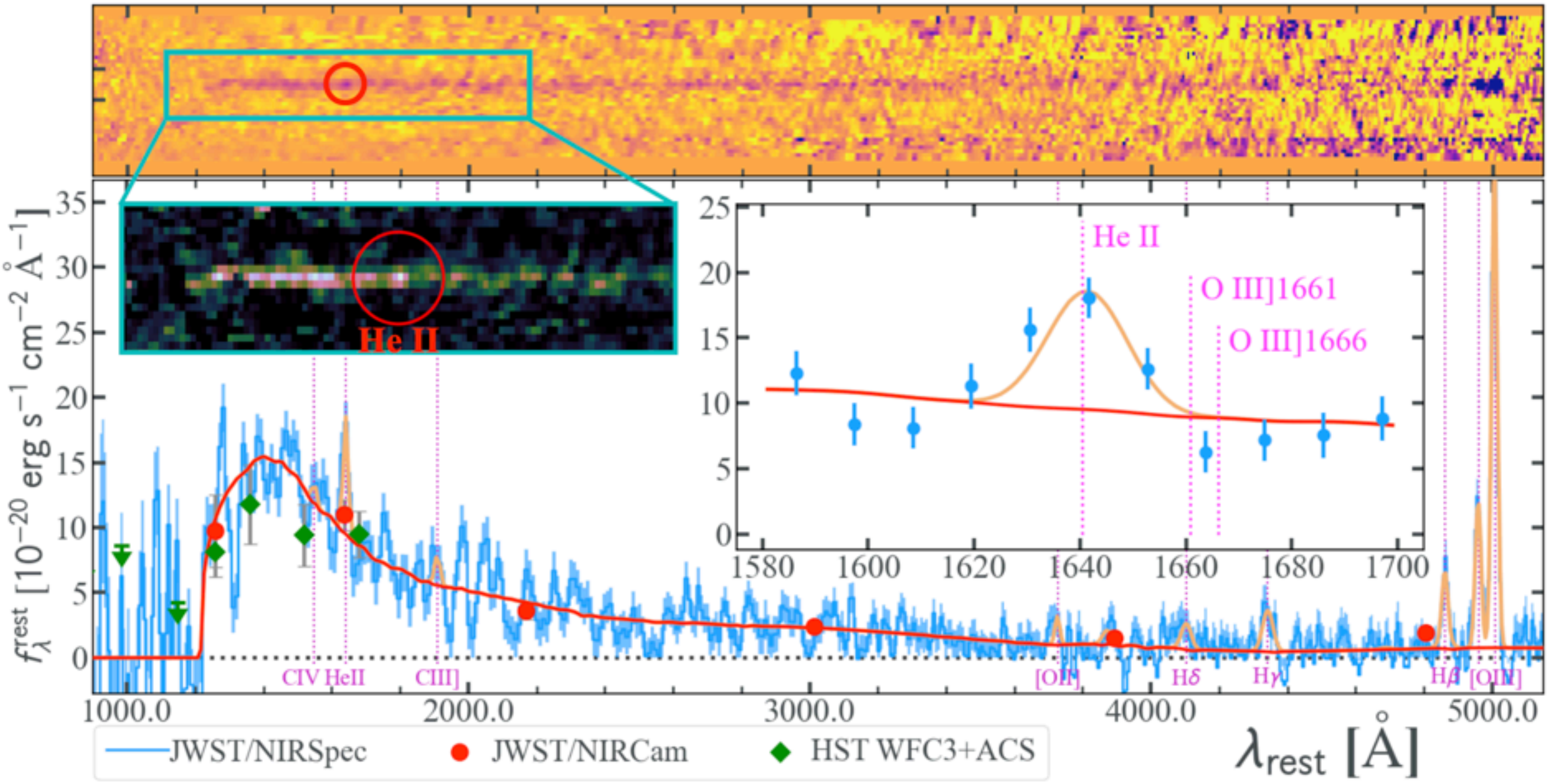
Wang et al. (2024) ApJL, 967, L42

- a strong emission-line galaxy at **z=8.16**
- lensed by the foreground galaxy cluster RXJ2129.7+0005 at *z*=0.234
- **candidate of a "hybrid" Pop III galaxy!**



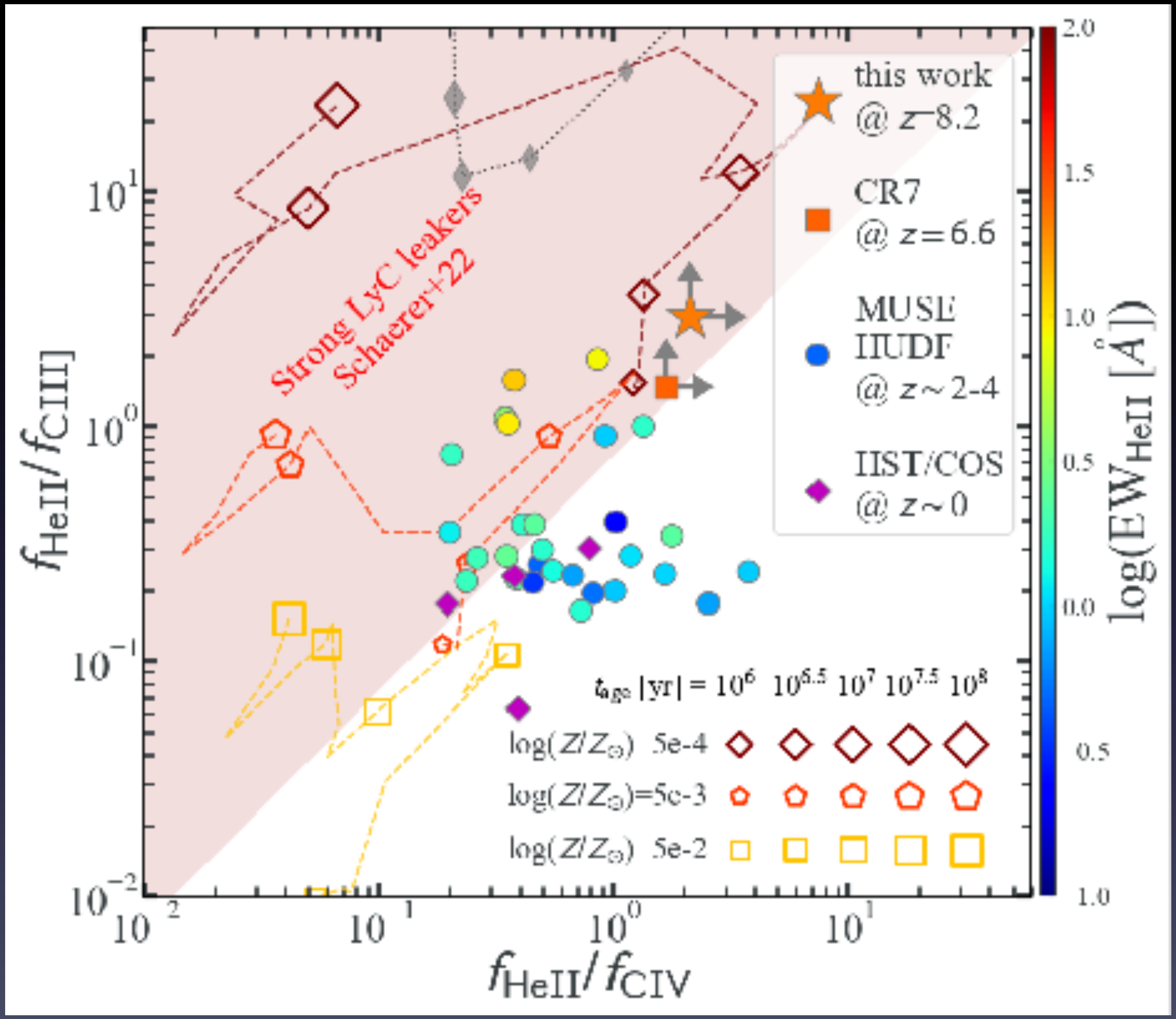


A He II λ1640 emitter with blue UV spectral slope at z=8.16

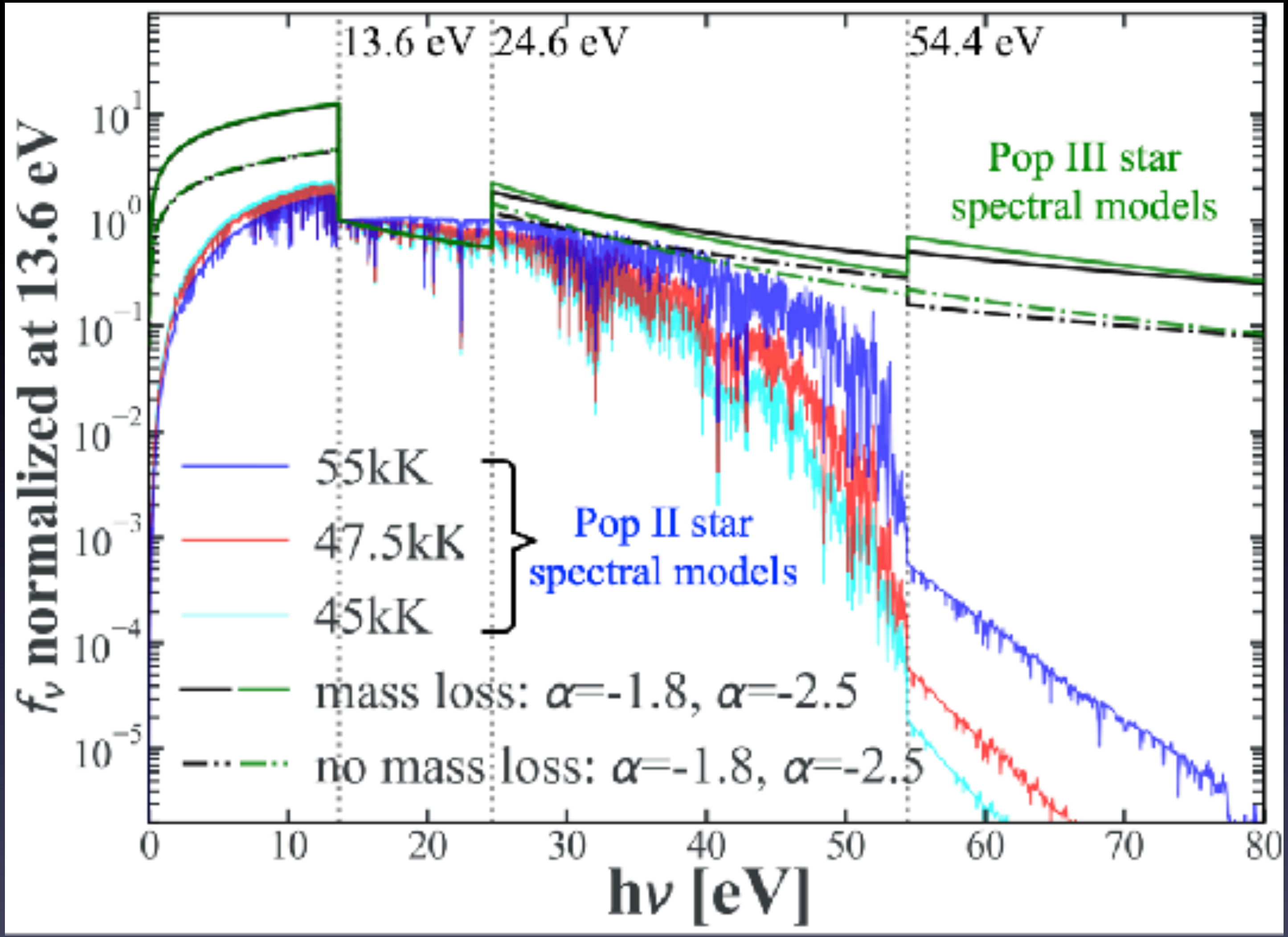


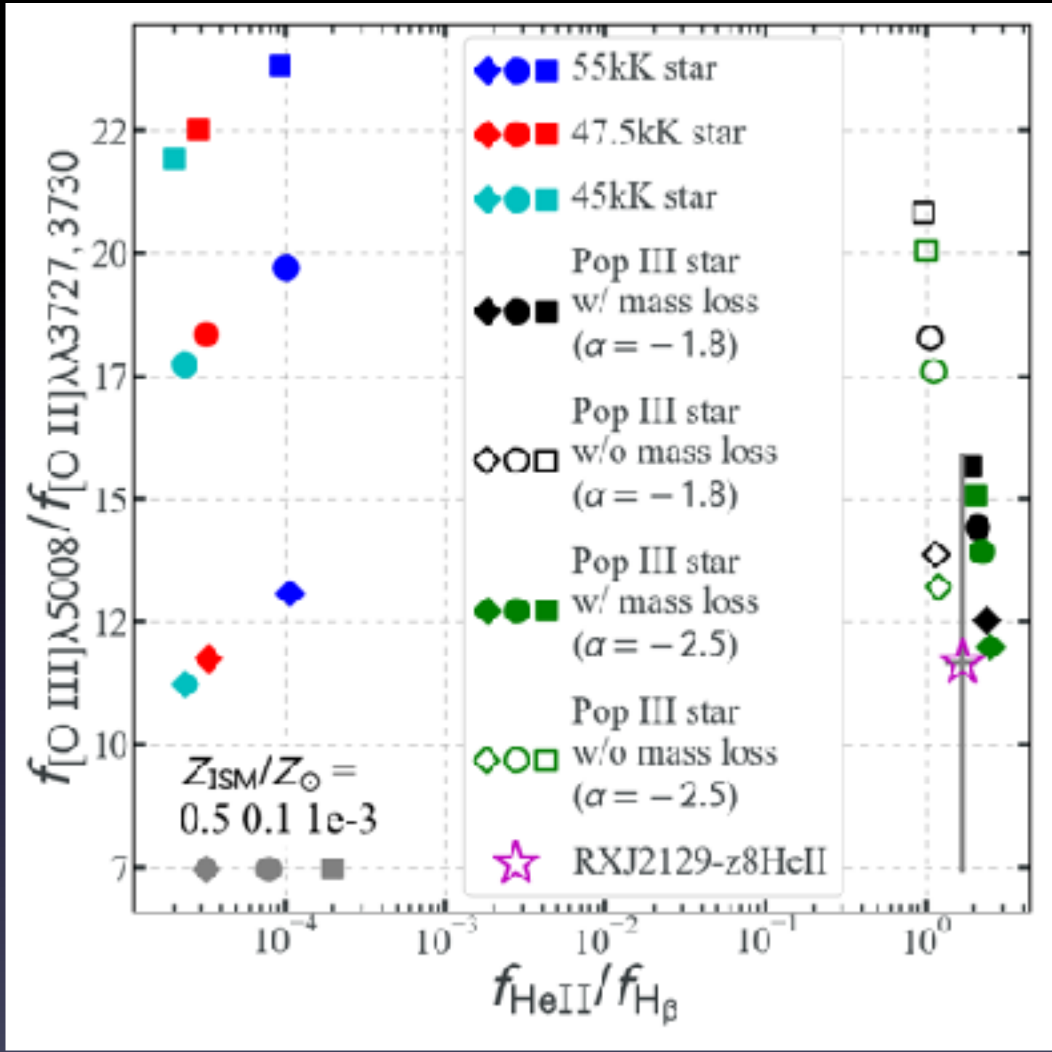
Physical properties of RXJ2129-z8HeII

- One of the highest redshift He II detection in the literature:
  - line flux (corr. for magnif and dust): 120±22 $\times 10^{-20}$ erg $s^{-1} cm^{-2}$
  - equivalent width: 21±4 Å
- Possible causes for strong He II emission:
  - Wolf-Rayet stars, stripped stars
  - active galactic nuclei
  - **Pop III stars** (high-mass, metal-free, first generation stars)



Photoionization models for Pop III stars

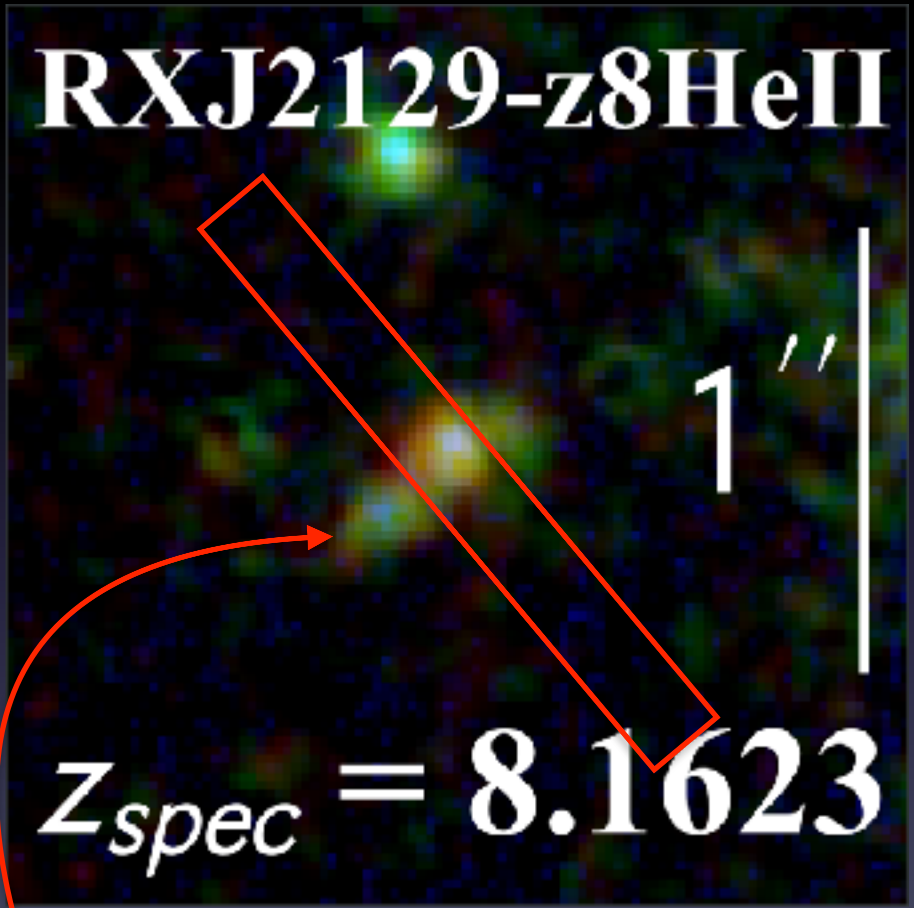


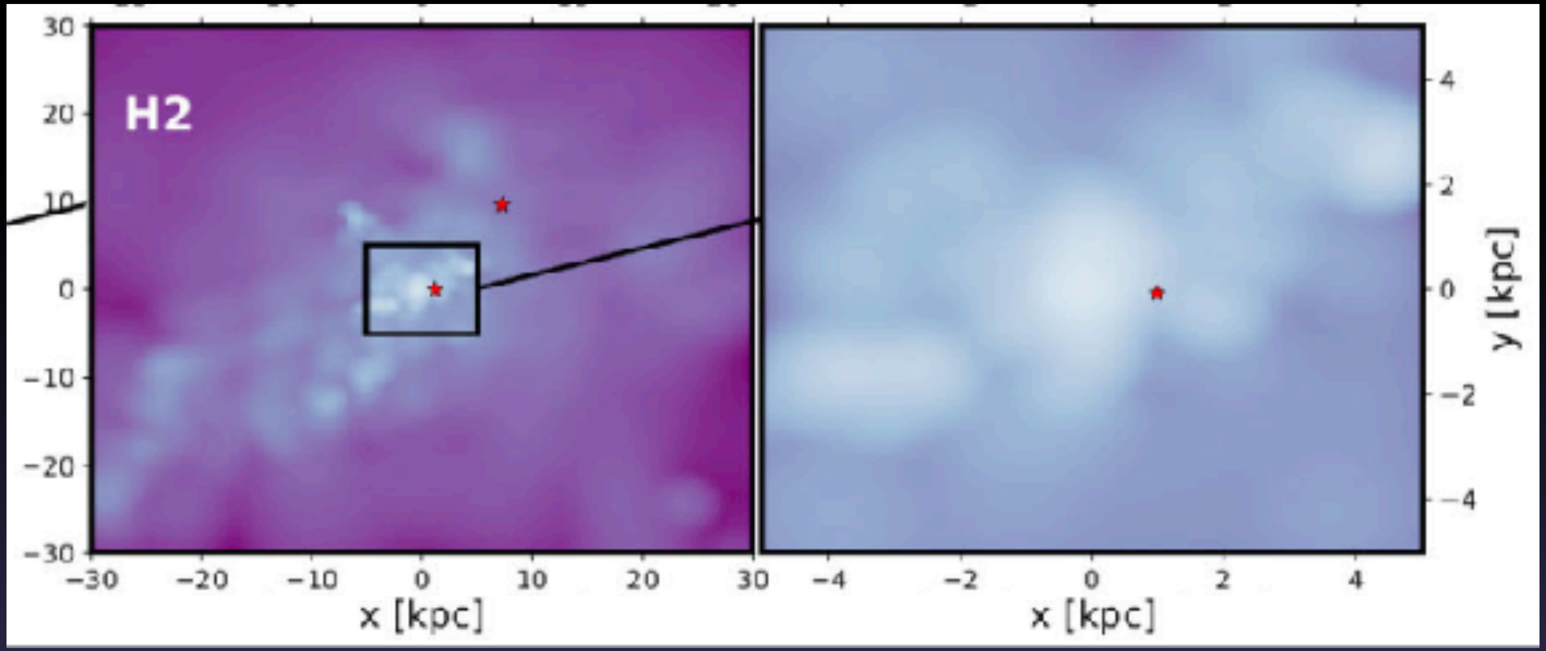


- based on the Pop III stellar evolution models of Schaerer 2002
- observed line ratios well reproduced by the Pop III models with mass loss and one tenth ISM metallicity

O32 alone: not a good proxy of Pop III

Physical origin of Pop III stars: pristine gas accretion?





where Pop III likely originates??

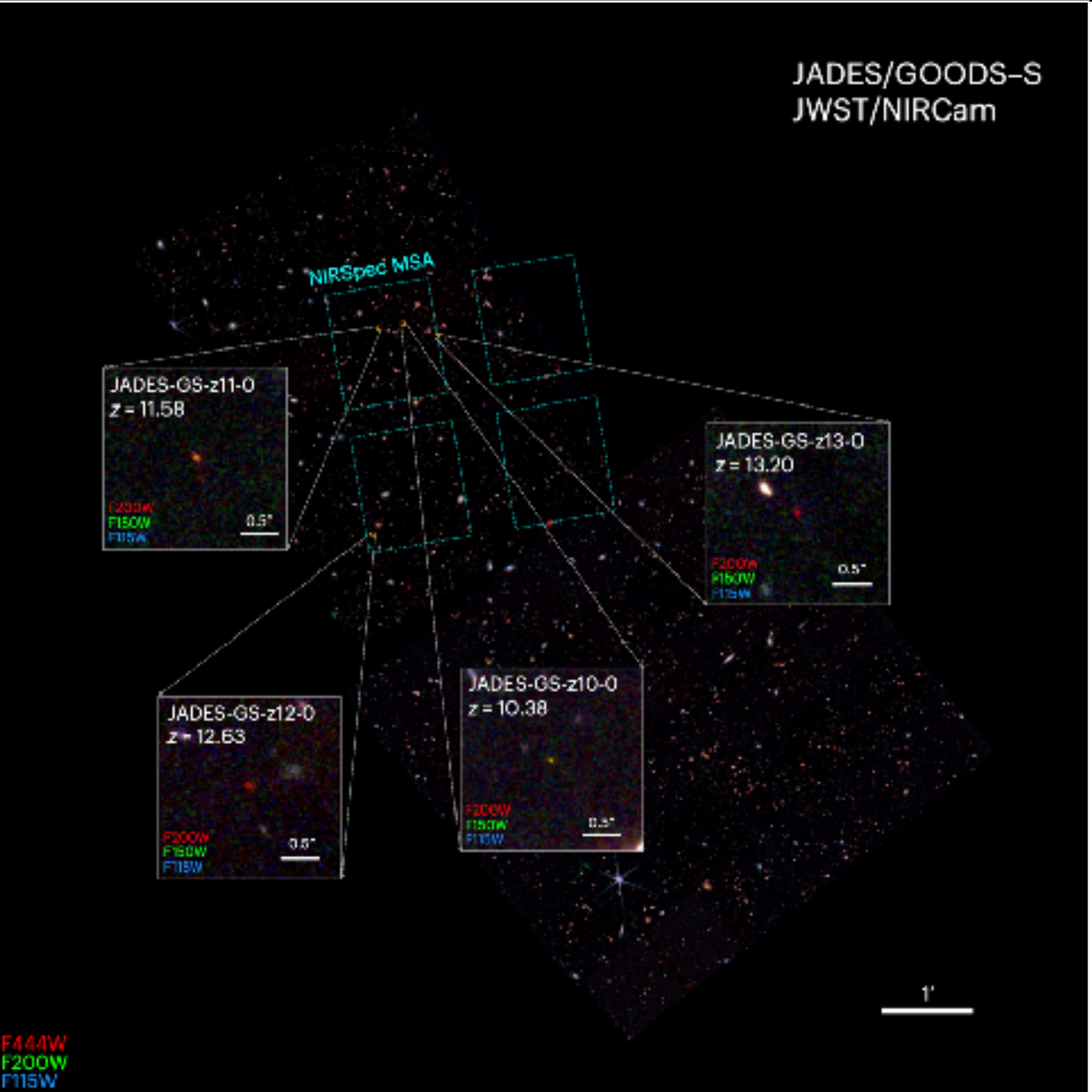
need deep NIRSpec/IFU observations!!

Simulations by Venditti et al. (2023) suggest that Pop III stars can be formed by the collapse of pristine gas during its accretion onto galaxy disks, making a "hybrid" galaxy

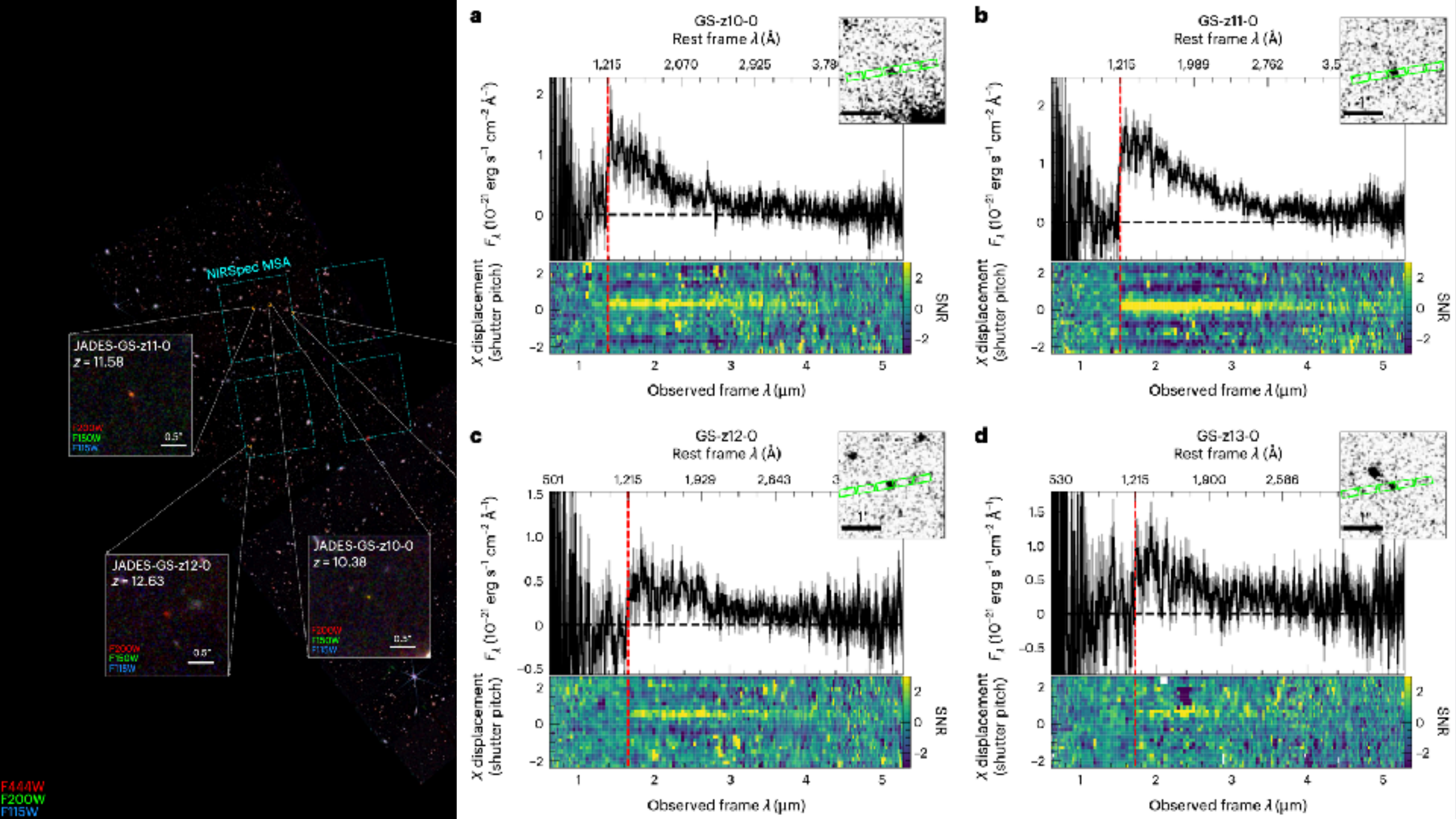
- Pop III SFR: 3–72% of the SFR from O/B stars from Hbeta
- total mass: $7.8 \pm 1.4 \times 10^5 M_\odot$ assuming Eddington limit

JWST keeps breaking the redshift record

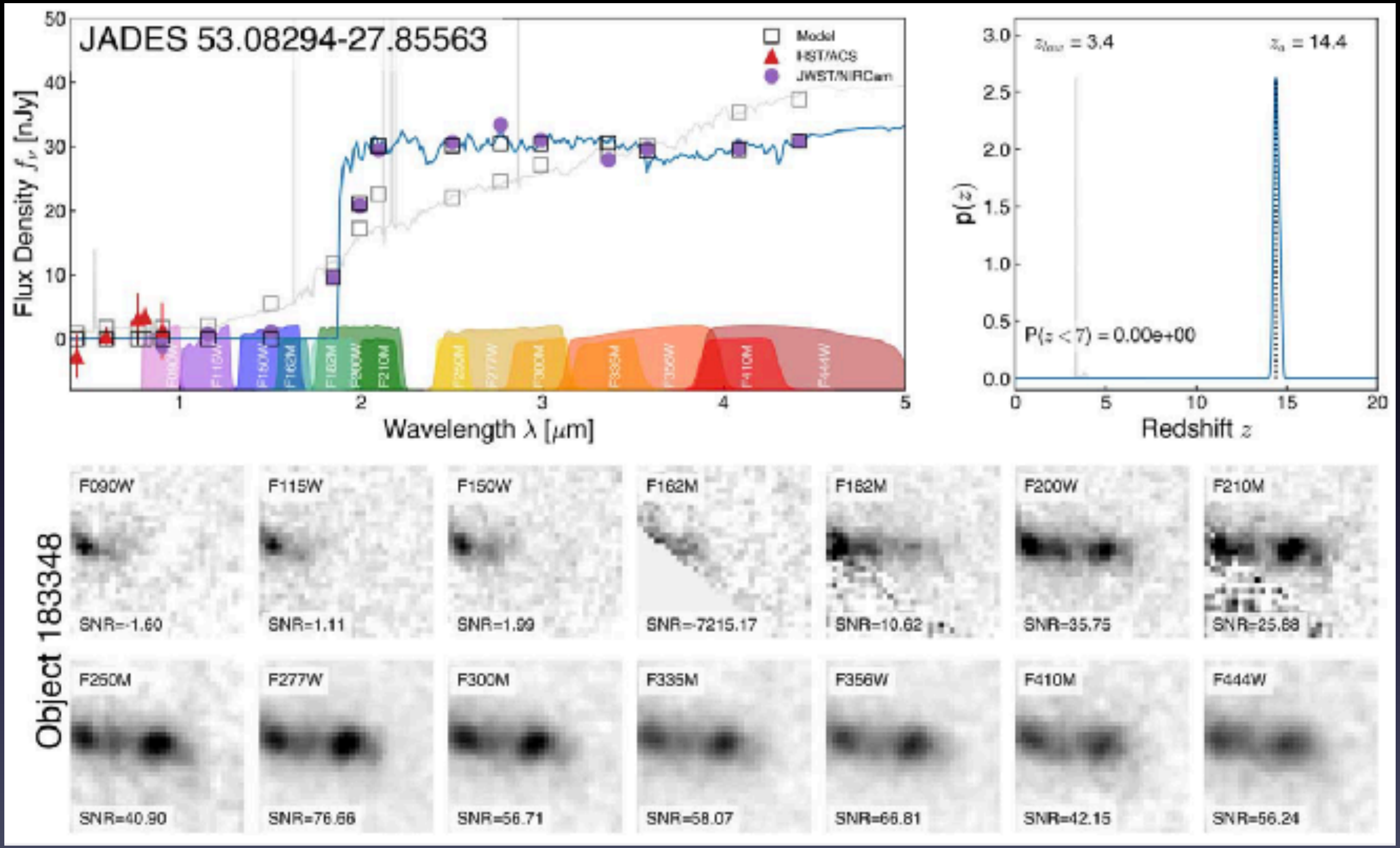
JWST Advanced Deep Extragalactic Survey



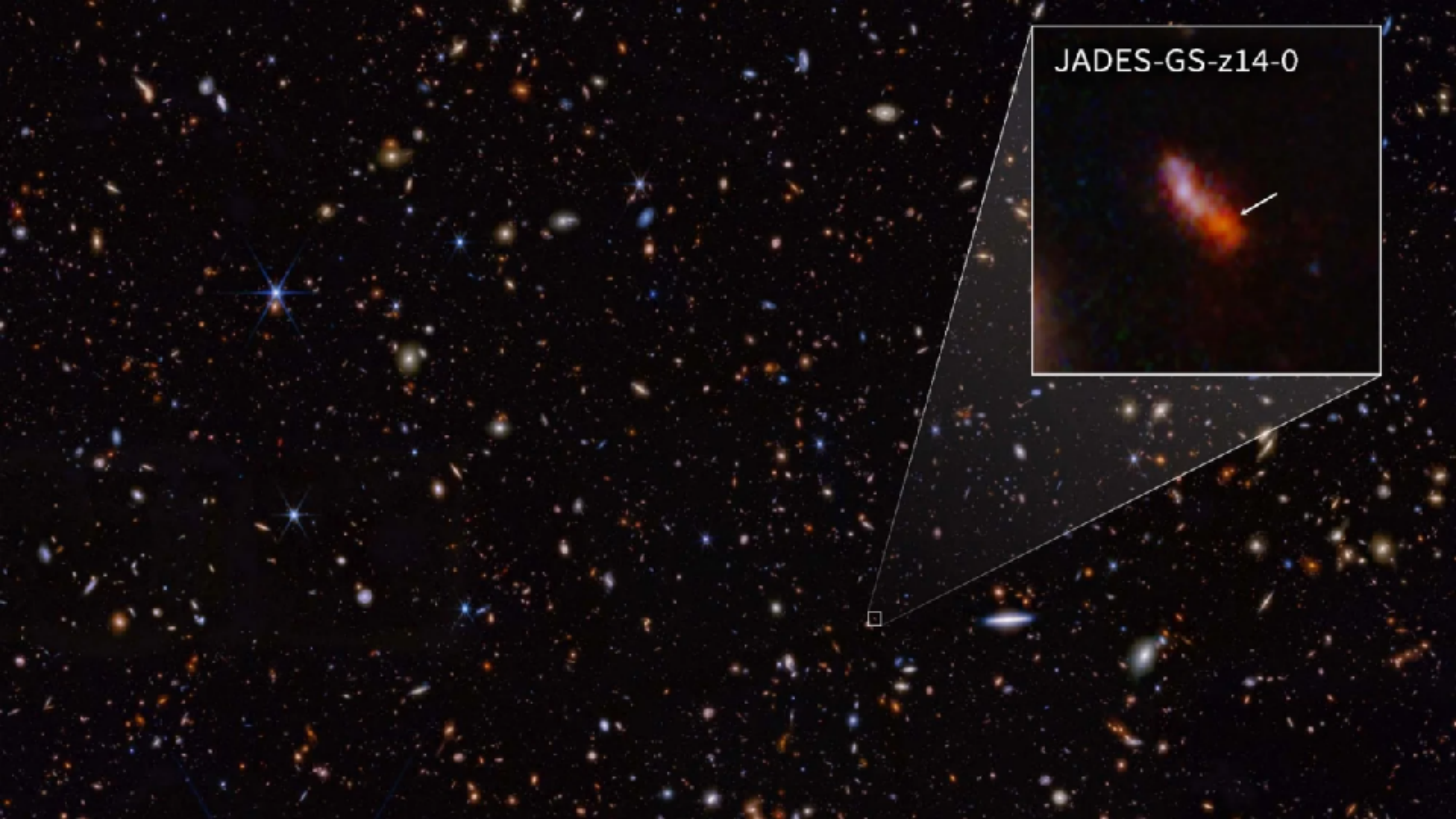
Robertson+23;
Curtis-Lake+23


NIRSpec MSA
JADES-GS-z11-0
z = 11.58
JADES-GS-z12-0
z = 12.63
JADES-GS-z10-0
z = 10.38
F200W
F150W
F115W
0.5"
F444W
F200W
F115W
a
GS-z10-0
b
GS-z11-0
c
GS-z12-0
d
GS-z13-0
Rest frame λ (Å)
Observed frame λ (μm)
F_λ (10^{-21} erg s^{-1} cm^{-2} Å^{-1})
X displacement (shutter pitch)
SNR
1"

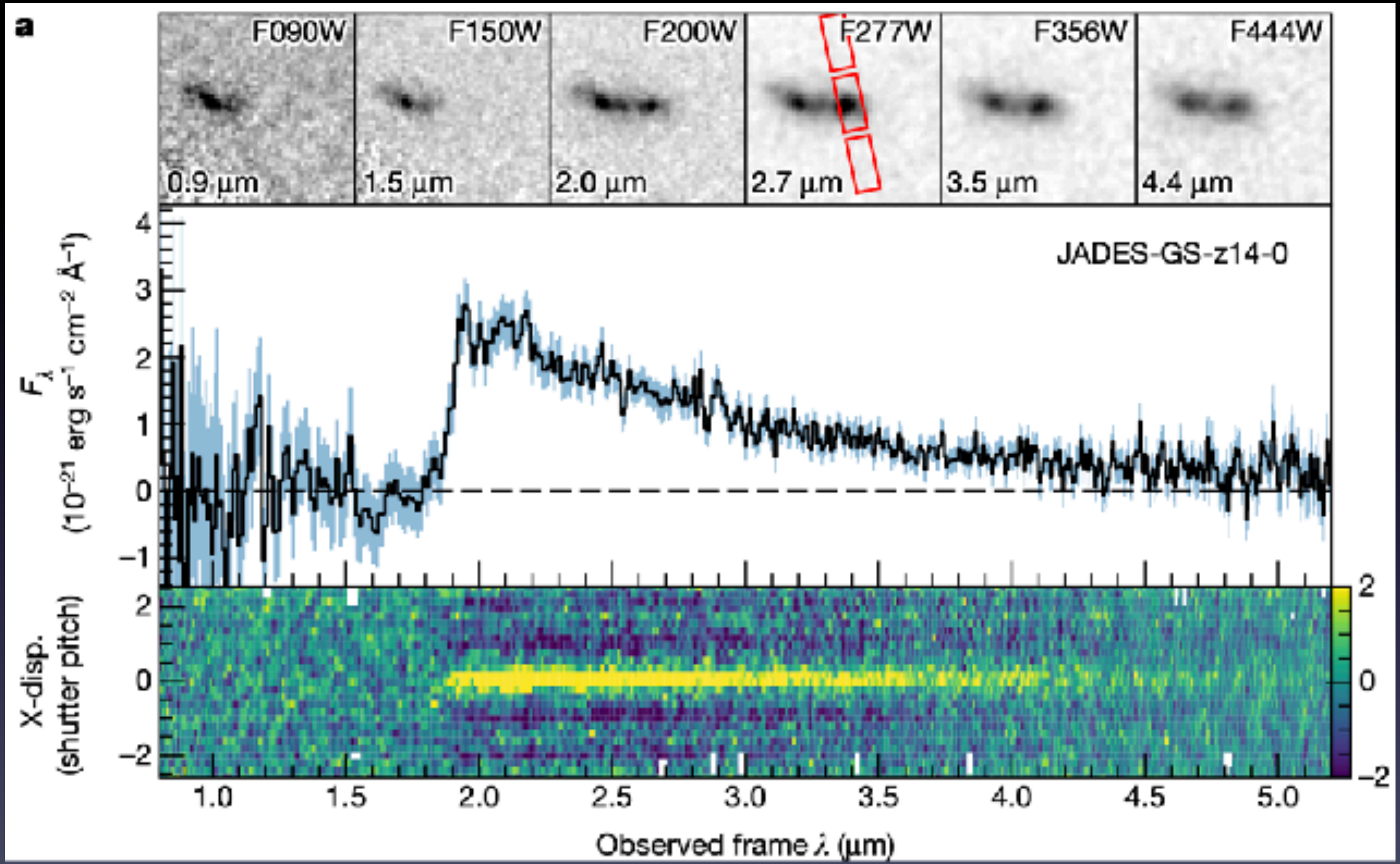
JADES-GS-z14-0: the current record holder



Photometric selection from the JADES Origins Fields (Robertson+24; Eisenstein+24)

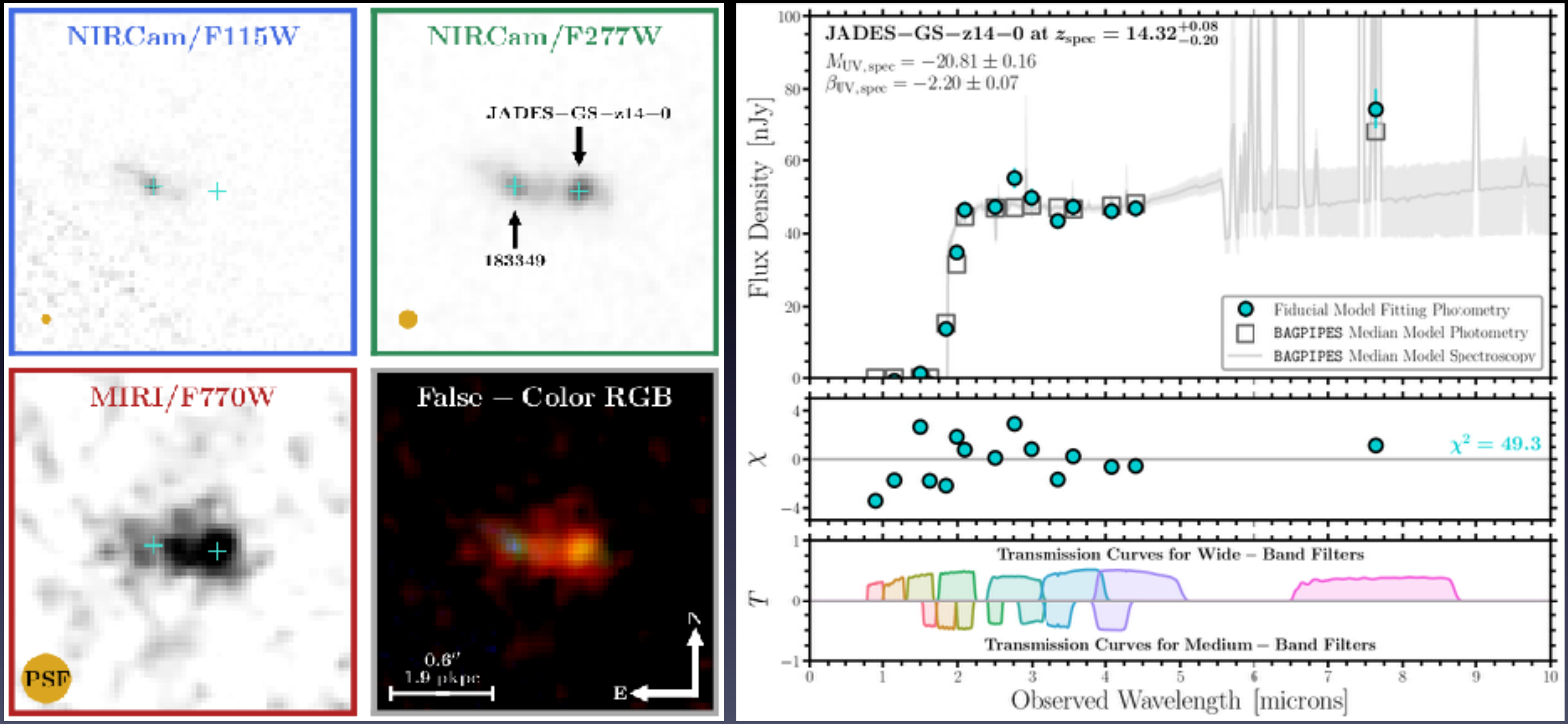

JADES-GS-z14-0

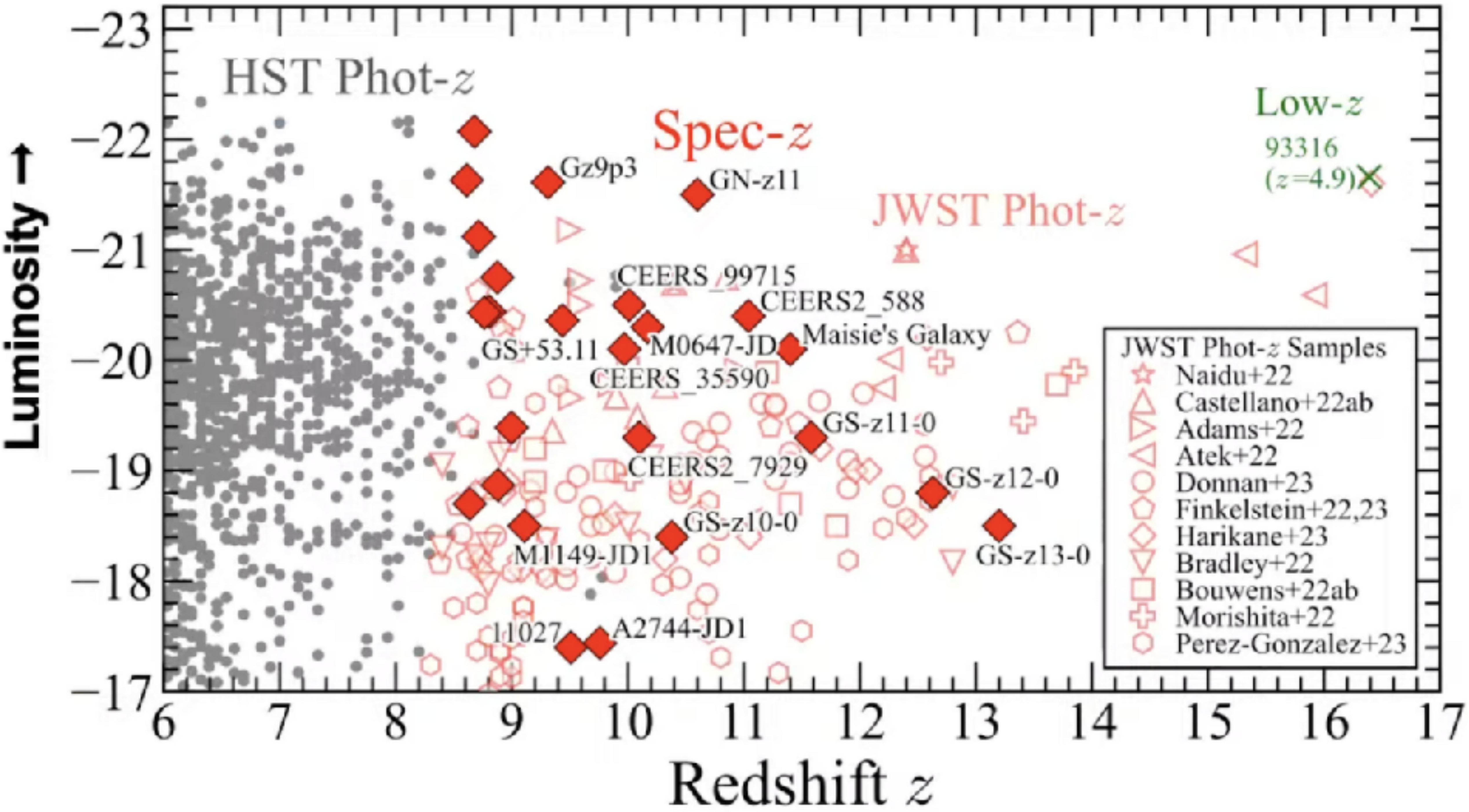
JADES-GS-z14-0: the current record holder



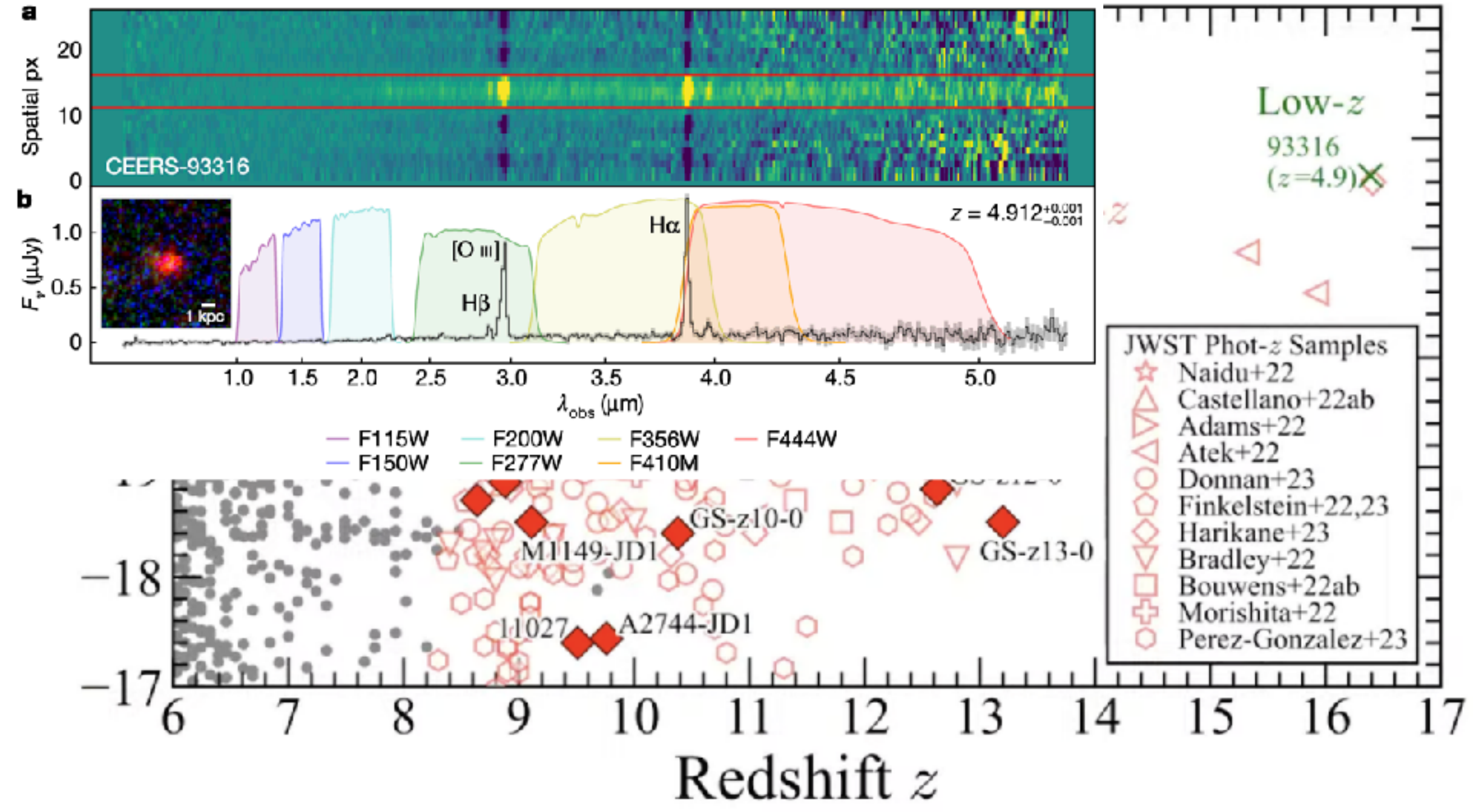
Redshift confirmation from NIRSpec prism and MIRI/770 (Carniani+24; Helton+25)

JADES-GS-z14-0: the current record holder



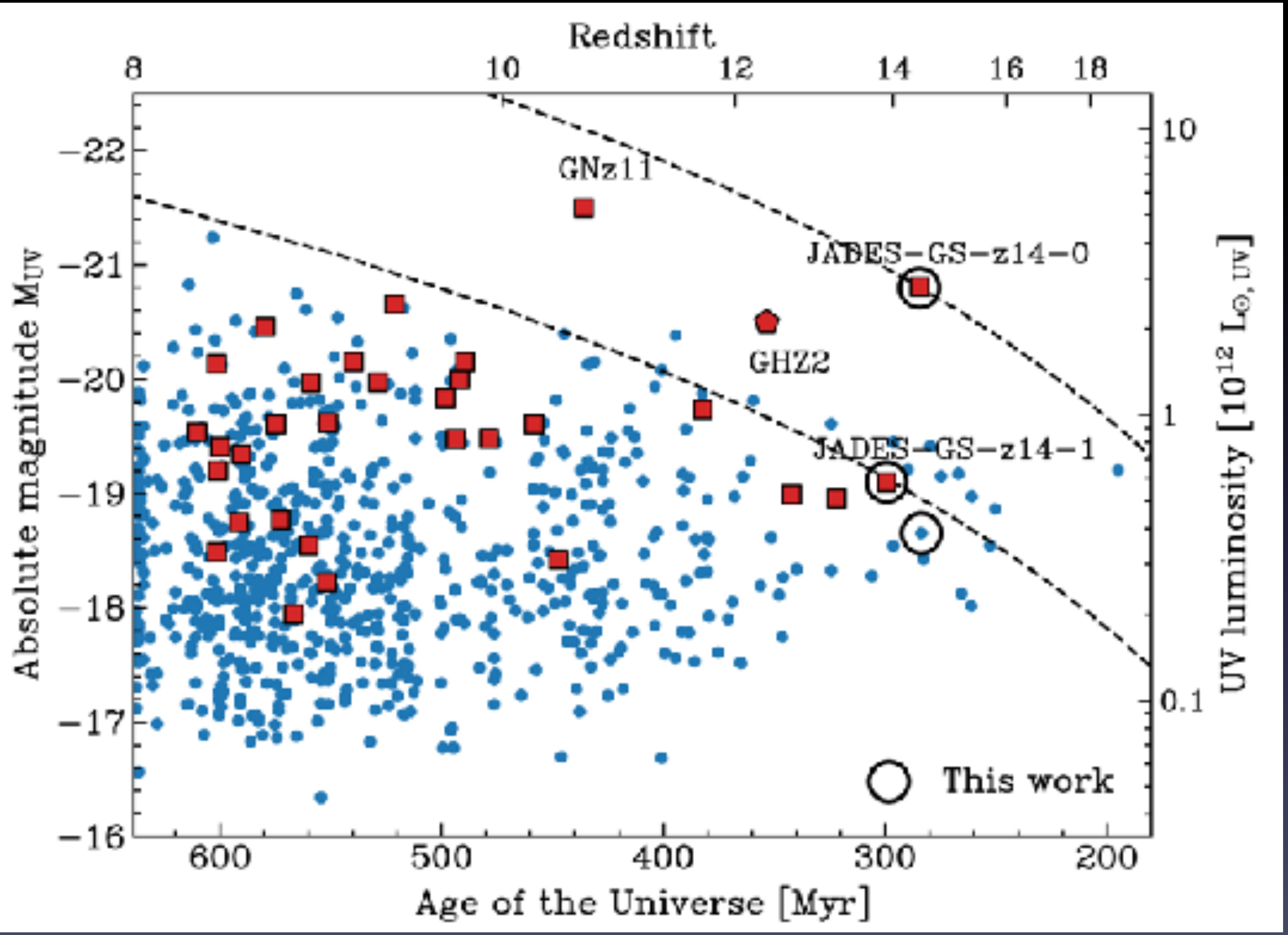


HST Phot-z
Spec-z
JWST Phot-z
Low-z
93316
(z=4.9)
Gz9p3
GN-z11
CEERS_99715
CEERS2_588
Maisie's Galaxy
GS+53.11
M0647-JD
CEERS_35590
GS-z11-0
CEERS2_7929
GS-z12-0
GS-z10-0
GS-z13-0
M1149-JD1
11027
A2744-JD1
JWST Phot-z Samples
Naidu+22
Castellano+22ab
Adams+22
Atek+22
Donnan+23
Finkelstein+22,23
Harikane+23
Bradley+22
Bouwens+22ab
Morishita+22
Perez-Gonzalez+23
Luminosity →
Redshift z
−23
−22
−21
−20
−19
−18
−17
6
7
8
9
10
11
12
13
14
15
16
17



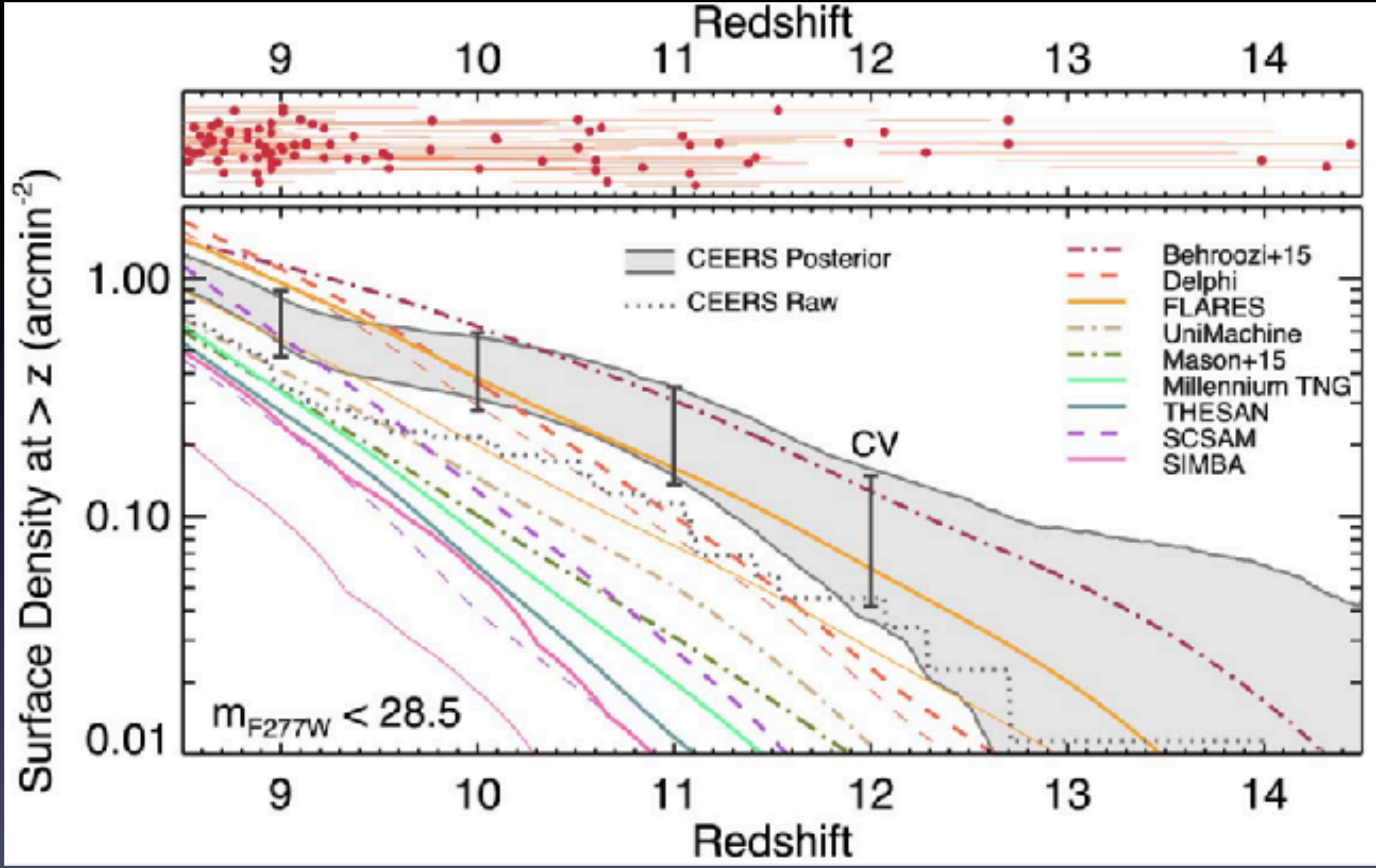
a
Spatial px
CEERS-93316
b
F_ν (μJy)
1 kpc
[O III]
Hβ
Hα
$z = 4.912^{+0.001}_{-0.001}$
λ_{obs} (μm)
F115W
F150W
F200W
F277W
F356W
F410M
F444W
Low-z
93316
(z=4.9)
JWST Phot-z Samples
Naidu+22
Castellano+22ab
Adams+22
Atek+22
Donnan+23
Finkelstein+22,23
Harikane+23
Bradley+22
Bouwens+22ab
Morishita+22
Perez-Gonzalez+23
GS-z10-0
M1149-JD1
GS-z13-0
11027
A2744-JD1
Redshift z

too many over-luminous galaxies in the early Universe?



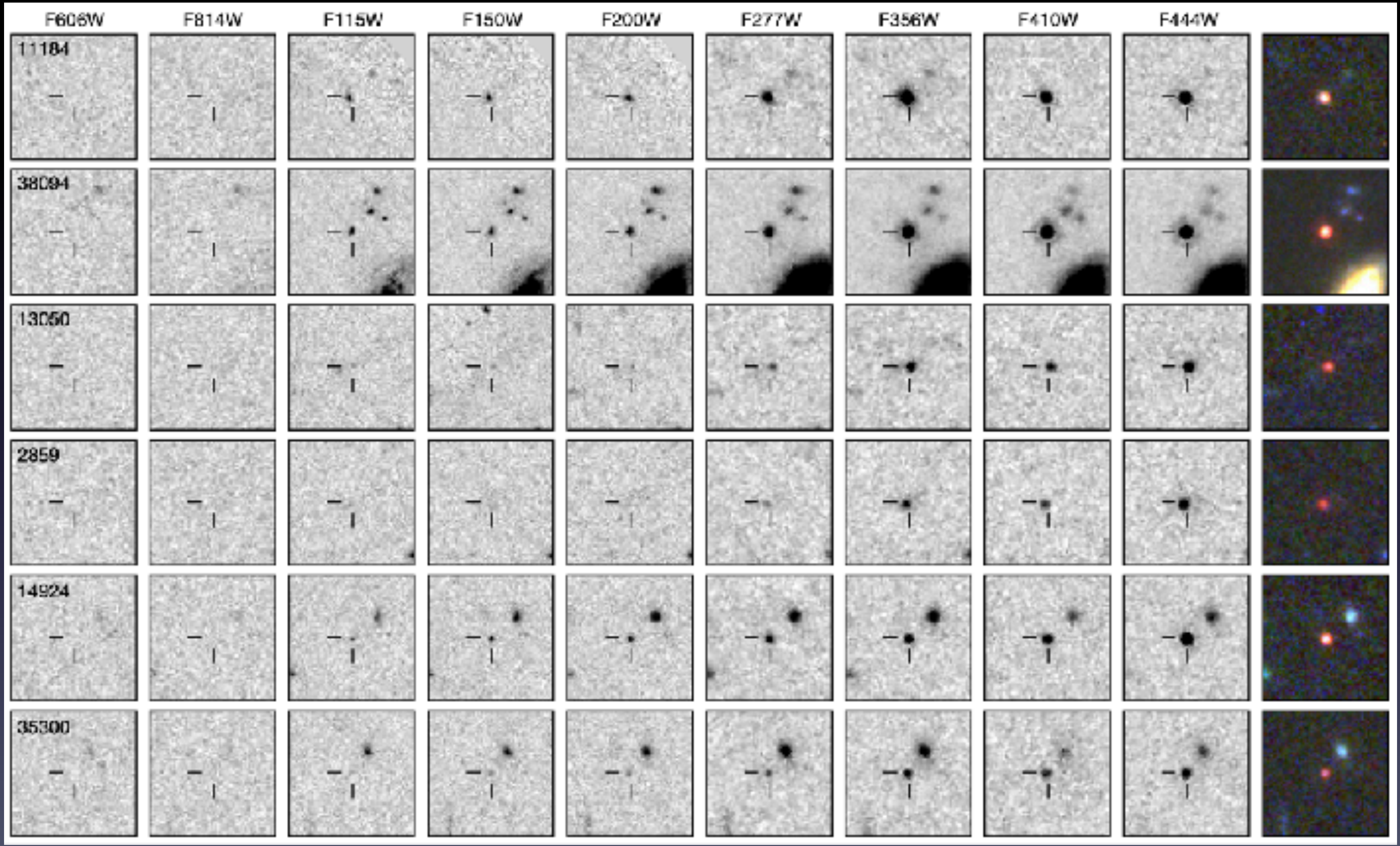
- red squares: spec. confirmed
- blue circles: photo-z candidates from JADES
- dashed lines: semi-empirical luminosity evolution of halo proportional to $(1+z)^{-4.5}$
- the halo mass threshold to yield a fixed comoving abundance varies as $(1+z)^{-6}$ (Maksimova et al. 2021)
- age of the Universe scales as $(1+z)^{-3/2}$

too many over-luminous galaxies in the early Universe?



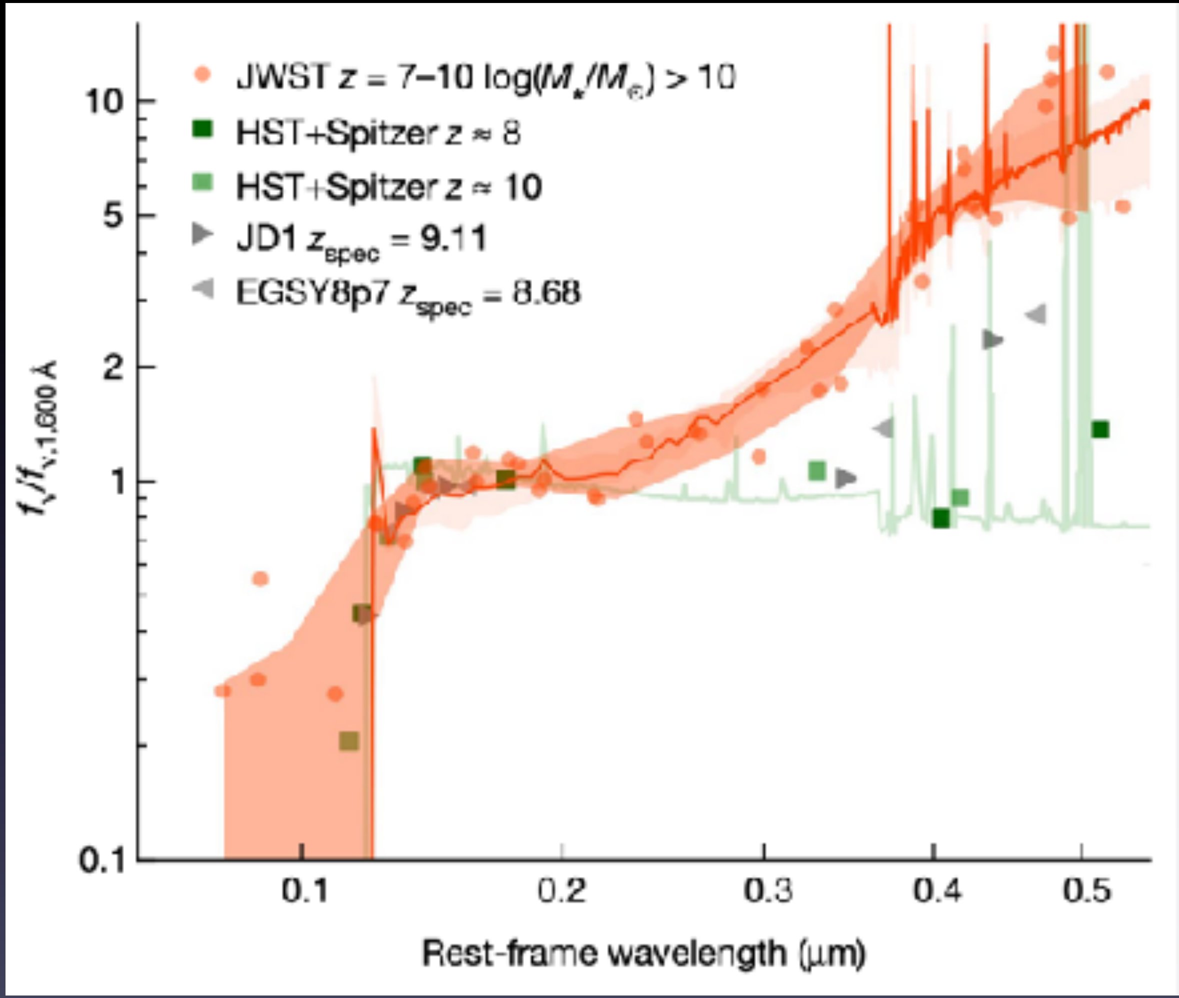
We see more galaxies at z>10 than nearly all theoretical predictions (Finkelstein+24)

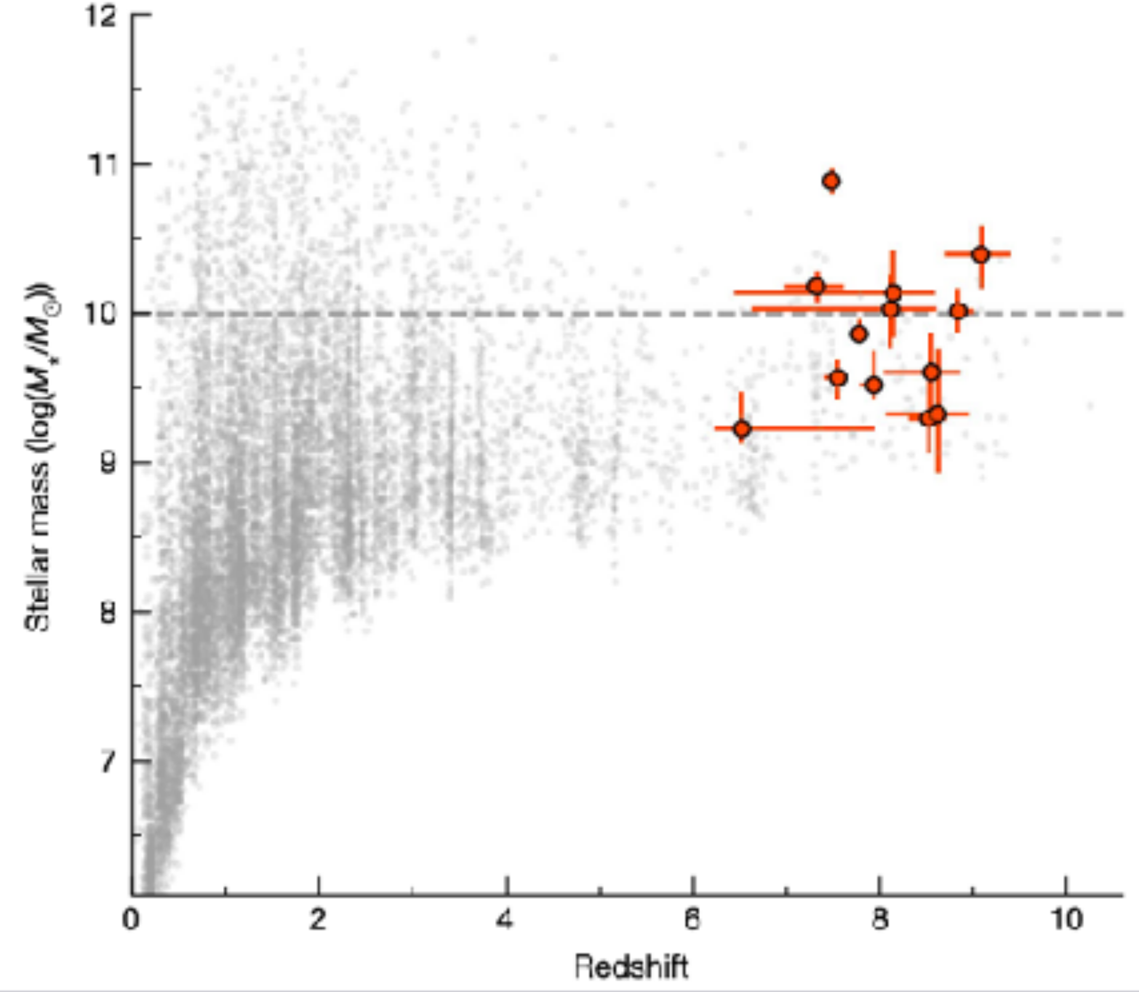
too massive too early? stress testing ΛCDM



Labbé+23

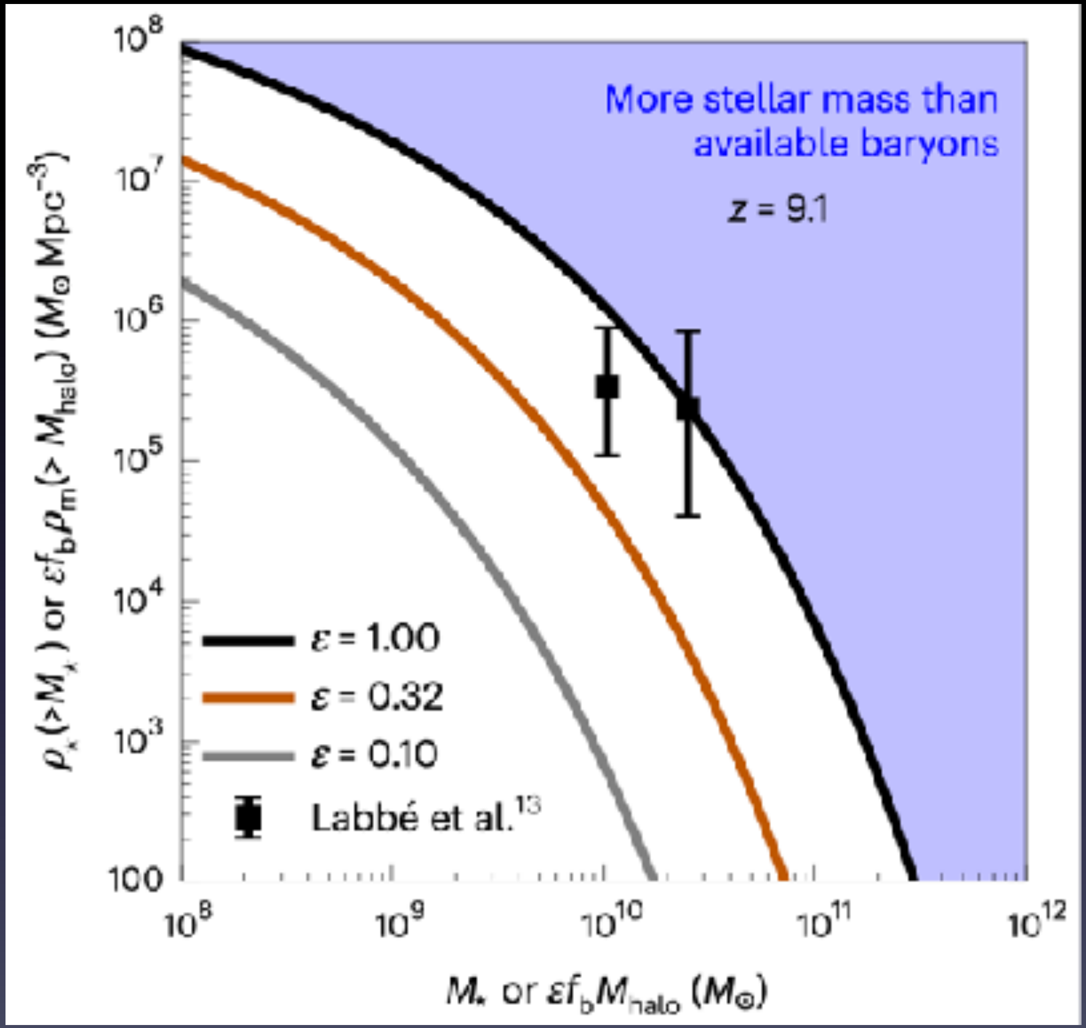
too massive too early? stress testing ΛCDM



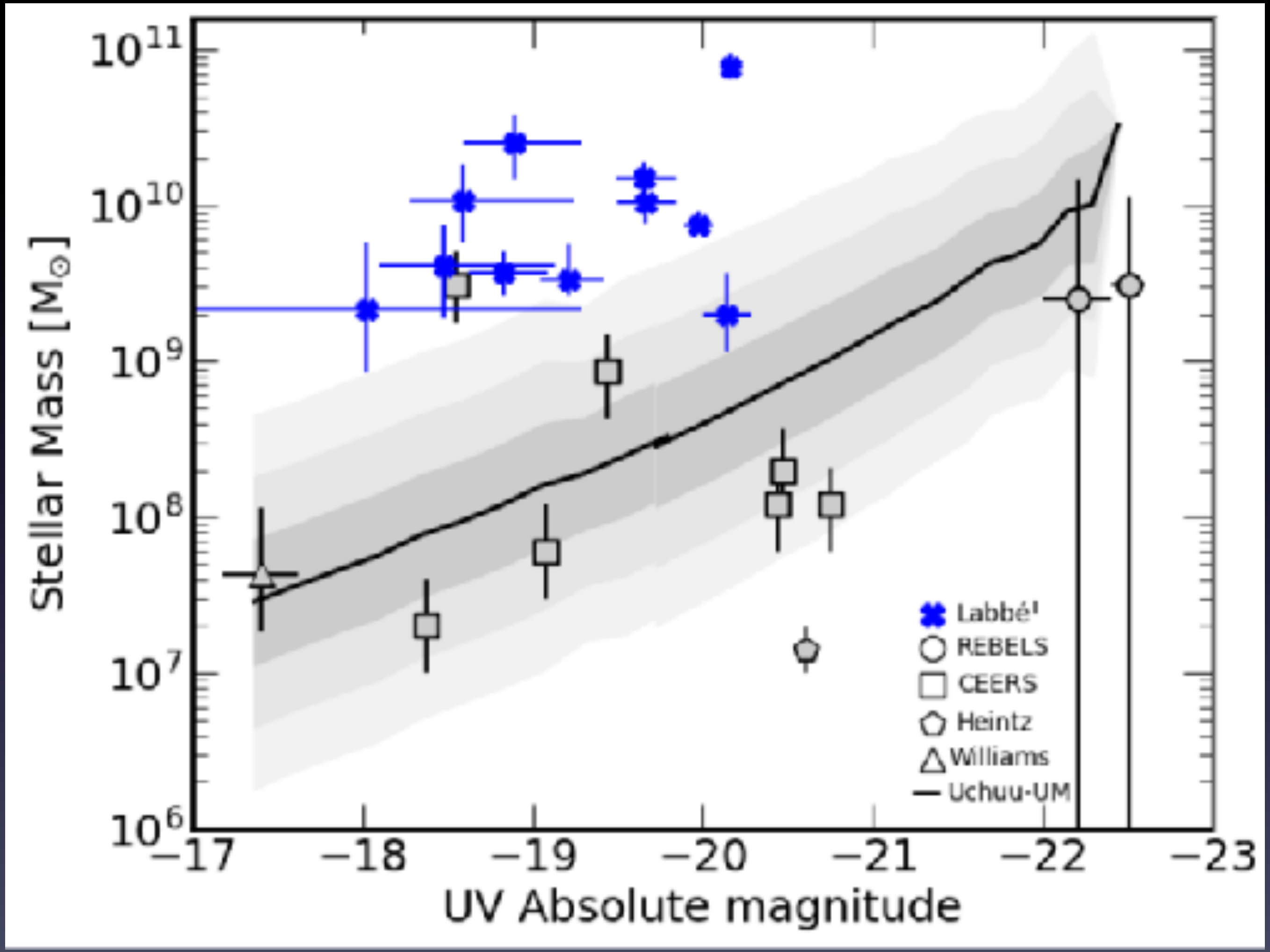


Labbé+23

too massive too early? stress testing ΛCDM

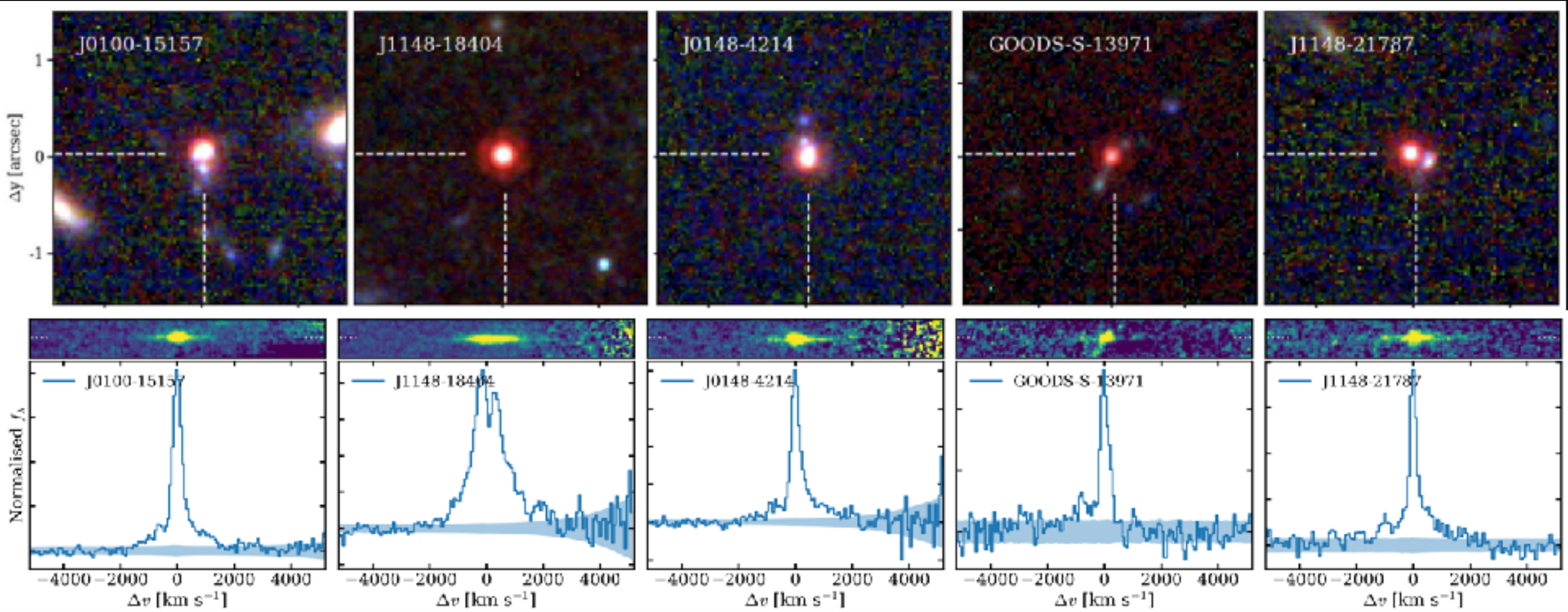


Boylan-Kolchin+23

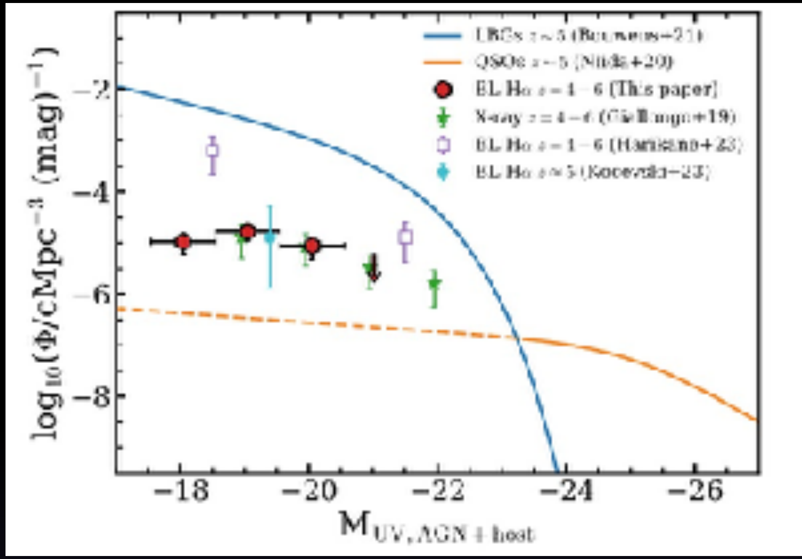


Prada+23

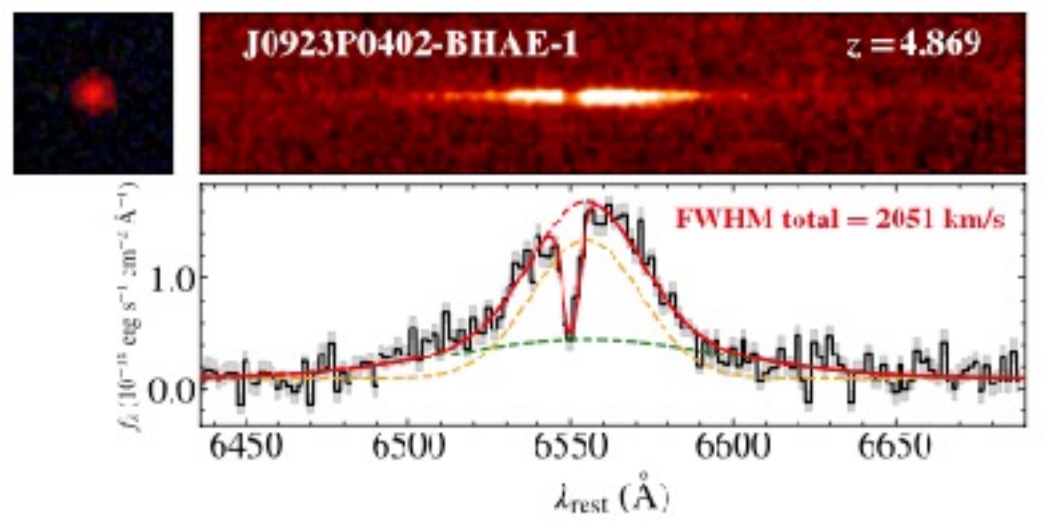
Solution and new puzzles: “Little Red Dots”



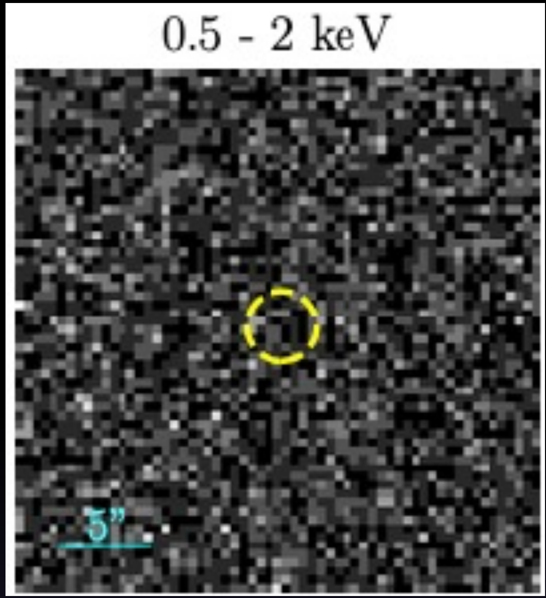
Faint AGNs (?) at z>4 unveiled by JWST (Matthee+24, Kocevski+24, Greene+24 …)



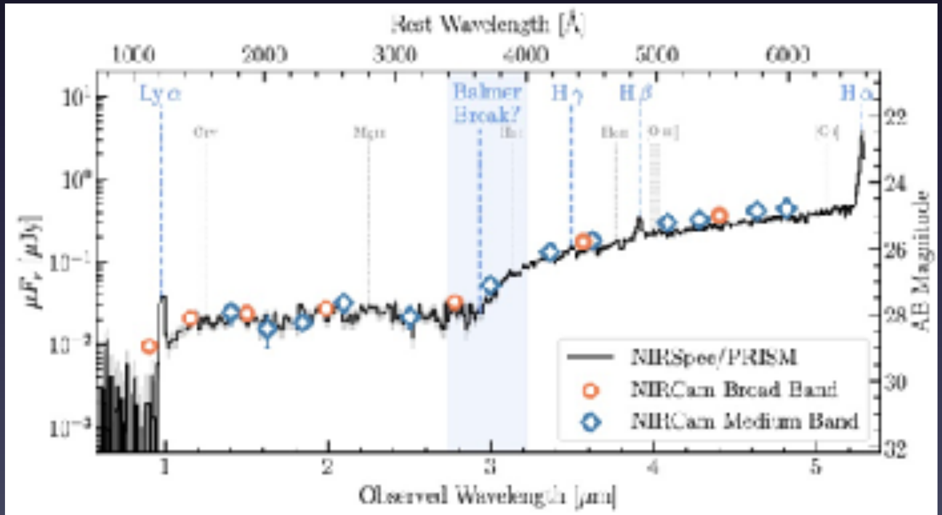
Too many! (Matthee+24)



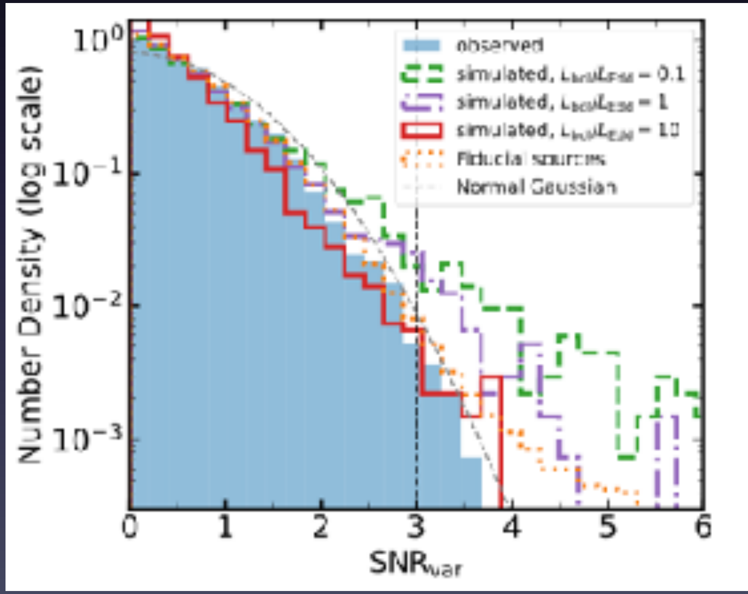
Absorption! (Lin+24)



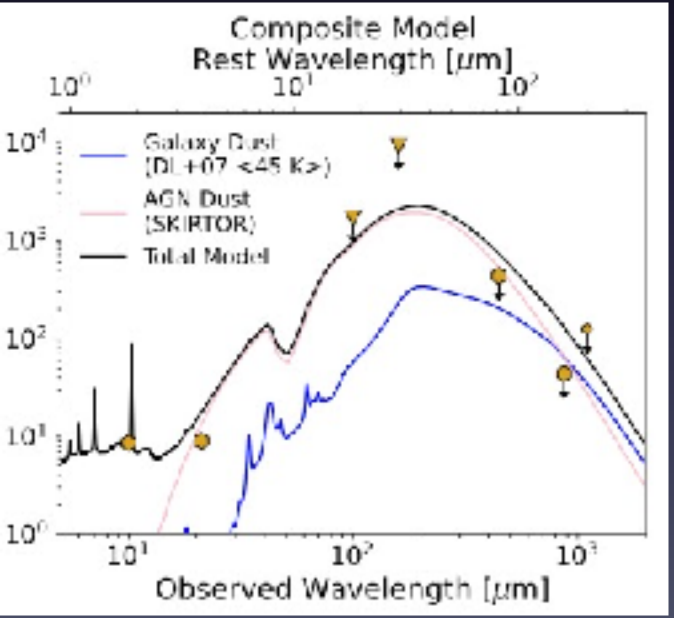
No X-ray! (Yue+24)



Balmer break! (Ma+25)

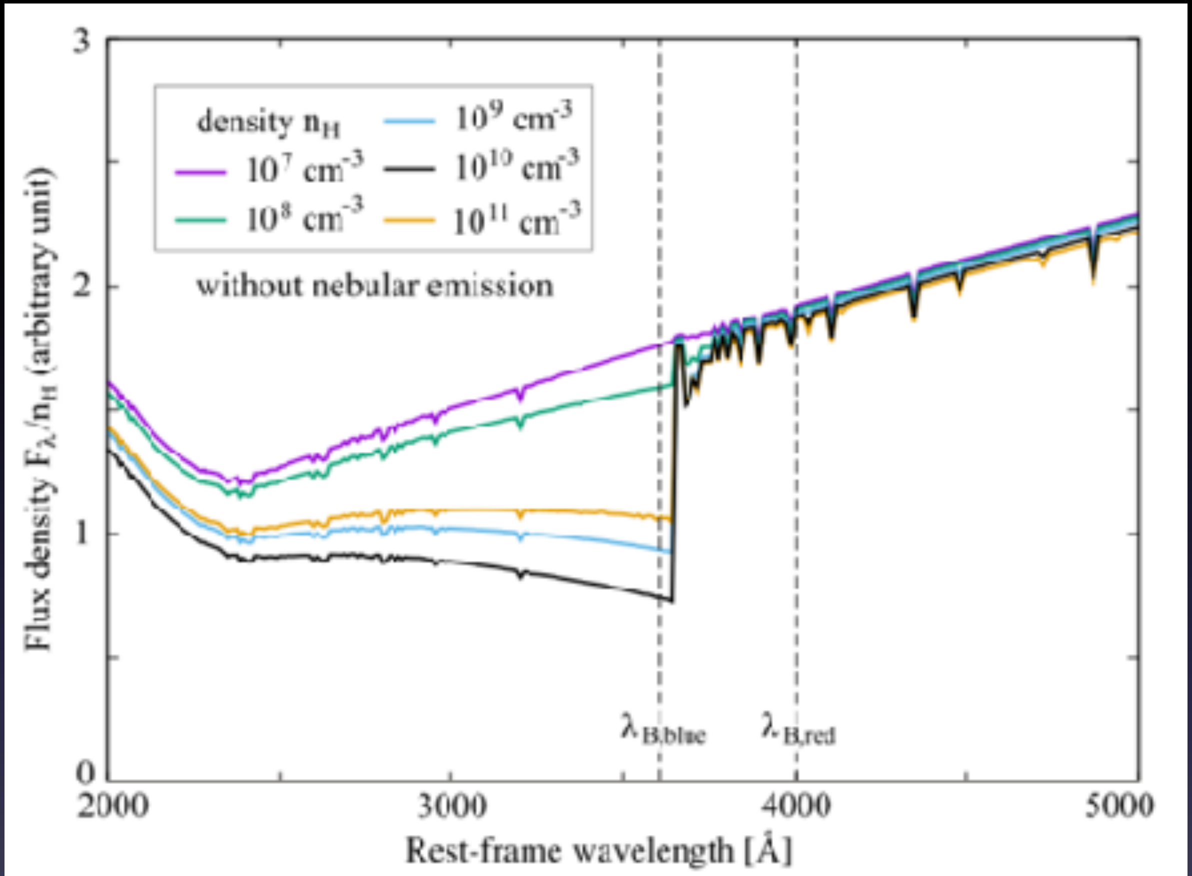


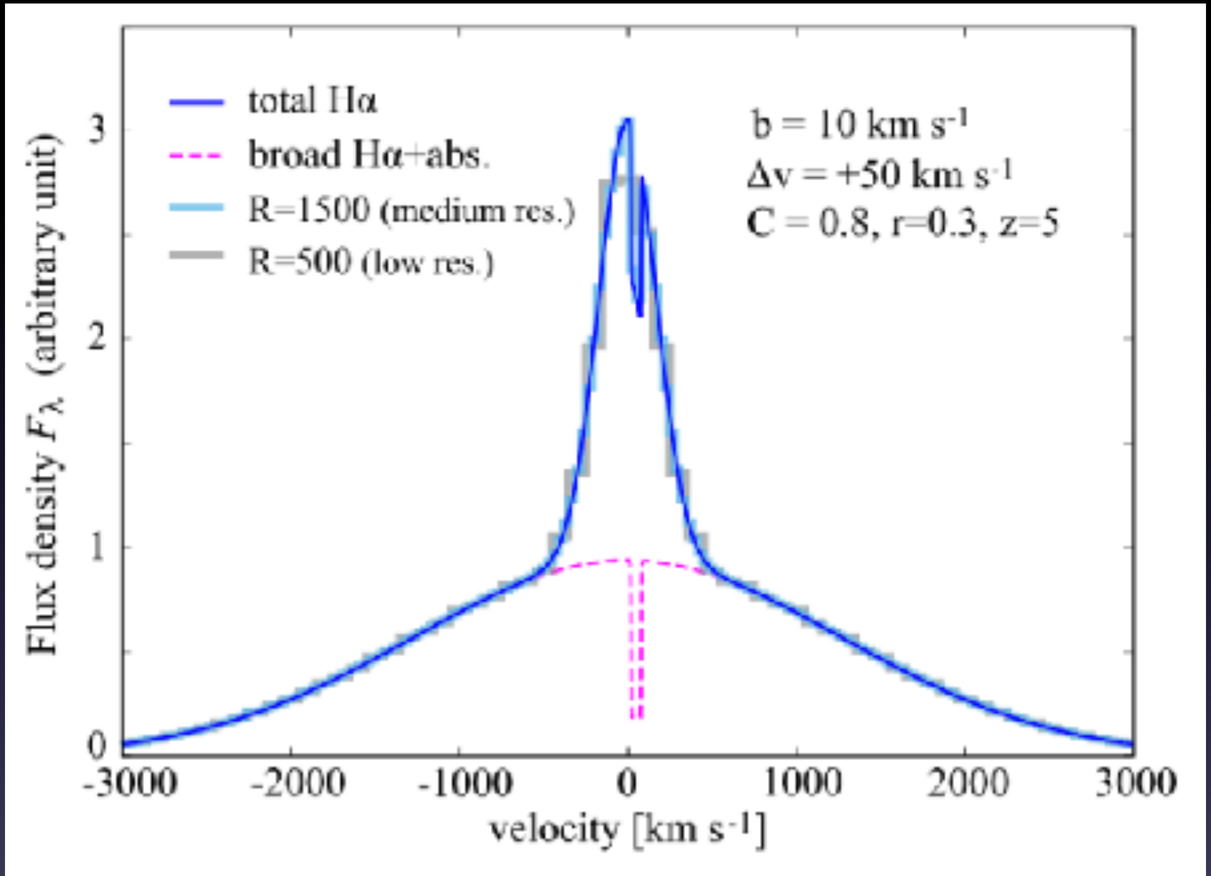
Weak variability! (Zhang+25)



No cold dust! (Setton+25)

Dense circumnuclear gas around accreting BHs

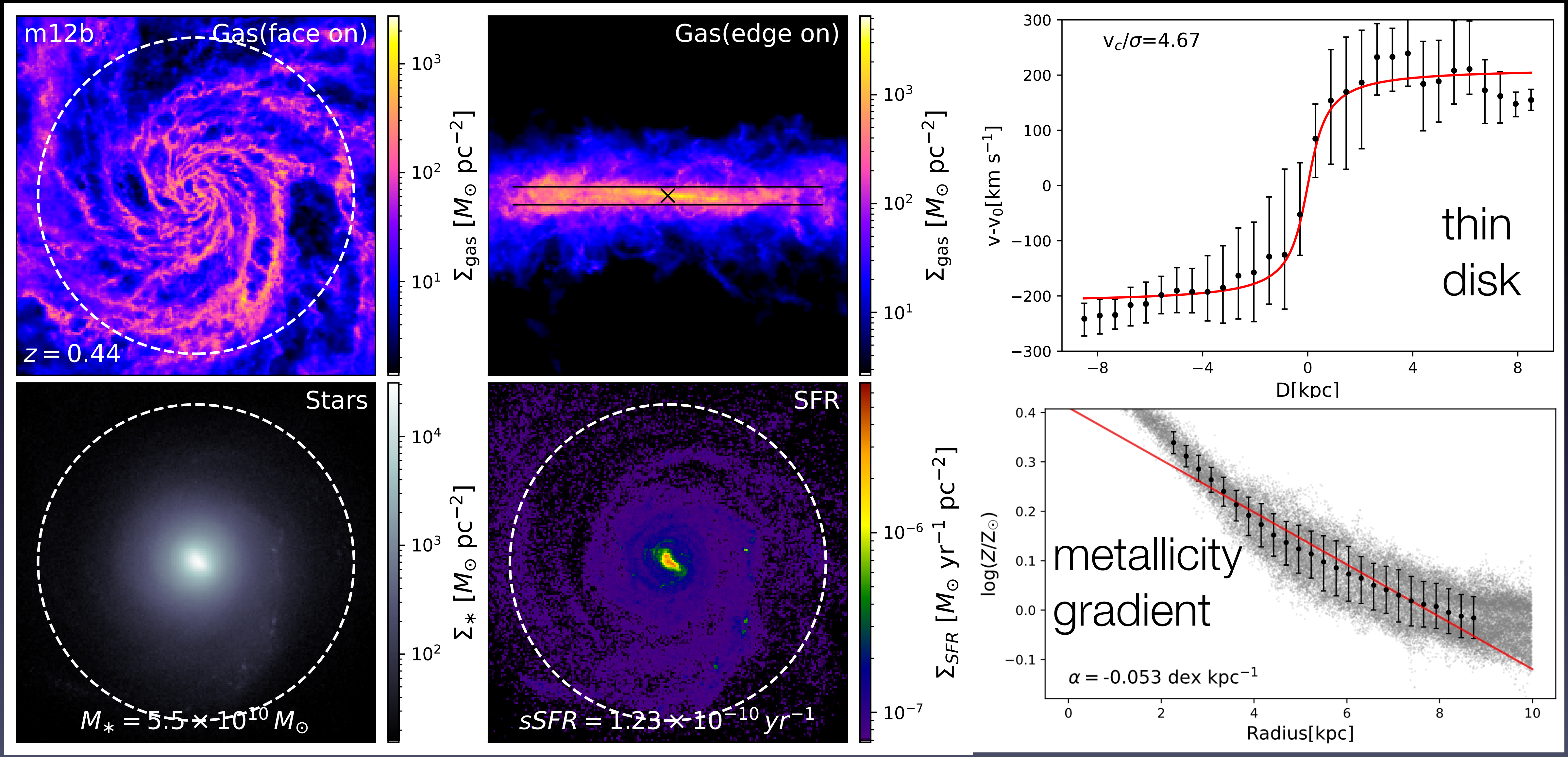




Balmer break in the LRD continuum and absorption in the broad Hα and Hβ emission lines can be reproduced with AGN SEDs attenuated through a gas slab (Inayoshi+24)

Resolving galaxy evolution with NIRSpec slit-stepping

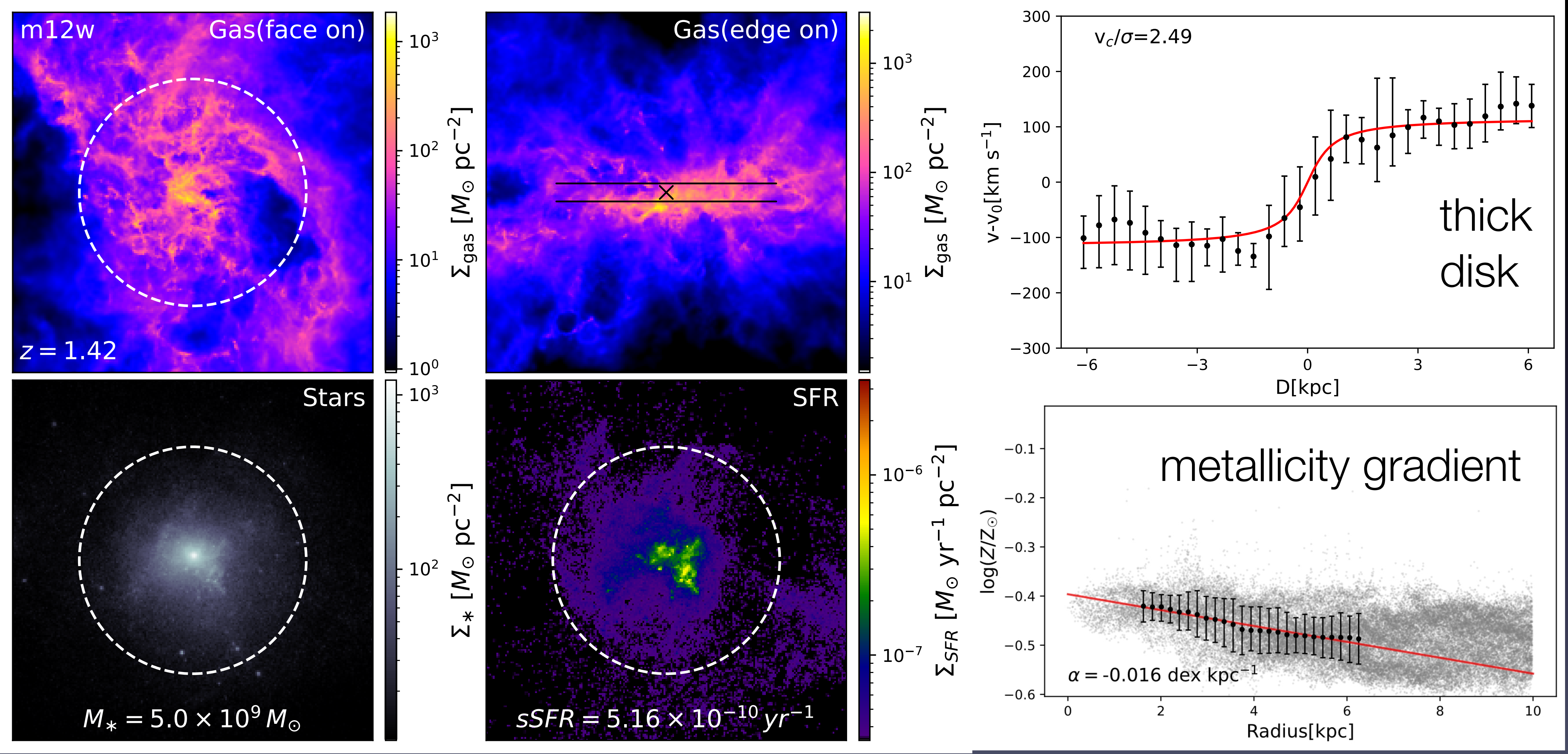
Temporal evolution of baryon cycling in individual systems



a MW progenitor at z=0.44 from FIRE-2

Sun, **WX**, +FIRE team 2025, ApJ in press

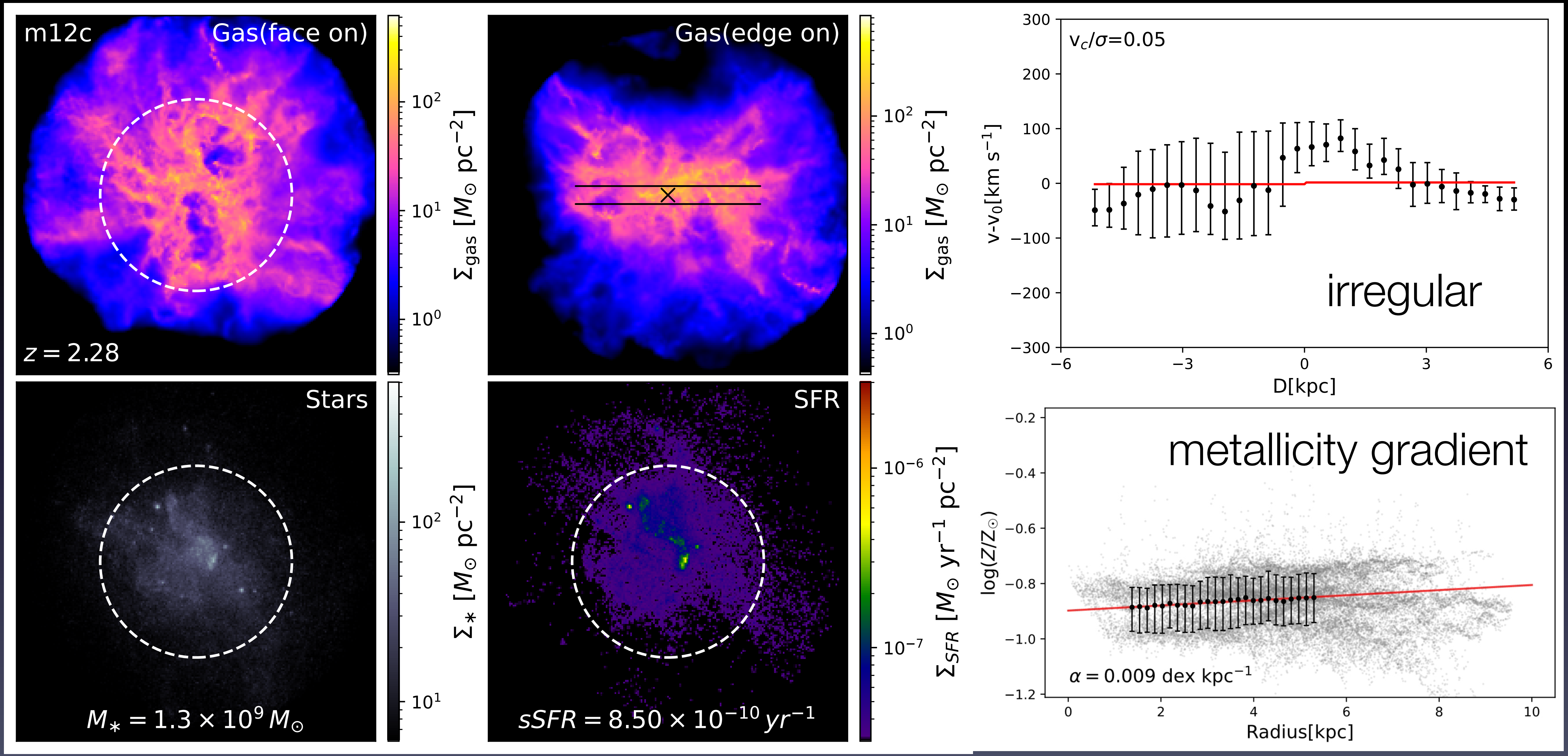
Temporal evolution of baryon cycling in individual systems



a MW progenitor at z=1.42 from FIRE-2

Sun, **WX**, +FIRE team 2025, ApJ in press

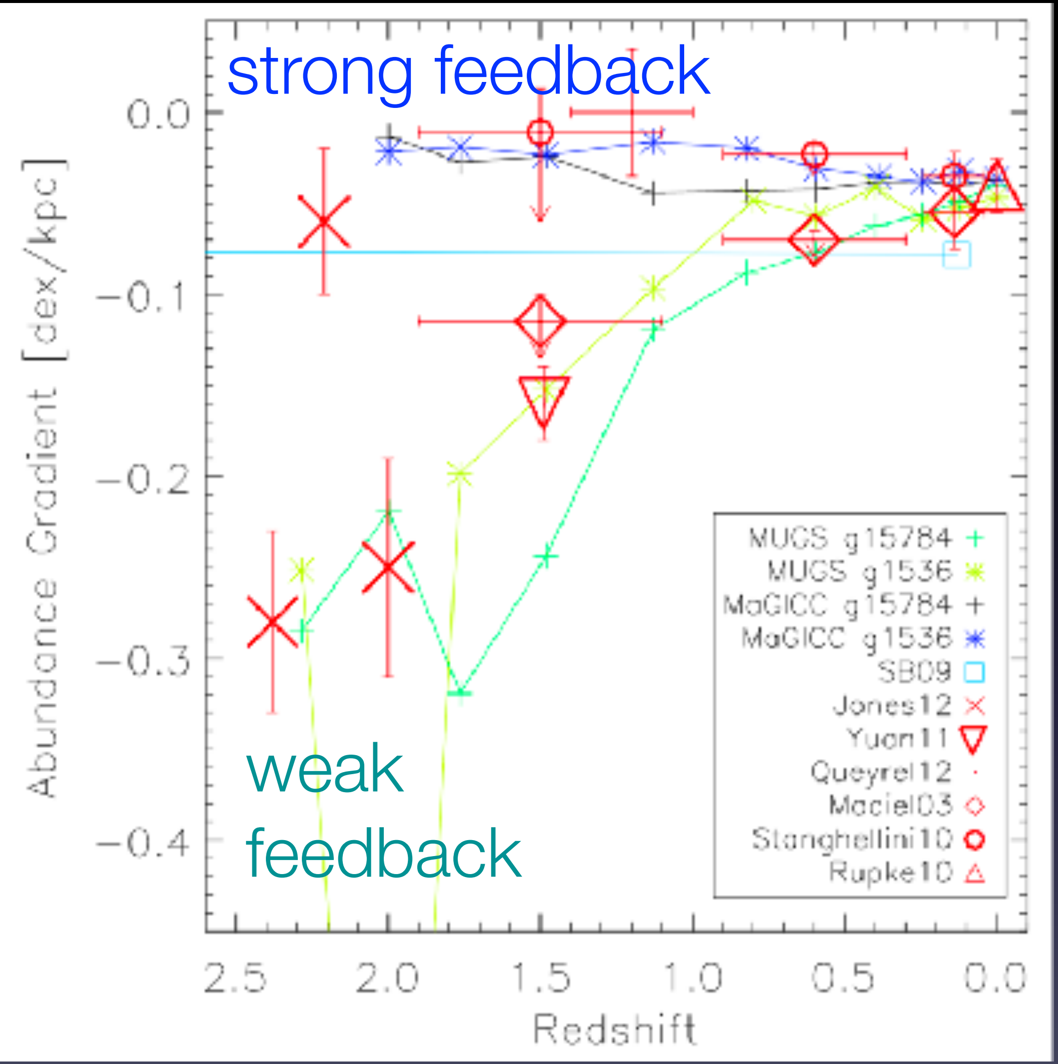
Temporal evolution of baryon cycling in individual systems

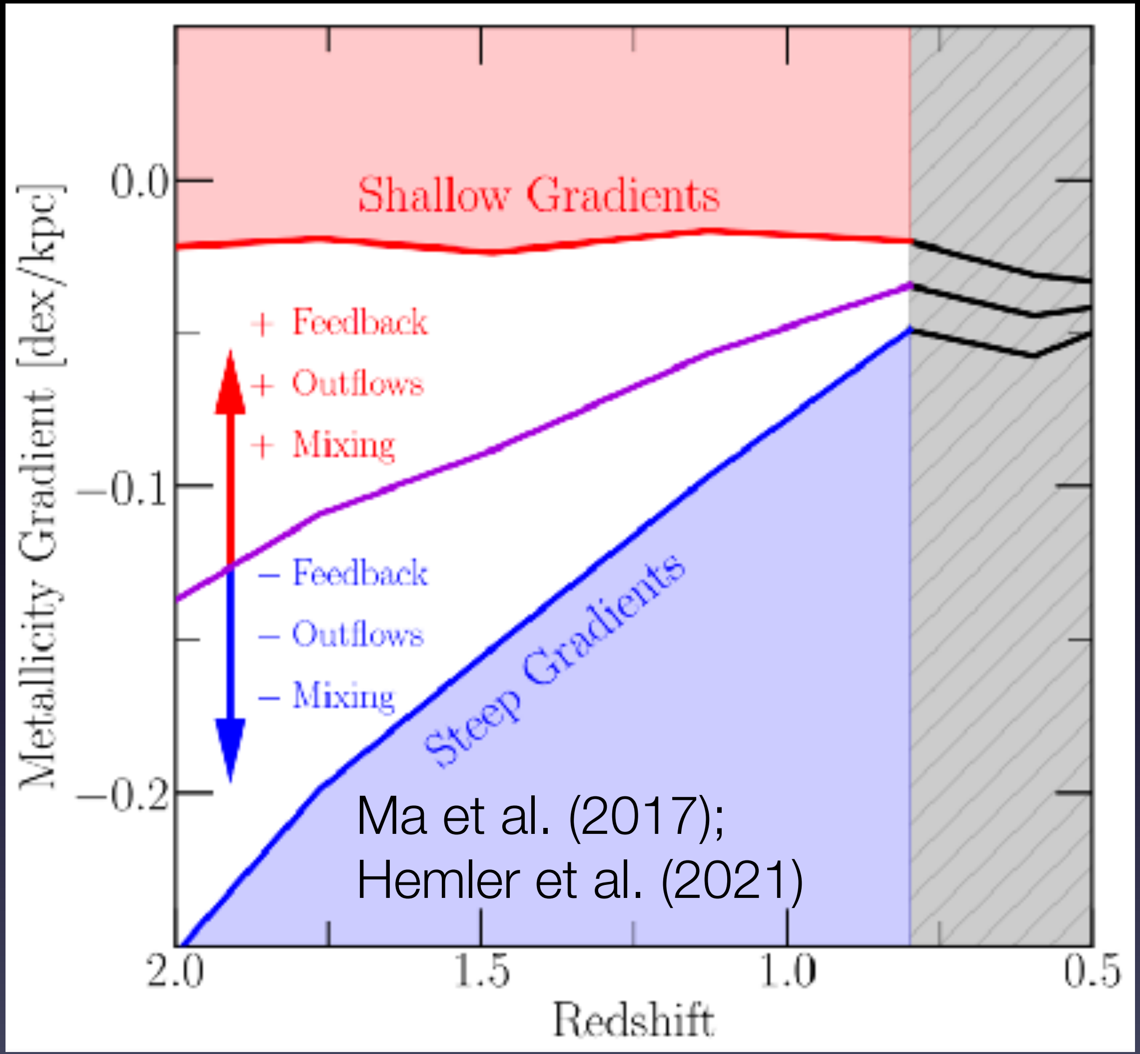


a MW progenitor at z=2.28 from FIRE-2

Sun, **WX**, +FIRE team 2025, ApJ in press

metallicity gradient as a better proxy of baryon cycle?

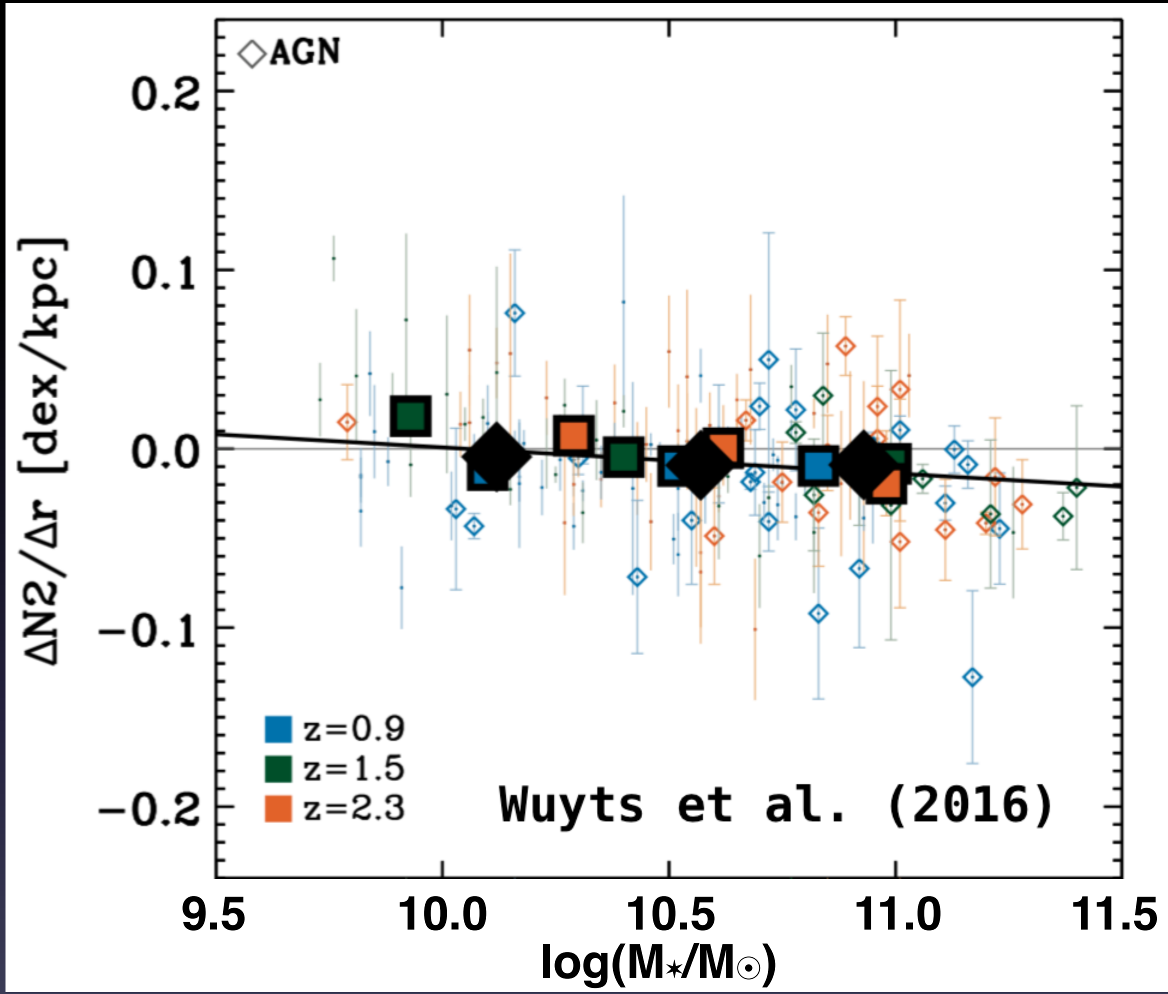


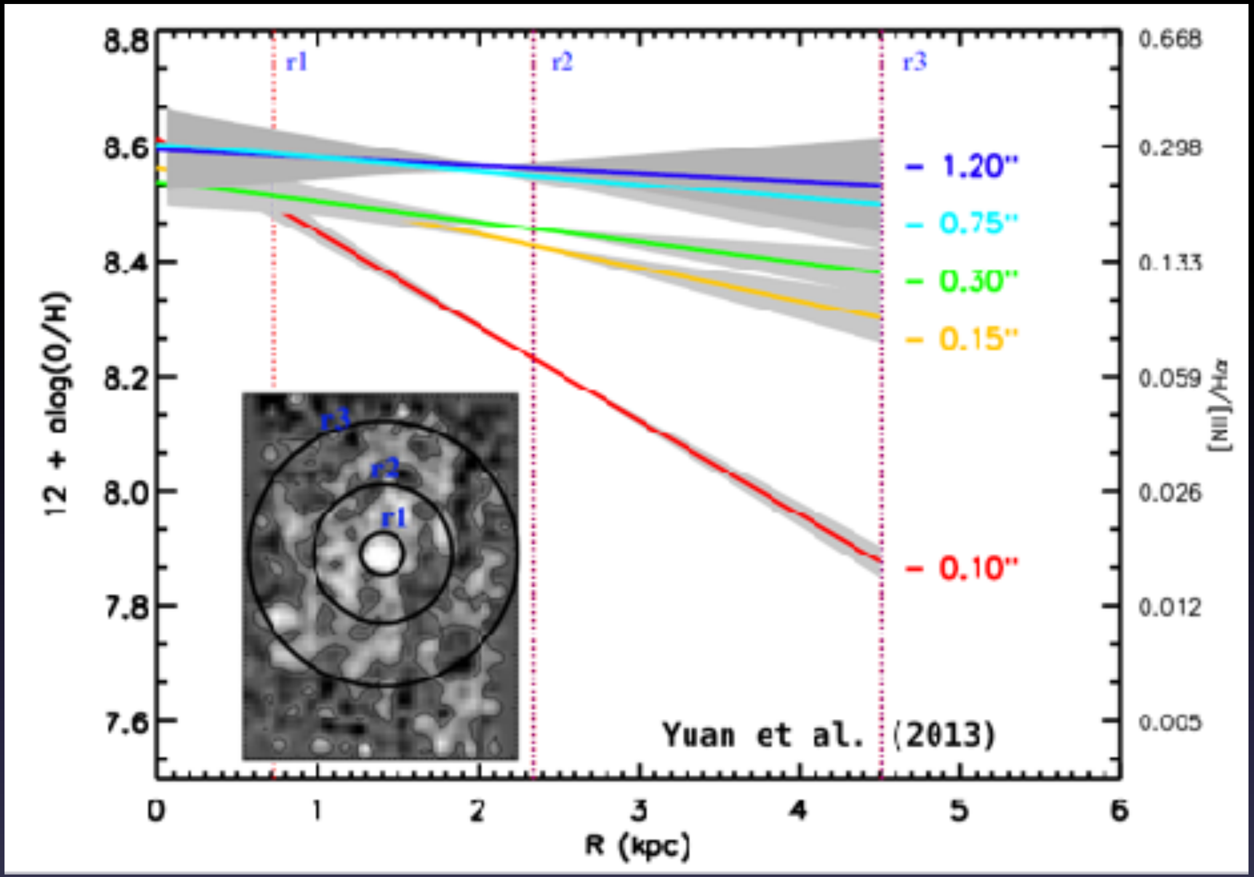


major limitation is observation ~10 yrs ago (Pilkington et al. 2012; Gibson et al. 2013)

metallicity radial gradient strongly constrains radial mixing and gas flows regulated by feedback

Angular resolution is crucial in spatially resolved analyses

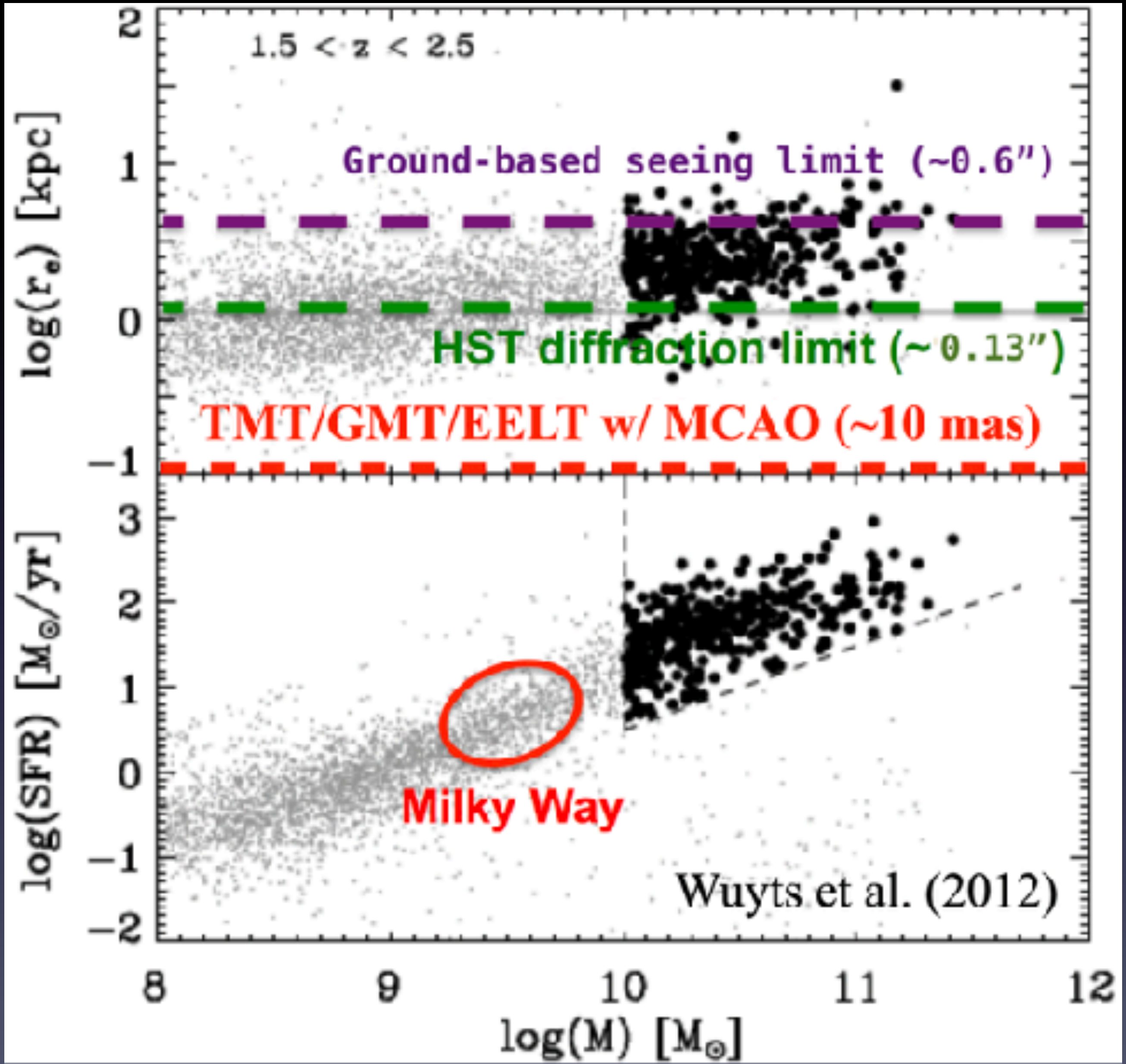




- seeing-limited observations often lead to flat gradients

- for L⋆ galaxies at z~2, observations with resolution coarser than kpc scale result in **spuriously flat metallicity gradients**
- correct for beam smearing is challenging

Angular resolution is crucial in spatially resolved analyses

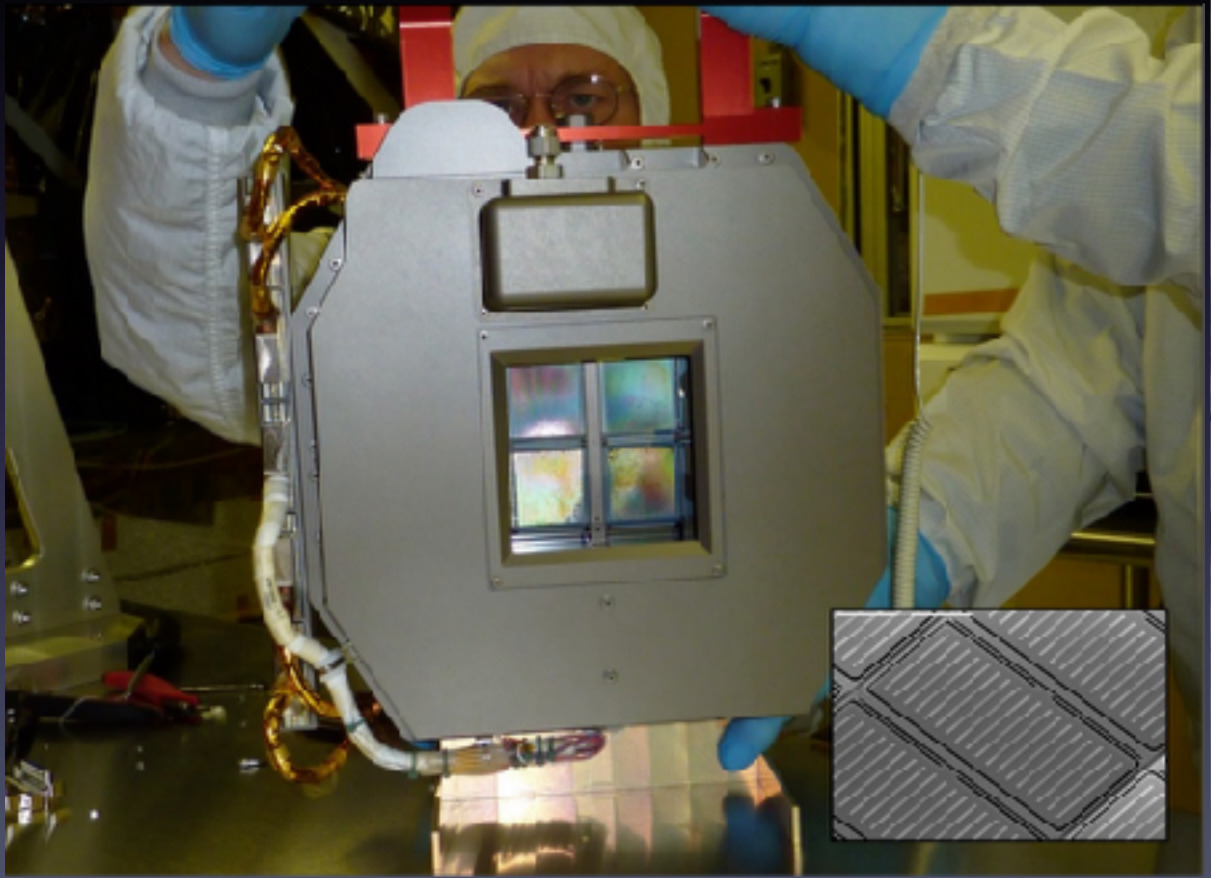


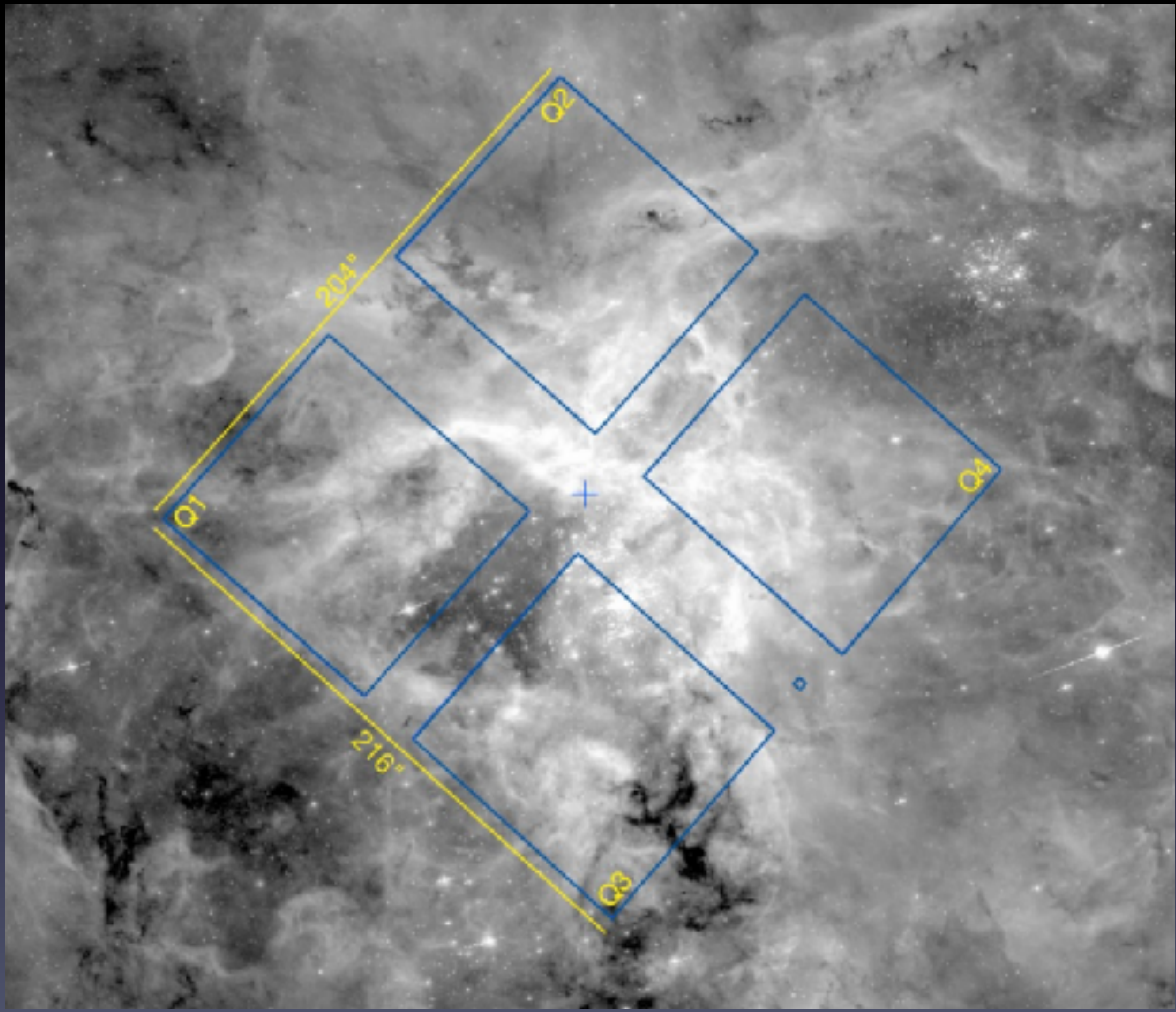
at z~2, our MW is a dwarf galaxy with $M_* \sim 2\times10^9\ M_\odot$

- optimal ground-based seeing => ~5 kpc resolution, twice the size of MW R_e!
- 2.5 (6.5) meter space telescope — HST (JWST) — achieves sub-kpc resolution!
- future ~30 meter sized telescopes with adaptive optics (e.g. TMT/GMT/E-ELT) => several tens of pc resolution!

The NIRSpec Micro-shutter Array (MSA)

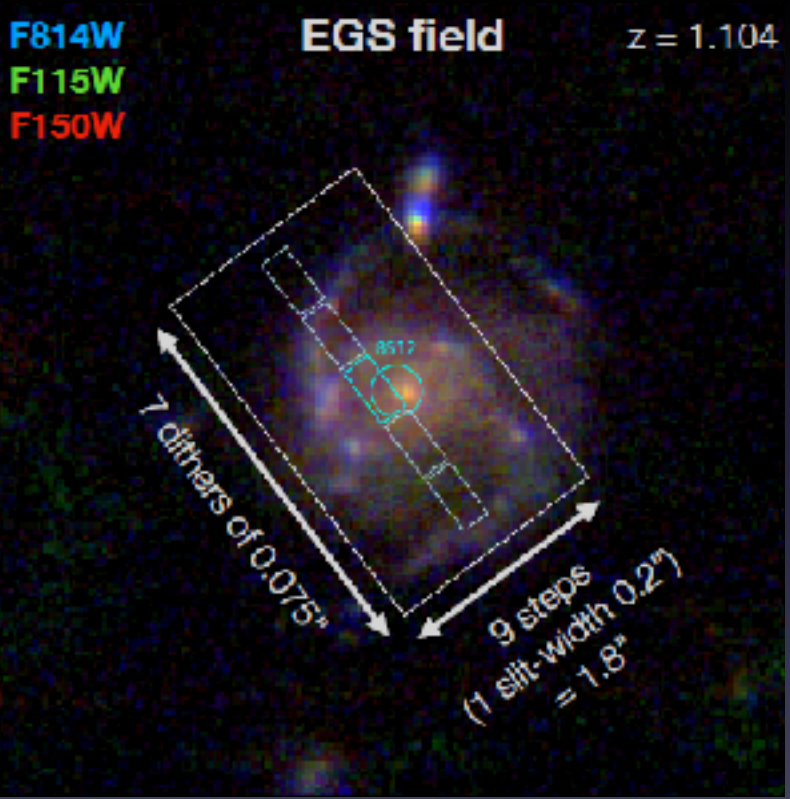
- ~250,000 micro-shutters in 4 quadrants
- physical size: 78micron
- 100s to 1000s of spectra simultaneously

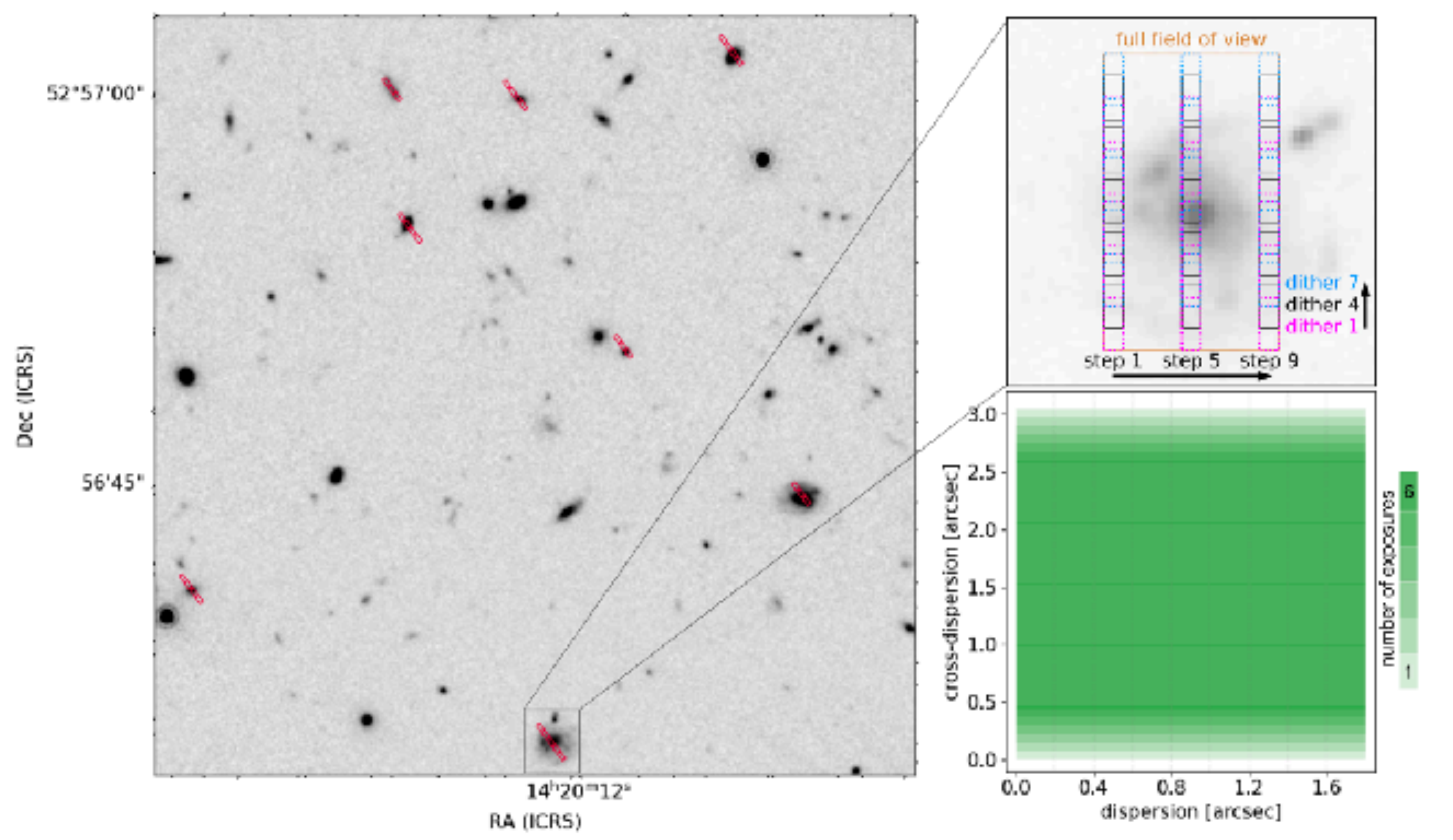




MSA **slit-stepping**: a novel high-efficiency IFU mode

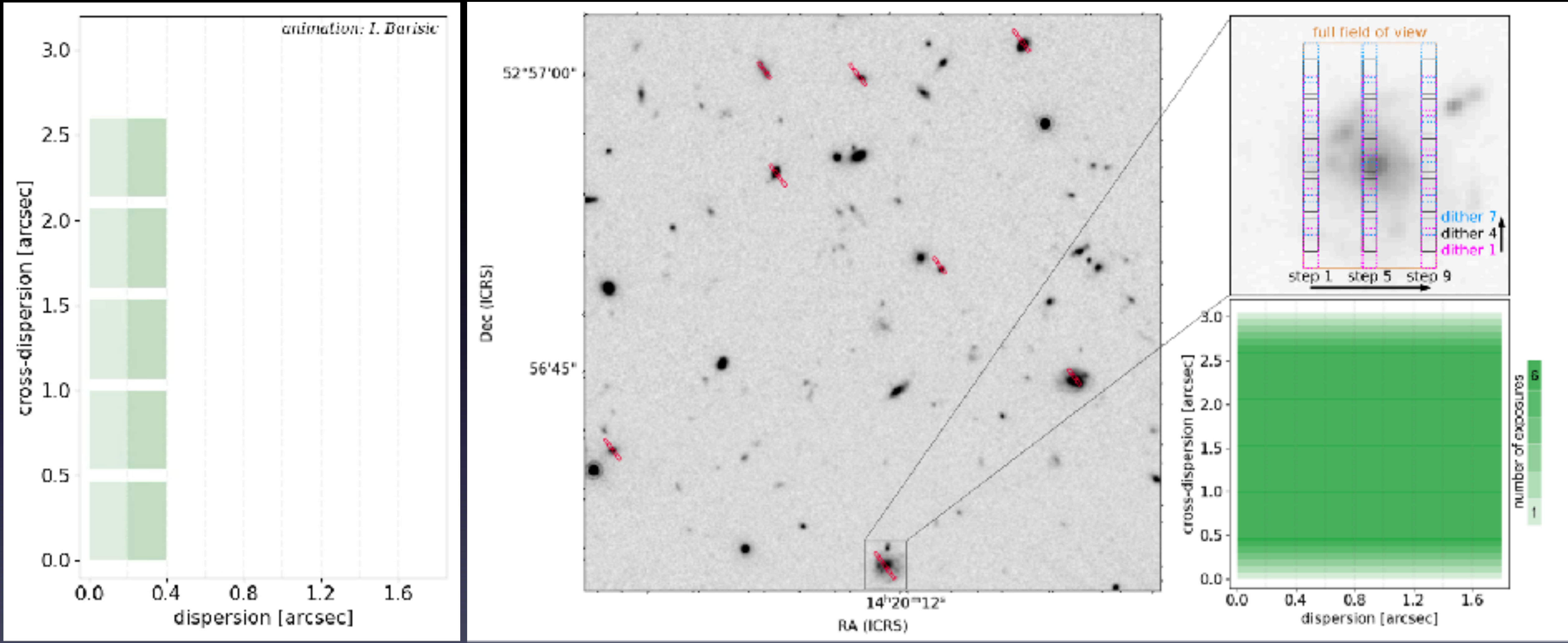
MSA-3D programs:
JWST GO-2136,3426





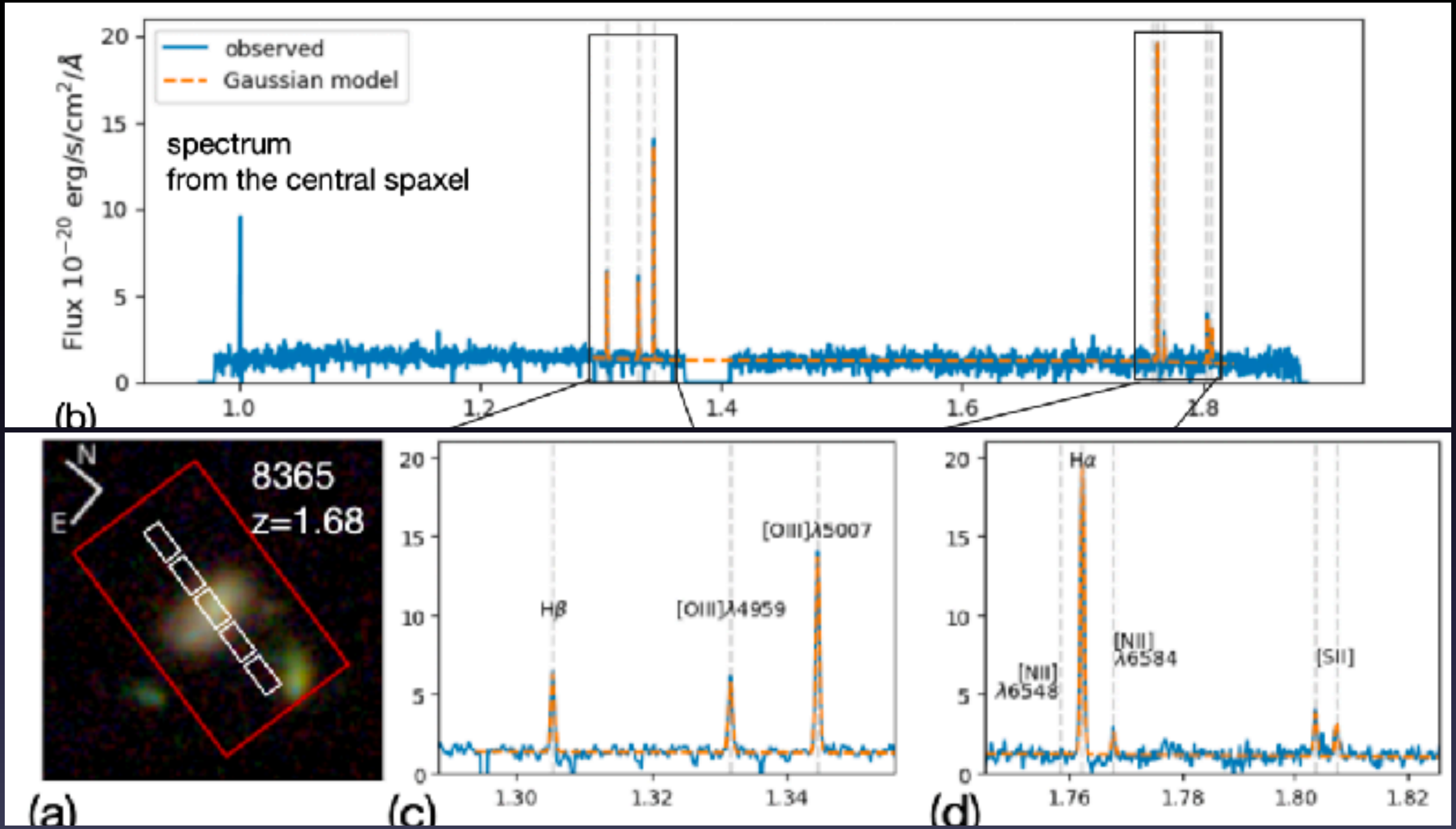
We invented this new technique faster than NIRSpec/IFU by >15x! (Barisic+25, Ju, **WX**+25)

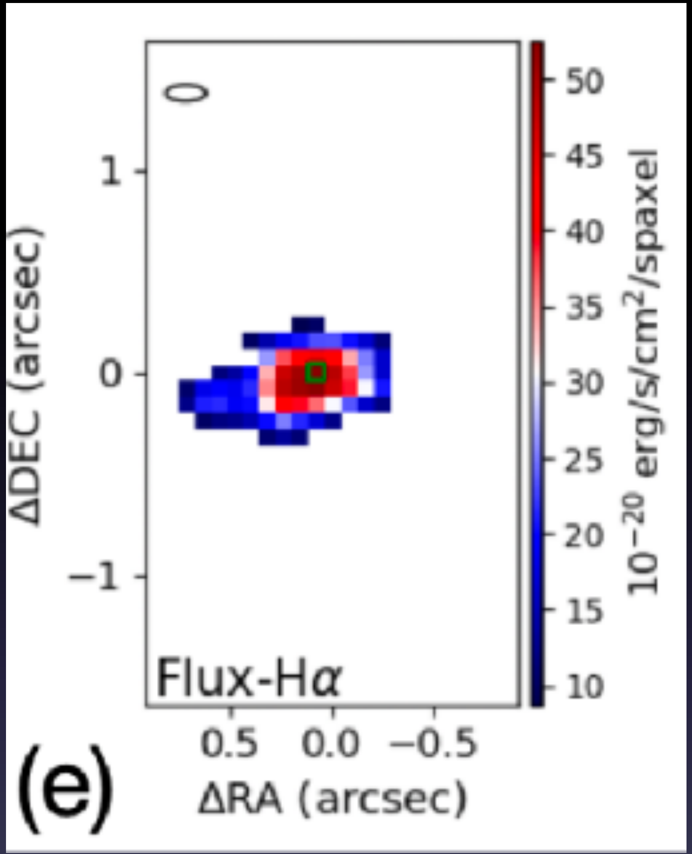
MSA **slit-stepping**: a novel high-efficiency IFU mode



We invented this new technique faster than NIRSpec/IFU by >15x! (Barisic+25, Ju, **WX**+25)

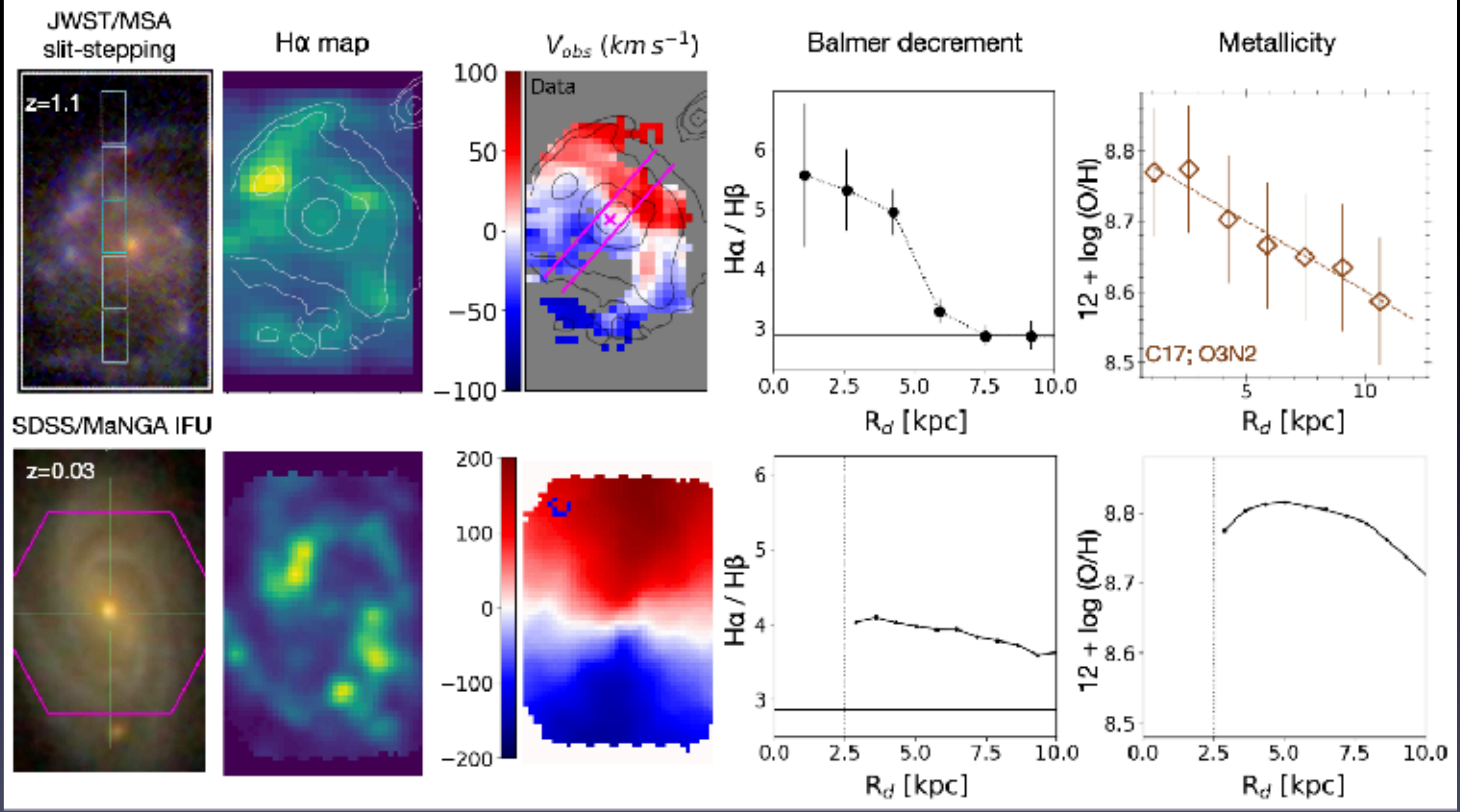
MSA-3D data





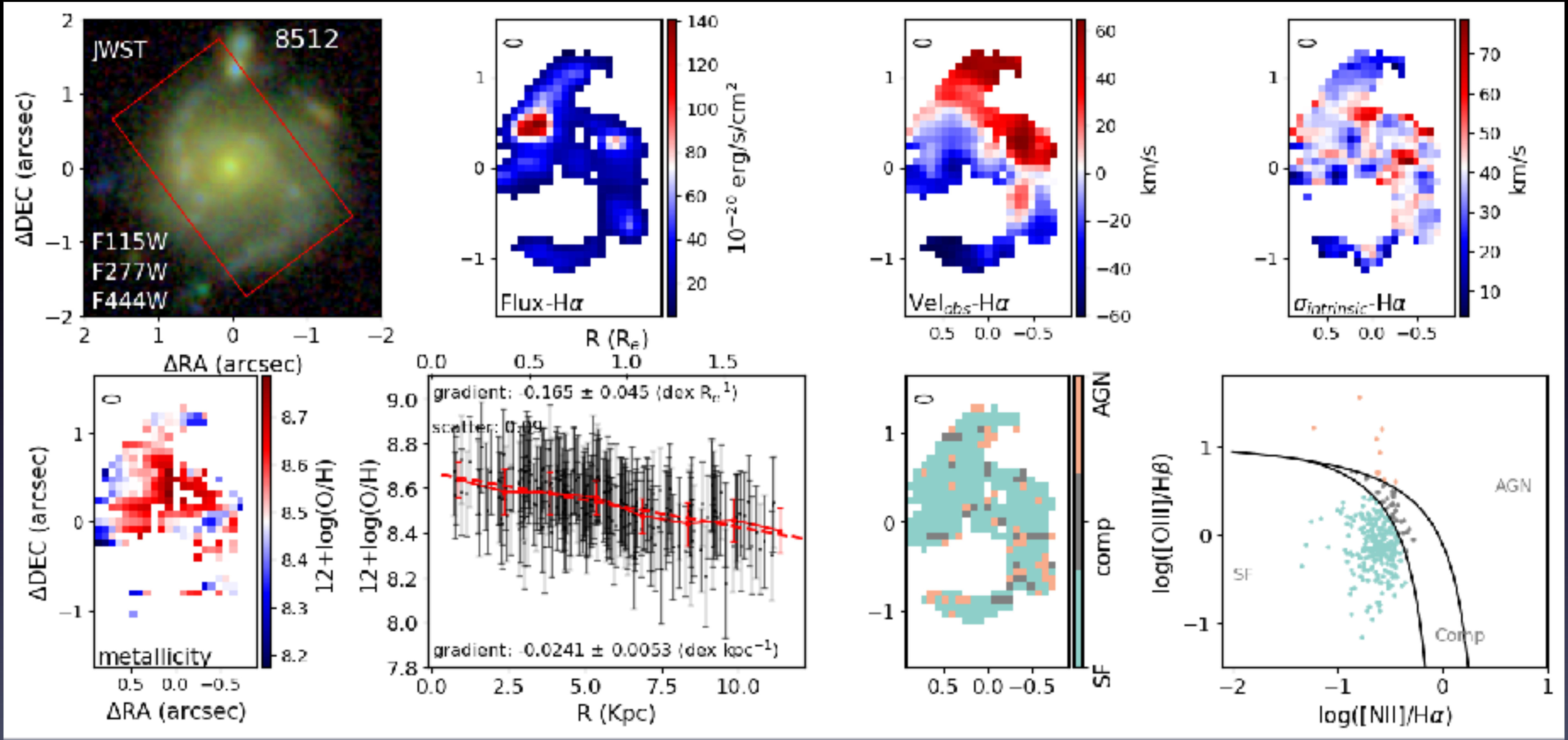
- spatial resolution element: 0.1”x0.2”
- spectral resolution: R~2700
- 10-sigma lim. SB: 7e-17
- wavelength coverage: [0.5,2] micron => 4300-7500Å at 0.5<z<1.7
- exposure time: ~20 hours on target

MSA-3D data on z~1 galaxies



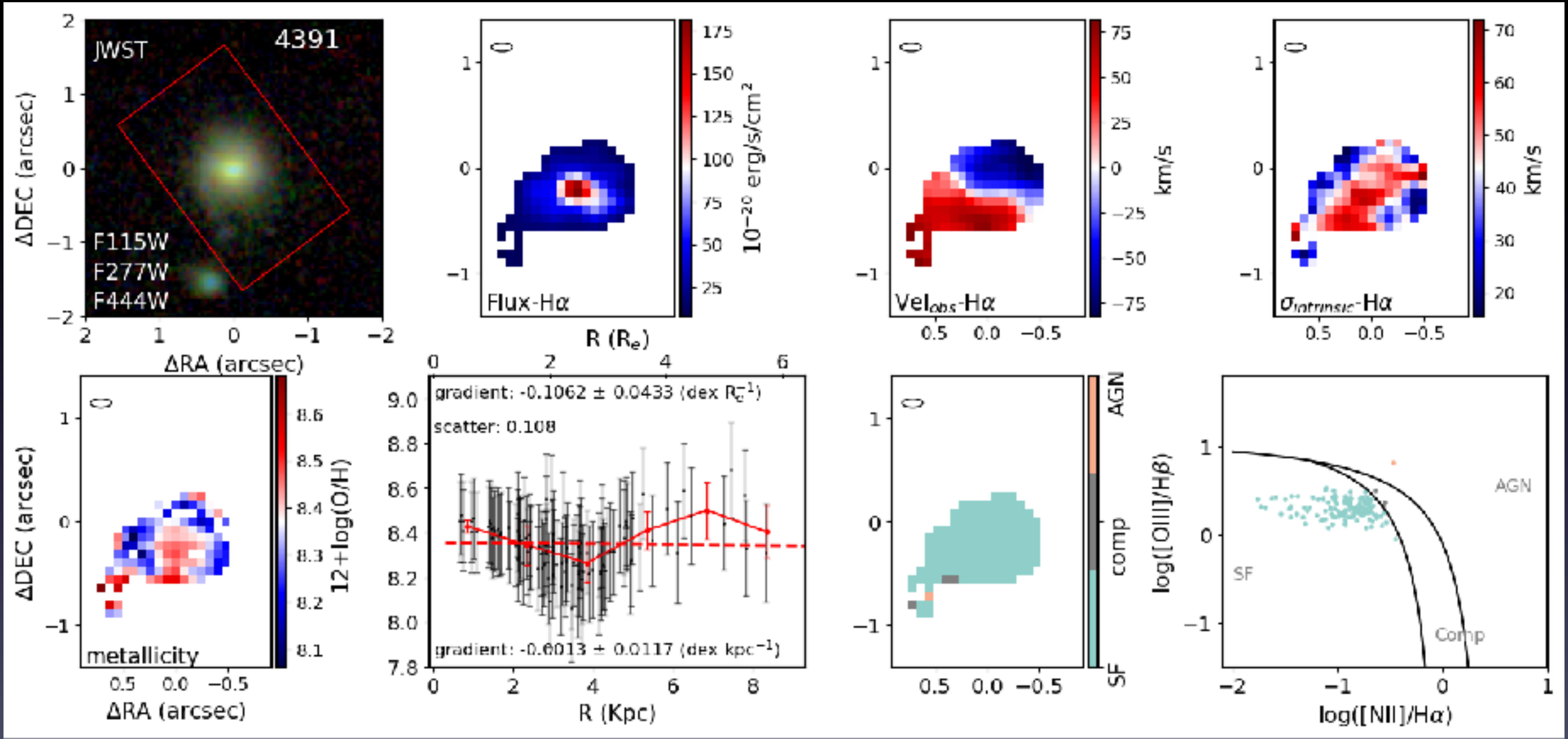
data quality comparable to MaNGA on z~0 galaxies (Bundy+15)

First science results from NIRSpec slit-stepping



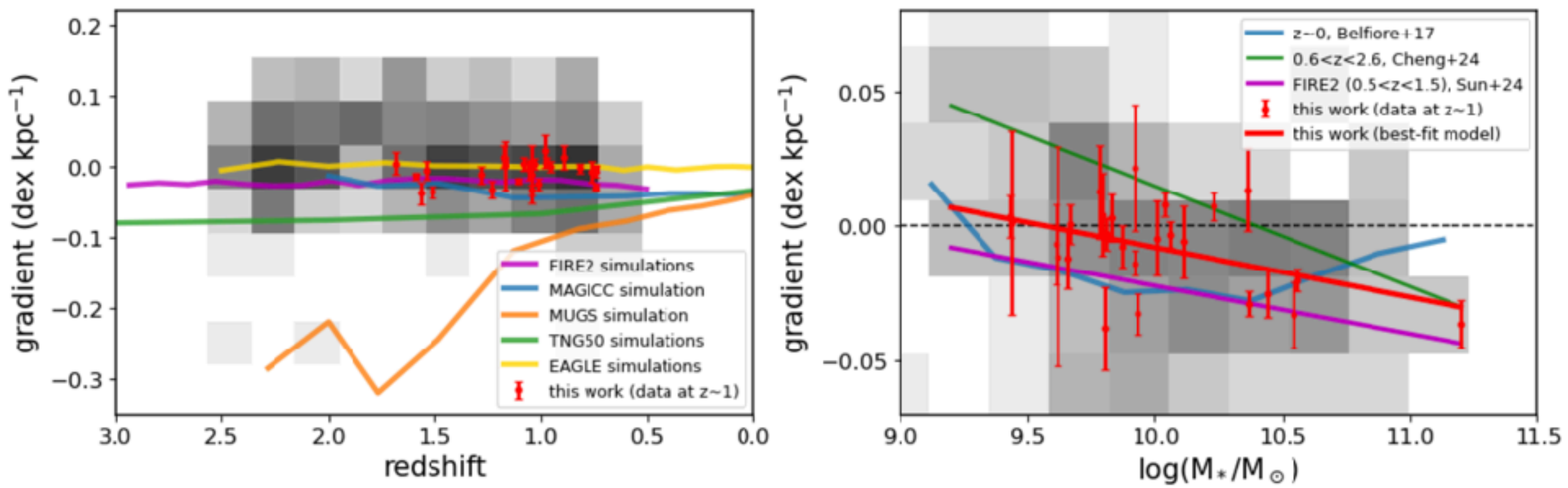
a thin disk at z=1 from JWST pseudo-IFU   Ju, **WX**, +MSA-3D team 2025, ApJL, 978, L39

First science results from NIRSpec slit-stepping



a thick disk at z=1 from JWST pseudo-IFU Ju, **WX**, +MSA-3D team 2025, ApJL, 978, L39

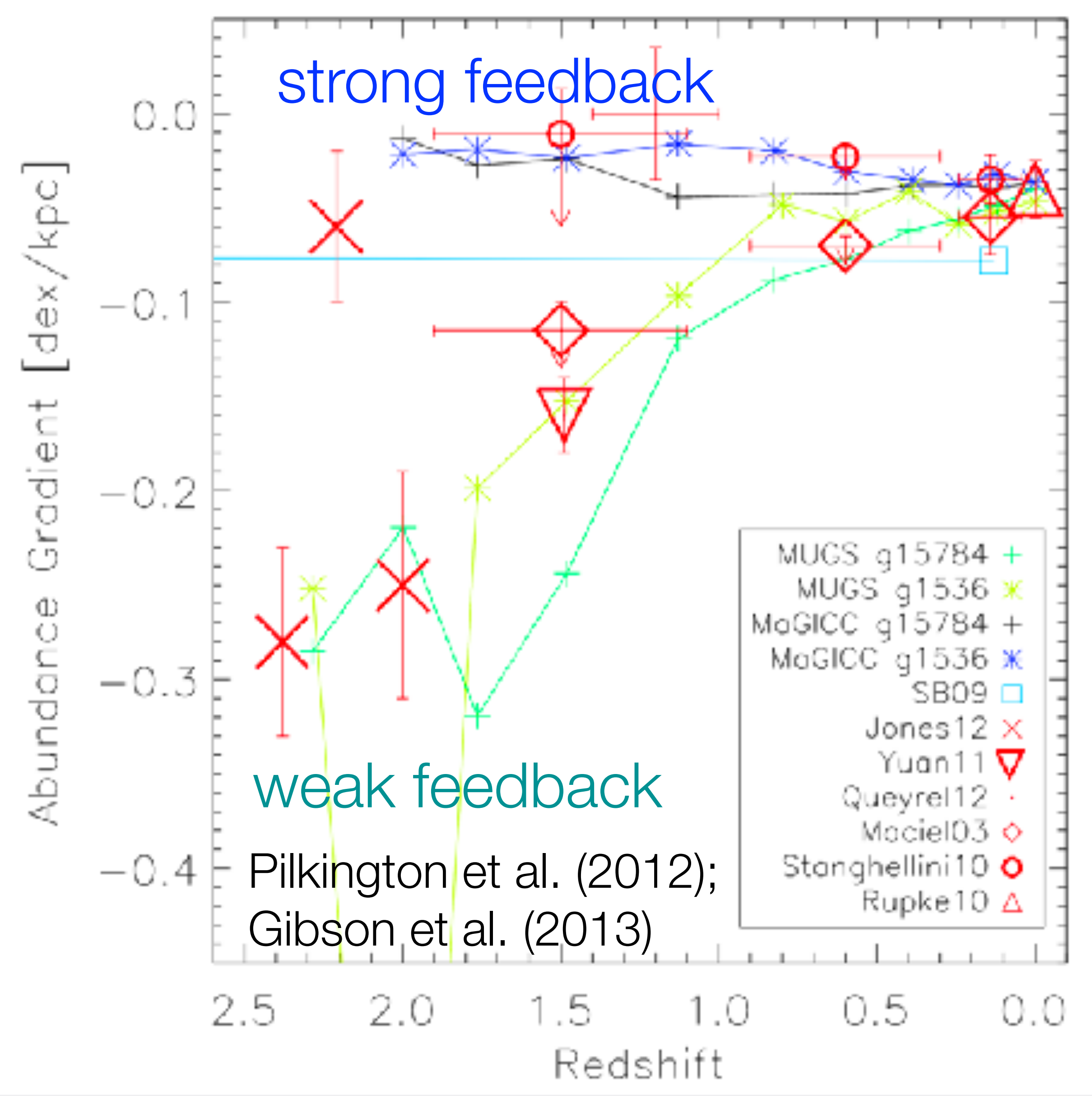
NIRSpec slit-stepping metallicity gradients

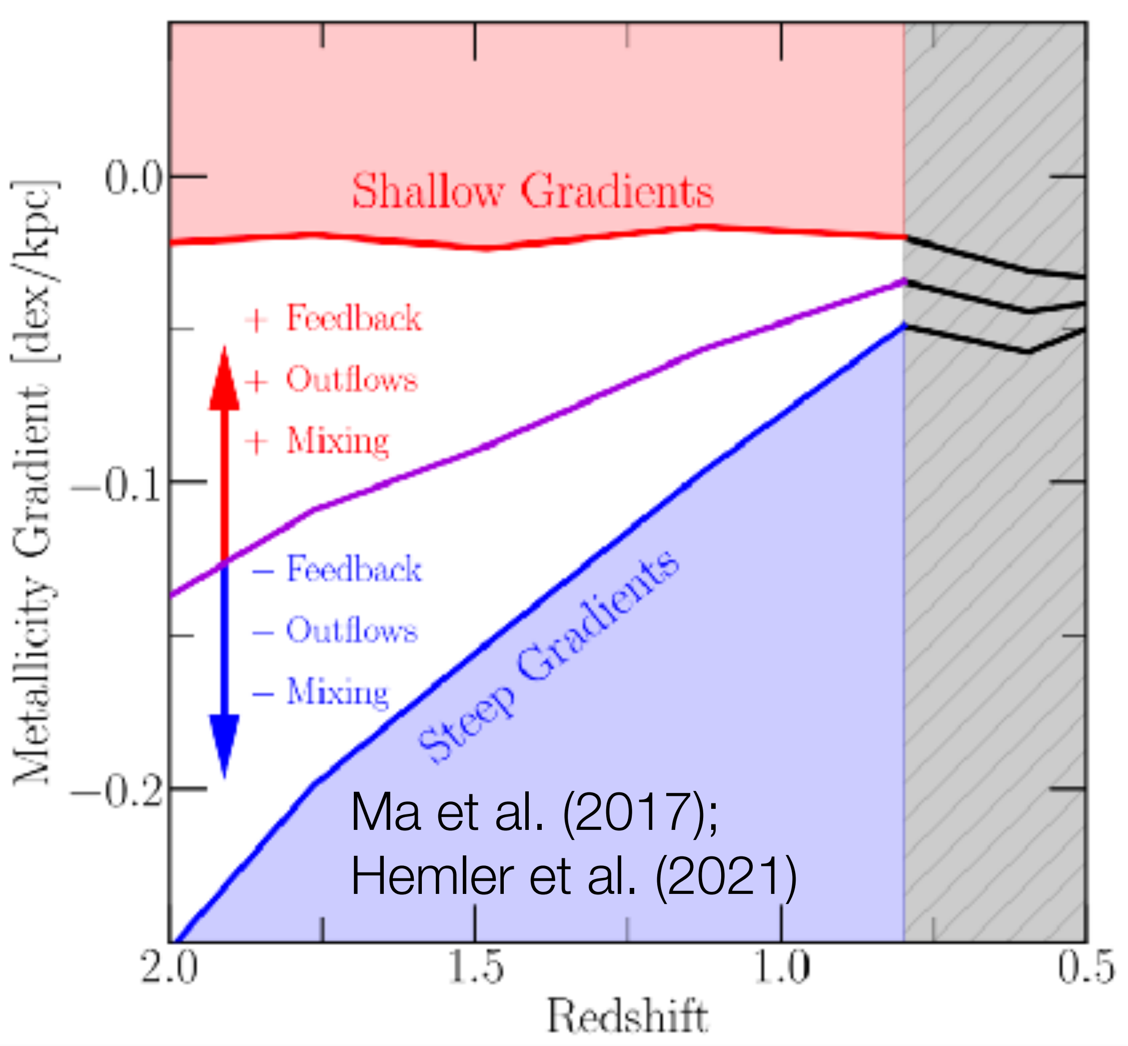


- our results filled the gap of high-res metal gradient measurements at z~1
- we found a strong negative mass dependence of metallicity gradients at z~1

temporal evolution and mass dependence consistent with FIRE-2 (Sun, **WX**+25)

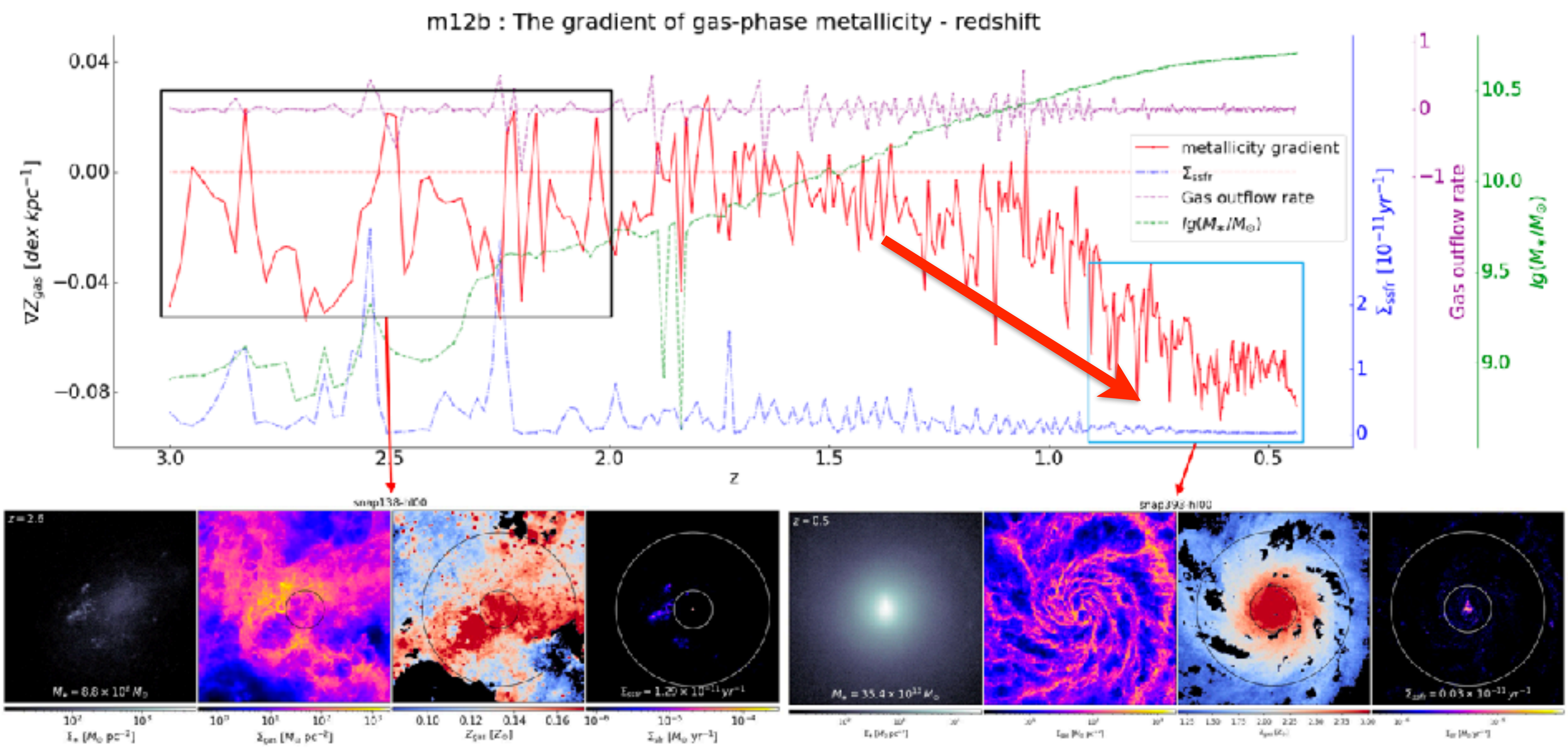
metallicity gradient as a key proxy of galaxy evolution



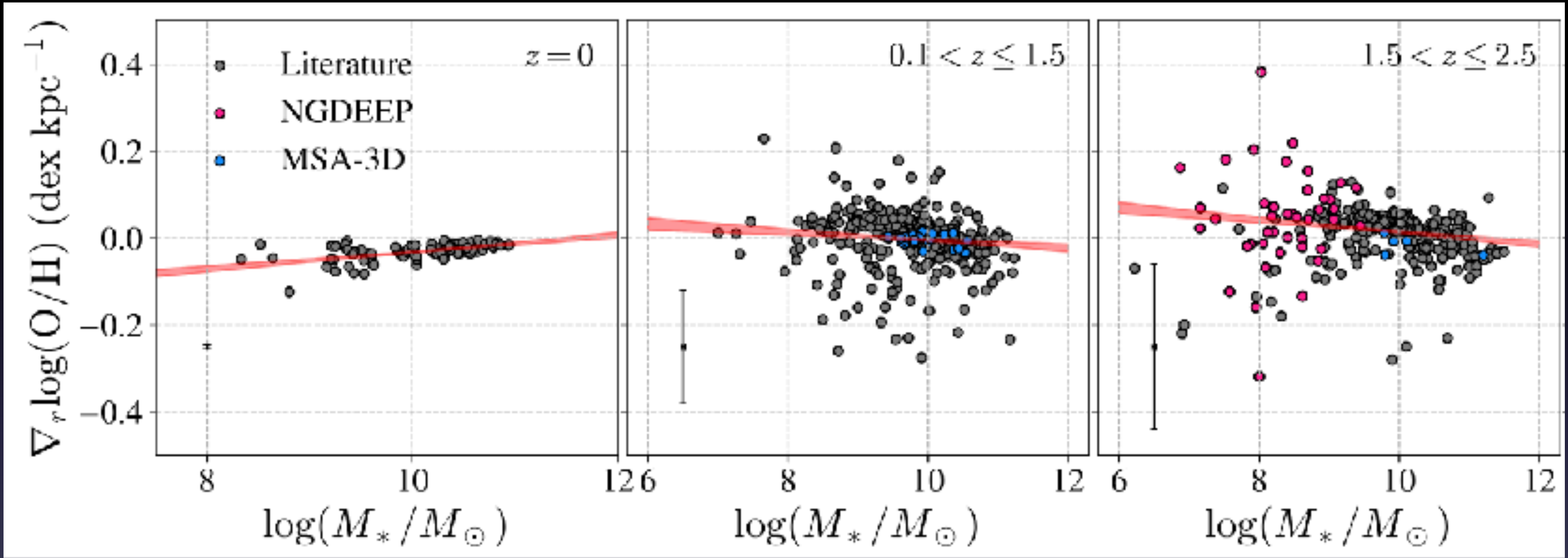


metallicity radial gradient strongly constrains feedback and gas flows!

Temporal evolution of MW progenitors in FIRE-2



Connection of disk formation and chemical enrichment

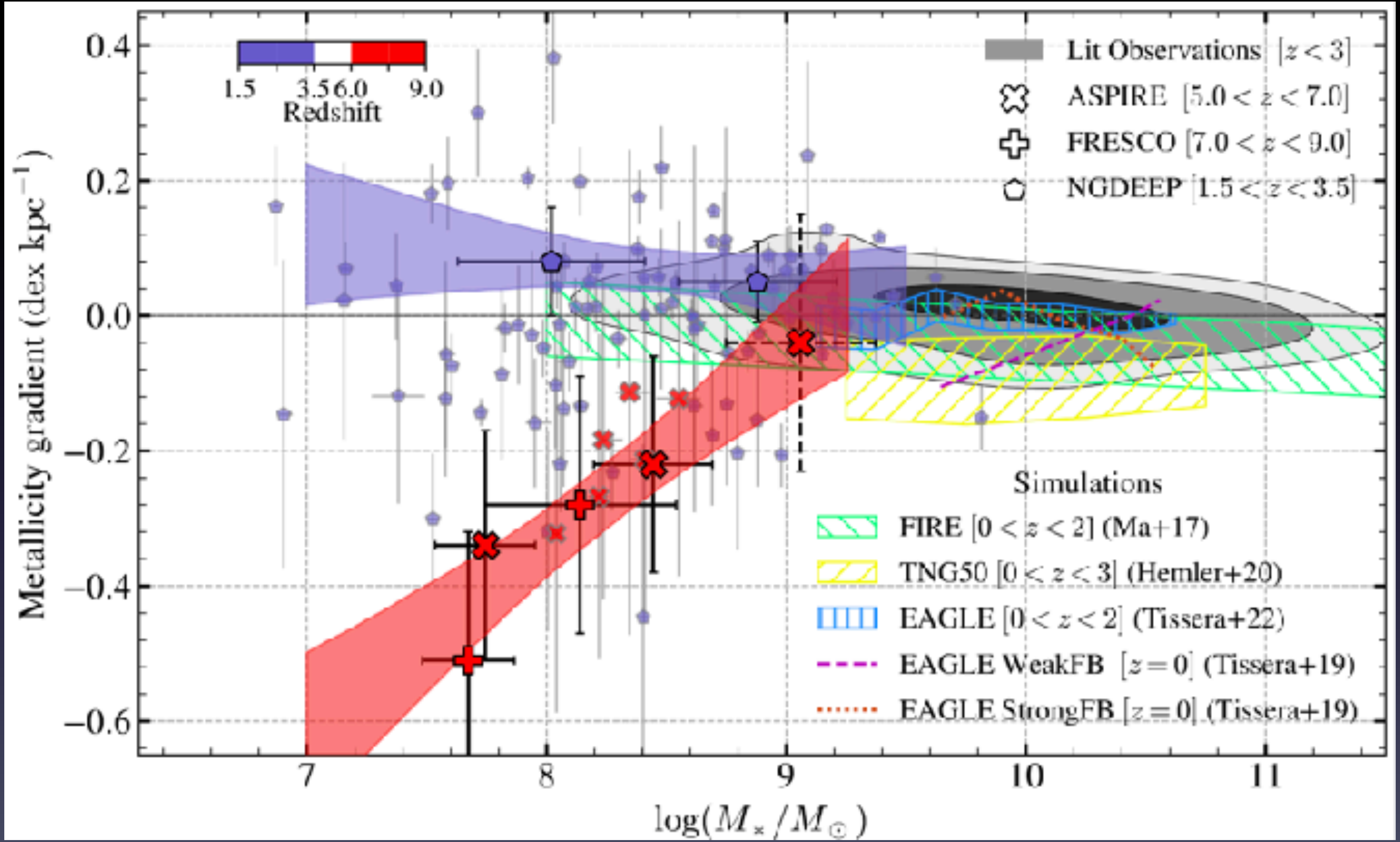


z~0: positive mass dependence → cosmic noon: negative mass dependence

inside-out growth

feedback-regulated starburst

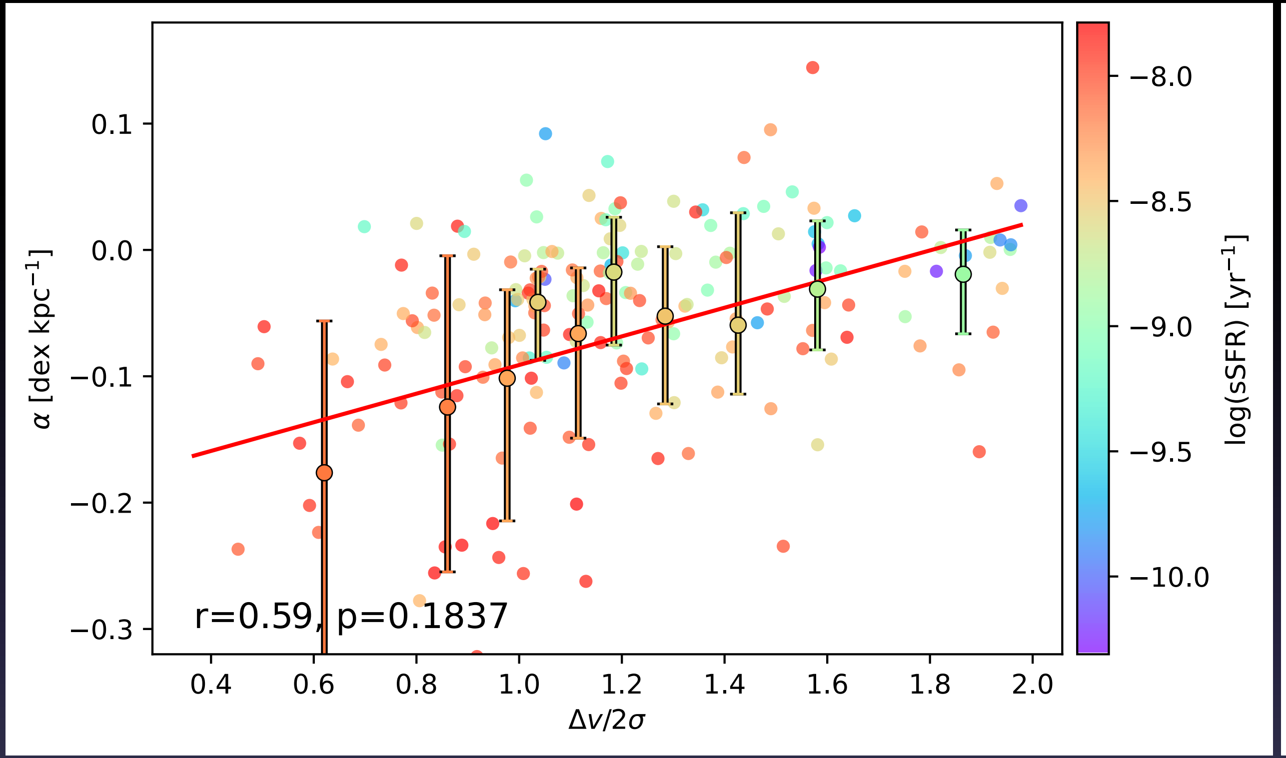
Connection of disk formation and chemical enrichment

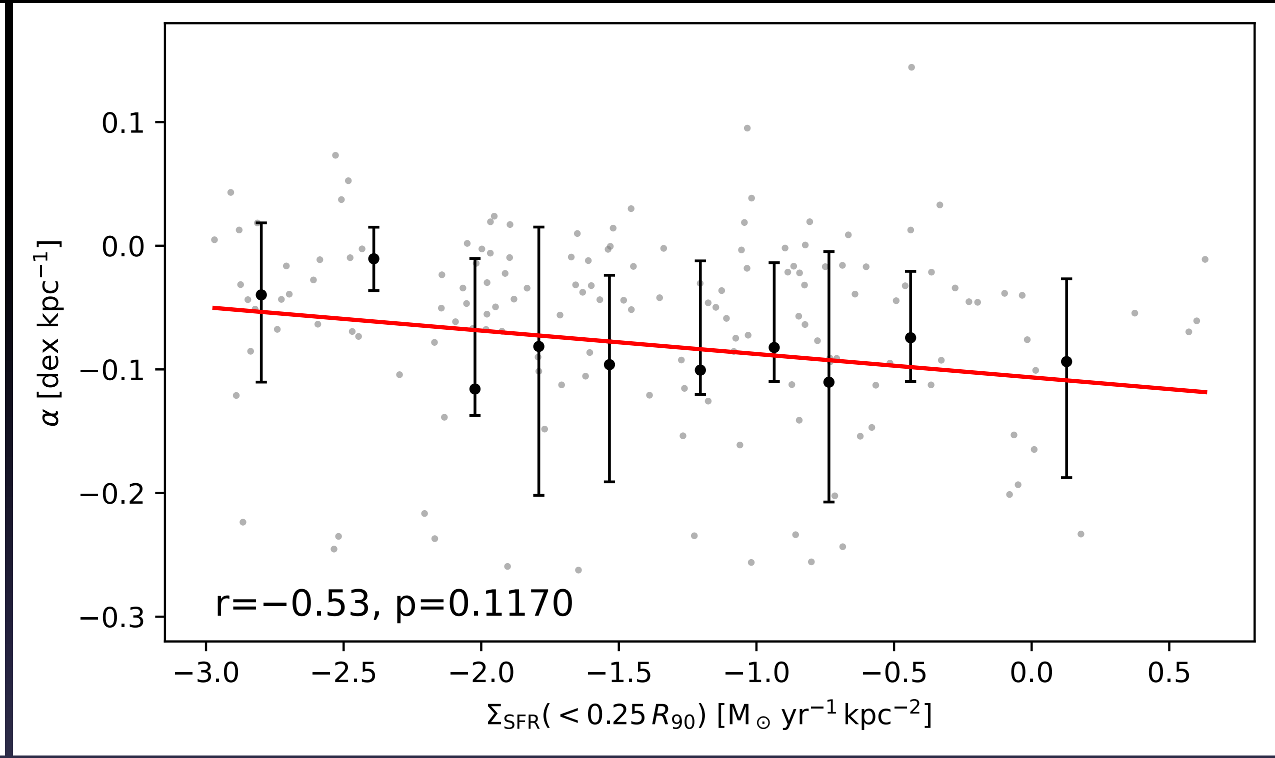


localized star formation in the EoR

→ reionization epoch: changing back to positive mass dependence

Metallicity gradients in the reionization epoch from FIRE-2

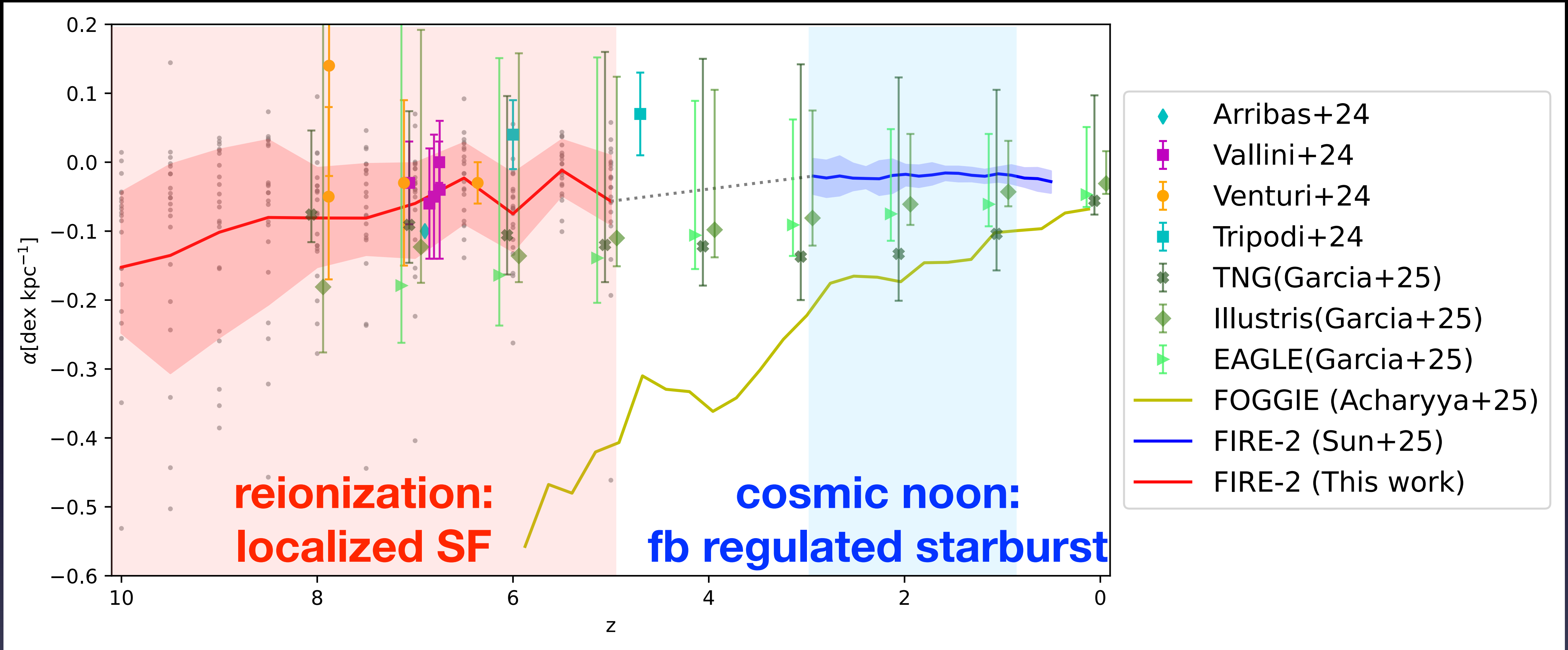




- z≥5 galaxies with smaller max velocity difference (normalized to dispersion) show steeper gradients and higher sSFR
- relatively strong anti-correlation between SFR surface density and metallicity gradient

Sun, WX et al. 2025b in prep

Metallicity gradients in the reionization epoch from FIRE-2



- A self-consistent theoretical framework for tracing the evolution of galaxy metallicity gradients from the epoch of reionization through to cosmic noon.

Sun, WX et al. 2025b in prep

Thanks for your attention!