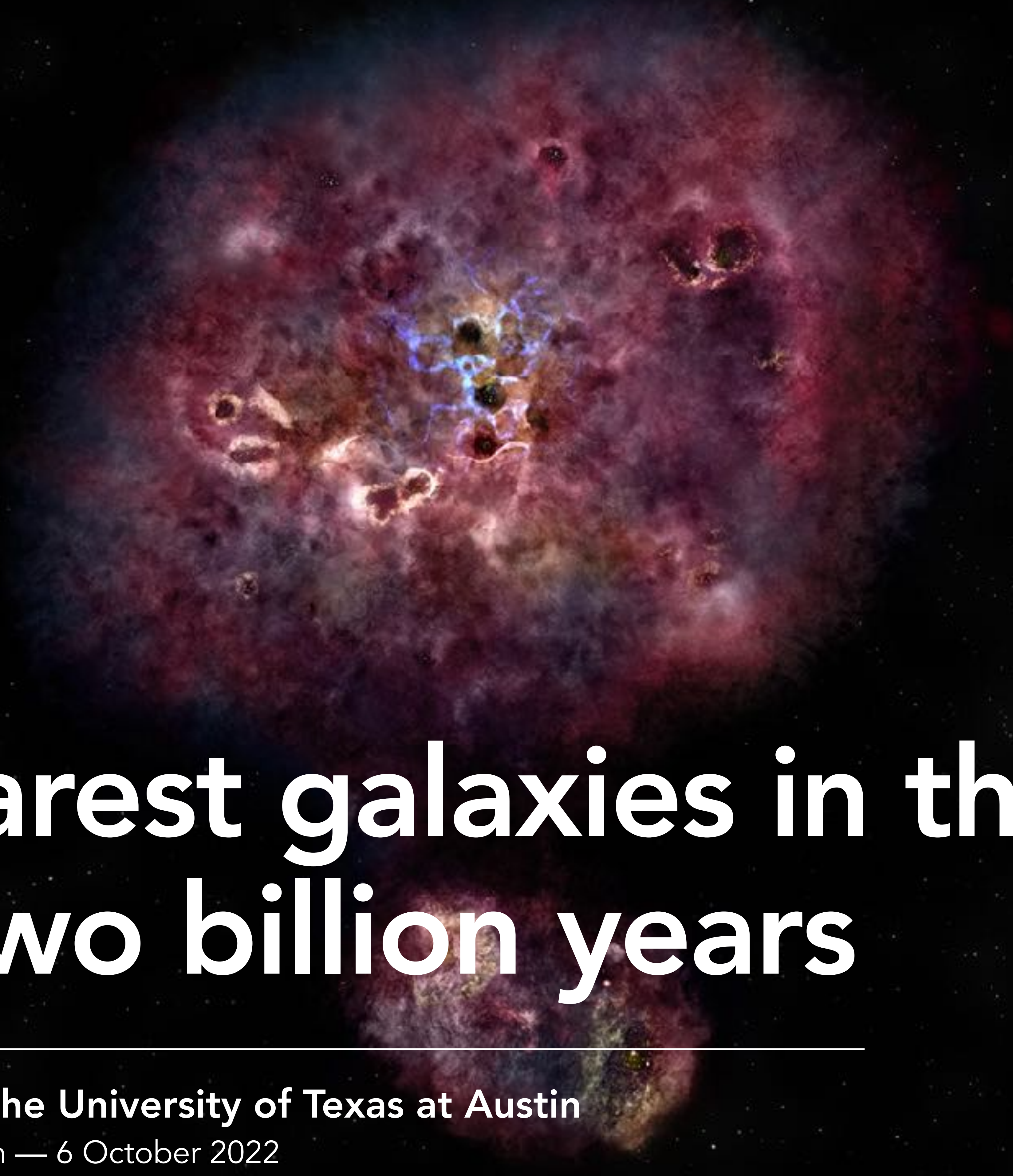

The rarest galaxies in the first two billion years

Caitlin M. Casey, The University of Texas at Austin

UC Berkeley Colloquium — 6 October 2022

Members of my group, past & present:

Postdocs: Chao-Ling Hung, Justin Spilker, Jorge Zavala, Jed McKinney, Max Franco, Arianna Long, Seiji Fujimoto

Grad Students: Sinclaire Manning, Patrick Drew, Jaclyn Champagne, Olivia Cooper, Hollis Akins

Undergrads: Aimee Schechter, Laney Wicker, Anne Burnham, Jake Magee, Mia Fong, Alfonso Melendez, Rachel Nere

+ members of the COSMOS Team

MORA

Mapping Obscuration to Reionization with ALMA

51 hour Cycle 6+8 Program

COSMOS WEB

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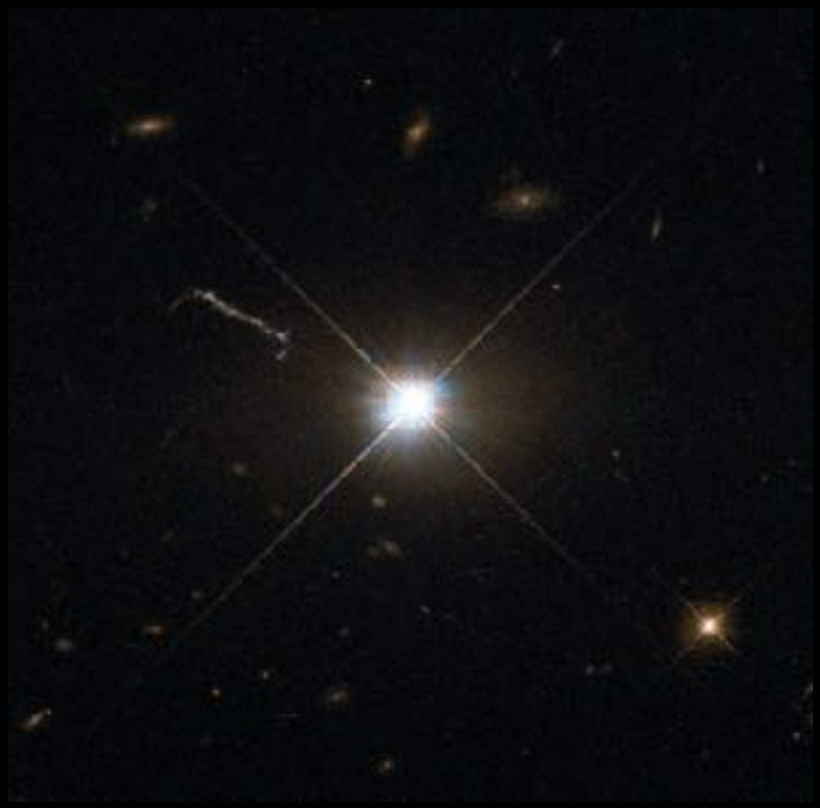
WERLS

Webb Epoch of Reionization Lyα Survey

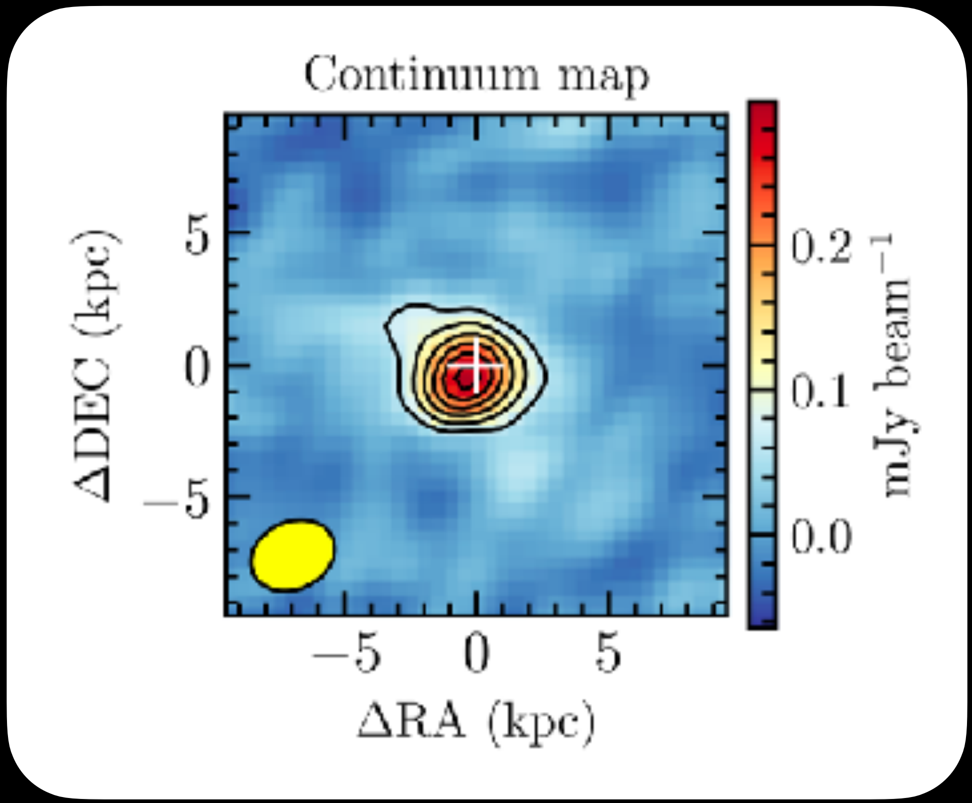
29night Keck KSMS Program

What can pathologically massive galaxies — formed incredibly quickly after the Big Bang — teach us about fundamental processes of halo growth, the ISM and galaxy formation?

The original class of pathological galaxies: **Quasars**



3C 273 at z=0.15
(Schmidt 1963)

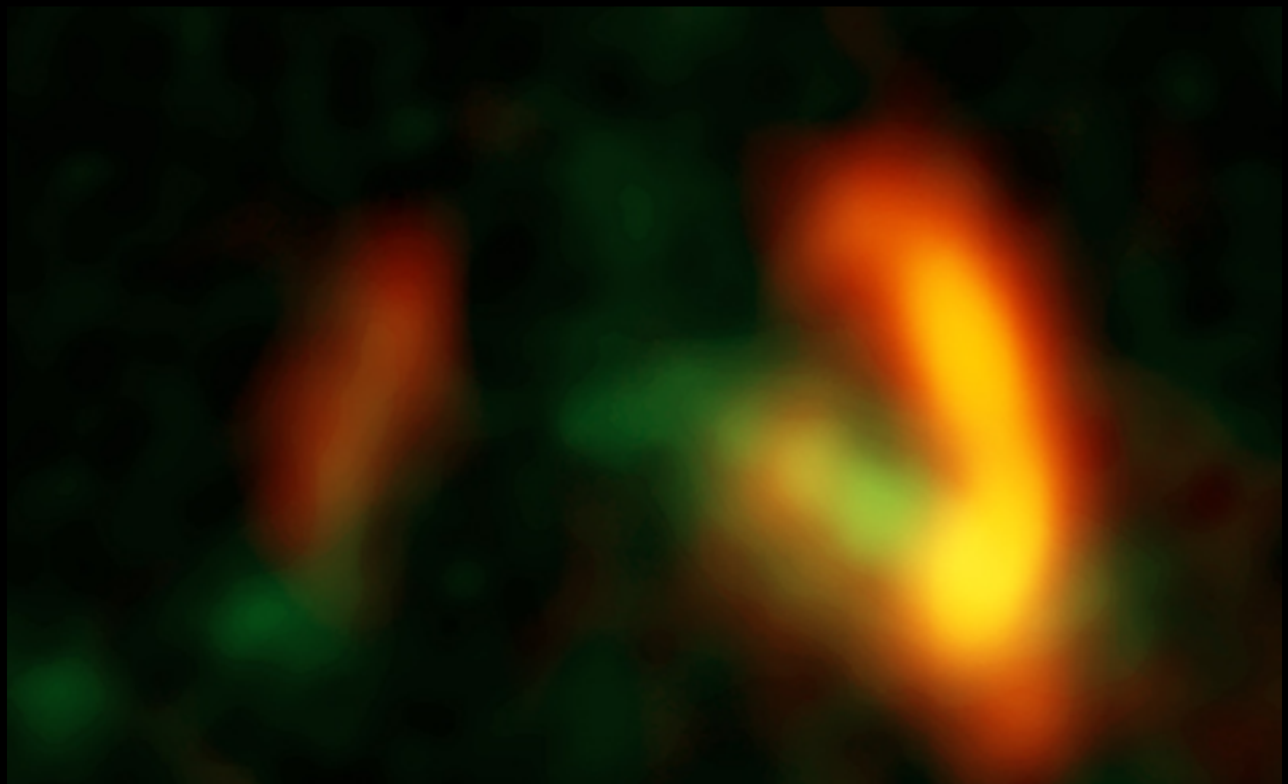


J0313—1806 at z=7.6
(Wang et al. 2021)

Forming a supermassive black hole with $\mathrm{M_{BH}} = 10^9\,\mathrm{M_\odot}$ at z~7 requires a ~1000$\mathrm{M_\odot}$ seed at $z \sim 30$ and a factor 10^6 growth at the Eddington limit!

The most extreme star-forming galaxies and dust reservoirs.

MAMBO-9 at z=5.9
(Casey et al. 2019, Akins et al. in prep)



SPT0311 at z=6.9
(Marrone et al. 2018)

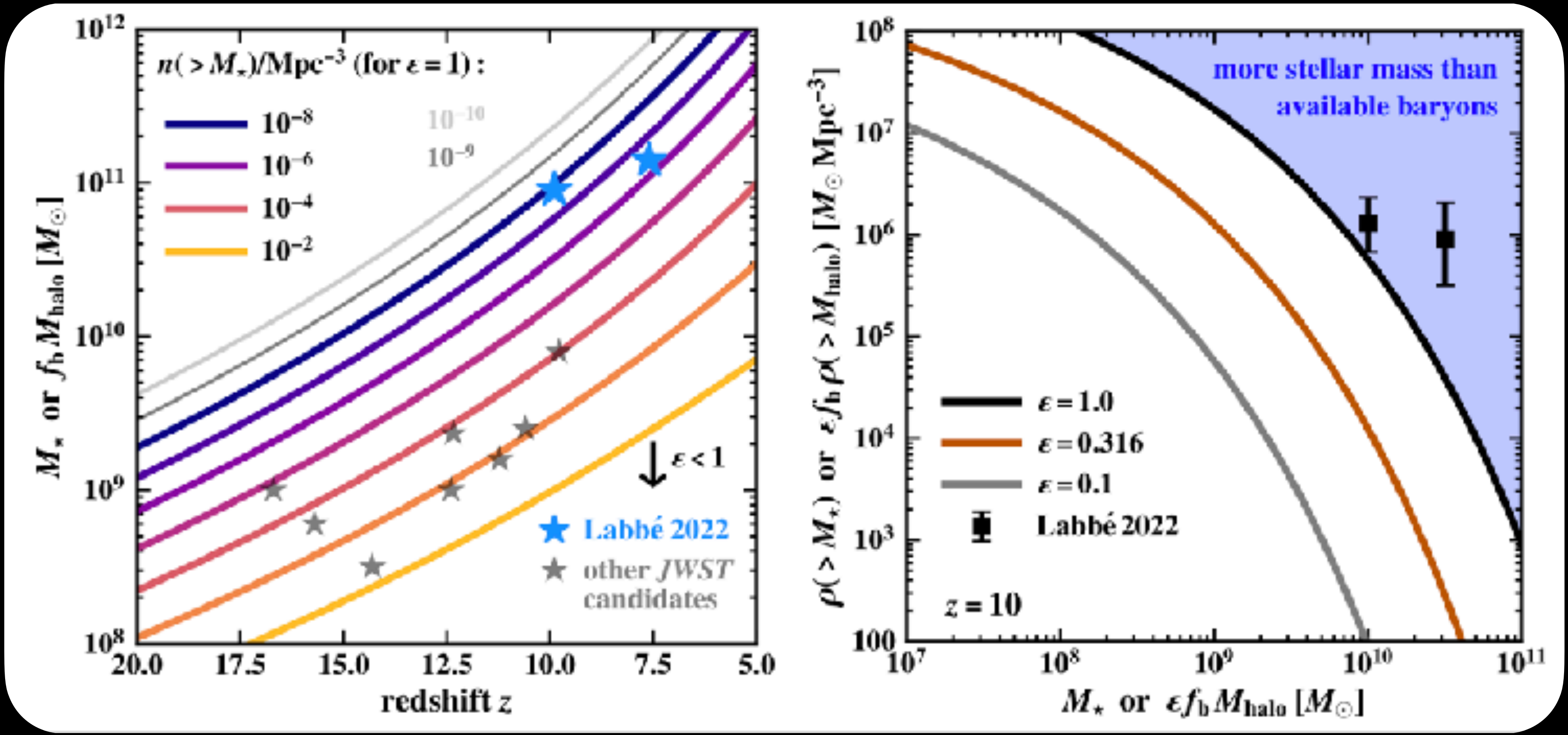
Forming a **massive, obscured starburst** with $M_{dust} = 10^9\,M_\odot$ at z~7 requires a SN-dominated dust formation mechanism that produces $\sim 2\,M_\odot$ of dust ejecta per supernova.

Schneider et al. 2004, Dwek & Cherchneff 2011

UV-bright massive galaxies at z>8 (z>10?)

Even assuming that all available baryons in all halos with enough baryons to form $10^{10} - 10^{10.5}\,\mathrm{M}_{\odot}$ *of stars at* $z = 10$ *have indeed been converted into stars by that point — an unrealistic limit — it is still not possible to produce the stellar mass density measured by Labbé et al. (2022) in* Λ*CDM with a Planck 2020 cosmology.*

—Boylan-Kolchin (2022)



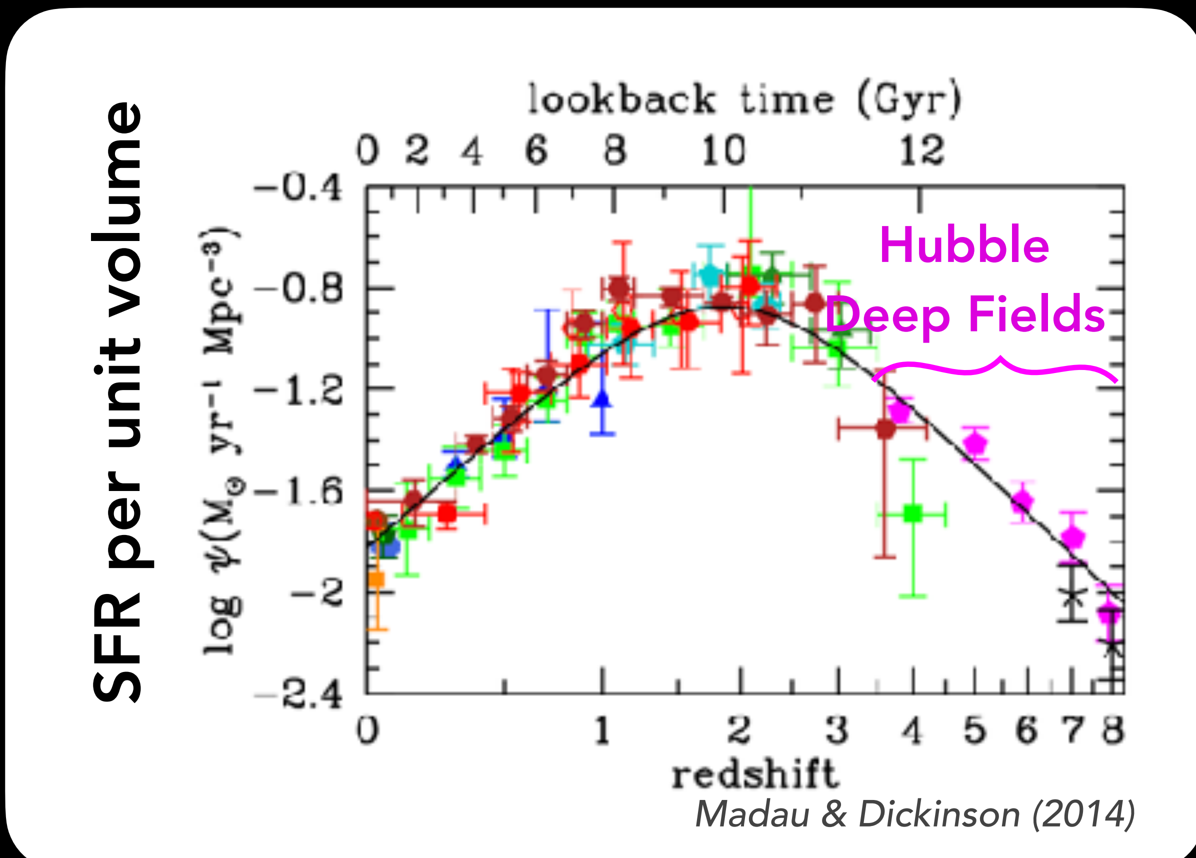
Forming UV-bright galaxies with $\mathrm{M}_\star = 10^{10}\,\mathrm{M}_\odot$ at z~10 with volume density $10^{-5}\,\mathrm{Mpc}^{-3}$ is not allowable in ΛCDM.

Forming a supermassive black hole with $\mathrm{M_{BH}} = 10^9\,\mathrm{M_\odot}$ at z~7 requires a ~1000$\mathrm{M_\odot}$ seed at $z \sim 30$ and a factor 10^6 growth at the Eddington limit!

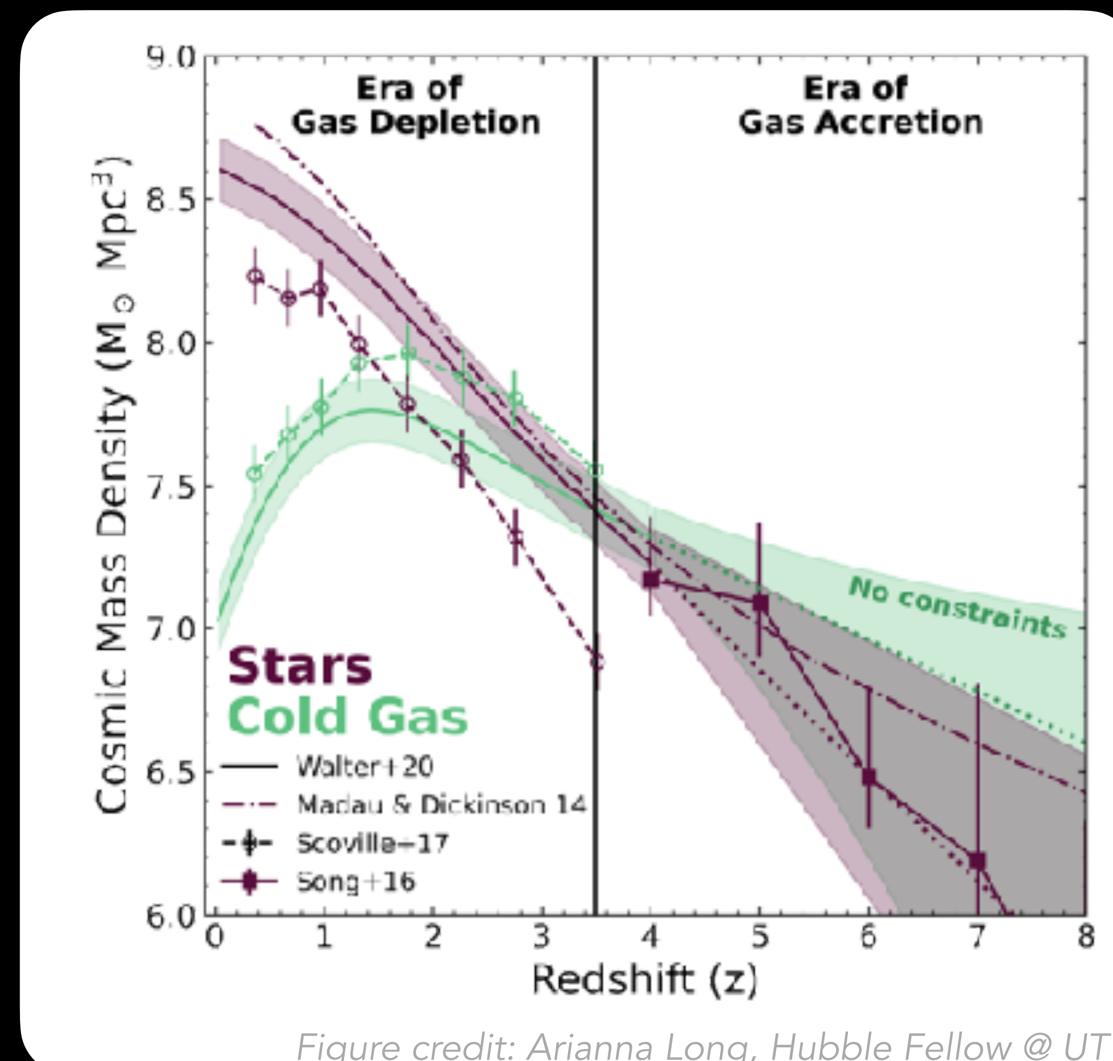
Forming a massive, obscured starburst with $\mathrm{M_{dust}} = 10^9\,\mathrm{M_\odot}$ at z~7 requires a SN-dominated dust formation mechanism that produces $\sim 2\,\mathrm{M_\odot}$ of dust ejecta per supernova.

Forming UV-bright galaxies with $\mathrm{M_\star} = 10^{10}\,\mathrm{M_\odot}$ at z~10 with volume density $10^{-5}\,\mathrm{Mpc^{-3}}$ is not allowable in ΛCDM.

Models fail to capture extreme, early sources; many of those models are calibrated against observations of a narrow subset of observations.



Simulations check consistency with galaxy luminosity functions in the rest-frame UV measured from pencil beam Hubble surveys.



Semi-analytic models pegged to stellar-to-halo-mass relations at epochs when stars do not dominate baryonic content.

MORA

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COSMOS WEB

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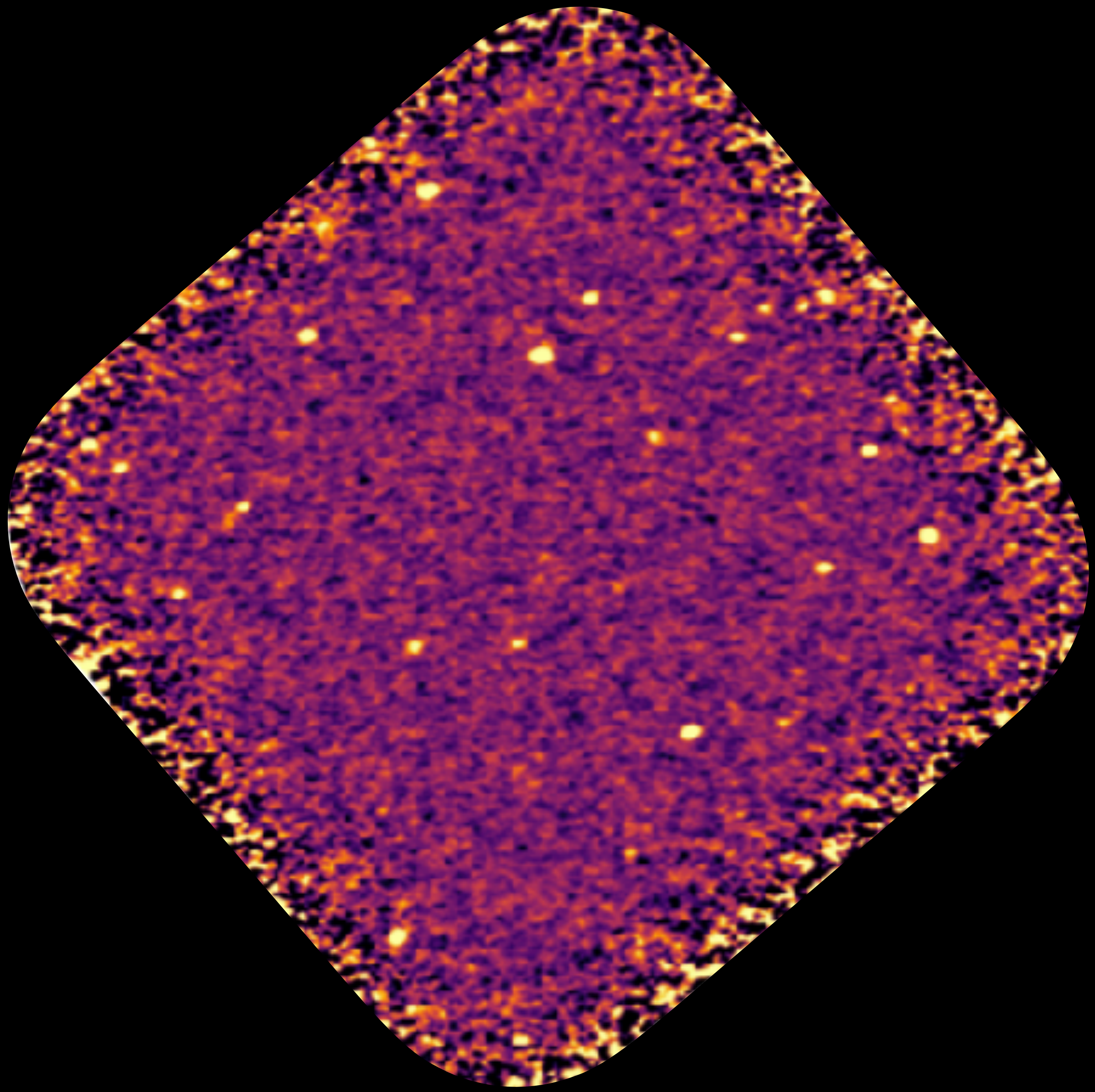
Fully capture obscured star-forming galaxies and constrain their luminosity function at $z > 3$.

~10,000 galaxies

HUDF

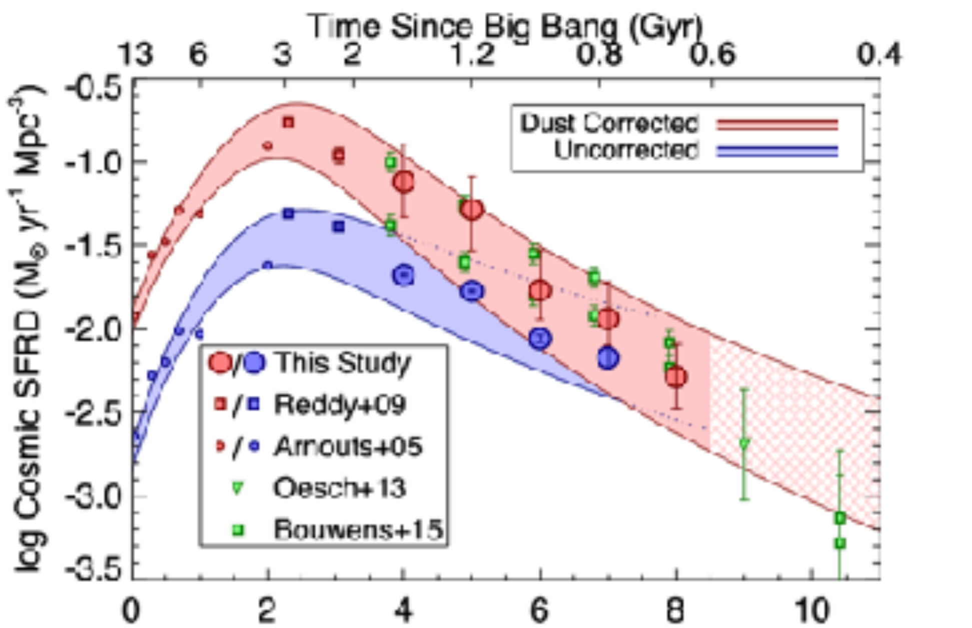
35 galaxies



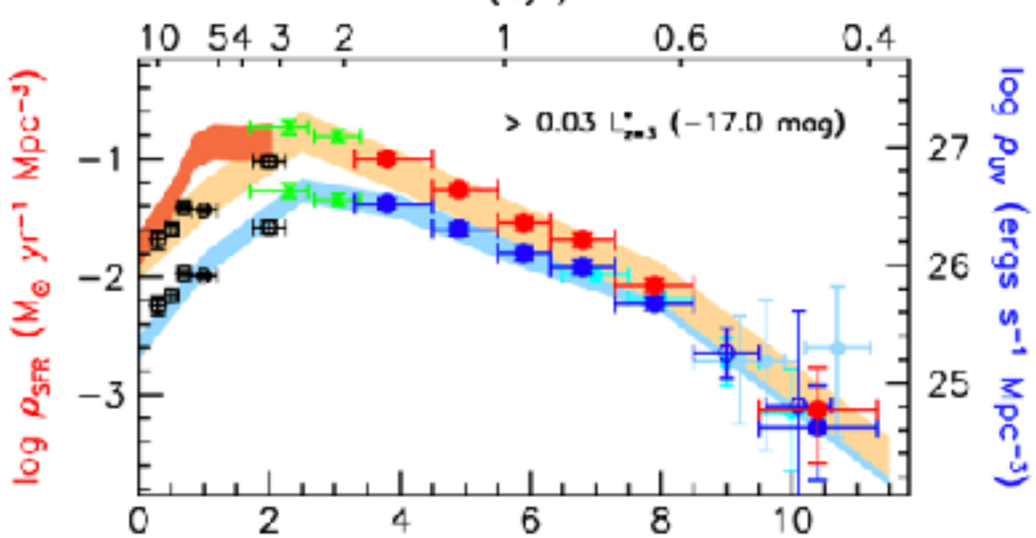
ALMA map of HUDF from ASPECS
González-López et al. (2020)

Why so few dusty galaxies?

Are early Universe galaxies devoid of dust?

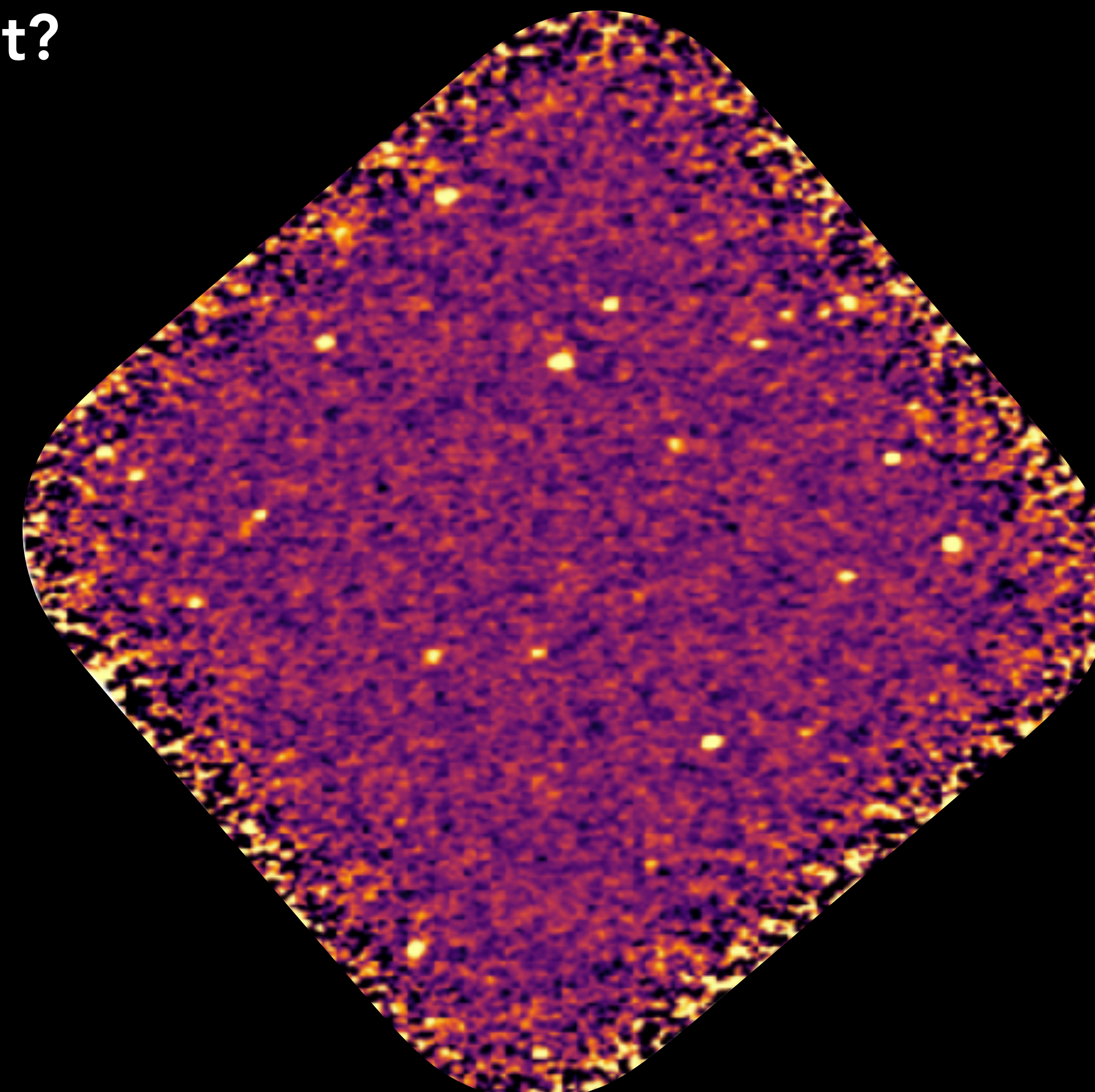


Finkelstein et al. (2015)



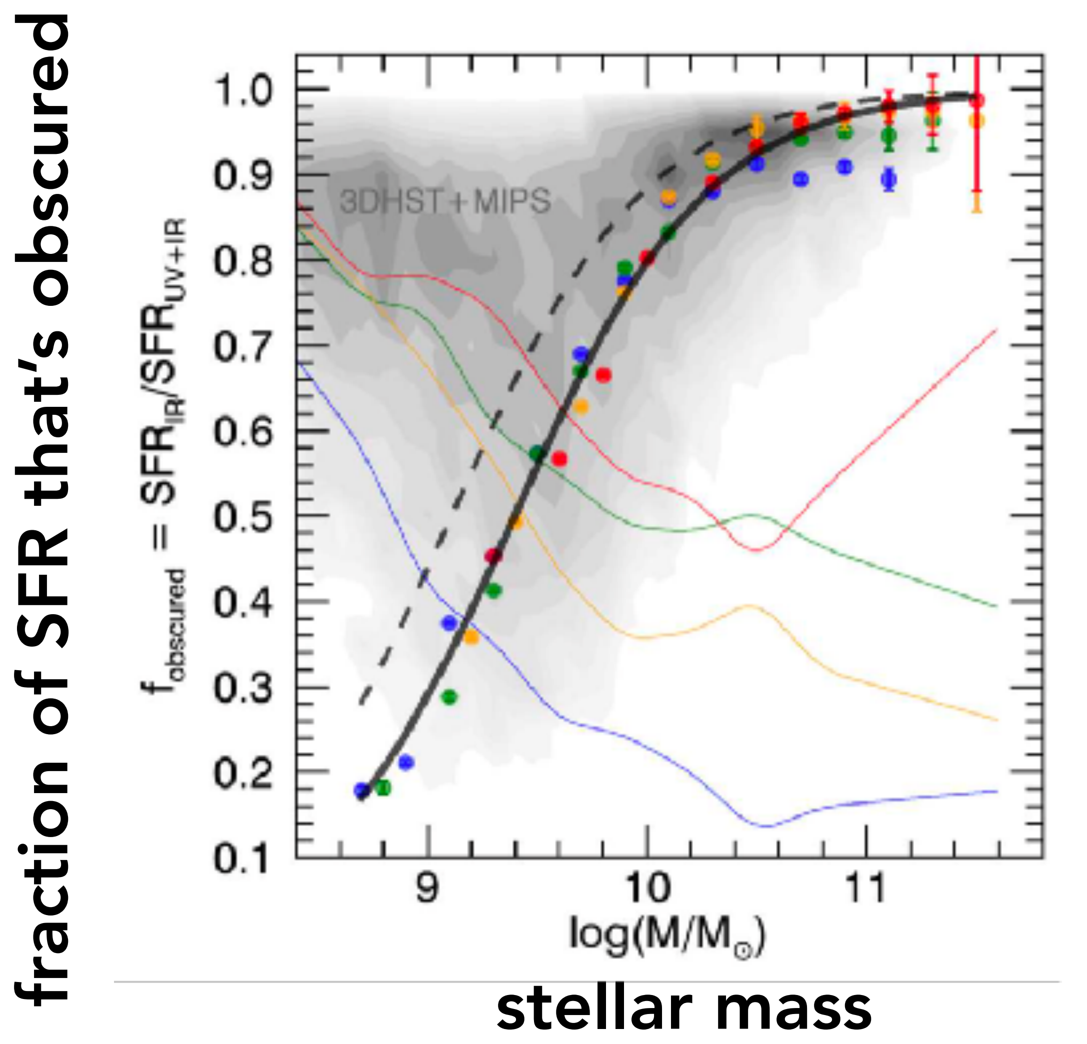
Bouwens et al. (2015)

35 galaxies



ALMA map of HUDF from ASPECS
González-López et al. (2020)

Dust preferentially lives in high-mass galaxies.

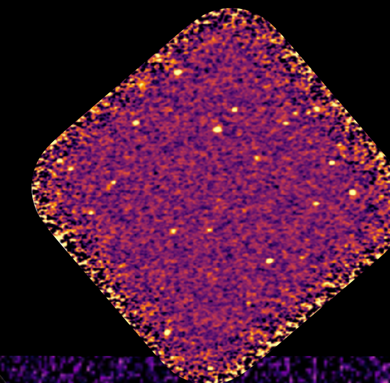


Whitaker et al. (2017)

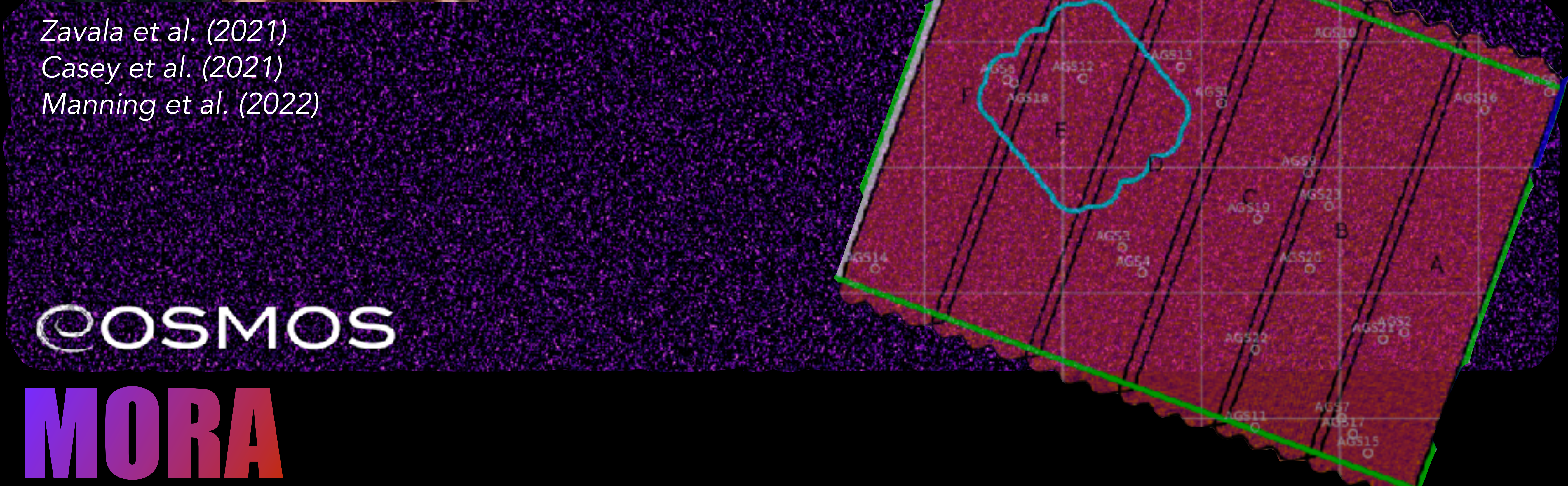
The volume density of massive galaxies is ~1/100th of "normal" galaxies.

"Pencil-beam" surveys will not see such intrinsically rare galaxies.

Pencil beam surveys doesn't work for finding the highest redshift dusty starbursts.



Zavala et al. (2021)
Casey et al. (2021)
Manning et al. (2022)



MORA

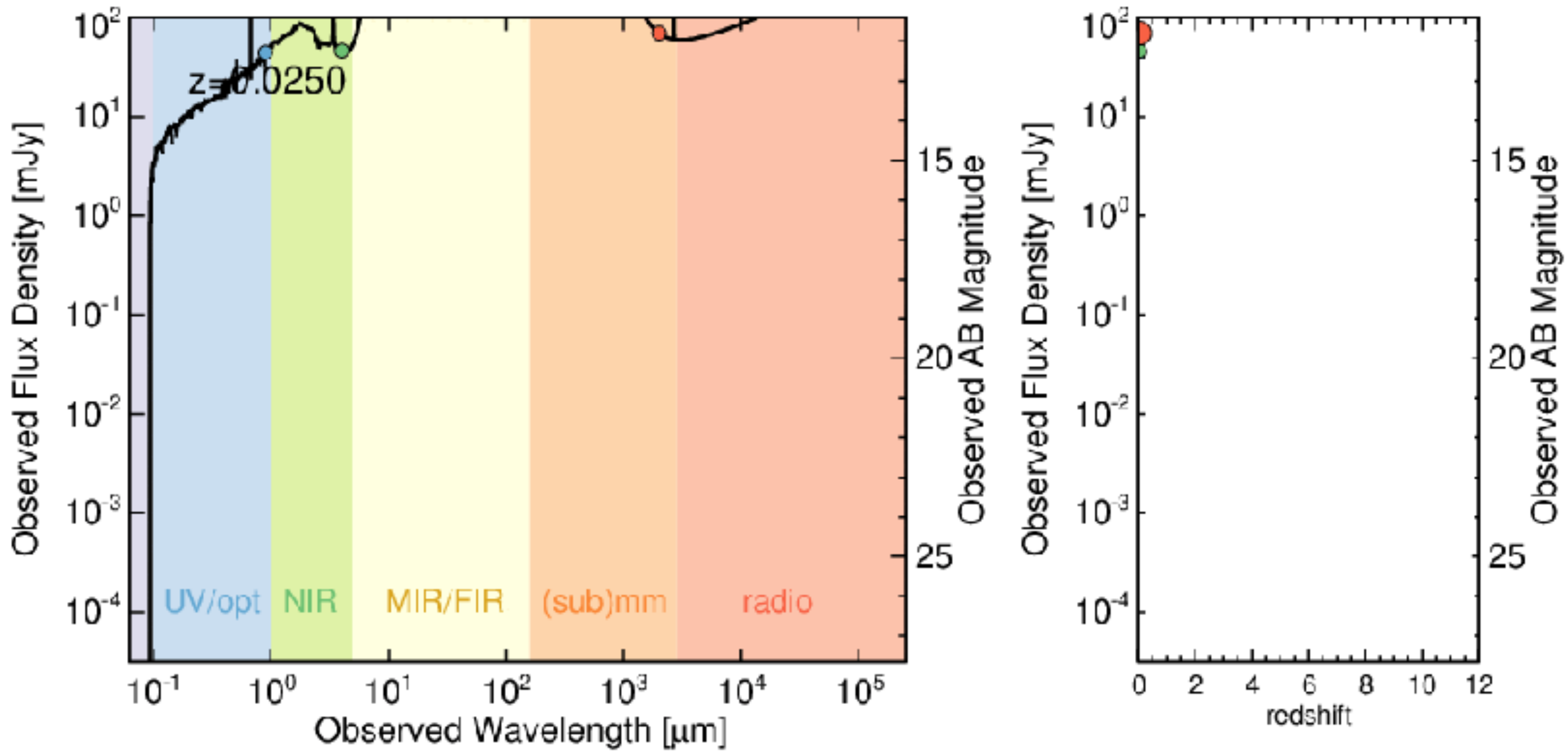
Mapping Obscuration to Reionization with ALMA: A 2mm blank field

ASPECS & GOODS-ALMA 1mm Surveys

ALMA Cycle 6 Program (15 hours) + ALMA Cycle 8 Program (37 hours)

2mm, 0.08mJy RMS,155arcmin^2 → 2mm, 0.08mJy RMS, 0.2deg^2

2mm filters out $z < 3$ emission — leaves massive obscured systems at the highest redshifts.



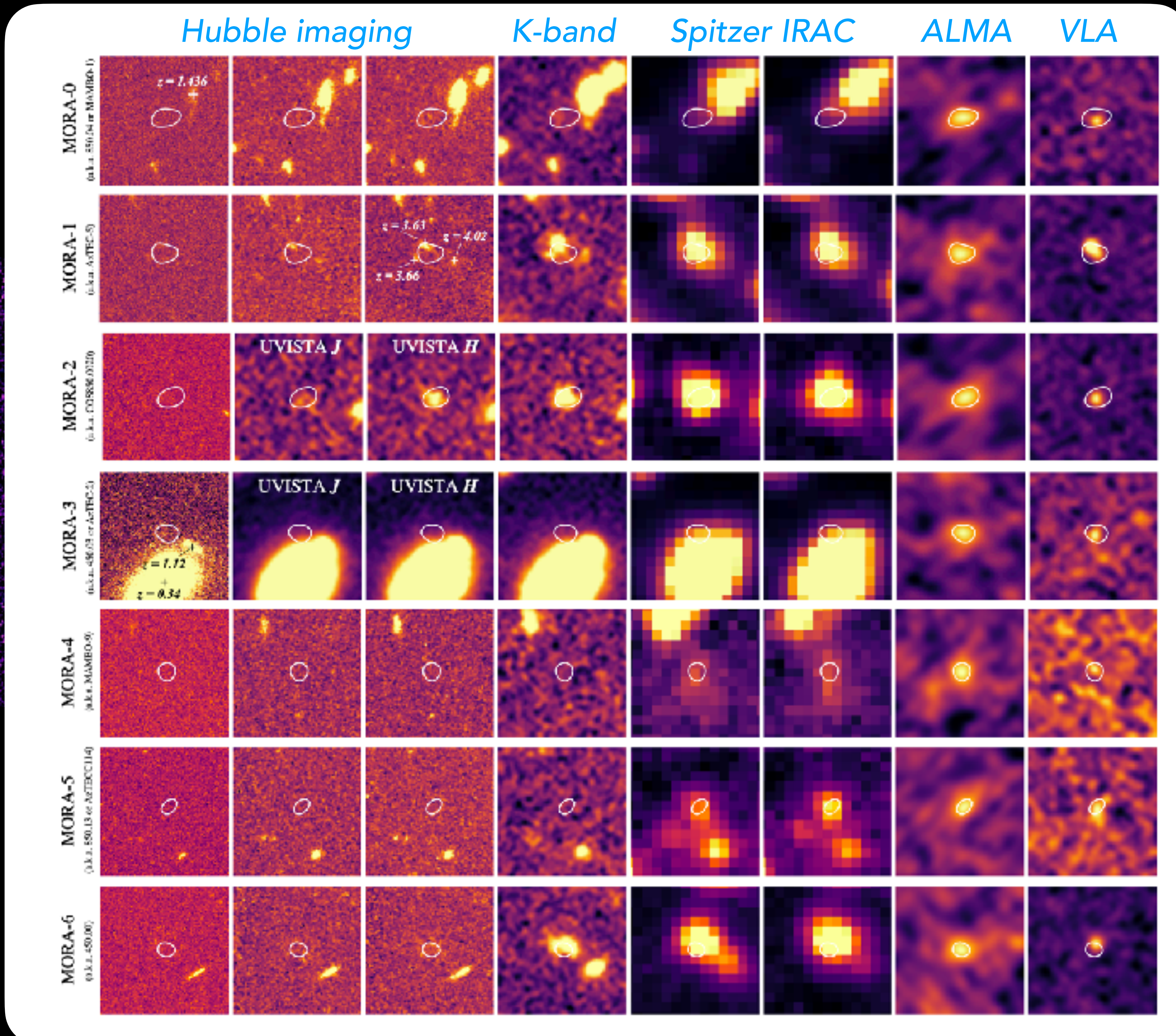
At higher redshifts, 2mm emission is brighter for fixed ~1mm flux density.

2mm detected sources are "OIR dark"

…peak at
$z \sim 3.6$
(span redshifts
$3 < z < 6$)

…are massive:
all detected by Spitzer / IRAC in the near-IR.

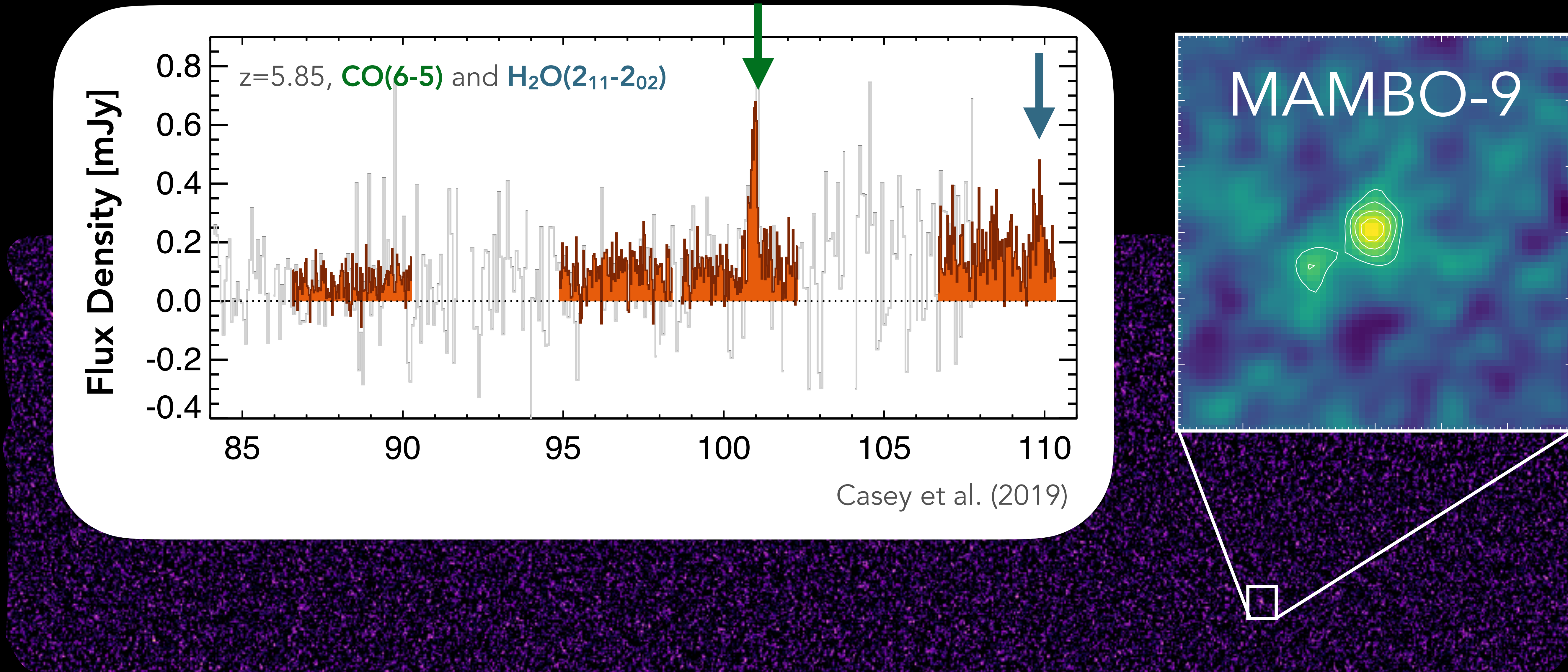
$10^{10} < M_{\star}/M_{\odot} < 10^{11.5}$
$10^{10.5} < M_{ISM}/M_{\odot} < 10^{11.5}$



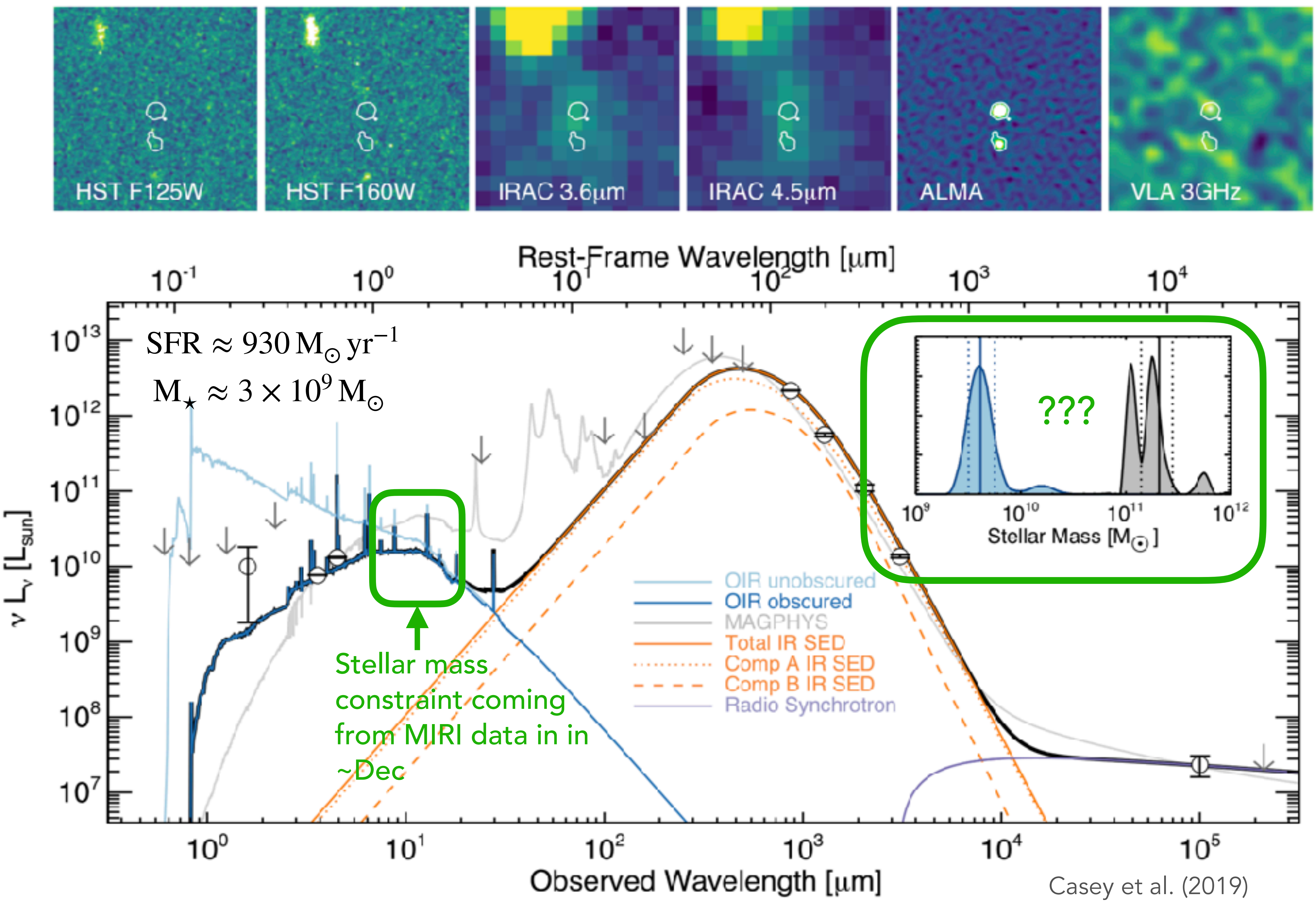
Casey et al. (2021)

ALMA Cycle 6 DDT for redshift confirmation

8 hours (!!) needed

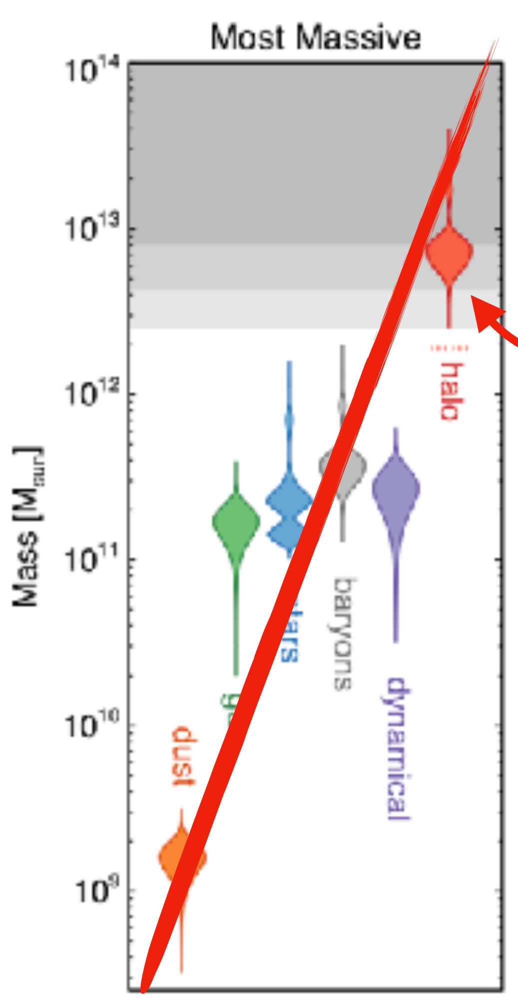


MAMBO-9: the most distant unlensed* DSFG at z=5.85



Casey et al. (2019)

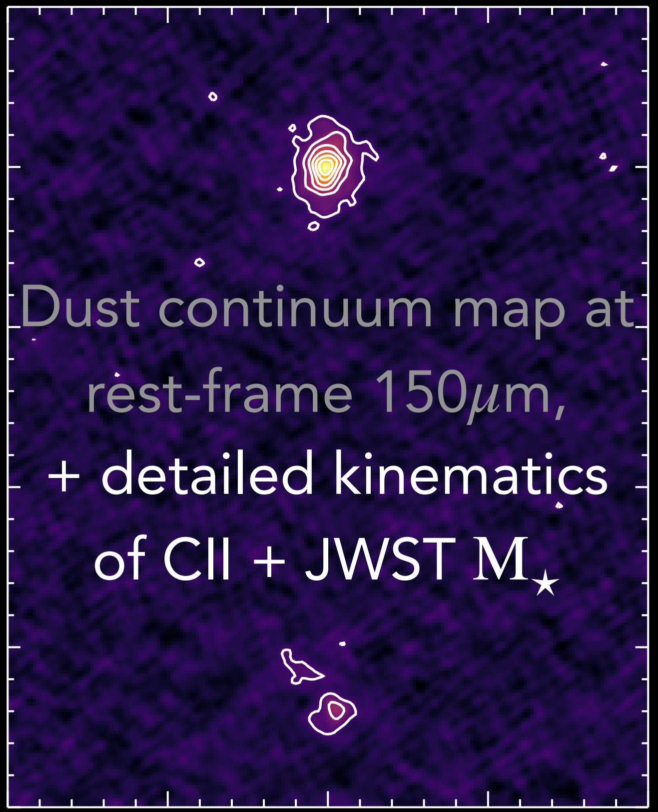
MAMBO-9: the most distant unlensed* DSFG at z=5.85



MAMBO-9 is too massive to have been discovered in MORA using classic mass estimates (!)

This gas to dust ratio does not make physical sense!

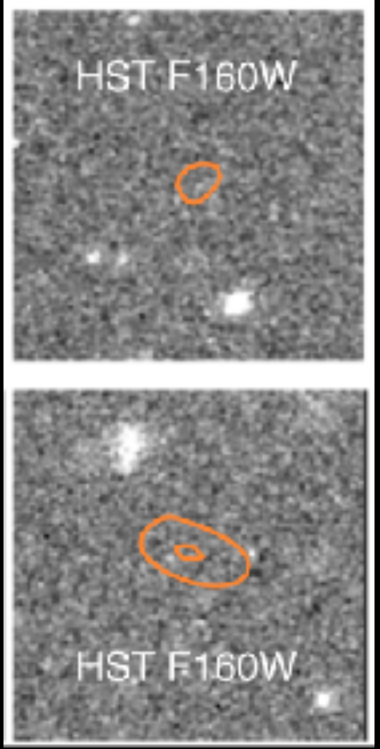
Casey et al. (2019)



Akins et al., in prep

Hollis Akins, UT grad student

Sinclaire Manning, UT→ UMass Hubble Fellow

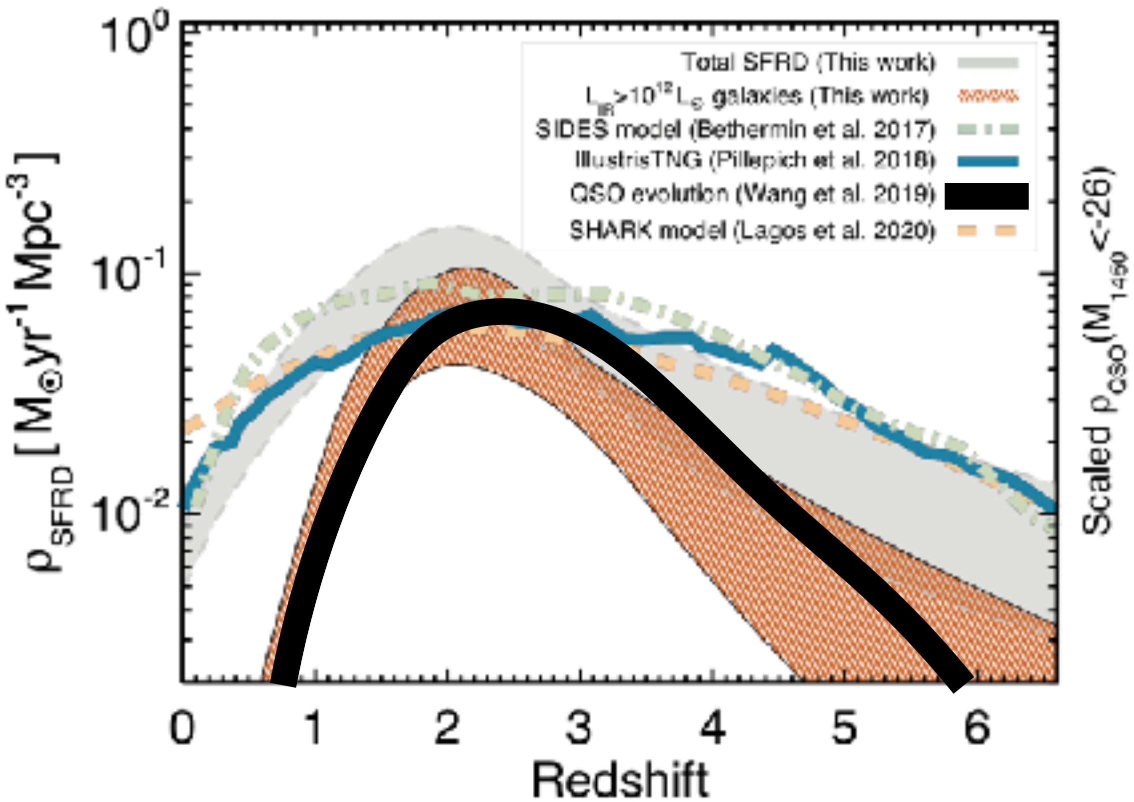


Manning et al. (2022)

Implies a significant population of massive systems ($M_{halo} \sim 10^{12.5} M_\odot$) with volume density $10^{-5}\,\mathrm{Mpc}^{-3}$ whose baryons are dominated (>95%) by molecular gas.

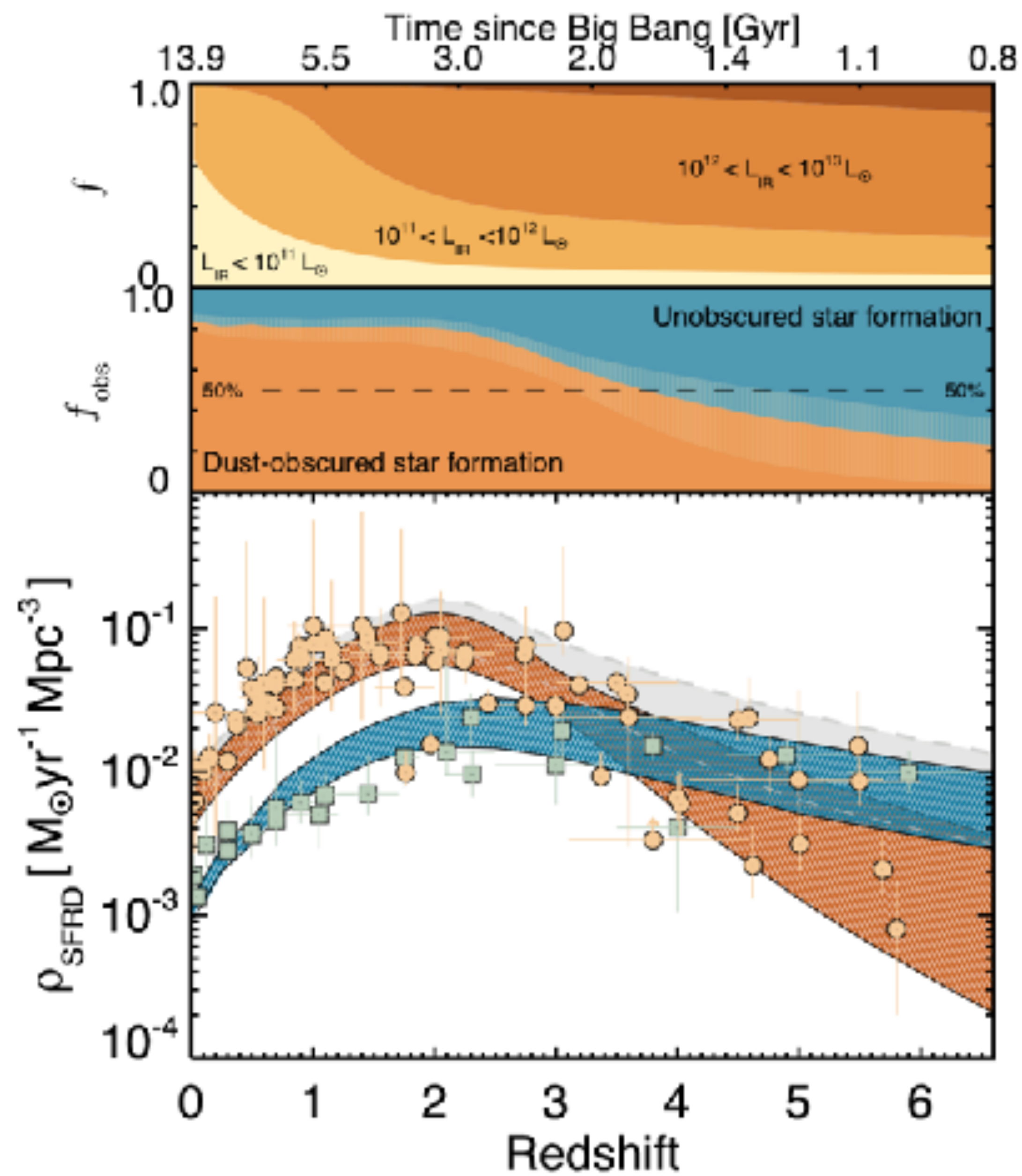
Jorge Zavala

Refining constraints on the obscured SFRD at z>4



Zavala et al. (2021)

First firm constraints on the obscured star-formation rate density at $4 < z < 7$.



Zavala et al. (2021)

MORA

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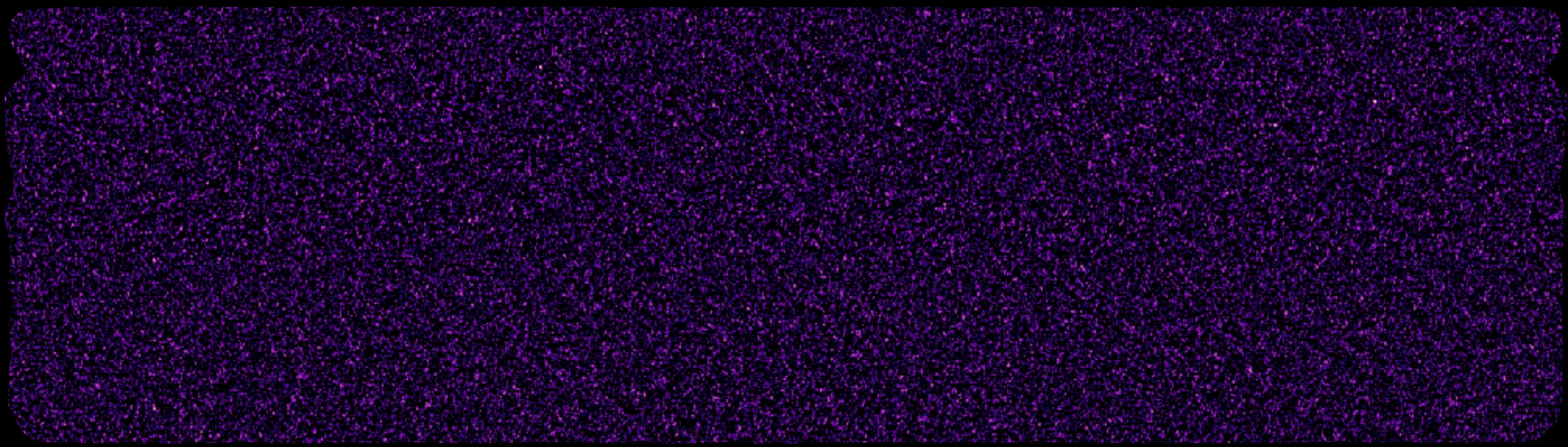
ALMA Cycle 6 Program (15 hours) + ALMA Cycle 8 Program (37 hours)

2mm, 0.08mJy RMS,155arcmin² → 2mm, 0.08mJy RMS, 0.2deg²



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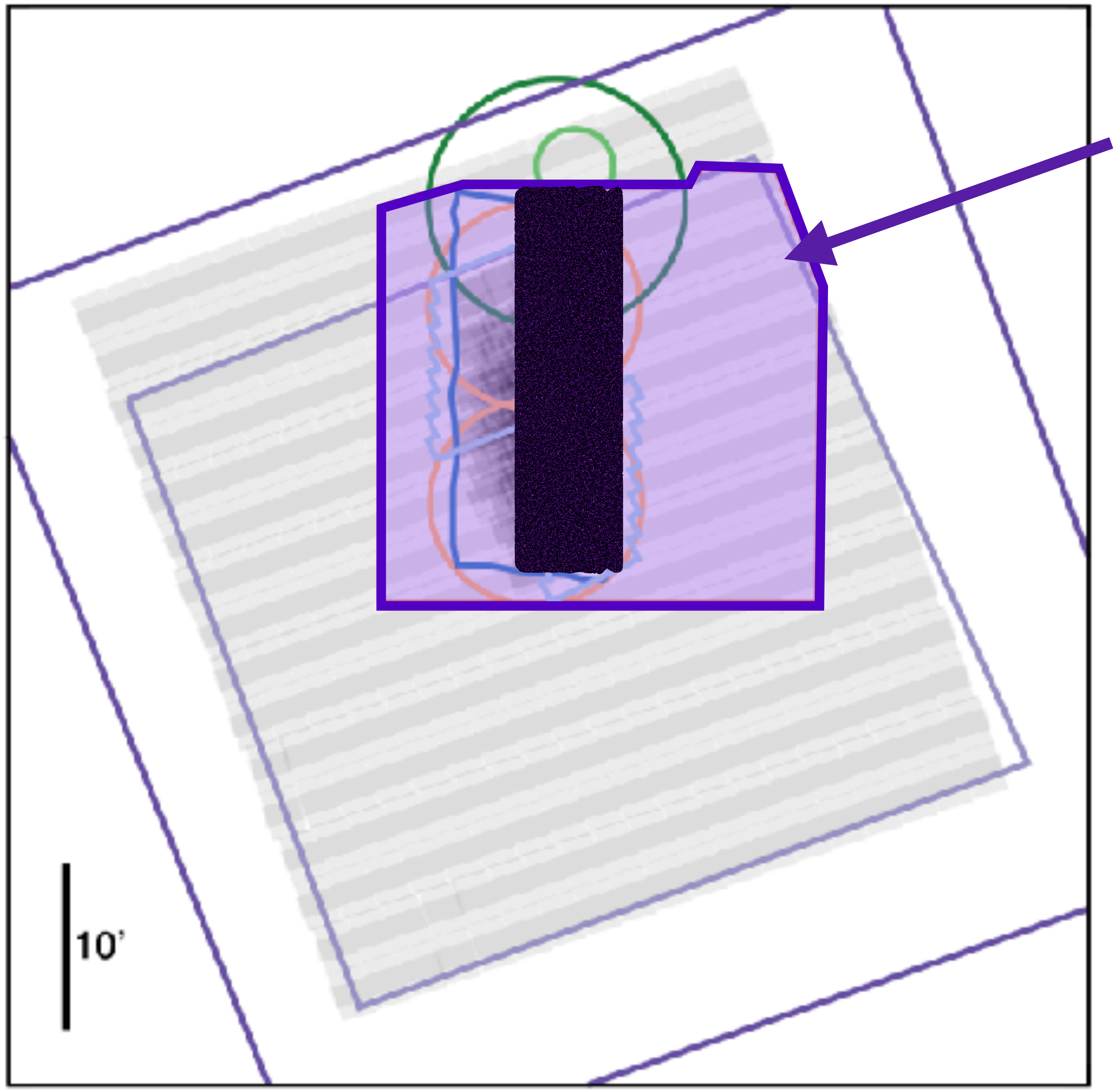
2mm, 0.08mJy RMS, $155 \mathrm{arcmin}^2$ → 2mm, 0.08mJy RMS, $0.2 \mathrm{deg}^2$

JWST NIRCam Coverage in COSMOS



Arianna Long,
Hubble Fellow

Olivia Cooper,
UT grad student,
NSF Fellow

MORA is being extended by a factor of 4x as we speak!

MORA

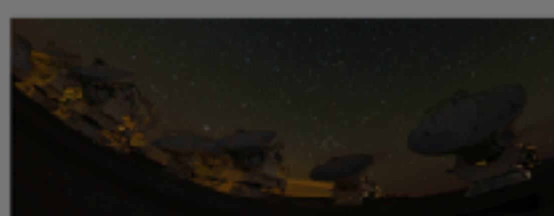
Mapping Obscuration to Reionization with ALMA:
A 2mm blank field

ALMA Cycle 6 Program (15 hours) + ALMA Cycle 8 Program (37 hours)

2mm, 0.08mJy RMS,155arcmin^2 → 2mm, 0.08mJy RMS, 0.2deg^2

MORA

Mapping Obscuration to Reionization with ALMA



51 hour Cycle 6+8 Program

COSMOS

WEB

218 hour Cycle 1 JWST Program

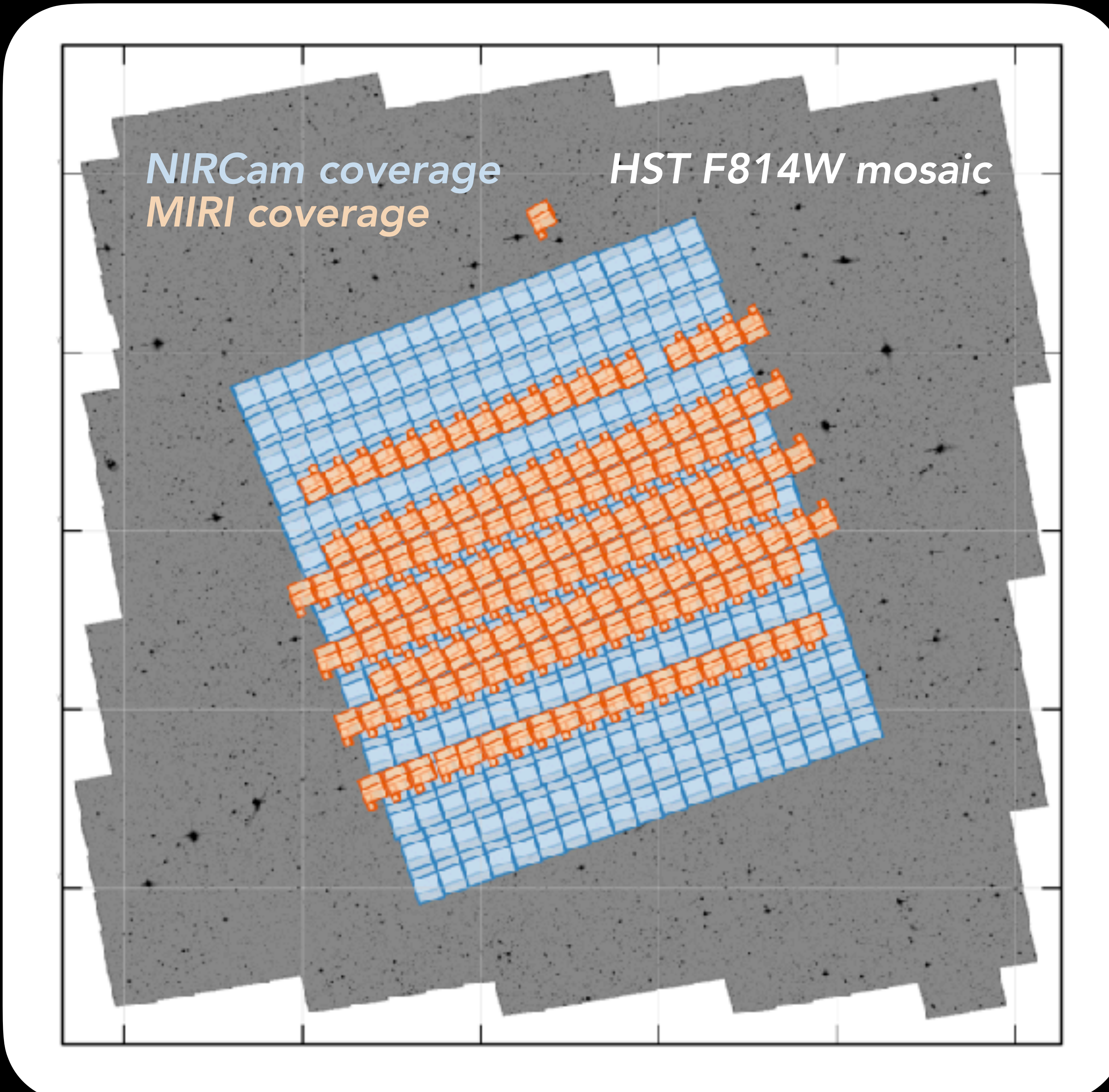
WERLS

Webb Epoch of Reionization Lyα Survey

29night Keck KSMS Program

The largest JWST deep field (0.54deg^2) in four NIRCam filters + 1 MIRI filter (covering 0.2deg^2).

COSMOS
WEB



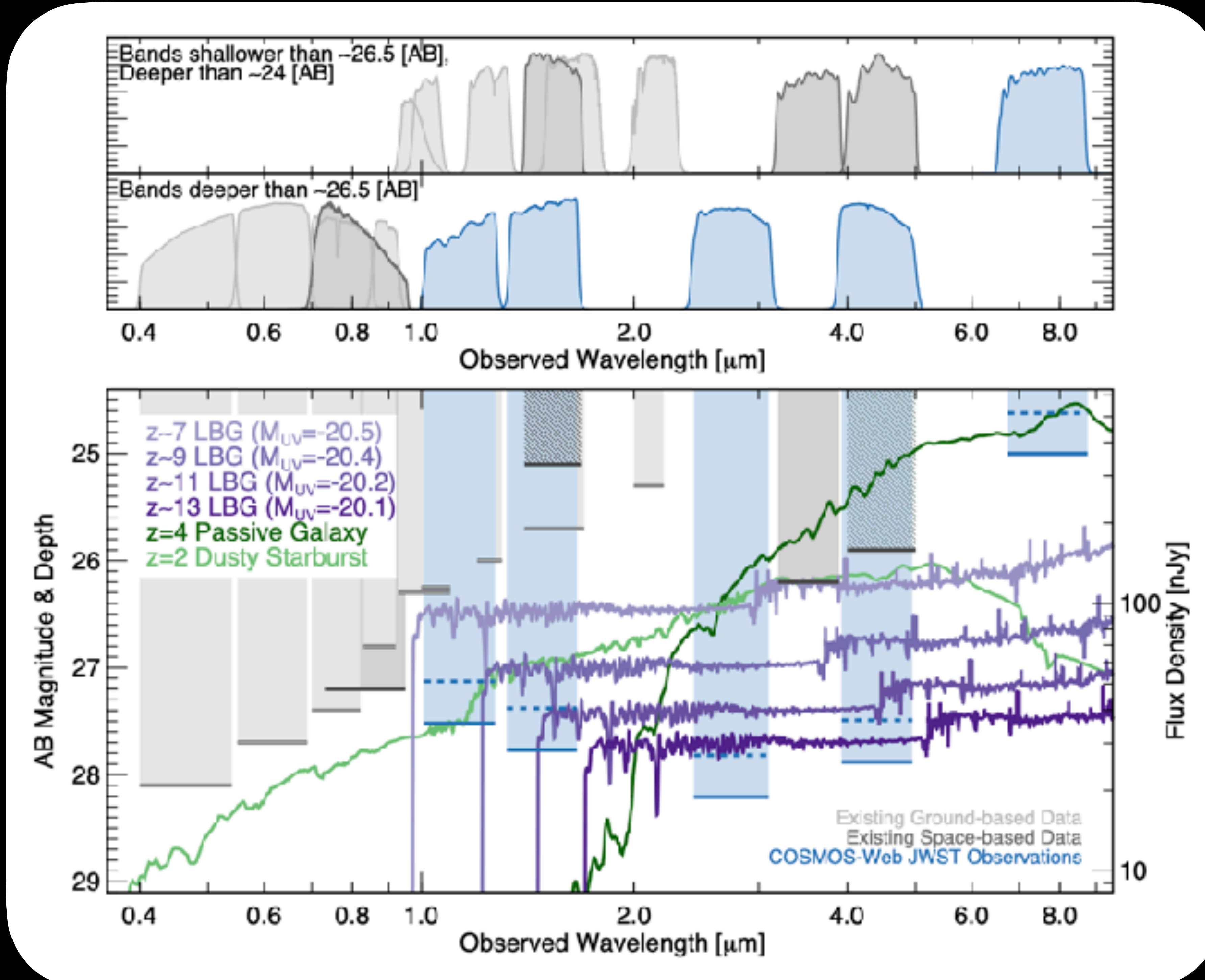
Casey et al. in prep

PIs: Caitlin Casey & Jeyhan Kartaltepe

+50 co-I's as part of the COSMOS collaboration.

The largest JWST deep field (0.54deg^2) in four NIRCam filters + 1 MIRI filter (covering 0.2deg^2).

COSMOS
WEB



PIs: Caitlin Casey & Jeyhan Kartaltepe

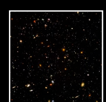
+50 co-I's as part of the COSMOS collaboration.

Casey et al. in prep

HUDF


A simulation of COSMOS-Web
RGB in F115W/F150W/F277W at depths of our program
prepared using **Deep Realistic Extragalactic Model (DREaM)** with realistic JWST PSF. Credit to Nicole Drakos, Bruno Villasenor, Brant Robertson and Ryan Hausen.
www.nicoledrakos.com/dream

COSMOS-Web will image 10^6 galaxies down to $[AB] \sim 27.5 - 28.3$ with NIRCam over $0.54\,\mathrm{deg}^2$



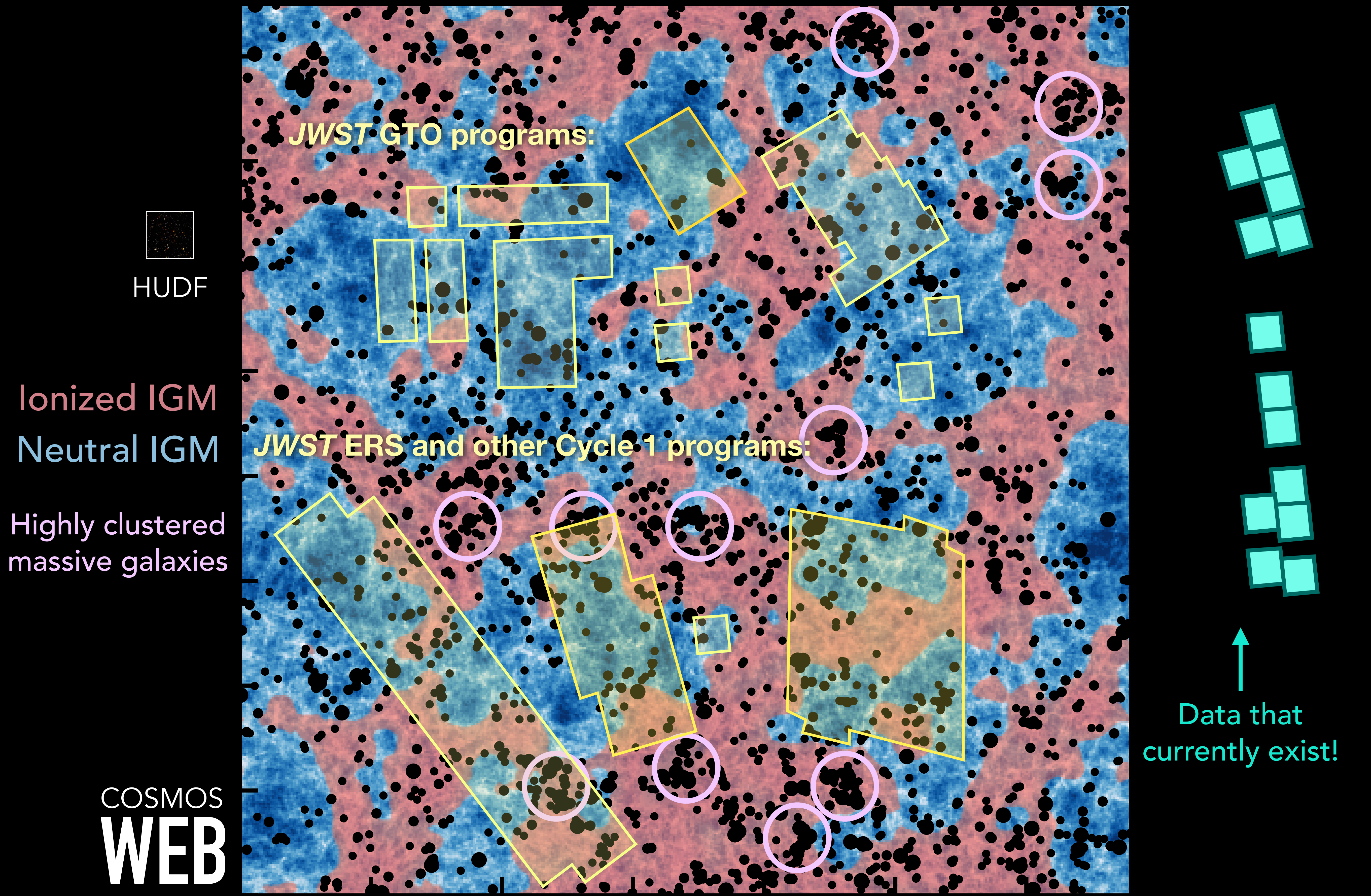
HUDF

$\sim 32{,}000$ galaxies will be detected in $0.2\,\mathrm{deg}^2$ with MIRI at $7.7\,\mu m$

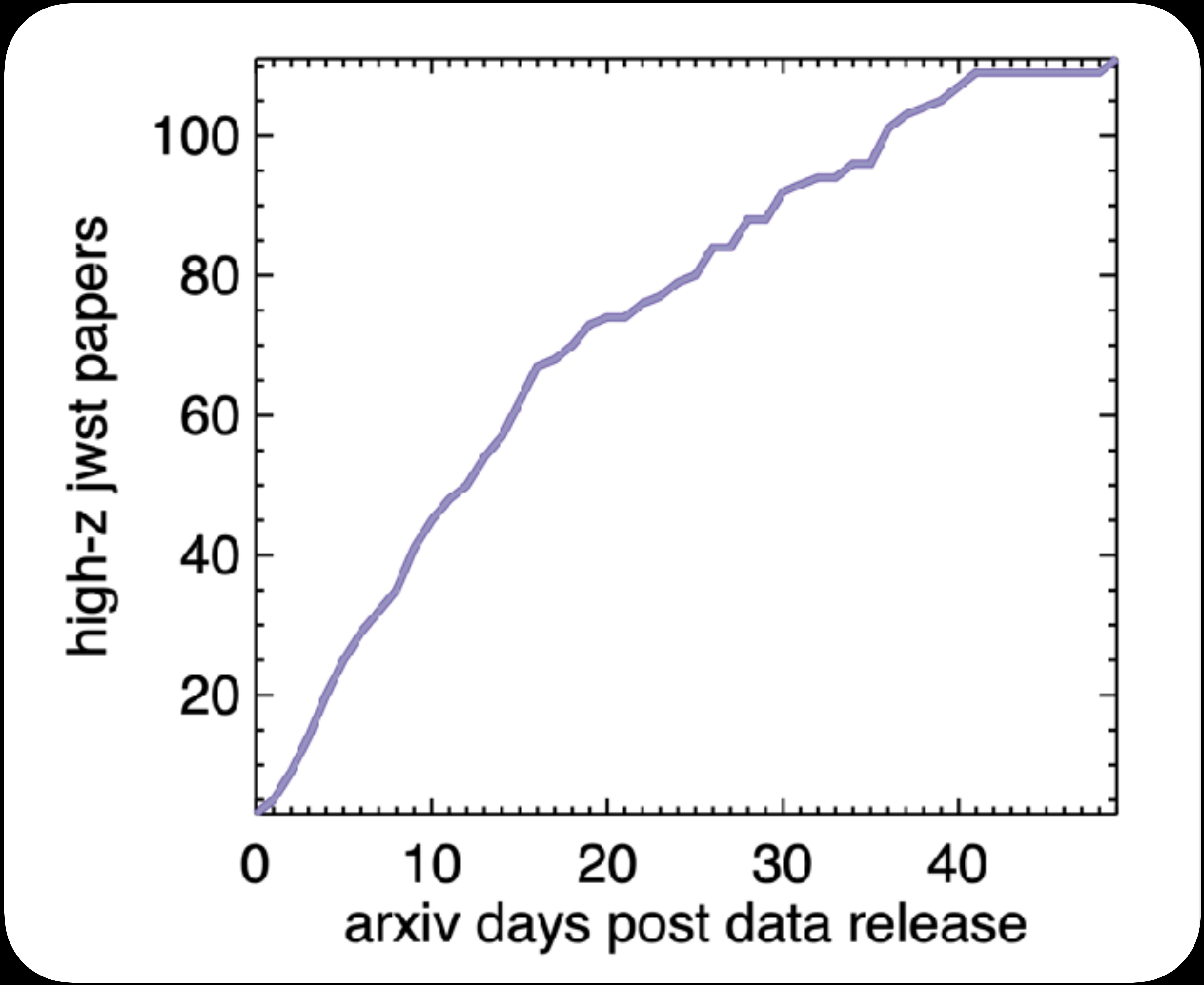
Why so **big?**

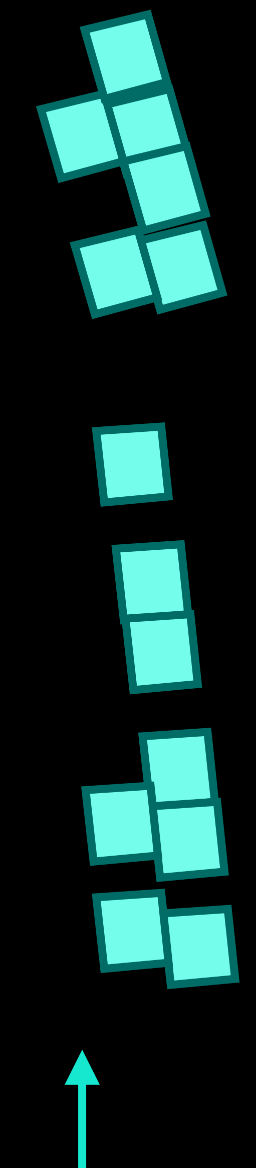
1. **Reionization:** detect ~ 5000 galaxies from $6 < z < 11$ at the bright end of the luminosity function and measure patchiness.
2. **Quiescent Galaxies:** find hundreds of massive quiescent galaxies at $4 < z < 6$ to place constraints on formation of first massive systems.
3. **Stellar-Mass-to-Halo-Mass:** use weak lensing to constrain the SMHR observationally to $z \sim 2.5$, anchoring cosmological simulations.

COSMOS WEB

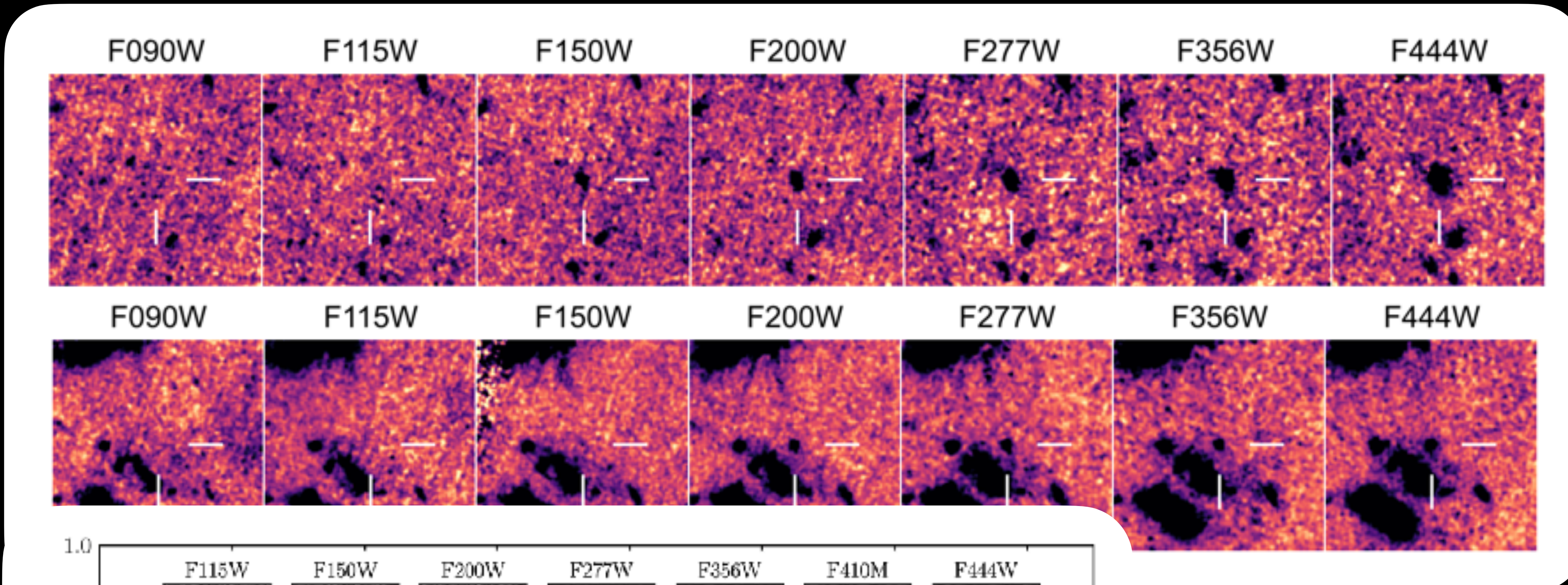

JWST GTO programs:
JWST ERS and other Cycle 1 programs:
HUDF
Ionized IGM
Neutral IGM
Highly clustered
massive galaxies
COSMOS
WEB
Data that
currently exist!

Enough data to spur a flurry of papers!

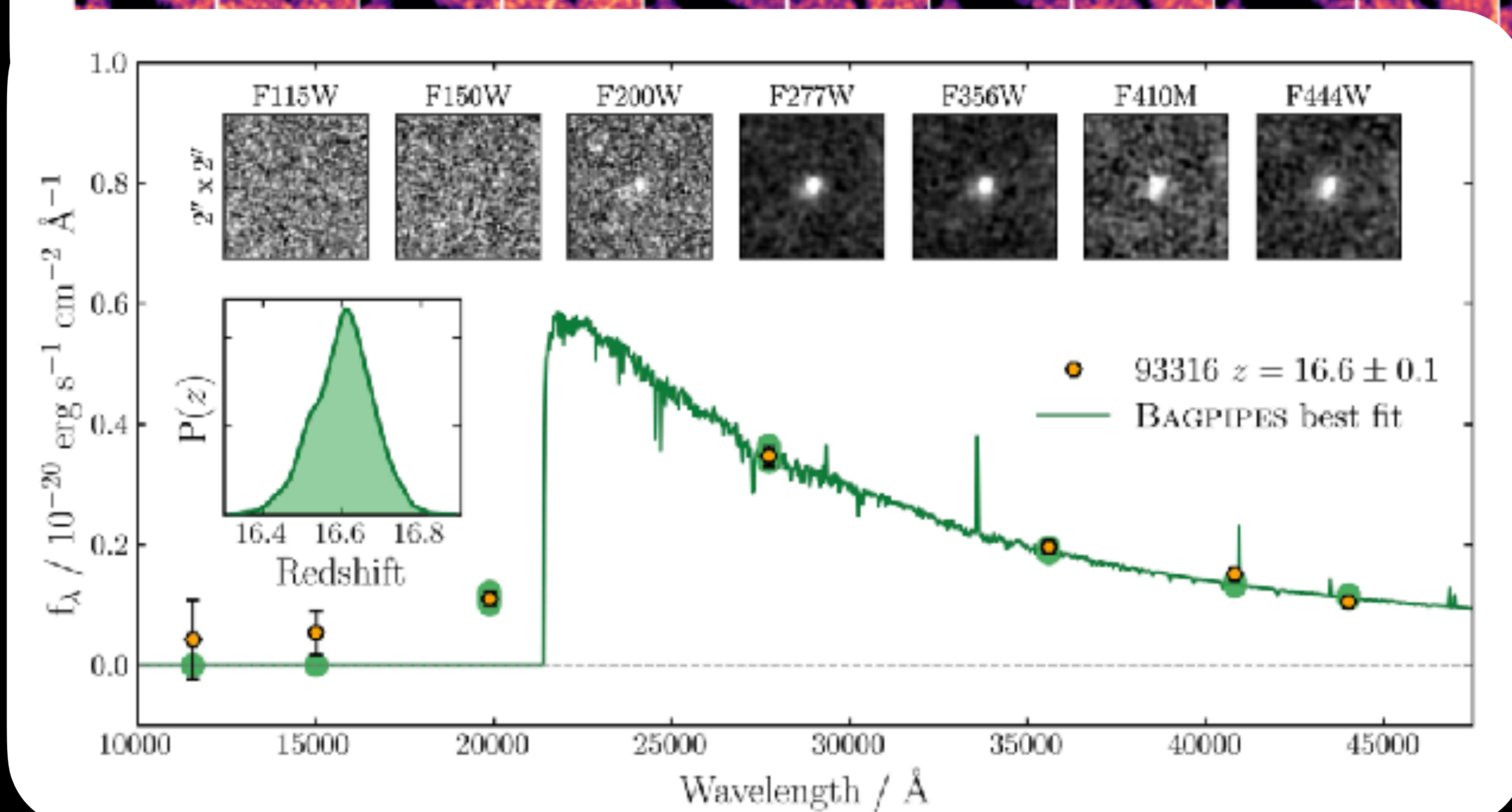




Lessons from JWST data: z<10 is possibly considered 'low' redshift.



o Castellano et al. (2022)



Donnan et al. (2022)

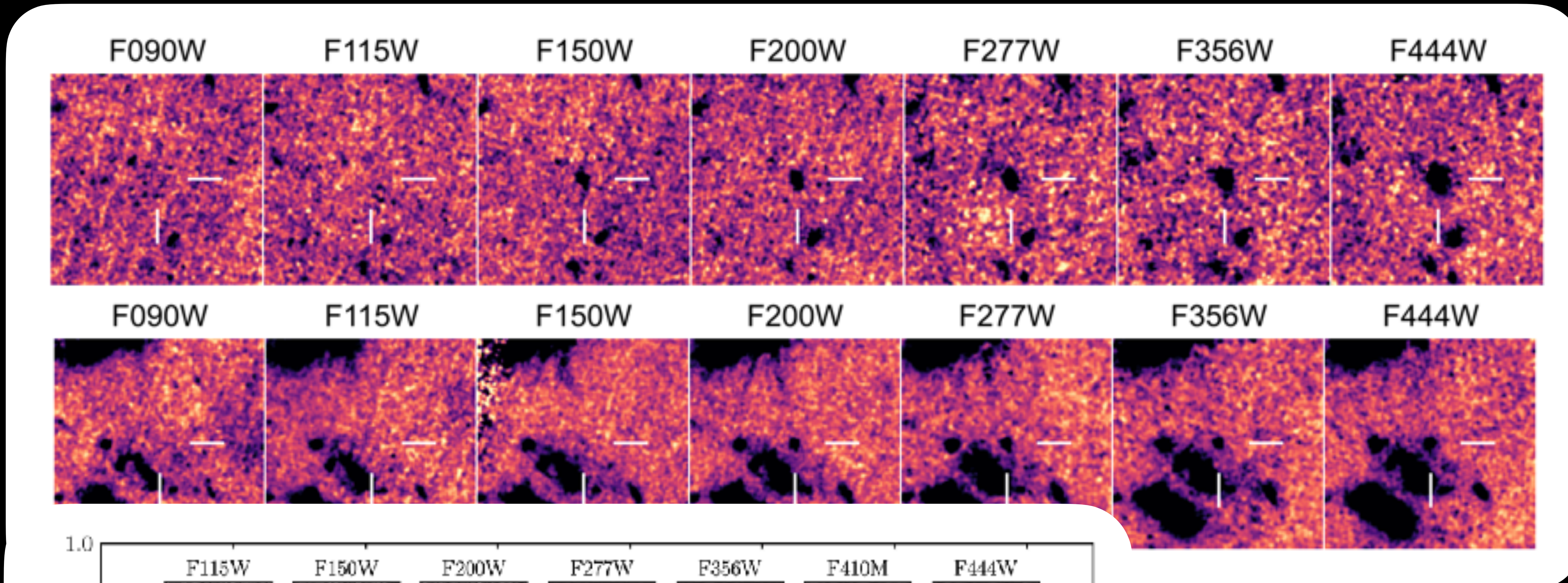
These two objects already place novel constraints on galaxy evolution in the cosmic dawn epoch. They indicate that the discovery of GNz11 was not simply a matter of good fortune, but that there is likely a population of UV luminous sources with very high star-formation efficiencies capable of compiling $> 10^9 M_\odot$ at $z > 10$. [Fig. 3, §5.2]

— Naidu et al. (2022)

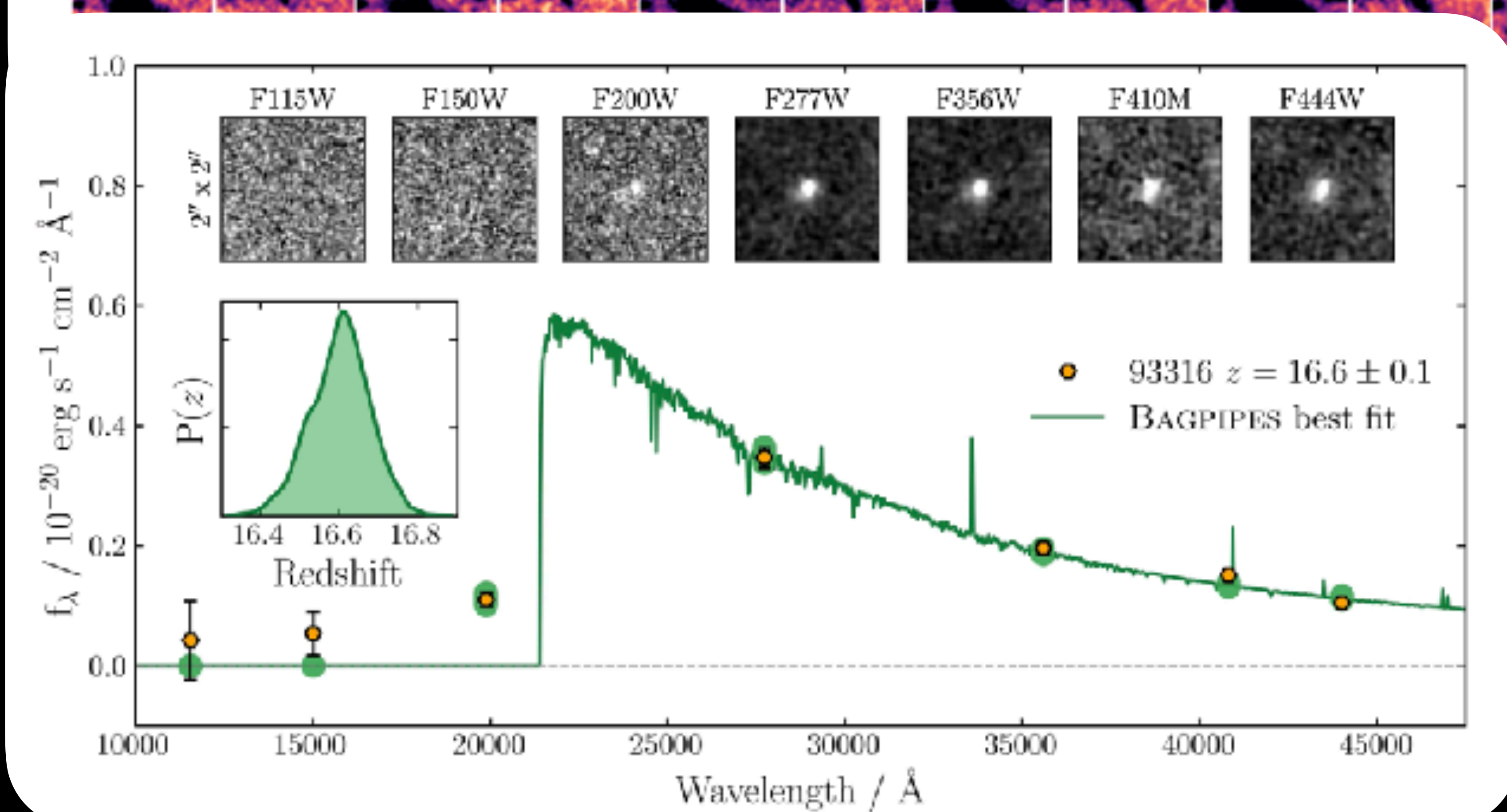
stars. Across our survey volume of $\simeq 10^5$ Mpc^3 from $15 < z < 17$ we find that our object falls close to, but does not significantly exceed the Λ−CDM limit calculated by Behroozi & Silk (2018).

— Donnan et al. (2022)

Lessons from JWST data: z<10 is possibly considered 'low' redshift.



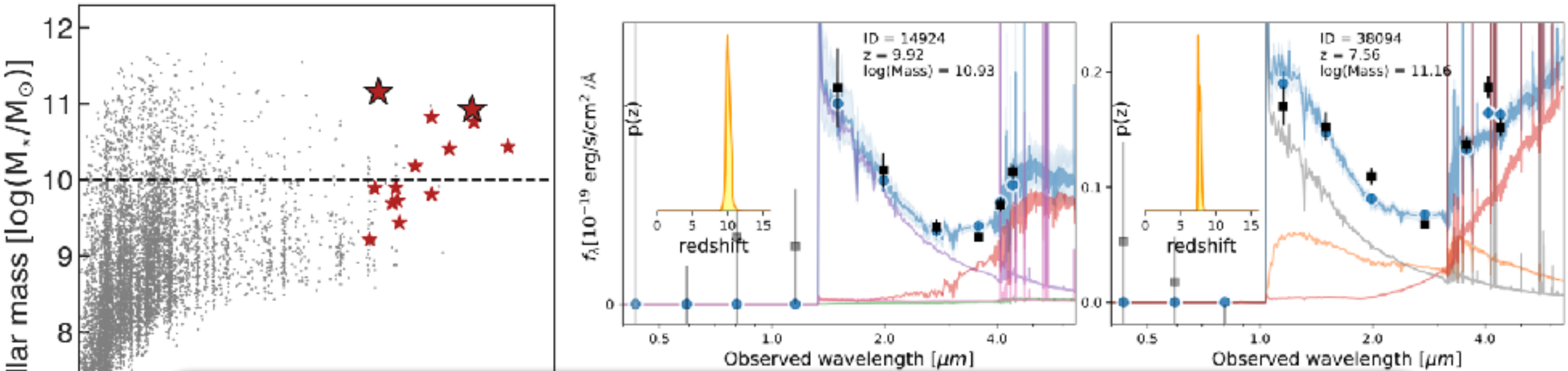
o Castellano et al. (2022)



Relatively straightforward discoveries: sufficiently bright to be found in COSMOS-Web (!) in much higher numbers.

Donnan et al. (2022)

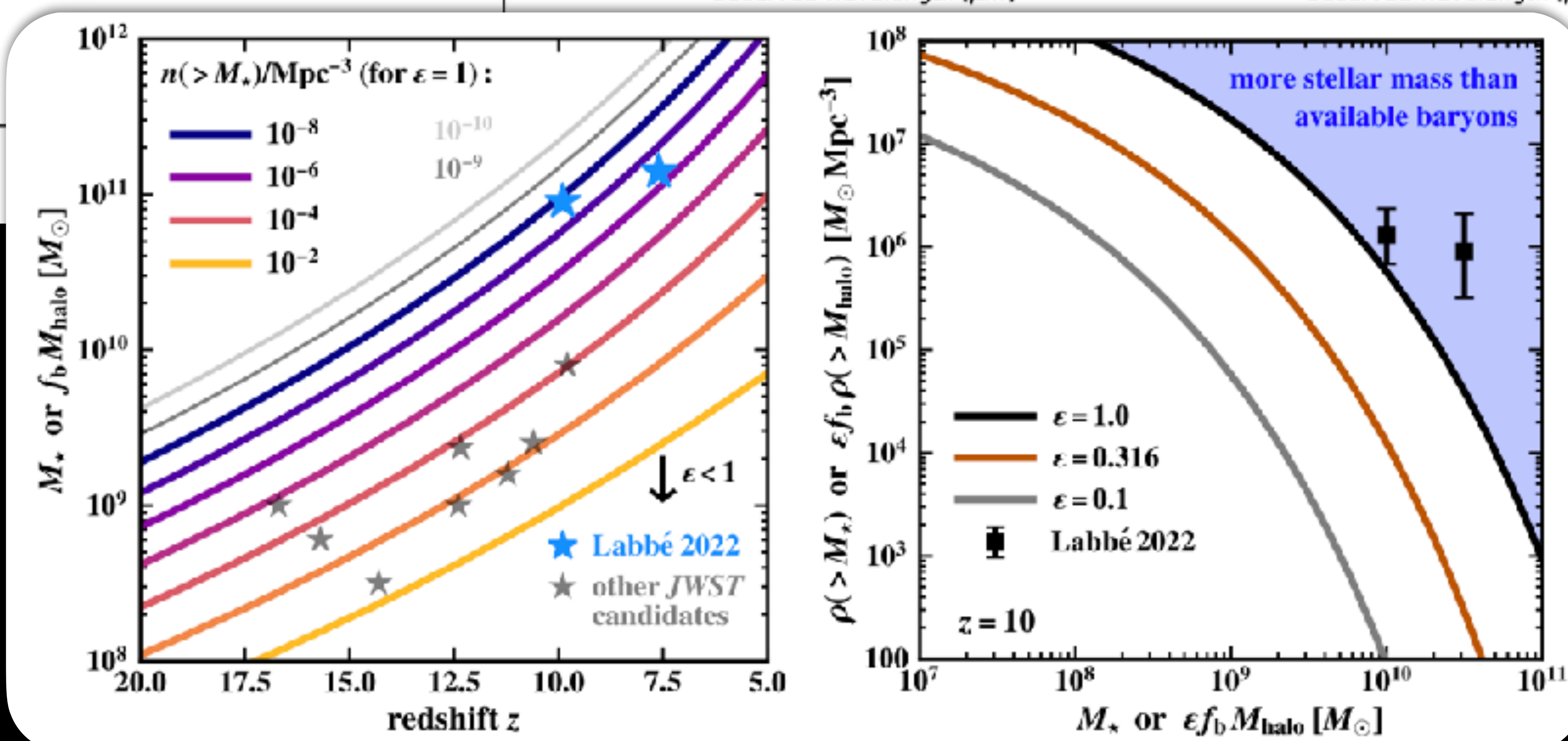
Lessons from JWST data: an unexpected, high volume density of z>10 galaxies.



7;

$z \sim 18$!

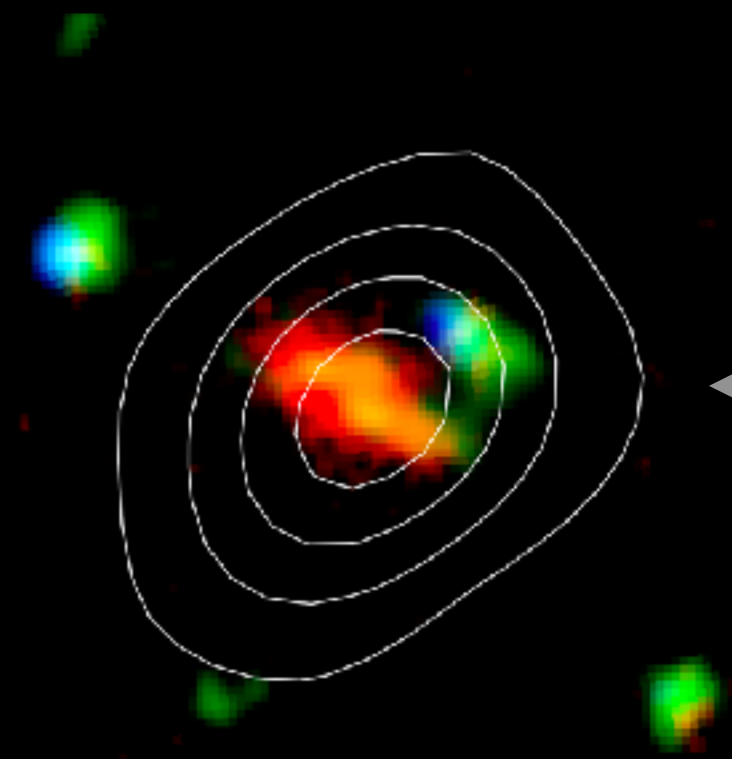
l. (2022)



Boylan-Kolchin (2022)

Lessons from JWST data: a cautionary note about ultra-high-redshift galaxies.

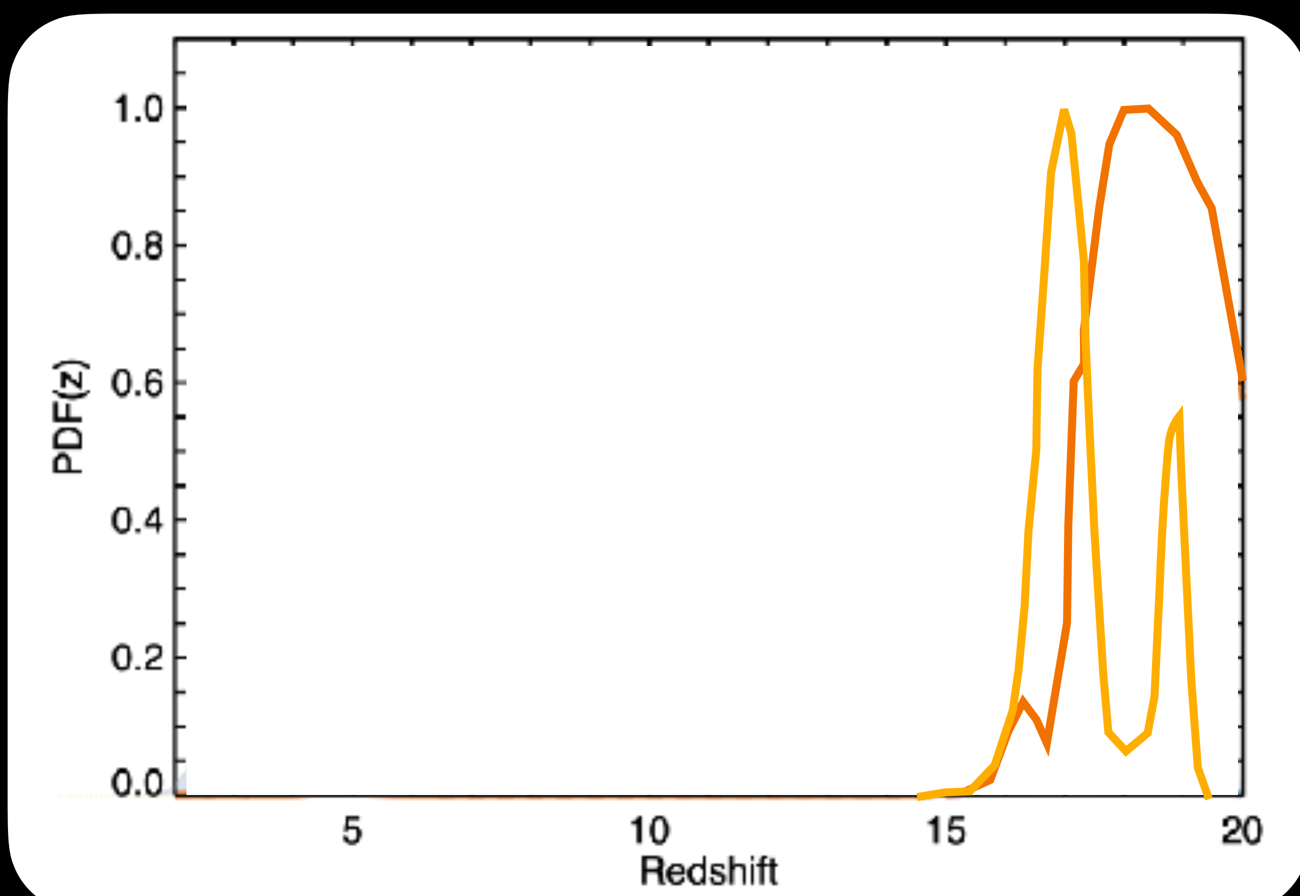
Jorge Zavala



Nominally fit to z~17-18!

However, the source has STRONG dust emission…

emission would probe the rest-frame $\sim 50\mu$m regime; in this scenario, the IR luminosity would, at minimum, be $\sim 4 \times 10^{12}\,L_\odot$ with a dust mass of $\sim 10^8\,M_\odot$. A system with such high dust mass found ~230 Myr after the Big Bang would surely be extraordinary, likely implausibly so (e.g., Dwek et al. 2014).

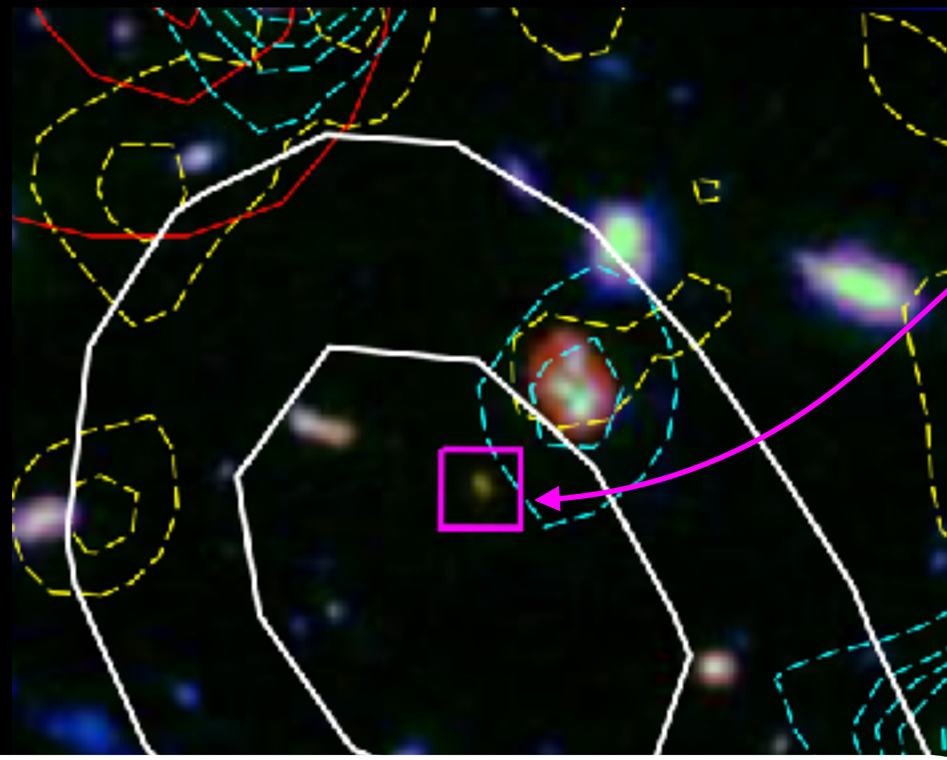


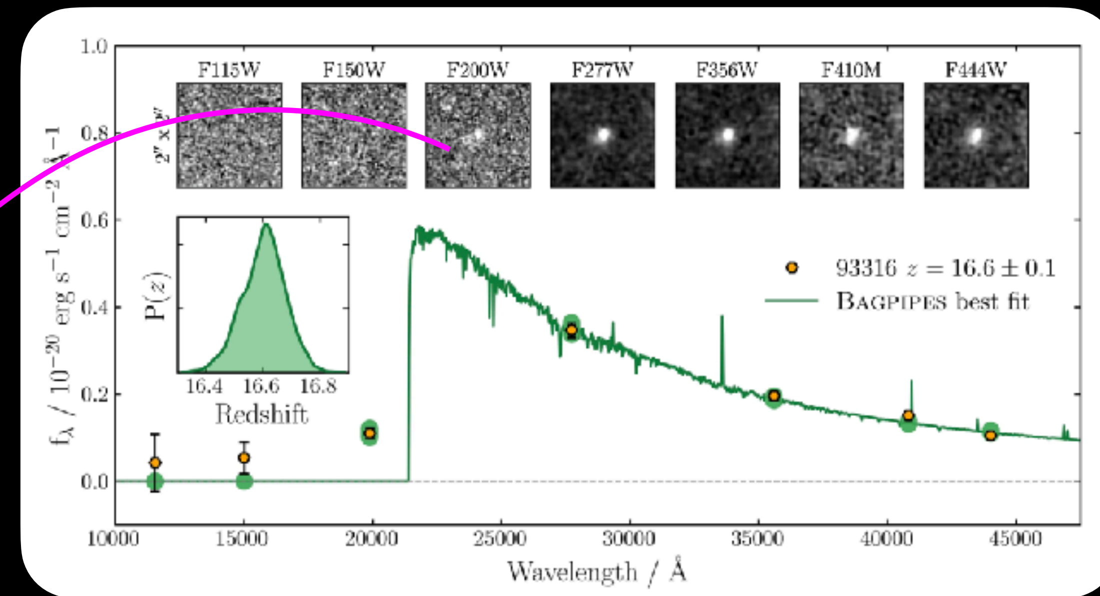
Zavala et al. (2022)

$z \sim 18$ is unlikely!
Adding the dust emission drops the redshift solution to $z \sim 5$.

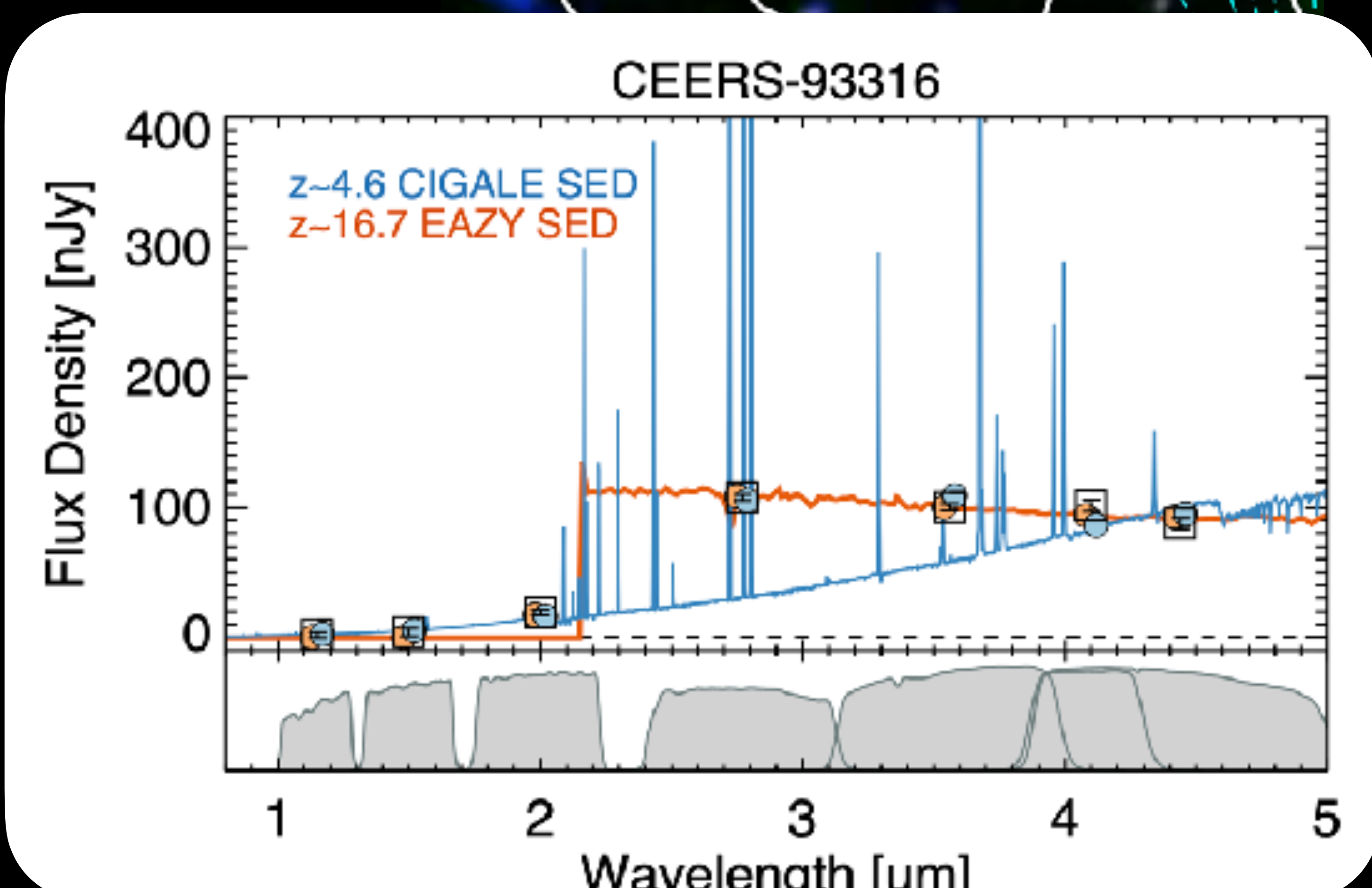
Lessons from JWST data: a cautionary note about ultra-high-redshift galaxies.

Jorge Zavala





The most confident $z \sim 17$ candidate in the literature, from Donnan et al. (2022)

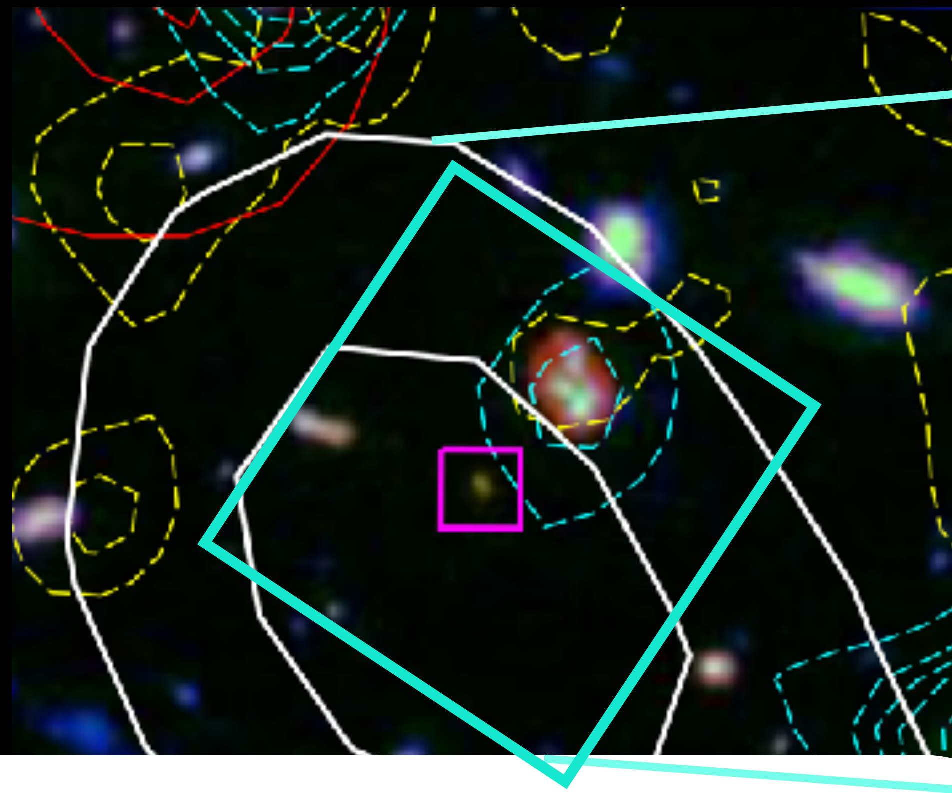


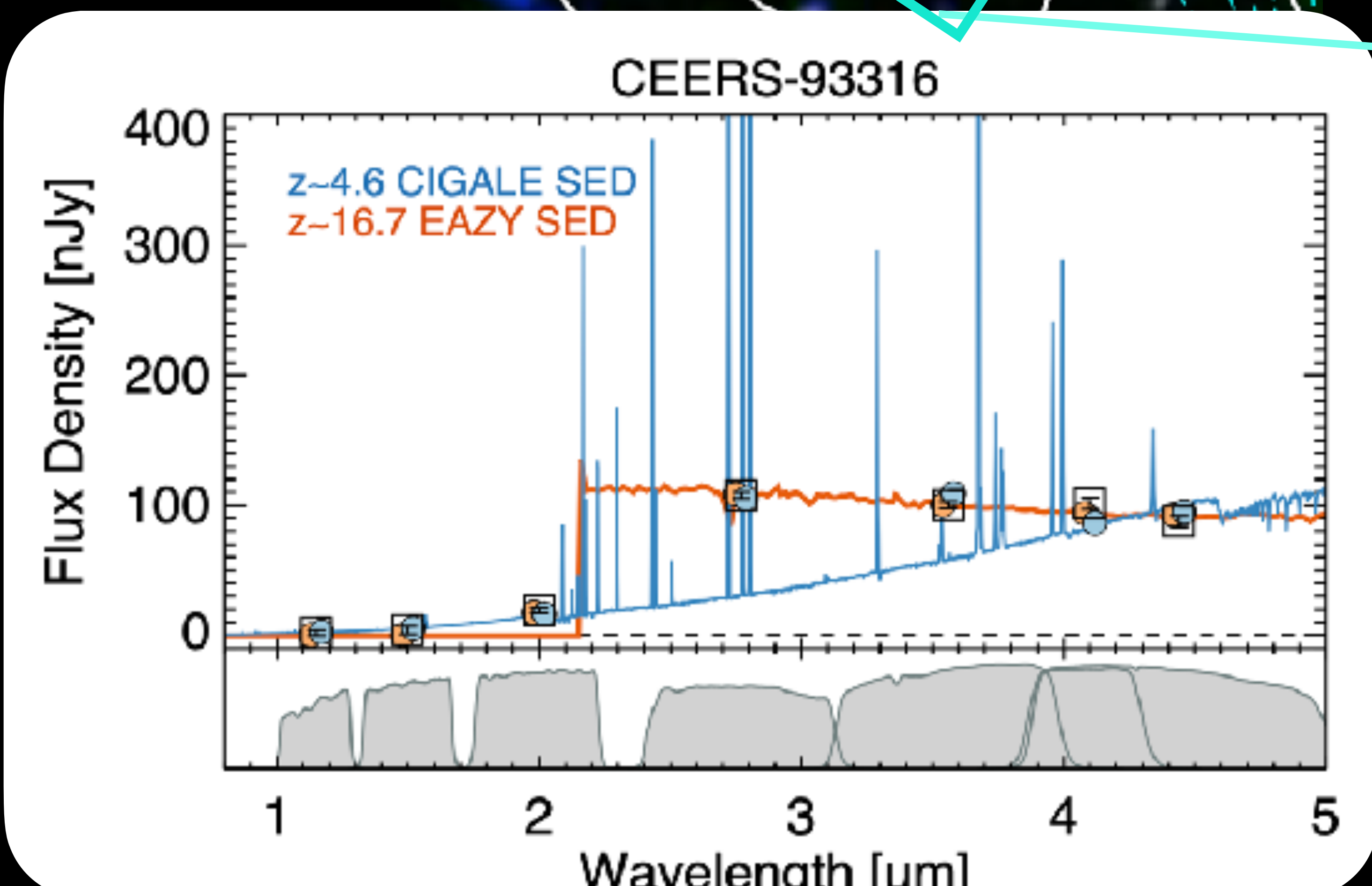
Zavala et al. (2022)

Strong rest-frame optical emission lines + moderate attenuation at $z \sim 5$ can conspire to create a perceived strong break at $z \sim 17$!

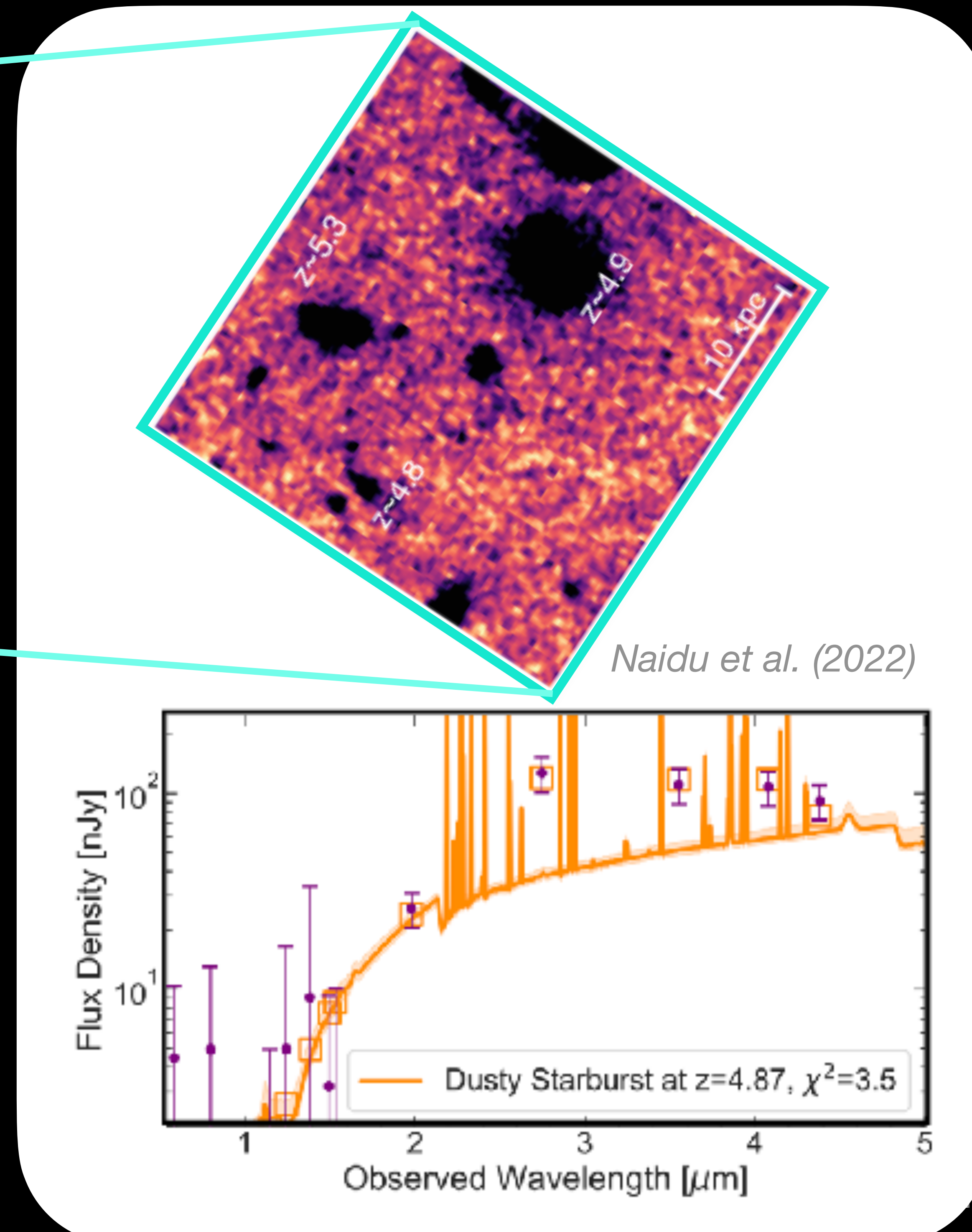
Lessons from JWST data: a cautionary note about ultra-high-redshift galaxies.

Jorge Zavala





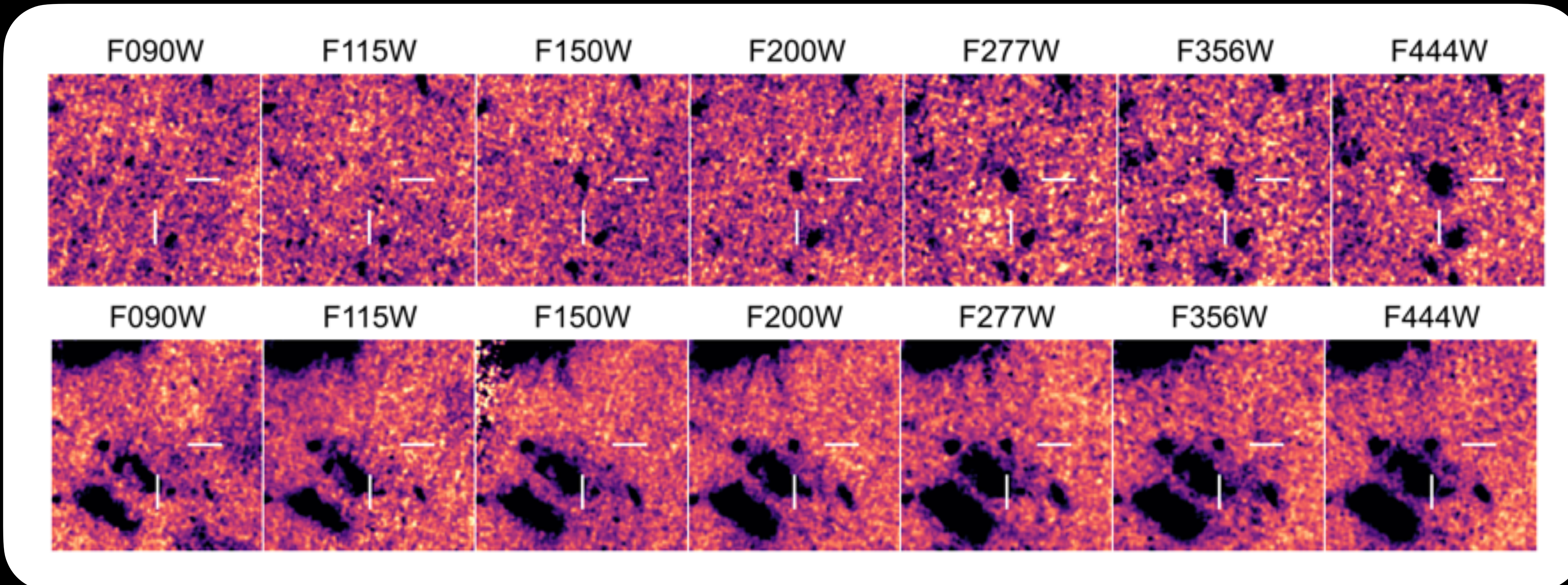
Zavala et al. (2022)



Naidu et al. (2022)

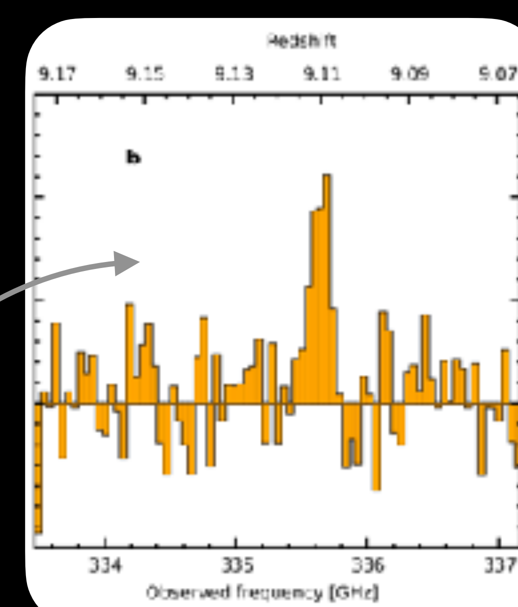
Reaffirmed the next day on arxiv using environmental arguments…

Can ALMA efficiently follow-up the highest-z JWST candidates?



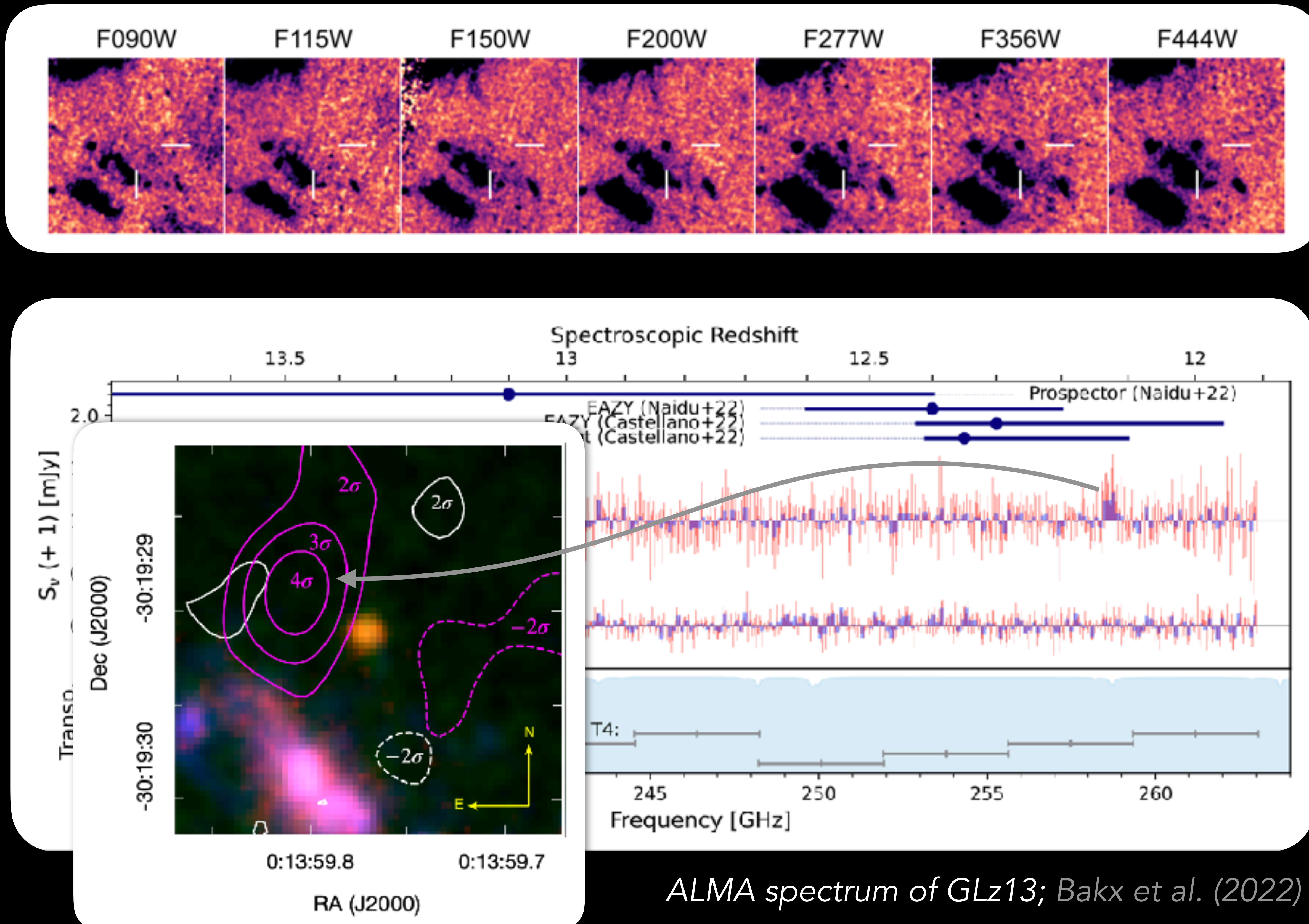
GLz11, GLz13; Naidu et al. (2022), also Castellano et al. (2022)

Both galaxies approved for generous ALMA DDT Projects to try to confirm them spectroscopically via [OIII] 88μm.



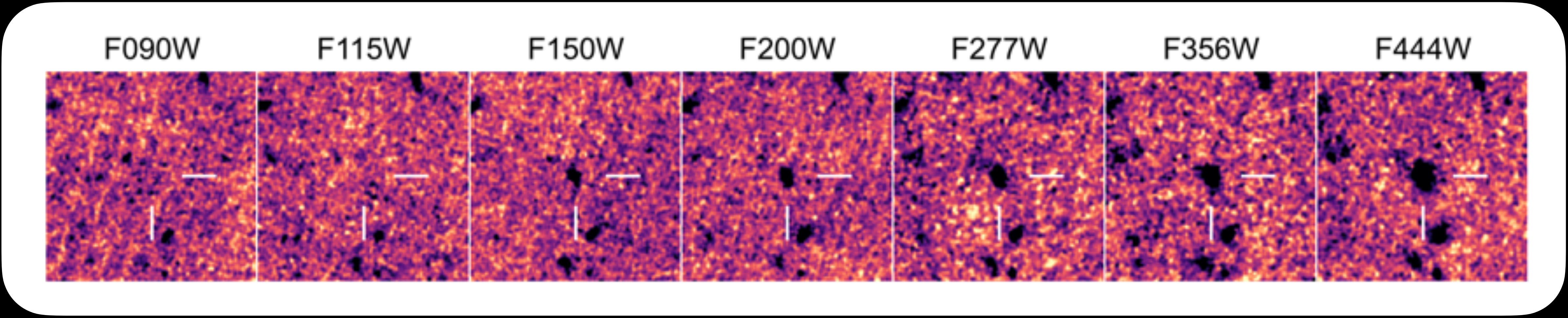
The highest-z spec confirmation at z=9.1 from [OIII]: Hashimoto et al. (2018)

Can ALMA efficiently follow-up the highest-z JWST candidates?



ALMA spectrum of GLz13; Bakx et al. (2022)

Can ALMA efficiently follow-up the highest-z JWST candidates?



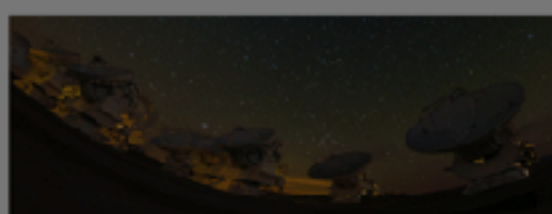
***Stay tuned** for the ALMA results on GLz11 from Yoon et al., in prep.*

Moral of the story: z>10 is much harder than $z \sim 9$!

But! So far these detections bode well for JWST surveys with thousands of galaxies out to $z \sim 9$, hundreds out to $z \sim 11$, and a few dozen at $z > 12$…

MORA

Mapping Obscuration to Reionization with ALMA



51 hour Cycle 6+8 Program

COSMOS WEB

218 hour Cycle 1 JWST Program

WERLS

Webb Epoch of Reionization Lyα Survey

29night Keck KSMS Program

*Measuring **where** reionization happened requires follow-up Lyα spectroscopy of a breadth of galaxies across the UVLF in different environments.*

The Webb Epoch of Reionization Lyman-α Survey (WERLS)

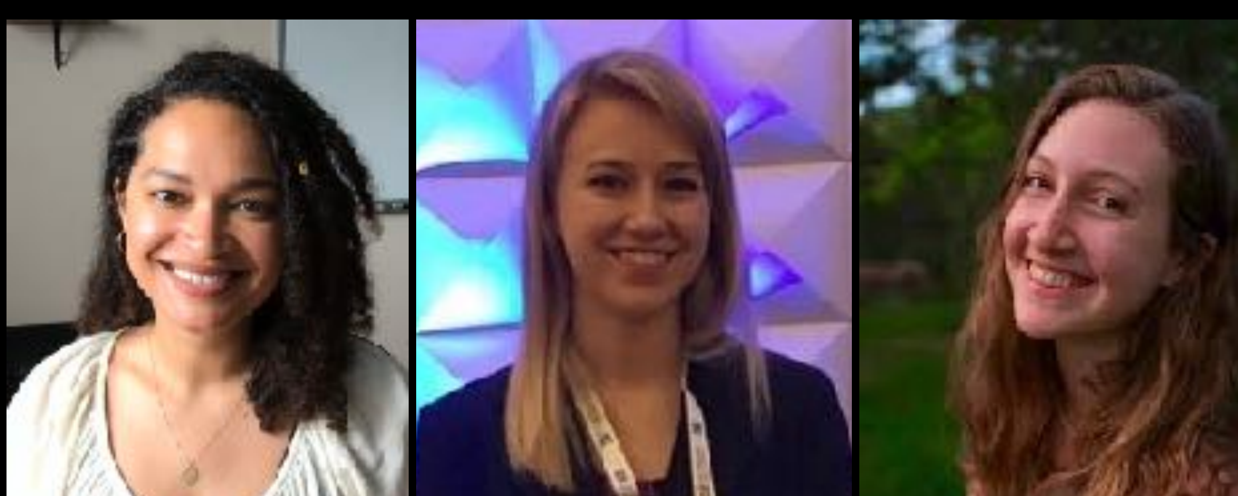
PIs: Caitlin Casey & Jeyhan Kartaltepe

29 night Keck Key Strategic Mission Support Program (2022-2024) with MOSFIRE and LRIS

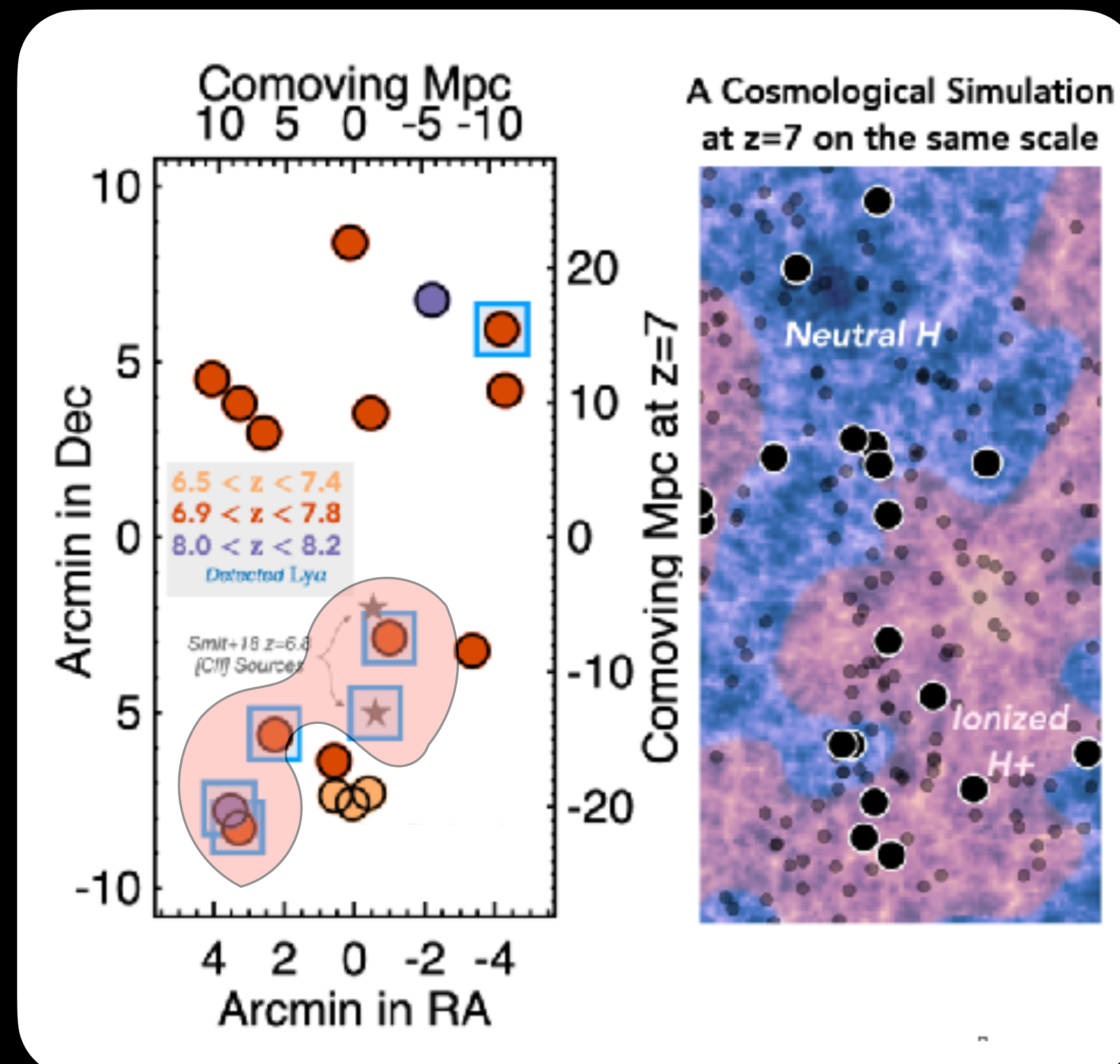
Targeting hundreds of EoR candidates in JWST Deep Fields.

Lyα → maps ionized bubbles

JWST imaging → maps galaxy density field

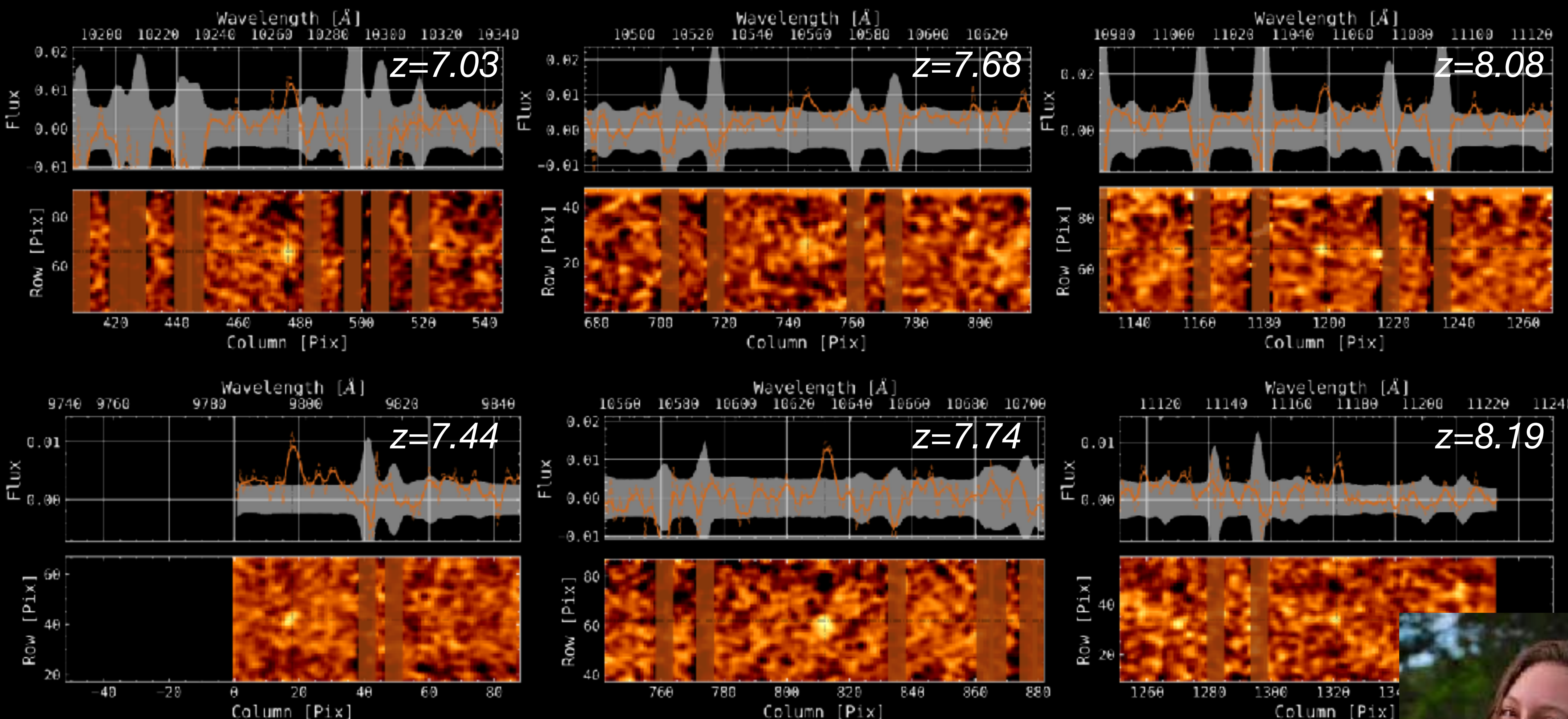


Arianna Long (UCI→UT), Stephanie Stawinski (UCI), Olivia Cooper (UT)



Preliminary findings from 2022A data

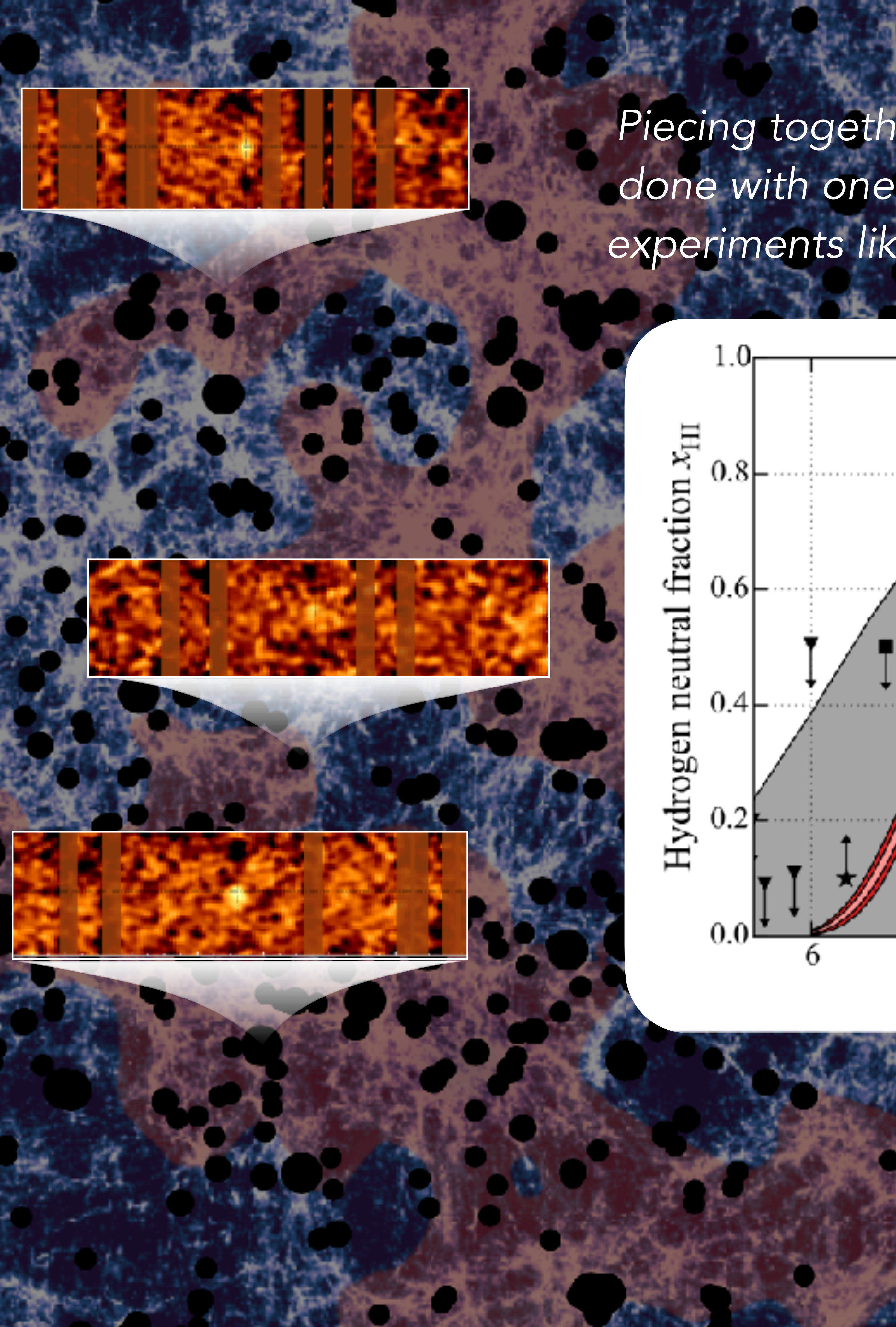
*Measuring **where** reionization happened requires follow-up Lyα spectroscopy of a breadth of galaxies across the UVLF in different environments.*



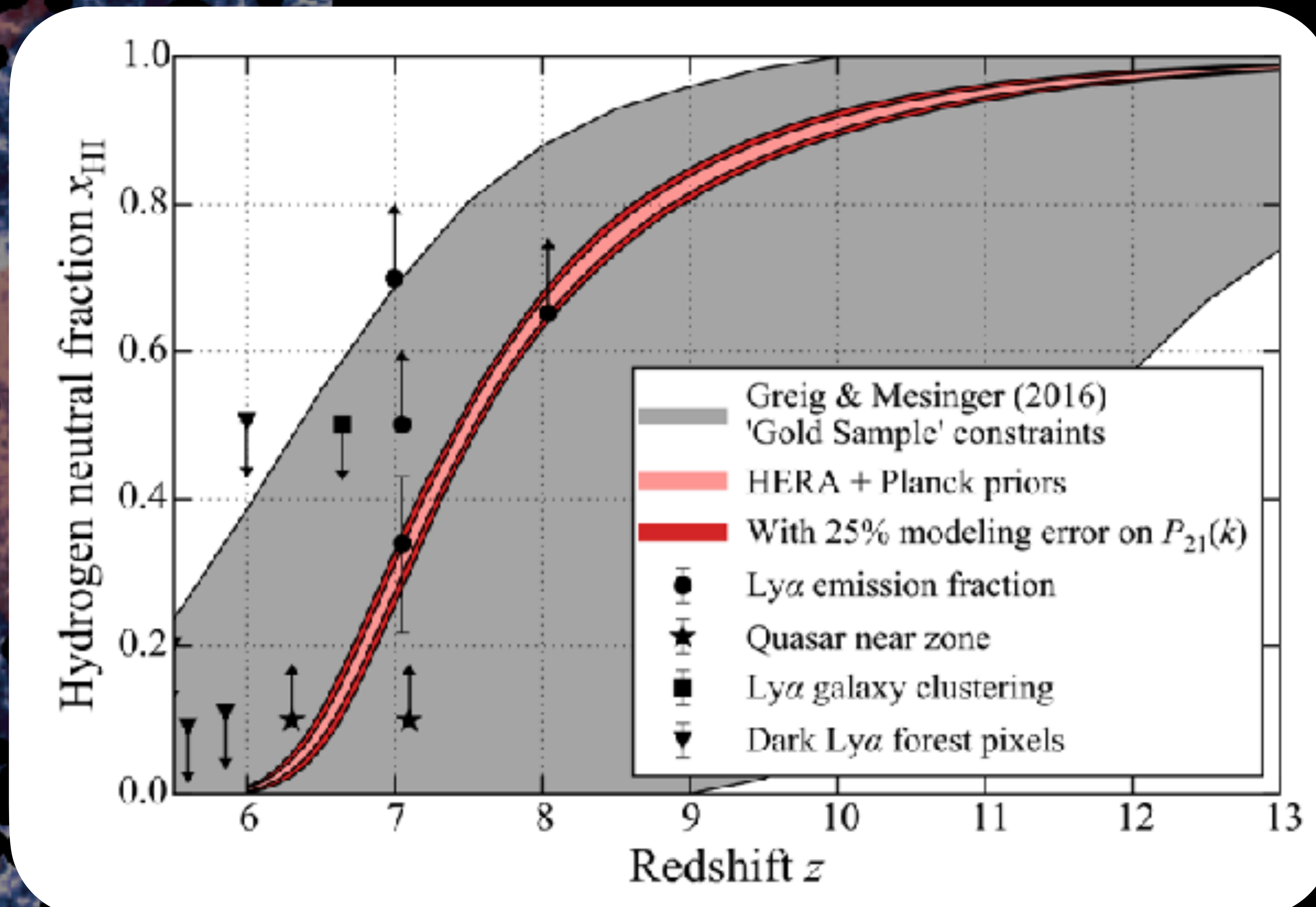
Cooper et al., in prep

A slew of exciting new z>7 discoveries, doubling the number of known, spectroscopically confirmed sources (pre-JWST).

Olivia Cooper



Piecing together the history of reionization cannot be done with one tracer alone: HI 21cm signal detection experiments like HERA, PAPER, & SKA complimentary.



DeBoer et al. (2016)

COSMOS
WEB

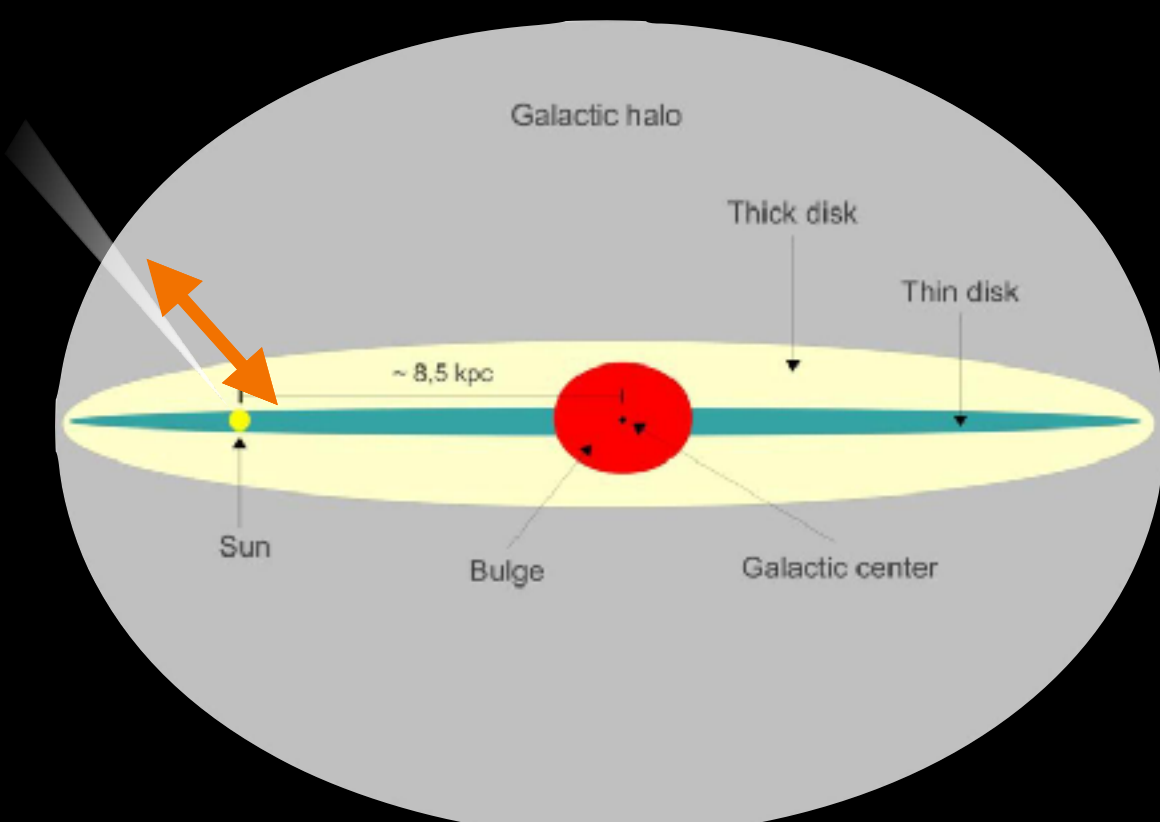
It’s not just about high-redshift galaxies (!)

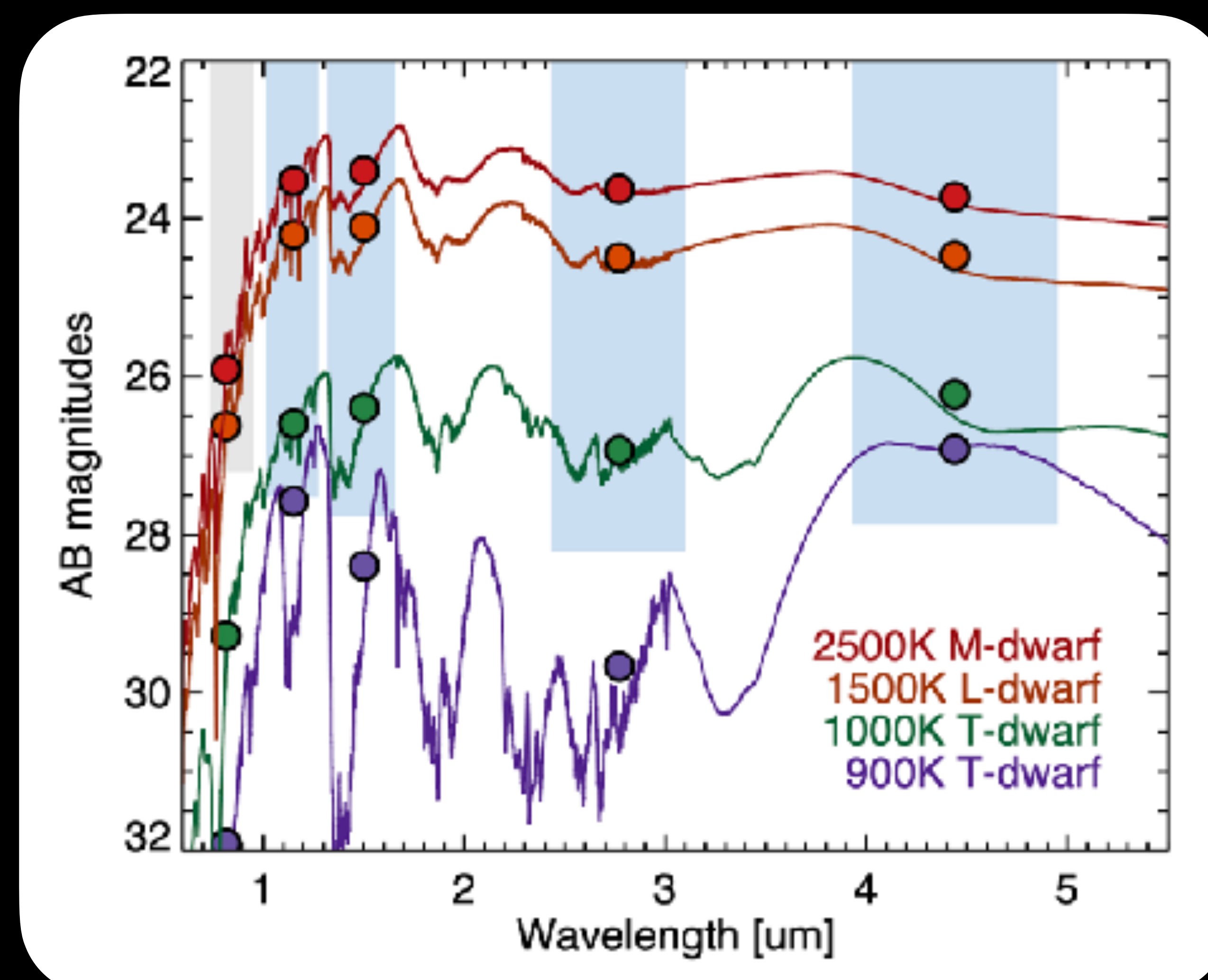
COSMOS WEB

It's not just about high-redshift galaxies (!)

Low Metallicity Brown Dwarfs

We'll find ~1000 MLTY-dwarfs to distances of ~2kpc, allowing precise measurements of the scale height of the Milky Way for low-mass objects.

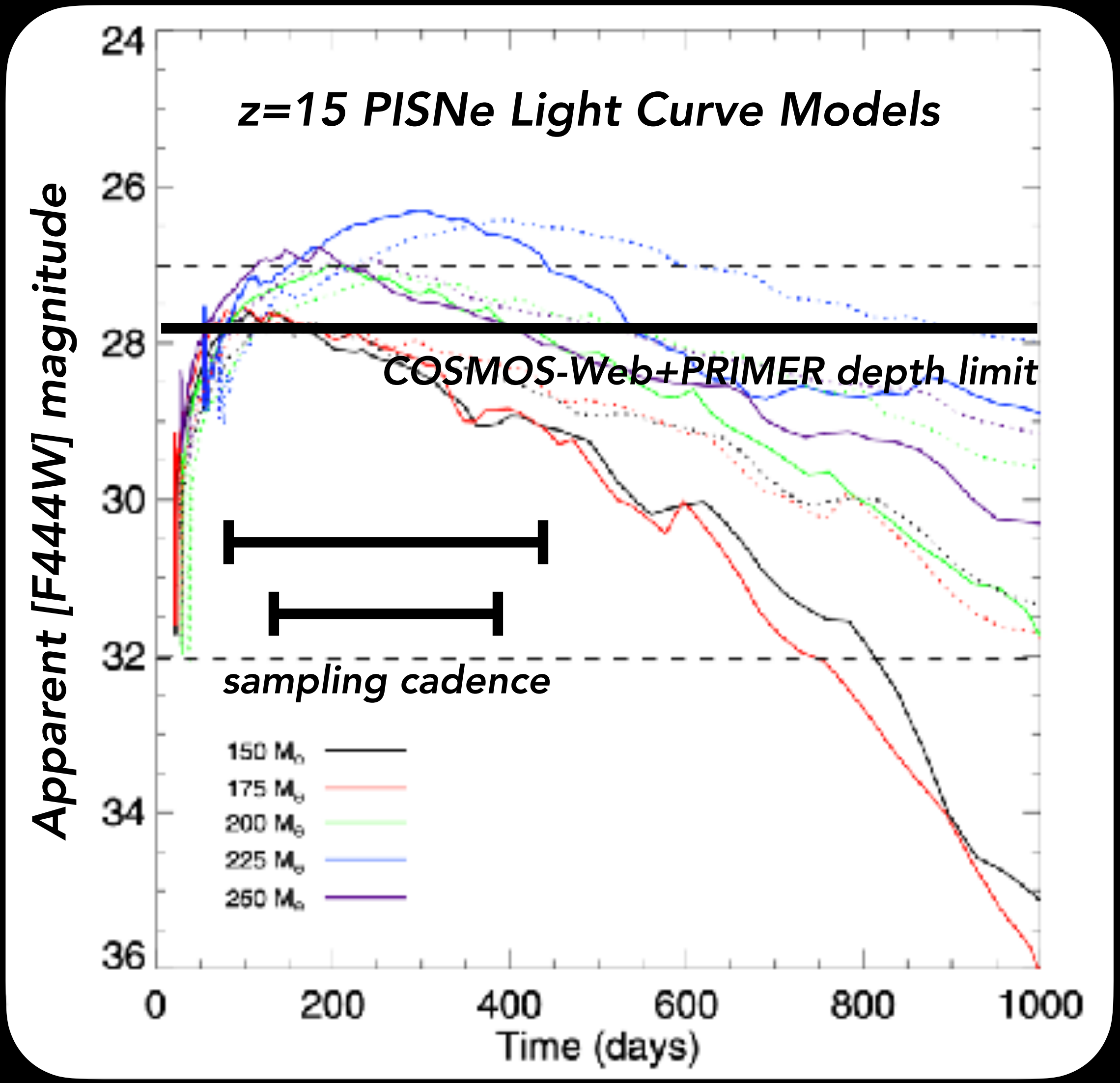




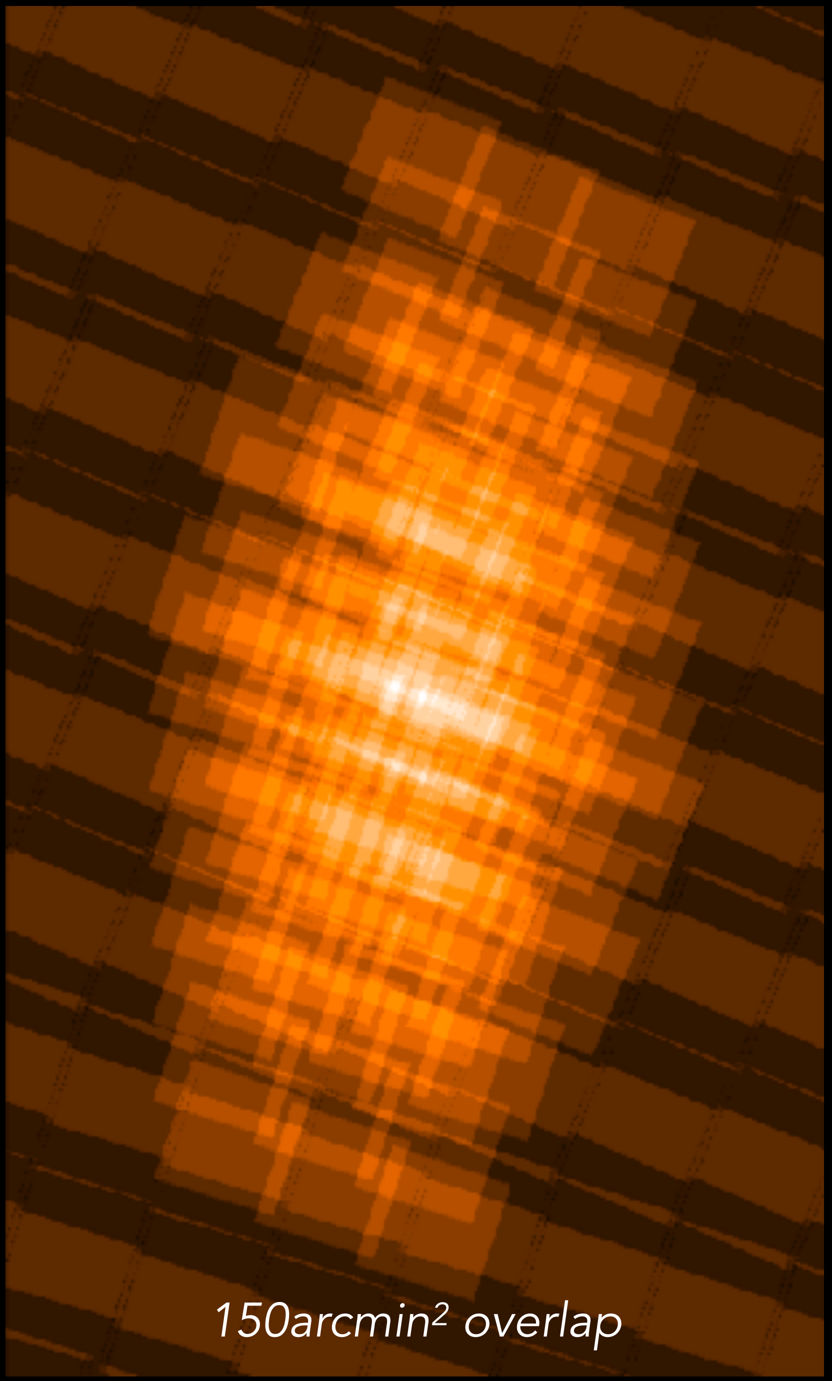
Casey et al, in prep

It's not just about high-redshift galaxies (!)

Searching for z>10 Pair-Instability Supernovae



Whalen et al. (2013)



COSMOS-Web + PRIMER Exposure Map

Full-circle: PISNe could be the origins of the first dust reservoirs producing $\sim 2\,\mathrm{M}_{\odot}$ of dust ejecta per supernova!

— Schneider et al. (2004)

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What can pathologically massive galaxies — formed incredibly quickly after the Big Bang — teach us about fundamental processes of halo growth, the ISM and galaxy formation?

Thank you! Feel free to reach out via email: cmcasey@utexas.edu

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Already found examples of obscured galaxies whose baryonic masses at $z \sim 6$ test the limits of dust formation mechanisms & ΛCDM.

MORA 2mm ALMA Survey will continue to push bounds in finding extreme, dusty galaxies in the EoR.

JWST has already changed our mindset and redshift horizon (now $z \sim 18?$)…

A legacy program poised for unique discoveries at the highest redshifts.

The ultimate EoR observational experiment: mapping reionization bubbles.

Mapping back to galaxy density maps will constrain sources of reionization on large scales.