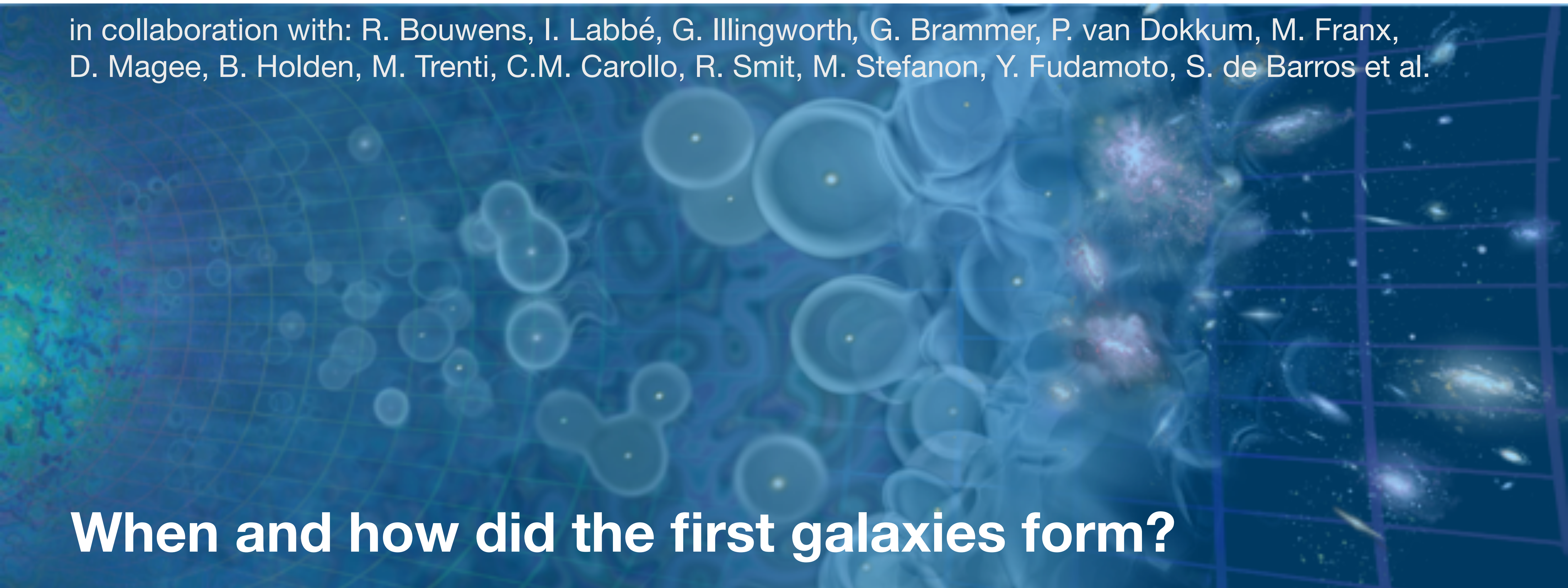
Early Galaxy Build-up and the End of the Dark Ages:
Hubble's Legacy into the JWST Era

Galaxy Evolution Across Time - Paris 2017

Pascal Oesch
Geneva Observatory



in collaboration with: R. Bouwens, I. Labbé, G. Illingworth, G. Brammer, P. van Dokkum, M. Franx, D. Magee, B. Holden, M. Trenti, C.M. Carollo, R. Smit, M. Stefanon, Y. Fudamoto, S. de Barros et al.

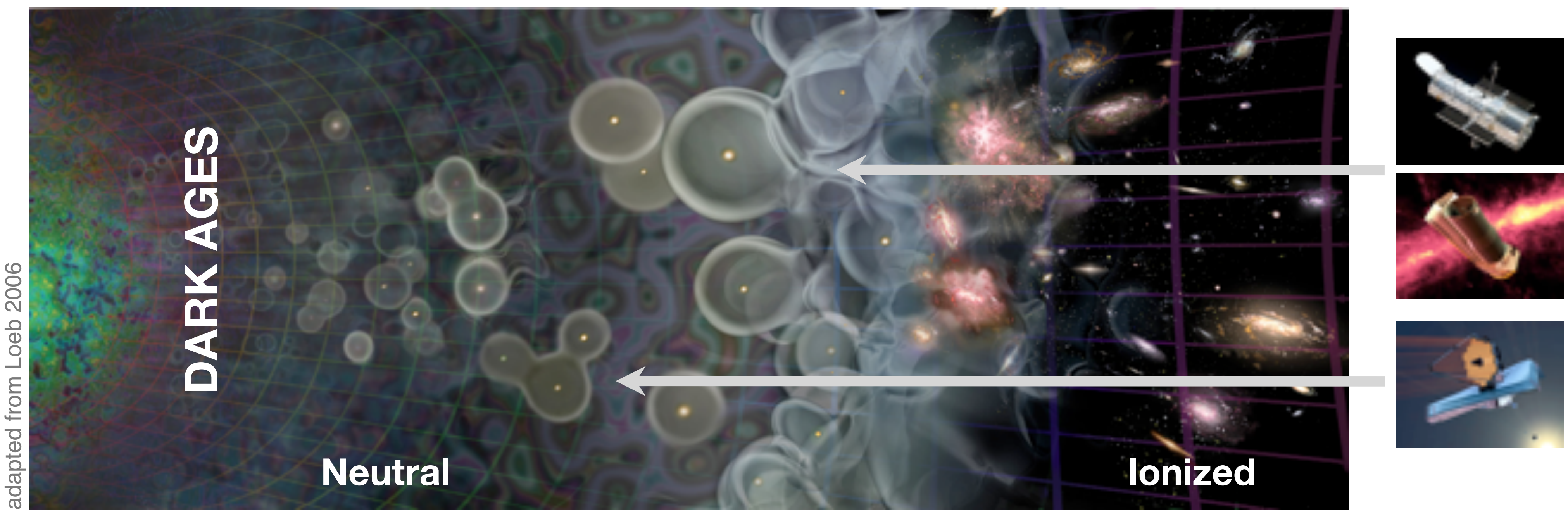
When and how did the first galaxies form?

Major Goal of JWST

The End of the Dark Ages: First Light & Reionization

Cosmic Microwave Background | First Stars | First Galaxies | Epoch of Reionization | Modern Galaxies

adapted from Loeb 2006



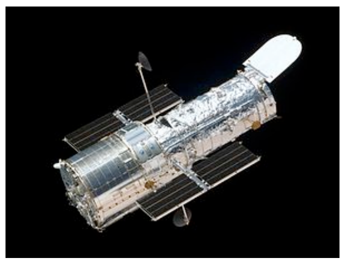
now

soon (2018)

Cosmic Age	380,000 yr	100-200 Myr?	200-300 Myr?	0.3-1 Gyr	13.8 Gyr
Redshift	z=1100	z~20-30?	z~15-20?	z~15-6	z=0

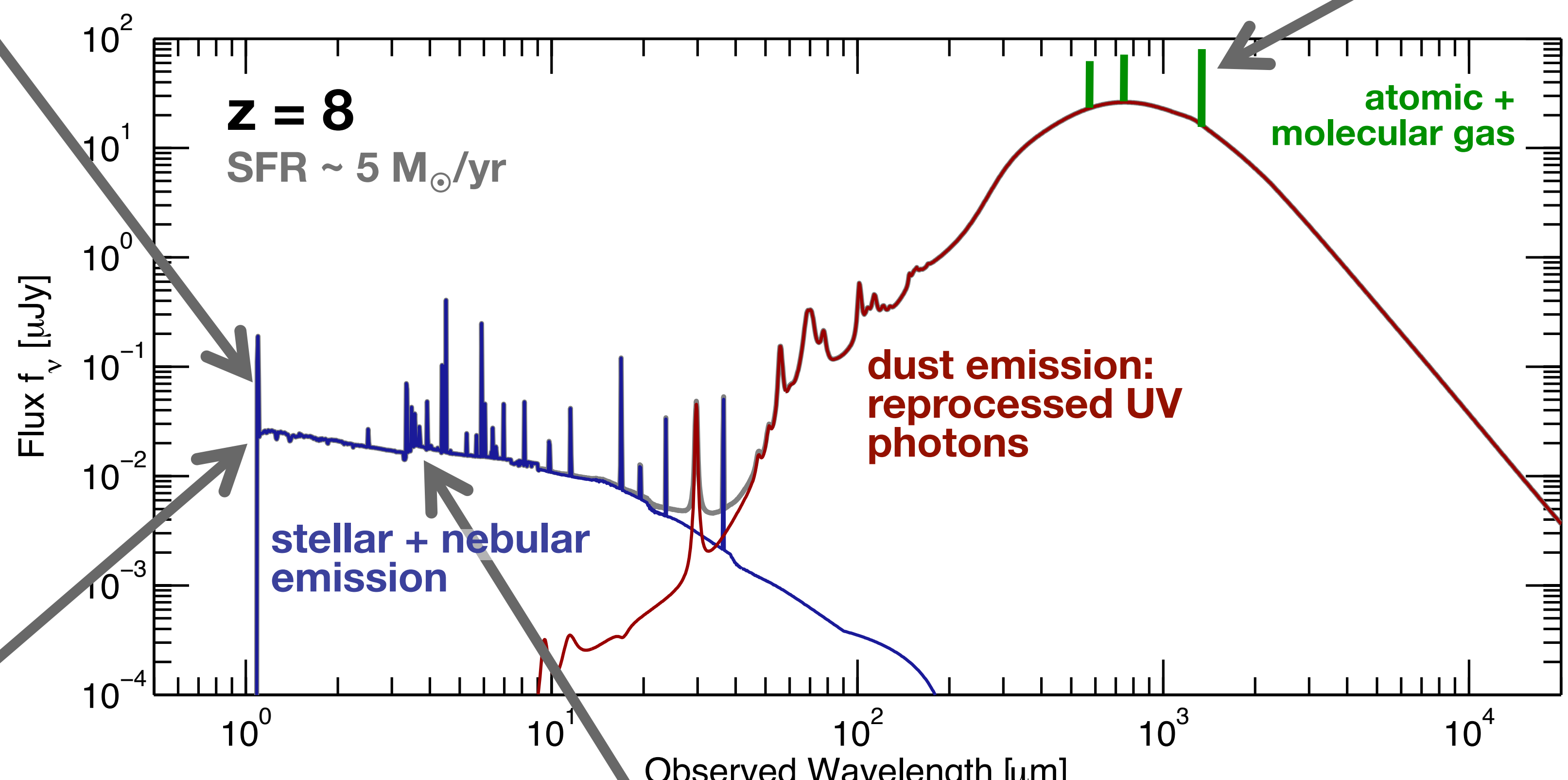
Where do we stand now with HST?

Our Multi-Wavelength Study of Early Galaxies

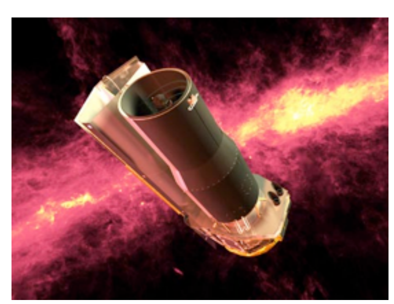


HST:
rest-frame UV
un-obscured SFR

ALMA/NOEMA:
cold gas
dust re-emission
closes energy balance



NIR Spectra:
rest-frame UV lines



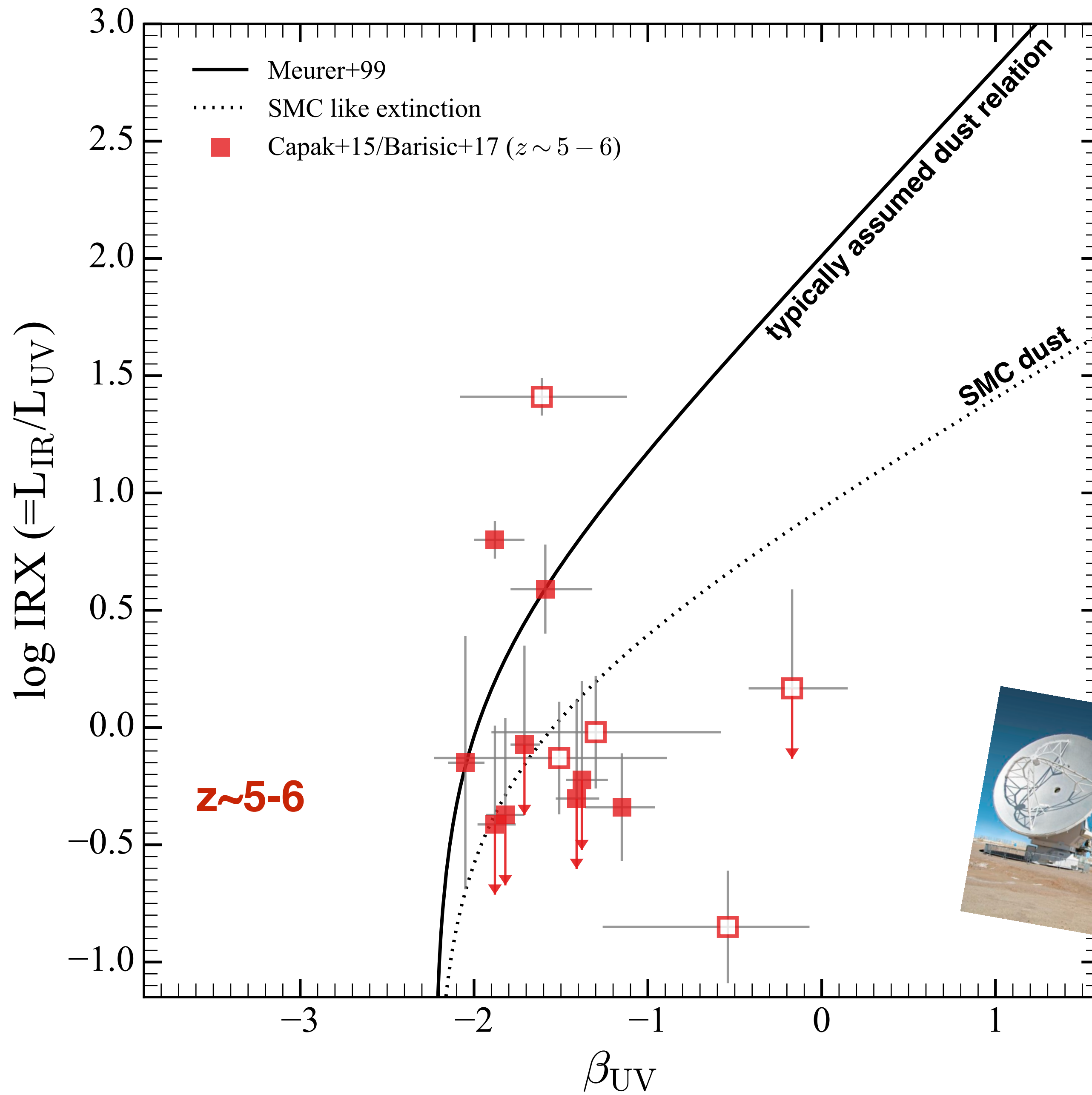
Spitzer:
rest-frame optical imaging
stellar masses, ages
rest-frame optical emission lines

First ALMA Constraints on LBG Dust Reemission

Much less emission in ALMA than expected at z>5!
Less dust than we thought from UV slopes?

Early observations of z~5.5 galaxies reveals only small fraction of detected sources.

>5x lower L_{IR} for bulk of observed galaxies than expected from z~0 relation.



See also: Capak+15, Bouwens+16, Dunlop+16, Scoville+16

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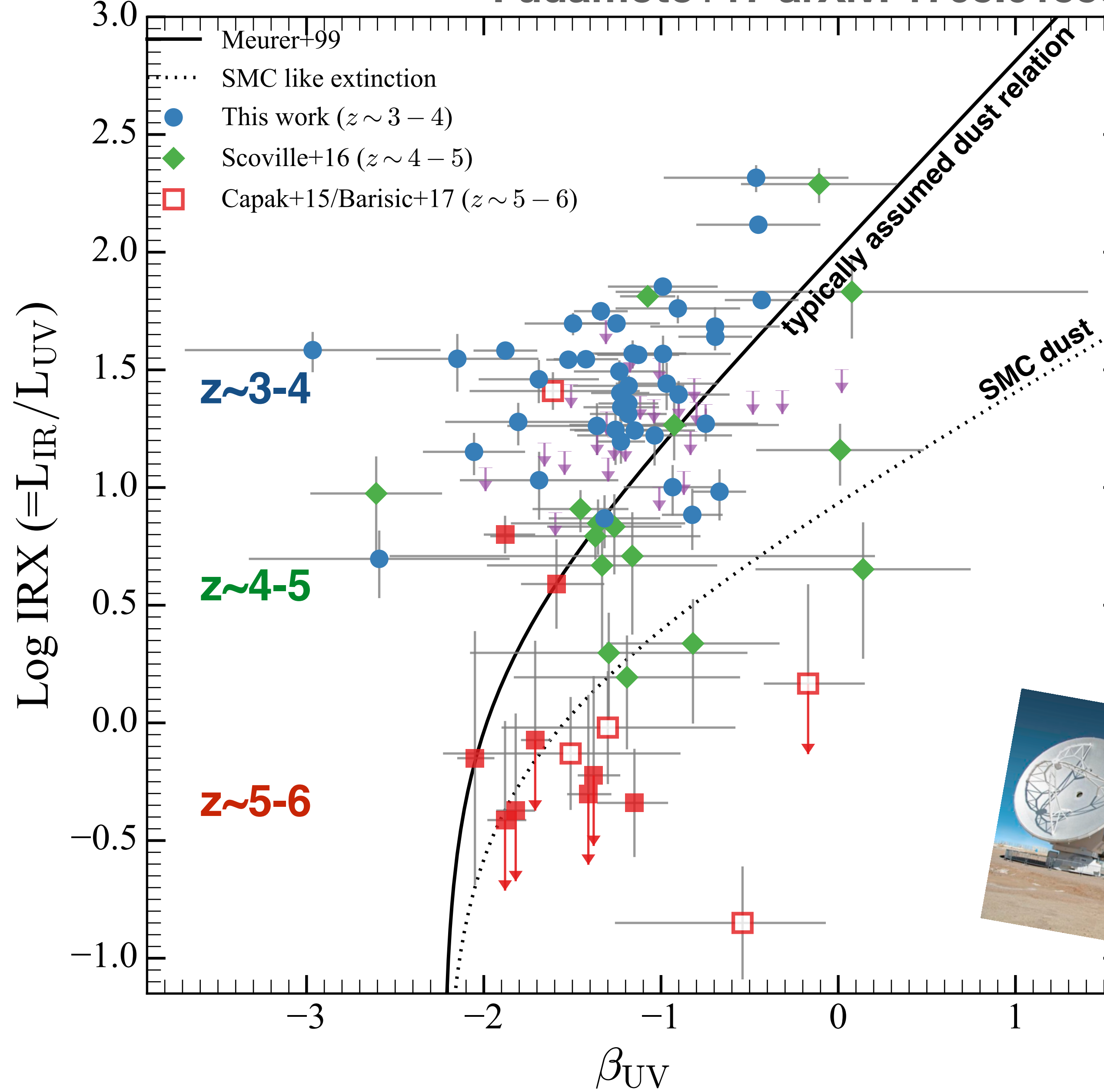
Fudamoto+17 arXiv: 1705.01559



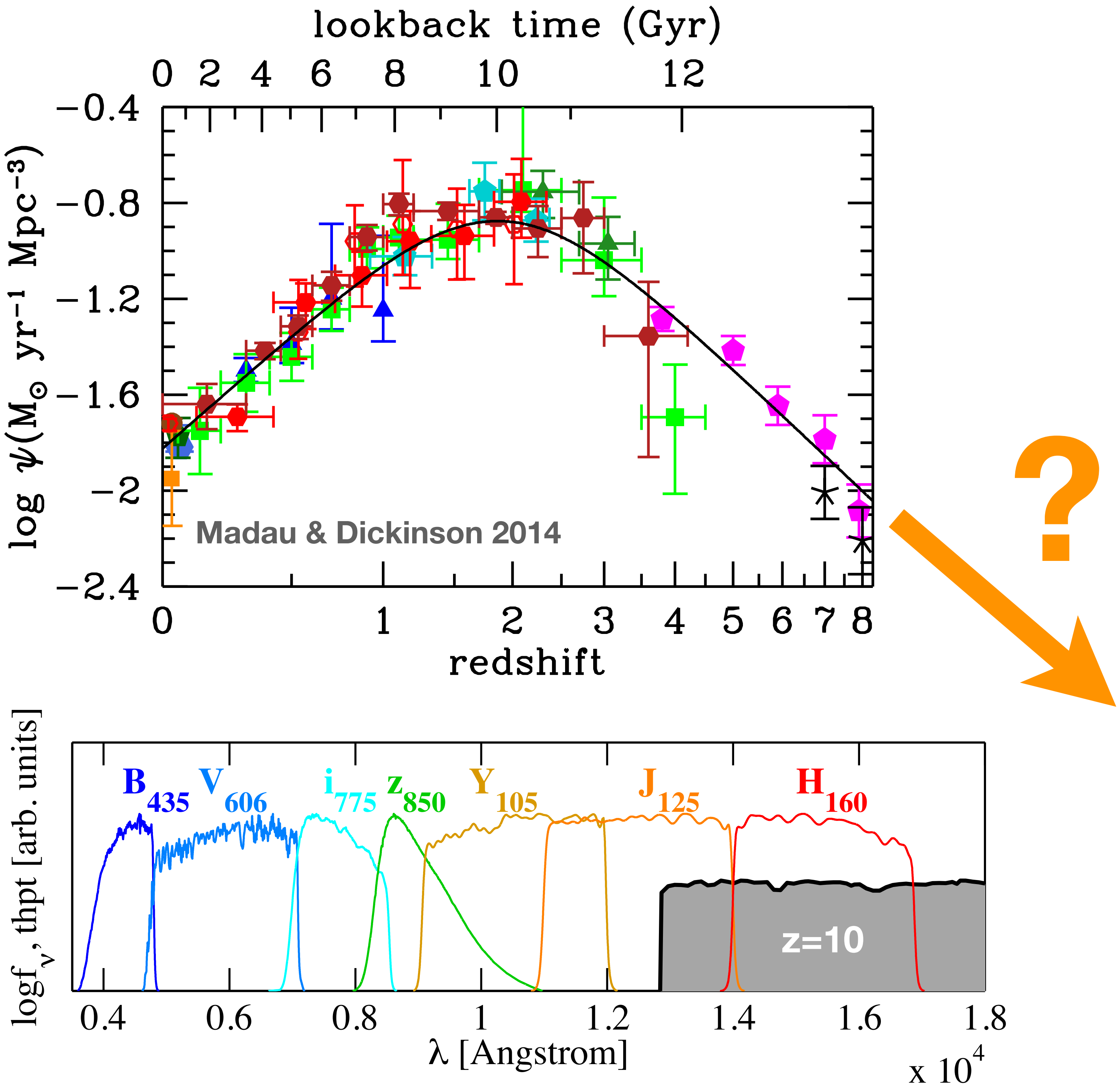
It turns out that massive z~3 galaxies still lie on (or above) the local relation!

Several assumptions that go into this: Dust temperature, IRX-Mass relation.

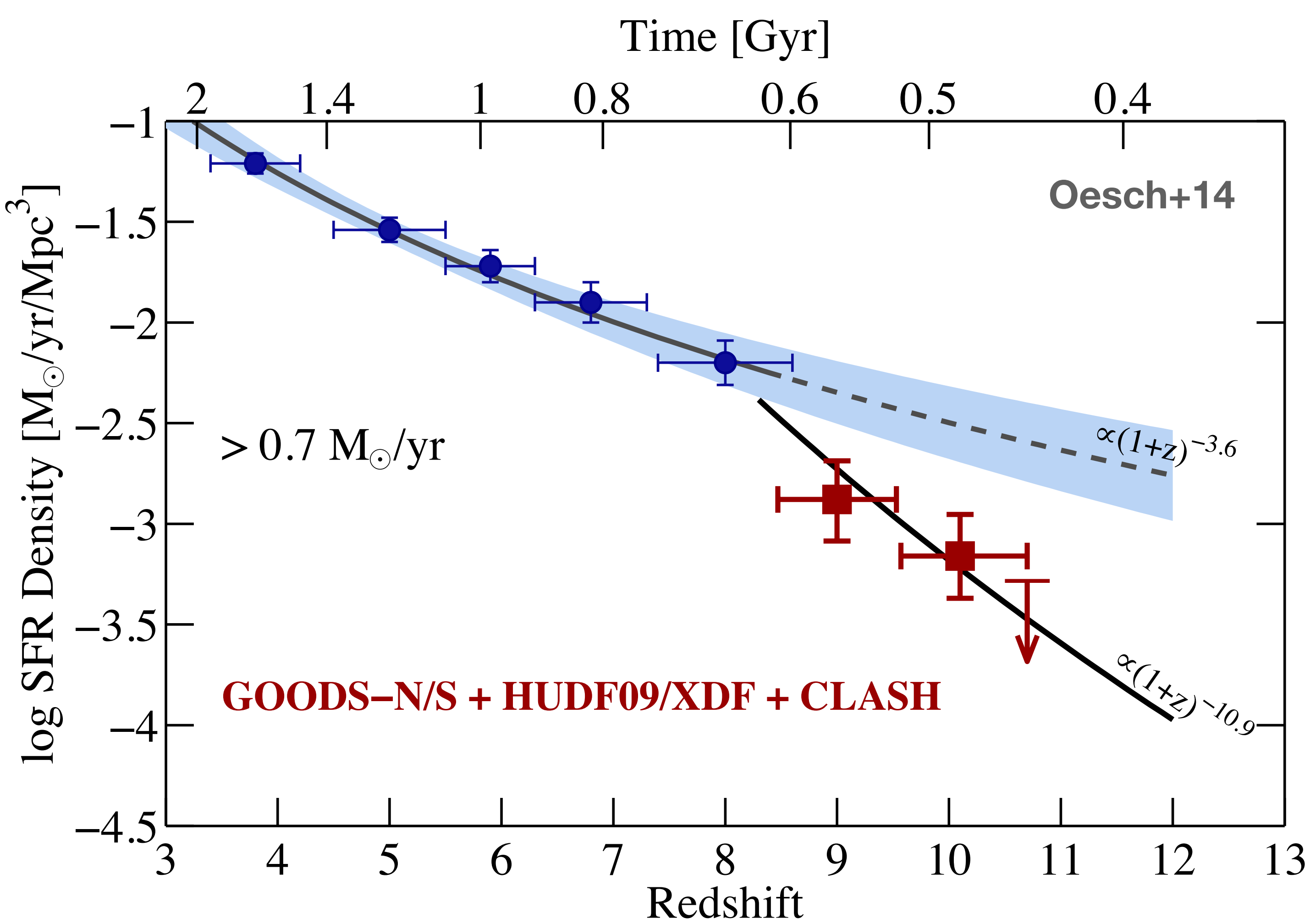
See Yoshi's poster outside!

See also: Capak+15, Bouwens+16, Dunlop+16, Scoville+16

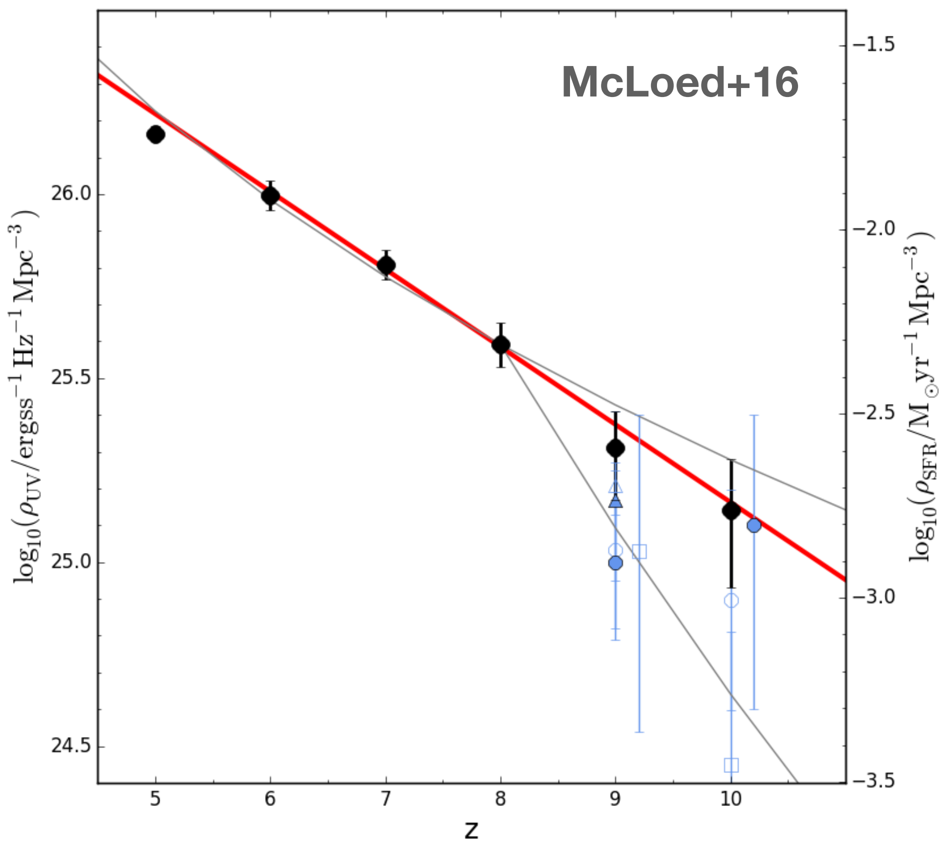
Probing the Frontier of Galaxies



The Star-Formation Rate Density at z~10?



vs

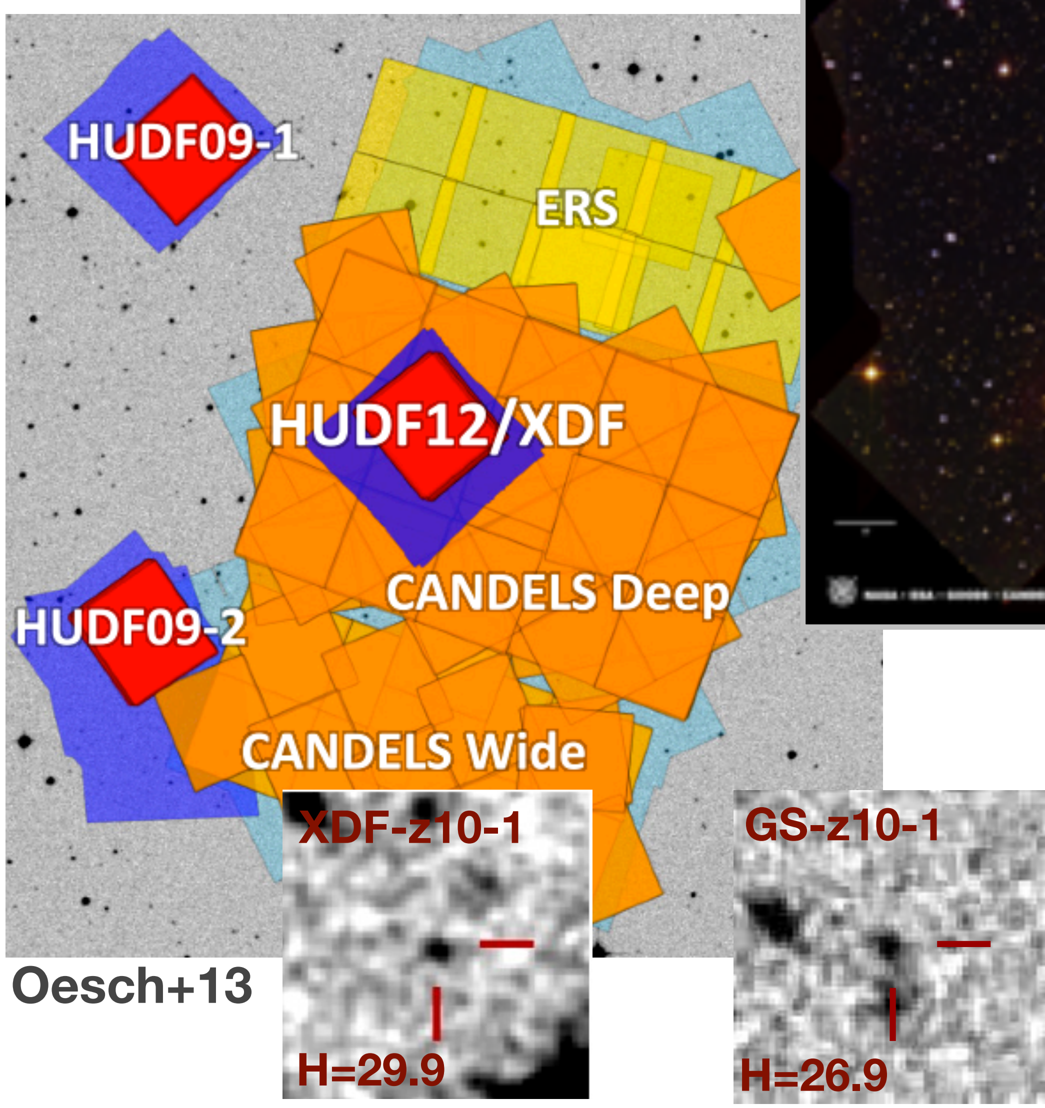


Unlike at lower redshift, SFRD at z~10 is still quite debated.
Until now…

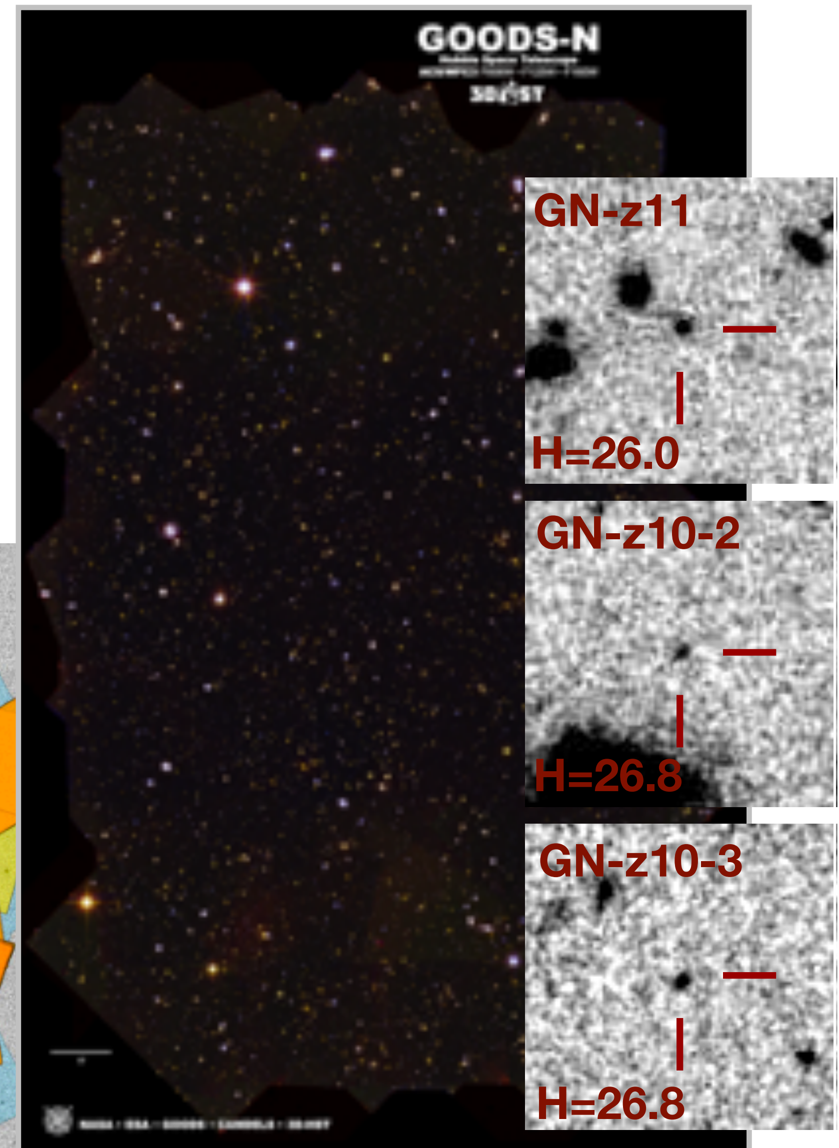
see also: Zheng+12, Coe+13, Bouwens+13/15, Ellis+13, McLure+13, Ishigaki+14

Combined HST Dataset for z~10 Search - CANDELS

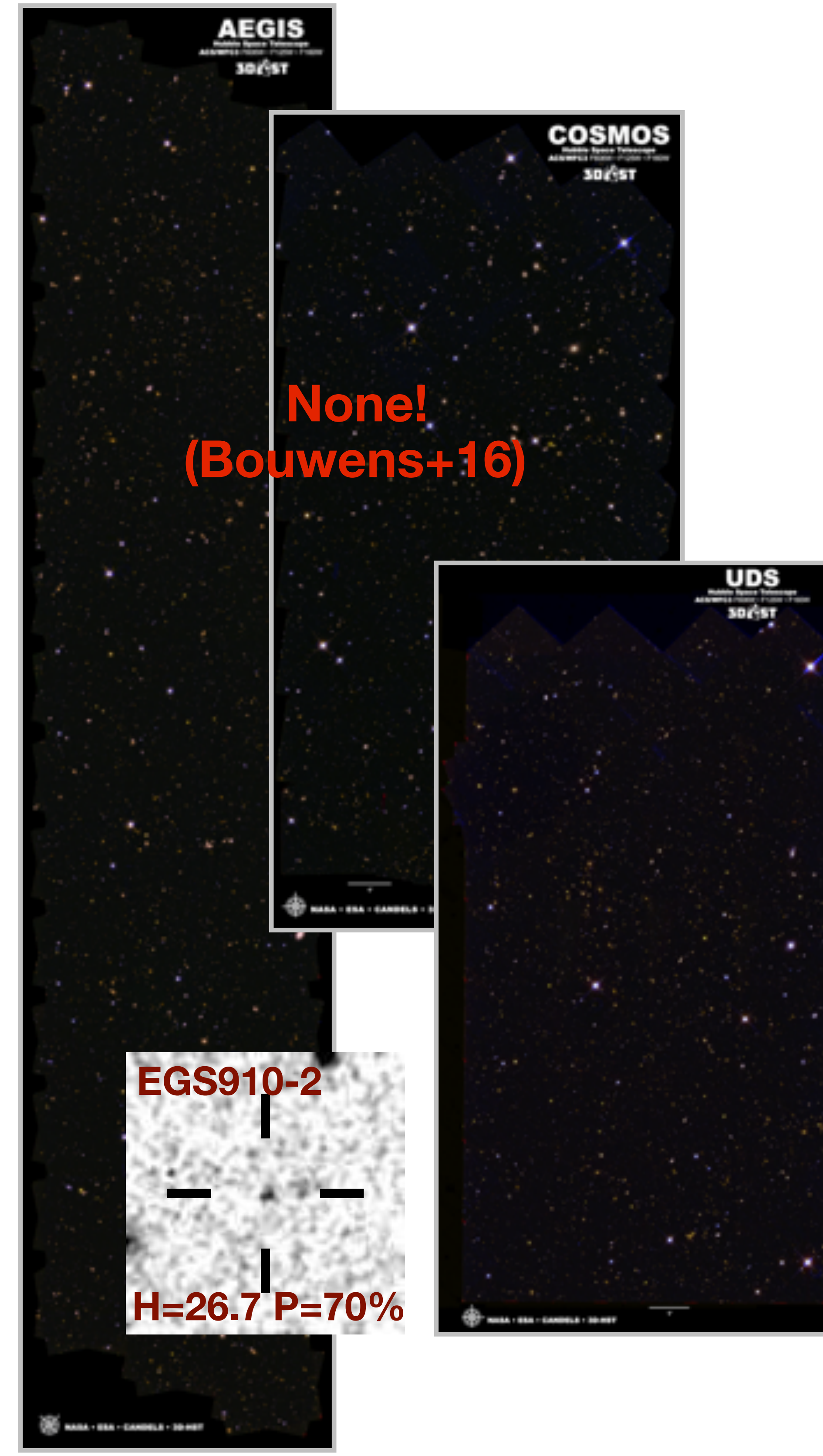
Five J-dropout candidates identified in CANDELS fields



Oesch+13



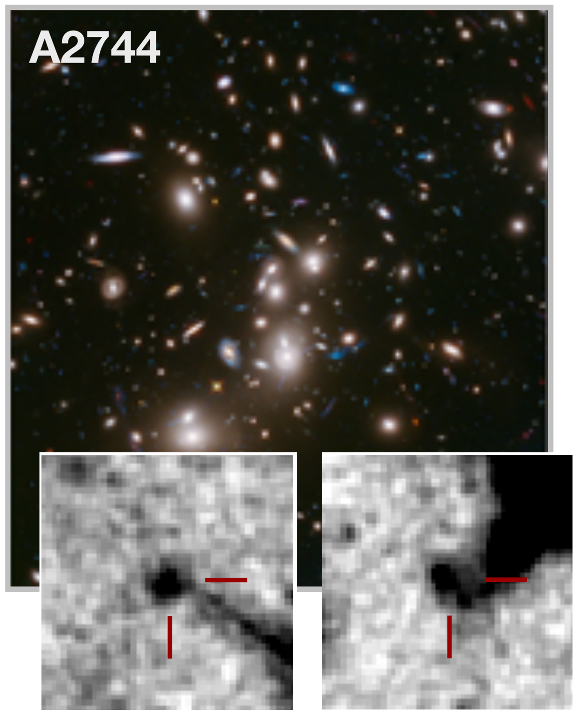
Oesch+14

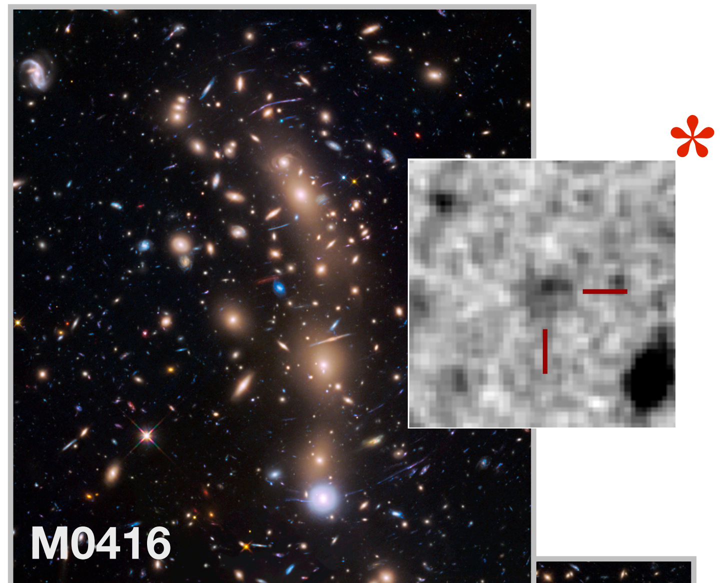


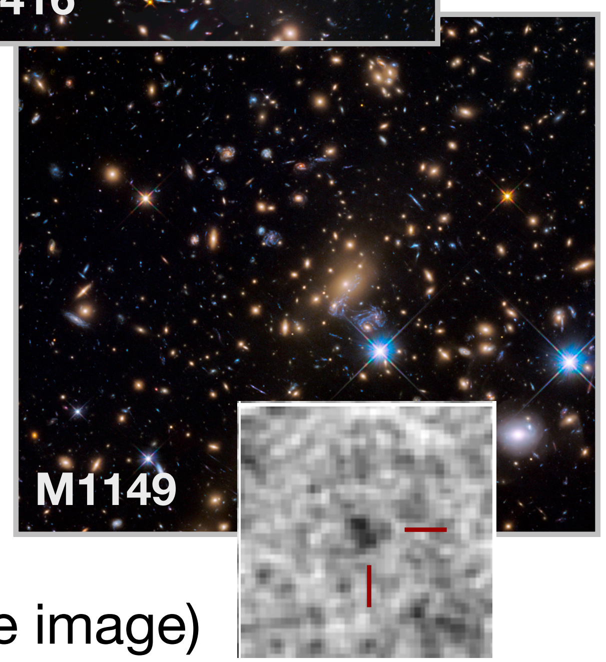
Combined HST Dataset for z~10 Search - HFF

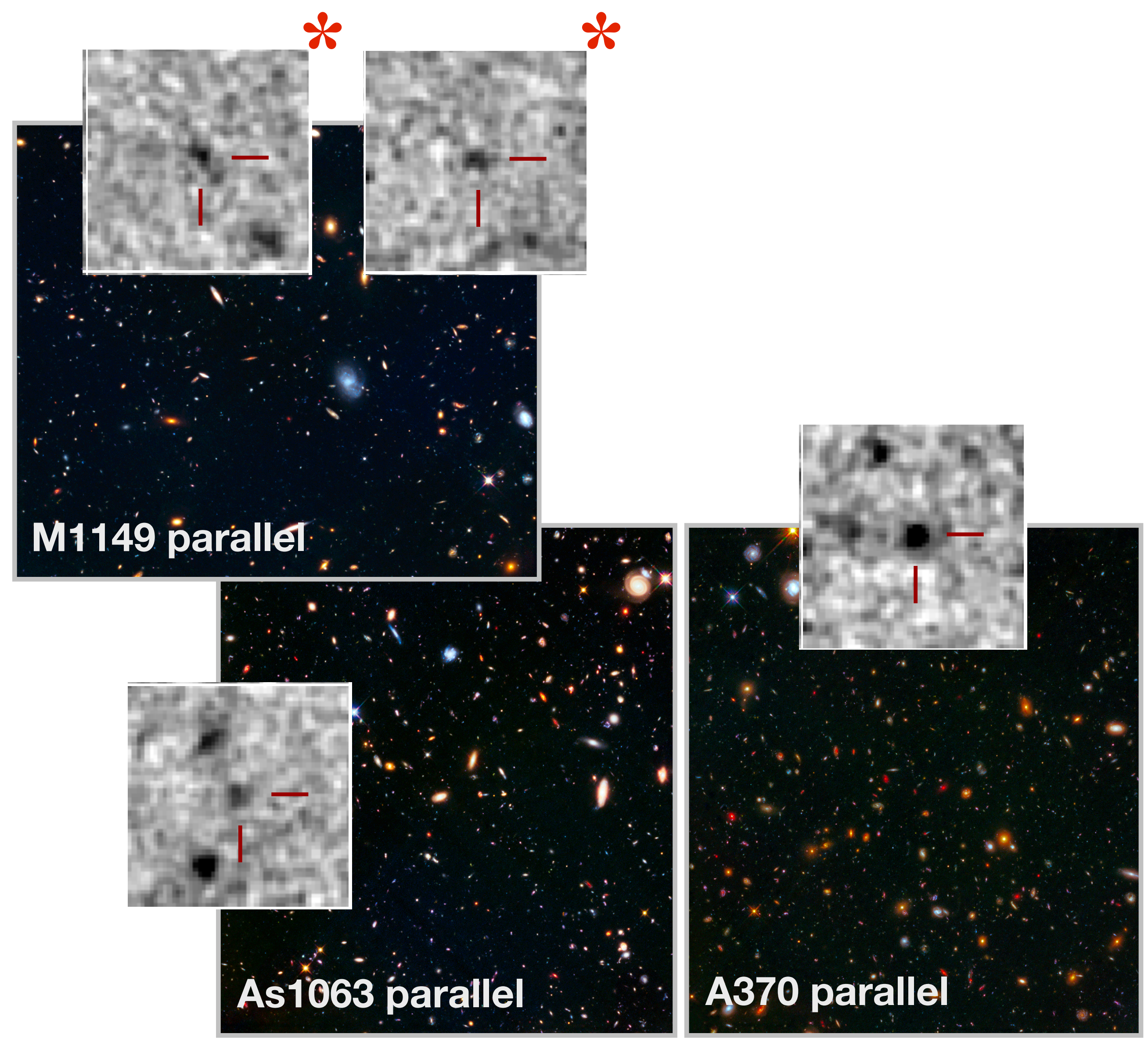
Oesch+17, in prep

Preliminary









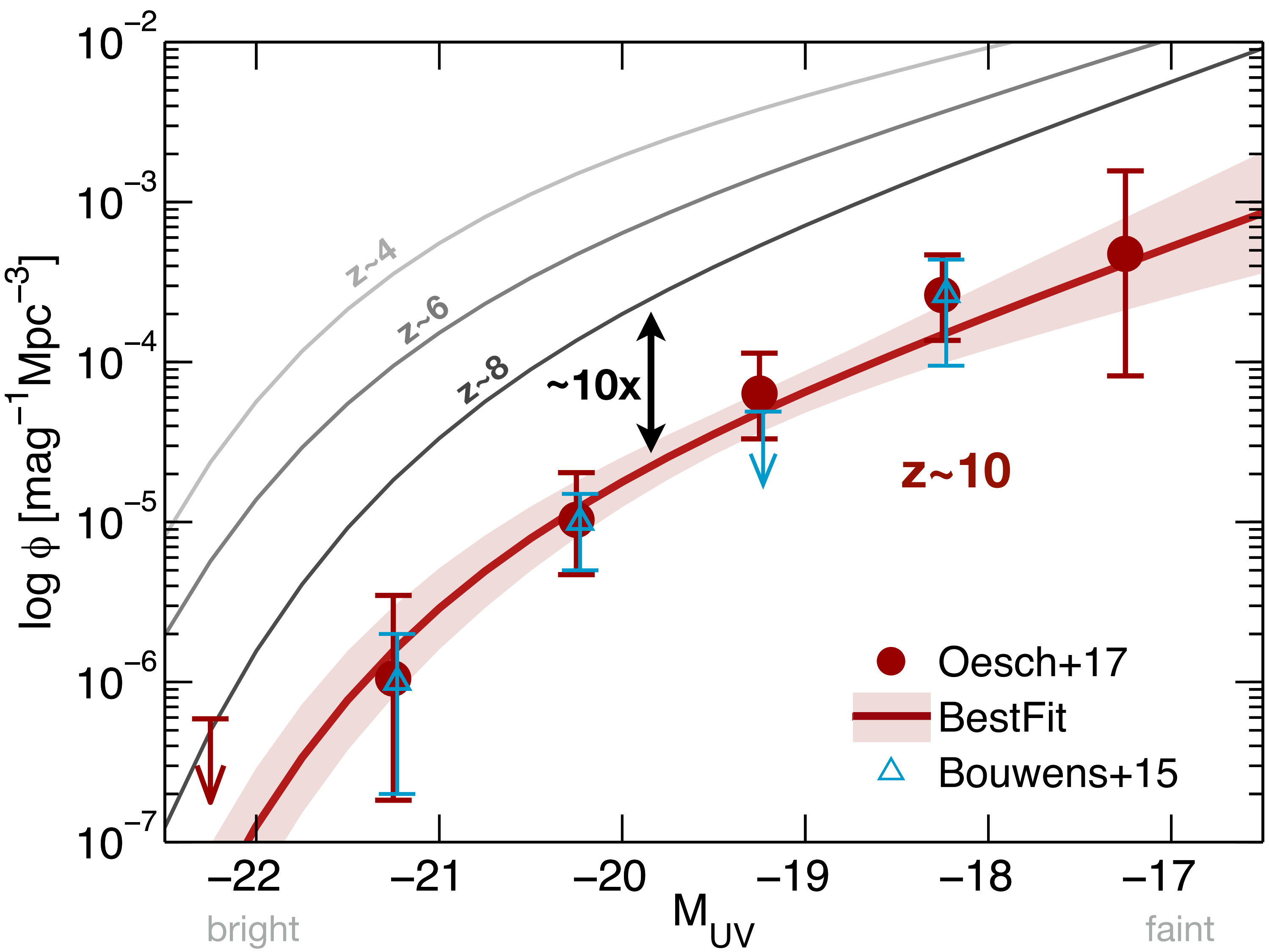
HFF z~10 candidates:

- **4** in clusters (one double image)
- **4** in parallel fields

➔ All prime HST fields combined:
at most 13 z~10 galaxy candidates

***Still under investigation: potential contaminants**

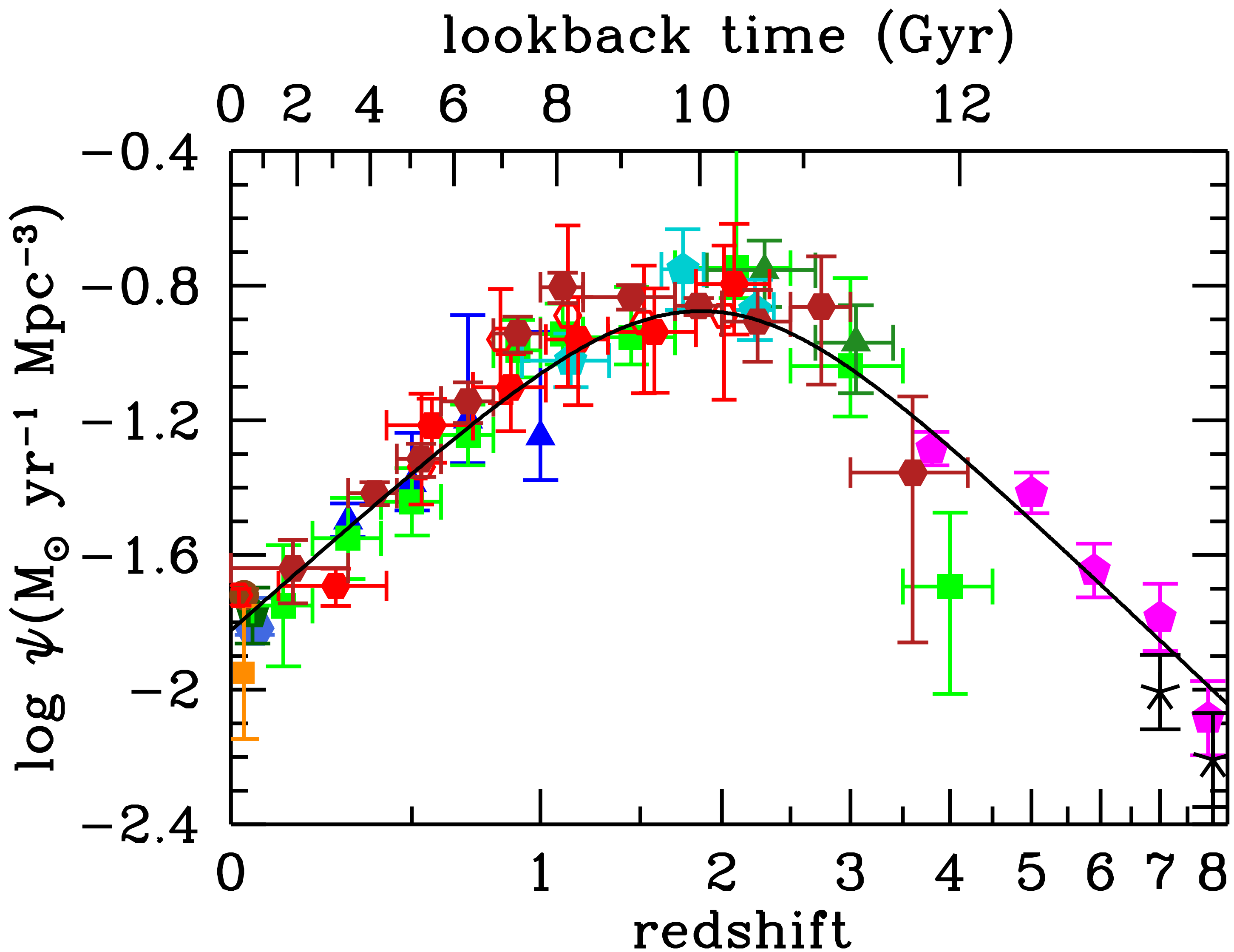
z~10 LF from Combined HST Fields



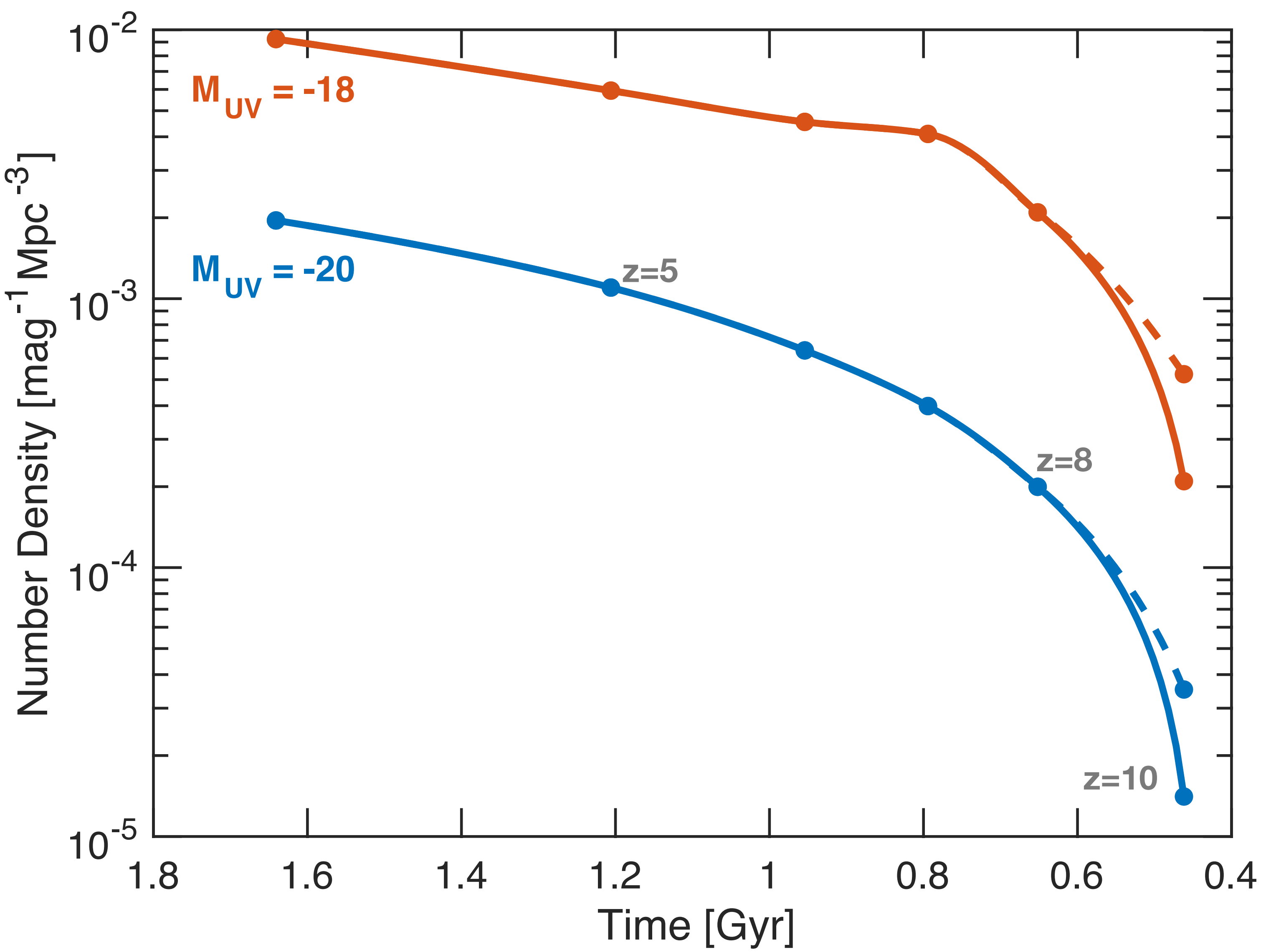
Including HFF, now have a reliable estimate of the UV LF at z~10

Best fit LF: almost exactly density evolution from z~8 LF by 10x

Evolution of the SFRD to z>8



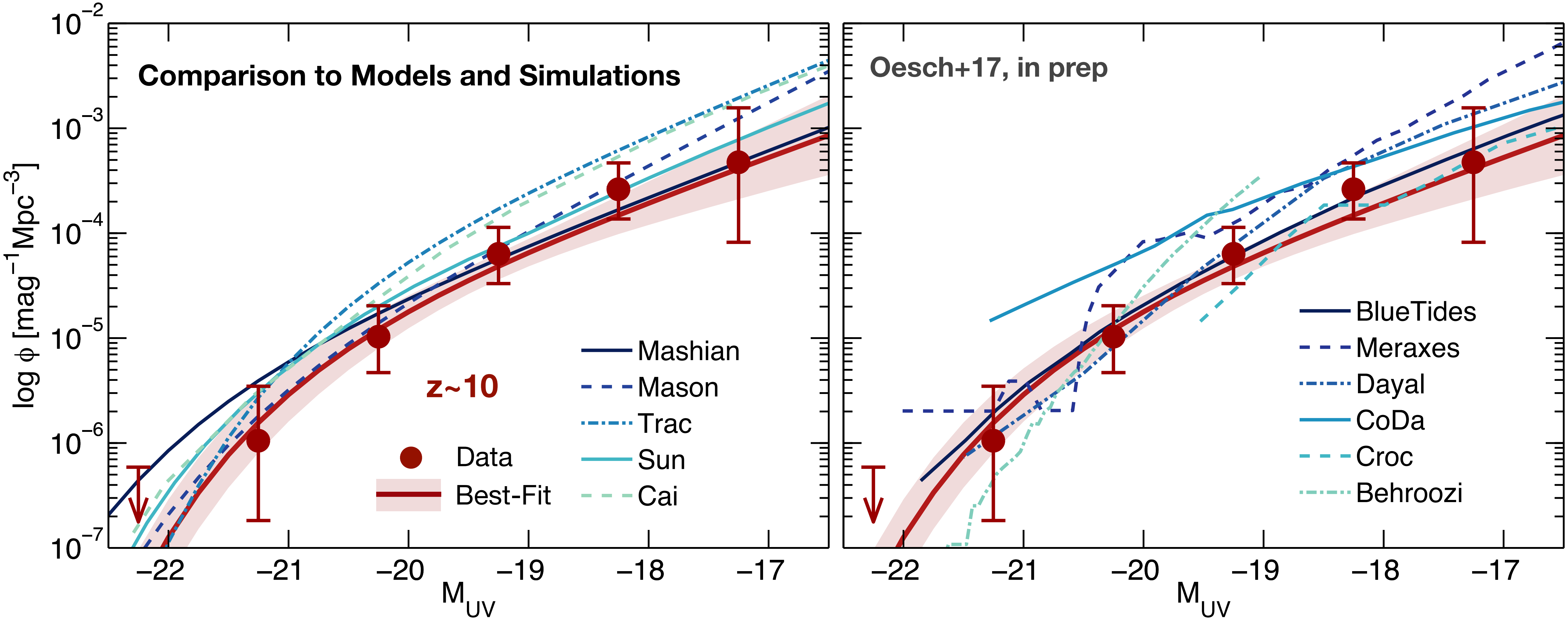
Build-up of High-z Galaxies



Galaxies are building up extremely rapidly across z~8 to z~4

With HST, we are already approaching cosmic dawn

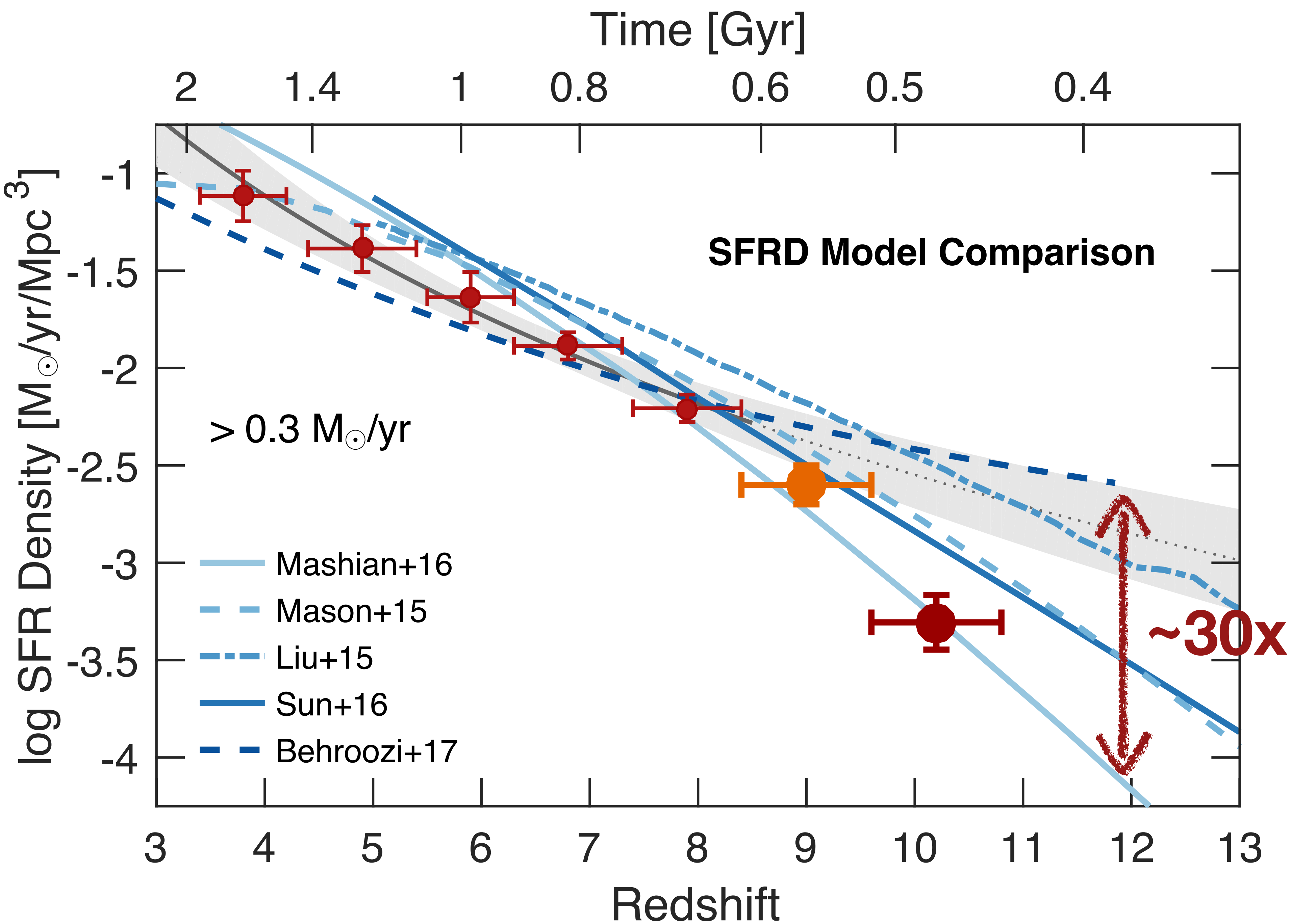
UV LF Model Comparison



Can now compare to lots of simulated UV LFs.

Observed UV LF at the low end of what is predicted by models.

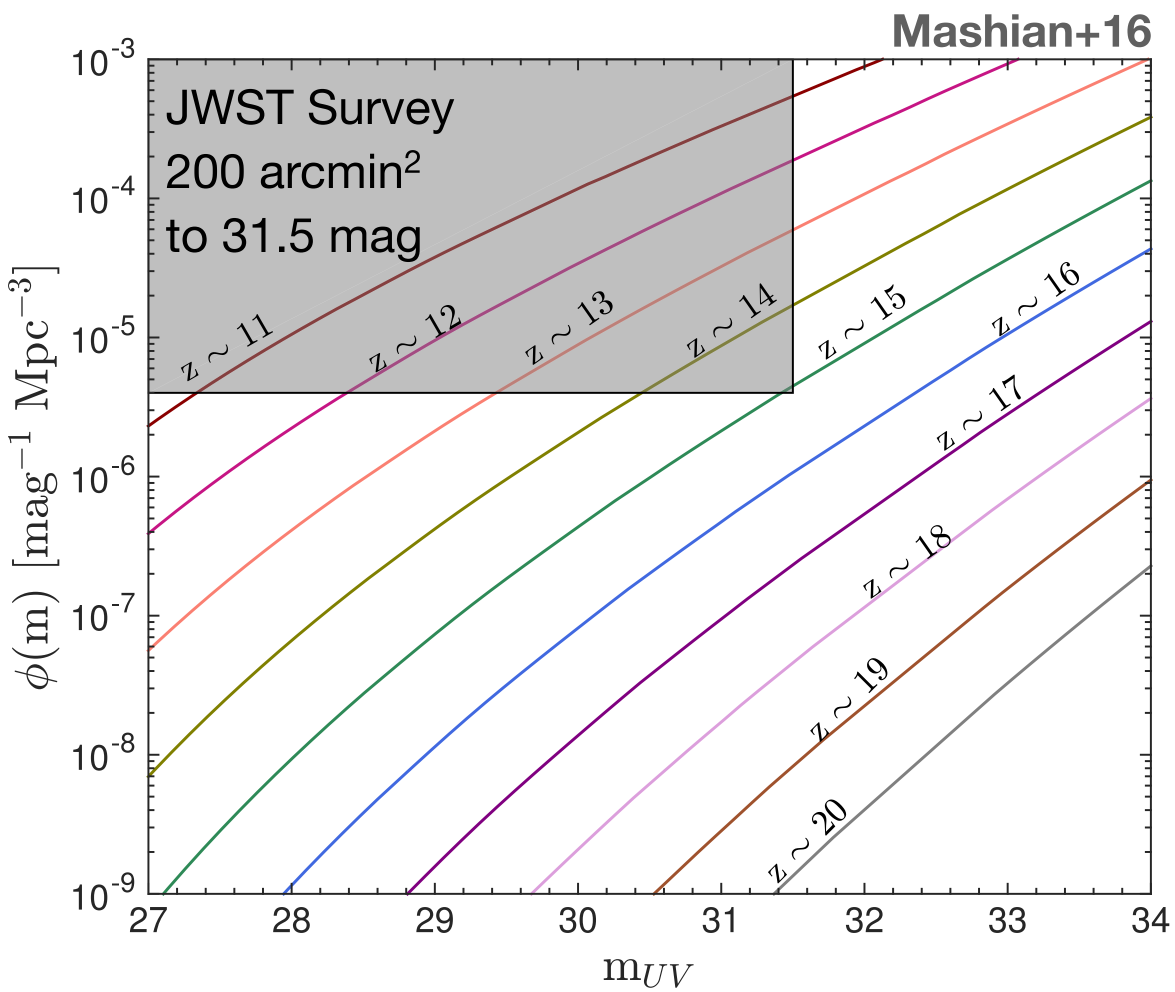
Model SFRD at z>8

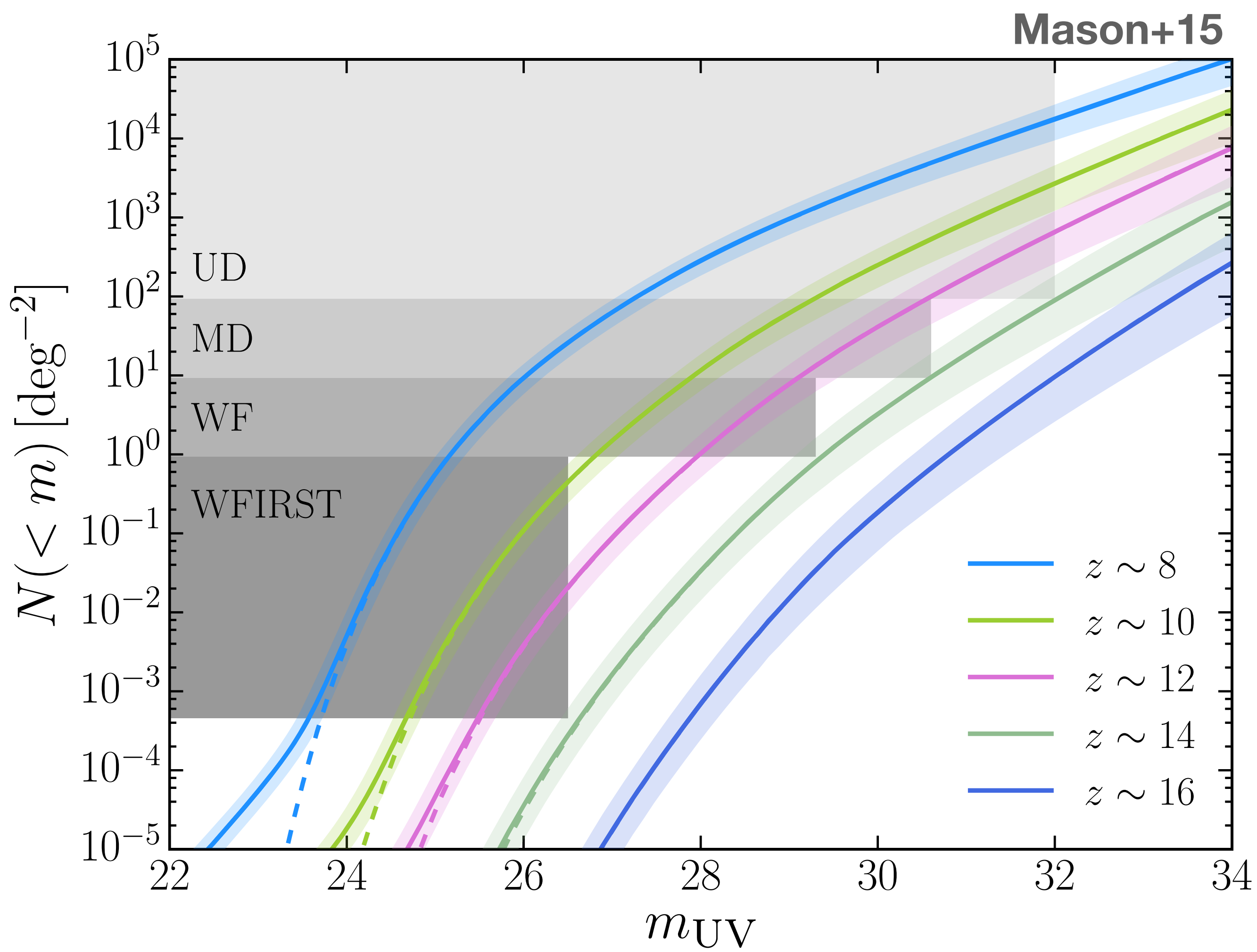


Models predict similarly rapid evolution, but most higher SFRD at z~10 than observed.

see also: Zheng+12, Coe+13, Bouwens+13/15, Ellis+13, McLure+13, Ishigaki+14

Implications for JWST Surveys

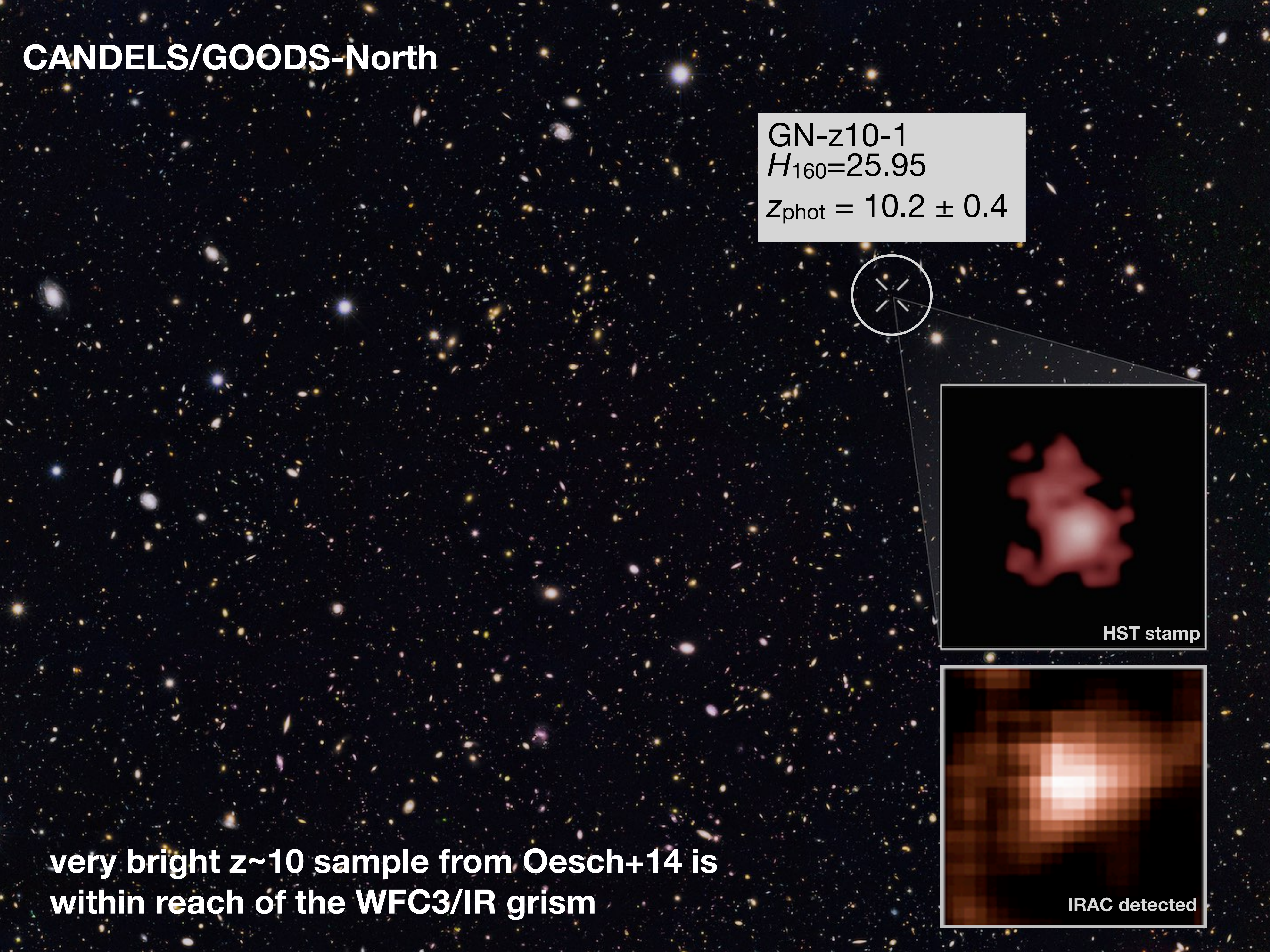




Most models that fit SFRD evolution at z>8 predict that deep JWST observations will reach to z~15 only.

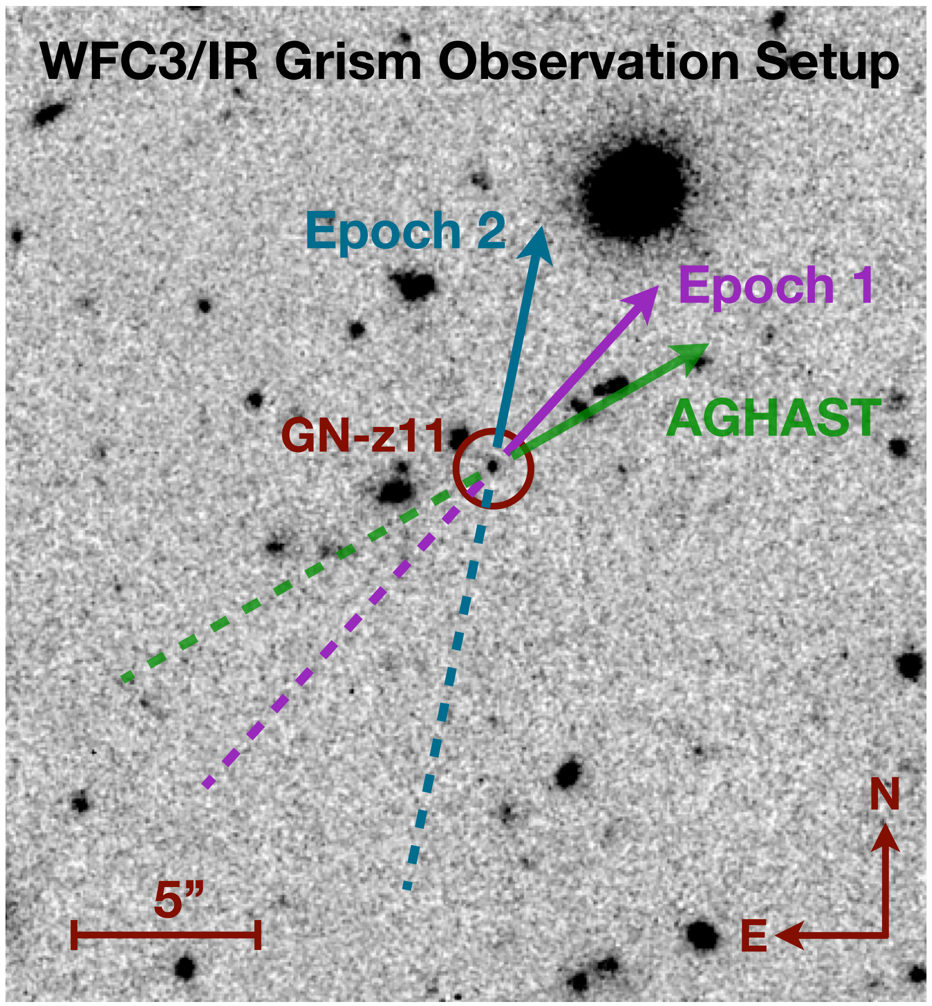
see also, e.g., Sun+16, Trac+15, Behroozi+14

But are we really finding z>10 galaxies?

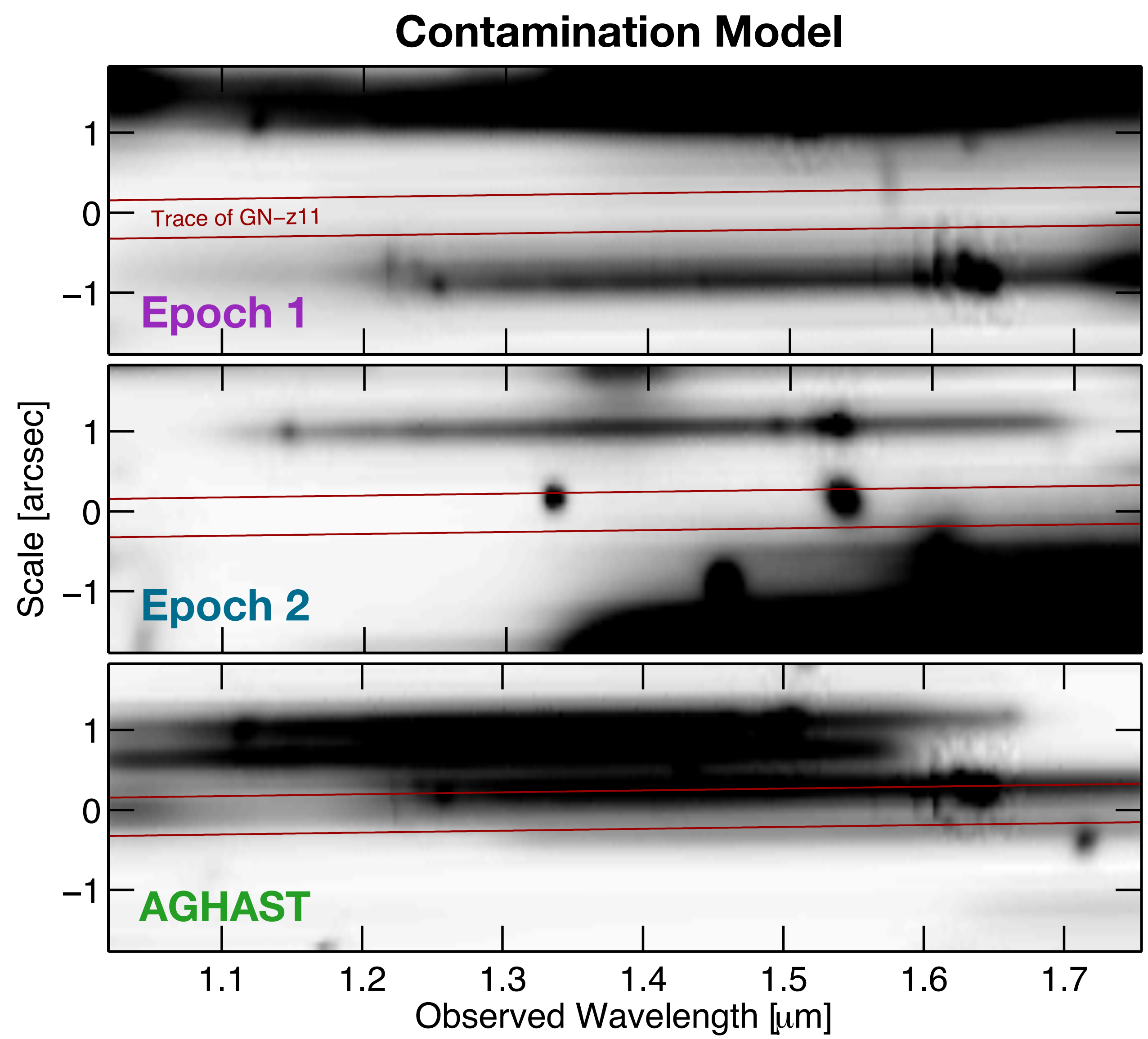

CANDELS/GOODS-North
GN-z10-1
H_{160}=25.95
z_{phot} = 10.2 ± 0.4
HST stamp
IRAC detected
very bright z~10 sample from Oesch+14 is
within reach of the WFC3/IR grism

Neighbor Contamination in Grism Spectra

Even in a blank field, it's difficult to identify orientations with minimal contamination. Previous AGHAST spectra heavily contaminated.

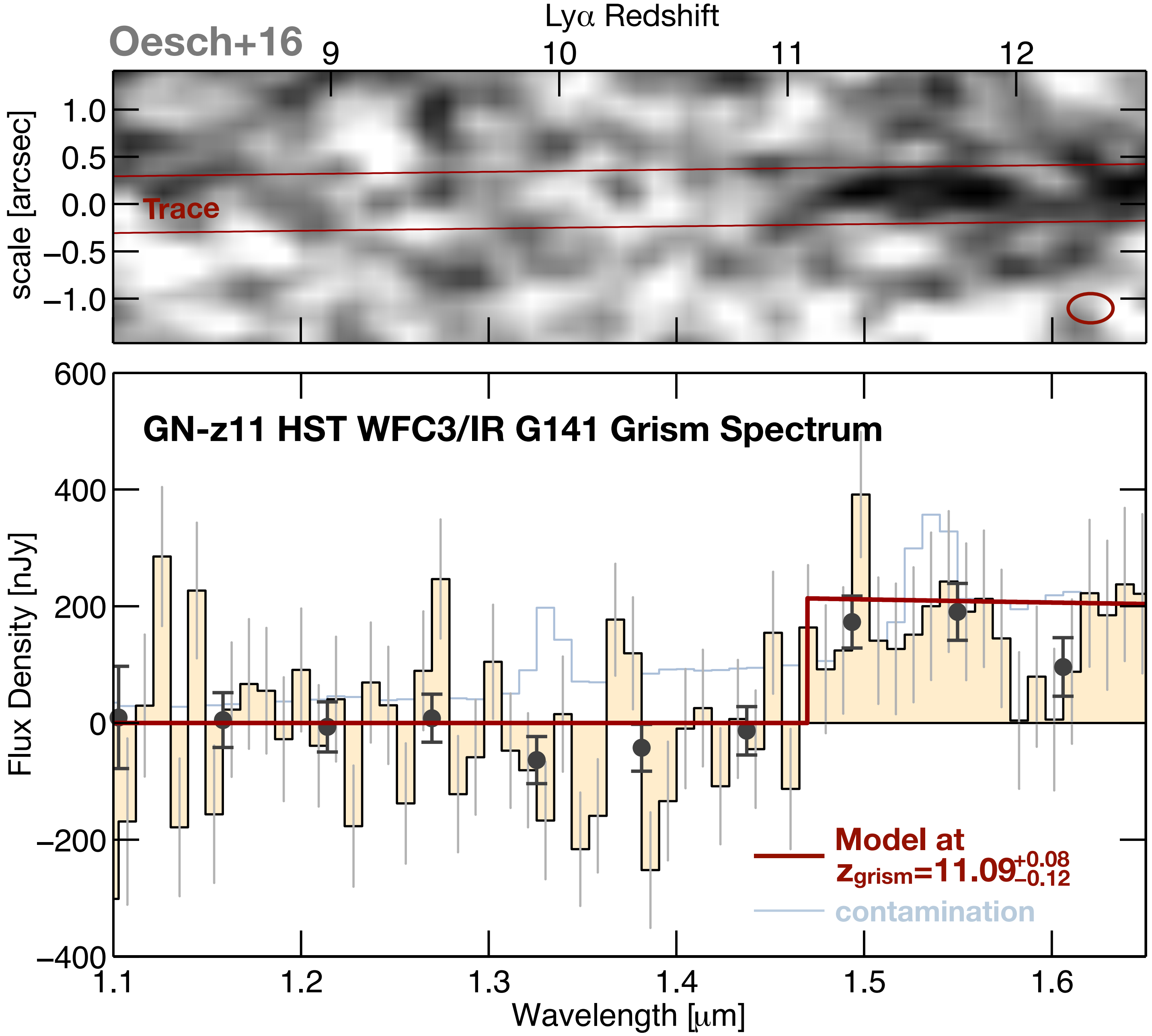


Oesch+16



Perform full 2D contamination modelling and neighbor subtraction (based on 3D-HST grism pipeline; Brammer+12, Momcheva+15)

Lyman Break Detection at z=11



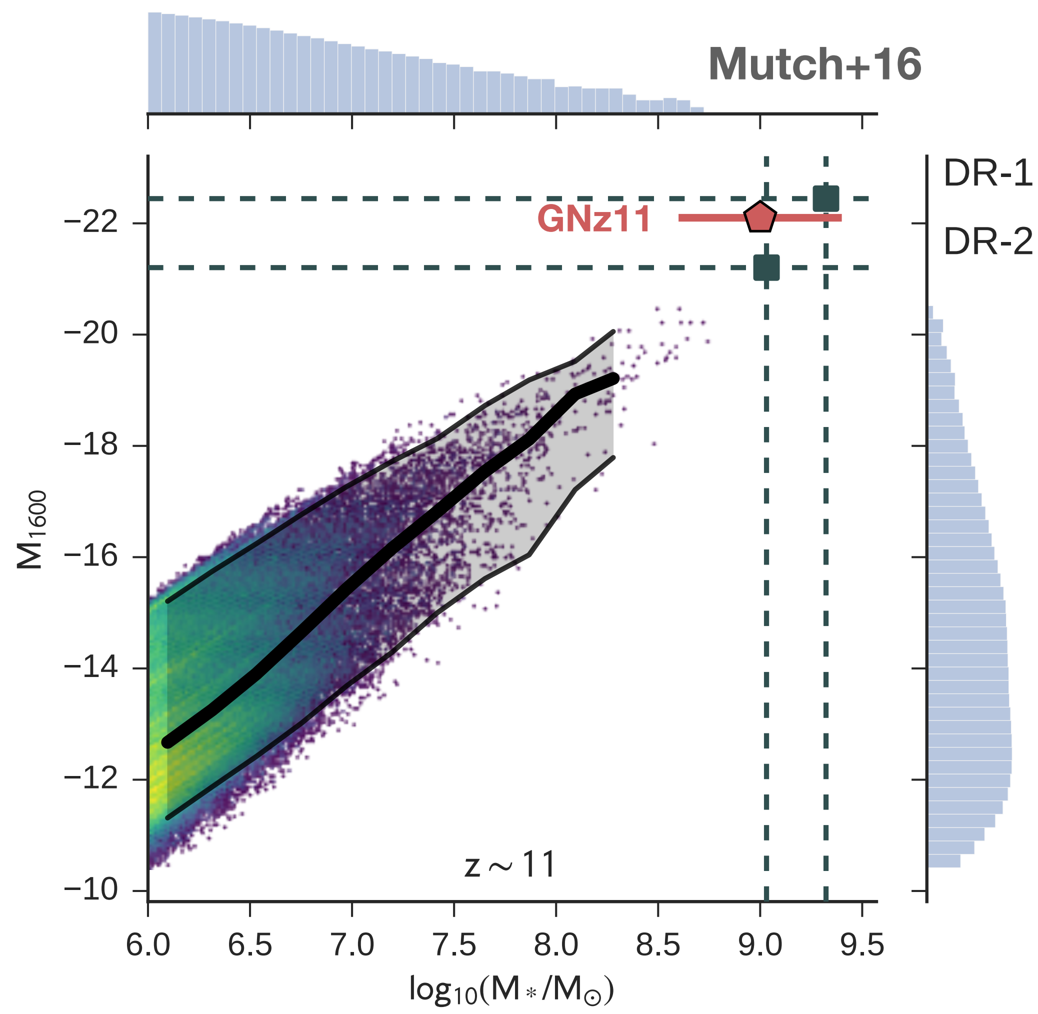
- 12 orbits of HST grism spectra with WFC3/IR
- Detect UV continuum (at 5.5σ) and a break at λ > 1.47 µm
- Rule out potential lower redshift solutions (quiescent galaxy at z~2 or strong emission line source)
- Best-fit redshift: z=11.09+-0.10

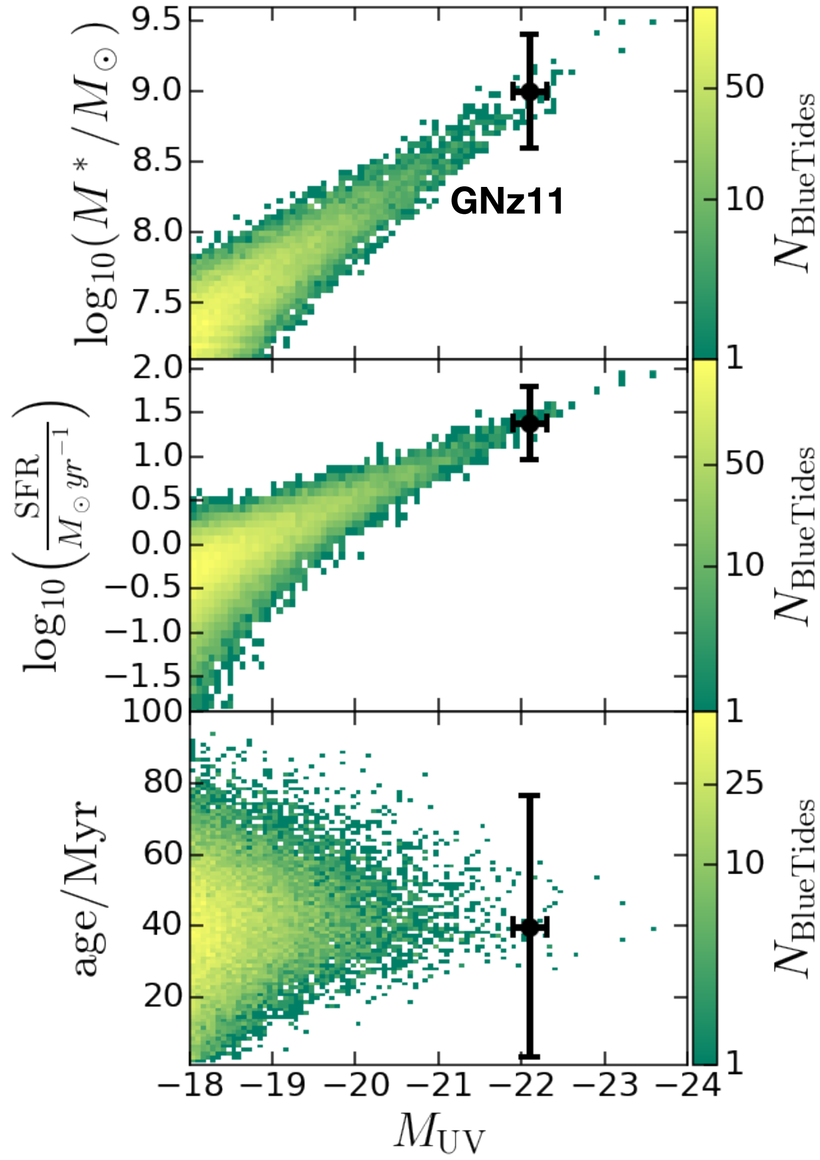
GN-z10-1 → GN-z11

Most distant source ever seen

Build-up of massive galaxies well underway at 400 Myr after Big Bang

Physical Properties of GN-z11 in Line with Models

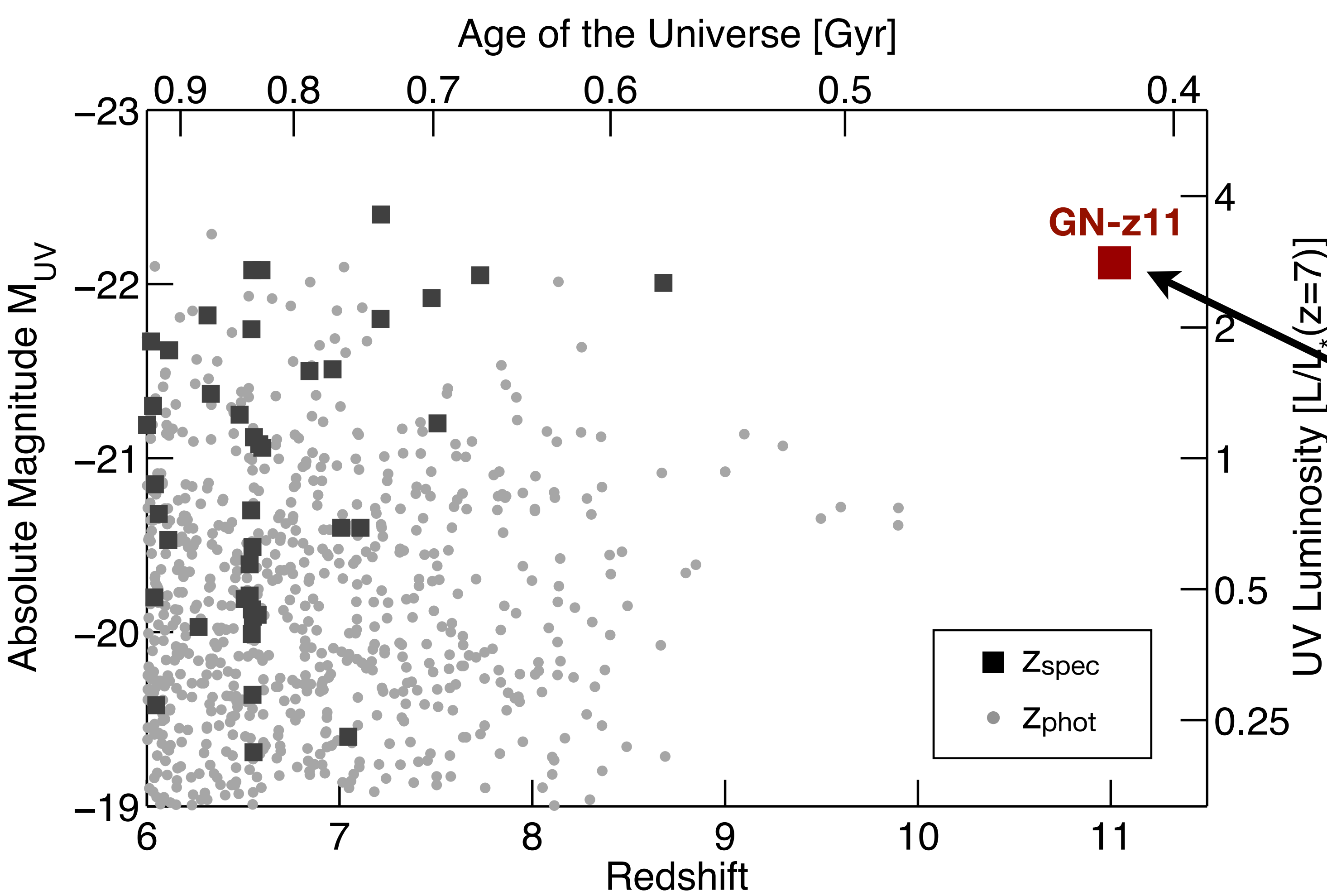




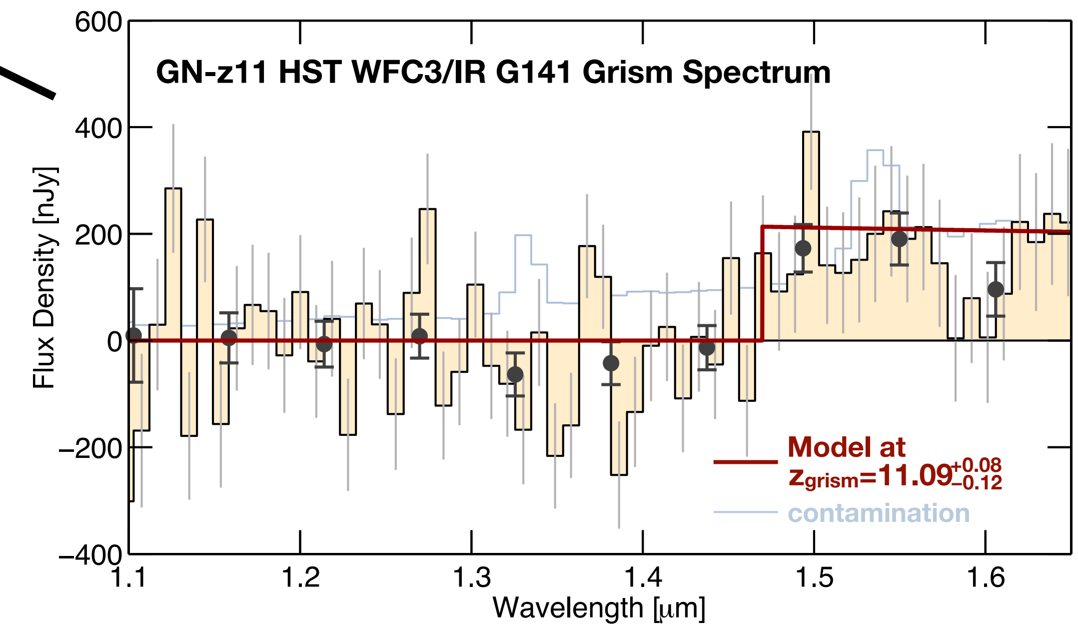
The derived physical properties (SFR, mass, and age) of GN-z11 are in very good agreement with expectations from large-volume simulations

However: did not expect to find such a source in the current HST fields

The Current Spectroscopic Frontier

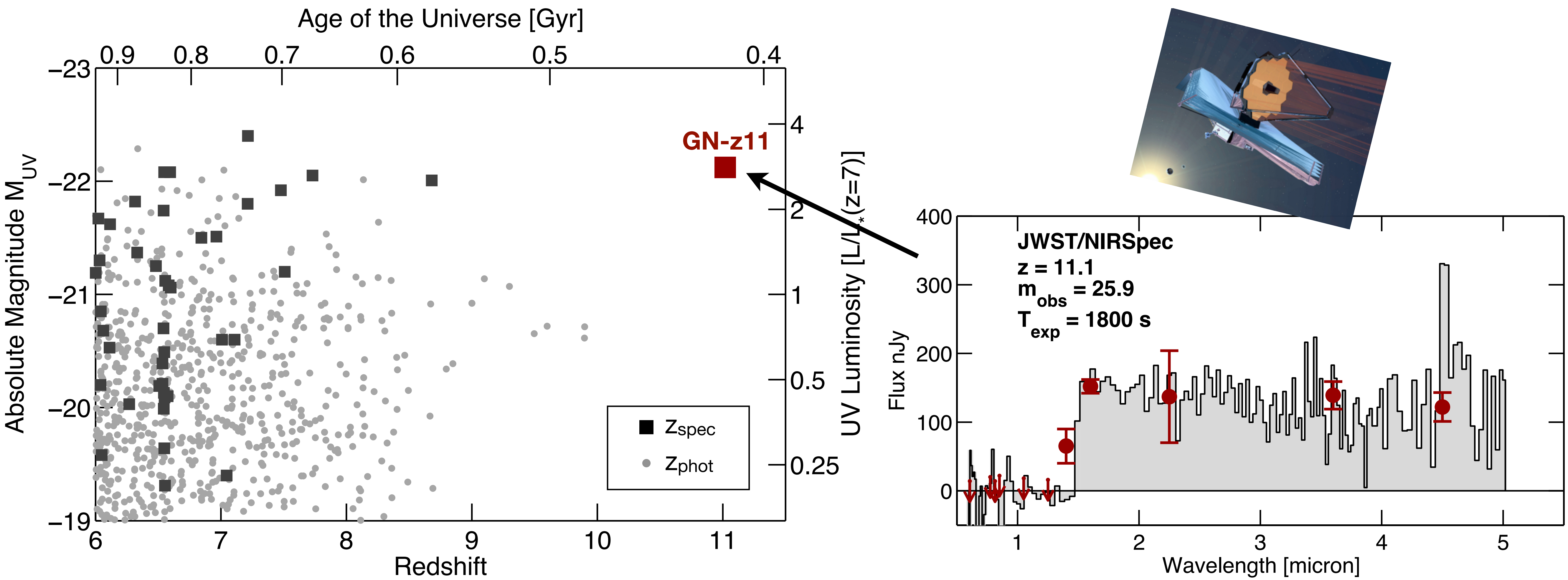


GN-z11 is by far the most distant confirmed source



With surprising discovery of GN-z11,
HST+Spitzer have already **reached into JWST territory**

Moving Forward with JWST NIRSPEC

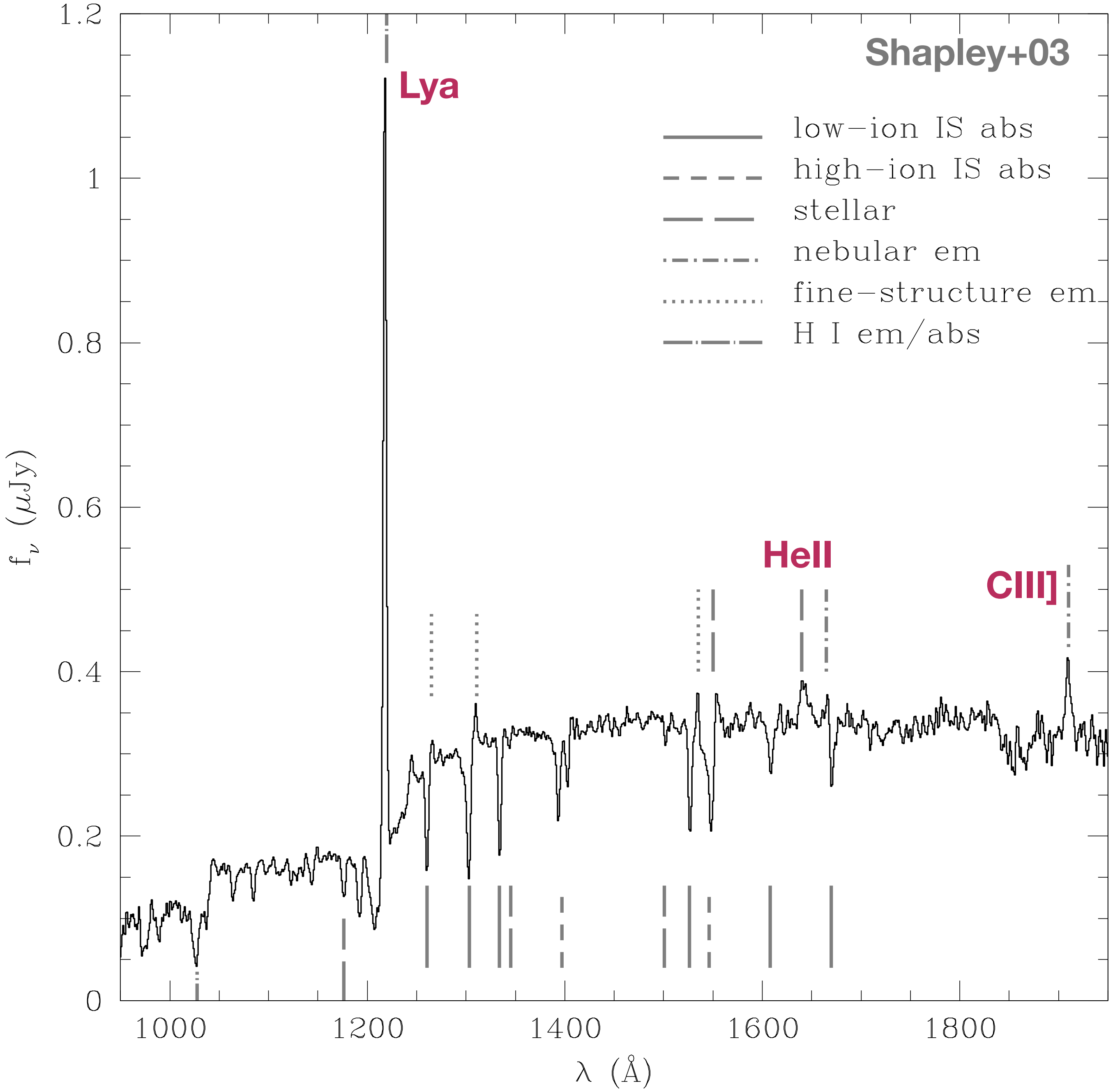


However, JWST spectroscopy will completely **revolutionize** this field!

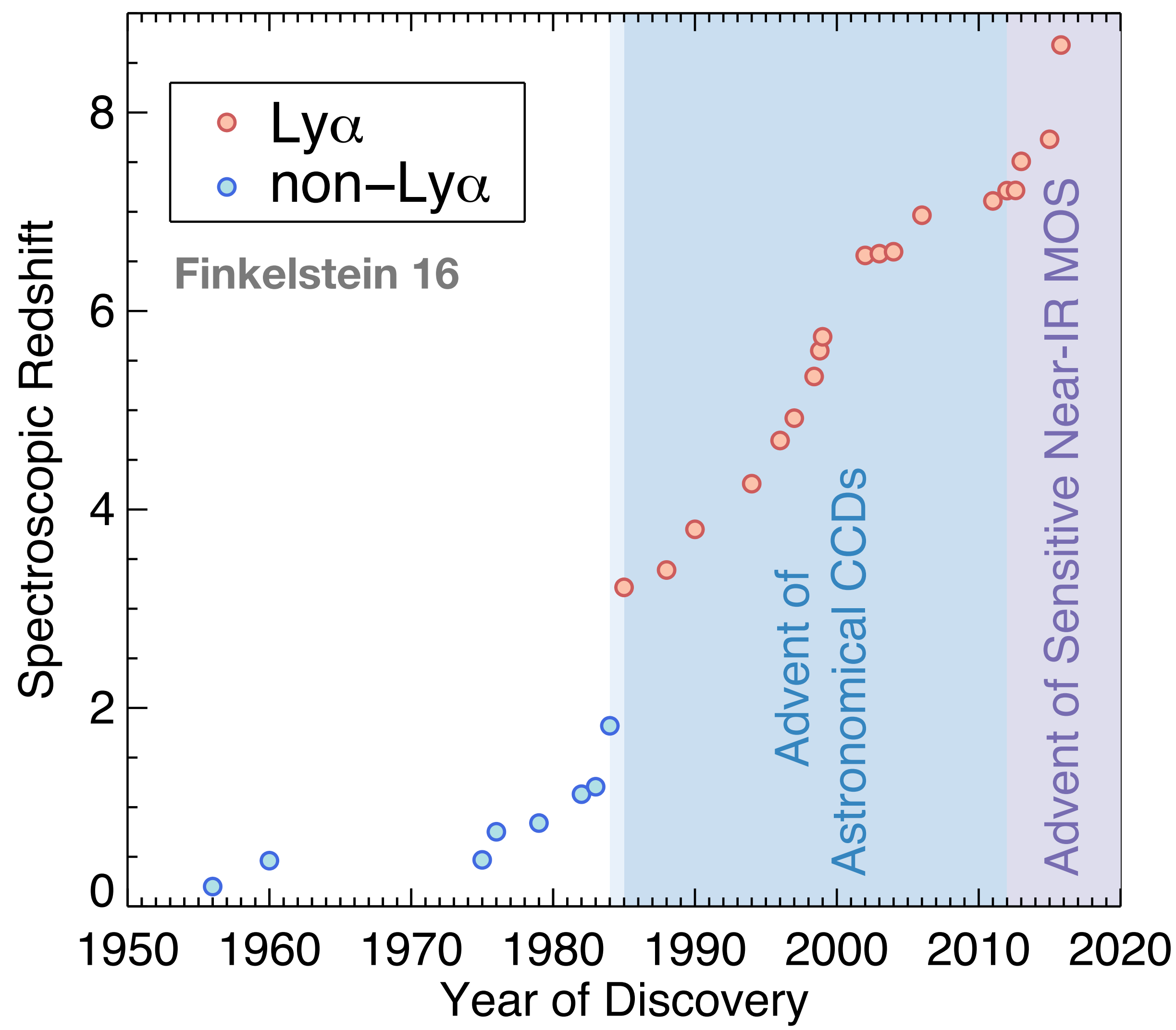
JWST can in principle get spectroscopic redshifts for every single source currently known with HST

What can we expect to see in JWST spectra?

Spectroscopic Features of High-z Galaxies

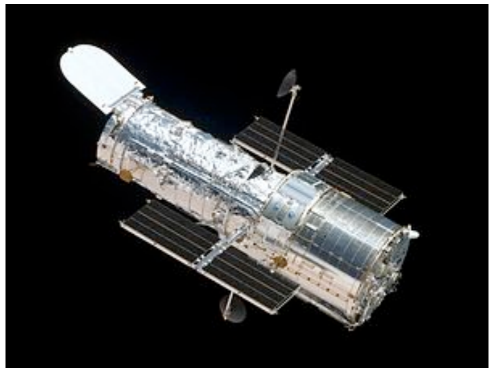


Lyα is the most promising feature of high-redshift spectra

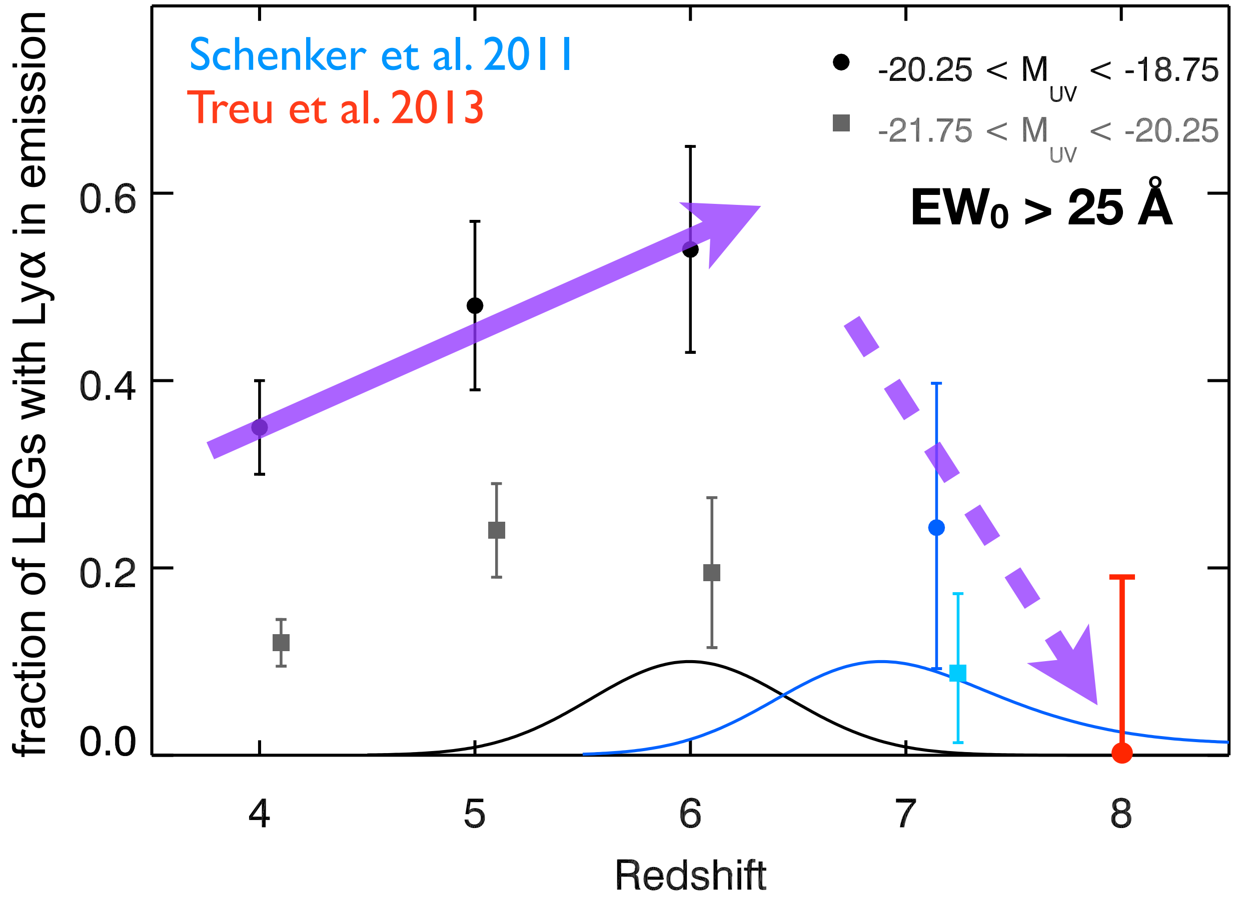


Lyman Alpha in the Reionization Epoch

Spectroscopic confirmation of sources in the reionization epoch has proven very difficult, even with new efficient NIR spectrographs.



+

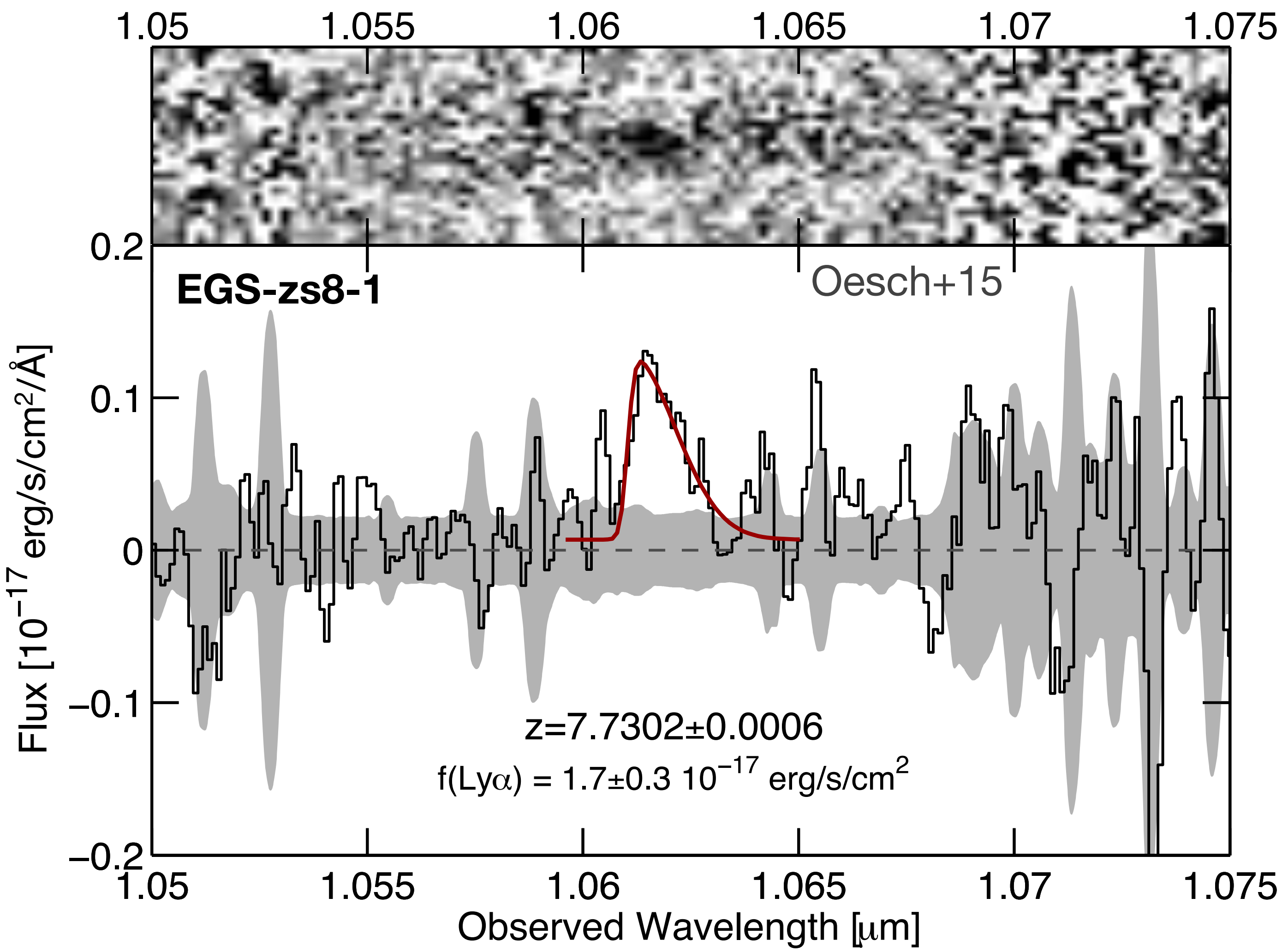


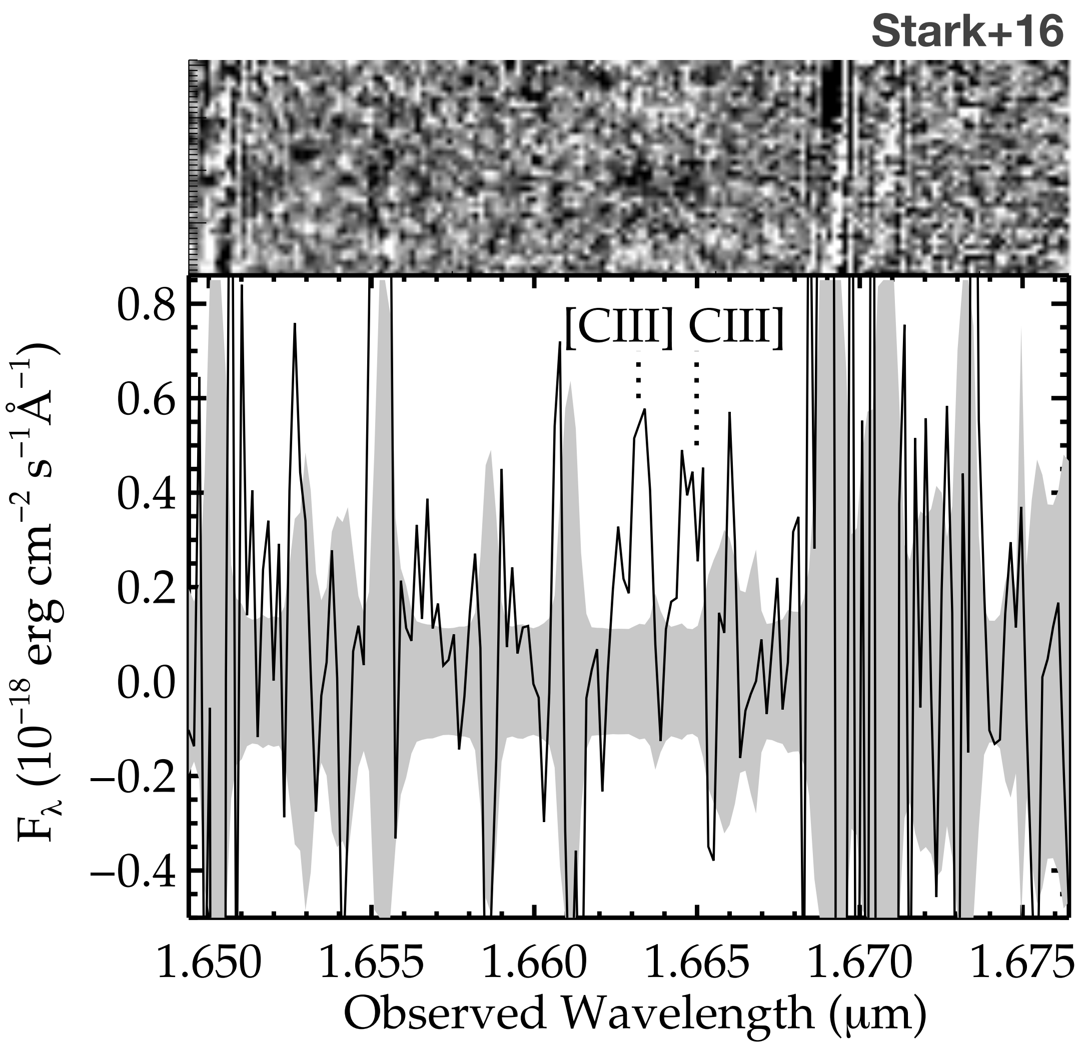
Fraction of Lyα line emitters drops across z=6.5 to z=7:
imprint of cosmic reionization

Bright z~8 Galaxies with Spectroscopic Redshifts

100% spectroscopic success rate via Lyα detection in luminous galaxies

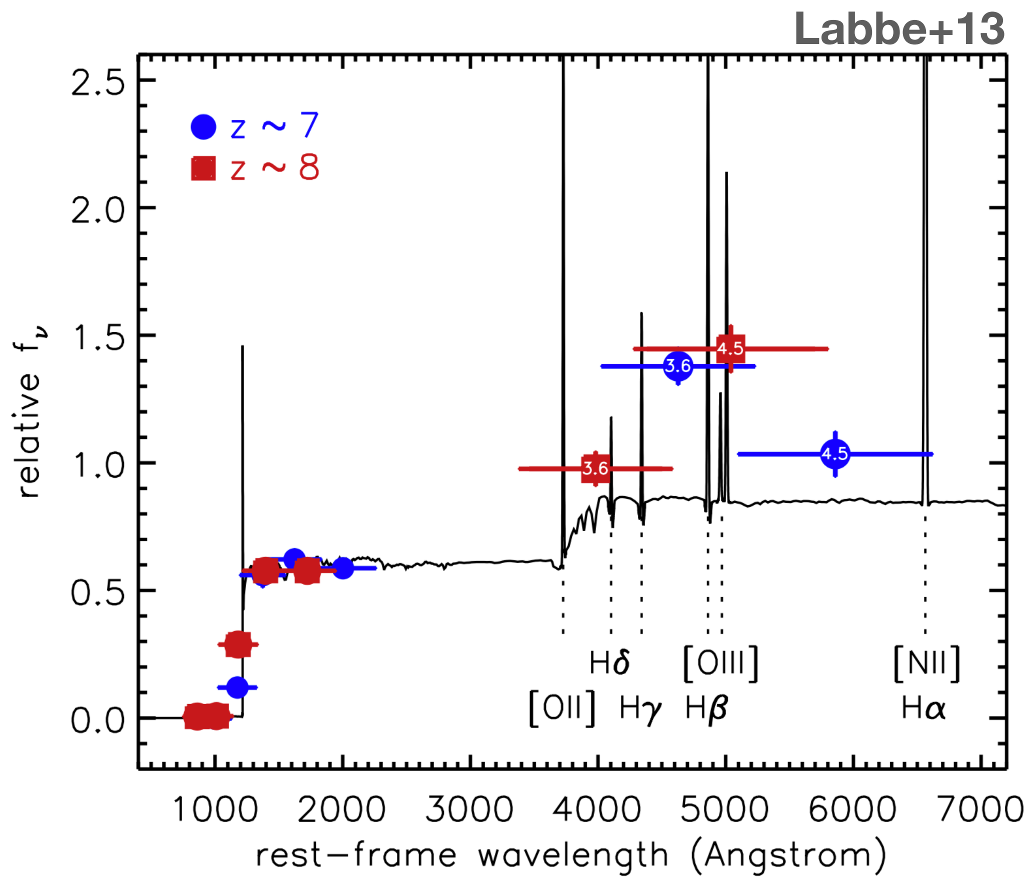
see: Roberts-Borsani+15 (z=7.48), Zitrin+15 (z=8.68), Stark+16 (z=7.15)

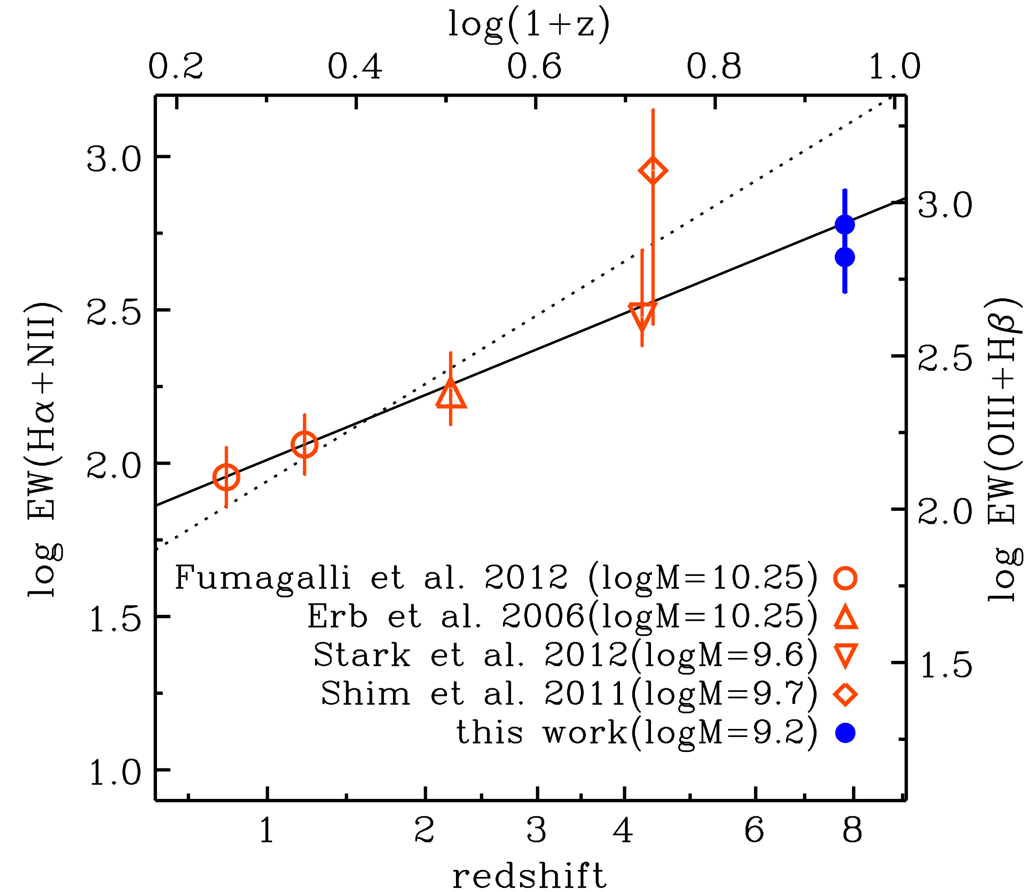




Very high EW CIII] emission (W_0=22+-2 Å),
implies strong radiation field and low metallicity

Extreme Rest-Frame Optical Emission Lines





see also: Schaerer&deBarros09, deBarros+14, Shim+11, Smit+14, Faisst+16

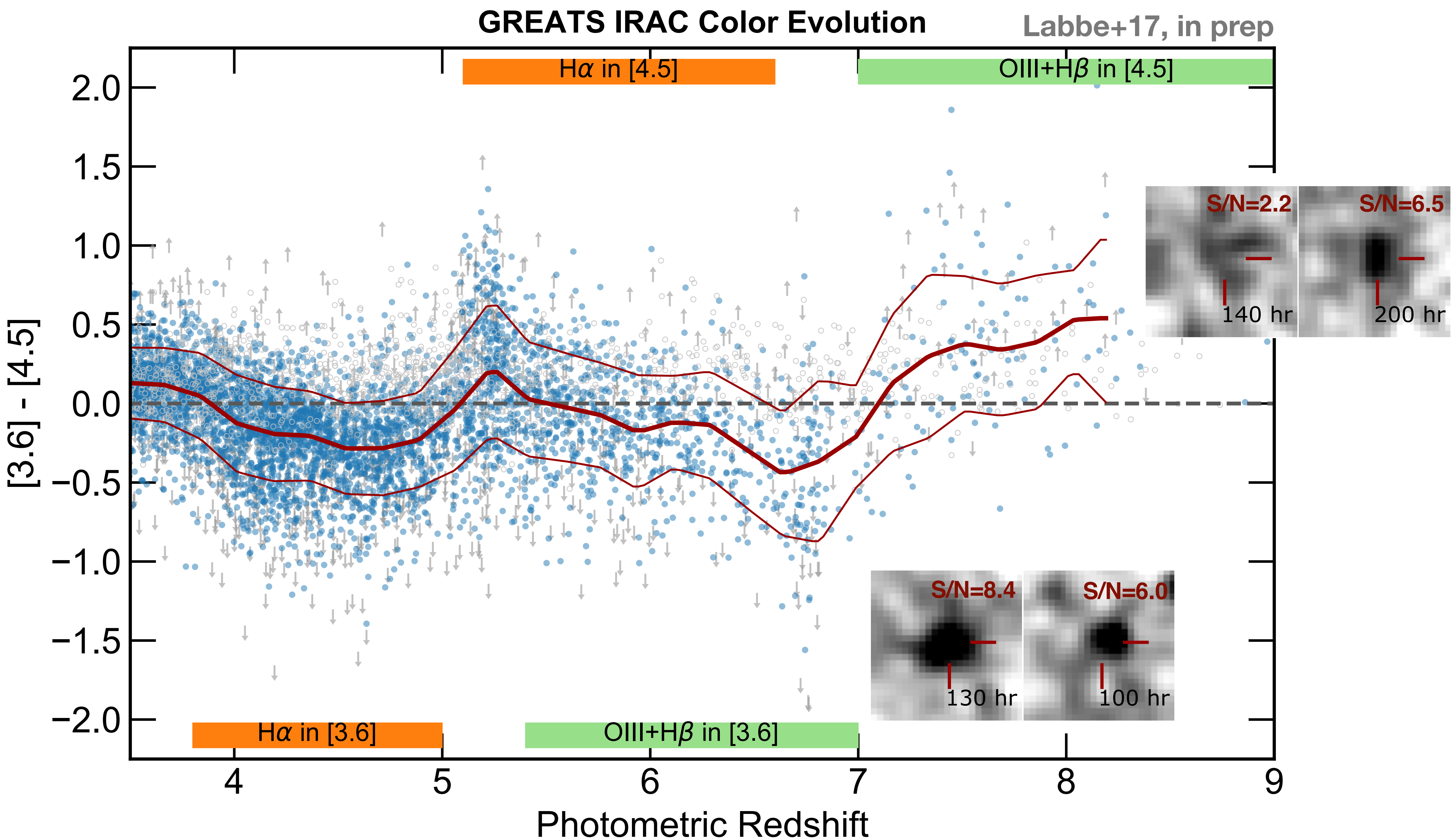
Spitzer/IRAC revealed: z~7-8 galaxies have extreme OIII+Hβ line emission

Rest-frame equivalent widths on **average** are 700 Å!

(<0.1% of local galaxies show such strong lines)

How can such strong lines be produced in the average galaxy?

Imprint of Strong Rest-Frame Optical Lines on IRAC Colors



Extreme colors require extreme conditions. Bursty star-formation!?

de Barros+17, in prep.

see also: Schaerer&deBarros09, deBarros+14, Shim+11, Smit+14, Faisst+16

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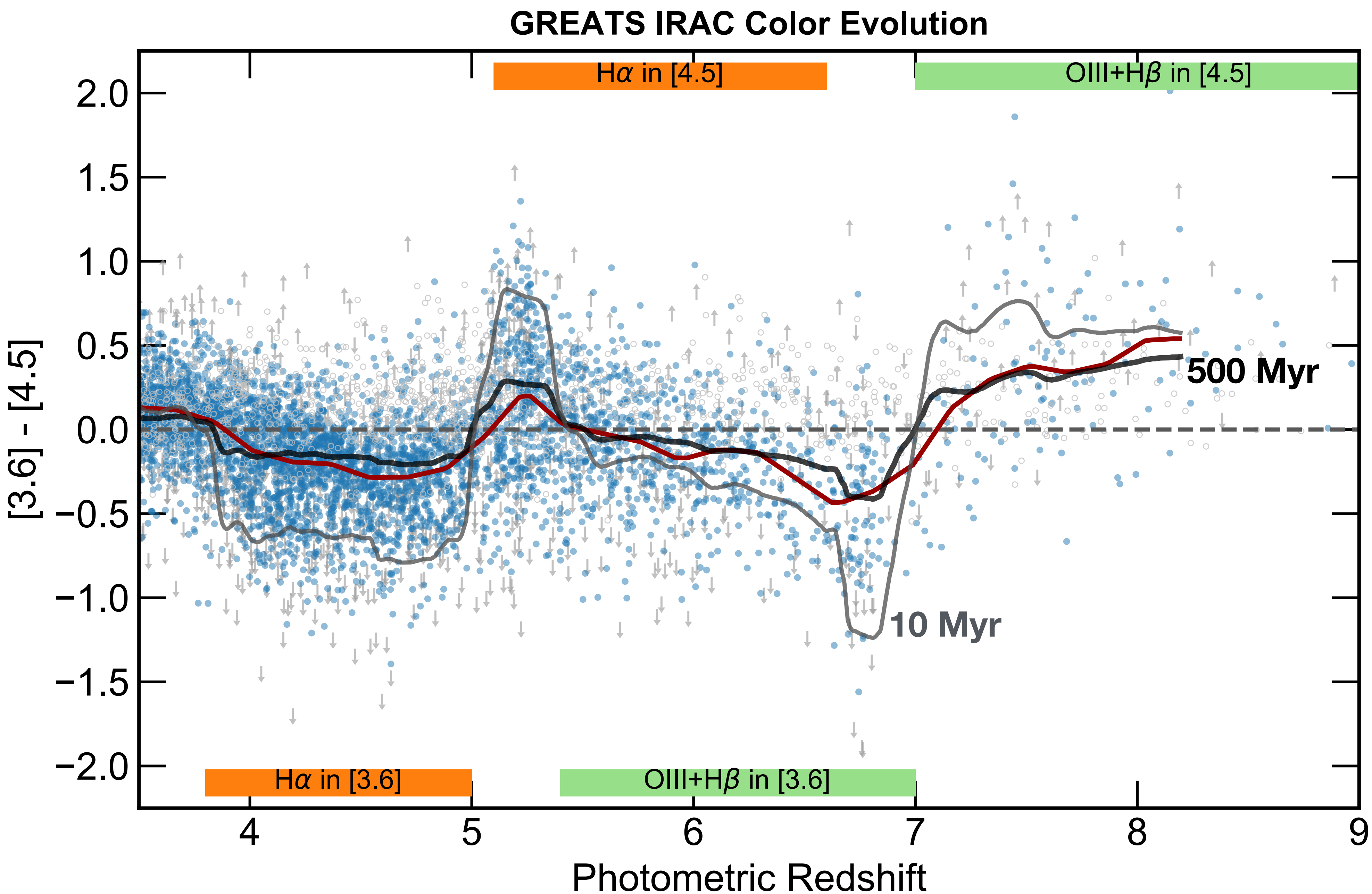

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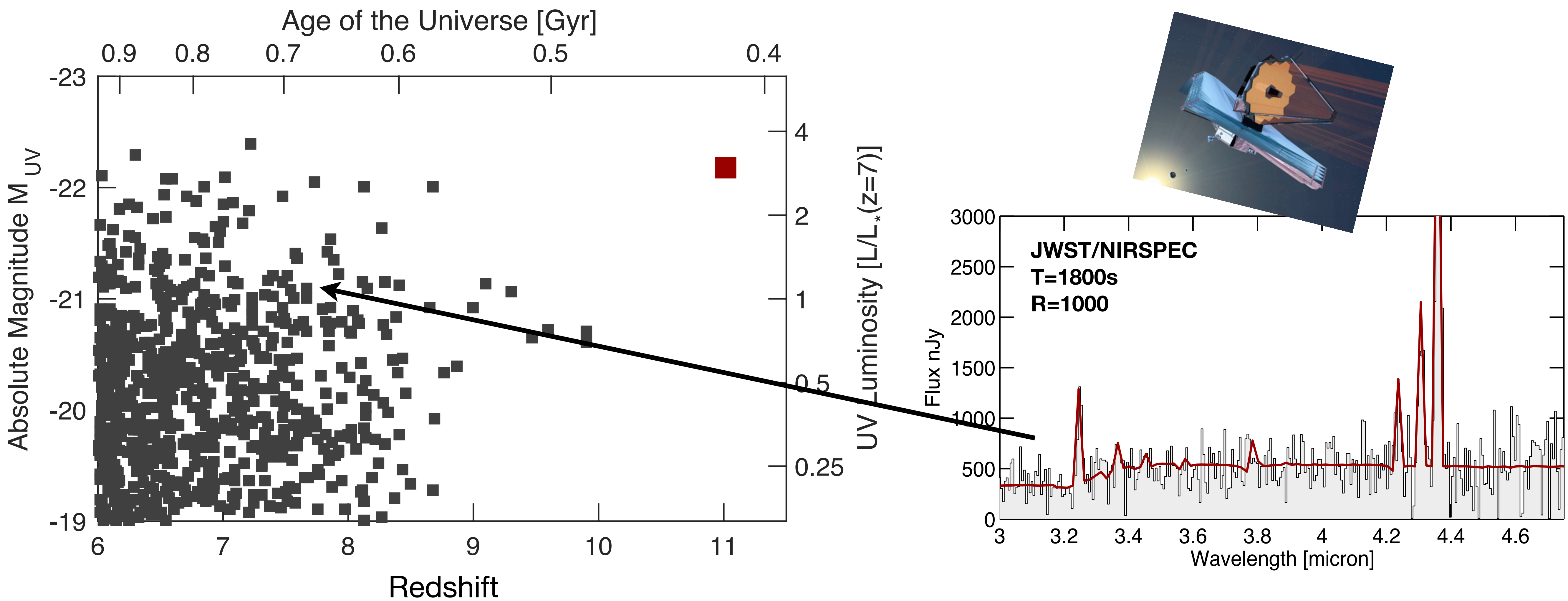

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Summary

- We have made **great progress** with HST (and Spitzer/IRAC) to search and characterize galaxies over **97% of cosmic history**
- The **cosmic SFRD** declines rapidly at **z>8** by a factor **~10x** in only 170 Myr, consistent with fast evolution of DM halo mass function
- Discovery of **GN-z11 in current search area is surprising** according to models: **Need larger area surveys** to confirm the number densities of bright galaxies at z>10. Needs to be done now with HST, likely won't be done with JWST!
- **JWST** will provide absolutely **revolutionary spectroscopy**, rest-frame optical lines and redshifts for all HST selected sources. We will finally get a handle on the **physics** of early galaxy build up