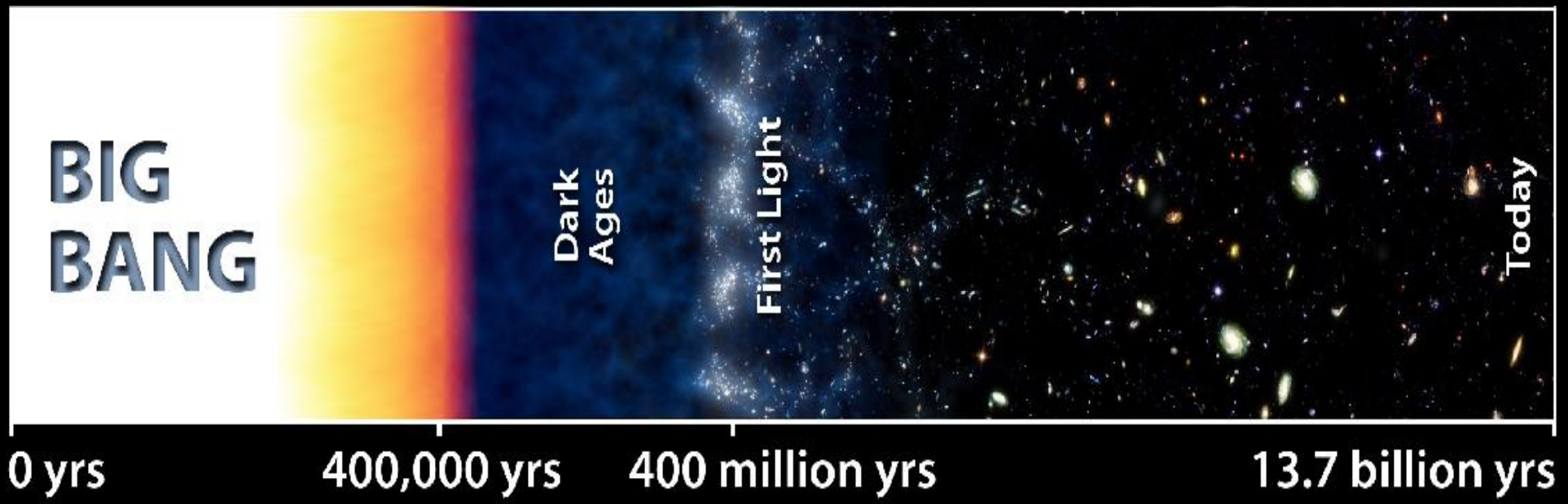
Galaxies in the first billion years



Jim Dunlop
Institute for Astronomy, University of Edinburgh

+
Ross McLure, Michele Cirasuolo, Brant Robertson, Richard Ellis

Did the first galaxies reionize the Universe?

Want to establish 3 things:

1. Number density of galaxies
   = Luminosity function

2. Number of ionizing photons produced per galaxy
   = stellar populations

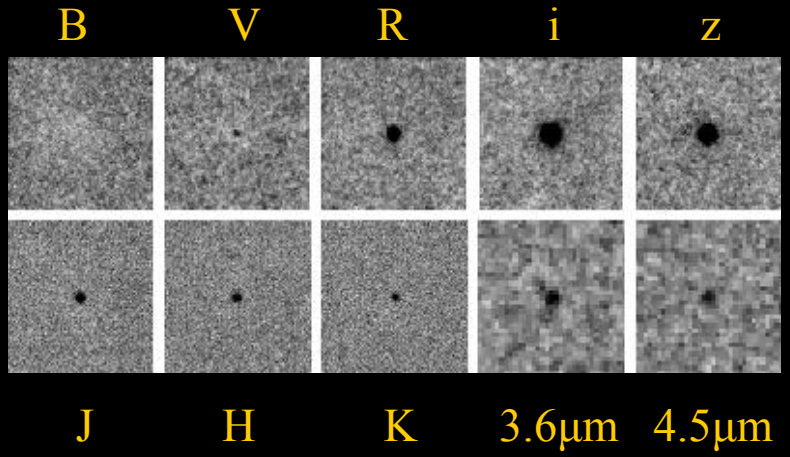
3. How many of these photons get out of galaxy to ionize the IGM
   = escape fraction

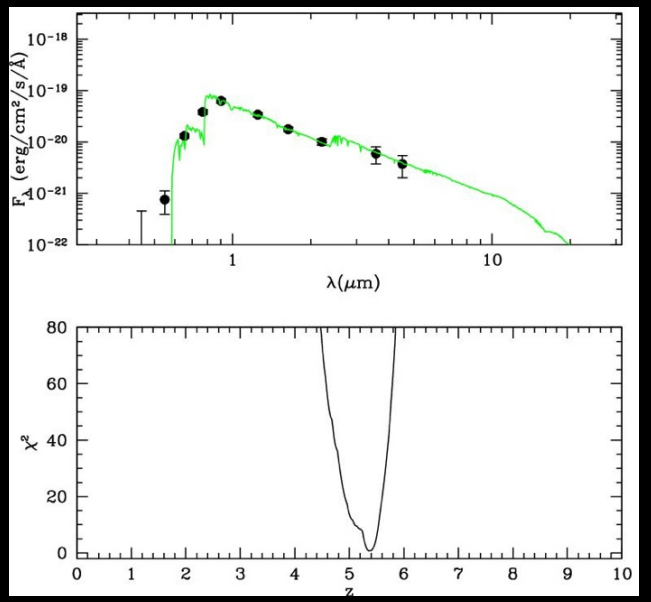
Our approach:

- No colour cuts – fit all photometry and use redshift probability distribution
- Combine ground-based and HST surveys for maximum dynamic range

High redshift galaxies: 4.5<z<6.5

stacked data for ~750 5<z<6 LBGs

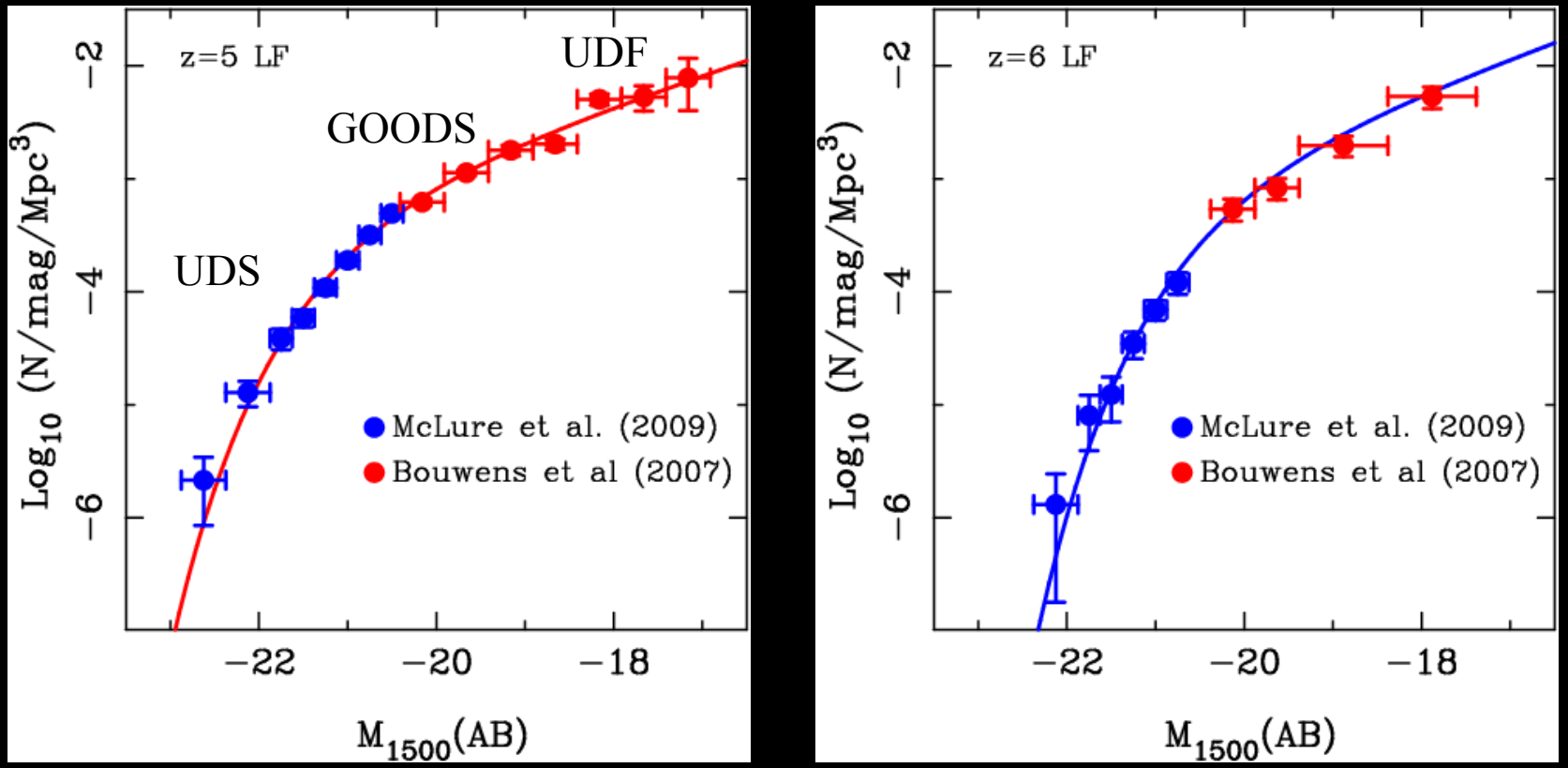




- $z_{phot} = 5.43$
- Av = 0.0
- Age = 400 Myr
- Mass = $10^{10.0}\ M_\odot$

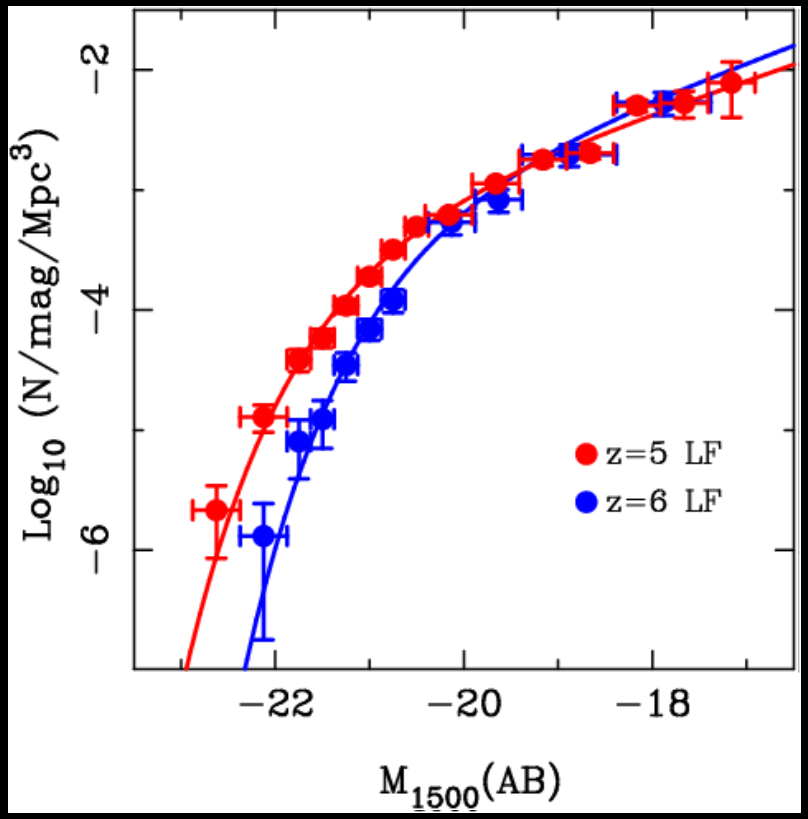
Photo-zs easy, and accurate,
given deep enough multi-band imaging

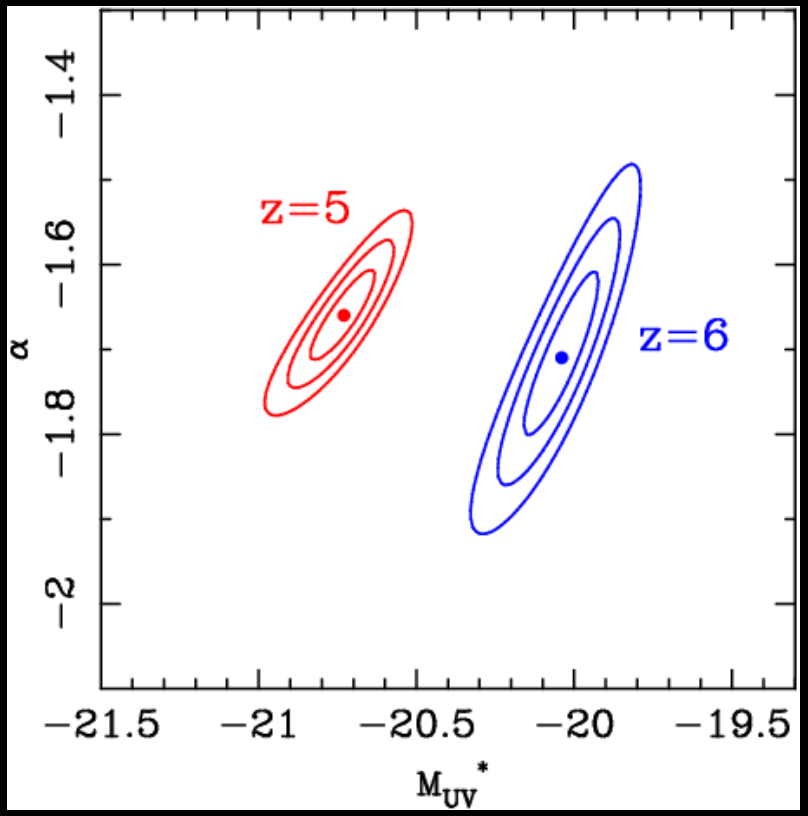
High redshift galaxies: 4.5<z<6.5



Combining UDS and HST data-sets provides 5 magnitudes of dynamic range

High redshift galaxies: 4.5<z<6.5



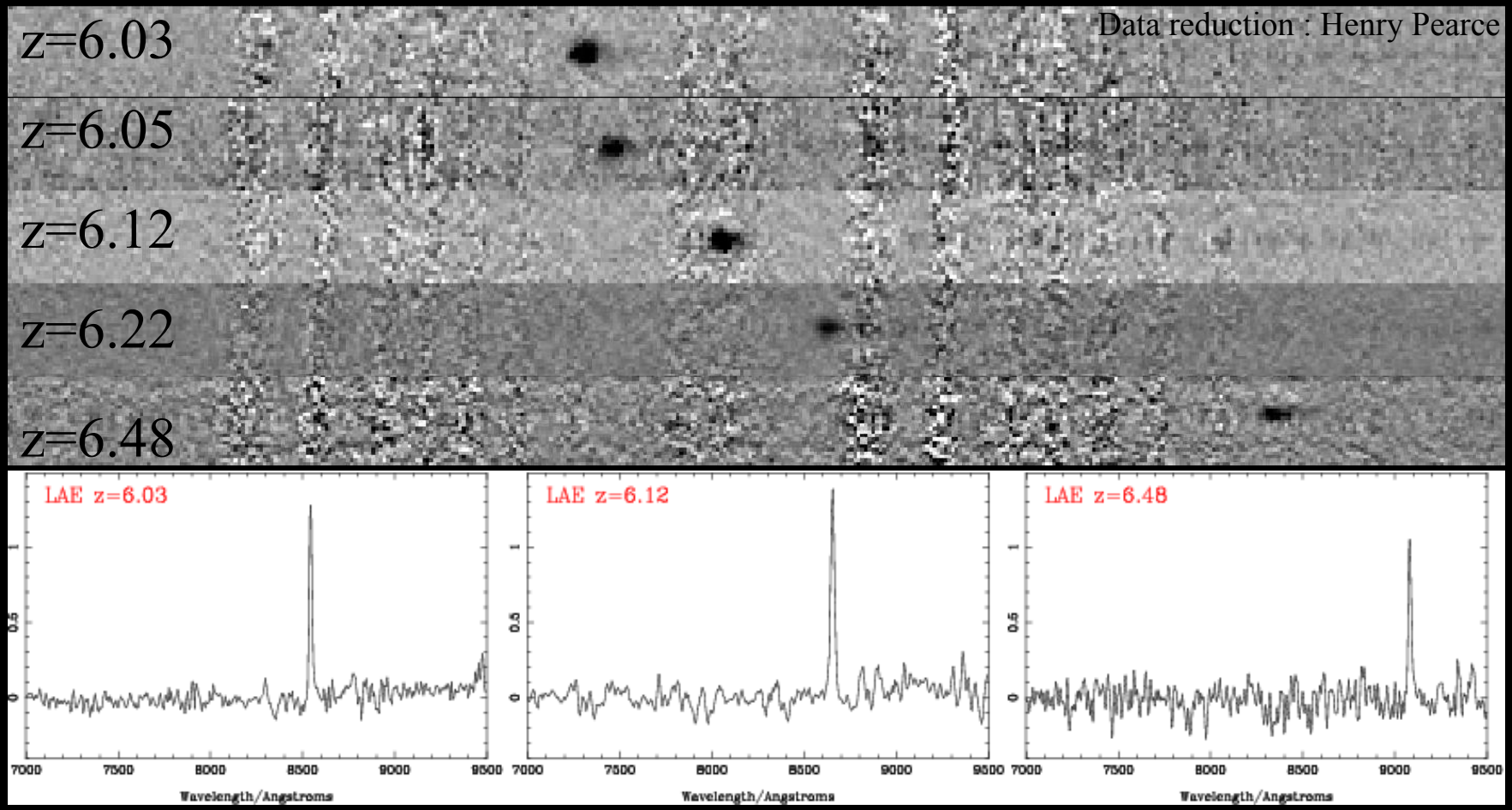


Combining UDS and HST data-sets provides 5 magnitudes of dynamic range

ML fits suggest M* brightens by ~0.7 magnitudes from z=6 to z=5

No significant evolution of normalization or faint-end slope

VLT spectroscopy - zUDS



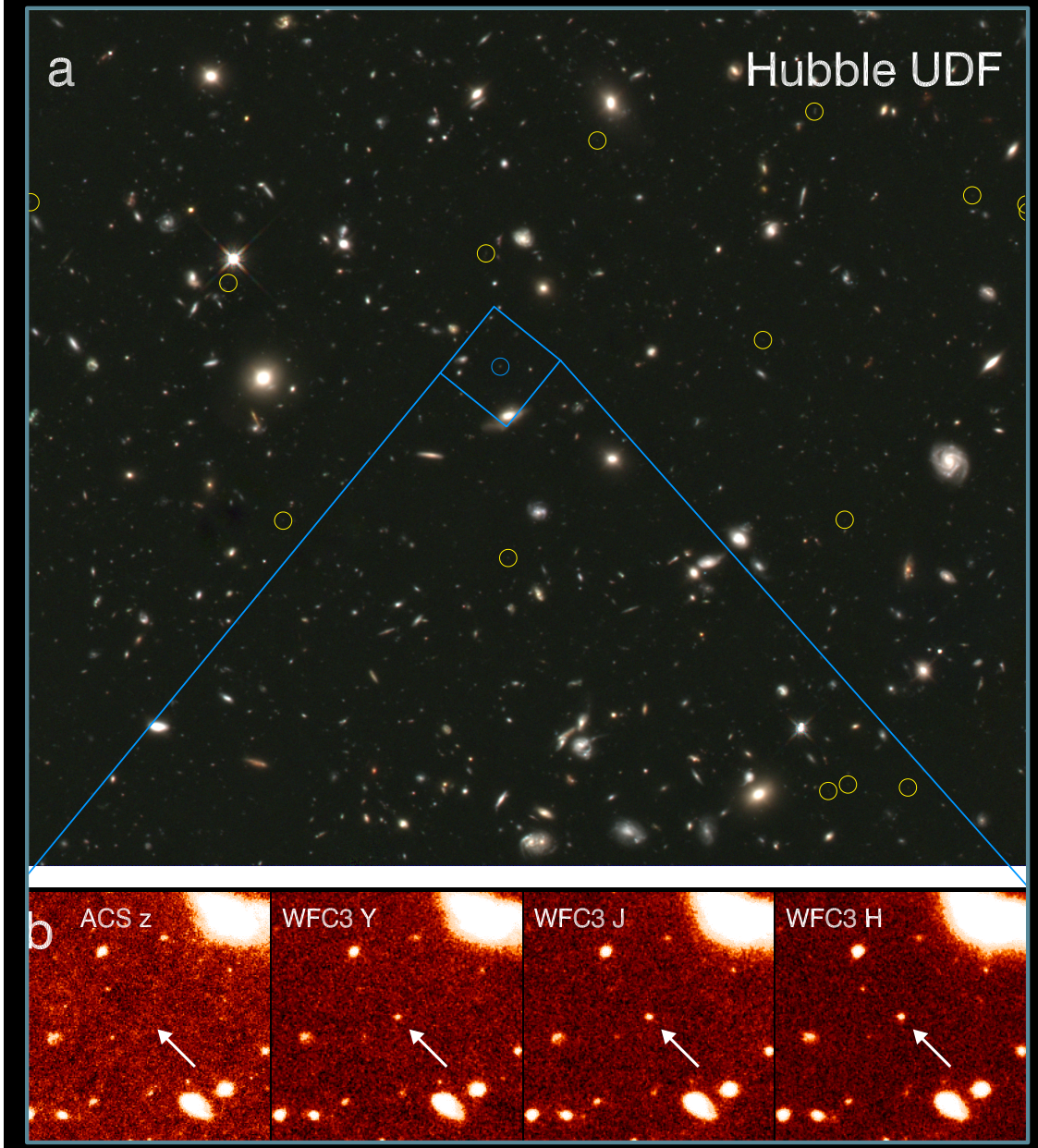
~50% of luminous LBGs observed at z>6 are strong LAEs

Lyα line fluxes are typically 3×10^{-17} cgs (EW_0~35 Angstroms), i.e. SFR~10 $M_\odot$ yr^{-1}

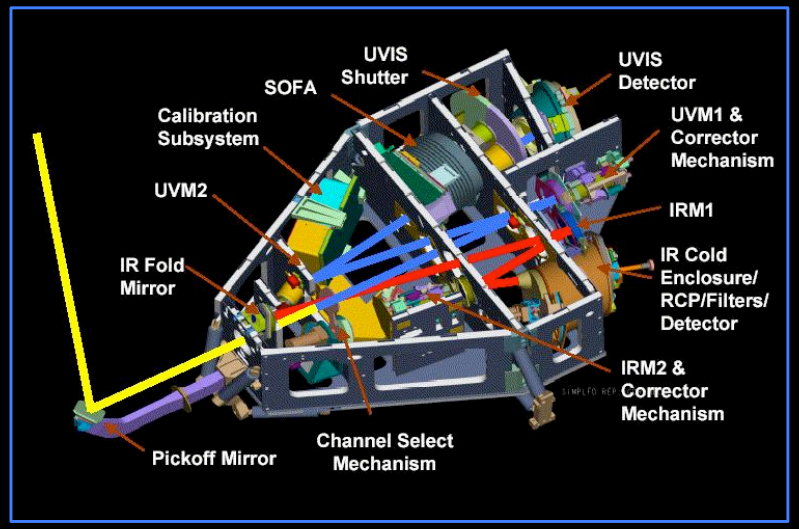
SED analysis (0.35μm-4.5μm) currently on-going - Curtis-Lake et al. (2011)

– see Schenker et al. (2011) & Pentericci et al. (2011) on declining Lyα fraction at z ~ 7

z > 7 - Wide Field Camera 3 (WFC3)



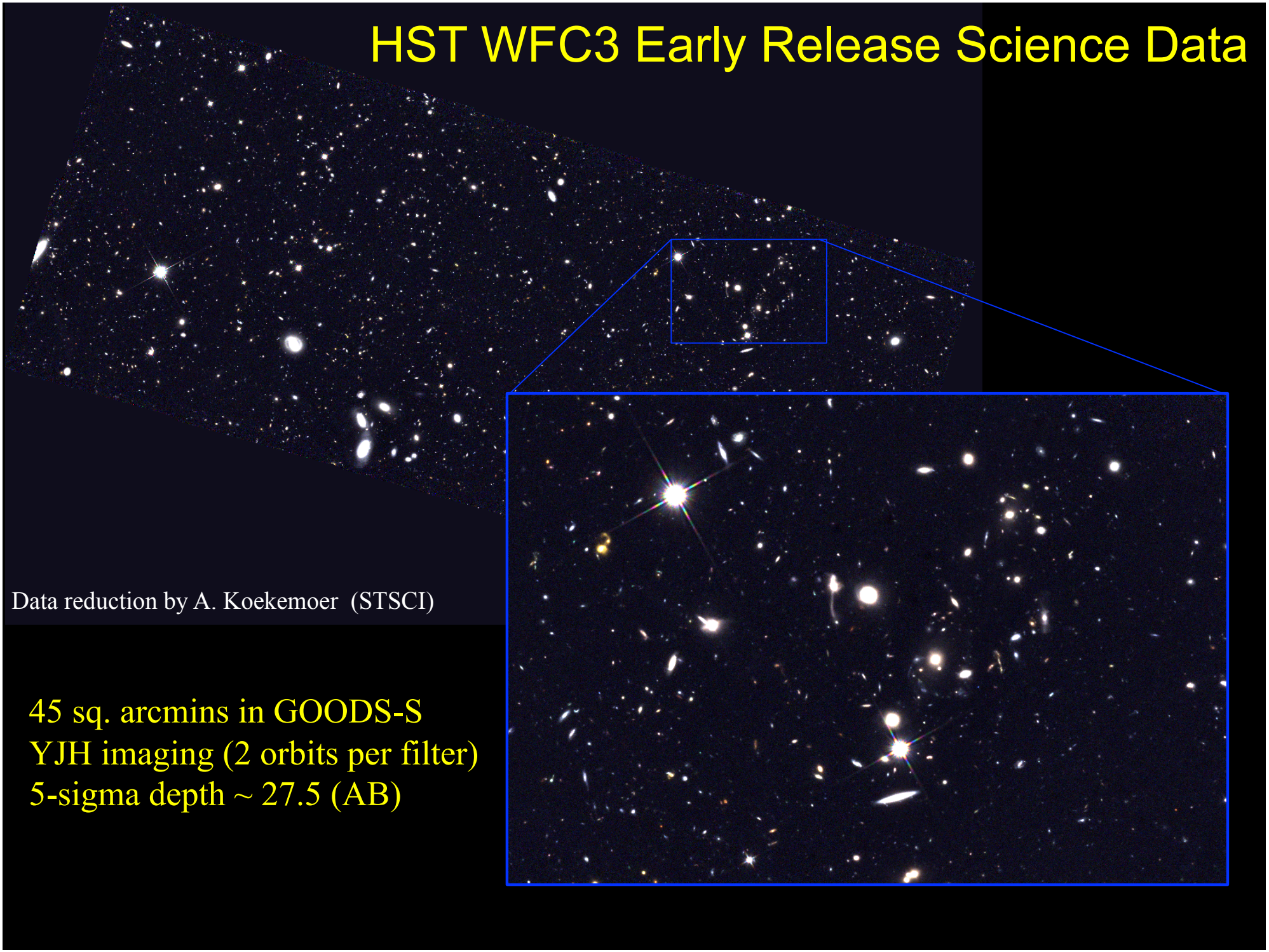
McLure, Dunlop et al (2010)



- Two channel, UVIS and NIR (YJH)
- NIR channel has 4.5 square arcmin FOV
- Image quality of ~0.15" FWHM
- Order of magnitude better that NICMOS

Y J H =29(AB) imaging allows
LBG selection out to 7 < z < 10

HST WFC3 Early Release Science Data

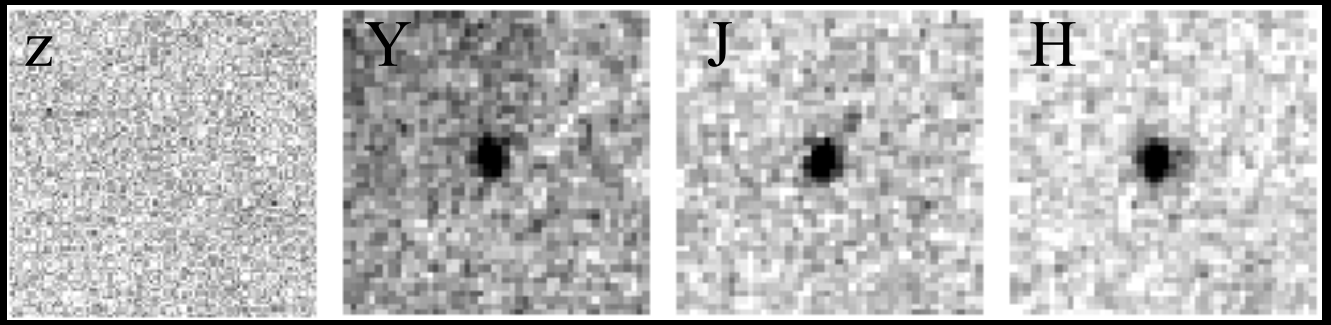


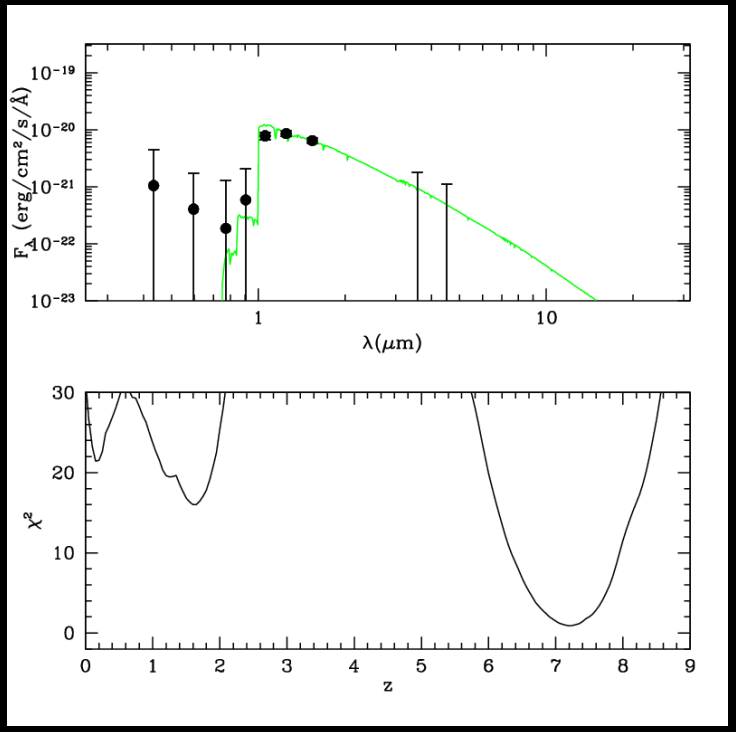
Data reduction by A. Koekemoer (STSCI)

45 sq. arcmins in GOODS-S
YJH imaging (2 orbits per filter)
5-sigma depth ~ 27.5 (AB)

WFC3 Imaging of the HUDF: Example SED fits

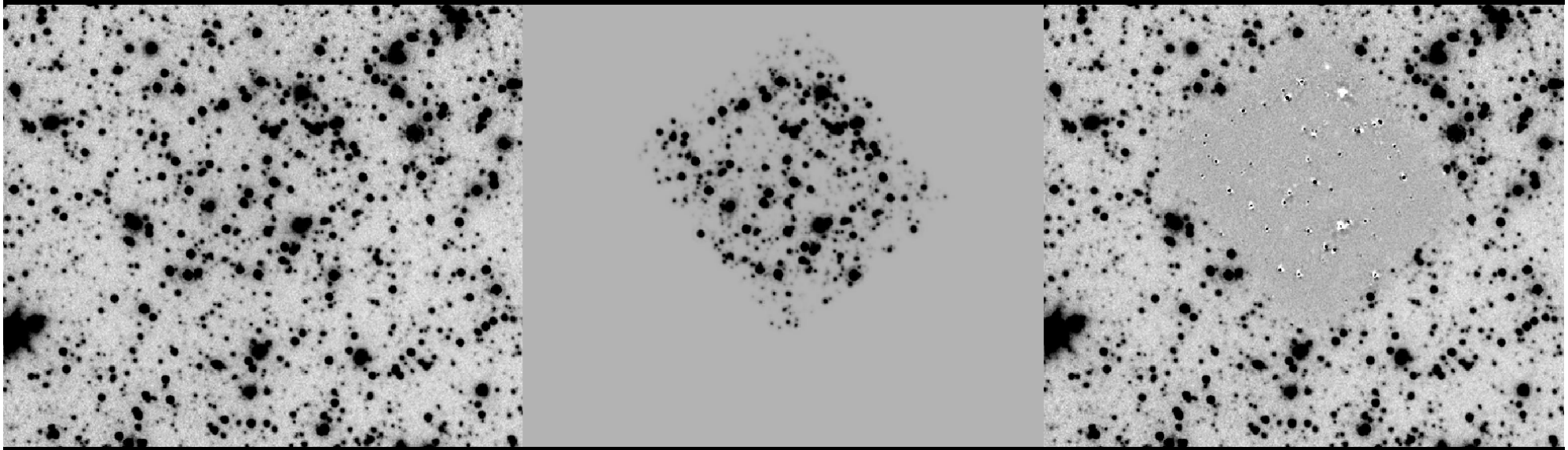
McLure, Dunlop et al. 2010





ID No. 835 z_{phot} = 7.20

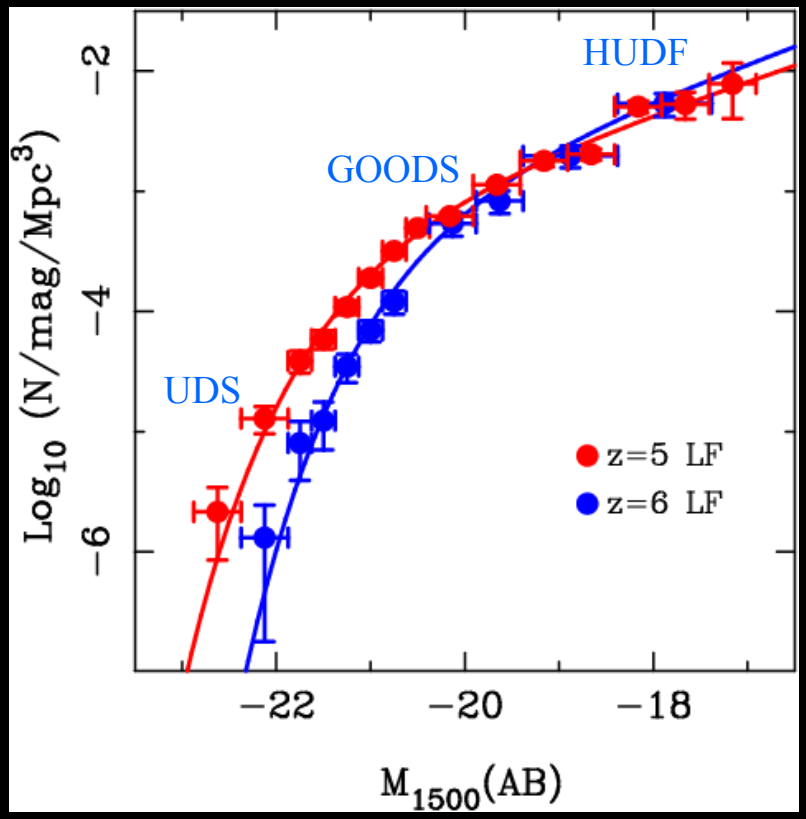
Now using IRAC data in object selection



IRAC deep 3.6 micron imaging deconfused with WFC3 H-band

McLure, Dunlop et al. (2011)

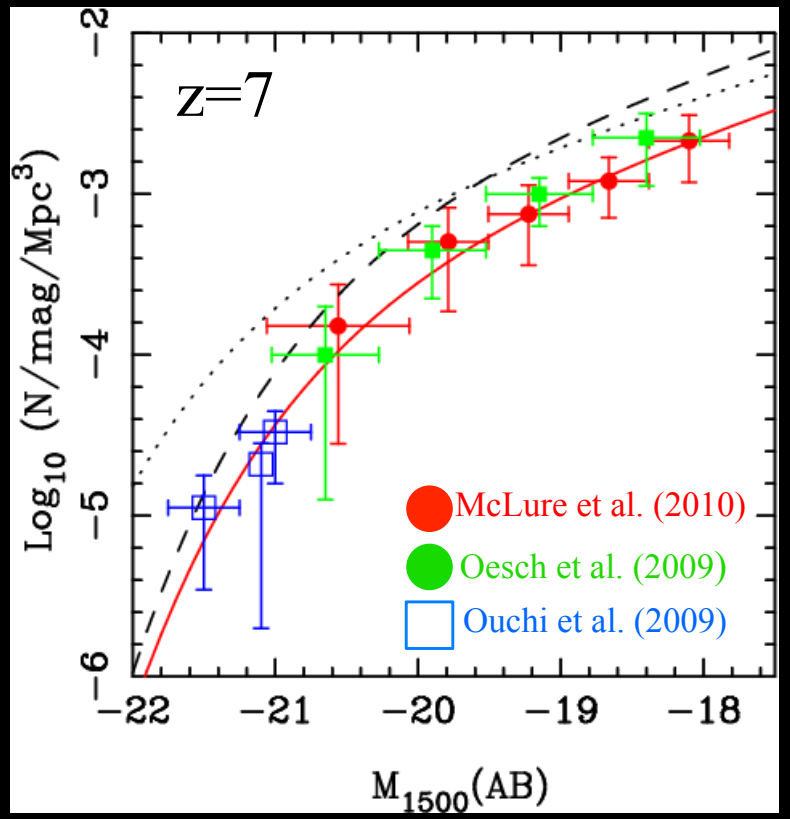
The rapidly evolving LF



McLure et al. (2009)

Combining UDS and HST data-sets provides 5 magnitudes of dynamic range

M* down by ~0.7 mag from z=5 to z=6 (~250 Myrs)



McLure, Dunlop et al. (2010)

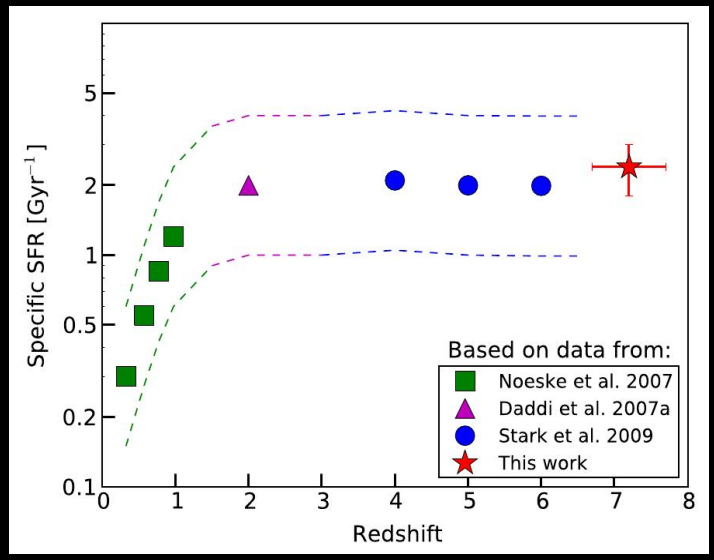
Now have reasonable constraints on z=7 LF

M* down again by ~0.5 mag from z = 6 to z = 7

see also Bouwens et al. (2011), and Grazian et al. (2011)

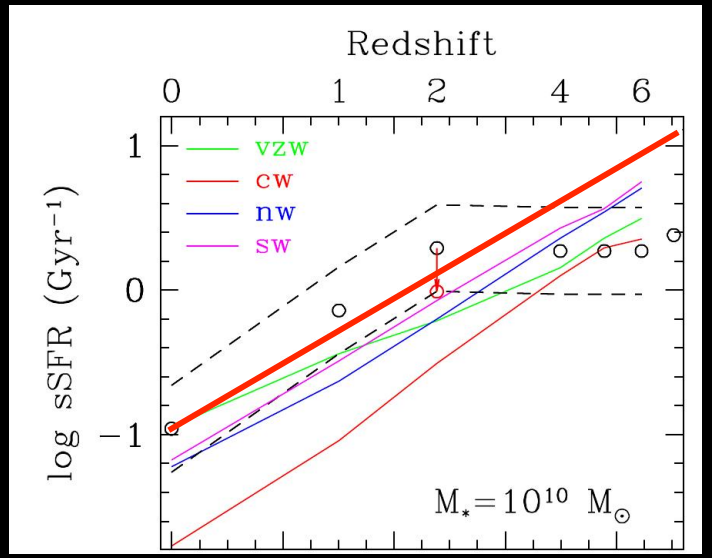
Stellar masses and star-formation rates at high-z

Recent observational results suggest sSFR may remains constant (~2 Gyr^{-1}) all the way from z=2 to z=7



Gonzalez et al. (2010)

Theoretically expect high gas inflow rate at high redshift, and that sSFR should increase as roughly $\sim (1+z)^{2.5}$



Dave et al. (2010)

Are these results incompatible?

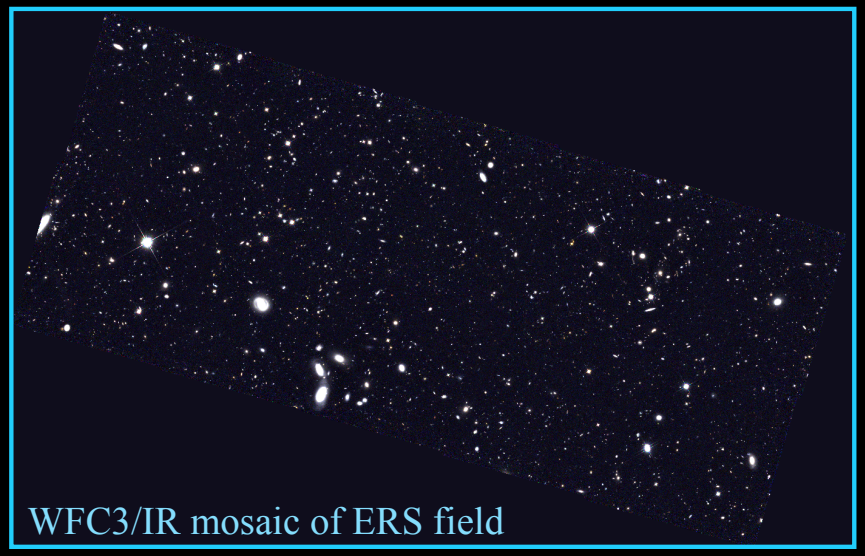
Stellar masses and star-formation rates at high-z

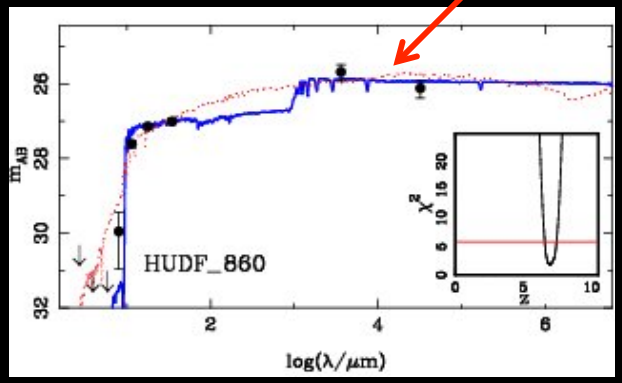
McLure, Dunlop et al. (2011)

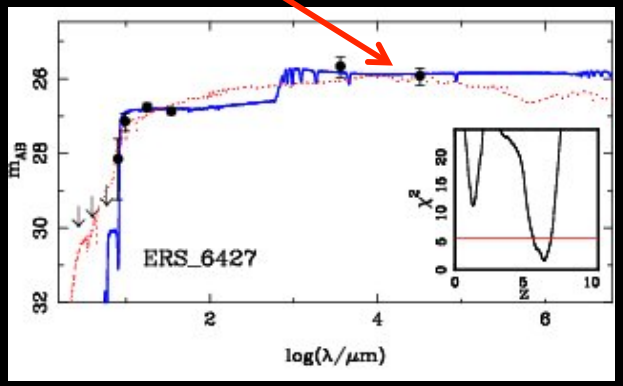
Full photo-z analysis of the z>6 population in the HUDF, HUDF09-2 & ERS fields

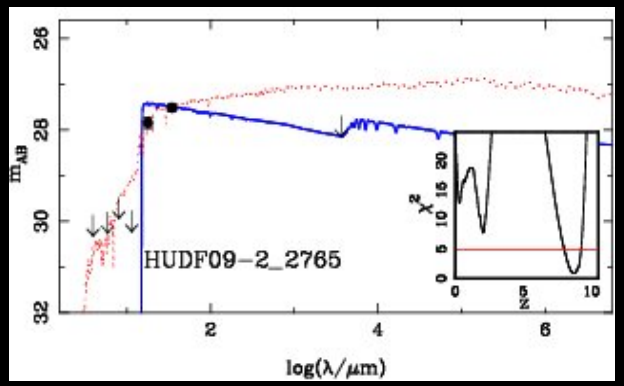
Focus on trying to construct the most robust sample of z>6 LBGs possible

Deconfusion analysis employed to include long-wavelength IRAC photometry in selection



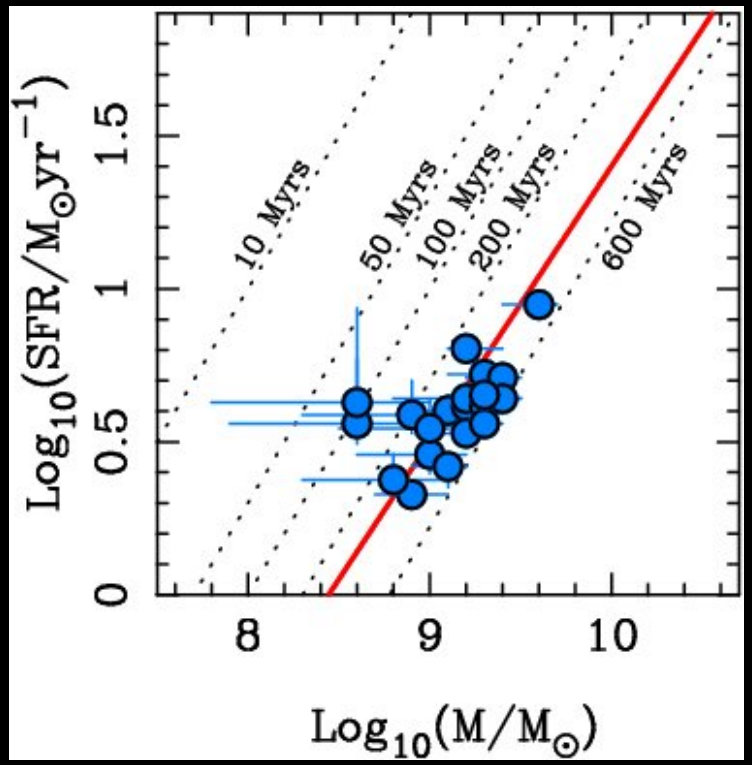


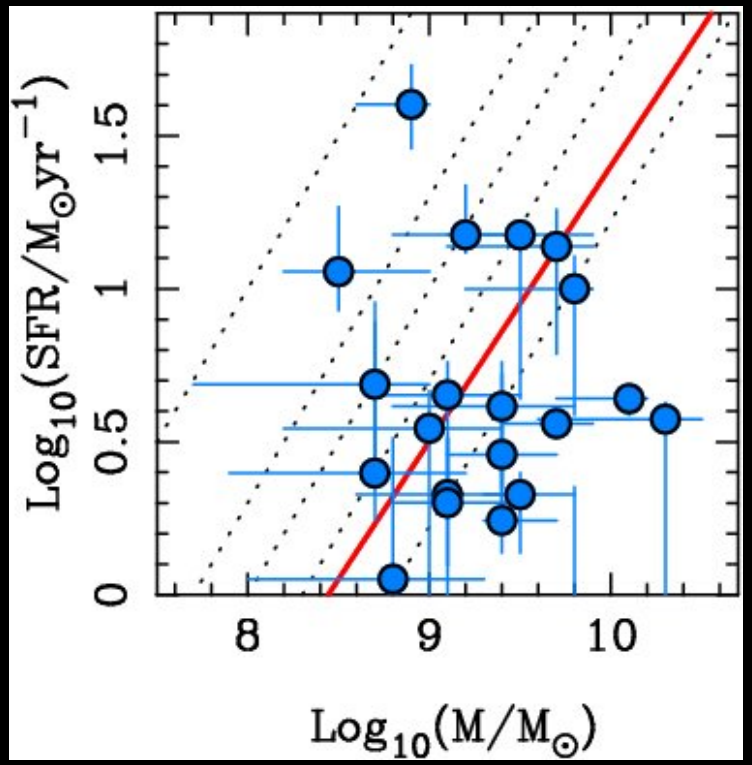




Stellar masses and star-formation rates at high-z

Red line shows the z=2 relation from Daddi et al. (2007)





Left: results from SED fits assuming constant SFH, Av=0, $0.2Z_{\odot}$

Right: results using plausible range of SFH, Av and metallicity

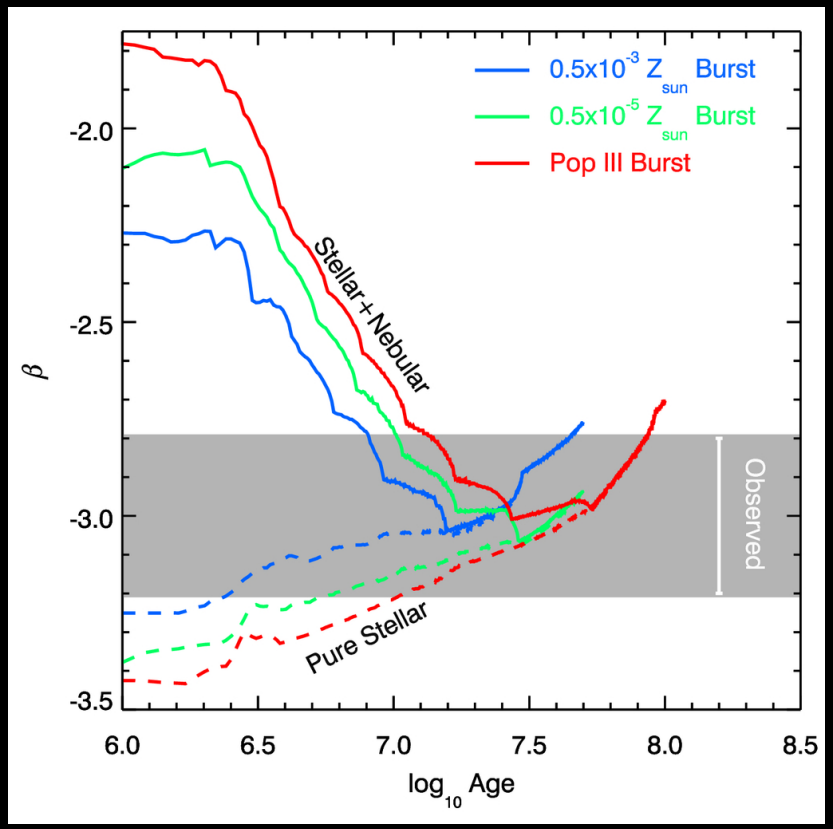
both give same average $<sSFR> \sim 2Gyr^{-1}$

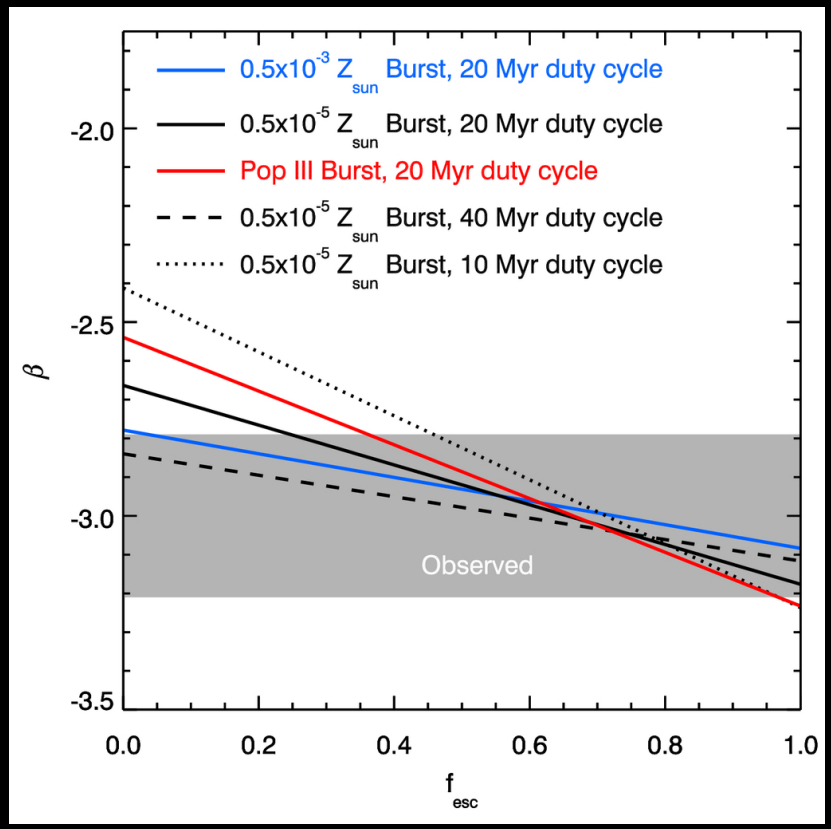
Available ionizing photons

Beta – UV spectral power-law index

Bouwens et a. 2010b, based on Schaerer models

See also Robertson et al. (2010) Nature review, & Finkelstein et al. (2010)

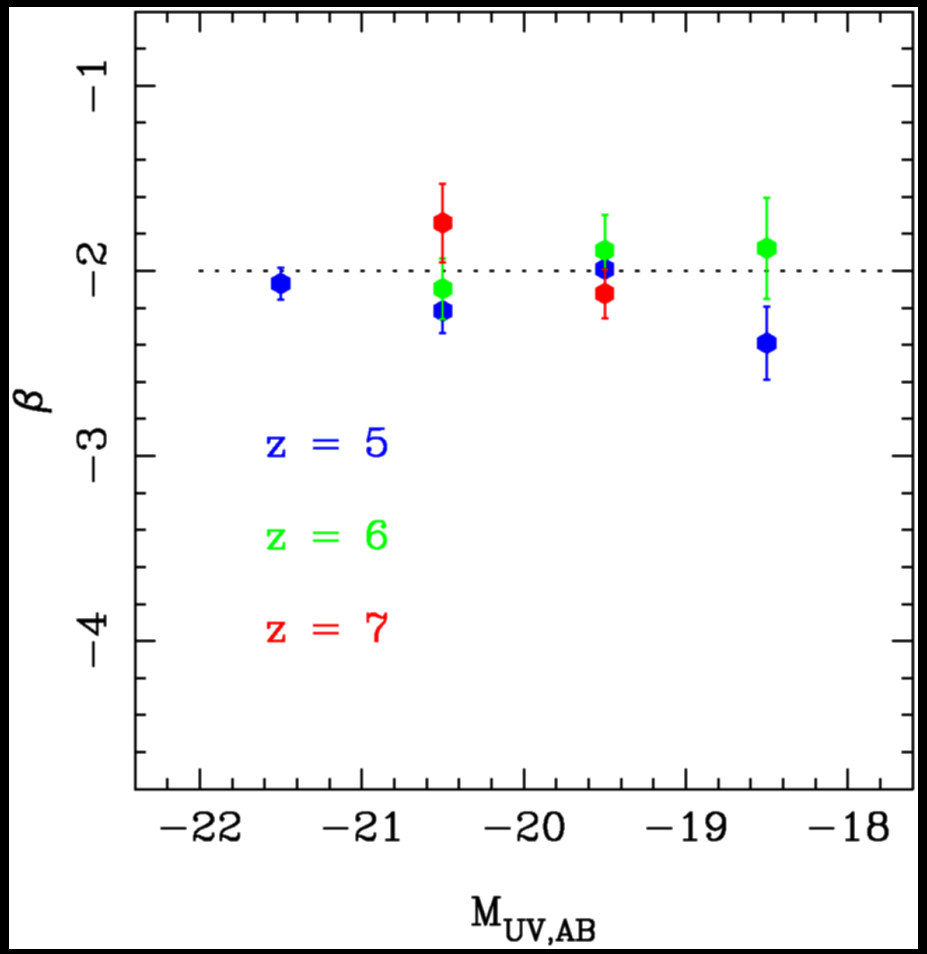


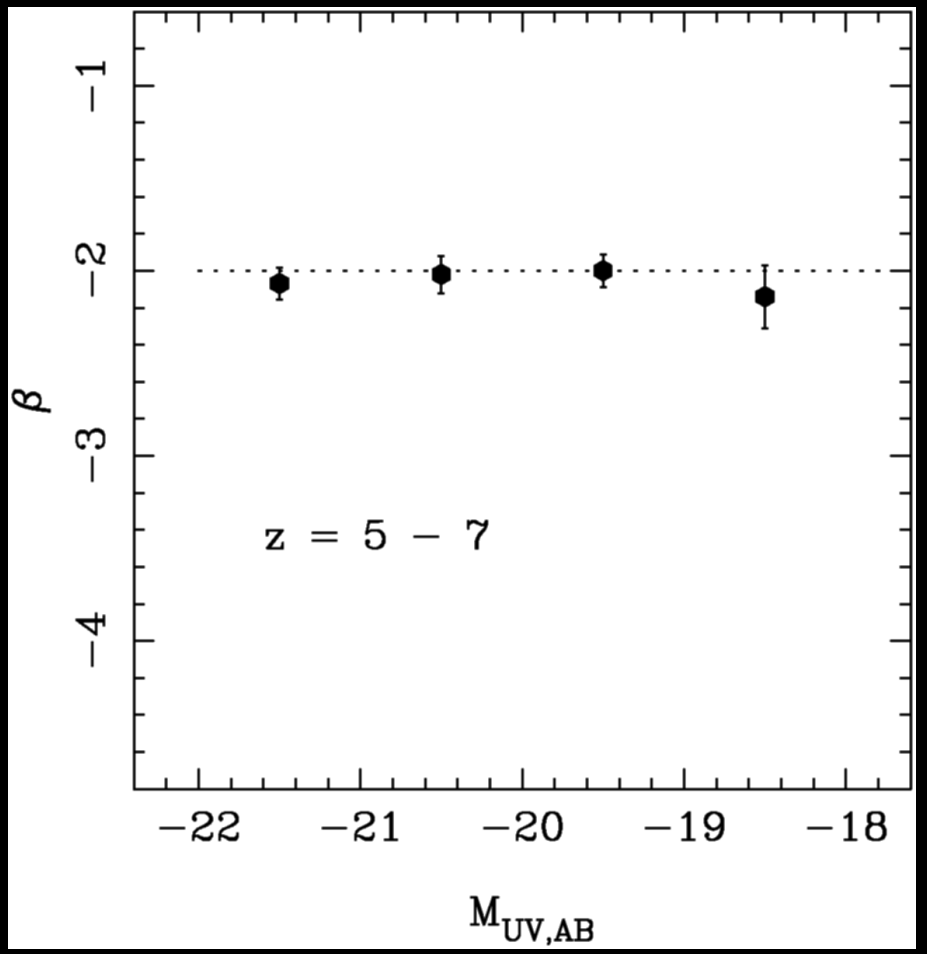


Beta – UV spectral power-law index

Dunlop et al. (2011), see also Wilkins et al. (2011)

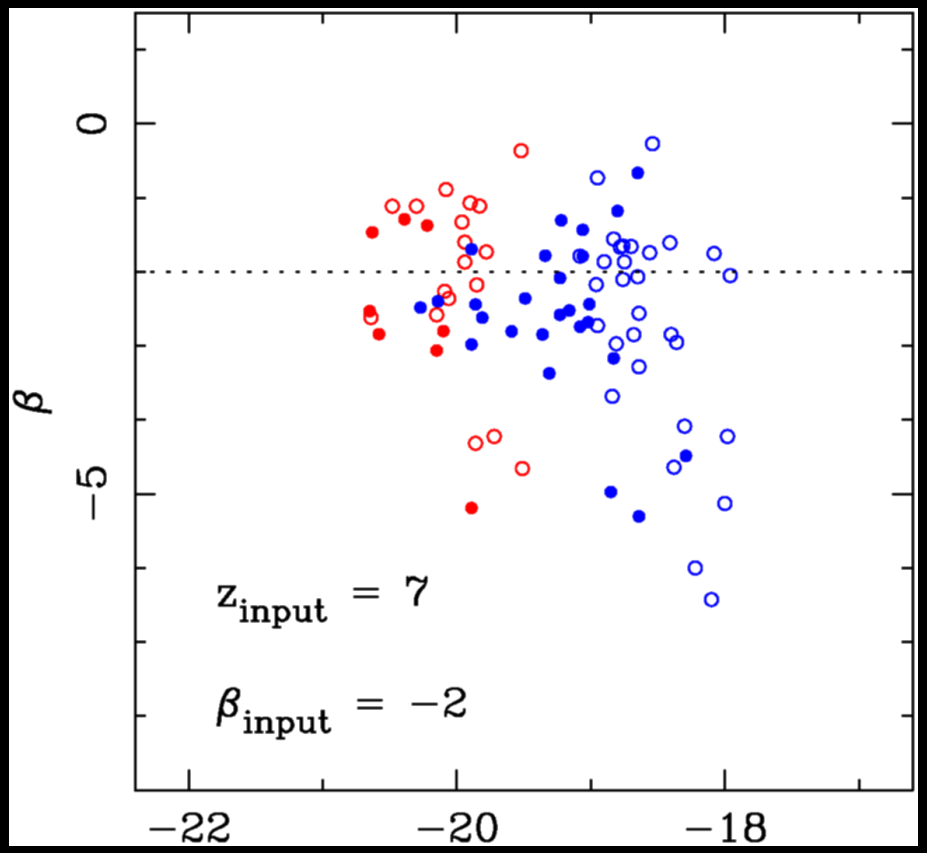
Beta = -2.1 if confine attention to >8-sigma detections

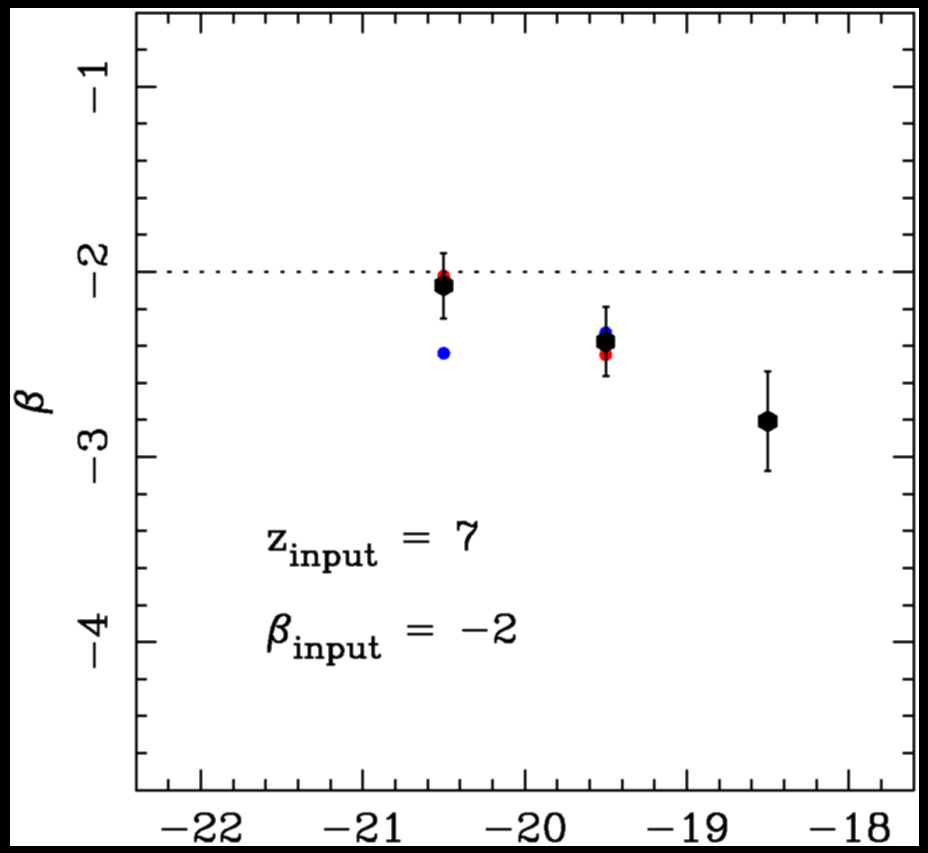




Beta bias - simple simulations

Dunlop et al. (2011)



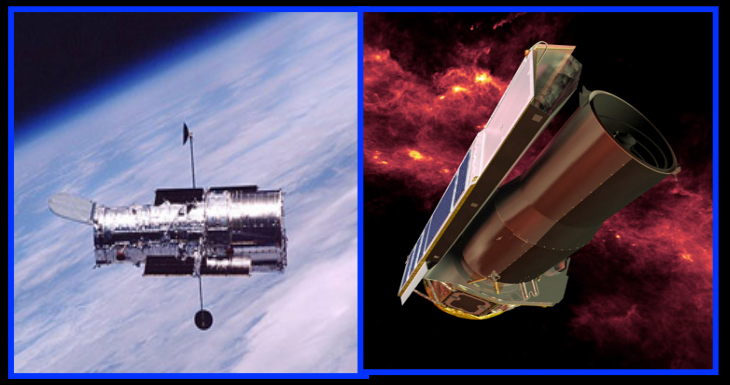


Need deeper data to establish beta at faintest luminosities

Future Prospects (near term)

1. Space-based

- HST CANDELS
- Spitzer SEDS
- deeper WFC3 data in HUDF



2. Ground-based

- VISTA surveys
- Suprime-cam zY imaging
- Hyper-Suprime cam

HST MCT - CANDELS

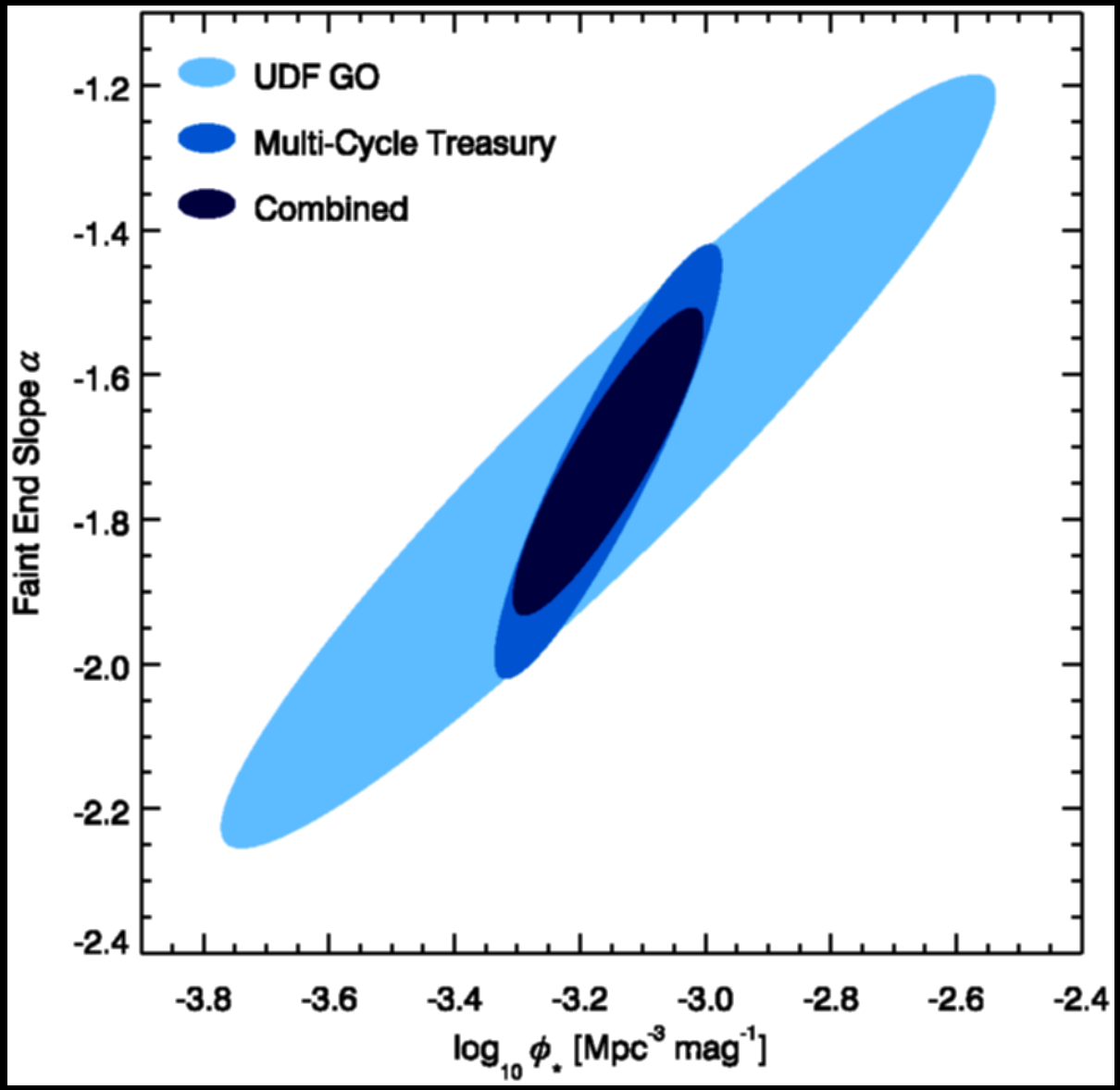
900 sq. arcmin of 2-orbit H, J, + I & V imaging in the SEDS fields
1. GOODS-N
2. GOODS-S
3. Groth Strip
4. COSMOS/UltraVISTA deep strip
5. UKIDSS UDS

150 sq. arcmin of 12-orbit Y,J,H + z, V imaging in the GOODS fields

~20 z > 1.5 Type Ia SN with near-infrared light curves

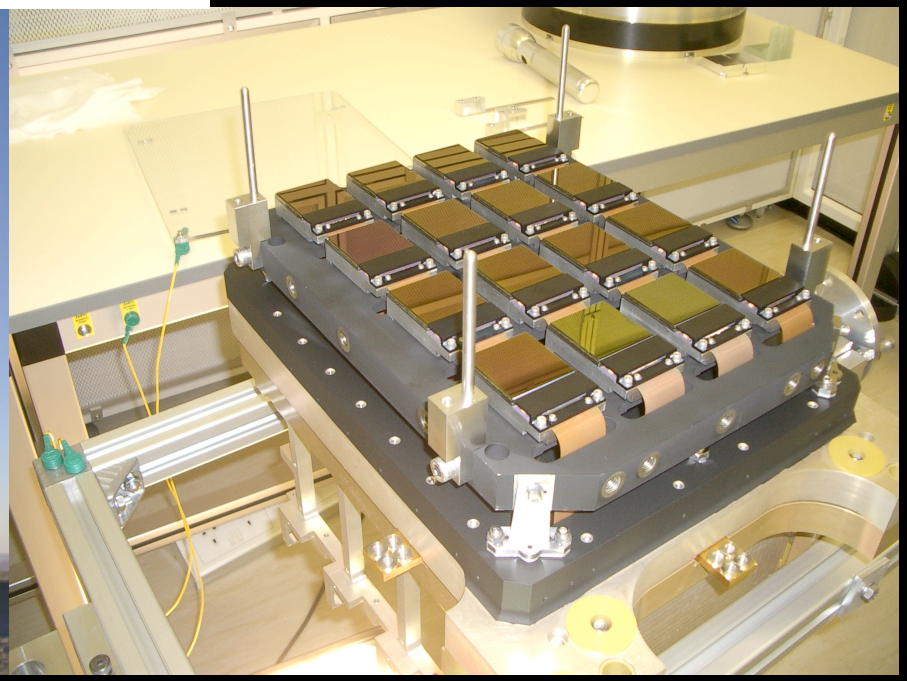
900 orbits (PIs: Faber & Ferguson)

HST Multi-cycle treasury proposal - CANDELS



New ground-based near-IR surveys

VISTA telescope: Paranal, Chile

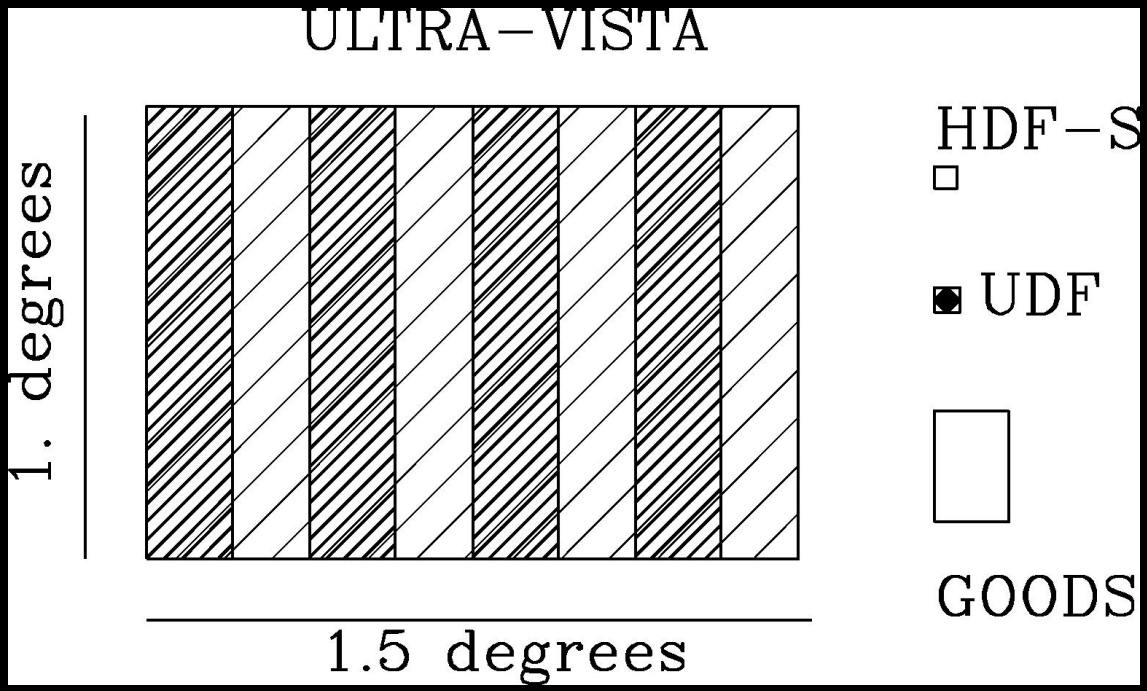


67 mega-pixel camera (1.5 sq. deg)

Survey operations now underway

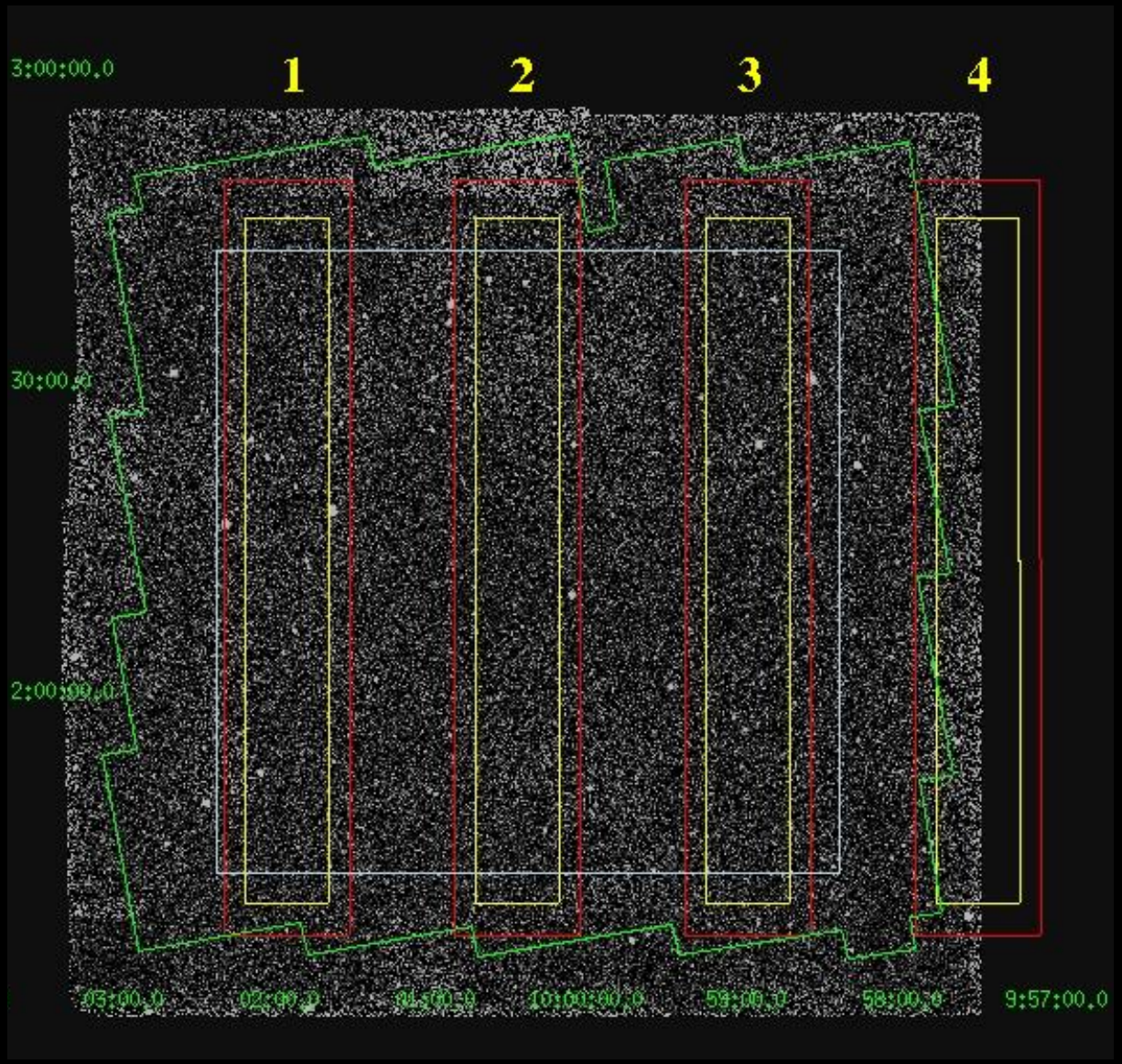
UltraVISTA – deepest public survey with Vista telescope

- PIs Dunlop, Franx, Le Fevre, Fynbo
- DEEP - 0.73 sq. deg., Y=26.7, J=26.6, H=26.1, K=25.6 (1408 hr)
- WIDE – 1.50 sq. deg., Y=25.3, J=25.2, H=24.7, K=24.2 (212 hr)
- Narrow-band survey, at 1.185 microns (z = 8.8 for Lyman-alpha) (180 hr)
- 1800 hours over 5 years – commenced Jan 2010

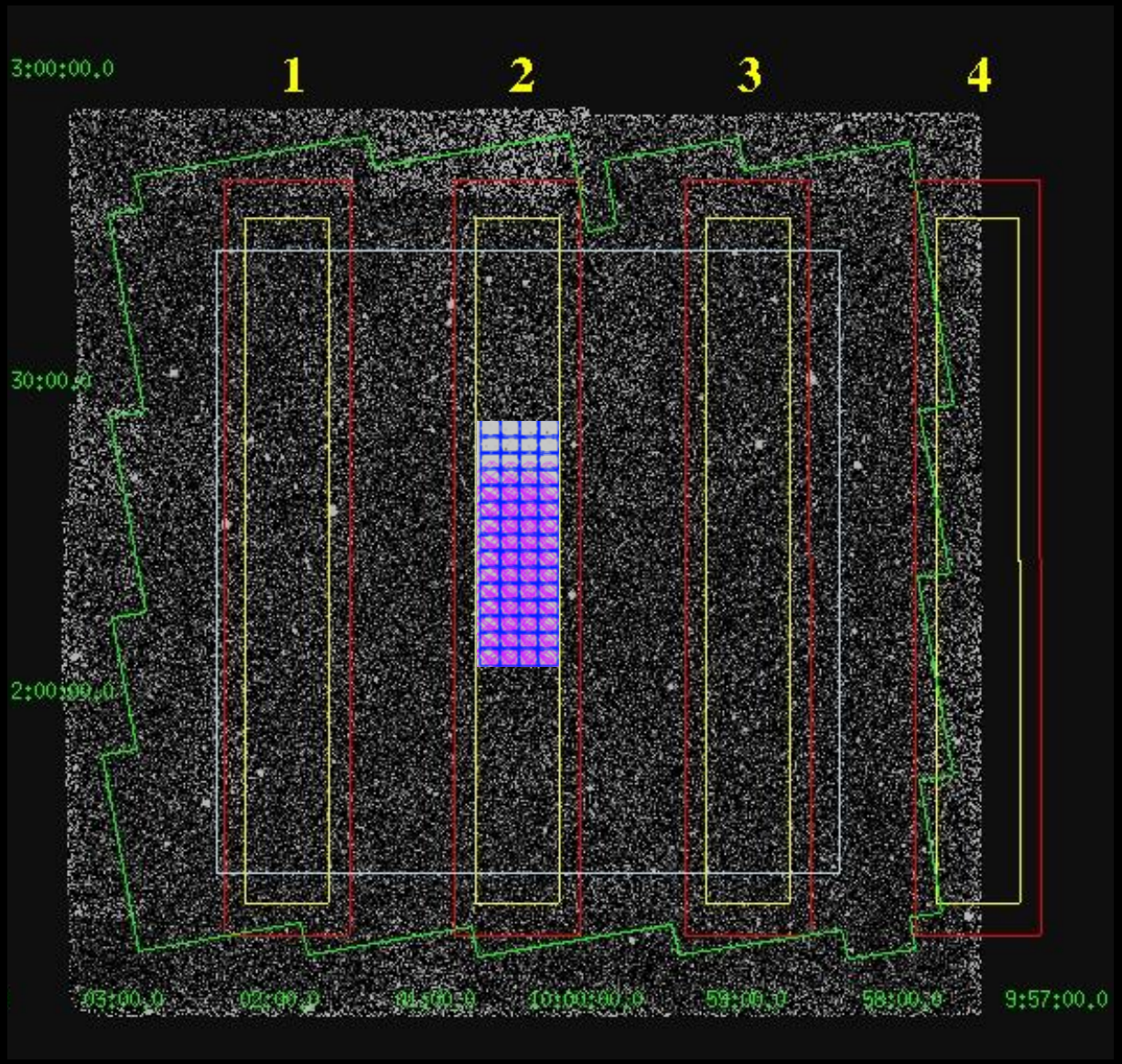


First ESO data release
August 2011

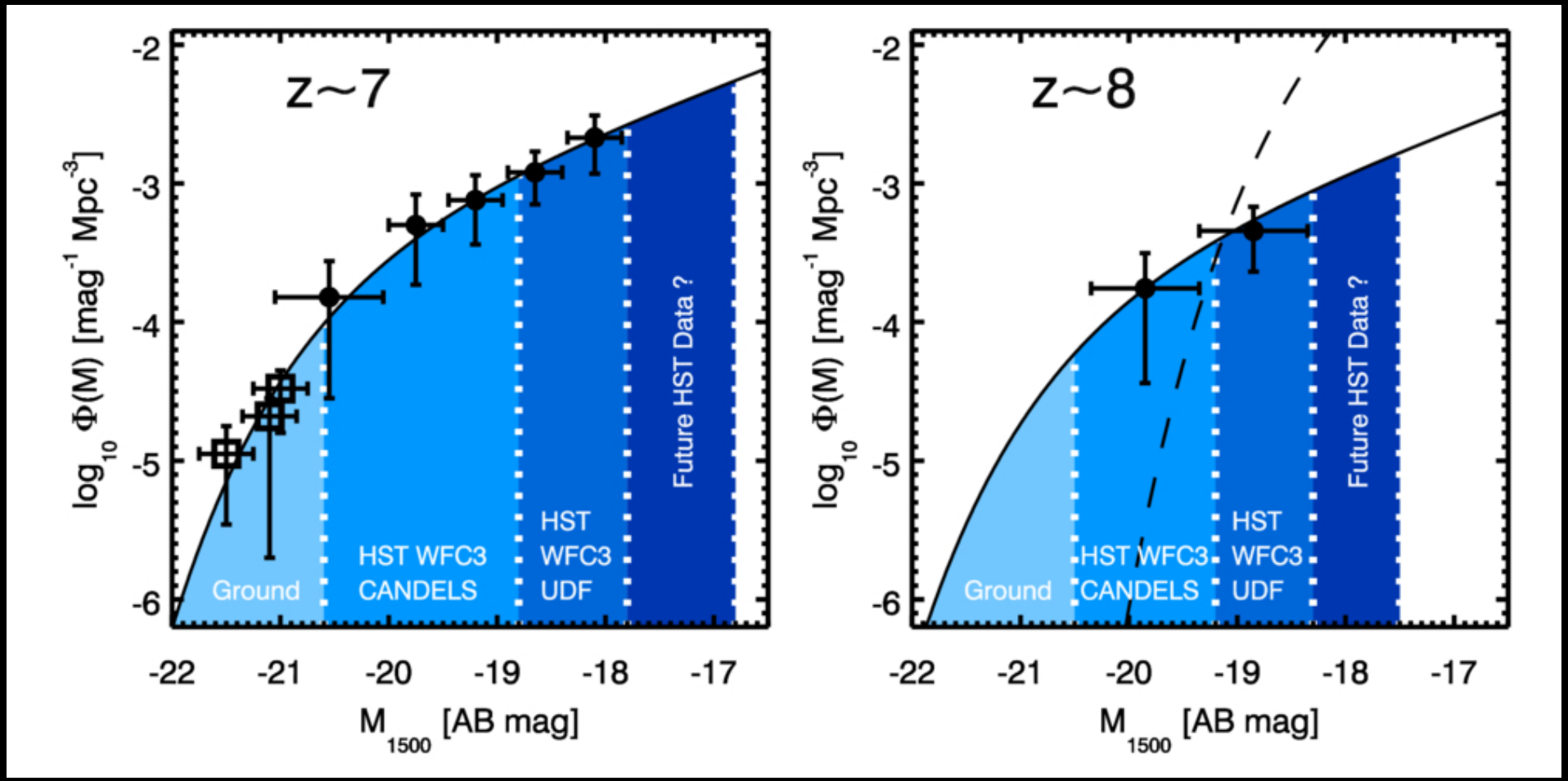
UltraVISTA



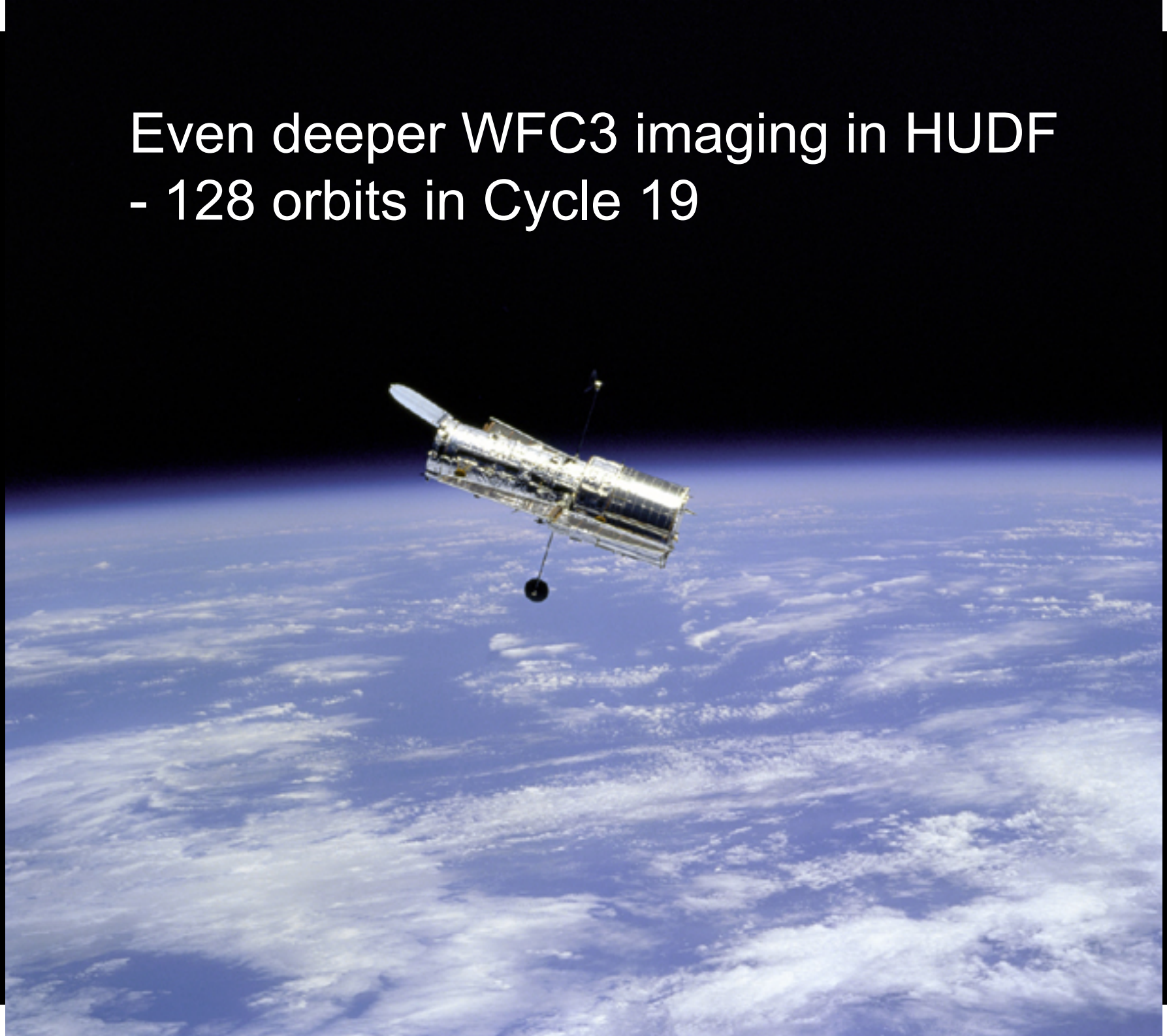
UltraVISTA + CANDELS



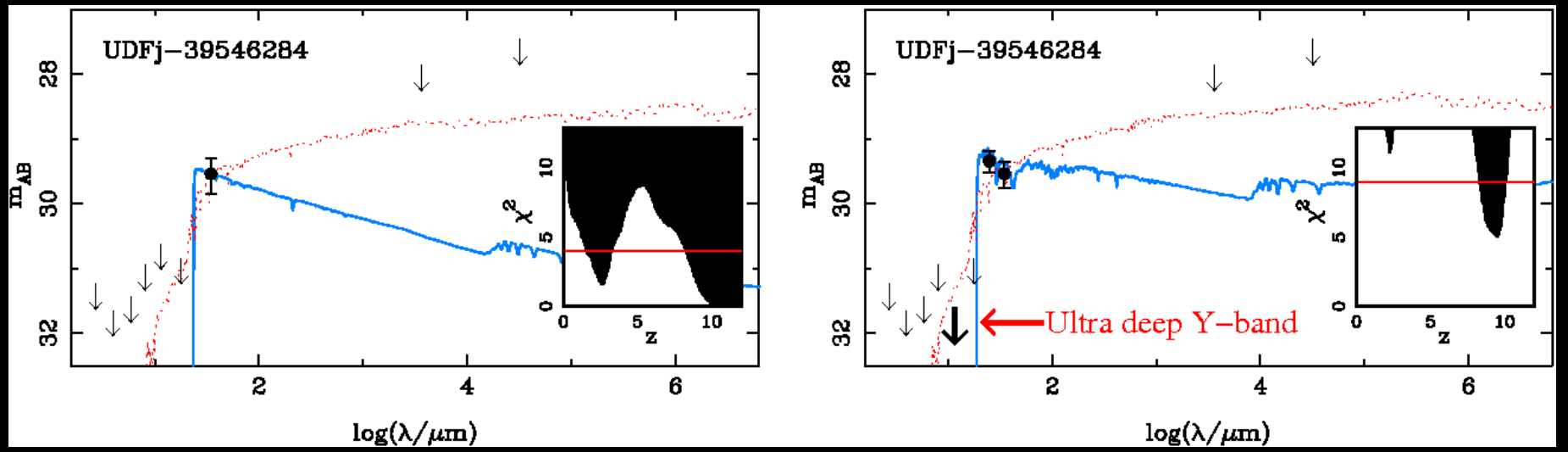
Building the wedding-cake……



Even deeper WFC3 imaging in HUDF
- 128 orbits in Cycle 19



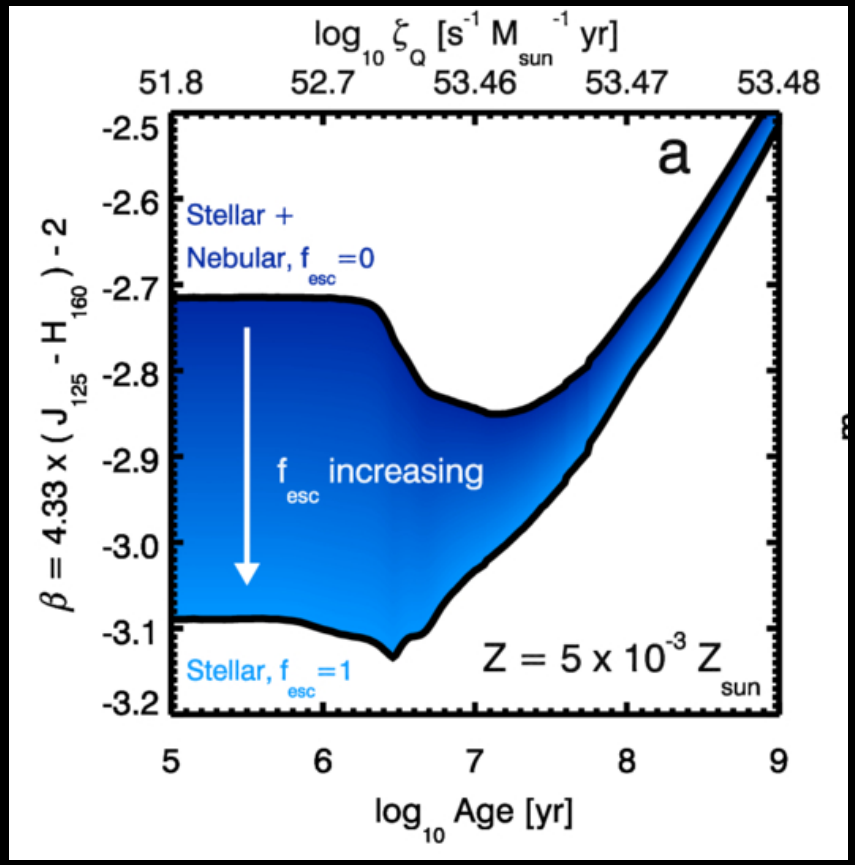
The most distant galaxies – z > 9

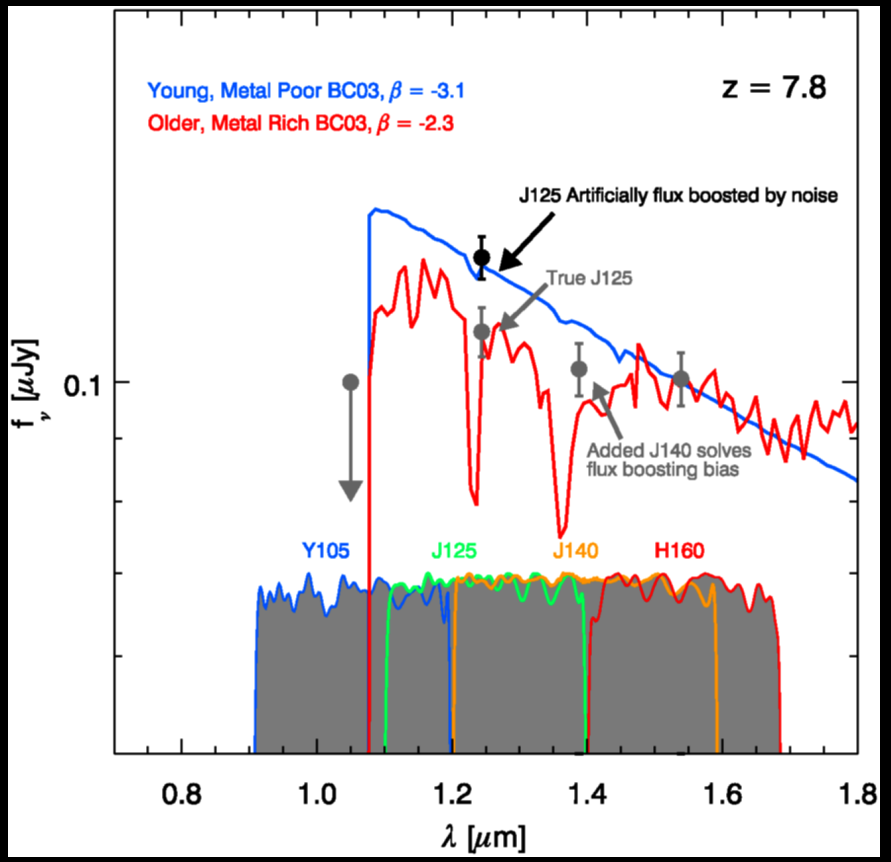


Bouwens et al. 2010, Nature
z = 10 galaxy ?

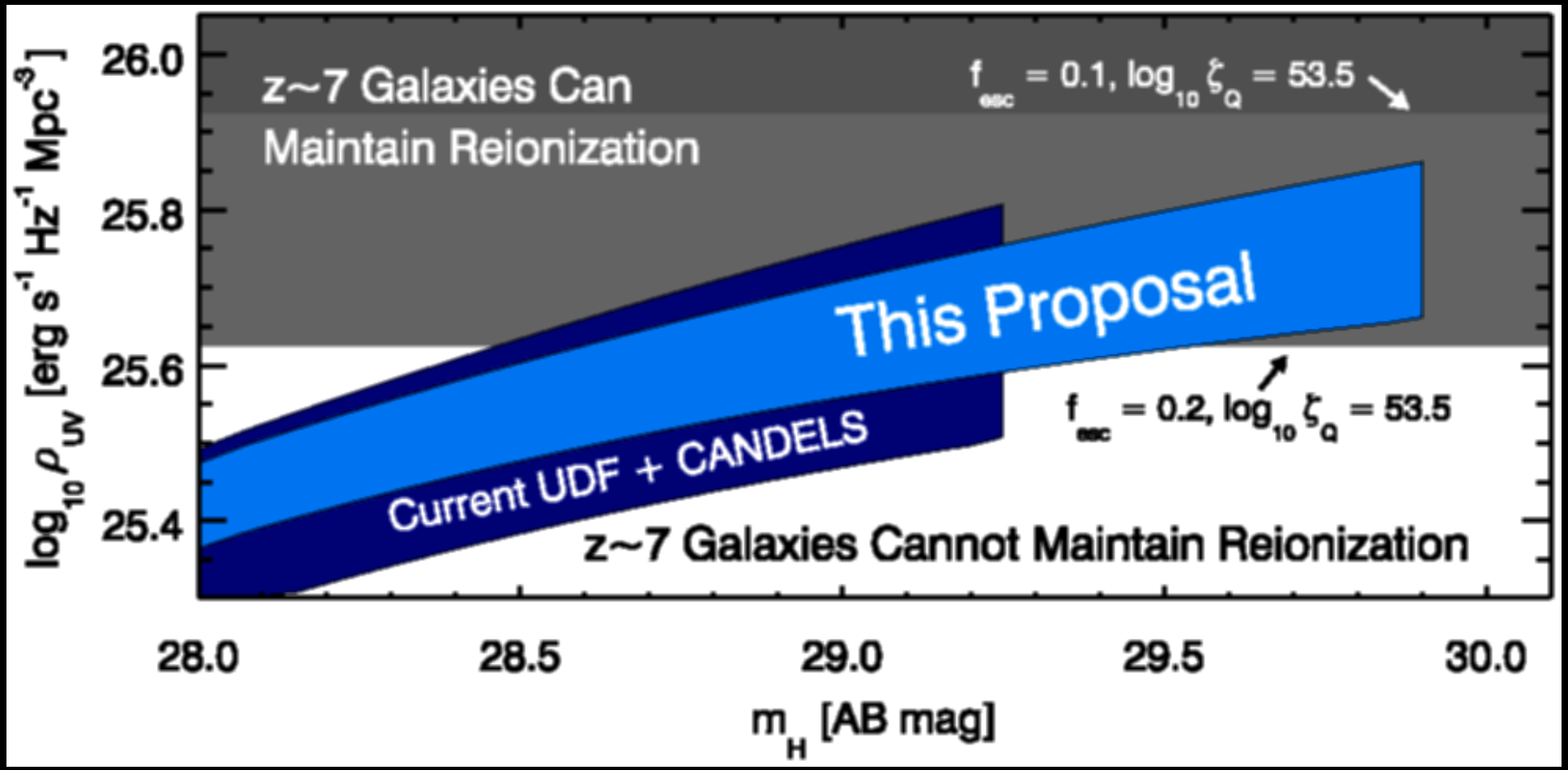
With new WFC3 photometry

Better UV slope measurements





Constraining the LF – Reionization?

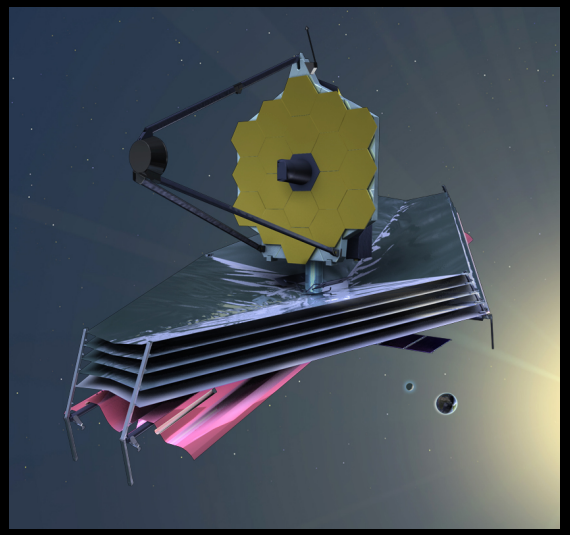


Future plan

- Establish robust, substantial samples of galaxies at z = 7 – 10
  - brighter/rarer ones with UltraVISTA
  - L* ones with HST CANDELS
  - very faint ones from HST ultra deep fields
  - better photometric constraints on beta/escape fraction

- Study the implications for galaxy formation & reionisation with Keck+MOSFIRE, VLT+KMOS

- Select targets for JWST in 2018



?

New award of 128 orbits in HST Cycle 19 to Ellis, Dunlop, McLure et al.

Table 1: Summary of HUDF WFC3/IR exposures (orbits) and depths (AB, 5-σ, 0.4″ apertures)

Program	$F105W$	$F125W$	$F140W$	$F160W$	$(F140W+F160W)$	**Total**
Final GO:11563	20	36	0	38	(38)	94
This Proposal	75	0	30	23	(53)	128
Orbit Totals	95	36	30	61	(91)	
Final Depth	30.0	29.5	29.5	29.5	29.9	