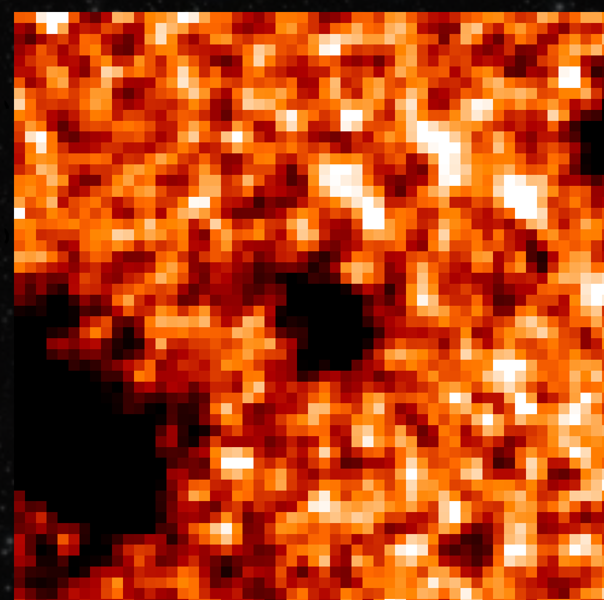
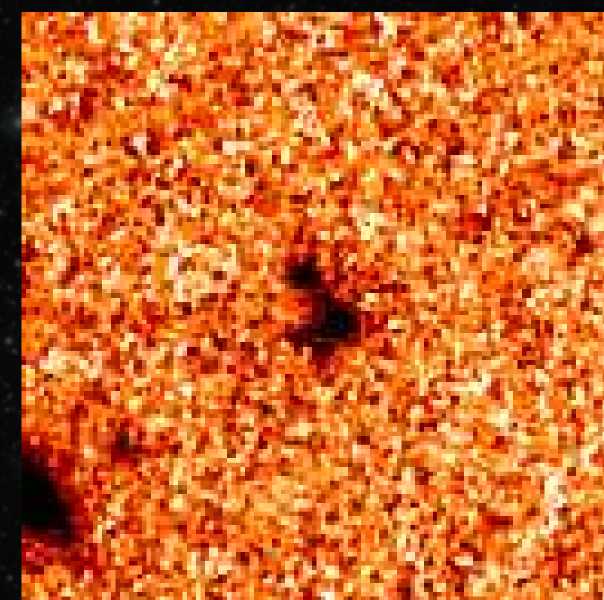
The evolution of bright galaxies at z > 6

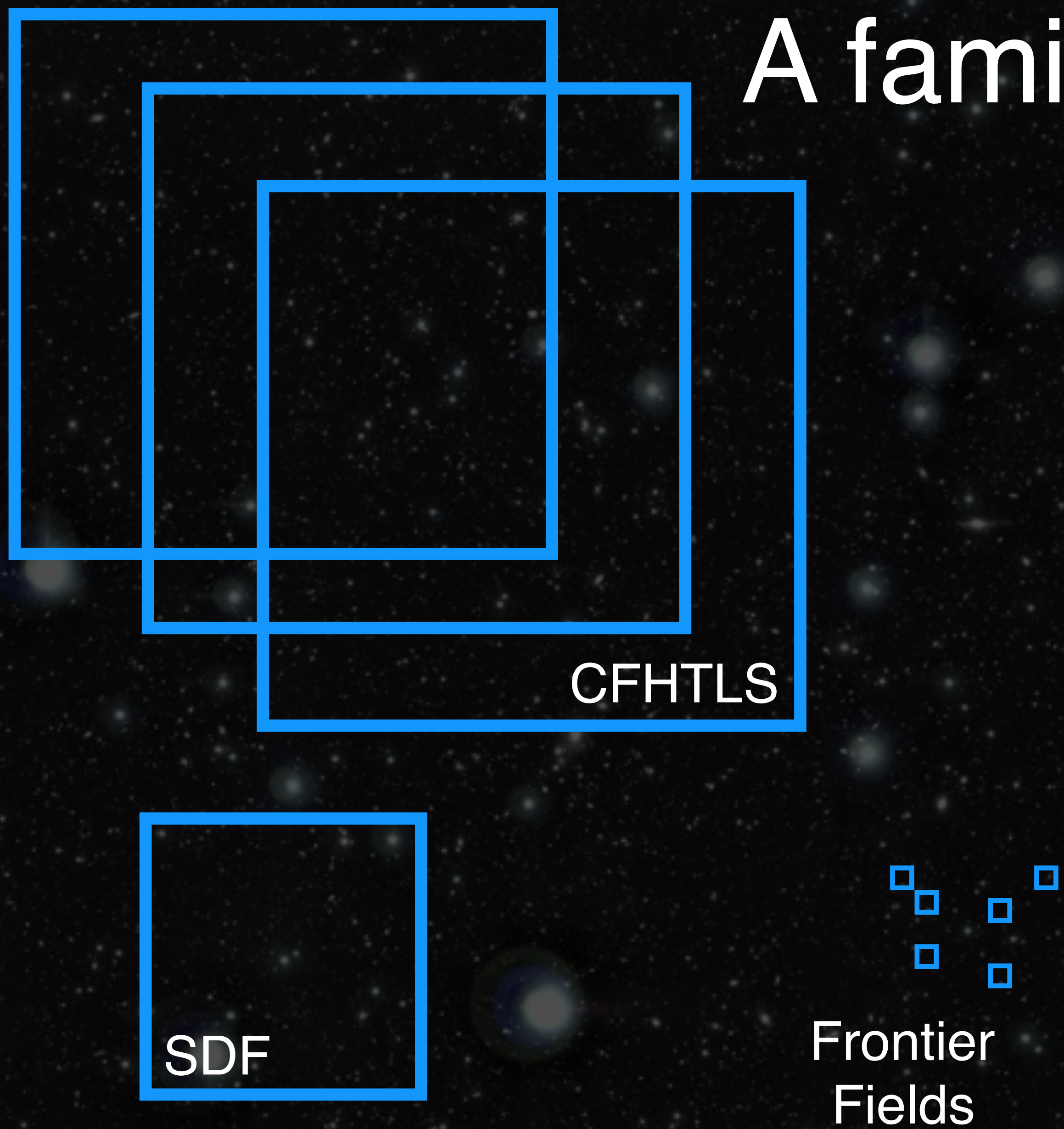
the power of degree-scale, near-infrared surveys

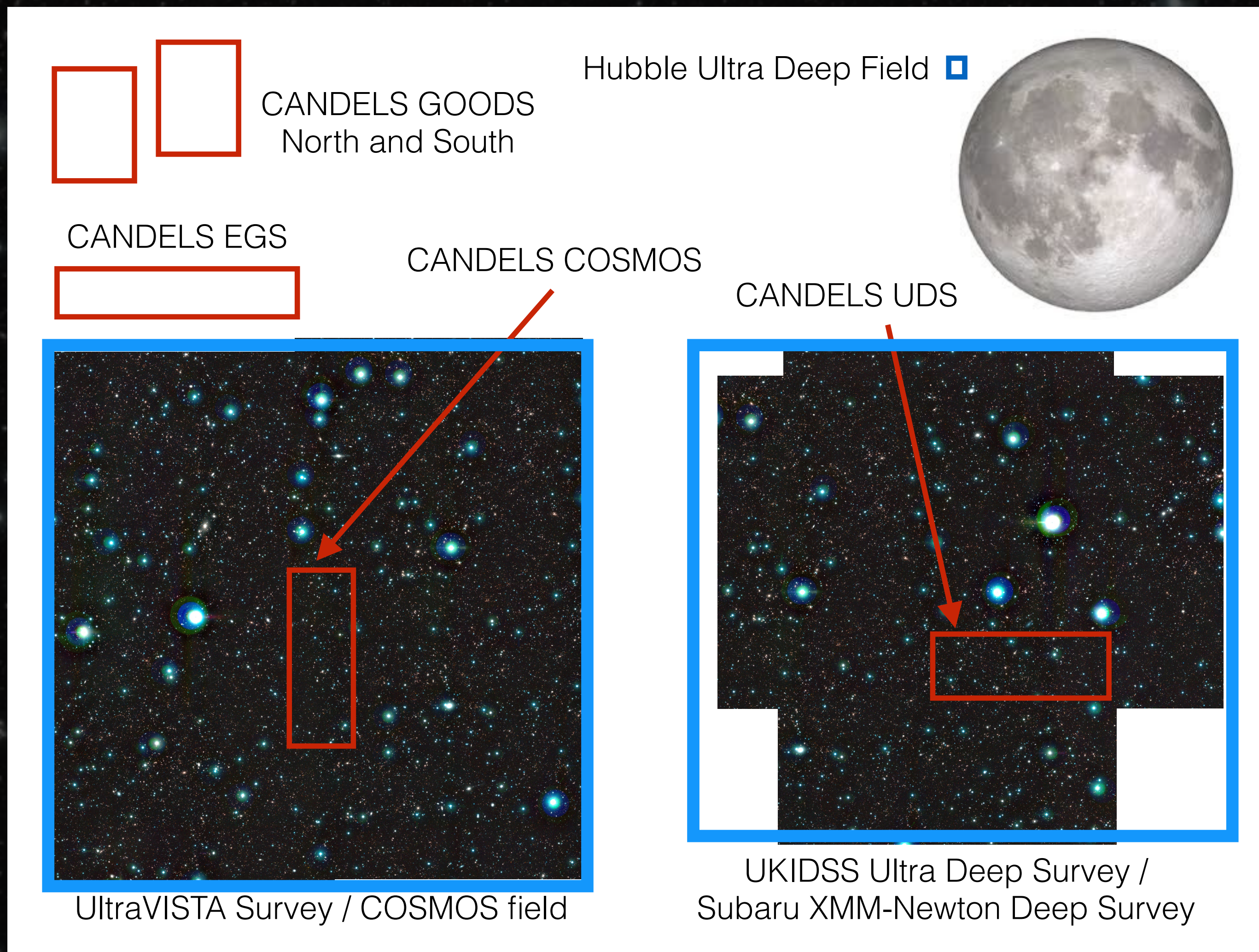





Rebecca Bowler
Hintze Fellow, University of Oxford

with Jim Dunlop, Ross McLure, Matt Jarvis, Derek McLeod, H. Furusawa, Y. Taniguchi and the UltraVISTA team

A family of surveys





- ★ Canada-France-Hawaii Telescope [Legacy Survey, 4 deg^2]
- ★ Suprime-Cam from Subaru [COSMOS/UDS/SDF+]
- ★ Hawk-I on the VLT
- ★ FourStar/Magellan-Baade Telescope (zFourge, medium-band filters)
- ★ Visible and Infrared Survey Telescope (VISTA)
- ★ UK infrared telescope (UKIRT)

Subaru/Suprime-Cam

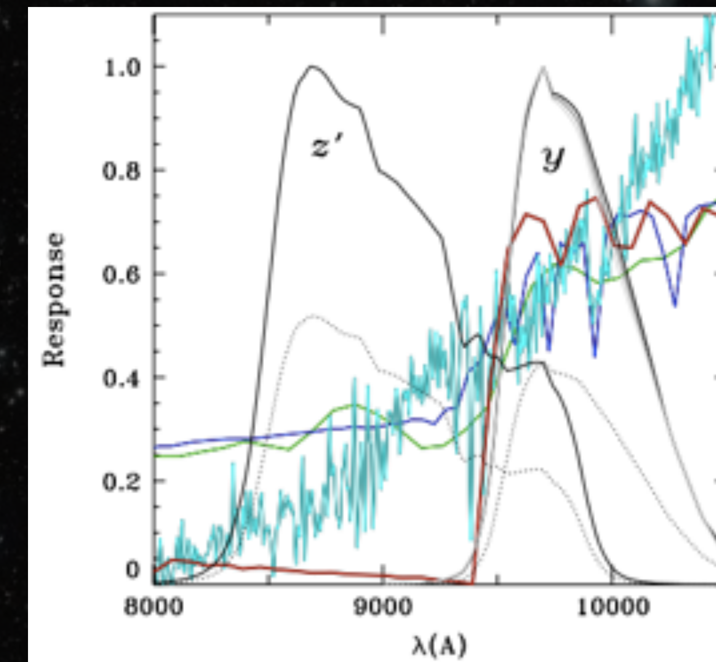
★ Subaru Deep Field [~0.25 deg²]

z ~ 5-6

e.g. Kashikawa et al. 2006
Jiang et al. 2013ab, 2016
Ota et al. 2008

z ~ 7

e.g. Ouchi et al. 2009
Ono et al. 2012
Ouchi et al. 2010



★ Subaru XMM-Newton Deep Survey (aka UKIDSS UDS) [~1 deg²]

e.g. McLure et al. 2006, 2009
Curtis-Lake et al. 2012, 2013
Rogers et al. 2014
Yoshida et al. 2006

e.g. Ouchi et al. 2010
Furusawa et al. 2016
Konno et al. 2014
Ono et al. 2010

★ COSMOS survey (+deep z'-band from Furusawa+16) [~2 deg²]

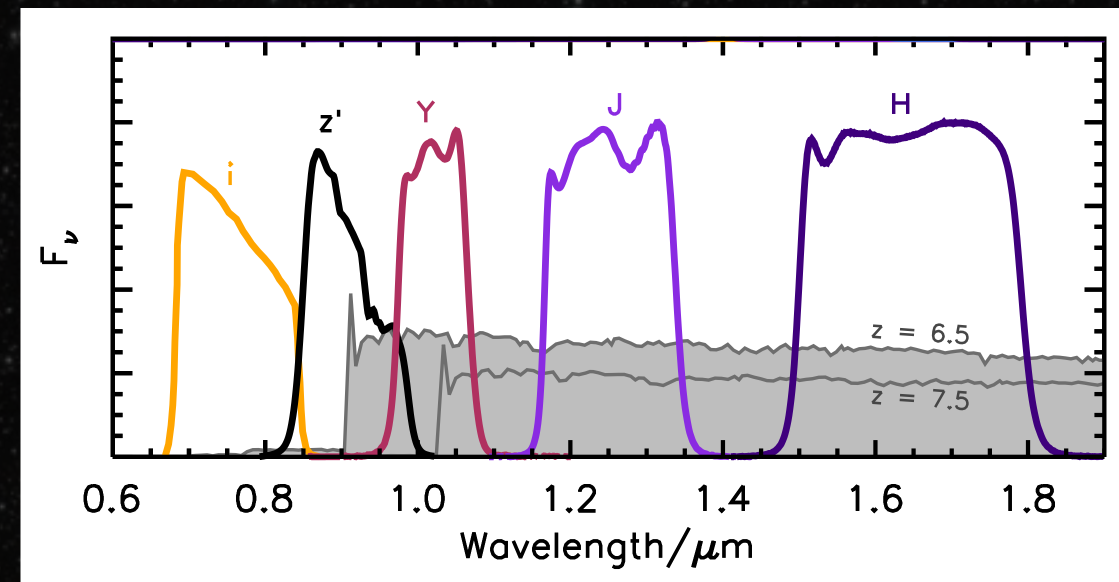
e.g. Willott et al. 2013
Bowler et al. 2015
VUDS: Le Fevre et al. 2014
Van der Burg et al. 2010

e.g. Taniguchi et al. 2009
Capak et al. 2011
Bowler et al. 2014
Matthee et al. 2015

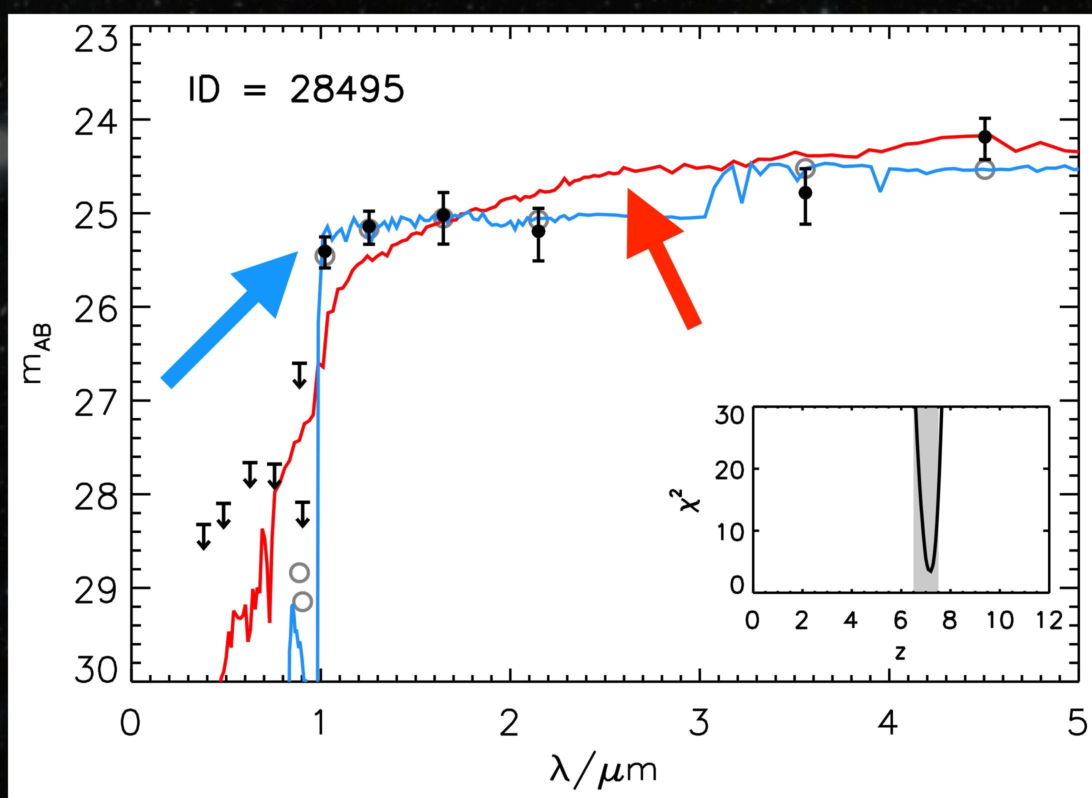
luminosity function | rest-frame UV slope | stellar pops. | Ly-a emitters | clustering | +++

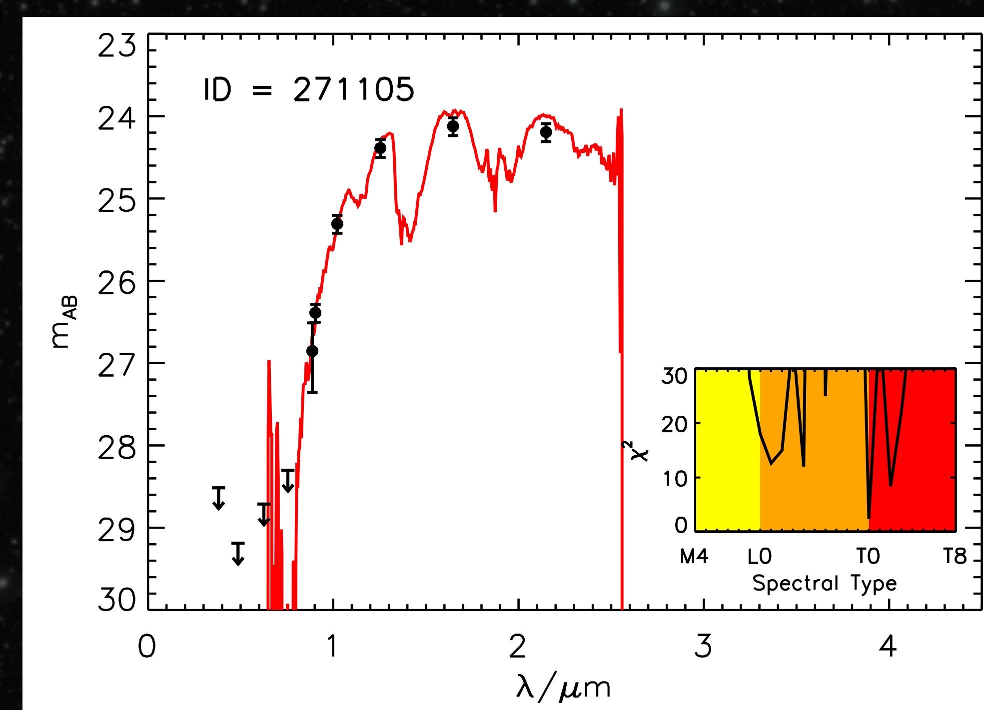
The key role of near-infrared data

★ Near-infrared essential for the detection of optical drop-outs!



★ And for the identification of contaminants…





High-z galaxy

Low-z galaxy

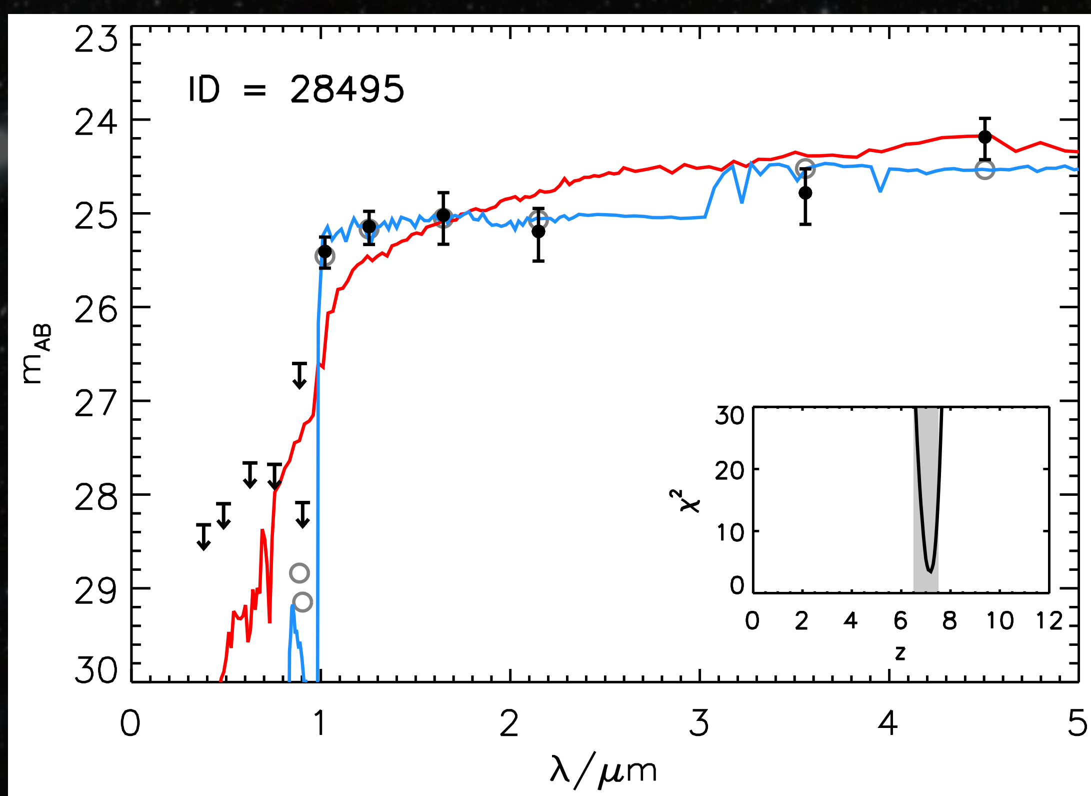
Galactic brown dwarf

The key role of near-infrared data

★ Deep optical **+** near-infrared photometry constrains high-z nature

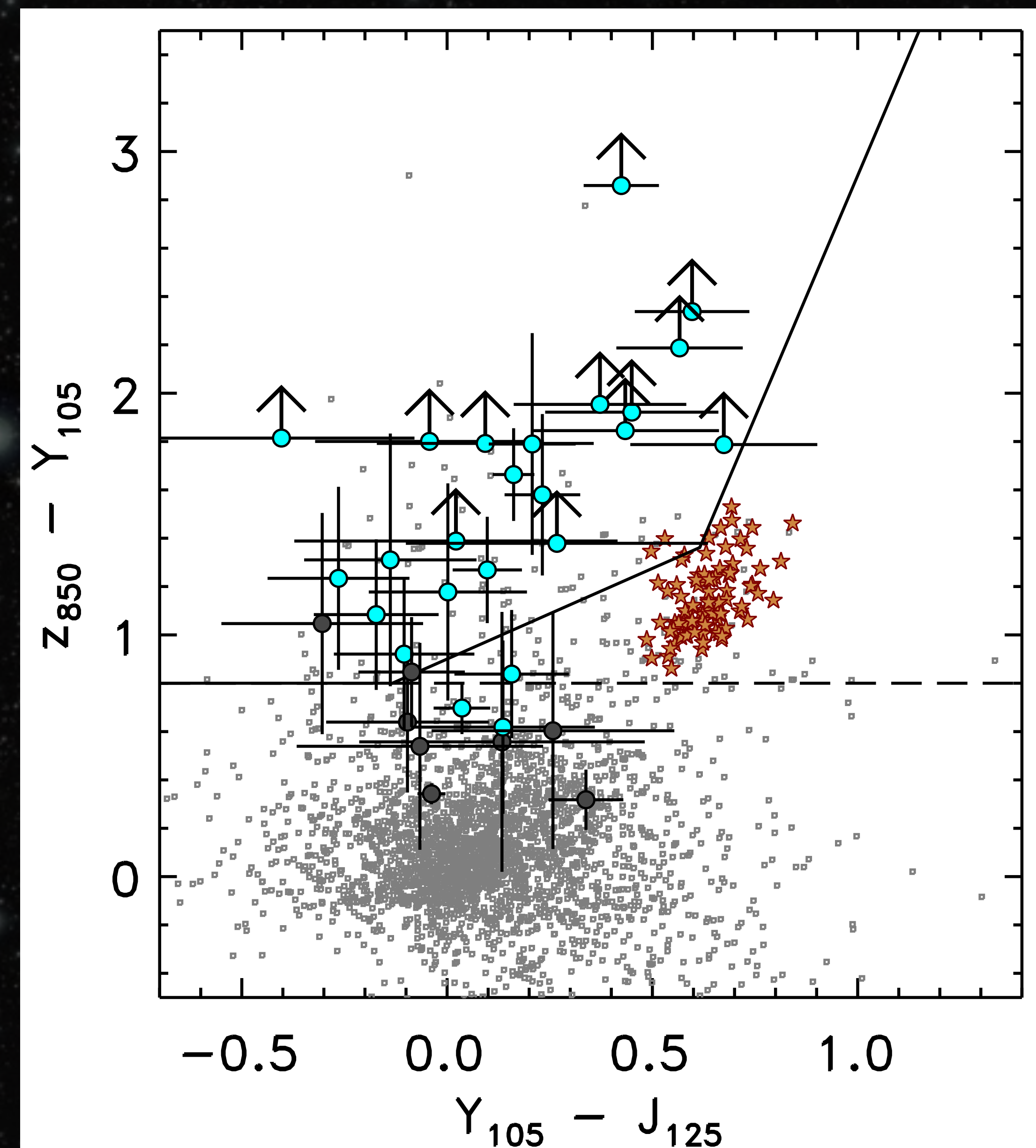
Strong break **+** blue continuum

Spitzer/IRAC removes red interlopers



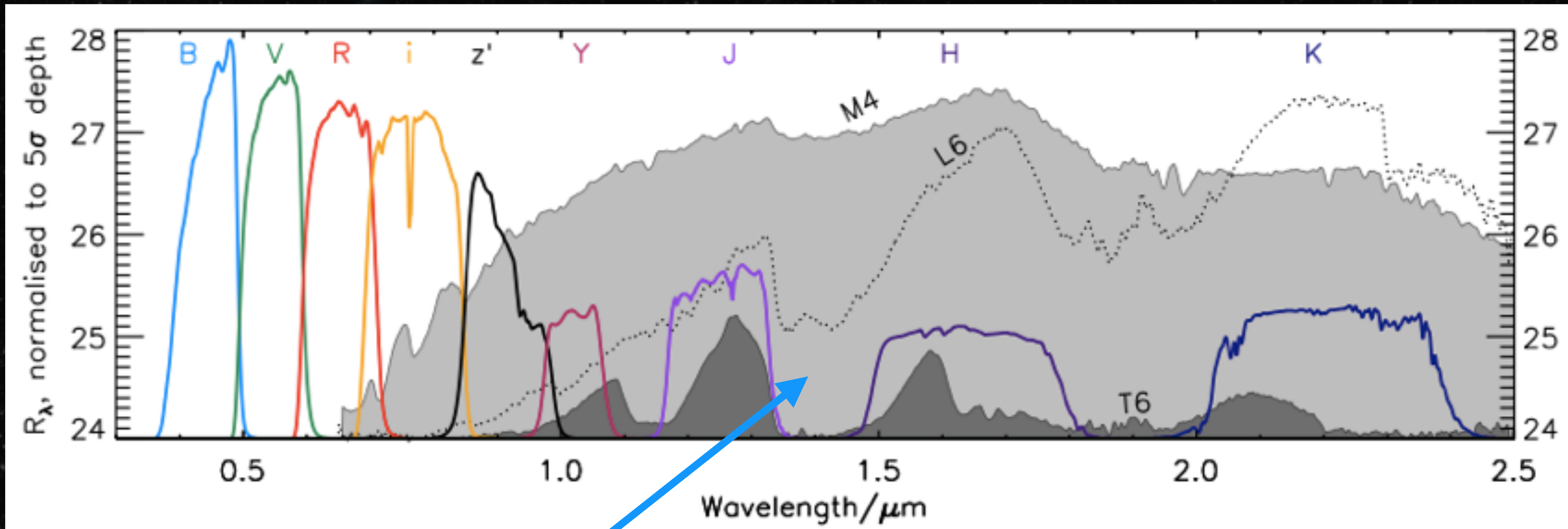
High-z galaxy

Low-z galaxy

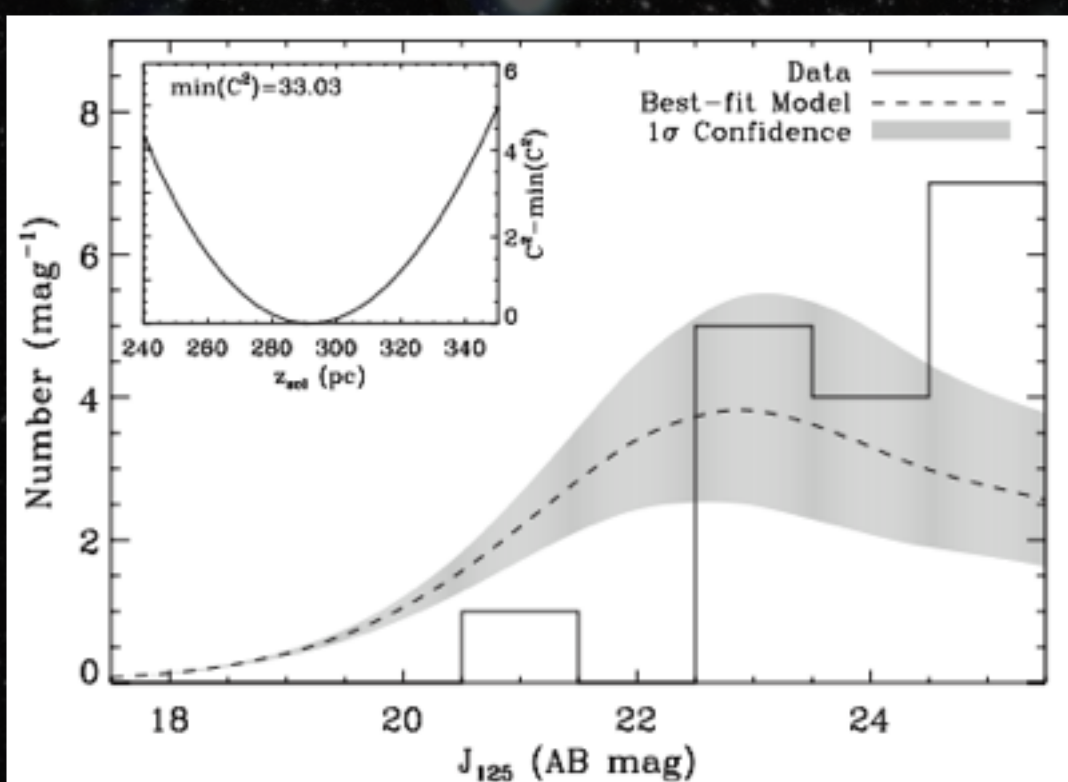


Finkelstein et al. 2010

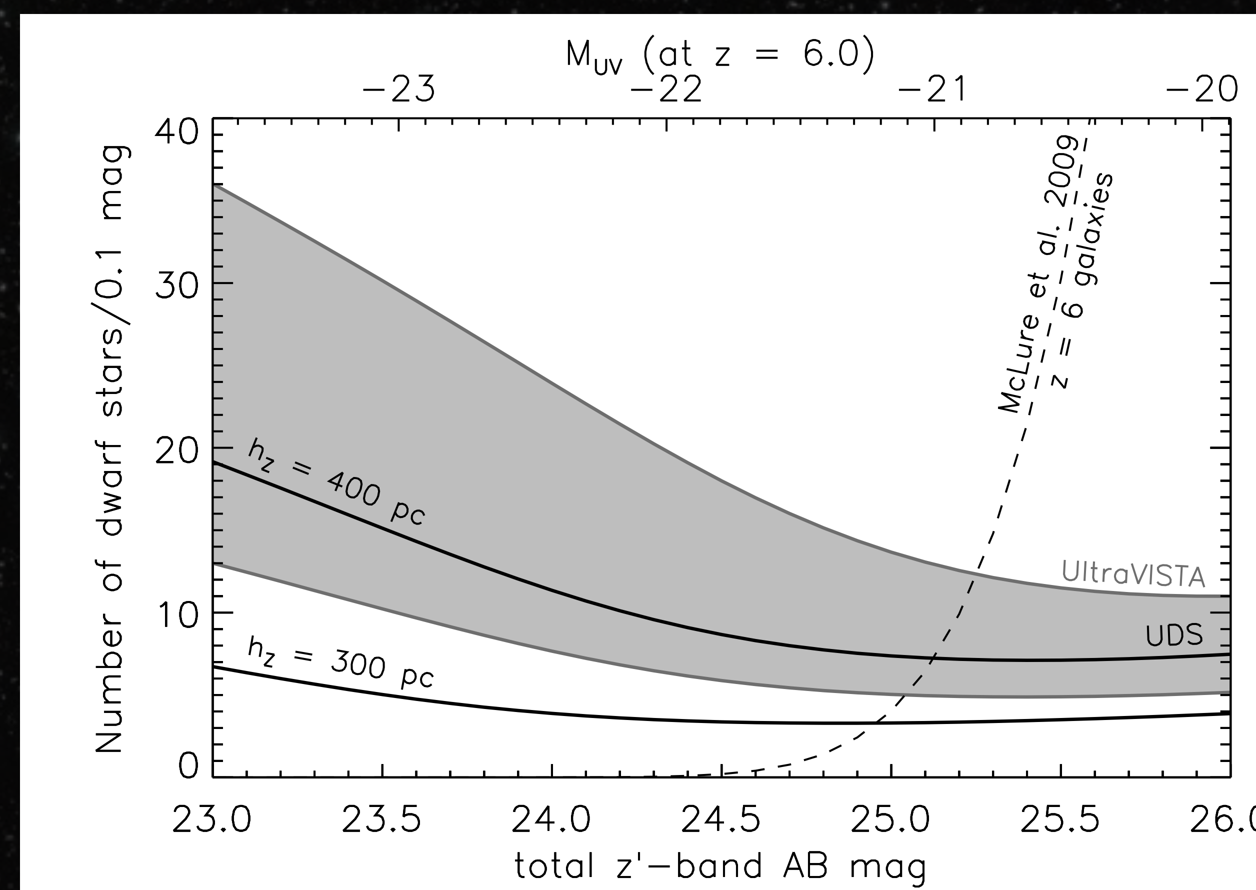
Contamination by cool galactic brown dwarfs



Water + methane absorption



Ryan et al. 2011



Bowler et al. 2015

Why study the brightest galaxies?

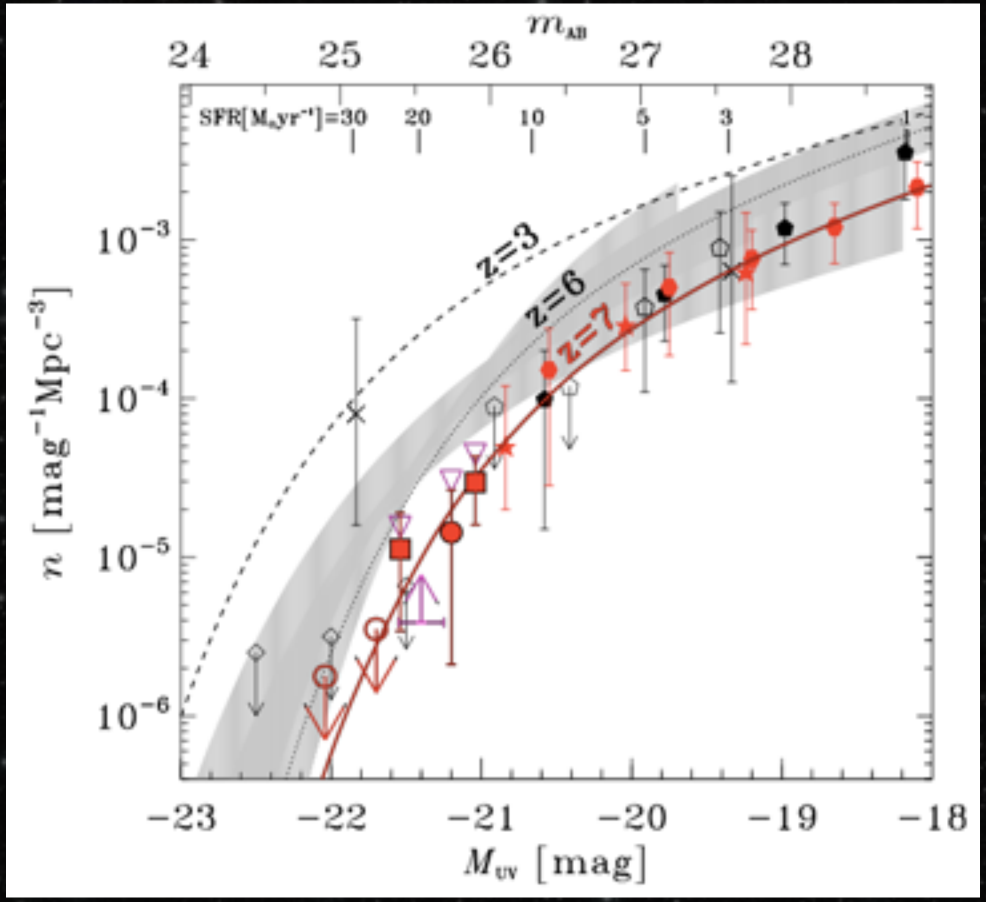
★ Constraining the luminosity function

★ Probing astrophysics at high-redshift

★ Accessible laboratories into the EoR

Why study the brightest galaxies?

★ Constraining the luminosity function



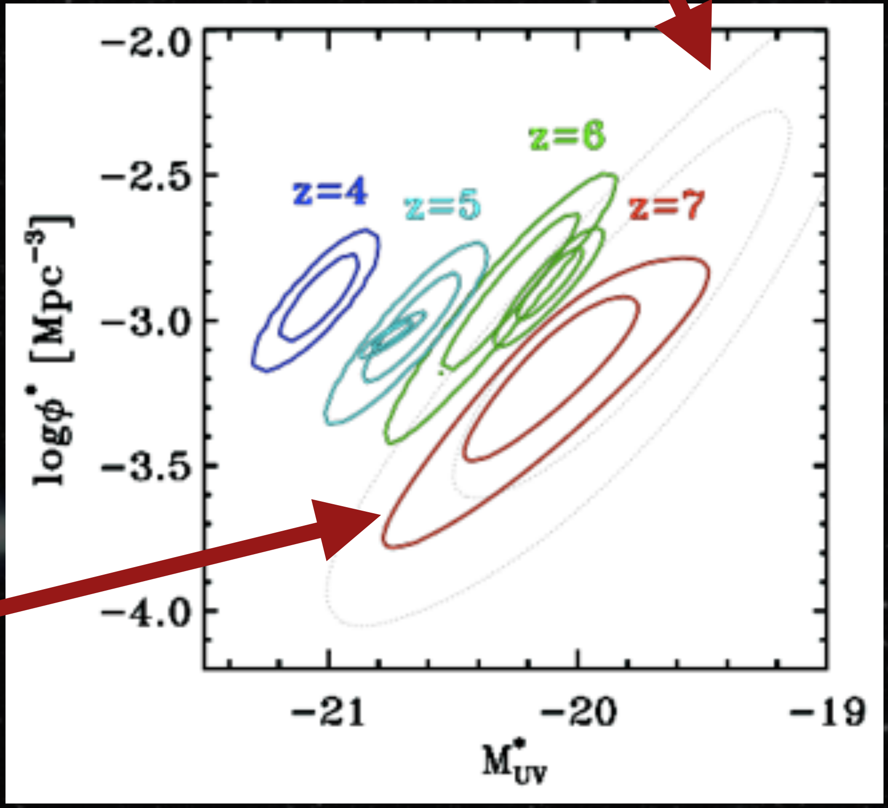
SDF + GN
Ouchi et al. 2009

★ Probing astrophysics at high-redshift

Only HST

★ Accessible laboratories into the EoR

Including ground-based data (Subaru Deep Field)



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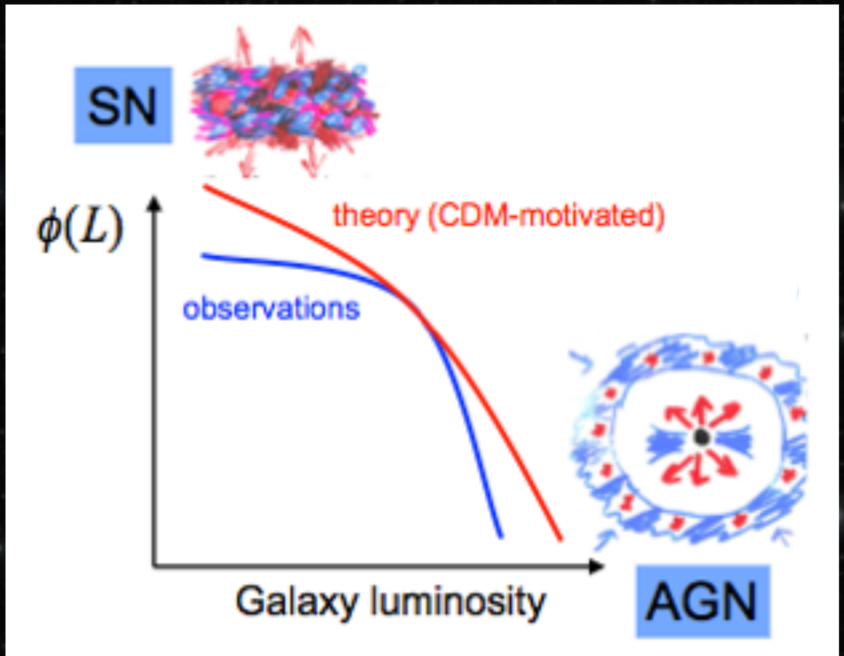
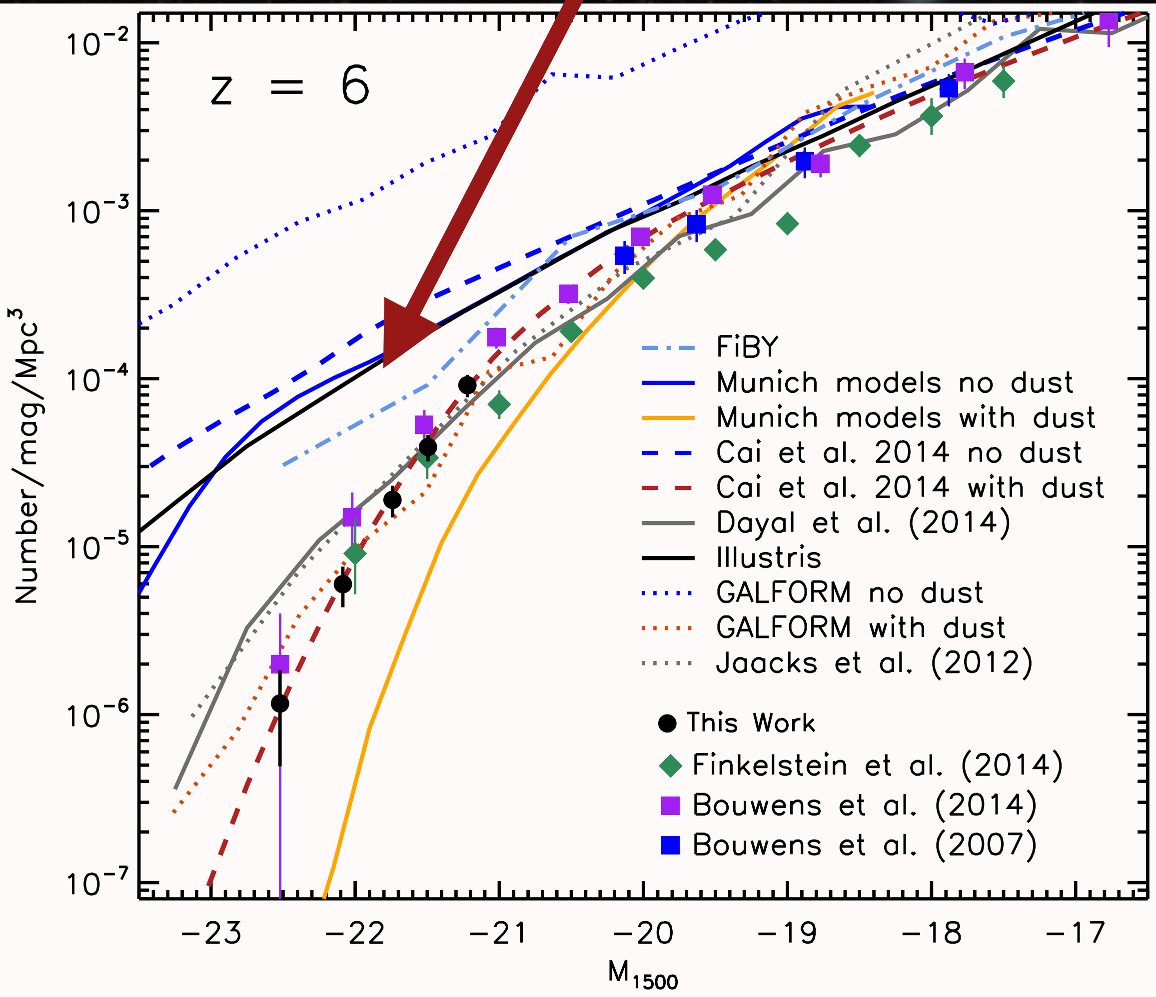


Silk & Mamon 2012

Simulations



Bowler et al. 2015

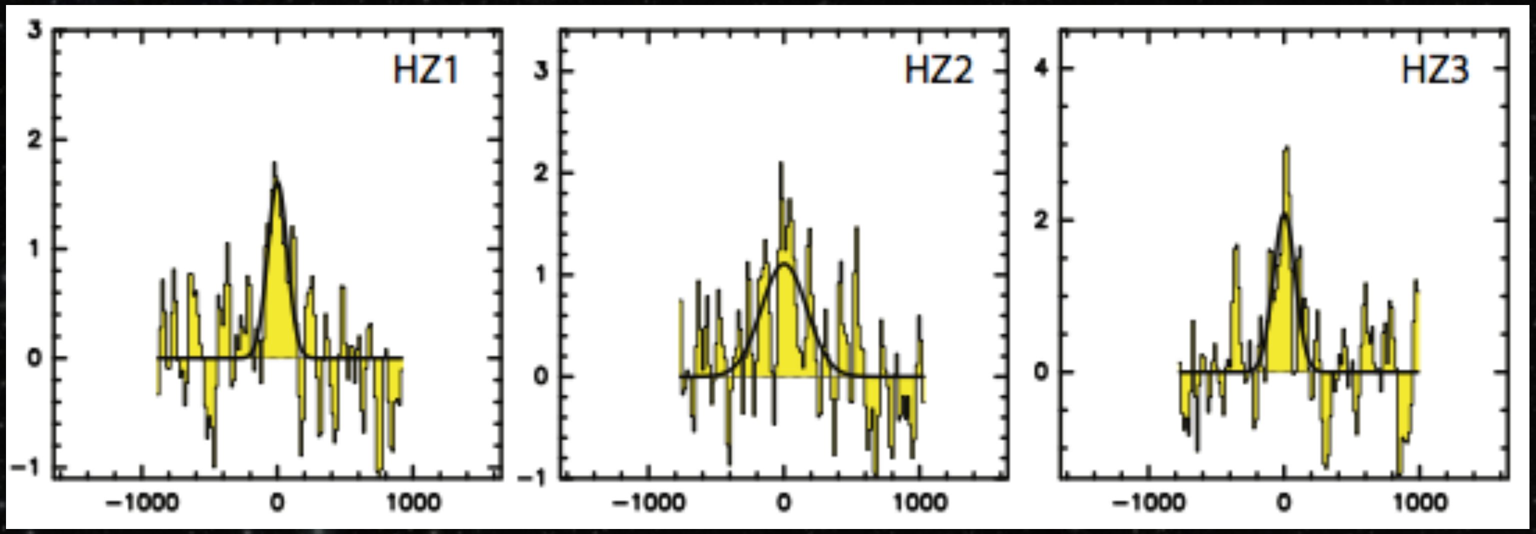
Why study the brightest galaxies?

★ Constraining the luminosity function

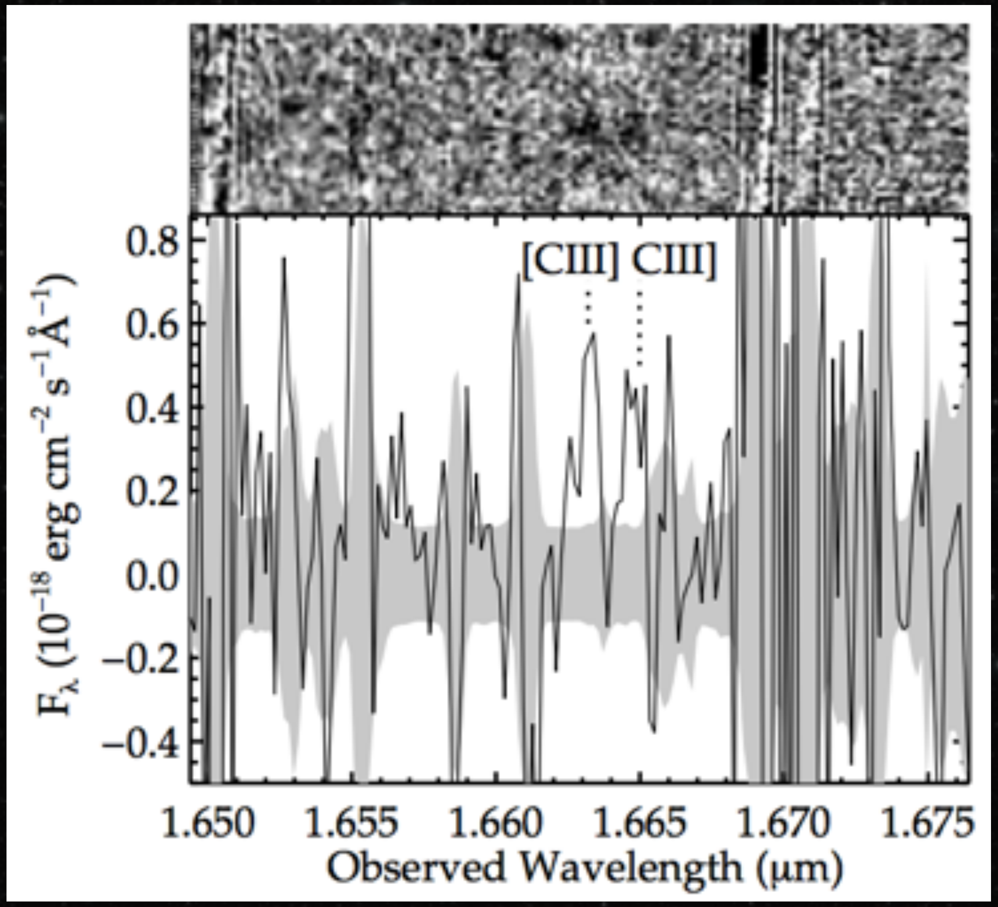
★ Probing astrophysics at high-redshift

★ Accessible laboratories into the EoR

[CII] 158 microns (z = 5-6) Capak et al. 2015

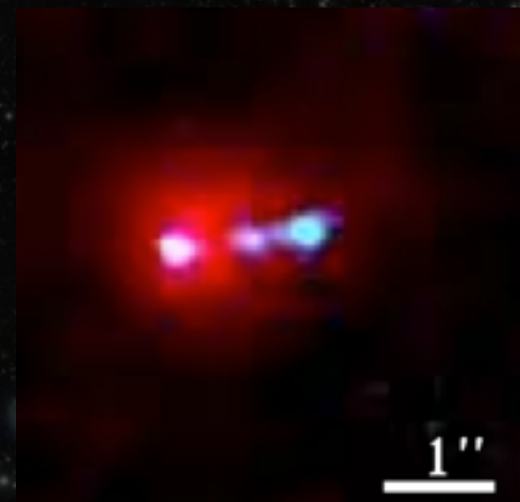


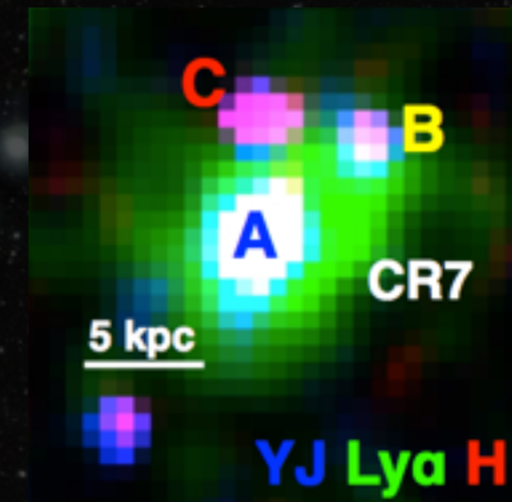
Stark et al. 2014, 2017

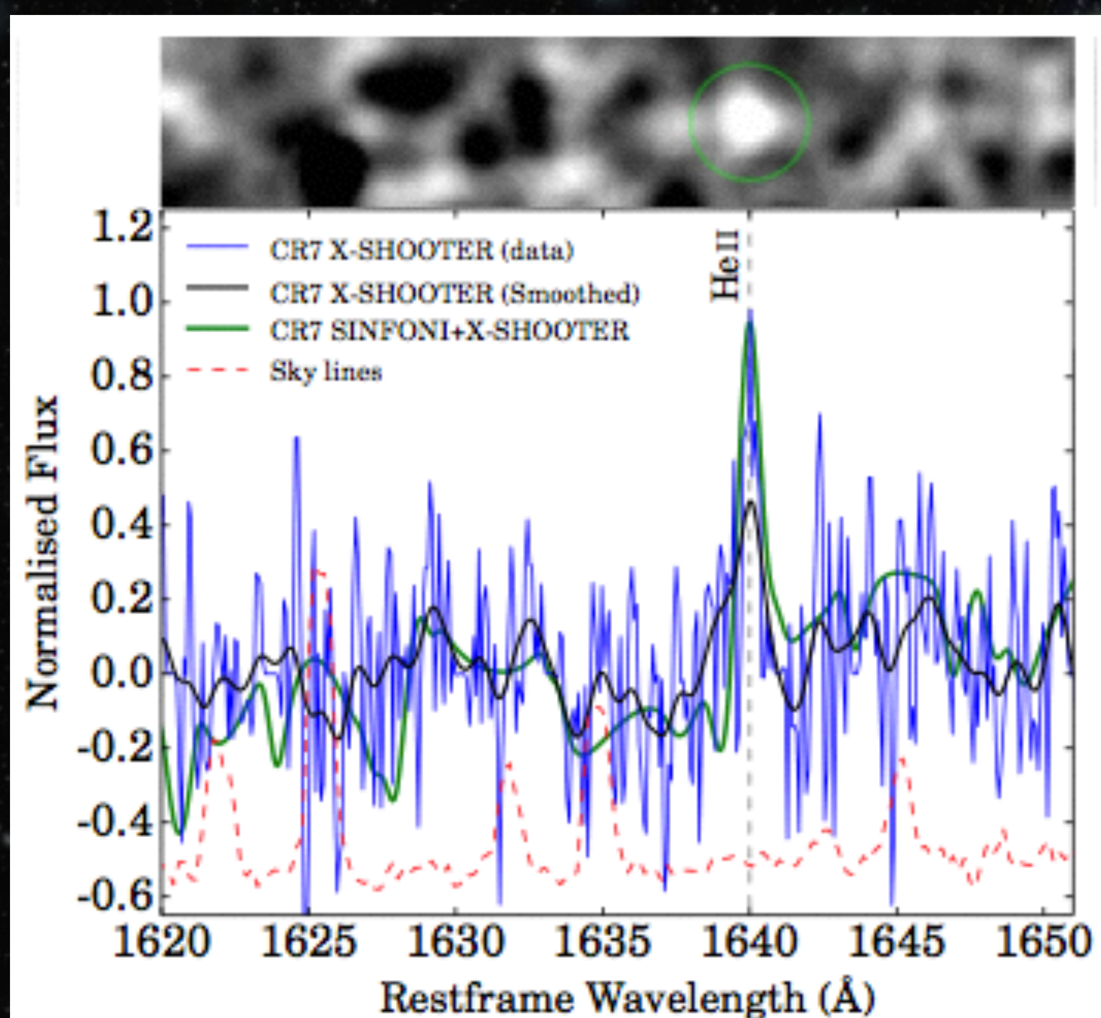


Why study the brightest galaxies?

name	Himiko	CR7
location	SXDS/UDS	COSMOS
special features	strong Lya > 200A triple merger system	strong Lya > 200A narrow HeII emission
	Ouchi+09,13	Sobral+15







➡ Pop III ?

➡ DCBH ?

➡ other ?

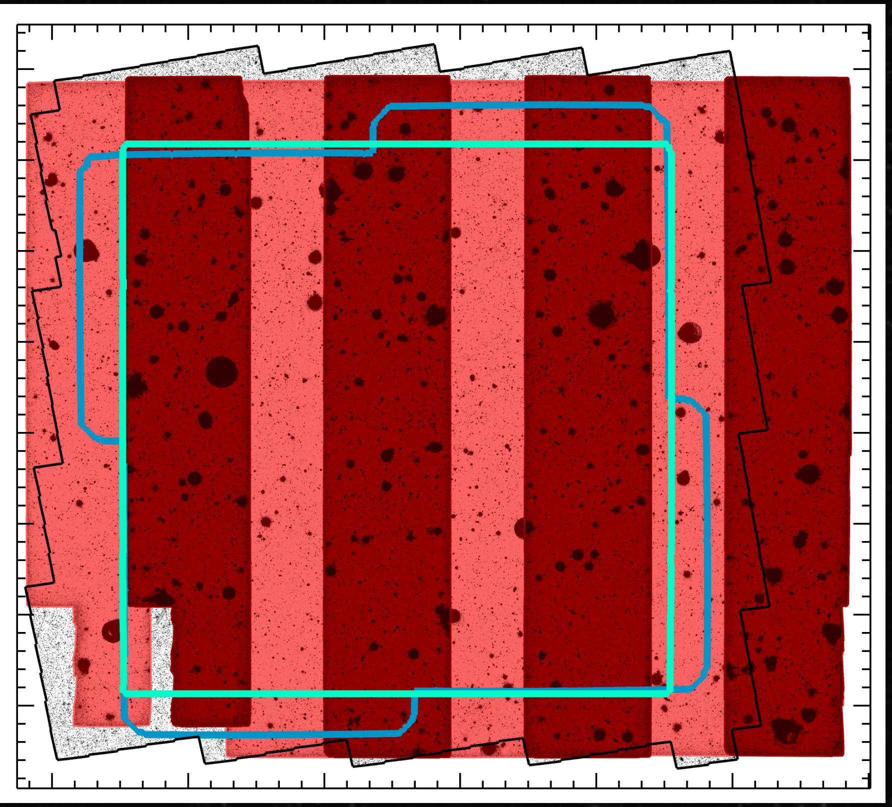
Sobral et al. 2015
Visbal et al. 2016
Pallottini et al. 2015
Hartwig et al. 2015
Agarwal et al. 2016
Smidt et al. 2016
Smith et al. 2016
Dijkstra et al. 2016
Bowler et al. 2016b

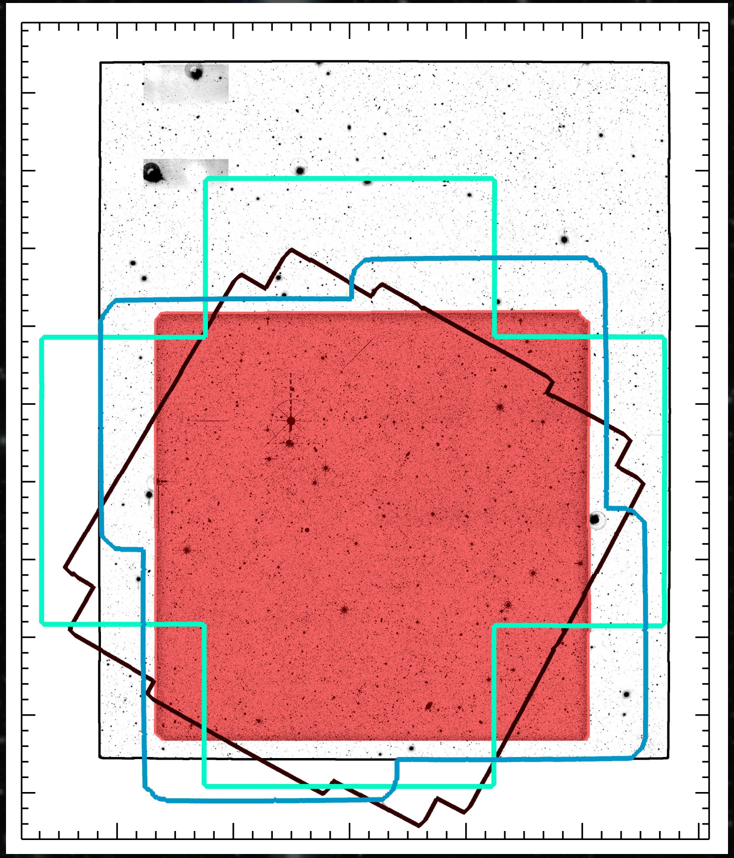
+ emission line results from:
Roberts-Borsani et al. 2016,
Stark et al. 2017, Zitrin et al. 2015

Finding z ~ 7 LBGs in the COSMOS + UDS

UltraVISTA/COSMOS

filters	telescope/program	AB 5σ depth
u*, g, r, i, z	CFHTLS	~ 27
i (814)	*HST*/ACS	~ 27
z’	Subaru	~ 26.5
Y, J, H, Ks	UltraVISTA DR2	~ 24-25, 25-26
3.6µm, 4.5µm	*Spitzer*/SPLASH	~ 25



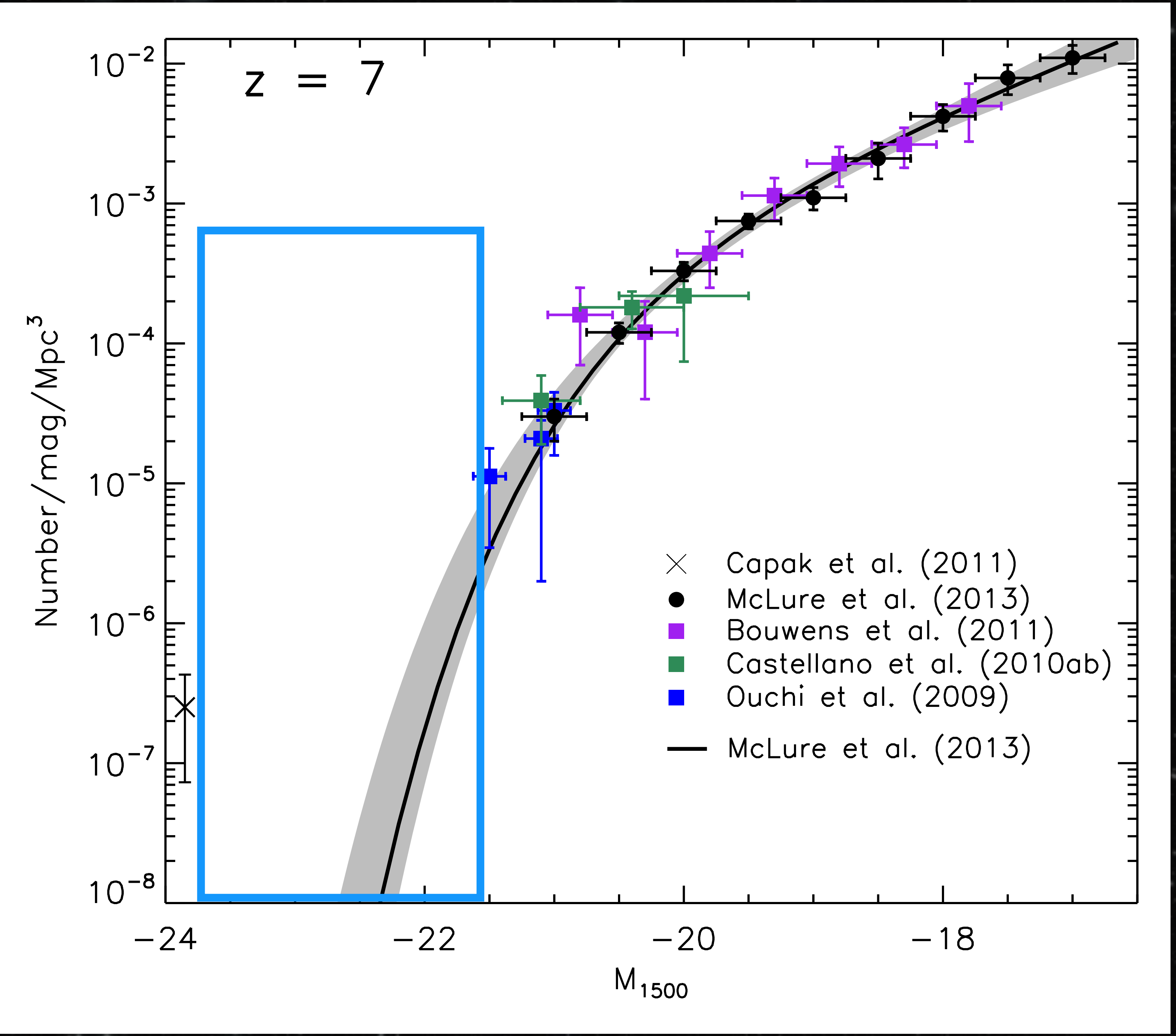


UDS/SXDS

filters	telescope/program	AB depth
B, V, R, i	Subaru/SXDS	~ 27
z’	Subaru (HF+16)	~ 26.5
Y	VISTA VIDEO	~ 25
J, H, K	UKIRT/UKIDSS	~ 25-26
3.6µm, 4.5µm	*Spitzer*/SPLASH	~ 25

The bright-end of the z ~ 7 luminosity function

Need wide-area, near-IR surveys!

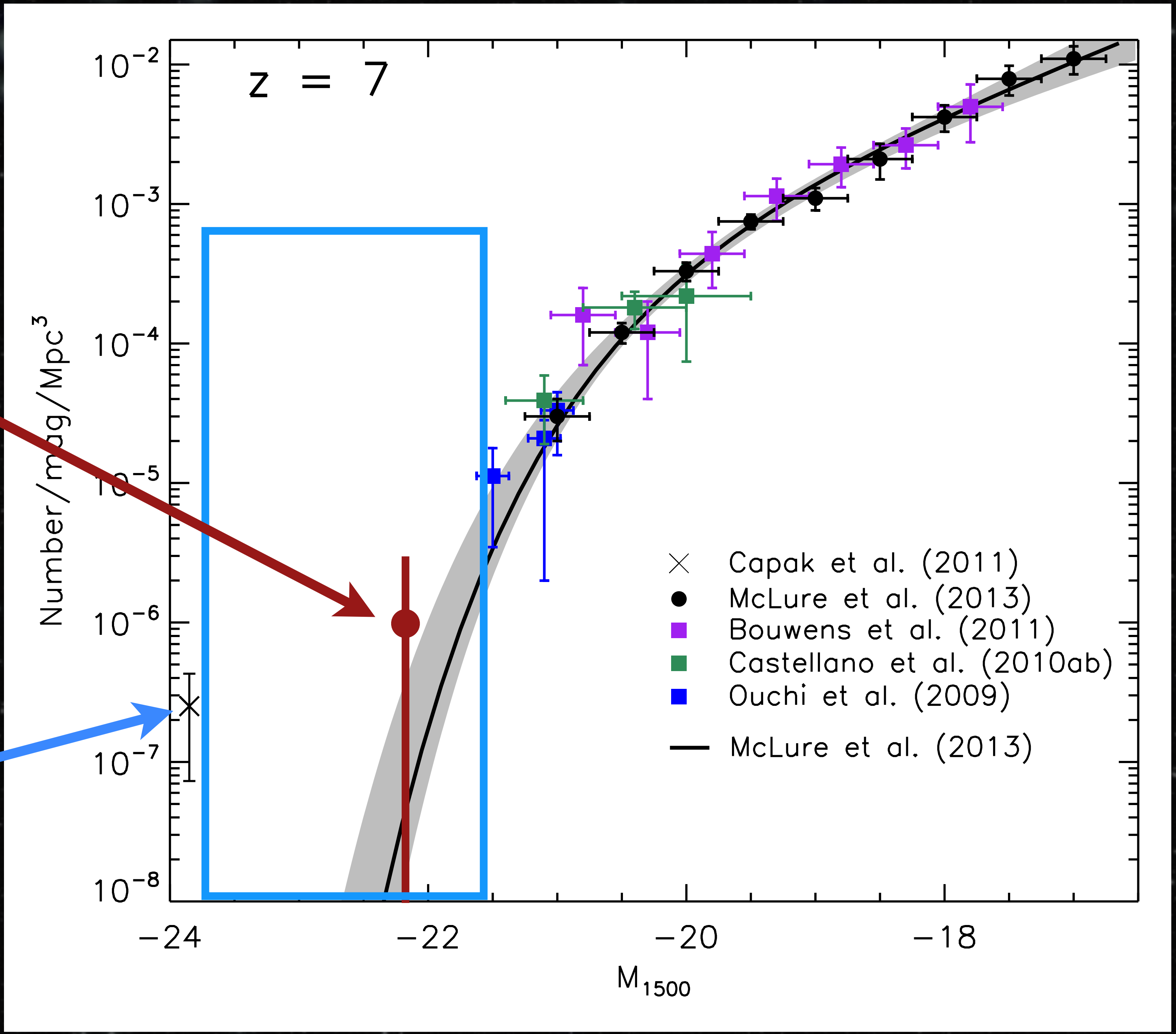


The bright-end of the z ~ 7 luminosity function

Need wide-area, near-IR surveys!

Brightest point from full CANDELS only ~ 1 galaxy

Previous CFHT/ UKIRT data not deep enough ("LBGs" all at z ~ 2)



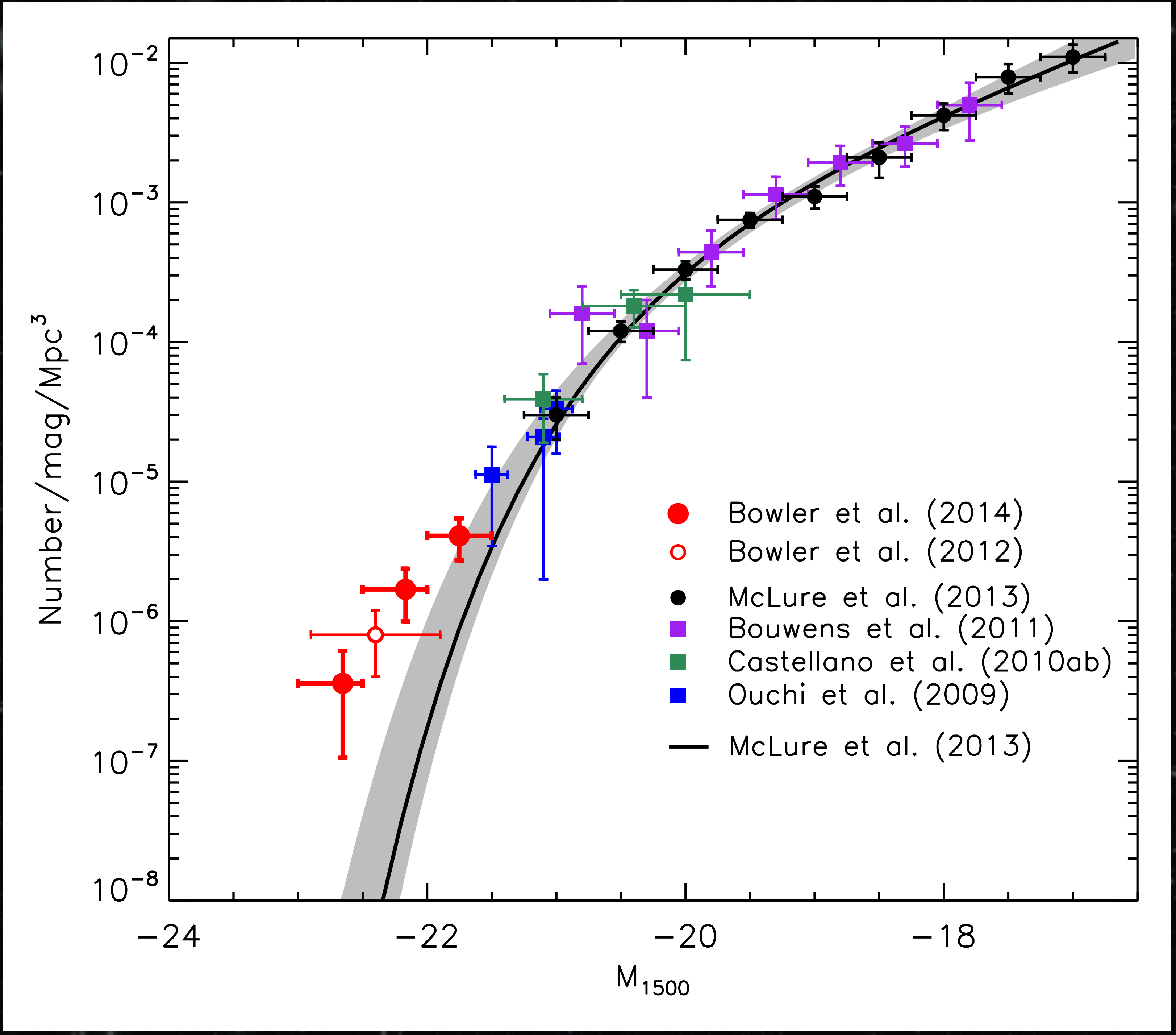
The bright-end of the z ~ 7 luminosity function

UltraVISTA DR2 + UDS/SXDS

1.65 sq. degrees

34 galaxies (including 9/10 Bowler et al. 2012 objects)

0.5-1 mag deeper near-IR data than DR1



The bright-end of the z ~ 7 luminosity function

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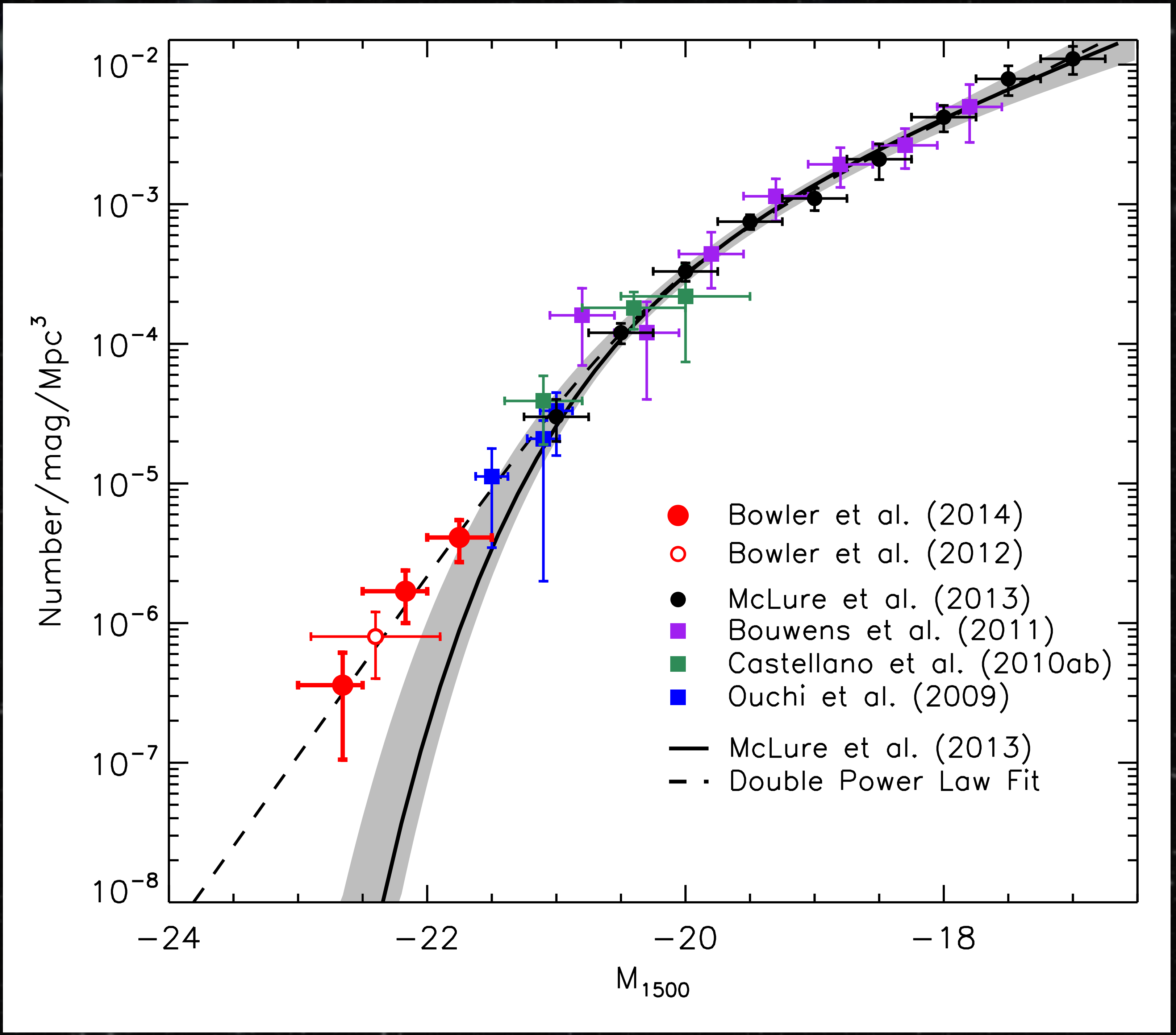
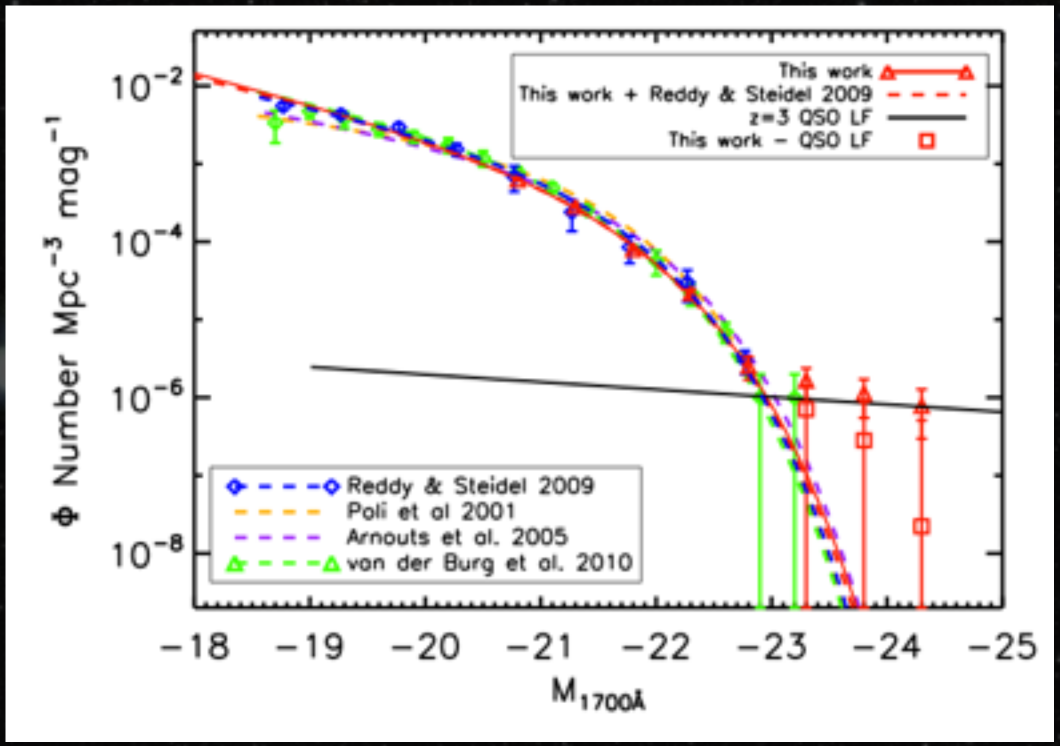
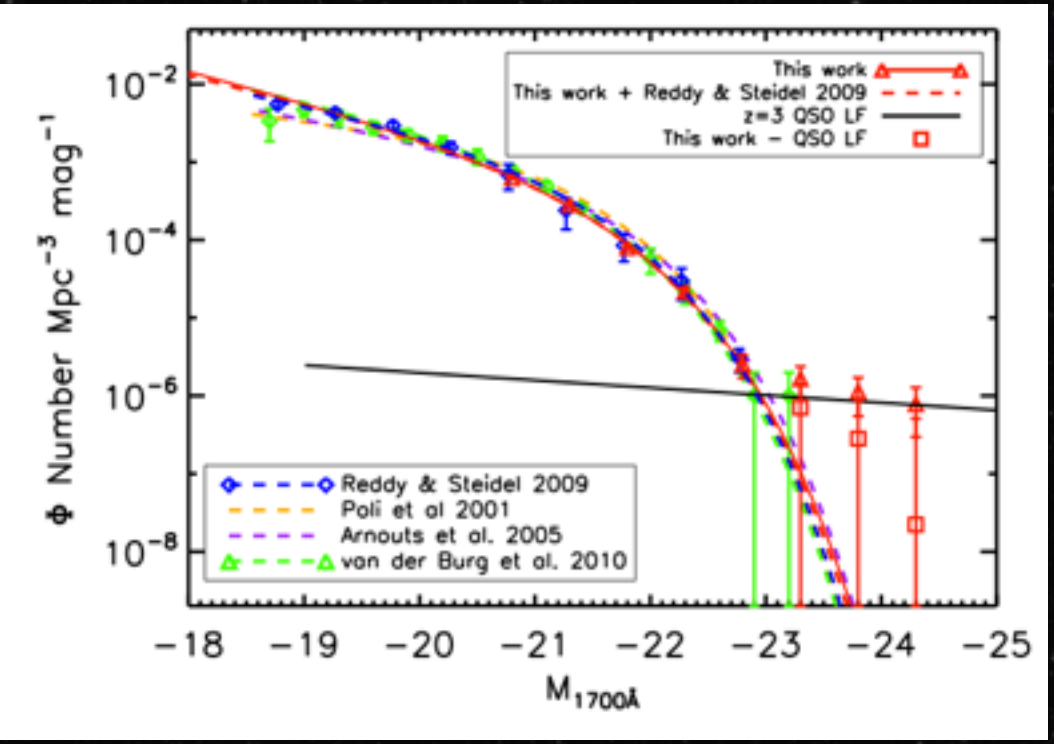


Quasar contamination / lensing

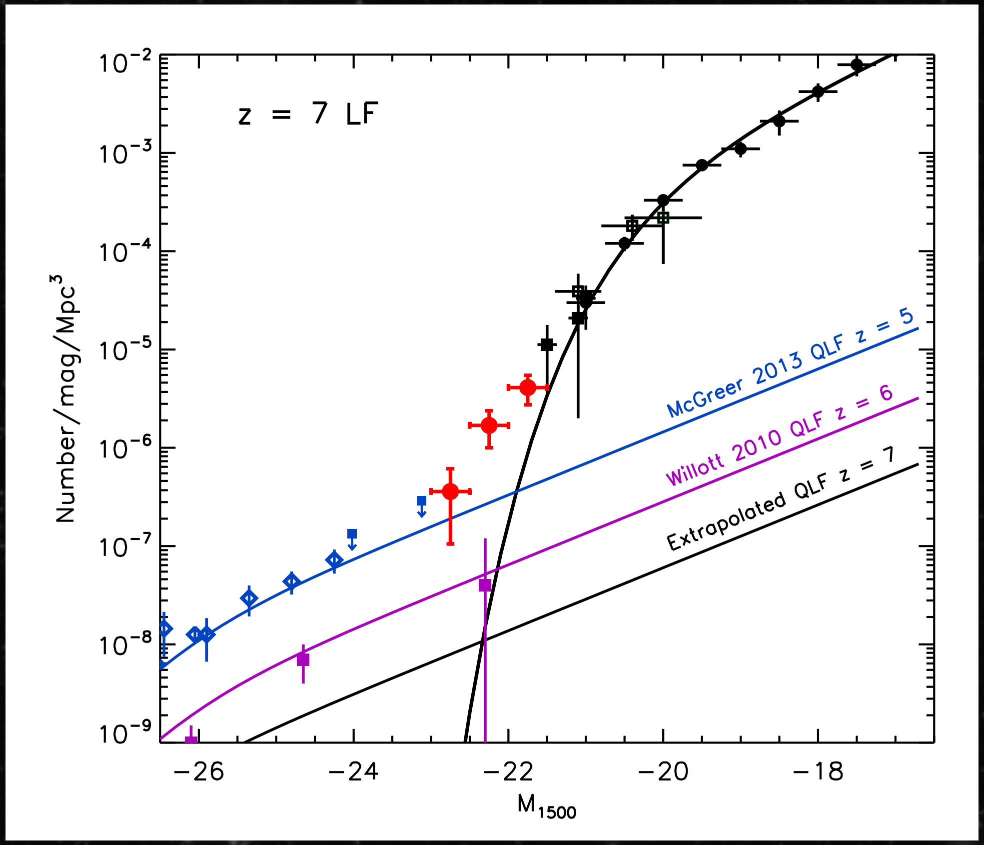


z = 3 LF from
Bian et al. 2013

Quasar contamination / lensing

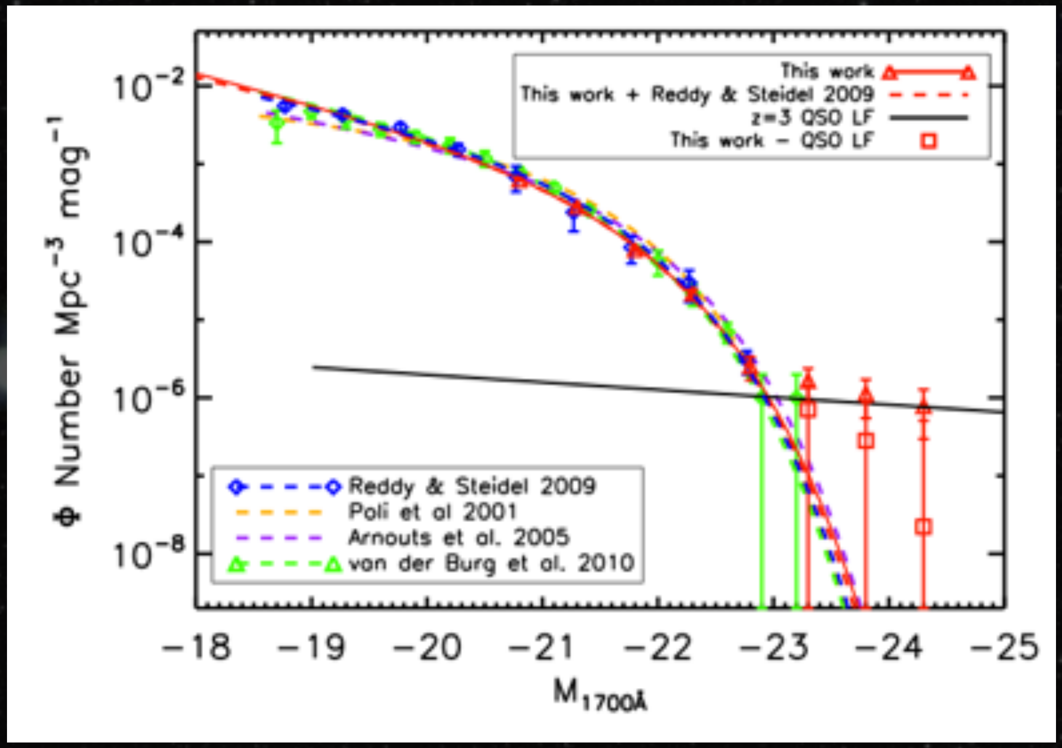


z = 3 LF from Bian et al. 2013

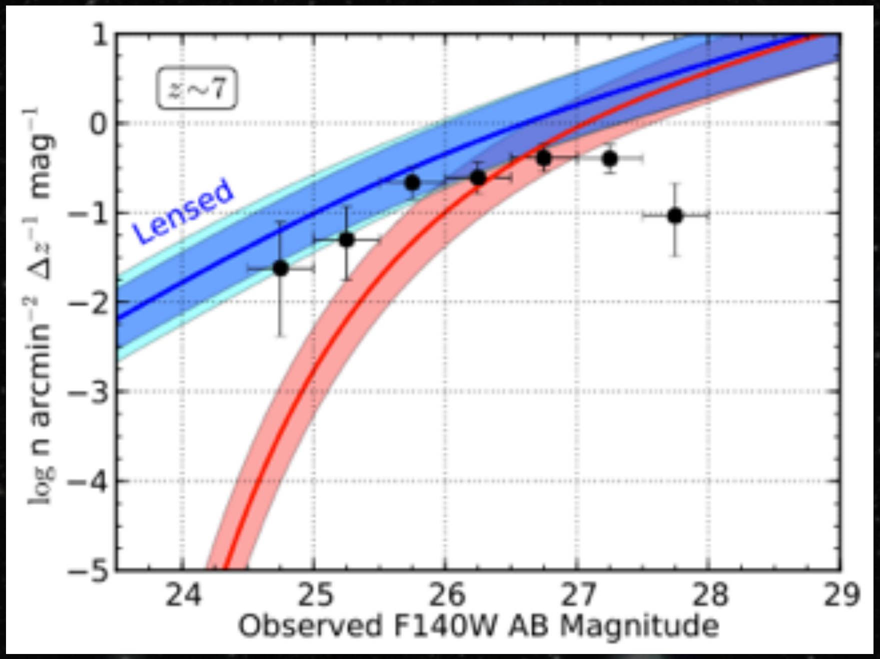


- Quasar contamination negligible

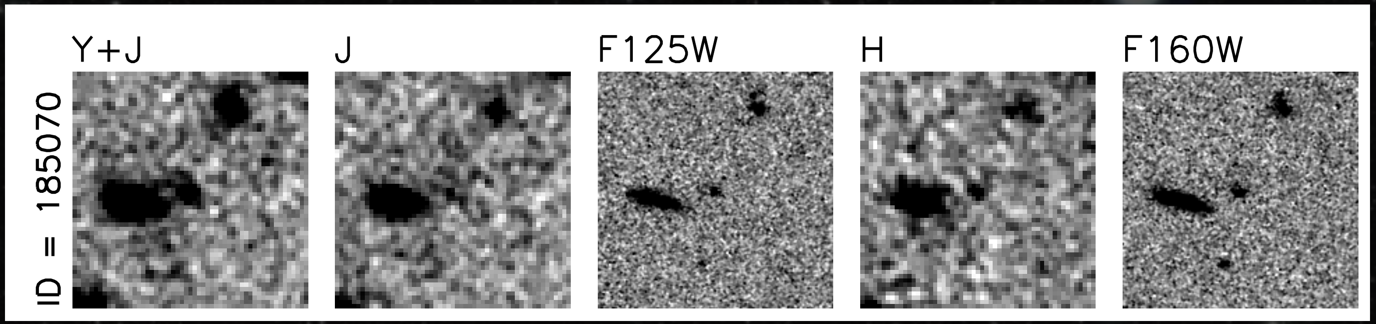
Quasar contamination / lensing

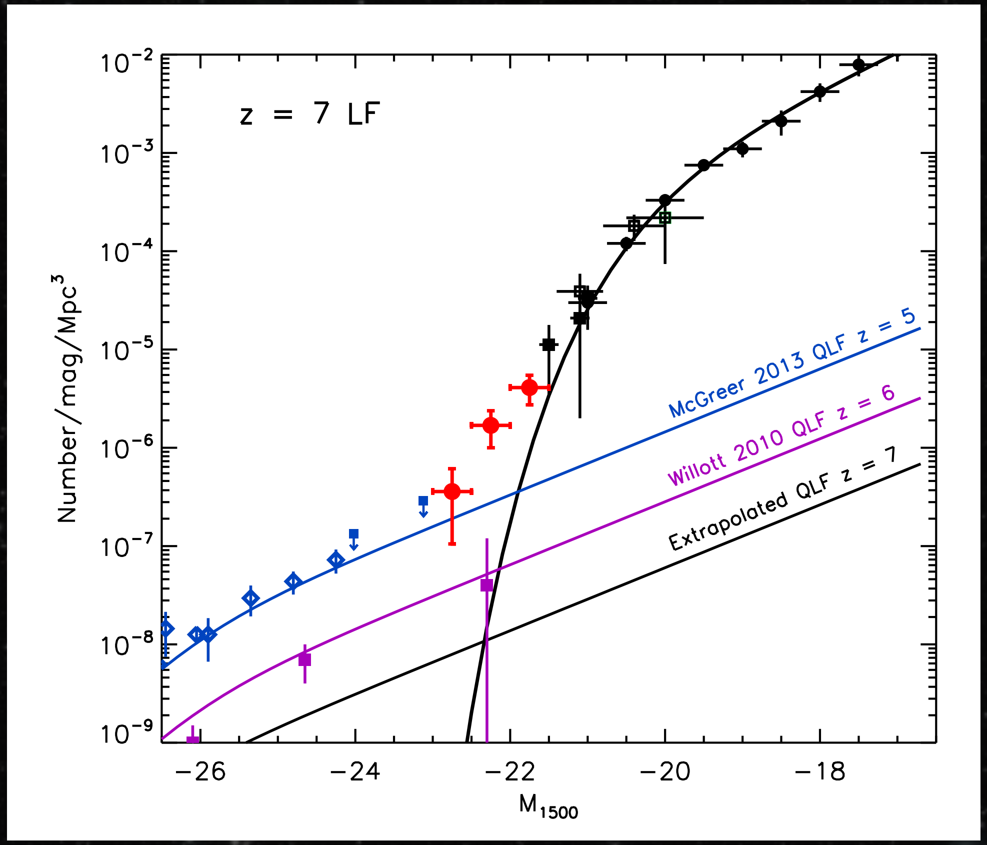


z = 3 LF from
Bian et al. 2013



Effect of strong lensing
from a galaxy cluster
Bradley et al. 2013





- Quasar contamination negligible
- Moderate gravitational lensing by foreground objects of ~ 0.1 mag is common (0.3 mag maximum)

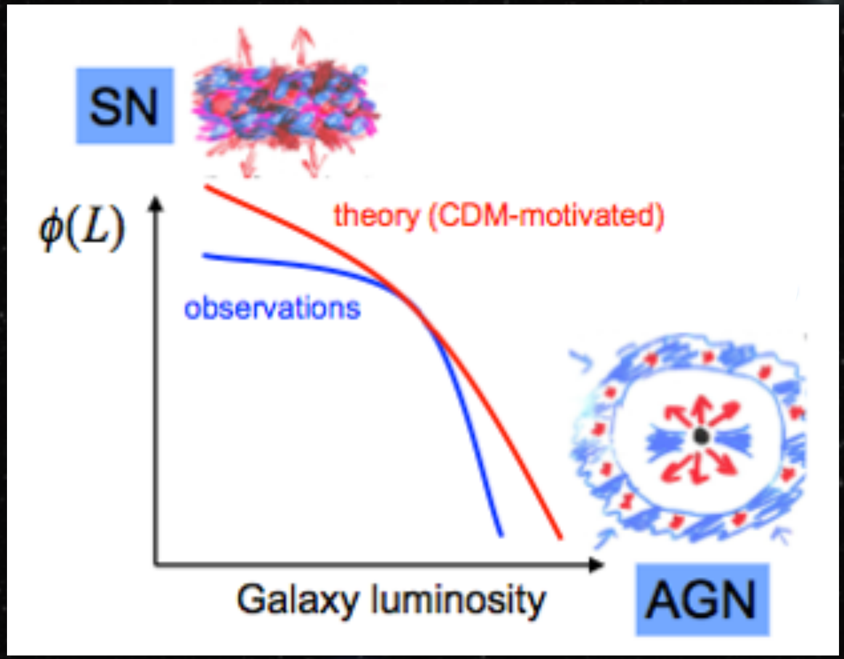
see also Mason et al. 2015, Fialkov et al. 2015, Barone-Nugent et al. 2015

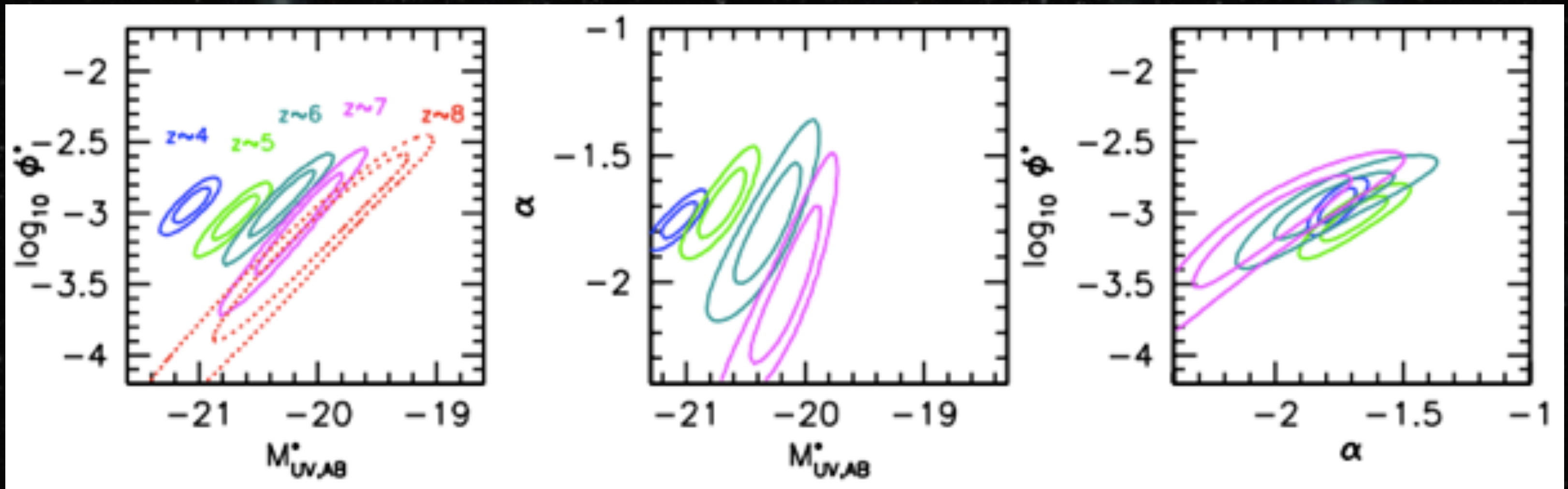
The evolution of the LF from z = 5-7

★ Is there an evolution in shape?

-> As predicted by onset of **feedback**?
-> Or from simulations which impose significant **dust** obscuration to match UV LF observations?

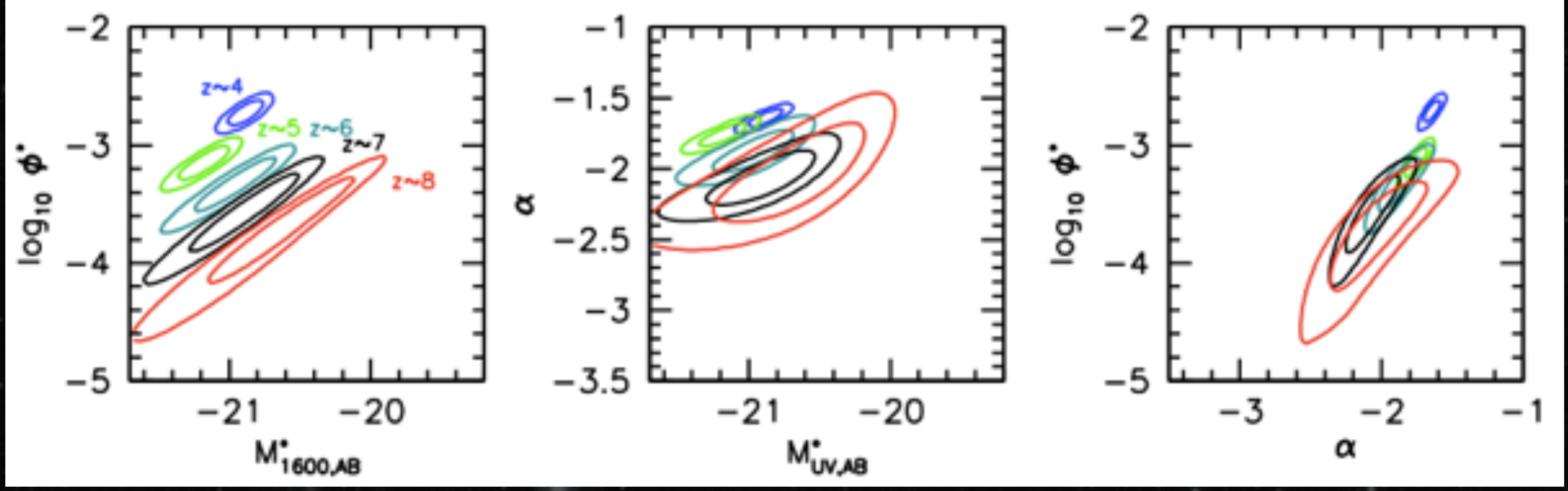
★ What is the form of the evolution?





Luminosity (M*) evolution?

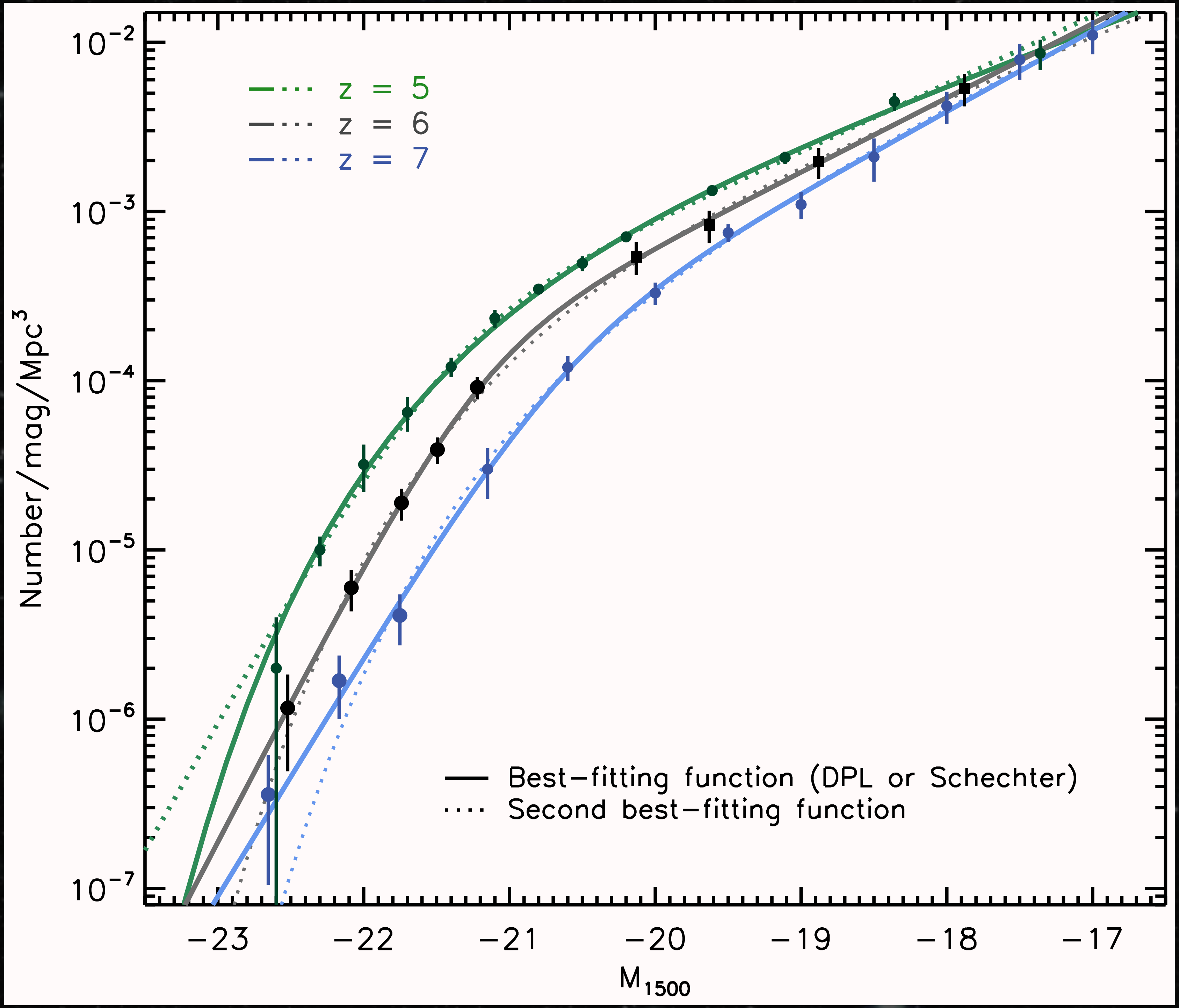
Bouwens et al. 2011
(also e.g. McLure et al. 2009)



Density (phi*) evolution?

Bouwens et al. 2015
(also Finkelstein et al. 2015)

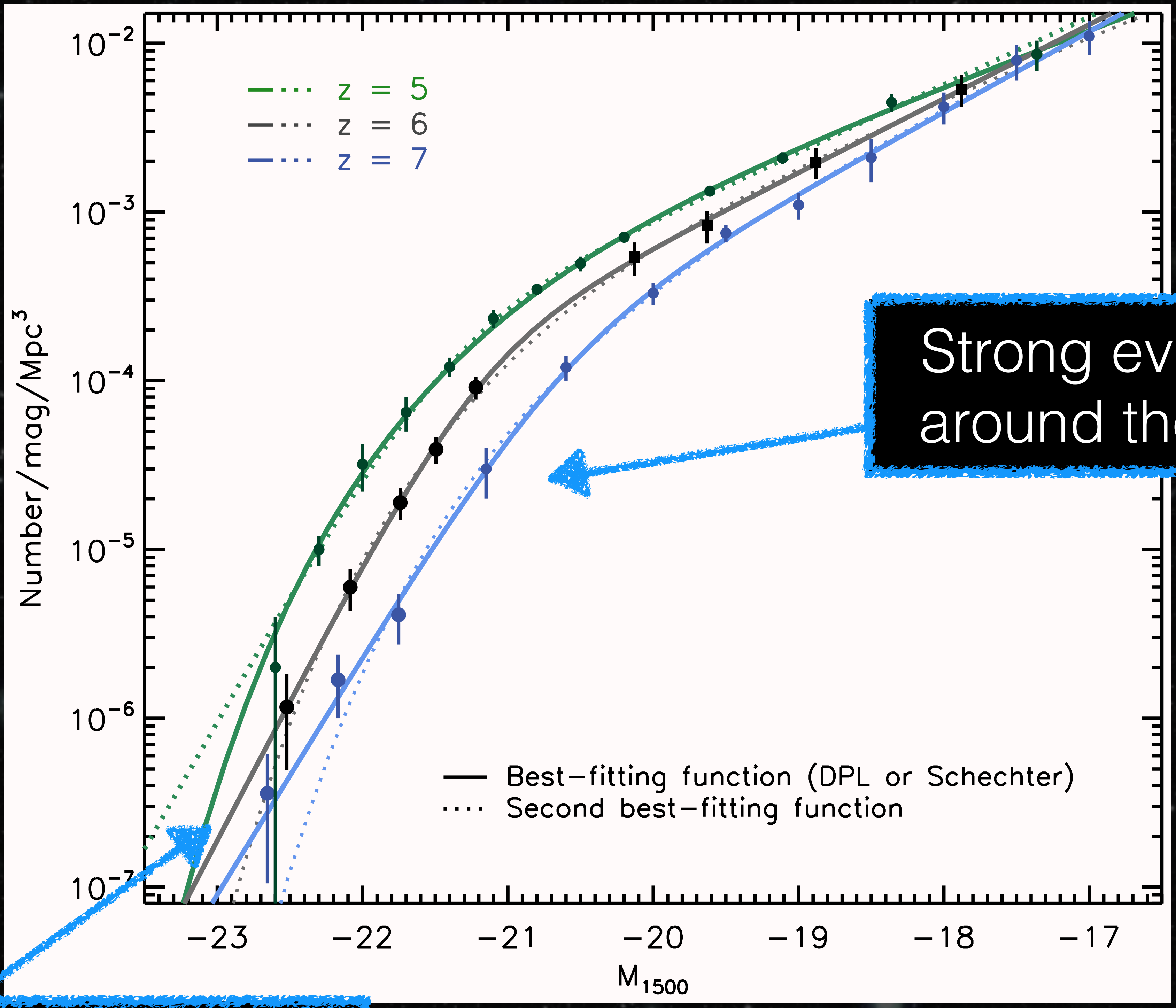
The evolution of the LF from z = 5-7



CFHTLS @ z = 5, COSMOS/UDS @ z = 6-7

(Van der Burg et al. 2010)

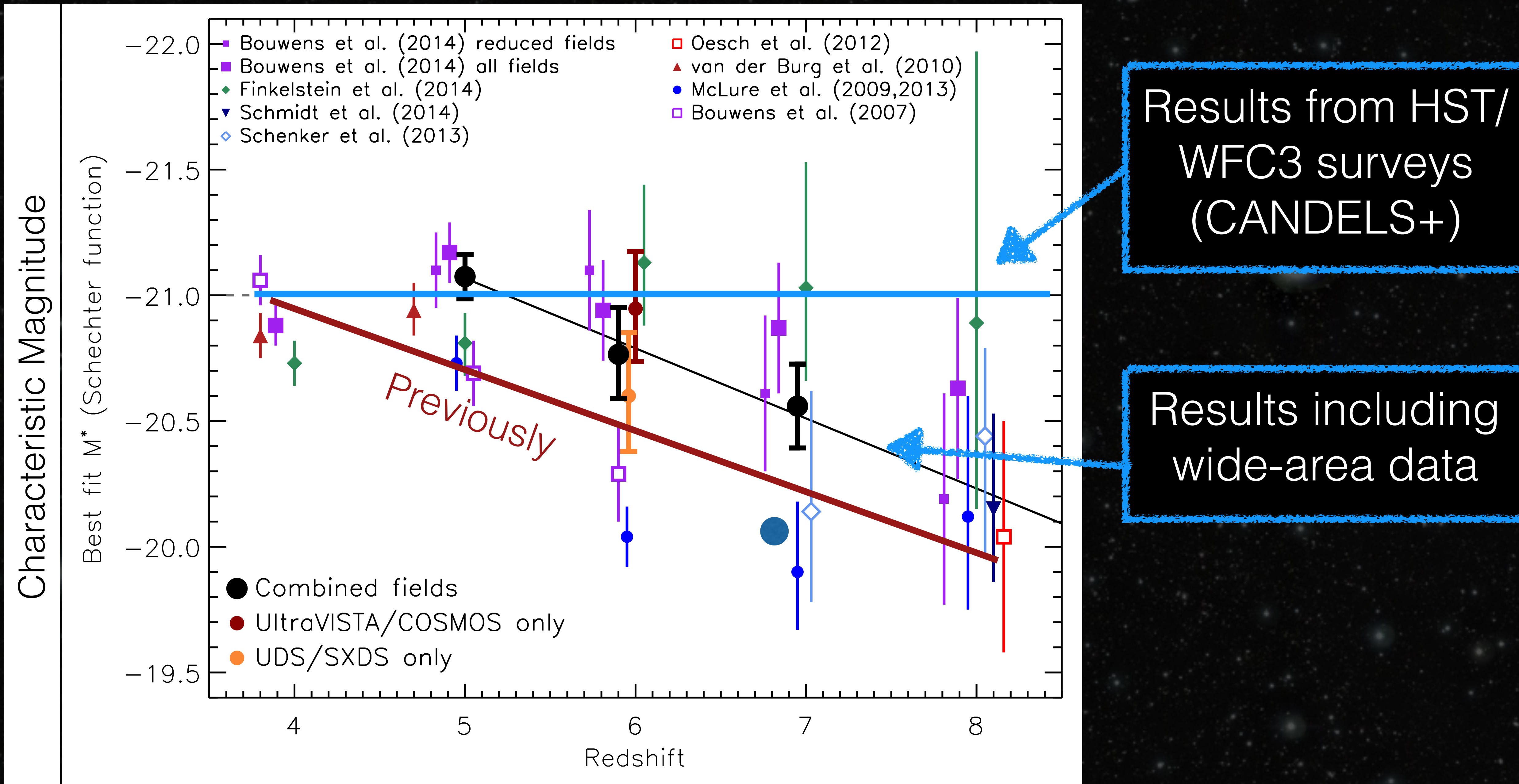
The evolution of the LF from z = 5-7



Strong evolution around the knee

Steepening of the bright-end at z < 7?

The evolution of the LF from z = 5-7

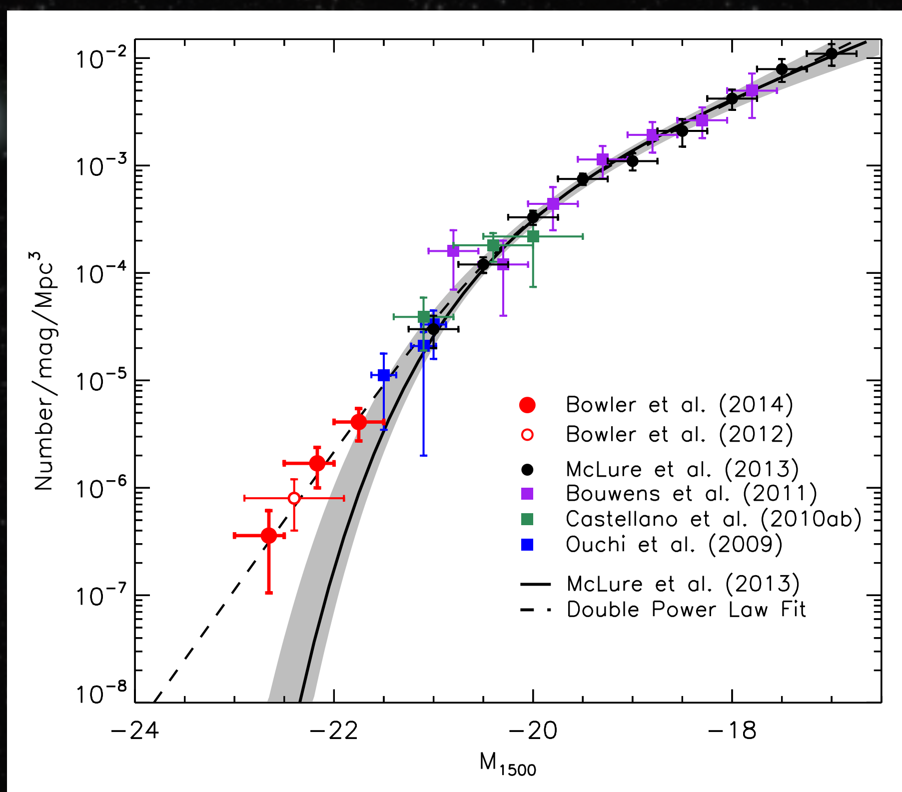


- ★ Not a consensus on the form of the evolution at z = 5-7
- ★ Ground-based data show an evolution in M*
- ★ Is a Schechter function appropriate? More power-law like?

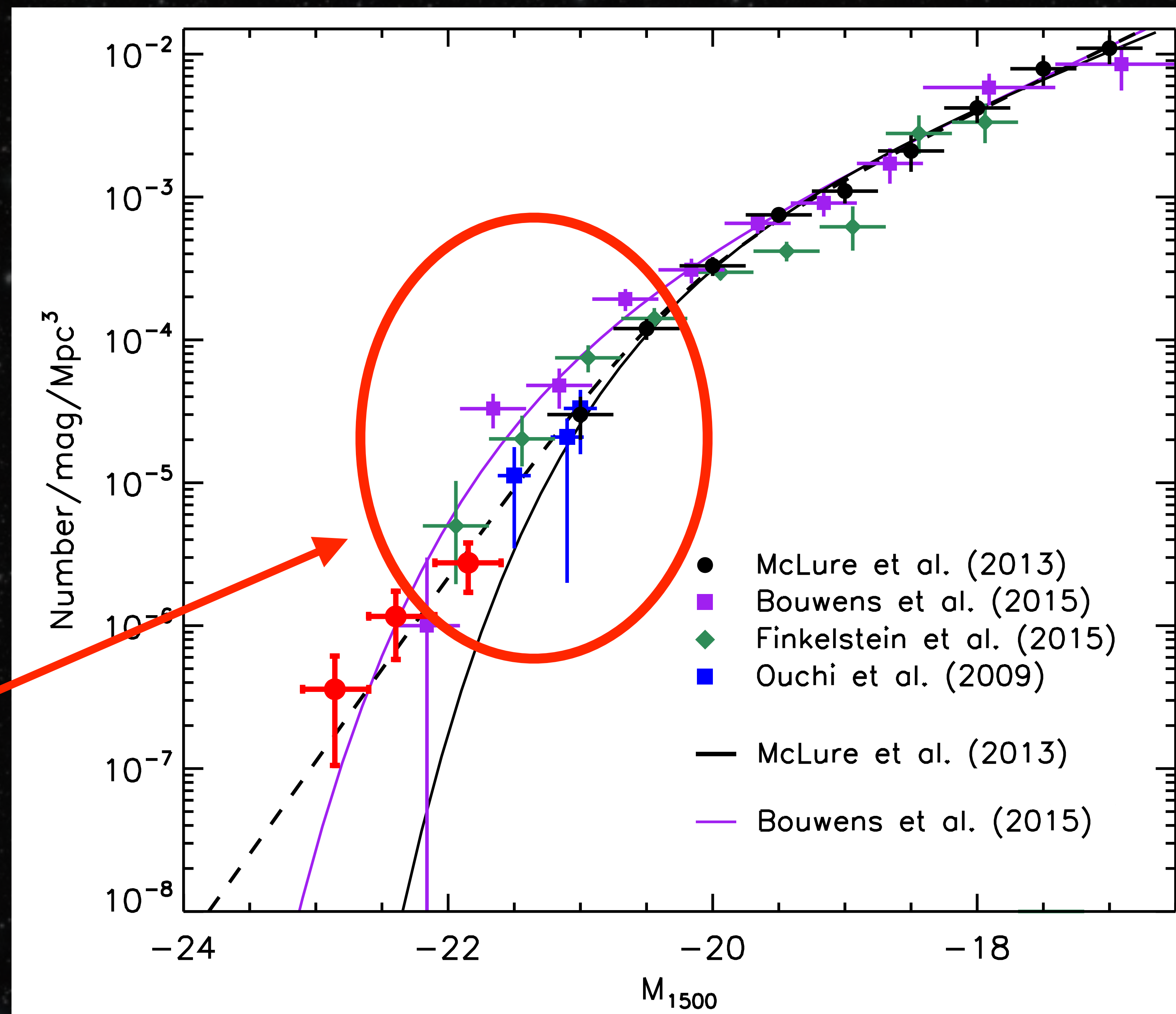
Constraining the knee of the z ~ 7 LF

Knee of the LF at z ~ 7 still uncertain…

2014



2016



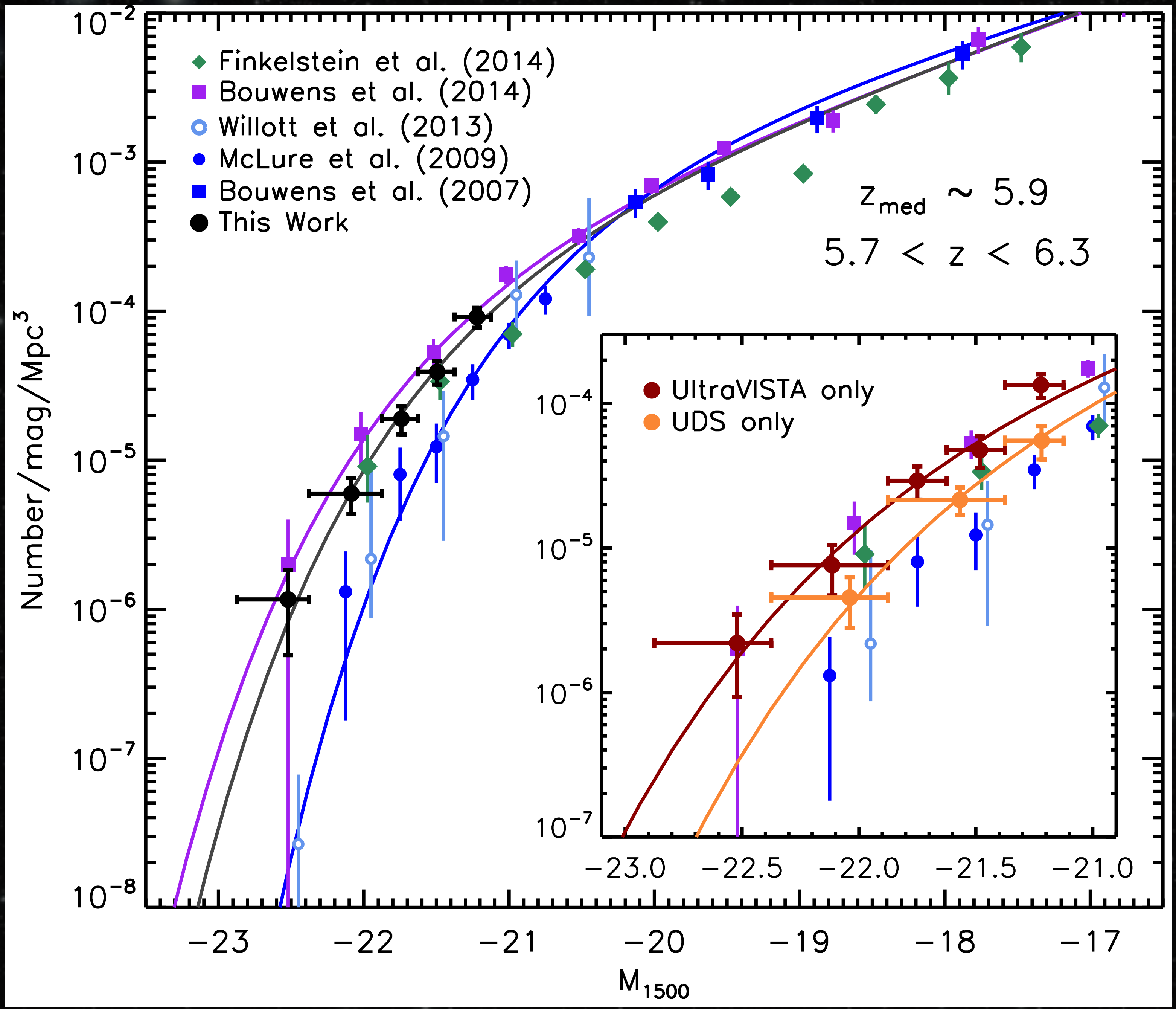
Future HSC + UltraVISTA DR3 + UDS/SXDS will help

see Bouwens et al. 2015, Finkelstein et al. 2015ab

Cosmic variance in the LF at z ~ 6

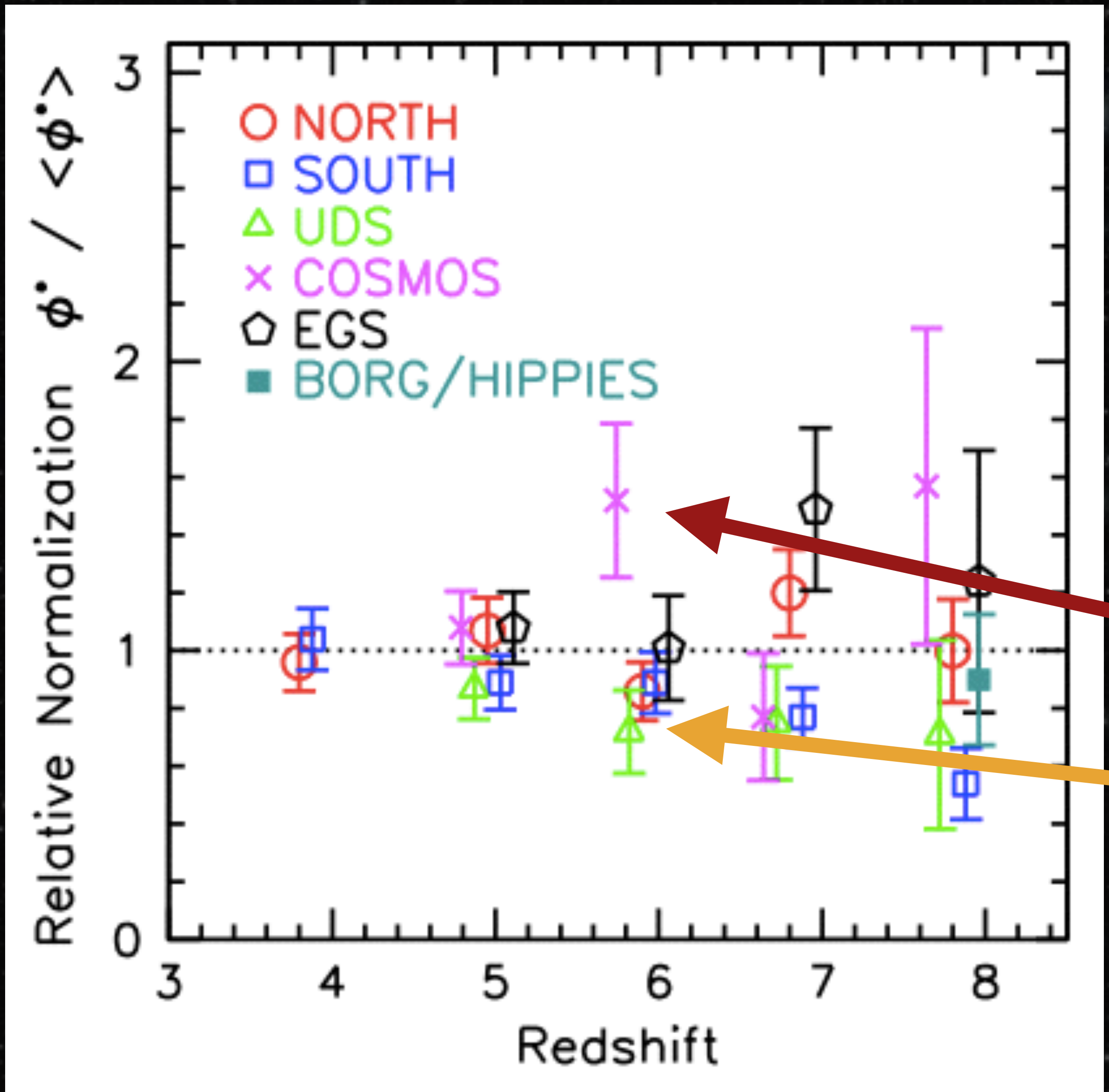
~ 2 x the number density of bright galaxies in UltraVISTA/COSMOS compared to the UDS/SXDS

McLure et al. 2009
~ 0.6 sq. degree UDS/SXDS field



z = 6 luminosity function from SXDS/UDS + COSMOS/UltraVISTA (Bowler et al. 2015)

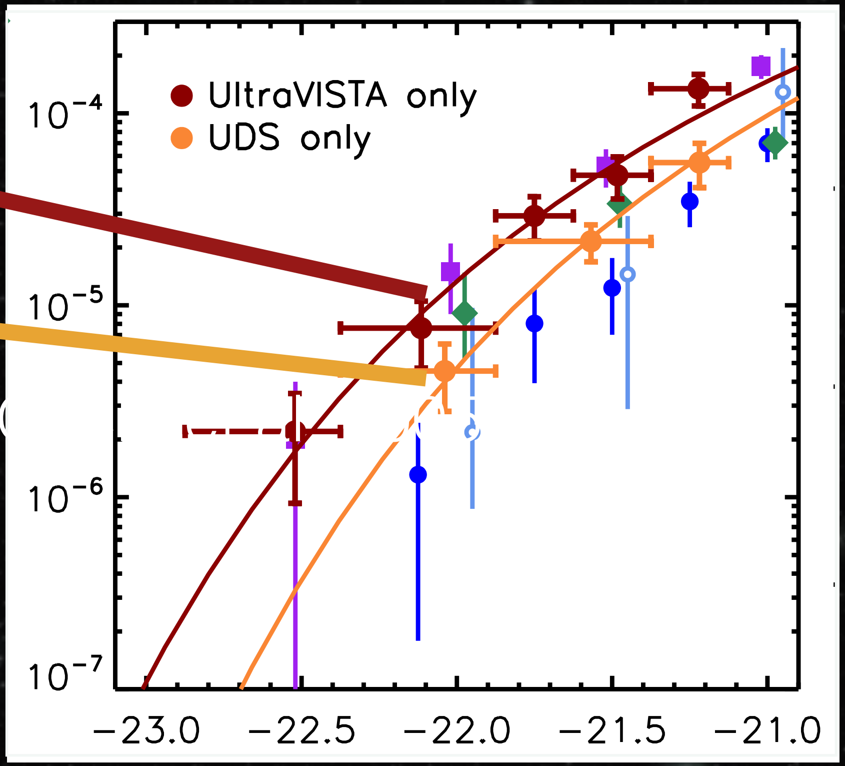
Cosmic variance in the LF at z ~ 6



CANDELS: Bouwens et al. (2015)

Also in CFHTLS (Willott et al. 2013)

And under-density of LAEs in SXDS (Ouchi et al. 2005)

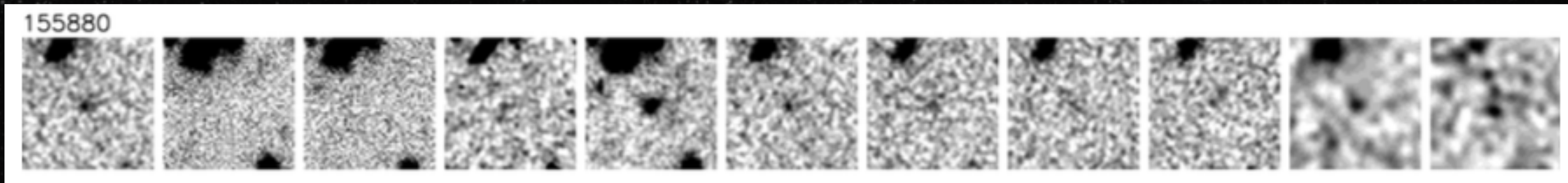


Large degree-scale fields with multiple sight-lines are required!

➡ HSC

➡ Euclid/LSST (40 deg²)

Revealing the nature of bright LBGs



These samples include the **brightest** known z ~ 7 galaxies, which are ideal targets for detailed follow-up:

… in relatively modest integration times:

- few hours with near-IR spectrographs (e.g. Oesch+2015, Roberts-Borsani+2015…)
- modest integrations with ALMA (e.g. Capak+2015, Maolino+2015…)

Revealing the nature of bright LBGs

HST can reveal sizes/ morphologies that are elusive in ground-based data

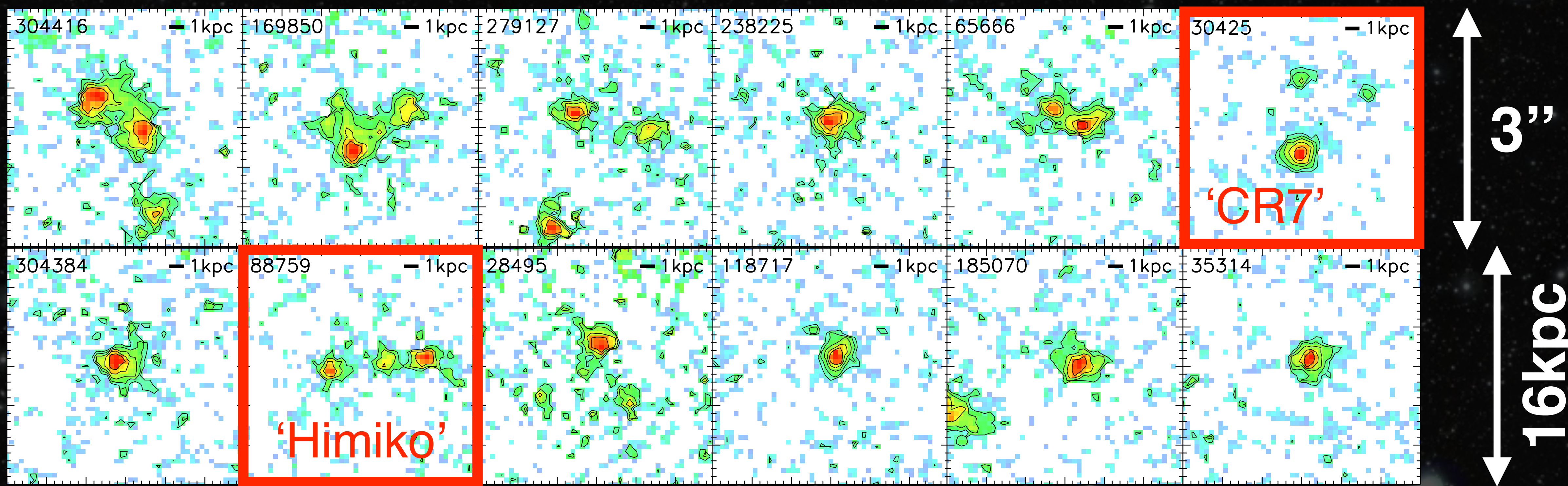
Optical and near-infrared spectroscopy can reveal rest-UV emission lines

ALMA provides unique view of dust emission

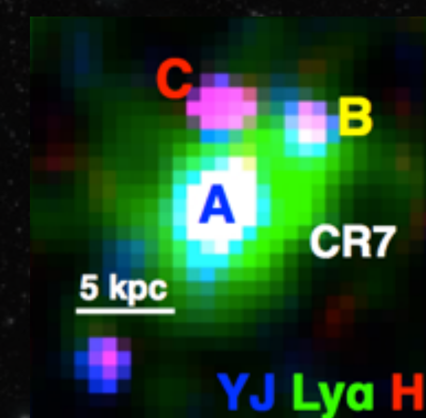
Revealing the nature of bright LBGs

HST can reveal sizes/
morphologies that are elusive
in ground-based data

HST/WFC3 imaging of bright LBGs



Ouchi et al. 2009, 2013



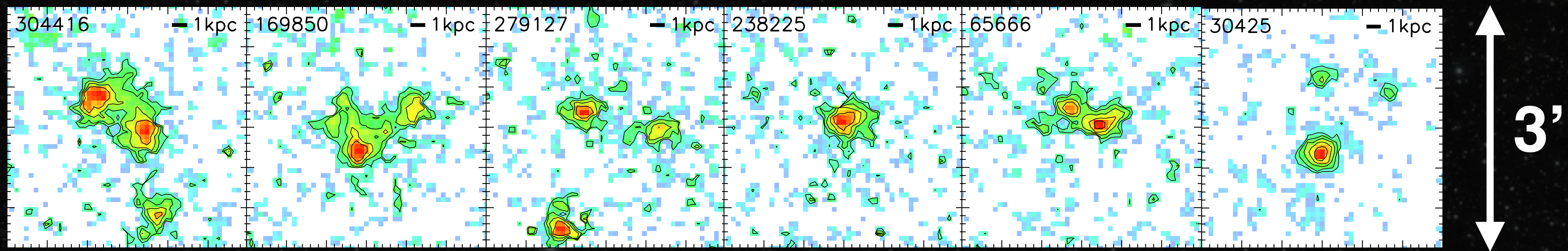
Sobral et al. 2015

- ⋆ The brightest Lyman-break galaxies at z ~ 7 are composed of multiple clumps at HST resolution - mergers or SF clumps?
- ⋆ Magnitude limited sample, not selected for line emission

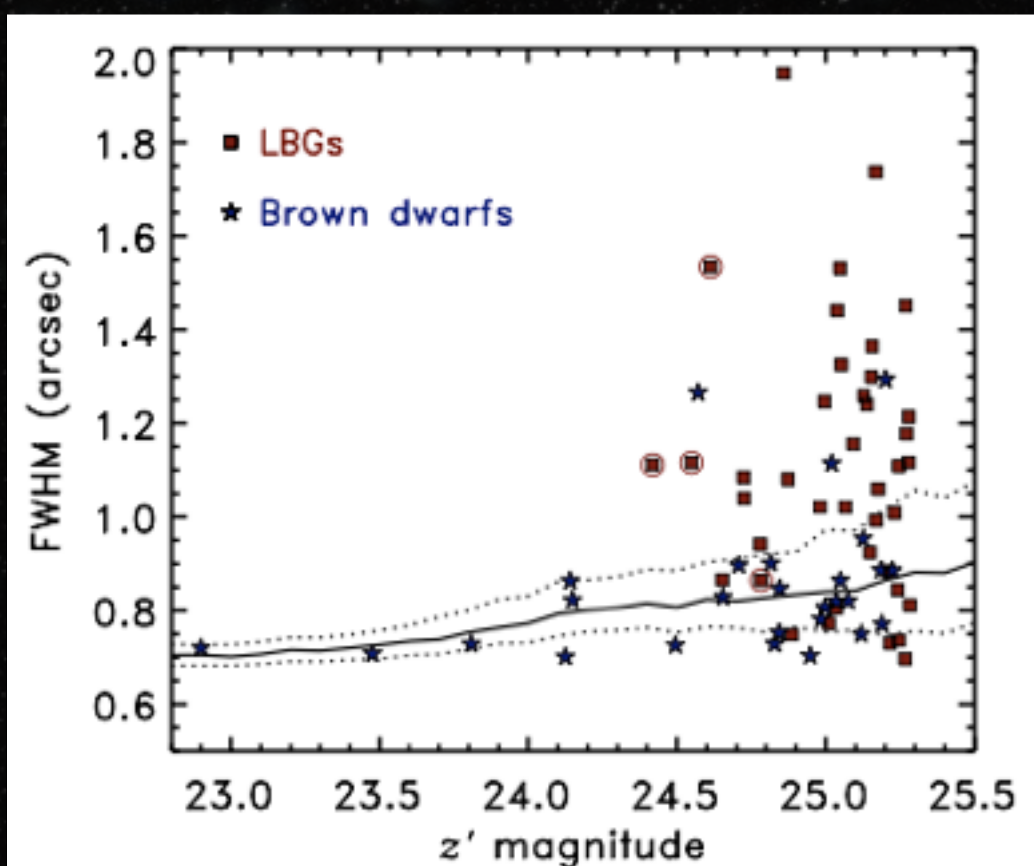
Bowler et al. 2016a

see also Jiang et al. 2013, Kawamata et al. 2015…

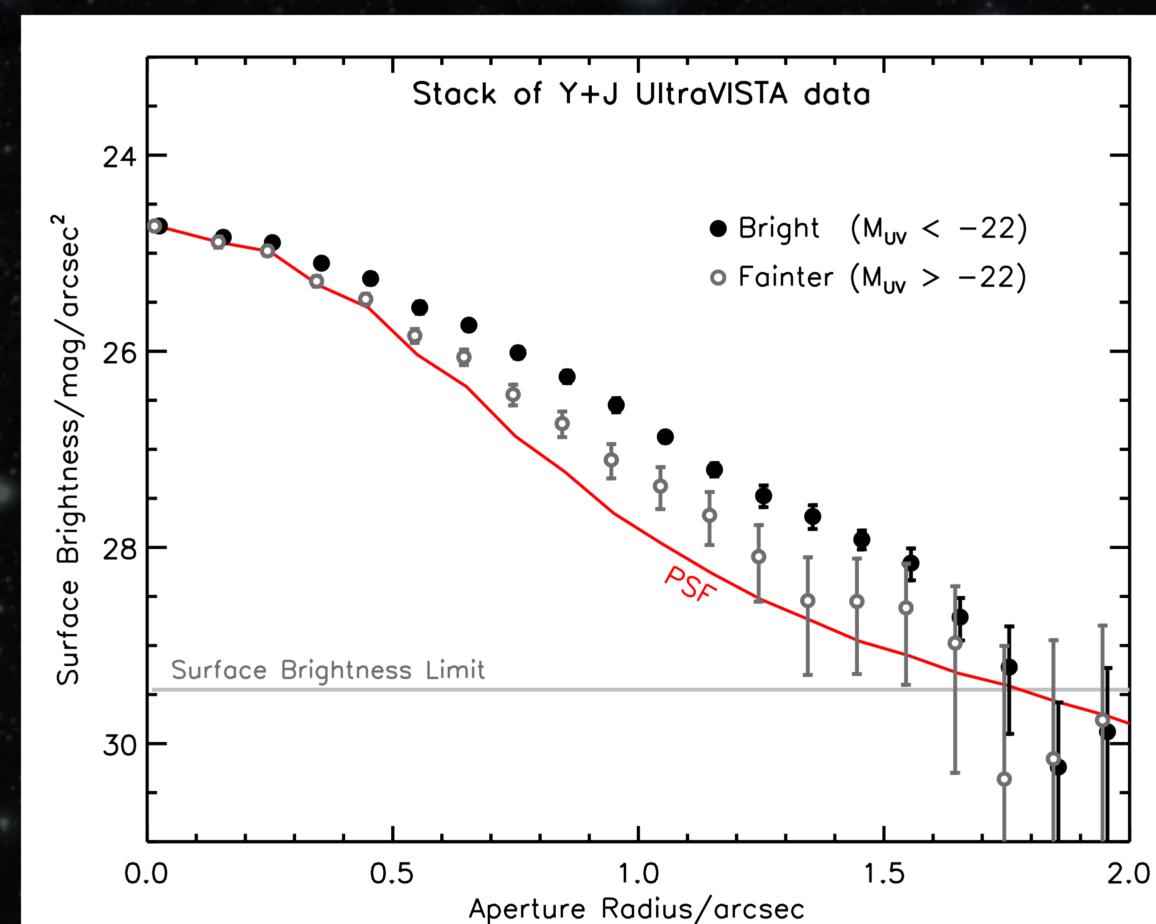
Measuring the sizes of bright LBGs



- Size measurement method and interpretation challenging
- Sizes can be inferred from the ground…



z ~ 6 LBGs, CFHT data (Willott+13)

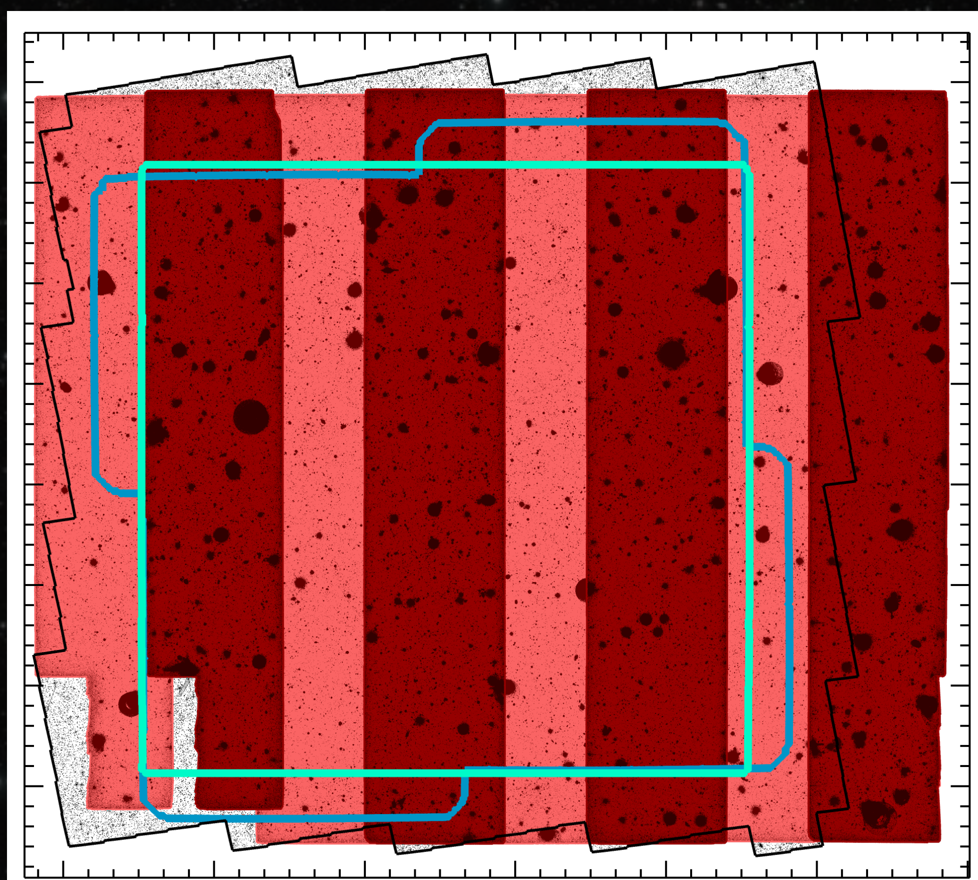


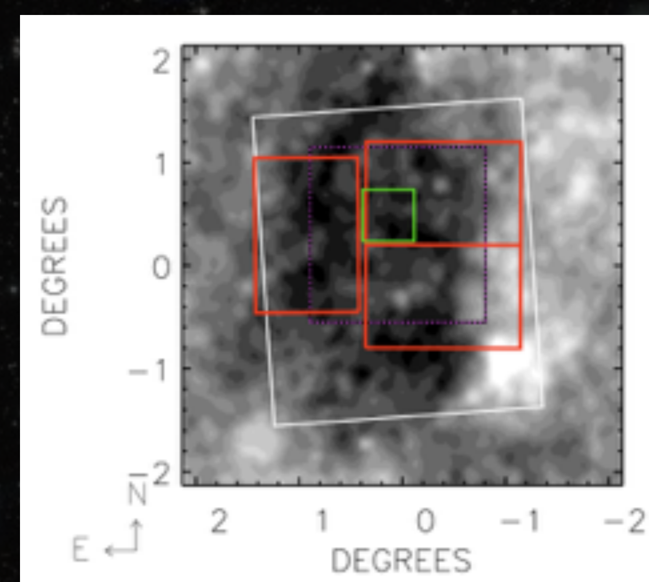
Bowler et al. 2016a

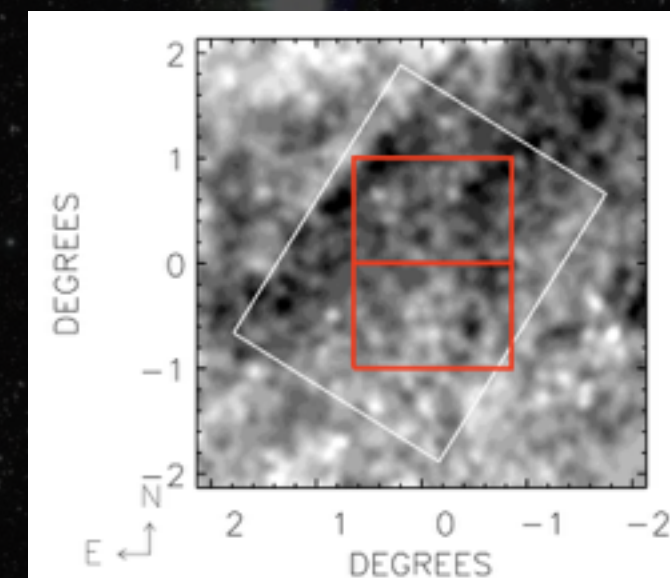
Upcoming and ongoing near-infrared surveys

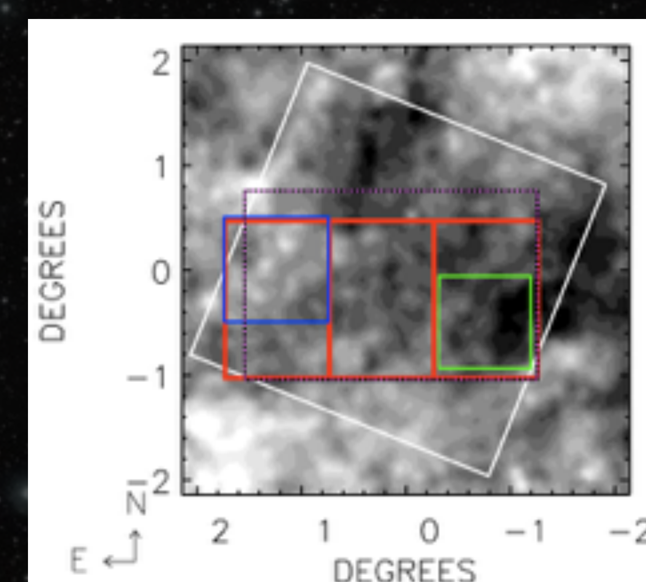
★ UltraVISTA
Extension will fill in ‘gaps’ to provide complete 1.5 deg^2 to 25-26 JHKs (y from HSC)

★ VIDEO -> VEILS
CDFS, Elias-S1, XMM-LSS
12 deg^2 to ~ 23.5-24.5 YJHKs
Extension will double area









★ Euclid - 40 deg^2 in deep fields should detect ~3000 LBGs @ z ~ 7 (and ~ 1000 in wide fields)

Summary

- ★ Near-infrared data is key for finding and studying z ~> 7 galaxies
- ★ Current leading fields are UltraVISTA/COSMOS and UDS/SXDS
- ★ Evolution in the rest-frame UV LF is around the knee (-> DPL?)
- ★ Bright galaxies are interesting! And ideal laboratories for further study





Exciting current and future science (biased!)

- ★ Form and evolution of the bright-end at $z \sim 7$ and $z > 7$
- ★ Lyman-a escape and astrophysics of UV/optical emission lines
- ★ More CR7/Himiko type-objects? Density of ~ 1 per deg^2
- ★ Overlap with quasars
- ★ Probing the dark matter haloes via clustering
- ★ The rest-frame optical view with JWST - mergers or clumpy objects?
- ★ ….