First Light
WFIRST-AFTA
What Requirements Would Allow Us To Do The Best Science?

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Pasadena, California
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WFIRS: Science and Techniques

Scientific Interest #1:

One of the primary interests in distant galaxies is to understand the early growth and build-up of galaxies.

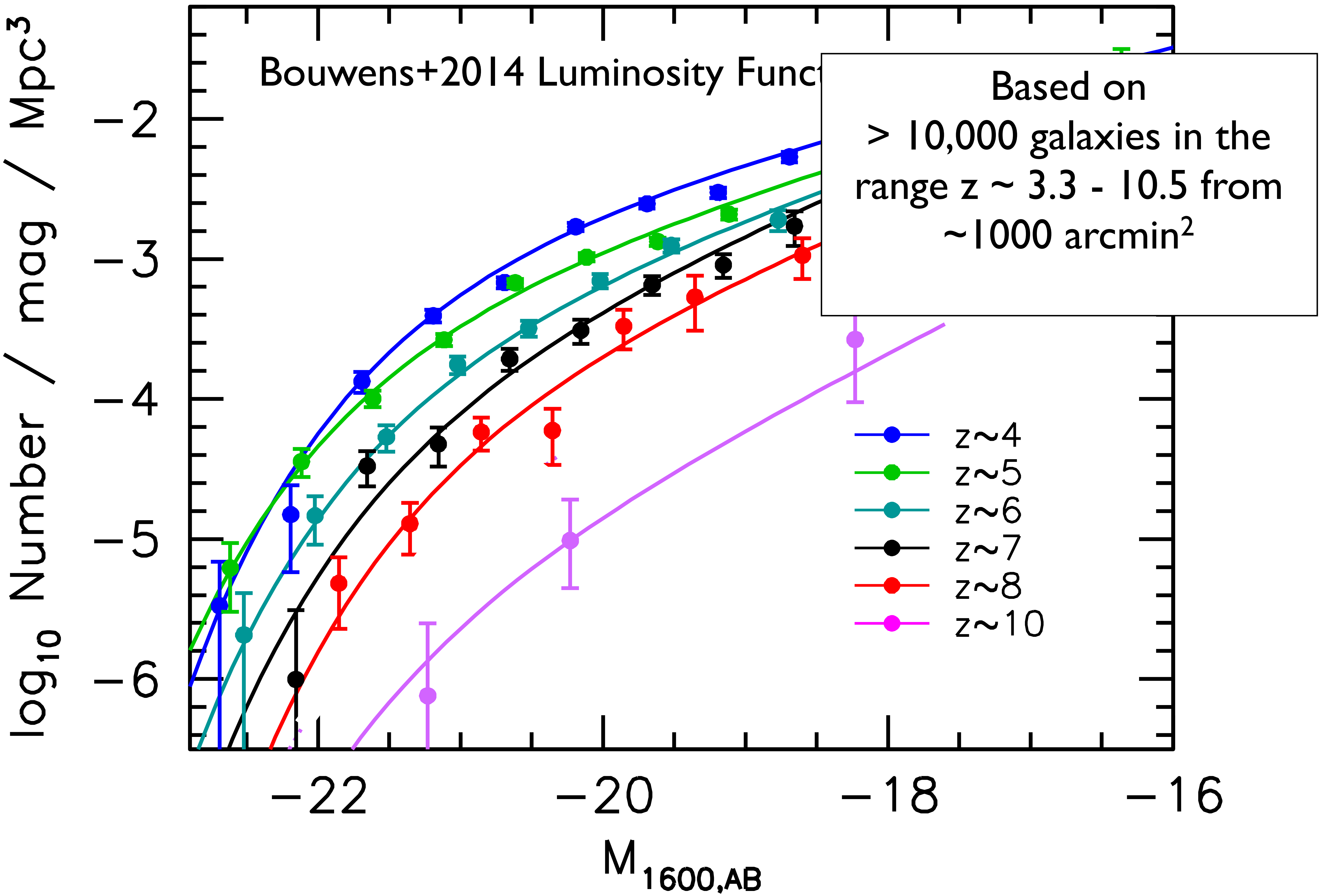
What requirements can we set on WFIRST to maximize what we learn about galaxy build-up?

Scientific Interest #2:

One of the primary interests in distant galaxies is to understand the contribution of these galaxies to the reionization of the universe.

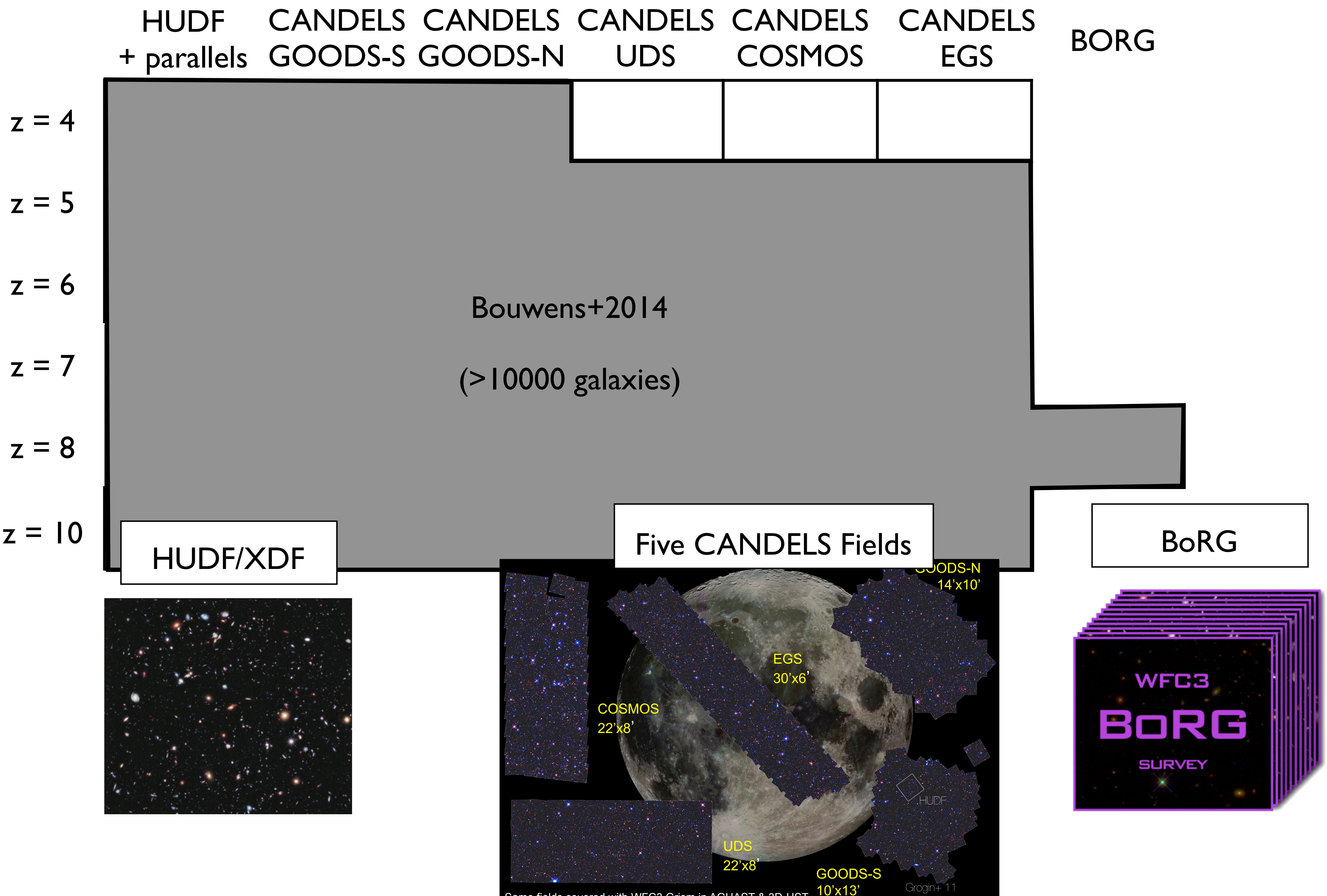
What requirements can we set on WFIRST to maximize the information we have on ultra-faint galaxies?

What is current observational baseline:

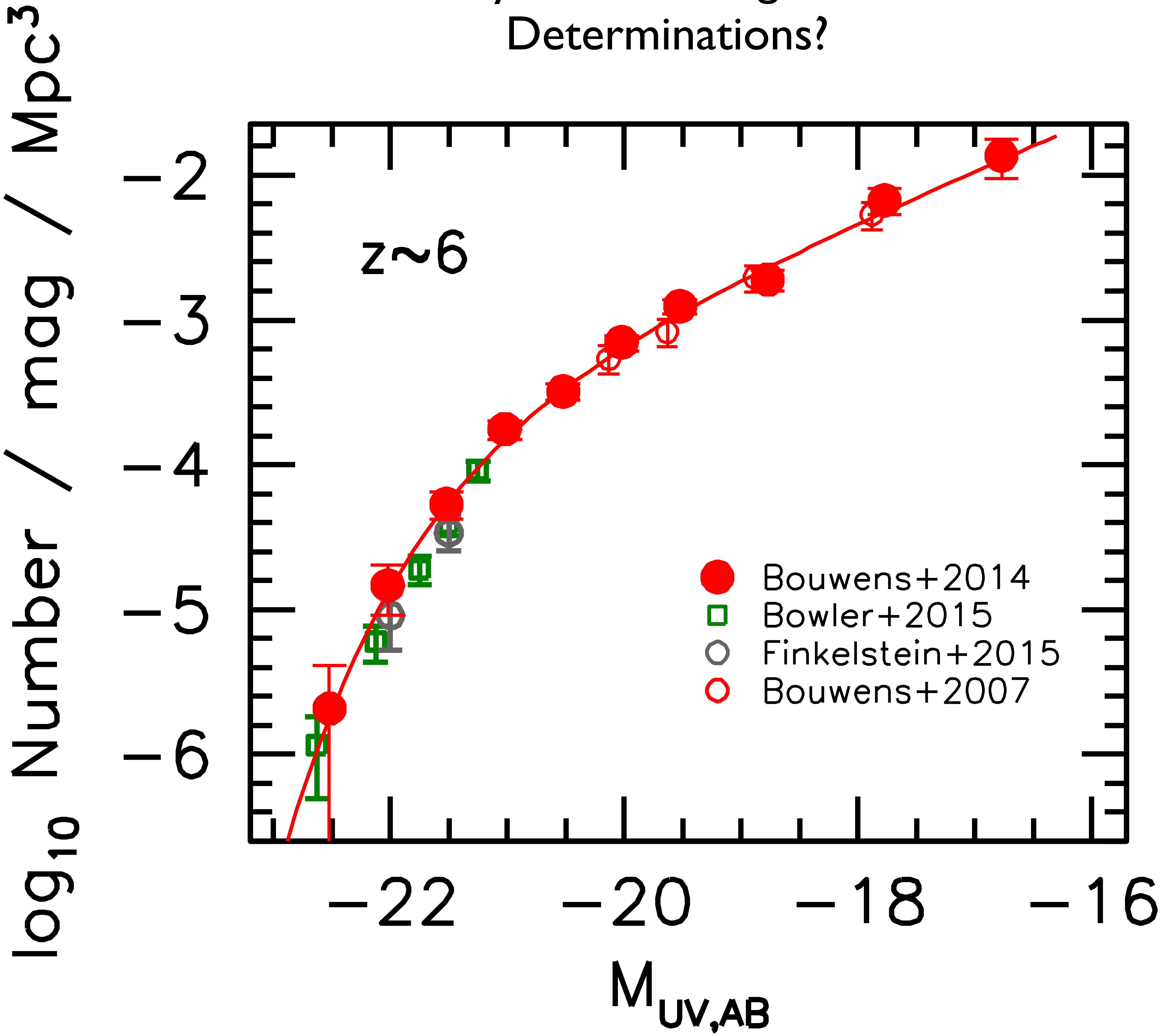


Bouwens+2014 (see also McLure+2013; Finkelstein+2014)

z~4, 5, 6, 7, 8, z~10 LF Baseline Derived from HUDF, HUDF parallels + full CANDELS program



Do these Luminosity Functions Agree with Other Recent Determinations?



Bouwens+2014; Bowler+2015; Finkelstein+2015; Bouwens+2007

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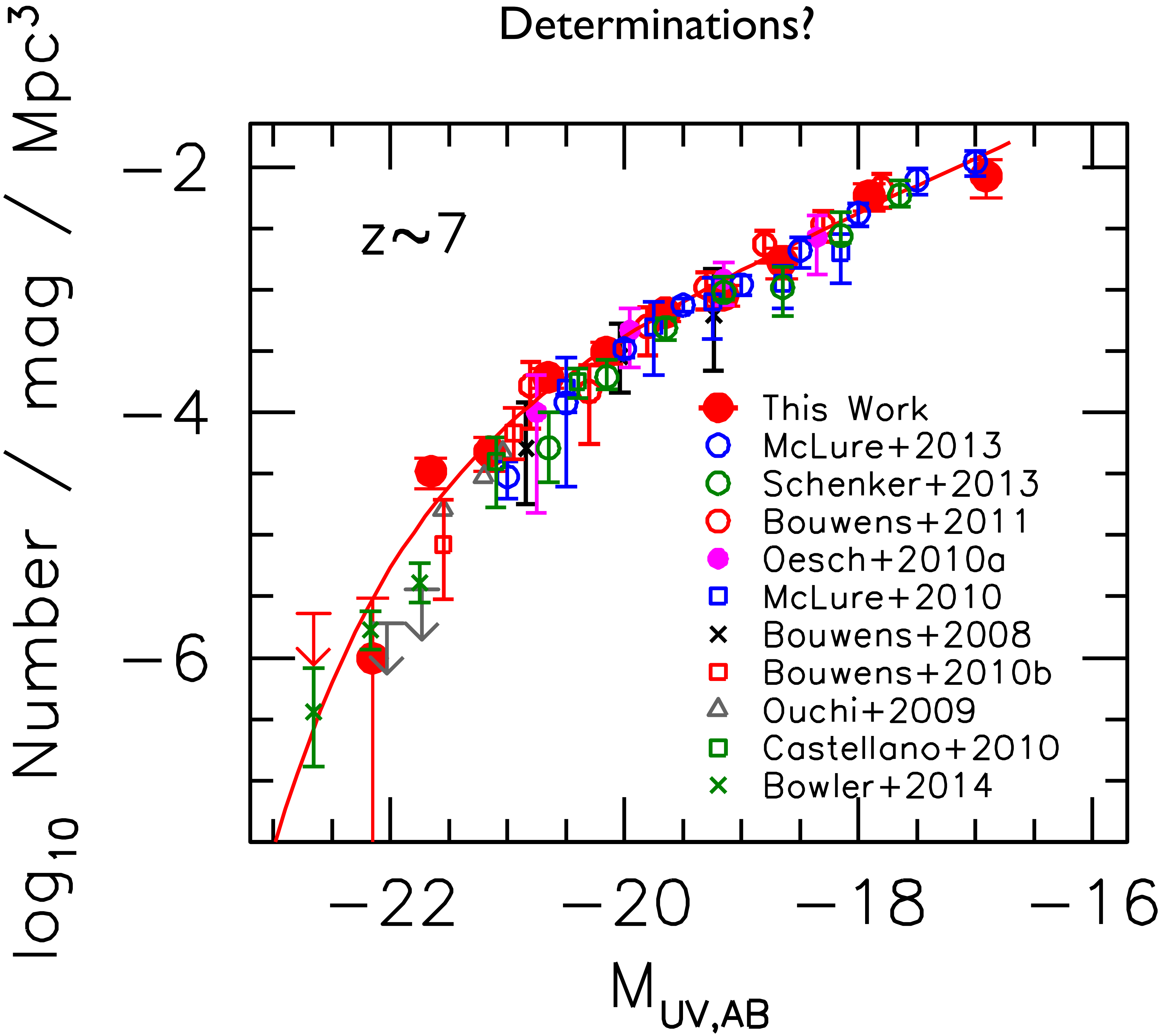

Bouwens+2014; McLure+2013; Schenker+2013; Bouwens+2011; Oesch+2010; McLure+2010

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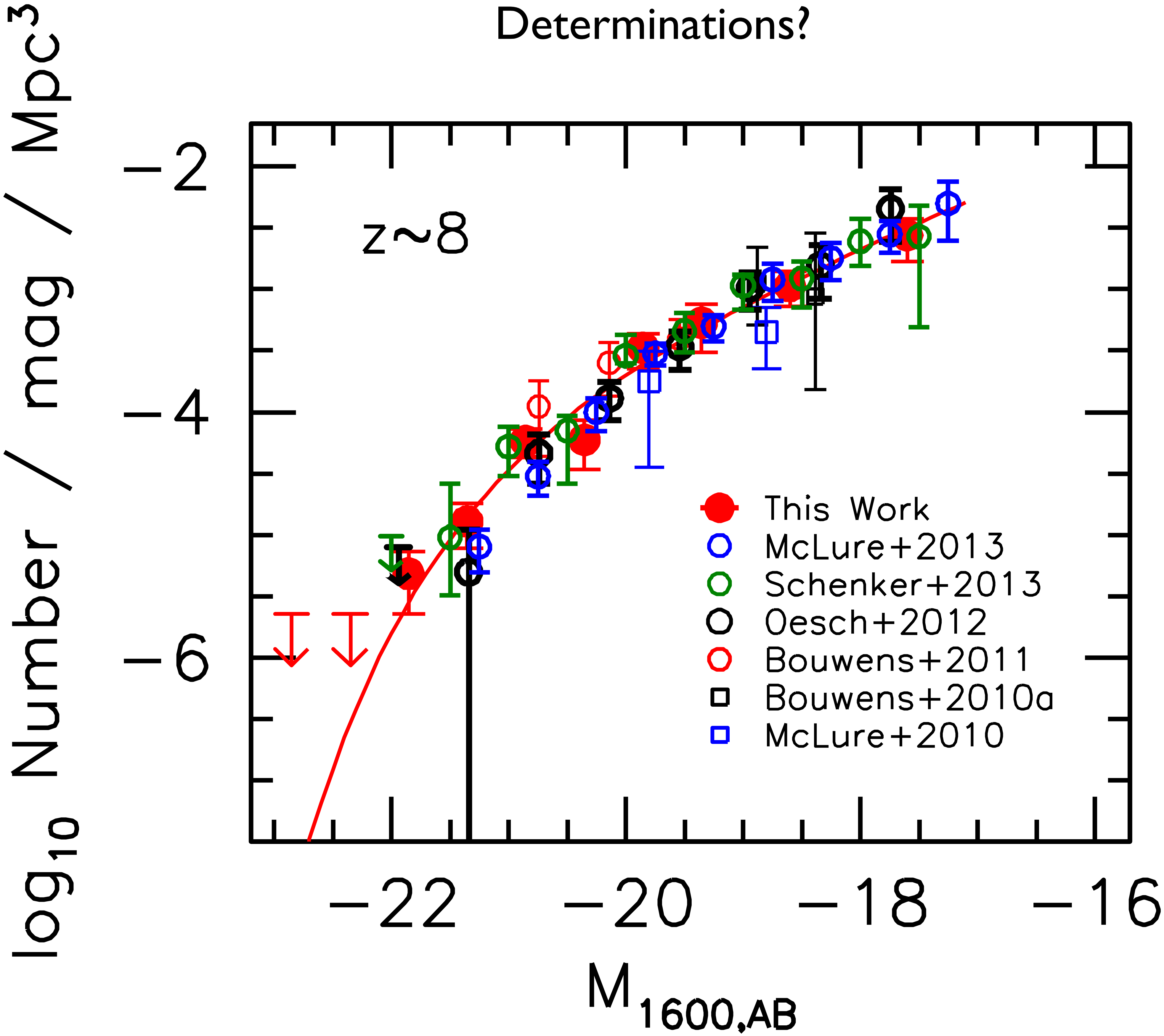
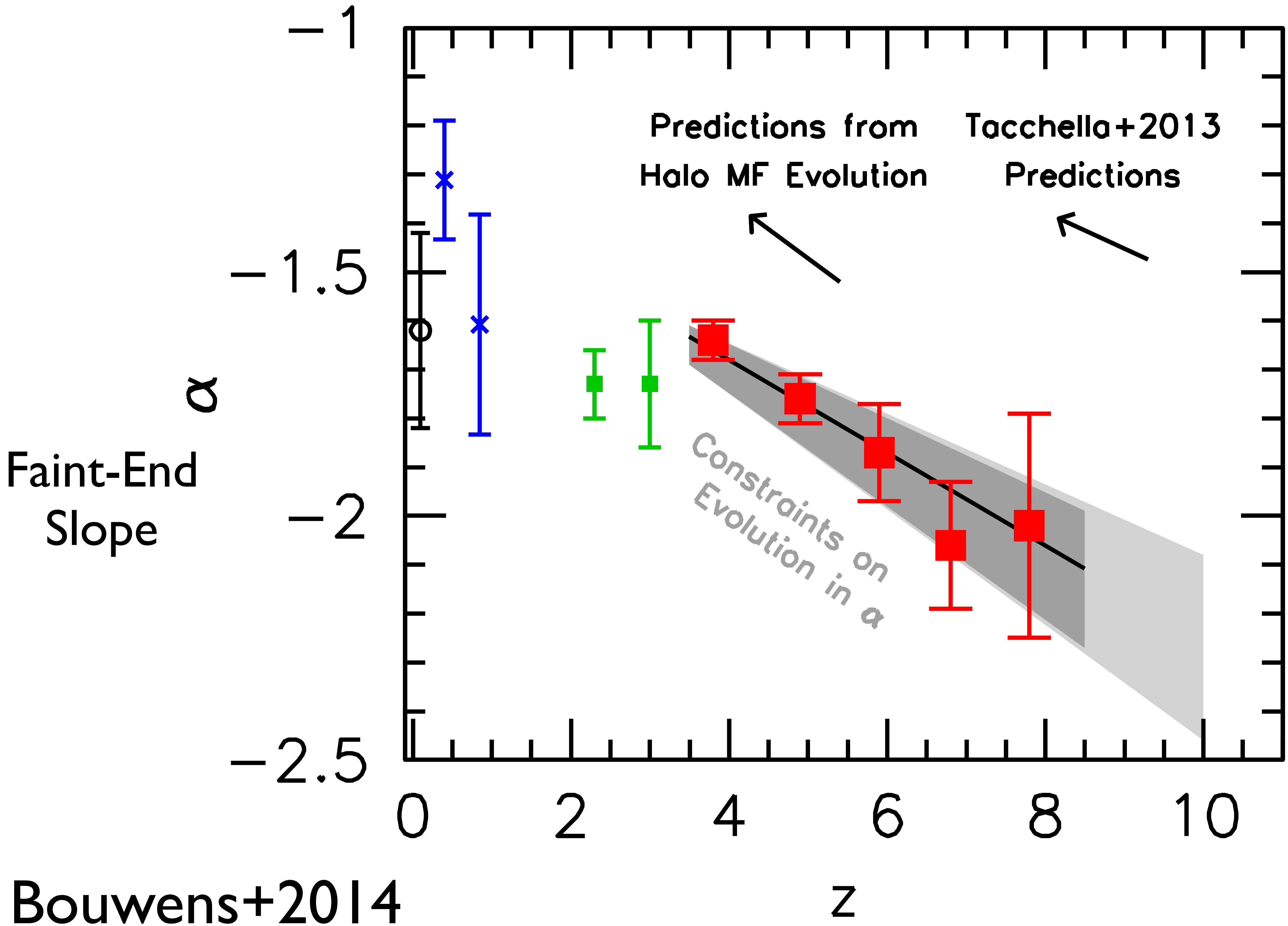


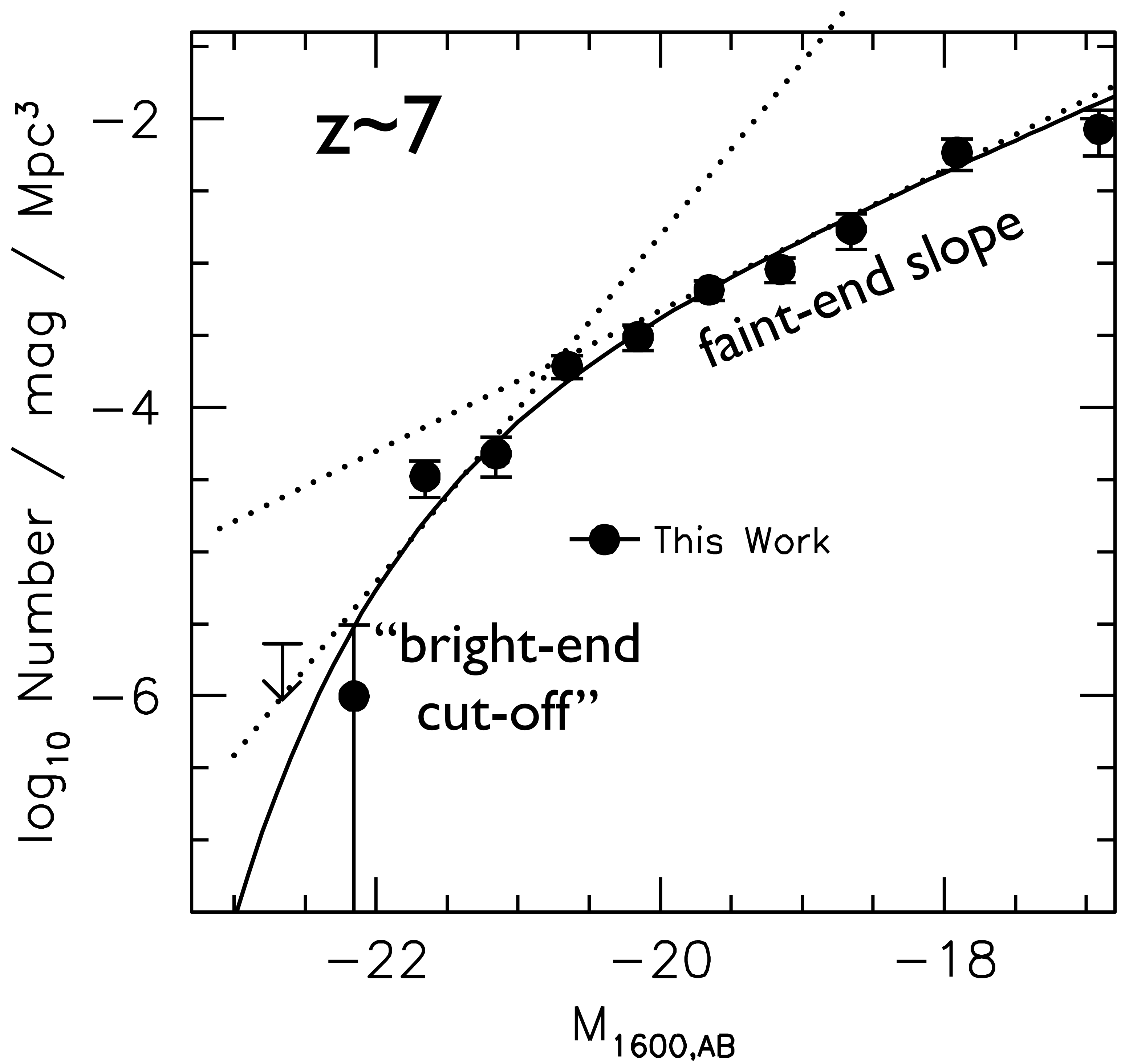
Bouwens+2014; Bowler+2014

Luminosity Function Steeper at Early Times



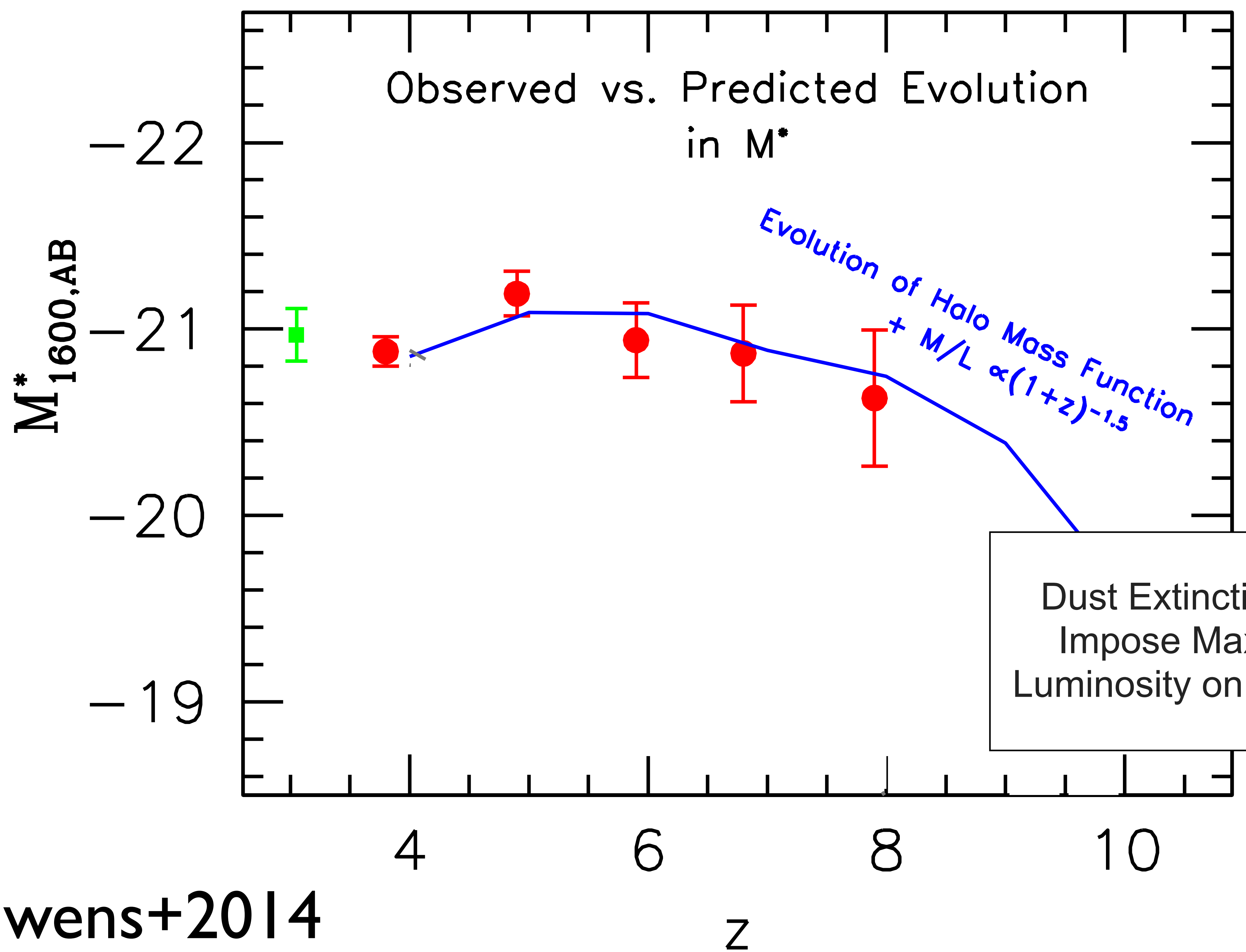
Bouwens+2014

UV LFs follow a clear power law at the faint end, but shows an apparent cut-off at the bright end



Bouwens+2014 (see also Bouwens+2011/Finkelstein+2015)

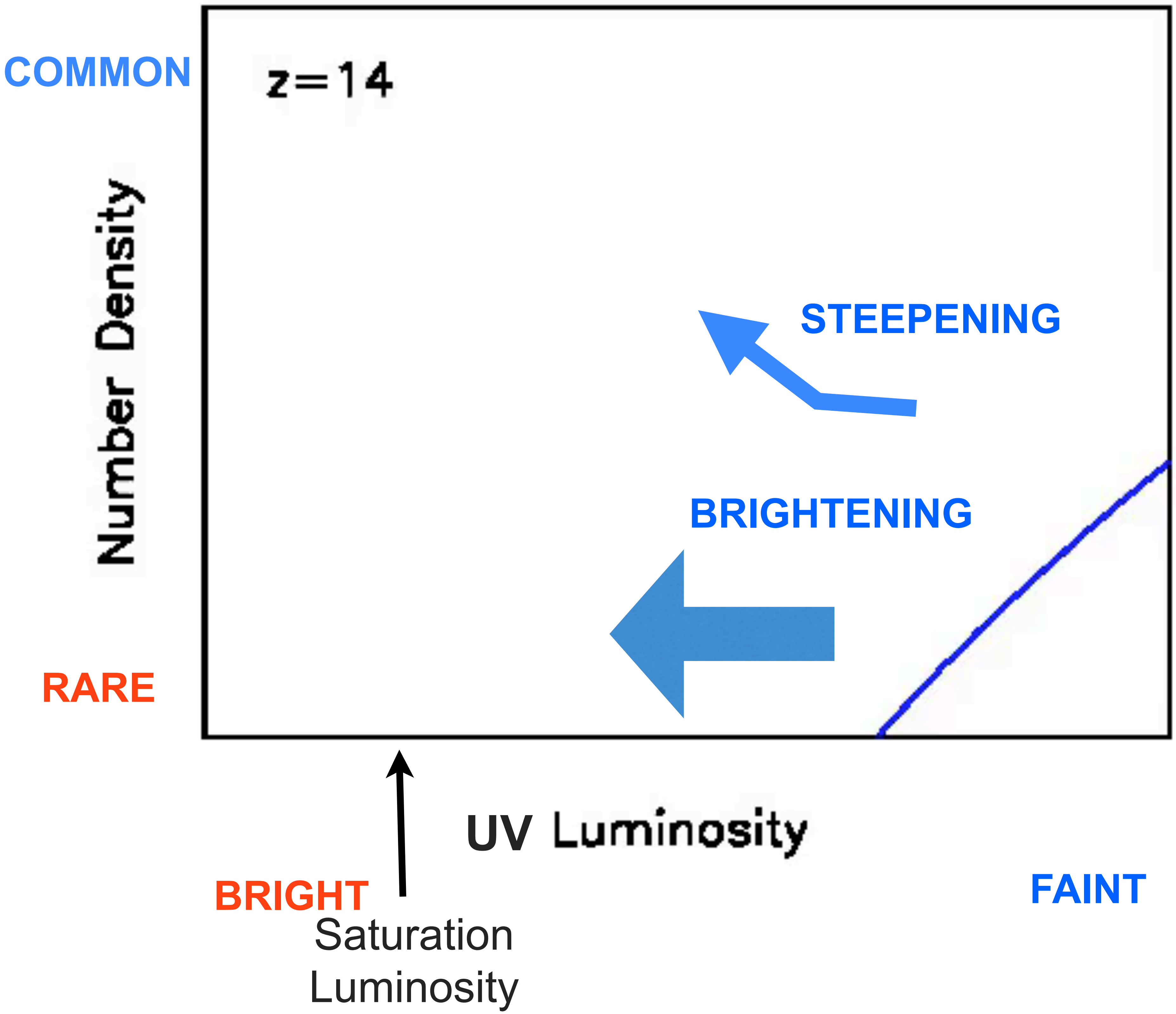
Bright End cut off (M*) does not evolve rapidly
(but becomes fainter at high redshift?)



Dust Extinction May Impose Maximum Luminosity on Galaxies

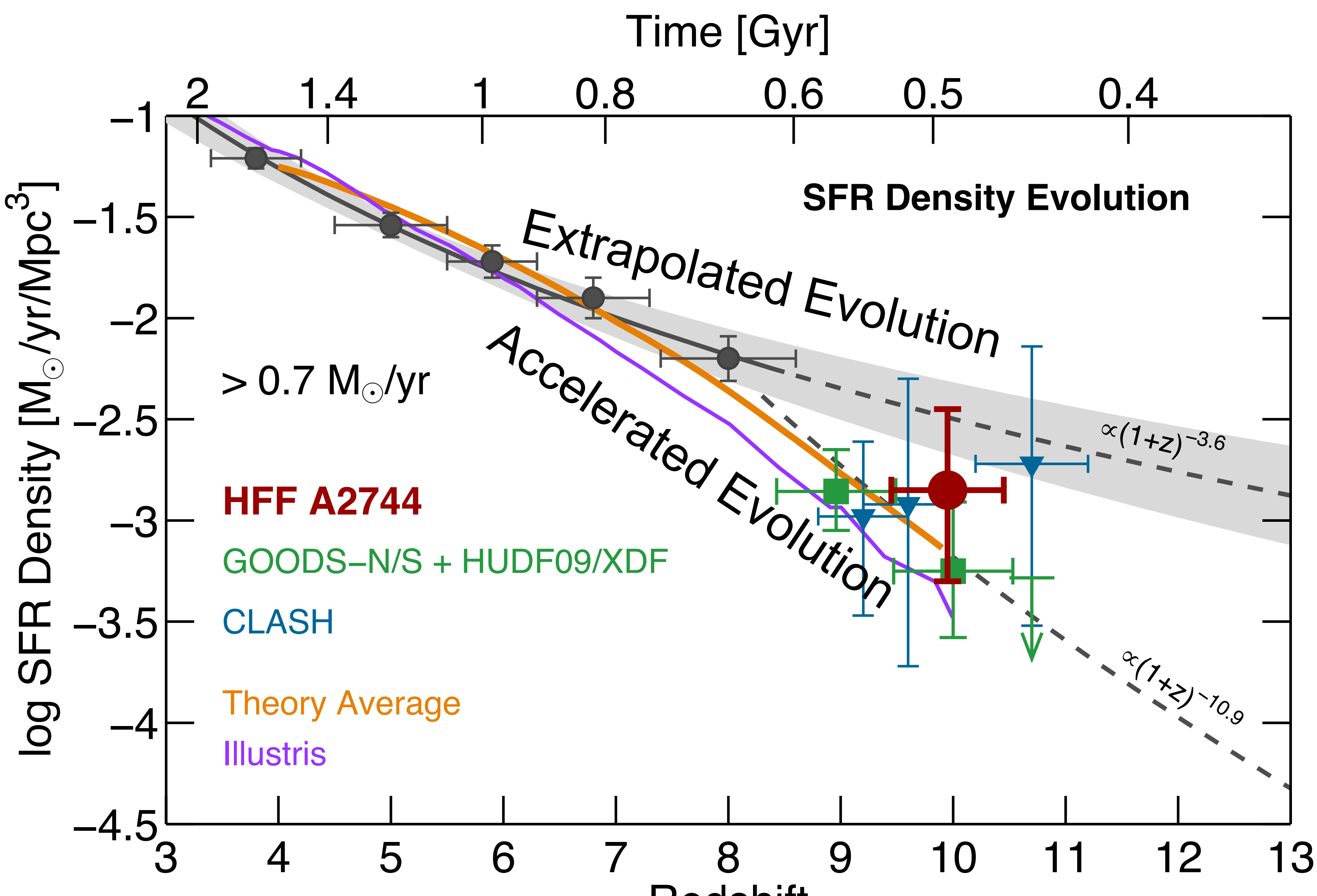
Bouwens+2014

Schematic Model: Luminosity function evolution seems to trace growth in dark-matter halos



Dust Extinction May Impose Maximum Luminosity on Galaxies

There is Some Uncertainty in Extrapolating the Evolution to z>8: Is the Evolution Faster Per Unit Redshift or Not?



Oesch+2014

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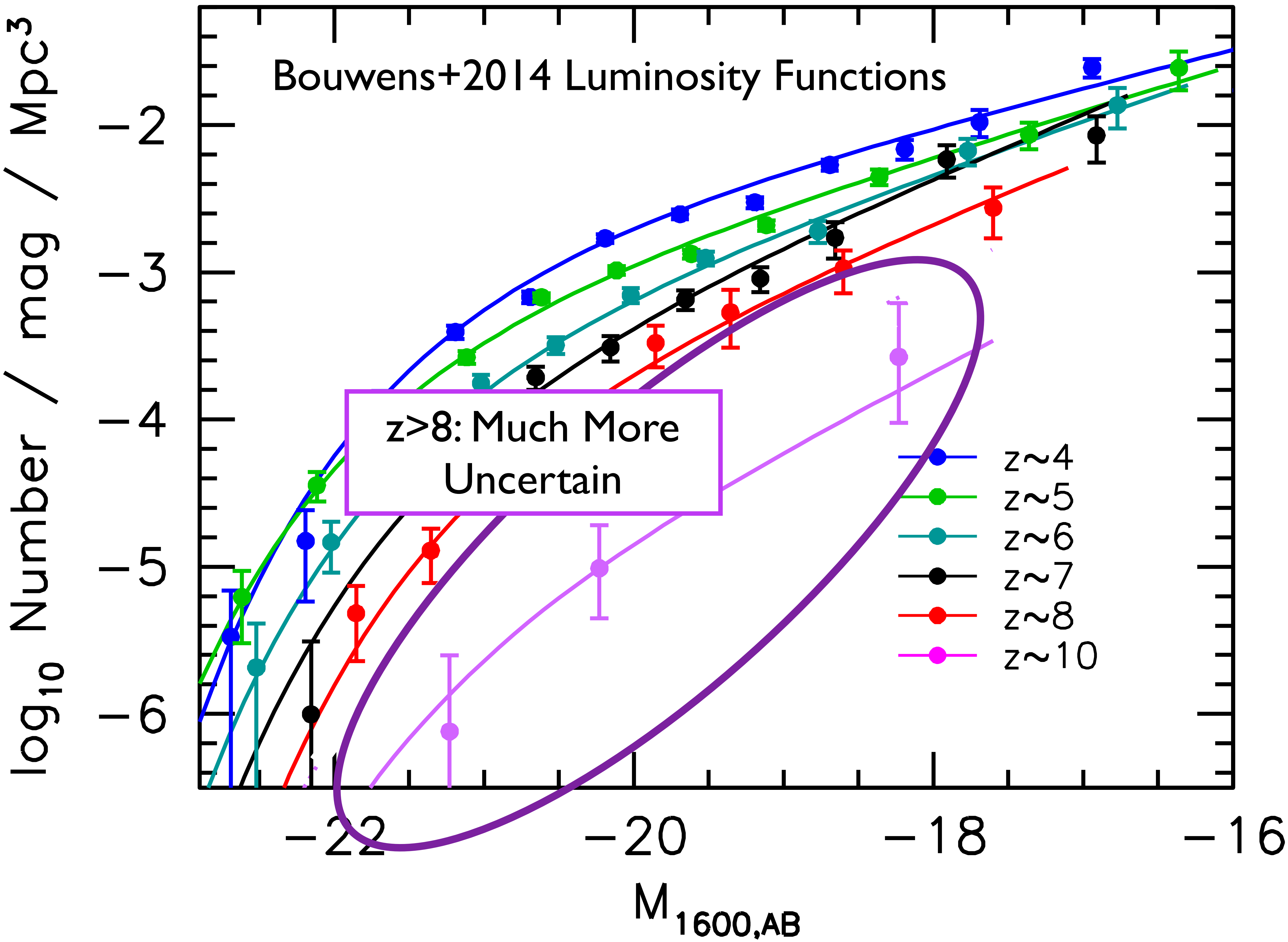


Bouwens+2014 (see also McLure+2013; Finkelstein+2014)

Three Cycle-22 Programs to Better Constrain Prevalence of z~9-10 Galaxies

FAINT

Frontier Fields Program:

Leverage 12 ultra-deep blank + cluster HST WFC3/IR fields to look for faint z~9-10 galaxies

>20-30 z~9-10 Galaxies

BRIGHT

Trenti+2015 $\text{BoRG}_{[z910]}$

(480 orbit program)

Bouwens+2015 CANDELS Follow-Up Program

Leverage 1000 arcmin^2 in search area (full CANDELS + 500 arcmin^2 in additional search

6 bright z~9-10 galaxies (Oesch+2014)

→ 20 bright z~9-10 galaxies

What Implications Do These Results Have for Future Programs with WFIRST?

Baseline Surveying Plan for WFIRST

High-Latitude Survey:

Y,J,H imaging to ~26.7-26.9 mag, F184 imaging to ~26.2 mag (5σ depth) over ~2000 deg^2

Medium/Deep SN Surveys:

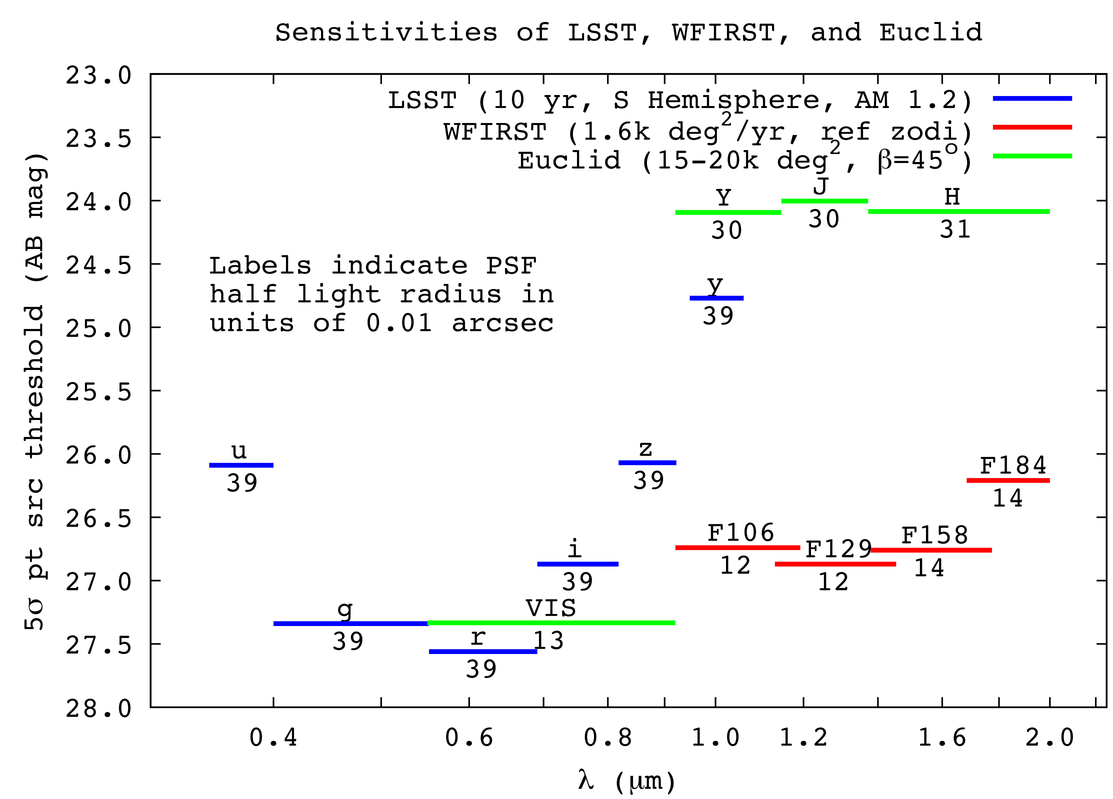
J,H imaging to ~27.6-28.1 mag, (5σ depth) over ~9 deg^2

J,H imaging to ~29.3-29.4 mag, (5σ depth) over ~5 deg^2

Baseline Survey Characteristics			
Survey	Bandpass	Area (deg^2)	Depth
Exoplanet Microlensing	Z, W	2.81	n/a
HLS Imaging	Y, J, H, F184	2000	Y = 26.7, J = 26.9 H = 26.7, F184 = 26.2
HLS Spectroscopy	1.35 – 1.95 μm	2000	0.5×10^{-16} erg/s/cm^2 @ 1.65 μm
SN Survey			
Wide	Y, J	27.44	Y = 27.1, J = 27.5
Medium	J, H	8.96	J = 27.6, H = 28.1
Deep	J, H	5.04	J = 29.3, H = 29.4

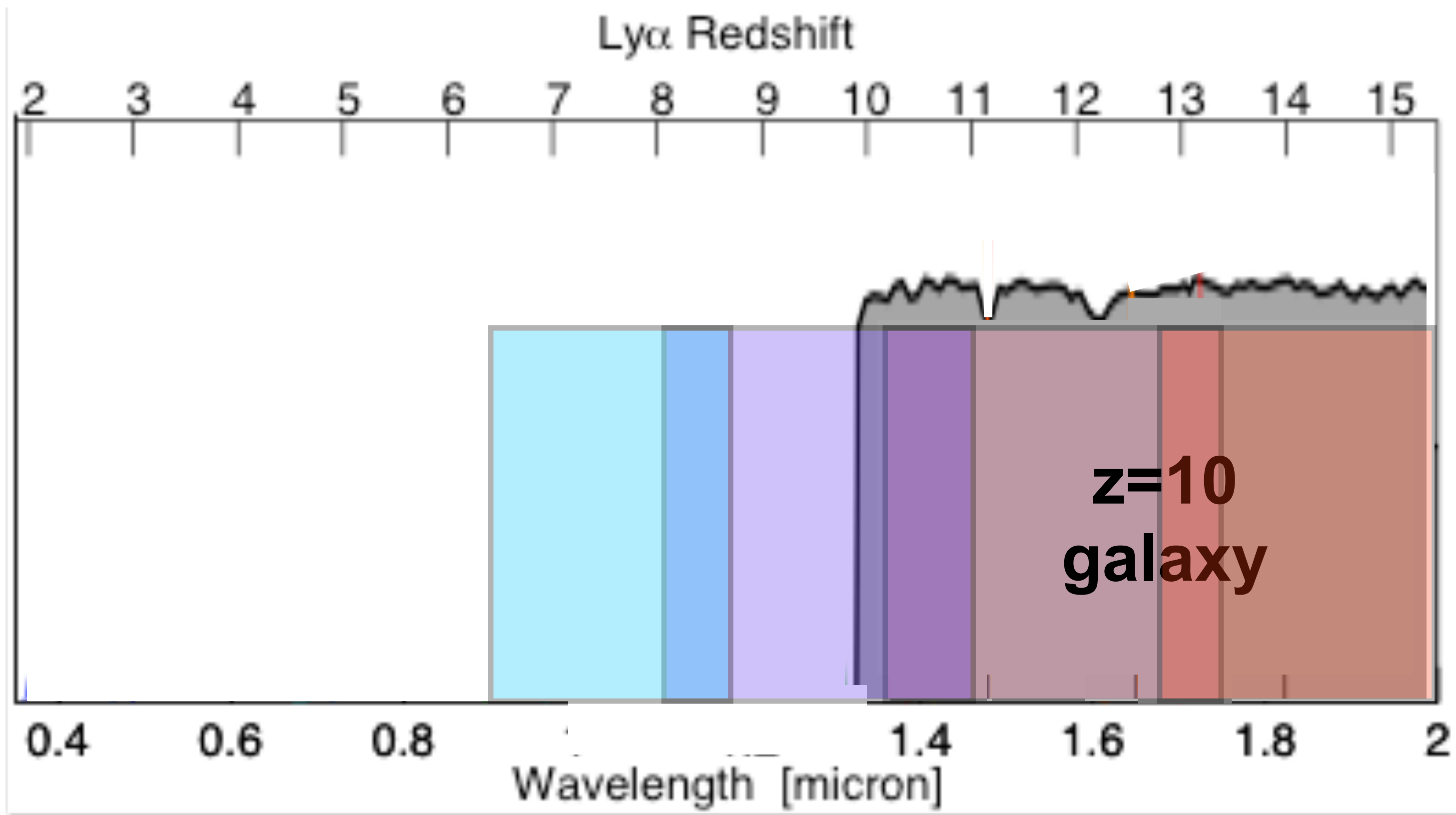
HLS and Deep SN survey are ~0.8 and ~3.3 mag deeper than with Euclid

This is important, as it will allow us to look below the probable knee of the luminosity function!



What can we expect for this baseline plan?

Use of Y, J, H, and F184 with WFIRST would allow for the efficient search for galaxies at z~8-12 (similar to HST)

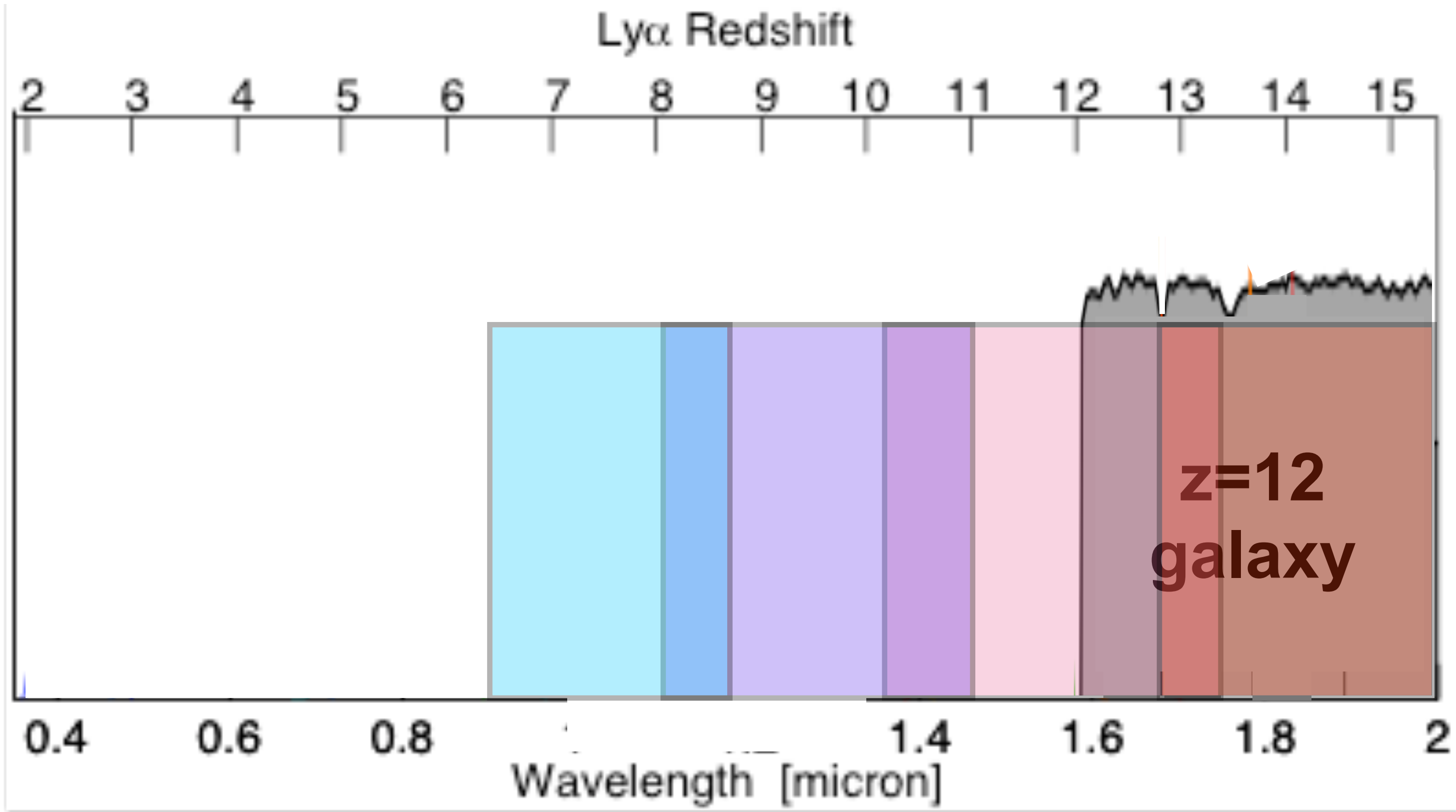


Need for deep observations blueward of the Lyman-break, i.e., "veto filters," may limit the usefulness of the program for selecting galaxies at z<10

(unless Z band observations are added to HLS)

What can we expect for this baseline plan?

The maximum redshift we could explore with the Y, J, H, and F184 bands are probably to z~12 (i.e., the same as with HST)



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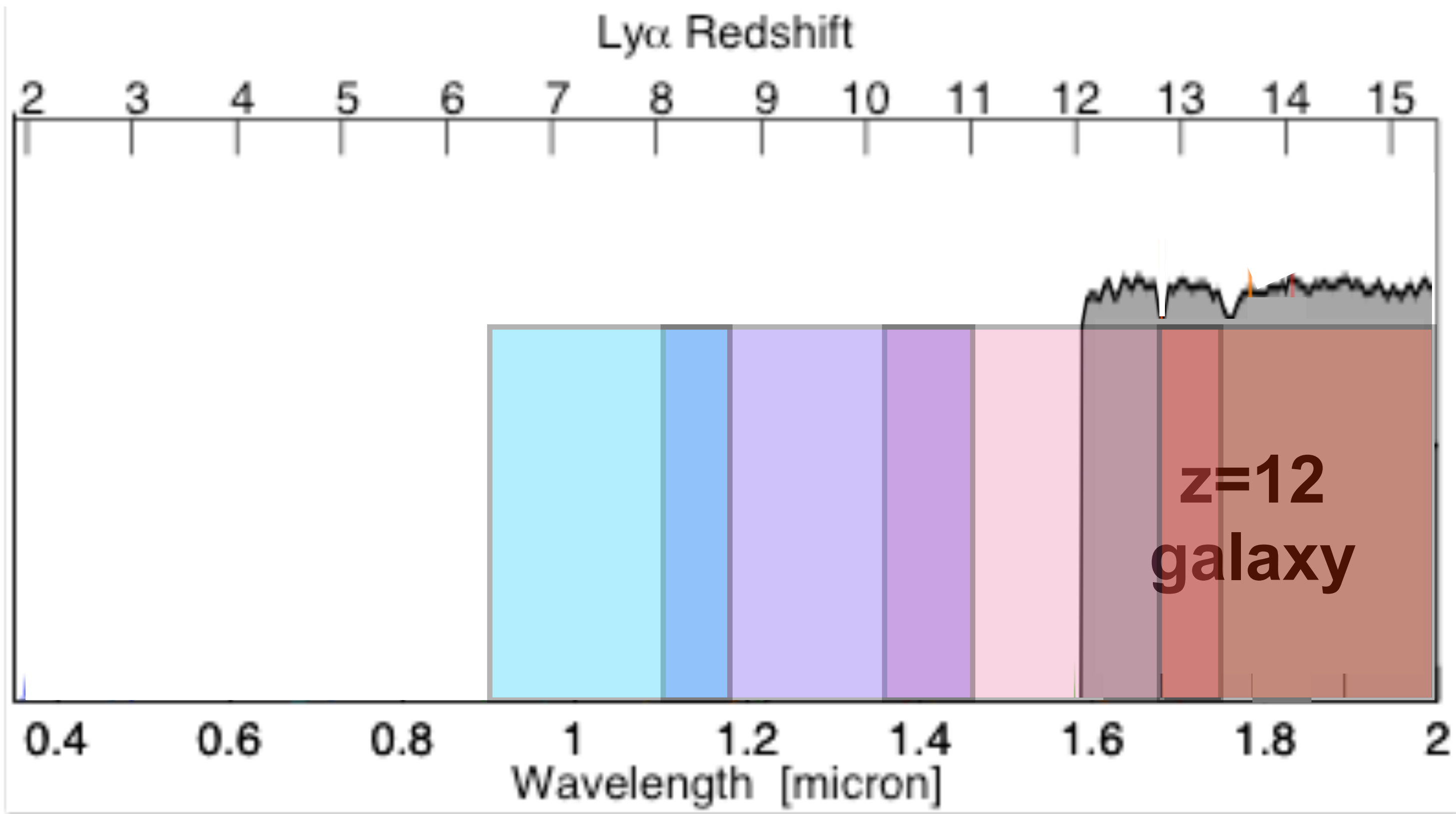

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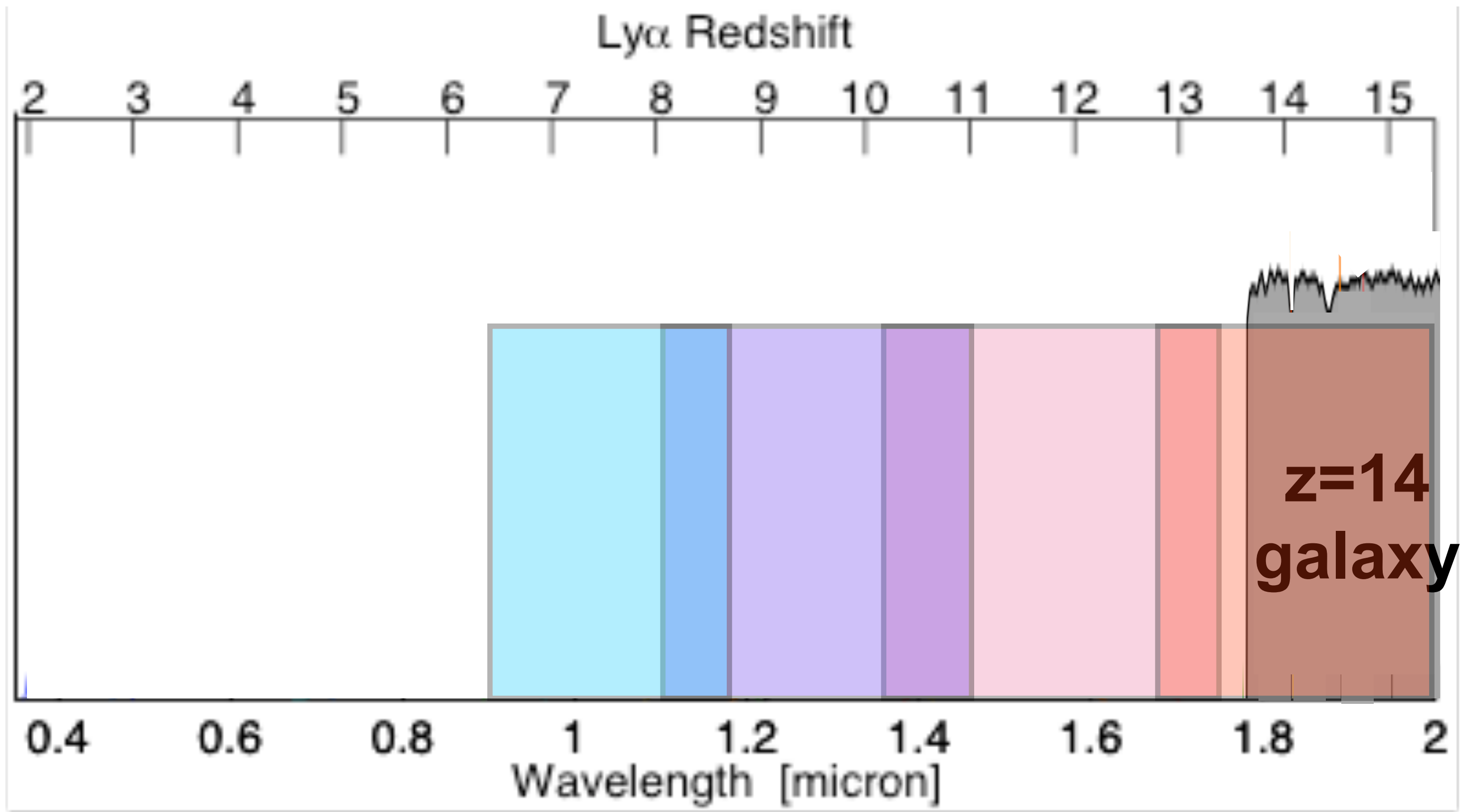

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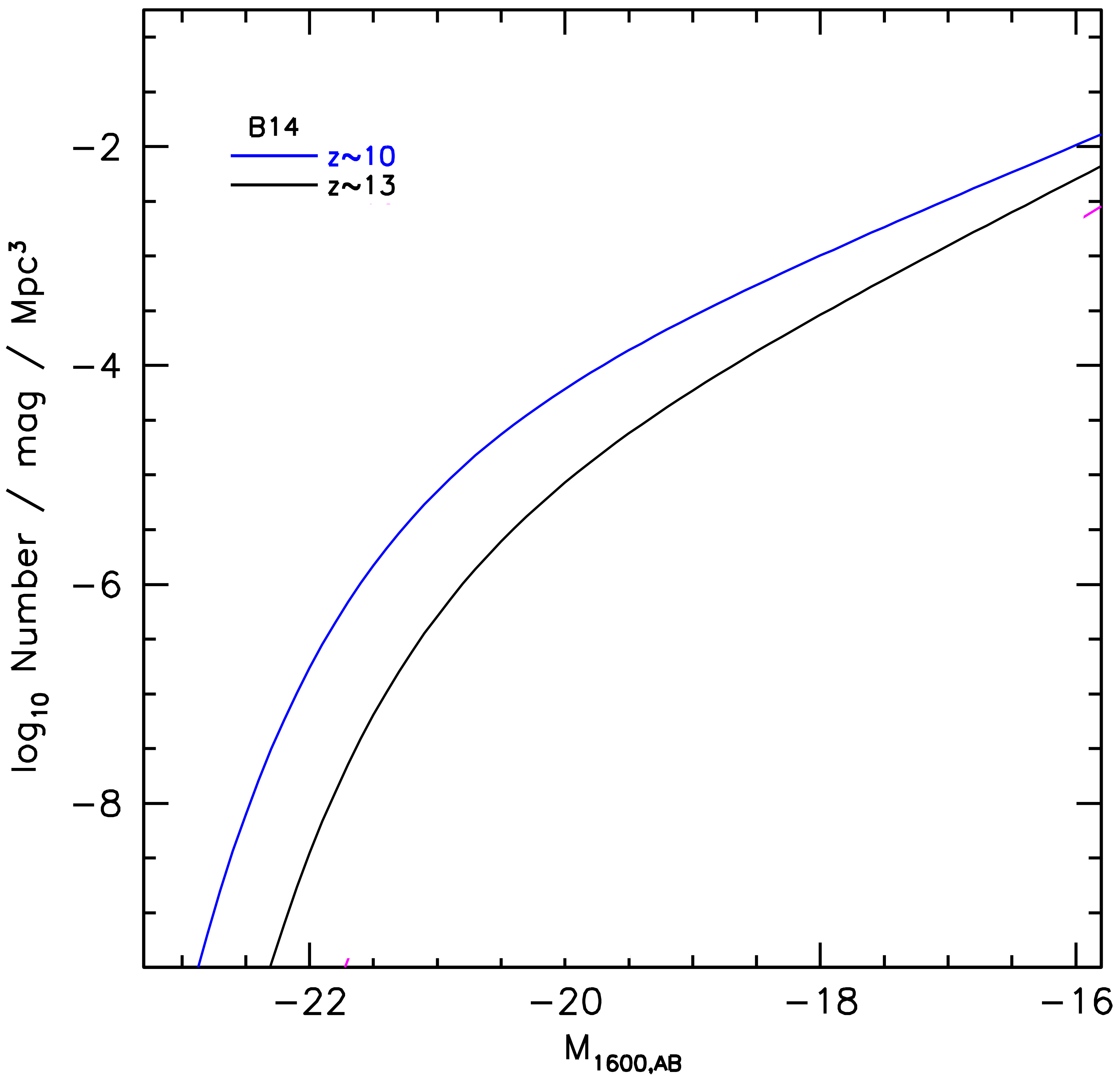
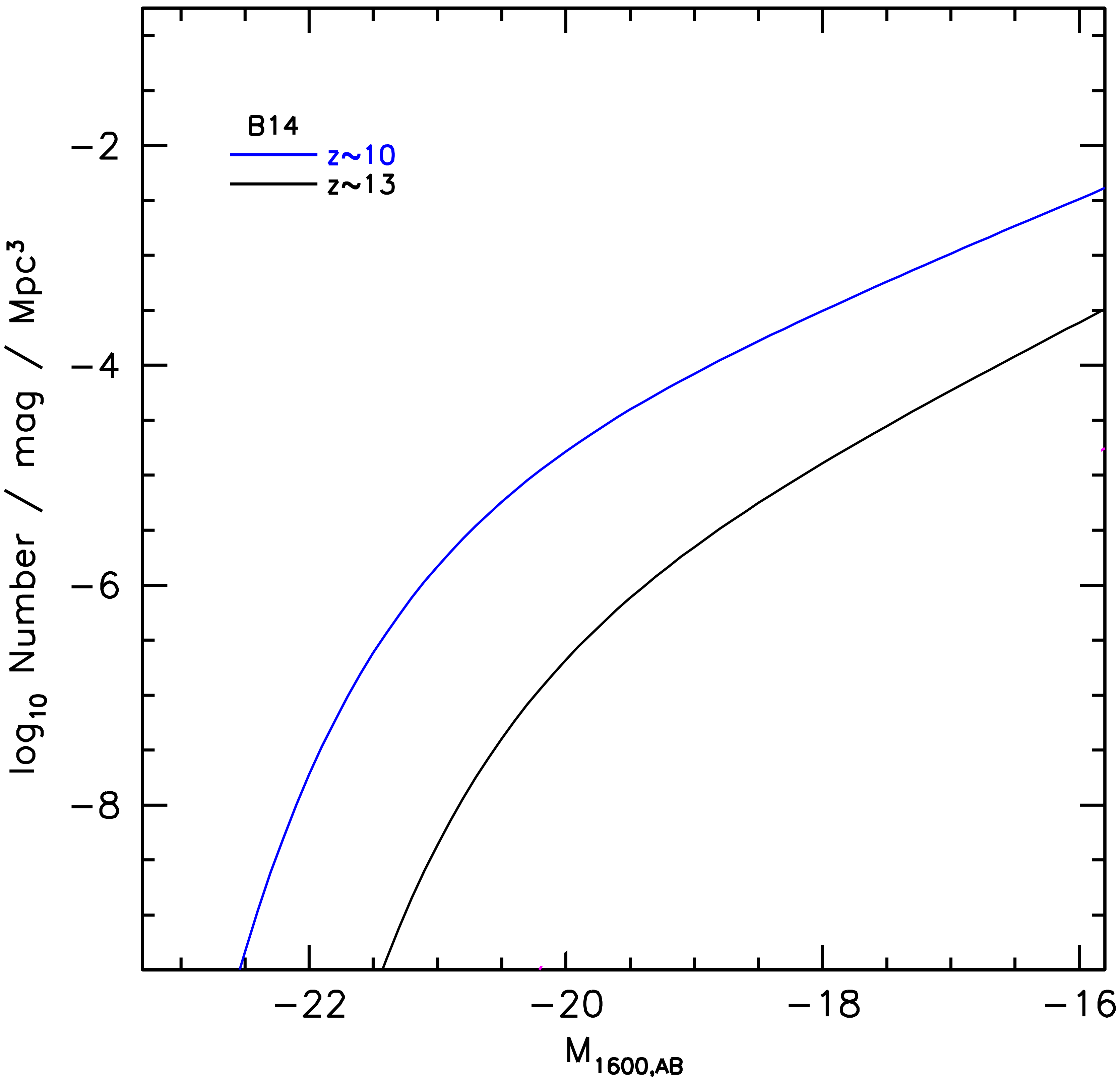
Selections to z~14 are probably possible albeit with substantial amounts of contamination

If we assume no acceleration in the evolution, here are the predicted LFs...



If we assume accelerated evolution (pessimistic scenario), here are the predicted LFs...



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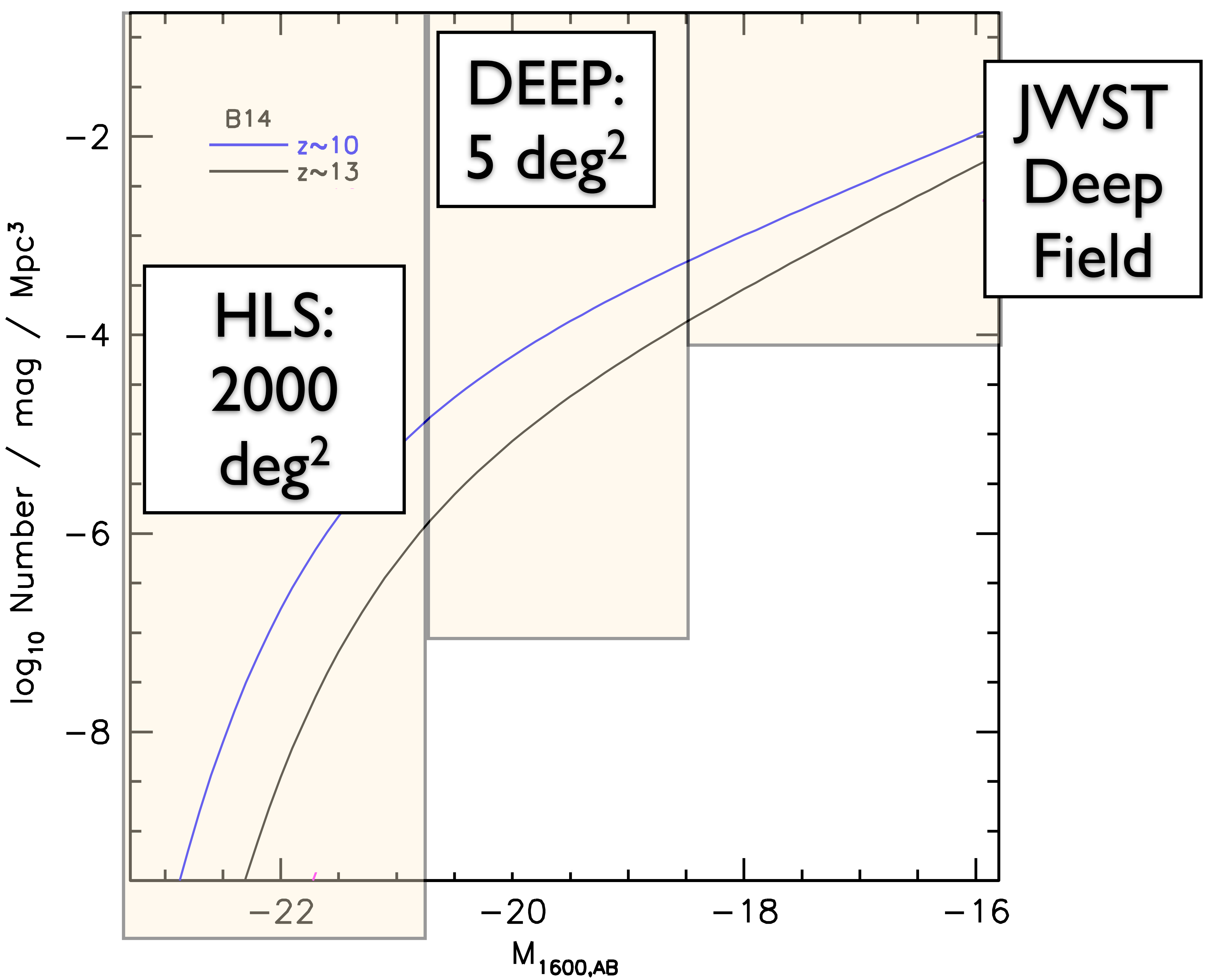
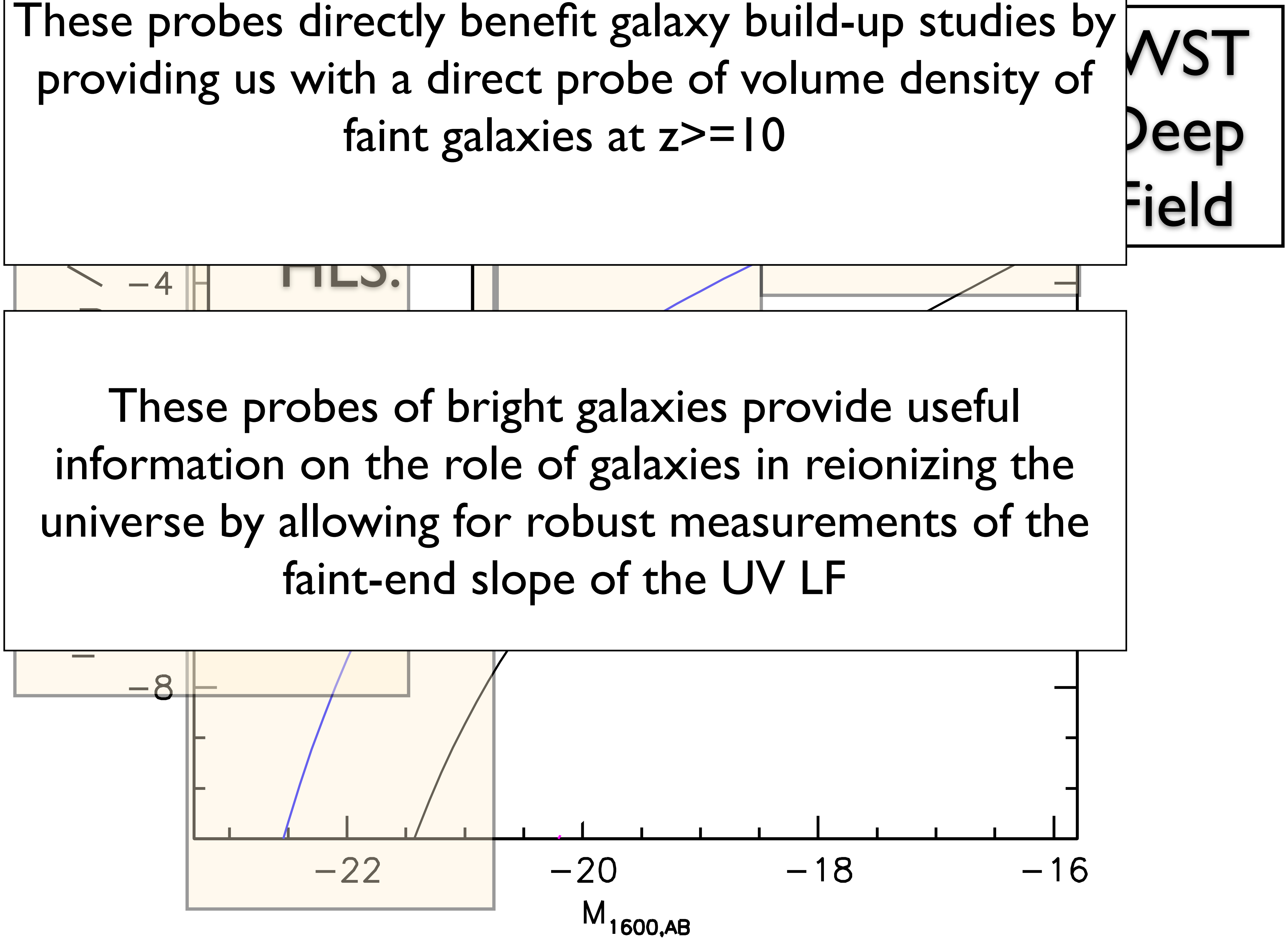


If we assume accelerated evolution (pessimistic scenario), here are the predicted LFs...

These probes directly benefit galaxy build-up studies by providing us with a direct probe of volume density of faint galaxies at z>=10



These probes of bright galaxies provide useful information on the role of galaxies in reionizing the universe by allowing for robust measurements of the faint-end slope of the UV LF

Deep F184 Observations Should be Added to Deep SN Survey:

This is in addition to deep Y-band data which should be added to serve as a "veto filter"

Likely allow for the discovery of faint z~12-14 galaxies in deep SN Survey

Cost ~300 hours [18 pointings x 216 x 240 seconds] to obtain ~29 mag depth in F184 filter

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Sensitivity at even redder wavelengths (> 2 microns) would also provide very useful constraints on even higher redshift galaxies:

With redder filters, could plausibly find galaxies to z~15

Or could work in synergy with future facilities like WISH which should have sensitivity at > 2 microns

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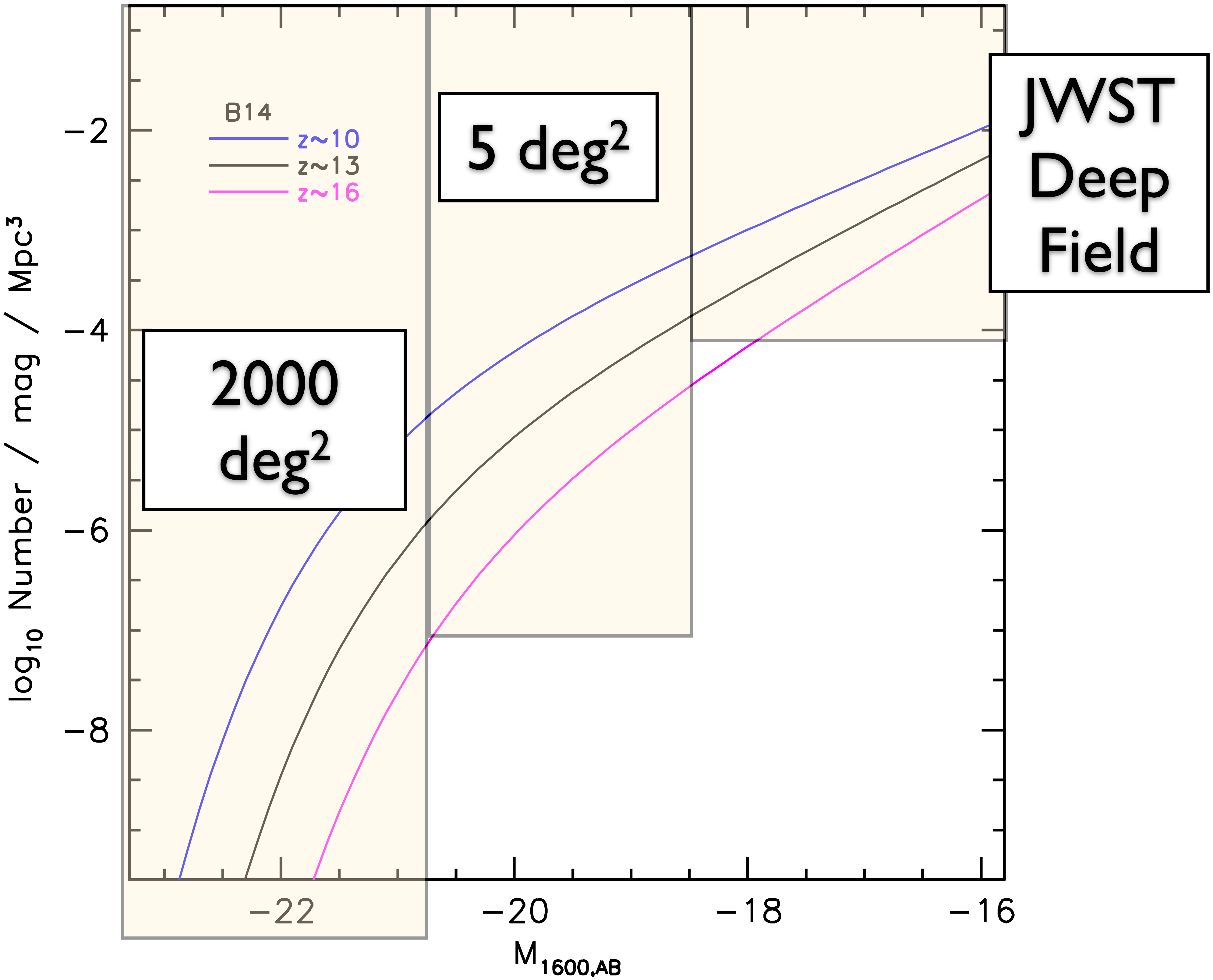

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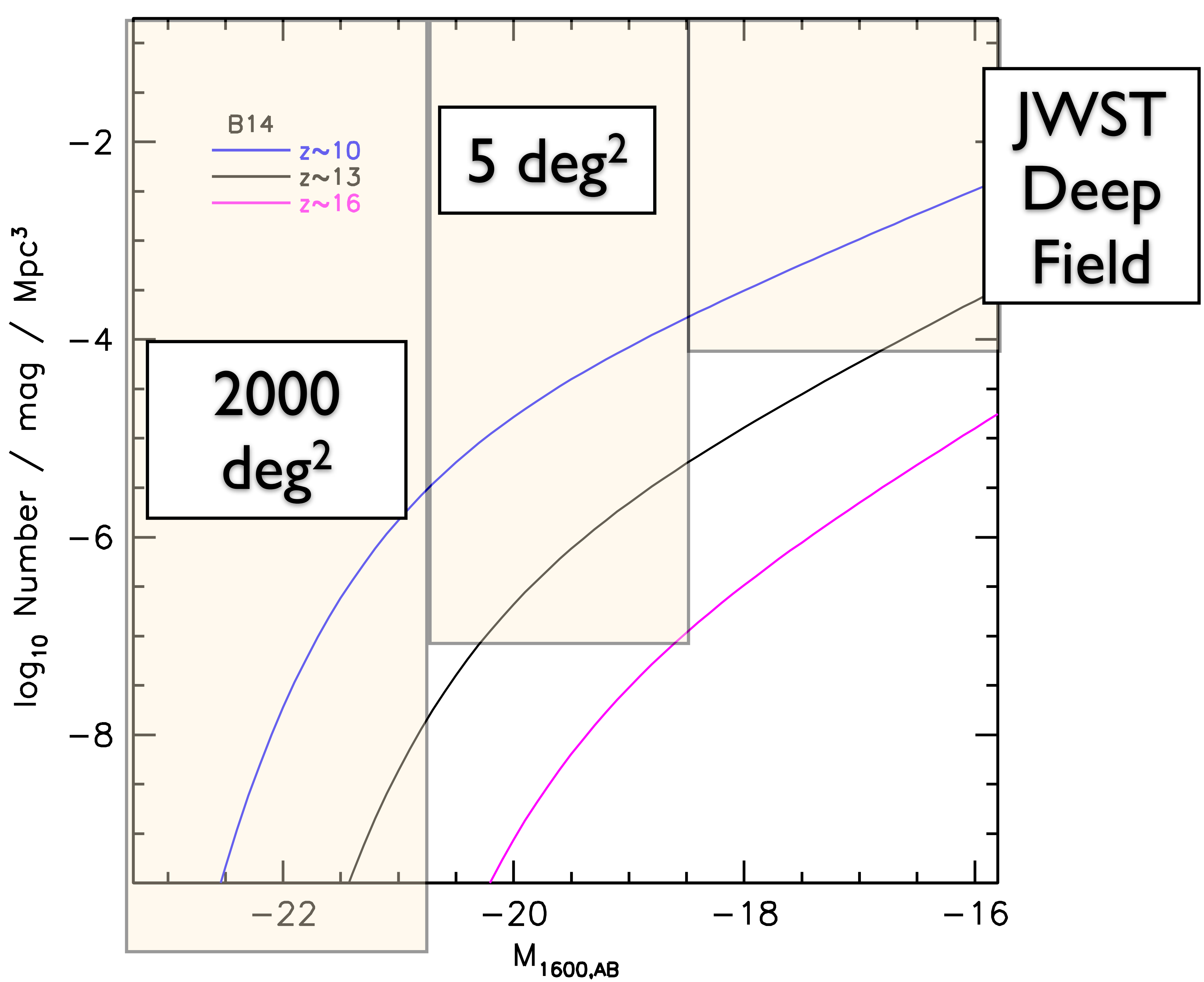
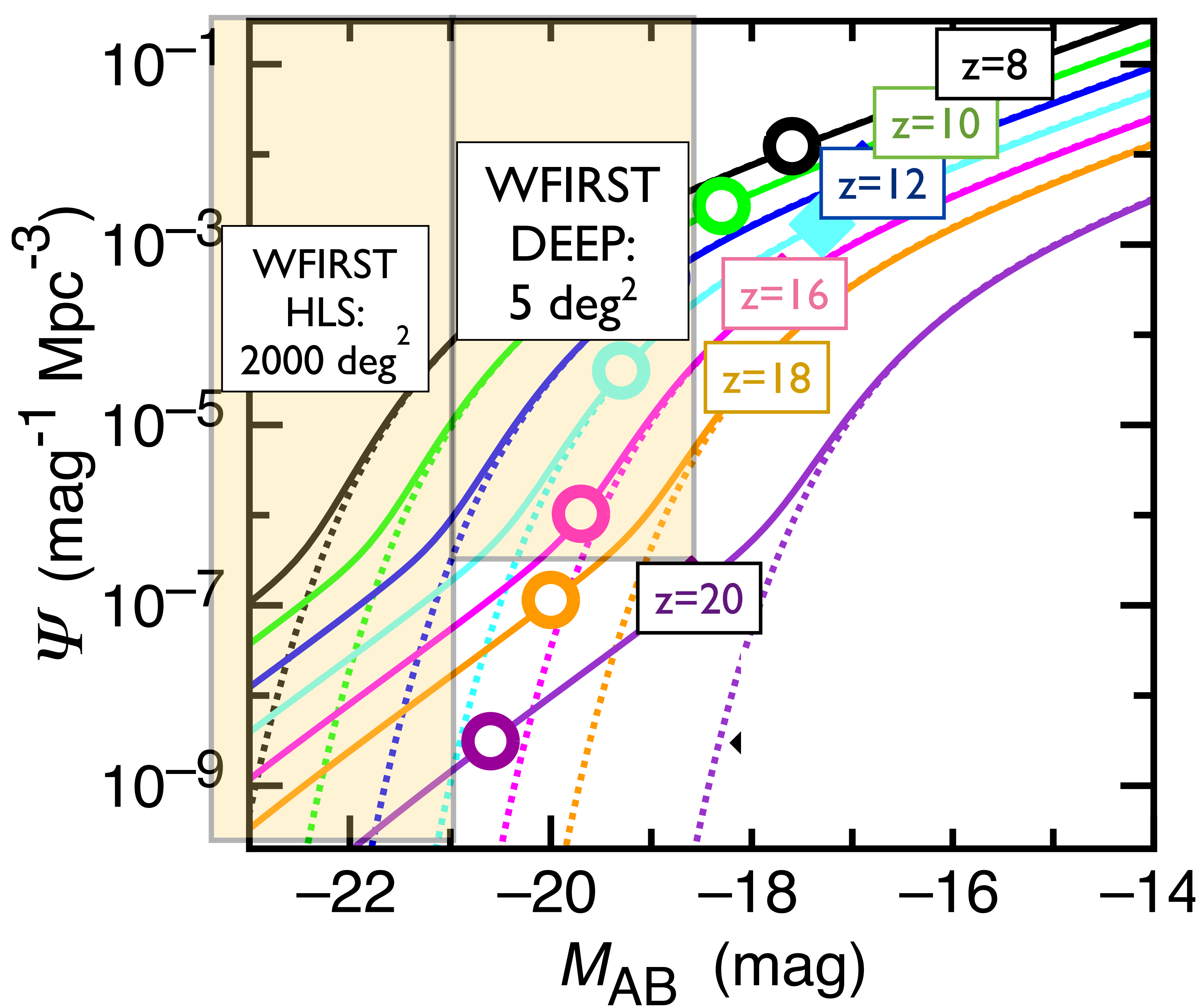


Gravitational lensing by foreground galaxies could help WFIRST to find large numbers of highly magnified z>~10 galaxies.



Wyithe+2011; Baron-Nugent 2014

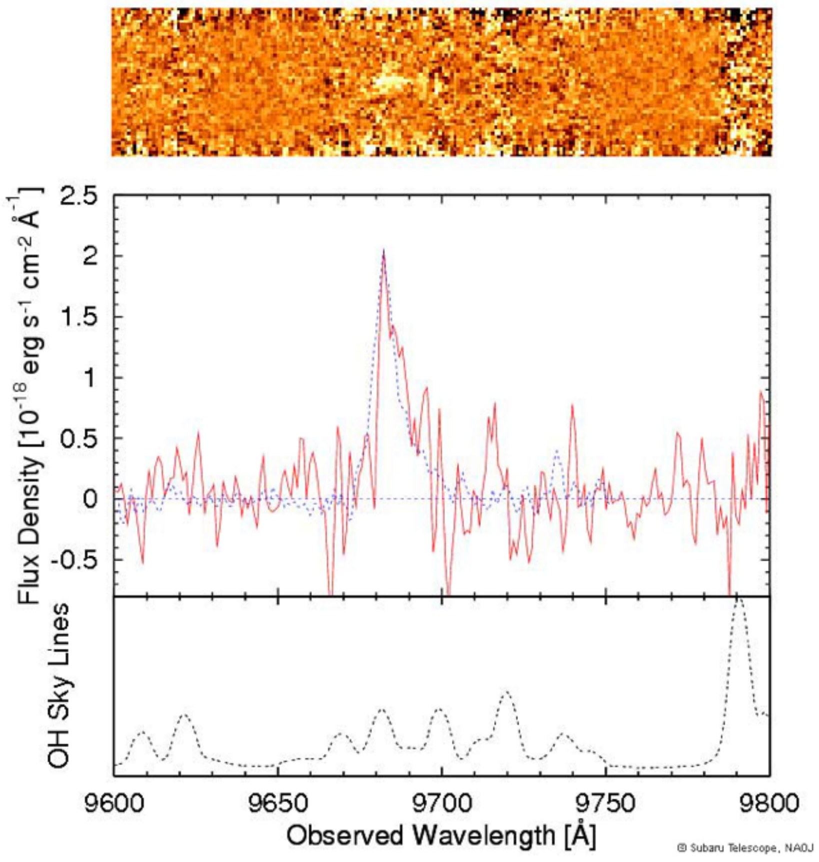
Scientific Interest #3:

There is also significant interest in the determination of the physical properties of galaxies and ionization state of the universe from a study of the emission lines and from precise redshift

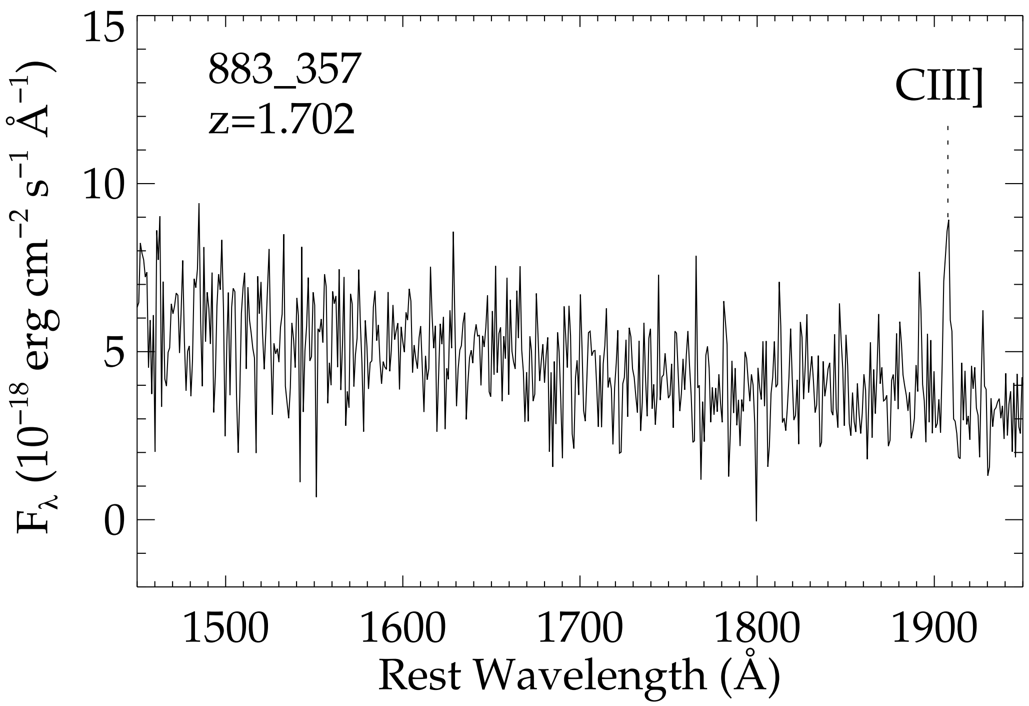
Can we make progress on these questions using spectroscopy with WFIRST?

Relevant Lines Include

Lyman alpha
1216 A



CIII] emission line
1907, 1909 A



Iye+2006; Ono+2012; Schenker+2012; Finkelstein+2013

What can be done here with spectroscopy?

HLS Spectroscopy	1.35 – 1.95 μm	2000	0.5×10^{-16} erg/s/cm^2 @ 1.65 μm	

Lyα (in principle visible z=10.1-15.0): Given that the scarcity of Lyα emission from galaxies at z>6.5, only likely to be useful if spectroscopy extended below 1.1 microns, with a 5x increase in sensitivity.

CIII] (visible z=6.1-9.2): HLS spectroscopy would need to be 20x more sensitive to detect this line for the brightest z~6-9 galaxies. Detections of individual galaxies possible in 100 hour integrations, but much more practical to follow up sources with JWST.

What about with JWST?

Spectroscopic follow-up of z>10 sources with JWST should work very well. It will be important for WFIRST to make significant progress on its observing program while JWST is still obtaining observations.

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What about from the ground?

Placement of the HLS in the South should make the candidates identified by WFIRST ideal for follow-up with the E-ELT and GMT, but not with TMT.

Summary

WFIRST should provide us with exceptional leverage in quantifying the build-up of all but the faintest galaxies in the early universe and quantifying their contribution to reionization.

Current z~4-10 LFs derived from HST -- derived from >10,000 galaxies over 5 independent sight lines -- provide us with a reasonable baseline for establishing expectations for future WFIRST results at z>=10

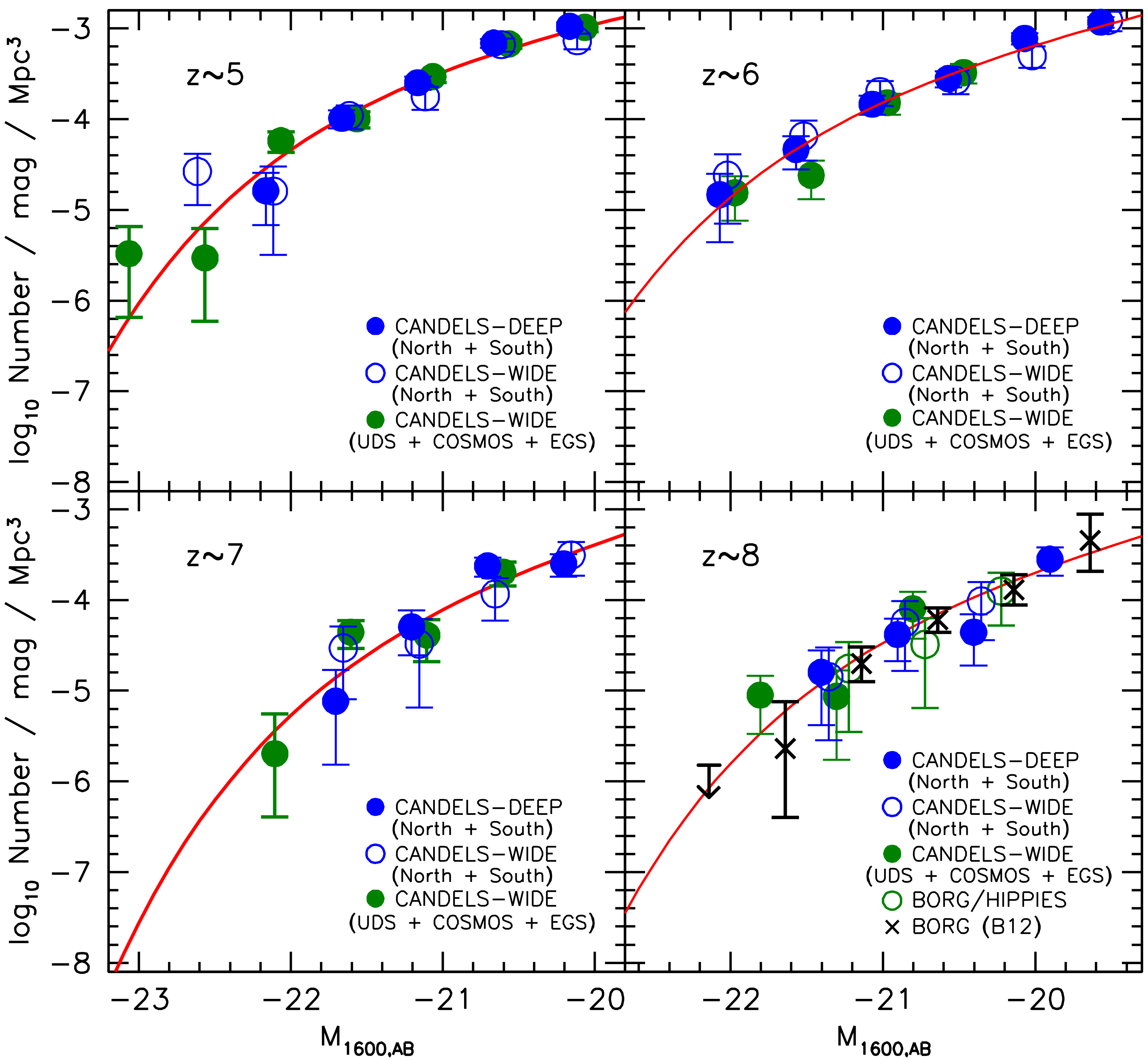
While uncertain, extrapolations of current results suggest that non-negligible numbers of z~12-14 galaxies will be found in the planned WFIRST HLS.

The WFIRST deep SN survey can also provide strong constraints on the volume density on much fainter galaxies at z~12-14, but deep observations with F184 will be required (~300 hour cost).

The WFIRST survey area and depth are such that it could also identify an "interesting" number of z~14-16 galaxies, if its sensitivity could be extended to > 2 microns.

The current spectroscopic facilities on WFIRST do not seem likely to provide useful information on first-light (z>6) galaxies, unless the capabilities are significantly upgraded or extended.

CANDELS WIDE fields provide very similar constraints on the UV LFs as the CANDELS GOODS-S+N fields

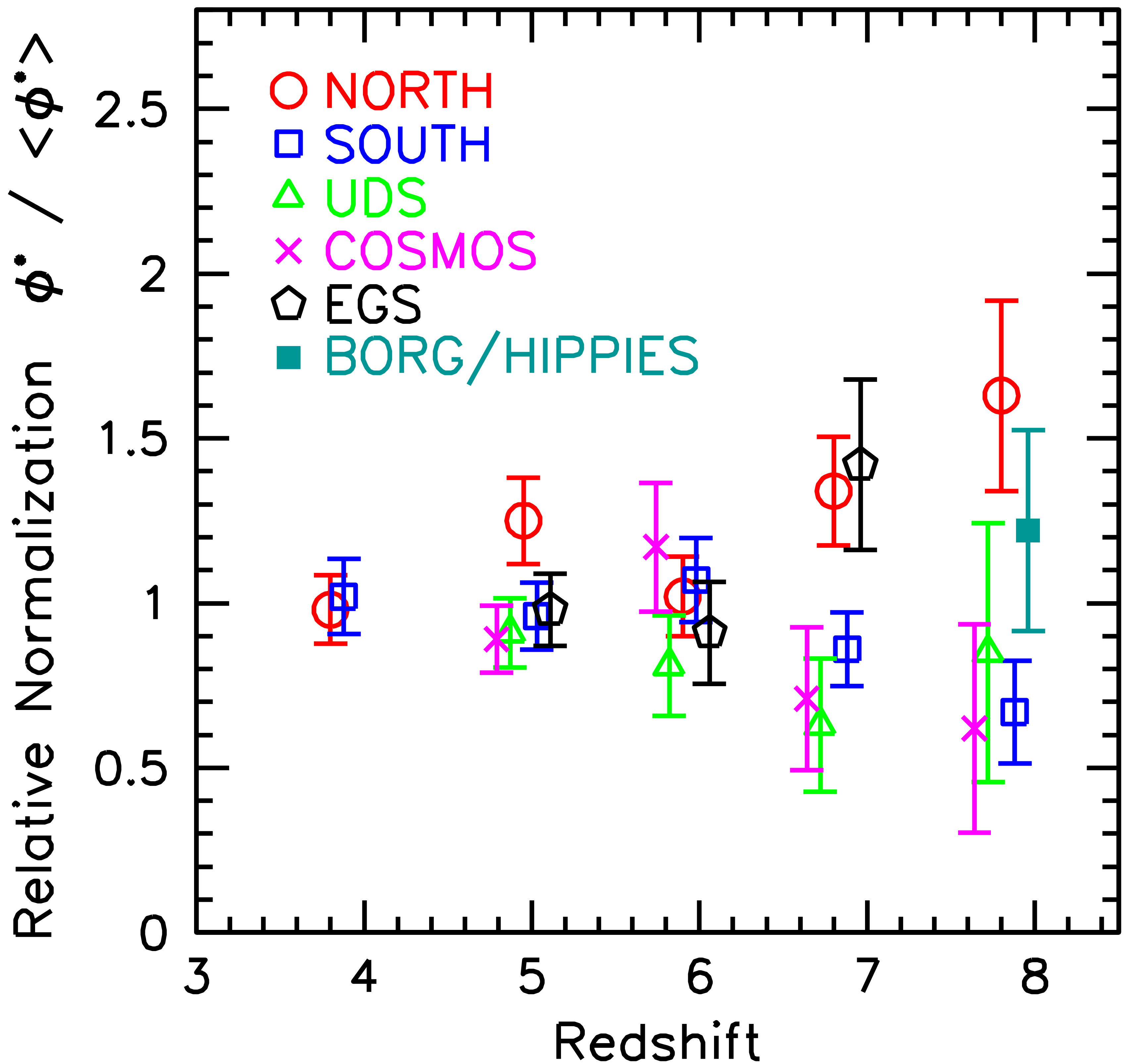


Independent Search Fields allow us to Overcome Large Field-to-Field Variance Observed at High Redshift

Estimated field-to-field variance for z~4-8 samples.

Field-to-field variance is substantial,

especially at high redshifts and at the bright end of the LF.

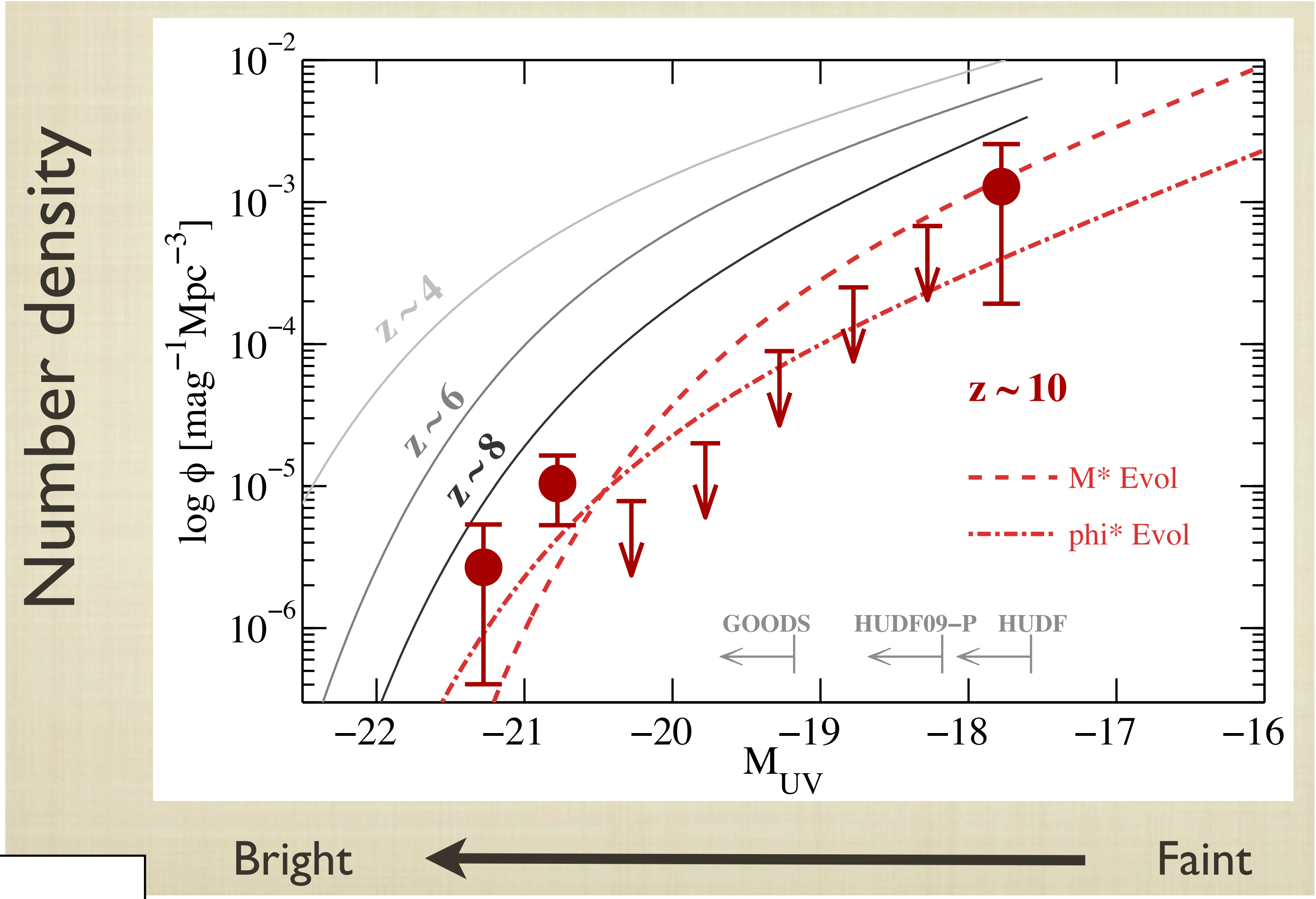


Bouwens+2014

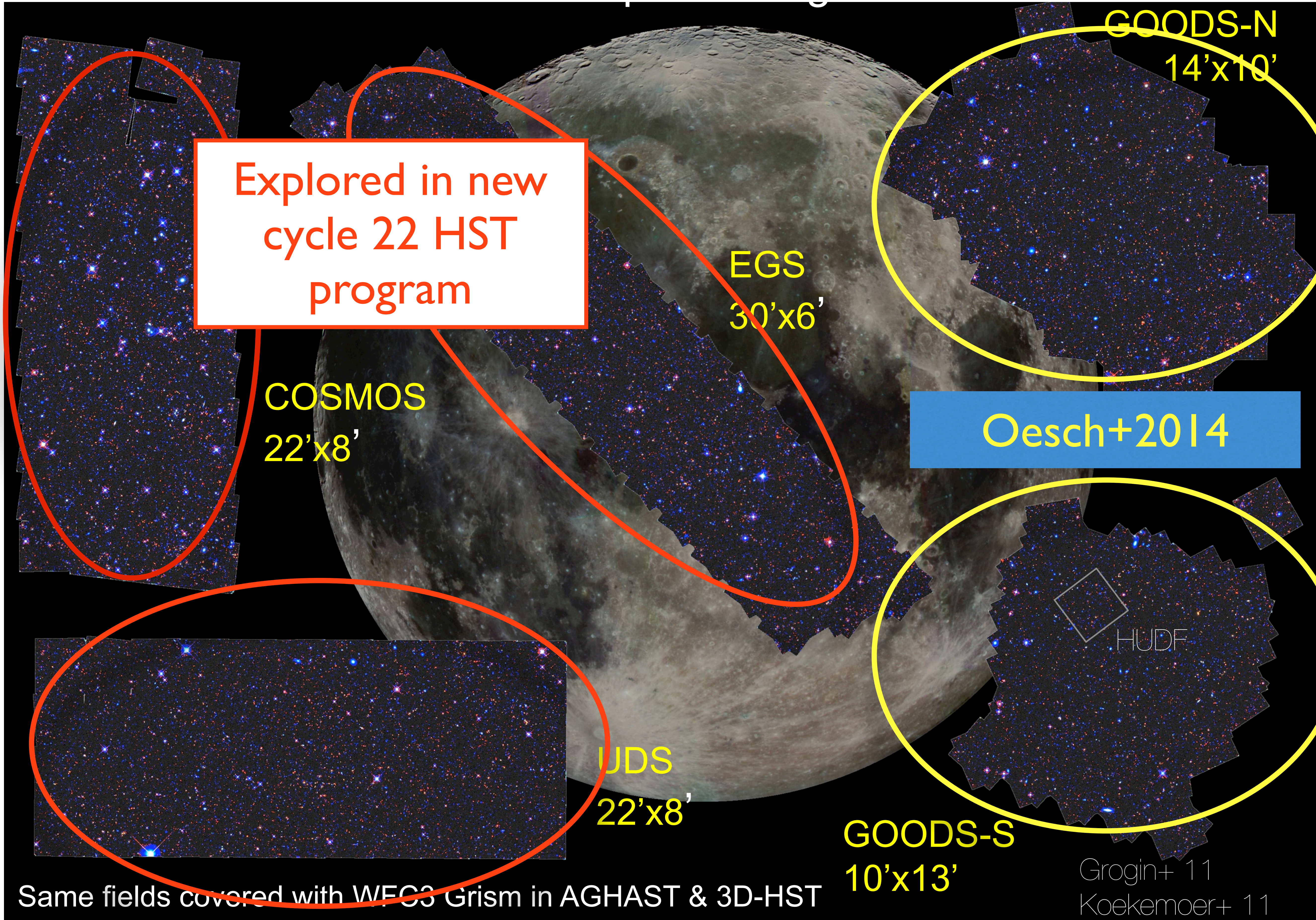
Volume Density of Bright z~9-10 Galaxies

Of particular interest for the new WISH surveys are the prevalence of z~9-10 galaxies

What work has been done on this?



Oesch+2014


Explored in new cycle 22 HST program
GOODS-N
14'x10'
EGS
30'x6'
COSMOS
22'x8'
Oesch+2014
HUDF
UDS
22'x8'
GOODS-S
10'x13'
Grogin+ 11
Koekemoer+ 11
Same fields covered with WFC3 Grism in AGHAST & 3D-HST