Galaxy Build-up and Evolution in the First 2 Billion Years of the Universe

Rychard Bouwens
Leiden Observatory

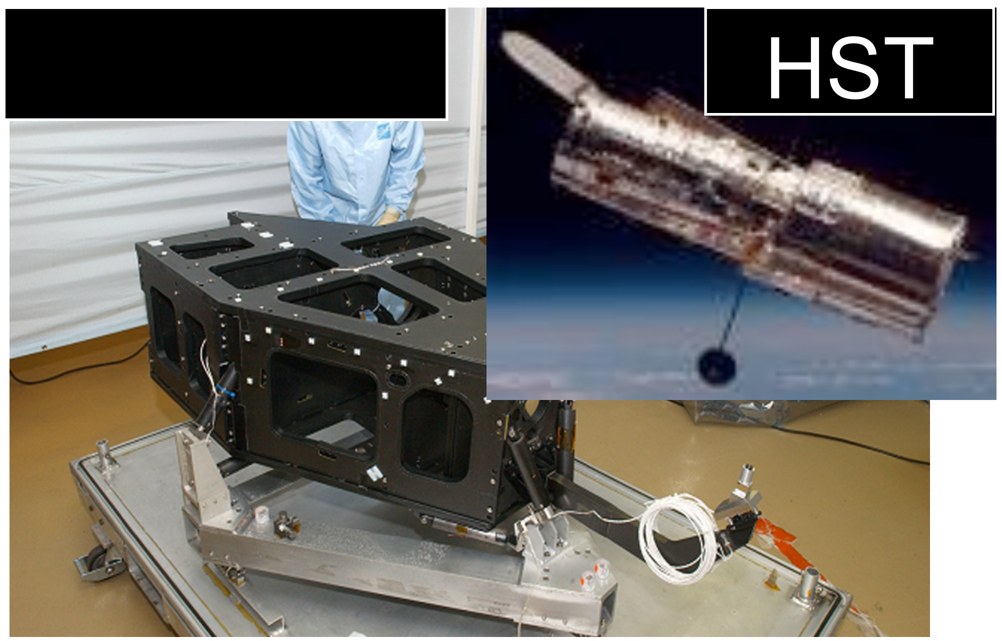
Special thanks to my collaborators Pascal Oesch, Ivo Labbe, Garth Illingworth, Renske Smit, Benne Holwerda...

Santa Cruz Galaxy Formation Workshop 2014

Santa Cruz, California August 11, 2014

State-of-the-Art Infrared Instrumentation is allowing for Great Progress

WFC3 camera on the Hubble Space Telescope



-- 4 arcmin field of view (6x larger than NICMOS)

-- excellent sensitivity (3-4x better than NICMOS)

-- excellent spatial resolution (2x higher than NICMOS)

IRAC Camera Spitzer Space Telescope

Very Wide-Area Ground-based Cameras

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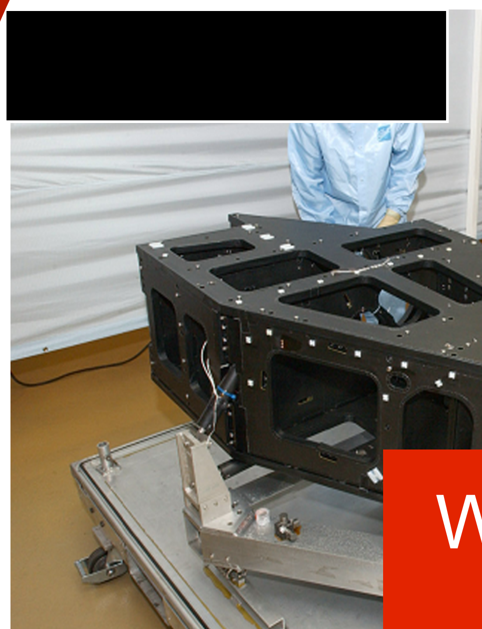

WFC3/IR increased search efficiency by 40x

-- 4 arcmin field of view (6x larger than NICMOS)

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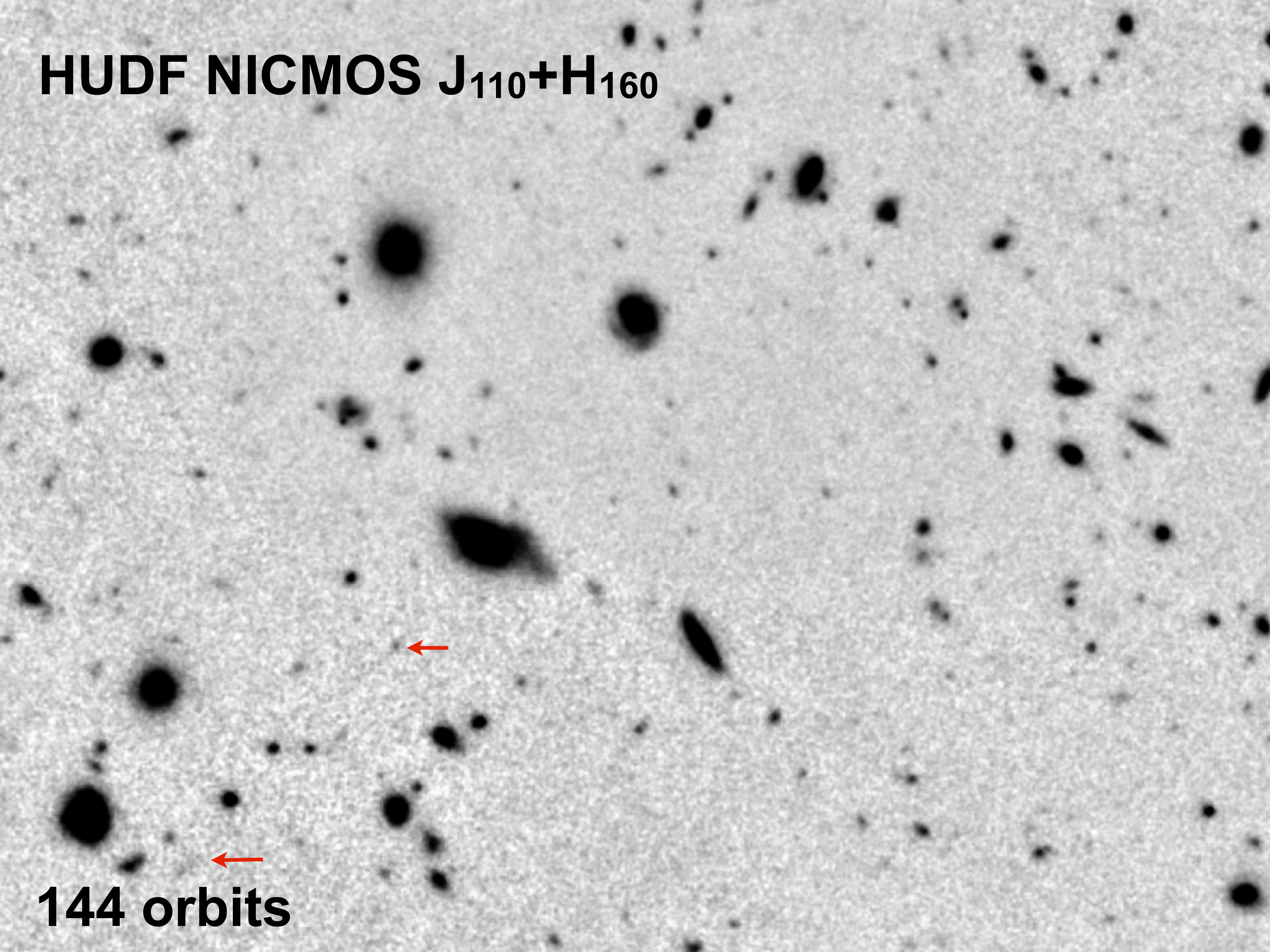
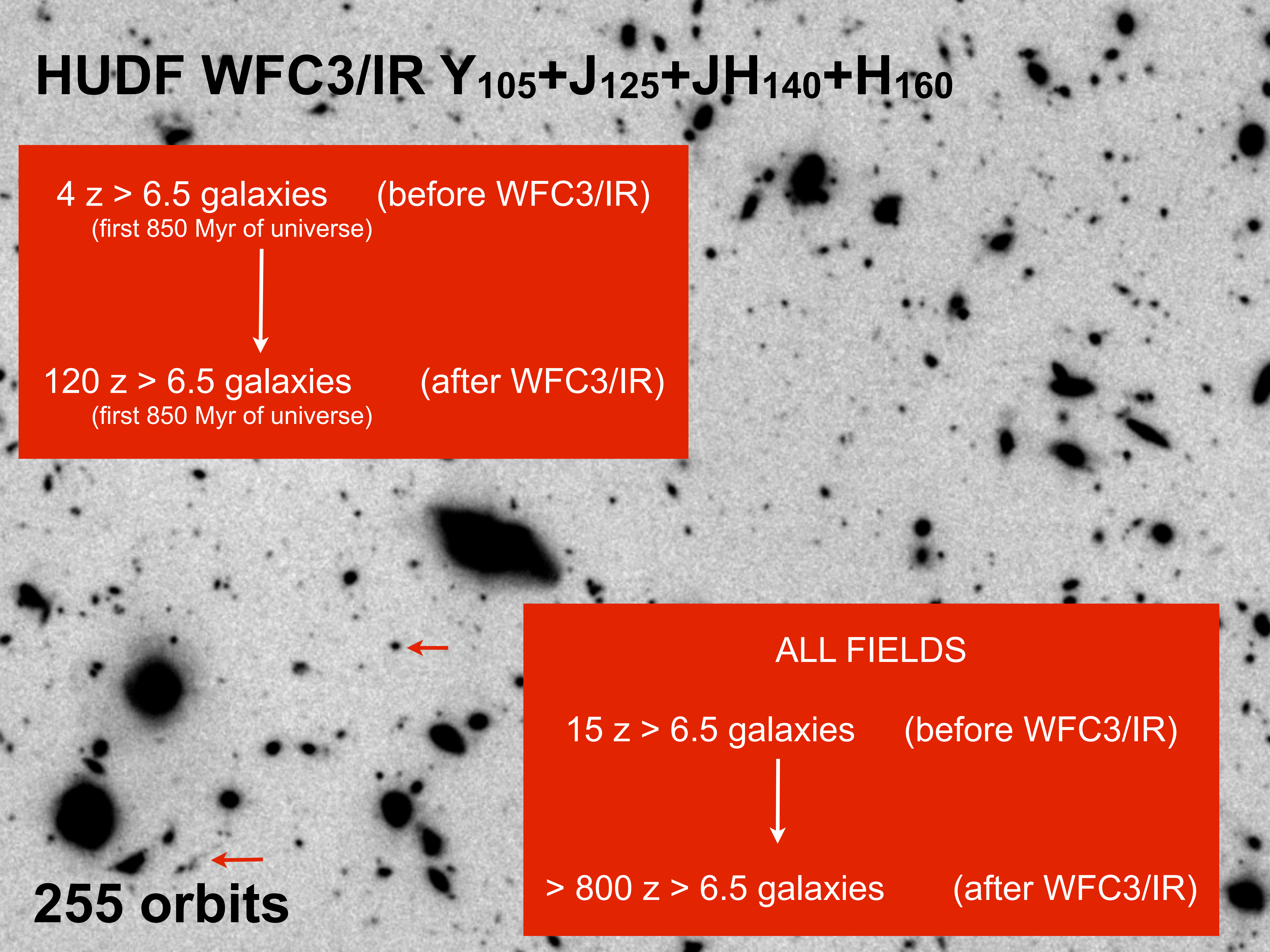

HUDF NICMOS J_{110}+H_{160}
144 orbits


HUDF WFC3/IR $Y_{105}+J_{125}+JH_{140}+H_{160}$
4 z > 6.5 galaxies (before WFC3/IR)
(first 850 Myr of universe)
120 z > 6.5 galaxies (after WFC3/IR)
(first 850 Myr of universe)
ALL FIELDS
15 z > 6.5 galaxies (before WFC3/IR)
> 800 z > 6.5 galaxies (after WFC3/IR)
255 orbits

Why are studies of galaxies at very high redshifts interesting?

-- It is when galaxies first form...

(halos of L* and sub-L* galaxies built up from z~30+ to z~3)

-- It is when the universe was reionized...

(galaxies are most likely driver, so by studying the formation of first galaxies perhaps we can gain insight)

Focus of this Presentation:

Galaxy Growth from z~10 to z~4

What are the different regimes to study galaxy growth?

"Normal" Population of Faint Galaxies (Most stars in universe form here)

How rapidly do faint (low mass) galaxies grow up?

⇒ Study using the Hubble Ultra Deep Field (and similar fields)

Rare Population of Bright Galaxies

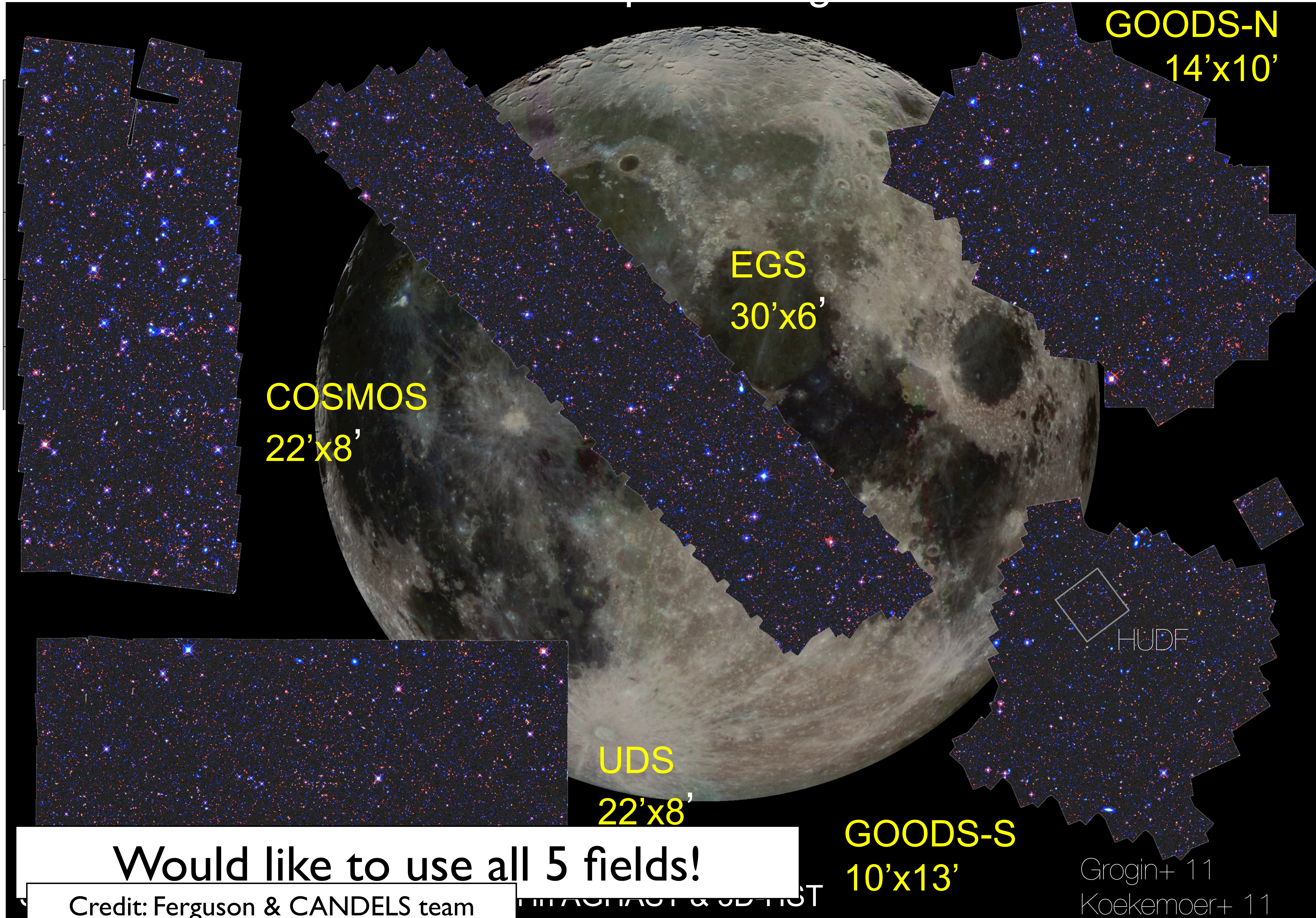
How rapidly do bright (massive) galaxies grow up?

How Bright / Massive can Galaxies Become?

⇒ Study using very wide-area fields

What can we learn based on current wide-area fields?

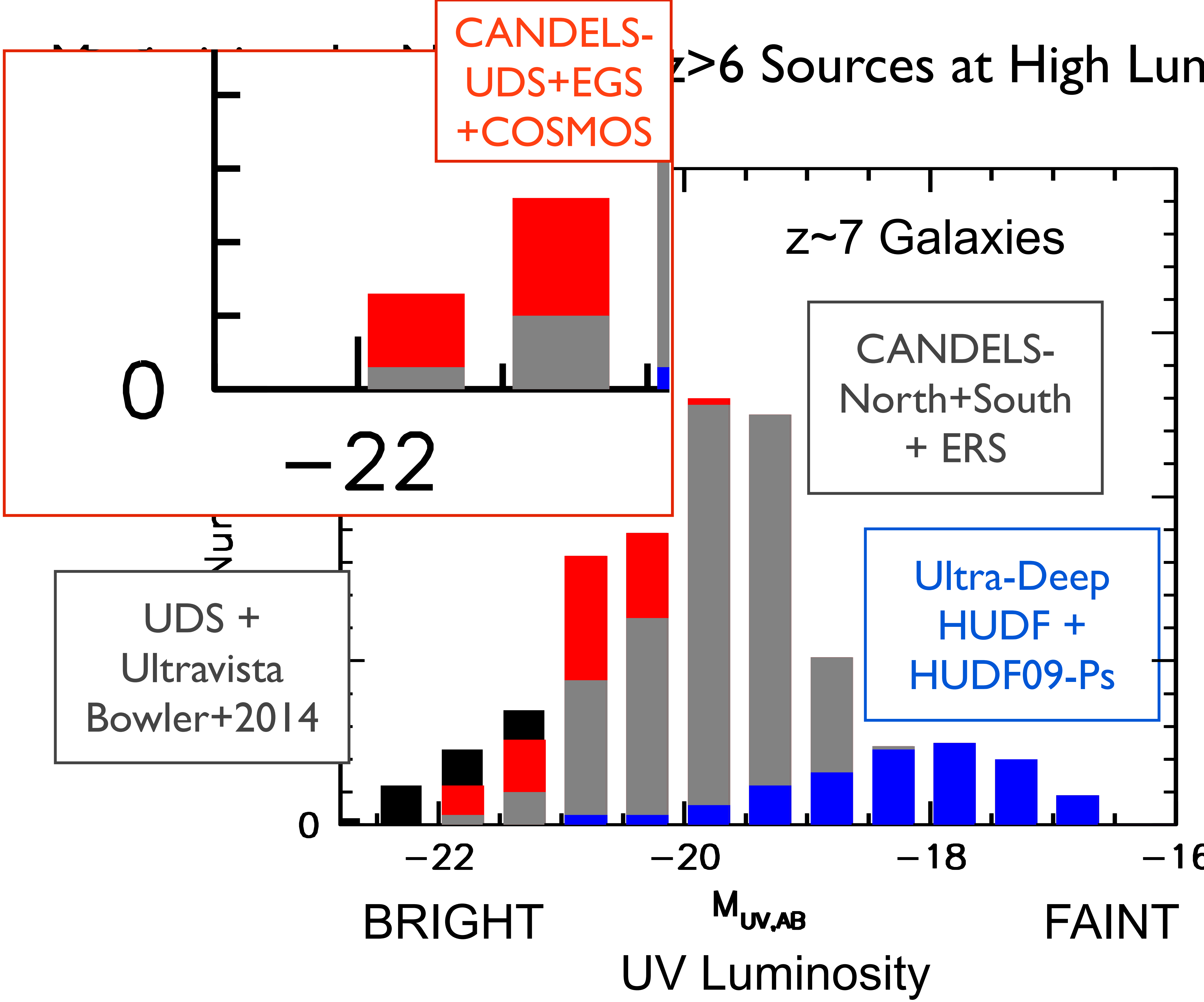
Full CANDELS Program (+ BORG + ERS) provides an ideal data set to study the properties of the most luminous galaxies



Would like to use all 5 fields!

Credit: Ferguson & CANDELS team

z>6 Sources at High Luminosity



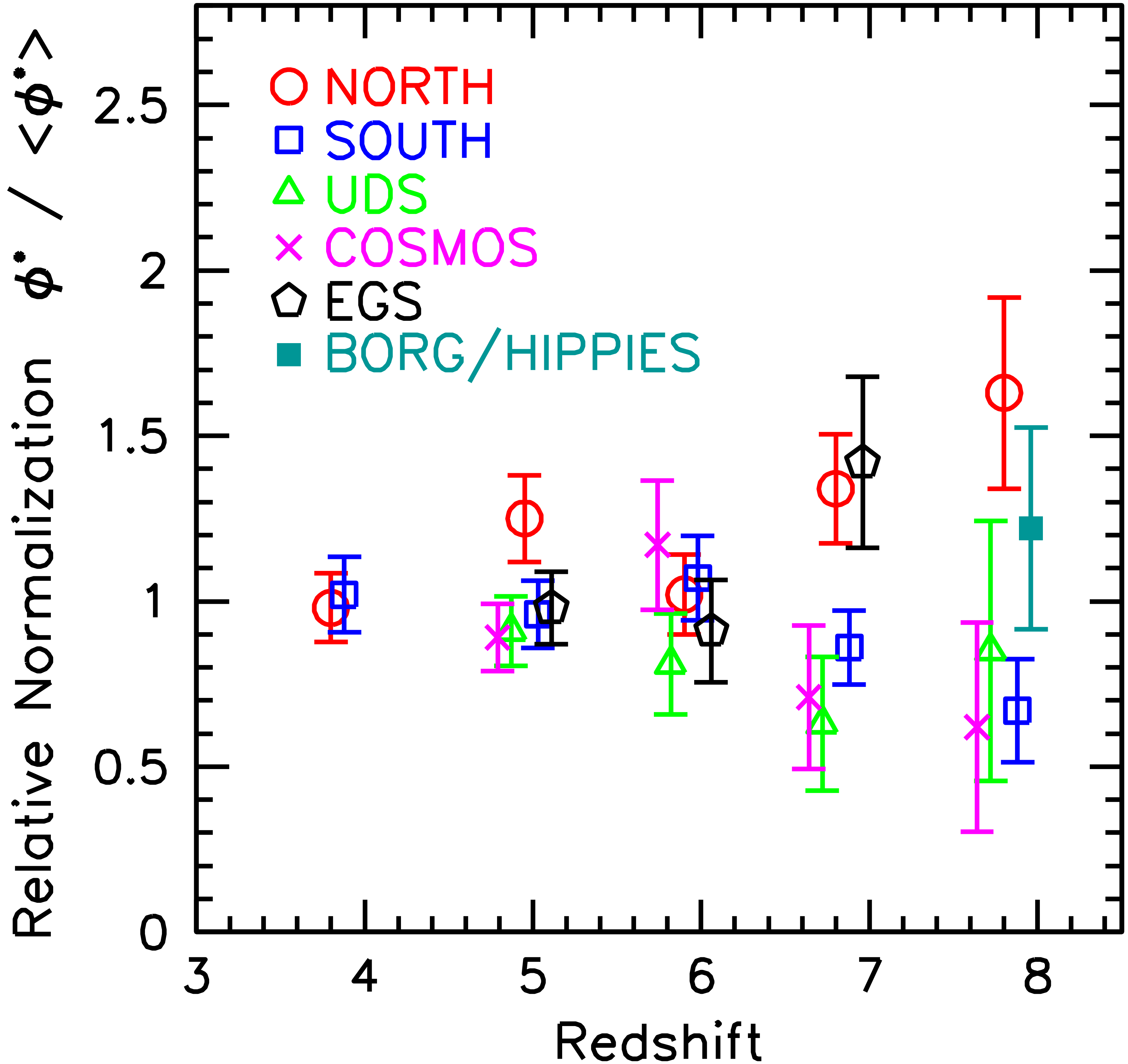
Bouwens+2014

Large Areas Required 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

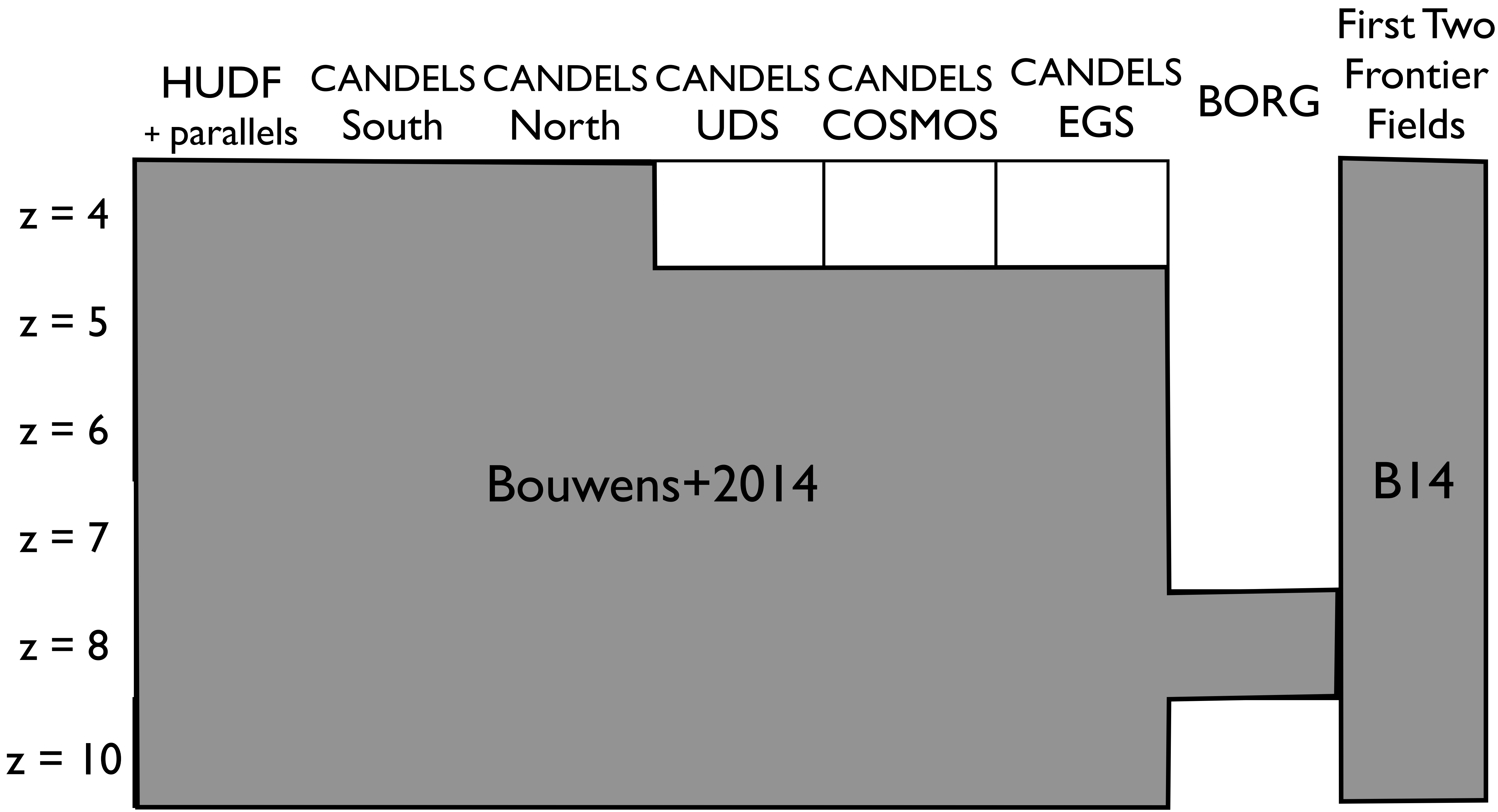
With lots of great data sets....

what can we learn about galaxy growth?

Let’s look at the z>=4 LFs

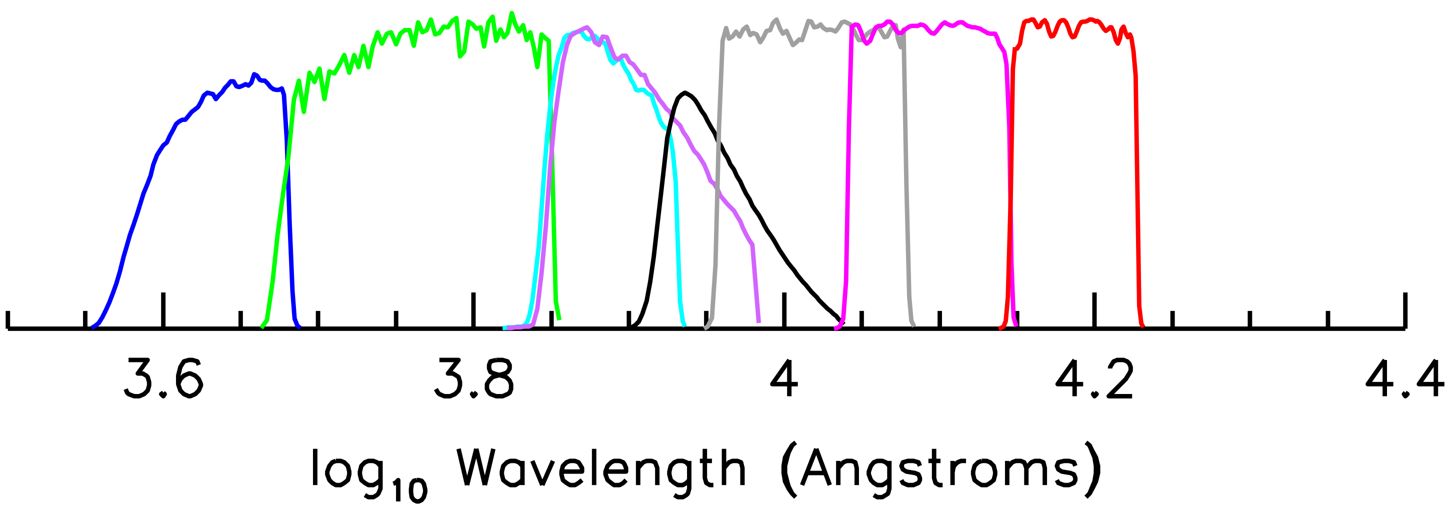
z~4-10 LFs from all CANDELS + HUDF + other legacy fields

(Bouwens et al. 2014, arXiv:1403.4295, 48 pages)



Possible to Make Use of Whole CANDELS area?

CANDELS-North/South:
Deep HST data over a
contiguous wavelength range



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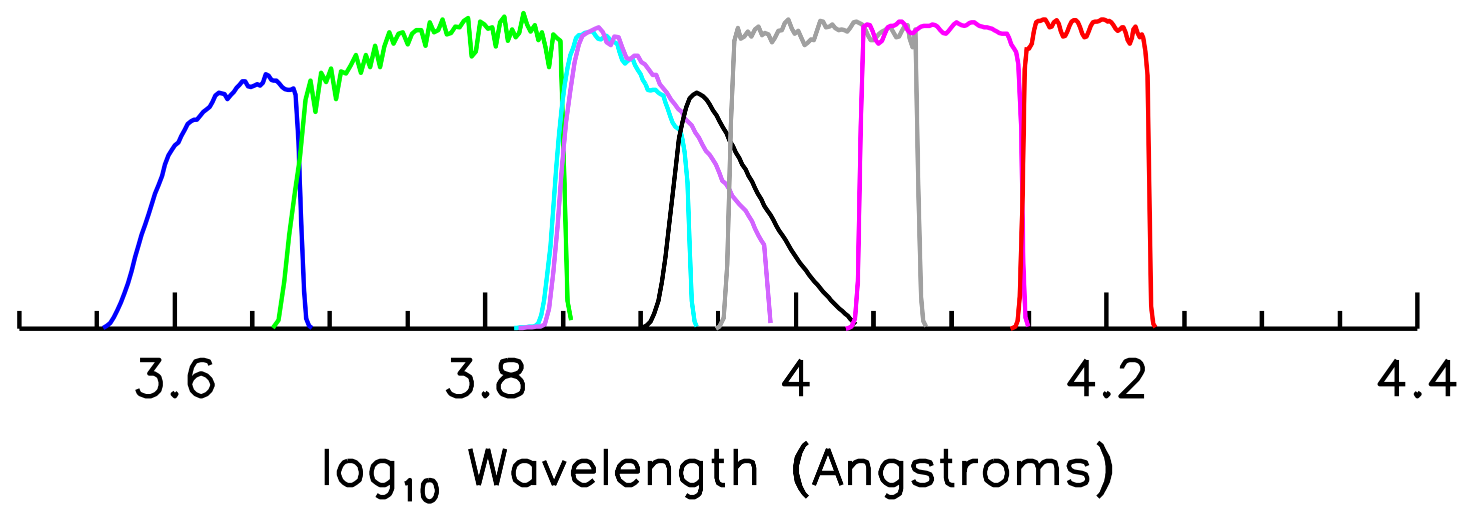
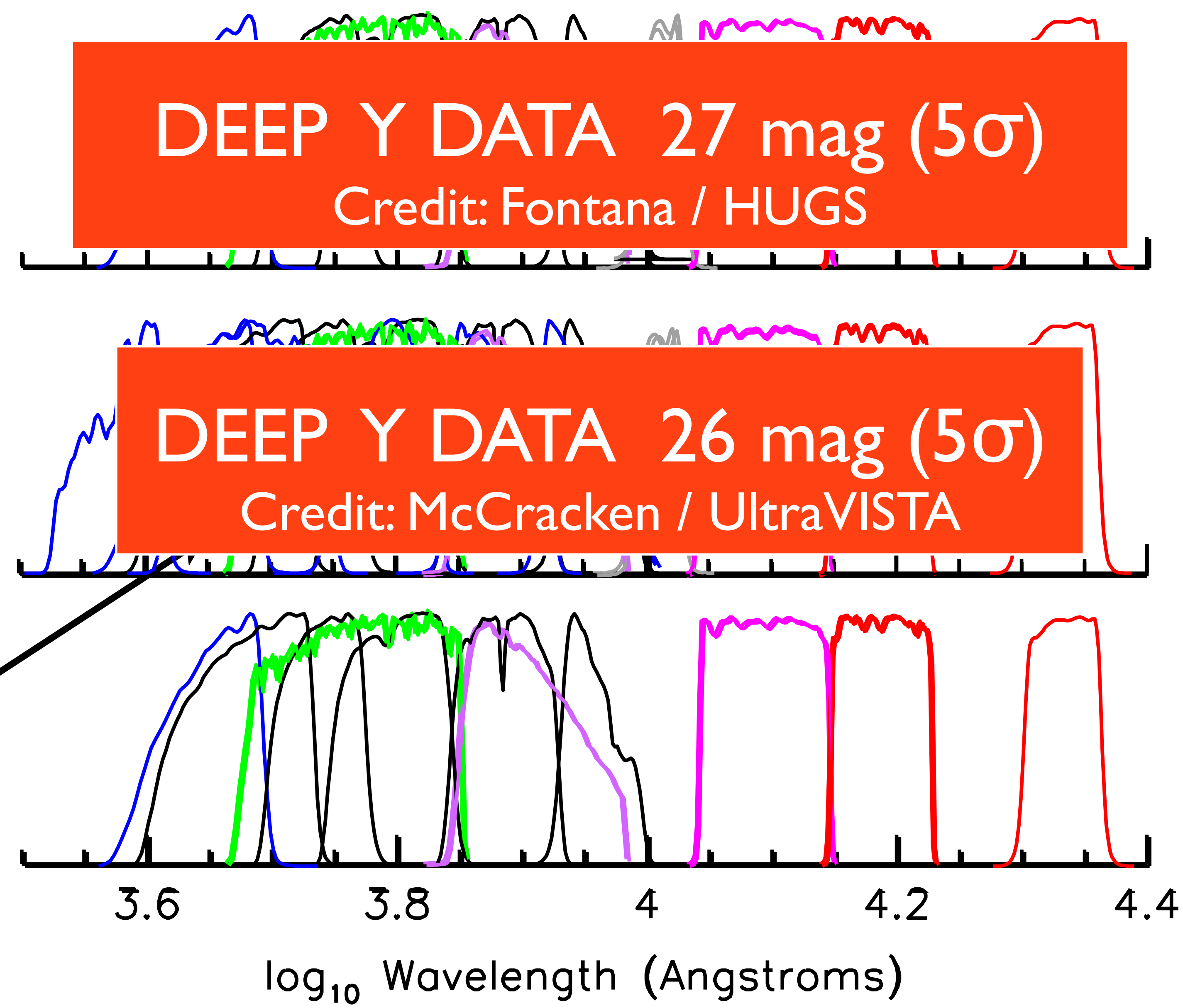


CANDELS-UDS

CANDELS-COSMOS

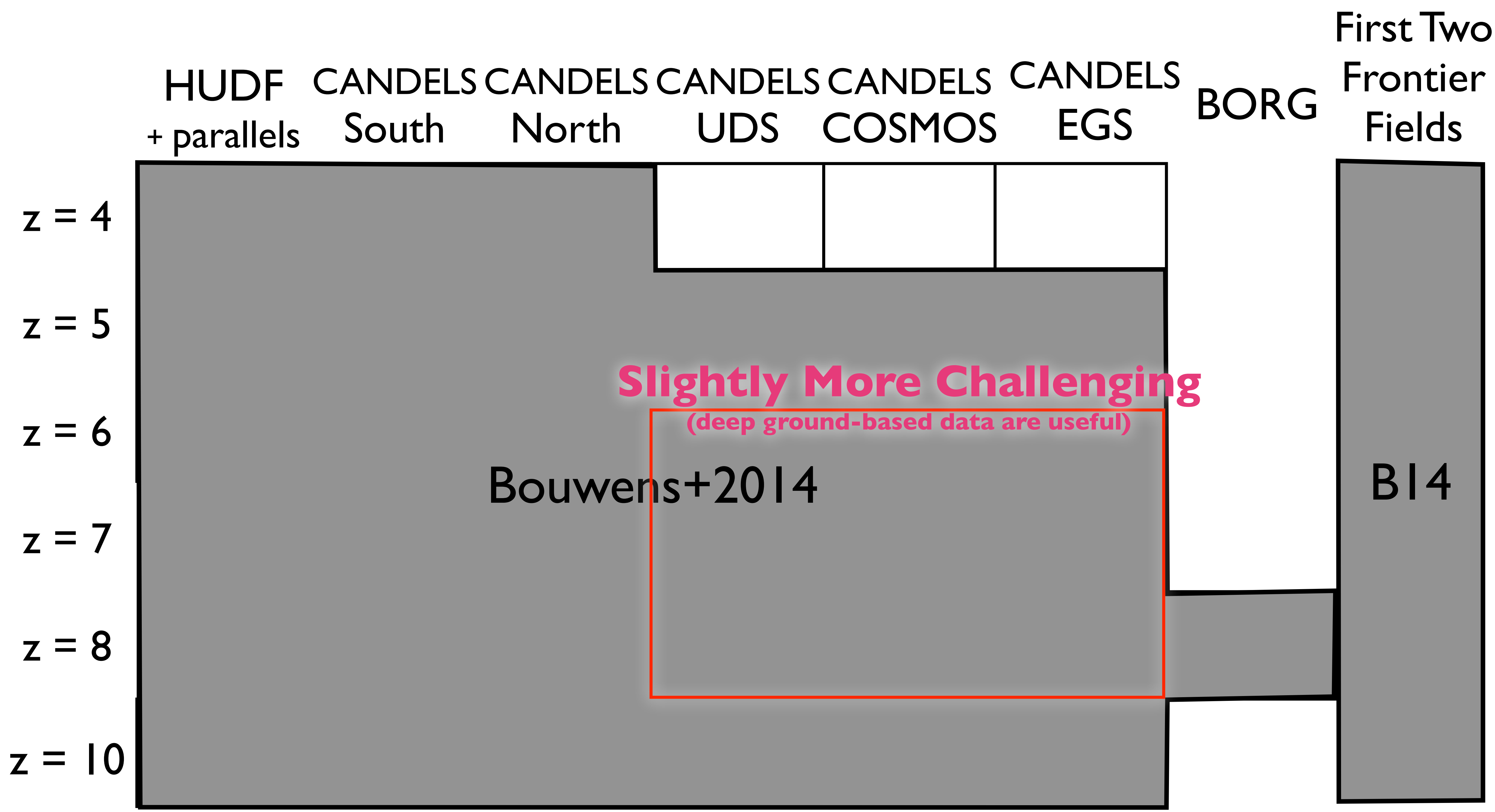
COSMOS-EGS:

BUT deep ground-based data fills in wavelength gaps (most >27 mag)!



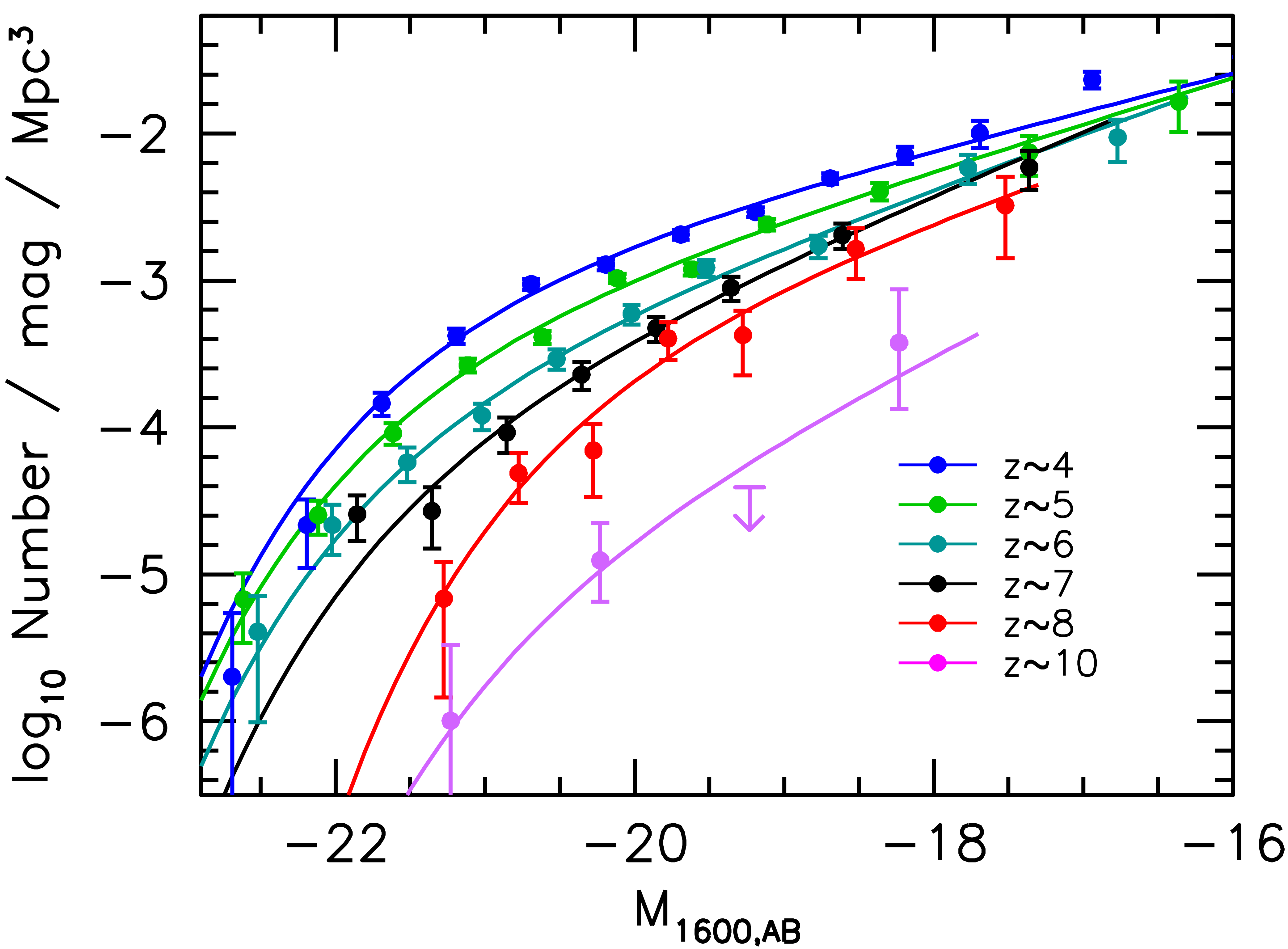
z~4-10 LFs from all CANDELS + HUDF + other legacy fields

(Bouwens et al. 2014, arXiv:1403.4295, 48 pages)



New determinations of UV LF at z~4, 5, 6, 7, 8, 10 from all HST Legacy Fields

(Bouwens et al. 2014, arXiv:1403.4295)



Highlights of Bouwens+2014:

> 800 likely z~7-8 galaxies

> 11000 z~4-10 galaxies

Provide First Determination of
z~10 Luminosity Function

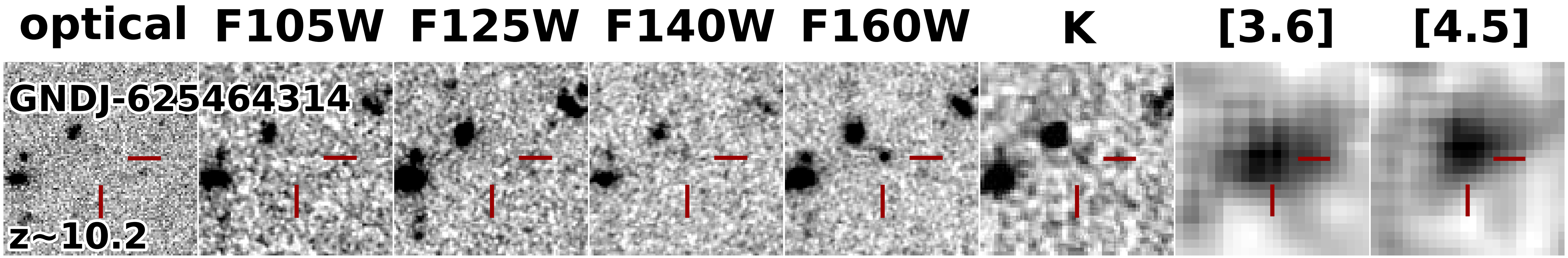
(together with Oesch+2014)

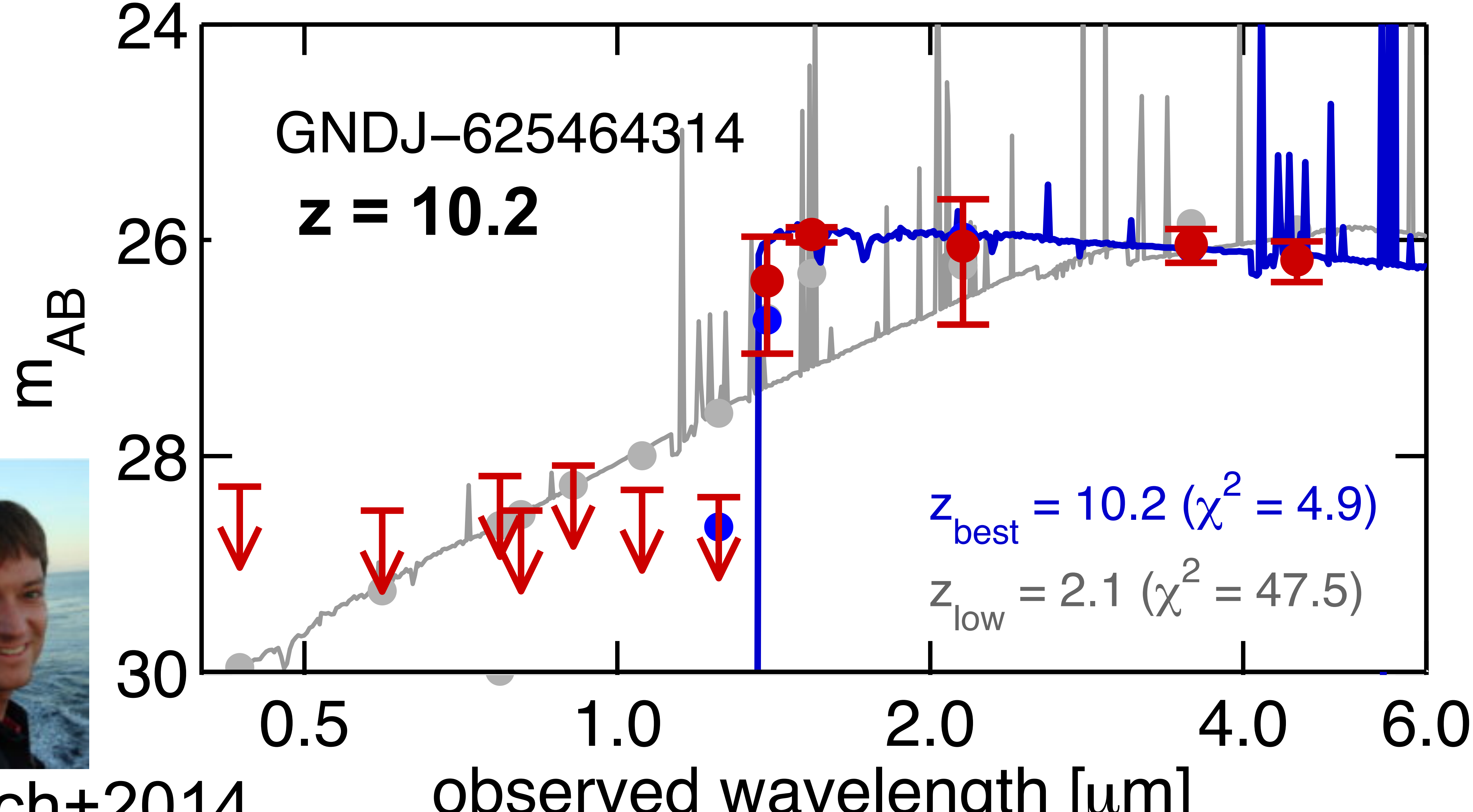
How Bright Can Galaxies Become at z~9-10?

Amazingly, ~10-20x Brighter than the z~9-10 Galaxies in the HUDF

Some of our best z~10 candidates are as bright as L* galaxies found at z ~ 3 by Steidel et al.

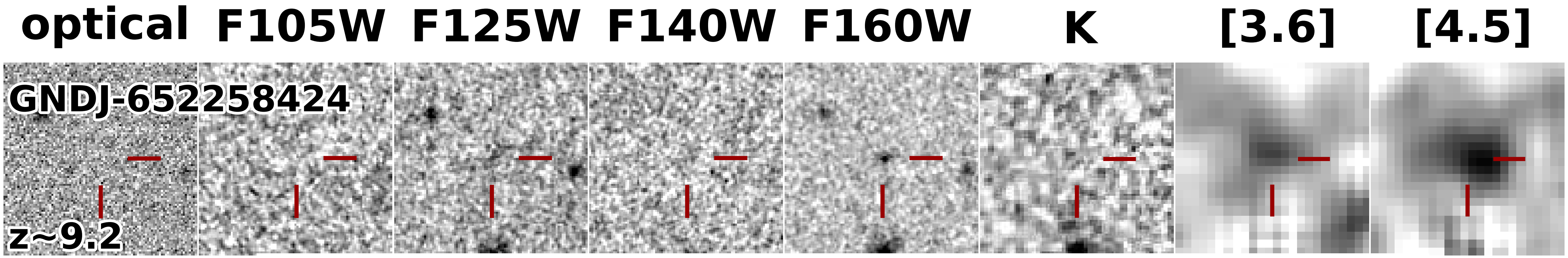
One of Six Bright z~9-10 Galaxies in CANDELS

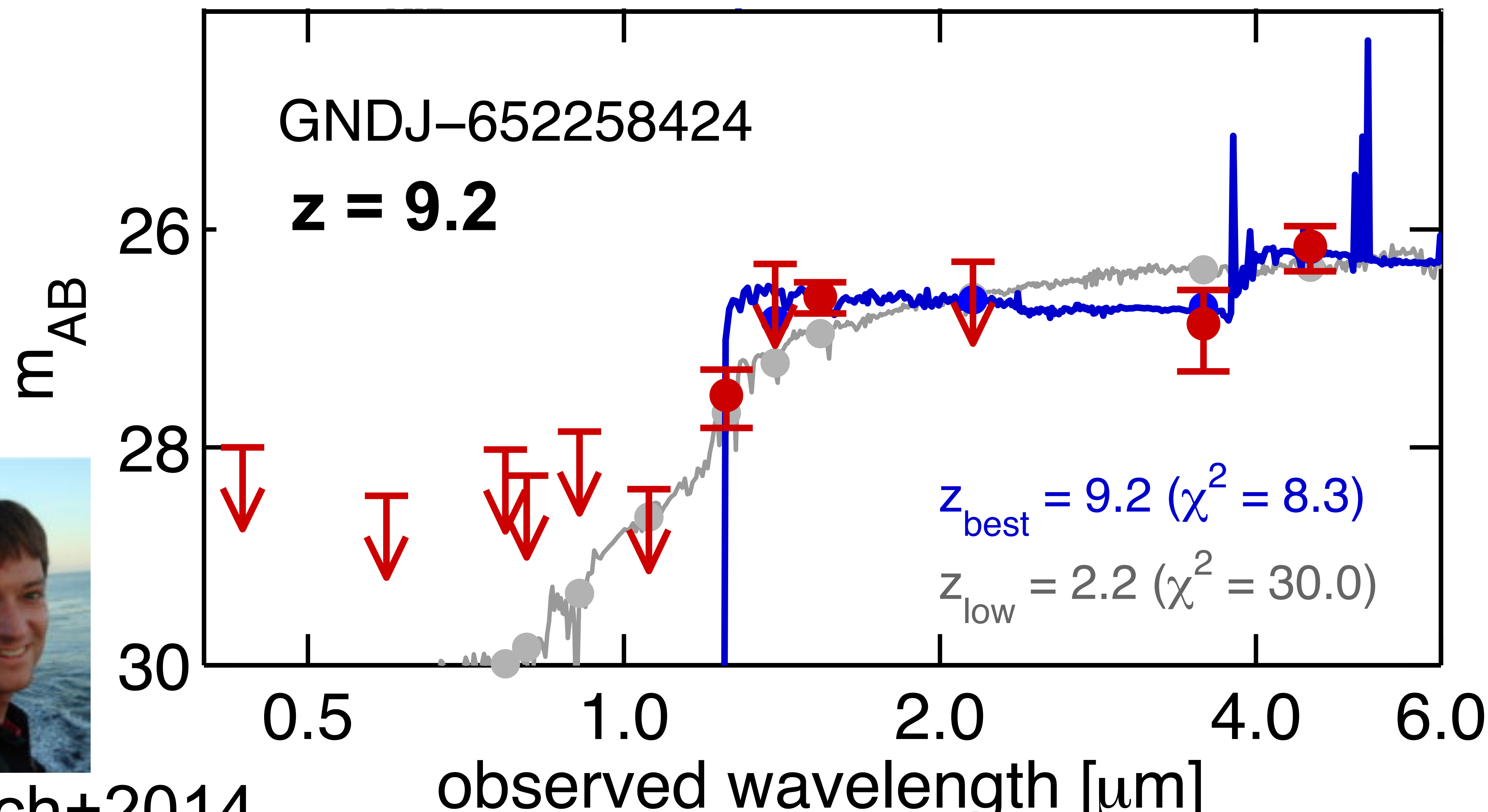




Oesch+2014

Another Bright z~9-10 Galaxy in CANDELS





Oesch+2014

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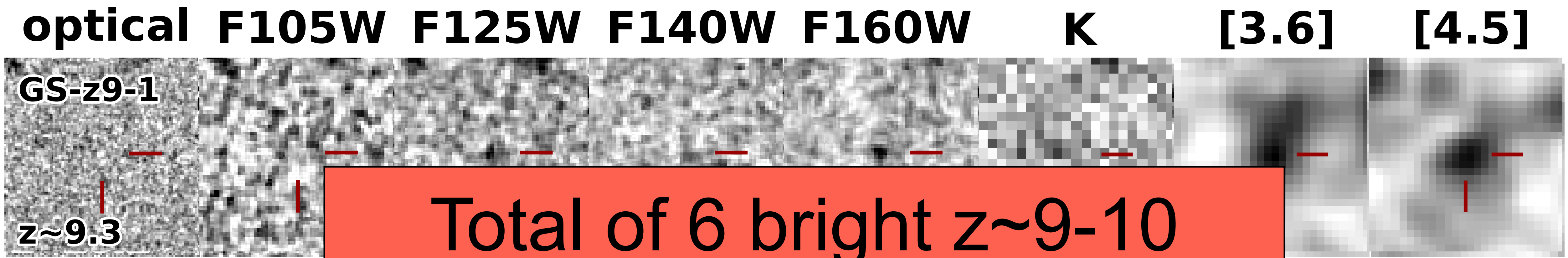
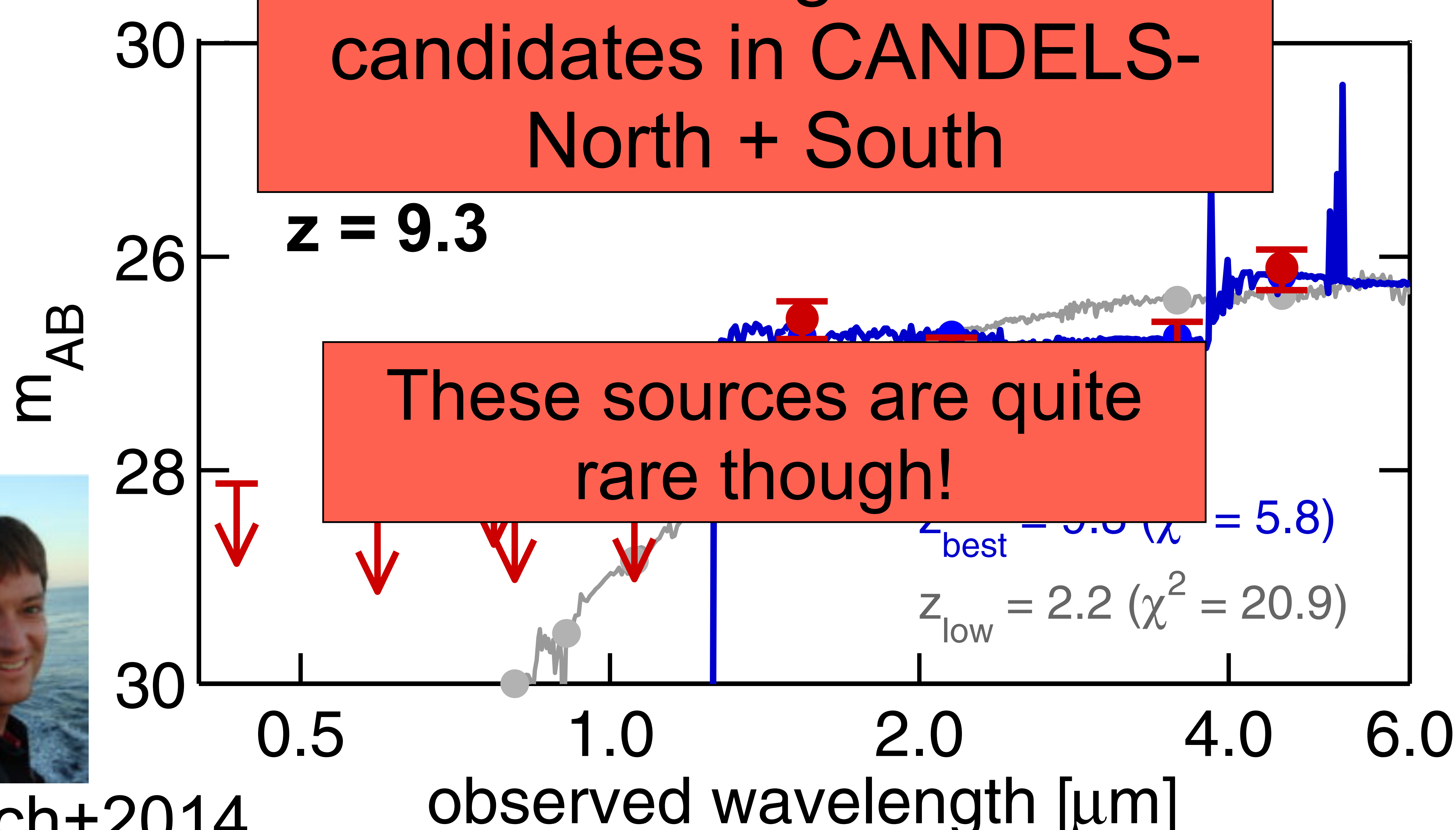




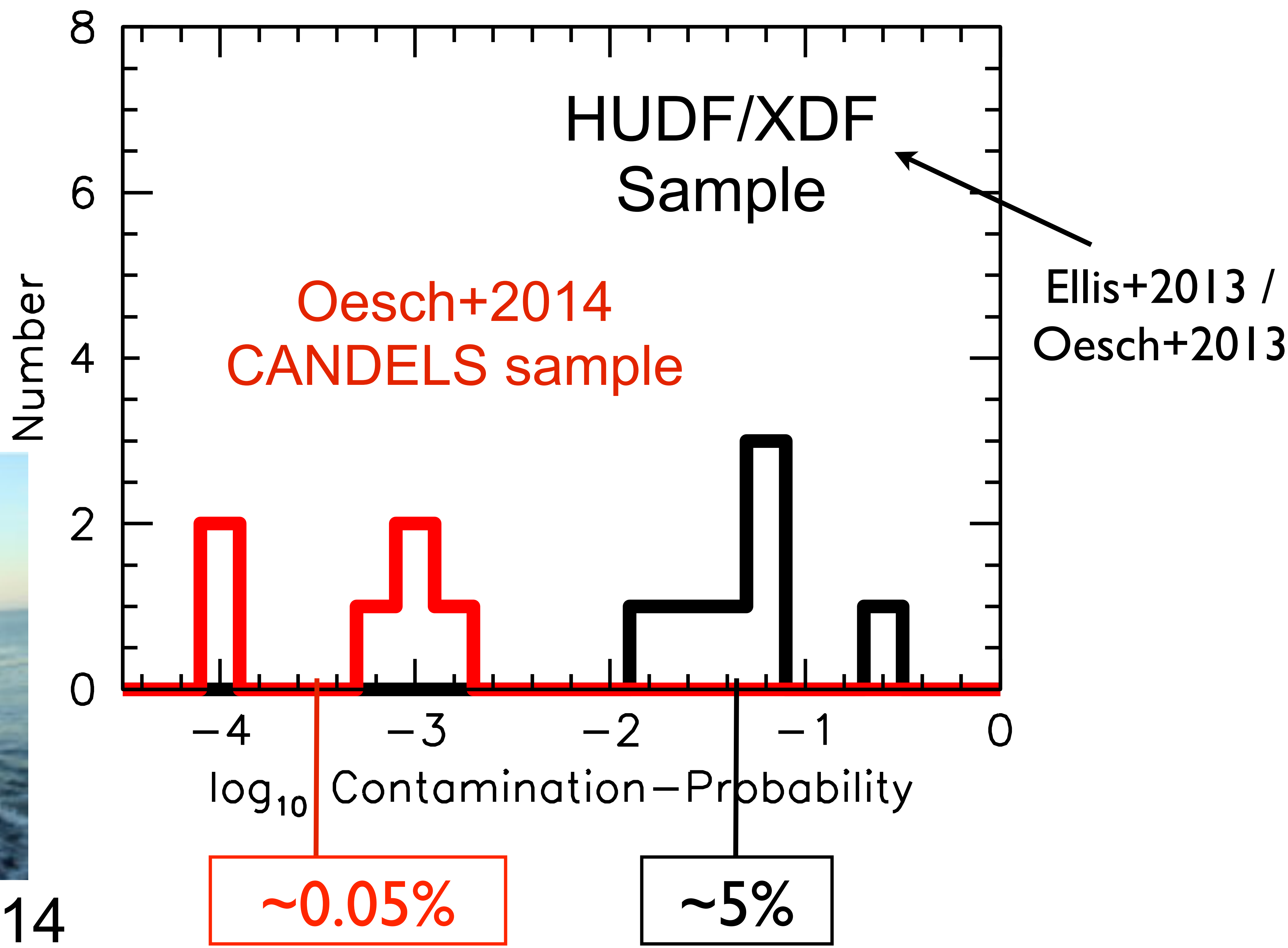
Total of 6 bright z~9-10 candidates in CANDELS-North + South

These sources are quite rare though!

Oesch+2014

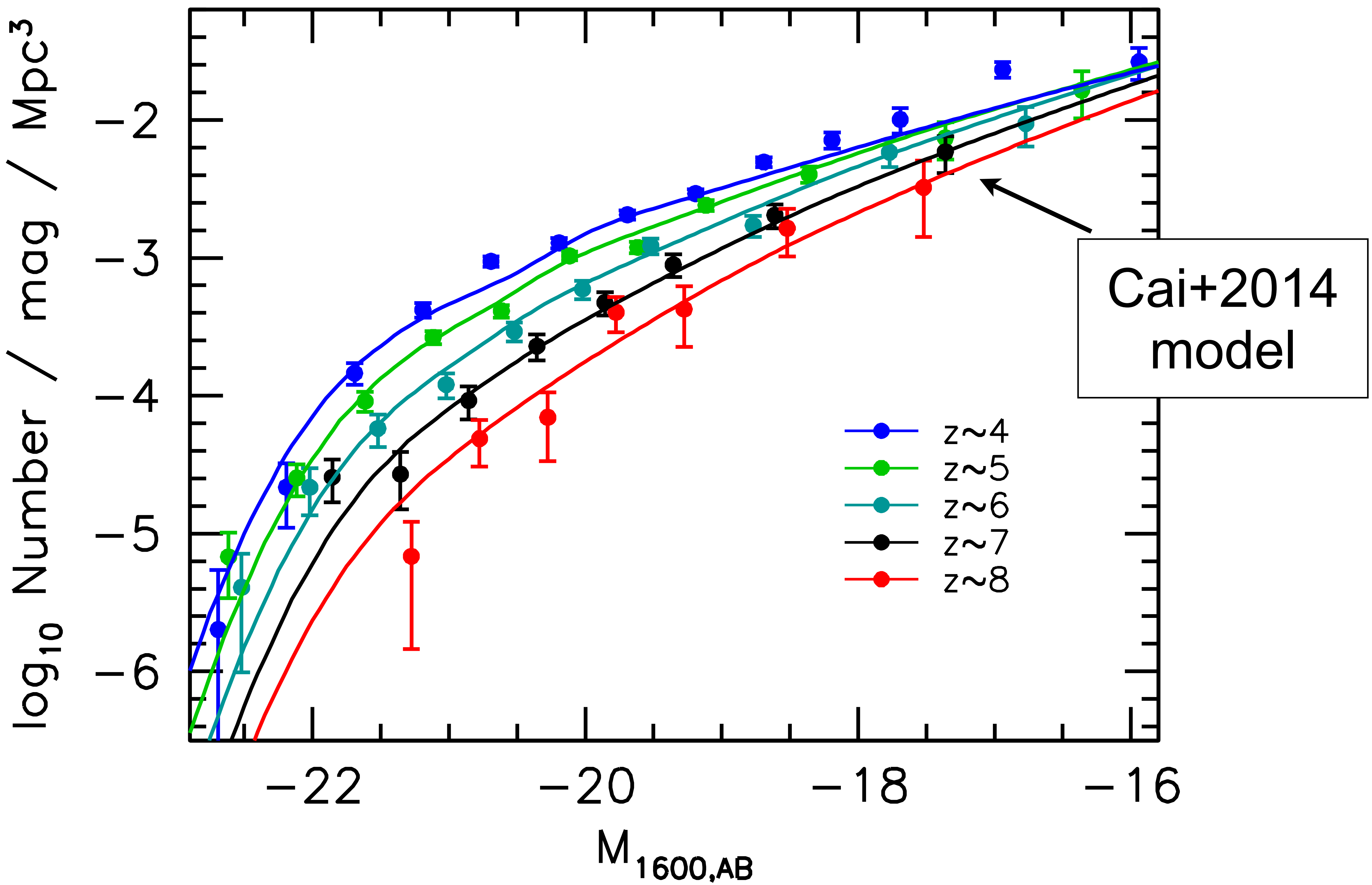
Very Low Formal Probability of Contamination

(CANDELS z~9-10 sample much more robust than HUDF z~9-10 sample)



Oesch+2014

How does the observed z~10 LF compare with extrapolations from lower redshift?



Cai+2014; Oesch+2014; Bouwens+2014

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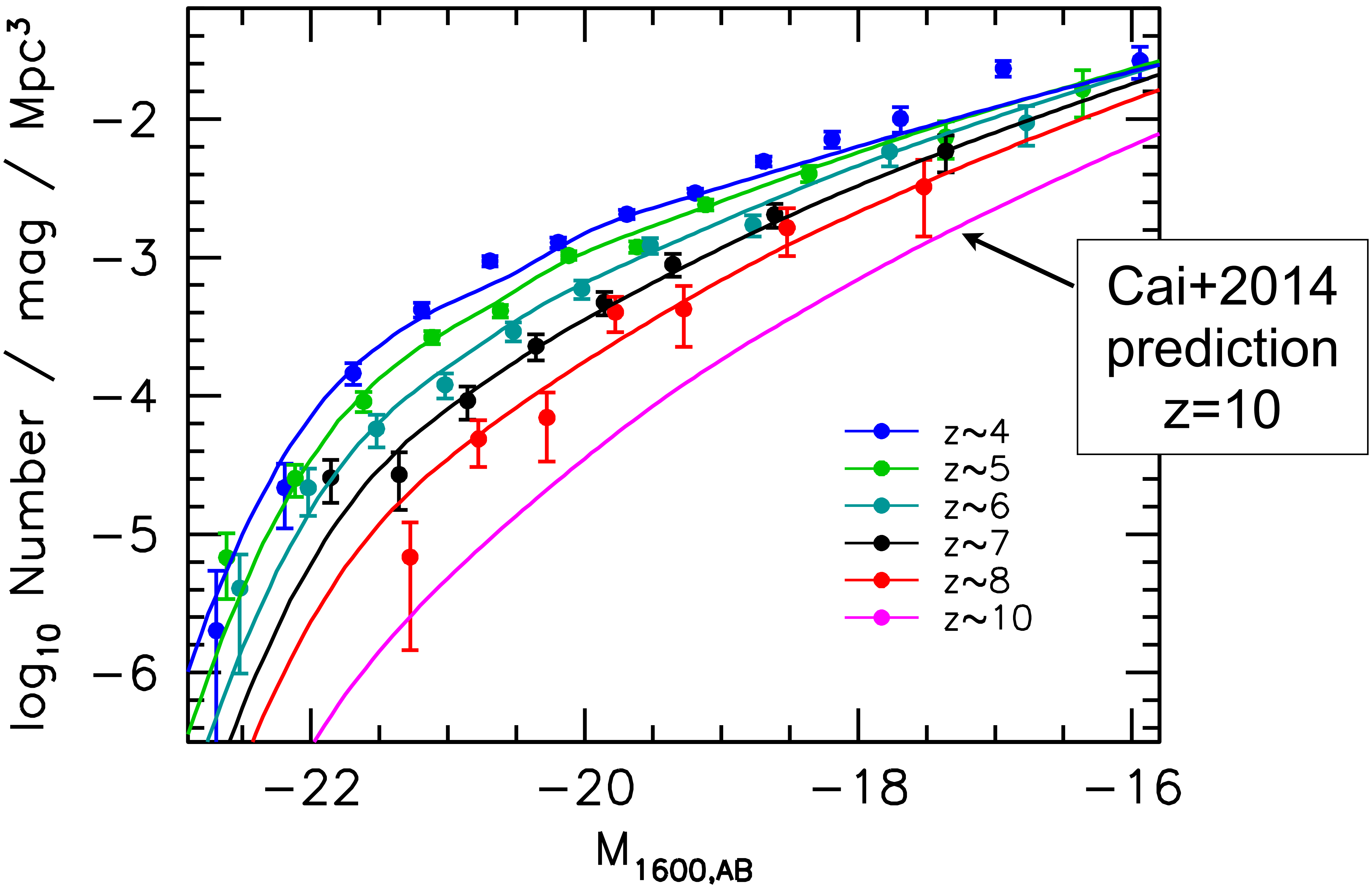

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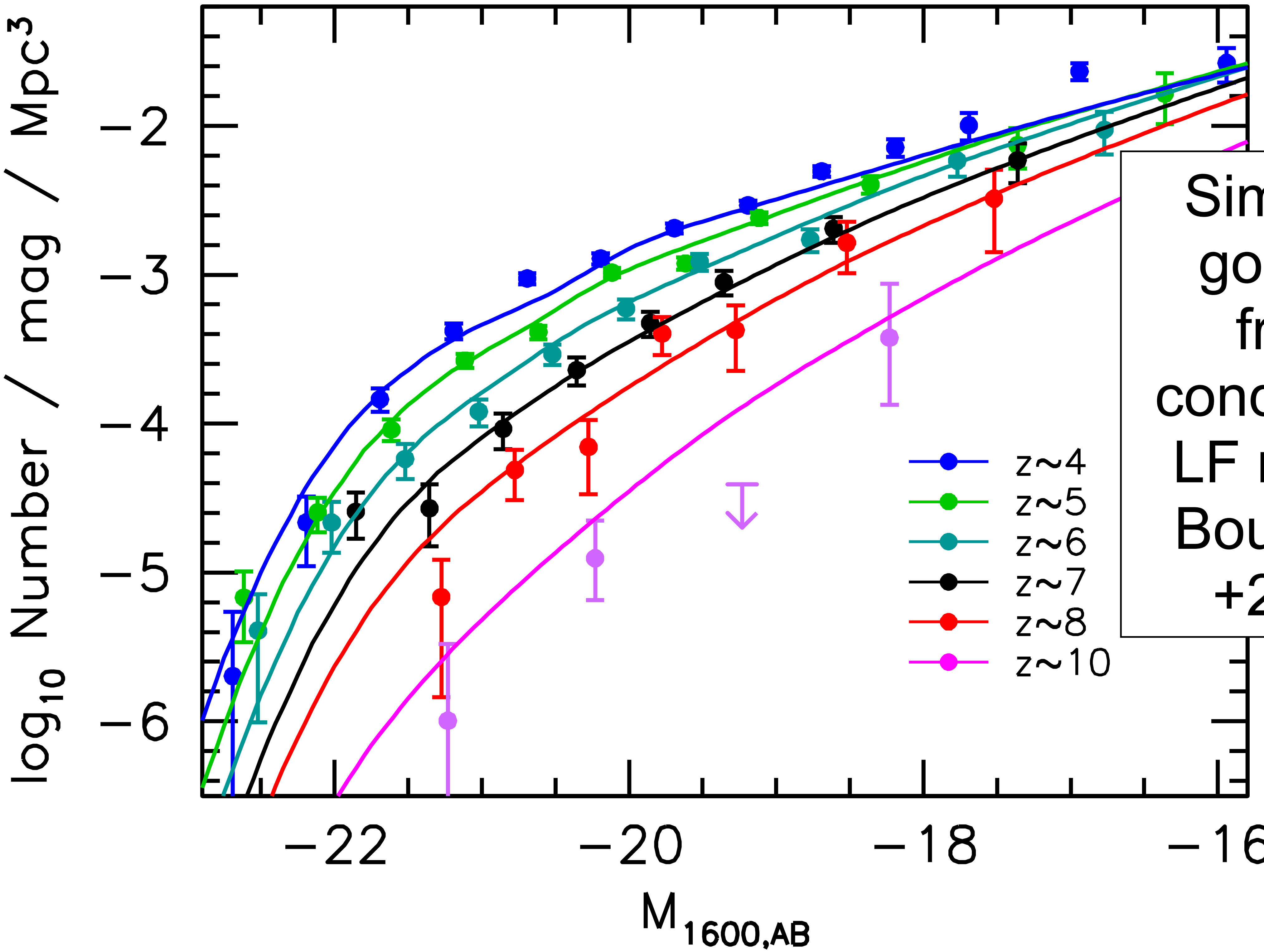
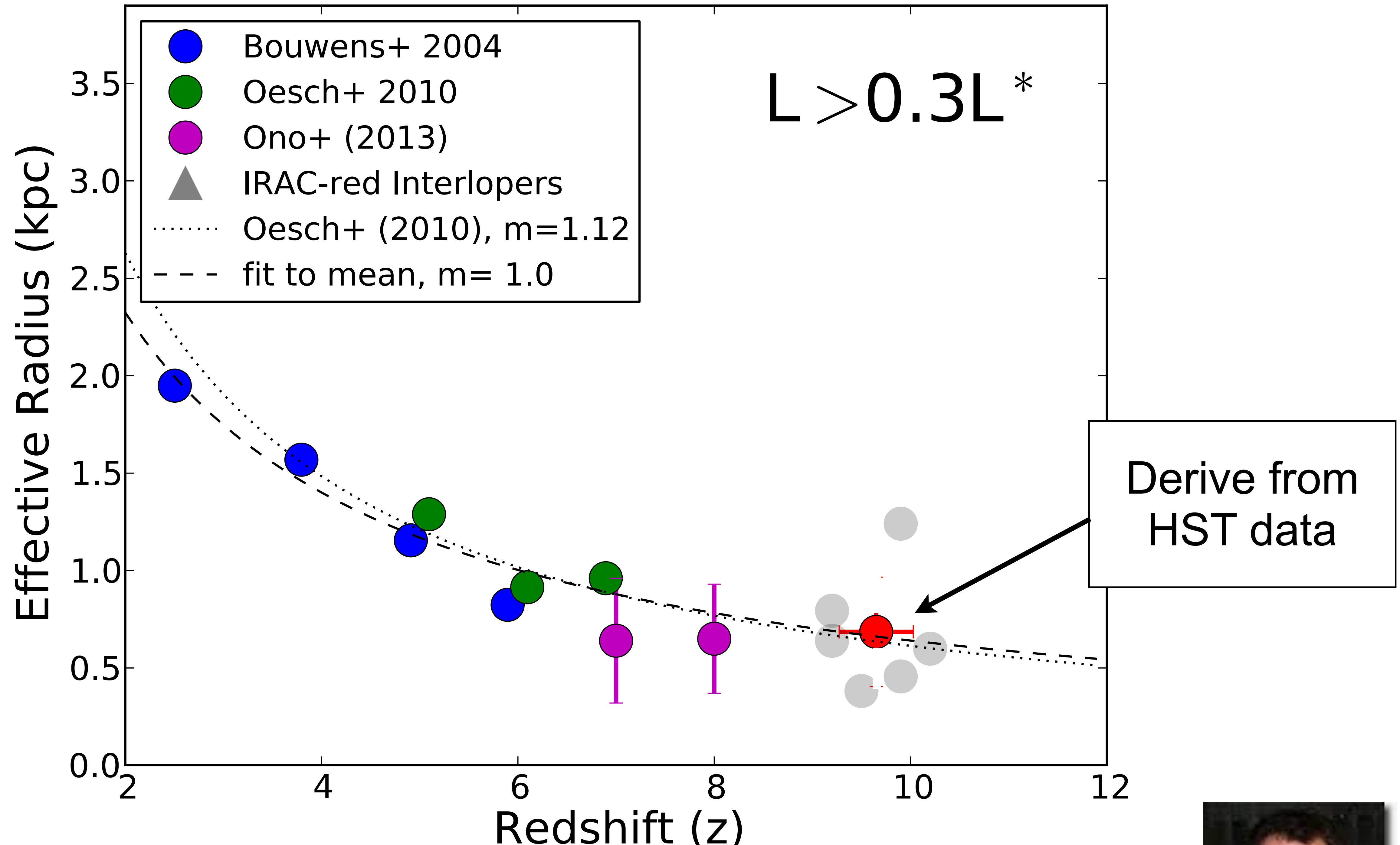


Similarly good fit from conditional LF model Bouwens +2008

Cai+2014; Oesch+2014; Bouwens+2014

The sizes of these z~9-10 candidates are exactly what we would expect...



Holwerda+2014 (resubmitted to ApJL after responding to referee report)

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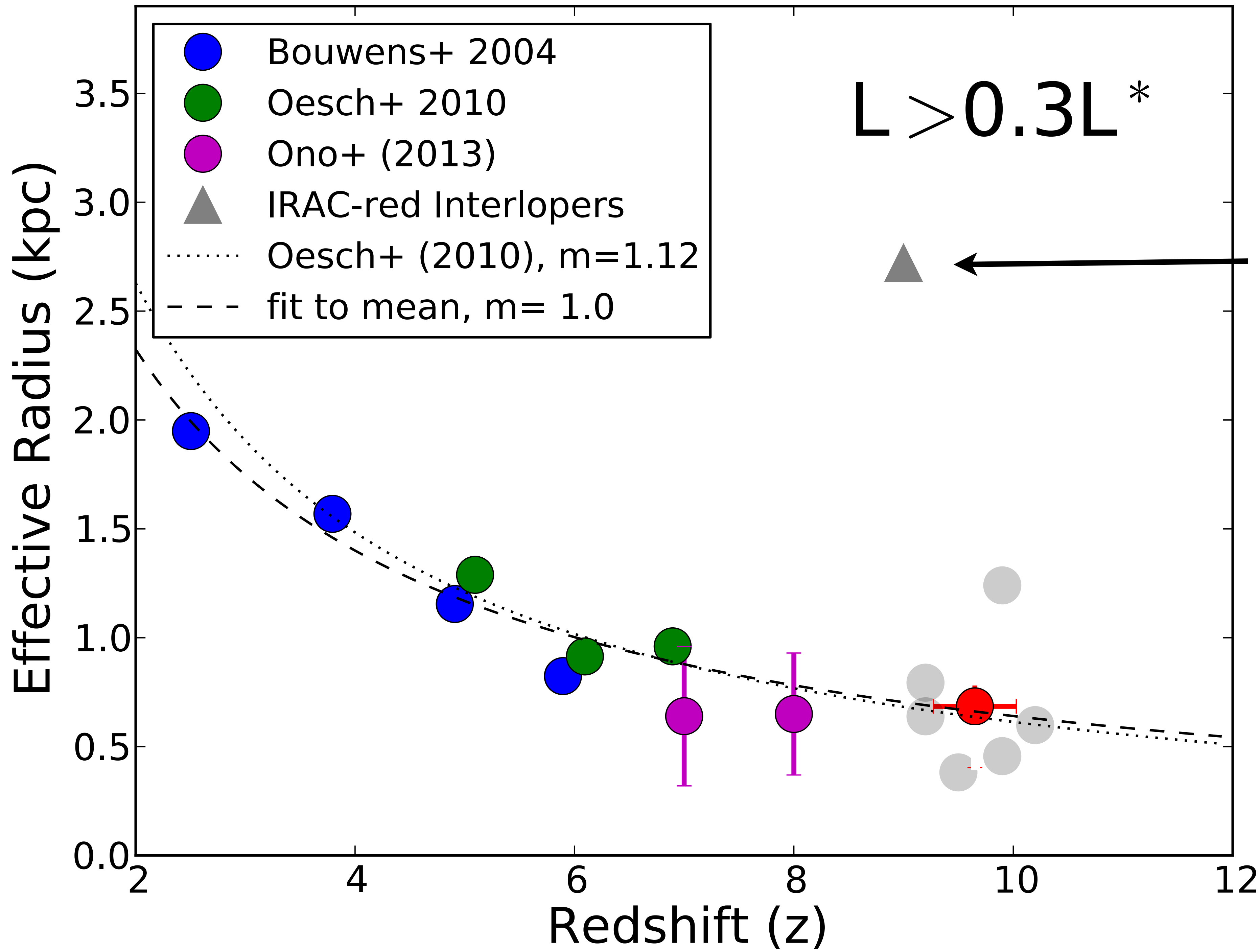
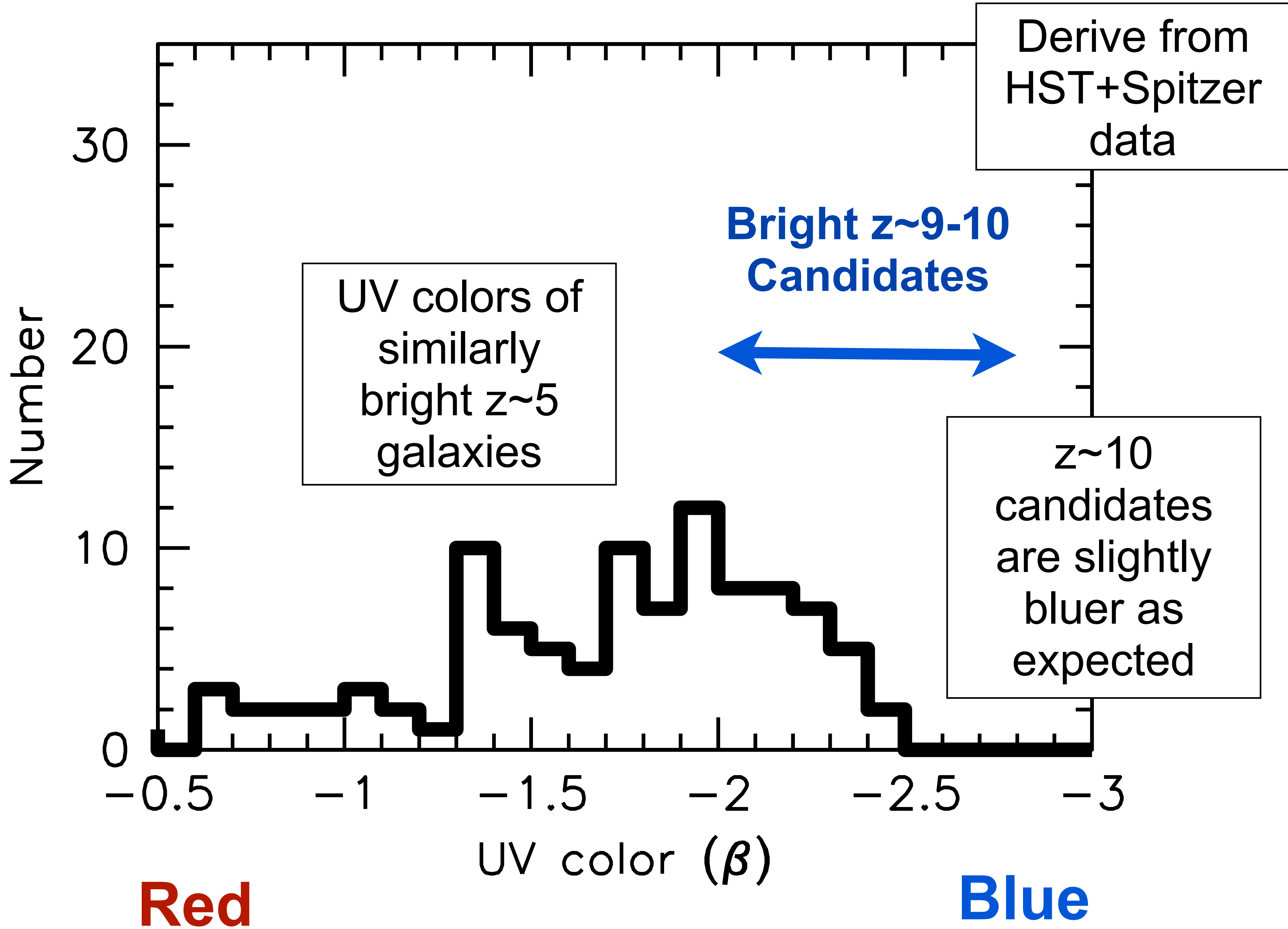


IRAC-red interlopers

Holwerda+2014 (resubmitted to ApJL after responding to referee report)

The colors of these z~9-10 candidates are exactly what we would expect...



Oesch+2014; Wilkins et al. 2014, in prep

How do the Oesch+2014 z~10 galaxies rank among the most distant galaxies ever discovered?

Name	Redshift	Discoverer
MACS0647-JD	10.8	Coe et al. (2013)
XDFj-38113353	9.8	Oesch et al. (2013) + Bouwens et al. (2011)
MACS1149-JD	9.6	Zheng et al. (2012)
HUDF12-42657049	9.5	Ellis et al. (2013)
HUDF09-2_247	9.4	McLure et al. (2013)
HUDF09-2_50104	9.0	McLure et al. (2013)
HUDF12-42657049	8.8	Ellis et al. (2013)

Lensed CLASH ...

HUDF12 sources

Revived Bouwens+2011

BEFORE OESCH+2014

How do the Oesch+2014 z~10 galaxies rank among the most distant galaxies ever discovered?

Name	Redshift	Discoverer
MACS0647-JD	10.8	Coe et al. (2013)
GN-z10-1	10.2	Oesch et al. (2014)
GN-z10-2	9.9	Oesch et al. (2014)
GS-z10-1	9.9	Oesch et al. (2014)
XDFj-		2013) + (2011)
MACS		(2012)
GN-z10-3	9.5	Oesch et al. (2014)

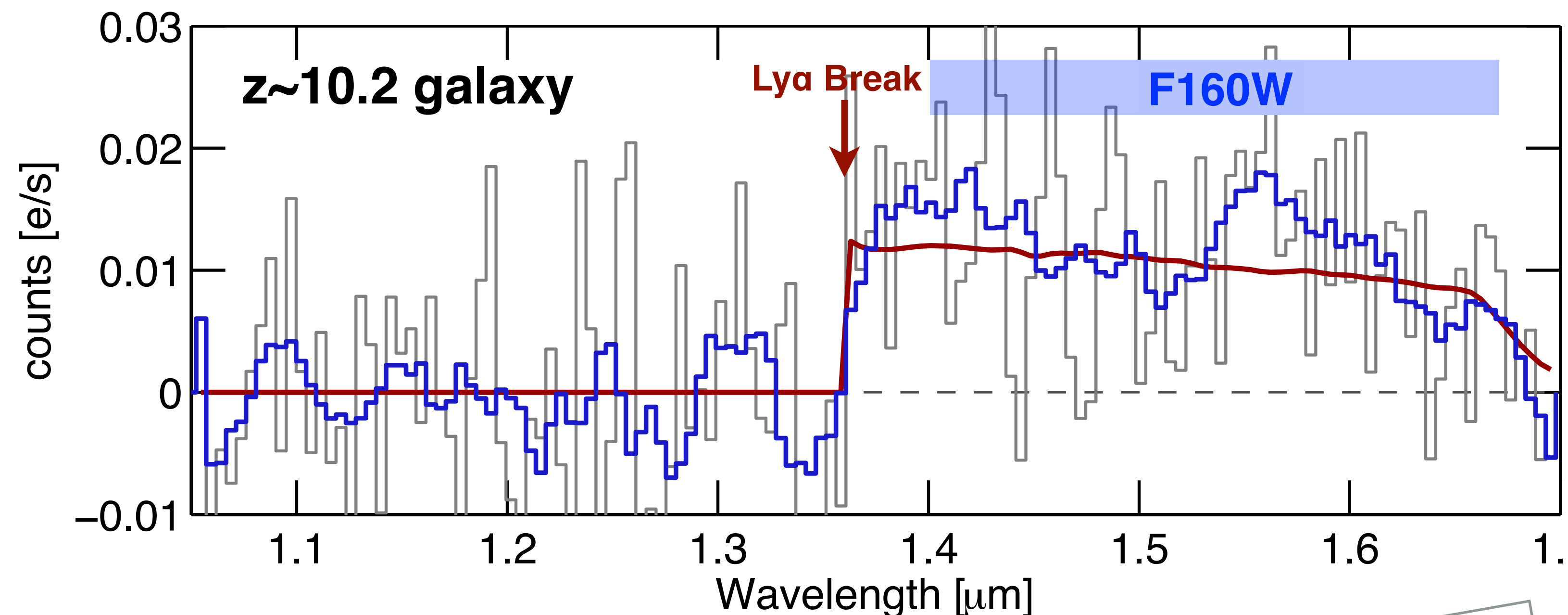
Three of the Four Most Distant Galaxies Known!

What new z~9-10 science can we expect in Cycle 22?

Follow-up bright z~10 galaxy with the HST Grism

PI: P. Oesch

Expected WFC3/IR Spectrum



Together with HST spectroscopy on the Coe+2013 candidate, these could kill the game to secure the most distant spectroscopically-confirmed galaxies in the universe with Lyα

What new z~9-10 science can we expect in Cycle 22?

Follow-up bright z~10 galaxy with the HST Grism

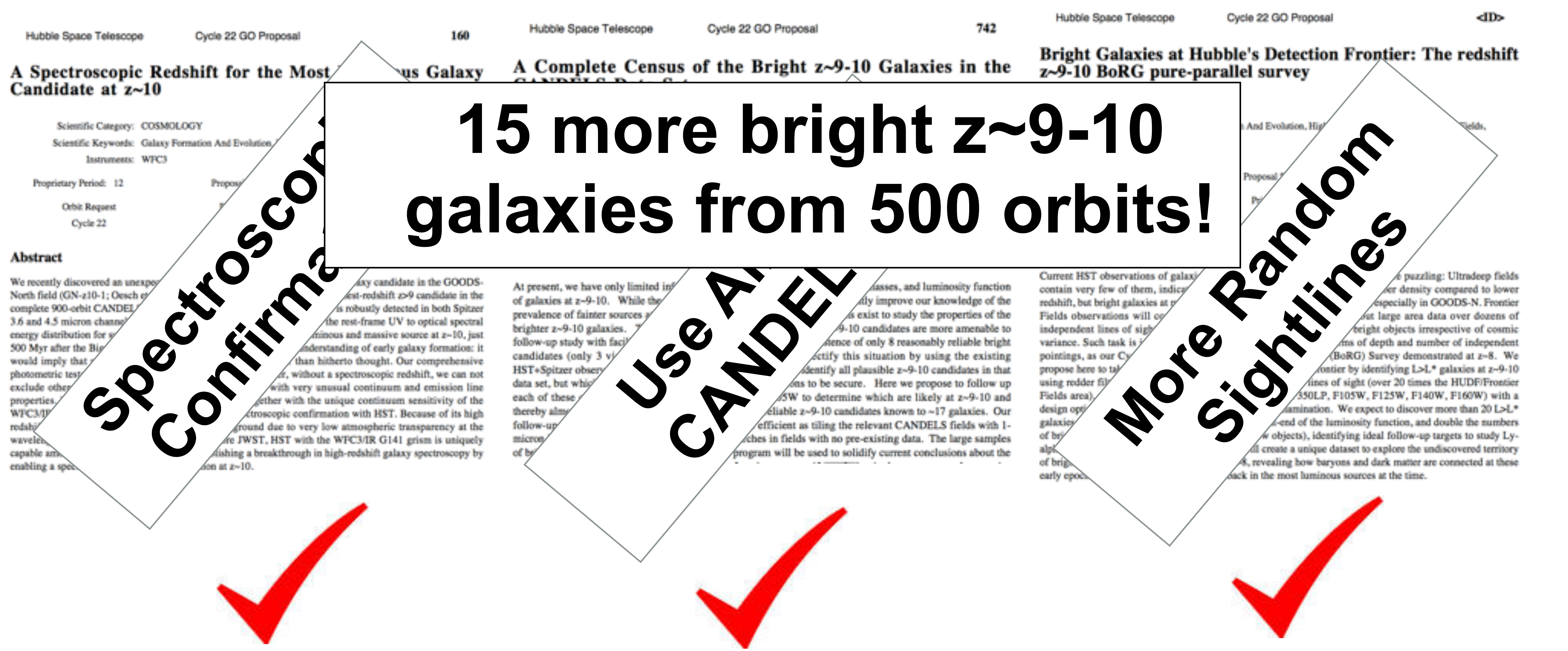
PI: P. Oesch

~7 more bright z~9-10 candidates using remaining CANDELS fields

PI: R. Bouwens

~9 more bright z~9-10 candidates using ambitious pure-parallel program

PI: M. Trenti



15 more bright z~9-10 galaxies from 500 orbits!

How Bright Can Galaxies Become at z~4-8?

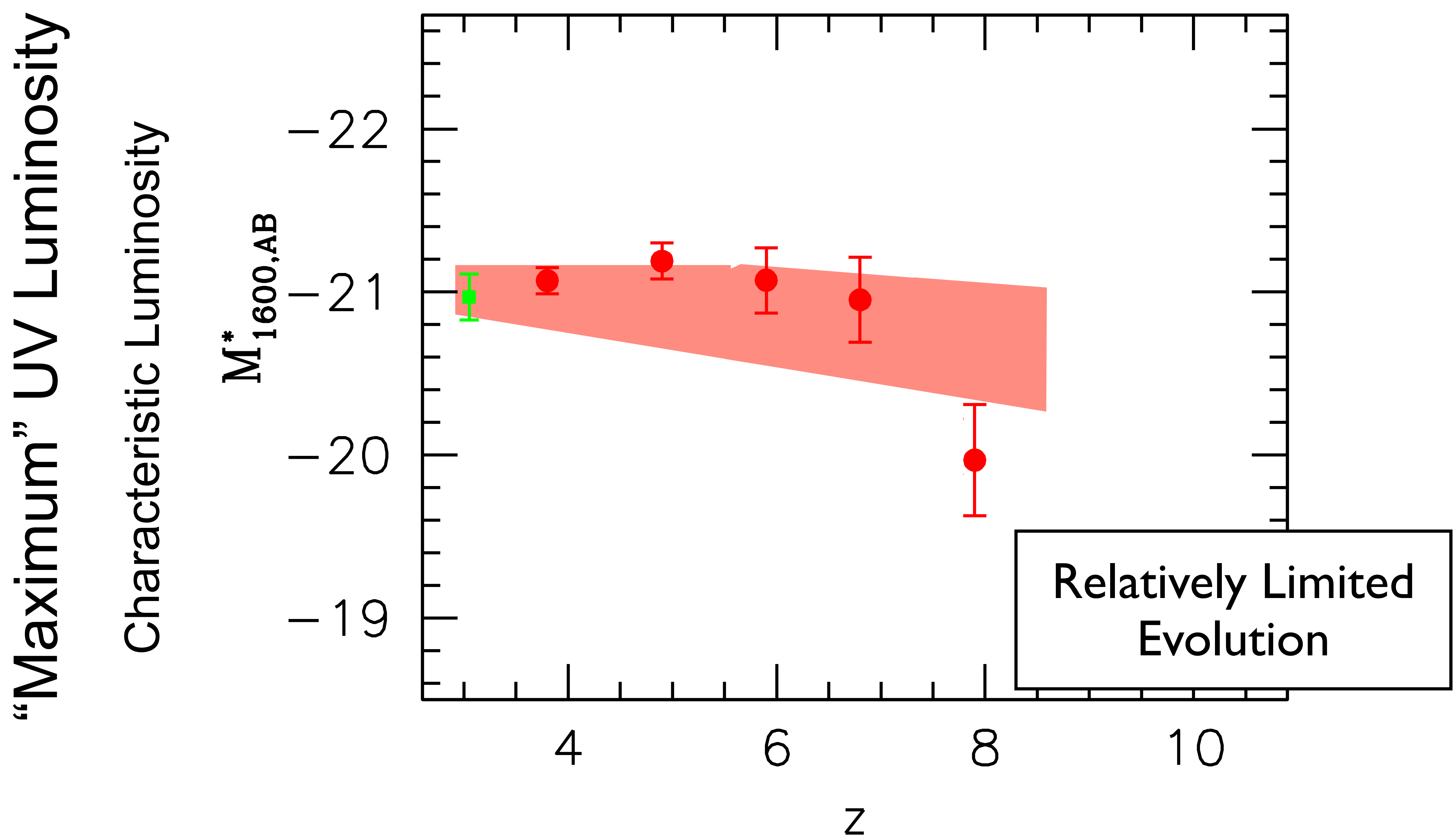
UV luminosities can reach ~3-4 L*(z=3)

Can approximately quantify using characteristic luminosity from Schechter fit

Best Derived Using All Wide-Area CANDELS fields

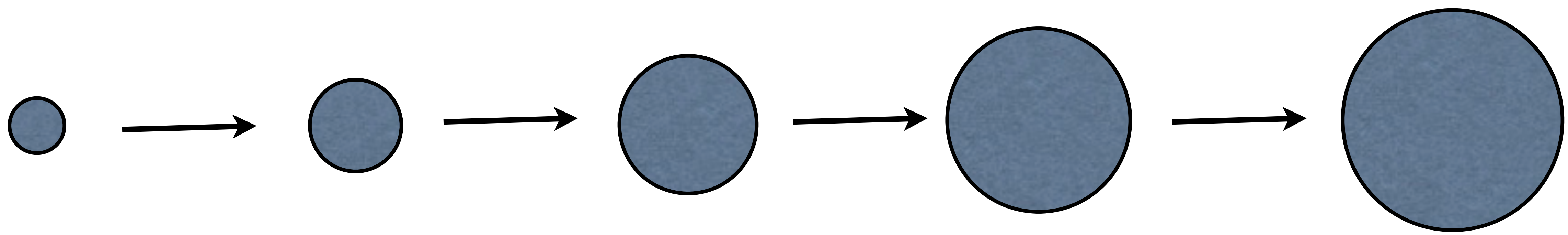
Bouwens+2014

How Bright Can Galaxies Become at z~4-8?



Bouwens+2014

But individual galaxies become more UV luminous with cosmic time (Bouwens+2007), no?



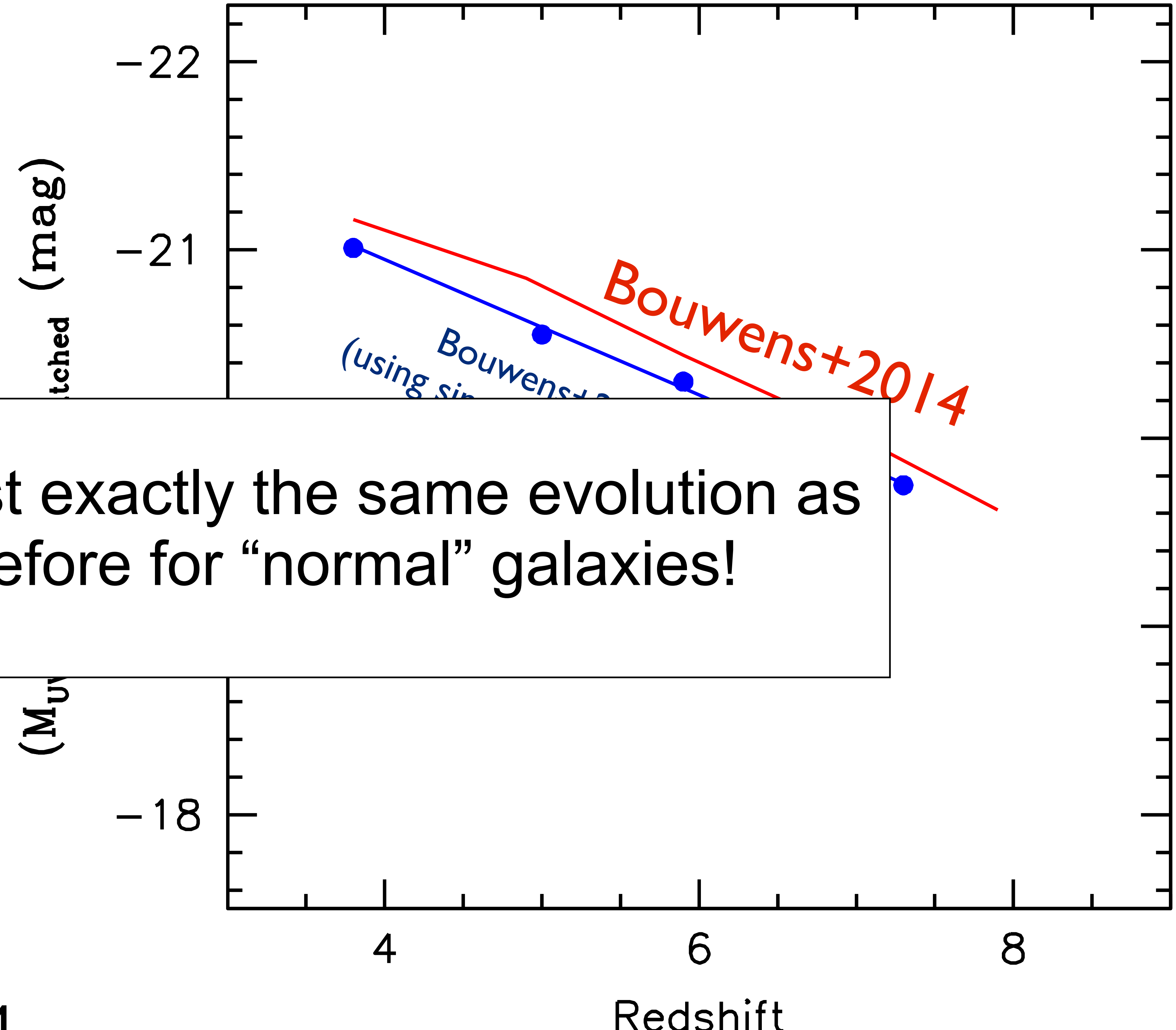
upsizing of galaxies in UV luminosity first quantified by Bouwens+2007

and later quantified in rest-frame optical (Stark+2009)

this upsizing of galaxies was "rediscovered" and more properly quantified by Papovich+2011 and Lundgren+2014 using a cumulative number-density matching formalism

Bouwens+2007 luminosity evolution is still true... but only for normal galaxies...

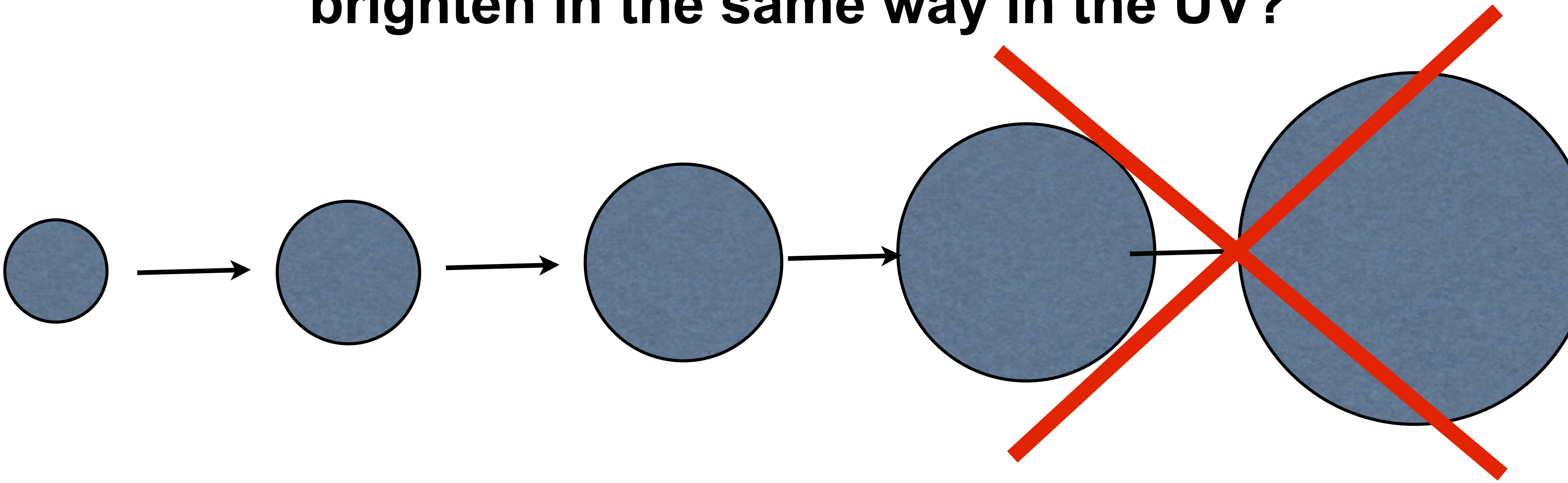
Evolution of UV Lumin[...]
(for a "n[...] gala[...]



Almost exactly the same evolution as before for "normal" galaxies!

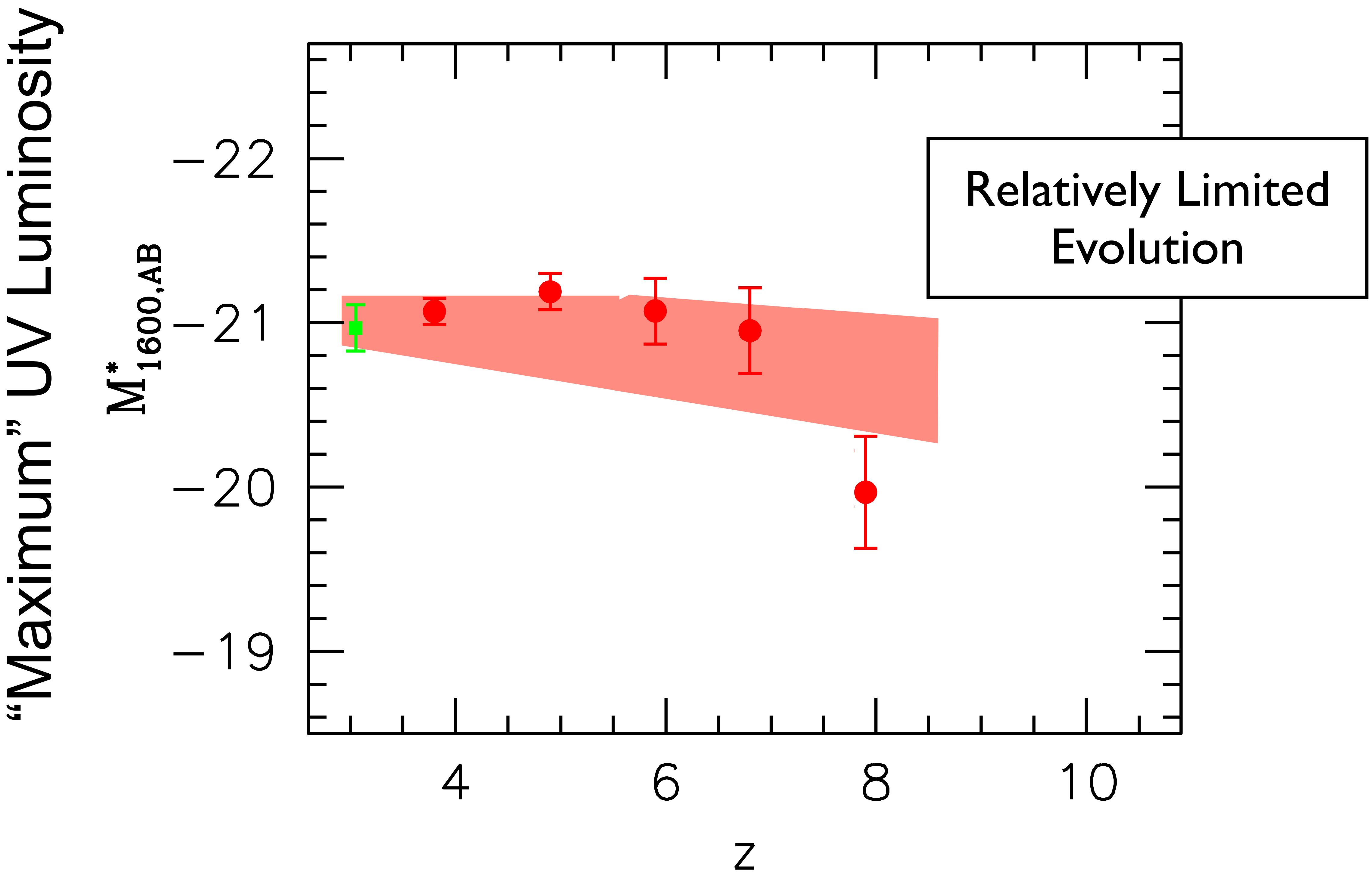
Bouwens+2014

One might guess that the brightest and rarest objects brighten in the same way in the UV?



But this does not seem to occur!

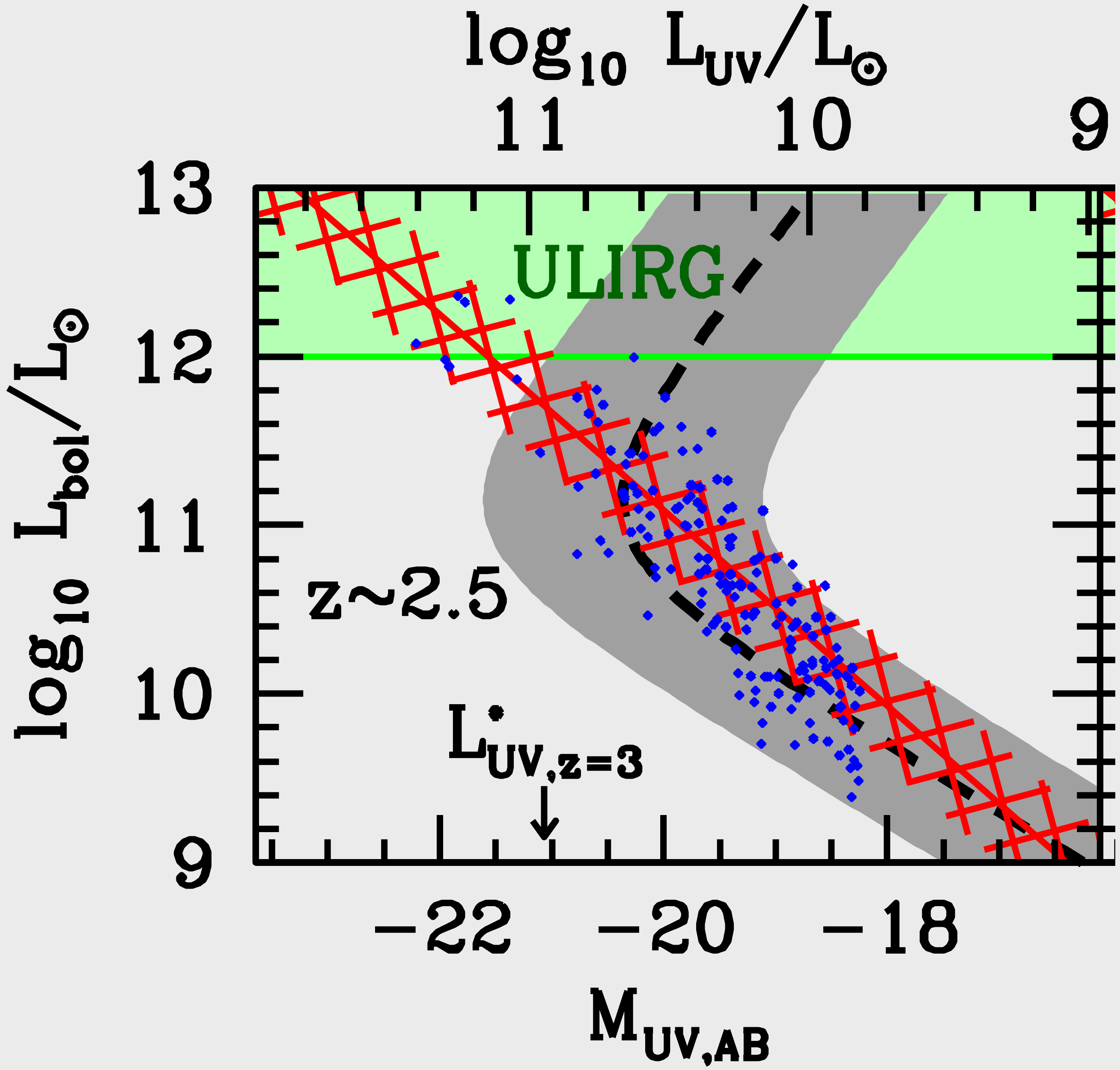
However, More Limited Evolution in UV luminosity for the brightest galaxies



Bouwens+2014

Why Little Evolution in Maximum Brightness of Galaxies in UV? Probably Dust Extinction

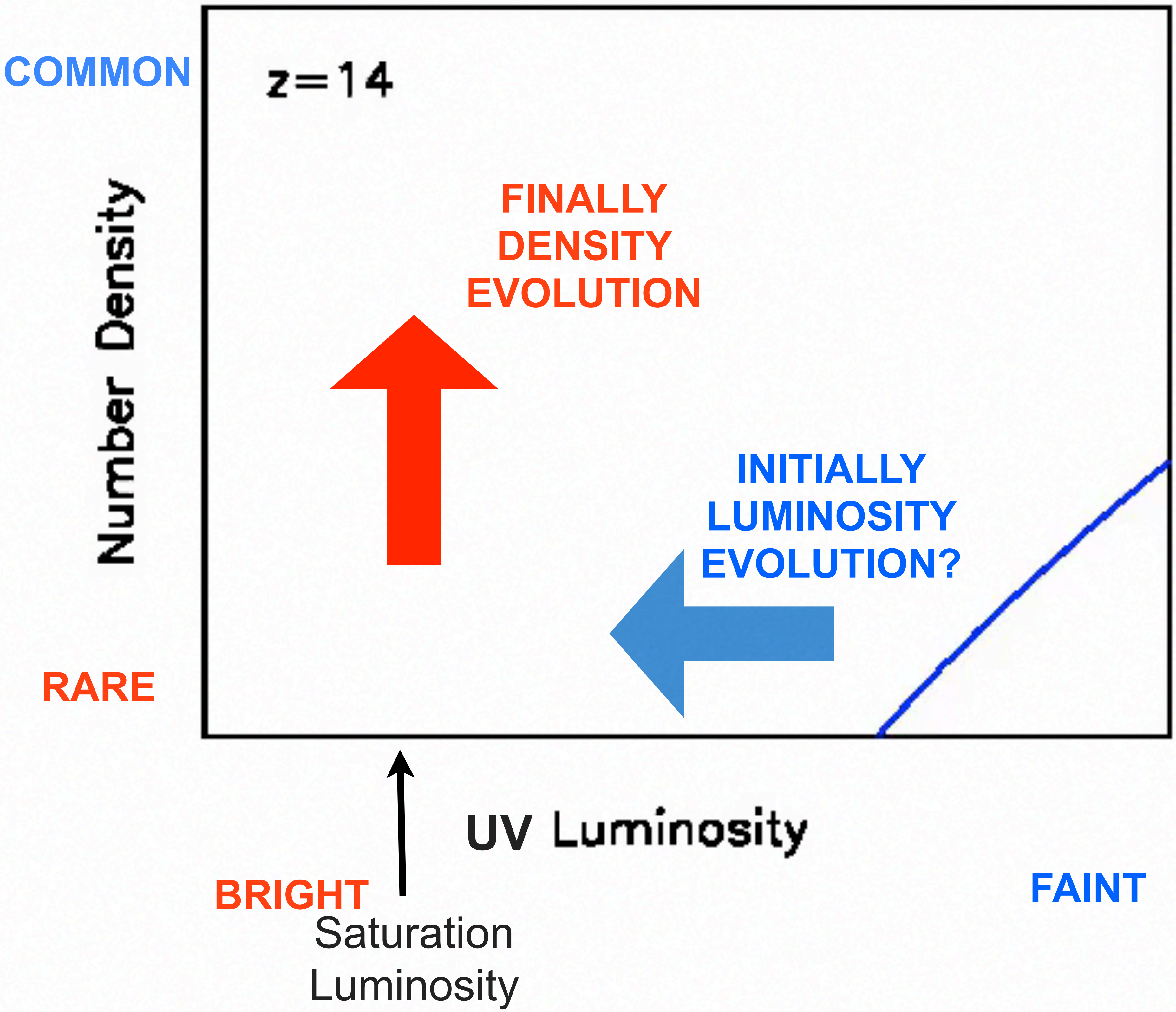
Idea that **L*(UV)** was set by **dust extinction**
first proposed by Bouwens+2009 and Reddy+2010



Bouwens+2009

Credit: Elbaz, Obergurgl 2007

If the UV luminosity of galaxies saturates at a maximum value, how would the UV LF evolve?

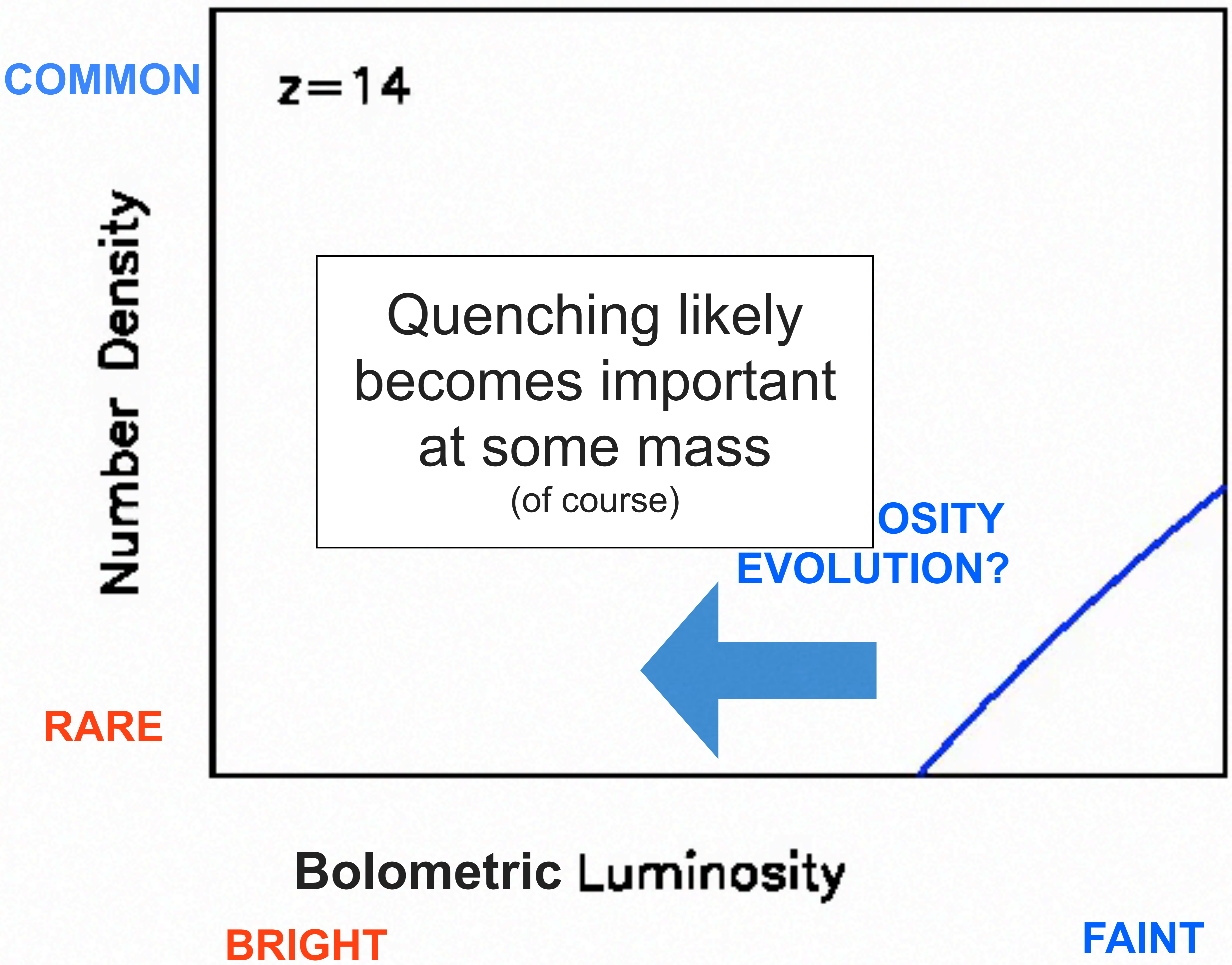


Develop simple LF model here

Assume galaxy light traces the the halo mass evolution

but UV light cannot exceed some maximum value

What about the bolometric LF?

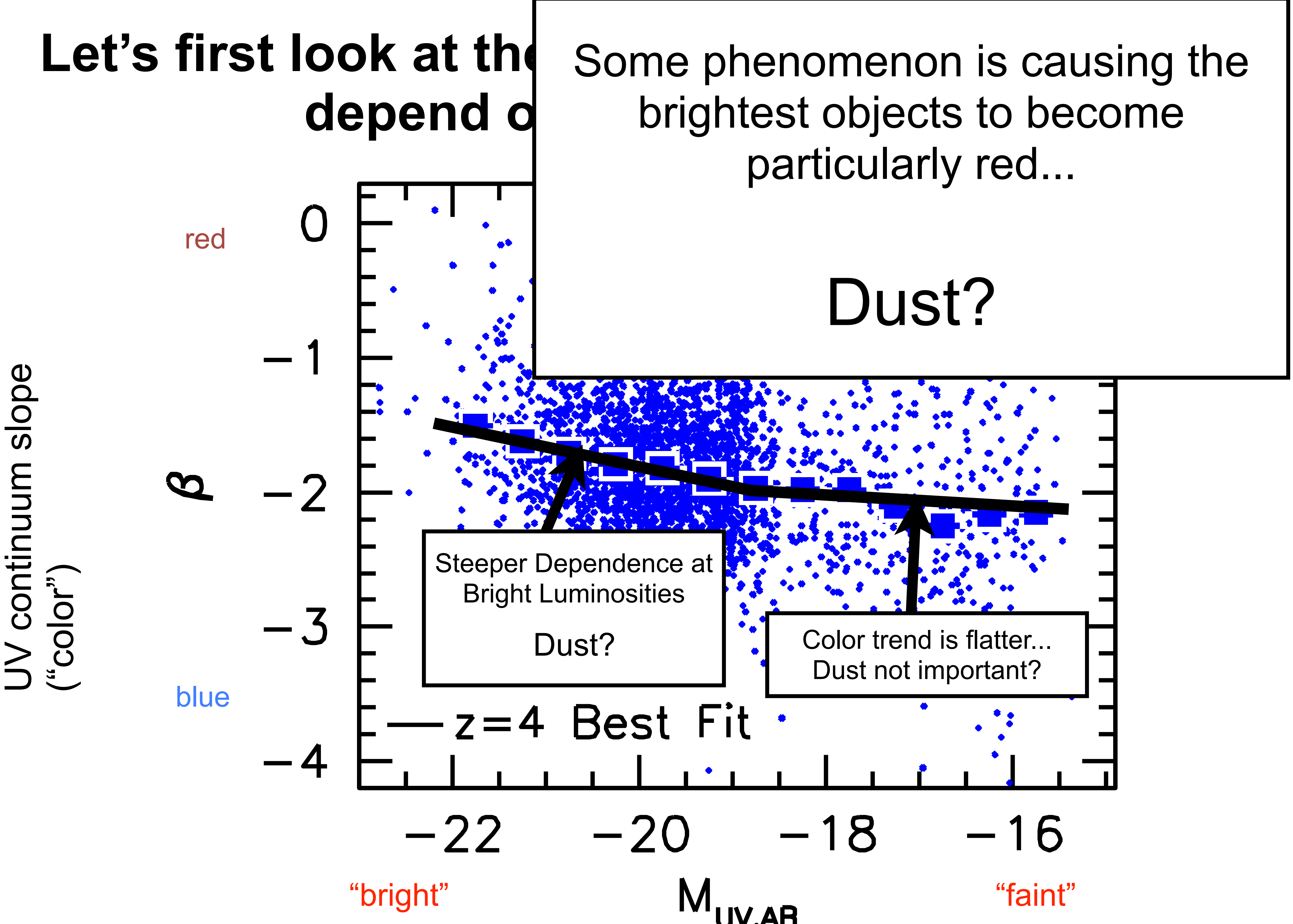


Develop simple LF model here

Assume galaxy light traces the the halo mass evolution

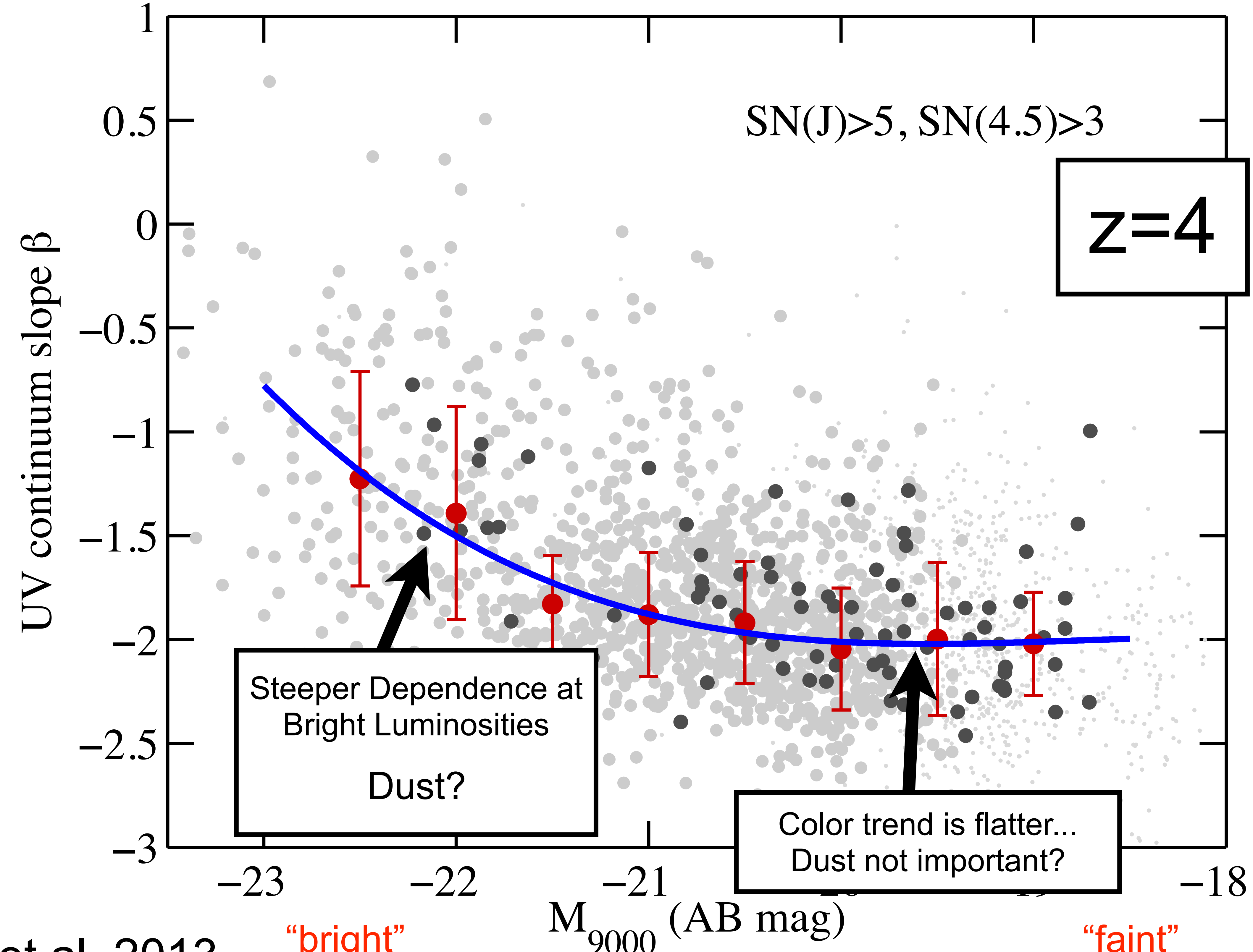
Could dust set an upper limit on UV luminosity of galaxies at z>=4 ?

Let's first look at the ... depend o...



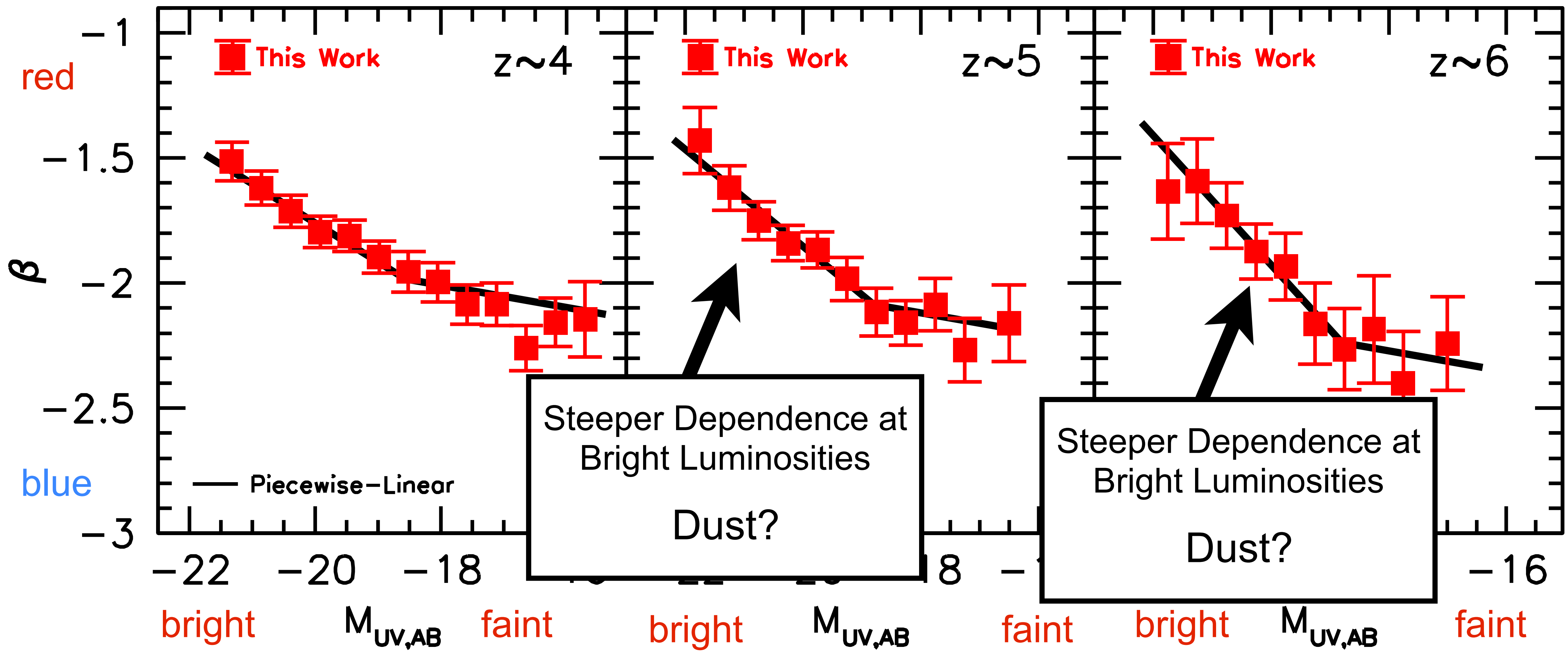
Bouwens et al. 2013; see also Bouwens et al. 2009, 2010, 2012; Wilkins et al. 2011; Dunlop et al. 2012; Castellano et al. 2012; Finkelstein et al. 2012

Trend between UV colors and luminosity becomes clear vs. optical luminosities



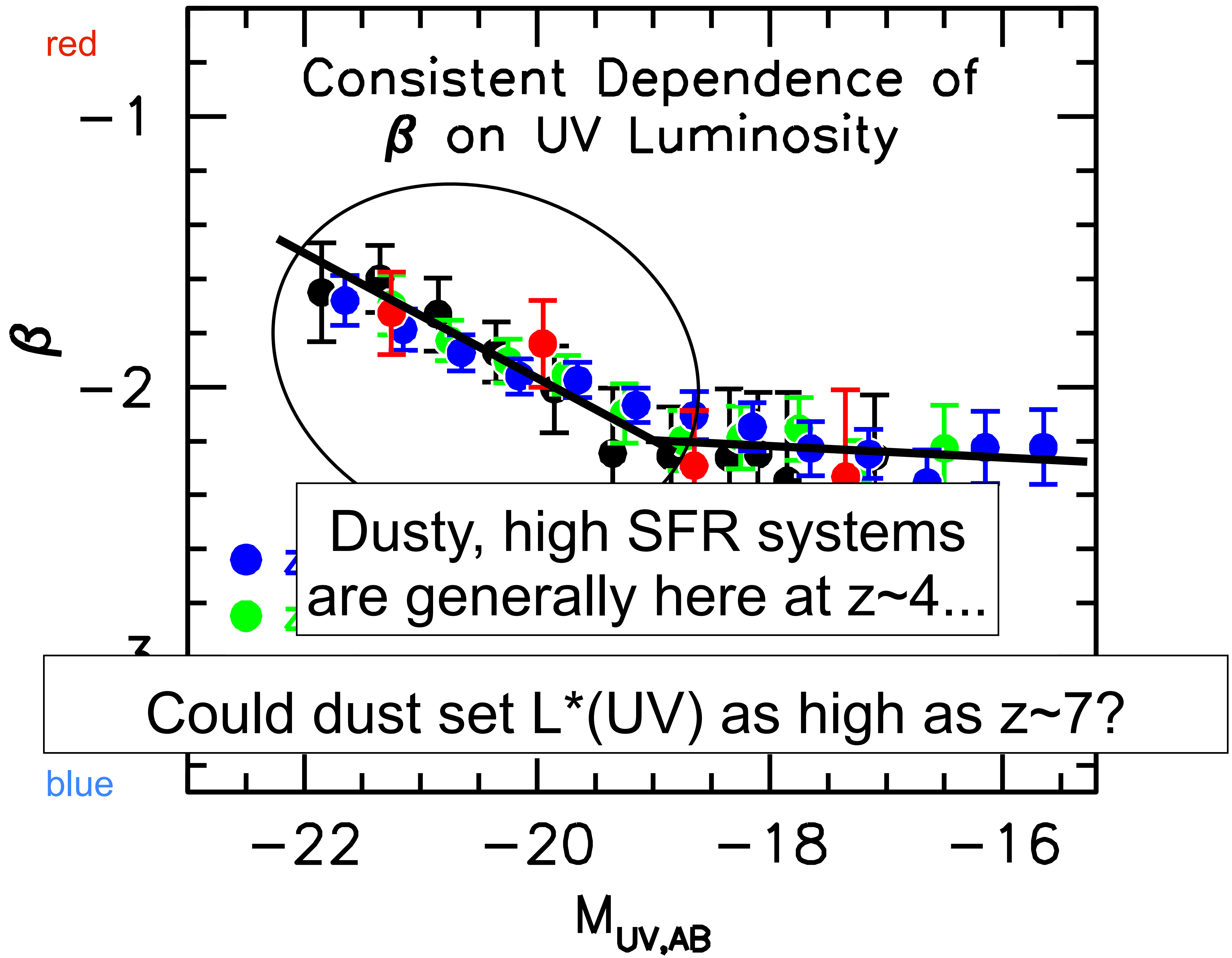
Oesch et al. 2013

z~5-6 galaxies show a similar dependence on UV luminosity as at z~4...



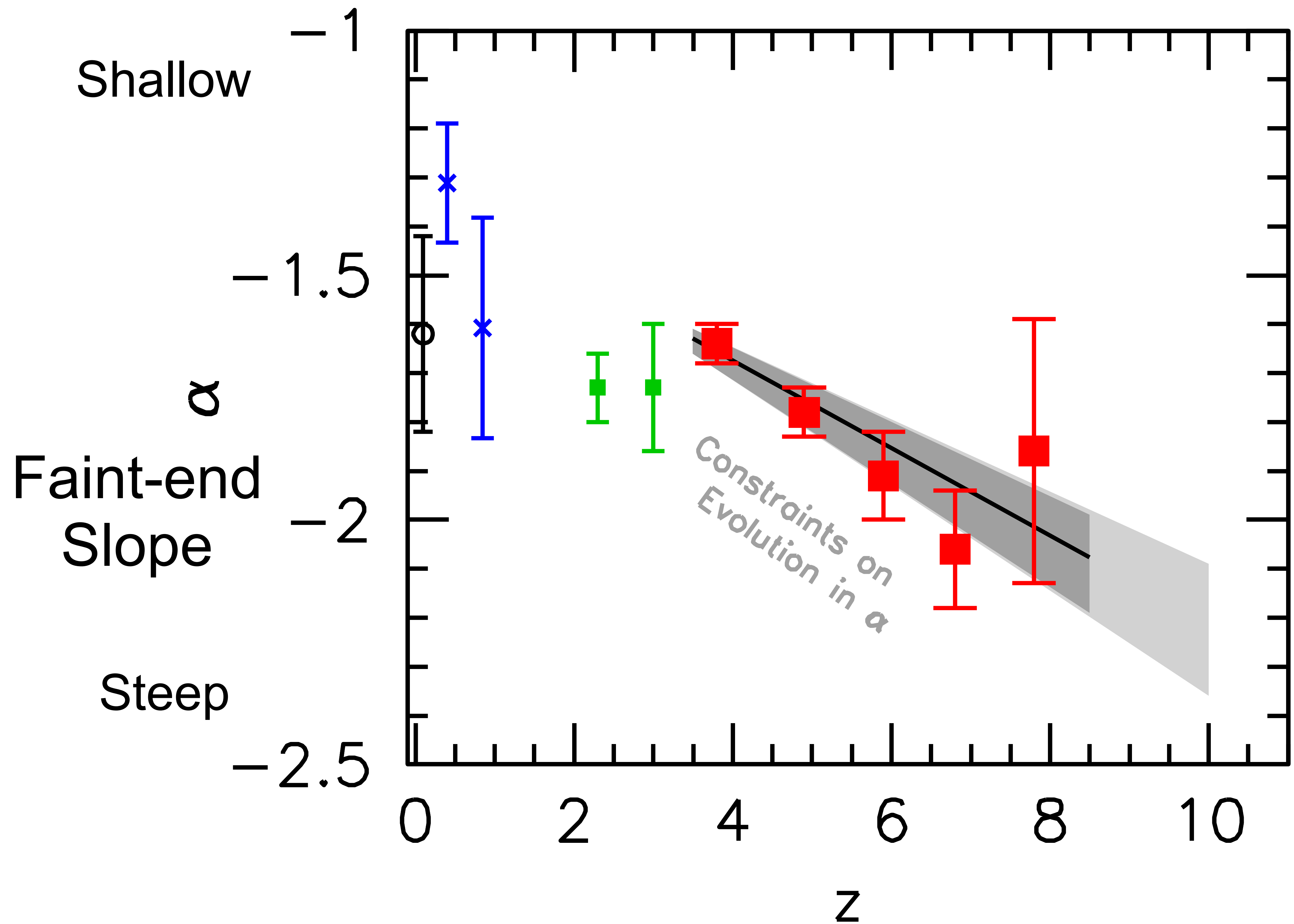
Bouwens et al. 2013

More generally that z~4-8 galaxies have similar colors as a function of luminosity



Bouwens+2014

How does the faint-end slope of the LF change with redshift?



Bouwens+2014

see also Bouwens+2011, Oesch+2012, Bradley+2012, McLure+2013, Schenker+2013; Schmidt+2014

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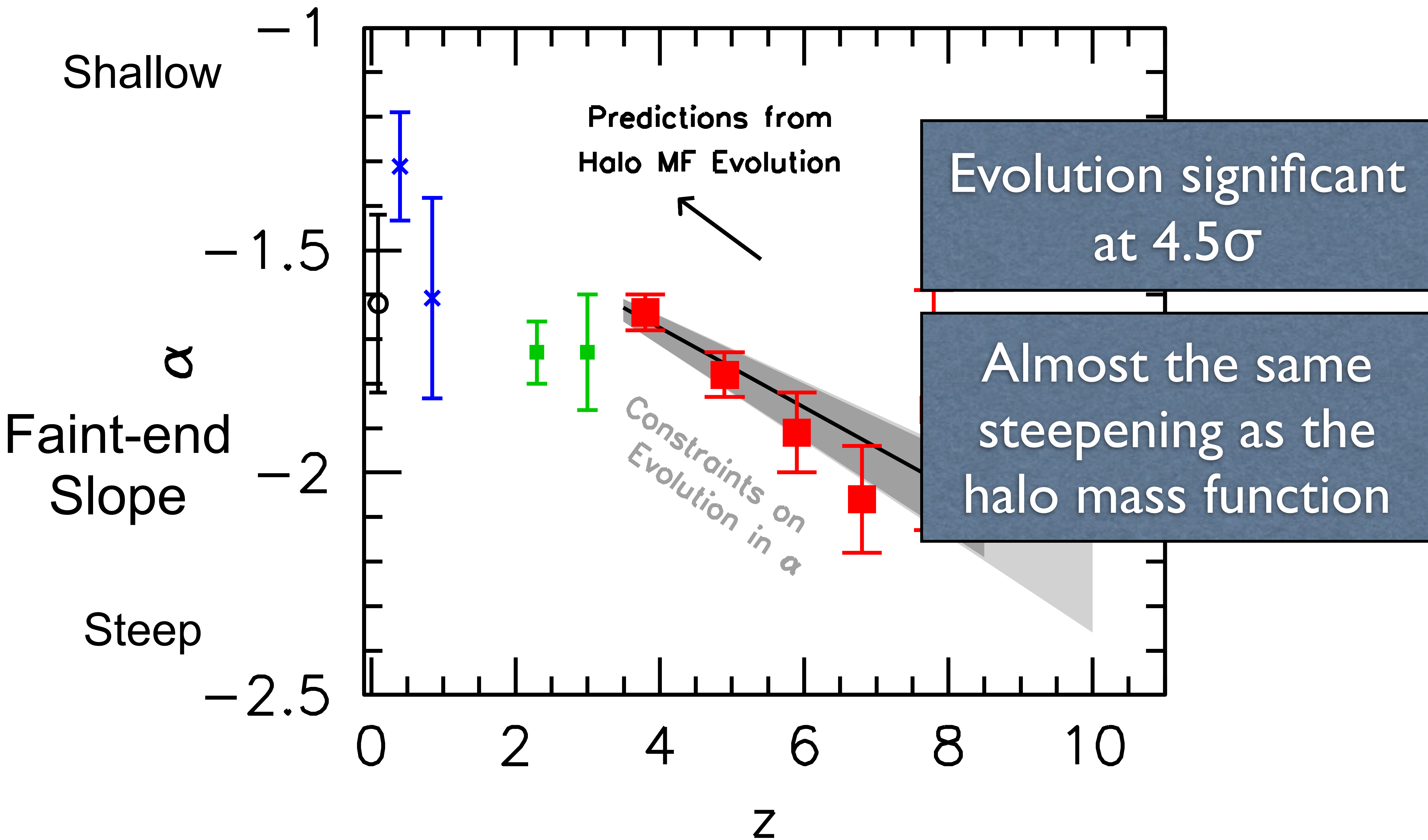
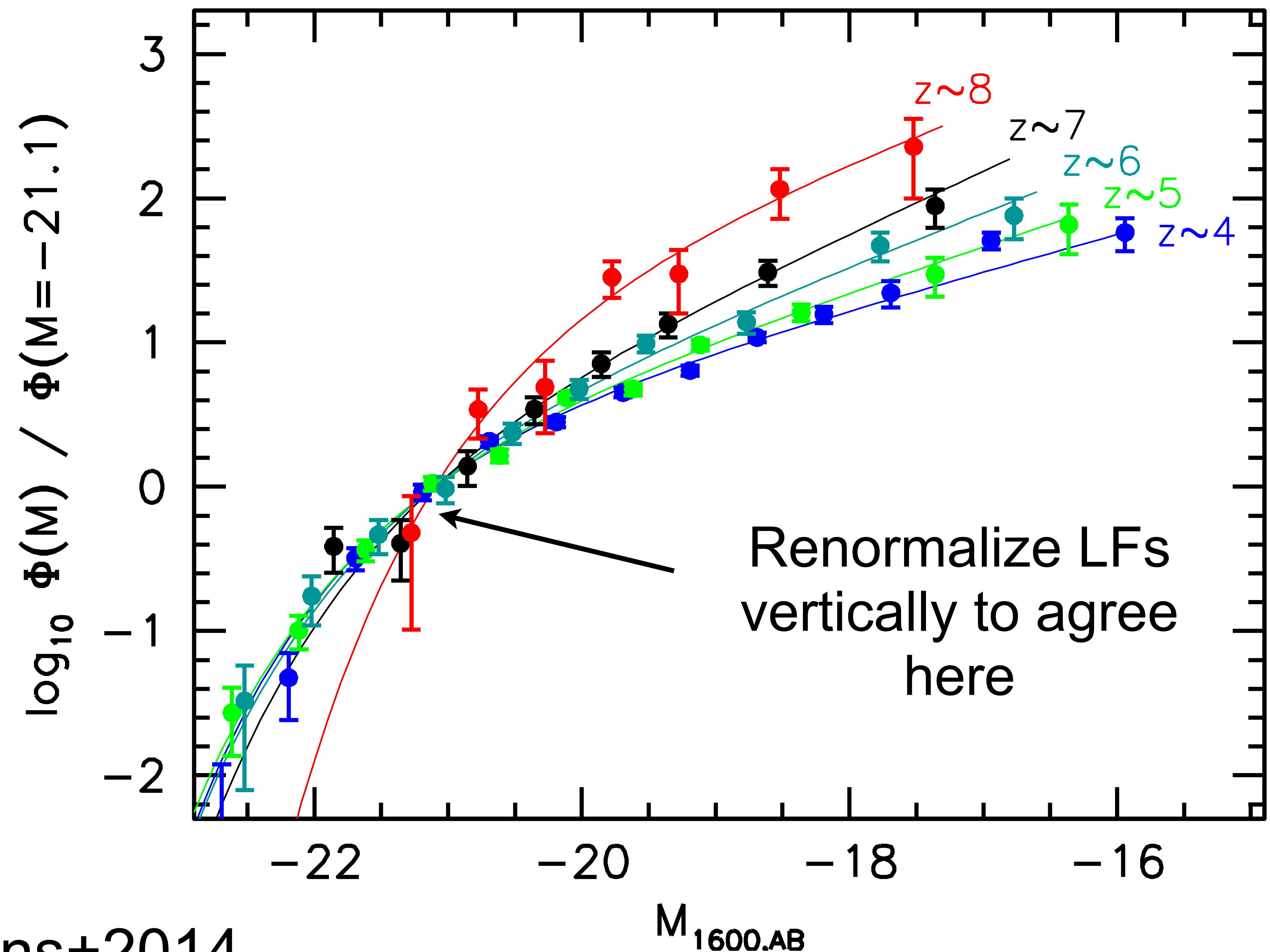


Bouwens+2014

see also Bouwens+2011, Oesch+2012, Bradley+2012, McLure+2013, Schenker+2013; Schmidt+2014

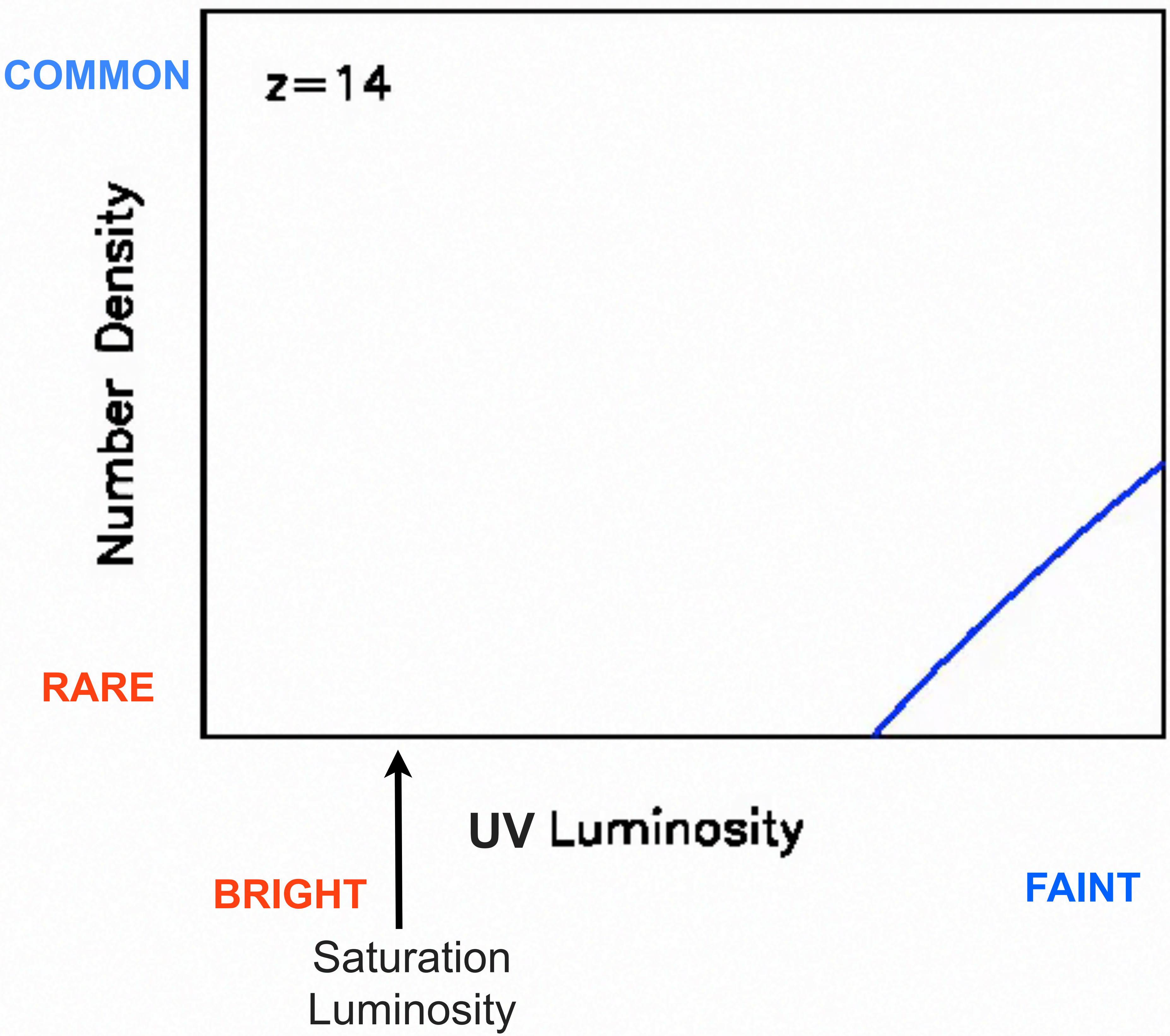
How does the shape of the LF change with redshift?

Also evident in parameter free way:



Bouwens+2014

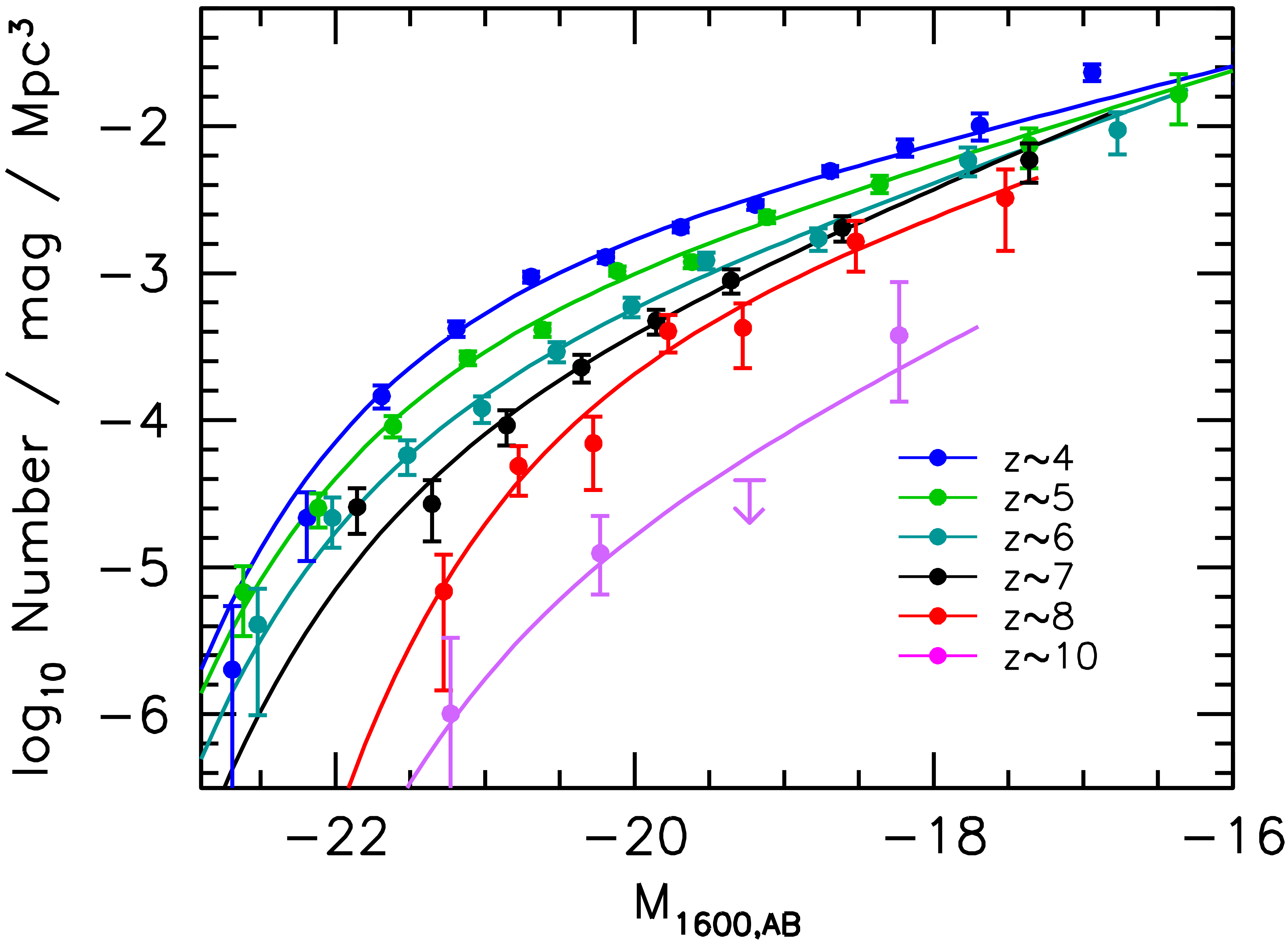
Evolution of the faint-end slope in the simple LF model shown earlier



Faint-end slope of the LF is much steeper at earlier times

New determinations of UV LF at z~4, 5, 6, 7, 8, 10 from all HST Legacy Fields

(Bouwens et al. 2014, arXiv:1403.4295)



Summary / Conclusions

Current HST data sets allow us to identify as many as >800 galaxies at z~7-8 and 15 galaxies at z~9-10...

Six luminous (~L*(z=3)) galaxy candidates at z~9-10 have been identified over CANDELS (Oesch+2014). These candidates have exactly the volume density, colors, and sizes we would expect if they were z~9-10 galaxies.

Amazingly, the newly discovered population of bright z~9-10 galaxies appear to be more robust than the fainter z~9-10 candidates in the HUDF.

Our large samples of bright z~4-7 galaxies from the 5 CANDELS + BORG fields allow us to set robust constraints on the volume density of bright galaxies. The characteristic luminosity M* at z~7 appears to be similar to z~3. We speculate this is due to the UV light saturating at a certain SFR.

The UV LF shows strong evidence (4.5σ) for being progressively steeper at high redshift to faint-end slope of -2.06 ± 0.12 at z=7. The observed evolution similar to expected evolution in halo mass function.