
Confirmed Invited Speakers:
Amy Barger, George Becker, Peter Behroozi, Marusa Bradac, Jim Dunlop, Andrea Ferrara, Jaqueline Hodge, Garth Illingworth, Sadegh Khochfar, Priya Natarajan, Jane Rigby, Joe Silk, and Rachel Somerville

SOUTH BY HIGH REDSHIFT

April 1 - 3, 2015
Austin, TX

www.as.utexas.edu/sxhz

Meeting Location:
The University of Texas at Austin
AT&T Executive Education and Conference Center
1900 University Ave
Austin, TX 78705

Topics Include:
Formation of first stars, galaxies and black holes
Reionization
Observations and theoretical insights into galaxy evolution at z = 10 to 4
Dusty star formation at the highest redshifts

Science Organizing Committee:
Steve Finkelstein, Dan Stark, Caitlin Casey, Volker Bromm, Rachael Livermore & Emily McLinden

Please contact SOC Chair Steve Finkelstein with any questions: stevenf@astro.as.utexas.edu

# *the first billion years: the growth of galaxies in the reionization epoch at z>6*

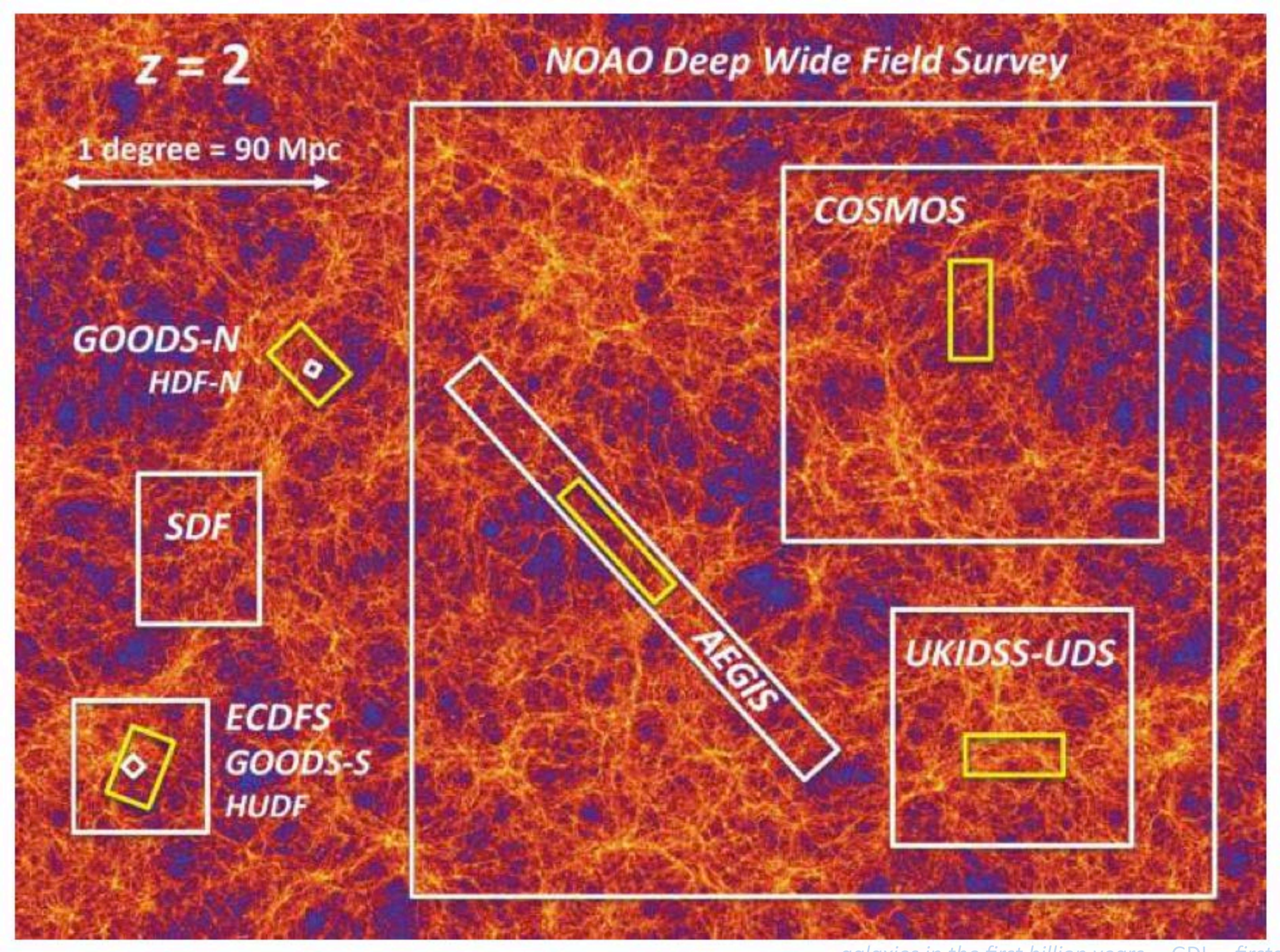
*Garth Illingworth*

*Rychard Bouwens,, Pascal Oesch, Ivo labbé, and the HUDF09/XDF science team*

www.firstgalaxies.org

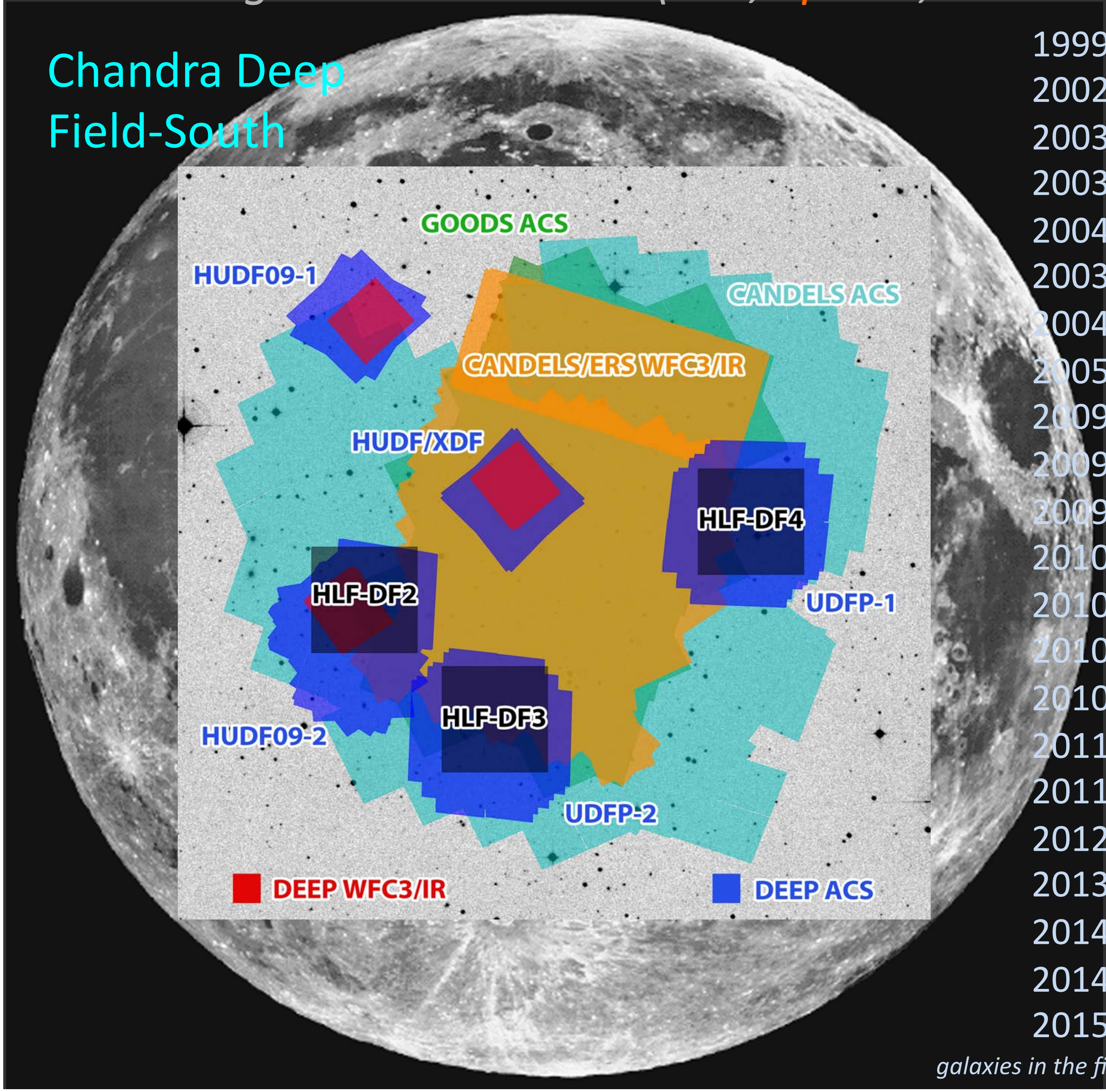
Madau & Dickinson 2014

# *surveys for high-z studies*



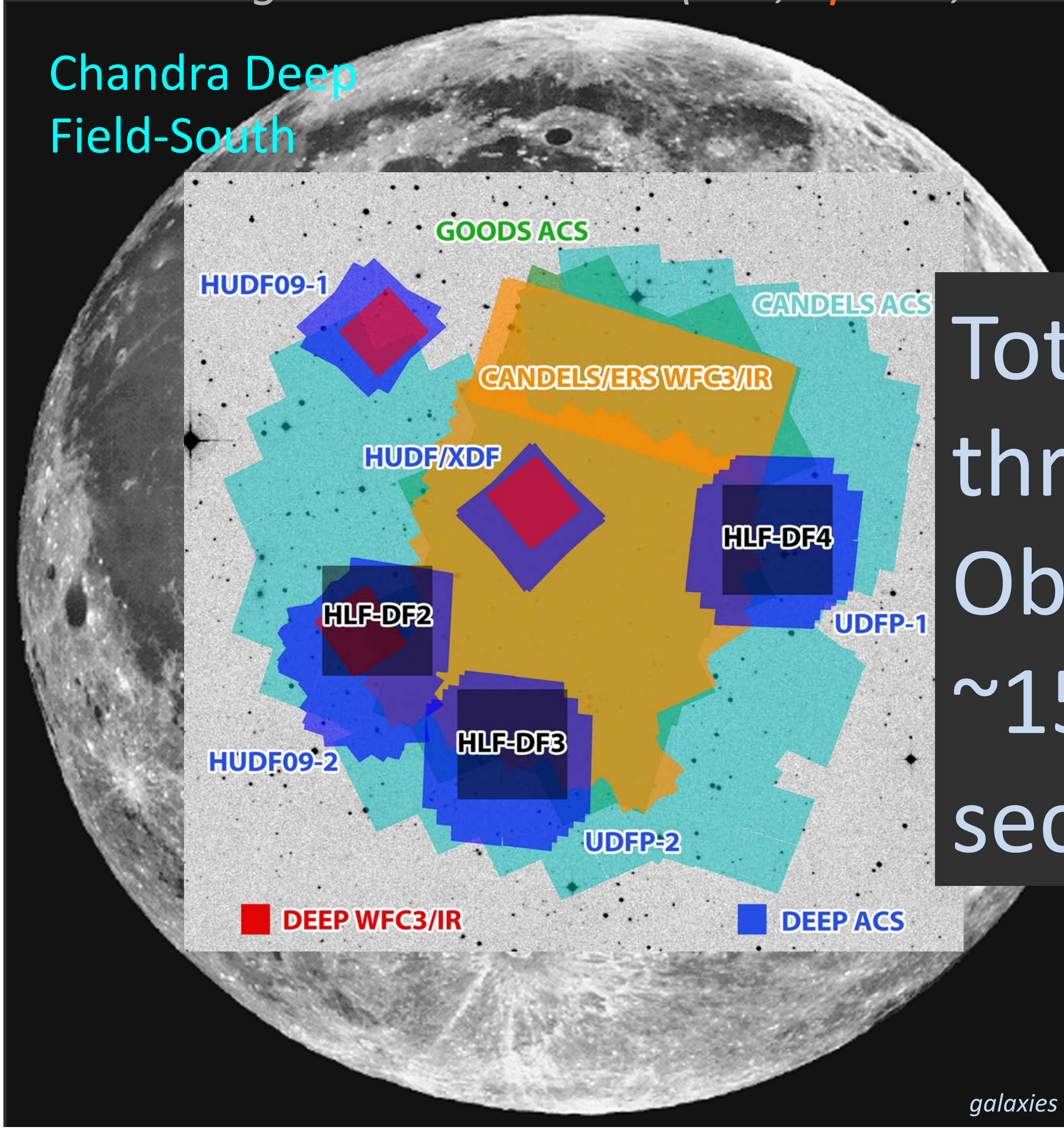
# *CDF-S region is rich in data (HST, Spitzer, Chandra, ground-based)*

Chandra Deep Field-South



| | |
|---|---|
| 1999-2000 | Chandra 1Ms |
| 2002-2003 | ACS GOODS |
| 2003 | ACS HUDF |
| 2003 | NICMOS HUDF |
| 2004 | Spitzer GOODS |
| 2003-2007 | NICMOS |
| 2004 | GRAPES |
| 2005 | HUDF05 |
| 2009 | ERS |
| 2009-2010 | HUDF09 |
| 2009-2010 | Spitzer SEDS |
| 2010-2011 | Chandra 3Ms |
| 2010-2012 | CANDELS |
| 2010-2012 | 3D-HST |
| 2010-2011 | Spitzer IUDF10 |
| 2011-2012 | Spitzer S-CANDELS |
| 2011-2012 | HUDF UVUDF |
| 2012 | HUDF12 |
| 2013 | Spitzer IGOODS |
| 2014 | HDUV |
| 2014 | FIGS |
| 2015 | Spitzer GREATS |

# *CDF-S region is rich in data (HST, Spitzer, Chandra, ground-based)*



Chandra Deep Field-South

| | |
|---|---|
| 1999-2000 | Chandra 1Ms |
| 2002-2003 | ACS GOODS |
| 2003 | ACS HUDF |
| 2003 | NICMOS HUDF |
| 2004 | Spitzer GOODS |
| 2013 | Spitzer IGOODS |
| 2014 | HDUV |
| 2014 | FIGS |
| 2015 | Spitzer GREATS |

Total time on three Great Observatories: ~15 million seconds!

*all optical ACS data and all WFC3/IR data from 2003-2013 combined into the XDF: eXtreme Deep Field*

*three key datasets: HUDF12, HUDF09, HUDF*

full XDF data release in MAST

includes above datasets plus CANDELS, SNe ACS data

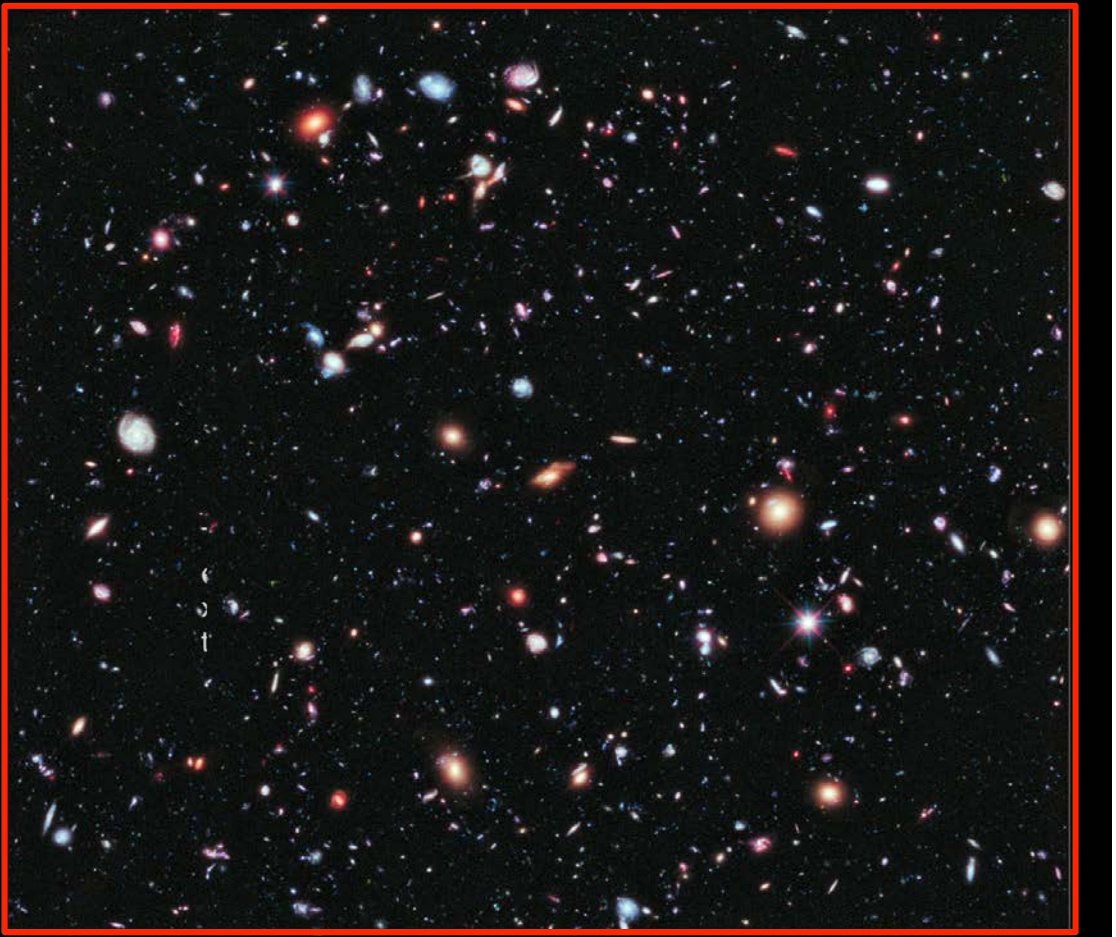
matched dataset is deepest image ever taken

reaches ~31 AB mag 5σ
or >32.5 AB mag 1σ

[http://xdf.ucolick.org/xdf.html](http://xdf.ucolick.org/xdf.html)

# XDF

HUBBLE SPACE TELESCOPE
XDF ▪ EXTREME DEEP FIELD

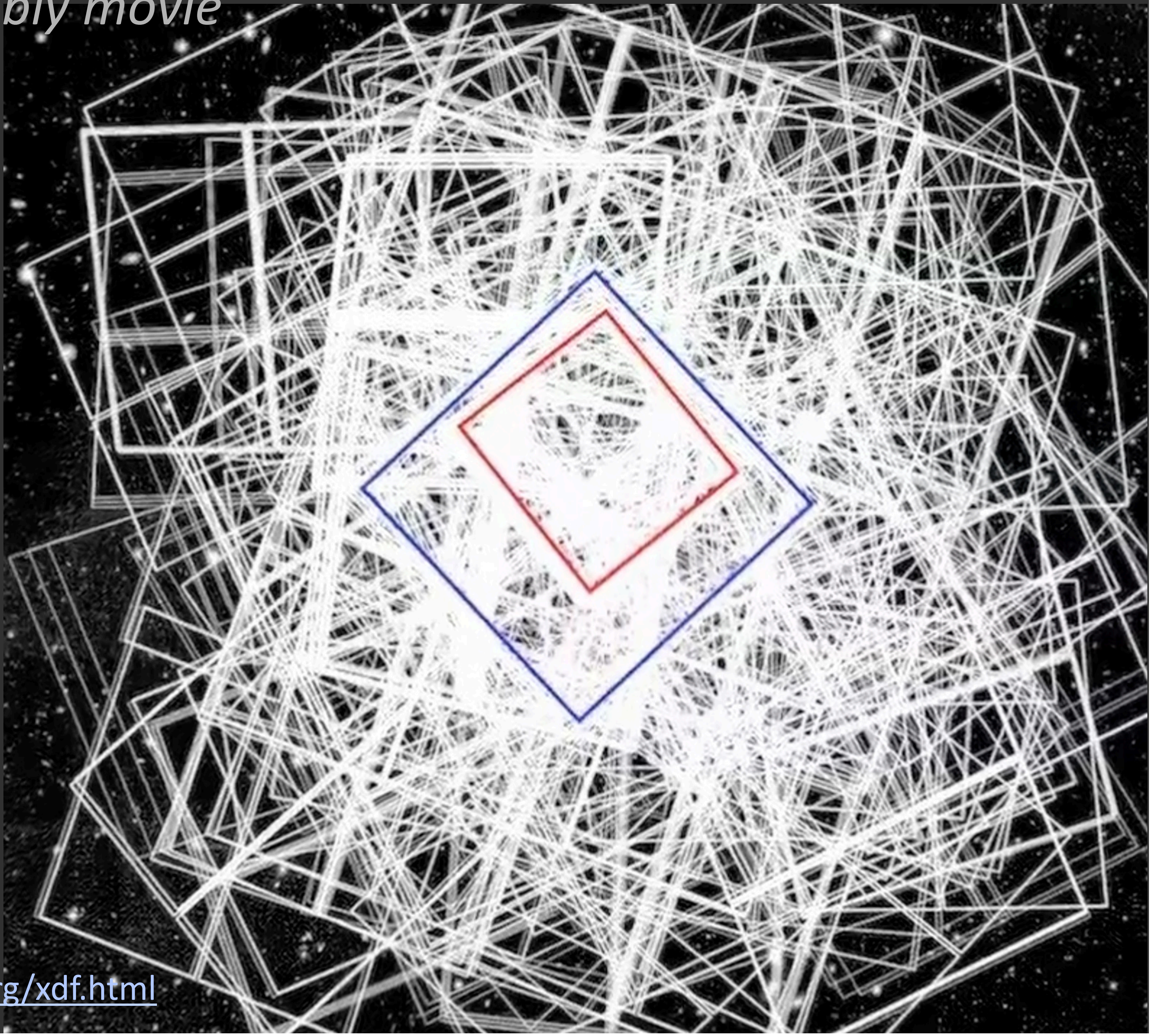


A decade of imaging on the Hubble Ultra Deep Field
The deepest image of the Universe

2012
NASA, ESA,
G. ILLINGWORTH, D. MAGEE, AND P. OESCH (UNIVERSITY OF CALIFORNIA, SANTA CRUZ),
R. BOUWENS (LEIDEN UNIVERSITY), AND THE XDF TEAM

# *XDF assembly movie*

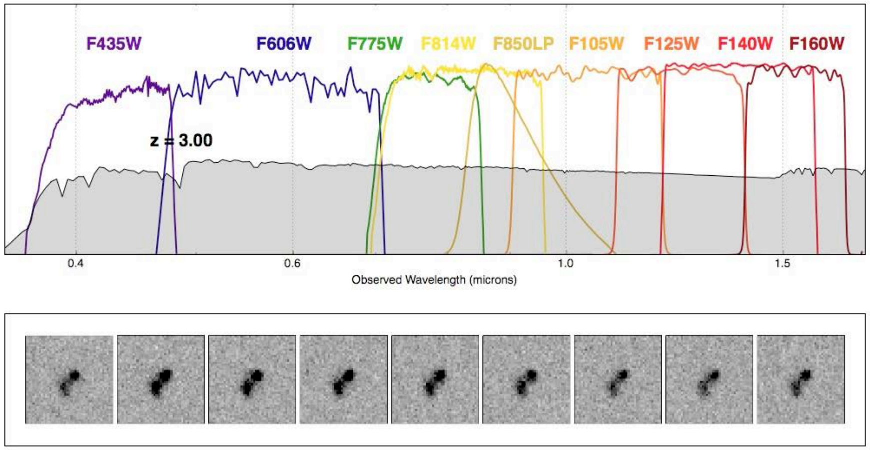
https://www.youtube.com/watch?v=H2oZ8xaICsg



3000 ACS and WFC3 images

total investment of HST time on HUDF region for XDF: 2 million seconds!

http://xdf.ucolick.org/xdf.html

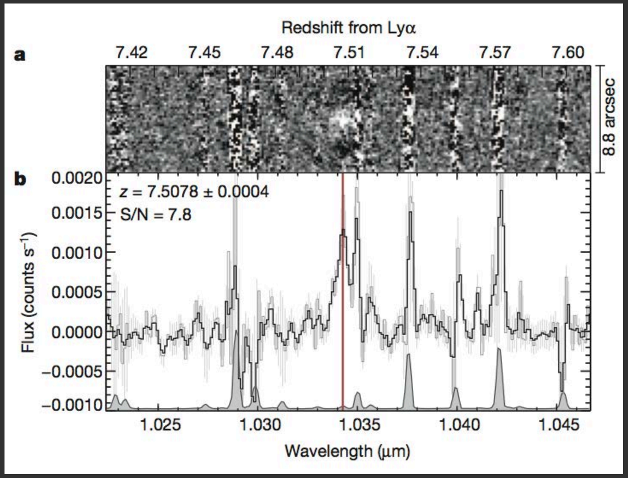


*ACS+WFC3/IR:*
*efficient detection of*
*galaxies to z~10+*

## *measuring the highest redshifts*

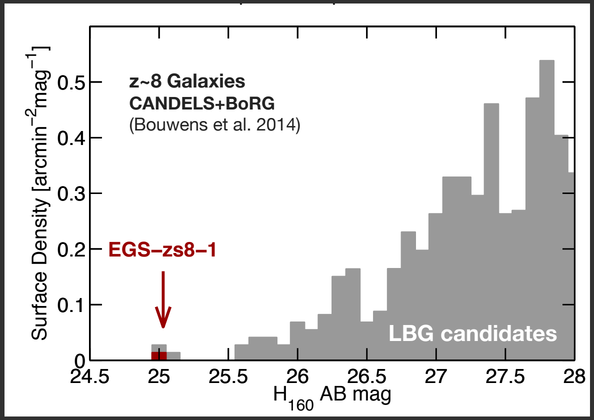
**Multi-Object Spectrometer for Infra-Red Exploration**

*ground spectra to z~8(+)*



# *luminous galaxies*

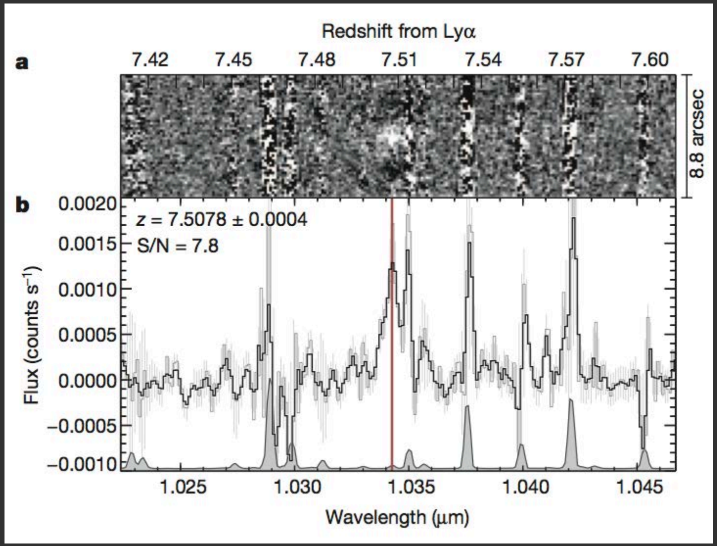
# *Lyα detections at z=7.5-7.7*



surprisingly bright galaxies!

Lyα z=7.5 from Keck MOSFIRE

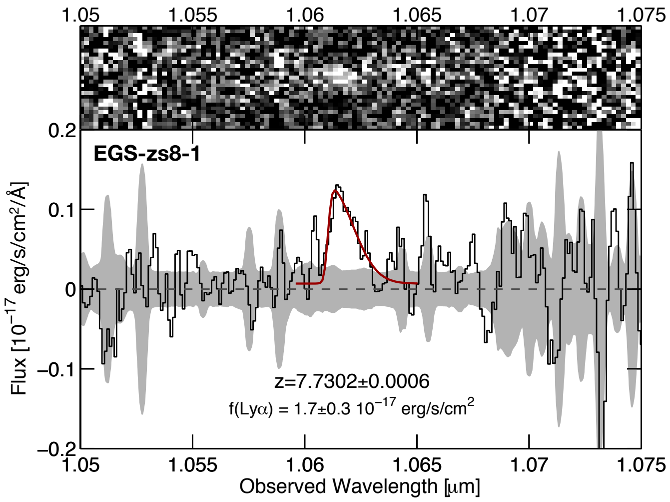
Finkelstein et al 2013



Lyα z=7.7 from Keck MOSFIRE

see Rychard and Pascal's talks for more on Keck MOSFIRE z~7.7 result

Oesch et al 2015



still only a few confirmed spectroscopic redshifts at z>7.0 (e.g,. Ono et al. 2012, Finkelstein et al. 2013, Oesch et al. 2015, Watson et al. 2015)

# ~30+ z~8.5-11 galaxy candidates!

## LBG dropouts/photo-z

z~8.6 HUDF
z~8.6 HUDF
z~8.8 HUDF
z~8.8 HUDF
z~8.9 HUDF
z~9.5 HUDF
z~9.8 HUDF
z~12 HUDF(?)

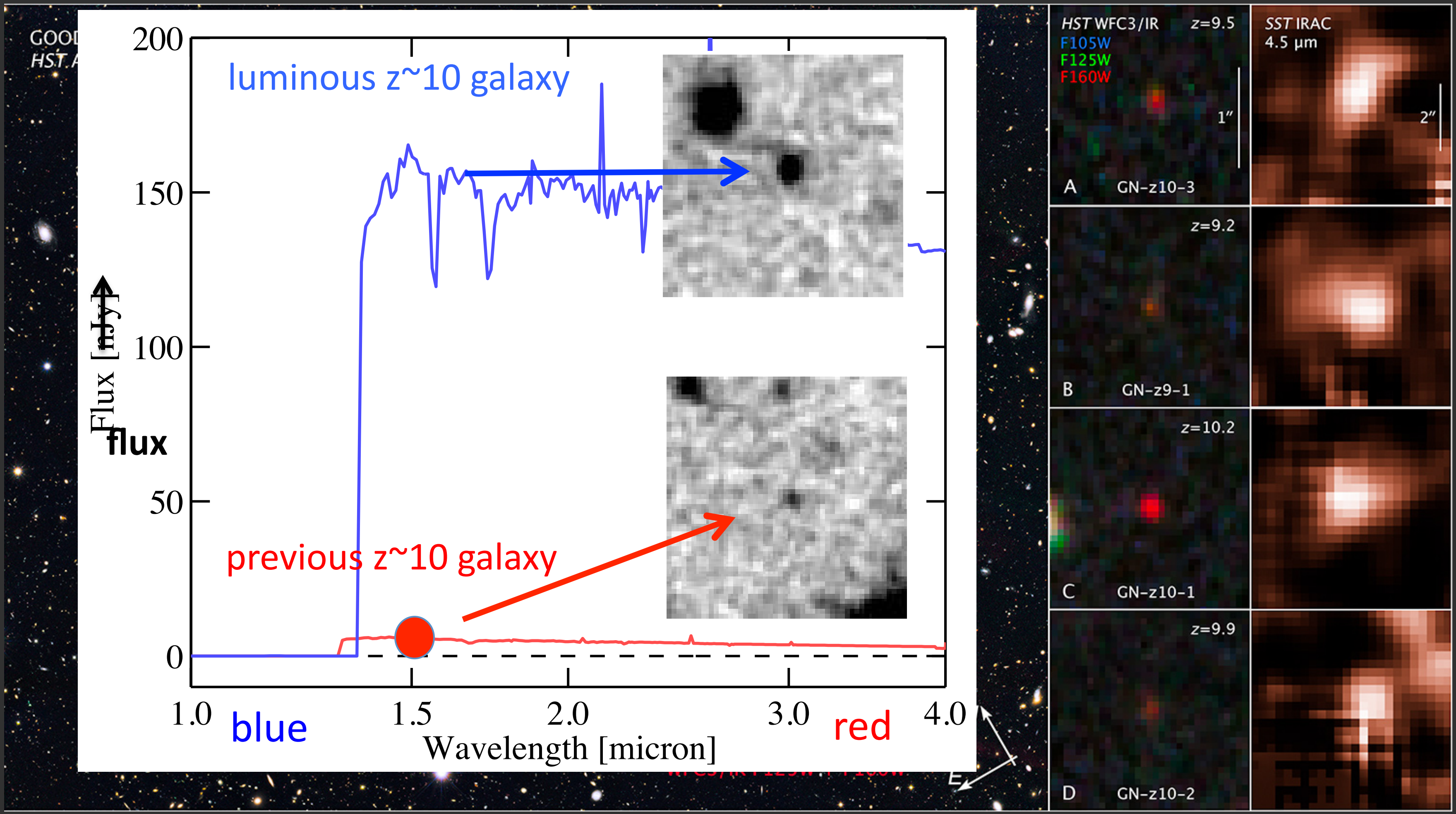
z~9.0 CANDELS
z~9.1 CANDELS
z~9.2 CANDELS
z~9.5 CANDELS
z~9.5 CANDELS
z~9.9 CANDELS
z~9.9 CANDELS
z~10.2 CANDELS

z~9 CLASH
z~9.2 CLASH
z~9.6 CLASH
z~10.8 CLASH

z~8.4 HFFs
z~8.4 HFFs
z~8.5 HFFs
z~8.5 HFFs
z~8.6 HFFs
z~8.6 HFFs
z~8.7 HFFs
z~8.7 HFFs
z~8.9 HFFs
z~9.0 HFFs
z~9.0 HFFs
z~9.0 HFFs
z~9.3 HFFs
z~9.8 HFFs

Bouwens et al. 2011, 2015a,b; Ellis et al. 2013; Oesch et al. 2013, 2014, 2015; Zitrin et al. 2014; Atek et al. 2015; Ishigaki et al. 2015; McLeod et al. 2015

# *very luminous galaxy candidates at redshift z~9-10*
# *10-20X more luminous than previous galaxies found at 500 Myr*

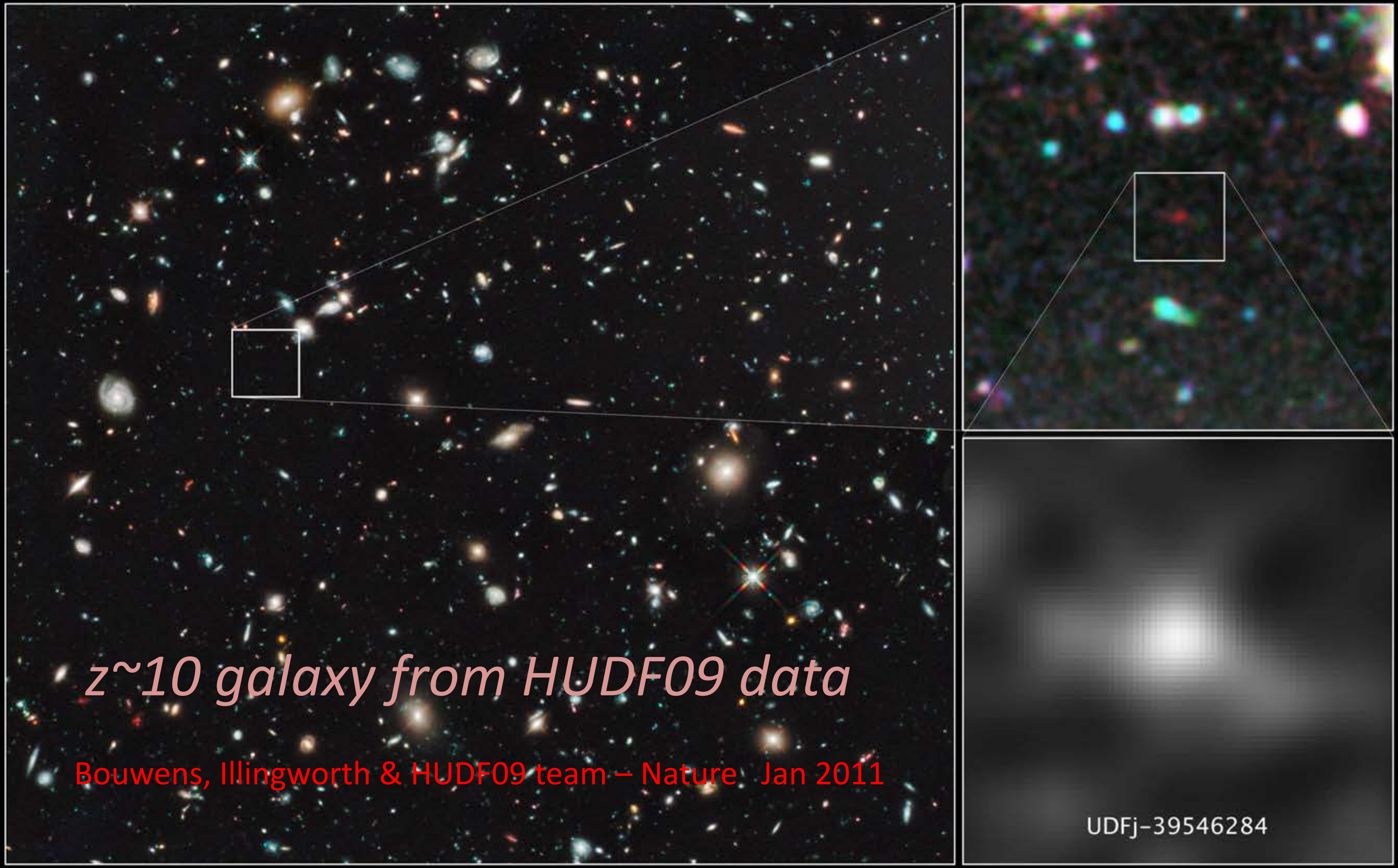


*see Pascal's talk*

Oesch et al 2014

## z~10 galaxy from HUDF09 data

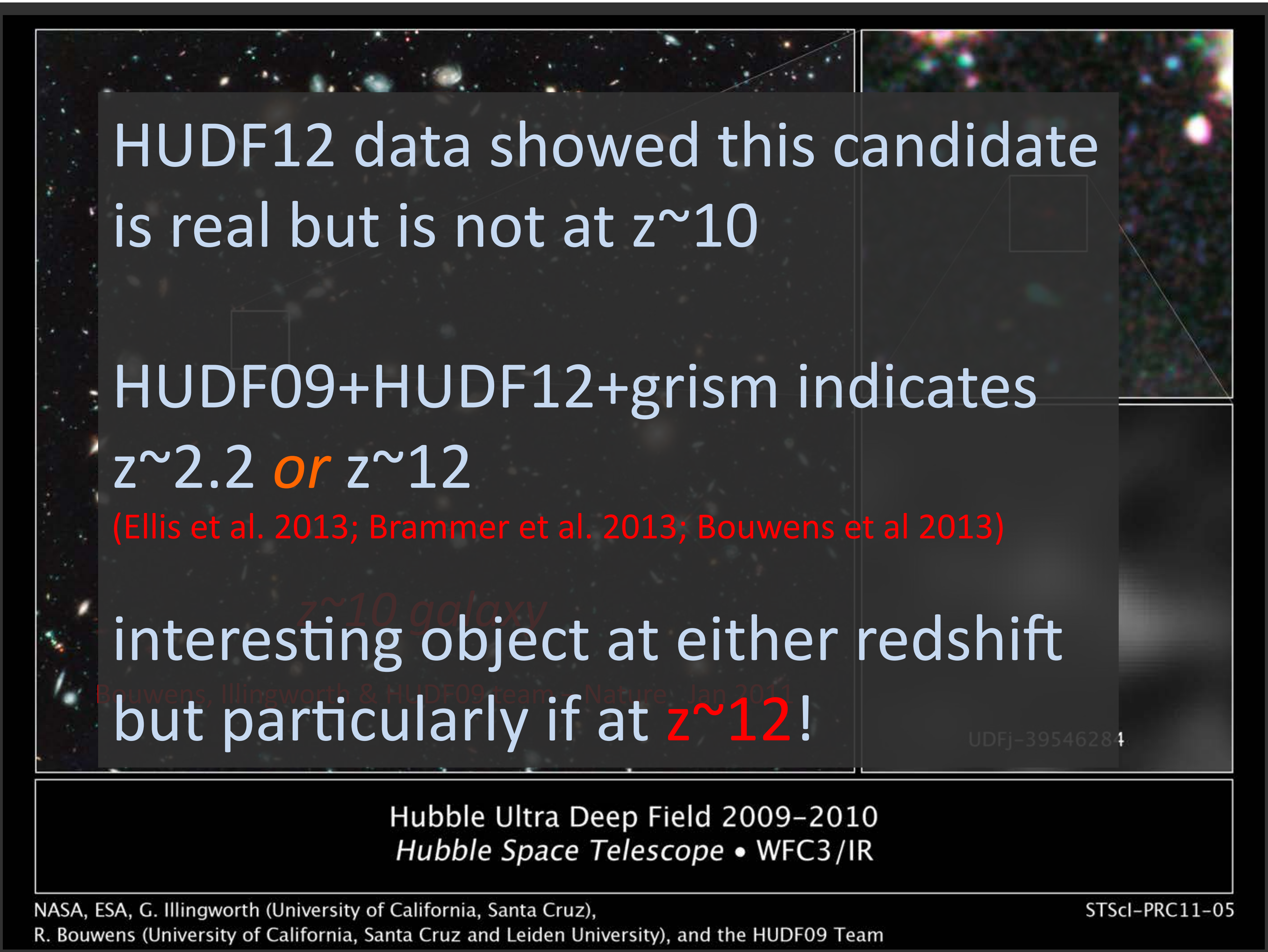
Bouwens, Illingworth & HUDF09 team – Nature Jan 2011



Hubble Ultra Deep Field 2009-2010
*Hubble Space Telescope* • WFC3/IR

NASA, ESA, G. Illingworth (University of California, Santa Cruz),
R. Bouwens (University of California, Santa Cruz and Leiden University), and the HUDF09 Team

STScI-PRC11-05



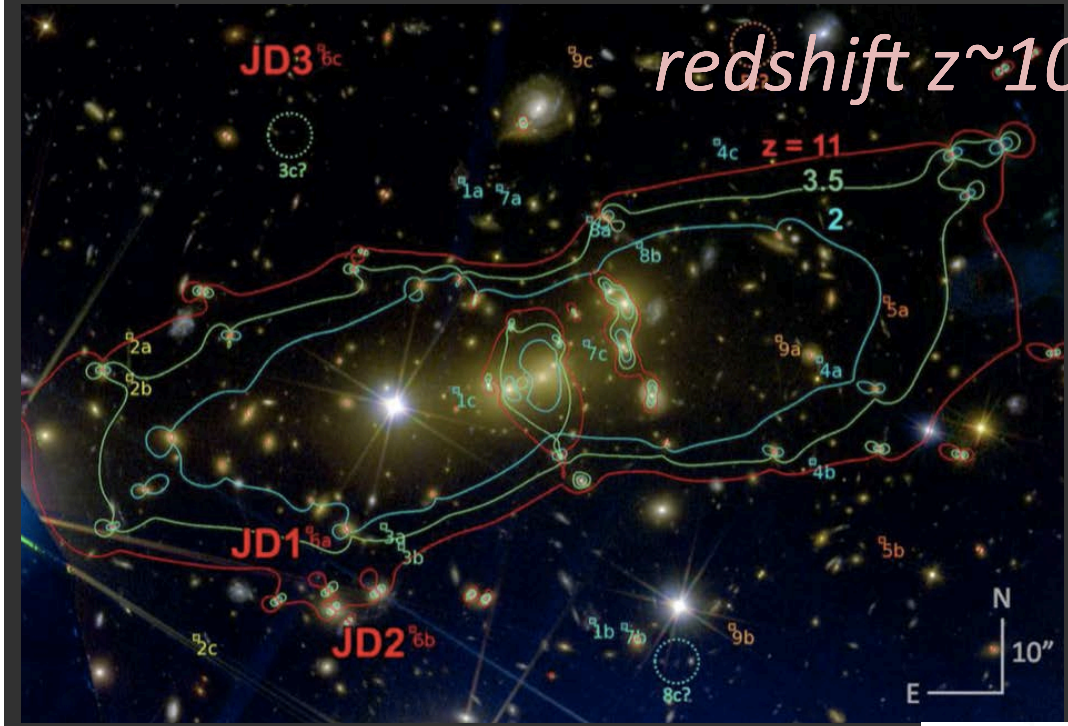
HUDF12 data showed this candidate is real but is not at z~10

HUDF09+HUDF12+grism indicates z~2.2 *or* z~12

(Ellis et al. 2013; Brammer et al. 2013; Bouwens et al 2013)

interesting object at either redshift but particularly if at z~12!

# *CLASH cluster MACS0647 has highest redshift z~10.7 galaxy candidate!*



highly magnified source: ~8X (JD1)

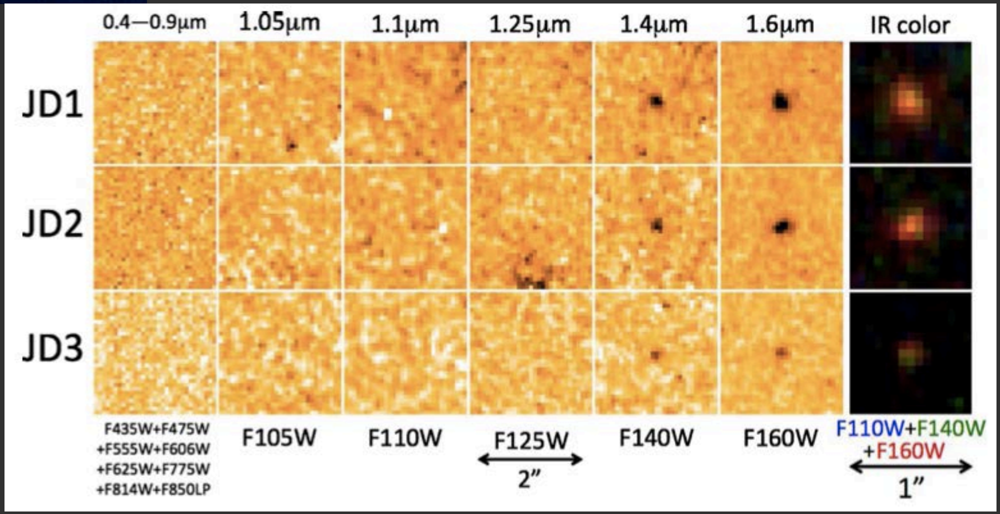
*MACS0647-JD*
*redshift z~10.7±0.5 (430 Myr)*
*25.9 AB H-band (for JD1 image)*

Coe et al 2013

recent HST grism spectroscopy: *lack of strong emission lines suggests not low redshift contaminant*

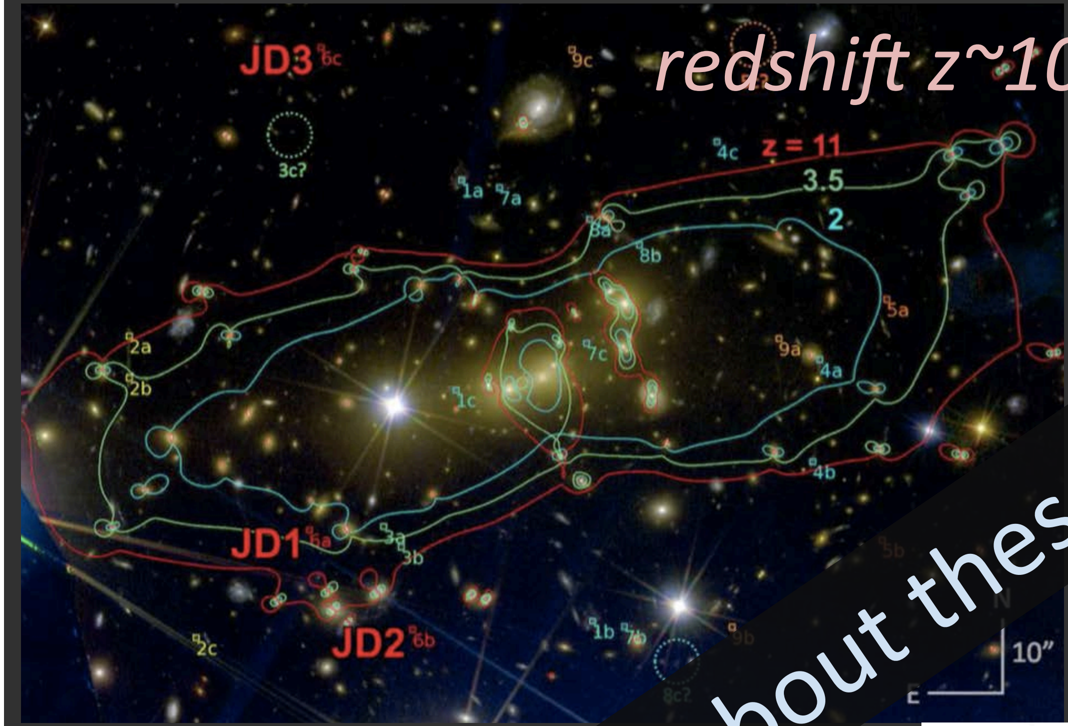
*MACS0647-JD more likely to be at z~11*

Pirzkal et al 2015



# *CLASH cluster MACS0647 has highest redshift z~10.7 galaxy candidate!*

why do we care about these highest z objects?



highly magnified source: ~8X (JD1)

*MACS0647-JD*

*redshift z~10.7±0.5 (430 Myr)*

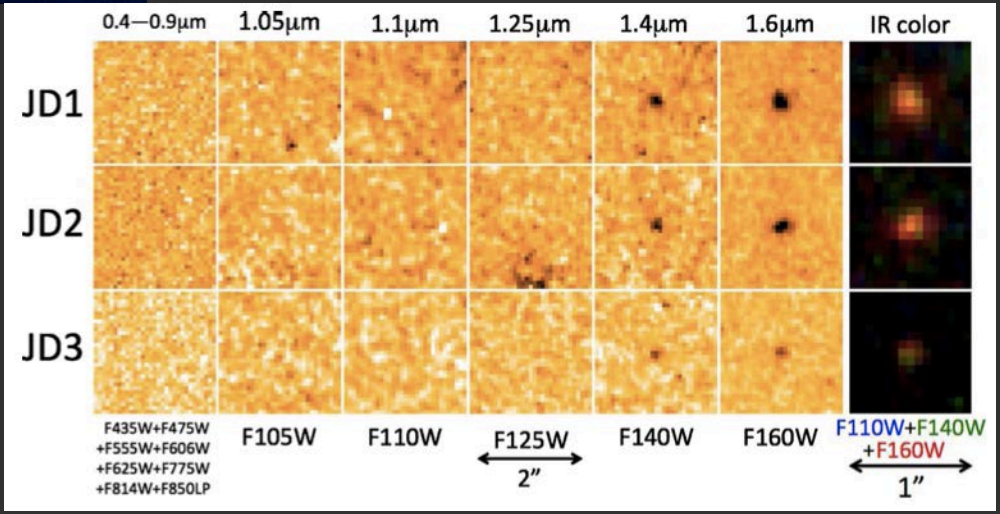
*25.9 AB H-band (for JD1 image)*

Coe et al 2013

recent HST grism spectroscopy: *lack of strong emission lines suggests not low redshift contaminant*

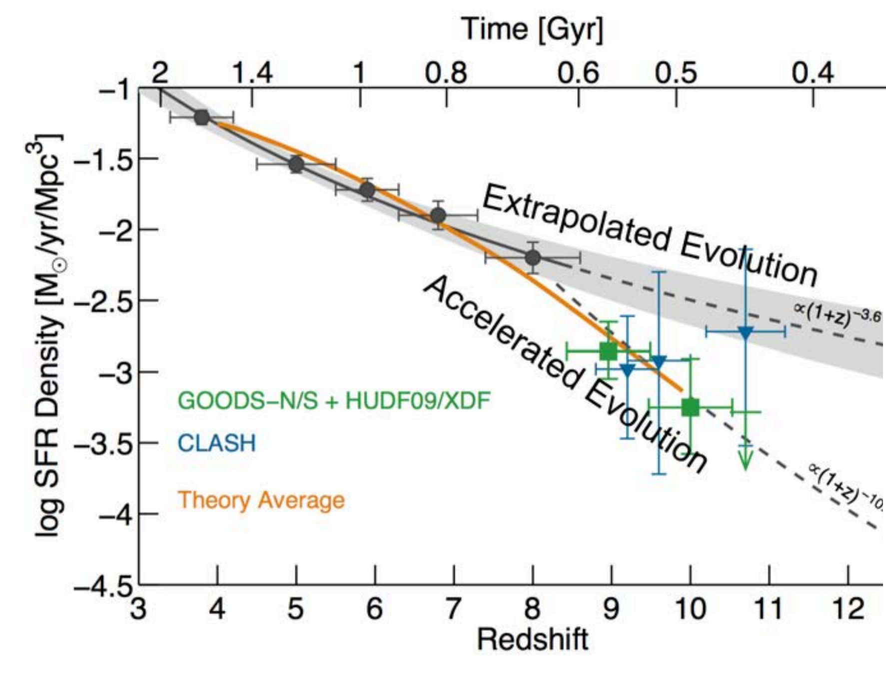
*MACS0647-JD more likely to be at z~11*

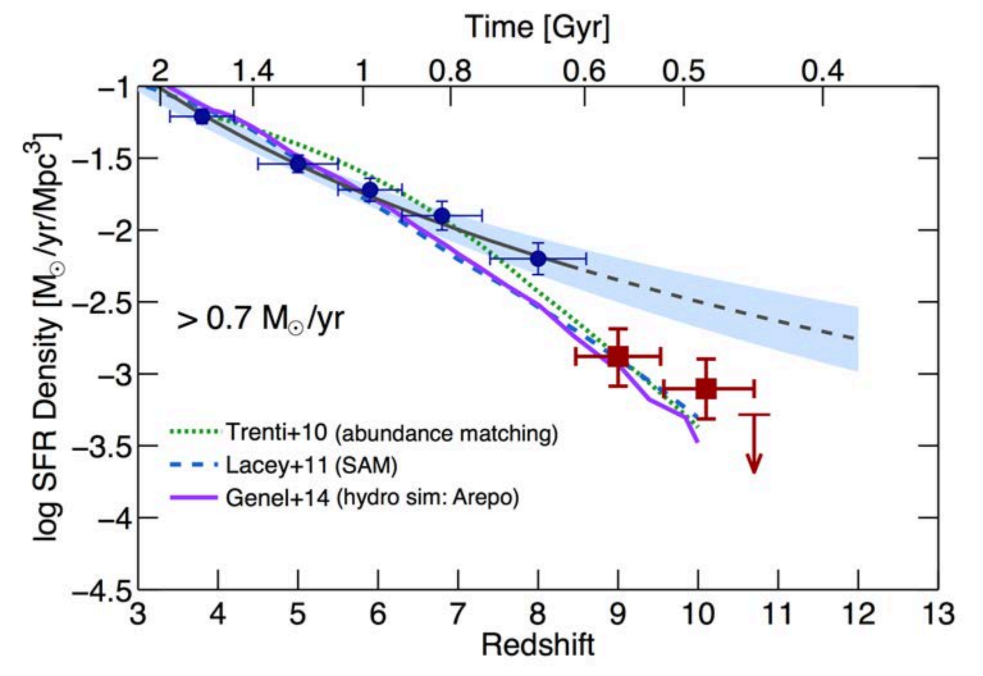
Pirzkal et al 2015



# *SFRD: accelerated evolution from z~10 to z~8 suggests a factor 10X change in just 170 Myr!*

combining the current constraints from all datasets: rapid evolution in the cosmic SFRD at z>8 (~10X in 170 Myr) but still indicative – needs more sources



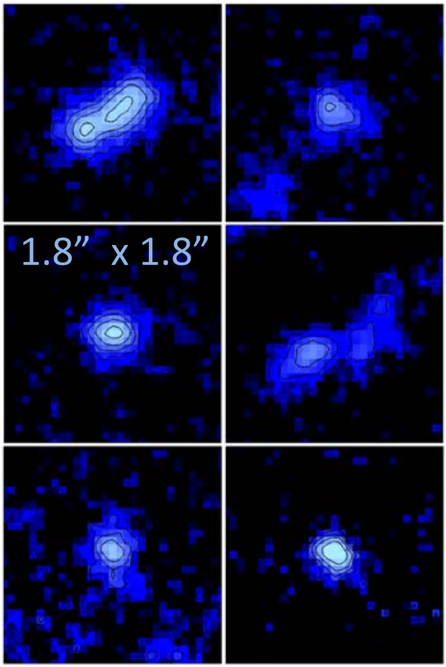


Oesch et al. 2014

see also, e.g.: Zheng+12, Coe+13, Bouwens+13/14, Ellis+13, McLure +13, Ishigaki+14, McLeod+14

note that "accelerated evolution" consistent with model expectations

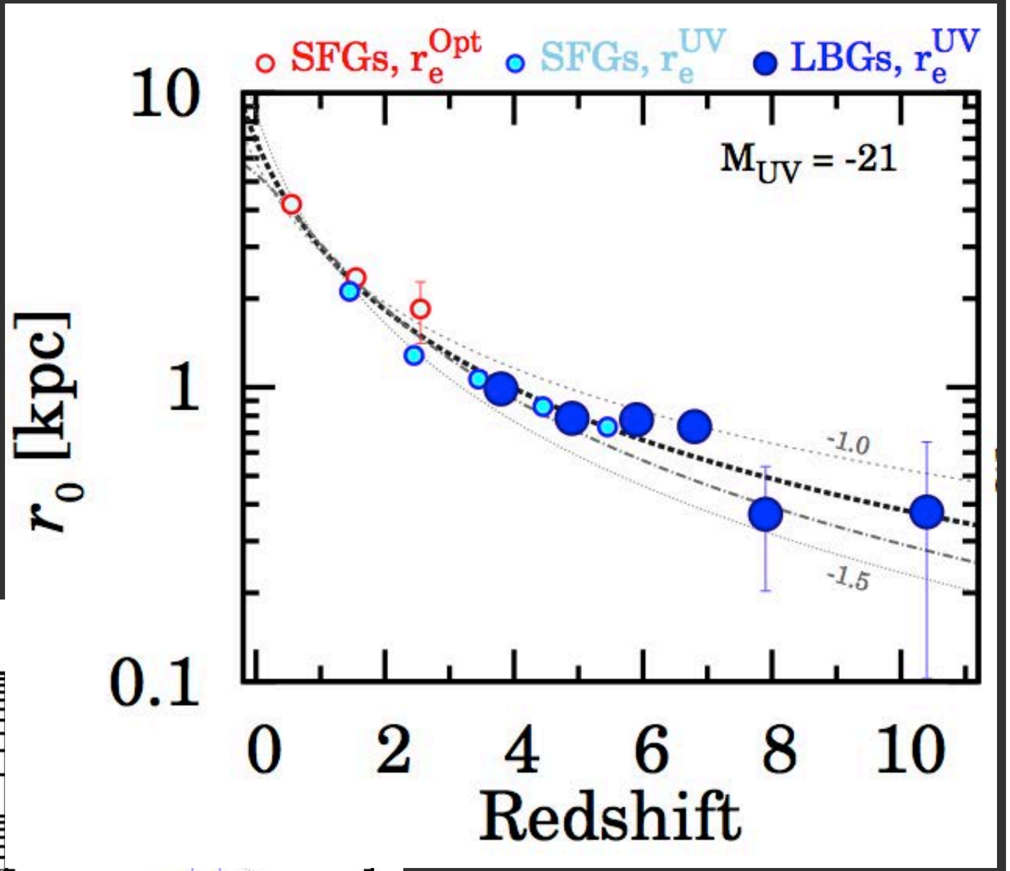
# *sizes and structure*



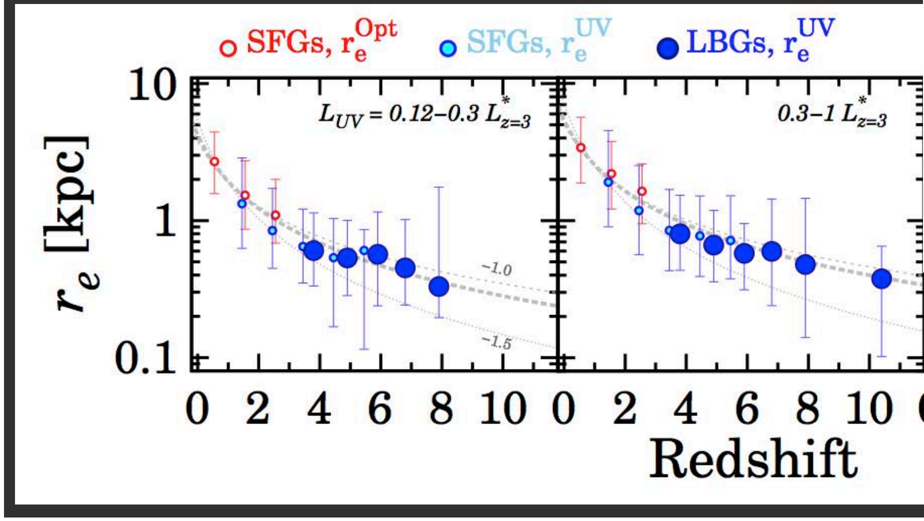
## *very comprehensive recent paper on sizes ($r_e$)*

measured ~190,000 galaxies from z~0 to z~10 – over 600 at z>~6

Shibuya et al 2015



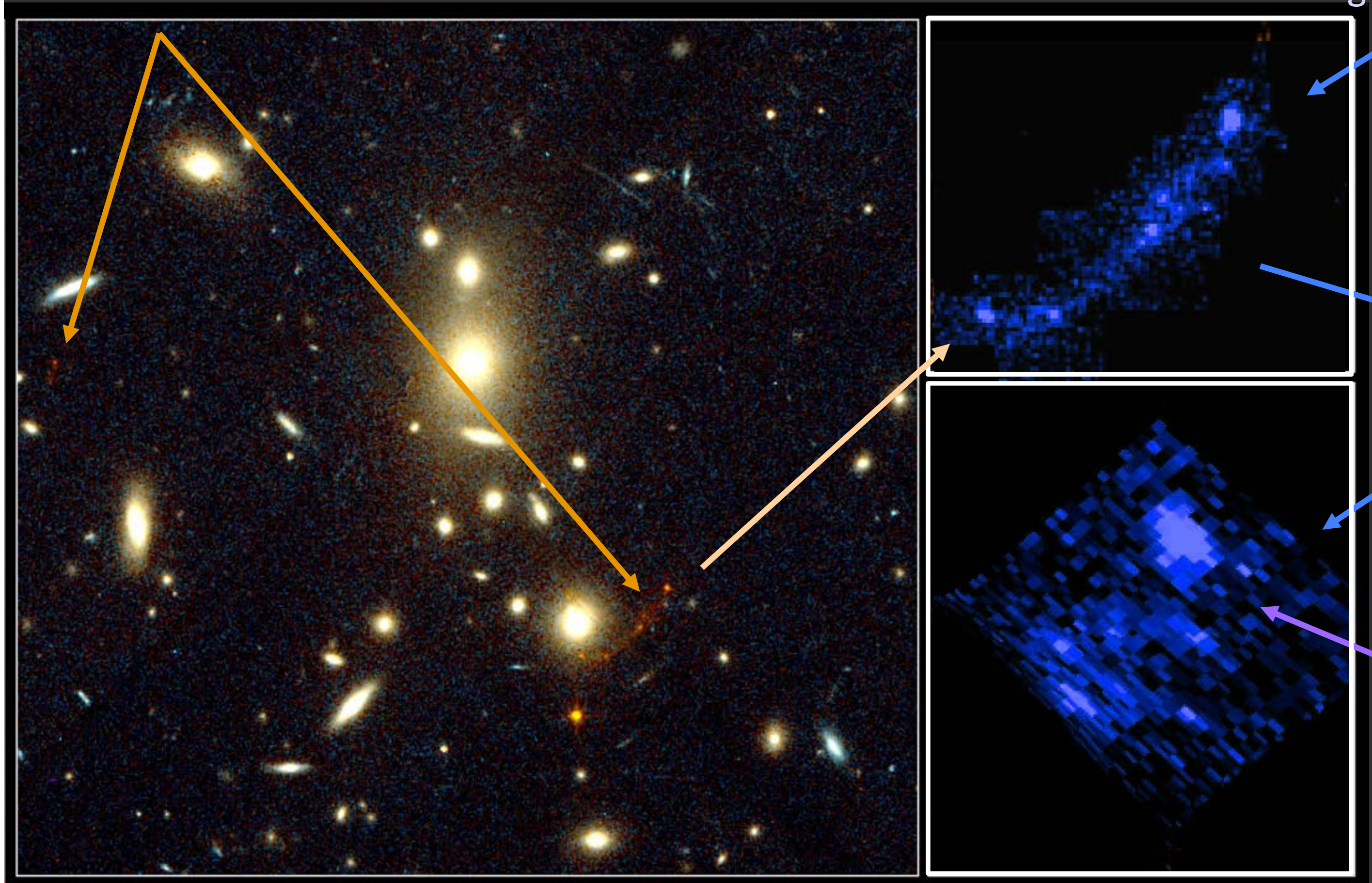
*cf.* Oesch et al 2010, Ono et al 2012; Curtis-Lake et al 2014



# *star formation occurs in compact regions*

Franx, Illingworth et al 1997

*lensed galaxy at redshift 4.9 – 12.4 billion years ago*
*– lensed by a rich cluster of galaxies at redshift z~0.3*



**Gravitationally Lensed Image of Highest Redshift Galaxy**
Hubble Space Telescope • WFPC2

distorted fold image of a 10-20x magnified, redshift 5 galaxy

remove the distortion caused by the cluster – get a >10x magnified image of a galaxy at redshift 5

- *significant fraction of total star formation in "blob"*
- *just a few hundred pc in size*

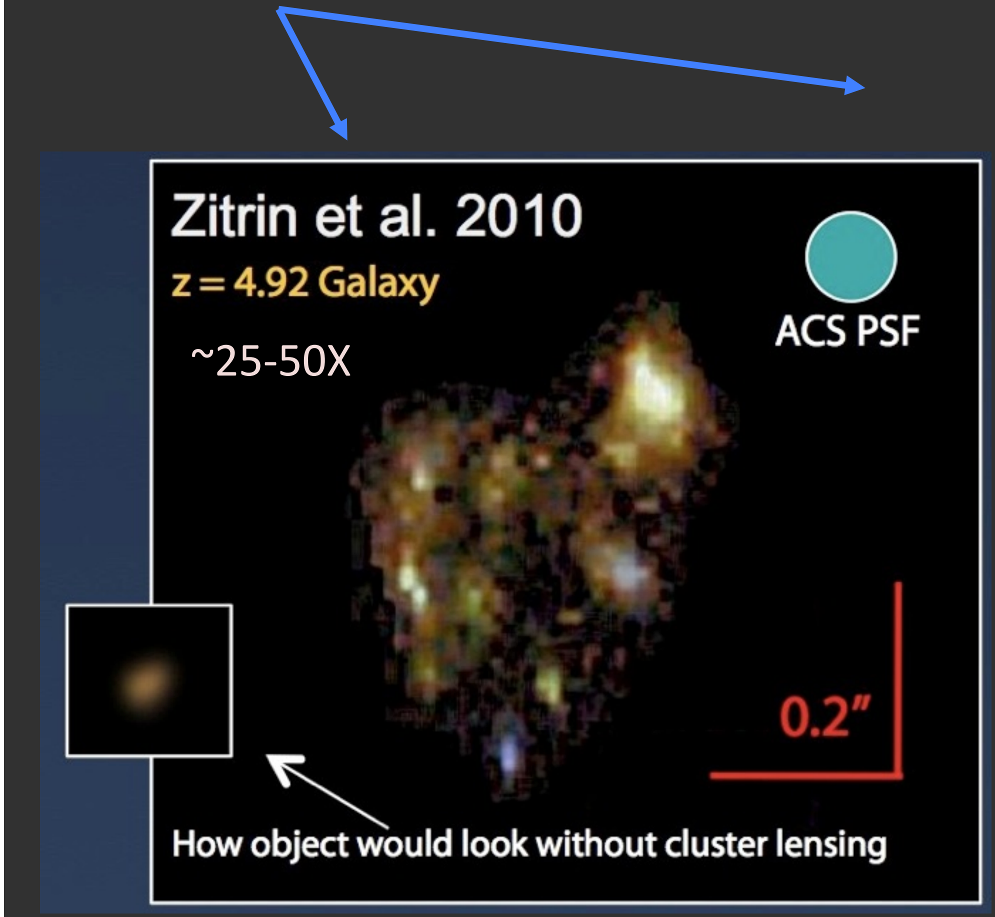
# *star formation occurs in compact regions*

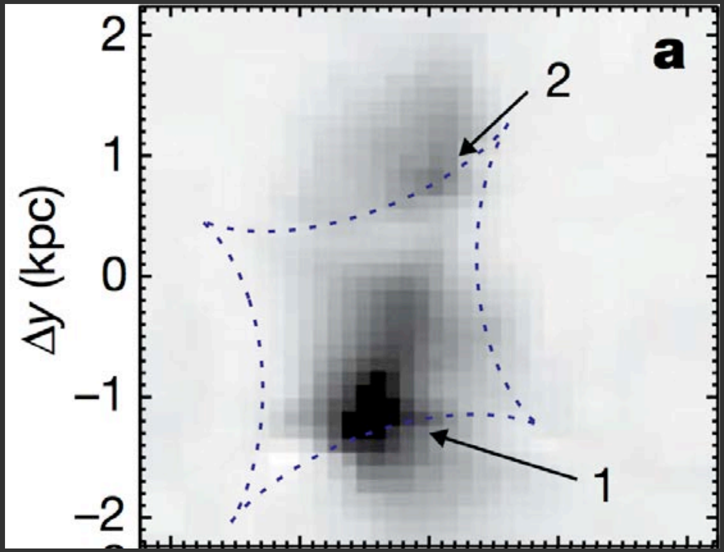
such highly-lensed galaxies are rare (very rare!) objects

*highly-lensed galaxies => give resolutions of ~100 pc or less – like 30-40 m telescope with AO*

cB58 also, though lower redshift

J2135-0102 – at z=3.1 magnified ~28X





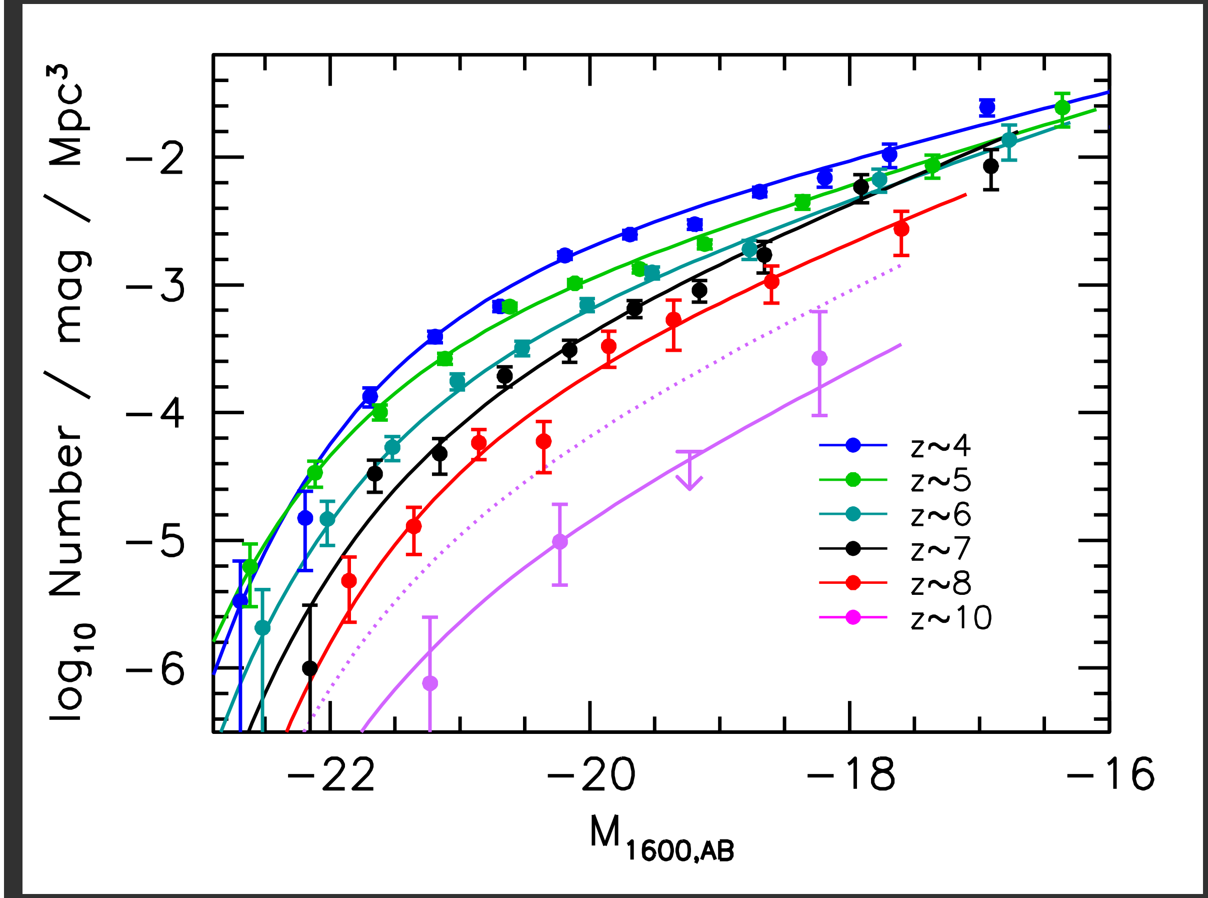
Stark et al 2008

- ➢ *these highly-magnified galaxies are important for assessing the nature of star forming regions at high redshift*

# *luminosity functions*

# *10,000 z~4-8 galaxies luminosity functions from deep & wide fields*

*HUDF12, HUDF09, HUDF (XDF), HUDF09-1, HUDF09-2, ERS, BORG and all 5 CANDELS Fields*



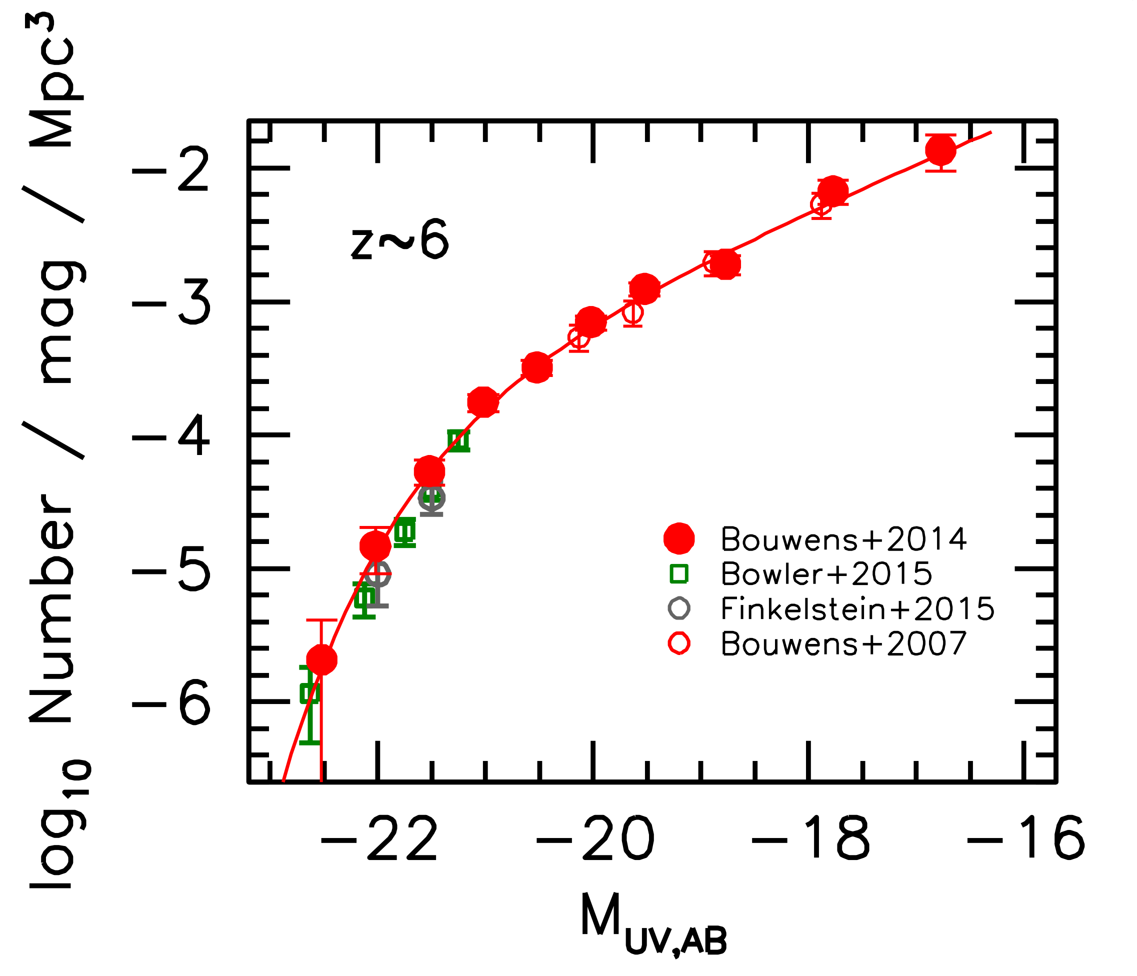
**UV luminosity decreases monotonically to higher redshift**

slope α is very steep at the faint end (α < ~-1.7 to -2)

no statistically-significant evidence for non-Schechter form

Bouwens et al. 2014

# *luminosity functions: consistent across many authors*



encouraging consistency

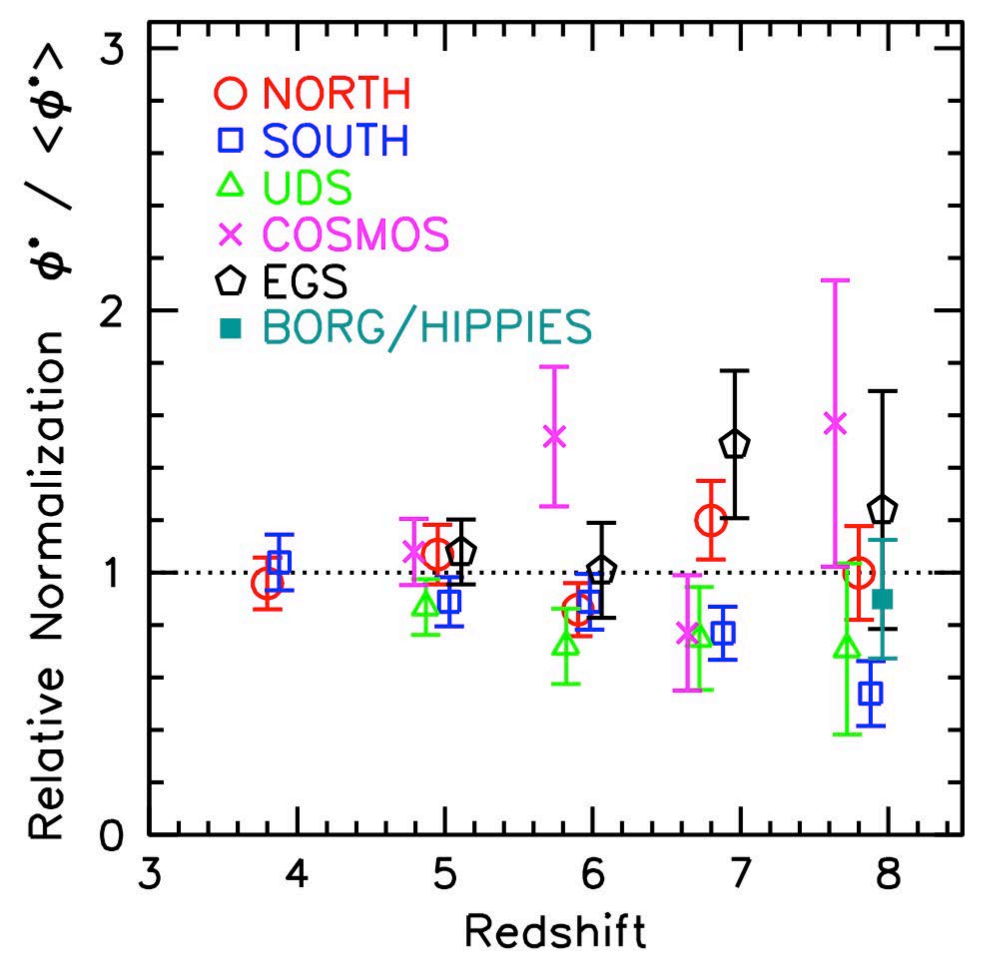
deviations still not very significant

and systematics are often a concern

caution needed in drawing conclusions from minimally significant 1-2σ differences

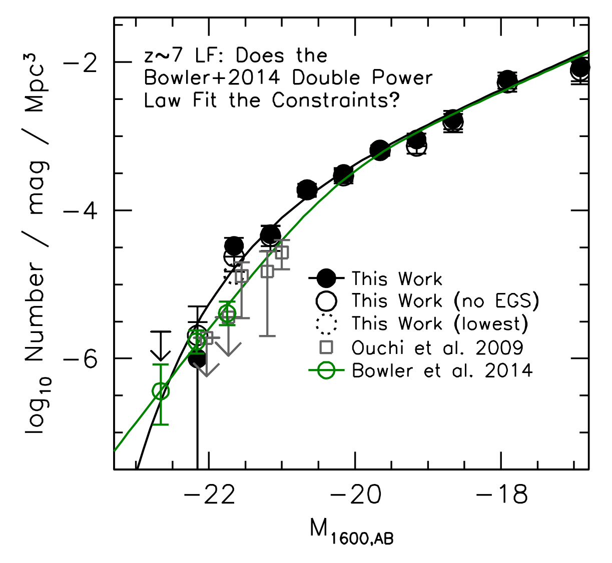
Bouwens et al. 2014; Bowler et al. 2015; Finkelstein et al. 2015; Bouwens et al. 2007

# *LF challenges: (1) substantial field-to-field variations*
# *(2) small numbers at bright end*



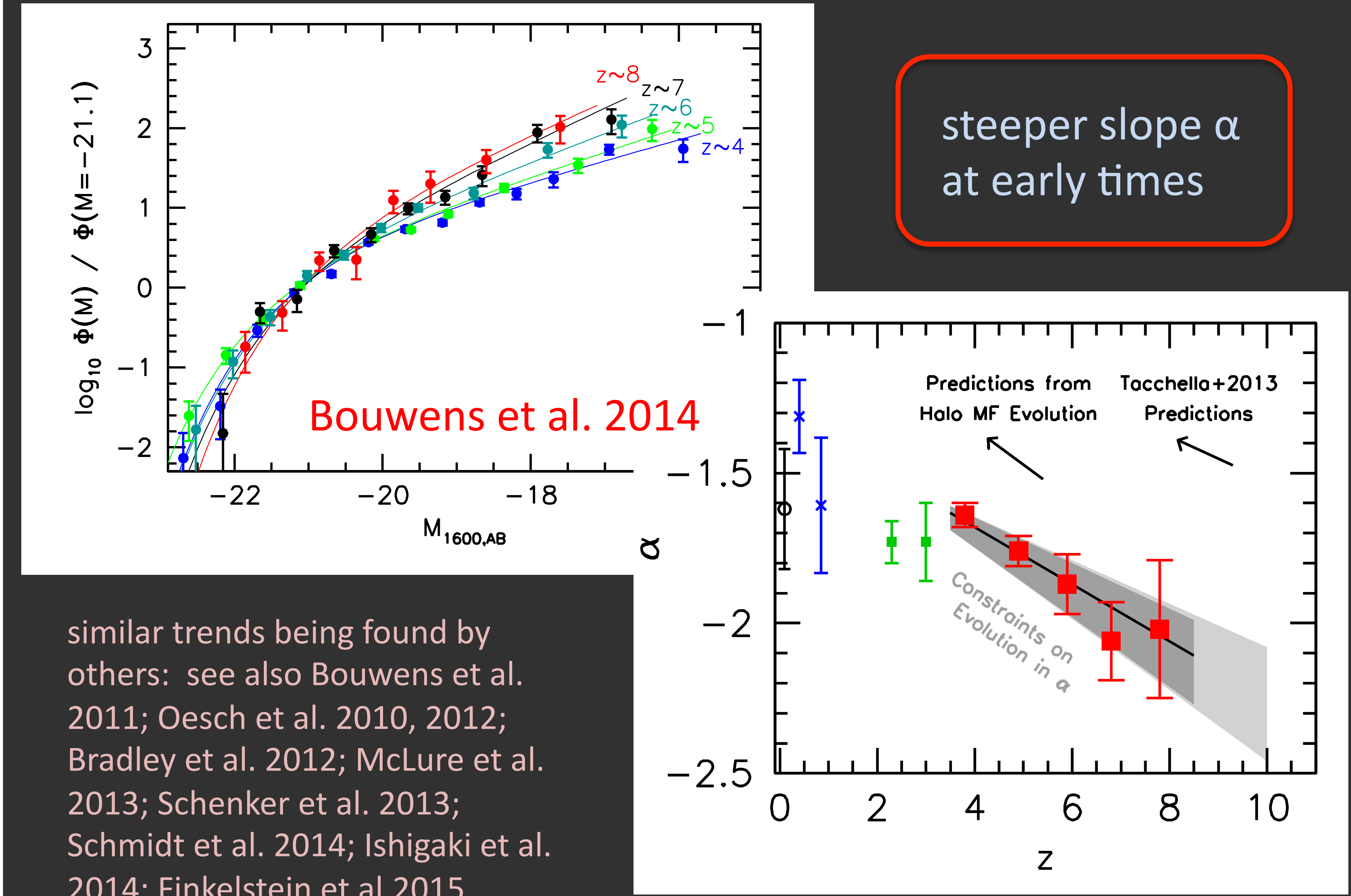
(1) more deep fields

(2) Larger wide fields



Bouwens et al. 2014

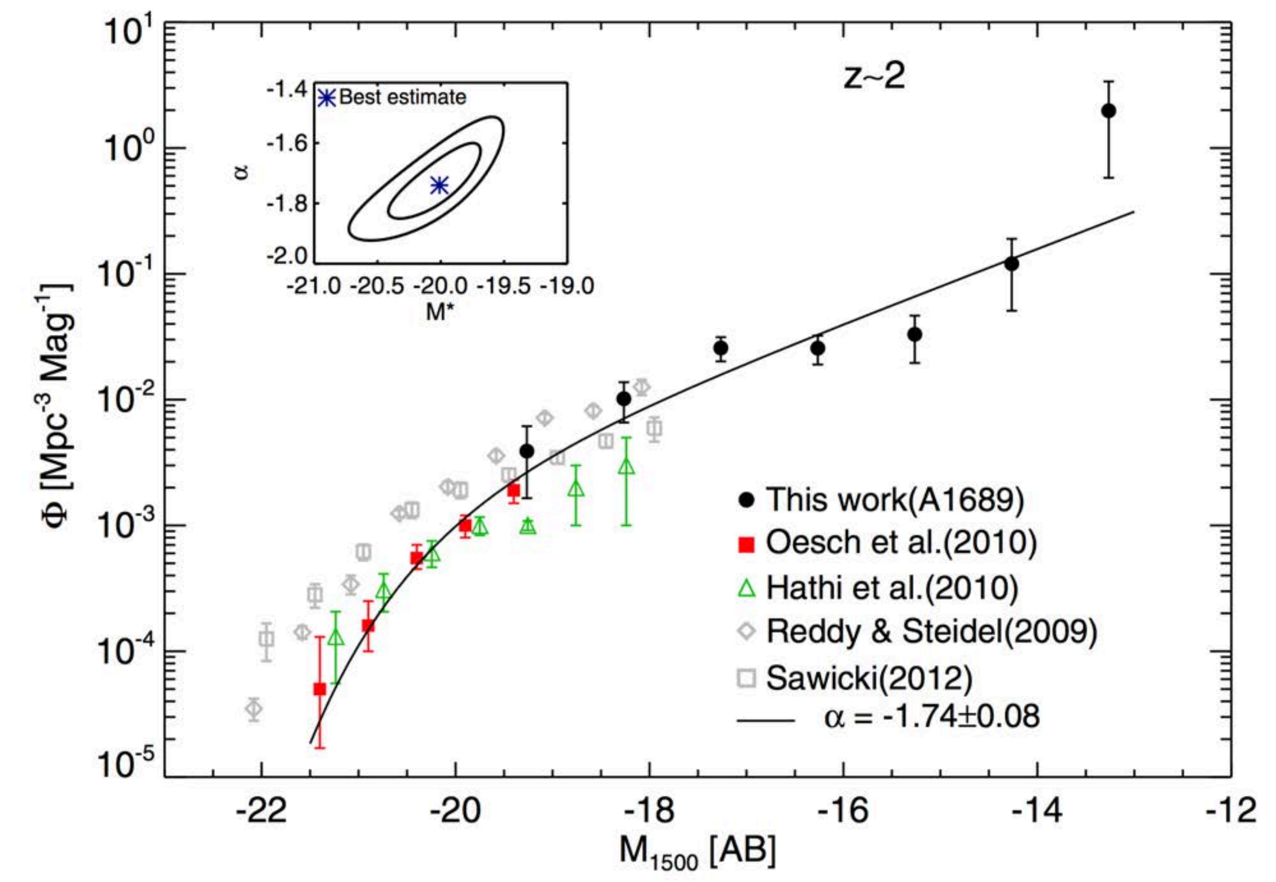
# *LFs: steep faint end slope α of luminosity function*



steeper slope α
at early times

similar trends being found by others: see also Bouwens et al. 2011; Oesch et al. 2010, 2012; Bradley et al. 2012; McLure et al. 2013; Schenker et al. 2013; Schmidt et al. 2014; Ishigaki et al. 2014; Finkelstein et al.2015

# *LFs: steep faint end slope α of luminosity function*



A1689 lensed galaxies: LF at z~2

similar for FF clusters per Anahita's talk

indicative of the existence of very faint galaxies at early times

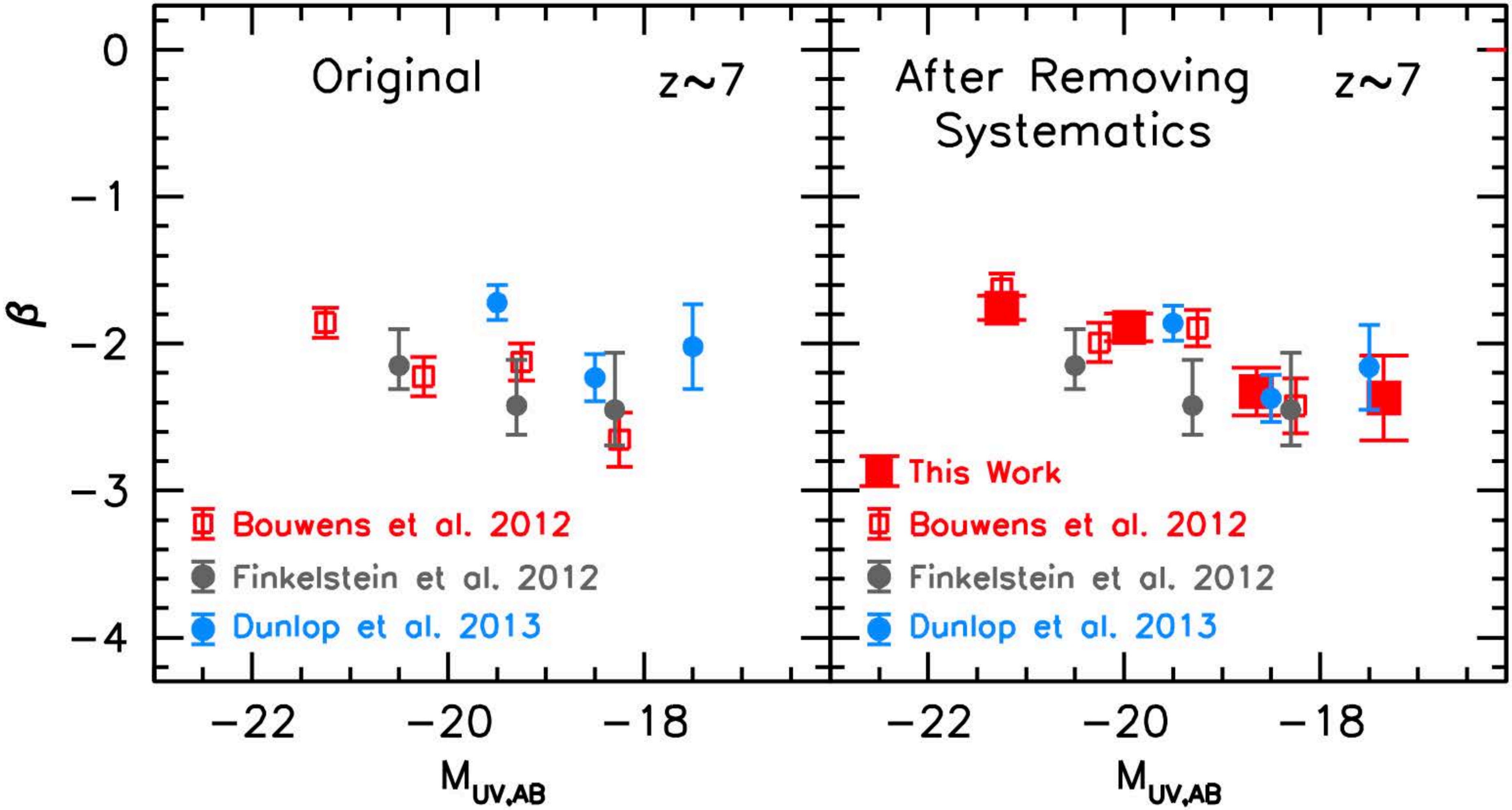
steep slope α – important for reionization

*cf.* Anahita's talk

Alavi et al. 2014

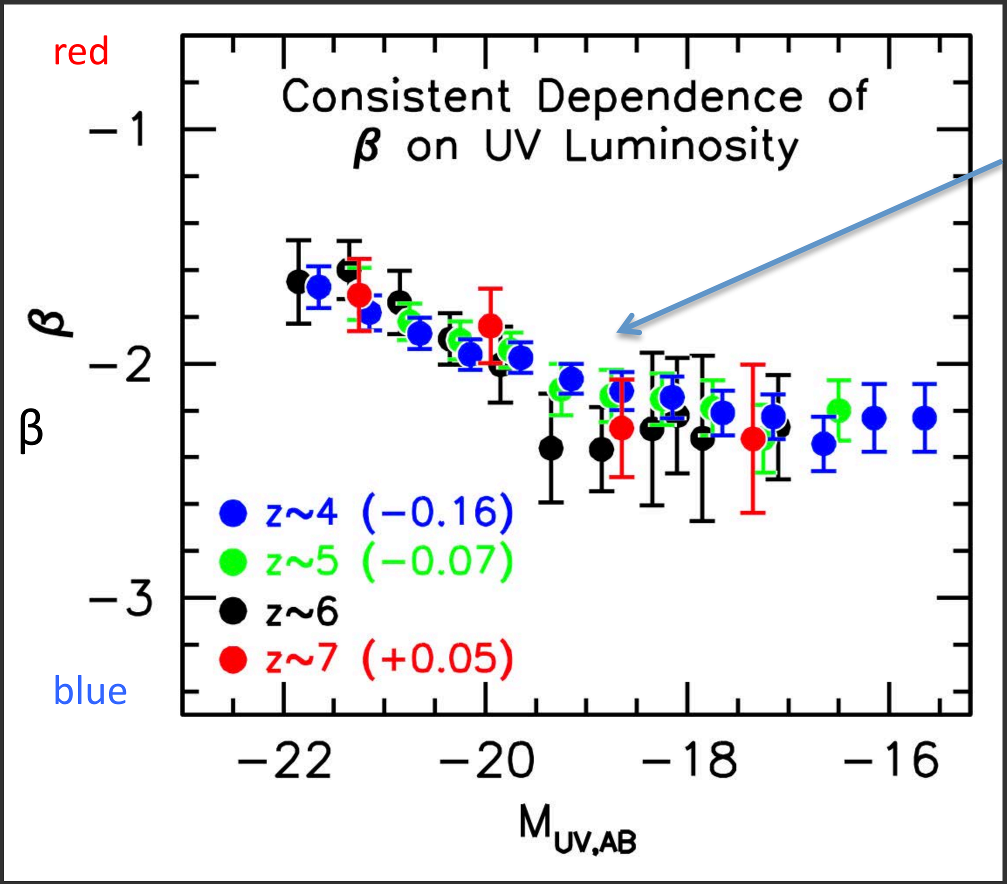
# *UV colors – beta* β

# *all beta measurements have been subject to systematics*



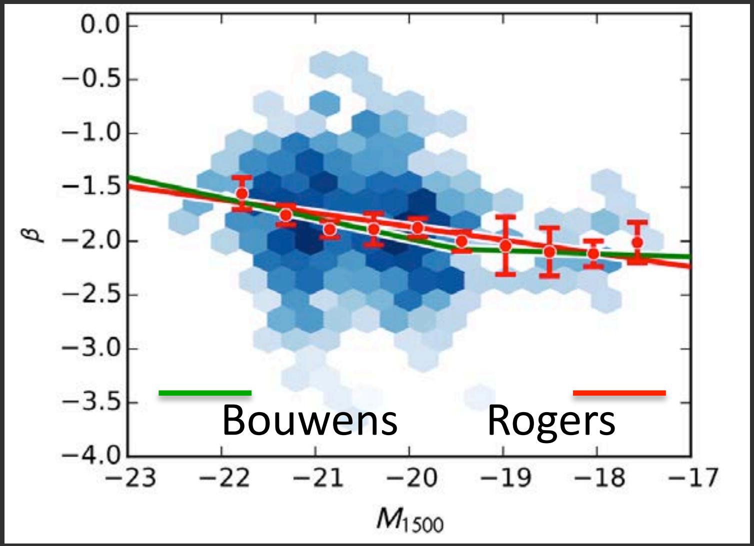
Bouwens, Illingworth, Oesch et al 2013

# z~4-7 galaxies get bluer at lower luminosity



low luminosity galaxies asymptote at M ~ -19

excellent agreement



Bouwens et al 2013

Rogers et al 2013

# *reionization epoch*

# *Planck* 2015 results. XIII. Cosmological parameters

Planck Collaboration: P. A. R. Ade[100], N. Aghanim[70], M. Arnaud[84], M. Ashdown[80,7], J. Aumont[70], C. Baccigalupi[99], A. J. Banday[111,11],
R. B. Barreiro[76], J. G. Bartlett[1,78], N. Bartolo[36,77], E. Battaner[114,115], R. Battye[79], K. Benabed[71,110], A. Benoît[68], A. Benoit-Lévy[27,71,110],
J.-P. Bernard[111,11], M. Bersanelli[39,58], P. Bielewicz[111,11,99], A. Bonaldi[79], L. Bonavera[76], J. R. Bond[10], J. Borrill[16,104], F. R. Bouchet[71,102],
F. Boulanger[70], M. Bucher[1], C. Burigana[57,37,59], R. C. Butler[57], E. Calabrese[107], J.-F. Cardoso[85,1,71], A. Catalano[86,83], A. Challinor[73,80,14],
A. Chamballu[84,18,70], R.-R. Chary[67], H. C. Chiang[31,8], J. Chluba[26,80], P. R. Christensen[94,43], S. Church[106], D. L. Clements[66], S. Colombi[71,110],
L. P. L. Colombo[25,78], C. Combet[86], A. Coulais[83], B. P. Crill[78,95], A. Curto[7,76], F. Cuttaia[57], L. Danese[99], R. D. Davies[79], R. J. Davis[79], P. de
Bernardis[38], A. de Rosa[57], G. de Zotti[54,99], J. Delabrouille[1], F.-X. Désert[63], E. Di Valentino[38], C. Dickinson[79], J. M. Diego[76], K. Dolag[113,91],
H. Dole[70,69], S. Donzelli[58], O. Doré[78,13], M. Douspis[70], A. Ducout[71,66], J. Dunkley[107], X. Dupac[46], G. Efstathiou[80,73] *, F. Elsner[27,71,110],
T. A. Enßlin[91], H. K. Eriksen[74], M. Farhang[10,97], J. Fergusson[14], F. Finelli[57,59], O. Forni[111,11], M. Frailis[56], A. A. Fraisse[31], E. Franceschi[57],
A. Frejsel[94], S. Galeotta[56], S. Galli[71], K. Ganga[1], C. Gauthier[1,90], M. Gerbino[38], T. Ghosh[70], M. Giard[111,11], Y. Giraud-Héraud[1], E. Giusarma[38],
Gjerløw[74], J. González-Nuevo[76,99], K. M. Górski[78,117], S. Gratton[80,73], A. Gregorio[40,56,62], A. Gruppuso[57], J. E. Gudmundsson[31],
[109,108], F. K. Hansen[74], D. Hanson[92,78,10], D. L. Harrison[73,80], G. Helou[13], S. Henrot-Versillé[81], C. Hernández-Monteagudo[15,91],
R. Hildebrandt[78,13], E. Hivon[71,110], M. Hobson[7], W. A. Holmes[78], A. Hornstrup[19], W. Hovest[91], Z. Huang[10],
[70], A. H. Jaffe[66], T. R. Jaffe[111,11], W. C. Jones[31], M. Juvela[30], E. Keihänen[30], R. Keskitalo[16], T. S. Kisner[88],
[20,70,3], H. Kurki-Suonio[30,52], G. Lagache[5,70], A. Lähteenmäki[2,52], J.-M. Lamarre[83], A. Lasenby[7,80],
[46], J. Lesgourgues[109,98,82], F. Levrier[83], A. Lewis[28], M. Liguori[36,77], P. B. Lilje[74],
M. Linden-V Macías-Pérez[86], G. Maggio[56], N. Mandolesi[57,37], A. Mangilli[70,81], A. Marchini[60],
P. G. Martin[10], M. S. Matarrese[36,77,49], P. Mazzotta[41], P. McGehee[67], P. R. Meinhold[34],
A. Melchiorri[38,60], J.-B. Melin M. Millea[33], S. Mitra[65,78], M.-A. Miville-Deschênes[70,10],
A. Moneti[71], L. Montier[111,11], G. Morgante Murphy[93], P. Naselsky[94,43], F. Nati[31], P. Natoli[37,4,57],
C. B. Netterfield[22], H. U. Nørgaard-Nielsen[19], F. No rrow[19], F. Paci[99], L. Pagano[38,60], F. Pajot[70],
R. Paladini[67], D. Paoletti[57,59], B. Partridge[51], F. Pasian L. Perotto[86], F. Perrotta[99],
V. Pettorino[50], F. Piacentini[38], M. Piat[1], E. Pierpaoli[25], D. Pietrobo
G. W. Pratt[84], G. Prézeau[13,78], S. Prunet[71,110], J.-L. Puget[70], J. P. Rac
M. Remazeilles[79,70,1], C. Renault[86], A. Renzi[42,61], I. Ristorcelli[111,11], G. Roc
d'Orfeuil[81], M. Rowan-Robinson[66], J. A. Rubiño-Martín[75,44], B. Rusholme[67],
M. Savelainen[30,52], G. Savini[96], D. Scott[24], M. D. Seiffert[78,13], P. Serra[70], E. P
R. Stompor[1], R. Sudiwala[100], R. Sunyaev[91,103], D. Sutton[73,80], A.-S. S
L. Toffolatti[21,76,57], M. Tomasi[39,58], M. Tristram[81], T. Trombetti[57], M. Tuc
J. Valiviita[30,52], B. Van Tent[87], P. Vielva[76], F. Villa[57], L. A. Wade[78], B. D.
A. Wilkinson[79], D. Yvon[18], A. Zac

reionization optical depth of $\tau = 0.066 \pm 0.016$, corresponding to a reionization redshift of $z_{\rm re} = 8.8^{+1.7}_{-1.4}$.

February 5 2015

### ABSTRACT

This paper presents *Planck* observations of temperature and polarization anisotropies of the cosmic mi-
crowave background (CMB) reement with the 2013 analysis of the *Planck* nominal-mission temperature
data, but with increased precision. ectra are consistent with the standard spatially-flat six-parameter
ΛCDM cosmology with a power-law spectru "base ΛCDM" in this paper). From the *Planck* tempera-
ture data combined with *Planck* lensing, for this cosm 7.8 ± 0.9) km s$^{-1}$Mpc$^{-1}$, a matter density parameter
$\Omega_{\rm m} = 0.308 \pm 0.012$, and a tilted scalar spectral index with $n_{\rm s}$ analysis. (In this abstract we quote 68 %
confidence limits on measured parameters and 95 % upper limits on lts of polarization measurements
with the Low Frequency Instrument at large angular scales. Combined with the se measurements give a
reionization optical depth of $\tau = 0.066 \pm 0.016$, corresponding to a reionization redsh tent with those
from WMAP polarization measurements cleaned for dust emission using 353 GHz polarization nt. We
find no evidence for any departure from base ΛCDM in the neutrino sector of the theory. For example,
astrophysical data we find $N_{\rm eff} = 3.15 \pm 0.23$ for the effective number of relativistic degrees of freedom, consiste
the Standard Model of particle physics. The sum of neutrino masses is constrained to $\sum m_\nu < 0.23$ eV. The spatial curv
found to be very close to zero with $|\Omega_K| < 0.005$. Adding a tensor component as a single-parameter extension to base ΛCDM w r
limit on the tensor-to-scalar ratio of $r_{0.002} < 0.11$, consistent with the *Planck* 2013 results and consistent with the *B*-mode polarization cons ts
from a joint analysis of BICEP2, *Keck Array*, and *Planck* (BKP) data. Adding the BKP *B*-mode data to our analysis leads to a tighter constraint of $r_{0.002} < 0.09$ and disfavours inflationary models with a $V(\phi) \propto \phi^2$ potential. The addition of *Planck* polarization data leads to strong constraints on deviations from a purely adiabatic spectrum of fluctuations. We find no evidence for any contribution from isocurvature perturbations or from cosmic defects. Combining *Planck* data with other astrophysical data, including Type Ia supernovae, the equation of state of dark energy is constrained to $w = -1.006 \pm 0.045$, consistent with the expected value for a cosmological constant. The standard big bang nucleosynthesis predictions for the helium and deuterium abundances for the best-fit *Planck* base ΛCDM cosmology are in excellent agreement with observations. We also analyse constraints on annihilating dark matter and on possible deviations from the standard recombination history. In both cases, we find no evidence for new physics. The *Planck* results for base ΛCDM are in good agreement with baryon acoustic oscillation data and with the JLA sample of Type Ia supernovae. However, as in the 2013 analysis, the amplitude of the fluctuation spectrum is found to be higher than inferred from some analyses of rich cluster counts and weak gravitational lensing. We show that these tensions cannot easily be resolved with simple modifications of the base ΛCDM cosmology. Apart from these tensions, the base ΛCDM cosmology provides an excellent description of the *Planck* CMB observations and many other astrophysical data sets.

Planck 2015

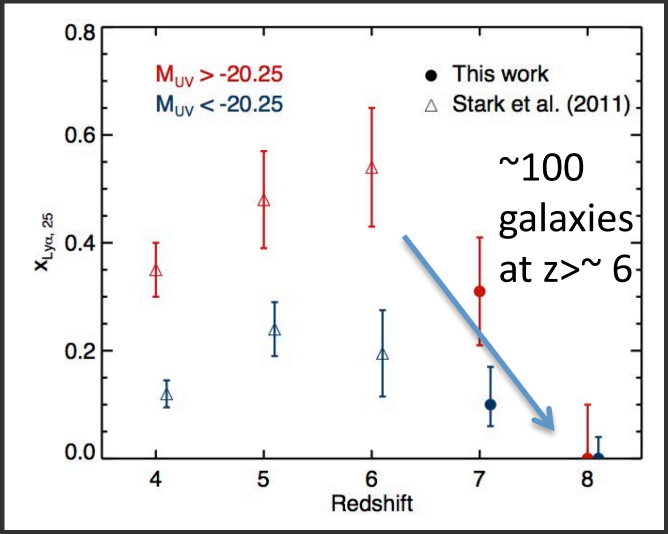
remarkable mission

# *increasing neutral fraction at z>6*

reionization "largely complete" at z~6 (950 Myr)

Robertson et al 2015

fraction of galaxies with Lyα EW > 25 Å



~100 galaxies at z>~ 6

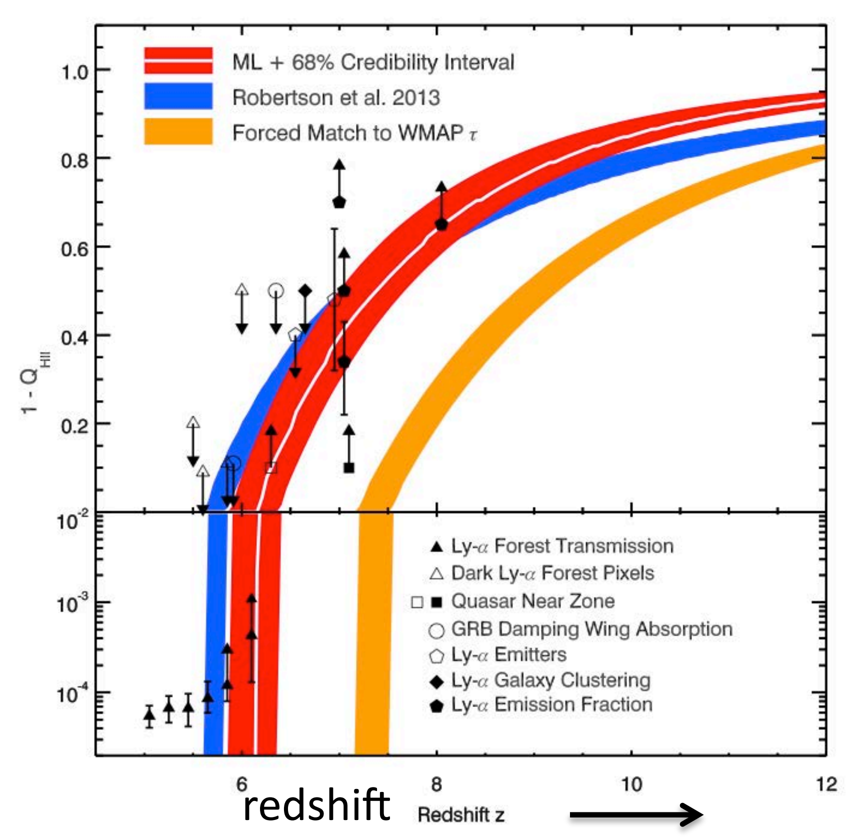
Universe increasingly neutral at z>6

Schenker et al 2015

*cf.* Vithal Tilvi talk also

contributions from Pentericci et al 2011, 2014; Tilvi et al 2014; Treu et al 2013; Stark et al 2010; Fontana et al 2010; Caruana et al 2012, 2014; Schenker et al. 2012; Ono et al 2012

neutral fraction

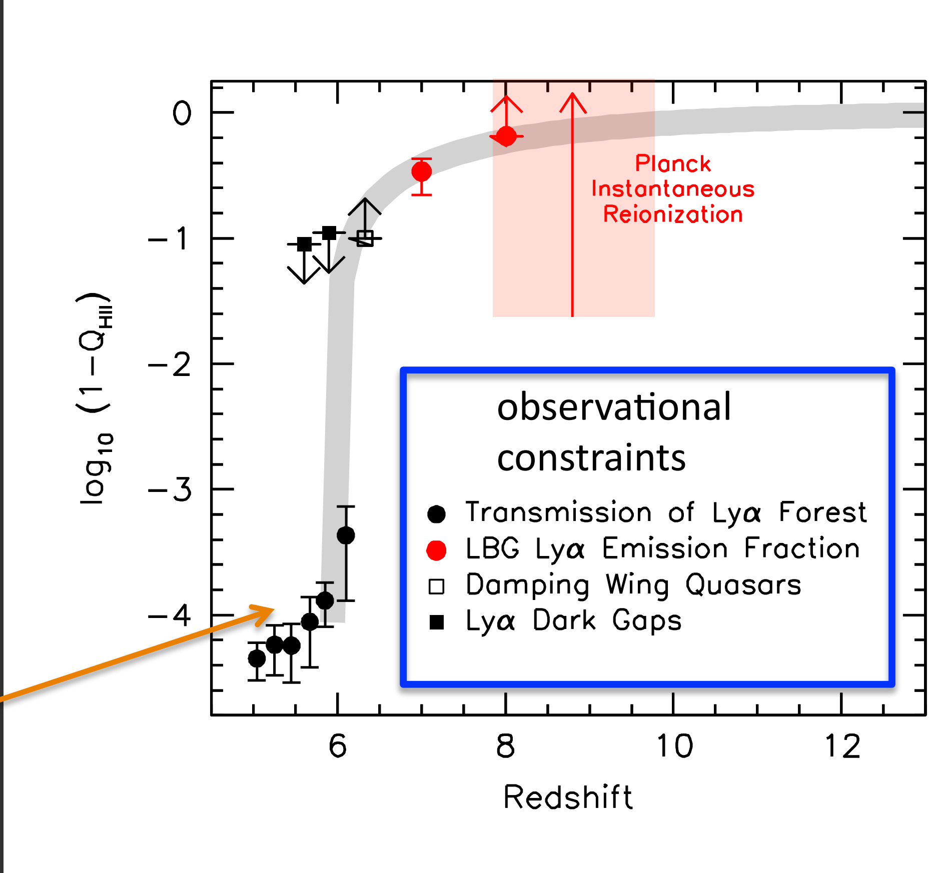


redshift

# *increasing neutral fraction at z>6*

Bouwens et al 2015

neutral
fraction



reionization “largely complete” at z~6 (950 Myr)

reionization epoch

Bouwens et al 2015

# *the ionizing background $\dot{N}_{ion}(z)$*

(1) determined the empirical evolution of the ionizing background at z>6 (when reionization essentially "ends")

(2) simple approach looking at trends in the ionizing background, $\dot{N}_{ion}(z)$ $s^{-1}$ $Mpc^{-3}$, consistent with quasar, Lyα and Planck constraints

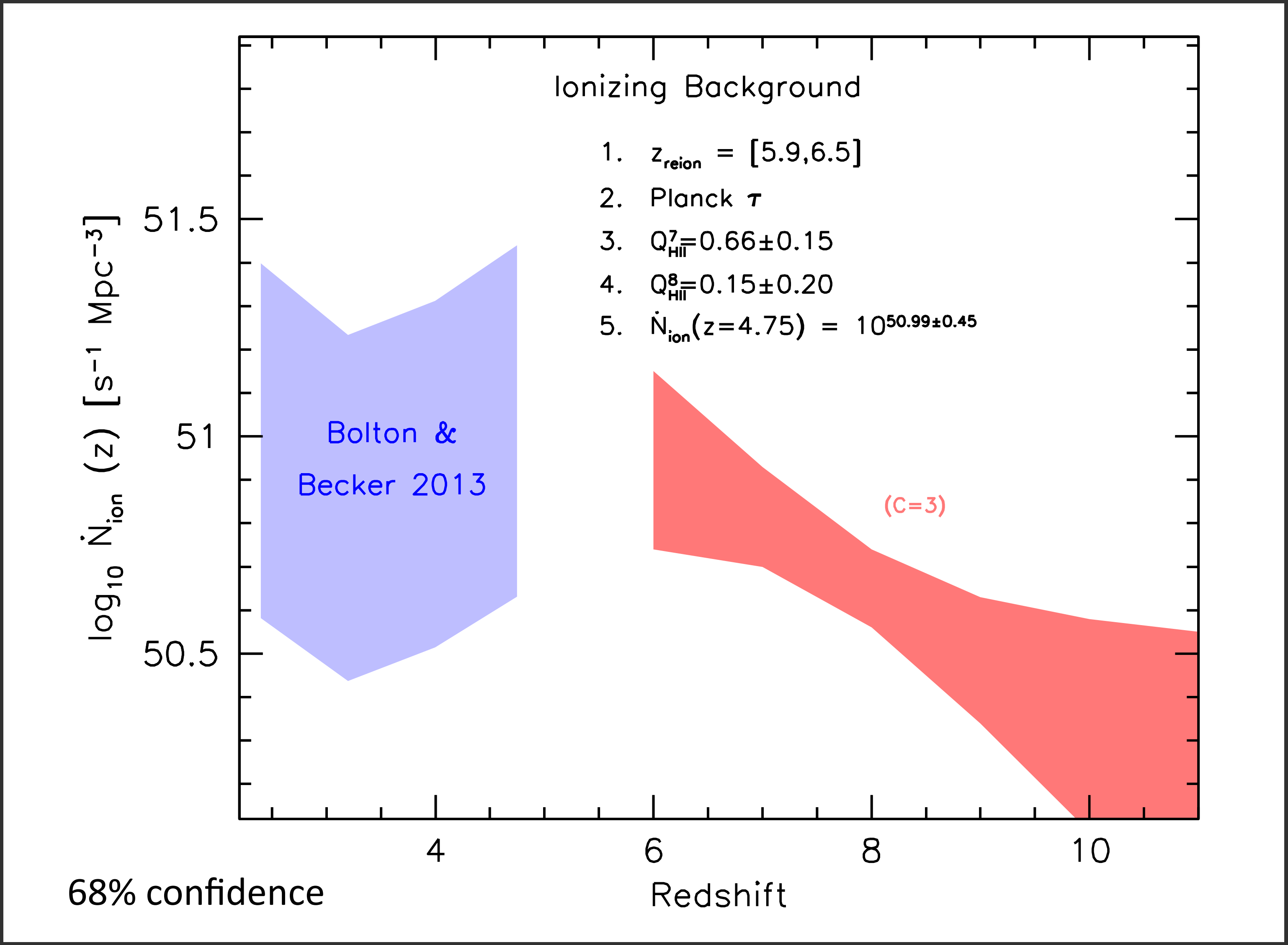
(3) this provides model-independent constraints that any source of the ionizing background must match

(4) then compared to trends in UV luminosity density for galaxies and for quasars/AGN

(5) similar trend seen when ionizing background evolution compared to that for galaxies with plausible normalization

# the ionizing background $\dot{N}_{ion}(z)$

## Planck τ and all the constraints

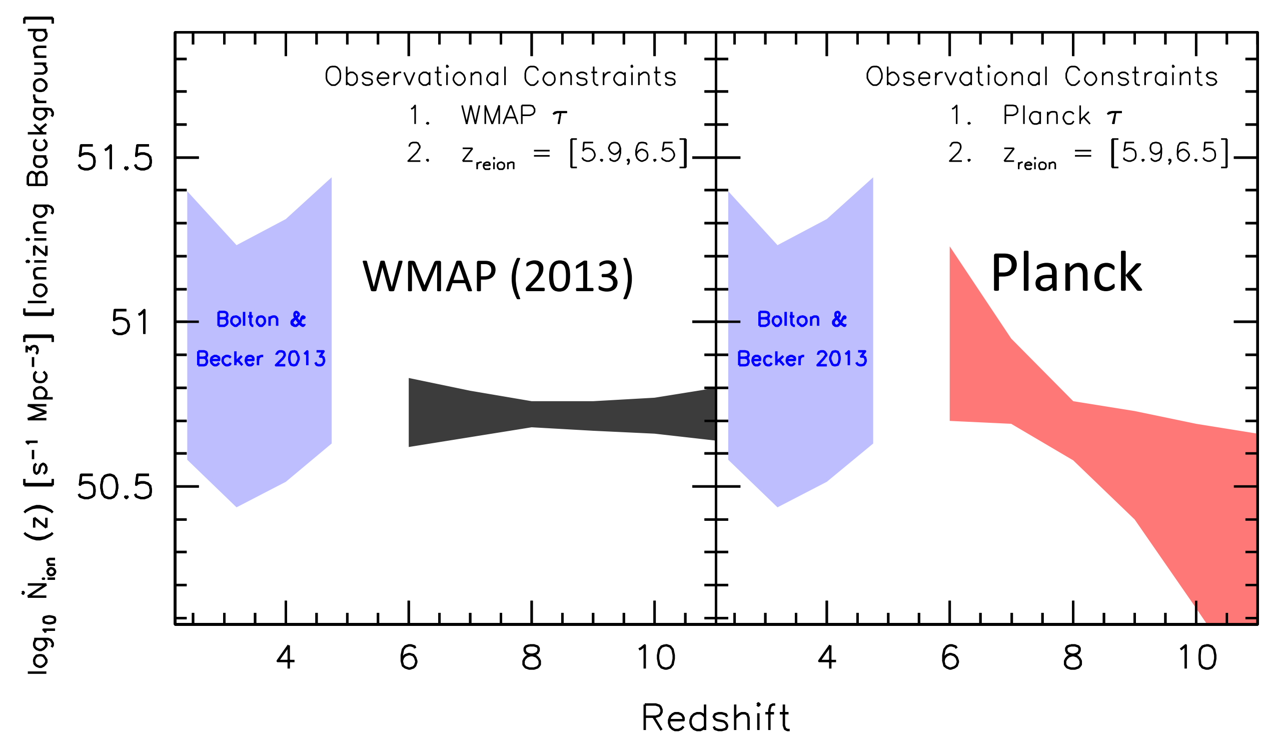


# *the ionizing background $\dot{N}_{ion}(z)$*

contrast of the ionizing background $\dot{N}_{ion}(z)$ for WMAP (2013) and Planck with constraints:

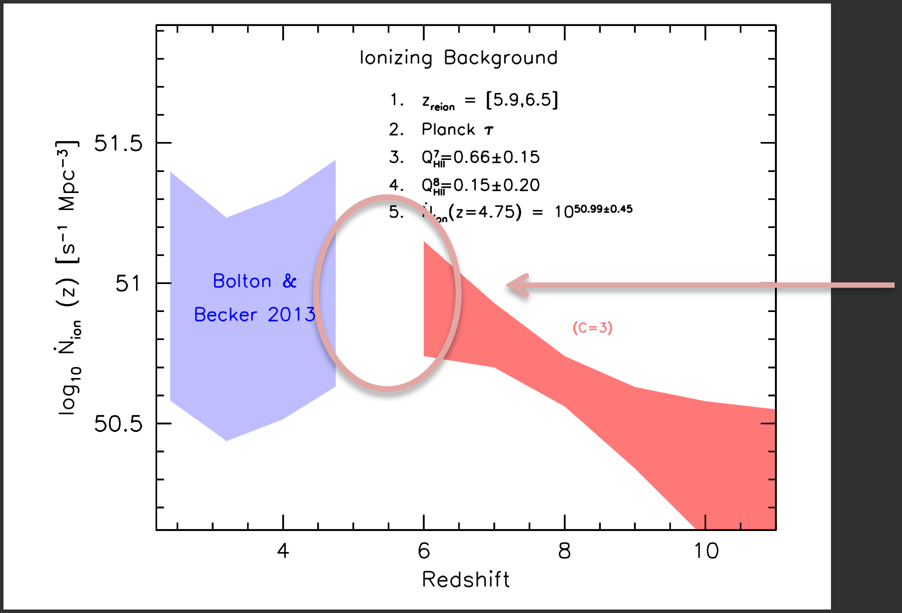
(1) reionization “largely complete” at z~6

(2) respective Thompson optical depths τ



Bouwens et al 2015

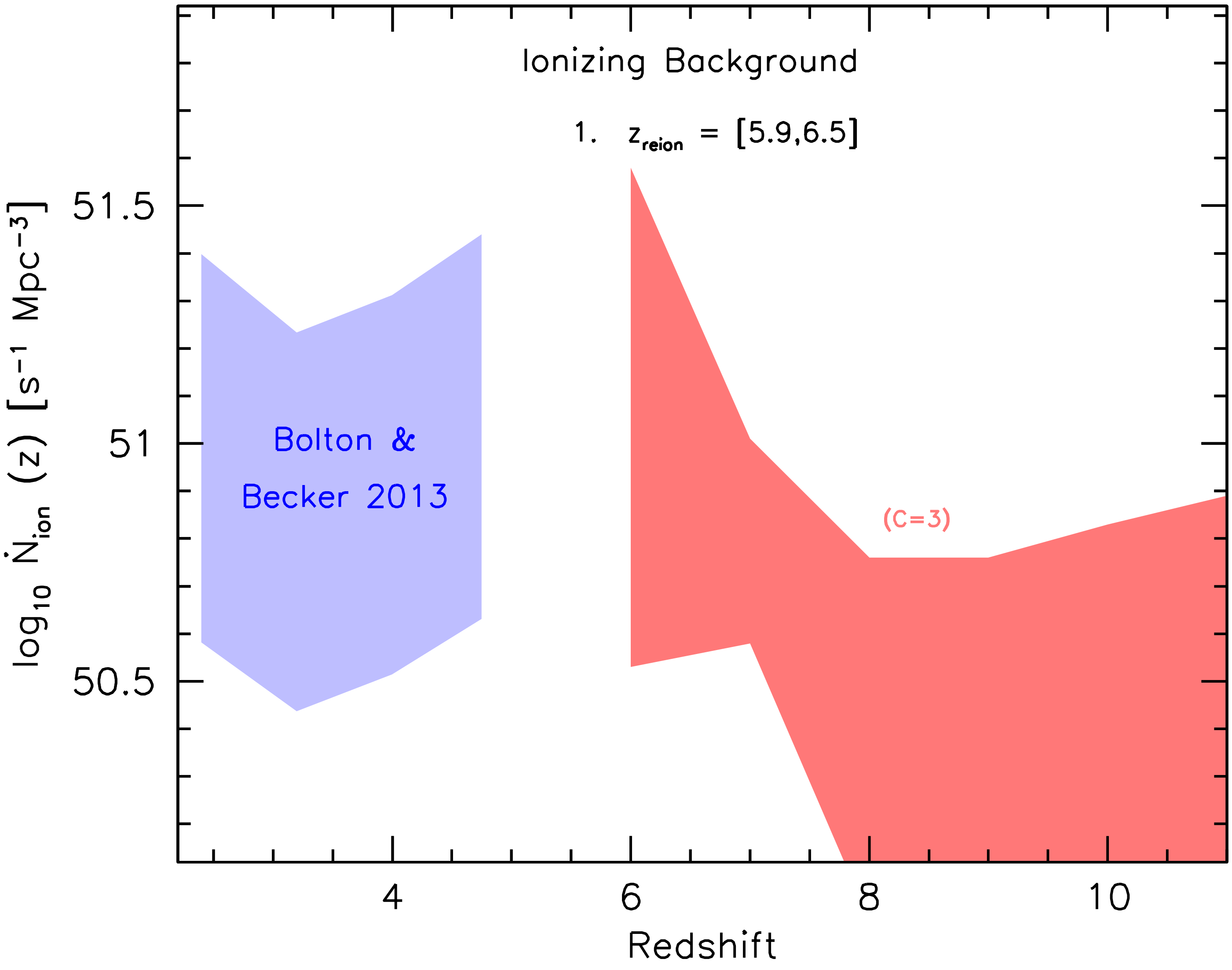
# *sequence showing constraints on the ionizing background $\dot{N}_{ion}(z)$ evolution*



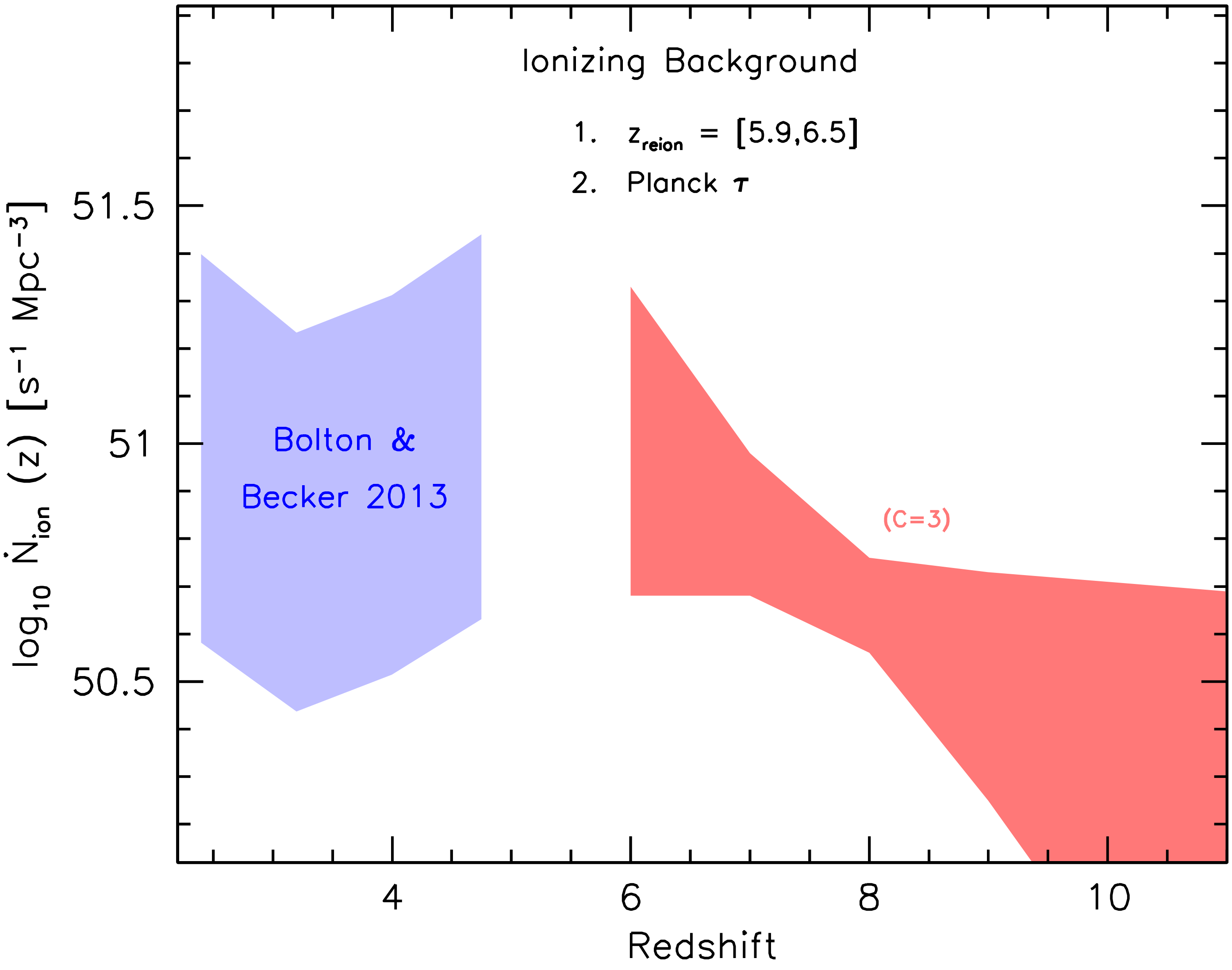
new results at z~5 to z~6 seen in George Becker's talk fill in the "gap"

the following sequence is of the ionizing background $\dot{N}_{ion}(z)$ with the constraints added one at a time

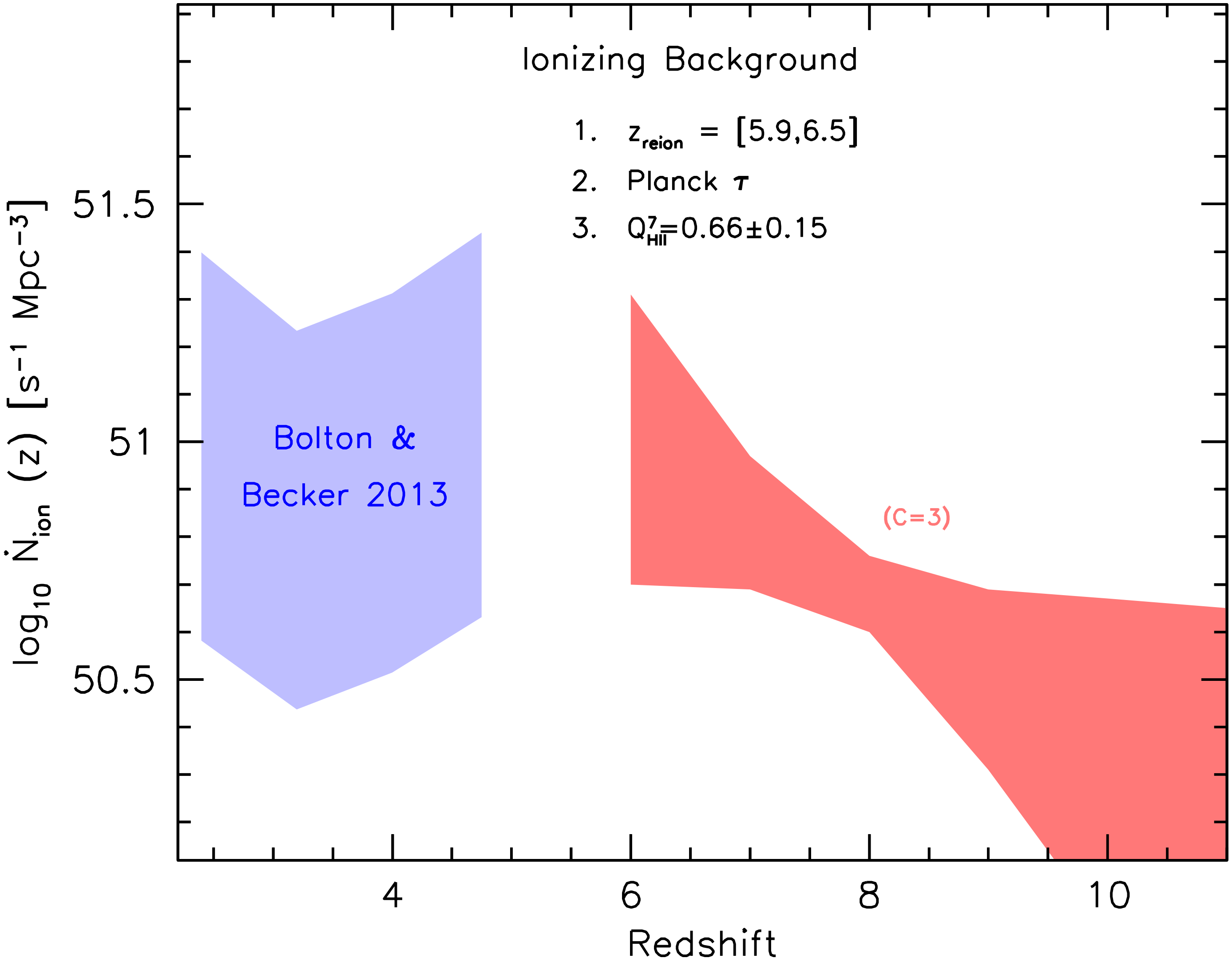
# *the ionizing background as constraints are added*



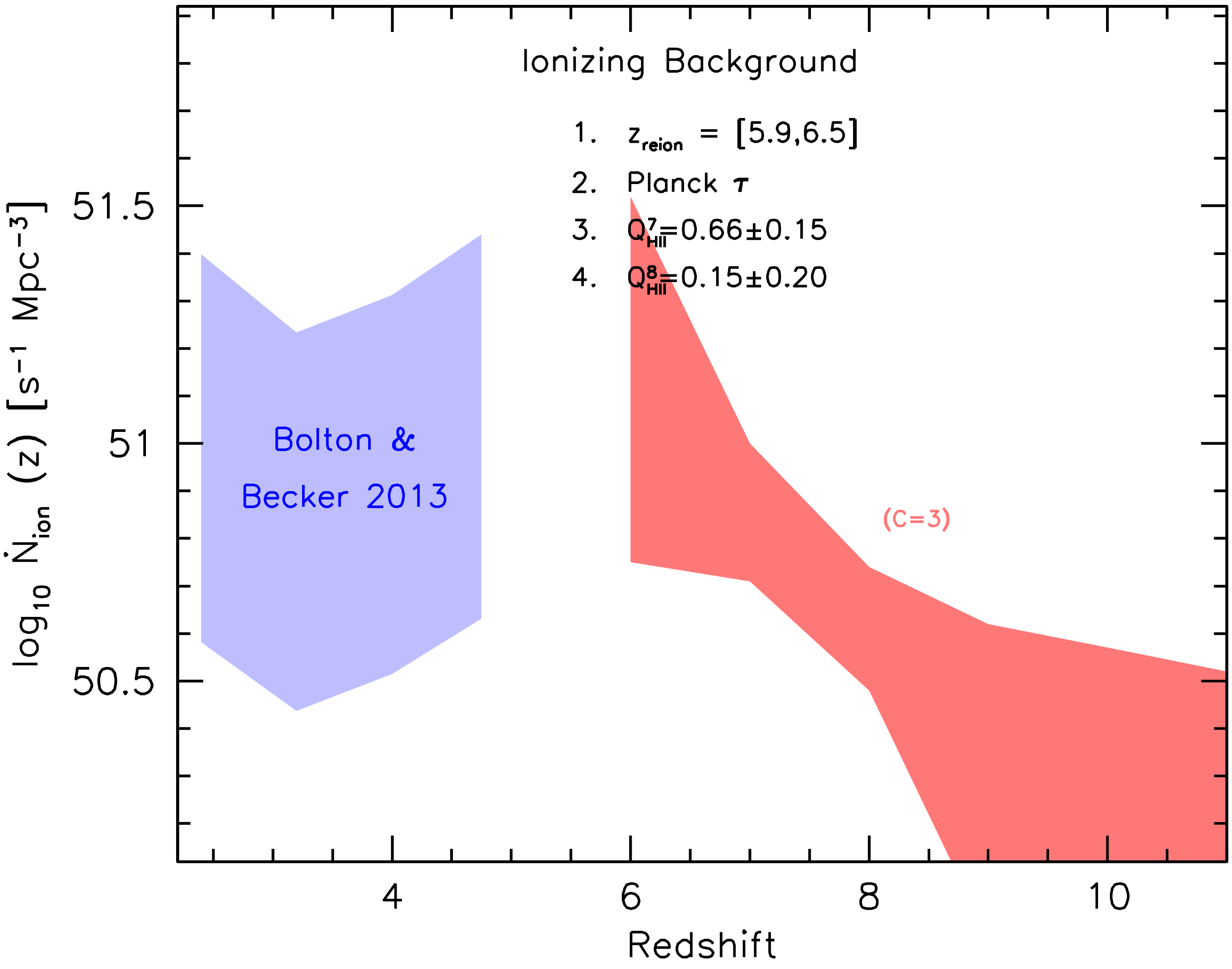
# *the ionizing background as constraints are added*



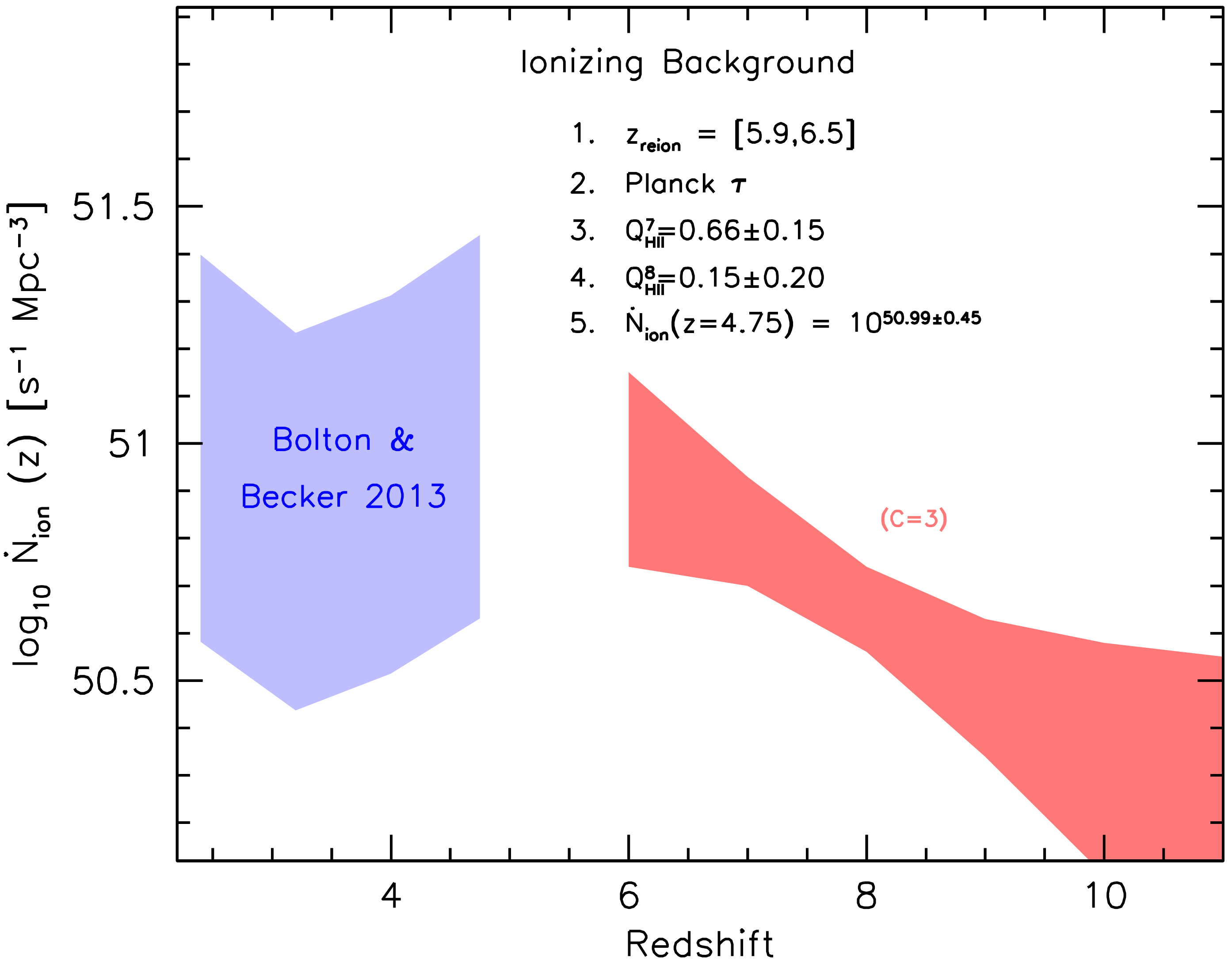
# *the ionizing background as constraints are added*



# *the ionizing background as constraints are added*

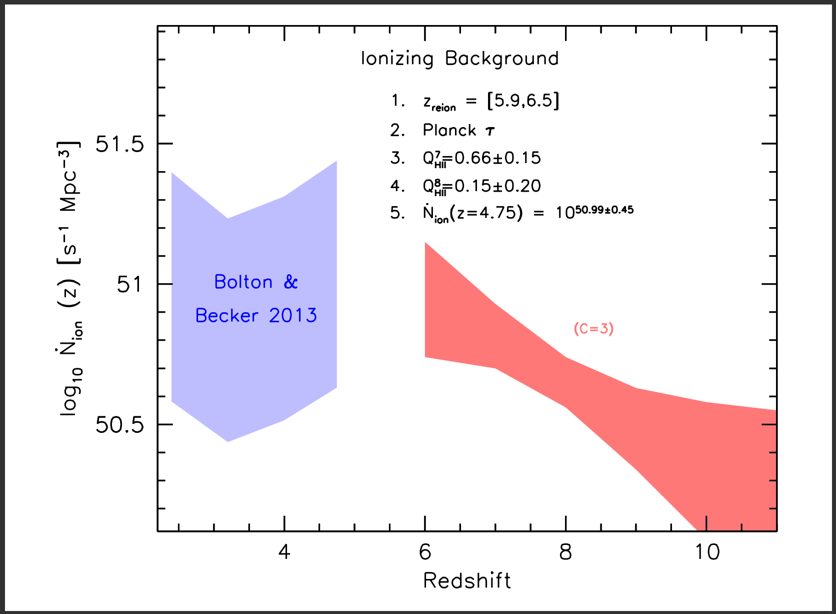


# *the ionizing background as constraints are added*



# *the ionizing background $\dot{N}_{ion}(z)$*

at this point we have the trend in the ionizing background $\dot{N}_{ion}(z)$ independent of what is the source of the ionizing flux

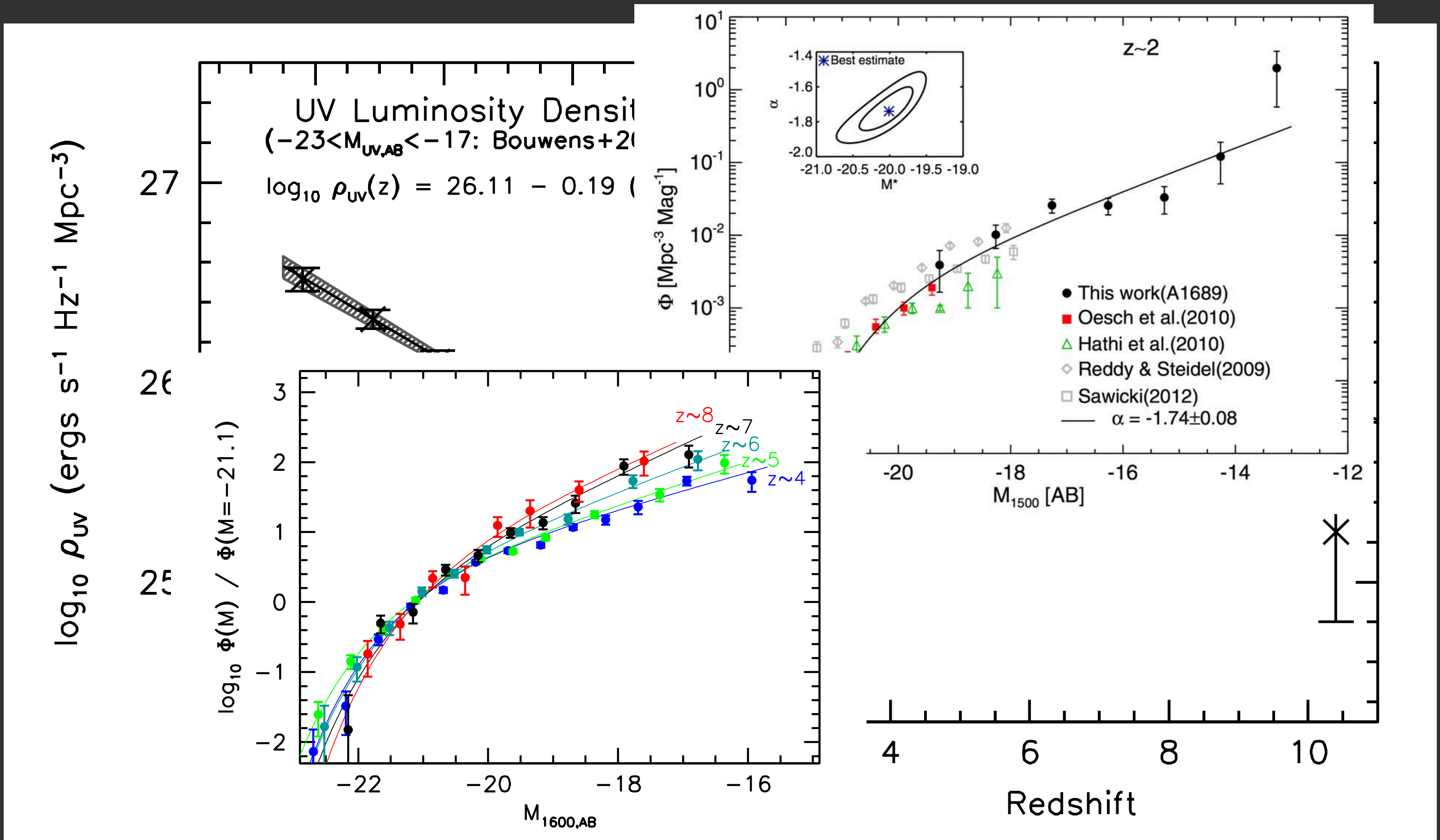


what are the implications if we look at sources?

as one would expect we looked at galaxies as the source

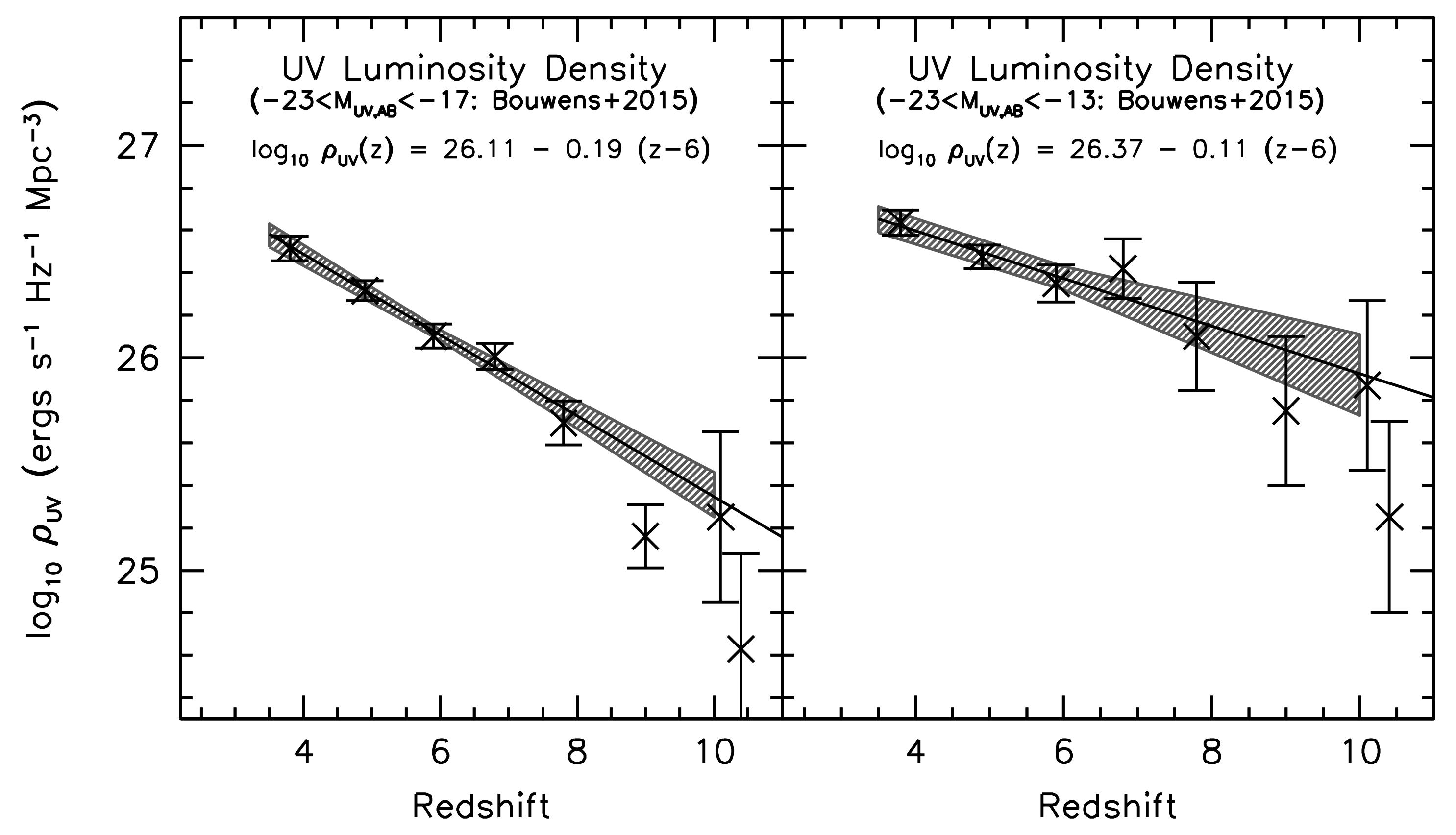
note that we considered quasars/ AGNs and found them lacking

# *derivation of the galaxy UV luminosity density to -13 from the observed -17*



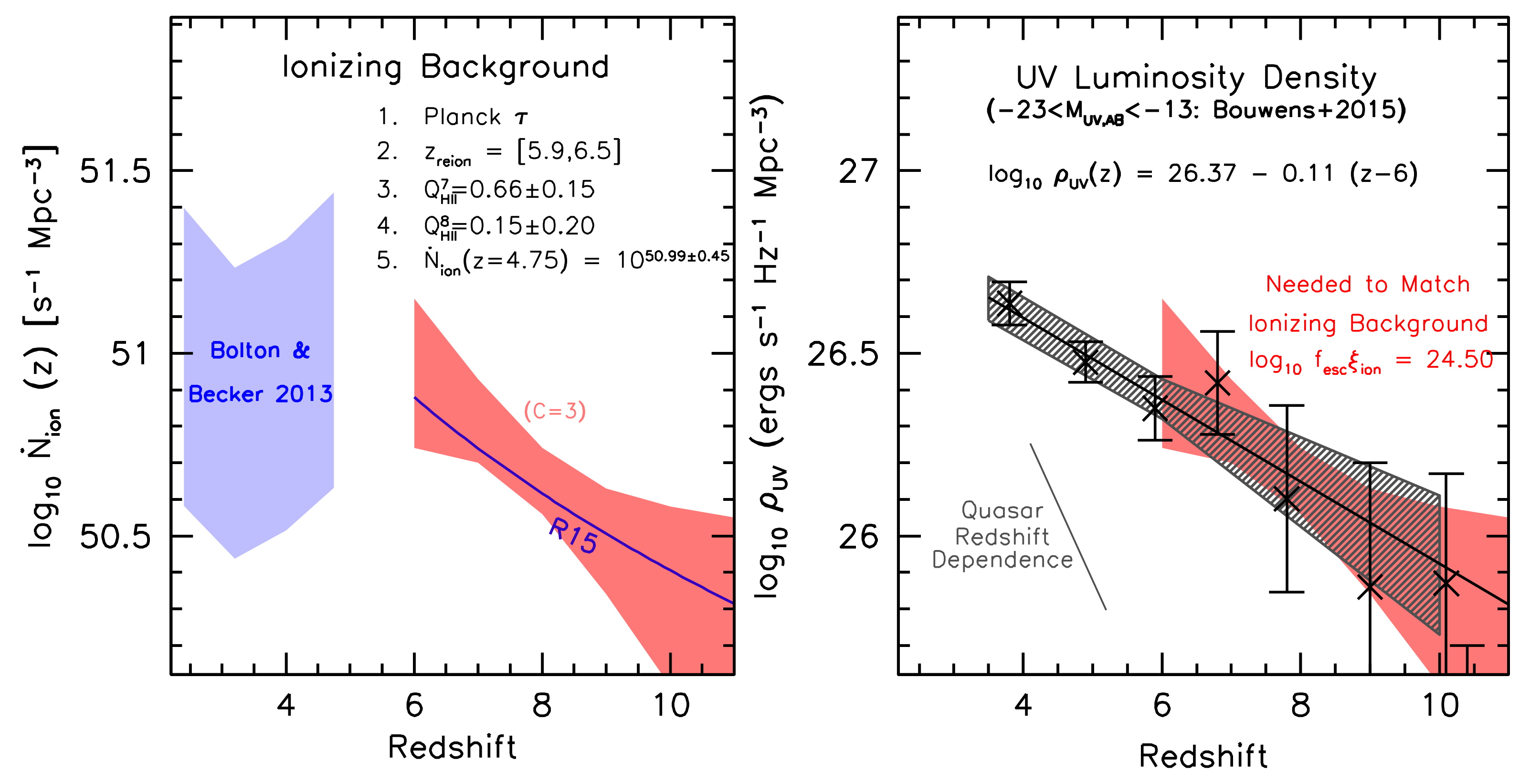
extrapolation necessary from -17 to -13 informed by the Bouwens et al 2014 LFs to -16 and -17, the Alavi et al 2014 results to -14 from the lensing cluster A1689 and simulations

# *derivation of the galaxy UV luminosity density to -13 from the observed -17*



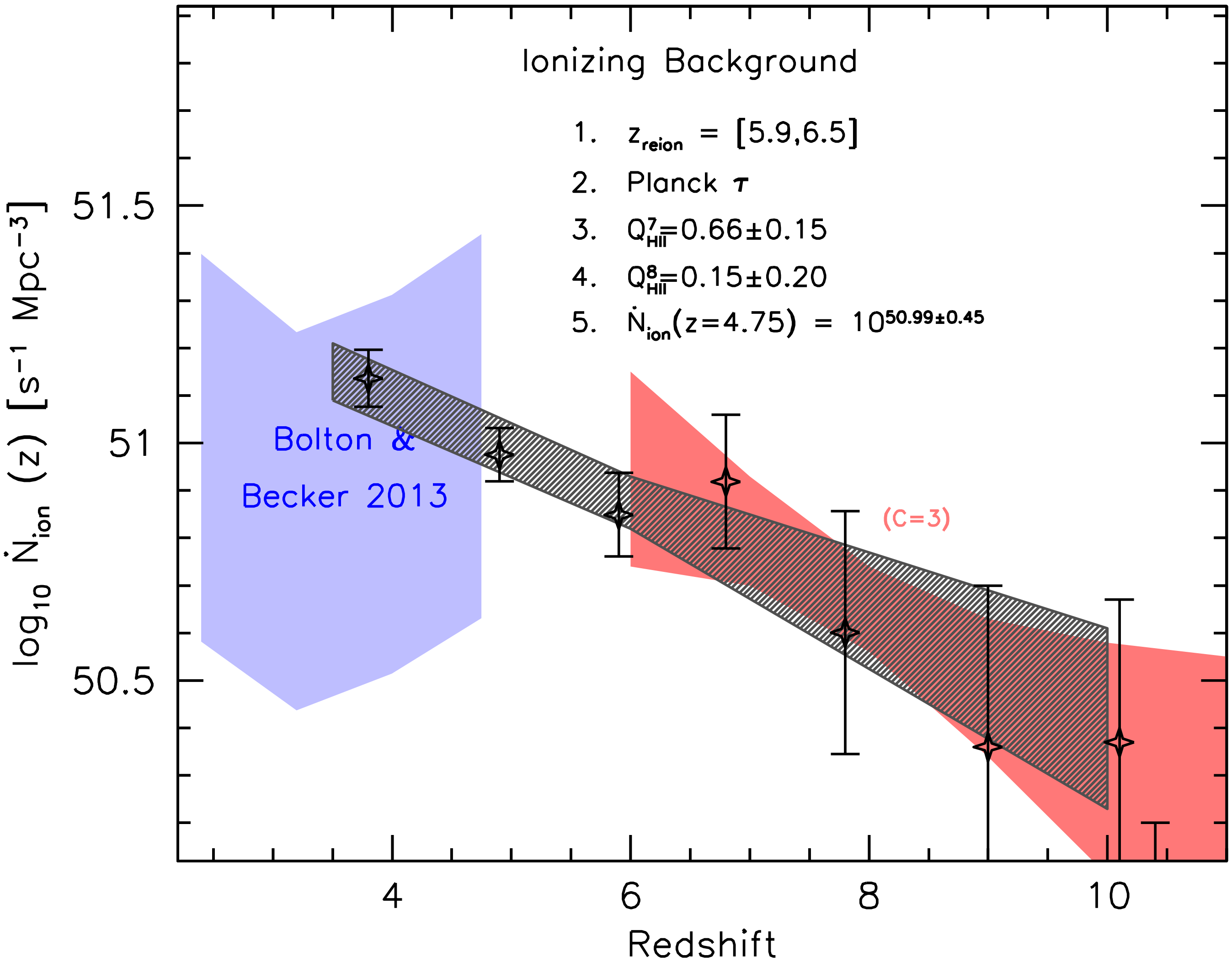
extrapolation necessary from -17 to -13 informed by the Bouwens et al 2014 LFs to -16 and -17, the Alavi et al 2014 results to -14 from the lensing cluster A1689 and simulations

# *similar trends in the ionizing background and the galaxy UV luminosity density with plausible normalization*



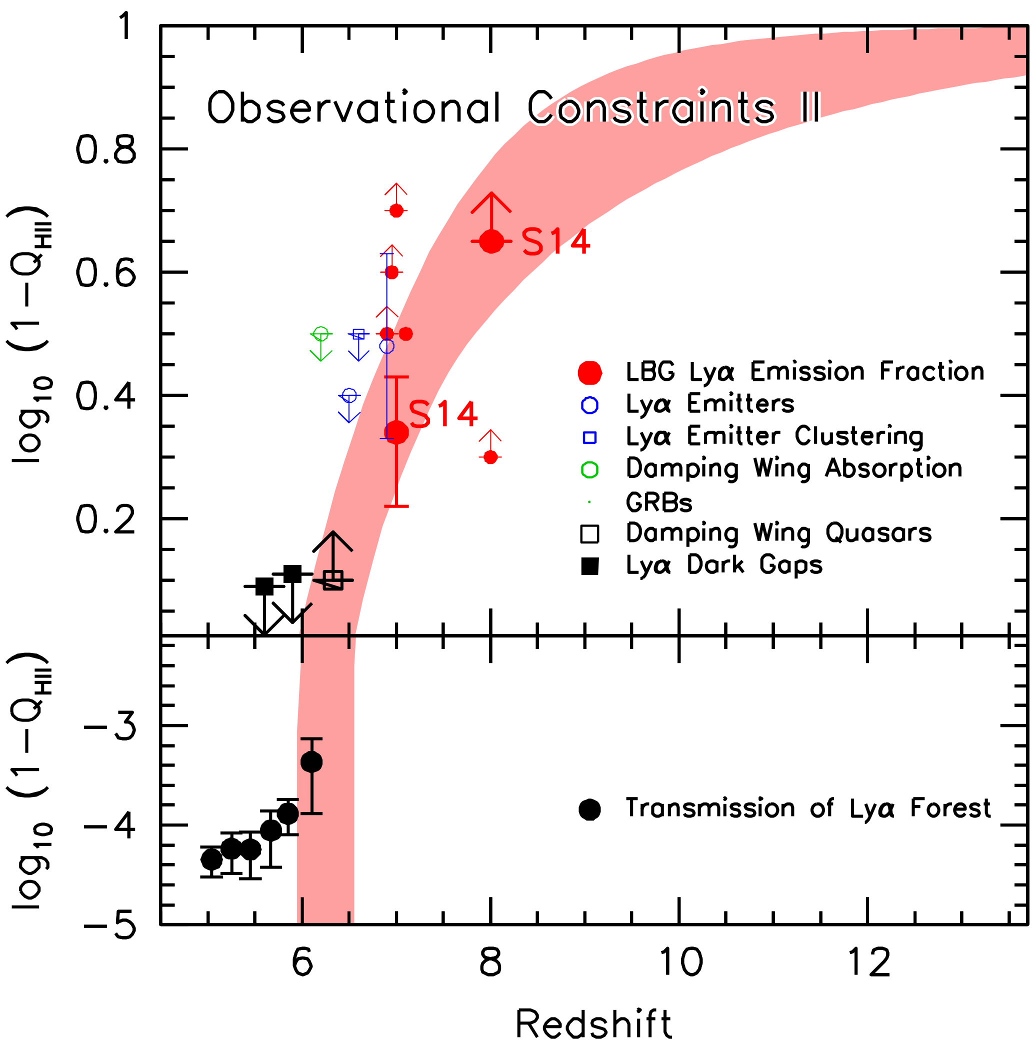
normalization for galaxies is product of the Lyman-continuum photon production efficiency $\xi_{ion}$ and the escape fraction $f_{esc}$
(the normalization is consistent with $\xi_{ion}$ & $f_{esc}$ routinely used values)

# *the ionizing background as constraints are added*

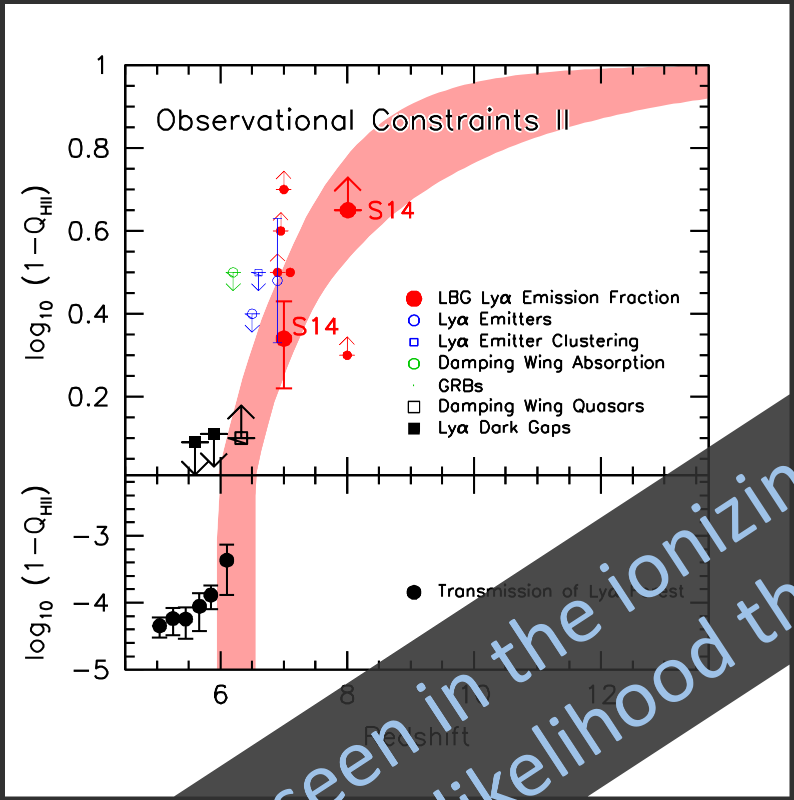


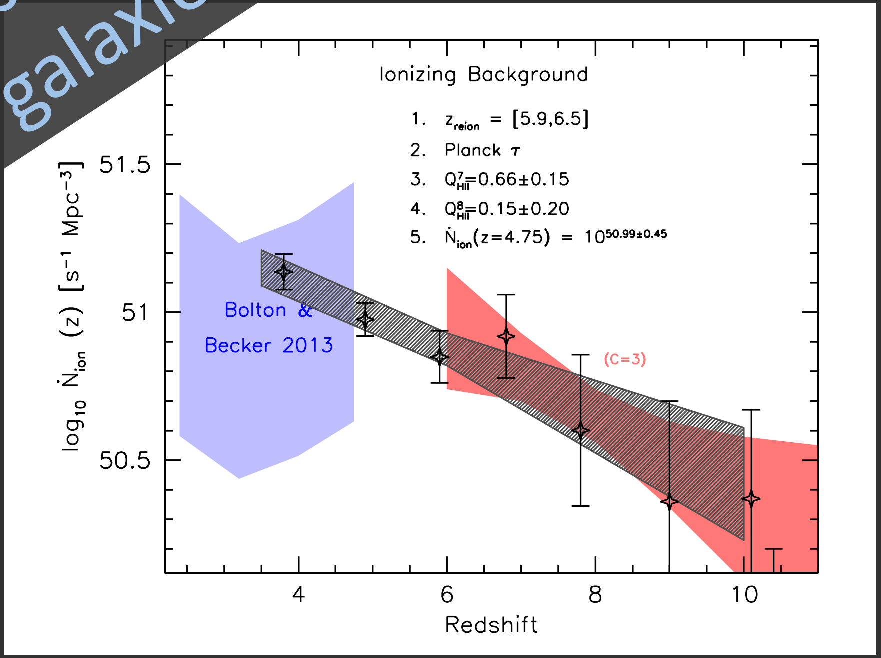
overlay with galaxy trend

# *comparison of the observational constraints with the ionizing background model results*



# *comparison of the observational constraints with the ionizing background model results*





the trend seen in the ionizing background gives added weight to the likelihood that galaxies reionized the universe

# *what's next?*

# *what's next?*

*before (and after) JWST: lots more to do with Hubble, Spitzer and on the ground!*

# *what’s next?*

Jane’s talk on JWST

JWST – model at “South by Southwest”

# what's next?

*future meeting in another fun place*

*The Reionization Epoch:*
*New Insights and Future Prospects*

*Early March 2016*

*Aspen Center for Physics*
*Winter Conference Series*