Galaxy-Galaxy Lensing of LBGs at 4<z<8 in CANDELS and the XDF

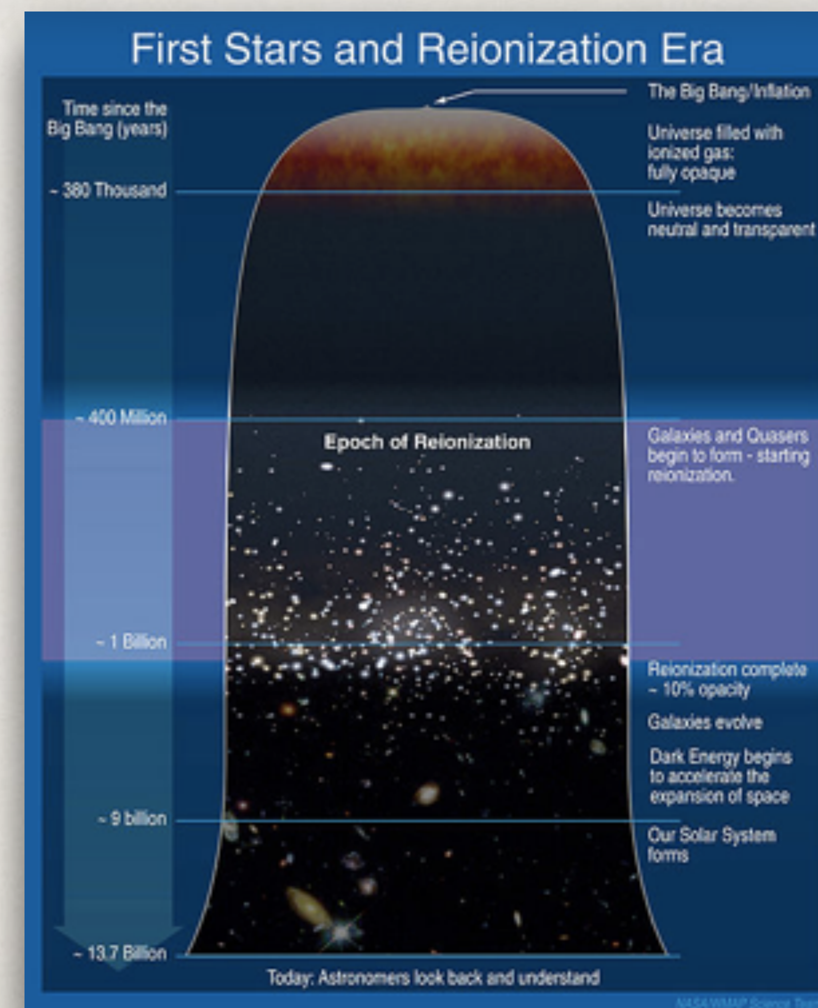
Robert Barone-Nugent
with
Stuart Wyithe,
Michele Trenti,
Tommaso Treu,
Pascal Oesch
&
Rychard Bouwens

Galaxies And Cosmology In Light Of Strong Lensing, Kavli IPMU - 20th November, 2014

Big Picture: Reionization

The period when the Universe transitioned from neutral to ionized

- Neutral Hydrogen in the IGM is reionized by the first stars and galaxies
- Thought to be finished by z~6-7 (Becker et al. 2001, Spergel et al. 2006)
- The question of what reionized the universe is still an open question

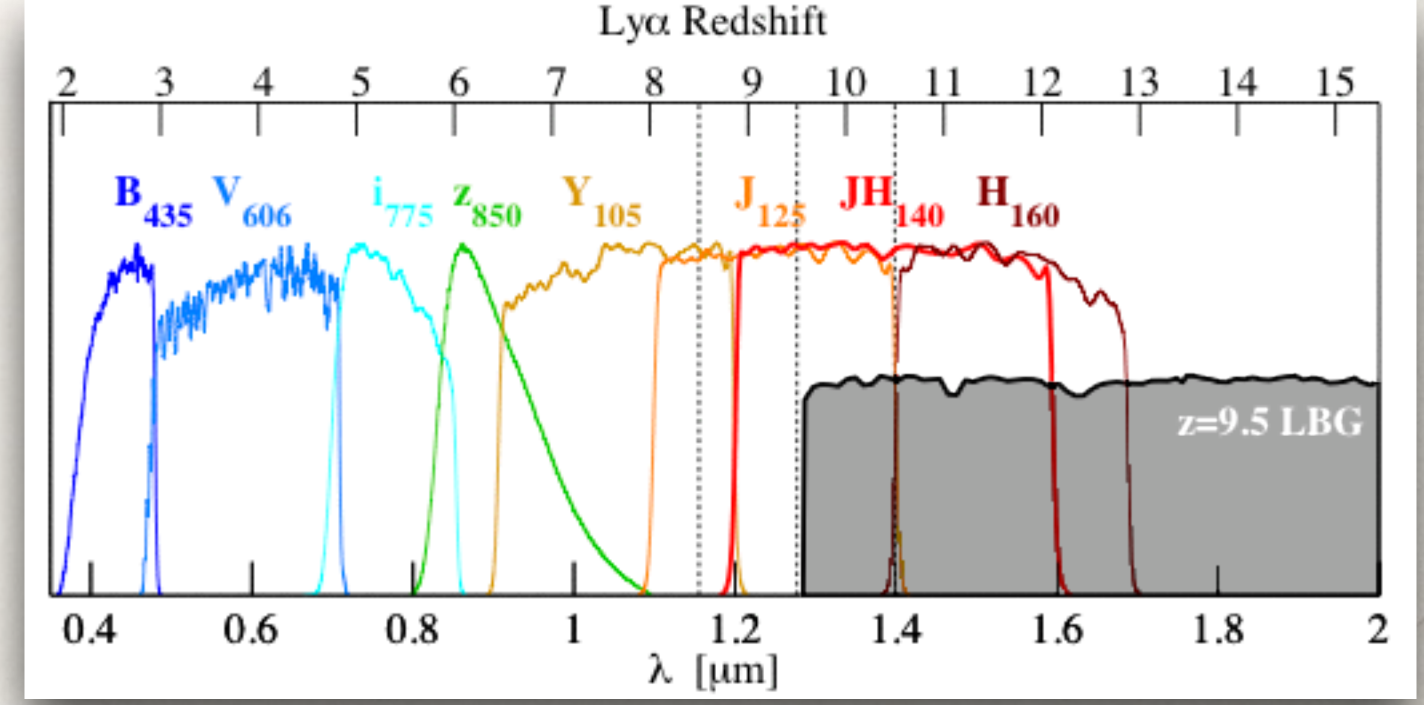


http://en.wikipedia.org/wiki/Reionization

High-Redshift Lyman-Break Galaxies

The search for galaxies that could have reionized the Universe

- Use the Lyman Break, beyond which spectra are heavily attenuated
- Identify galaxies at different redshifts using colour-colour criteria
- Filters a galaxy "drops out" in indicates its redshift

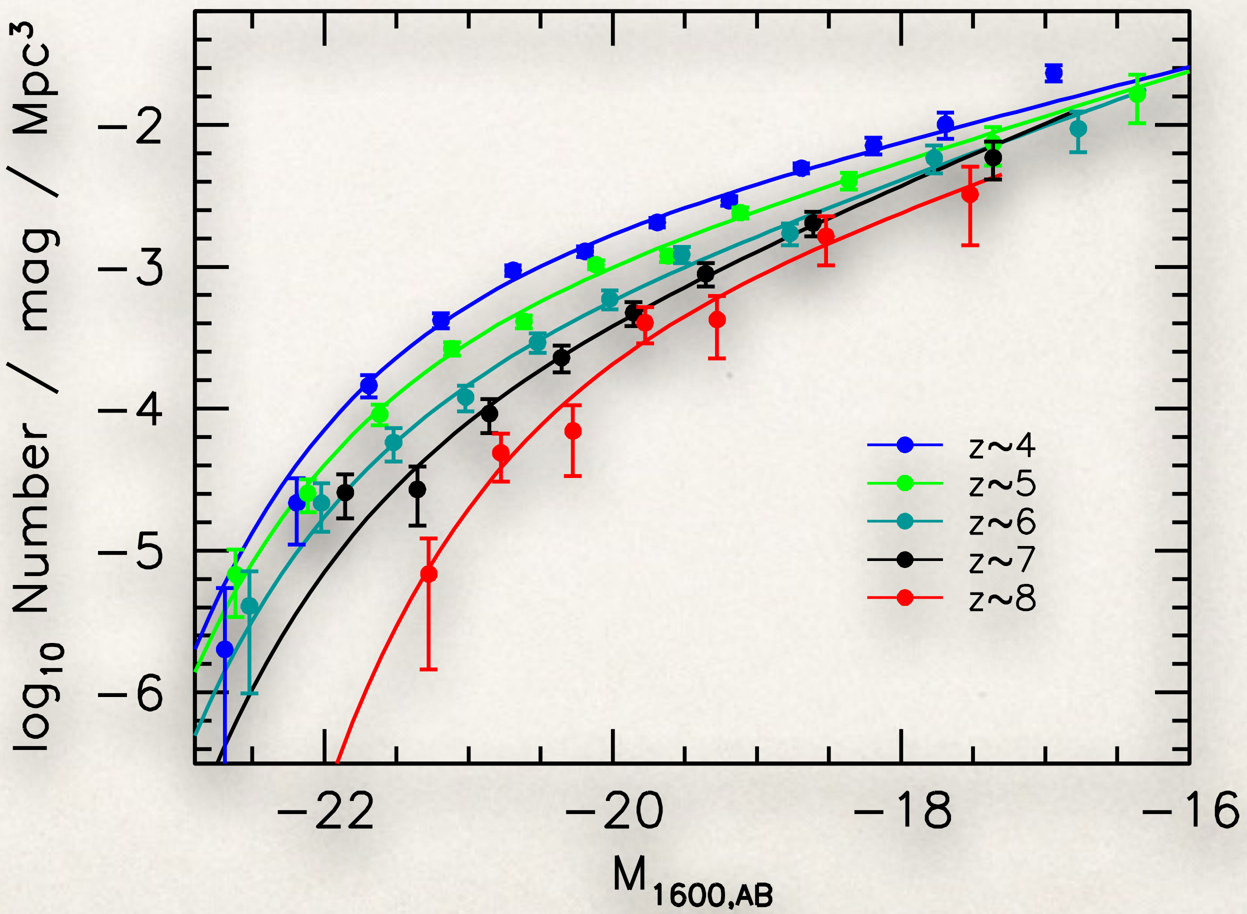


Oesch et al. 2013

The Luminosity Function

A census of star-forming activity at high-redshift

- The luminosity function (LF) makes a census of star-forming activity at high-redshift
- Many independent studies mostly agree (Schmidt et al. 2014, Bowler et al. 2014, Finkelstein et al. 2012 etc.)
- The faint-end slope is seen to be very steep at high-*z*, so faint LBGs could have reionized the universe



Bouwens et al. 2014

Gravitational Lensing & Magnification Bias

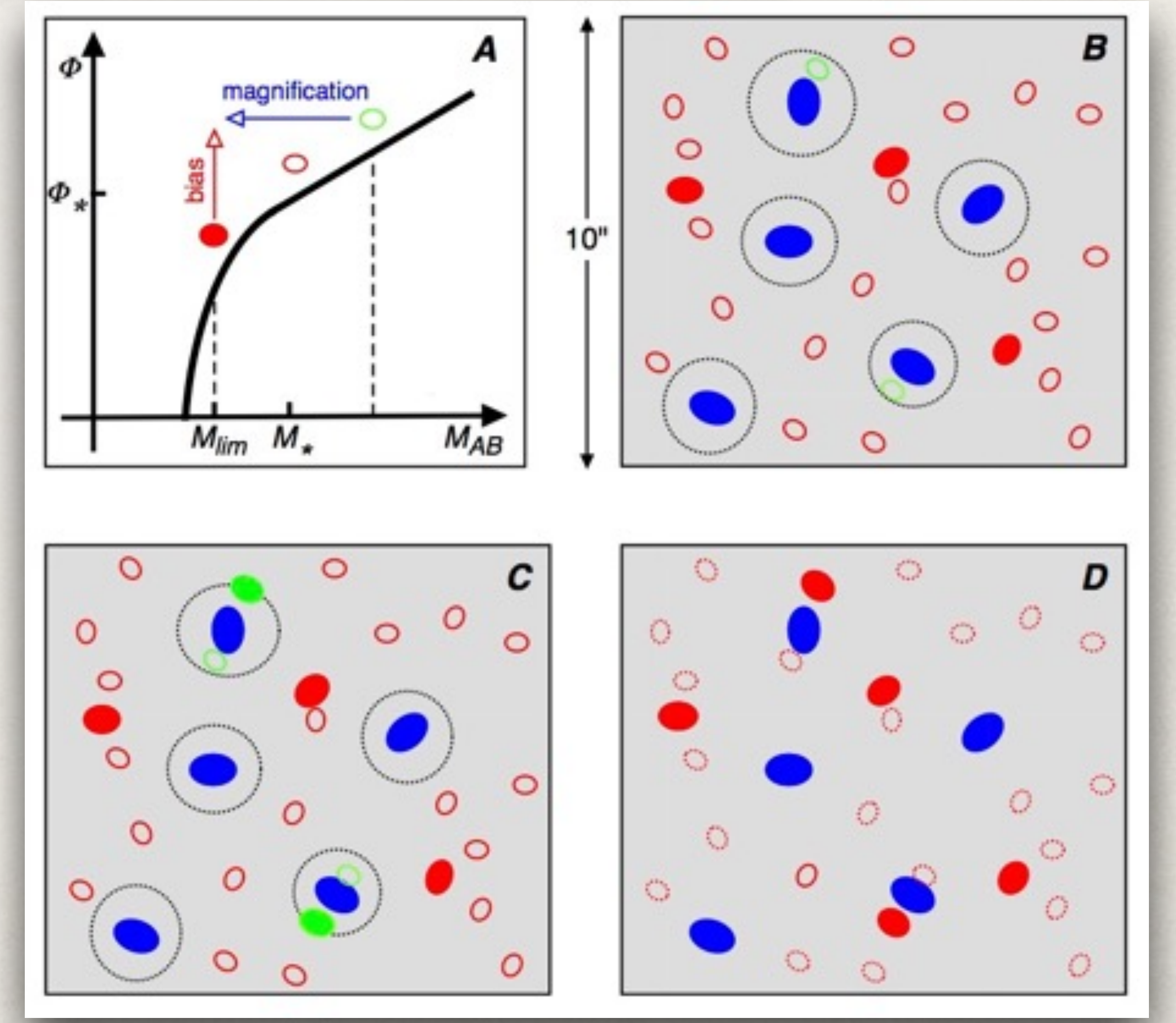
A bias that could skew the luminosity function

- Probability of *strong lensing* given an observed magnitude:

$$P(SL|M) = \frac{P(M|SL)}{P(M)} P(SL)$$

$$B(L) = \frac{\int_{\mu_{\rm min}}^{\mu_{\rm max}} \frac{d\mu}{\mu} \frac{dP}{d\mu} \Psi(L/\mu)}{\Psi(L)}$$

$$B(L > L_{\rm lim}) = \frac{\int_{\mu_{\rm min}}^{\mu_{\rm max}} d\mu \int_{L_{\rm lim}}^{\infty} dL \frac{dP}{d\mu} \Psi(L/\mu)}{\int_{L_{\rm lim}}^{\infty} dL \Psi(L)}$$

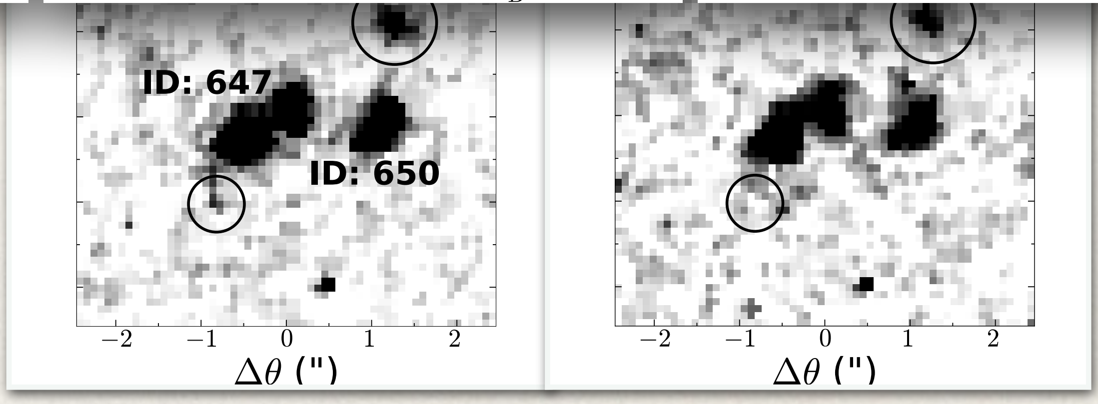


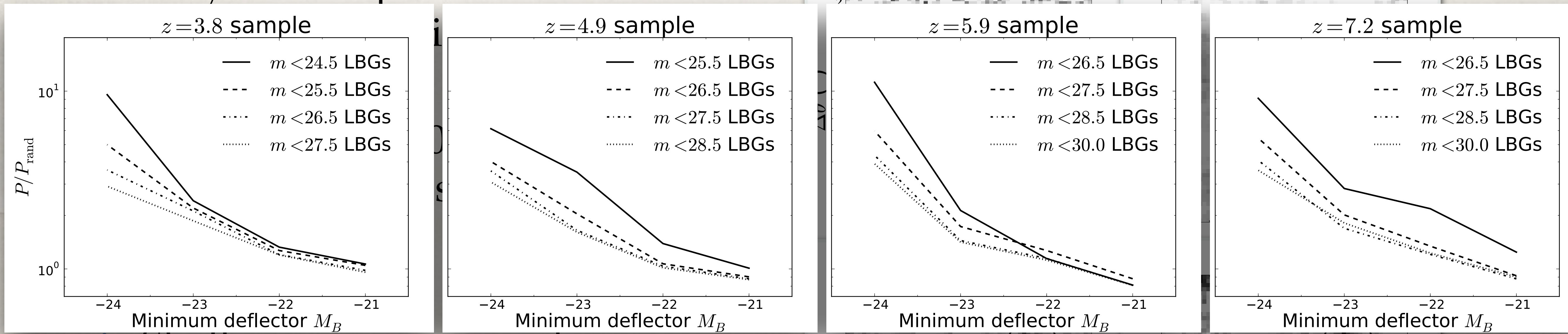
Wyithe et al. (2011)

Is Magnification Bias There?

There *should* be gravitationally lensed galaxies in current surveys

- Very hard to prove individual





- Shallower surveys, such as Brightest of Reionizing Galaxies survery (PI: Trenti), should have a high lensed fraction

Our Search

Use Bouwens et al. (2014) samples of LBGs at z~4, 5, 6 & 7 to search for a statistical signal of magnification bias

- We estimate the magnification, μ, of each LBG at z~4, 5, 6 & 7
- For each pair of LBG and nearby foreground object, use:
  - Source and deflector redshift — Bouwens et al. (2014) & 3D-HST
  - Deflector luminosity — 3D-HST
  - Separation between LBG & deflector

$$\theta_{ER} = 4\pi(\frac{\sigma_\star}{c})^2 \frac{D_{LS}}{D_S},$$

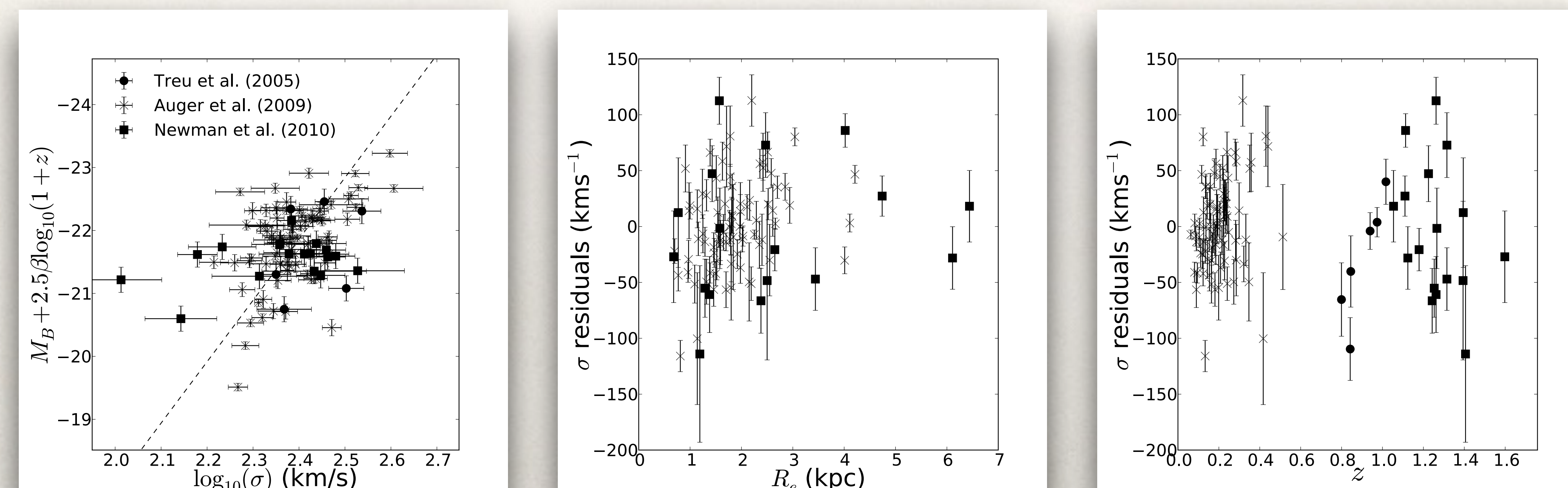
$$\mu = \frac{|\theta_{\rm sep}|}{|\theta_{\rm sep}| - \theta_{ER}},$$

The Faber-Jackson Relation

A way of estimating velocity dispersion from luminosity

- Most deflectors will be at z~1-2, where local FJRs aren't applicable
- Calibrate a redshift dependent FJR using Treu+05, Auger+09 & Newman+11 sample to account for evolution in the mass-to-light

$$L_B = m\sigma_\star^\alpha (1+z)^\beta,$$



Barone-Nugent et al. (in prep.)

Strong Lensing Probabilities

Assigning a probability that an LBG has been gravitationally lensed

- Ask two questions about each LBG-deflector pair:
    - *What deflector velocity dispersion is required for strong lensing (μ=2)?*
    - *What is the chance that that deflector has a velocity dispersion equal to or greater than that required?*

$$\mu = \frac{|\theta_{\rm sep}|}{|\theta_{\rm sep}| - \theta_{ER}},$$

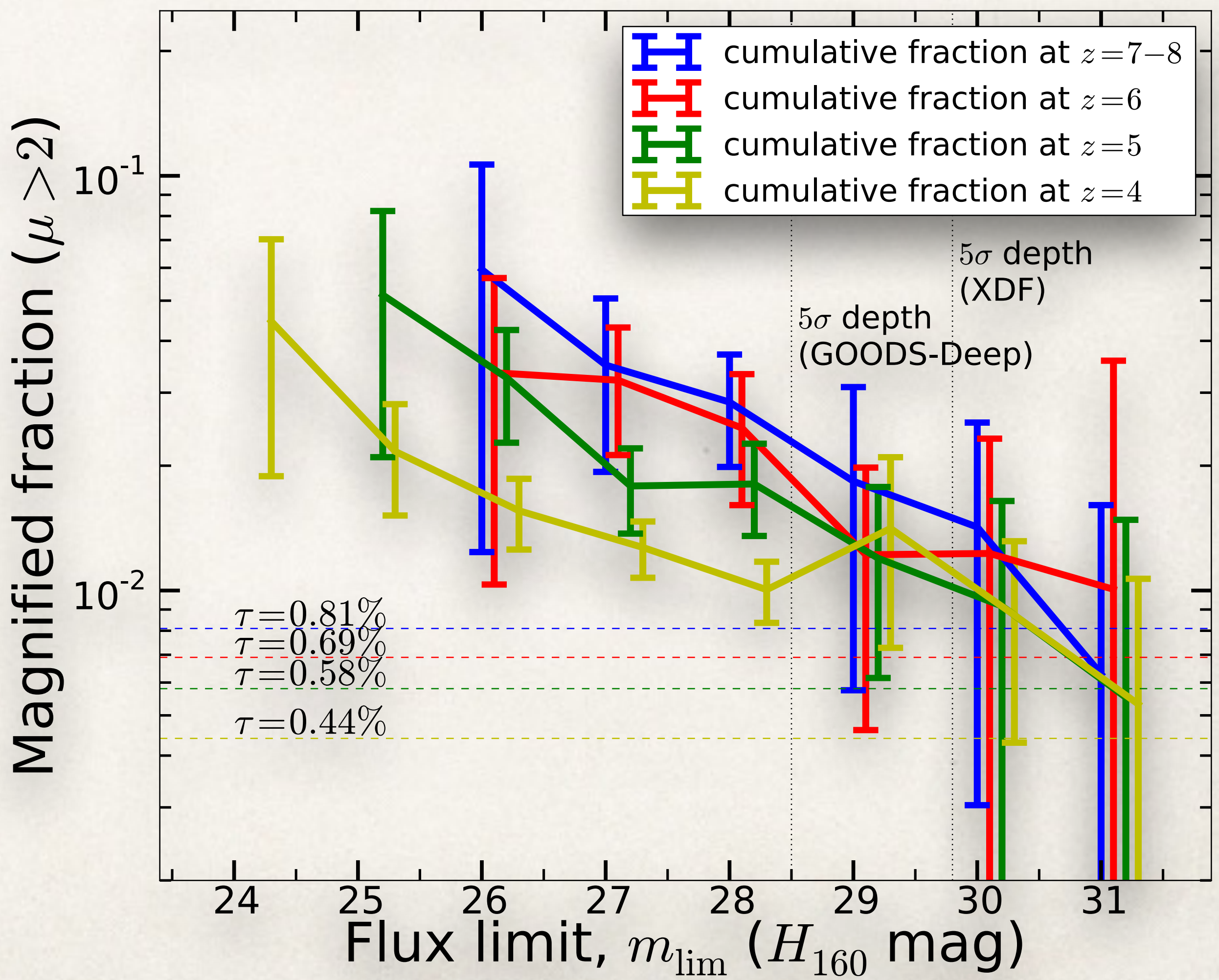
$$2 = \frac{|\theta_{\rm sep}|}{|\theta_{\rm sep}| - 4\pi(\frac{\sigma_{\star,\rm req}}{c})^2 \frac{D_{LS}}{D_S}}$$

$$\mathscr{L} = \frac{1}{2}\mathrm{erfc}\Big(\frac{\sigma_{\star,\rm req} - \sigma_{\star,\rm inf}}{\sqrt{2}\epsilon_{\rm FJR}}\Big)$$

Results - Lensed Fraction

The fraction of strongly lensed LBGs above a flux limit

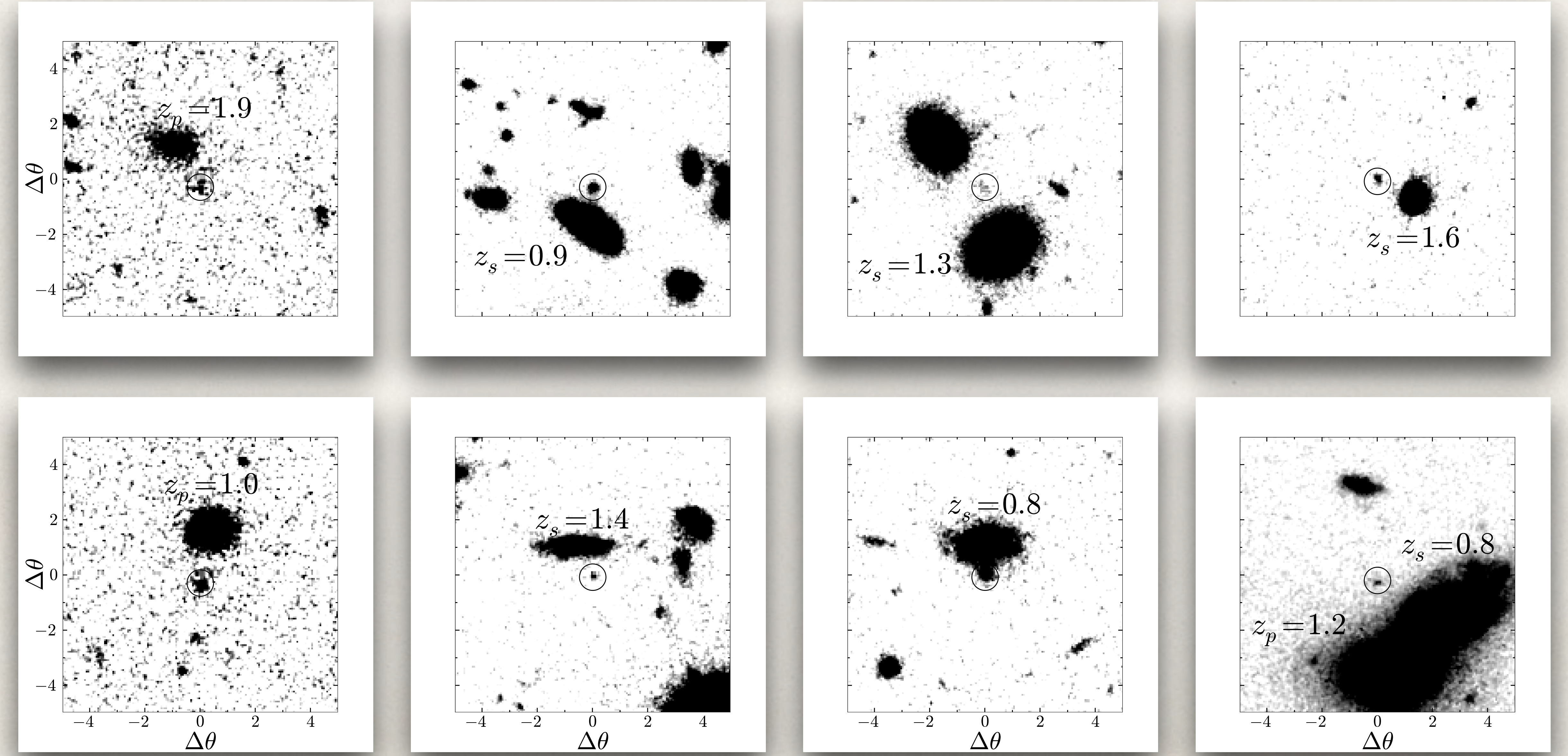
- Assess the lensed fraction at multiple flux limits for samples at z~4, 5, 6, & 7
- See a monotonic increase in the lensed fraction for brighter flux limits
- Also see increase in the lensed fraction with redshift



Barone-Nugent et al. (in prep.)

Results - Lensed Fraction

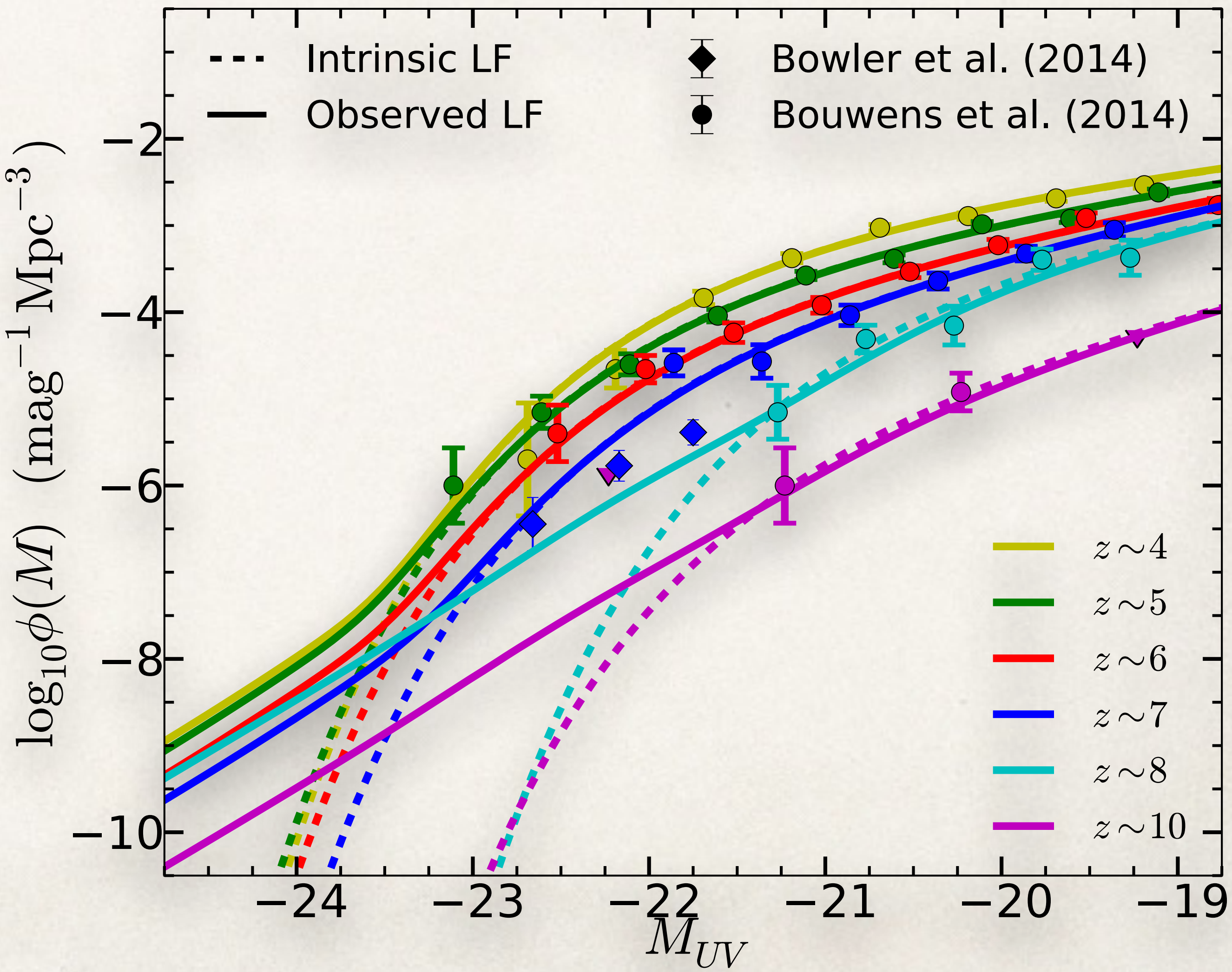
Examples of possibly-lensed LBGs



Effect on the Luminosity Function

Does this lensing affect current LFs?

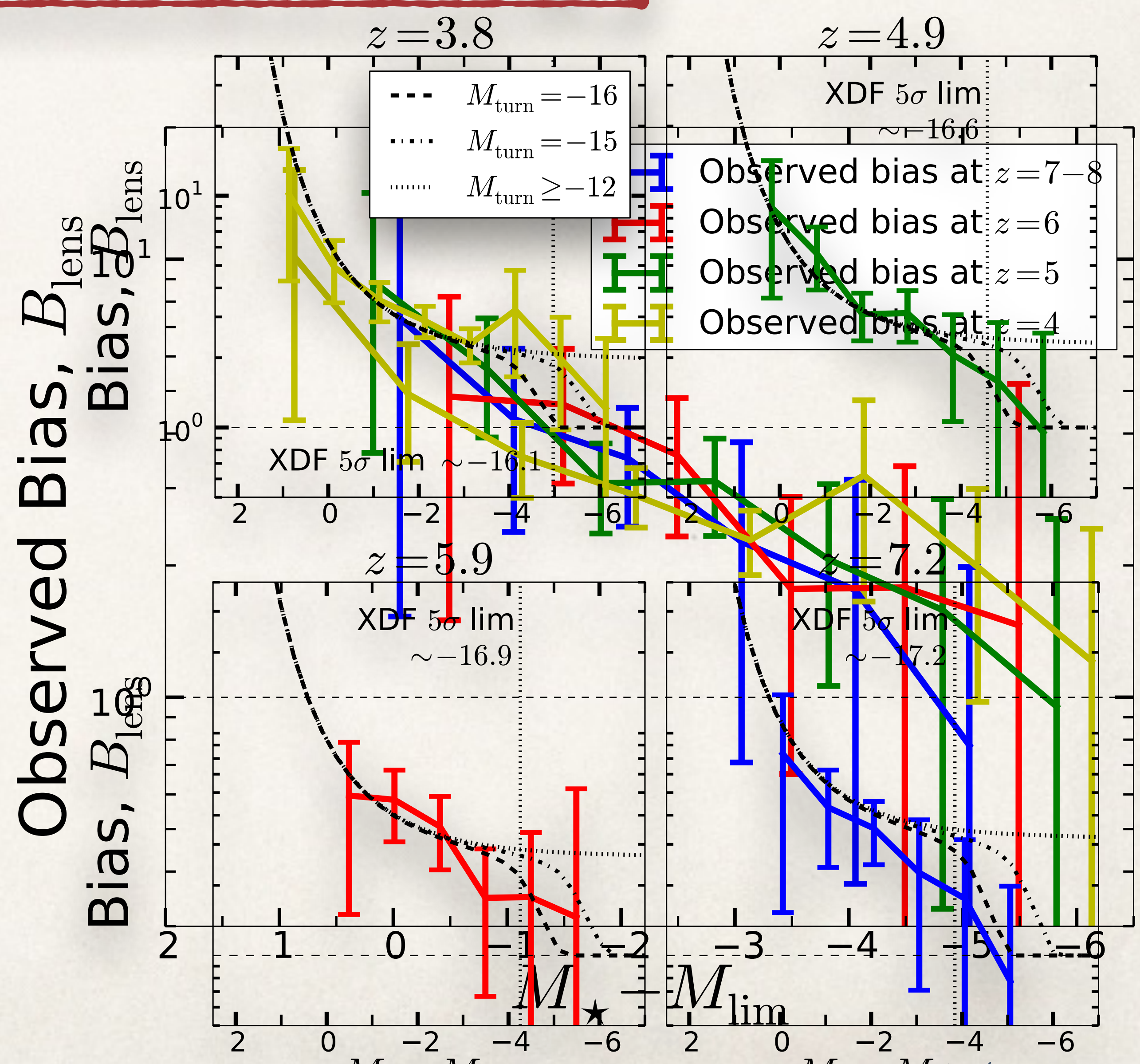
- Compute the *observed* luminosity function given an *intrinsic* luminosity function
- Current LFs out to z~8 are not significantly affected
- Future surveys at z>10, however, will be affected



Results - Magnification Bias

The excess probability of lensing

- The *magnification bias* is the strongly-lensed fraction divided by the optical depth, τ
- Calculate the optical depth by assessing the lensed fraction of random source positions
- Compare observed magnification bias with theoretical bias

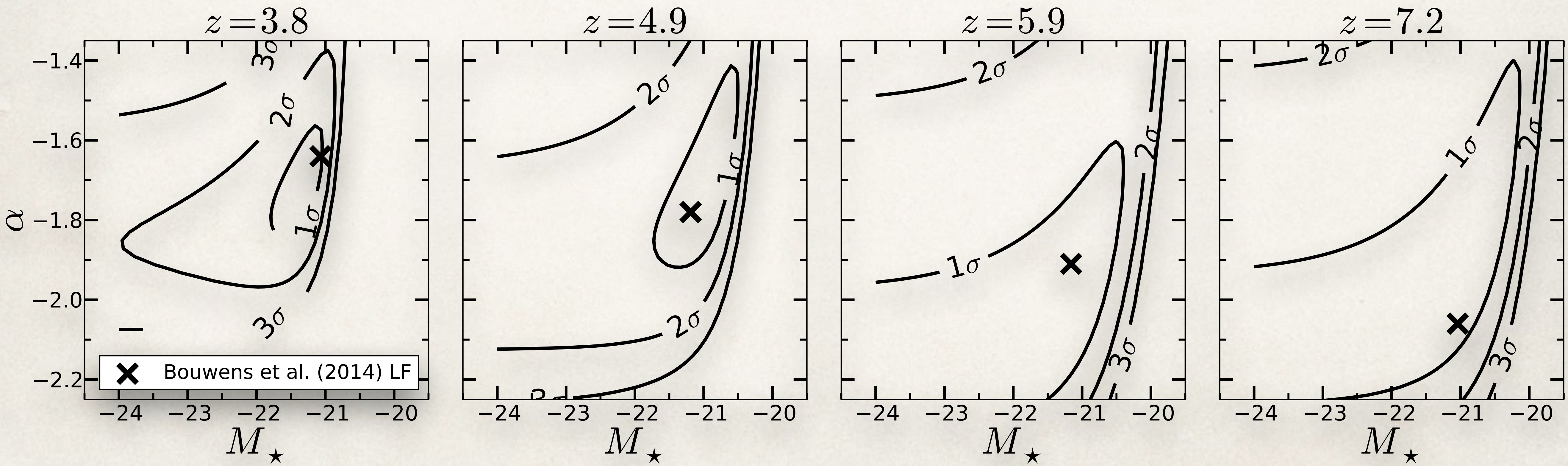


Barone-Nugent et al. (in prep.)

A New Way to Fit the LF

An alternative method to number counts of galaxies

$$B(L) = \frac{\int_{\mu_{\min}}^{\mu_{\max}} \frac{d\mu}{\mu} \frac{dP}{d\mu} \Psi(L/\mu)}{\Psi(L)},$$

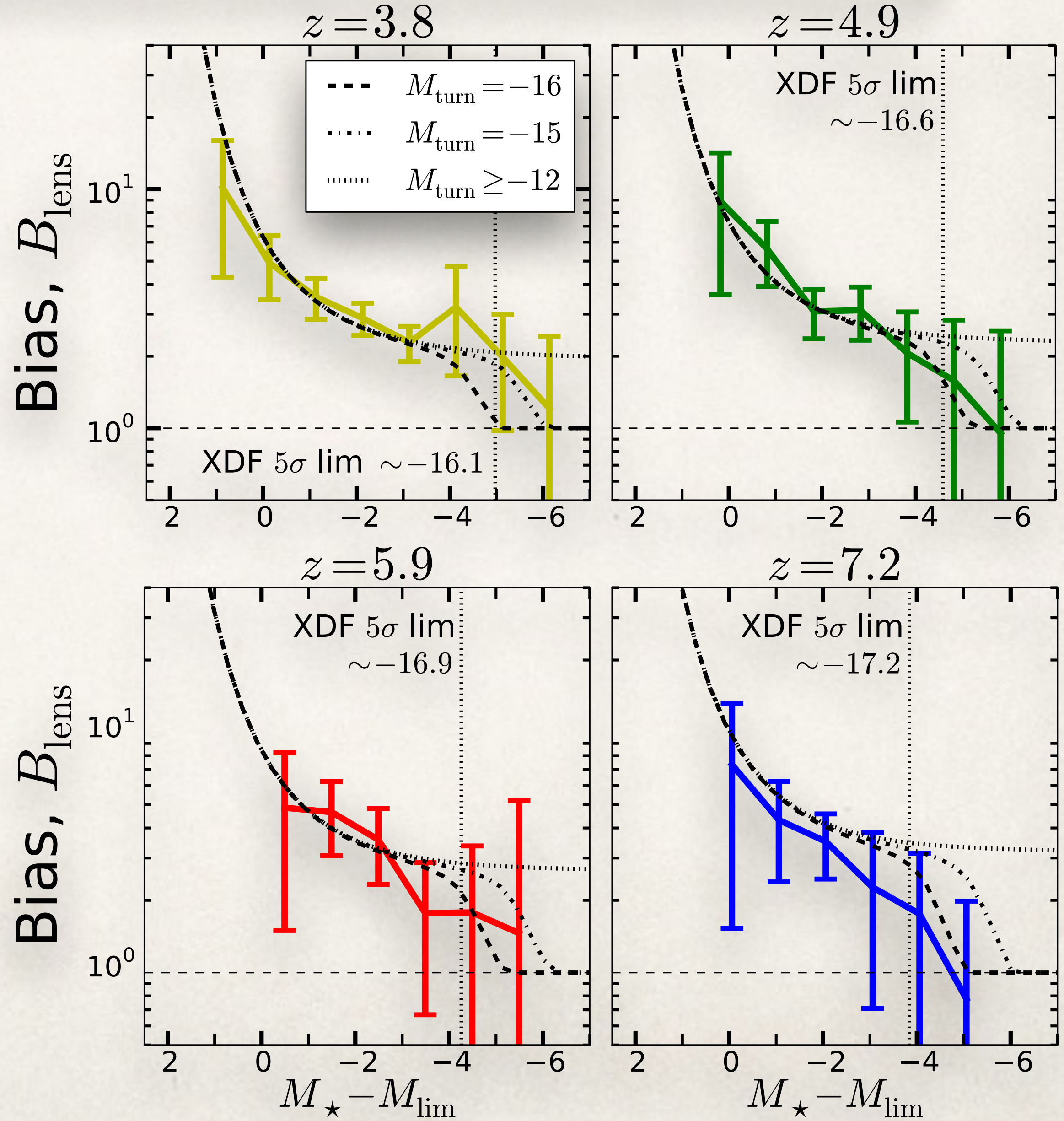


Barone-Nugent et al. (in prep.)

Beyond Current Flux Limits

Magnification bias allows us to look beyond survey limits

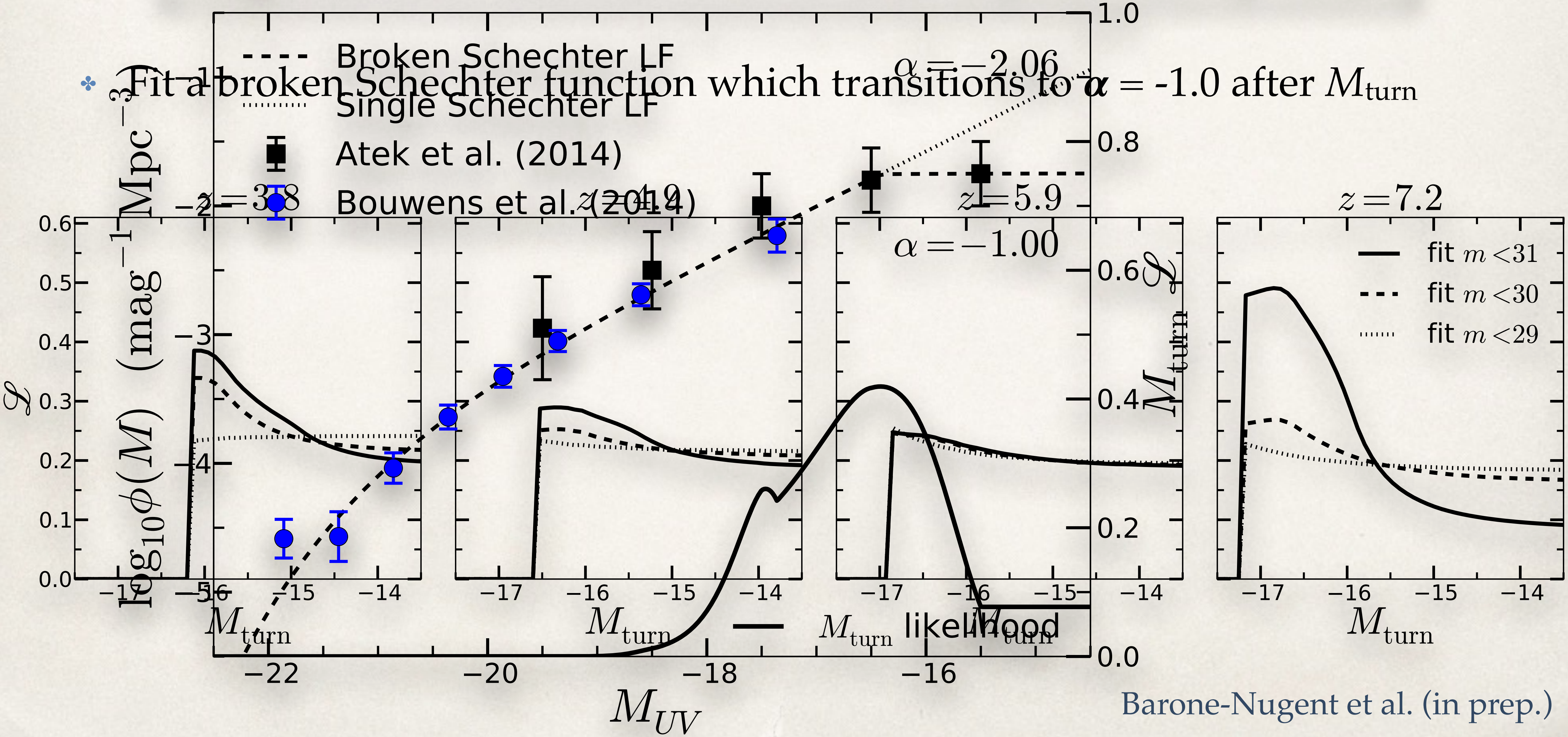
- Bias at a flux limit depends directly on the LF to a few magnitudes deeper than that limit
- Observed magnification bias approaches unity in each of the samples from z~4 to z~7
- This may be caused by a flattening LF beyond flux limits



Beyond Current Flux Limits

Magnification bias allows us to look beyond survey limits

- Fit a broken Schechter function which transitions to α = -1.0 after M_{turn}

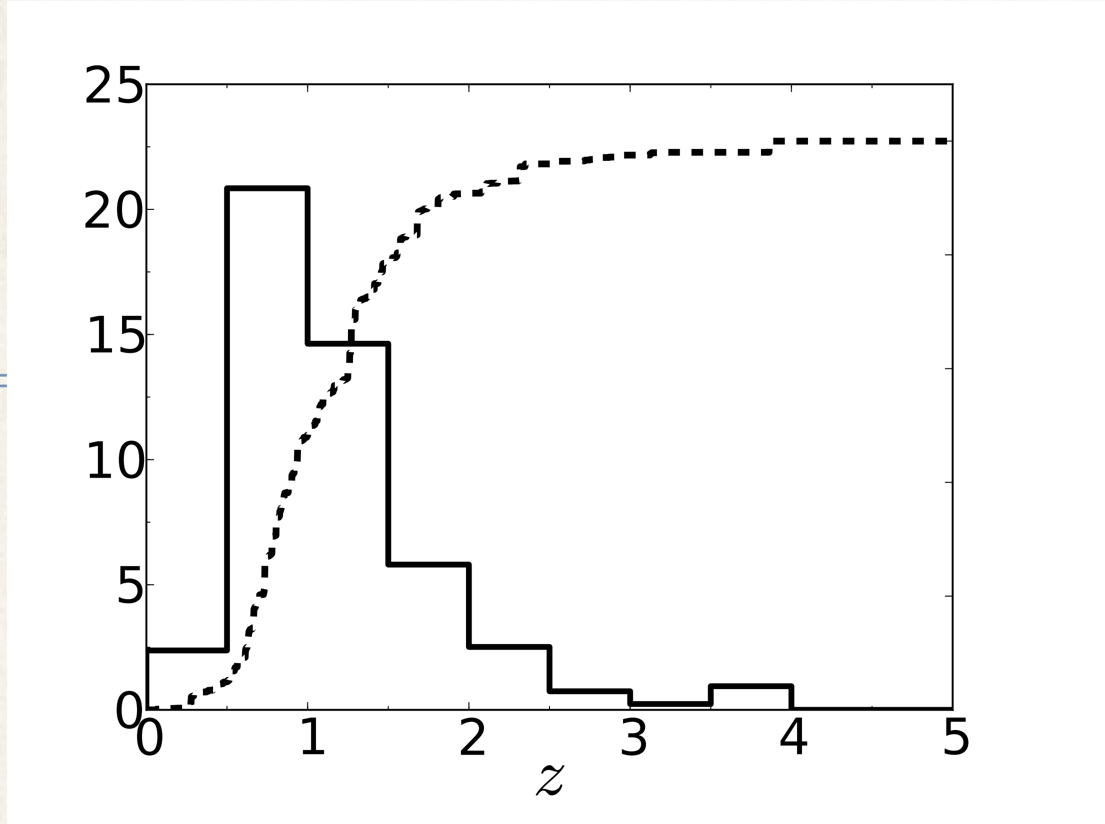


Barone-Nugent et al. (in prep.)

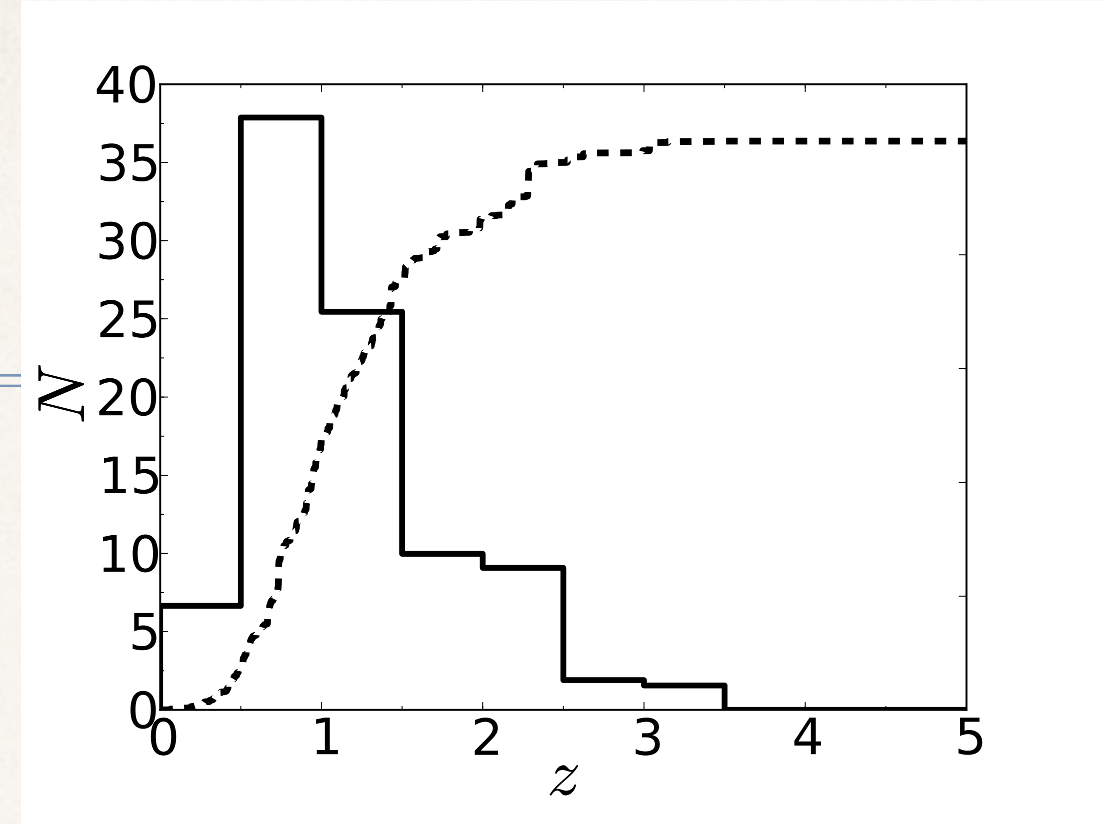
Conclusions

- Magnification bias exists in current surveys, with ~10% of LBGs brighter than M_* at z~7 strongly lensed,
- Future surveys using JWST of LBGs at z>10 will need to compensate for its effect on the LF,
- Most or all LBGs detected at z>10 may be strongly lensed,
- Measuring the bias can be used to constrain the LF independently of galaxy number counts,
- The measurements imply the possibility of a deviation from a steep faint-end slope a few magnitudes beyond current flux limits, which has repercussions for the photon budget of reionization.

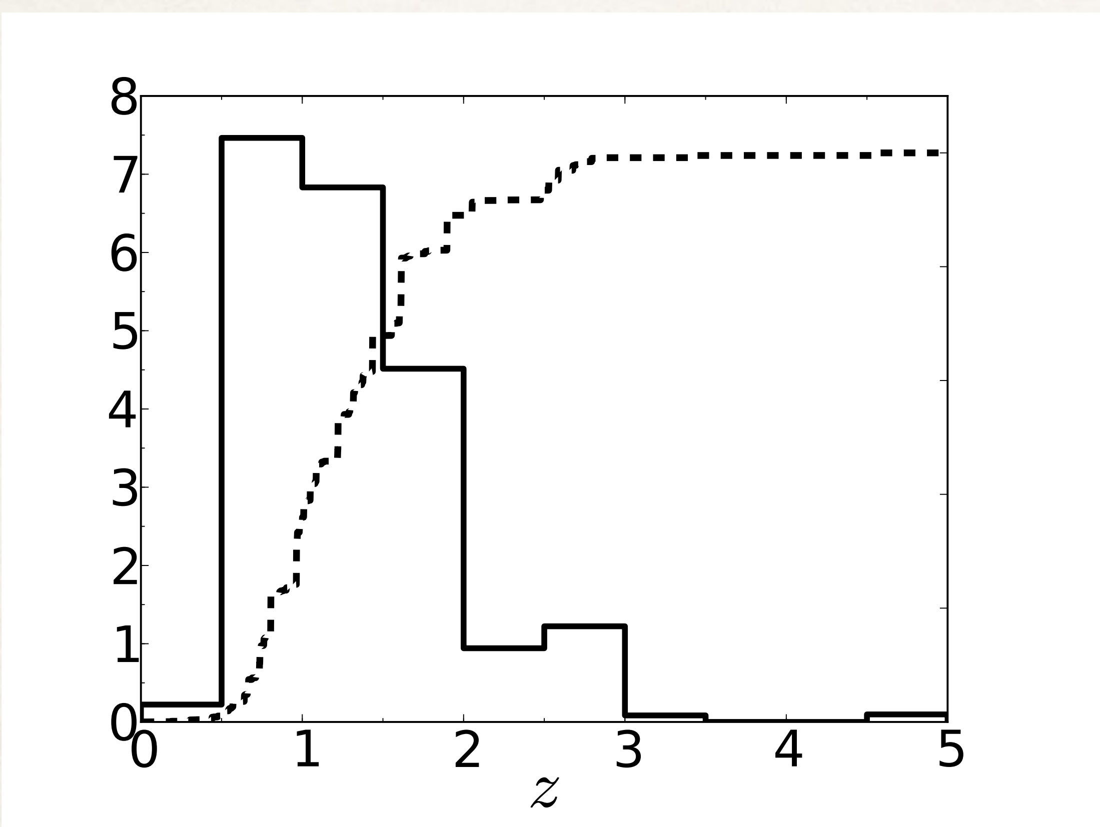
z=3.8



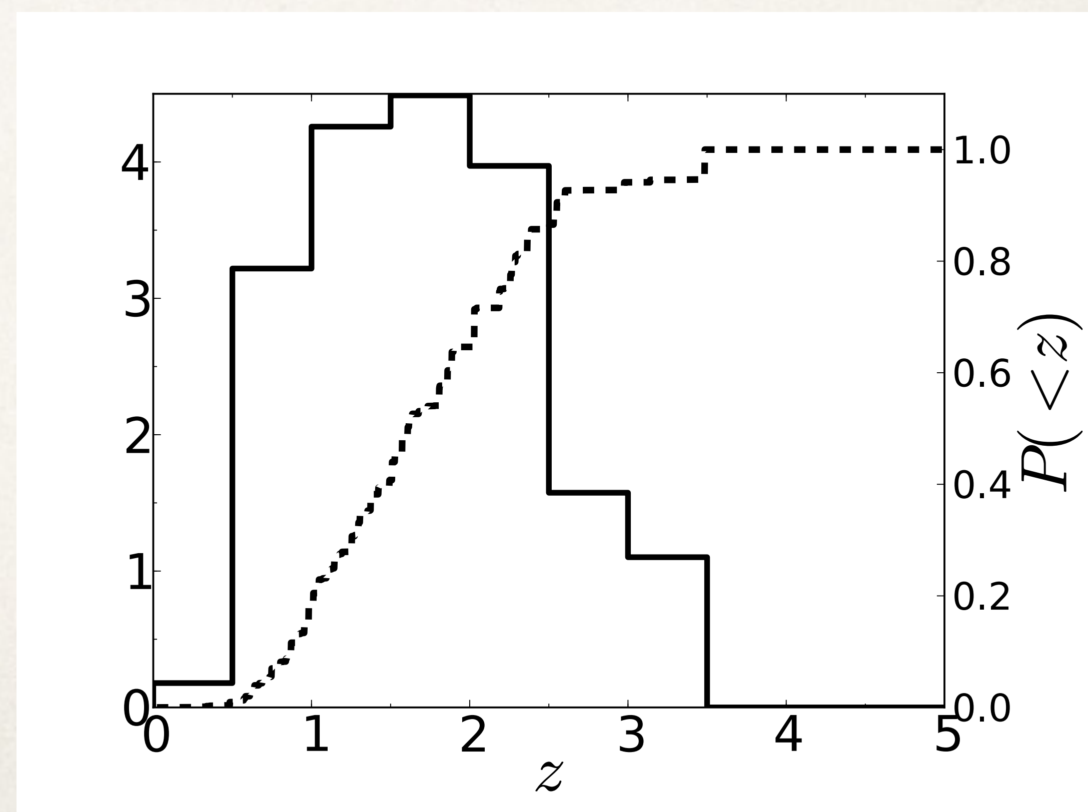
z=4.9



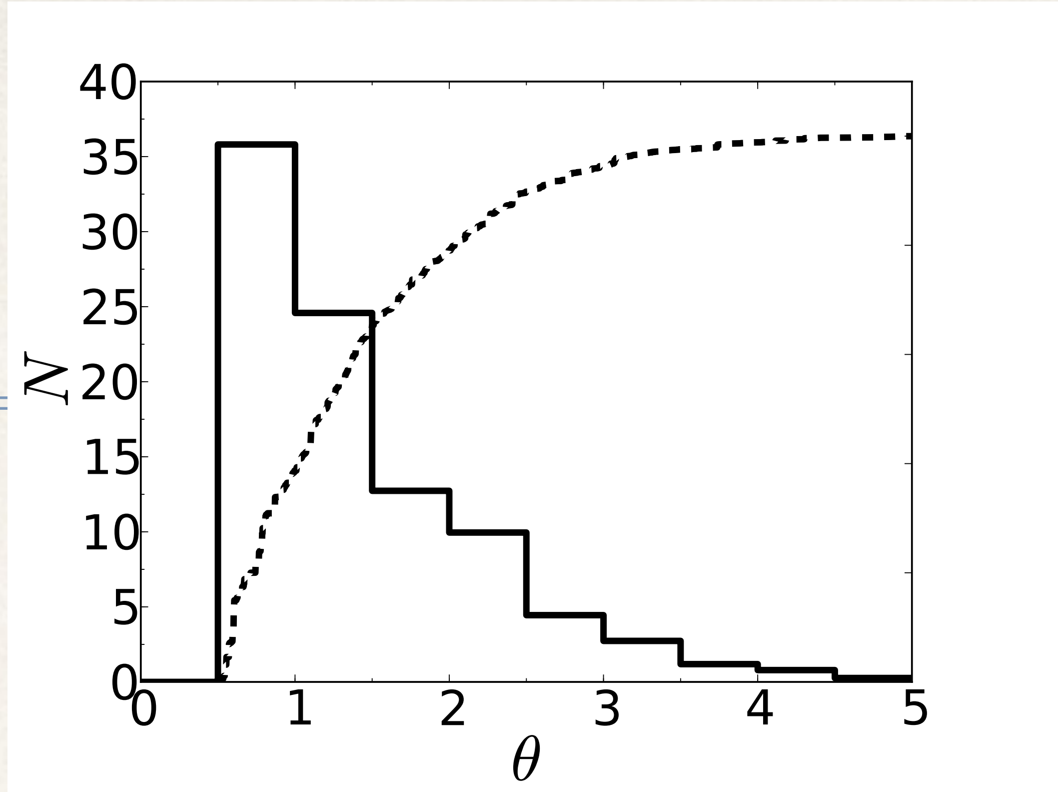
z=5.9



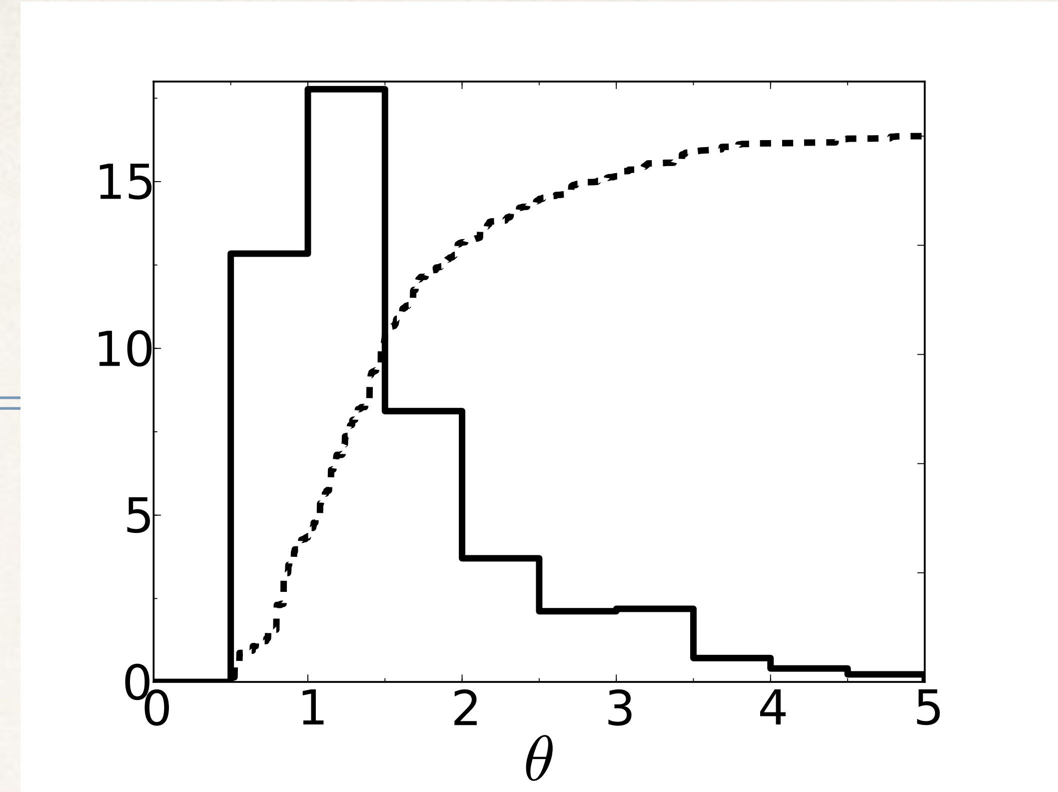
z=7.2



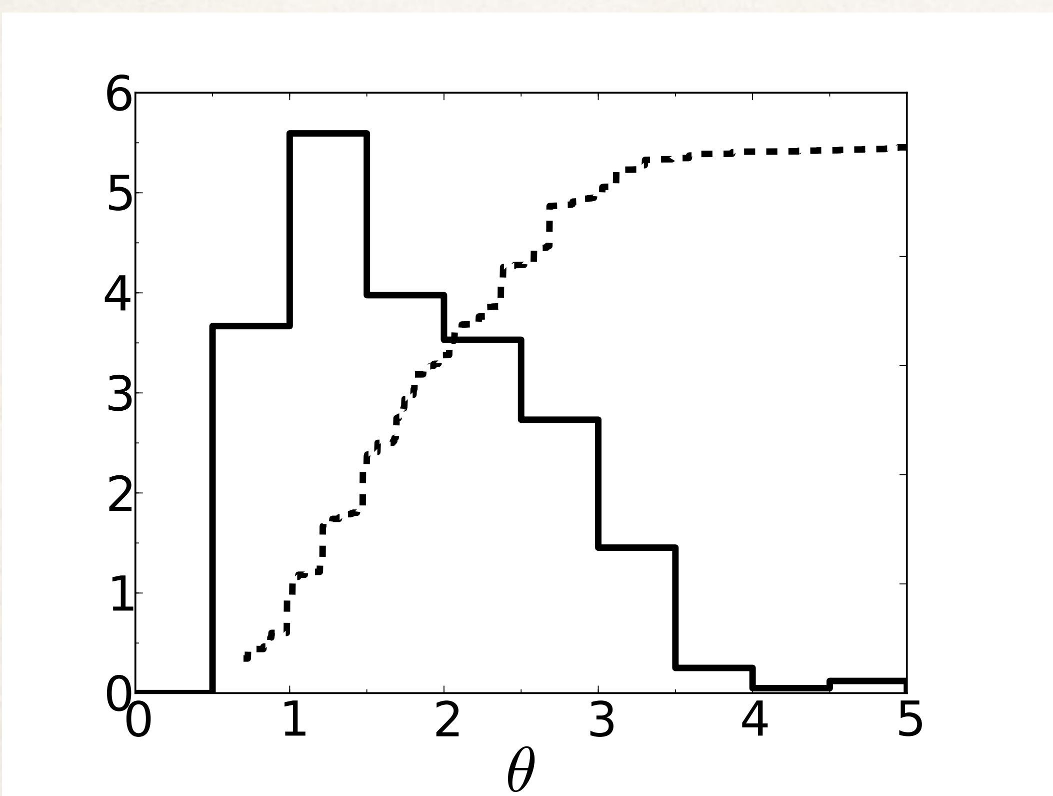
z=3.8



z=4.9



z=5.9



z=7.2