Searching for the First Galaxies

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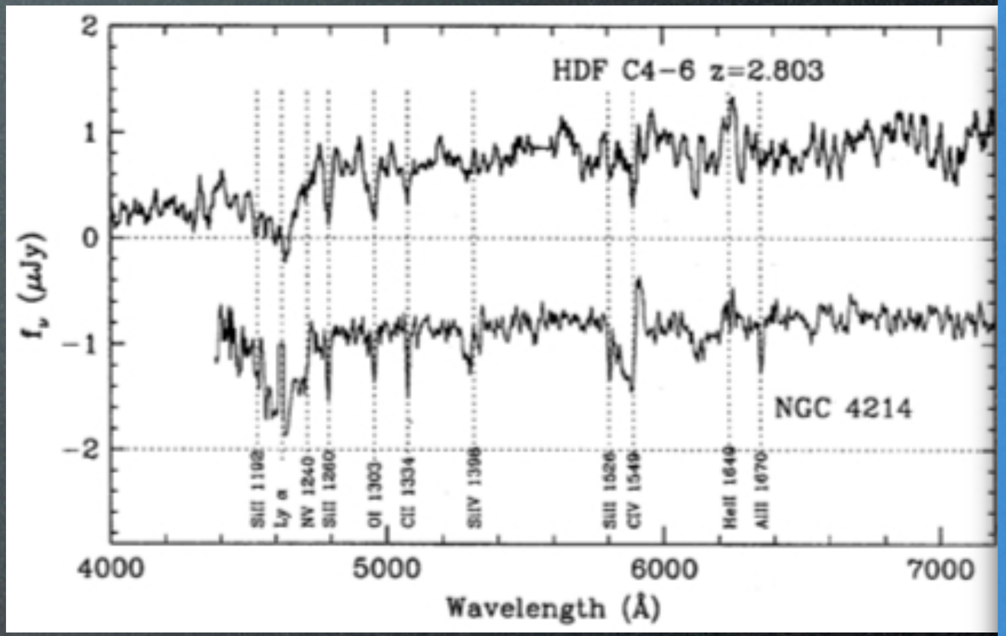
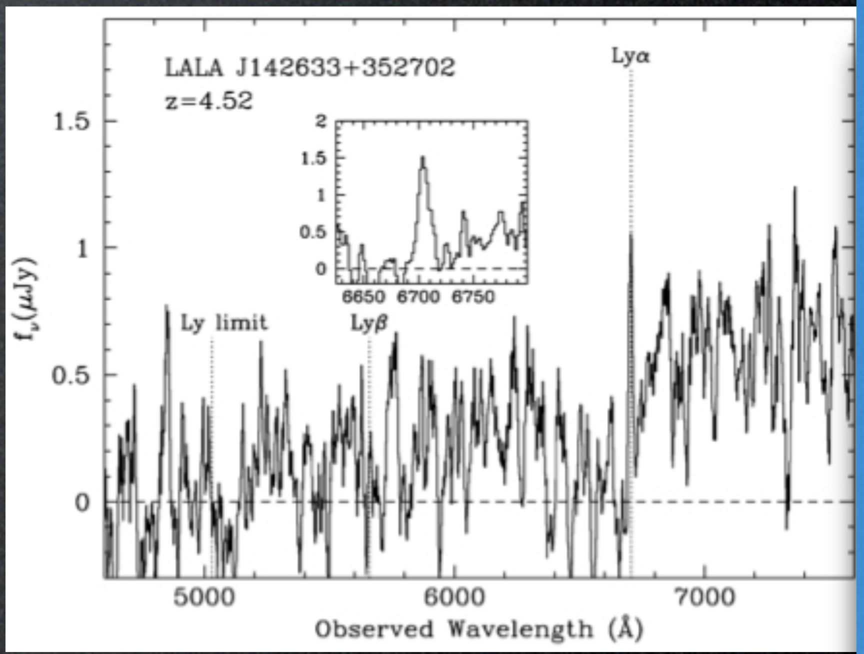
High-Redshift Galaxies

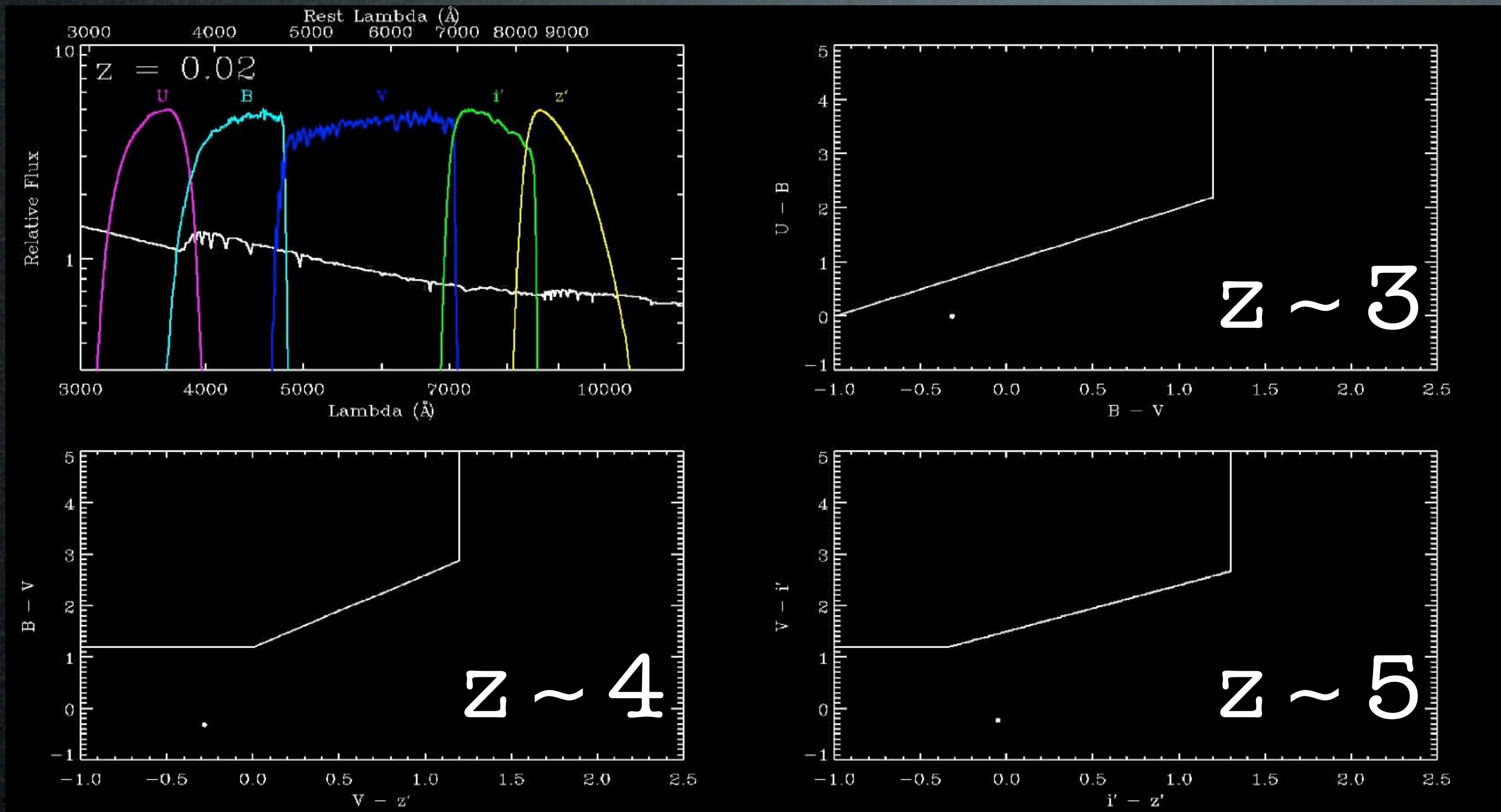
- Largest samples fall into two categories:
  - Lyman break galaxies (LBGs; e.g., Steidel et al. 1996)
    - Selected on the basis of a continuum break
  - Lyman alpha emitters (LAEs; e.g., Cowie & Hu 1998; Rhoads et al. 2000)
    - Selected on the basis of a strong emission line.



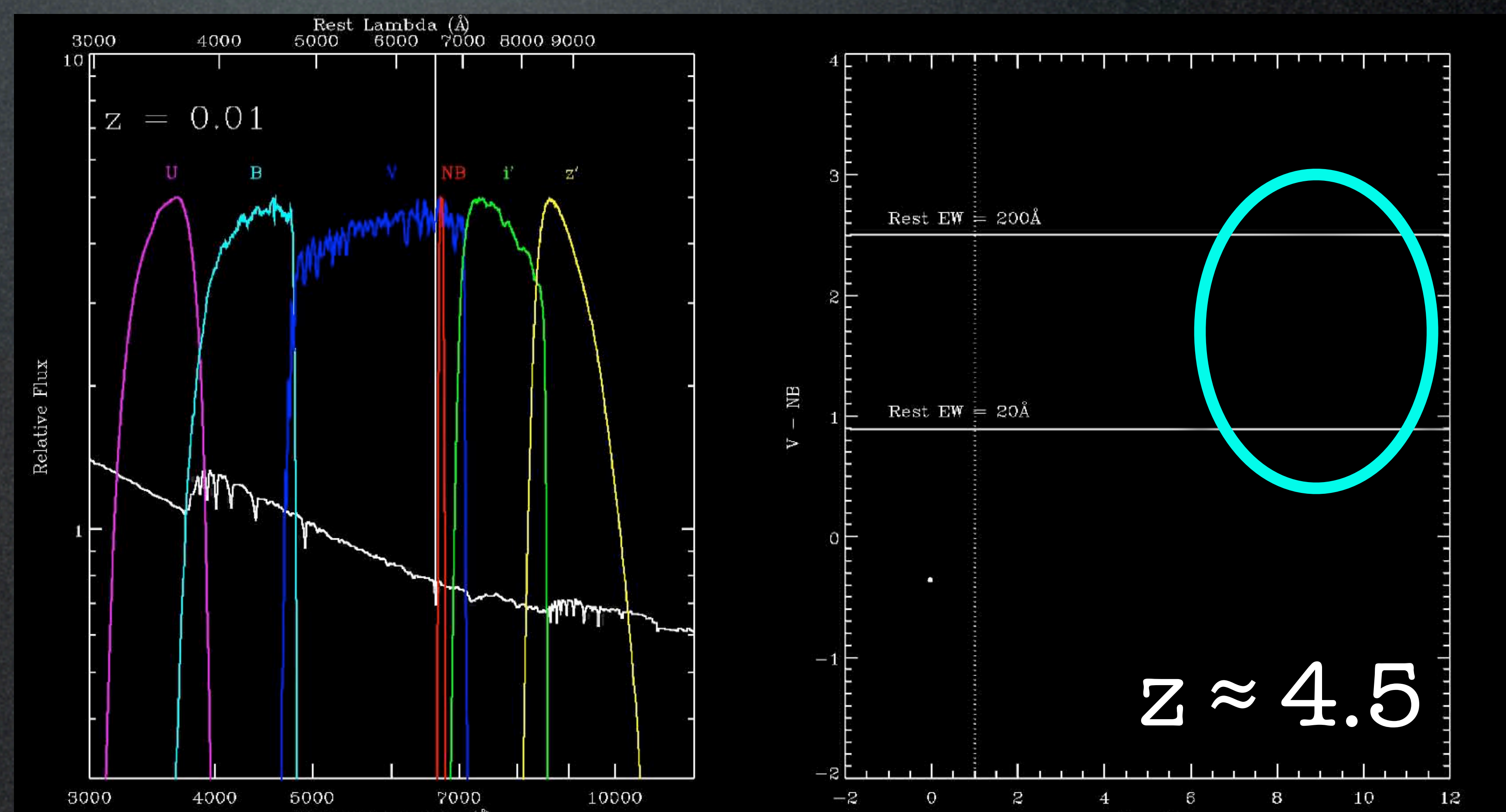
Steidel et al. (1996)



Rhoads et al. (2000)



LBGs:
Selected in color-color planes.
Δz ~ 1

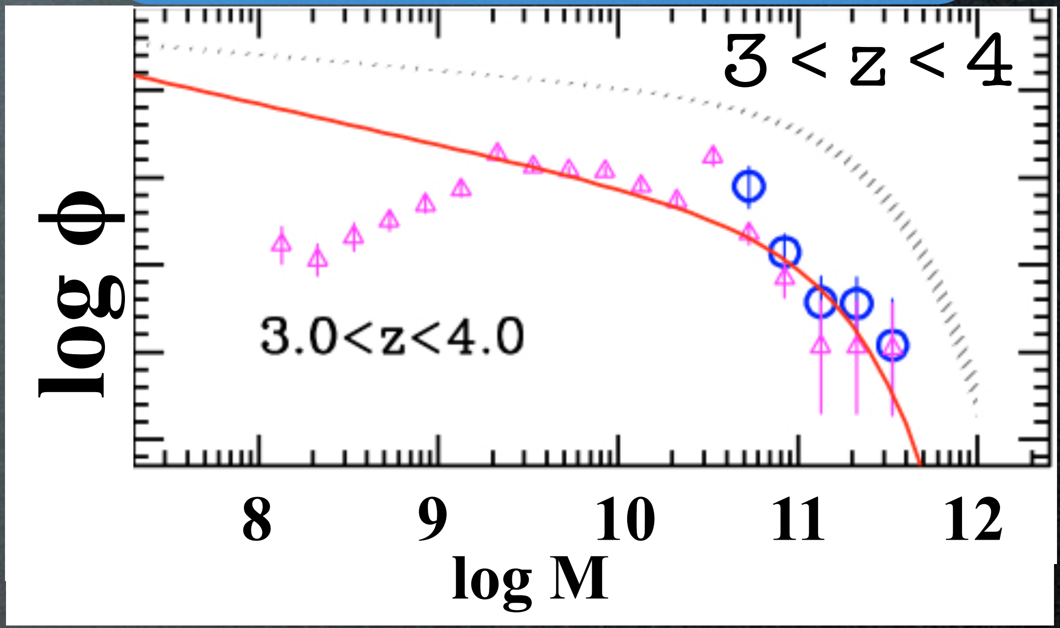


LAEs:
Selected via narrowband excess.
Δz ~ 0.1

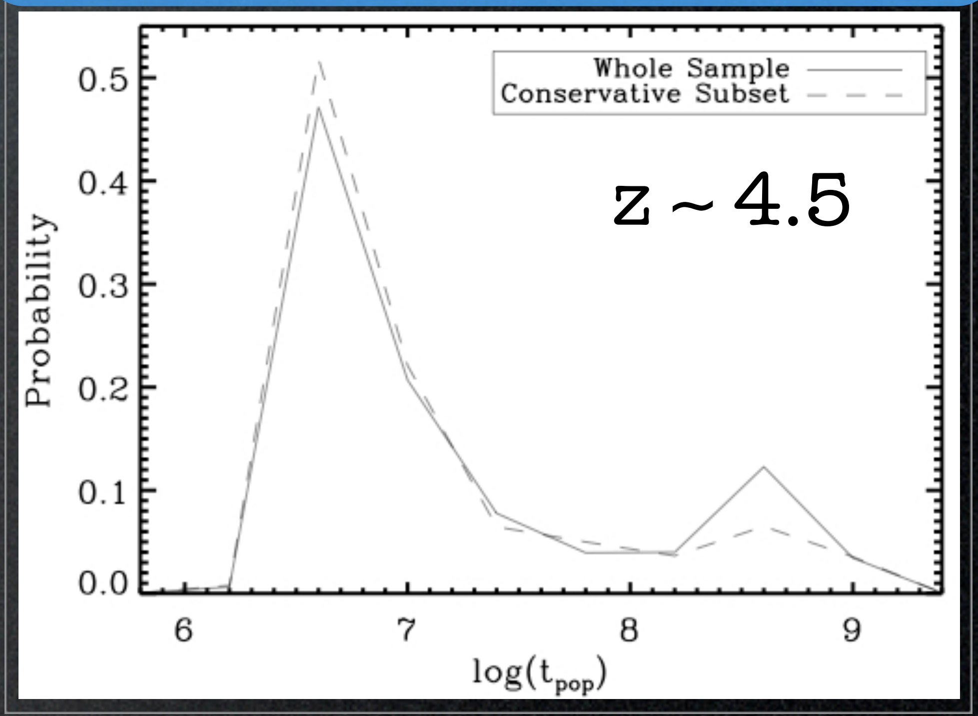
Are these objects related?

- Using SED fitting analyses:
  - LBGs (see e.g., Papovich et al. 2001; Shapley et al. 2001; Yan et al. 2005, 2006; Fontana et al. 2006):
    - Ages: 100 Myr - 1 Gyr
    - Stellar Masses = 5 x 10^9 - 10^{11} $M_\odot$
    - Extinction: A_V ~ few tenths - 2 mag.
  - LAEs (see e.g., Gawiser et al. 2006; Lai et al. 2007, 2008; Pirzkal et al. 2007; Finkelstein et al. 2007, 2008, 2009a)
    - Ages = 1 Myr - 100 Myr
    - Stellar Masses = few x (10^7 - 10^9) $M_\odot$
    - Extinction: A_V ~ 0 - 1 mag.
- **LBGs are more evolved than LAEs!**

Fontana et al. (2006)

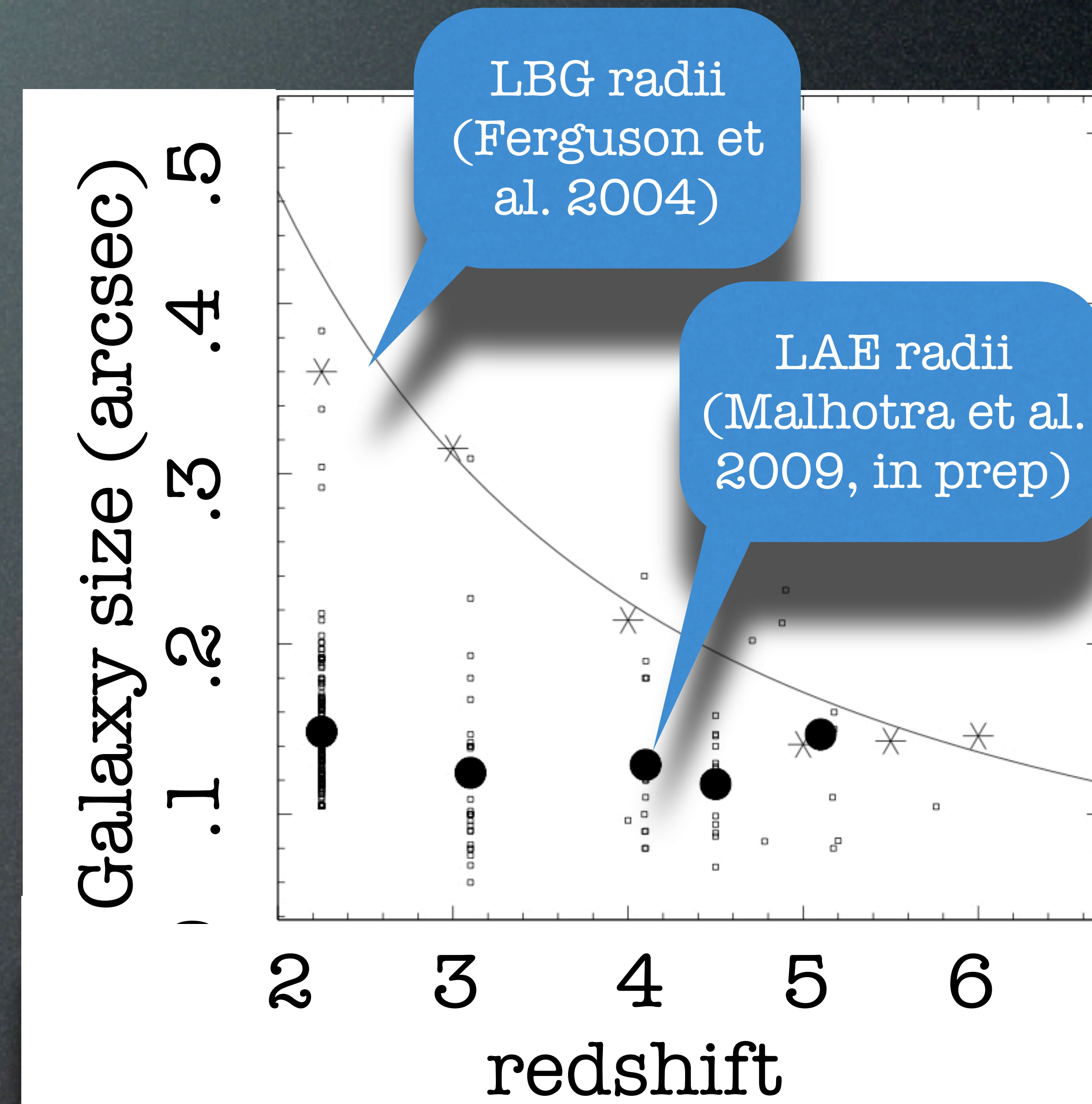


Finkelstein et al. (2009a)



LBGs vs. LAEs

- Could they be similar objects, with differences in Lyα observed properties due to ISM properties and/or viewing angle (i.e. Verhamme et al. 2008)?
    - Possibly not, as we see LAEs with dust extinction, and LBGs, even with Lyα in emission, tend to be more massive and more evolved than average LAEs (Papovich et al. 2001; Shapley et al. 2001; Pentericci et al. 2009).
- Evidence is pointing towards different classes of objects, or at least different evolutionary states.
    - LBGs become more massive and larger with decreasing redshift, while LAEs stay the same.
- This implies that LAEs may be the building blocks of larger galaxies.



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The Universe at z > 7

- Evidence also points to increasing incidence of Lyα in emission in LBGs at higher redshift (see Shimasaku et al. 2006 at z ~ 5.7).

- Are LAEs the dominant population at high redshift?

- Use new near-IR data in the Hubble Ultra Deep Field (HUDF) with WFC3 to select galaxies at z ≥ 7.

    - Y (1.05 μm), J (1.25 μm), H (1.6 μm) down to m_{AB} ~ 29

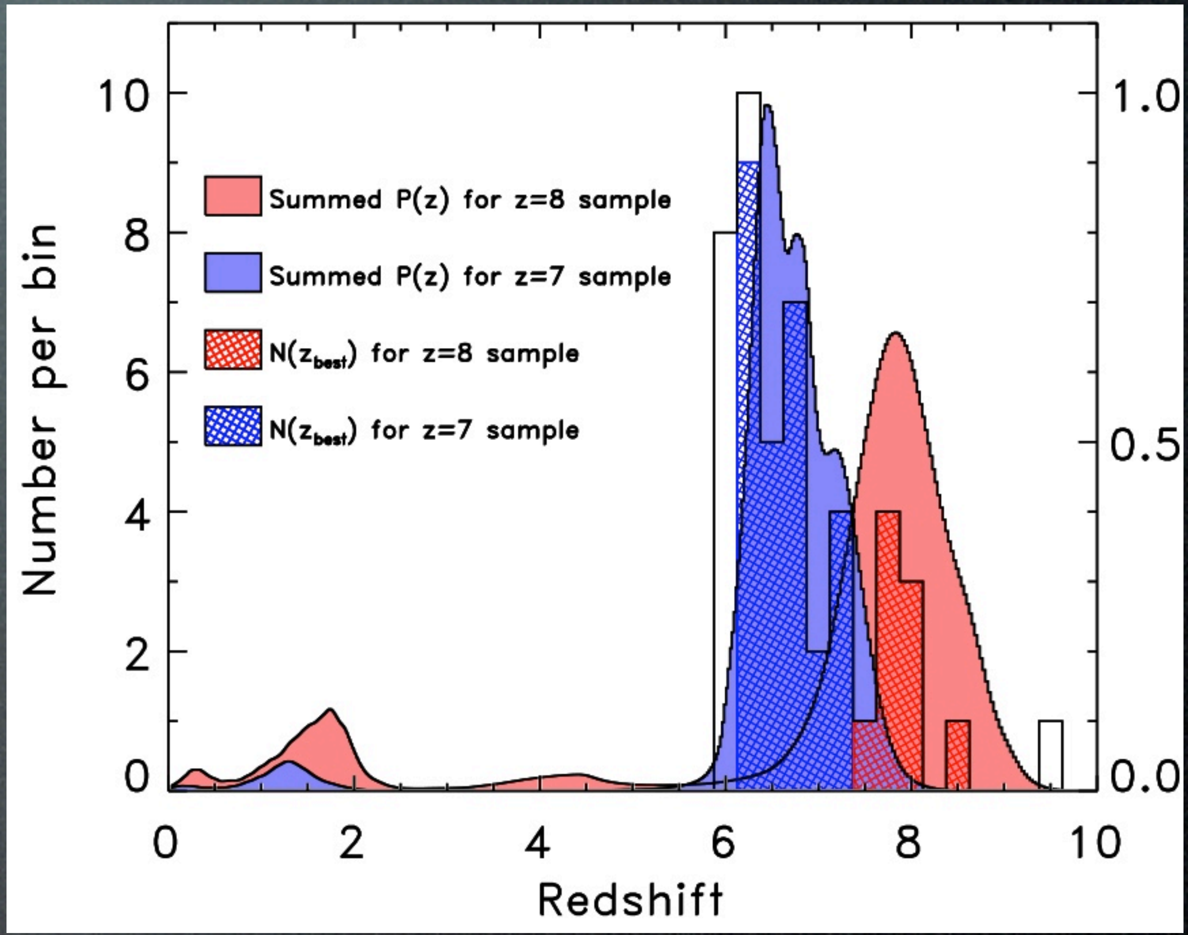
    - Our goal: Study their physical properties, and see how they compare to lower redshift galaxies.

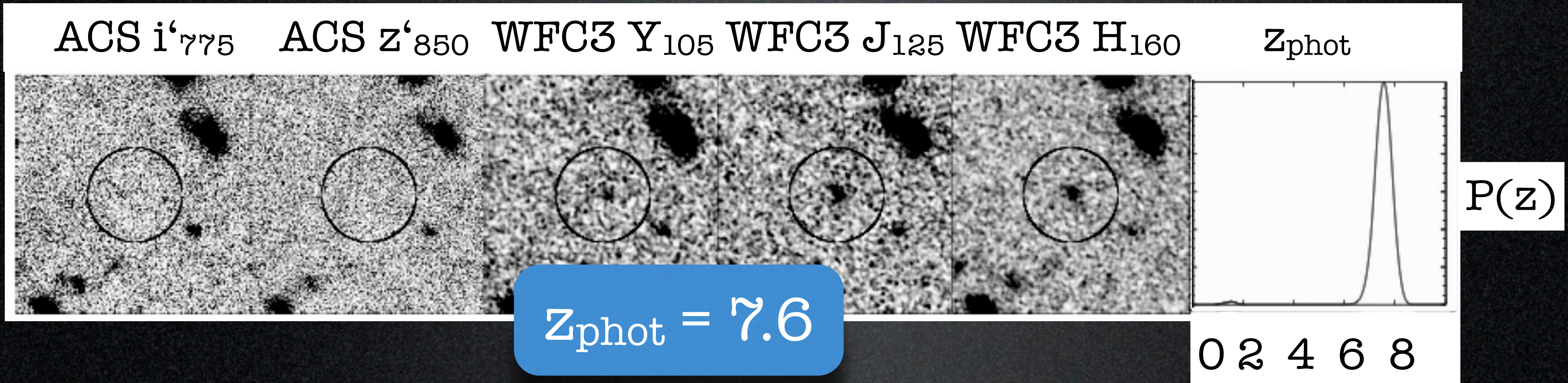
- A number of studies have published dropout samples (Bouwens et al. 2009; Oesch et al. 2009; Bunker et al. 2009; Yan et al. 2009) or photo-z samples (McLure et al. 2009).

    - They did not perform a detailed study of their physical properties.

The Universe at z > 7

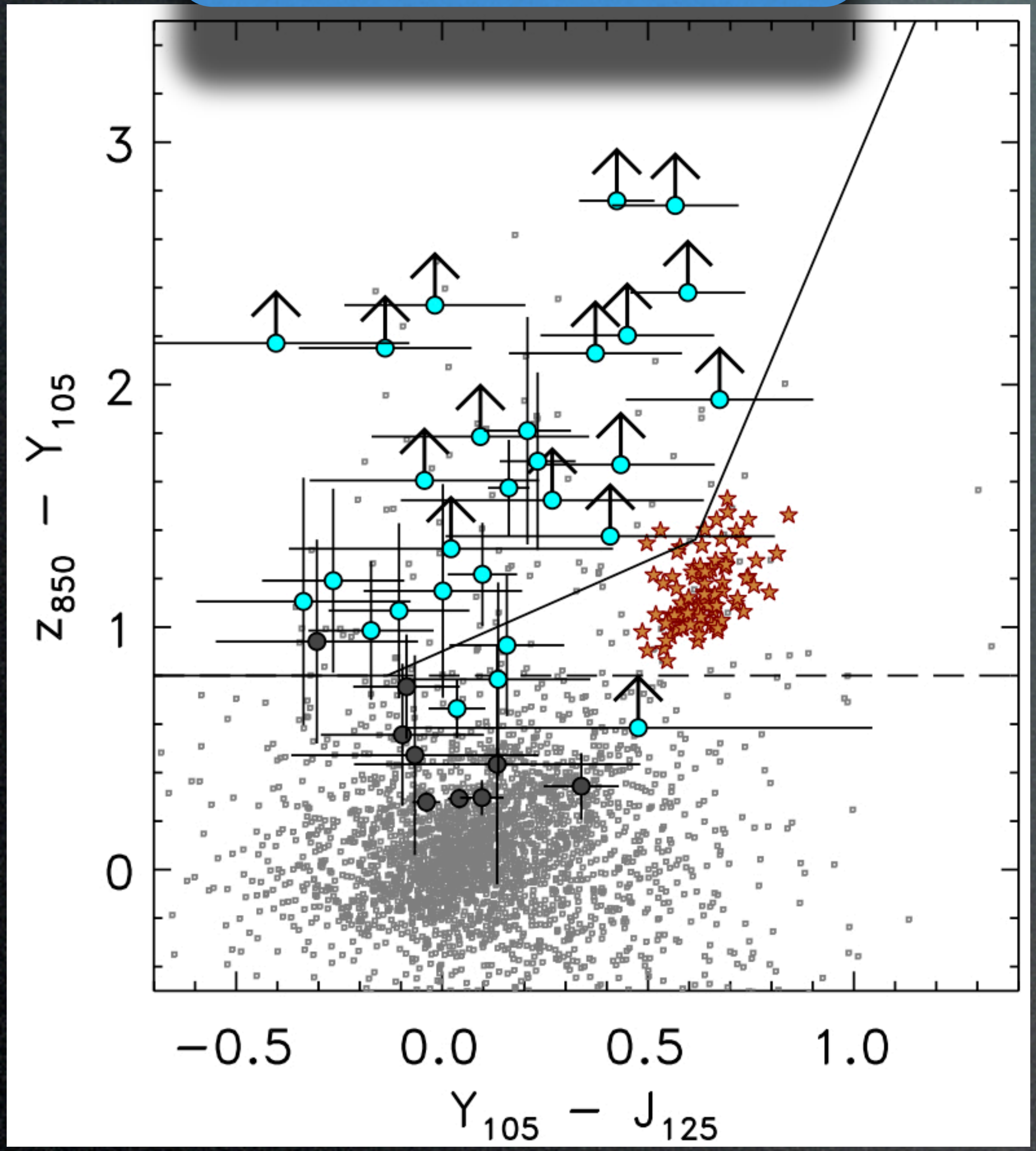
- Using an updated reduction of the WFC3 data, we have performed an independent photometric redshift analysis.
    - Finkelstein & Papovich et al. (on astroph soon)
- Found 35 candidate galaxies at 6.3 < z < 8.7.
    - Universe is ~ 10-15% of its current size.
    - Time since Big Bang ~ 500 Myr



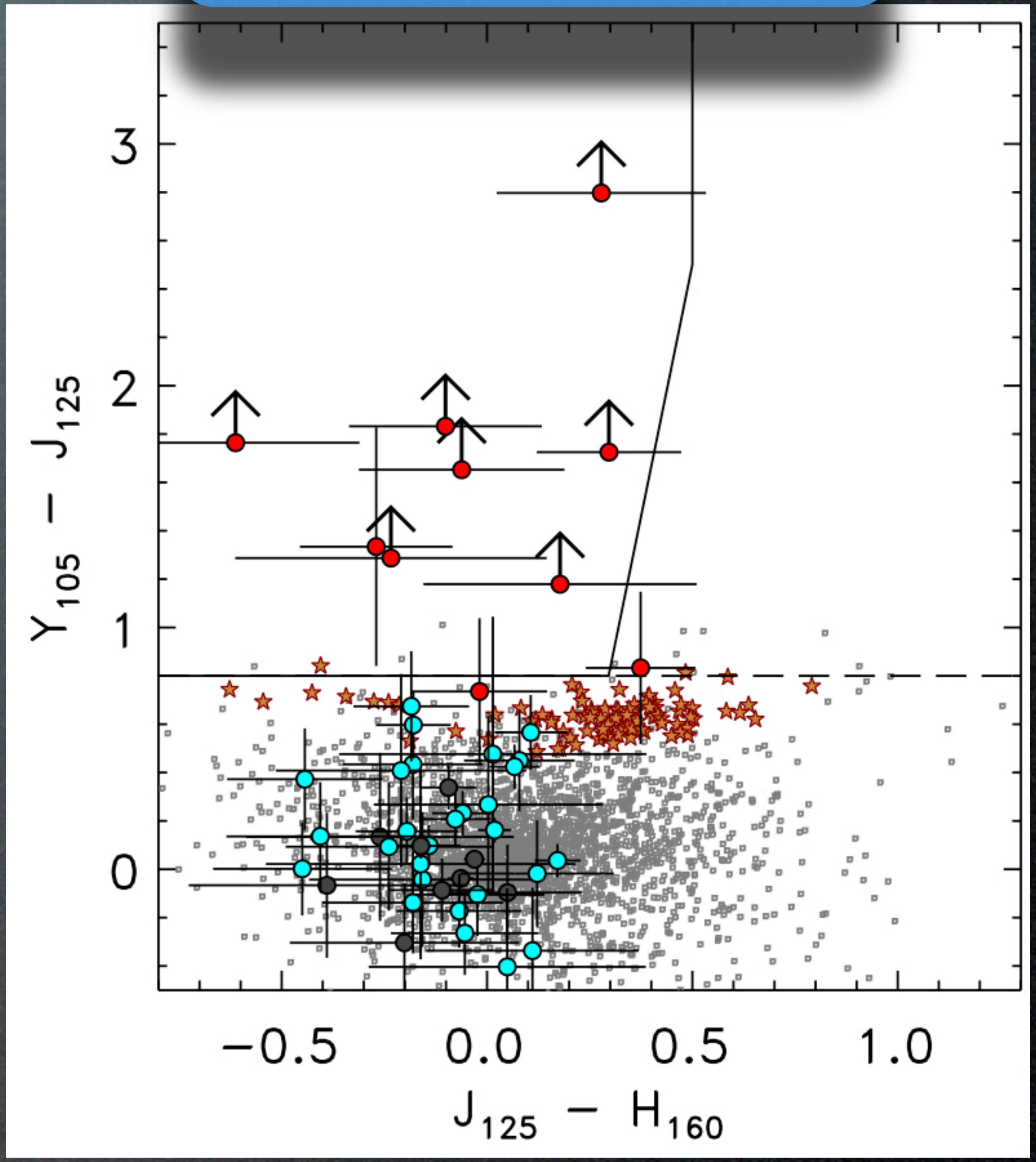


The Universe at z > 7

Oesch et al. (2009) color criteria

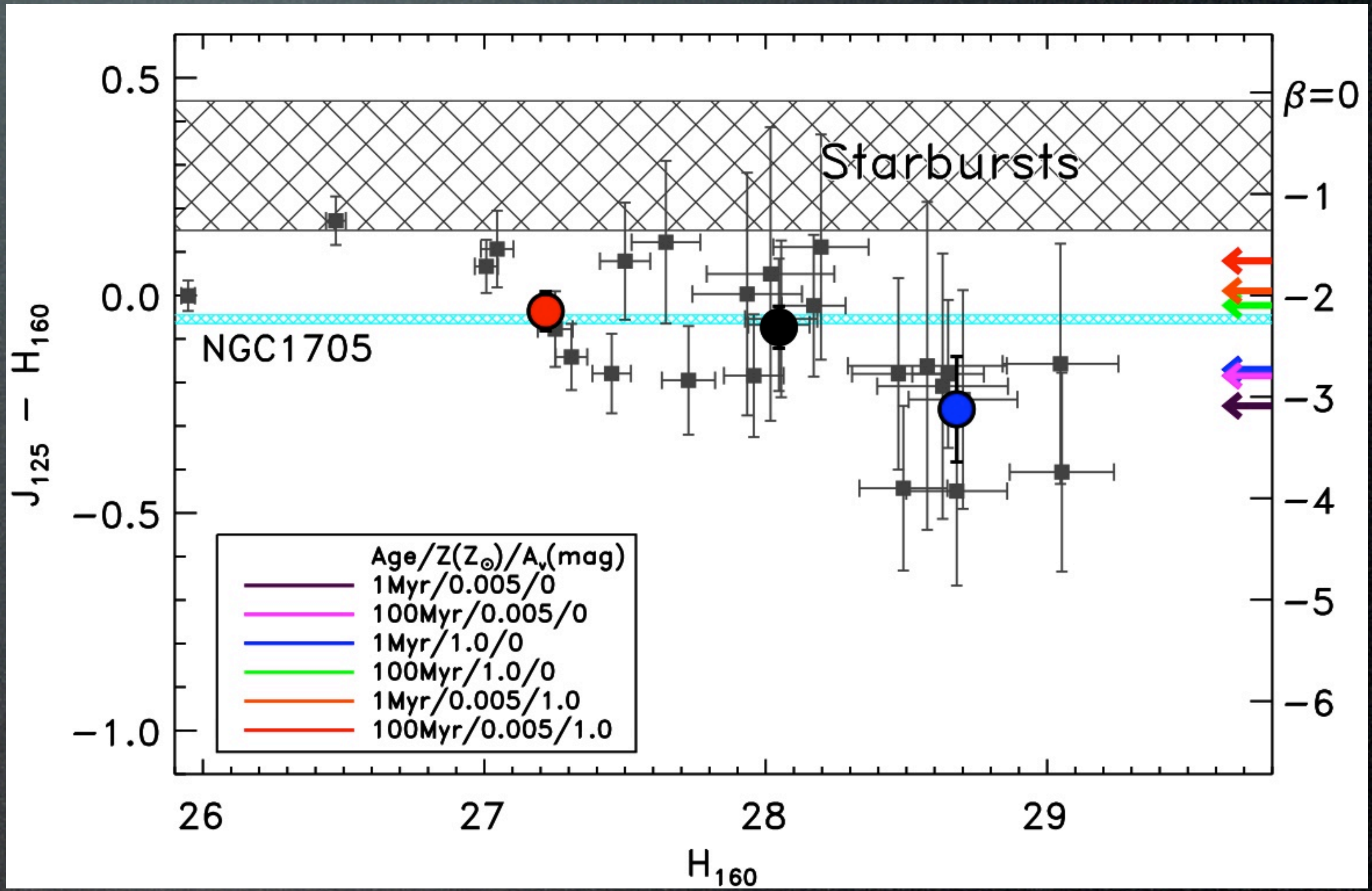


Bouwens et al. (2009) color criteria

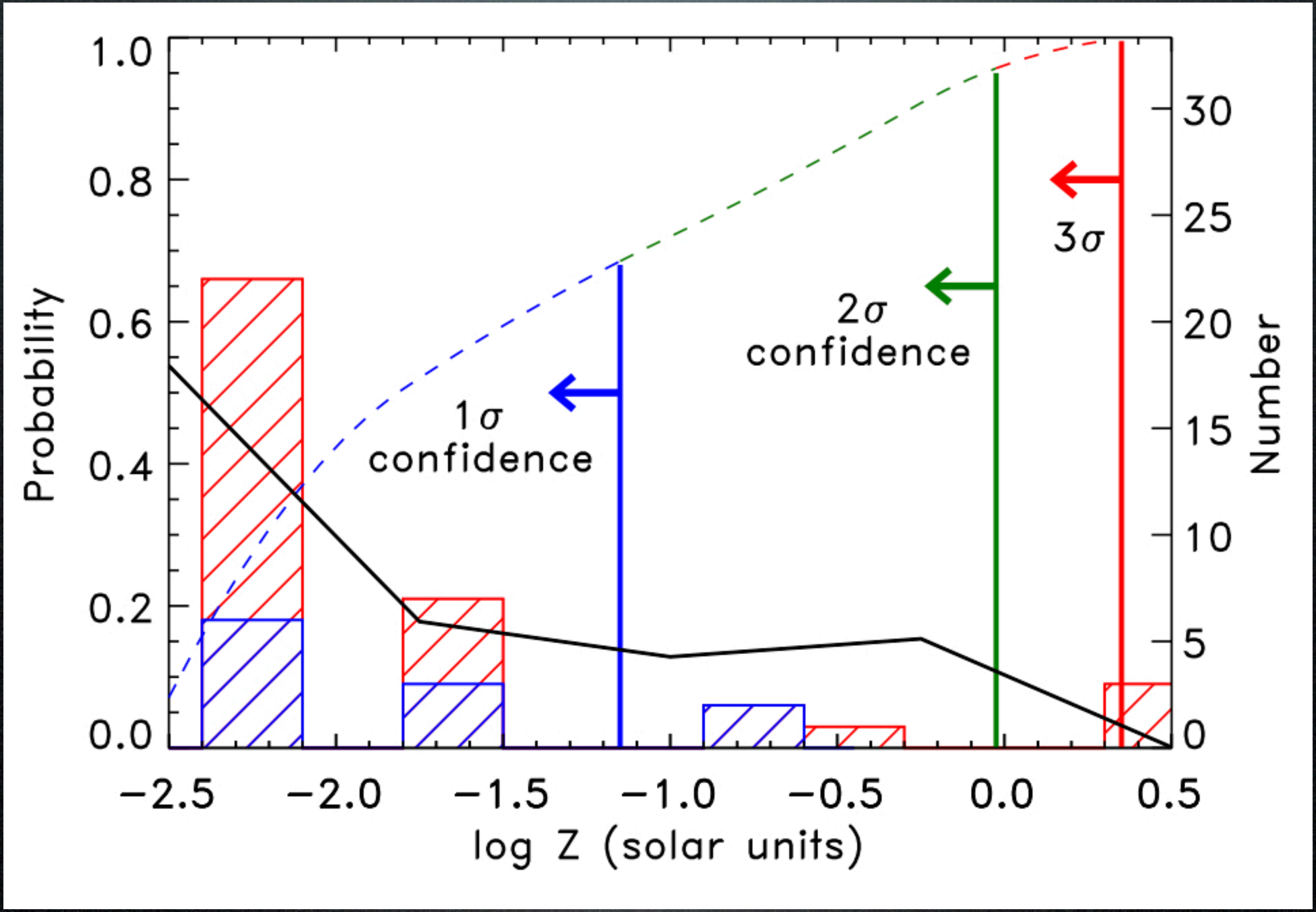


Colors of z ~ 7 Galaxies

- Average our objects due to large individual photometric uncertainties.
- Bluer than the local starbursts of Kinney et al. (1996).
- Faintest galaxies bluer than NGC1705, the bluest local galaxy known.
    - Consistent with little dust extinction, sub-solar metallicities and low ages.



SED Fitting

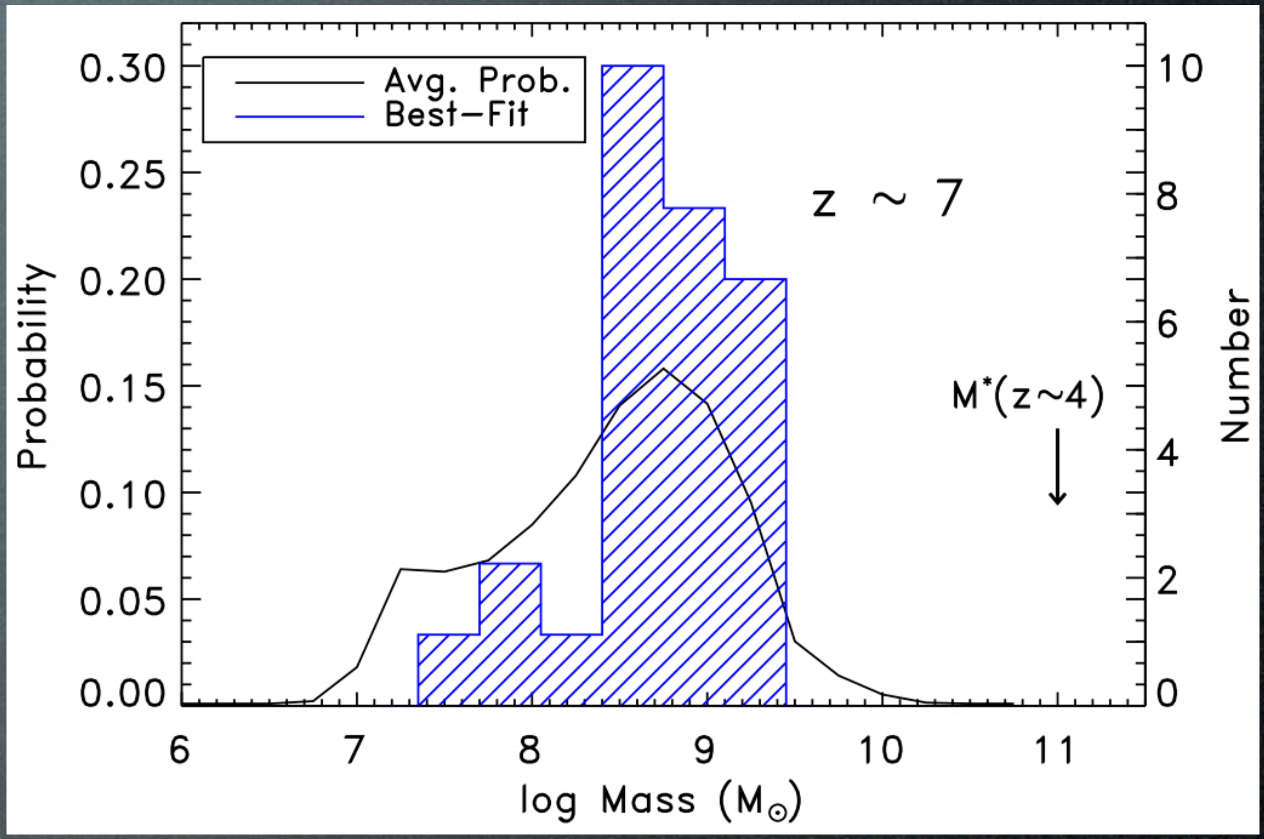


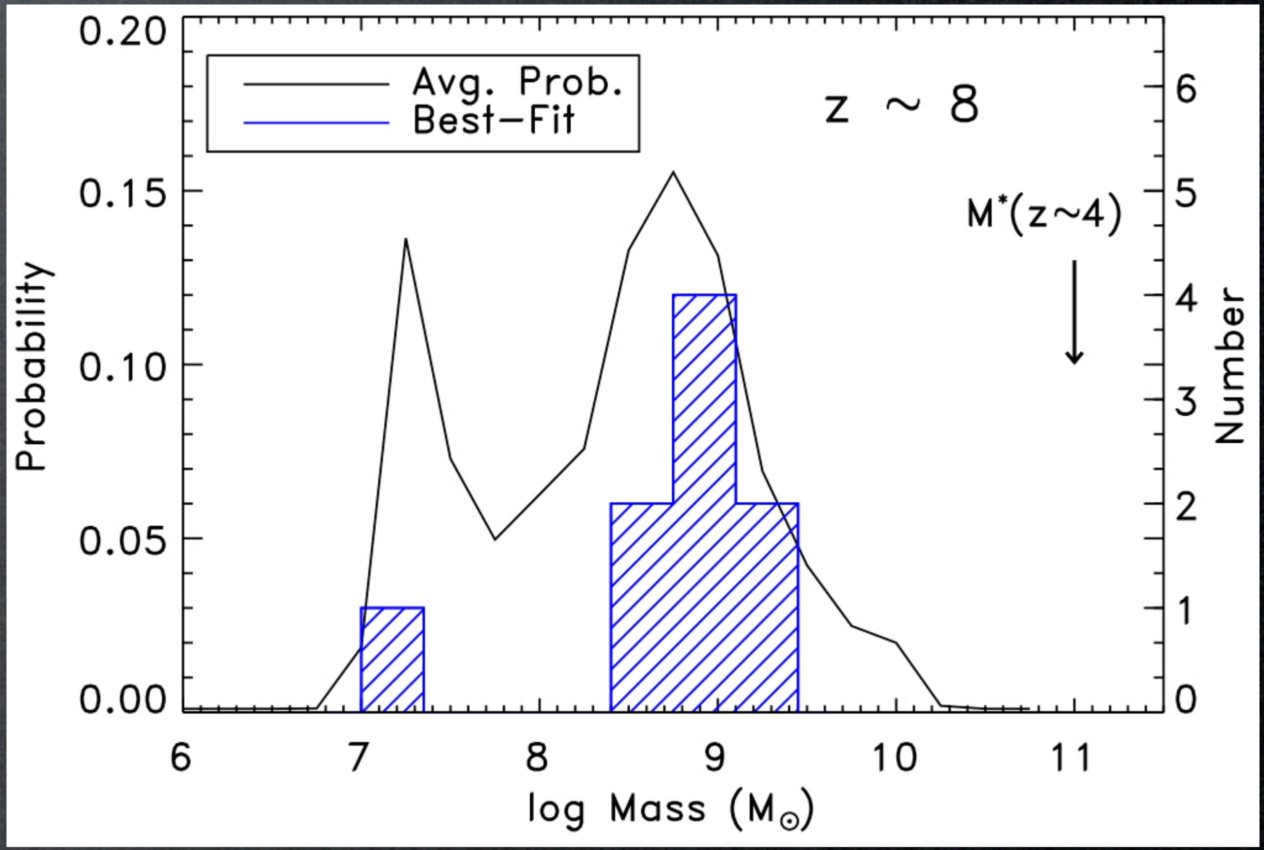
Probability
Number
log Z (solar units)
1σ
confidence
2σ
confidence
3σ
1.0
0.8
0.6
0.4
0.2
0.0
30
25
20
15
10
5
0
−2.5
−2.0
−1.5
−1.0
−0.5
0.0
0.5

SED Fitting

Fit their SEDs using HST + upper limits from Spitzer.

- Age and dust are not well constrained individually.
    - Age < 100 Myr
    - A_V < a few tenths.
- Metallicity is actually fairly well constrained, with $Z < 0.1\ Z_\odot$ (1σ)
- Mass is much better constrained.
- They are very low mass, most 10^8 - $10^9\ M_\odot$
- Maximum masses (90% of mass is forced to form at z=20) are only a few times higher.
    - Mass is well constrained due to the young age of the Universe.





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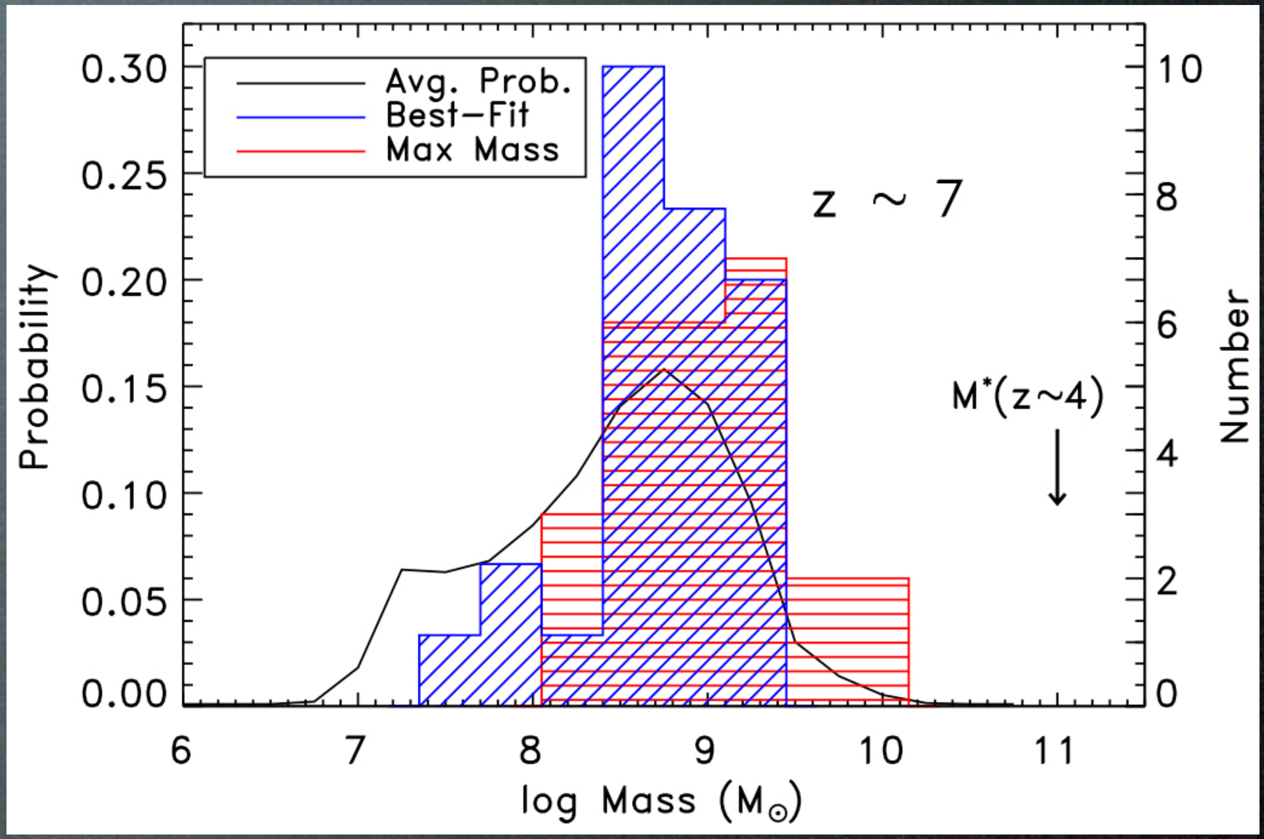
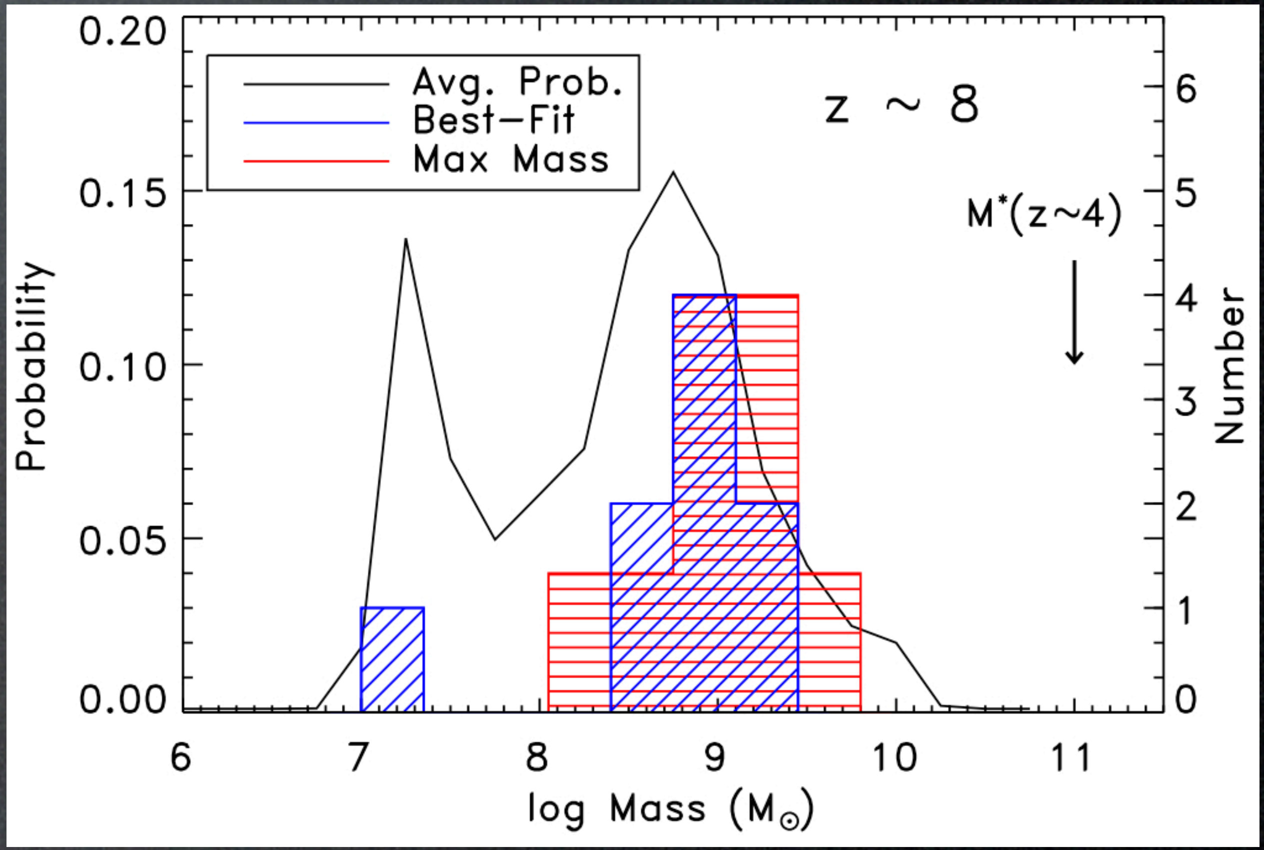
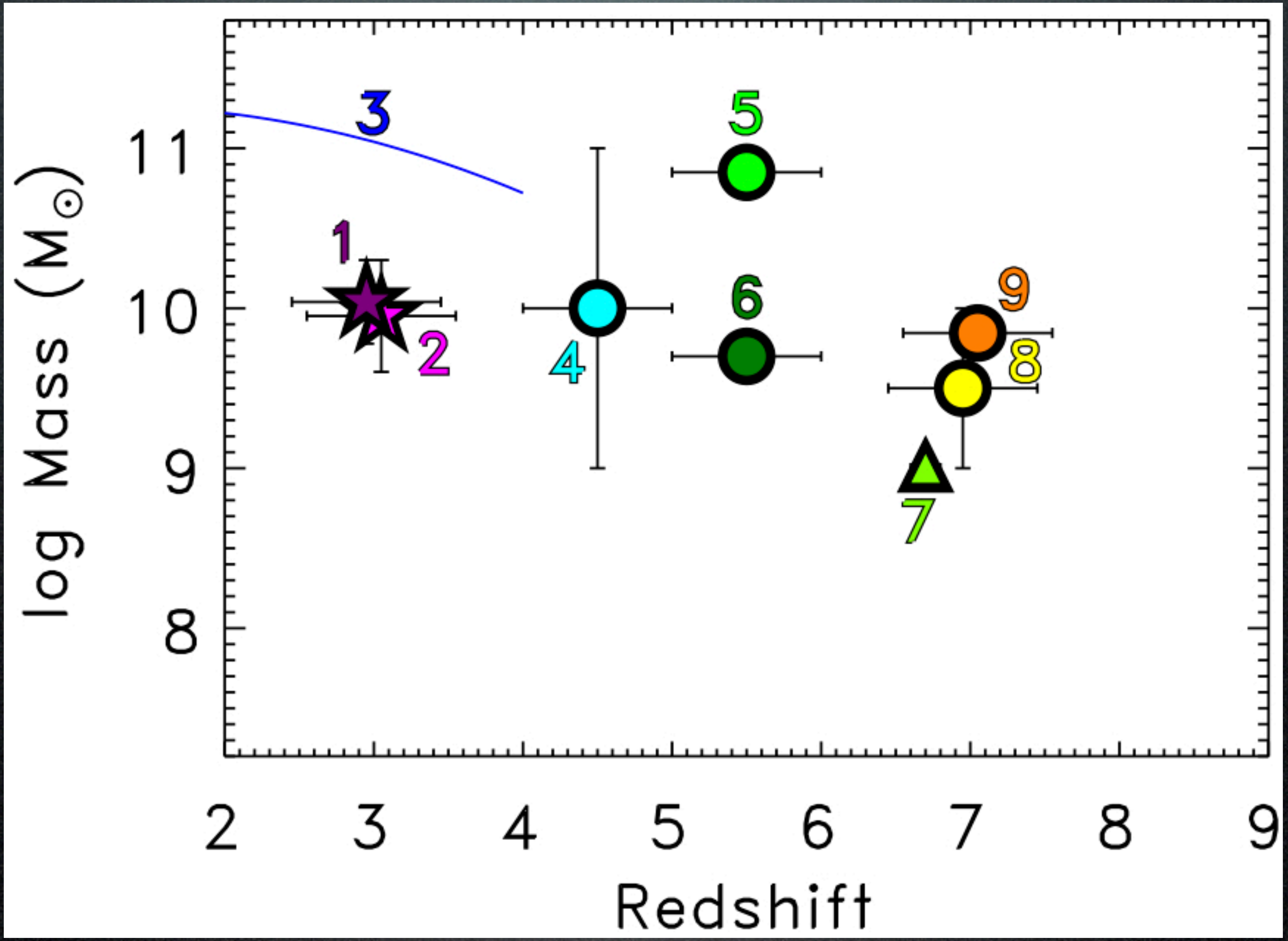




Comparing to Lower-z LBGs



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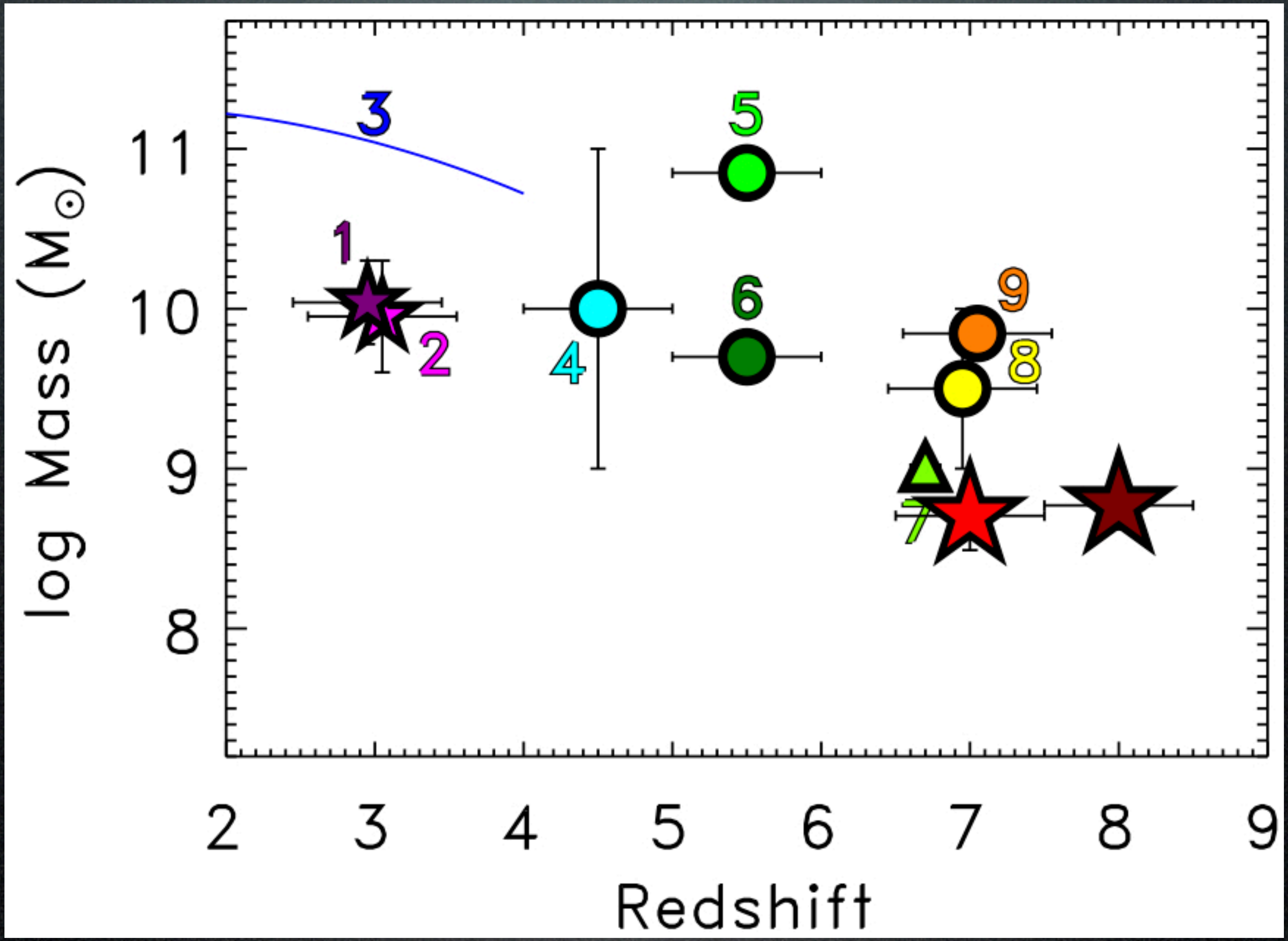
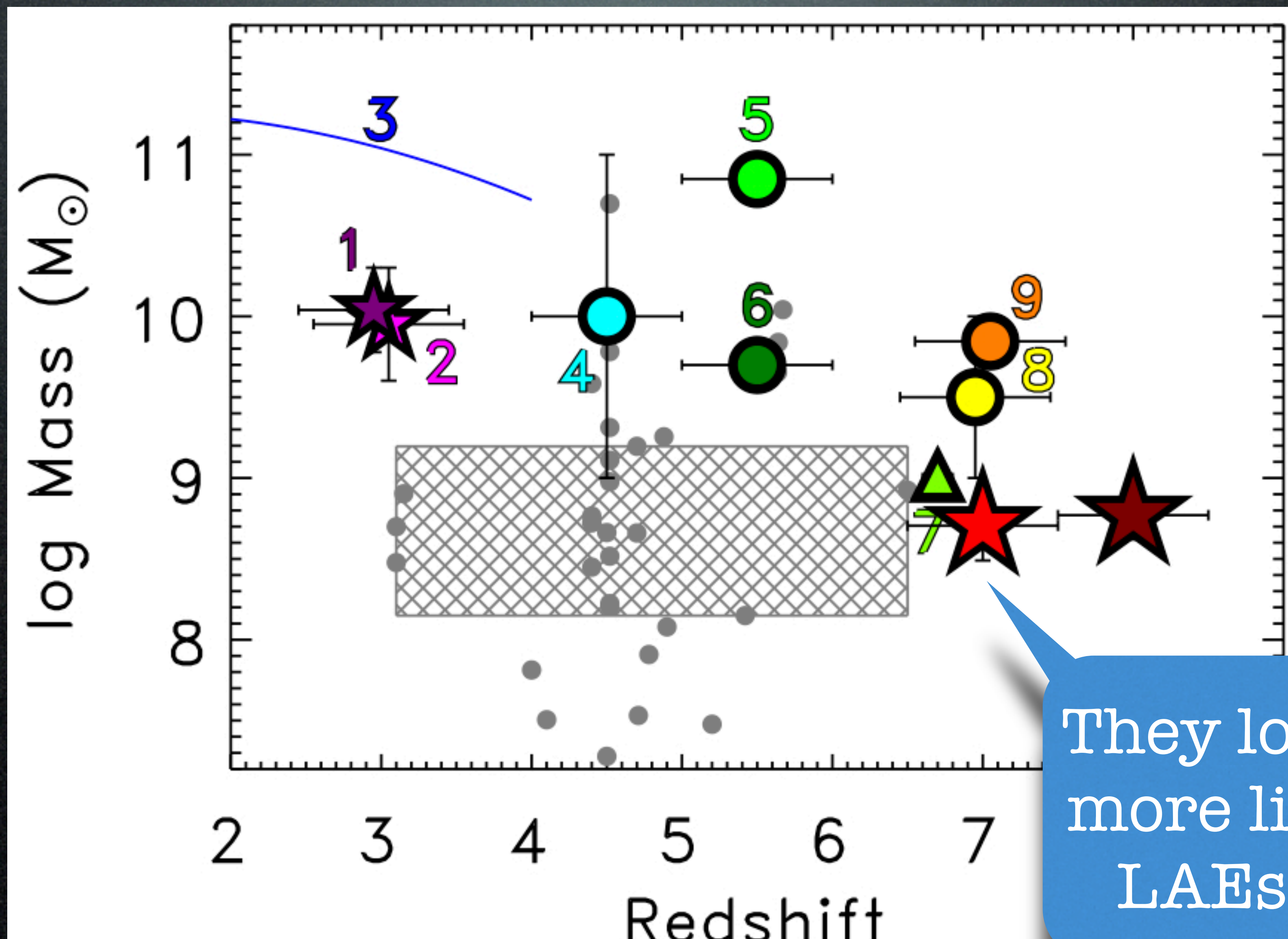


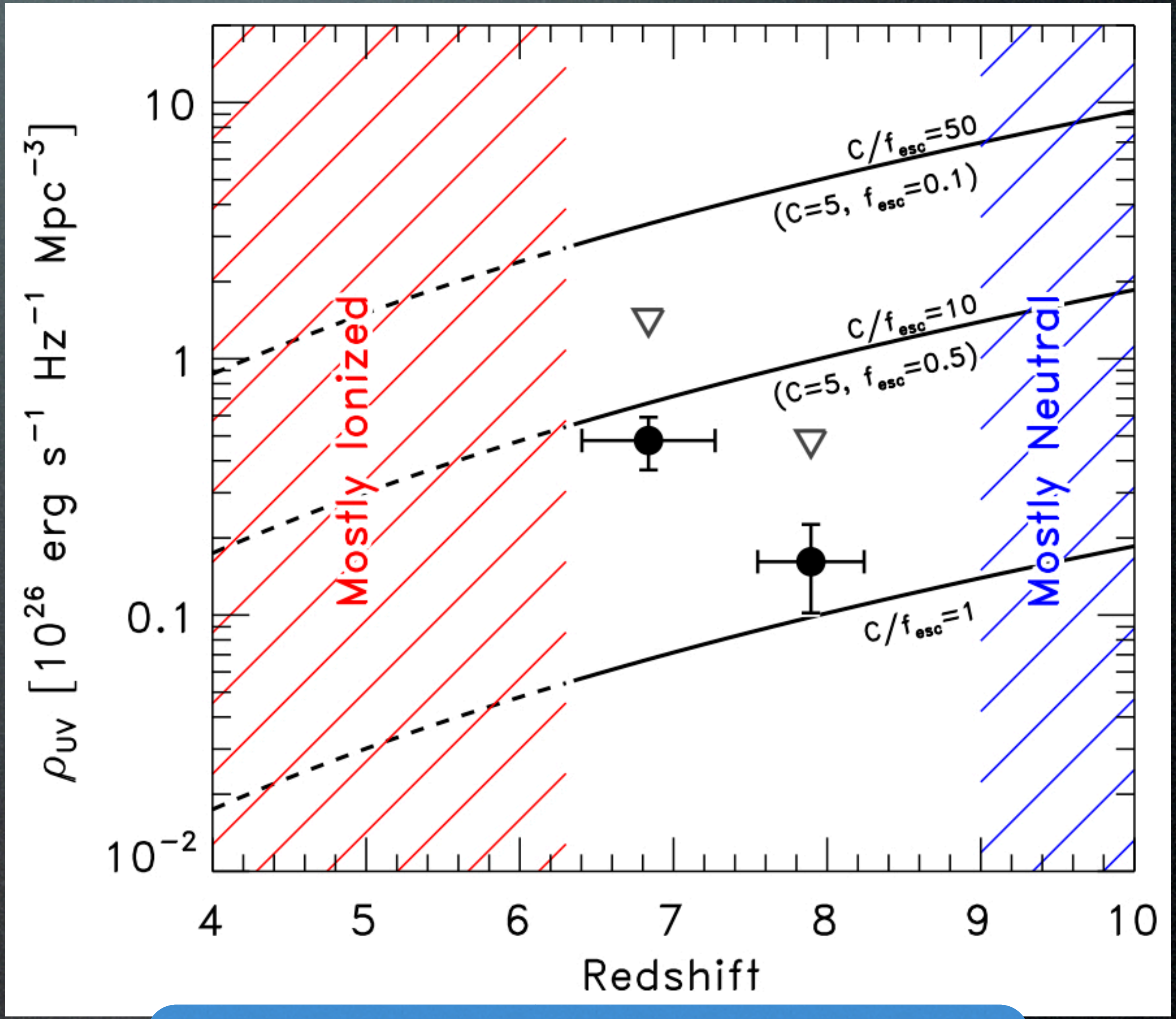
Comparing to Lower-z LBGs



They look more like LAEs!

Reionization

- If we simply add up the observed rest-UV fluxes, our observed galaxies are sufficient to reionize the universe for values of f_{esc} > 0.5
- Assuming hydrogen clumping factor likely ~ 5-10 (Pawlik et al. 2009; Finlator et al. 2009).
- Accounting for unseen galaxies pushes this limit a little lower.
- Fainter ones likely driving reionization.
    - Less dust => higher f_{esc}.



Galaxies are the dominant source of ionizing photons!

Conclusions

- LBGs and LAEs can be found in large numbers at high redshifts ($z \geq 3$) using color selection techniques.
- LAEs primarily appear to be much less evolved than LBGs.
    - Young (< 100 Myr), low-mass (< 10^9 $M_\odot$).
- LAEs do not significantly evolve with redshift, thus they may be building blocks of larger galaxies at each redshift.
- LBGs at $z > 7$ appear similar to LAEs in physical characteristics.
    - Could it be that at $z > 7$, only these LAE building blocks exist?

Thanks!