Rest-Frame UV Studies of z > 4 Galaxies and Their Observability with CCAT

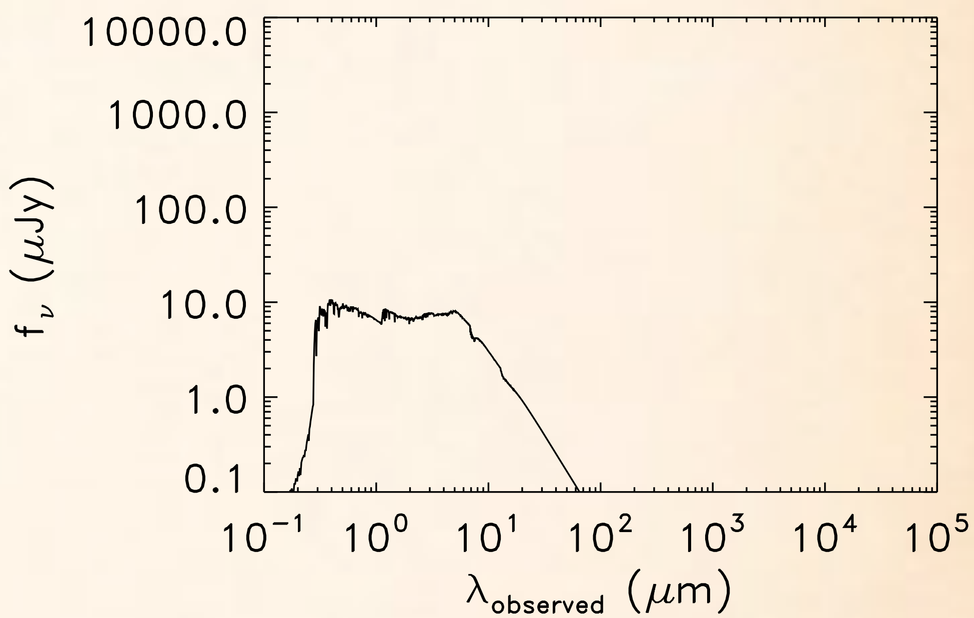
Steven Finkelstein

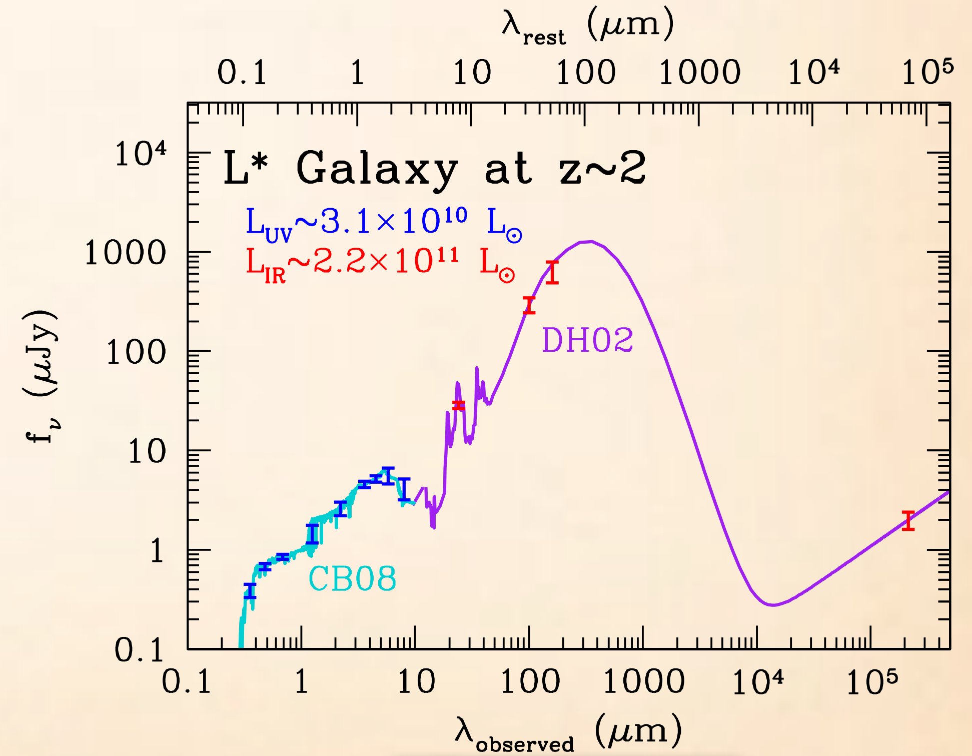
The University of Texas at Austin

with Casey Papovich, Harry Ferguson, Mark Dickinson, Mauro Giavalisco + CANDELS Team

MEASURING THE SFR

- Studying the star-formation rates of distant galaxies is one of the most useful parameters we can observe.
    - In particular, the star-formation histories tells us about how galaxies build up their stellar mass with time; a key observable we can compare to theoretical models.
- HST studies of high-redshift galaxies probe only the rest-UV light from galaxies.
    - Dominated by recent star-formation, thus measuring the quantity of UV light, we should be able to deduce the star-formation rates of galaxies.
- But, the UV doesn't tell the whole story; dust obscures the UV, causing one to underestimate the SFR.

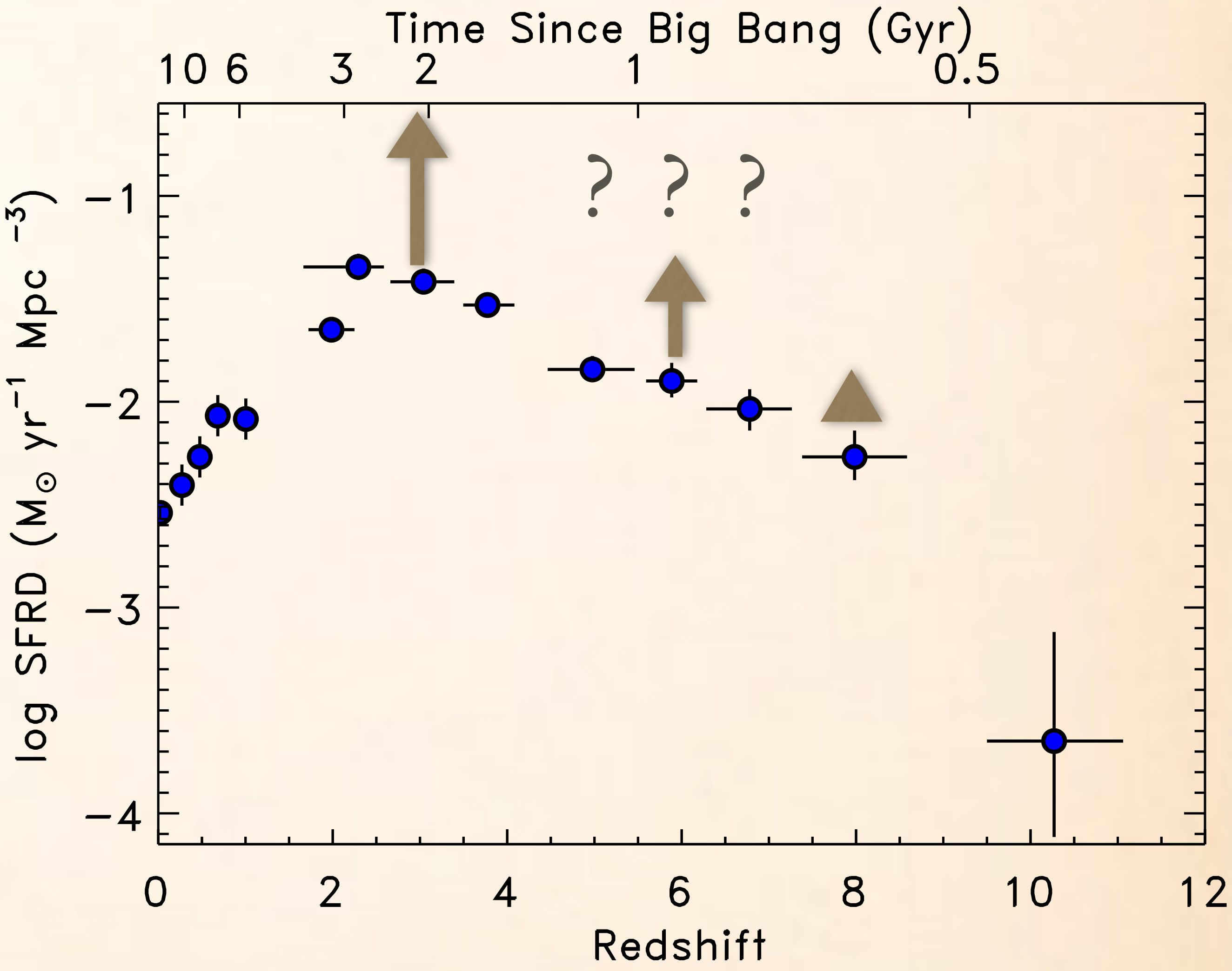




Reddy+2012

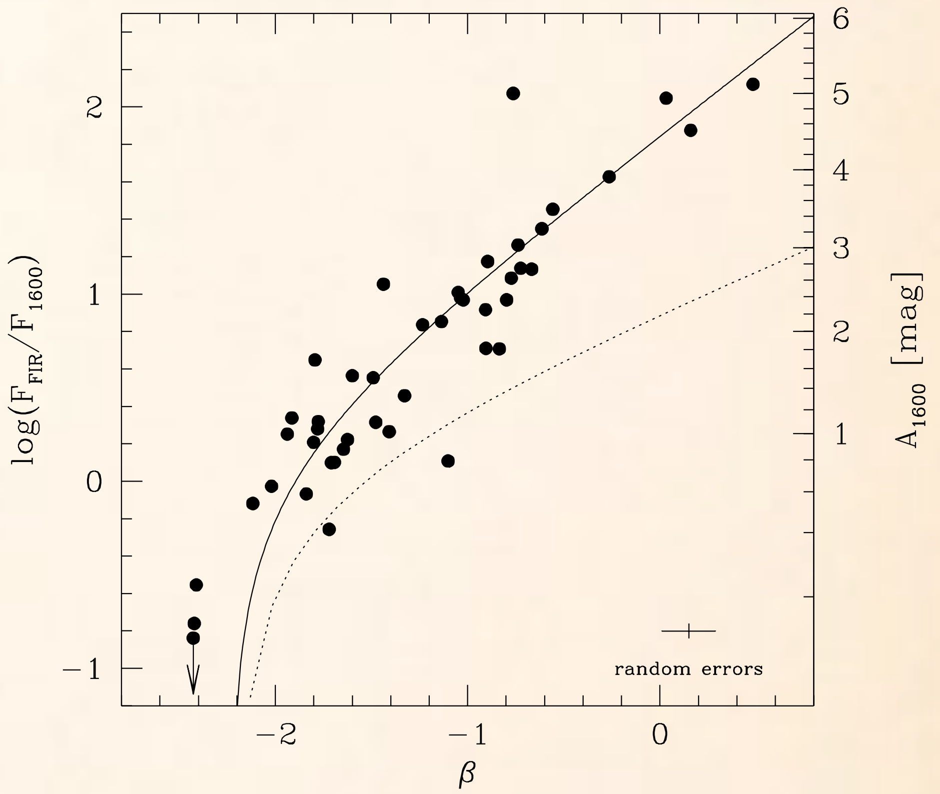
STAR FORMATION RATES

- Star-formation rate density versus redshift.
    - From UV measurements at each redshift.
    - Just one magnitude of extinction in the V-band reduces the derived SFR by a factor of 2.5.



MEASURING THE TRUE SFR

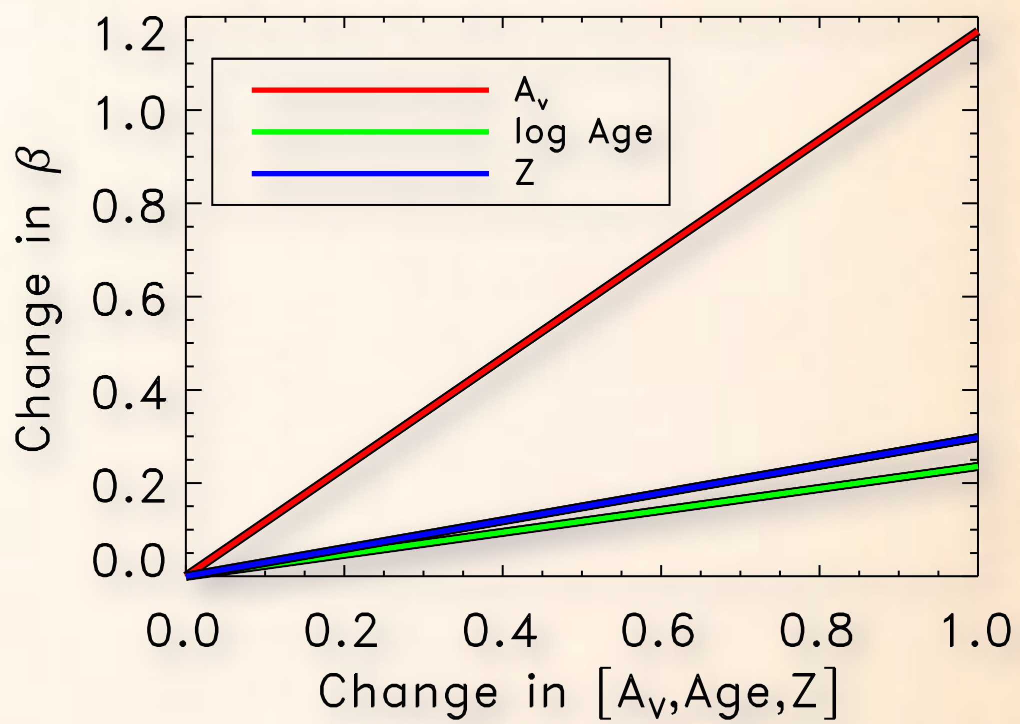
- How do we handle this?
  - Correct for the obscuration.
    - If we knew how much UV light the dust was attenuating, we could correct for it!
  - Quantified in Meurer et al. (1999)
    - Found that the slope of the UV part of the spectrum correlated with the ratio of FIR/UV emission.
      - $f_\lambda \propto \lambda^\beta$
      - $A_{1600} = 4.43 + 1.99*\beta$
  - If this holds at all redshifts, then simply rest-frame UV observations can provide us an estimate of the total SFR.

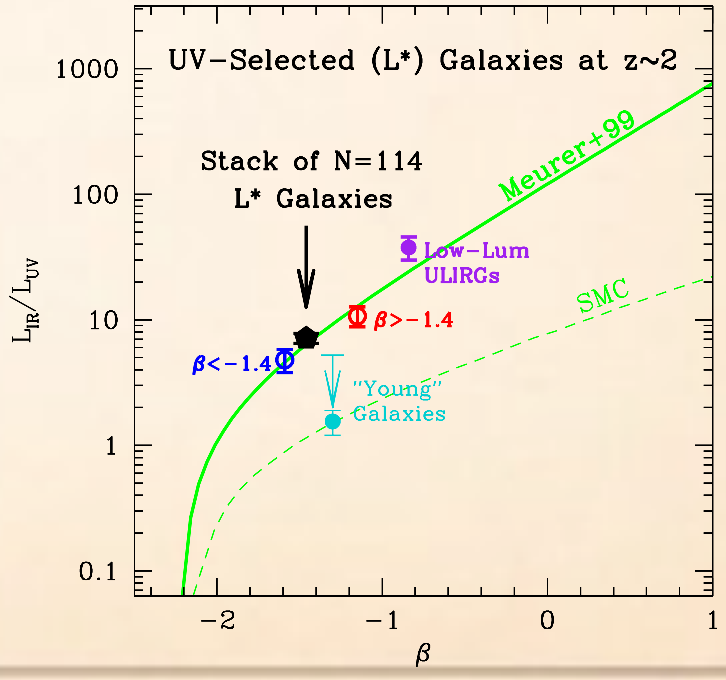


Meurer et al. 1999
Local UV-selected starburst galaxies measured with IUE and IRAS

IS BETA A GOOD DIAGNOSTIC?

- How much does the value of β track the dust extinction?
- Does this relation even hold at high-redshift?
  - Evidence that it does for L* galaxies. Perhaps not for young galaxies (different extinction curve?).



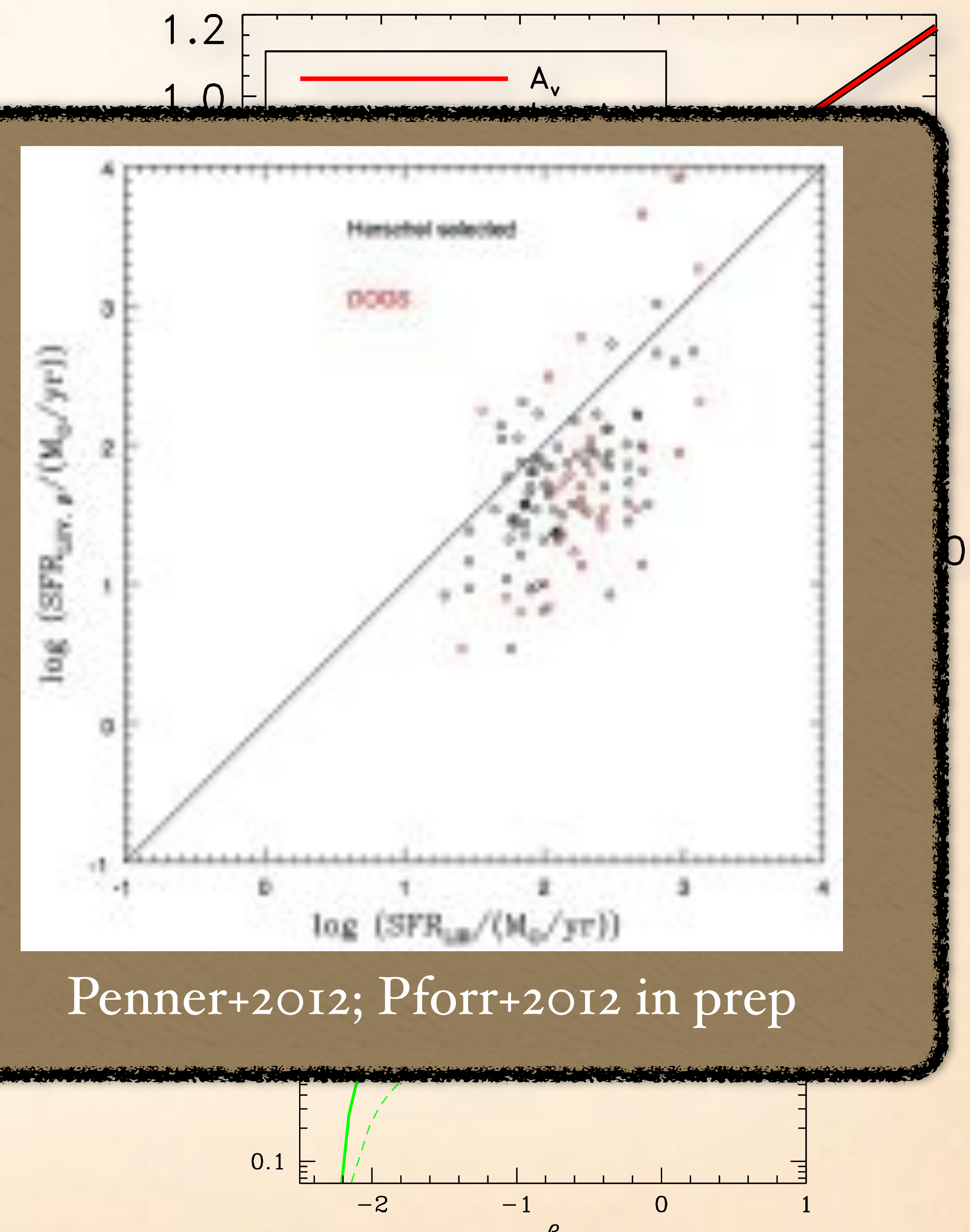


IS BETA A GOOD DIAGNOSTIC?

The UV spectral slope *may* be able to correct the UV for extinction at high-redshift.

However, uncertainties are high, so a dust-corrected SFR will be highly uncertain, and it doesn't work well for highly attenuated objects.

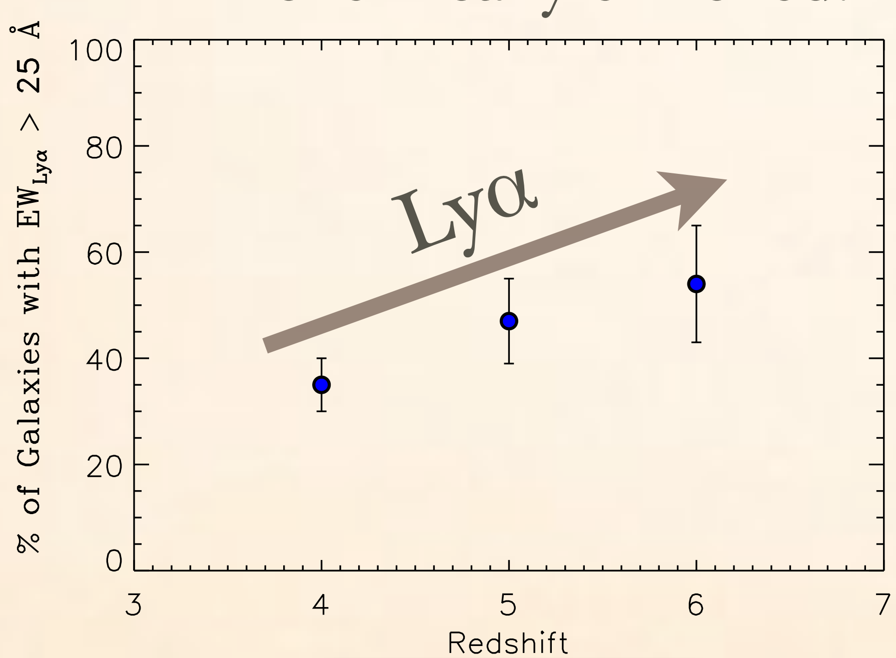
Ideal: UV (or Hα) + FIR



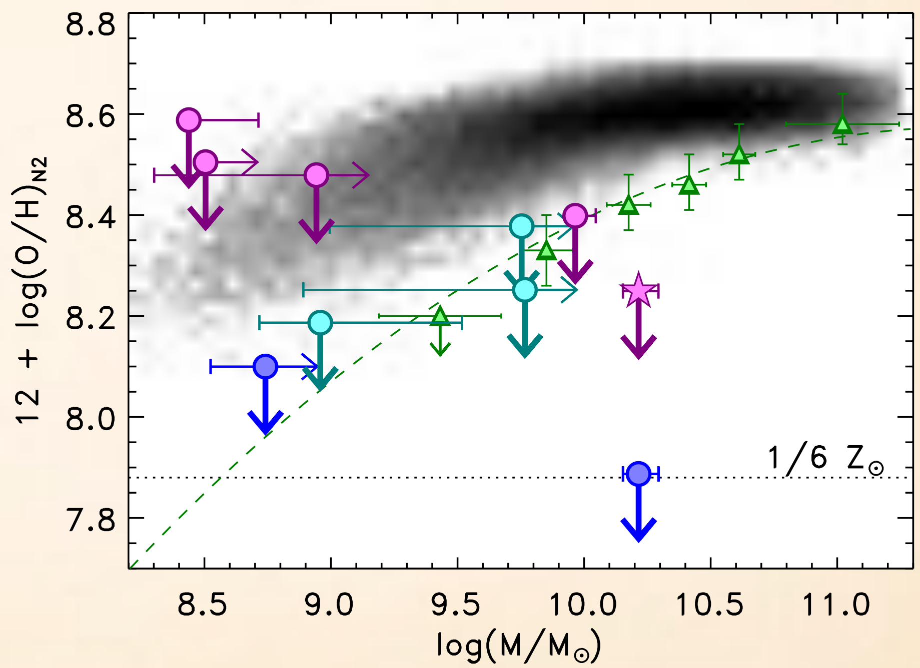
Penner+2012; Pforr+2012 in prep

IS THIS EVEN A PROBLEM?

- At $z > 4$, where we think galaxies are building up in earnest, is there even enough dust around to be a problem?
  - $z=4$ is only ~1.25 Gyr from $z=15$ (a reasonable estimate for the epoch of galaxy formation).
    - Is that enough time for large dust reservoirs to form?
      - Some evidence already that these galaxies might not be too chemically enriched.



Stark+11



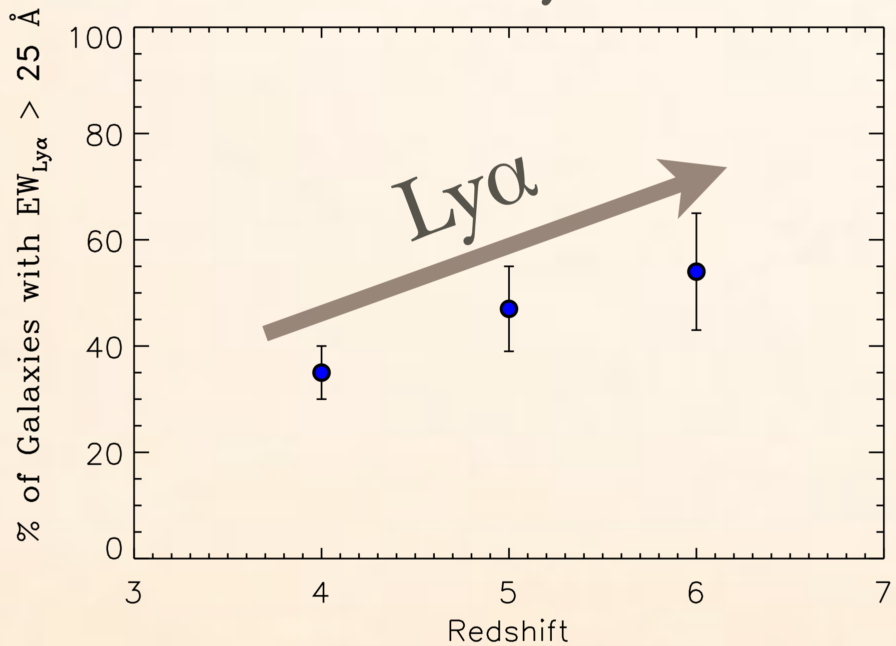
Finkelstein+11; Mimi Song+12 in prep

IS THIS EVEN A PROBLEM?

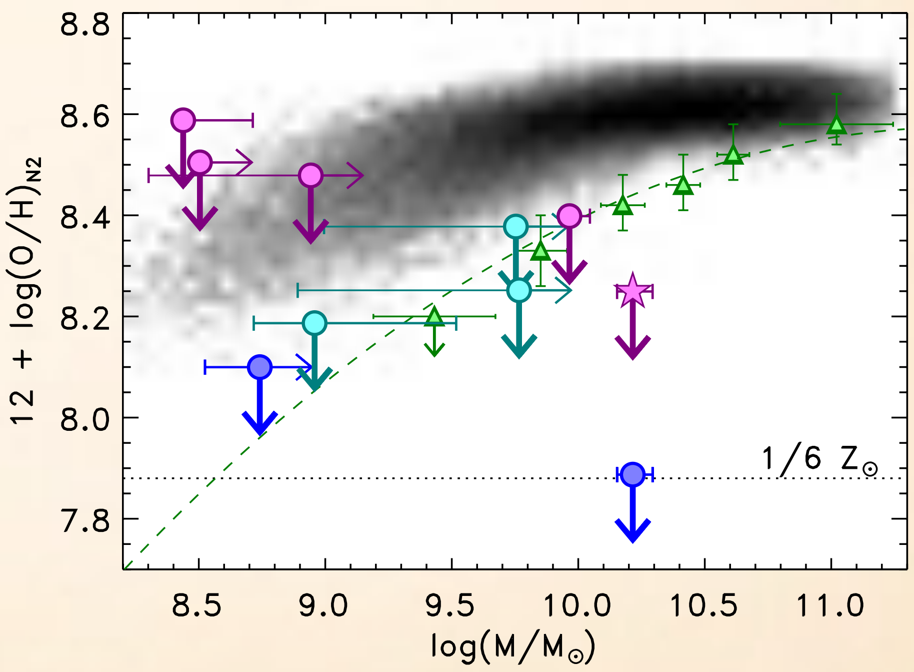
- At z > 4, whe ere even enough dust
  - z=4 is onl epoch of galaxy fo
    - Is tha
      - So e too chemically enriched.

We would expect dust to track metals.
But, dust can build-up quickly:

SNe: ~immediate (if the dust survives)
AGB stars: ~500 Myr



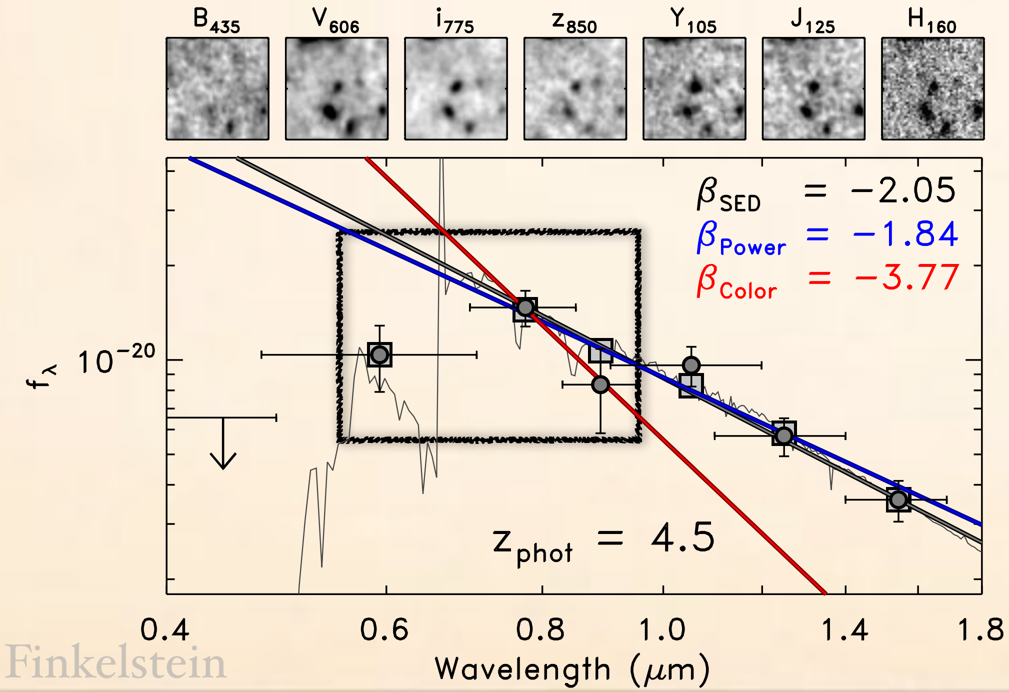
Stark+11

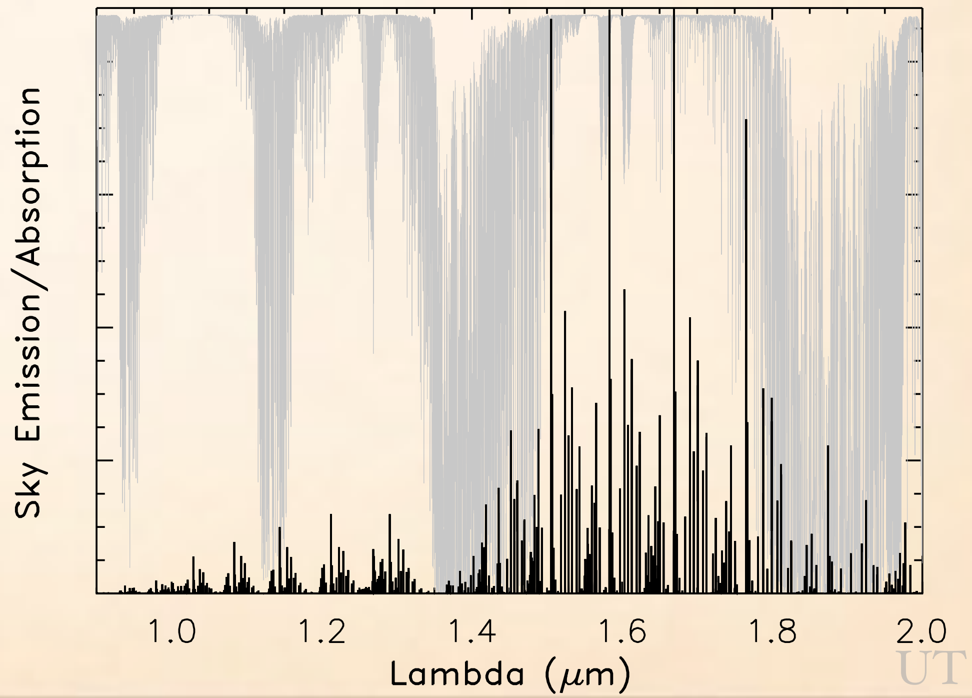


Finkelstein+11; Mimi Song+12 in prep

WE NEED TO FIND OUT WHETHER DUST IS PRESENT AT HIGH-REDSHIFT

- This has been a major focus of my work, which centers on:
  - Discovering galaxies at all high redshifts (z ≥ 4)
  - Robustly measuring their colors.
  - Inferring their physical properties, and the evolution of these properties with redshift.
- This requires deep near-infrared imaging to measure robust colors at z=4, 5 and 6, and to discover the galaxies at z=7 and 8.





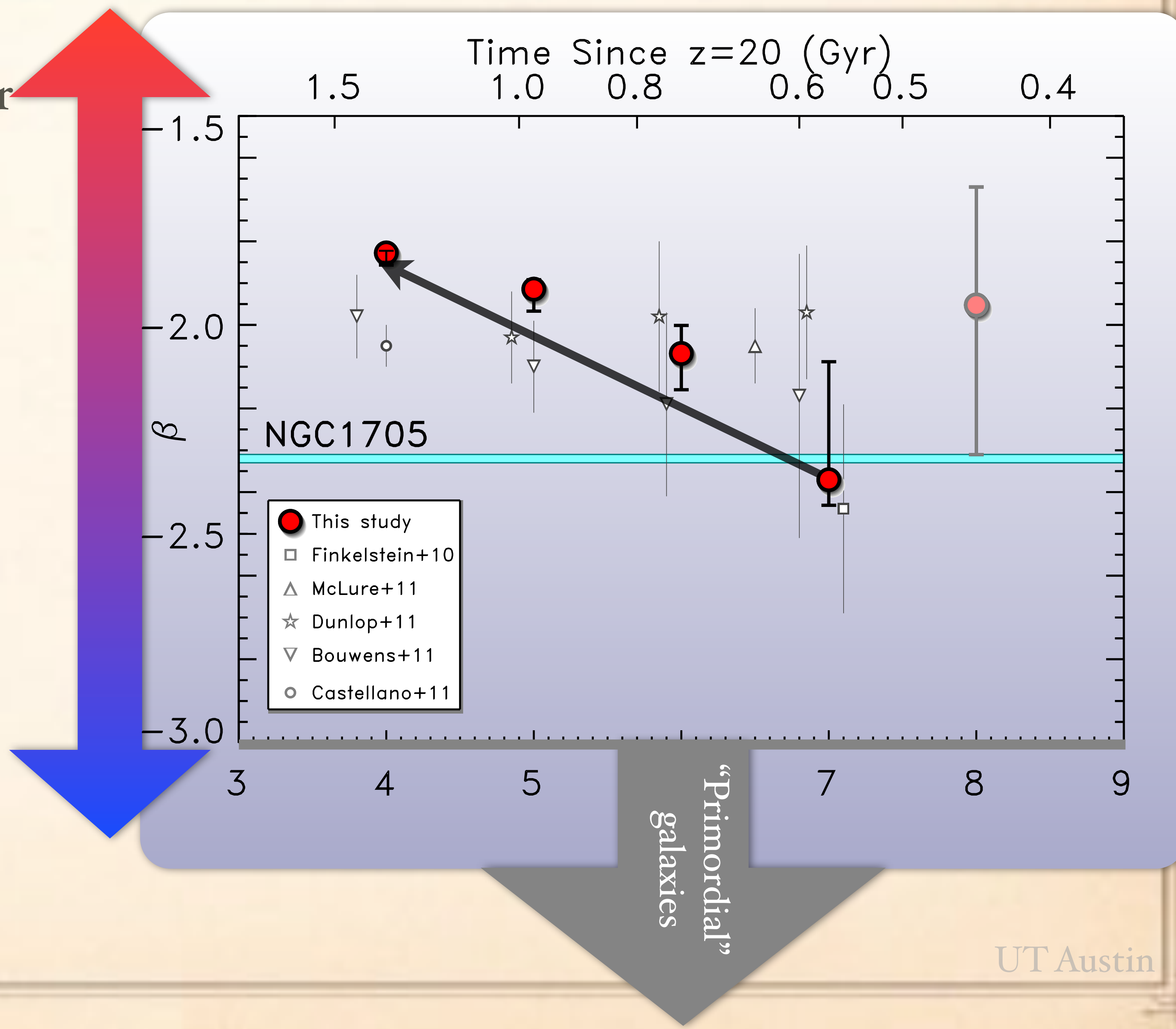
Initial papers used these data to probe the colors of very high redshift galaxies ($z > 7$), finding them consistent with no dust (Bouwens+10; Finkelstein+10).

Hubble Ultra Deep Field
Hubble Space Telescope • Advanced Camera for Surveys

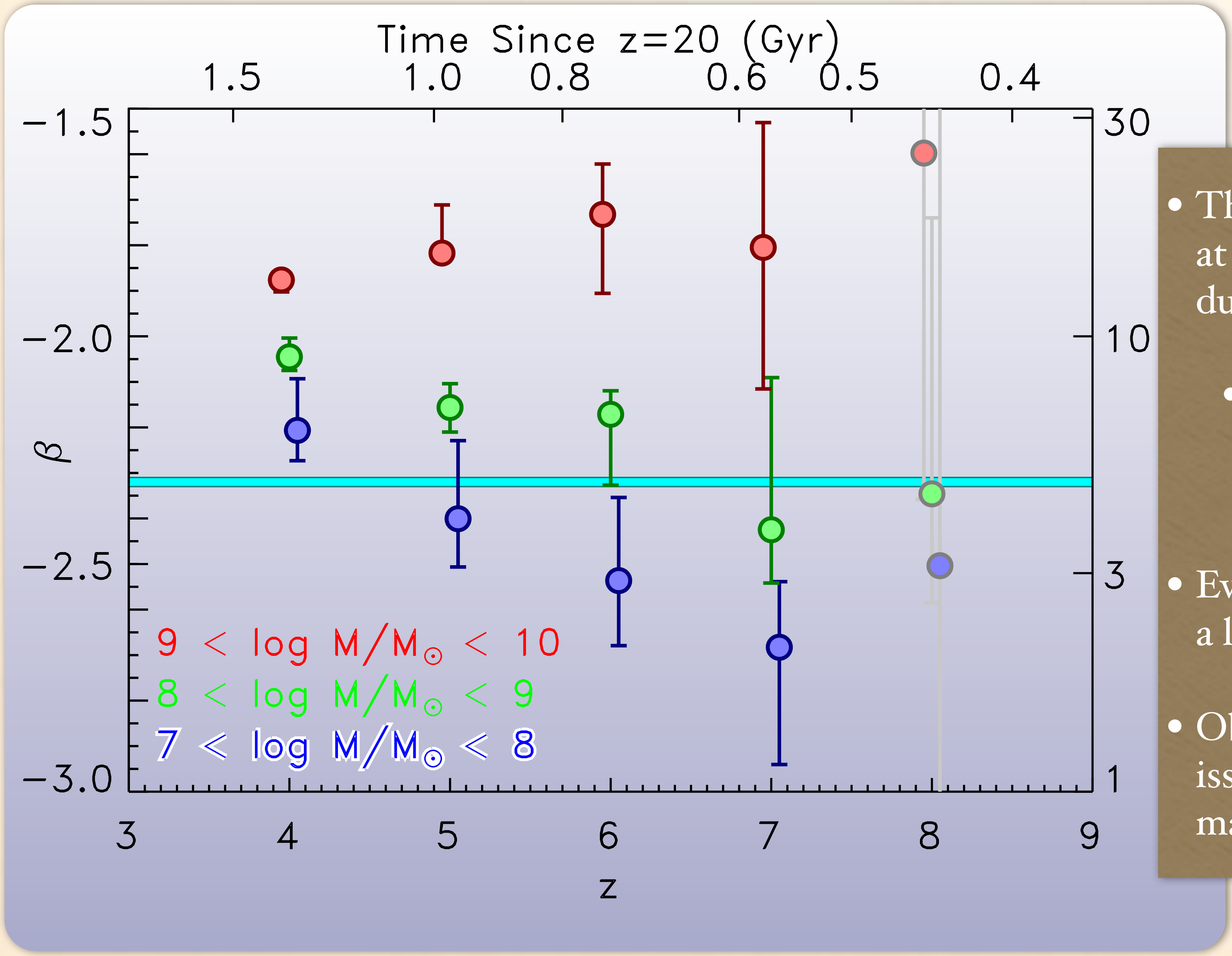
Hubble Ultra Deep Field
Hubble Space Telescope • Advanced Camera for Surveys

GALAXIES GET REDDER WITH COSMIC TIME

- Measured β for each galaxy in our sample via SED fitting.
    - Less scatter and bias than other commonly used methods.
- Measured the median β at each redshift.
    - What about the faint galaxies at z=7?
- β increases by ~ 0.5 in < 1 Gyr of cosmic time.
    - A_V = 0 ➜ 0.3-0.4 mag
    - Galaxies build up their dust reservoirs quickly!



DUST DOES FORM AT HIGH REDSHIFT, BUT ONLY STICKS IN MASSIVE GALAXIES



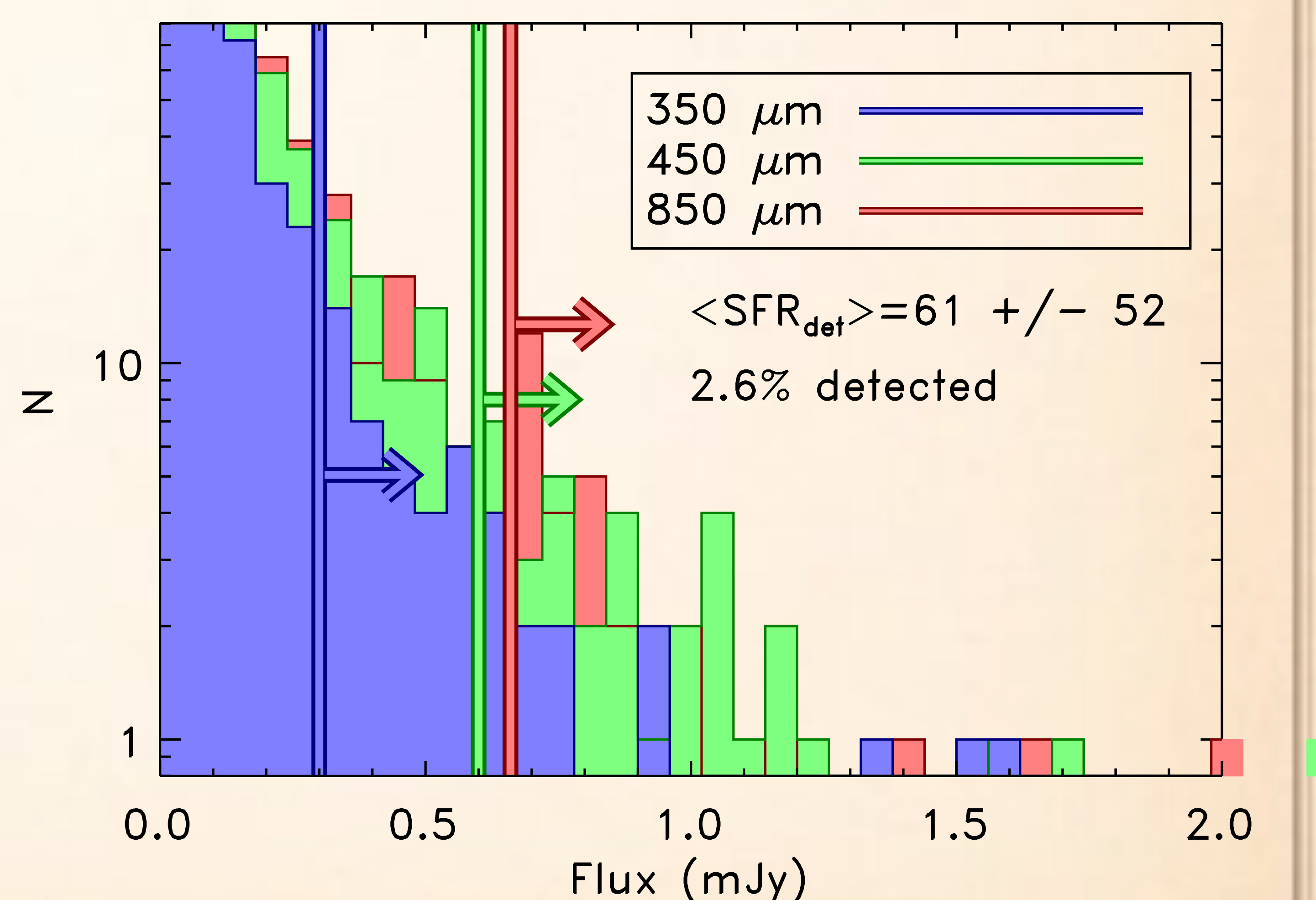
- The most massive galaxies are dusty at z=7. Could outflows be removing dust from the lower mass galaxies?
  - Similar to the mass-metallicity relation observed at lower redshift.
- Even relatively low-mass galaxies are a little dust at z=6.
- Obscured star-formation is a real issue at z > 4 for all but the least massive galaxies.

CAN WE OBSERVE THIS DUST IN EMISSION?

- Dust does form early, so we need to account for it (though its impact may lessen with decreasing mass).
- Most robust way to do this is by directly measuring the dust in emission. Can this be done for “normal” galaxies at high redshift?
  - Following the Meurer relation, we can “predict” what the FIR SEDs of these galaxies will look like (assuming T_{dust} = 28 K).
    - I first made use of this to predict the observability of z=4.5 LAEs w/ ALMA (Finkelstein+2009, MNRAS, 393, 1174).
  - Use the observed UV luminosity + β to build a FIR (modified) blackbody, redshift it, and examine its flux in the wavelength window of choice.
  - I examined all of my high-redshift galaxies in this way, “measuring” their flux densities at 350, 450 and 850 μm
  - For the CCAT sensitivities, I assumed the 3σ confusion limits of: 0.3, 0.6 and 0.66 mJy.

OBSERVING Z=4 "NORMAL" GALAXIES WITH CCAT

- At z=4, we can detect a decent number of "normal" galaxies at 350 µm (~70 galaxies).
  - Mean SFR ~ 30 M☉/yr.
  - Majority have log M ~ 10.5 - 11.5 M☉
- Even though the flux density rises for galaxies at 450 and 850 µm, the increasing confusion limit yields the 350 µm band the best options.



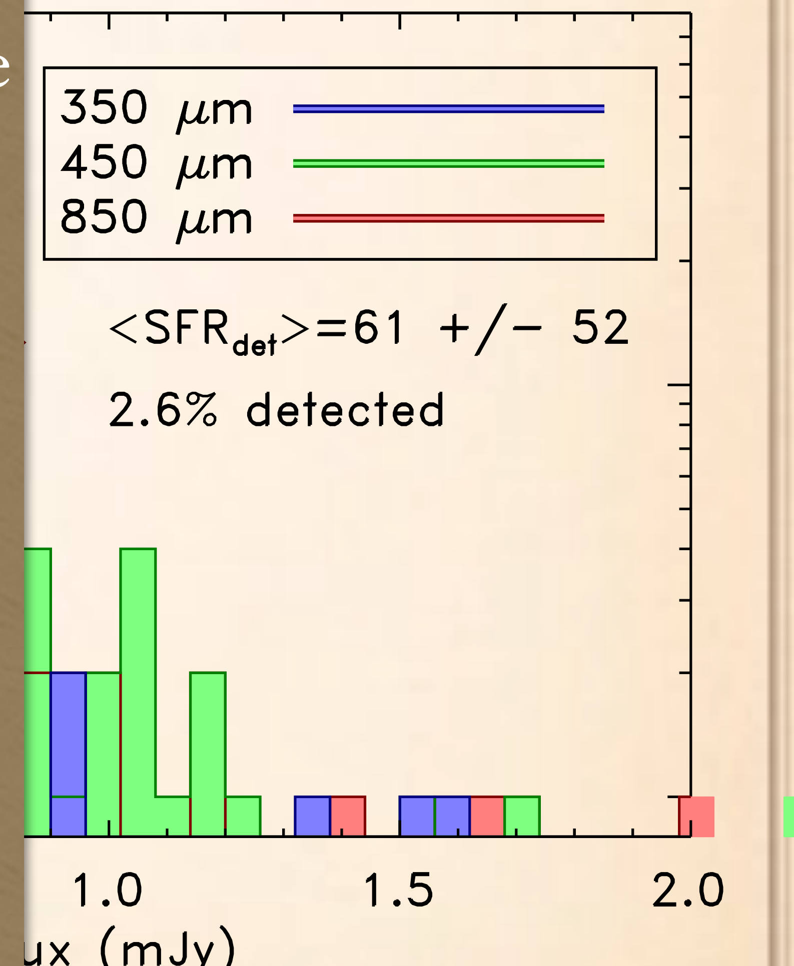
OBSERVING Z=4 "NORMAL" GALAXIES WITH CCAT

- At z=4, we can detect
number of "normal" g
350 µm (~70 galaxies).
  - Mean SFR ~ 30 M
  - Majority have log
11.5 M☉
- Even though the flux
rises for galaxies at 45
µm, the increasing co
limit yields the 350 µ
the best options.

Prospects improve dramatically if we can get below the confusion limit.

Done with other observatories by using higher resolution imaging at nearby wavelengths and performing template fitting.

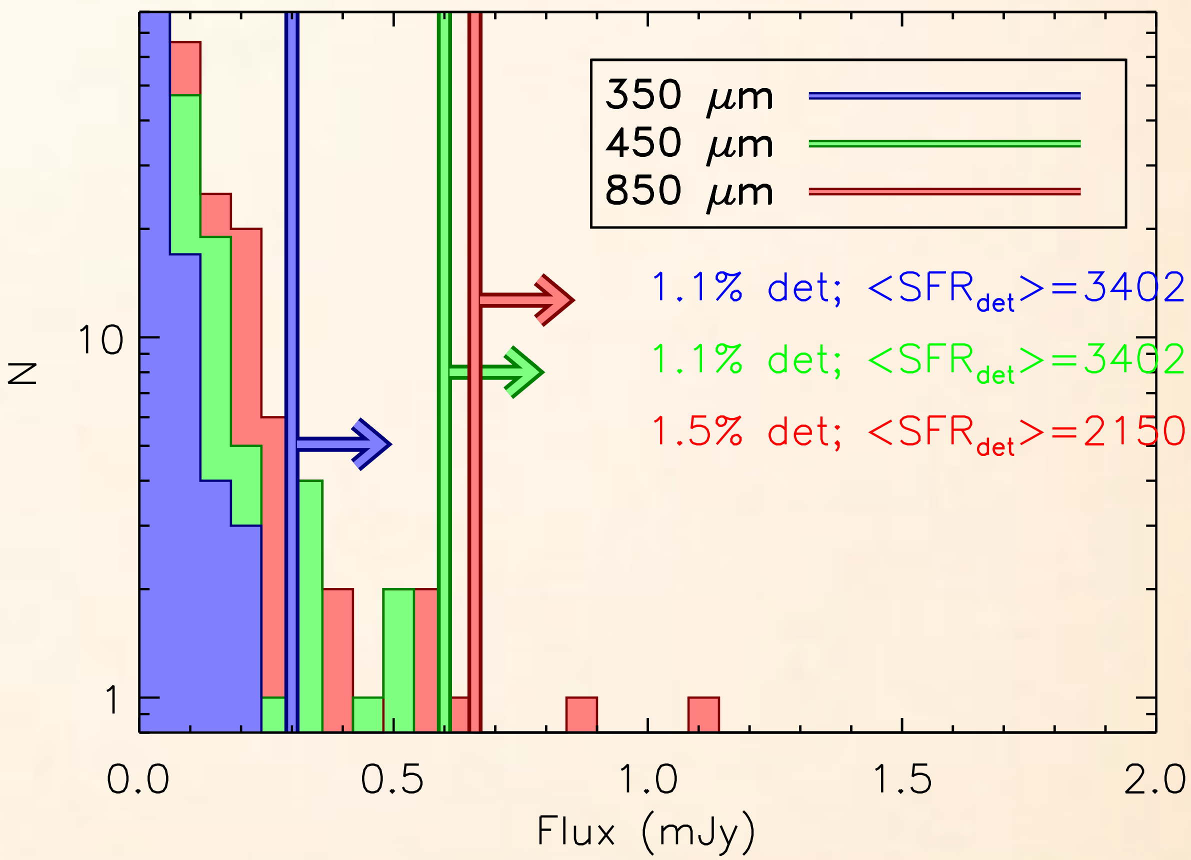
e.g., HST for Spitzer/IRAC; MIPS 24 µm for Herschel.



HOW DO WE DO AT HIGHER REDSHIFT?

- Play the same game at z=5 and 6.
  - A couple galaxies may be detected, but now we're talking about SMG equivalents.
  - No detections at z=7.

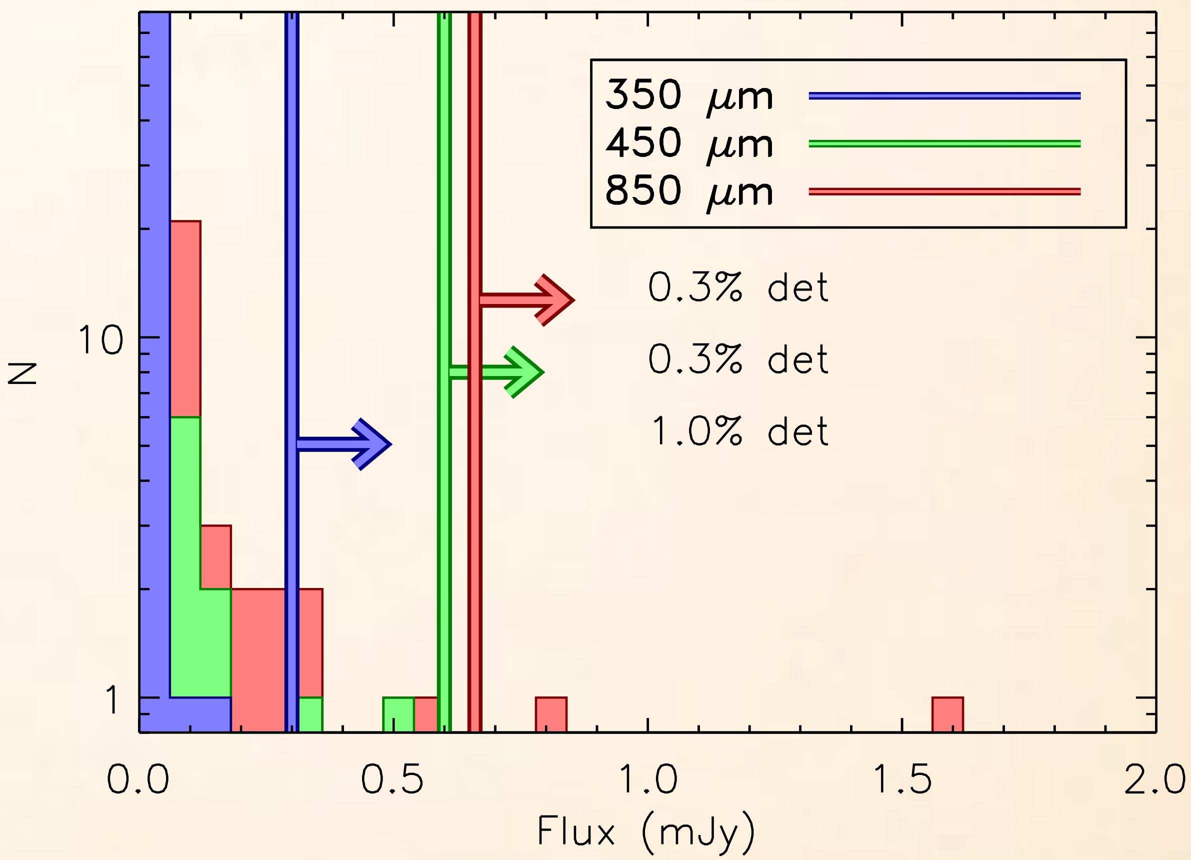
z=5 galaxies



HOW DO WE DO AT HIGHER REDSHIFT?

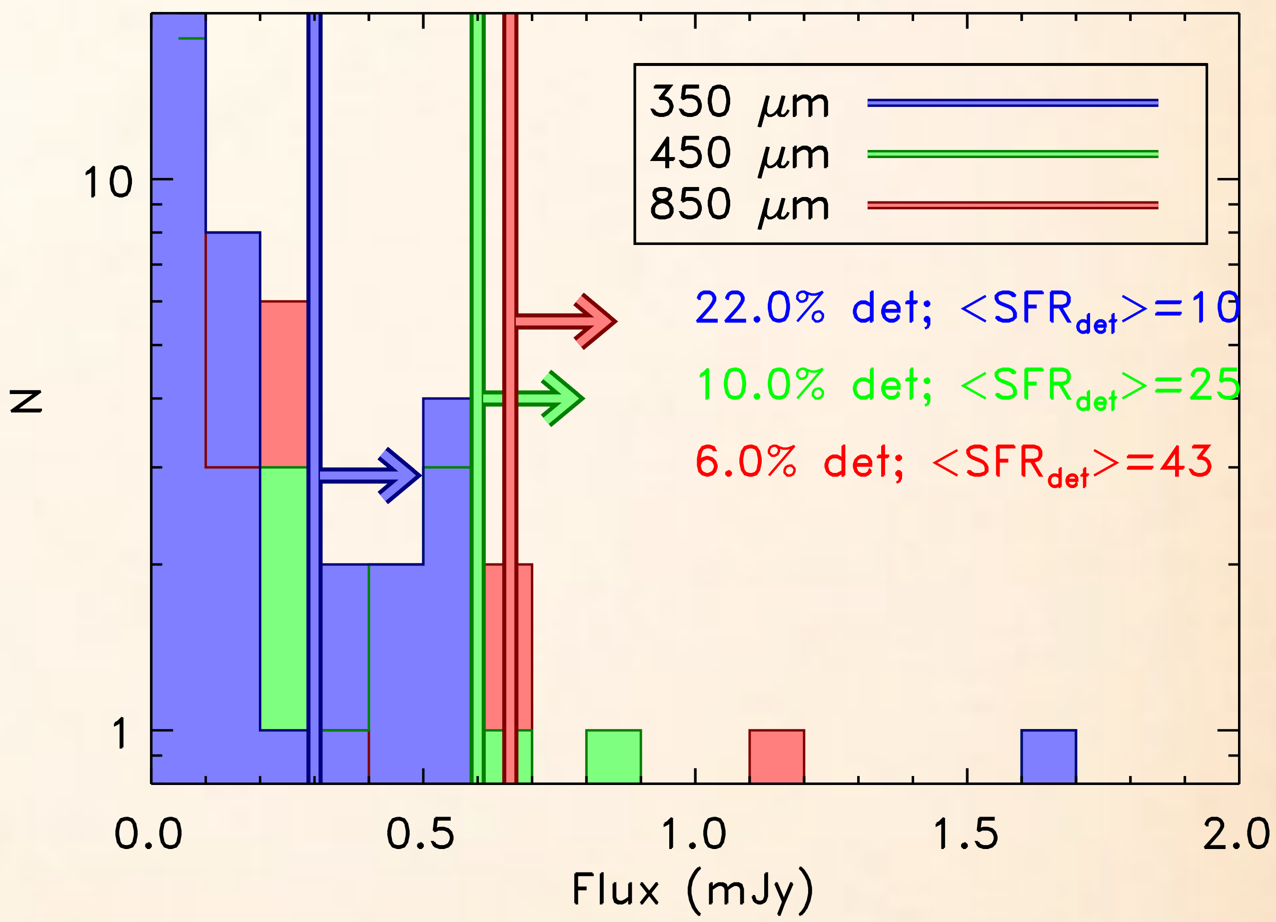
- Play the same game at z=5 and 6.
  - A couple galaxies may be detected, but now we're talking about SMG equivalents.
  - No detections at z=7.

z=6 galaxies



WHERE CAN WE LEARN THE MOST?

- While CCAT has potential for studies at z=4, what about at z=2-3, where even Herschel cannot detection individual normal galaxies?
  - Examined ~50 galaxies from the HETDEX pilot survey for which I've previously measured β.
  - CCAT can detect >20% of these galaxies!
    - Some of these are as small as ~10^9 $M_\odot$!



SUMMARY

- Measuring the star-formation rates and histories of galaxies is one of the major diagnostics we have of how the universe builds its stellar mass with time.
- Rest-frame UV/optical observations only tell half of the story.
  - Dust attenuation is significant and must be accounted for at $z = 4$-6 for all but the lowest mass galaxies.
    - And even in the highest mass galaxies at $z = 7$.
- CCAT can detected significant numbers of “normal” galaxies at $z=4$; only extreme galaxies at $z > 5$.
  - We can make a lot of progress at $z=2$-3, where CCAT can detect SFR~10 $M_\odot$/yr.