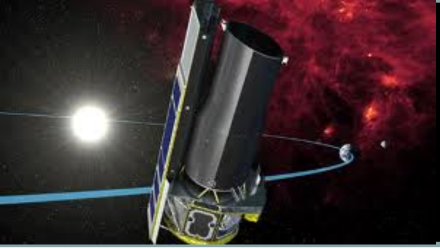


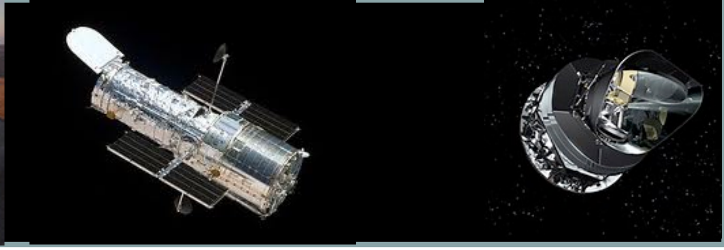

The First Billion Years: What, When and How of Reionization

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U.S. Planck Data Center/IPAC
California Institute of Technology

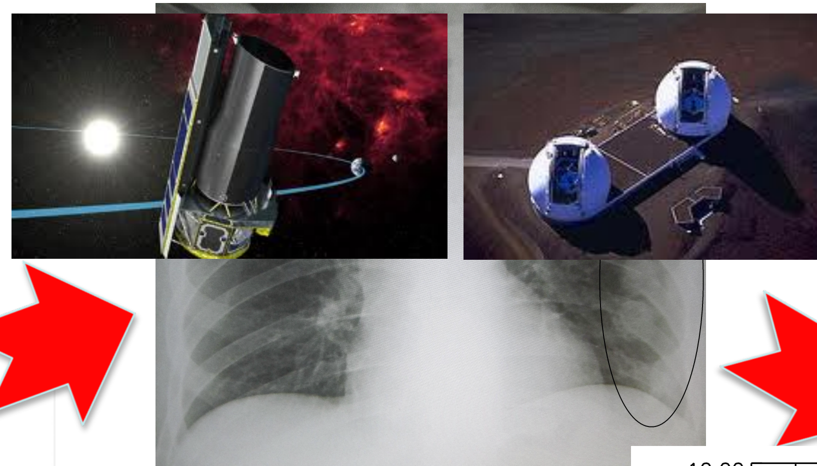
September 2016, Monash University

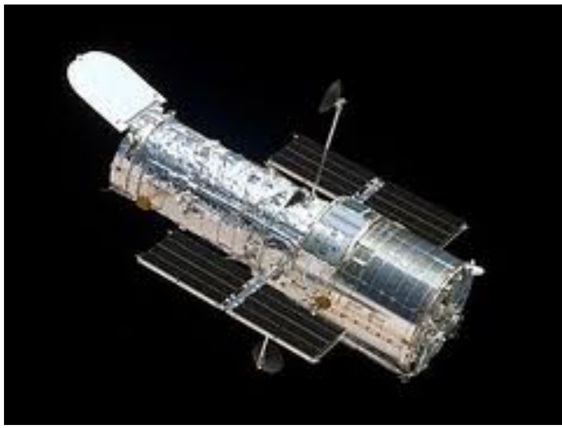
Former Postdoc:
Hyunjin Shim (Caltech→Kyungpook National University, S.Korea)

Key Collaborators:
Mark Dickinson (NOAO)
GOODS team

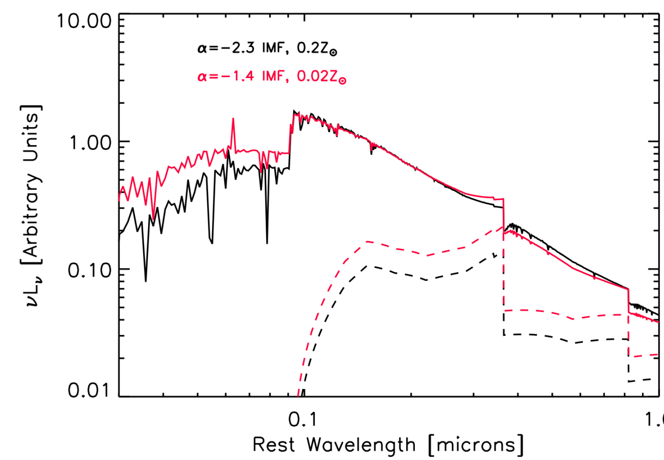
Spitzer Science Center

Caltech



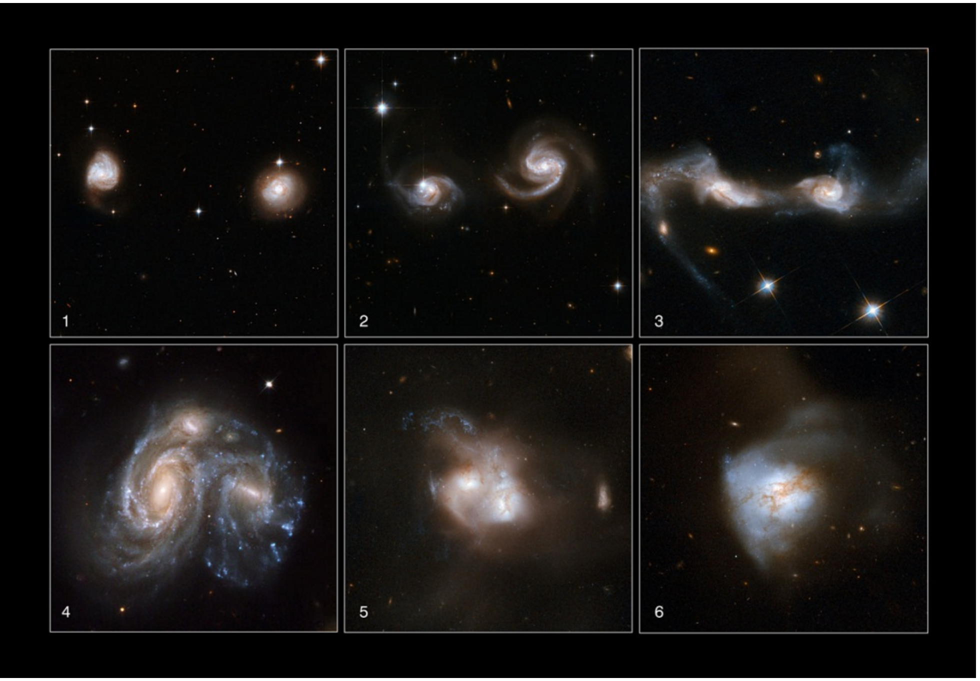


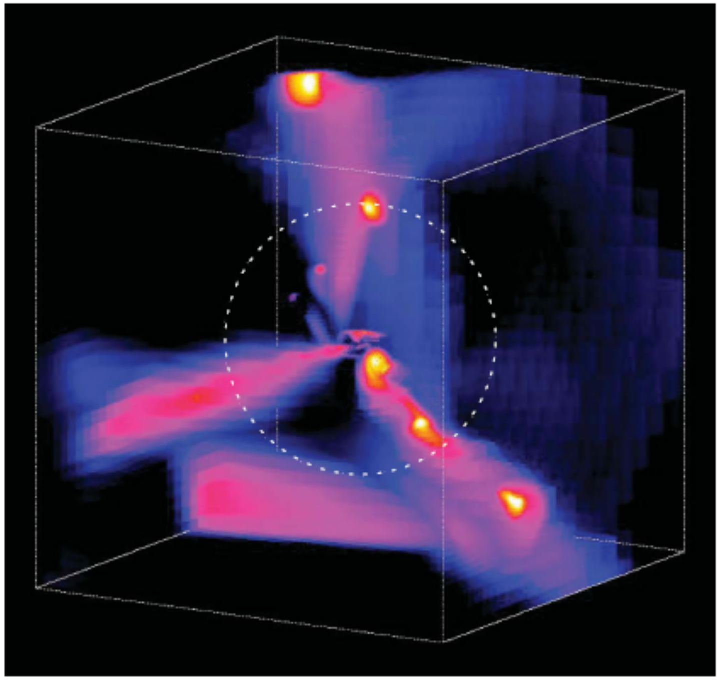
Studying reionization is like investigating a crime scene!



SFR
Stellar Mass
Age
IMF
Dust Content

How is Star-Formation Fed in Galaxies?



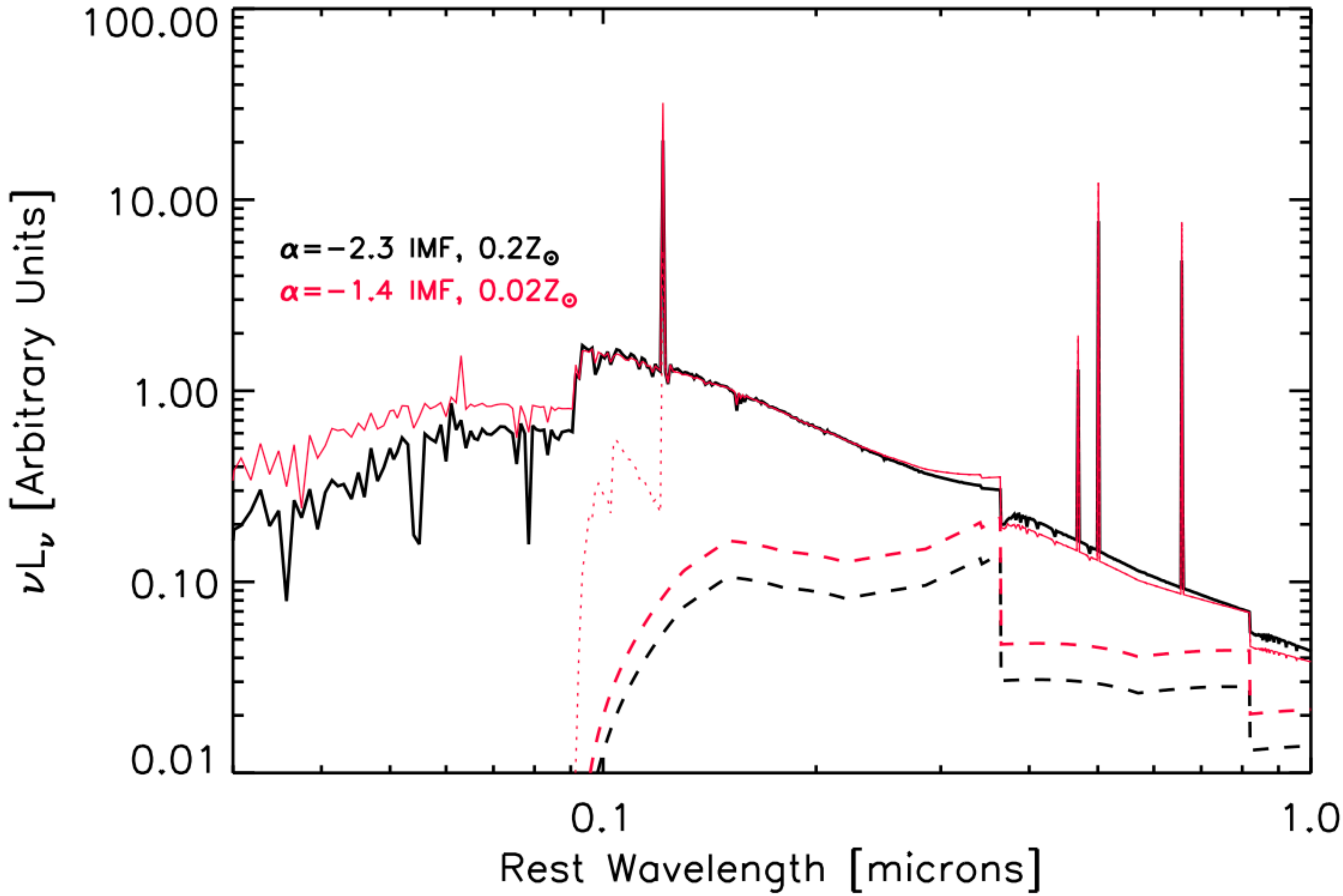


- Voracious tigers = growth by mergers
- Stochastic process due to feedback
- Could be extremely violent with unusually high star-formation rates

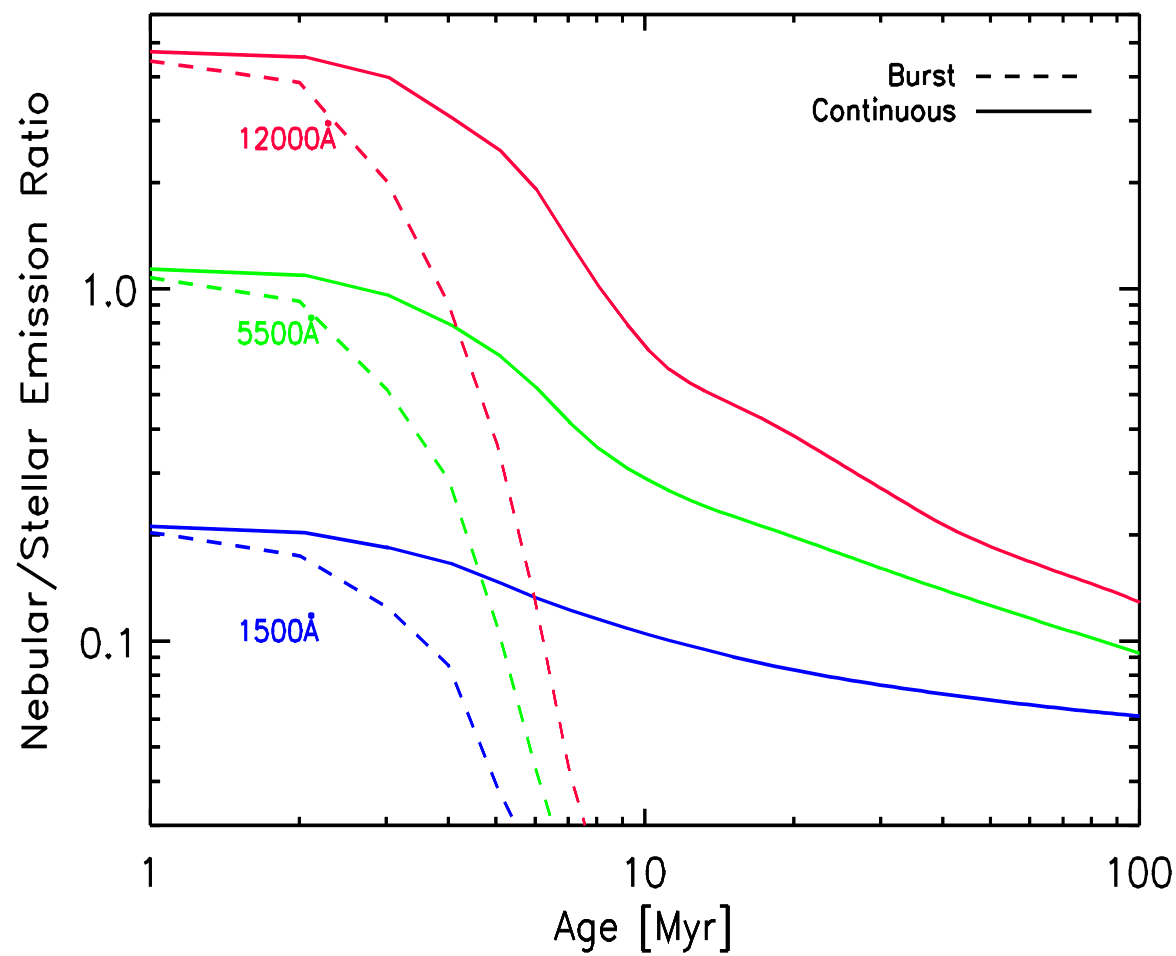
- Grazing cows = growth by accretion
- Quasi-continuous process
- Modest star-formation rates for extended time intervals

Dekel et al. 2009

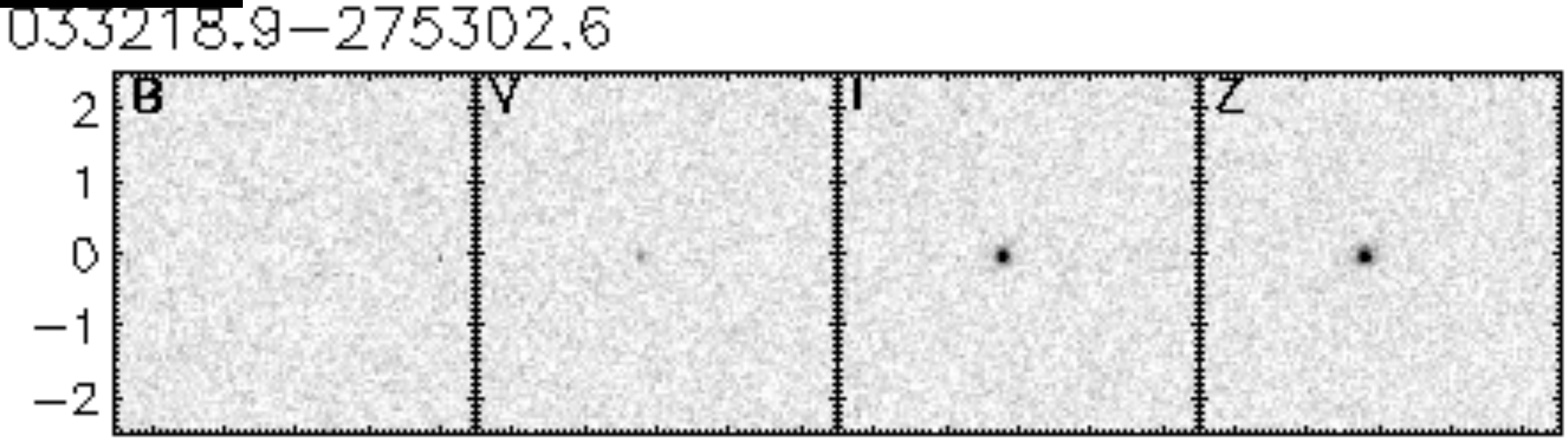
Nebular Emission:
Line and Continuum Emission from Ionized Gas

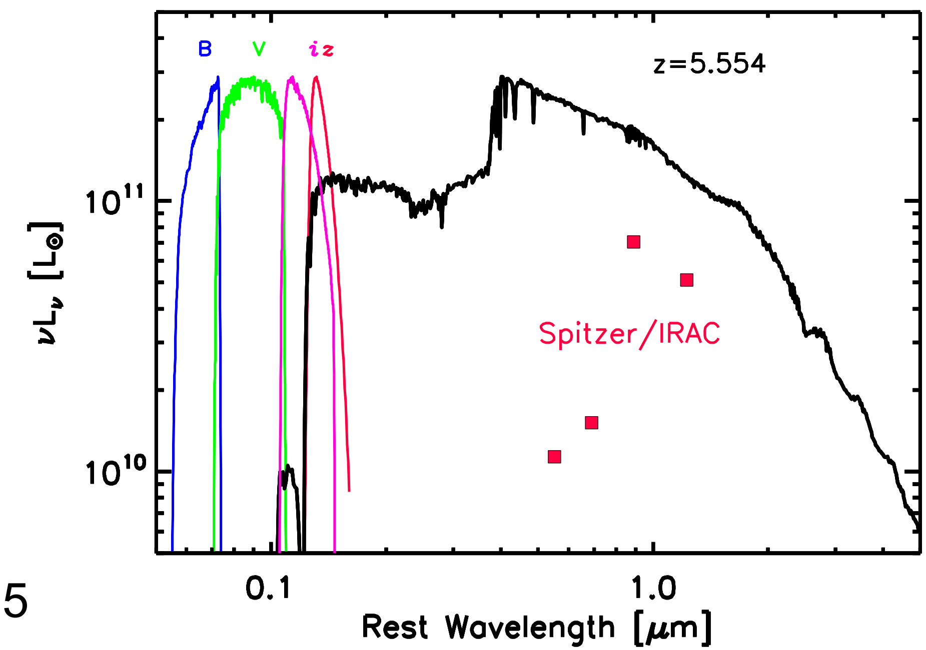


Probing Instantaneous SFR: The Boon of Nebular Emission



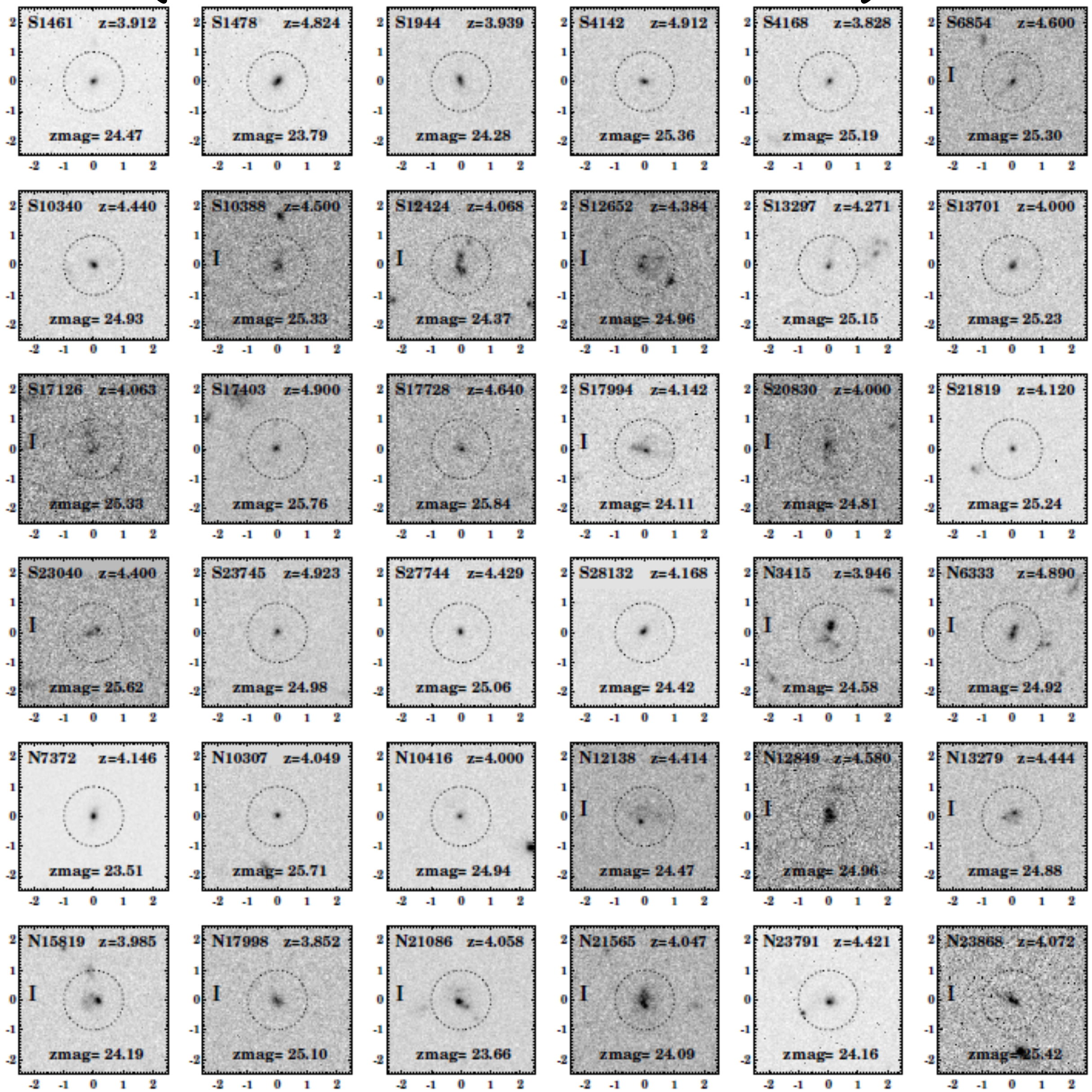
Detecting z>5 Galaxies/QSOs: Lyman Break Technique

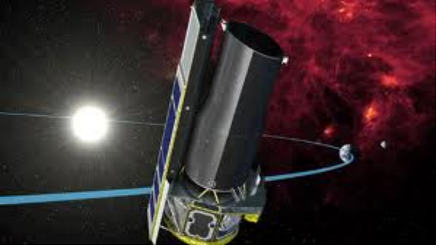




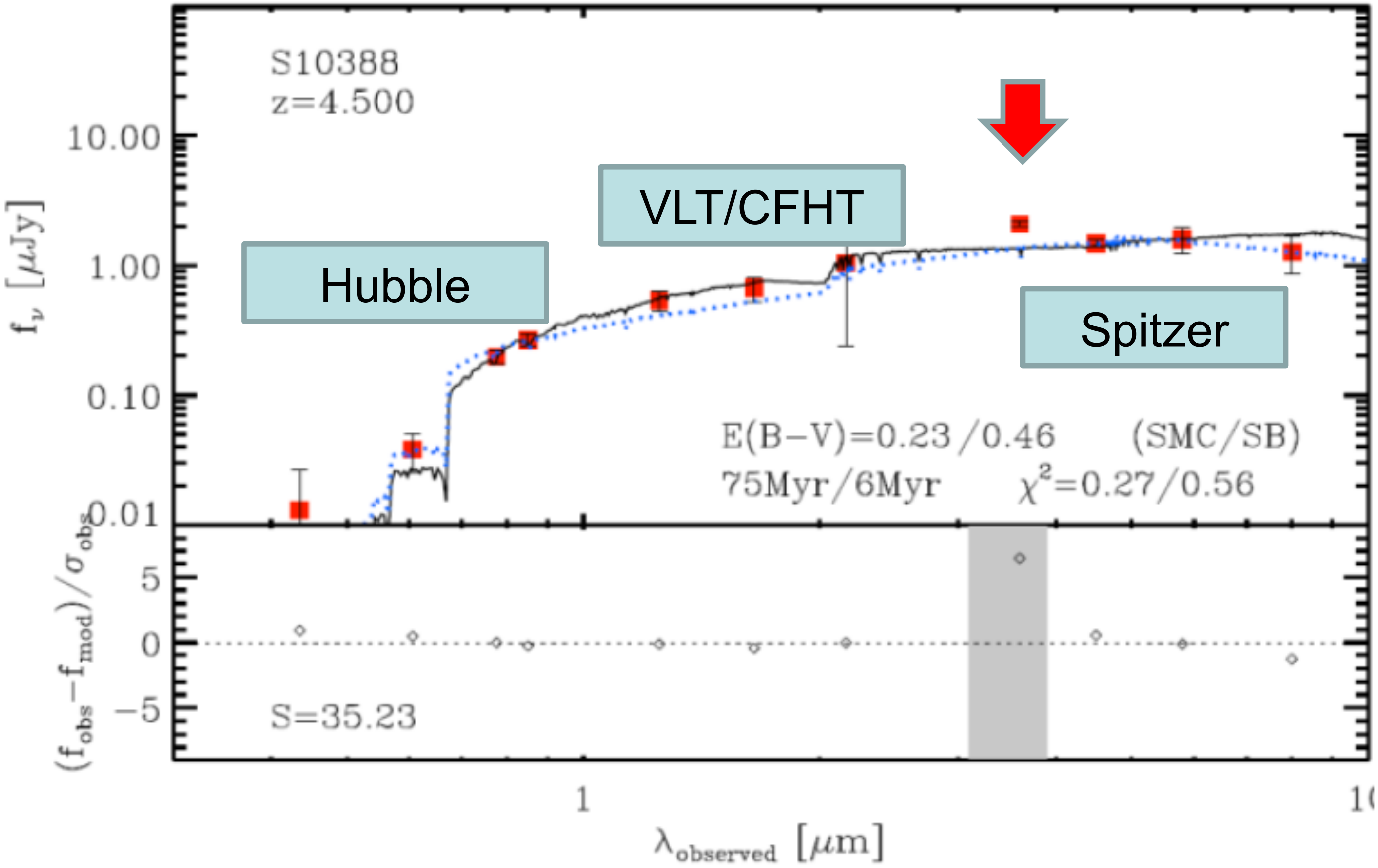
e.g. Chary et al. 2005

z~5 Lyman-Break Galaxy Morphologies (Hubble ACS+WFC3)





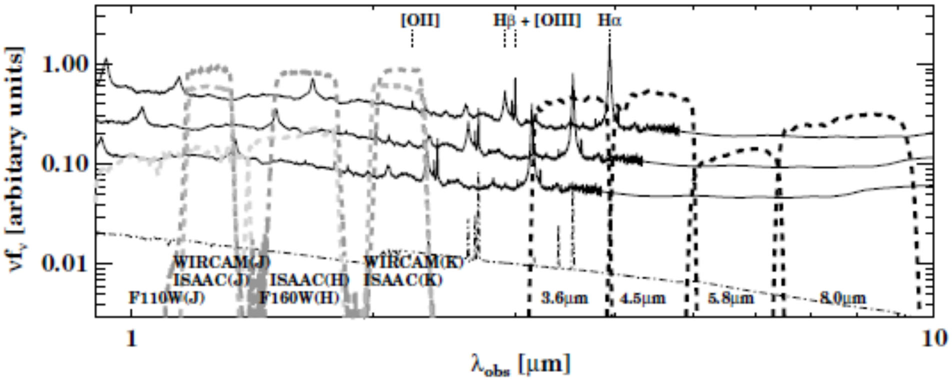
The Surprising Excess in a Broad band

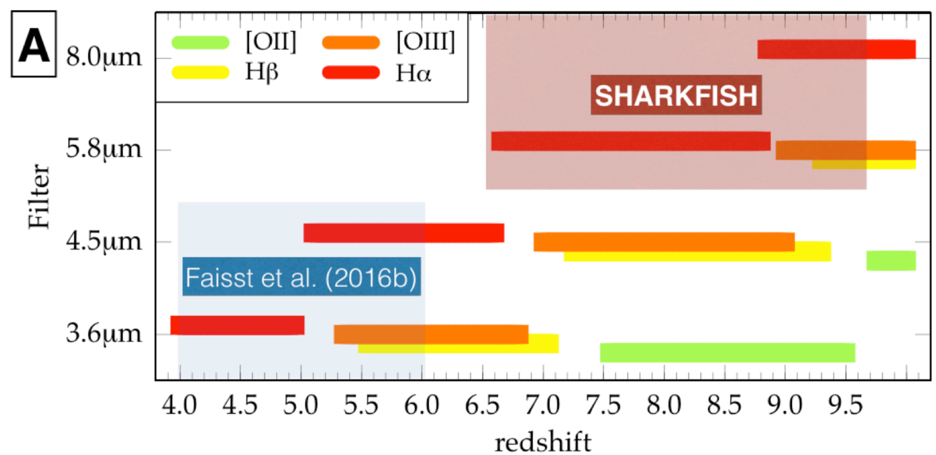


Halpha nebular emission: seen in 70% of 3.8<z<5 galaxies in Spitzer data

Chary et al. 2005
Shim, RC, et al. 2011

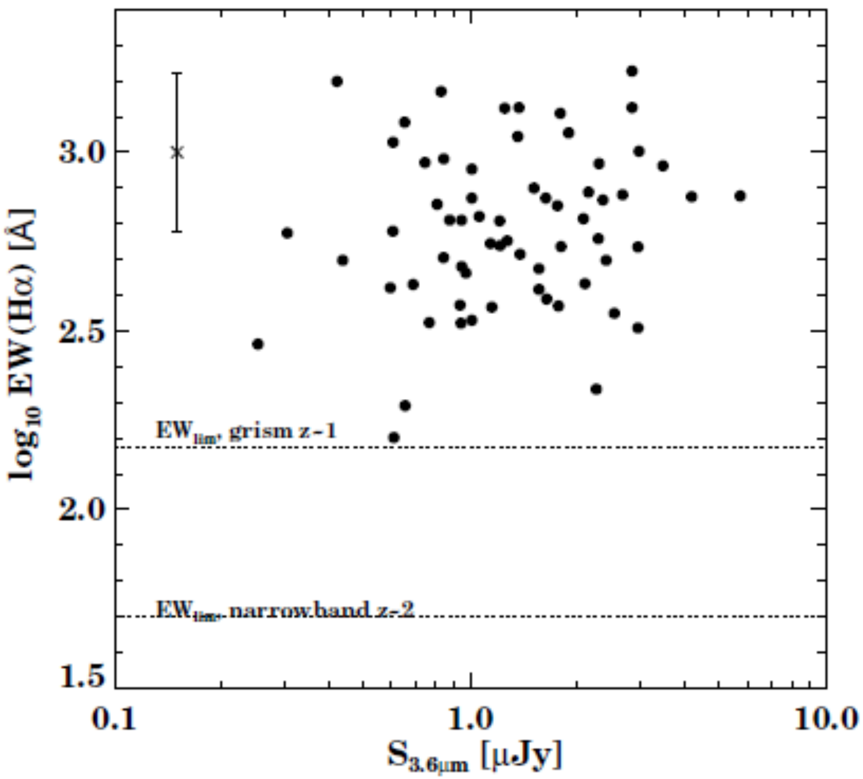
Only works in certain redshift ranges e.g 3.8<z<5





- <u>Only spec-z selected sources</u>
- Good NIR K-band (2.2micron) photometry

Unusual objects compared to other star-forming galaxies at lower redshifts



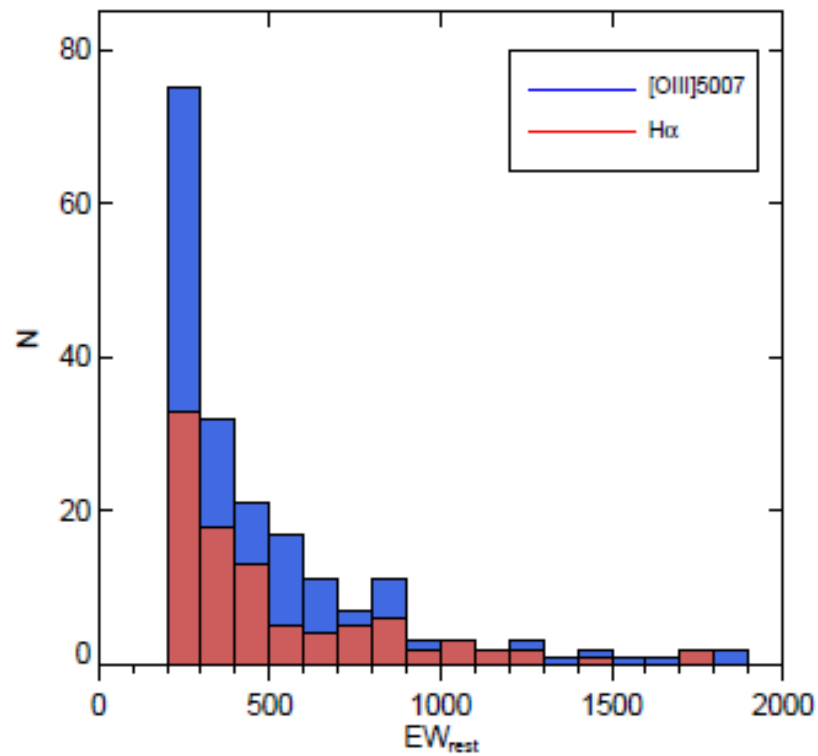


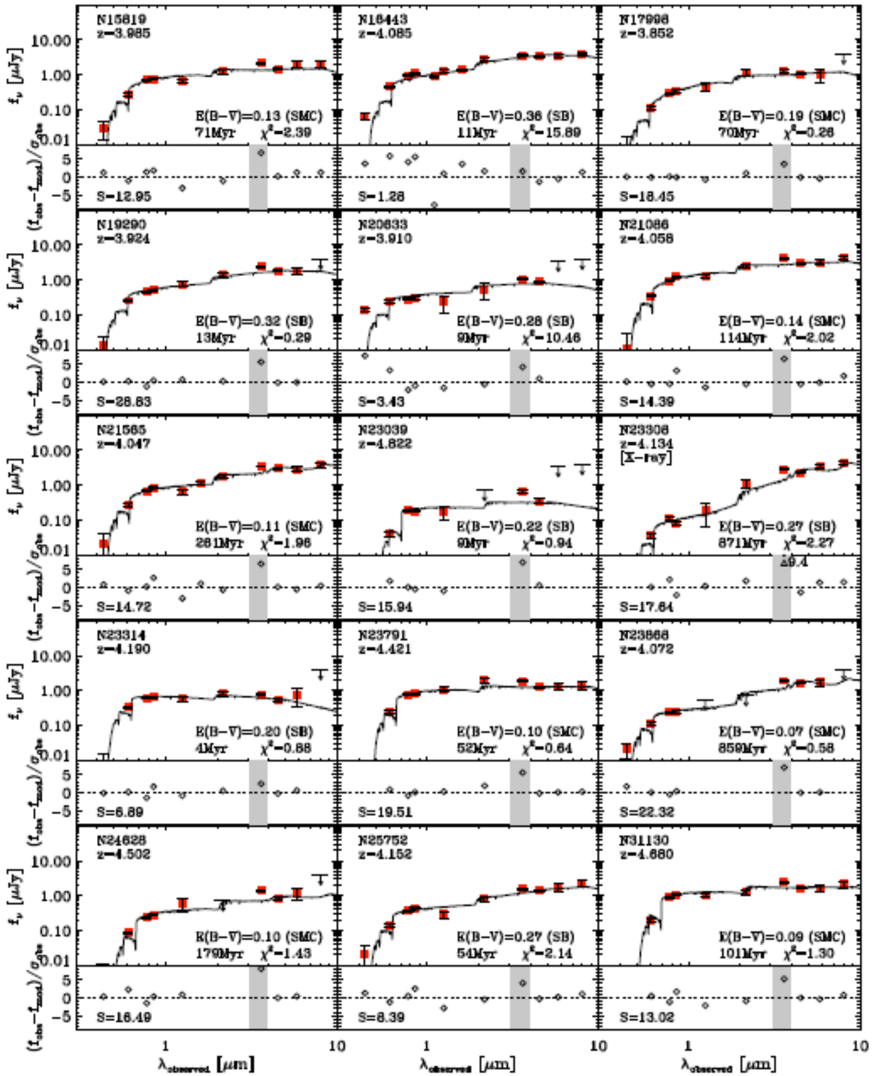
FIG. 2.— Rest-frame equivalent width distribution for objects with EW ≥ 200 Å in the WISP Survey. The total number in each bin is divided into the [OIII] λ5007 line (presented in blue) and the Hα line (presented in red).

Atek et al. 2011, have found them in grism surveys with HST and we have found them in Sloan.

Possible origins for strong Halpha

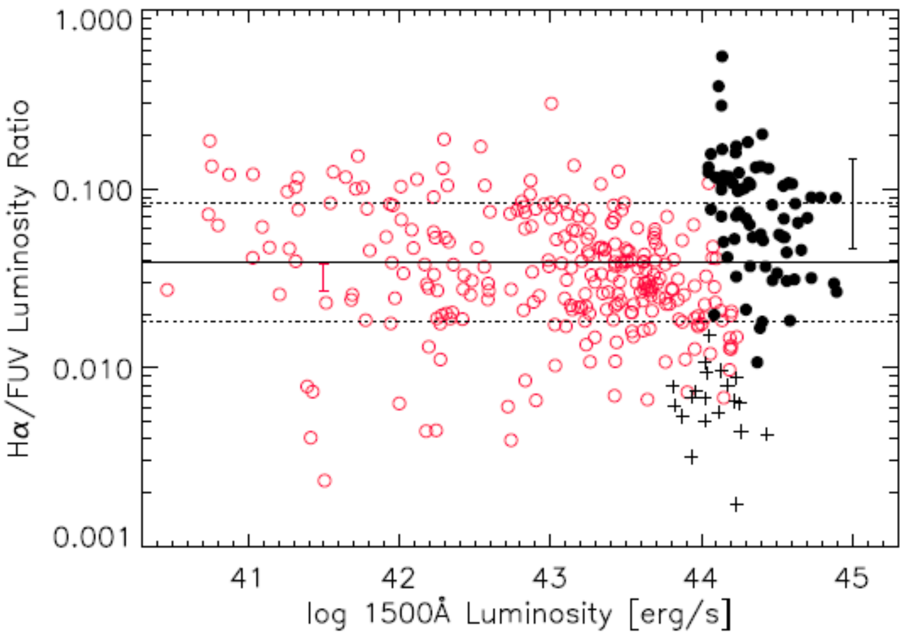
- Age of starburst
  - Large EW in star-forming systems <10 Myr
- Halpha is excited by ionizing UV photons
  - More sources of UV photons i.e. O stars?
- Dust is obscuring other wavelengths
  - Are these dusty objects?
- Active Galactic Nucleus (AGN)

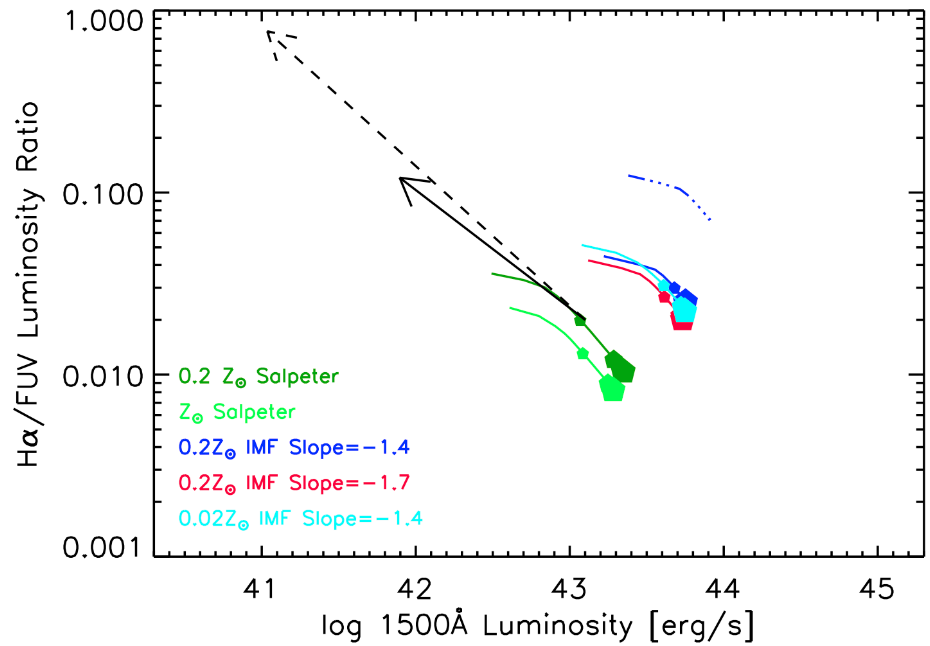
Booming Halpha Emission in z~5 galaxies: Are these young bursts?



Chary et al. 2005
Shim, RC, et al. 201

The Unusual Properties of Halpha Emitters: Sloan + GOODS



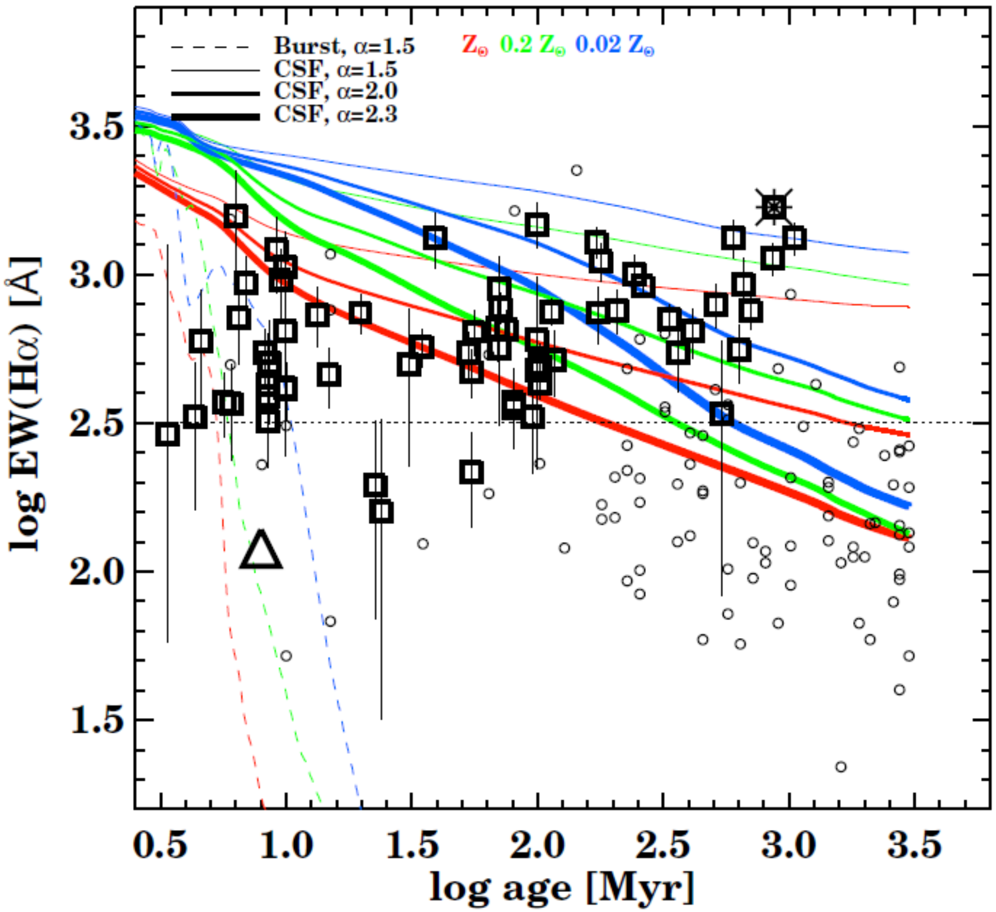


Shim, RC et al. 2011
Shim & RC 2013, ApJ

Evidence for high angular momentum in stars or just more massive, hot stars due to an increased binary fraction?

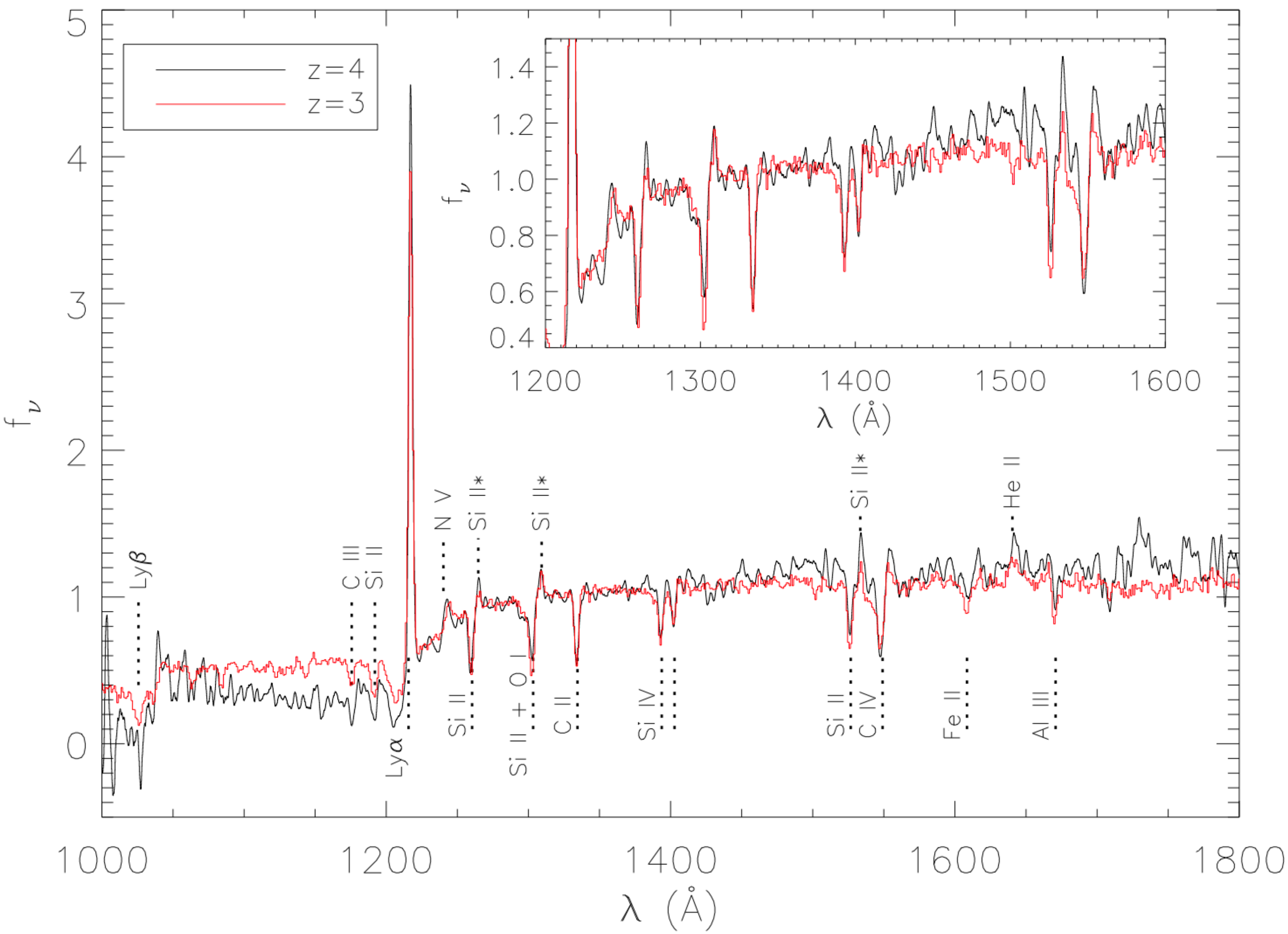
Levesque et al. 2012
Ekstrom et al. 2012

So they arent all 10 Myr old systems.



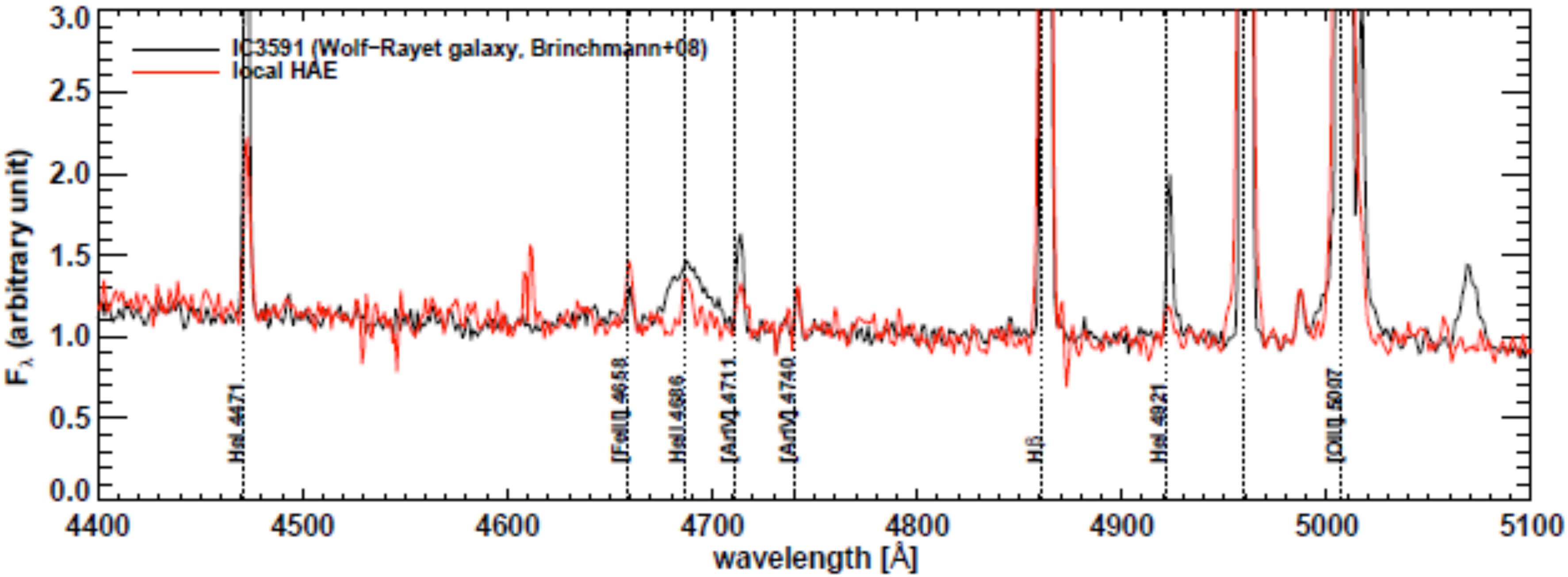
- 70% of z~5 galaxies are HAEs. If they were 10 Myr bursts, ~1% of galaxies would show strong Halpha. So they must be continuously forming stars.
- Really need HeII: classic signature of massive stars in local analogs

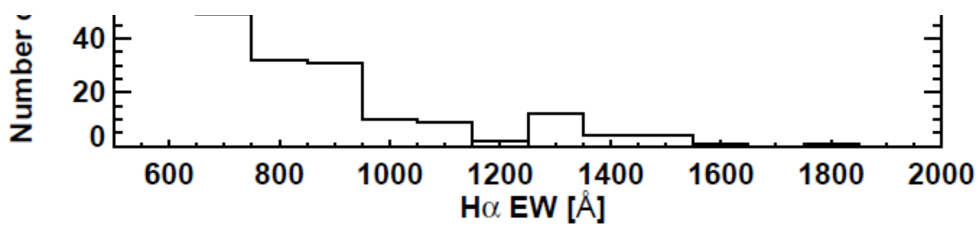
HeII detection at z~4



T. Jones et al. 2012

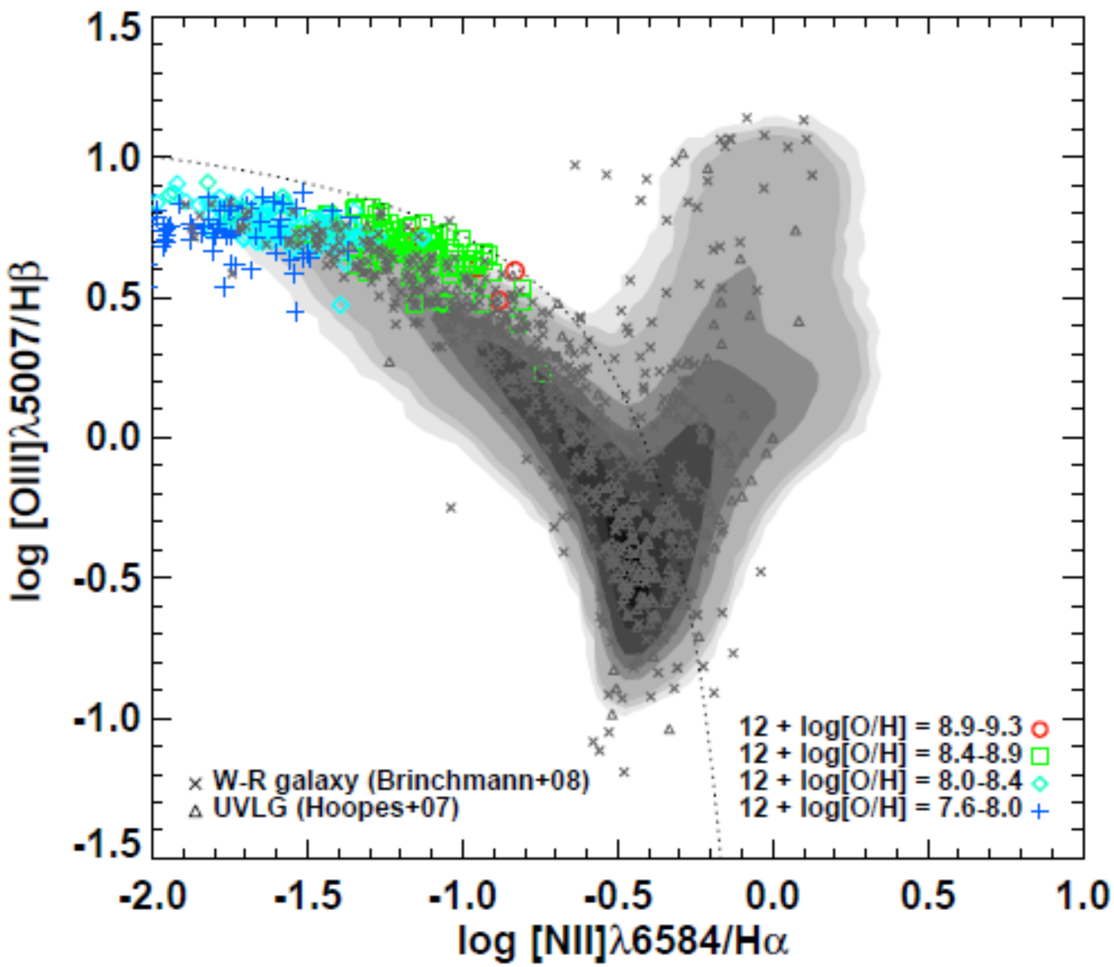
Looking at Local Analogs of High-z Galaxies gives us better S/N





~300 local galaxies out of 1.5Million(!), show strong Halpha And HeII. So massive O-type stars are clearly present….

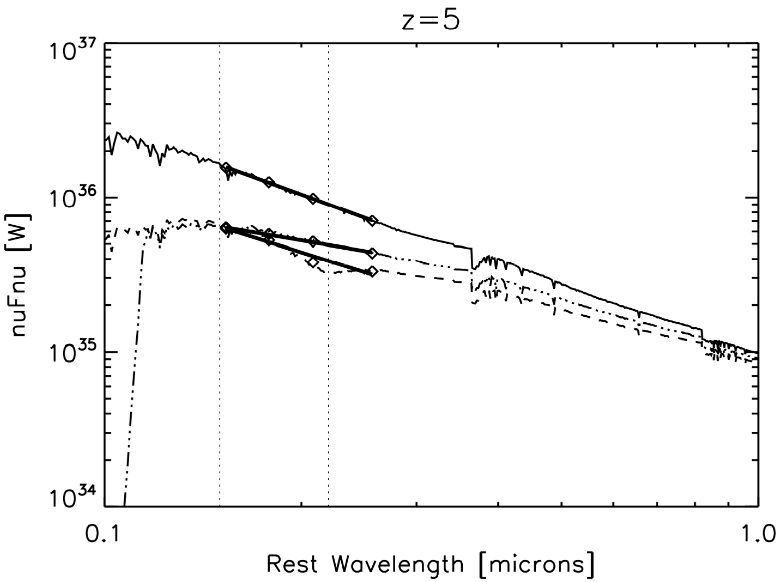
The Low-z Analogs of the HAEs are definitely not AGN

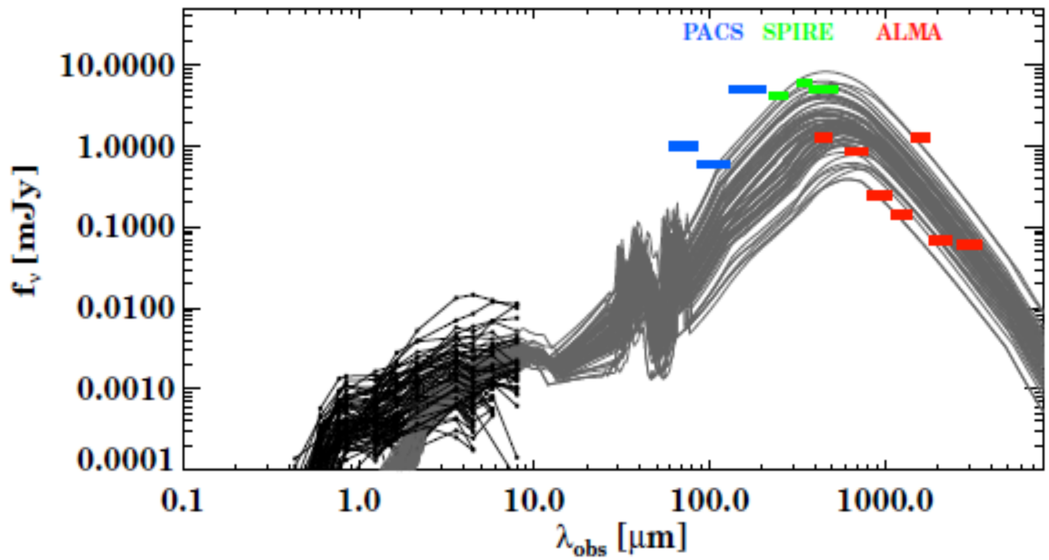


The high-z ones don't appear to be based on the strong upper limits from X-ray stacking

DEFINITELY NOT

Is it Dust Extinction?





- No detections with Herschel
- Strong limits with pdBI on 1 additional source; Kanekar, RC et al. 2013

DOES NOT APPEAR SO

Possible origins for strong Halpha

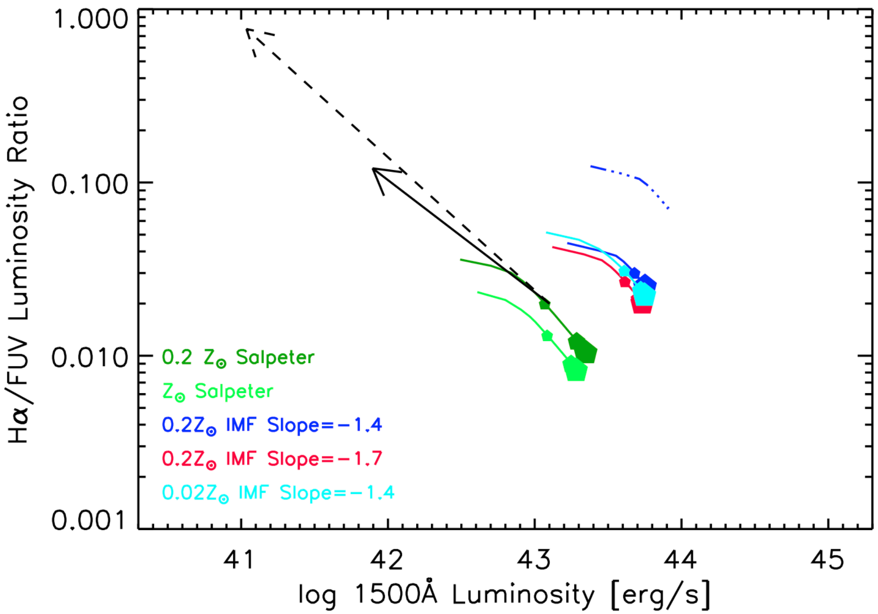
- Age of starburst **IN SOME CASES**
  - Large EW in star-forming systems <10 Myr

- Dust is obscuring other wavelengths
  - Are these dusty objects? **HERSCHEL APPEARS TO RULE IT OUT**

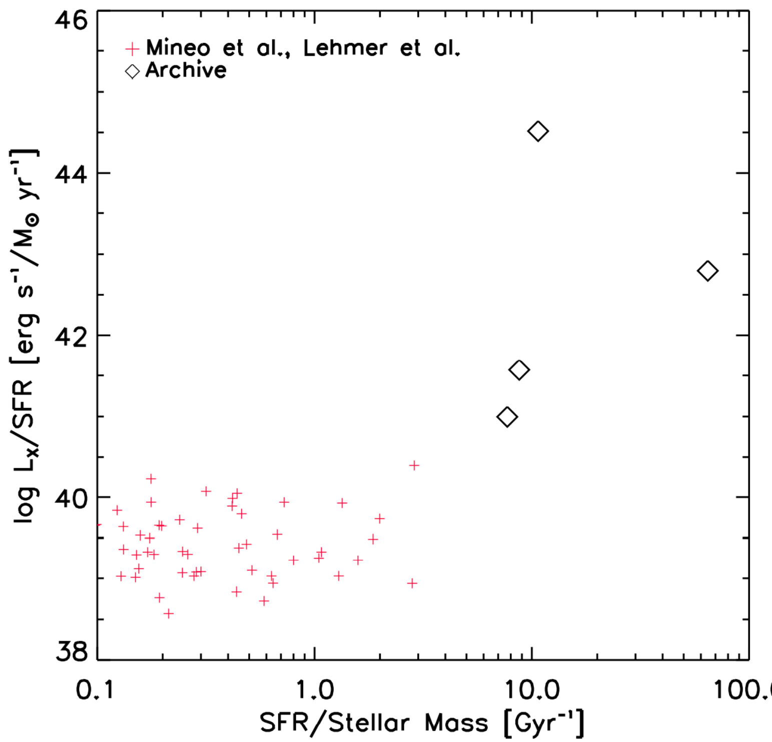
- Halpha is excited by ionizing UV photons
  - More sources of UV photons i.e. O stars? **YES**
  - Unclear if due to stars with angular momentum or due to increased binary fraction
- AGN **DEFINITELY NOT**

The Origin of Hot, Massive Stars is Uncertain

Stars with Angular Momentum



More Binaries i.e HMXBs



A great doctoral thesis project…..

So what does the occurrence and ubiquity of Halpha mean?

Duration of Burst * Rate of Bursts/Cosmic Time = Fraction of Galaxies

10 Myr * (2 or 3)/1 Gyr = 2-3%
This is not 70%!

Combined with the stellar age estimates, implies that half the galaxies at z~5 are powered by cosmological accretion of gas resulting in continuous star-formation with a non-standard IMF.

Implications for Reionization

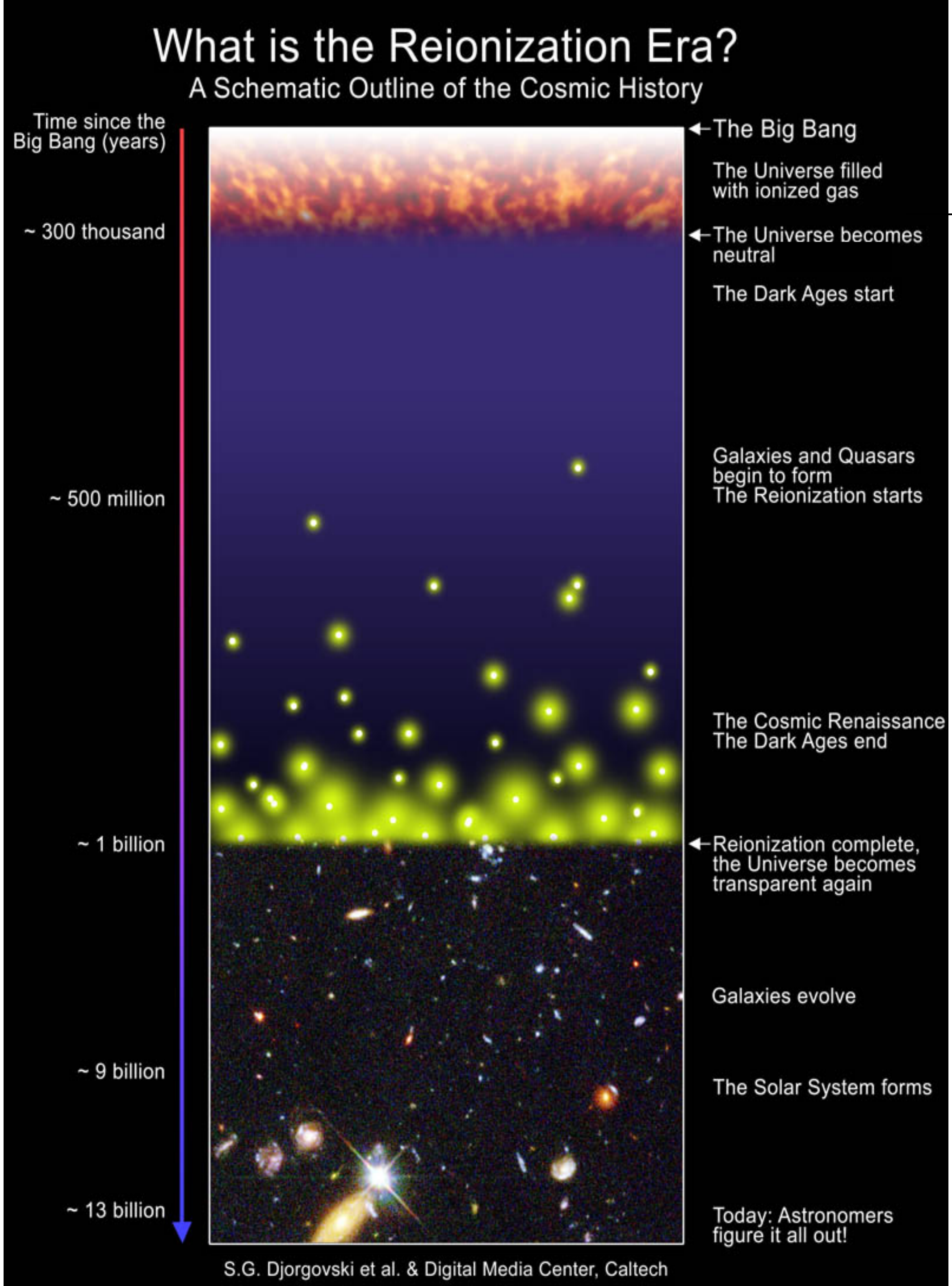
z=1000

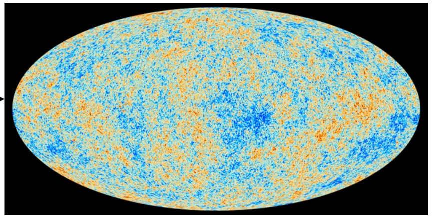
z=10

z=6

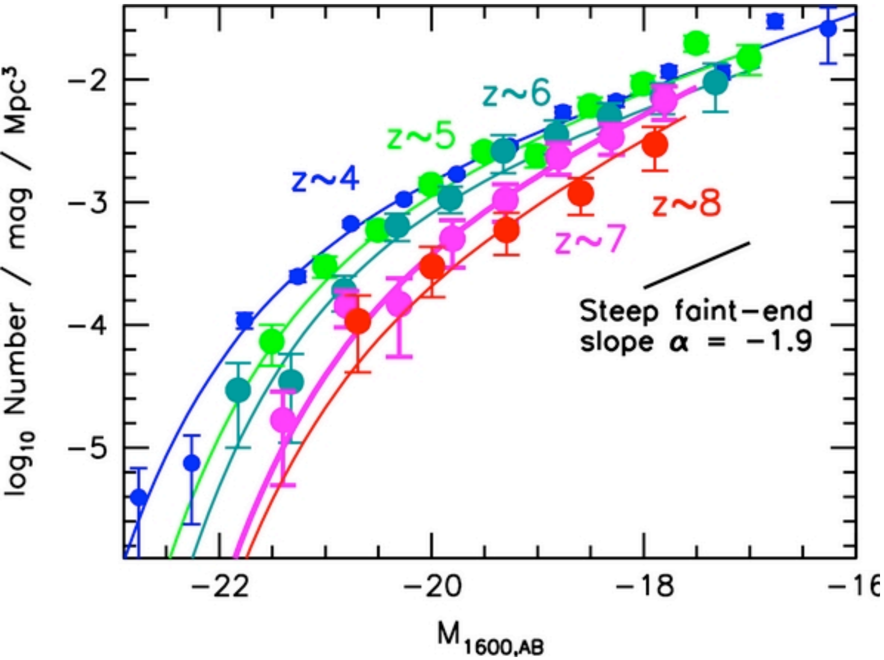
z=1.5

z=0

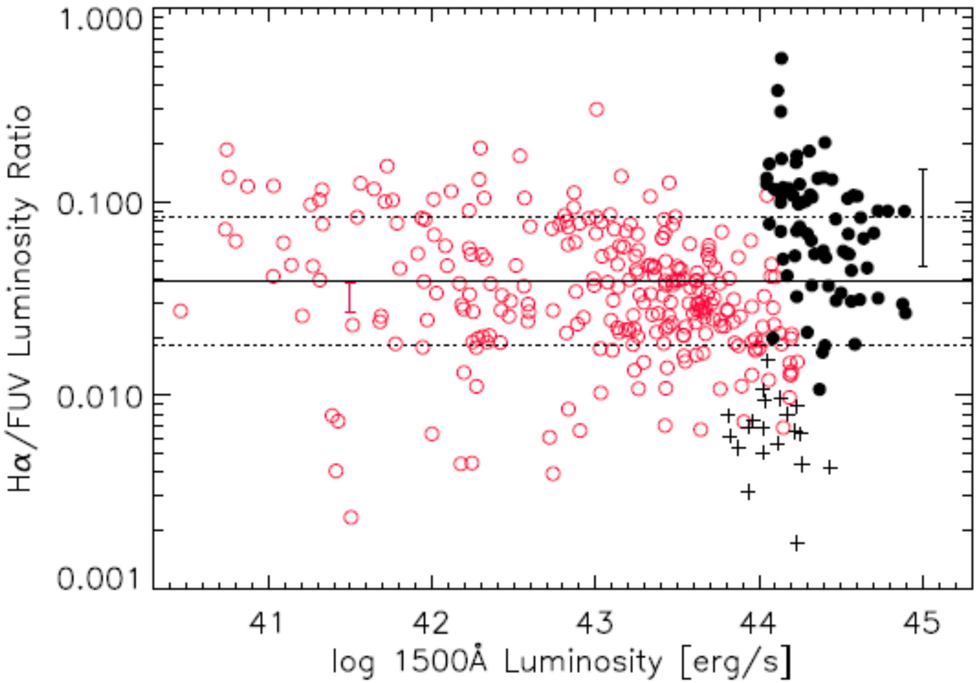




Convolve the observed UV Luminosity Function of Galaxies
with the Halpha/UV ratios of Halpha Emitters



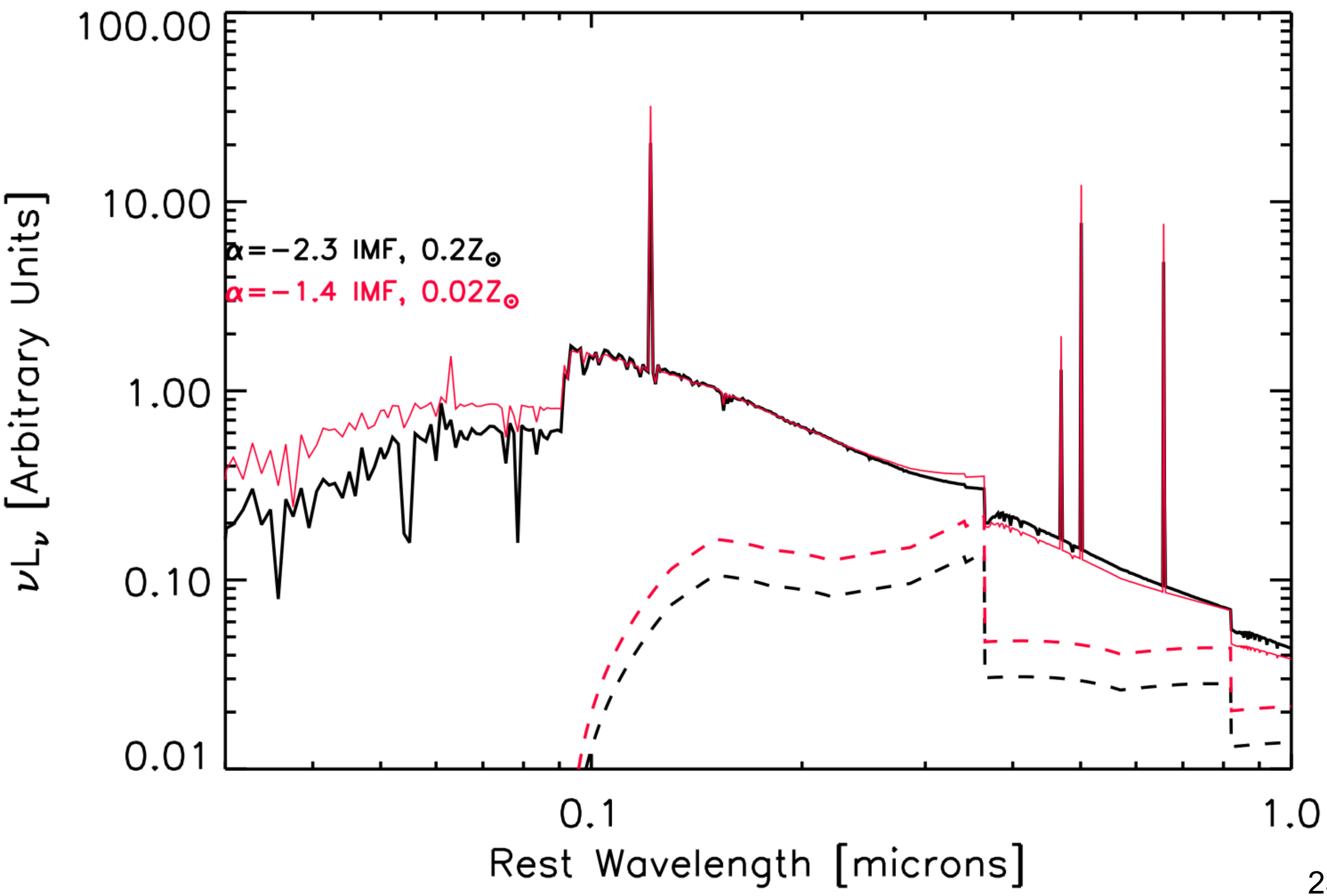
Bouwens et al. 2012



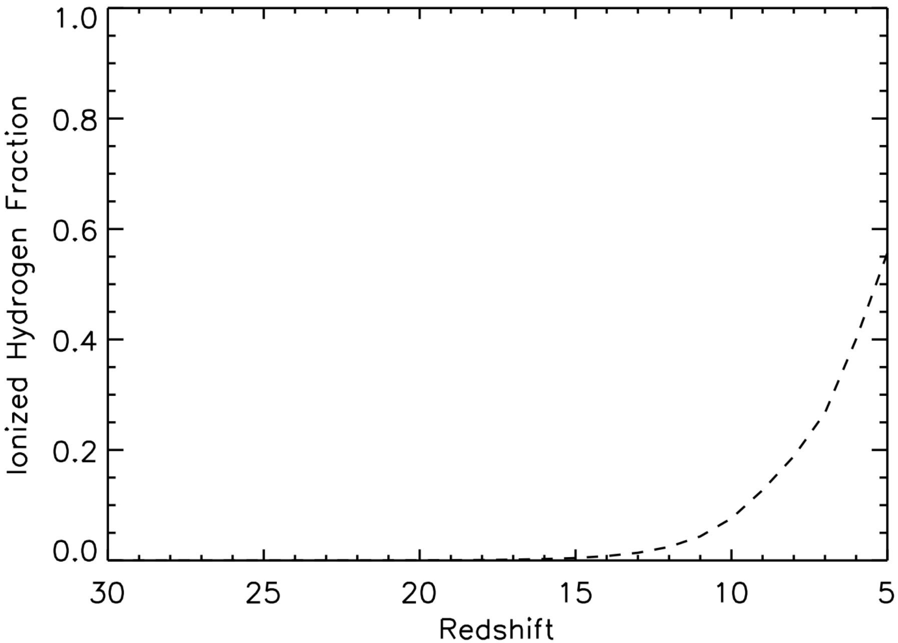
$$N(z=6) = 0.93 + 6.475 \times 10^{-20} \times \int_{z'=z_0}^{z'=6} C\chi_{\mathrm{H\,II}}(\chi_{\mathrm{H\,II}} + \chi_{\mathrm{He\,II}})(1+z')^3 \frac{dt}{dz'}\, dz'.$$

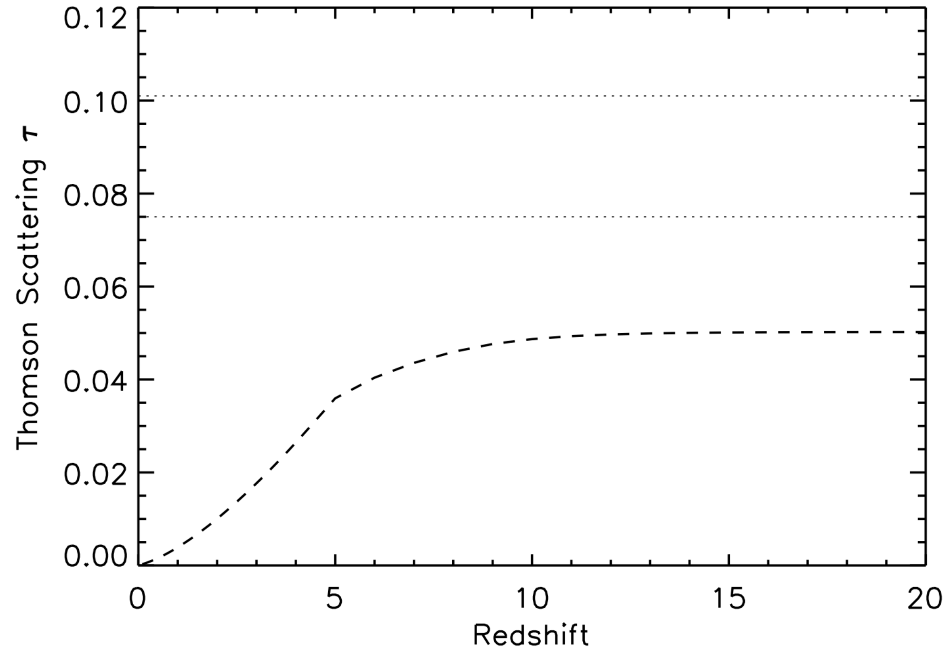
RC2009

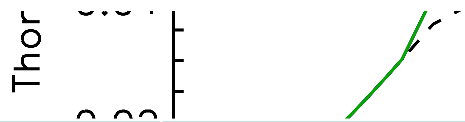
We use the measured nebular emission to provide a measurement of the Ionizing photon flux from the galaxies



Reionization: A Mystery Solved



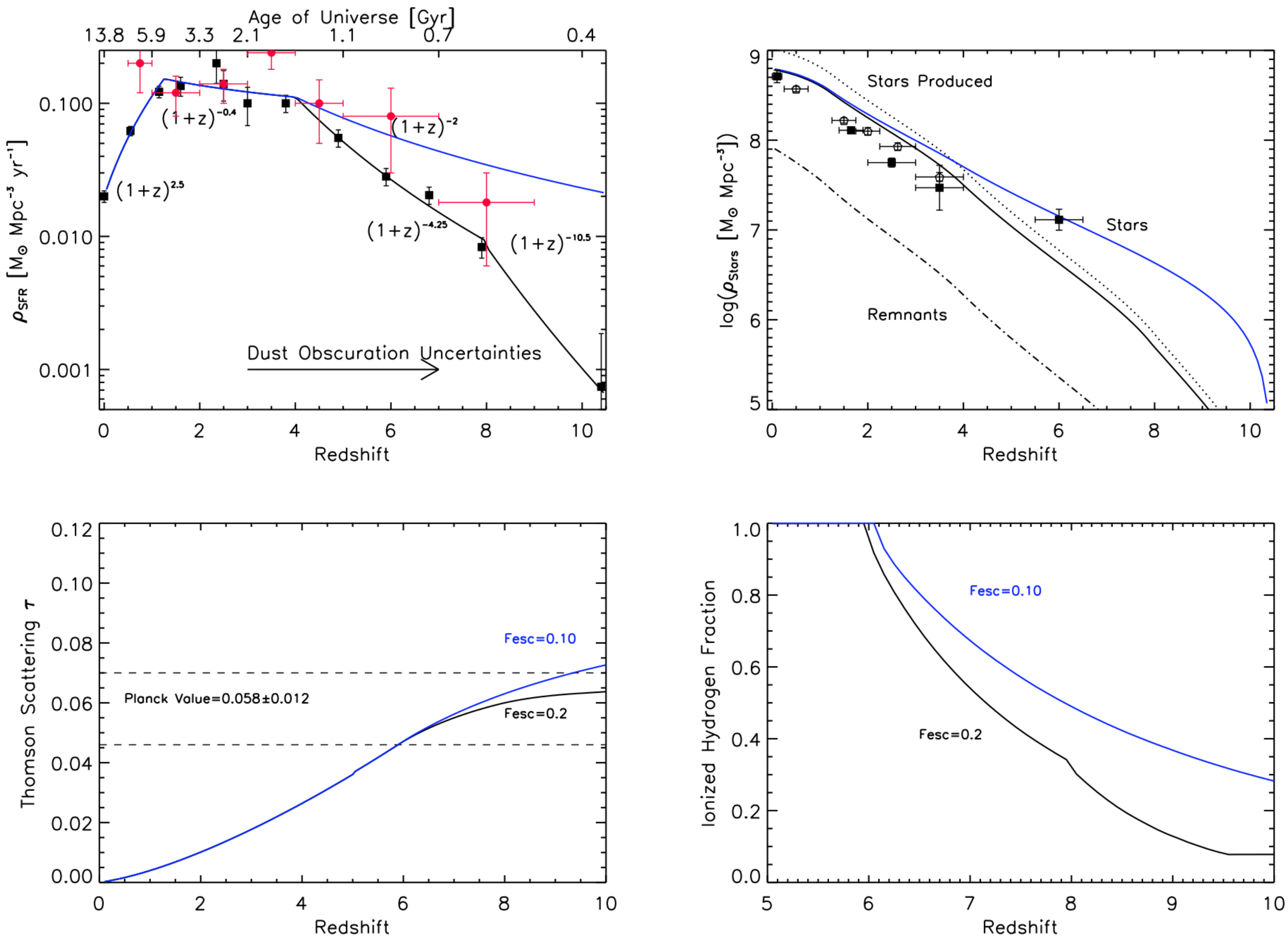




$$\tau = \int_0^{z_e} dz \sigma_T n_e(z) c \frac{dt}{dz}$$

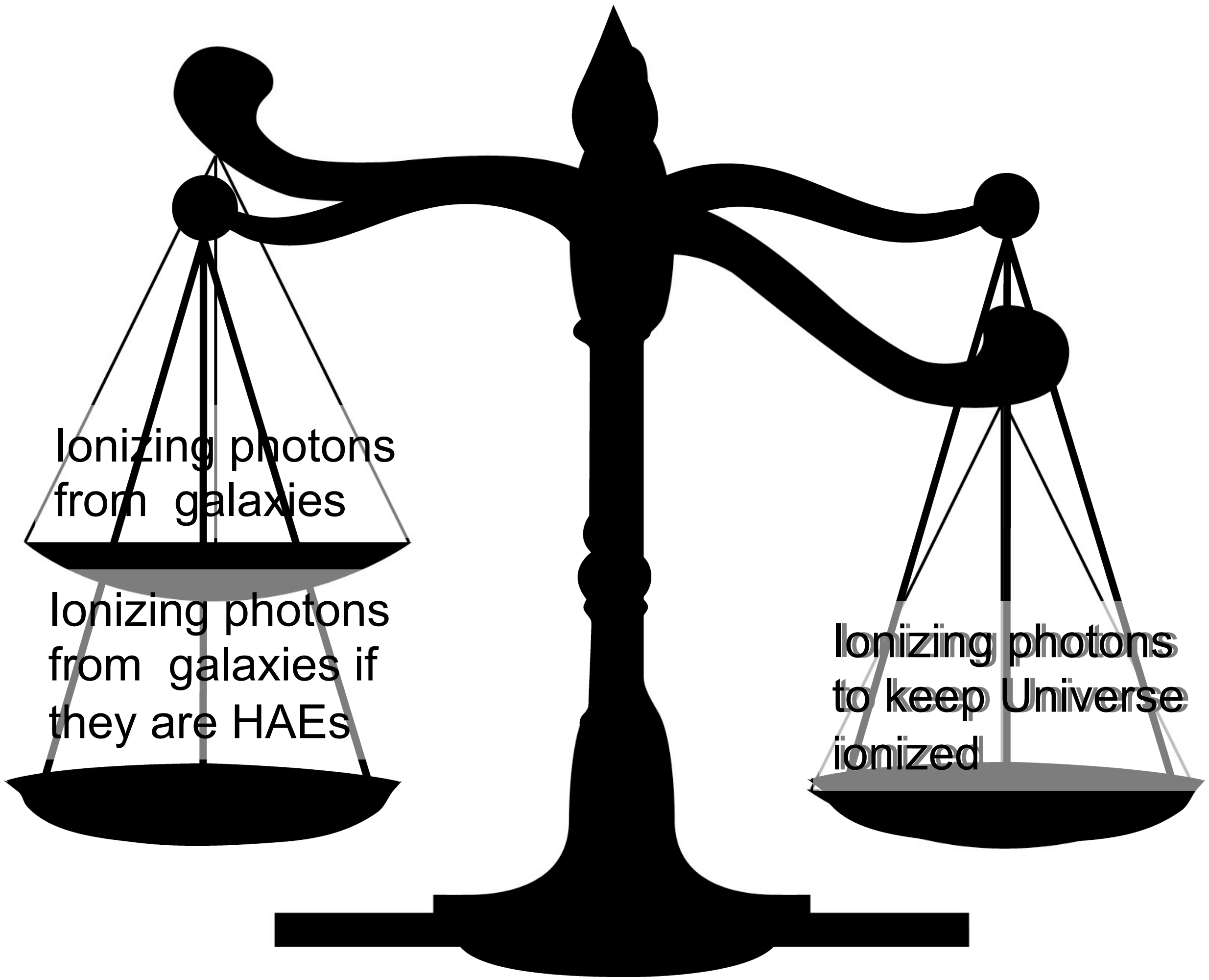
Color	UVLF Alpha	HAEs?	Luminosity Cut	Tau
black	-2.0	No	1E7 Lsun	0.05
red	-1.84	Yes	1E7 Lsun	0.092
blue	-2	Yes	1E7 Lsun	0.1
green	-1.84	Yes	5E8 Lsun	0.079

The Full Monty with Planck Results



RC et al., 2016, Space Science Reviews

Balanced at least one budget.... thanks to Halpha Emitters



Summary

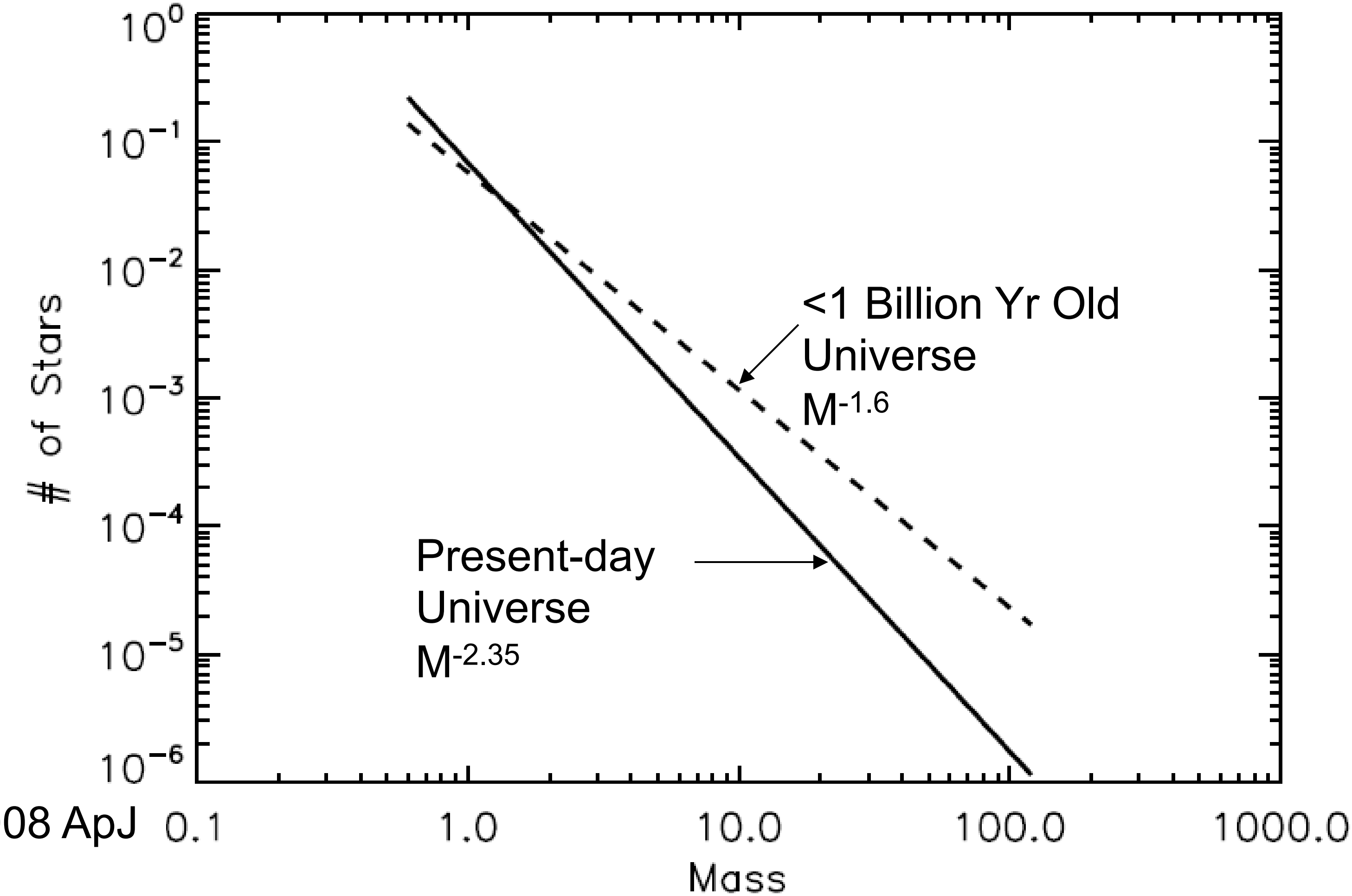
- Thanks to the Great Observatories (both ground & space) we are beginning to really understand star-forming galaxies that formed within 1 billion yrs of the Big Bang
  - The majority of z~5 galaxies show strong Halpha nebular emission detectable in a broad bandpass, x10 higher than expected.

- [HOW & WHAT] Galaxy growth appears to be different at early times
  - Evidence for Quasi-continuous star-formation
  - Less than half are consistent with mergers
  - At least some of them need a top-heavy initial mass function with stars showing significant angular momentum

- 0.04% of the local Universe galaxies show similarities in emission line properties with the z~5-6 galaxies but JWST spectra will help reveal massive stars through HeII lines

- [WHEN] Reionization occurred once and is a slow, extended process starting from z~10 with rapid end stages at z~6
  - Halpha emitters are key for completing reionization with small escape fractions of 0.1

Checks & Balances:
To agree with the stellar mass density at z~6, independently needs a top-heavy IMF

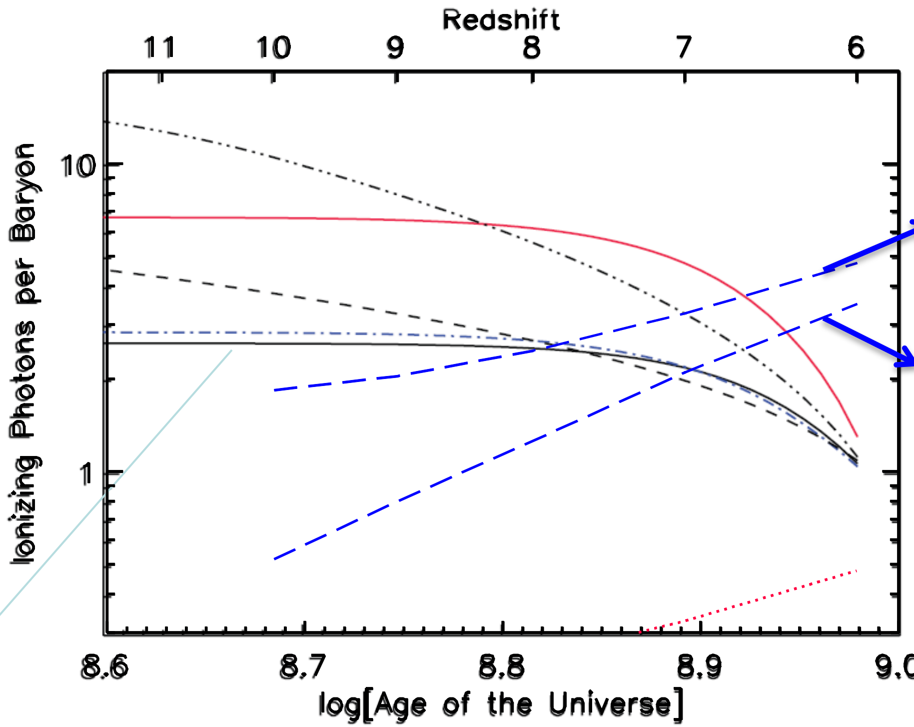


Chary 2008 ApJ

The Beauty of This Solution

- Normal, low escape fraction of ~10%
- No need to extrapolate to zero luminosity in the UV LF of galaxies
- Does not require an outrageously large number of faint galaxies (i.e. L^{-2} faint end slope)
- Normal IGM conditions which doesn’t require a low recombination rate
- Can reproduce WMAP tau=0.085.

Are Halpha Emitters the Solution to Reionization?



Integrating all Lsun

Integrating only above 1E7 Lsun

This is the minimum number of ionizing photons required

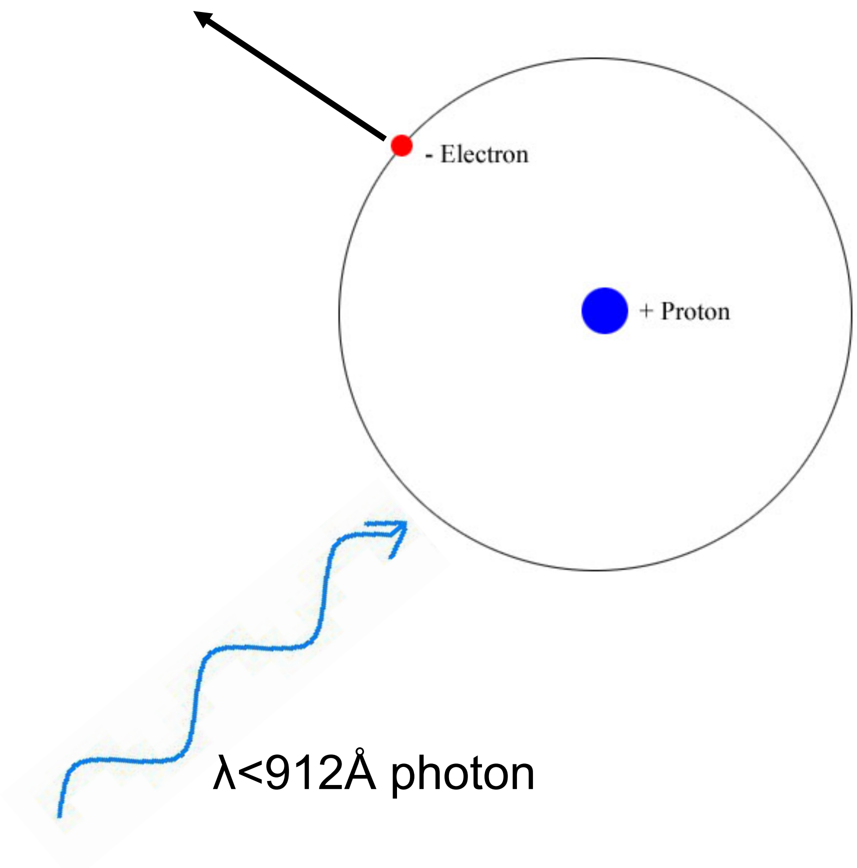
After including HAEs,
Photon Production Rate > Hydrogen Ionization + Recombination Rate

So YES!

Reionization: Why should we understand it ?

- Sets the temperature and metallicity of the ISM which determines the nature of subsequent generations of stars
- Size of Stromgren spheres defines the formation of early globular clusters and early dwarfs
- Regulates the early growth of galaxies
- Seeding of first generation of black holes

Need 1 photon/baryon to start reionization



$$R = n_e n_{\mathrm{H\,II}} \alpha_{\mathrm{B}} C \ \mathrm{s}^{-1} \ \mathrm{Mpc},^{-3}$$

Sensitive to:

1. Clumpiness of the gas
2. Temperature of the gas
3. Co-moving electron density

Need ~3-10 photons/baryon to maintain ionized hydrogen due to recombination

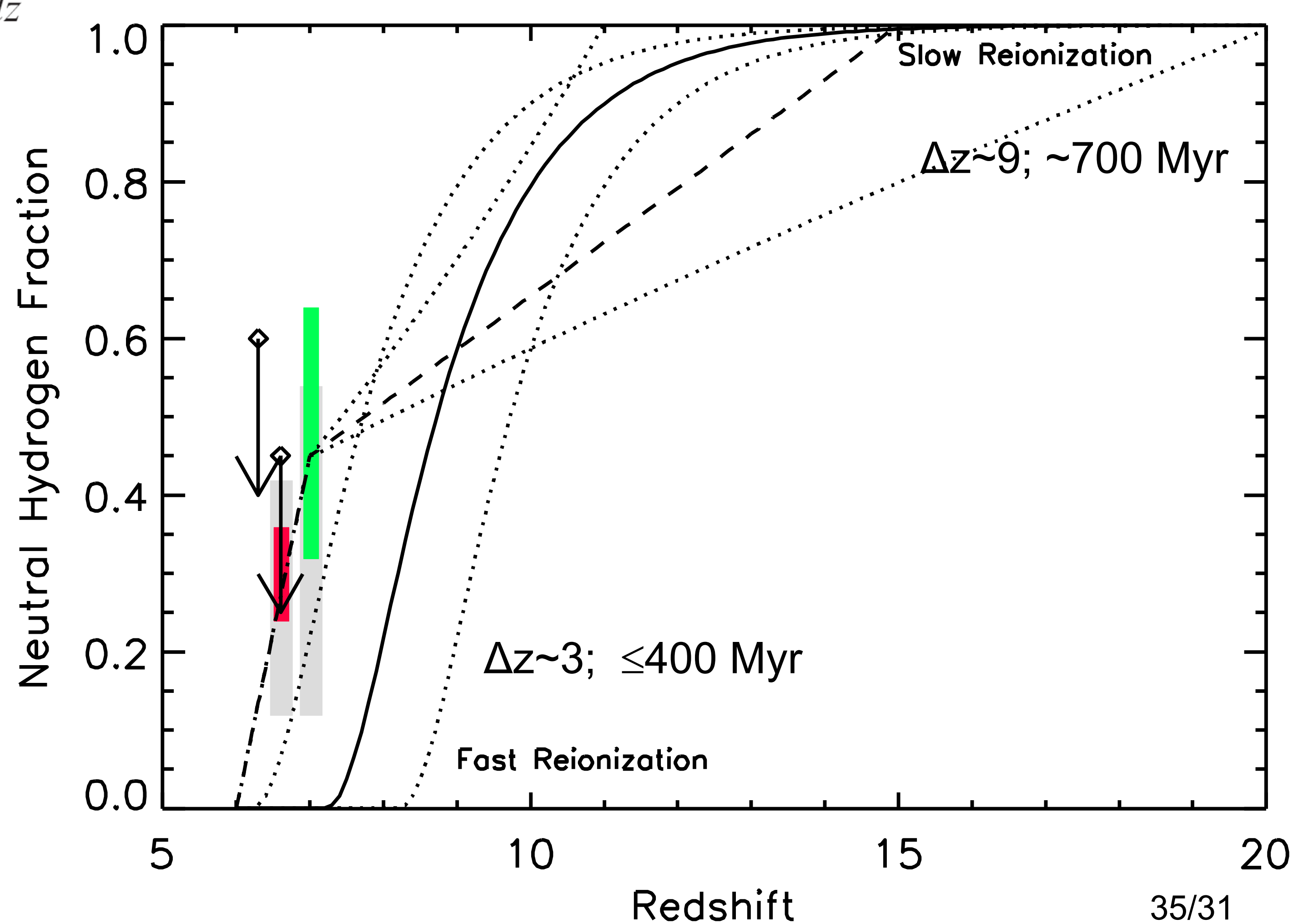
Could be Fast, Could be Slow…Which is it?

$$\tau = \int_0^{z_e} dz \sigma_T n_e(z) c \frac{dt}{dz}$$

WMAP Tau = 0.084+/-0.016

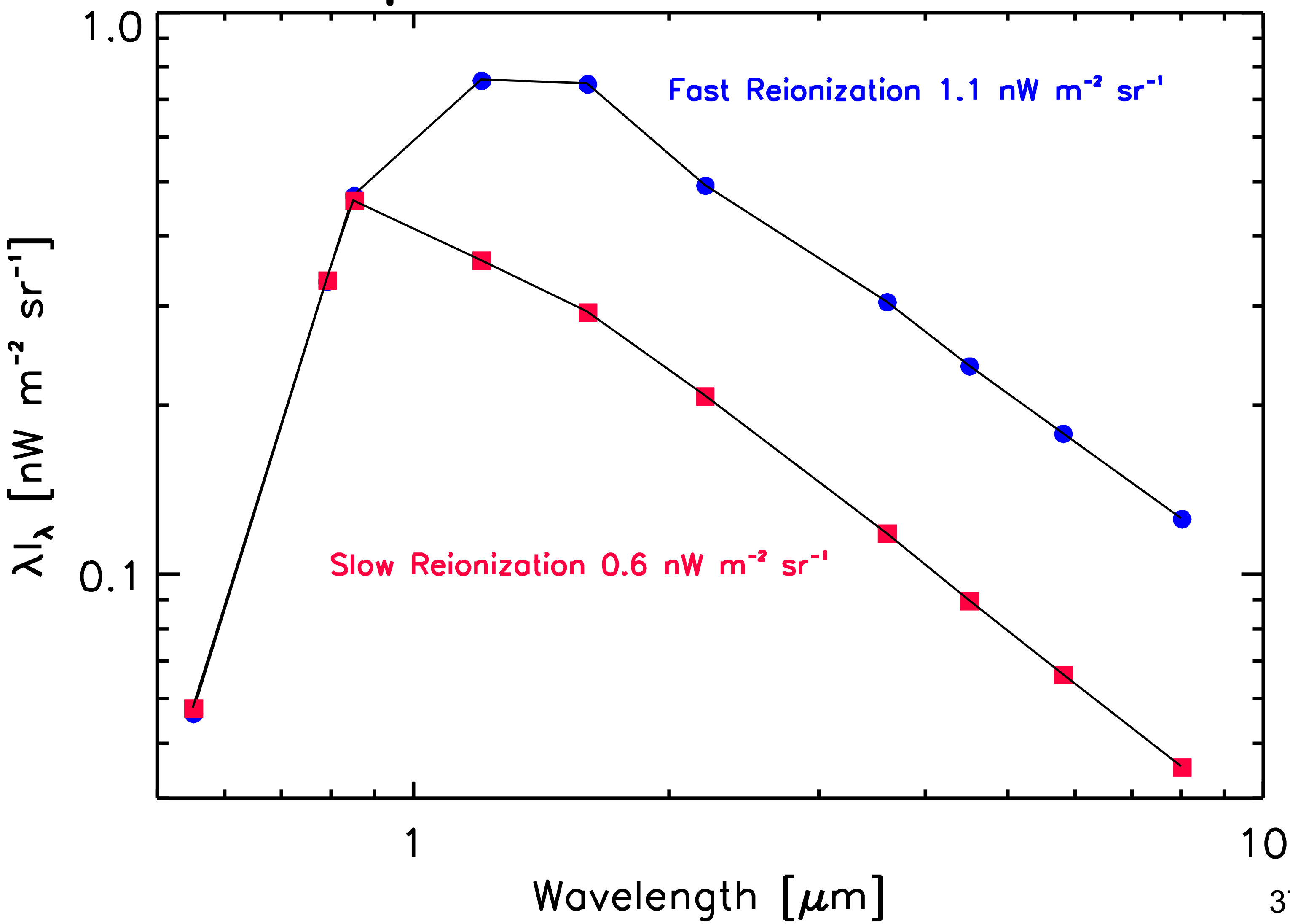
z<6 contributes ~0.04

So 0.044+/-0.016 measures reionization history.

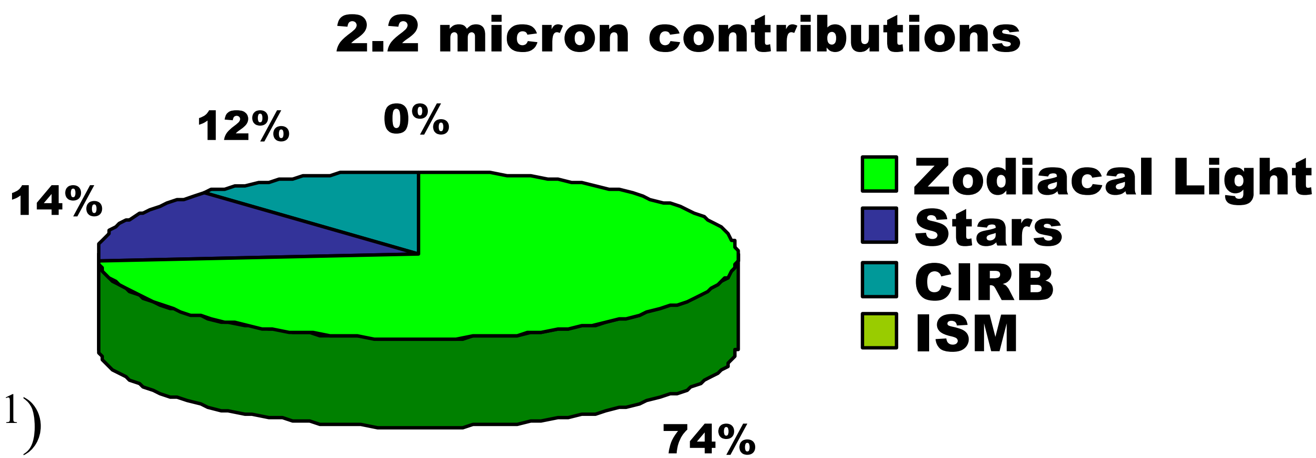


Looking into the Future: Absolute Intensity Measurements using ZEBRA

In principle, absolute CIB measurements will provide the answer



Unfortunately Sky Background at Infrared Wavelengths is Dominated By Zodiacal Light

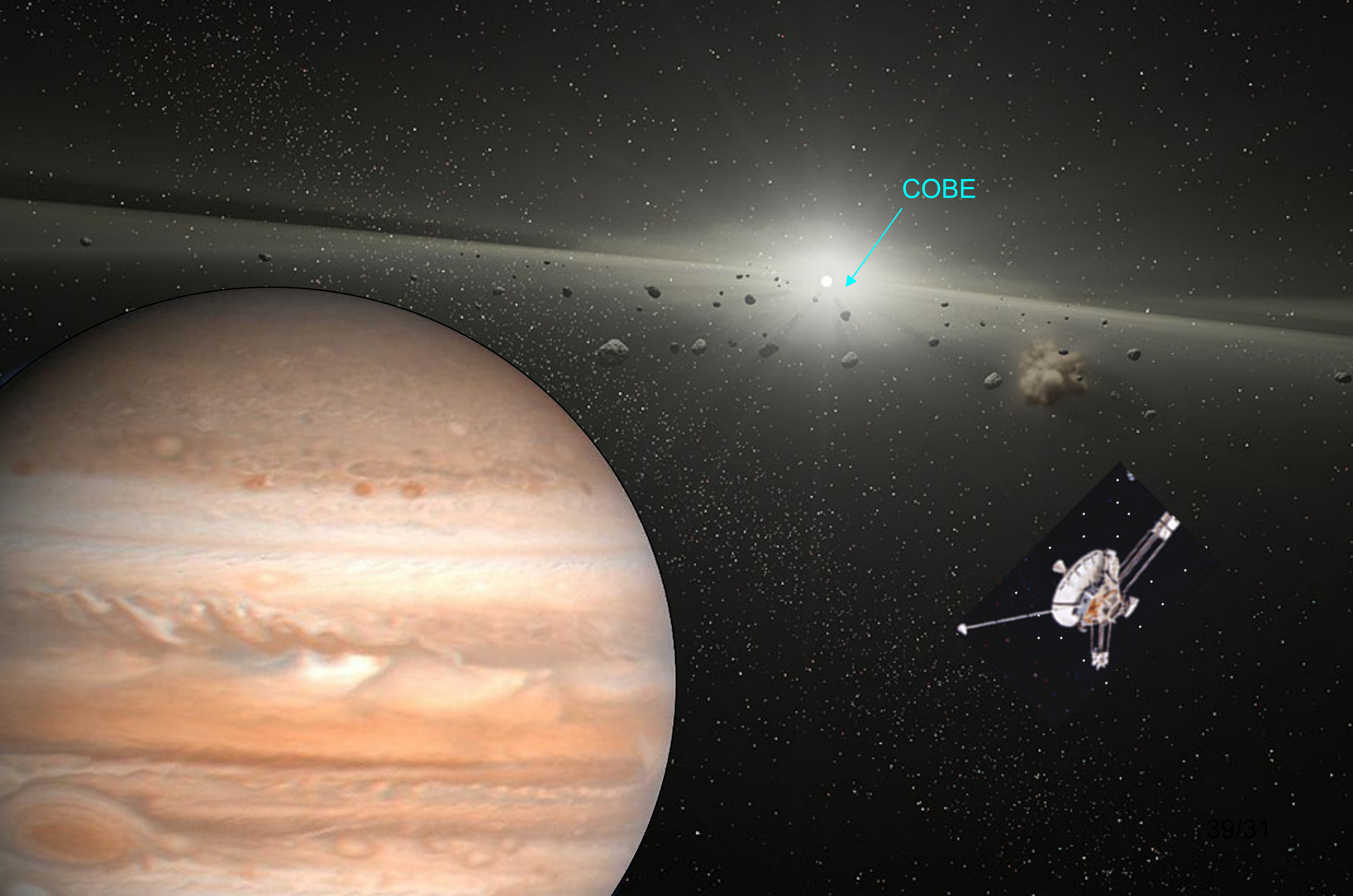


CIRB (nW m^{-2} sr^{-1})

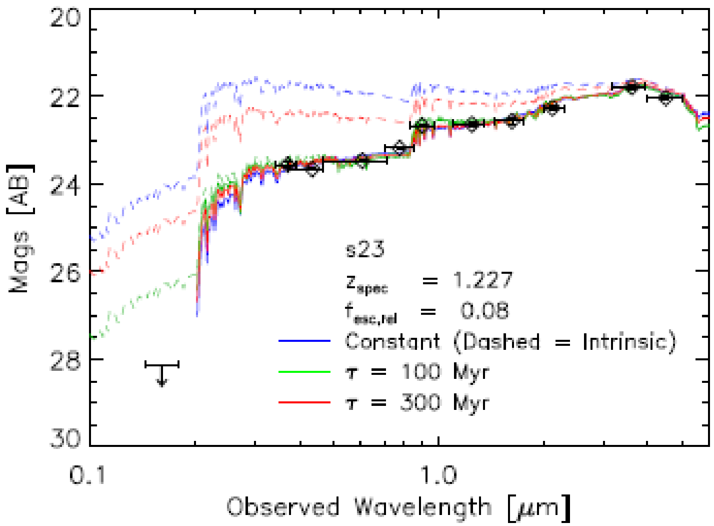
λ	νI_ν
2.2:	22.4±6.0
3.5:	11.0±3.3

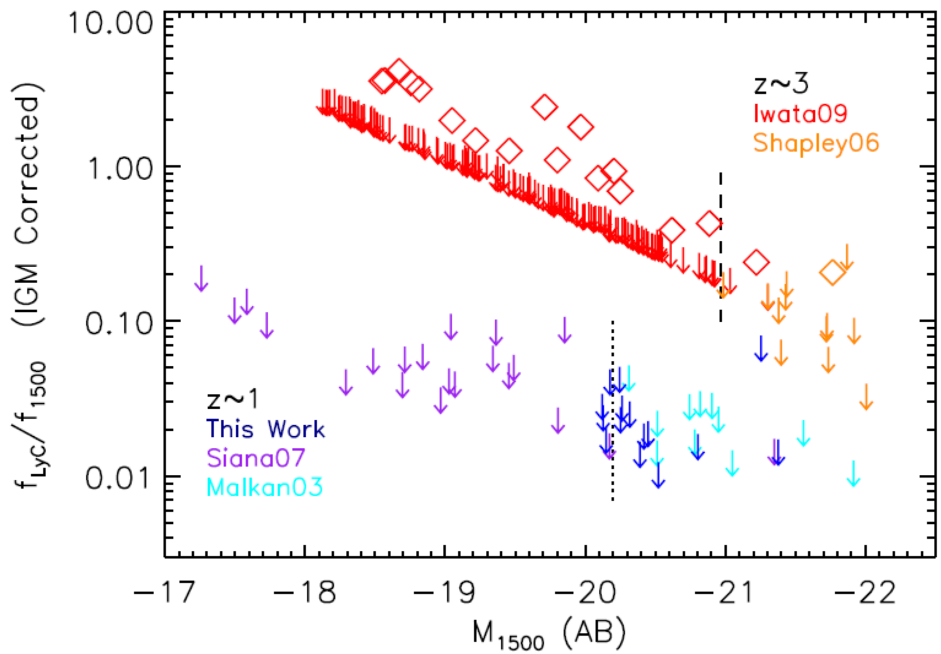
We want to measure 0.5+/-0.1 nW m^{-2} sr^{-1}
We are literally searching for a needle in a haystack!

ZEBRA: Probing reionization by flying outside the zodiacal cloud



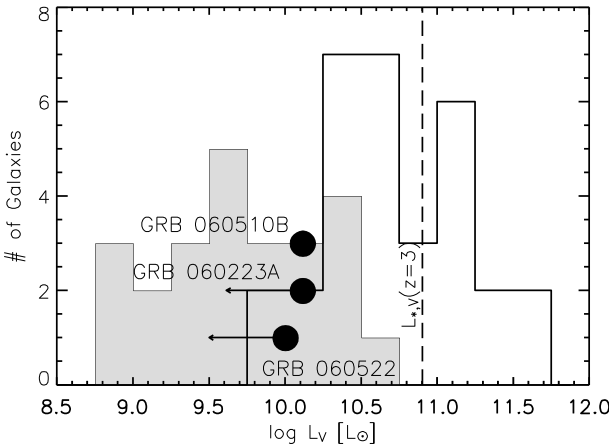
And the Escape Fraction is poorly known

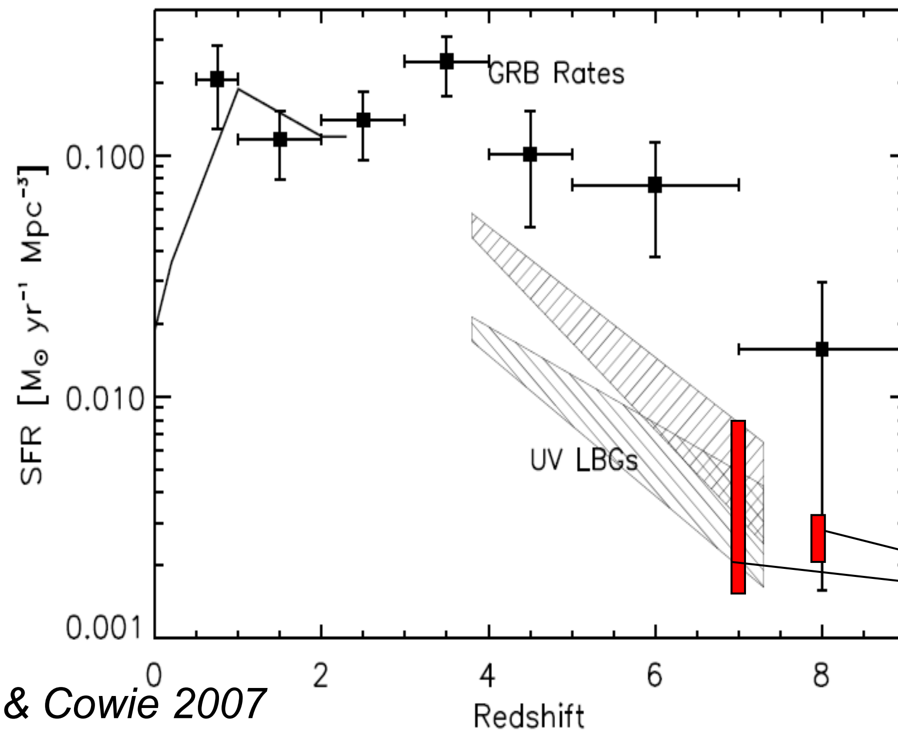




Iwata et al., Siana et al. 2010

Hint of a higher SFR at z~6 from GRB Hosts





Chary, Berger & Cowie 2007

GRBs suggest a larger ionizing photon flux from faint galaxies

But we need at least two pieces of evidence....

The integral of the star-formation history is preserved in the stellar mass density of galaxies

- The evidence is strongly in favor of more massive stars at z>6 = non-Salpeter IMF.
  – Top-heavy, $dN/dM \sim M^{-1.6}$

- Massive stars die quickly and go off as Gamma-Ray Bursts and Type II Supernovae which can be detected in wide-field NIR surveys.

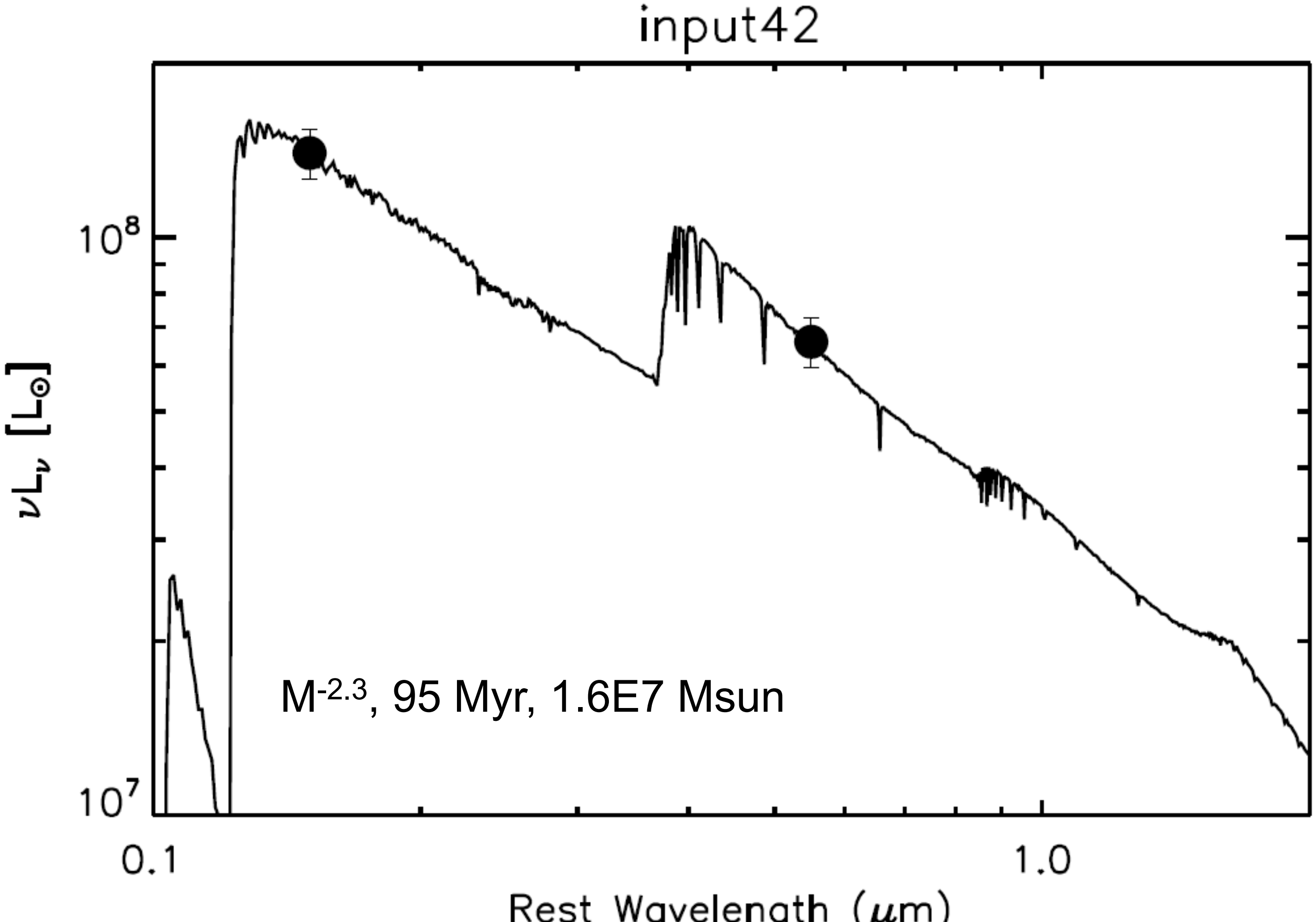
- Good physical motivation = ISM temperature is higher by (1+z), density is low, fewer metal cooling lines. Jeans mass $\propto T^{3/2}\rho^{-1/2}$

- As for humans, more activity (star-formation) and healthy diet (more minerals/metals), gets rid of a top-heavy IMF.

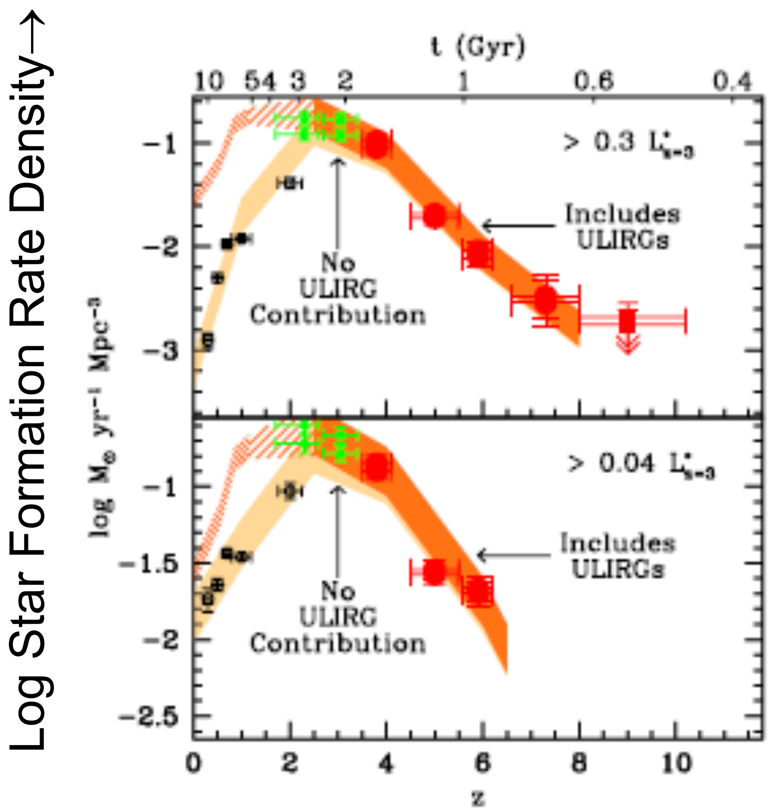
- Both mergers and cold-accretion appear to be powering star-formation

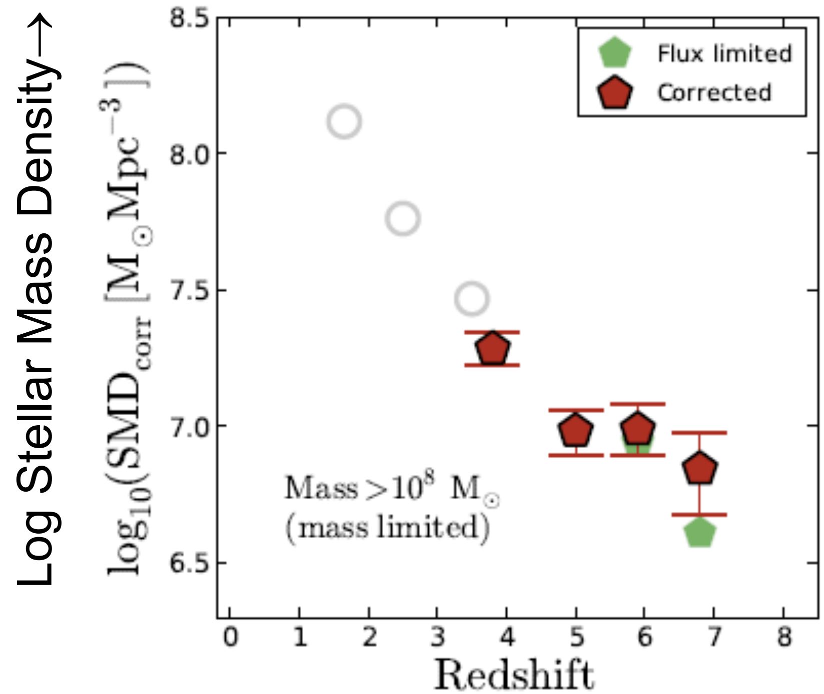
Reason for Concern?

- The stellar IMF is unknown



A Key Goal is to Understand the Evolution of SFR and SMD with redshift

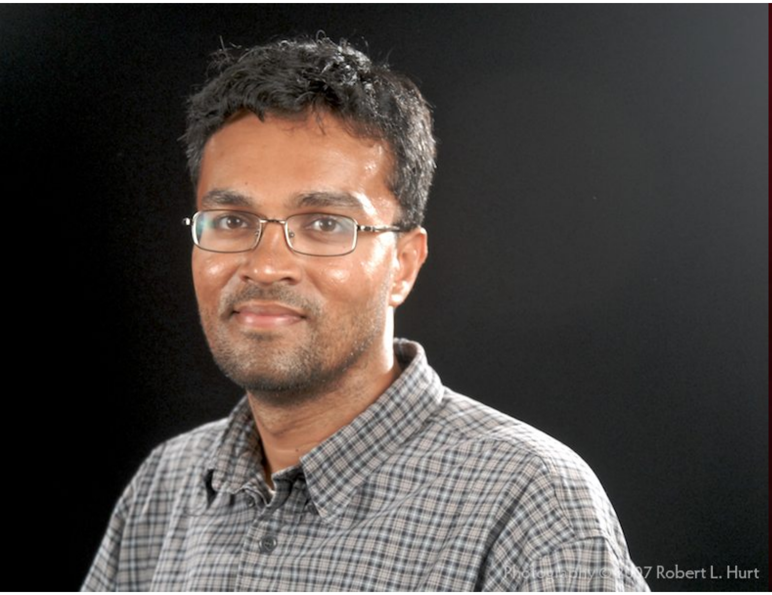




Bouwens et al. + RC 2010

Gonzalez et al. 2011
RC 2009

The Need for Different Wavelengths



The Hubble View

The Spitzer View

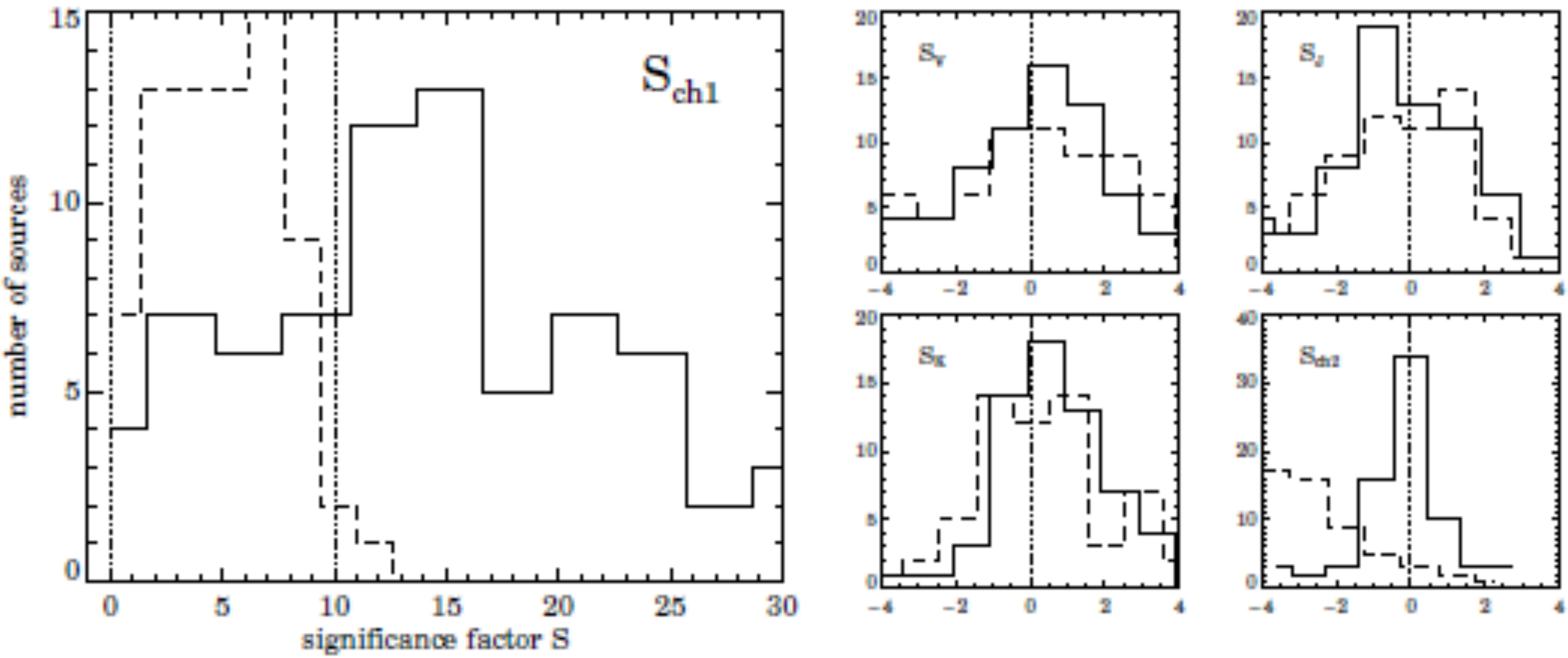
The Chandra View

The Basic Premise

- Rest-frame FUV Continuum + Nebular emission = Star Formation Rate

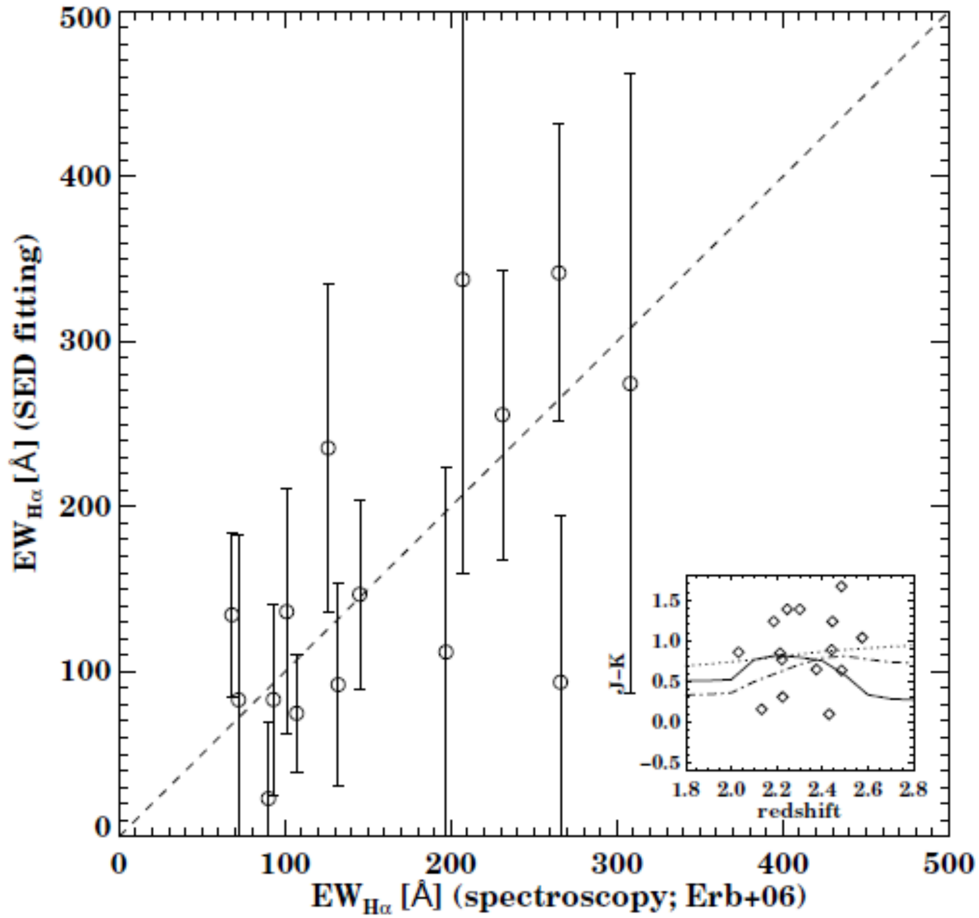
- FUV + Optical Continuum = Stellar Mass and Age of Stellar Population

An extensive search for systematics



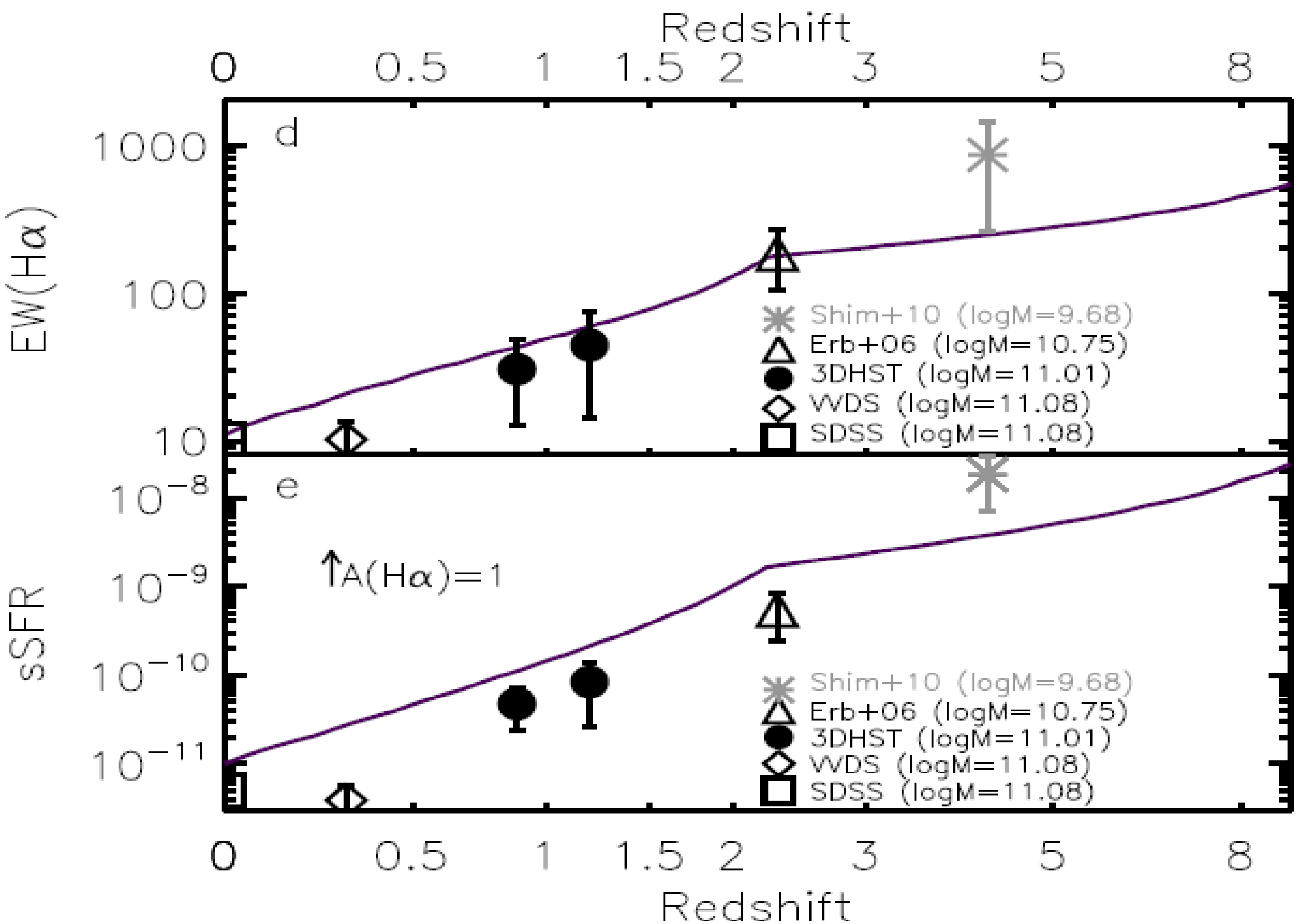
- Can only be done in fields with excellent multiwavelength data

Testing the Method at Lower Redshifts



- No bias found when comparing with spec-z at z~2
- Admittedly uncertainties are large at low-z

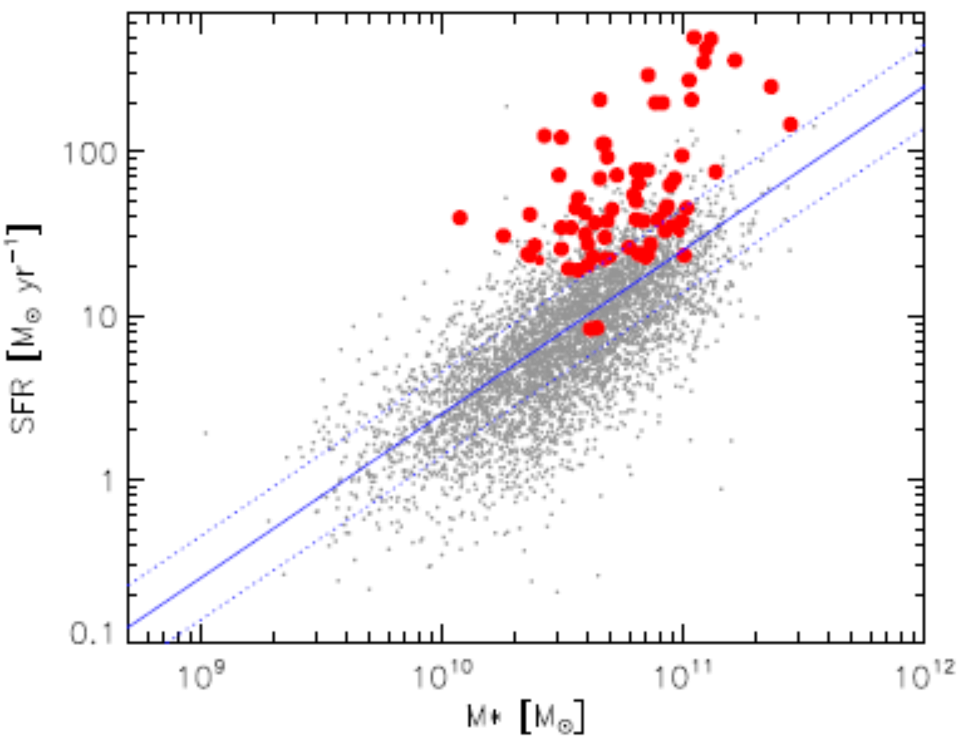
Evolution of Nebular Emission with Redshift



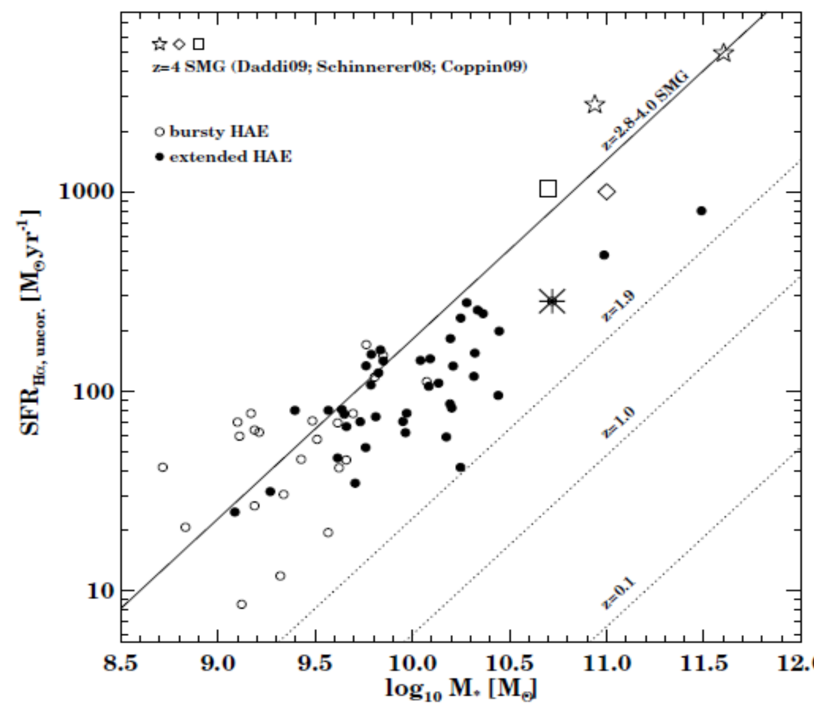
Fumagalli et al. 2012

The Specific SFR is Elevated at z~5

- Specific SFR = SFR/Stellar Mass
- There is apparently a "main sequence" for galaxies i.e. a particular SFR for a particular stellar mass



z=0; Elbaz et al. 2011



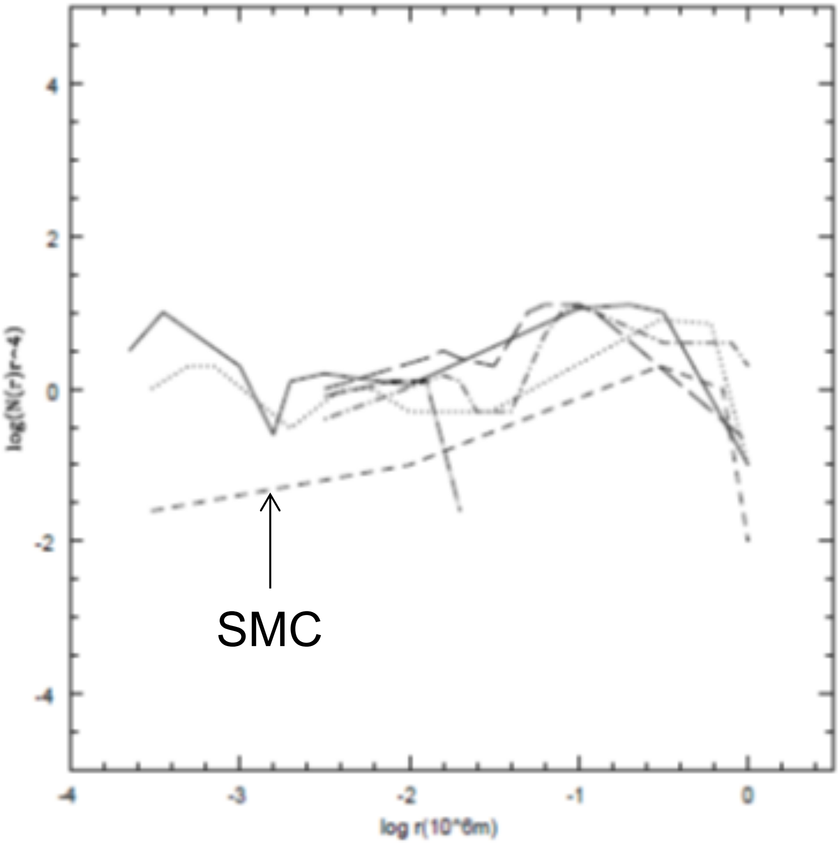
z=5, Shim, RC et al.

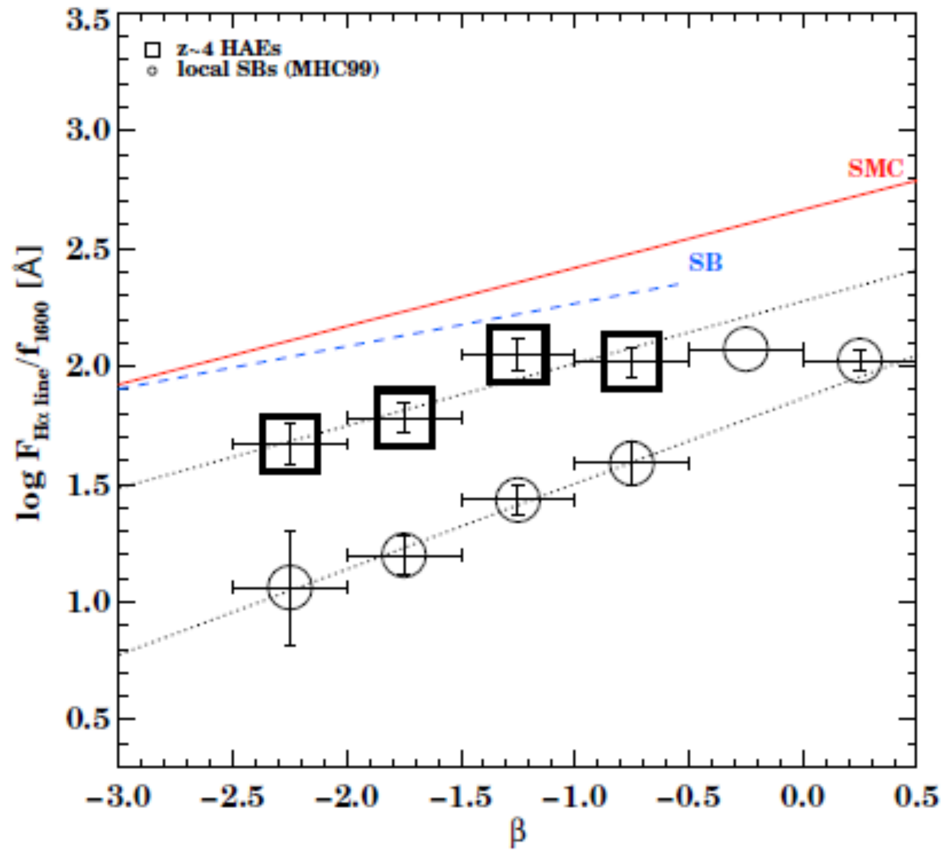
See also Noeske et al., Daddi et al., Lada et al. 2012

z~5 sSFR is similar to that of mergers/bursts

- The higher sSFR at z=5 is consistent with the increased gas density in halos
- But this makes it hard to use the sSFR as a diagnostic of bursts vs accretion in the high-z Universe as is done in the z=0 Universe

Maybe evidence for low-metallicity dust





- Should be nailed with ALMA observations