Over the coming Decade, what will Hyper-SC and PFS be doing to study *Cosmic Evolution of Star Formation*?

Matt Malkan's fearless predictions

- We'll be studying large numbers of galaxies across the full redshift range back to the epoch(s?) of formation, ruthlessly exploiting every spectral signature, in every available waveband.

  This review will consider each of them, in increasing wavelength order.

- Bias and incompleteness will remain big concerns:
- The first step is to be sure we FIND all the galaxies in each redshift window we search

- Next, we will continue to agonize over how to measure cleanly the 'recent' Star Formation, free from problems of extinction and AGN contamination

- (Except for mentioning gravitational lensing), I'll *ignore spatial information*, treating galaxies as integrated point sources--even though all-sky AO is becoming a big deal

At z>1, our Survey starts in the rest-frame Ultraviolet

The single strongest feature in the entire spectrum
of (nearly) all galaxies, especially at higher redshifts, is

The Lyman
Break (partly intrinsic, partly IGM)

Finding 'LBGs' in a given redshift band "Only" requires
EXTREMELY DEEP imaging in
Our *shortest observed waveband* (space UV, GALEX, HST),
Or U-band (thinned CCDs on big ground-based telescopes)

Search for Lyman "Dropouts" has been a tremendous success story

- However, it does have some significant limitations:

- 1) many galaxies, especially the bigger ones, are either too ….a) dust-reddened, or
- b) too old

to produce sufficiently dominant UV continuum to produce a detectable Lyman break ('LBG')

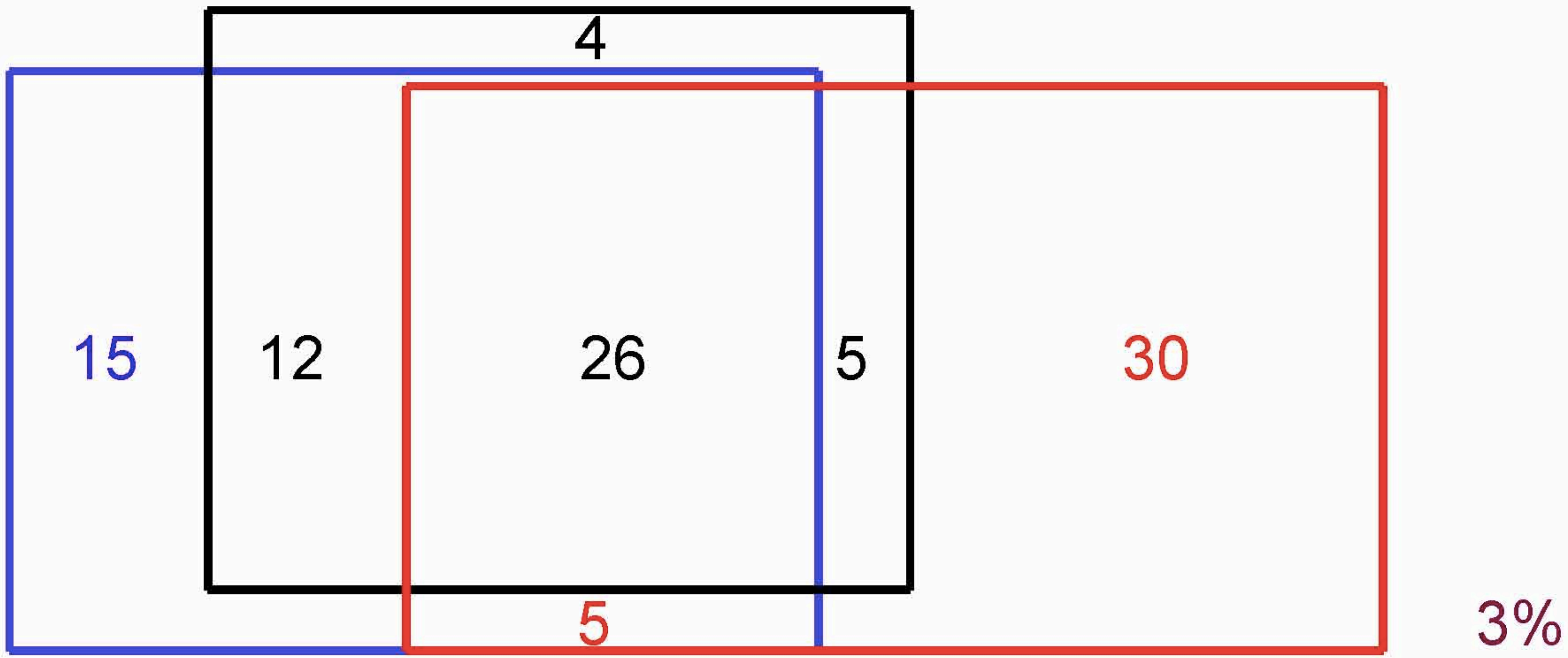
2) At higher redshifts there are a lot of imposters, including

a) very red stars

b) very reddened galaxies at intermediate redshifts $1<z<3$

c) galaxies with such strong emission lines that they can contaminate the 'broadband' magnitude on the red side of the alleged 'break'

BX/BM(57%) NUV-drop(LBG-48%) sBzK(68%) pBzK(3%)



Venn diagram for Subaru Deep Field-depth observations, at z~2

As z increases, more galaxies shift to the left side (bluer and younger):

--> LBG method becomes the most practical.

Ly et al. UCLA thesis

Conclusions from the Subaru Deep Field
The limitations of broad-band color selection of Galaxies at z=1--3

1. 1. No single "color" selection technique is able to identify the broad range of galaxies at *z*=1-3 with current depth. Must merge at least two of them including near-IR photometry. Then we can get ~90% of them.

2. 2. Over half of the SFR density (from K<24 galaxies) consists of galaxies with E(B - V) > 0.25 mag. Dusty galaxies are important, and we may not trust their observed UV Luminosity to give us reliable SFR

3. 3. Our narrow-band (7 filters) selection finds a broad range of Subaru Deep Field **emission-line** galaxies at specific known redshifts.

   At z~1.5 most galaxies have rest-frame optical emission lines.

1. 4. At z>3, everything gets very problematic

Follow-up Spectroscopy of NB Line Emitters in SDF

1. 5 Narrow-band filters in SDF cover one third of 0<z<1.0 redshift space, and two Intermediate-band filters double that

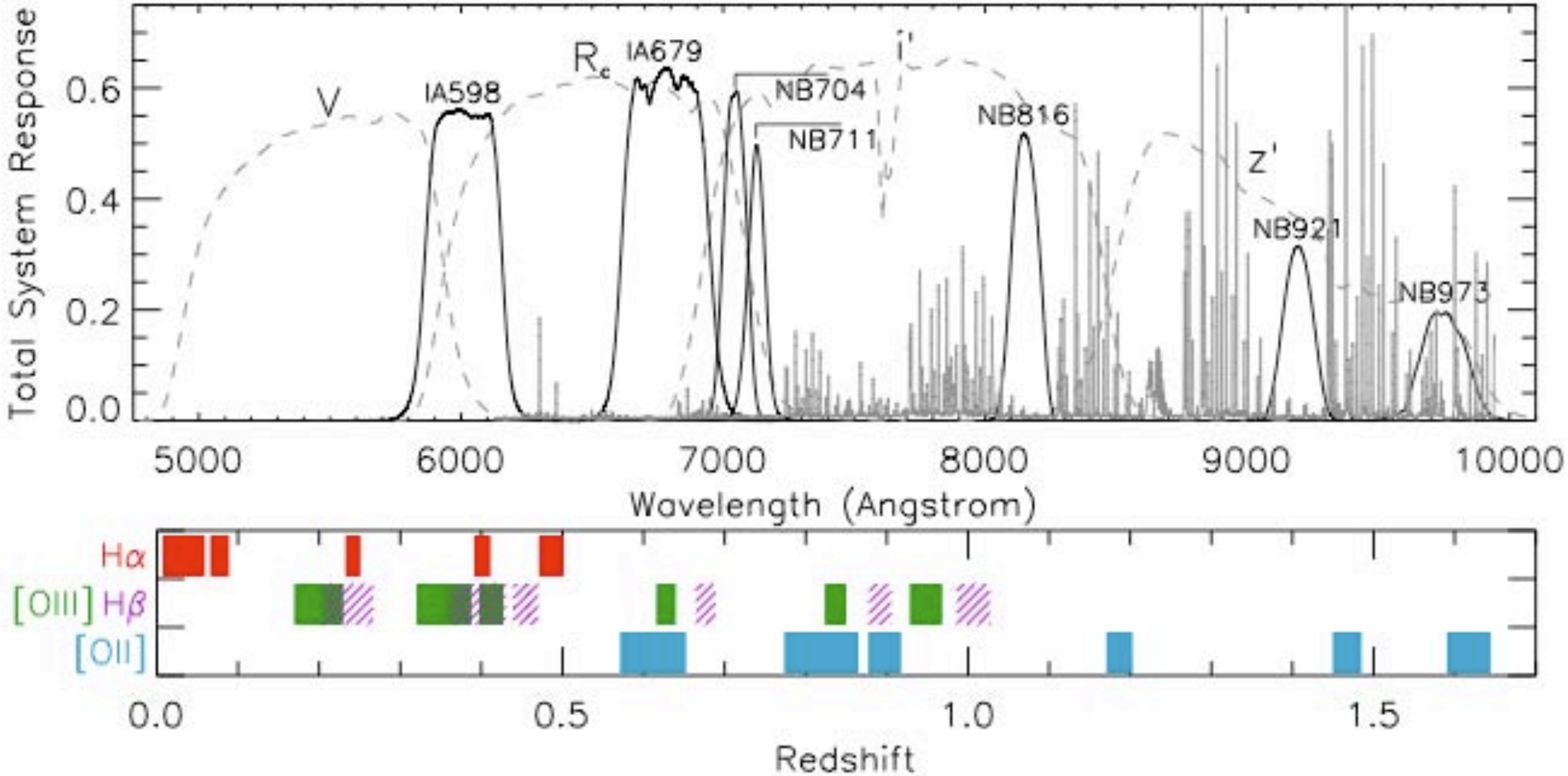
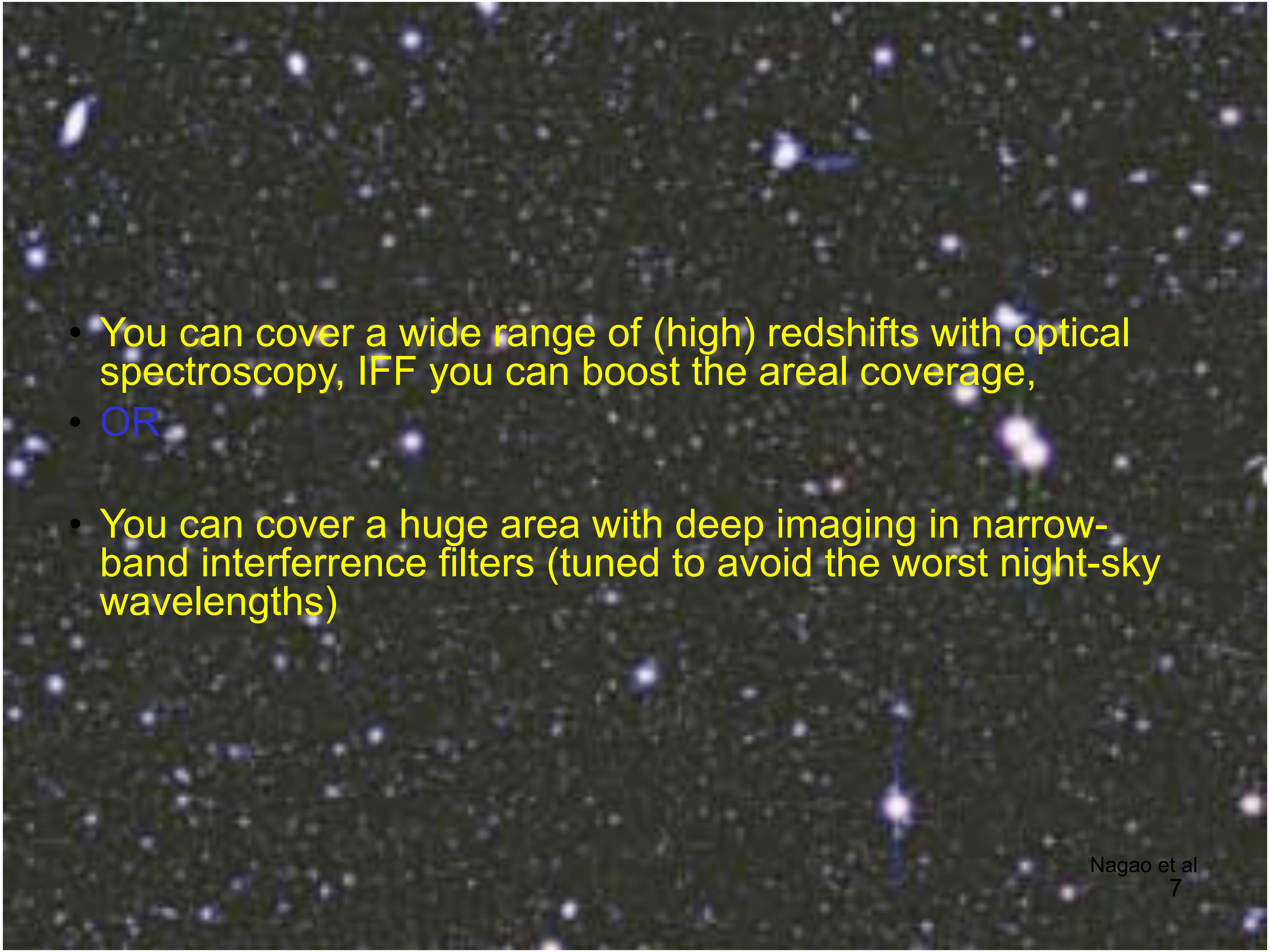


FIG. 1.— *Top:* Total system throughput for the $VR_Ci'z'$ filters (gray dashed lines) and the IA598, IA679, NB704, NB711, NB816, NB921, and NB973 filters (black solid lines). *Bottom:* Redshift ranges probed when Hα, [O III], Hβ, and [O II] are redshifted into these filters. The SDF probes 64% of redshift space and 67% of comoving volume at $z \leq 1.03$.

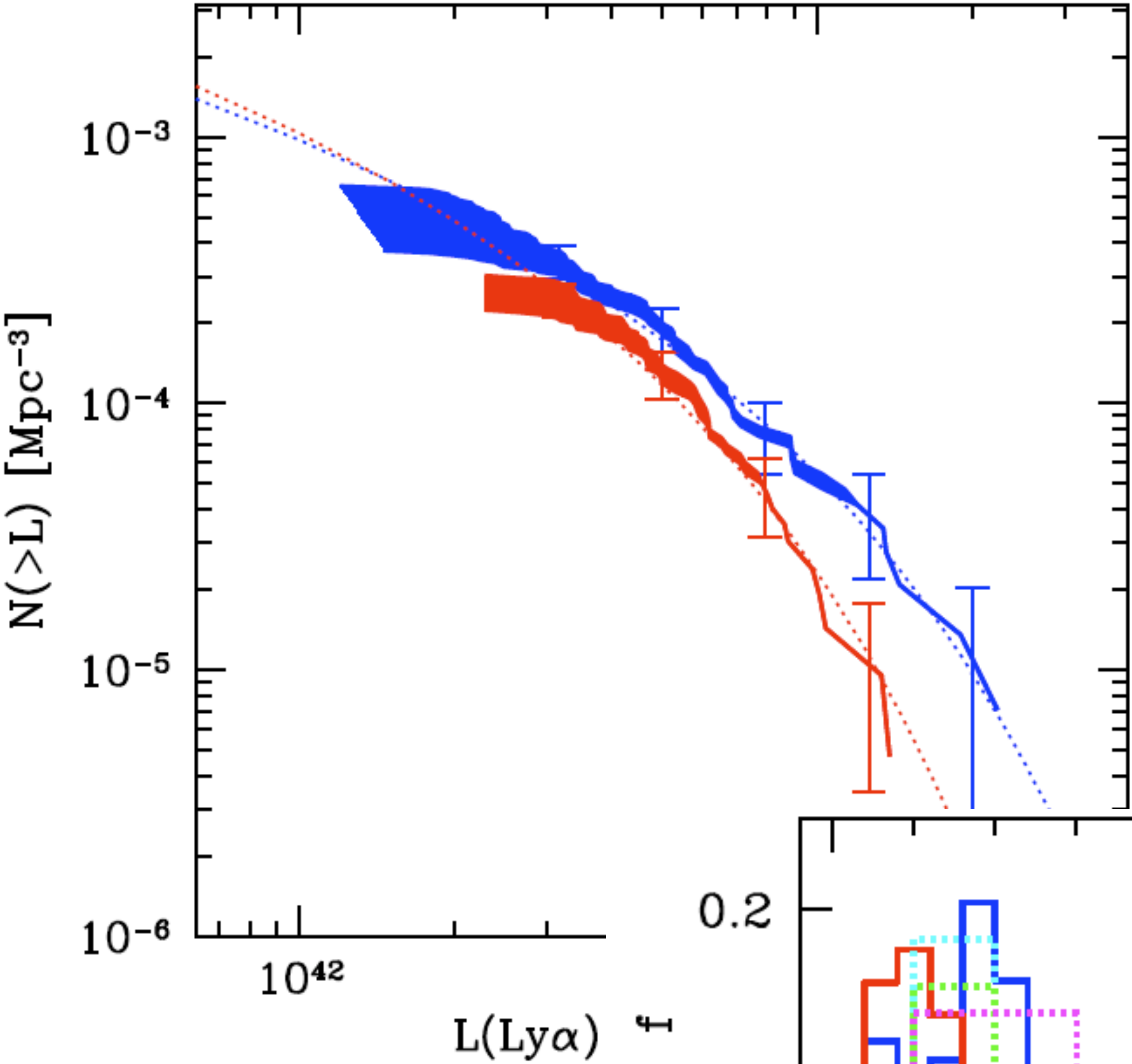


- You can cover a wide range of (high) redshifts with optical spectroscopy, IFF you can boost the areal coverage,
- OR
- You can cover a huge area with deep imaging in narrow-band interferrence filters (tuned to avoid the worst night-sky wavelengths)

Nagao et al

Lyman-α seems ideal for our purposes, at first…

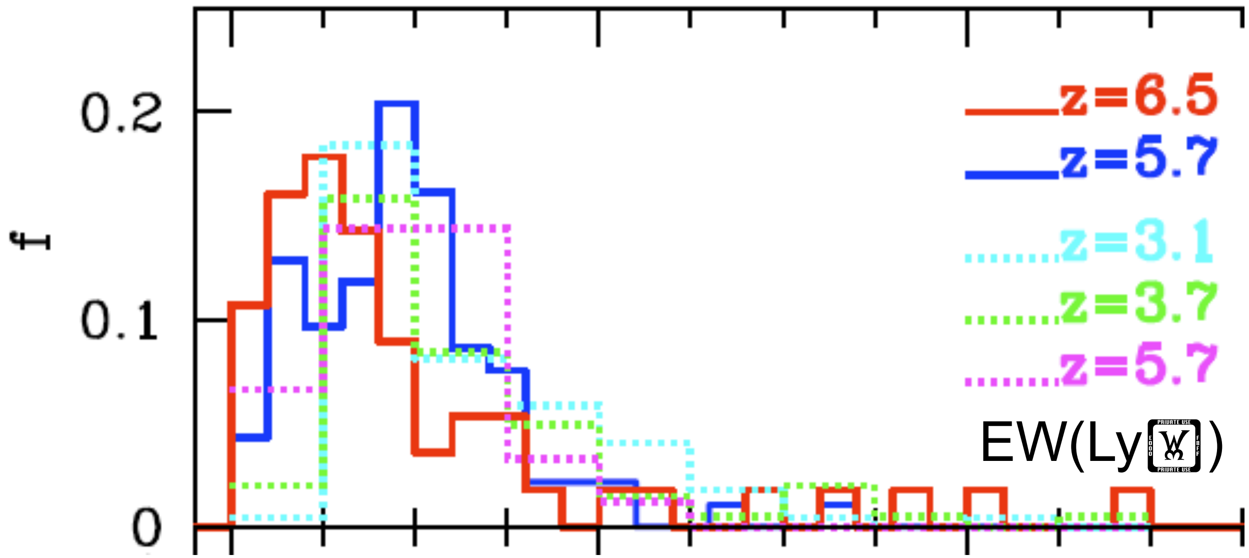
- It is recombination line emission from HII regions around hot (young) stars, and
- It is stronger as you go to higher redshifts (ie more likely in emission, with larger Equivalent Width)
- The Big Problem is knowing how much Lyman-α escapes the galaxy and reaches Earth



In SDF, Kashikawa, MM et al found that number of LAEs falls sharply from z=5.7 to 6.6

(since there is no such drop in UV-continuum emitting galaxies, is this signature of cosmic reionization, with HI in IGM preferentially absorbing Lyα ?)

At z=3, only ~1/3 of LBGs have strong Lyα emission, While MOST LBGs do at Z~6 -->



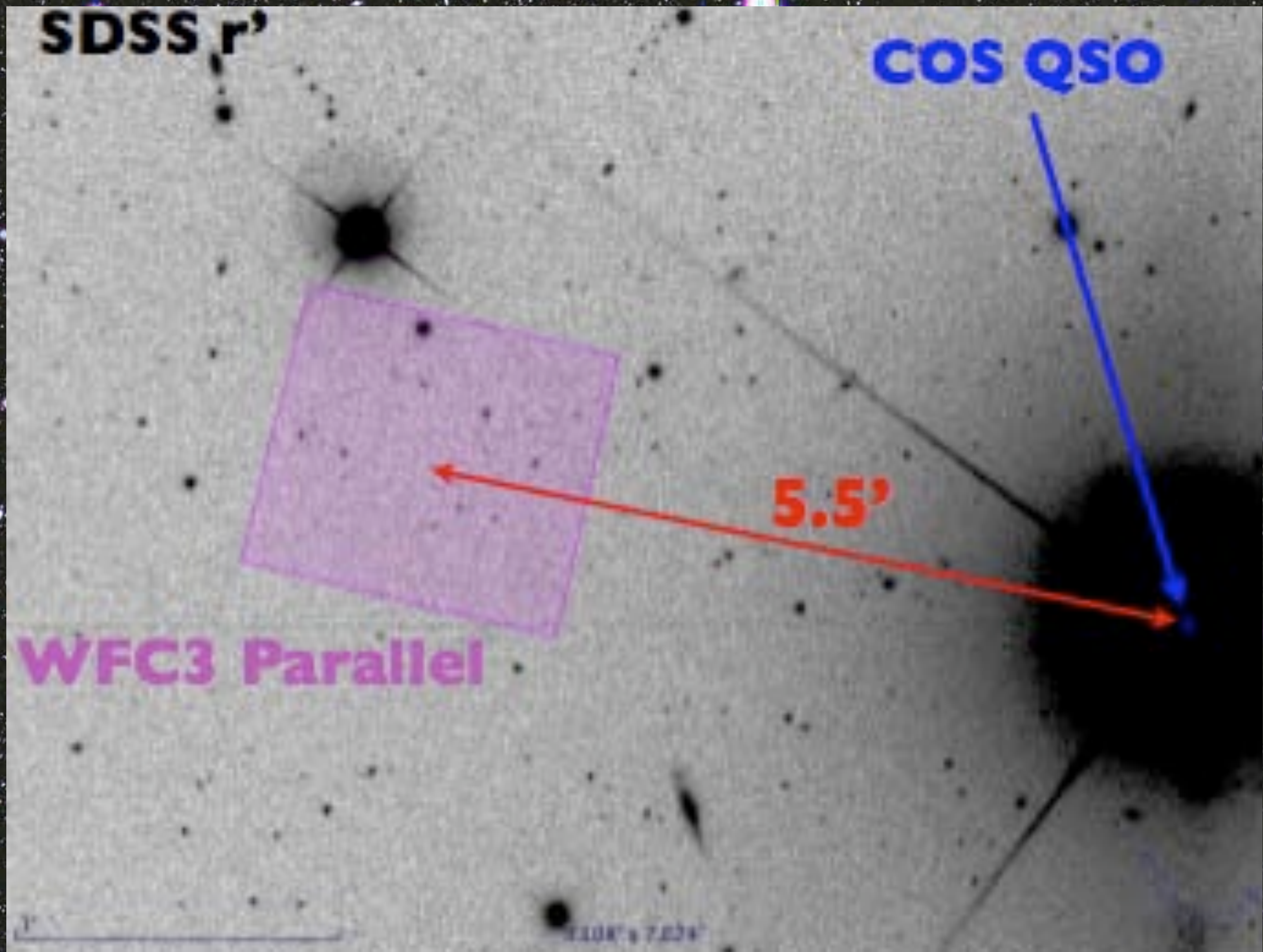
Wouldn't it be wonerful if we
Could get Slitless Spectroscopy
So that we would combine both
The wide redshift range AND the
Multi-object speed gains..
And do this in the IR, where our best
Diagnostic lines get redshifted!

Hubble makes the Dream come true:
Wide Field Camera-3 Installed. Its IR
imaging and slitless (Grism) spectroscop
are ~20 times faster than NICMOS.
It can operate in "Parallel" observing
mode, staring deeply at sky regions
'for free', while another Hubble
instrument hammers at its primary target

WFC3 Infrared Spectroscopic *Parallel* Survey

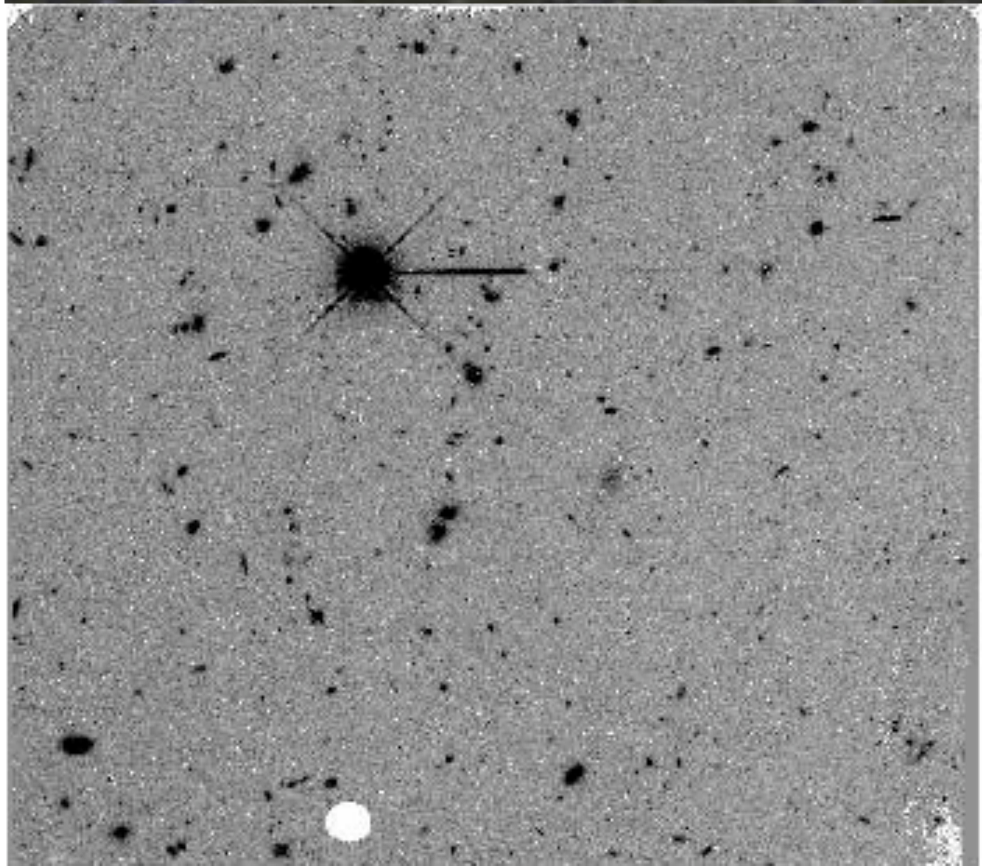
We are getting good science at 'no cost' to HST

1. Random fields near some bright objects of interest to COS

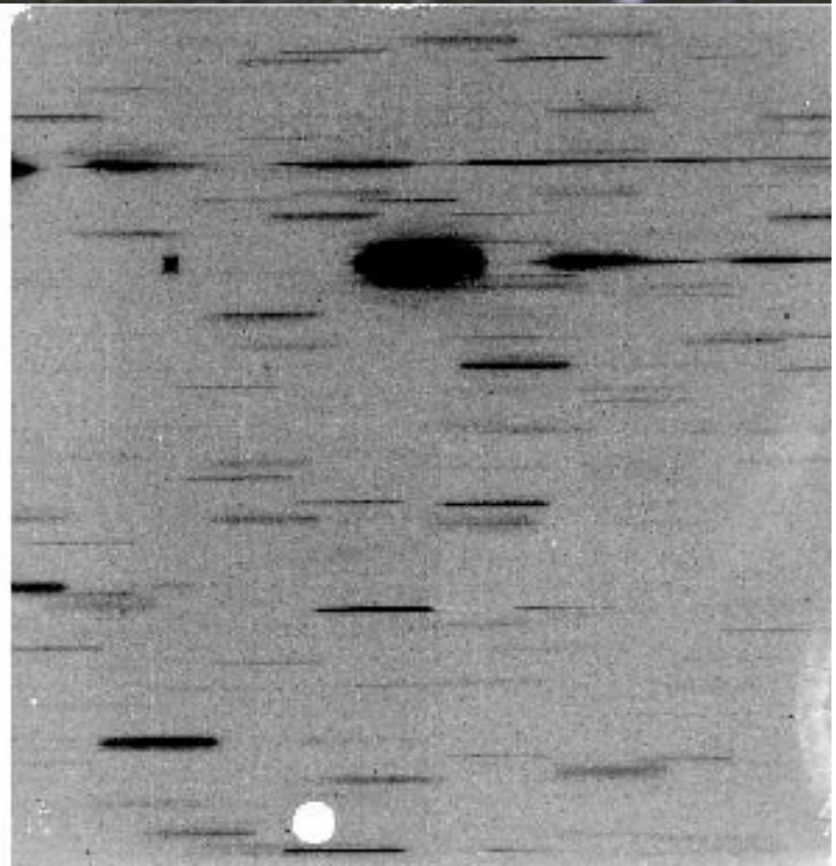


WISP Observations since 2010:

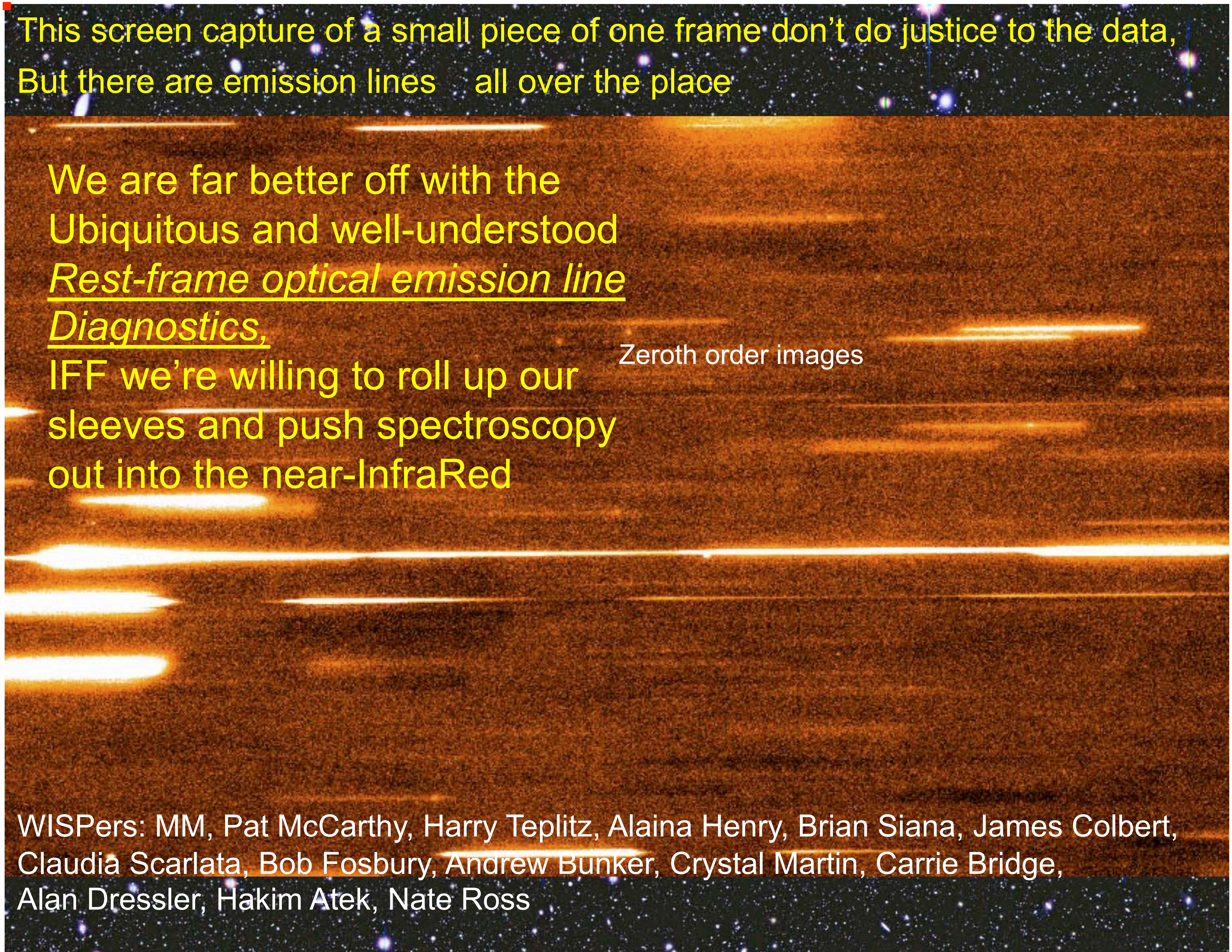
1.6um Direct Image (3 Arcmin FOV)



Prism-dispersed Image



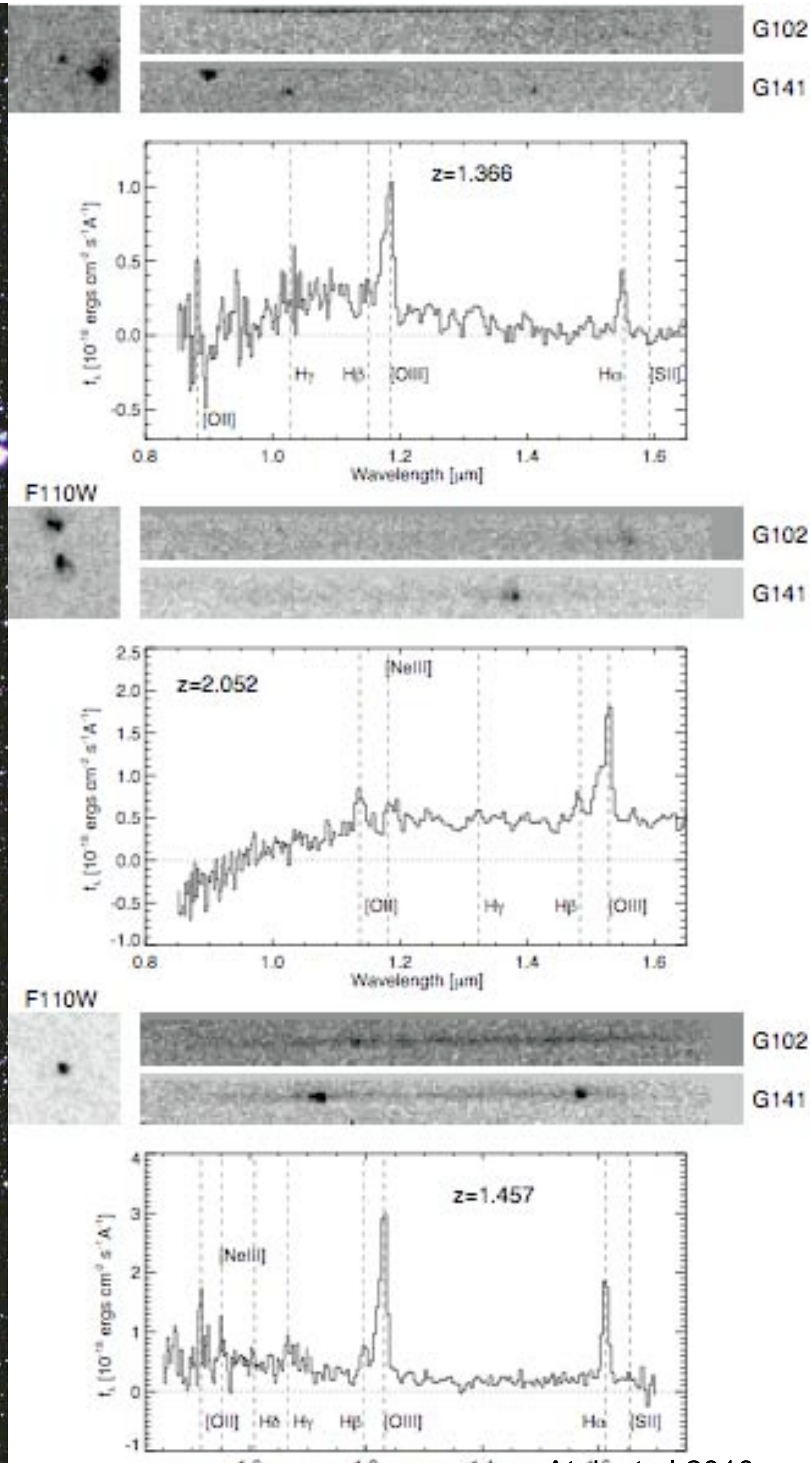
1. Search in IR, where strong optical emission lines shift at higher z;
2. Continuous wide spectral coverage (0.8--1.7um) samples large 3D volume in multiple lines
3. Many independent fields (>300 so far), overcoming Cosmic Variance

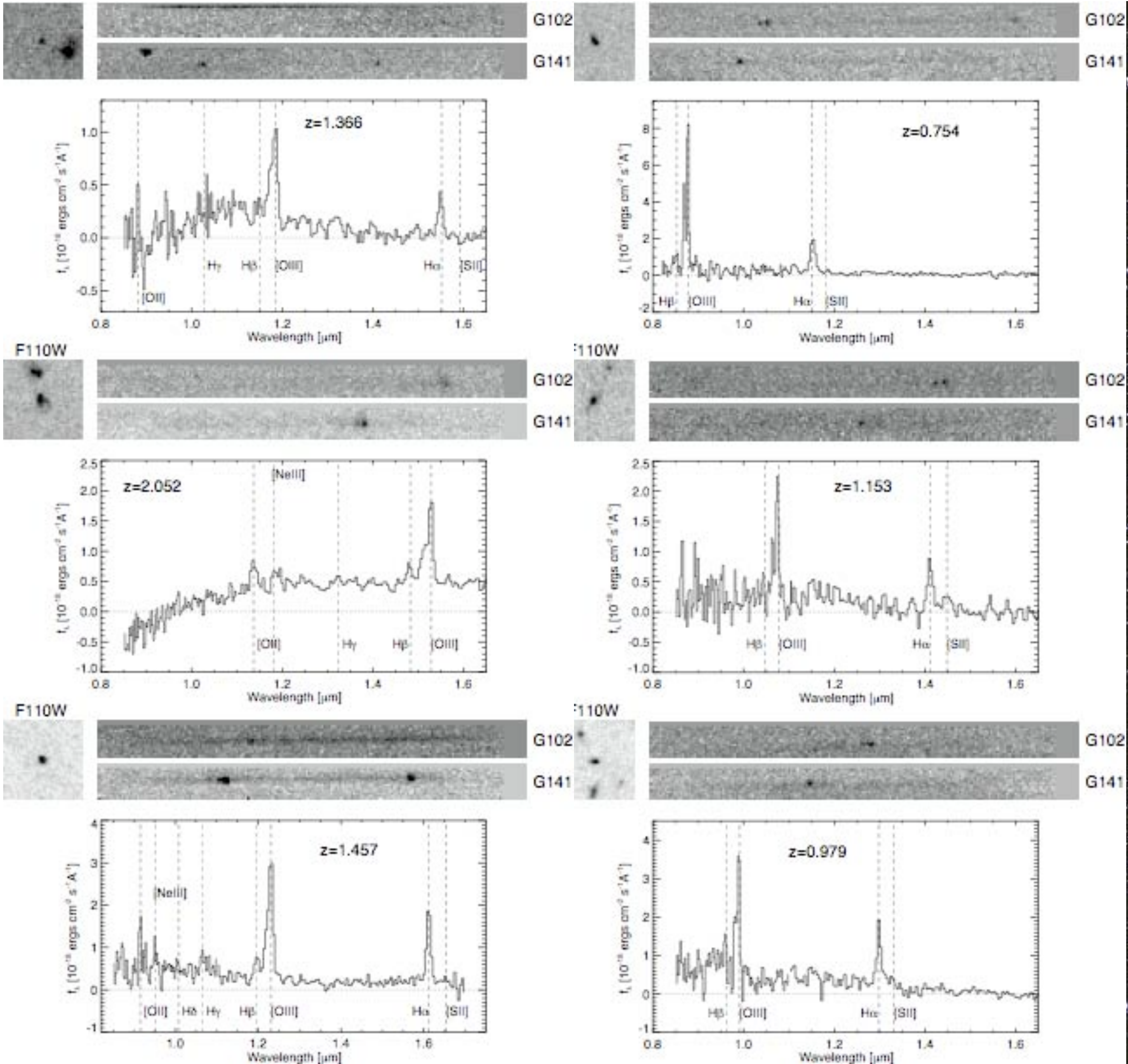

This screen capture of a small piece of one frame don't do justice to the data,
But there are emission lines all over the place
We are far better off with the
Ubiquitous and well-understood
Rest-frame optical emission line
Diagnostics,
IFF we're willing to roll up our
sleeves and push spectroscopy
out into the near-InfraRed
Zeroth order images
WISPers: MM, Pat McCarthy, Harry Teplitz, Alaina Henry, Brian Siana, James Colbert,
Claudia Scarlata, Bob Fosbury, Andrew Bunker, Crystal Martin, Carrie Bridge,
Alan Dressler, Hakim Atek, Nate Ross

WFC3 Infrared Spectroscopic *Parallels* --WISP's combination of two(overlapping) Grisms gives wide spectral coverage (0.8--1.7um). (At these wavelengths, *slitless spectroscopy* from ground is impossible.)

Having >2 times wavelength range of continuous spectral coverage gives WISP a Full range of optical diagnostics, from [OII], [NeIII], Hβ, [OIII], Hα, [SII], [SIII], He I--> **Line Ratios**

On compact galaxies, we can resolve the [OIII]5007/4959 emission line doublet



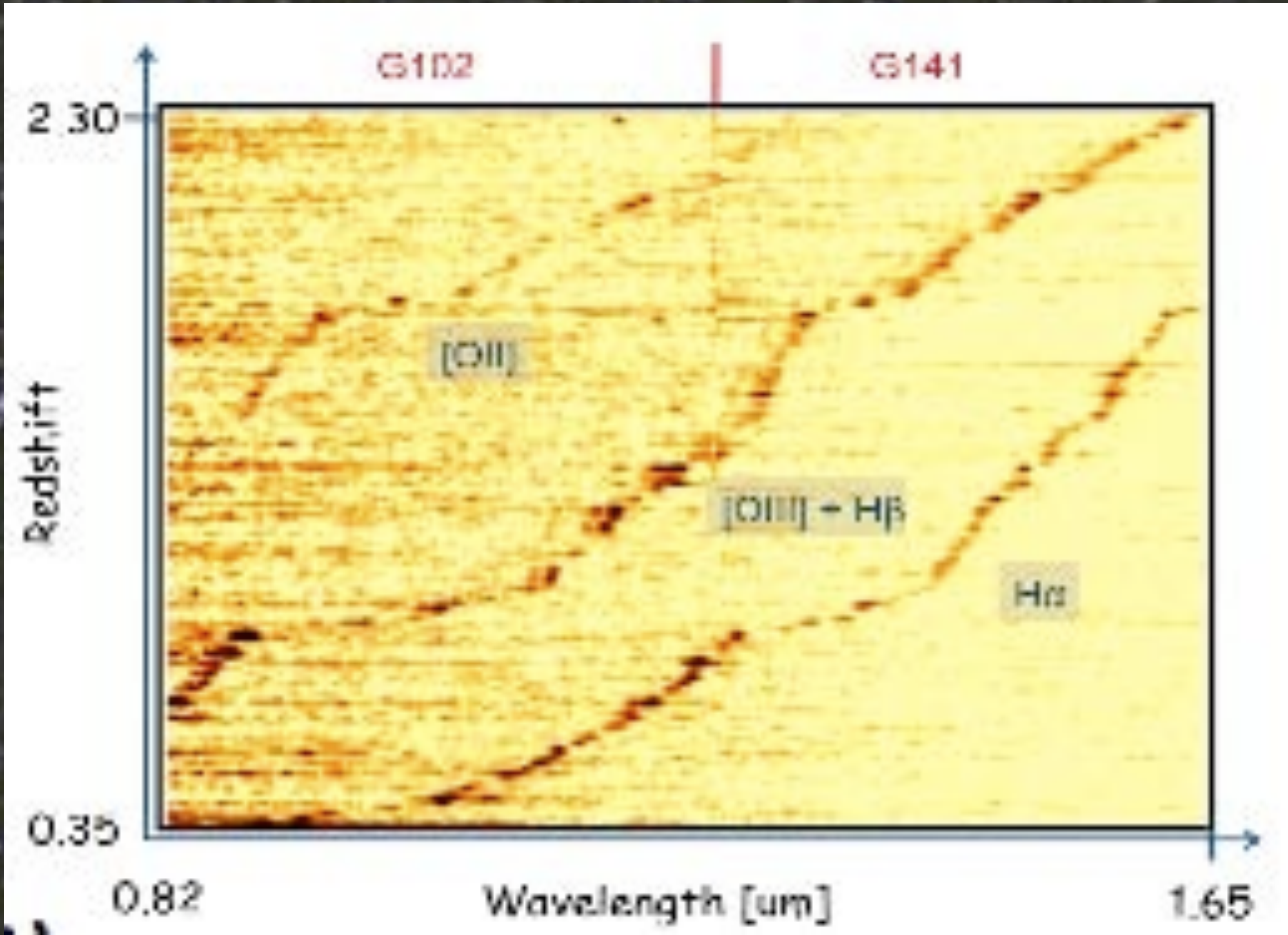


Combination of two (overlapping) Grisms
Gives wide spectral coverage (0.8--1.7um)

Excellent focus (~2 pixels) means that we resolve [OIII]5007/4959 doublet in compact galaxies

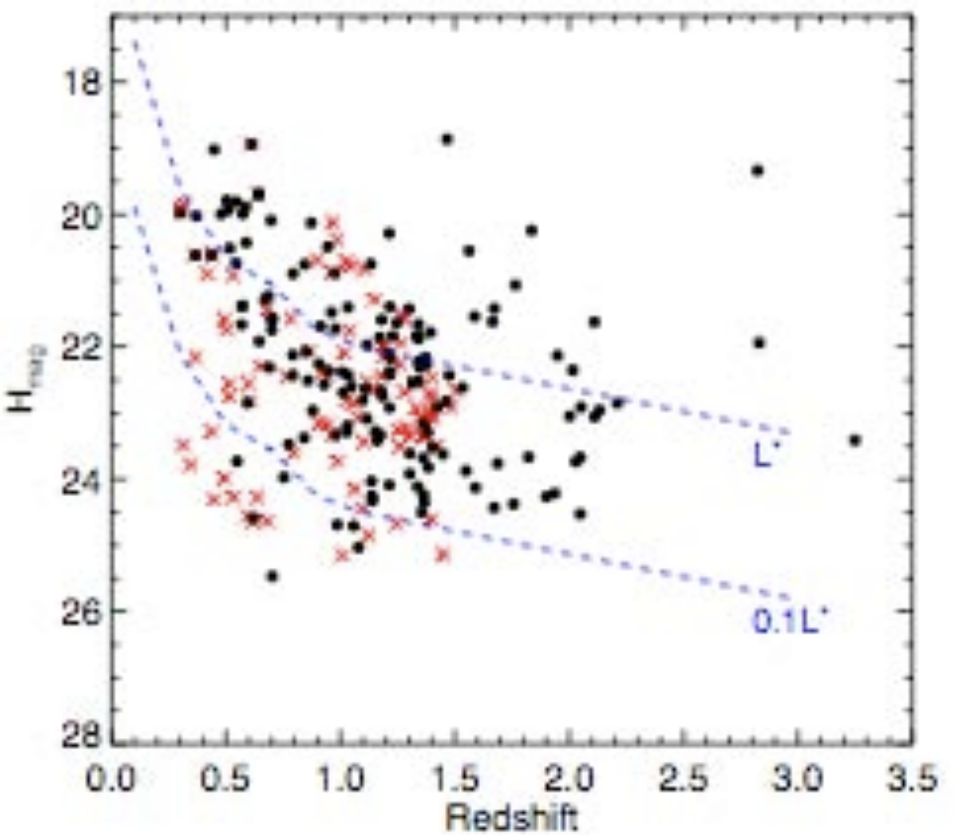
Atek et al. 2010

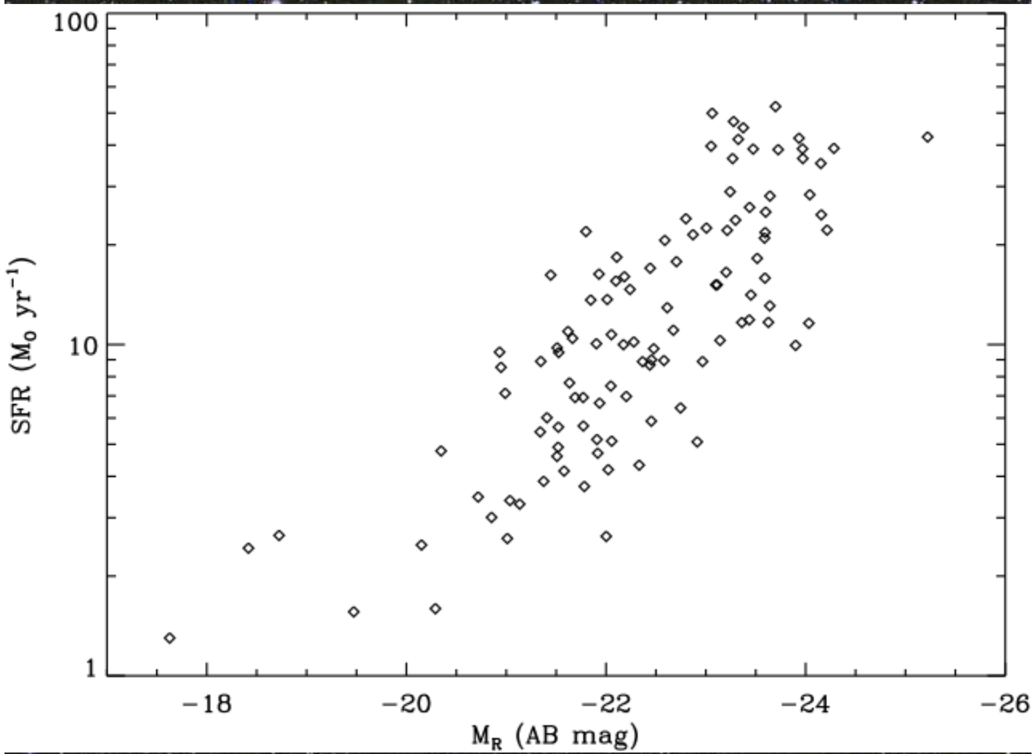
Montage of prelim high-EW subsample (Atek et al. 2011)



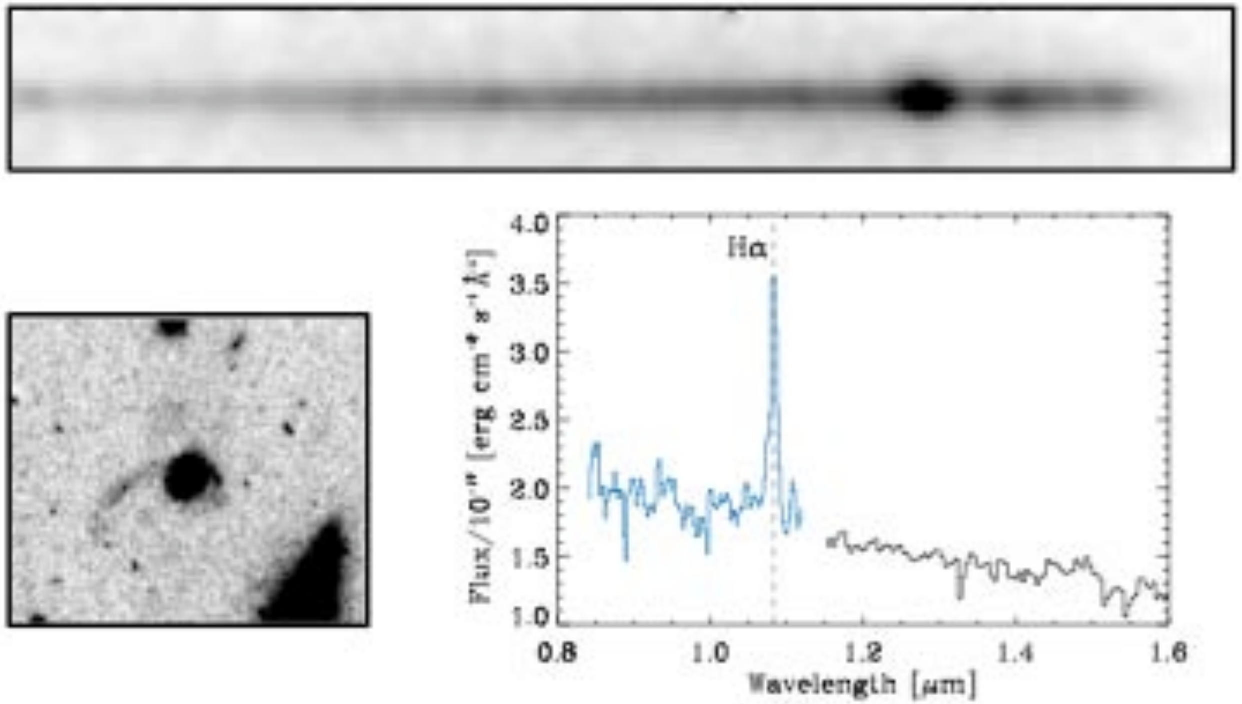
WISP reaches very Deep,
down to H>25 ‘Dwarf’ ie Typical Galaxies from Z=0.5--3

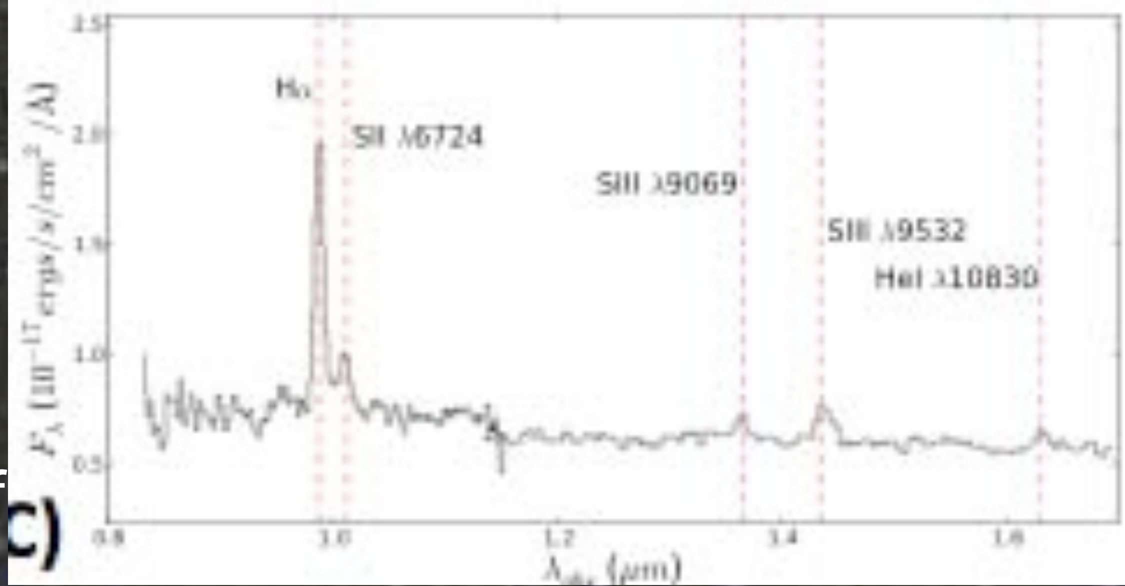
Preliminary results from a few percent of the full Survey (only highest significance):





Broad-line (Seyfert 1) Active Galactic Nuclei



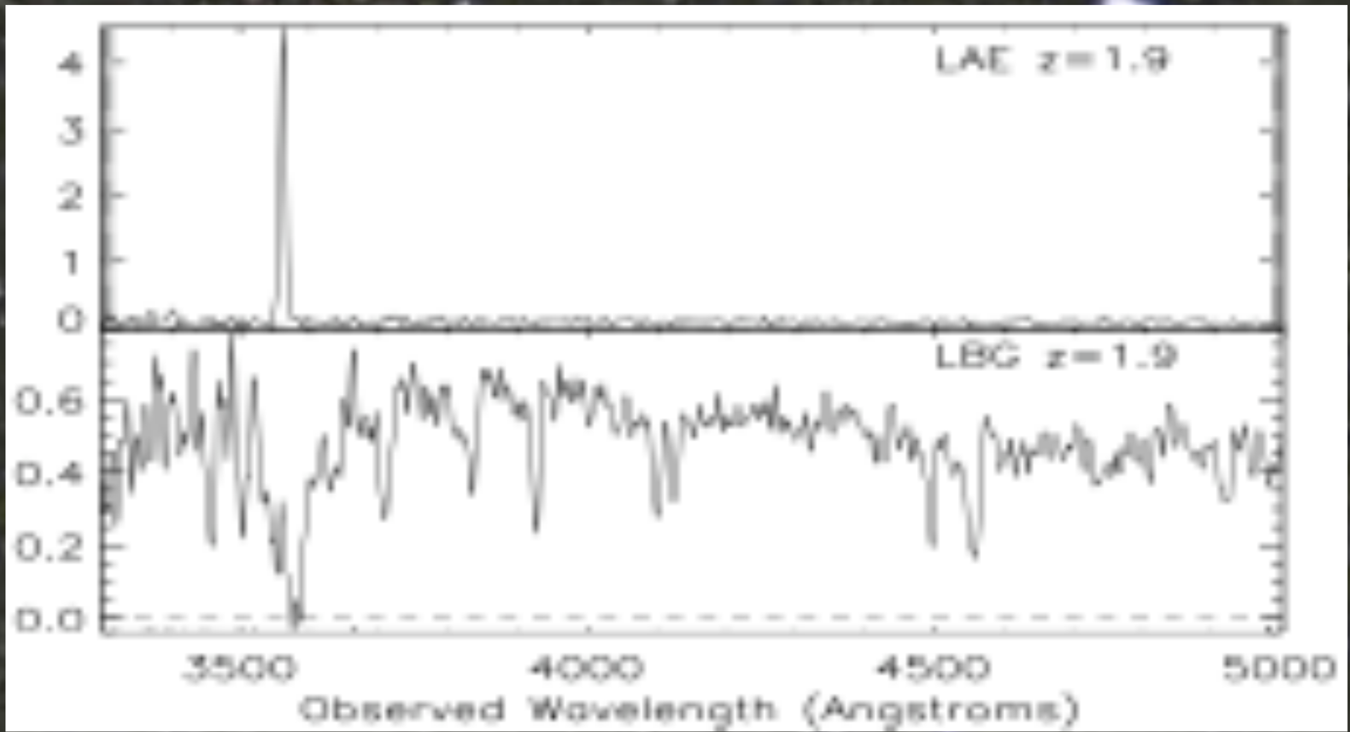


Strong S lines say this is The Narrow Line Region of a Seyfert 2

Are the WISP extreme-emission-line galaxies just z<2 LAEs?
…Not only…

- Ground-based followup--imaging and spectroscopy

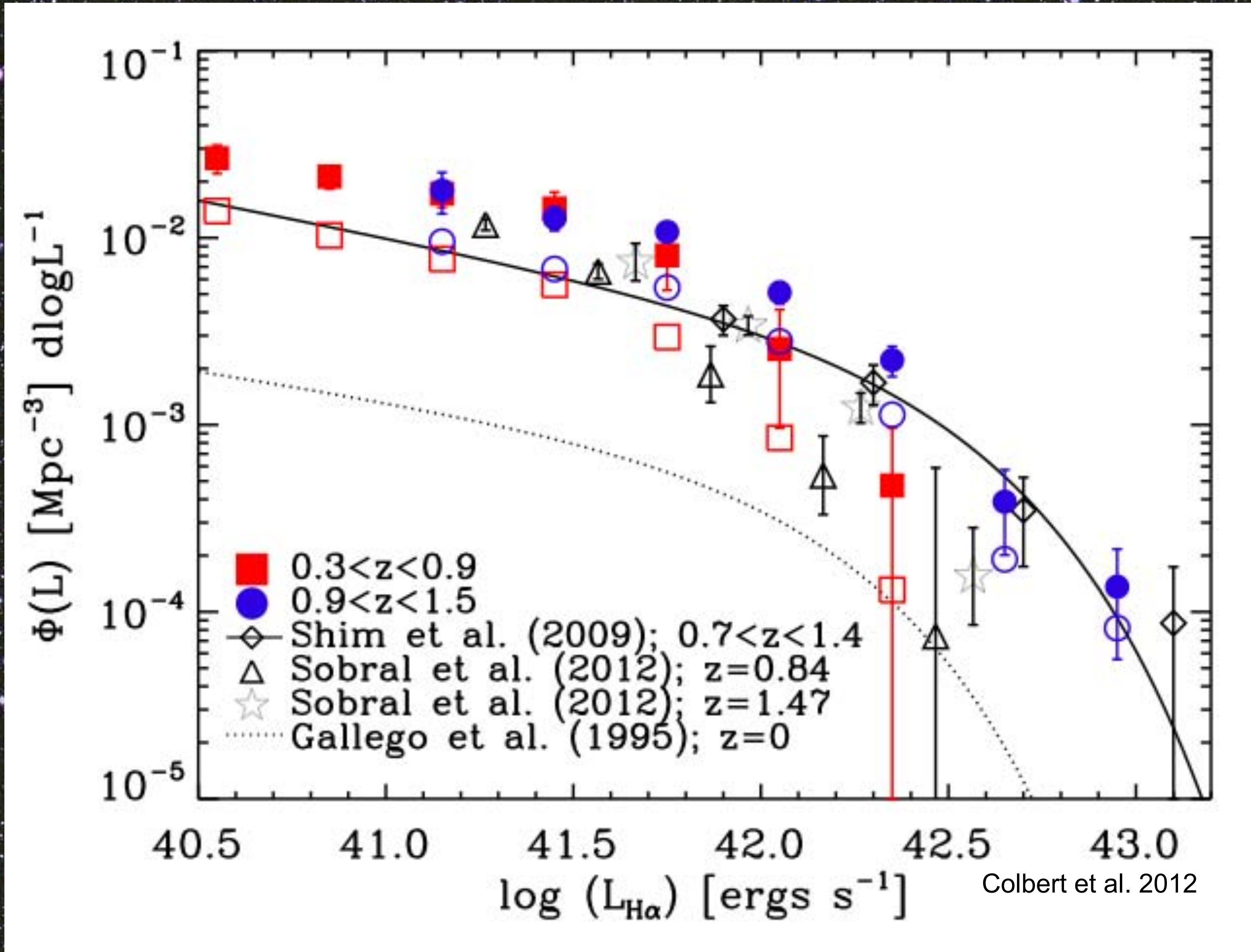
- Keck/LRIS spectra of two WISP galaxies with equally strong [O III] emission lines in the near-IR:



It’s very hard to predict Lyα, at z=2.
How about at z>6??

WISP is so sensitive to faint Hα (the 'Gold Standard' Star Formation Rate indicator) at z=0.7 (blue points are z=1.2)

WISP reaches the same dwarf Irregulars at the bottom of the *local* (z~0) LF (<0.1 Solar Mass/Year)



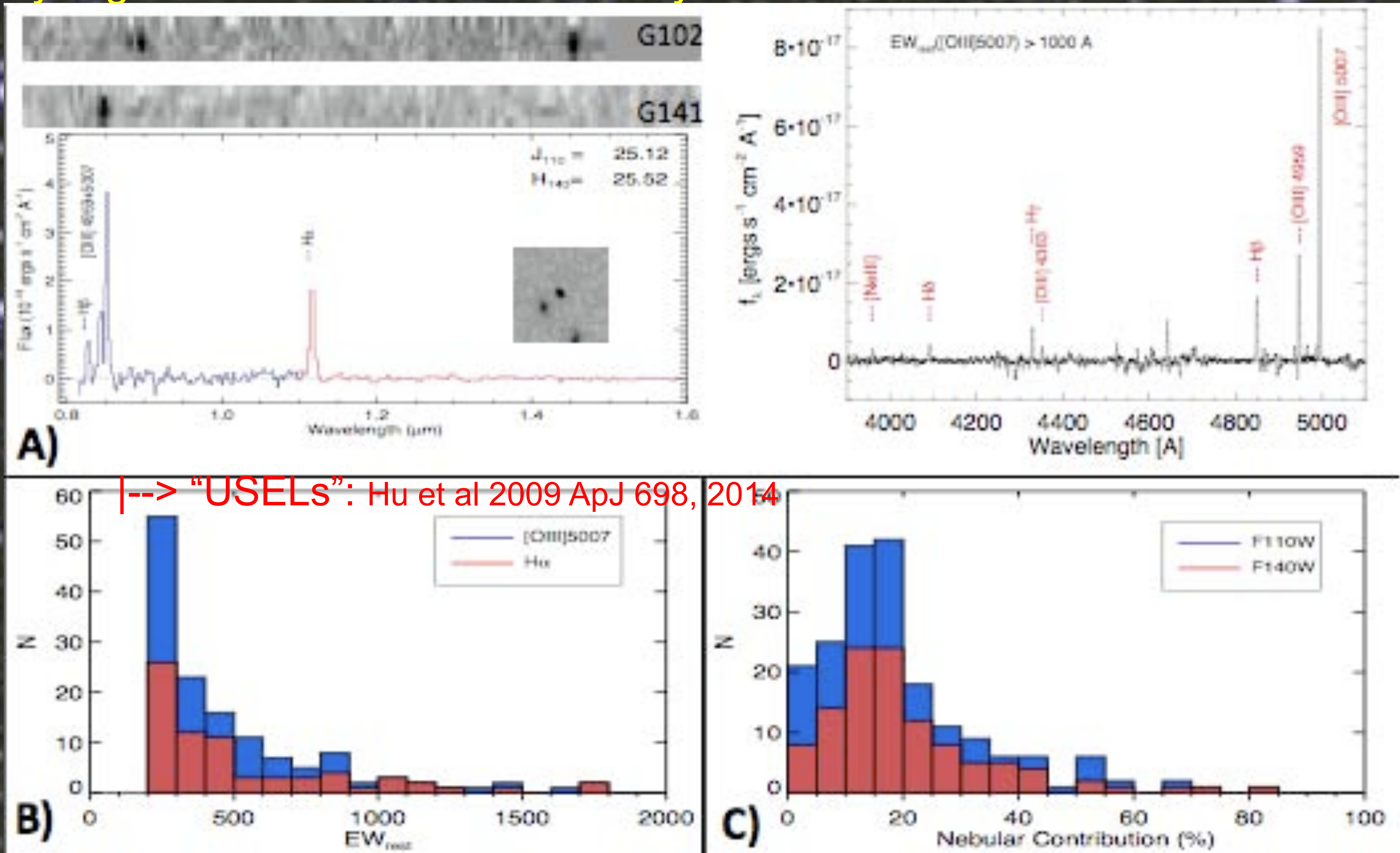
Colbert et al. 2012

Extreme Line-Emitters are numerous!

Huge Equivalent Widths -->

Huge Specific Star Formation Rate (mass-normalized)

Very High Ionization--> Low Metallicity

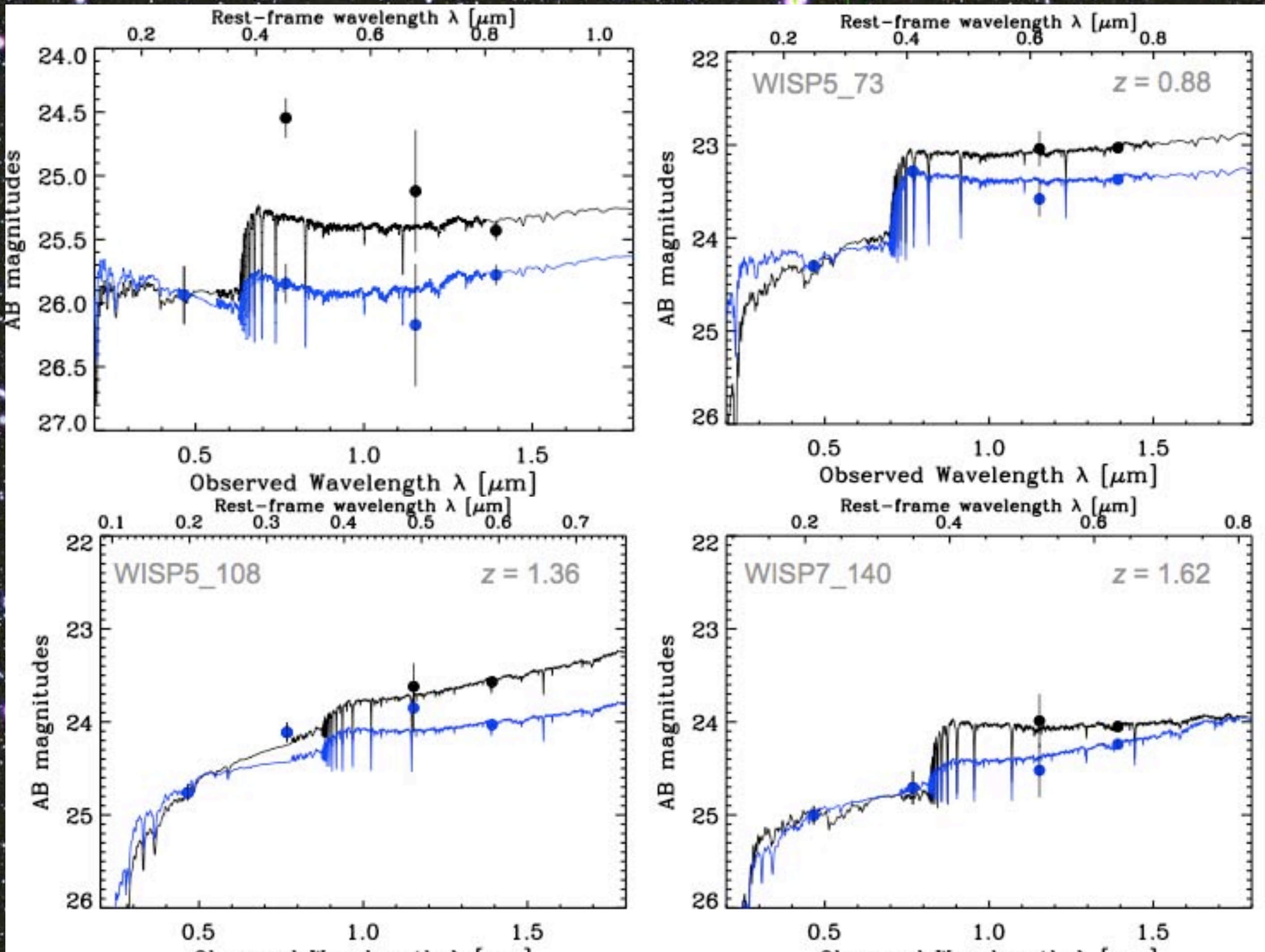


|--> “USELs”: Hu et al 2009 ApJ 698, 2014

Lines are strong enough to significantly contaminate Broadband mags

Broadband Spectral Energy Distributions seriously altered By Emission Lines

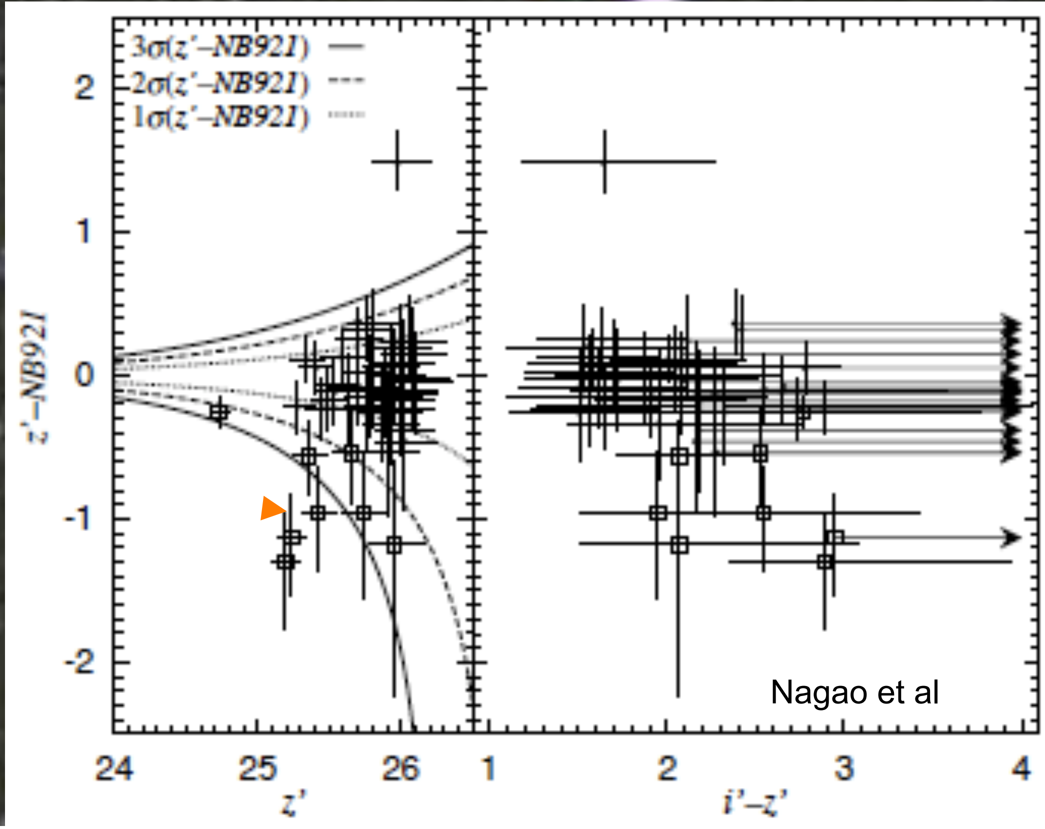
SEDs uncorrected for EM lines (black) will overestimate stellar mass, sometimes by factors of several, and also mess up other params (eg age), and produce *FAKE DROPOUTS*



Instead, let's turn strong emission lines to our advantage: Let's do (alternate) search for the Lyman-α emission line

- You can cover a wide range of (high) redshifts with optical spectroscopy, IFF you can boost the areal coverage,
- OR
- You can cover a huge area with deep imaging in narrow-band interferrence filters (tuned to avoid the worst night-sky wavelengths)

- OR
- You can embrace the strong Lines, and even cover a wide redshift range AND area if you search for narrow-band DEPRESSORS-- spectroscopically confirmed at Keck (Nagao et al 2008).
- [yes,
- Depression makes
- me Happy!]



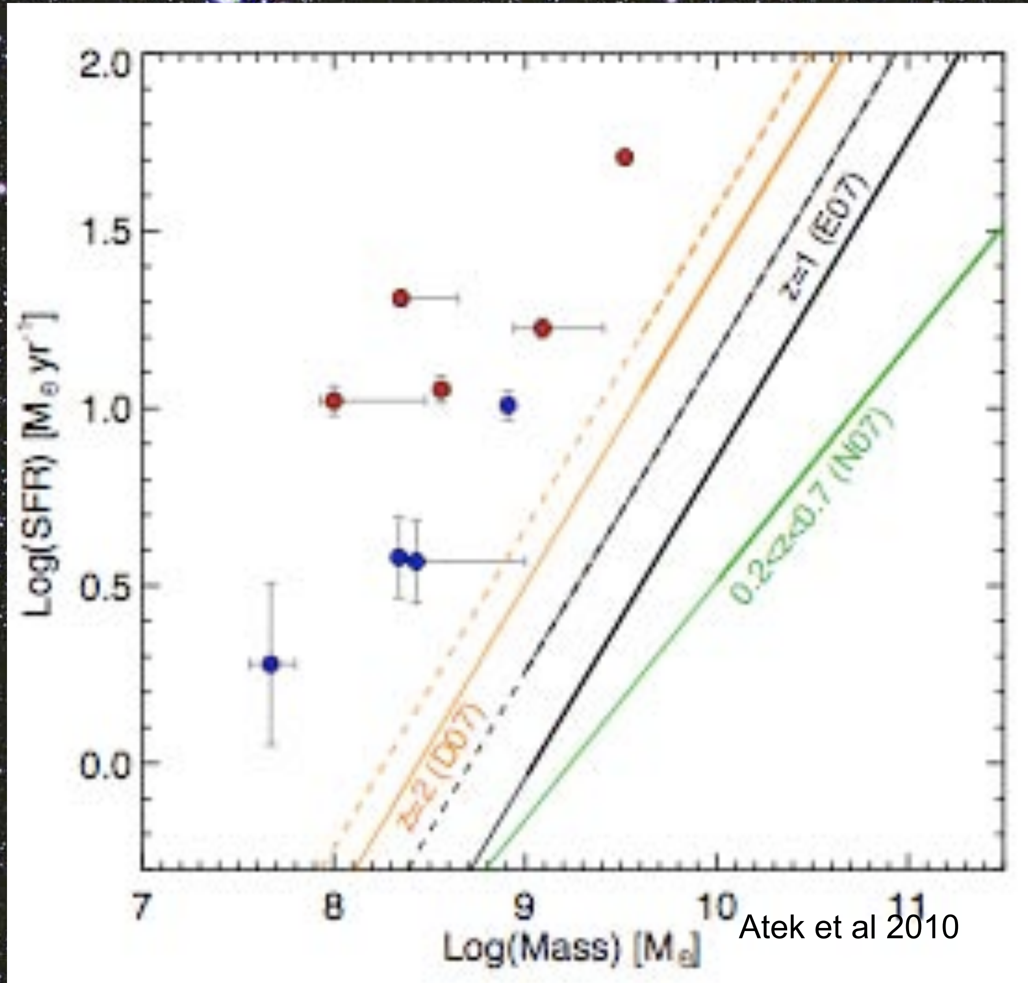
Selecting Galaxies Thru their Line Emission Provides a Completely Different Perspective on their Evolution

1. Ex.: Is the nice claimed correlation of stellar mass with SFR partly an artifact of selection based on continuum magnitudes?

Lower right side is censored because old/red/dead galaxies are very faint.

Upper left side has plenty of strong-line-emitters previously ignored, but found by WISP.

1. A spread of 100's x is NOT A "MAIN SEQUENCE". It is an 'average', with a trend, once again showing the dangers of ploting Luminosity (UV) versus Luminosity (near-IR) and reading too much into the resulting slope=1 correlation



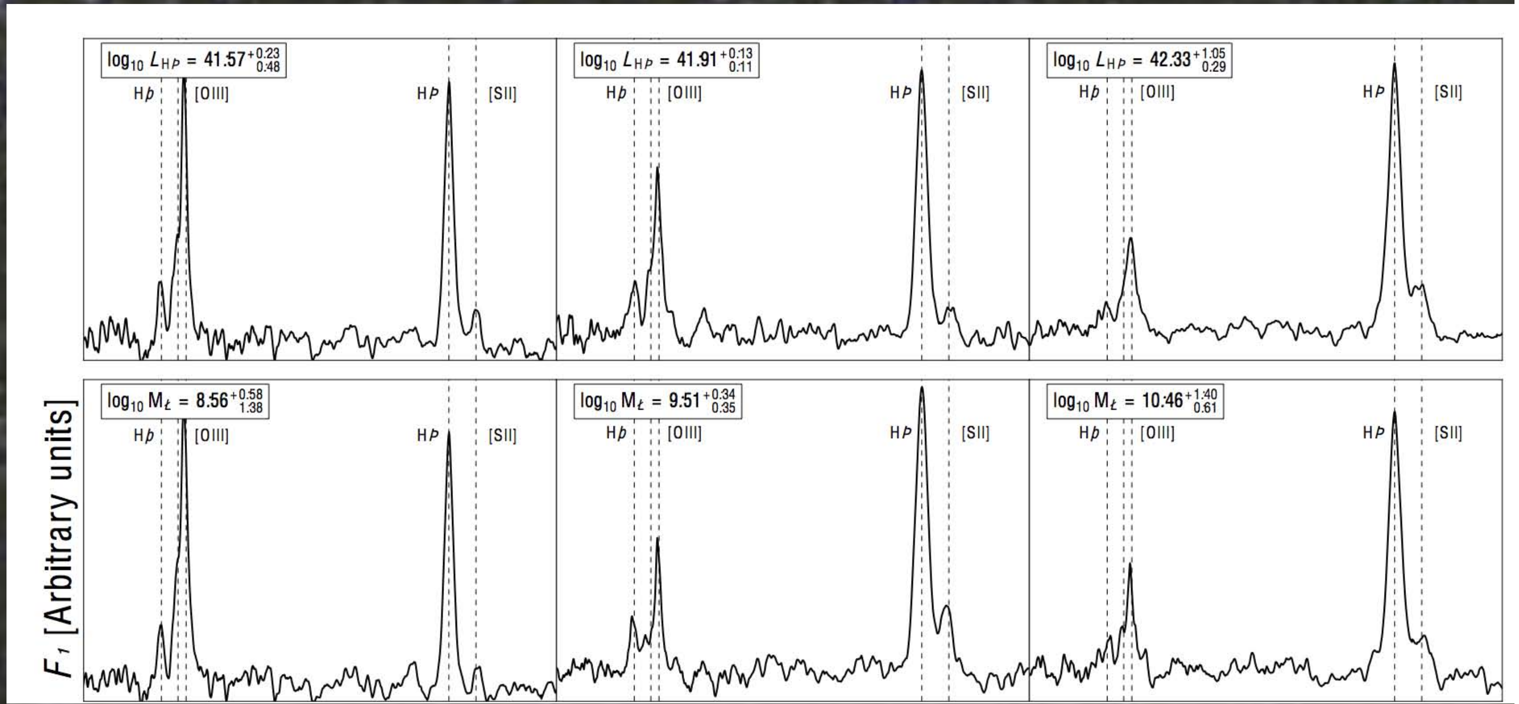
Atek et al 2010

What About Correcting SFR for dust Extinction?

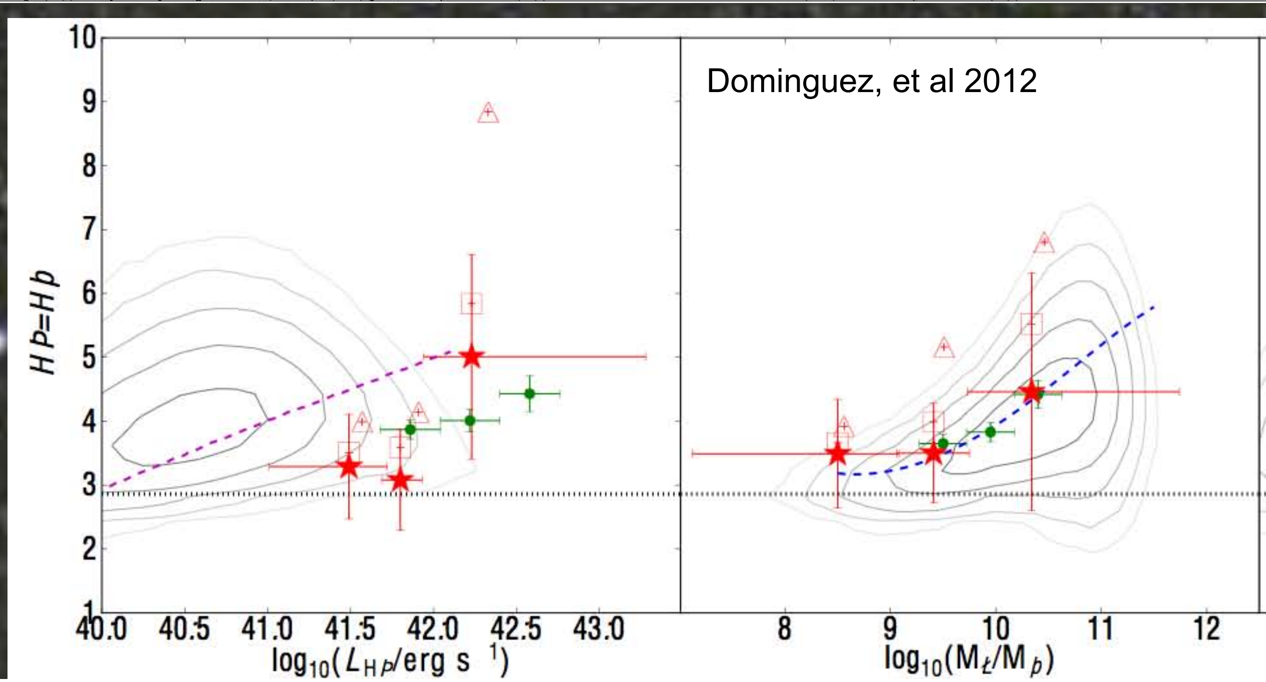
- Simple Kennicutt assumption of one magnitude correction to $H\alpha$ may be incorrect
- We now have the near-IR spectroscopy to start checking

L/M Trends in WISP Emission Line Galaxies at z~1.5

- More luminous/ massive galaxies have weaker H[illegible] and [OIII]



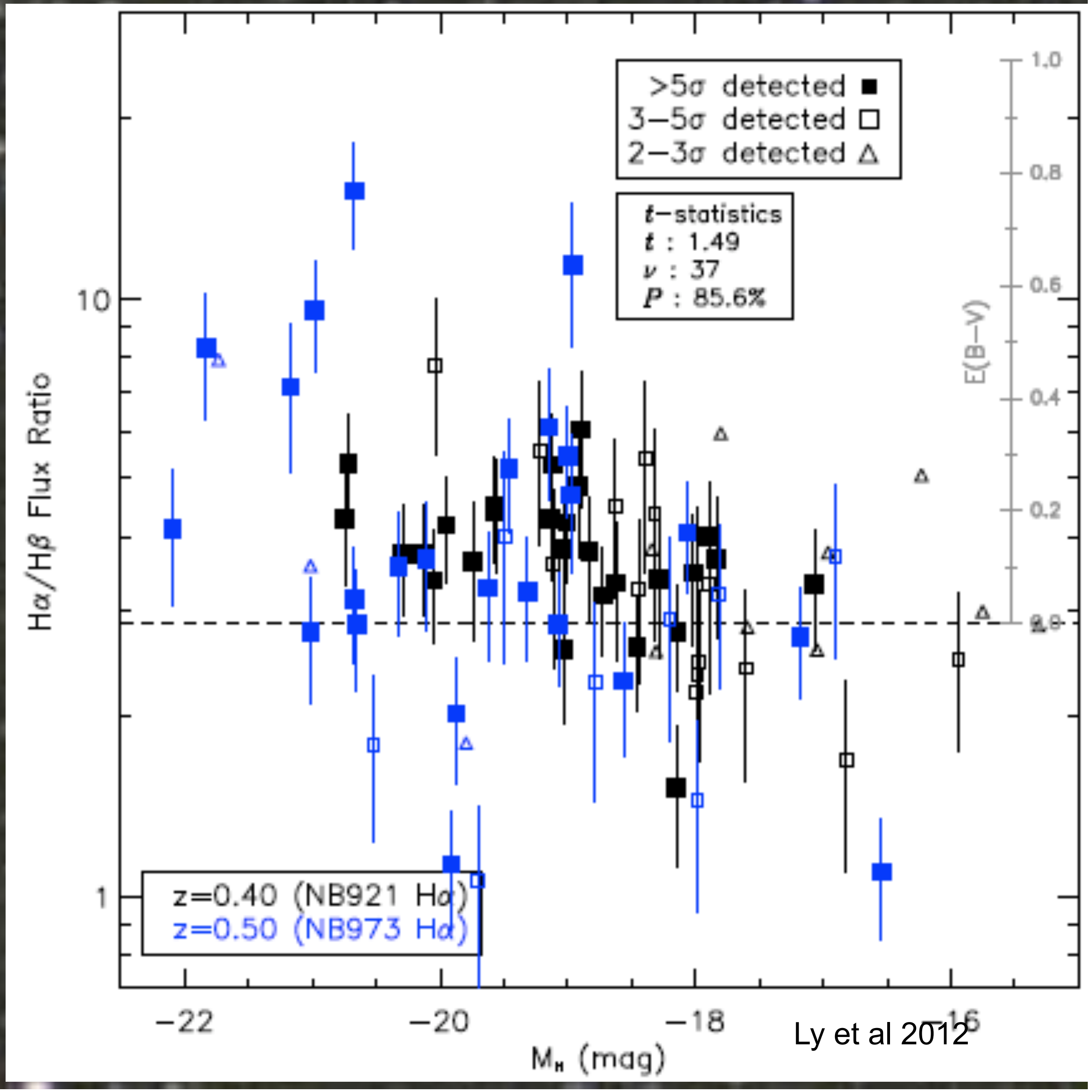
Balmer decrements give reddenings which are on average small, except for massive galaxies



Balmer Decrements in SDF: Gold Standard for Av<2

- Gas reddening increases with stellar mass [Claus mentioned that UV continuum from stars is also more reddened in more massive galaxies]

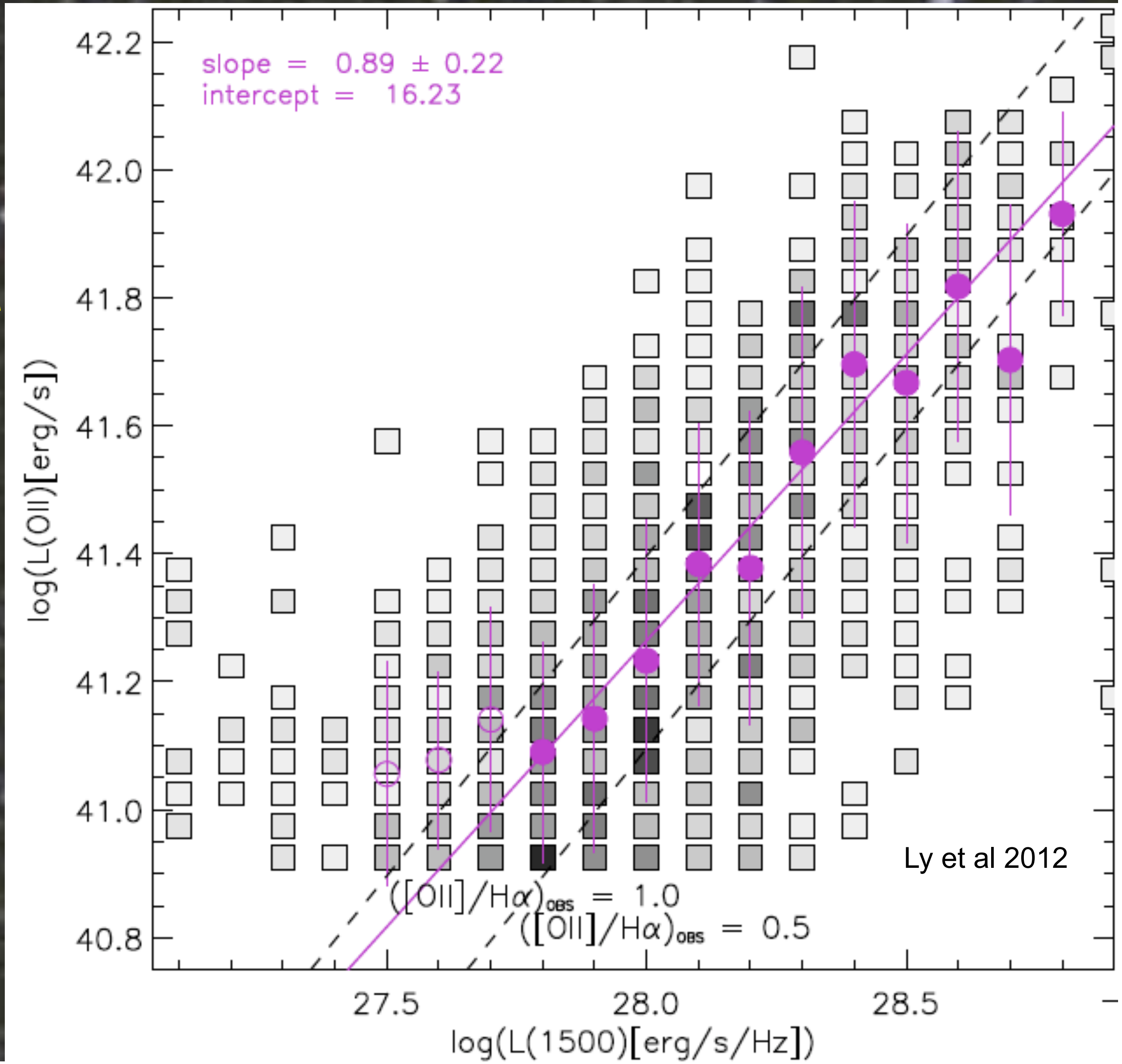
- In most numerous (sub-Lstar) galaxies, extinction at H[illegible] is much less than the ‘canonical’ 1 magnitude (Kennicutt, local spirals)



Ly et al 2012

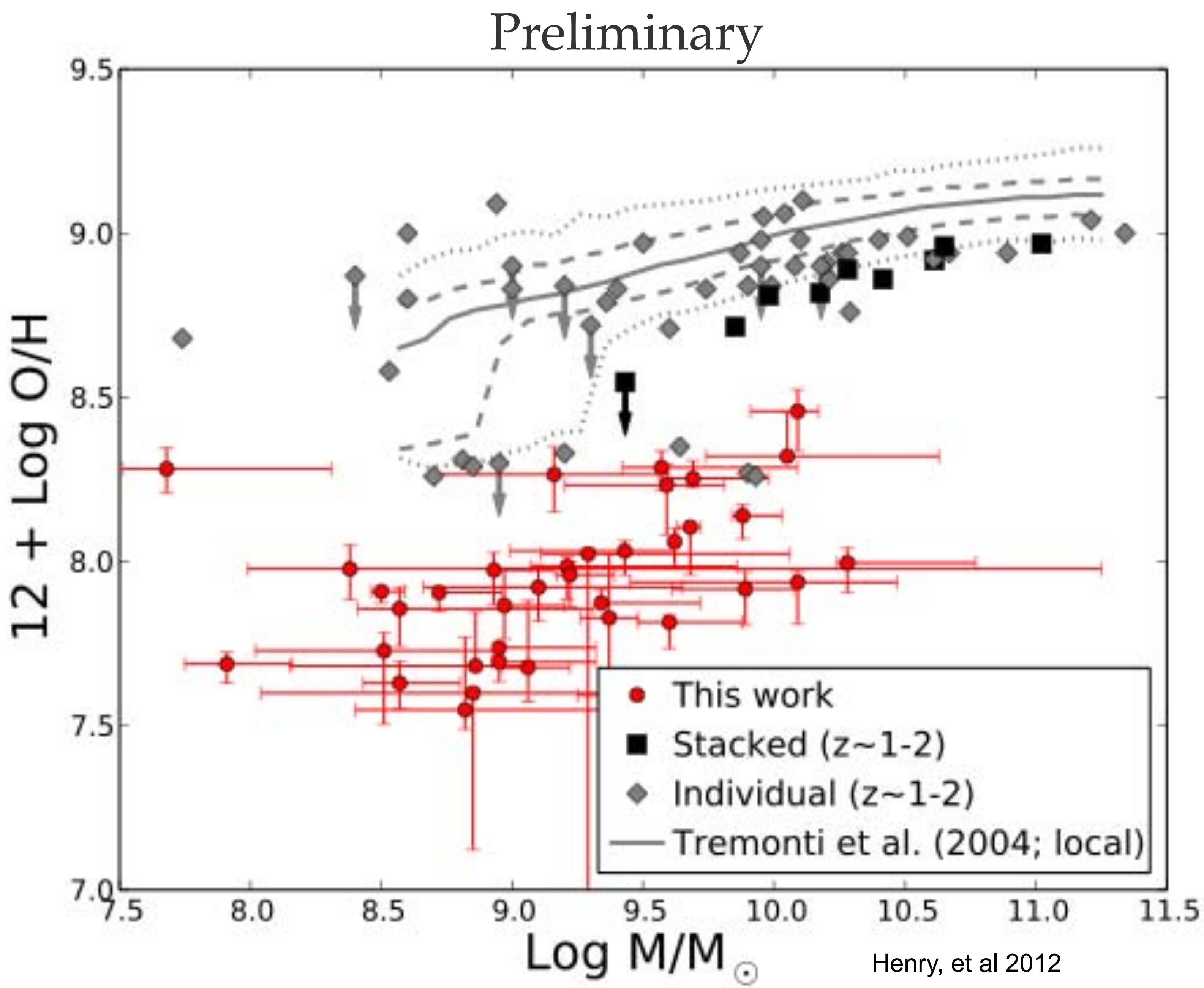
Can we salvage SFRs at higher redshifts from The far more accessible [OII]3727 line?

- Probably yes--we can Predict Ha from UV Continuum, or from [OII] and both of these SFR Indicators are consistent
- But it is far more sensitive to dust extinction, so caution is needed



WISP Galaxies have Remarkably Extreme Low Metallicities

Line ratios appear to be wrecking all Mass/ Metallicity relations, Unless it is their extreme high sSFR values



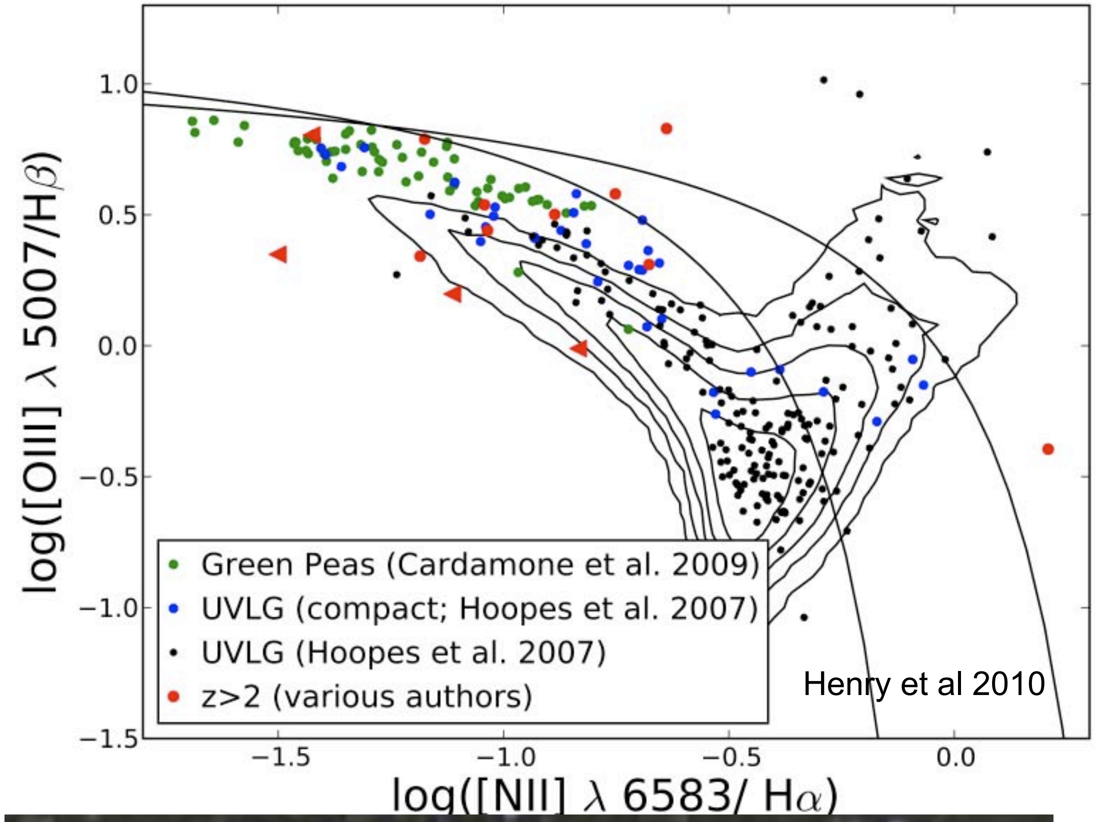
Henry, et al 2012

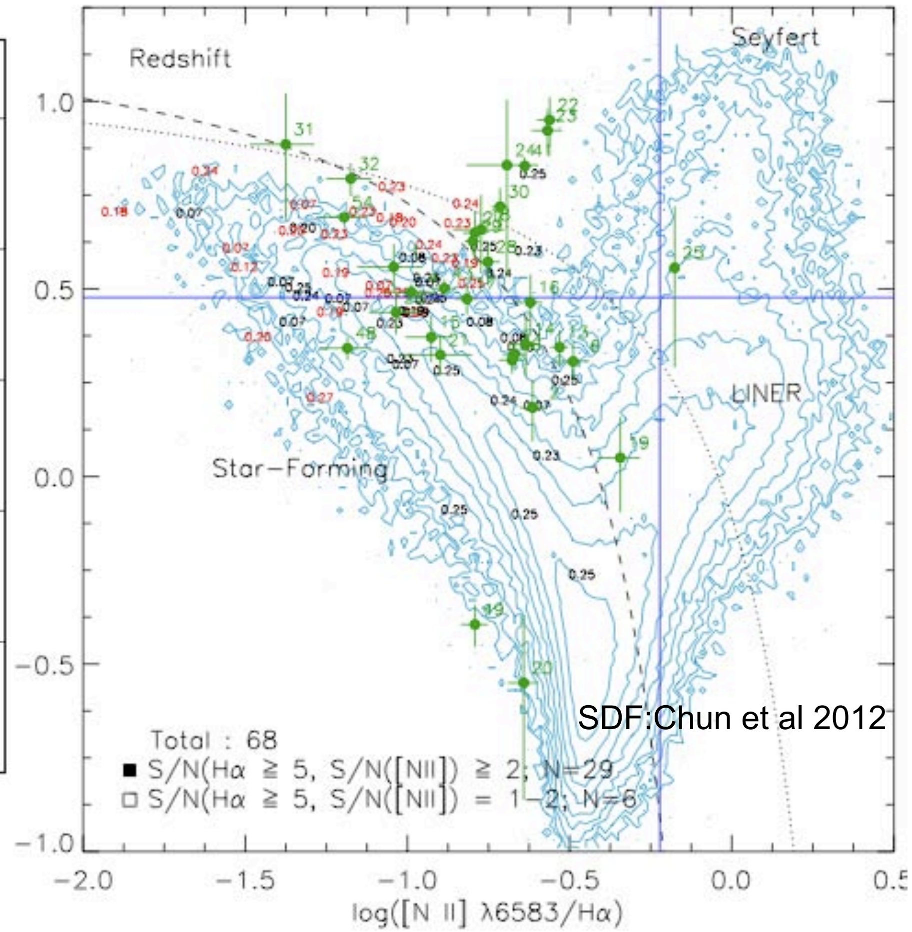
The [OIII] Problem at z>0

Starburst Galaxies are Different from local ones:
Extremely High-Ionization at Low Luminosity

It may mess up our key line ratio diagnostics, such as the BPT diagram:

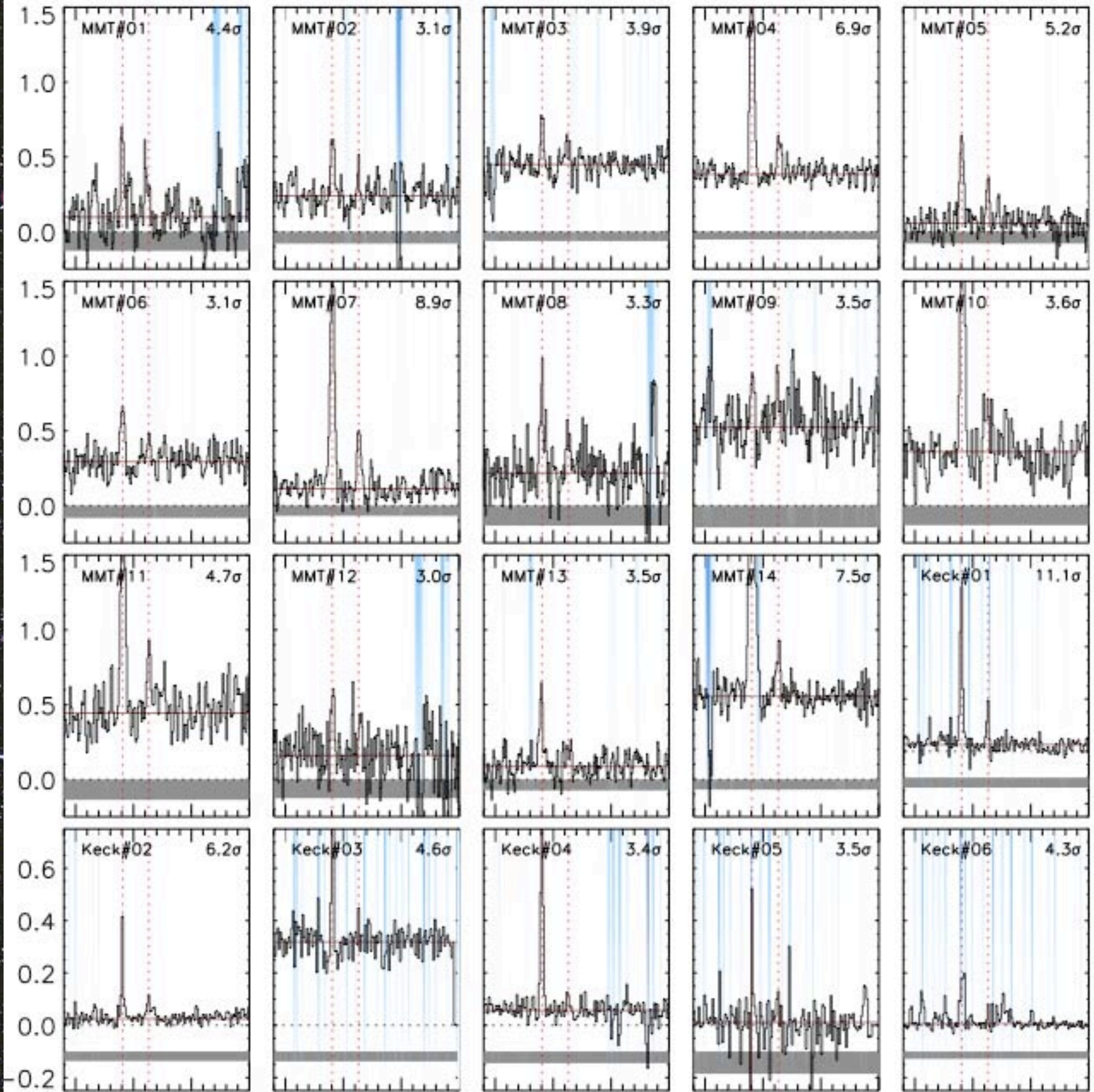
- Purely (?) Star-forming galaxies are shifted towards the "Composite" (AGN+HII) region, due to their excessive ionization





Follow-up Spectroscopy of NB Line Emitters in SDF

1. Analyzing ~1000 SDF spectra, primarily from MMT/Hectospec and Keck/ DEIMOS, Chun Ly found twenty with [OIII] 4363 line emission-->
2. "Direct Te Method" for Metallicity-->

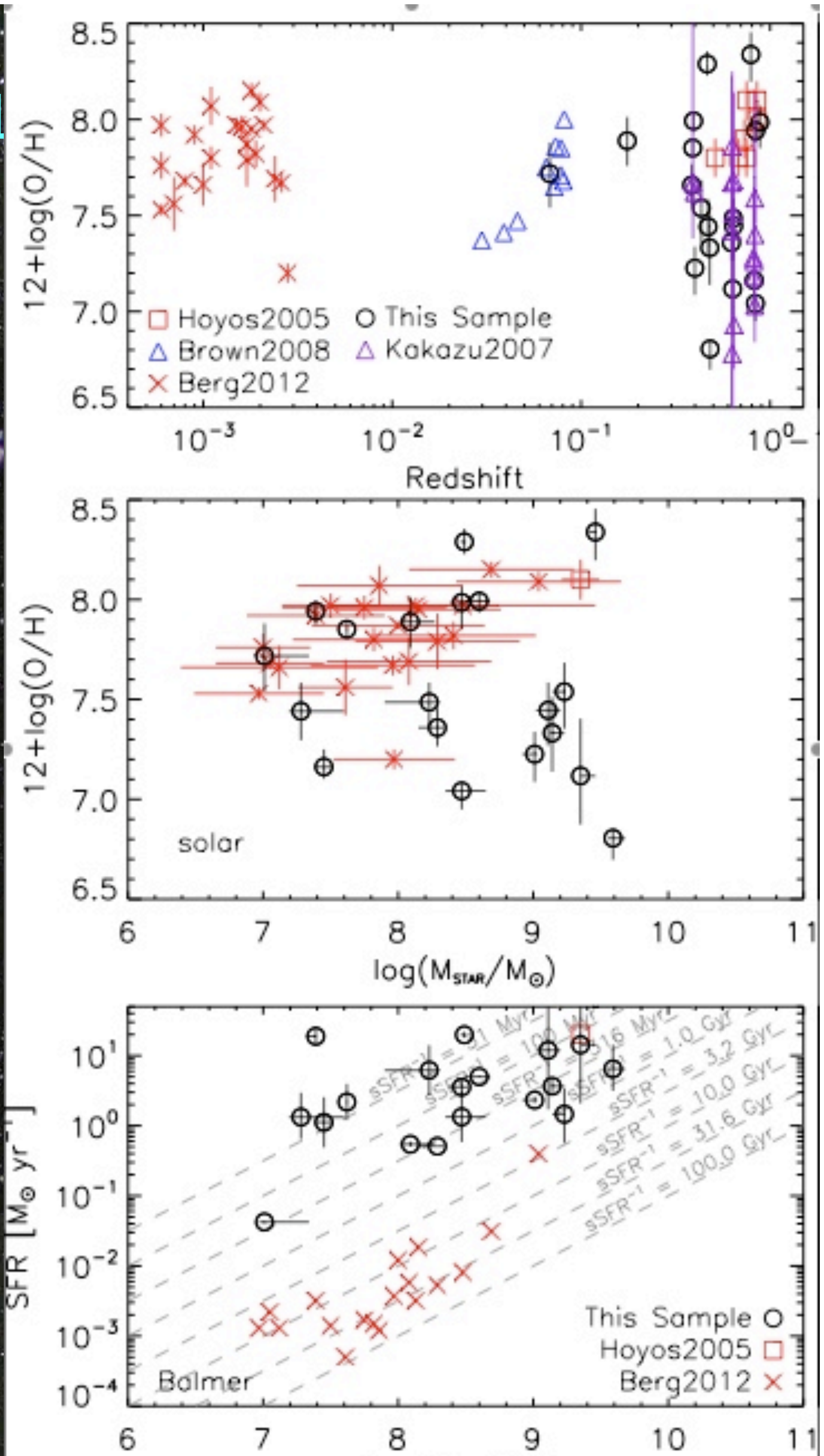


Follow-up Spectroscopy of NB L

1. Analyzing ~1000 SDF spectra, primarily from MMT/Hectospec and Keck/DEIMOS, Chun Ly found twenty with [OIII] 4363 line emission-->

2. “Direct Te Method” for Metallicity-->

3. Most of these galaxies are metal poor, some as low as the lowest O/H values seen in local universe (in a million Sloan spectra)



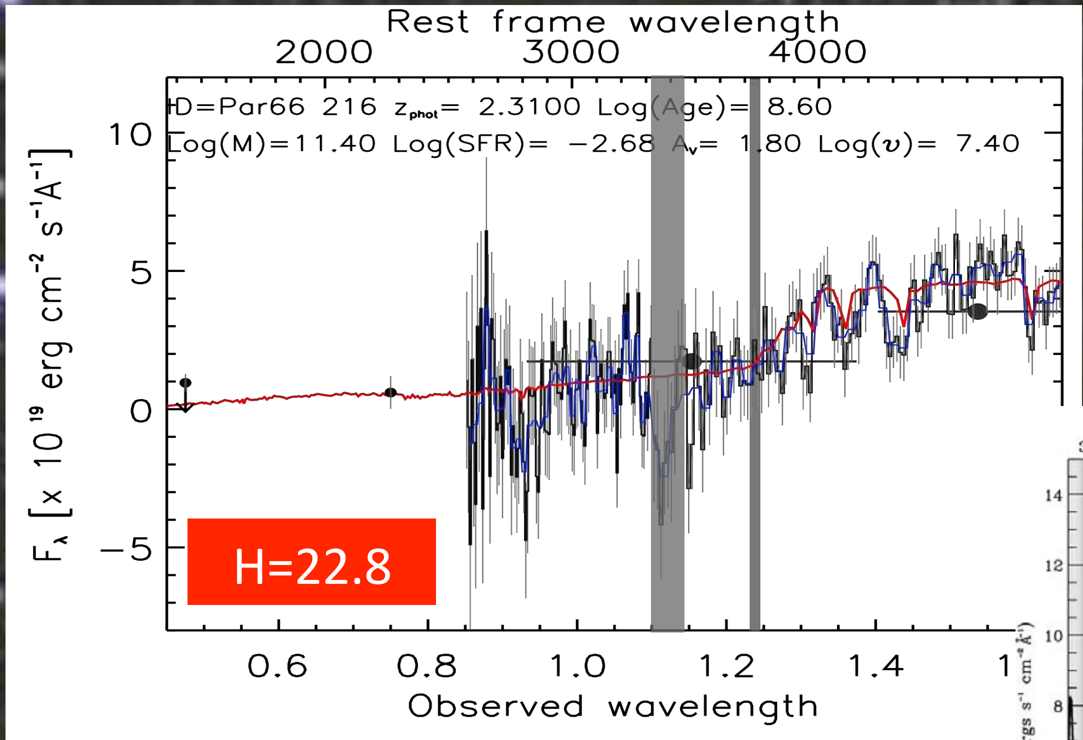
WISP

WFC3 Infrared Parallel Survey

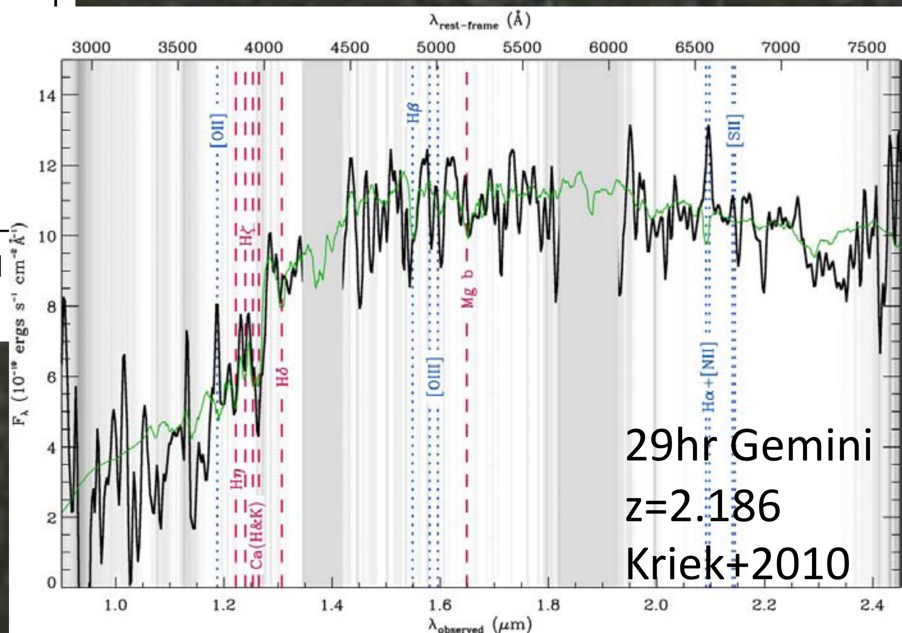
Bedregal et al 2012

Passive Galaxies

Among the ‘brighter’ WISP galaxies, MANY have Identifiable *absorption line spectra*, especially the HK/Balmer break, so our survey does not miss the massive ‘red/dead’ population



A factor of two fainter than from 8m class telescopes!



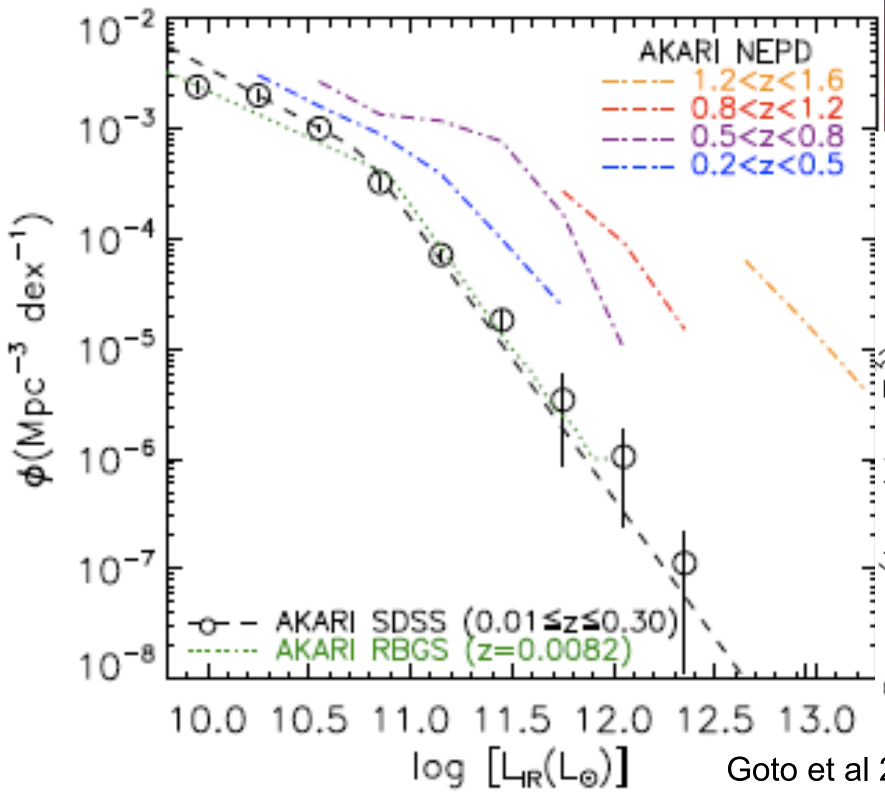
What about the Obscured Star Formation?

(Av>3mag starbursts have optical line emission is buried)

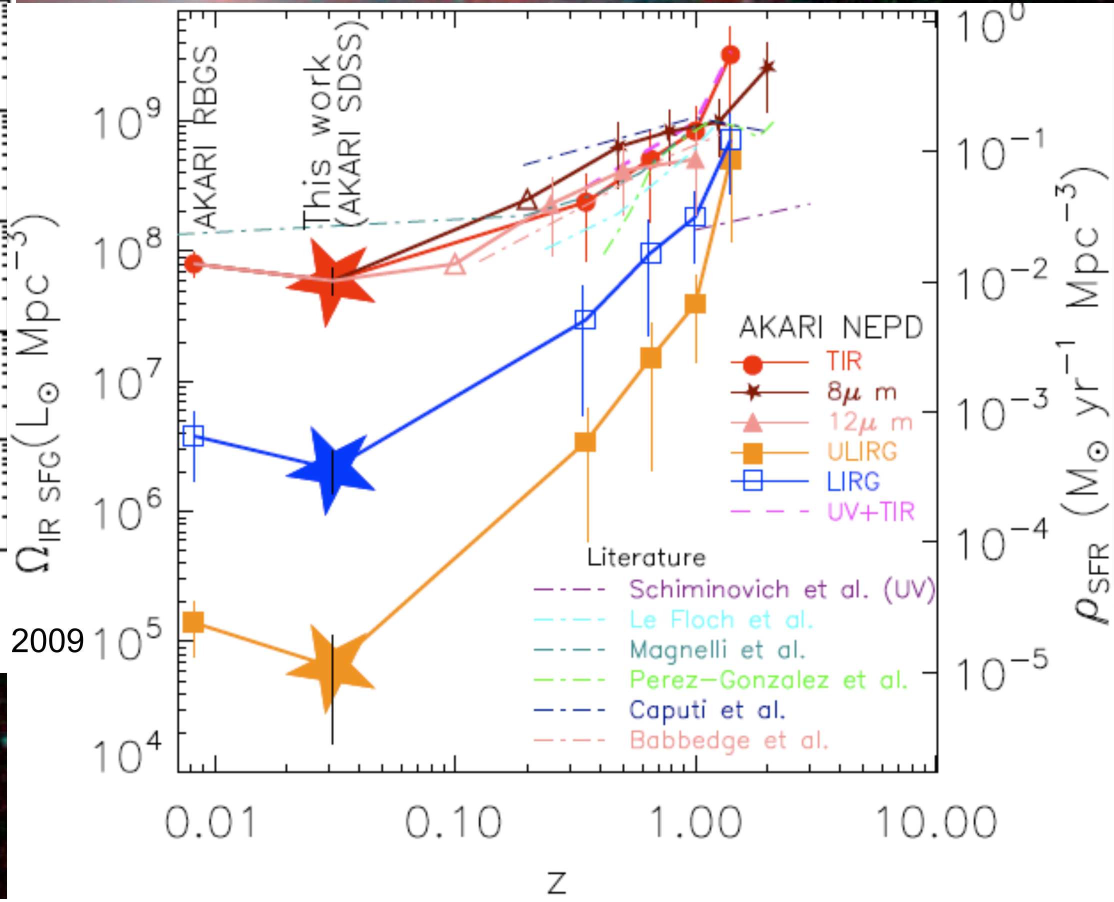
We can study it locally with IR recombination lines, but at z>0, we must observe Re-radiated Thermal IR Emission from Dust,

Although this is less specific than optical emission lines, Likely to fail at low SFR (where Cirrus is relatively strong), or where an Active Nucleus warms 60um dust (ISOPHOT--Spinoglio, Andreani, Malkan 2001)

- IR Luminosity shows Large Redshift Evolution, same as H
- True equally for L(8um) and L(TIR)



Goto et al 2009



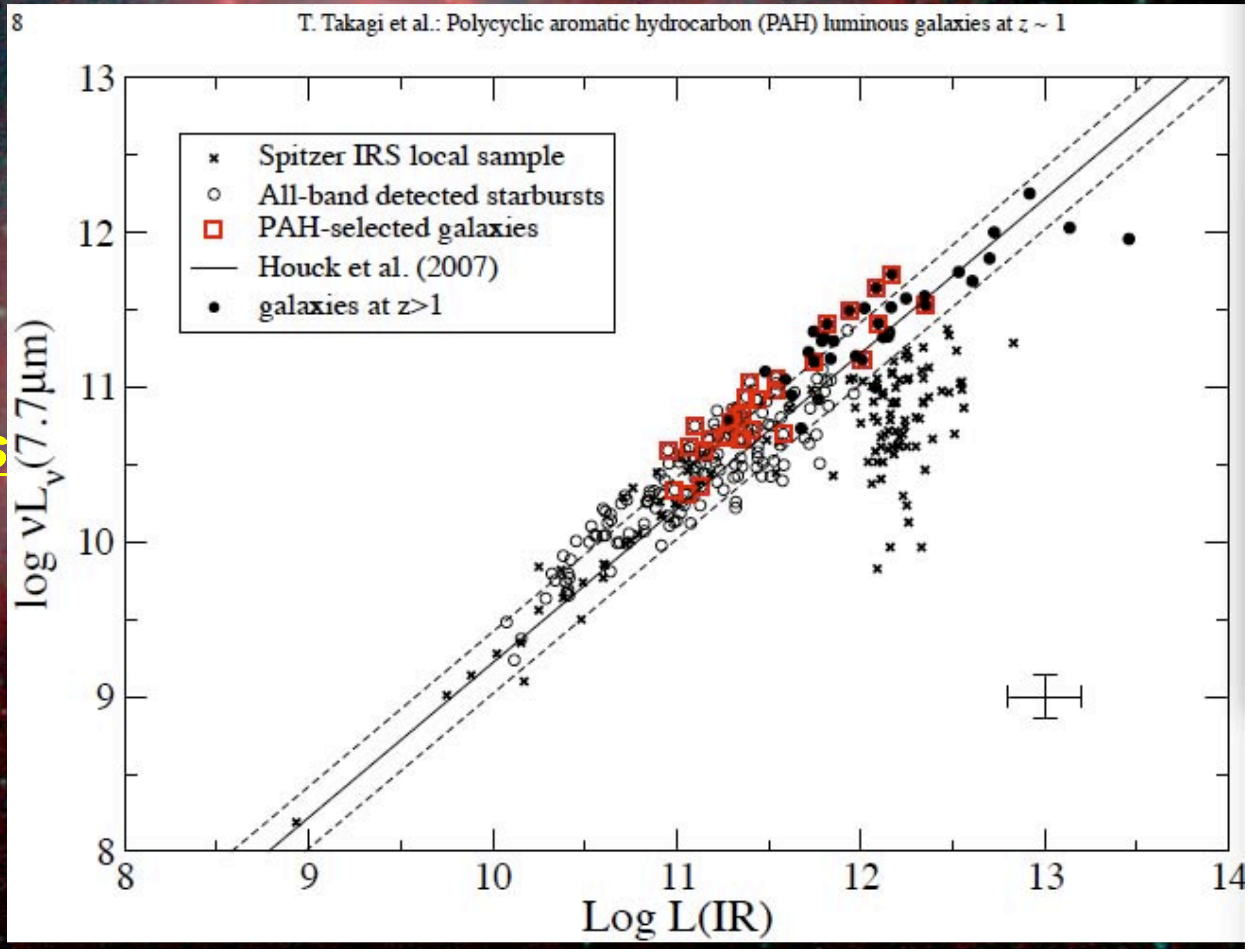
7.7um PAH feature is the strongest and most informative spectral signature, Mostly powered by young stars

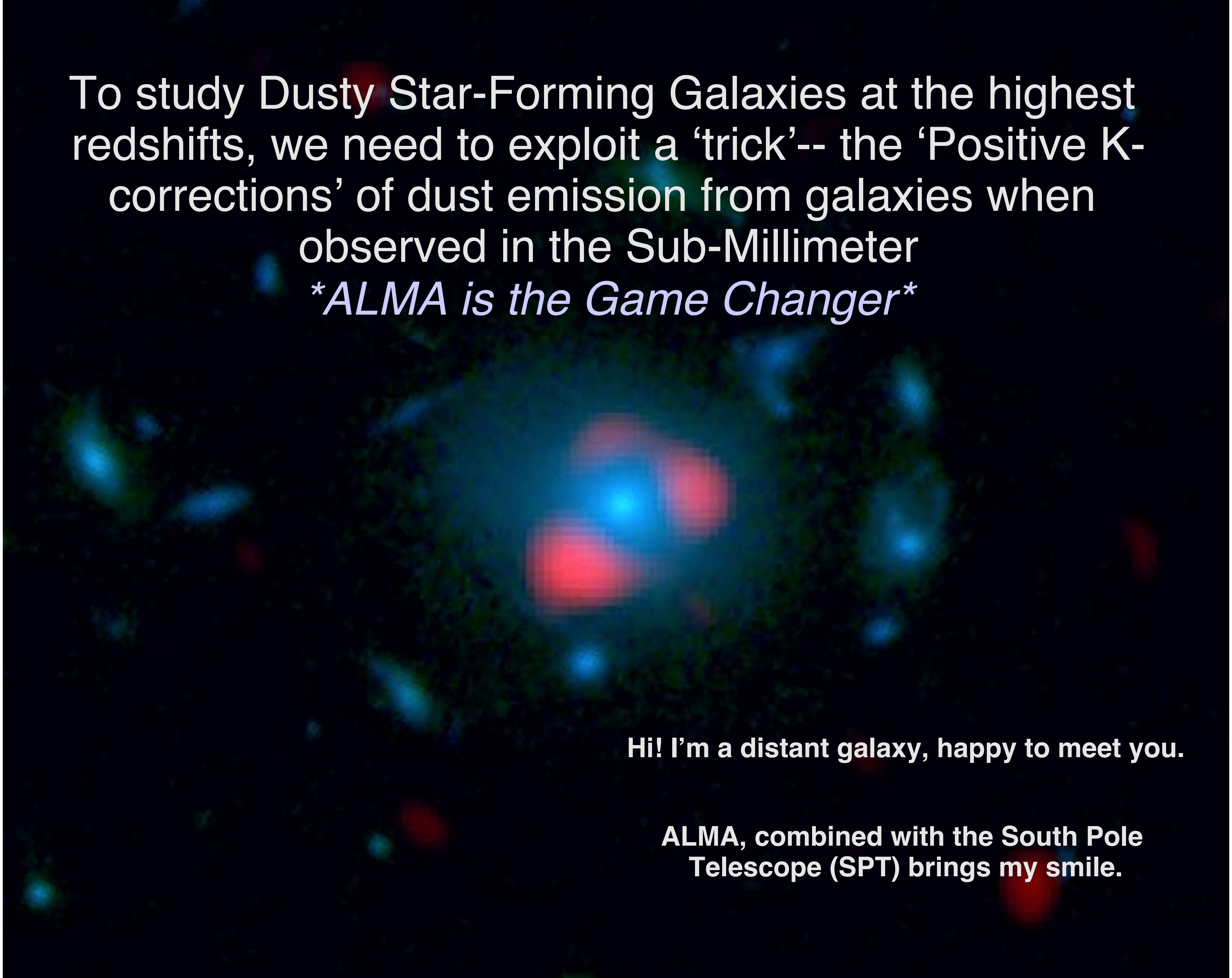
- PAHs can dominate an entire broad mid-IR band
- Now AKARI/IRC/NEP (with 9 IR filters 3--24um) can measure them at z>1:

In local galaxies, the PAHs become weaker in ULIRGs and in Seyfert nuclei

<u>But at higher redshifts</u>
<u>It's a different story!</u>
<u>The 'ULIRGs' instead</u>
<u>Are just like 10x</u>
<u>scaled-up</u>
<u>'Normal' Spirals</u>
<u>(global starbursts?)</u>

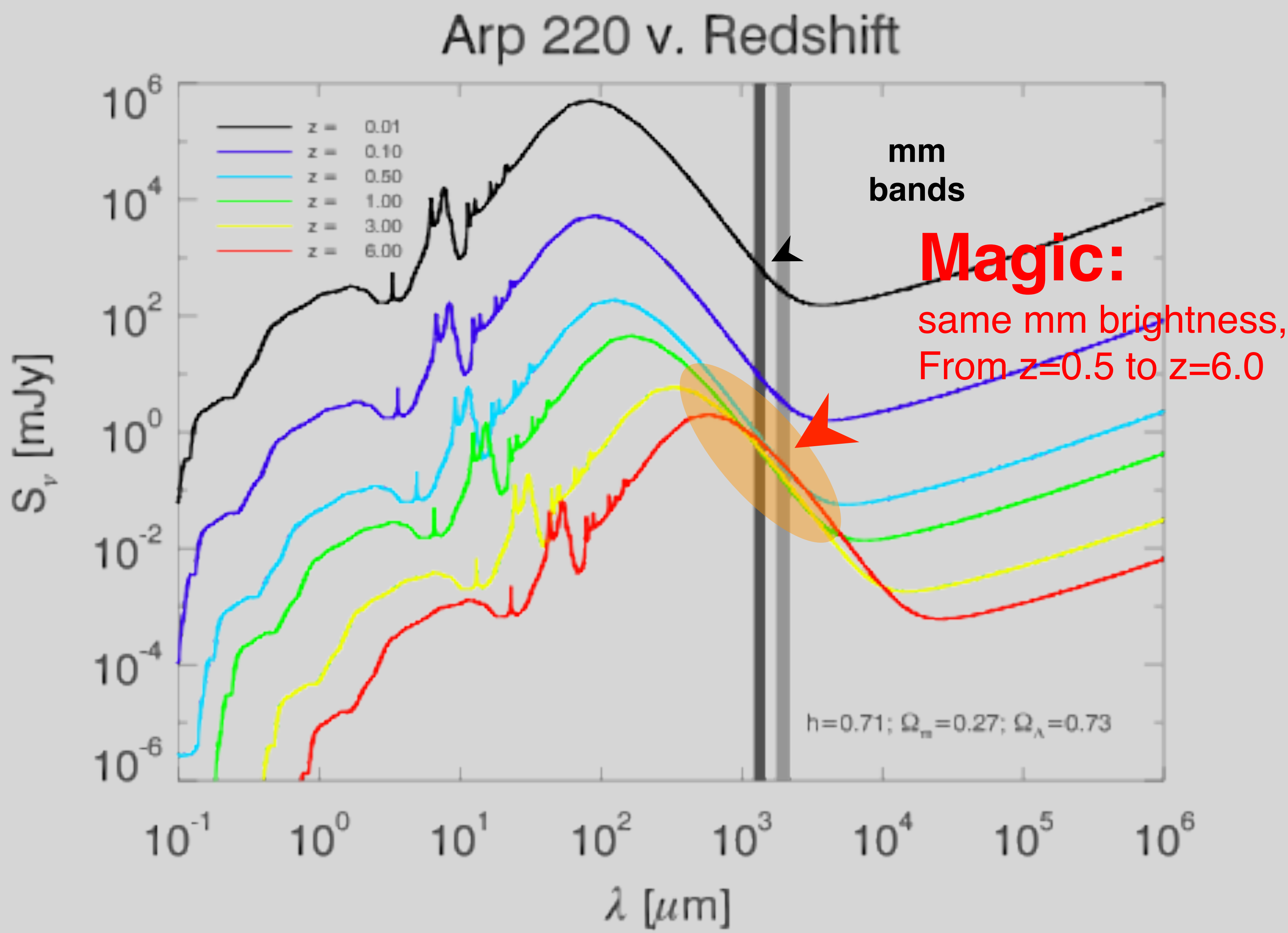
NGC 1097 SINGS




To study Dusty Star-Forming Galaxies at the highest redshifts, we need to exploit a ‘trick’-- the ‘Positive K-corrections’ of dust emission from galaxies when observed in the Sub-Millimeter
ALMA is the Game Changer
Hi! I’m a distant galaxy, happy to meet you.
ALMA, combined with the South Pole Telescope (SPT) brings my smile.

Are the strong emission-line galaxies found by WISP And SDF also Lyman-α Emitters?

1. Some ARE
2. Some ARE NOT (WISP finds far MORE galaxies)


Arp 220 v. Redshift
z = 0.01
z = 0.10
z = 0.50
z = 1.00
z = 3.00
z = 6.00
mm
bands
Magic:
same mm brightness,
From z=0.5 to z=6.0
h=0.71; Ω_m=0.27; Ω_Λ=0.73
S_ν [mJy]
λ [μm]

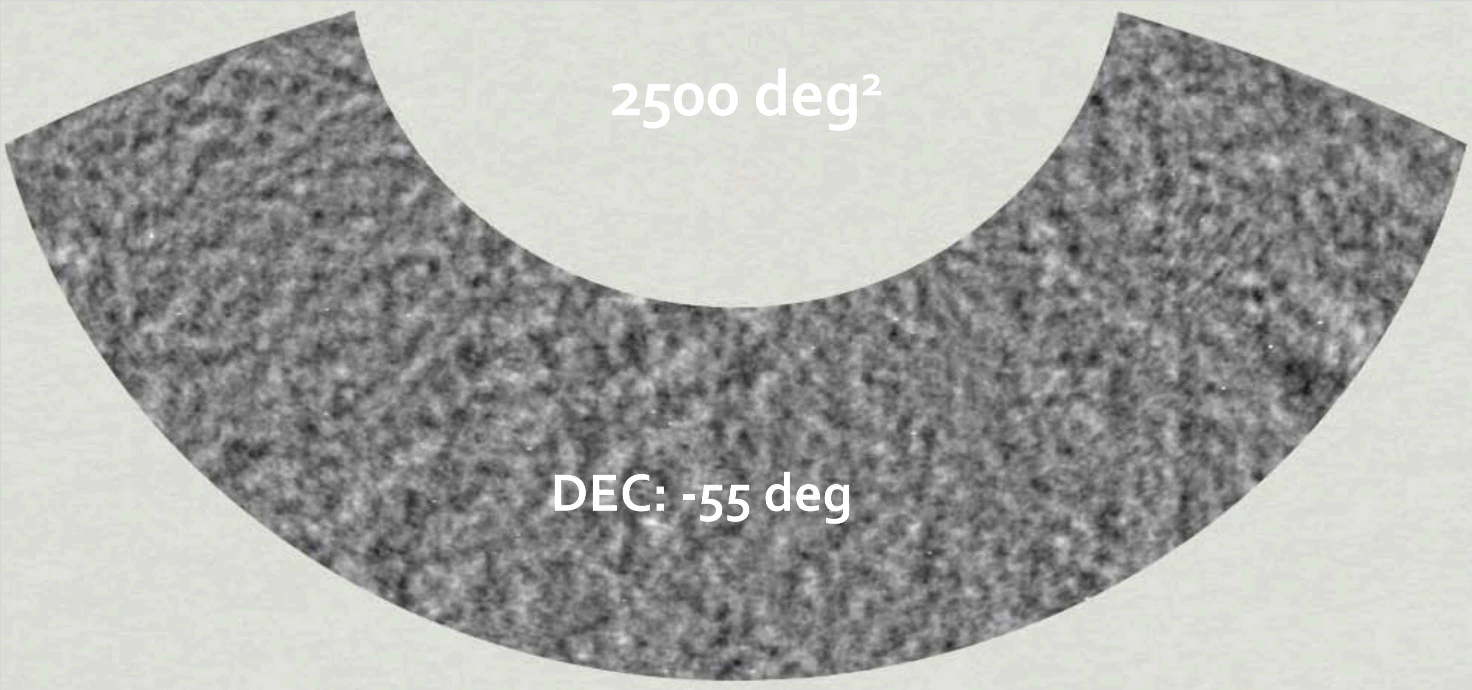
The South Pole Telescope Survey

PI: John Carlstrom (Chicaco)

- Cosmological survey to study CMB find structure & SZ signal from Galaxy clusters

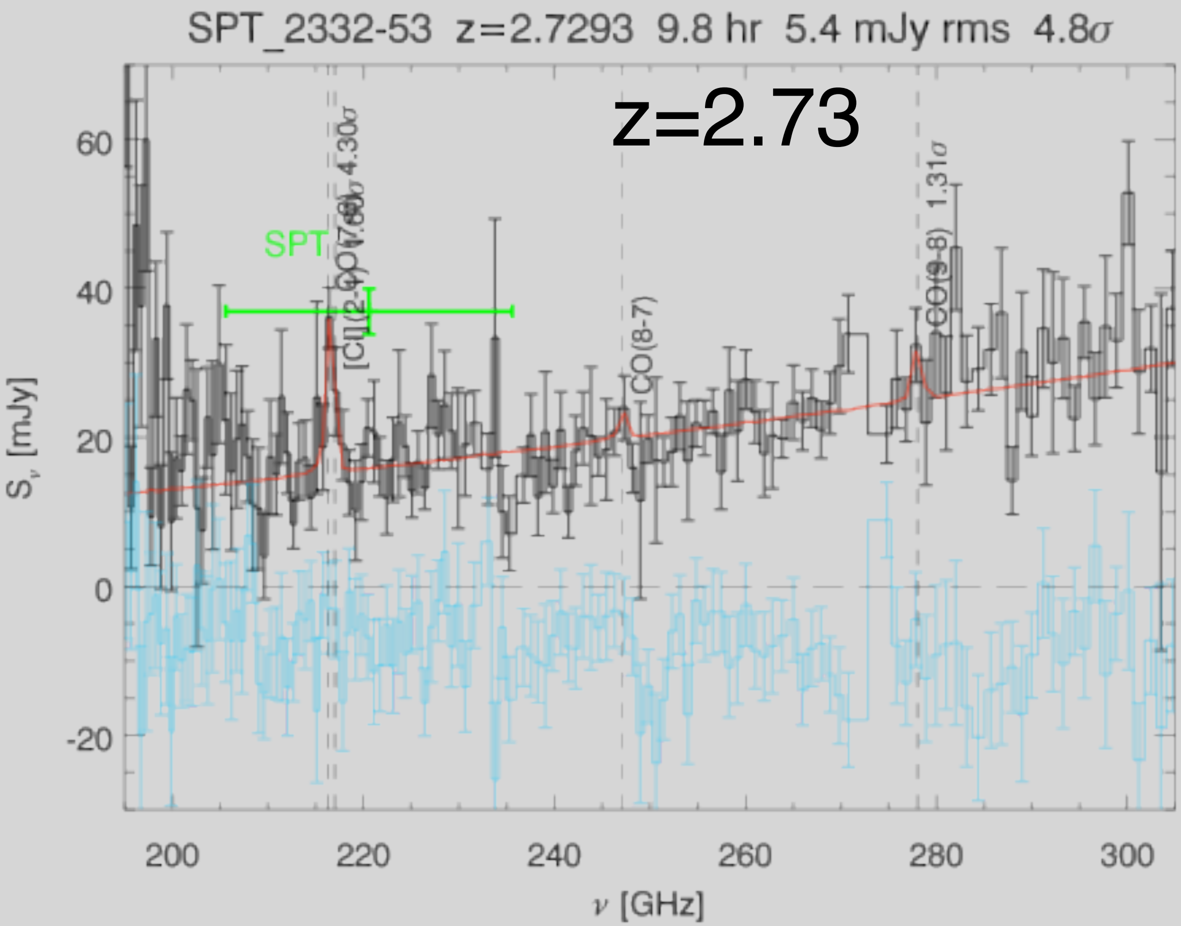
- SPT operates a 3-color bolometer array at 3,2 & 1mm
- Survey covers 2500 deg^2 ; typical rms at 1mm: 3.5 mJy

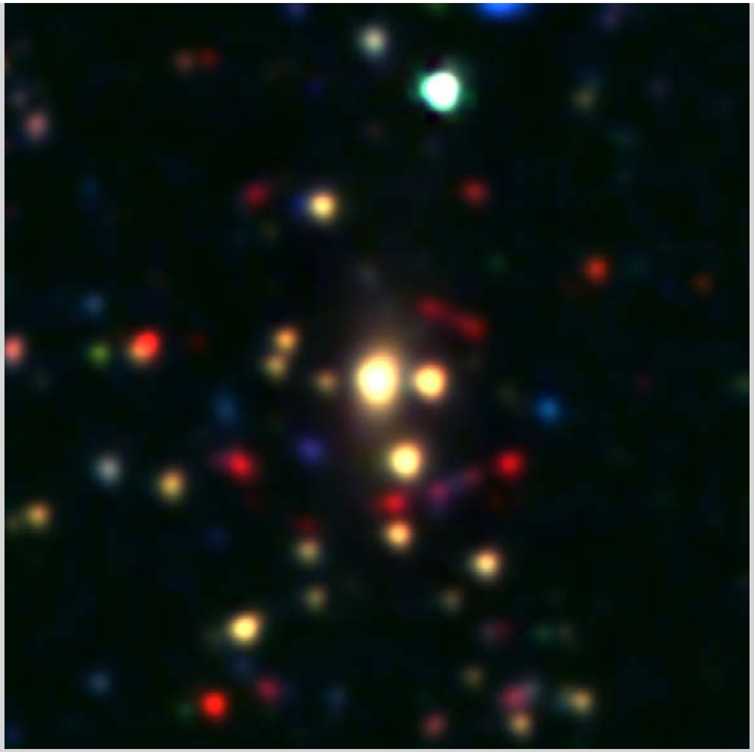
- Byproduct: large sample of strongly lensed high-z sources

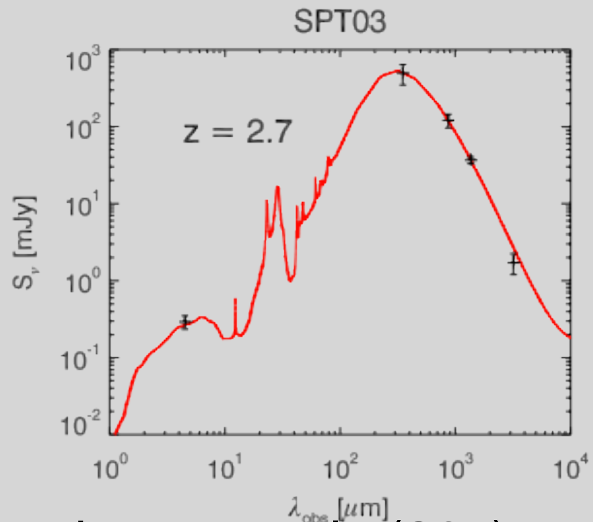


SPT (byproduct) surveys thousands of square degrees; some are far enough

north to use SMA for localization







Cluster lens @ z=0.404, background SPT source is a strongly (20x) gravitationally lensed TRIPLE,

But most SPT sources don't look like this!

What are strongly lensed DSFGs good for?

Background Source:

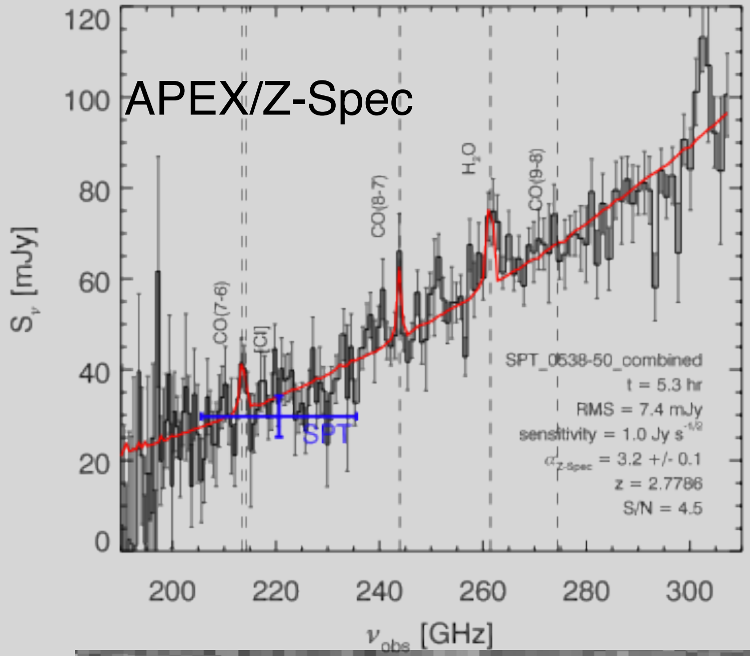
- Provides random sample individual sources which make up the CIB in great detail. x10 brighter ⇒

  ~100x less telescope time

- Lensing increases angular diameter on the sky. ⇒

We have a cosmic microscope to provide high angular resolution of the ISM at high redshift, probing Kpc scales

- Detailed spectroscopy of CO, C+, H2O (and other lines) is finally possible at high redshifts.

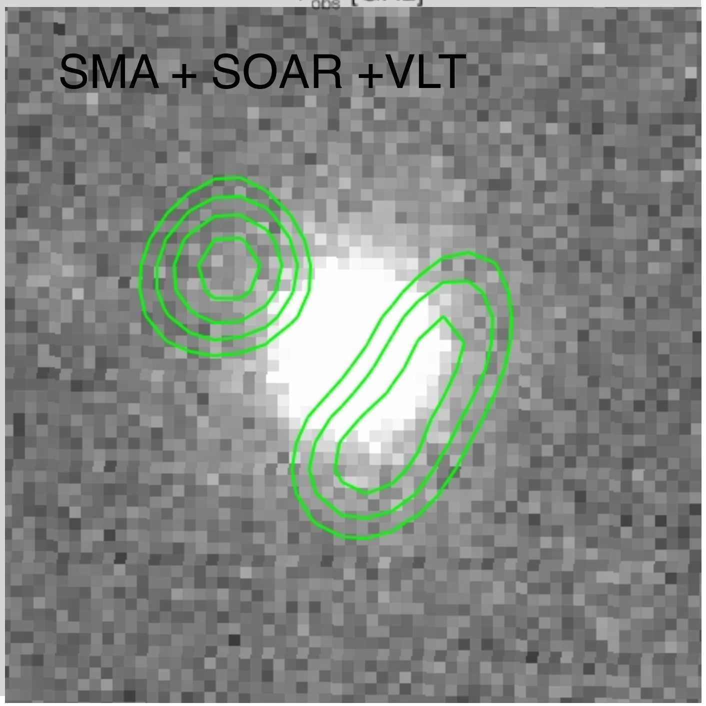


Foreground Lens:

Study in detail the (foreground) lens galaxy ⇒

Study M/L ratios of massive halos out to high redshift,

and Sub-structure in lensing halos



ALMA observations of strongly lensed high redshift SMGs from the South Pole Telescope survey

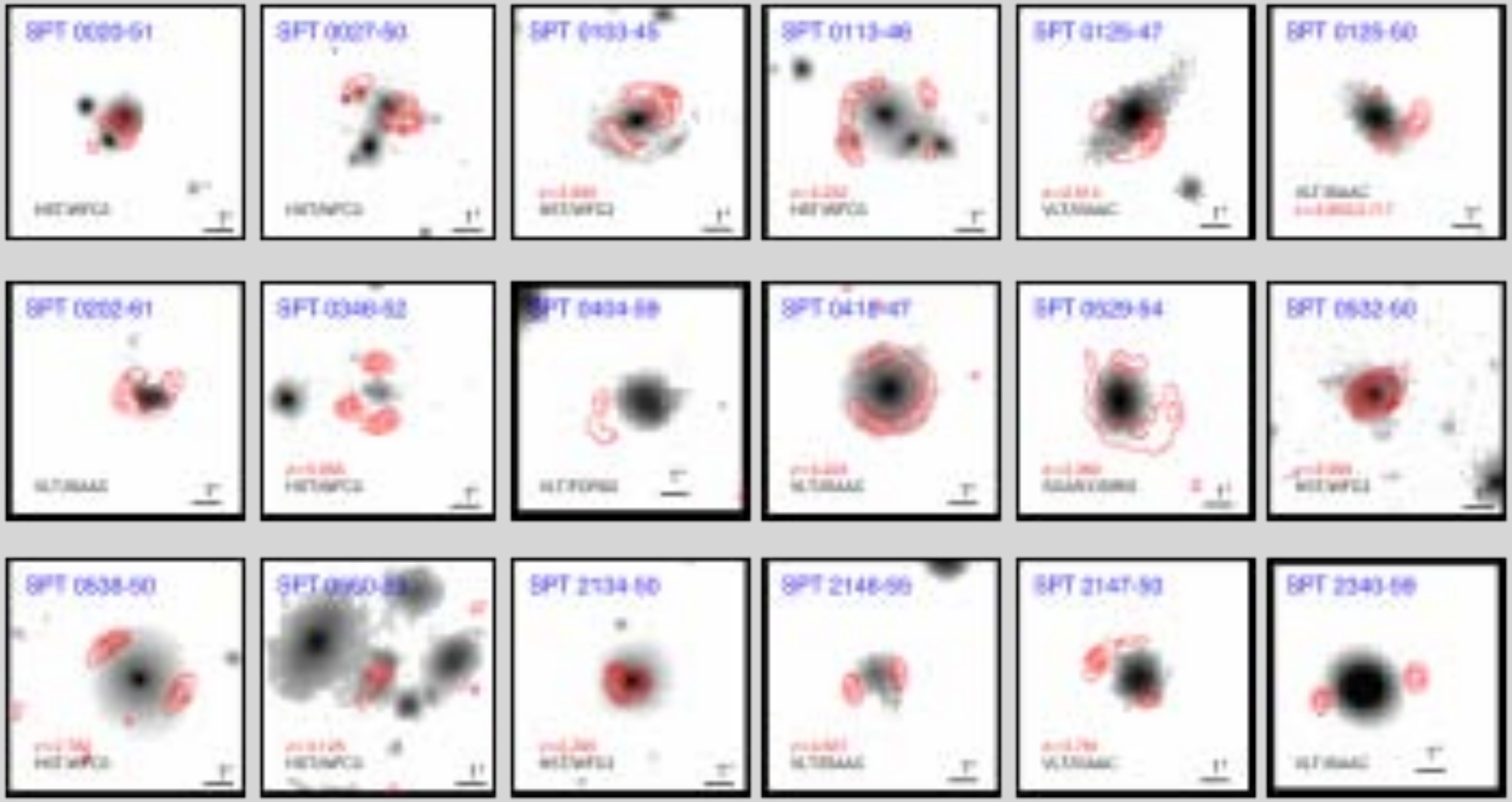
the SPT-SMG team

James Aguirre (UPenn)
Matt Ashby (CfA)
Matt Bothwell (Arizona)
John Carlstrom (Chicago)
Scott Chapman (Cambridge)
Tom Crawford (Chicago)
Carlos DeBreuck (ESO)

Chris Fassnacht (Davis)
Anthony Gonzalez (Florida)
Thomas Greve (Copenhgn.)
Yashar Hezaveh (McGill)
Matt Malkan (UCLA)
Dan Marrone (Arizona)

Eric Murphy (Carnegie)
Michael Rosenman (Penn)
Keren Sharon (Chicago)
Justin Spilker (Arizona)
Brian Stalder (Harvard)
Tony Stark (CfA)
Joaquin Vieira (Caltech)
Axel Weiss (MPIfR)

ALMA Band 7 350 GHz extended configuration 1 minute snapshots:
Because of the steep fall-off of the LF, observing z=3--6 SMGs
Greatly increases odds of **gravitational lensing,** from *single galaxy*



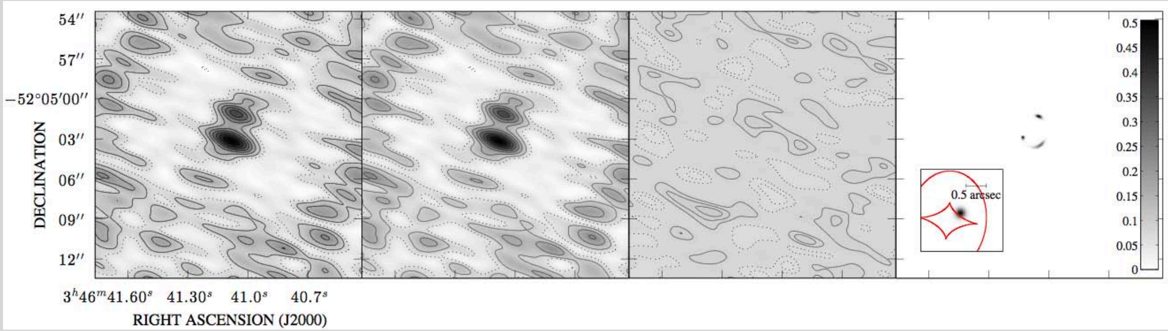
Only through the combination of strong gravitational lensing, the SPT selection, and ALMA followup is this result possible

Lens models

dirty image model image residual source model

SPT 0346-52

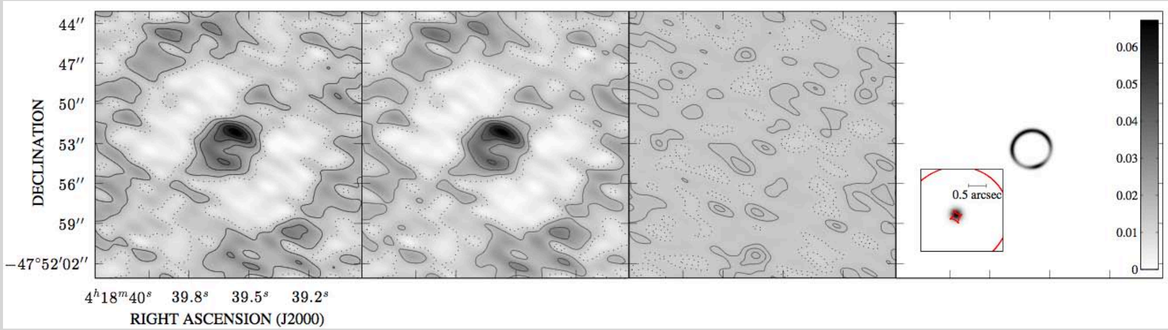
$z_S = 5.67$; $z_L \sim 0.8$
$r_E = 1.1$ arcsec
$M_L = 3.7 \times 10^{11}\ M_{sun}$
$\mu = 5.4$
$R_{1/2} = 0.6$ kpc
$L_{FIR} = 3.7 \times 10^{13}\ L_{sun}$
$S_{850\mu m} = 25.5$ mJy



SPT 418-47

$z_S = 4.22$; $z_L = 0.27$
$r_E = 1.4$ arcsec
$M_L = 2.4 \times 10^{11}\ M_{sun}$
$\mu = 21$

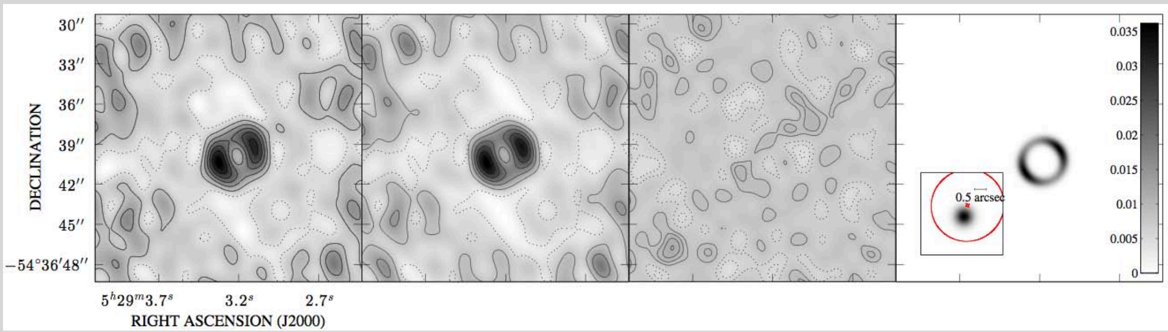
$R_{1/2} = 1.1$ kpc
$L_{FIR} = 3.8 \times 10^{12}\ L_{sun}$
$S_{850\mu m} = 4.8$ mJy



SPT 0529-54

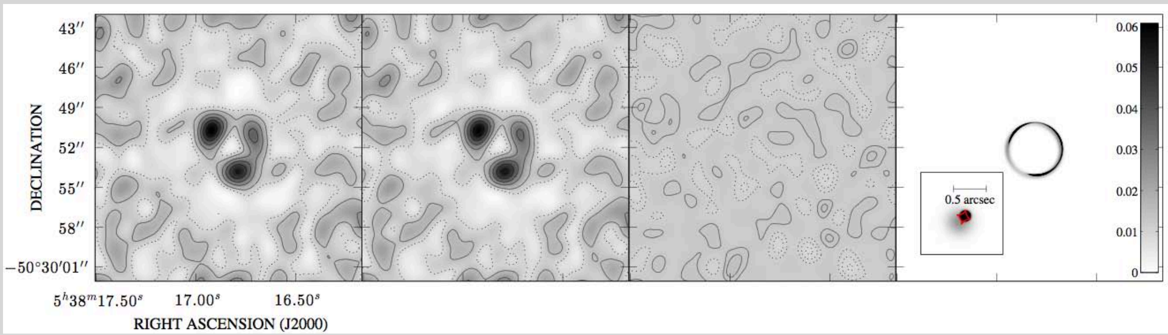
$z_S = 3.37$; $z_L = 0.13$
$r_E = 1.5$ arcsec
$M_L = 1.6 \times 10^{11}\ M_{sun}$
$\mu = 9.4$

$R_{1/2} = 2.4$ kpc
$L_{FIR} = 3.8 \times 10^{12}\ L_{sun}$
$S_{850\mu m} = 13$ mJy



SPT 0538-50

$z_S = 2.782$; $z_L = 0.4$
$r_E = 2.0$ arcsec
$M_L = 7.2 \times 10^{11}\ M_{sun}$
$\mu = 20.5$
$R_{1/2} = 1.0$ kpc
$L_{FIR} = 4.5 \times 10^{12}\ L_{sun}$
$S_{850\mu m} = 6.1$ mJy



Gravitational Lens Modeling

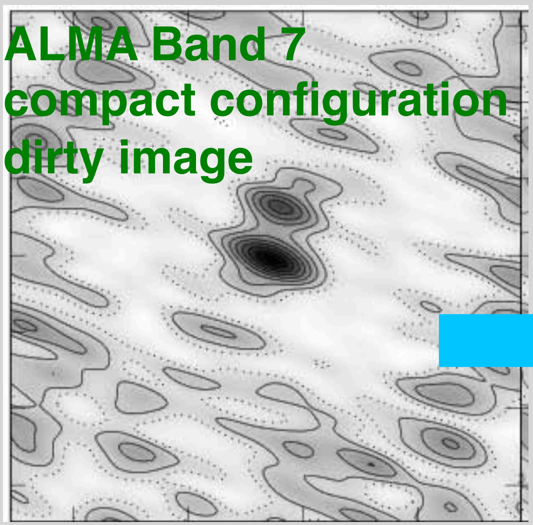
Yashar Hezaveh (McGill grad student)

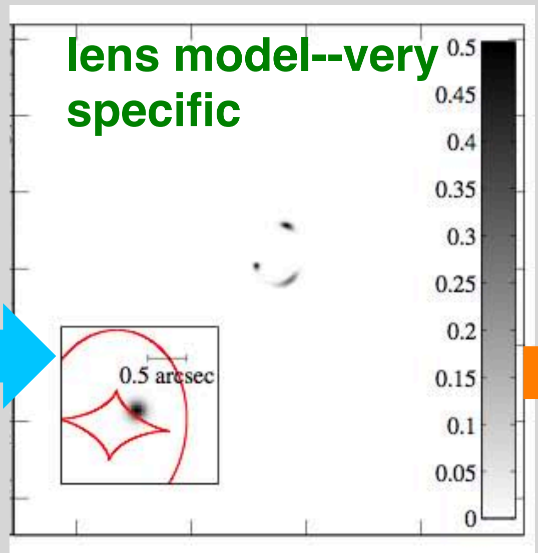
Hezaveh, Marrone, Fassnacht, Vieira, *et al.* 2012, Submitted to ApJ

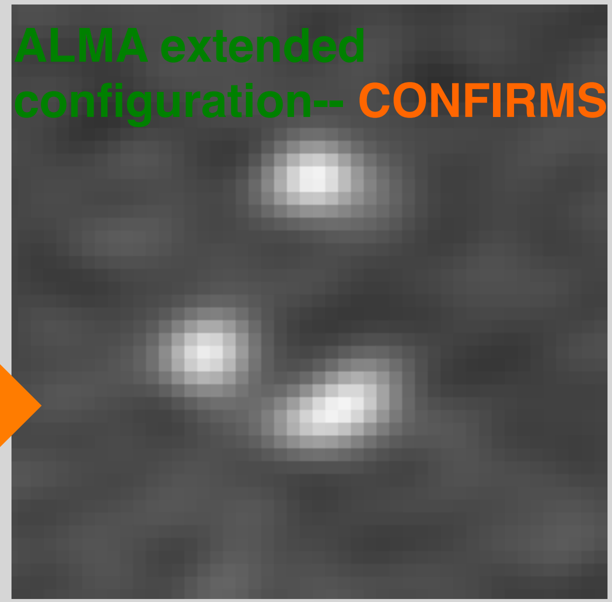
- model ALMA visibilities with a custom and statistically robust technique
- we know there are phase errors in the antennas, we incorporate the self-cal phases into the MCMC model fitting

-->models work amazingly well!

- this technique can set limits on dark matter substructure

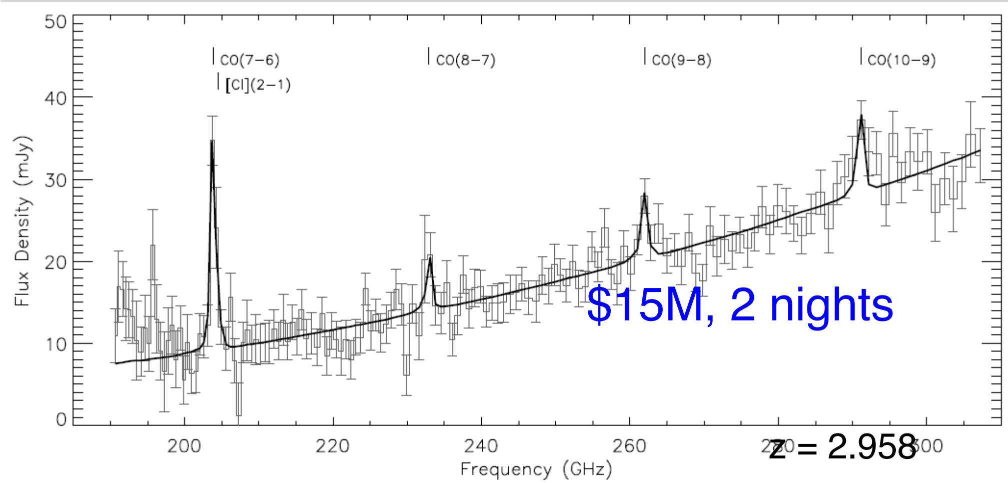


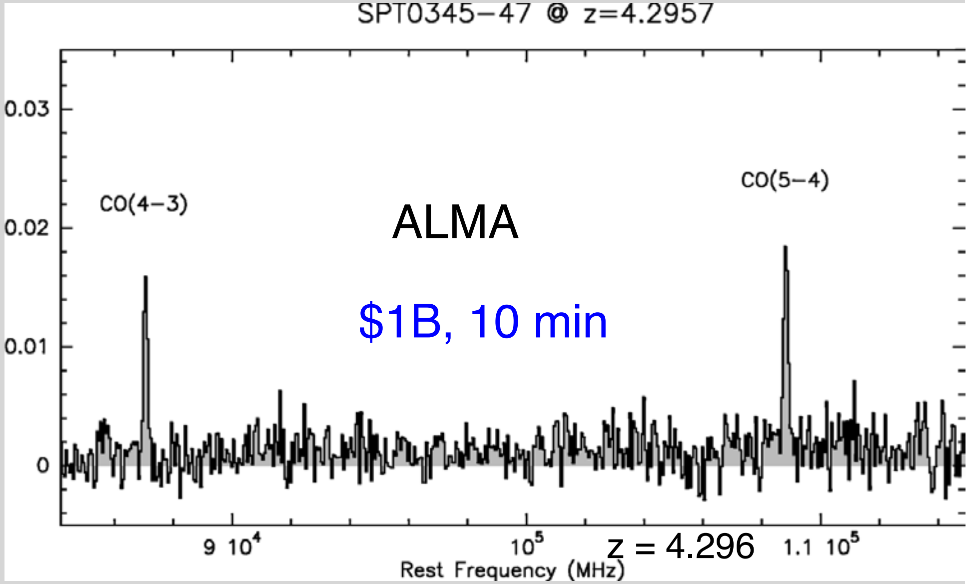


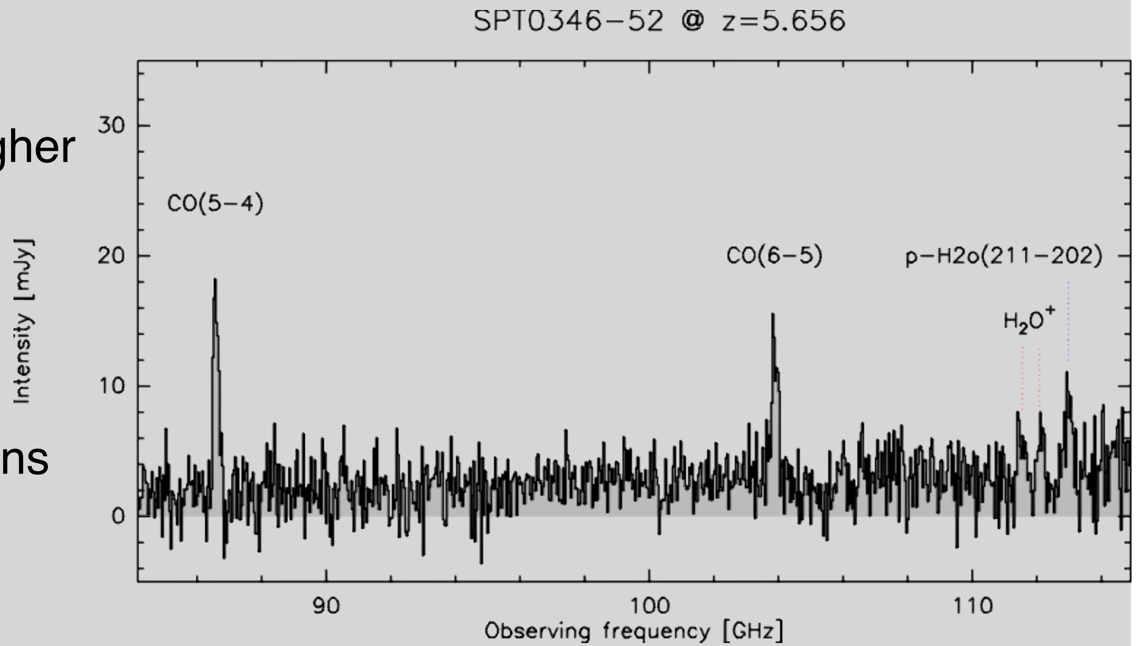


Did you mistrust those single-dish spectroscopic redshifts with carbon monoxide?

CSO/Z-Spec Scott et al. 2011

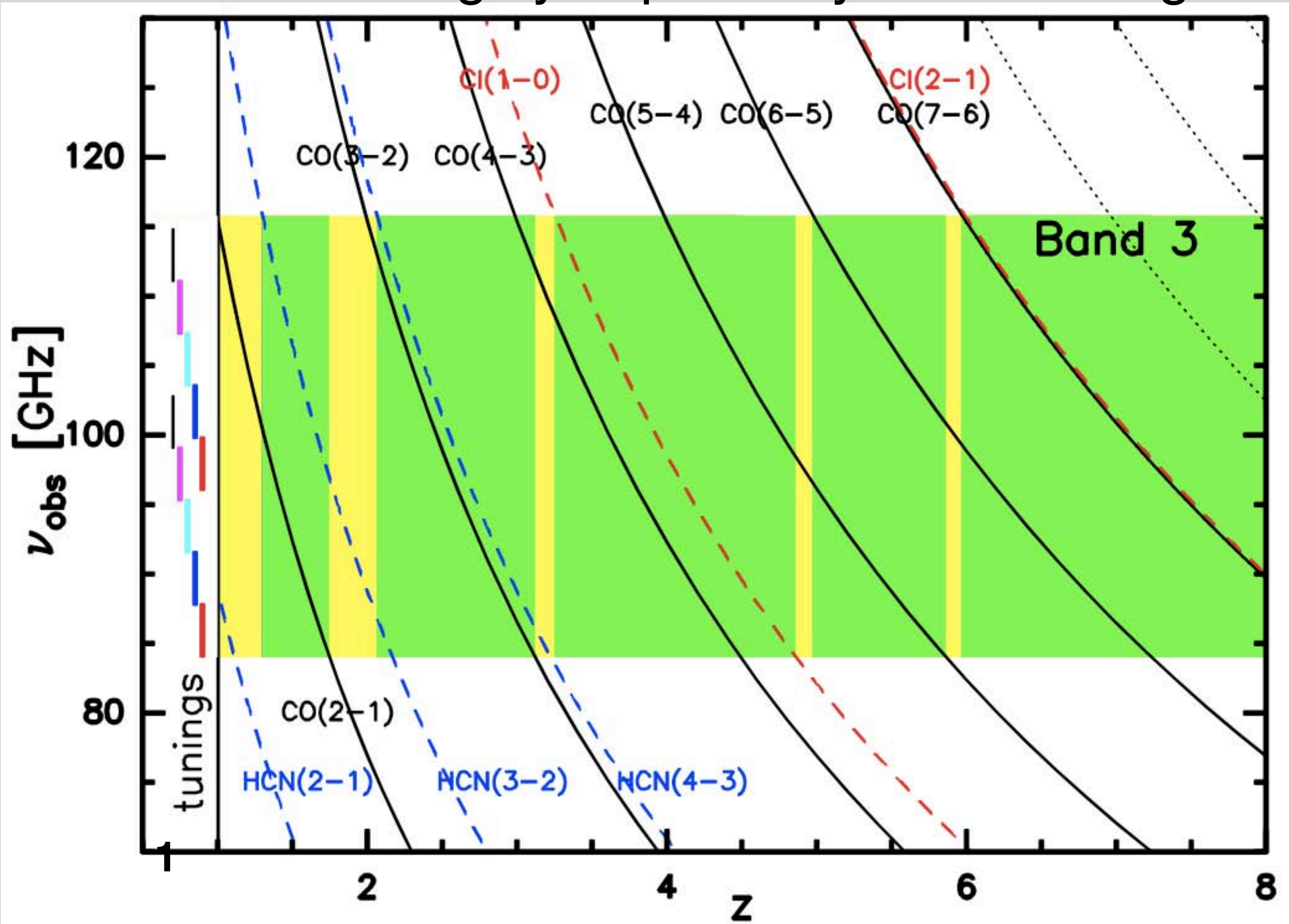






- CO ladder at 115 GHz spacing; the higher the redshift, the more lines
- 2 lines gives a secure redshift, width gives dynamical mass
- CO traces molecular gas, dust mass
- CO line SED excitation ladder constrains conditions of molecular gas

ALMA Band 3 CO *Blind Redshift* search:
With 5 tunings you probably cover enough

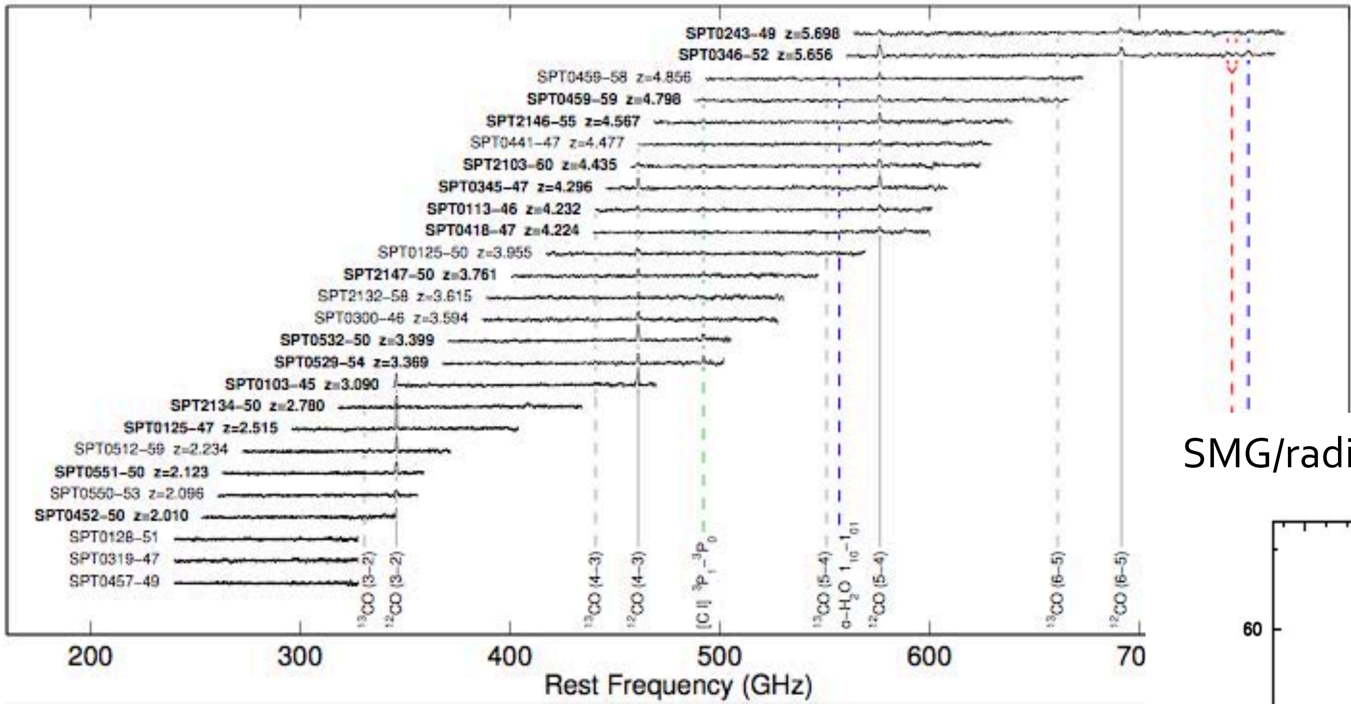


= 2 lines, unambiguous *z*

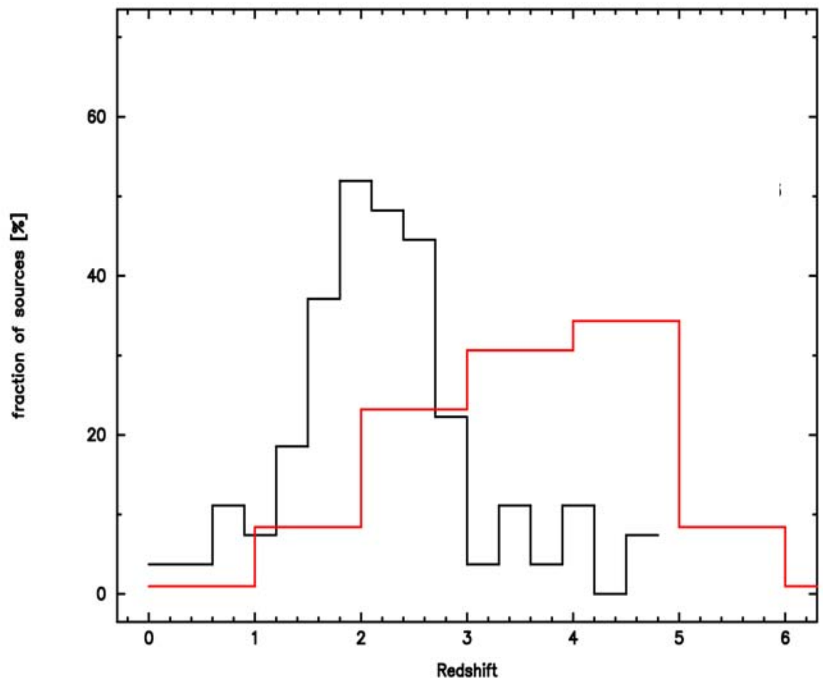
= 1 line, ambiguous *z*

First blind CO redshift survey with ALMA--works beautifully

ALMA Band 3 3mm compact configuration
26 sources: 44 lines detected
5 tunings in the 3 mm band
10 minutes per source



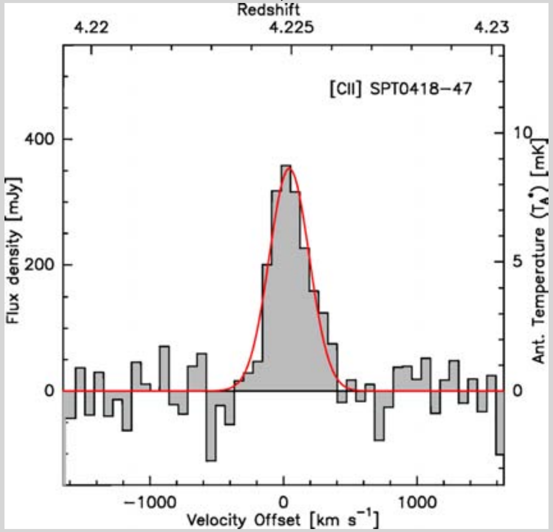
SMG/radio;ALMA/SPT (best guess)



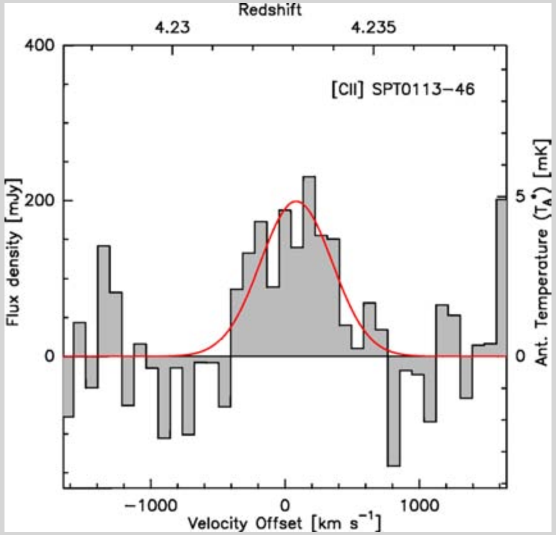
Vieira, Marrone, Chapman, DeBreuck, Weiss, *et al.* Nature *submitted*

[CII]158um at *z* > 4 detected with APEX/FLASH in ~few hours: Opens a new window on ionized gas in most distant galaxies

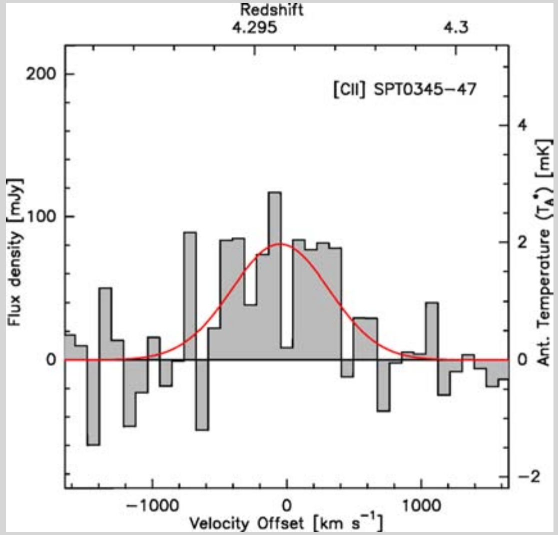
z = 4.23 ; t = 1.5h



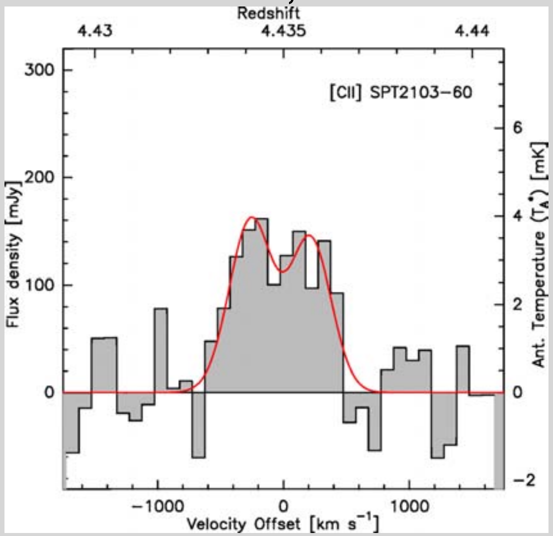
z = 4.23 ; t = 2.3h



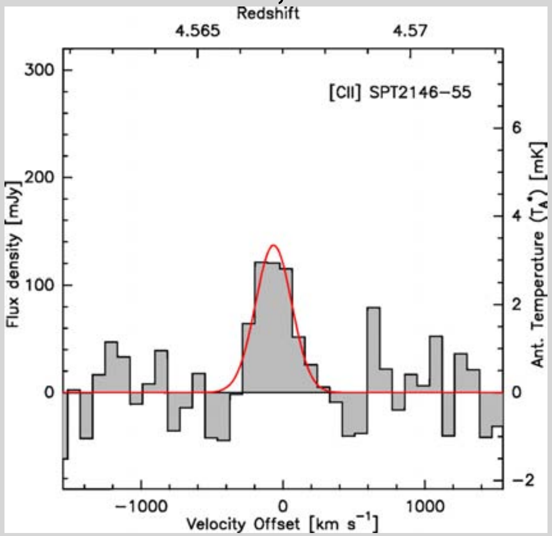
z = 4.30 ; t = 2.3h



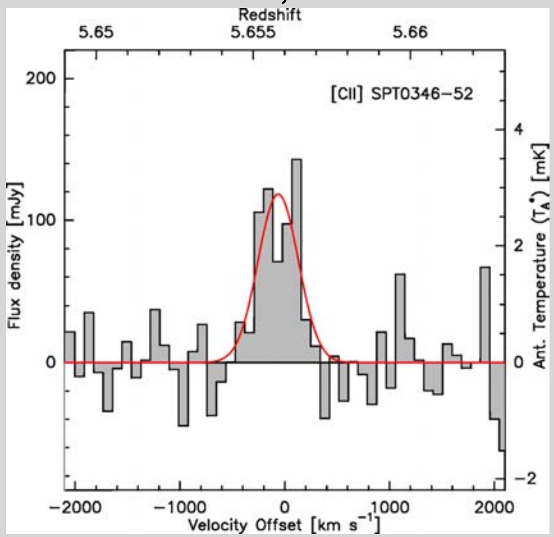
z = 4.43 ; t = 1.5h

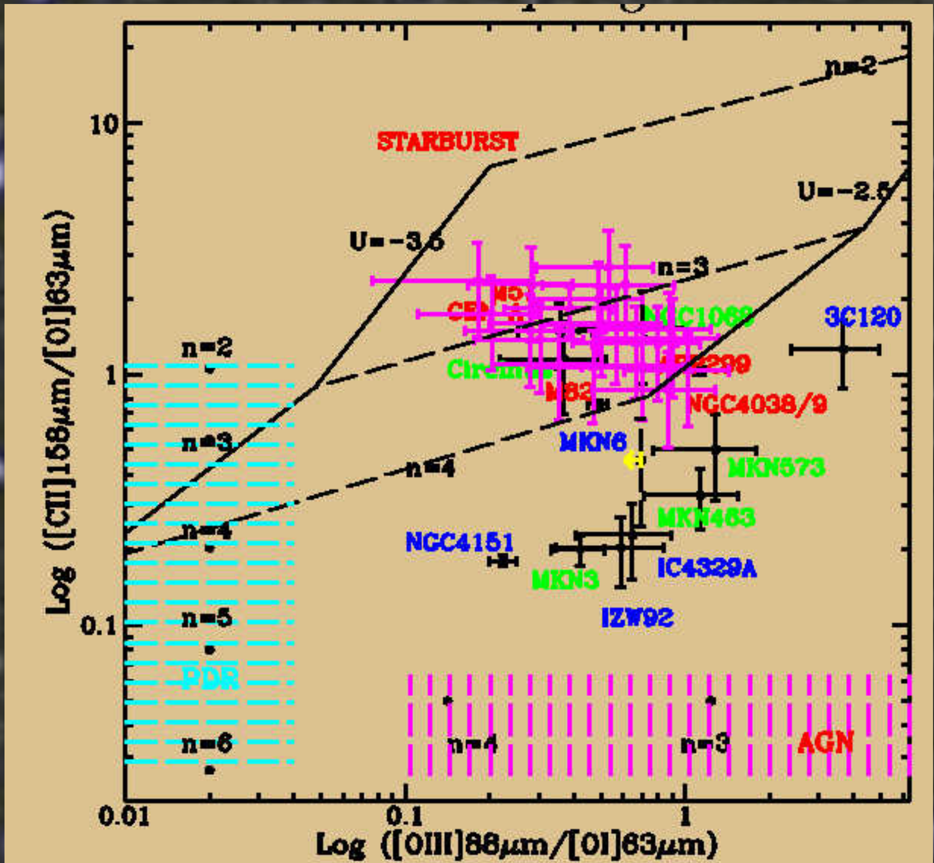


z = 4.57 ; t = 3.0h



z = 5.66 ; t = 1.4h





Conclusion:

ALMA can find NORMAL Galaxies at ‘any’ redshifts;

When BAND 10 is ready, ALMA can study them in almost the same detail as we have been doing for Local galaxies

•ISO/LWS Spinoglio & Malkan proposed Strong far-IR []line diagnostics:
quiescent galaxies are PDR-dominated,
starbursts produce more O++, while Seyfert has O I from denser gas
ALMA Band 10 will allow this for galaxies out to the highest redshifts!