

# The SPT+ALMA CO redshift survey of dusty star forming galaxies



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ISMS

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# SPT-SMG Collaboration

## July 2016, Urbana, IL



**Sreevani Jarugula**  
**U. Illinois**

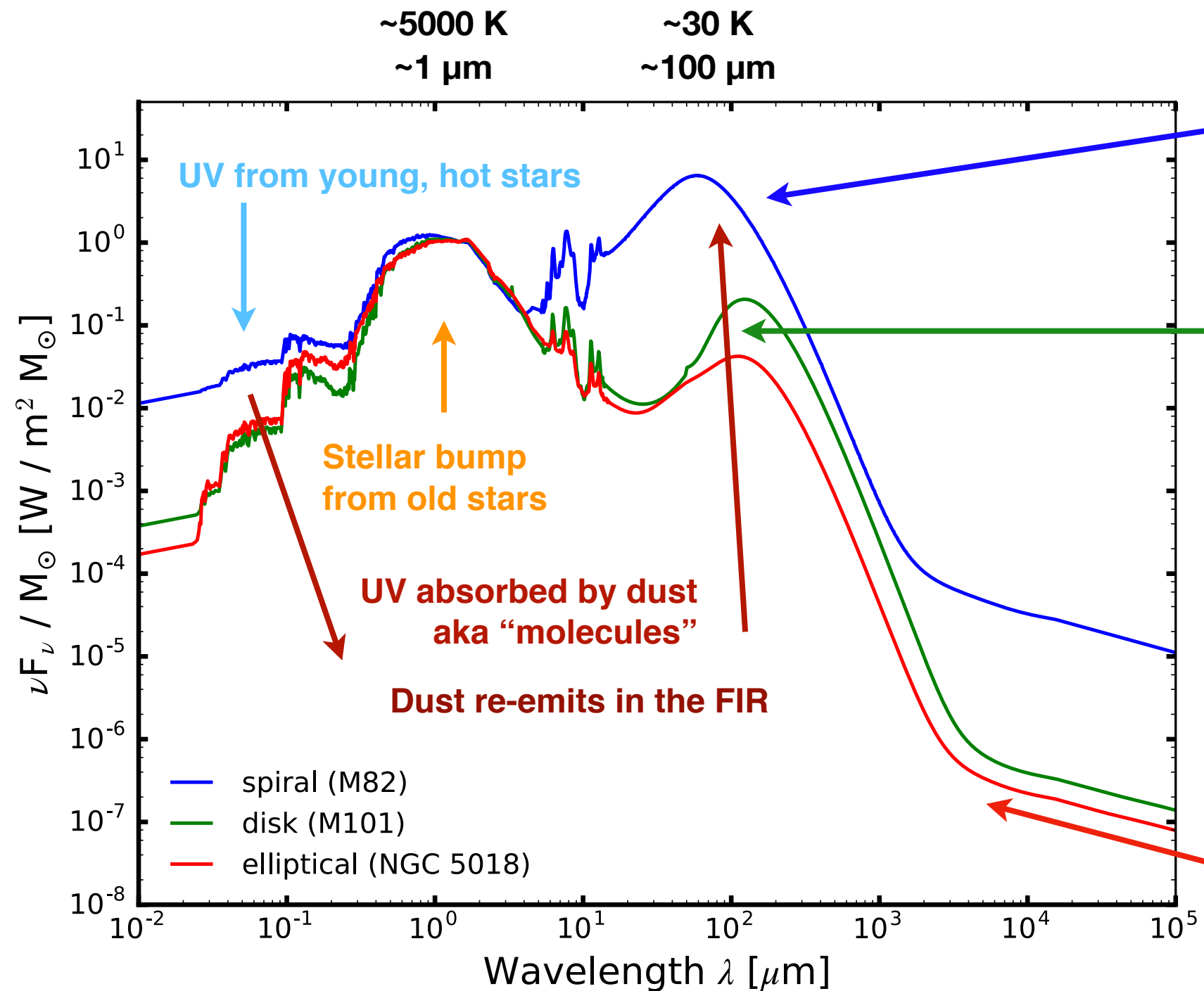
**Maria Strandet**  
**MPIfR**

**Justin Spilker**  
**U. AZ**

**Jingzhe Ma**  
**U. Florida**



# Spectral Energy Densities of Galaxies

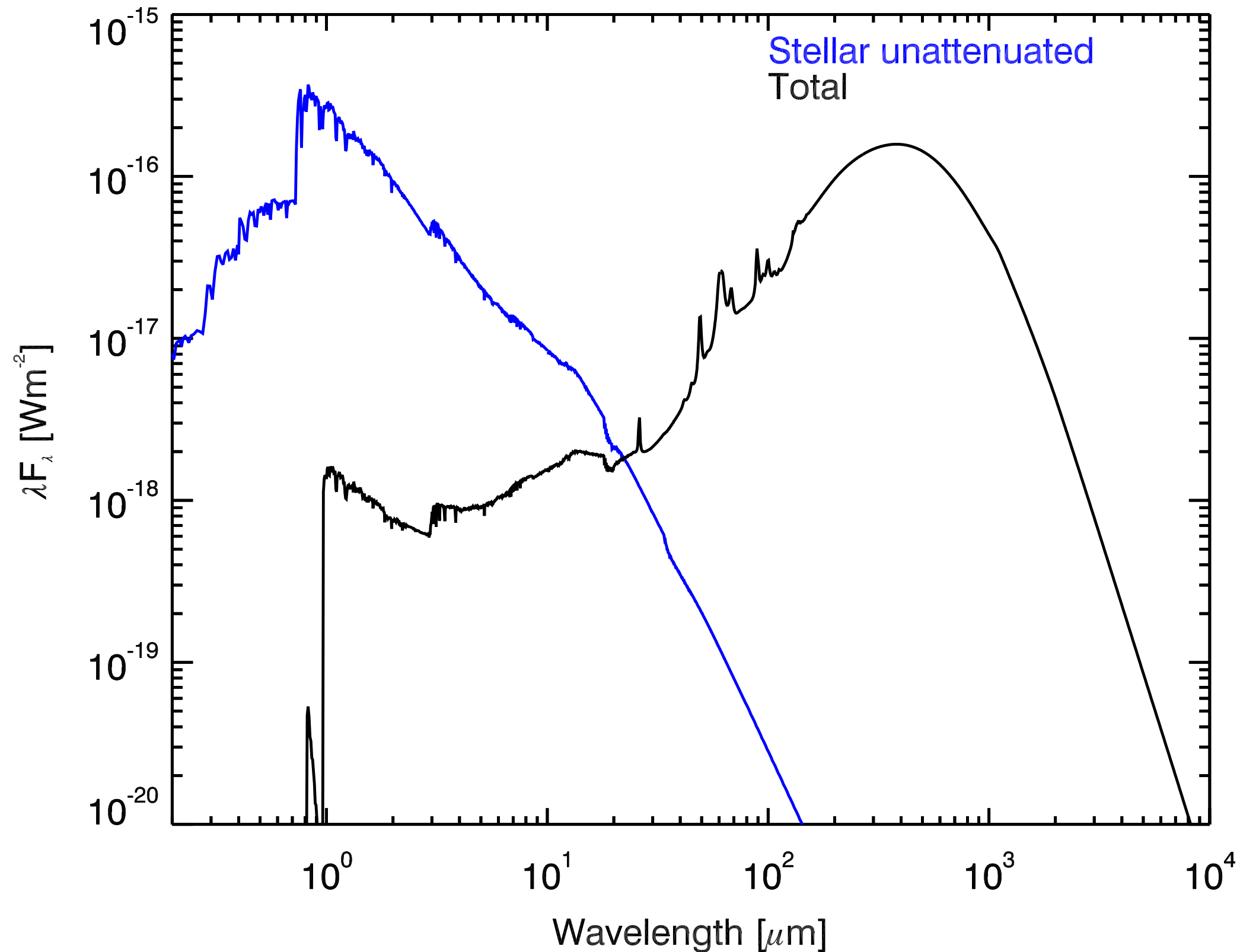


see Lagache *et al.* 2005 ARA&A  
plot by U. Illinois undergraduate Brooke Polak

# The color of a dusty galaxy

SMG  $\equiv$  submillimeter galaxy  
DSFG  $\equiv$  dusty star forming galaxy

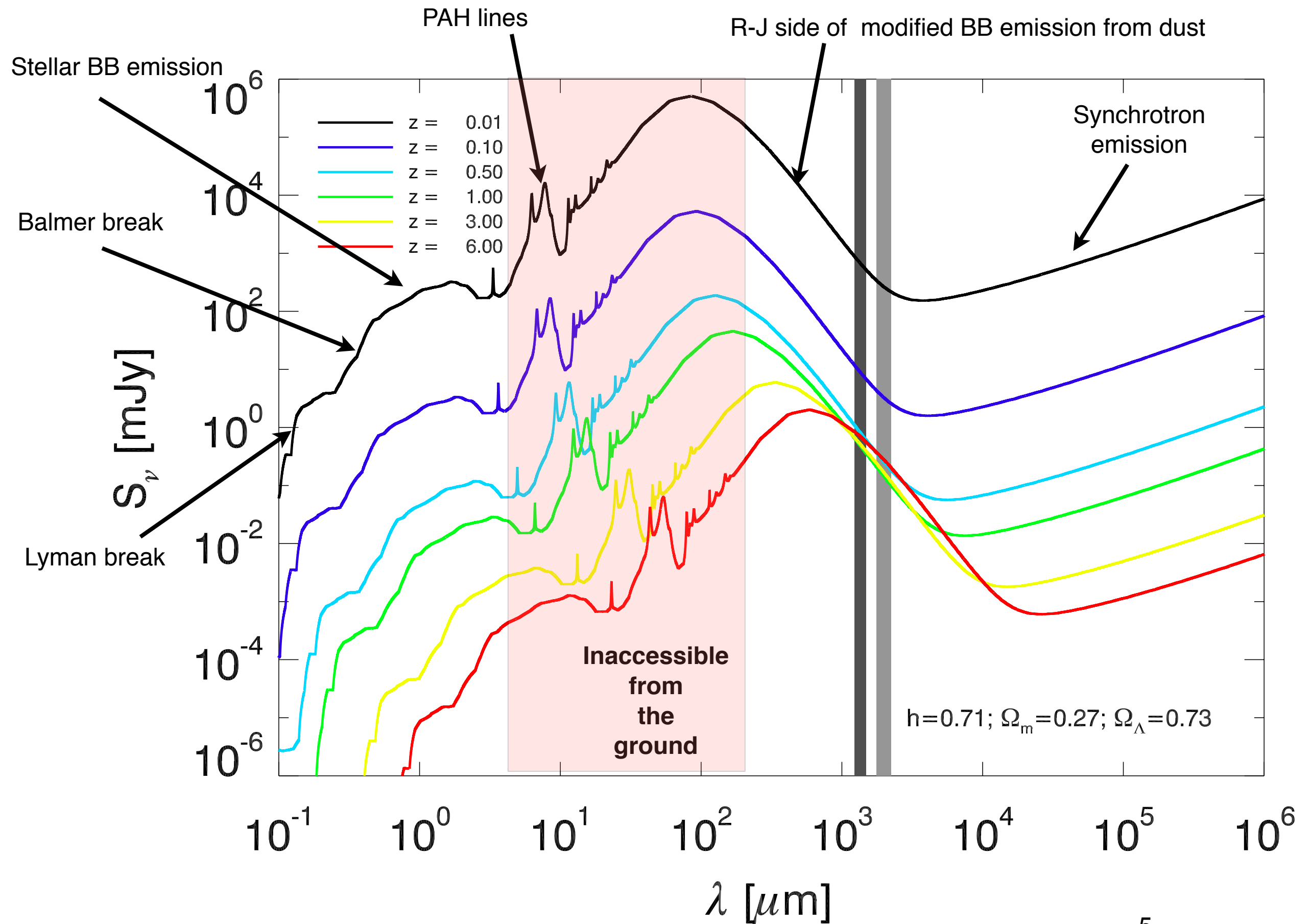
plot by U. Illinois graduate student Kedar Phadke





# The color of a dusty galaxy

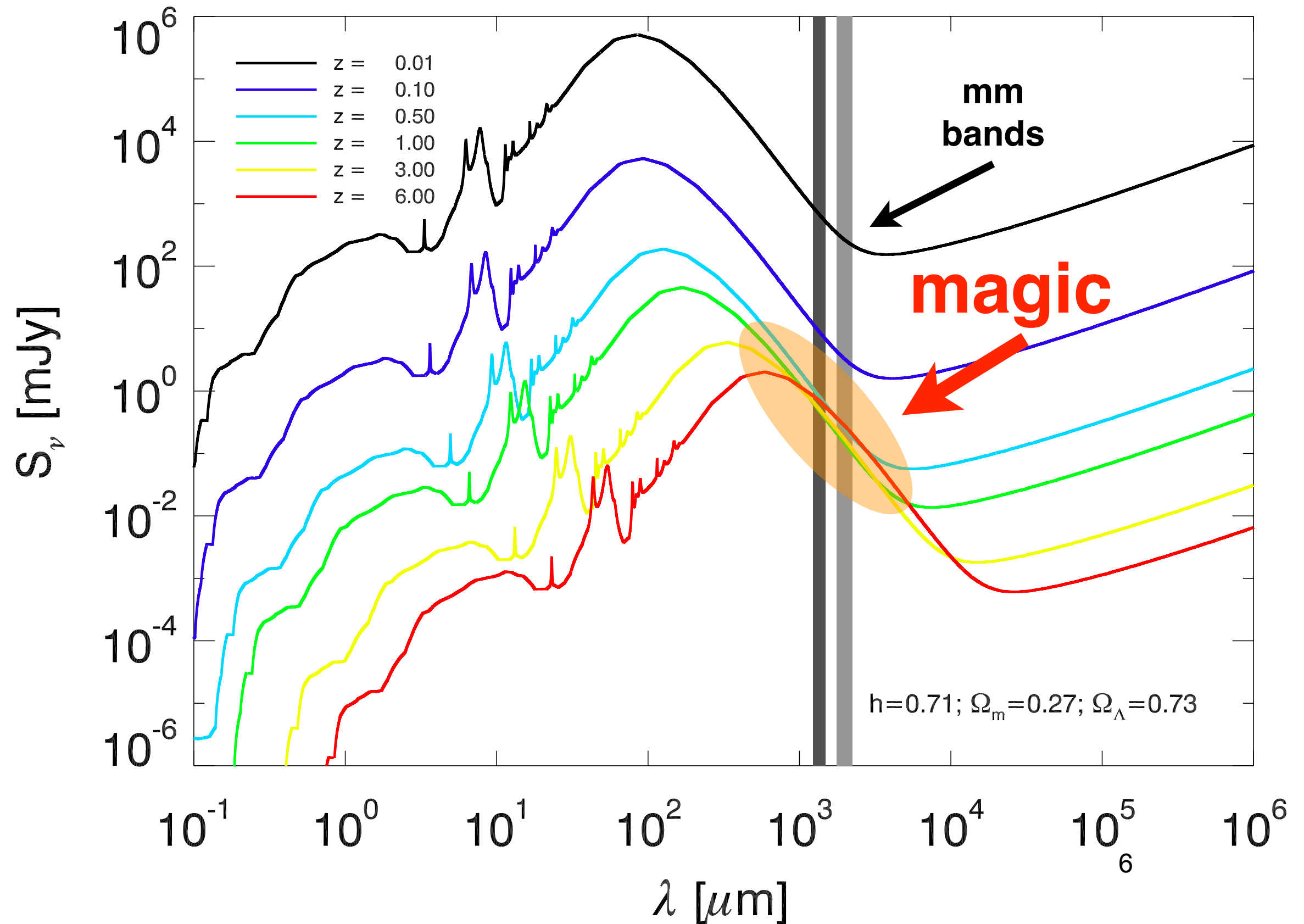
SMG  $\equiv$  submillimeter galaxy  
DSFG  $\equiv$  dusty star forming galaxy



# The color of a dusty galaxy

SMG  $\equiv$  submillimeter galaxy  
DSFG  $\equiv$  dusty star forming galaxy

## Arp 220 v. Redshift

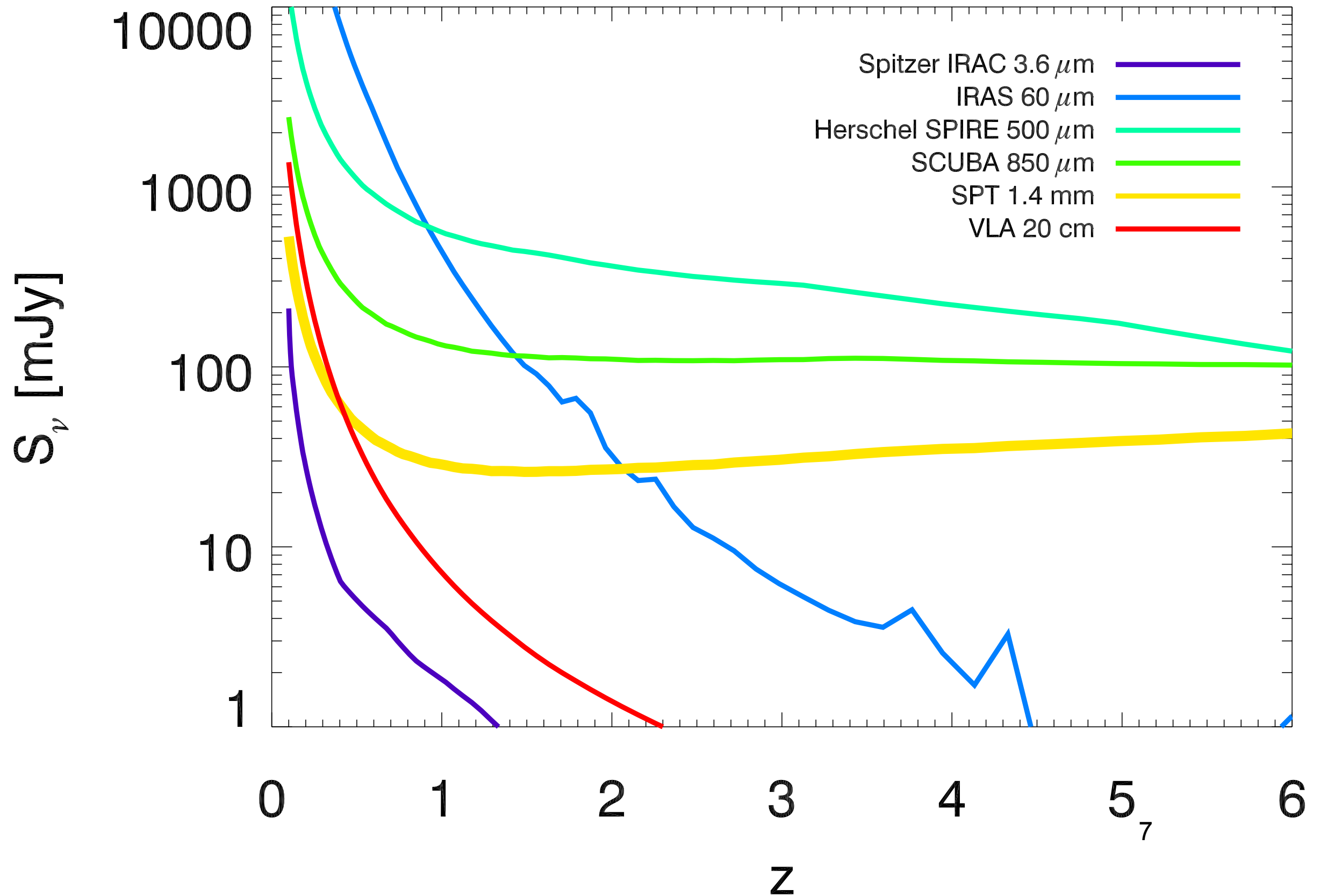




# Sub-mm magic

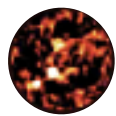
See Franceschini *et al.* 1991 and Blain & Longair 1993

## Arp 220 Flux Density v. Redshift



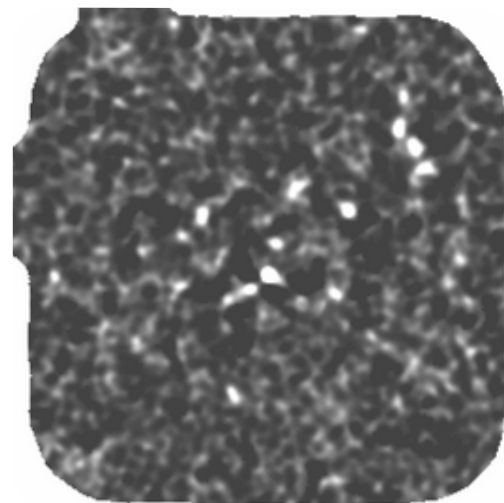
# The JCMT view of GOODS-N

First SCUBA map  
Hughes+ 1998



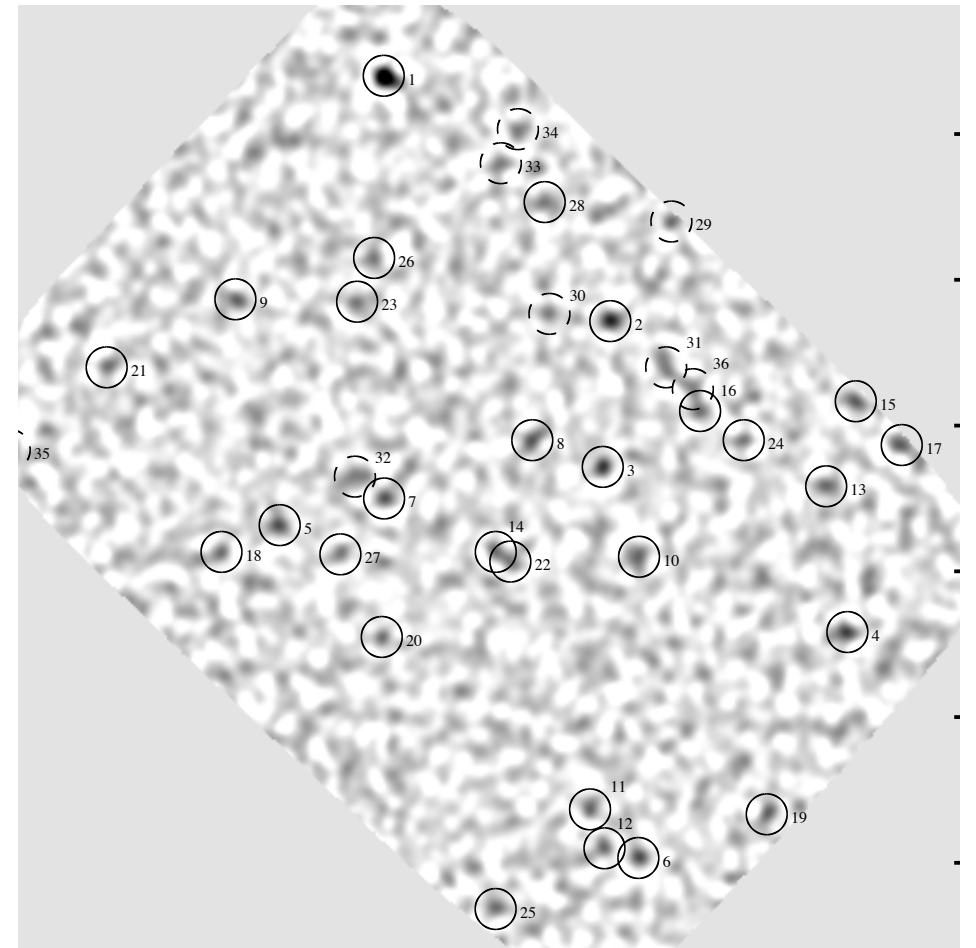
2.2 arcmin<sup>2</sup>

SCUBA "super map"  
Borys+ 2003



165 arcmin<sup>2</sup>

AzTEC  
Perera+ 2008



245 arcmin<sup>2</sup>

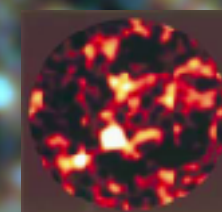
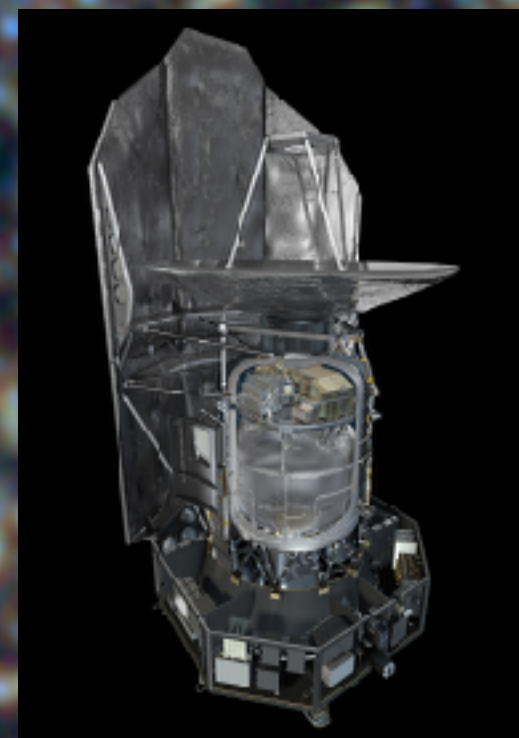




# SPIRE map of GOODS-N

c. 2009

400 arcmin<sup>2</sup>



250  $\mu\text{m}$

350  $\mu\text{m}$

500  $\mu\text{m}$

10 arcmin

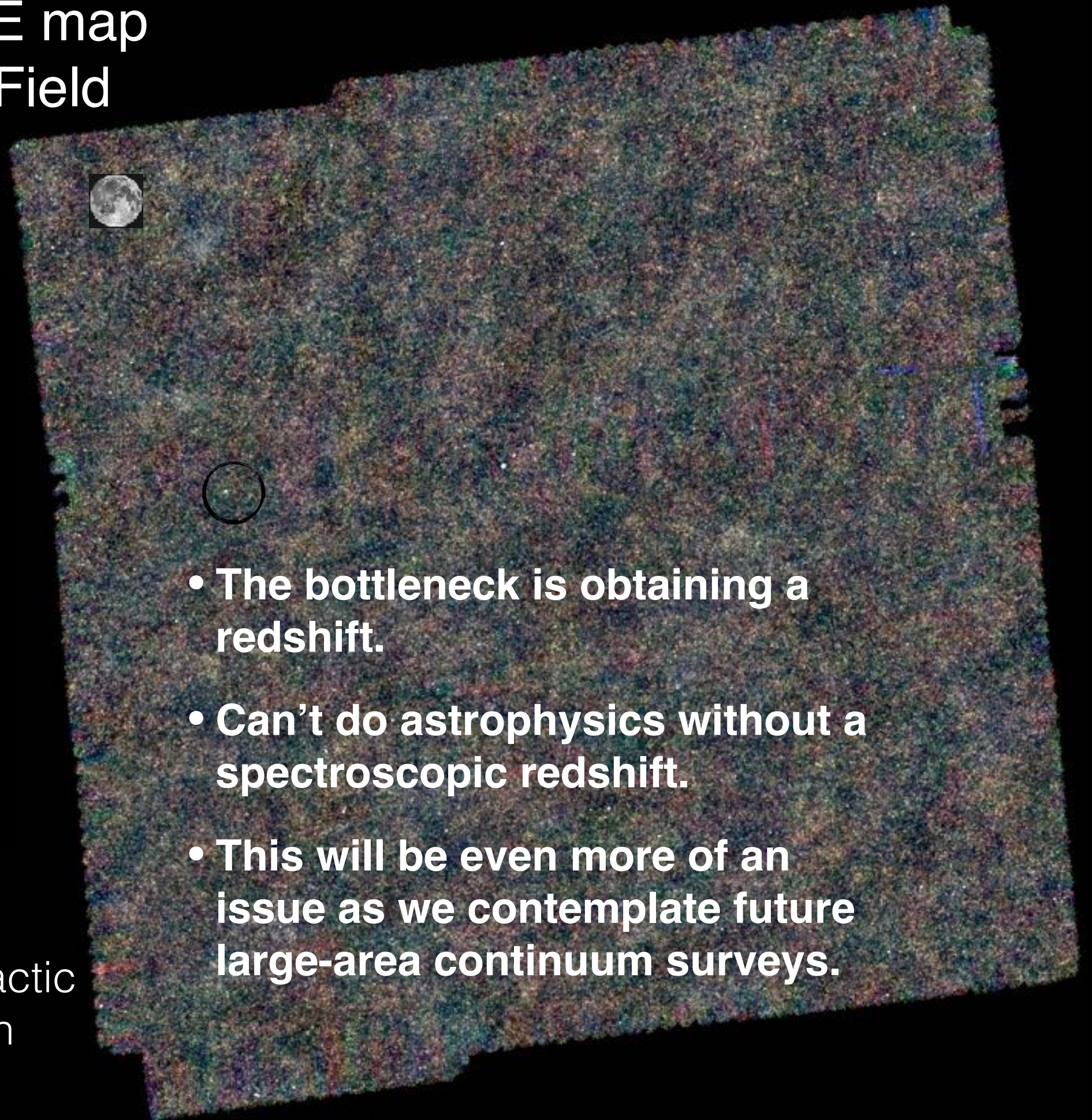




# 100 deg<sup>2</sup> SPIRE map of SPT Deep Field c. 2012



~750 deg<sup>2</sup> extragalactic  
sky surveyed with  
Herschel/SPIRE

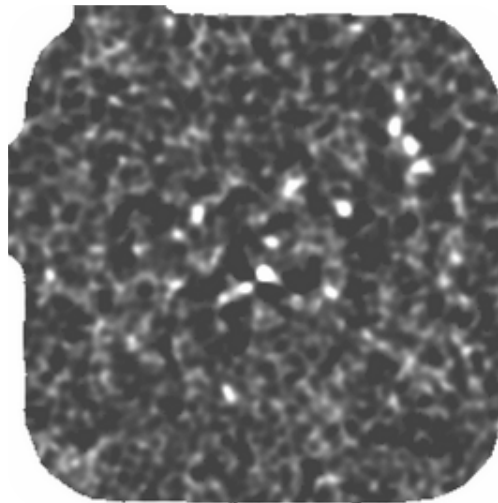


- The bottleneck is obtaining a redshift.
- Can't do astrophysics without a spectroscopic redshift.
- This will be even more of an issue as we contemplate future large-area continuum surveys.

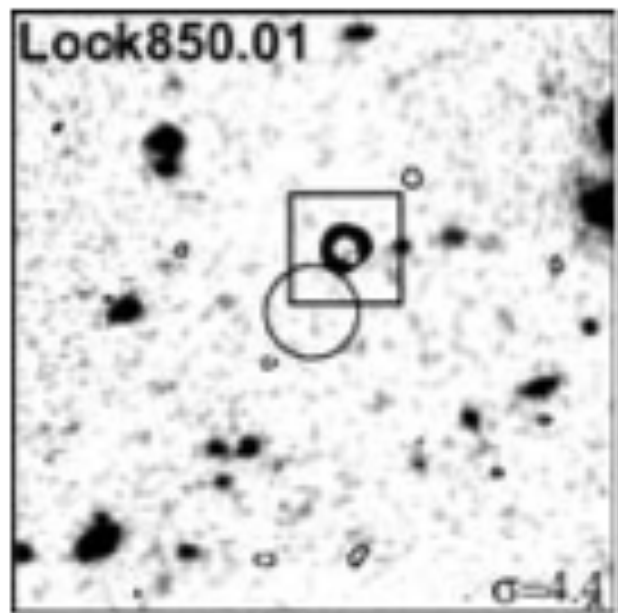
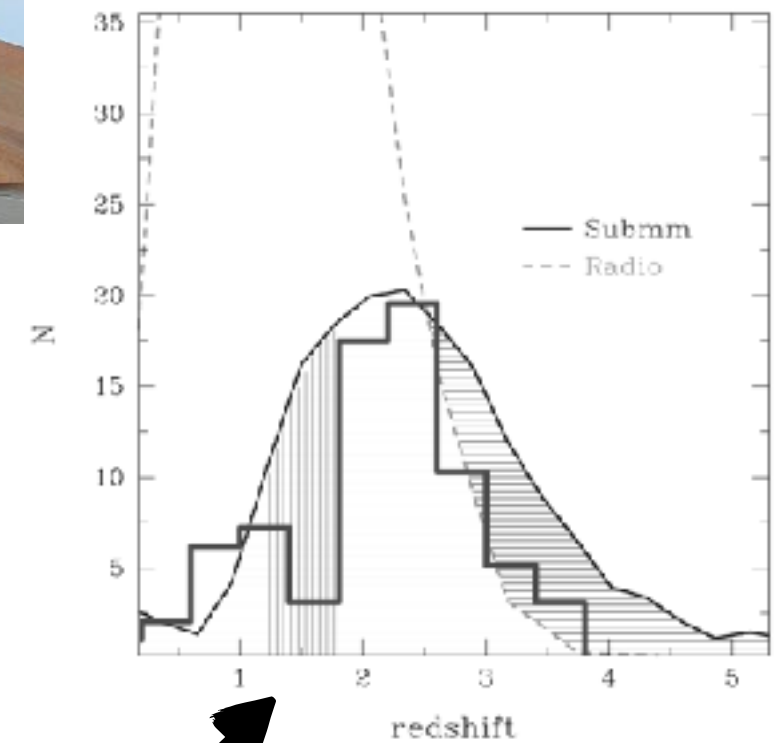


# Spectroscopic redshifts of SMGs: Good

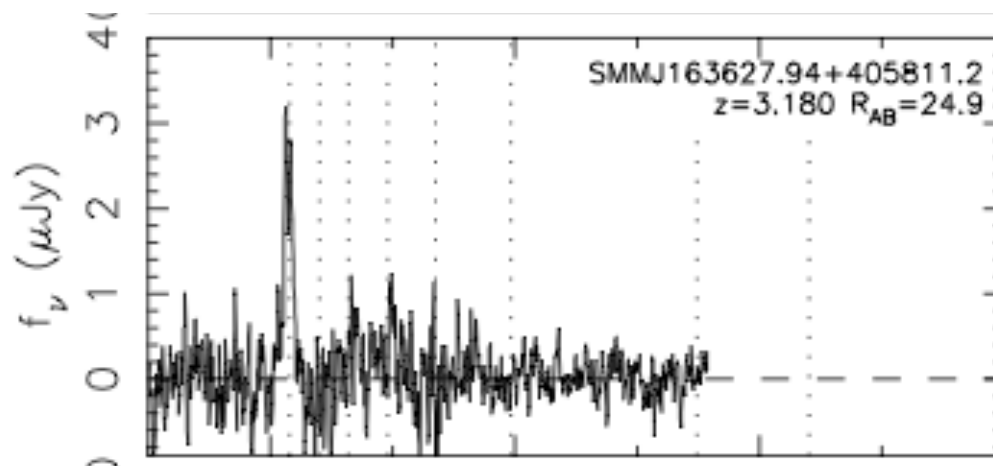
1) Blank field submm survey



4) Estimate  $n(z)$   
Chapman et al ApJ 2005



2) Find radio counterpart to SMG  
Ivison et al. MNRAS 2002, 2007



3) Obtain Keck spectroscopy  
Chapman et al. Nature 2003, ApJ 2005



# Spectroscopic redshifts of SMGs: Better

JCMT



1) Blank field submm survey

SMA



2) Followup with submm interferometer

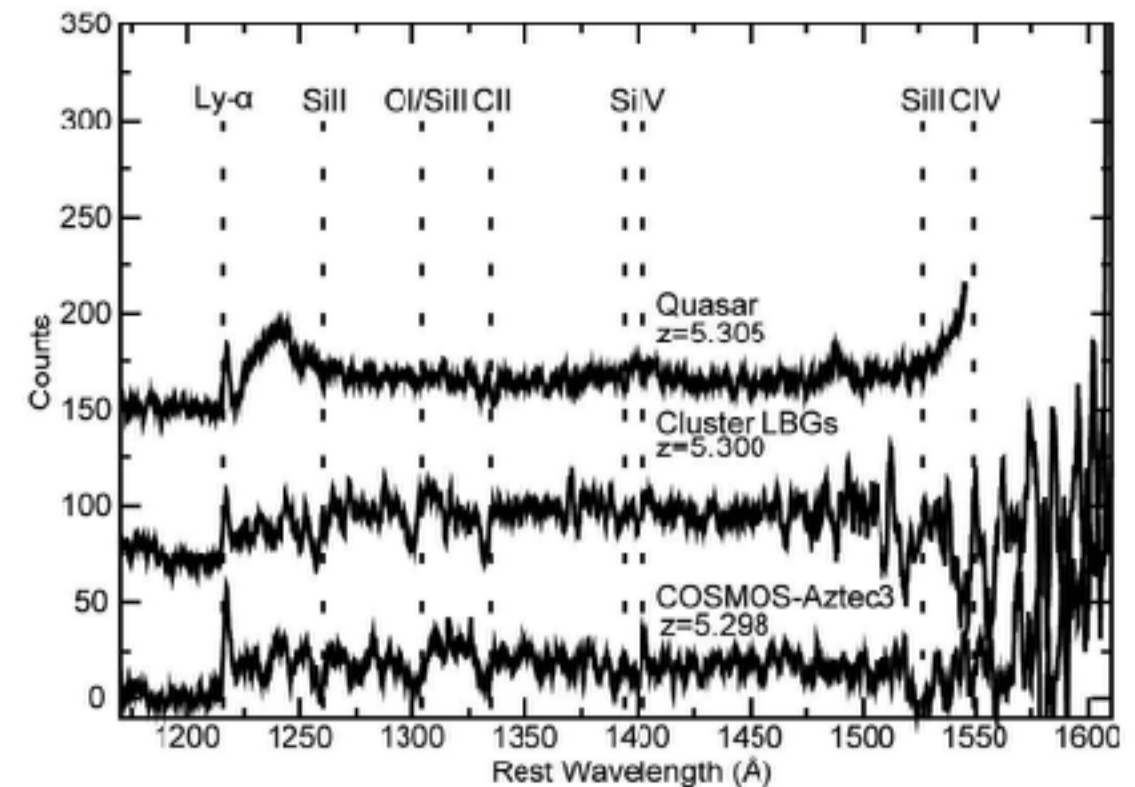
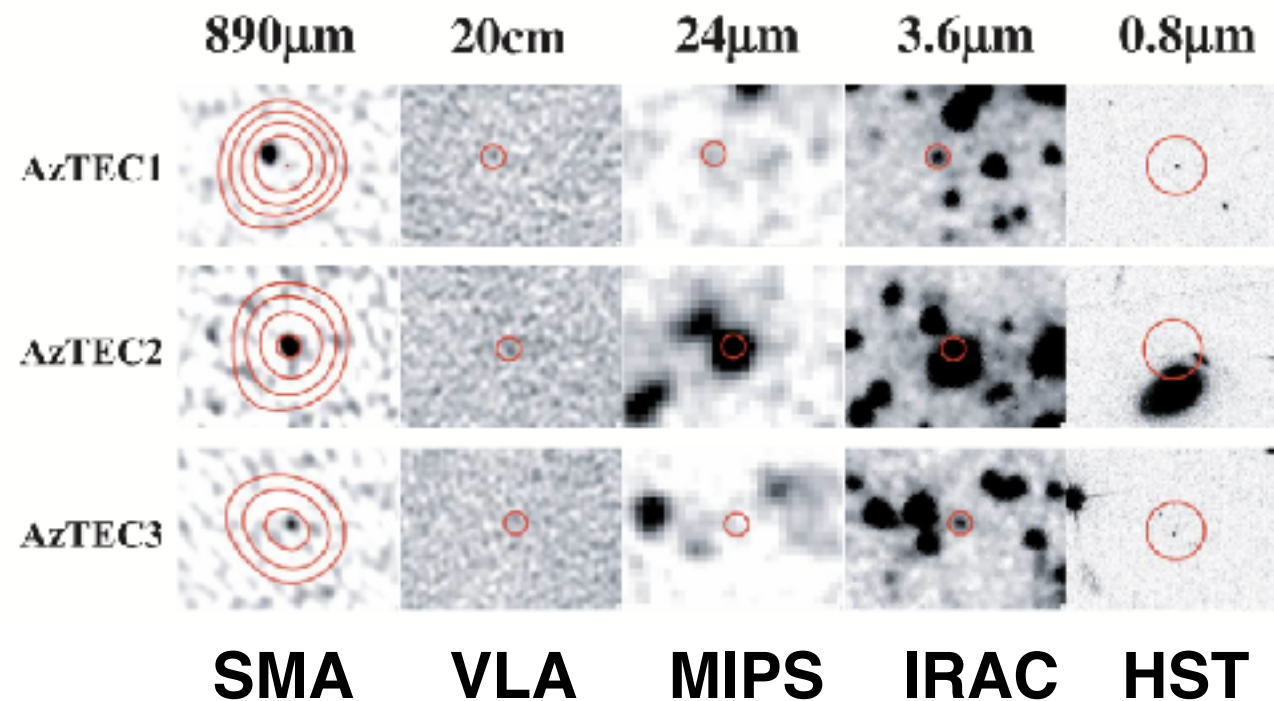
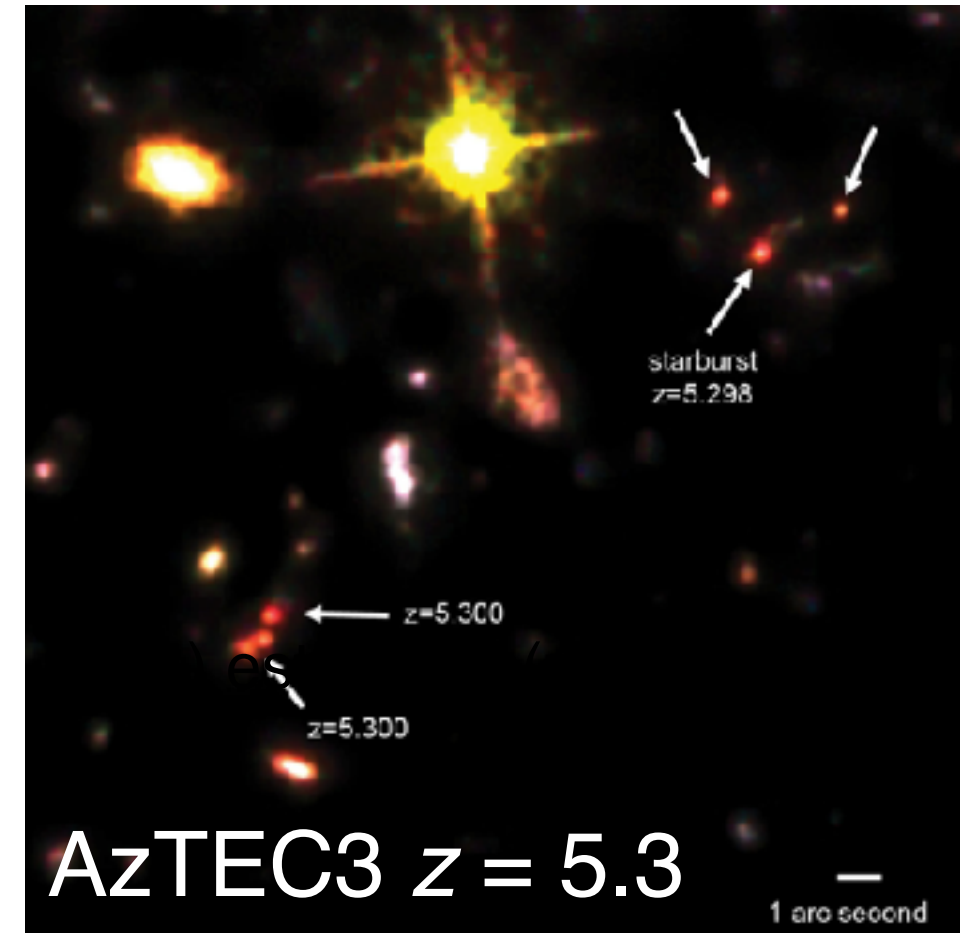
Younger *et al.* ApJ 2007, Smolcic *et al.* A&A 2012

Keck



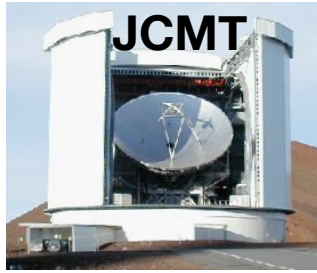
3) Obtain Keck spectroscopy

Capak *et al.* Nature 2011





# Spectroscopic redshifts of SMGs: **Better**

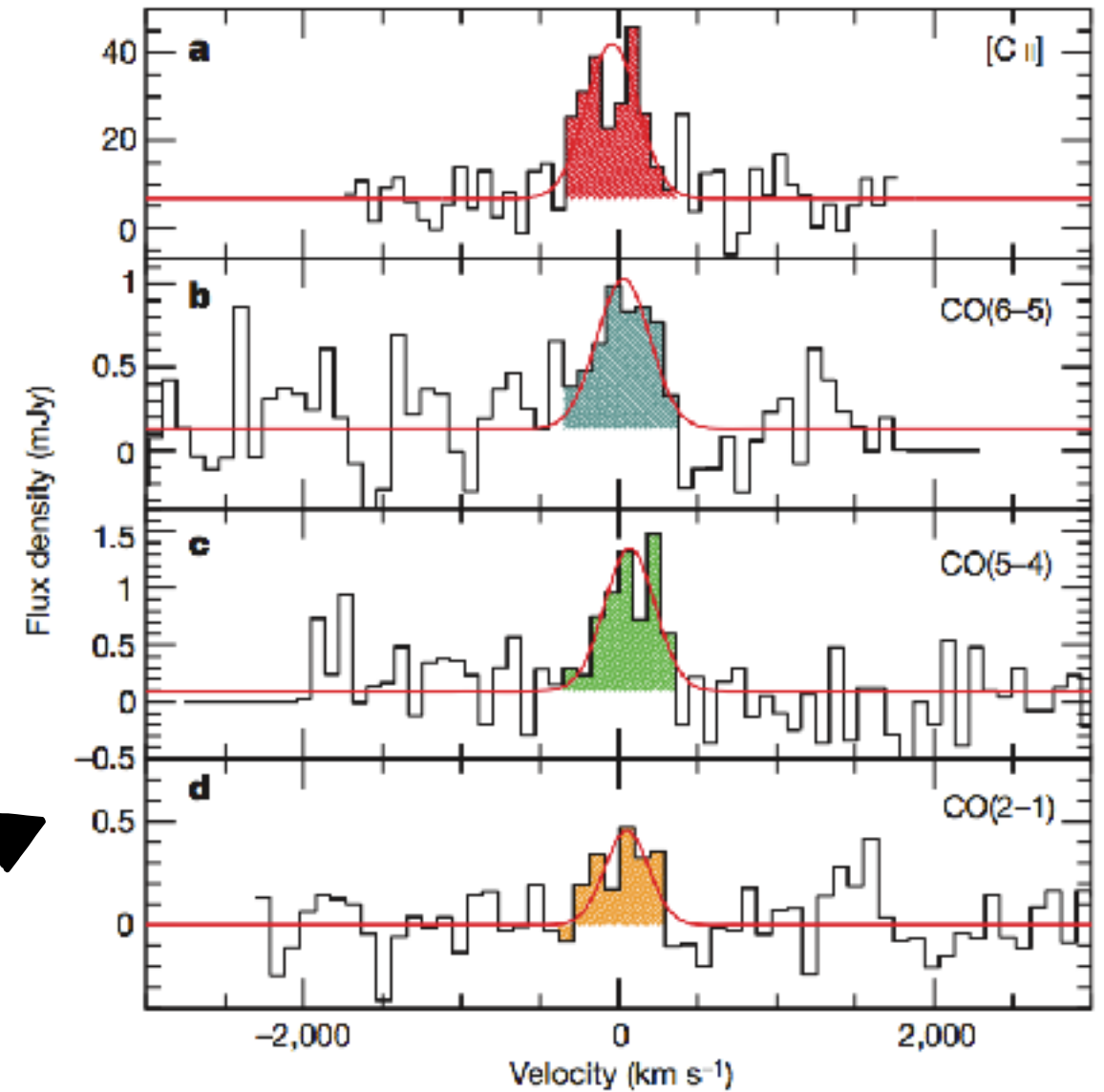
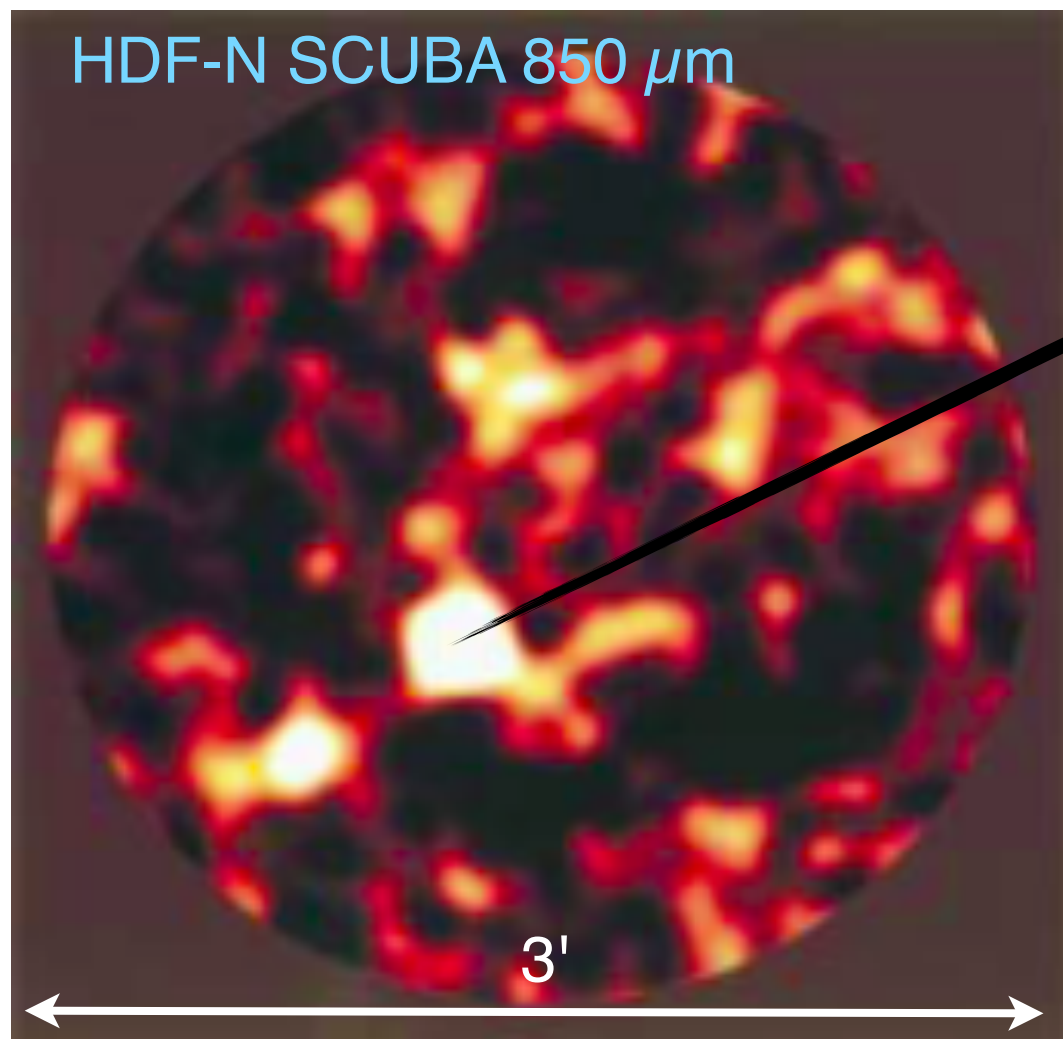


1) Blank field submm survey

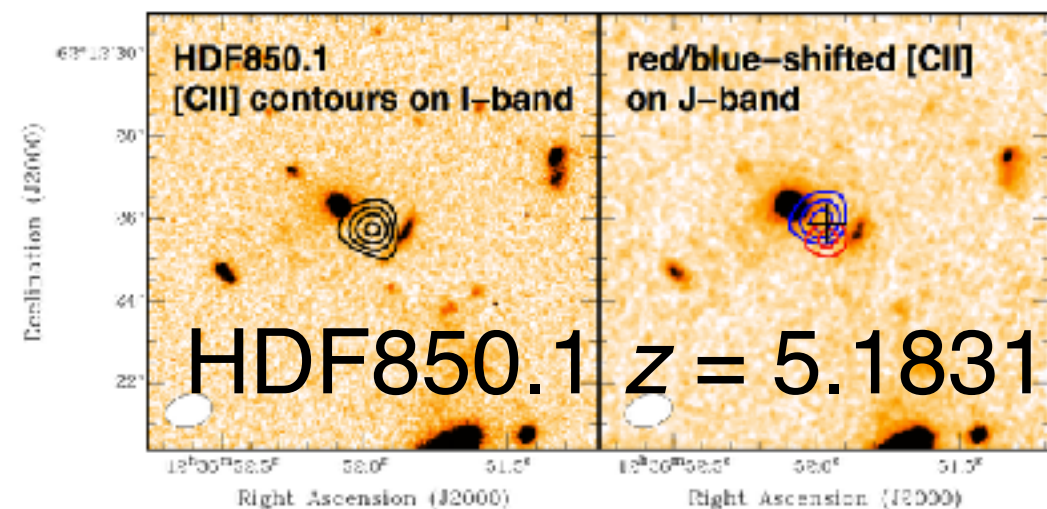


2) Followup with mm spectroscopy, directly obtain redshifts from the dust

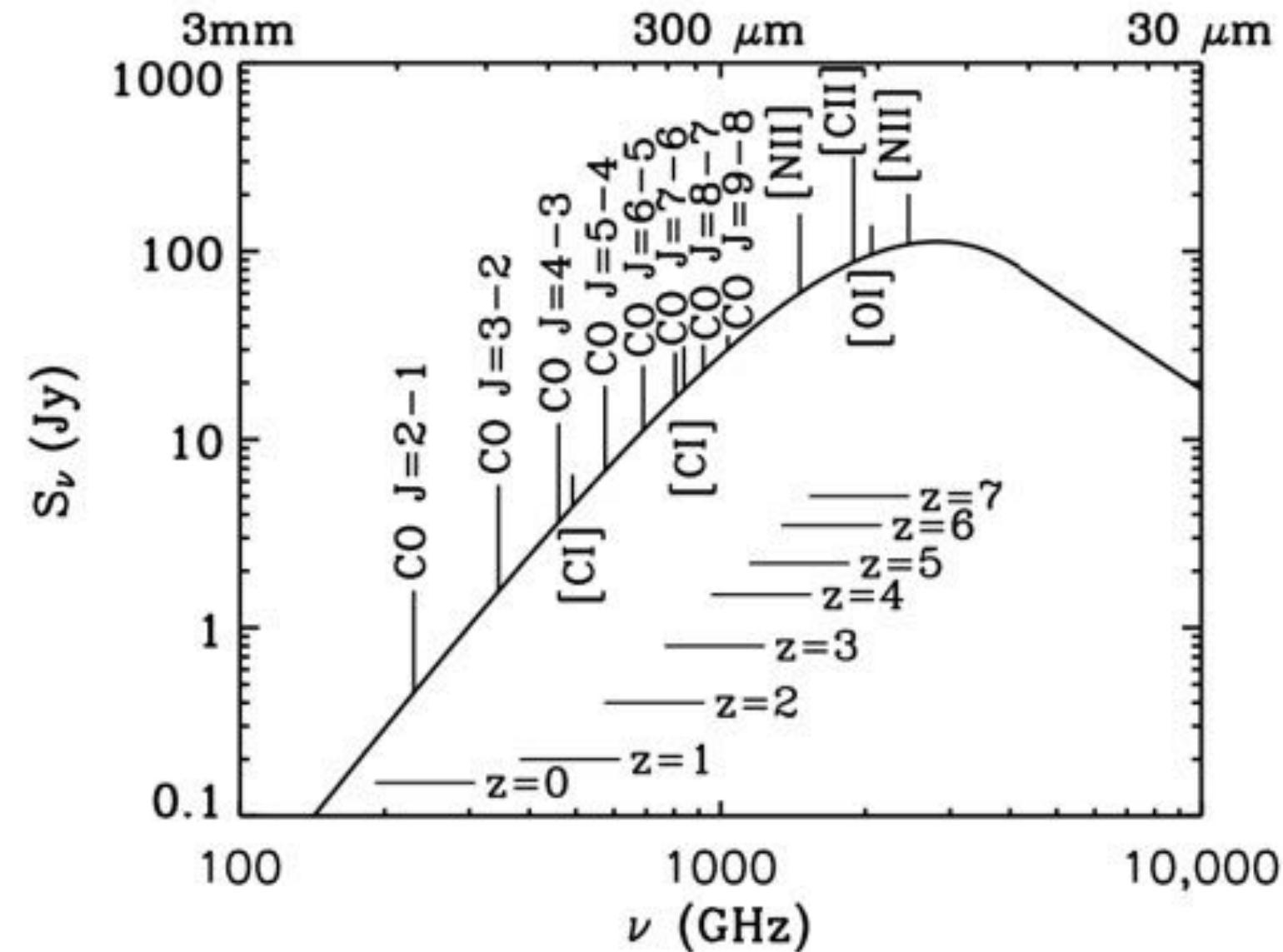
Hughes *et al.* Nature 1998



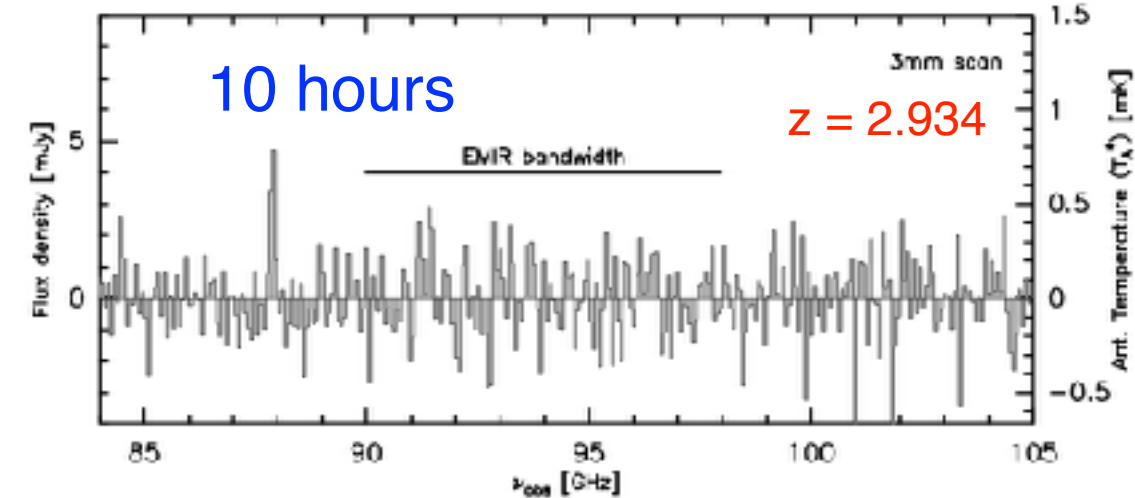
Walter *et al.* Nature 2012 100 hours (!) with PdBI



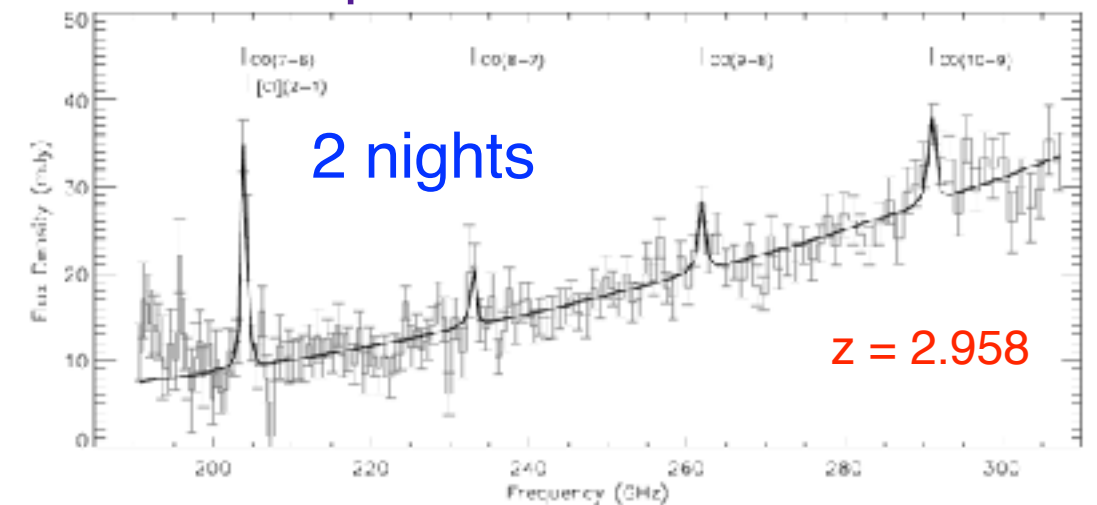
# spectroscopic redshifts with carbon monoxide



IRAM 30m/EMIR Weiss et al. 2009



CSO/Z-Spec Scott et al. 2011

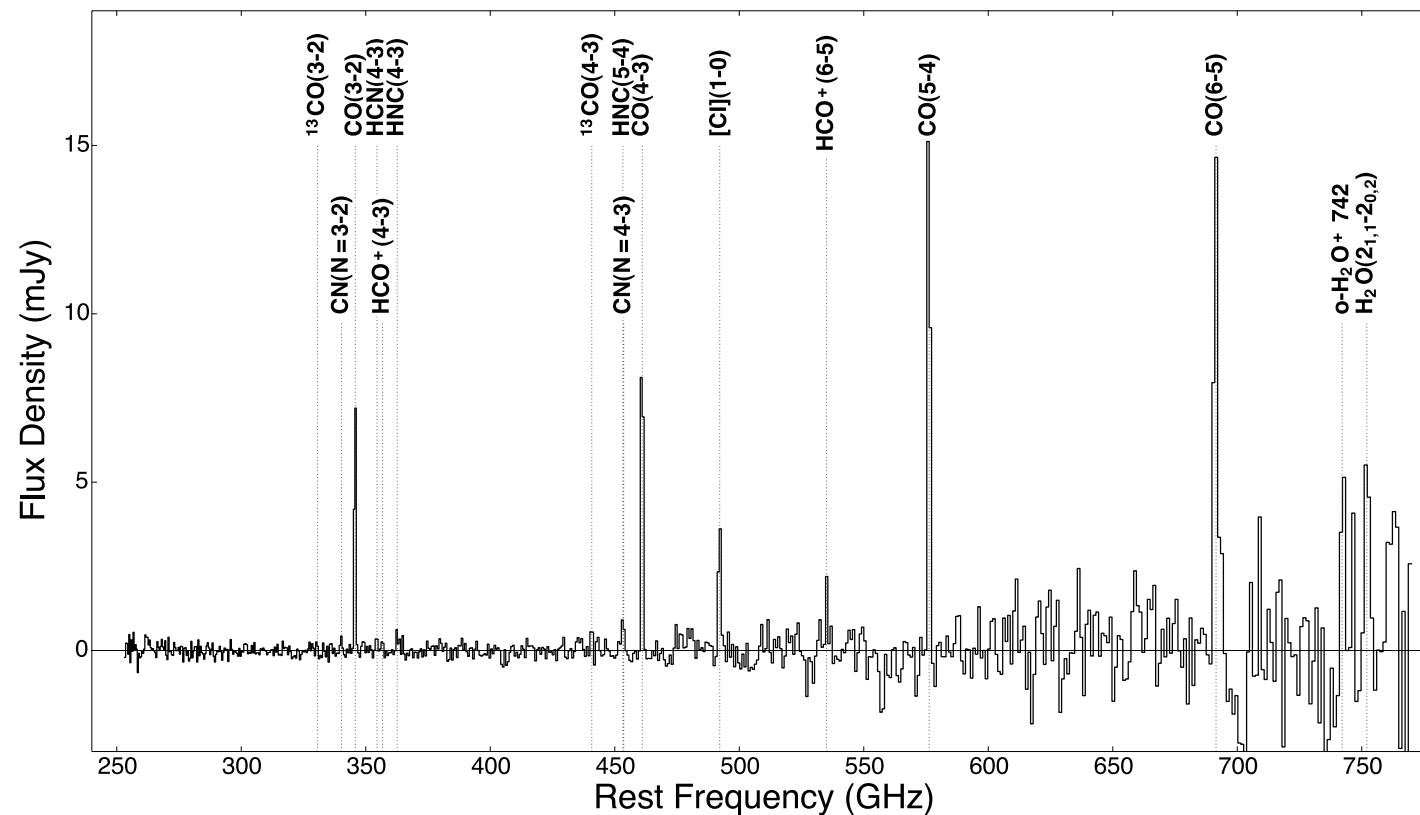


- Most abundant molecule after  $H_2$
- $L_{CO} / L_{FIR} \sim 10^{-5}$
- CO ladder at 115 GHz spacing  $\rightarrow$  2 lines gives a redshift
- CO traces molecular gas  $\rightarrow$  star formation potential
- line width gives dynamical mass
- excitation ladder constrains conditions of ISM



# Blind CO Redshifts

ALMA composite CO spectrum of SPT sources from Spilker et al. 2014



>200 SMGs (mostly lensed) now have redshifts derived from CO

- **IRAM/EMIR: 1st CO redshift, 10 hours**; Weiss *et al.* 2009; **11 *Planck* sources**; Canameras *et al.* 2015
- **CSO/Z-Spec: 5 *Herschel* sources at  $0.9 < z < 3$  including SDP81 (~10hrs each)**; Negrello *et al.* 2010 *Science*, Lupu *et al.* 2012; **APEX/Z-Spec: ~5 *Herschel* + ~3 SPT sources**
- **GBT/zspectrometer: 11 *Herschel* sources  $2.1 < z < 3.5$** ; Harris *et al.* 2012
- **PdBI/NOEMA: 100 hours HDF850.1  $z=5.2$** ; Walter *et al.* 2012 *Nature*,
- **CARMA: >15 *Herschel* sources including FLS3  $z=6.3$** ; Riechers *et al.* 2013 *Nature*, Wardlow *et al.* 2013
- **ALMA: >70 SPT sources  $1.8 < z < 6.9$ , 10 minutes each**; Weiss *et al.* 2013, Vieira *et al.* 2013 *Nature*, Strandet *et al.* 2016, Strandet *et al.* 2017; + ***Herschel* /SPIRE sources**
- **LMT/RSR: ~20 sources**, e.g. Geach *et al.* 2015, Zavala *et al.* 2015, Harrington *et al.* 2016, etc.





# SPT

## The South Pole Telescope

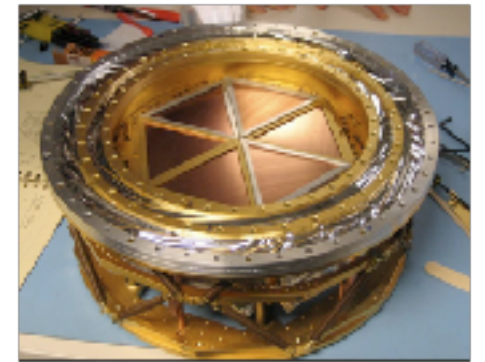


### Telescope

- 10 meter off-axis sub/mm telescope
- located at the geographic south pole
- 1 deg<sup>2</sup> field of view
- ~1' beams
- optimized for fine scale anisotropy measurements

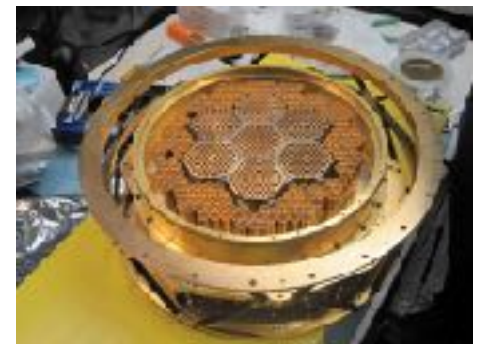
### SPT-SZ Camera (1st Generation):

- 2007 – 2011
- 960 pixel mm camera, 1 deg<sup>2</sup> FOV
- 1.4, 2.0, and 3.0 mm
- completed 2500 deg<sup>2</sup>
- 18  $\mu$ K-arcmin depth, ~1 mJy



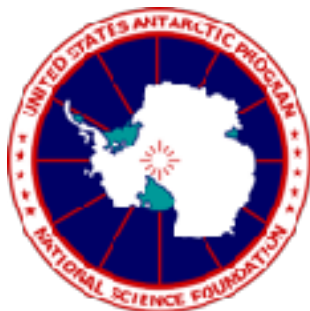
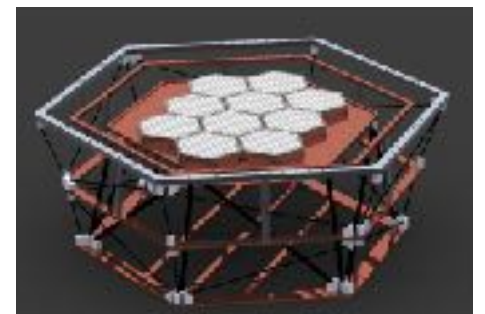
### SPT-pol Camera (2nd Generation):

- 2012 – 2015
- 1600 detector mm camera, 1 deg<sup>2</sup> FOV
- 2 and 3 mm + polarization
- currently surveying 500 deg<sup>2</sup>
- 4.5  $\mu$ K-arcmin depth



### SPT-3G Camera (3rd Generation):

- 2016 – 2020
- 15k detector mm camera, 2.4 deg<sup>2</sup> FOV
- 1.4, 2, 3 mm + polarization
- planned 2500 deg<sup>2</sup> x8 deeper
- 2.5  $\mu$ K-arcmin depth

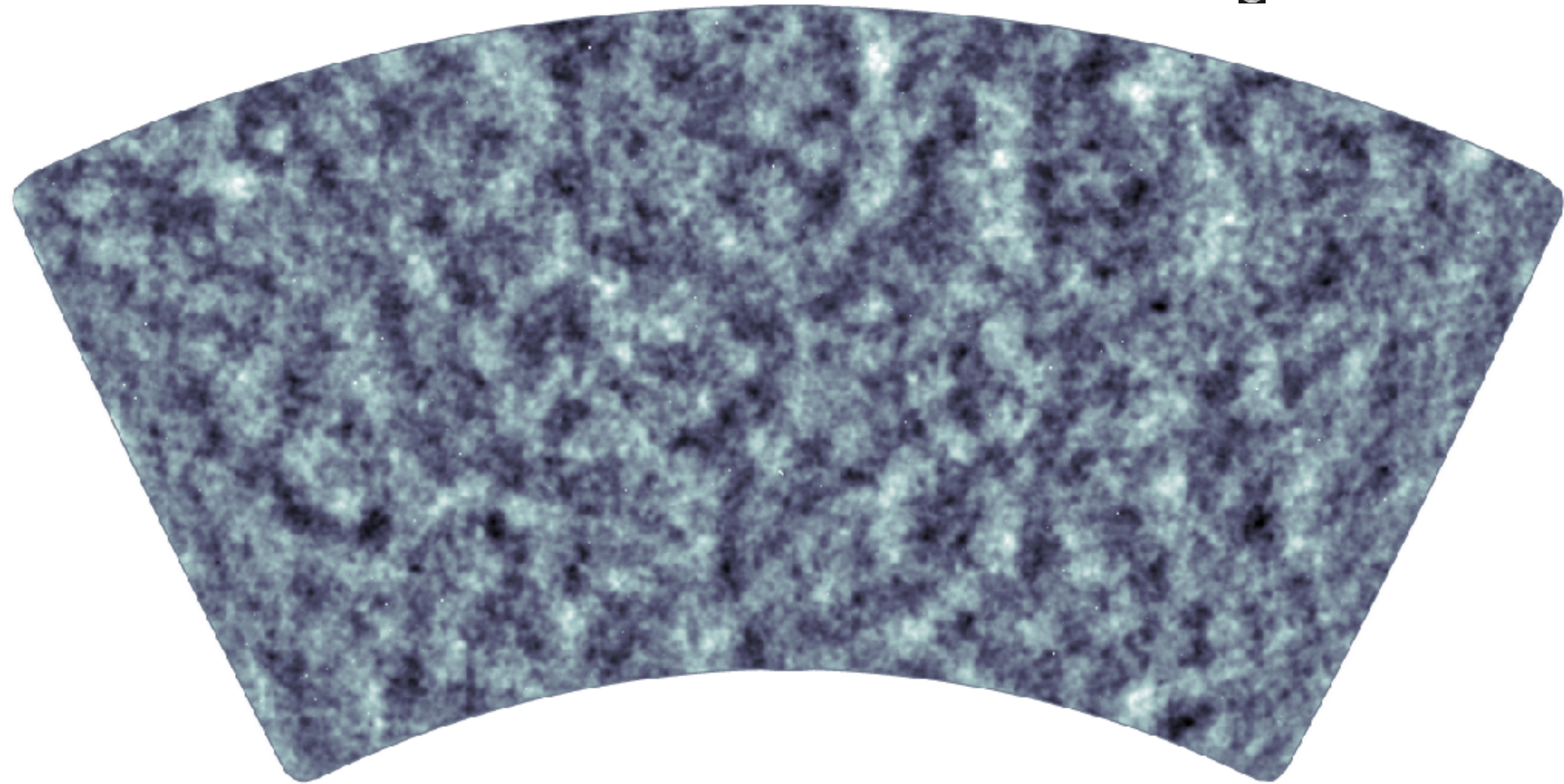




# South Pole Telescope

500 deg<sup>2</sup> survey at 150 GHz with arcminute resolution

full moon for scale



# South Pole Telescope

## 2 mm data

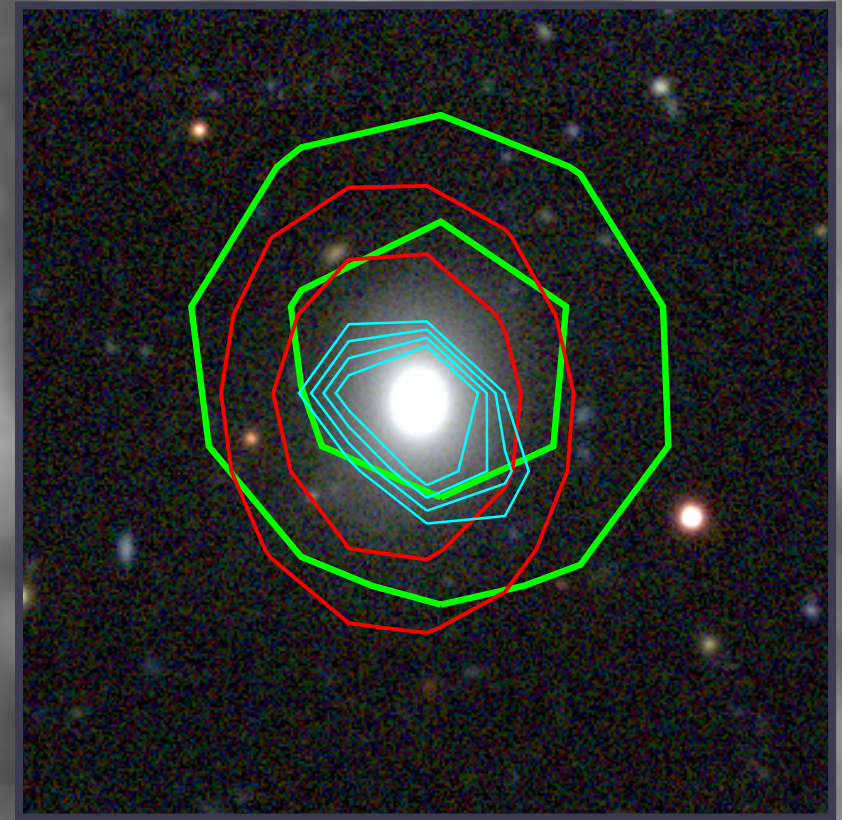




# South Pole Telescope

## 2 mm data

Majority of the SPT sources are high redshift AGN with the jets pointed at us. They have radio, x-ray, and sometimes gamma-ray counterparts.



# South Pole Telescope

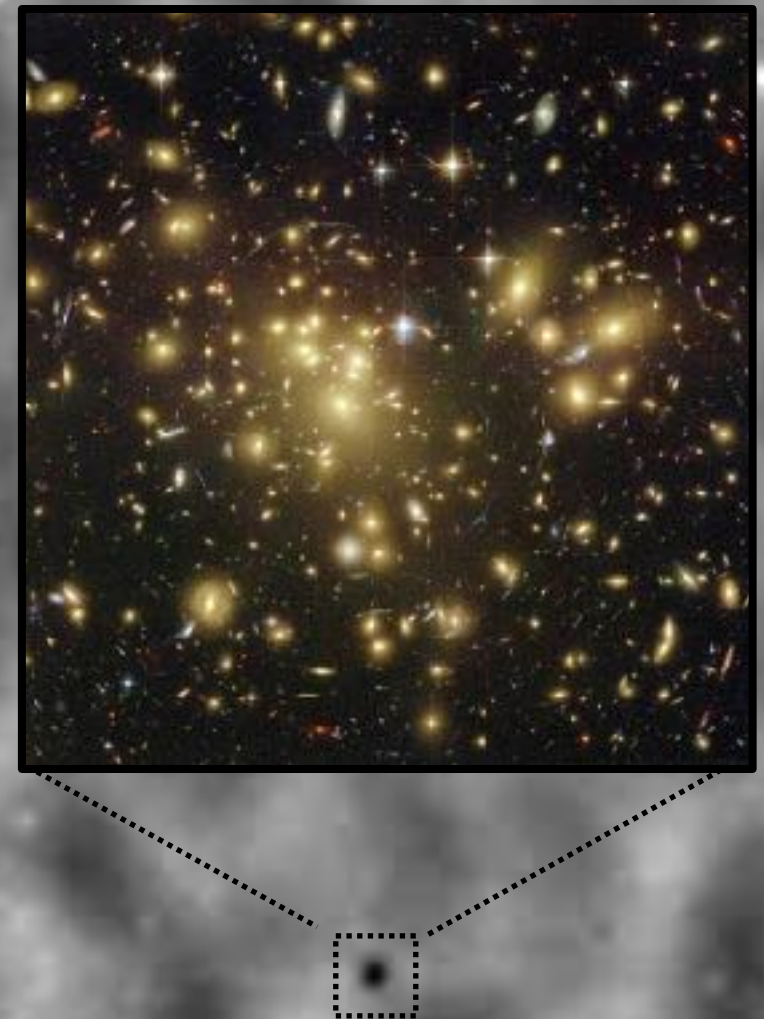
## 2 mm data

Galaxy Clusters detected with the  
Sunyaev-Zeldovich effect

“Shadows” in the cosmic microwave  
background from inverse compton  
scattering

Use ‘em to measure Dark Energy

Probes the 2nd half of the history of  
the universe



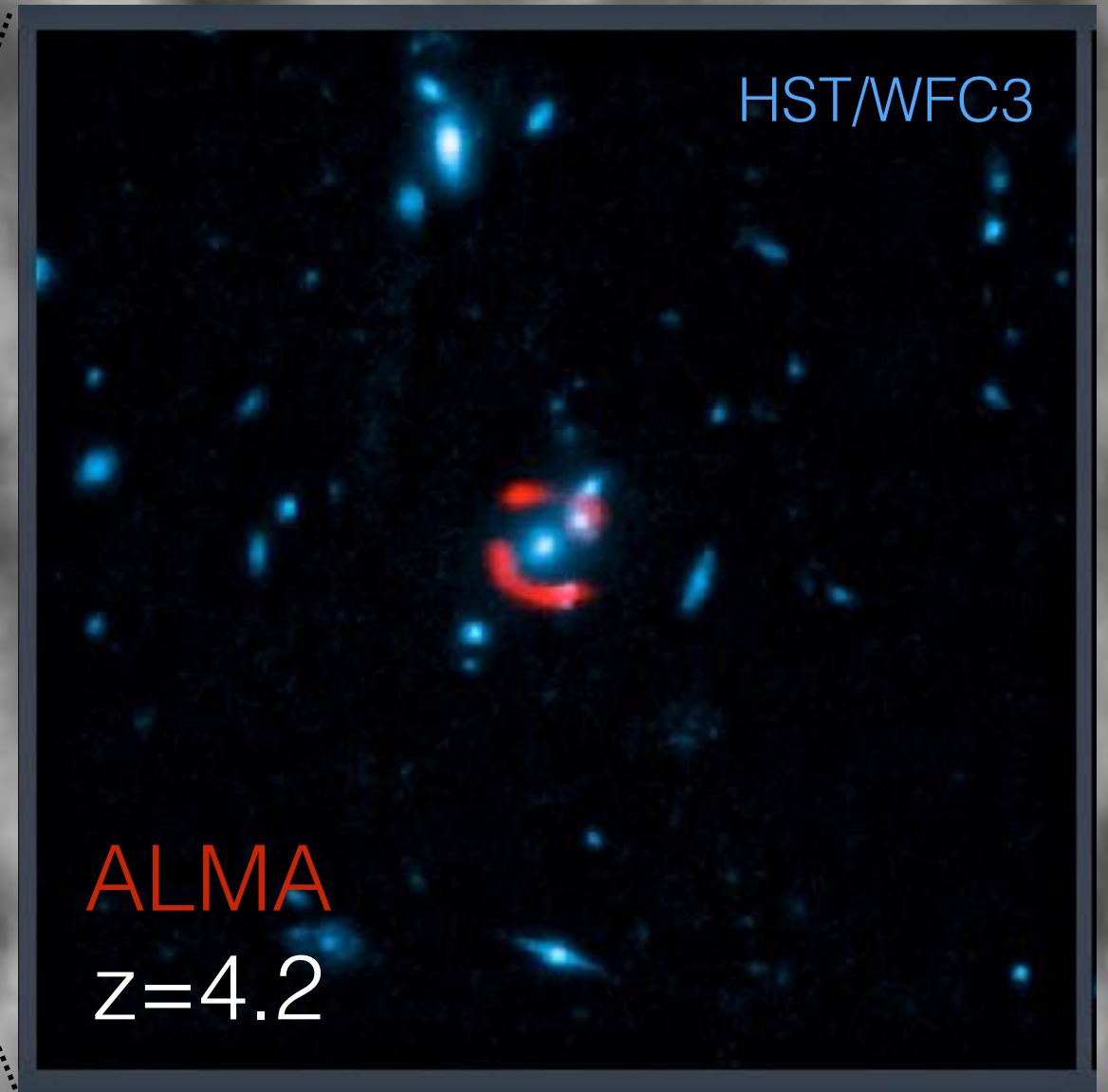


# South Pole Telescope

## 2 mm data

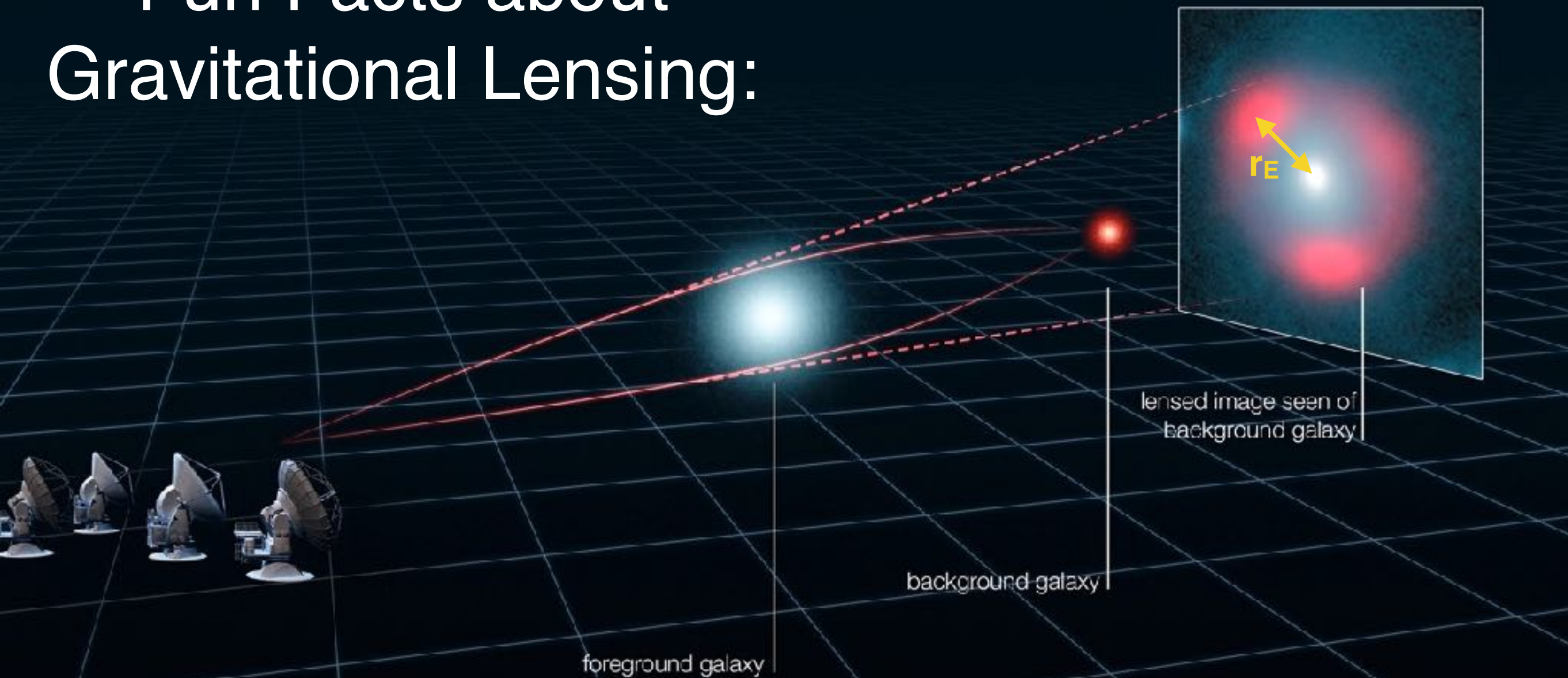
high redshift  
strongly lensed  
dusty starforming  
galaxies

Use gravitational lensing  
as a cosmic telescope to  
study the first galaxies  
and directly image dark  
matter





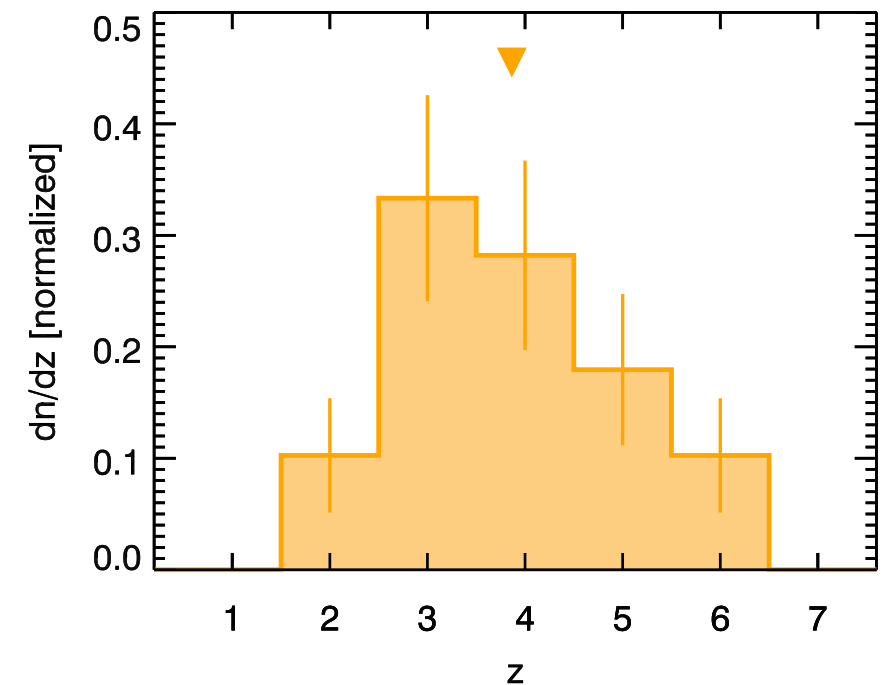
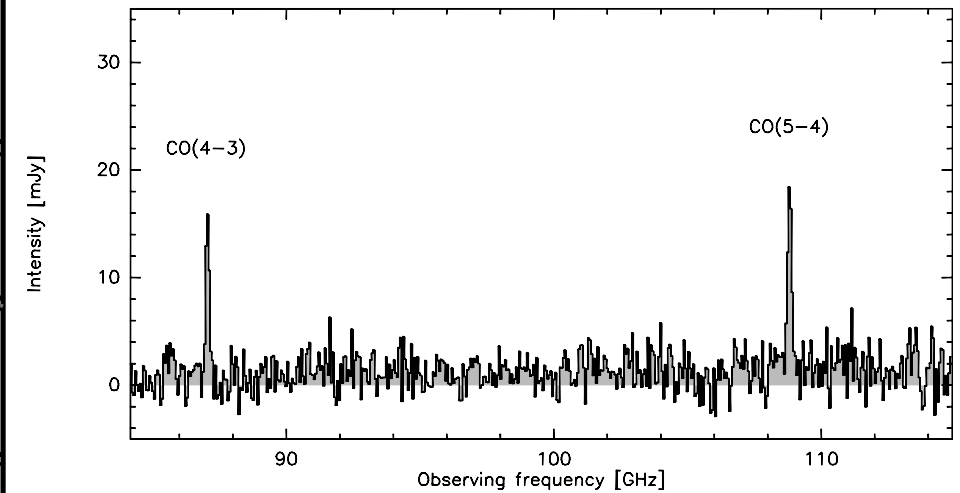
# Fun Facts about Gravitational Lensing:



- Typical magnification  $\sim 10$
- Lensing preserves surface brightness
- Lensing is achromatic
- Measure an Einstein radius and you have measured the mass of the lens
- The lensing mass is  $\sim 1/2$  DM and  $\sim 1/2$  baryons
- Probability of lensing increases with source redshift, but flattens out above  $z > 1$
- cluster = larger cross section ; galaxy = more opportunities for lensing
- $\sim 1/200$  massive early-type galaxies is a strong lens

# CO redshift searches with ALMA Band 3

SPT0345-47 @  $z=4.296$

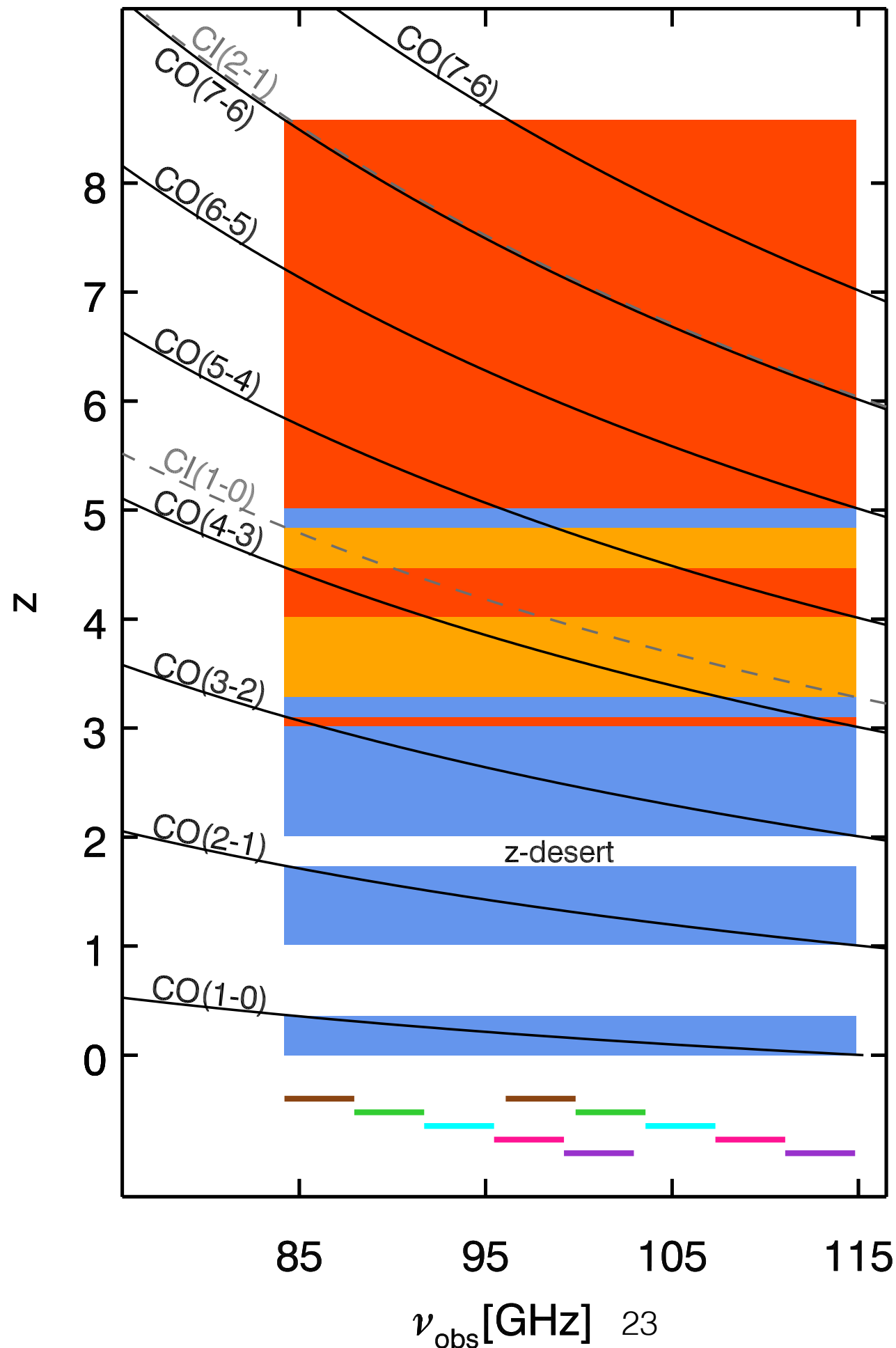


$\langle z \rangle = 4.1$

82 observed 67 confirmed (so far)

$1.8 < z < 6.9$

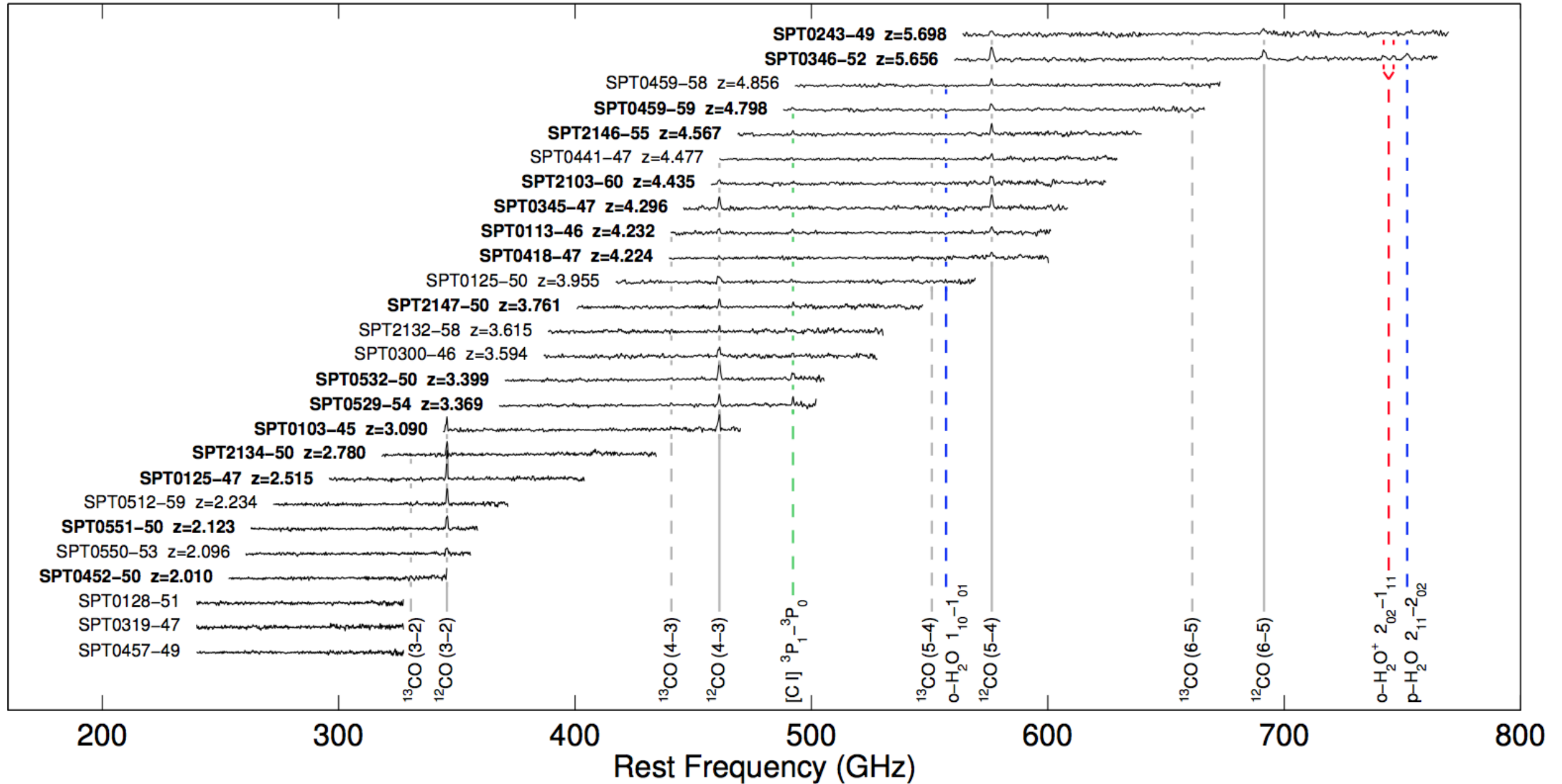
35 sources at  $z > 4$





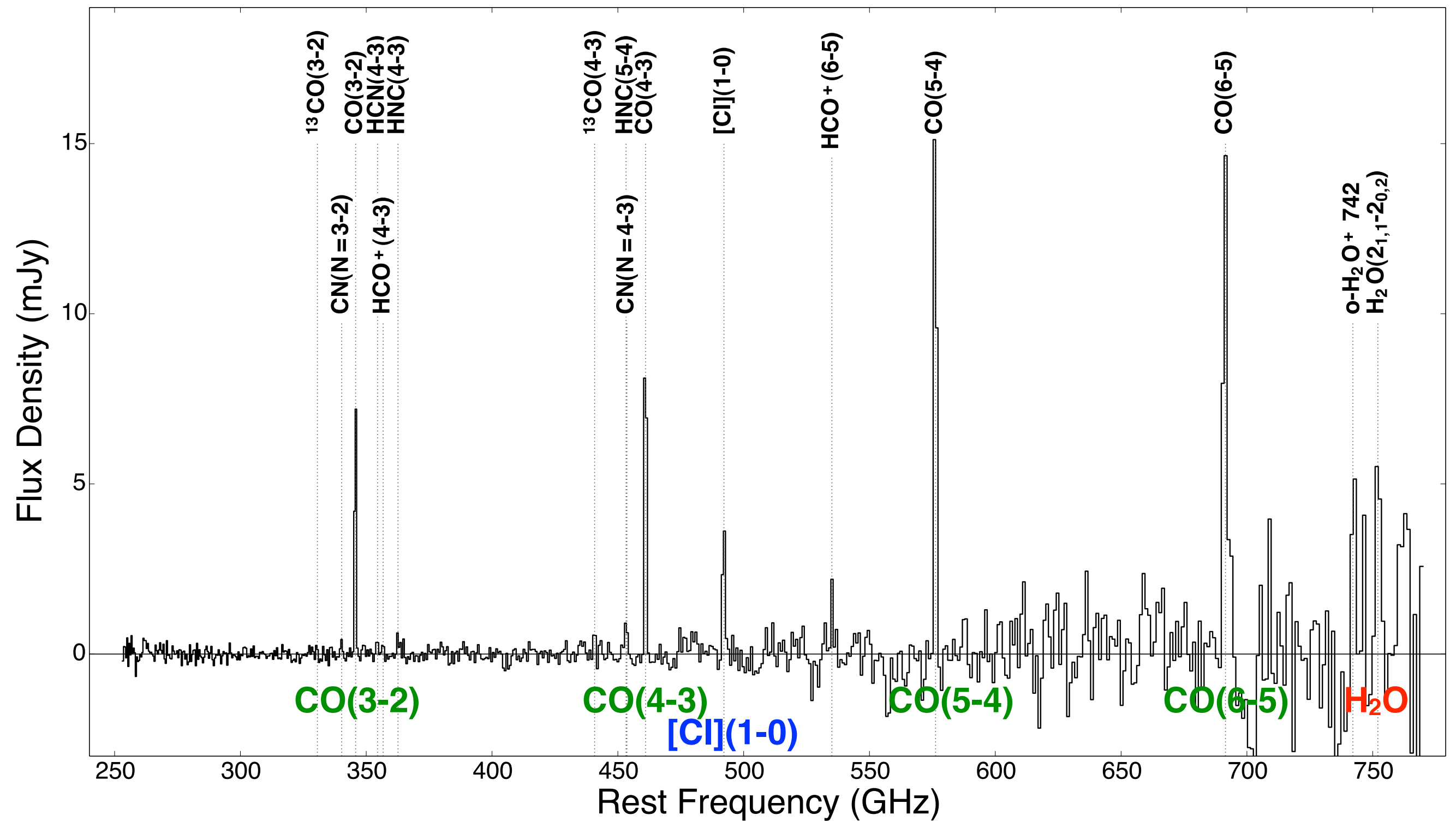
# Spectroscopic redshift survey with ALMA

ALMA Cycle 0 Band 3  
100 GHz compact configuration  
26 sources  
5 tunings in the 3 mm band  
~20 minutes per source



Vieira *et al.* 2013 Nature

# Composite CO spectrum



$T_{\text{EX,CO}} < 50\text{K}$

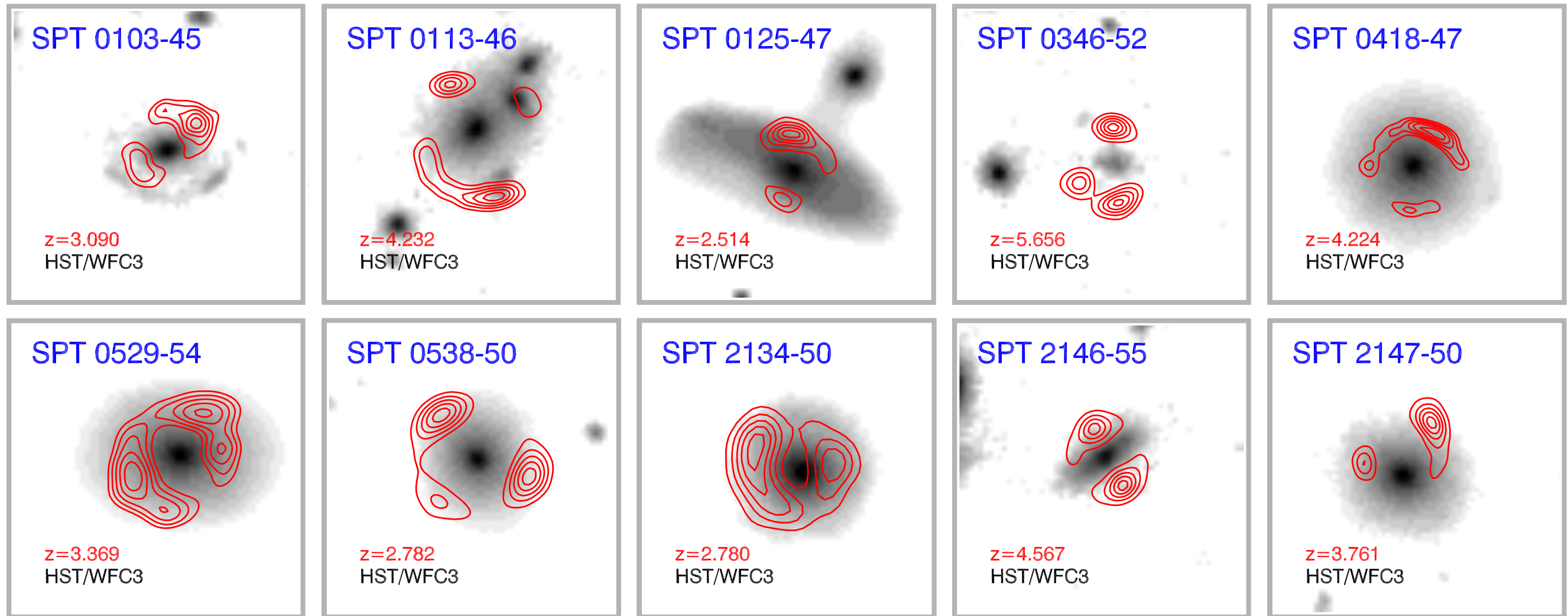
$1 < \tau_{\text{CO}(1-0)} < 10$

Spilker *et al.* ApJ 2014



# ALMA Cycle 0 Band 7 350 GHz

## 2 minute snapshots with 16 antennas



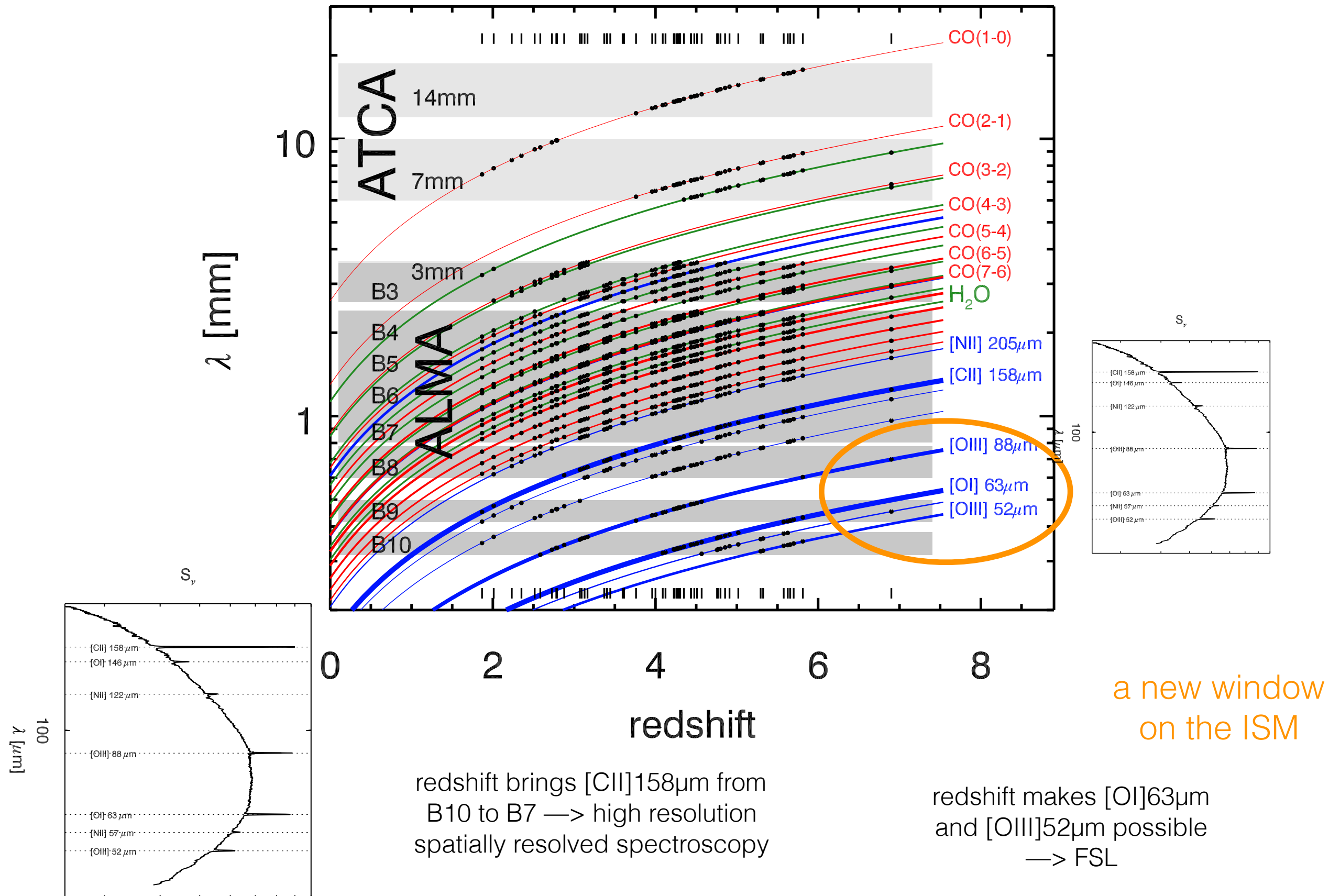
8" x 8" boxes

— = 1 orbit HST/WFC3 imaging  
— = 2 minute ALMA 350 GHz snapshot

# Future line line studies:

now: CO, H<sub>2</sub>O, HCN, OH, ...

future: HD, CH, ... ?



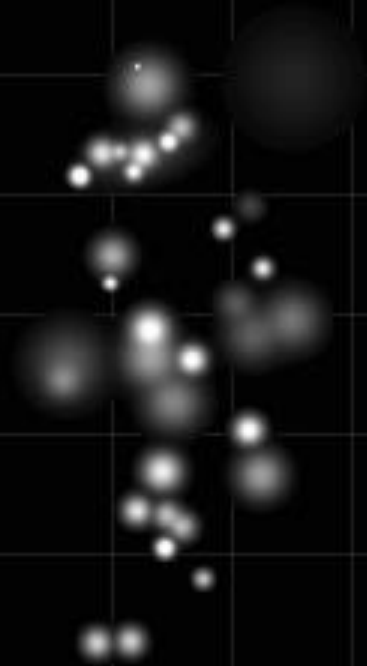


ALMA  
SDP 81  
 $z=3.042$



Strong lensing allows us to resolve galaxies

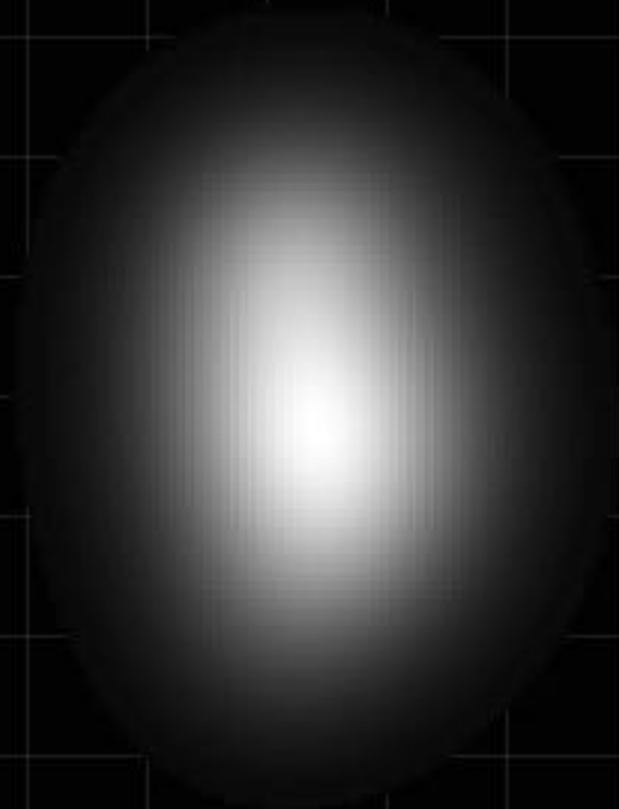
SDP81 lensing reconstruction



ALMA + gravitational lens



ALMA

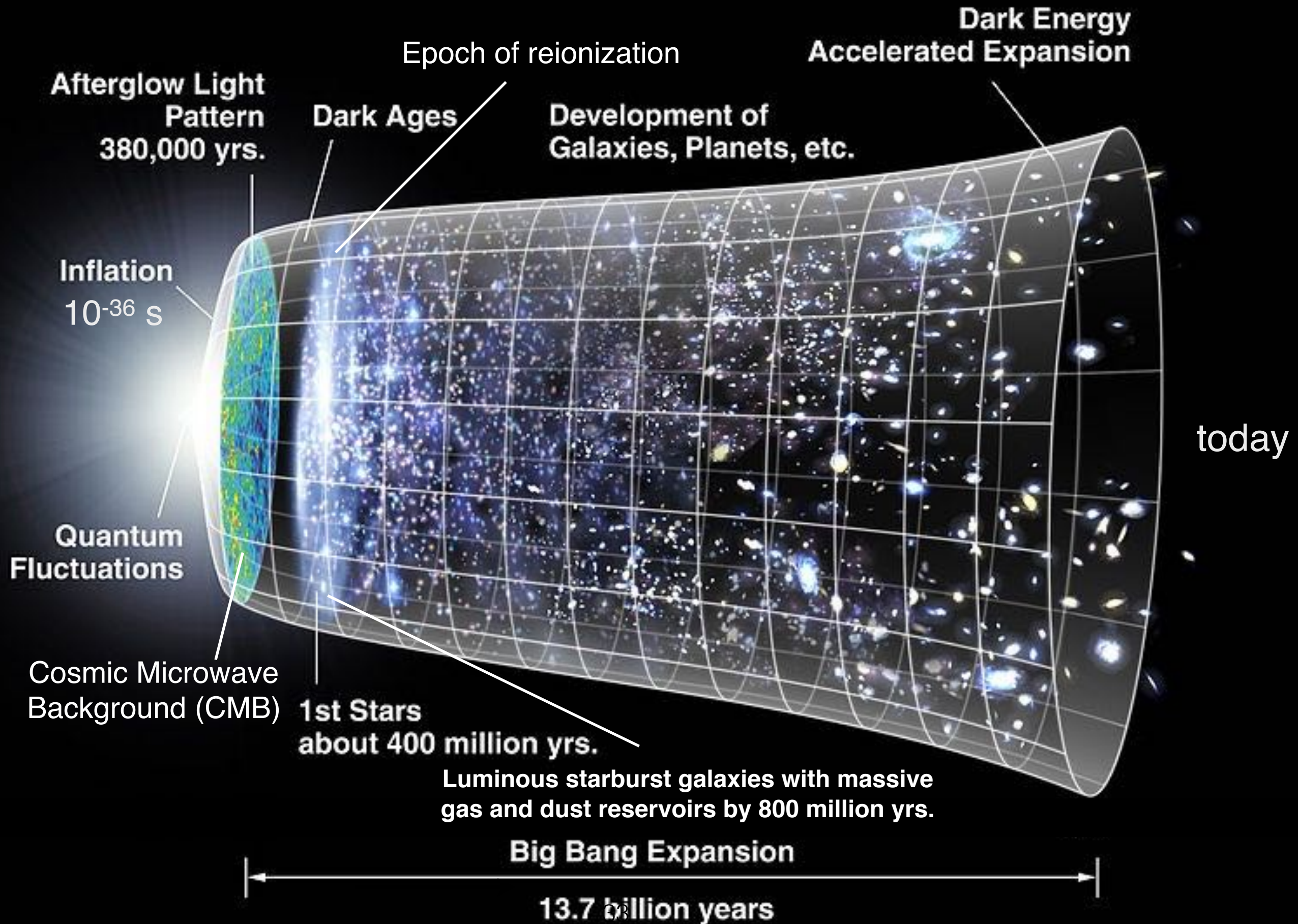


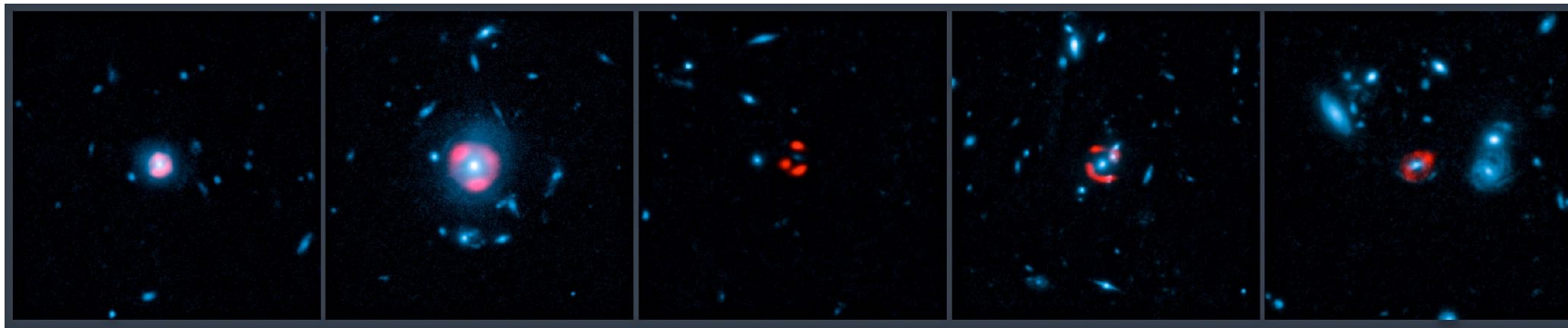
Hubble Space Telescope

Strong lensing = Cosmic Microscope

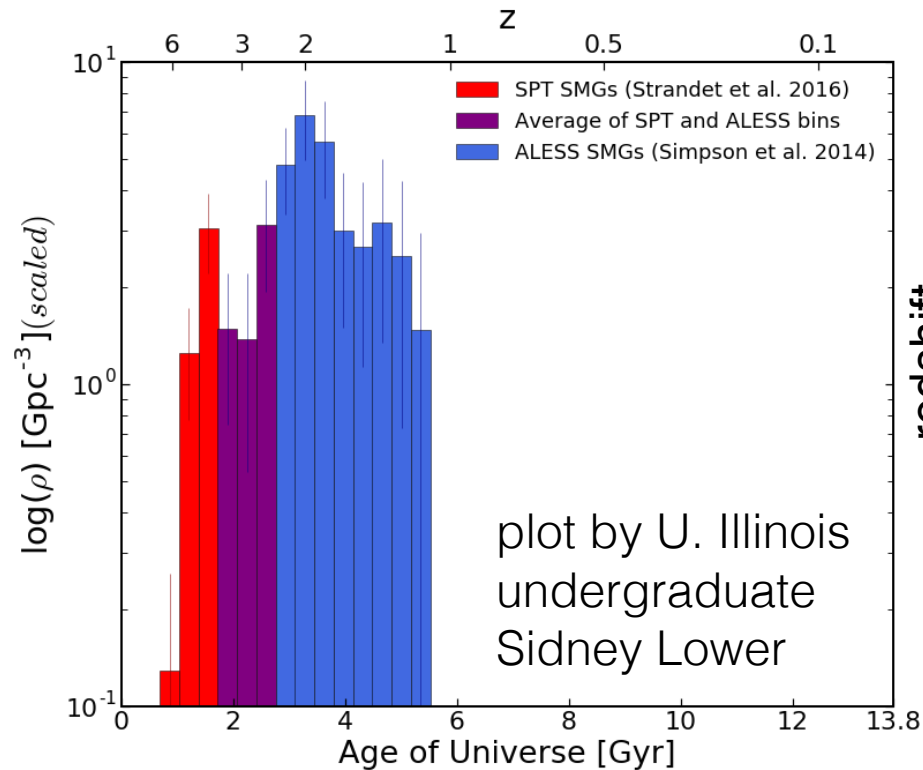


# Brief History of the Universe

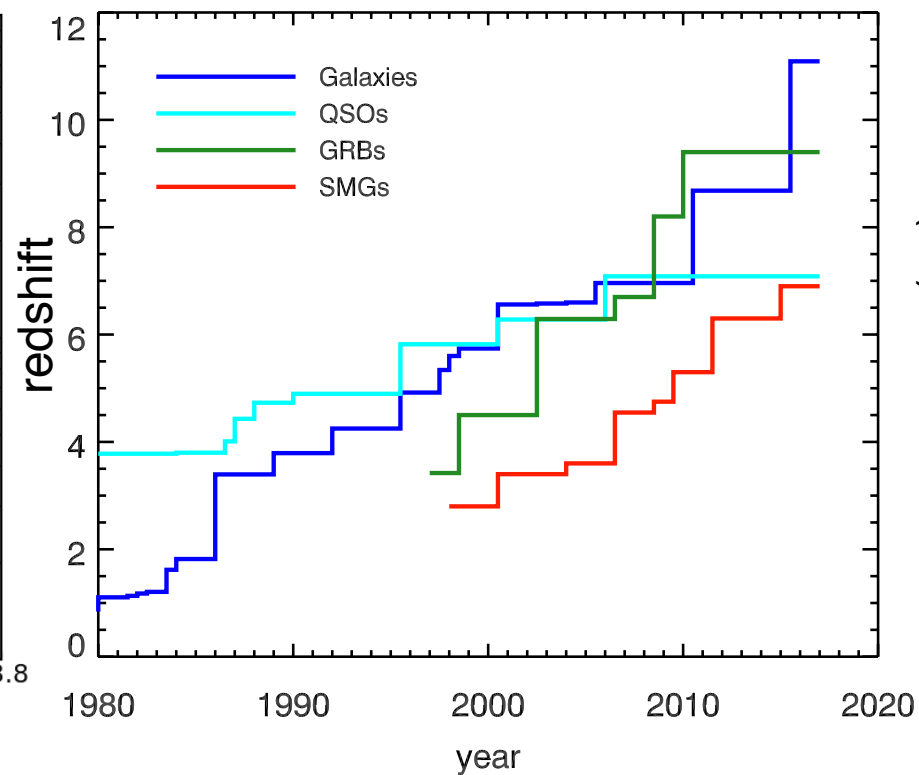




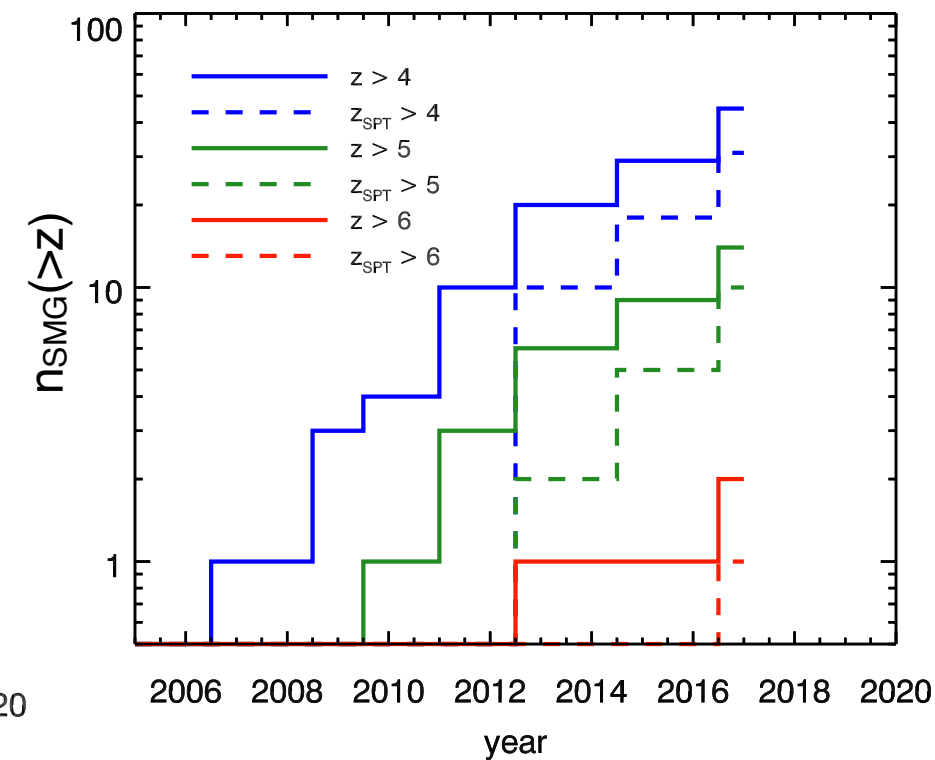
space density of SMGs



Most distant astronomical object



$N_{\text{SMG}}(>z)$  v. year



- 82 with  $S_{870\mu\text{m}} > 25$  mJy from 2500 deg<sup>2</sup> SPT-SZ survey —> All have ALMA 3mm spectra. This is among the largest samples of lensed galaxies in the literature.
- 67 with confirmed and unambiguous spectroscopic redshifts (82% complete so far). This is among the highest spectroscopic completeness of any sample of high redshift galaxies
- $1.9 < z < 6.9$  ; median  $\langle z \rangle = 4.1$ ; 35 at  $z > 4$ , 11 at  $z > 5$ , highest  $z = 6.9$
- SPT has discovered 70% of dusty star forming galaxies at  $z > 4$





## Conclusions

- CMB experiments have made huge impacts in the fields of cosmology and astrophysics and will continue to do so into the next decade.
- SPT has constructed one of the most unique samples of high redshift galaxies and possibly the best sample for molecular studies.
- SPT-3G has deployed and is in commissioning. U. Illinois grad student Andrew Nadolski is the first season winter over.
- Many exciting years ahead with ALMA and JWST.