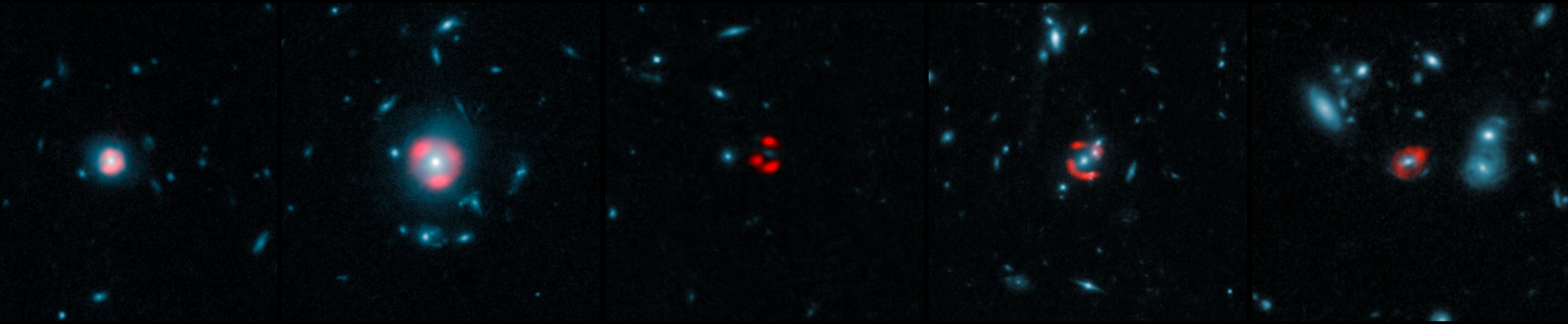
High redshift starburst galaxies revealed by SPT, ALMA, and gravitational lensing



Joaquin Vieira

Caltech

IAP

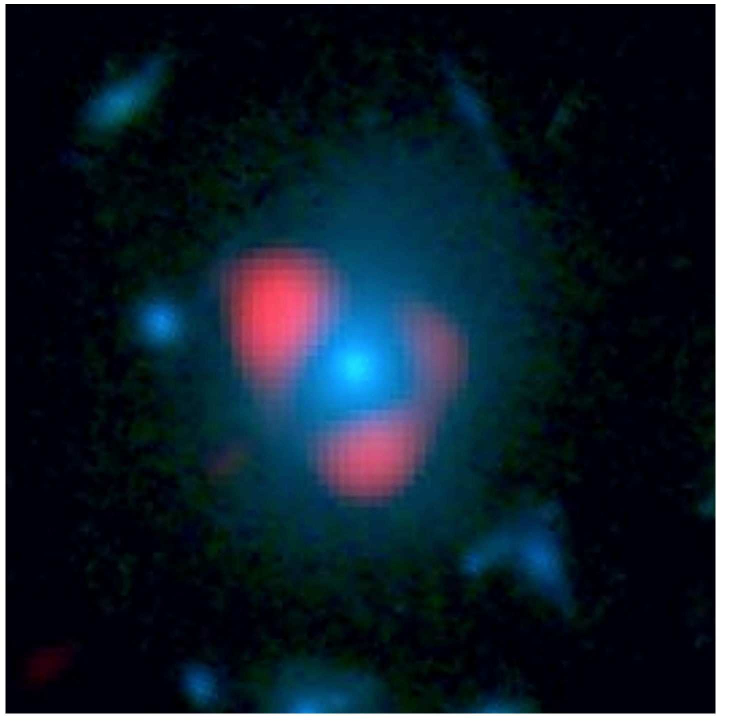
05 April 2013

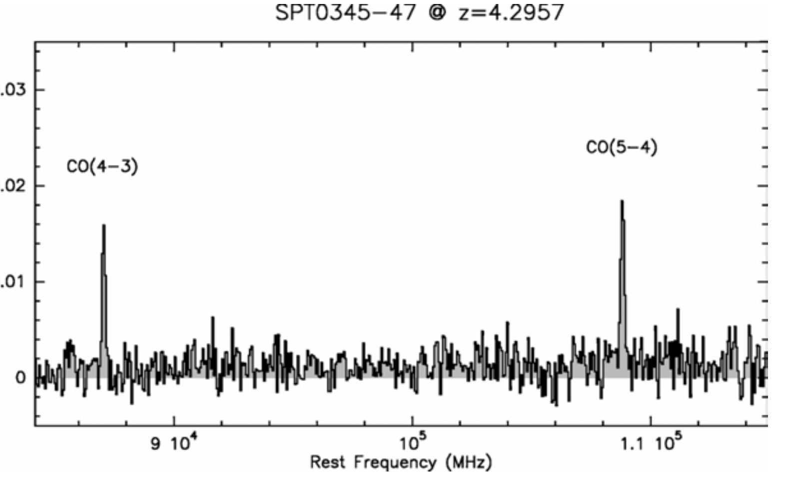
Things I am trying to understand:

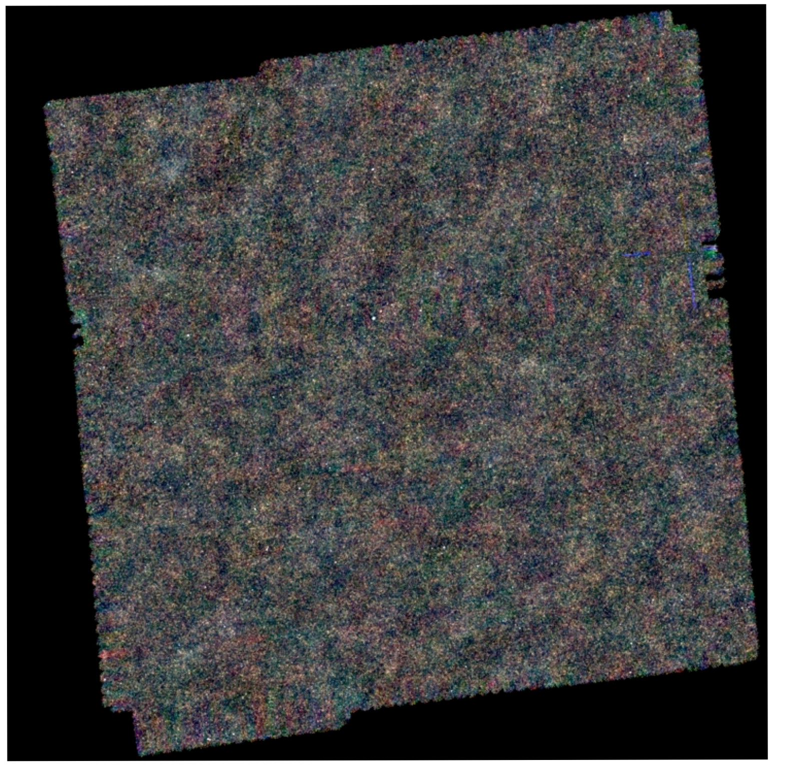
- What is the Universe made of? Why?
- How do the baryons, dark matter, and dark energy evolve with cosmic history?
- How does the universe emerge from the dark ages and what drives the epoch of reionization?

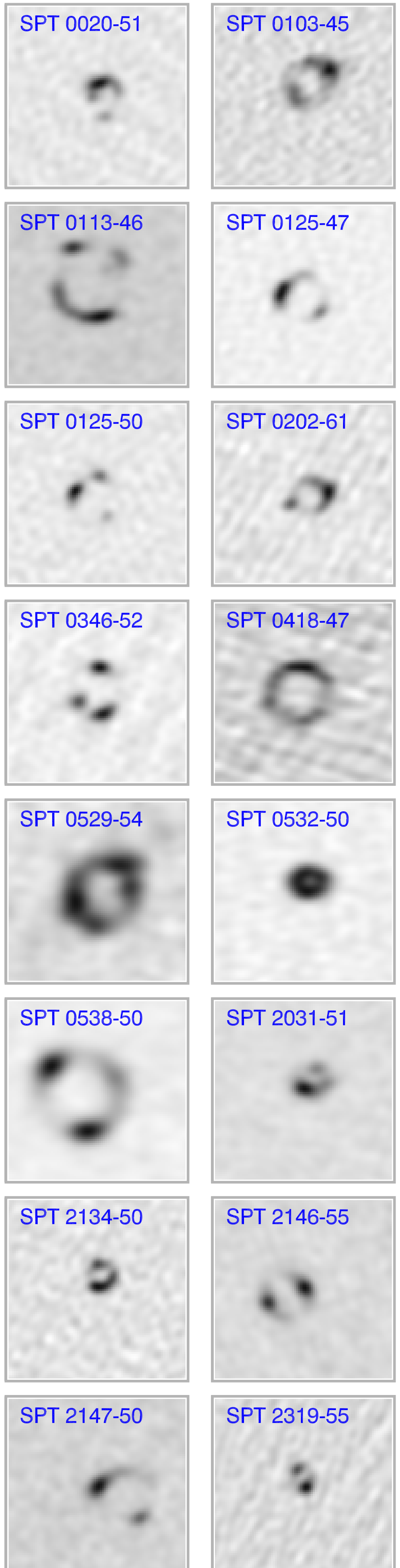
Topics I'm not going to discuss, but ask me about them if we talk:

- Measuring fluctuations in the CMB and CIB to constrain cosmology and the epoch of reionization
- Aggregate statistical studies of the CIB and the star formation history of the Universe
- SZ surveys
- Instrumentation







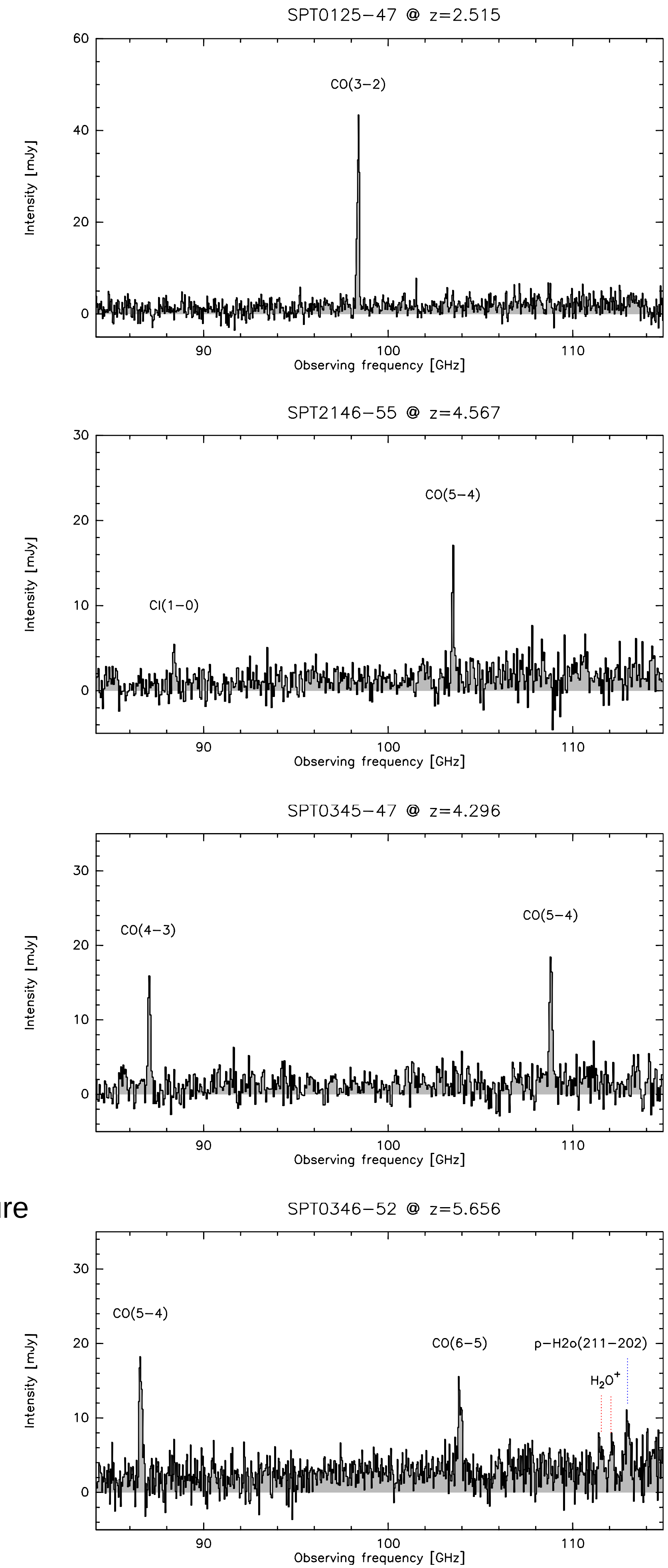


Outline:

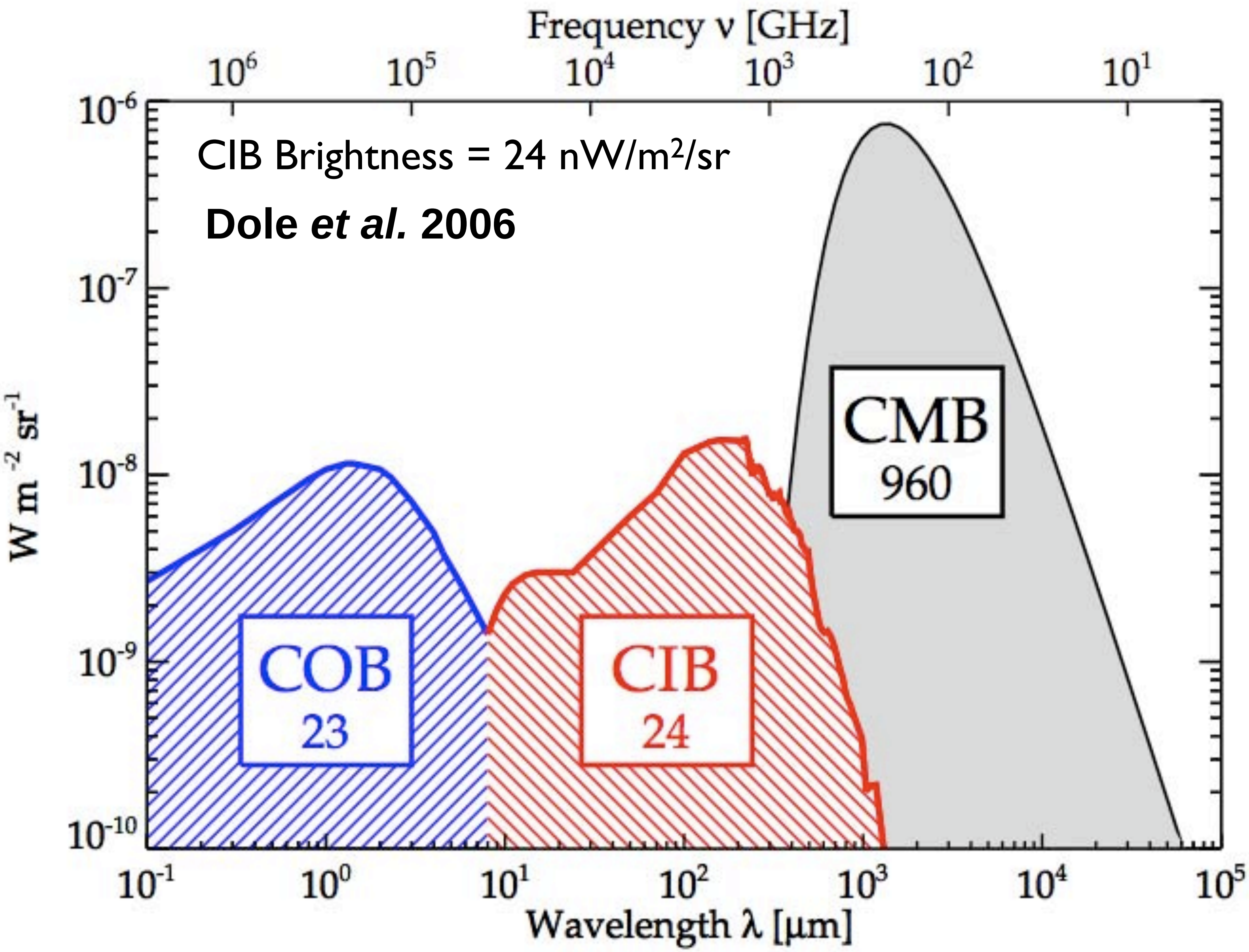
- background/overview
- Introduction to SPT
- ALMA data and results
- Redshift distribution of SMGs
- Future directions

Three Publications:

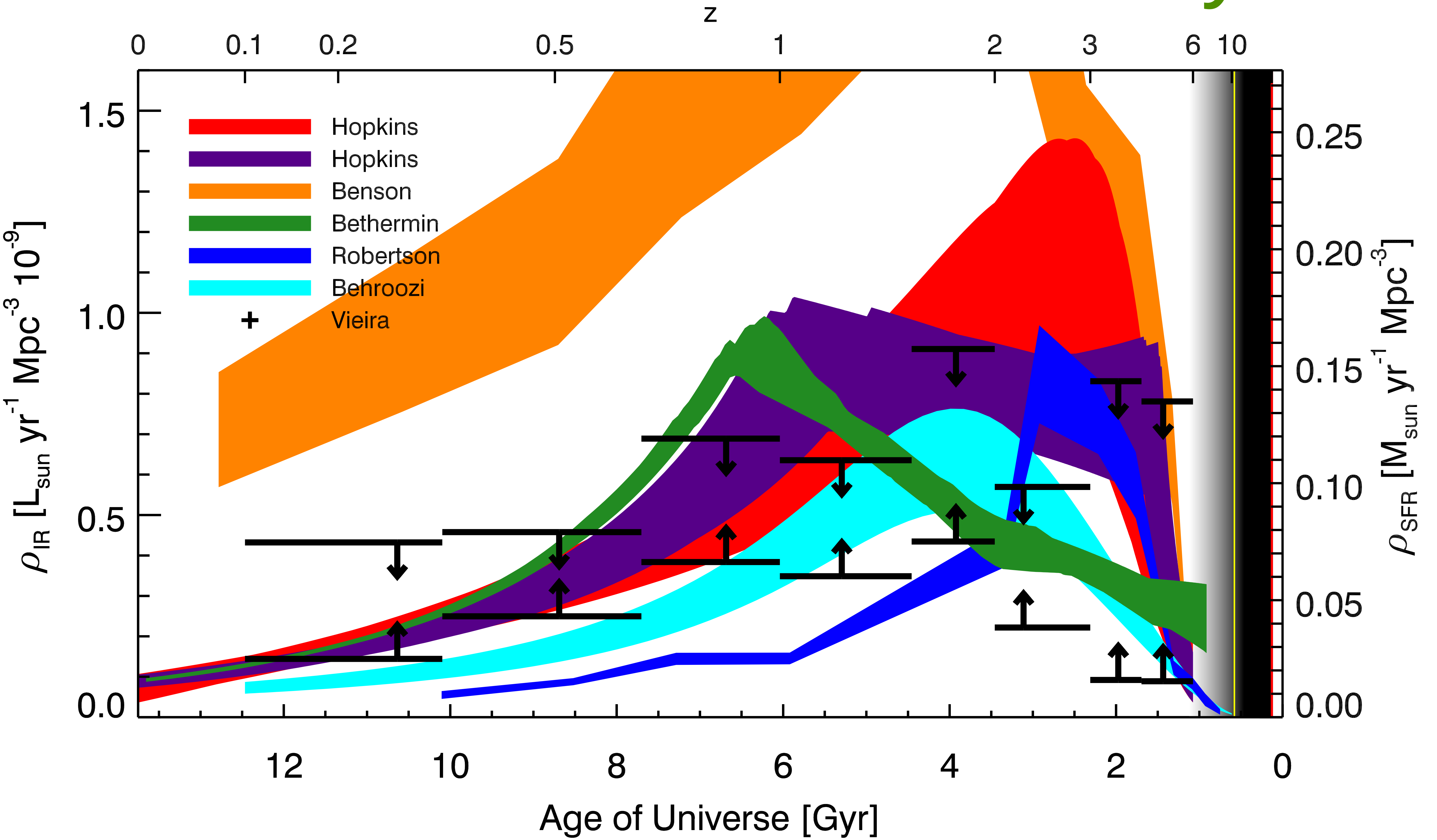
- Vieira, Marrone, Chapman, DeBreuck, Hezaveh, Weiss, *et al.*, 2013, Nature
- Weiss, De Breuck, Marrone, Vieira, *et al.*, 2013, ApJ
- Hezaveh, Marrone, Fassnacht, Vieira *et al.*, 2013, ApJ



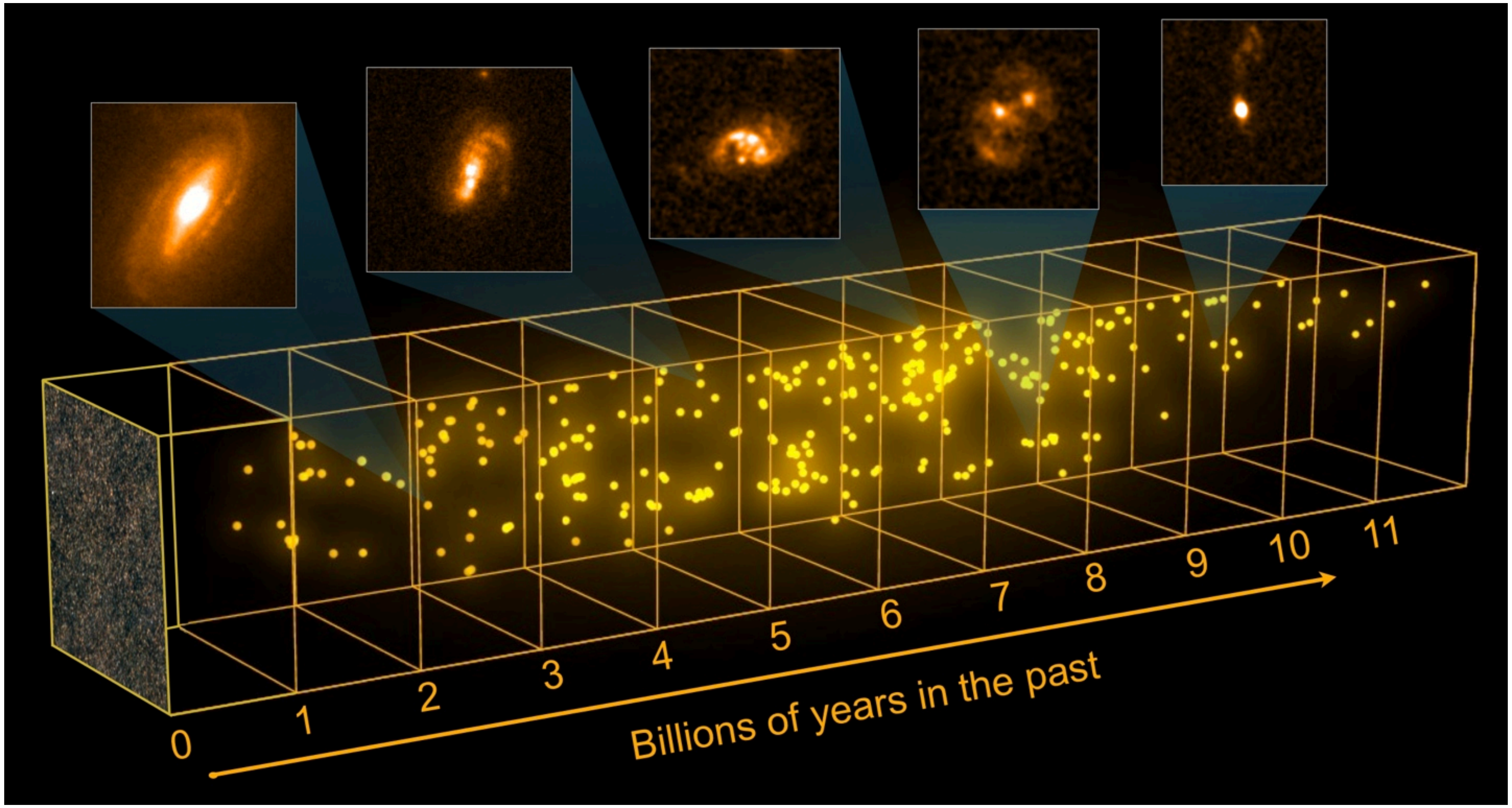
The Cosmic Infrared Background (CIB)



Cosmic star formation history



Vieira *et al in prep*



High redshift dusty star forming galaxies and sub-millimeter galaxies:

- Responsible for the bulk of the star formation history and the assembly of stellar mass in the Universe
- Forming stars at 100-1000 $M_{\odot}$/yr, enshrouded in dust, linked with mergers
- 1000 times more abundant at z~1 than today
- Progenitors of quiescent early-type galaxies seen today in massive galaxy clusters
- Key to models of galaxy formation and evolution

New era for the study of the dusty universe:

- Herschel, SPT, Planck, CCAT → large surveys
- ALMA, JWST → detailed studies

How to understand evolution: spectroscopy

Dusty galaxies form stars at prodigious rates, hundreds to thousands of Solar masses per year, and signify the rapid formation of the most massive, quiescent elliptical galaxies in the local Universe.

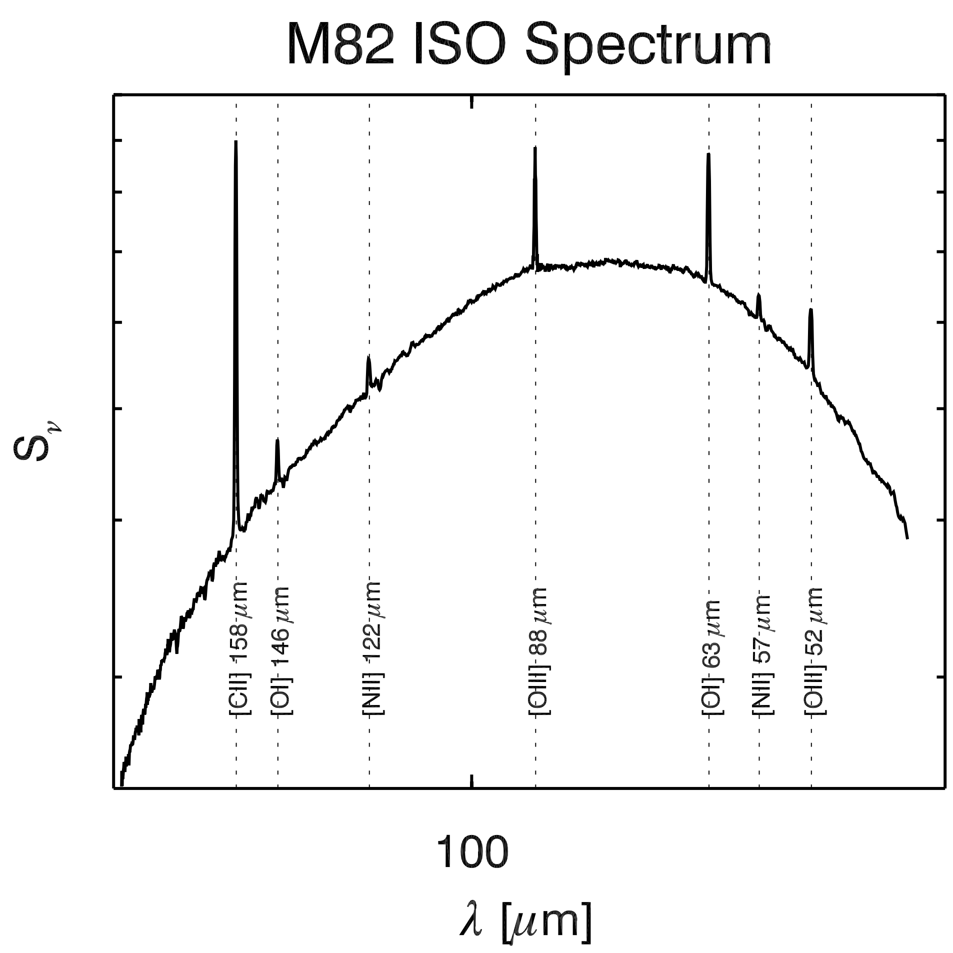
Our understanding of galaxy formation, evolution, and star formation is not complete without a measure of their total bolometric energy output.

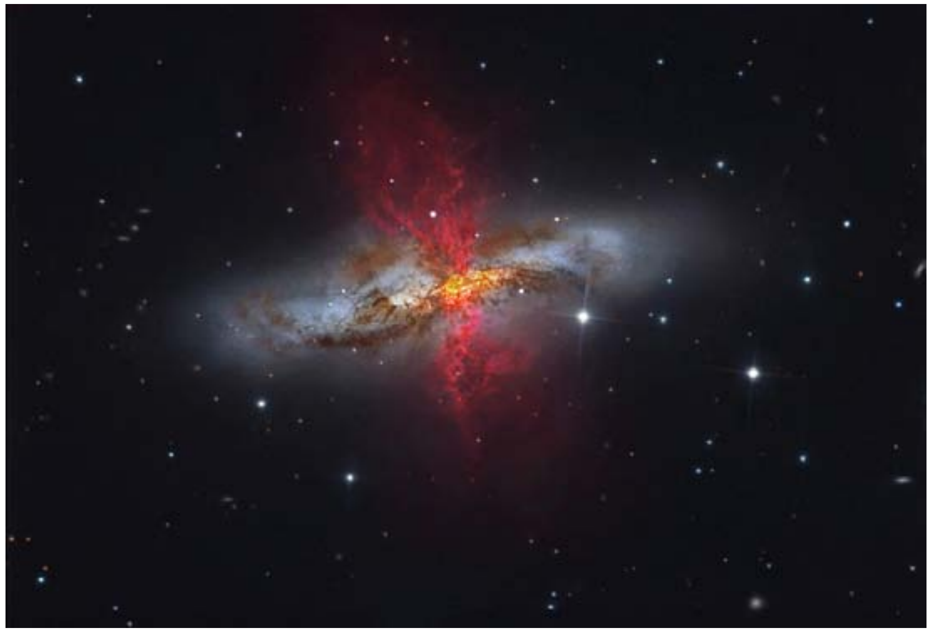
Studying dusty high redshift galaxies is critical to understanding how the Universe went from neutral to ionized and emerged from the dark ages in the epoch of reionization.

Outstanding questions:

- What is the intrinsic redshift distribution of these SMGs?
- How early did the most massive galaxies form?
- What is the total bolometric power radiated by the highest redshift galaxies?
- Is star formation fueled by accretion onto disks or is it driven by major mergers?
- How did the ISM cool and evolve verses cosmic time?
- What begins, fuels, and then shuts off the process of star formation and black hole accretion?

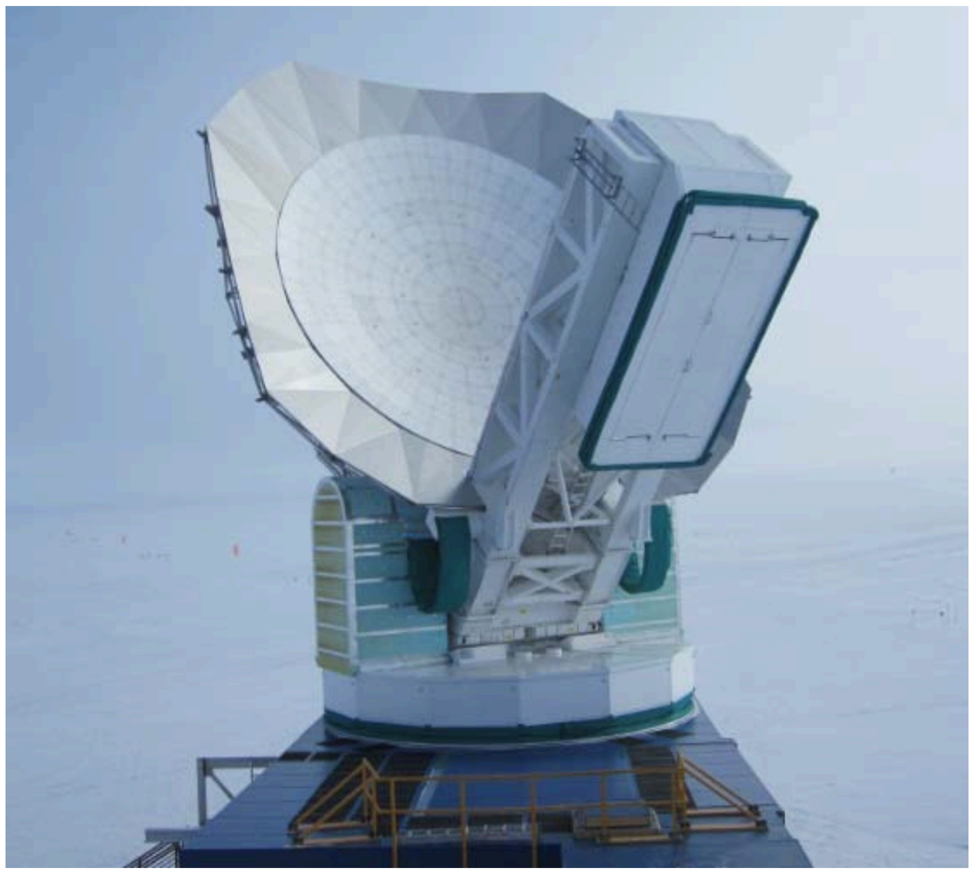
The best prospects for answering these questions are through spectroscopic studies of atomic and molecular lines.





SPT

The South Pole Telescope



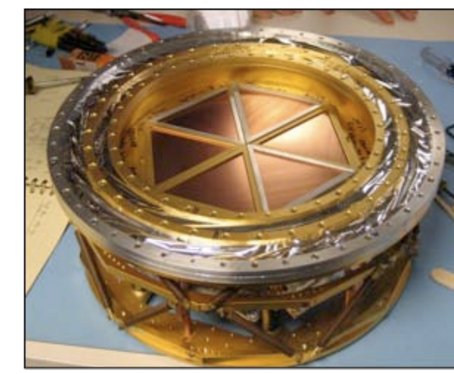
Funded by NSF

Telescope

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

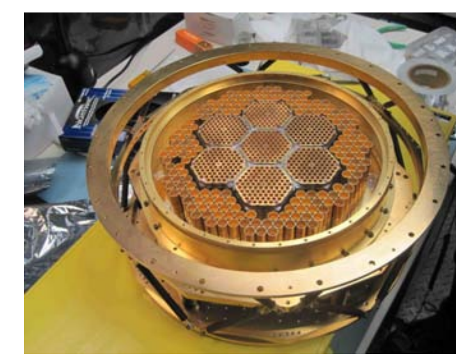
SPT-SZ Camera (1st Generation):

- 2007 – 2011
- 960 pixel mm camera
- 1.4, 2.0, and 3.0 mm
- completed 2500 deg^2
- 18 μK-arcmin depth, ~1 mJy



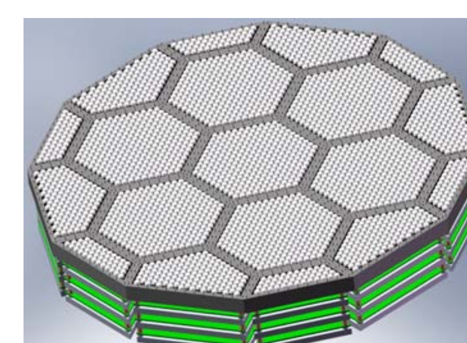
SPT-pol Camera (2nd Generation):

- 2012 – 2015
- 1600 pixel mm camera
- 2 and 3 mm + polarization
- currently surveying 600 deg^2 x4 deeper
- 4.5 μK-arcmin depth

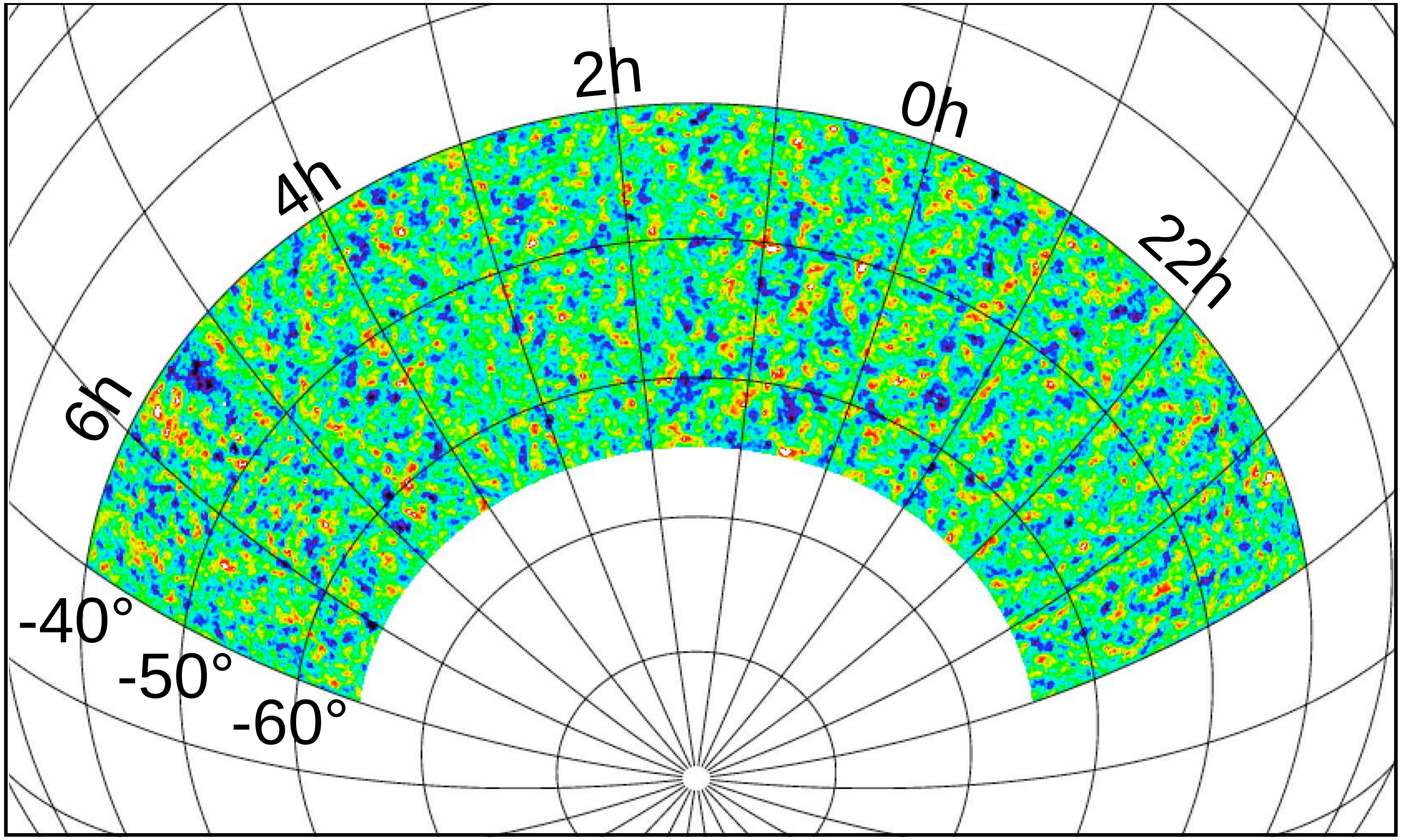


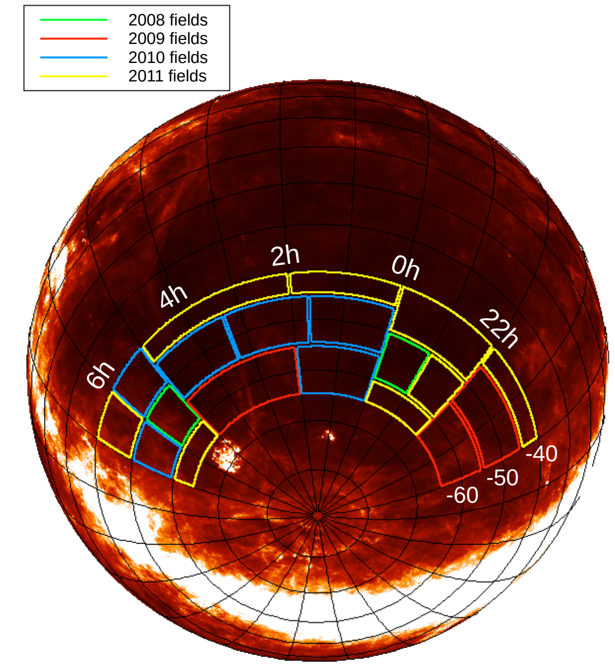
SPT-3G Camera (3rd Generation):

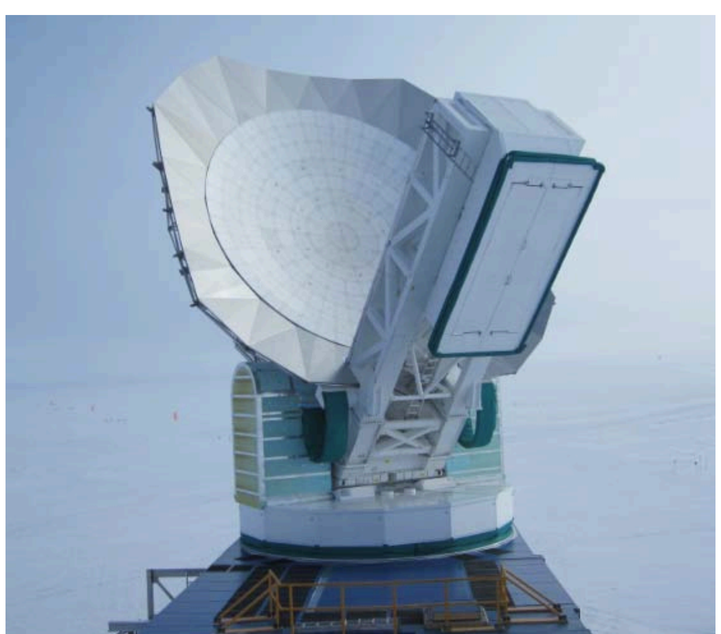
- 2016 – 2020
- 15k pixel mm camera
- 1.4, 2, 3 mm + polarization
- planned 2500 deg^2 x8 deeper
- 2.5 μK-arcmin depth



2500 deg^2 SPT-SZ Survey







		SPT-SZ	2008 → 2011	Deep Field	2008 → 2011	SPTpol	2012 → 2014	SPT3G	2015 → 2017
band [mm]	FWHM [']	uK-arcmin	RMS mJy/beam	uK-arcmin	RMS mJy/beam	uK-arcmin	RMS mJy/beam	uK-arcmin	RMS mJy/beam
3.0	1.7	42	2.0	42	2.0	6.5	0.3	4.2	0.2
2.0	1.2	18	1.3	13	0.9	4.5	0.3	2.5	0.2
1.4	1.0	85	6.8	35	3.0	--	--	4.0	0.4
area [deg^2]		2500		200		600		2500	

SPT Team February 2007

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Kavli Institute for Cosmological Physics at the University of Chicago

THE UNIVERSITY OF CHICAGO

Berkeley University of California

McGill

Harvard-Smithsonian Center for Astrophysics

Berkeley Lab

ASTRONOMY University of Illinois at Urbana-Champaign

UCDAVIS University of California

Case Case Western Reserve University

Colorado University of Colorado at Boulder

Cardiff University Prifysgol Caerdydd

SPT SMG Team 2012

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Scott Chapman (Cambridge)
Tom Crawford (Chicago)
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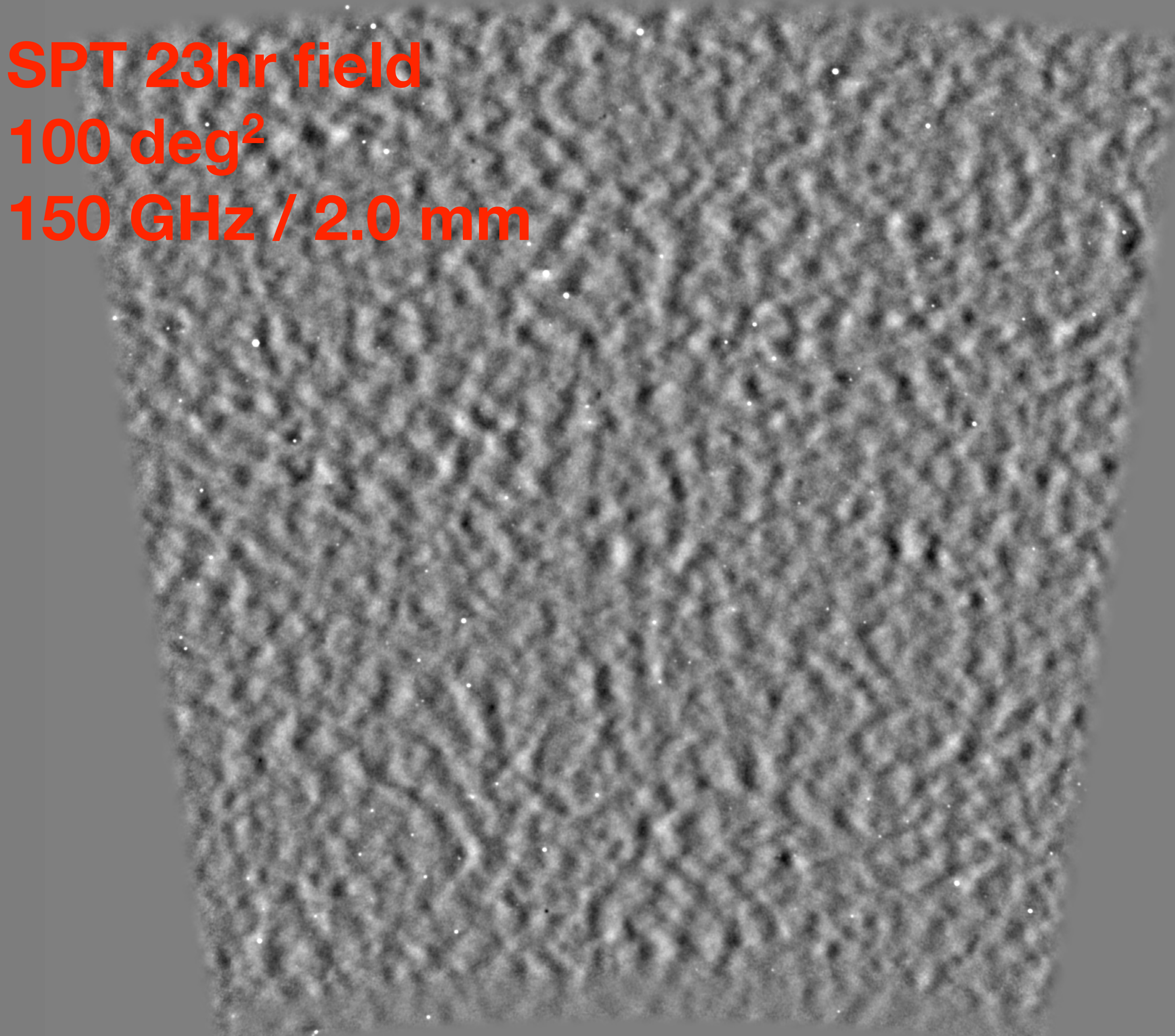
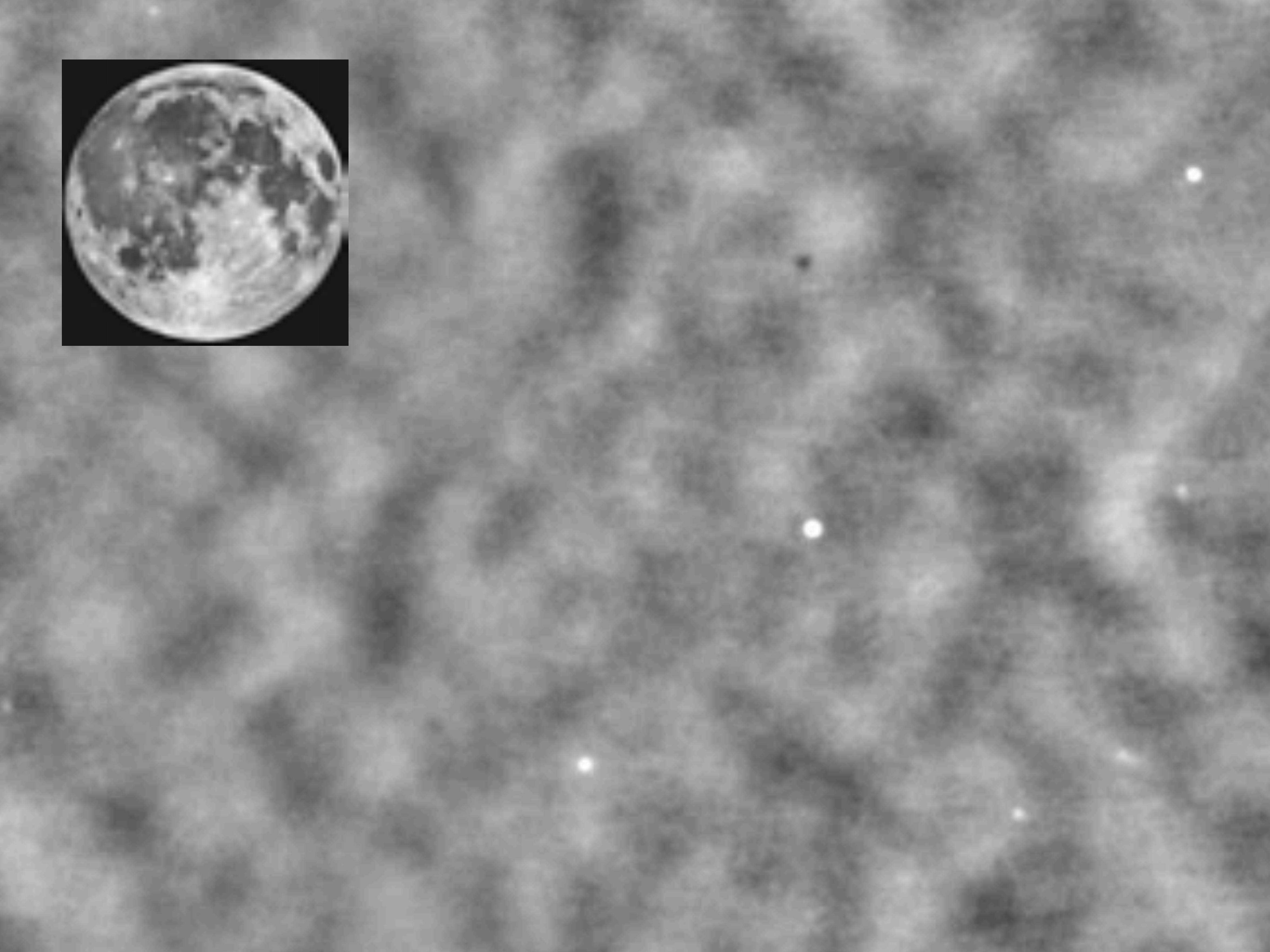
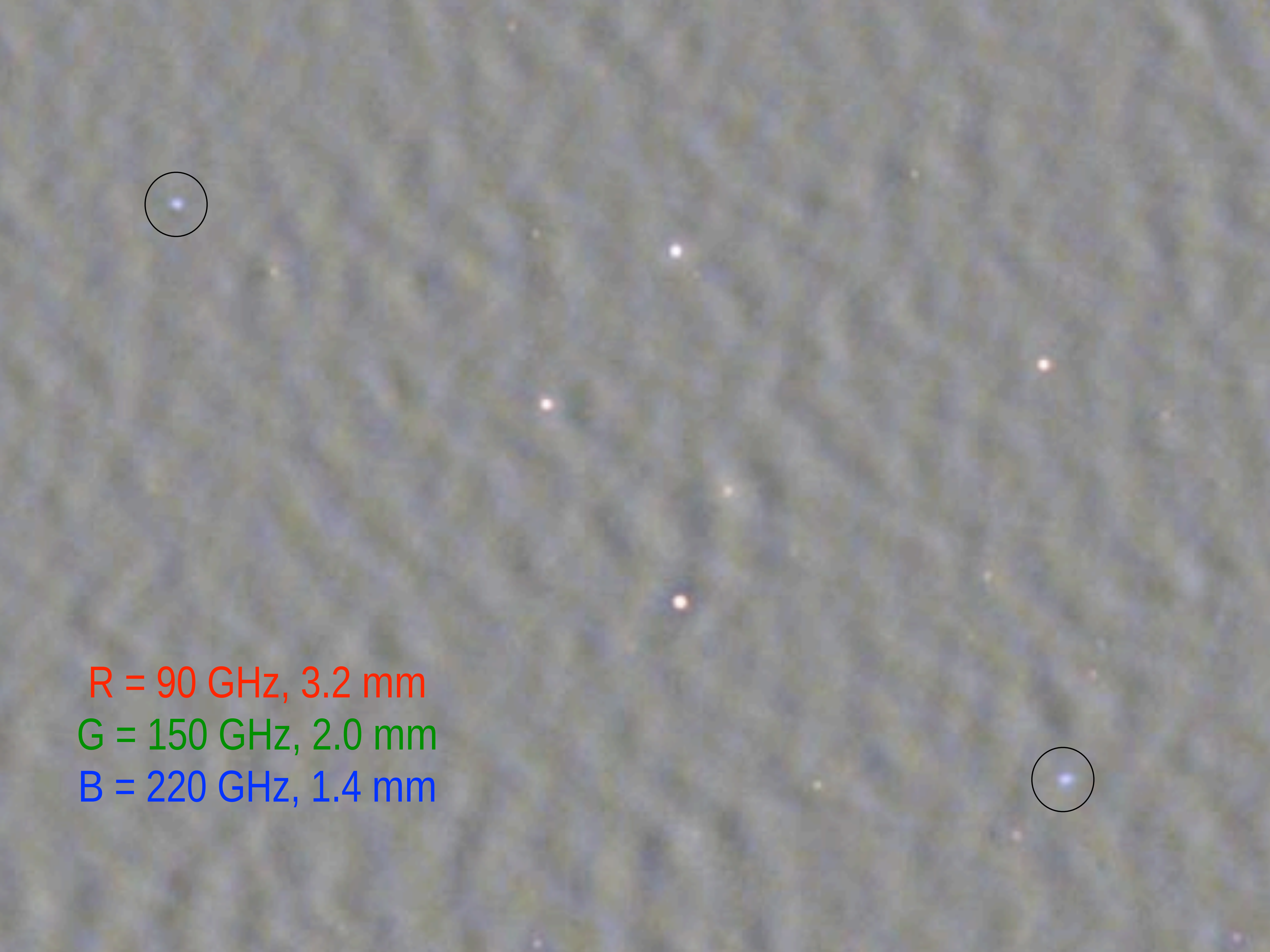
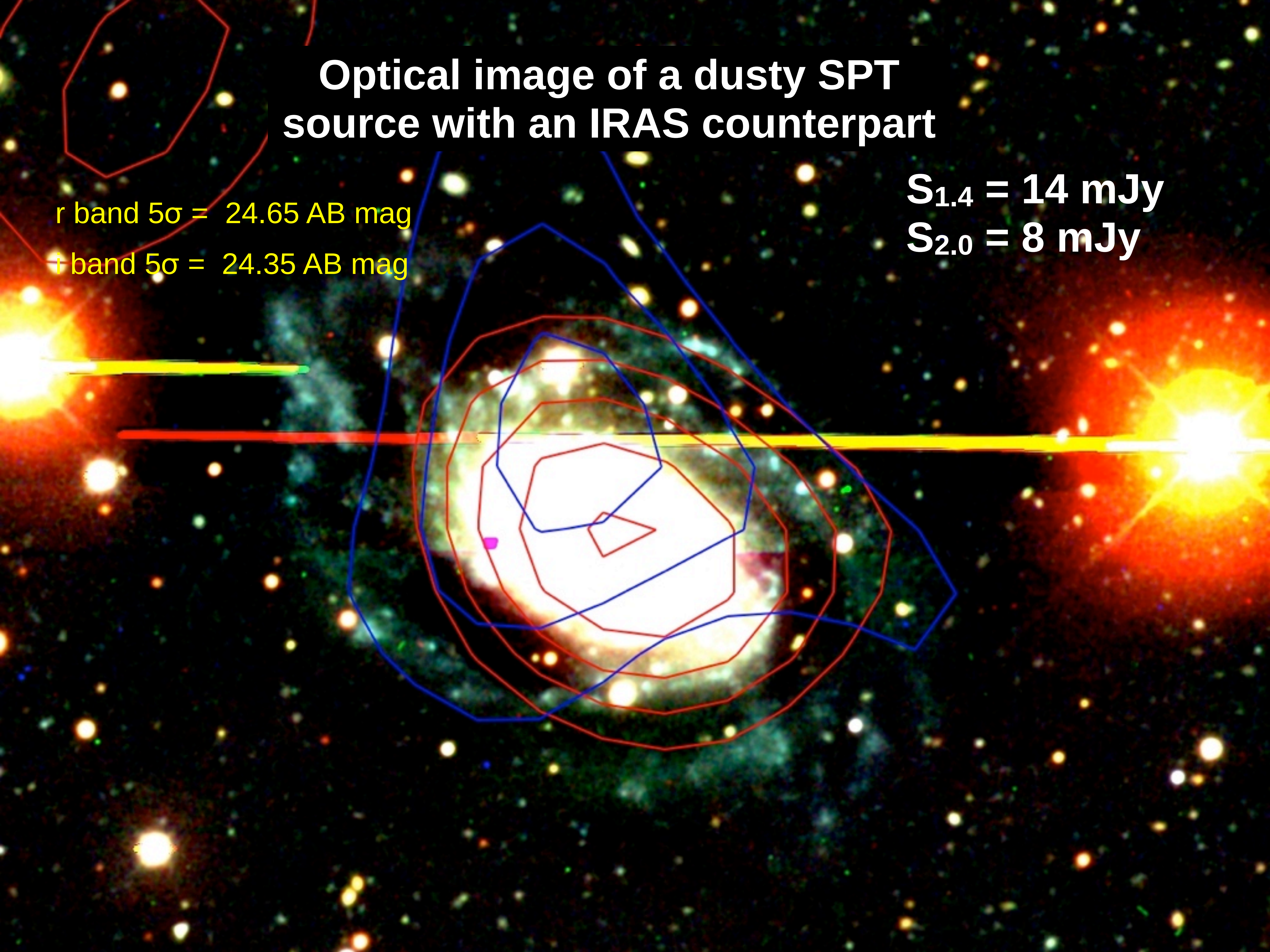
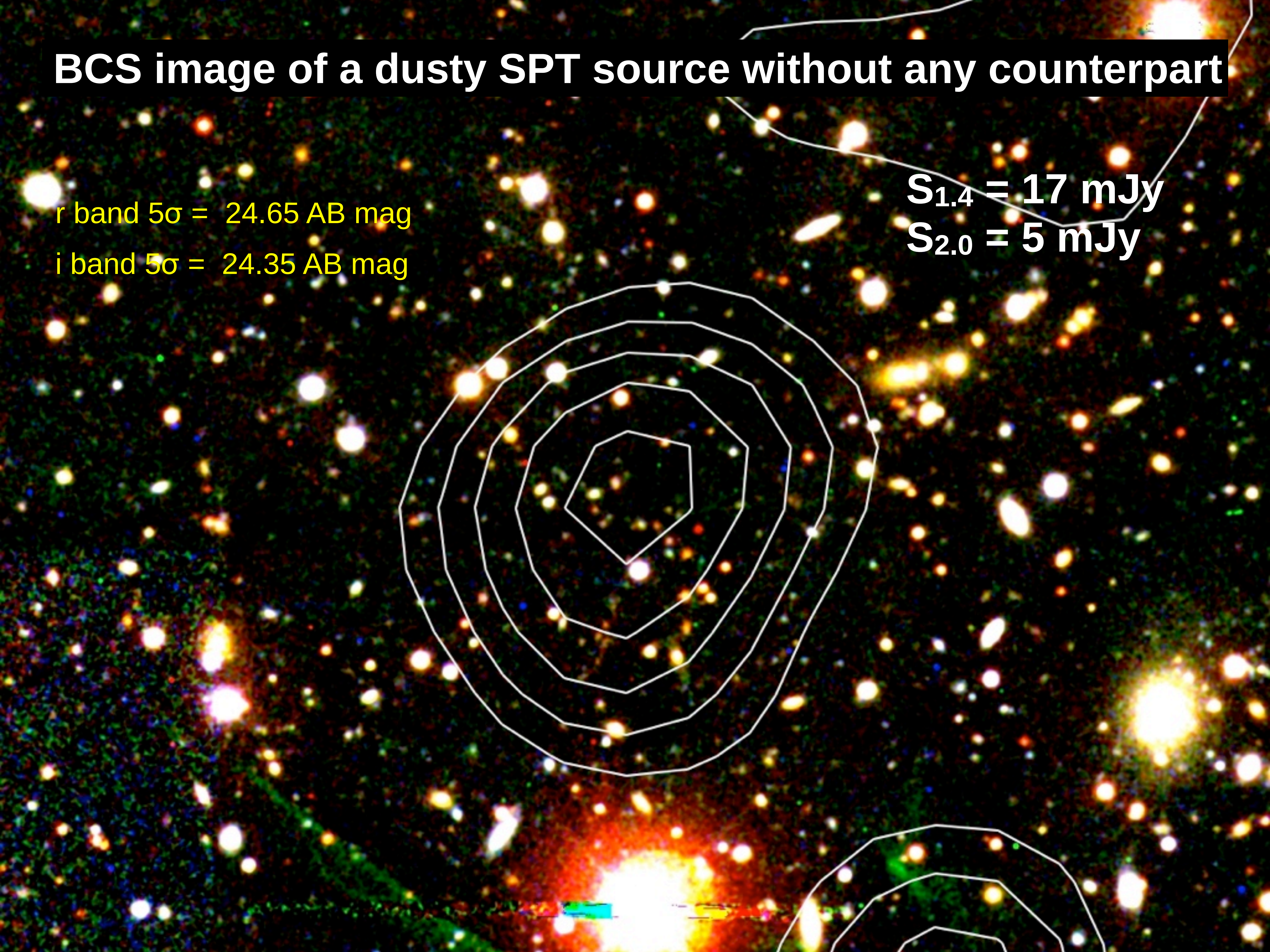
Justin Spilker (Arizona)
Brian Stalder (Harvard)
Tony Stark (CfA)
Maria Strandet (MPIfR)
Joaquin Vieira (Caltech)
Axel Weiss (MPIfR)


SPT 23hr field
100 deg^2
150 GHz / 2.0 mm



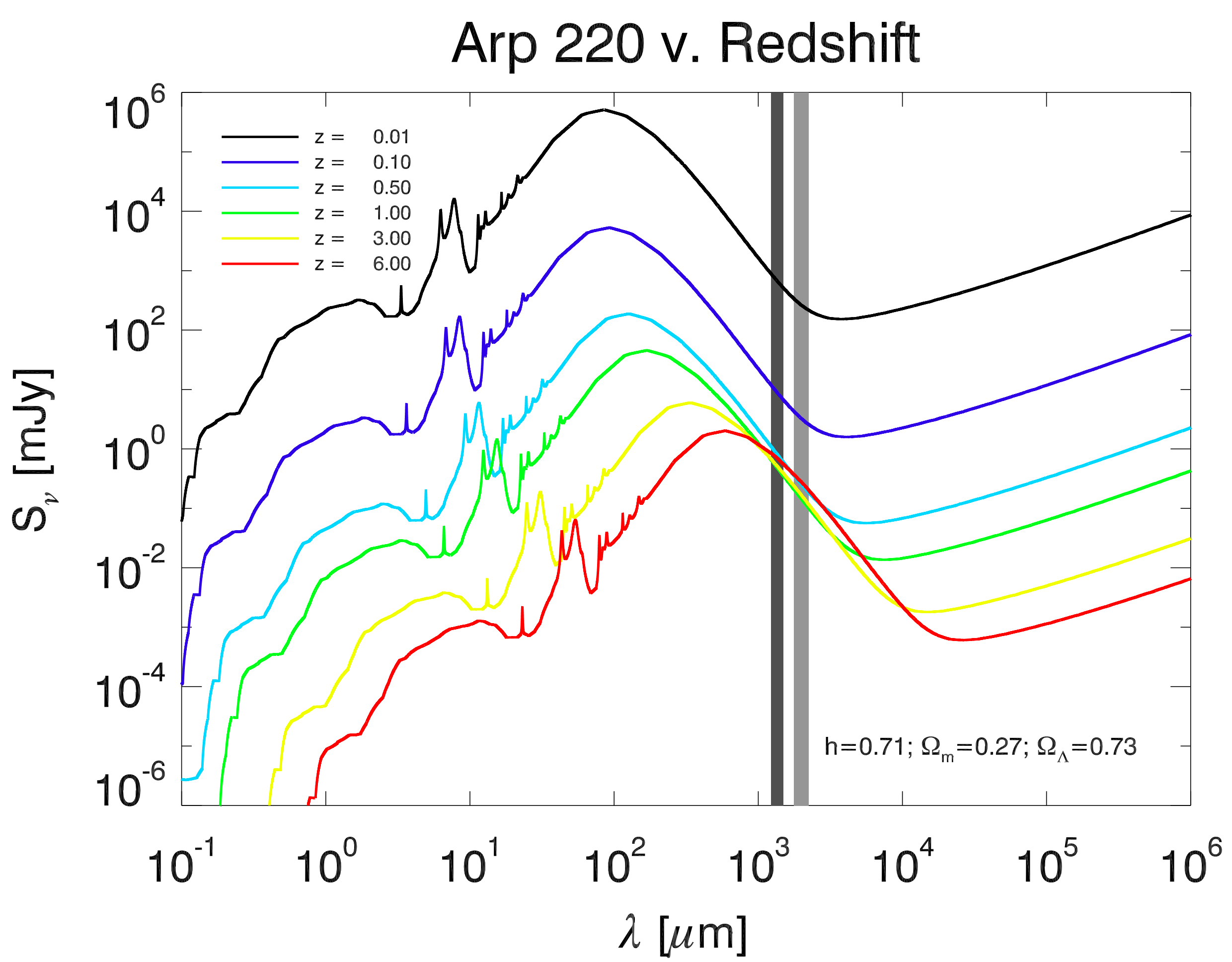

R = 90 GHz, 3.2 mm
G = 150 GHz, 2.0 mm
B = 220 GHz, 1.4 mm

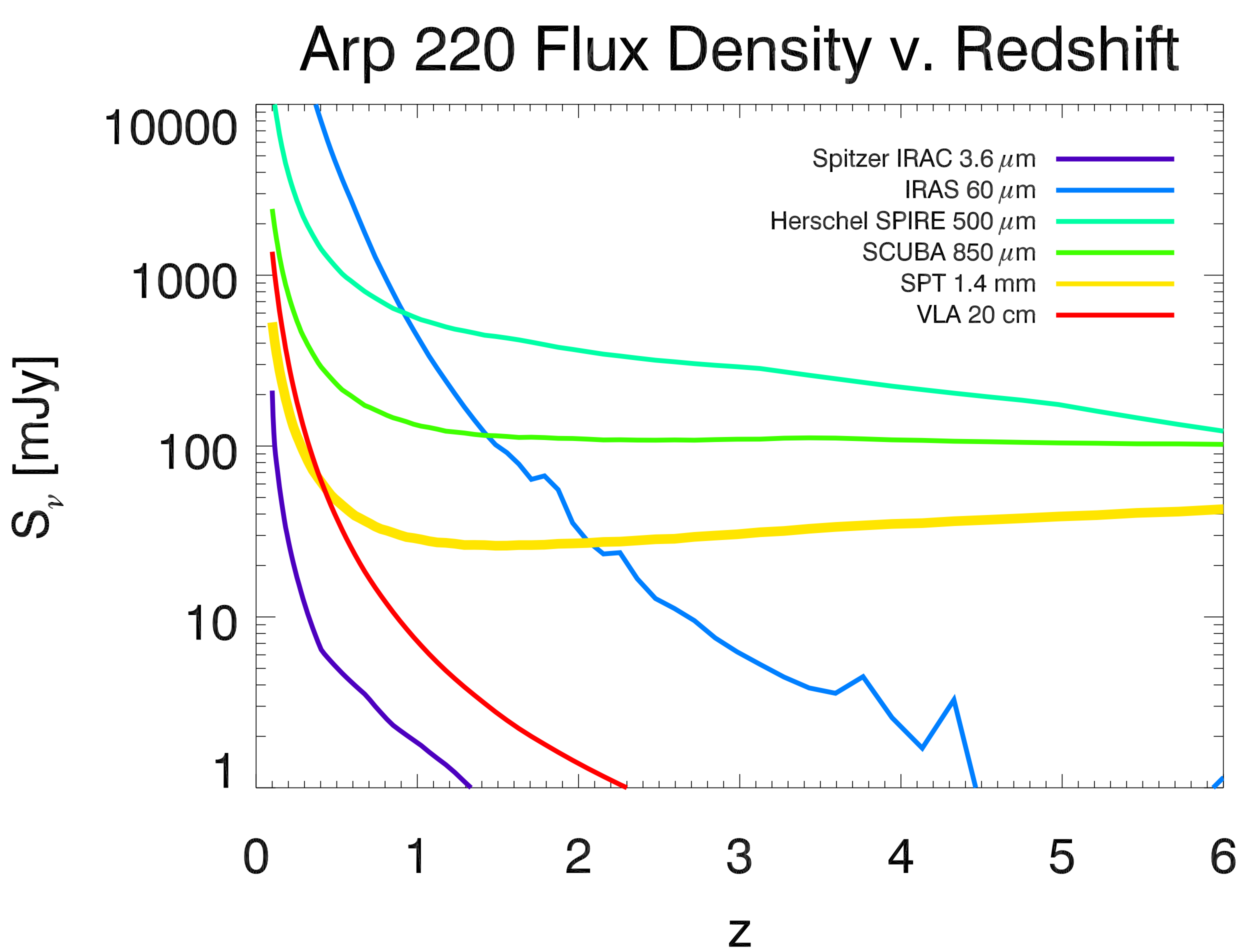

Optical image of a dusty SPT source with an IRAS counterpart
r band 5σ = 24.65 AB mag
i band 5σ = 24.35 AB mag
S1.4 = 14 mJy
S2.0 = 8 mJy


BCS image of a dusty SPT source without any counterpart
r band 5σ = 24.65 AB mag
i band 5σ = 24.35 AB mag
S1.4 = 17 mJy
S2.0 = 5 mJy

Sub-mm magic

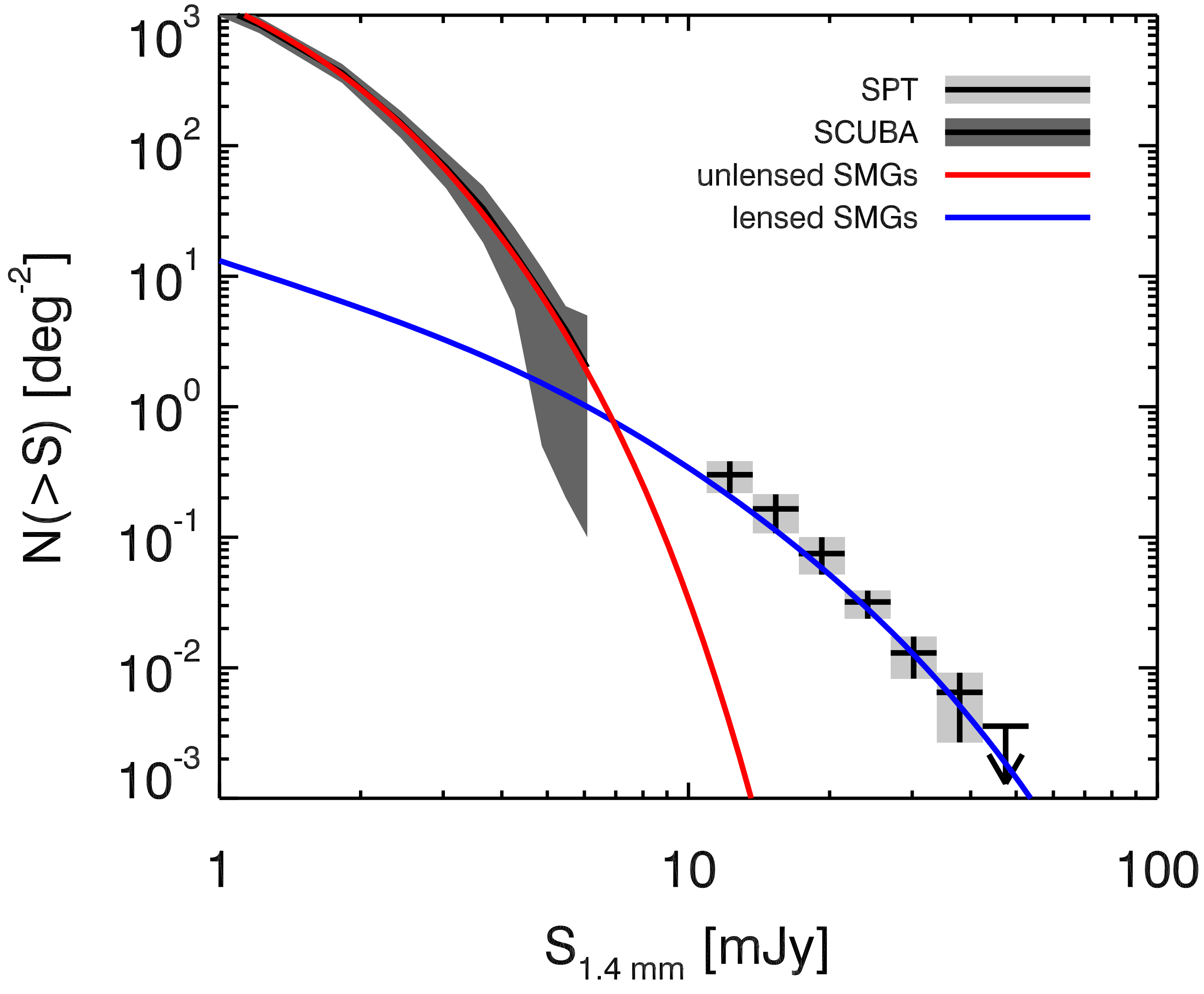
See Franceschini *et al.* 1991 and Blain & Longair 1993



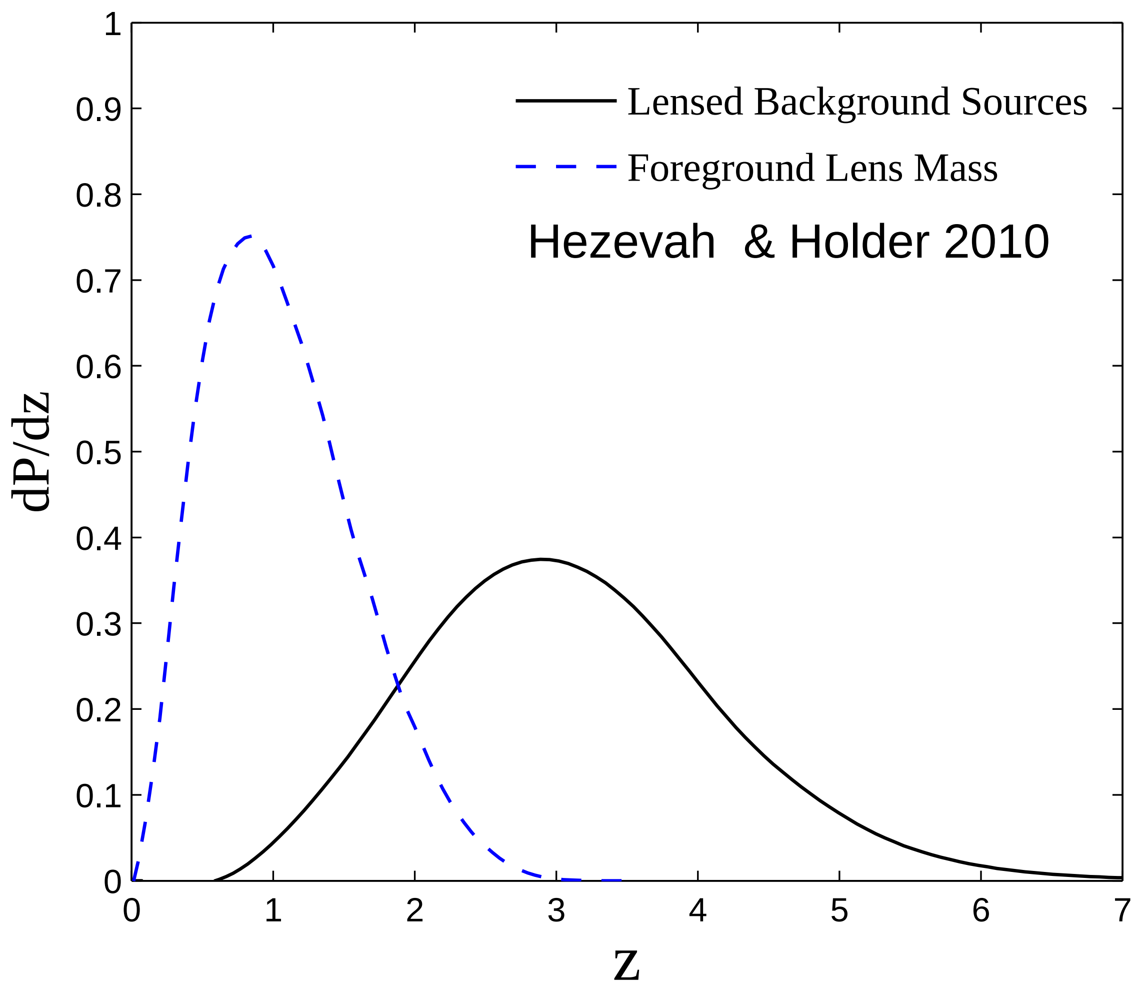


Model of lensed sources for SPT sample

Negrello *et al.* 2007 model and
Vieira *et al.* 2010 source counts

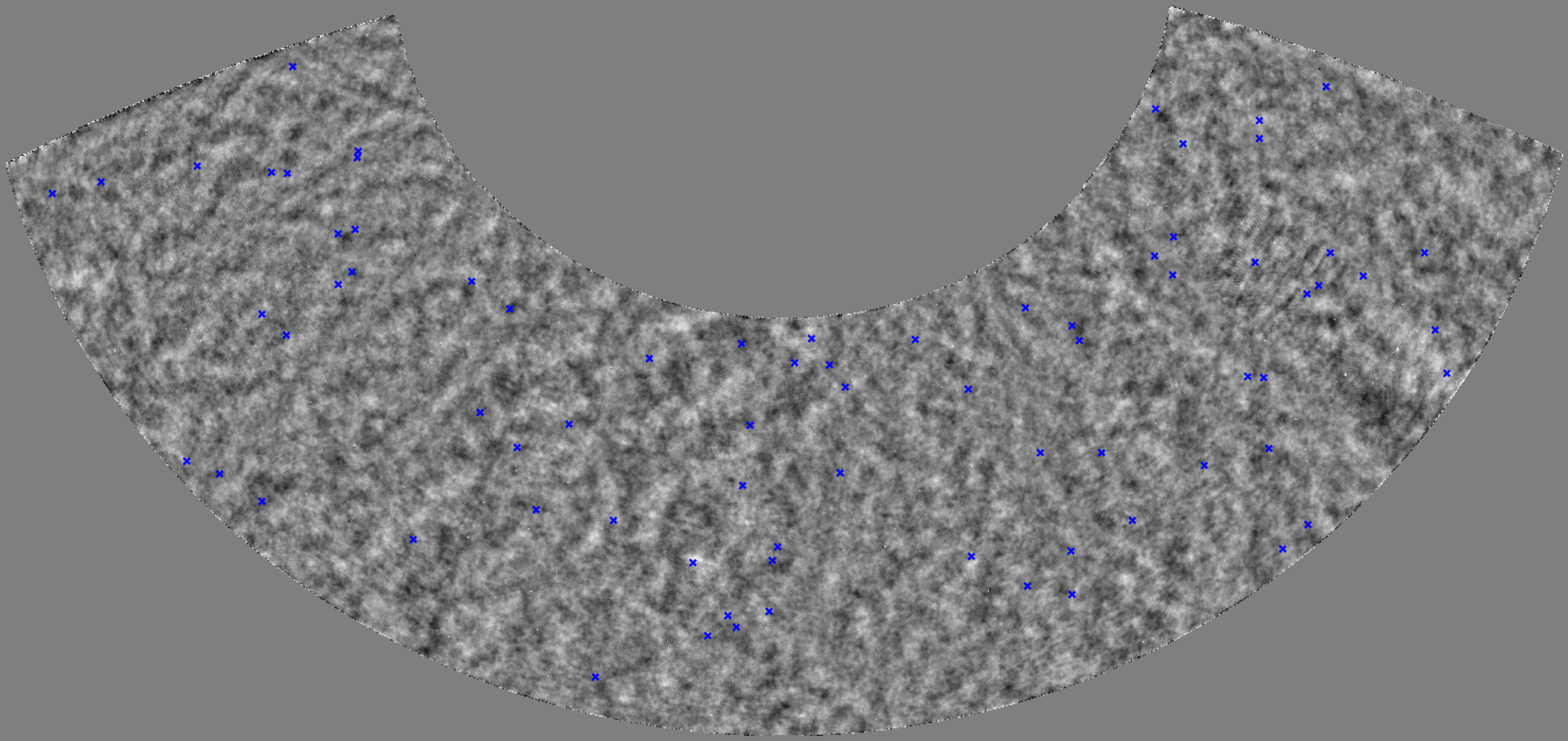


n(z) for foreground lenses and background sources



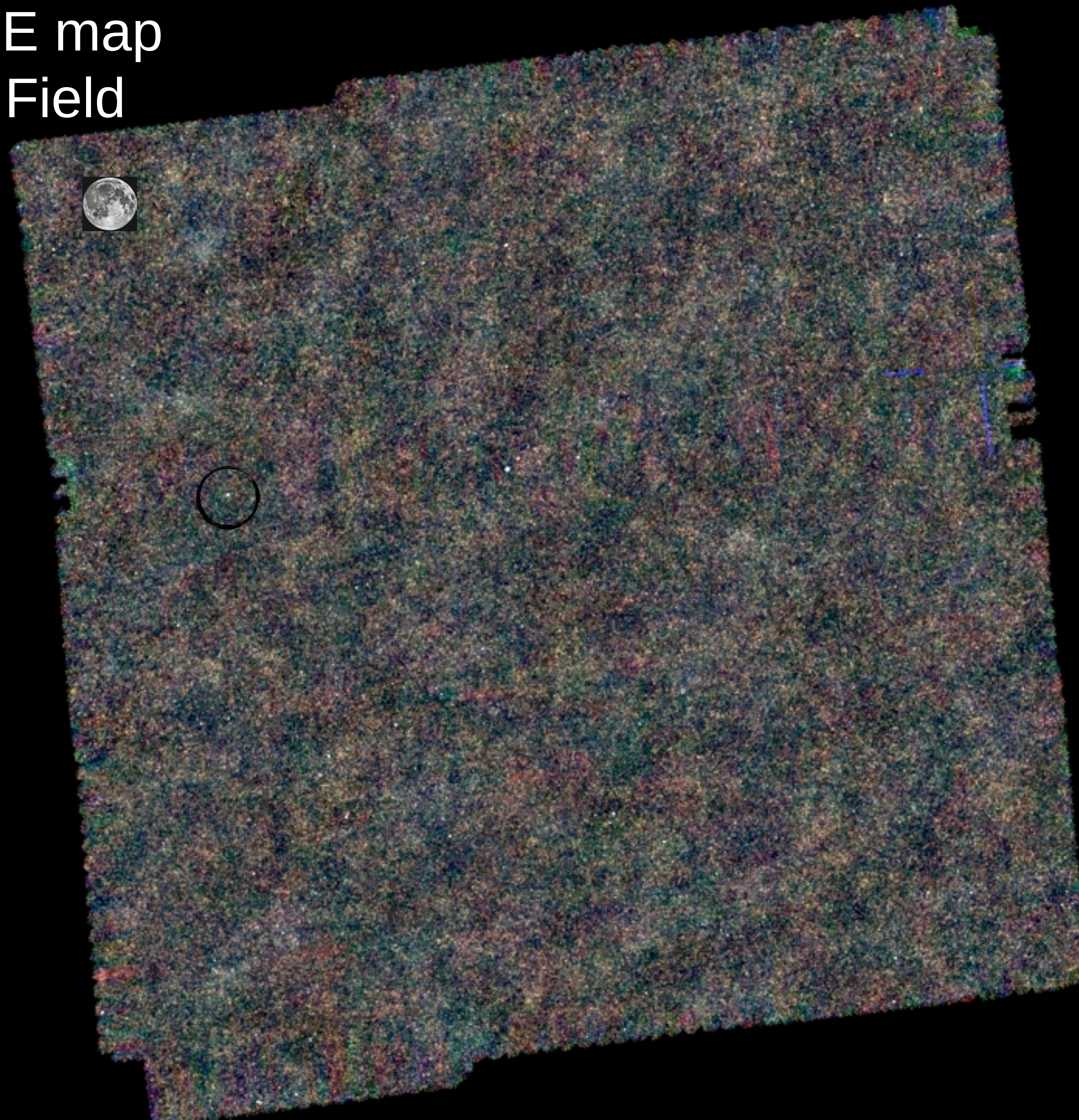
2500 deg^2 SPT survey

76 strongly lensed SMGs at $S_{1.4mm}$ > 20 mJy

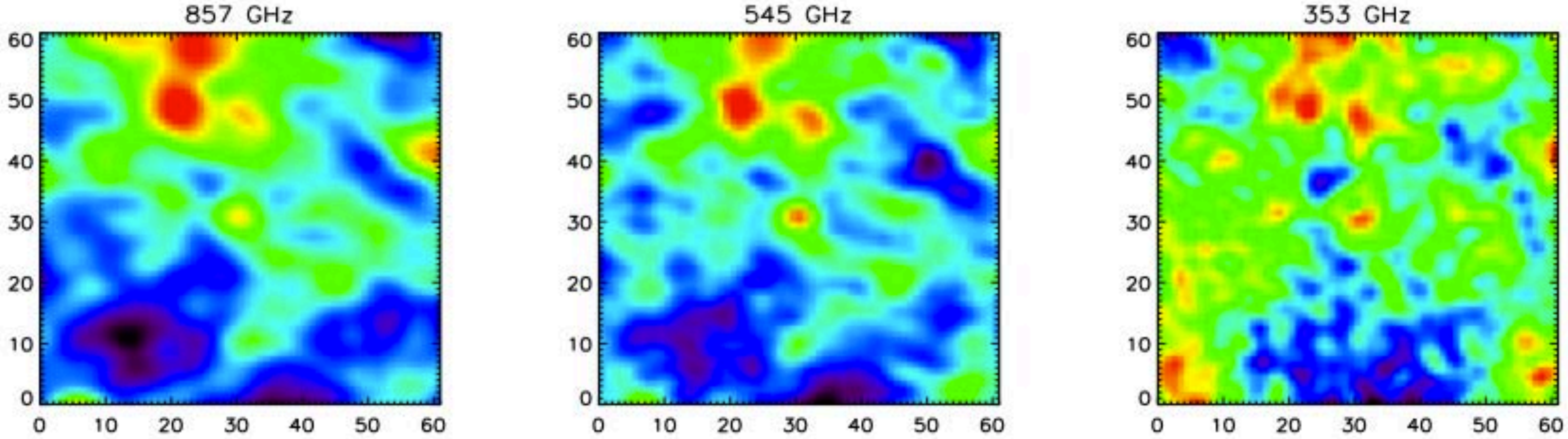


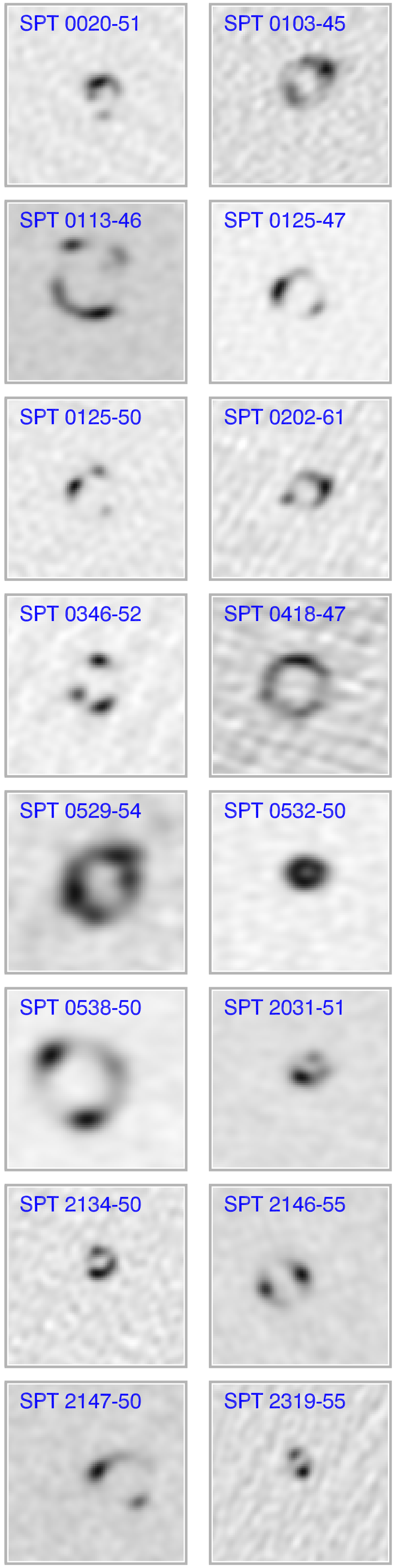
~100 sources when we include deep fields
Could go lower in S/N and get ~200 sources, but we are already limited by the amount of telescope time we can get

100 deg^2 SPIRE map of SPT Deep Field



SPT sources in the raw Planck maps





What are strongly lensed SMGs good for?

Background Source:

- **Allows us to randomly sample individual sources which make up the CIB in great detail. ~x10 brighter ⟹ ~x100 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 and probe kpc scales**

- **Detailed spectroscopy of CO, C+, H2O (and other lines) is finally possible at high redshifts. ⟹ We can do chemistry**

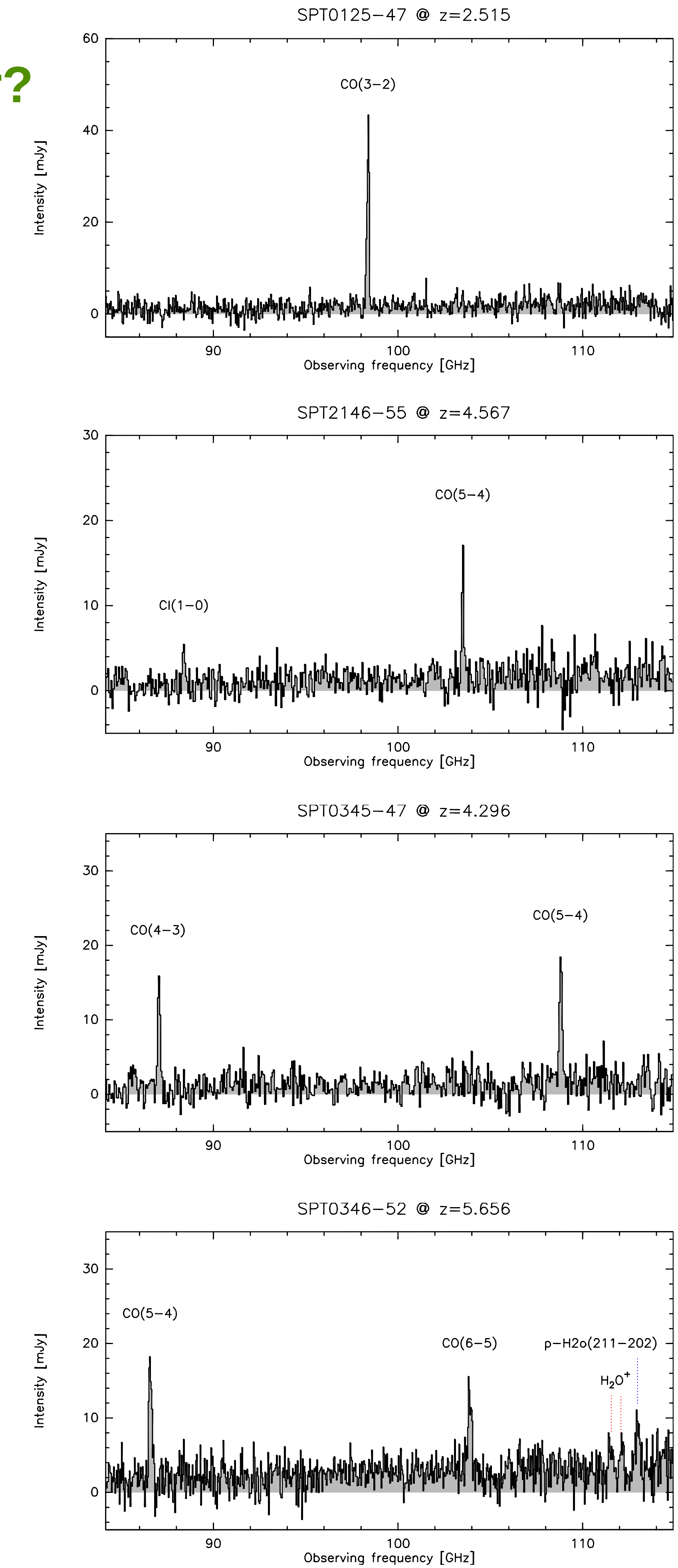
- **The highest redshift sources provide us with a new method of probing the ISM near the end of the epoch of reionization.**

Foreground Lens:

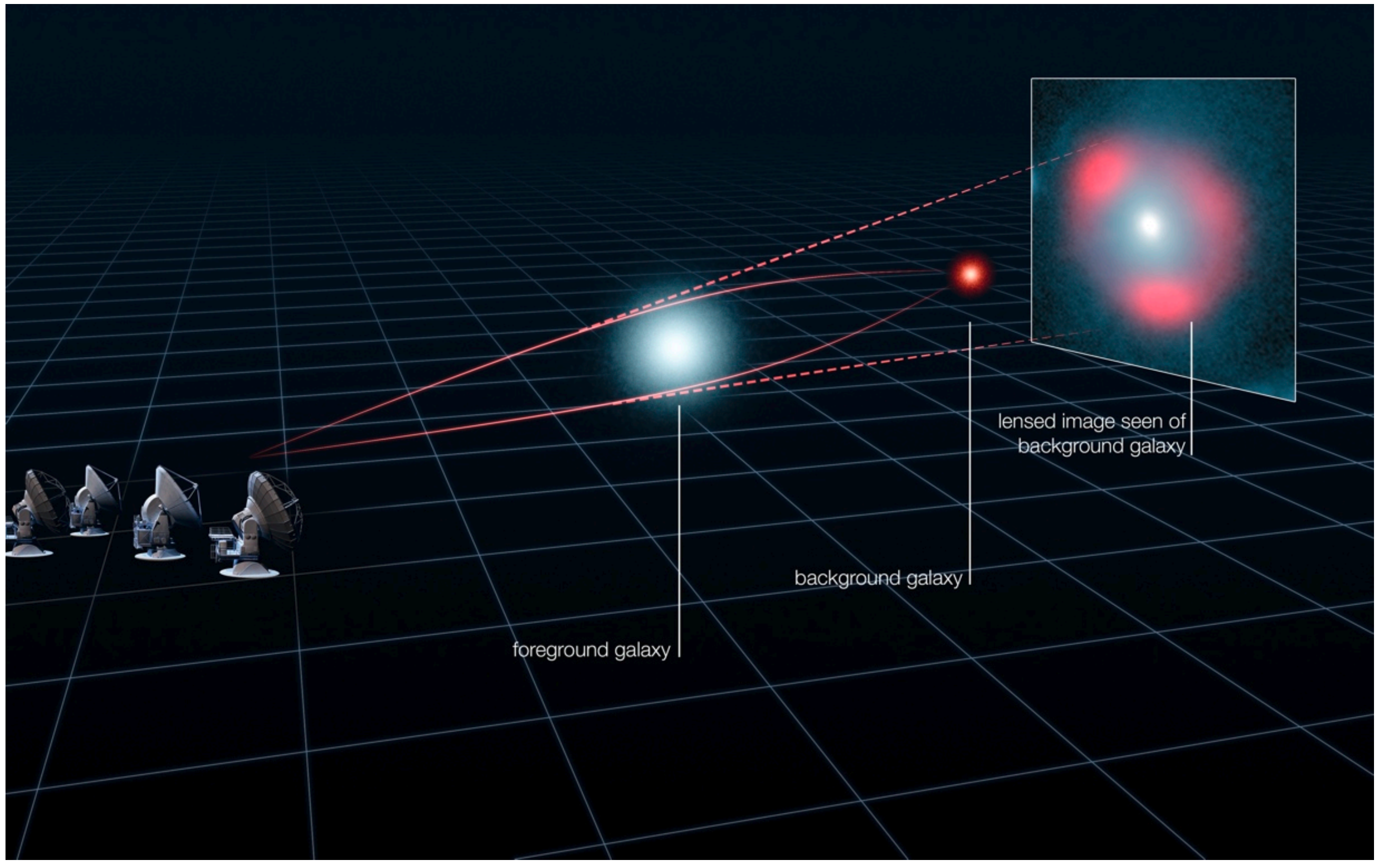
- **Study in detail the lens. ⇒ Study M/L ratios of massive halos out to high redshift.**

- **Can be used as a probe of large scale structure ⇒ may one day be used for cosmology**

- **Sub-structure in lensing halos ⇒ direct probe of DM (sub) structure.**

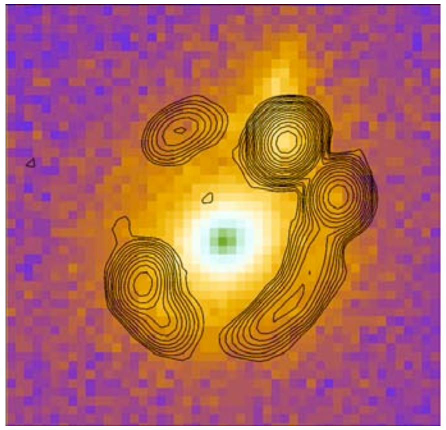


Fun Facts about Gravitational Lensing:

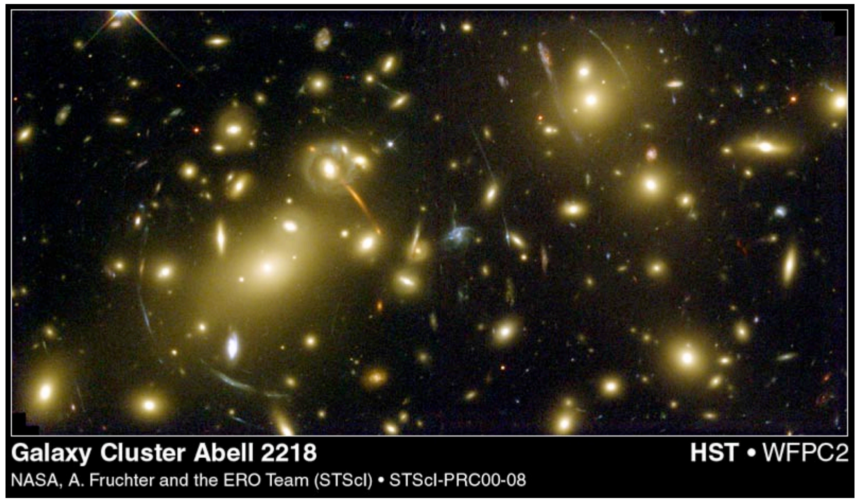


- Measure an einstein radius and you have measured the mass
- The lensing mass is ~1/2 DM and ~1/2 baryons
- Lensing largely achromatic, but can have differential magnification
- Probability of lensing increases with source redshift, but flattens out above z>1
- cluster = larger lensing cross section ; galaxy = more opportunities for lensing
- ~1/200 massive early-type galaxies is a strong lens
- ~1/50 strong lensing galaxies can lens 2 sources

How to find lensed sources:

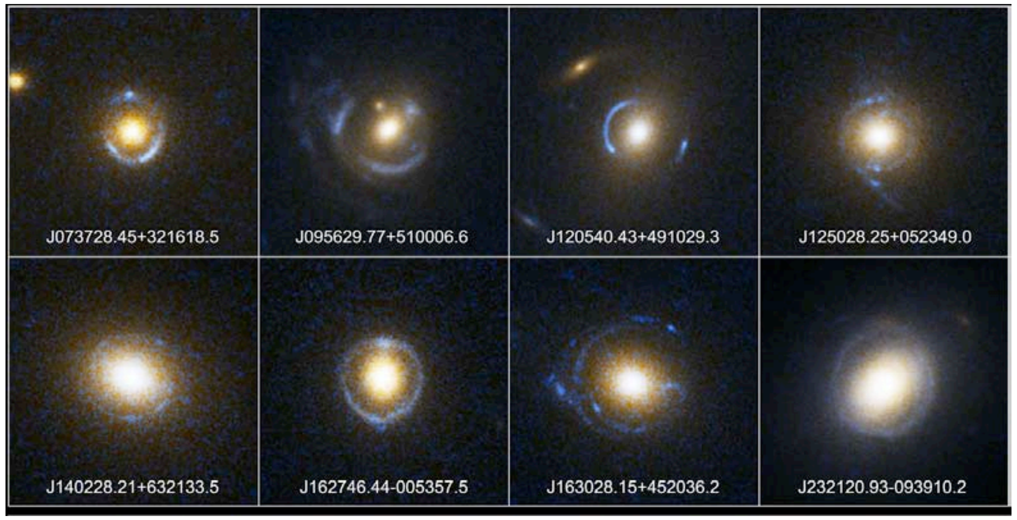


- **Radio** mid 90's: (e.g. CLASS) select flat spectrum sources, followup with high resolution radio.
- **Clusters** late 90's--today: (e.g. CLASH, HLS) Target massive clusters of galaxies in optical and/or submm.
- **Optical** 00's: (e.g. SLACS) Use large spectroscopic surveys to sift through millions of spectra, find lensed candidates, and followup with HST ... or just sift through thousands of images by eye.
- **sub/mm** 2010's: (e.g. SPT, Herschel/SPIRE) Survey large areas of sky in the submm and find the rare, bright sources.



All methods have their individual quirks and selection biases.

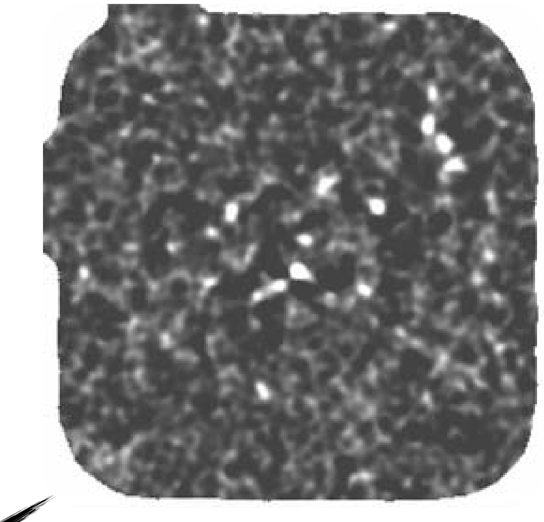
sub/mm method is nice in that:
1. lots of faint sources at z~2, few bright sources
2. largely independent of redshift for source and lens
3. independent of einstein radius
4. flux limited and easy/trivial to identify lensed sources
5. has doubled the number of lensed systems in the last two years



Difficult because:
1. optically faint
2. redshifts are unknown and DIFFICULT to obtain

but...
everything changes with ALMA !

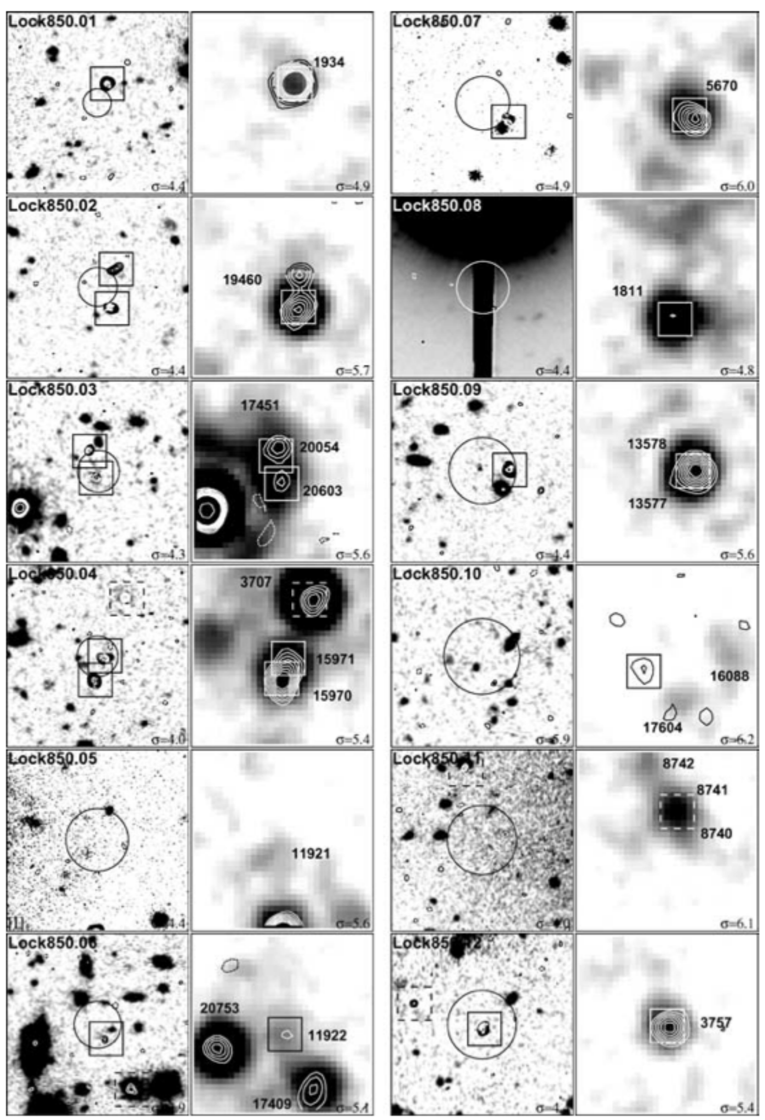
Redshifts: Good



1) Blank field submm survey

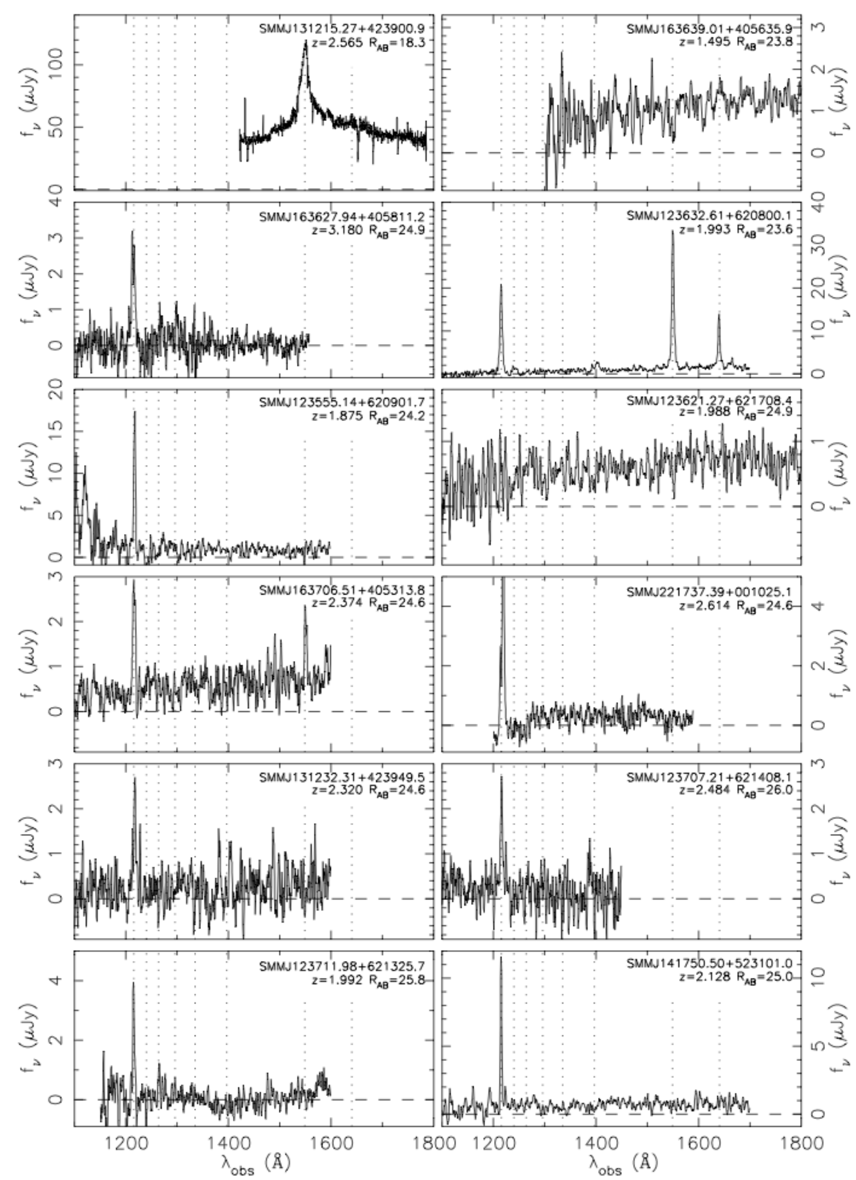
2) Find radio counterpart to SMG

Ivison *et al.* MNRAS 2002, 2007



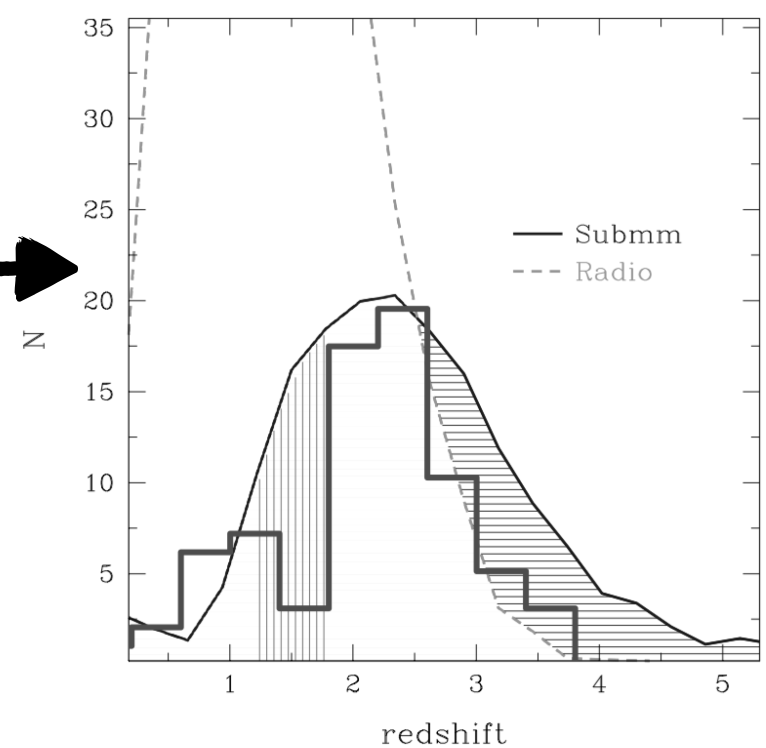
3) Obtain Keck spectroscopy

Chapman *et al.* Nature 2003, ApJ 2005

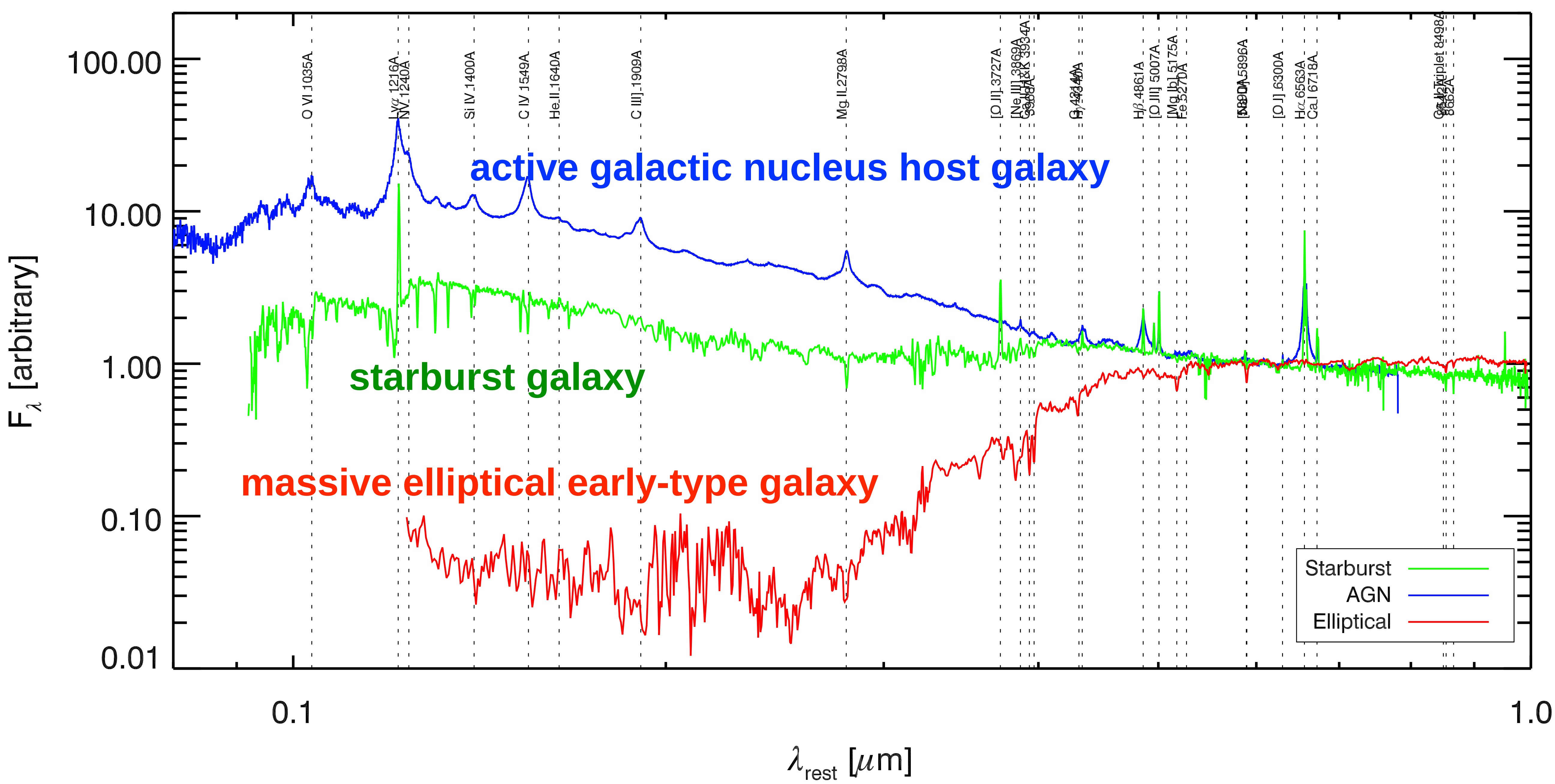


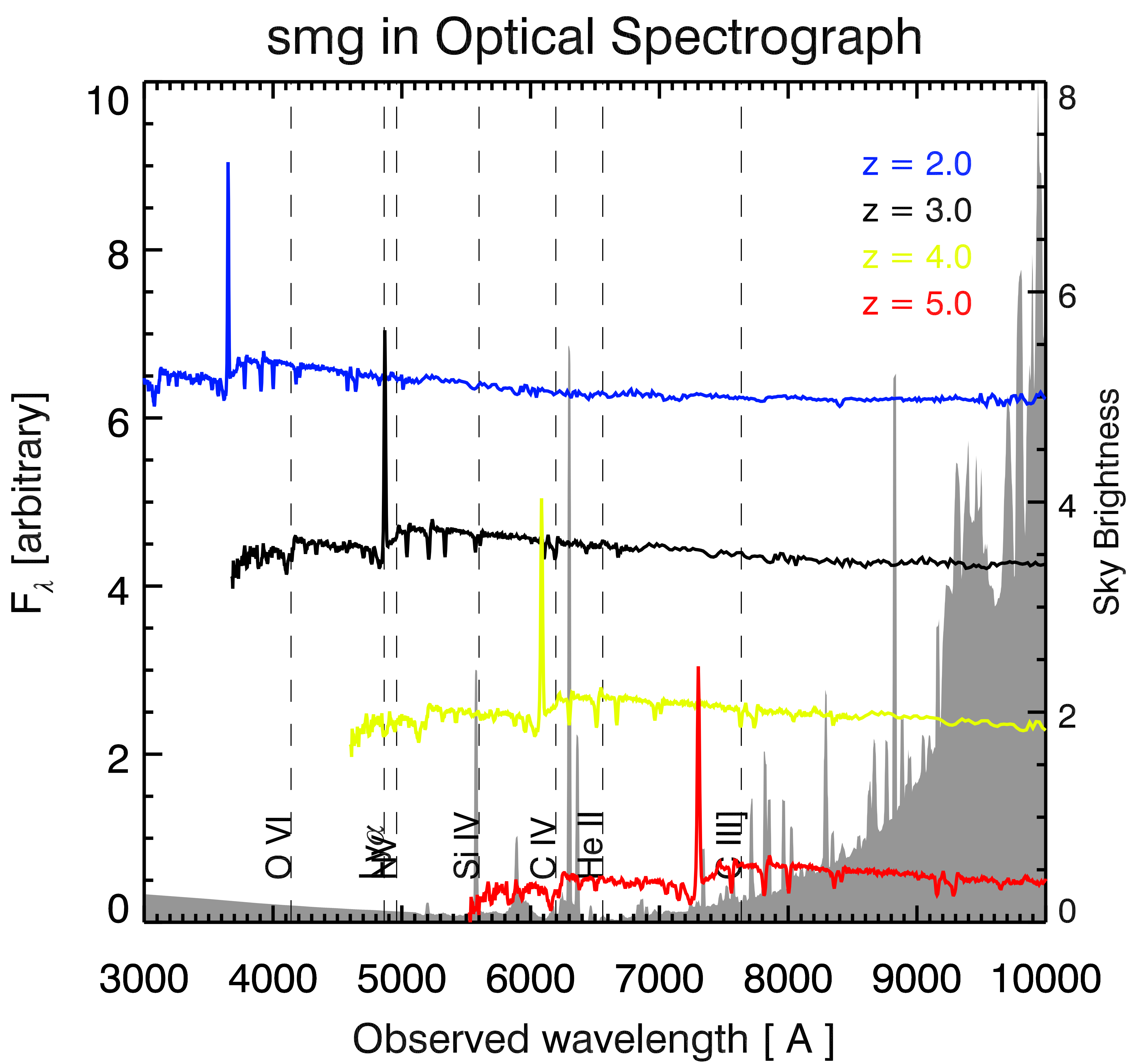
4) Estimate n(z)

Chapman et al ApJ 2005



Optical SED by Galaxy type





smg in Optical Spectrograph
z = 2.0
z = 3.0
z = 4.0
z = 5.0
O VI
Lyα
N V
Si IV
C IV
He II
C III]
10
8
6
4
2
0
3000
4000
5000
6000
7000
8000
9000
10000
F_λ [arbitrary]
Sky Brightness
Observed wavelength [A]

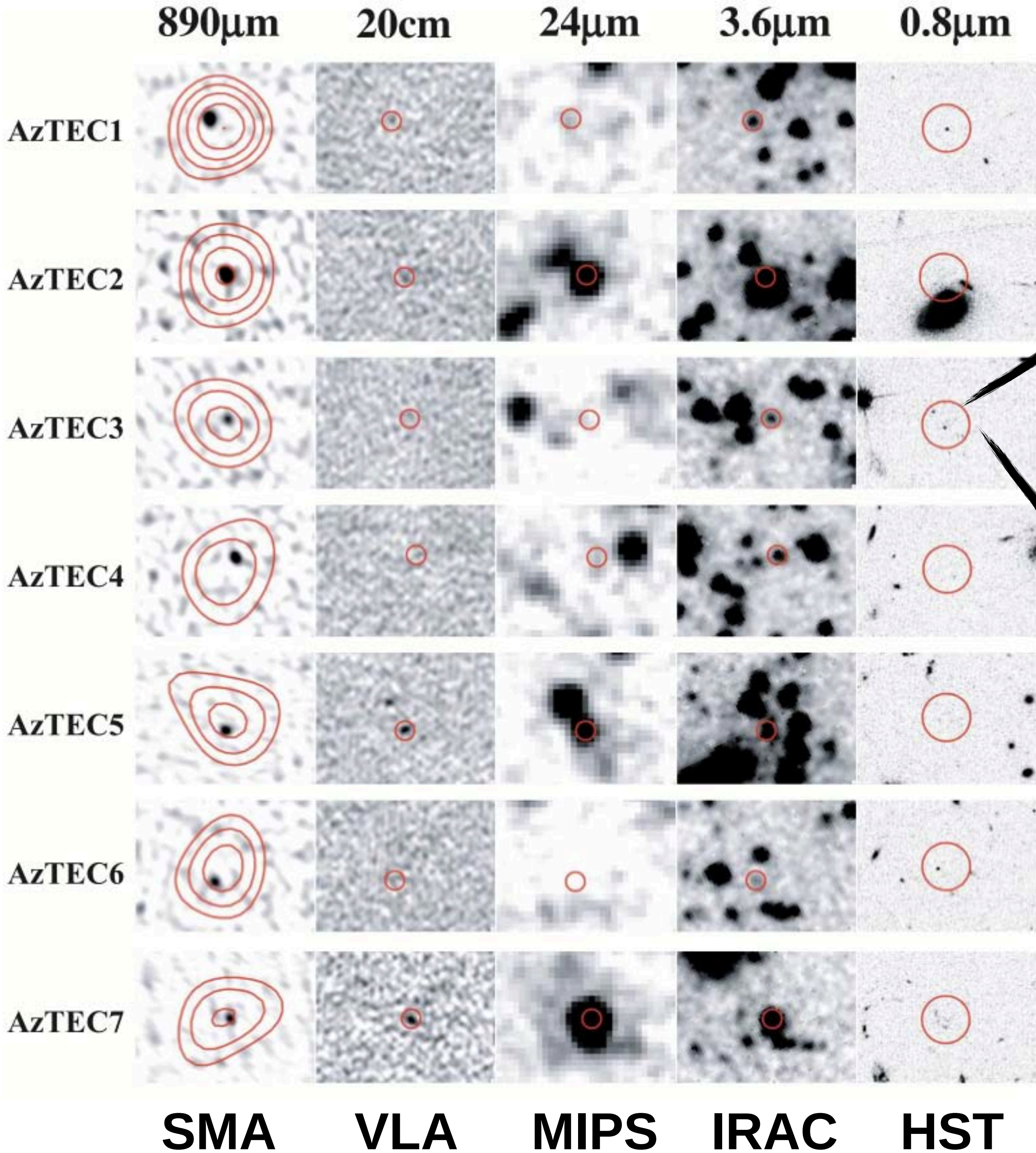
Redshifts: Better

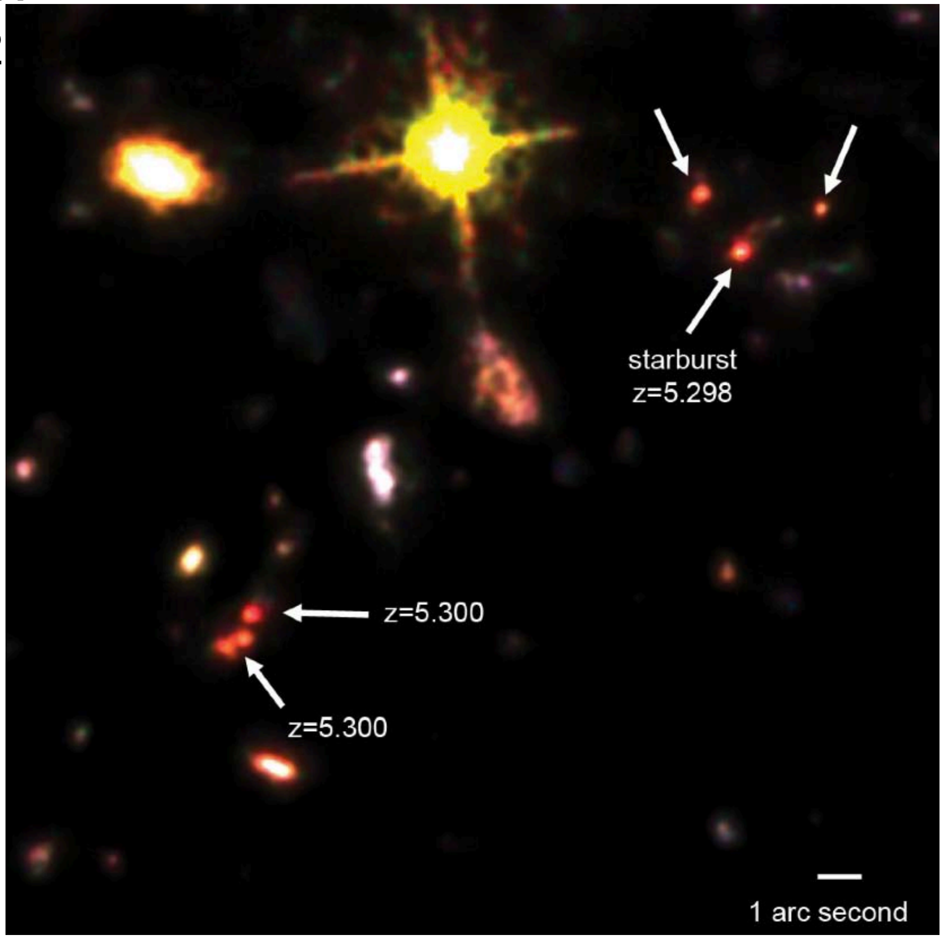
1) Blank field submm survey

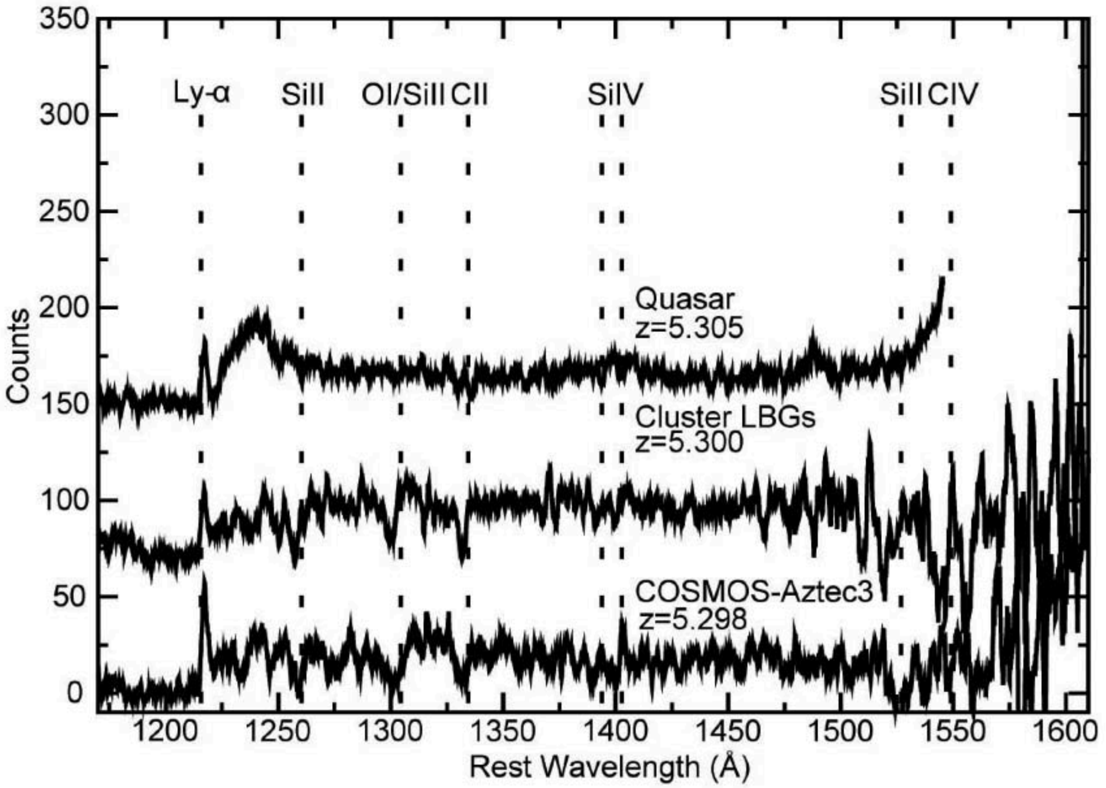
2) Followup with submm interferometer
Younger *et al.* ApJ 2007, Smolcic *et al.* A&A 2012

3) Obtain Keck spectroscopy
Capak *et al.* Nature 2011

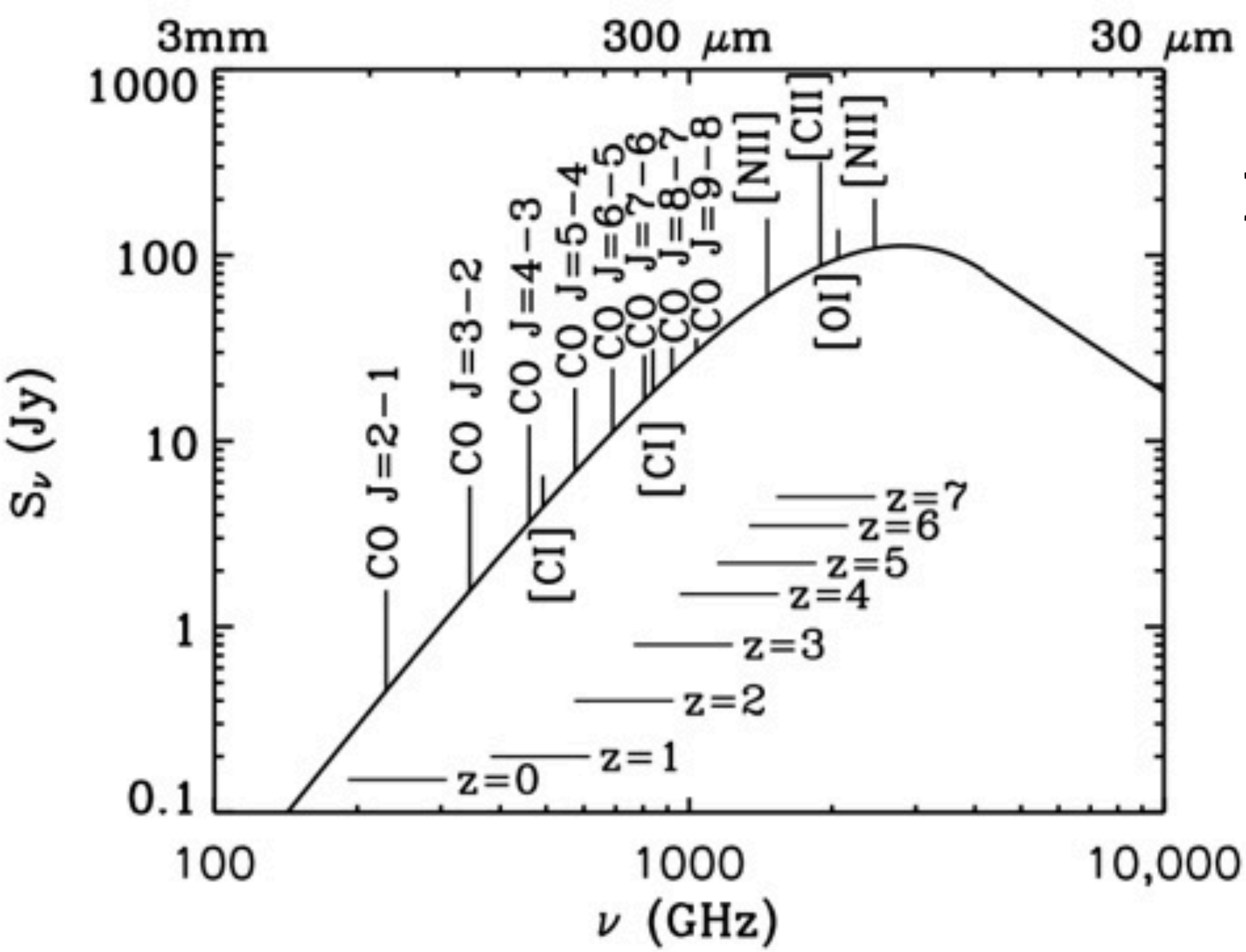
AzTEC3 z = 5.3



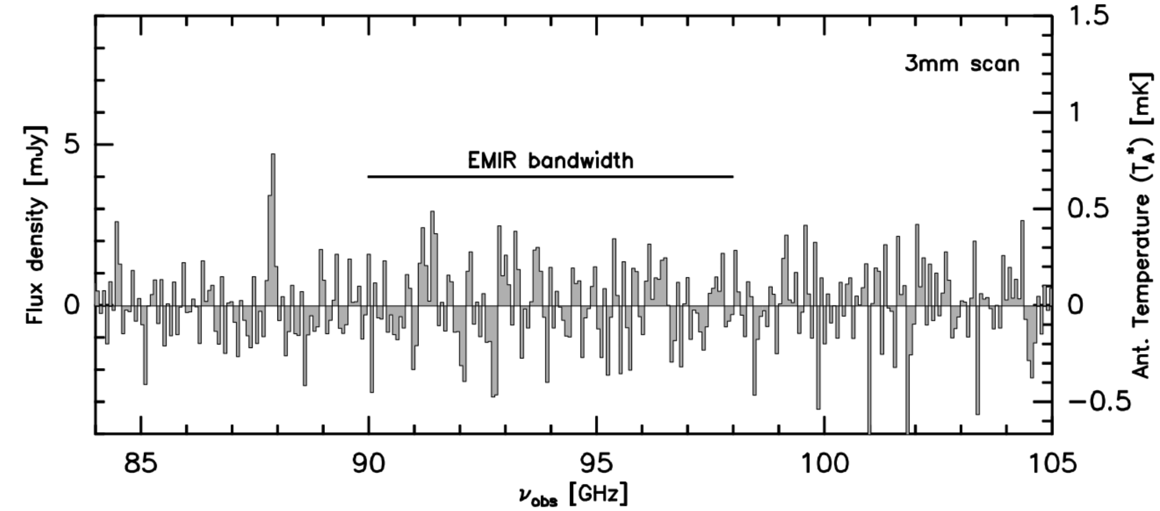




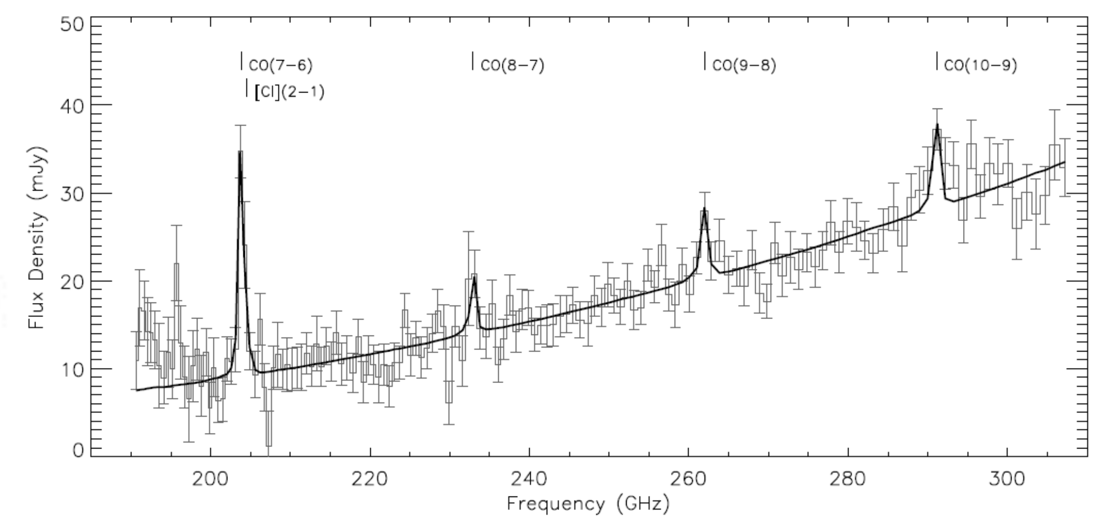
spectroscopic redshifts with carbon monoxide



IRAM/EMIR Weiss *et al*. 2009



CSO/Z-Spec Scott *et al*. 2011



- $L_{CO} / L_{FIR} \sim 10^{-5}$
- CO ladder at 115 GHz spacing → 2 lines gives a redshift
- CO traces molecular gas, dust mass
- width gives dynamical mass
- excitation ladder constrains conditions of molecular gas

Redshifts: Best

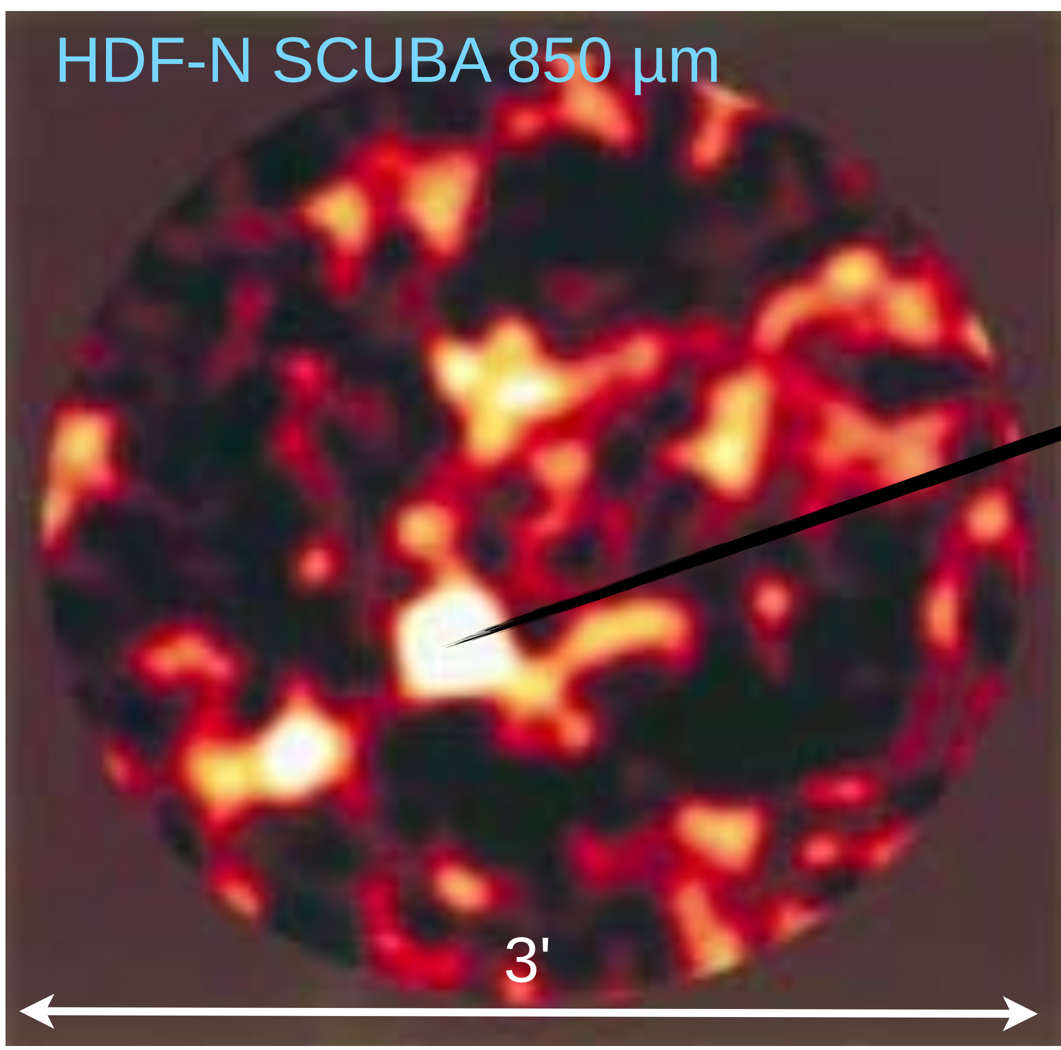
HDF850.1 z = 5.2

100 hours with PdBI

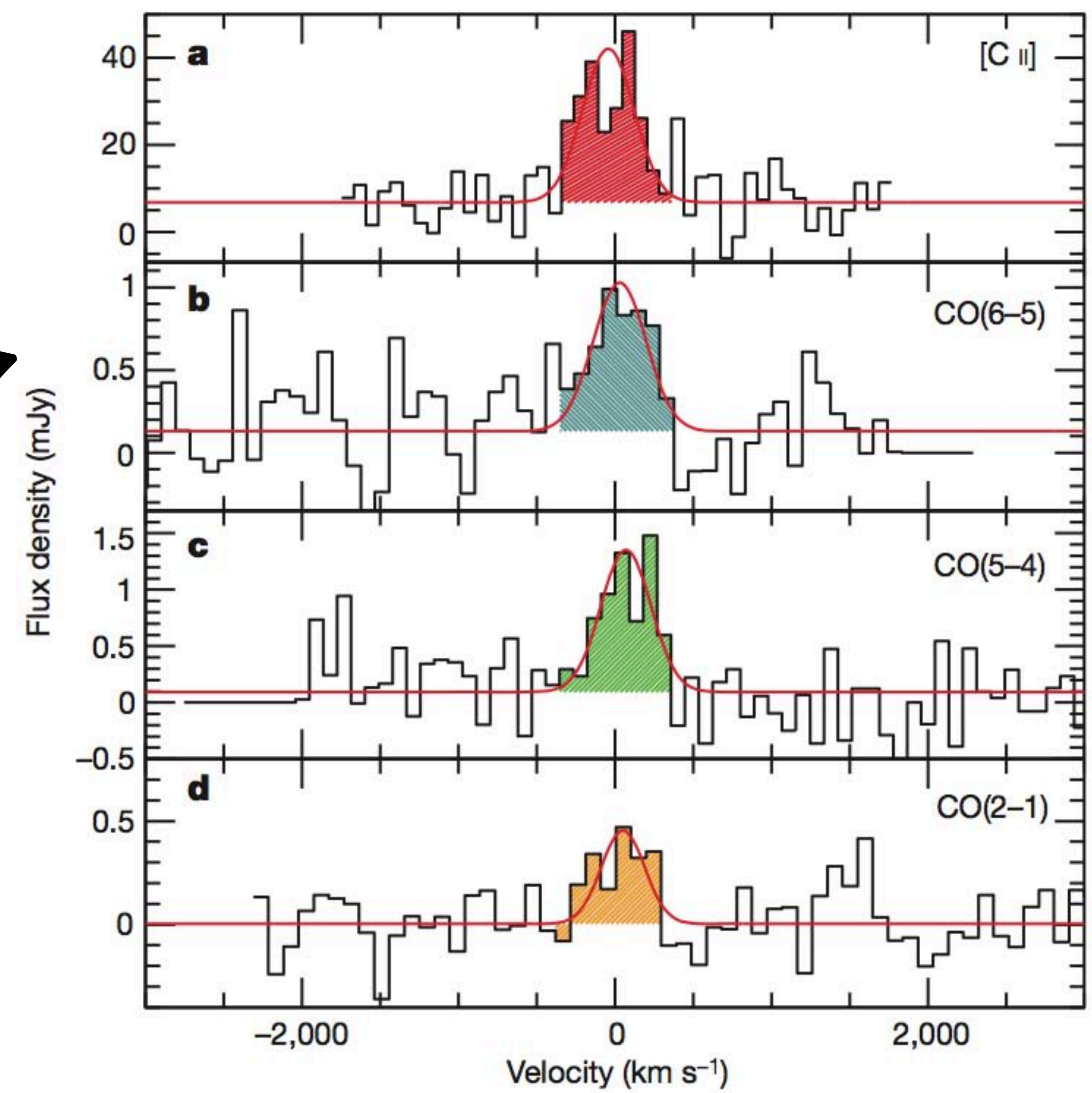
1) Blank field submm survey

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

Hughes *et al.* Nature 1998



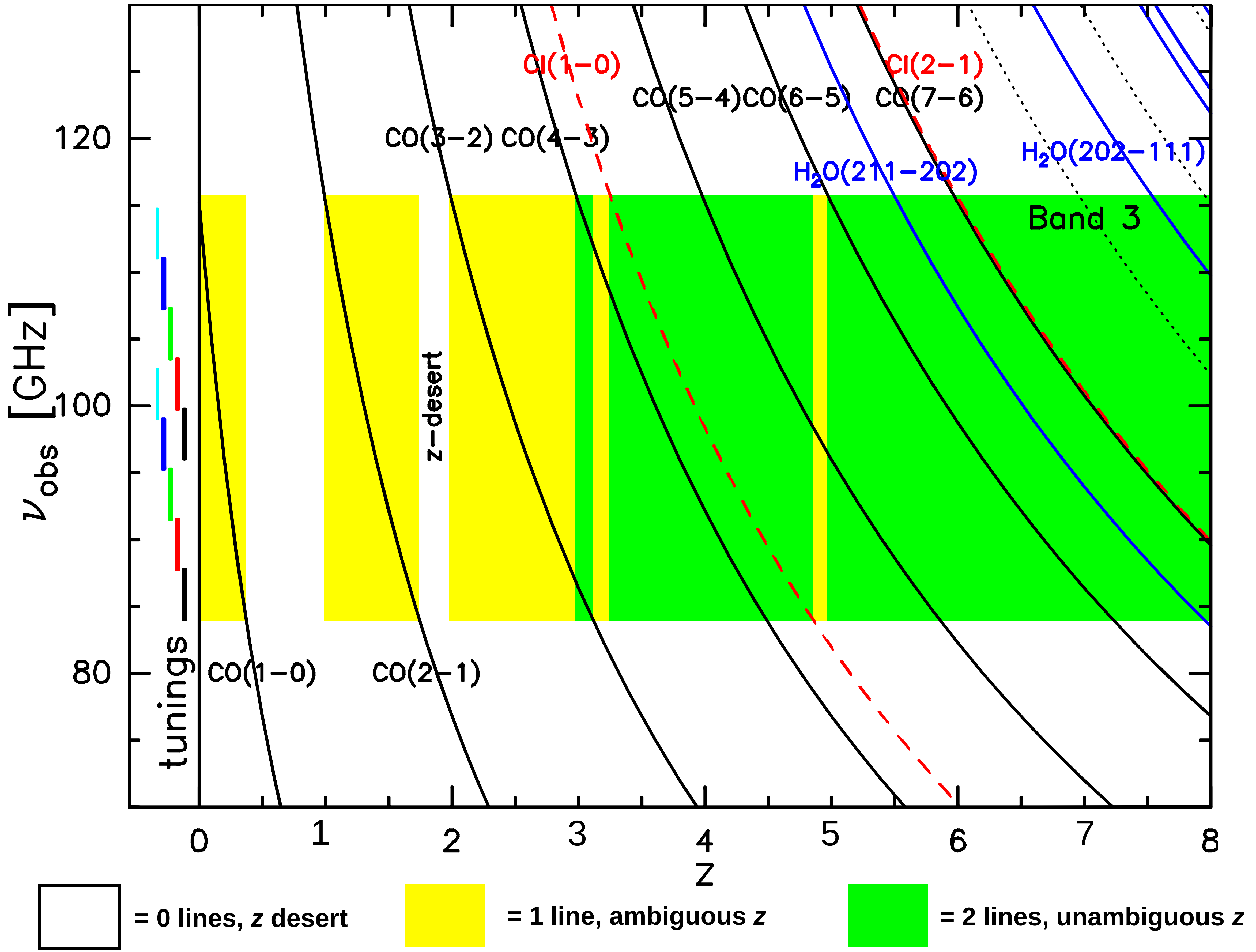
Walter *et al.* Nature 2012



ALMA: Atacama Large (sub) Millimeter Array

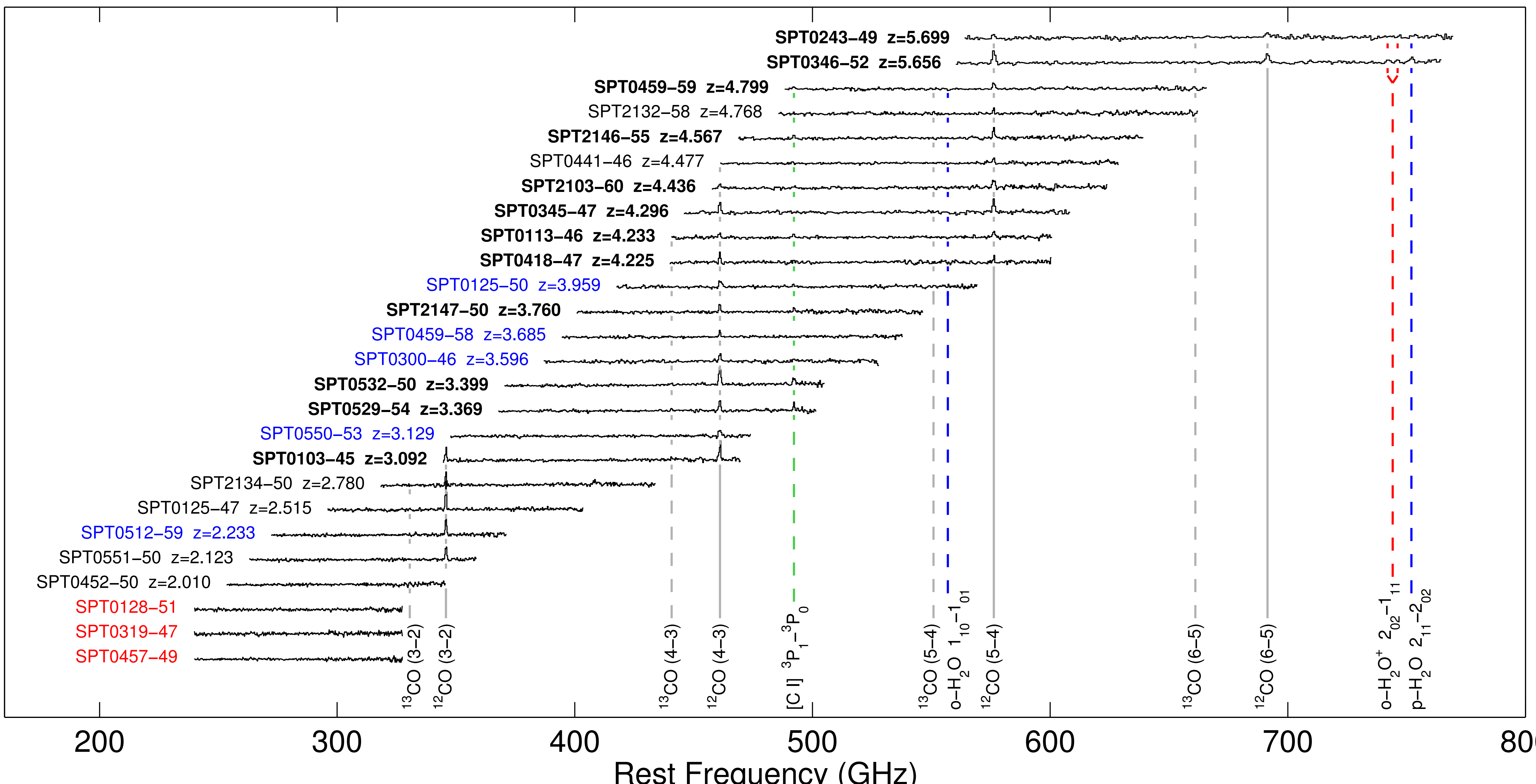
- Largest ground based astronomy project of all time (~$1B)
- Joint partnership between ESO, North America, and Asia
- Located at 5000m on the Atacama Plateau in Chile
- 50x12m antennas operating between 30-1000 GHz
- Resolution greater than Hubble
- Unprecedented sensitivity
- Started taking data in 2012
- First call was x10 oversubscribed

SPT+ALMA CO z-search



First spectroscopic redshift survey with ALMA

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



Vieira *et al.* 2013 Nature

Bold = unambiguous redshift from ALMA

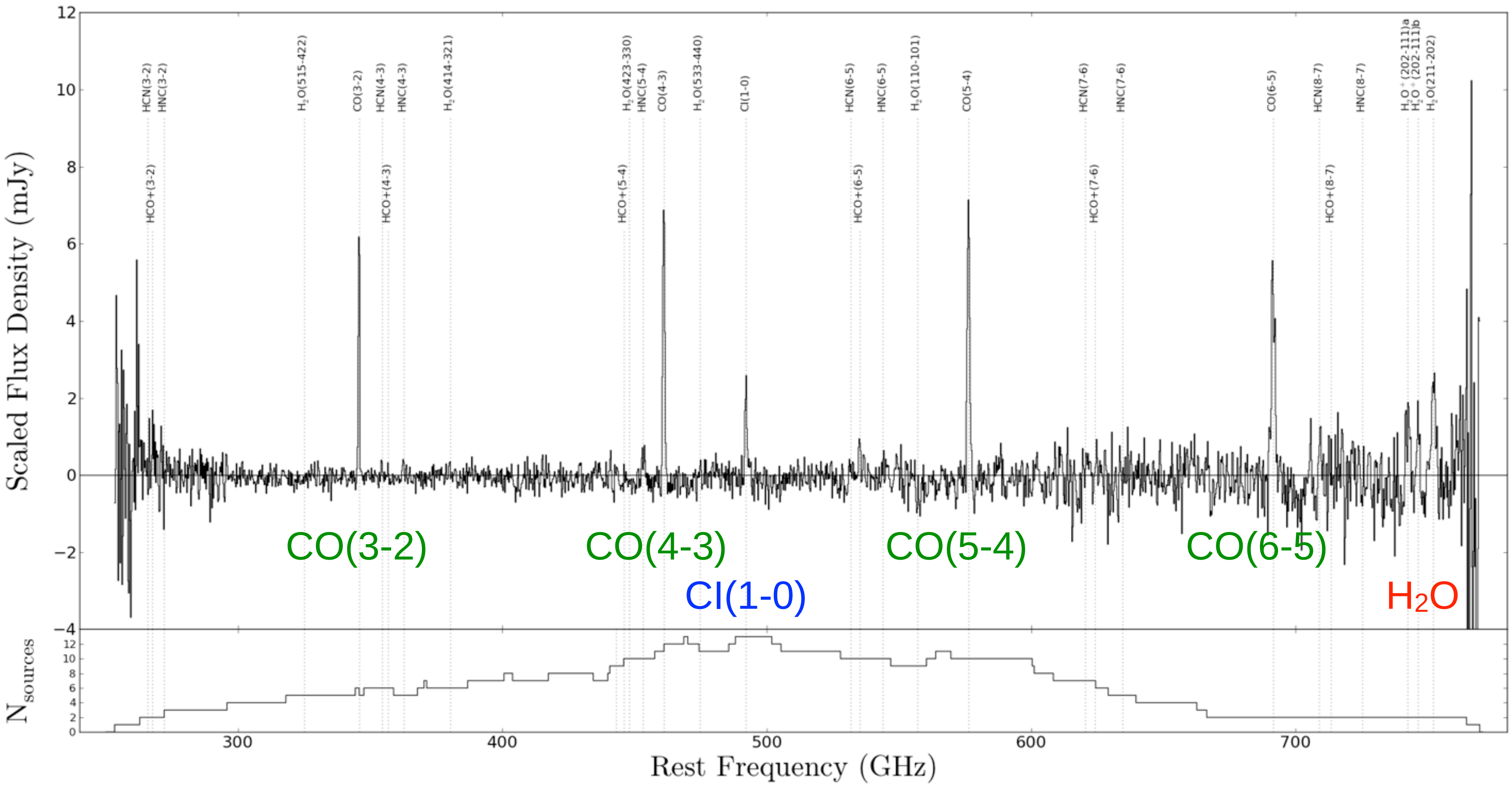
black = single lines with ALMA, confirmed with C+ or CO(1-0) with APEX or ATCA

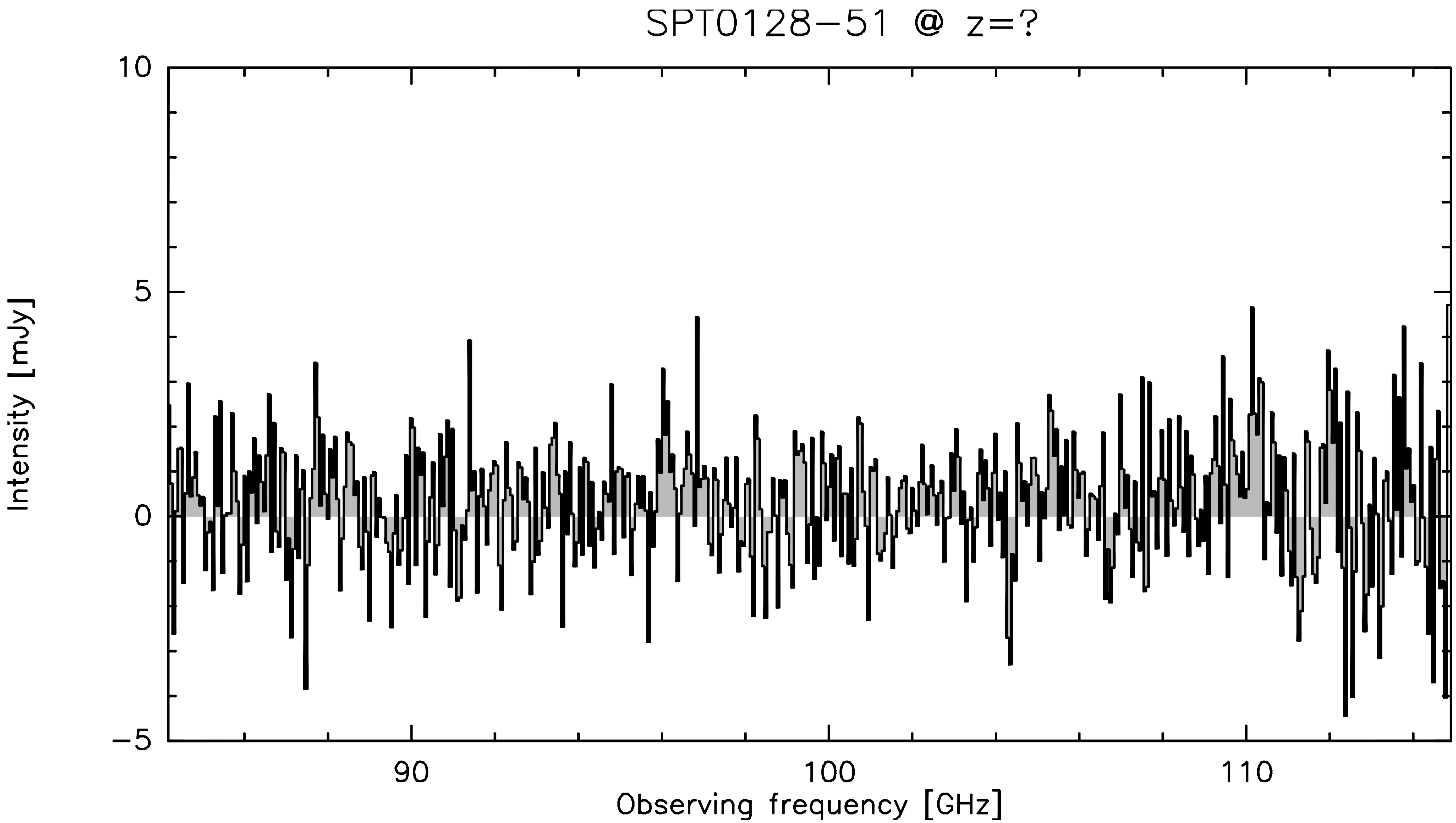
blue = single line detected with redshift, most likely redshift from photo-z

red = no line detected

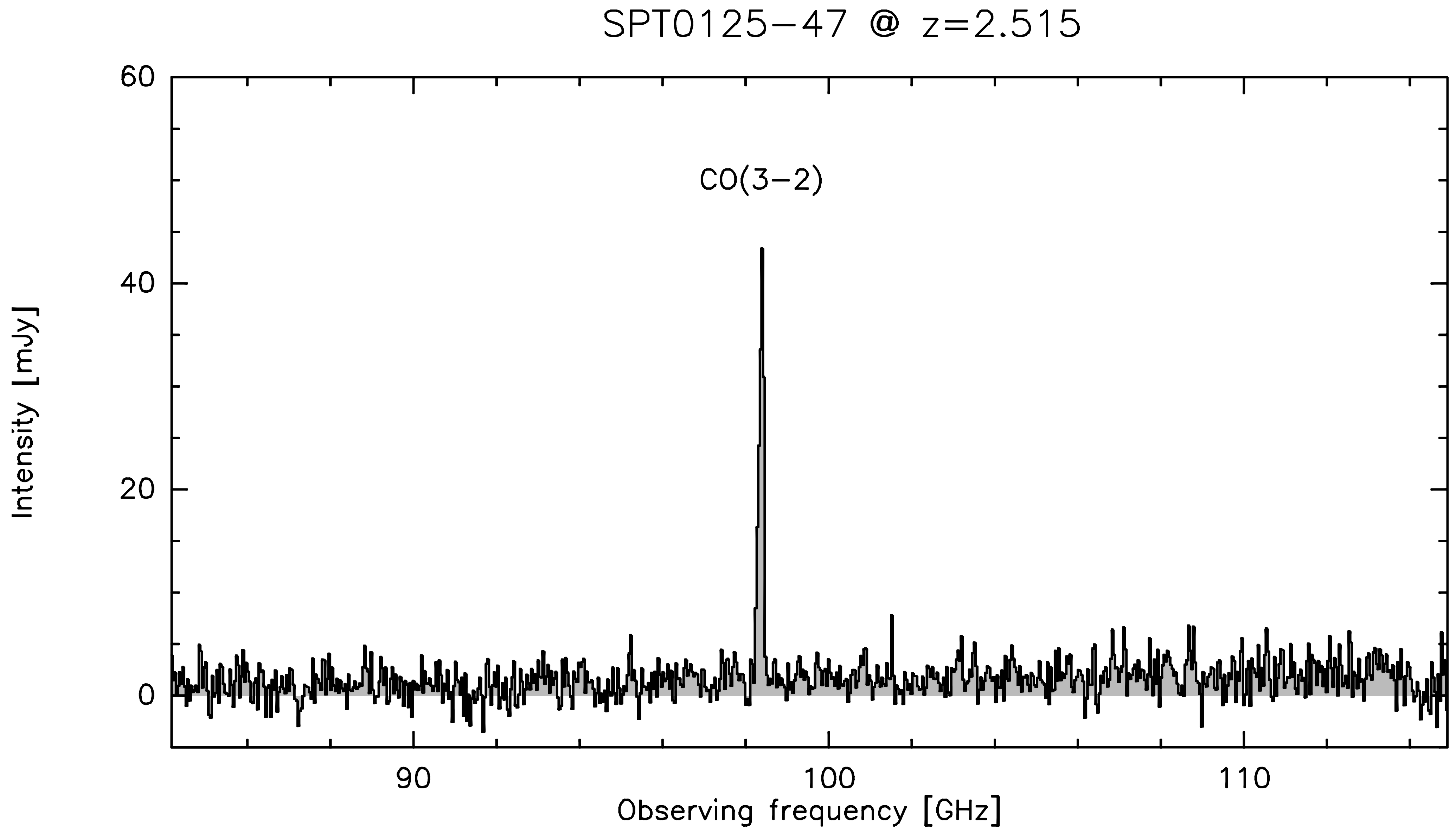
Stacked spectra

Spilker *et al. in prep*

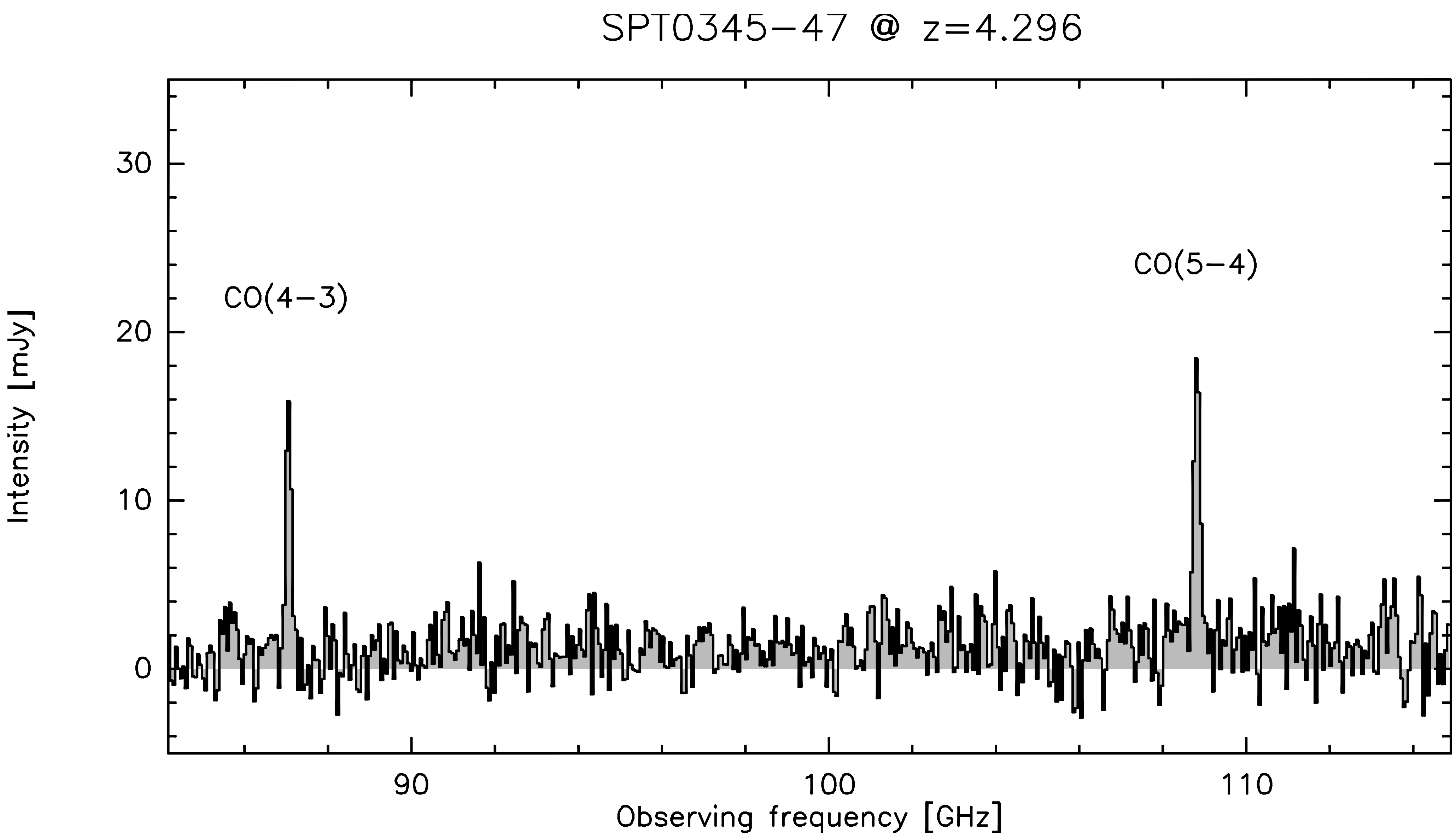




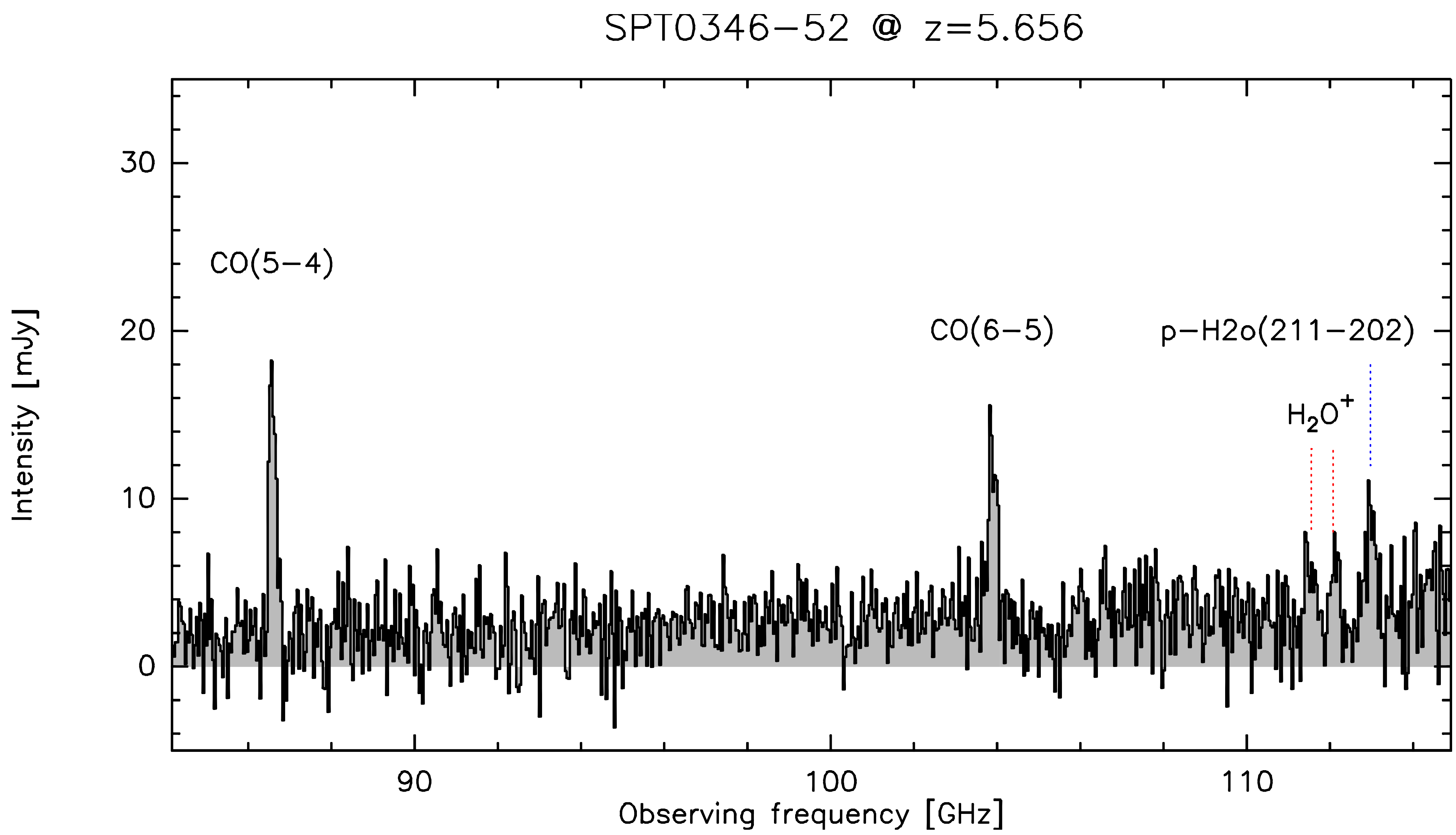
3/26 sources have no lines.
All sources are detected in the continuum.
Initially, we are conservatively placing them in the redshift desert between $1.7 < z < 2.0$



11/26 have single lines detected
For 6 sources we can break the redshift degeneracy with Z-Spec, VLT, APEX, or ATCA
The others (5) we use FIR photo-z's



12/26 have two or more lines detected.



we found some cool stuff !

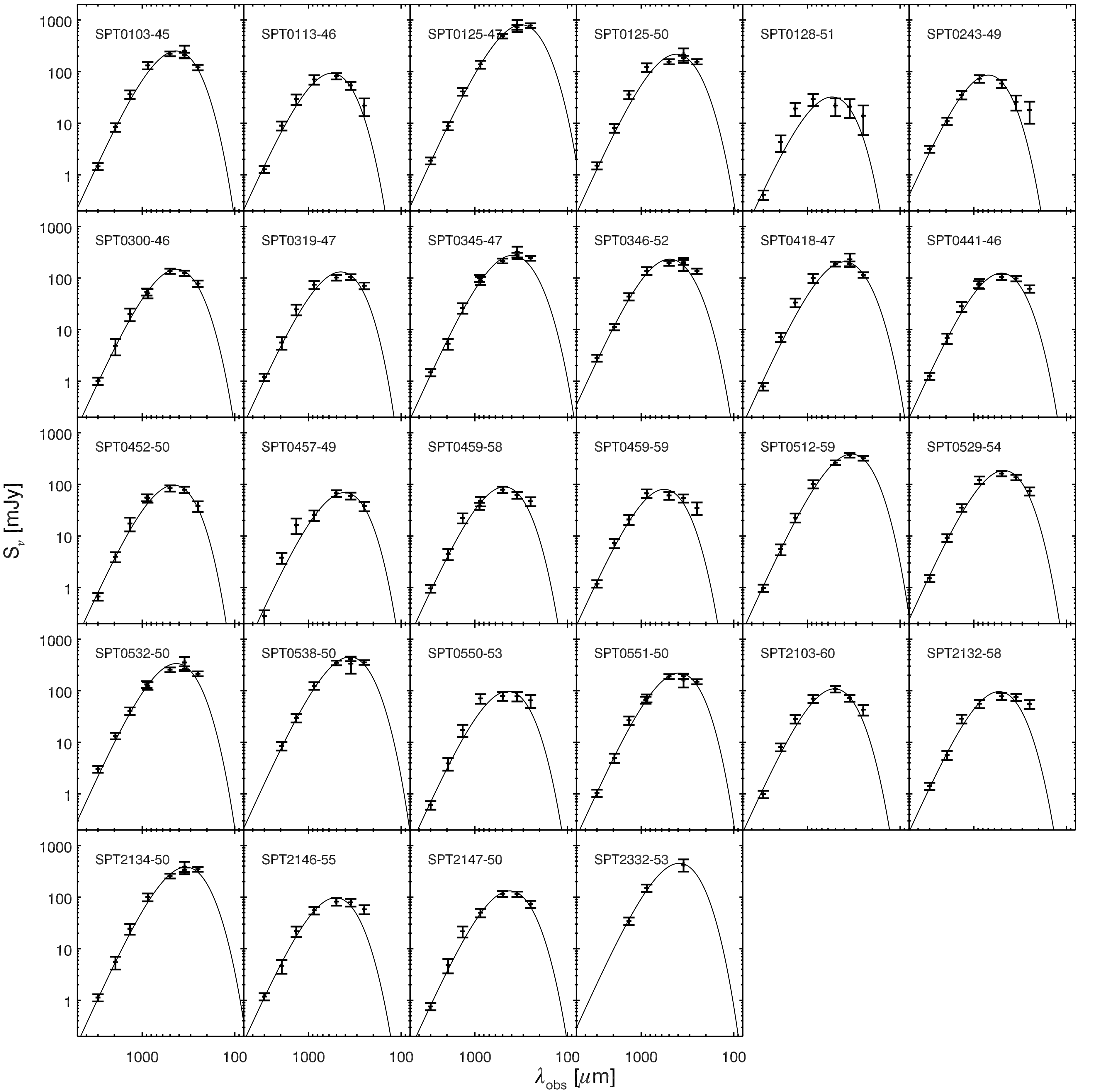
SED fits to all sources

ALMA 3 mm

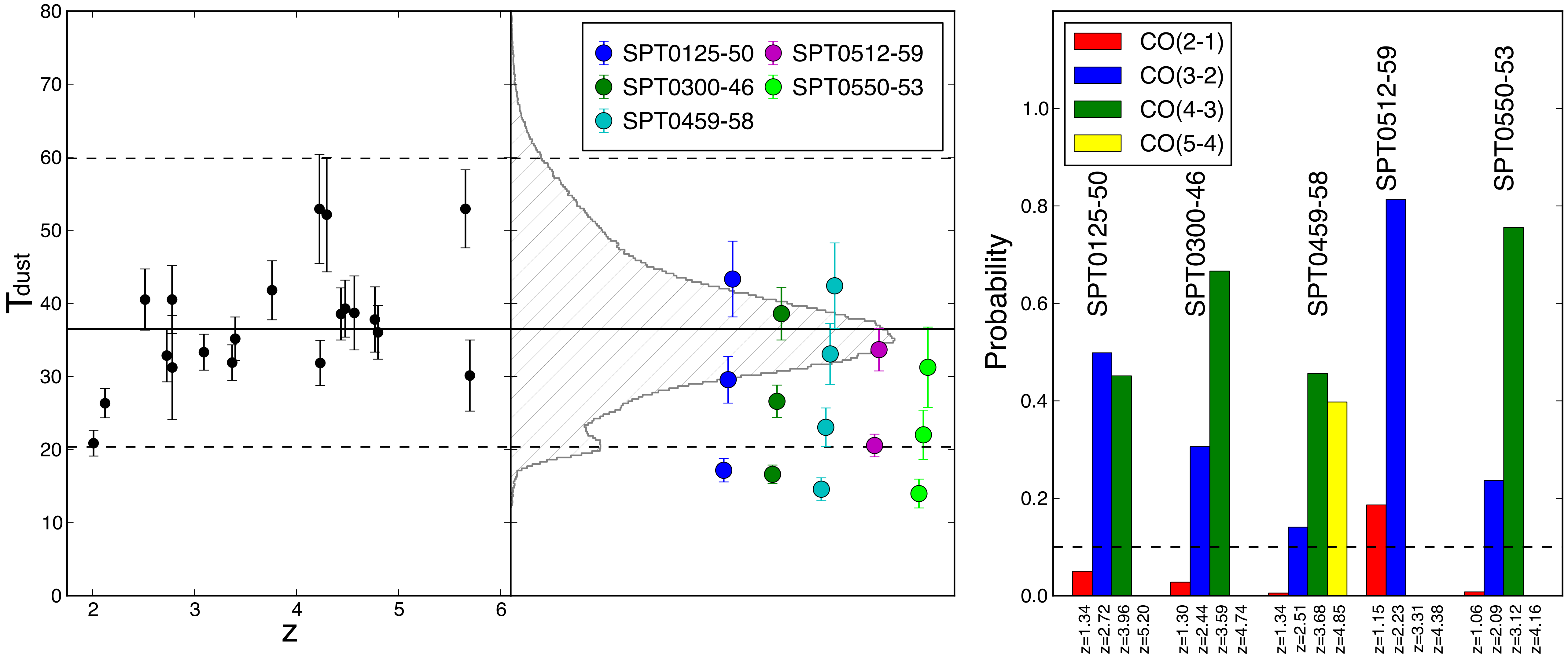
SPT 1.4 + 2.0 mm

LABOCA 870 µm

SPIRE 250+350+500 µm



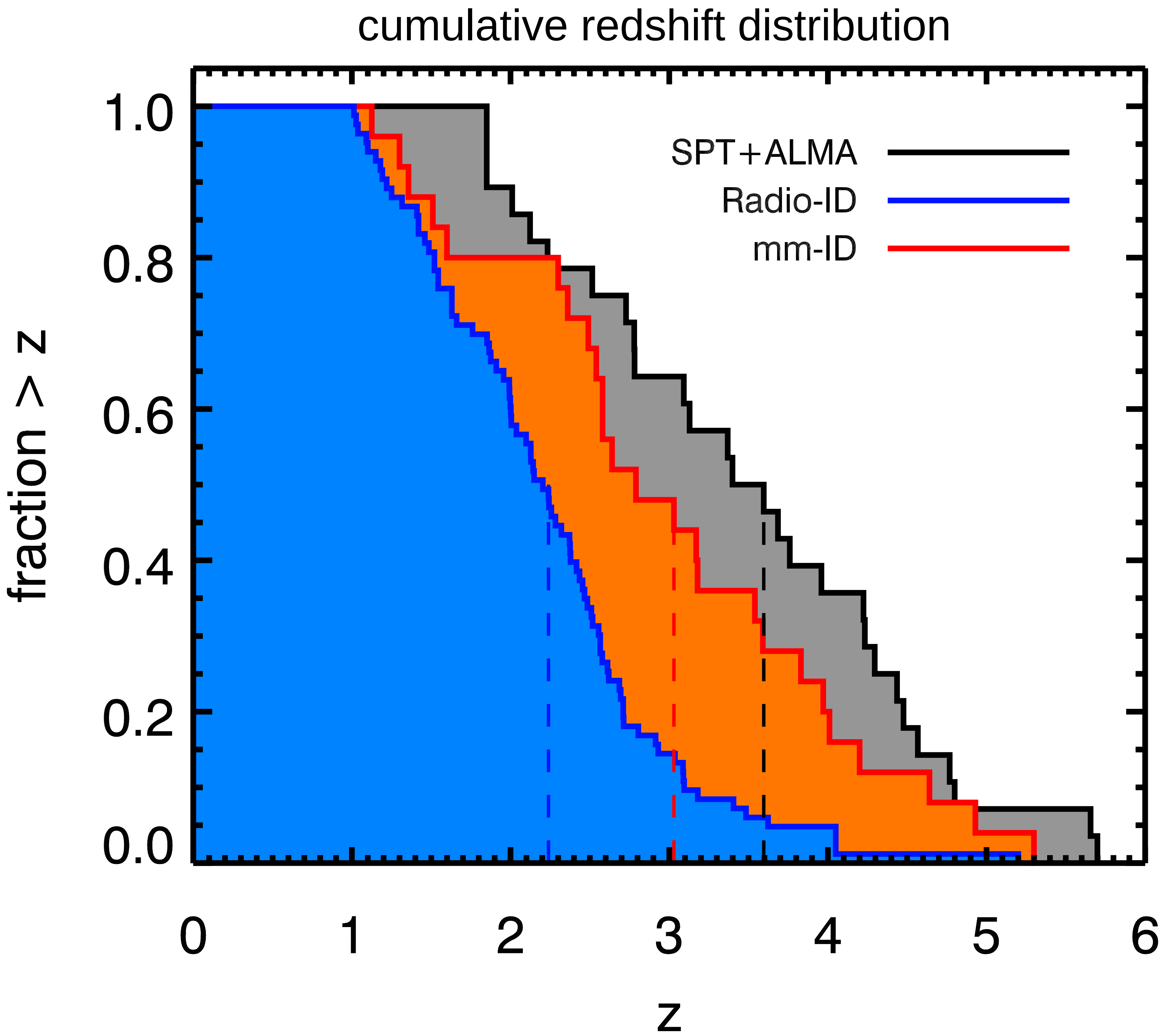
distribution of T_d ⇒ z probability estimator



For the sources with ambiguous (single line) redshifts, we can assign a most probable redshift based off of FIR photo-z's

Weiss *et al.* 2013 ApJ

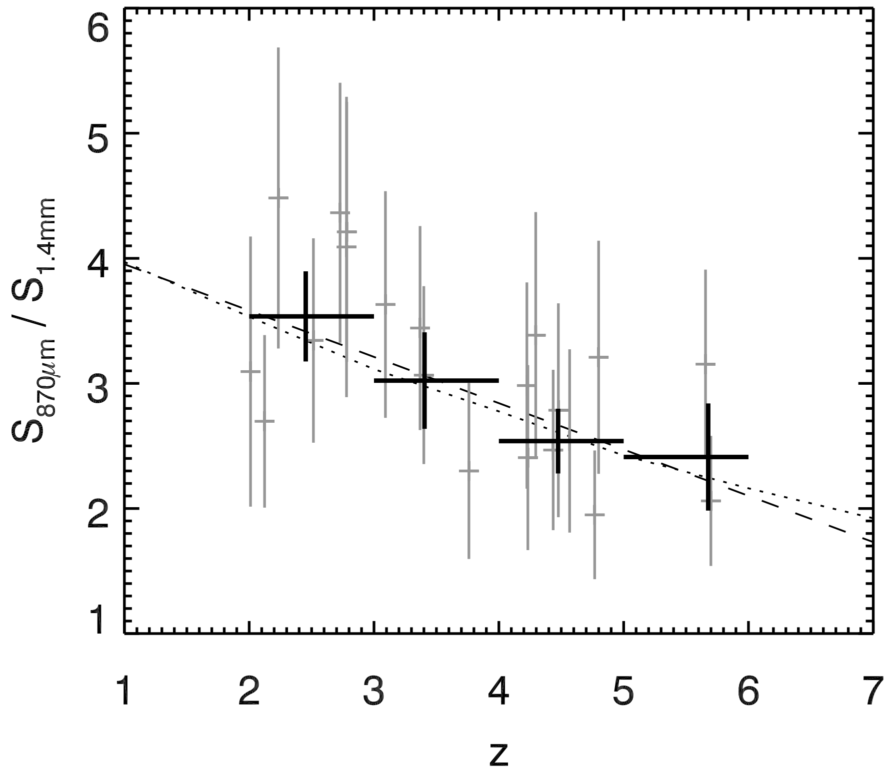
SPT + ALMA n(>z)



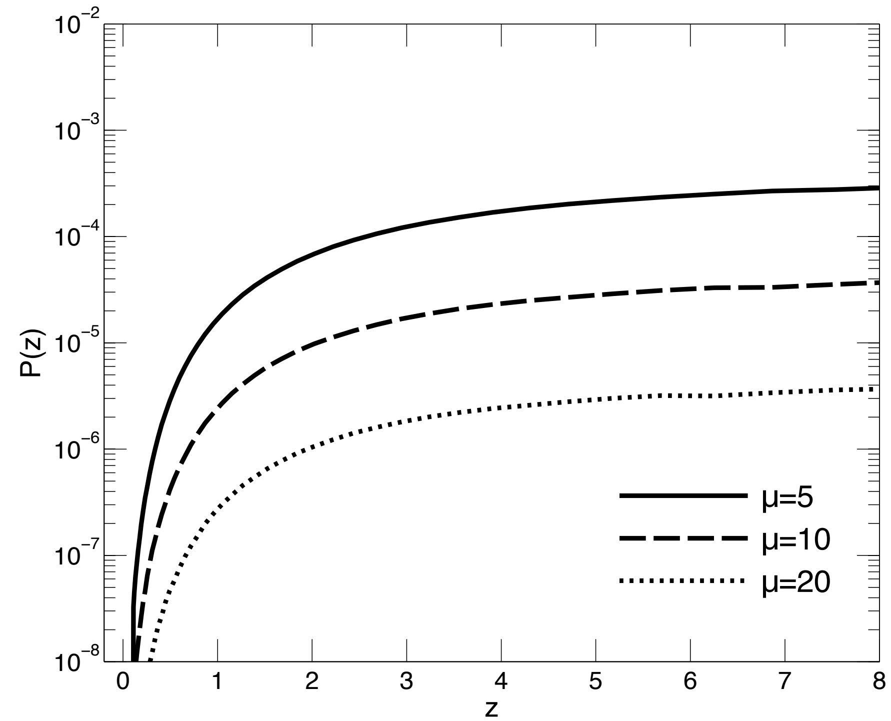
Vieira *et al.* 2013 Nature

Biases on n(z)

long wavelength selection

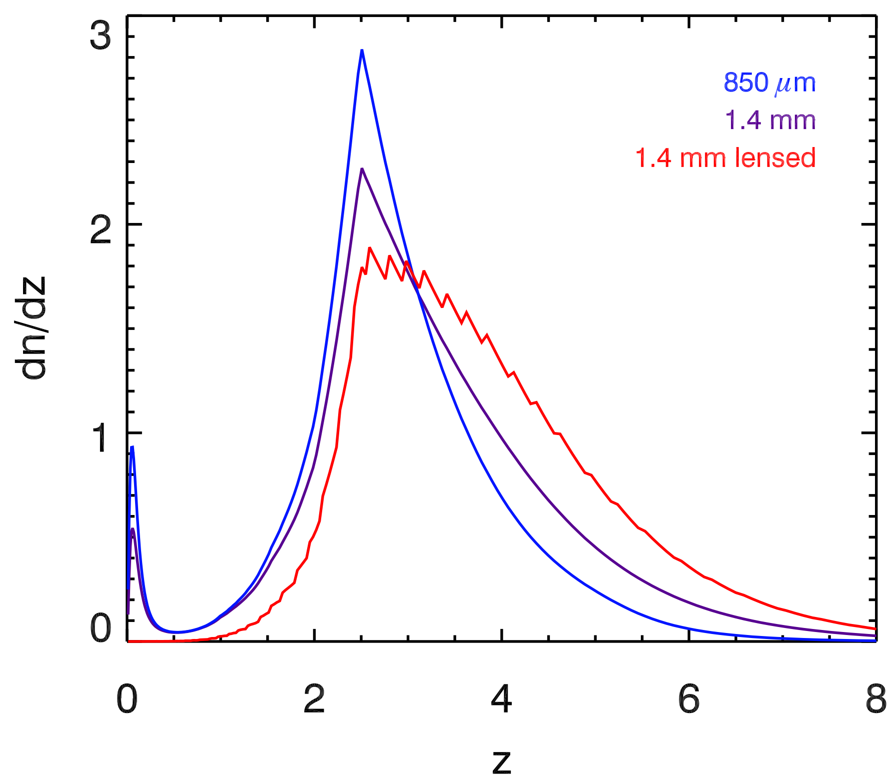


bias due to strong lensing



Hezaveh & Holder 2011 lens model

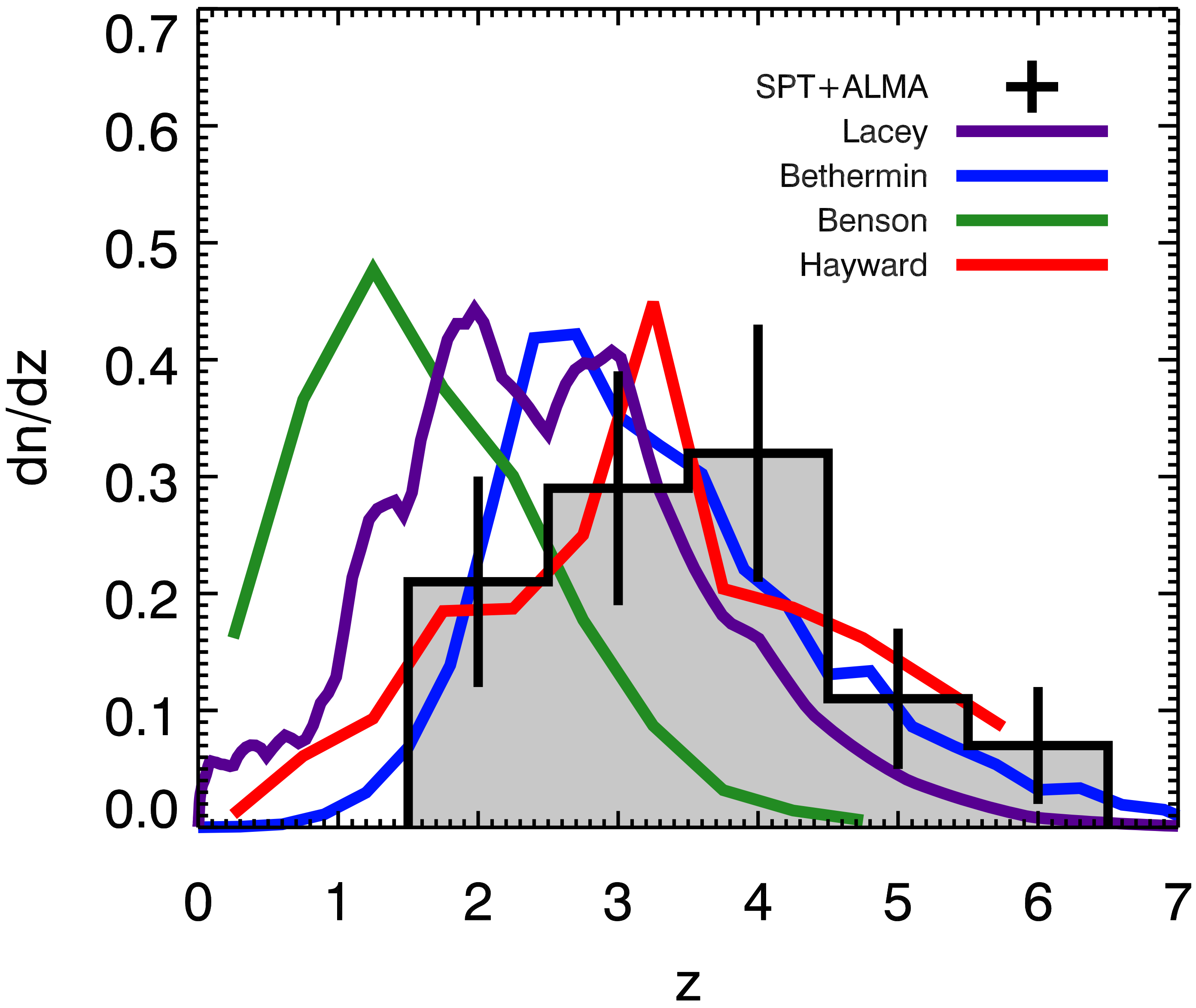
combined effect



Bethermin 2012 CIB model
+
Hezaveh lens model

SPT+ALMA redshift distribution

Weiss *et al.* 2013 ApJ



- We have a well-defined selection function based off of a uniform flux cut
- We obtained redshifts for 90% of sources without any additional selection biases
- This redshift distribution already provides powerful constraints for models of galaxy evolution

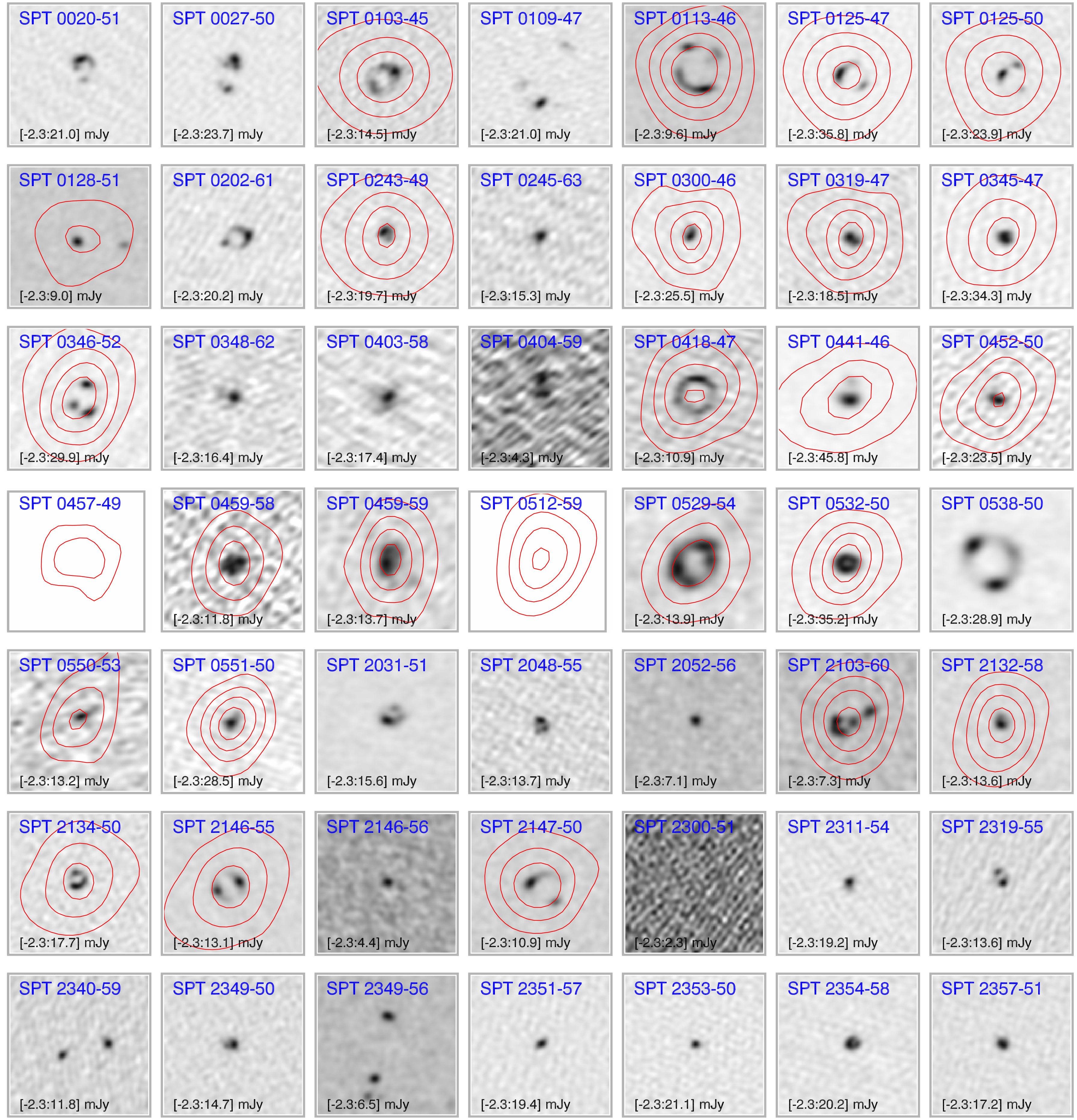
ALMA Cycle 0

Imaging

Band 7 350 GHz
47 sources
2 minute snapshots
~0.5" resolution
PI: D. Marrone

Redshift Search

Band 3 100 GHz
26 sources
10 min integrations
5 tunings
~6" resolution
PI: A. Weiss



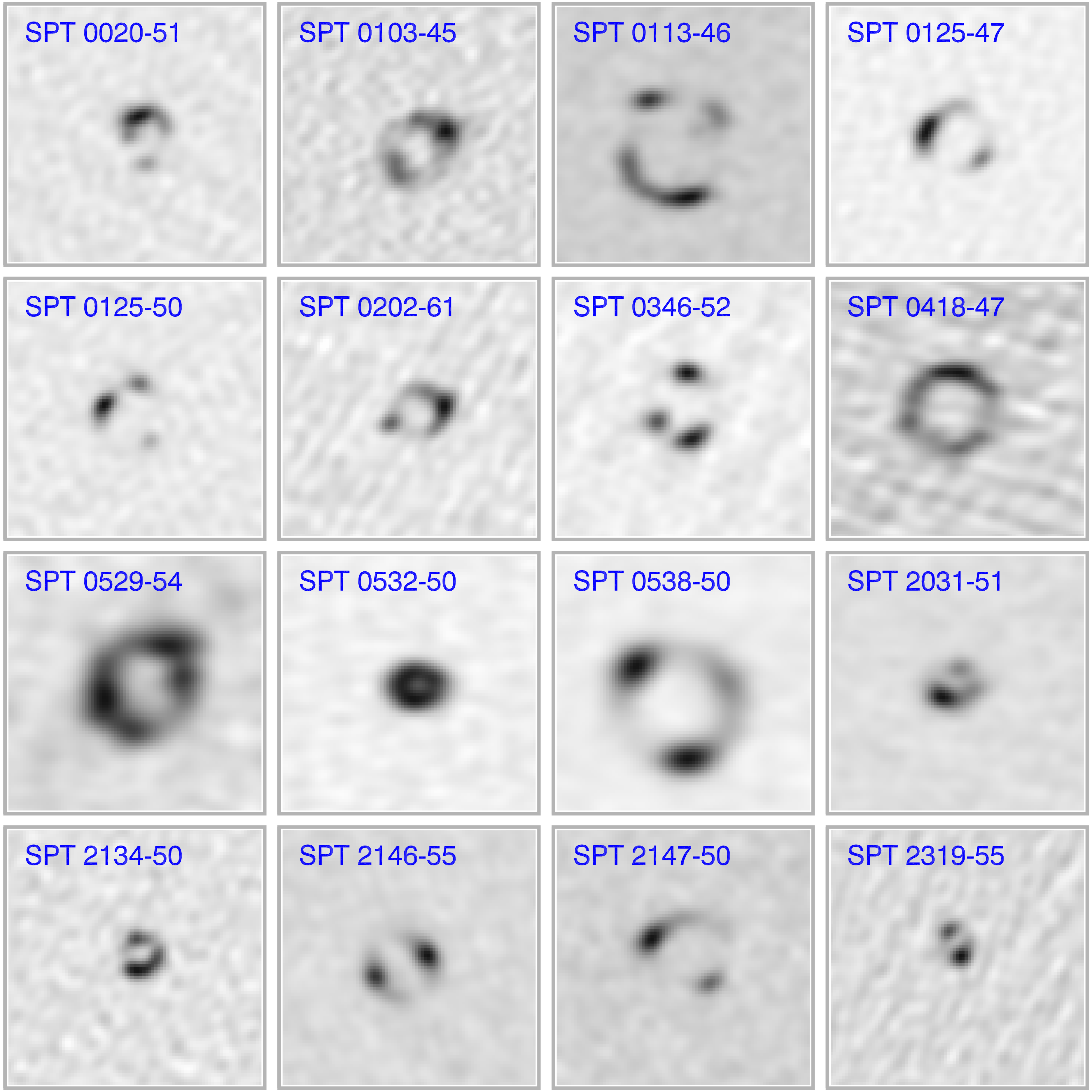
= 850 µm continuum

= 3 mm continuum

ALMA Cycle 0

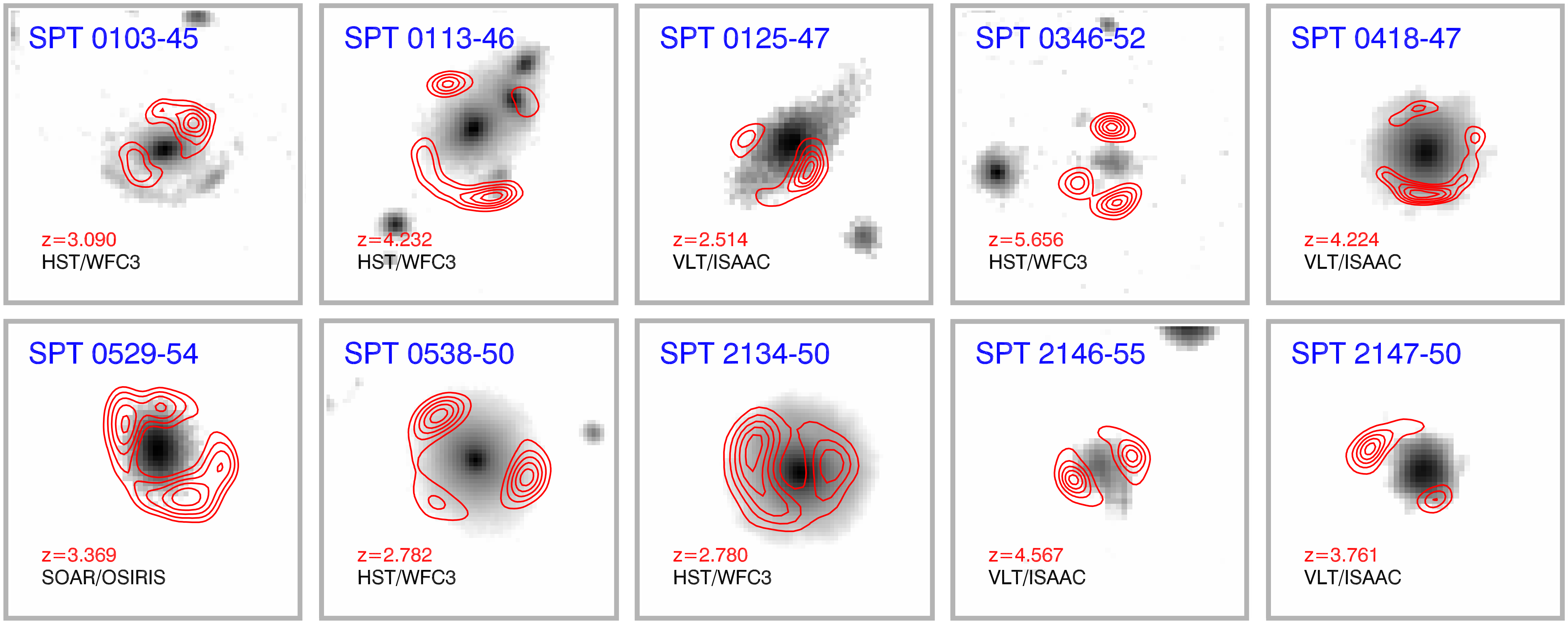
Imaging

Band 7 350 GHz
~0.5" resolution
8"x8" thumbnails
2 minute snapshots



ALMA Cycle 0 Band 7 350 GHz
2 minute snapshots

Vieira *et al.* 2013 Nature



8" x 8" boxes

= deep NIR imaging

= 2 minute ALMA 350 GHz snapshot

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

Lens models

SPT 0346-52

$z_S = 5.67$; $z_L \sim 0.8$
$r_E = 1.1$ arcsec
$M_L = 3.7 \times 10^{11}\ M_\odot$
$\mu = 5.4$

$\Sigma_{FIR} = 24\text{x}10^{12}\ L_\odot/\text{kpc}^2$
$R_{1/2} = 0.6$ kpc
$L_{FIR} = 3.7 \times 10^{13}\ L_\odot$
$S_{850\mu m} = 25.5$ mJy

SPT 418-47

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

$\Sigma_{FIR} = 0.74\text{x}10^{12}\ L_\odot/\text{kpc}^2$
$R_{1/2} = 1.1$ kpc
$L_{FIR} = 3.8 \times 10^{12}\ L_\odot$
$S_{850\mu m} = 4.8$ mJy

SPT 0529-54

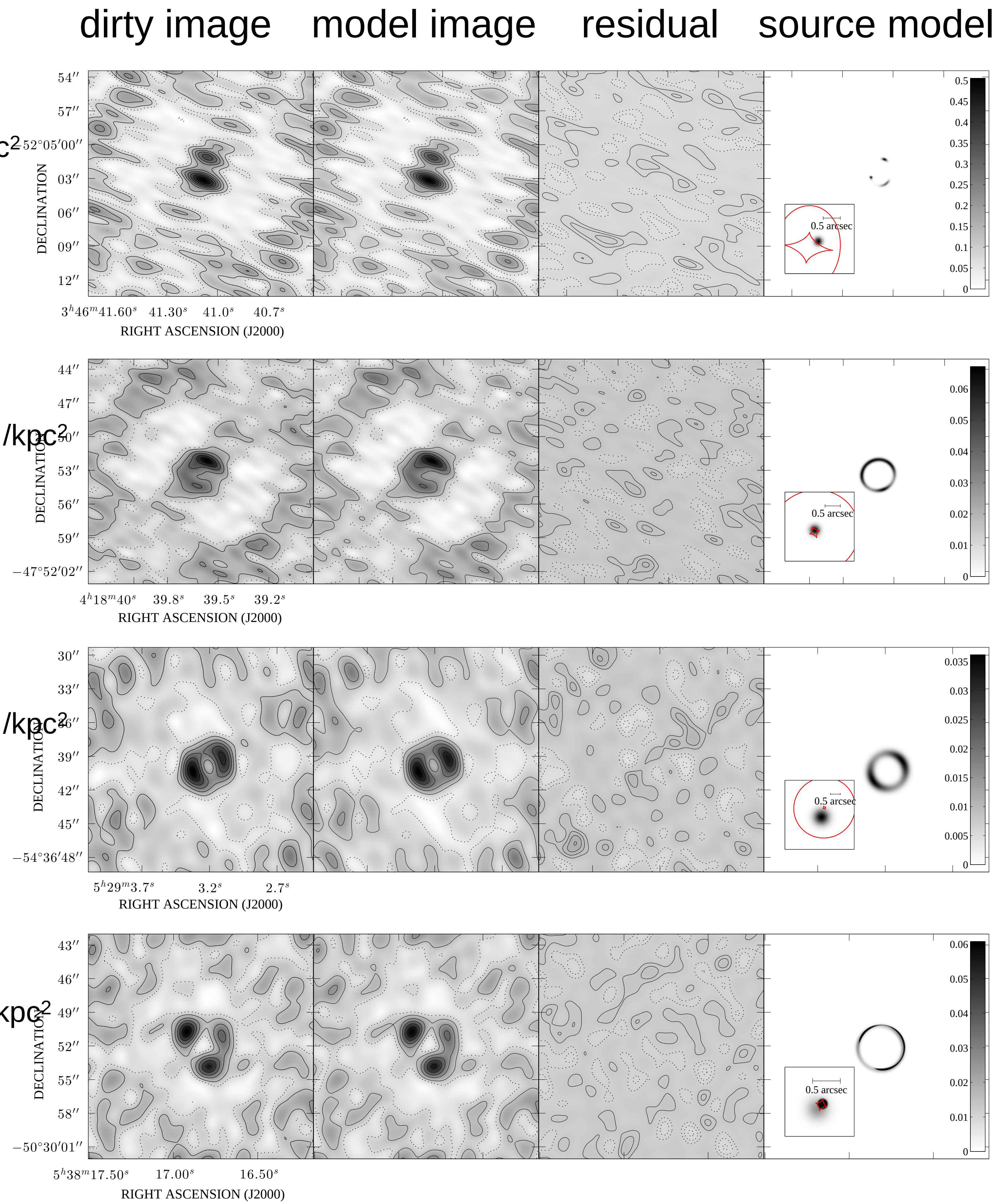
$z_S = 3.37$; $z_L = 0.13$
$r_E = 1.5$ arcsec
$M_L = 1.6 \times 10^{11}\ M_\odot$
$\mu = 9.4$

$\Sigma_{FIR} = 0.15\text{x}10^{12}\ L_\odot/\text{kpc}^2$
$R_{1/2} = 2.4$ kpc
$L_{FIR} = 3.8 \times 10^{12}\ L_\odot$
$S_{850\mu m} = 13$ mJy

SPT 0538-50

$z_S = 2.782$; $z_L = 0.4$
$r_E = 2.0$ arcsec
$M_L = 7.2 \times 10^{11}\ M_\odot$
$\mu = 20.5$

$\Sigma_{FIR} = 1.0\text{x}10^{12}\ L_\odot/\text{kpc}^2$
$R_{1/2} = 1.0$ kpc
$L_{FIR} = 4.5 \times 10^{12}\ L_\odot$
$S_{850\mu m} = 6.1$ mJy

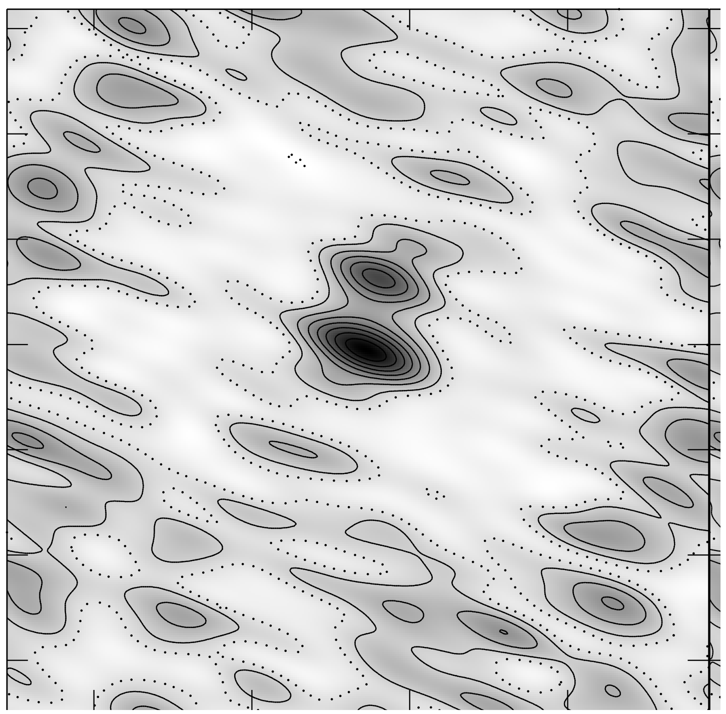


Hezaveh *et al.* 2013, ApJ

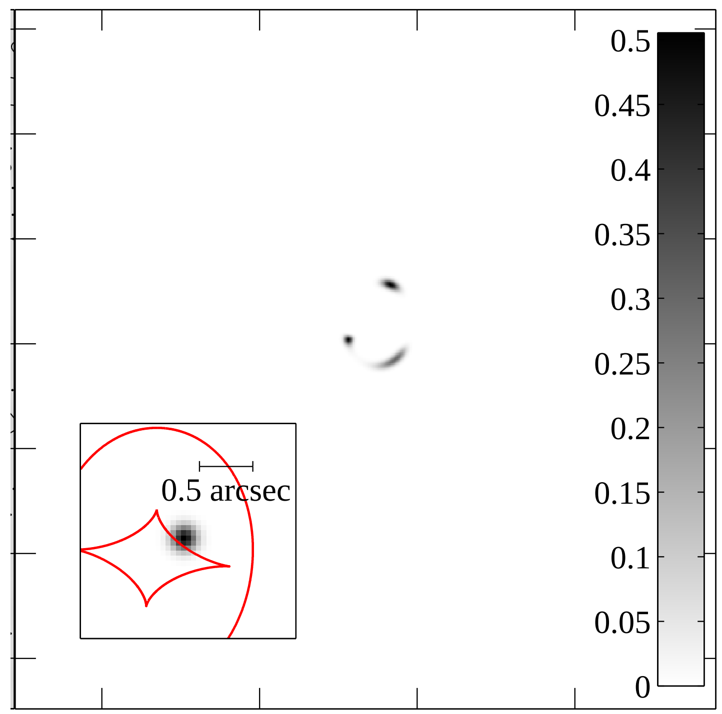
Lens Modeling

Hezaveh, Marrone, Fassnacht, Spilker, Vieira, *et al.* 2012, ApJ

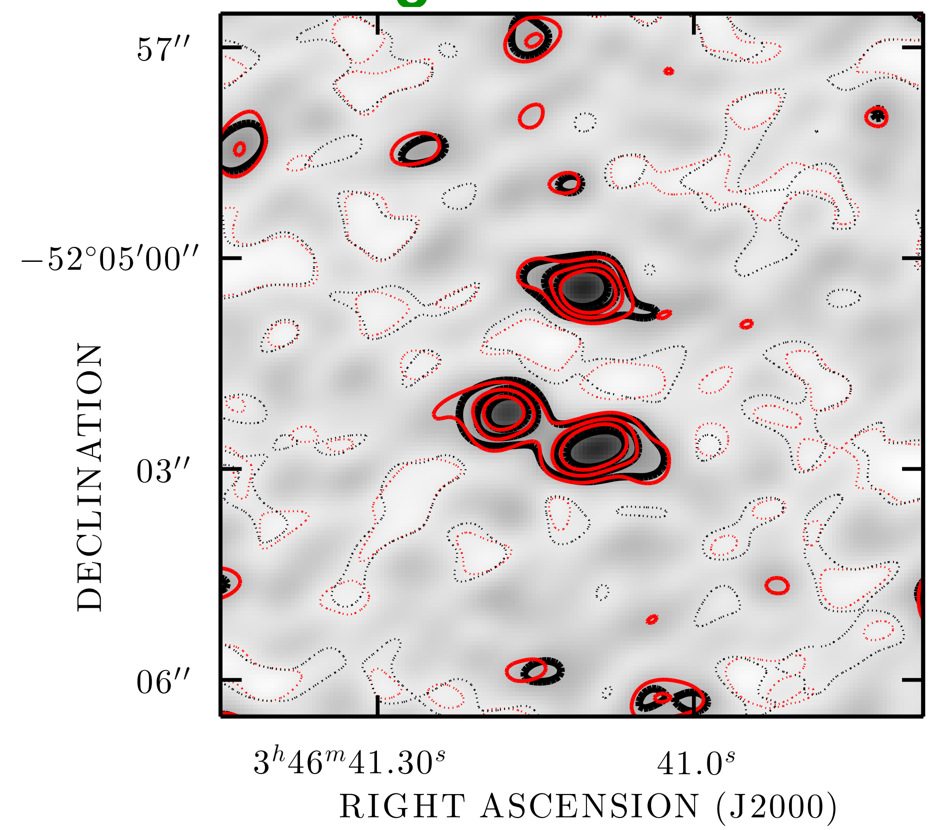
ALMA Band 7 compact configuration dirty image



lens model

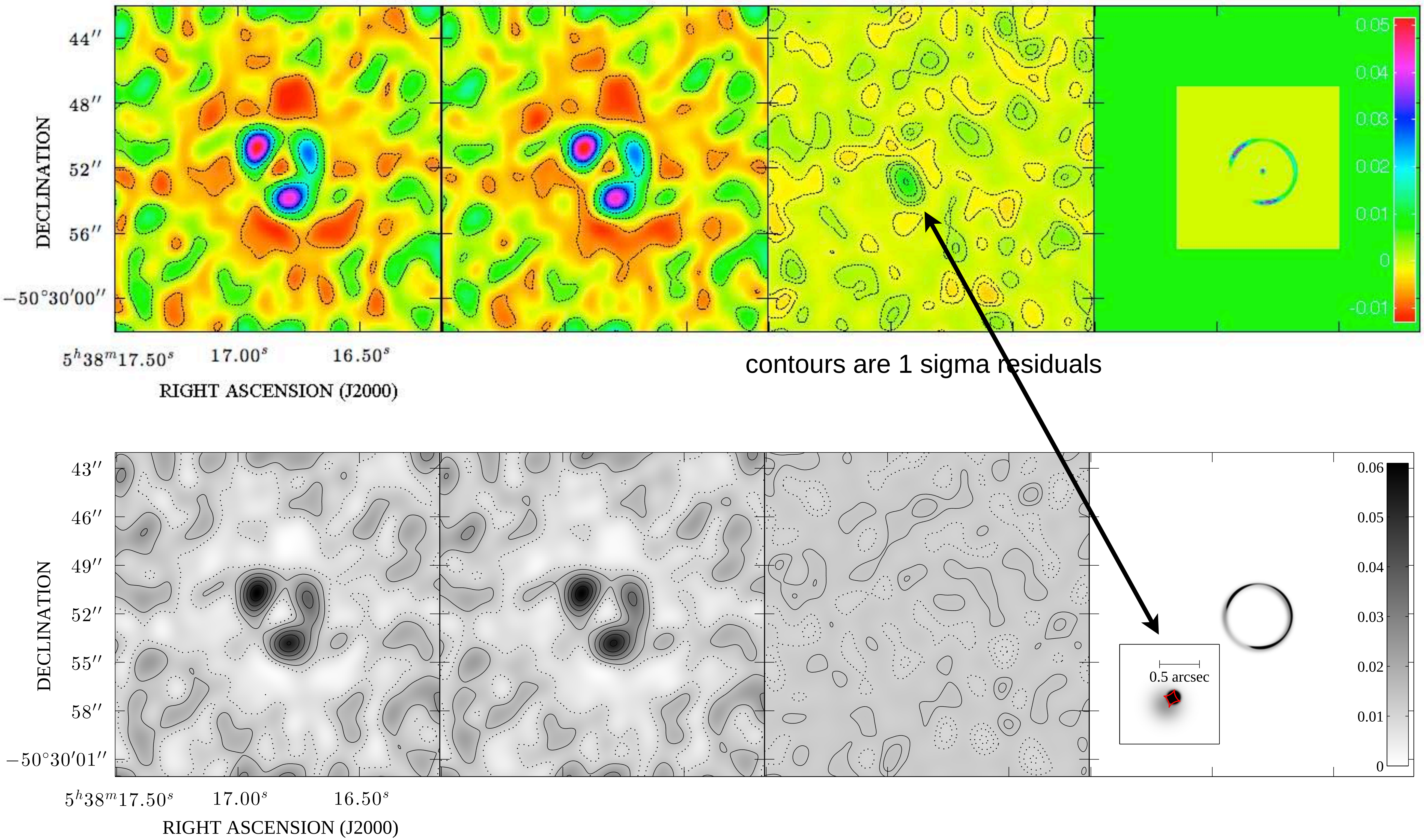


ALMA extended configuration



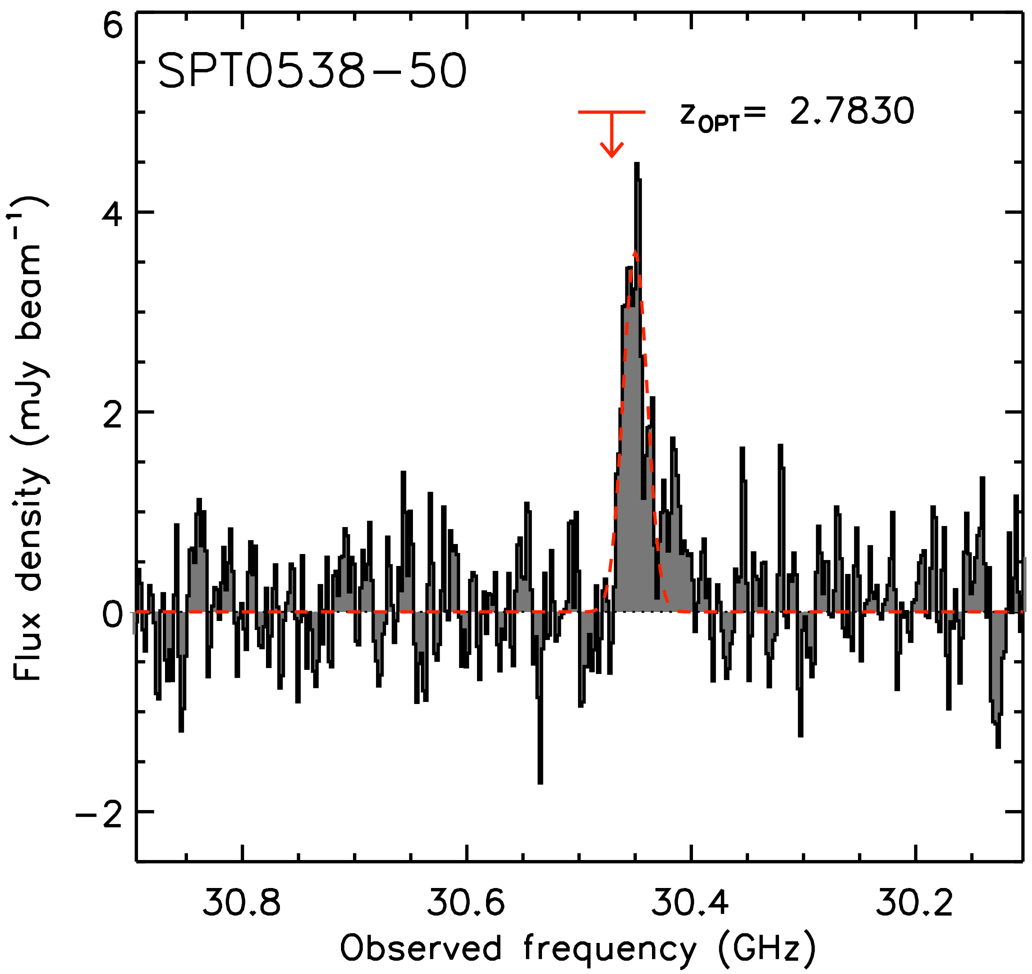
- we model ALMA visibilities with a custom and statistically robust technique
- we know there are phase errors in the antennas, we incorporate the self-cal phases into the MCMC model fitting, we capture the additional model uncertainties
- our models are working amazingly well
- we are working towards using this technique to set limits on dark matter substructure in cycle 1

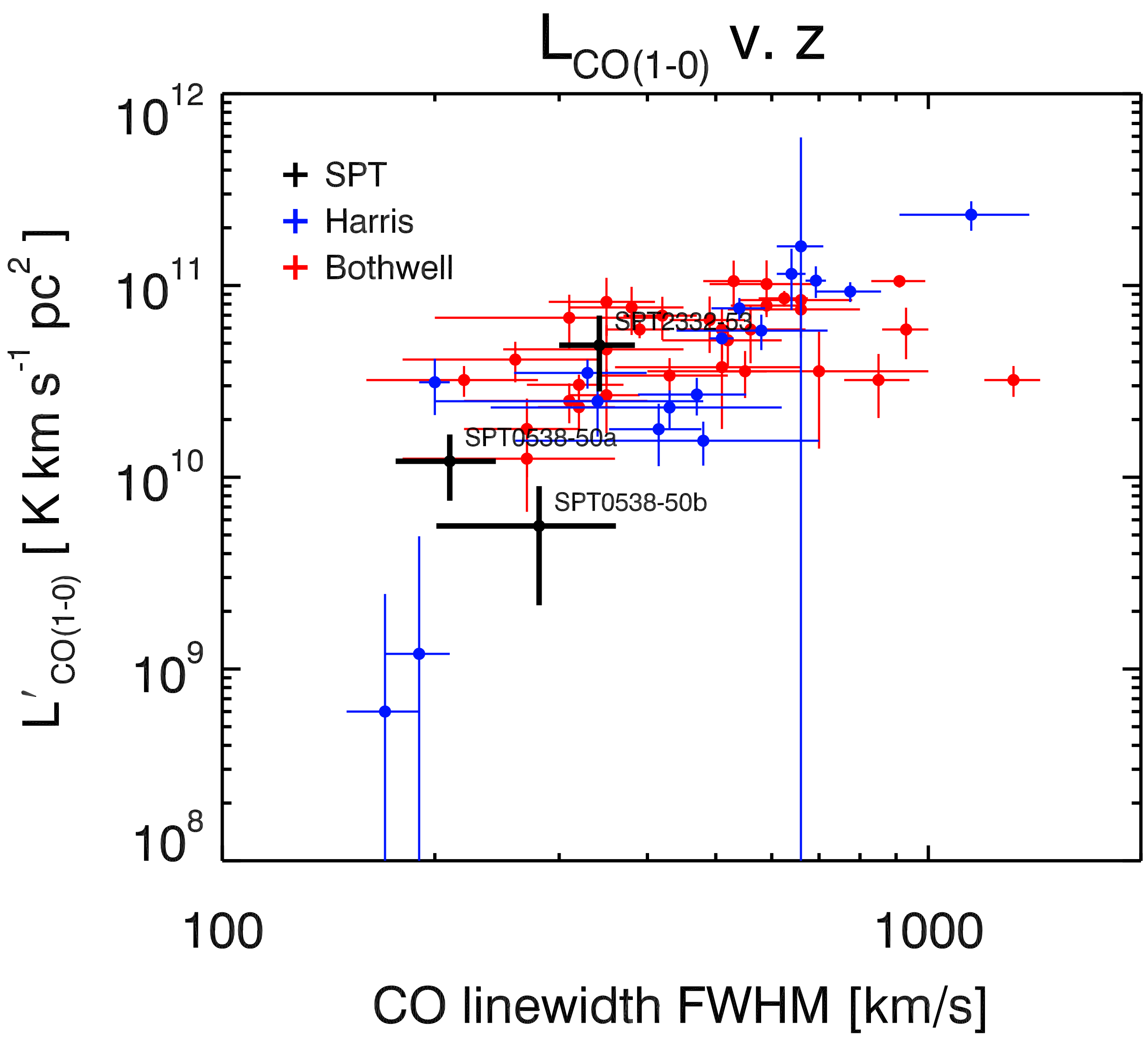
the lens model tells us details we can't see by eye



Comparison to unlensed SMGs

Aravena *et al.* 2013 MNRAS submitted



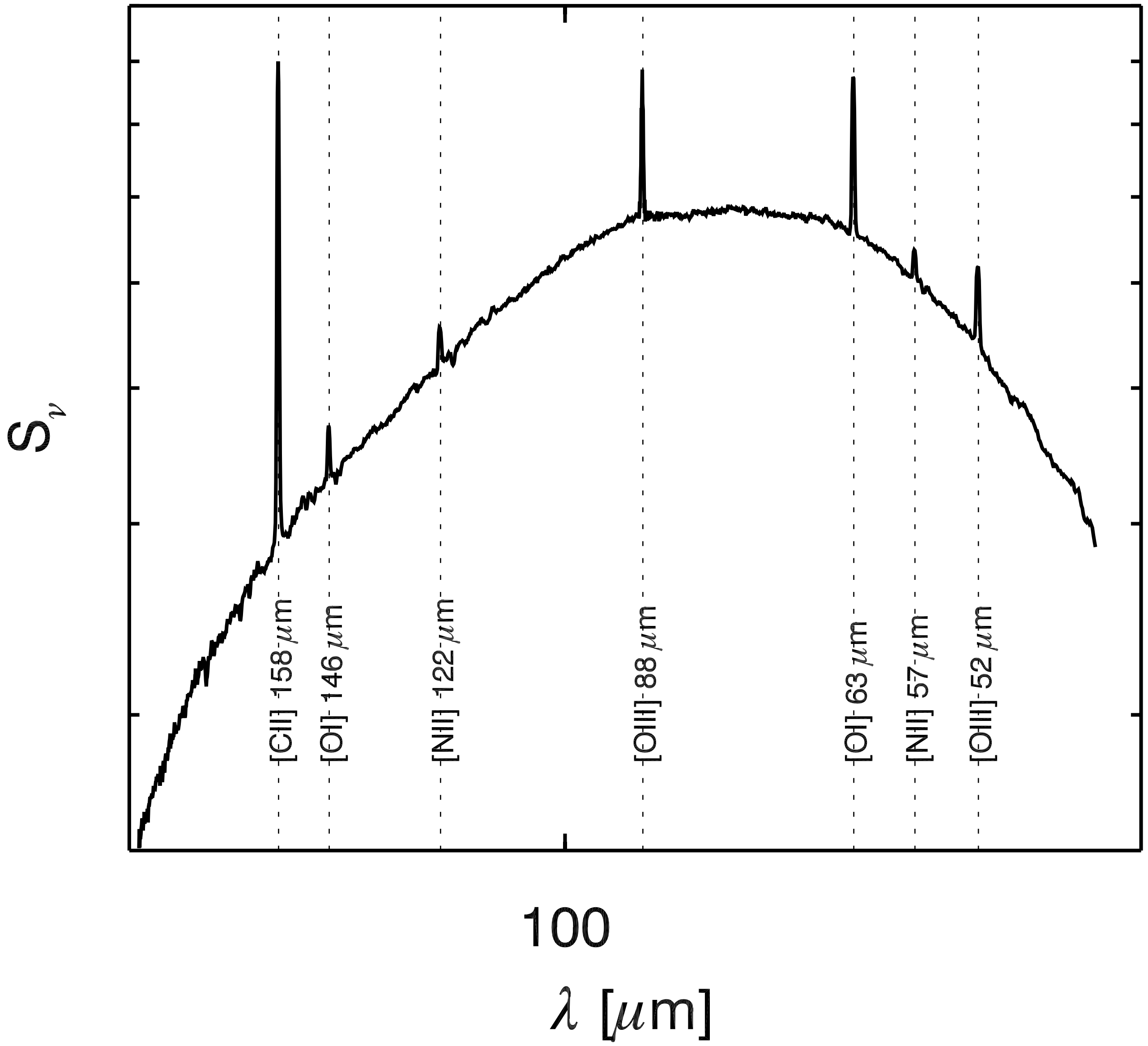


⇒ SPT sources look just like regular SMGs, but magnified by ~x10

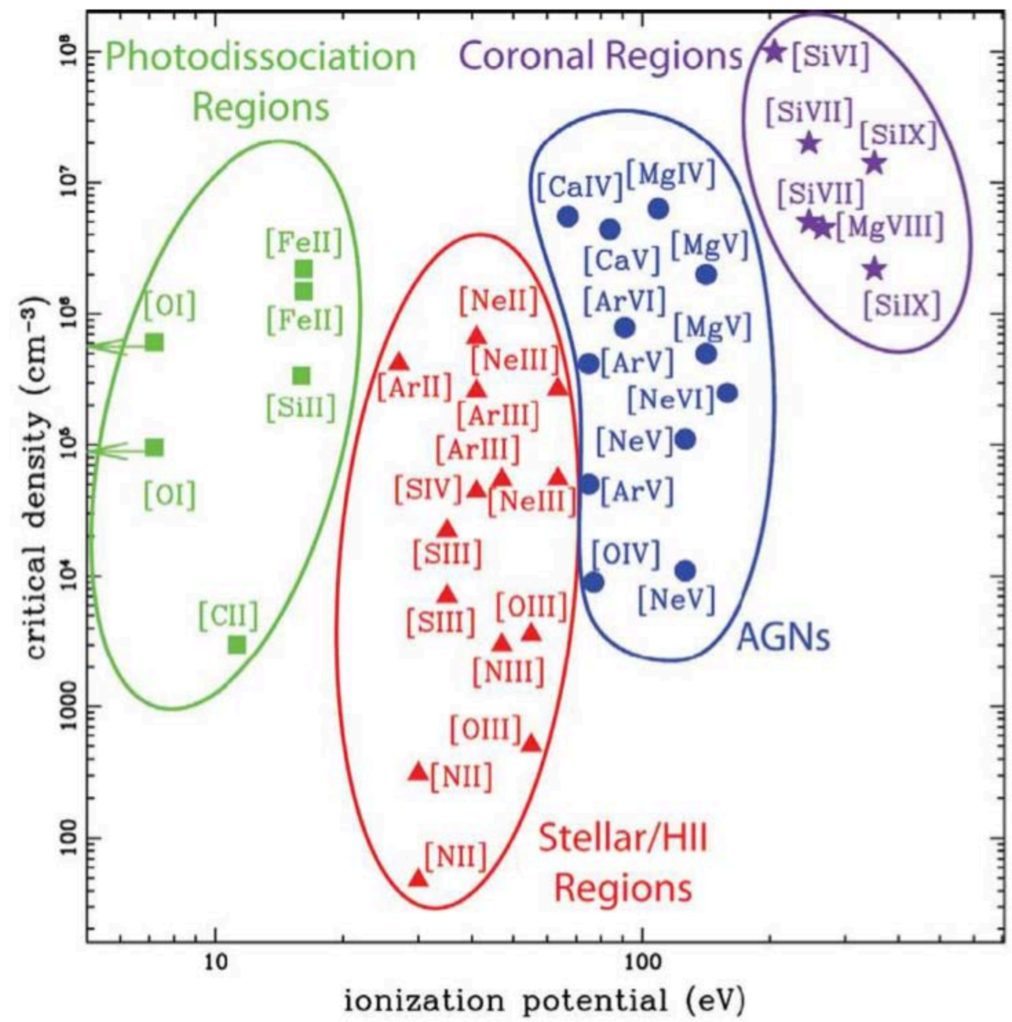
DSFG = dusty star forming galaxy

Fine structure lines

M82 ISO Spectrum

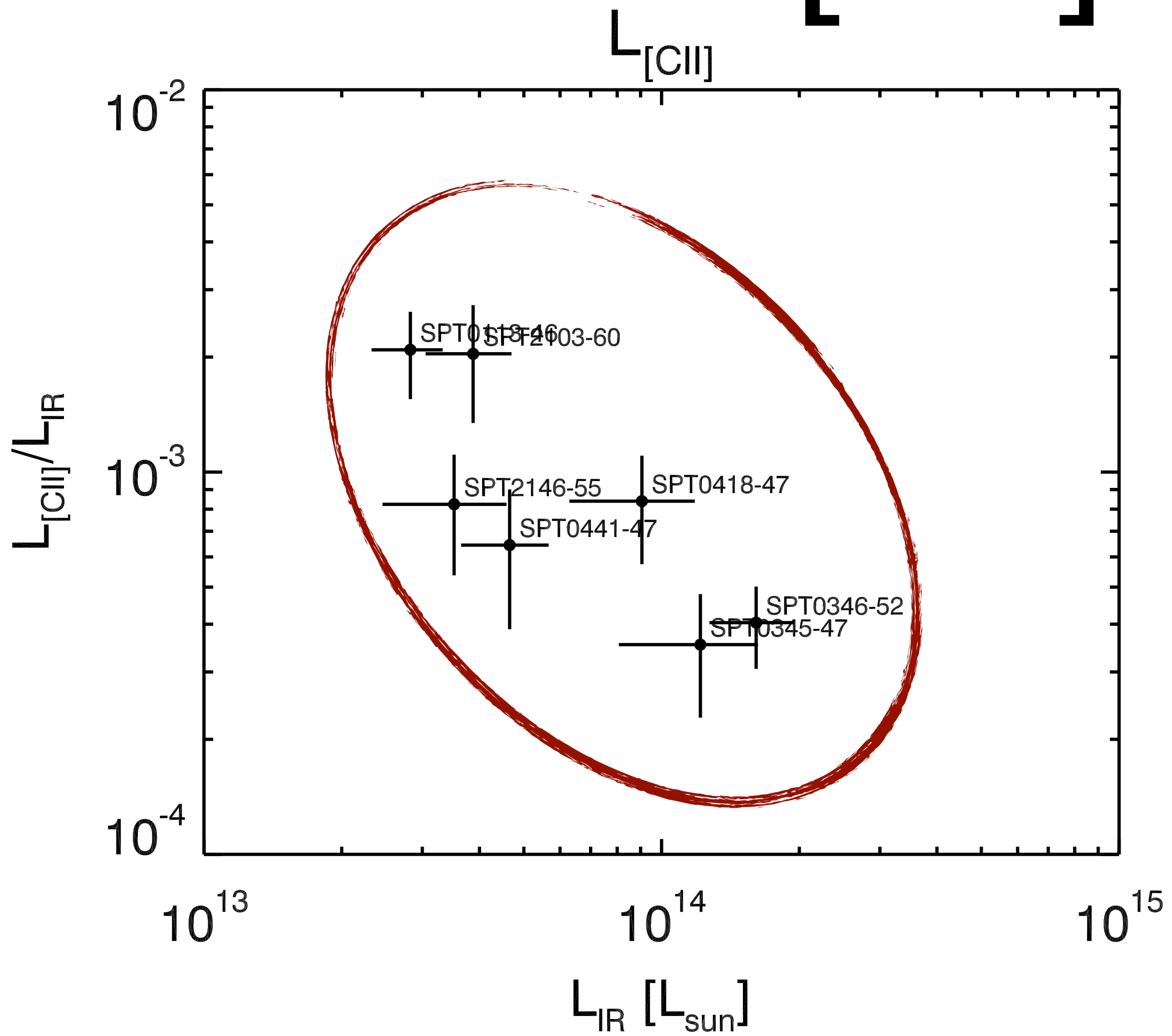


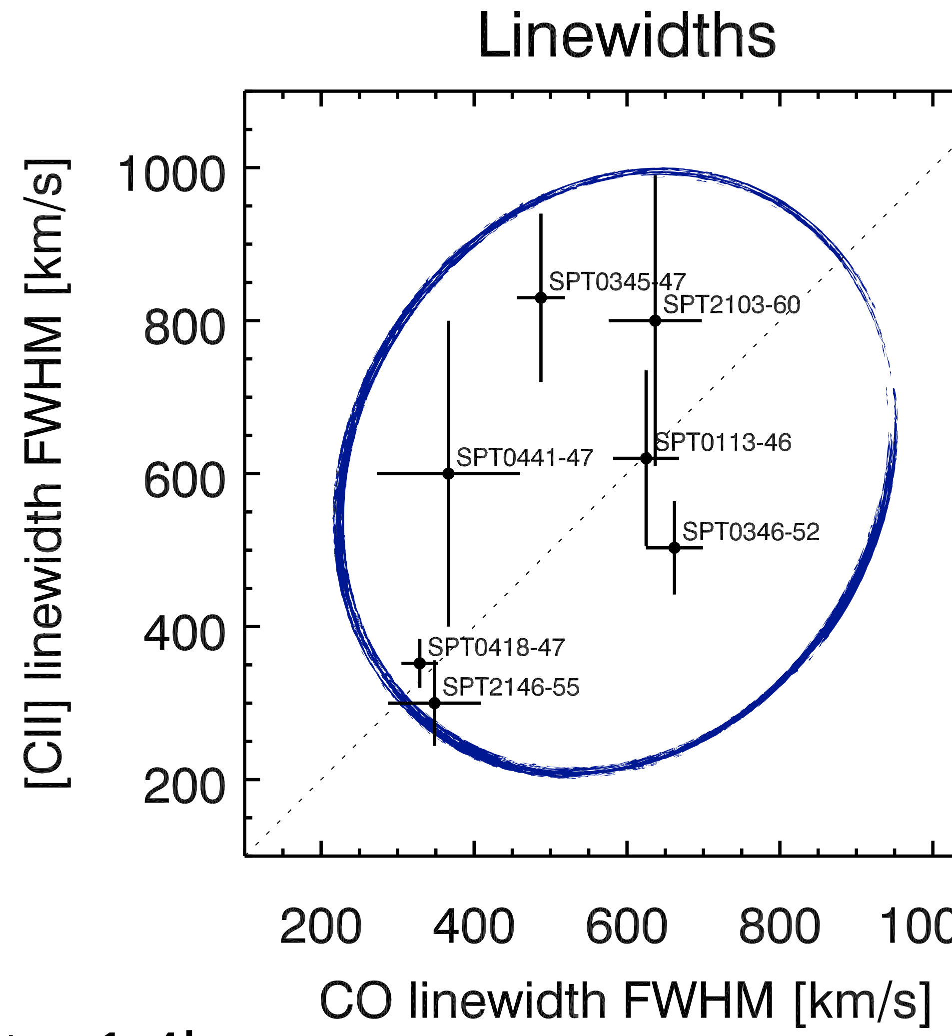
Spignolio 1992 and 2009



- Major coolants for ISM in DSFGs ⇒ C+ can be ~0.1% of total L_{FIR}
- extinction free probe of physical conditions of gas and radiation fields
- ratio of lines disentangles relative SF and AGN contribution
- ISO studied z~0, progress being made with *Herschel*, APEX, ALMA at high redshift

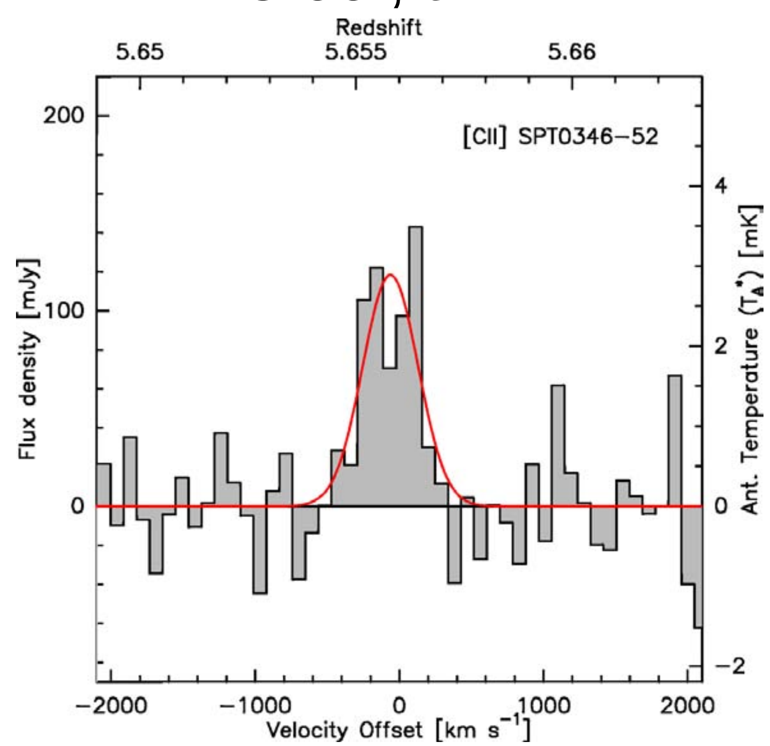
[CII] at z > 4





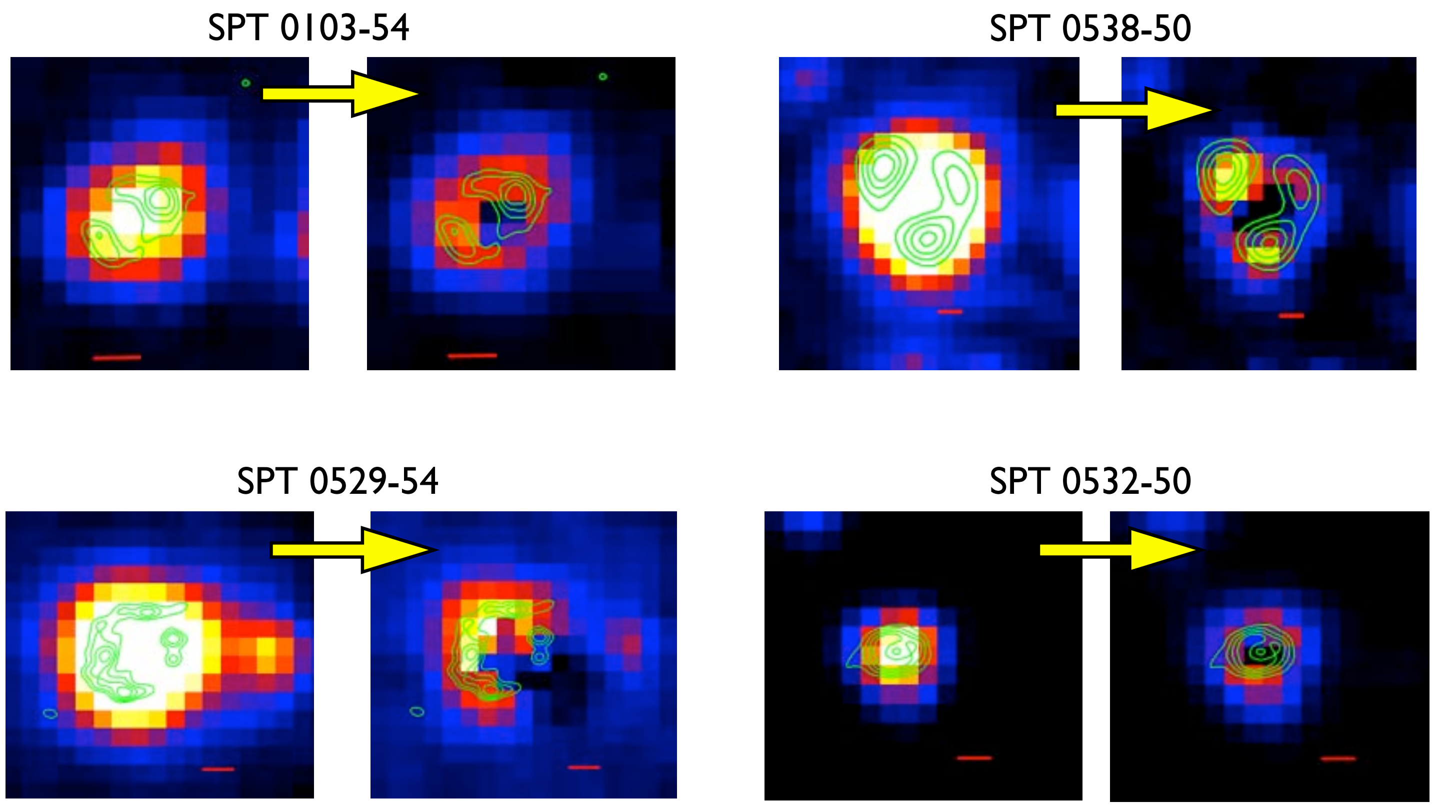
$L_{[CII]}/L_{IR}$ ratio is normal for starburst galaxies. (not high, not low...)

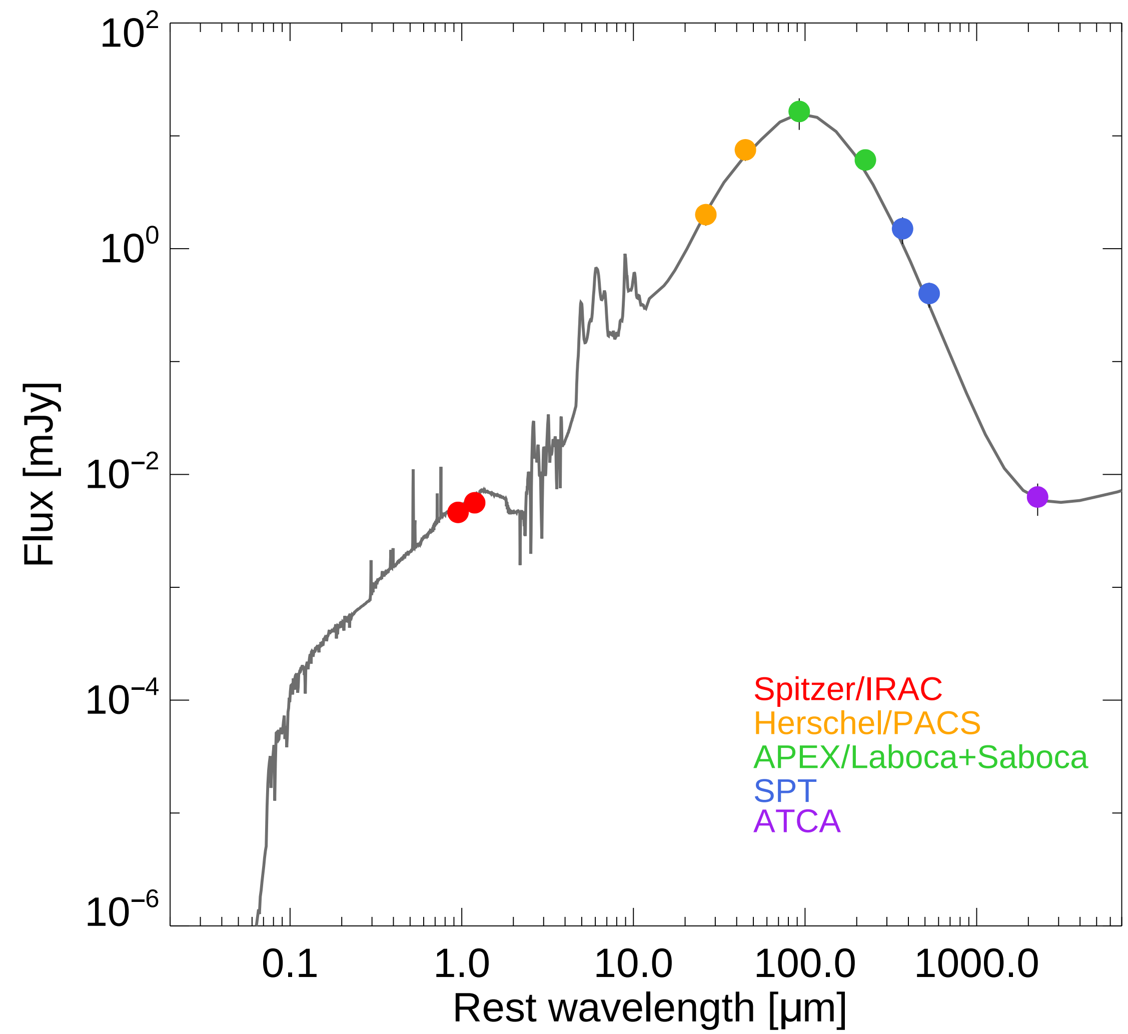
z = 5.66 ; t = 1.4h



linewidths between [CII] and CO differ ...

Deblending Spitzer/IRAC with ground-based K-band constraining stellar masses





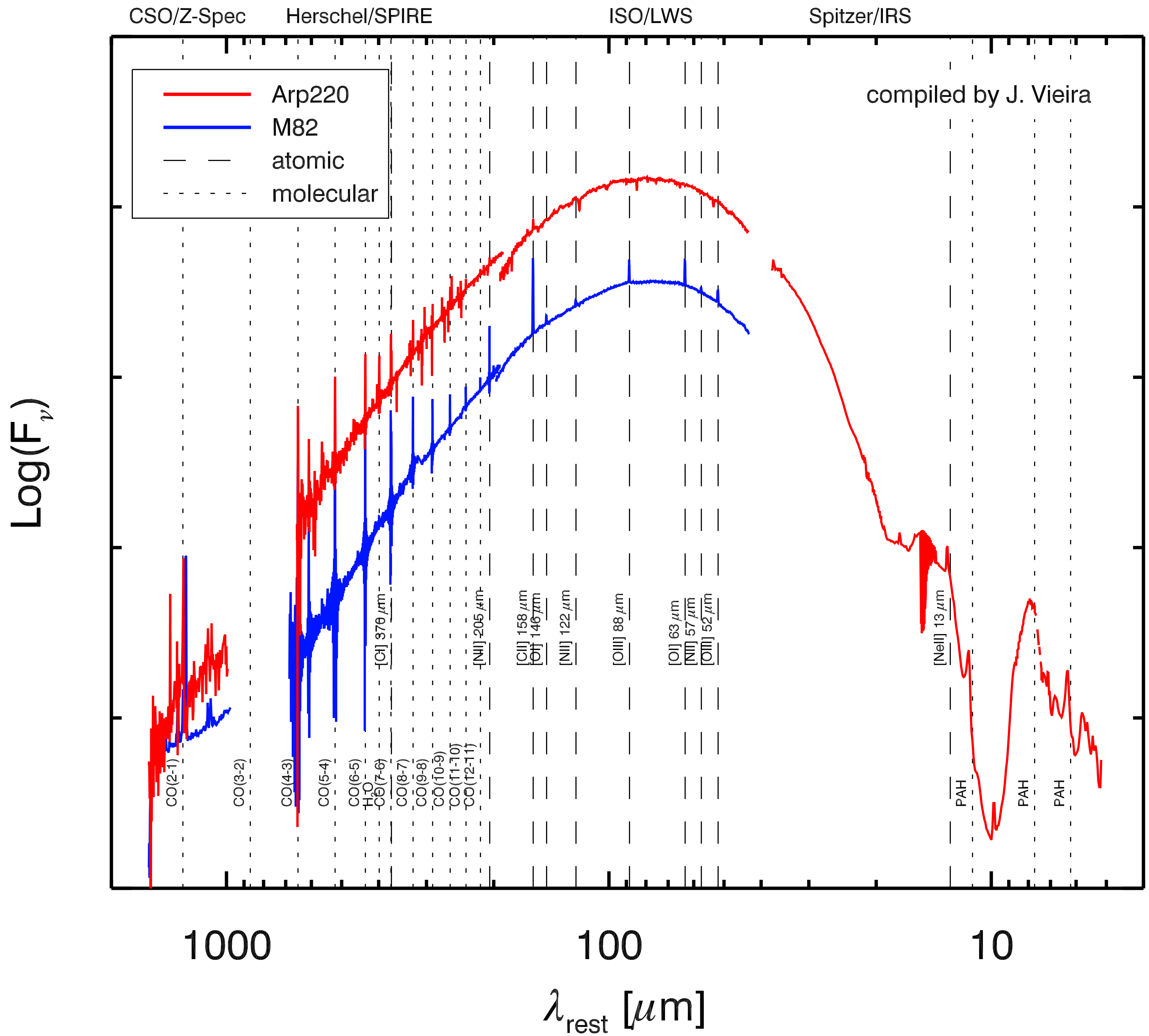
$L_{IR} = 3.1 \times 10^{12} L_\odot$

$SFR = 780 M_\odot/yr$

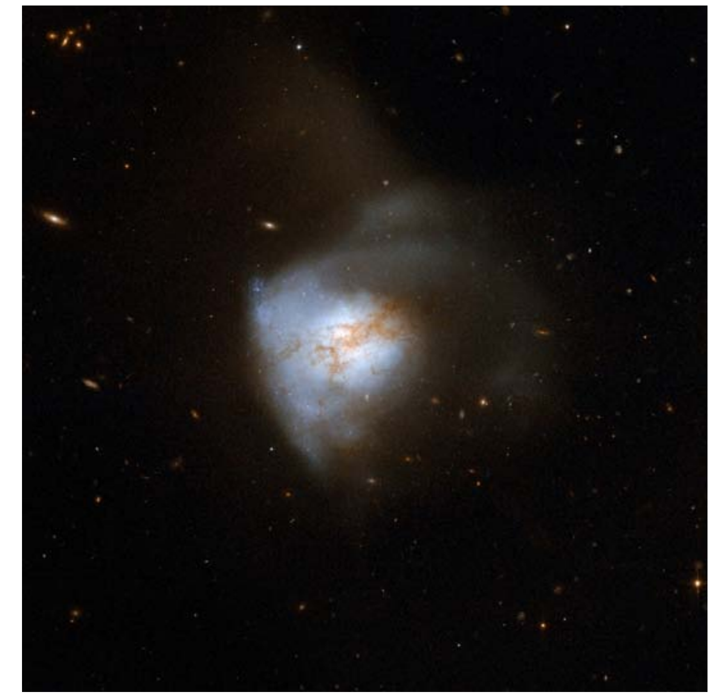
stellar mass = $4 \times 10^{10} M_\odot$

Where is this going?

FIR molecular and atomic spectroscopic line measurements comparable nearby systems



Arp220
z = 0.0181
$L_{IR} \sim 2 \times 10^{12} L_\odot$
SFR ~ 300 $M_\odot$/yr



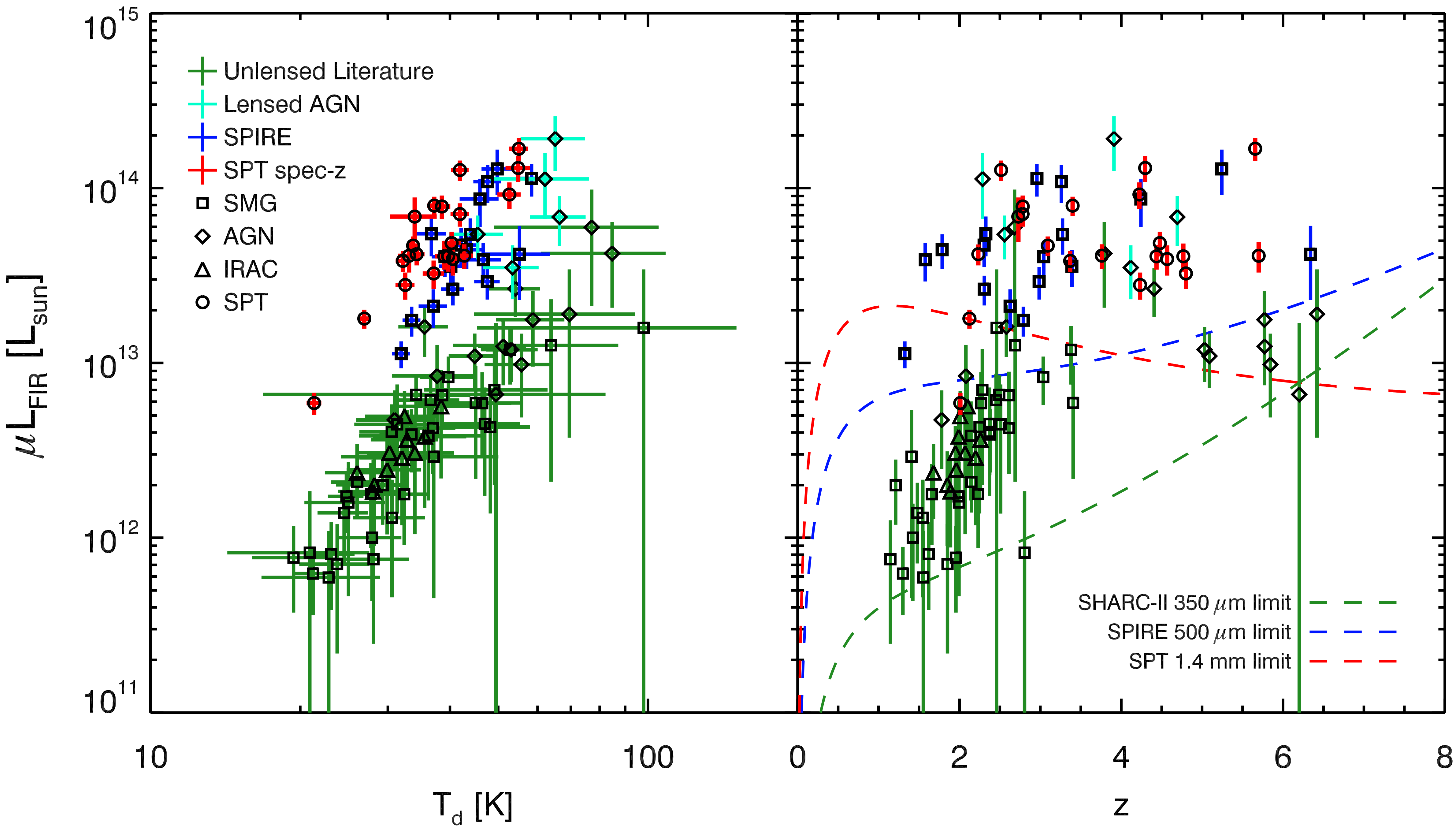
M82
z = 0.000677
$L_{IR} \sim 7 \times 10^{10} L_\odot$
SFR ~ 10 $M_\odot$/yr

Plotting all high redshift objects from the literature with spectroscopic redshifts and 350 μm and mm photometry

Fit with an optically thick greybody at λ_{rest} > 50 μm with β = 2 and μm_o = 100 μm

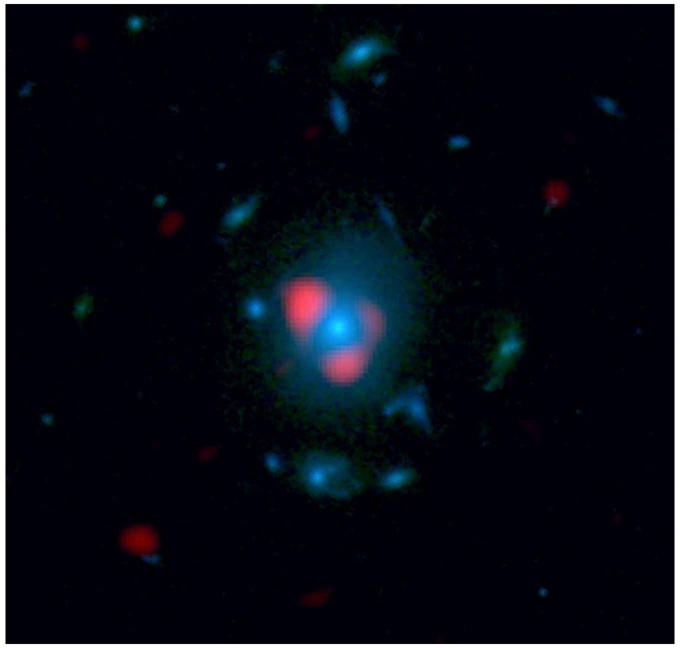
L_{IR} v. T_d

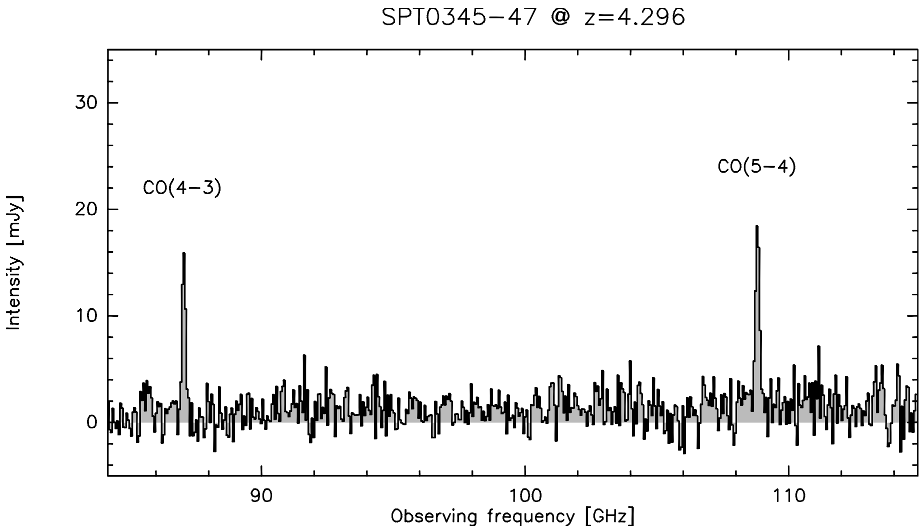
L_{IR} v. redshift

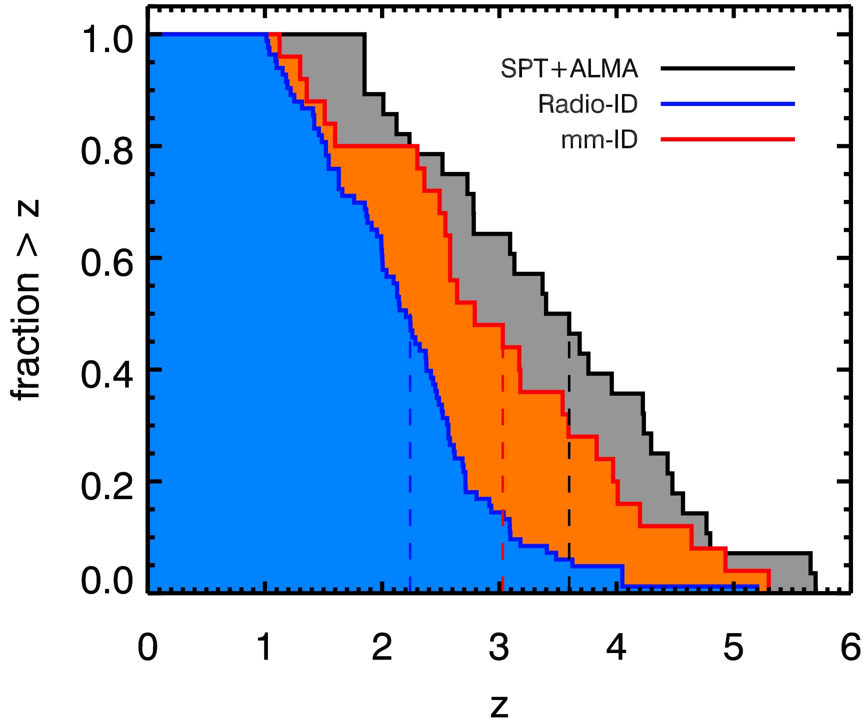


SPT sources

- Complete followup with Herschel SPIRE+PACS, APEX/LABOCA, and VLT/ISAAC
- majority show structure indicative of gravitational lensing
- 90% of have a line detection with ALMA
- 25 spec-z's so far; median z = 3.6
- 35% of spec-z's are at z > 4 (doubled the number)
- sample already has 2 of the highest redshift SMGs in the literature today (z=5.7)
- As of today we have redshifts for ~20 foreground lenses, with <z> = 0.55 +/- 0.3
- only ~25% of the entire SPT sample
- 3 more programs in the ALMA Cycle 1 queue

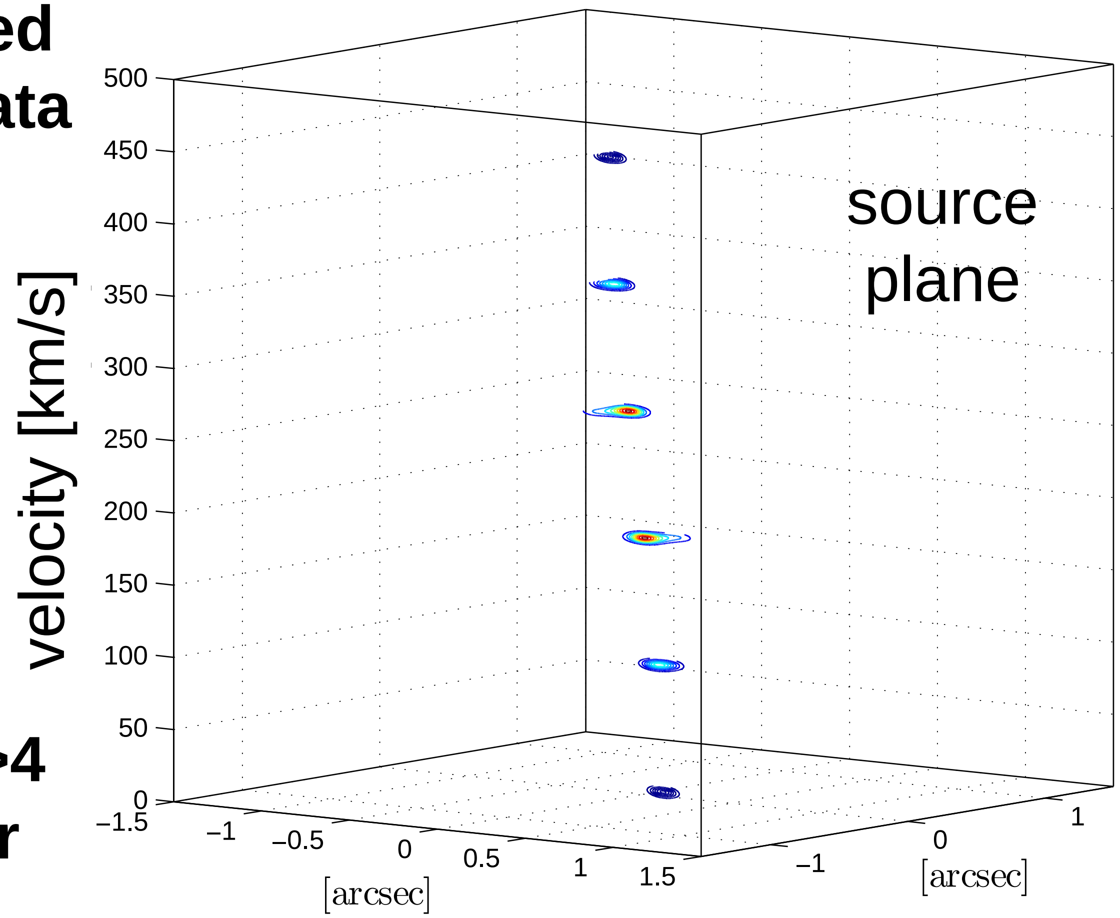


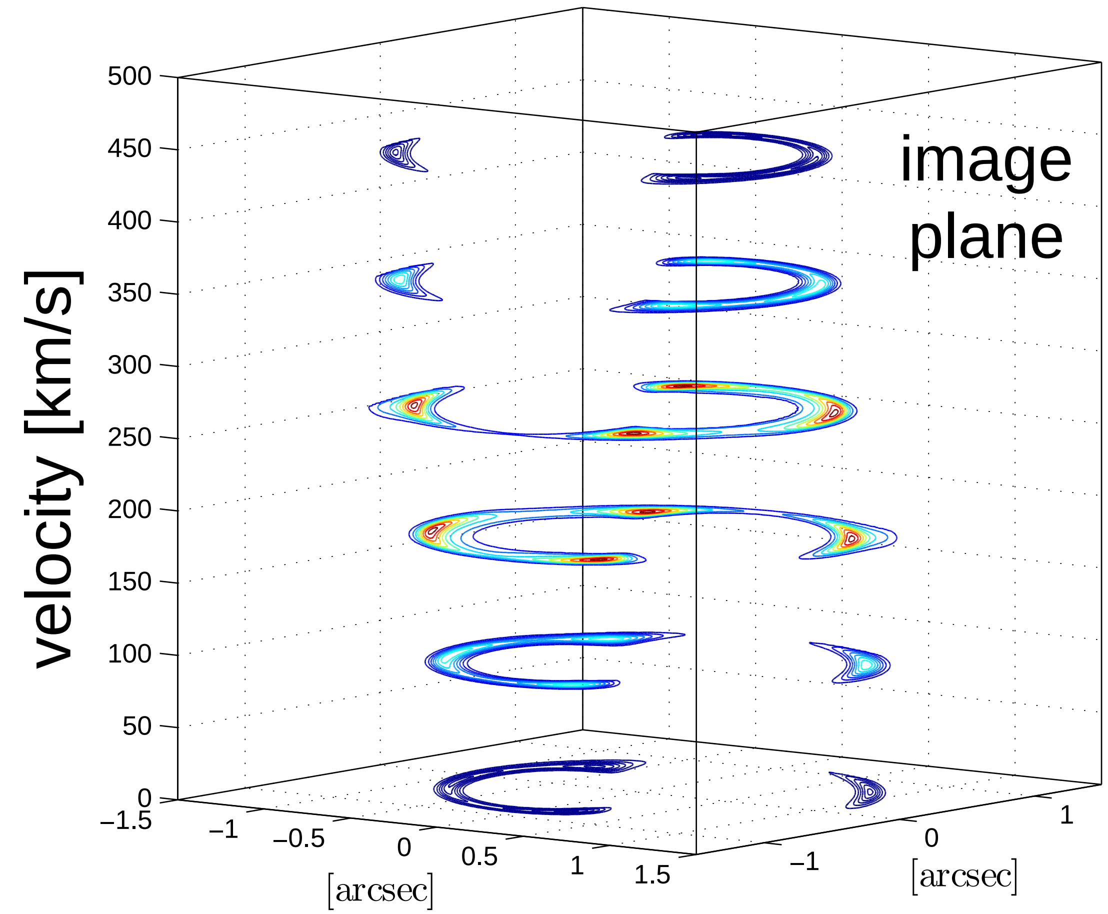




Detecting dark matter substructure at z~1

simulated ALMA data cube





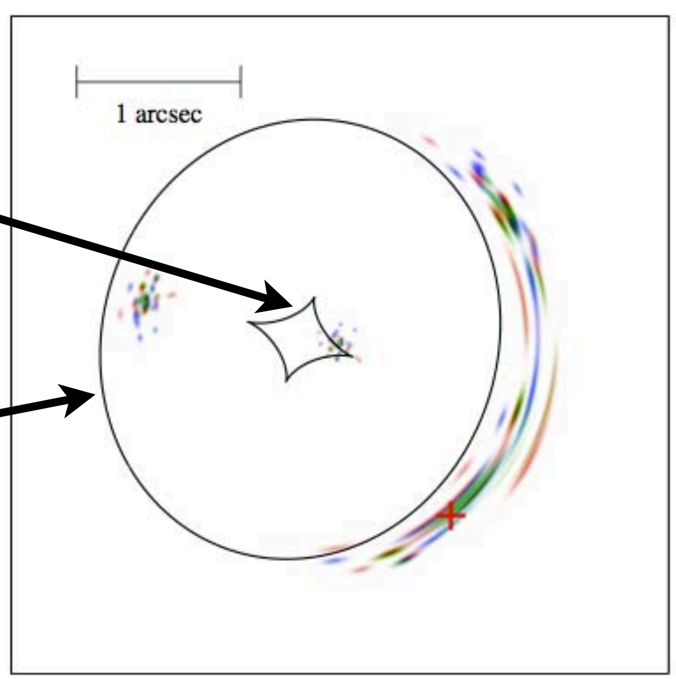
C+ at z>4 in ~1 hr

lens model

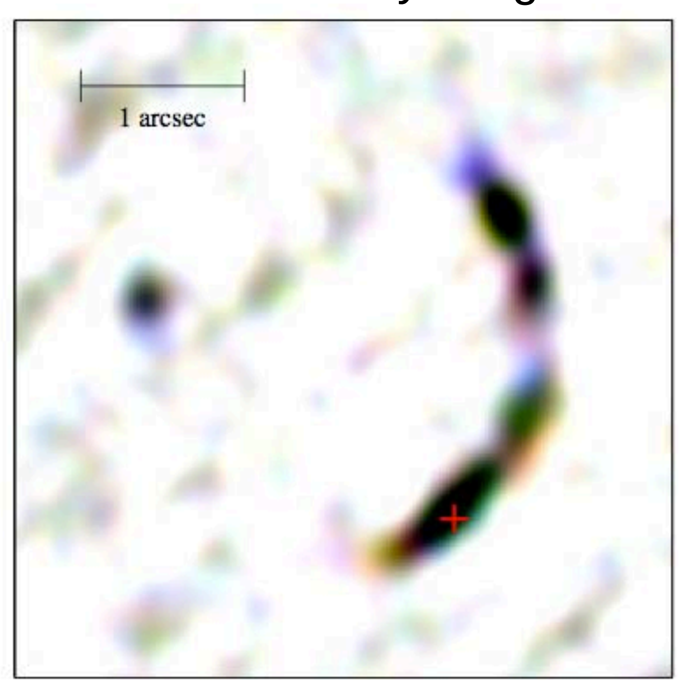
source plane caustic

image plane critical curve

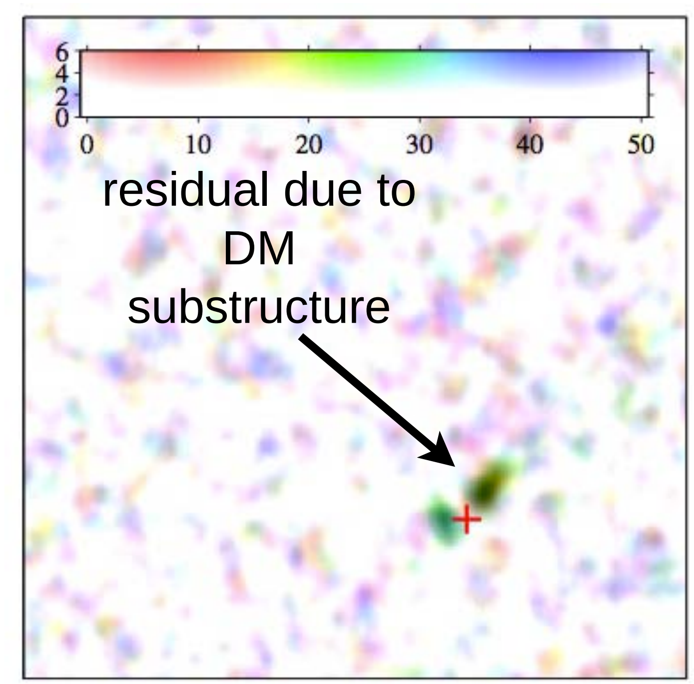
source model



simulated dirty image



residual

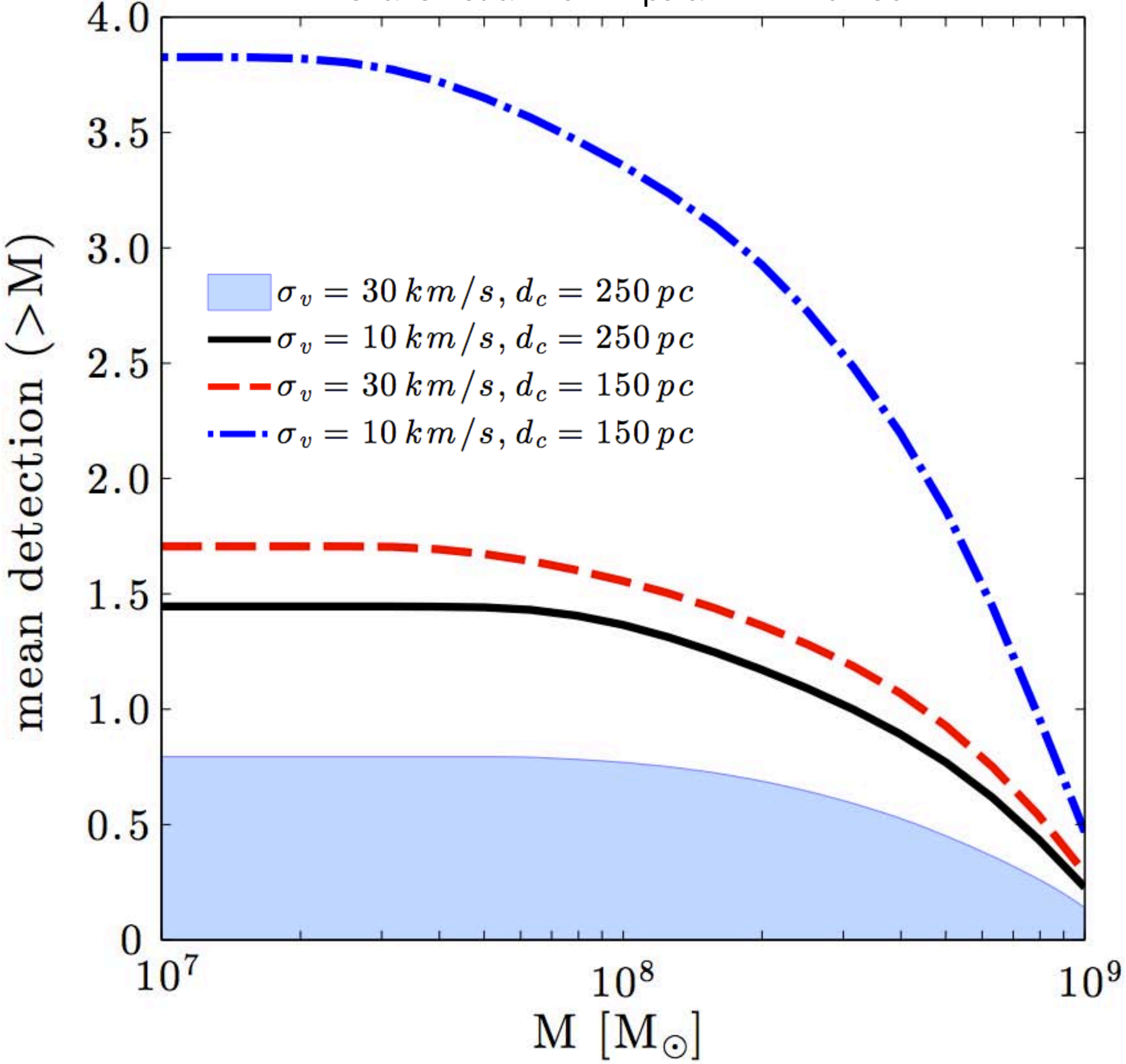


Hezaveh *et al.* 2012 ApJ arXiv:1210.4562

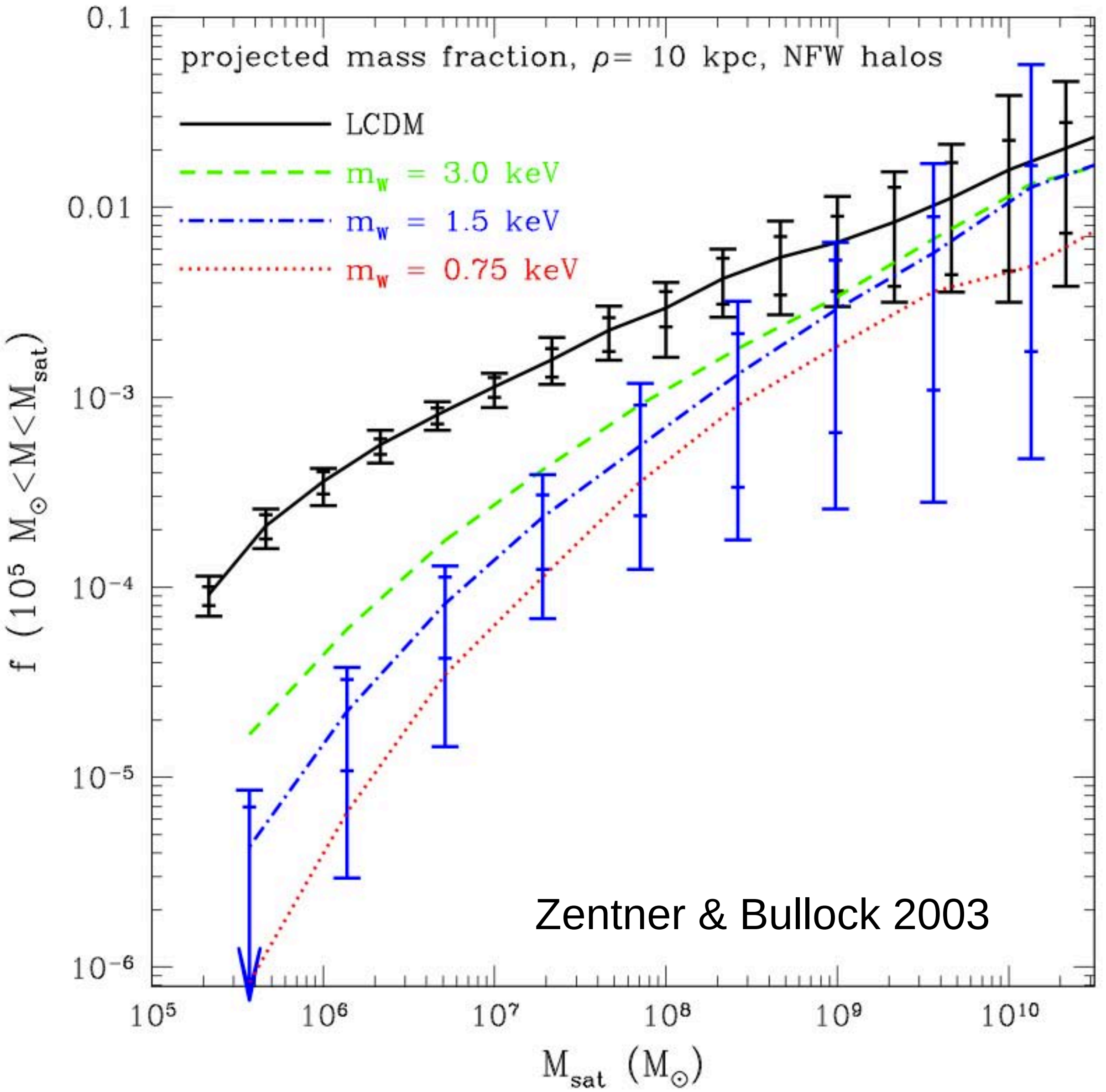
Detecting dark matter substructure at z~1

What will it tell us?

Hezaveh *et al.* 2012 ApJ arXiv:1210.4562



SIMULATION:



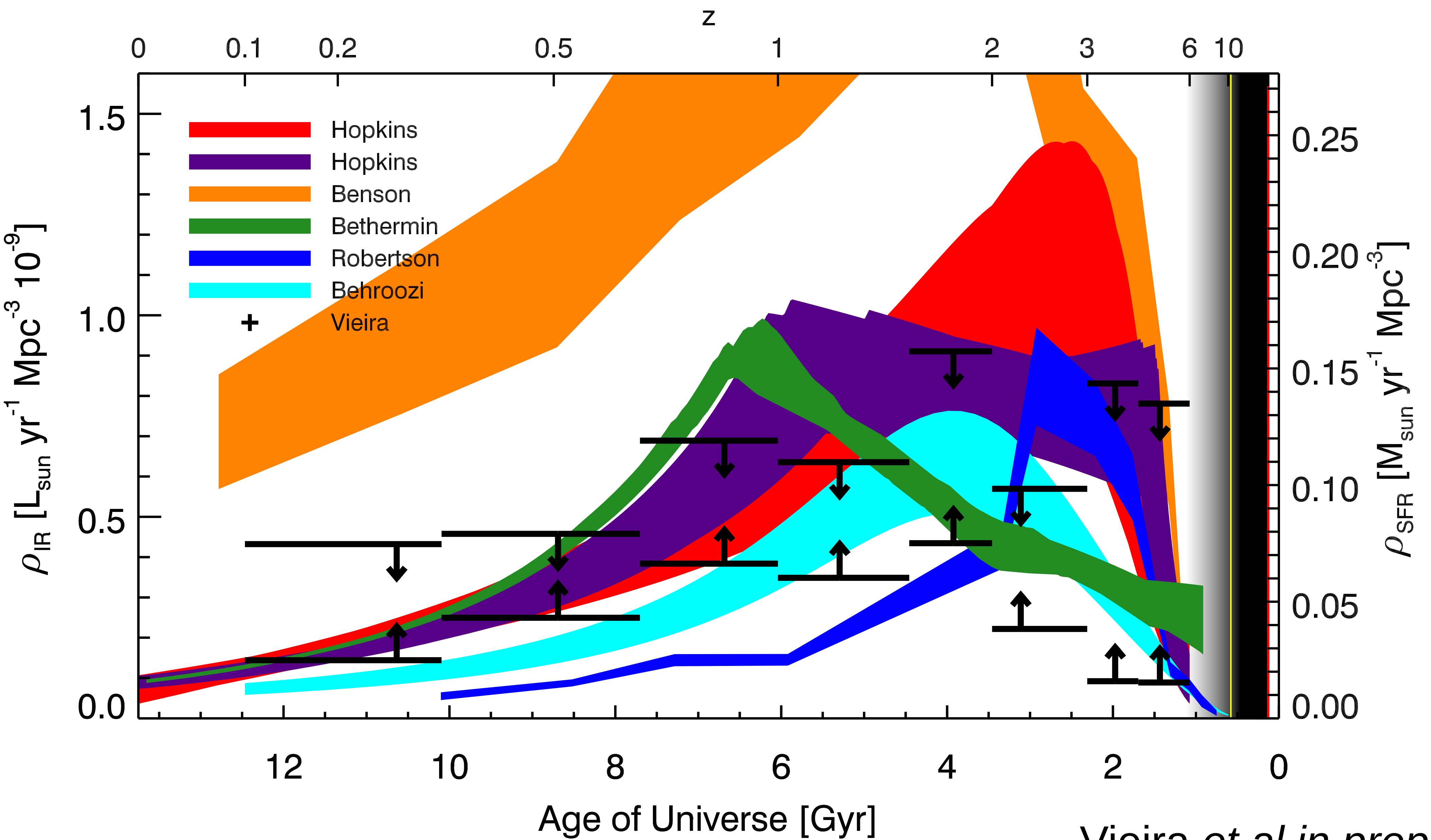
We will detect ~1 $M_{sat} > 10^8\ M_{sun}$ dark matter subhalo per lensed system with about 1 hour per source with ALMA

We can constrain models of DM, in particular, prove or disprove the existence of warm DM

SPT ALMA Cycle 1 Programs:

- 15 more redshifts from 100 deg2 deep field (PI: Weiss)
- CO followup to break redshift degeneracies (PI: De Breuck)
- Resolved C+ at z=5.7 for dark matter substructure (PI: Marrone)

Cosmic star formation history



Vieira *et al in prep*

- **we are finding and studying luminous sources at z~6**
- **we are able to study them in great detail**
- **we have the possibility of finding even higher redshift sources**

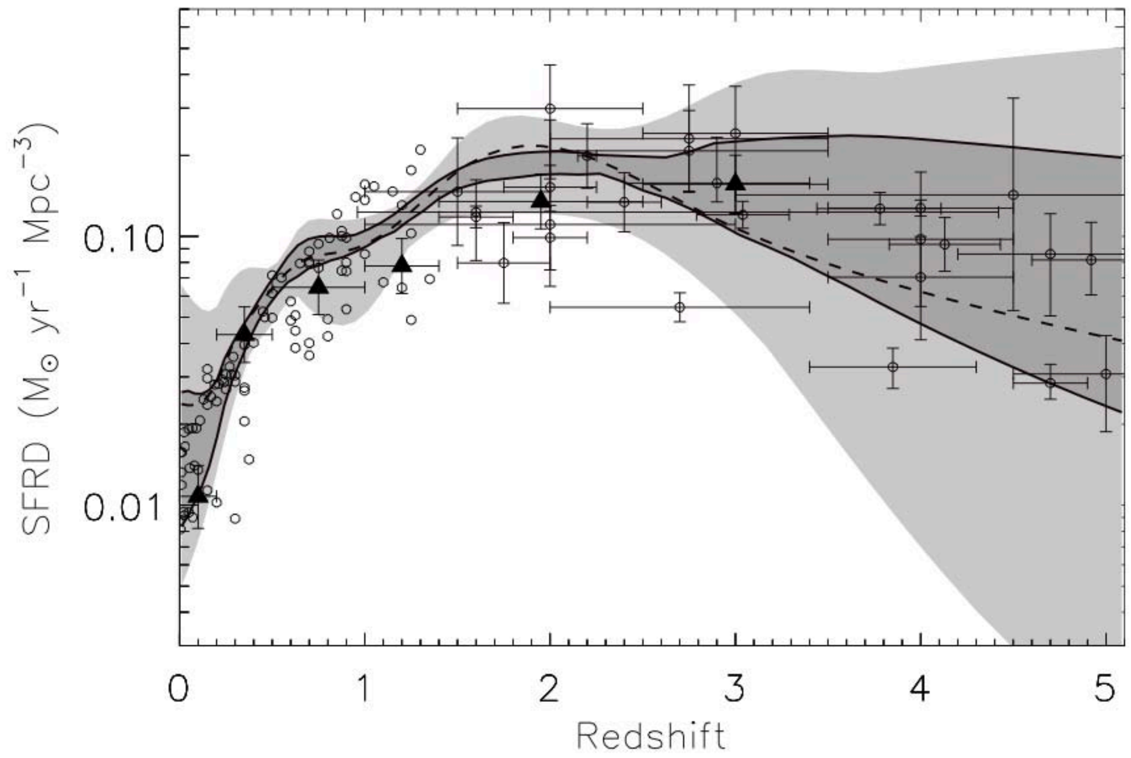
The Future with CCAT

- 25m telescope at a great site will make submm astronomy object-oriented
- Beam size will allow us to get optical redshifts directly → no need for intermediate followup.
- Extragalactic Instrument Suite:
  - 350 μm camera (Cornell/JPL)
  - 0.85/1.1/1.4/2.0mm camera (Caltech/JPL)
  - X-Spec 1mm spectrometer (JPL)

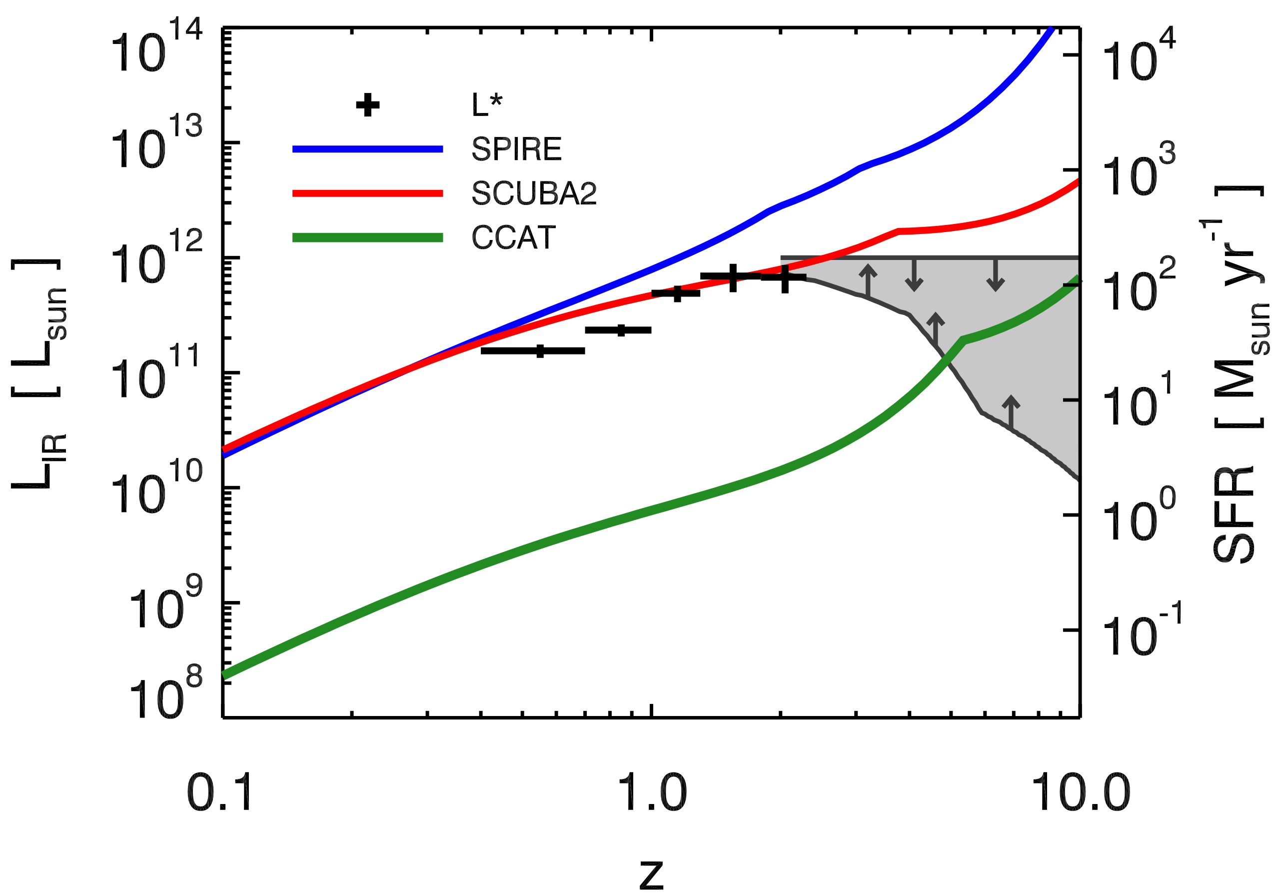
Instrument	[μm]	aperture [m]	FWHM [arcsec]
Spitzer/IRAC	3.6-8	0.85	2
Spitzer/MIPS	24	0.85	6
Herschel/PACS	70	3.5	5.2
Herschel/SPIRE	250	3.5	18
SPT	1400	10	70
SCUBA	450	15	8
SCUBA	850	15	15
LMT	1100	30 (50)	10 (6)
CCAT	350	25	3.5
CCAT	850	25	8.5

CCAT Extragalactic Survey #1:

Directly Measure the Cosmic Star Formation History



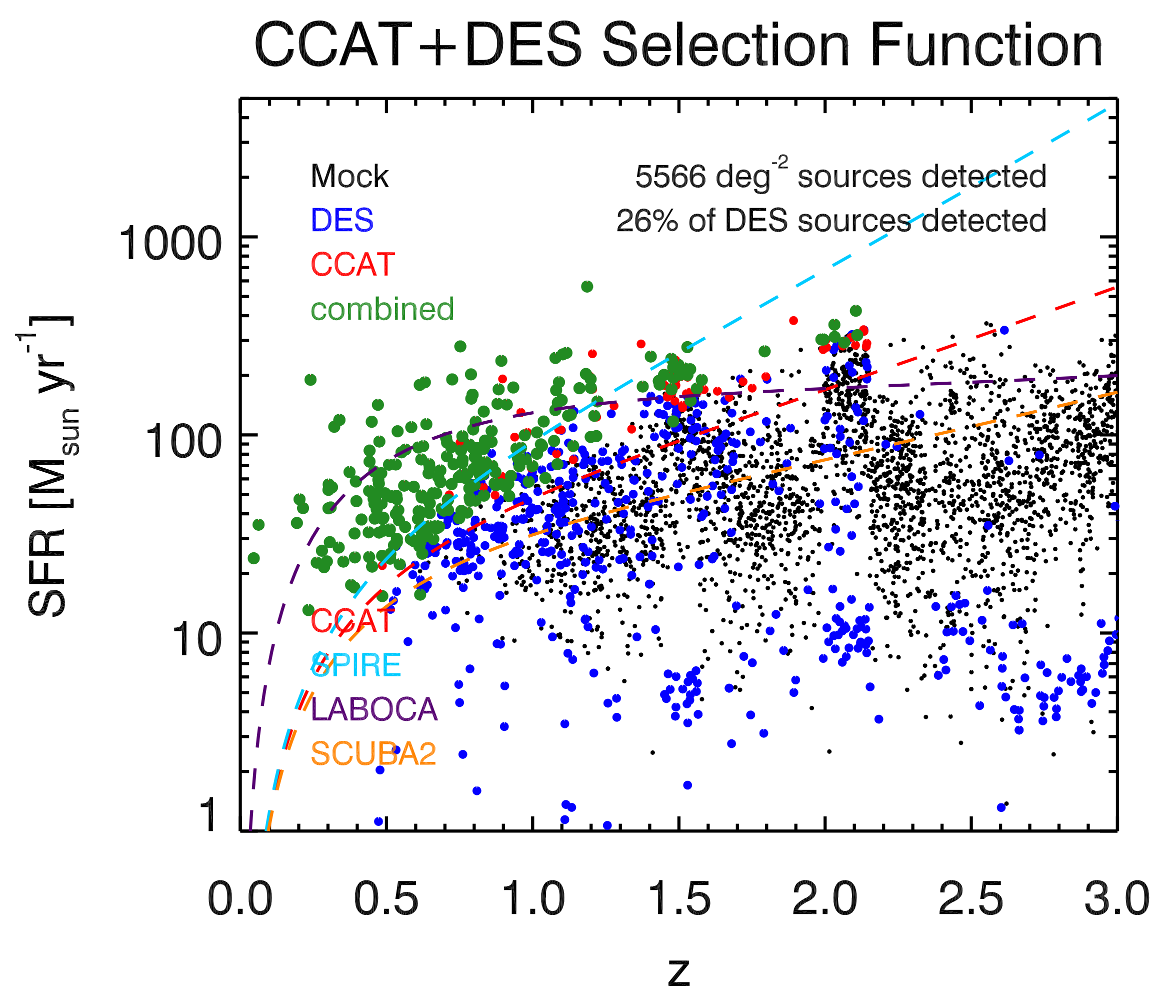
- Resolve the 350 μm background into discrete sources in 2 deg^2 COSMOS field. (~1000 hours)
- Get 850 μm for photo-z, T_d, and L_{IR}.
- Get optical/IR spectroscopy (Ly-a, H-a) from Keck and VLT → Should get ~90% of sources. Chase remaining 10% with ALMA.
- Measure the star formation history, constrain models, find interesting sources, inform reionization.
- Requires:
    - 350 and 850 μm cameras on CCAT
    - followup with 10m optical telescopes (~20 nights)
    - followup with ALMA (~1 hour per source?)



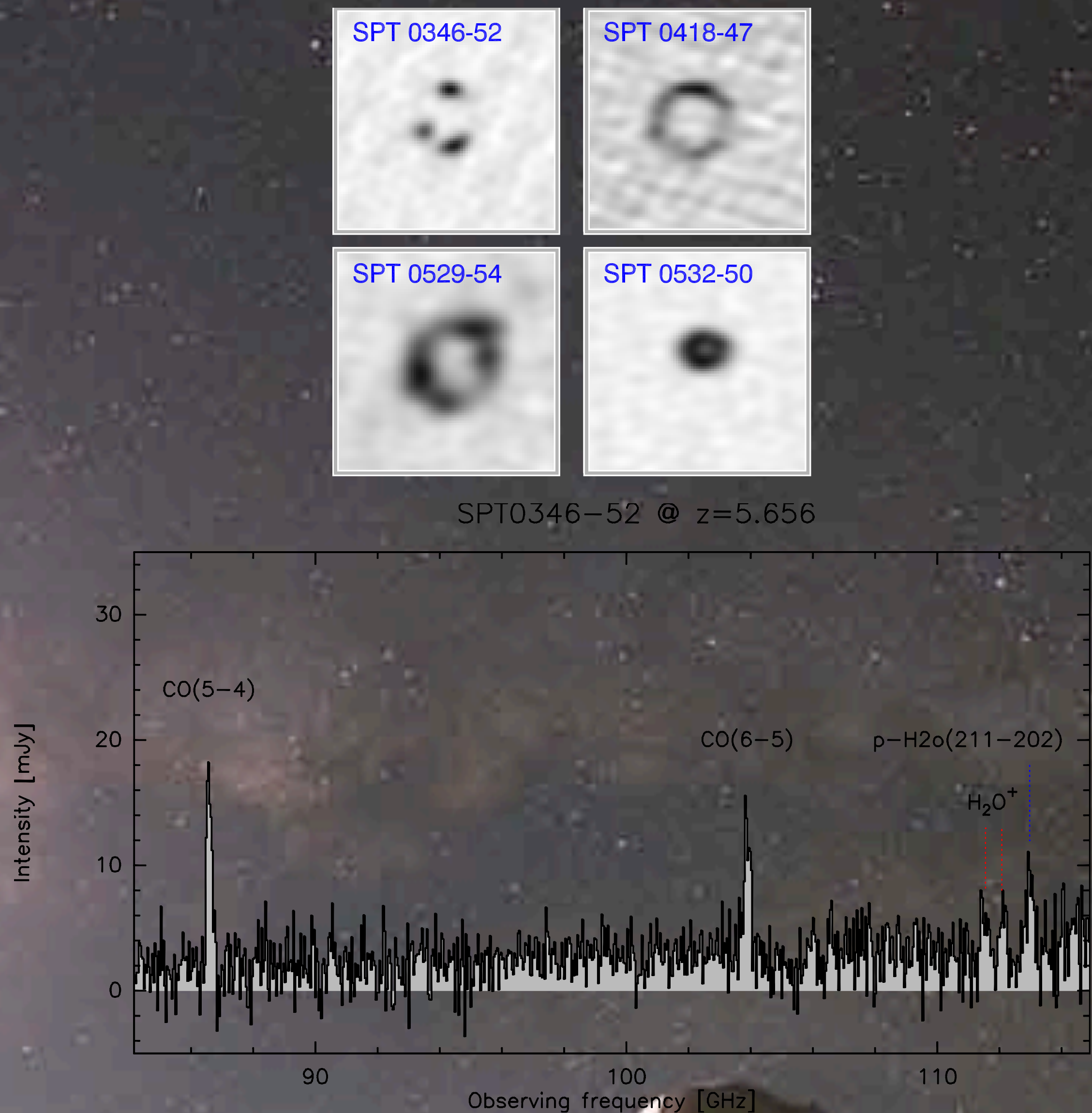
CCAT Extragalactic Survey #2:

Wide field object-oriented lower z astronomy (and some fluctuations)

- Use bad weather time to map ~2000 deg^2 SPT/DES/LSST southern sky at 350 and 850 μm in 1000 hours
- Provide a submm flux for every optical galaxy at z<0.5 in the southern sky.
- FFT sky, get power spectrum,
- Find lensed sources.
- Link up with powerspectrum from SPT.
- Enable stacking of optical galaxies.



Conclusions:



- We are in the middle of a renaissance for submm and mm instrumentation and observations, and a new window has opened onto the cosmic infrared background, the cosmic star formation history, and the dust-obscured Universe.

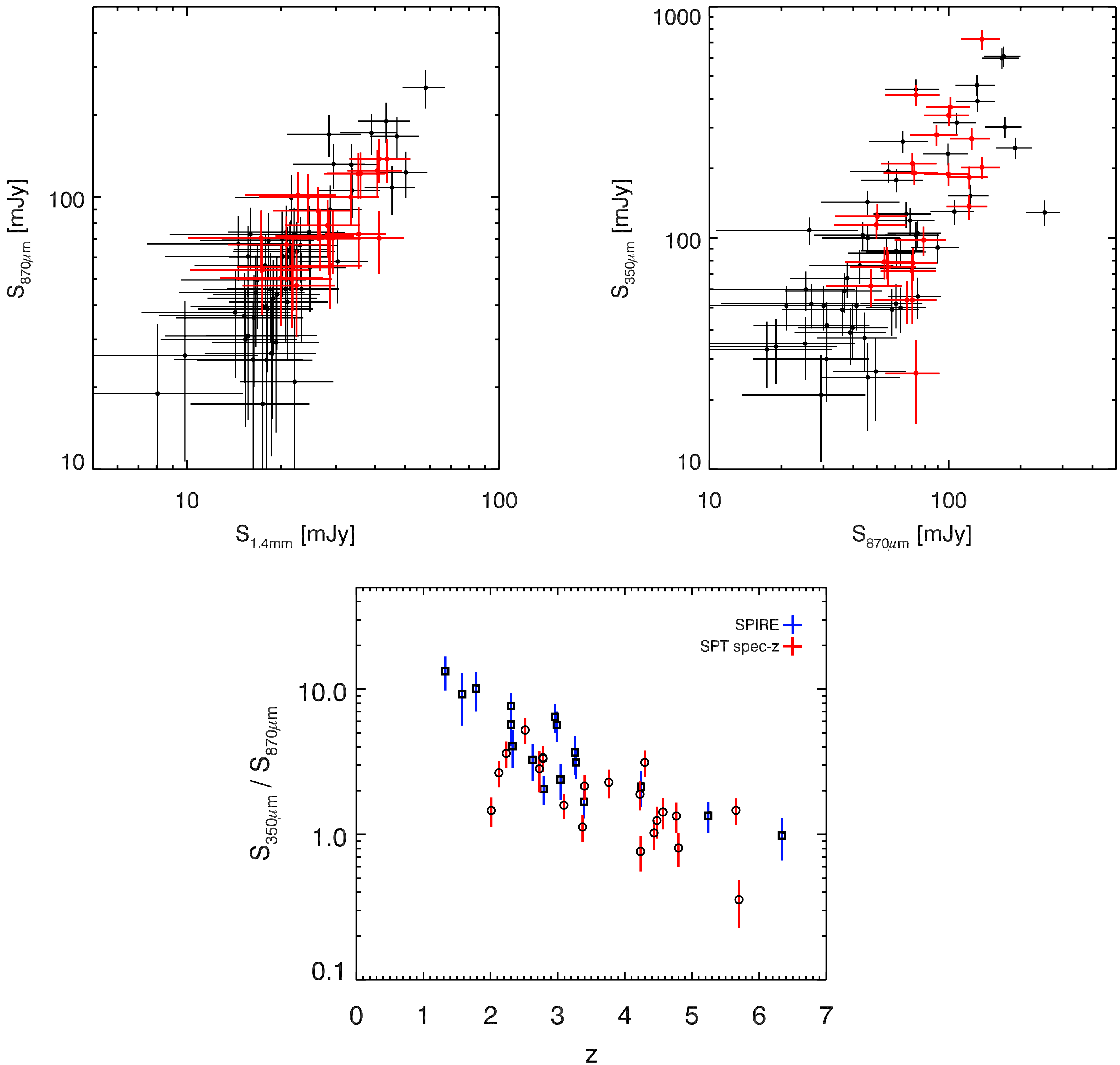
- Strong gravitationally lensed sources are enabling us to discover and study high-z starbursts in comparable detail to low-z starbursts.

- The first spectroscopic CO redshift survey with ALMA has demonstrated that the fraction of SMGs at high redshift is far greater than previously thought.

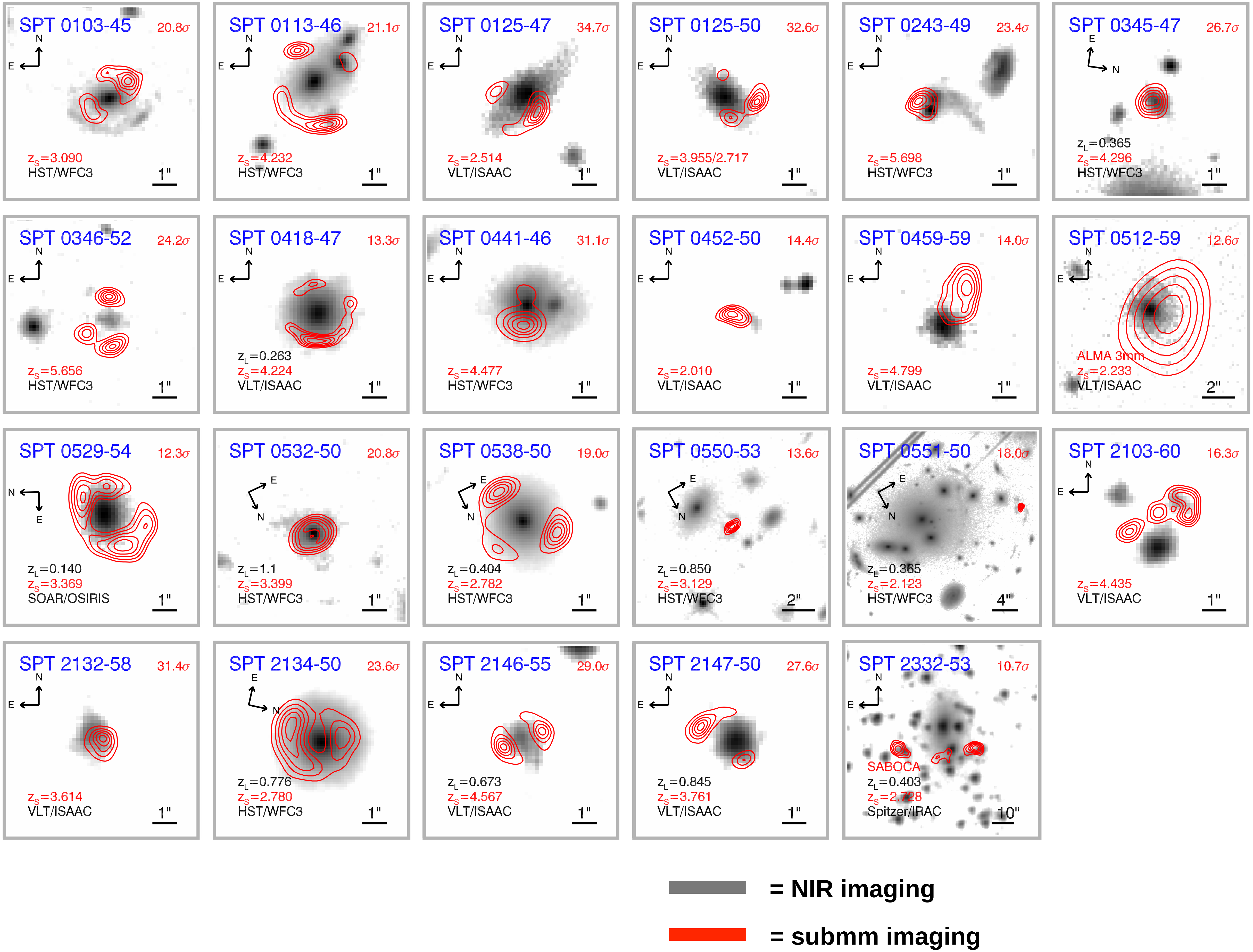
- We are now studying the ISM in great detail at the end of the epoch of reionization

- Future observations should allow us to detect dark matter substructure and shed light on it's nature.


FIN



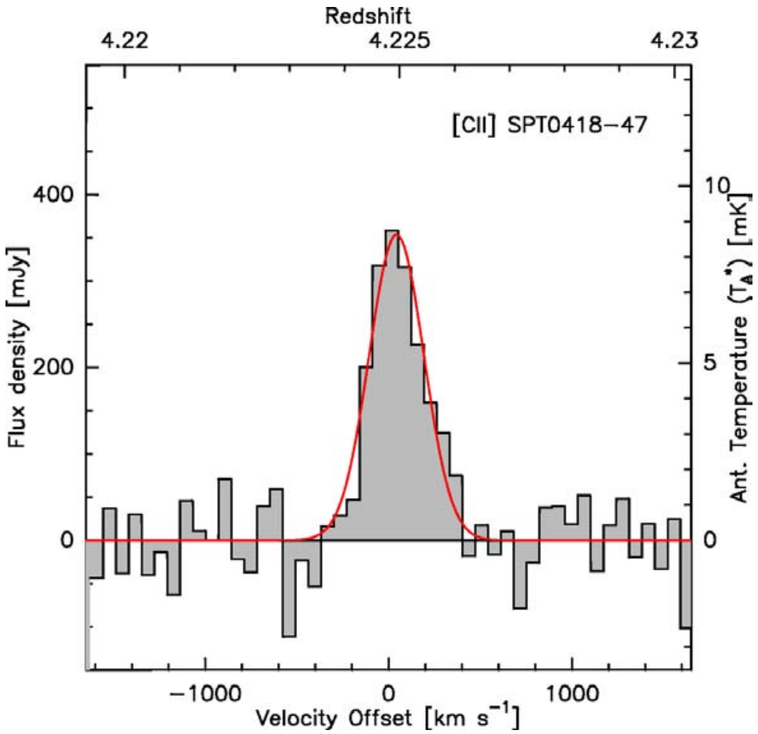
100
10
10
100
S870μm [mJy]
S1.4mm [mJy]
1000
100
10
10
100
S350μm [mJy]
S870μm [mJy]
SPIRE
SPT spec-z
10.0
1.0
0.1
0
1
2
3
4
5
6
7
S350μm / S870μm
z



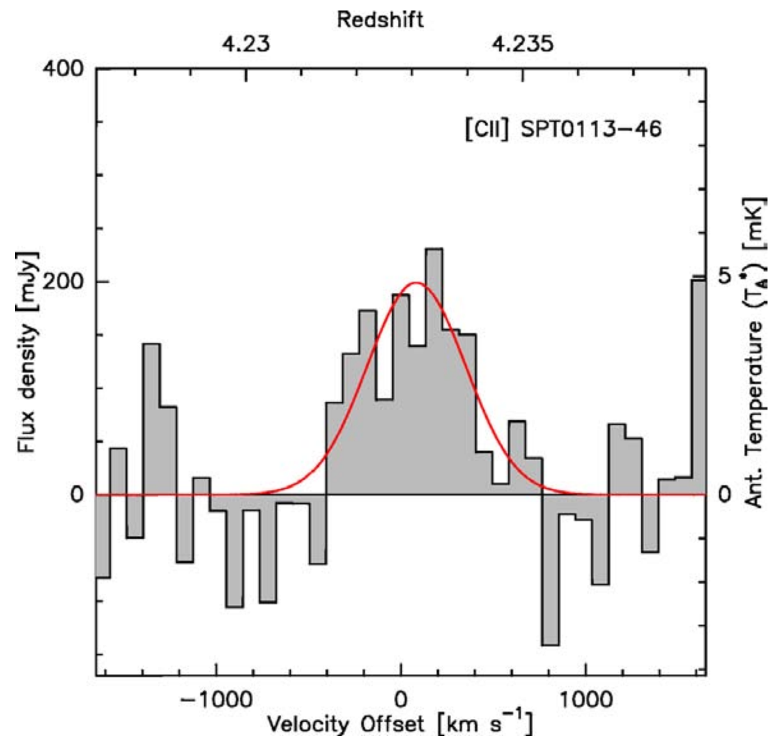
SPT 0103-45 20.8σ
z_S=3.090
HST/WFC3
1"
SPT 0113-46 21.1σ
z_S=4.232
HST/WFC3
1"
SPT 0125-47 34.7σ
z_S=2.514
VLT/ISAAC
1"
SPT 0125-50 32.6σ
z_S=3.955/2.717
VLT/ISAAC
1"
SPT 0243-49 23.4σ
z_S=5.698
HST/WFC3
1"
SPT 0345-47 26.7σ
z_L=0.365
z_S=4.296
HST/WFC3
1"
SPT 0346-52 24.2σ
z_S=5.656
HST/WFC3
1"
SPT 0418-47 13.3σ
z_L=0.263
z_S=4.224
VLT/ISAAC
1"
SPT 0441-46 31.1σ
z_S=4.477
HST/WFC3
1"
SPT 0452-50 14.4σ
z_S=2.010
VLT/ISAAC
1"
SPT 0459-59 14.0σ
z_S=4.799
VLT/ISAAC
1"
SPT 0512-59 12.6σ
ALMA 3mm
z_S=2.233
VLT/ISAAC
2"
SPT 0529-54 12.3σ
z_L=0.140
z_S=3.369
SOAR/OSIRIS
1"
SPT 0532-50 20.8σ
z_L=1.1
z_S=3.399
HST/WFC3
1"
SPT 0538-50 19.0σ
z_L=0.404
z_S=2.782
HST/WFC3
1"
SPT 0550-53 13.6σ
z_L=0.850
z_S=3.129
HST/WFC3
2"
SPT 0551-50 18.0σ
z_L=0.365
z_S=2.123
HST/WFC3
4"
SPT 2103-60 16.3σ
z_S=4.435
VLT/ISAAC
1"
SPT 2132-58 31.4σ
z_S=3.614
VLT/ISAAC
1"
SPT 2134-50 23.6σ
z_L=0.776
z_S=2.780
HST/WFC3
1"
SPT 2146-55 29.0σ
z_L=0.673
z_S=4.567
VLT/ISAAC
1"
SPT 2147-50 27.6σ
z_L=0.845
z_S=3.761
VLT/ISAAC
1"
SPT 2332-53 10.7σ
SABOCA
z_L=0.403
z_S=2.728
Spitzer/IRAC
10"
= NIR imaging
= submm imaging

[CII] at z > 4 detected with APEX/FLASH in ~hours

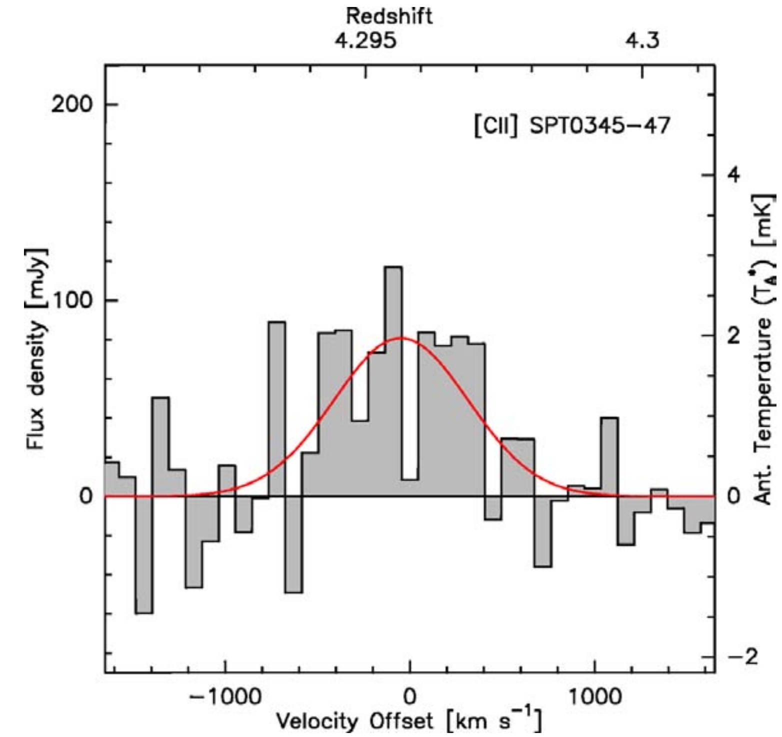
z = 4.23 ; t = 1.5h



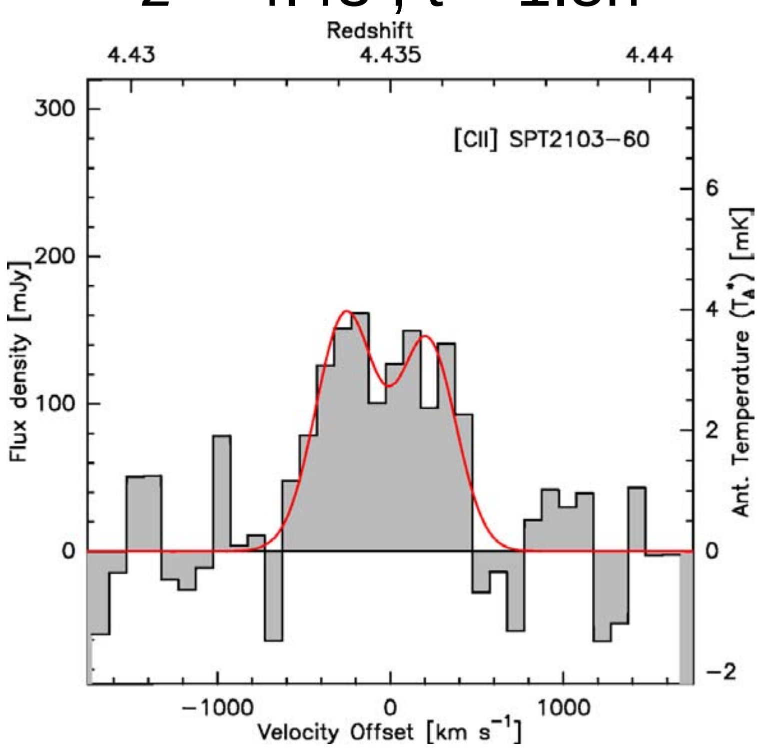
z = 4.23 ; t = 2.3h



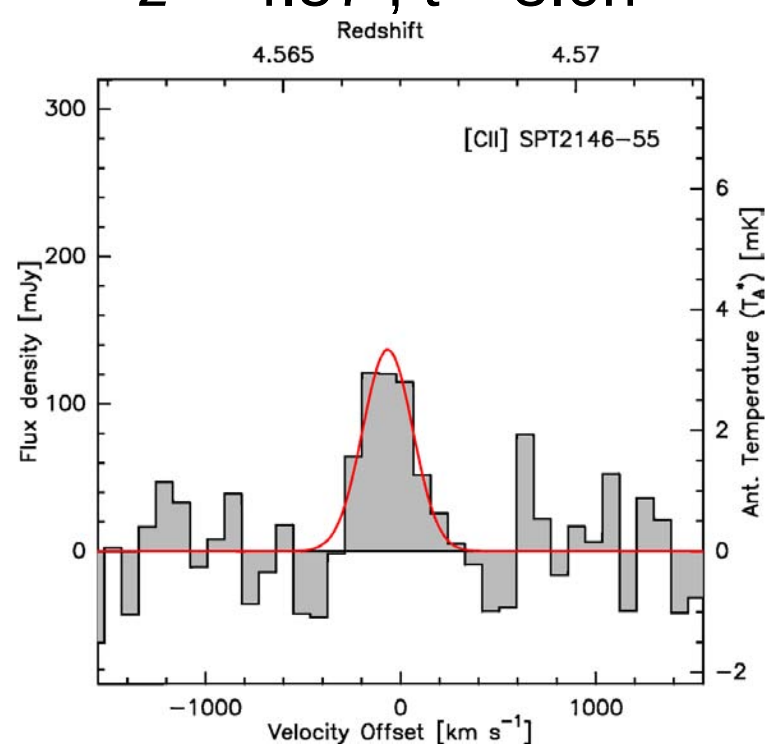
z = 4.30 ; t = 2.3h



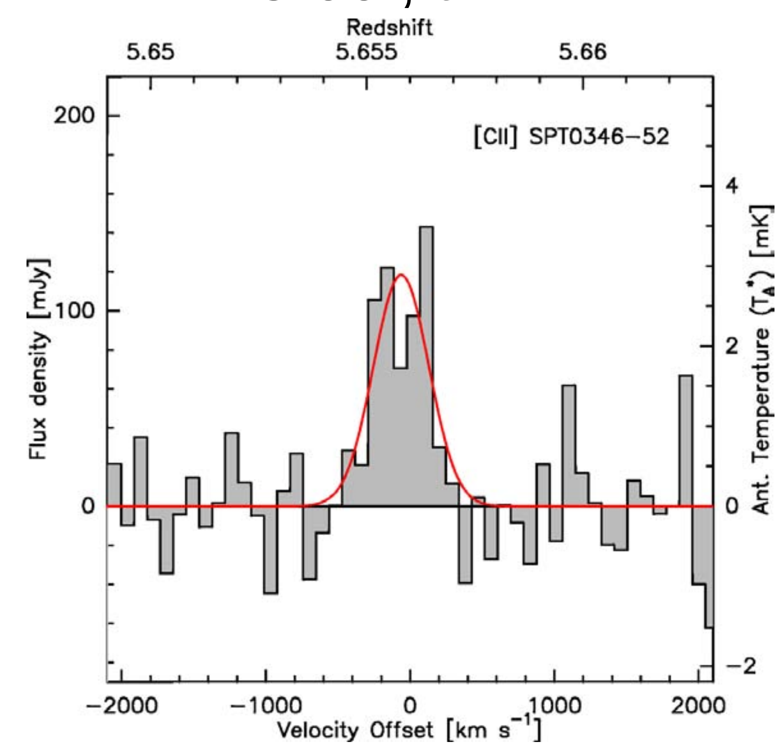
z = 4.43 ; t = 1.5h

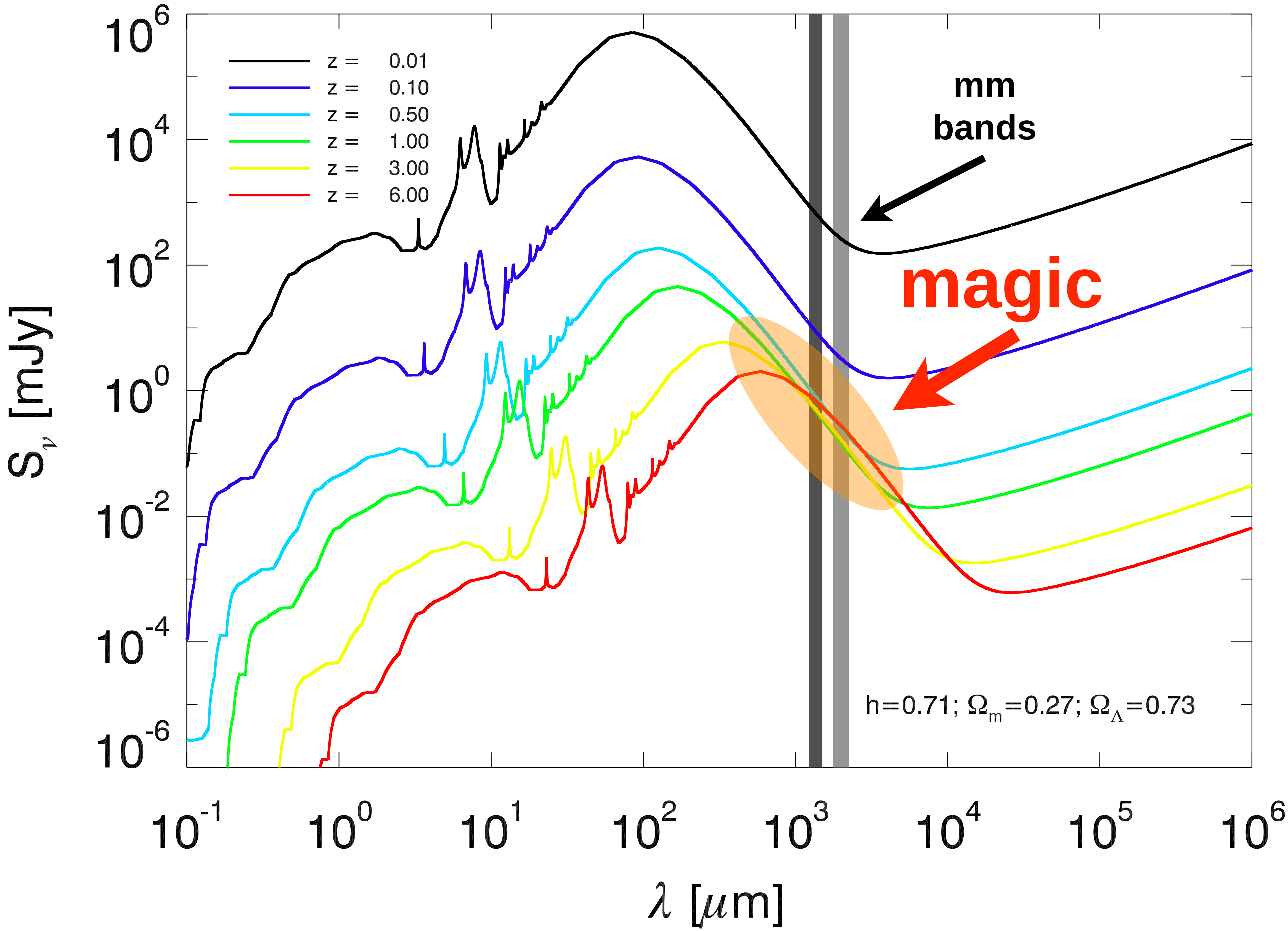


z = 4.57 ; t = 3.0h



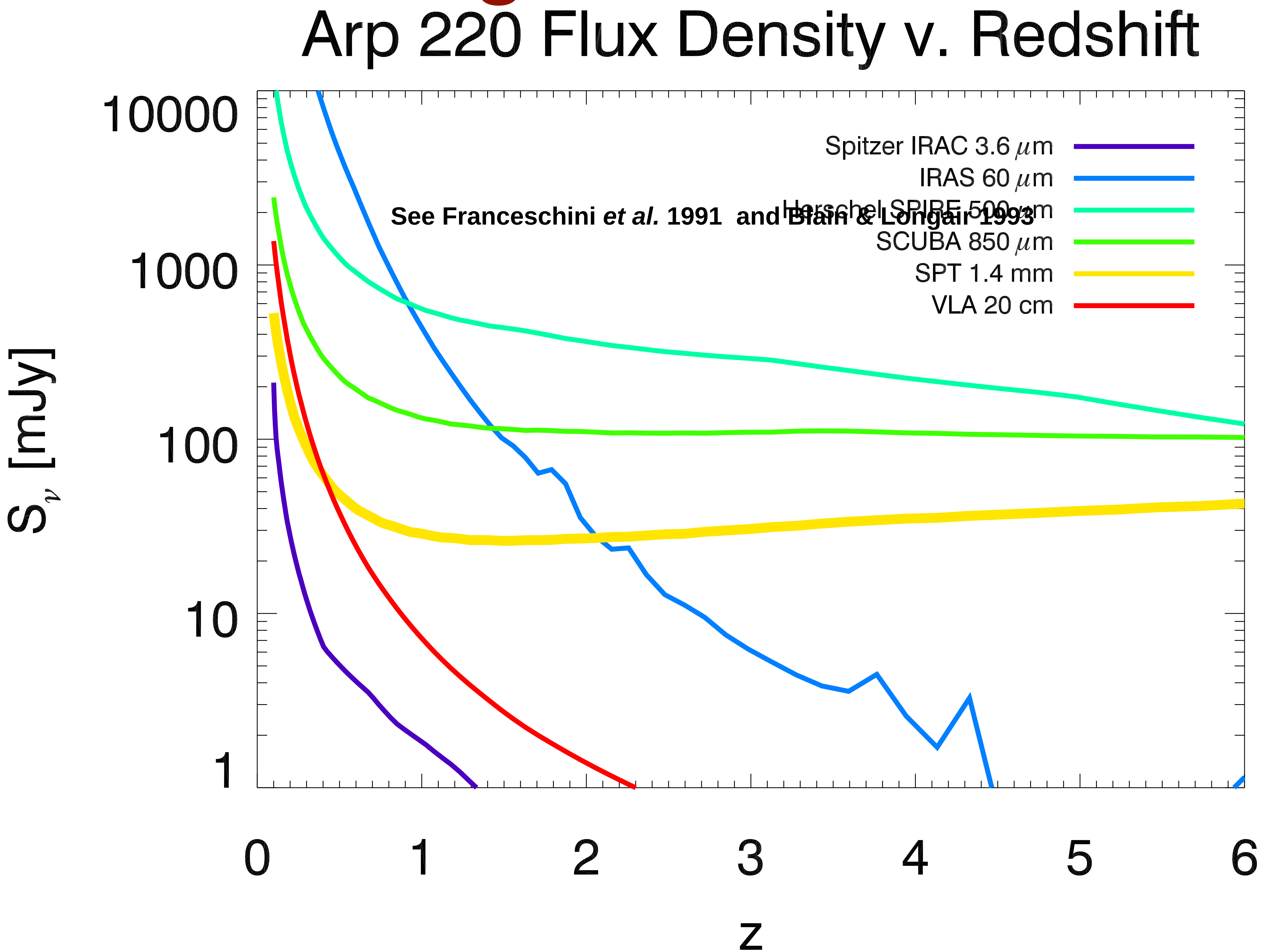
z = 5.66 ; t = 1.4h





z = 0.01
z = 0.10
z = 0.50
z = 1.00
z = 3.00
z = 6.00
mm bands
magic
h=0.71; Ω_m=0.27; Ω_Λ=0.73
S_ν [mJy]
λ [μm]
10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4} 10^{6}
10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}

Sub-mm magic

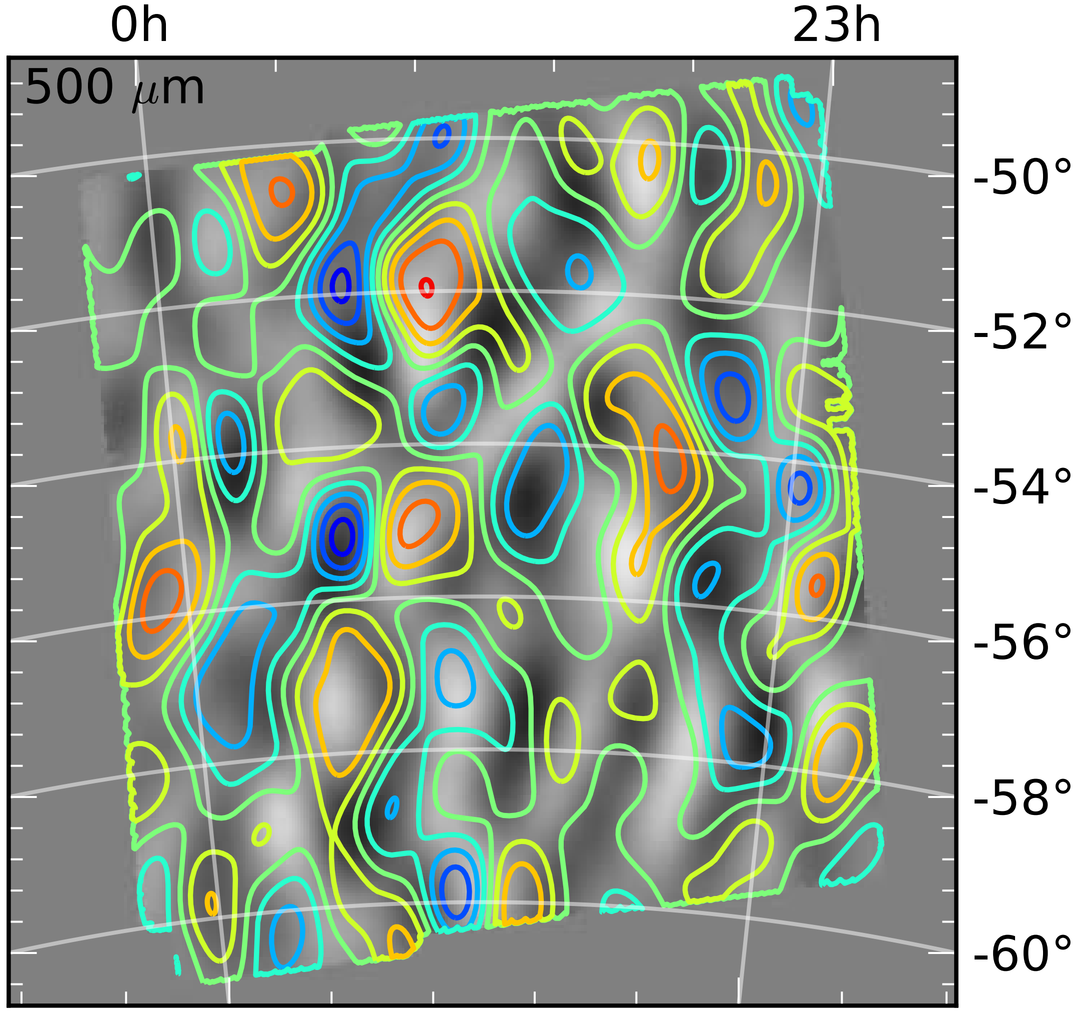


Arp 220 Flux Density v. Redshift
10000
1000
100
10
1
S_ν [mJy]
0
1
2
3
4
5
6
z
Spitzer IRAC 3.6 μm
IRAS 60 μm
Herschel SPIRE 500 μm
SCUBA 850 μm
SPT 1.4 mm
VLA 20 cm
See Franceschini et al. 1991 and Blain & Longair 1993

Full SPT 2500 deg² survey results this year

(Including CMB lensing, SZ cluster survey, high ℓ 2nd CMB→ tSZ, kSZ & reionization)

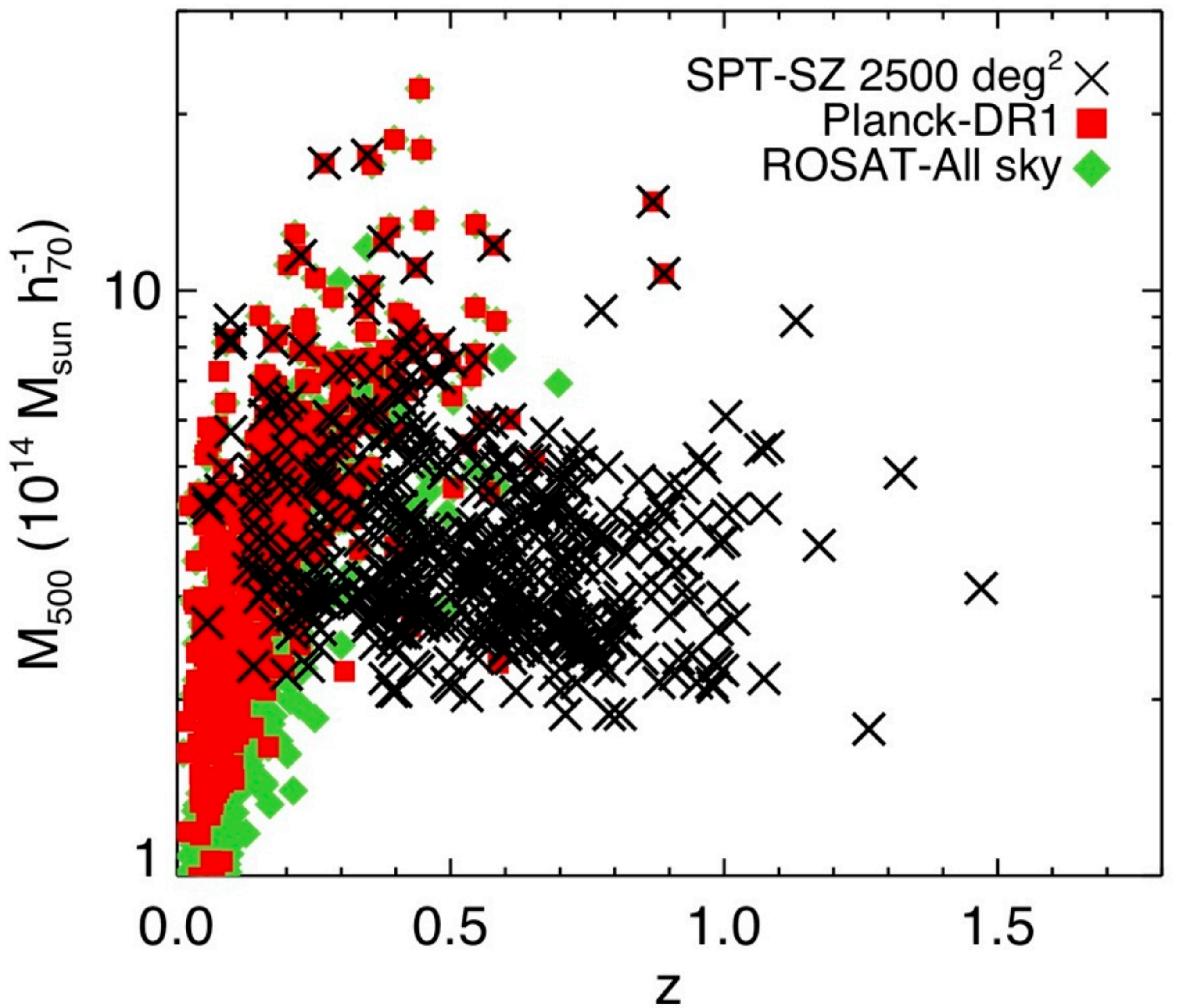
SPT CMB lensing maps



100 deg² SPT CMB lensing mass map (contours) overlaid on Herschel 500 um galaxy densities (greyscale) smoothed to degree resolution (Holder et al., arXiv:1303.5048)

SPT 2500 deg2 CMB lensing mass maps and cosmological results expected Spring 2013.

SPT SZ Cluster Survey

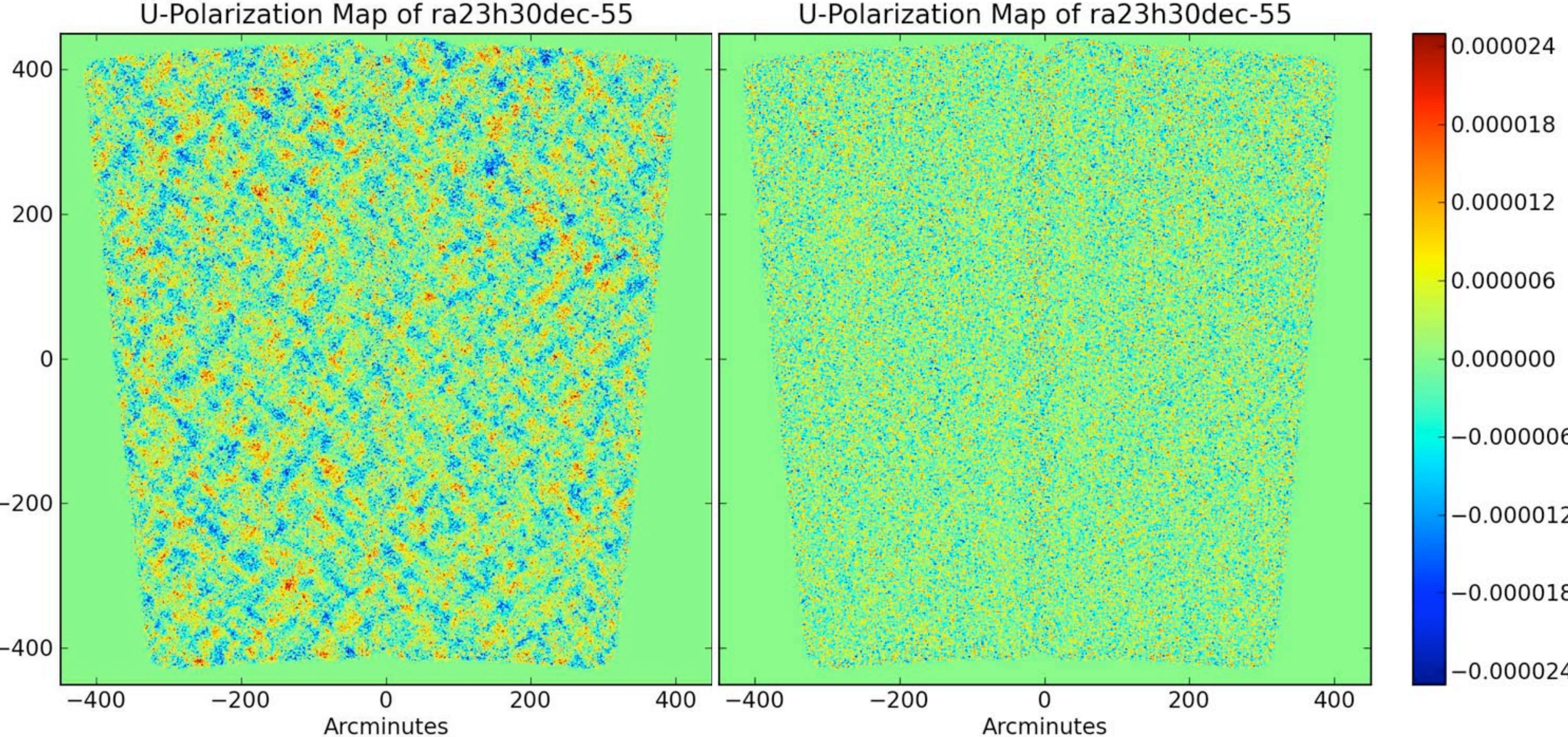


SPT 2500 deg² SZ cluster catalog and the cosmological results expected Summer 2013

SPT 1st yr 100 deg² polarization maps

Sum

Difference



Already have SPT data for exquisite E-mode spectrum and first detection of lensing B-mode spectrum.