Dust is the Stuff :

A new population of dusty sources discovered with the South Pole Telescope (and what it means)

Joaquin Vieira

Caltech

Berkeley Cosmology Seminar

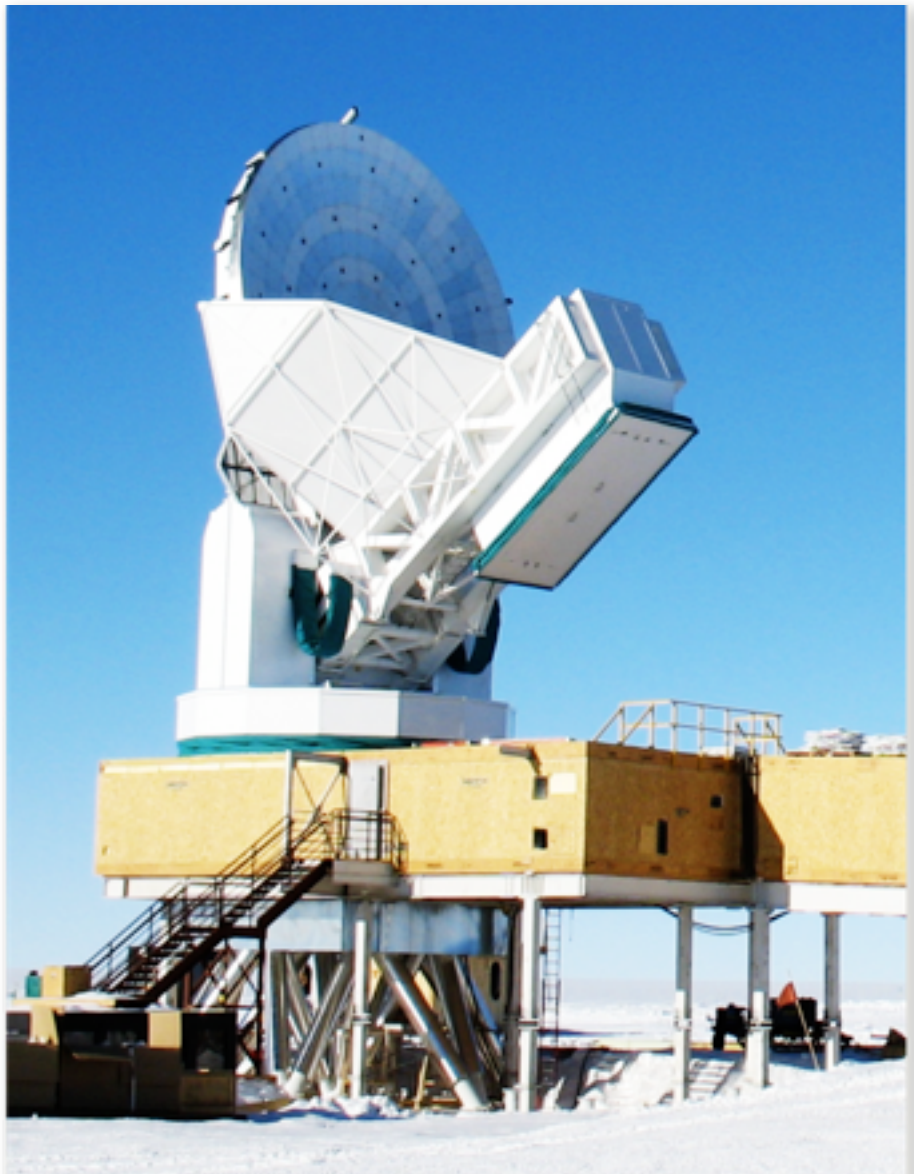
13 April 2010

Photo credit: Keith Vanderlinde
SPT 2nd season winter-over

OUTLINE

- Quick intro to SPT
  (I'm not going to bring coal to Newcastle)
- Biased and naive review of the history of extragalactic sub-mm astronomy.
- SPT sources and followup program.
- What's next?

The South Pole Telescope (SPT)



Funded by NSF

An experiment optimized for fine-scale anisotropy measurements of the CMB

- Dedicated 10-m telescope at the South Pole
- Background-limited 960-element mm camera

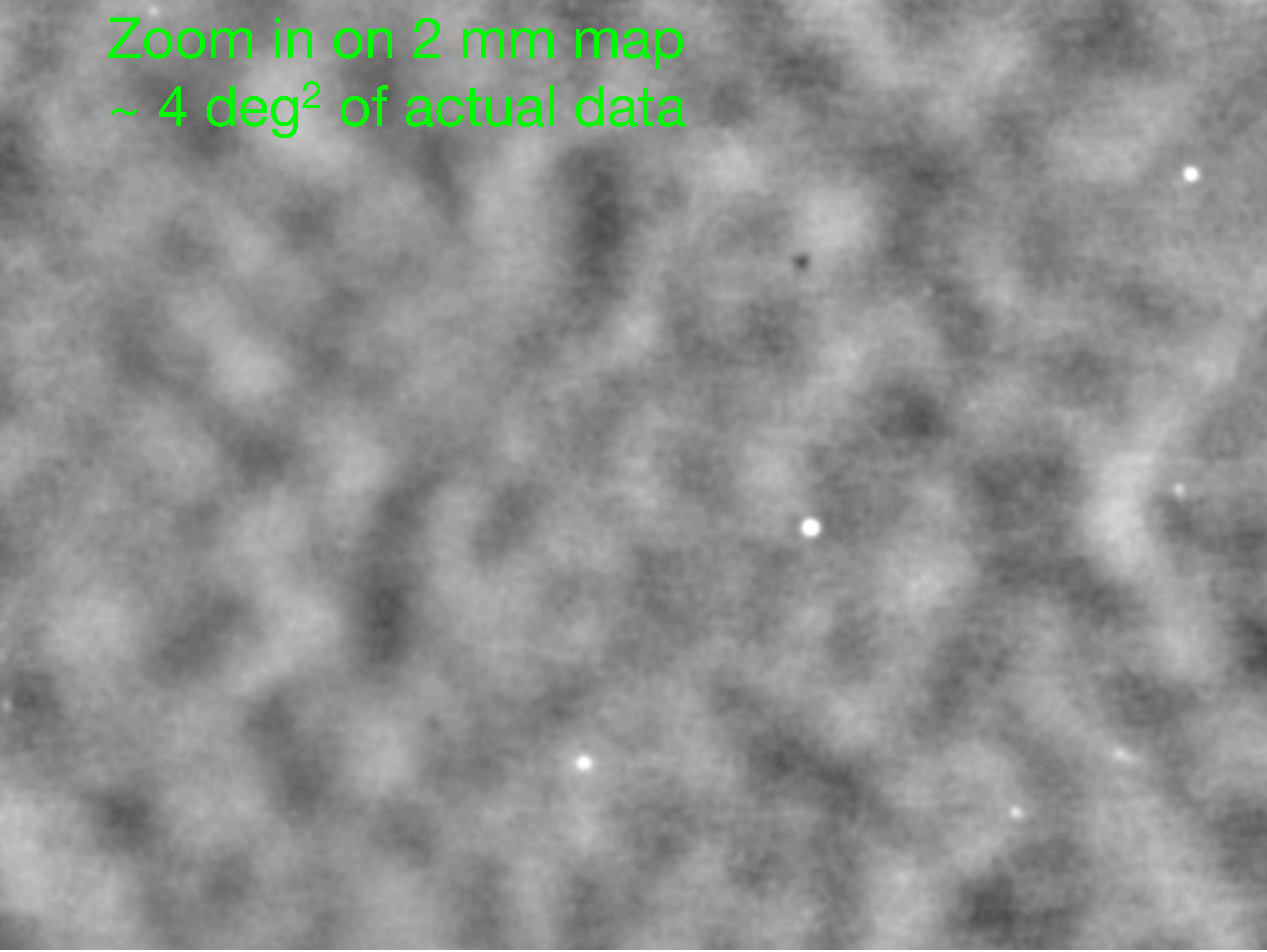
Science Goals:

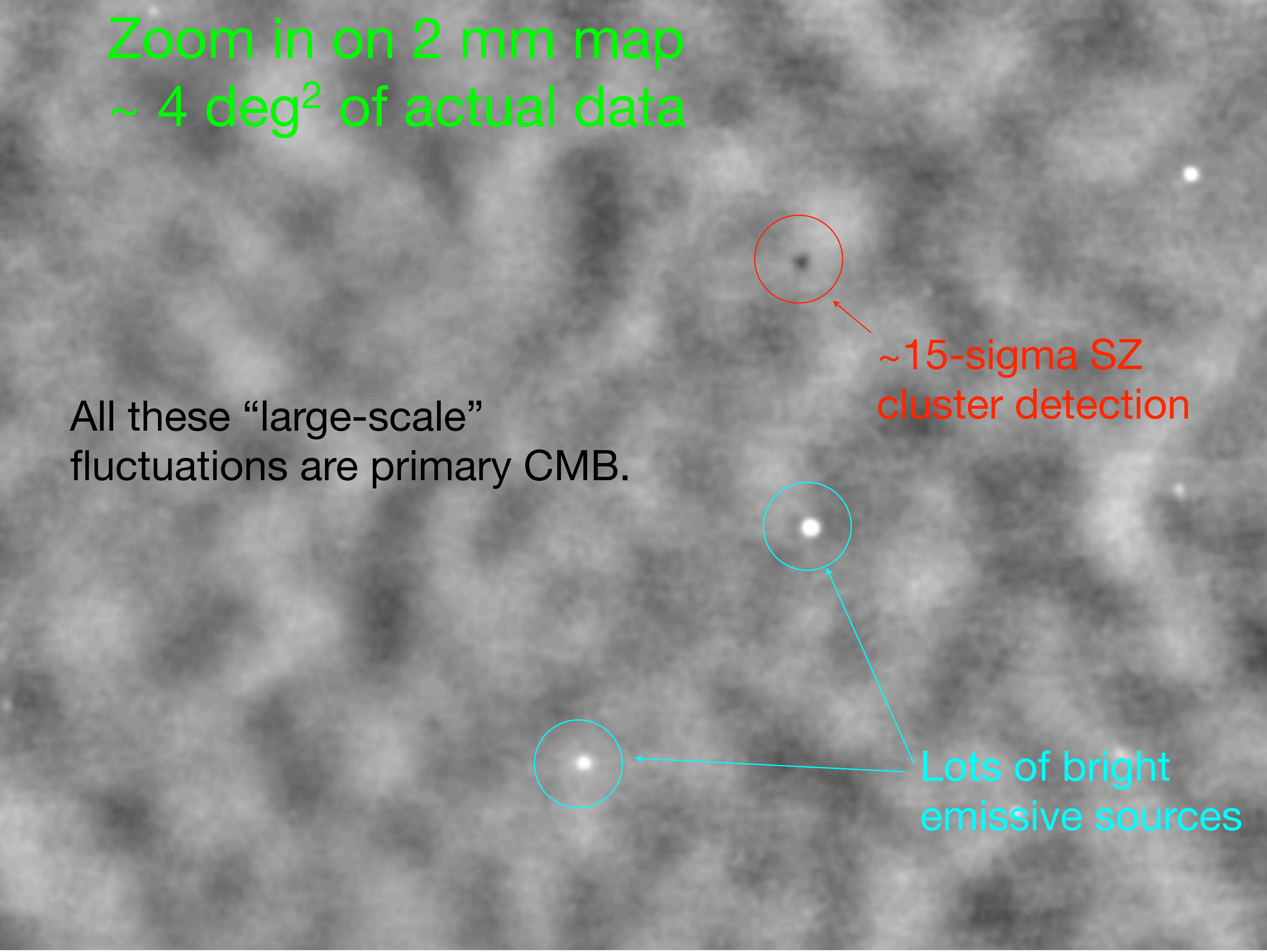
- Mass-limited SZ survey of galaxy clusters
  - study growth of structure, dark energy equation of state
- Fine-scale CMB temperature anisotropies
  - tSZ power spectrum to measure σ_8
  - kSZ power spectrum to constrain reionization
- mm sources
  - dusty star forming galaxies
  - AGN
  - Other rare objects

- NEXT: Polarization

Zoom in on 2 mm map

~ 4 deg^2 of actual data




Zoom in on 2 mm map
~ 4 deg² of actual data
~15-sigma SZ
cluster detection
All these “large-scale”
fluctuations are primary CMB.
Lots of bright
emissive sources

SPT Team February 2007

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

UC Davis University of California

Case Western Reserve University

Colorado University of Colorado at Boulder

Cardiff University Prifysgol Caerdydd

KICP Kavli Institute for Cosmological Physics at the University of Chicago
Berkeley University of California
Astronomy University of Illinois at Urbana-Champaign
Case Western Reserve University
McGill
The University of Chicago
Harvard-Smithsonian Center for Astrophysics
Berkeley Lab
Cardiff University Prifysgol Caerdydd
UC Davis University of California
Colorado University of Colorado at Boulder

SPT Collaboration

May 2008

7 Results as of April 2010

- First blind SZ detection of a galaxy cluster
  Staniszewski+2009 ApJ 701, 32

- SZ radial profiles of 15 targeted clusters out to the virial radius
  Plagge+2009 accepted to ApJ arXiv:0911.2444

- Detection of a new population of dusty mm sources.
  Vieira+2010 accepted to ApJ arXiv:0912.2338

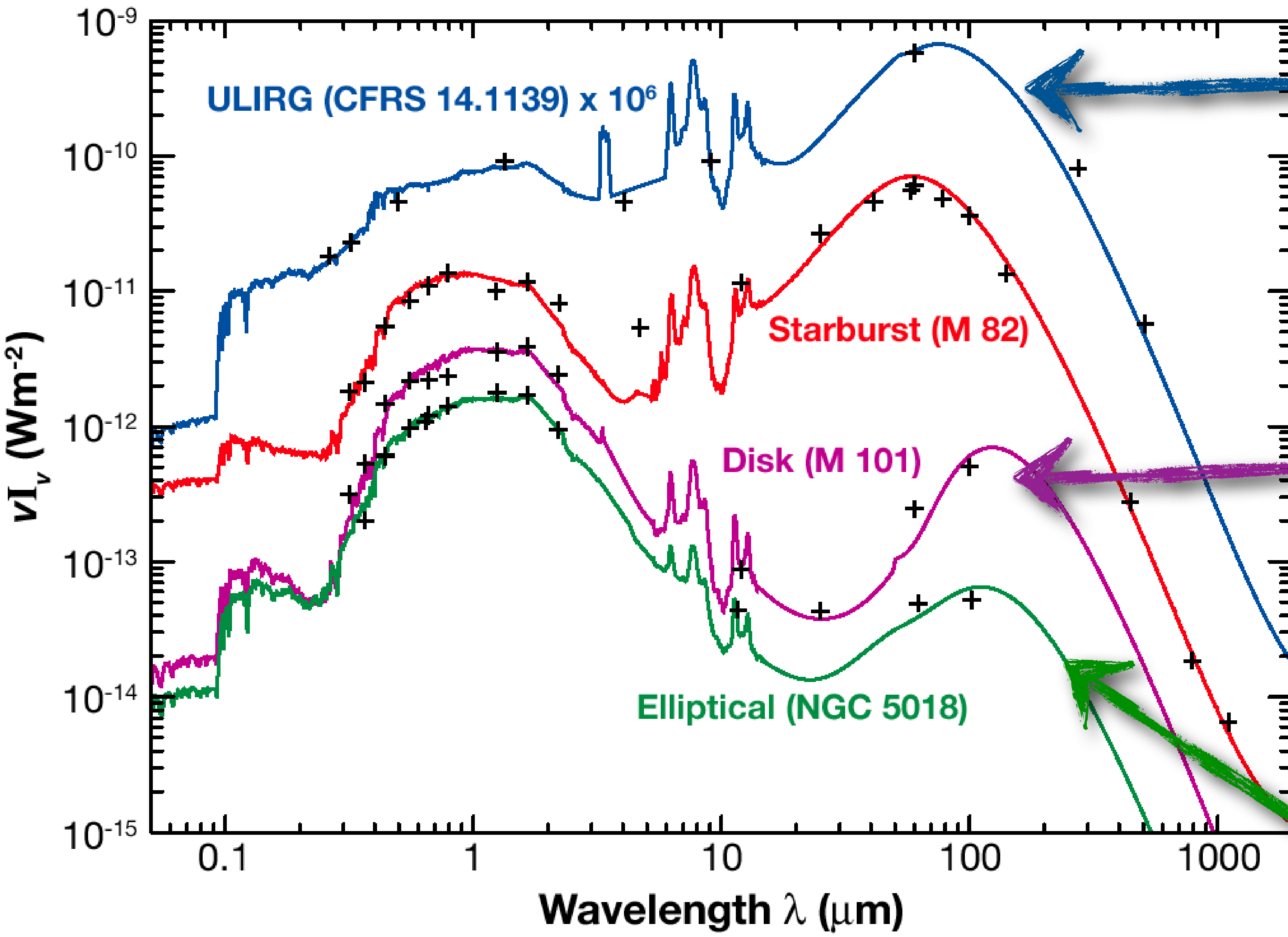
- First detection of clustered signal of extragalactic CIB sources in the mm
  Hall+2010 submitted to ApJ arXiv:0912.4315

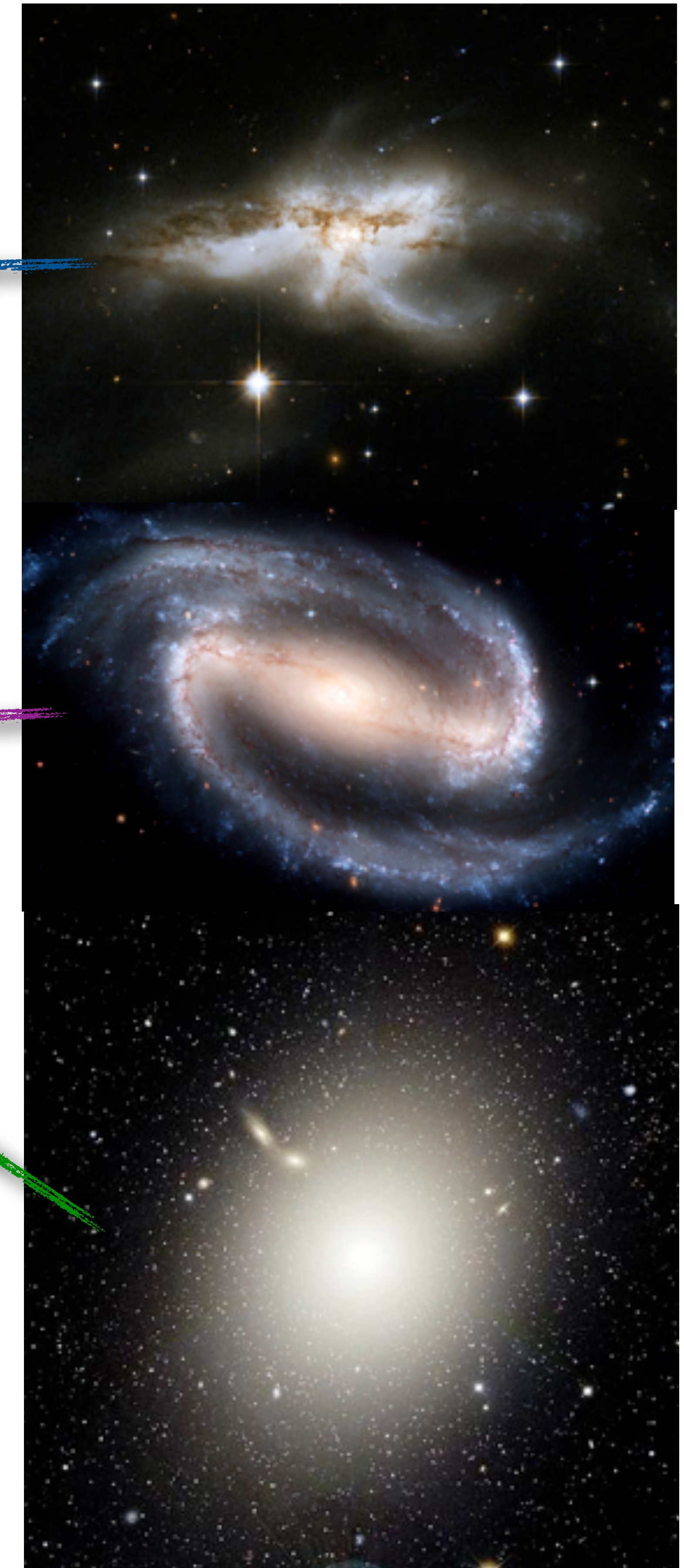
- First detection of tSZ in the CMB powerspectrum
  Lueker+2010 submitted to ApJ arXiv:0912.4317

- First SZ selected cluster catalog
  Vanderlinde+2010 submitted to ApJ arXiv:1003.0003

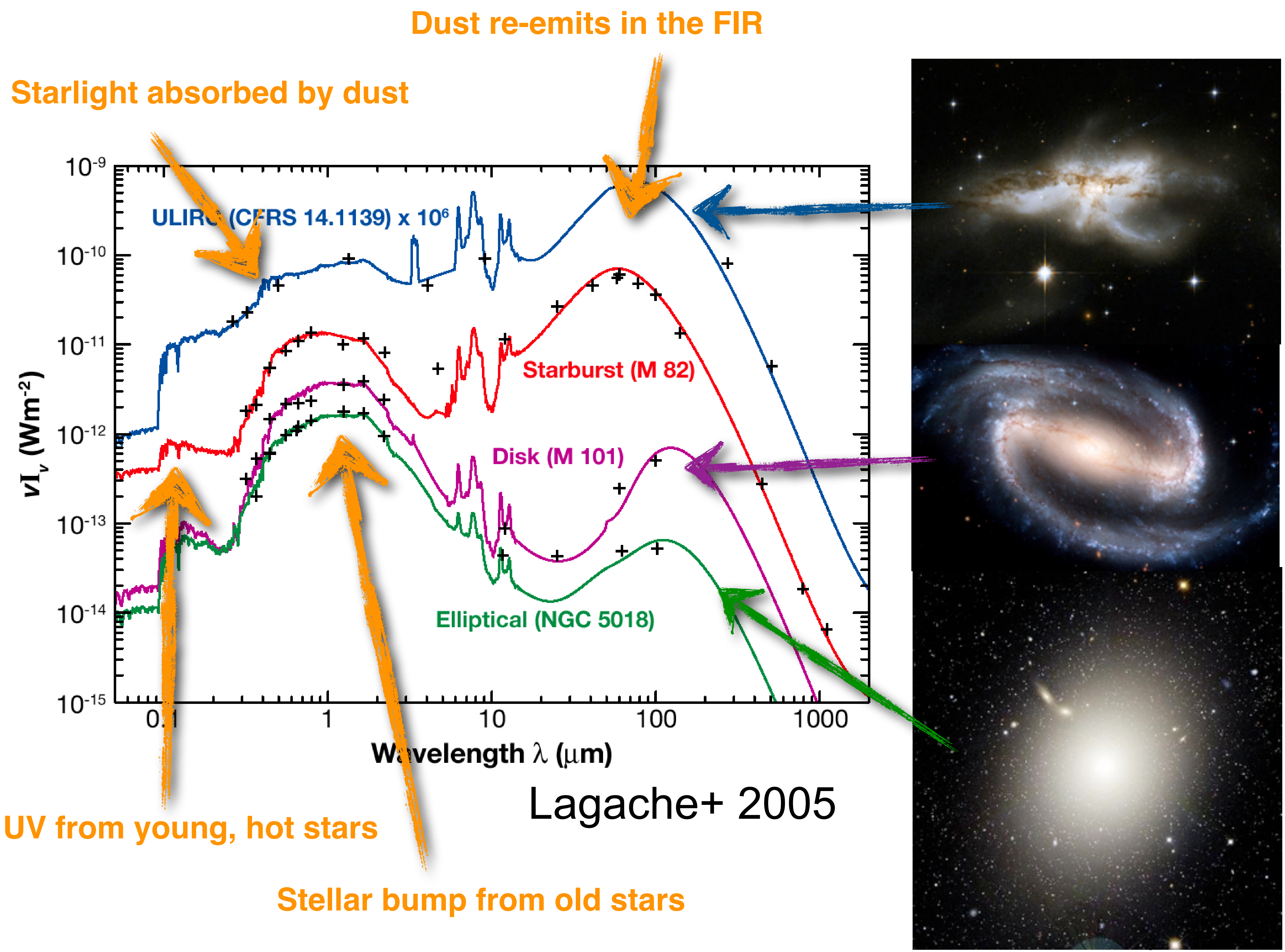
- Redshift distribution of SZ clusters
  High+2010 submitted to ApJ arXiv:1003.0005

Dust in Galaxies



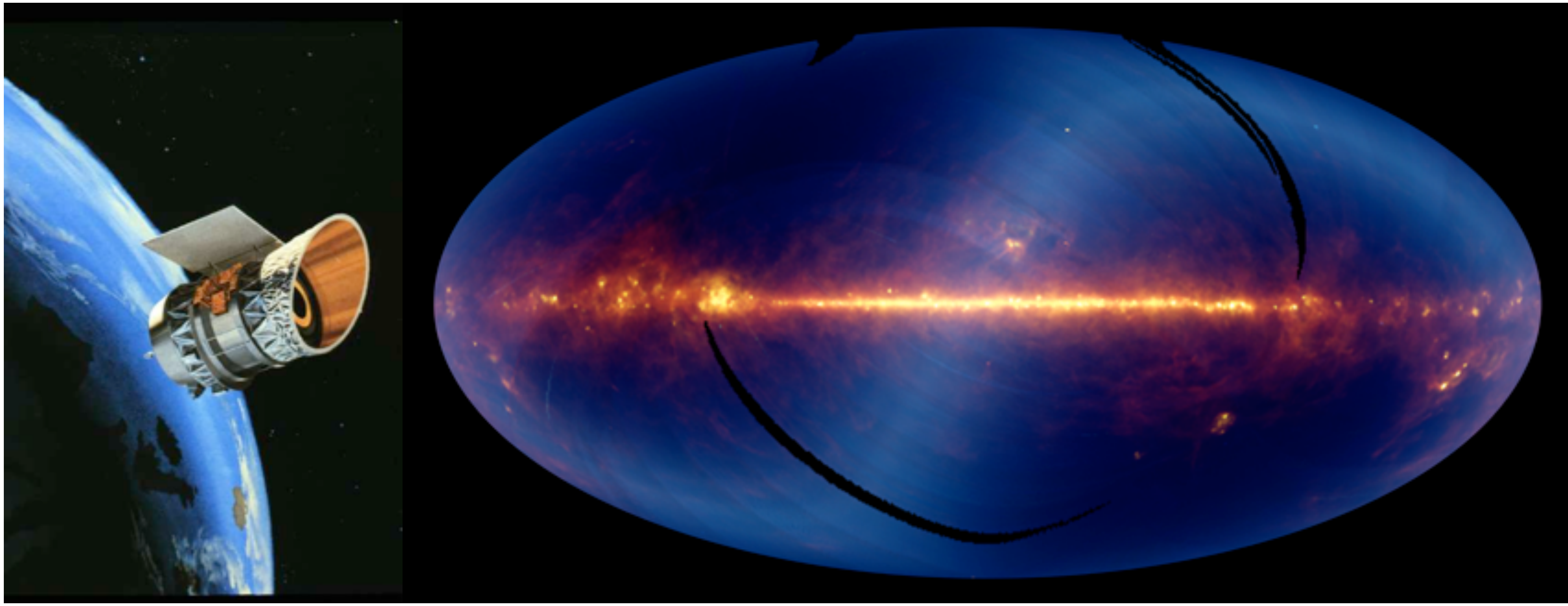


Lagache+ 2005



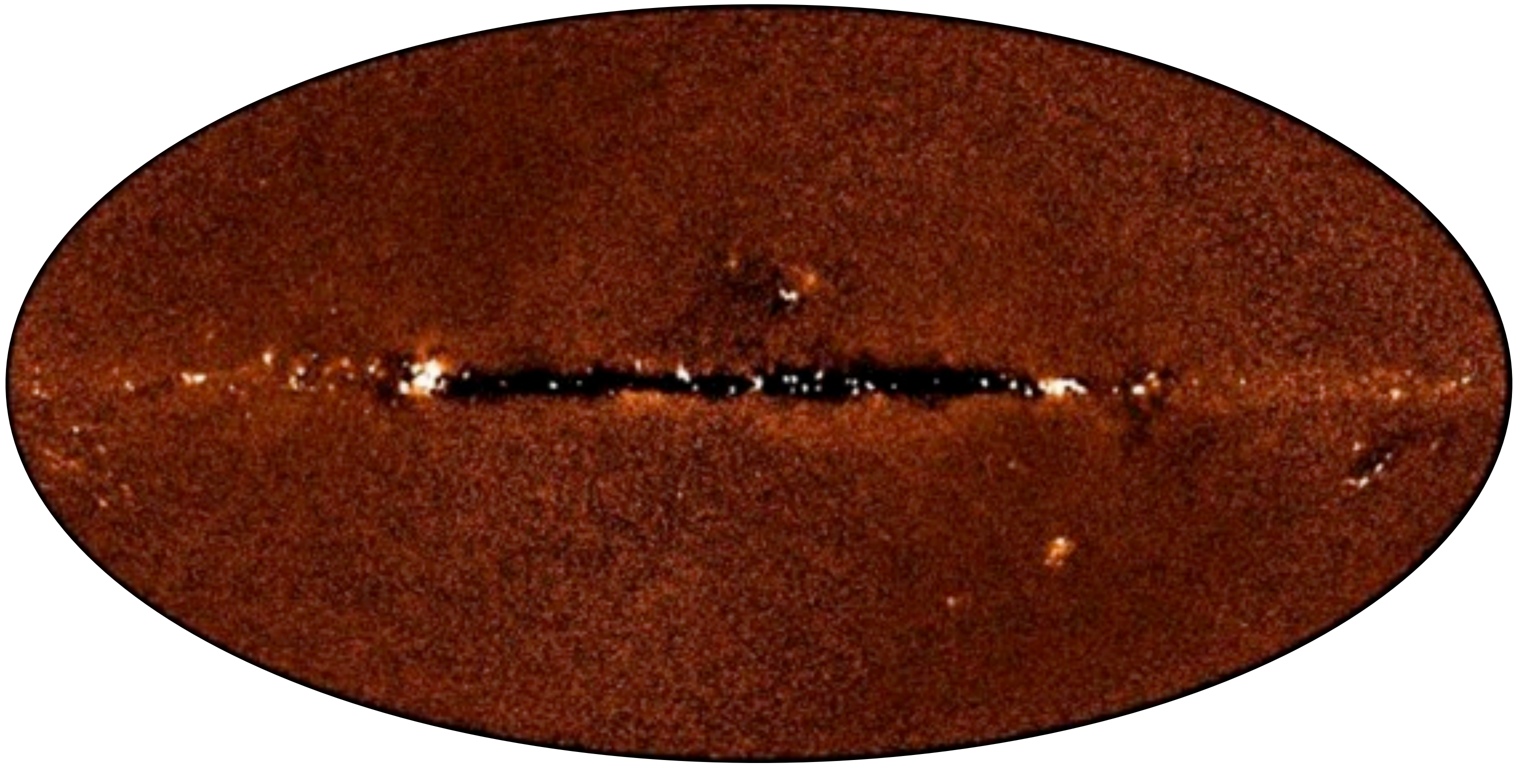
Dust re-emits in the FIR
Starlight absorbed by dust
ULIR (CFRS 14.1139) x 10^6
Starburst (M 82)
Disk (M 101)
Elliptical (NGC 5018)
νI_ν (Wm^{-2})
10^-9
10^-10
10^-11
10^-12
10^-13
10^-14
10^-15
0.1
1
10
100
1000
Wavelength λ (μm)
Lagache+ 2005
UV from young, hot stars
Stellar bump from old stars

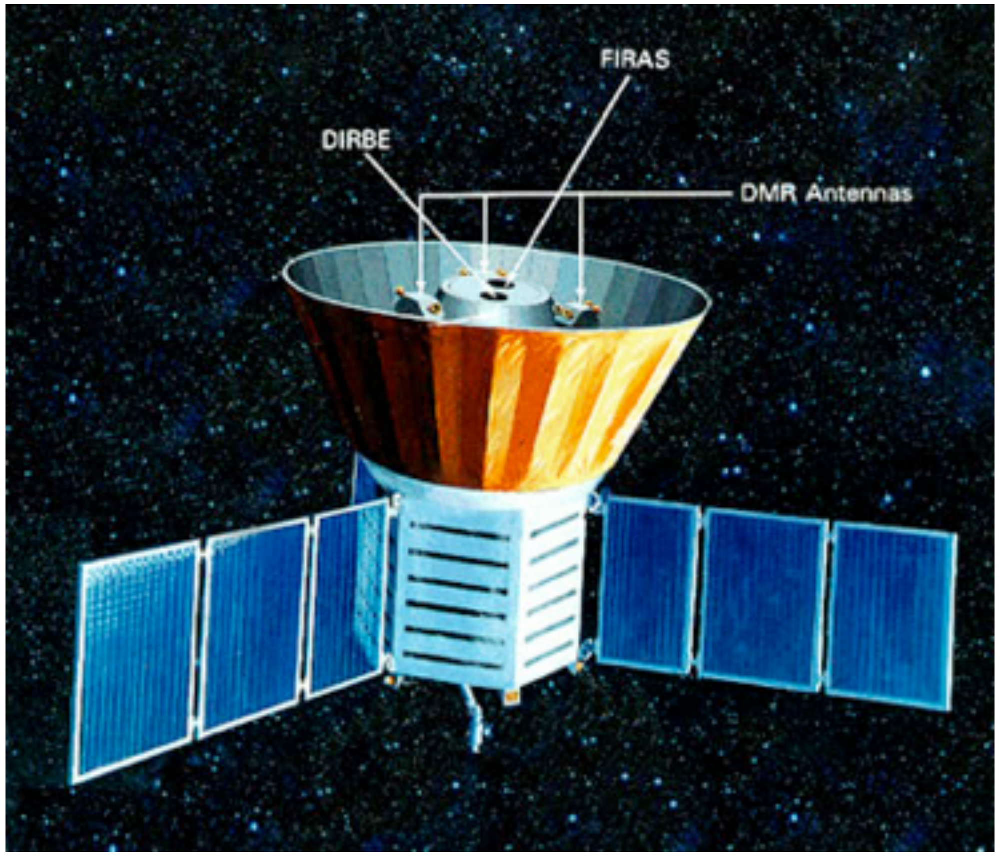
IRAS



- 1983 first all-sky infrared survey
- 12, 25, 60, 100 μm from 20" to 2' resolution
- systematic detection of ~ 75k starburst galaxies
- detected IR emission from interacting galaxies
- discovered IRAS F10214+4724 - the most luminous galaxy in the universe.
- faint source catalog is $S_{60\mu m}$ > 200 mJy
- theses still being written with this data!

COBE and the CIB





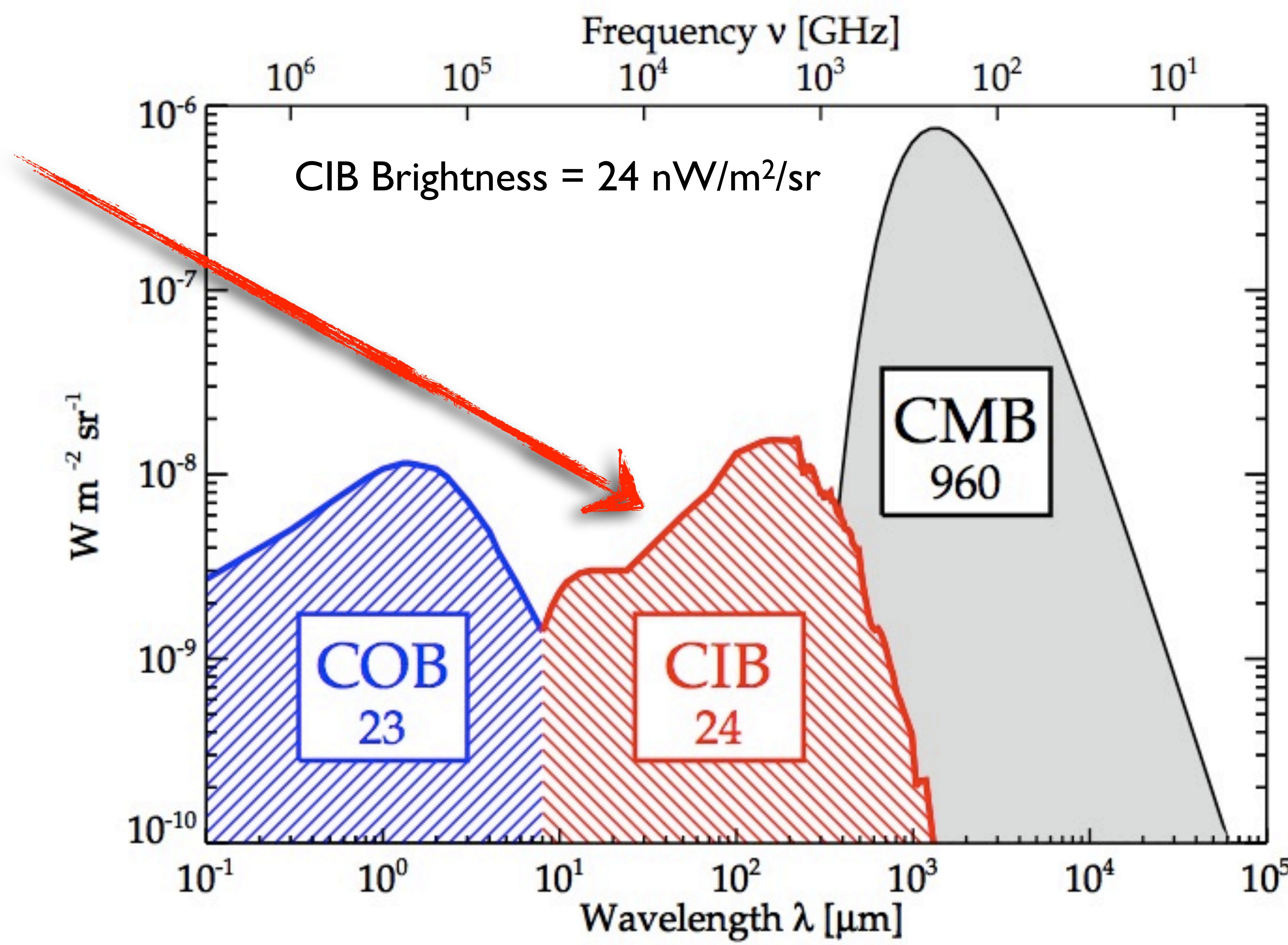
DIRBE Extragalactic Background

- Partridge & Peebles (1967) predict a diffuse extragalactic background, which would retain the imprint of the history of structure formation (they thought of starlight, not dust emission).
- 1989 COBE launches with DIRBE+FIRAS
- 1996 Puget et al publish first (tentative) detection of cosmic infra-red background (CIB) from FIRAS data at 240 μm, then with DIRBE at 140 and 240 μm (SFD 1998, Hauser+ 1998, Fixsen+ 1998) and many papers since.
- The cosmic far-infrared background demonstrates that half the energy produced since the surface of last scattering has been reprocessed by dust. 12

Dusty sources are cosmologically important

Over half of the energy produced since the surface of last scattering has been absorbed and re-emitted by dust.

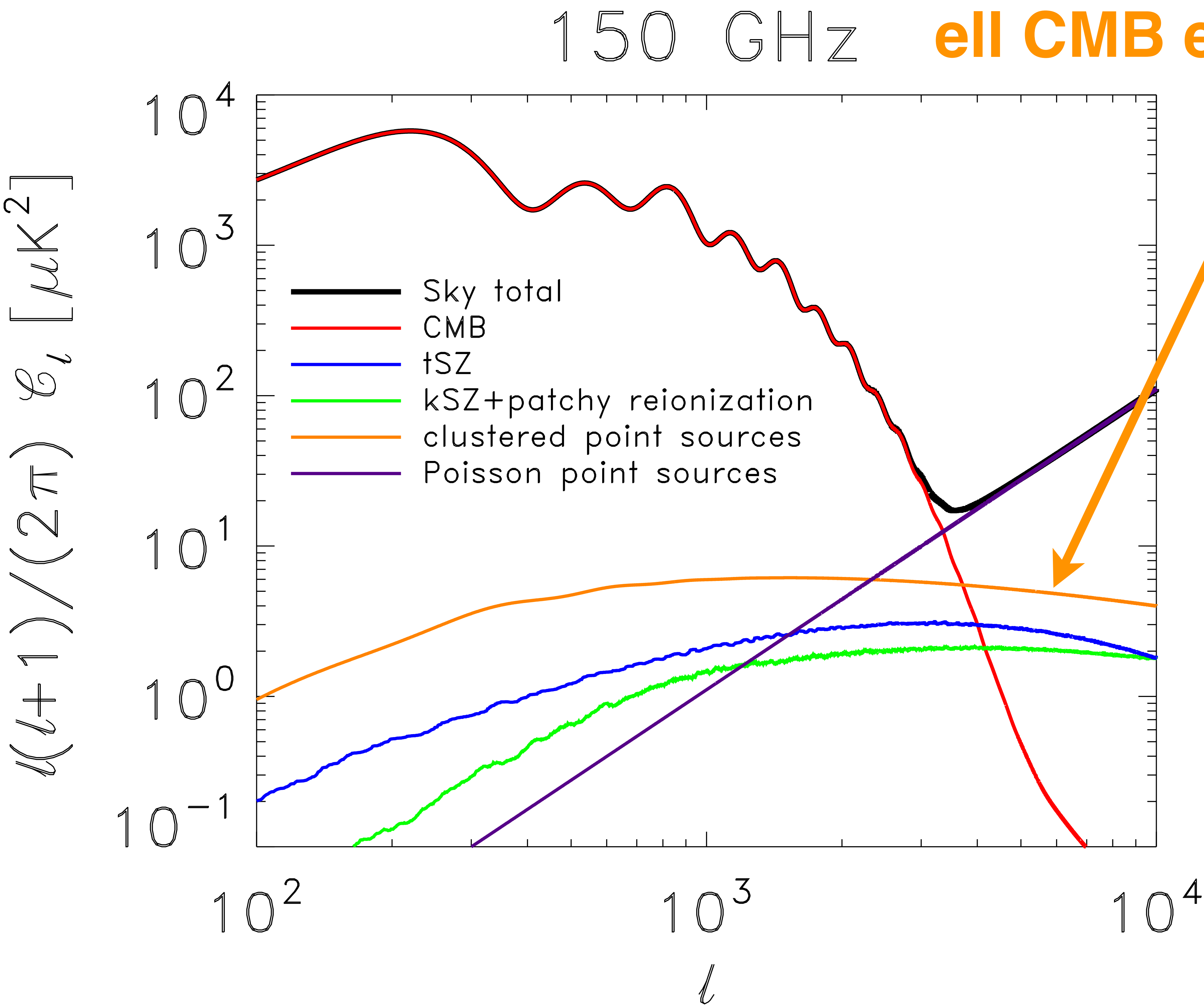
This background of dusty galaxies makes up the Cosmic Infrared Background (CIB)



Dole *et al.* 2006

They can also be a nuisance...

These dusty sources are also a difficult foreground for high-ell CMB experiments



cosmic downsizing = more massive objects form earlier and evolve faster than small things

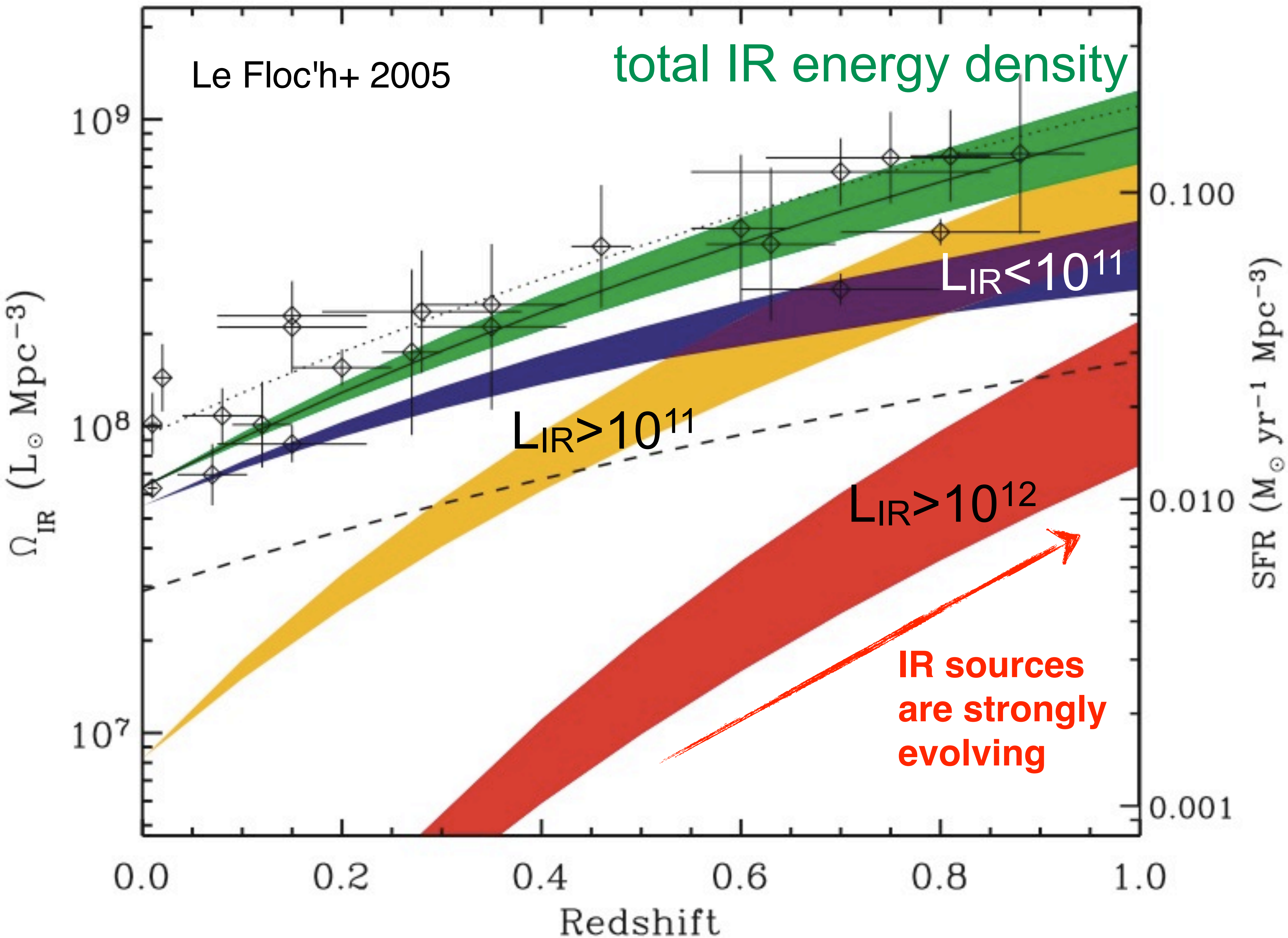
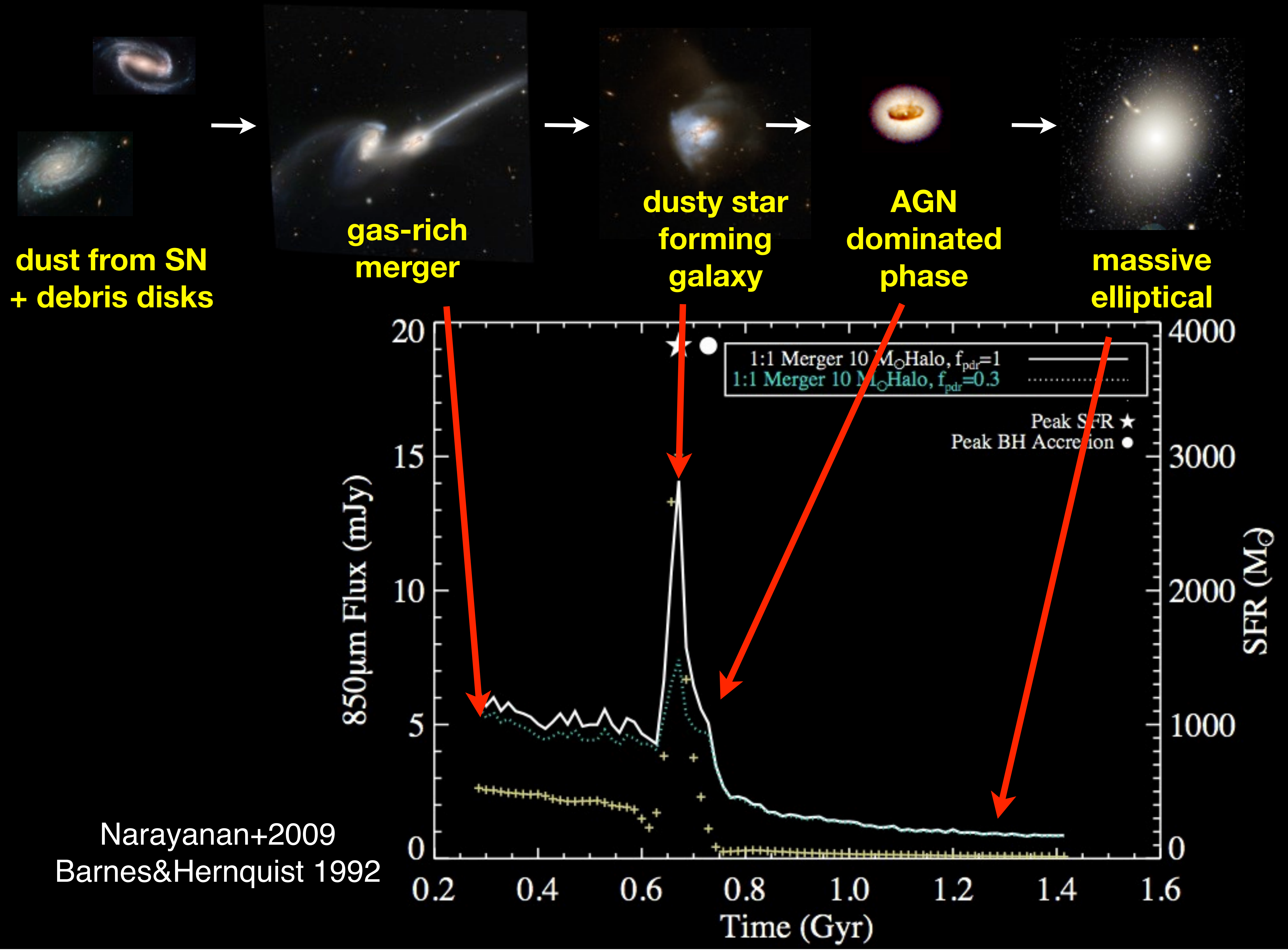
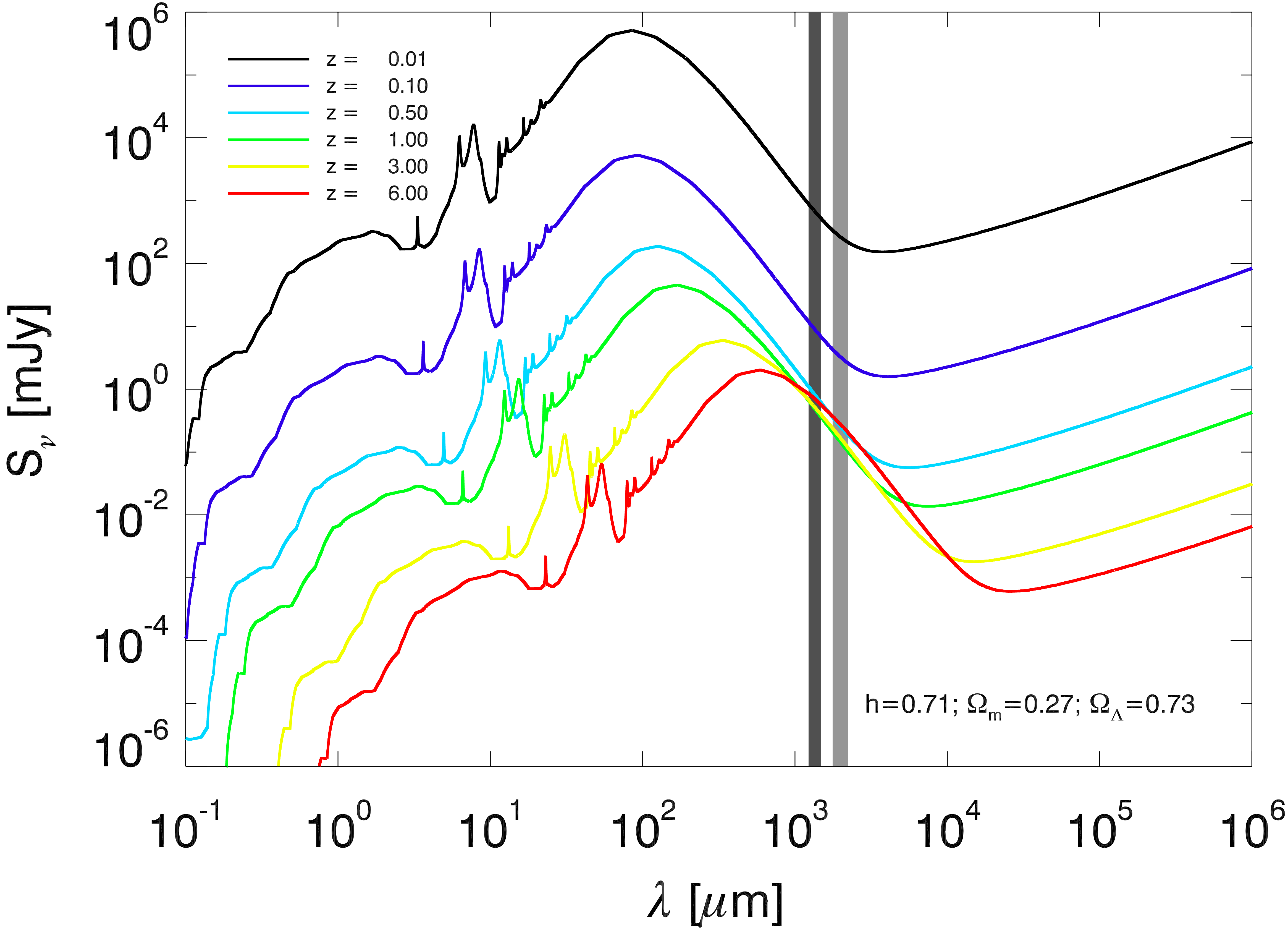


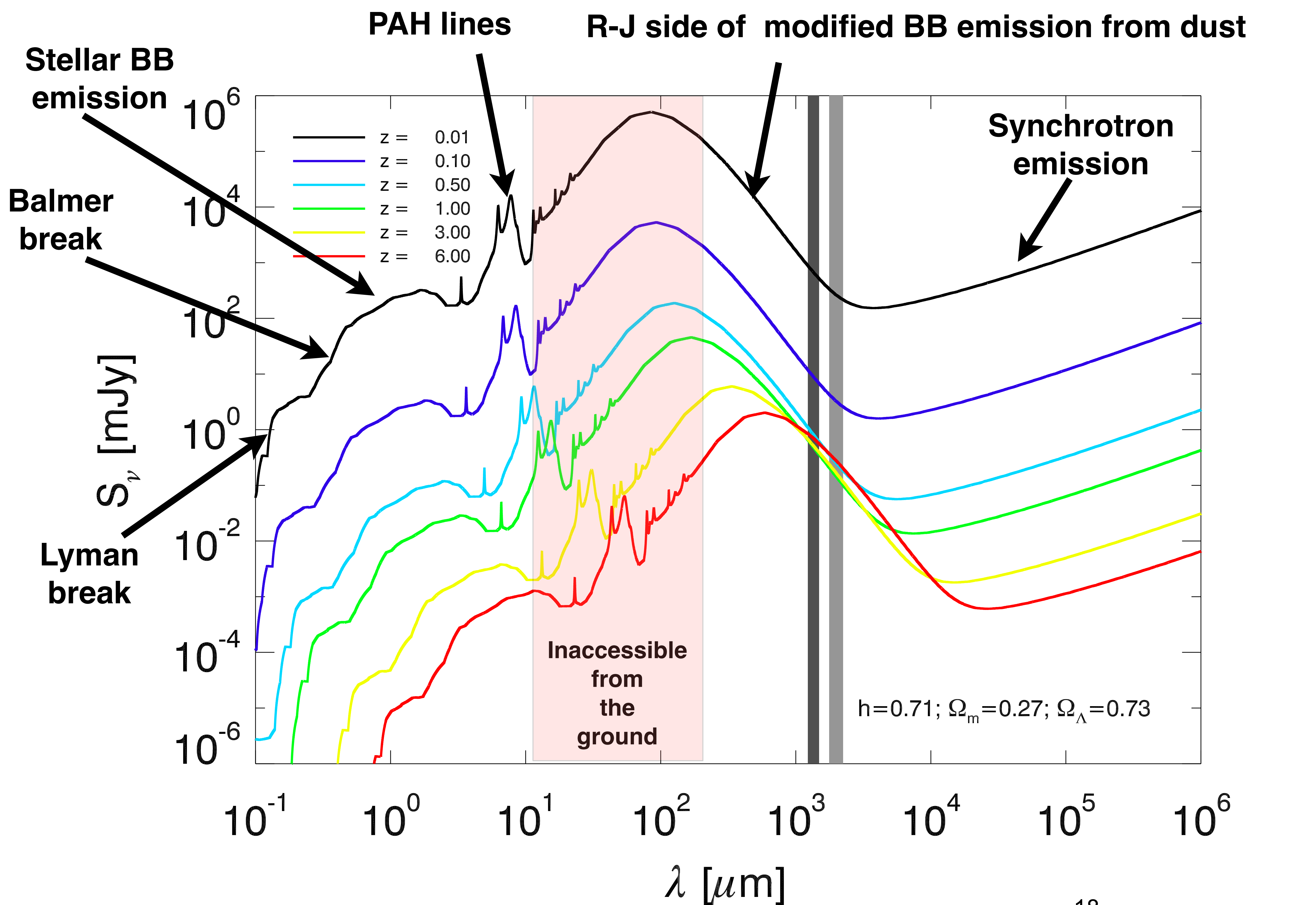
FIG. 14.—Evolution of the comoving IR energy density up to $z = 1$ (*green filled region*) and the respective contributions from low-luminosity galaxies (i.e.,



dust from SN
+ debris disks
gas-rich
merger
dusty star
forming
galaxy
AGN
dominated
phase
massive
elliptical
1:1 Merger 10 M☉Halo, f_{pdr}=1
1:1 Merger 10 M☉Halo, f_{pdr}=0.3
Peak SFR ★
Peak BH Accretion ●
850μm Flux (mJy)
SFR (M☉)
Time (Gyr)
0
5
10
15
20
0
1000
2000
3000
4000
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Narayanan+2009
Barnes&Hernquist 1992

Arp 220 v. Redshift





PAH lines
R-J side of modified BB emission from dust
Stellar BB emission
Synchrotron emission
Balmer break
Lyman break
z = 0.01
z = 0.10
z = 0.50
z = 1.00
z = 3.00
z = 6.00
Inaccessible from the ground
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}

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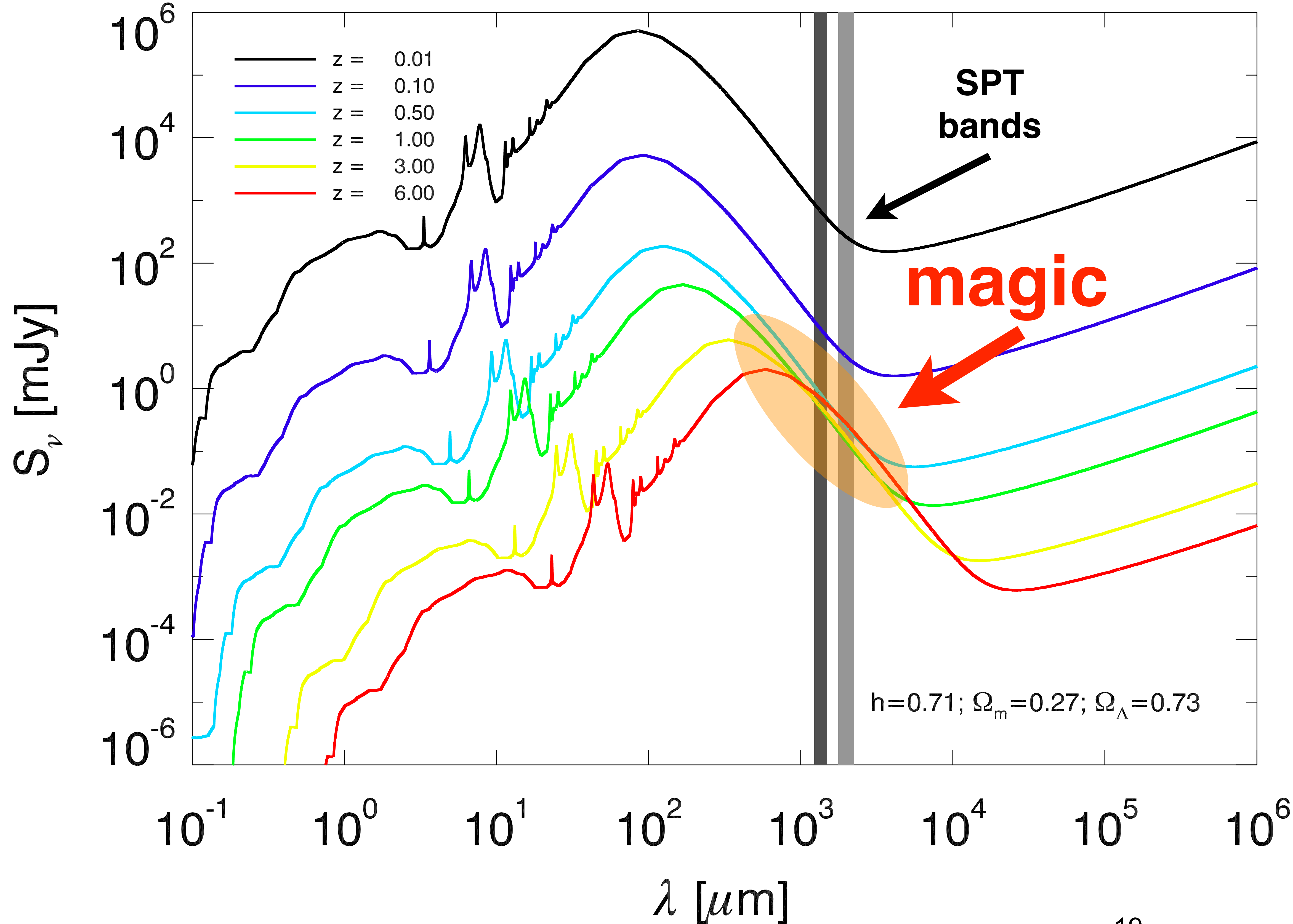

z = 0.01
z = 0.10
z = 0.50
z = 1.00
z = 3.00
z = 6.00
SPT bands
magic
h=0.71; Ω_m=0.27; Ω_Λ=0.73
S_ν [mJy]
λ [μm]

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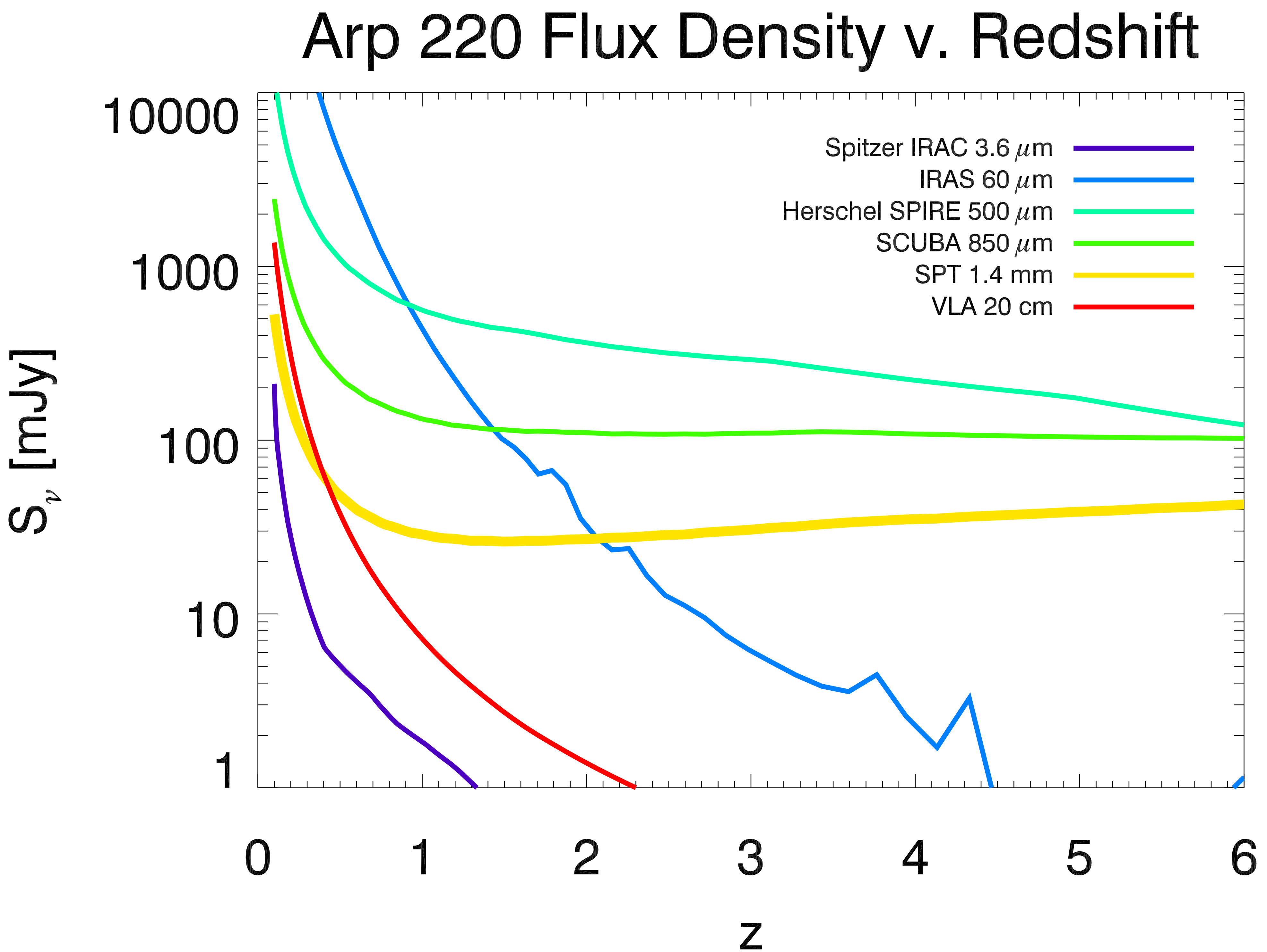
Sub-mm magic

First pointed out in Blain & Longair 1993



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Lagache+ 2005

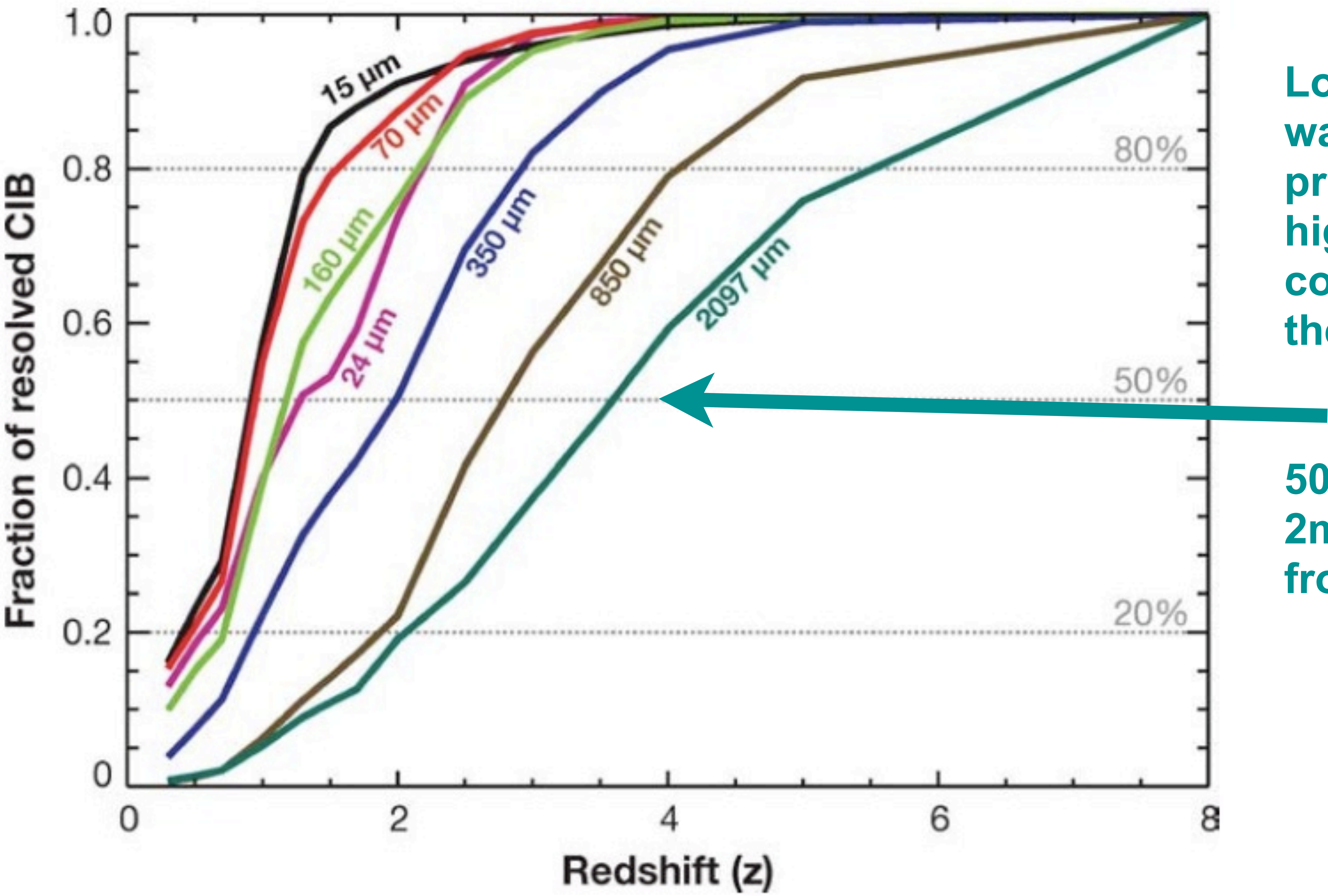

Figure 5 Cumulative fraction of the CIB content as a function of redshift for various wavelengths, from the model of Lagache et al. (2004).

Longer wavelengths probe the higher redshift component of the CIB

50% of CIB at 2mm comes from z>4

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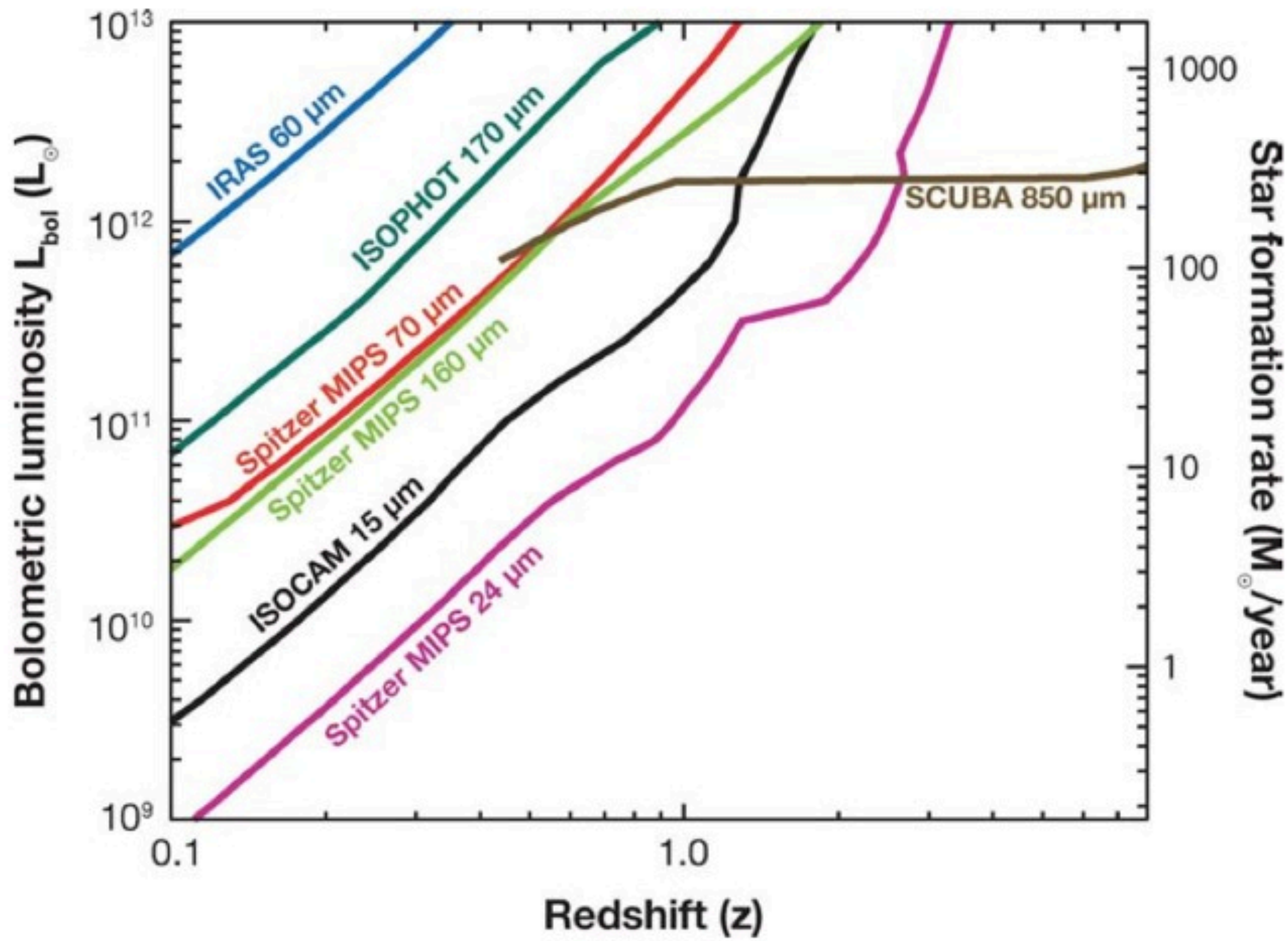
then there was...

- ISO 1995
- Spitzer 2003
- AKARI 2006
- Herschel 2009
- WISE 2009
- ALMA 2011
- JWST 2014



Lagache+ 2004, 2005

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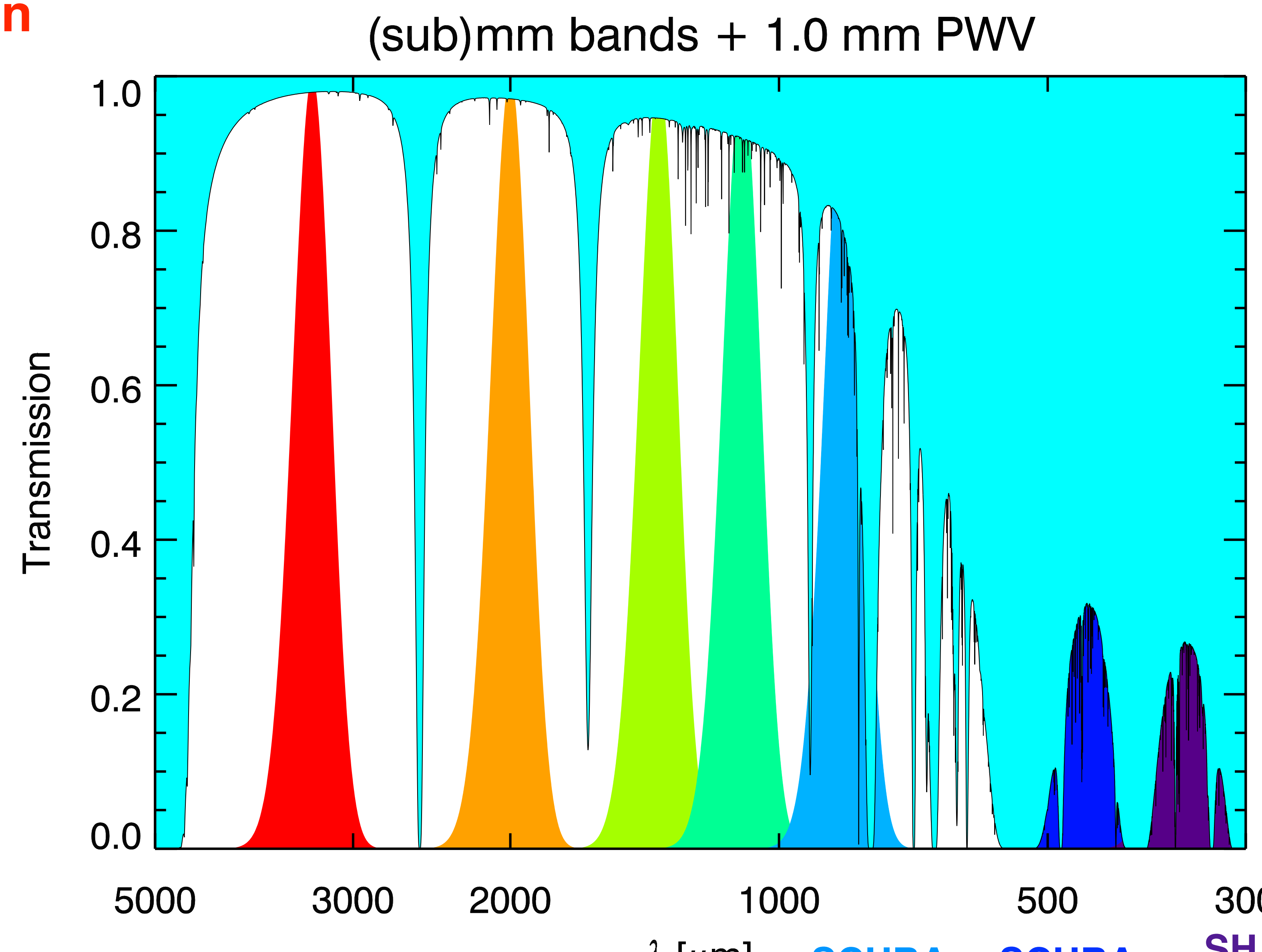
better atmosphere
larger beam
higher confusion limit
favors high redshift dust
more synchrotron
EASY!

worse atmosphere
smaller beam
probe the peak of the SED
TOUGH! (unless you go to space)



SPT
Mustang
SZA
CARMA

SPT
BOLOCAM
APEX-SZ
ACT

SPT
ACT

MAMBO
BOLOCAM
AzTEC
ACT

SCUBA
LABOCA

SCUBA
SHARC2
BLAST
SPIRE

SHARC2
SABOCA
BLAST
SPIRE

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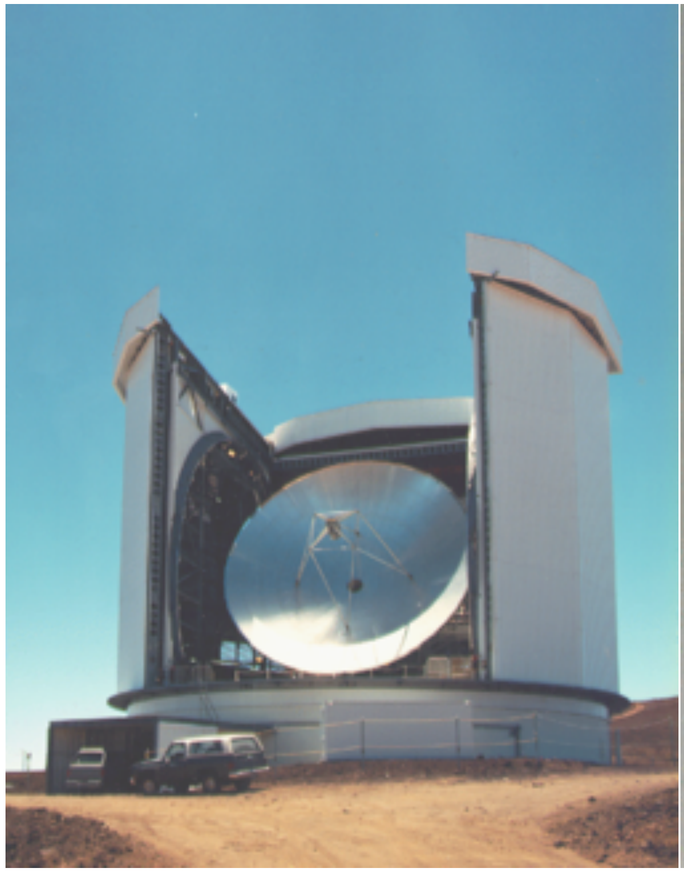
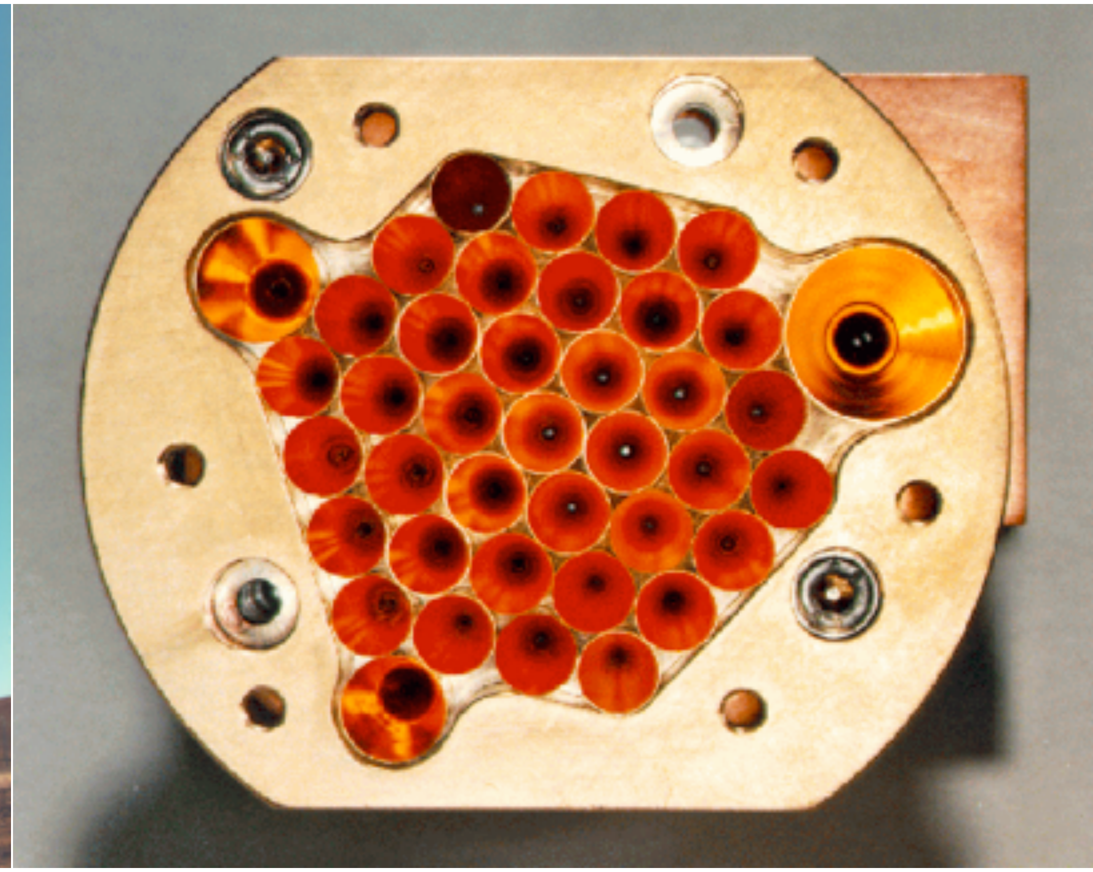
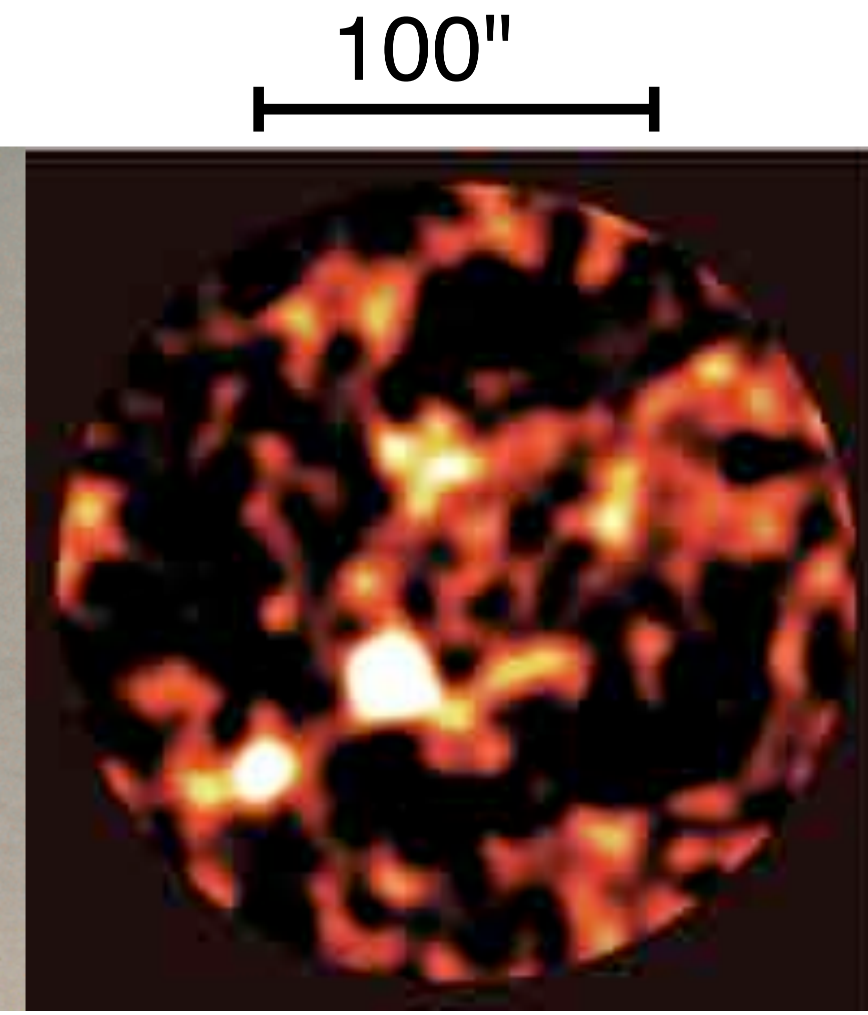
SCUBA on the JCMT







First experiment to resolve individual sources of the CIB
SCUBA on the JCMT at 850 μm = 15" beam
HDFN Hughes et al 1998 Nature
Also, Smail+1997, Barger+ 1998
No obvious correlation with sources in the Hubble image.

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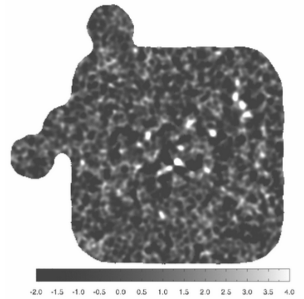
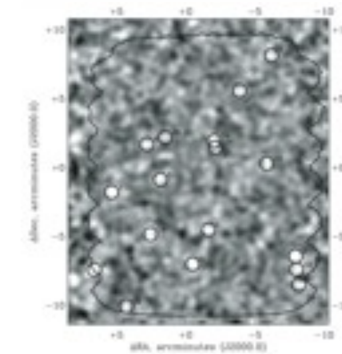
SCUBA 850 um on 15-m JCMT
MAMBO 1.2 mm on 30-m IRAM
Bolocam 1.1 mm on 10-m CSO

- **Total area surveyed up until 2008 was ~0.5 deg^2**
- **SCUBA died a slow and painful death.**
- **MAMBO never got enough time on the 30m.**
- **Bolocam had noise problems.**

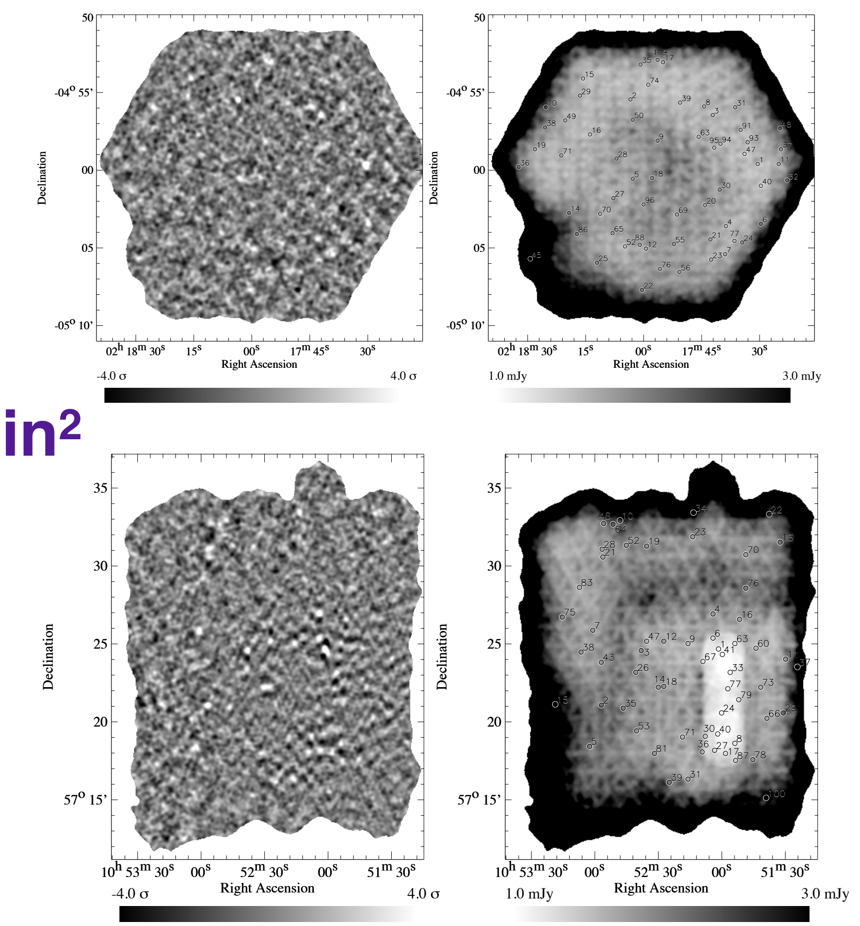
Borys+ 2003
HDFN 165 arcmin^2



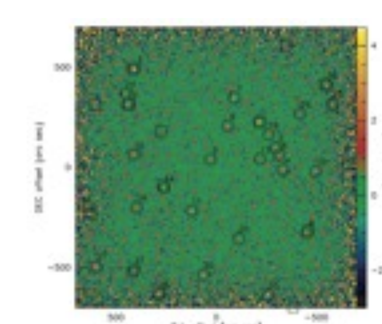
BOLOCAM
Laurent+ 2005
LH 324 arcmin^2



SHADES
Coppin+ 2006
SXDF 405 arcmin^2
LH 450 arcmin^2



COSBO
Bertoldi+ 2006
COSMOS 400 arcmin^2



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Lockman Hole
SCUBA v. BOLOCAM v. MAMBO

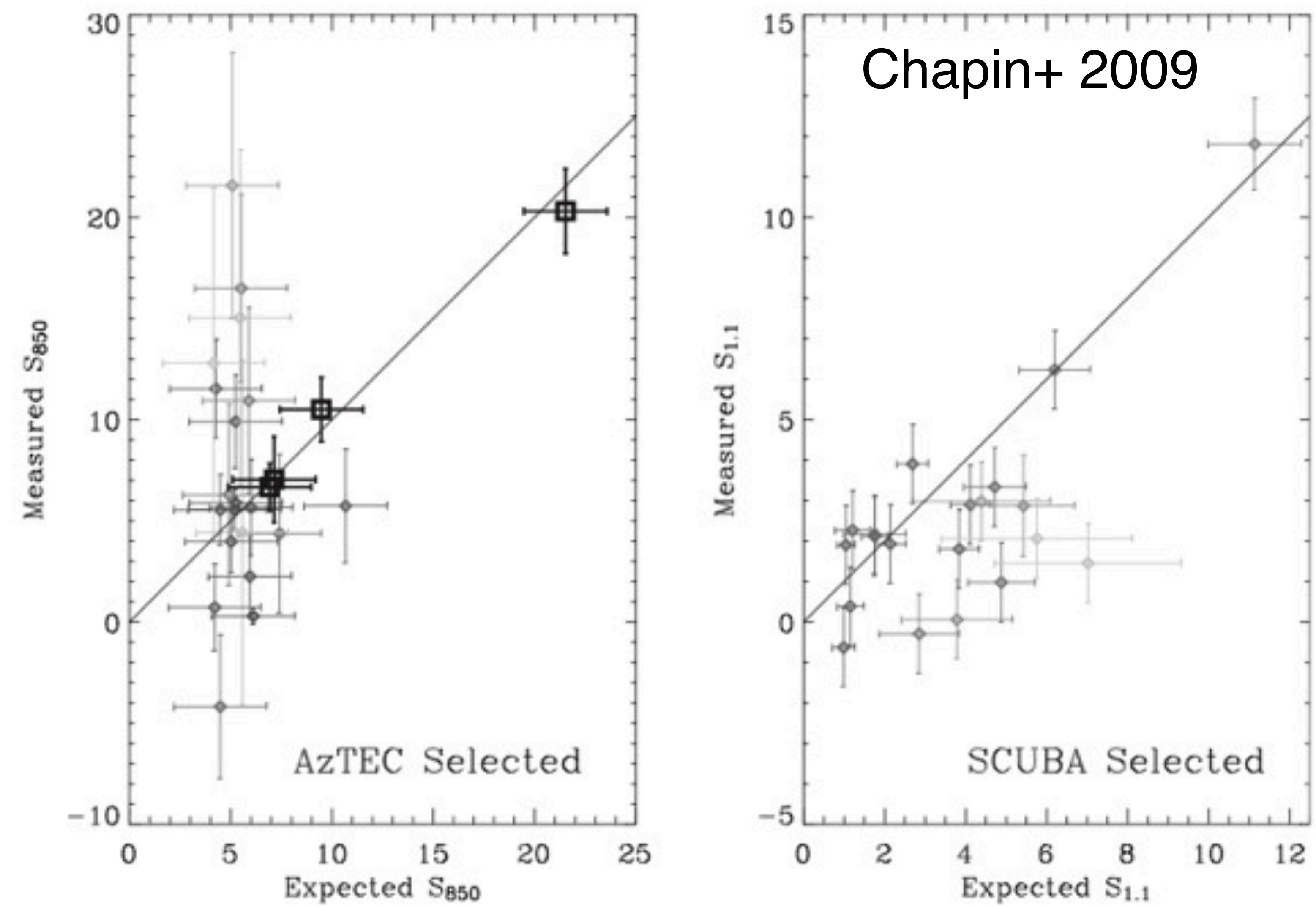
LAURENT ET AL.

TABLE 3
SUMMARY OF COINCIDENT DETECTIONS

Survey	Fraction of Galaxy Candidates Detected: Bolocam	SCUBA	MAMBO	Radio	Accidental Radio
Bolocam/CSO	...	6/8	7/11	12/17	6
JCMT SCUBA	7/31	...	8/31	15/31	3
IRAM MAMBO	8/23	8/17	...	11/23	1

GOODS-N
SCUBA v. MAMBO

false detections
or
"sub-mm dropouts" ?
Eales+ 2003
Greve+ 2008



Chapin+ 2009

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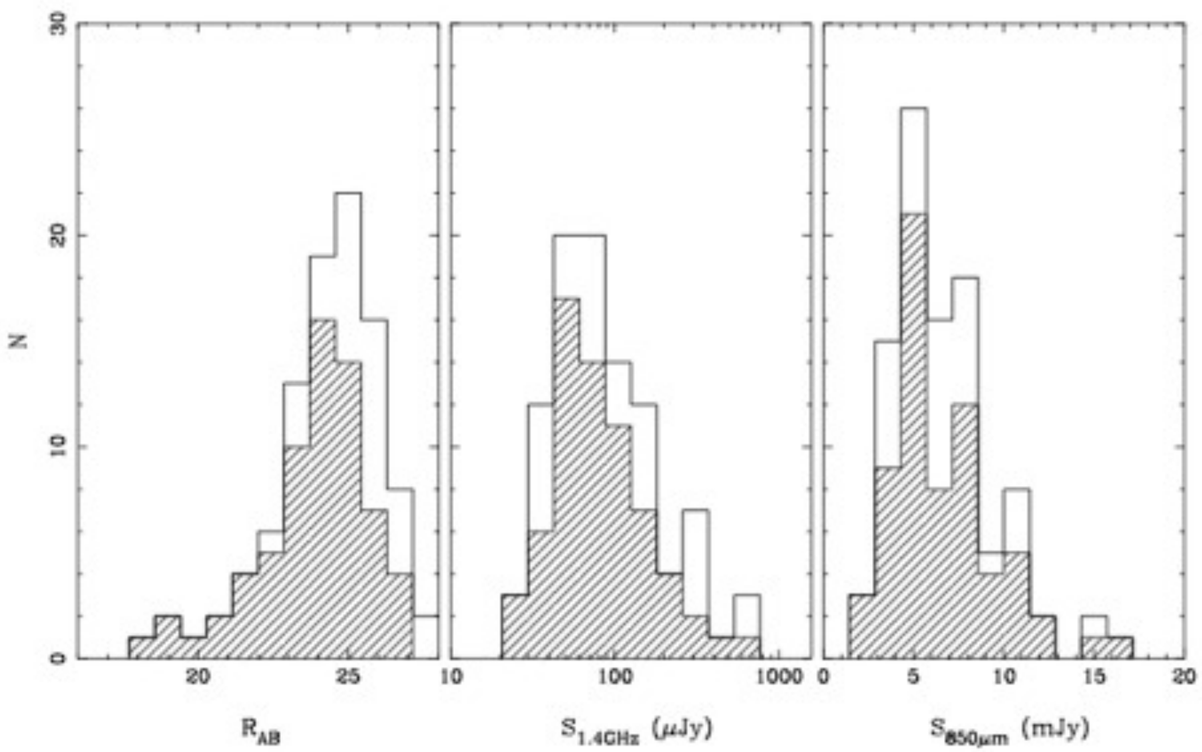
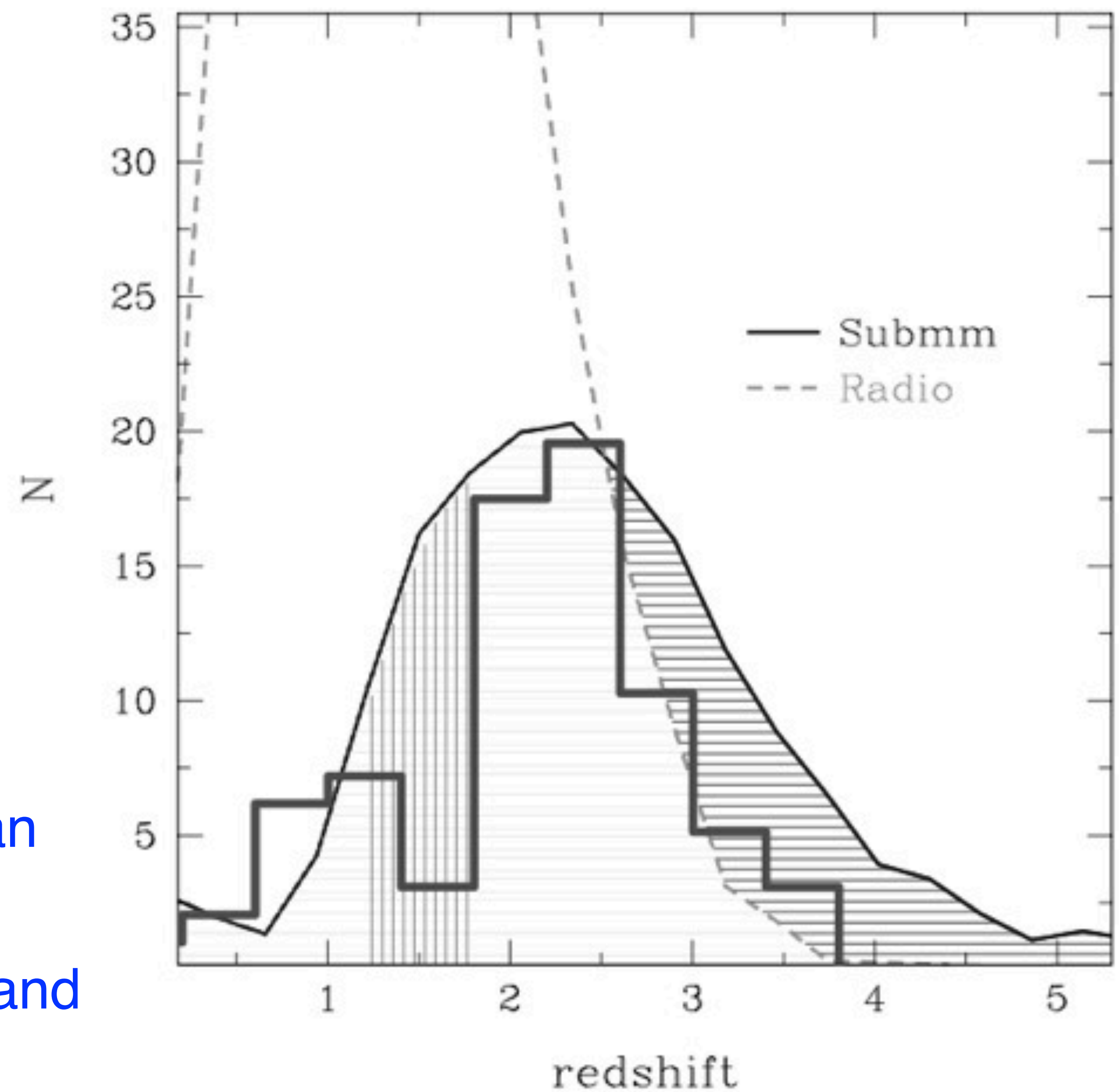
n(z)

A REDSHIFT SURVEY OF THE SUBMILLIMETER GALAXY POPULATION

S. C. Chapman,[1] A. W. Blain,[1] Ian Smail,[2] and R. J. Ivison[3,4]

Received 2004 July 22; accepted 2004 December 13





- Take advantage of the radio-FIR correlation to get a position good to an arcsec.
- Get some Keck time to get redshifts and hope for Ly-α
- Measure n(z)

This is a biased sample, but executed systematically.
Redshifts enable real studies to be done.

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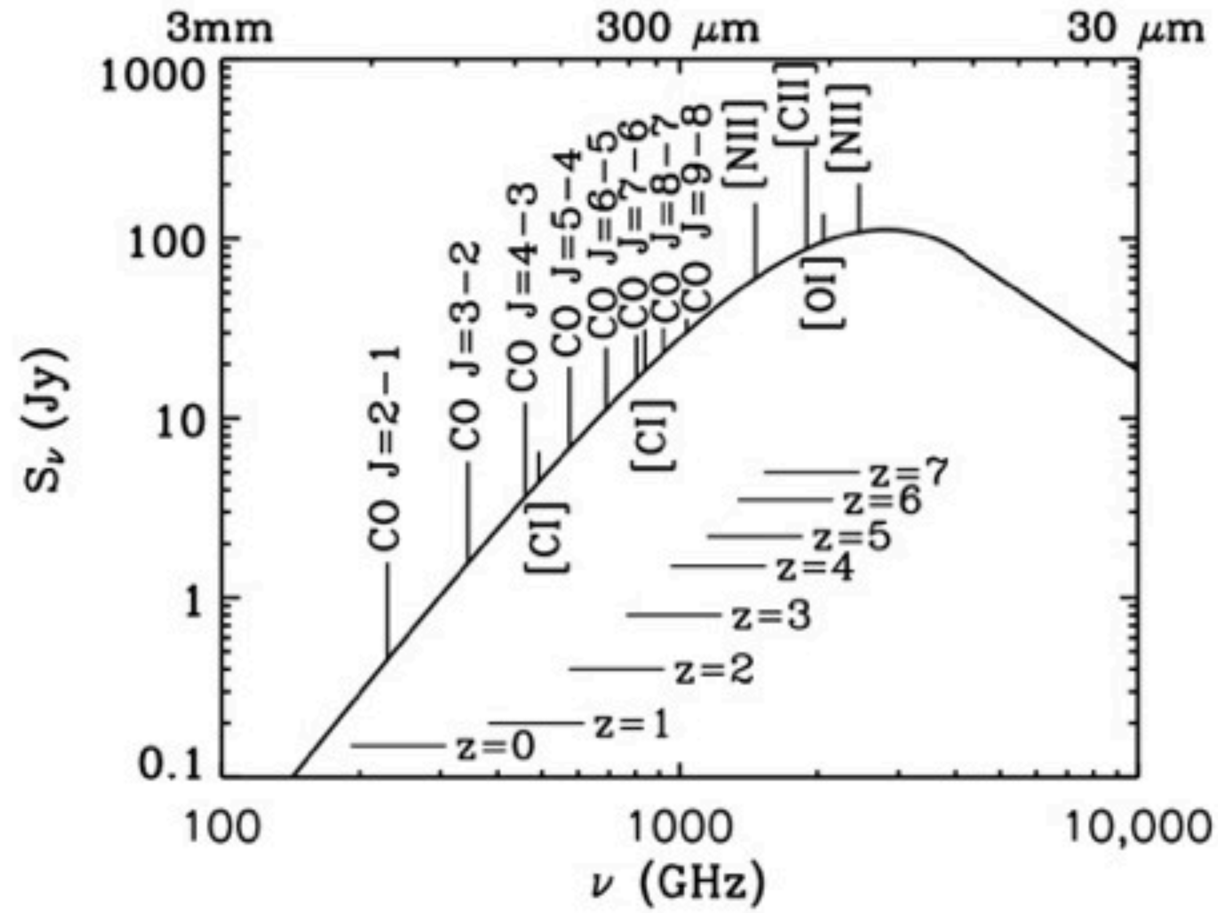
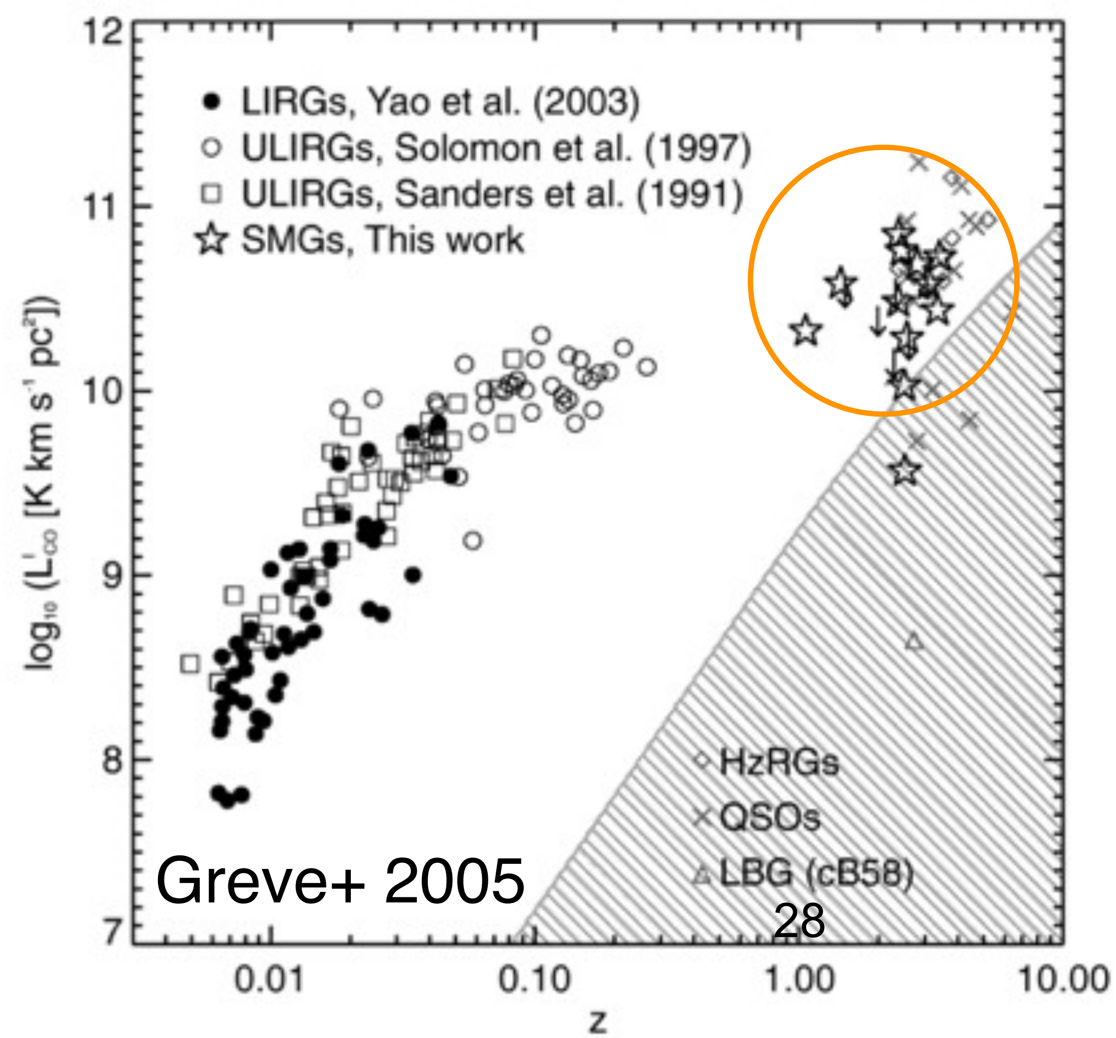
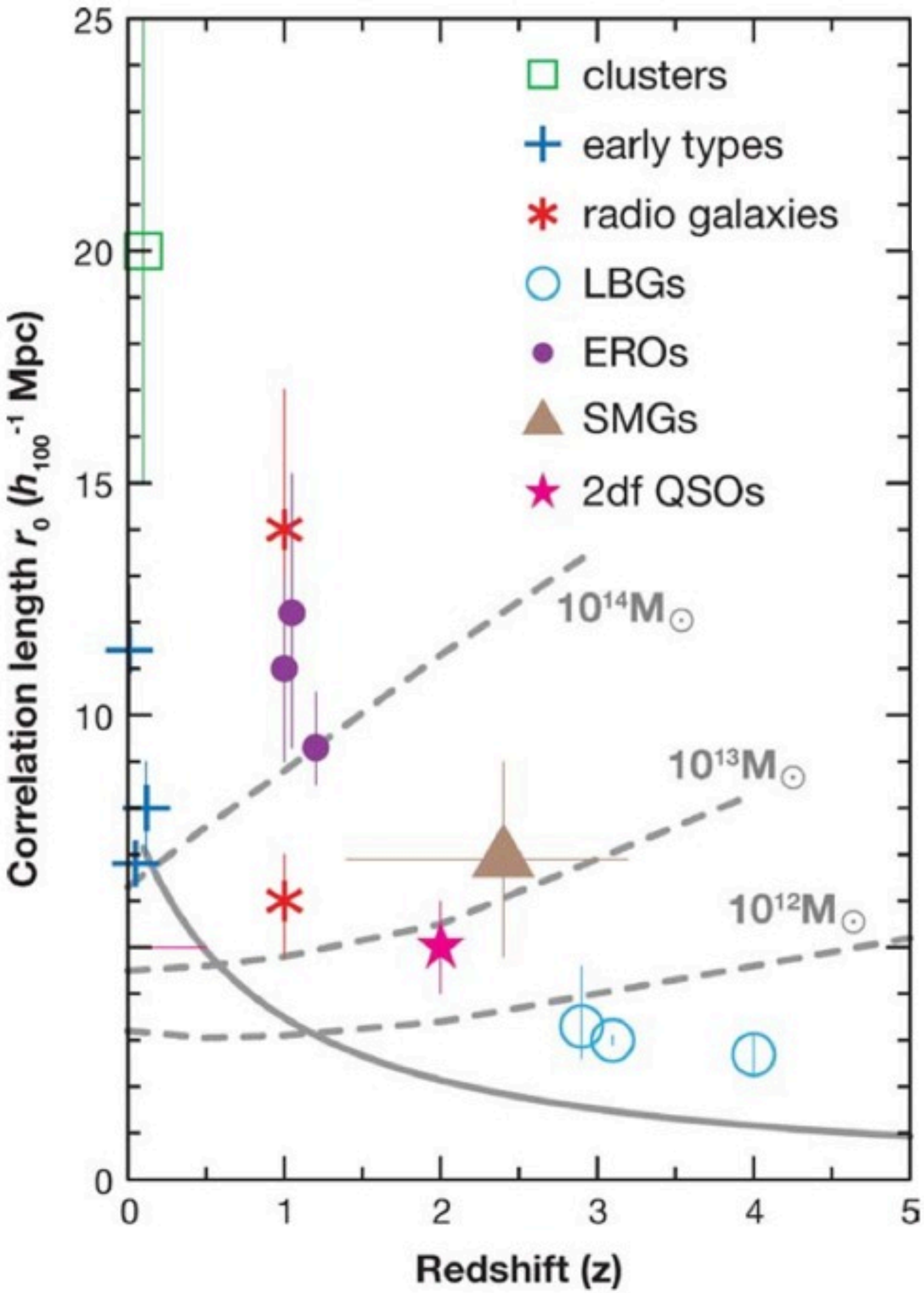
CO is special

- Once you have a redshift you can study molecular lines and get dust masses, dynamical masses and temperatures.
- Not enough bandwidth in the current generation of heterodyne receivers to blind redshift searches.
- The







CLUSTERING OF SUBMILLIMETER-SELECTED GALAXIES

A. W. Blain and S. C. Chapman
California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125
Ian Smail
Institute for Computational Cosmology, University of Durham, Durham, UK
and
Rob Ivison
UK-Astronomy Technical Centre, Royal Observatory, Blackford Hill, Edinburgh; and Institute for Astronomy, University of Edinburgh
Blackford Hill, Edinburgh, UK
Received 2004 January 6; accepted 2004 May 3

With redshifts you can also turn these pencil beam surveys into a spatial correlation length which implies a halo mass

Blain+ 2004

SMGs trace massive density peaks and reside in the most massive halos in their epoch of structure formation

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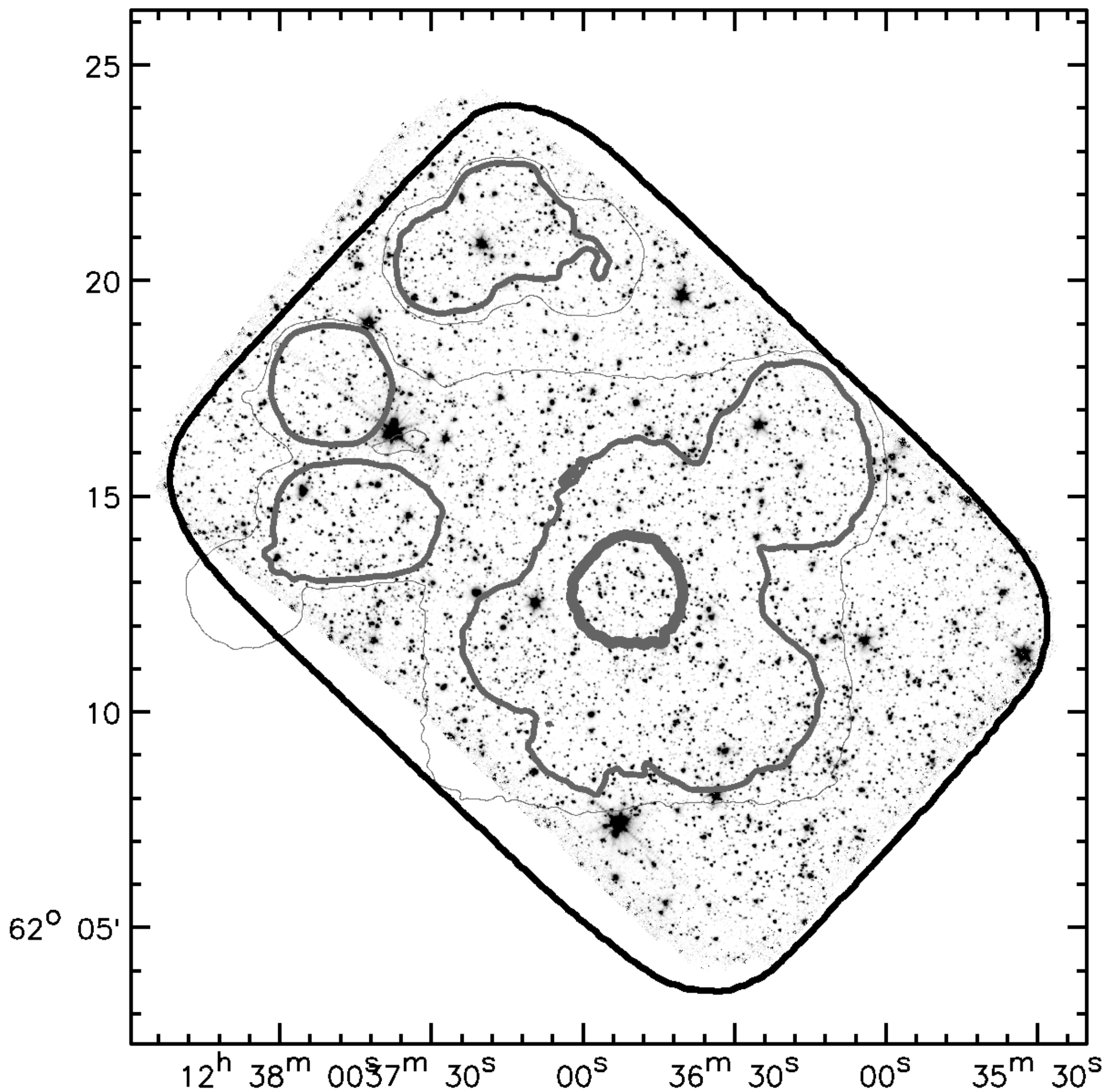
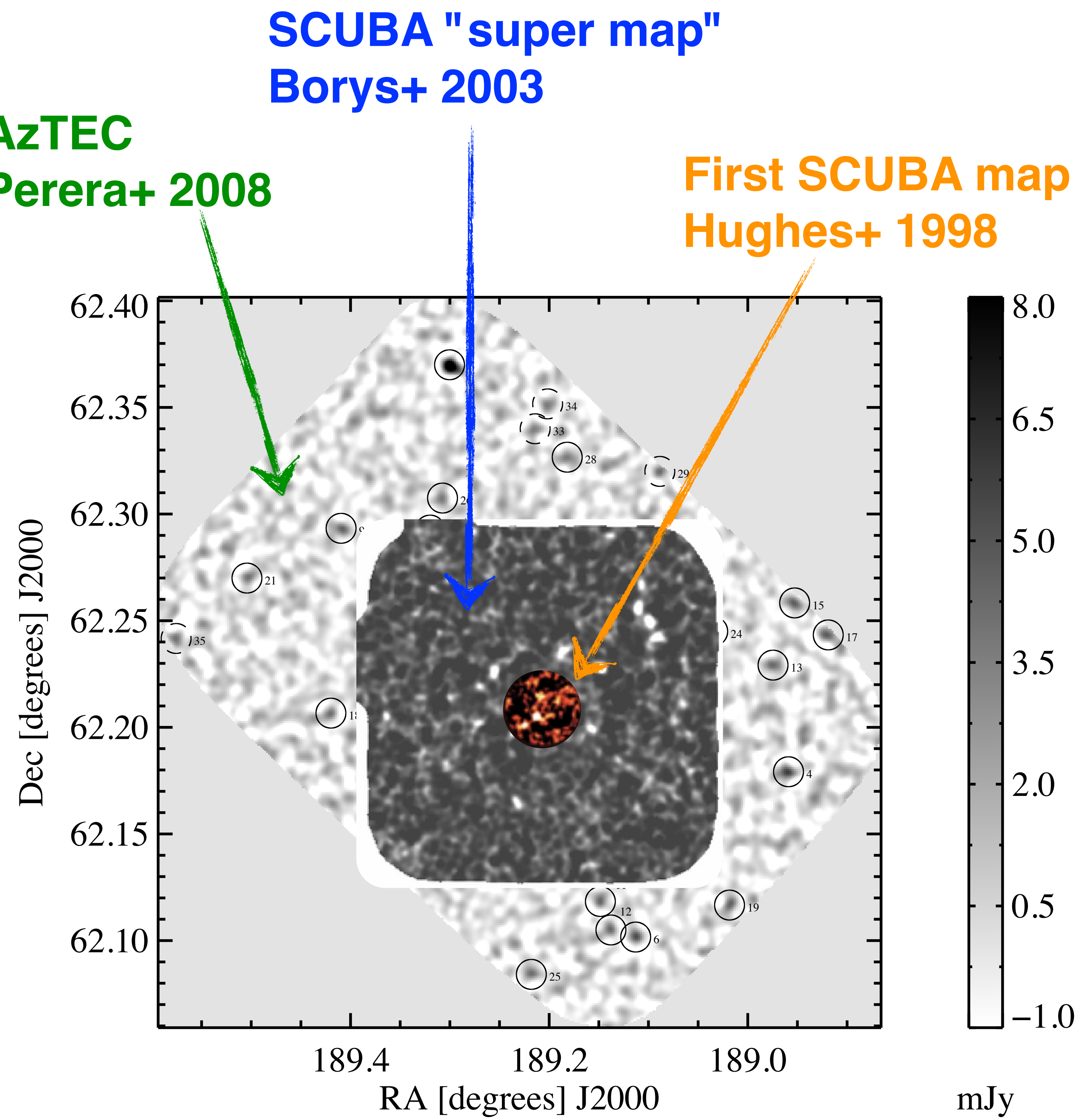
AzTEC on JCMT





AzTEC on JCMT
~duplicate of Bolocam (lower readout noise)
Perera+ 2008
245 arcmin^2 with CMB-style mapping and analysis

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AzTEC on JCMT

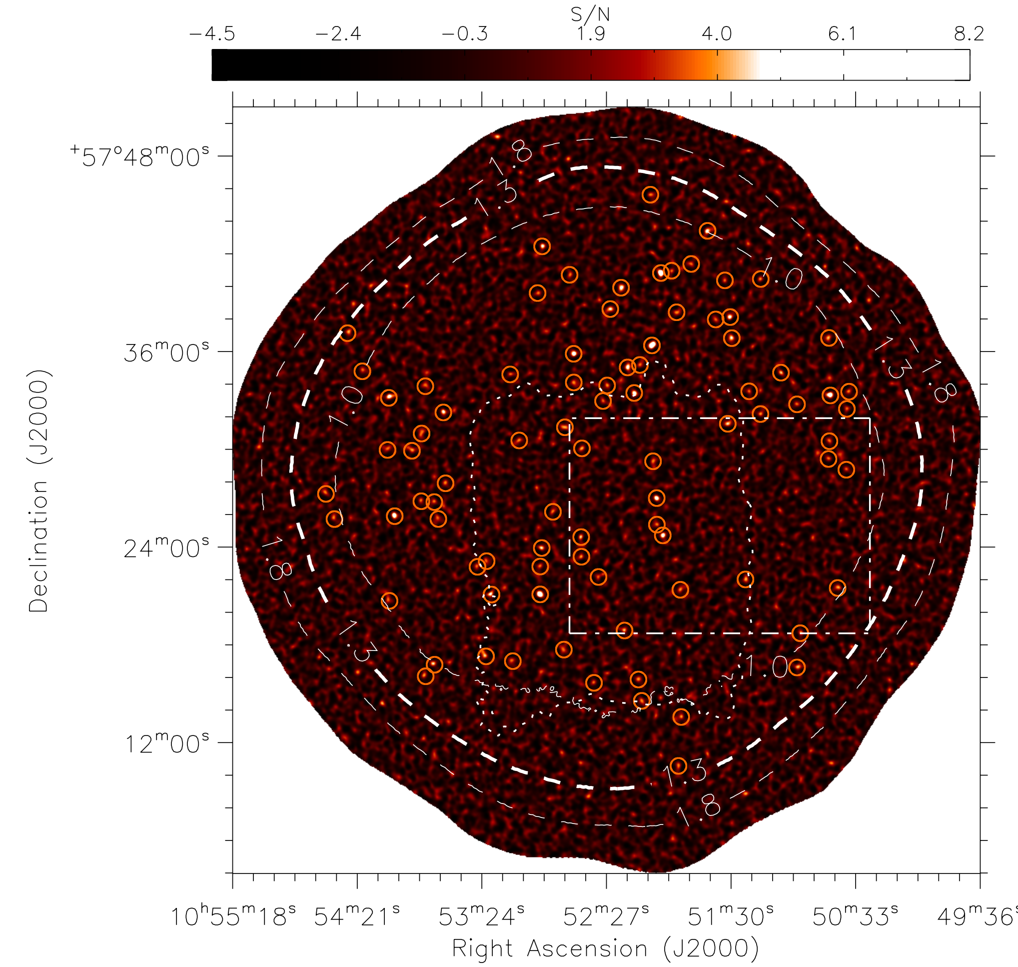
Perera+ 2008 GOODS-N 0.07 deg^2
Scott+ 2008 COSMOS 0.15 deg^2
Austermann+ 2009 SHADES 0.31 deg^2

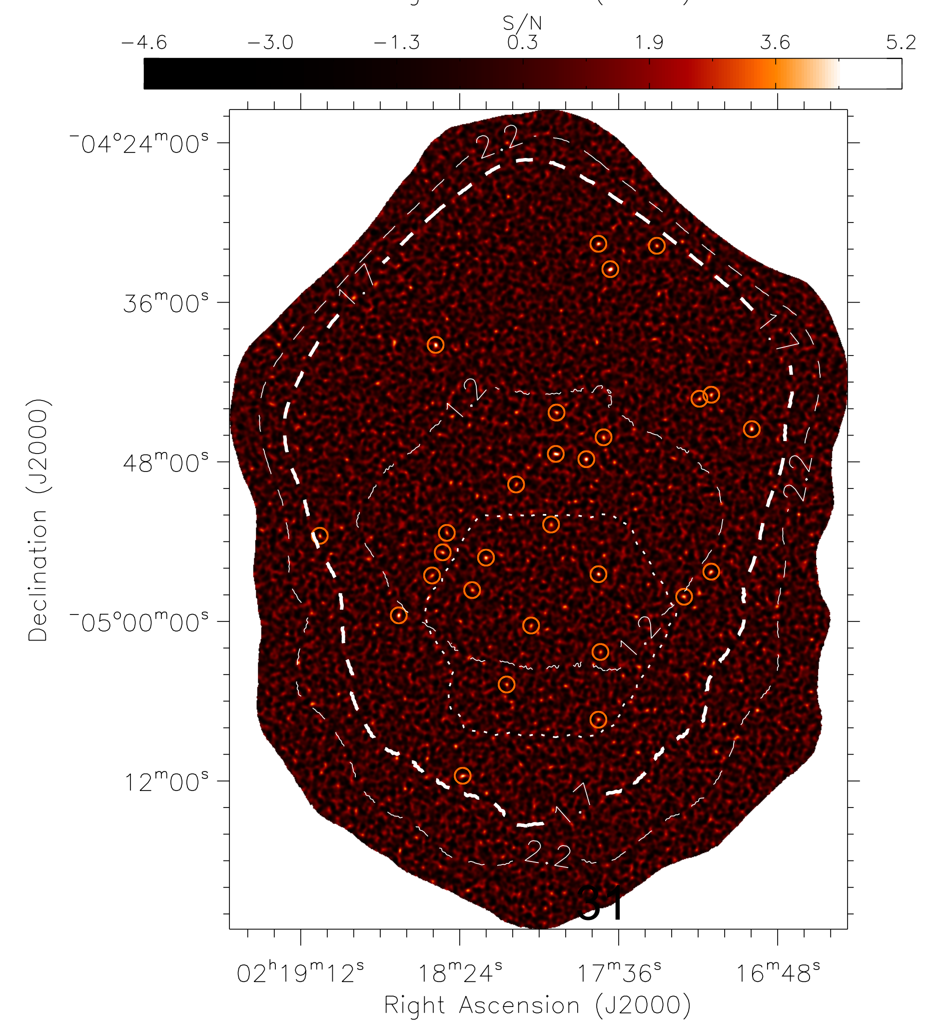
AzTEC on ASTE

Scott+ 2010 GOODS-S 0.08 deg^2
+ wide COSMOS field
+ cluster fields
+ AGN fields

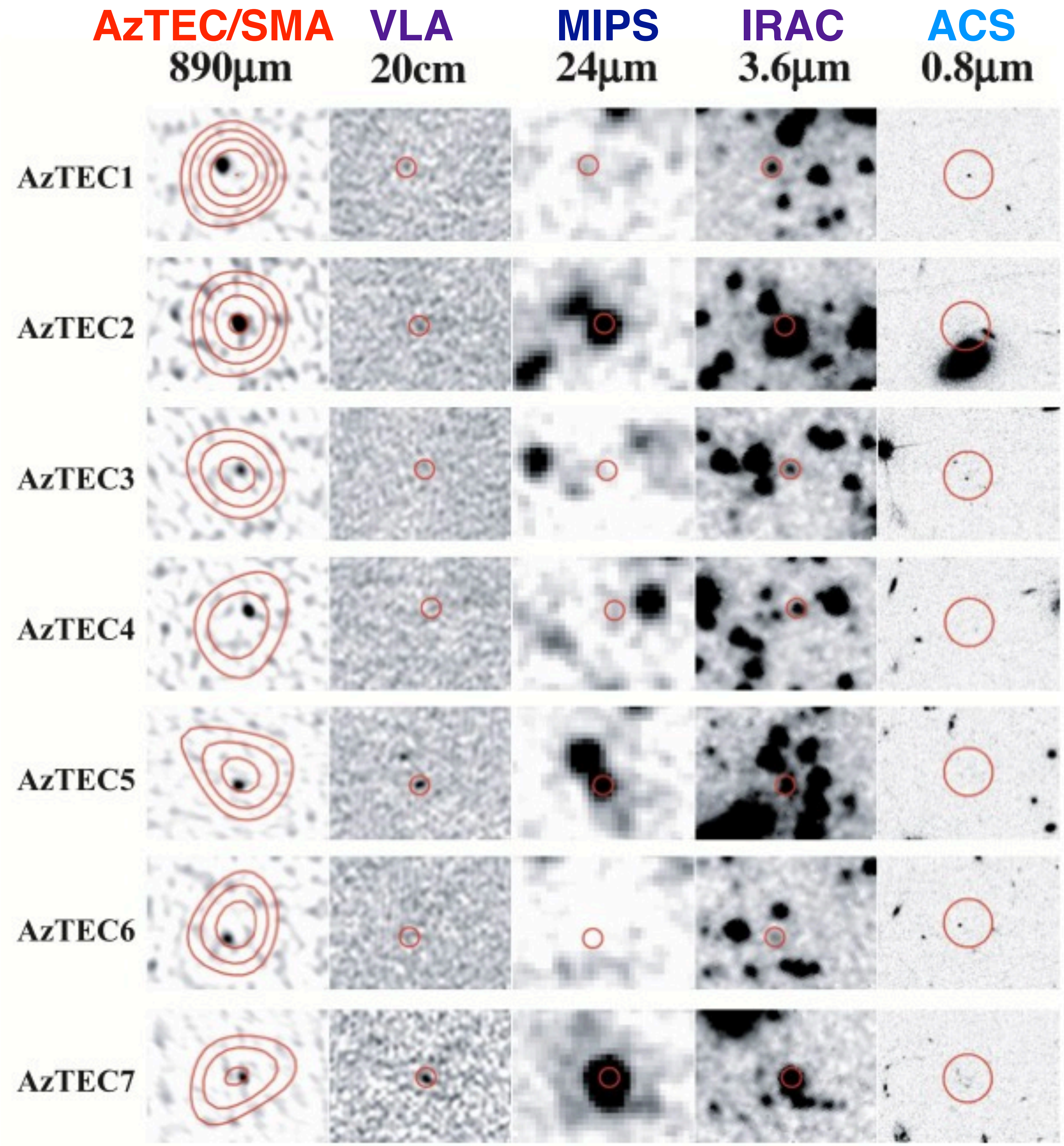
= ~ 2 deg^2

(soon AzTEC on the LMT)





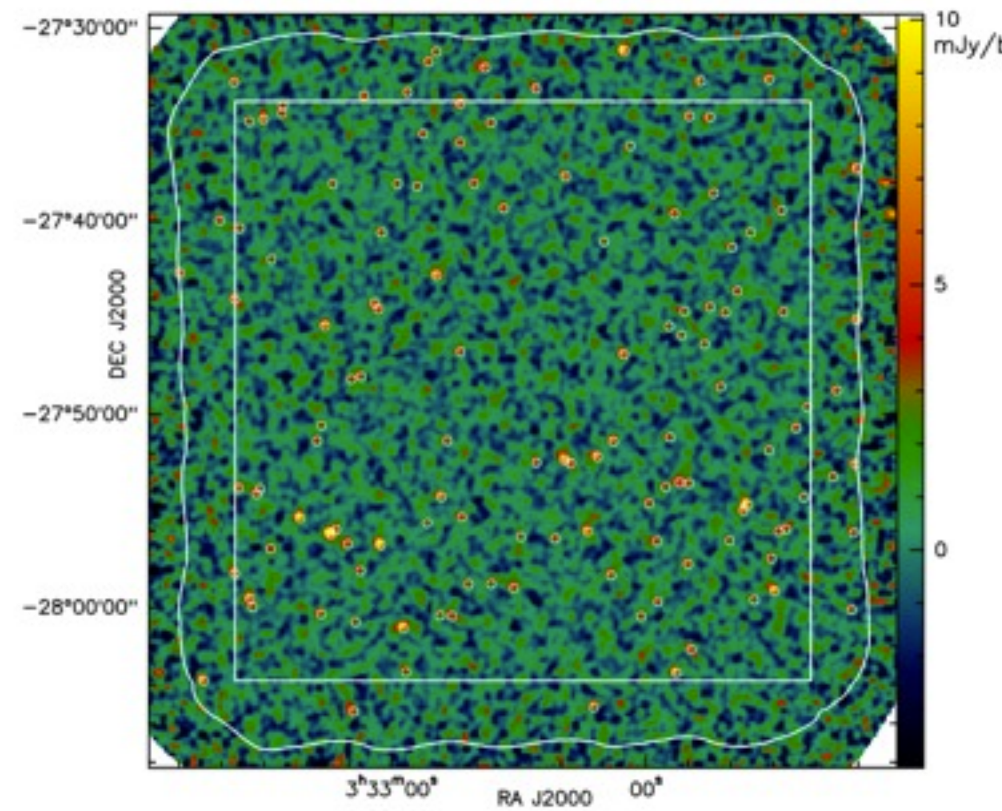
Enter SMA ... Younger+ 2007



- Target a field with pre-existing deep, multi-wavelength data. (COSMOS-AzTEC)
- Target the brightest sources with a sub-mm interferometer to get a position directly from the dust continuum.
- Still, the sources are very faint, even in deep HST images.

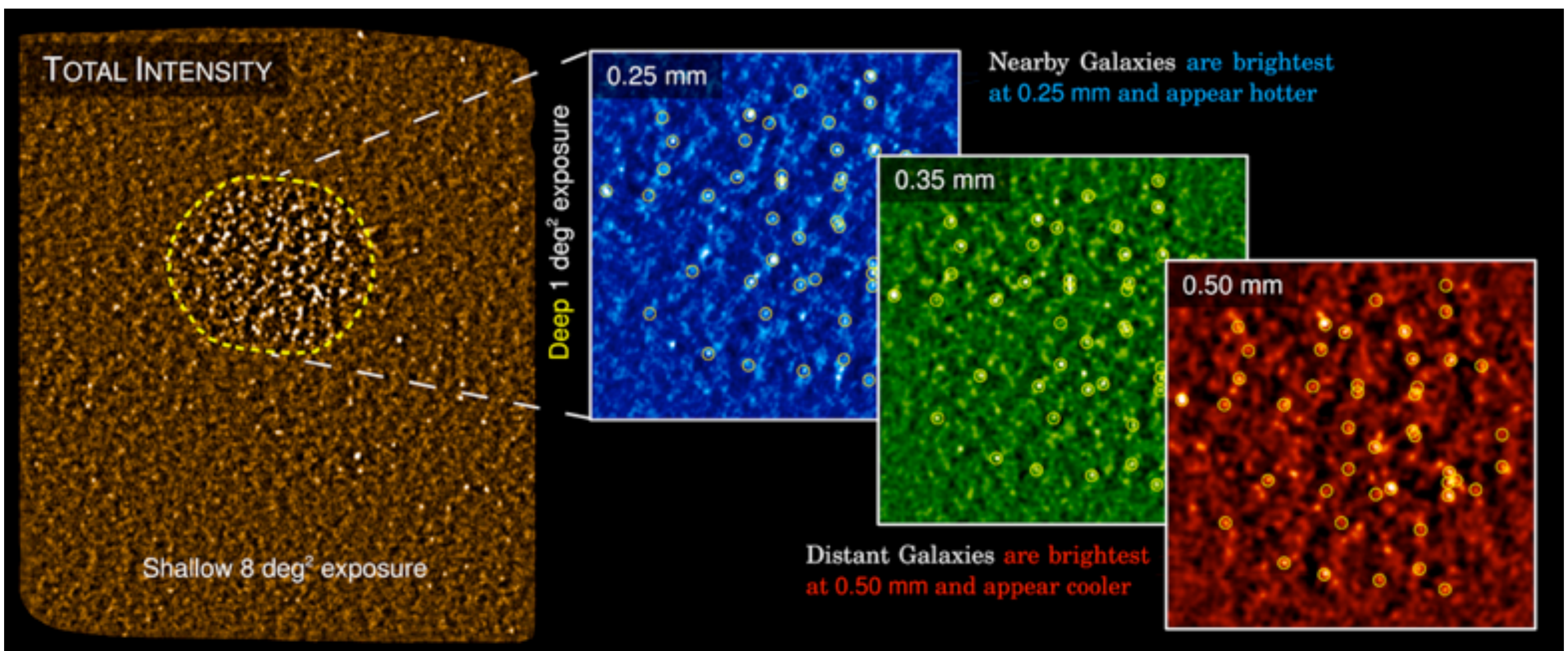
LABOCA on APEX

870 um on APEX 12-m (MAMBO team)
0.25 deg² ECDFS
Weiss+ 2010



BLAST

SPIRE duplicate on a balloon with a 2.5-m dish
250, 350, 500 um
0.87 deg² shallow, 0.8 deg² deep ECDFS
Devlin+2009
Chapin+2010



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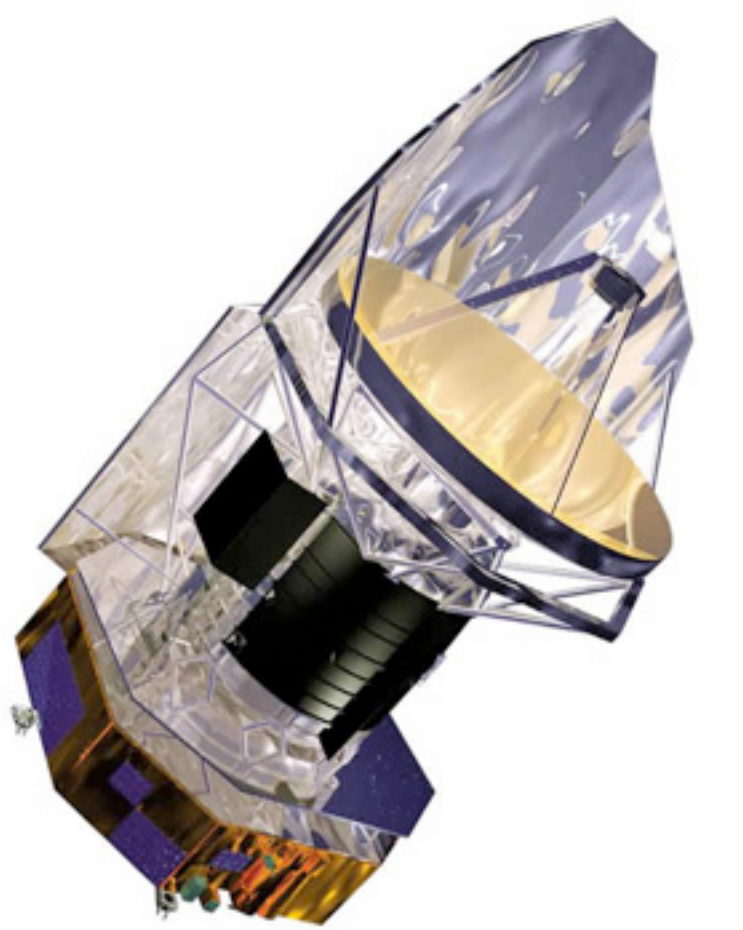
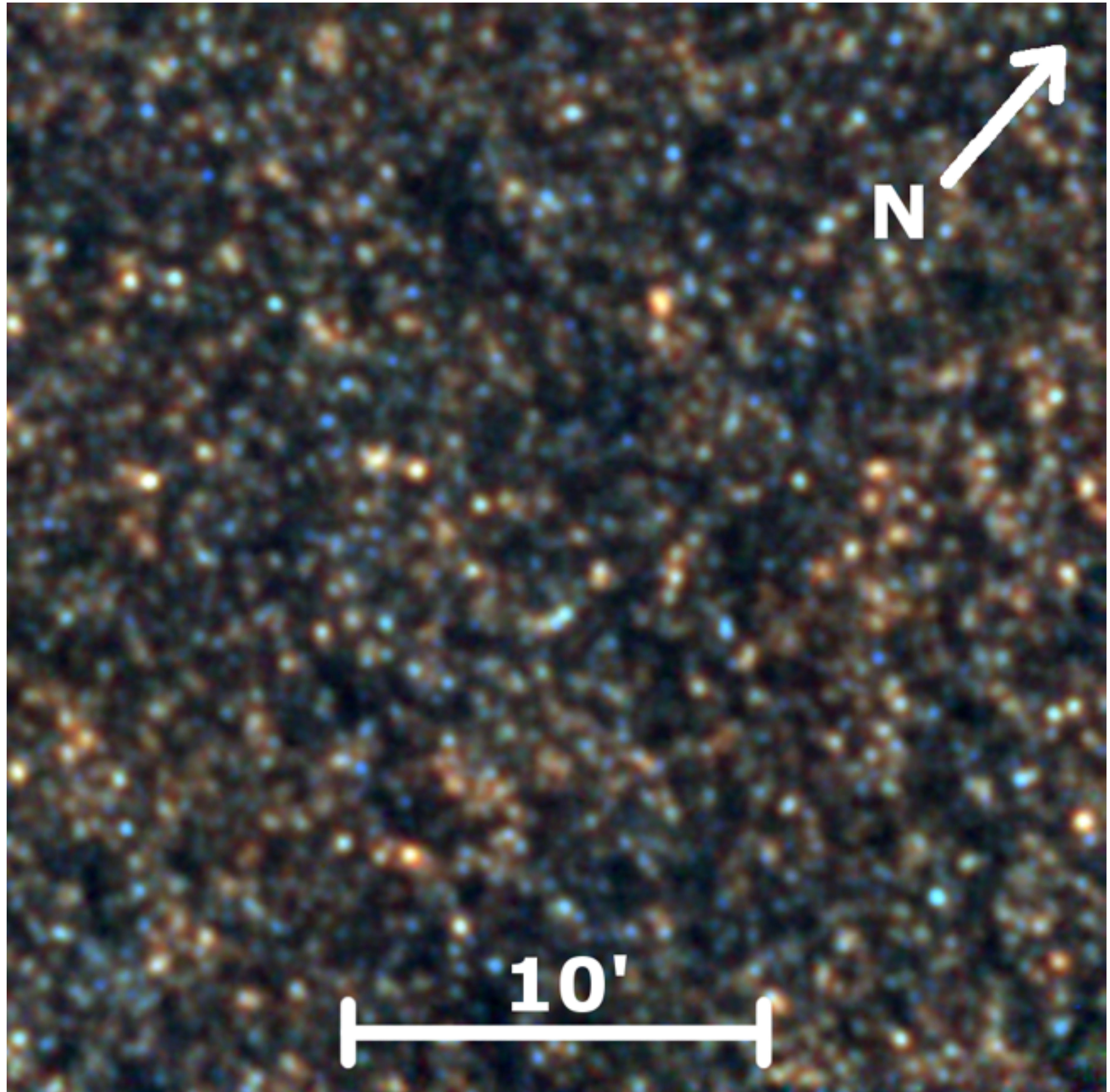


Herschel/SPIRE
250,350, 500 um
map of GOODS-N

72 deg^2 deep (HeRMES)
550 deg^2 wide (ATLAS)

SPIRE maps are nearly confusion limited in a single observation



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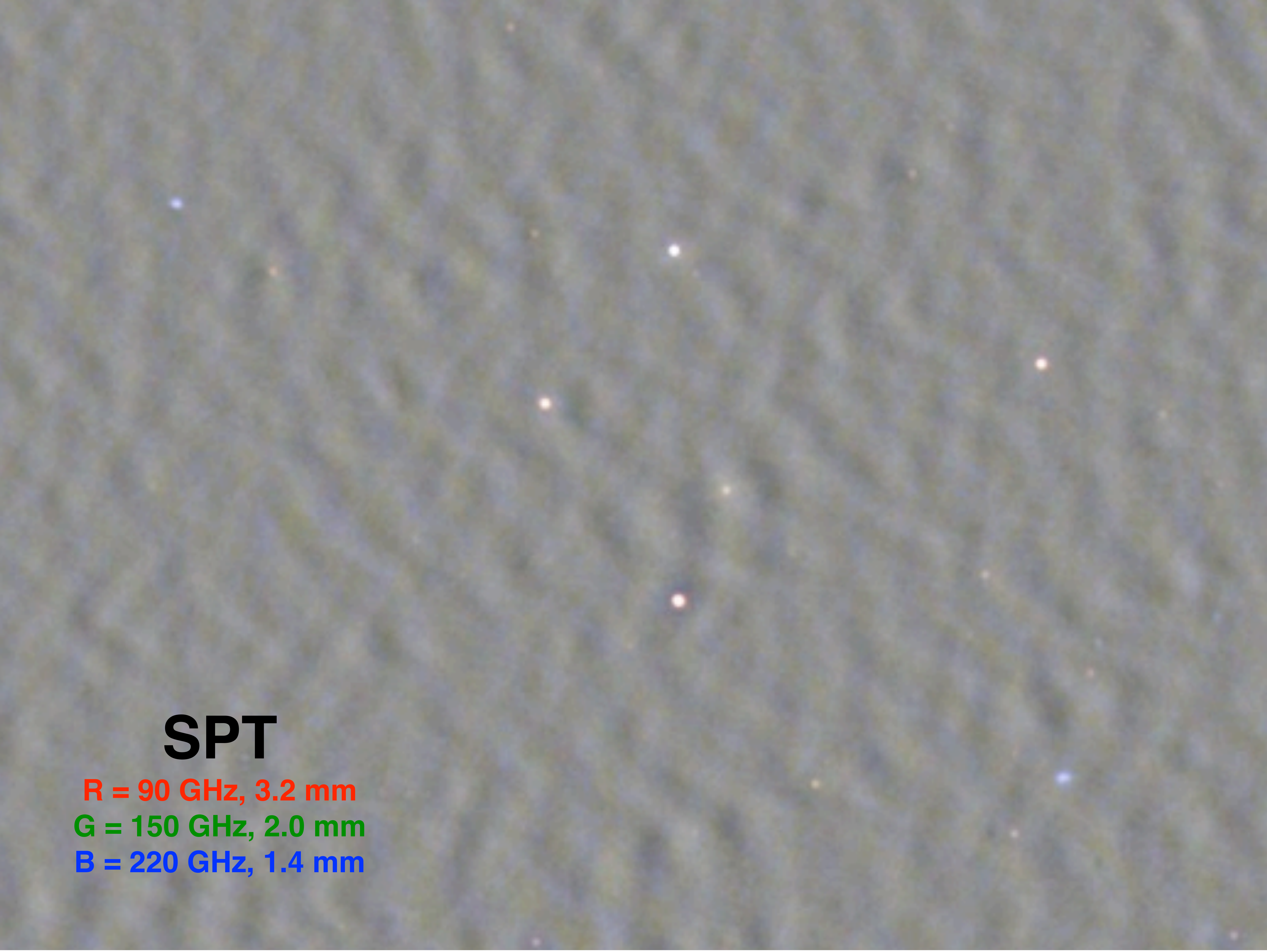
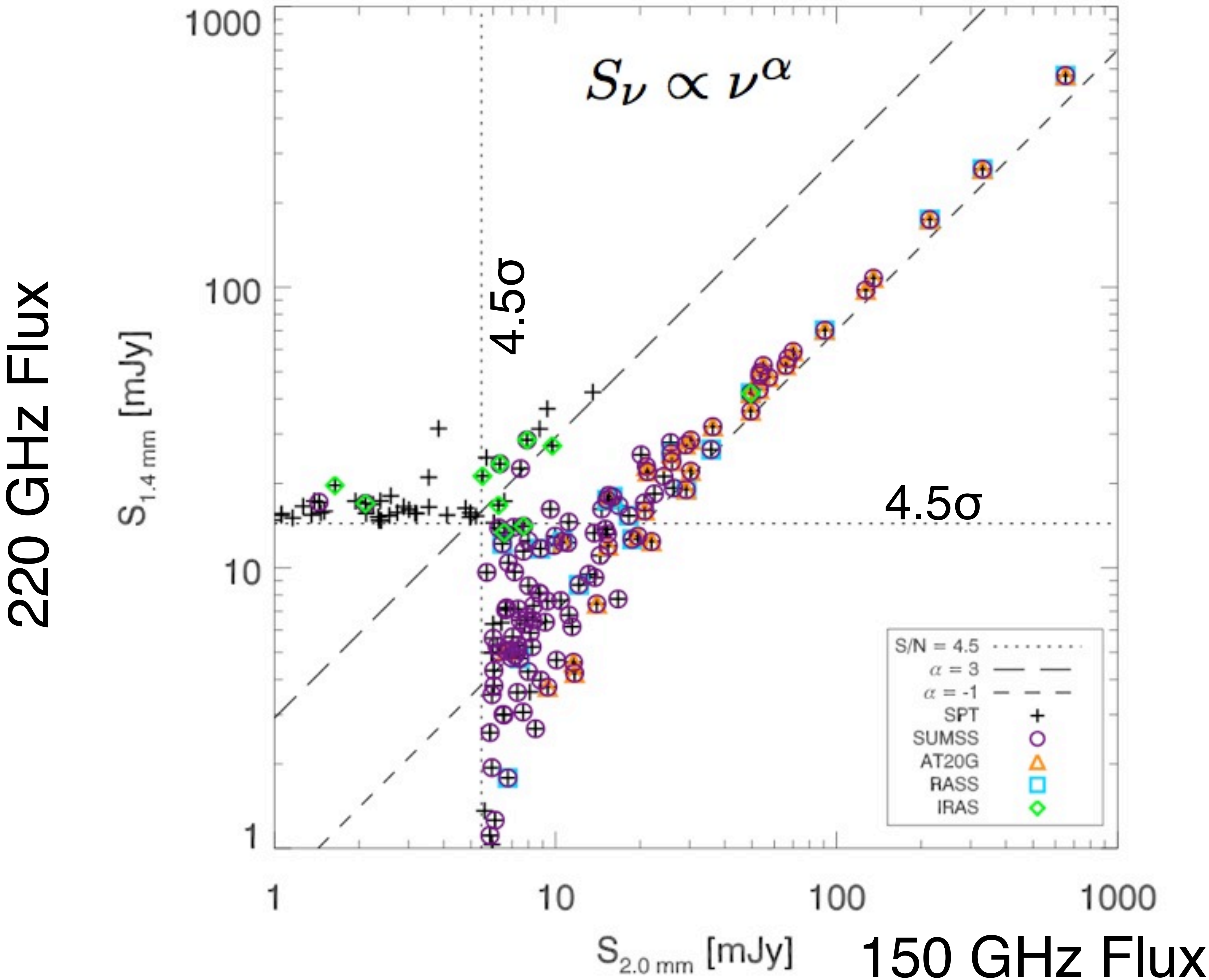
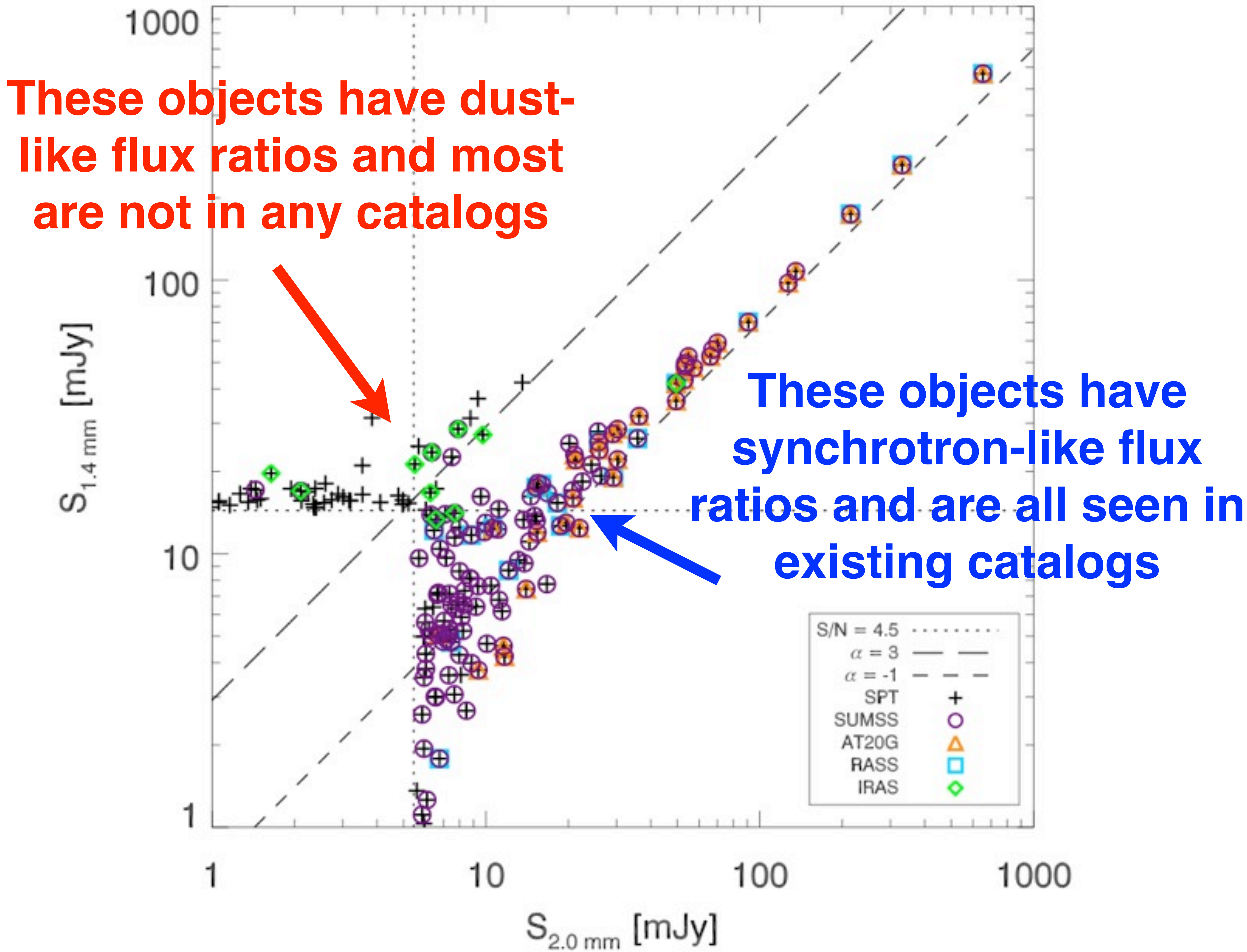
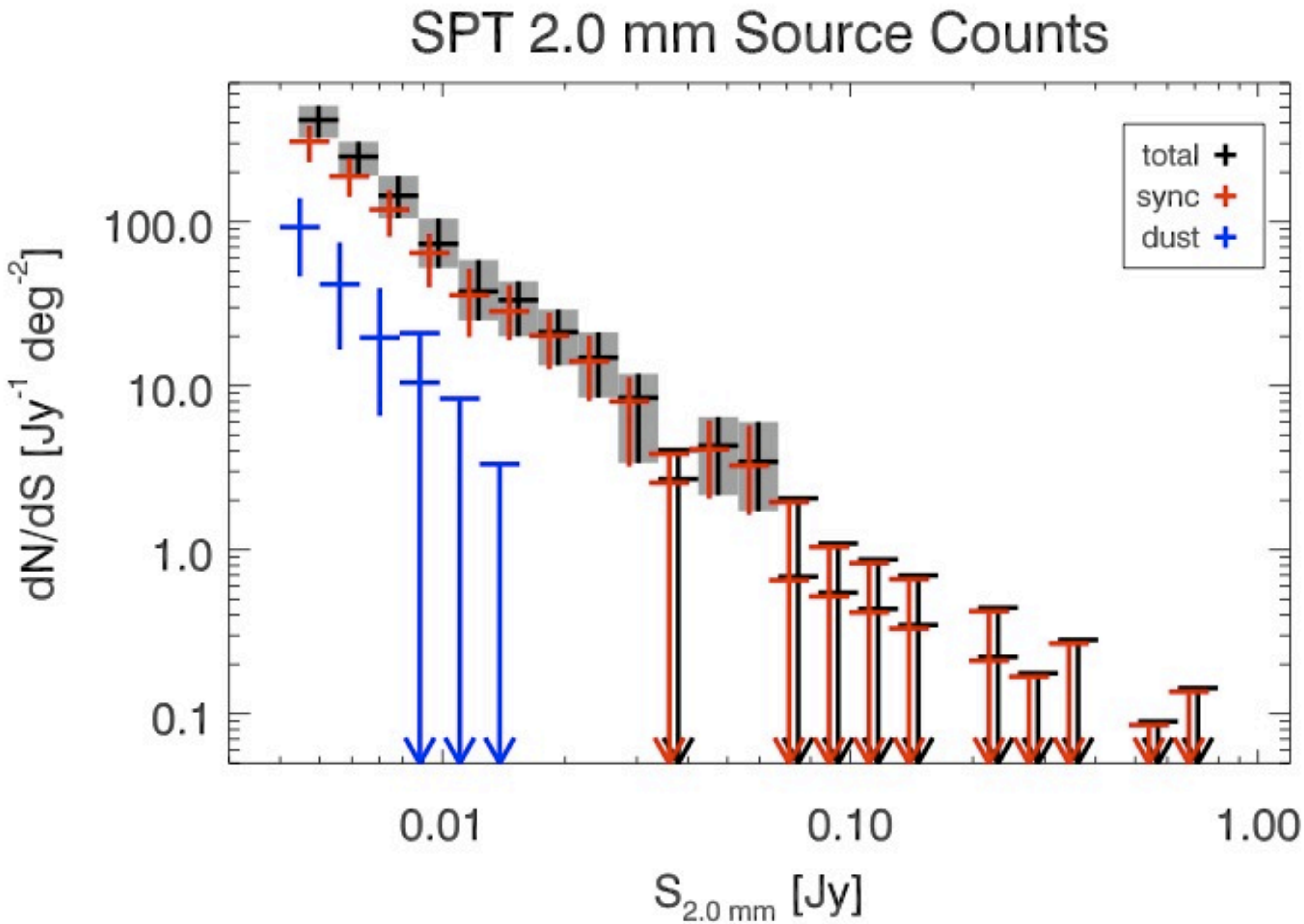
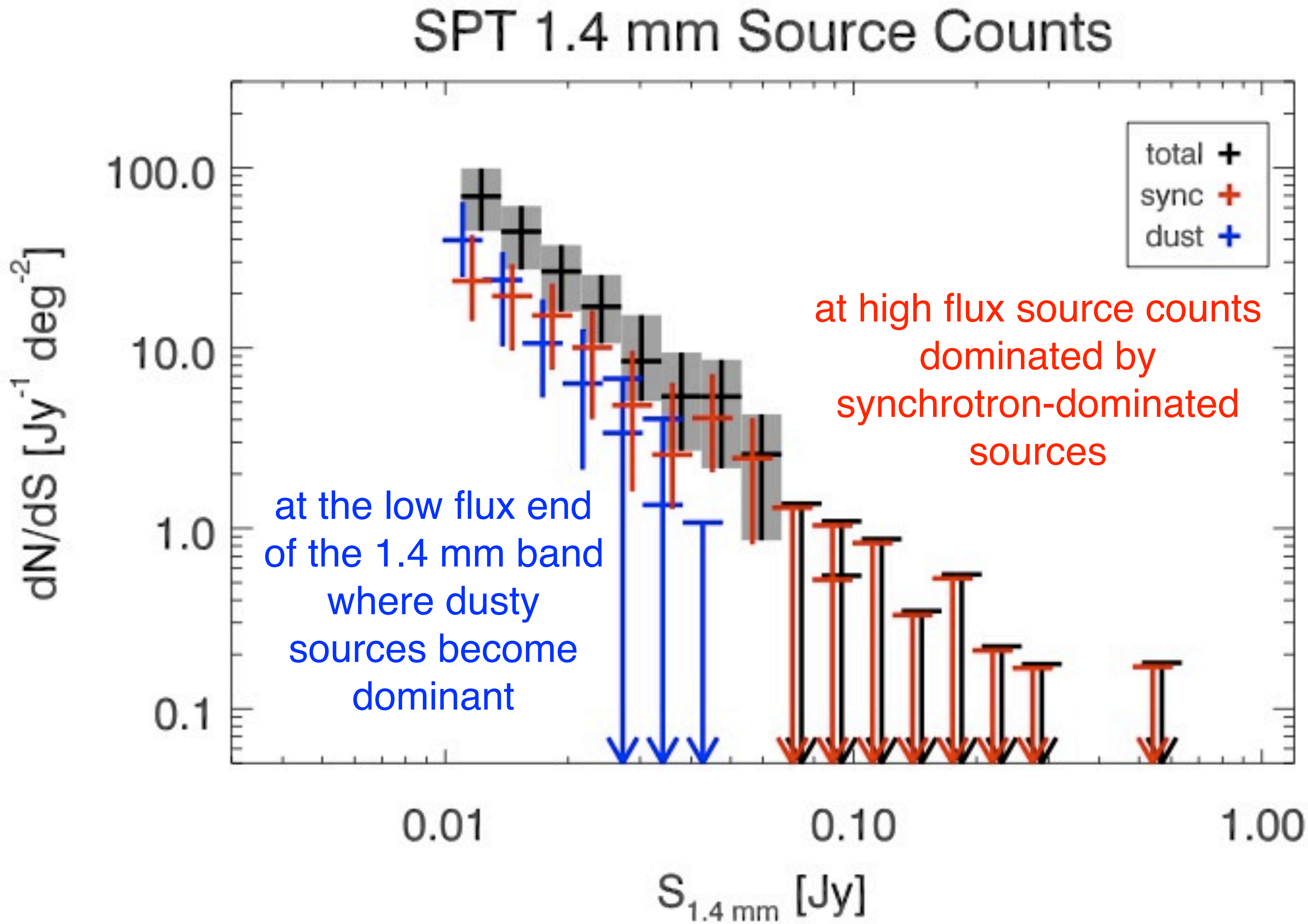

SPT
R = 90 GHz, 3.2 mm
G = 150 GHz, 2.0 mm
B = 220 GHz, 1.4 mm


$S_\nu \propto \nu^\alpha$
4.5σ
4.5σ
1000
100
10
1
1
10
100
1000
$S_{1.4\,mm}$ [mJy]
$S_{2.0\,mm}$ [mJy]
S/N = 4.5
α = 3
α = -1
SPT
SUMSS
AT20G
RASS
IRAS
220 GHz Flux
150 GHz Flux


These objects have dust-like flux ratios and most are not in any catalogs
These objects have synchrotron-like flux ratios and are all seen in existing catalogs
1000
100
10
1
$S_{1.4\,mm}$ [mJy]
$S_{2.0\,mm}$ [mJy]
S/N = 4.5
α = 3
α = -1
SPT
SUMSS
AT20G
RASS
IRAS

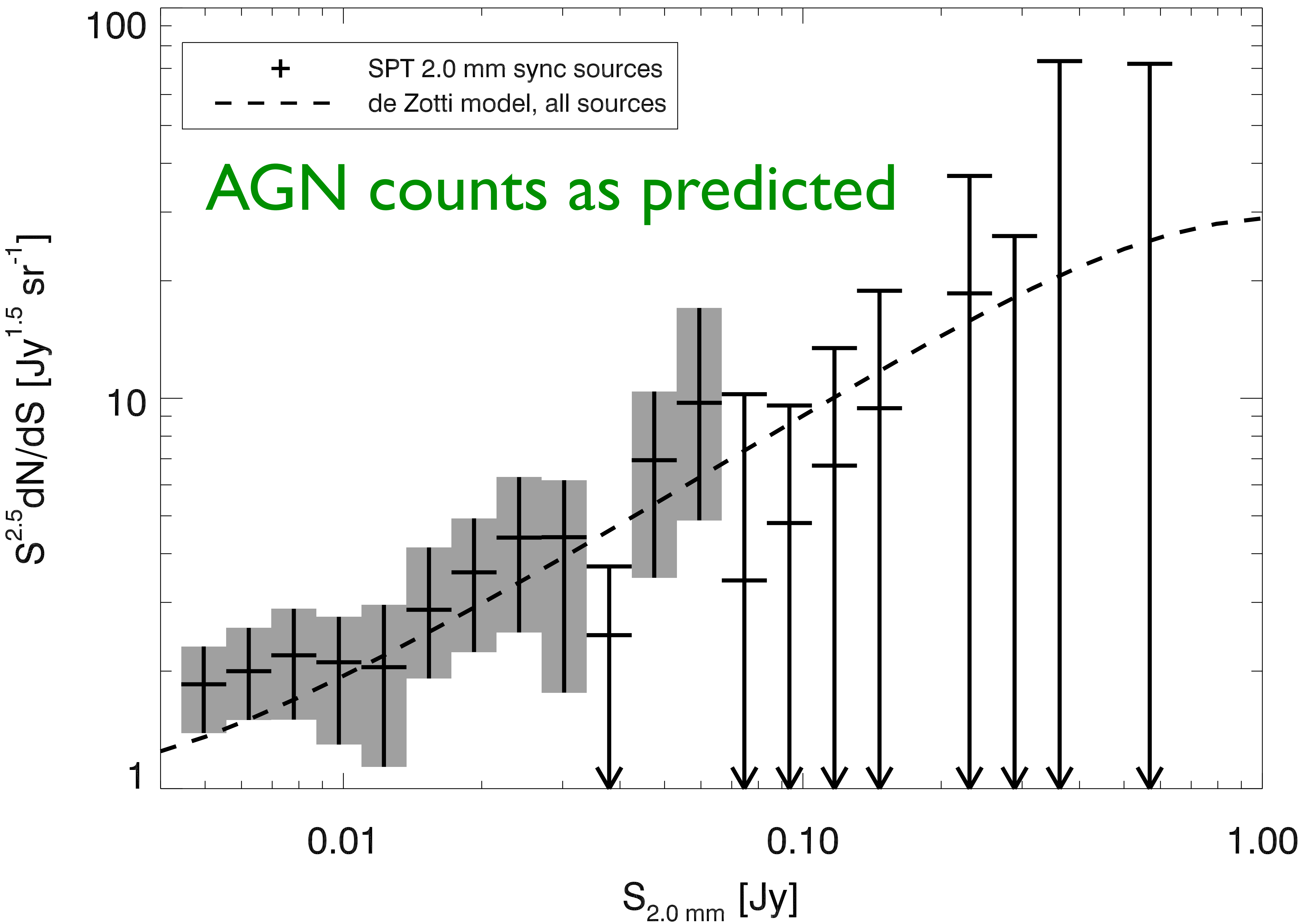


Mostly synchrotron-dominated sources.



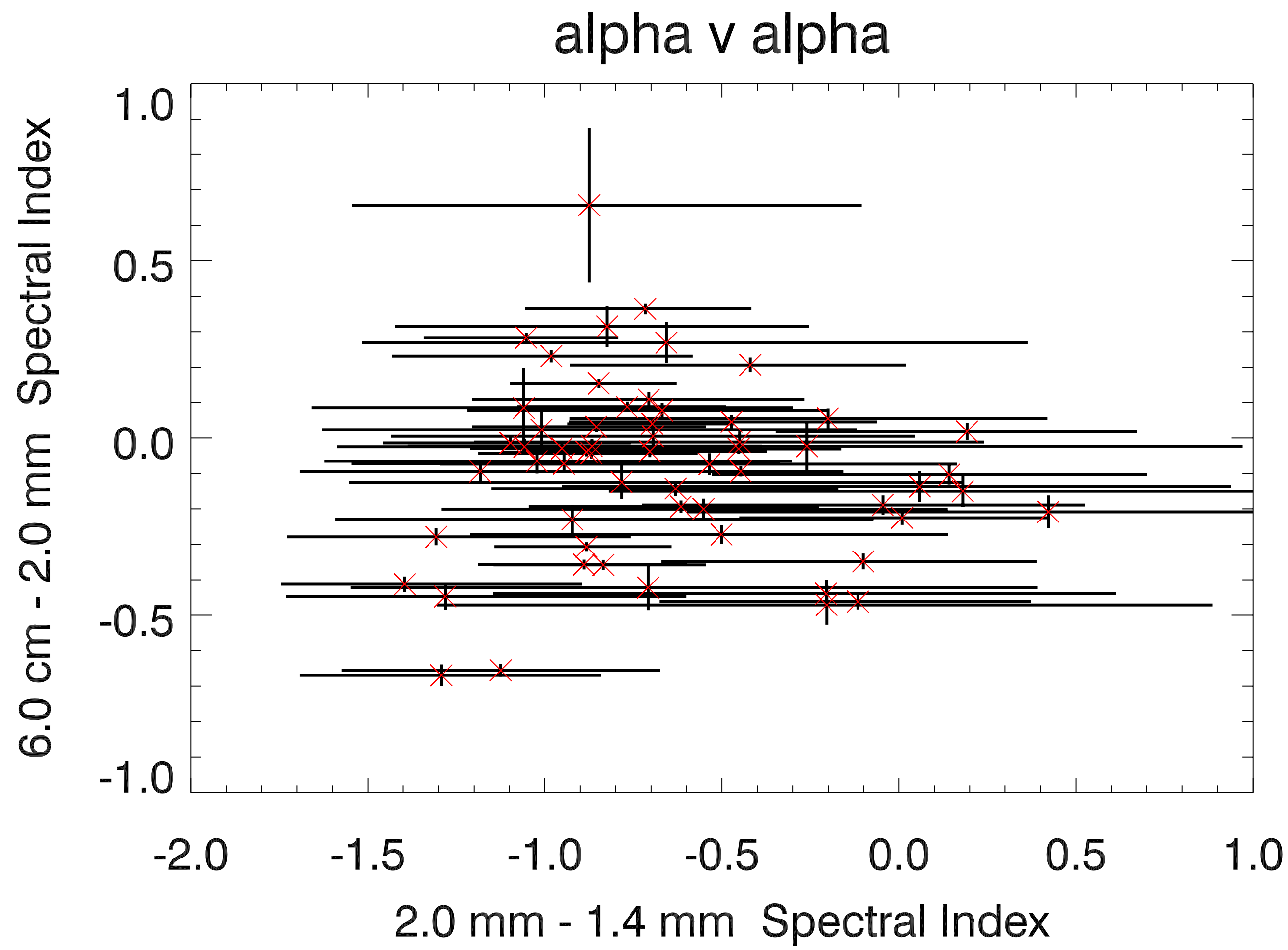
Mixture of synchrotron and dust-dominated sources.

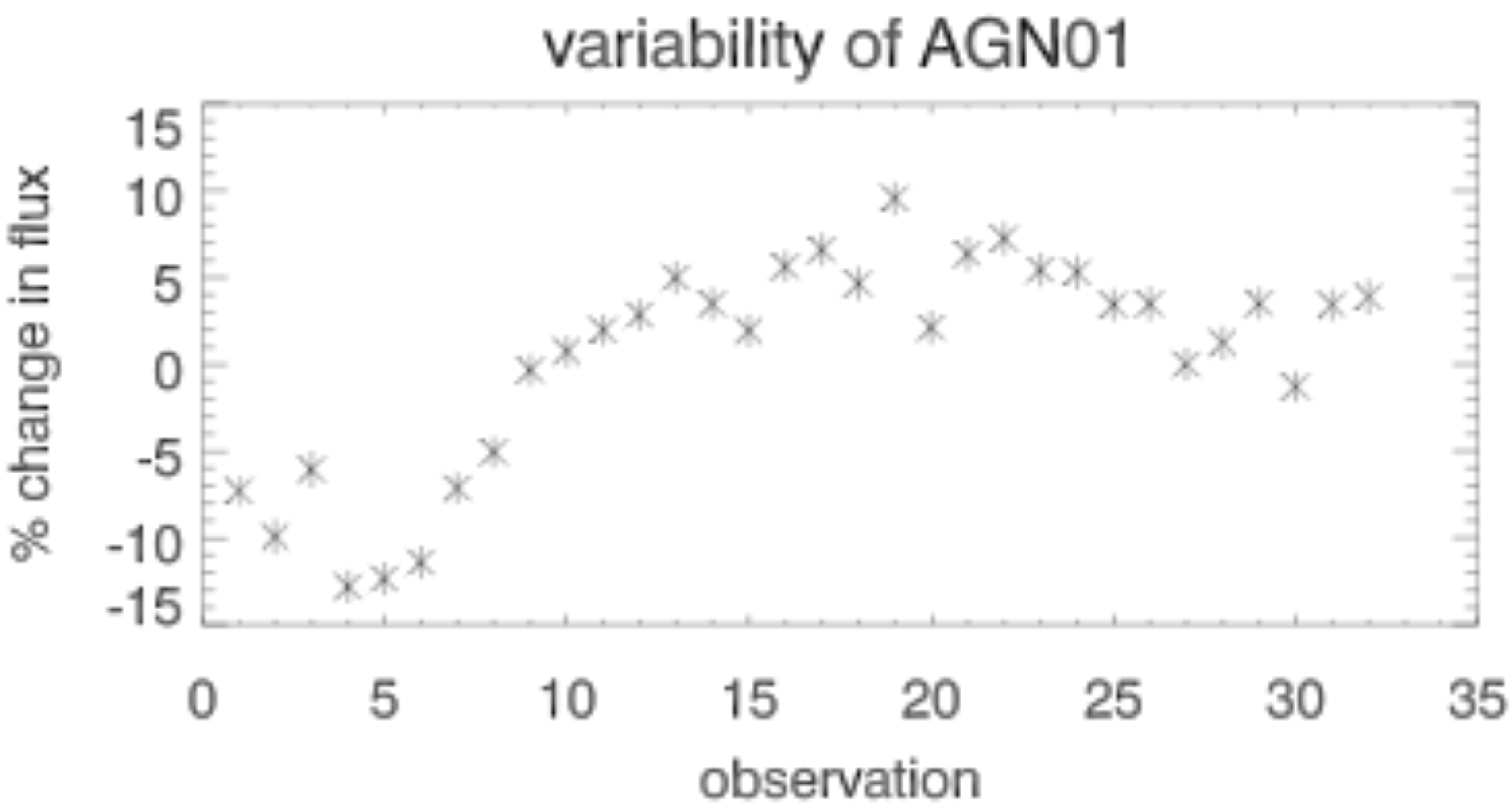
Synchrotron Counts



SPT AGN

- **SPT AGN are FSRQ**
- **Spectral index steepens between 150 and 220 GHz**
- **The mm is a very efficient way of finding blazars**

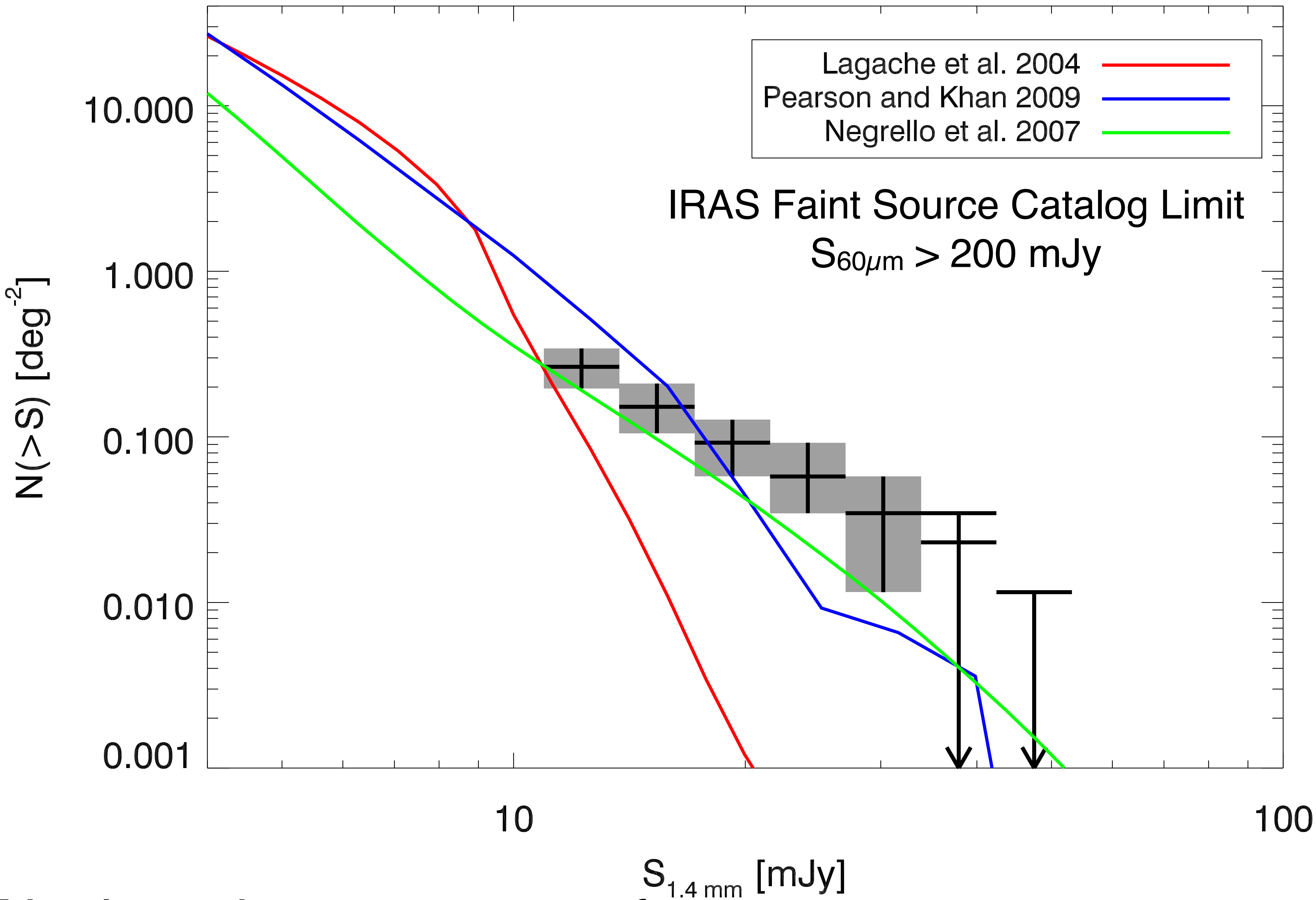




- **Sources are also highly variable**
- **Our observation strategy naturally monitors variability**

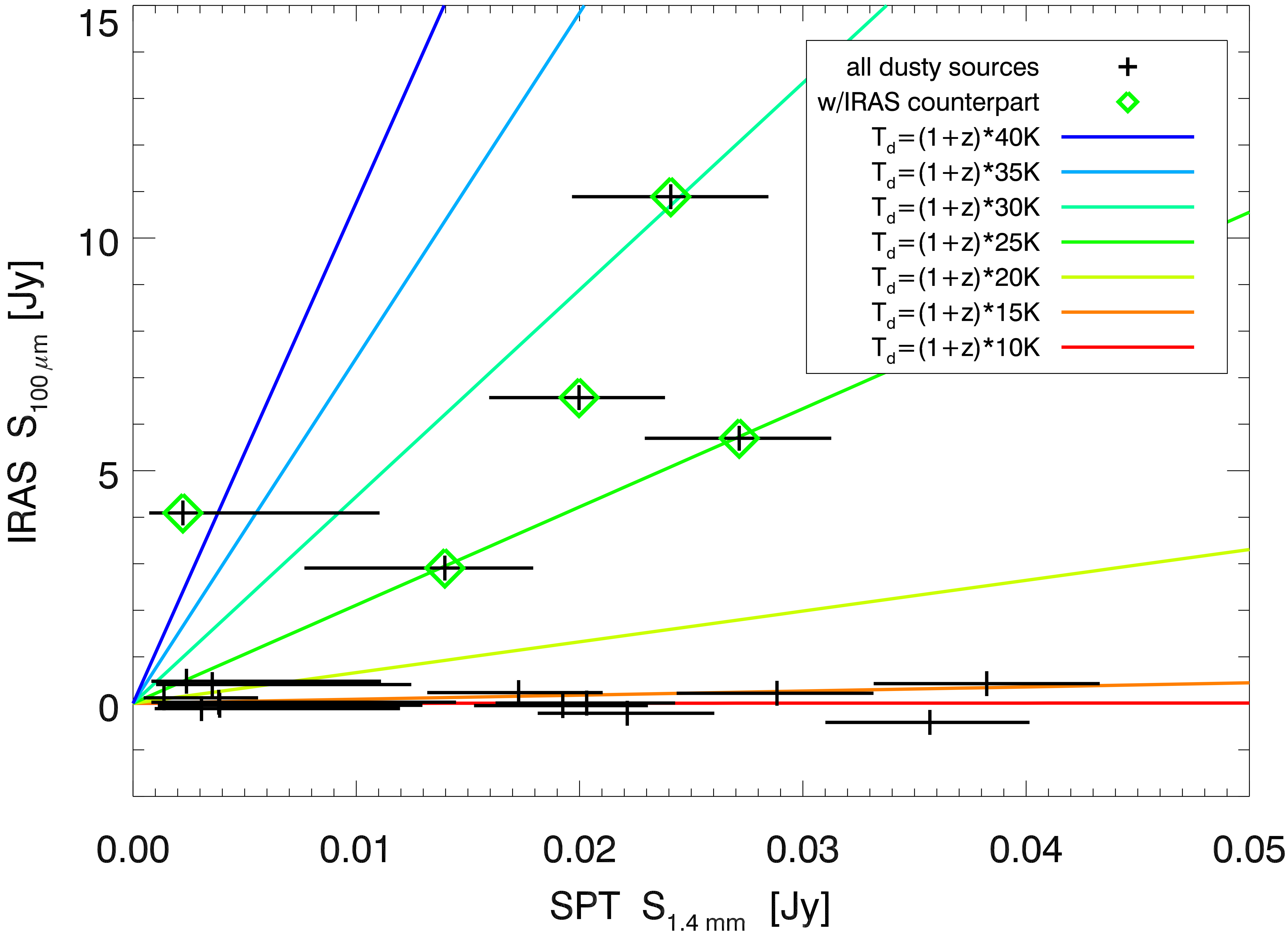
dusty source counts

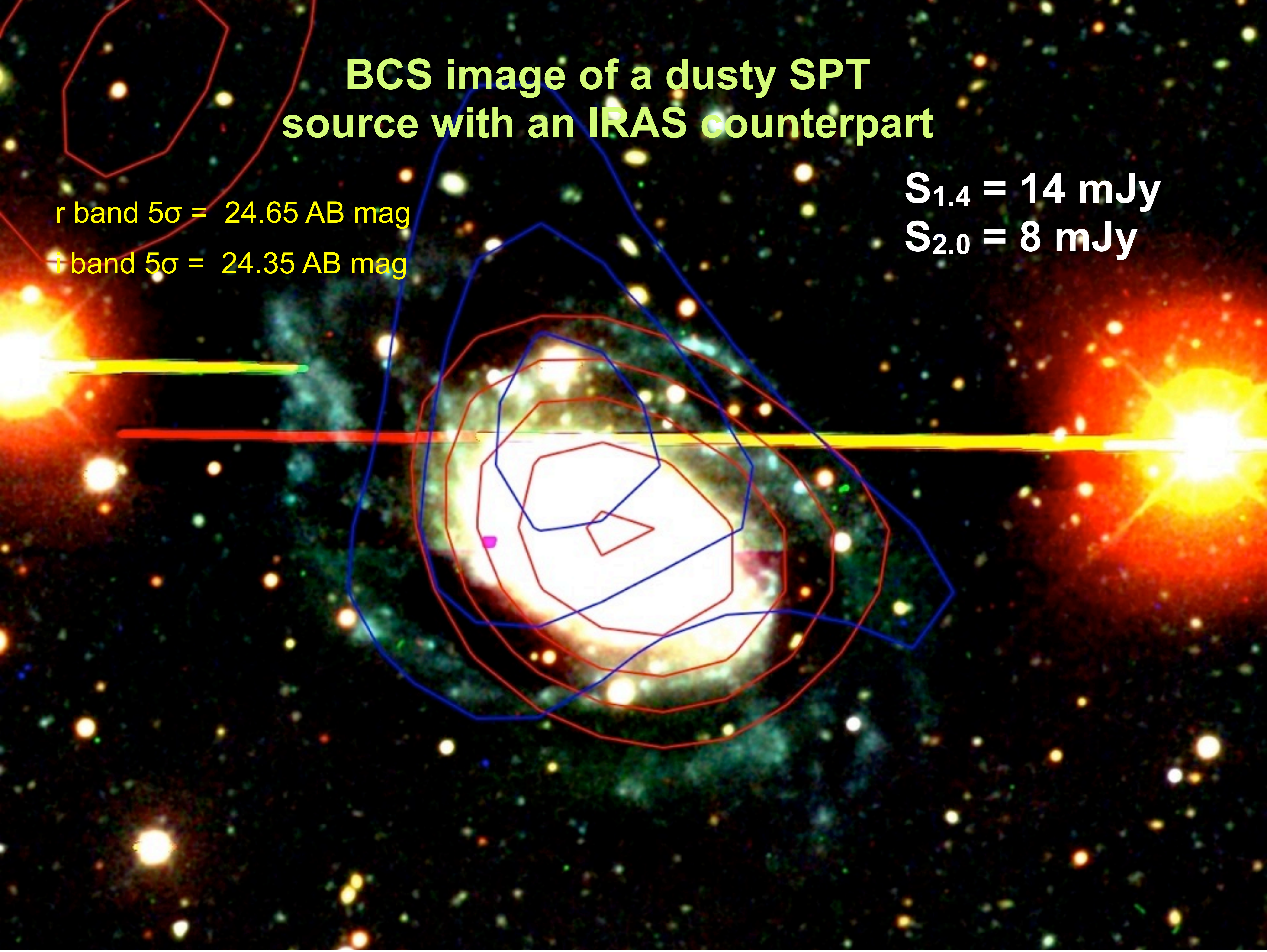
(WITH IRAS SOURCES REMOVED)



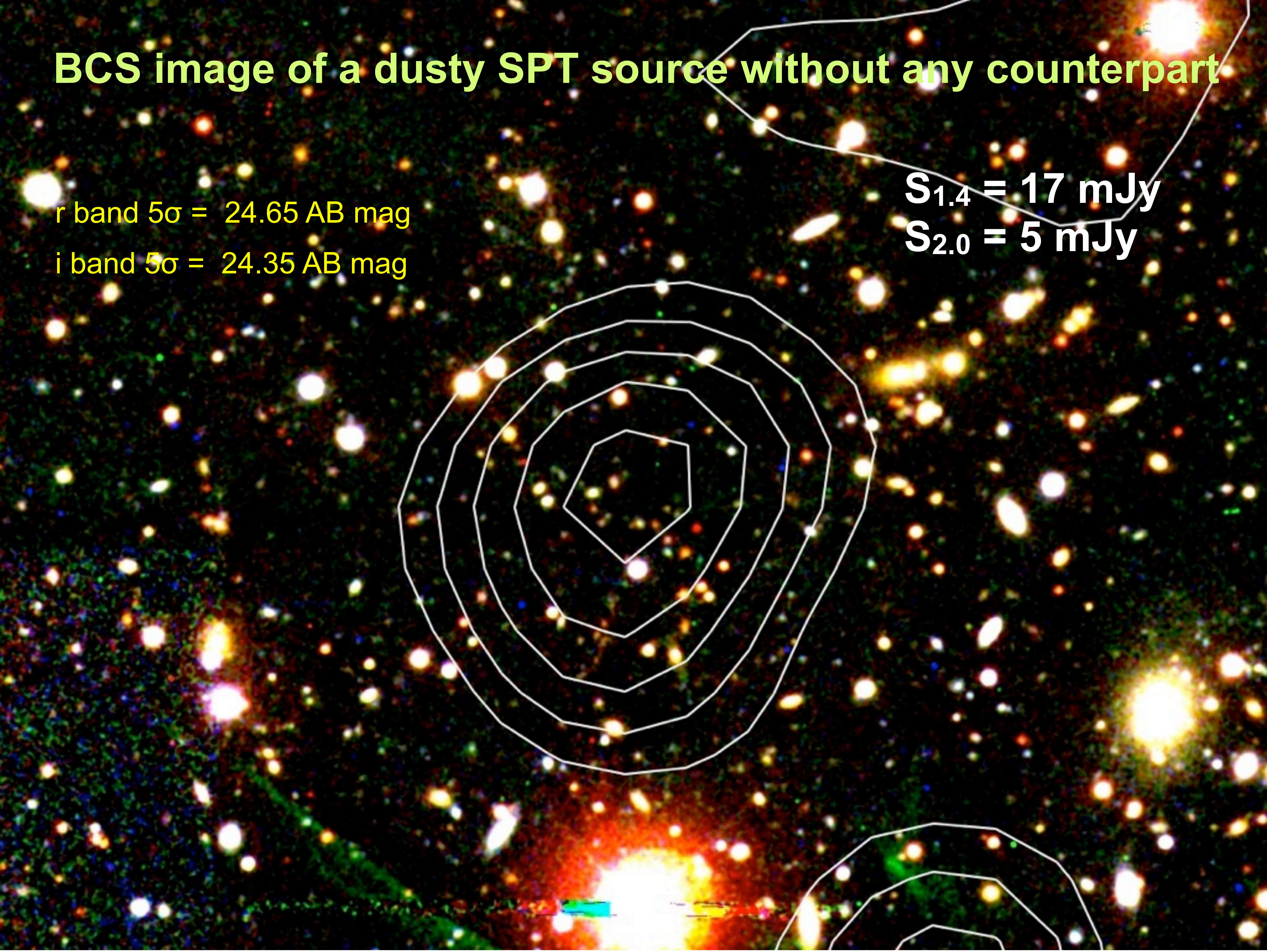
SPT is detecting an excess of sources above model predictions.

SPT Dusty Sources in IRAS

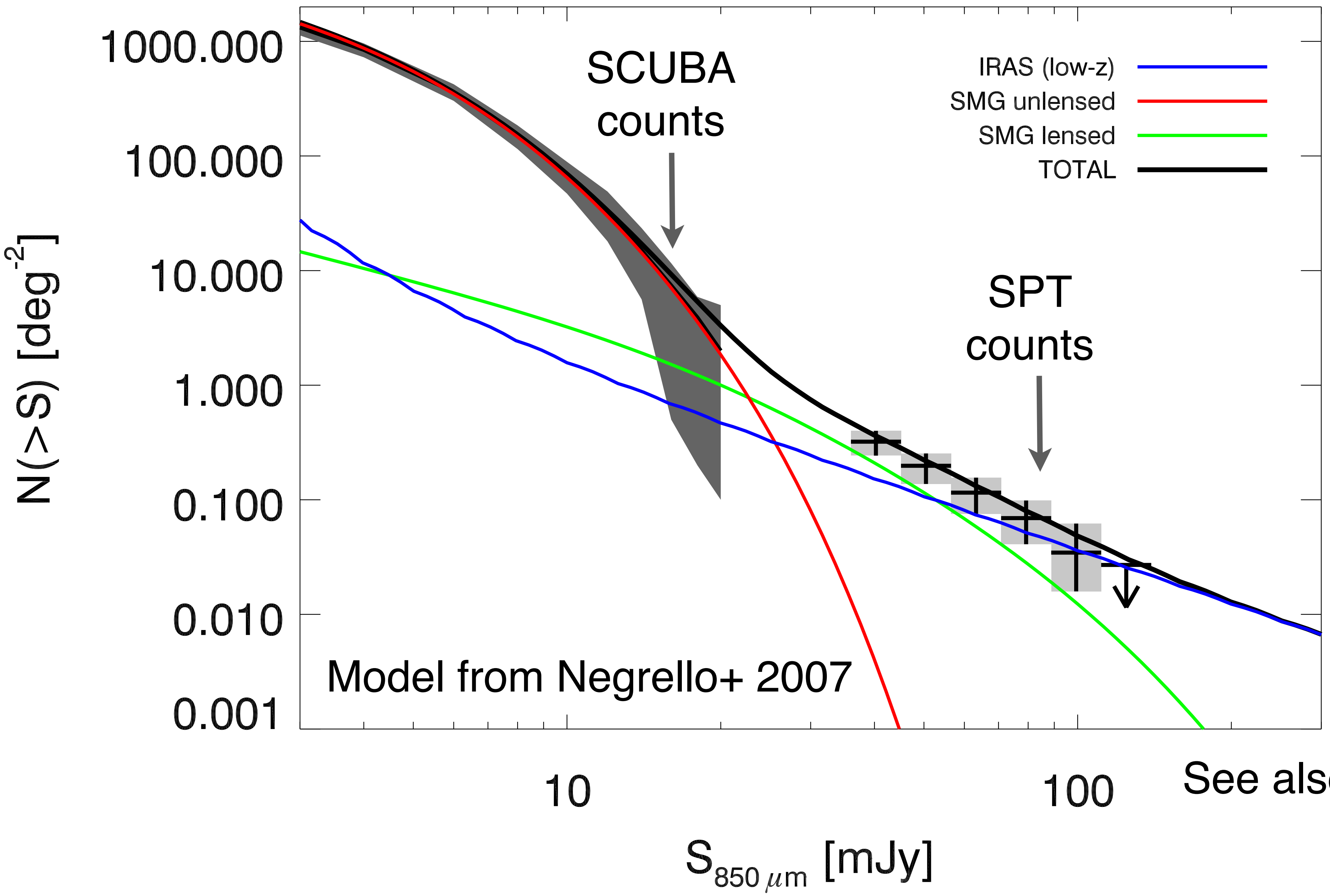



BCS image of a dusty SPT source with an IRAS counterpart
r band 5σ = 24.65 AB mag
i band 5σ = 24.35 AB mag
$S_{1.4}$ = 14 mJy
$S_{2.0}$ = 8 mJy

BCS image of a dusty SPT source without any counterpart

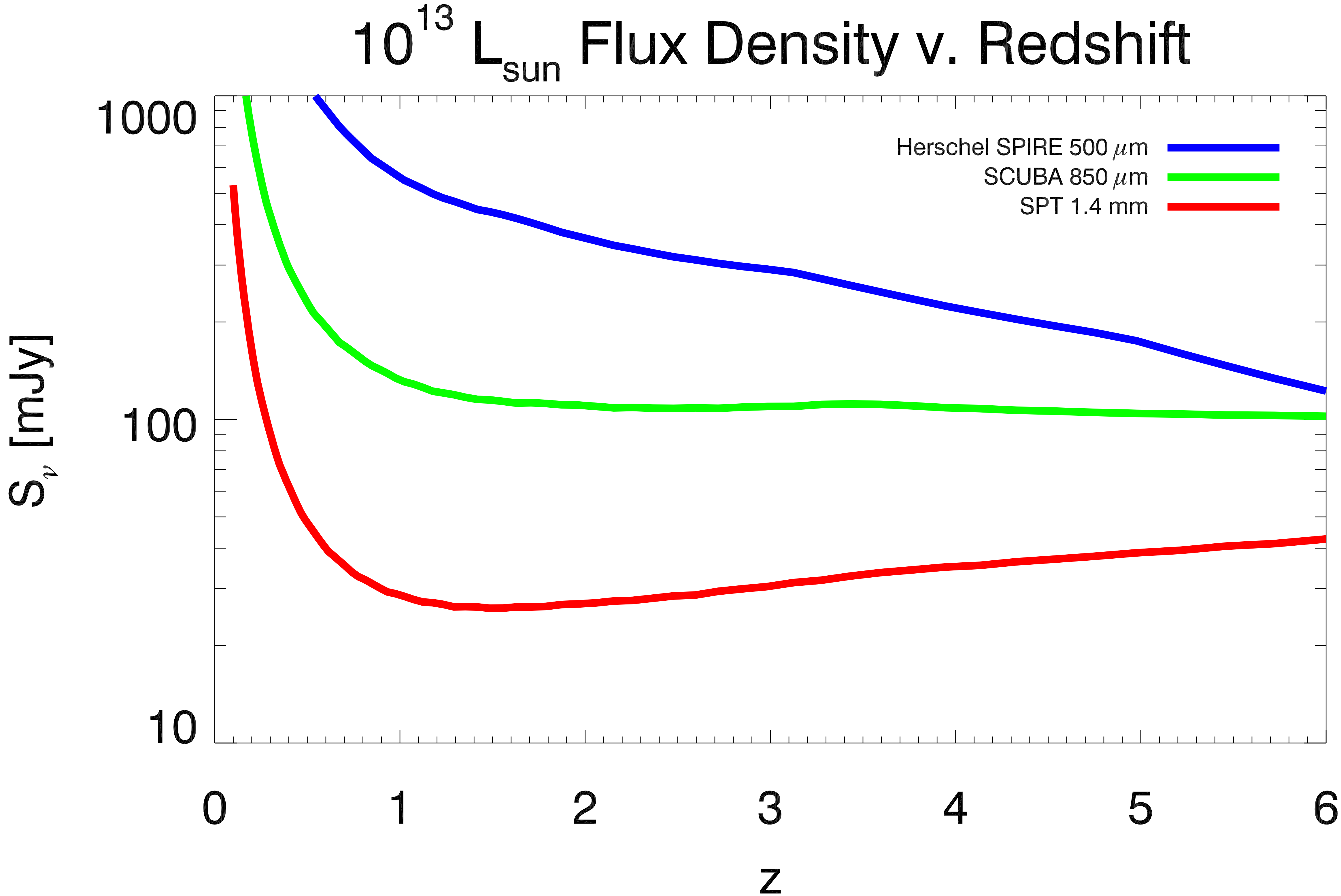


strong lensing offers one possible explanation which is attractive and plausible.



See also Blain 1996

SPT has surveyed so wide that we will probably find some weird things...

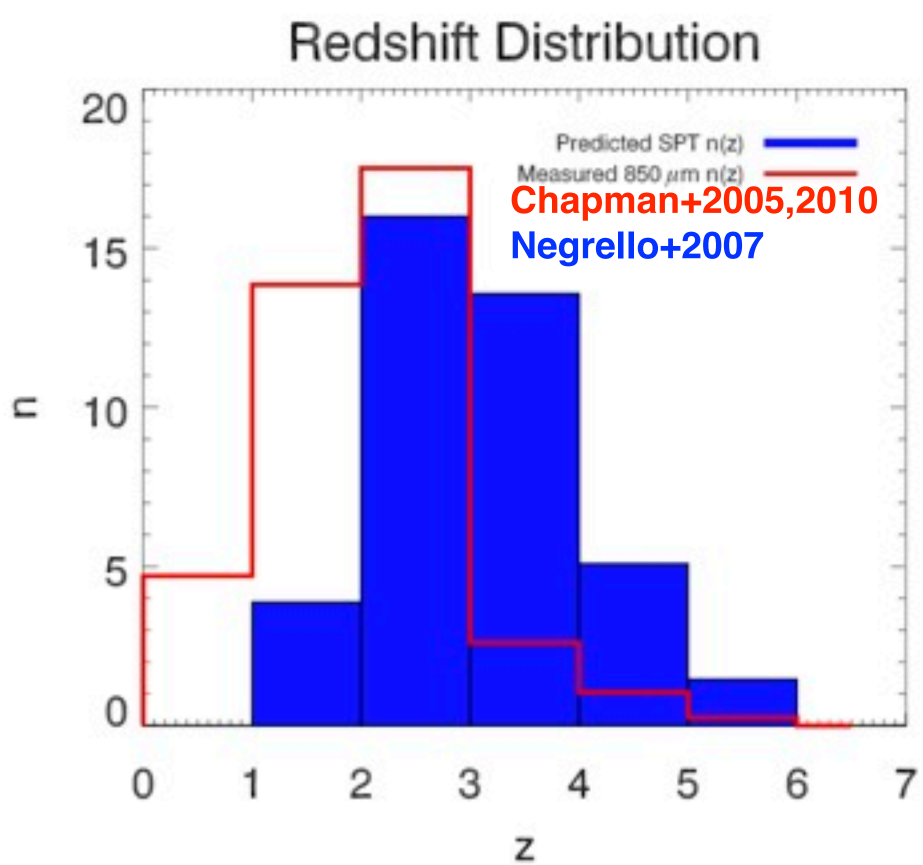


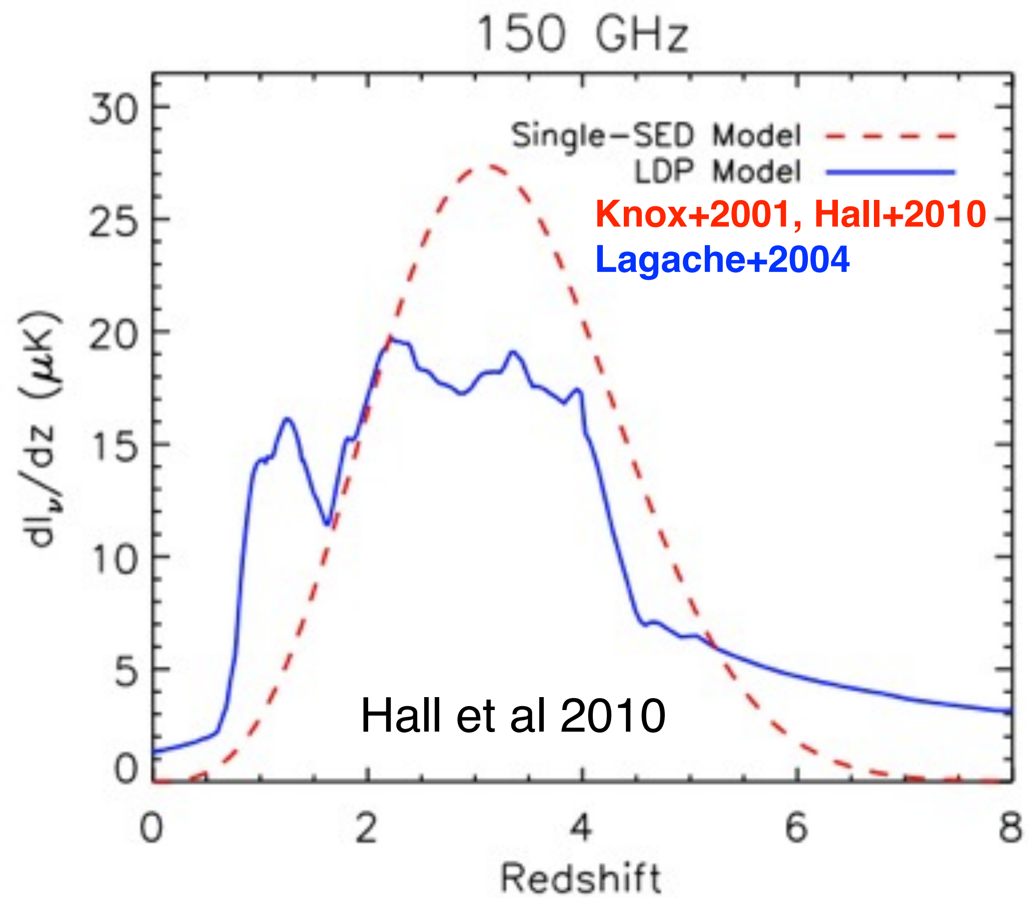
SPT selection favors higher redshift and/or colder systems than previously studied samples.

47

Redshift distribution predictions

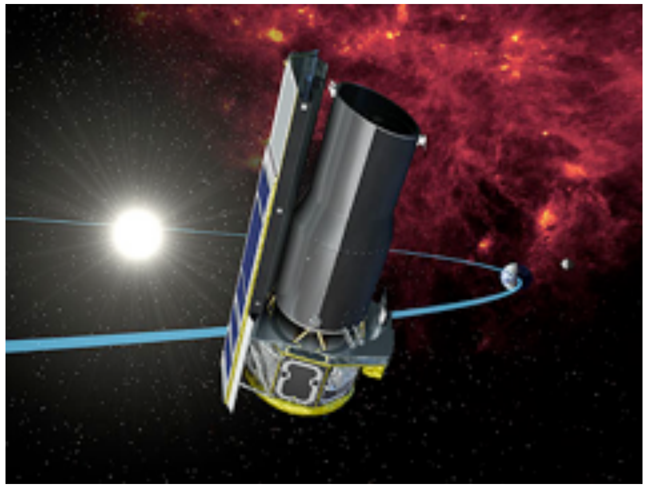
~1/2 of these sources should be at z>3

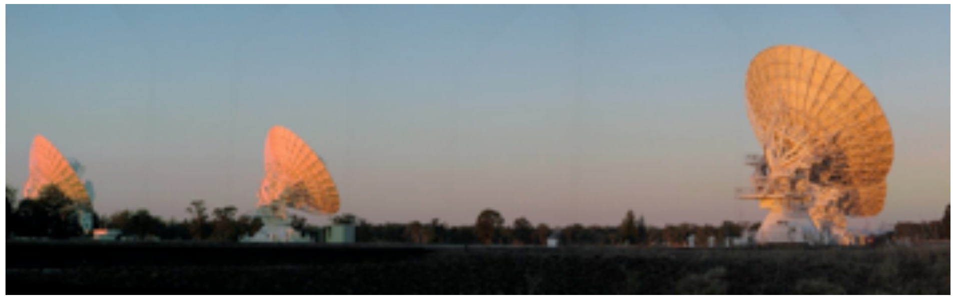




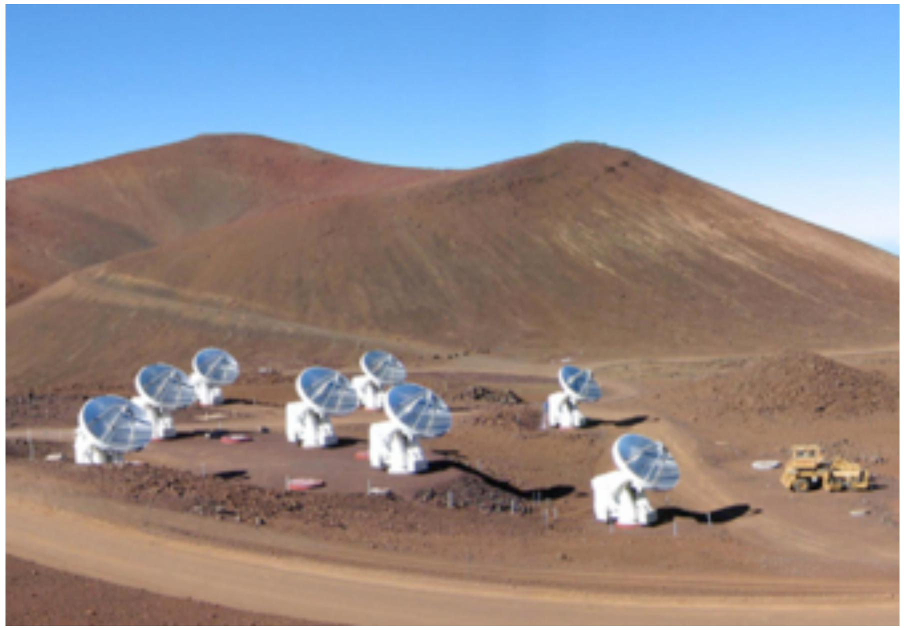
- SPT is at ***longer wavelengths*** than other sub-mm experiments, and so more sensitive to ***higher redshift objects***.
- Because of the K-correction, the ***lensing probability increases with redshift***, meaning that high redshift sources have a higher probability of being strongly lensed.
- By mapped such a ***wide area***, there is a greater chance for discovering ***rare, high redshift objects***.

Followup Campaign





- Because the SPT beam is large (~1 arcmin) we cannot unambiguously identify an optical counterpart.



- Because these sources are high redshift, highly dust obscured, and optically faint, they are difficult to identify.
- As the sources are so far south (DEC<-50), the traditional facilities (VLT, PdBI, IRAM, JCMT, CSO, Keck) used to locate and characterize SMGs are not available.
- We are helped by the fact that these sources are x10 brighter than the canonical samples of SMGs

- For the past 2 years we have undertaken an extensive followup campaign with Spitzer, SMA, ATCA, Gemini, and VLT to characterize these sources

SPT SMG Followup Team

University of Chicago / KICP

Lindsey Bleem
John Carlstrom
Tom Crawford
Dan Marrone
Mike Gladders
Eric Switzer

Harvard / CfA / SAO

Matt Ashby
Mark Brodwin
Giovanni Fazio
Brian Stalder
Tony Stark

ESO

Carlos De Breuck

Cambridge

Scott Chapman

U. Copenhagen

Thomas Greve

McGill

Gil Holder

UCLA

Matt Malkan

U Florida

Anthony Gonzalez

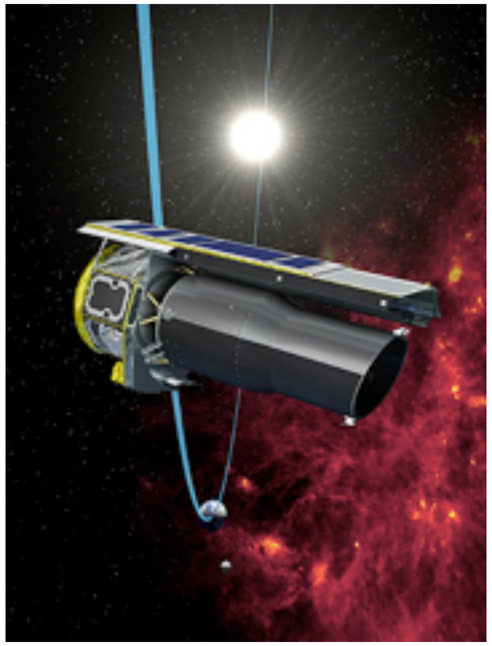
Caltech

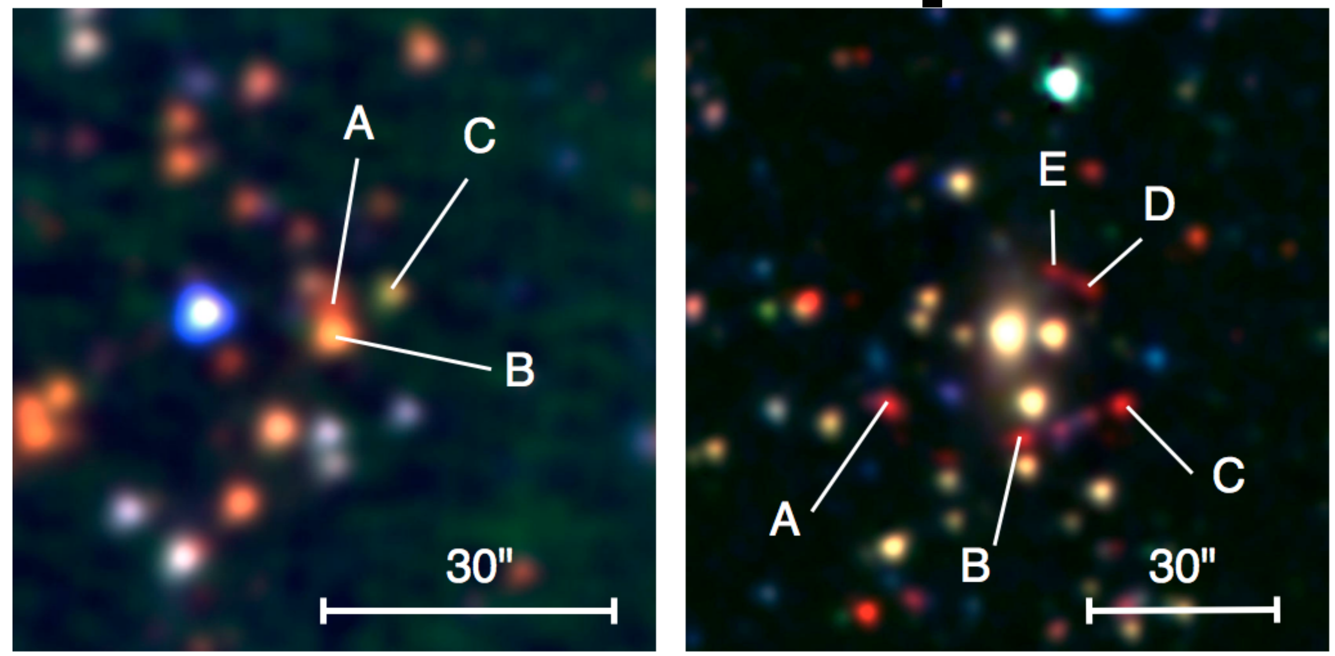
Joaquin Vieira

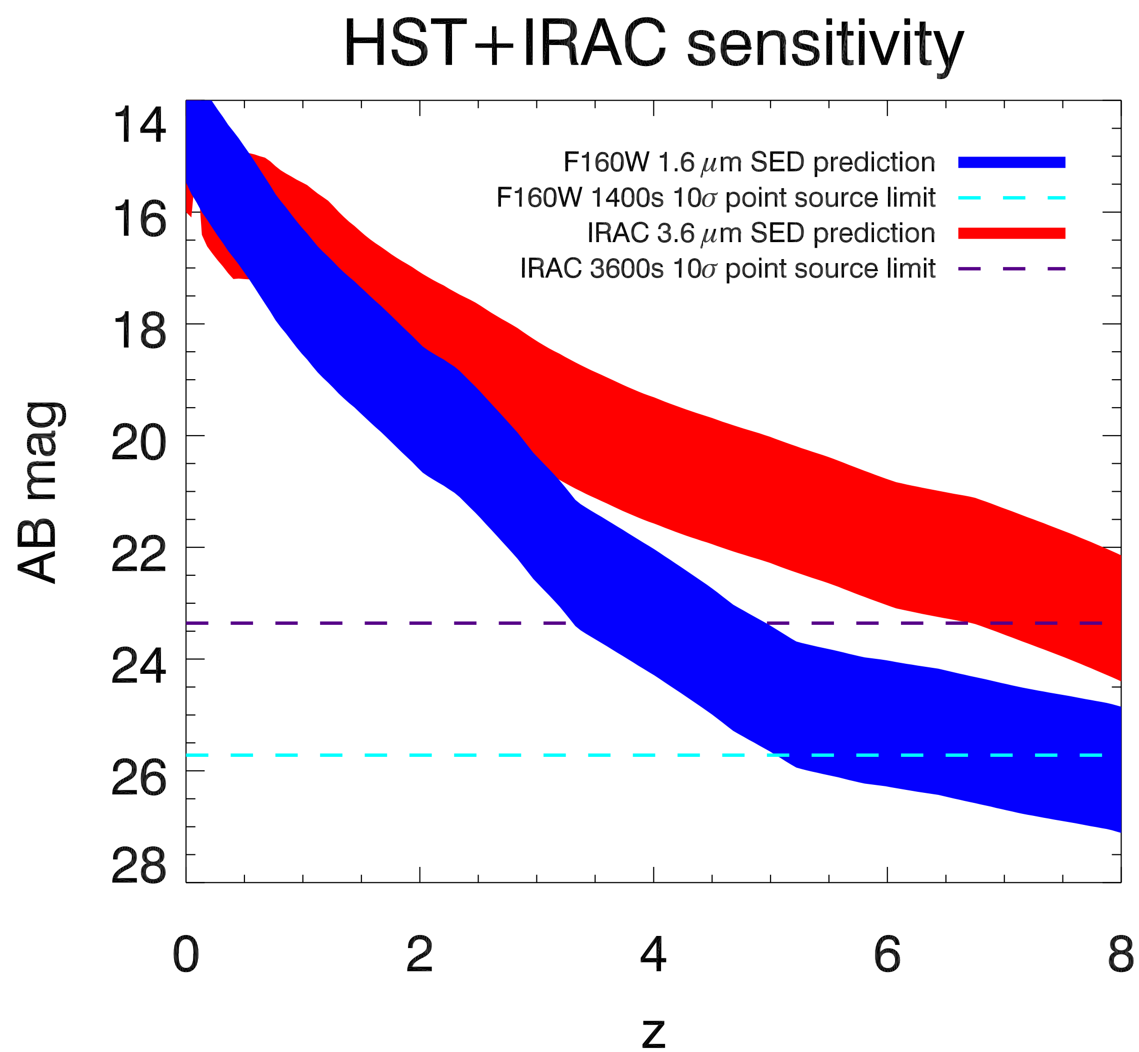
UC Davis

Chris Fassnacht

Spitzer/IRAC Followup

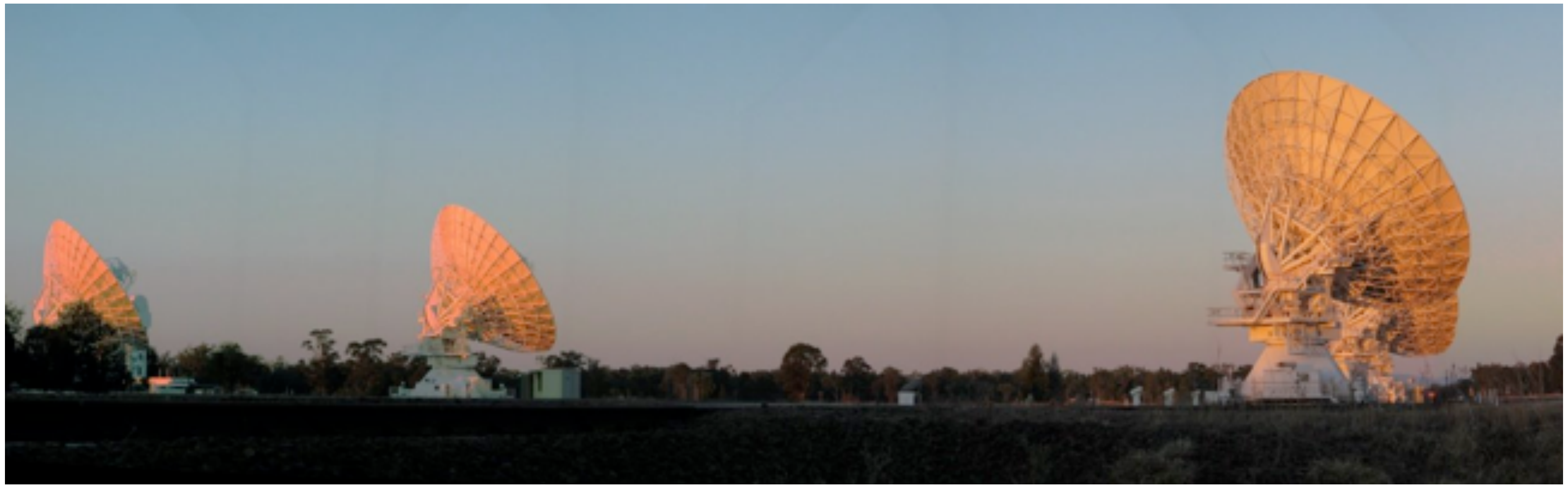


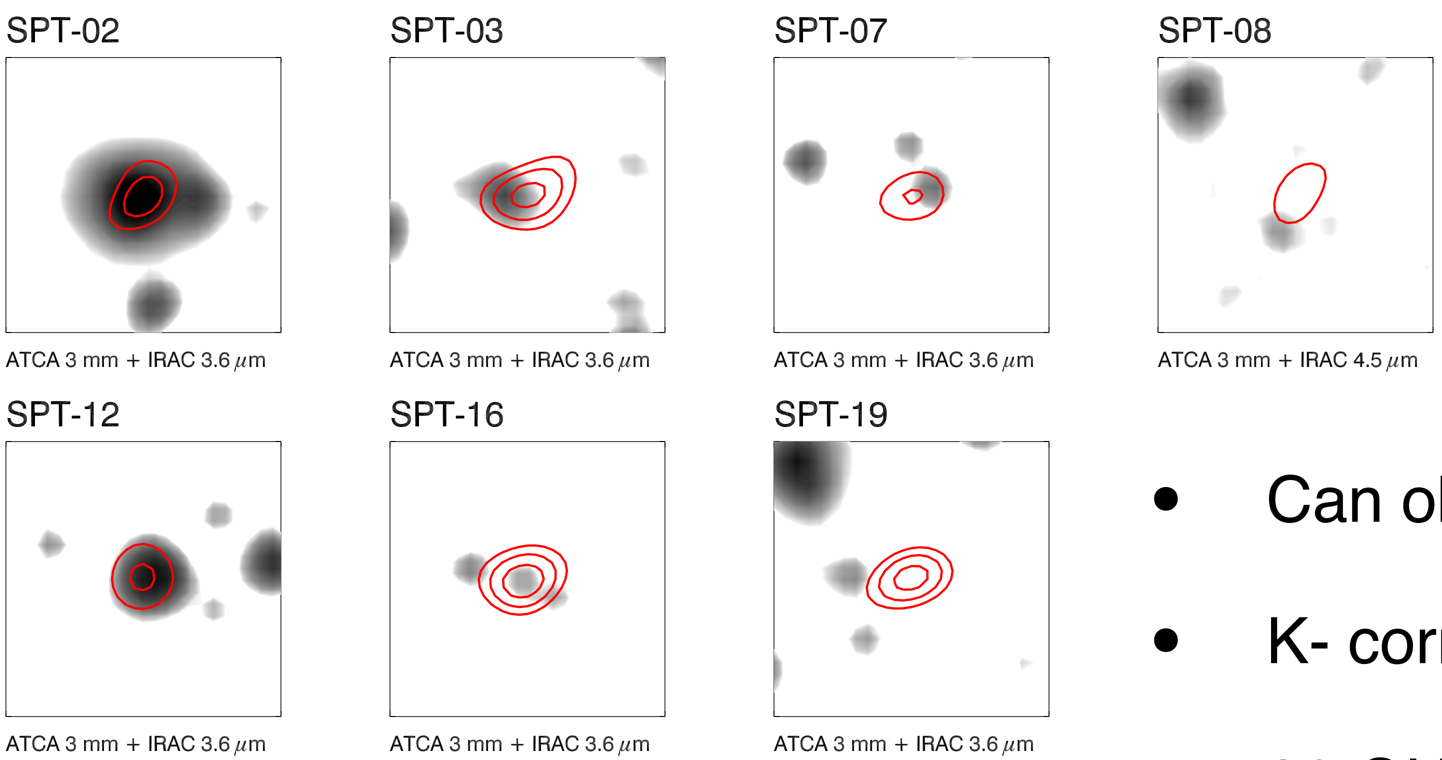




- We followed up 40 sources from the 2008 survey.
- We went down took a 1 hour exposure at 3.6 um (<1uJy RMS) and a 15 min exposure at 4.5 um
- We expect to be able to detect all sources out to z<5-6

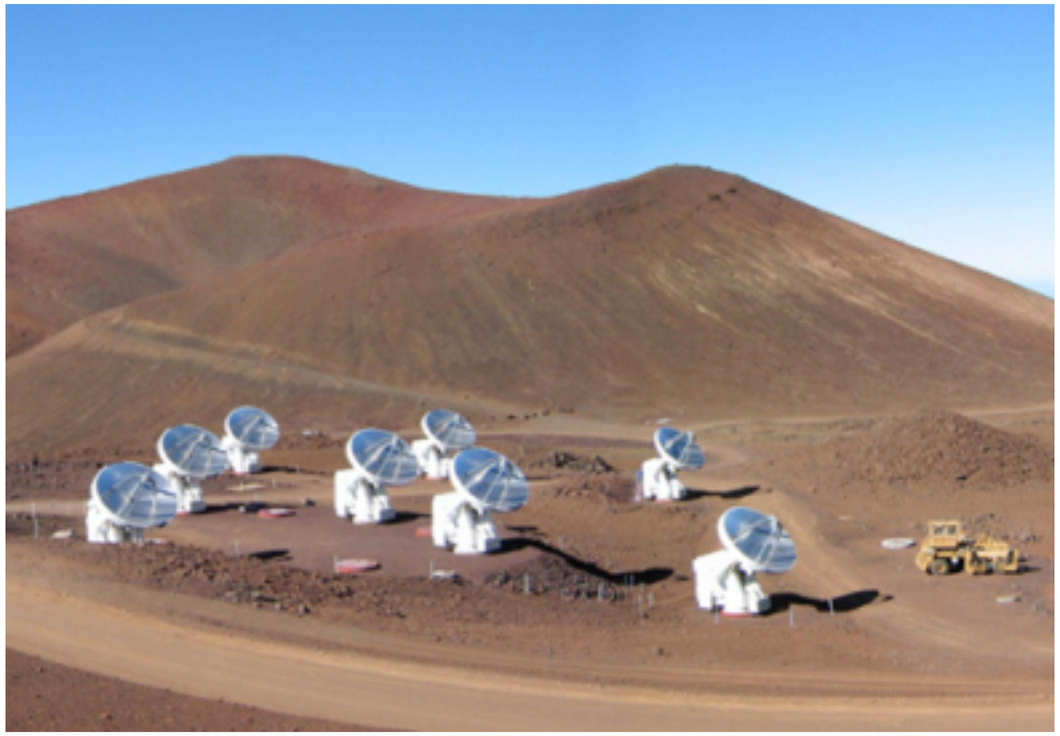
ATCA Followup

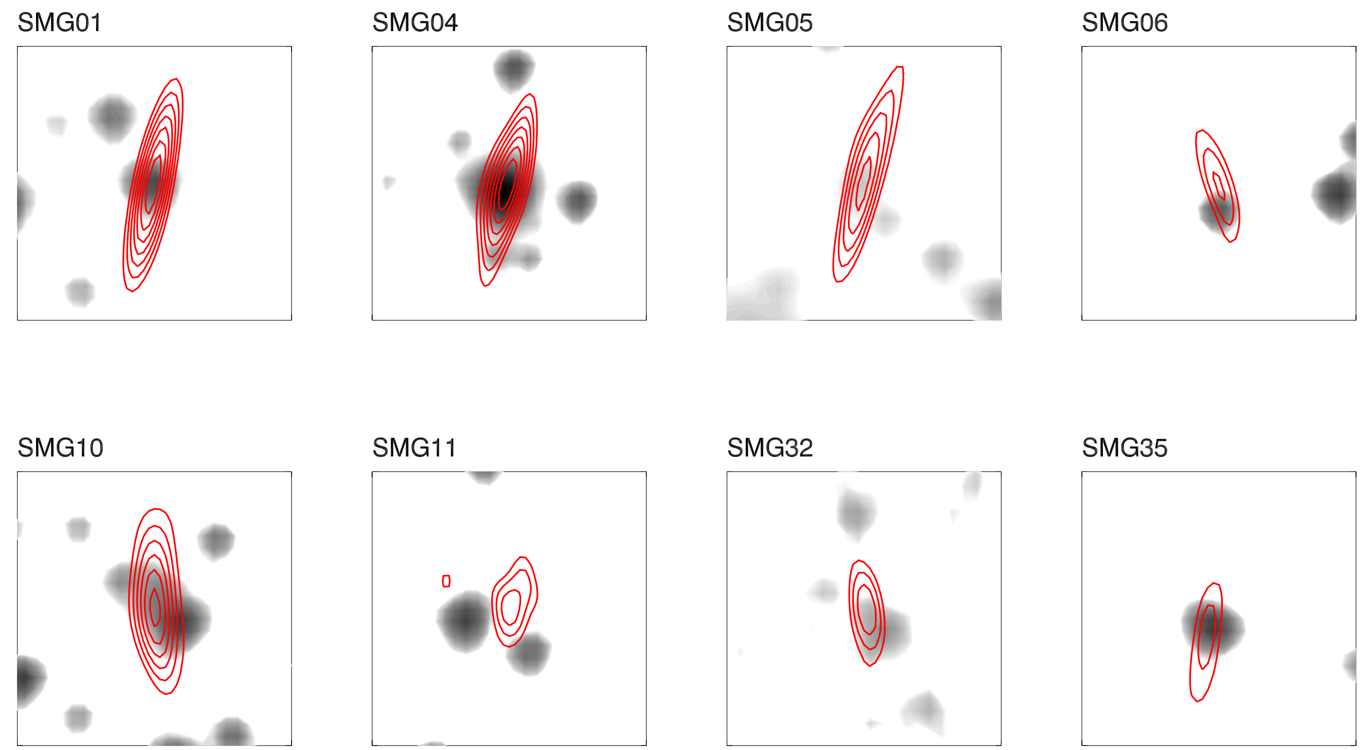


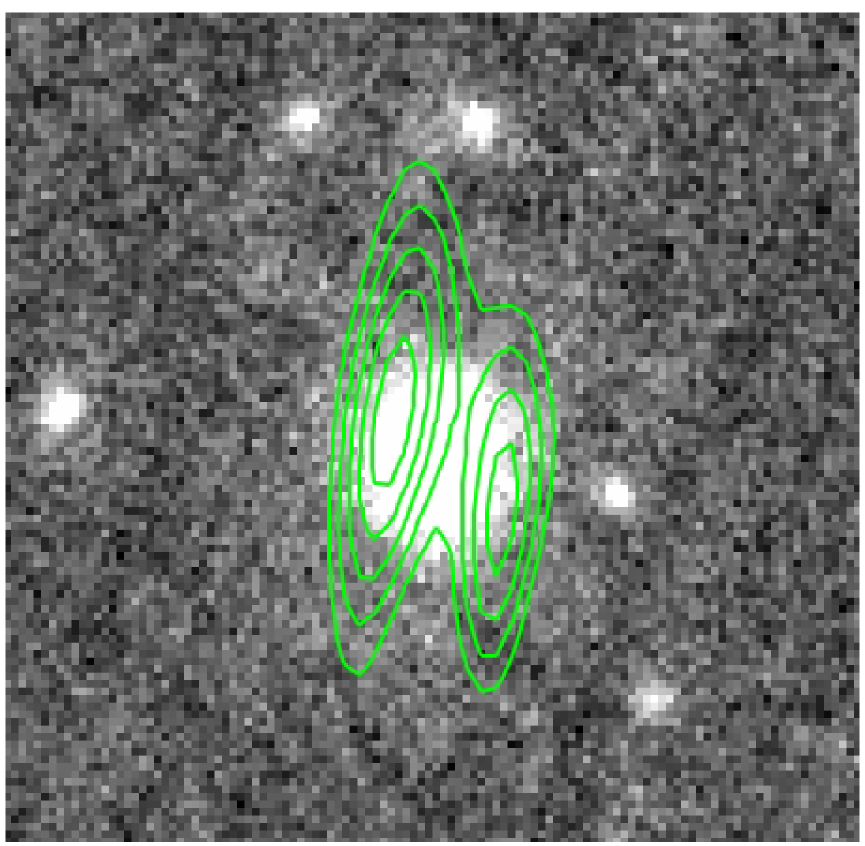


- Can observe all SPT fields
- K- correction favors higher redshift sources
- 90 GHz tough from sea-level!

SMA Followup

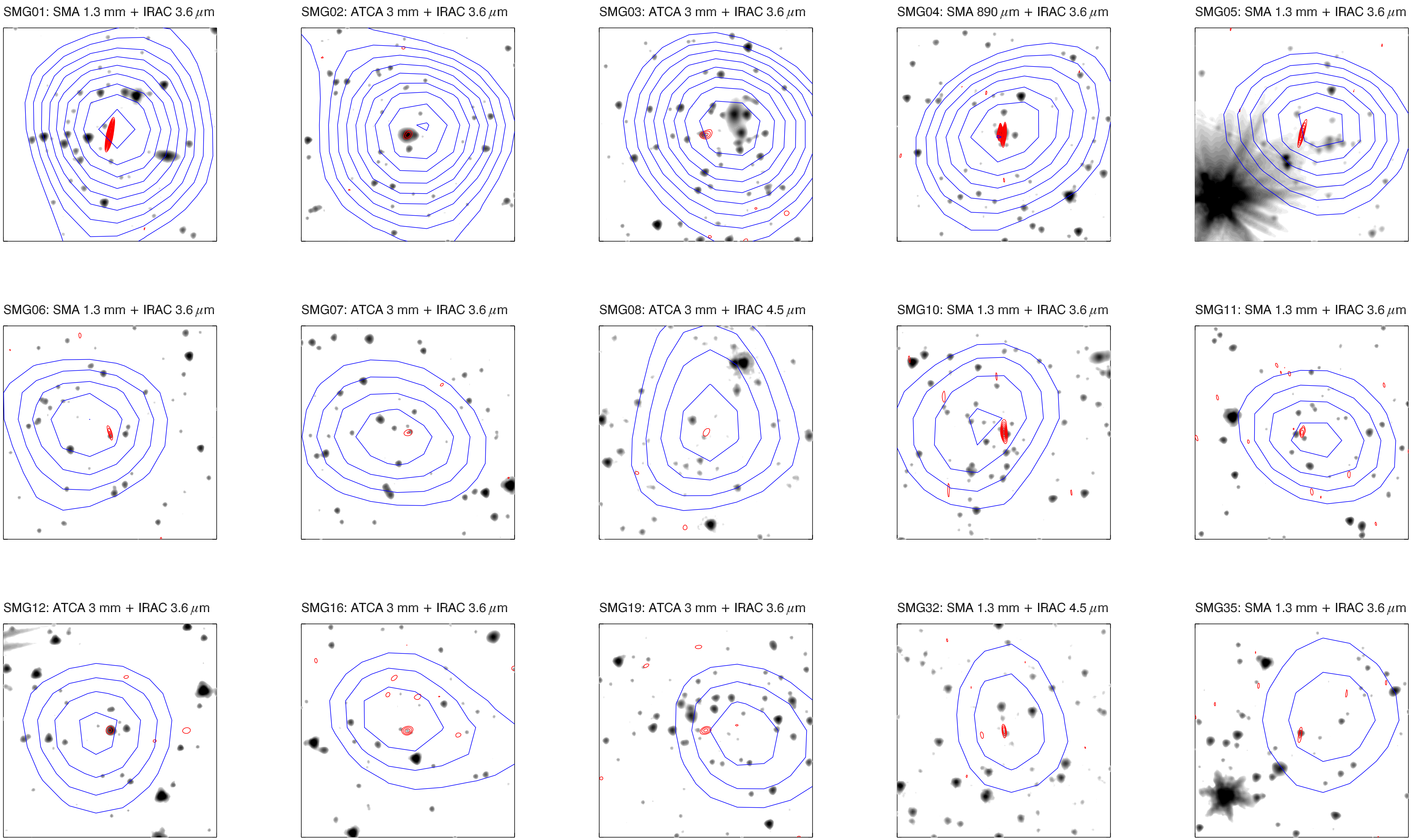






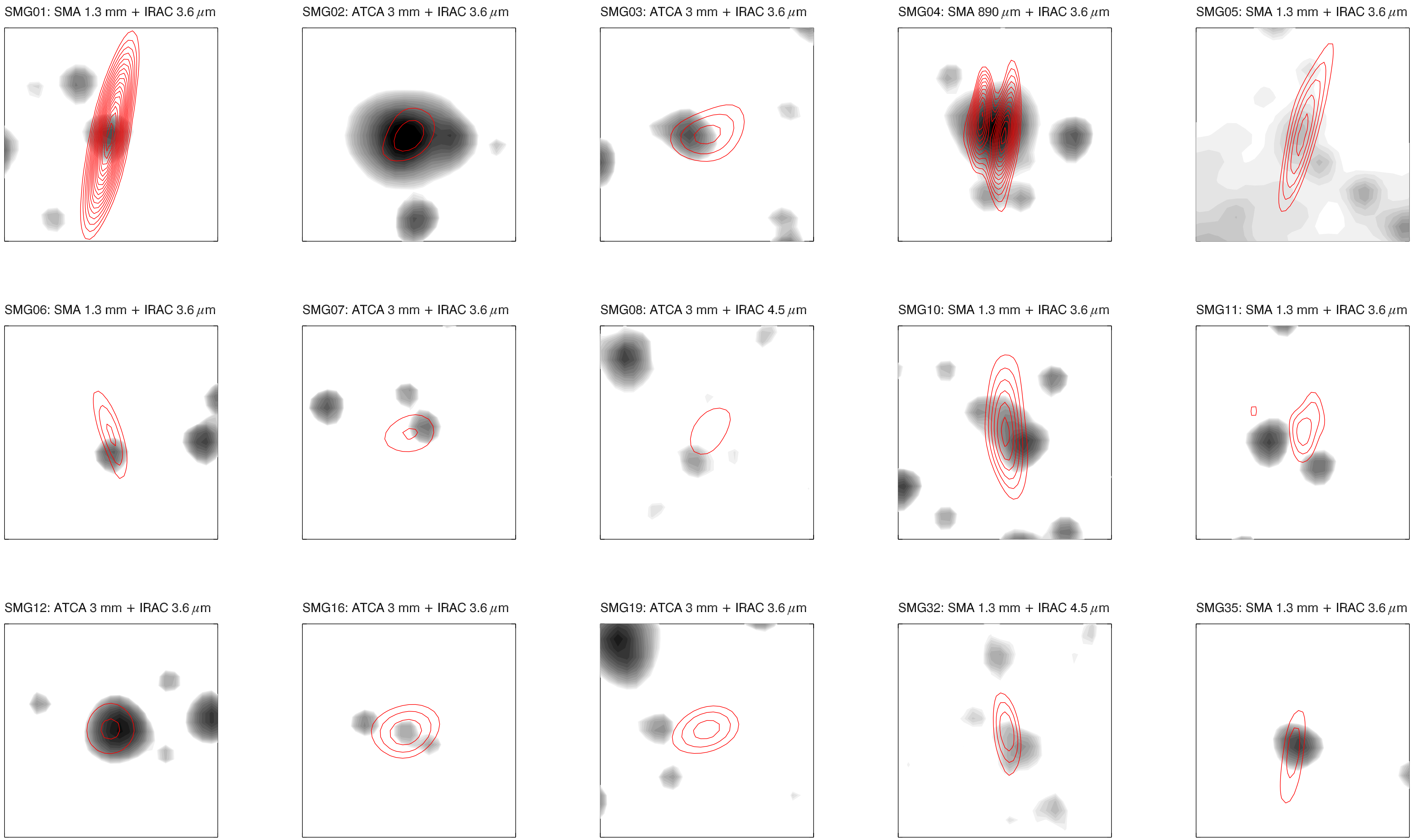
- We can observe the most northern few degrees of the SPT survey area.
- The SPT sources transit ~15 deg EL, so a very large airmass
- We get a really funny synthesized beam due to the poor UV coverage
- We had a very successful campaign to get 1.3mm continuum detections for 8 sources, and we used 890 um for hgiher resolution images.

15 mm interferometry detections

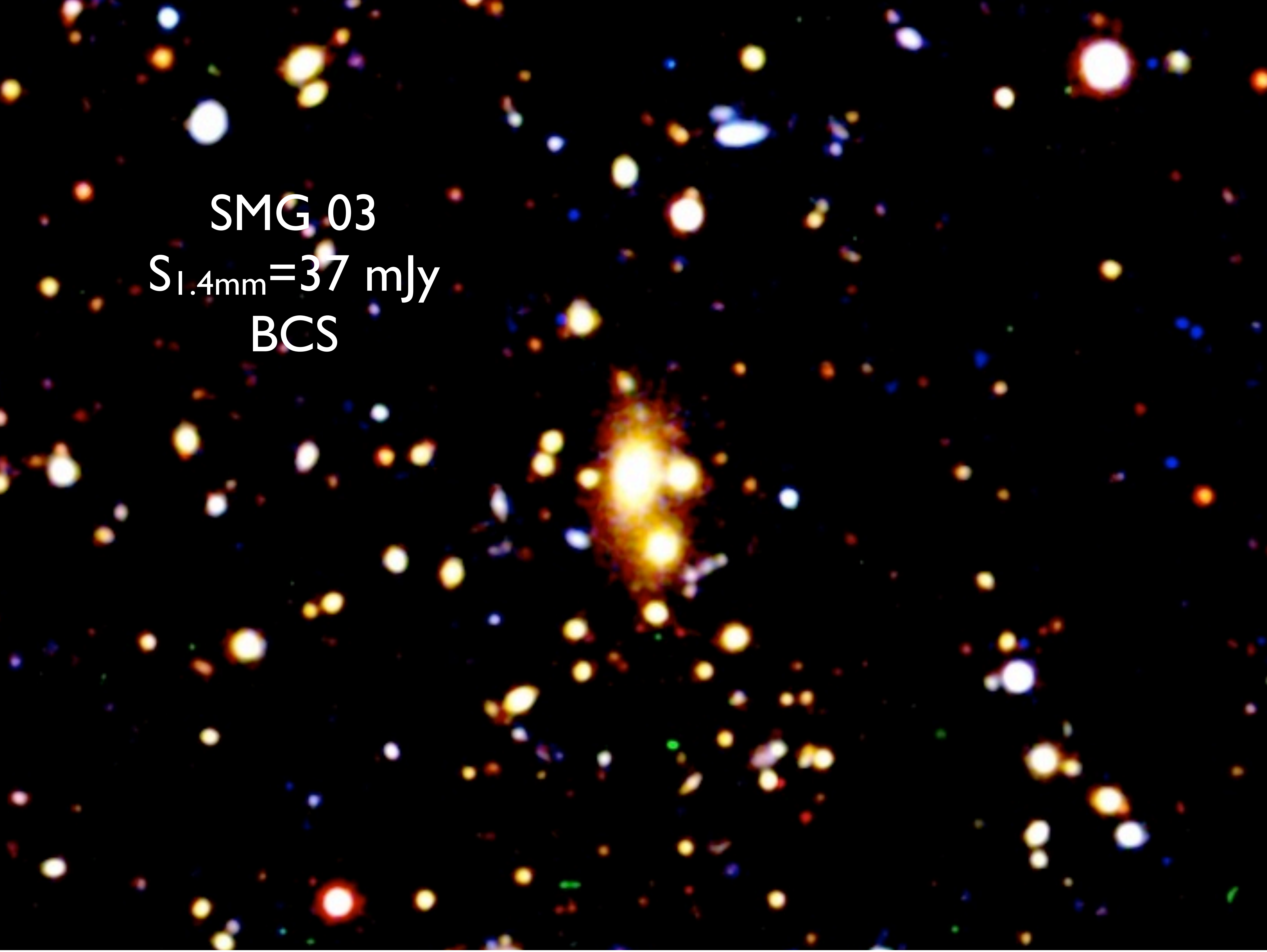


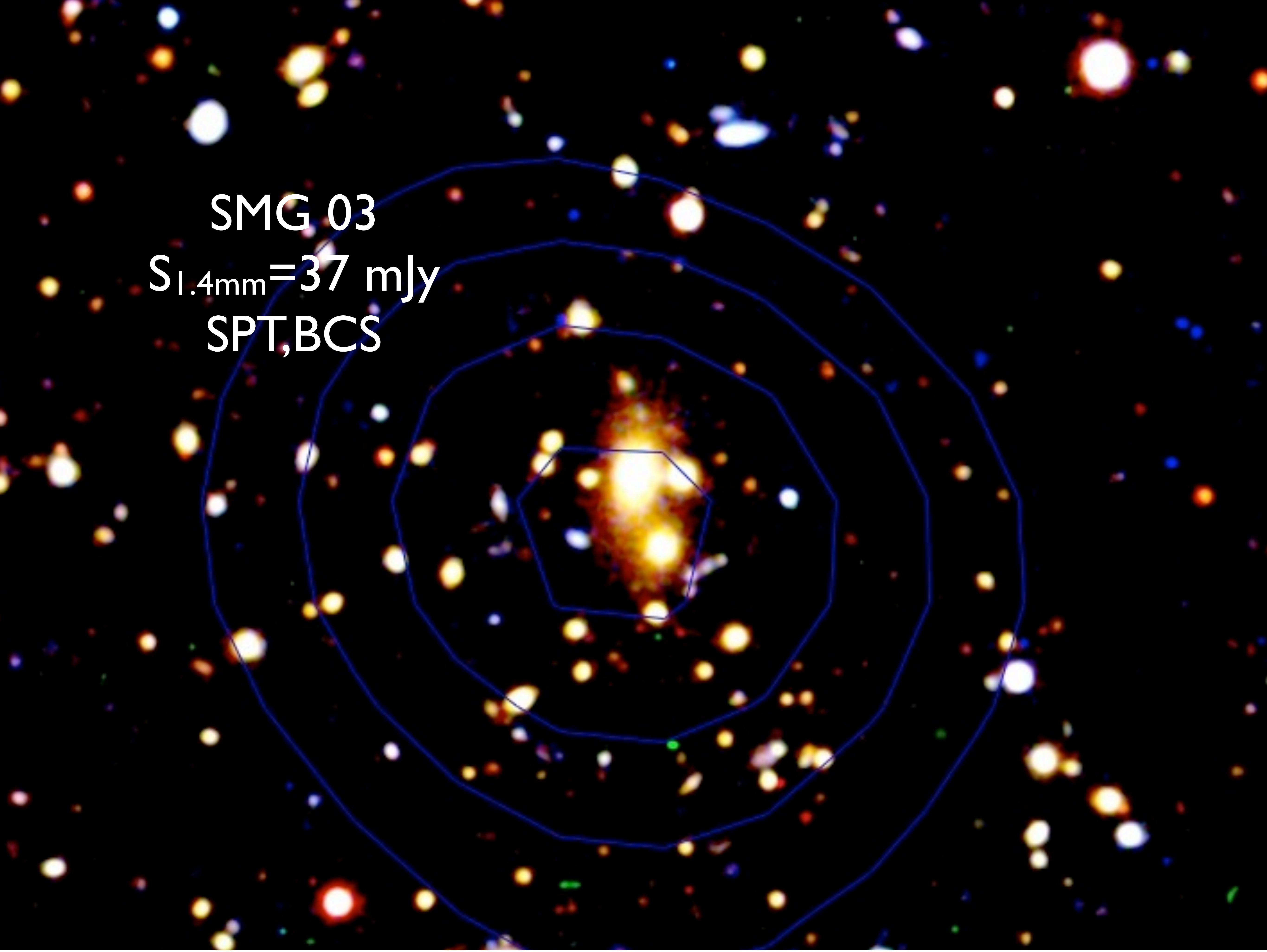
2'x2' thumbnails

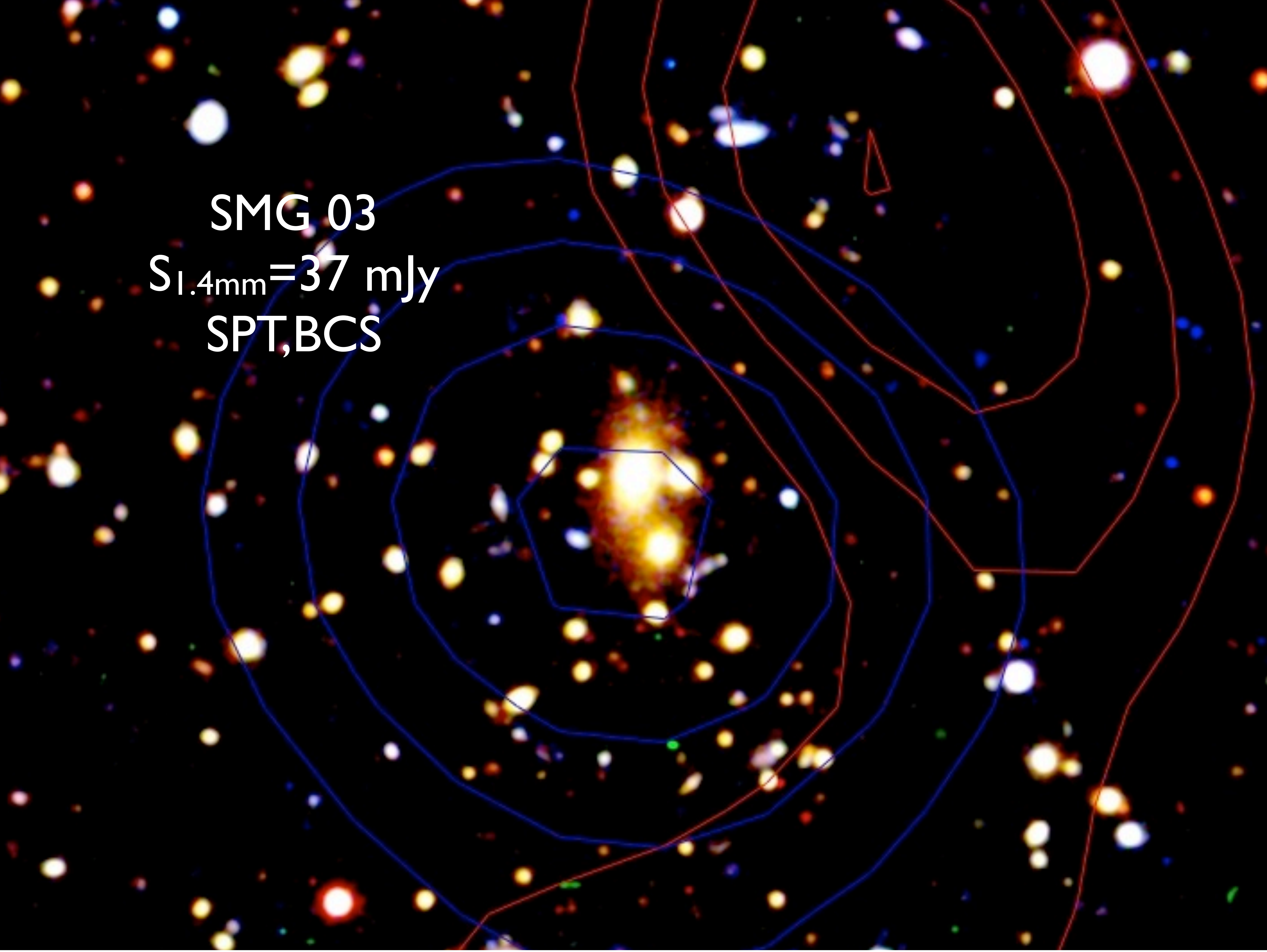
15 mm interferometry detections

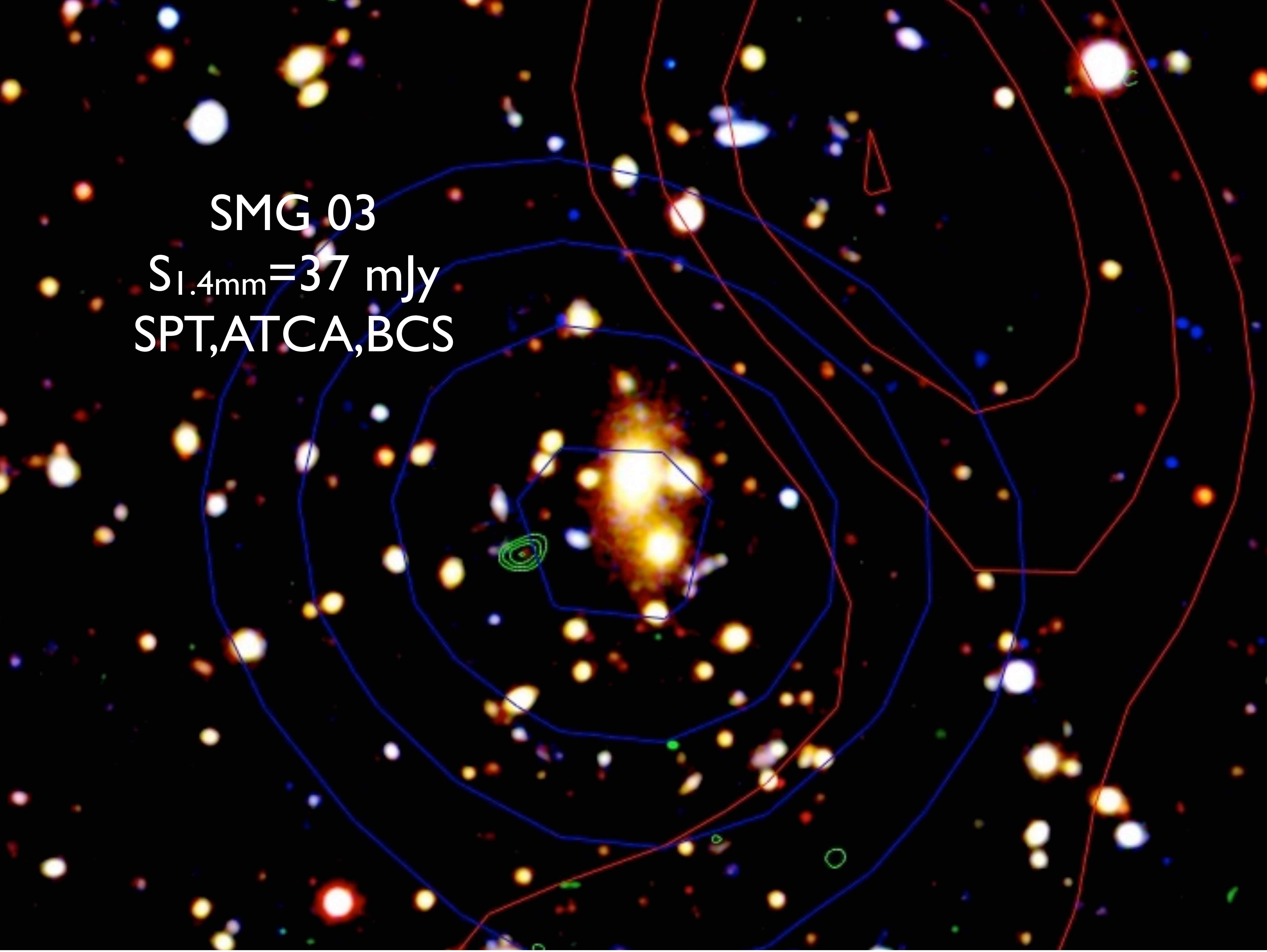


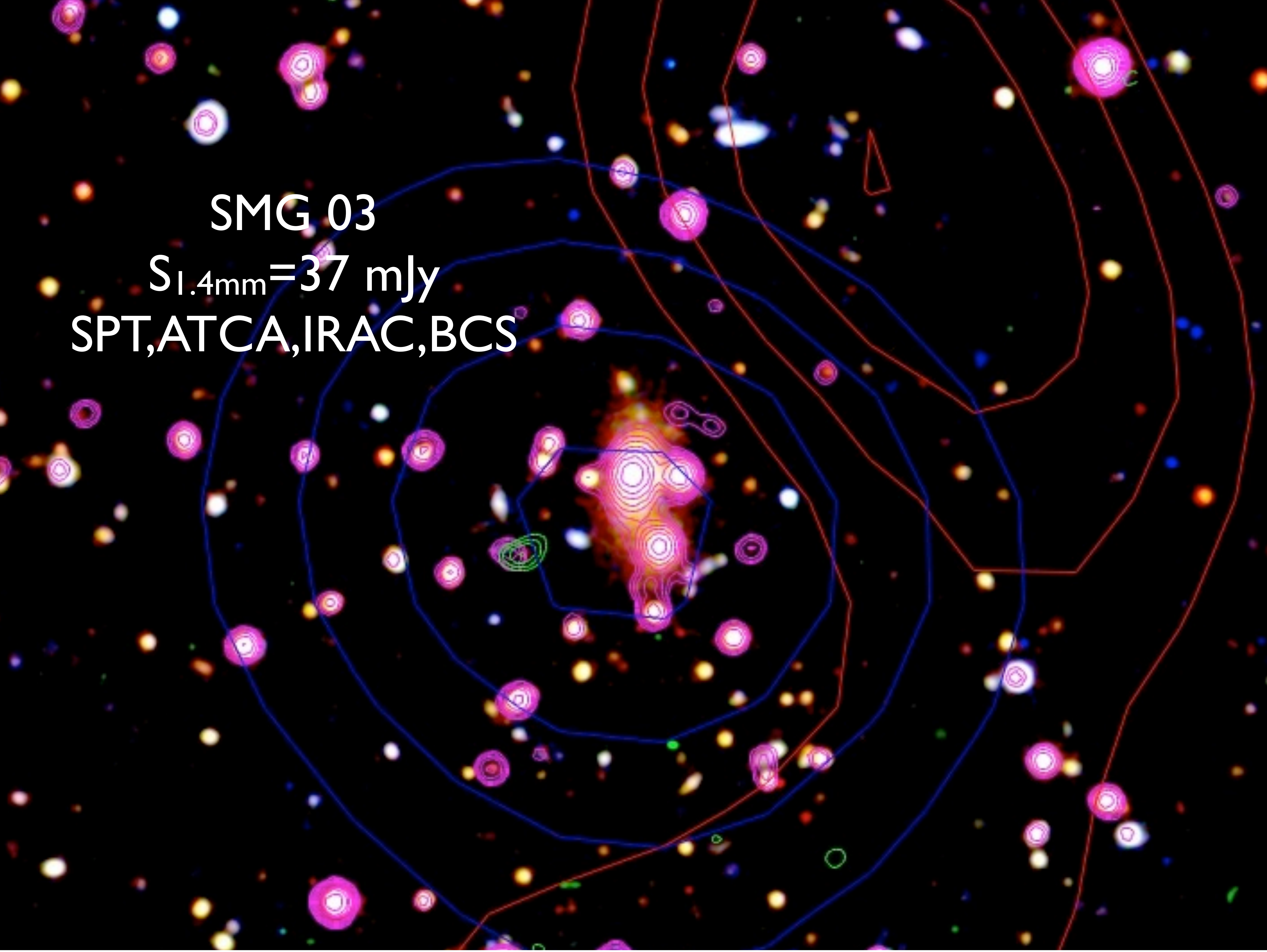
20"x20" thumbnails

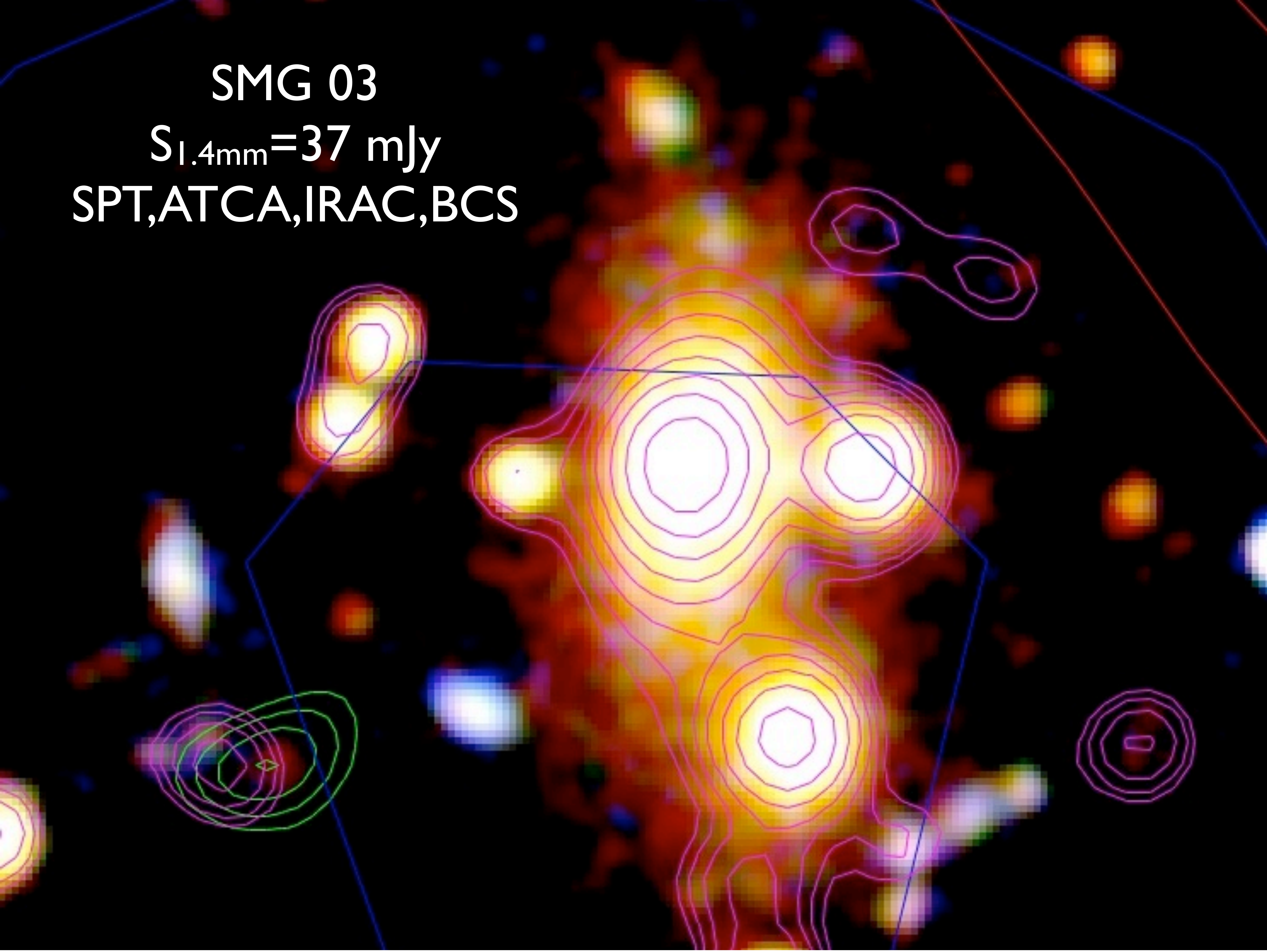

SMG 03
S1.4mm=37 mJy
BCS

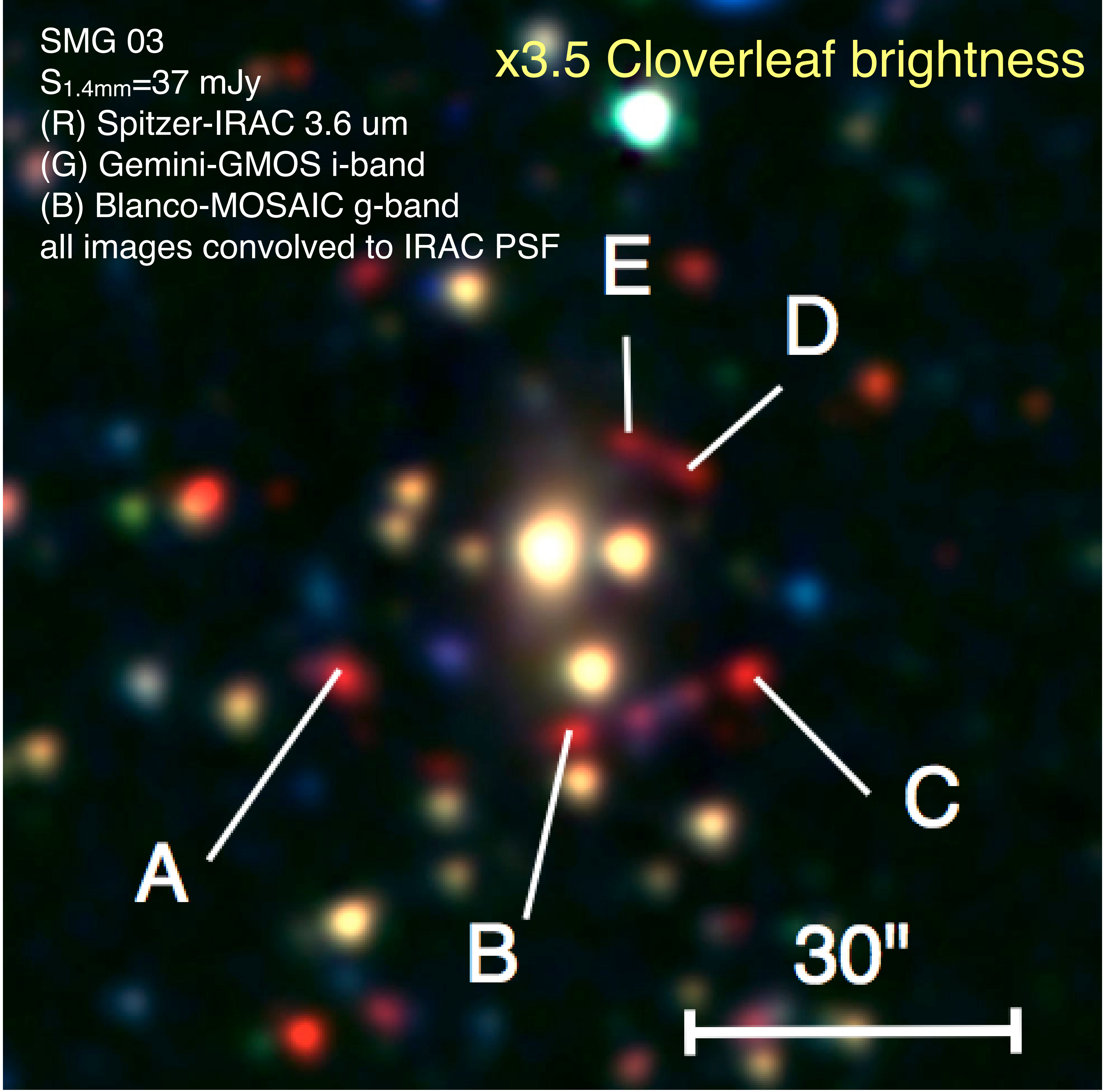

SMG 03
S1.4mm=37 mJy
SPT,BCS


SMG 03
$S_{1.4mm}$=37 mJy
SPT,BCS


SMG 03
$S_{1.4mm}$=37 mJy
SPT,ATCA,BCS


SMG 03
$S_{1.4mm}$=37 mJy
SPT,ATCA,IRAC,BCS

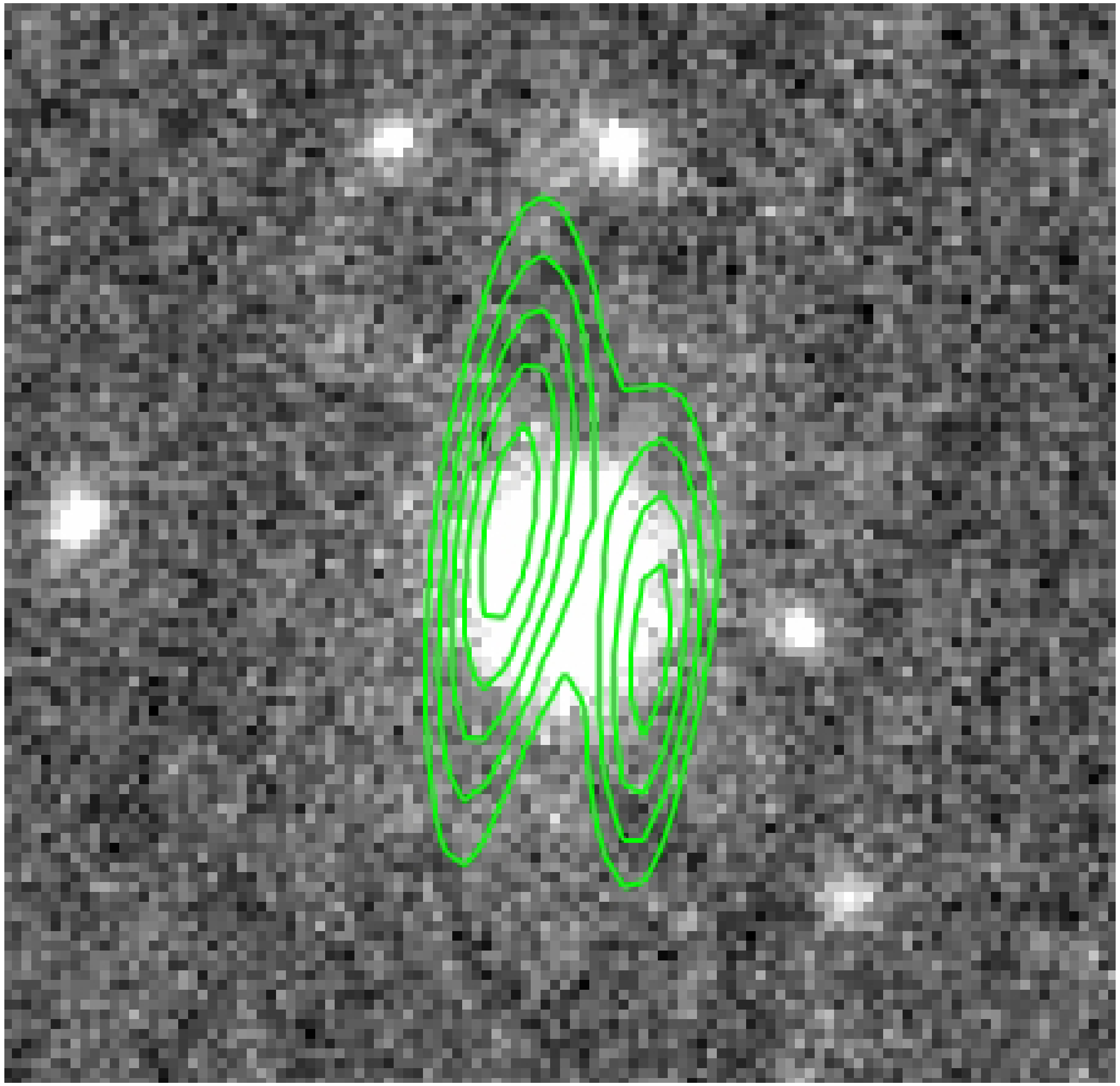

SMG 03
$S_{1.4mm}$=37 mJy
SPT,ATCA,IRAC,BCS


SMG 03
S1.4mm=37 mJy
(R) Spitzer-IRAC 3.6 um
(G) Gemini-GMOS i-band
(B) Blanco-MOSAIC g-band
all images convolved to IRAC PSF
x3.5 Cloverleaf brightness
E
D
A
B
C
30"

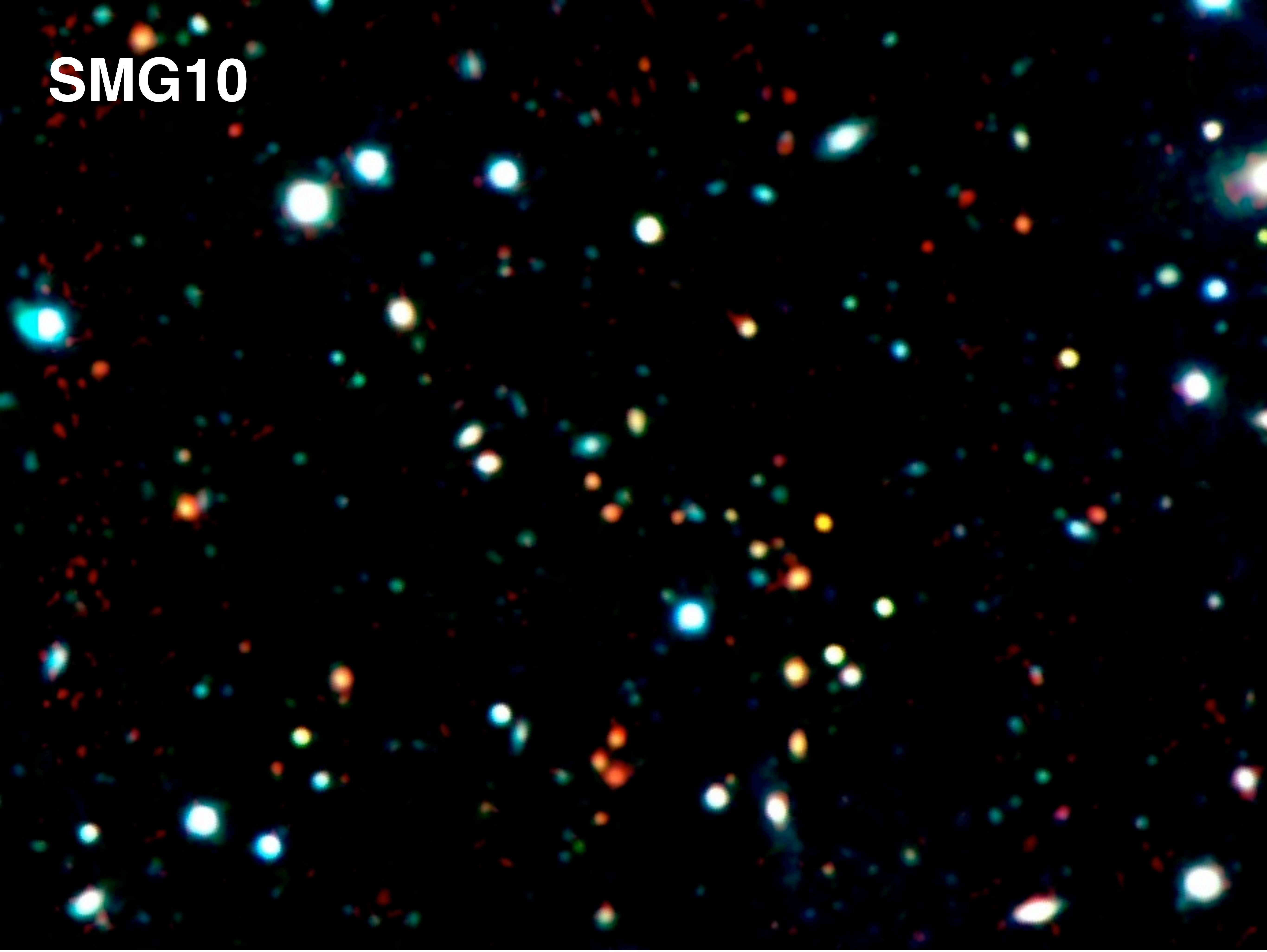
x3 Cloverleaf brightness

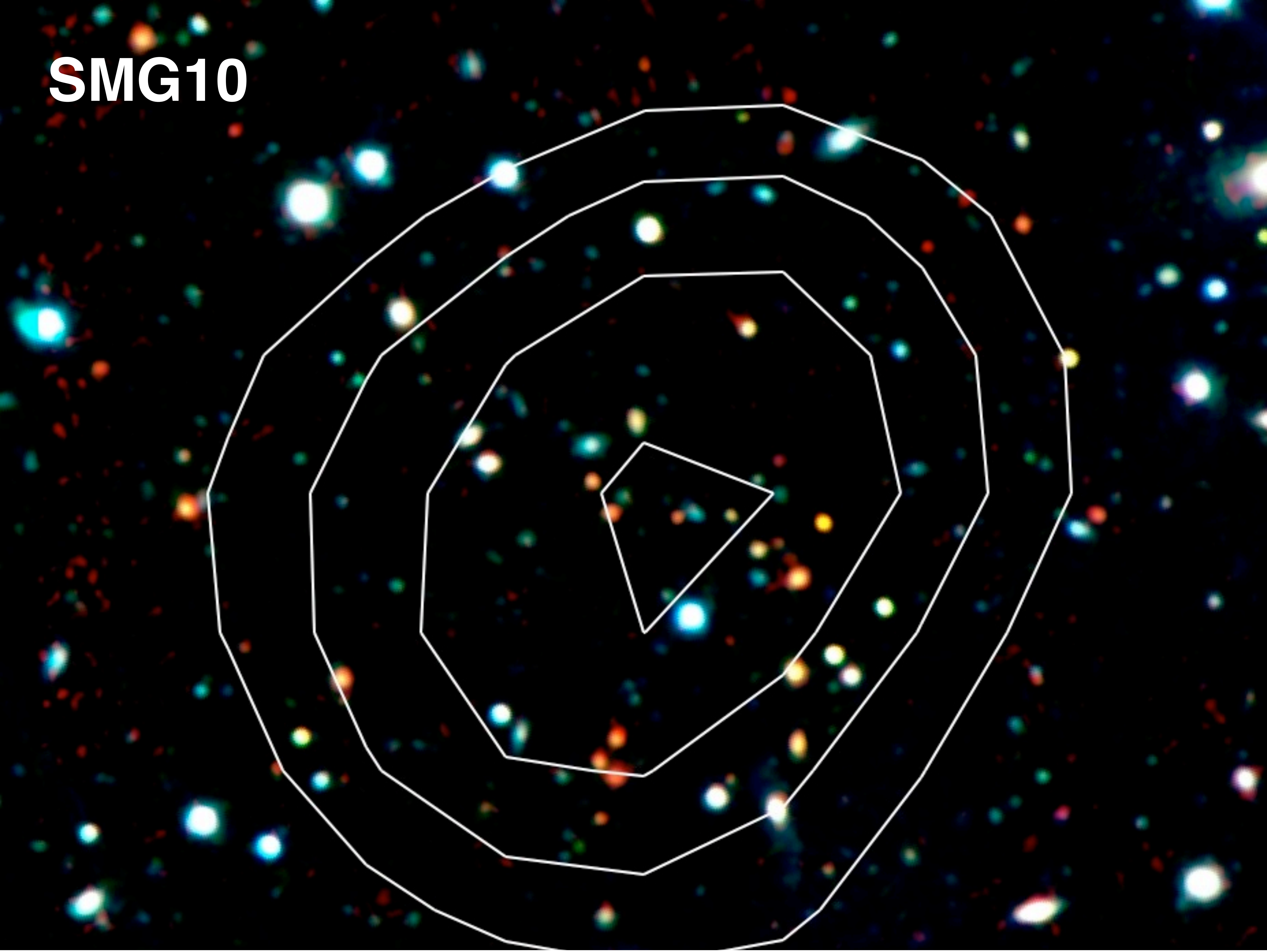
SMG04

grey scale = VLT-ISAAC 2.2 um
contours = SMA 890 um
lens at z=0.5
SMG at z=3.4
lensing amplification = 2x20

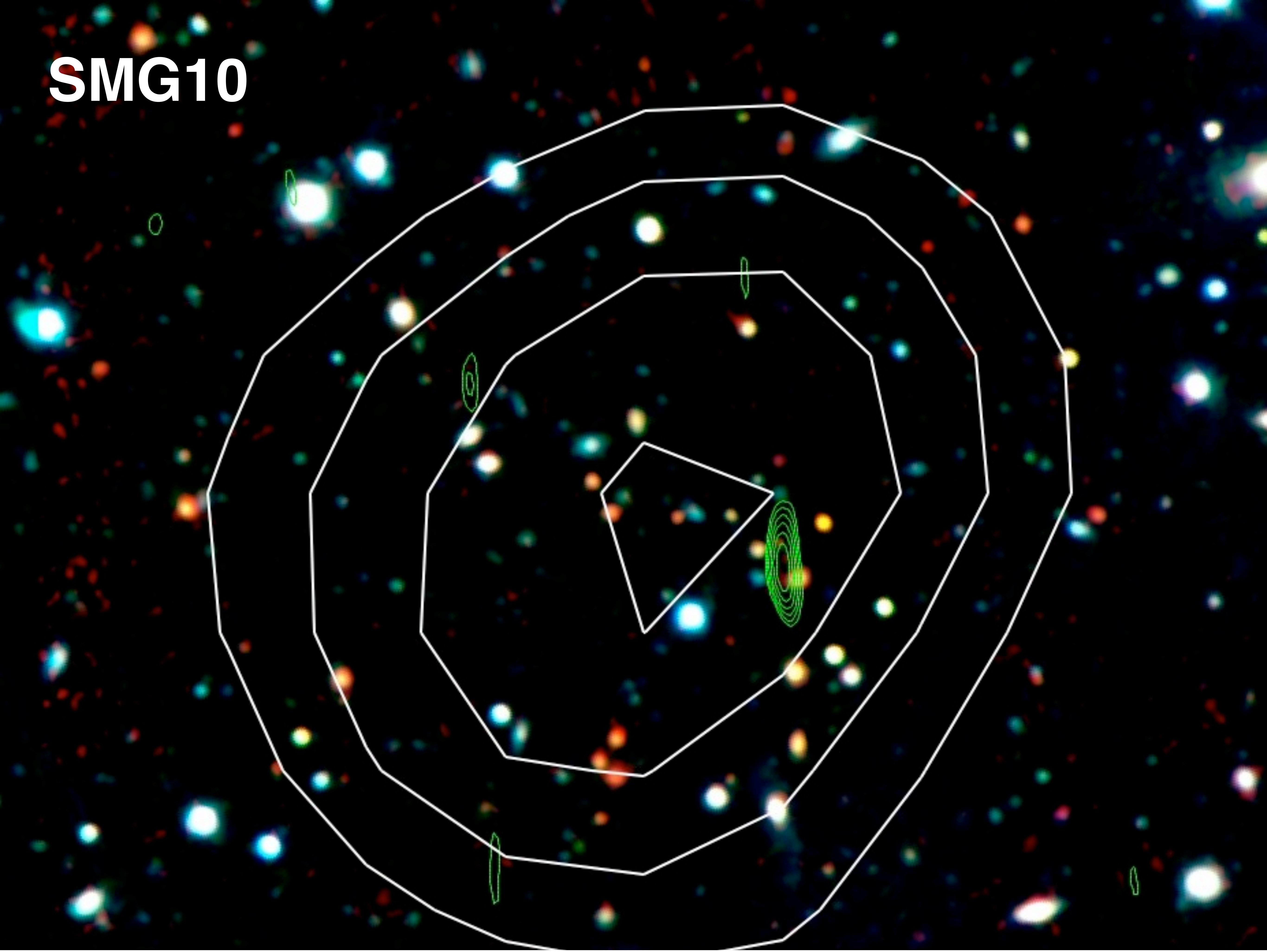


SMG10

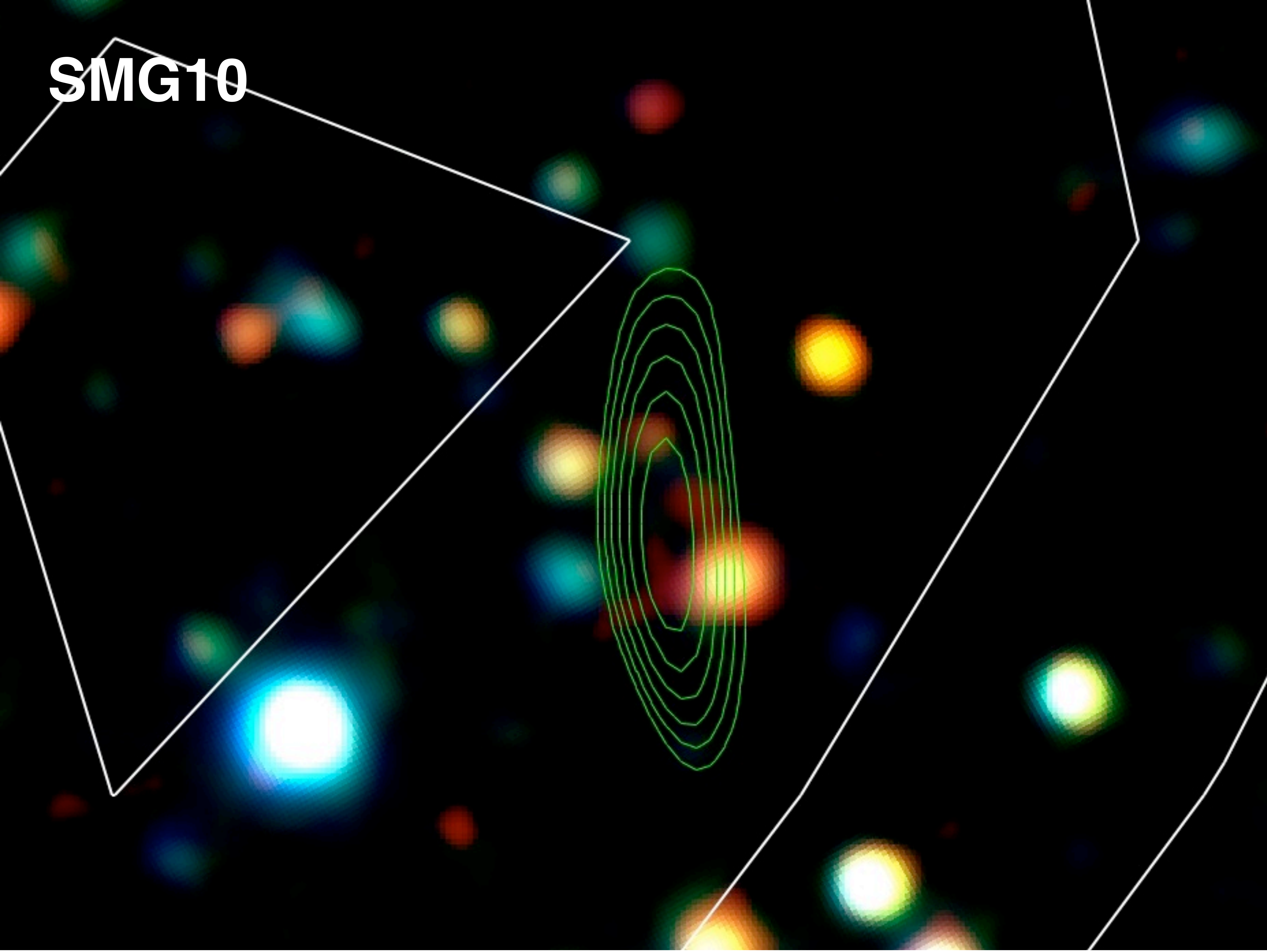


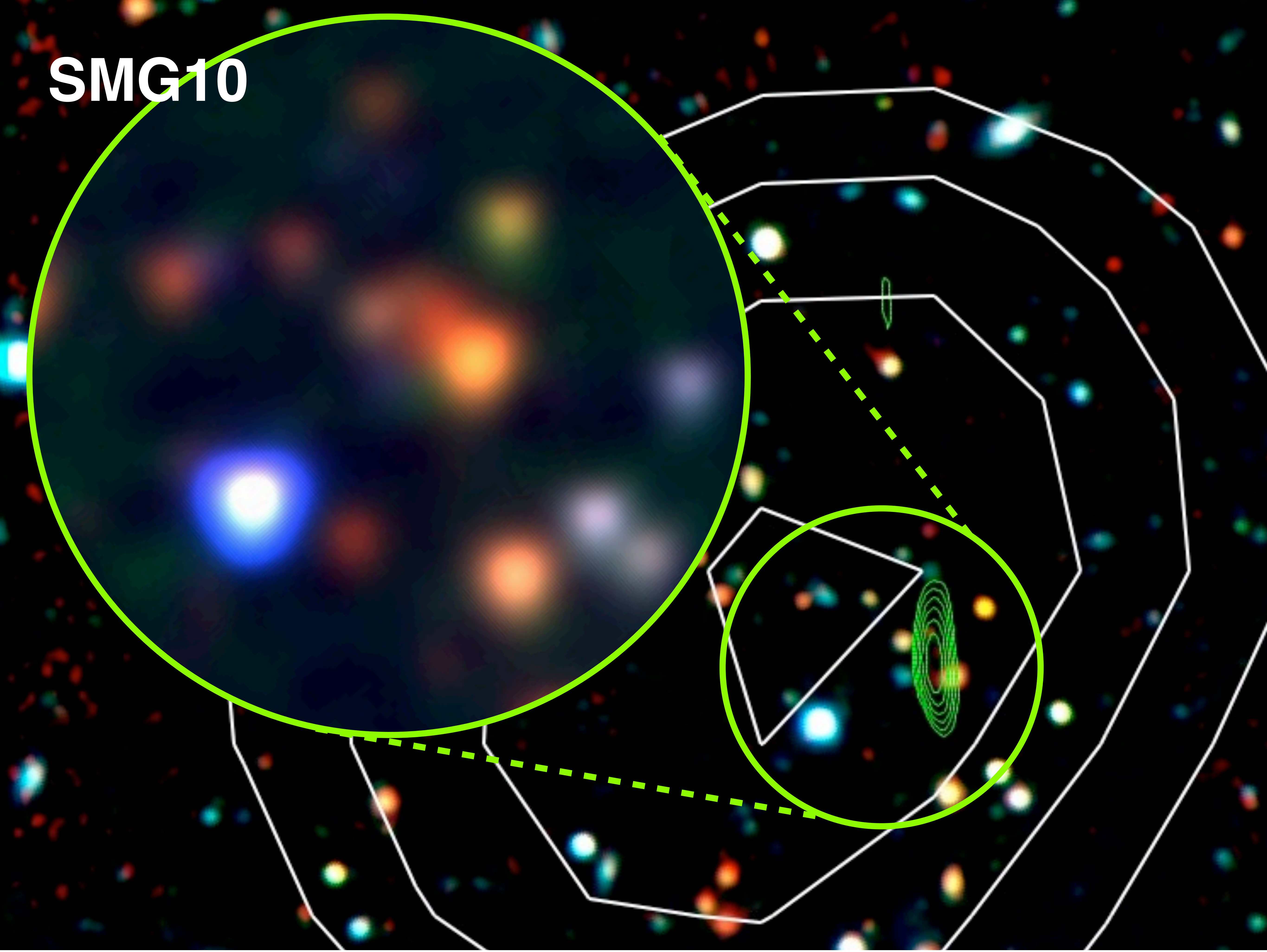

SMG10

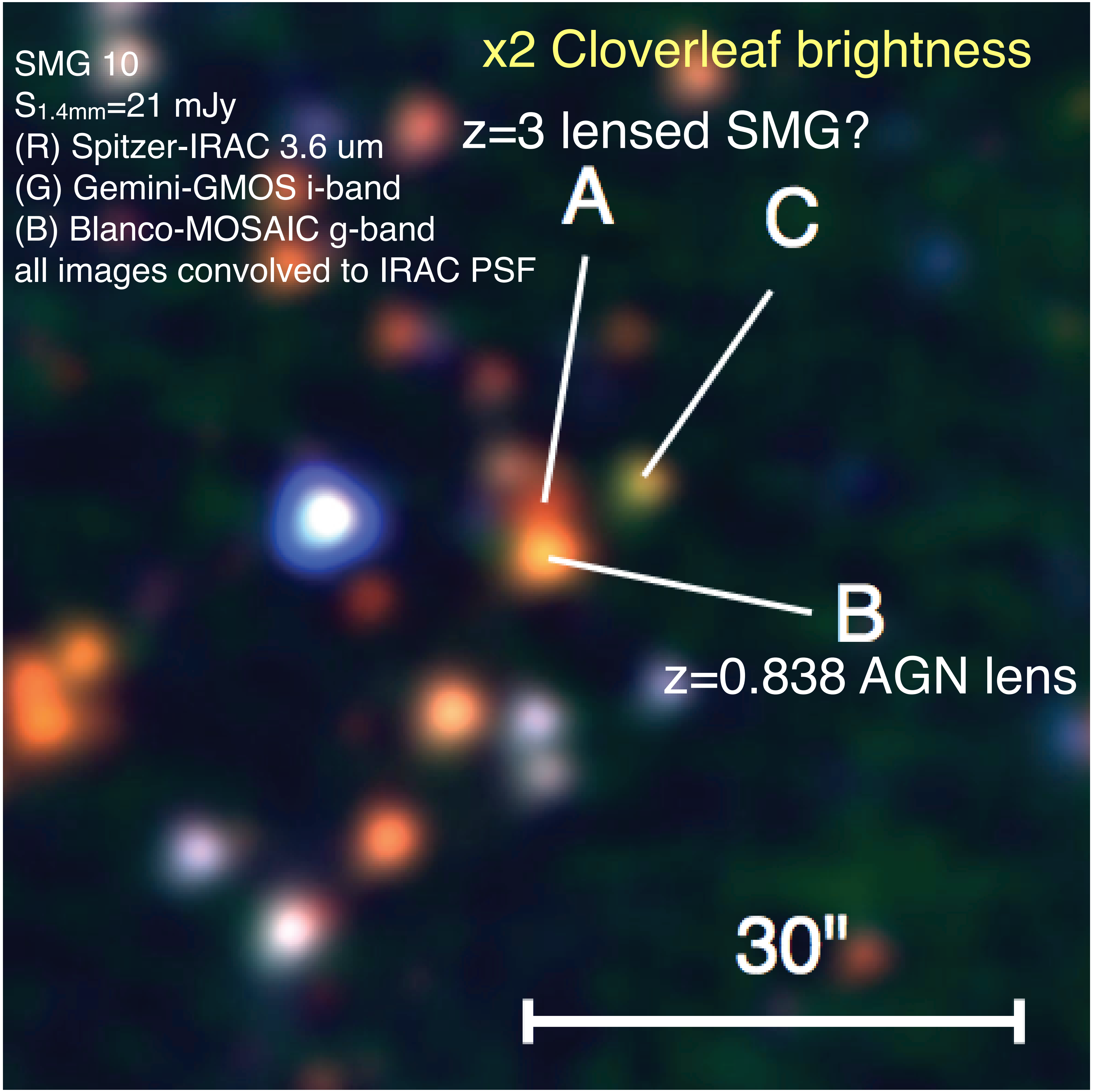
SMG10

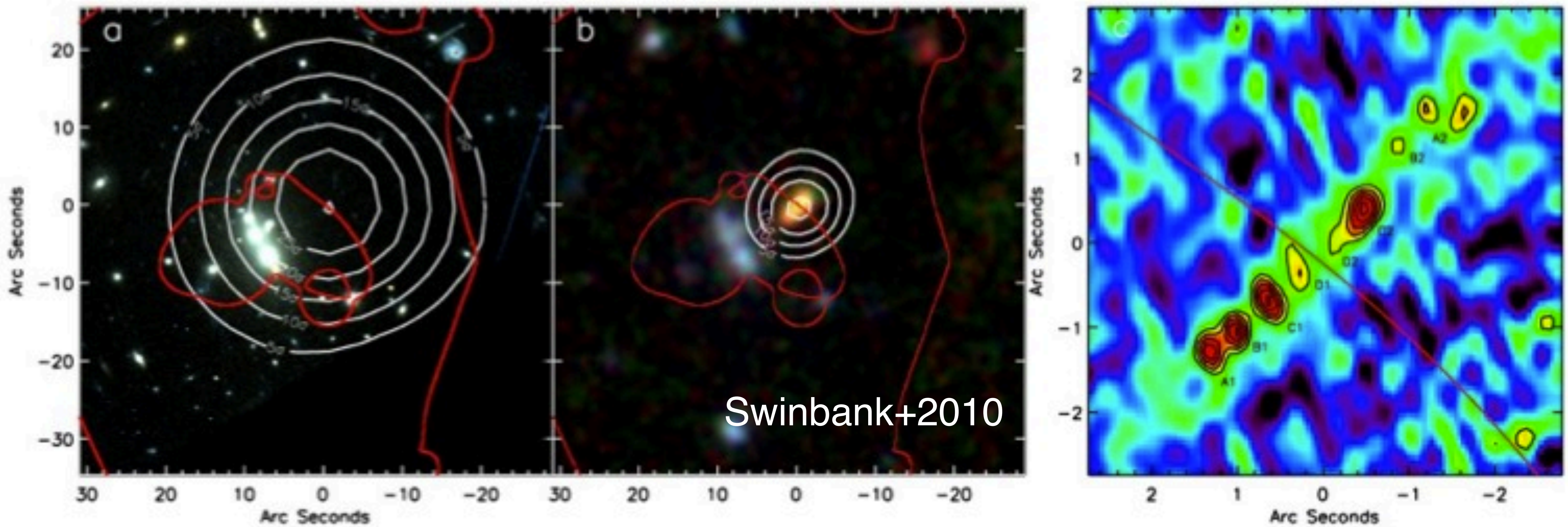


SMG10




SMG10

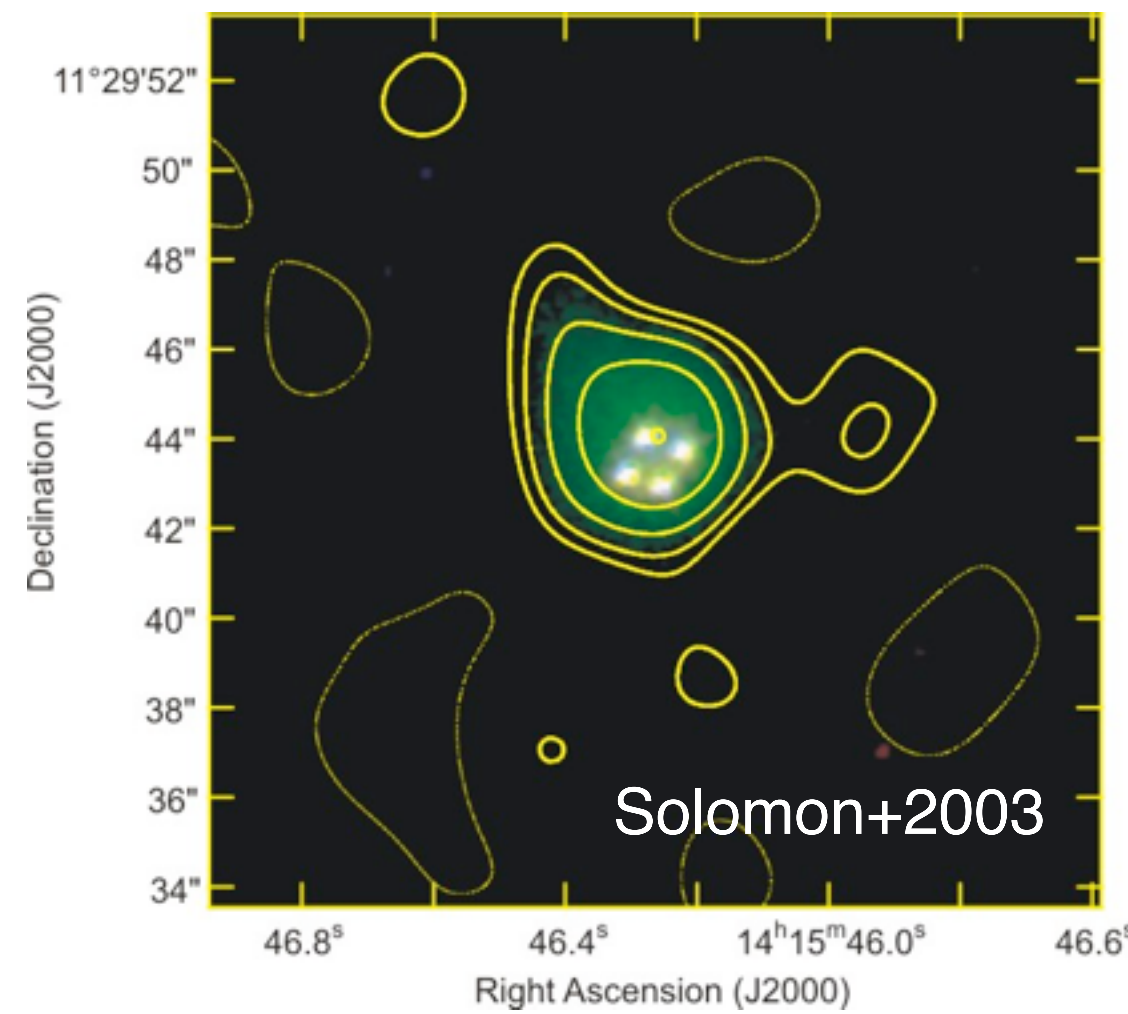

SMG 10
S1.4mm=21 mJy
(R) Spitzer-IRAC 3.6 um
(G) Gemini-GMOS i-band
(B) Blanco-MOSAIC g-band
all images convolved to IRAC PSF
x2 Cloverleaf brightness
z=3 lensed SMG?
A
C
B
z=0.838 AGN lens
30"



A similar source was recently discovered recently by LABOCA
Swinbank+2010, Nature
z=2.3, S_{870um}=106 mJy, $S_{1.4mm}$~20 mJy

Also, historical serendipitous discoveries such as the cloverleaf.

SPT is now systematically uncovering dozens of theses sources. (possibly 100s)



Assorted serendipitous discoveries of lensed dusty galaxies:

name	year	type	z	lens	mag	$S_{1.4mm}$ [mJy]
Cloverleaf H1413+1143	1984	QSO	2.6	galaxy	11	10
IRAS FSC10214+4724	1991	ULIRG	2.3	galaxy	17	20
SMM J02399–0136	1997	SMG	2.8	cluster	3	6
SMM J16359+6612	1997	SMG	2.6	cluster	45	12
APM 08279+5245	1998	QSO	3.9	galaxy	7-100	24
SDSS J1428+5251	2003	QSO	6.4	galaxy	27	4
Bullet	2008	SMG	2.8	cluster	80	10
Eyelash SMM J2135-0102	2010	SMG	2.3	cluster	32	20
SPT-SMG 03	2010	mm	~2.5	cluster	~50	39
SPT-SMG 04	2010	mm	3.4	galaxy	40	30

+38 others, in progress, from 200 deg^2 of 2008 data
+100s in 1200 deg^2 of 2009-2010 data

Where SPT stands

We have 40 dusty sources with no IRAS or radio counterpart from 200 deg^2 of 2008 data

40 are $S_{225GHz} > 15$ mJy
12 are $S_{225GHz} > 20$ mJy
4 are $S_{225GHz} > 30$ mJy

Cloverleaf is S_{225GHz}=10 mJy

All have deep IRAC imaging, but due to the galaxy-galaxy lenses we are confused.
15 have mm interferometry detections
12 have optical imaging with VLT, Gemini, SOAR, and Blanco

We assume these are strongly lensed SMGs, possibly with higher mean redshifts ($\langle z \rangle \sim 3$) than the Chapman 2005 sample ($\langle z \rangle \sim 2.5$).

We have 600 deg^2 from 2009. We already have another 250 deg^2 from 2010.

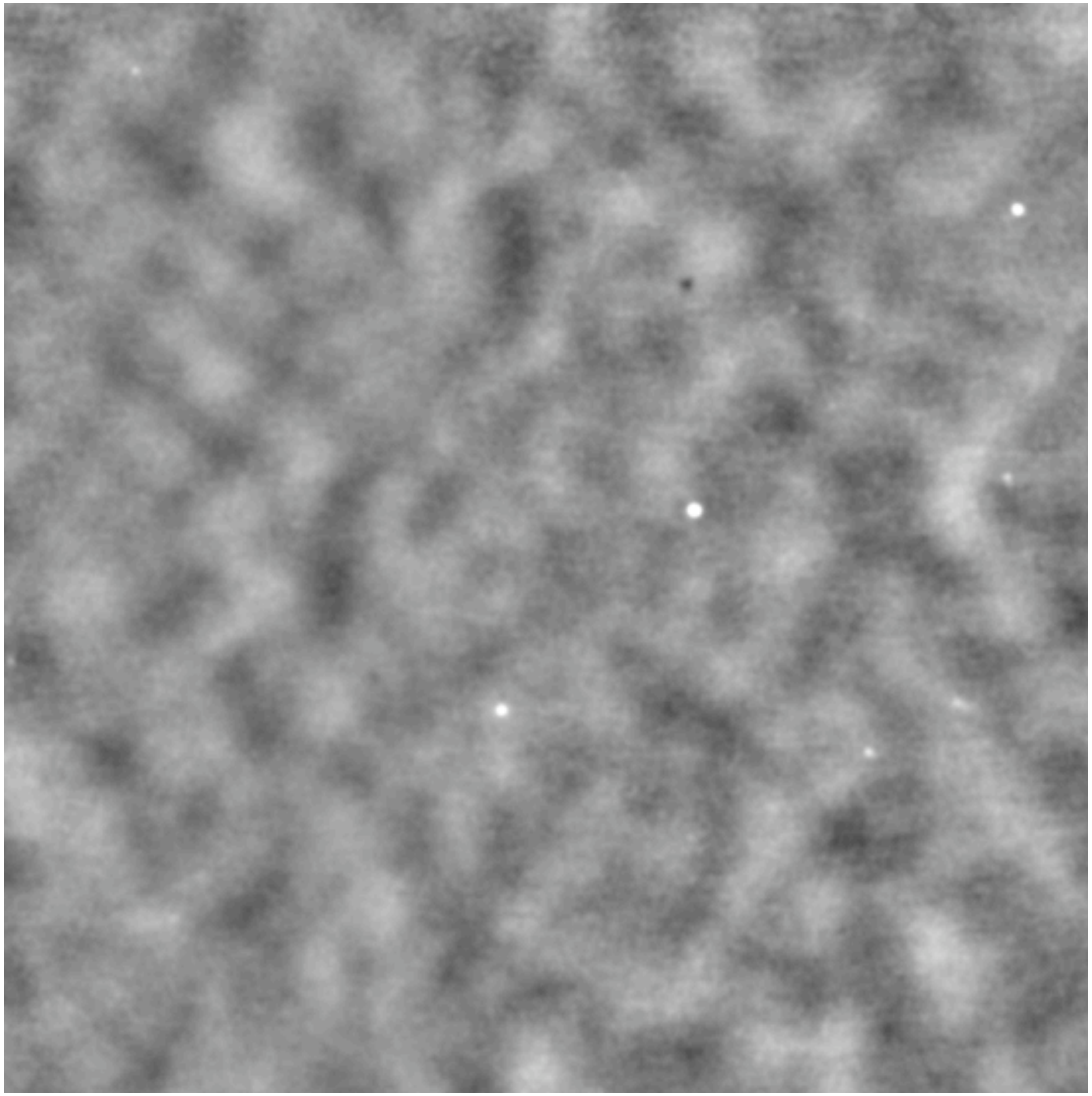
We are *really* hurting for redshift information.

Future Followup Plan

- Move Z-Spec from CSO to APEX to access the SPT sources. (We have the instrument and a slot in the receiver cabin, awaiting time from the ESO and Swedish TACs)

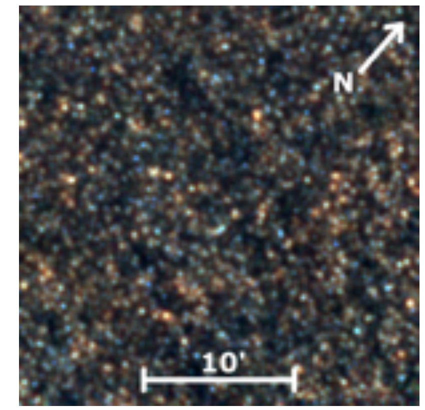
- In parallel, use ALMA ~ 1.3 mm (band 6) to get source position from the mm continuum and also resolve morphology.

- Once a redshift is obtained with Z-Spec, perform detailed line studies with ALMA.



90, 150, 220 GHz
1.6, 1.2, 1.0 arcmin FWHM

SPT

+ 

SPIRE

600, 850, 1200 GHz
36, 24, 18 arcsec FWHM

In 1 hour SPIRE can map 1 deg^2 down to 10 mJy RMS in 3 bands.

It is reasonable to propose for 100 hours to map the entire SPT Deep Region.

Lots of complementary science could be done when linking the best mm mapper with the best submm mapper.

Conclusions

- Mapping speed and multiple bands has enabled SPT to detect new population of rare and bright dust emitting mm sources.
- This new sample of sources is selected at longer wavelengths than previous experiments and are likely high-redshift strongly-lensed SMGs at $z>2$
- SPT has discovered a highly efficient way of locating dusty high redshift strongly lensed systems and by the end of the survey will have 100s of these sources.
- Due to the lensing amplification, these sources will allow detailed studies of high redshift dusty star forming galaxies, at a time when many new observatories are coming on-line (Herschel, ALMA).


FIN