Dusty Galaxies at the Highest Redshifts

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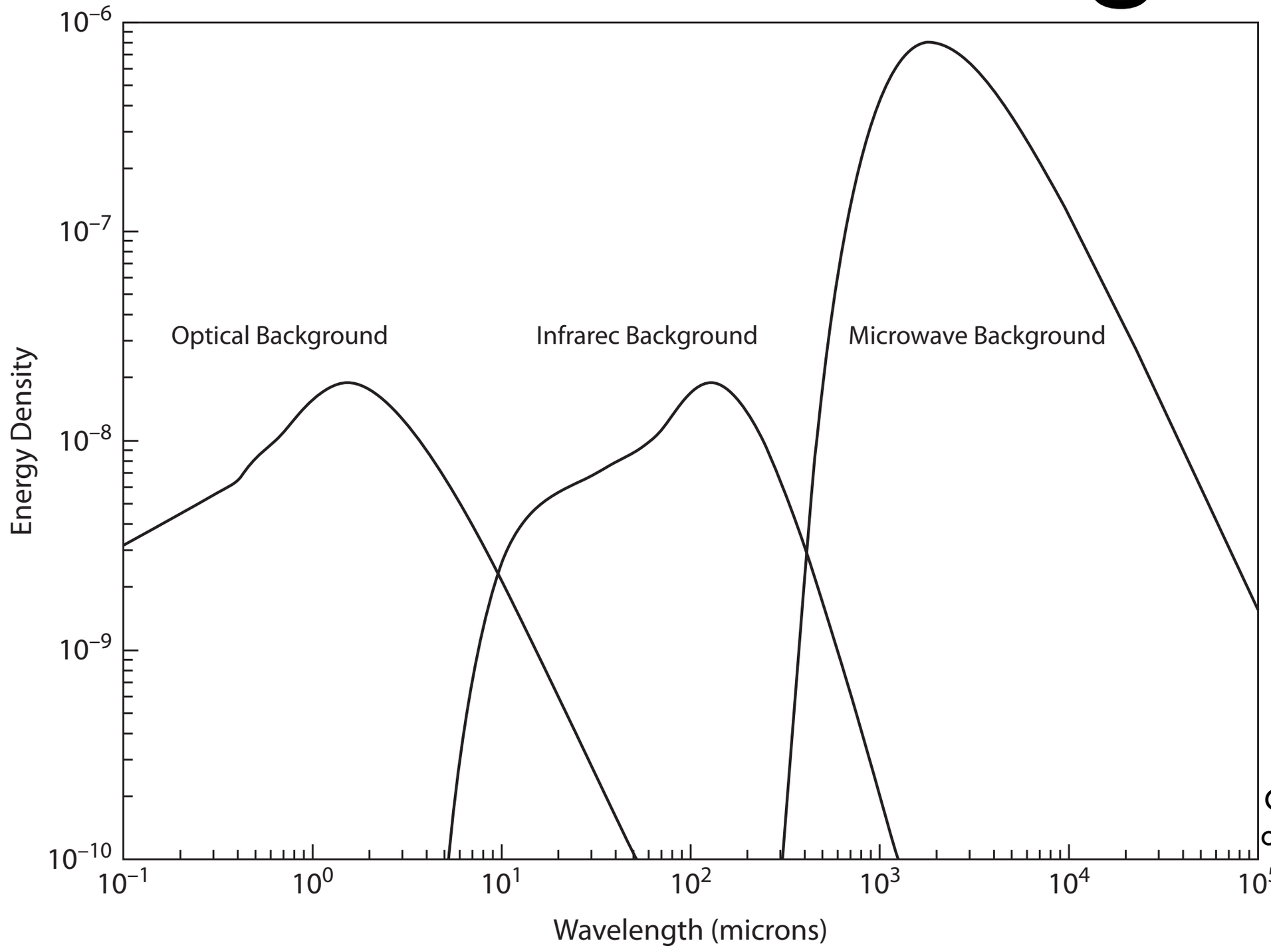
Imperial College London

The HerMES Red Collective
The HerMES & H-ATLAS Consortia

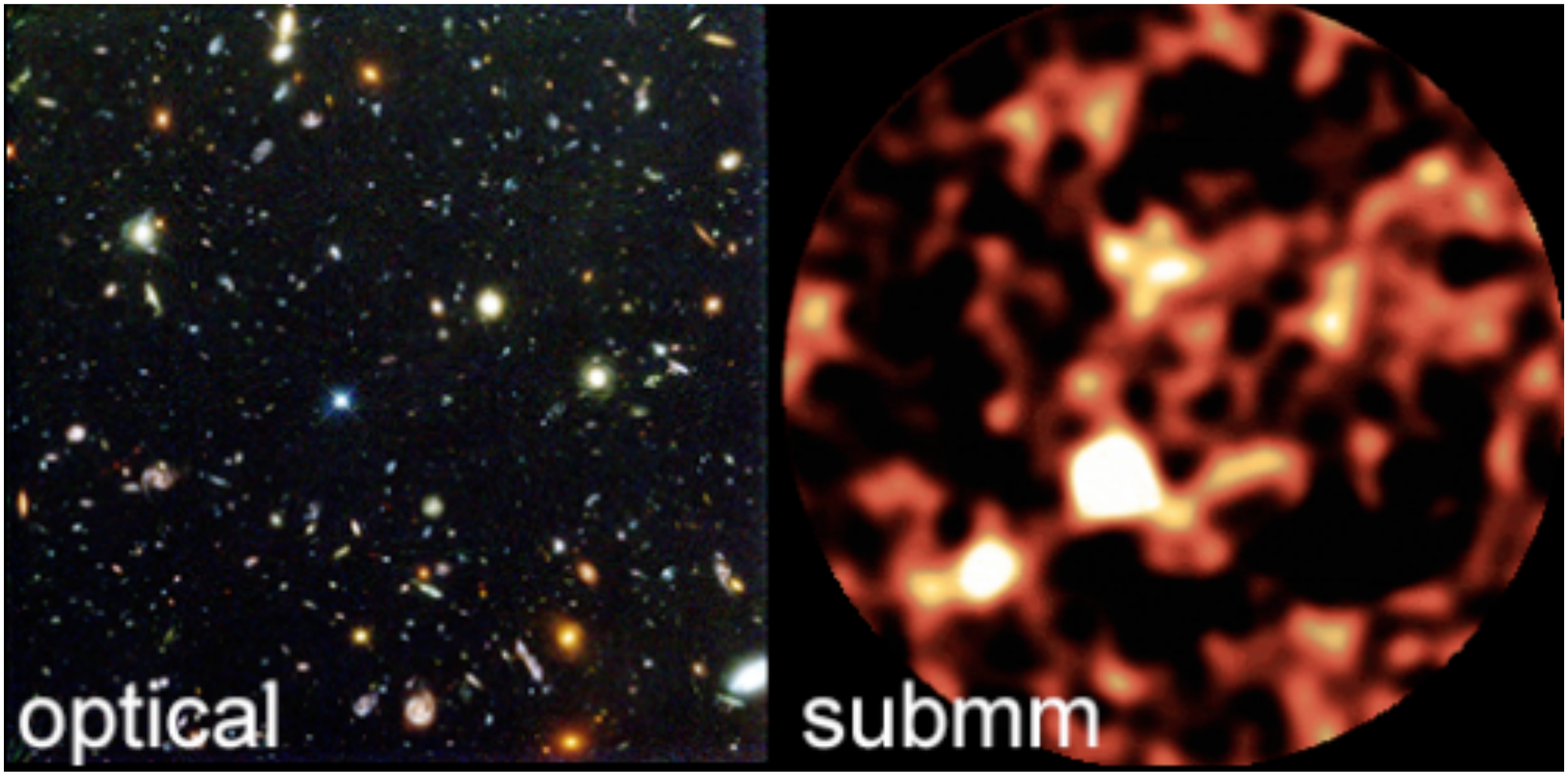
Cosmic Infrared Background



Clements, 2014, from original by Dole, 2006

CIB demonstrates that ~50% of energy generated by stars/AGN is reprocessed to far-IR by dust

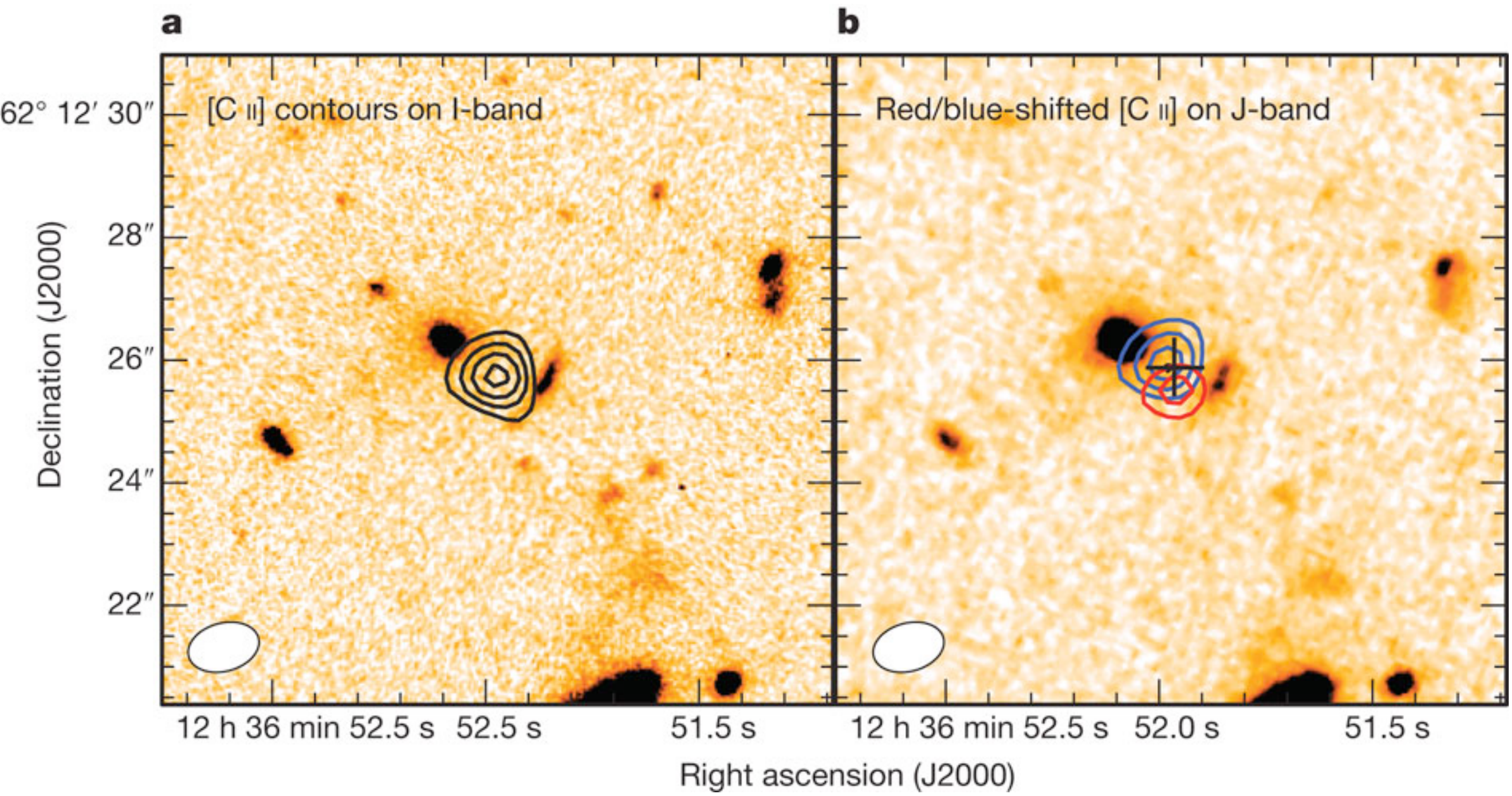
CIB Galaxies: Different



~2000 optically selected galaxies

5 submm selected galaxies

HDF850.1

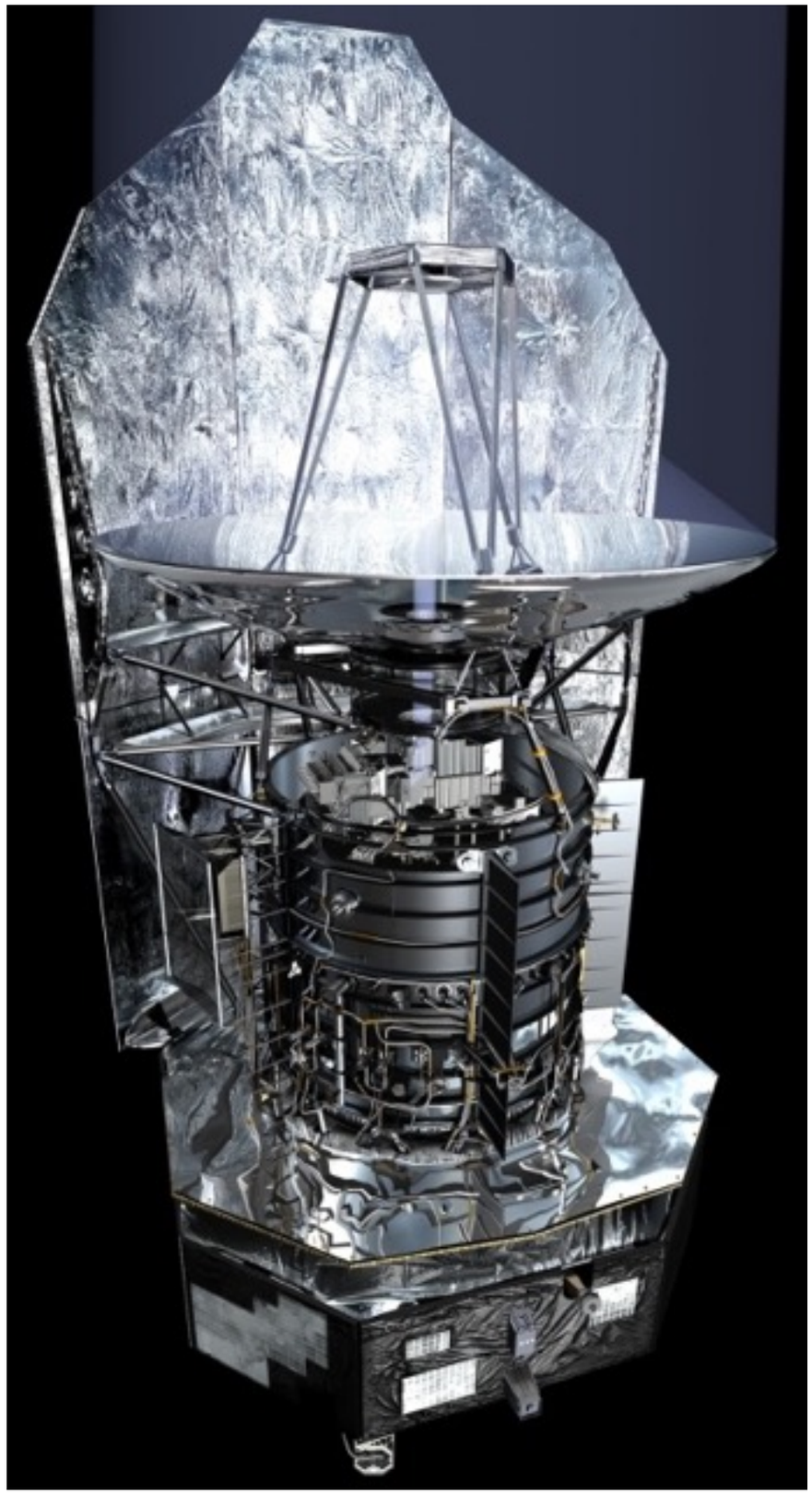


Brightest submm source in HDF undetected in optical/IR. Lies at z=5.18 and has SFR ~ 850 M_{sun}/yr

Walter et al., 2012

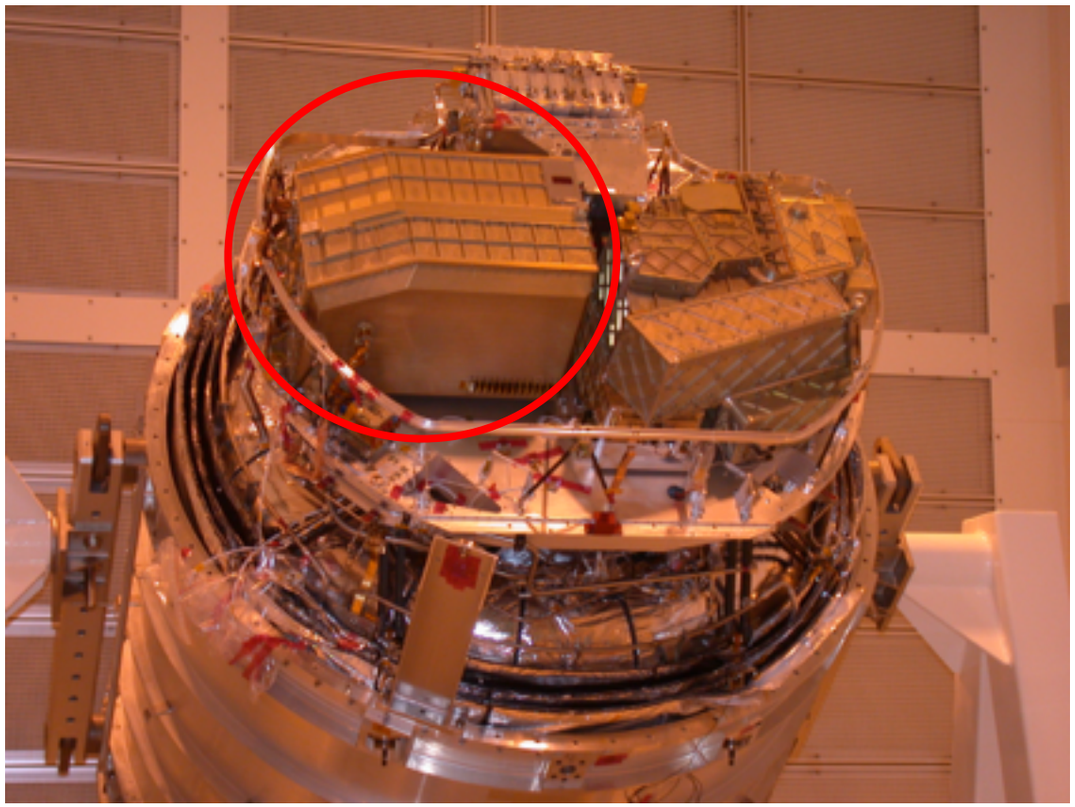
The Herschel Space Telescope

- Launched May 14 2009
- ESA cornerstone mission
- Far-infrared Space Telescope: 60-600μm wavelength
- 3.5m primary: largest mirror ever launched into space
  – Limited by launch vehicles
- 3 cryogenically cooled instruments (one led by UK)
- Largest and most ambitious ESA astronomy mission yet



SPIRE

- Longest wavelength instrument
- Photometer and spectrometer
  - Large area cosmological surveys for dusty distant galaxies powering the CIB
  - Galactic plane survey
  - Search for new protostars
  - Spectral line surveys of stars and galaxies
- UK led instrument (Cardiff University, Rutherford Appleton Lab, U. Leth and others)



HerMES GOODS-N: ~700 galaxies in 8 hours

250 microns

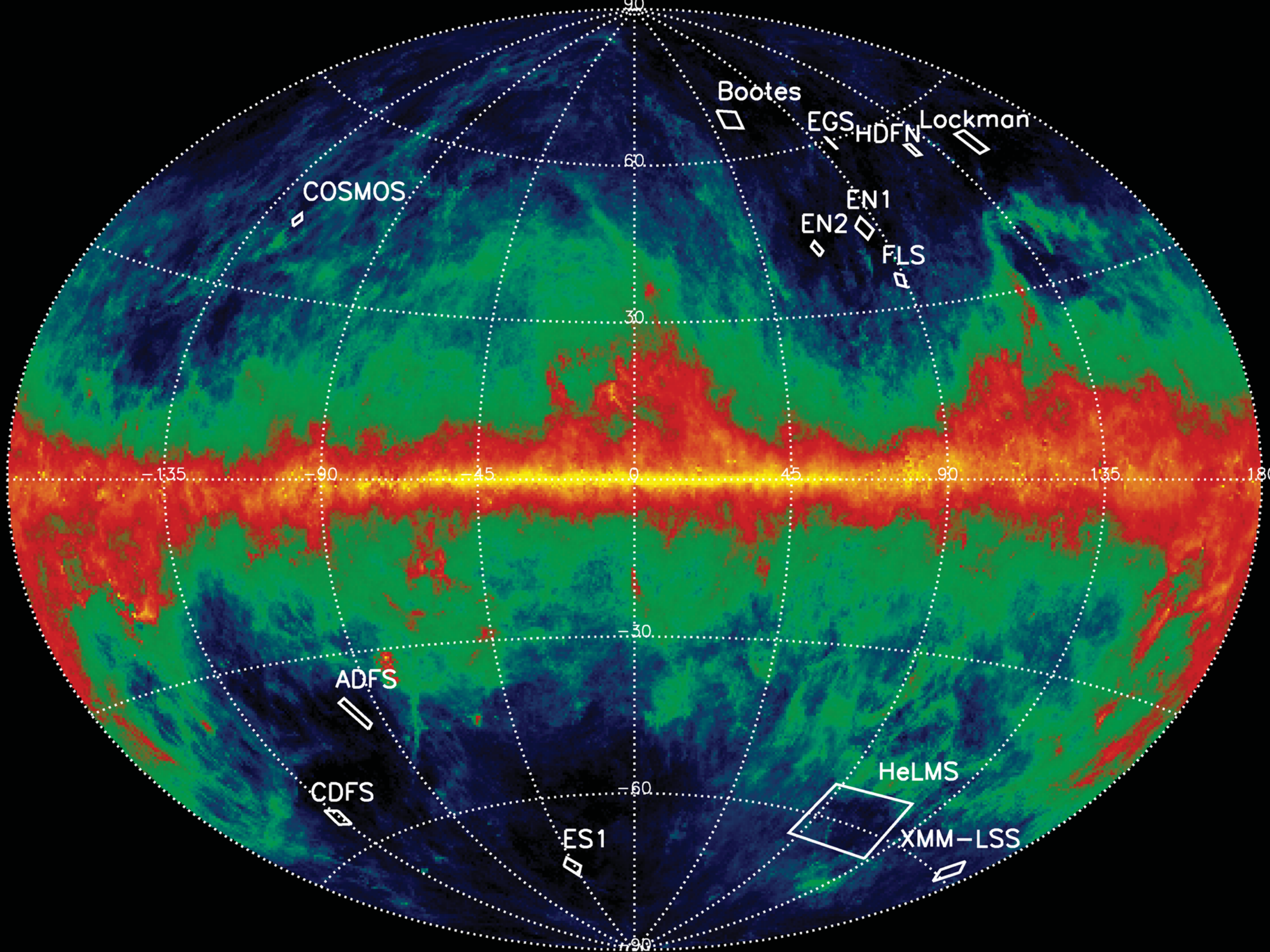
350 microns

500 microns

10 arcmin

Herschel Far-IR Surveys

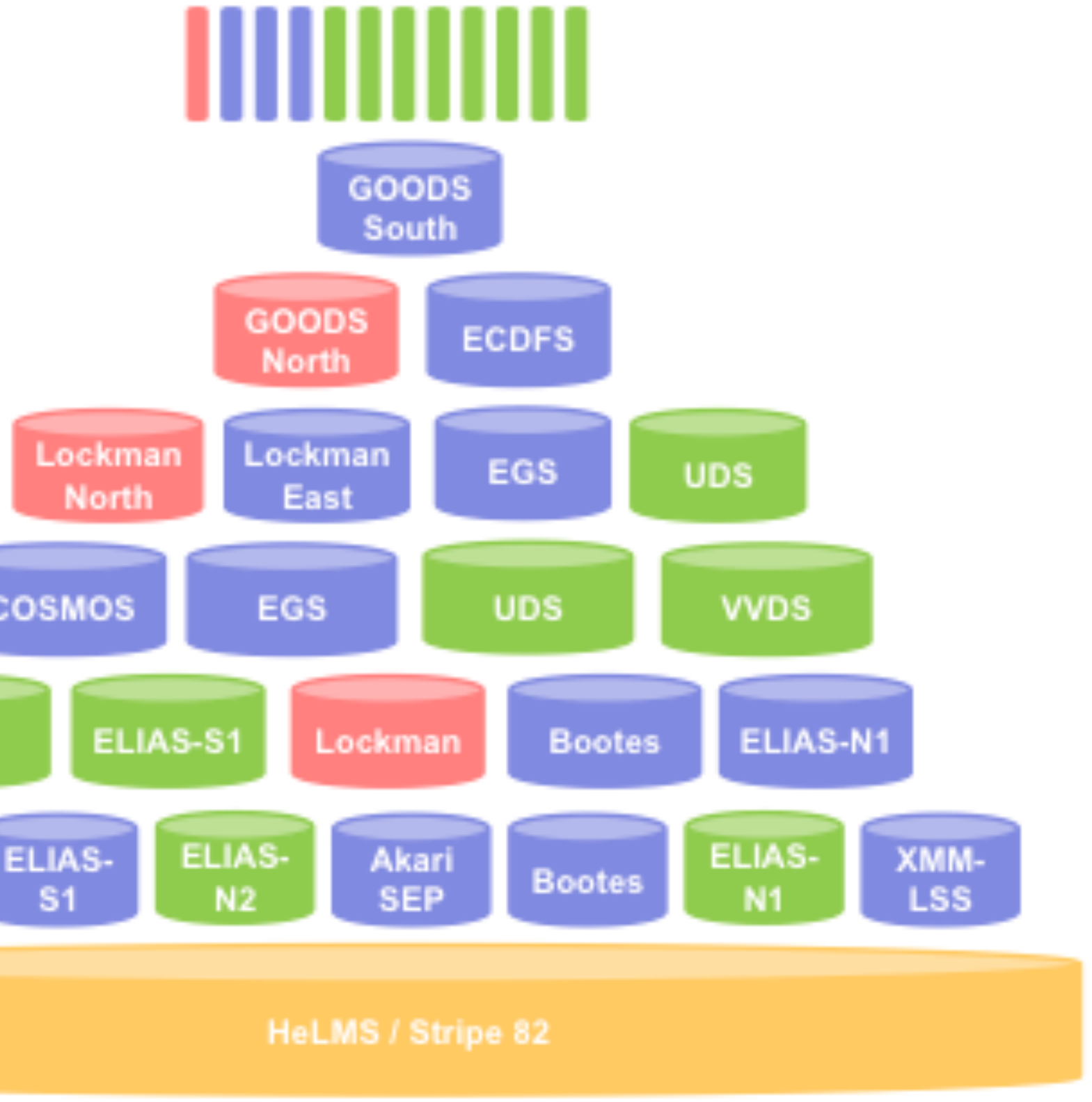
- HerMES wedding cake survey (Oliver+12)
  - Total area about 350 sq. deg. incl. HeLMS extension to Stripe 82
- H-ATLAS survey (Eales+10) about 660 sq. deg. in NGP, SGP & GAMA regions
- Total coverage ~1000 sq. deg. for about 10^6 FIR/ submm selected galaxies
- An improvement on the few 100 from SCUBA etc.


90
60
30
−30
−60
−90
−135
−90
−45
0
45
90
135
Bootes
EGS
HDFN
Lockman
COSMOS
EN1
EN2
FLS
ADFS
CDFS
ES1
HeLMS
XMM−LSS

HerMES: Wedding Cake Survey

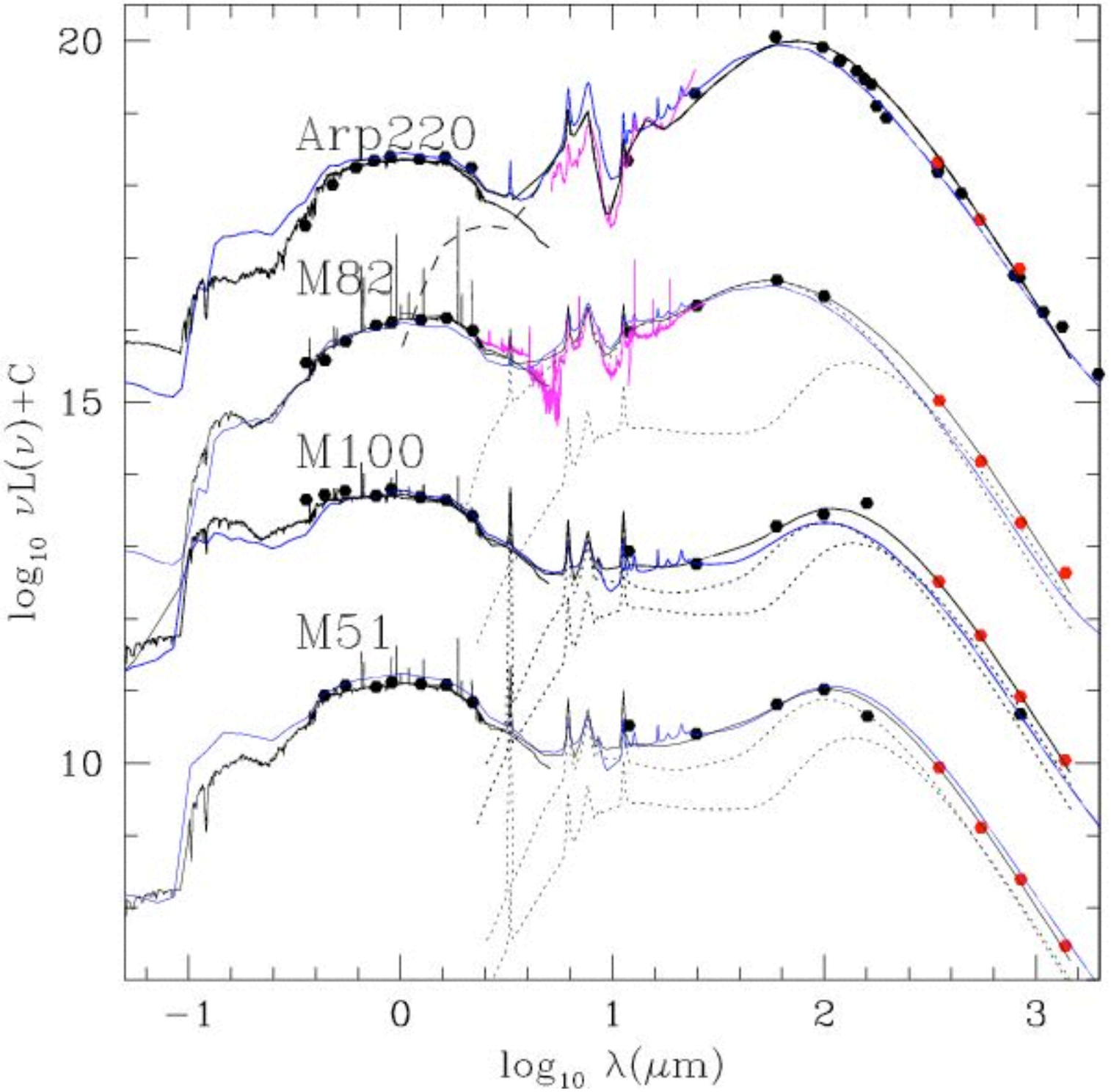
Clusters

L1	**0.11 □°**
L2	**0.36 □°**
L3	**1.25 □°**
L4	**4 □°**
L5	**30 □°**
L6	**40 □°**
L7	**270 □°**

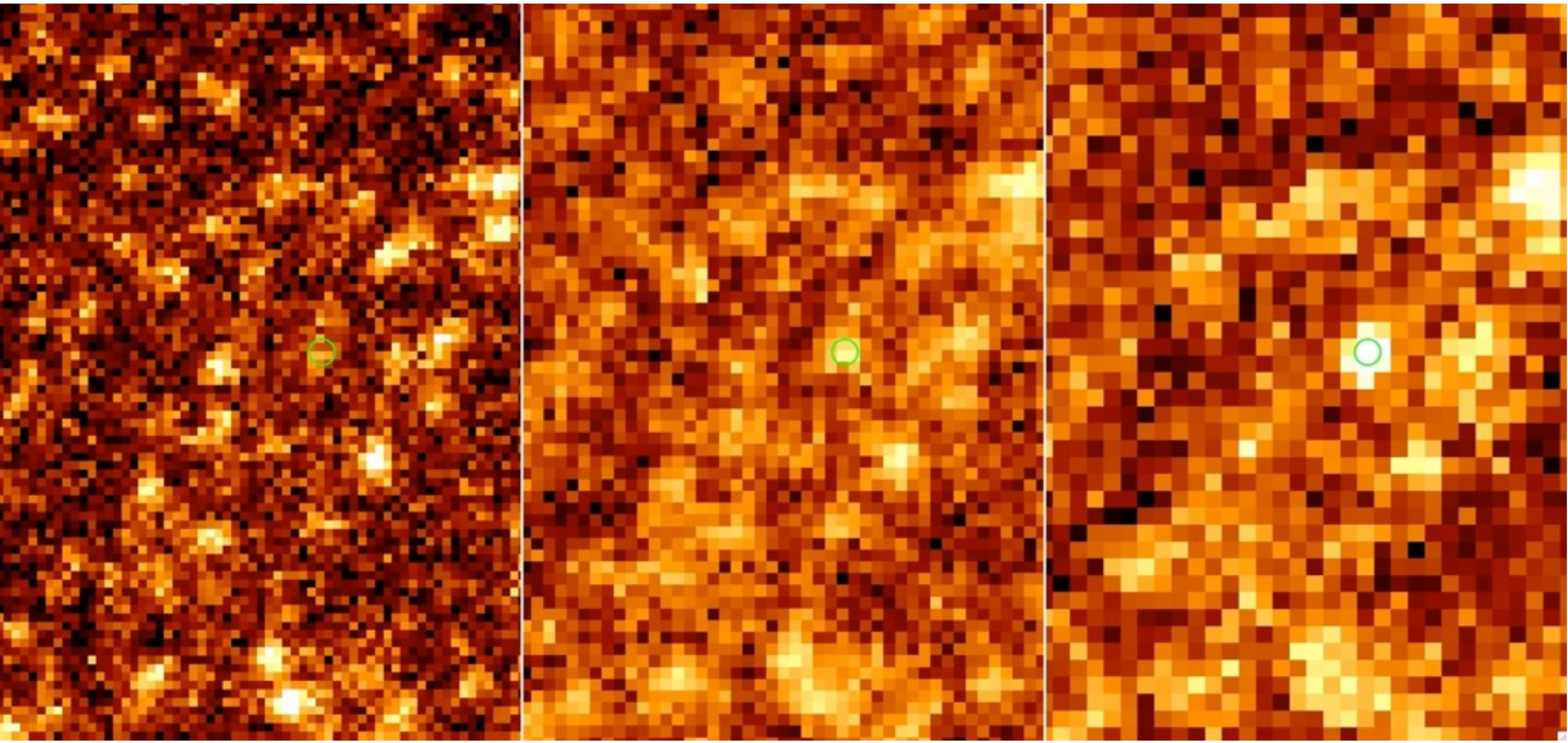


Colour Selection

- The 3 colours observed simultaneously with SPIRE provide indications of redshift
- At z>5 SED peak is at wavelengths longer than 500 microns:



Do Such red Sources Exist?



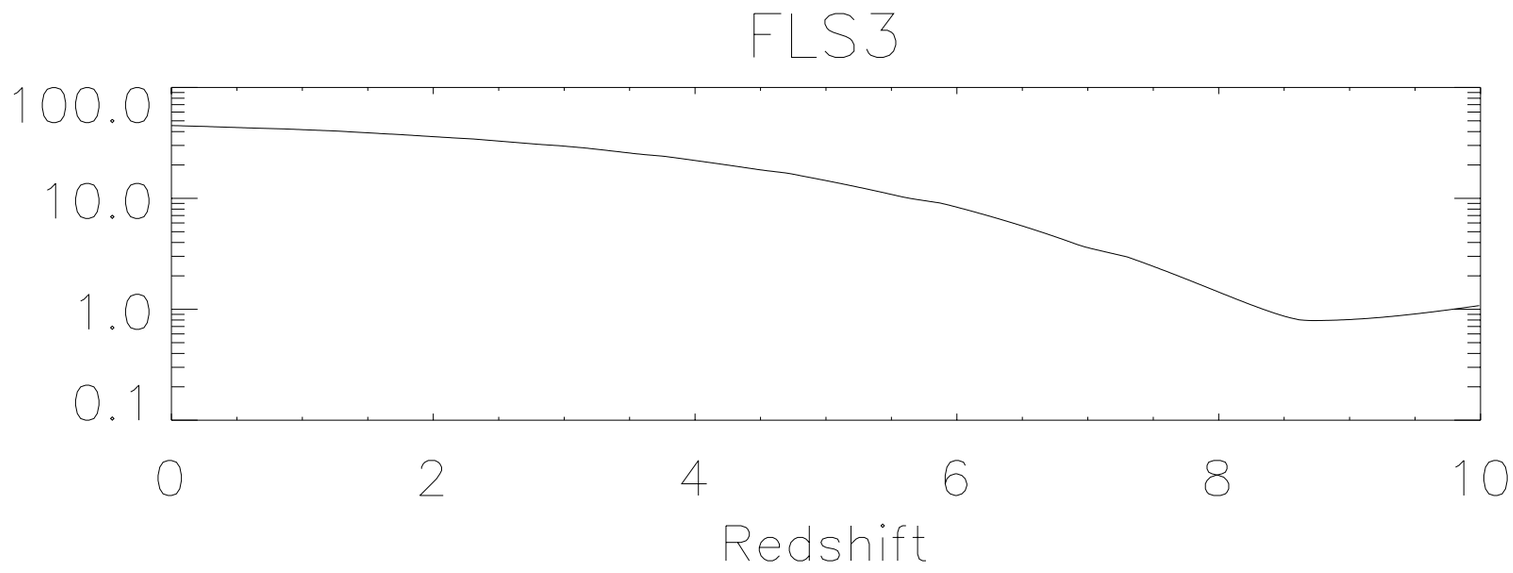
250 microns

350 microns

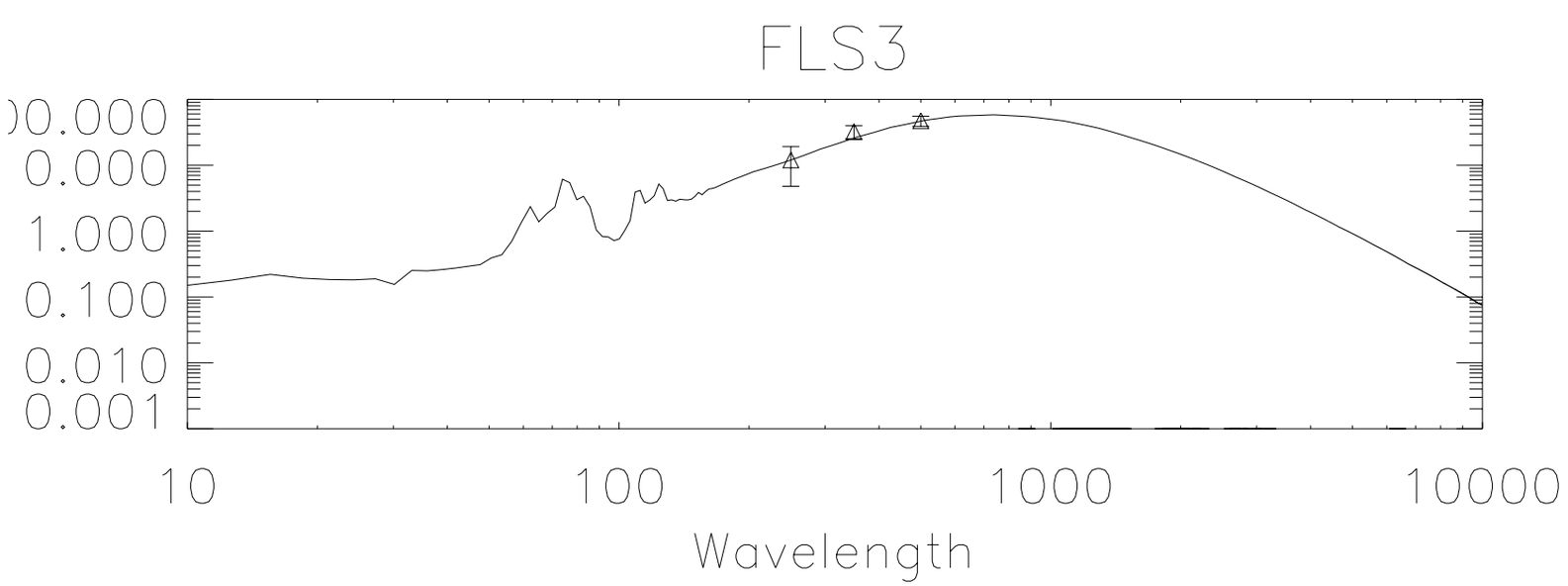
500 microns

Additional Flux: Submm Photo-z

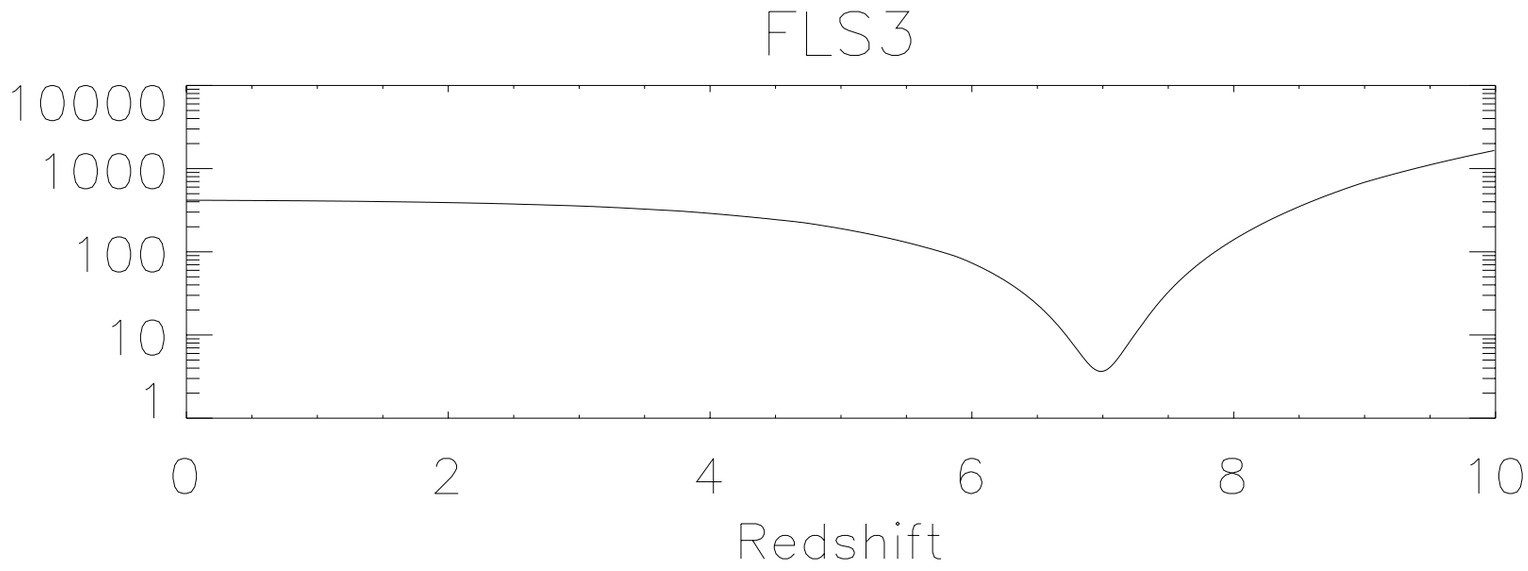
- Can use model far-IR SEDs as templates in a crude photo-z estimator
- With Herschel data alone similar to red selection
- Additional submm data greatly improves photo-z accuracy



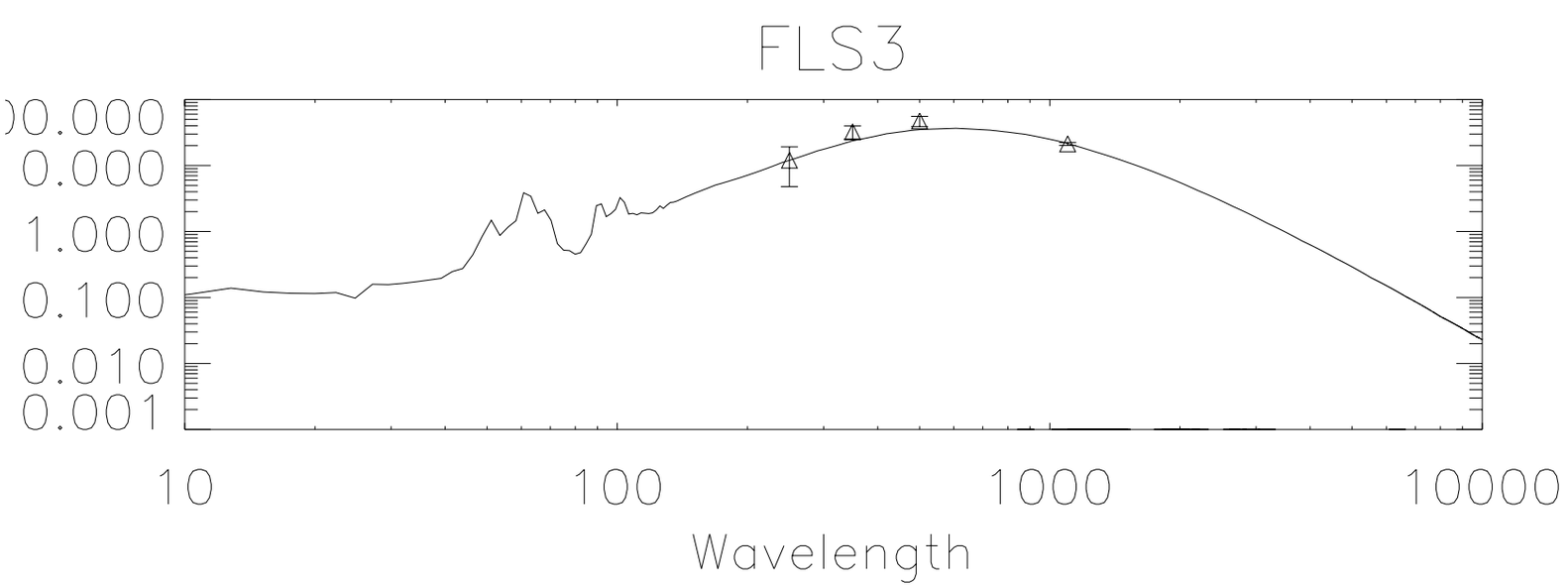
Redshift Likelihood



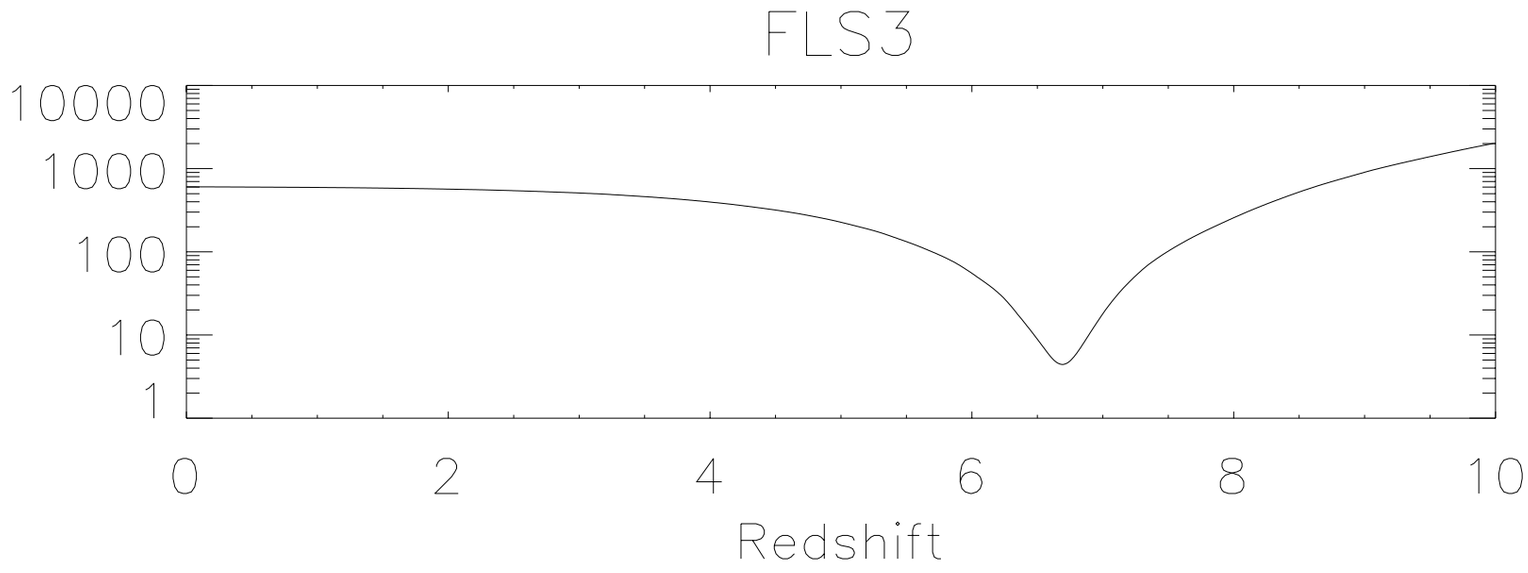
Fitted SED



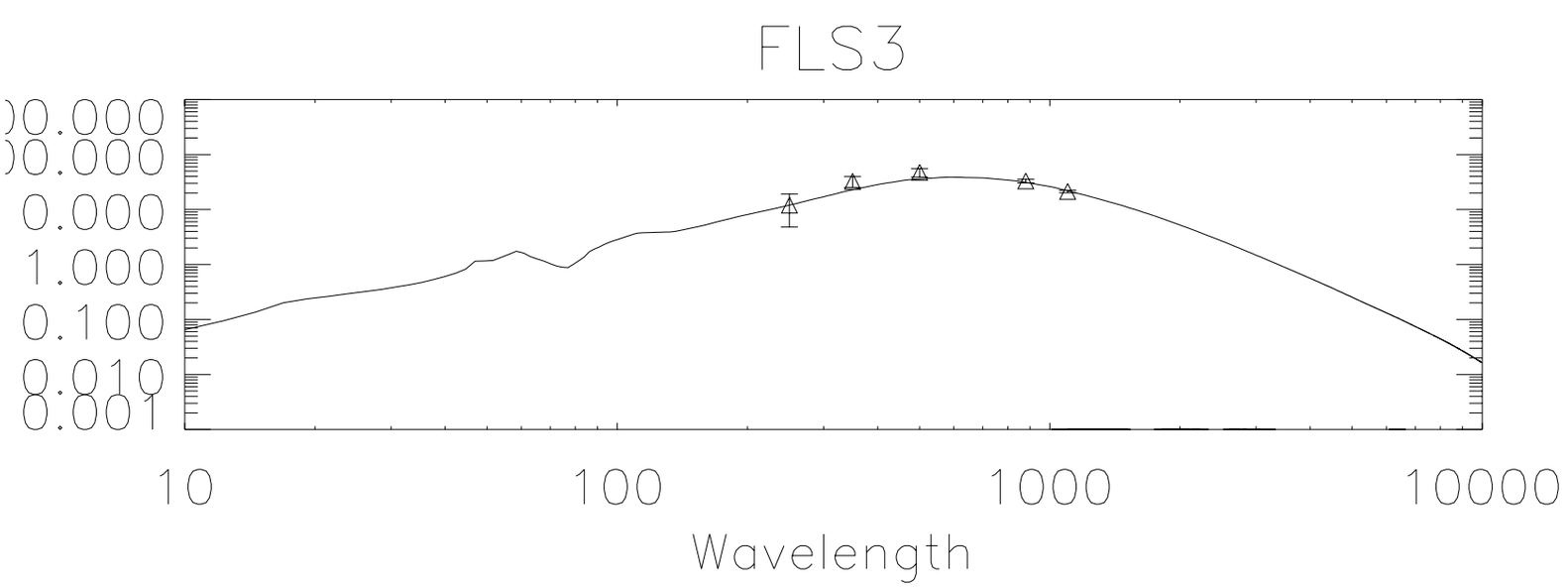
Redshift Likelihood



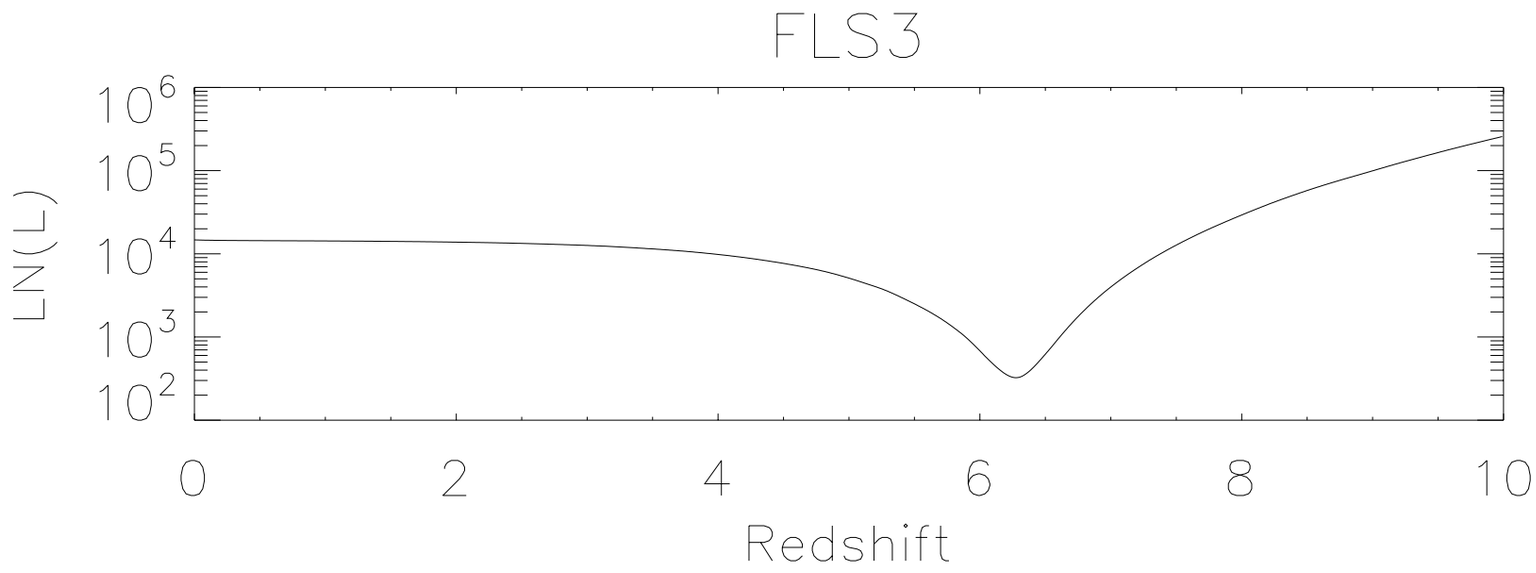
Fitted SED



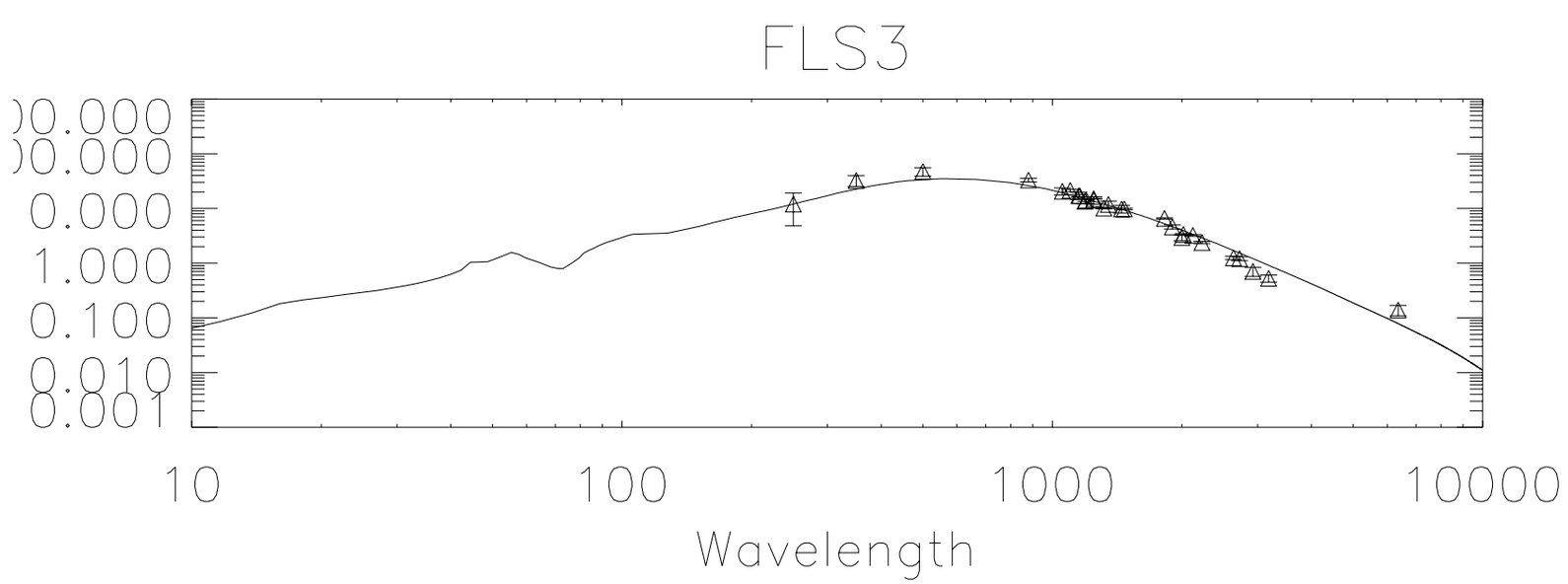
Redshift Likelihood



Fitted SED

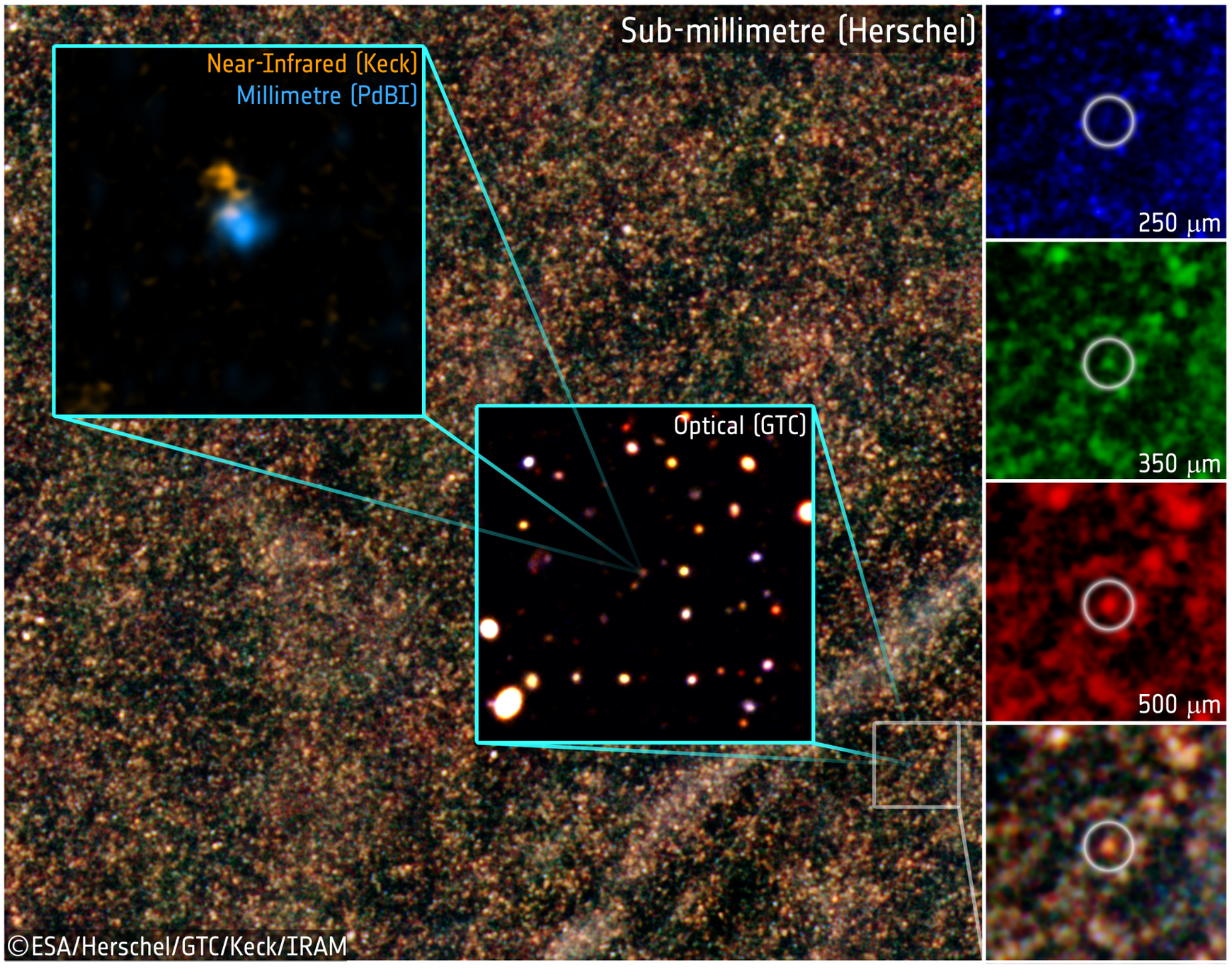


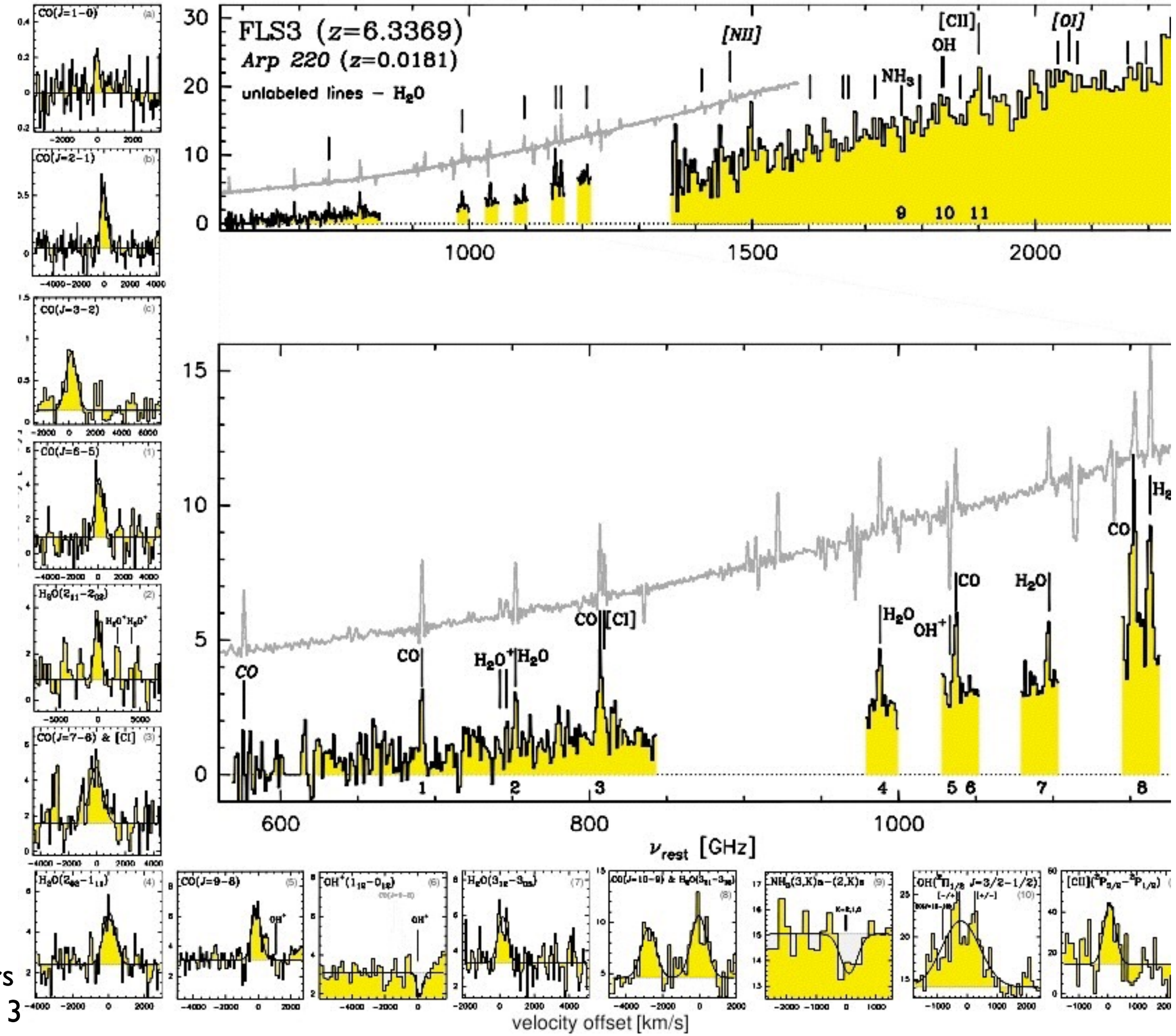
Redshift Likelihood



Fitted SED

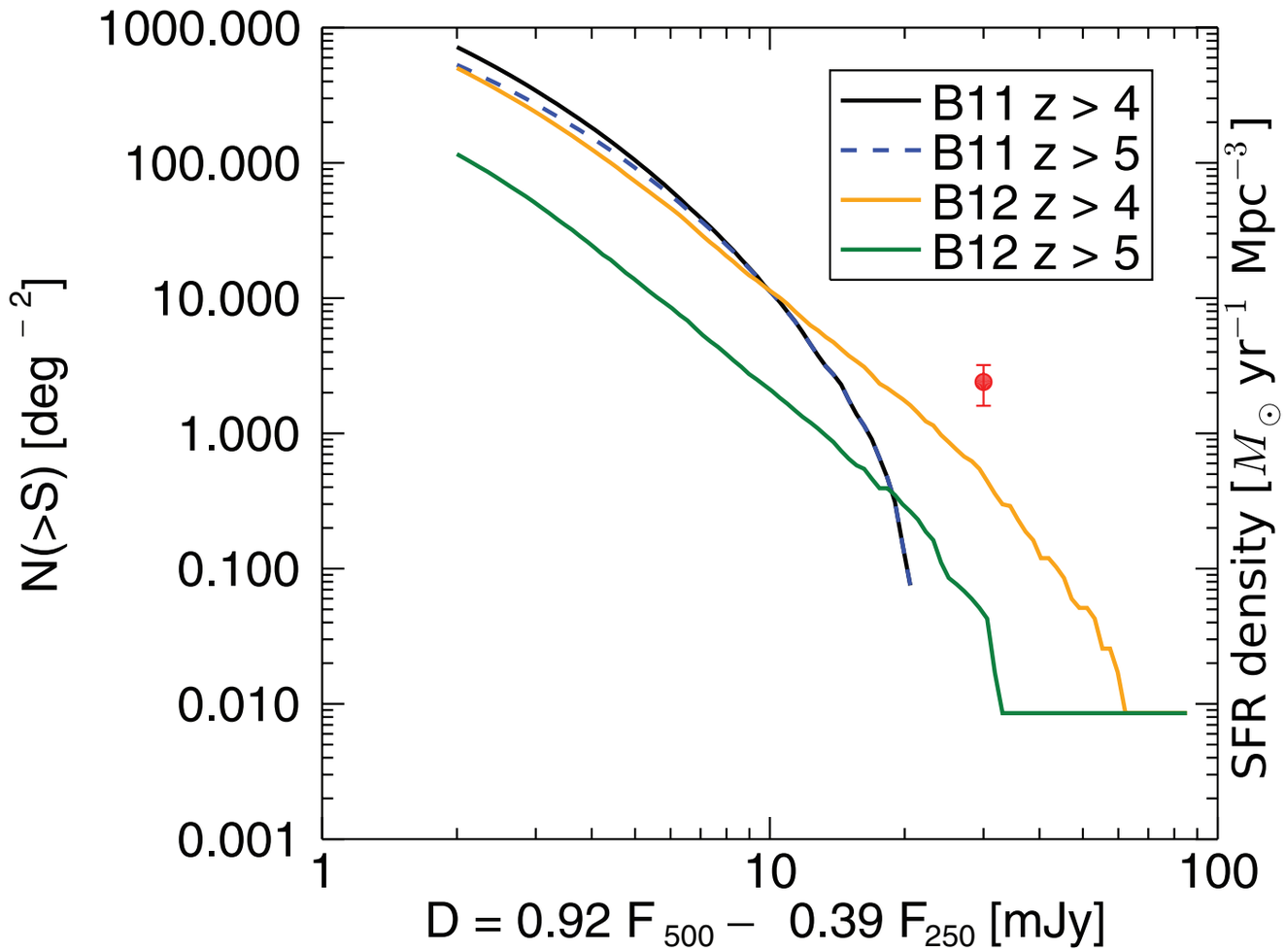
The Highest Redshift dusty galaxies



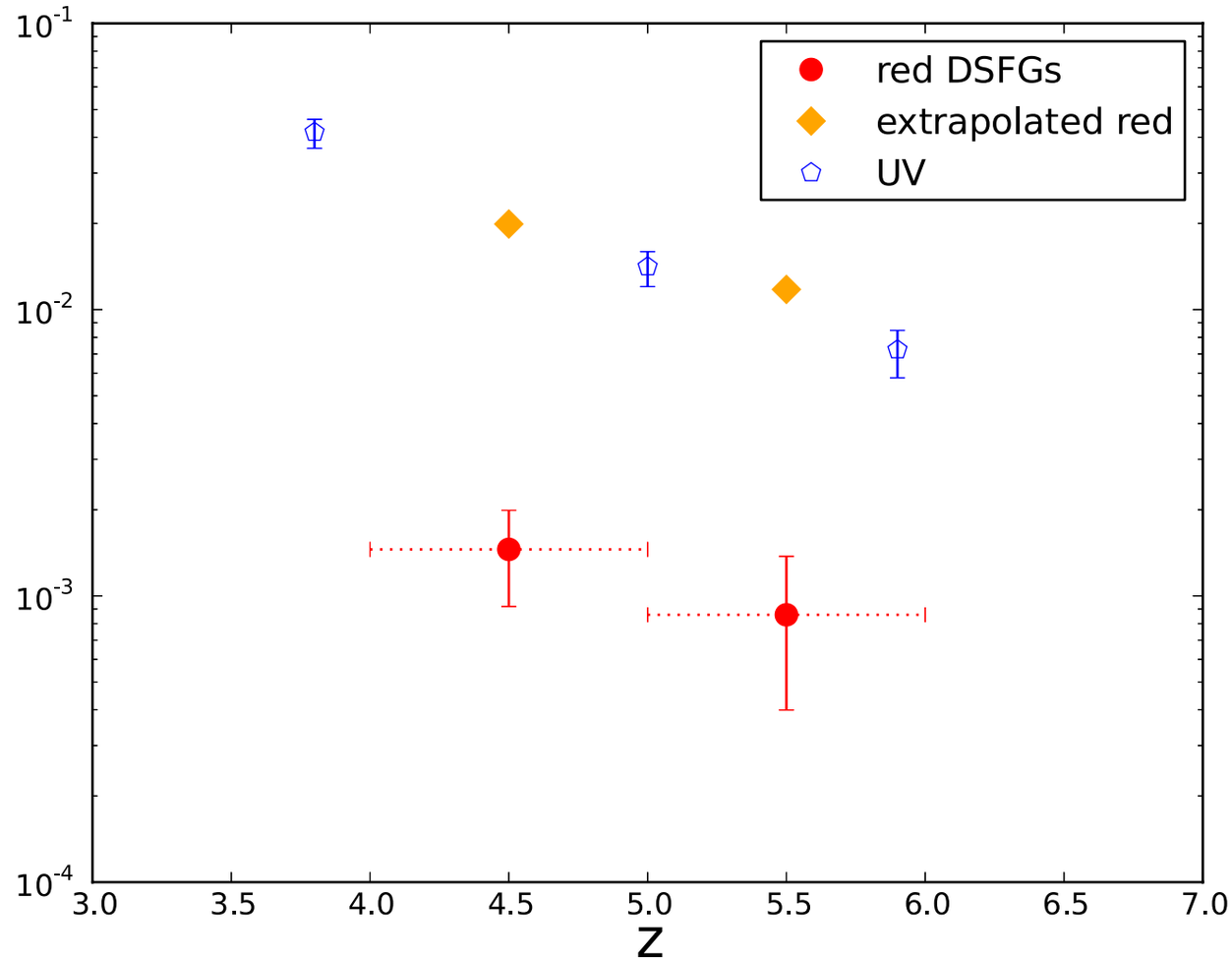


Riechers et al 2013

DSFGs at z>4: Unexpectedly Common



We find more than current models predict

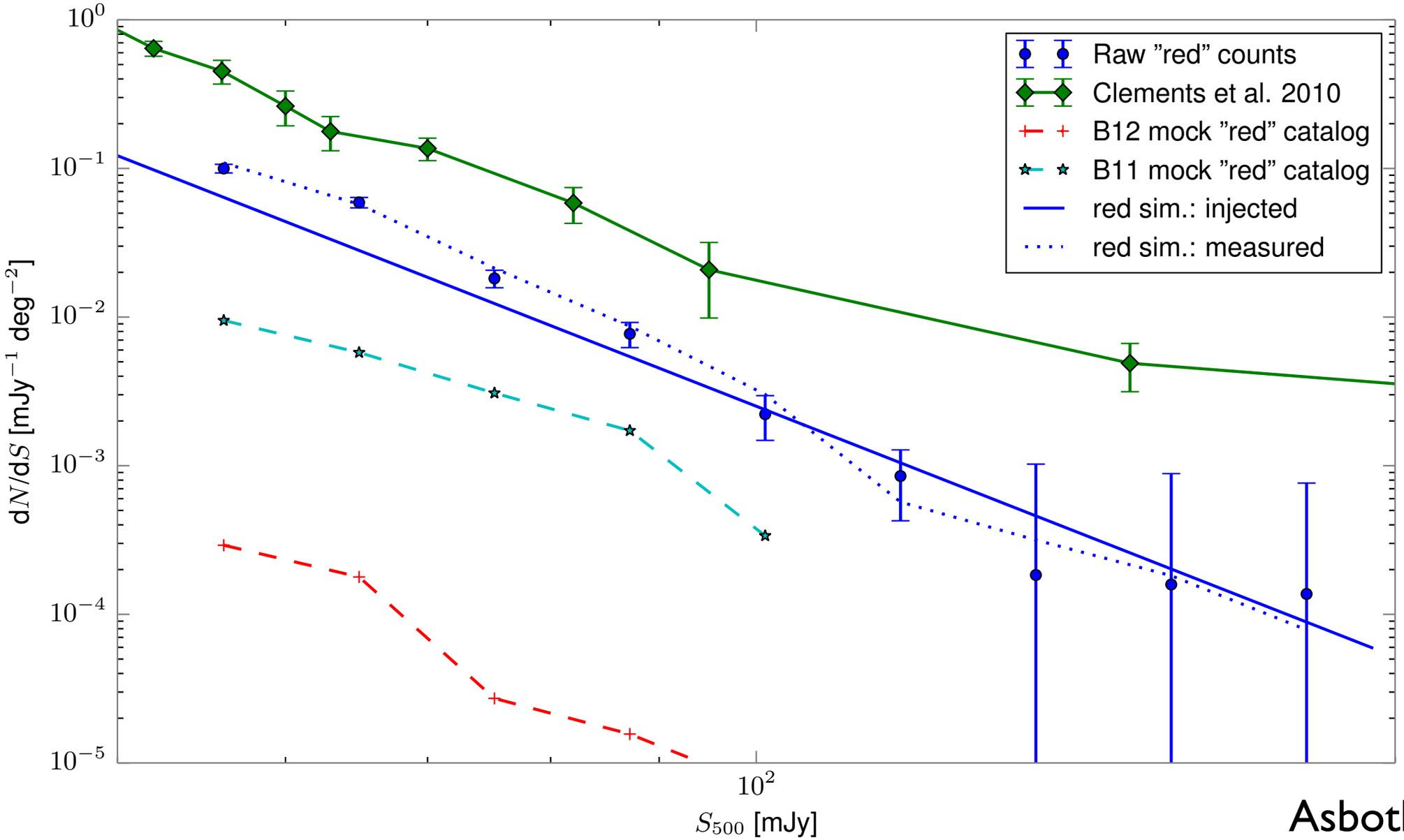


Comparison of SFRD of z>4 DSFGs & UVGs

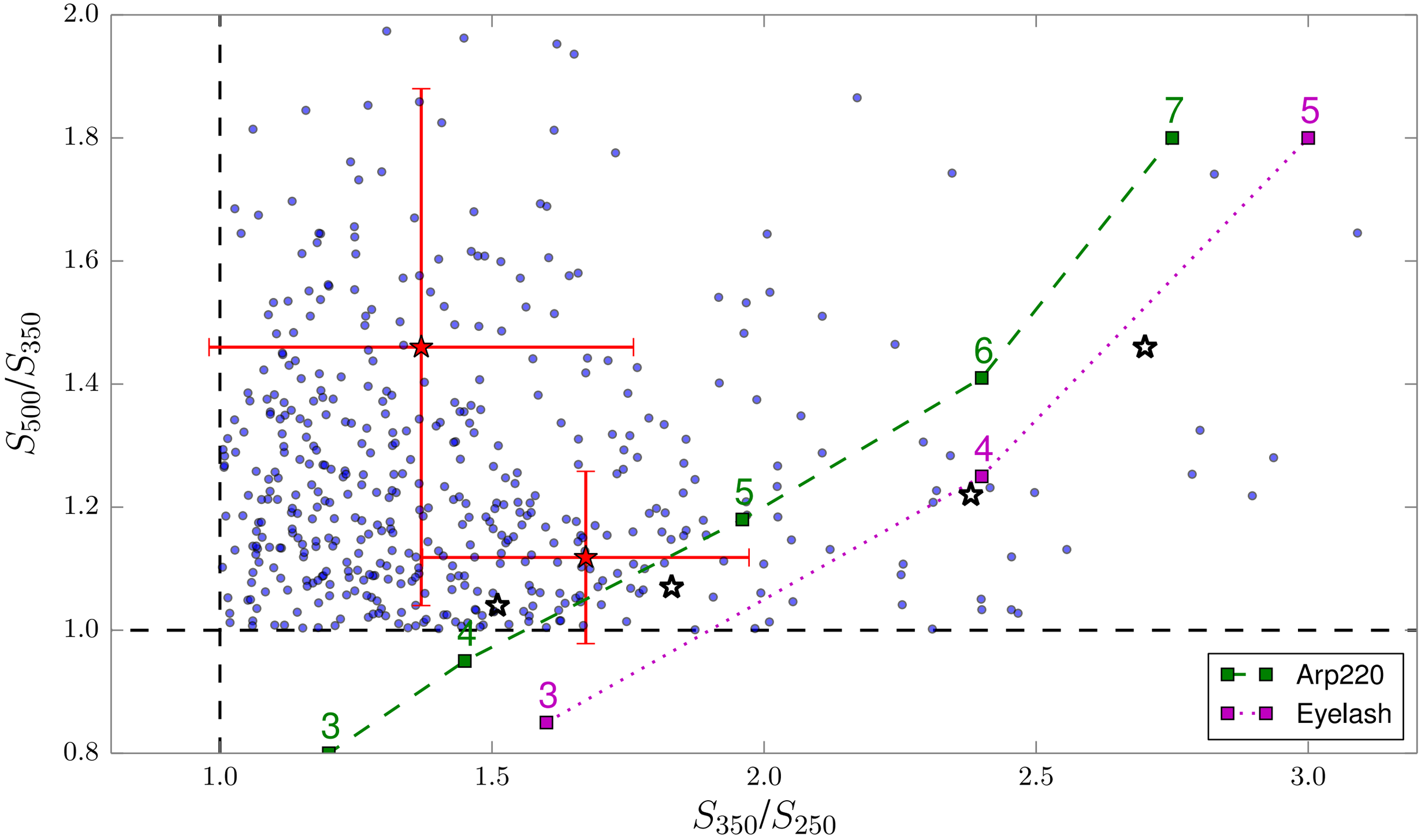
Dowell et al. 2014

z>4 Sources: Status

- Dowell et al, 2014: 38 candidates over 21 sq. deg.
- Asboth et al. (2016): 477 over 273 sq. deg. in HeLMS

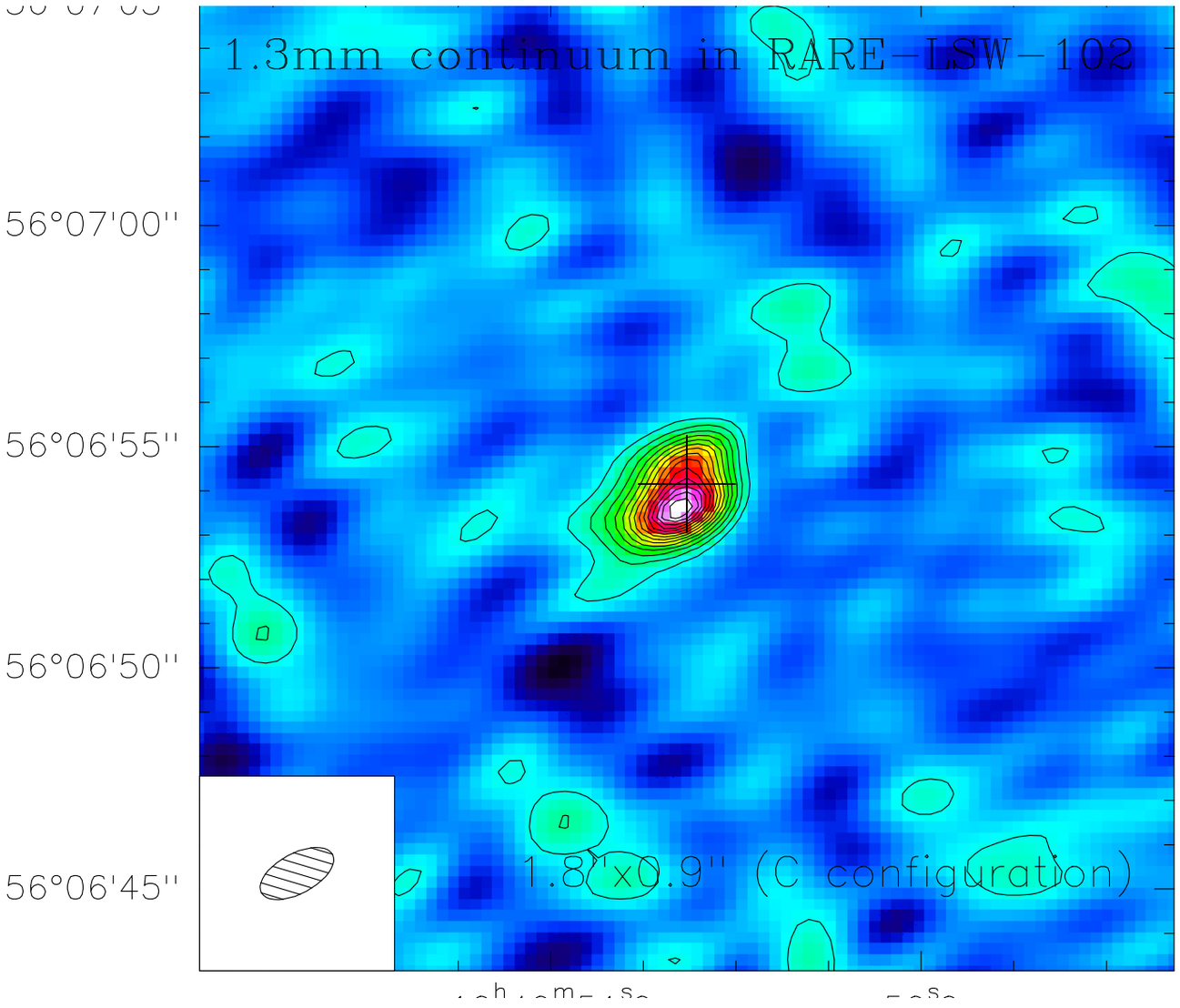


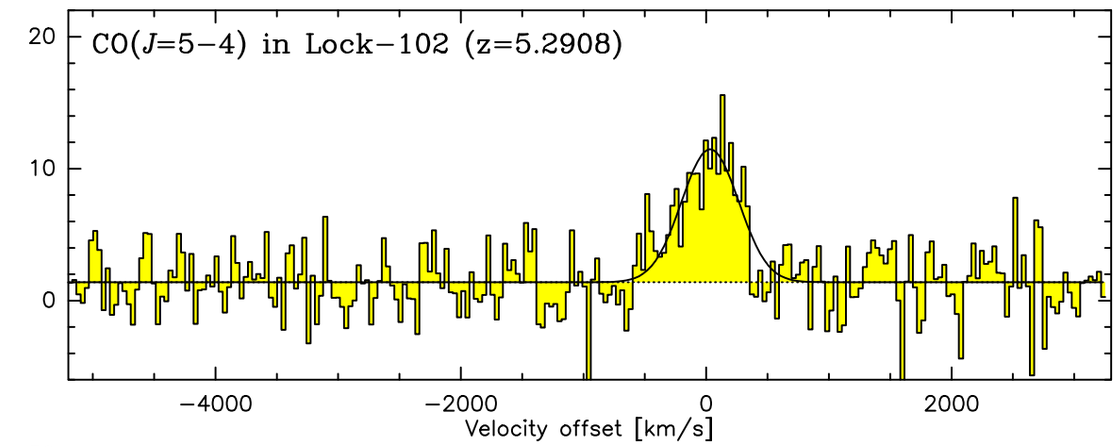
Asboth et al. 2016

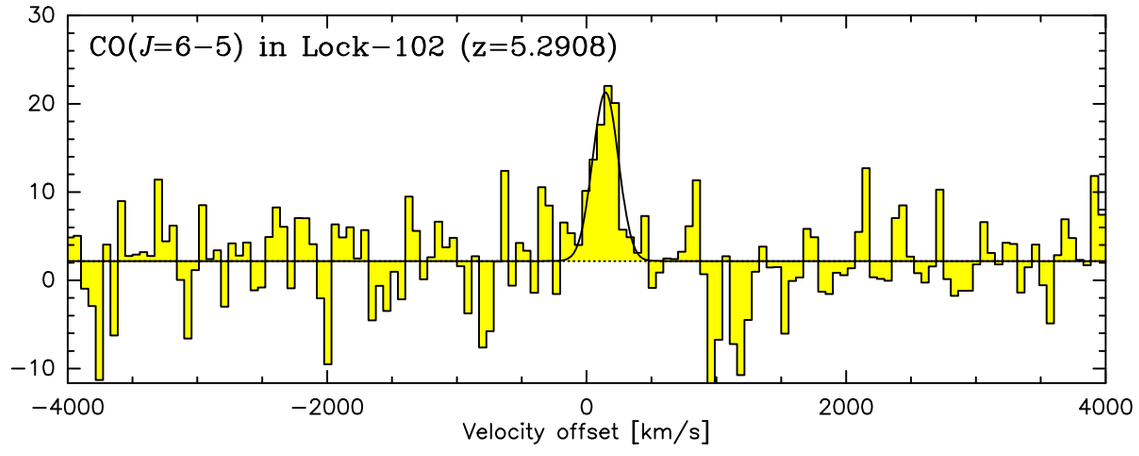


Asboth et al. 2016

Some Surprises

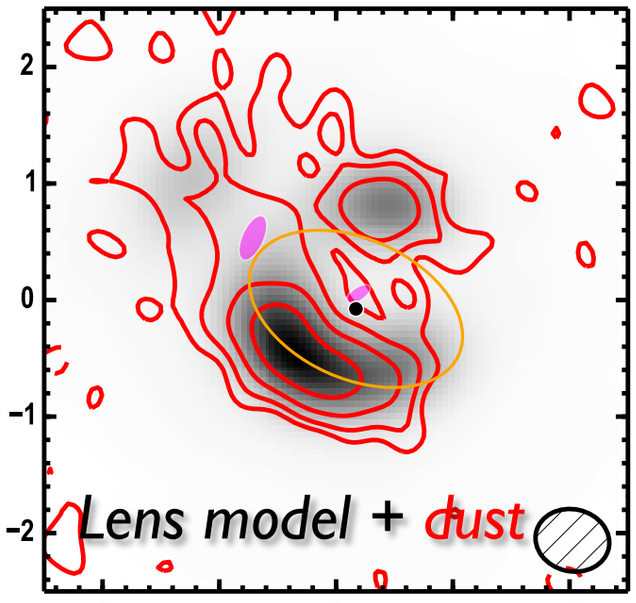


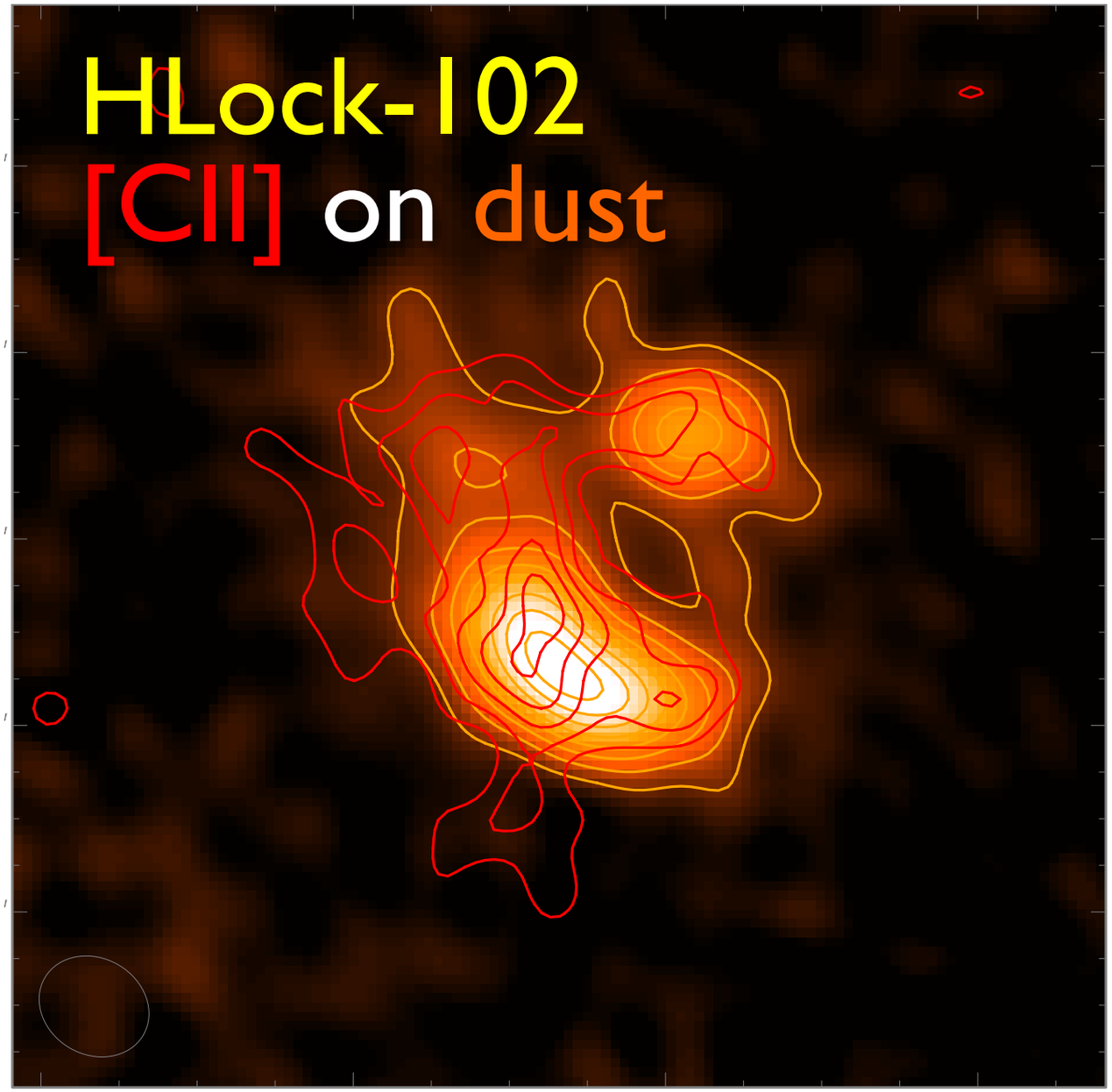


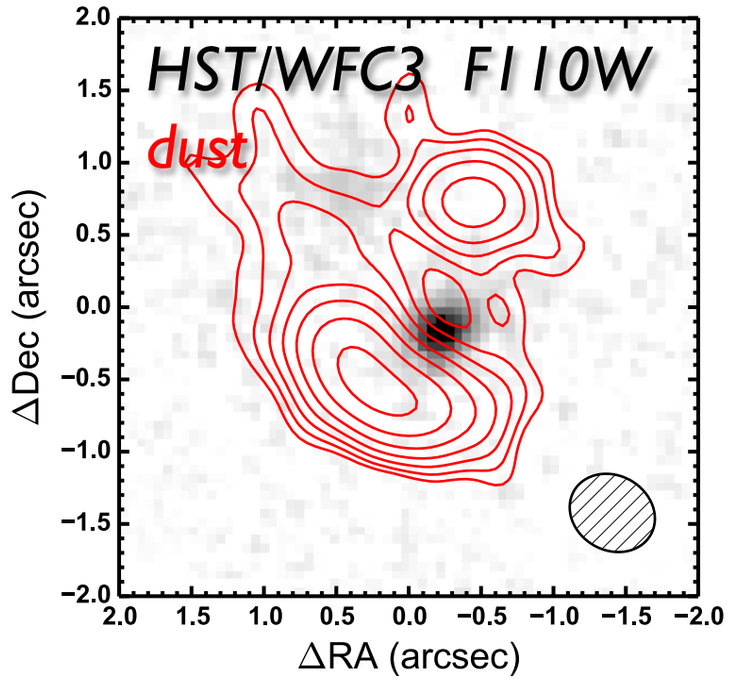


Lockman-102: very bright - 140mJy at 500 microns - but very high redshift: z=5.29

Lock-102: Lensed







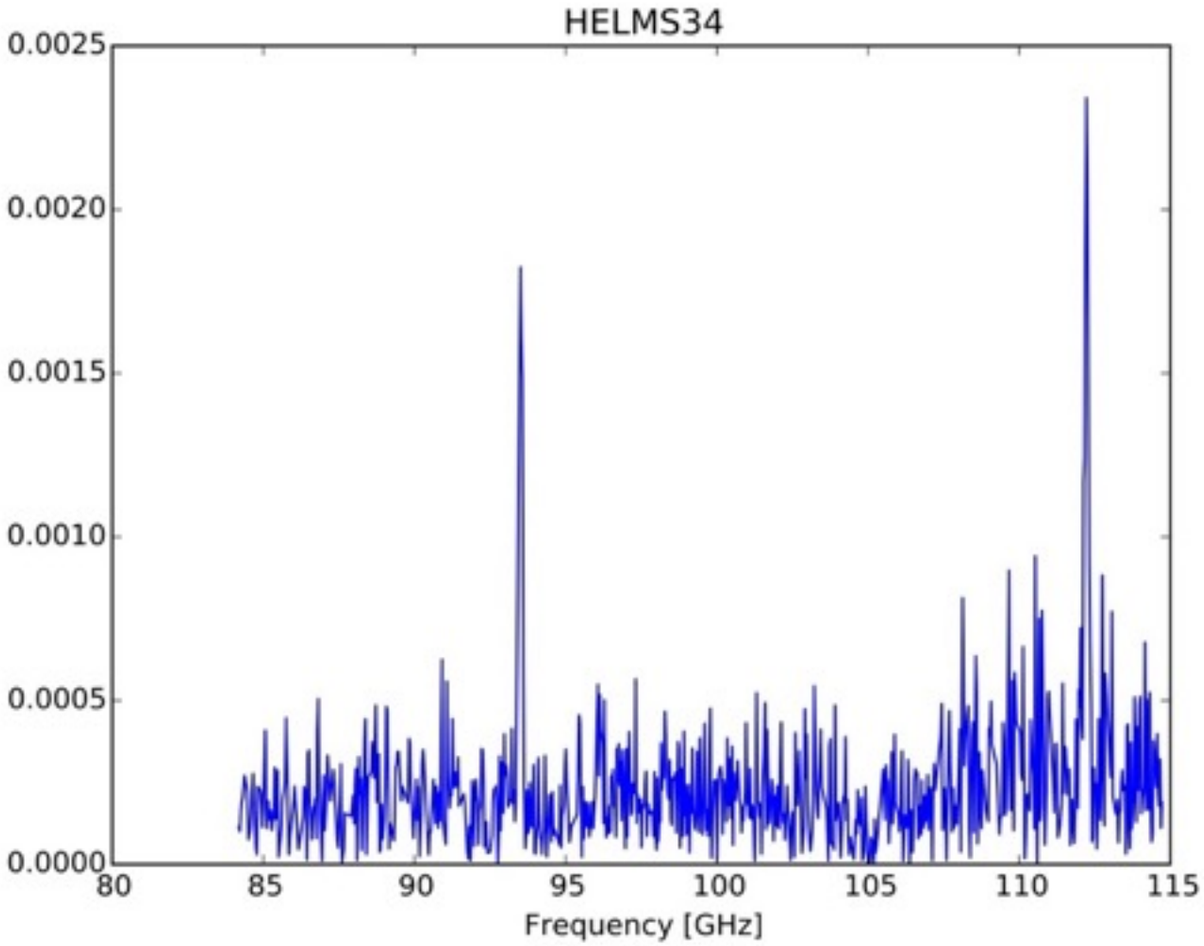
Wardlow, et al. in prep;

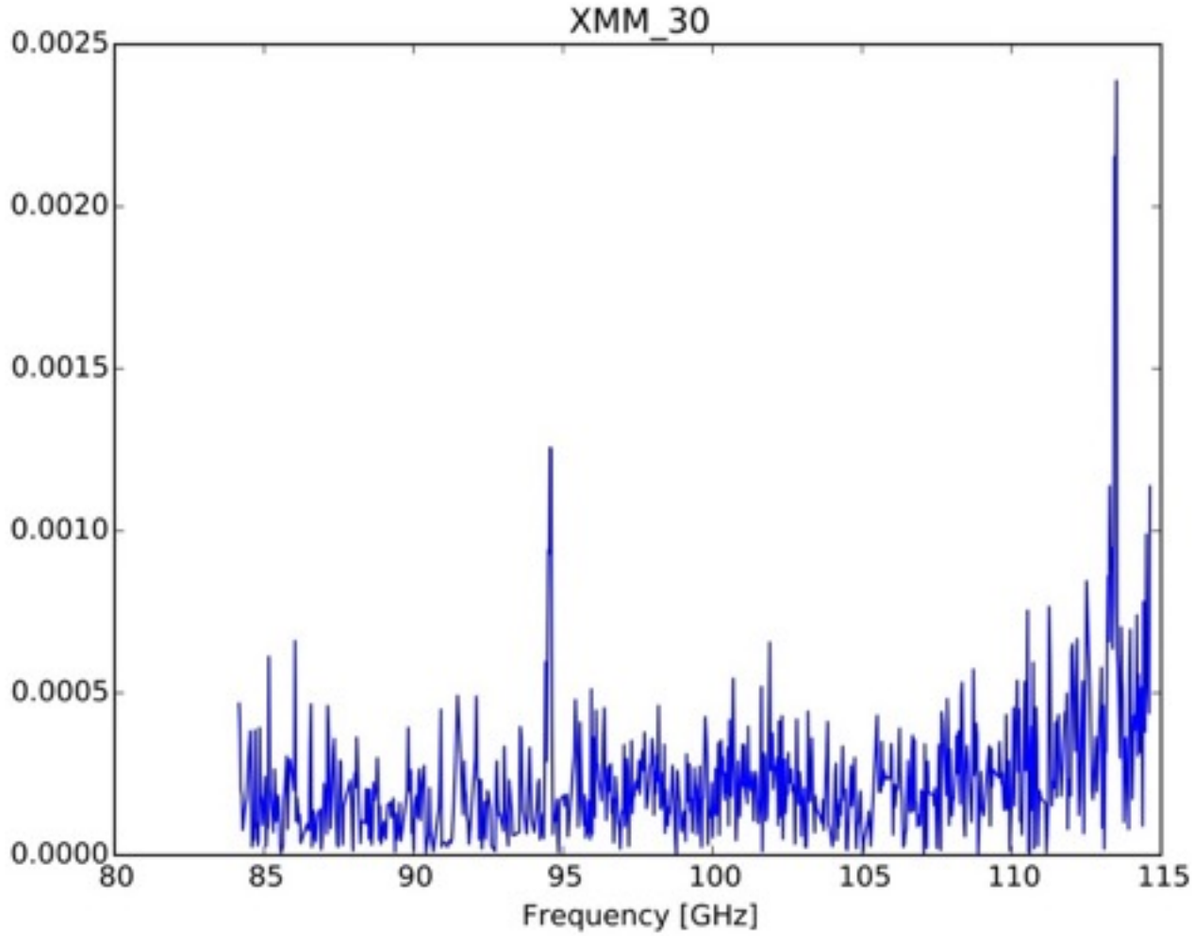
Bussmann uvmcmcfit lens fitting code

Lens not yet fully identified - highest z lens to date?

SMA data looking at kinematics of CII line at z=5.29

ALMA Spectra



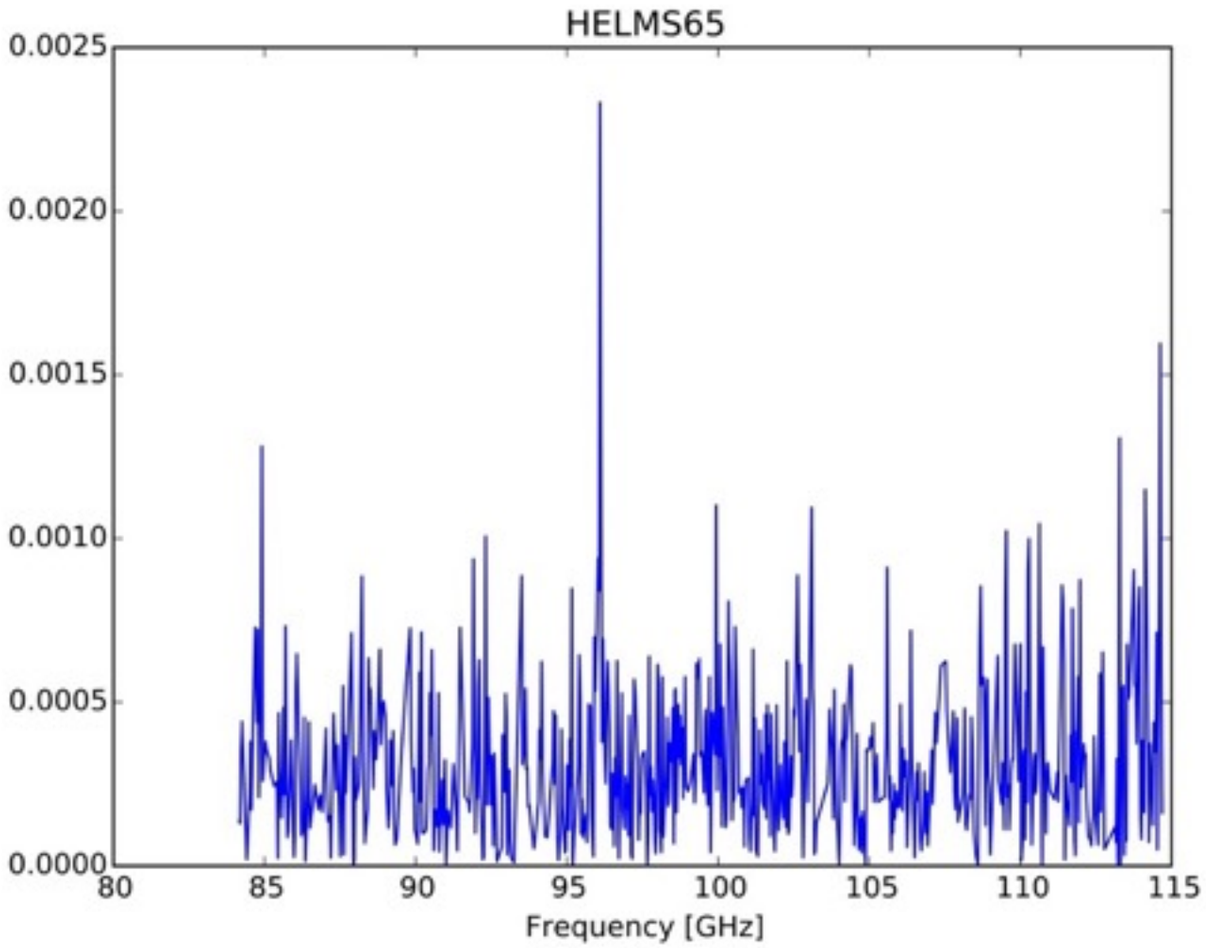


z=5.162

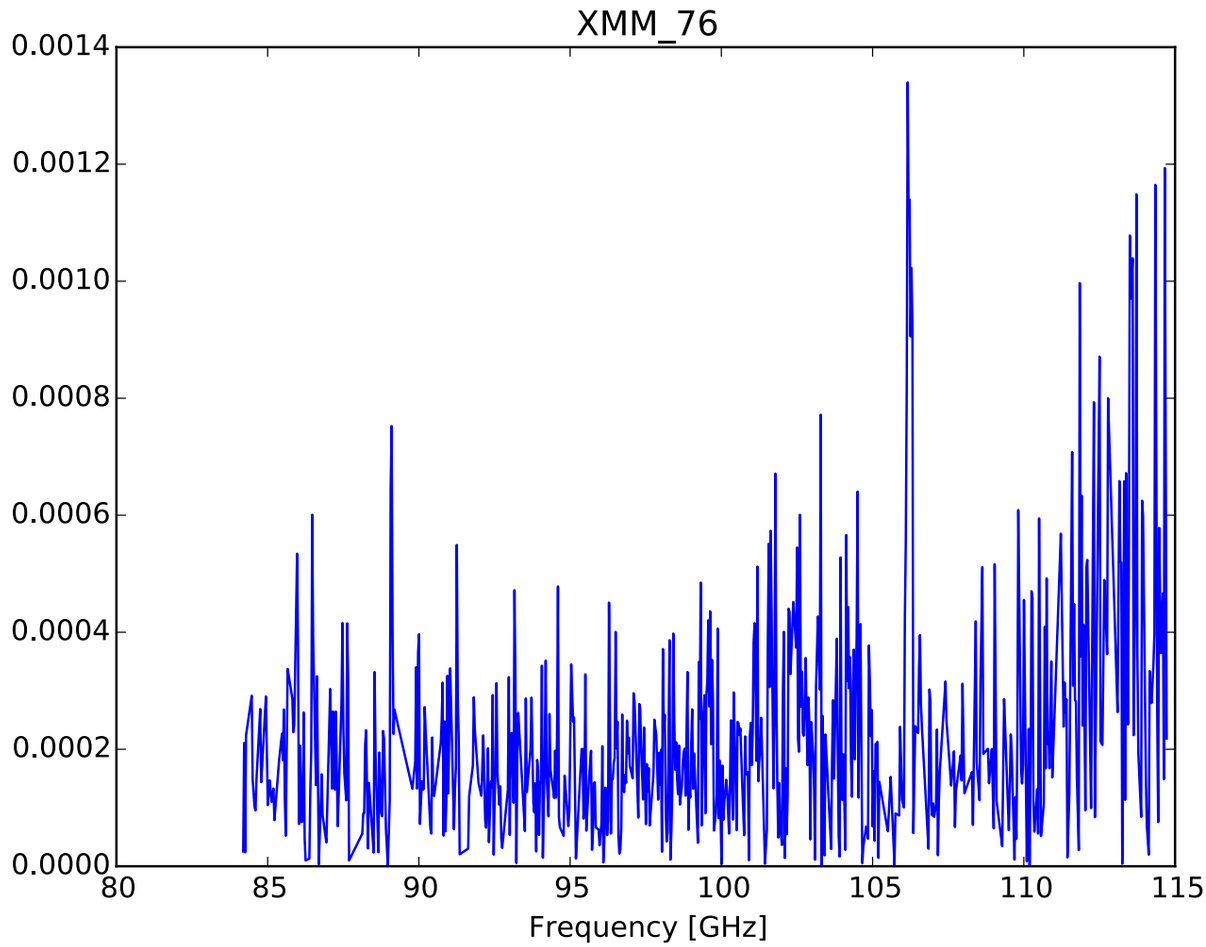
z=5.093

- Multiple spectral scans to cover large enough frequency range to ensure line detection - a ‘special mode’ and with high overheads in AO2 & 3

More ambiguous cases

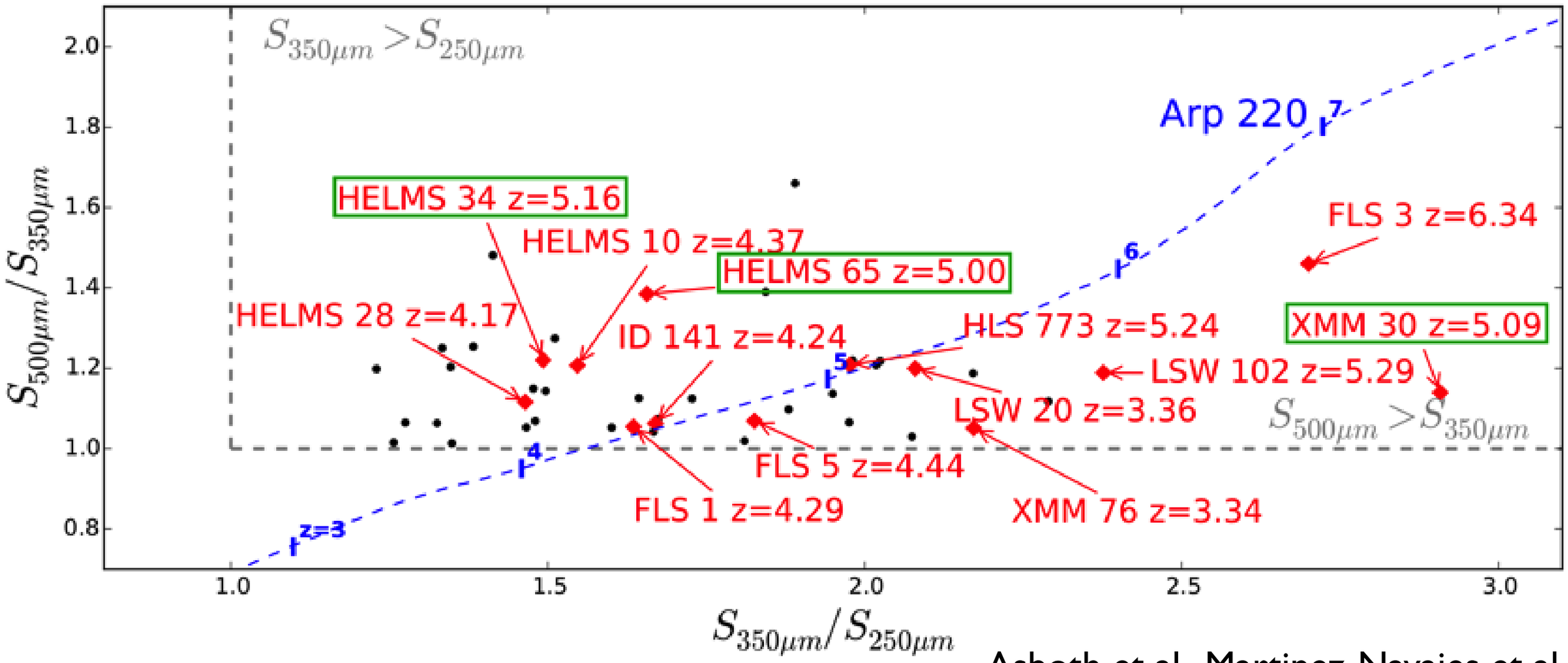


z=3.798 or 4.997



z=3.34 based on not seeing other lines

Ideally want high spectral range receiver on sensitive submm interferometer - SMA with 32GHz b/w SWARM coming soon

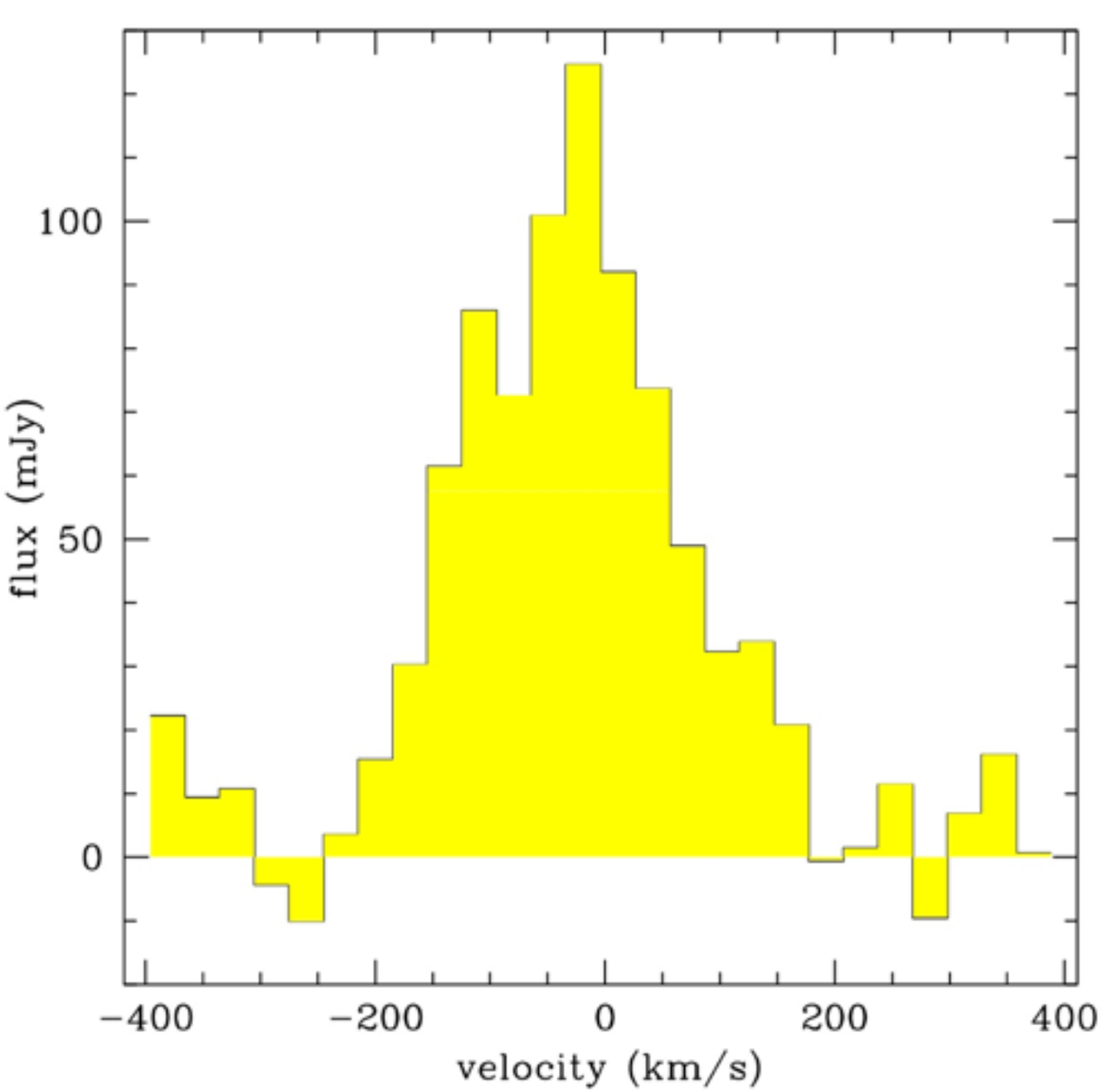


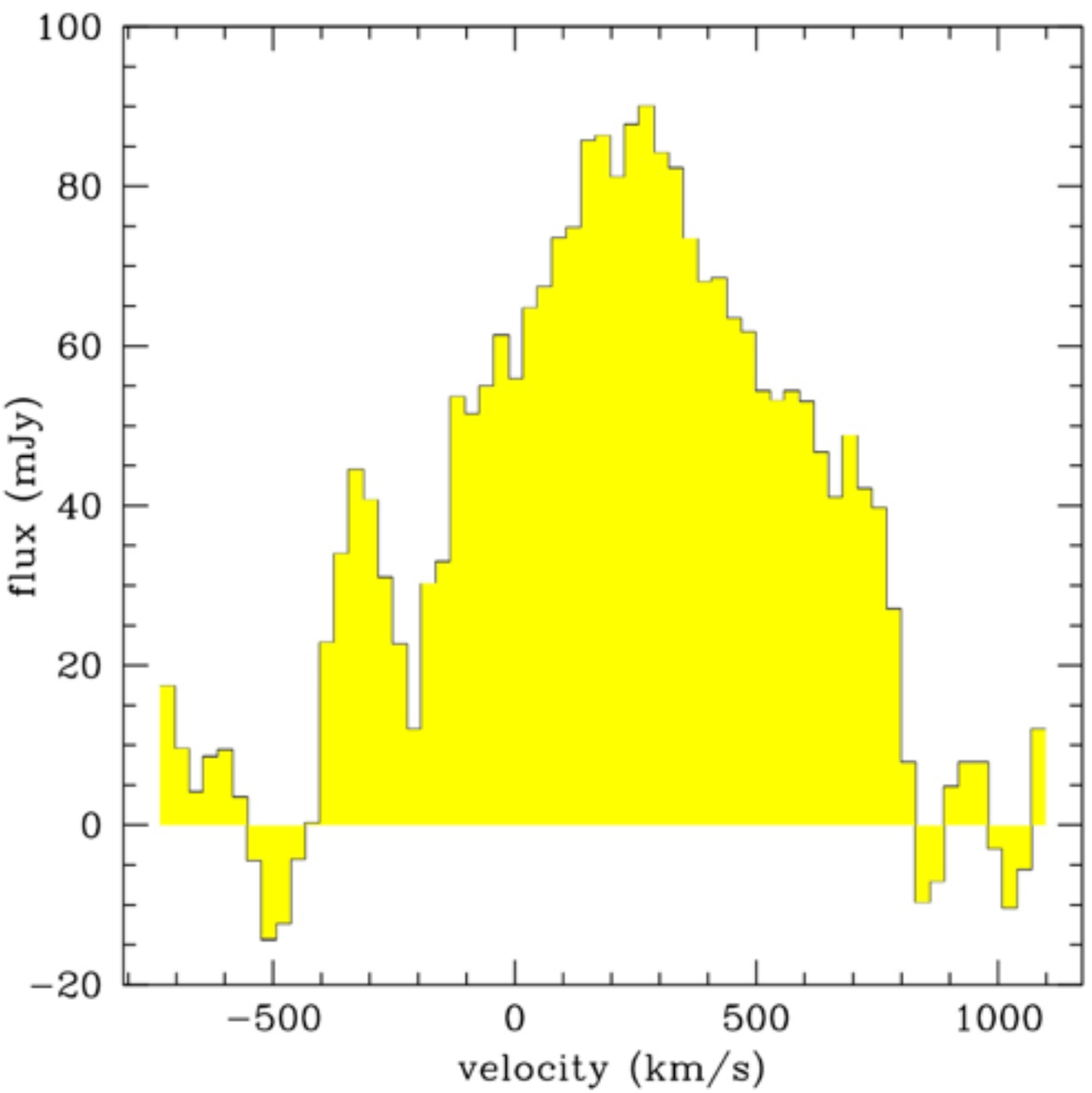
Asboth et al., Martinez-Navajes et al.

Now have 10 HerMES red sources with spectroscopic redshifts confirmed at z>4

Followup studies

- Include ALMA & HST high resolution imaging
- Multiband photometry to understand SEDs, determine stellar mass, SF history etc.
- Additional spectroscopy to study multiple lines eg. [CII]



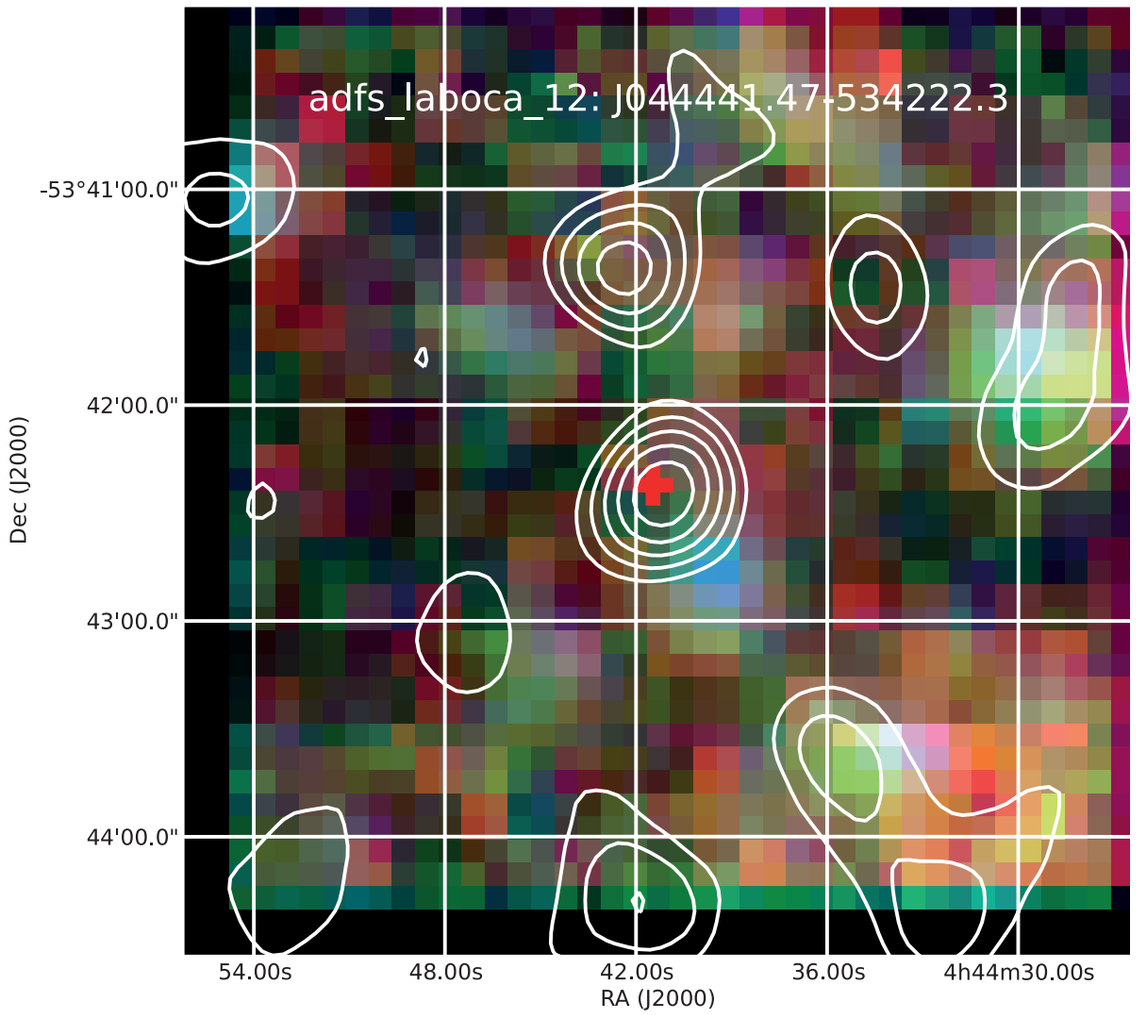


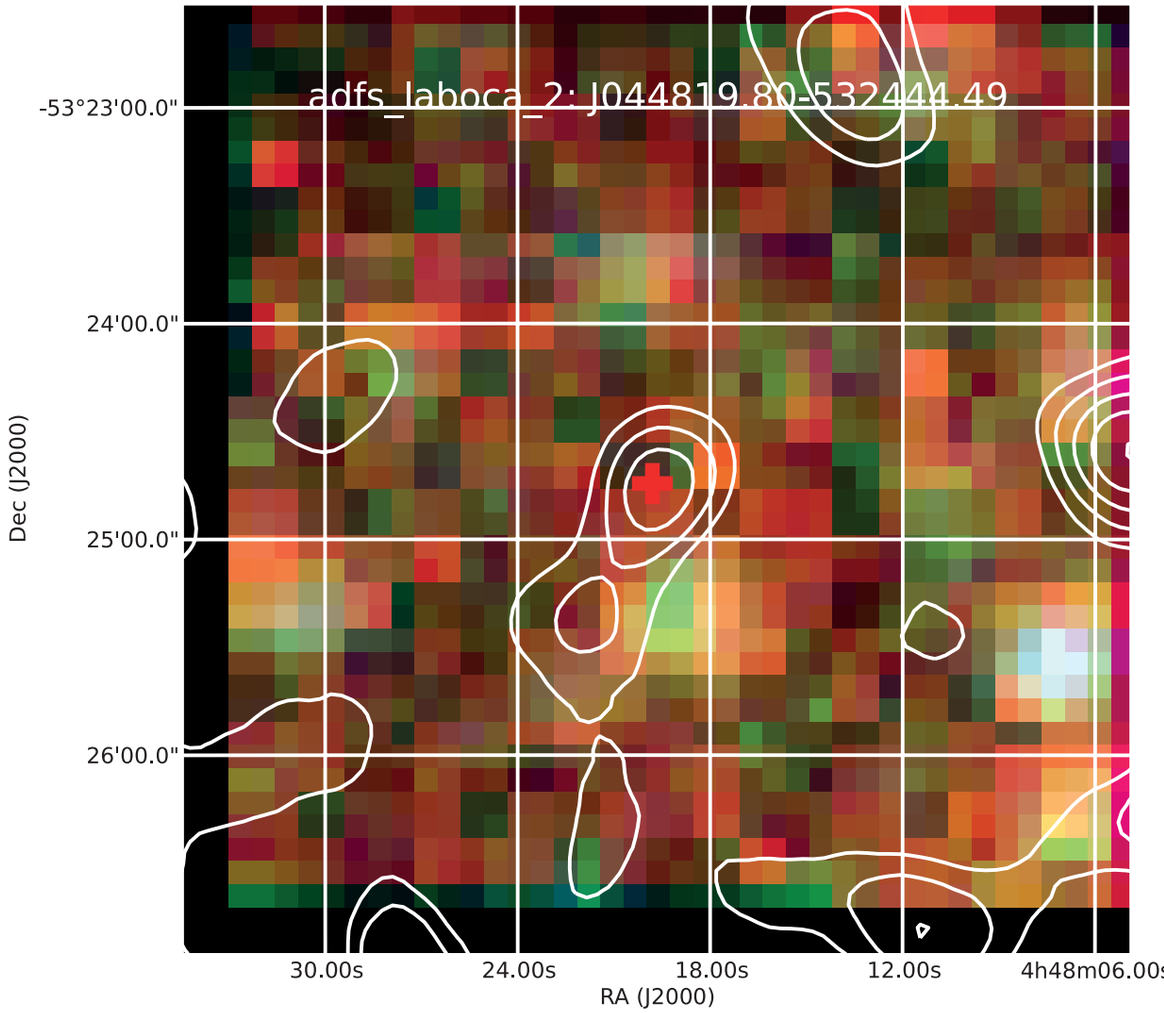
Initial [CII] spectroscopy of two high z dusty objects from JCMT - Chapman et al. (in prep). Note very different velocity widths.

Hopes for higher z?

- Proper understanding of the z>5 dusty star forming galaxy population needs to push to lower luminosities - say >2x fainter than HFLS3
- Such objects will not appear in SPIRE images - too faint - but will appear in submm (0.85, 1.25mm) images
- Objects at z>>>6 would also appear as such ‘SPIRE dropouts’
- May be needed to explain sources like A1689-zD1 the dusty, massive evolved galaxy at z~7.5 (Watson et al., 2015)

SPIRE Dropouts

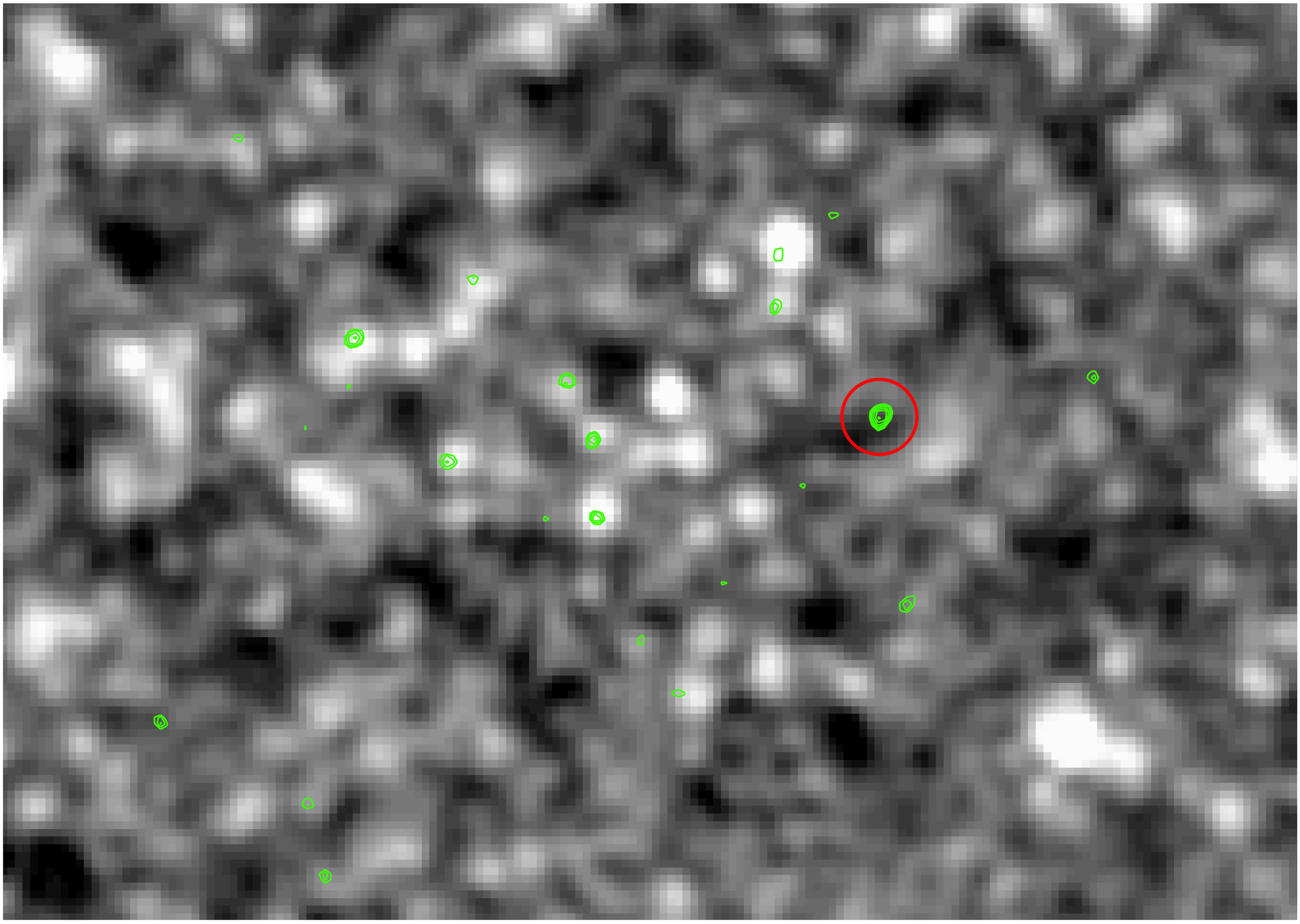


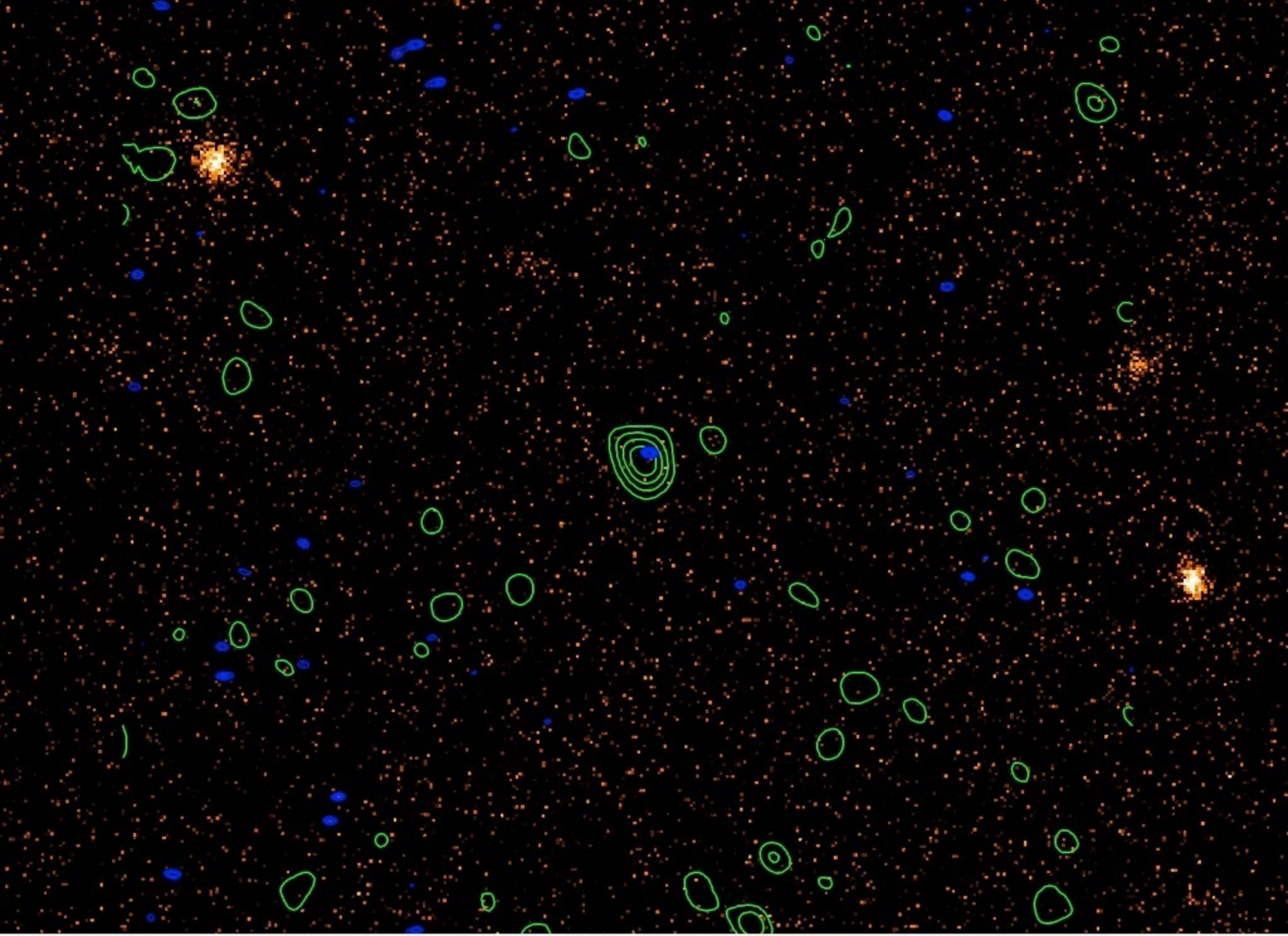


Herschel 3 colour SPIRE images compared to 1.25mm AzTEC contours (Hatsukade et al., 2011)

870μm followup coming (Greenslade et al.)

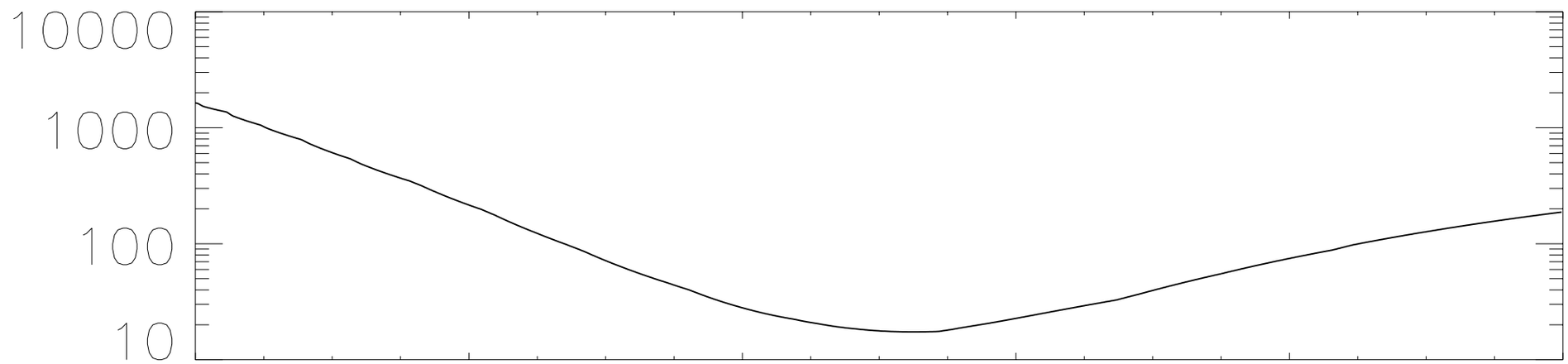
SPIRE Dropouts: NGP6_d1



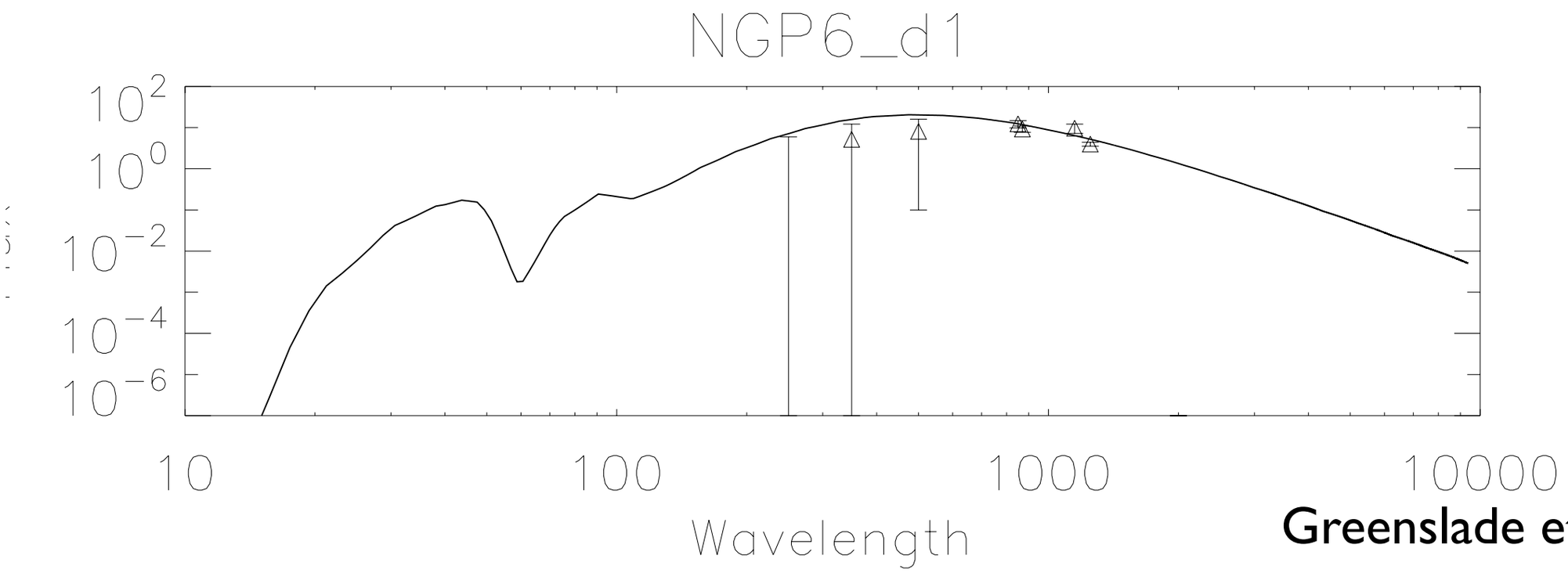


NGP6 Observations

- Herschel, no detection; SCUBA2, SMA, NIKA - detections



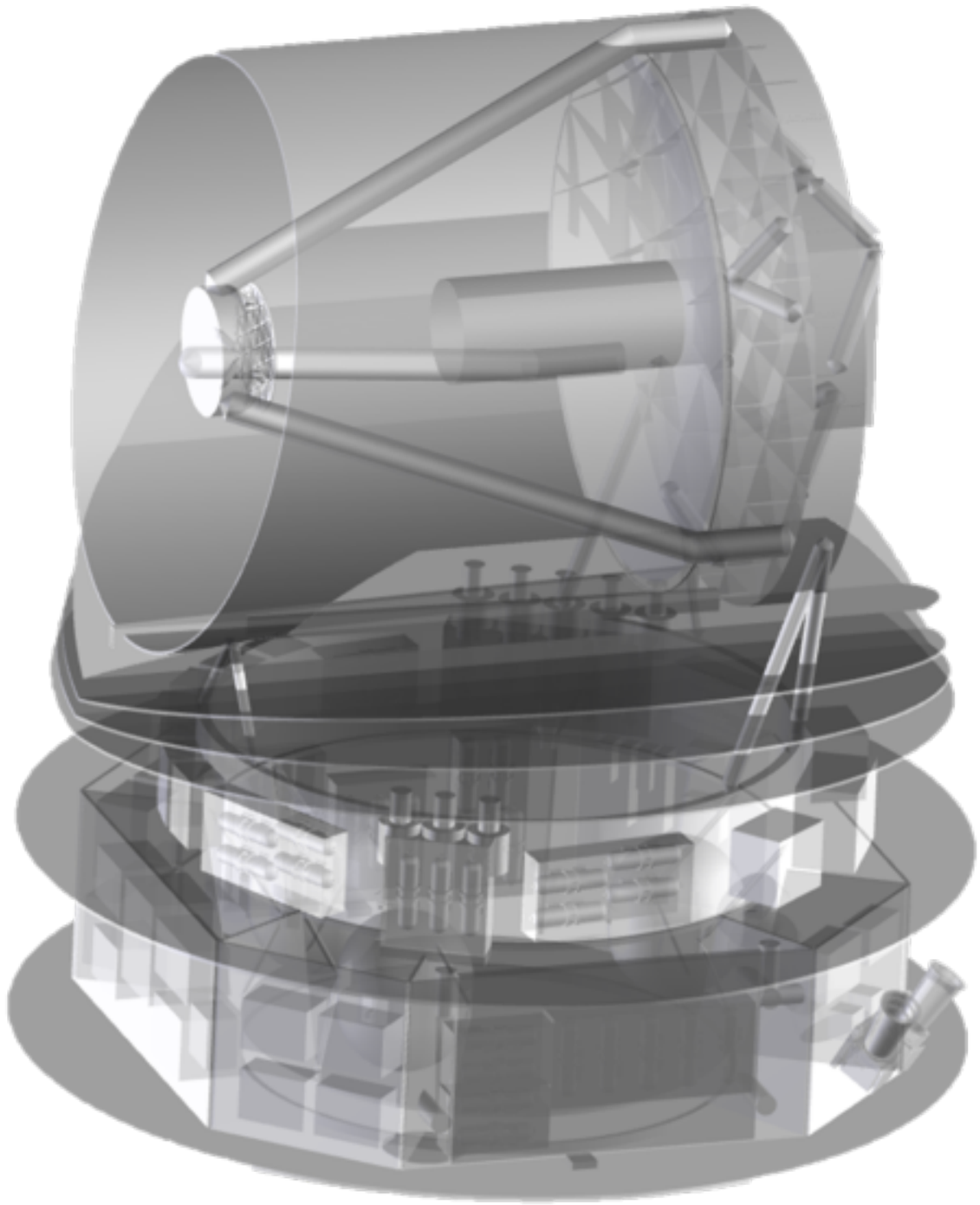
z~5.25

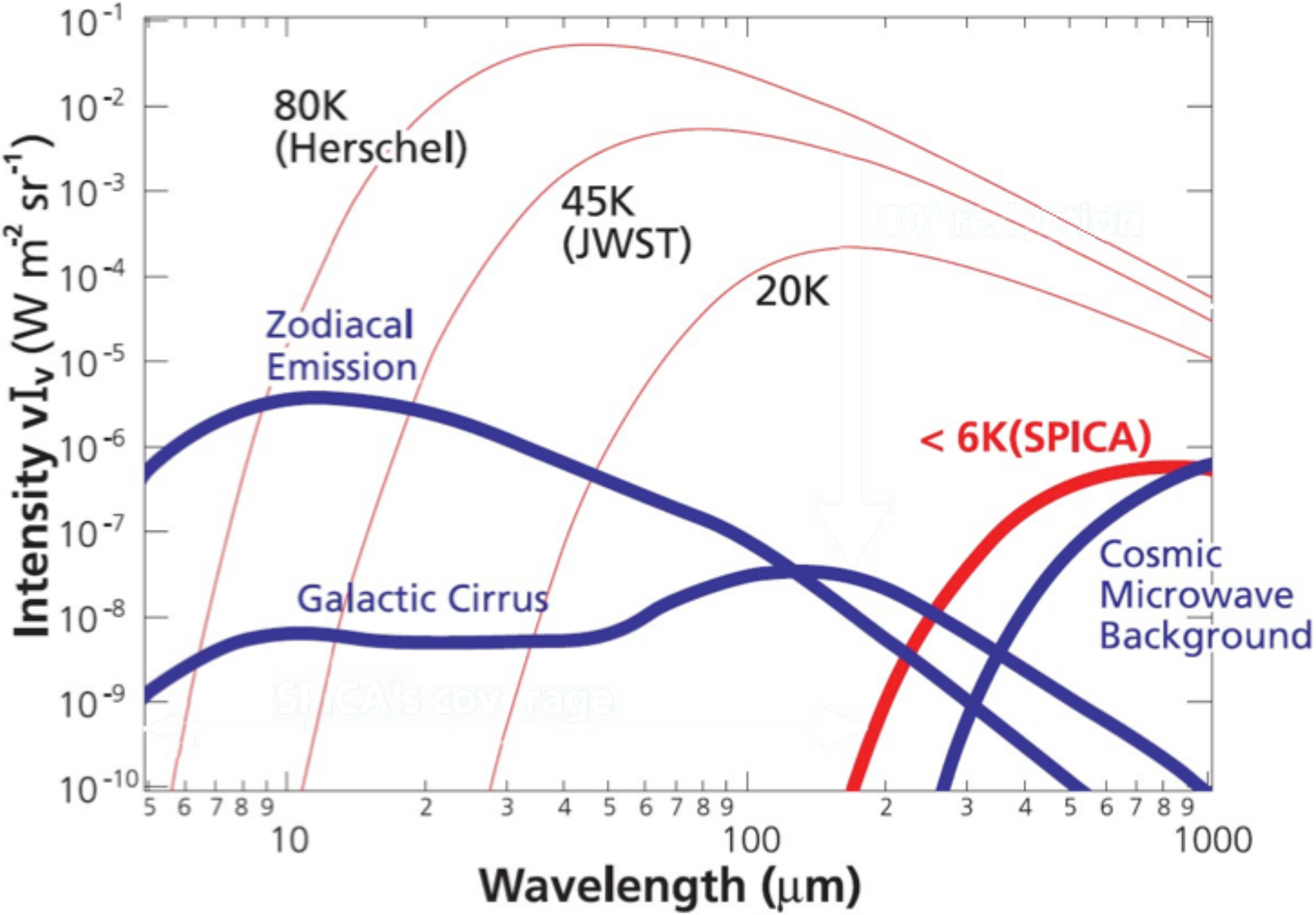


Greenslade et al., in prep

What Next?: SPICA

- Proposed ESA-JAXA mission for mid to far-IR spectroscopy
- 2.5m diameter, telescope cooled to 8K
- Two instruments: mid-IR & far-IR




80K
(Herschel)
45K
(JWST)
20K
< 6K(SPICA)
Zodiacal
Emission
Galactic Cirrus
Cosmic
Microwave
Background
Intensity νI_ν (W m^-2 sr^-1)
Wavelength (μm)
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
5 6 7 8 9
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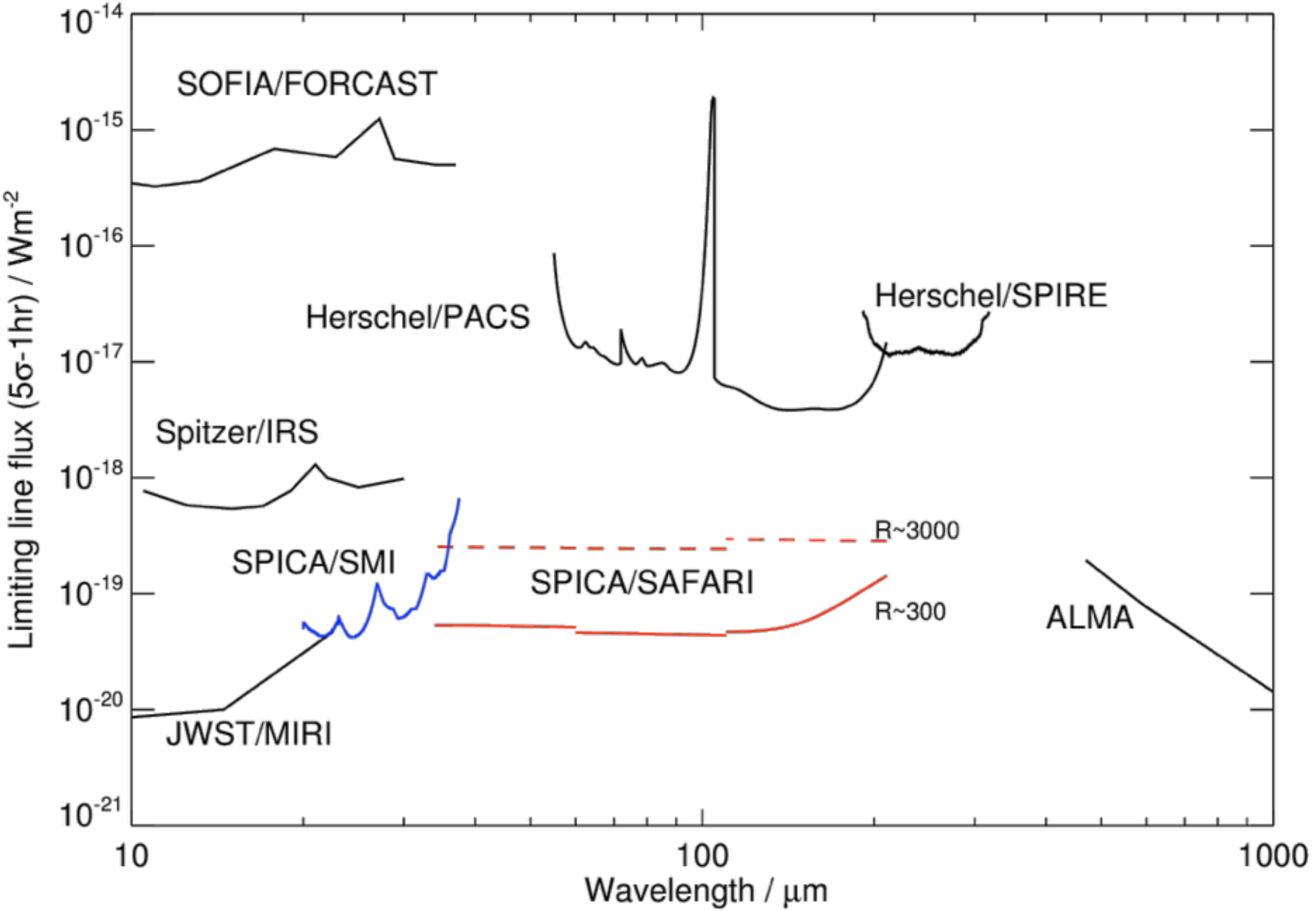
SOFIA/FORCAST
Herschel/PACS
Herschel/SPIRE
Spitzer/IRS
SPICA/SMI
SPICA/SAFARI
R~3000
R~300
JWST/MIRI
ALMA
Limiting line flux (5σ-1hr) / Wm-2
Wavelength / μm
10-14
10-15
10-16
10-17
10-18
10-19
10-20
10-21
10
100
1000

Conclusions

- Far-IR luminous galaxies at z>4 more common than models predict
- May make significant contribution to SFRD
- Good way of finding high-z lenses
- Increasing number of z>5 sources coming from ALMA
- SPIRE dropouts may push to lower L and/or even higher z