Cosmological Applications of Wide-field Imaging at Sub-mm Wavelengths

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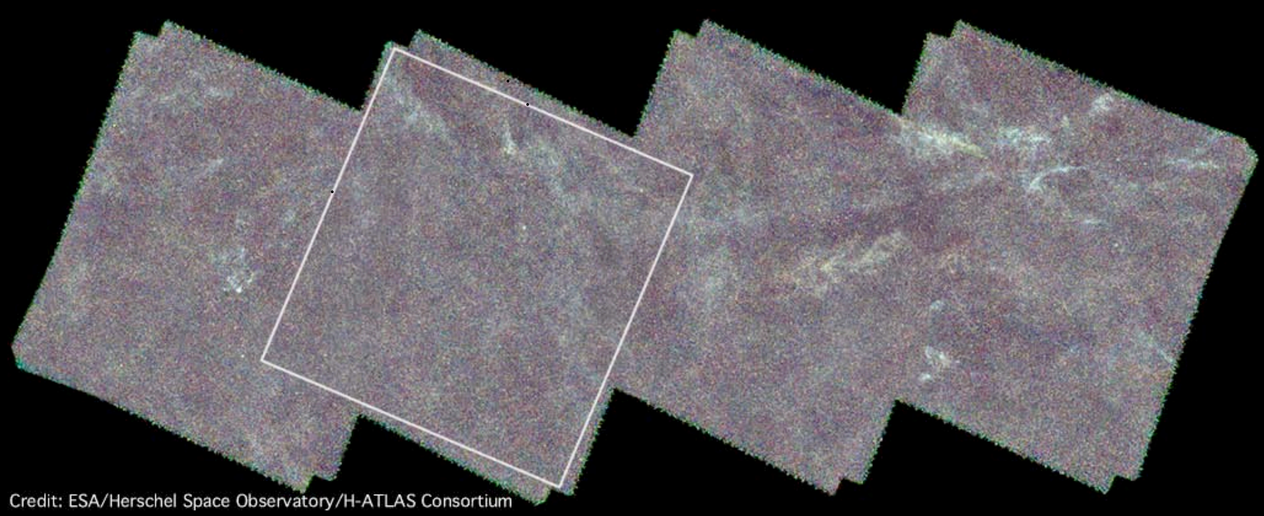
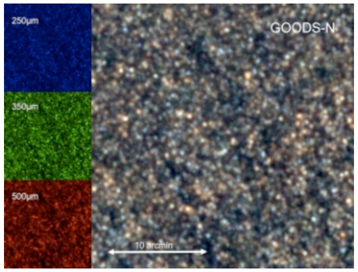


(for Asantha Cooray)

Herschel Large-area Extragalactic Programs



HerMES: *Herschel* Multi-tiered Extragalactic Survey

- PACS + SPIRE
- 70 sq deg from 20′×20′ to 3.6°×3.6° (850 hours) + 12 clusters
- Bolometric luminosities of galaxies, cosmic SFH
- Wedding cake to probe range of luminosities and environments

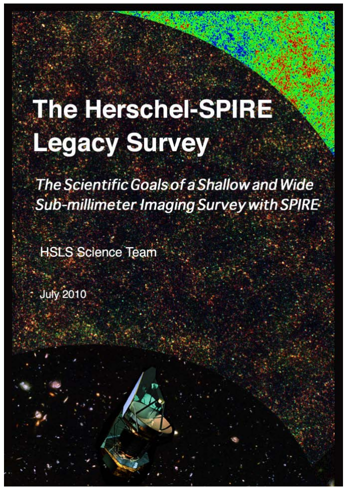
H-ATLAS: *Herschel*-Astrophysical Terahertz Large Area Survey

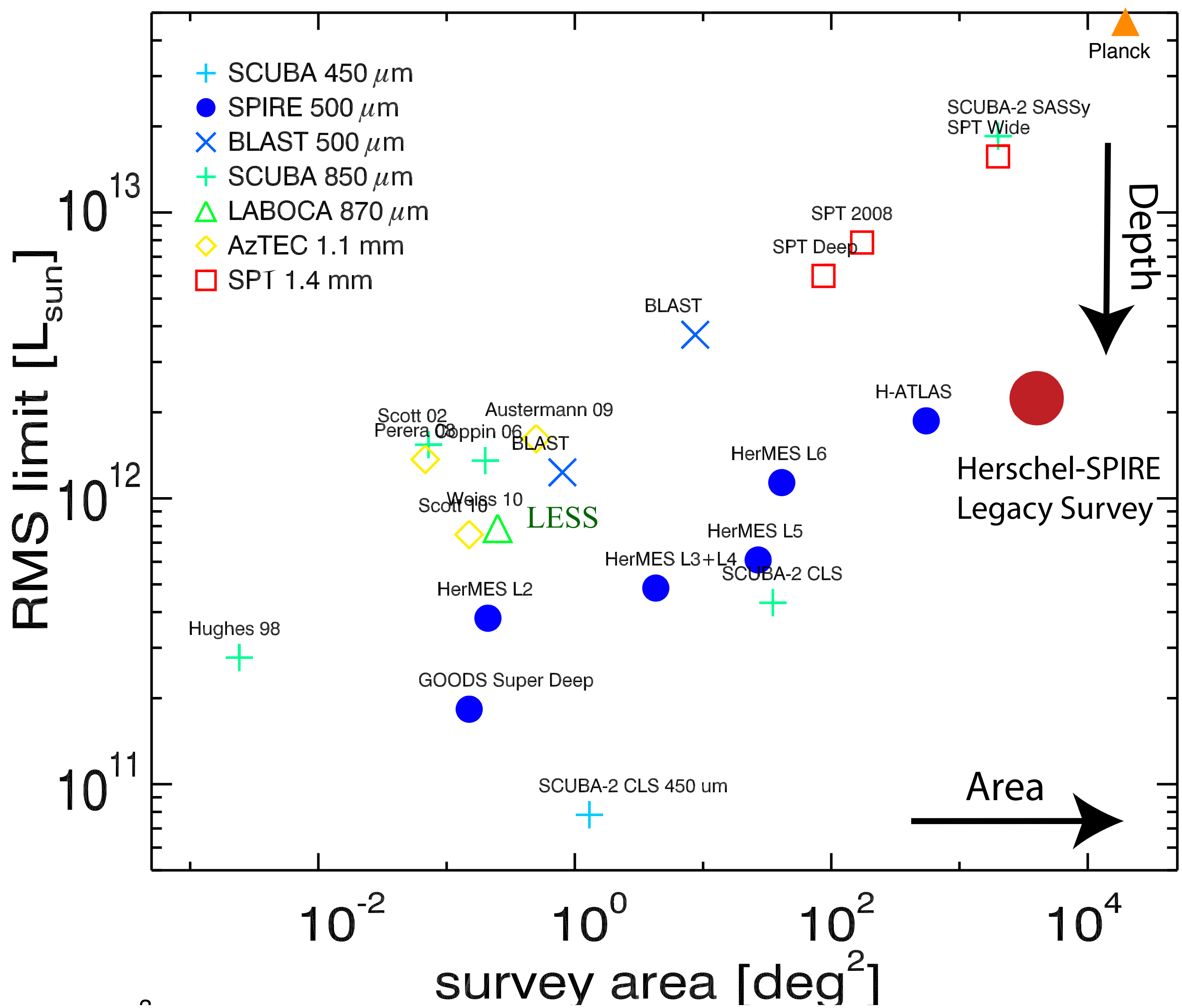
- PACS + SPIRE
- 550 sq deg (600 hours) in 3 GAMA fields; 200 sq deg NGP & SGP
- Low-z sciences, lensed sources, AGN
- Expect ~500,000 detections to z~3, majority at 250 & 350 um
- Steve Eales, Cardiff, PI; Asantha Cooray, UCI, US (NASA) PI

HSLS: *Herschel*-SPIRE Legacy Survey

(proposed for Open-Time, but declined by HOTAC for OT1; community will resubmit in OT2)

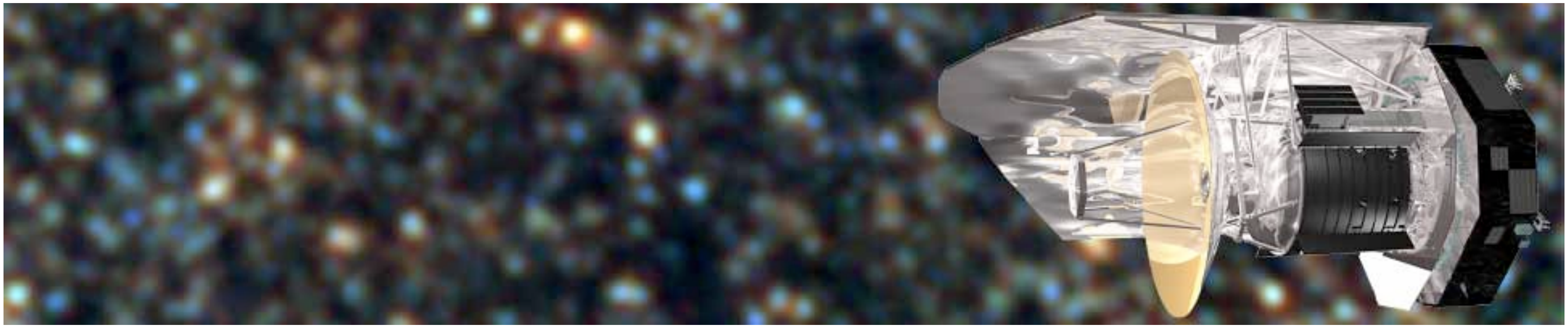
- 4000 sq deg (780 hours), includes 1000 sq. deg in Stripe-82
- 2.5 to 3.0 million source detections; 10,000 at z >4 and 1000 at z > 5; 2000 strongly lensed bright sources; 200 "proto-clusters" at z~2
- Cosmology driven: e.g., joint Planck+HSLS studies, ISW, SZ, CMB lens
- Asantha Cooray, UCI, PI; Steve Eales, Cardiff, Co-PI





SCUBA 450 μm
SPIRE 500 μm
BLAST 500 μm
SCUBA 850 μm
LABOCA 870 μm
AzTEC 1.1 mm
SPT 1.4 mm
Planck
SCUBA-2 SASSy
SPT Wide
SPT 2008
SPT Deep
BLAST
Depth
H-ATLAS
Herschel-SPIRE
Legacy Survey
Scott 02
Perera 08
Coppin 06
Austermann 09
BLAST
HerMES L6
Scott 10
Weiss 10
LESS
HerMES L5
HerMES L3+L4
SCUBA-2 CLS
HerMES L2
Hughes 98
GOODS Super Deep
SCUBA-2 CLS 450 um
Area
RMS limit [L_{sun}]
survey area [deg^2]

SPIRE Instrument team's Extragalactic survey



HERSCHEL MULTI-TIERED EXTRAGALACTIC SURVEY

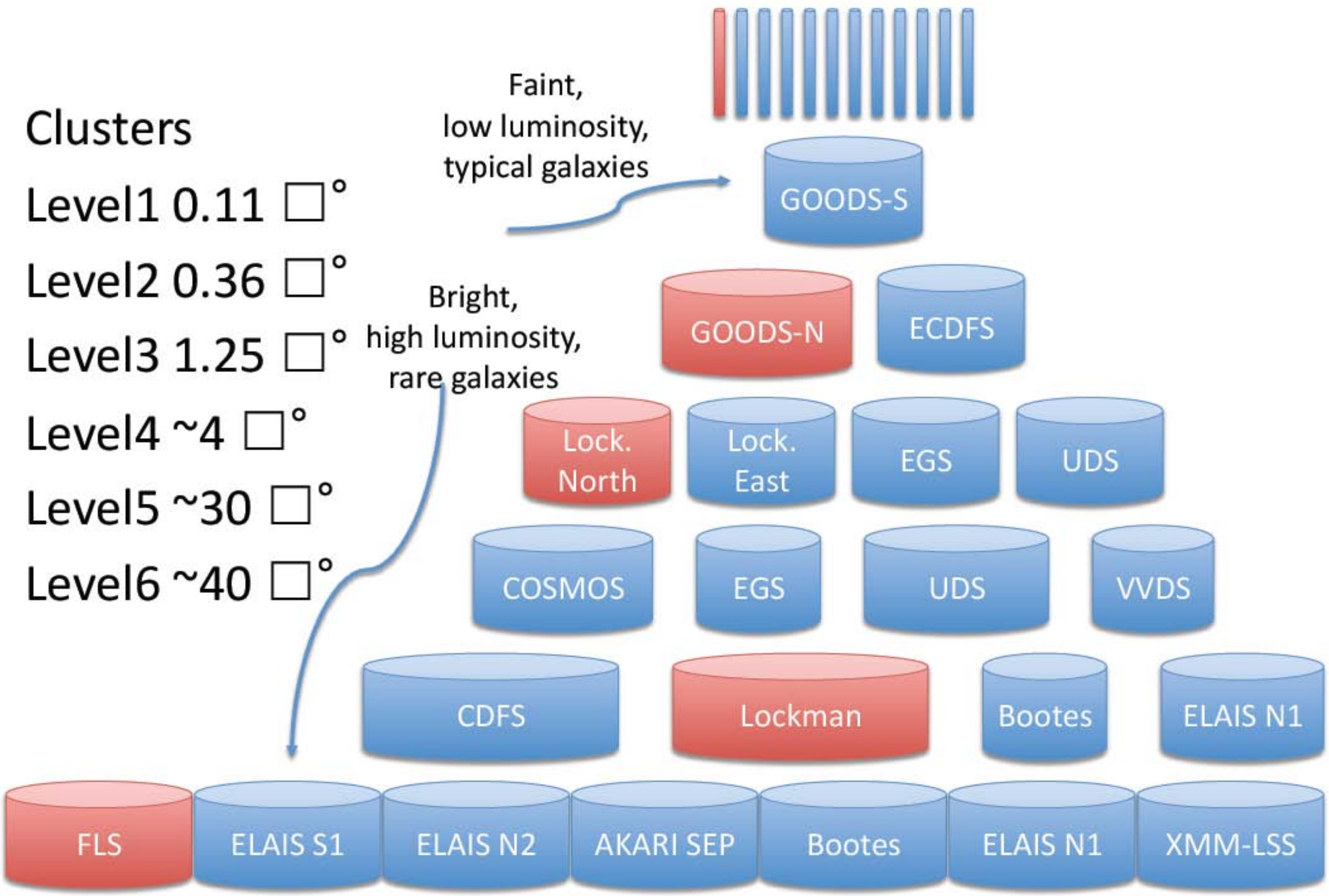
SPIRE GT Program

Bruno Altieri, **Alex Amblard,** Vinod Arumugam, Robbie Auld, Herve Aussel, Tom Babbedge, Alexandre Beelen, Matthieu Bethermin, **Andrew Blain, Jamie Bock,** Alessandro Boselli, **Carrie Bridge,** Drew Brisbin, Veroniquw Buat, Denis Burgarella, Nieves Castro-Rodriguez, Antonio Cava, Pierre Chanial, Ed Chapin, Scott Chapman, Michele Cirasuolo, Dave Celments, Alex Conley, Luca Conversi, **Asantha Cooray,** Gianfranco DeZotti, **Darren Dowell,** Naomi Dubois, Jim Dunlop, Eli Dwek, Simon Dye, Steve Eales, David Elbaz, Erica Ellingson, Tim Ellsworth-Bowers, Duncan Farrah, Patrizia Ferrero, Matt Fox, Alberto Franceschini, Ken Ganga, Walter Gear, Elodie Giovannoli, **Jason Glenn,** Eduardo Gonzalez-Solares, Matt Griffin, Mark Halpern, Martin Harwit, Evanthia Hatziminaoglou, Sebastian Heinis, **George Helou,** Jiasheng Huang, Peter Hurley, HoSeong Hwang, Edo Ibar, Olivier Ilbert, Kate Isaak, Rob Ivison, Ali Ahmed Khostovan, Martin Kunz, Guilaine Lagache, Louis Levenson, Carol Lonsdale, **Nanyao Lu**, Suzanne Madden, Bruno Maffei, Georgios Magdis, Gabriele Mainetti, Lucia Marchetti, Elizabeth Marsden, Gaelen Marsden, **Jason Marshall,** Ketron Mitchell-Wynne, Glenn Morrison, Angela Mortier, **Hien Nguyen,** Brian O'Halloran, Seb Oliver, Alain Omont, Frazer Owen, Mathew Page, Maurillo Pannella, Pasquale Panuzzo, Andreas Papageorgiou, Harsit Patel, Chris Pearson, Ismael Perez-Fournon, Michael Pohlen, Naseem Rangwala, Jason Rawlings, Gwen Raymond, Dimitra Rigopoulou, Laurie Riguccini, Davide Rizzo, Giulia Rodighiero, Isaac Roseboom, Michael Rowan-Robinson, Miguel Sanchez-Portal, Rich Savage, **Bernhard Schulz,** Douglas Scott, Paolo Serra, Nick Seymour, **David Shupe,** Anthony Smith, Jason Stevens, Veronica Strazzullo, Myrto Symeonidis, Markos Trichas, Katherine Tugwell, Mattia Vaccari, Elisabetta Valiante, Ivan Valtchanov, **Joaquin Vieira, Marco Viero,** Laurent Vigrouz, Lingyu Wang, Rupert Ward, Julie Wardlow, Don Wiebe, Gillian Wright, **Kevin Xu, Mike Zemcov**

Faculty and Researchers, Postdocs, Students, **(US participants)**

SPIRE

HERMES



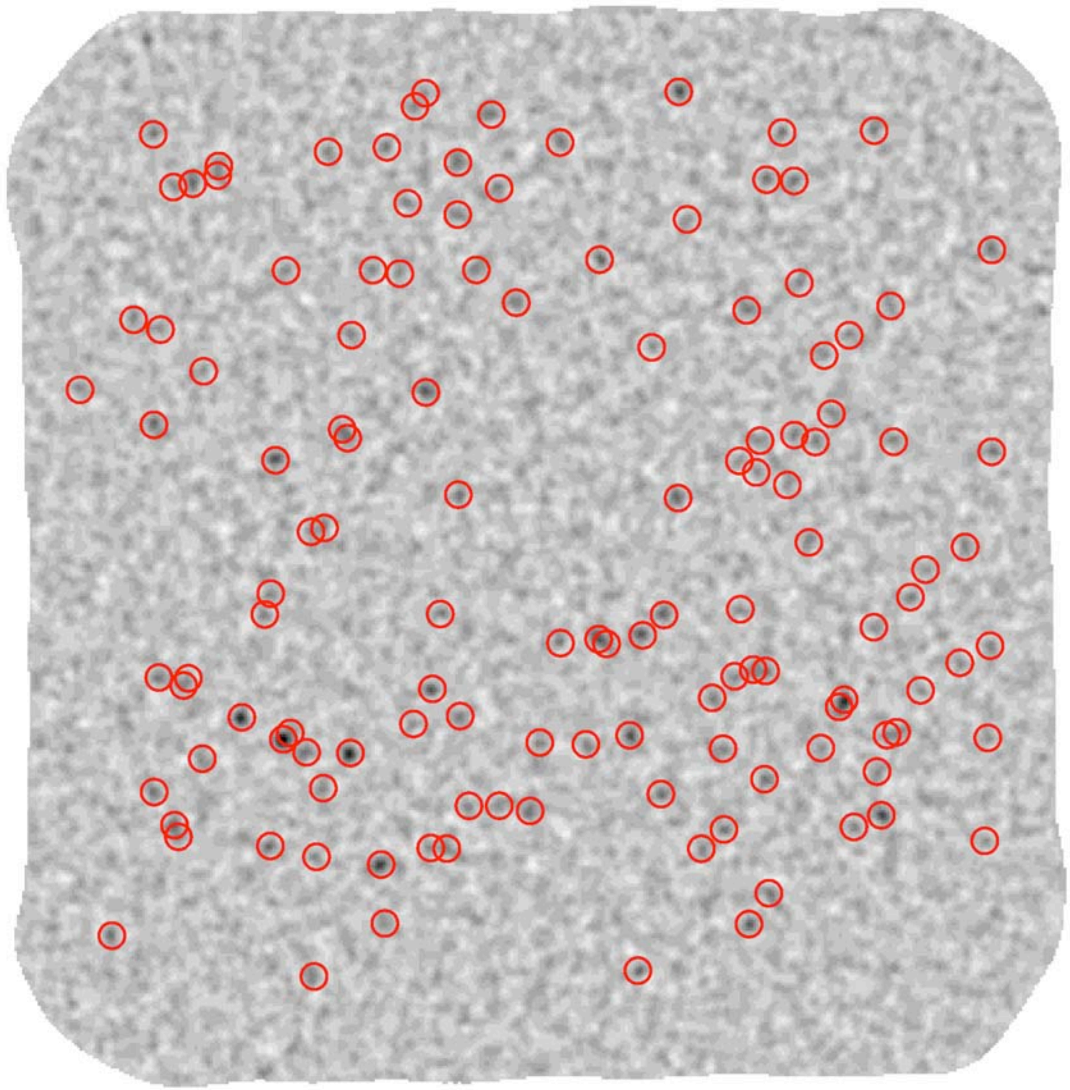
Science Demonstration Phase: 7 % of our total time

27,000 sources > 20 mJy @ 250 um

9 A&A papers + ~ 40 MNRAS papers in press/prep

data releases from http://hedam.oamp.fr/HerMES/

The LABOCA ECDFS Submillimetre Survey (LESS)



Weiss et al., 2009; Biggs et al. MNRAS submitted

870μm survey

- 30'x30' ECDFS
- σ~1.2mJy/beam
- Angular resolution = 19.2"
- 126 sources at >3.7σ
- Robust IDs for 75 SMGs
  (from radio, 24μm and IRAC)

Ian Smail (ESO co-PI)
Fabian Walter (ESO co-PI)

Axel Weiß (MPI PI)

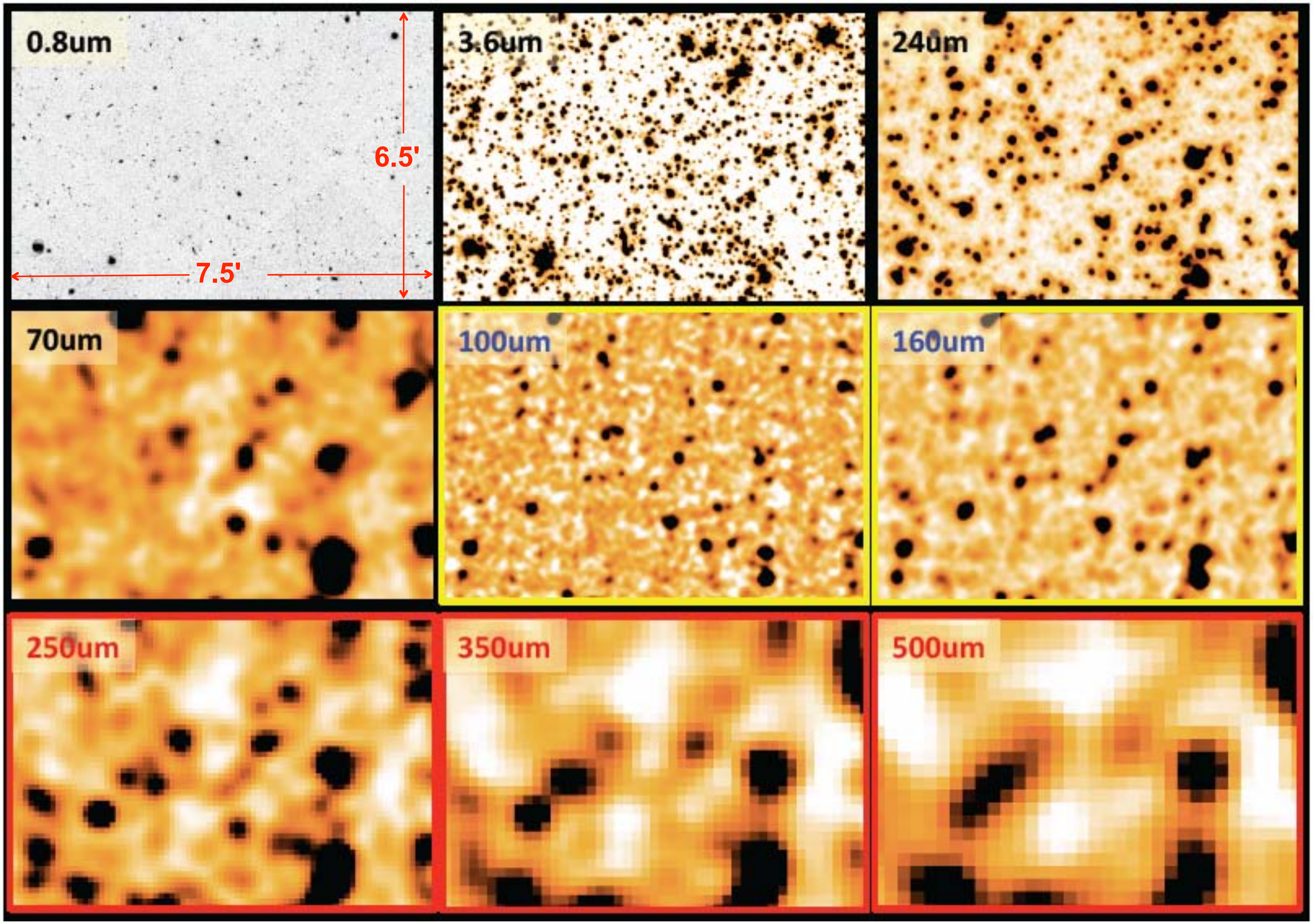
Including work led by:
Axel Weiß ,Andy Biggs,

Ryan Hickox,

Julie Wardlow (for PhD thesis,

Durham 2010)

The Confusion Challenge



D. Elbaz

Three Ways to Deal with Confusion

Herschel Source Photometry (Oliver et al. 2010)

- Need to be careful about bias (sources on background peaks)
- Blending of multiple sources, especially at 500 um
- Blind follow-up in large beam is laborious (~SCUBA)
- However these are the most interesting source populations!

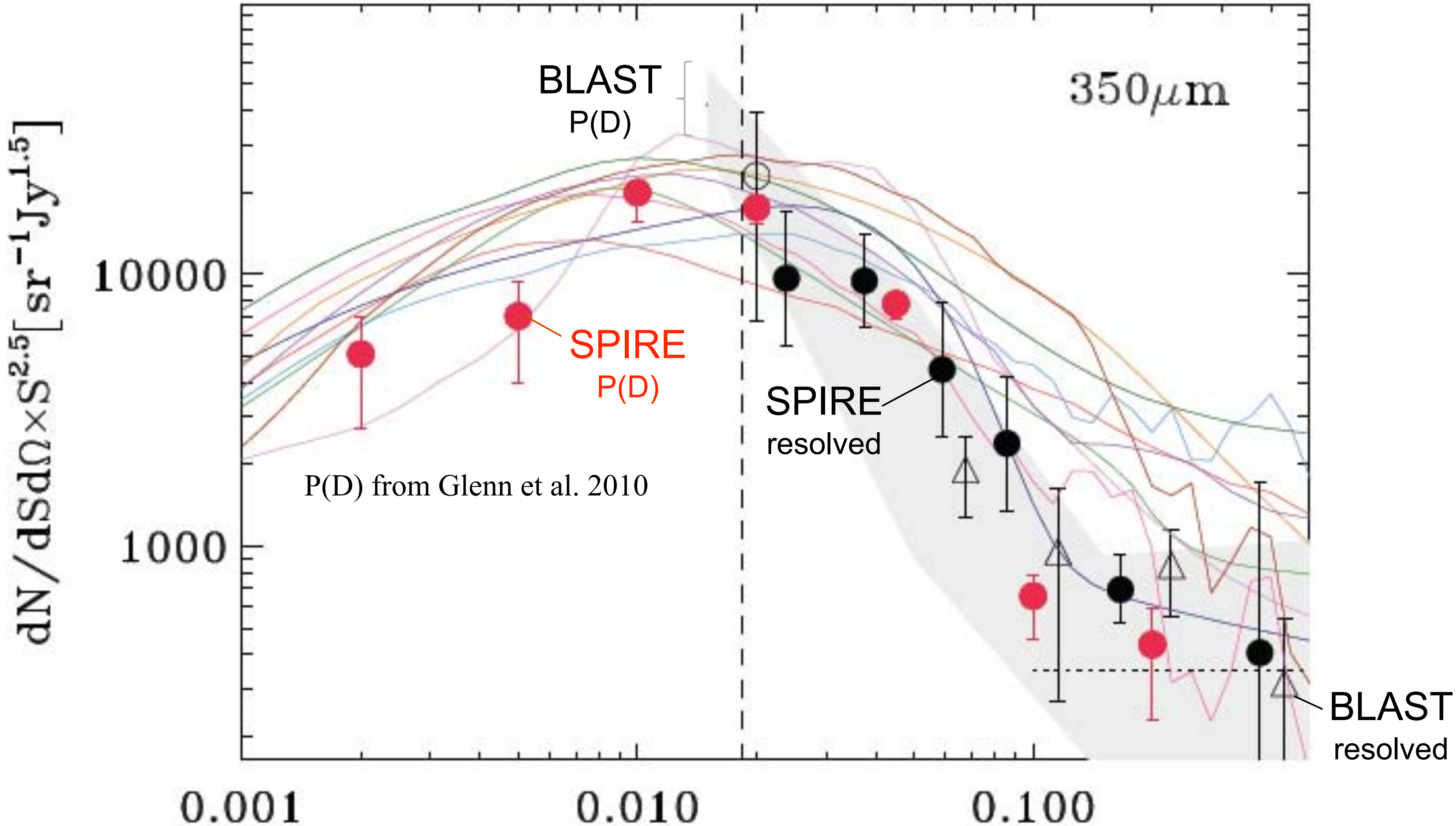
Pre-Existing Source Catalogs (Roseboom et al. 2010)

- Assign source flux from Herschel maps
- Reliable to within confusion noise
- Choose fields with comprehensive ancillary coverage
- Follows bias inherent in finder catalog

Map-Based Analysis (Glenn et al. 2010; Amblard et al. 2010)

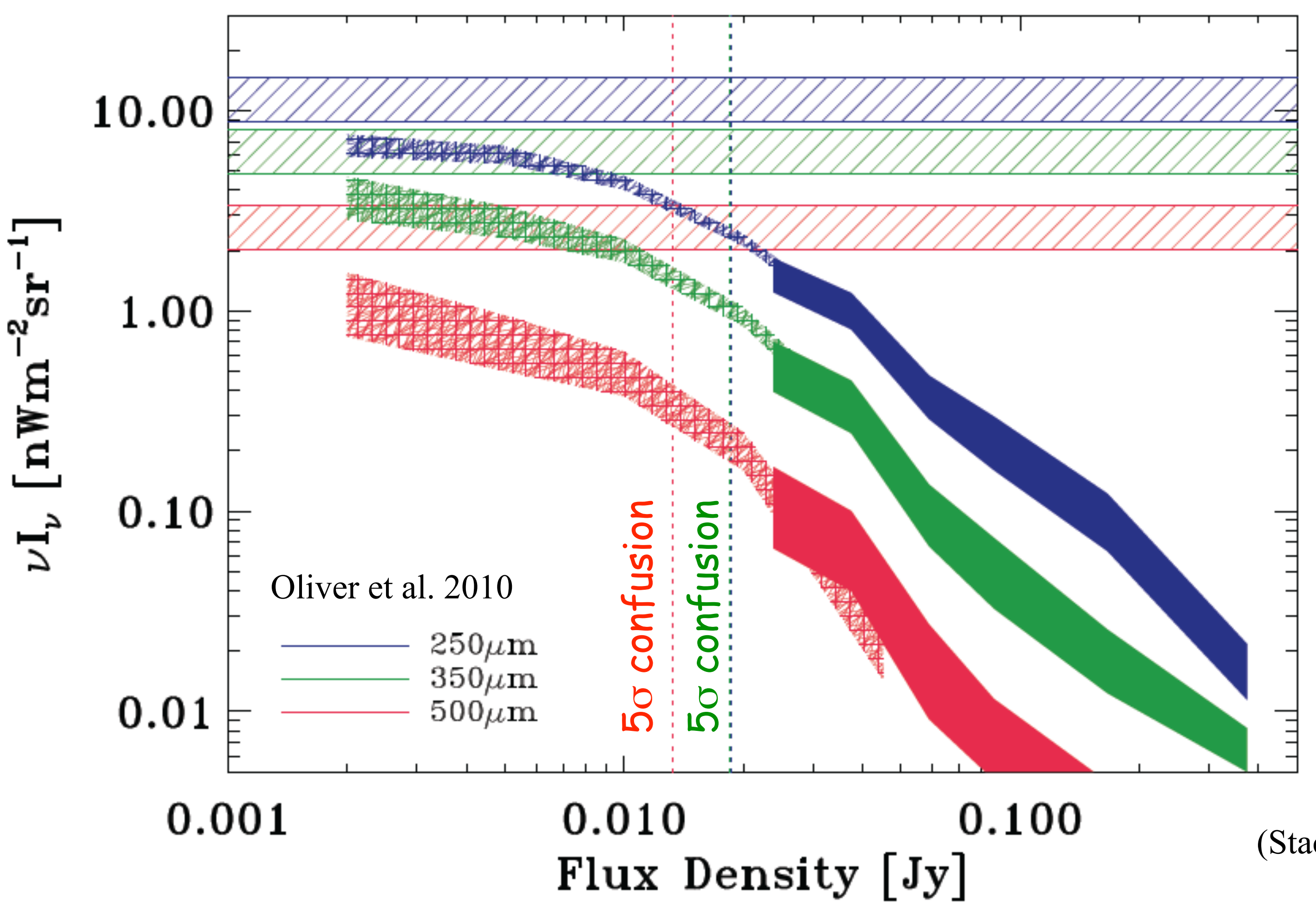
- Much more information in map than in reliable sources
- Tends to be ensemble information: P(D), fluctuations
- Maps have high statistical fidelity!

SPIRE Source Counts



- Number counts of bright galaxies (ULIRGS+) over-predicted by models
- Bright-end counts are steeper than models generically

Resolving the FIR Background



- **Source Counts**

250, 350, 500 μm
15%, 10%, 6%

- **P(D)**

250, 350, 500 μm
65%, 60%, 45%

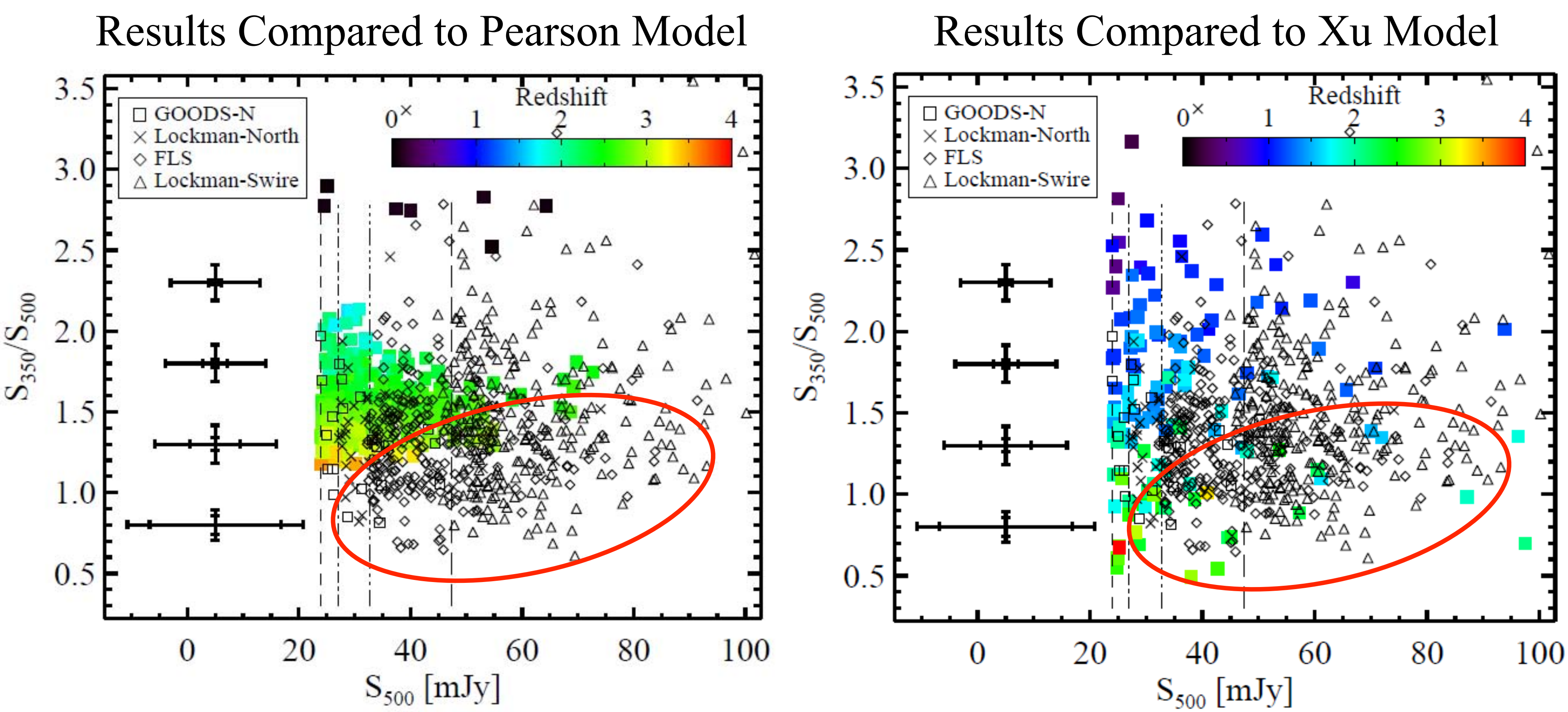
- **Stacking**

250, 350, 500 μm
80%, 80%, 85%

(Stacking papers to appear soon)

<u>Of course</u>: The remainder may be the most interesting sources!
E.g. the z > 3 galaxy population.

SPIRE Galaxy Colors

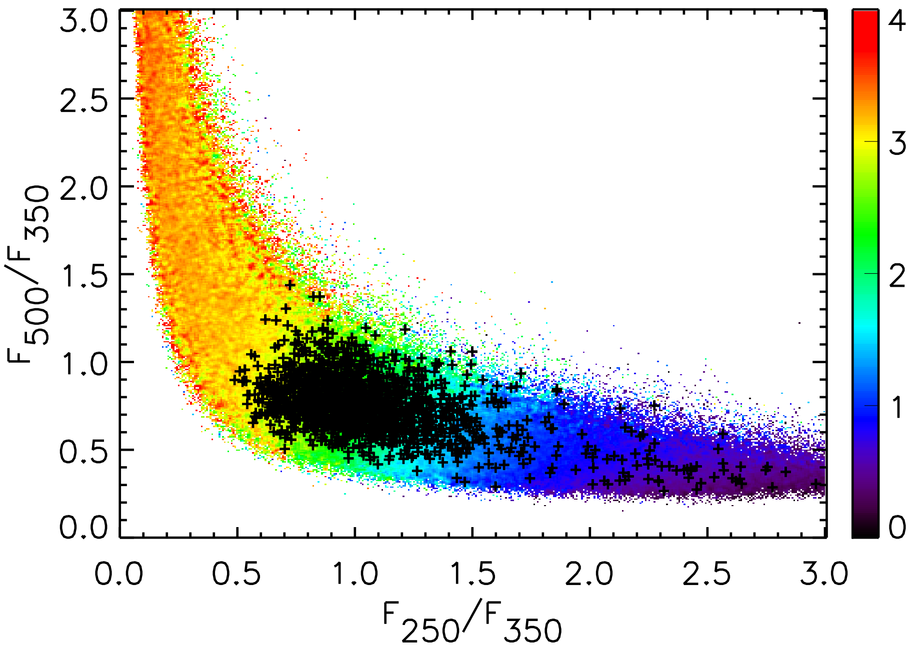


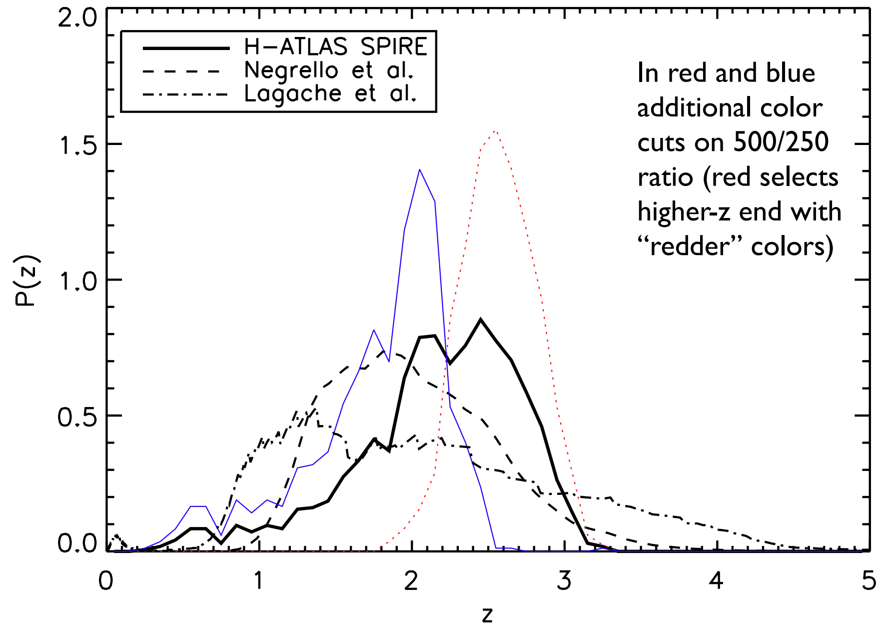
Schulz et al. 2010

Colors generally spread redder than models predict
- colder dust and/or higher z populations?

Redshift distribution of SPIRE Sources?

350μm selected galaxies > 5σ are at mostly at z = 2.2 ± 0.6





The surface density of 350 μm selected sources (z~1.8 to 3) S_{350} > 30 mJy is ~350/deg²

The "statistical" redshift distribution implied by SPIRE colors for the 1686 sources
[equivalent to fitting each SED with a single-temp model and marginalizing over T,β] *(Hughes et al 2002; Aretxaga et al. 2007)*

Amblard et al. 2010

Abundance of z > 3 sources?

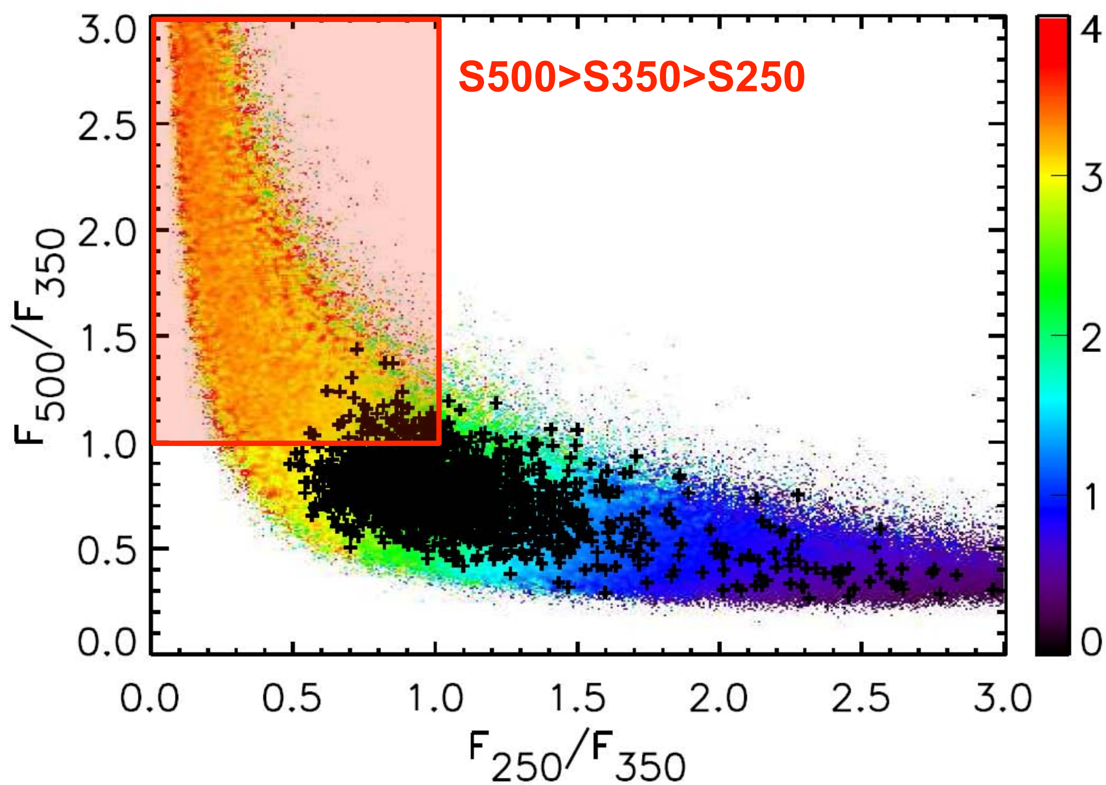
H-ATLAS:

In 14 sq. deg, out of 6800 sources, 281 sources with $S_{500} > S_{350}$

55 detected above 5σ (>45 mJy)

49 detected above 5σ in all 3 bands.

One of these is a blazar at z~1.02, in Fermi all-sky/WMAP catalog.



Amblard et al. 2010

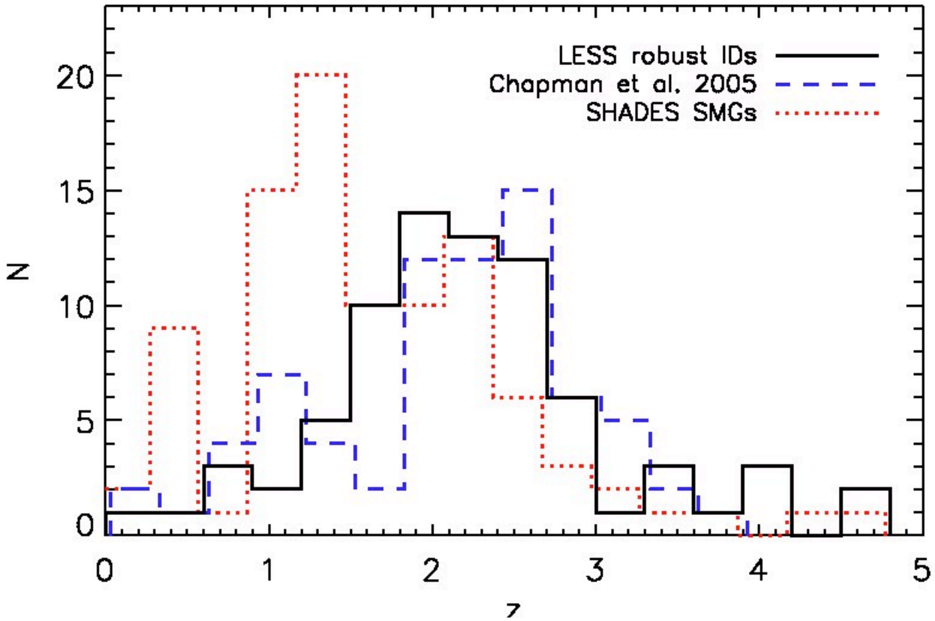
Are all the 281 sources at z > 3?

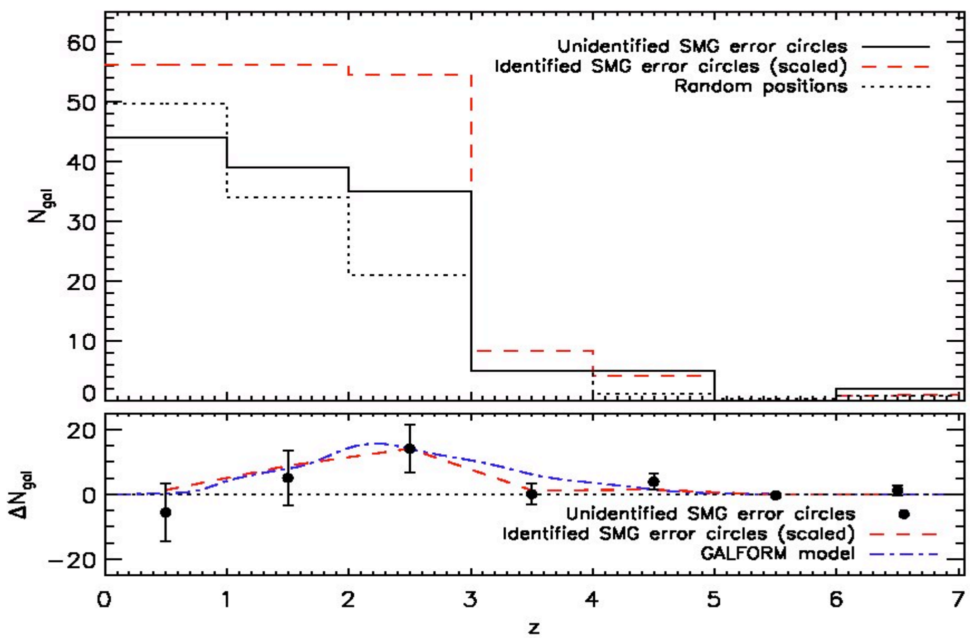
Unclear! We need follow-up data, especially near-IR.

CO-line redshifts?

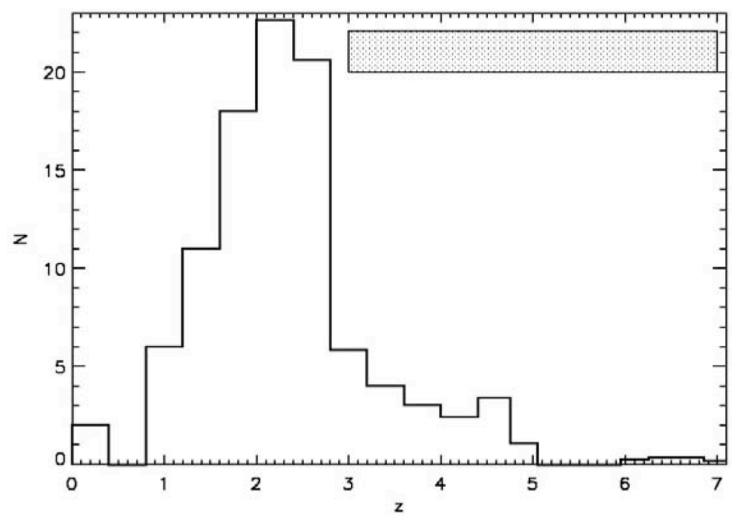
Assuming all 281 sources are z > 3, a rough lower limit on the surface density of z > 3 sources down to S_{500} > 45 mJy is ~20/deg^2

Photometric redshift distribution of LESS 870μm SMGs





- Median z=2.2
- High-redshift tail: several members spectroscopically confirmed (e.g. Coppin et al., 2009, 2010)
- Unidentified SMGs are likely to be mainly cold z~2 SMGs
- Median z=2.5±0.2
- <45% of SMGs are at z>3



Wardlow et al. MNRAS submitted

Herschel Followup: A new paradigm

SCUBA followup: deep VLA to get radio positions, Keck spectroscopy at radio positions; took a 4 year effort to get the SCUBA z-distribution for 70 or so sources (Chapman et al. 2004,2005)

Herschel HerMES followup: 24 micron Spitzer MIPS as a way to ID counterparts (then 24 micron to IRAC channels); usually we can identify 60% of our sources down to SWIRE depth with Spitzer. 20% no clear counterparts even in deep Spitzer imaging.

Bright lensed source follow-up (lensed, high-z etc): coordinates to SMA and other sub-mm facilities, coordinates to CO spectrometers and CO imaging facilities (CARMA, PdBI, GBT). IR IFU spectroscopy on CO redshifts. *No blind optical redshift measurements attempted.*

We seem to be finding about ~0.5 to 1 very bright lensed source per sq. degree (500 micron > 100 mJy and 870 micron > 20 mJy).

The expectation is Herschel will find about ~300 lensed SMGs in HerMES and H-ATLAS.

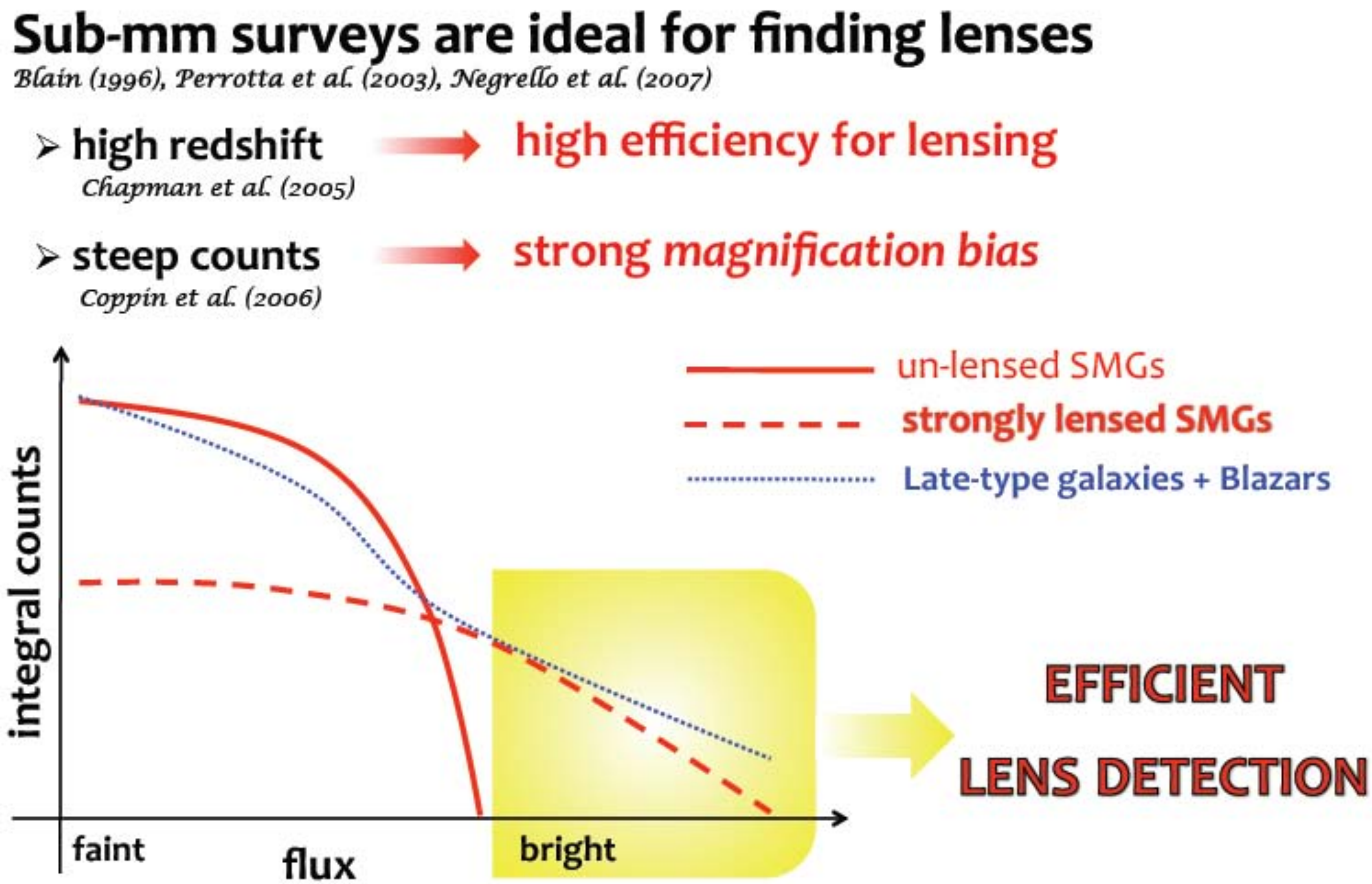
large programs at SMA, CARMA, PdBI, GBT (Zpectrometer), z-spec

The era of sub-mm astronomy:

Telescope	Instrument	Frequency Range	Bandwidth
GBT	Zpectrometer	25.6 – 36.1 GHz	34%
CSO	Z-Spec	190 – 305 GHz	46%
CSO	ZEUS[a]	632 – 710 GHz	4%
IRAM 30m	EMIR[a]	83 – 117 GHz	8%
PdBI	WideX[a]	80 – 116 GHz	3.6%
CARMA[a,b]		85 – 116 GHz	8%
EVLA[c]		12 – 50 GHz	53–18%
LMT[c]	RSR	74 – 111 GHz	40%
ALMA[a,c]		84 – 116 GHz	8%

(Frayer et al. 2010)

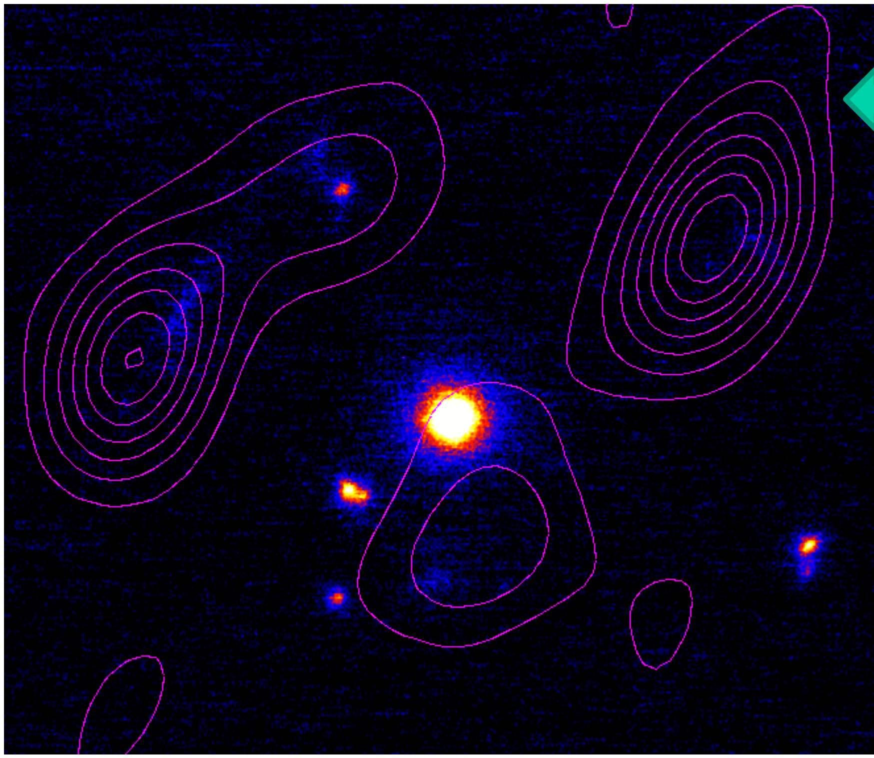
100% efficiency of identifying Lensed Galaxies



Negrello et al. Science, Oct 22nd issue; 3 parallel papers in ApJ on the same five sources (Lupu et al; Frayer et al; Hopwood et al)

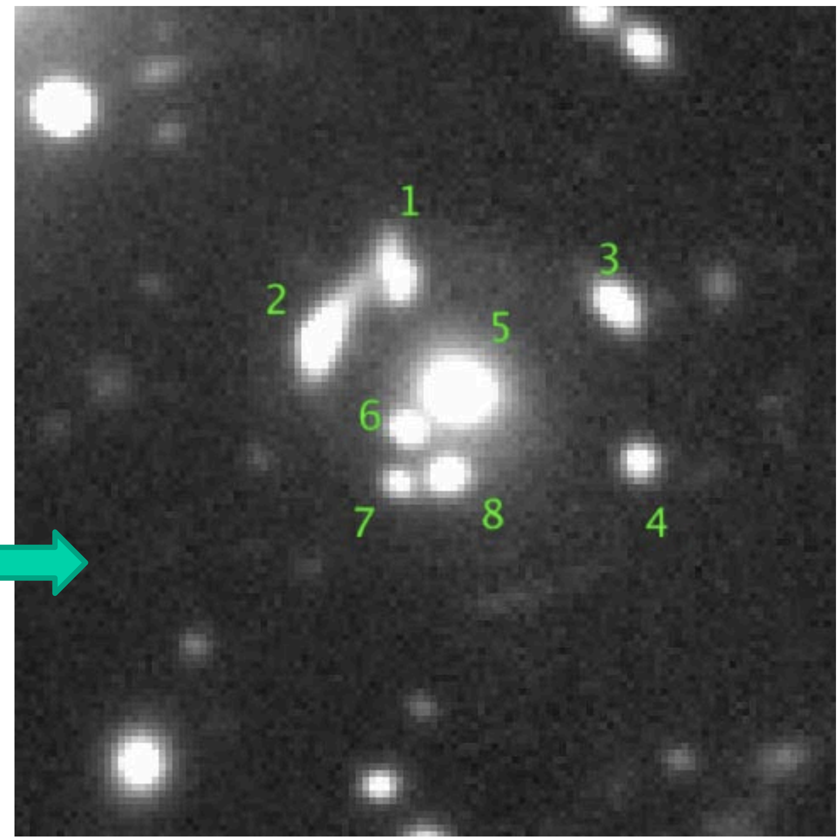
Lensed SMGs in HerMES: An example

9" Lensed Galaxy in HerMES
(brightest extragalactic SMG found by Herschel so far;
250 micron = 420 mJy, 15% brighter than eye-lash)

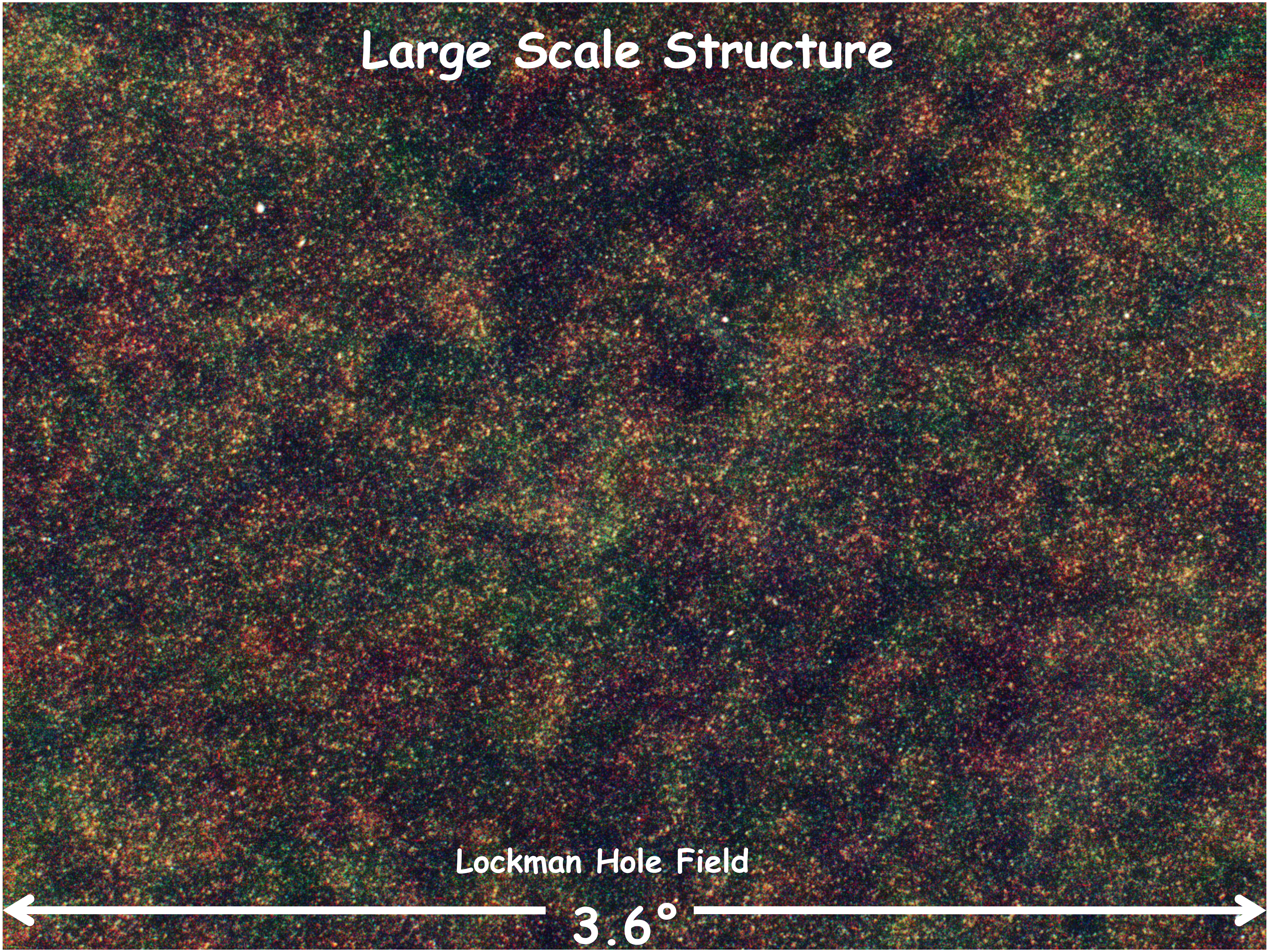


SMA 870 micron + Keck NIRC2 LGS AO

Subaru image

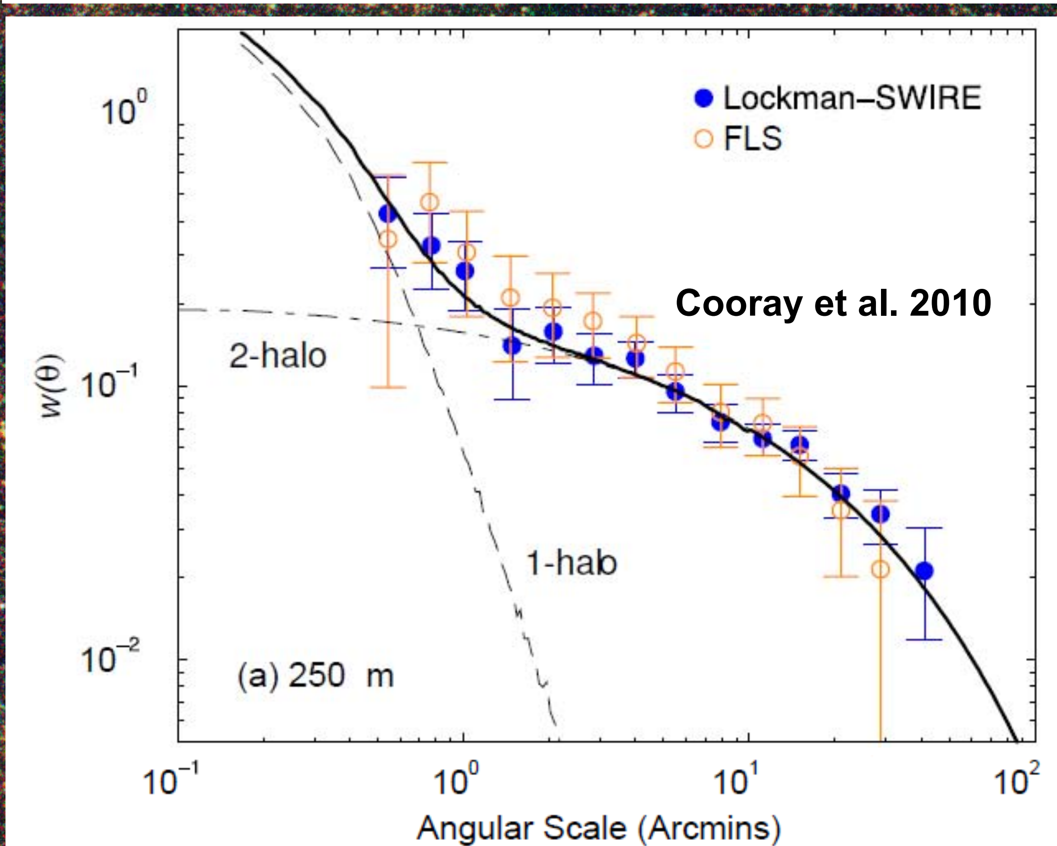


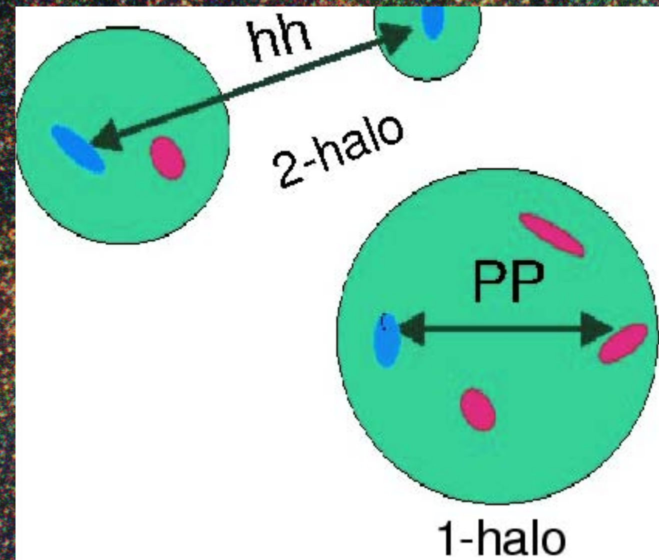
(4 papers soon in ApJL: Conley et al; Riechers et al; Scott et al; Gavazzi et al.)


Large Scale Structure
Lockman Hole Field
3.6°

Large Scale Structure

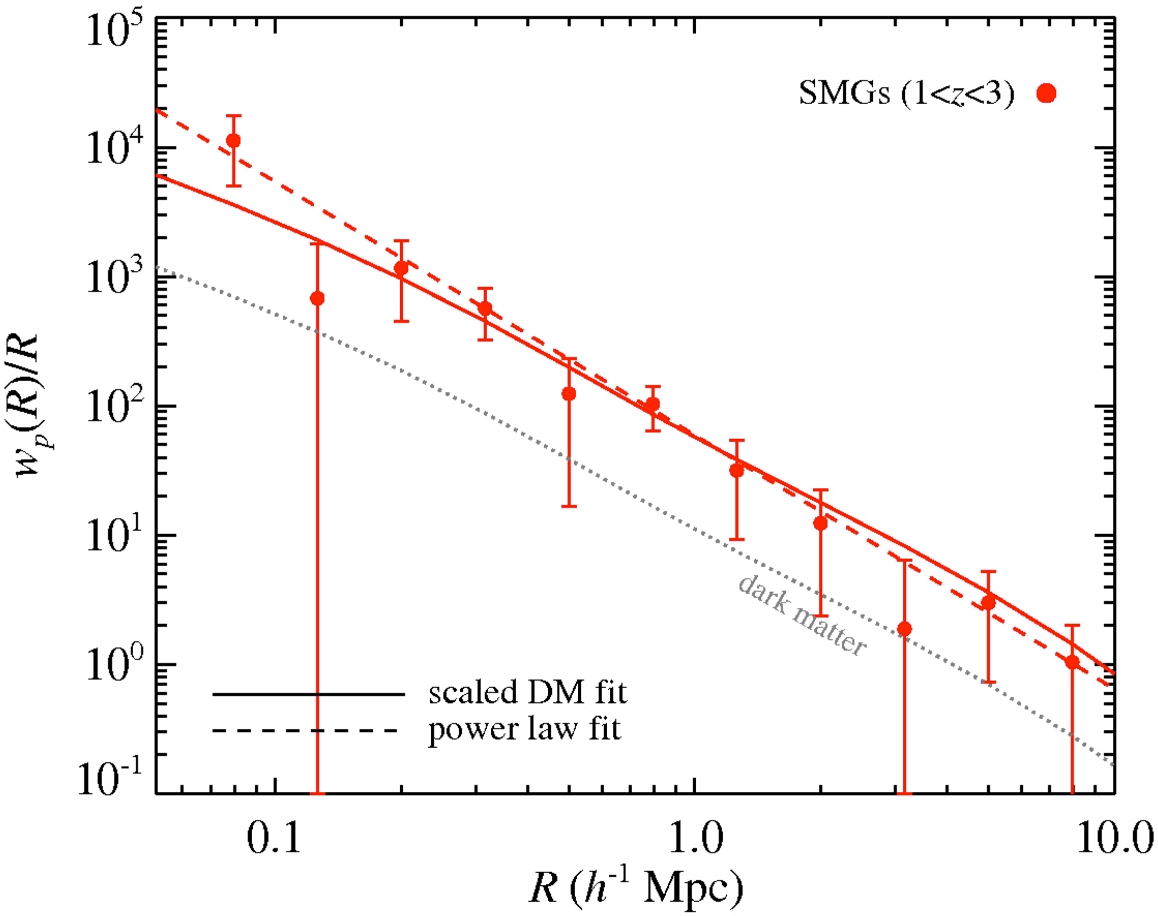
Angular Correlation of Detected Galaxies





- Spatial clustering of bright SMGs compared to halo model
- Halo needed to host a S_{250} > 30 mJy FIR galaxy: M = $10^{12.6}$ M_{solar}
- ~15% appear as satellites in more massive halos M ~ $10^{13.1}$ M_{solar}
- Population statistics consistent with so-called "dust obscured galaxies"

Clustering of LESS 870μm SMGs



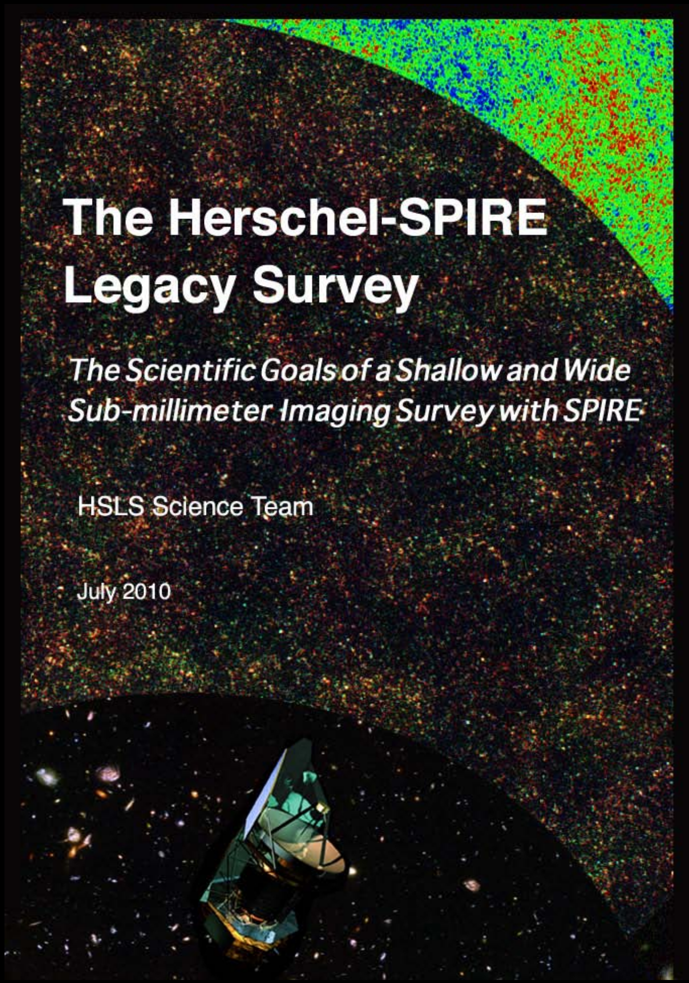
- Use P(z) for photo-zs of SMGs and IRAC-selected galaxies
- $b_{SMG}b_{gal}$=5.2±1.7
- B_{SMG}=2.6±0.9
- $M_{halo;SMG}$ = $10^{12.8}M_{sun}$
- Simulations show these evolve into $10^{14}M_{sun}$ halos at z=0
- **Progenitors of massive clusters**

Hickox et al. in prep.

870-μm selected galaxies have similar halo masses to Herschel-SPIRE 250-μm selected sources, and to Spitzer-selected dust-obscured galaxies, and to SDSS QSOs.

*Herschel-SPIRE Legacy Survey (HSLS)**

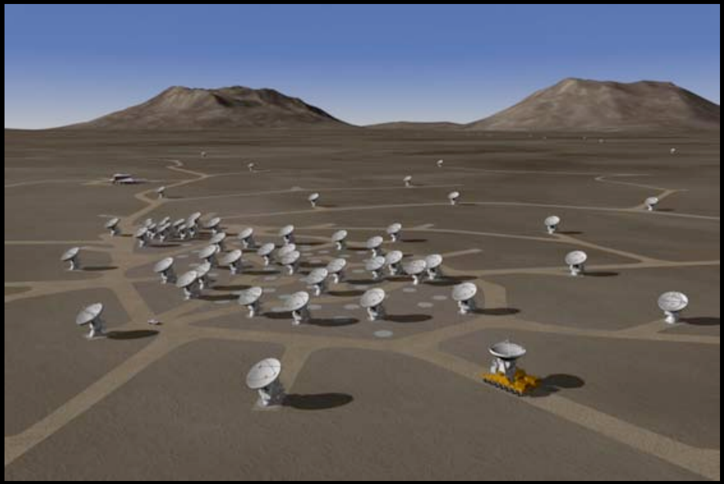
Map 4000 sq. degrees on the sky with SPIRE instrument in fast scan mode starting 2011.
780 hours to complete, single scans in SPIRE fast-mode (60"/sec)

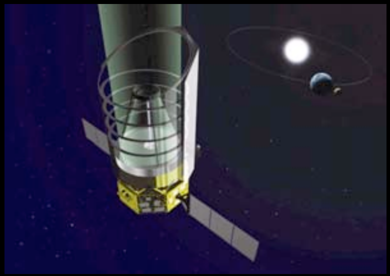


The HSLS will find 2.5 to 3 million dusty galaxies, ~1.5 million at z~2, 10,000 at z>4, ~1000 at z >5. Follow-up targets for ALMA, SPICA etc.

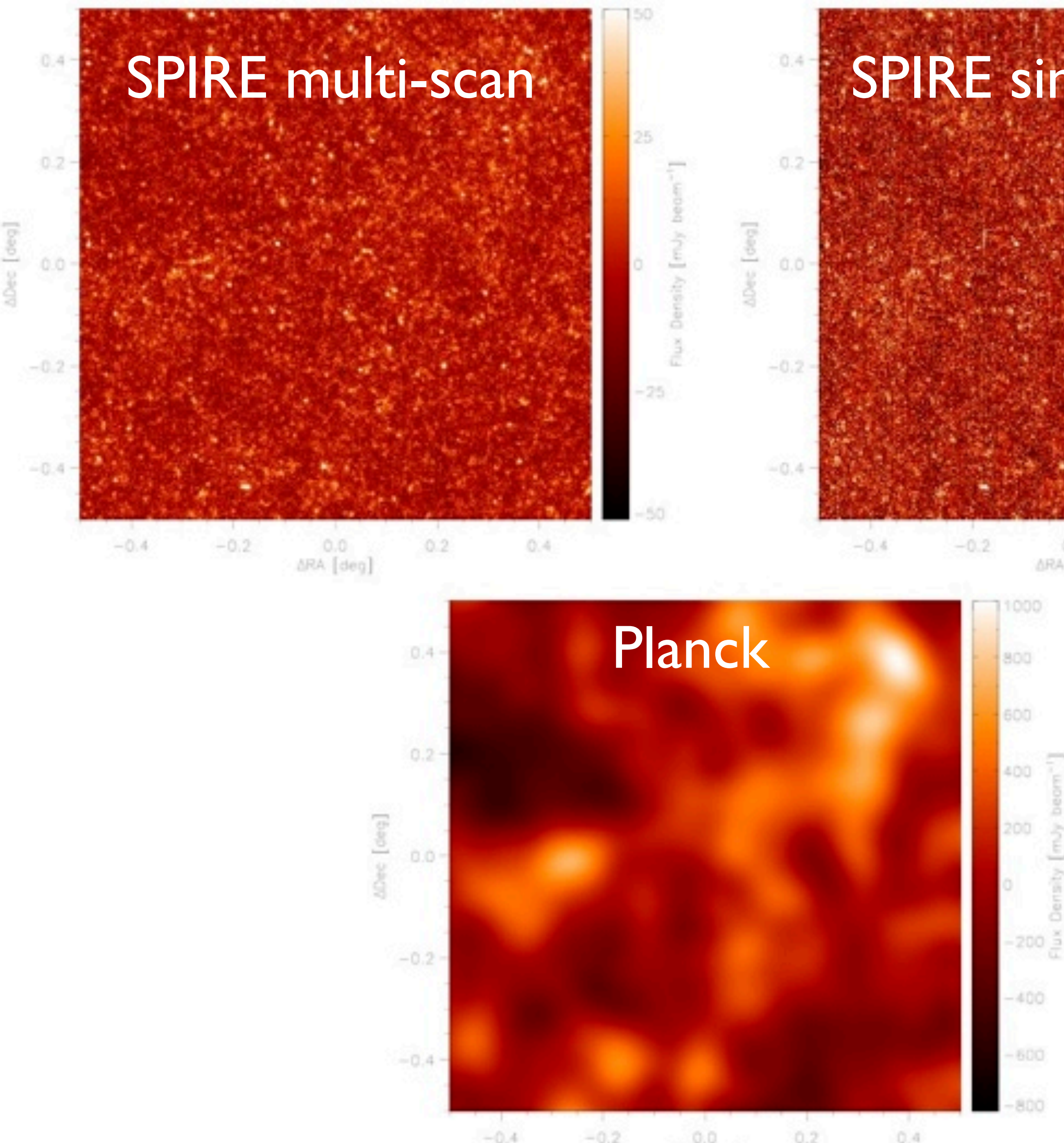
~2000 strongly lensed bright sources easily identified, a goldmine for cosmology!

see the HSLS White Paper on the arxiv 1007.3519 now



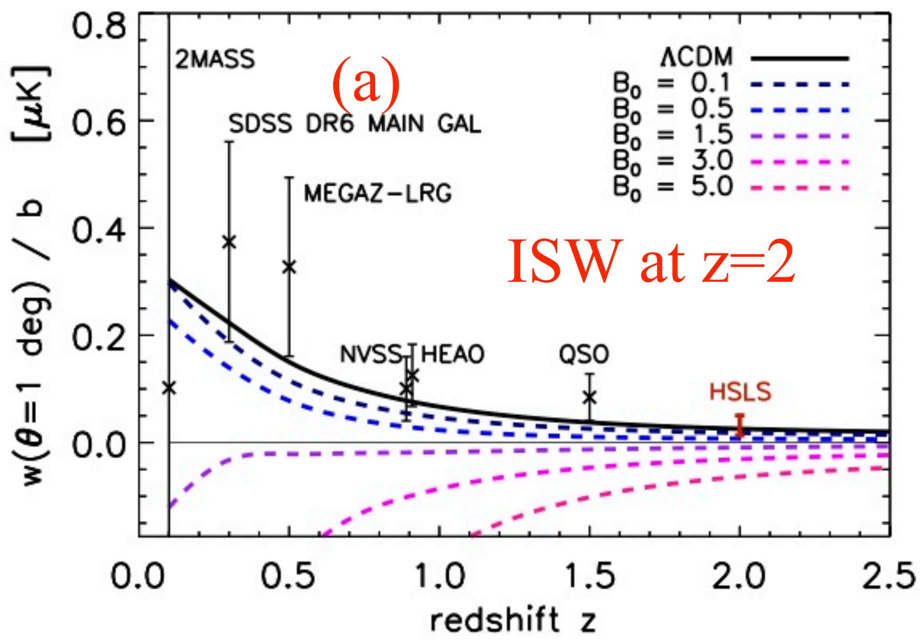


*Time not allocated by HOTAC due to programmatic reasons

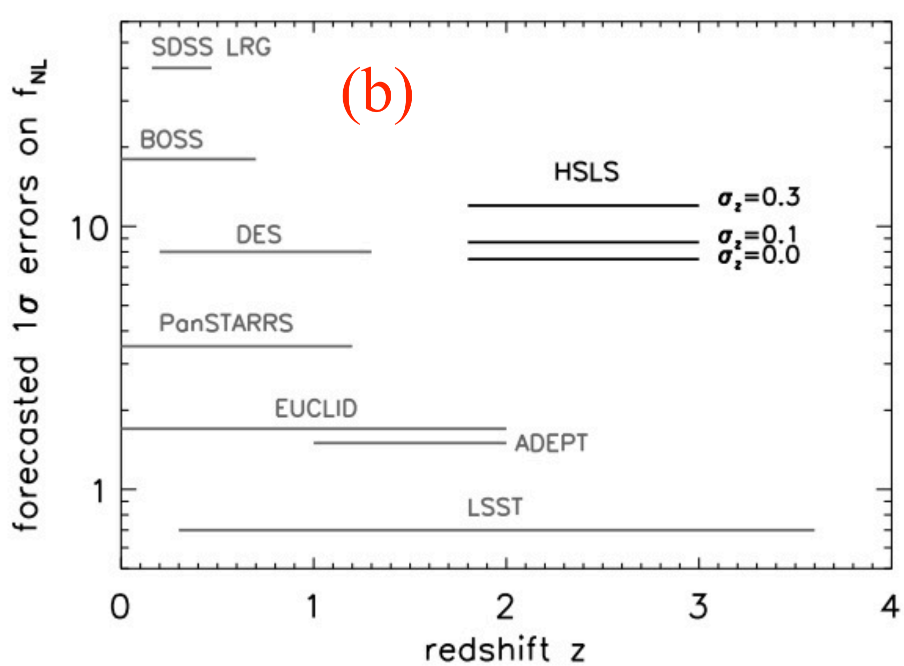

SPIRE multi-scan
SPIRE single-scan
Planck
ΔRA [deg]
ΔDec [deg]
Flux Density [mJy beam⁻¹]
50
25
0
-25
-50
1000
800
600
400
200
0
-200
-400
-600
-800

Cosmological Applications with HSLS

(a) ISW at z=2: A strong probe of modified gravity theories for acceleration



(b) large-scale clustering constrain primordial non-Gaussianity with a higher z probe than Euclid/LSST



Please see HSLS white paper on the web for more details, arxiv.org:1007.3519

Conclusions

Exciting results from Herschel and ground-based facilities, many more to come!

A wide area survey with CCAT at 870 microns would be an interesting addition to cosmological surveys (also complement HSLS).

The science case for a wide-field sub-mm cosmological survey is already written up as part of the HSLS study to ESA,

see arxiv.org:1007.3519