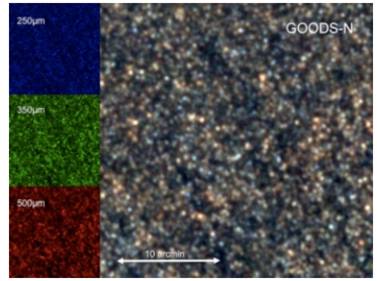
Gravitational Lensing at Sub-mm Wavelengths: New Insights from Herschel

Asantha Cooray

Herschel High-z Key Projects

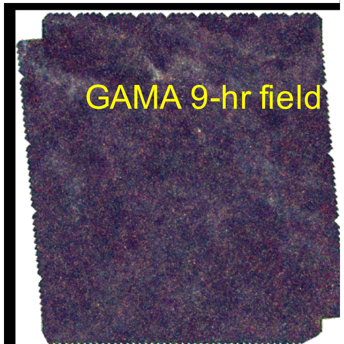
HerMES: *Herschel* Multi-tiered Extragalactic Survey



- PACS + SPIRE
- GT1: 70 sq deg from 20′×20′ to 3.6°×3.6° (800 hours) + 12 clusters
- New in GT2: 270 sq degrees in Stripe-82 with 2 scans (for CIB fluctuations + rare sources) - (~100 hours)
- Bolometric luminosities of galaxies, cosmic SFH
- Wedding cake to probe range of luminosities and environments

(see Jamie's talk for more details and recent results)

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

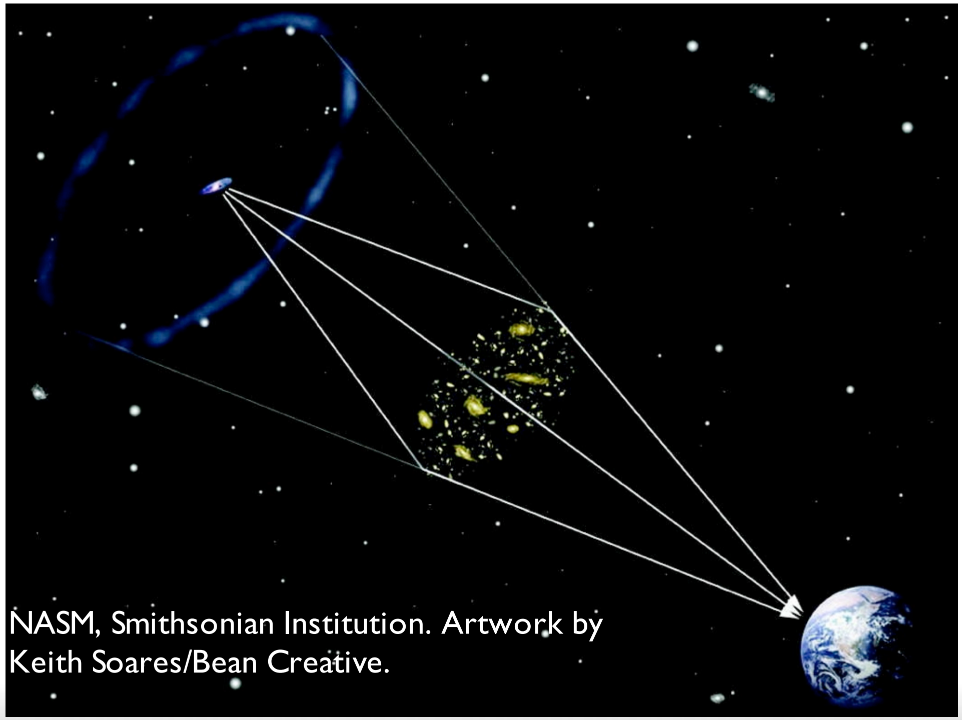


3-col SPIRE H-ATLAS SD field

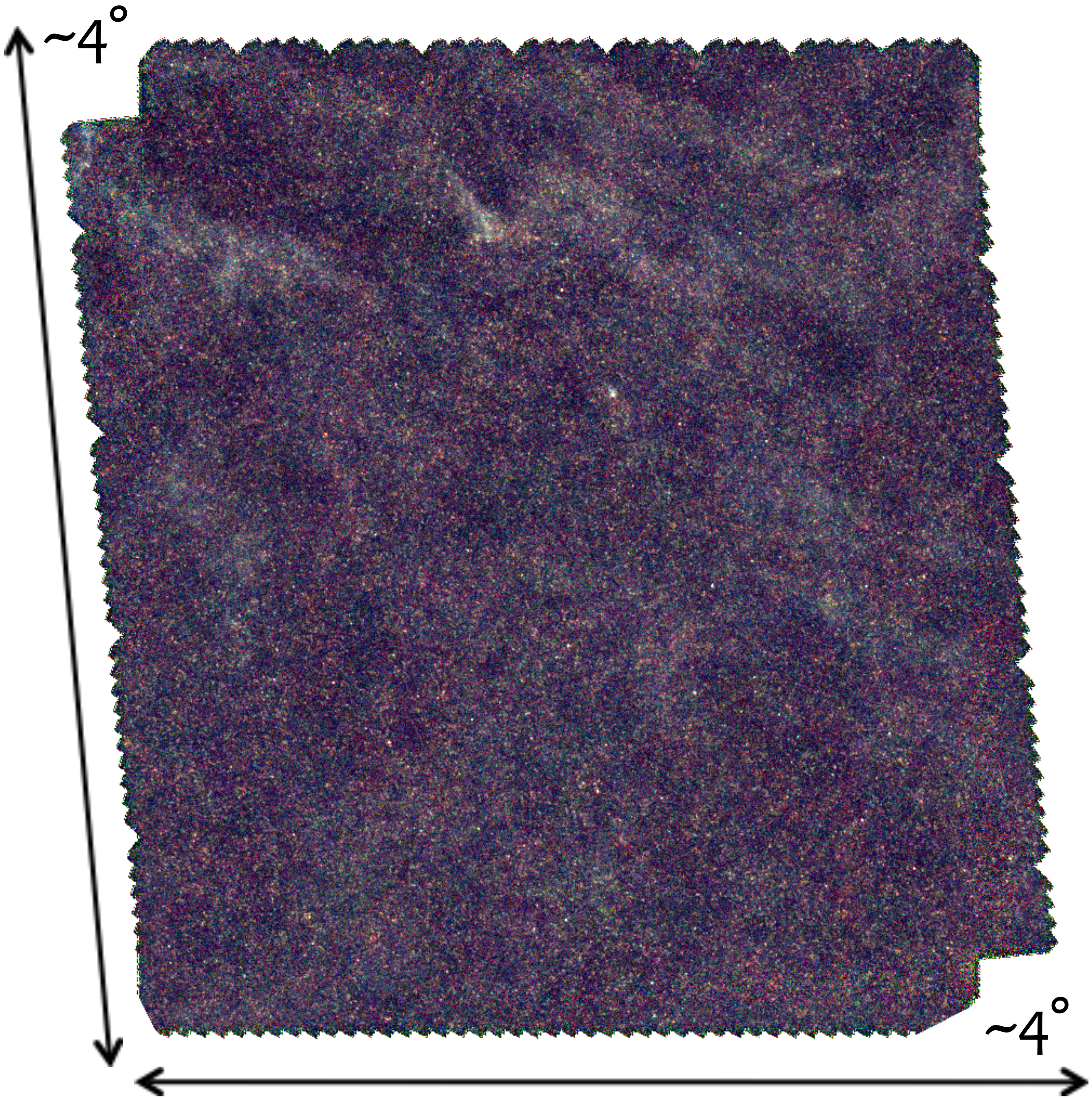
- PACS + SPIRE
- 550 sq deg (600 hours) in 3 GAMA fields; 200 sq deg NGP & SGP
- Low-z sciences, lensed sources, AGN
- Expect ~500,000 detections to z~3, majority at 250 & 350 um

Gravitational lensing

- Light affected by intervening mass (galaxy).
- Flux boosted (magnified): Can study fainter objects than usually available. - Useful at sub-mm wavelengths since source detection is confusion limited (SPIRE 350 micron: ~6 mJy) With lensing, the hope is we can study faint sources with intrinsic fluxes below confusion
- Increase in spatial resolution: Study properties of the dust, gas, and stellar emissions down to few 100 pc scales (e.g., 200 pc scale resolution in “Cosmic Eyelash” - Swinbank et al. 2010)
- Gravitational determination of mass of foreground galaxy.



500 µm BRIGHTEST GALAXIES IN H-ATLAS SDP



H-ATLAS SDP field

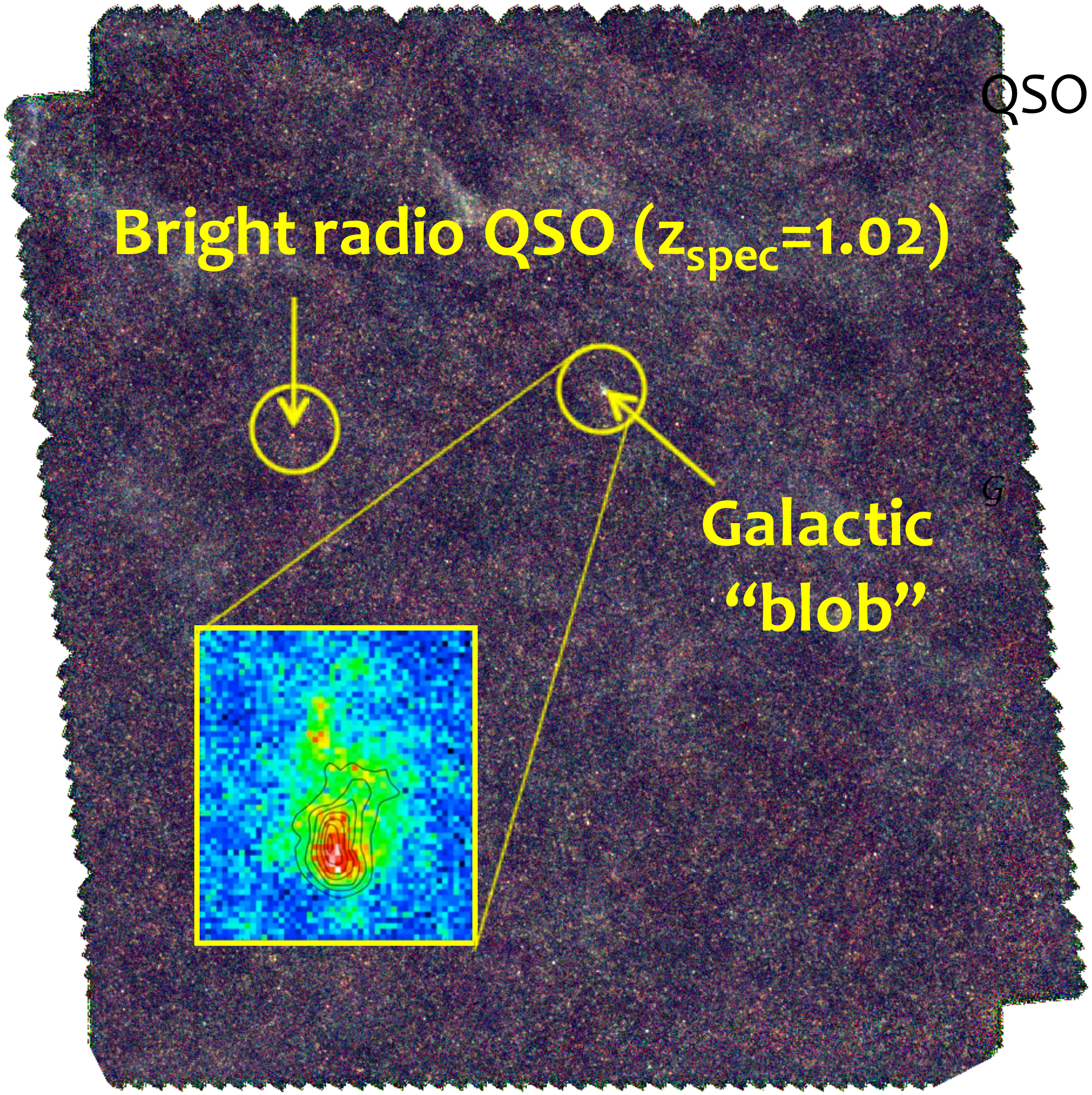
- ~ 14.4 deg²
- ~ 7000 sources

11 sources with

$S_{500\mu m}$ > 100 mJy

ATLAS slides from Mattia Negrello

500 μm BRIGHTEST GALAXIES IN H-ATLAS SDP



QSO: $S_{250\mu m}$ = 159.6 mJy

$S_{350\mu m}$ = 193.8 mJy

$S_{500\mu m}$ = 265.8 mJy !

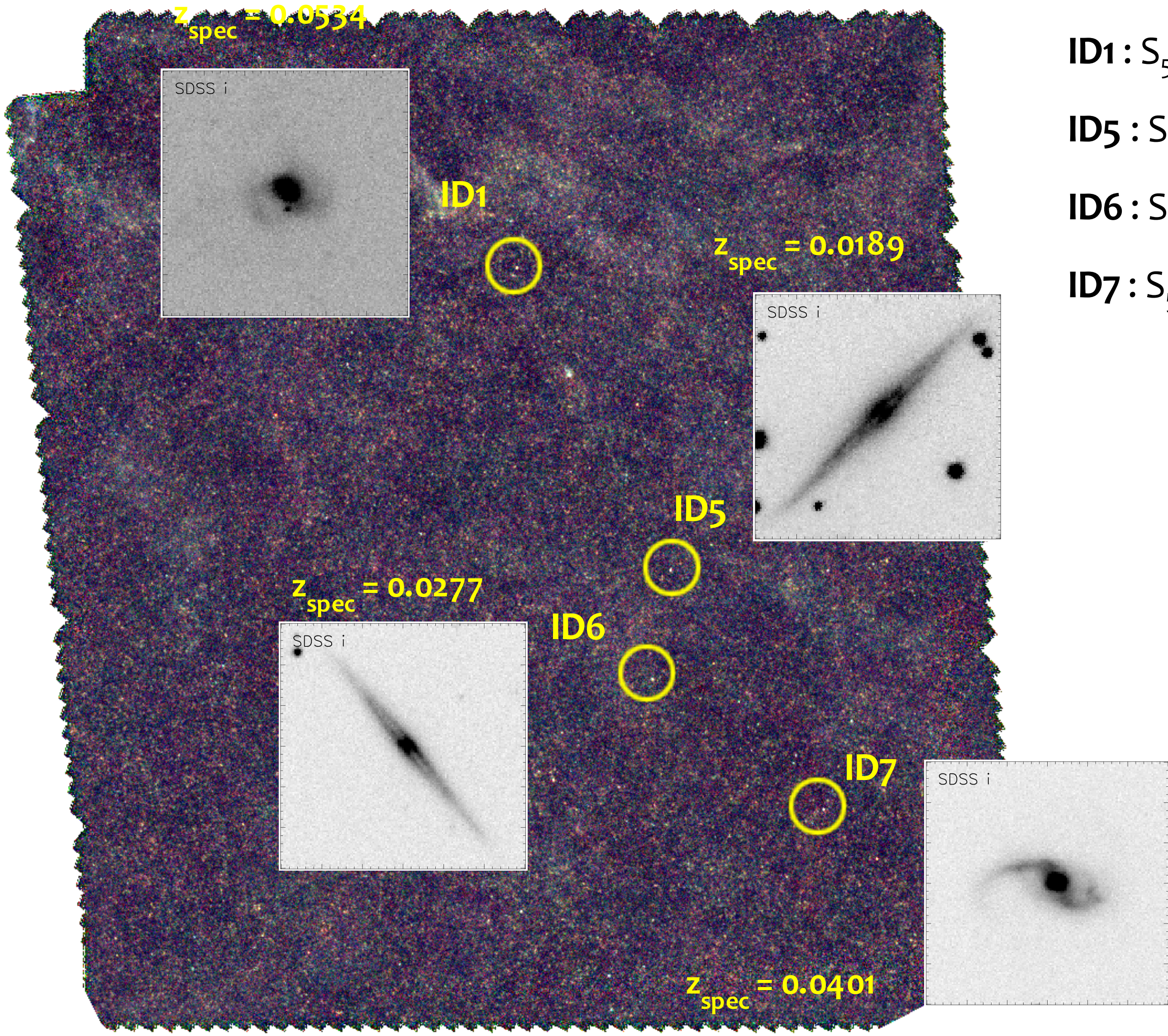
$S_{1.4GHz}$ = 571.7 mJy

in WMAP point source catalog!

prediction: **~0.1 deg^{-2}**

De Zotti et al. (2005)

500 μm BRIGHTEST GALAXIES IN H-ATLAS SDP



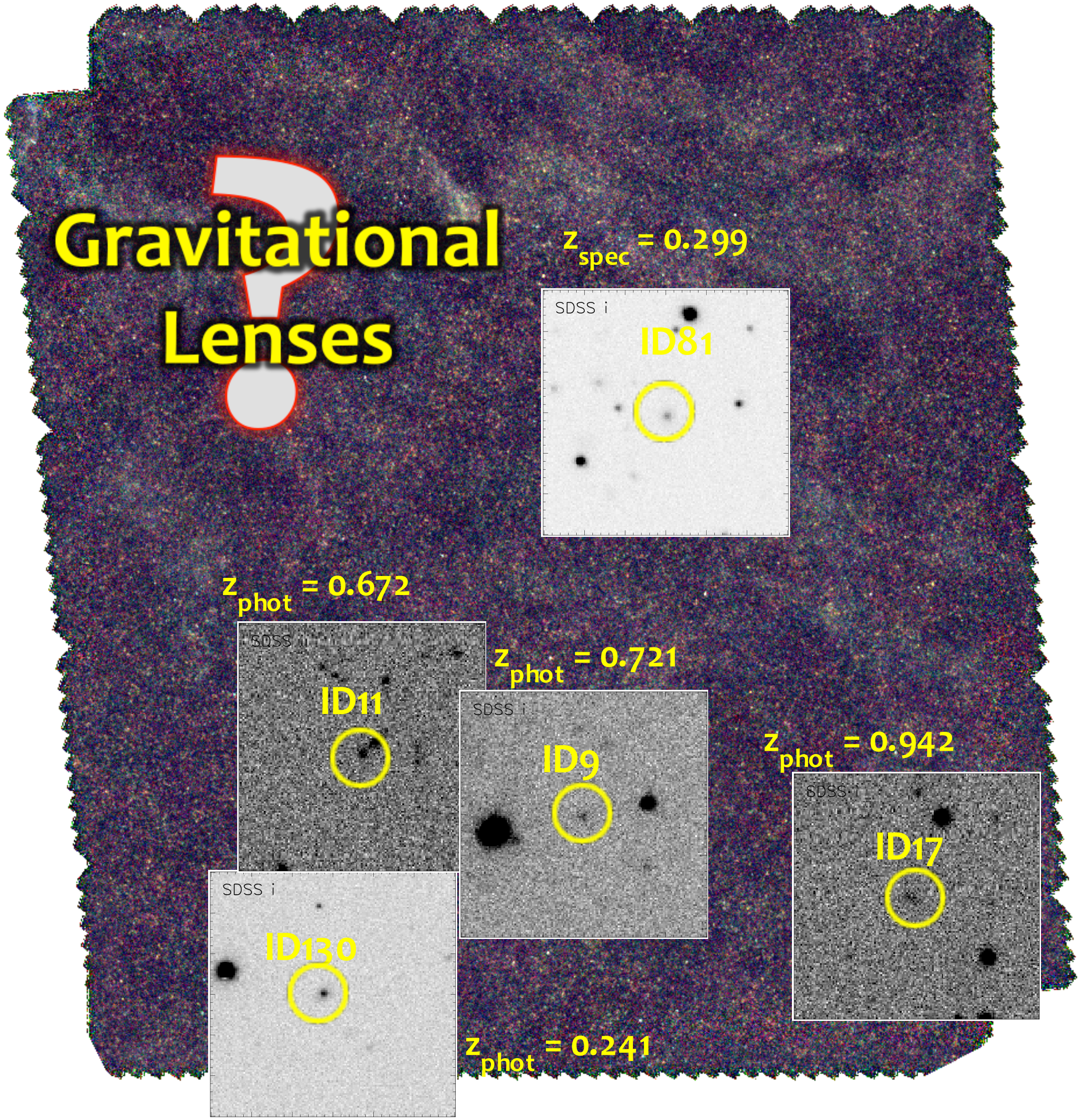
ID1 : $S_{500\mu m} = 177 \pm 28$ mJy

ID5 : $S_{500\mu m} = 122 \pm 20$ mJy

ID6 : $S_{500\mu m} = 112 \pm 19$ mJy

ID7 : $S_{500\mu m} = 104 \pm 18$ mJy

500 μm BRIGHTEST GALAXIES IN H-ATLAS SDP



ID9 : $S_{500\mu m}$ = 175 ± 28 mJy

ID11 : $S_{500\mu m}$ = 238 ± 37 mJy

ID17 : $S_{500\mu m}$ = 220 ± 34 mJy

ID81 : $S_{500\mu m}$ = 166 ± 27 mJy

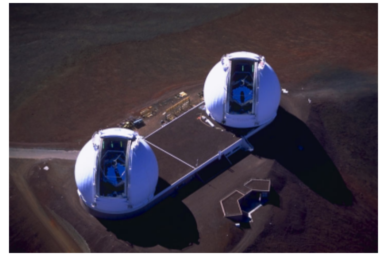
ID130 : $S_{500\mu m}$ = 108 ± 18 mJy

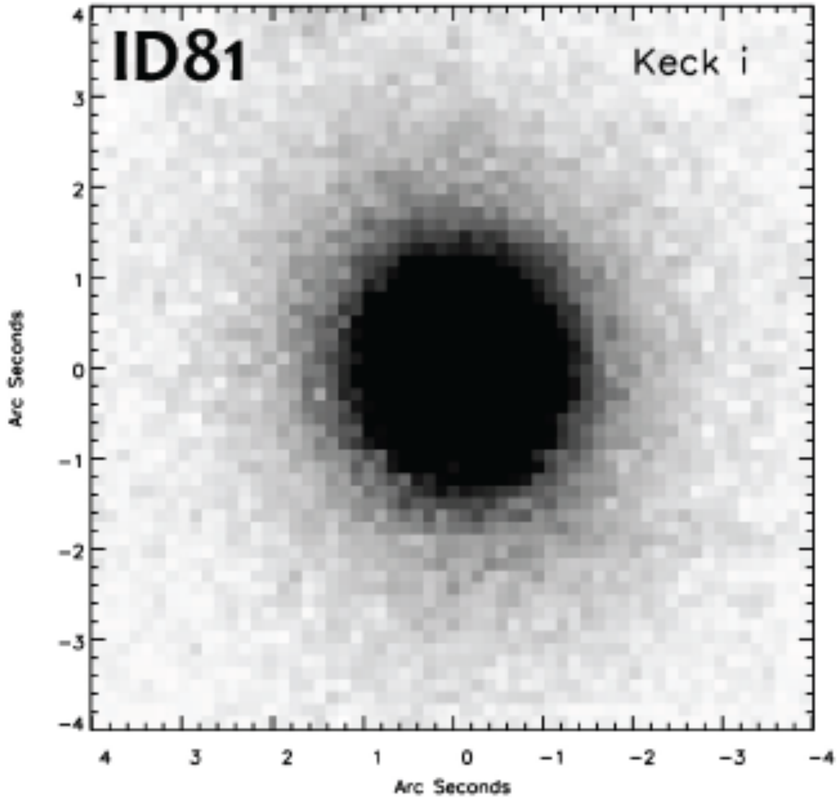
optical counterparts

$z_{phot/spec}$ < 1.0

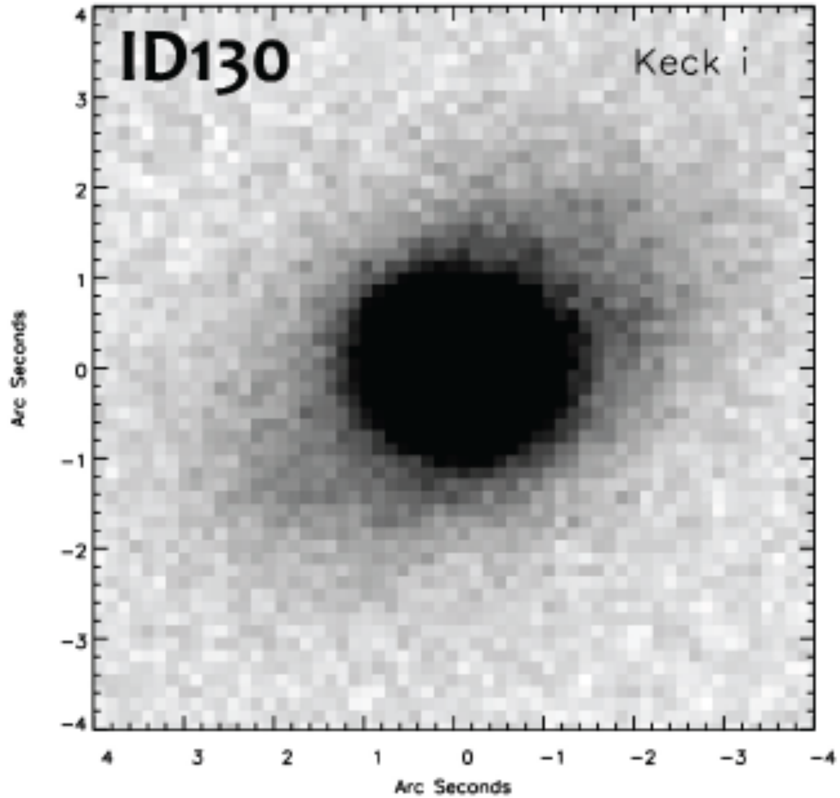
Lensing Candidates ID81 & ID130

Keck imaging in **g** and **i** bands





z=0.299



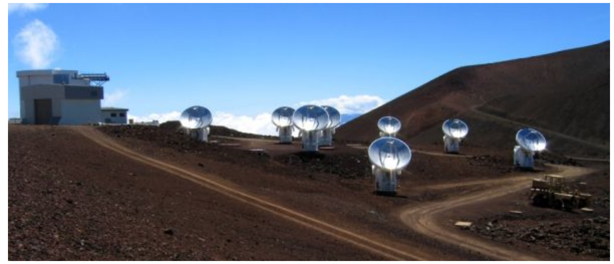
z=0.223

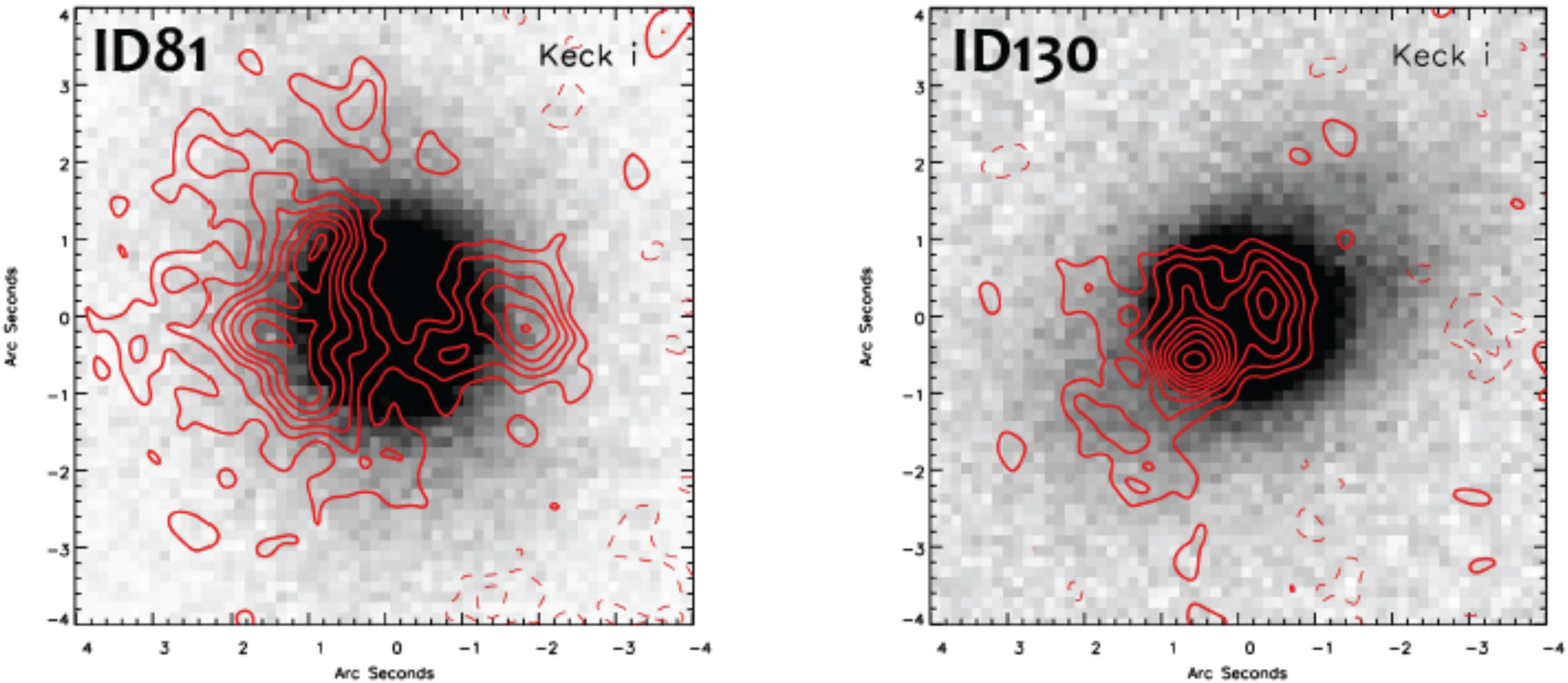
(Sam Kim; UCI student)

Lensing Candidates ID81 & ID130

Sub **M**illimeter **A**rray follow-up at **870 µm**

(*very-extended*, *sub-compact* and *compact* configurations)

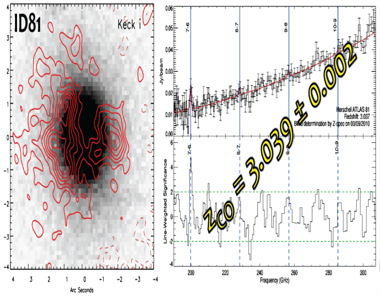


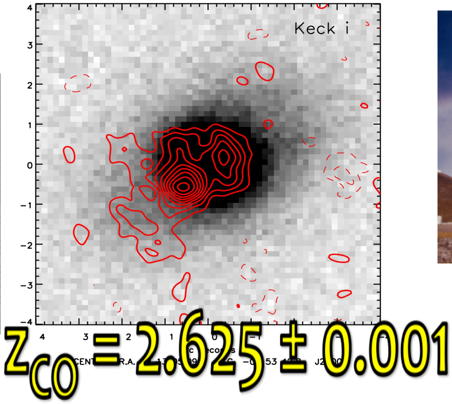


CREDITS: Mark Gurwell (CfA)

First Herschel CO Redshifts

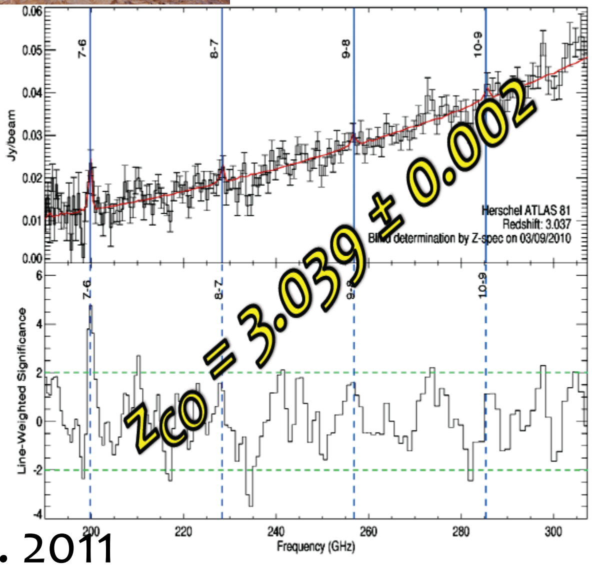
/Z-spec blind redshift determination for ID81 (March 09 2010)
n observations of the CO ladder

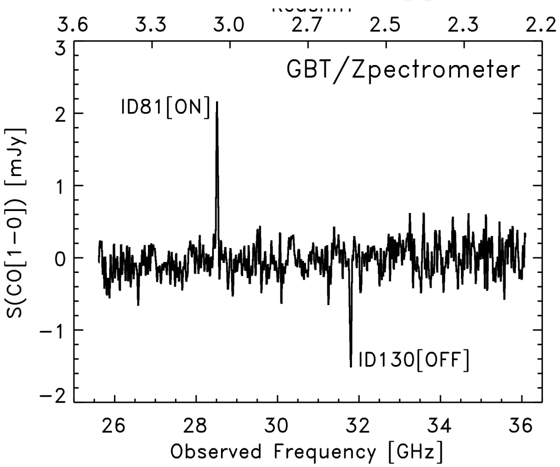




z-spec: Lupu et al. 2011

(March 09 2010)

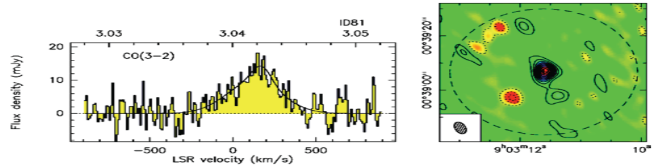




GBT:

Frayer et al. 2011

-ups with the PdB Interferometer
ctrometer (March 25 2010)



PdBI; Neri, Omont, Cox et al.

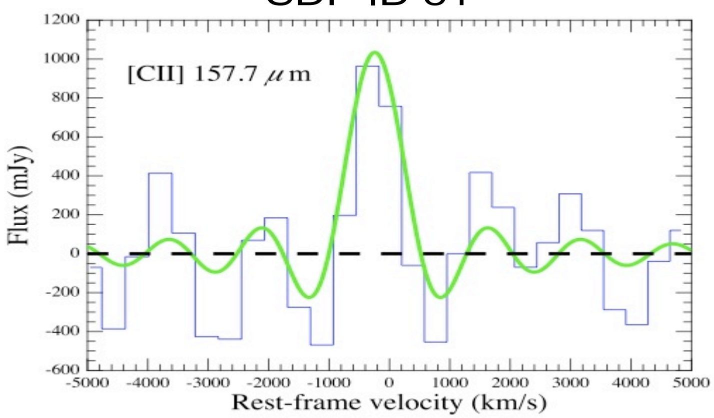
SPIRE FTS Observations:Bright lensed sources make it easier for Herschel spectroscopy

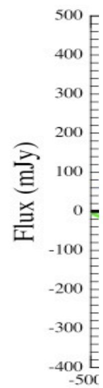
SPIRE FTS has been successful so far for sources with S350 > 180 mJy

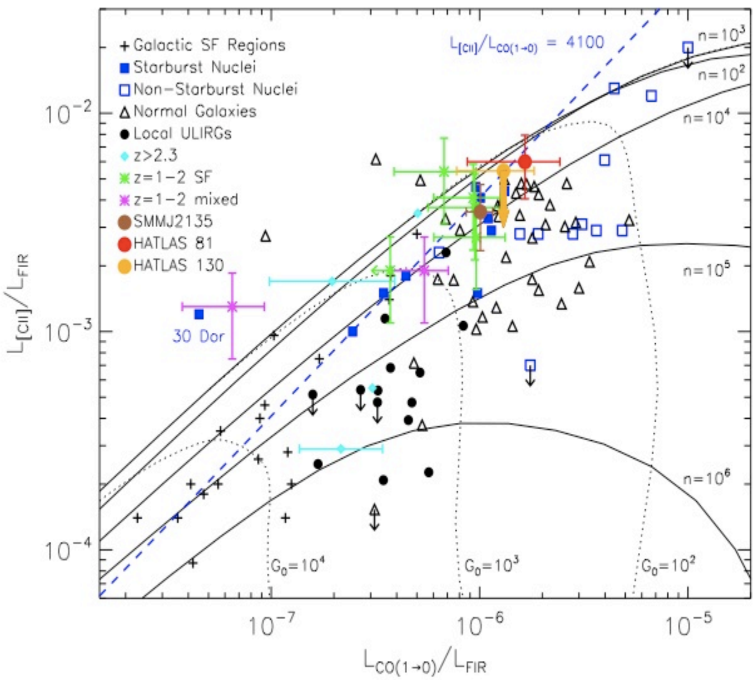
Bright submm surveys: [OIII], [CI]

- SPIRE FTS observations of z=3.0 H-ATLAS lens ID 81
- First detection of 88 μm line at z>
- High [OIII]/FIR and limit on [OI]/[
  contributes ionizing radiation, as

SDP ID 81



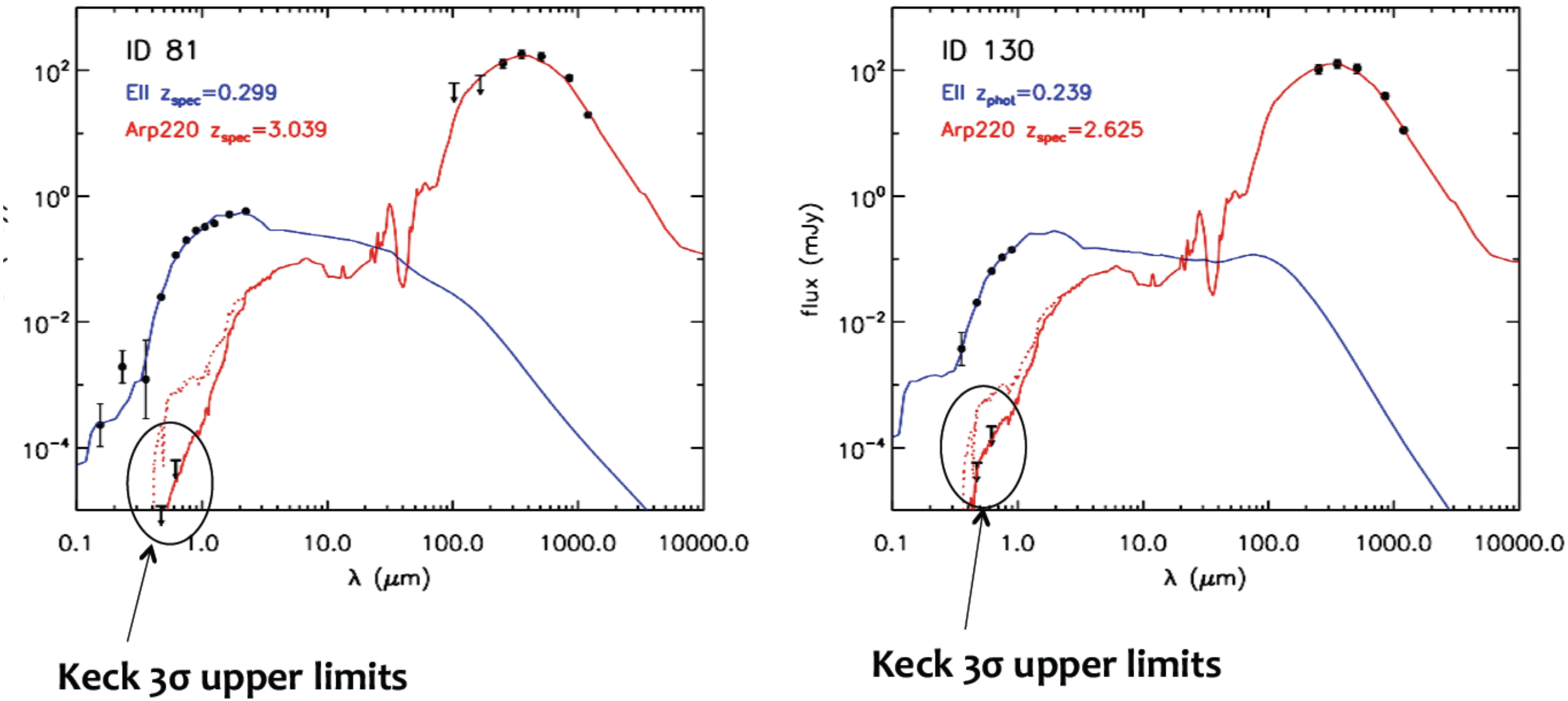




Valtchanov et al. 2011 MNRAS in press (arXiv:1105.3

Atlas First Gravitational Lenses

These systems are **missed in the optical !**



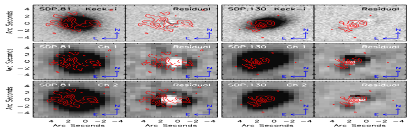
Atlas First Gravitational Lenses

Background galaxies seen in Spitzer
!!!

et al.

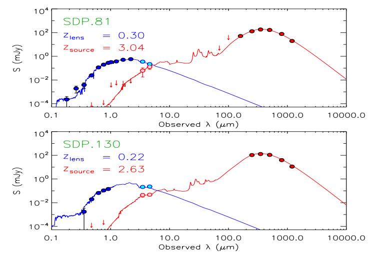
ampled, and combined into a mosaic image. For this, we used the SSC's Mopex software suite, version 18.3.1 (Makovoz & Marleau 2005). The IRAC mosaics have a pixel size is 0.6″, while these images provide angular resolution of 2 to 2.5″ in channels 1 and 2. For photometry of the mosaicked images, we utilized the Apex software to perform point-source extraction. This step included background subtraction of the images, and the fitting of a resampled point response function (PRF), making use of the most recent (April 2010) PRF file as provided by the SSC [31].

For the analysis presented here, we also make use of deep optical imaging of the two sources. These imaging observations were acquired on 10 March 2010 using the dual-arm LRIS on the Keck I telescope. Each target field received simultaneous 110 × 3 second integrations with the g-filter and 60 × 3 seconds integrations with the i-filter using the blue and red arms of LRIS. A 20″ dither pattern was employed to generate on-sky flat field frames when incorporating all five fields. In addition, 1 second integrations were acquired in the g- and i-filters for photometric calibration of bright stars in each field. The seeing FWHM for the science exposures was ∼ 0.8″. The data were reduced using IDL routines and combined and analyzed using standard IRAF tasks. The images and additional details related to Keck data are available in Negrello et al. (2010).



(1100 seconds integrations/pixel)

d et al.



log L_{dust} = 12.7 ± 0.05

log M_{dust} = 8.9 ± 0.03 (Herschel/MAMBO/SMA SED)

log M_{stars} = 11.7 ± 0.3 (Spitzer SED)

log M_{gas} = 10.1 ± 0.5 (CO line spectra)

log SFR = 2.5 ± 0.1

Av = 4.4 ± 0.6

Gas fraction = (5-8)%

Hopwood, AC et al ApJL 2011 (Spitzer DDT 548)

et al.

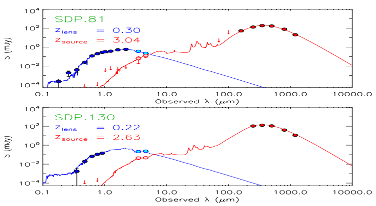
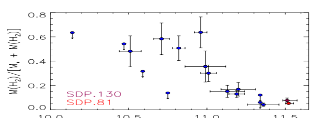
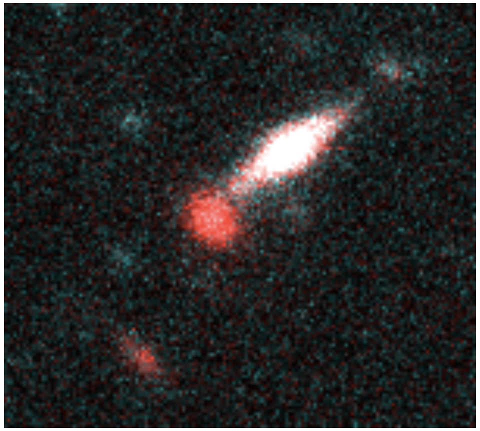


FIG. 3.— Photometry and best fit SEDs for the foreground elliptical (blue) and background SMG (red) for SDP.81 and SDP.130. The photometric points and upper limits are taken from Negrello et al. (2010), with updated PACS flux density at 160 μm and upper limit at 70 μm. Photometry from the best fitting light profiles to the IRAC data have been added for the foreground lens galaxies (turquoise points) and for the background SMG (pink points). The photometric SEDs were fitted using the models of da Cunha et al. (2008) and provide information on the physical properties for the lensed systems (see table table 1). High levels of visual extinction were required ($A_v > 4$) to be consistent with the optical to NIR data.



Atlas First Gravitational Lenses

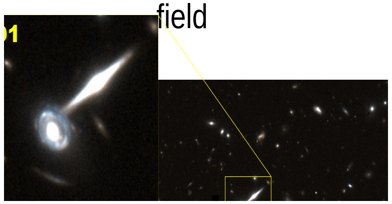
New: Background galaxies seen in HST/WFC3 (Negrello et al. in prep)



Keck Optical

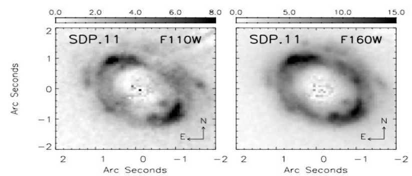
ID11

H-ATLAS: lenses in the SDP field

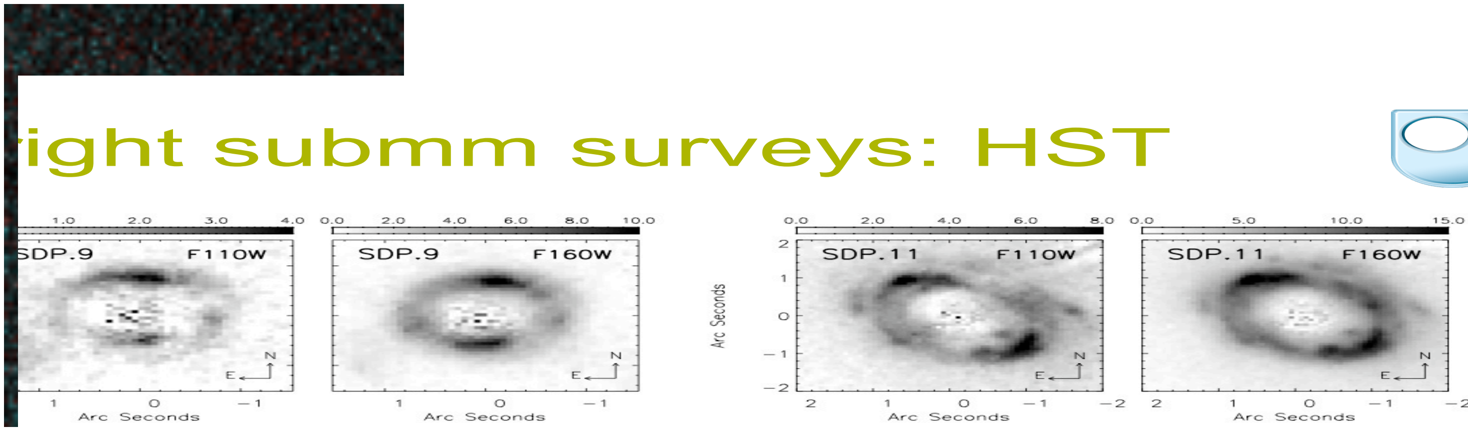


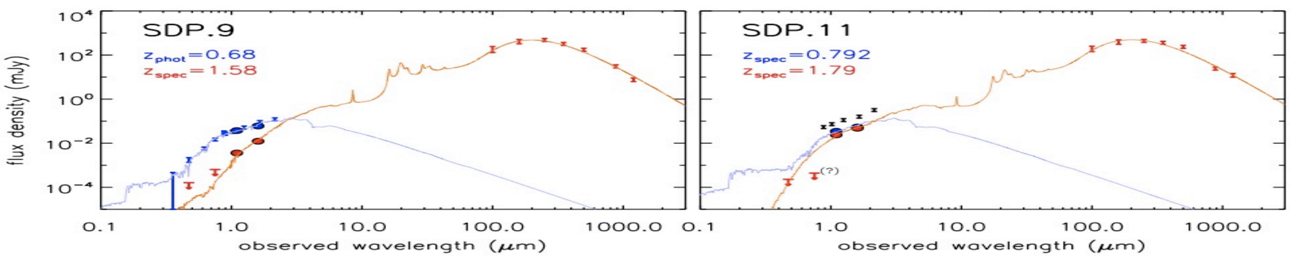
HST/WFC3 Near-IR

rveys: HST



ight submm surveys: HST





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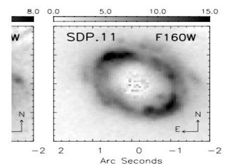


rial)

Strong lensing Studies with Herschel-SPIRE

RESEARCH ARTICLES

The Detection of a Population of Submillimeter-Bright, Strongly Lensed Galaxies

Mattia Negrello,[1*] R. Hopwood,[1] G. De Zotti,[2,3] A. Cooray,[4] A. Verma,[5] J. Bock,[6,7] D. T. Frayer,[8] M. A. Gurwell,[9] A. Omont,[10] R. Neri,[11] H. Dannerbauer,[12] L. L. Leeuw,[13,14] E. Barton,[4] J. Cooke,[4,7] S. Kim,[4] E. da Cunha,[15] G. Rodighiero,[16] P. Cox,[11] D. G. Bonfield,[17] M. J. Jarvis,[17] S. Serjeant,[1] R. J. Ivison,[18,19] S. Dye,[20] I. Aretxaga,[21] D. H. Hughes,[21] E. Ibar,[18] F. Bertoldi,[22] I. Valtchanov,[23] S. Eales,[20] L. Dunne,[24] S. P. Driver,[25] R. Auld,[20] S. Buttiglione,[2] A. Cava,[26,27] C. A. Grady,[28,29] D. L. Clements,[30] A. Dariush,[20] J. Fritz,[31] D. Hill,[25] J. B. Hornbeck,[32] L. Kelvin,[25] G. Lagache,[33,34] M. Lopez-Caniego,[35] J. Gonzalez-Nuevo,[3] S. Maddox,[24] E. Pascale,[20] M. Pohlen,[20] E. E. Rigby,[24] A. Robotham,[25] C. Simpson,[36] D. J. B. Smith,[24] P. Temi,[37] M. A. Thompson,[17] B. E. Woodgate,[38] D. G. York,[39] J. E. Aguirre,[40] A. Beelen,[34] A. Blain,[7] A. J. Baker,[41] M. Birkinshaw,[42] R. Blundell,[9] C. M. Bradford,[6,7] D. Burgarella,[43] L. Danese,[3] J. S. Dunlop,[18] S. Fleuren,[44] J. Glenn,[45] A. I. Harris,[46] J. Kamenetzky,[45] R. E. Lupu,[40] R. J. Maddalena,[8] B. F. Madore,[47] P. R. Maloney,[45] H. Matsuhara,[48] M. J. Michaowski,[19] E. J. Murphy,[49] B. J. Naylor,[6] H. Nguyen,[6] C. Popescu,[50] S. Rawlings,[5] D. Rigopoulou,[5,51] D. Scott,[52] K. S. Scott,[40] M. Seibert,[47] I. Smail,[53] R. J. Tuffs,[54] J. D. Vieira,[7] P. P. van der Werf,[19,55] J. Zmuidzinas[6,7]

lengths can particularly benefit from gravitational lensing because submillimeter telescopes have limited spatial resolution and consequently high source confusion, which makes it difficult to directly probe the populations responsible for the bulk of background submillimeter emission (*5*, *6*). In addition, galaxies detected in blank-field submillimeter surveys generally suffer severe dust obscuration and are therefore challenging to detect and study at optical and near-infrared (NIR) wavelengths. By alleviating the photon starvation, gravitational lensing facilitates follow-up observations of galaxies obscured by dust and in particular the determination of their redshift (*7*). Previous submillimeter searches for highly magnified background galaxies have predominantly targeted galaxy cluster fields (*8*). In fact, a blind search for submillimeter lensing events requires a large area because of their rarity and sub-arcseconds angular resolutions to reveal multiple images of the same background galaxies.

Although the first requirement has recently been fulfilled, thanks to the advent of the South

First 5 with the first 10 sq. degrees of Herschel mapped in Negrello et al. Science, 2010 (Nov 5th issue)

DRAFT VERSION AUGUST 9, 2011
Preprint typeset using LaTeX style emulateapj v. 08/22/09

check missing names from data teams - for data used in the paper

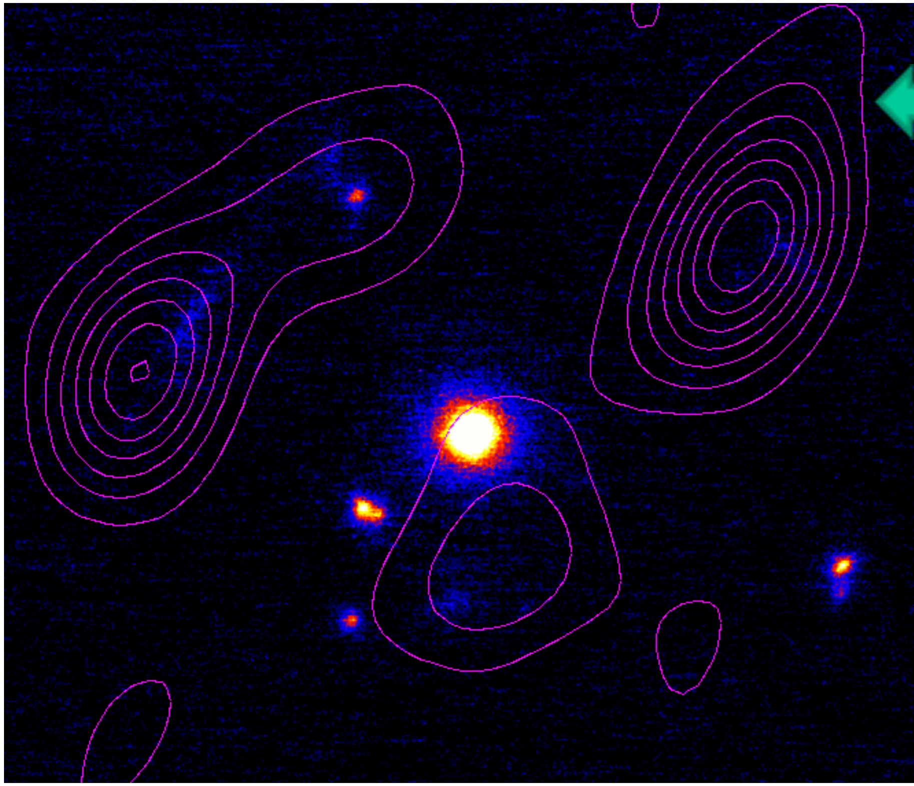
HERMES: CANDIDATE GRAVITATIONALLY LENSED GALAXIES AND LENSING STATISTICS AT SUB-MM WAVELENGTHS

HerMES: Coordinates of 86 candidates and followup of ~11 lensed sources in Julie Wardlow (UCI postdoc) et al. (2011)

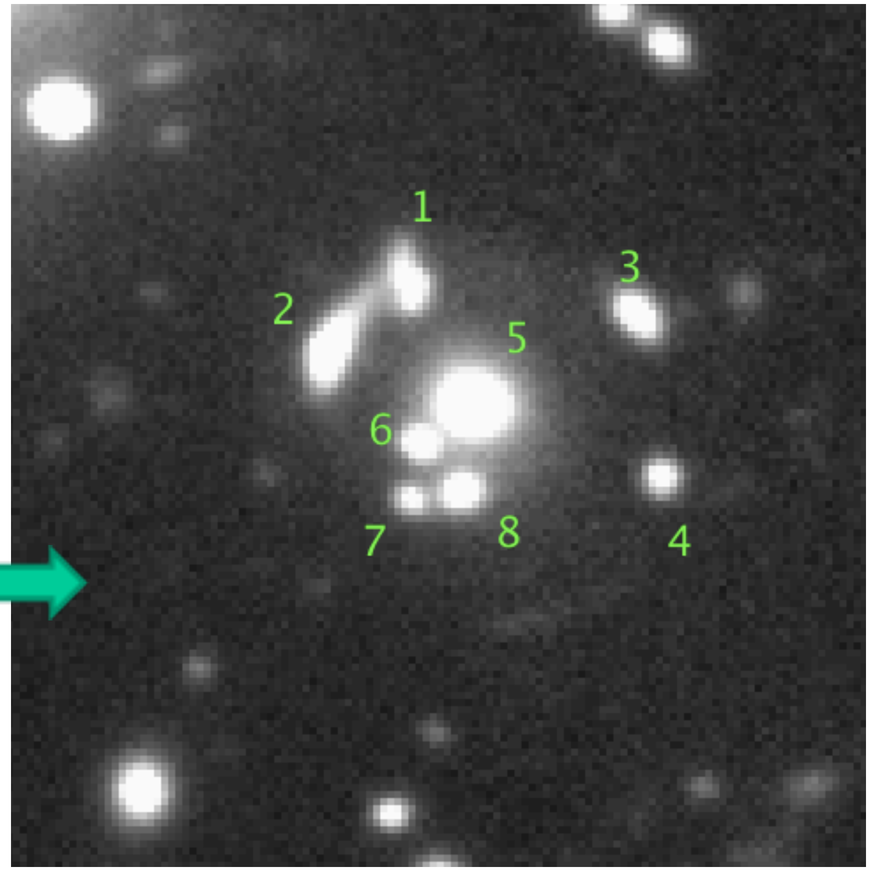
In context: ~250 strongly lensed galaxies known so far. Largest samples from SDSS ~87 (SLACS: Treu et al) and 24 from Sloan quasar lensing (Oguri et al). In radio 22 from CLASS (Jackson et al). Rest serendipitous.

Lensed SMGs in HerMES: An example

9" Lensed Galaxy in HerMES
(brightest extragalactic SMG found by Herschel so far;
250 micron = 420 mJy)



SMA 870 micron + Keck NIRC2 LGS AO

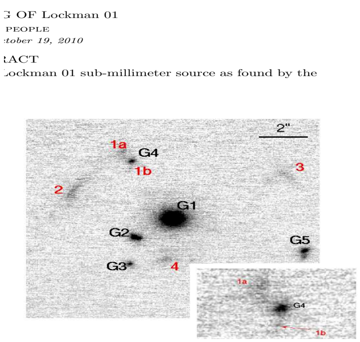


Subaru image

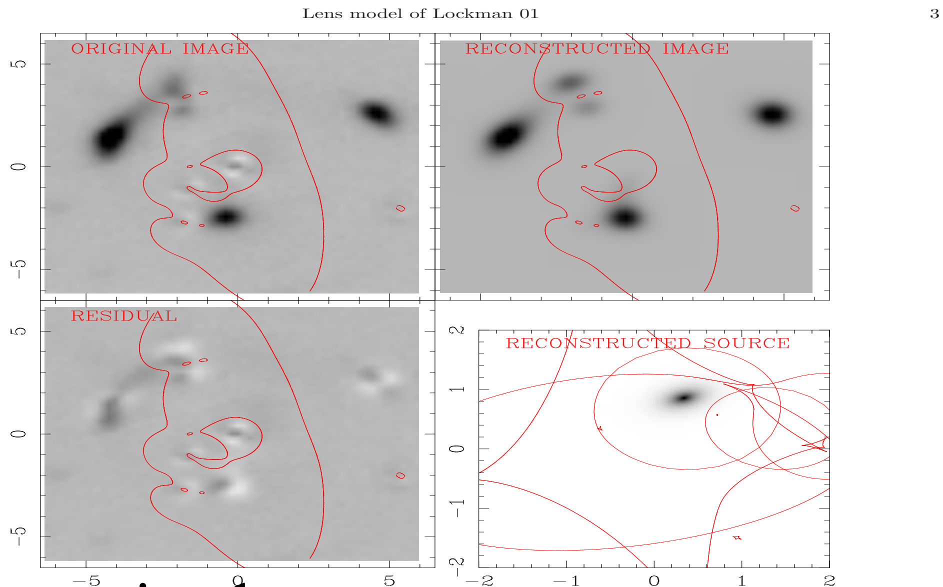
(4 papers now in ApJL: Conley et al; Riechers et al;
Scott et al; Gavazzi et al.)

Not all Herschel lenses are compact

(HerMES example: brightest extragalactic SMG found by Herschel so far; 250 micron = 420 mJy)



5 lenses, G1 at z=0.59; redshifts of rest unclear

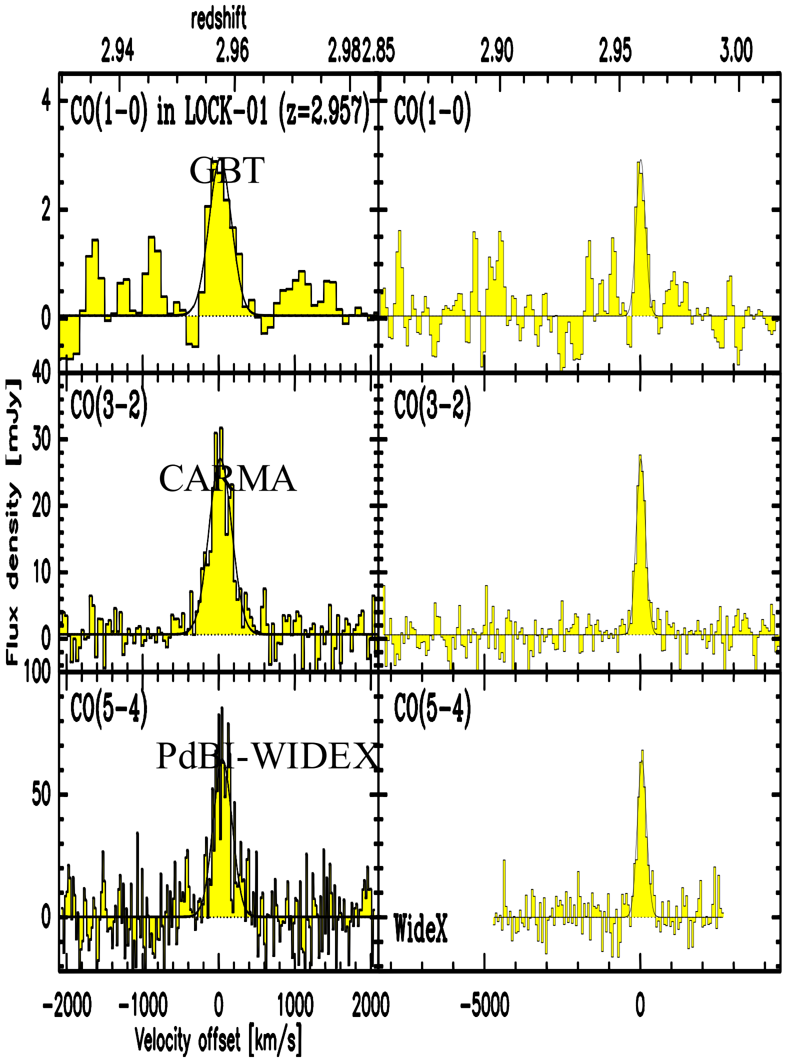


G1 and G4 masses are well determined

Gavazzi, AC et al. 2011

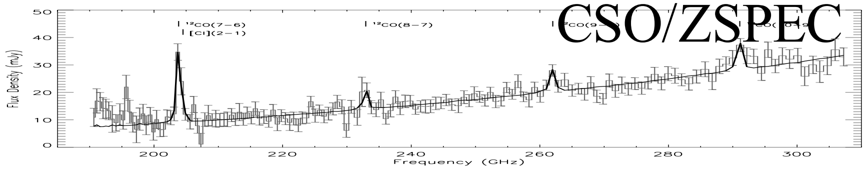
Not all Herschel lenses are compact

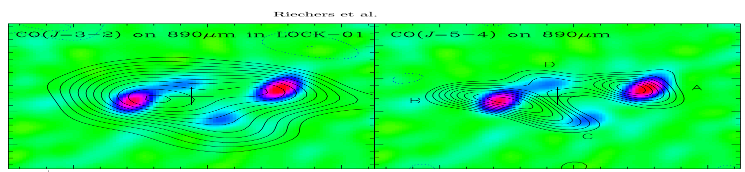
(HerMES example: brightest extragalactic SMG found by Herschel so far; 250 micron = 420 mJy)



Riechers, AC et al. 2011

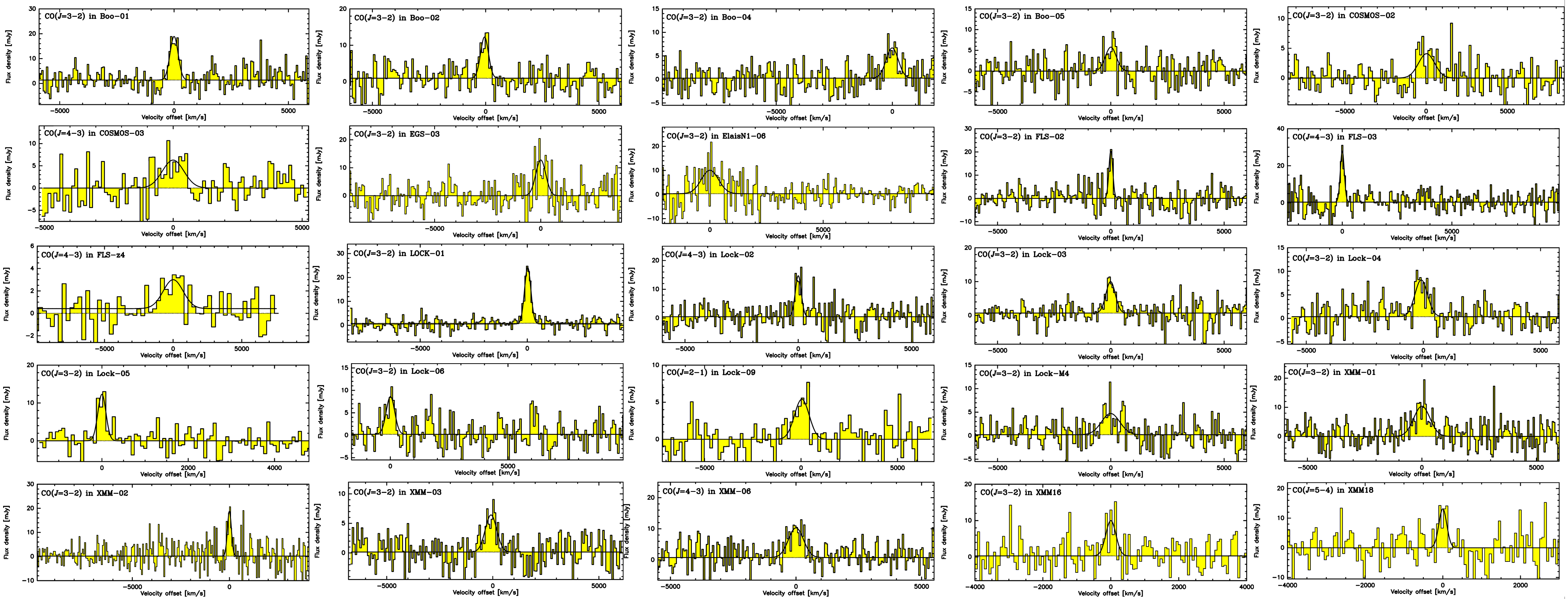
Scott et al. 2011





CO already spatially resolved in the 5-4 PdBI map

"Blind" CO Redshifts for Herschel/SPIRE-selected SMGs



(z~1.7-4.4)

1998-2009: ~20 SMGs detected in CO emission (all selected w/ optical spec-z)

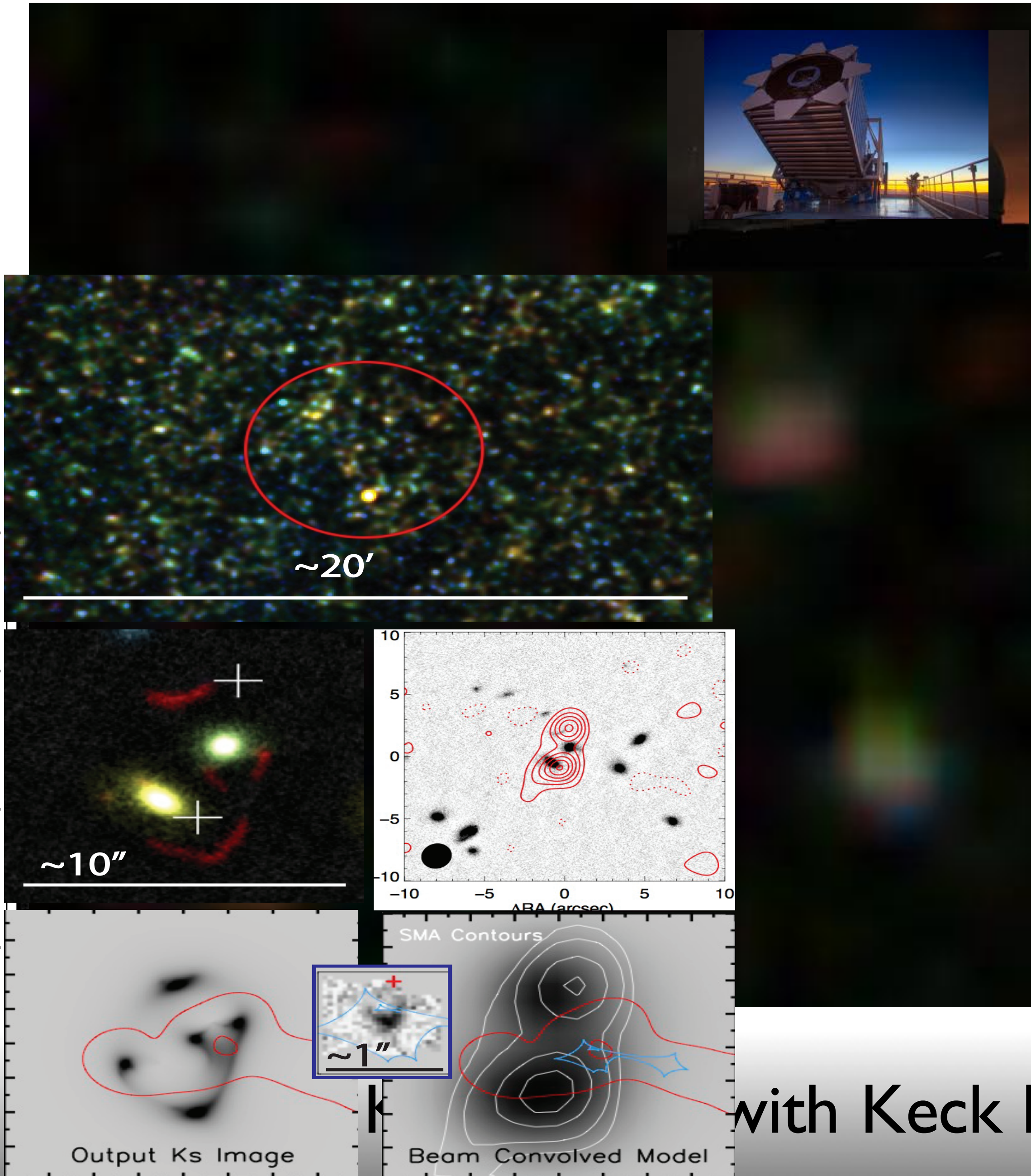
Since 9/2010: 25 new Herschel-selected SMGs obs. w/ *CARMA* (all 'blind' CO z)*

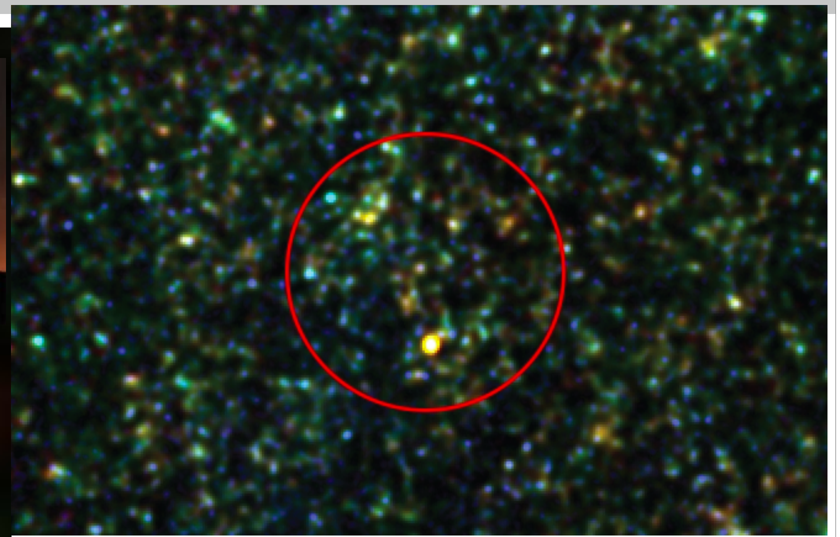
* HERMES re detected in CO w/ *CARMA* (z from *Zpectr*

\+ Herschel ATLAS

Riechers et al. in prep.

A Bright Planck/Herschel Source seen in Keck





(a) ~1 Jy in Planck HFI (beam in red)

(b) Central source is 400 mJy in SPIRE, z=3.2 from CO

(c) other sources add to ~1Jy

(d) an overdensity of SMGs with similar SPIRE, are they at the same redshift?

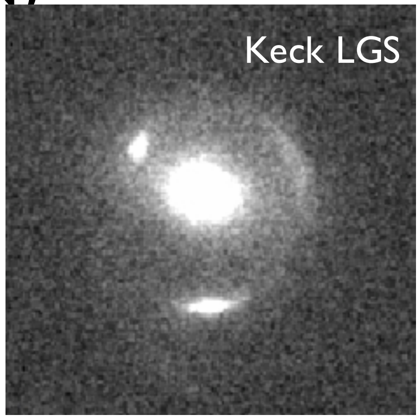
Lens model, details: Hai Fu, AC et al. in prep

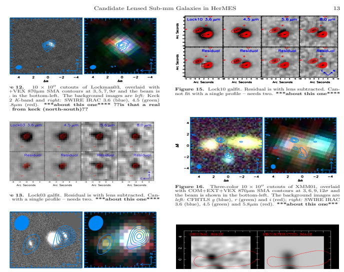
with Keck LGS

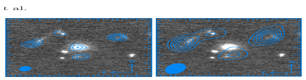
Example lensed from HerMES

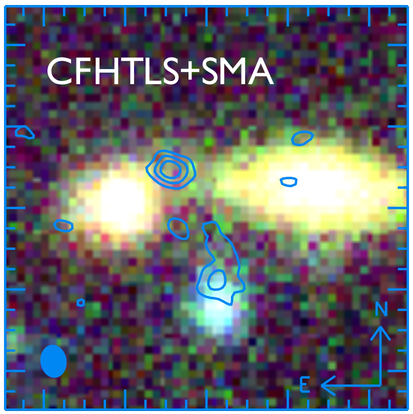
- GT1: 70 sq. degrees: 86 lensed candidates with S500≥80mJy (& not spirals or radio-loud AGN)

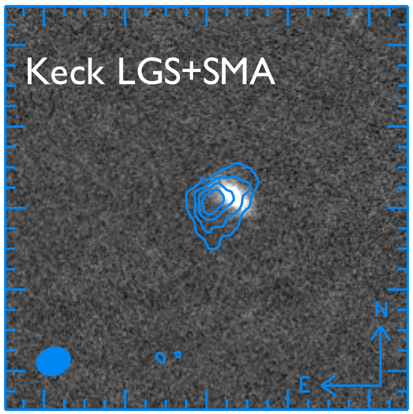
Keck LGS+SMA

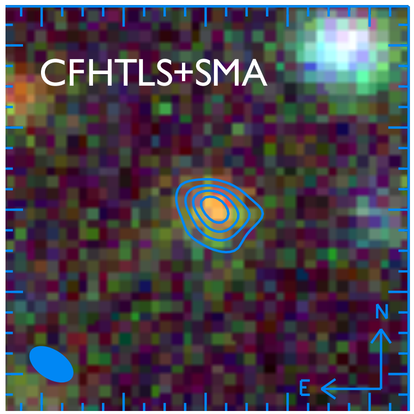


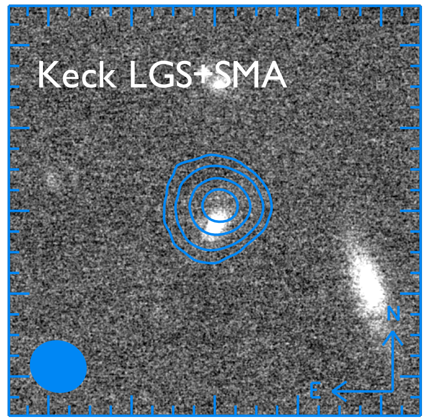


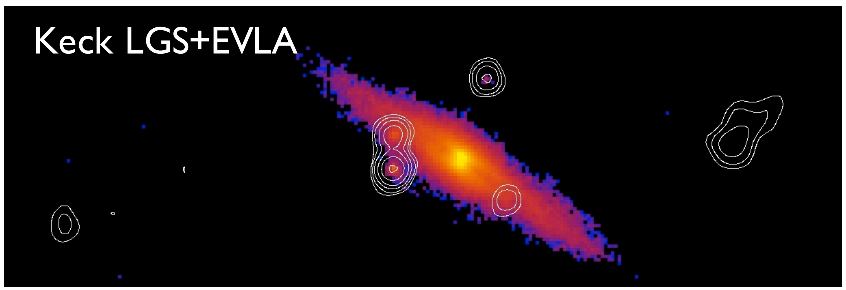






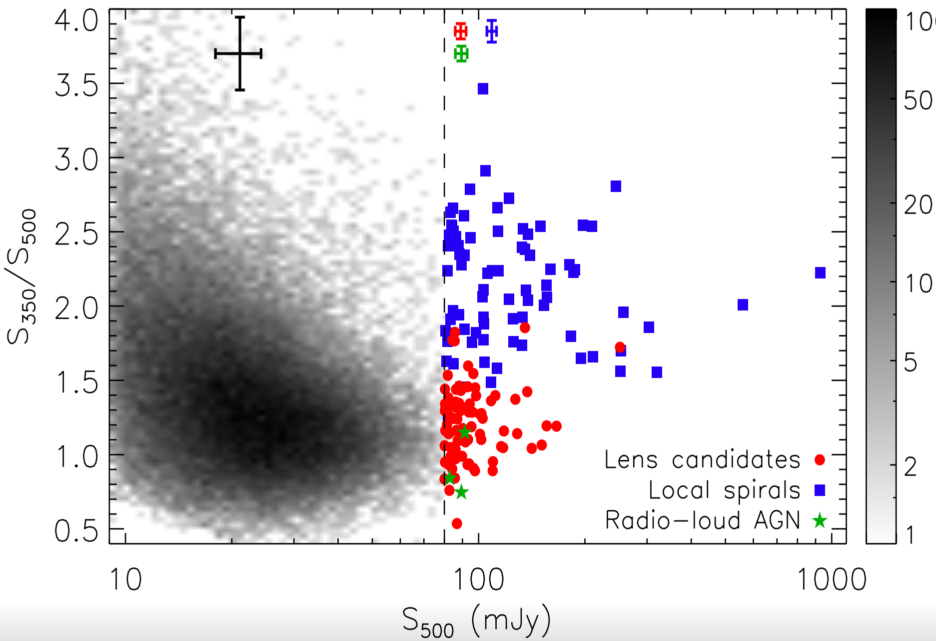


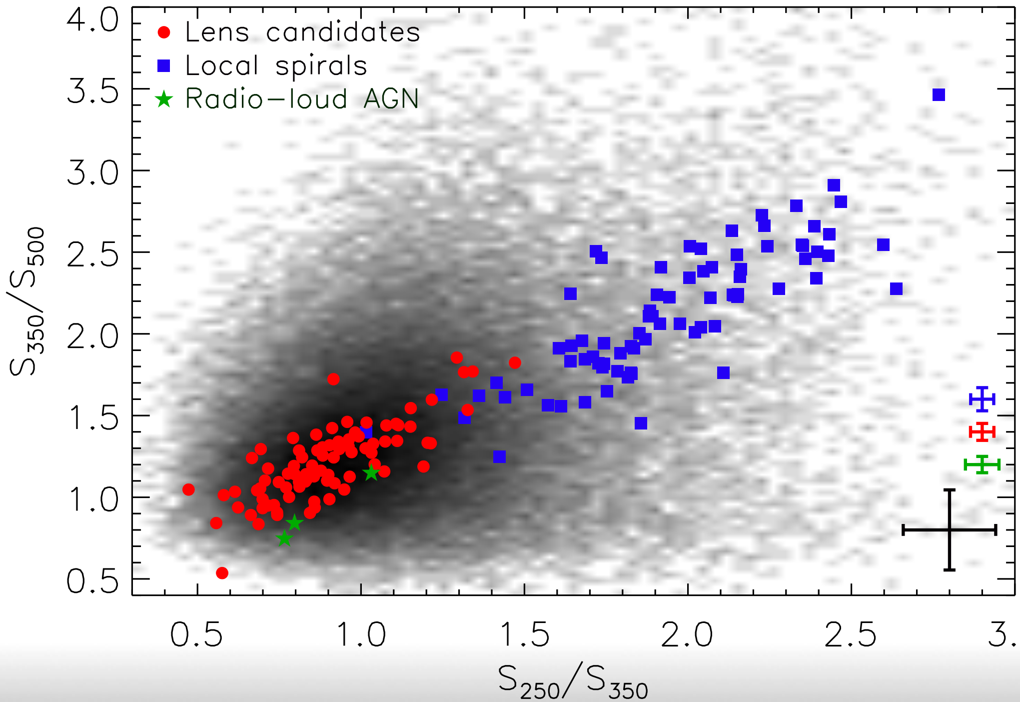




Lensed galaxies are easily identifiable as bright and have “red” colors

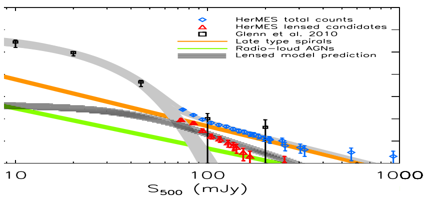
Nearby spiral galaxies are bright at sub-mm; can be removed with SDSS etc.
Same for radio-loud AGNs (NVSS, Fermi)

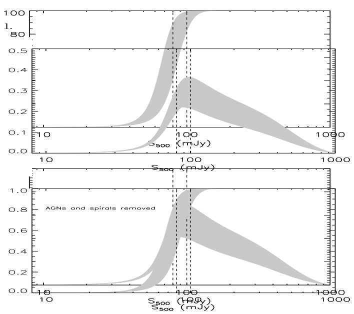


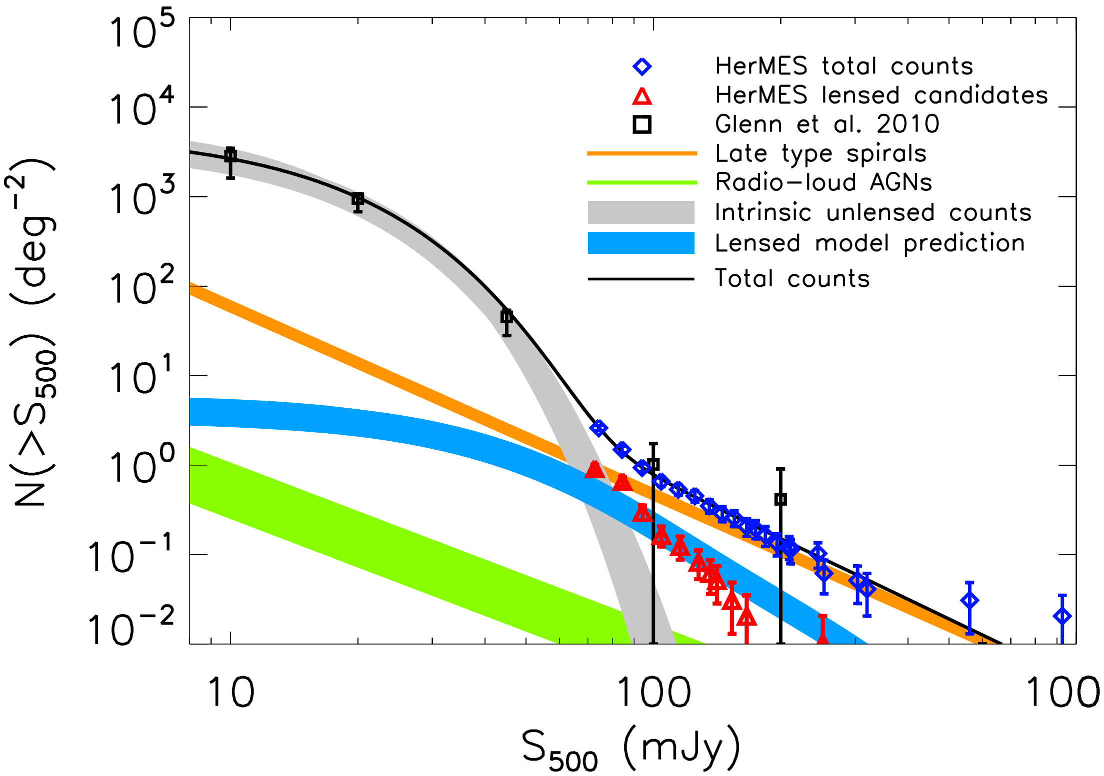


Modeling strong lensing

- Consider NFW & SIS density profiles & lens "intrinsic" N(>S)
- Parameters constrained by requiring fit to observed N(>S)
- μ>2 for "strong" lensing
- Magnification bias ~ 3



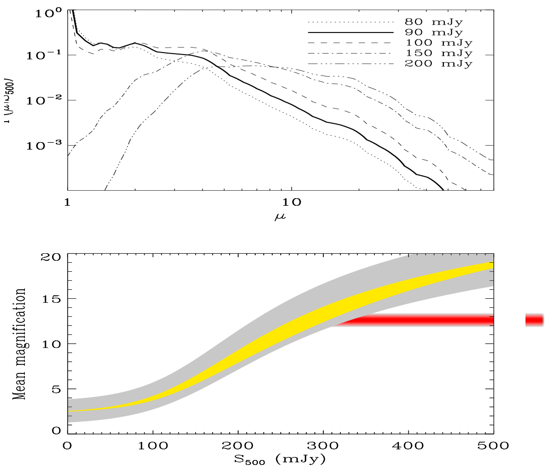


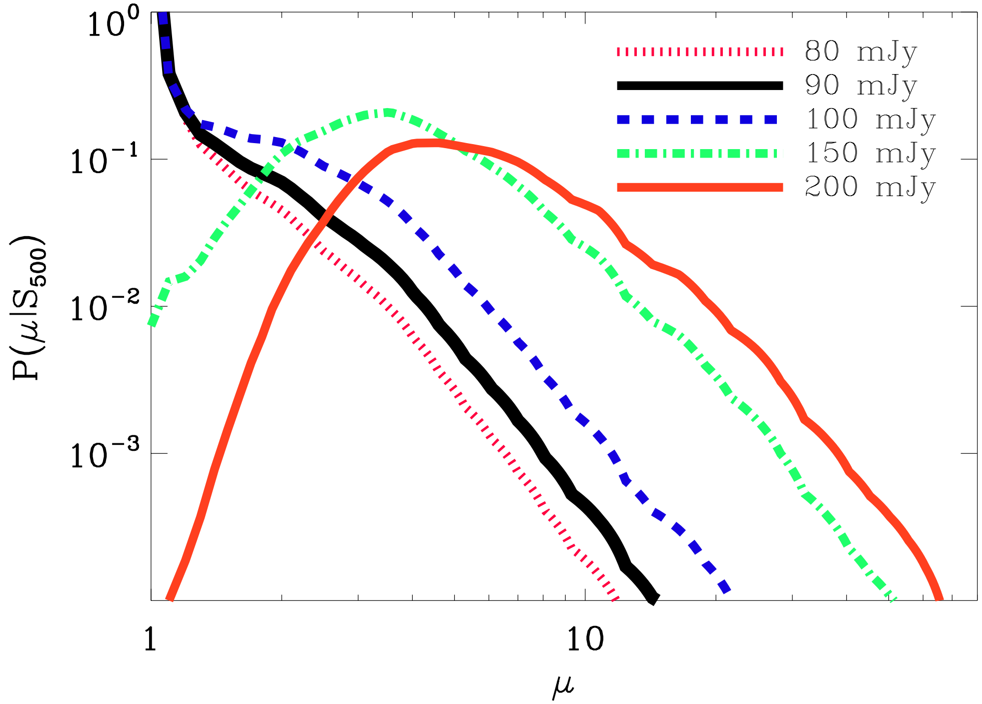


20% to 30% lensing fraction among all bright sources; but non-lensed sources are easily identifiable in shallow optical and radio surveys
Close to 100% efficiency once spirals and AGNs removed!!!

Wardlow et al. 2011

Mean magnification is ~ 4 to 8



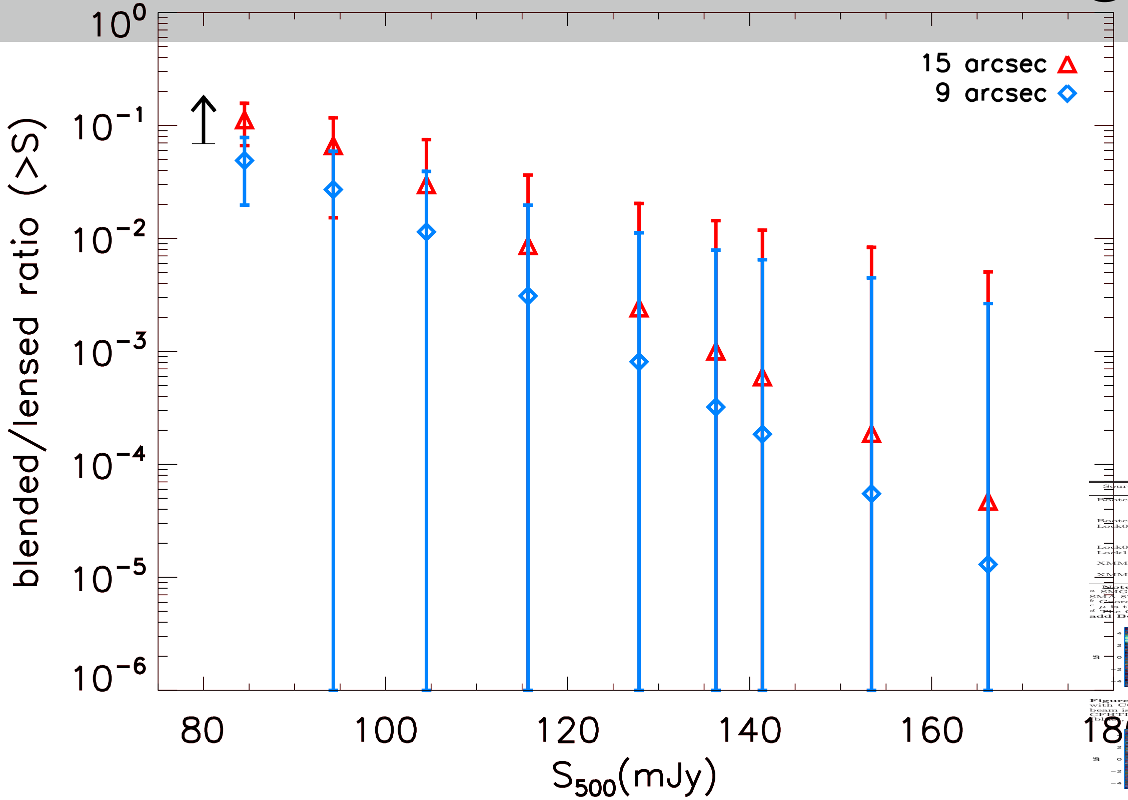


Most SMG galaxy lenses involve intrinsically "normal" (~20mJy) SMGs. *We are not always seeing the intrinsically sub-confusion faint sources. They are rare.*

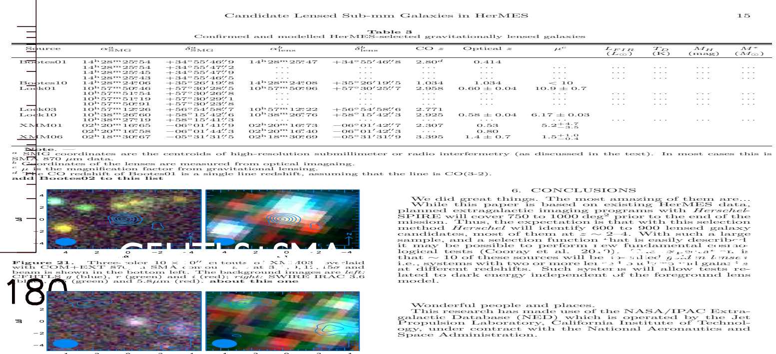
Brightest of lensed SMGs (>150 mJy) are magnified by factors of 10 to 20. But such lenses are rare (1 in 10 sq. degrees)

Wardlow et al. 2011

Is source blending an issue?



SPIRE beams are 18, 25, 36 arcsecs.
Could bright 500 micron sources be blends?



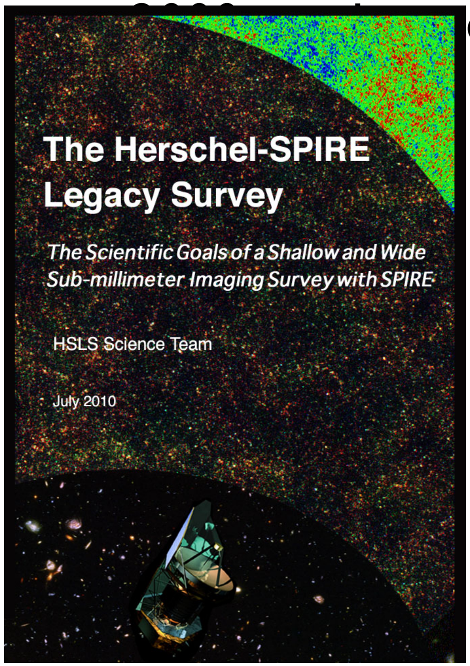
One example (?) out of ~12 with followup in Wardlow et al. 2011

Combine 500 and 250 microns to remove clear blends from two 250 micron sources as one in 500 micron.

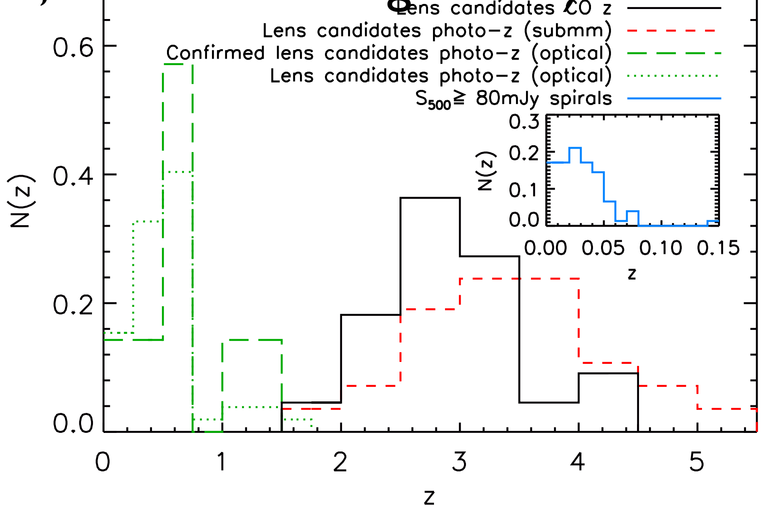
Simulations show we are accounting for blends down to ~12 arcsec separations.
~10% of the S(500) > 80 mJy lensing candidates are likely remaining blends.

Promise of Herschel in Lensing Studies

- 0.85/sq. deg (S500>80 mJy) lensed source! - identified 90% efficiency. (S500 > 100 mJy identified 100% efficiency - but 0.25/sq. degree)
- HerMES + ATLAS: ~800 sq. degrees, so ~600 lensed galaxies.
- Proposed Herschel-SPIRE Legacy Survey (OT1 declined; OT2 resubmitted for … es, ~1500 lensed galaxies)



HSLS White Paper
arxiv:1007.3519



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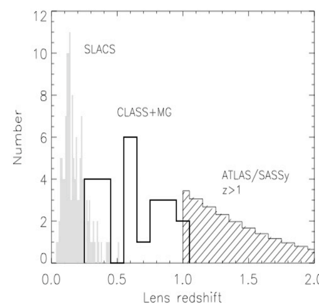

Largest sample of gravitationally lensed sources, with a selection function easy to describe (great for cosmology!)
Extend lensed galaxies to z > 6 (HSLS will find ~100 z > 6 SMGs, most lensed!)
Extend foreground lenses to z~2 (SDSS lenses z~0.5; radio~1)

Conclusions

Herschel has opened up the dusty universe in a new wavelength regime for the first time.

large sample of lenses. what do we get out?

~200 from HerMES and ATLAS. ~1500 from proposed HSLS over 2000 sq. degrees.

More to come over the next two years.