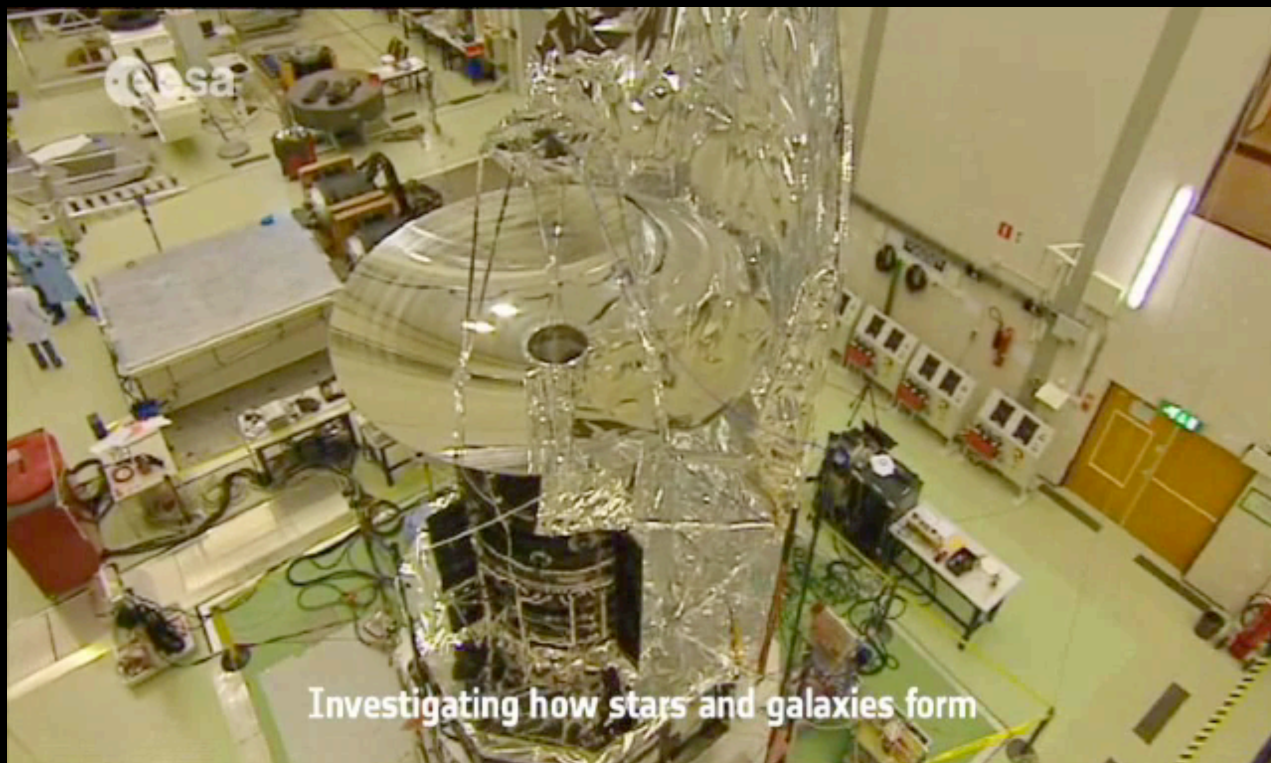
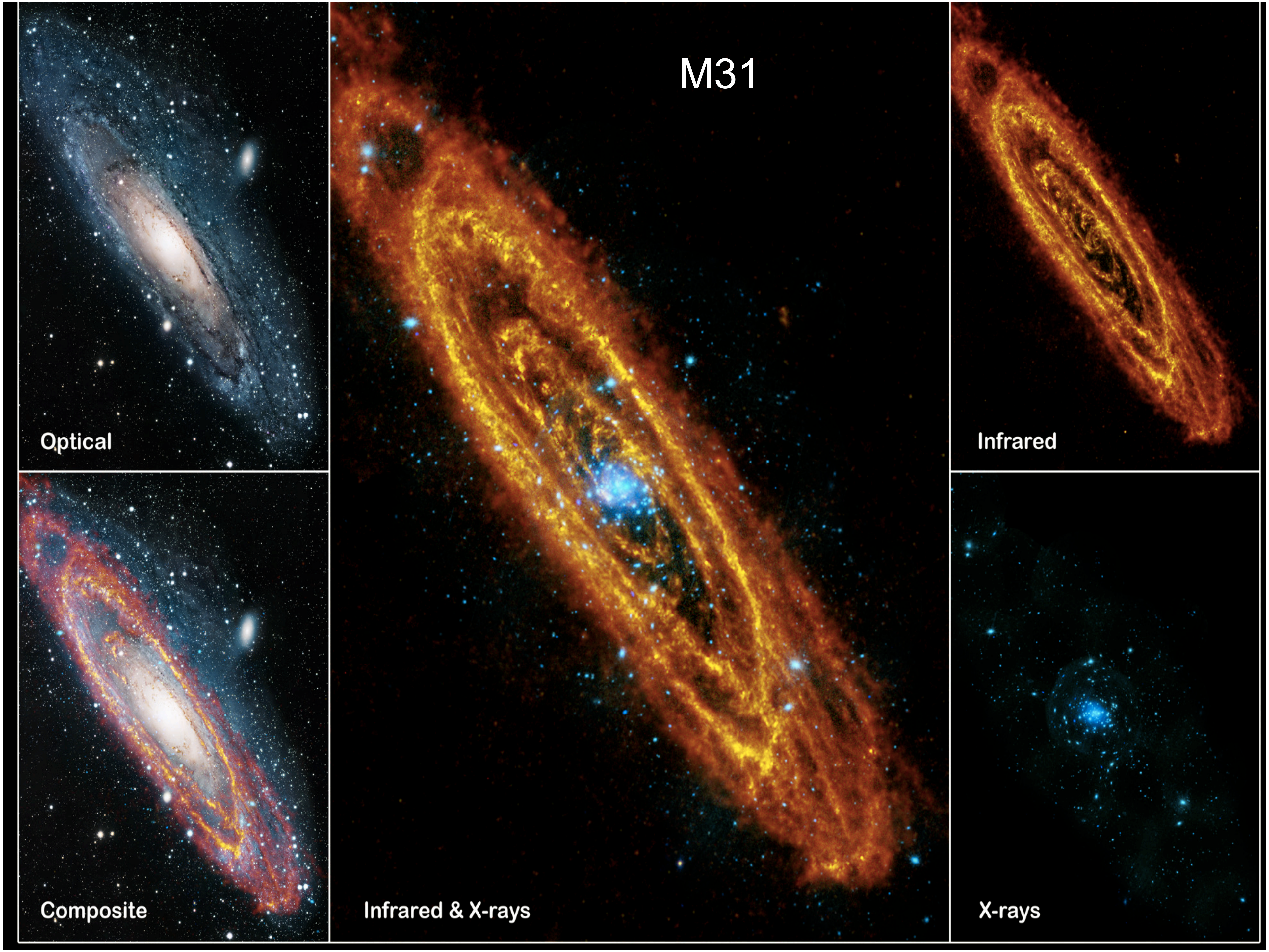
Unveiling the Dusty Extragalactic Universe: Recent Results from Herschel

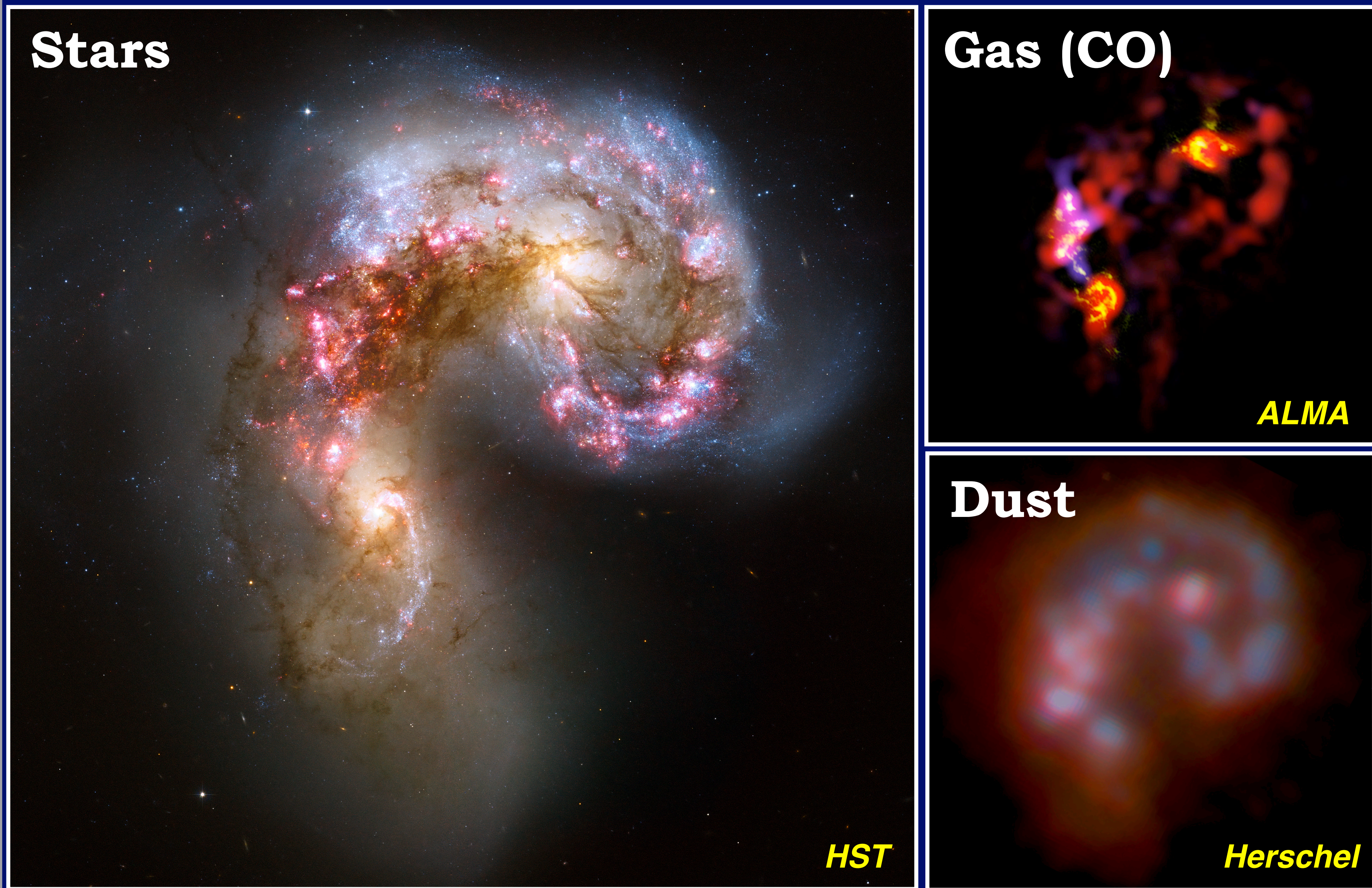


Asantha Cooray

UCIrvine
University of California, Irvine

LSS/high-z coordinator of HerMES (SPIRE GTO; 350 sq. deg.)
US PI of Herschel-ATLAS (600 sq. deg)


M31
Optical
Infrared
Composite
Infrared & X-rays
X-rays

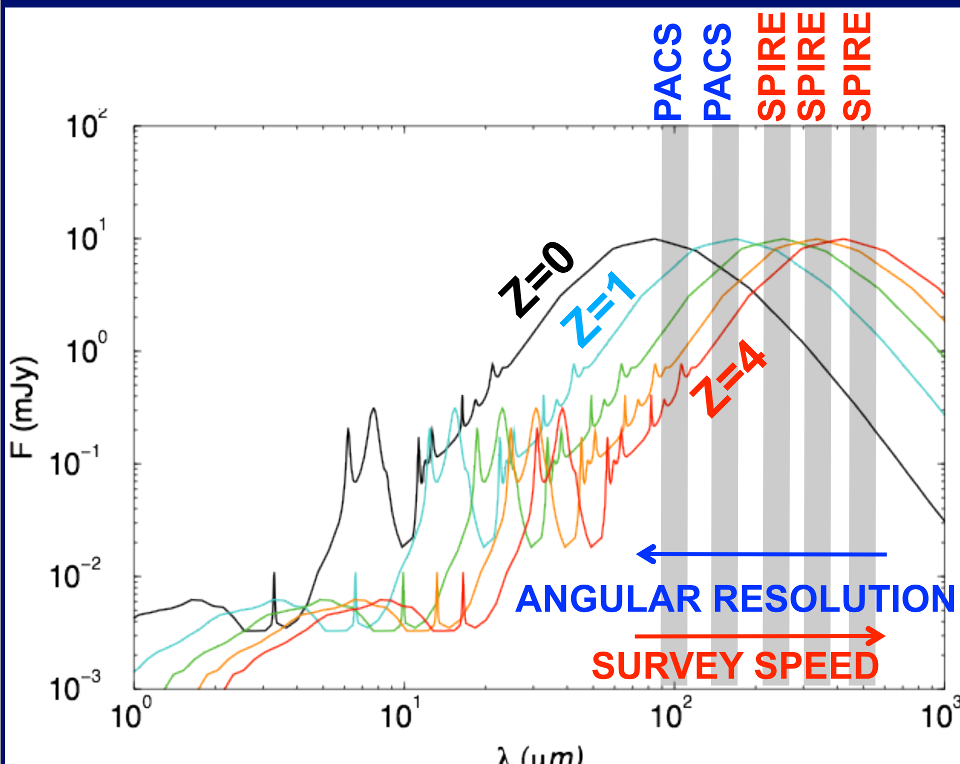


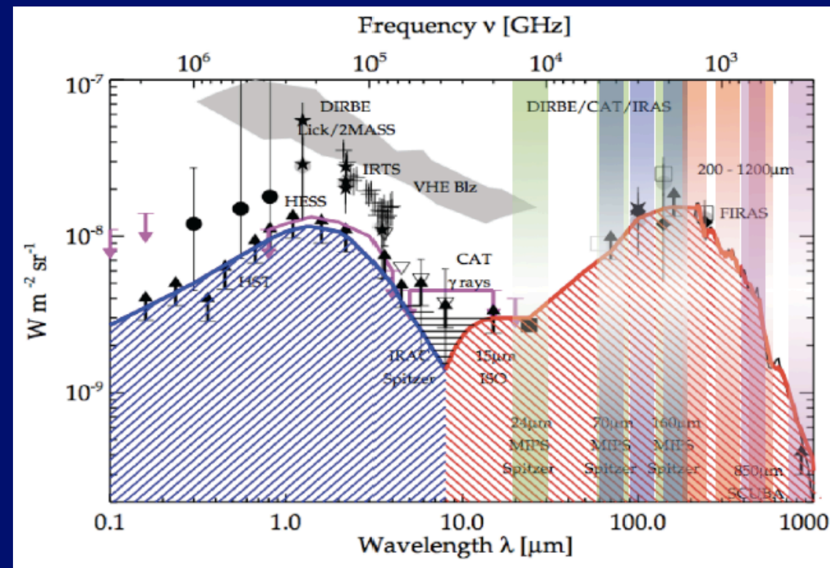
Dust, Gas and Stars in Galaxies

the Antennae at d = 20 Mpc

Unsolved problems in sub-mm astronomy?

- How do sub-mm galaxies assemble and evolve over time?
- Where have luminous SMGs gone today?
- How do FIR galaxies relate to dark matter?
- What is the role of dust in star formation?
- What is the connection between dusty star formation and AGNs?





Herschel Extragalactic Surveys
- Observe at SED peak
- Bolometric far-IR luminosities
- Large and uniform samples

Herschel Science Motivation

HERMES INFORMATION ON THE WEB: HERMES.SUSSEX.AC.UK AND HERSCHEL.UCI.EDU

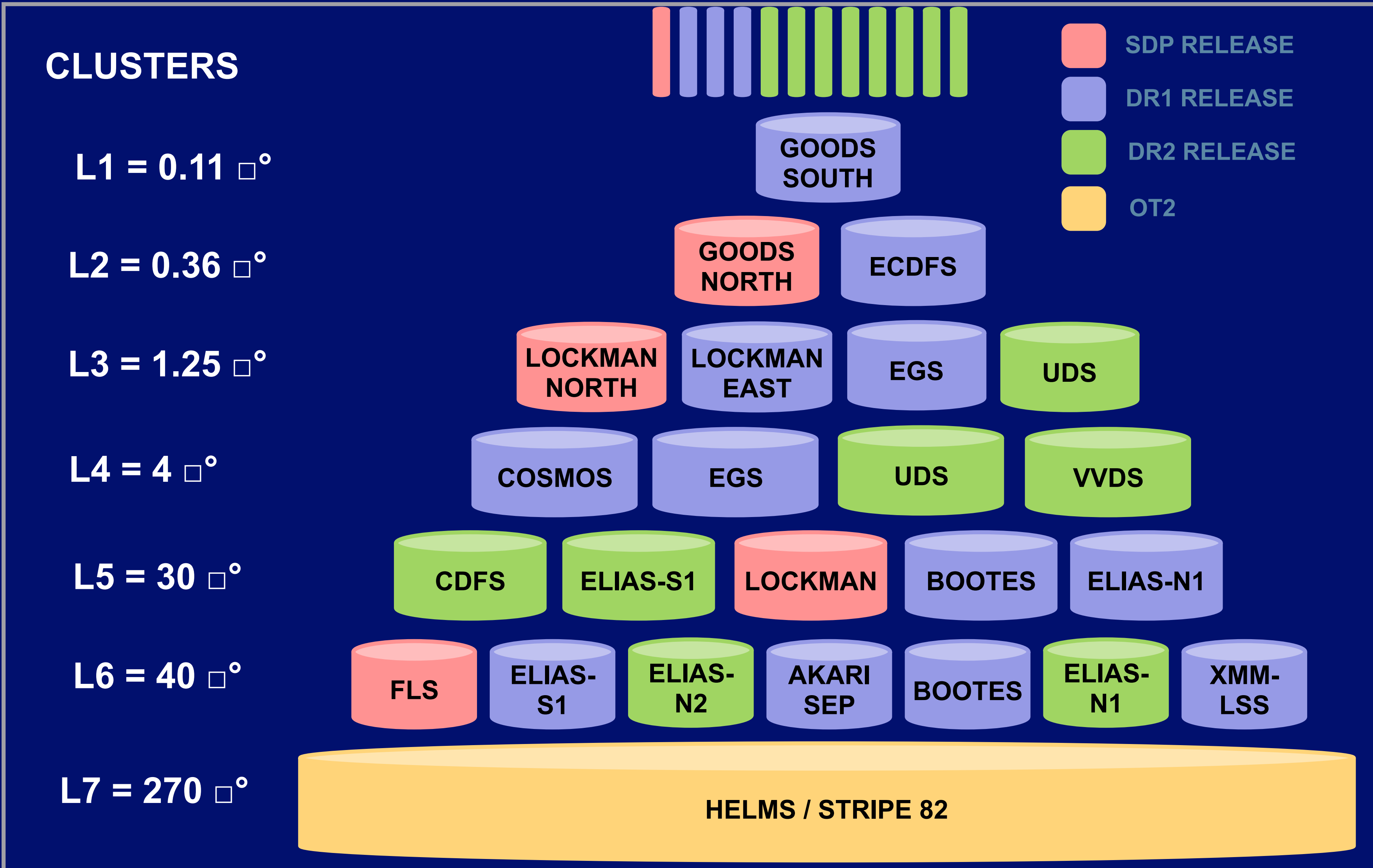
Herschel-SPIRE Instrument science team

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, Veronique Buat, Denis Burgarella, Nieves Castro-Rodriguez, Antonio Cava, Pierre Chanial, Ed Chapin, Scott Chapman, Michele Cirasuolo, Dave Celments, Alex Conley, Luca Conversi, Asantha Cooray, Darren Dowell, Naomi Dubois, Eli Dwek, Simon Dye, Steve Eales, David Elbaz, Duncan Farrah, Patrizia Ferrero, Matt Fox, Alberto Franceschini, Walter Gear, Elodie Giovannoli, Jason Glenn, Eduardo Gonzalez-Solares, Matt Griffin, Mark Halpern, Martin Harwit, Evanthia Hatziminaoglou, Sebastian Heinis, Peter Hurley, HoSeong Hwang, Edo Ibar, Olivier Ilbert, Kate Isaak, Rob Ivison, Guilaine Lagache, Louis Levenson, Nanyao Lu, Suzanne Madden, Bruno Maffei, Georgios Magdis, Gabriele Mainetti, Lucia Marchetti, Gaelen Marsden, Jason Marshall, Angela Mortier, Hien Nguyen, Brian O'Halloran, Seb Oliver, Alain Omont, Francois Orieux, Mathew Page, Pasquale Panuzzo, Andreas Papageorgiou, Harsit Patel, Chris Pearson, Ismael Perez-Fournon, Michael Pohlen, Jason Rawlings, Gwen Raymond, Dimitra Rigopoulou, Laurie Riguccini, Davide Rizzo, Giulia Rodighiero, Isaac Roseboom, Michael Rowan-Robinson, Miguel Sanchez-Portal, Bernhard Schulz, Douglas Scott, Nick Seymour, David Shupe, Anthony Smith, Jason Stevens,, Myrto Symeonidis, Markos Trichas, Katherine Tugwell, Mattia Vaccari, Elisabetta Valiante, Ivan Valtchanov, Joaquin Vieira, Laurent Vigrouz, Lingyu Wang, Rupert Ward, Don Wiebe, Gillian Wright, Kevin Xu, and Mike Zemcov, + *Consultants and Working Members*

FACULTY AND RESEARCHERS, POSTDOCS, STUDENTS

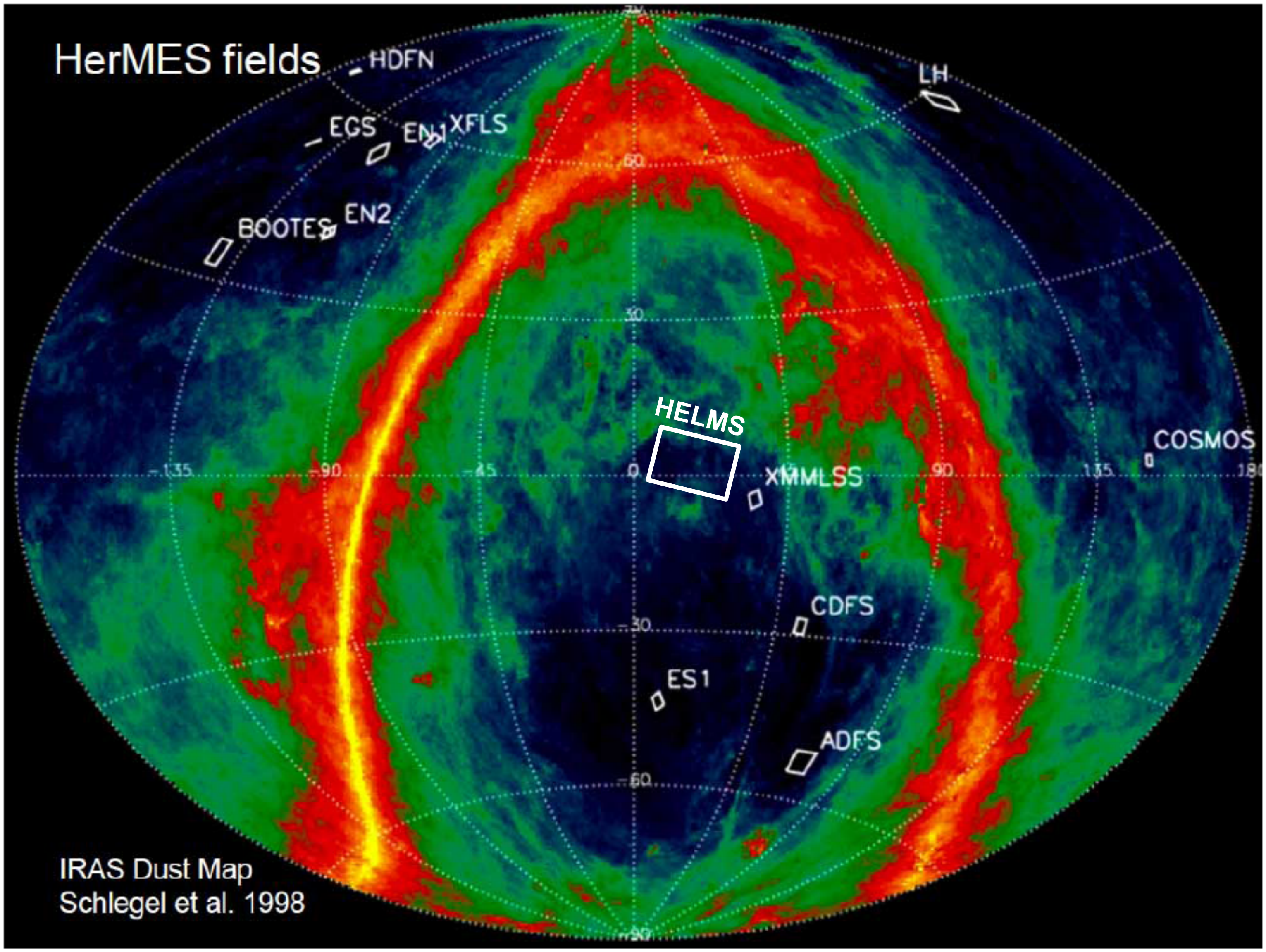
US SPIRE Instrument Team Institutions = Caltech/JPL, Colorado, UC Irvine

Matt Griffin (Cardiff; PI)   Jamie Bock (US PI)



HerMES “wedding cake” Survey

HERMES INFORMATION ON THE WEB: HERMES.SUSSEX.AC.UK AND HERSCHEL.UCI.EDU

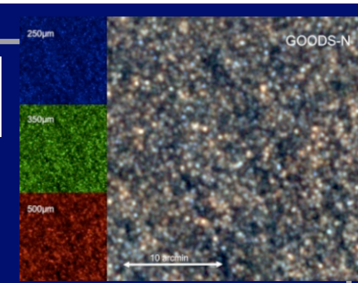


HerMES Fields on the sky

HERMES INFORMATION ON THE WEB: HERMES.SUSSEX.AC.UK AND HERSCHEL.UCI.EDU

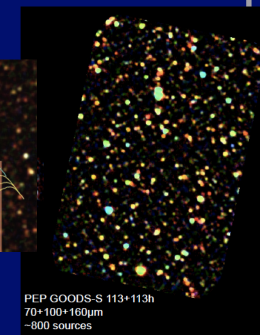
HerMES: *Herschel* Multi-tiered Extragalactic Survey

- PACS + SPIRE
- 340 sq deg from narrow to wide (900 hours) + 12 clusters
- Bolometric luminosities of galaxies, cosmic SFH
- Wedding cake to probe range of luminosities and environments



PEP: PACS Evolutionary Probe

- PACS only
- 2.7 sq deg from 10′×15′ to 85′×85′ (655 hours) + 10 clusters
- Resolve CFIRB; L_{FIR} & SFRs



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

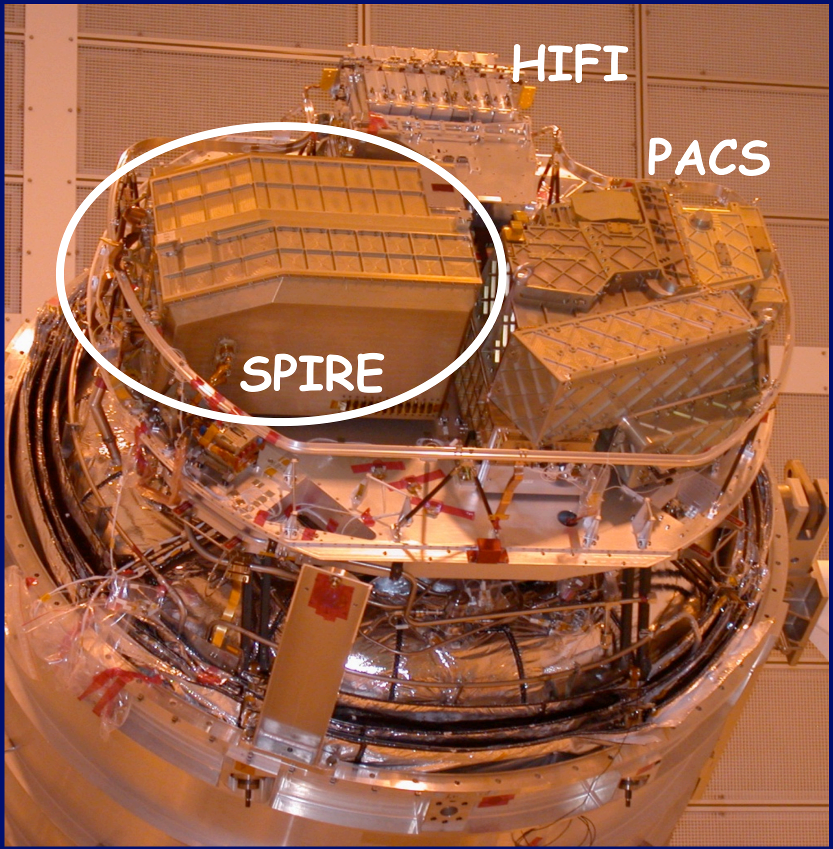
- PACS + SPIRE
- 550 sq deg (600 hours)
- Large-scale structure, AGN, rare objects
- Expect ~500,000 detections to z~3, majority at 250 & 350 um

H-GOODS: Herschel-Great Observatories Origins Deep Survey

- PACS very deep imaging of the GOODS Field (330 hours)
- SPIRE deep imaging of the GOODS Field (30 hours)

Herschel Large Extragalactic Surveys/Key Programs

SPECTRAL AND PHOTOMETRIC IMAGING RECEIVER



PHOTOMETER

- **250, 350, 500 µm (simultaneous)**
- **4 x 8 arcminute field of view**
- **Diffraction limited beams(18, 25, 36”)**

Fast scan mapping at long wavelengths

IMAGING FTS

- 200 - 670 µm
- 2.6 arcminute field of view
- $\Delta\nu$ = 1.2 GHz high resolution mode
- $\Delta\nu$ = 25 GHz low resolution mode

Wide instantaneous bandwidth, map making

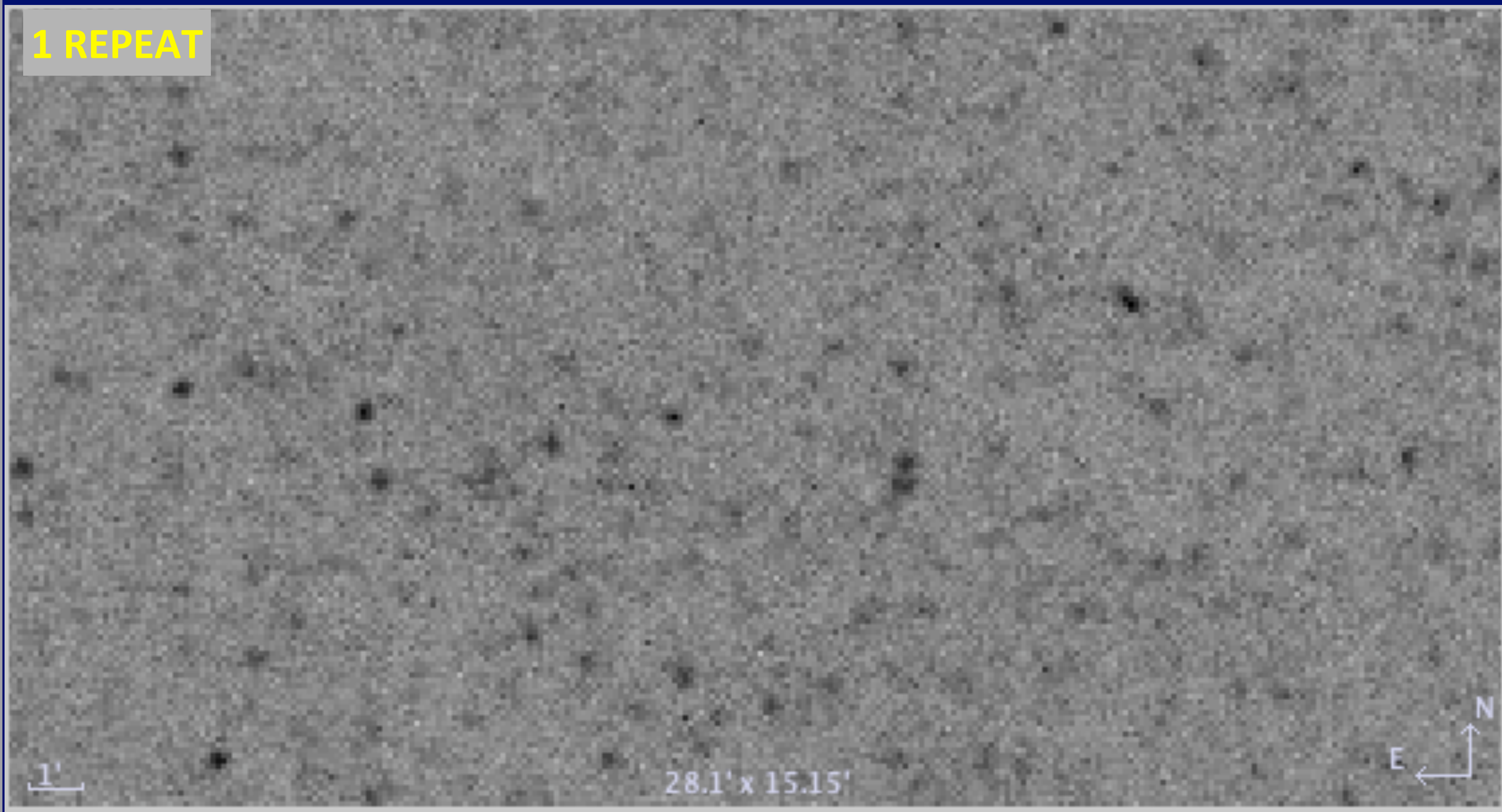
DESIGN PRINCIPLES

- ^{3}He cooled detector arrays (0.3 K)
- Feedhorn-coupled spider-web bolometers
- Minimal use of mechanisms Beam steering mirror; FTS mirror drive
- Optimized for scan-mapped surveys

HERMES = SPIRE GT PROGRAM

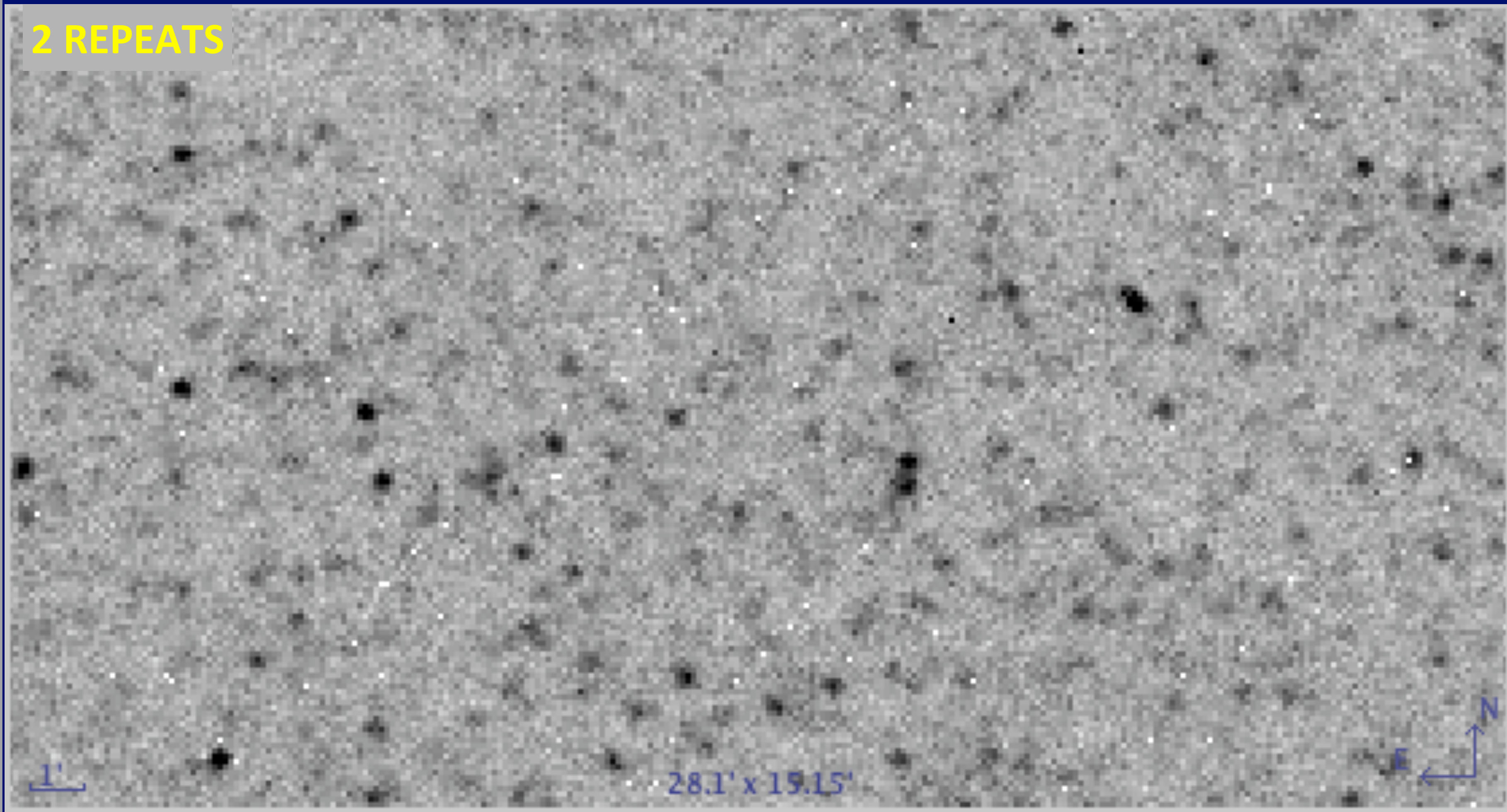
HERMES INFORMATION ON THE WEB: HERMES.SUSSEX.AC.UK AND HERSCHEL.UCI.EDU

Mapping to the Confusion Limit



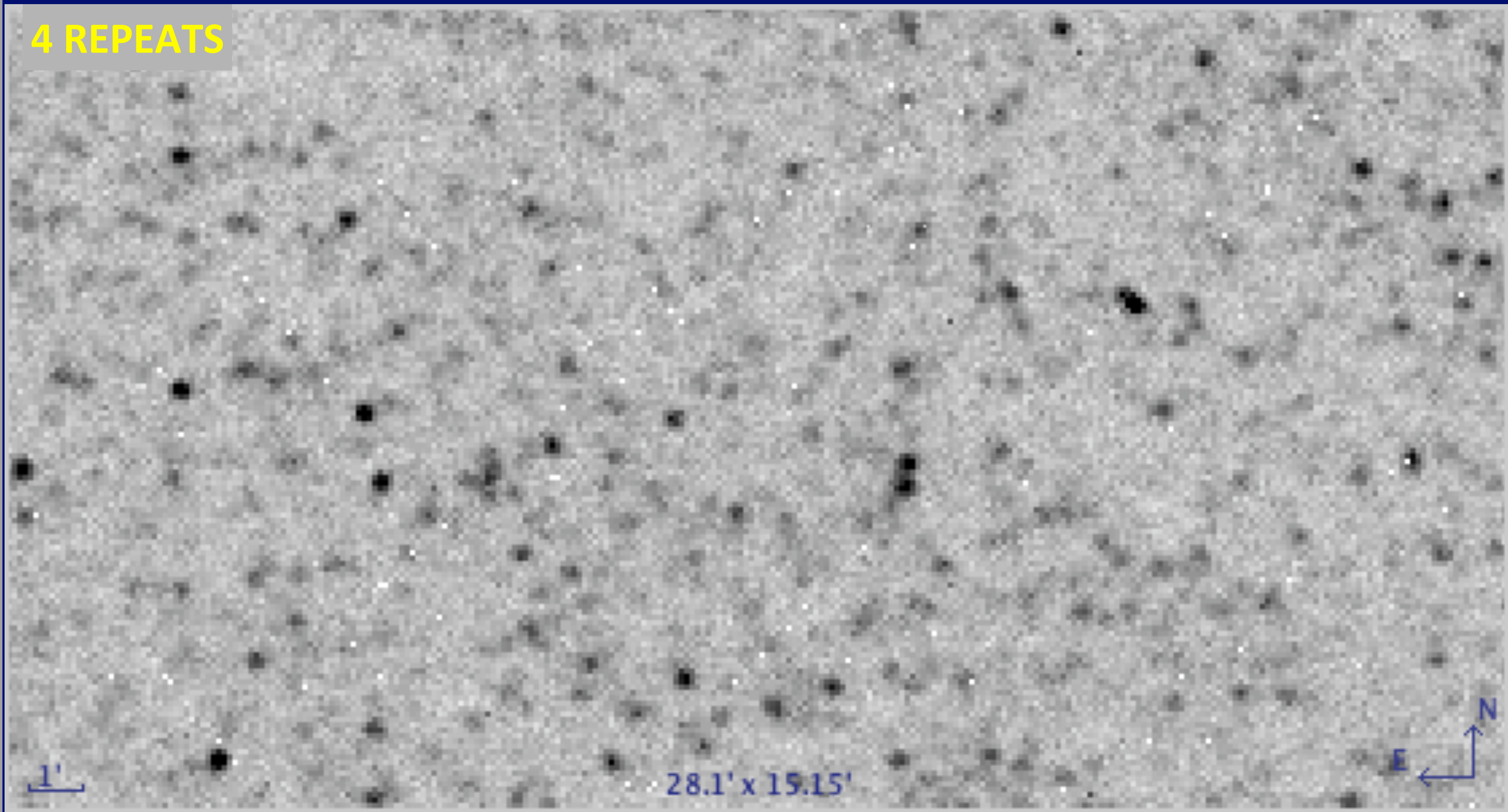
0.7 h for 1 sq. deg

Mapping to the Confusion Limit



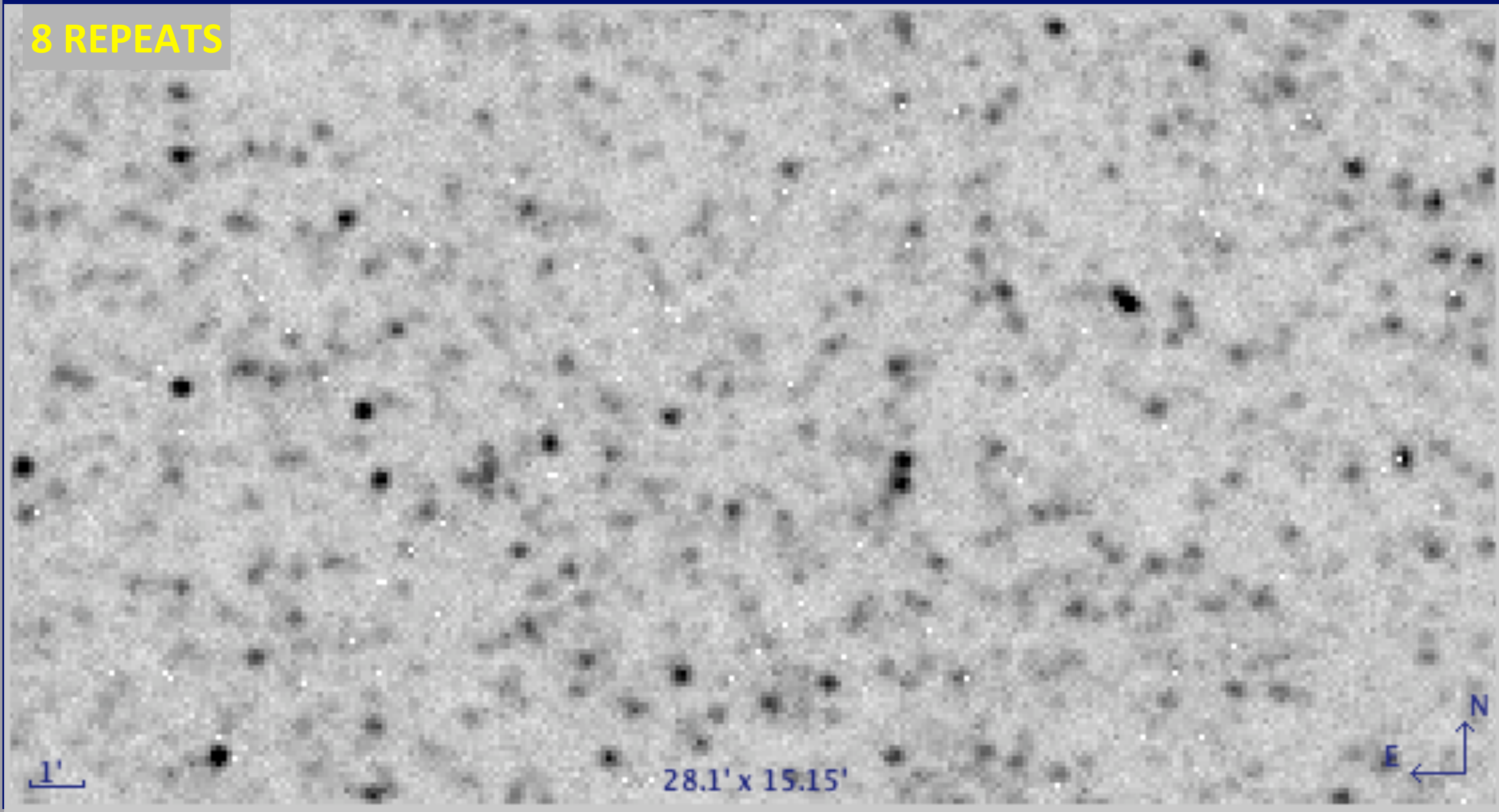
1.5 h for 1 sq. deg

Mapping to the Confusion Limit



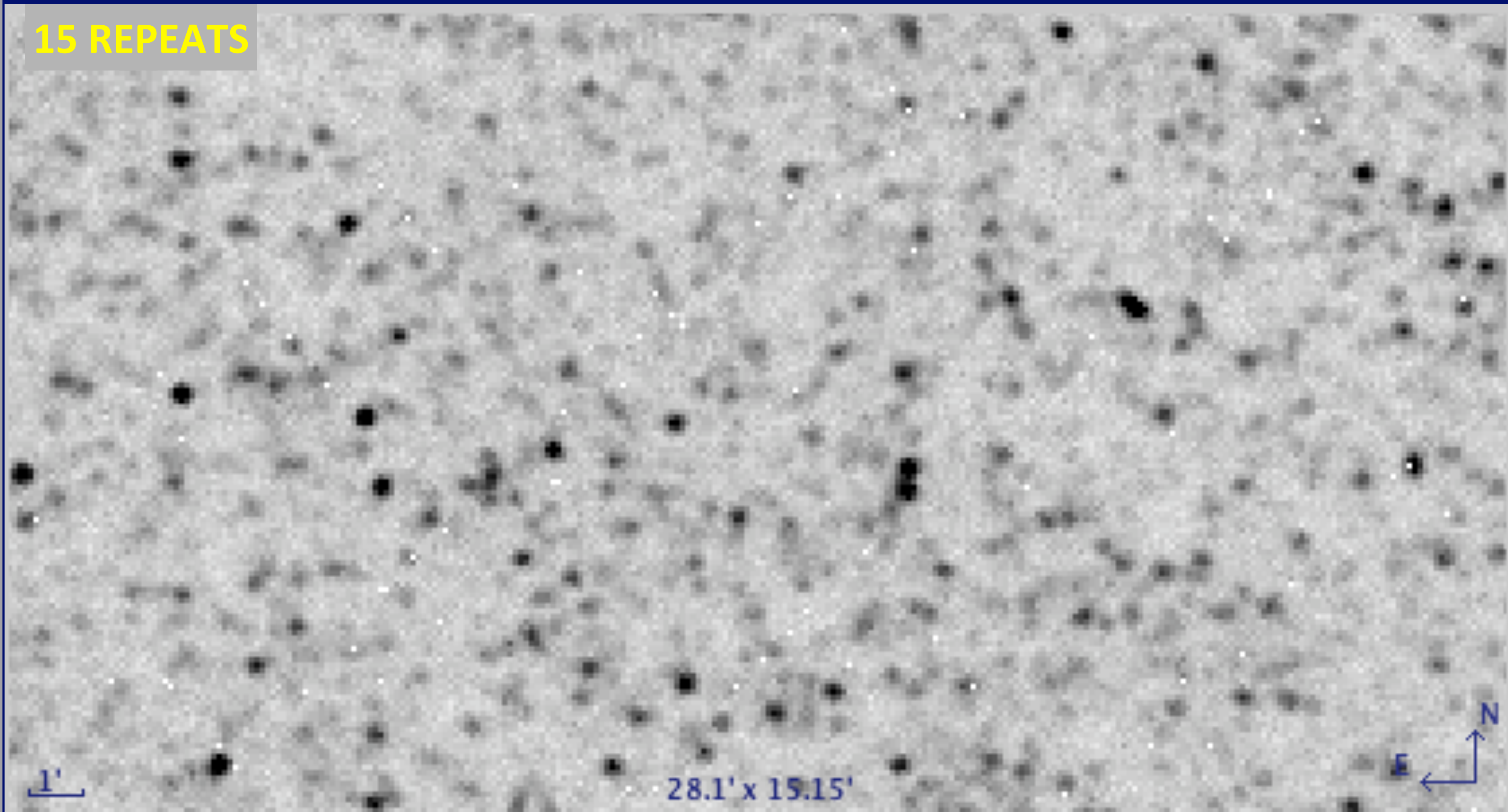
3 h for 1 sq. deg

Mapping to the Confusion Limit



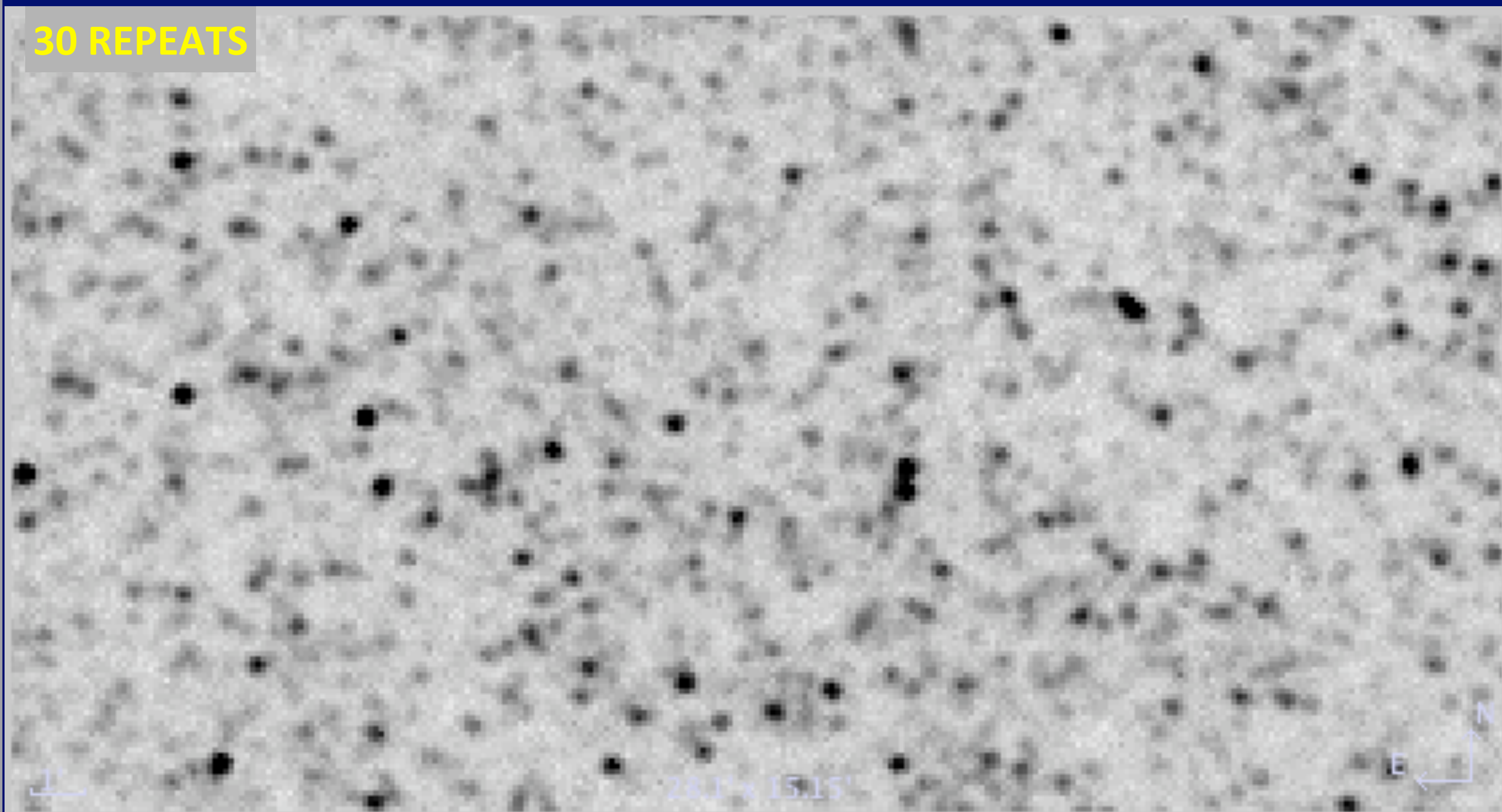
6 h for 1 sq. deg

Mapping to the Confusion Limit



11h for 1 sq. deg

Mapping to the Confusion Limit

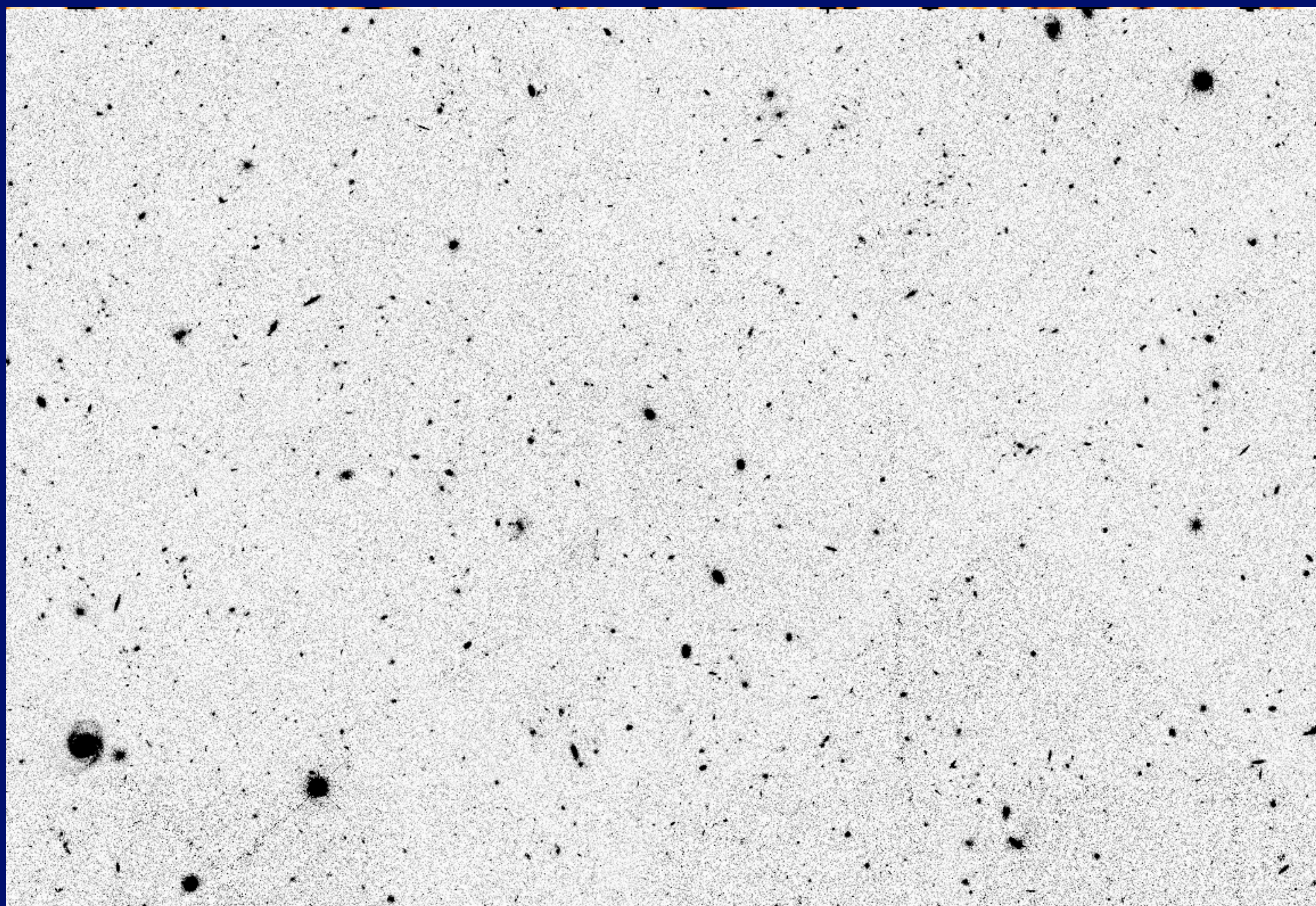


22 h for 1 sq. deg

The power of multi-wavelength imaging against confusion

500 350 250 160 100 24 3.6 0.8

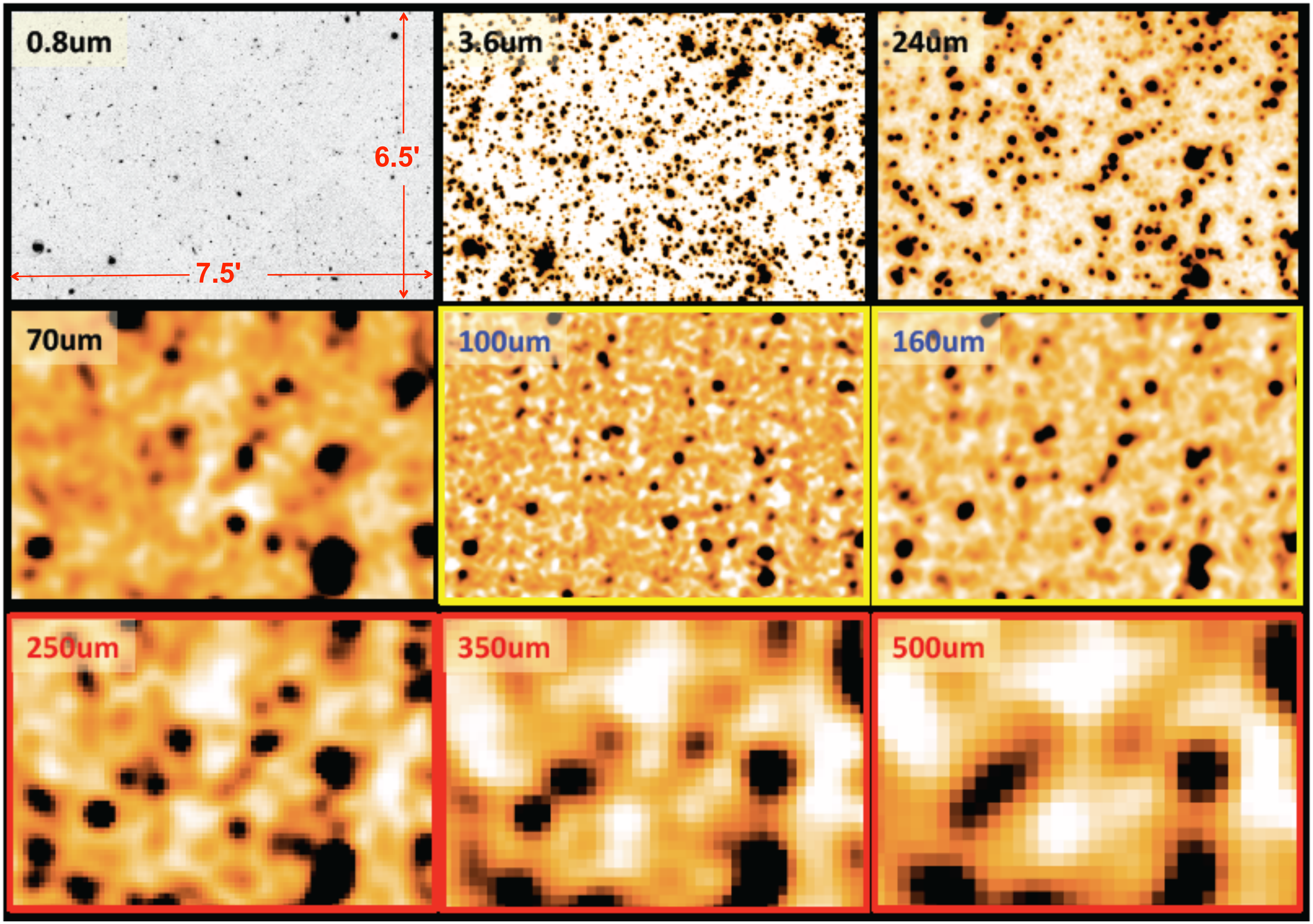
7.5' x 6.5' zoom on the GOODS-North field (10' x 15')



6.5'

7.5 arcmin

The Confusion Challenge



D. Elbaz

Three Ways to Deal with Confusion

Herschel Source Photometry

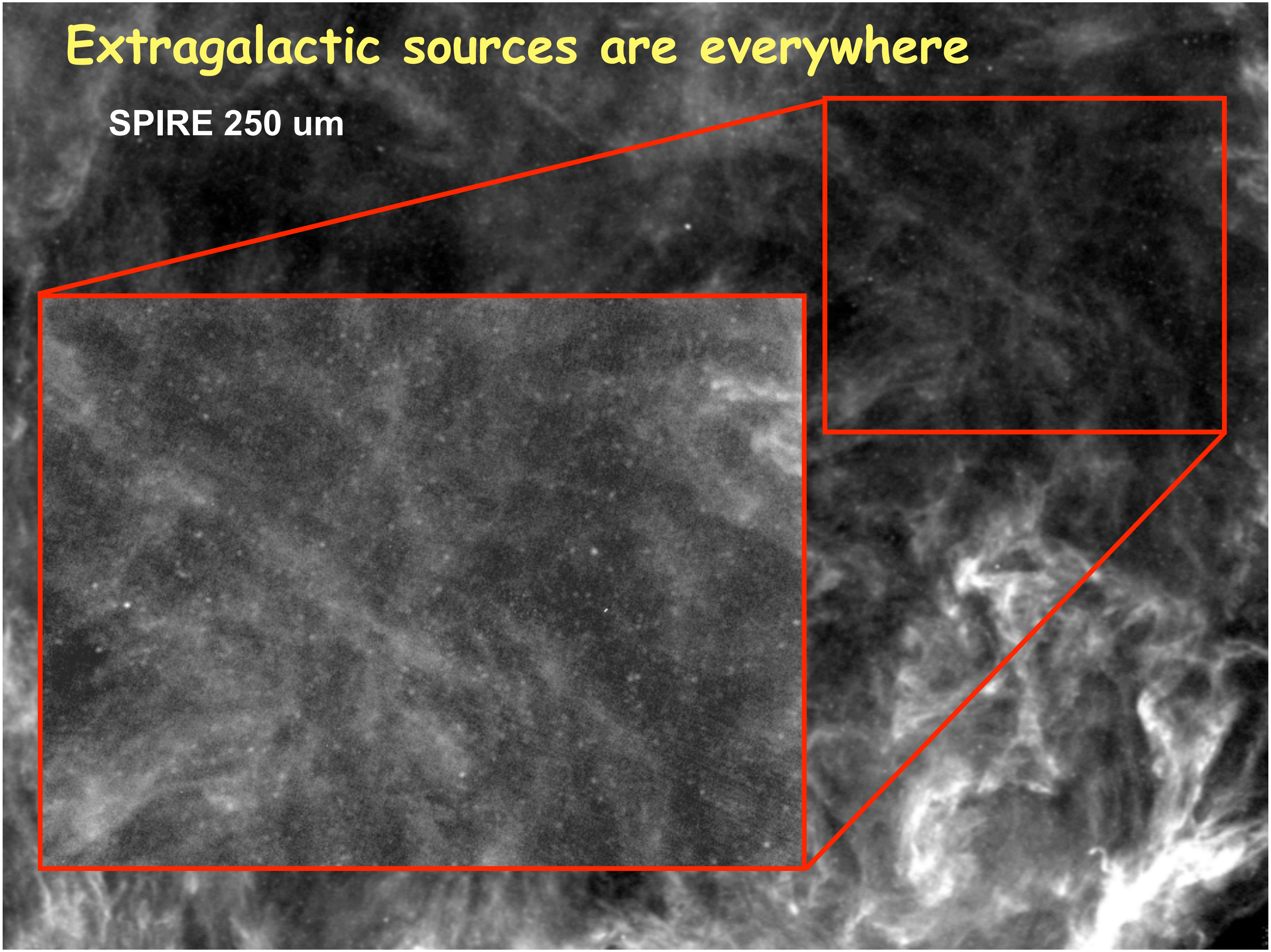
- Need to be careful about bias and source blending
- Blind follow-up in large beam is laborious (~SCUBA)
- However these are the most interesting source populations!

Pre-Existing Source Catalogs

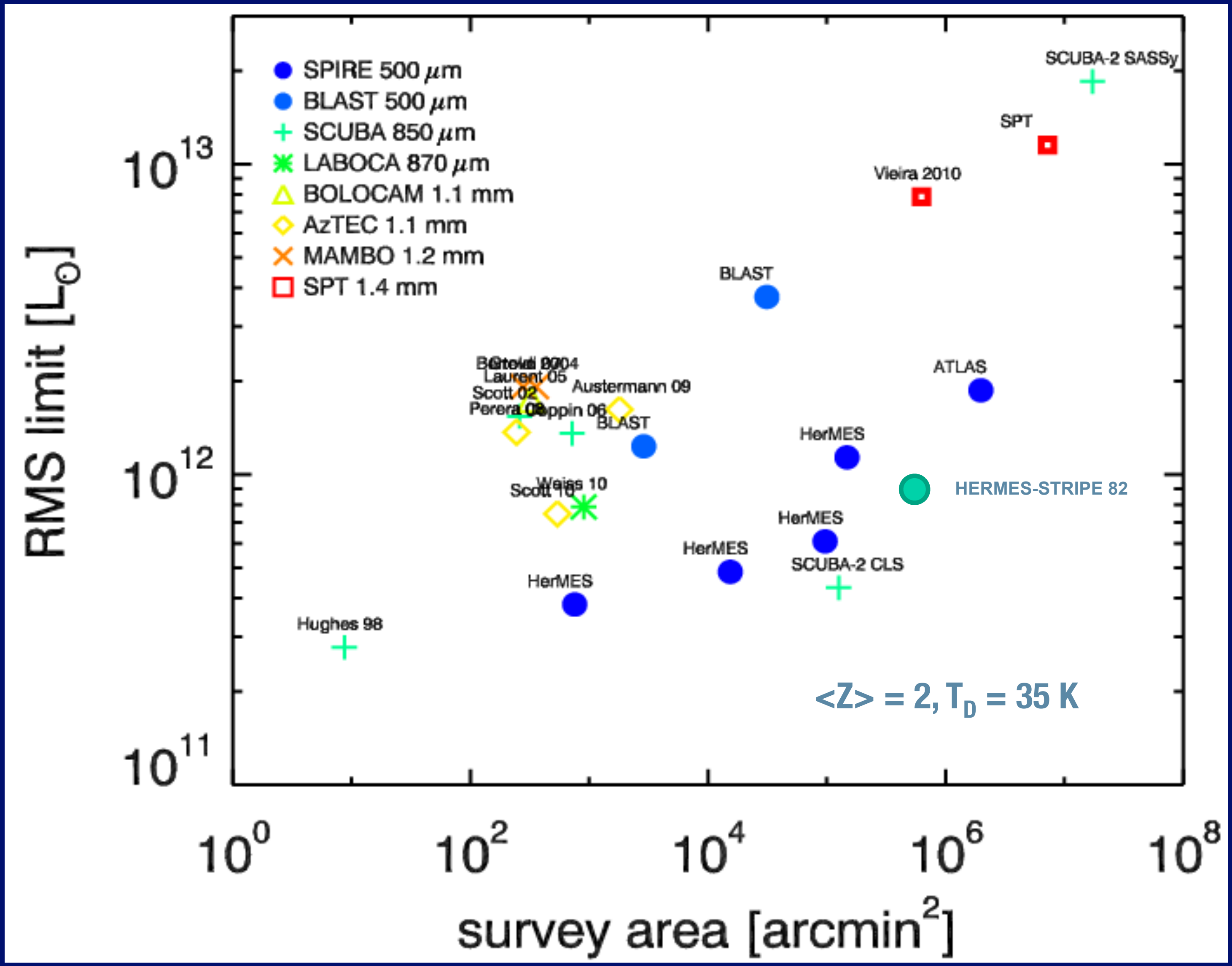
- Assign Herschel flux of known ancillary source
- Reliable to within confusion noise
- Follows bias inherent in finder catalog

Map-Based Analysis

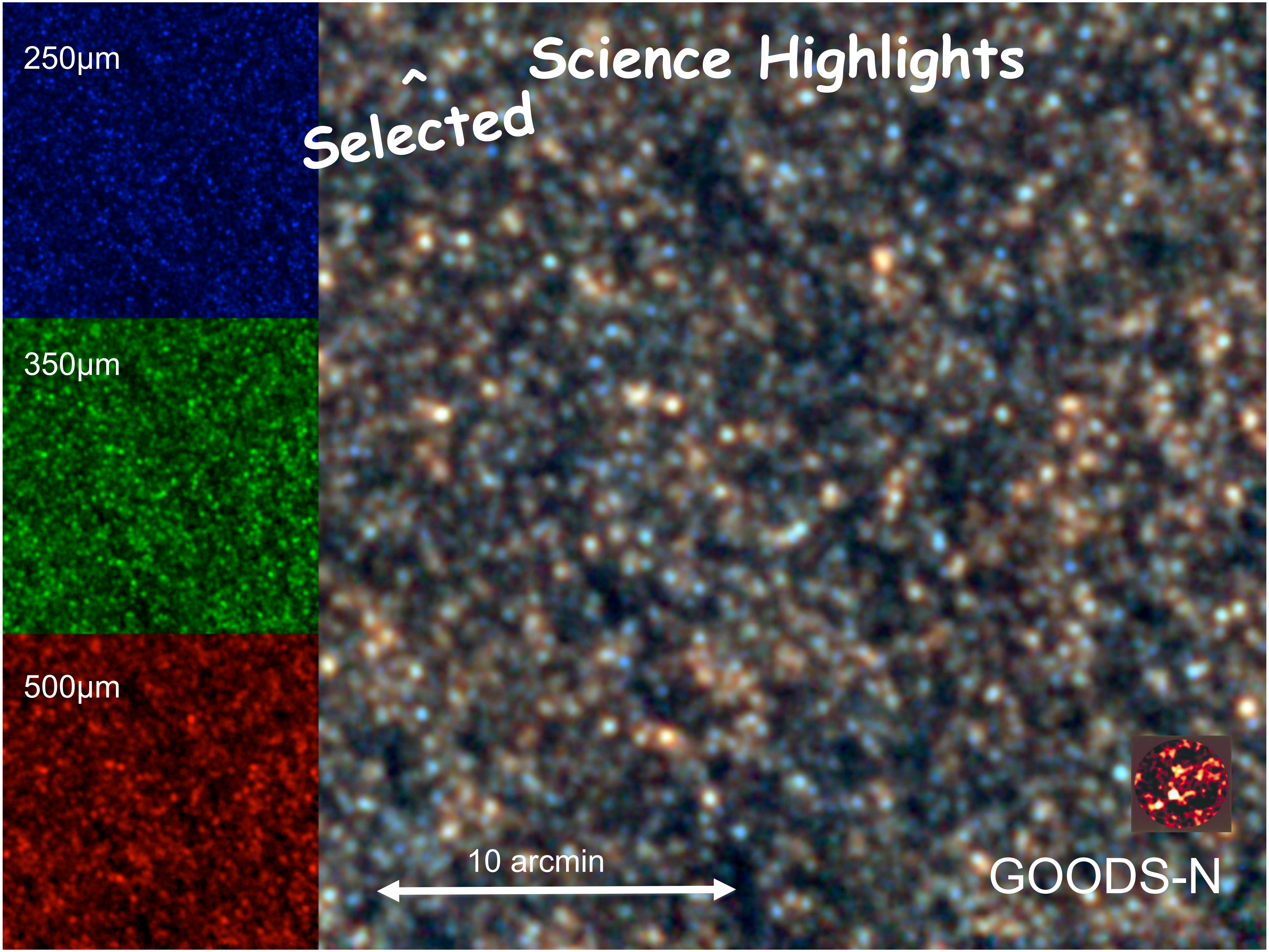
- Much more information in map than in reliable sources
- Tends to be ensemble information: P(D), fluctuations
- Maps have high statistical fidelity!

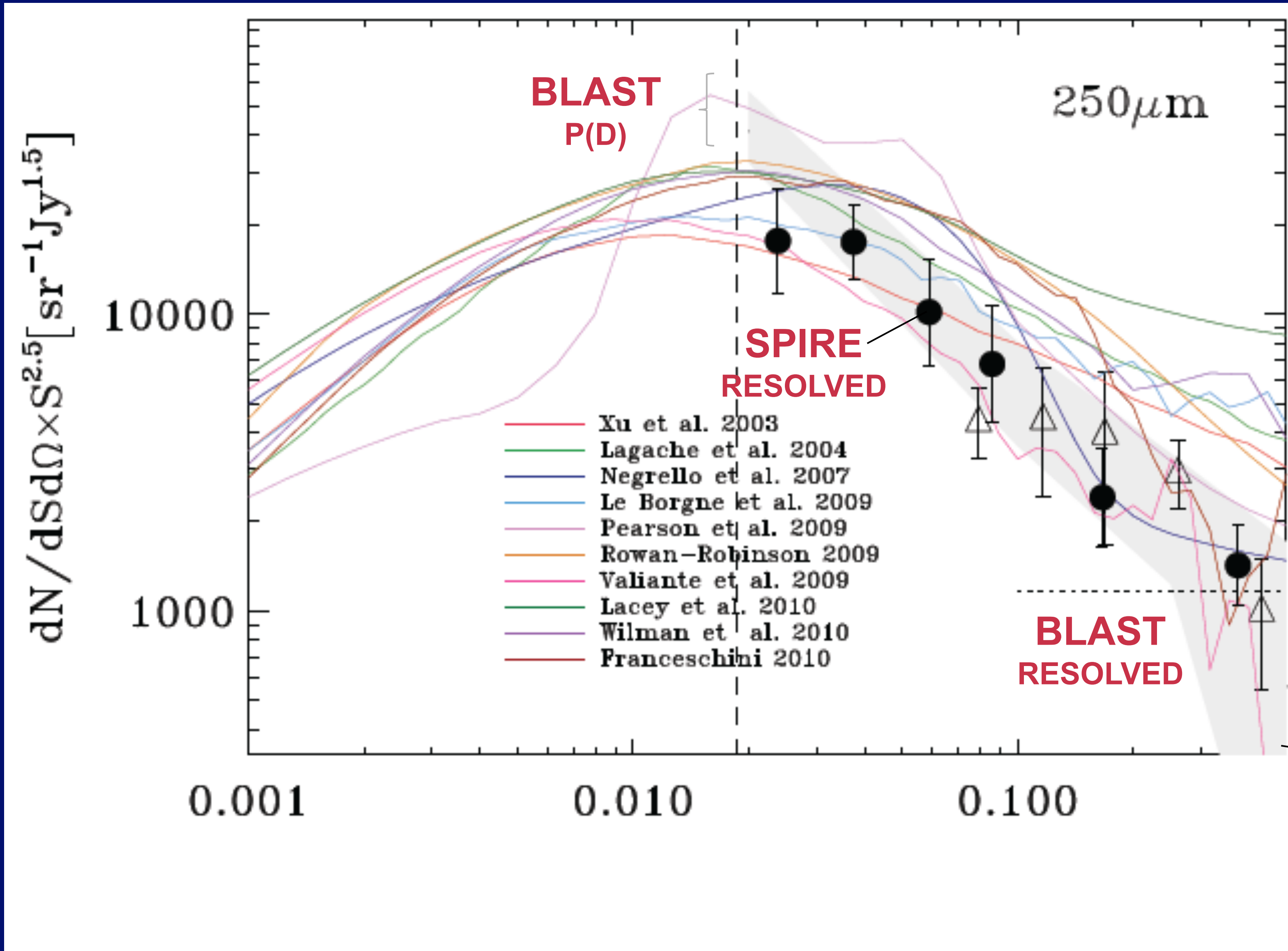


Extragalactic sources are everywhere
SPIRE 250 um



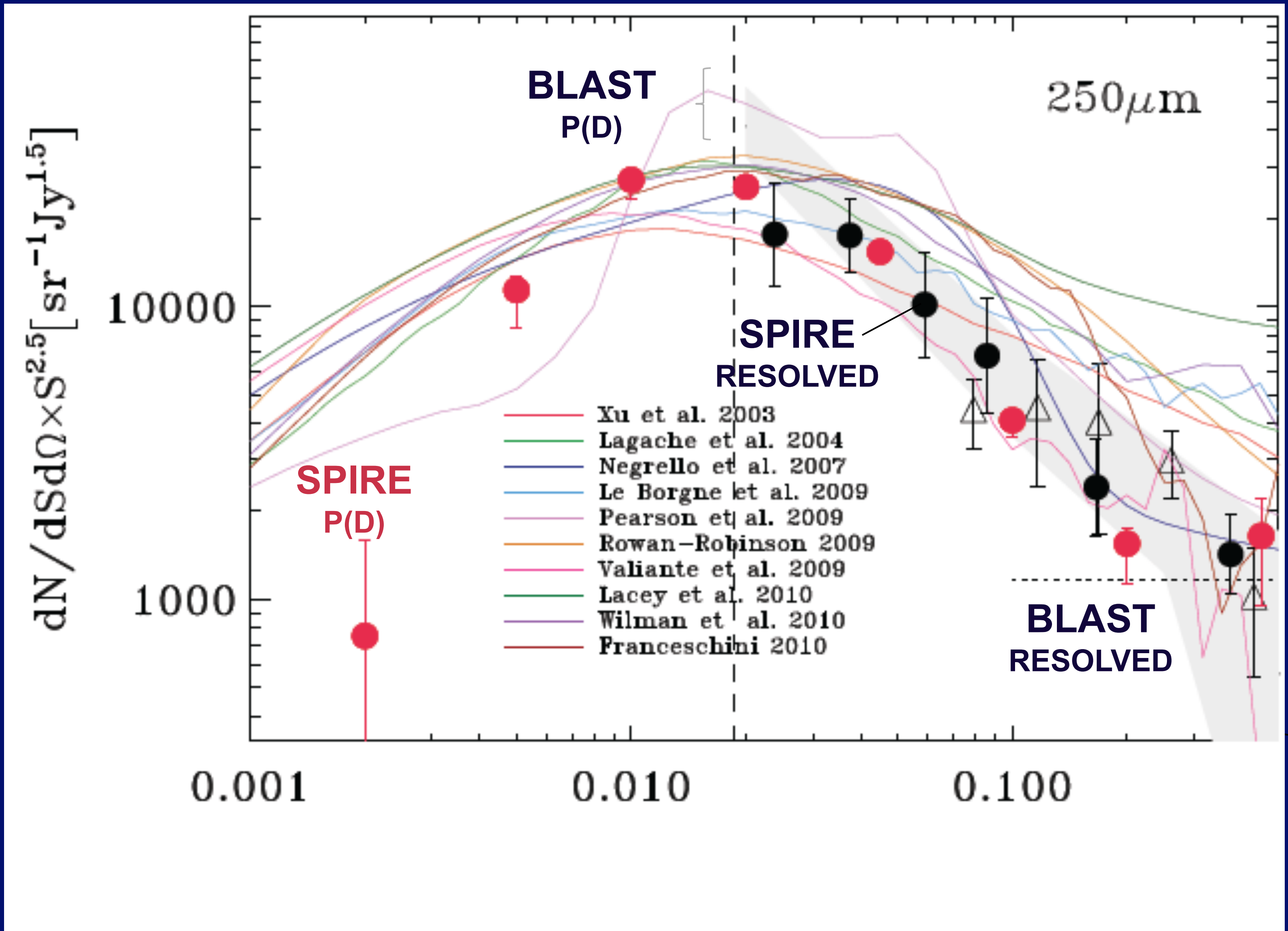
Herschel surveys vs. ground-based mm-wave surveys


Science Highlights
Selected
250μm
350μm
500μm
10 arcmin
GOODS-N



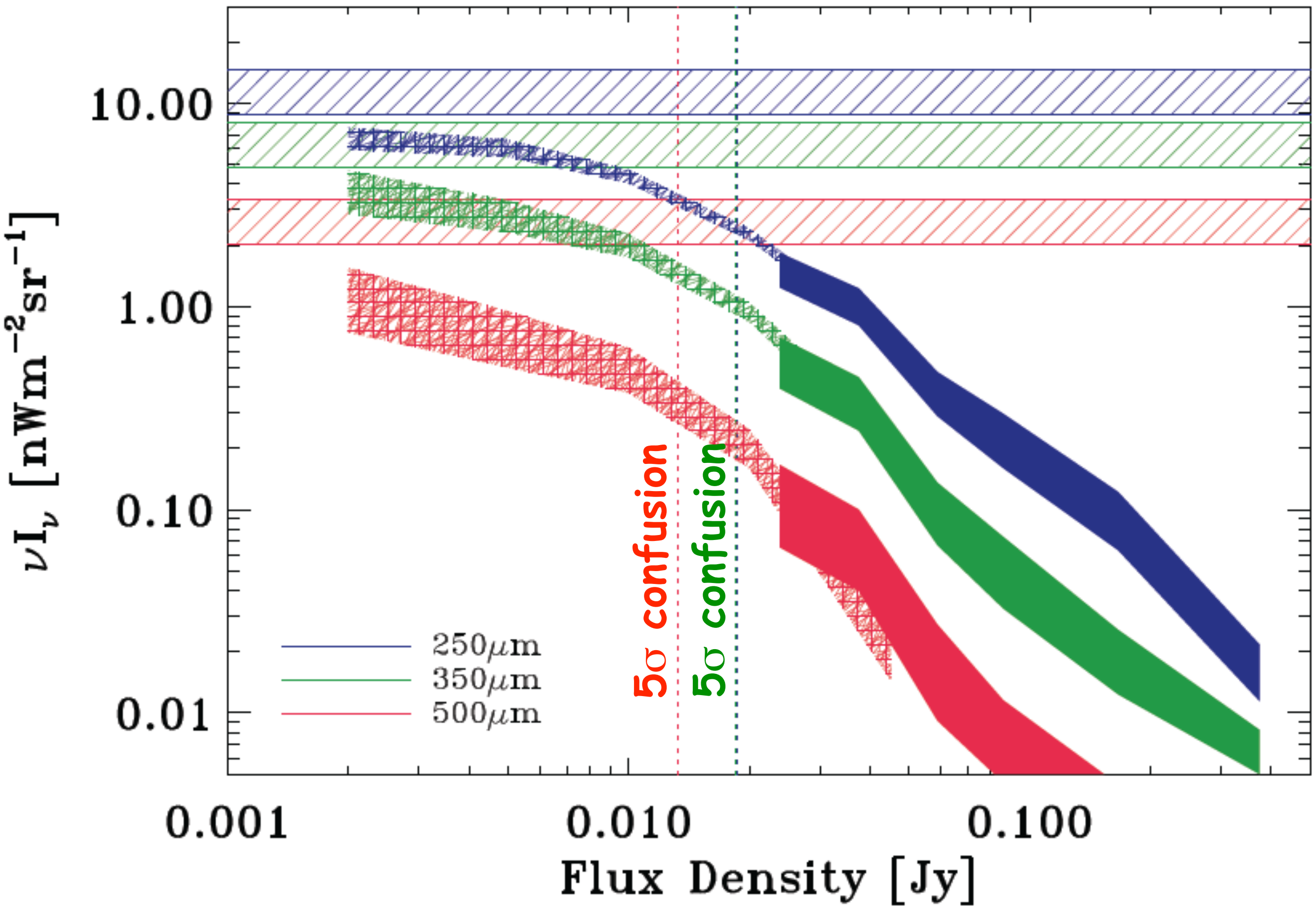
HerMES-SPIRE Source Counts

HERMES: SPIRE GALAXY NUMBER COUNTS AT 250, 350, AND 500 MM OLIVER ET AL. A&A 518, L21



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

HERMES: DEEP GALAXY NUMBER COUNTS FROM P(D) OF SPIRE SDP OBSERVATIONS, GLENN ET AL. 2010, MNRAS 409, 109

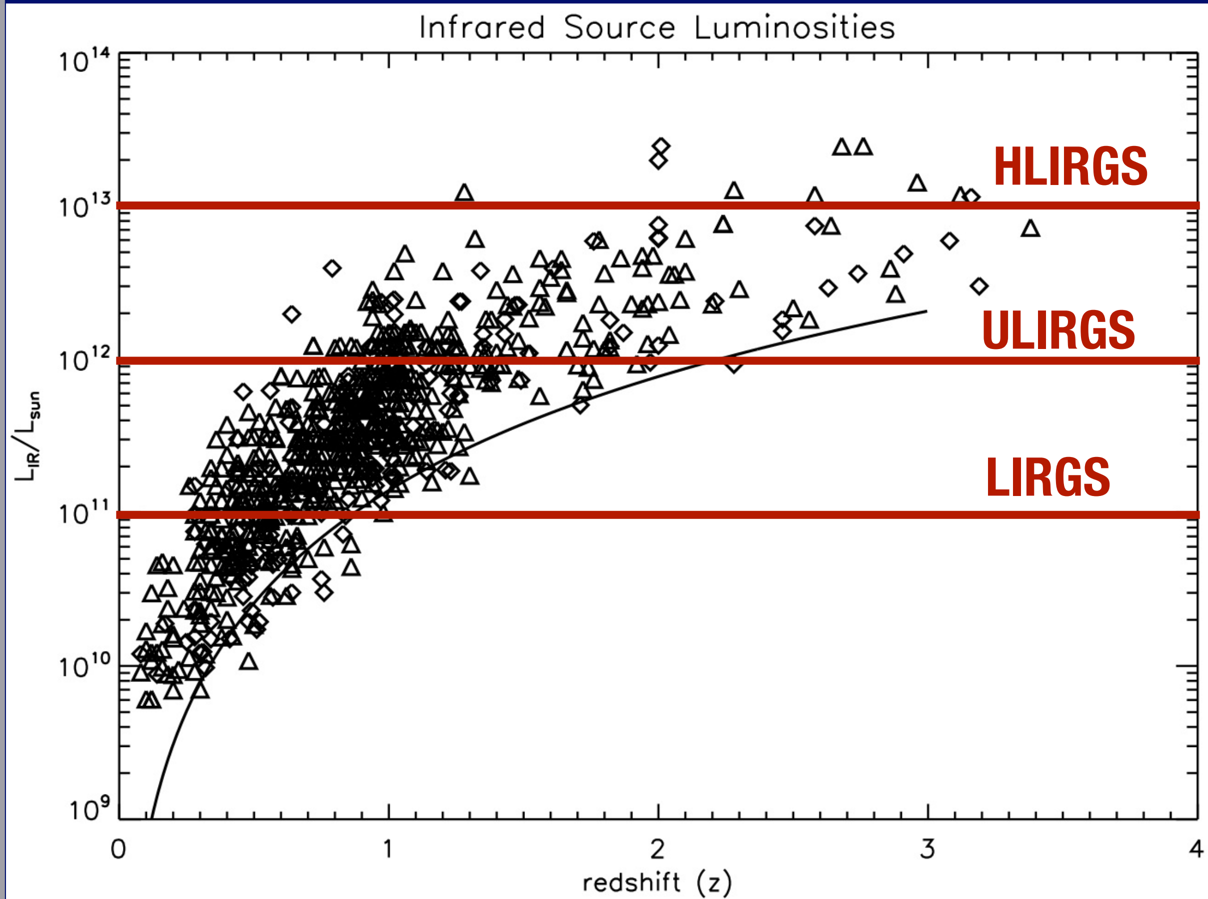


- **Source Counts**
  250, 350, 500 μm
  15%, 10%, 6%
- **P(D)**
  250, 350, 500 μm
  65%, 60%, 45%
- **Stacking:**
  250, 350, 500 μm
  80%, 80%, 85%

Of course: The remainder are the most interesting sources!
E.g. z > 3 galaxy populations

Resolving the Far-IR Background (FIRAS)

HERMES: DEEP GALAXY NUMBER COUNTS FROM P(D) OF SPIRE SDP OBSERVATIONS, GLENN ET AL. 2010, MNRAS 409, 109



2000

200

20

2 (~Milky-way SFR)

Star-Formation Rate in solar masses per year

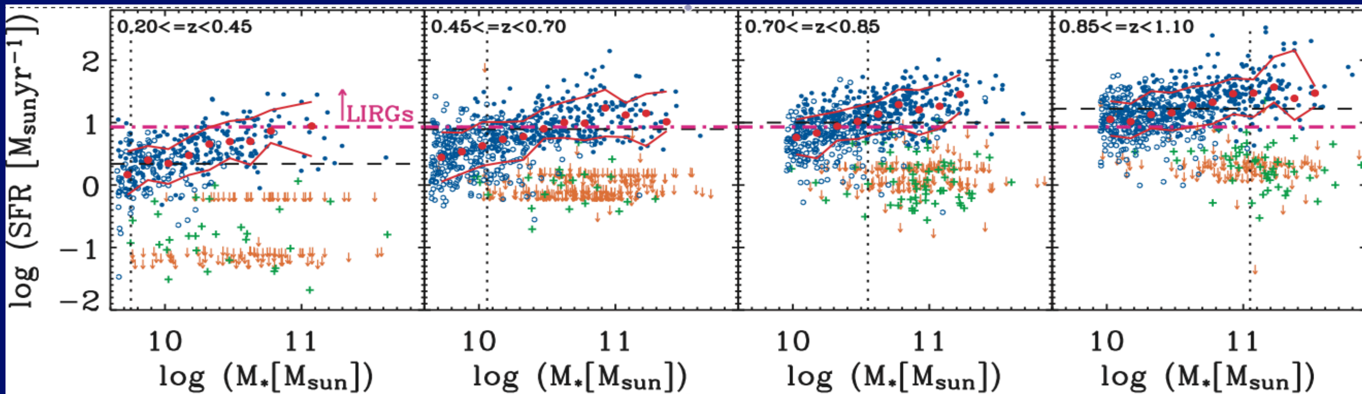
(i) ULIRGS/HyLIRGS typically have about ~10^{10} solar masses in stars

(ii) So the time scale for star-formation is [M*/(dM*/dt)] ~ 5 to 100 Million years

(star-bursting galaxies!)

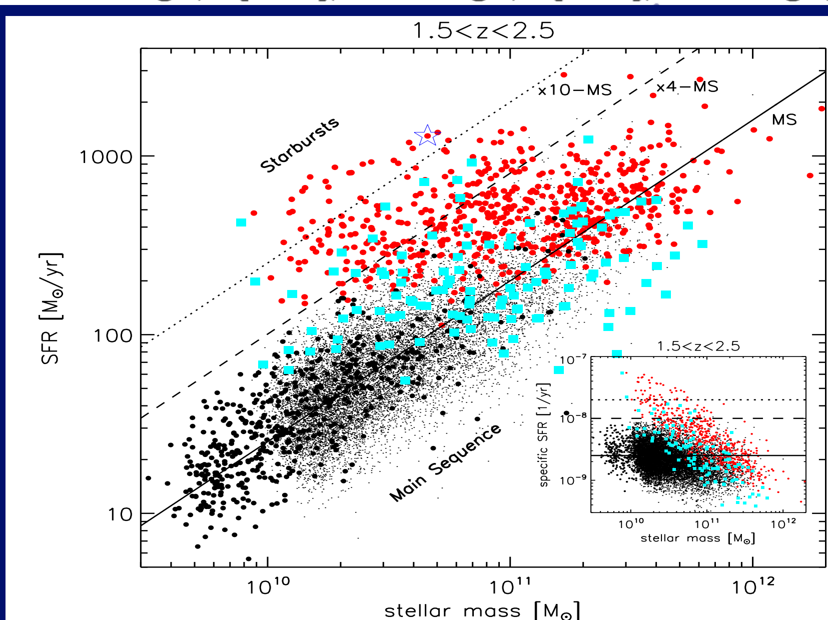
(iii) at z < 0.5 we also detect typical late-type galaxies (spirals).

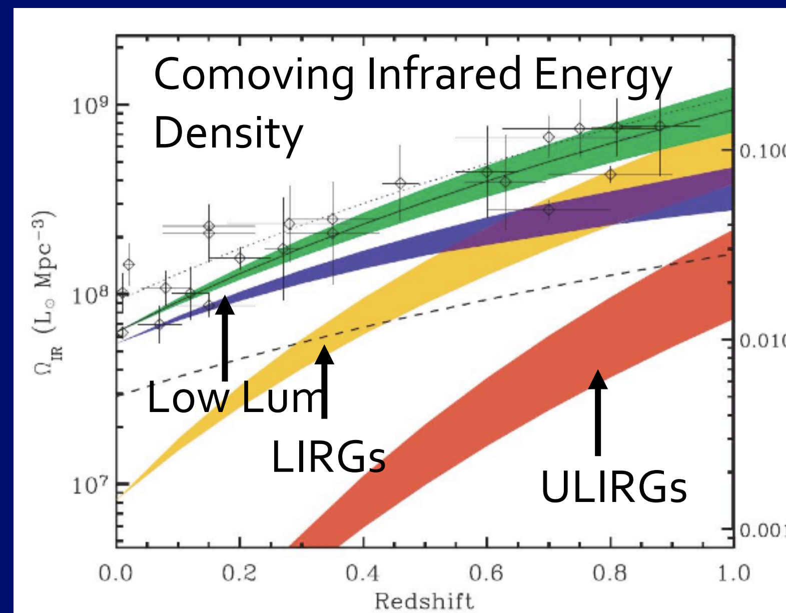
What kind of galaxies do we detect with Herschel?



Star-formation rate is correlated with stellar mass and evolving rapidly.

Noeske, K. et al. 2007, ApJ, 660, L39





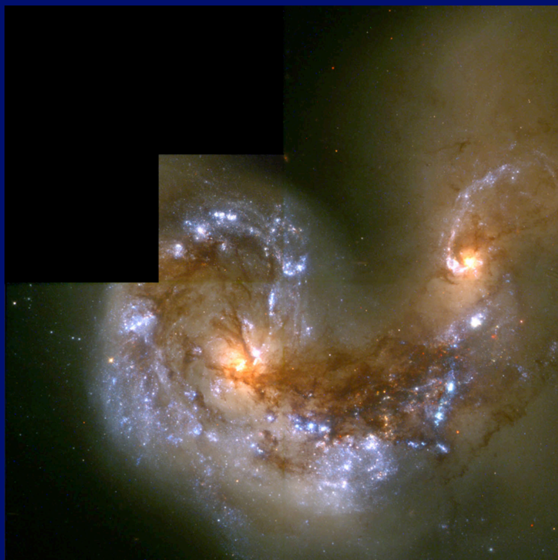
Star-burst galaxies are elevated above the "main sequence" occupied by typical galaxies.

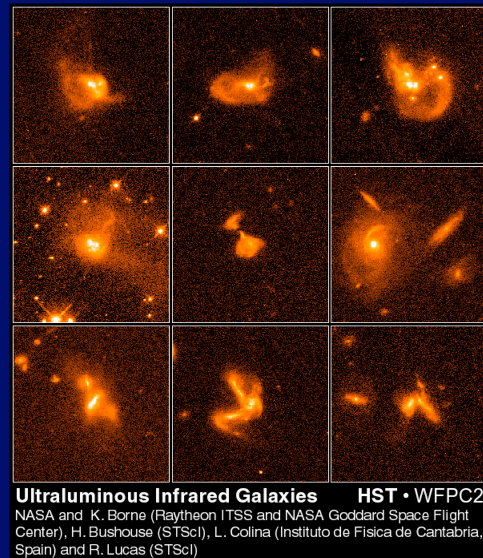
Star-bursts dominate the cosmic star-formation rate of the Universe at z > 2.

What are Dusty Starbursting Galaxies?

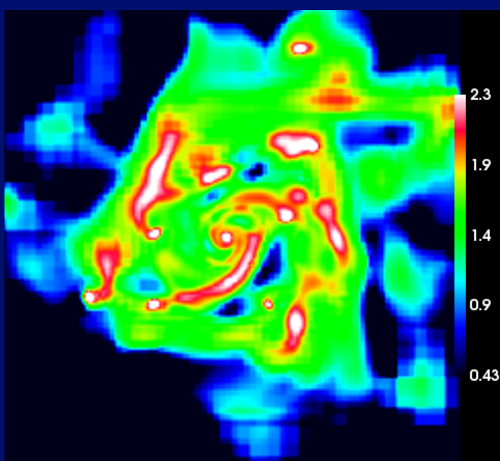
Elbaz, D. et al. 2011, A&A, 533, 119

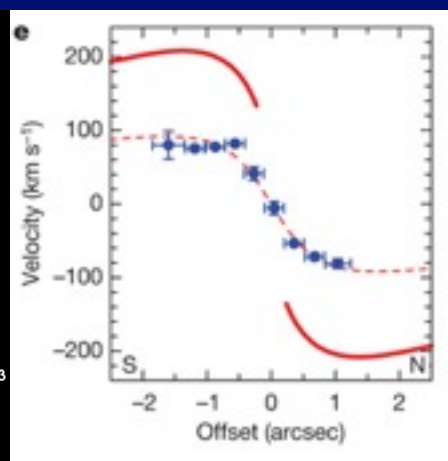
Le Floch, E. et al. 2005, ApJ, 632, L169





In the local Universe ~100% of starbursts are driven by gas-rich galaxy mergers.





But at z ~ 1 to 2, observations show that some starburst galaxies are simple disks.

Is there a different mechanism to trigger a starburst at high redshifts?

(theorists: cold accretion mode)

Tacconi, L. J. et al. 2008, ApJ, 680, 246

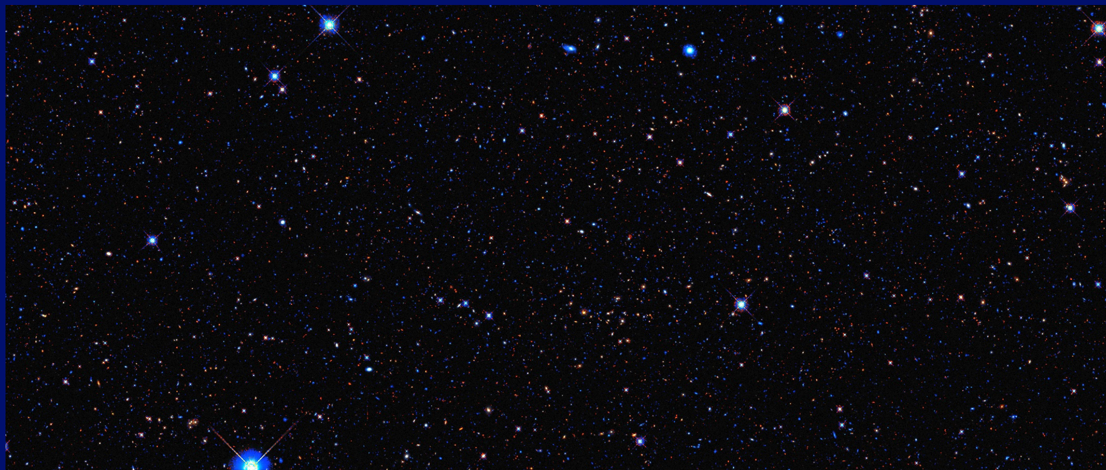
Dekel, A. et al. 2009, ApJ, 703, 785

(a) What fraction of starbursts are mergers/cold flows?

(b) What are the properties of gas, dust, stars in these starburst galaxies?

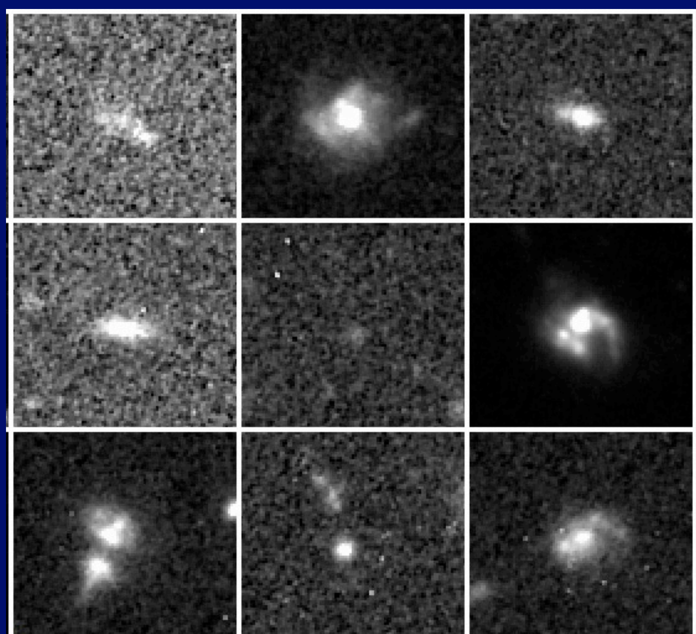
What are Dusty Starbursting Galaxies?

LOCAL ULIRGS REVIEW: SANDERS, D. AND MIRABEL, I. 1996, ARAA, 34, 749

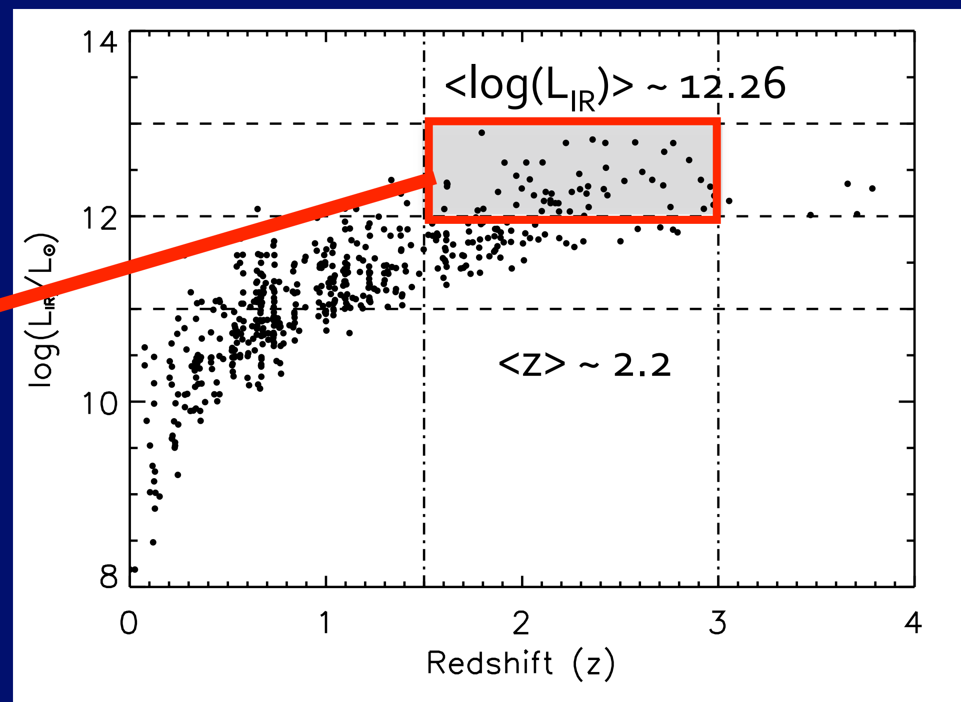


CANDELS, a multi-cycle program with Hubble Space Telescope.
website: candels.ucolick.org

HST resolution needed to study morphologies of starbursts at z~2



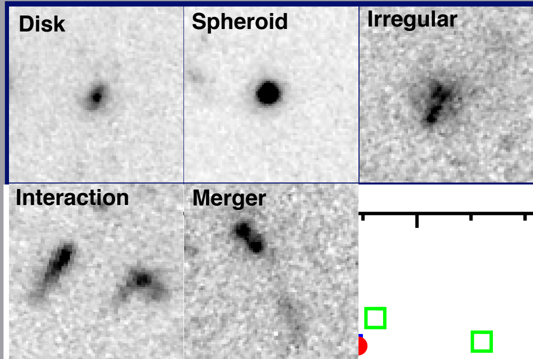
z=2 starbursts as seen by Hubble

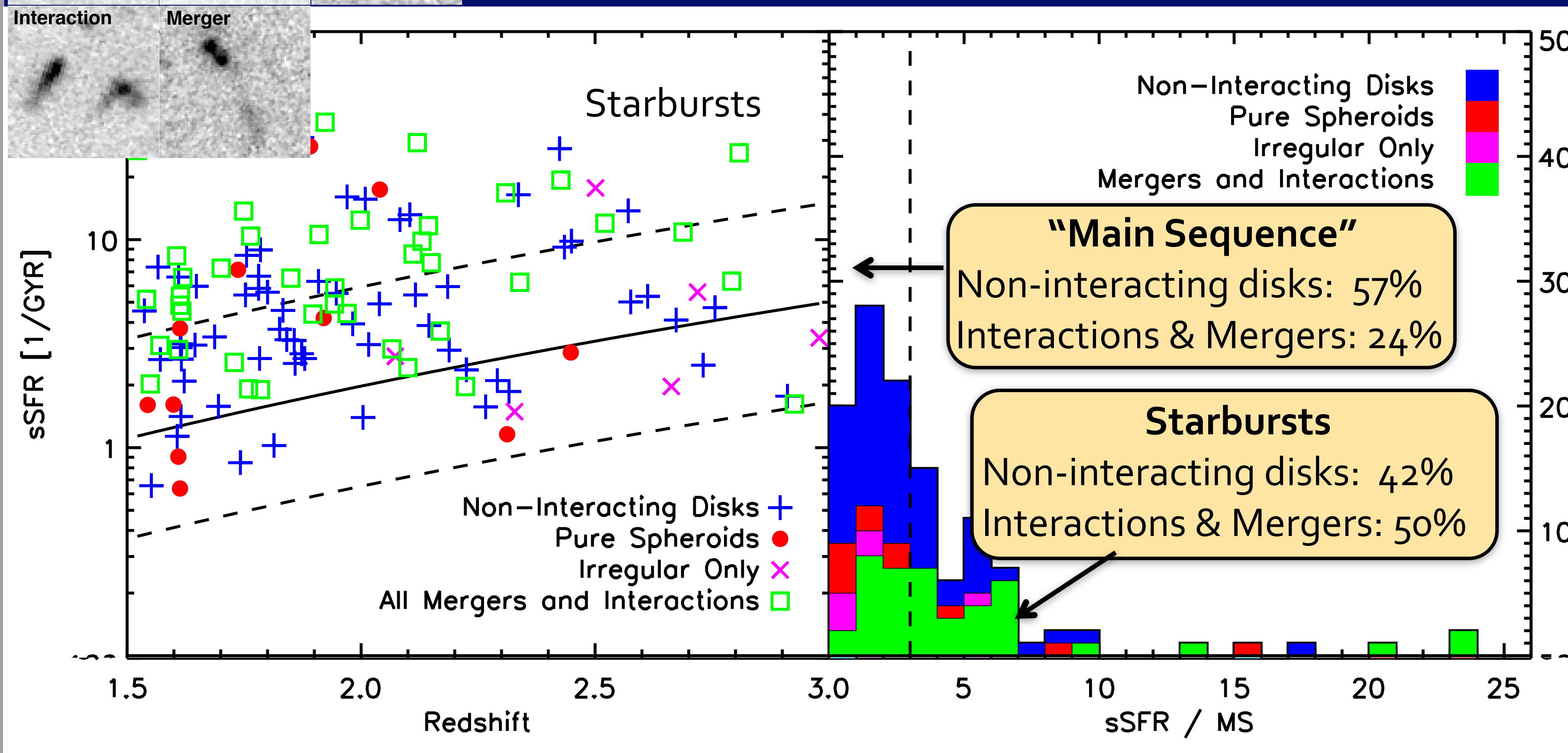


What are Dusty Starbursting Galaxies?

Kartaltepe, J. et al. 2011, ApJ submitted (arXiv.org: 1110.4057)

Based on visual classification of Herschel galaxies and main sequence (non-Herschel) galaxies



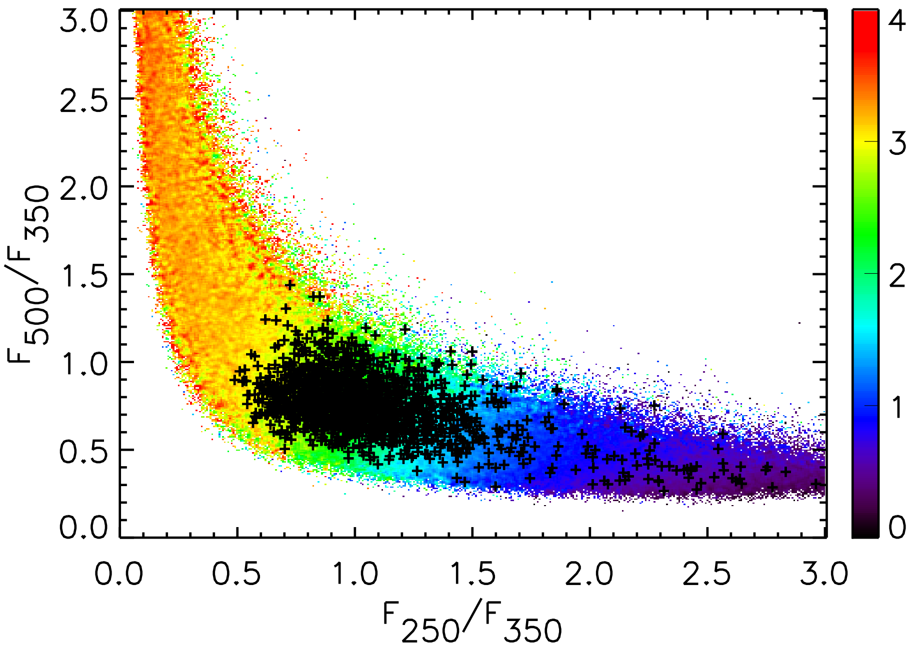


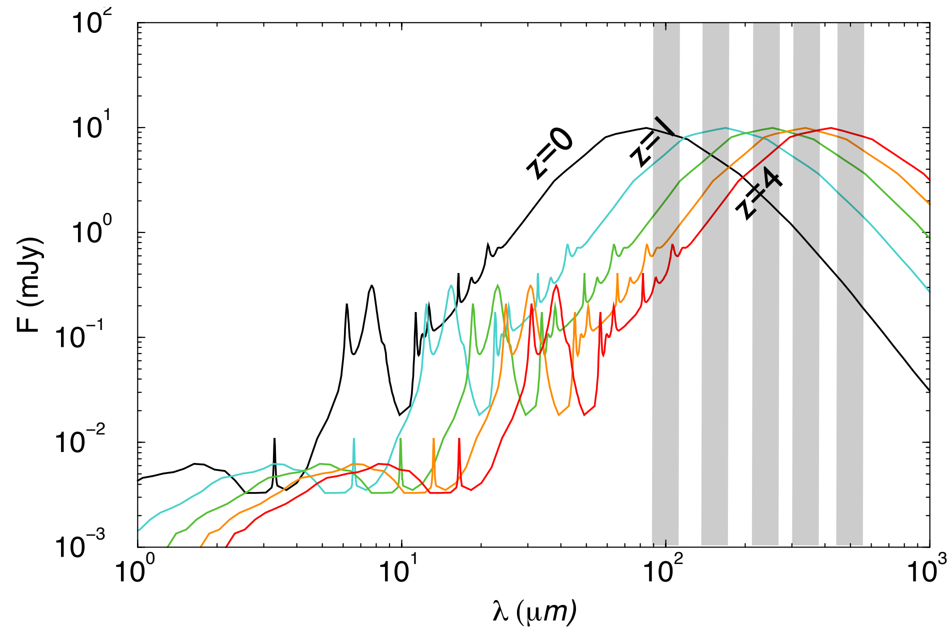
- ~50% of z~2 Herschel starbursts are mergers (study is inconclusive, however)
- Are there SMG disks accreting cold gas?

What are Dusty Starbursting Galaxies?

Kartaltepe, J. et al. 2011, ApJ submitted (arXiv.org: 1110.4057)

Redshift distribution of SPIRE Sources?





The surface density of 350 μm selected sources (z~1.8 to 3) S_{350} > 20 mJy is ~800/deg²

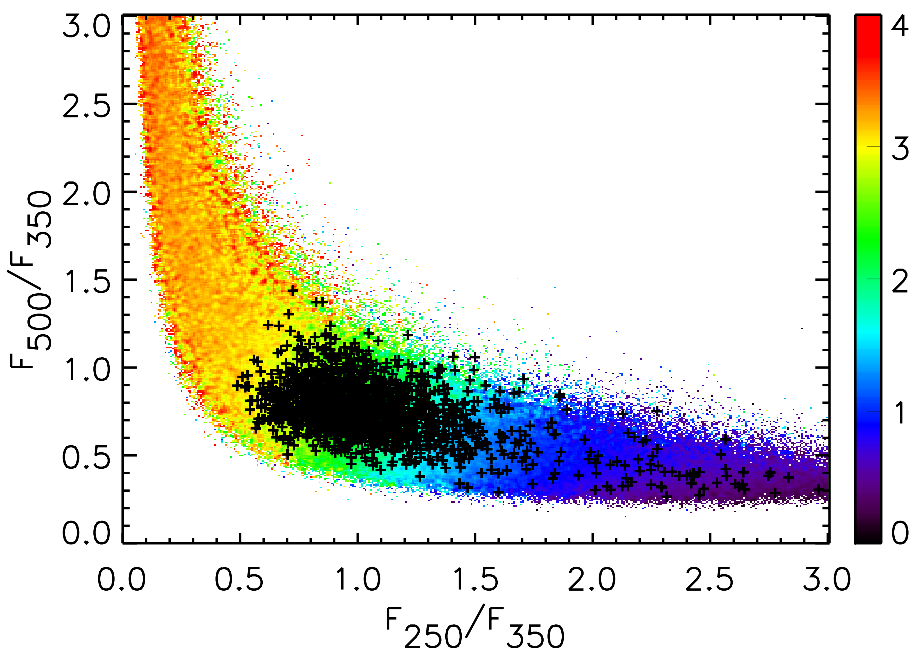
Naive expectation based on the SED:
$S_{250} > S_{350} > S_{500}$: z < 2
S_{250} <~ $S_{350} > S_{500}$: z ~ 2 to 3
$S_{250} < S_{350} < S_{500}$: z > 4

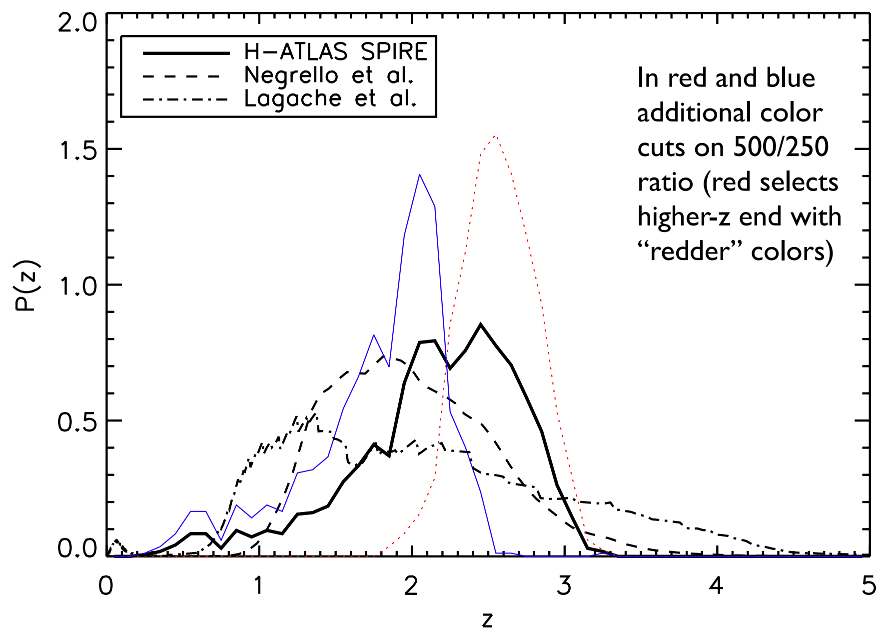
Amblard et al. 2010

sub-mm colors as a mechanism to select z > 2 galaxies

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} > 20 mJy is ~800/deg^2

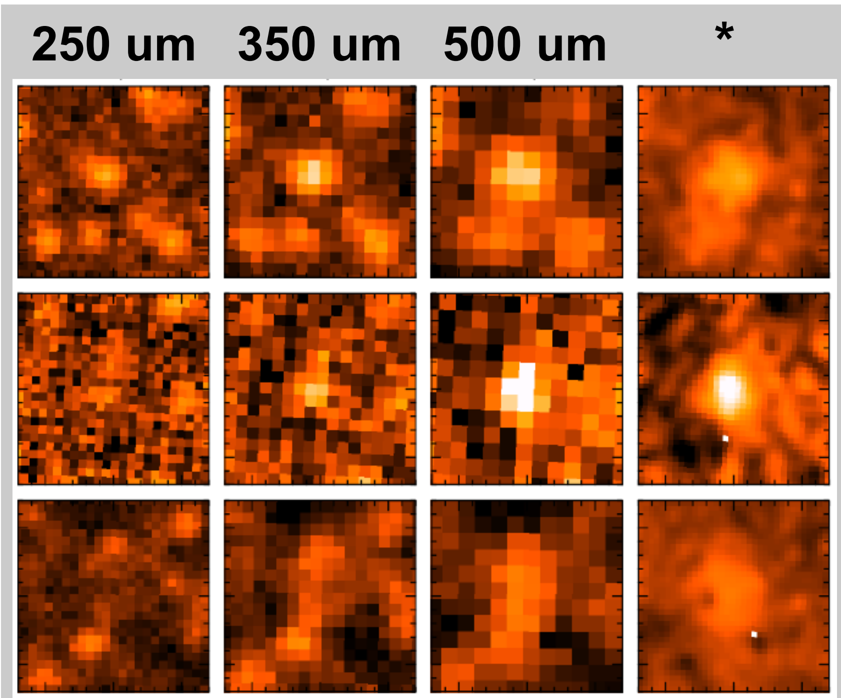
The "statistical" redshift distribution implied by SPIRE colors for the 1686 sources
[equivalent to fitting each SED with a single-temp model and marginalizing over T,β] *(Hughes et al 2002; Aretxaga et al. 2007)*

Amblard et al. 2010

High Redshift Candidates?

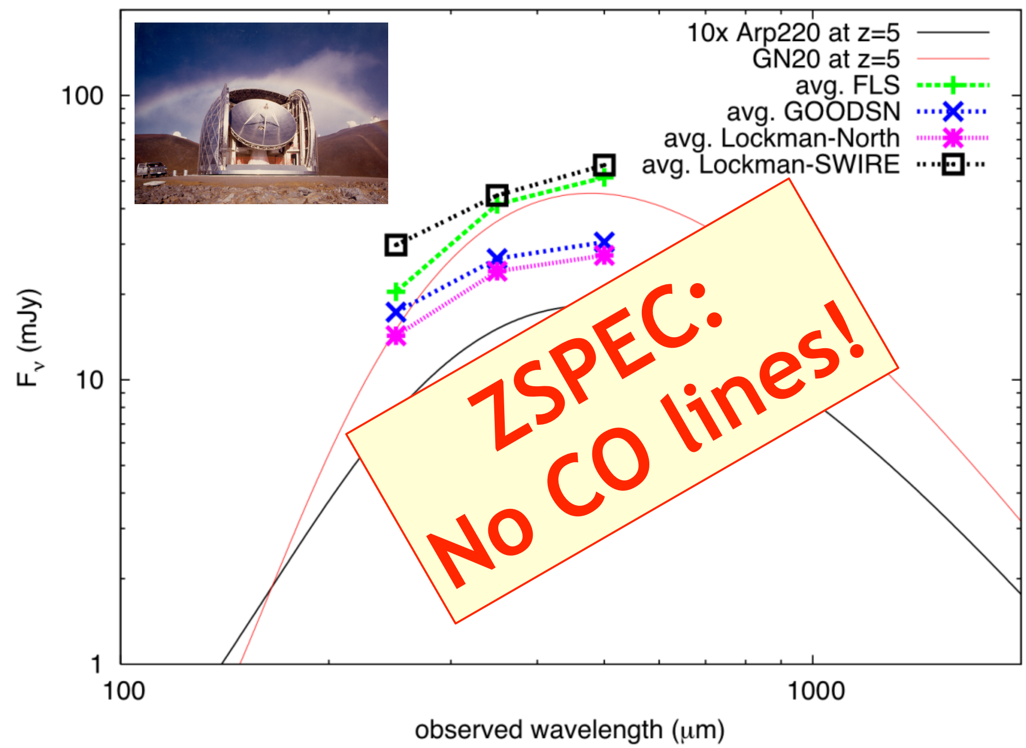
500 um peaked sources $S_{250} < S_{350} < S_{500}$: $z > 4$?

Three examples:



*Confusion reduced S(500) – fS(250)

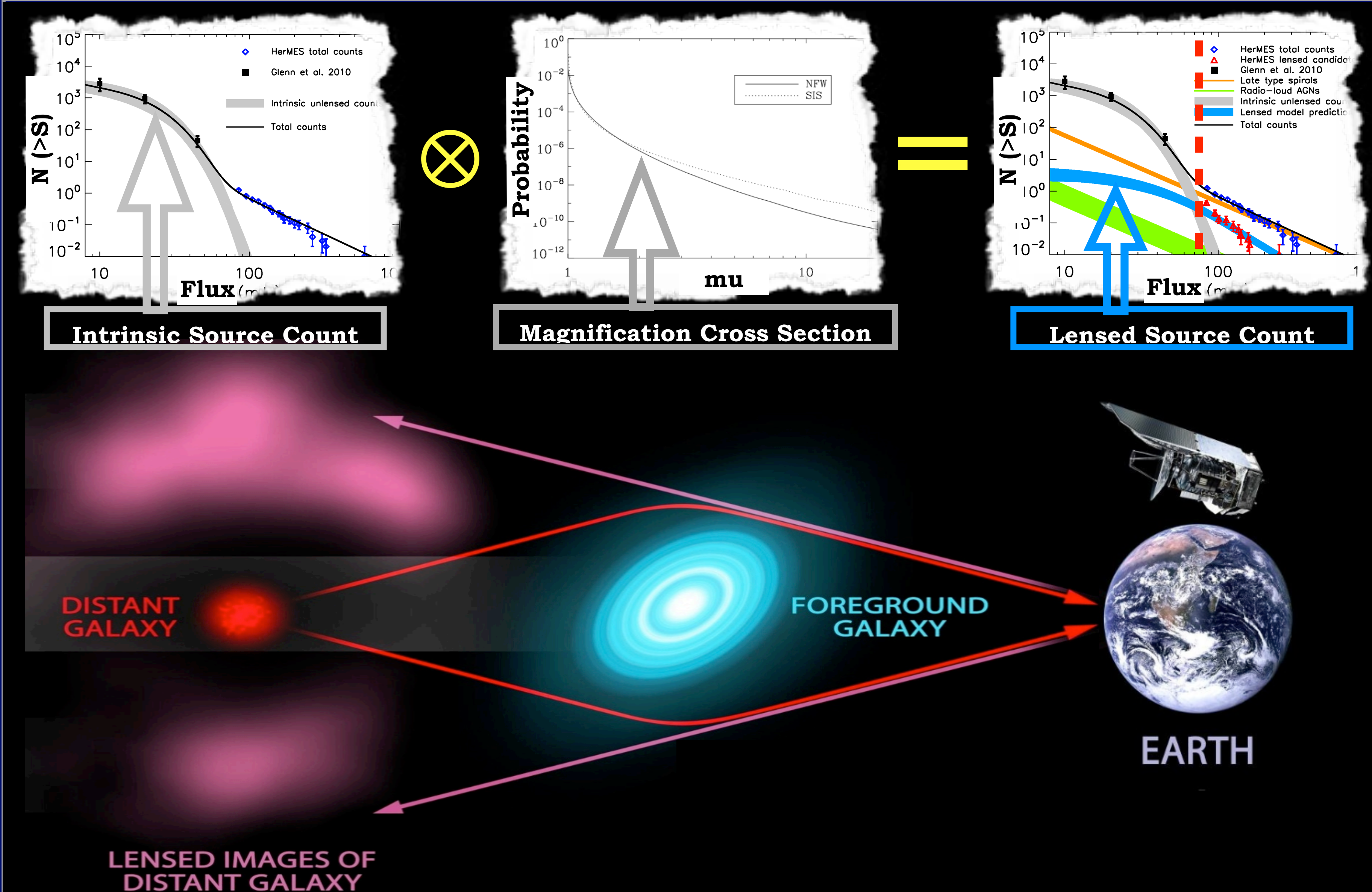
Average spectra of sources detected in 4 HerMES fields compared to templates:



These could be:

~~*z = 1.5, T_{dust} = 20 K ULIRGs or*~~

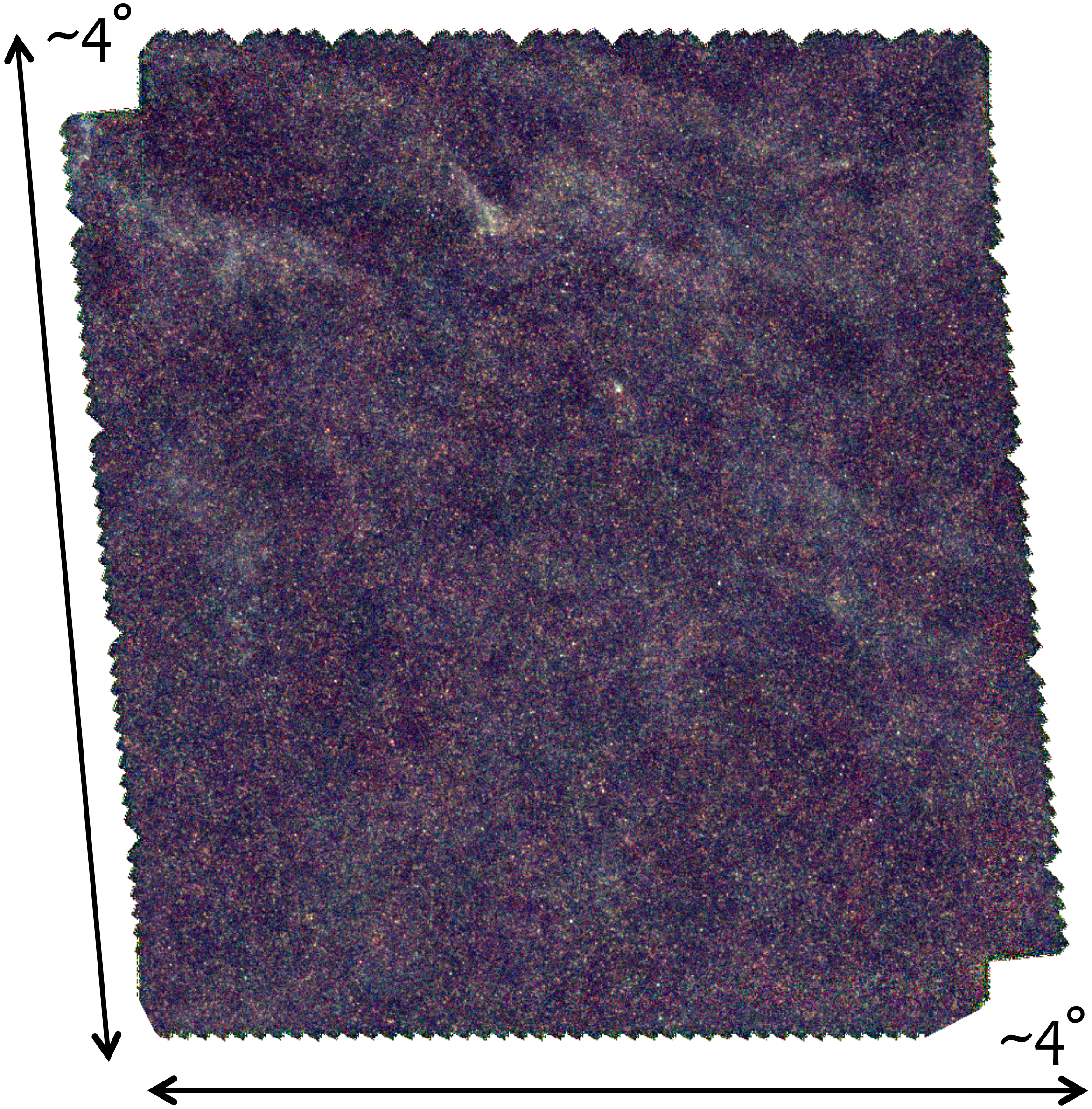
z = 5, T_{dust} = 35 K HLIRGs…



Efficient Selection of Strongly Lensed SMGs

Blain (1996), Negrello et al. (2007), Wardlow et al. (2012)

500 μm BRIGHTEST GALAXIES IN H-ATLAS SDP



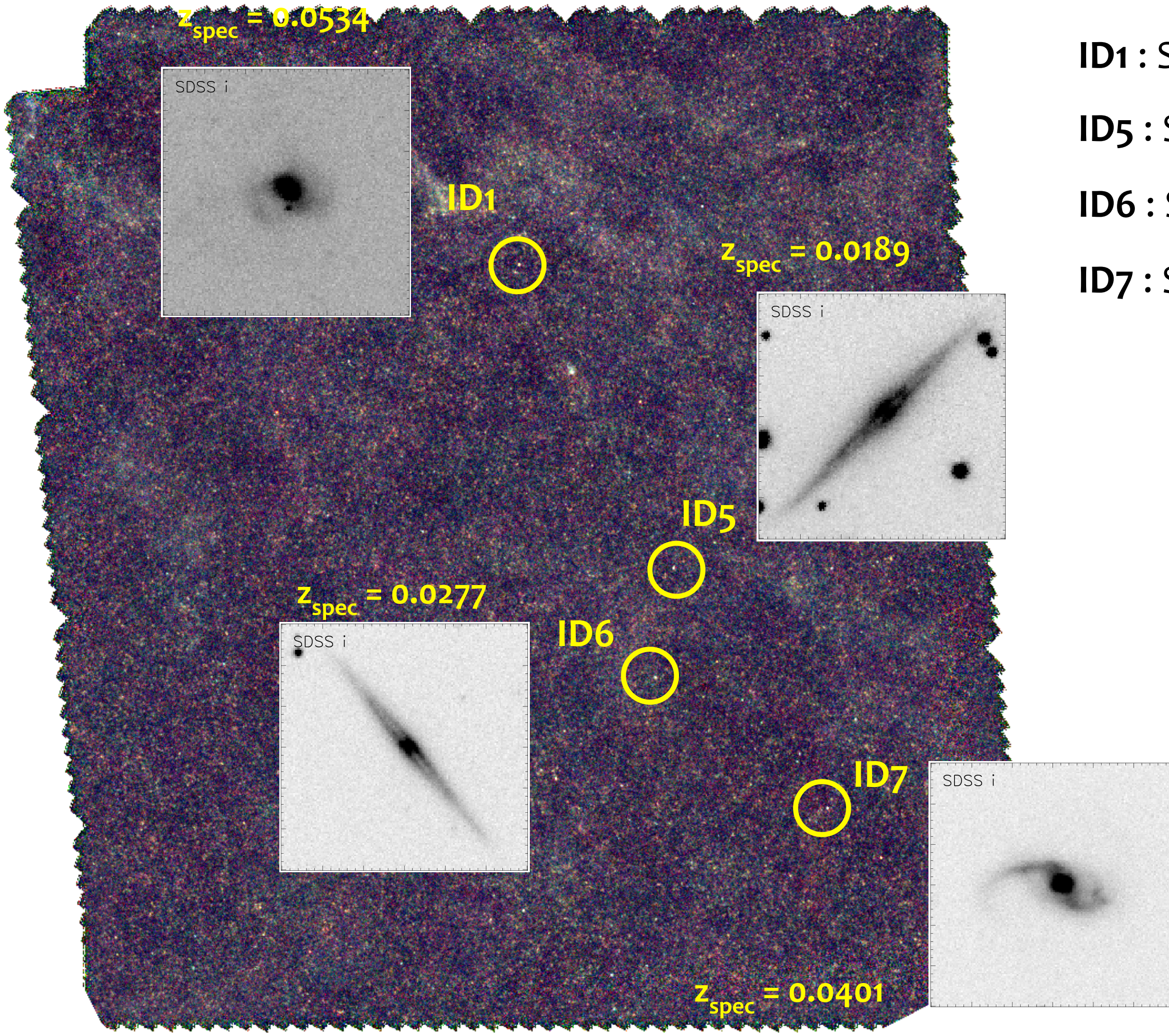
H-ATLAS SDP field

- ~ 14.4 deg^2
- ~ 7000 sources

11 sources with

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

500 μm BRIGHTEST GALAXIES IN H-ATLAS SDP



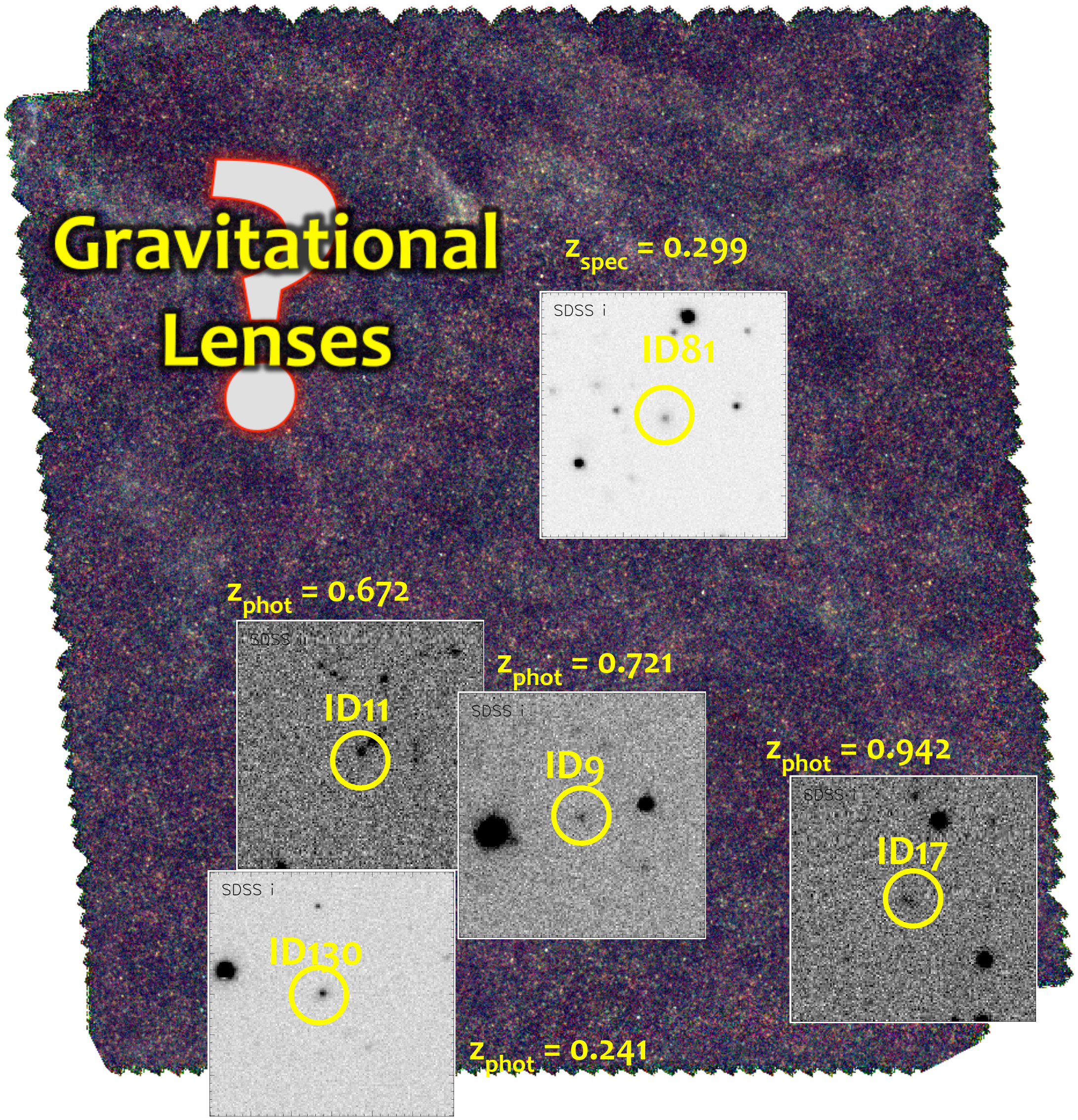
ID1 : $S_{500\mu m}$ = 177 ± 28 mJy

ID5 : $S_{500\mu m}$ = 122 ± 20 mJy

ID6 : $S_{500\mu m}$ = 112 ± 19 mJy

ID7 : $S_{500\mu m}$ = 104 ± 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

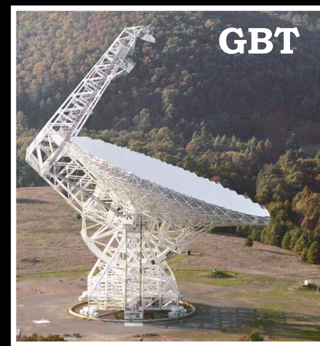
ID81 : $S_{500\mu m}$ = 166 ± 27 mJy

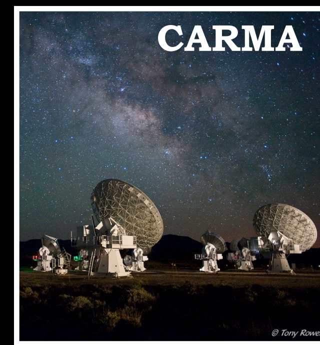
ID130 : $S_{500\mu m}$ = 108 ± 18 mJy

optical counterparts

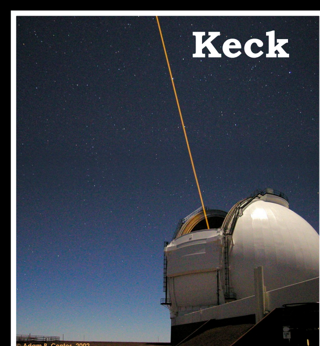
$z_{phot/spec} < 1.0$

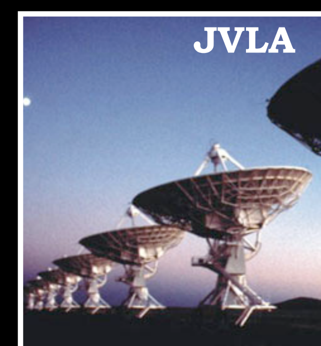
Source CO Redshift





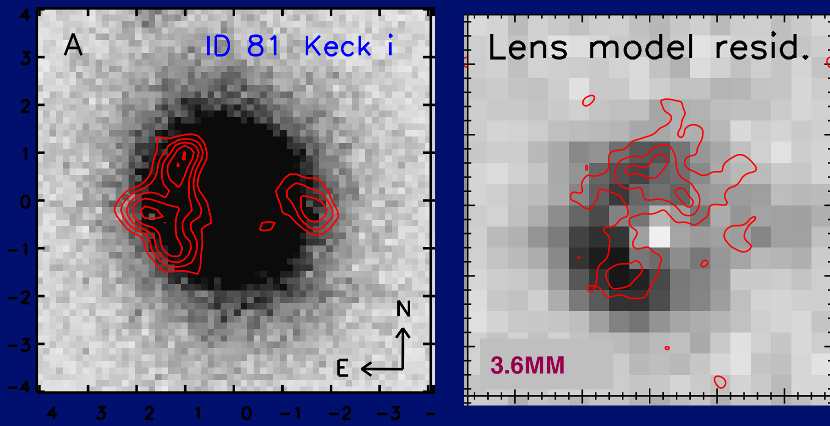
High-Resolution Imaging



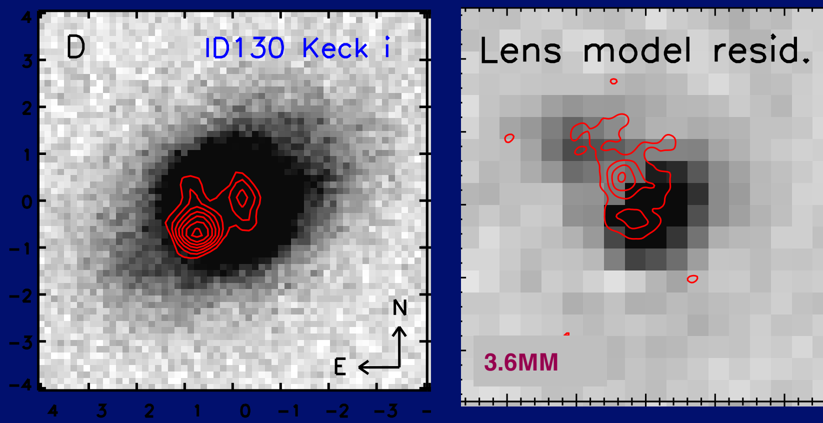


Extensive Ground-based Follow-up Observations

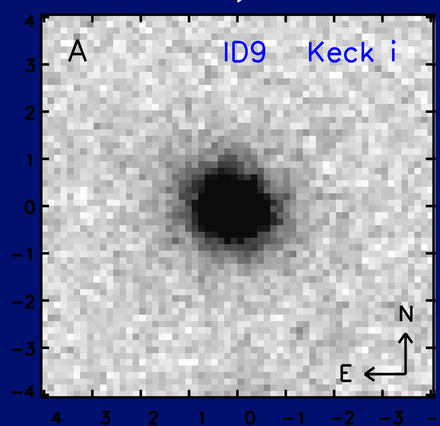
z_{SMG}=3.04; z_{LENS}=0.30
M=25±7



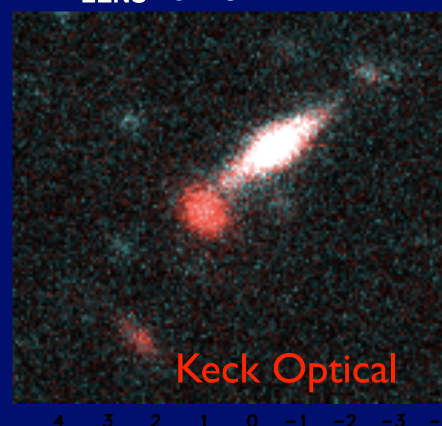
z_{SMG}=2.62; z_{LENS}=0.22
M=6±1



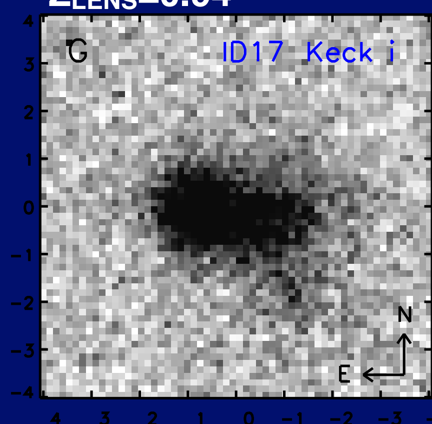
z_{SMG}=1.58; z_{LENS}=0.7



z_{SMG}=1.79;
z_{LENS}=0.79

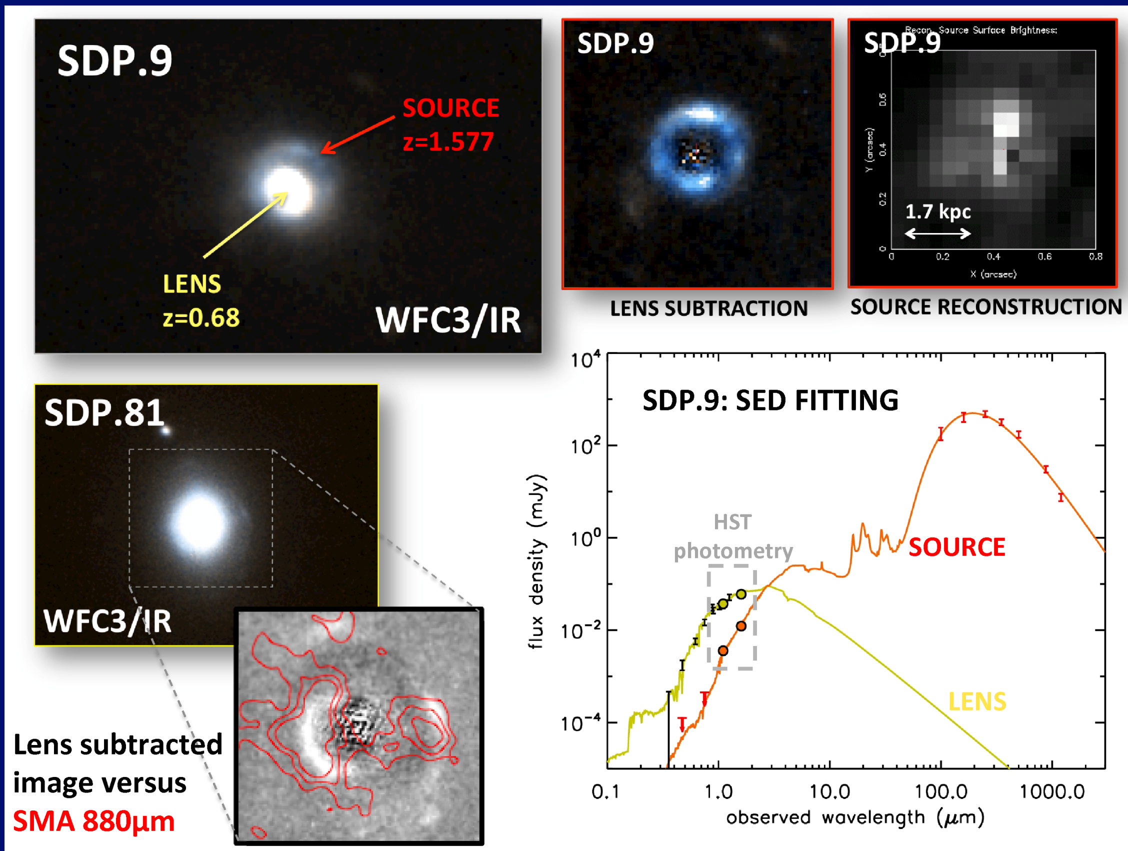


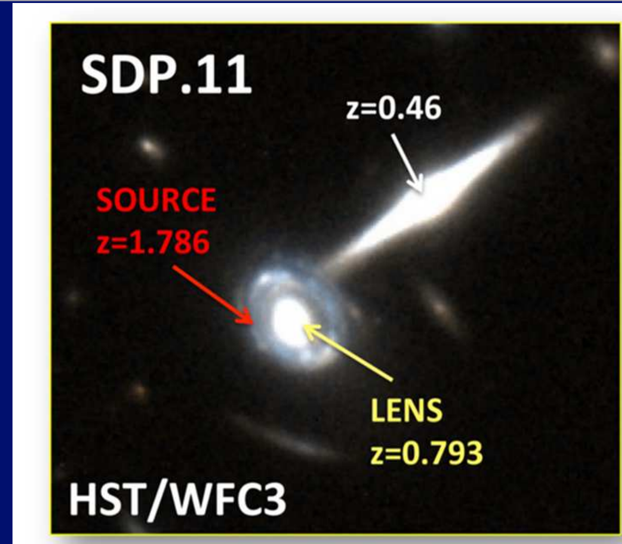
z_{SMG}=2.30;
z_{LENS}=0.94

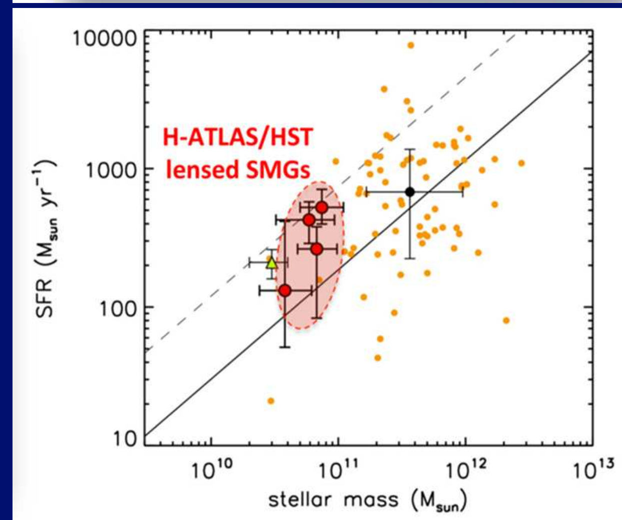


Negrello, M. et al. 2010, The detection of a population of sub-mm bright, strongly lensed galaxies, Science, 330, 800

The First Herschel Lensed Galaxies

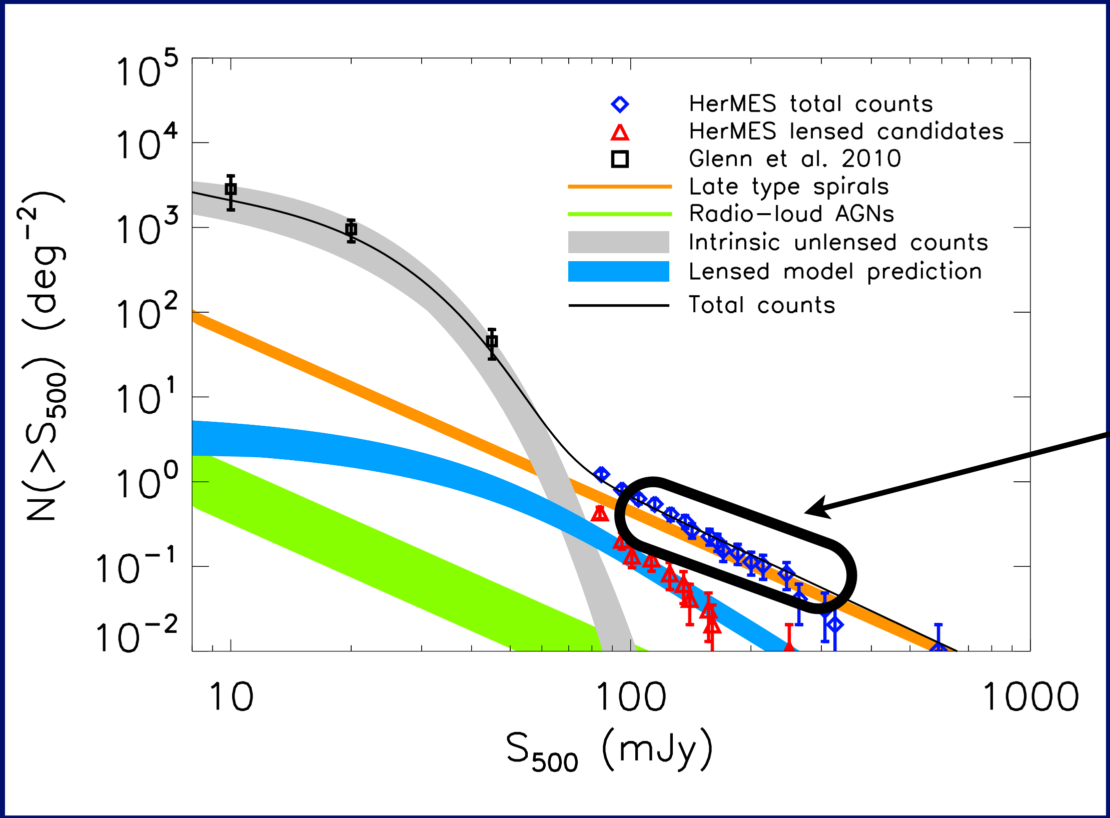






Negrello, M. et al. 2010, The detection of a population of sub-mm bright, strongly lensed galaxies, Science, 330, 800

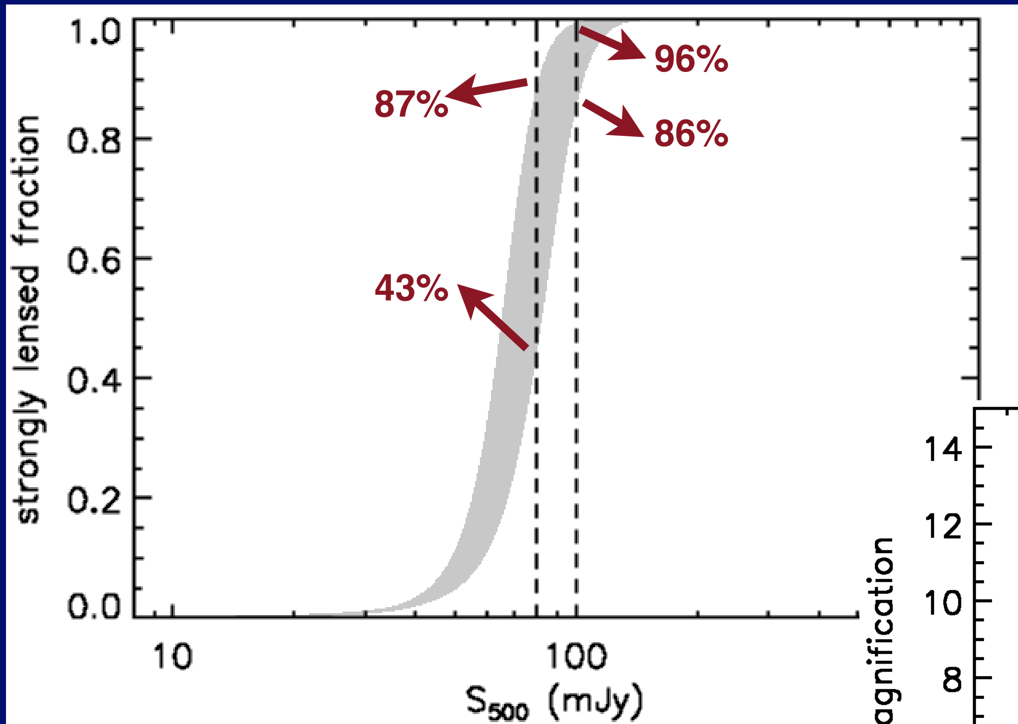
The First Herschel Lensed Galaxies



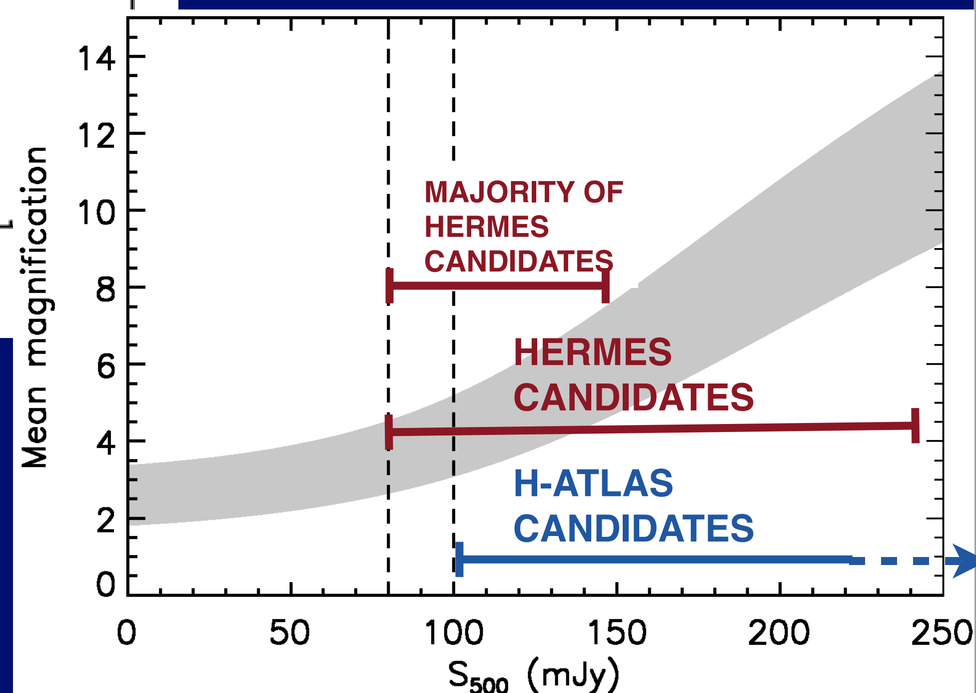
- **Lensing: Flux boosted (magnified) and image distorted**
- **Can study fainter objects than usually available.**
- **Can study spatial distribution of gas, dust, stars at higher resolution than with normal galaxies at the same distances.**

The Nature of Brightest high-z Herschel Galaxies

LENSING AT SUB-MM WAVELENGTHS: BLAIN, A. 1996, MNRAS, 283, 1340



The model predicts that μ_{mean} ~3-8 for majority of lenses



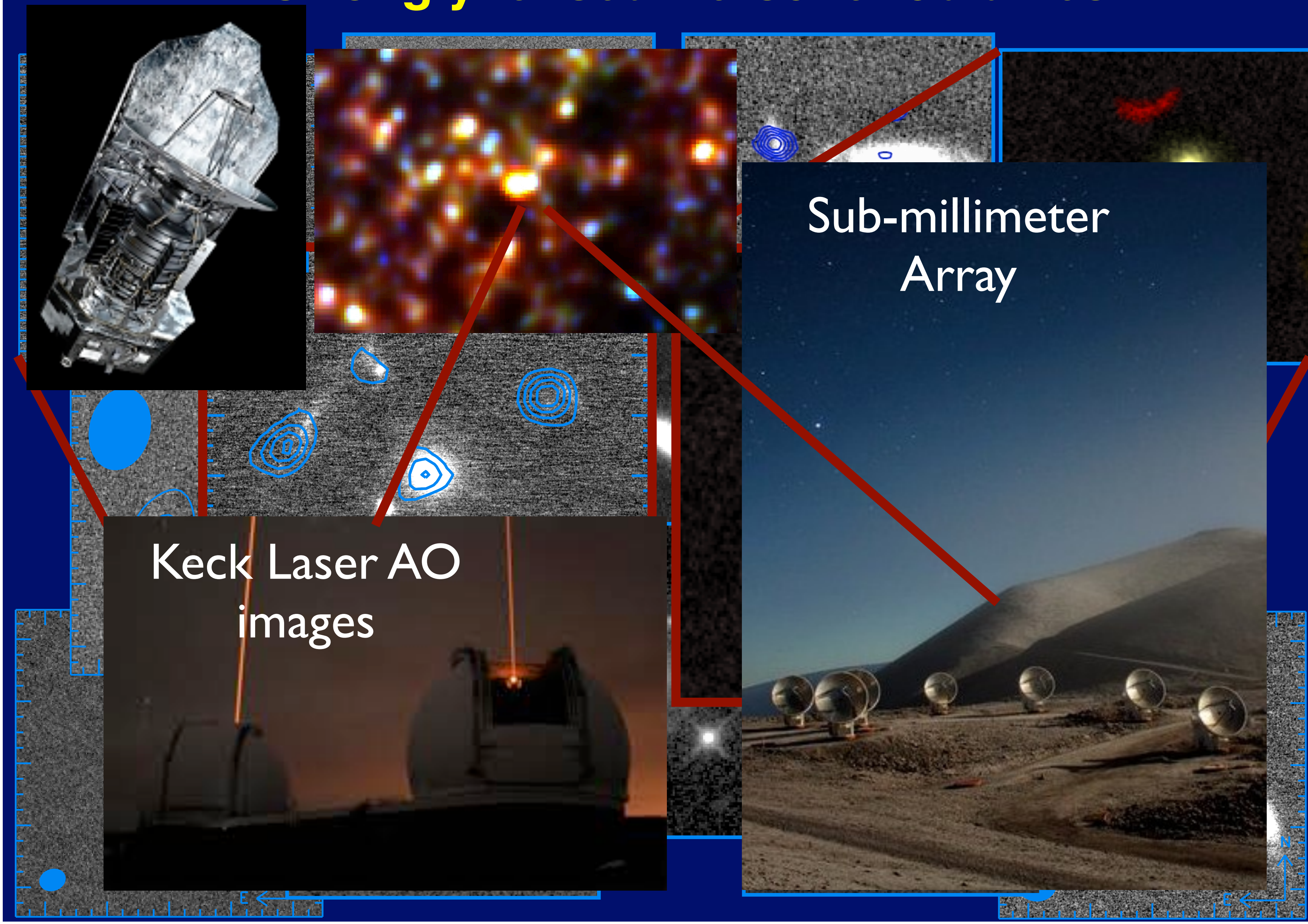
Cosmological models predict that
~40-90% of S_{500}>80 mJy &
~85-95% of S_{500}>100 mJy
brightest, non-local (z<0.1) Herschel galaxies are gravitationally lensed

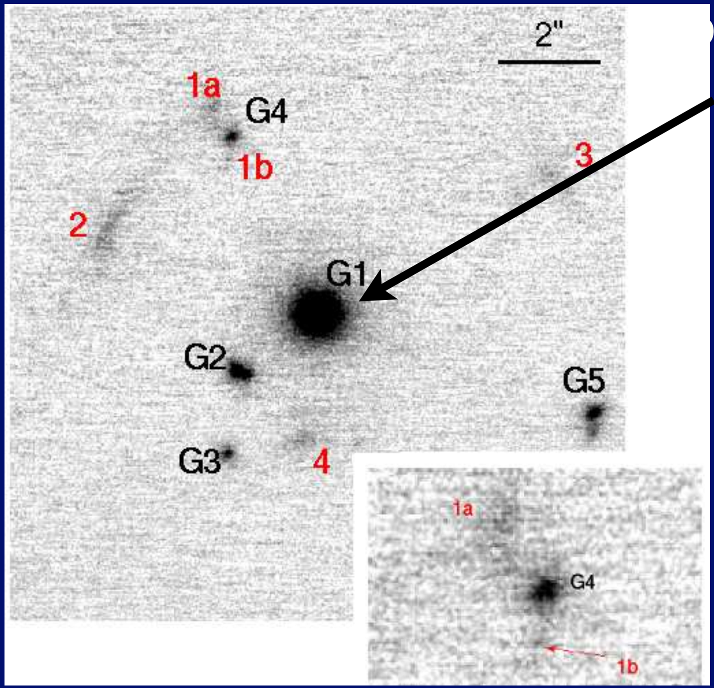
>95% efficiency at identifying those lensed galaxies!

High Fidelity Catalogs of Lensed Galaxies from Herschel

Wardlow, Julie* et al. 2012 (HerMES team) (*UCI postdoc)

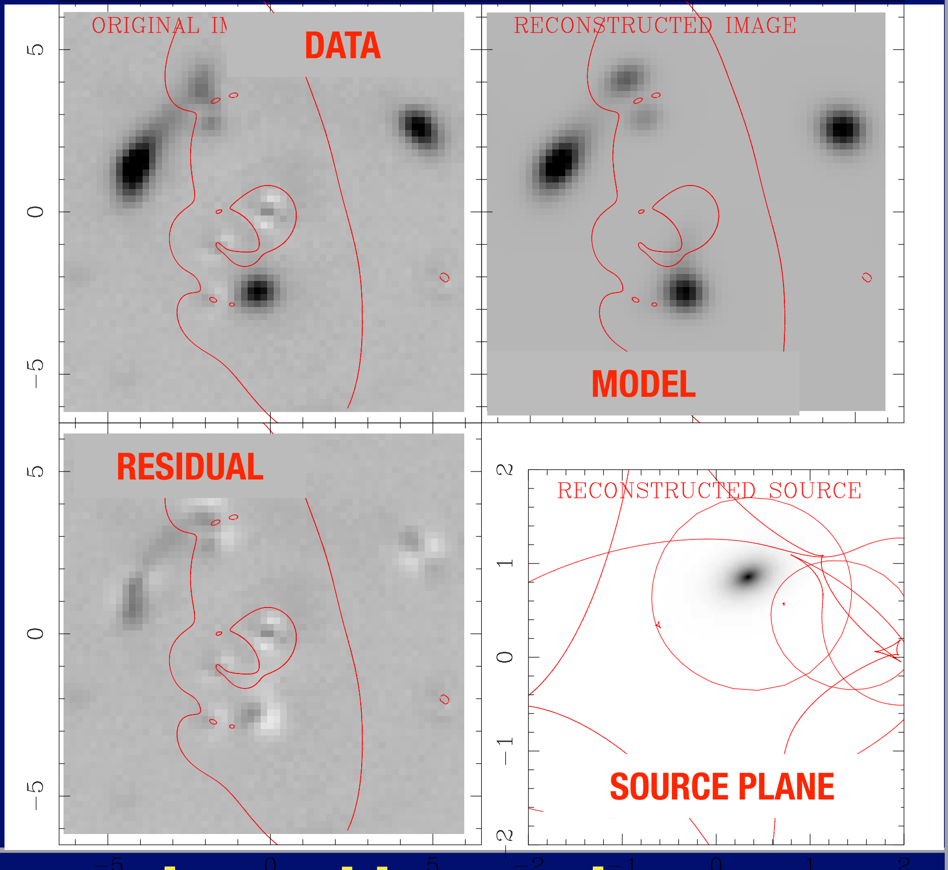
Strongly lensed Herschel Galaxies





Z=0.60 ± 0.04

Other lens redshifts are unclear but
$R_{Ein} = 4.02 \pm 0.03$
=> σ_v = 480 ± 20 km/s
....indicative of a small group deflector



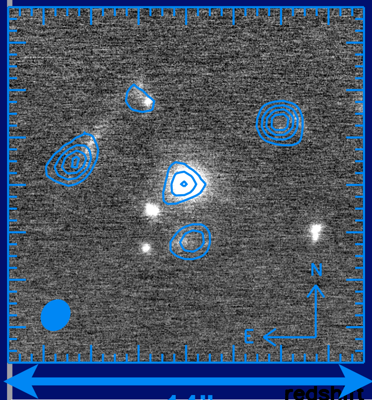
Half-light radius of the SMG:
$R_{eff,s}$ = 1.9 ± 0.1 kpc.

Magnification:
μ = 10.9 ± 0.7

A HerMES source lensed by a galaxy group

Conley, A. et al. 2011, ApJ, 732, L35; Gavazzi, R. et al. 2011, 738, 125

EVLA 1.4GHZ + KECK K-BAND



Z_{CO}=2.957

T_{KIN} = 86 – 235 K

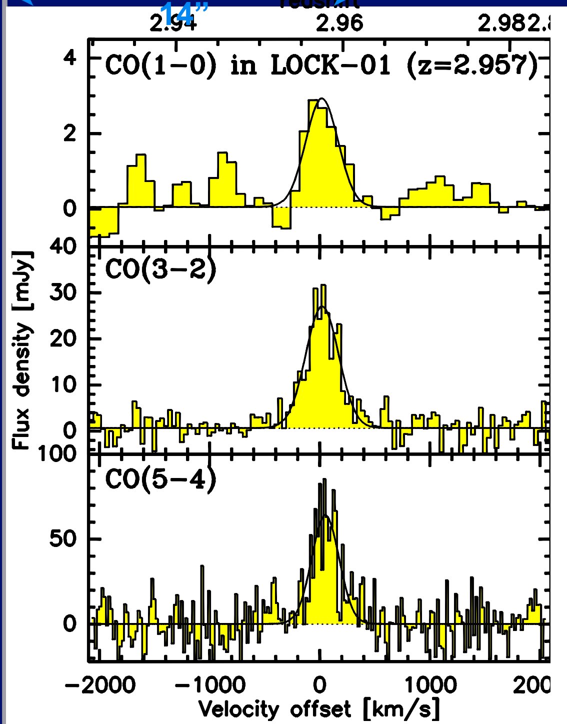
n_{H2} = (1.1 – 3.5) ×10^3 cm^{-3}

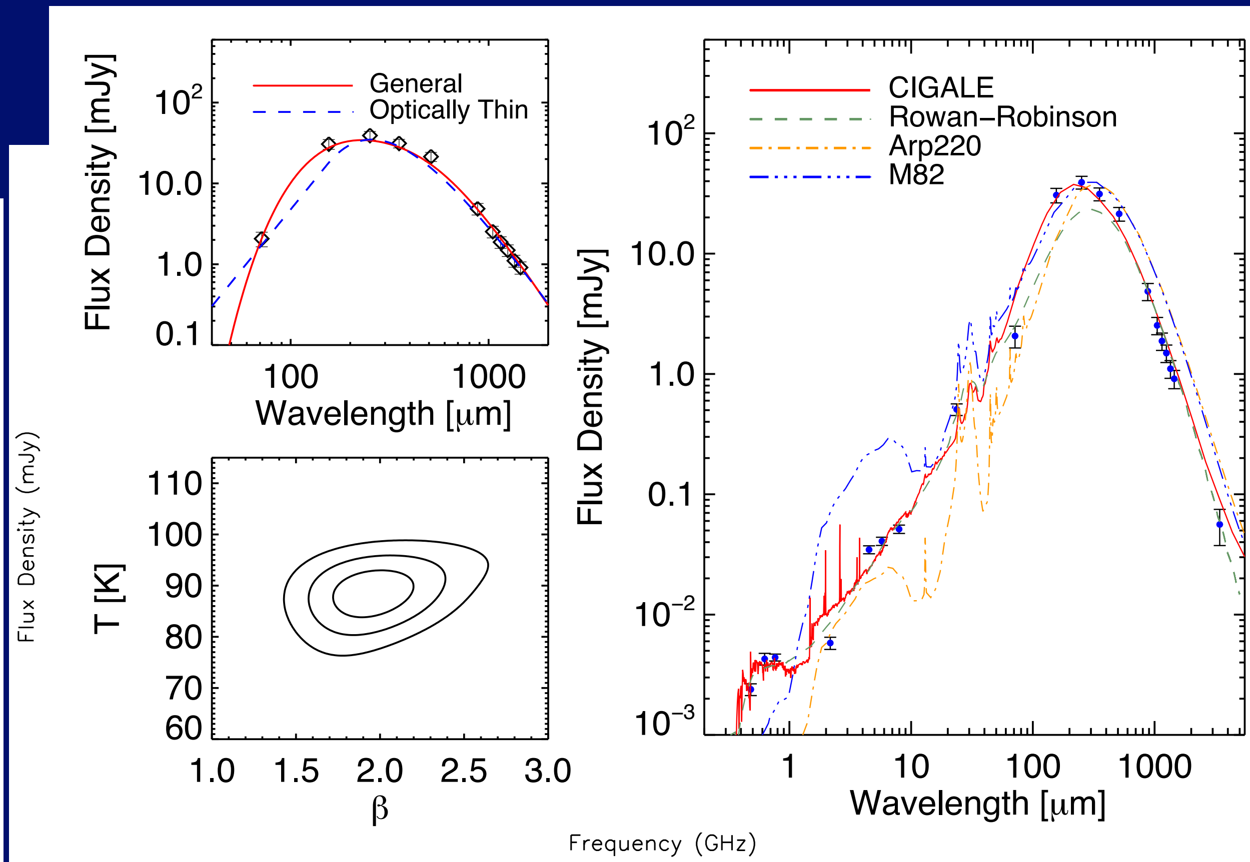
L_{FIR} = 1.4 X10^{13} $L_\odot$

SFR ~ 2500 $M_\odot$/yr

T_{DUST} = 88 ± 3 K

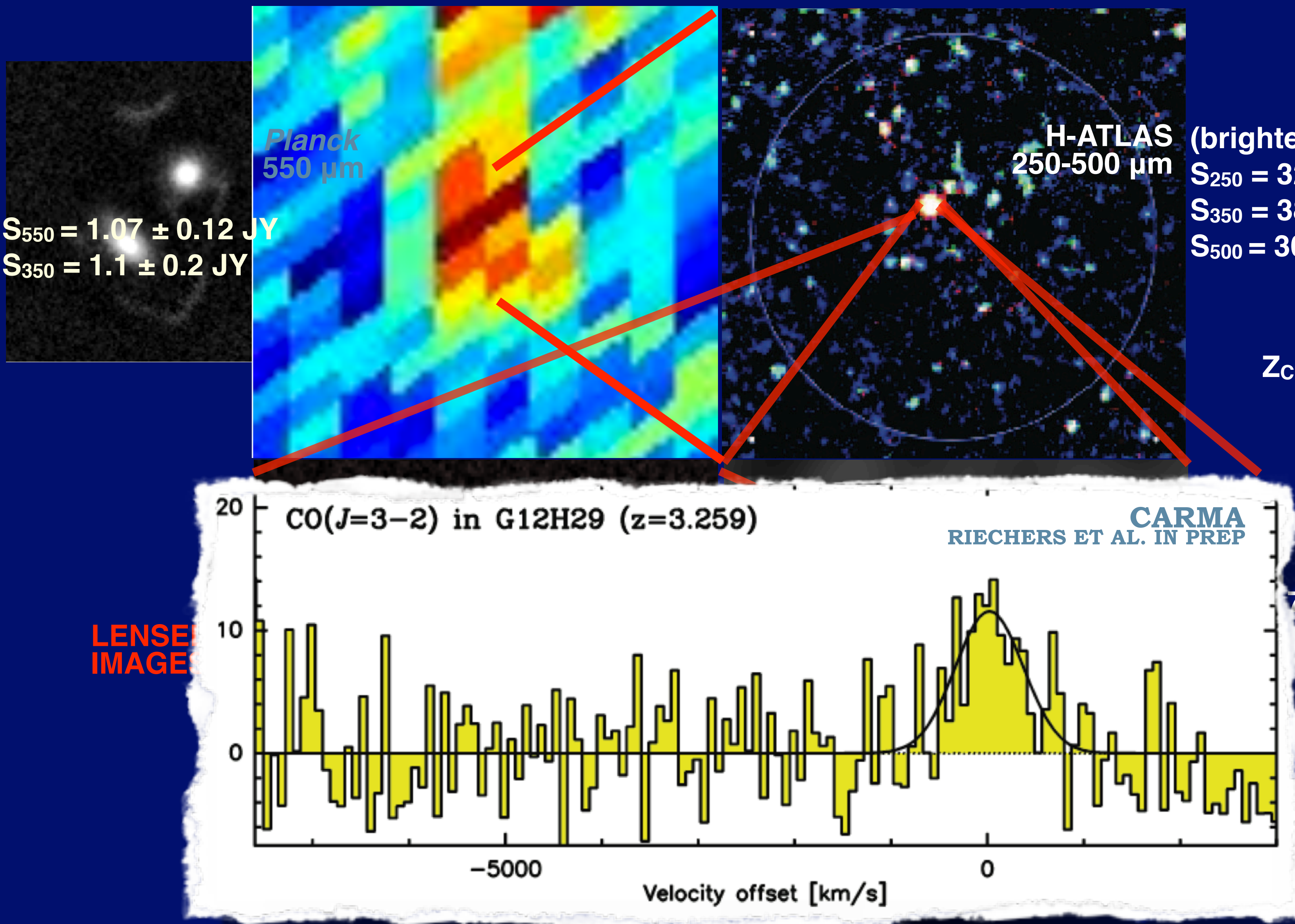
M_{DUST} ~ 10^8 $M_\odot$





A HerMES source lensed by a galaxy group

Riechers, D. et al. 2011, ApJ, 733, L12; Scott, K. et al. 2011, ApJ, 733, 29



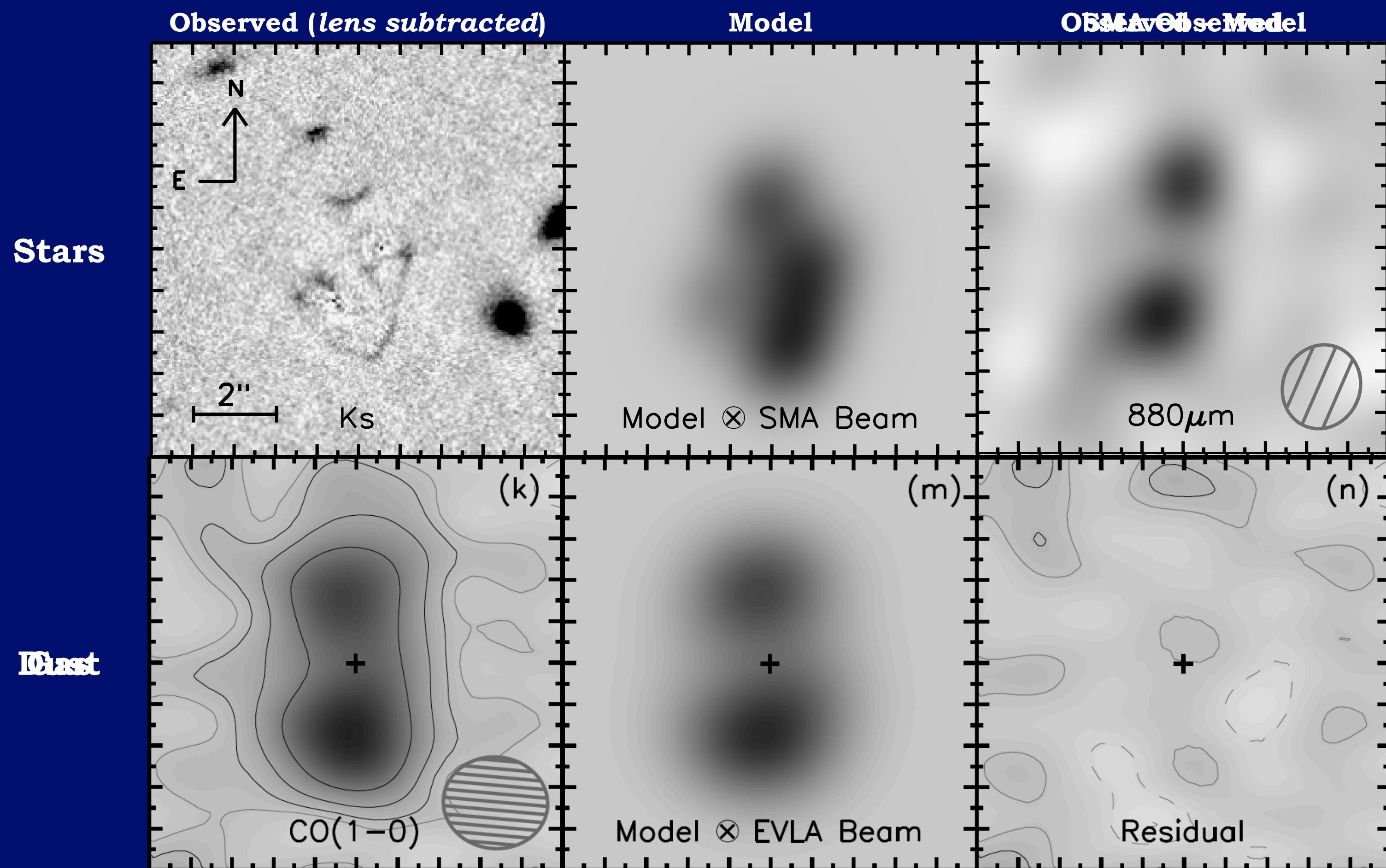
(brightest source)
S_{250} = 320 ± 20 mJy
S_{350} = 380 ± 60 mJy
S_{500} = 300 ± 20 mJy

Z_{CO} = 3.26

70 ± 10 mJy

A lensed Planck source resolved by Herschel (in ATLAS)

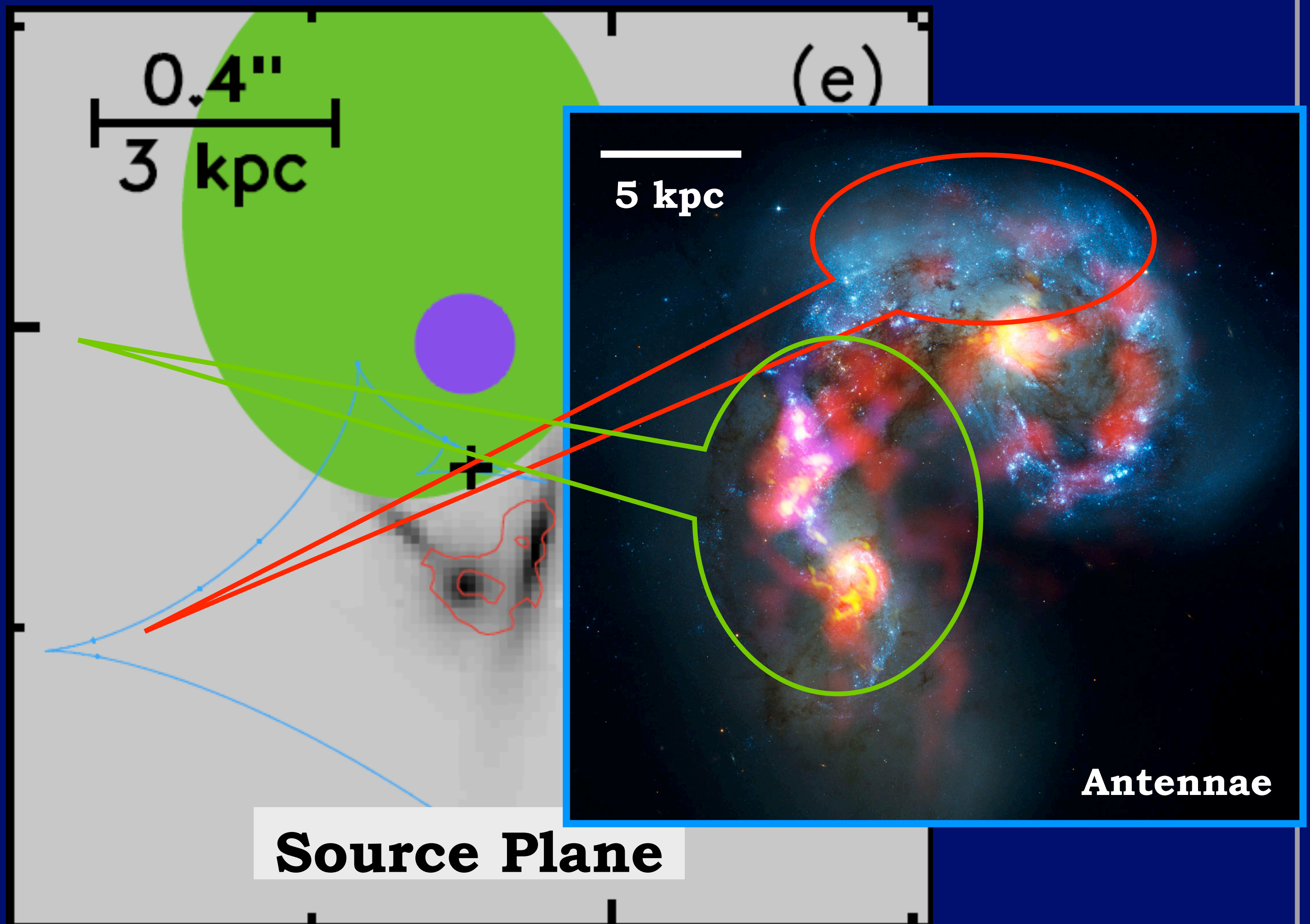
Fu, Hai* et al. 2012, ApJ (arXiv.org:1202.1829) (*UCI postdoc)



Fu, Hai* et al. 2012, ApJ submitted (arXiv.org:1202.1829) (*UCI postdoc)

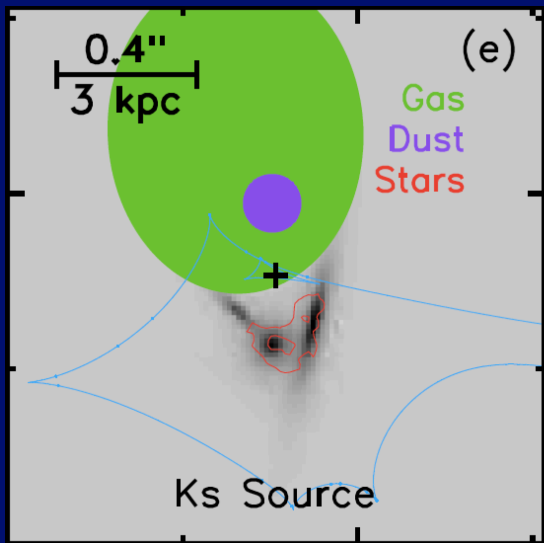
Differential Magnification:

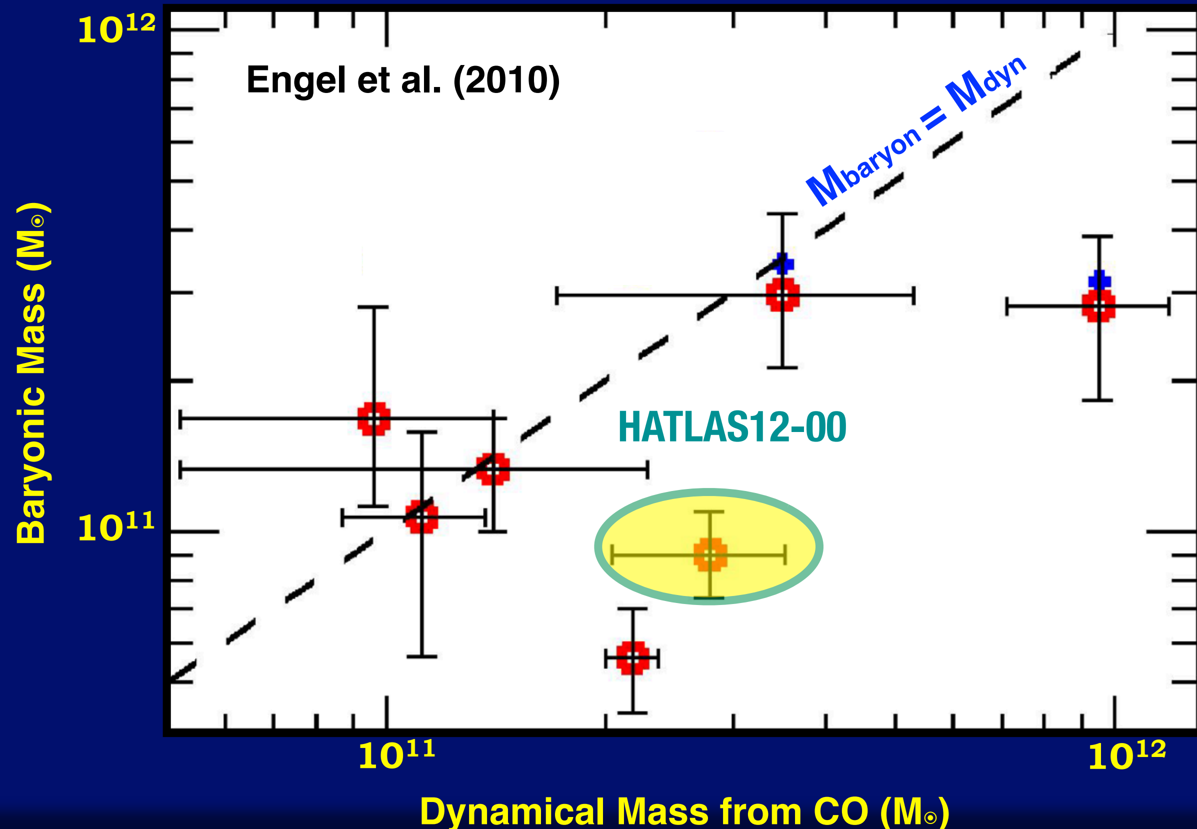
μ(Stars) ≈ 17, μ(Dust) ≈ 8, μ(Gas) ≈ 7



Fu, Hai* et al. 2012, ApJ submitted (arXiv.org:1202.1829) (*UCI postdoc)

Source Plane Morphologies

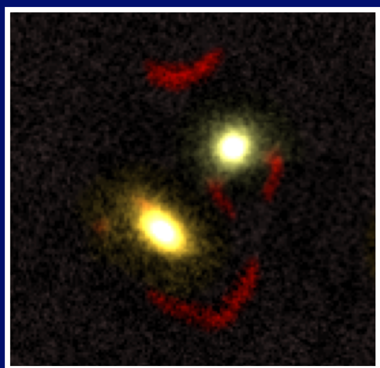


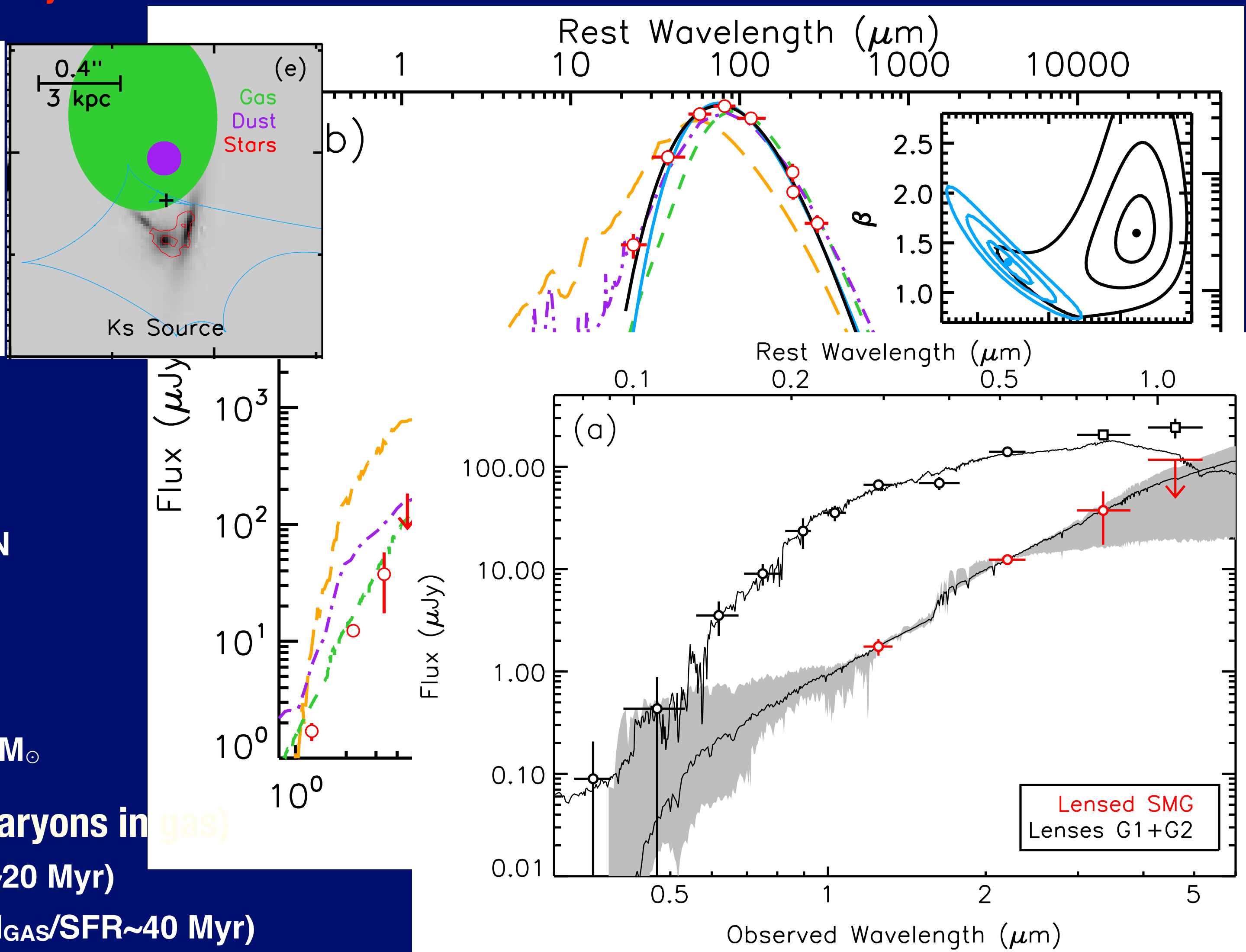


- Extended gas distribution (relative to dust and stars; 1.2 kpc for dust vs. 7 kpc for gas).
- Gas disk is mostly stable to fragmentation?
- Clumpy stellar distribution (galaxy merger?)

Source Plane Morphologies

Lensed Herschel Galaxy z_{CO}=3.26





L_{FIR} = 1.6 X10^{13} $L_\odot$
SFR ~ 1900 $M_\odot$/yr
T_{DUST} = 62 ± 3 K

No evidence for AGN

M_{DUST} = 6 X10^8 $M_\odot$
M_{STARS} = 3 X10^{10} $M_\odot$
M_{GAS} = 7 X10^{10} $M_\odot$
$M_{DYNAMICAL}$ = 3 X10^{11} $M_\odot$

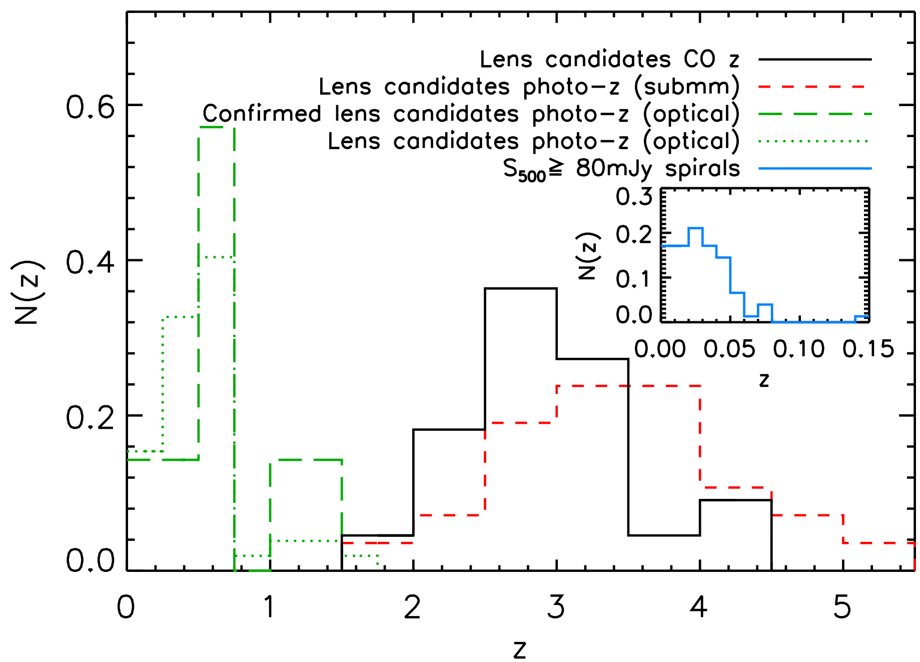
Gas-rich (70% of baryons in gas)
Young (M_{STARS}/SFR~20 Myr)
Short Star-burst (M_{GAS}/SFR~40 Myr)

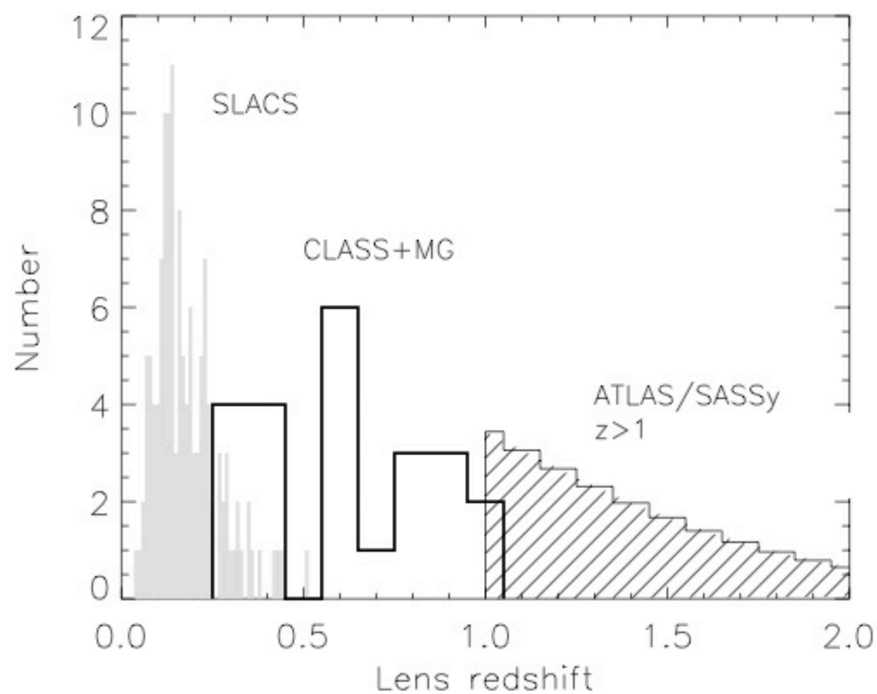
Spectral Energy Distribution

Fu, Hai* et al. 2012, ApJ (arXiv.org:1202.1829) (*UCI postdoc)

Promise of Herschel in Lensing Studies

- 0.5/sq. deg (S500>100 mJy) lensed source! - identified >95% efficiency.
- Herschel Cosmological surveys: ~1200 sq. degrees, so ~600 lensed galaxies.
- Compared to ~200 lensed galaxies now known in optical and radio

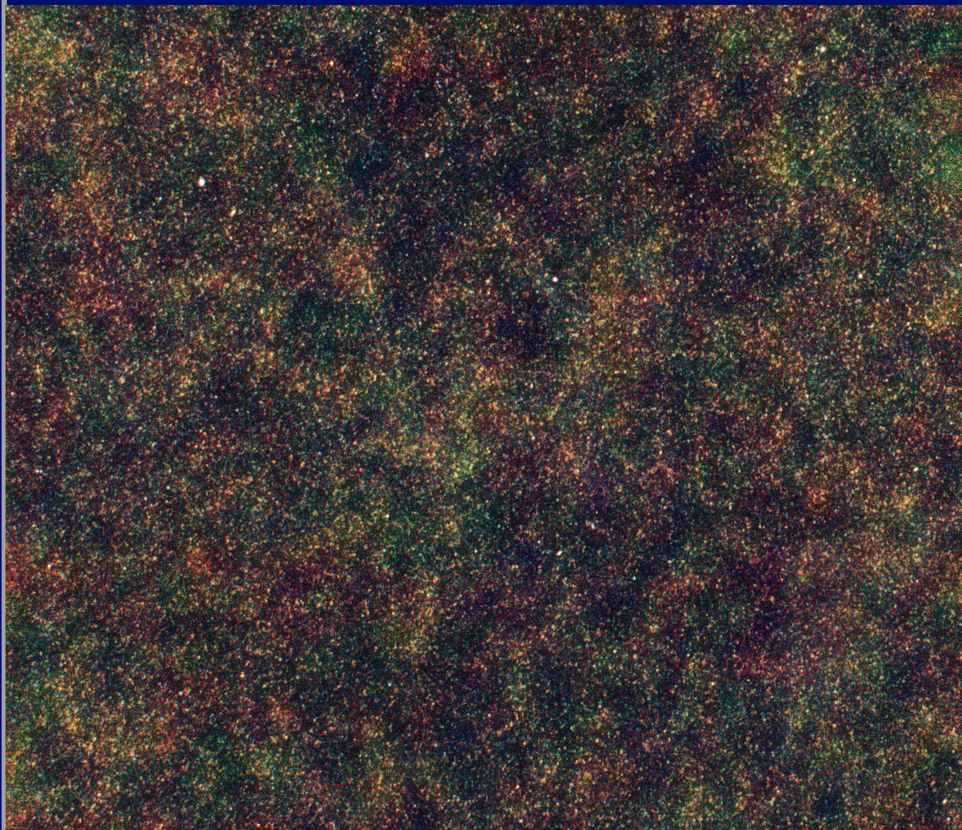




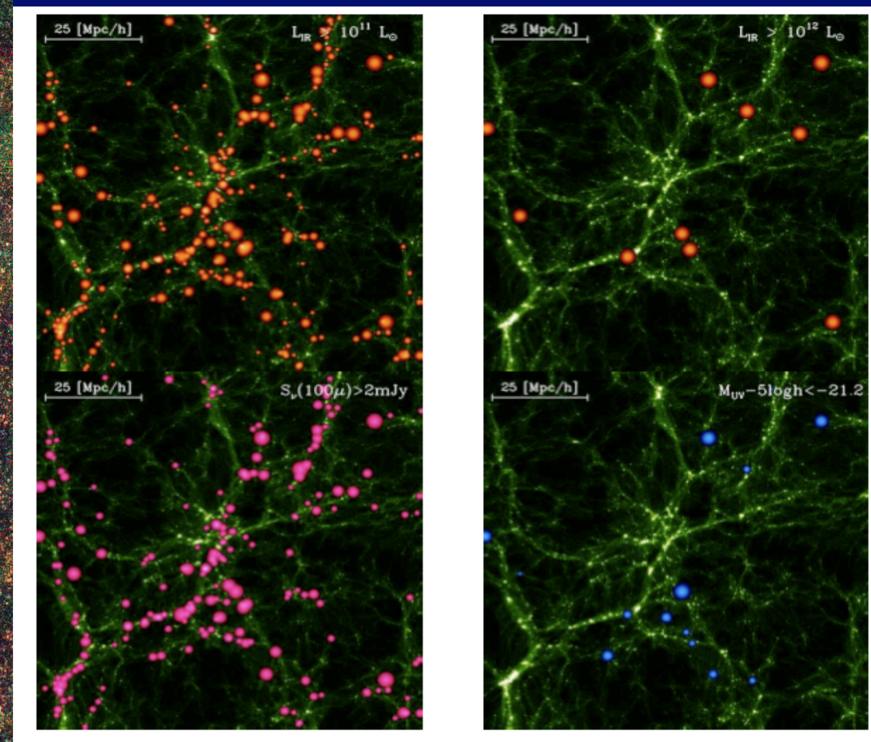
(a) Herschel will produce the largest sample of gravitationally lensed sources, with a selection function easy to describe (great for cosmology!)

(b) Extend lensed SMGs to z > 6 (at least ~30 in over 1200 sq. degrees)

(c) Extend foreground lenses (at least 100) to z~2 (SDSS lenses z~0.5; radio to z~1)



HerMES Lockman North



Lacey, C. et al. 2010, MNRAS, 405, 2

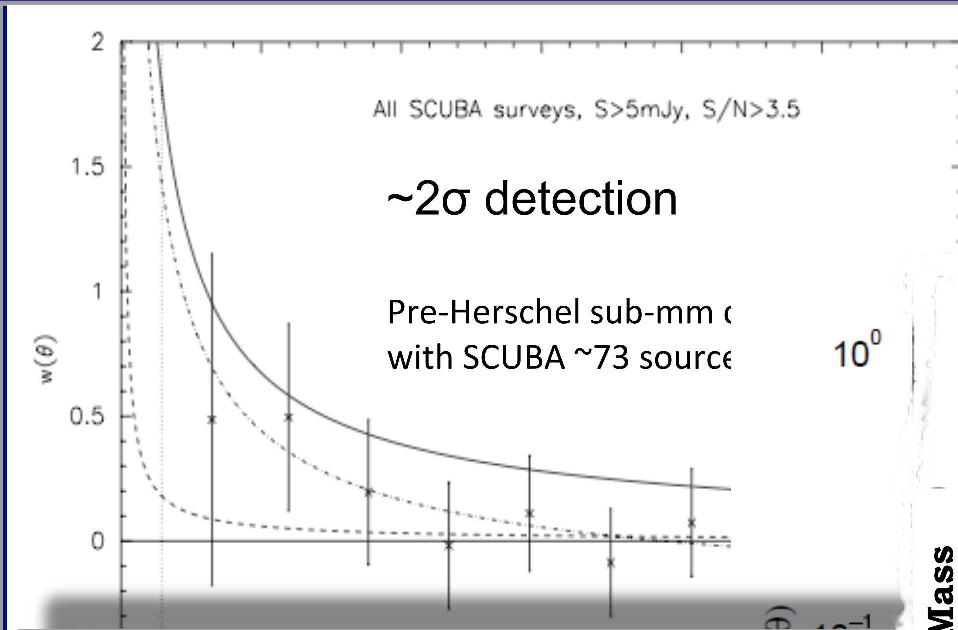
test specific predictions of clustering properties of starbursting galaxies

Where are the Starbursting Galaxies in the Universe?

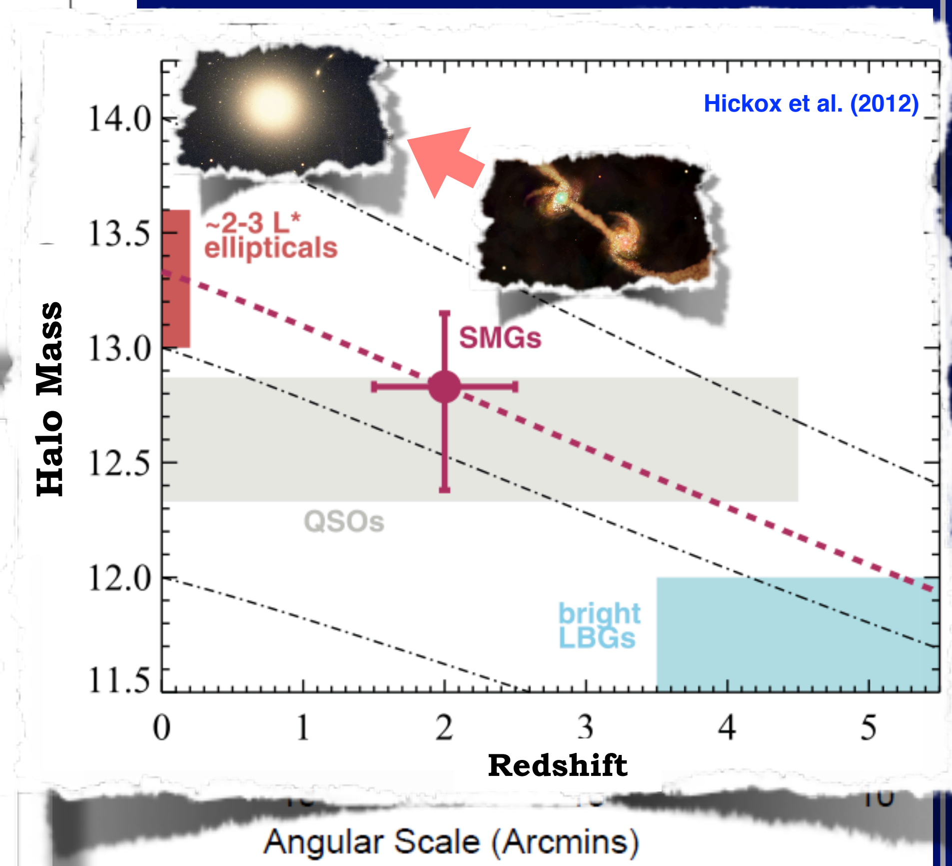
HALO MODEL REVIEW: COORAY, A. & SHETH, R. 2002, PHYSICS REPORTS, 372, 1

Angular Correlation Function

Scott, S. et al. 2006, MNRAS, 370, 1057



- **Dark matter halo hosting a S_{250} > 30 mJy galaxy ~ $10^{12.6}$ M_{solar}**
- **~15% appear as satellites in more massive halos ~ $10^{13.1}$ M_{solar}**
- ***Evolutionary path is z~2 S_{250} ~ 30 mJy Herschel source will evolve to be (2-5)L_{star} elliptical galaxy at z~0***

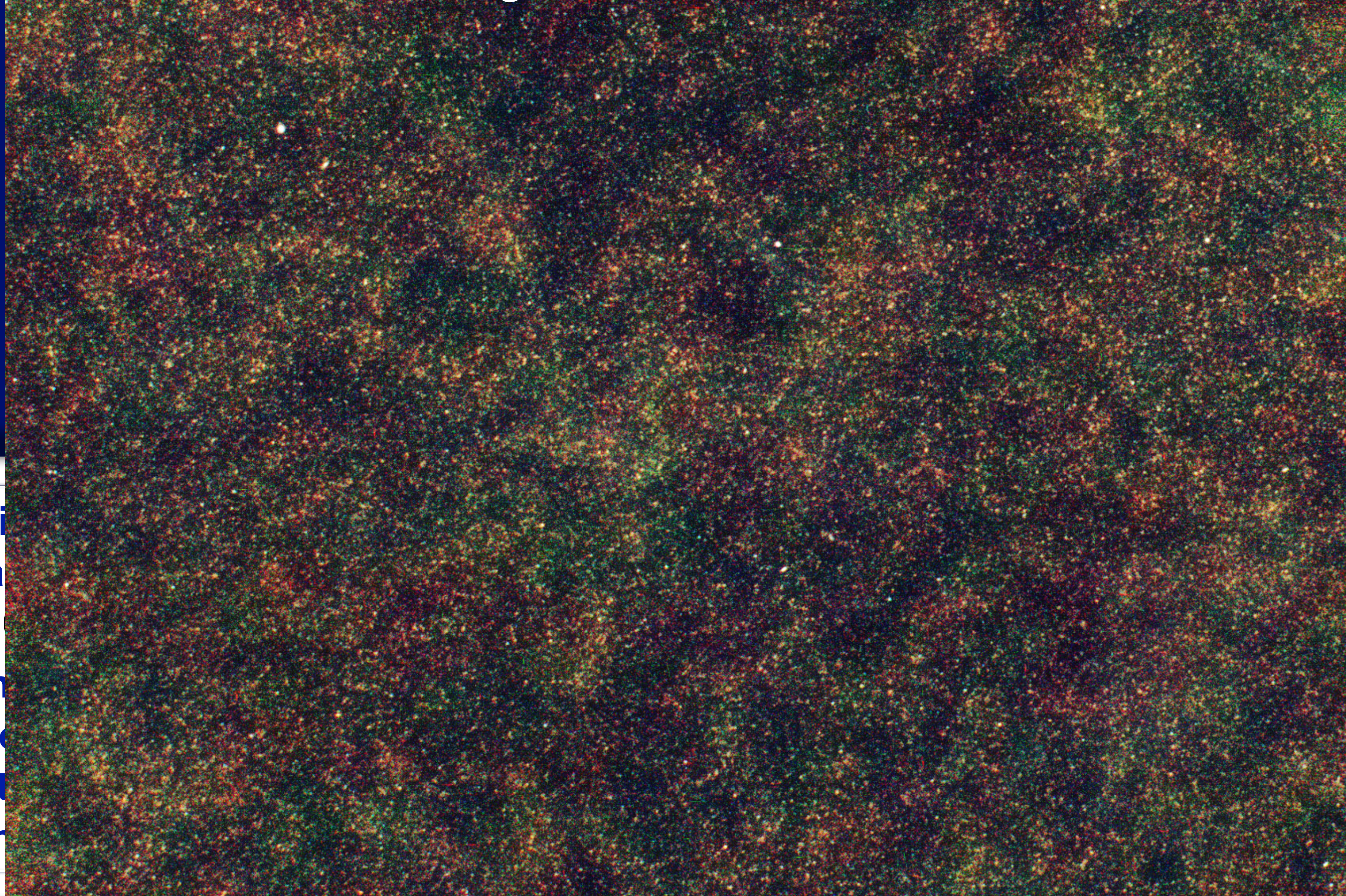


Cooray, A. et al. 2010, A&A, 518, L22

Where are the Starbursting Galaxies in the Universe?

HALO MODEL REVIEW: COORAY, A. & SHETH, R. 2002, PHYSICS REPORTS, 372, 1

Cosmic Infrared Background Fluctuations with SPIRE



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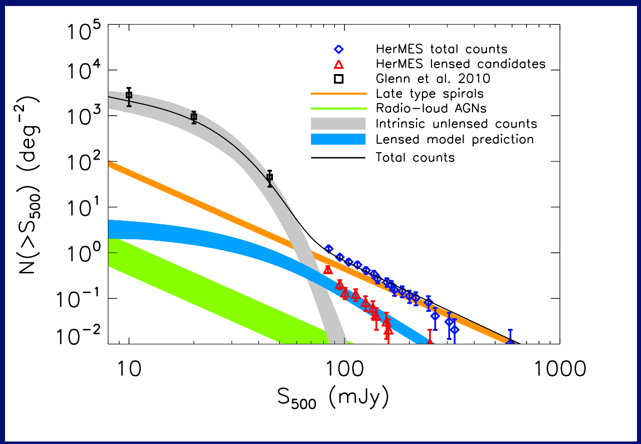
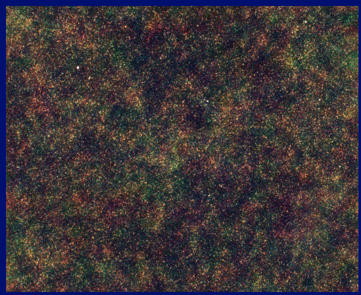
Amblard, Alex*, Cooray et al. 2011, Sub-millimetre Galaxies reside in dark matter halos with mass greater than 3x1011 Msun, Nature, 470, 510   (*UCI postdoc)

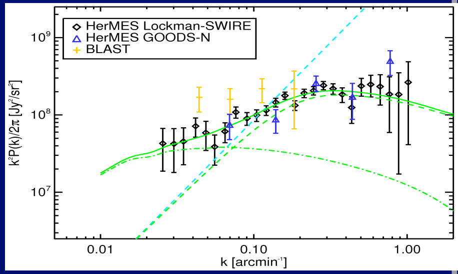
Wide-area, submm surveys can efficiently identify strongly lensed galaxies by simply selecting the brightest sources
(Negrello et al. 2010 Science paper)



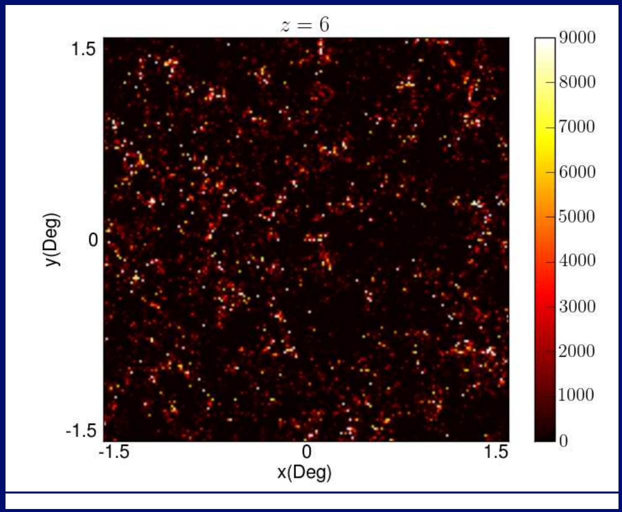
Extensive followup programs are providing a detailed view of high-z star-formation, the relative distribution of gas, dust, and stars.

Anisotropy studies already indicate a minimum dark matter halo mass to host starbursting galaxies *(Amblard et al. 2011, Nature paper)*





A bright future in sub-mm mapping with CCAT and CII intensity mapping for reionization



Summary

THIS TALK AVAILABLE AT HERSCHEL.UCI.EDU