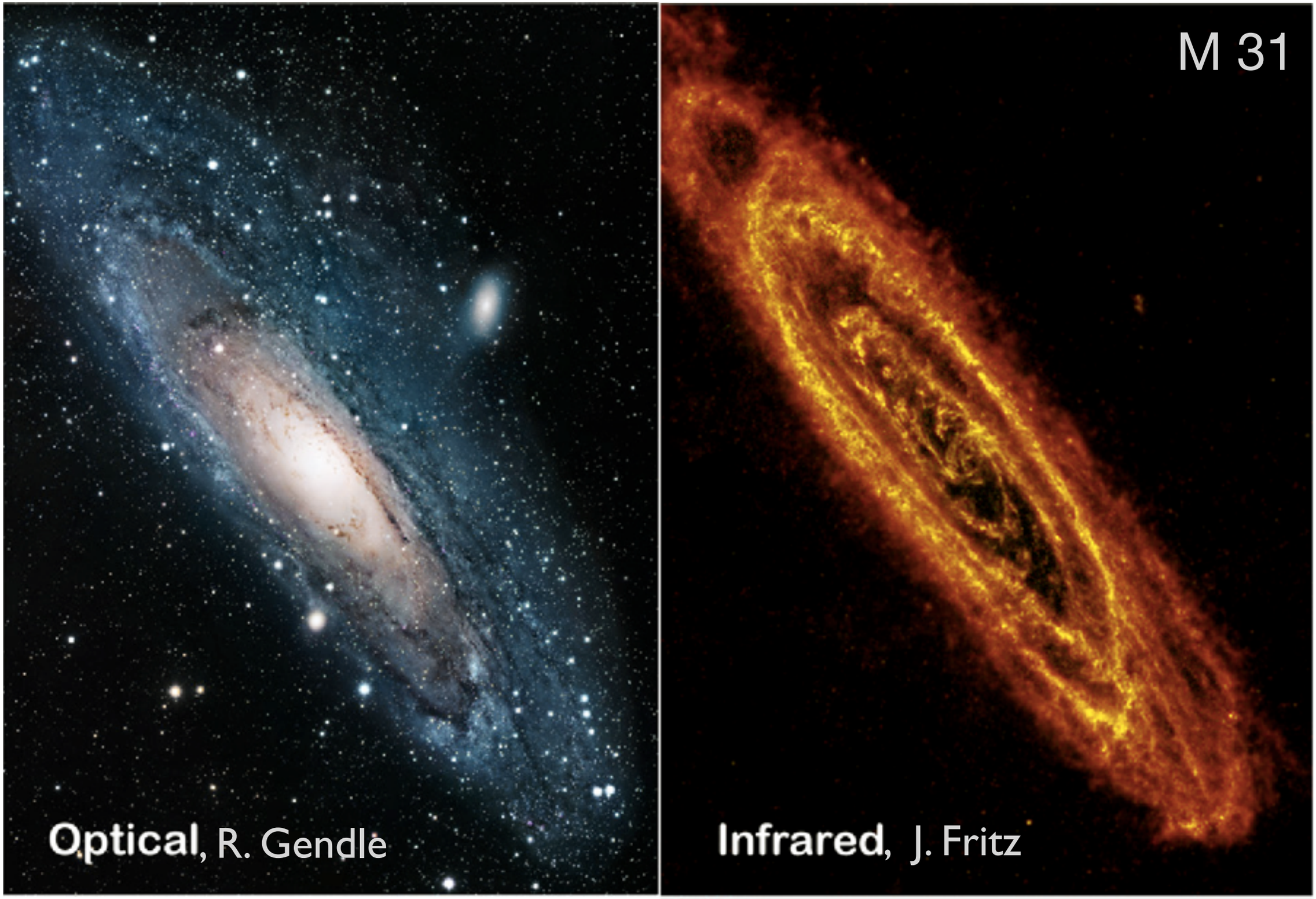
# The Role of Large Herschel Surveys in Galaxy Evolution and Cosmology

Marco Viero - Caltech

# Outline

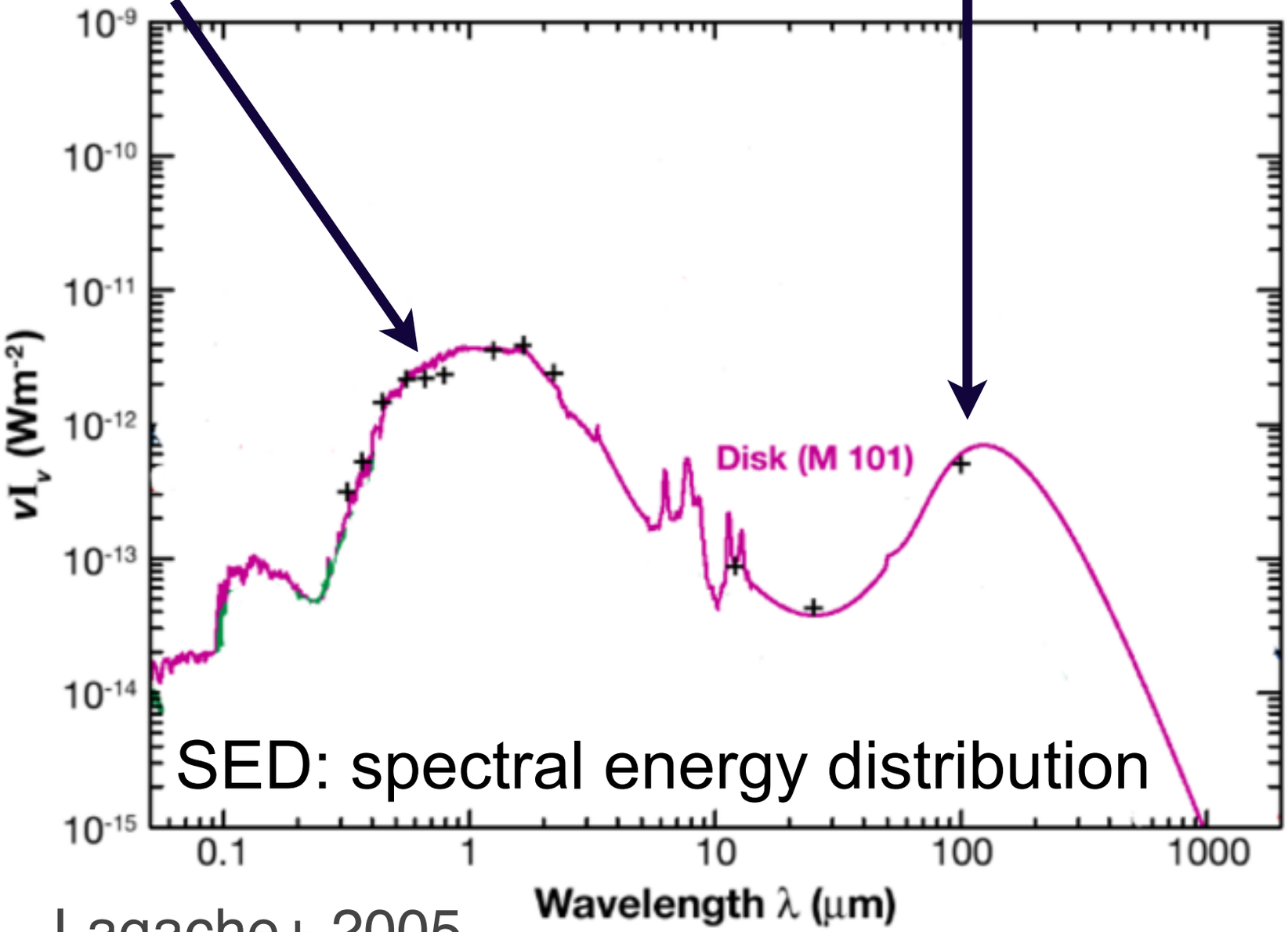
- Why the Cosmic Infrared Background (CIB)?
- Auto and cross-correlations of CIB as a tool to:
  - determine the host-halos of dusty star-forming galaxies through their clustering properties
  - determine the COB-CIB connection
  - cosmological applications
- The Future in Surveys




far-infrared/submillimeter:
dust warmed by stars

Dust re-emits in the FIR

Optical/UV Starlight absorbed by dust

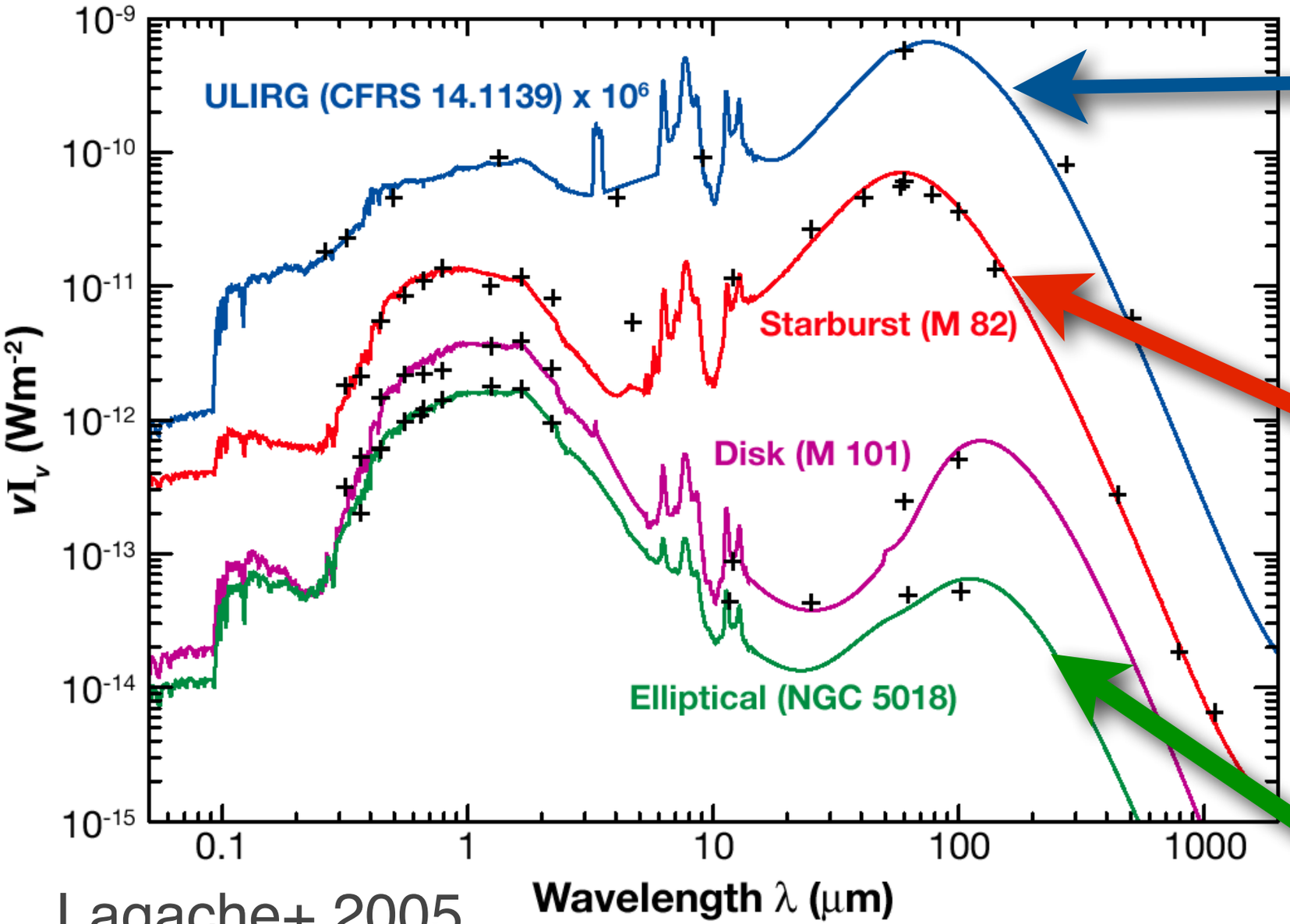



Lagache+ 2005



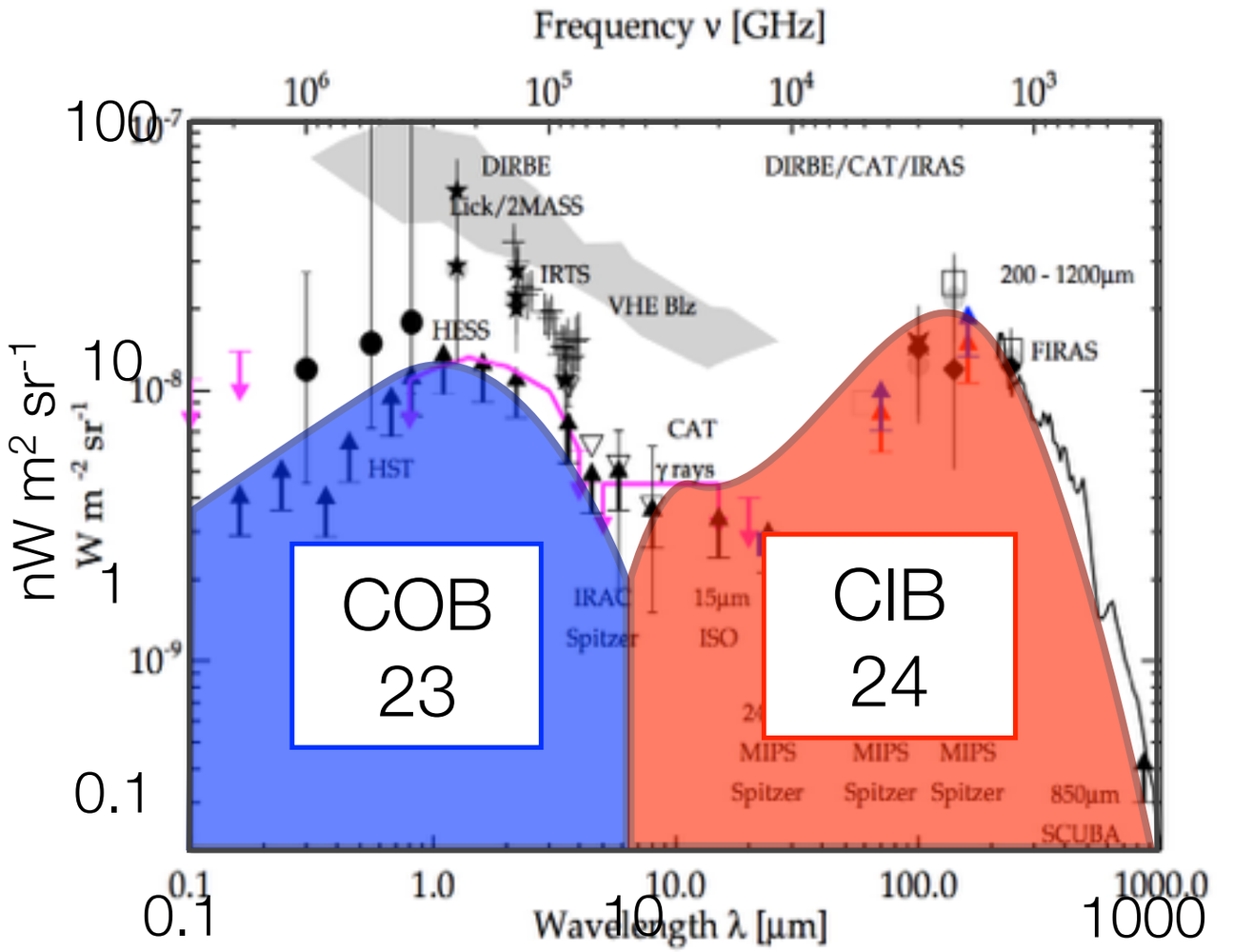
# UV/Optical and FIR/submm SED

# Dusty Star-Forming Galaxies (DSFGs)




Lagache+ 2005

# Optical and FIR SED

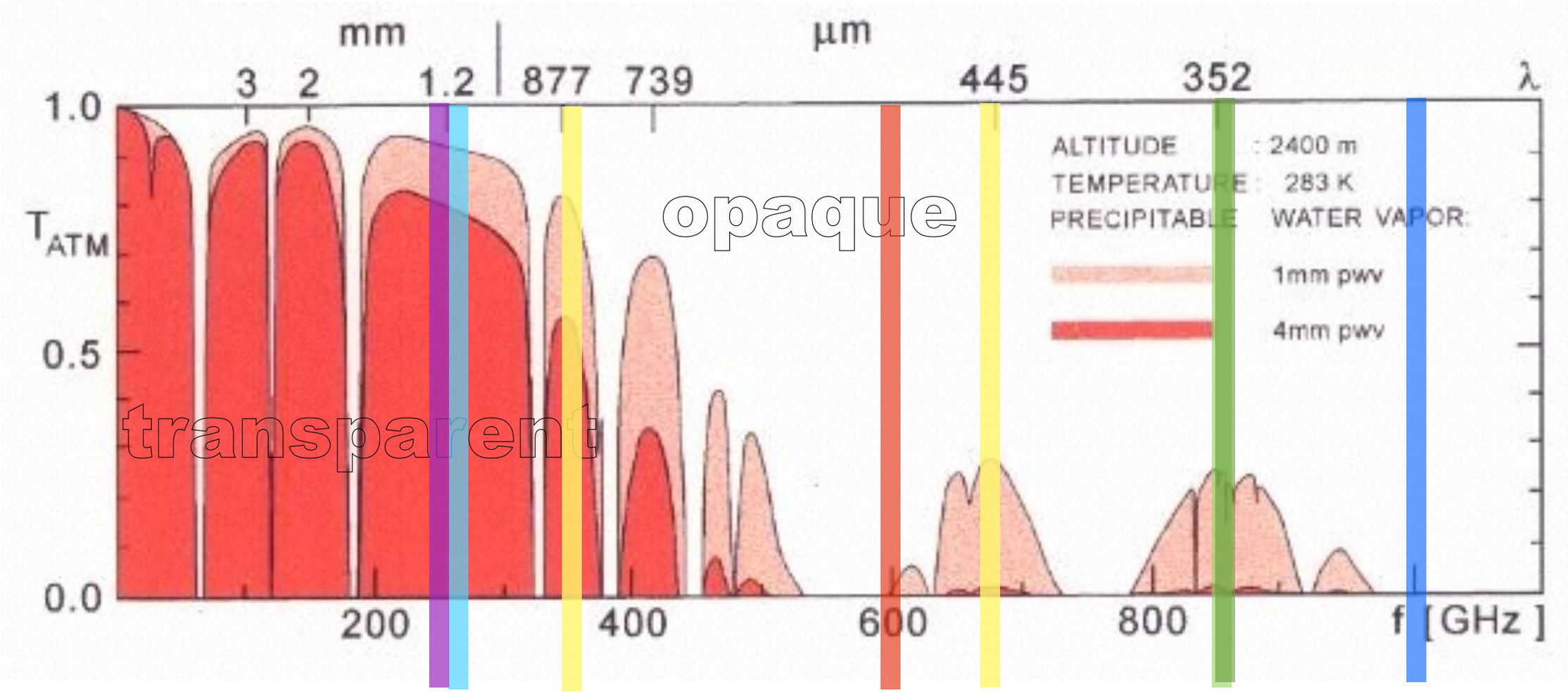



Wavelength (μm)

Dole+ (2006)

# optical and infrared backgrounds

Ground-Based Observatories




BLAST/SPIRE

MAMBO

AzTEC

SCUBA

500

SHARC

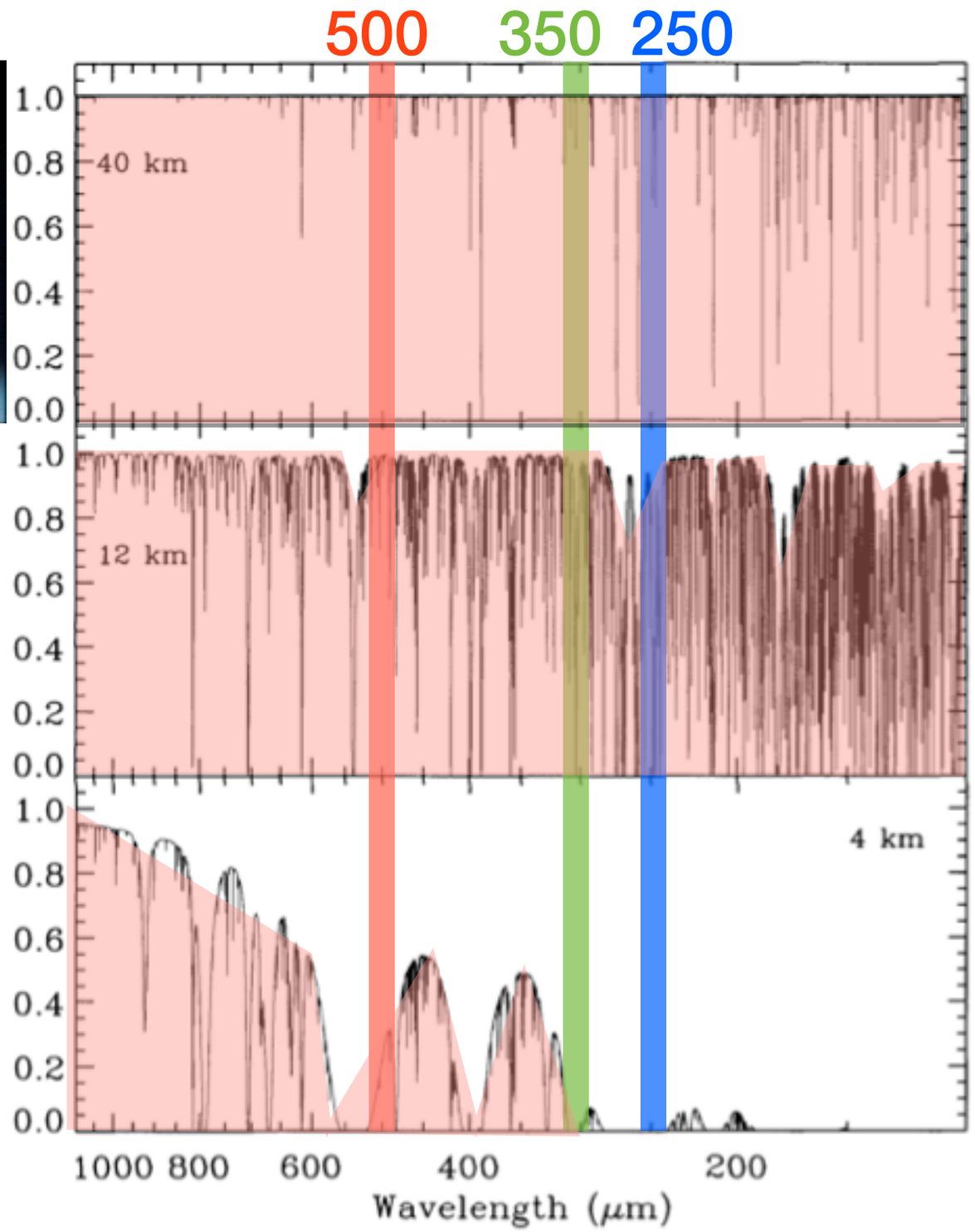
350

250

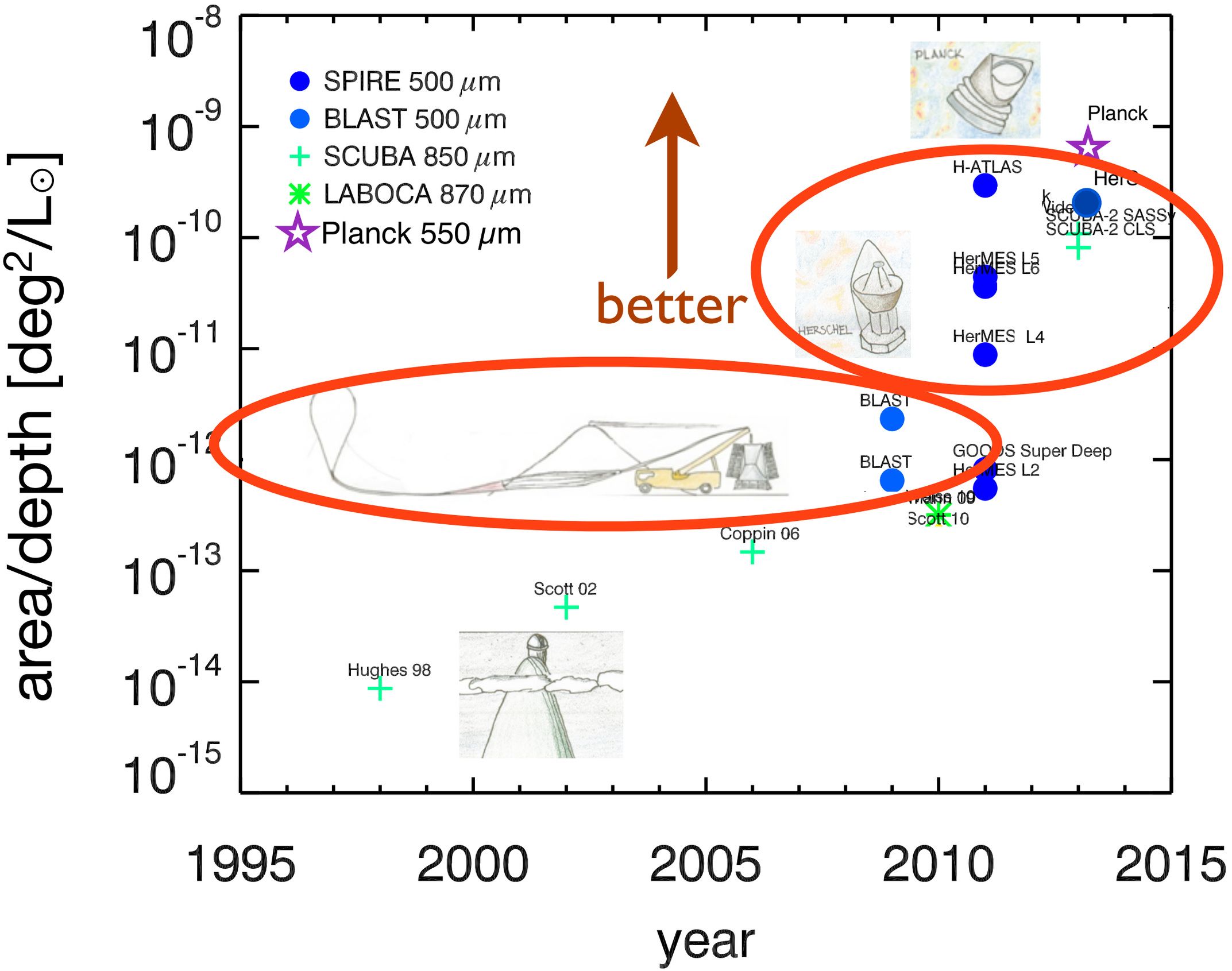
# Submm Visibility

# Submm Visibility










# Explosion of Submillimeter Data

250 µm

350 µm

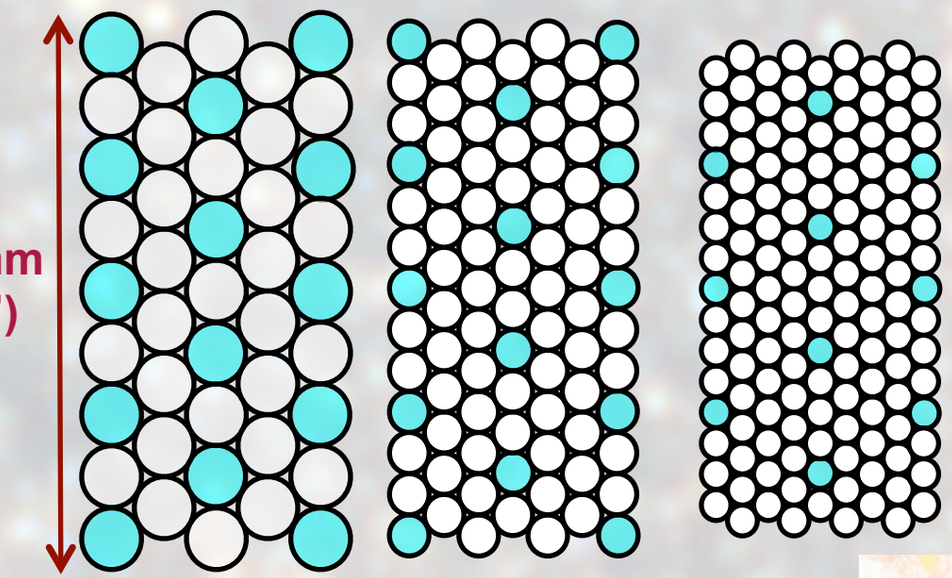
500 µm

Beam size
(FWHM)

250 µm - 16”

350 µm - 25”

500 µm - 36”





HERMES

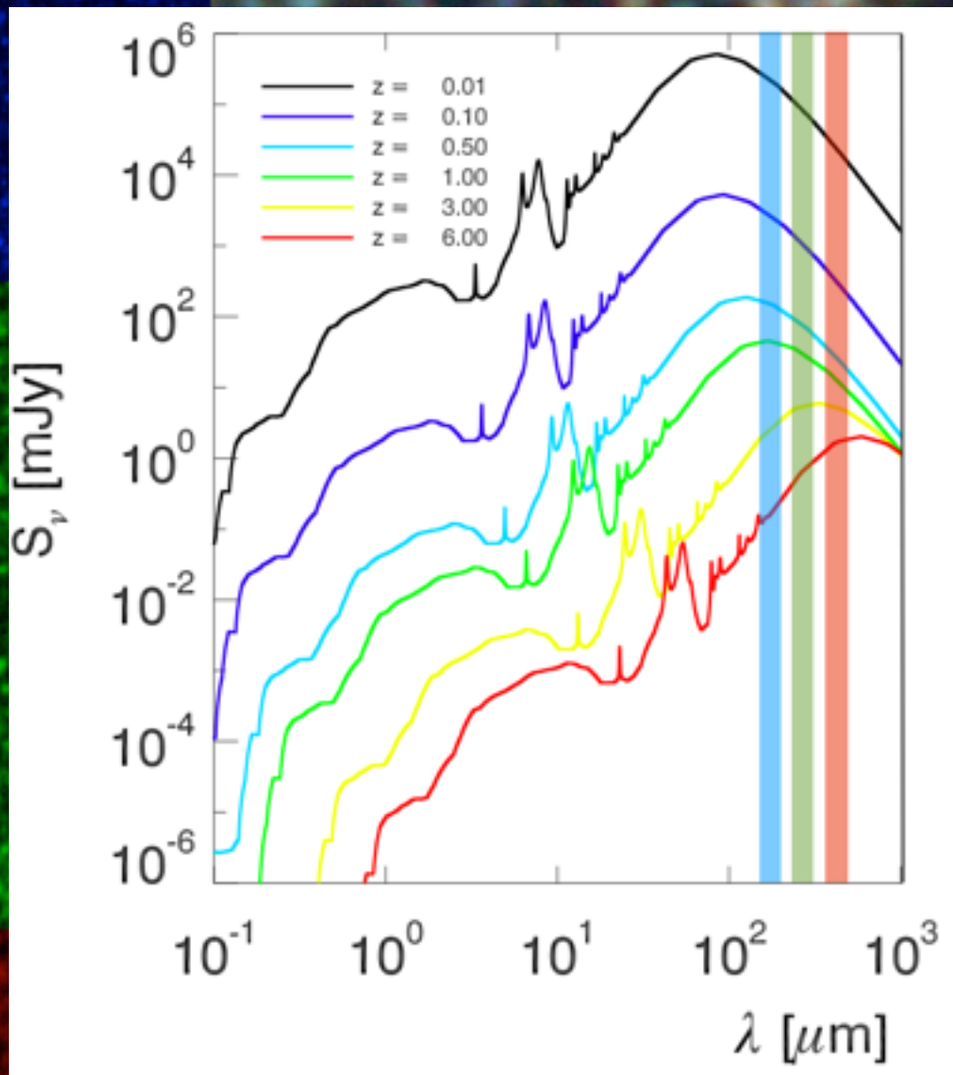
Herschel/SPIRE

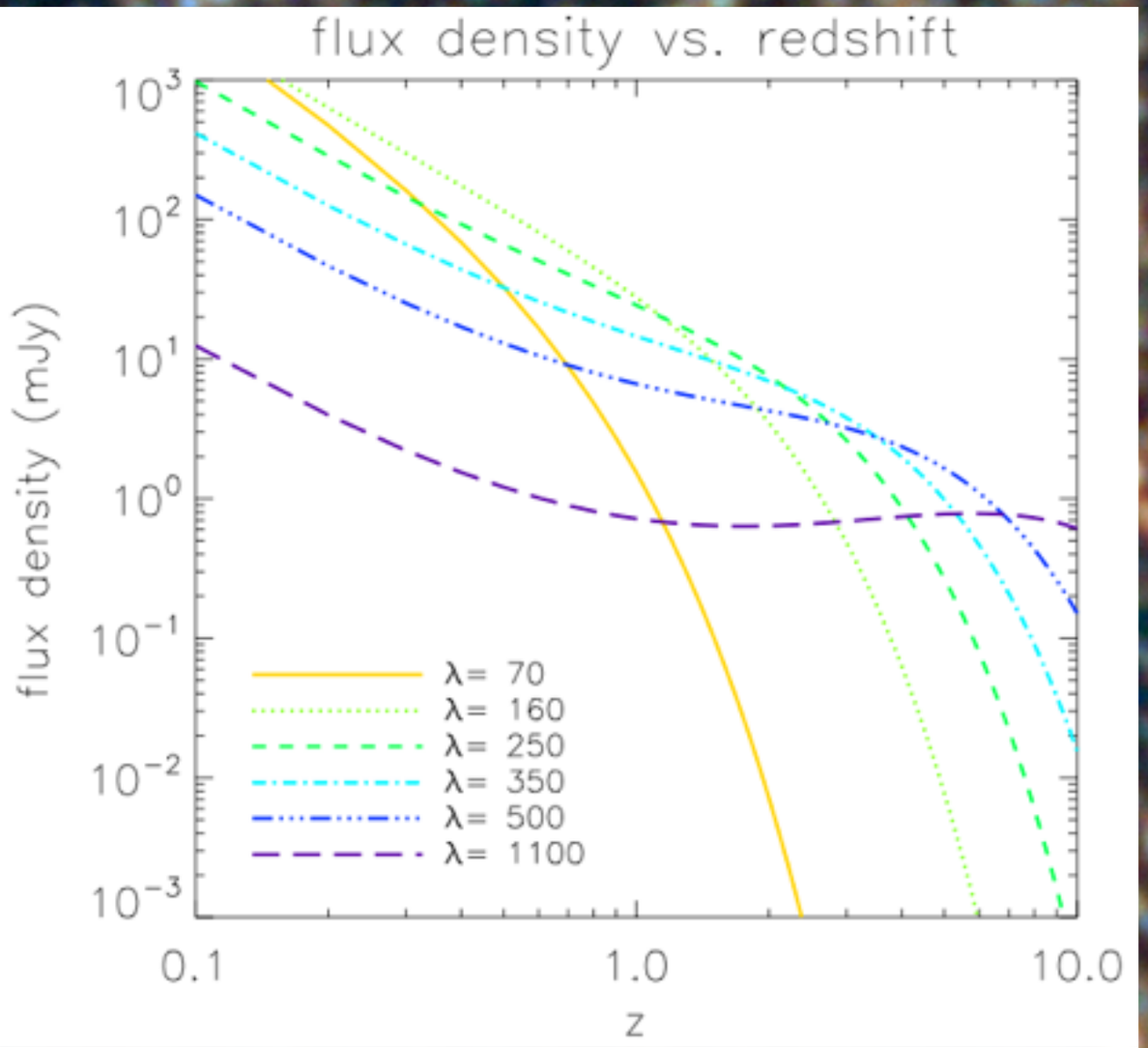
250 μm
16”

350 μm
25”

500 μm
36”

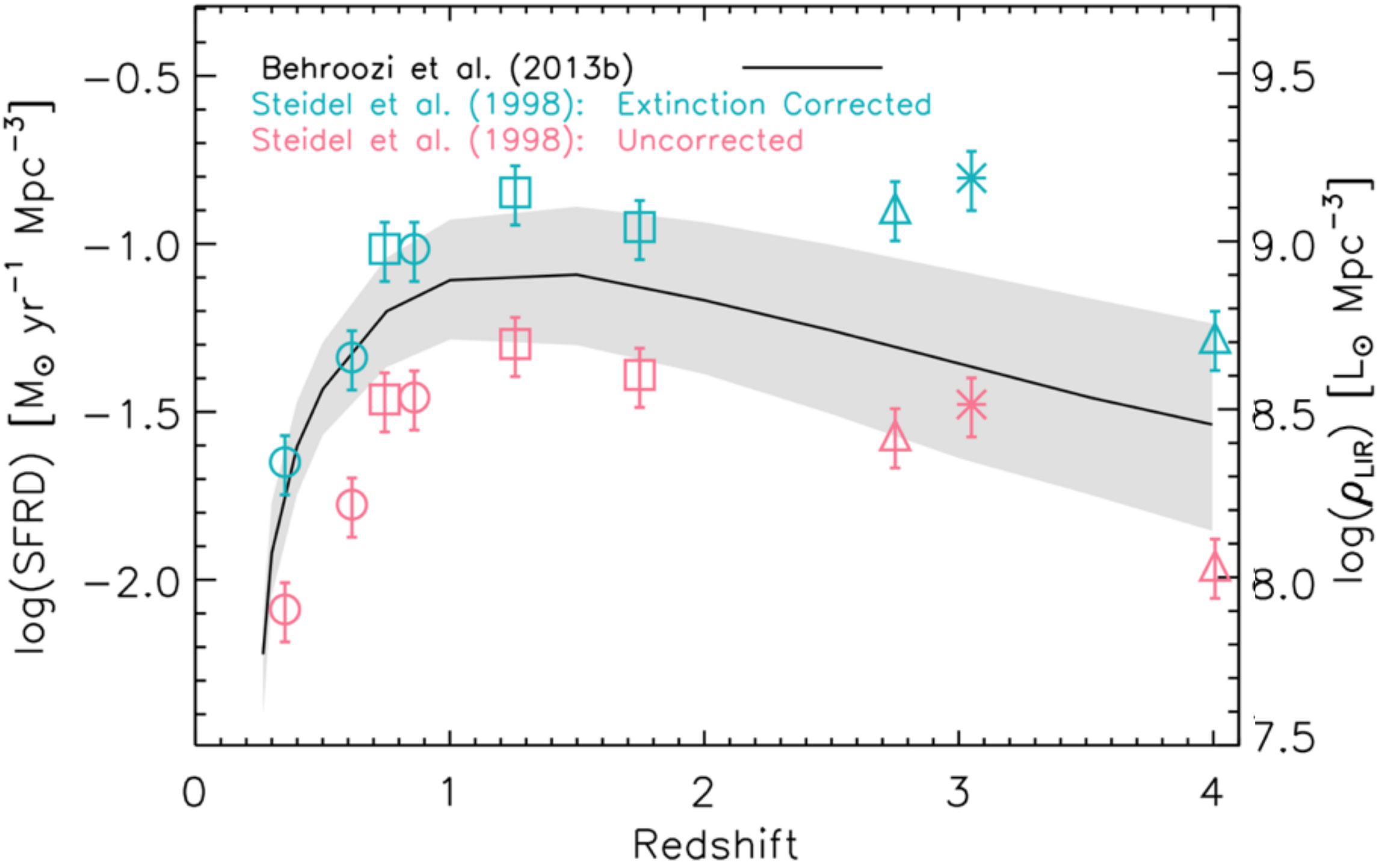
HERMES




# Herschel/SPIRE

# Star Formation History



HERMES

# HerMES - Herschel Multi-tiered Extragalactic Survey

To study the evolution of galaxies in the distant Universe
The biggest project on the Herschel Space Observatory
A European Space Agency mission

Astronomy Technology Centre
California Institute of Technology
Cardiff University
CEA, Saclay
Cornell
ESAC
Godard Space Flight Centre
Imperial College, London
Infrared Processing Analysis Centre
Institut d'Astrophysique de Paris
Institut d'Astrophysique Spatiale
Institute Astrophysica Canarias
Jet Propulsion Lab.
Laboratory of Astrophysics of Marseilles
Mullard Space Science Laboratory
OAPd University of Padova
UC Irvine
University of British Columbia
University of Colorado
University of Hertfordshire
University of Sussex

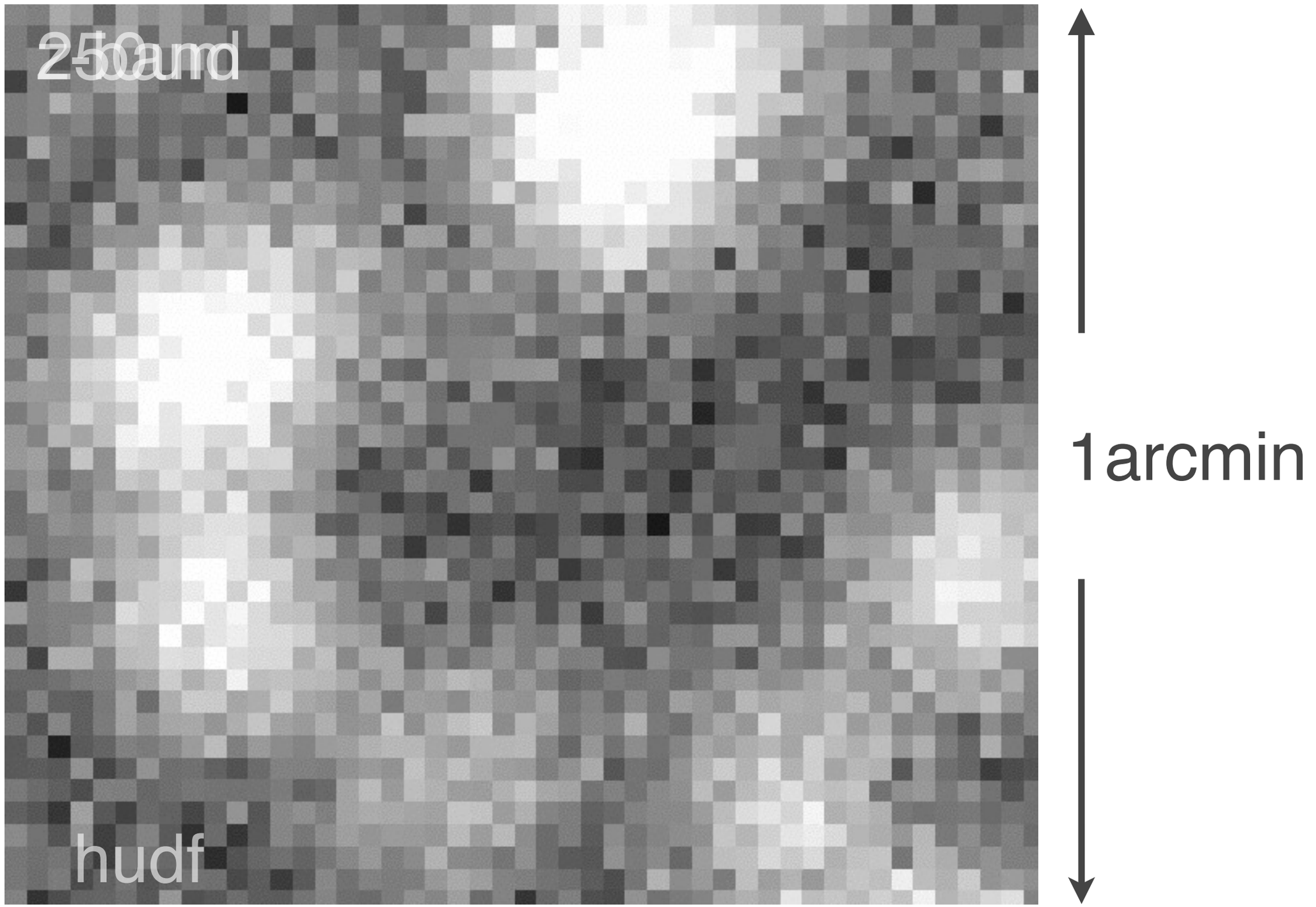
HERMES

# The Team

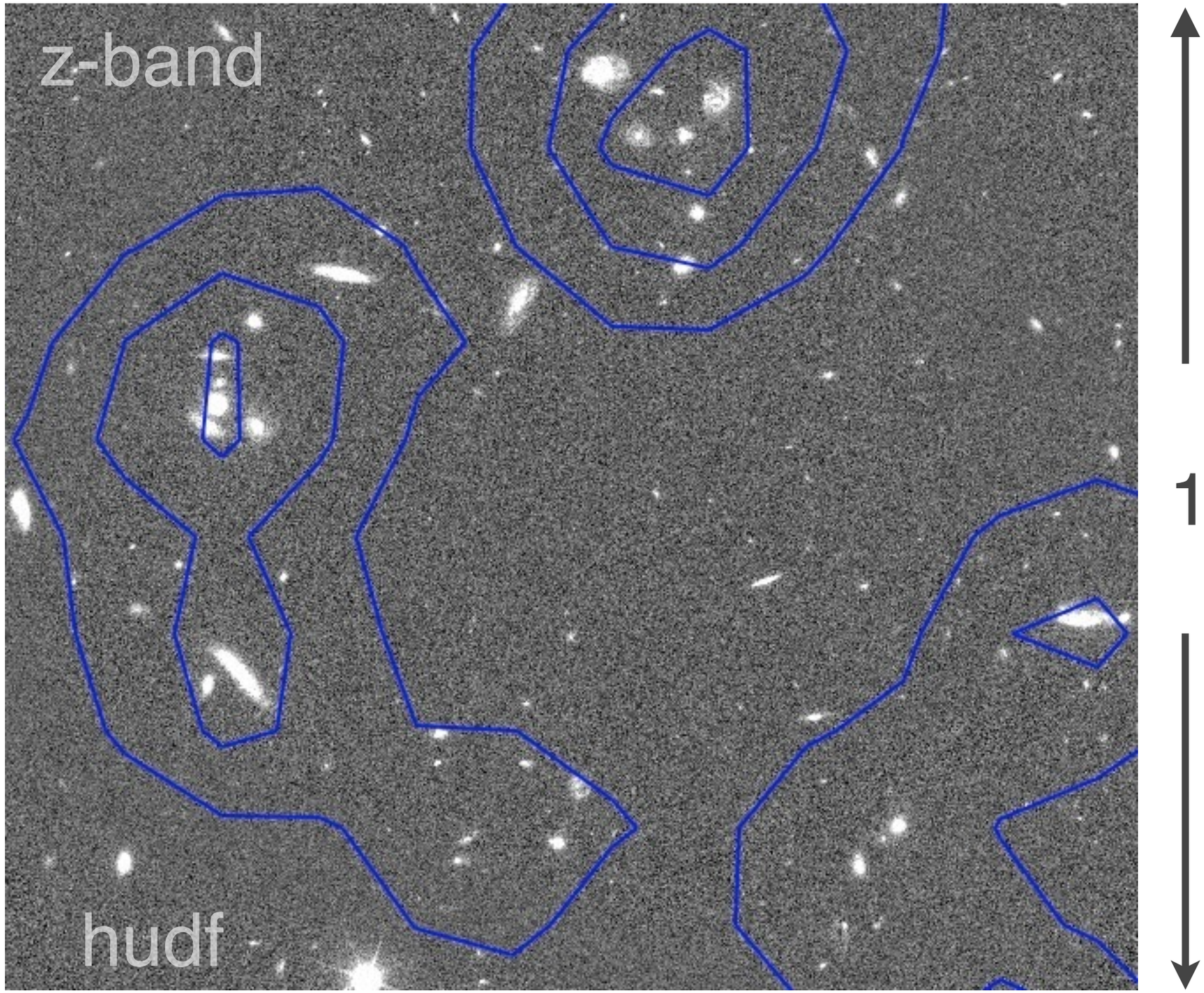
Bruno Altieri, Alex Amblard, Rick Arendt, Vinod Arumugam, Robbie Auld, Herve Aussel, Alexandre Beelen, Andrew Blain, Jamie Bock, Alessandro Boselli, Carrie Bridge, Drew Brisbin, Veronique Buat, Denis Burgarella, Nieves Castro-Rodriguez, Antonia Cava, Pierre Chanial, Ed Chapin, Michele Cirasuolo, Dave Clements, Alex Conley, Luca Conversi, Asantha Cooray, Emanuele Daddi, Gianfranco De Zotti, Darren Dowell, Jim Dunlop, Eli Dwek, Simon Dye, Steve Eales, David Elbaz, Erica Ellingson, Tim Ellsworth-Bowers, Duncan Farrah, Patrizia Ferrero, Mark Frost, Ken Ganga, Elodie Giovannoli, Jason Glenn, Eduardo Gonzalez-Solares, Matt Griffin, Mark Halpern, Martin Harwit, Evanthia Hatziminaoglou, George Helou, Jiasheng Huang, Ho Seong Hwang, Edo Ibar, Olivier Ilbert, Kate Isaak, Rob Ivison, Martin Kunz, Guilaine Lagache, Glenn Laurent, Louis Levenson, Carol Lonsdale, Nanyao Lu, Suzanne Madden, Bruno Maffei, Georgios Magdis, Gabriele Mainetti, Lucia Marchetti, Gaelen Marsden, Jason Marshall, Glenn Morrison, Angela Mortier, Hien Trong Nguyen, Brian O'Halloran, Seb Oliver, Alain Omont, Francois Orieux, Frazer Owen, Matthew Page, Biswajit Pandey, Maruillo Pannell, Pasquale Panuzzo, Andreas Papageorgiou, Harsit Patel, Chris Pearson, Ismael Perez Fournon, Michael Pohlen, Naseem Rangwala, Jason Rawlings, Gwen Raymond, Dimitra Rigopoulou, Laurie Riguccini, Guilia Rodighiero, Isaac Roseboom, Michael Rowan-Robinson, Miguel Sanchez Portal, Bernhard Schulz, Douglas Scott, Paolo Serra , Nick Seymour, David Shupe, Anthony Smith, Jason Stevens, Veronica Strazzu, Myrto Symeonidis, Markos Trichas, Katherine Tugwell, Mattia Vaccari, Elisabetta Valiante, Ivan Vatchanov, Joaquin Vieira, Marco Viero, Lingyu Wang, Don Wiebe, Kevin Xu, Michael Zemcov

Faculty & Researchers PostDocs PhD Students

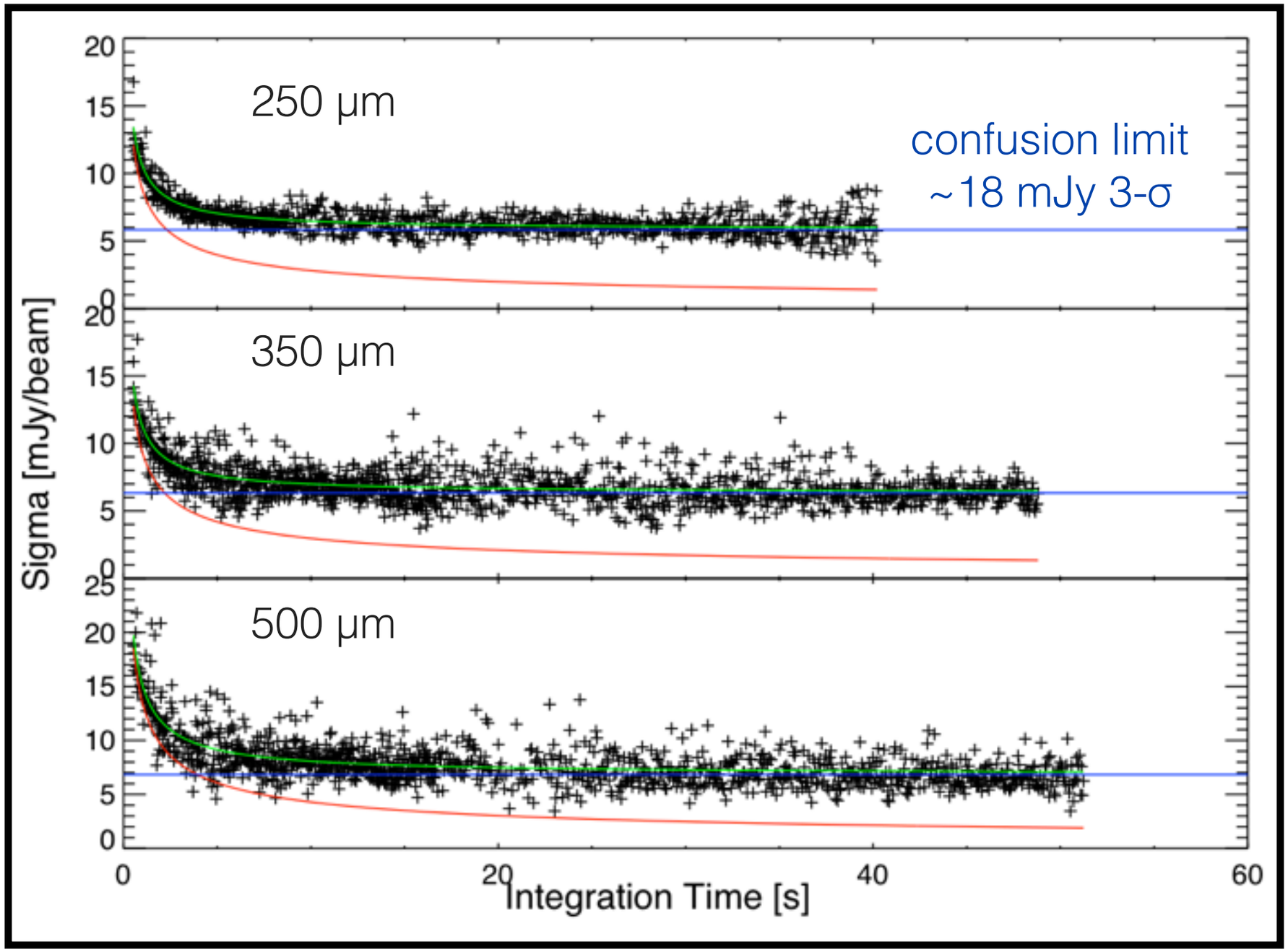
Plus engineers, instrument builders, software developers etc.




# source confusion



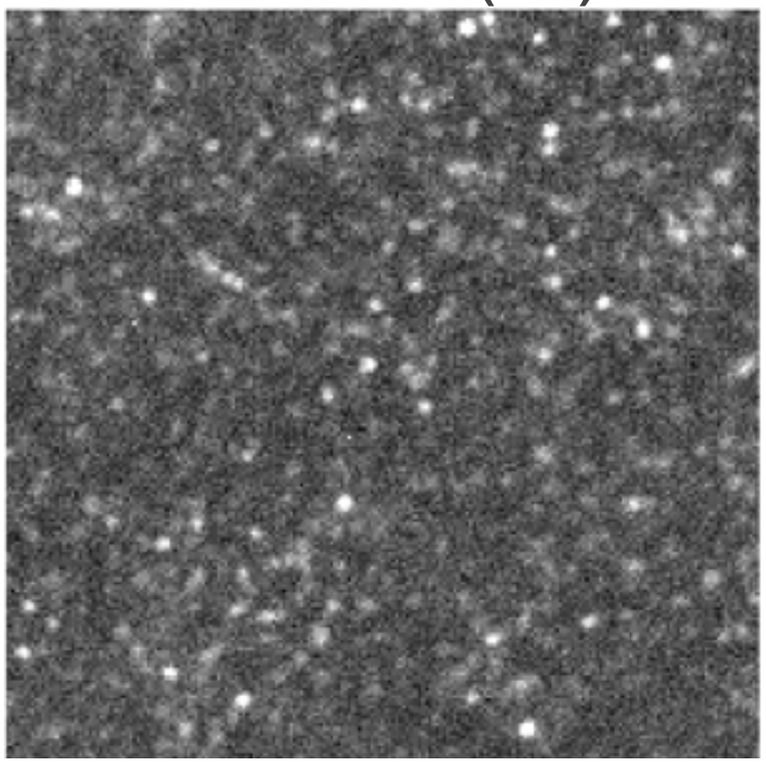

# source confusion




Nguyen et al. (2009)

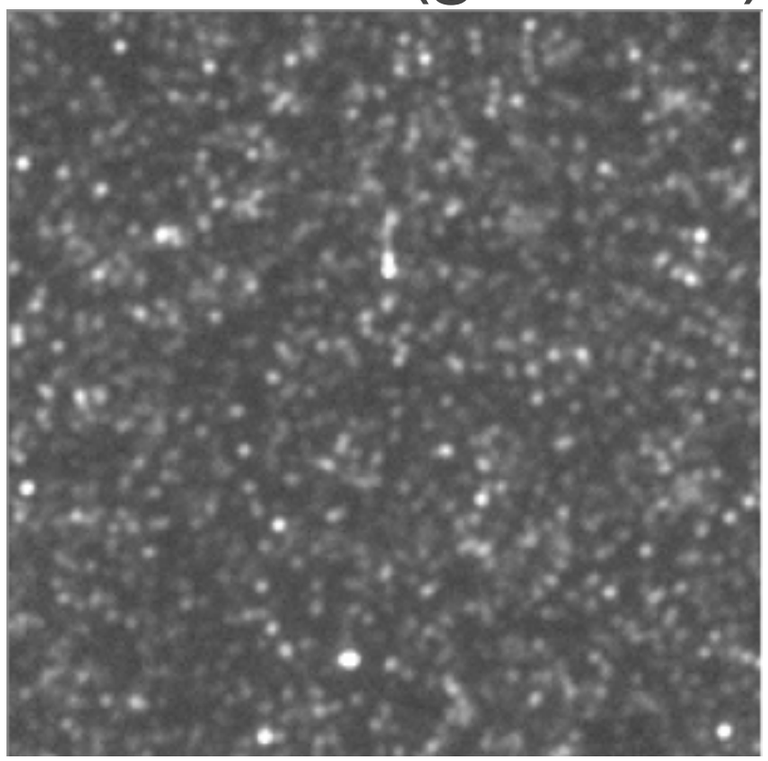
# source confusion

4 scans (fls)



RMS = 33.5 mJy (3σ)

152 scans (goods-s)



20.2 mJy (3σ)

# source confusion

# Correlations in the CIB

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  - determine the COB-CIB connection
  - cosmological applications
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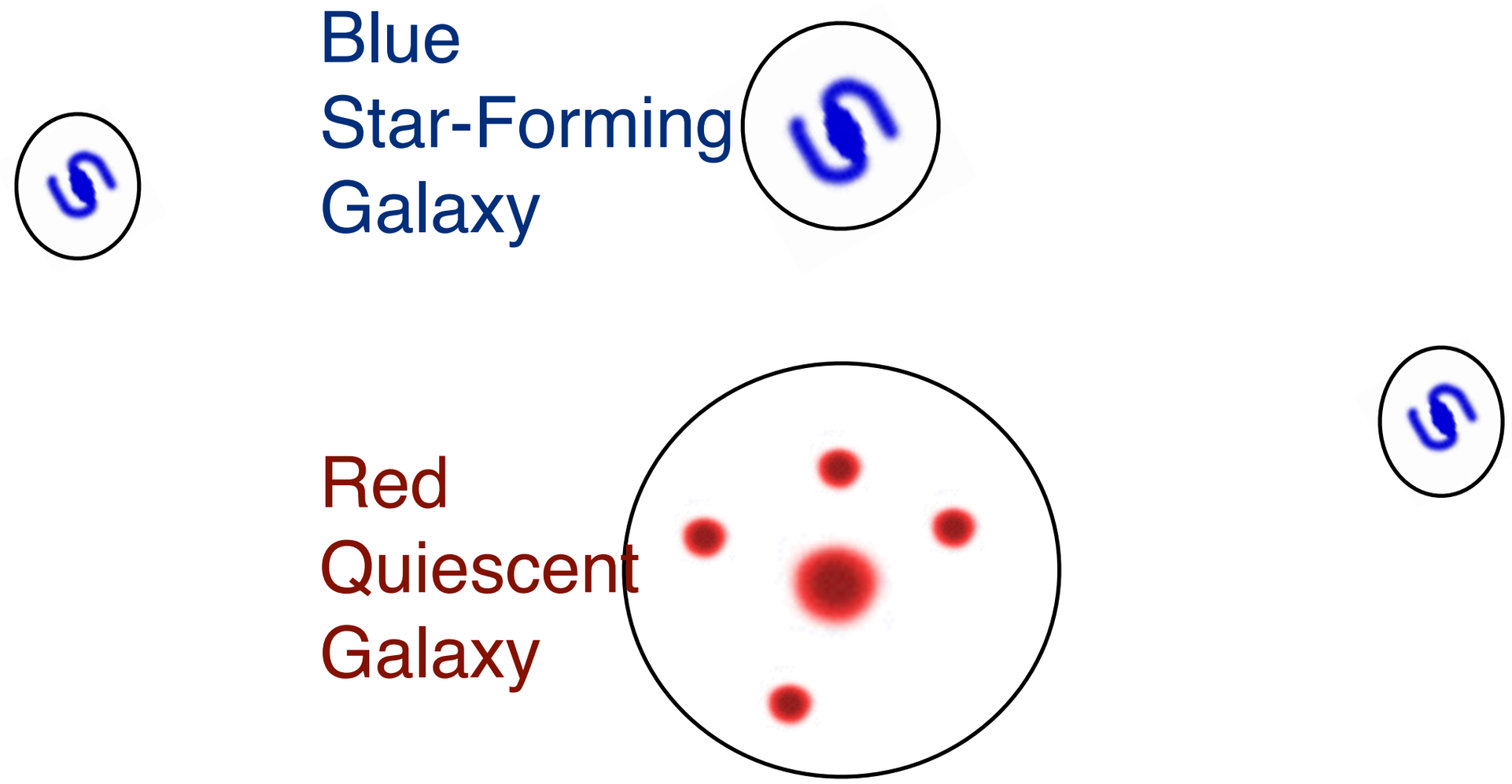
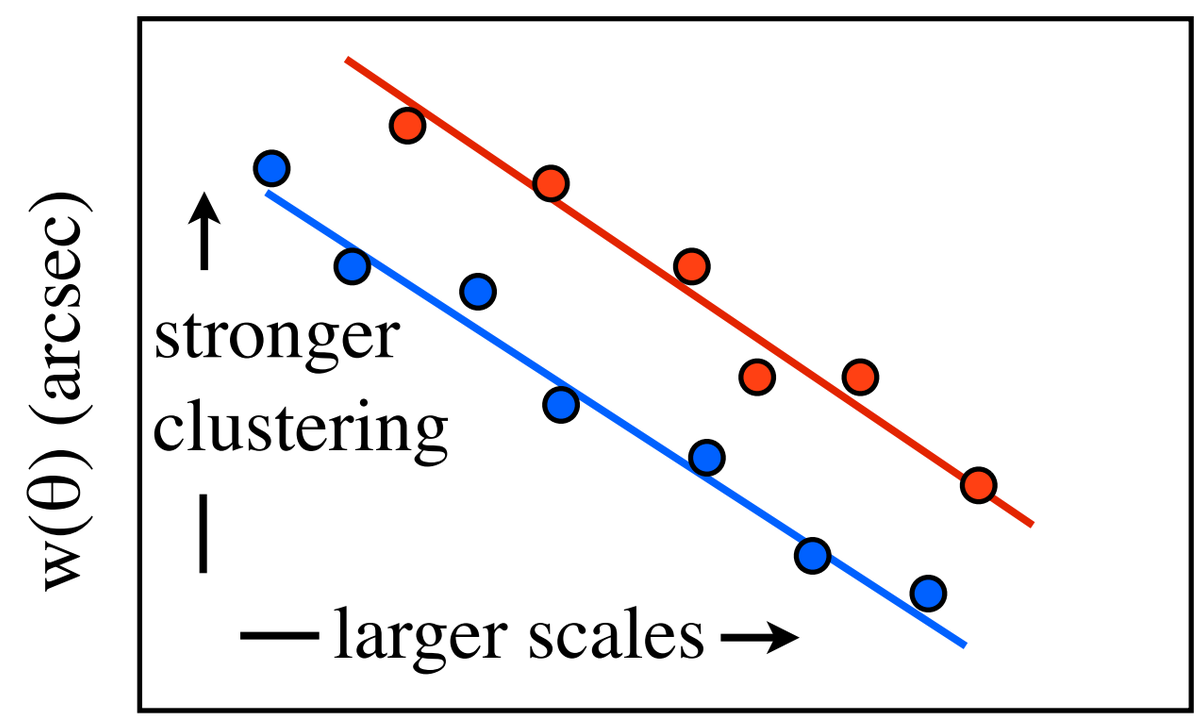
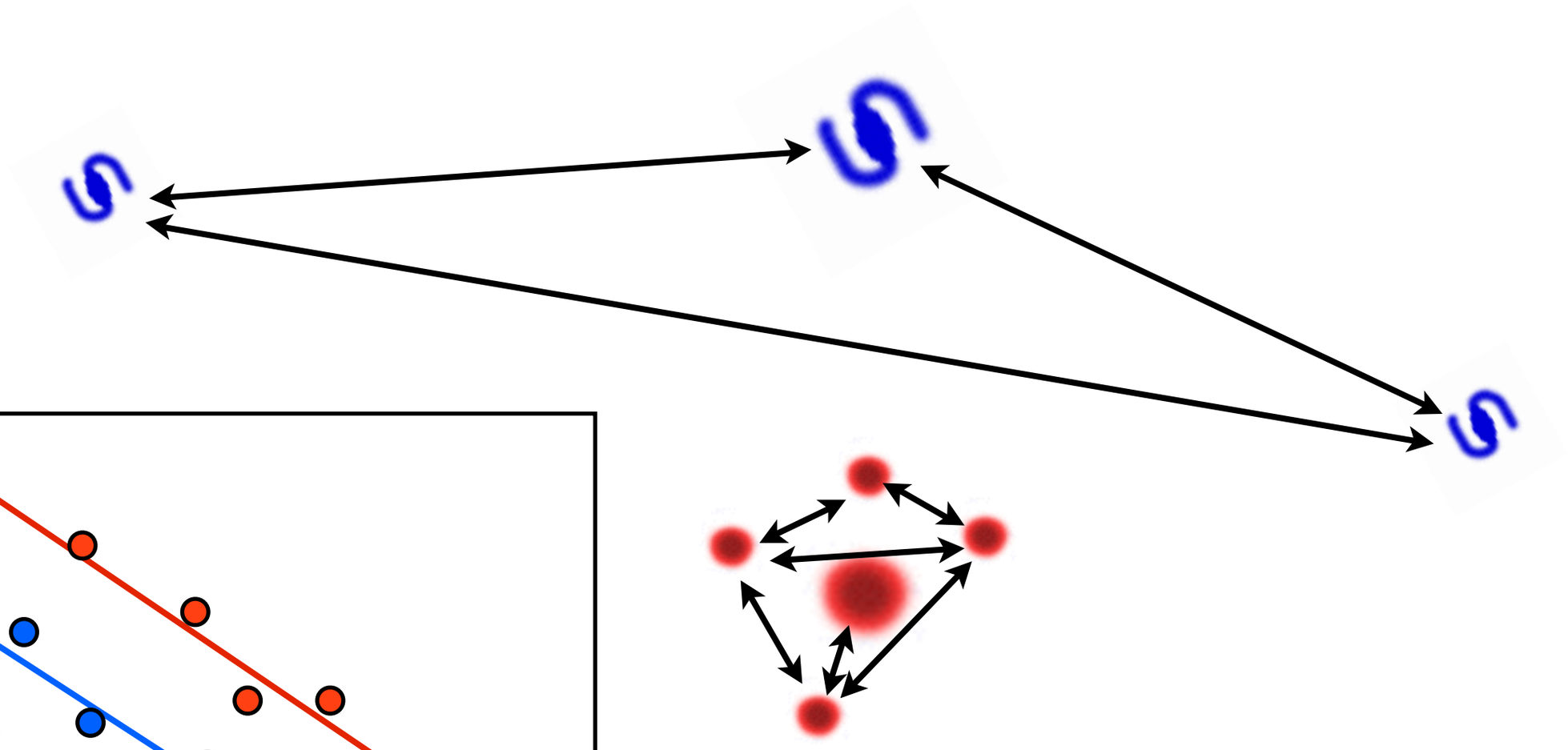
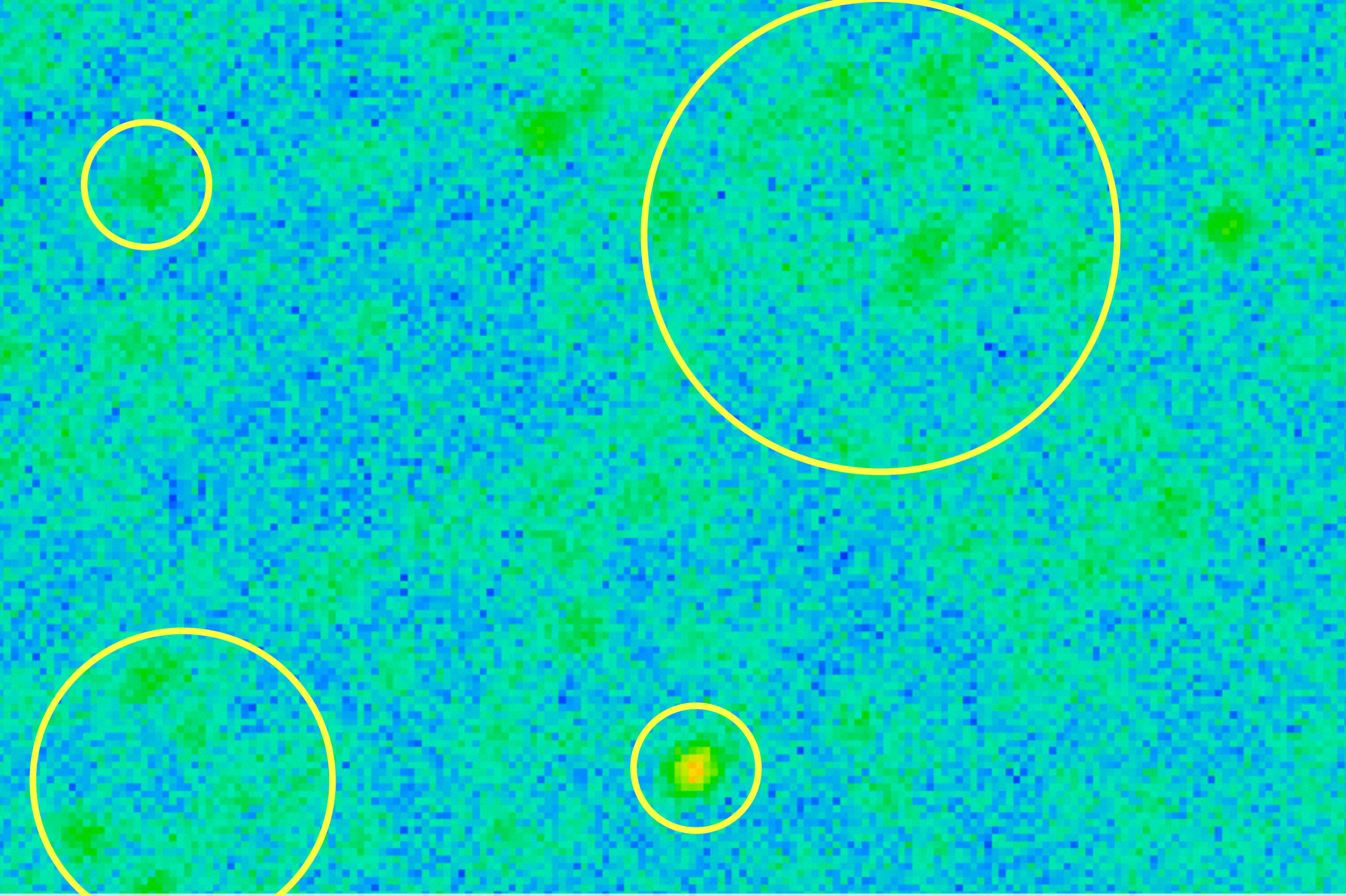



# galaxy clustering



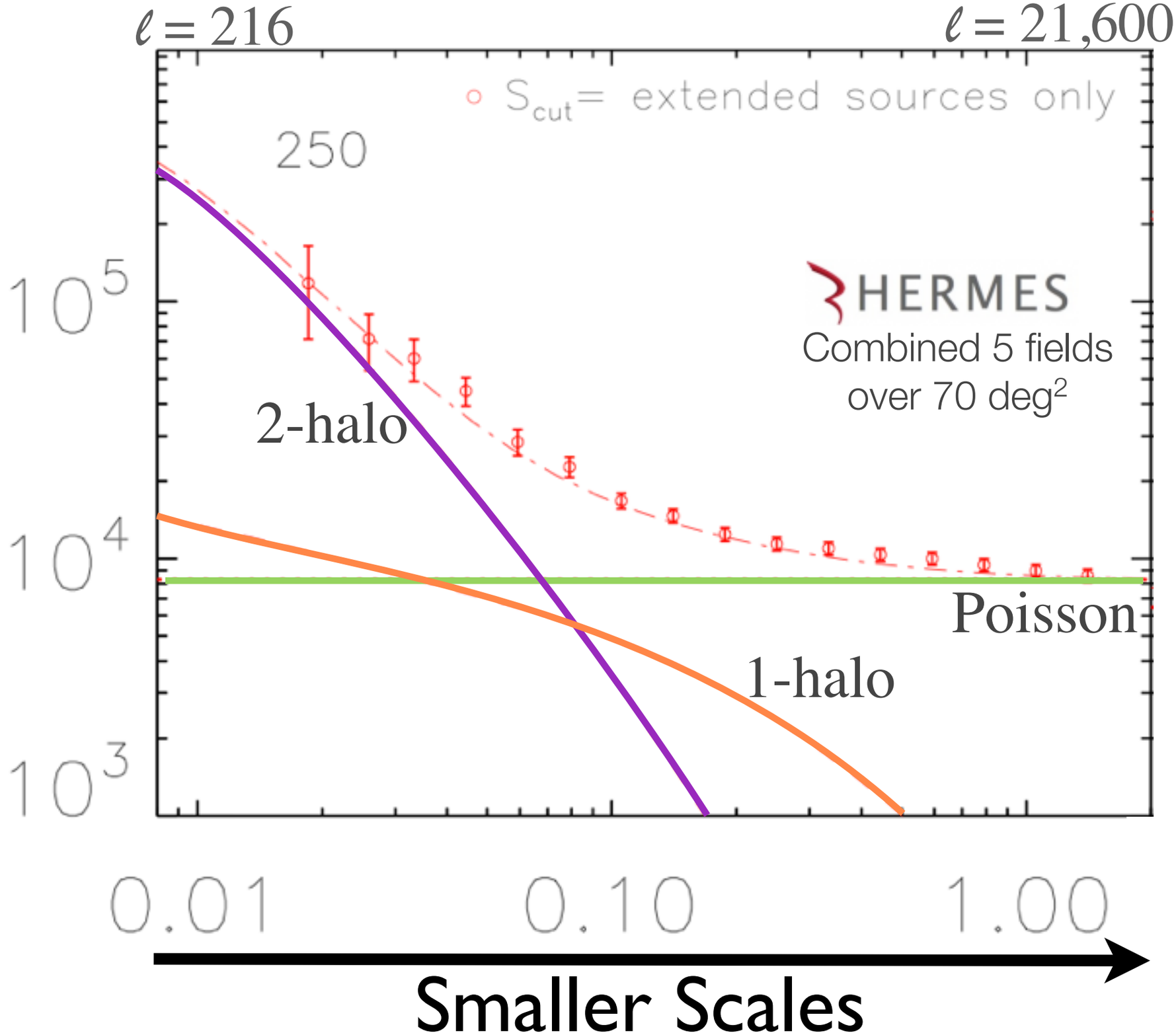



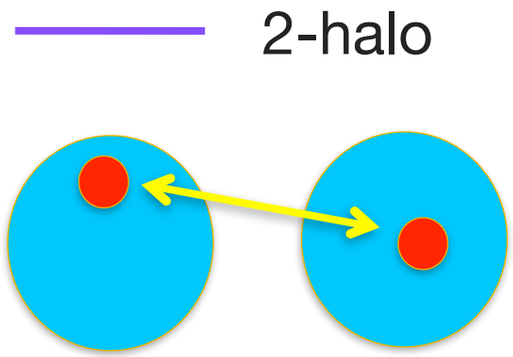
# correlation function

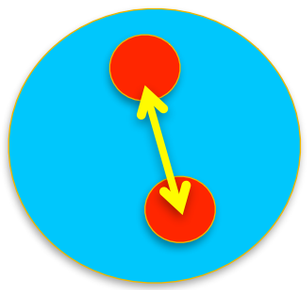


# Power Spectrum of CIB Anisotropies

# CIB Power Spectrum



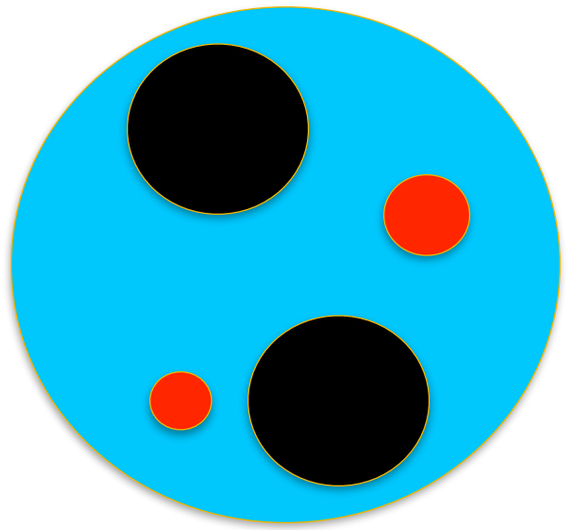




Halo Model: see e.g., Cooray & Sheth (2000), Zehavi et al. (2005, 2008)

# DSFG Clustering

1-Halo (non-linear) Term



1-halo

2-halo

HERMES

Combined 5 fields over 70 deg²

$P(k_\theta)$ (Jy² sr⁻¹)

$k_\theta$ (arcmin⁻¹)

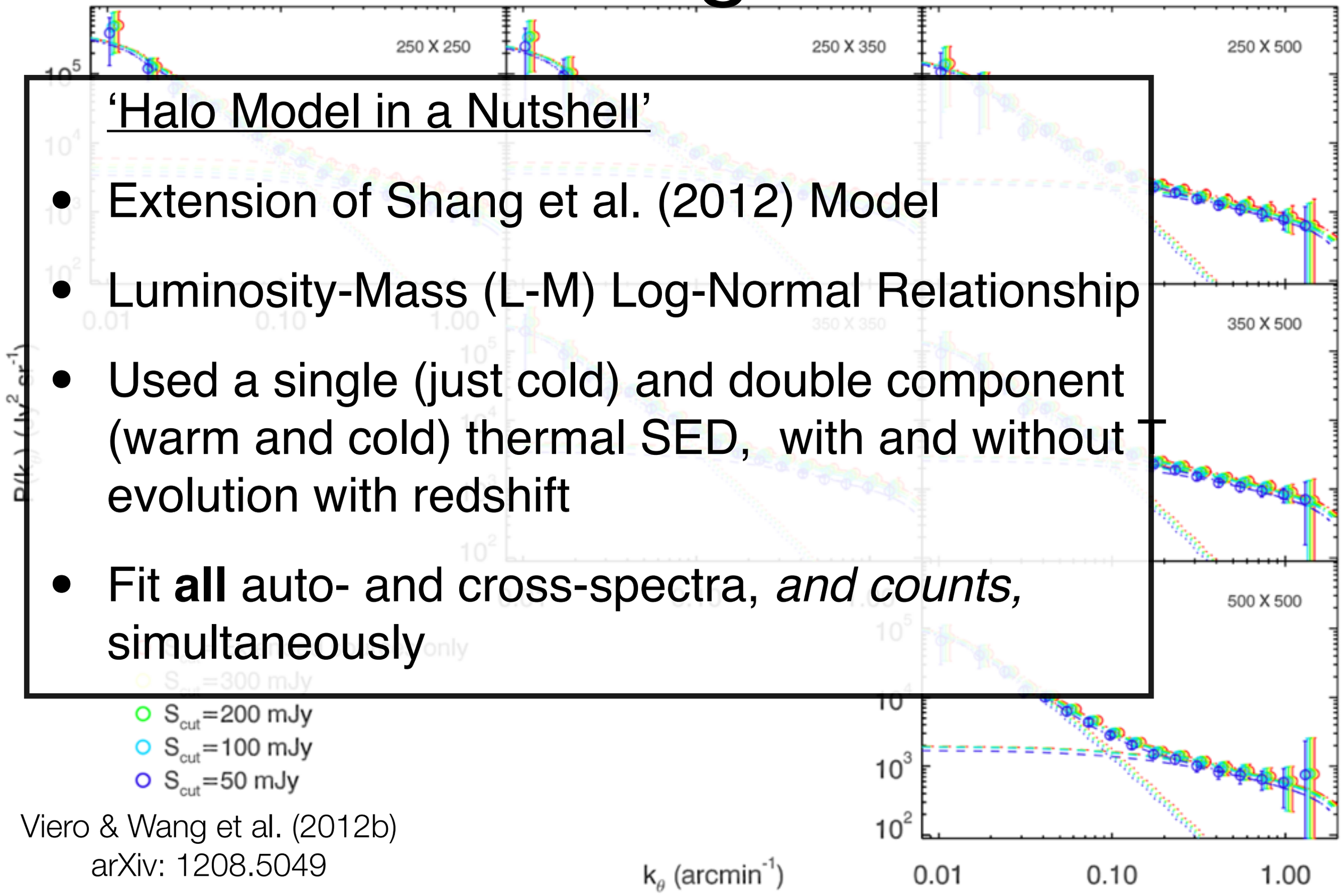
0.01 0.10 1.0

Viero & Wang et al. (2012b)
arXiv: 1208.5049

# DSFG Clustering

‘Halo Model in a Nutshell’

- Extension of Shang et al. (2012) Model
- Luminosity-Mass (L-M) Log-Normal Relationship
- Used a single (just cold) and double component (warm and cold) thermal SED, with and without T evolution with redshift
- Fit **all** auto- and cross-spectra, *and counts,* simultaneously

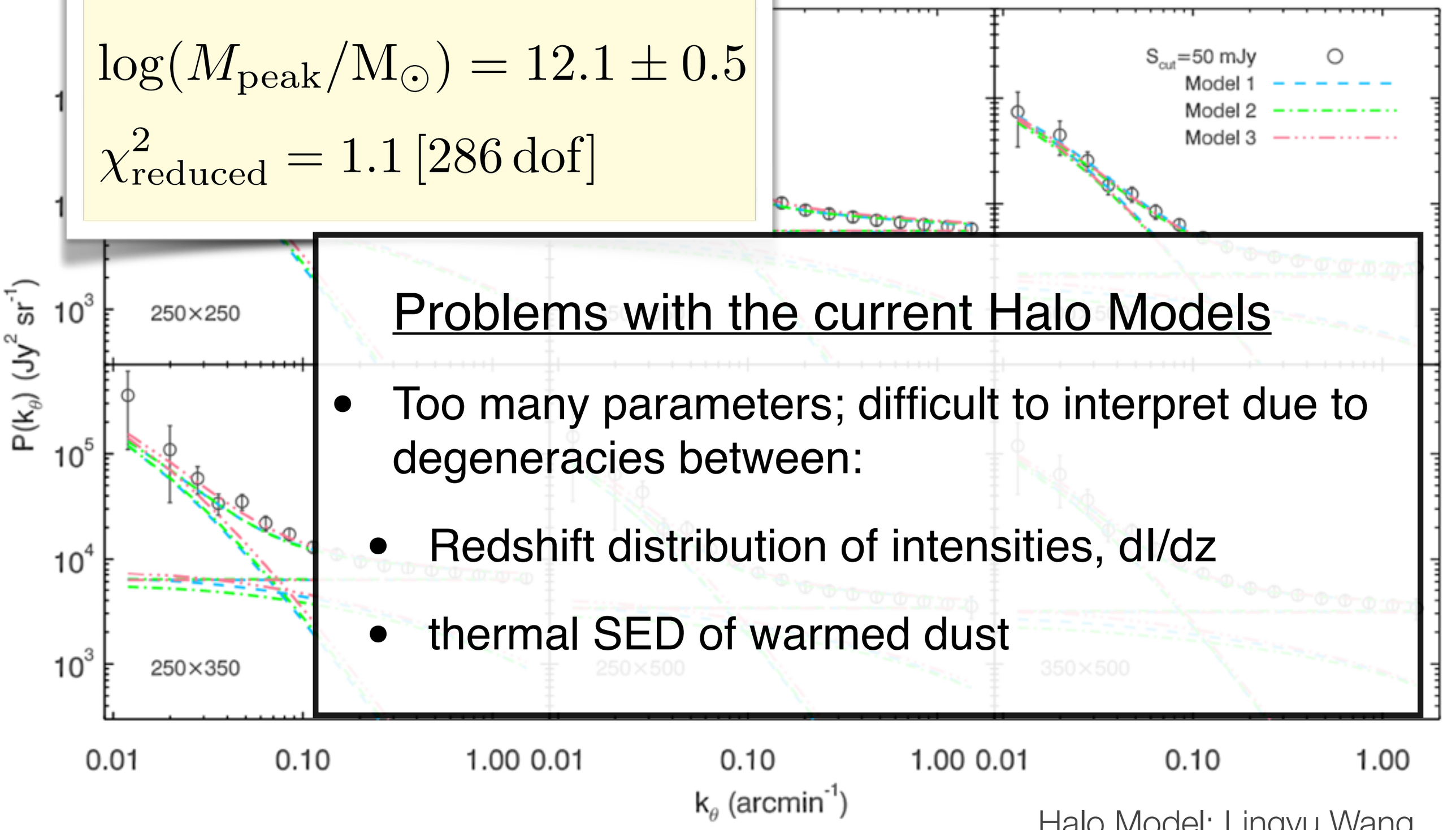



Viero & Wang et al. (2012b)
arXiv: 1208.5049

# Best-Fit Halo Models

$$\log(M_{\rm peak}/{\rm M}_\odot) = 12.1 \pm 0.5$$

$$\chi^2_{\rm reduced} = 1.1\,[286\,{\rm dof}]$$




## Problems with the current Halo Models

- Too many parameters; difficult to interpret due to degeneracies between:
  - Redshift distribution of intensities, dI/dz
  - thermal SED of warmed dust

Halo Model: Lingyu Wang

# Take-away from Clustering

- DSFG emission traces the dark matter distribution
  - SFGs most efficient in $\log(M_{\rm peak}/{\rm M}_\odot) = 12.1 \pm 0.5$
  - The redshift distribution depends on the wavelength
- More massive halos (groups and clusters!) host very luminous DSGFs
  - subsequently tSZ-CIB correlation complicates estimates of kSZ signal
- Halo Model interpretations suffer from degeneracies, requiring *more constraints*!

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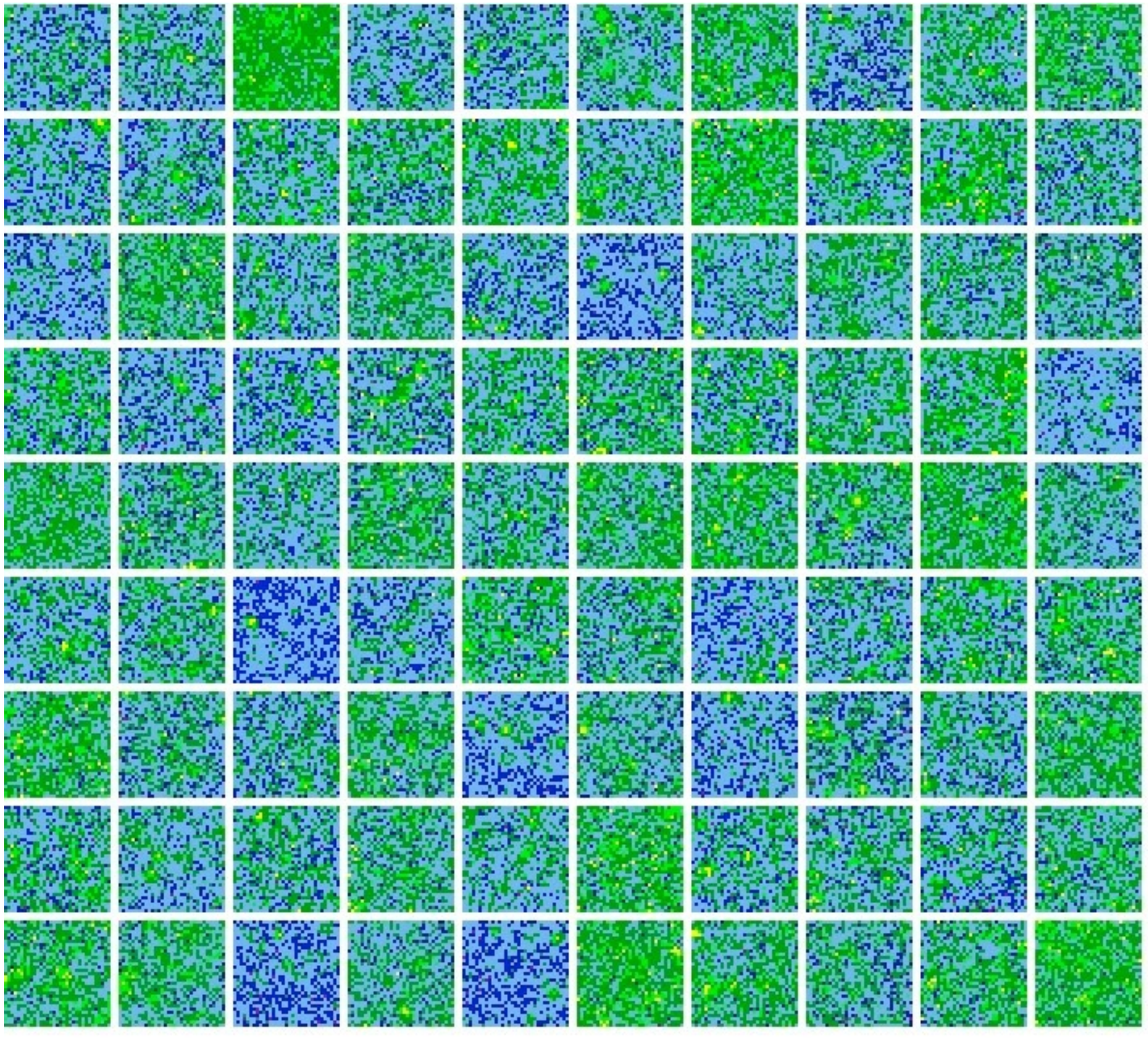
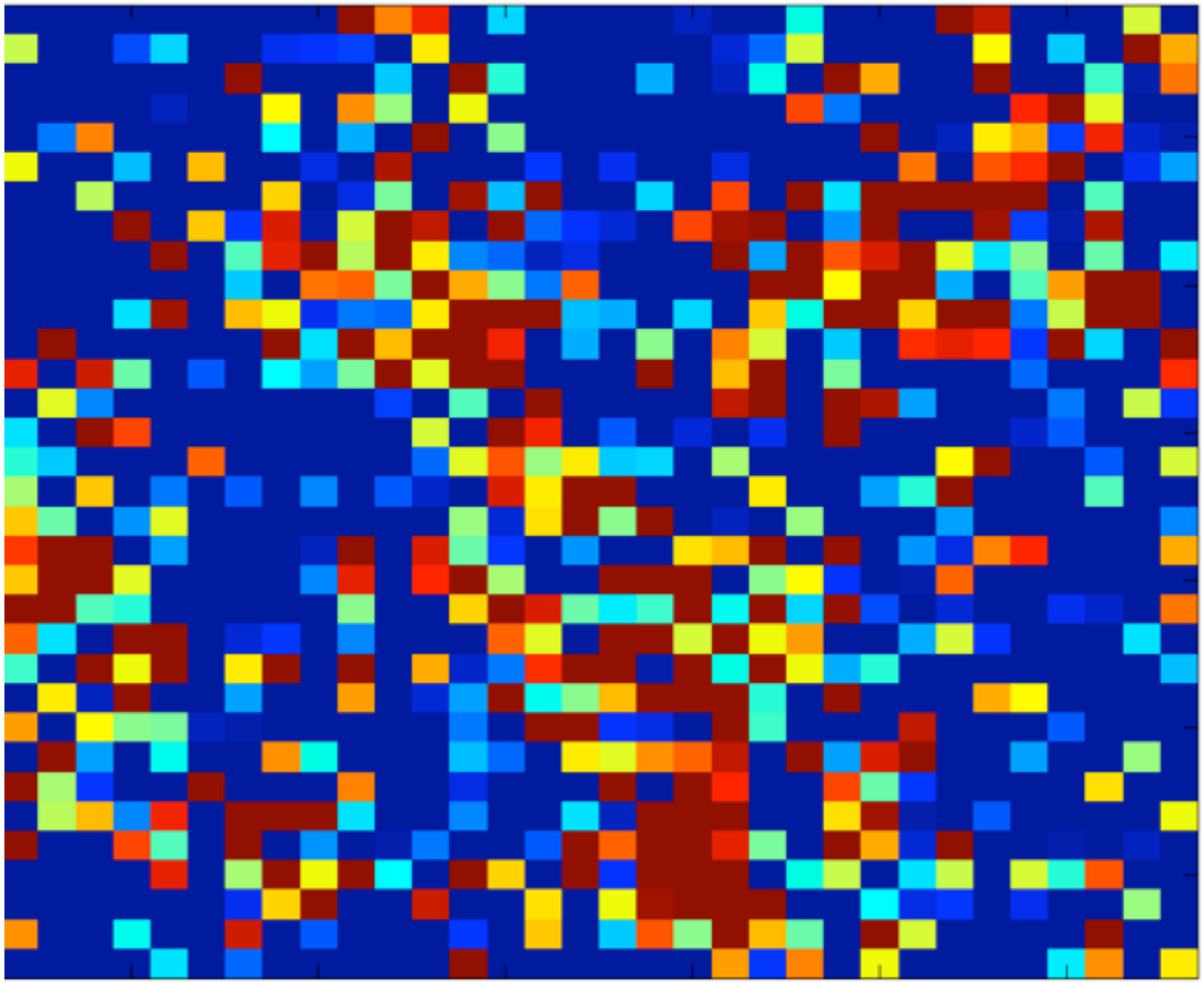
# Cross-Correlations w/ Ancillary Catalogs

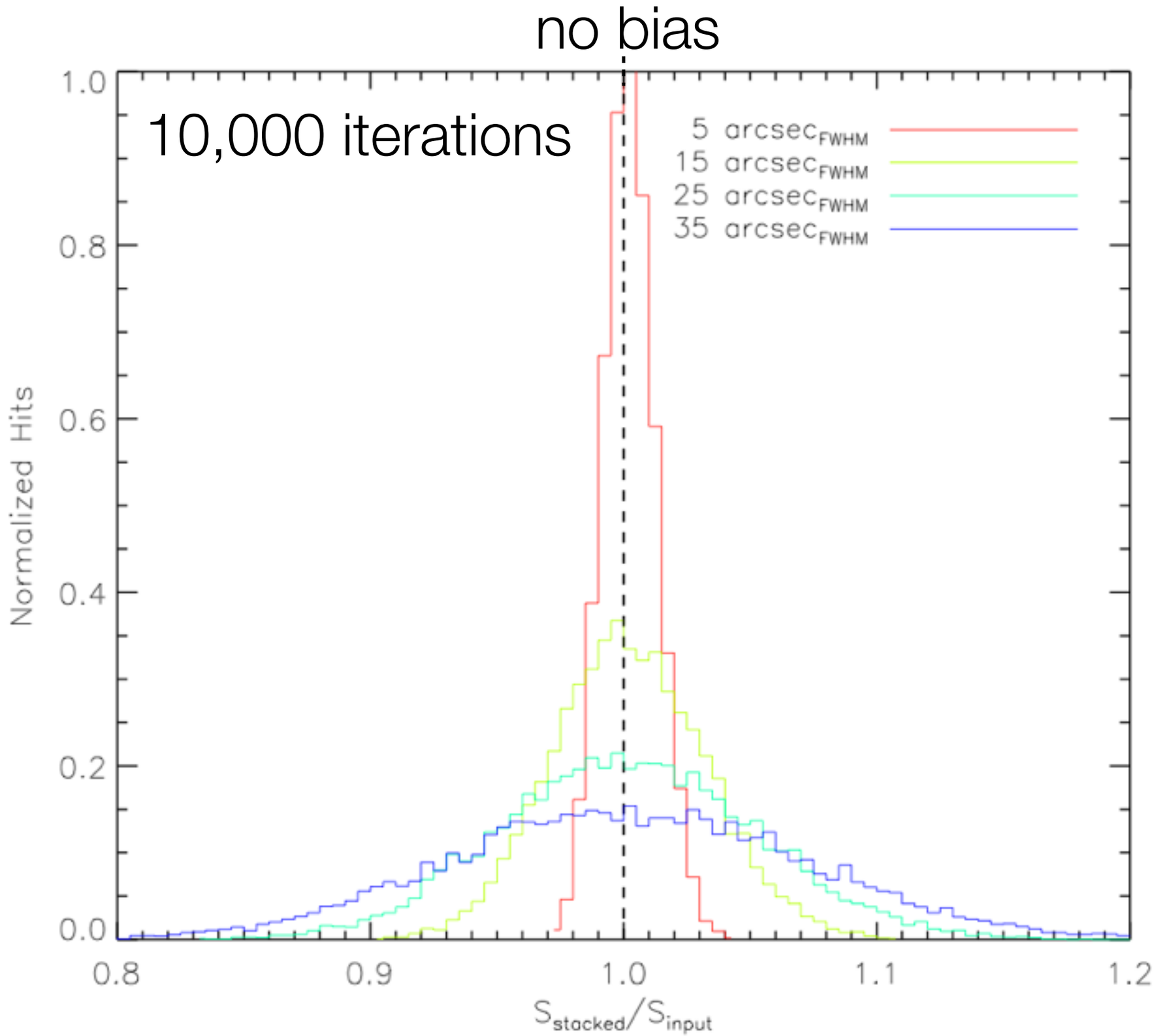


traditional stacking

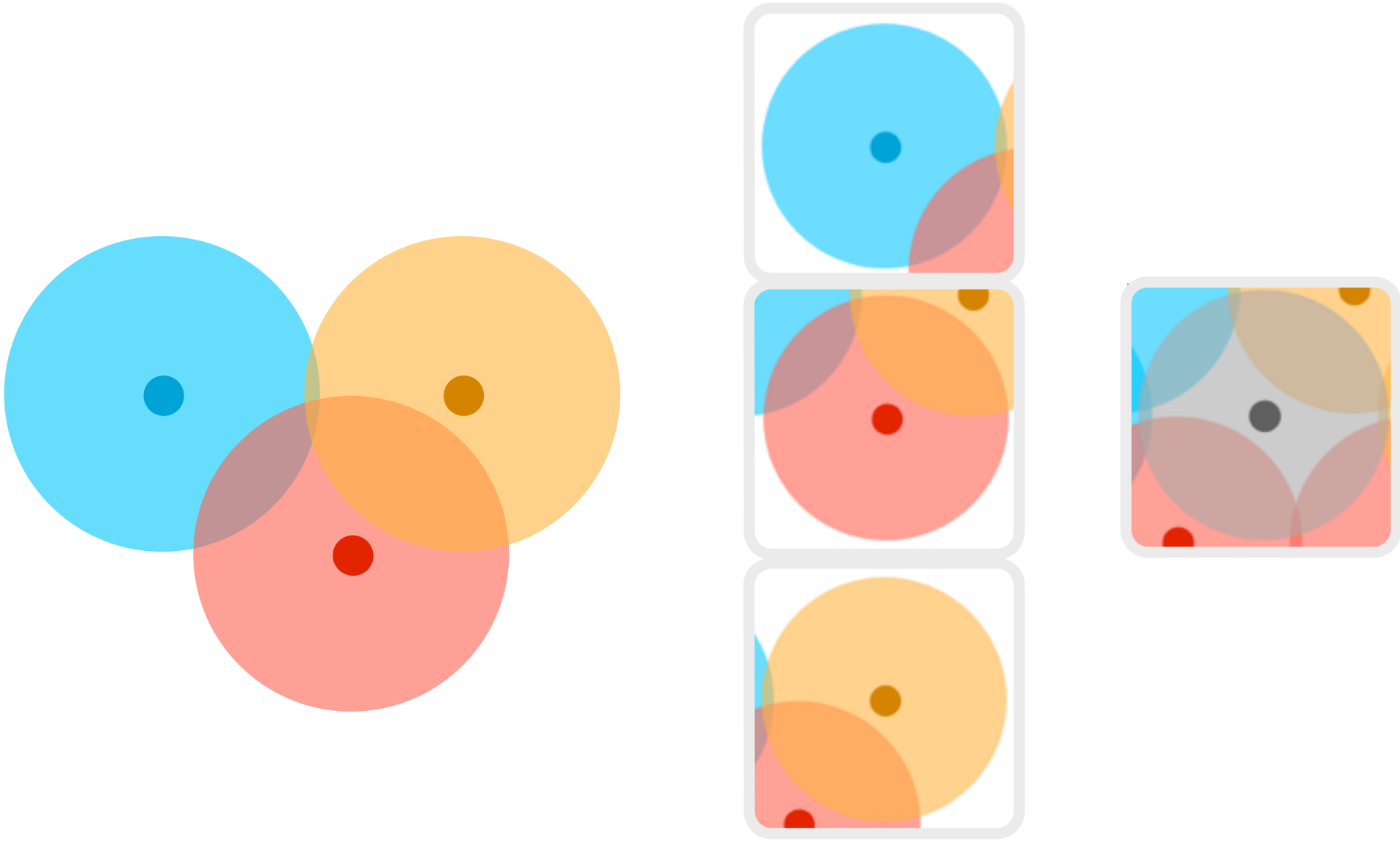


Phil Korngut (Caltech)

# traditional stacking



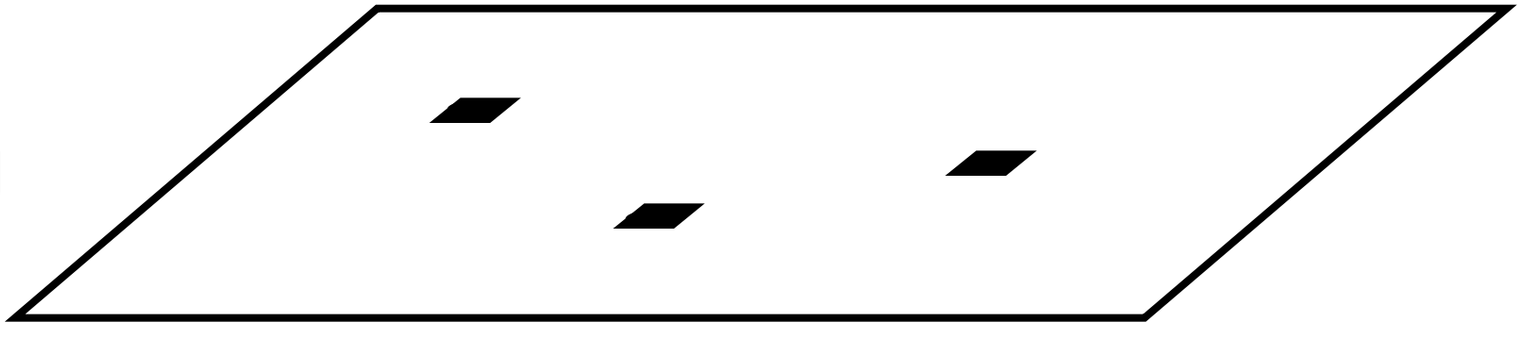

uncorrelated (random) source simulation



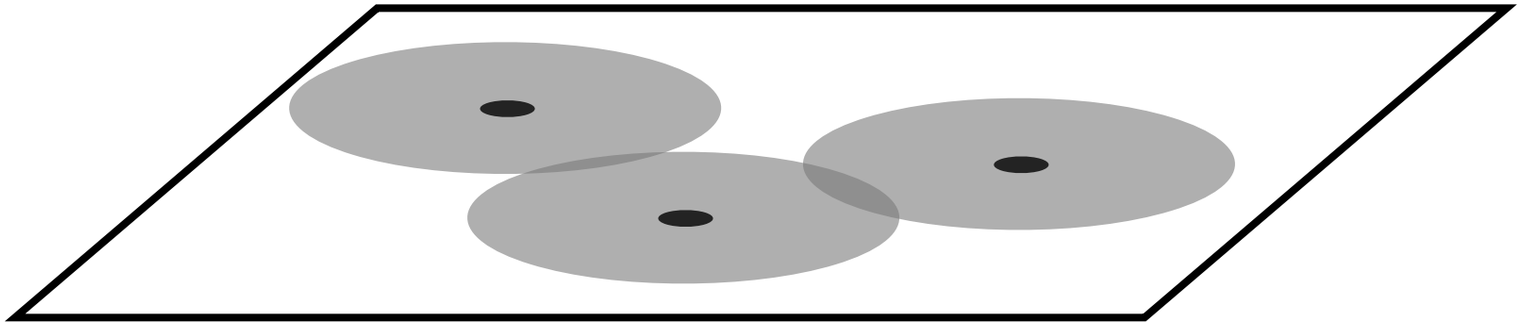
# clustering induced bias

# simultaneous stacking (SIMSTACK)

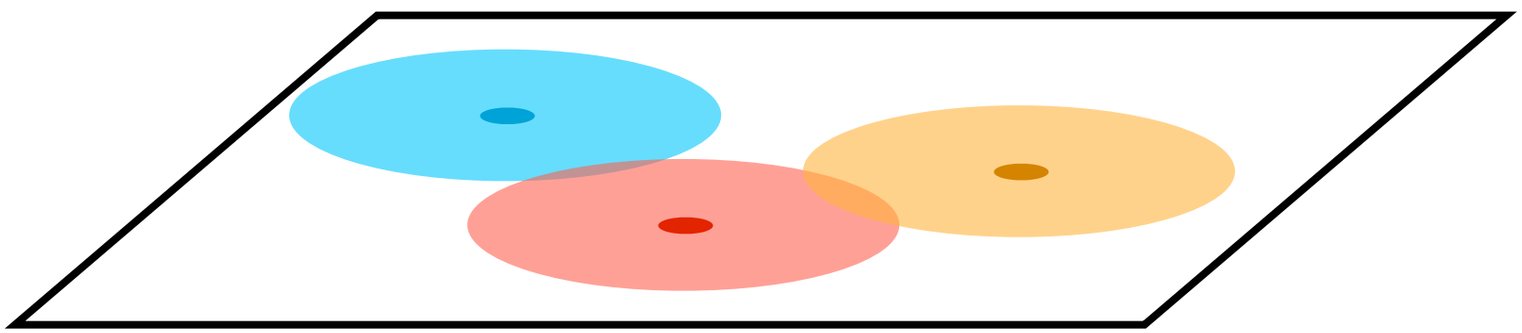
make hits map from catalog



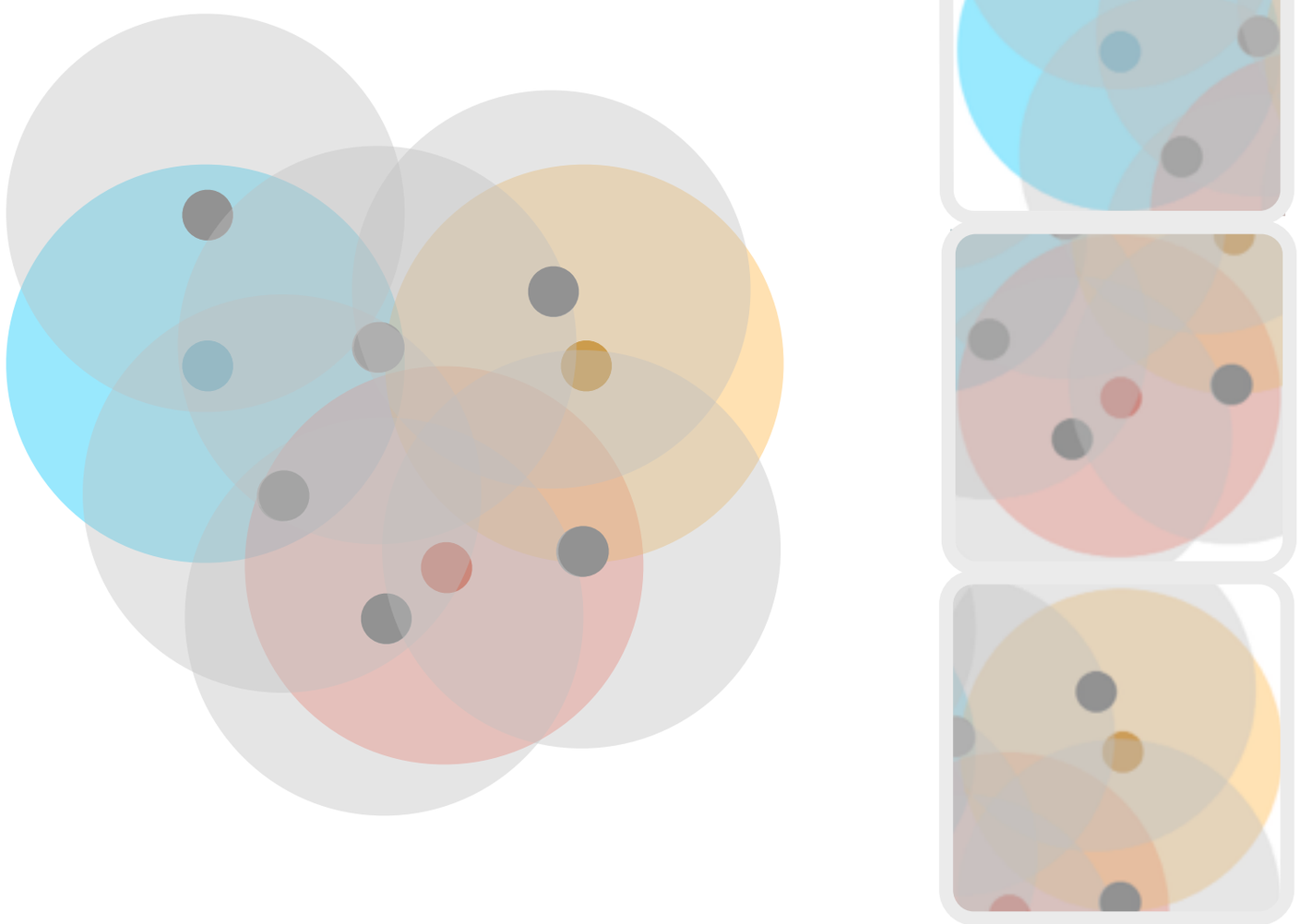
convolve with map p.s.f.



regress to find stacked flux

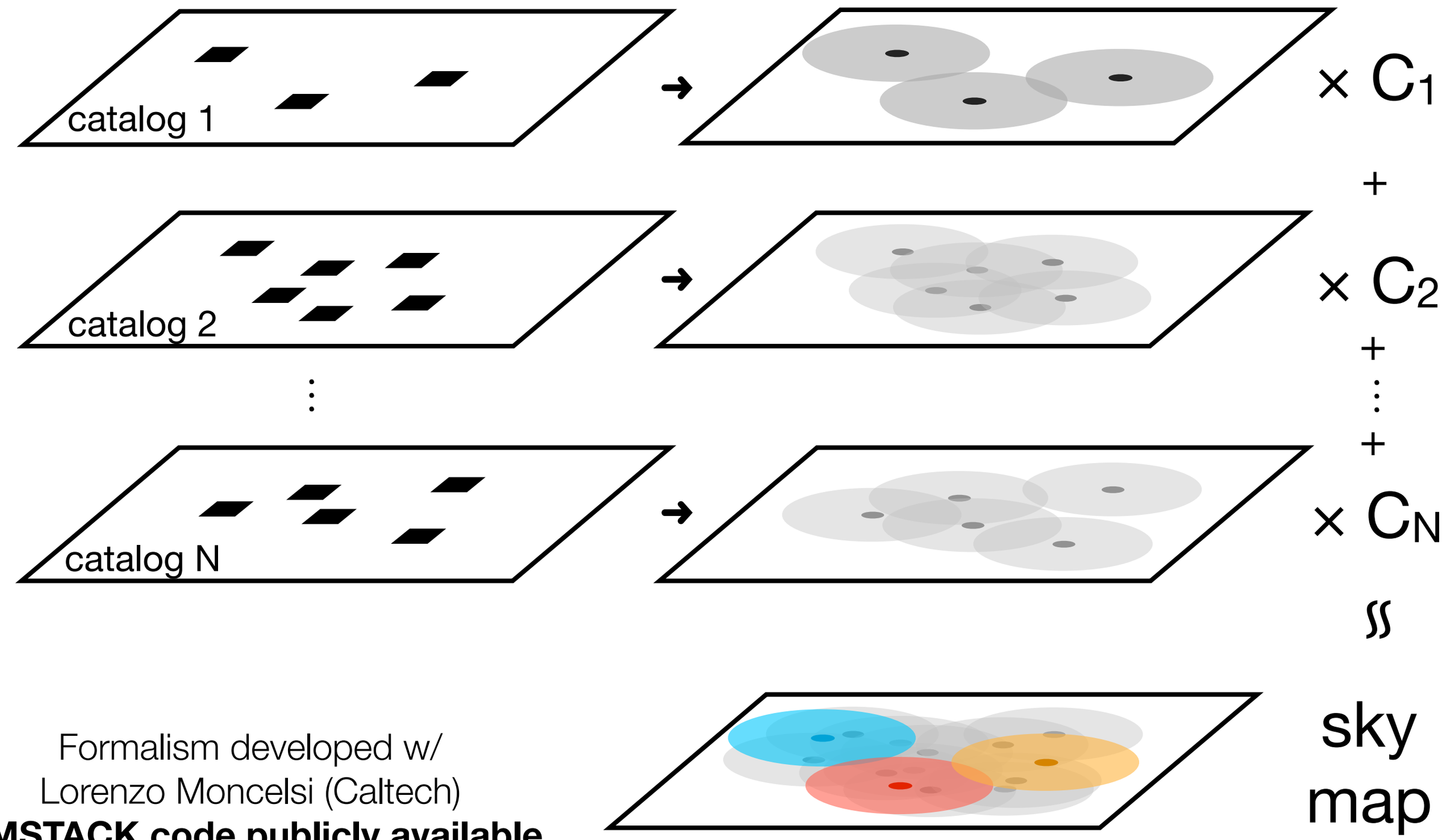


Formalism developed w/ Lorenzo Moncelsi (Caltech);
also see Kurczynski & Gawiser (2010), Roseboom et al. (2010)
**SIMSTACK code publicly available in arXiv:1304.0446**



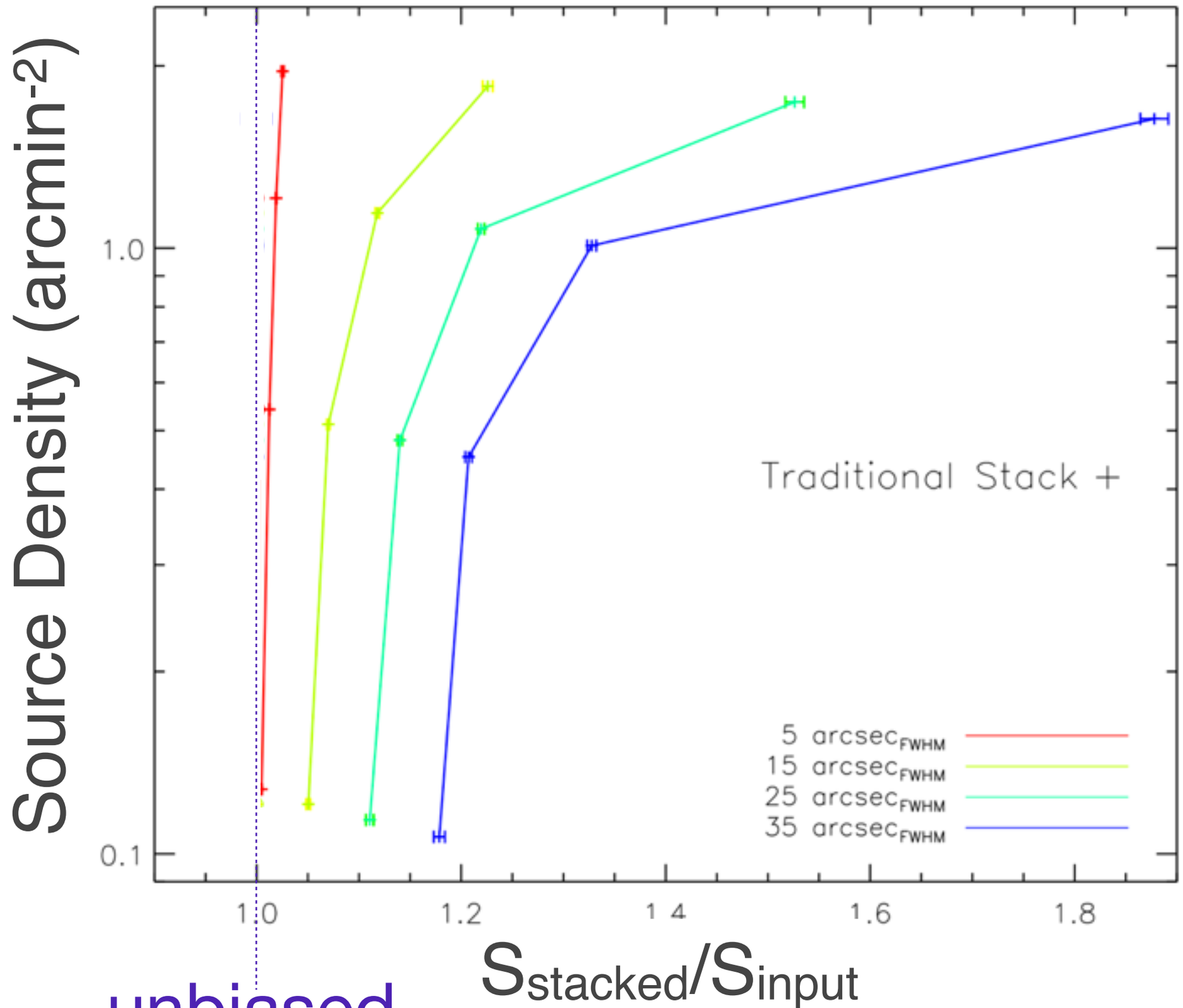
# non-target induced bias

# simultaneous stacking




Formalism developed w/
Lorenzo Moncelsi (Caltech)
**SIMSTACK code publicly available**
**see arXiv:1304.0446**

# simultaneous stacking sim

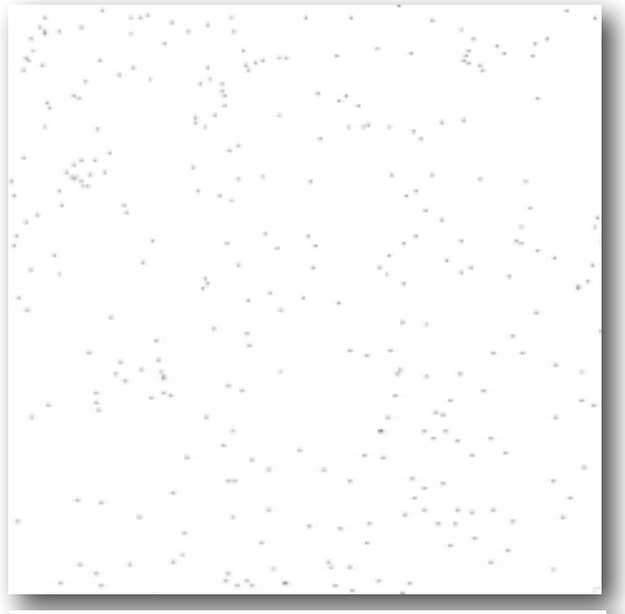


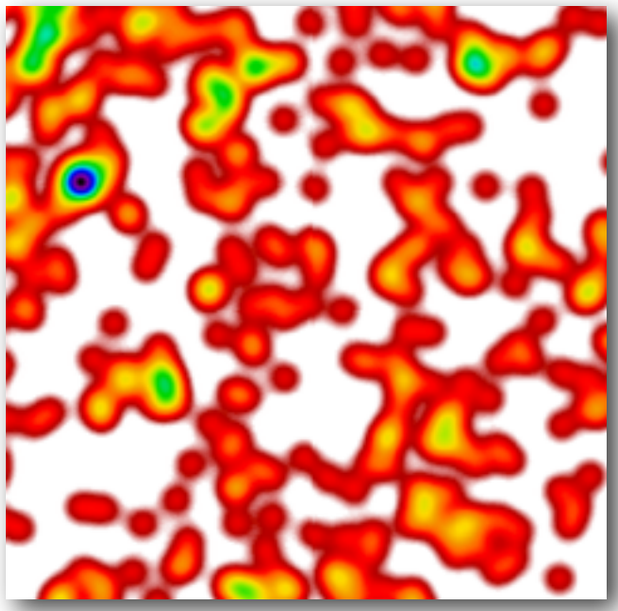

Viero, Moncelsi, Quadri et al. (2013)
arXiv:1304.0446

z=1.0 to 1.5

M = 9.5-10

| X | Y |
|---|---|
| 996 | 1009 |
| 55 | 1011 |
| 187 | 1010 |
| 501 | 1011 |
| 336 | 1012 |
| 127 | 1011 |

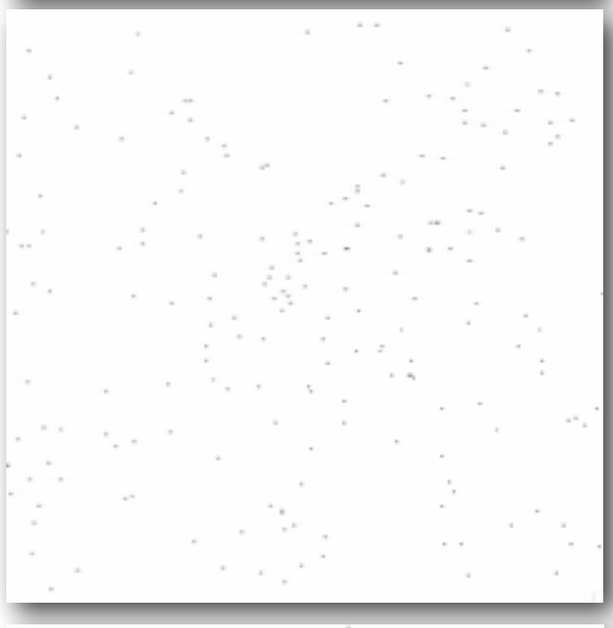


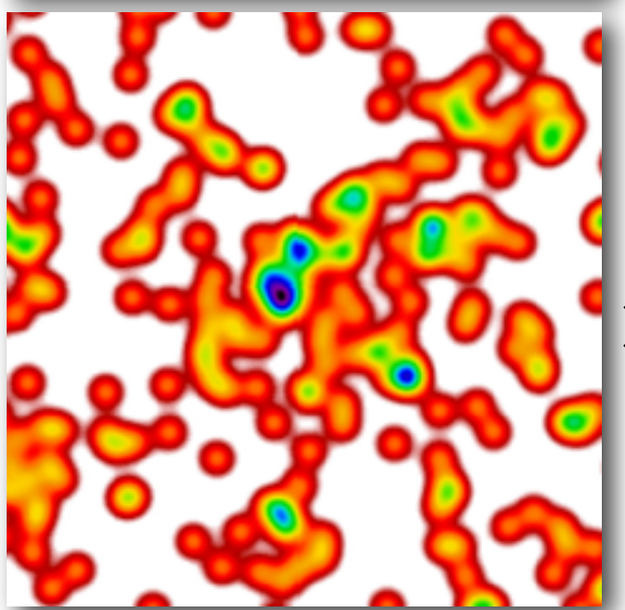


$\times C_1$ +

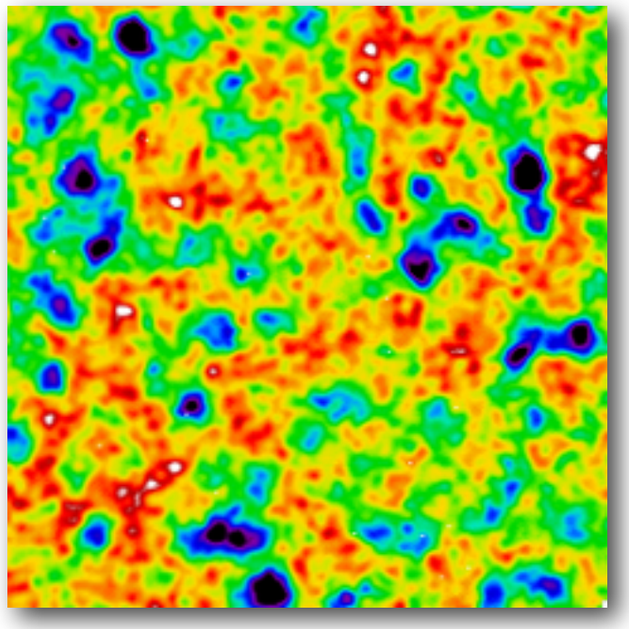
M = 10-10.5

| X | Y |
|---|---|
| 535 | 1026 |
| 345 | 1029 |
| 340 | 1029 |
| 517 | 1027 |
| 805 | 1031 |
| 805 | 1031 |





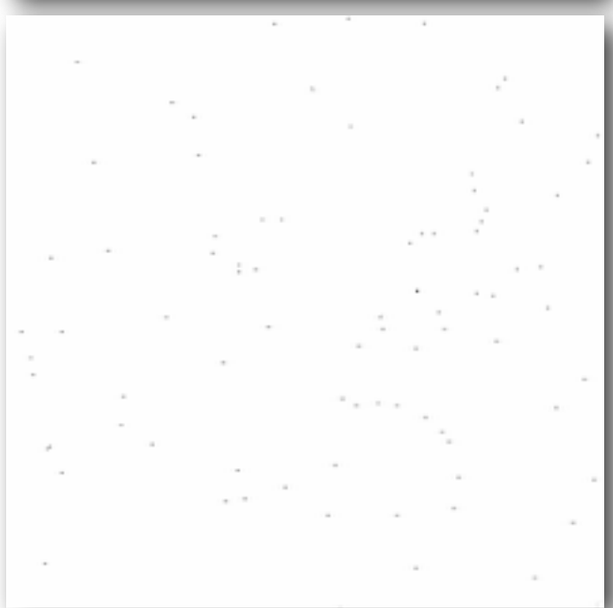
$\times C_2 \approx$

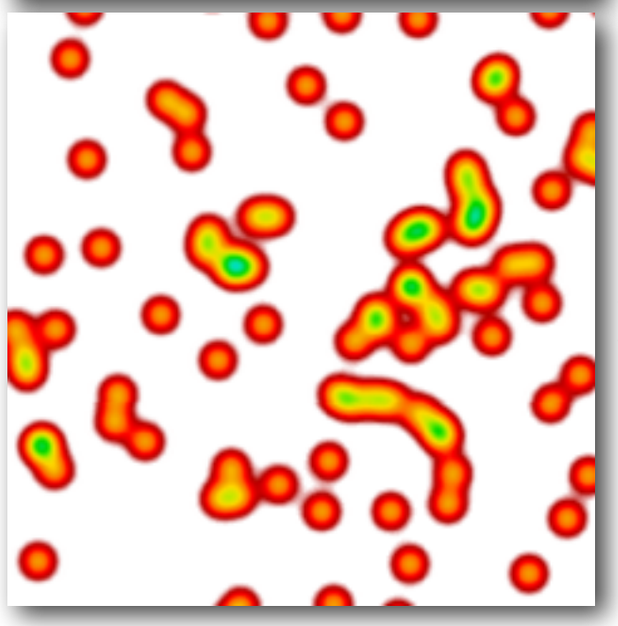


+ ⋮ +

M = 10.5-11

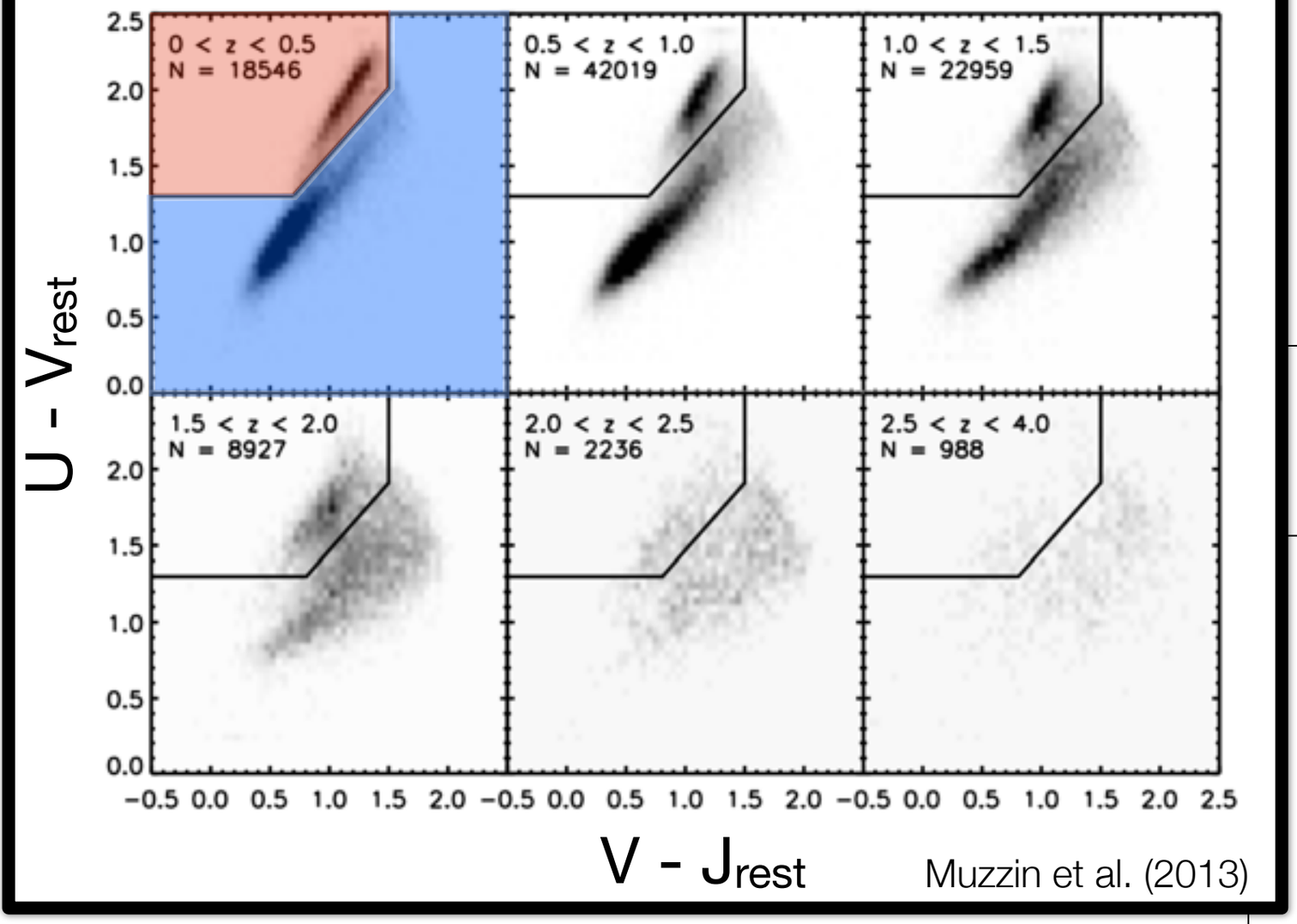
| X | Y |
|---|---|
| 345 | 1029 |
| 340 | 1029 |
| 517 | 1027 |
| 805 | 1031 |
| 805 | 1031 |
| 238 | 1032 |
| 359 | 1033 |
| 841 | 1034 |





$\times C_N$

## Separating Quiescent from Star-forming




Viero, Moncelsi, Quadri et al. (2013)
arXiv:1304.0446

## catalog (Williams & Quadri, in prep.)

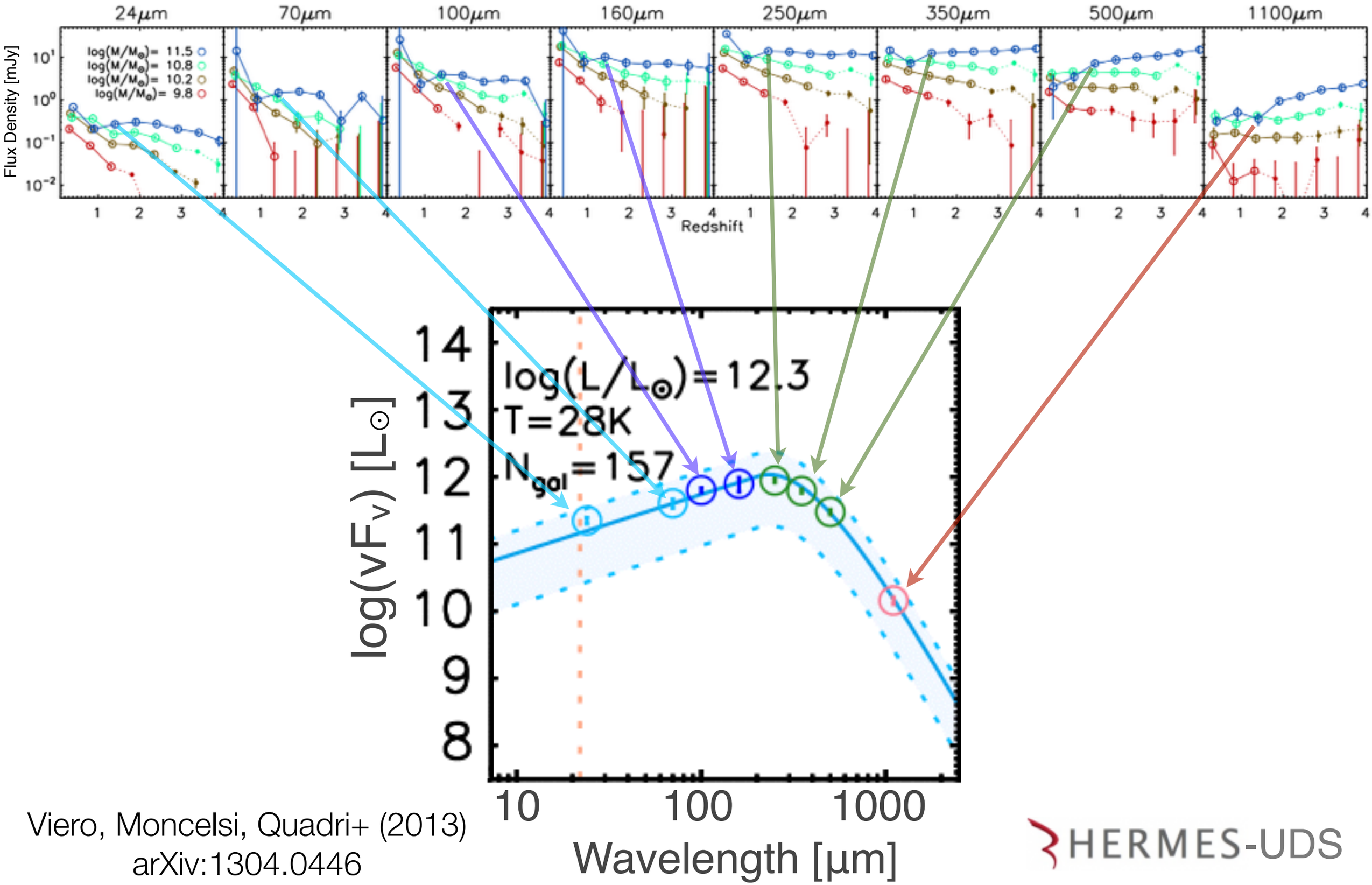
- UKIDSS/UDS [2/3 deg$^2$]
  - uBVRizJHK + IRAC ch1234
  - K-band magnitude cut 24 AB
  - 81,000 sources in ~0.63 deg$^2$
- redshifts - EAZY (Brammer 2008)
- masses - FAST (Kriek 2009)

HERMES-UDS

## maps (HerMES; Oliver et al. 2012)

- *Spitzer*/MIPS
  - 24, 70um
- *Herschel*/PACS
  - 100, 160um
- *Herschel*/SPIRE
  - 250, 350, 500um
- ASTE/AzTEC
  - 1100um

# stacked flux



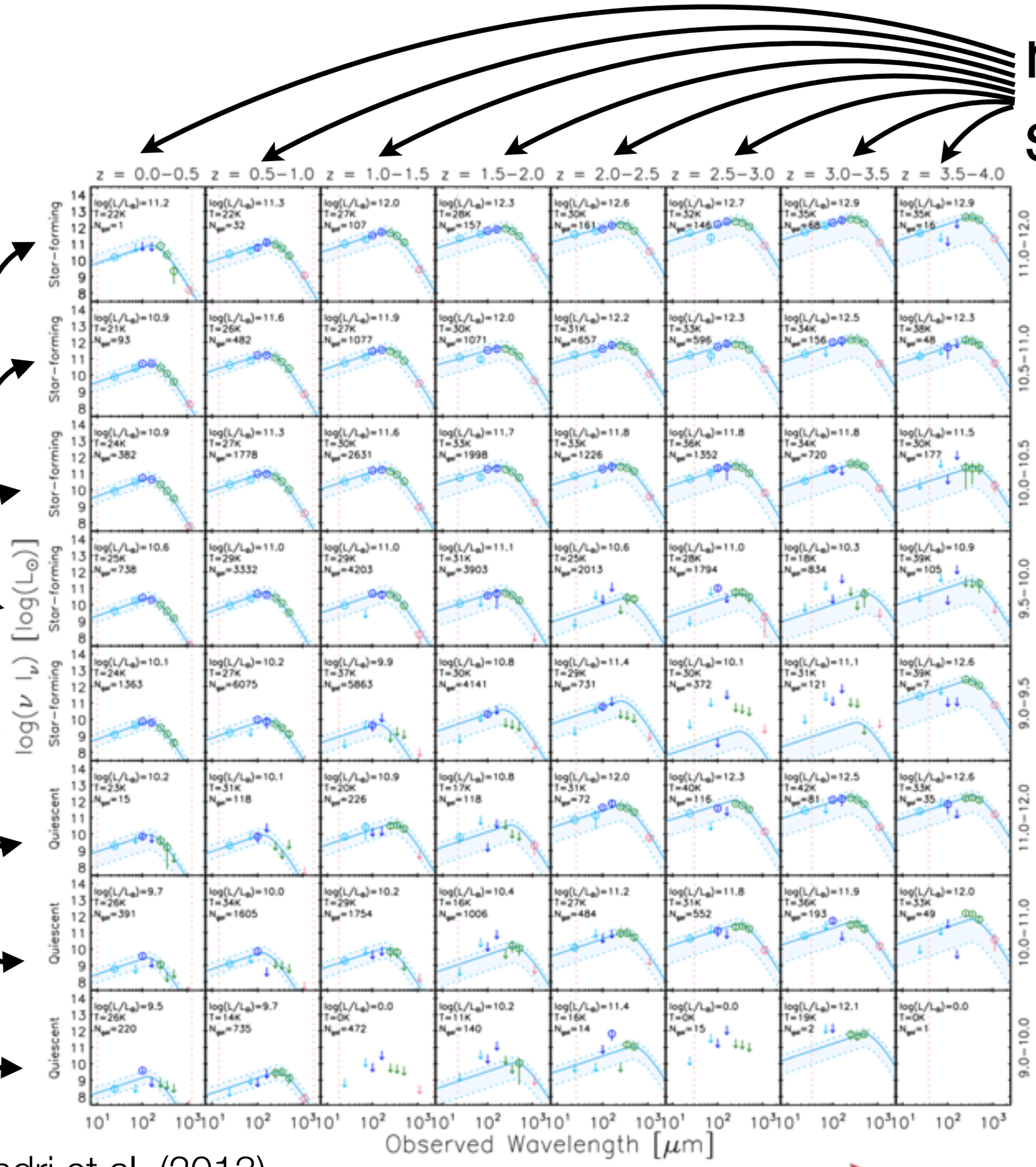

Viero, Moncelsi, Quadri+ (2013)
arXiv:1304.0446

HERMES-UDS

# SEDs

redshift slices

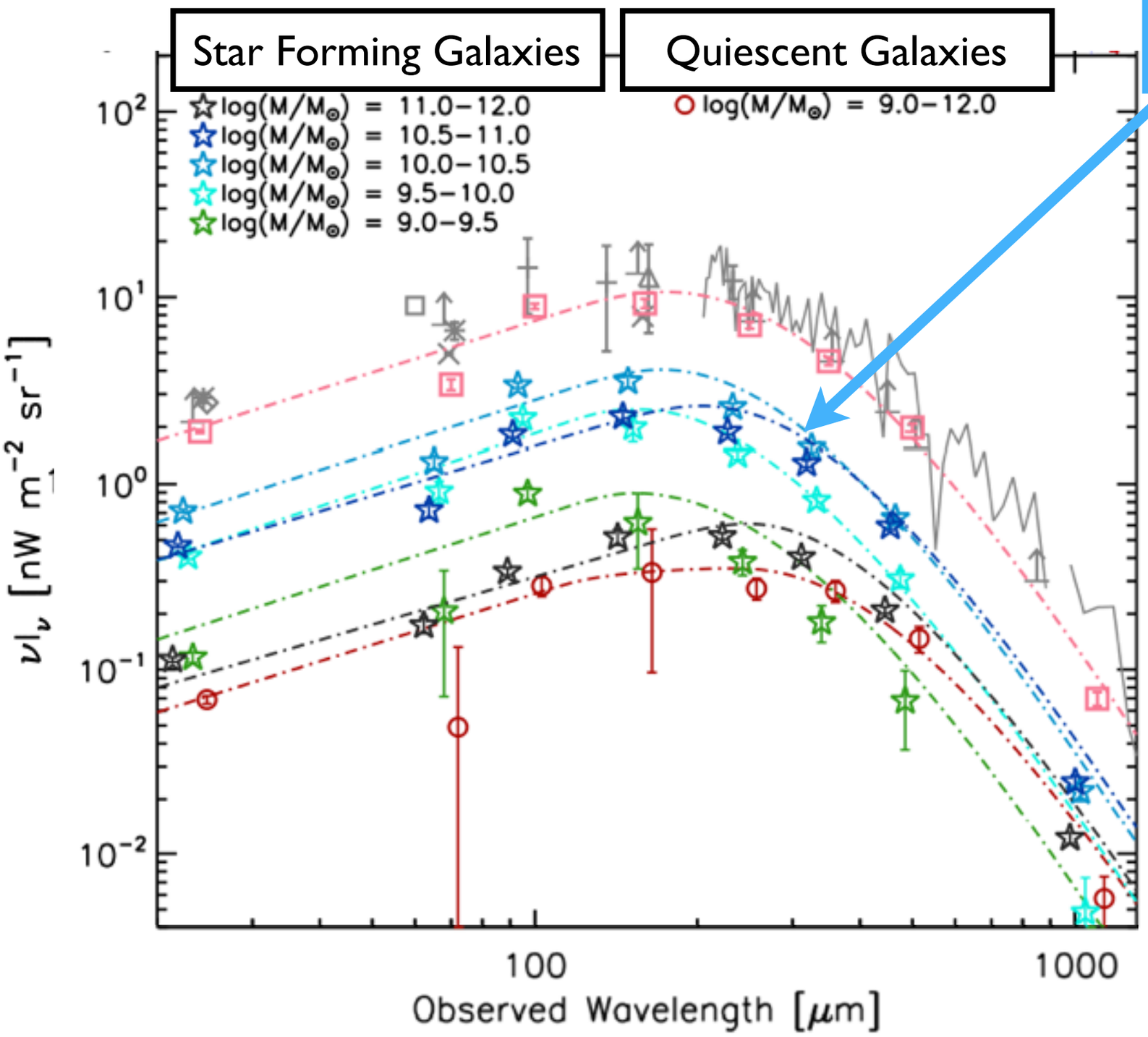
stellar mass slices




Viero, Moncelsi, Quadri et al. (2013)
arXiv:1304.0446

HERMES-UDS

# stacked CIB



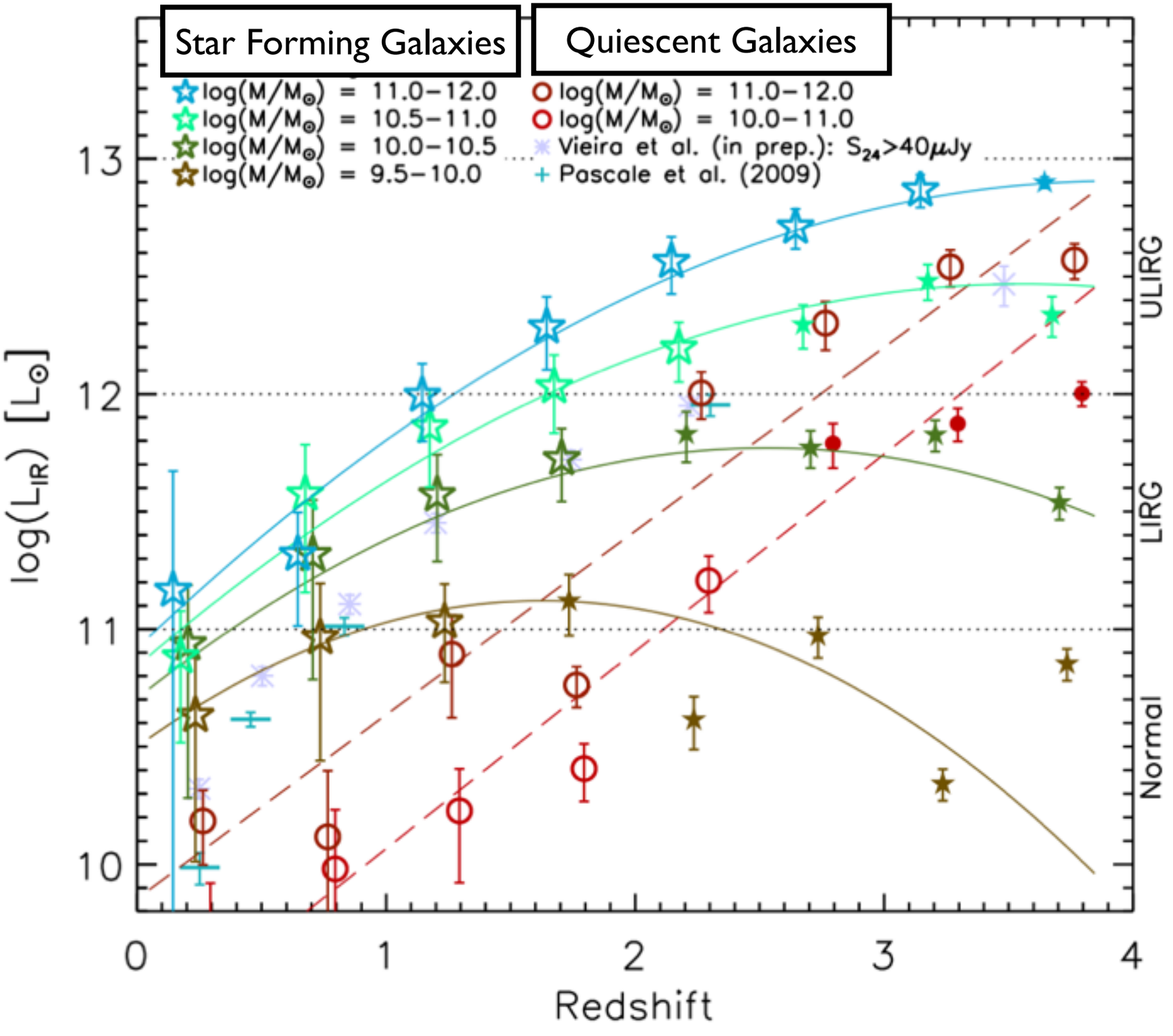

log(M/M⊙~10-11)
i.e., M ≲ M*

~80% at SPIRE wavelengths

Viero, Moncelsi, Quadri et al. (2013)
arXiv:1304.0446

HERMES-UDS

# Infrared Luminosities

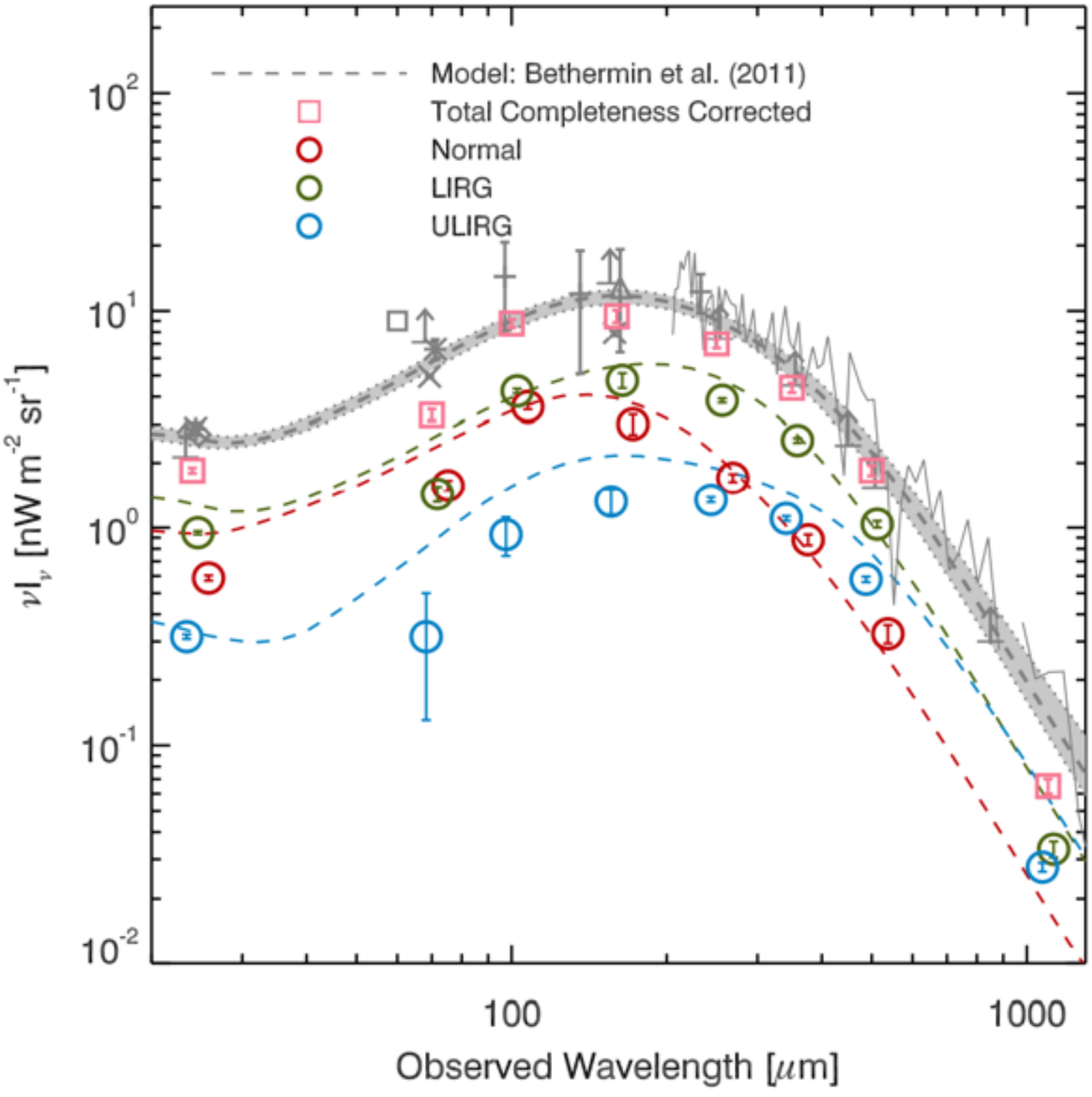



Viero, Moncelsi, Quadri et al. (2013)
arXiv:1304.0446

HERMES-UDS

# CIB by Luminosity Class

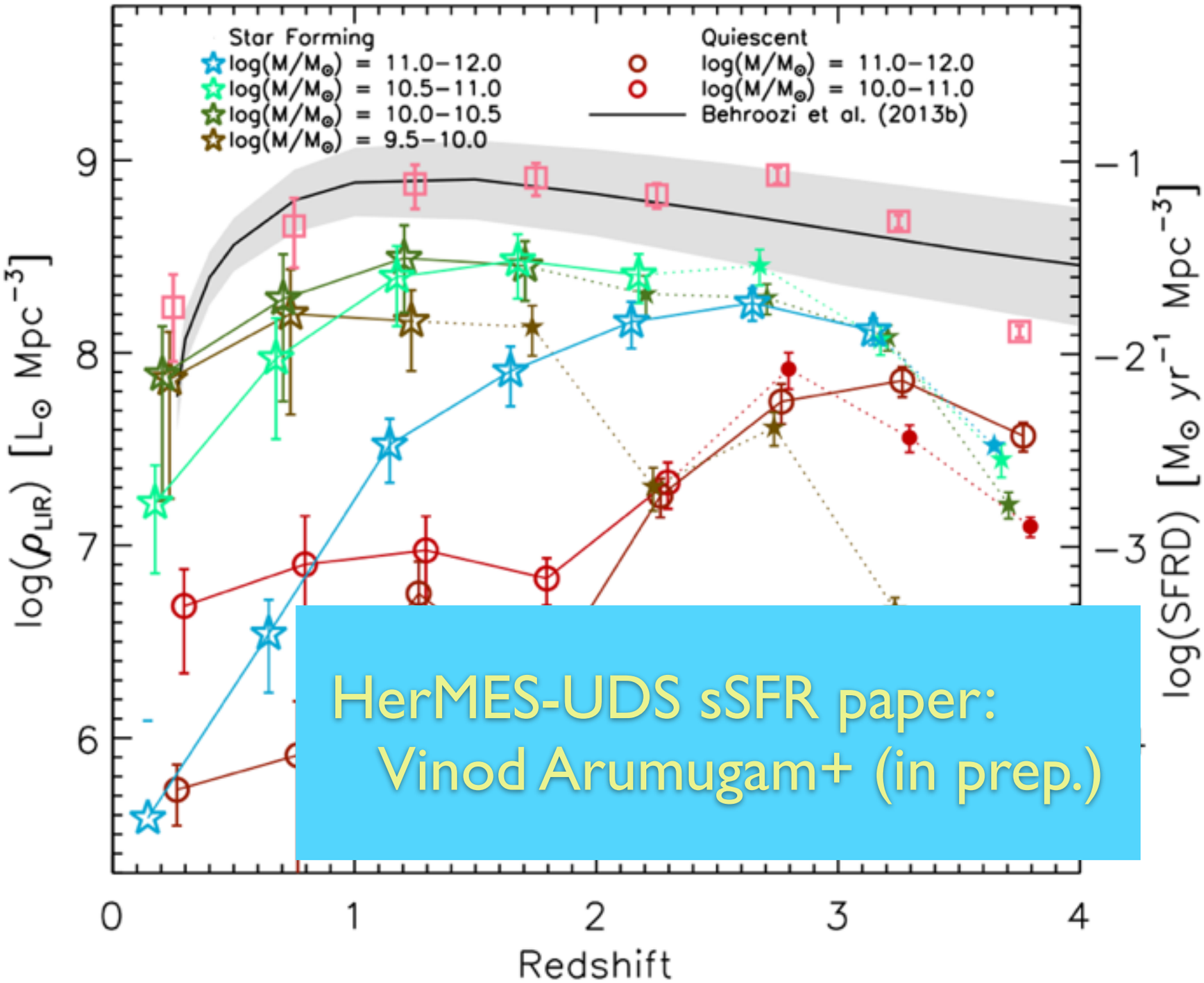
- ULIRG:
  $12 < \log(L/L_\odot) < 13$
- LIRG:
  $11 < \log(L/L_\odot) < 12$
- “Normal”:
  $\log(L/L_\odot) < 11$




Viero, Moncelsi, Quadri et al. (2013)
arXiv:1304.0446

HERMES-UDS

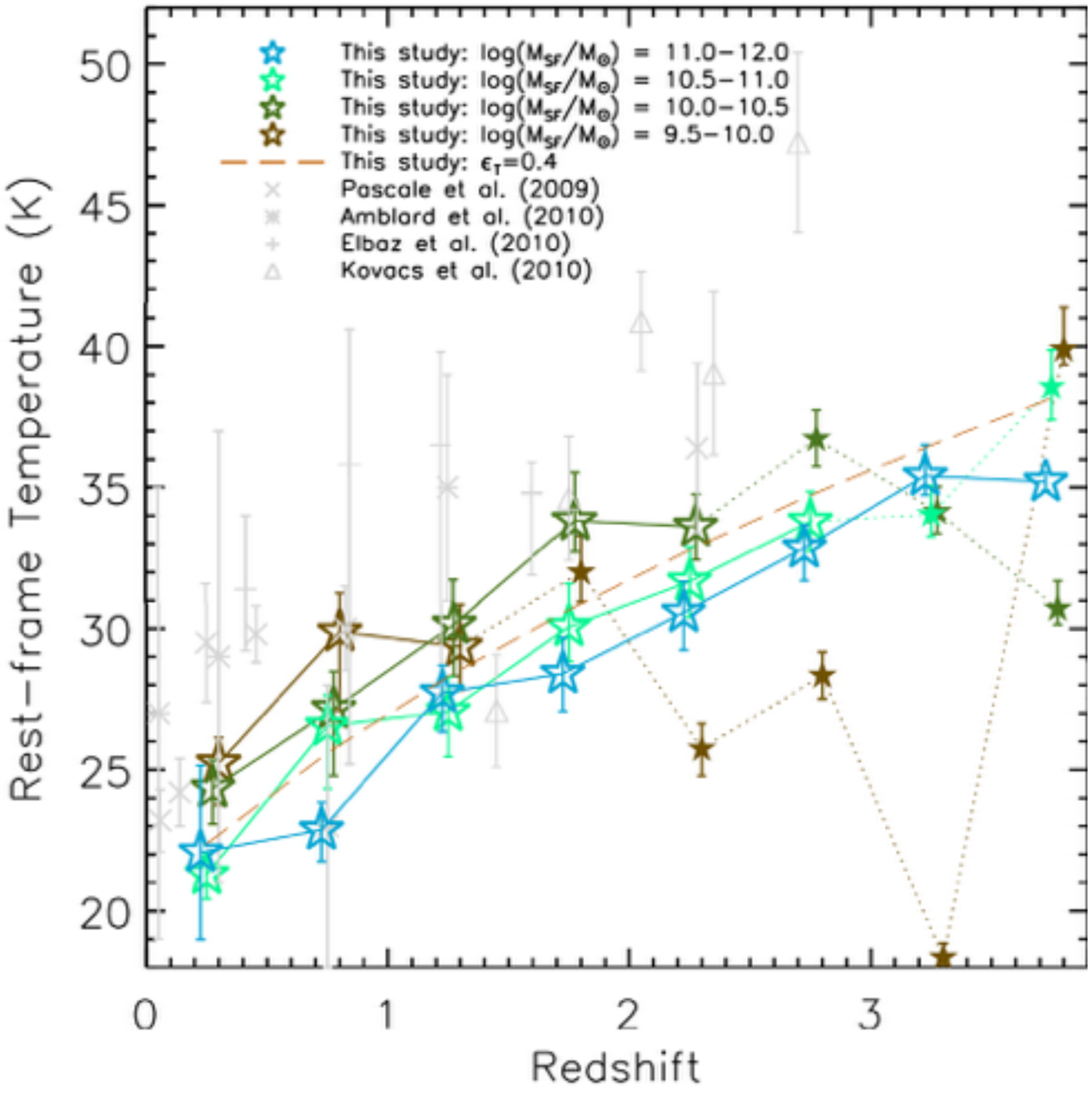
# Infrared Luminosity Density

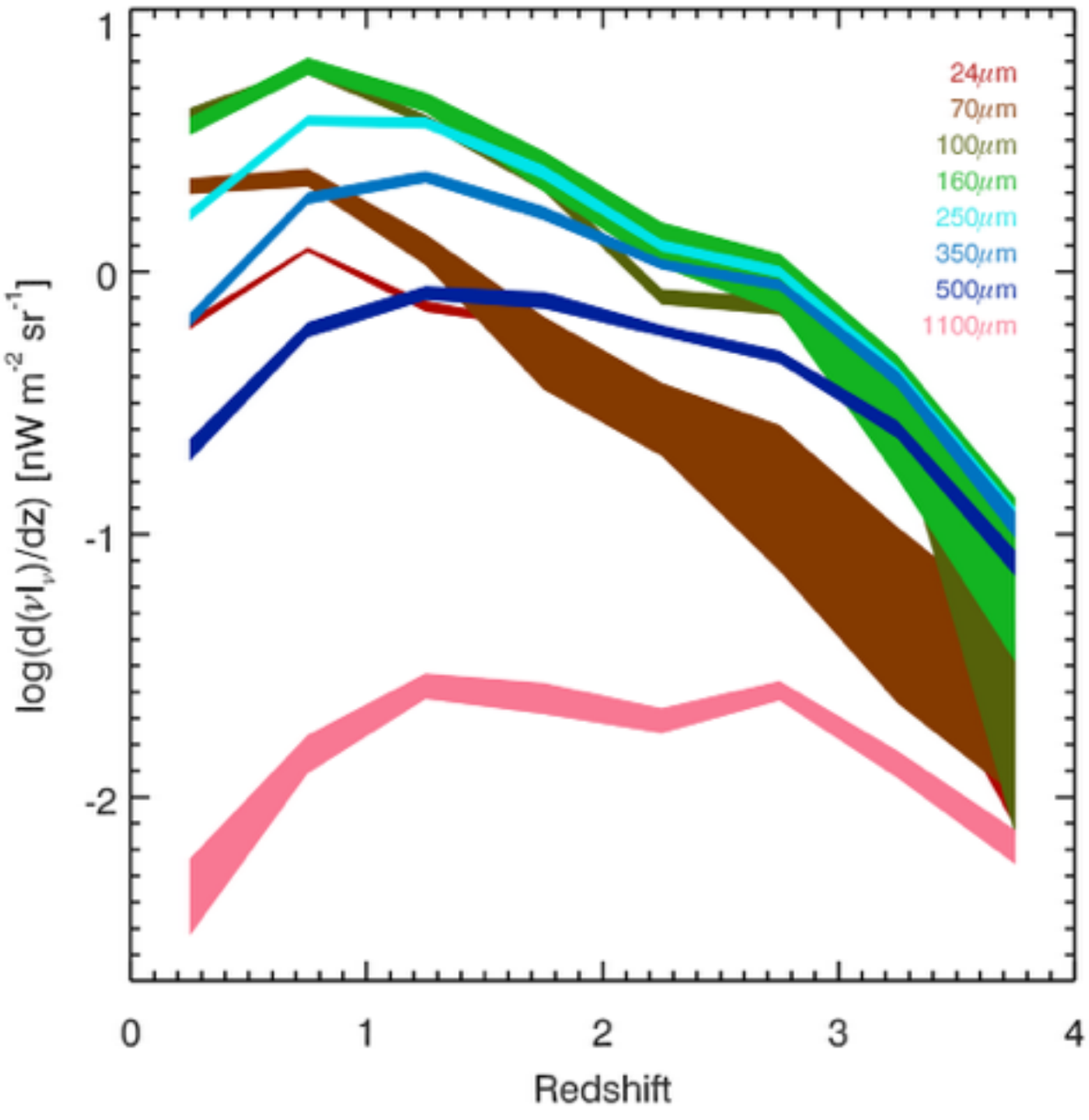



Viero, Moncelsi, Quadri et al. (2013)
arXiv:1304.0446

HERMES-UDS

# Temperature and Redshift Distribution




- Powerful Constraints for Galaxy and Halo Models

Viero, Moncelsi, Quadri et al. (2013)
arXiv:1304.0446

HERMES-UDS

# Take-away from Stacking

- mass-selected sources (optical/NIR) make up ~80% of the CIB
- Mid-mass galaxies responsible for most of the CIB
- BUT, Higher-mass galaxies make up most of the luminosity density at higher redshifts
- Puzzling signal from highest-redshift quiescent galaxies
- L-M-z relationship a strong constraint for future models

# Outline

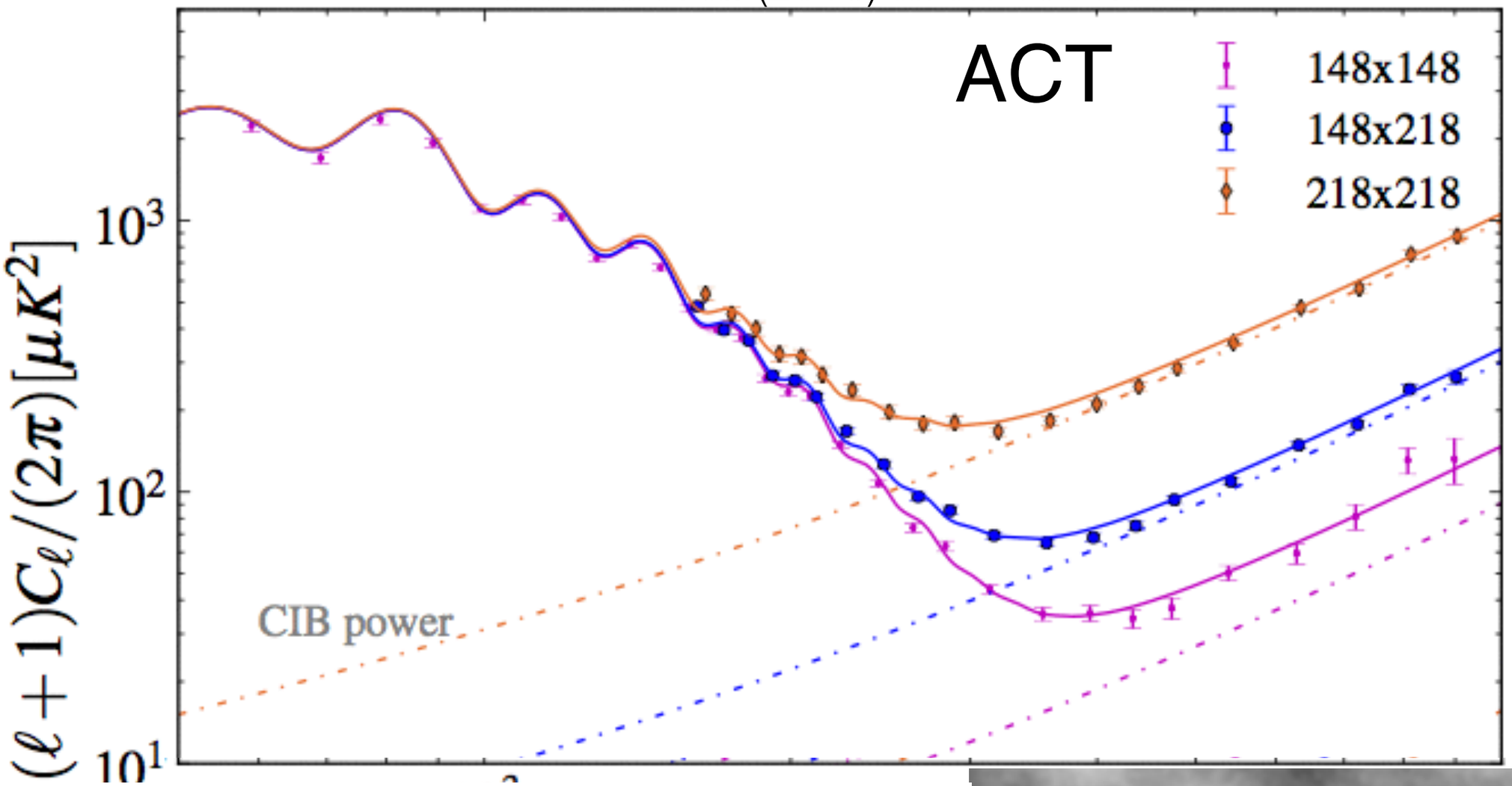
- Why the Cosmic Infrared Background (CIB)?
- Auto and cross-correlations of CIB as a tool to:
  - determine the host-halos of dusty star-forming galaxies through their clustering properties
  - determine the COB-CIB connection
  - cosmological applications
- The Future in Surveys

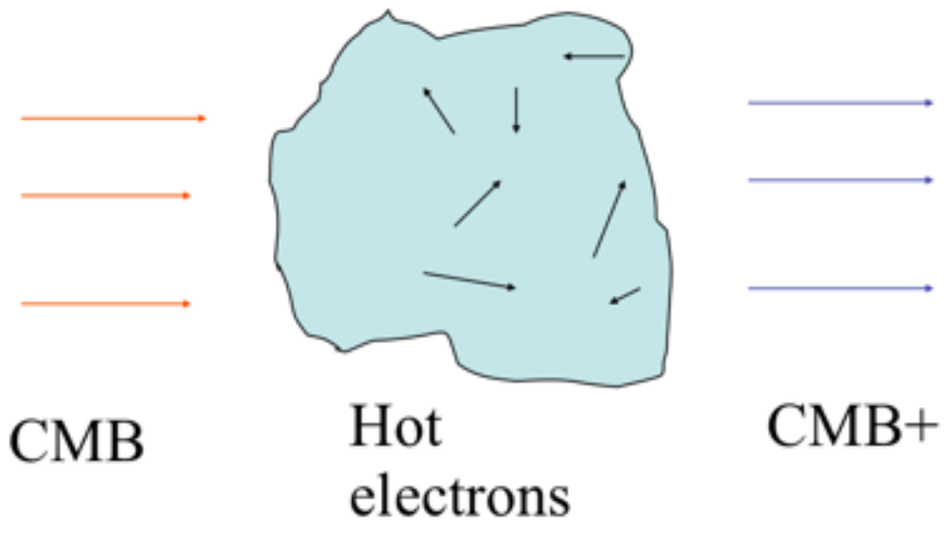
Dusty Galaxies a significant contaminant at 150 and 220 GHz

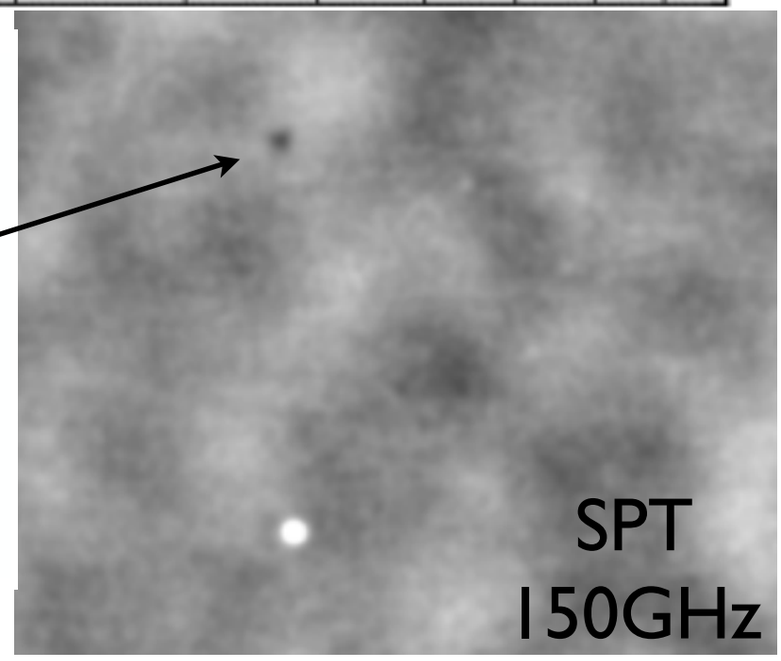
SZ effect distortion of CMB by Compton scattering in massive clusters

kSZ a probe of duration of reionization

Sievers et al. (2013) arXiv: 1301.0824



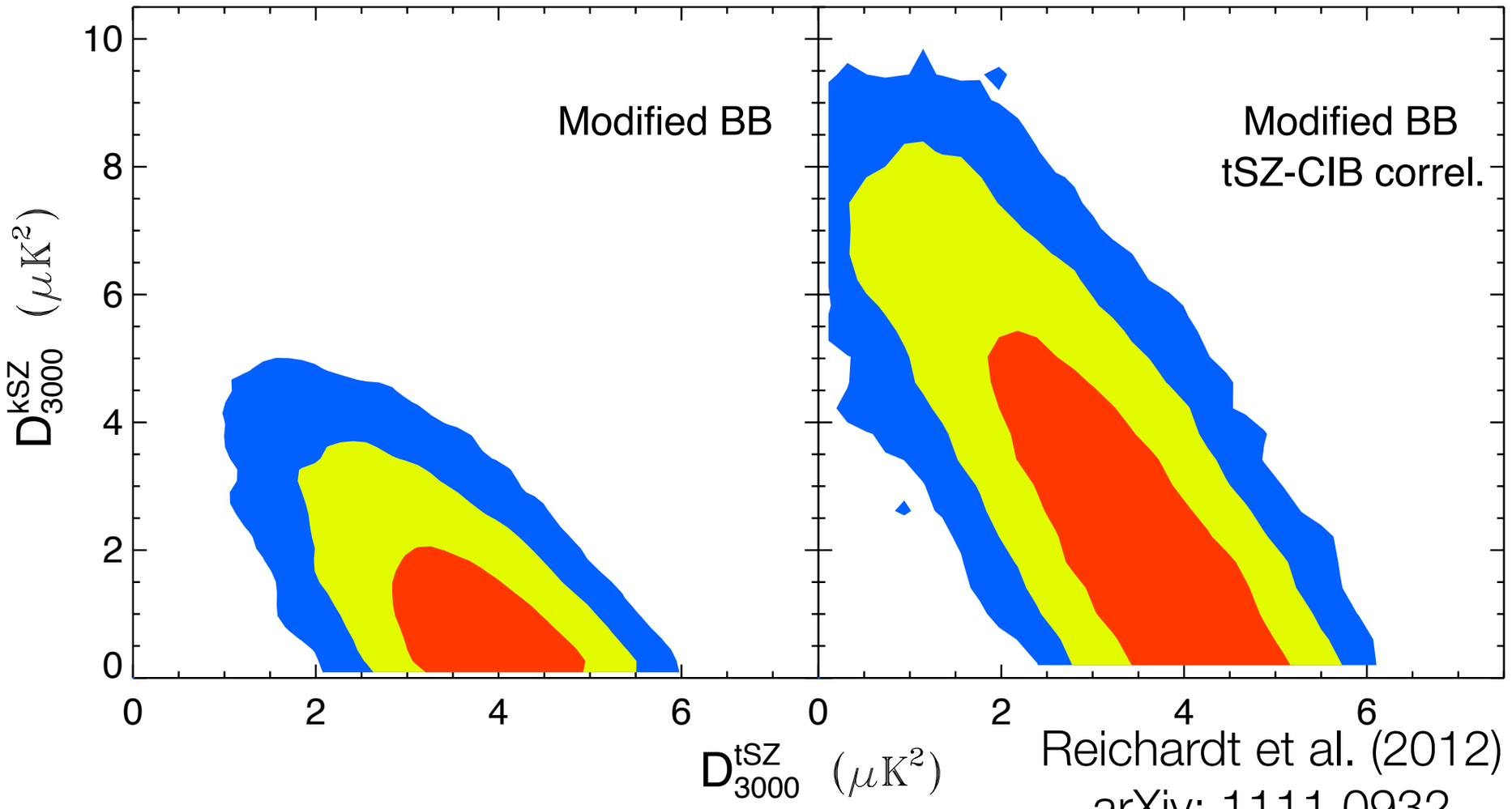



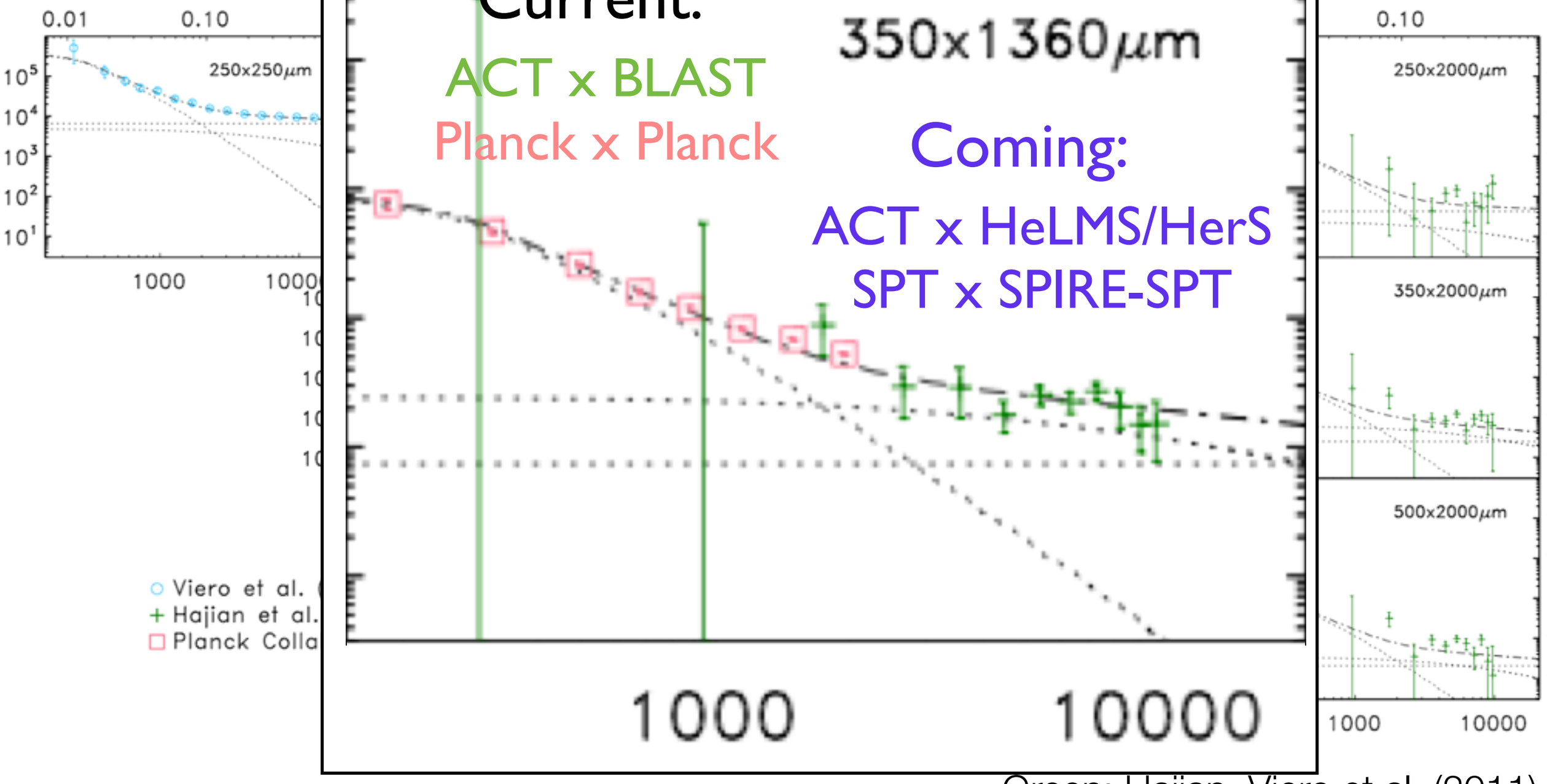

# CIB as CMB Foreground

# thermal SZ-CIB correlation?

- uncertain degree of tSZ and CIB correlation makes it very hard to separate components




Reichardt et al. (2012)
arXiv: 1111.0932

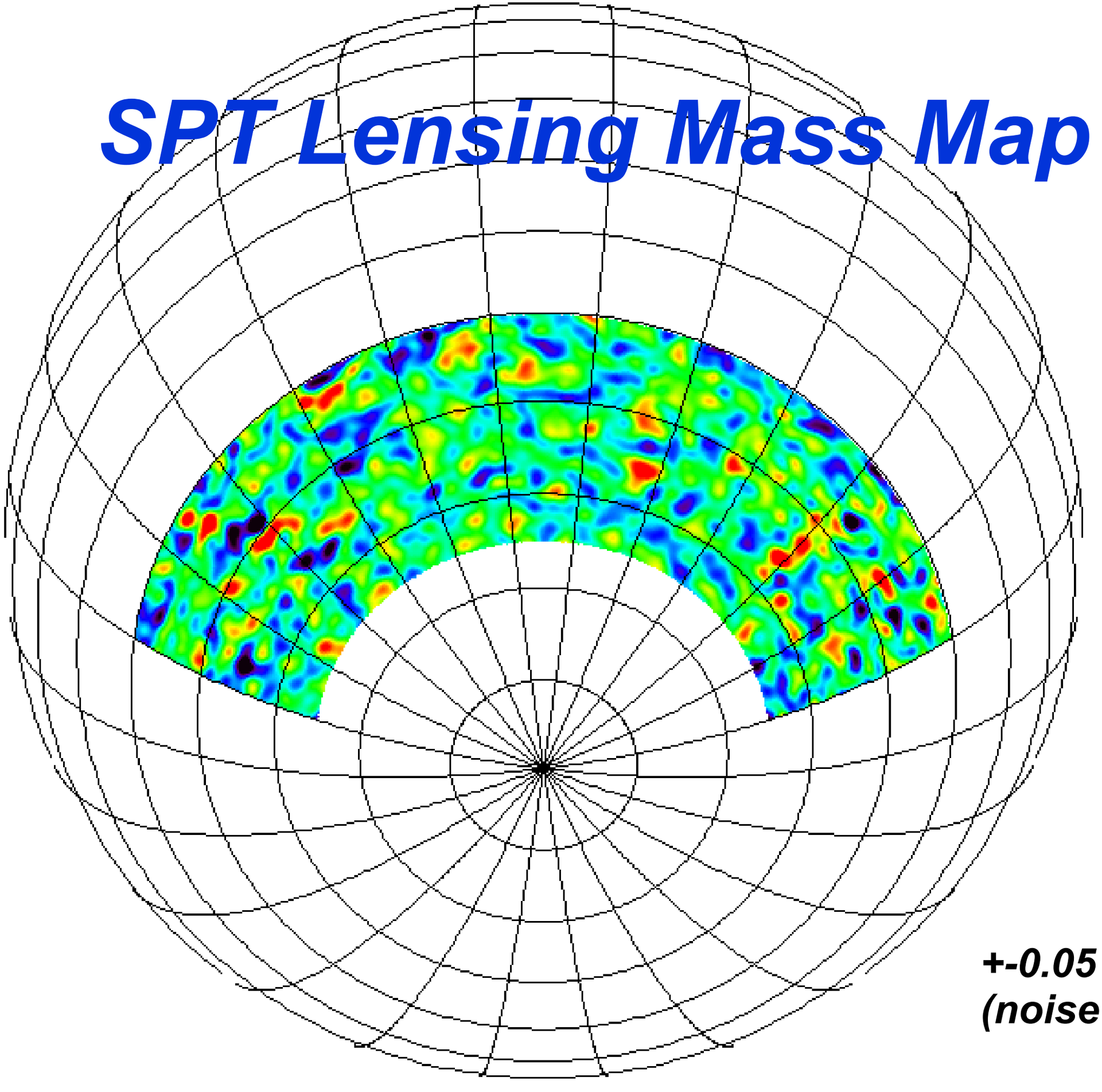



Green: Hajian, Viero et al. (2011)
Blue: Viero et al. (2013)
Red: Planck Collaboration (2013)

# Cross-Correlating CIB and CMB

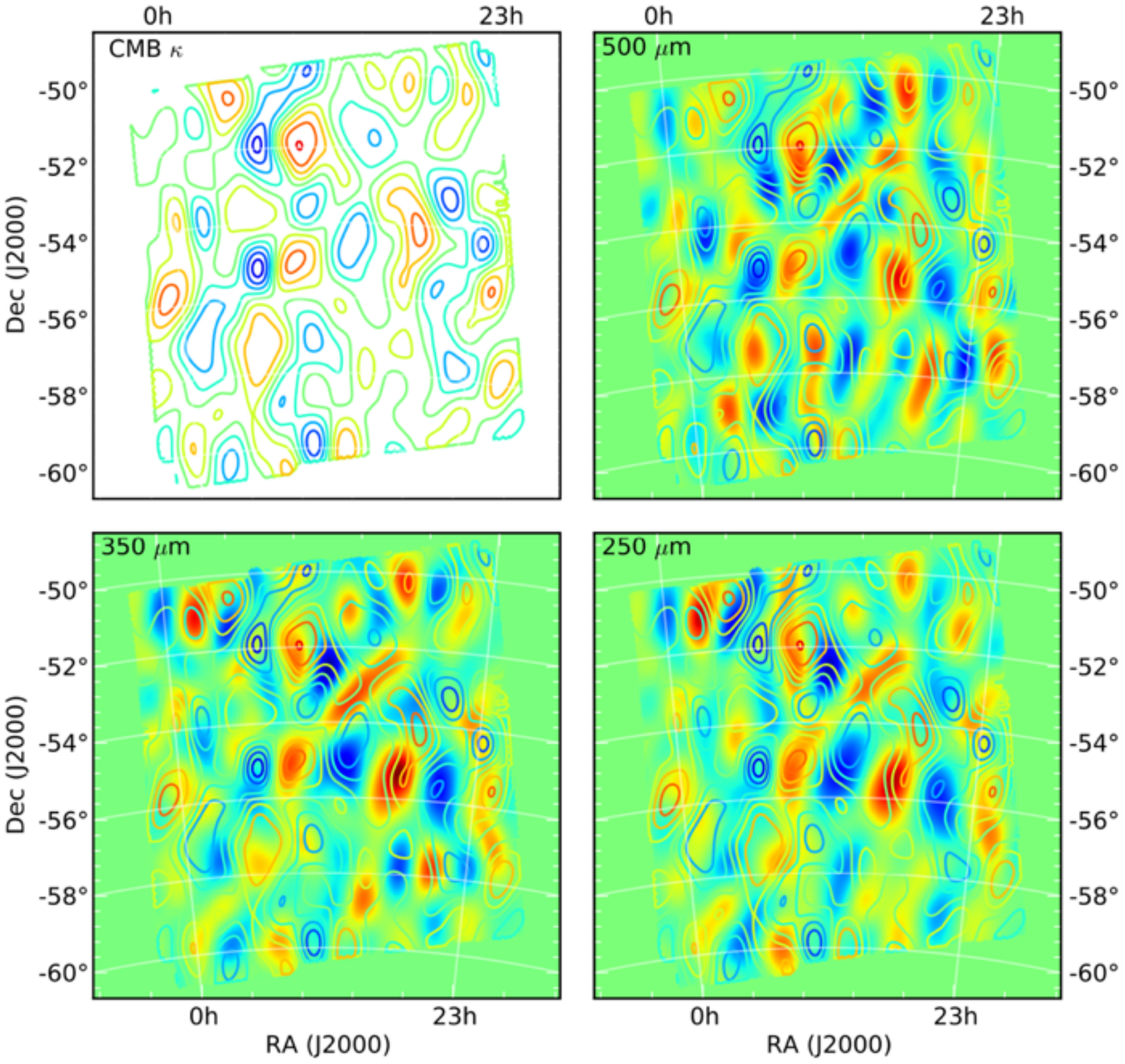
# Cross-Correlations with CMB Lensing

# SPT Lensing Mass Map



*+-0.05 color bar*
*(noise ~0.01)*

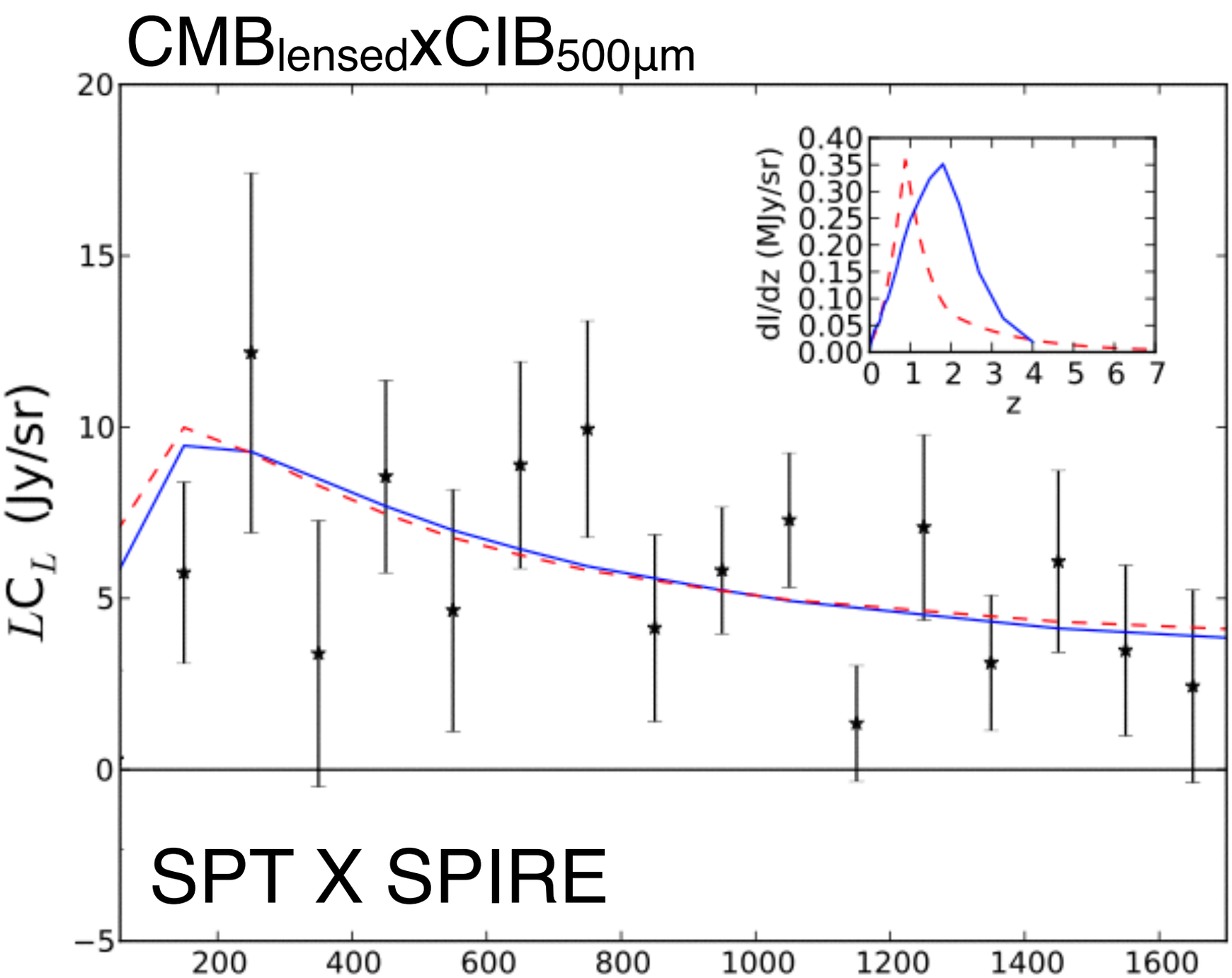
# SPT X SPIRE




# Lensed CMB x CIB

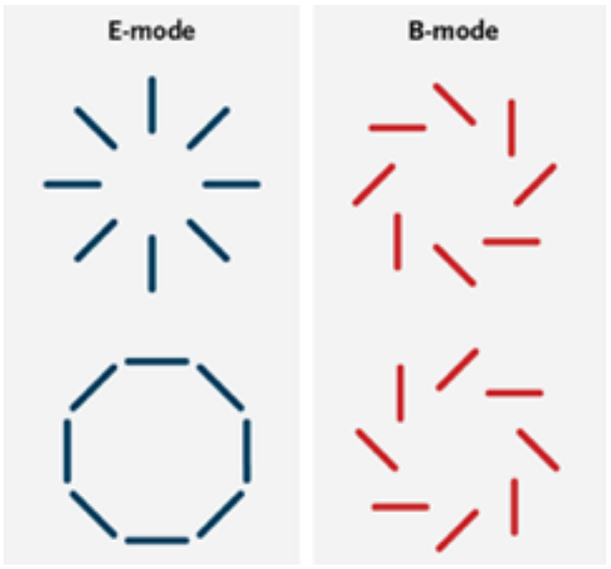
Holder, Viero, Zahn et al. (2013)
arXiv:1304.0446

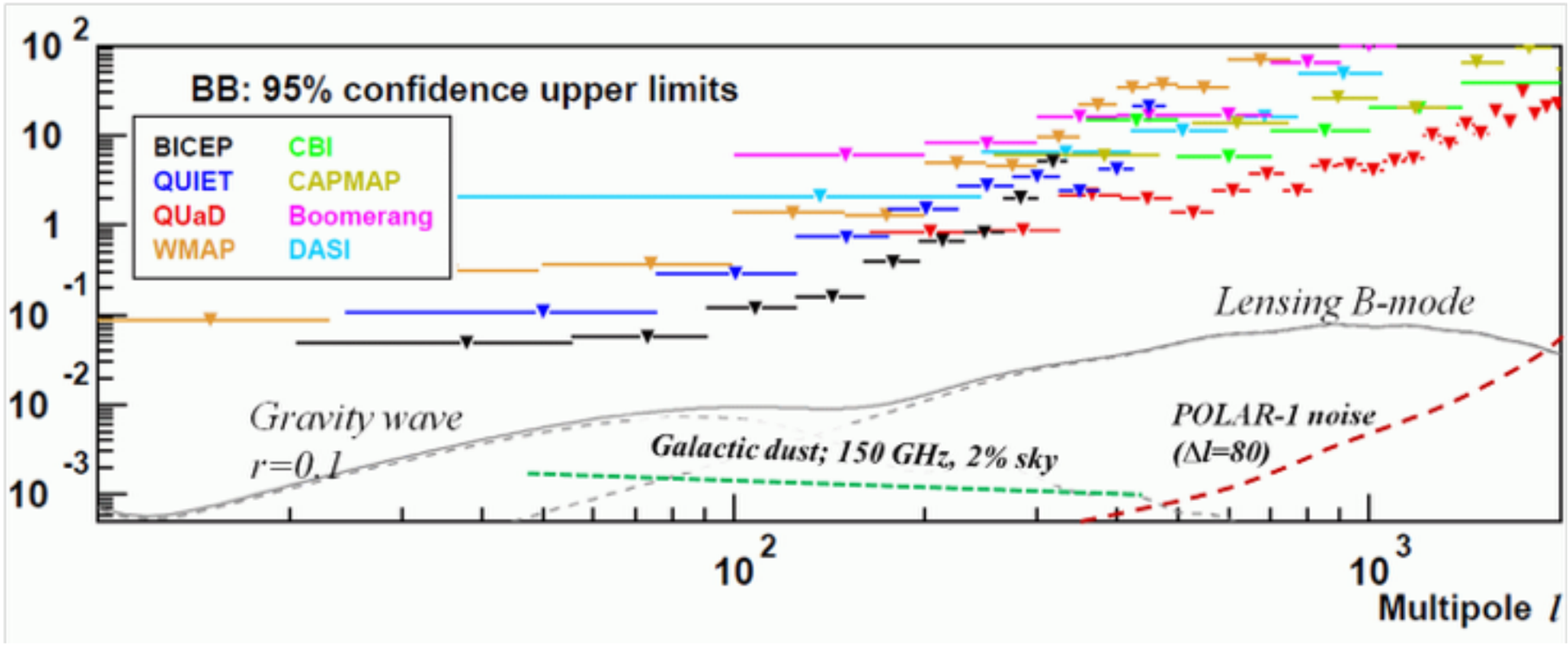
- 6.7-8.8σ detection (Planck 42σ!)
- bias = 1.3-1.8, strongly model dependent



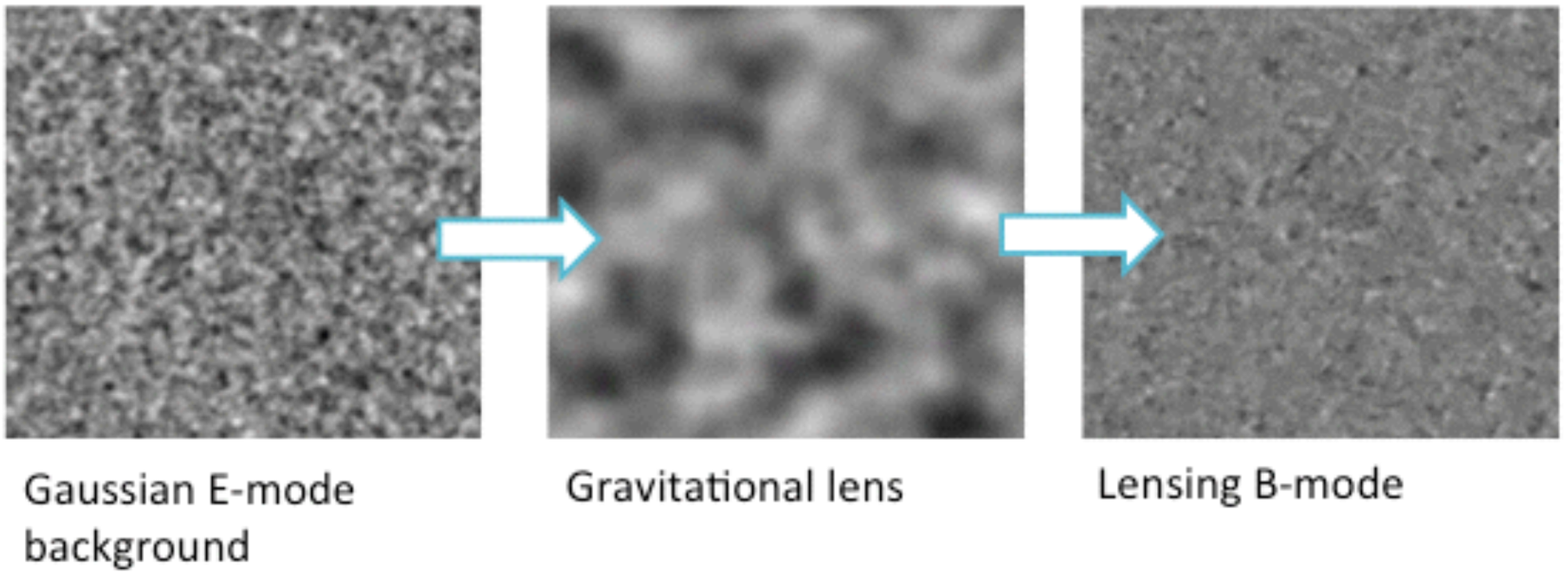

Holder, Viero, Zahn et al. (2013) arXiv:1304.0446

# Measuring the CIB bias

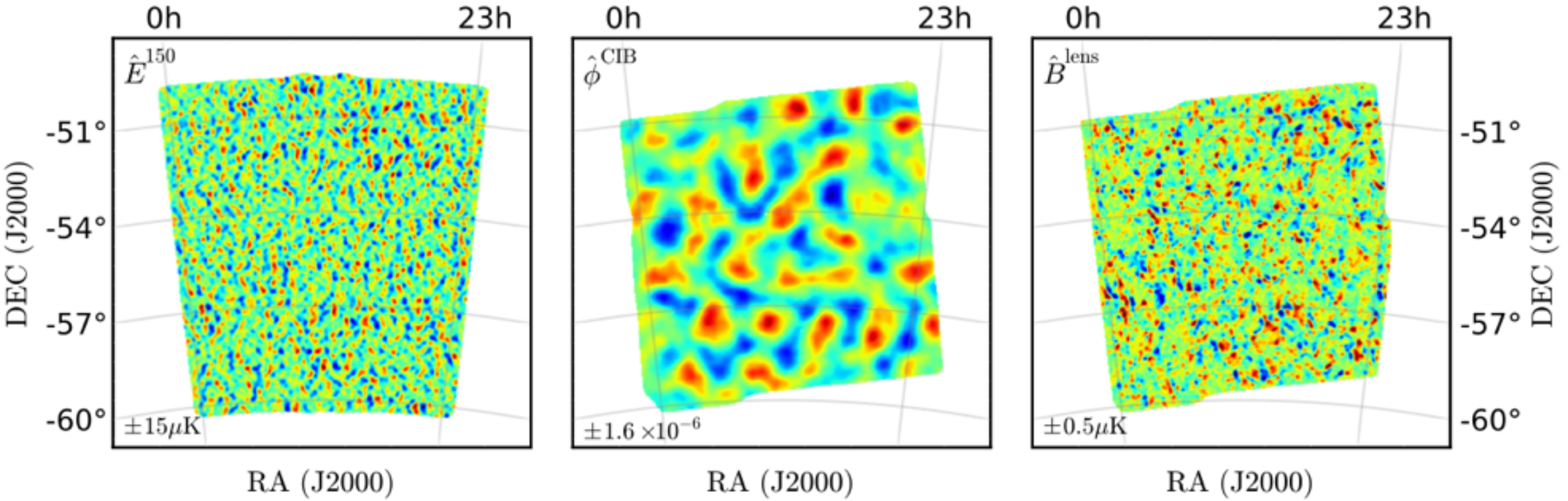


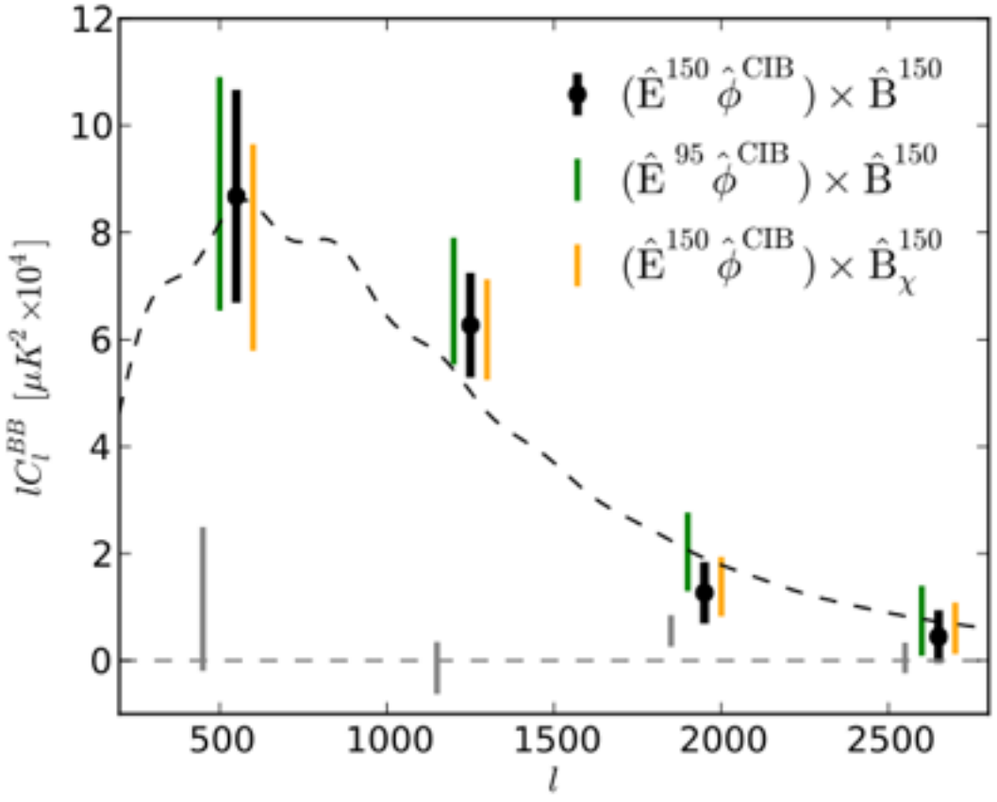

- Lensing mixes E-modes into B-modes




# CMB Lensing B-modes




- 7.7σ detection of B-mode signal




# CMB Lensing B-modes

# Outline

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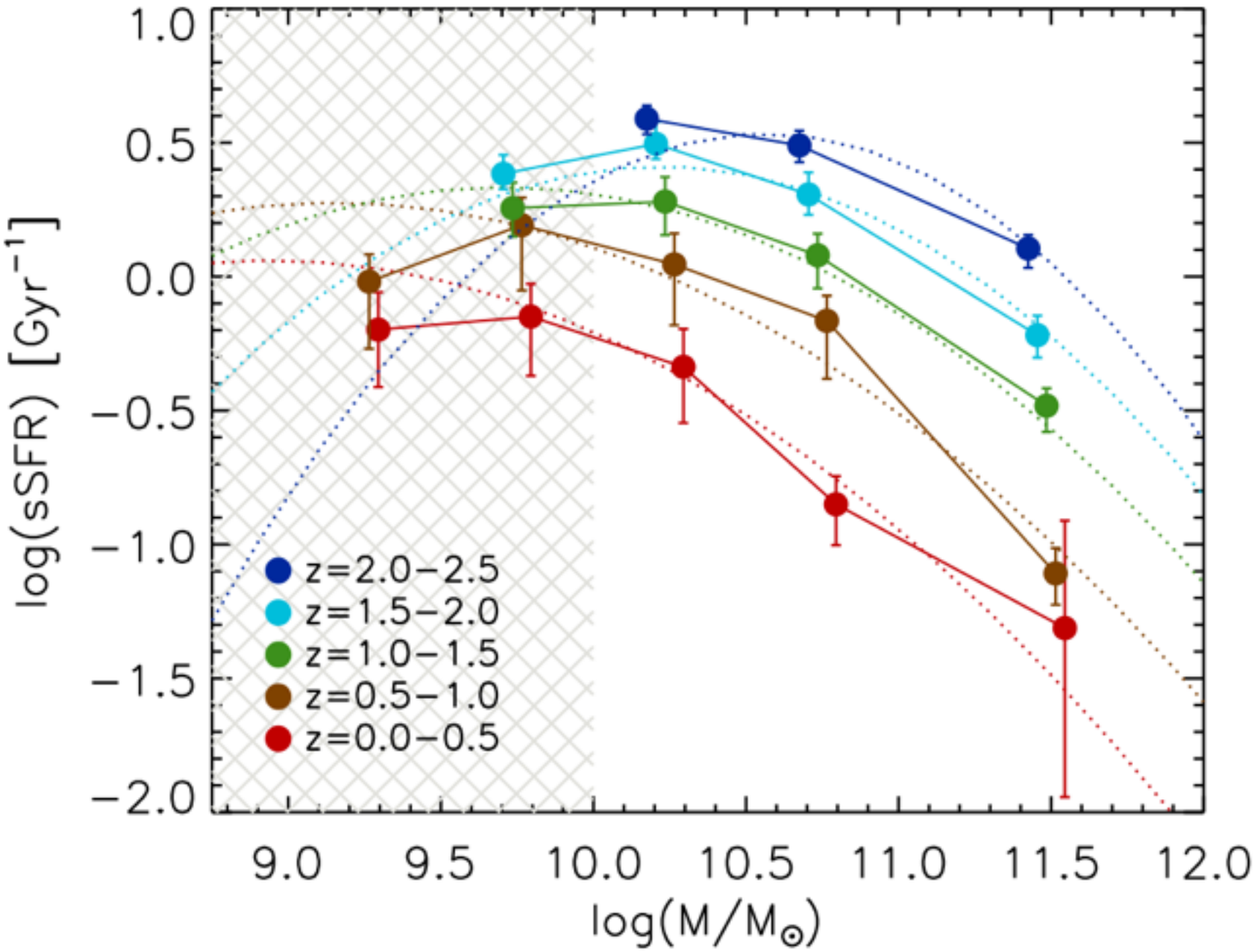
- Auto and cross-correlations of CIB as a tool to:
  - determine the host-halos of dusty star-forming galaxies through their clustering properties
  - determine the COB-CIB connection
  - cosmological applications
- The Future in Surveys

# Moving Forward

Galaxy Evolution models critically fail to match low mass galaxies at intermediate redshifts (e.g., Guo+ 2011, Weinmann+ 2011,2012)

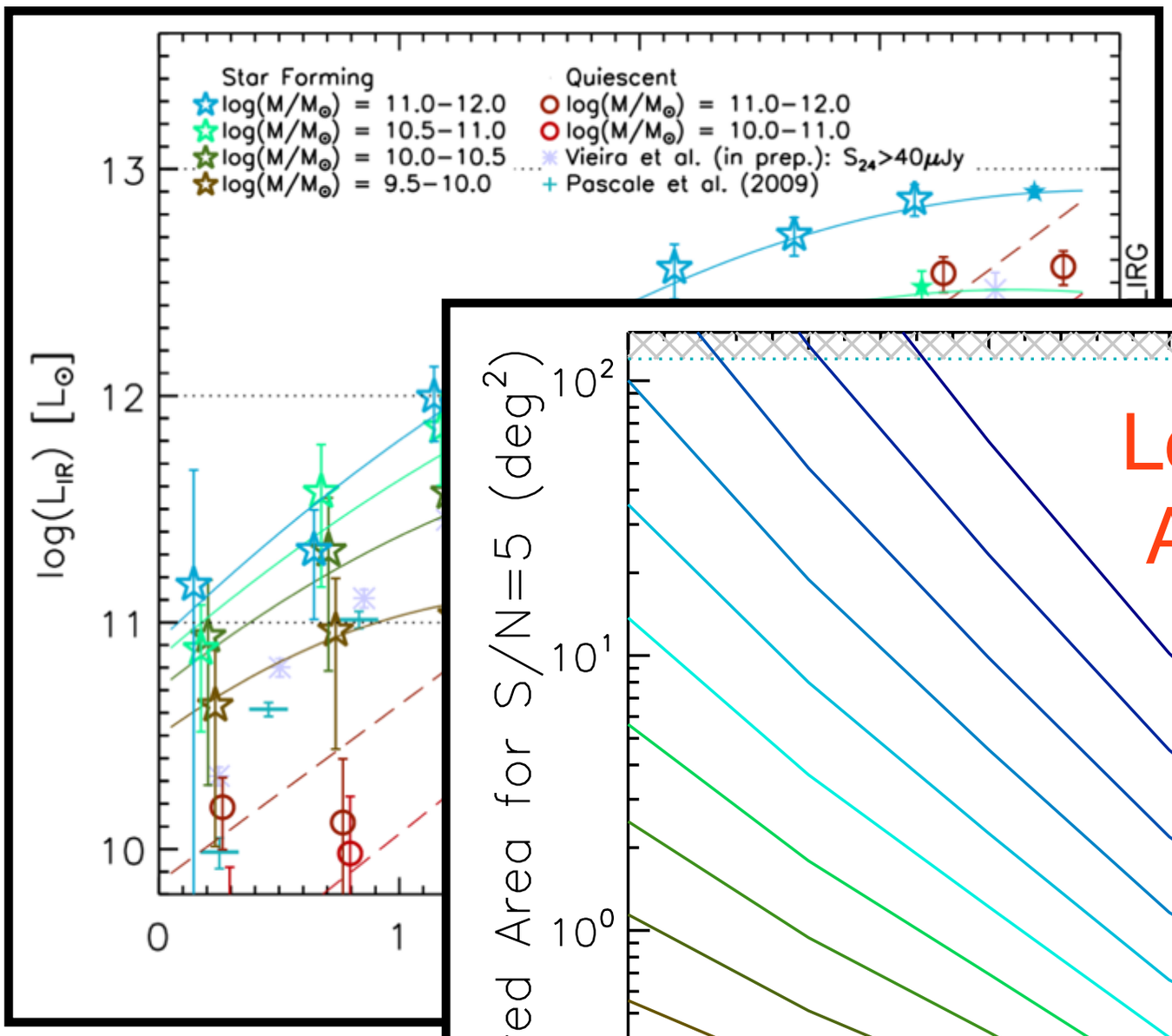
They require accurate LIRs/ SFRs for this faint population, and that of their progenitors



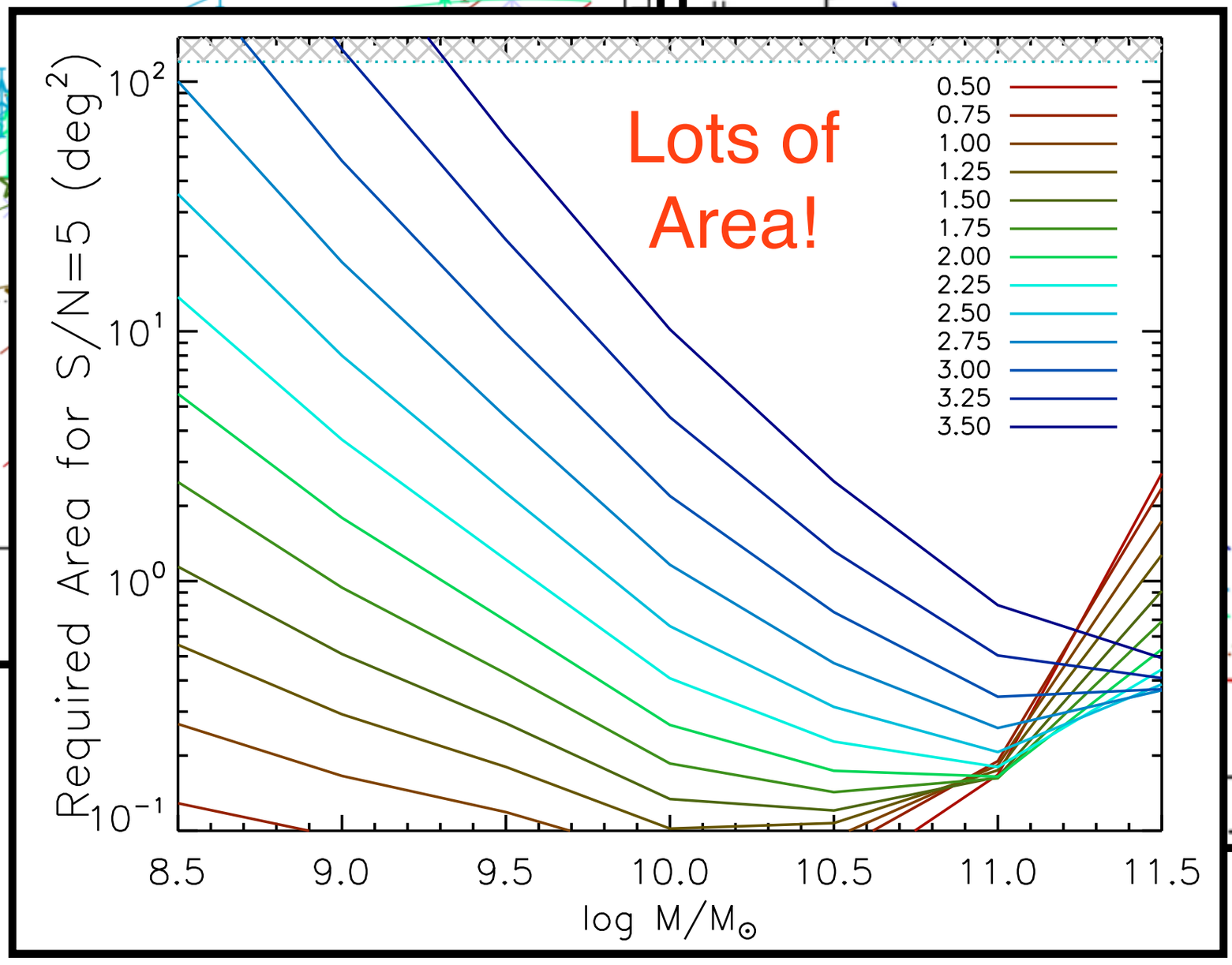

Arumugam, Viero, Quadri et al. (in prep.)

# Moving Forward

Lots of sources to probe small masses




L-M*-z







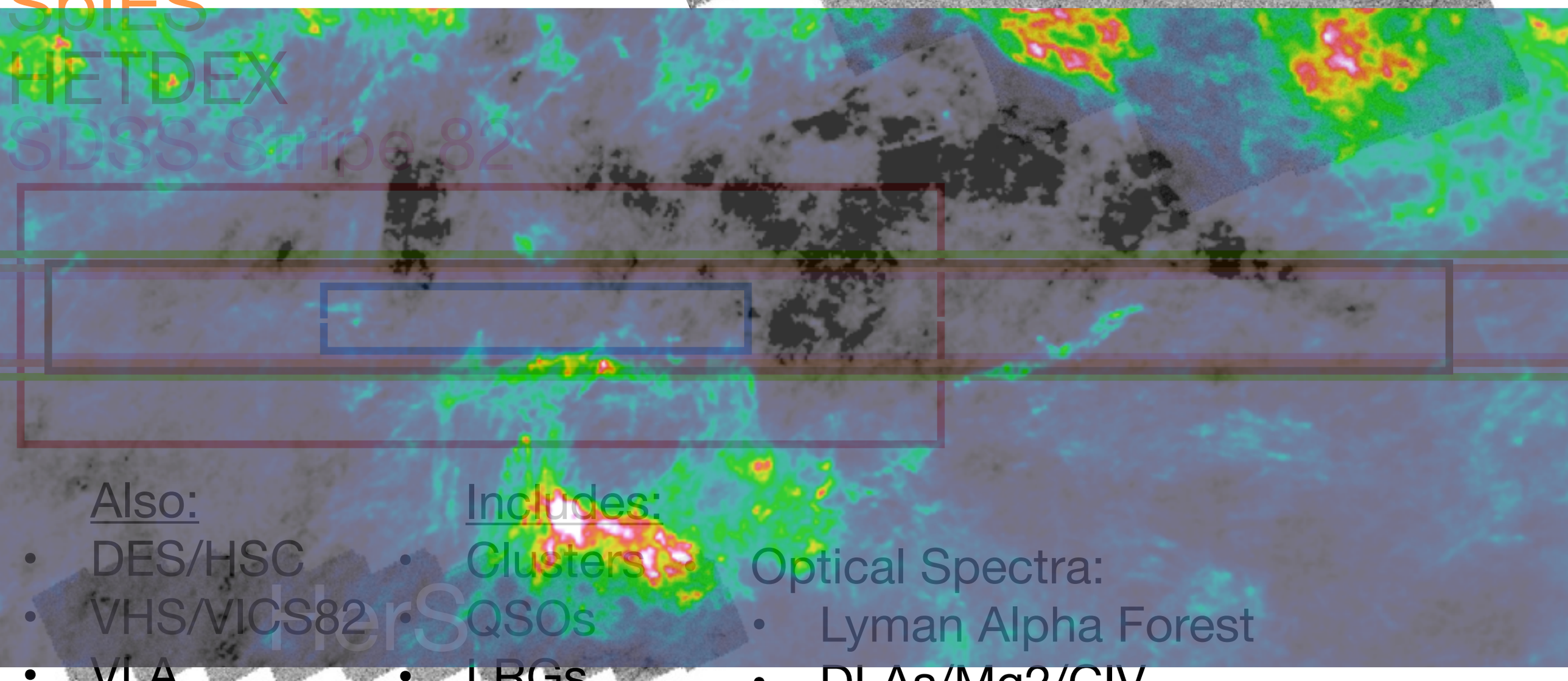
estimated using mass function of Muzzin et al. 2013

Viero+ 2013, Herschel Stripe 82 Survey; arXiv:1308.4399

Find Maps/Catalogs at: http://www.astro.caltech.edu/hers

ACT
SHELA
SpIES
HETDEX
SDSS Stripe 82

HeLMS



HerS

Also:
- DES/HSC
- VHS/VICS82
- VLA
- Wiggle-z
- LSST

Includes:
- Clusters
- QSOs
- LRGs
- maxBCGs
- HI

Optical Spectra:
- Lyman Alpha Forest
- DLAs/Mg2/CIV

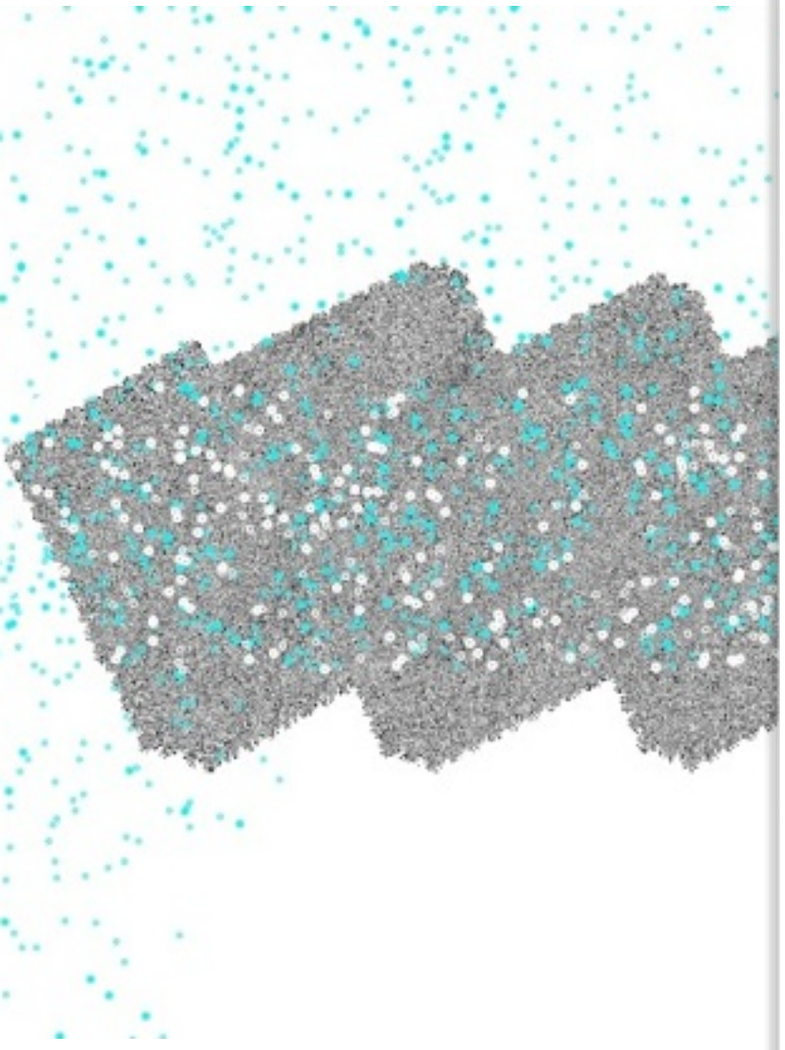
Viero+ 2013, Herschel Stripe 82 Survey; arXiv:1308.4399

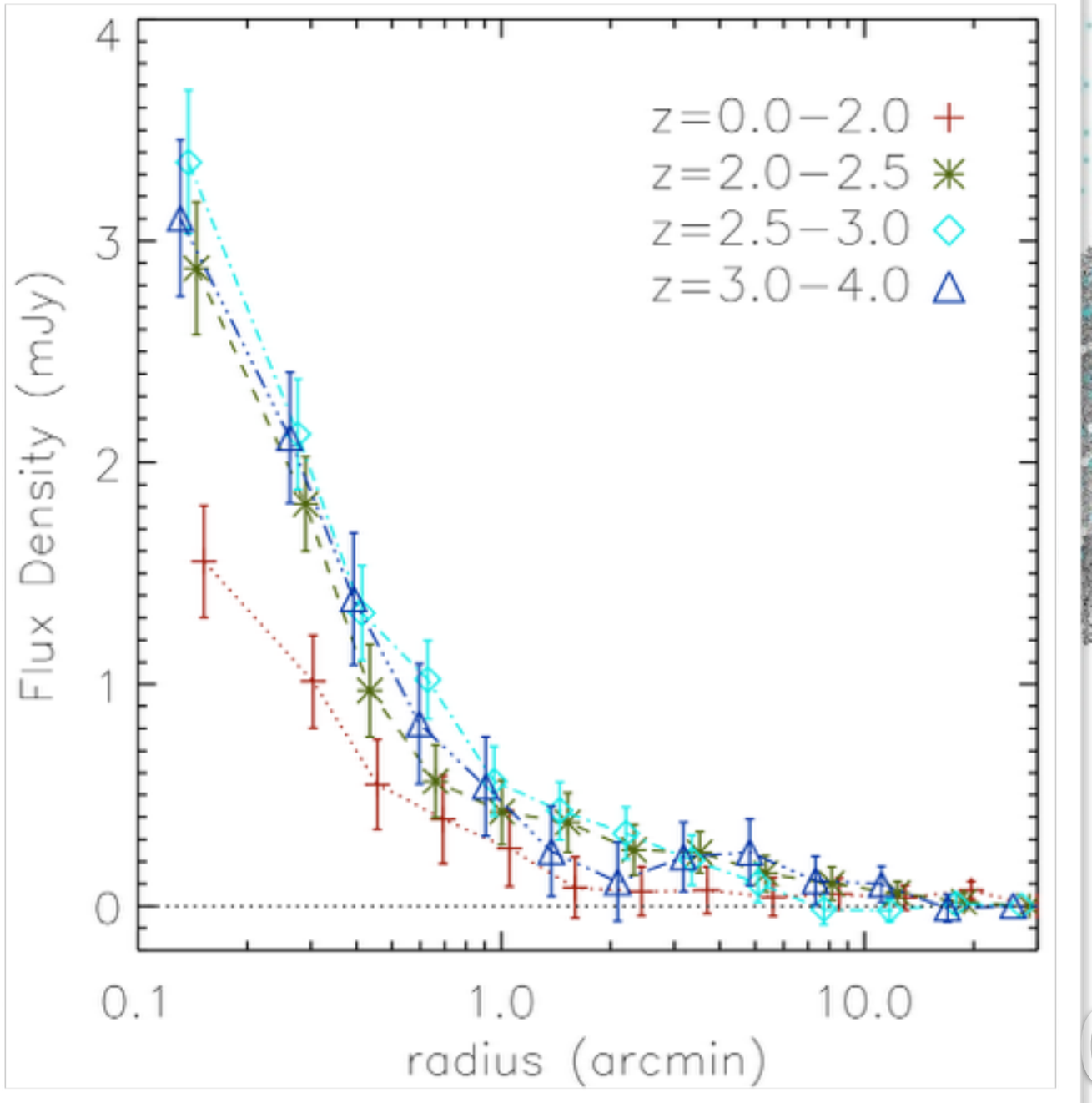
Find Maps/Catalogs at: http://www.astro.caltech.edu/hers

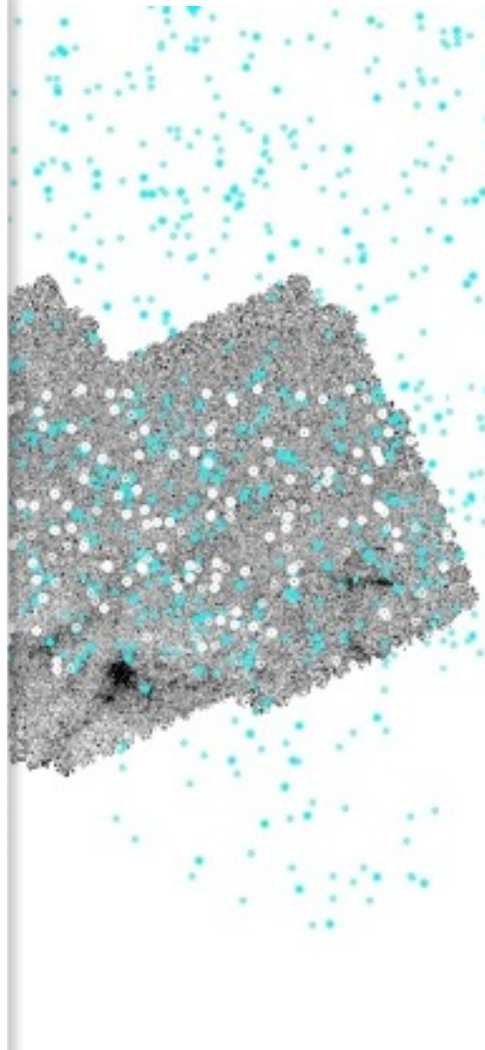

Marco Viero - Risa Wechsler - Rik Williams - Mike Zemcov

Viero+ 2013, Herschel Stripe 82 Survey; arXiv:1308.4399

Find Maps/Catalogs at: http://www.astro.caltech.edu/hers





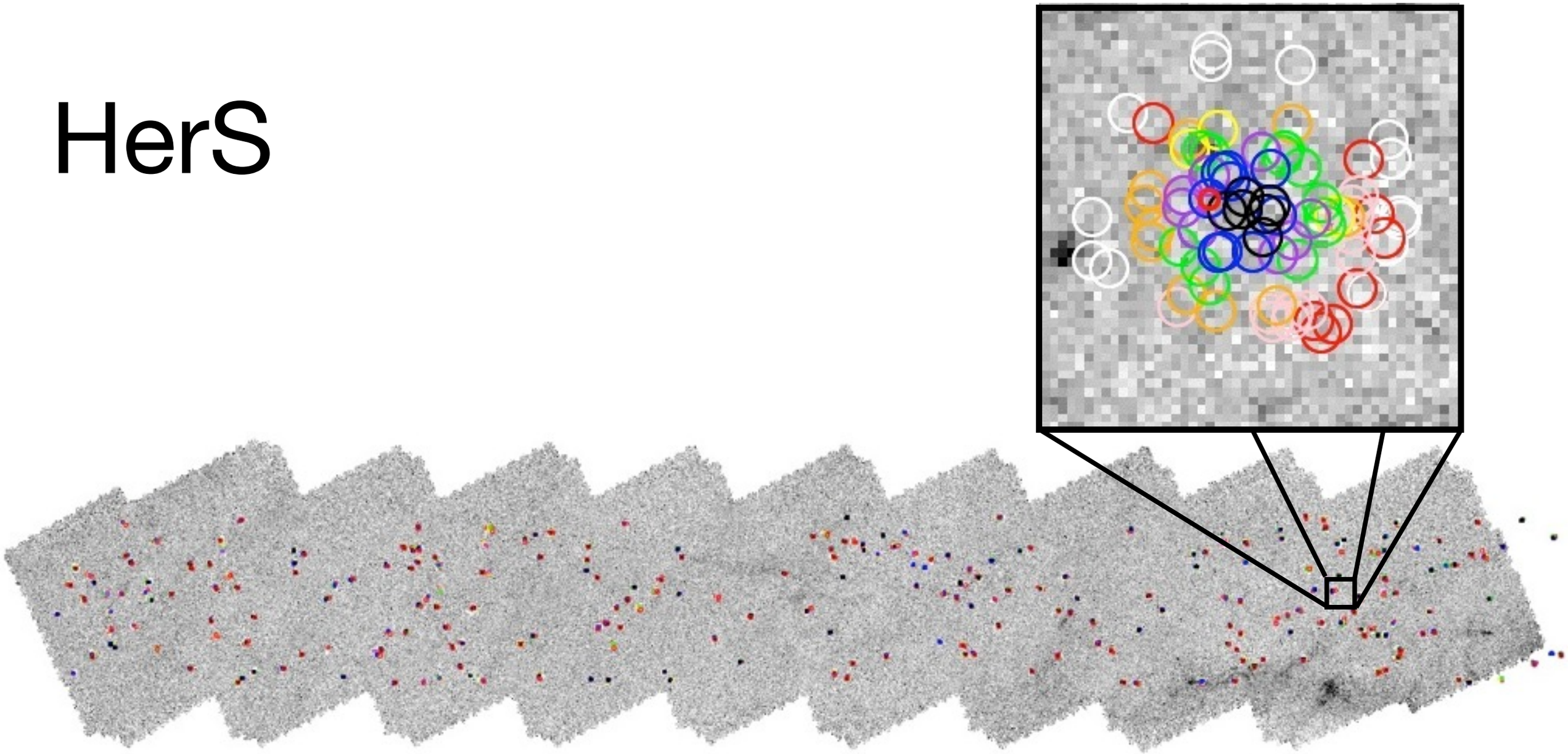



HerS

- C… 012)
- BOSS quasars

Wang, Viero et al. (2013)
arXiv:1304.0446

# HerS

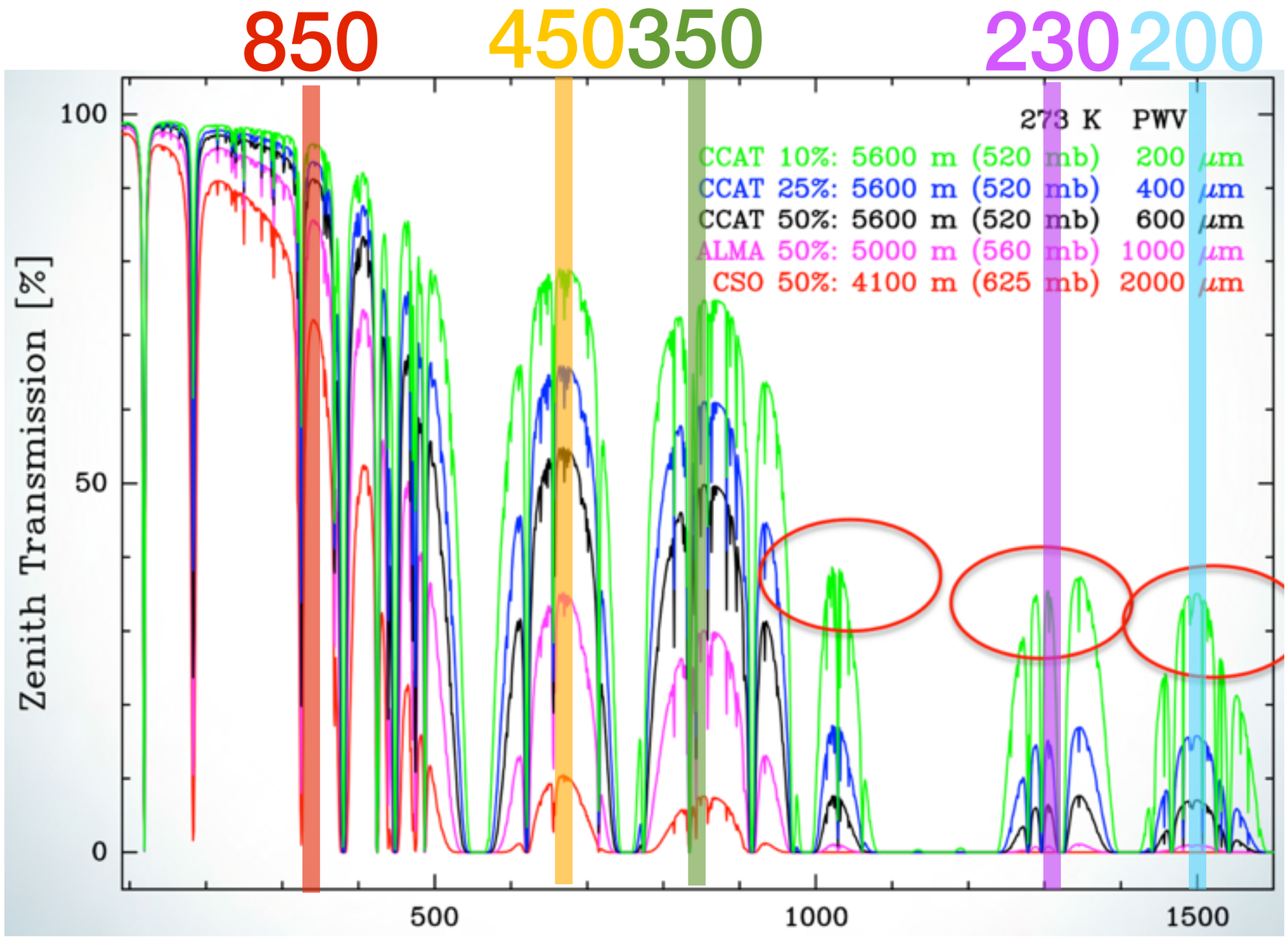


- Cluster Members

Viero+ 2013, Herschel Stripe 82 Survey; arXiv:1308.4399

Find Maps/Catalogs at: http://www.astro.caltech.edu/hers

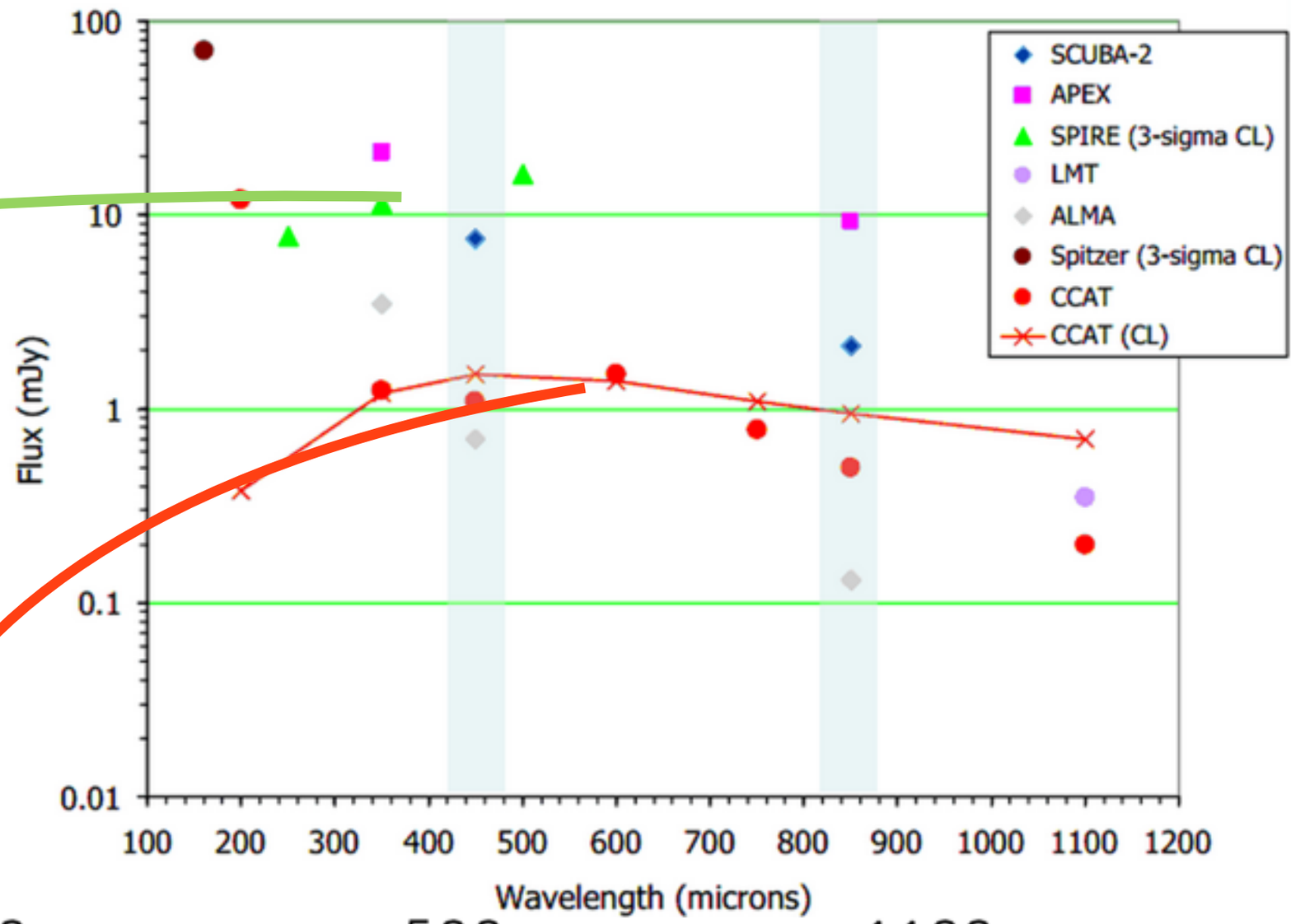
# CCAT Site:
# The extra 600m helps!

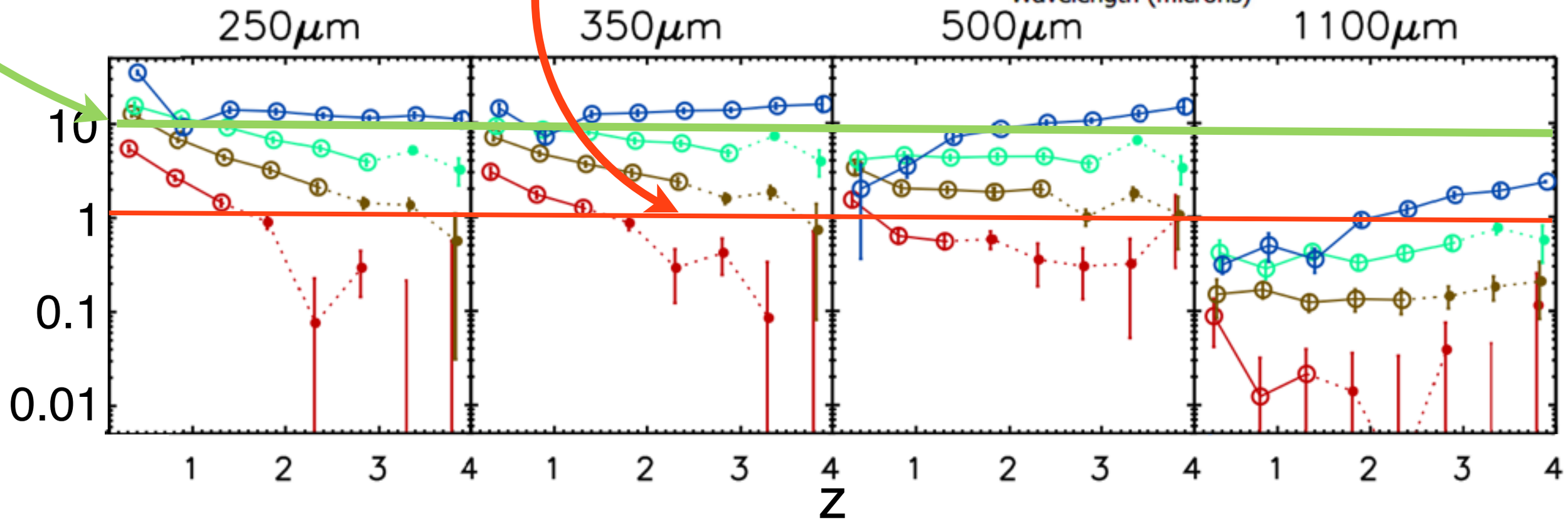



G. Stacey

# CCAT

- Will resolve to the SPIRE stacked limit
- Must stack to probe lower mass and higher-z



# Future Work with Surveys

- Immediately: Cross-correlations with
  - CMB to quantify CIB - SZ correlation
  - Clusters and cluster members to study CIB-tSZ correlation, and infall radius, etc.
    - SDSS-identified QSOs and DLAs to study their dust properties and bias
    - IGM Scattered Starlight to measure dust grain sizes
    - SNa host star-formation properties
- Farther in future: Star Formation History of lower mass and higher redshift galaxies

# Summary

- Dusty Star-forming FIR/submm Galaxies are biased tracers of Dark Matter
- The CIB is made up mostly of typical galaxies from optical/NIR surveys
- Cross-Correlating large data sets is a powerful tool for answering many questions in Galaxy Evolution and Cosmology
  - HerS data publicly available at: http://www.astro.caltech.edu/hers
  - SIMSTACK code publicly available at: http://www.astro.caltech.edu/~viero/viero_homepage/toolbox/