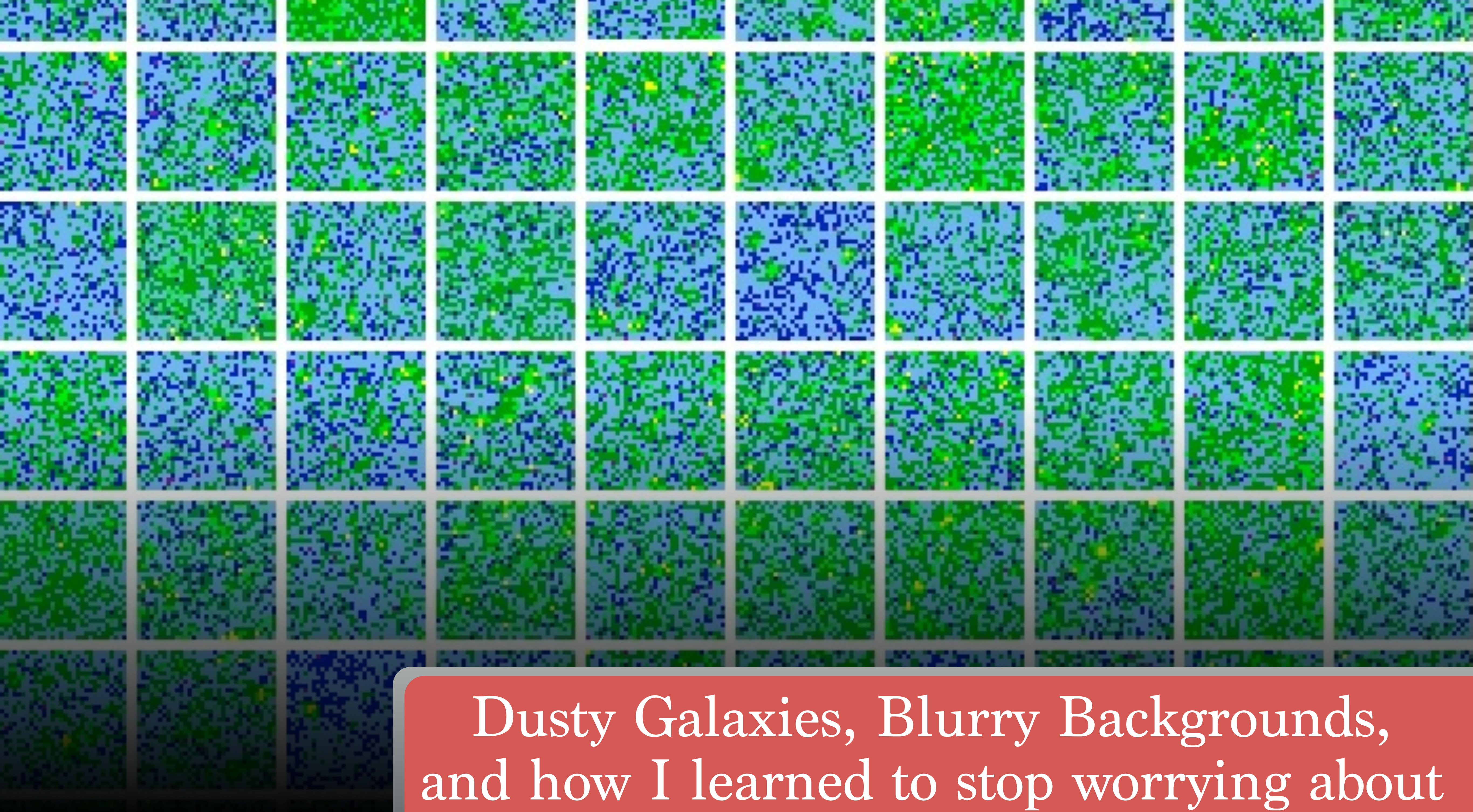


# Dusty Galaxies, Blurry Backgrounds, and how I learned to stop worrying about and love statistical methods.

Marco Viero - Caltech

University of Wyoming - Colloquium

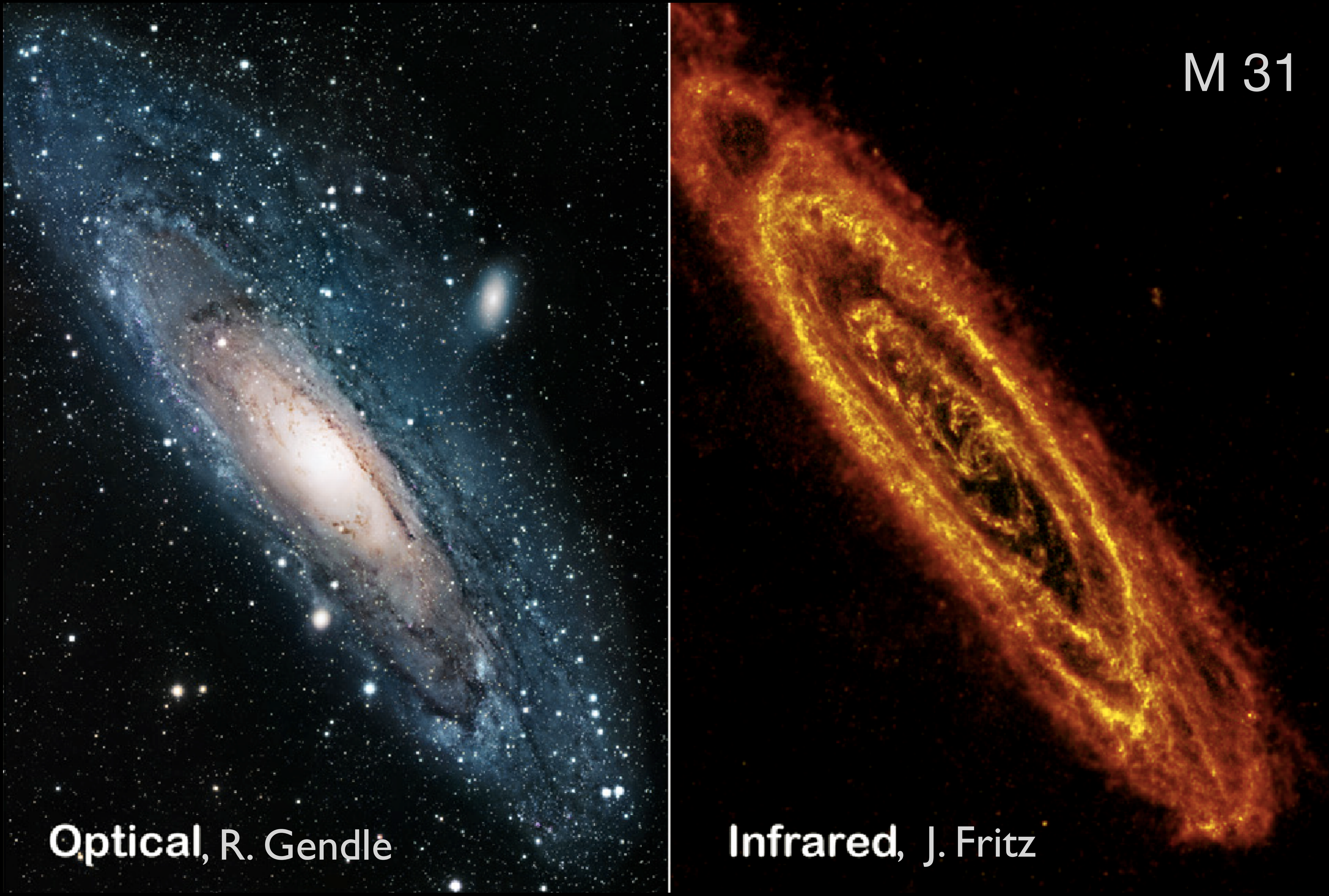

Students, I’m sorry I missed Lunch!!
ROAD
CLOSED

# Outline of Themes

1. What are dusty galaxies, and why are they important? And what's this about confusion?
2. Overcoming **confusion** with statistical methods.
3. Relating Galaxy Luminosity (i.e., SFR) to Stellar and Dark Matter Halo Mass directly.
4. Future Work.

CIB = Cosmic Infrared Background
SMG = Submillimeter Galaxy
DSFG = Dusty Star-Forming Galaxy

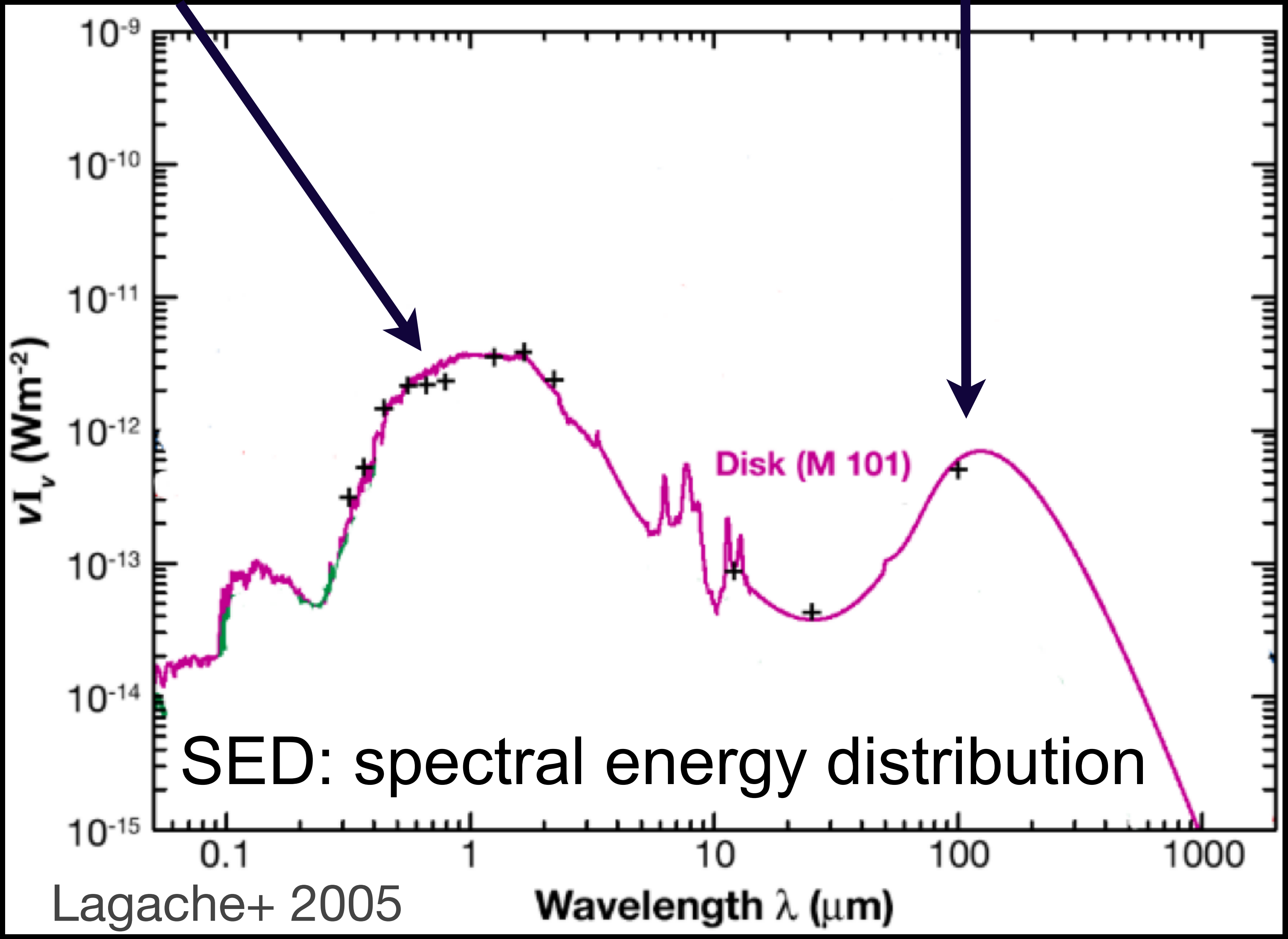
# FIR/submillimeter: dust warmed by stars



# UV/Optical and FIR/submm SED

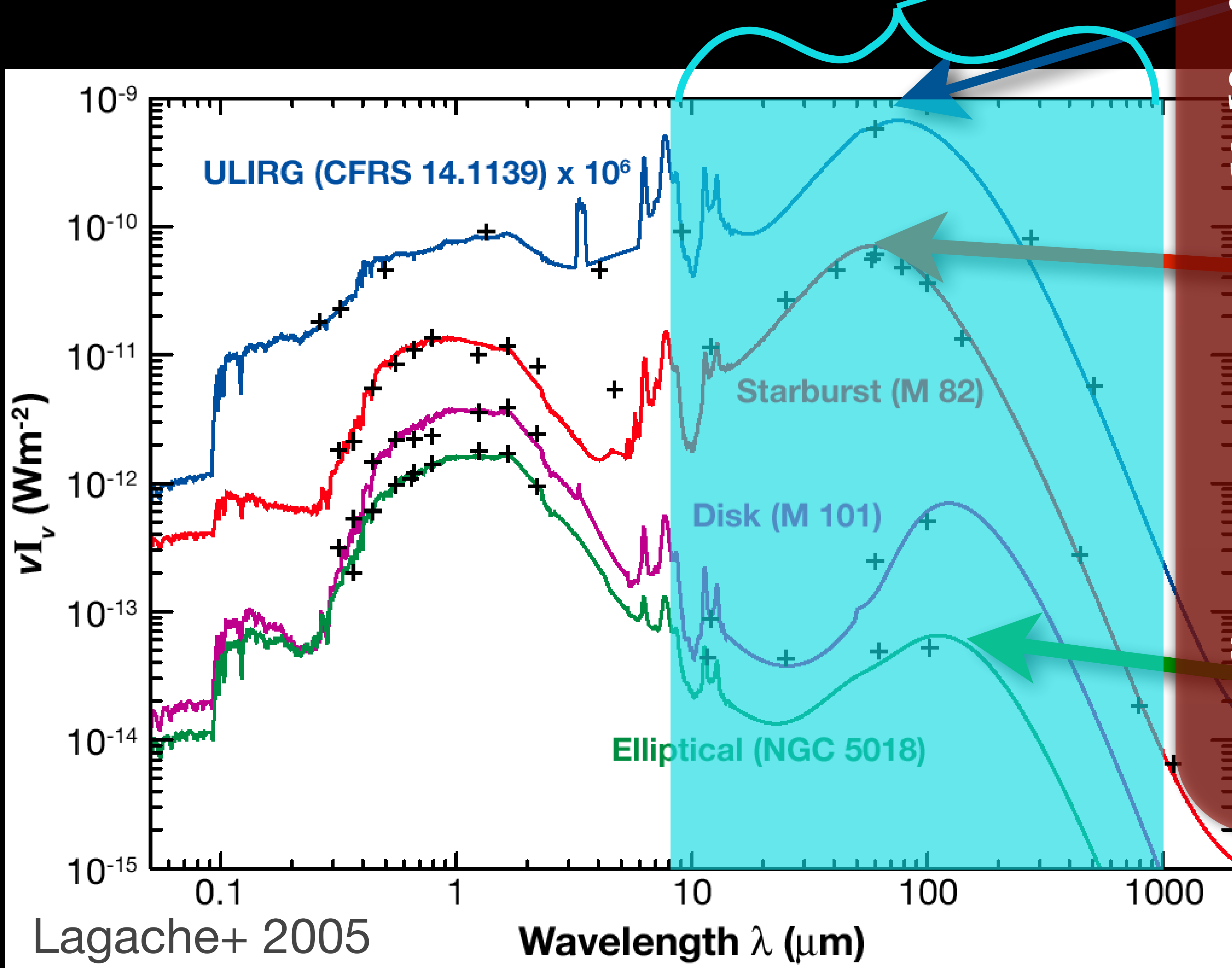
Dust re-emits in the FIR

Optical/UV Starlight absorbed by dust





# UV/Optical and FIR/submm SED




**Infrared Luminosity**

$L_{IR}$ = integral from 8 to 1000 µm

Star-formation rate

SFR ∝ $L_{IR}$

ULIRGS:

- $\log(L_{IR}/L_\odot)$ = 12-13
- SFR ≈ 100–1000 $M_\odot$/yr

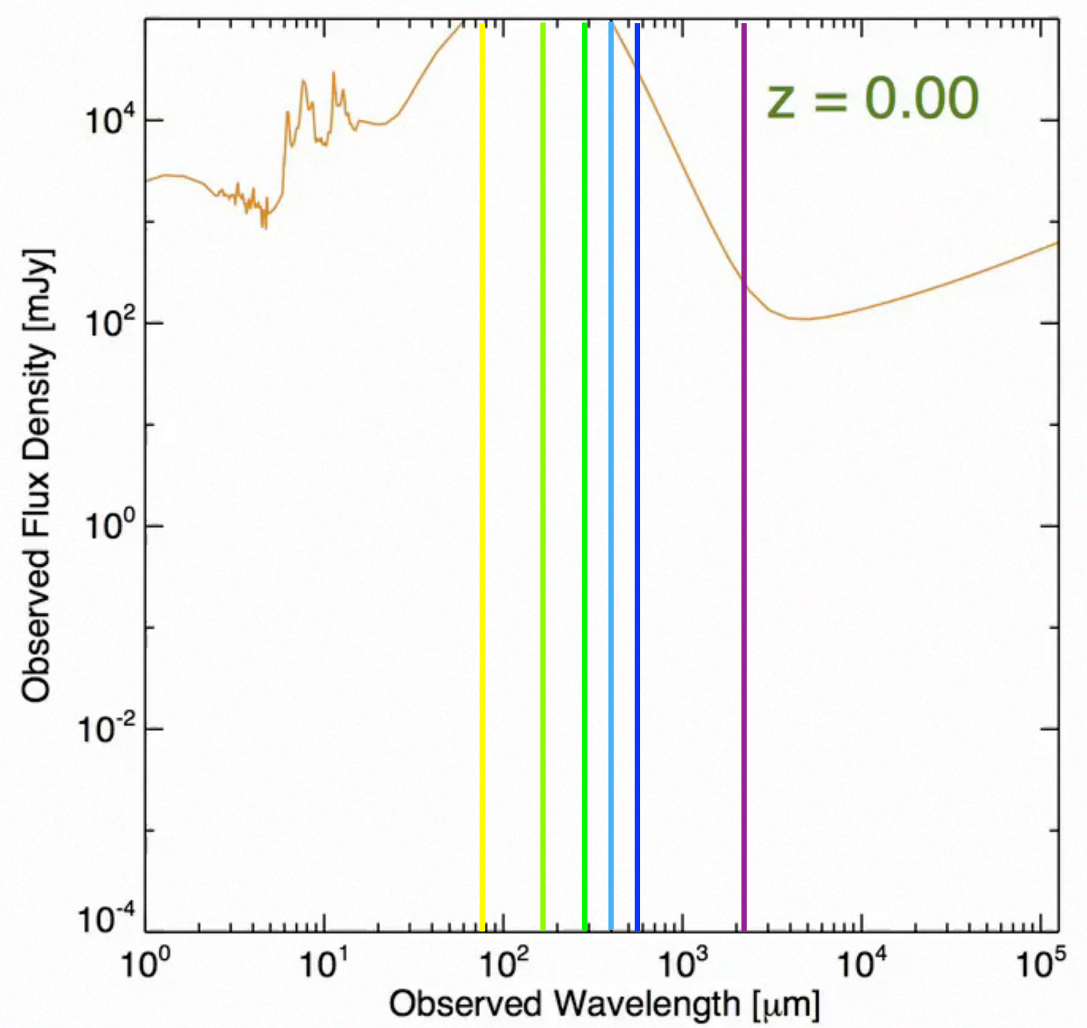
LIRGS:

- $\log(L_{IR}/L_\odot)$ = 11-12
- SFR ≈ 10-100 $M_\odot$/yr

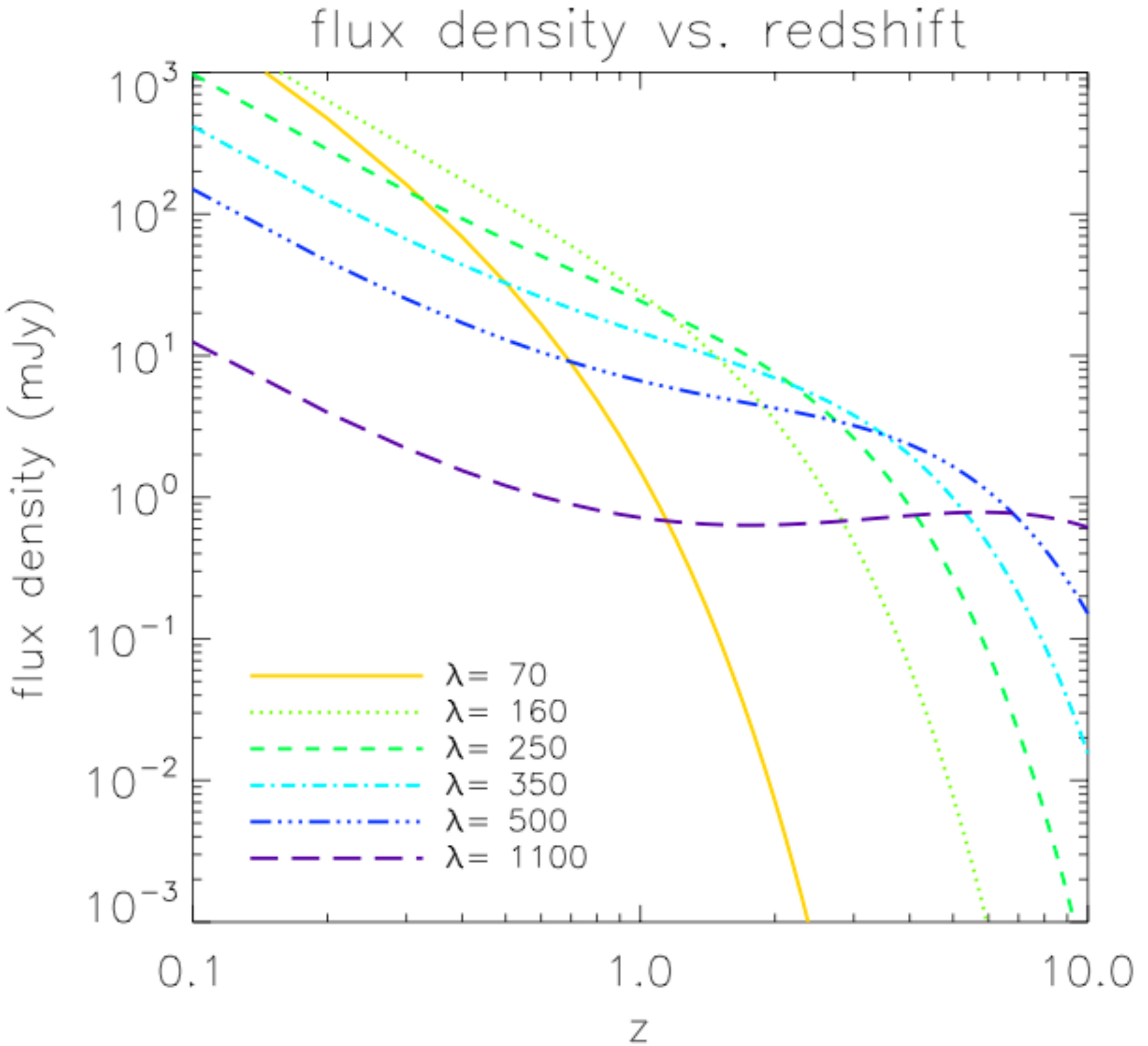
sub-LIRGS (“normal”):

- $\log(L_{IR}/L_\odot)$ < 11
- SFR ≲ 10 $M_\odot$/yr

# Submillimeter: Window to High Redshift Star-Forming galaxies



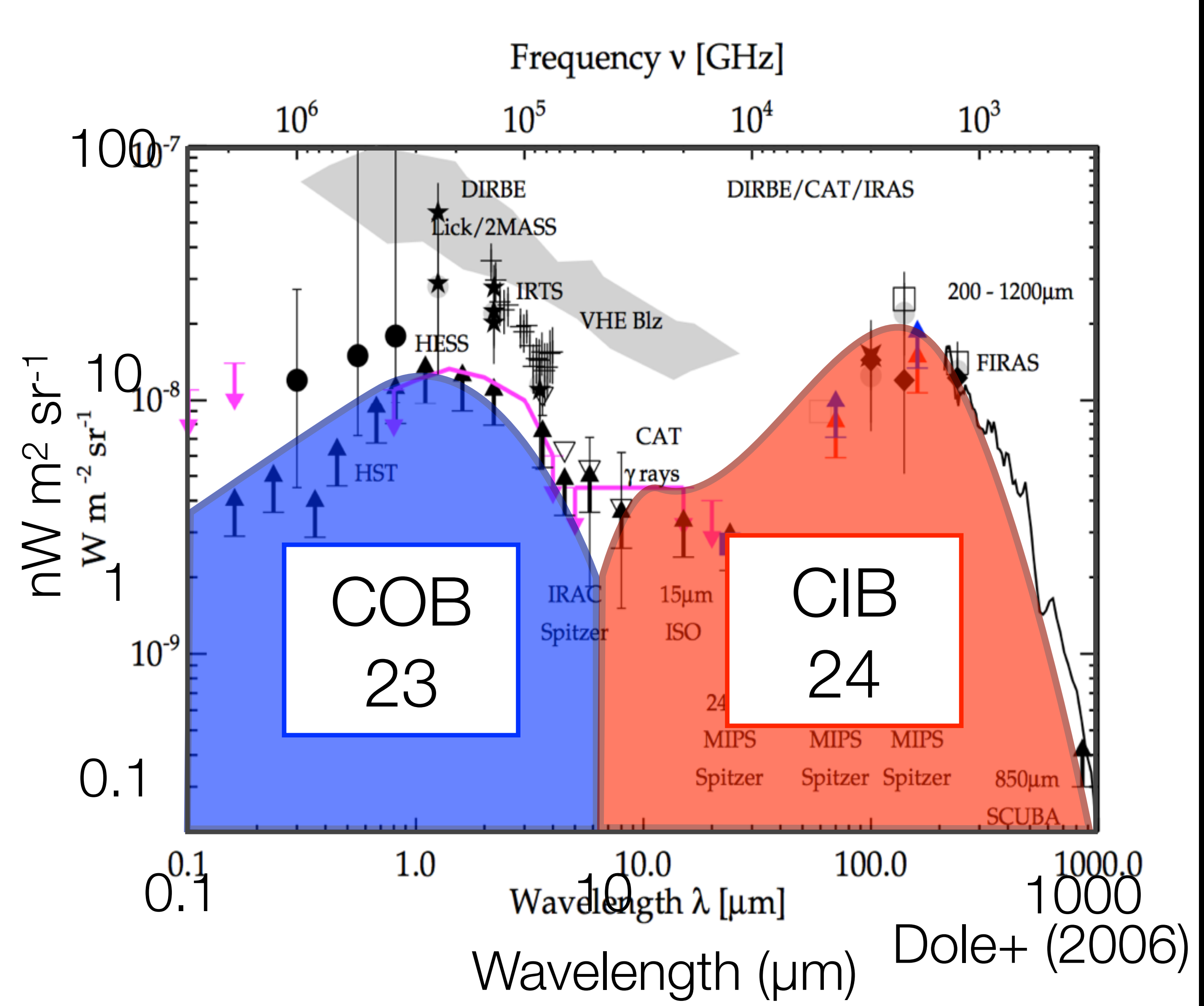

Caitlin Casey (UC Irvine)



# Cosmic UV/Optical and FIR/submillimeter Backgrounds

Approximately equal energy in the Far-infrared/ submillimeter as the UV/Optical/Near-infrared background.

Can we understand the infrared component of galaxies in the same detail as the optical?

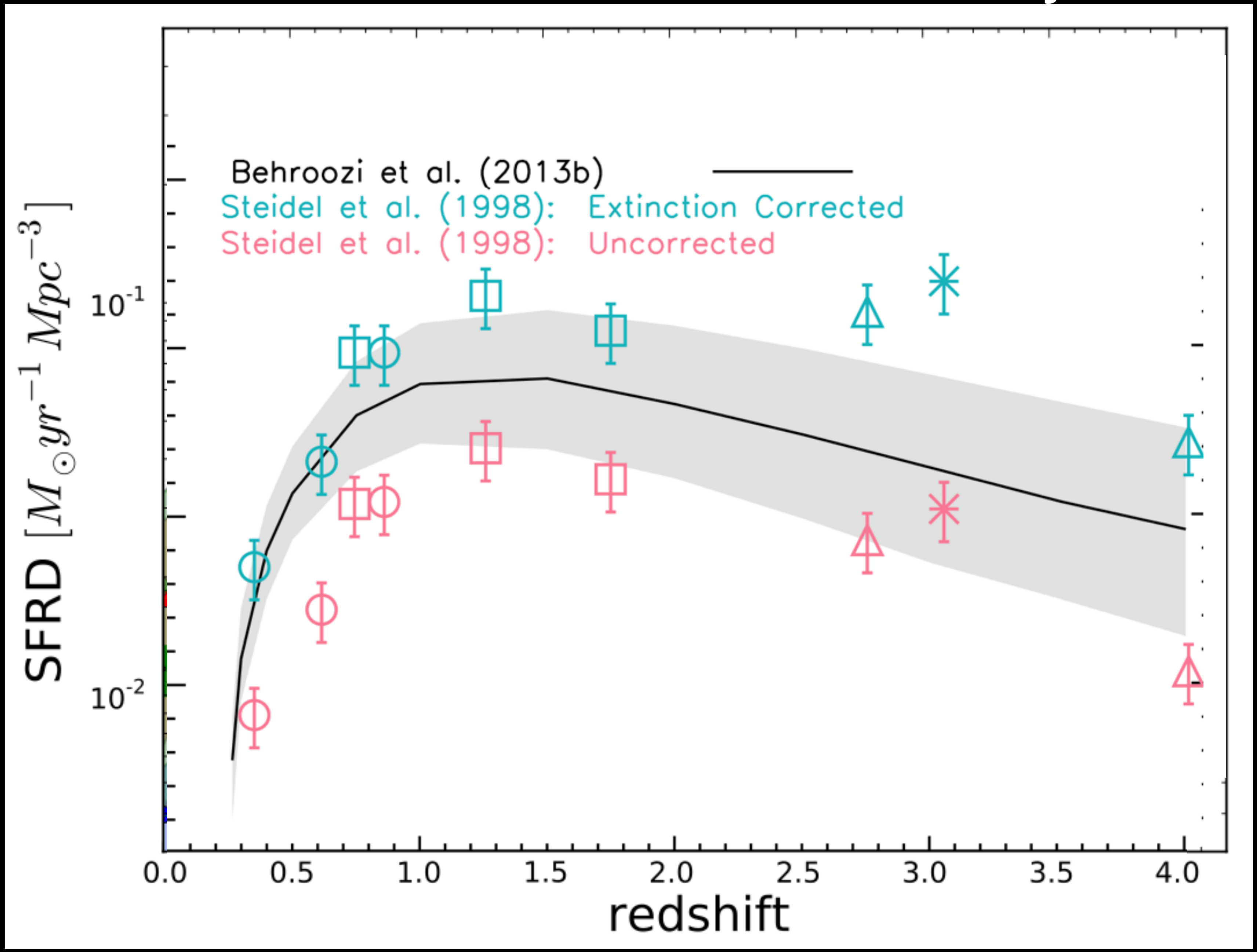



Dole+ (2006)

# Motivation #1: History of Cosmic Star Formation

Traditional, Lyman break galaxy (i.e., UV-selected) estimates need to correct for dust extinction

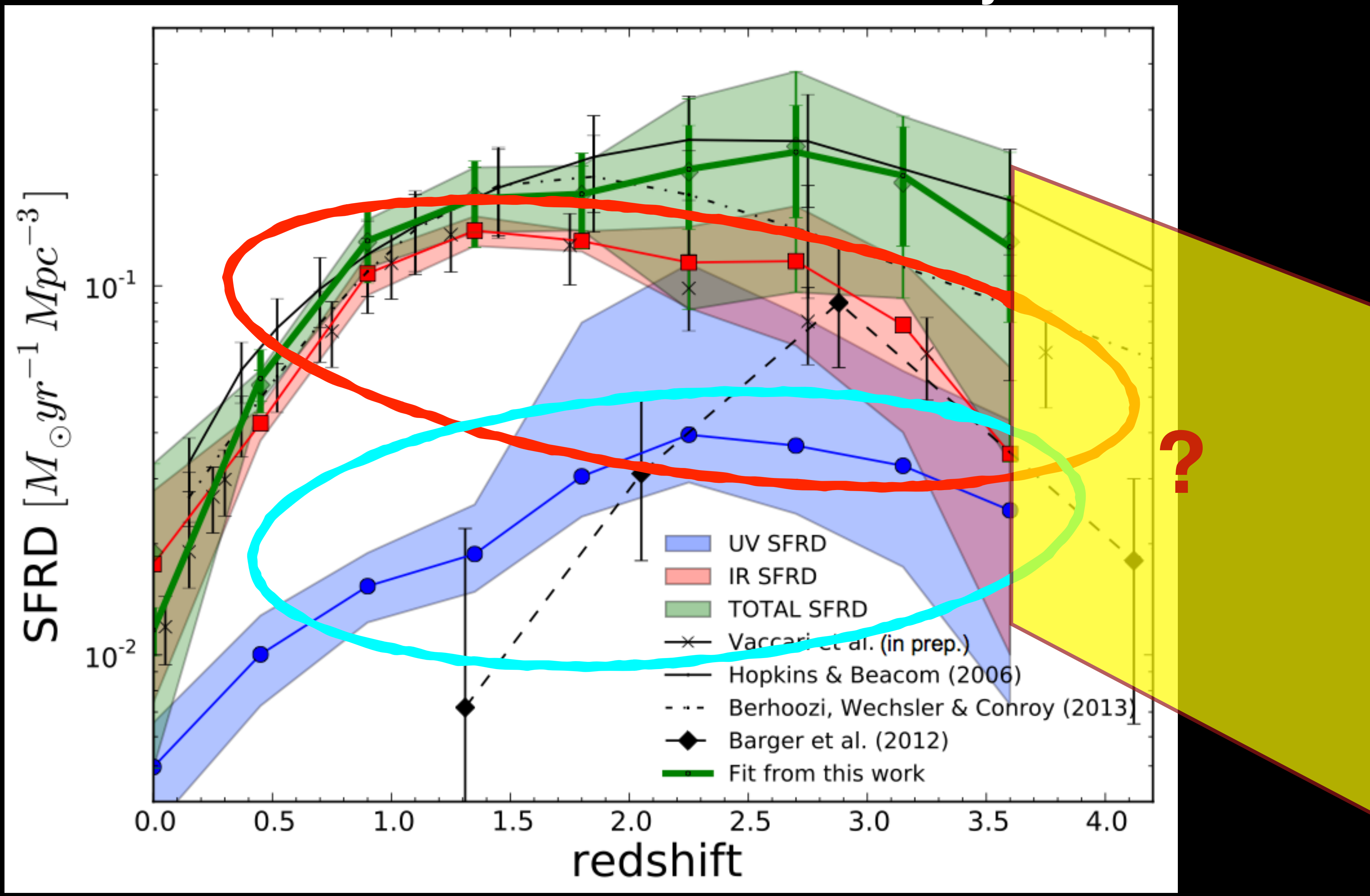
Star-Formation Rate Density



# Motivation #1: History of Cosmic Star Formation

- Systematic Biases
- Selection Biases
- What about at higher z?

Star-Formation Rate Density



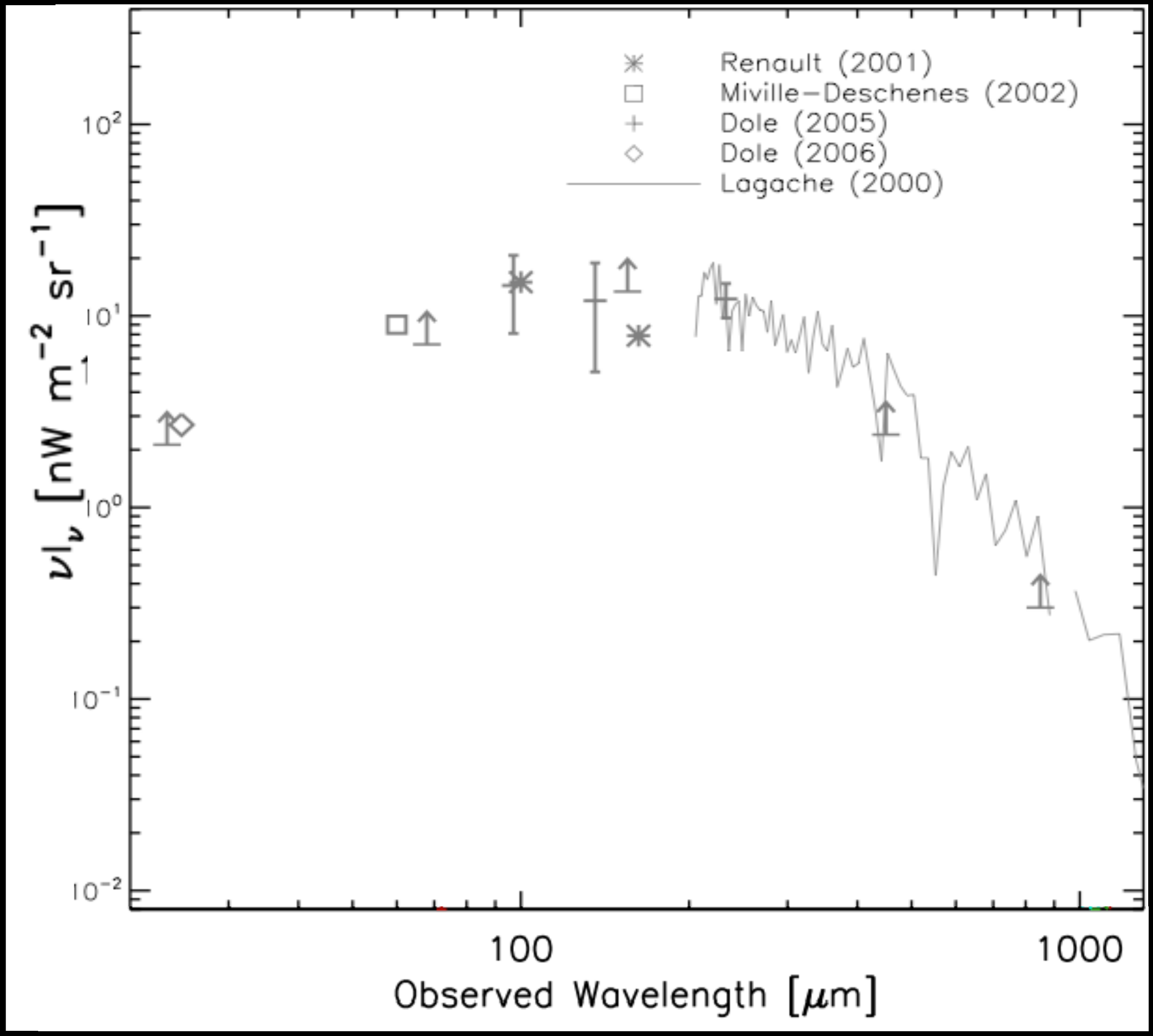

Burgarella+2013

# Motivation #2: Origin of the Cosmic Infrared Background

How much of the CIB is made up of galaxies we already know well in the optical/NIR?

How does it break down? By Stellar Mass? Redshift? SMGs? DSFGs? AGN? Other??

What about the rest? Is it mostly dust-obscured galaxies? Faint galaxies? Other??

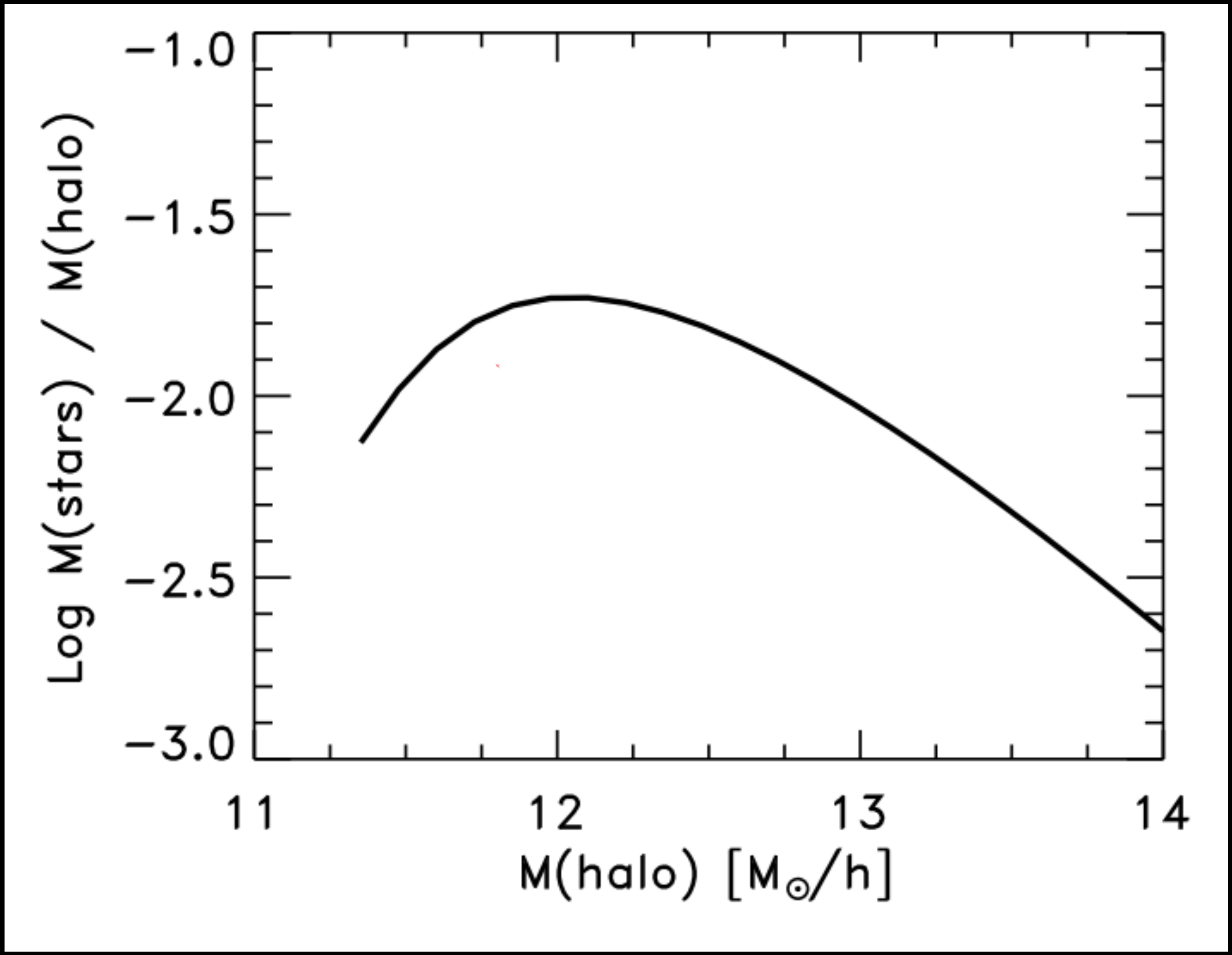


# Motivation #3: Growth of Stellar Mass

The stellar mass-halo mass (SM-HM) relation measures the efficiency in which galaxies form stars.

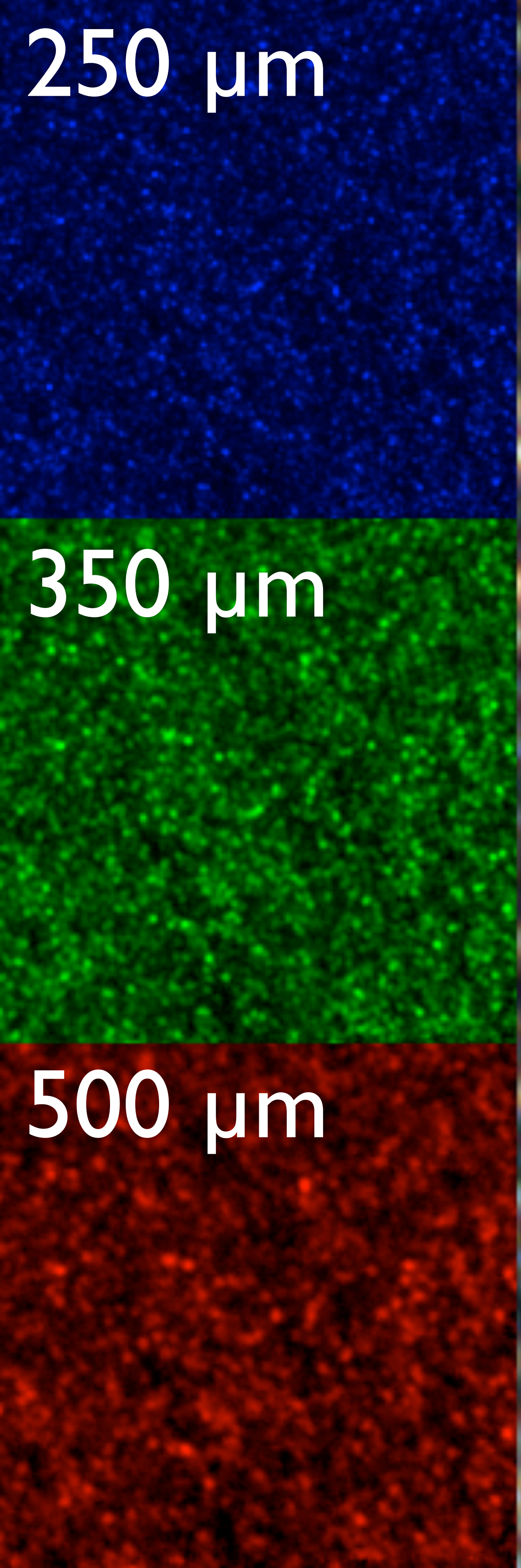
Can we *directly*:

- identify the mechanisms (e.g., star formation vs. mergers) responsible for stellar mass growth?
- relate suppression of star formation to the environment?

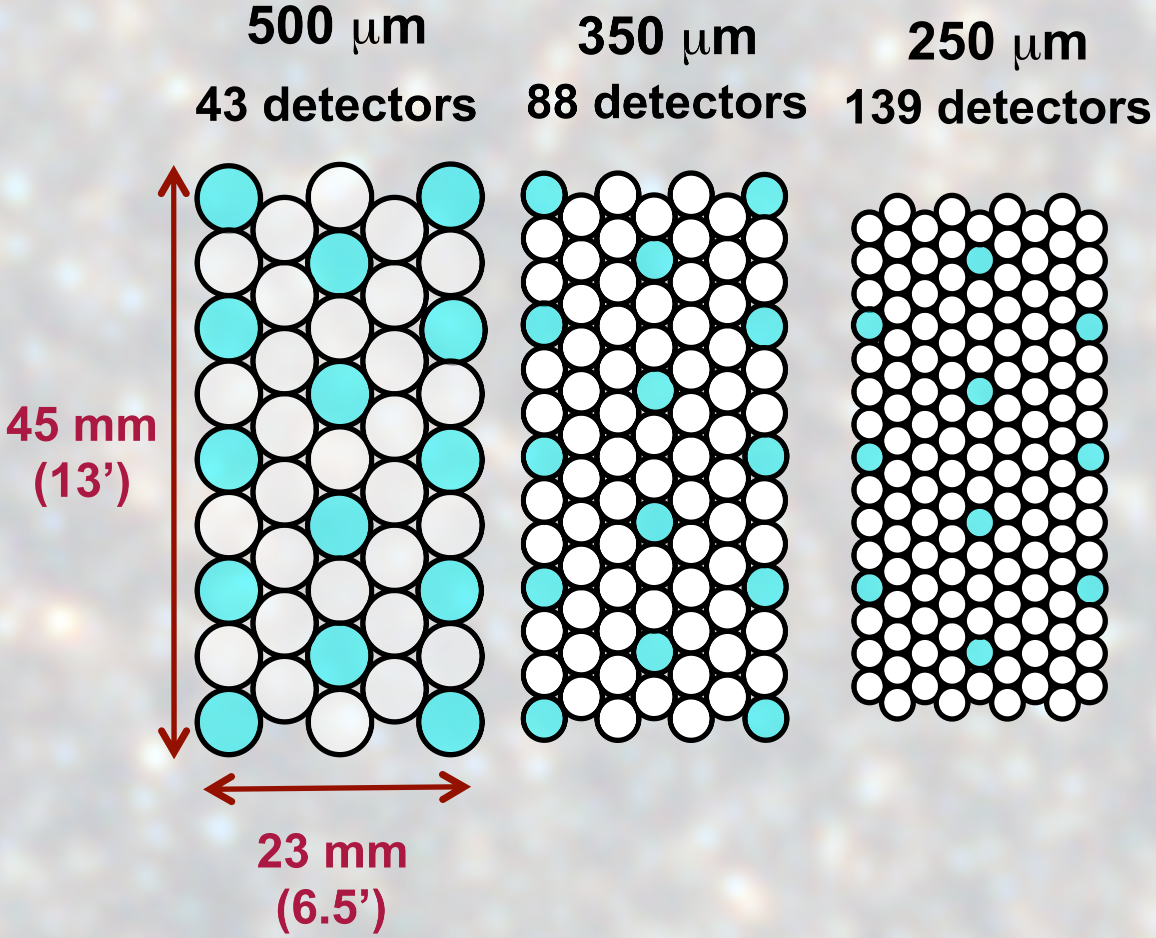



Behroozi+2010 (see also Moster+2010)

# Hershel/SPIRE




PSF size
(FWHM)
250 µm - 16”
350 µm - 25”
500 µm - 36”

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esa

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

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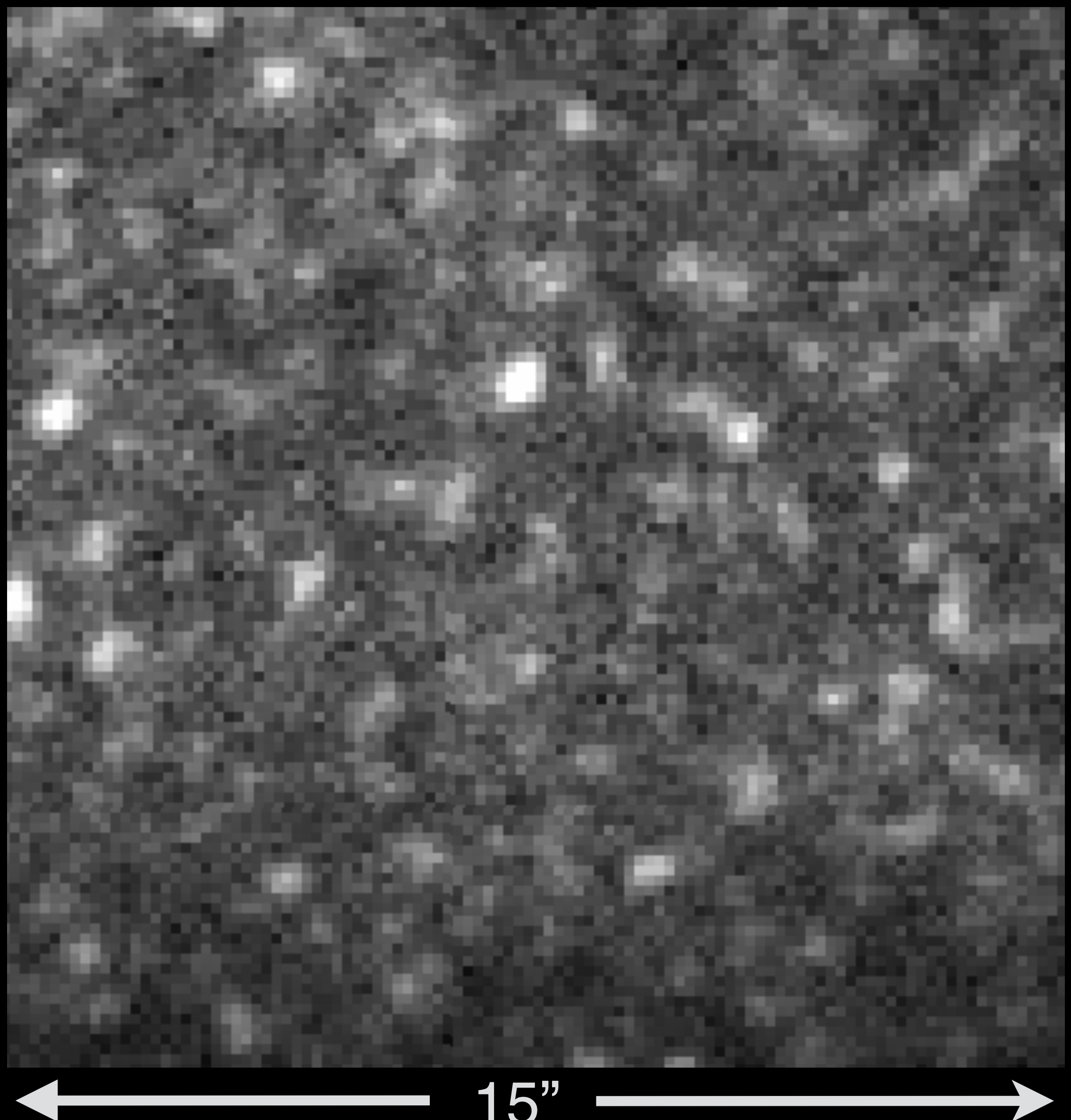
# The Team

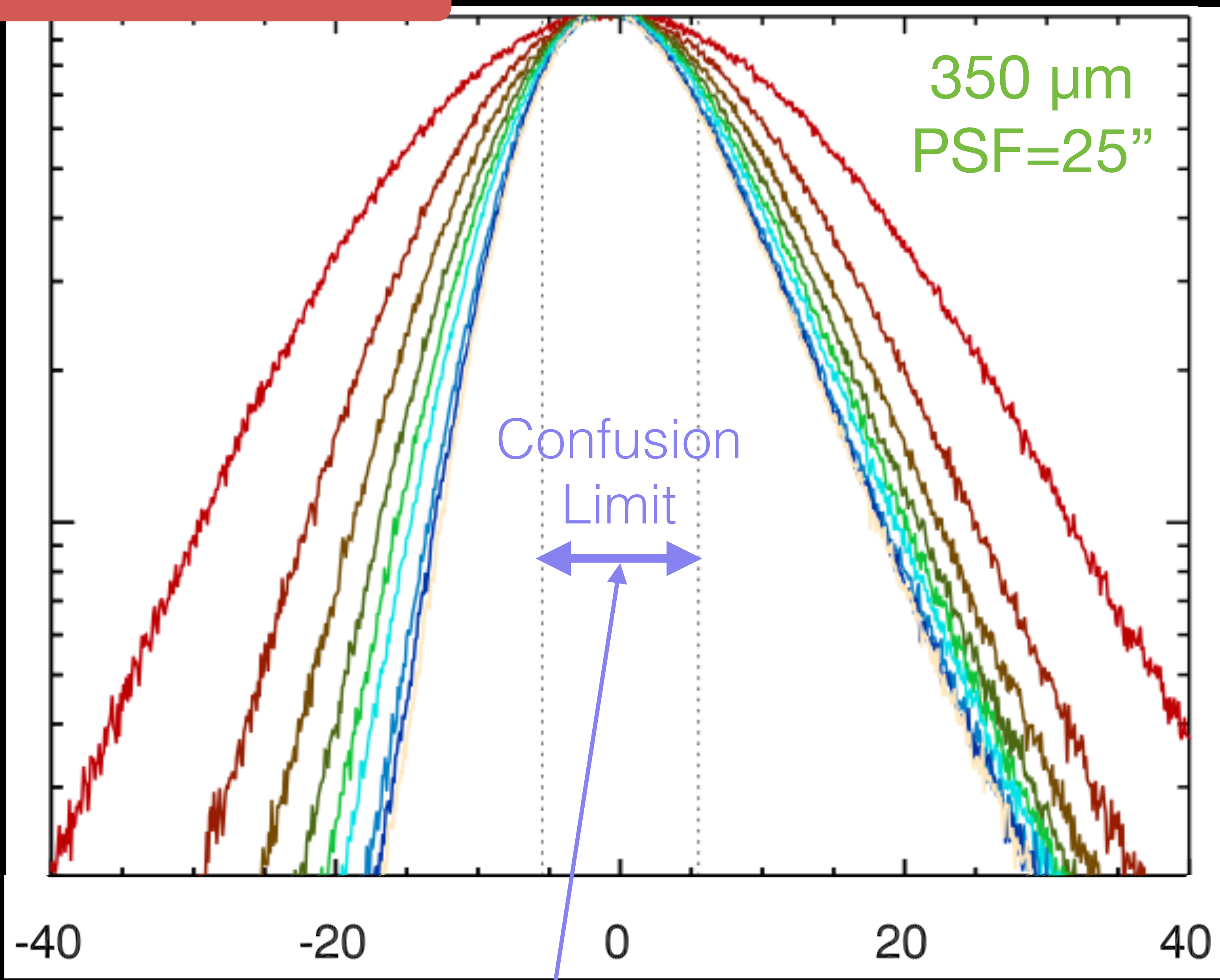
Bruno Altieri, Alex Amblard, Rick Arendt, Vinod Arumugam, Robbie Auld, Herve Aussel, Alexandre Beelen, Andrew Blain, Jamie Bock, Alessandro Boselli, Carrie Bridge, Drew Brisbin, Veronique Buat, Denis Burgarella, Nieves Castro-Rodriguez, Antonia Cava, Pierre Chanial, Ed Chapin, Michele Cirasuolo, Dave 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

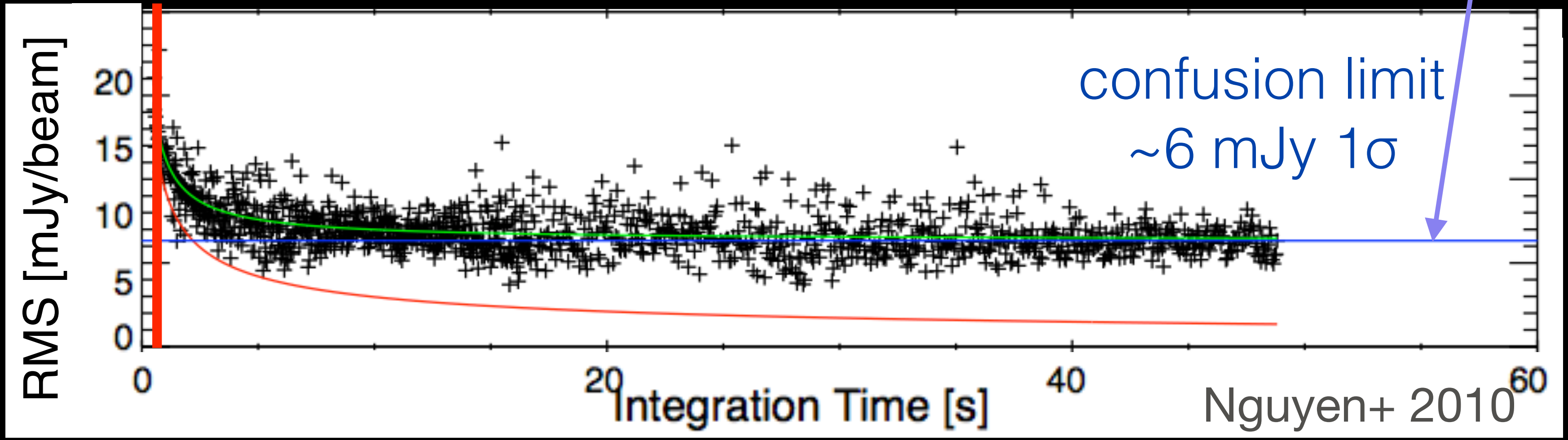
Faculty & Researchers PostDocs PhD Students

Plus engineers, instrument builders, software developers etc.

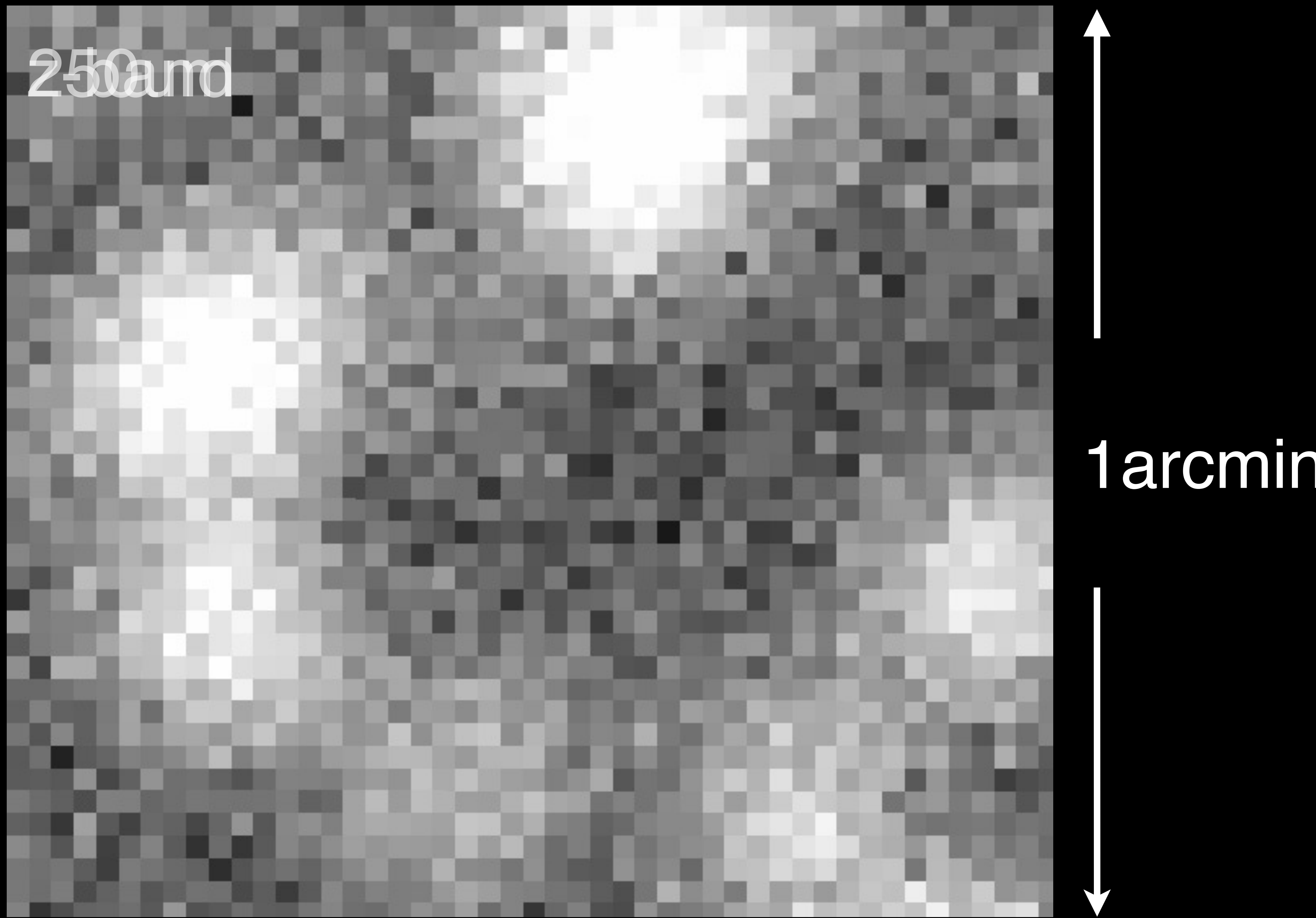
# Confusion vs. Instrument Noise



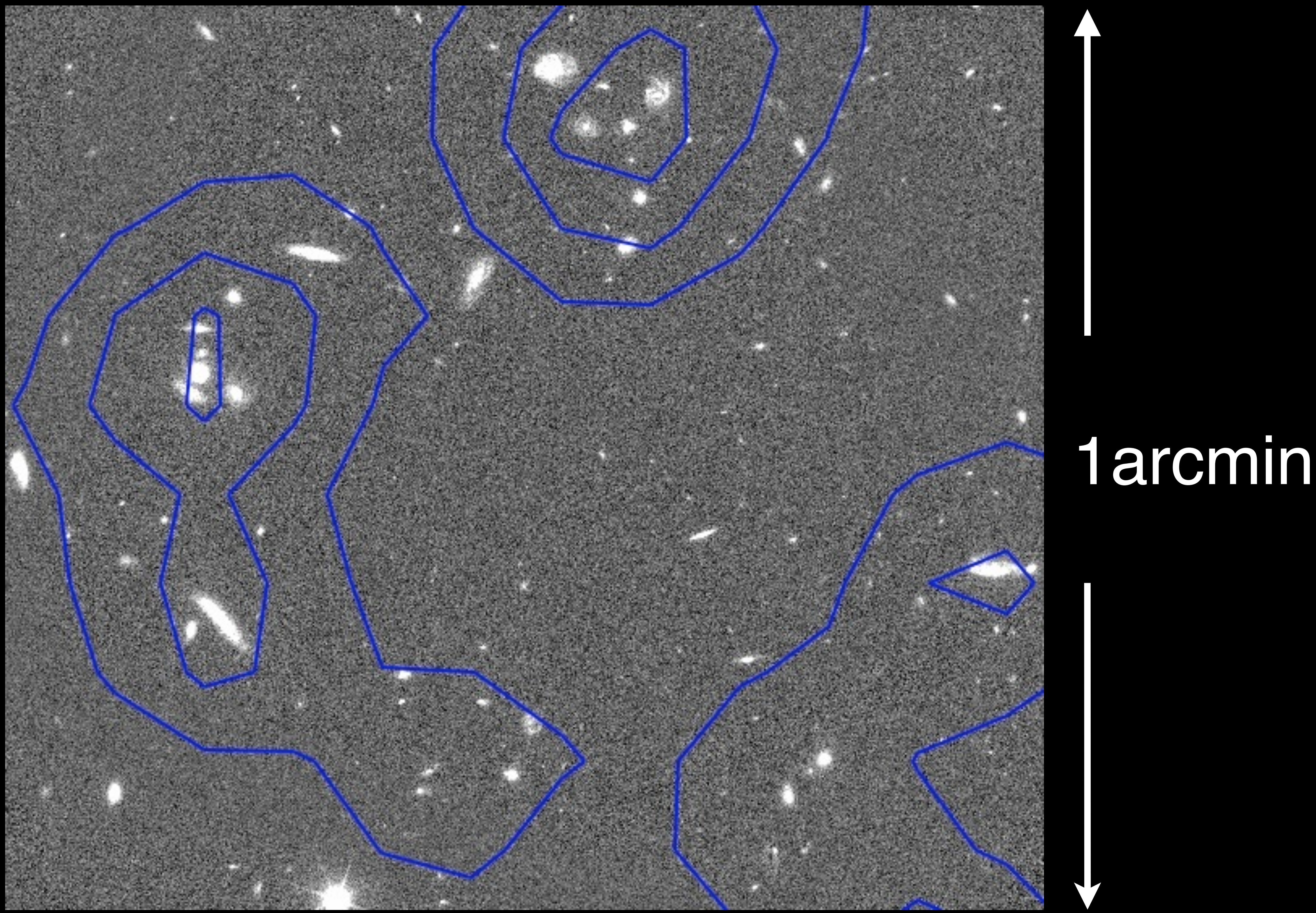



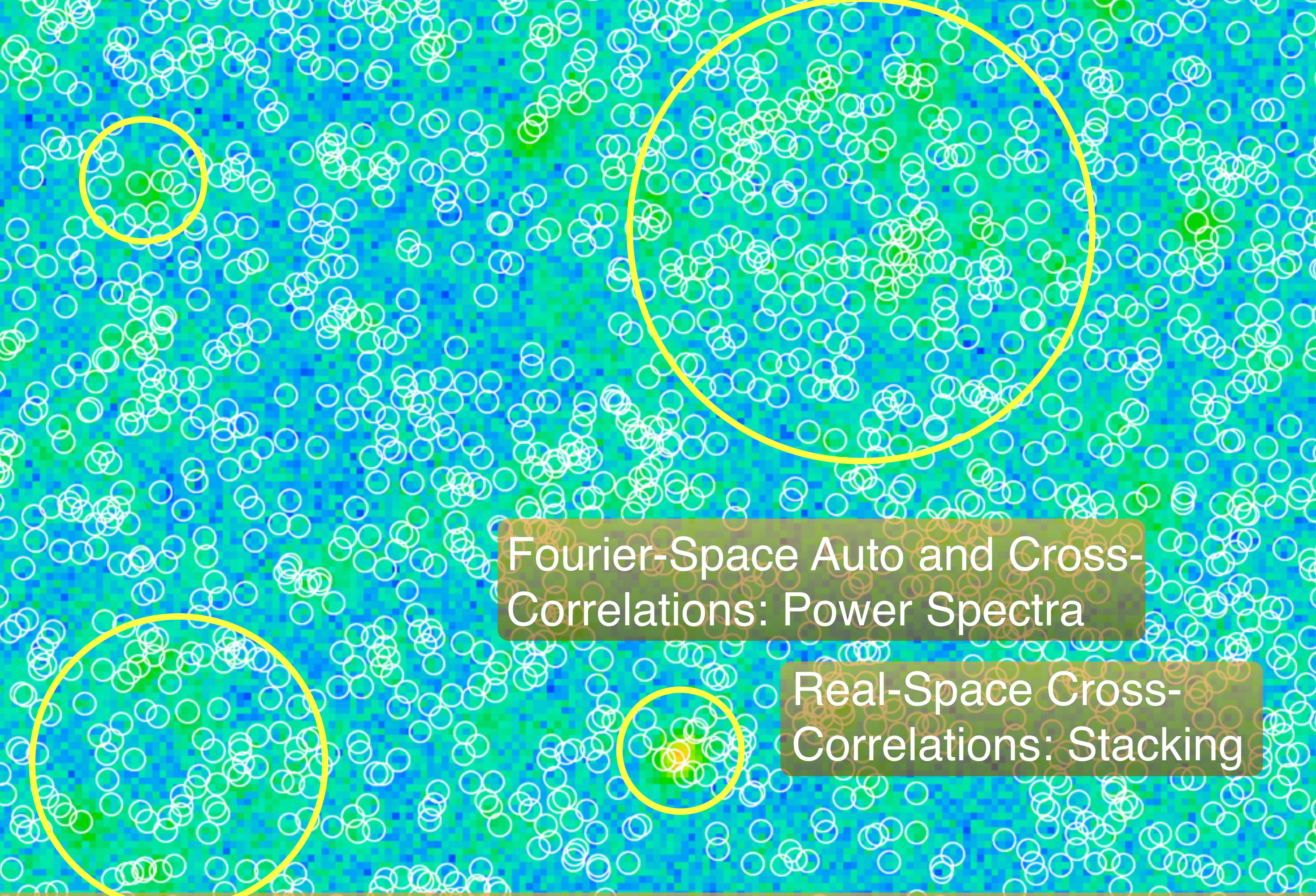



# Confusion Noise



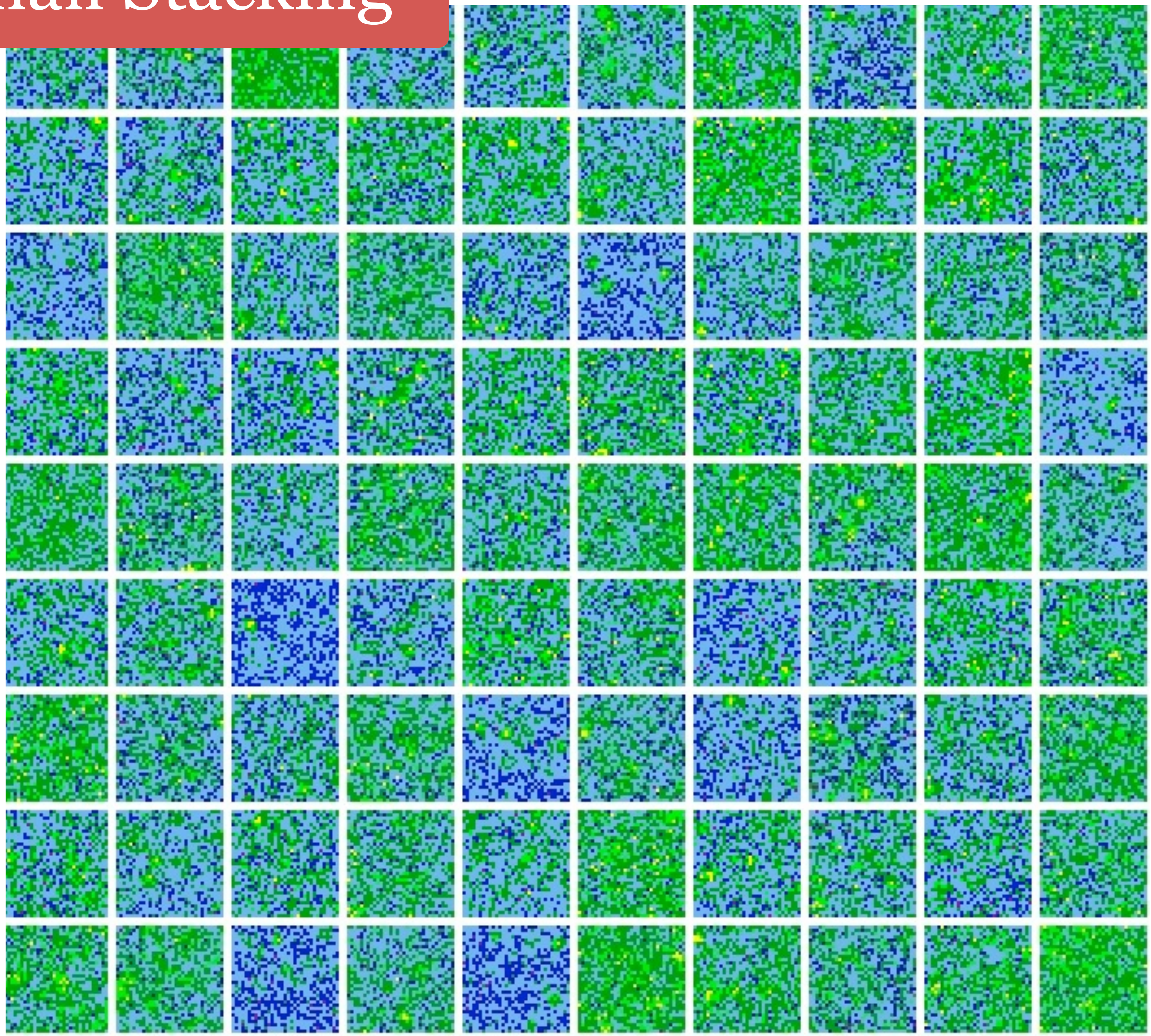
# Confusion Noise



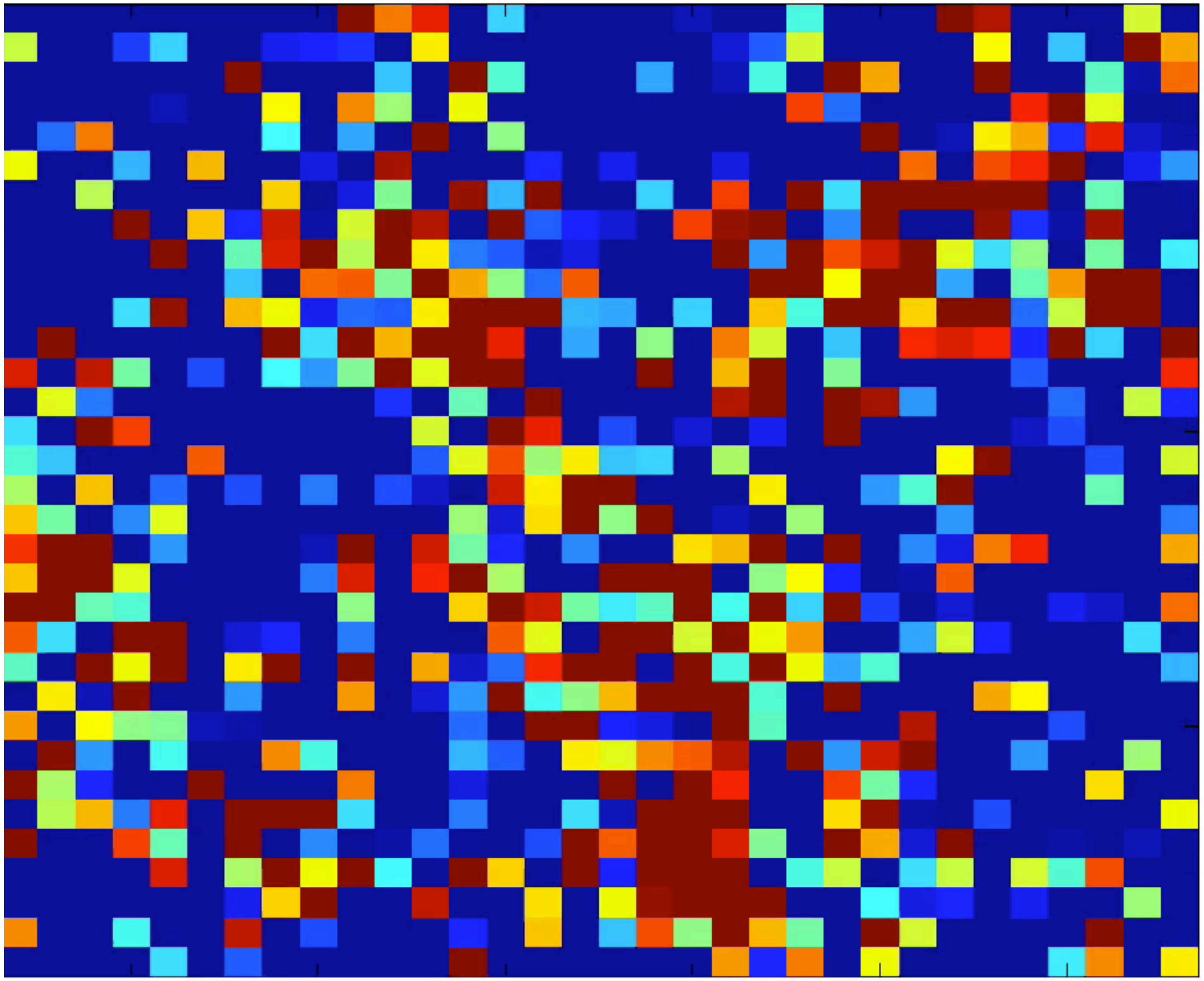



# Overcoming Confusion Noise with Statistical Methods

# Thumbnail Stacking

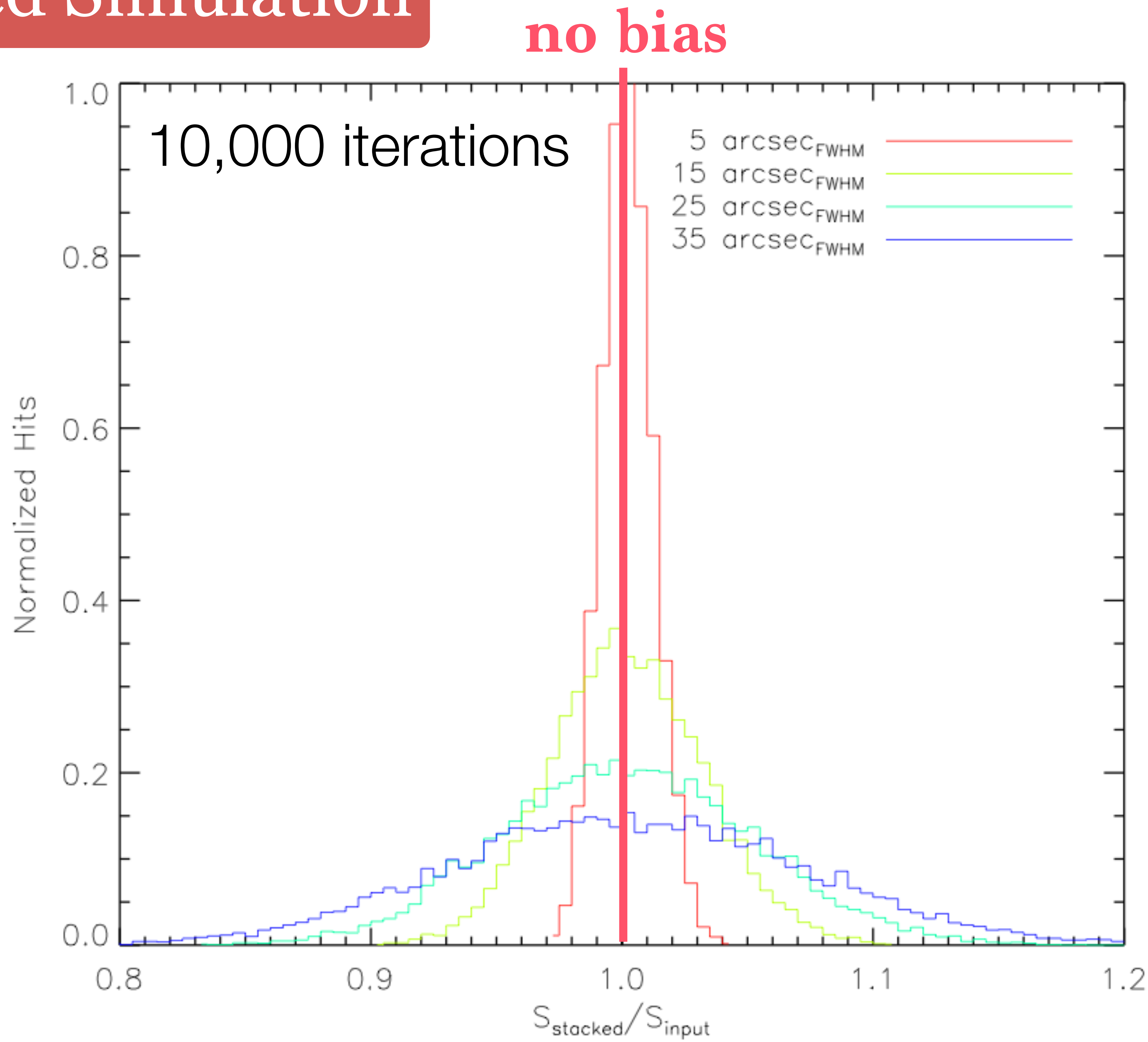


# Thumbnail Stacking

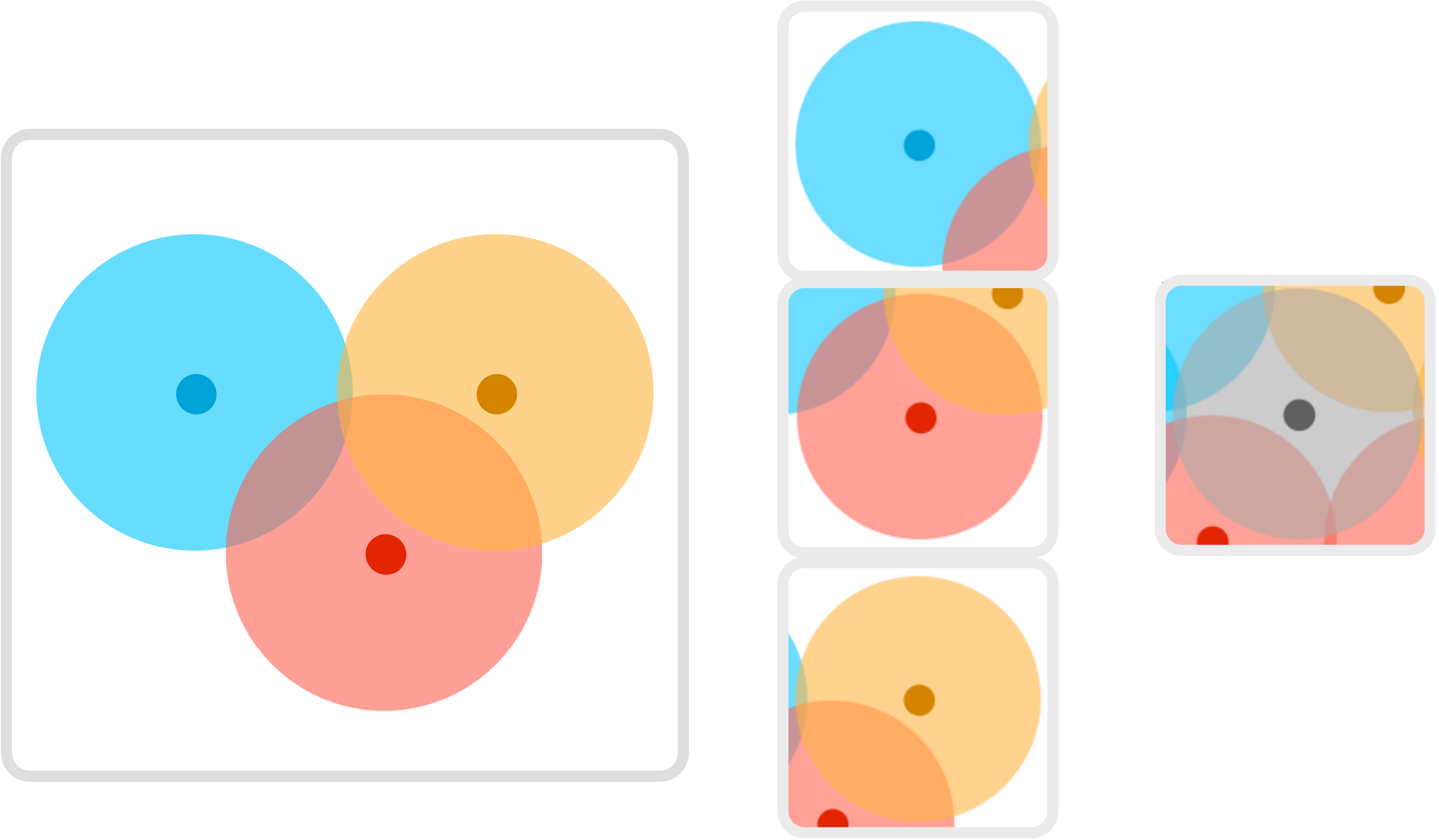


Phil Korngut (Caltech)

# Uncorrelated Simulation



# Correlation (clustering) Induced Bias



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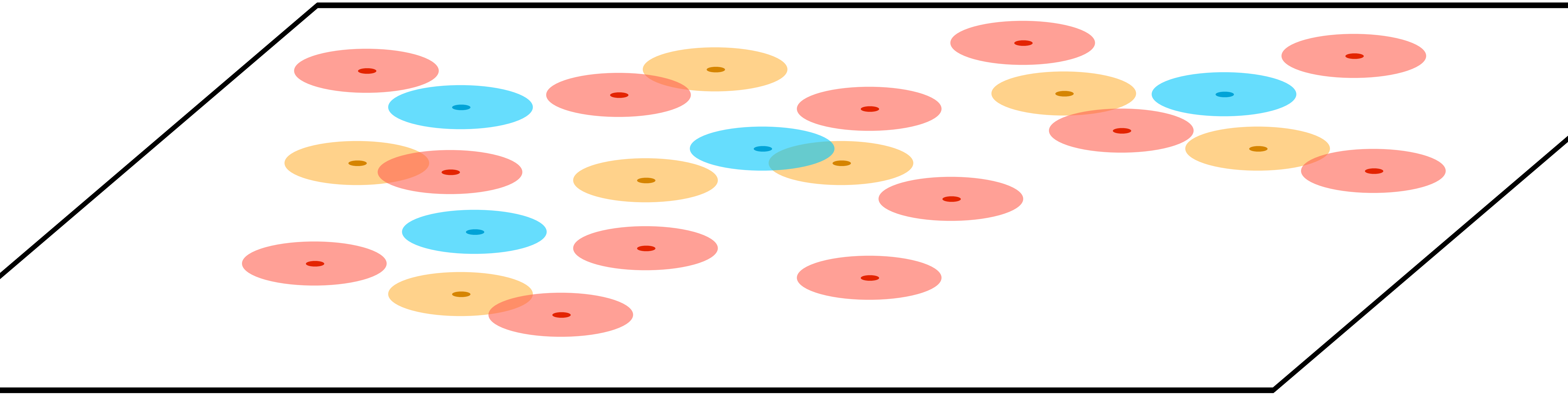
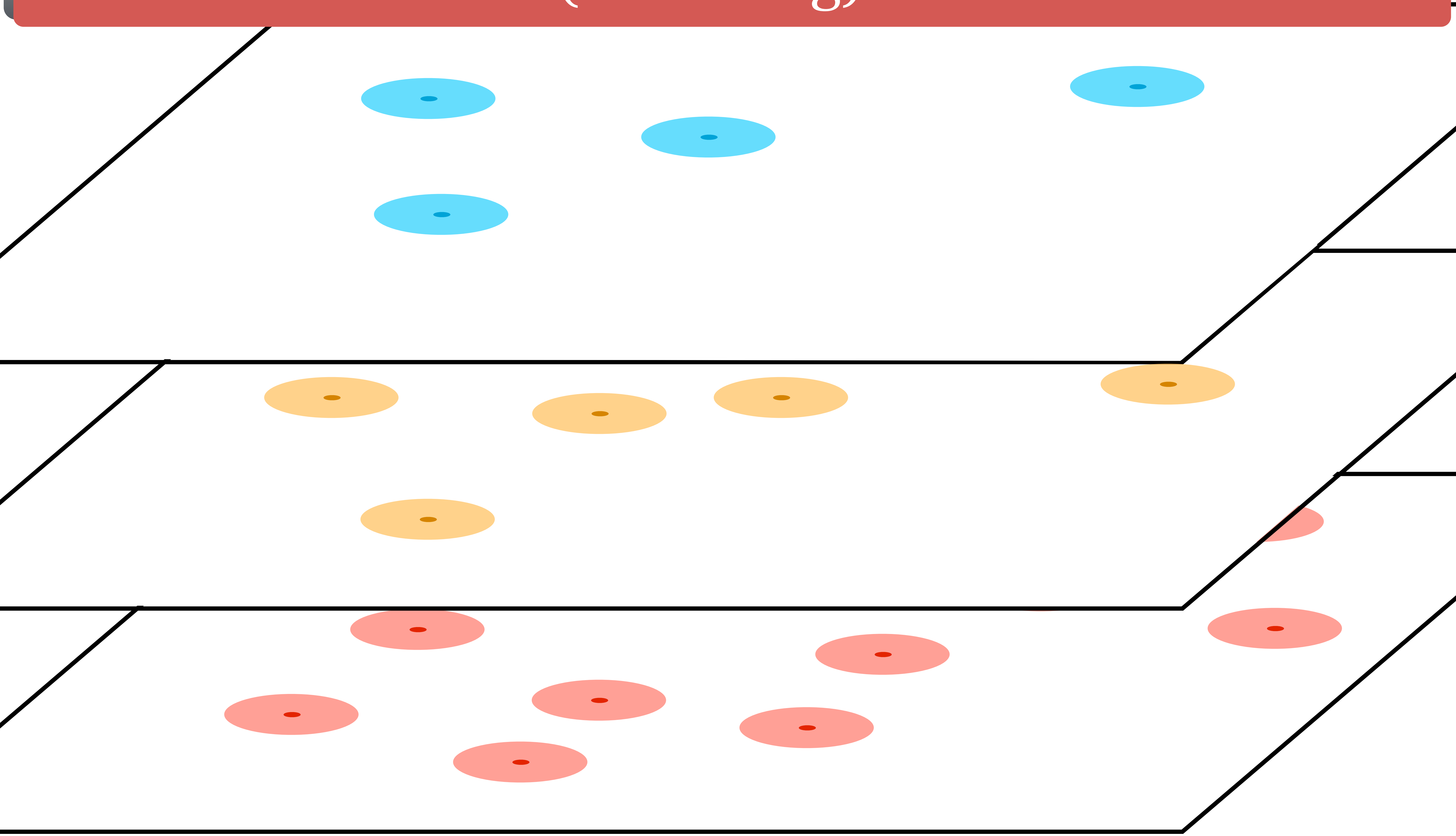
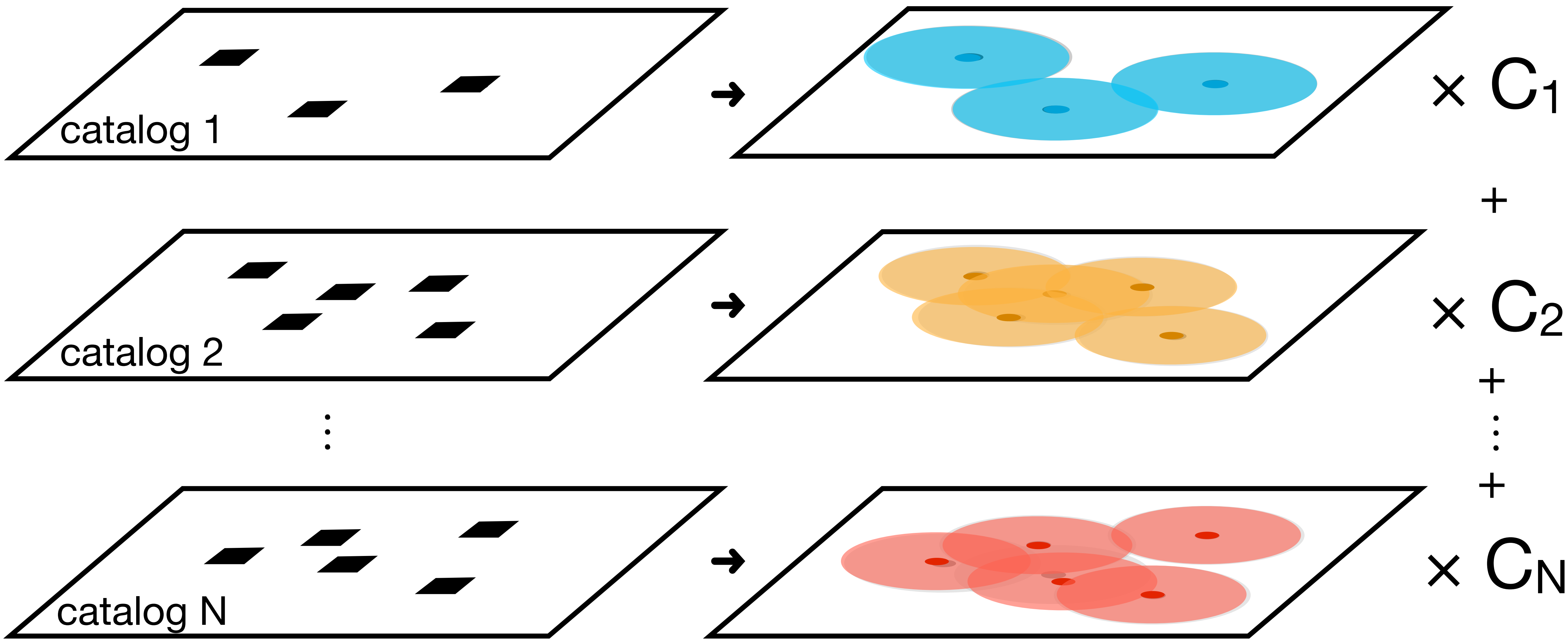
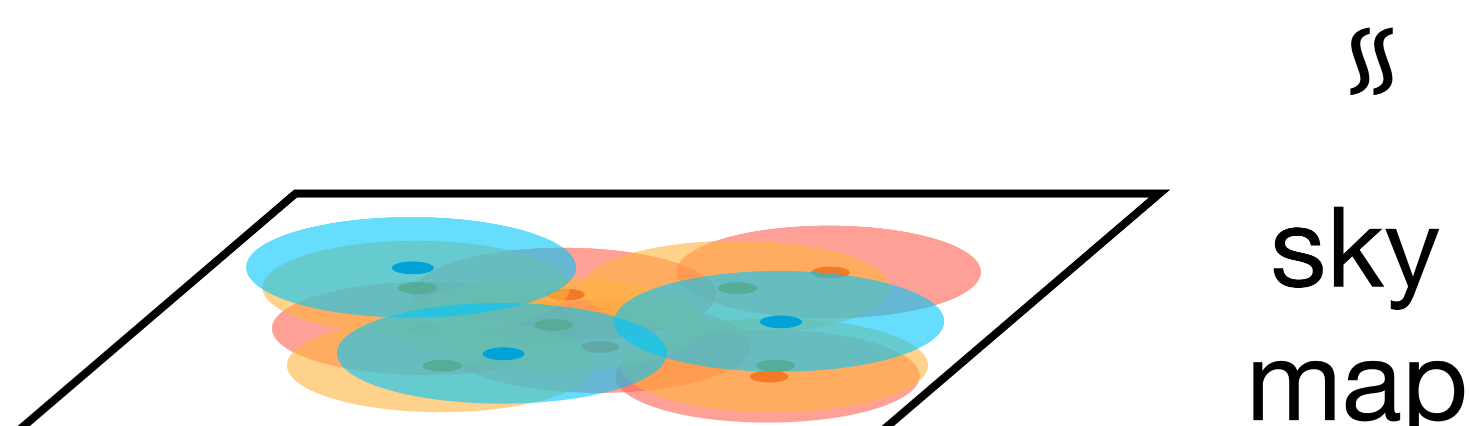


# Correlation (clustering) Induced Bias

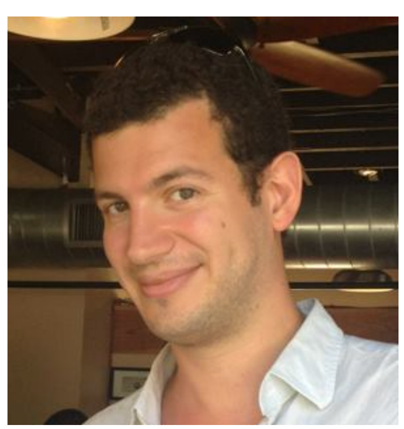


# SIMSTACK: Simultaneous Stacking Algorithm



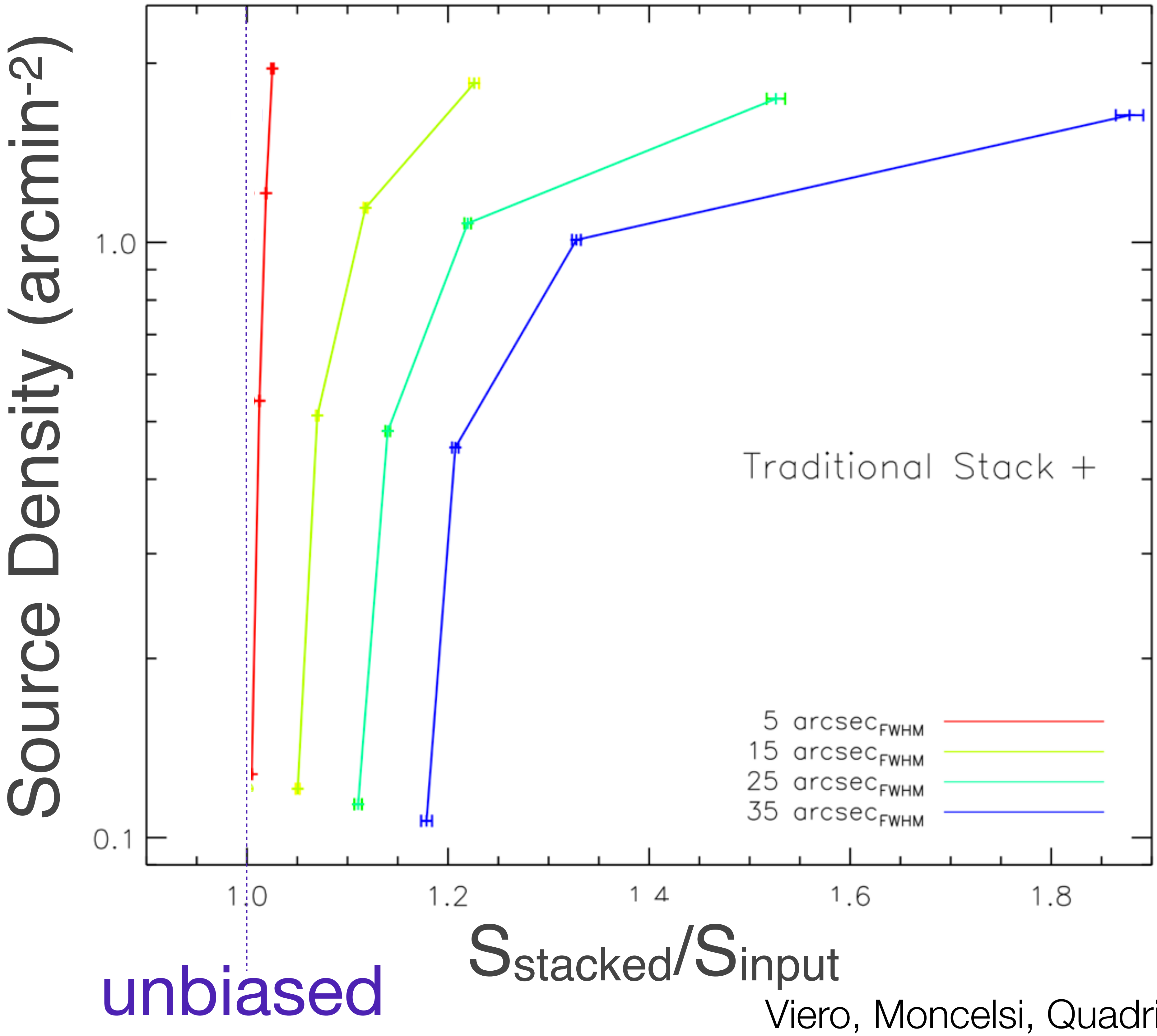




Formalism developed w/ Lorenzo Moncelsi (Caltech)



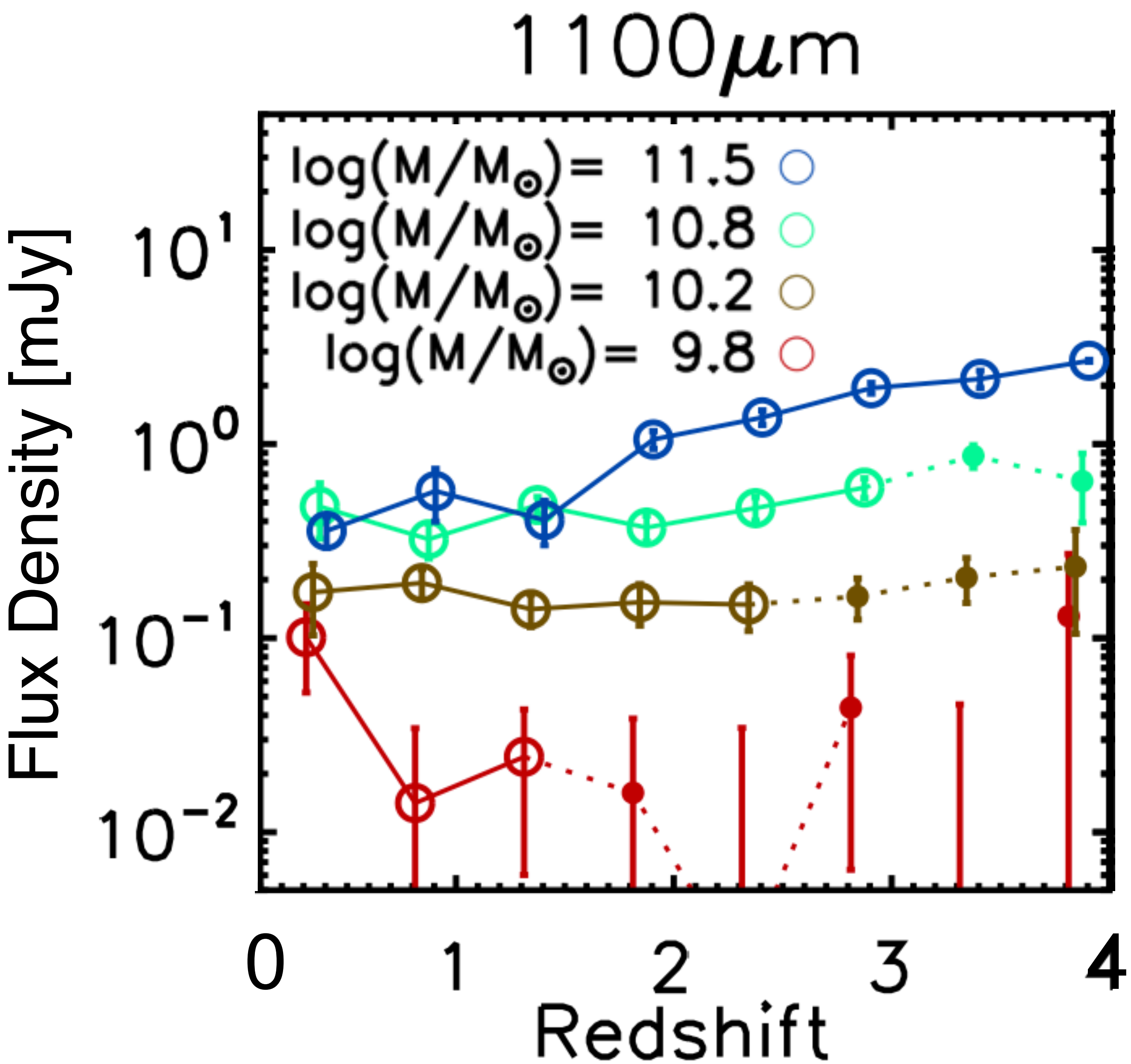
**SIMSTACK code publicly available see arXiv:1304.0446**

# SIMSTACK: Simultaneous Stacking Algorithm




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

# SIMSTACK of Galaxies by Stellar Mass and Redshift




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

catalog (Williams & Quadri, in prep.)

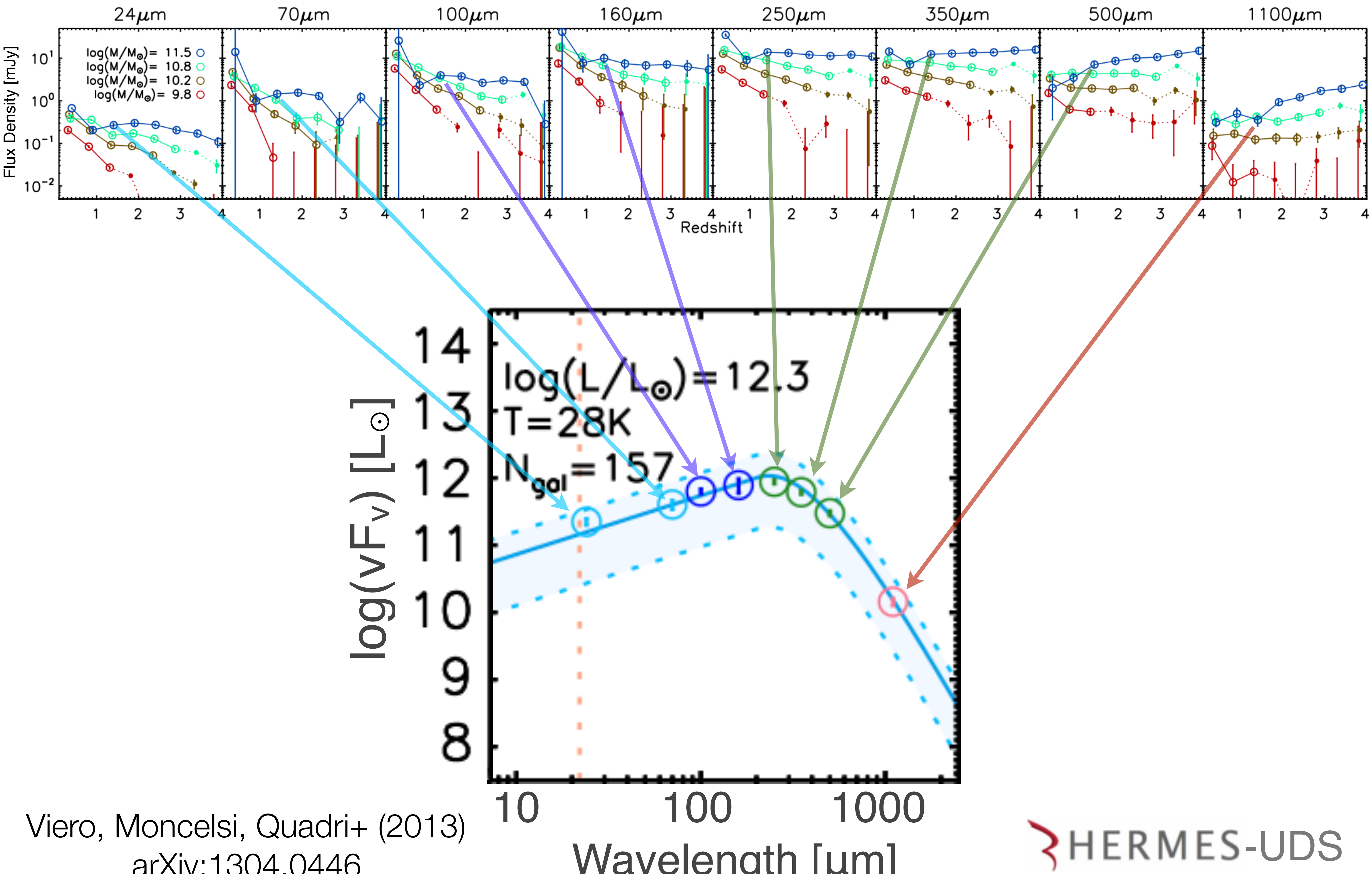
- UKIDSS/UDS [2/3 deg$^2$]
  - uBVRizJHK + IRAC ch1234
  - K-band magnitude cut 24 AB
  - 81,000 sources in ~0.63 deg$^2$
- redshifts - EAZY (Brammer 2008)
- masses - FAST (Kriek 2009)

HERMES

maps (HerMES; Oliver et al. 2012)

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

# SIMSTACK of Galaxies by Stellar Mass and Redshift

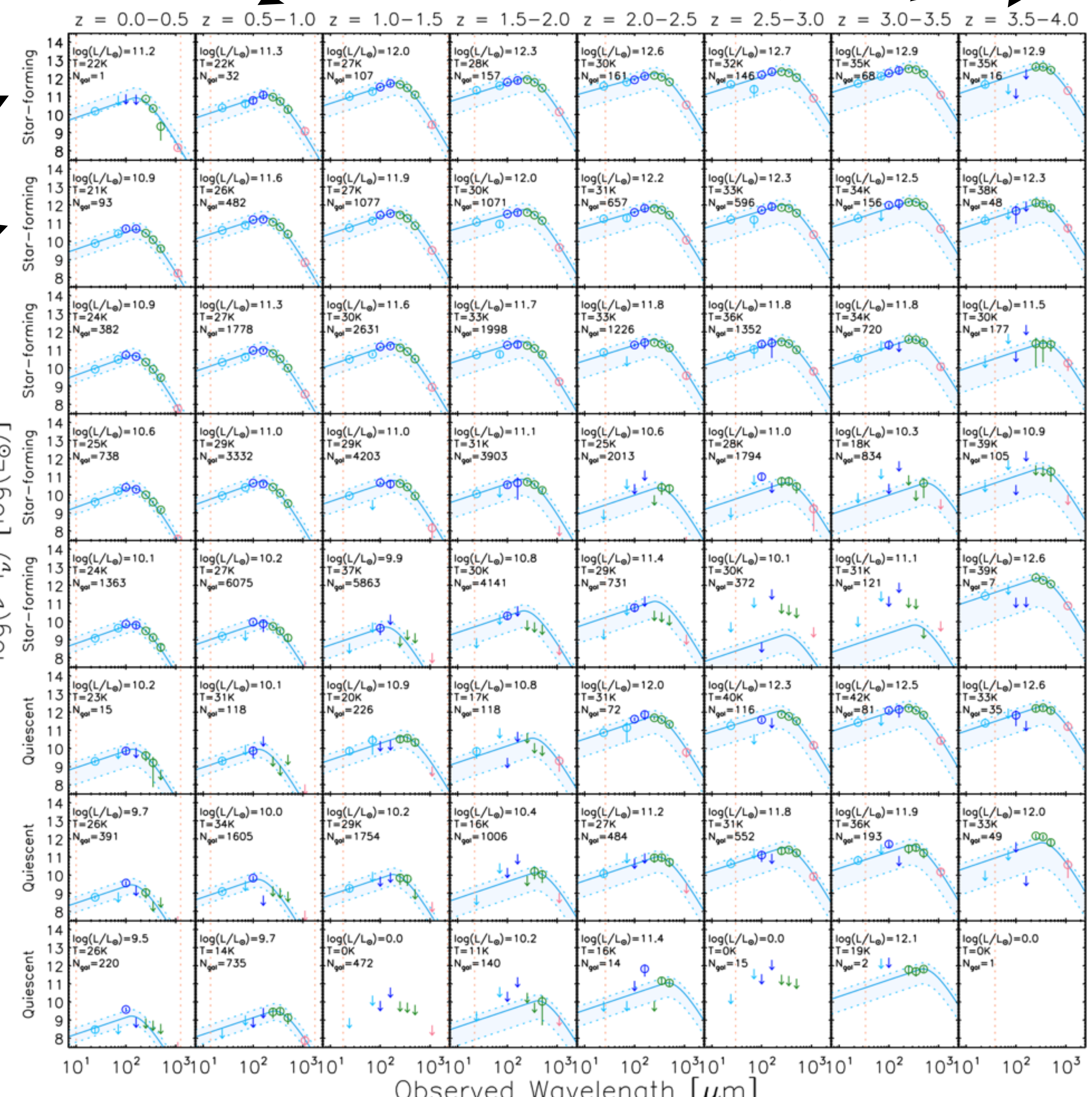



Viero, Moncelsi, Quadri+ (2013)
arXiv:1304.0446

# SEDS

redshift slices

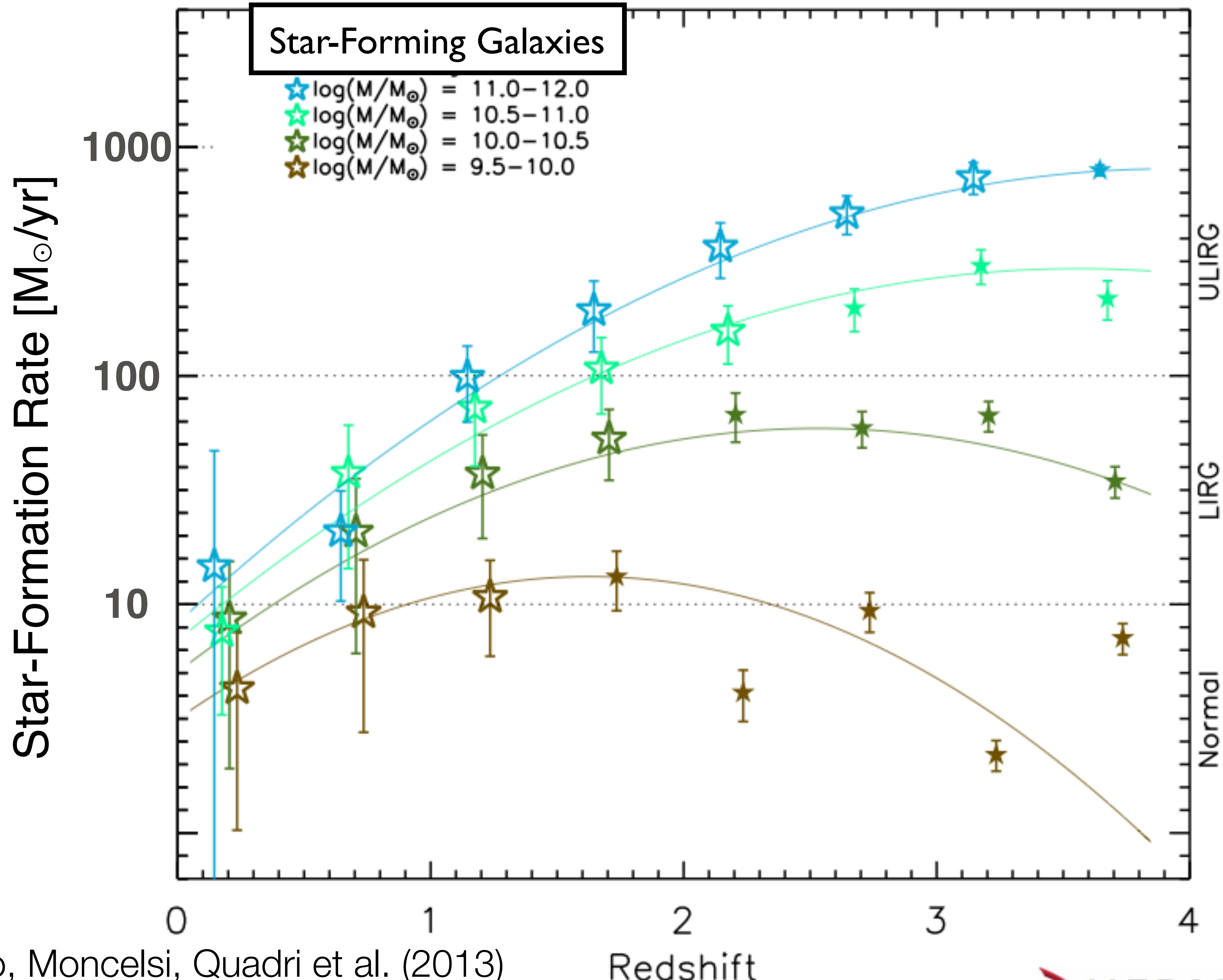
stellar mass slices




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

HERMES-UDS

# Average Galaxy Infrared Luminosity by Stellar Mass and Redshift




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

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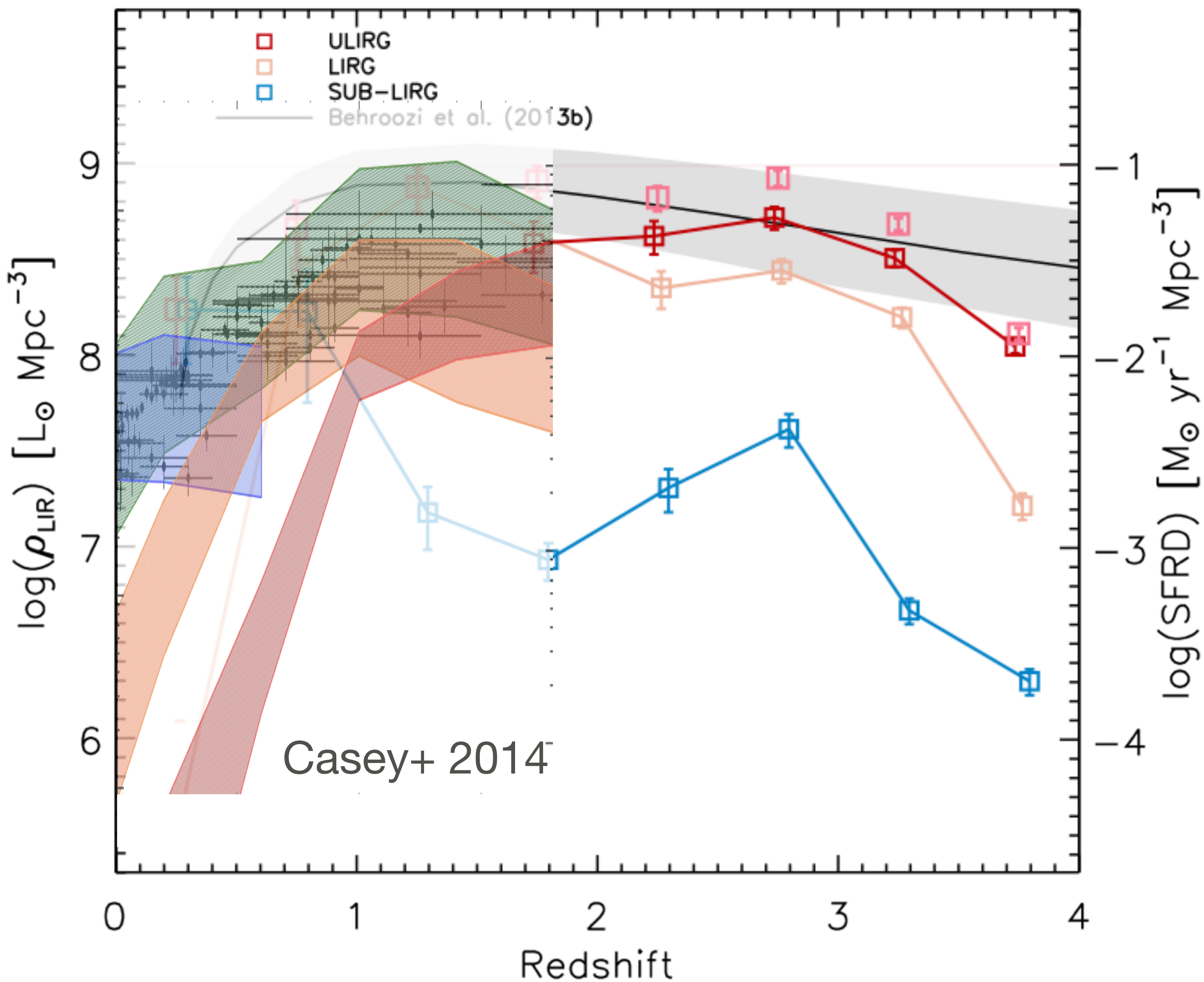
# Motivation Recap

1. History of Cosmic Star Formation
2. Origin of the CIB
3. Growth of Stellar Mass

# Stacked Infrared Luminosity Density




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

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# Motivation Recap

1. History of Cosmic Star Formation
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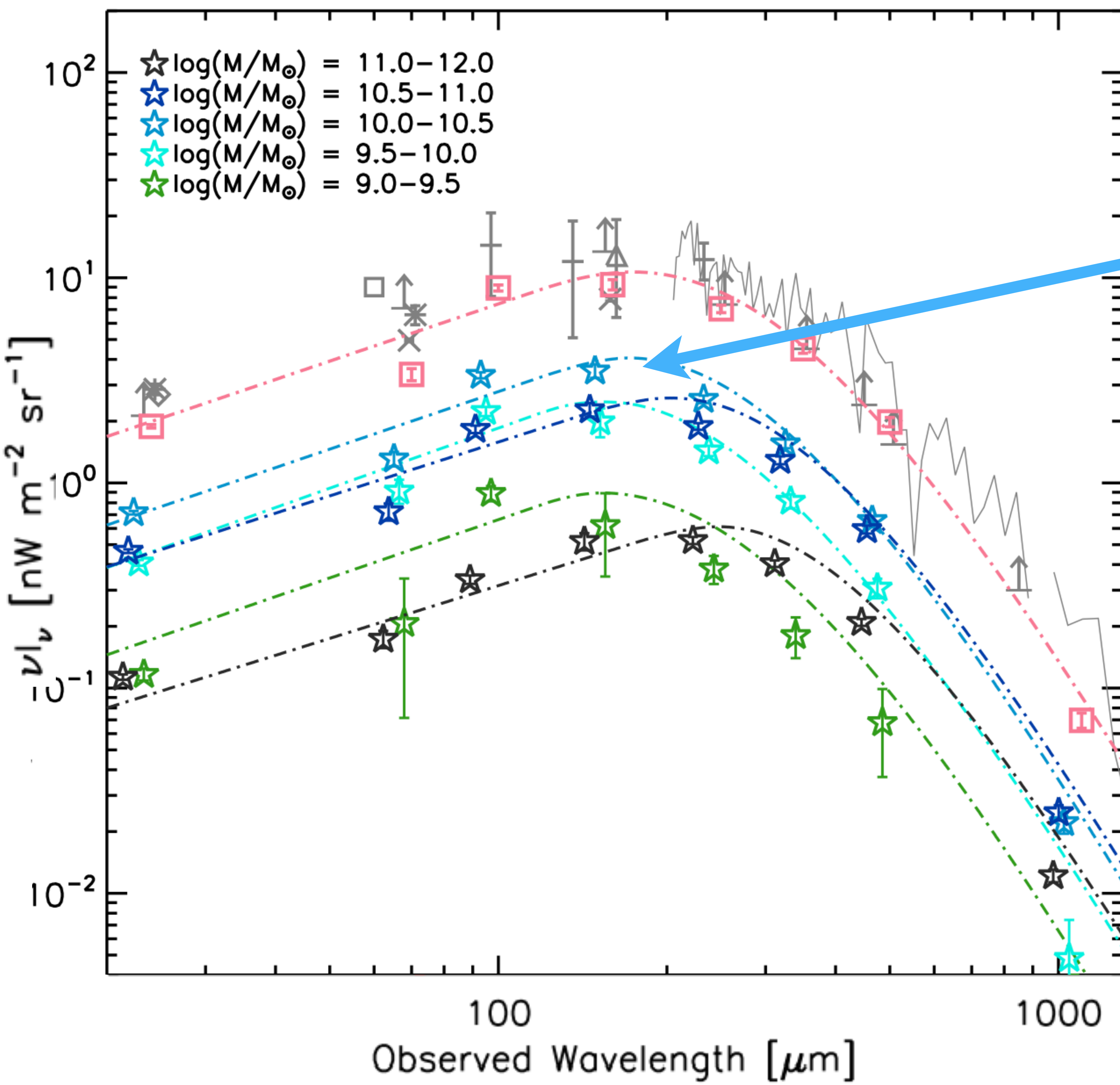
# Stacked CIB




~70% at SPIRE wavelengths

log(M/M$_\odot$~10-11)
i.e., M ≲ M$_*$

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

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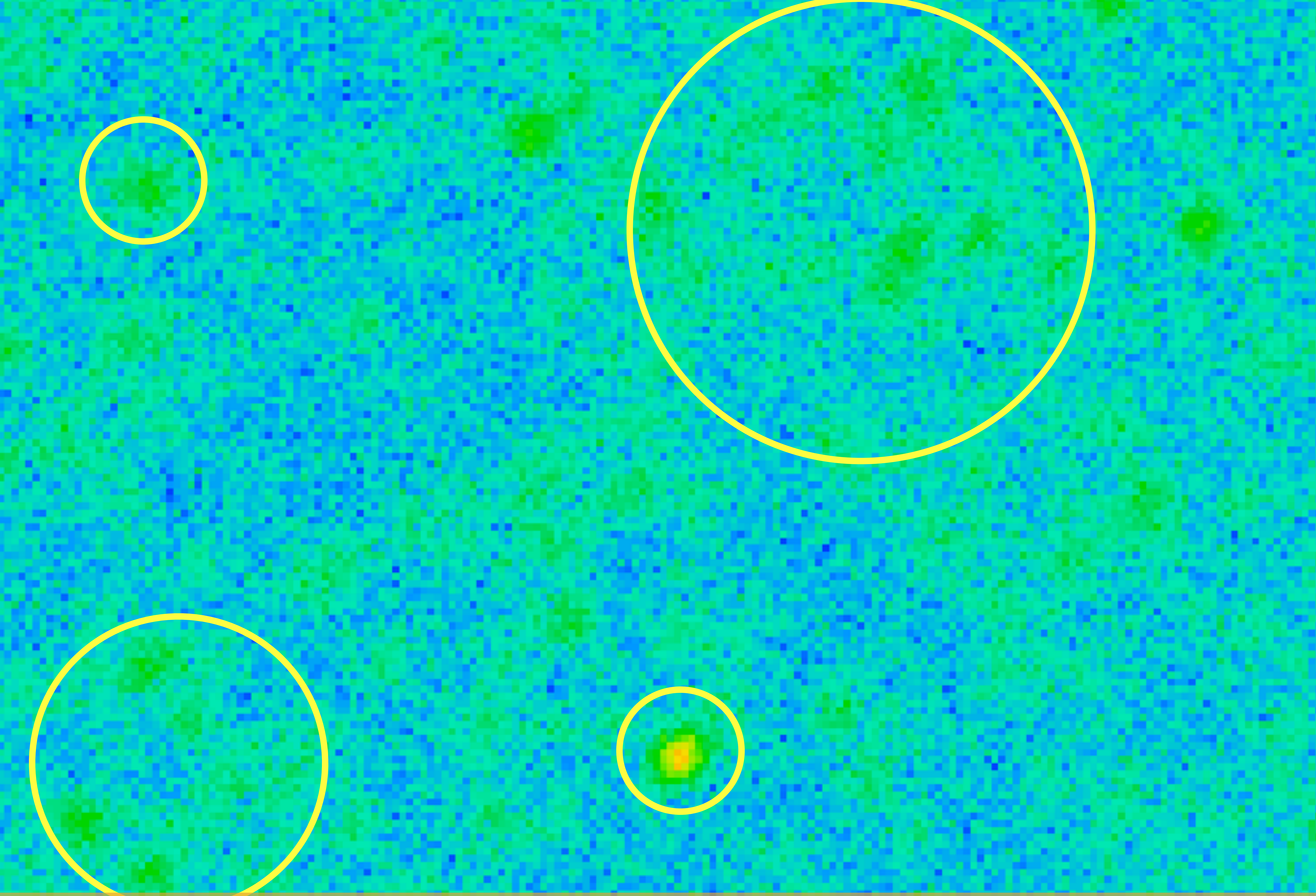
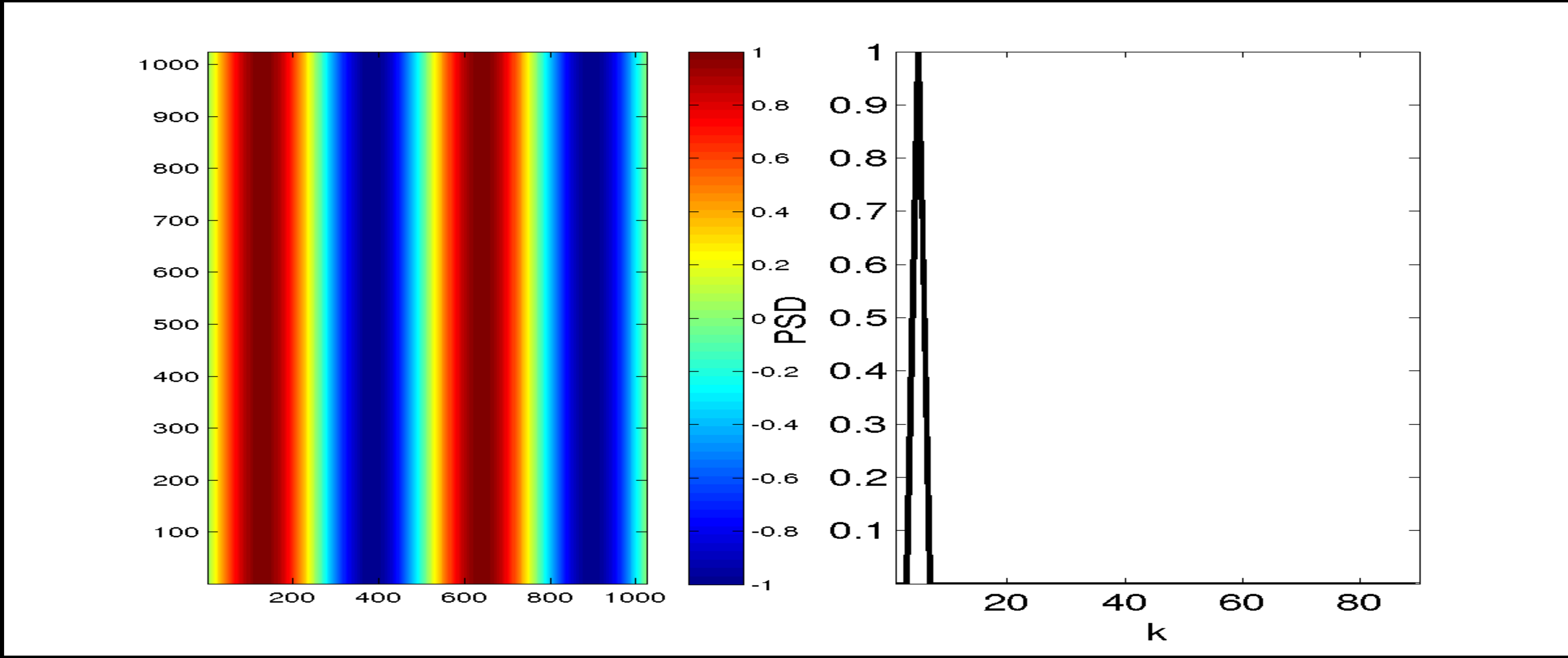


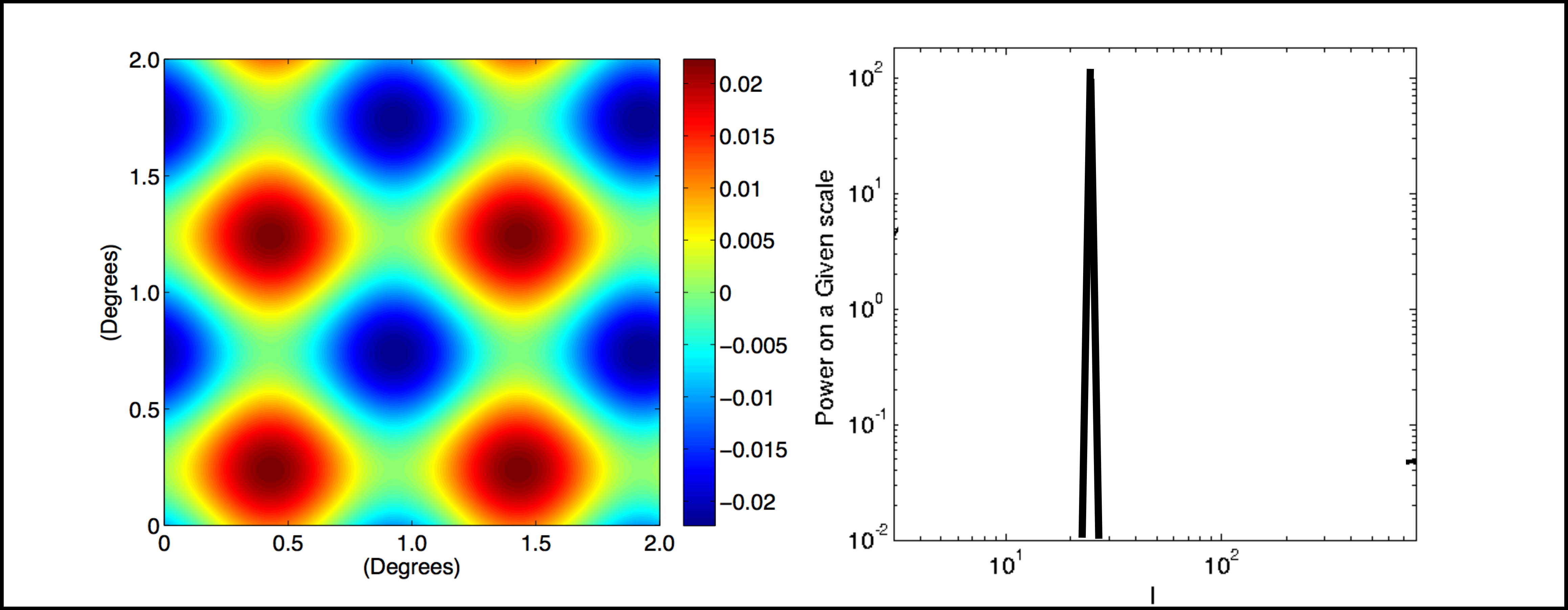
Power Spectrum of Background Fluctuations

# Power Spectrum



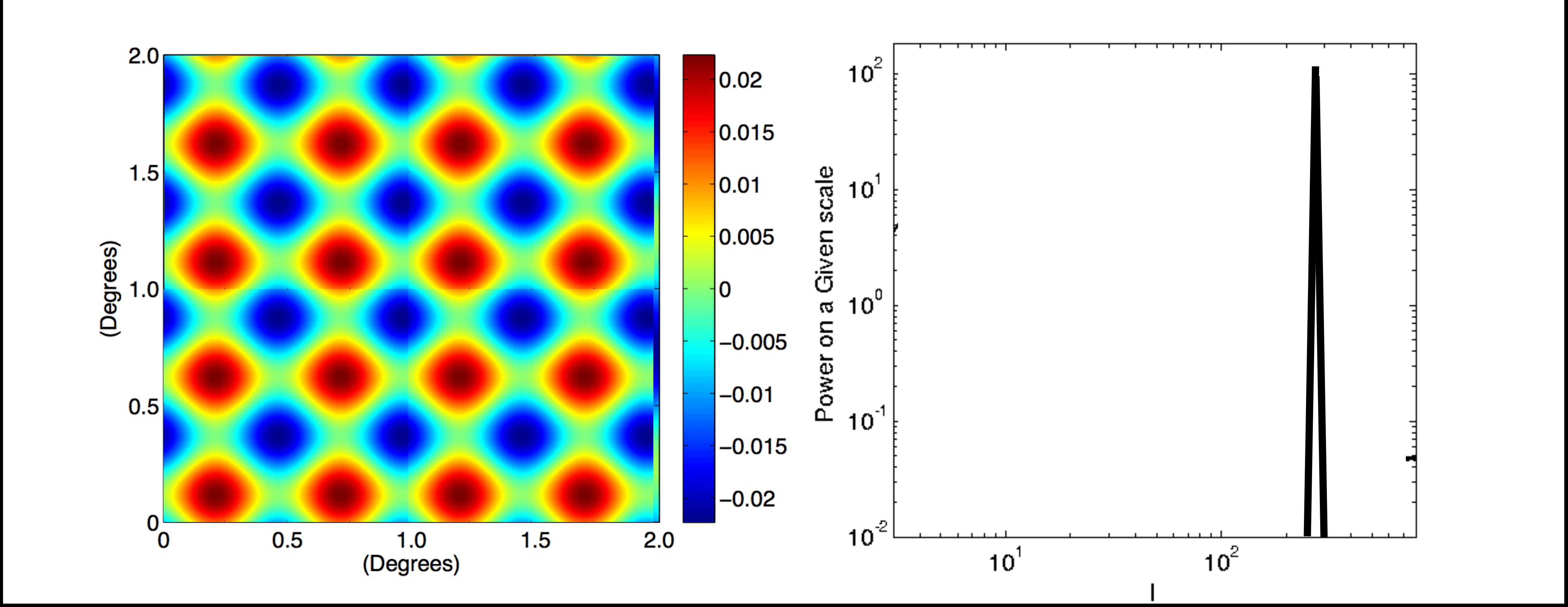

Phil Korngut (Caltech)

# Power Spectrum



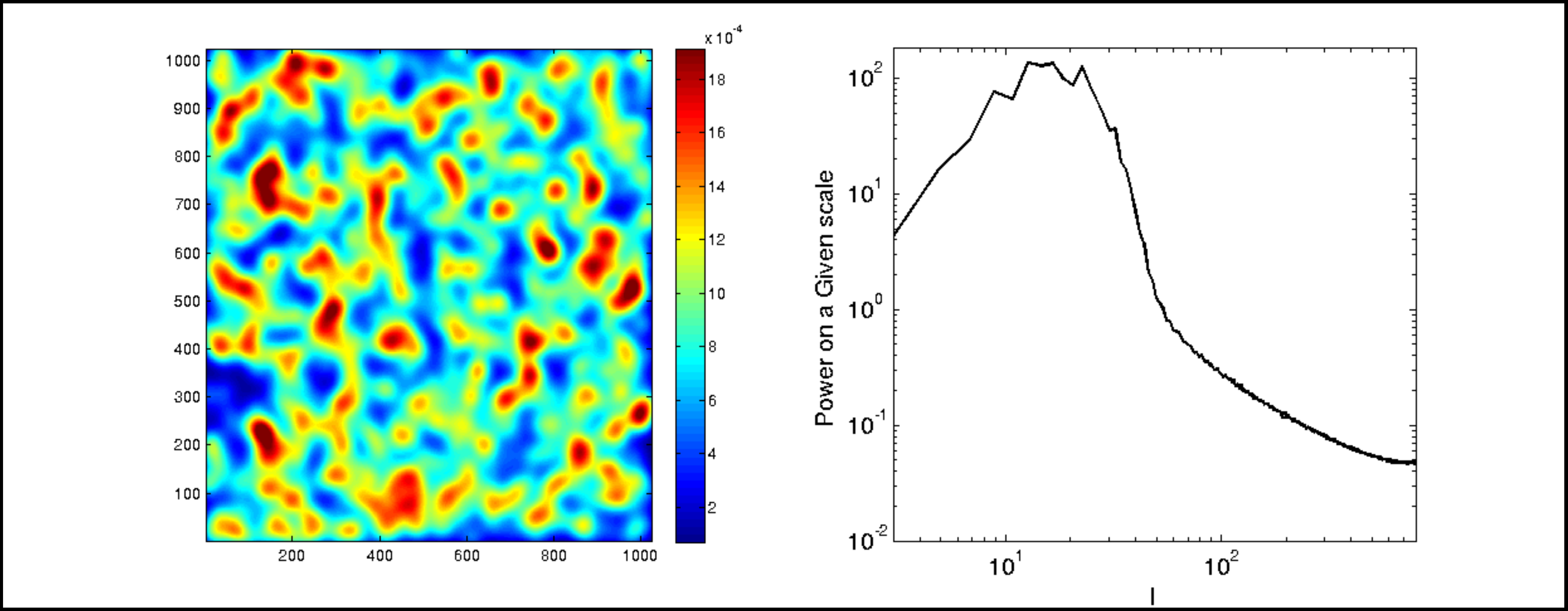

Phil Korngut (Caltech)

# Power Spectrum




Phil Korngut (Caltech)

# Power Spectrum




Phil Korngut (Caltech)

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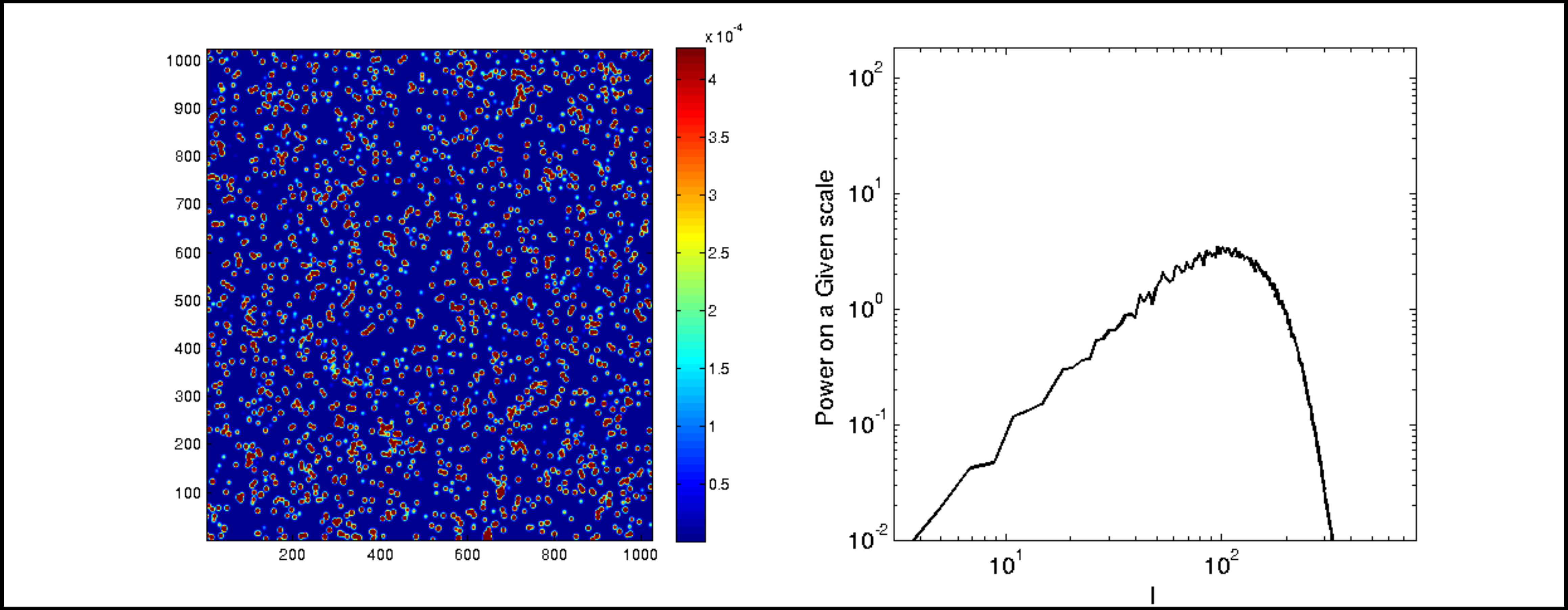
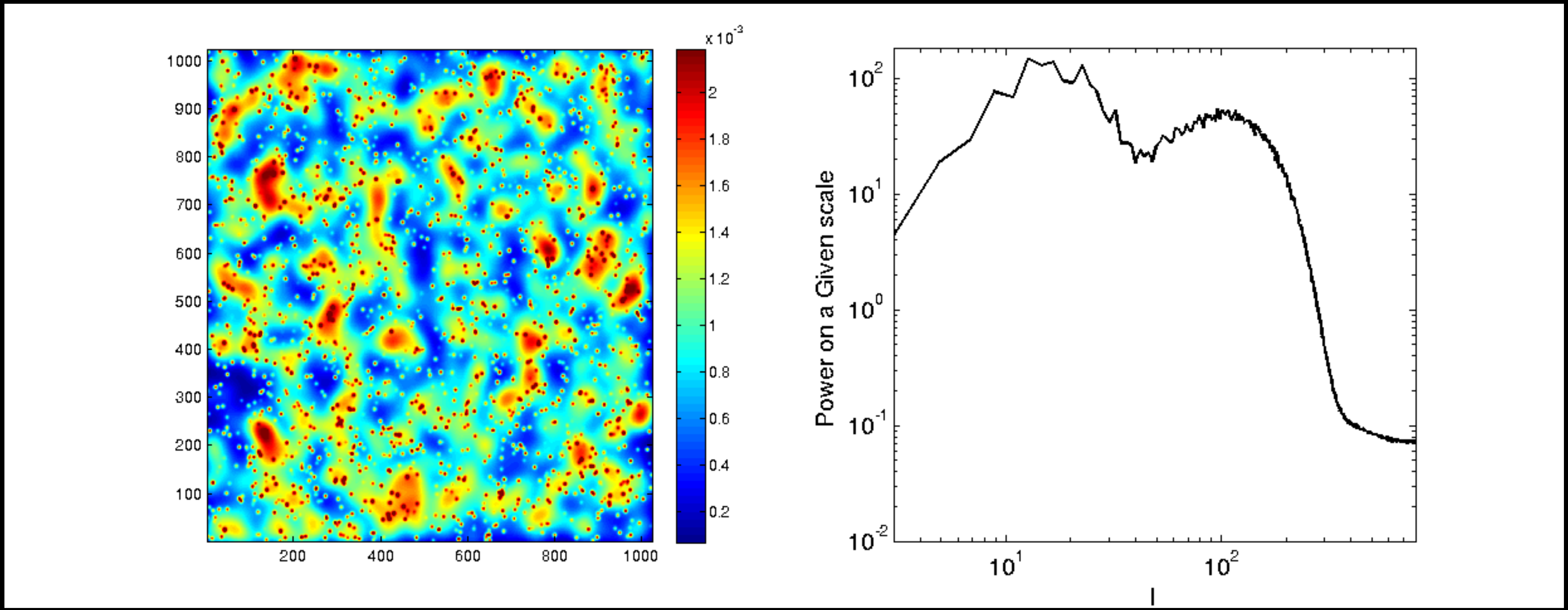


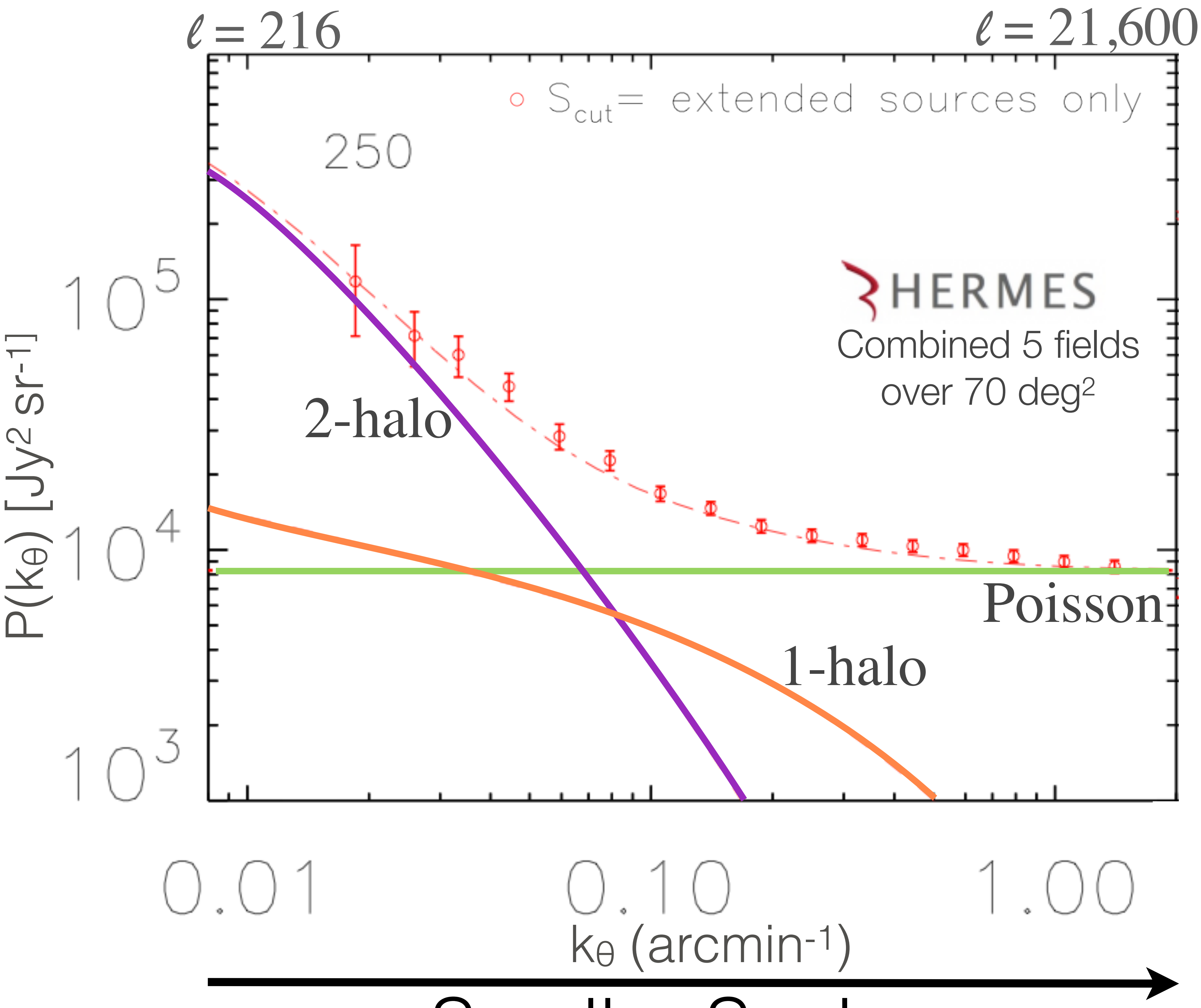

Phil Korngut (Caltech)

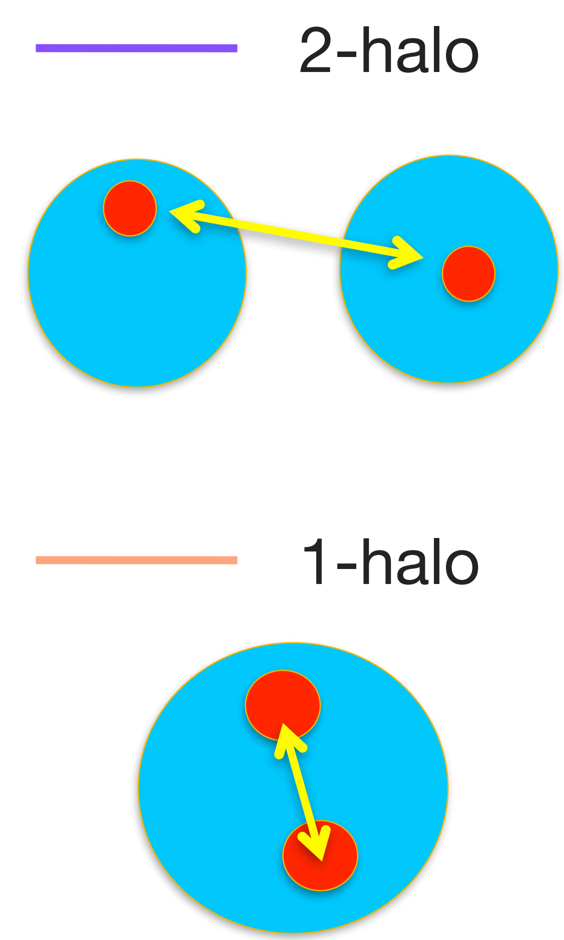
# Power Spectrum




Phil Korngut (Caltech)

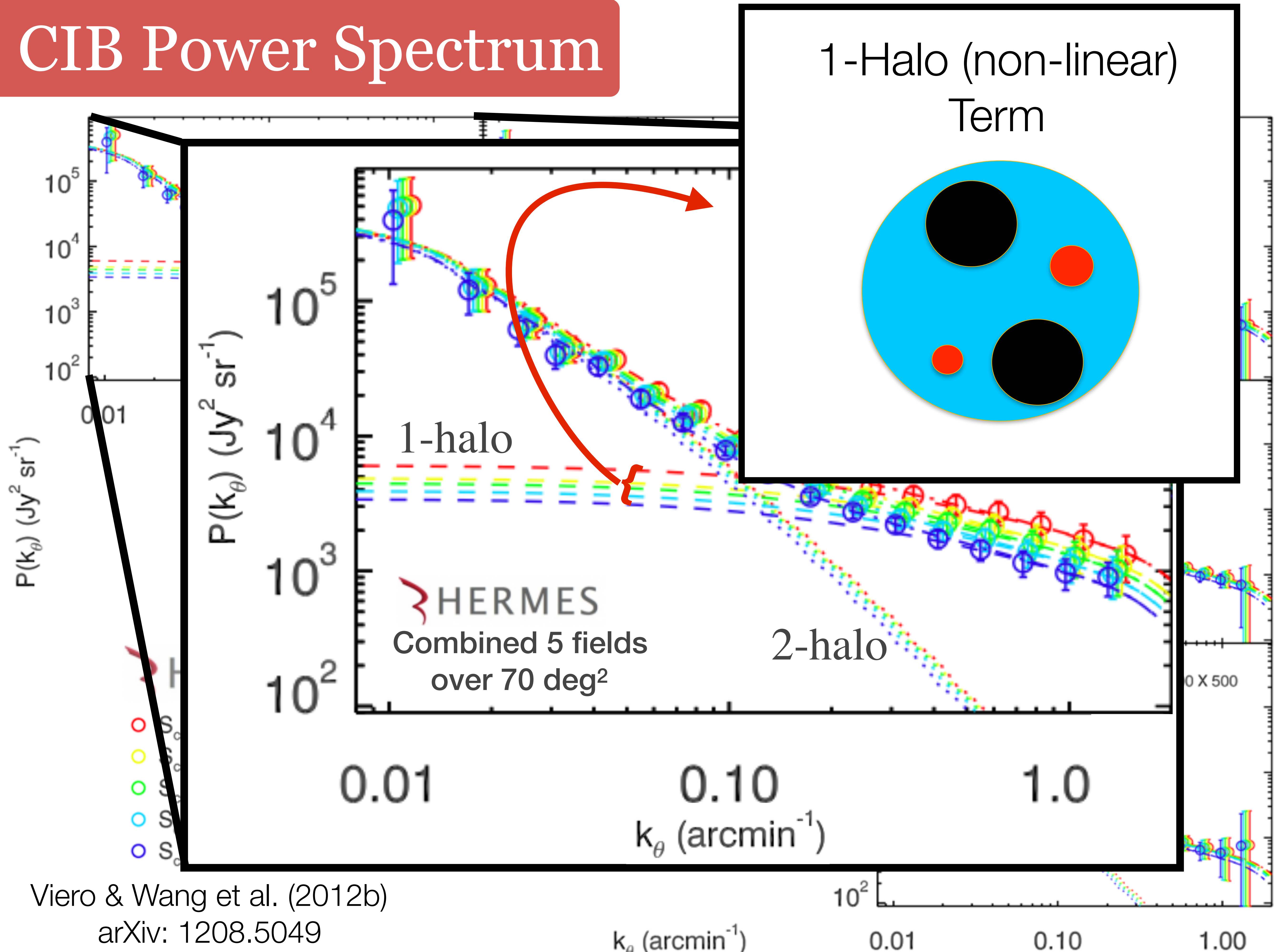
# CIB Power Spectrum




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

# CIB Power Spectrum




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

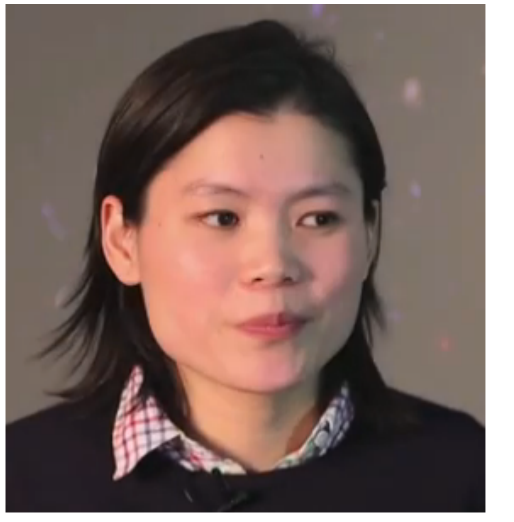
# Motivation Recap

1. History of Cosmic Star Formation
2. Origin of the CIB
3. Growth of Stellar Mass

# Halo Model (in a Nutshell)

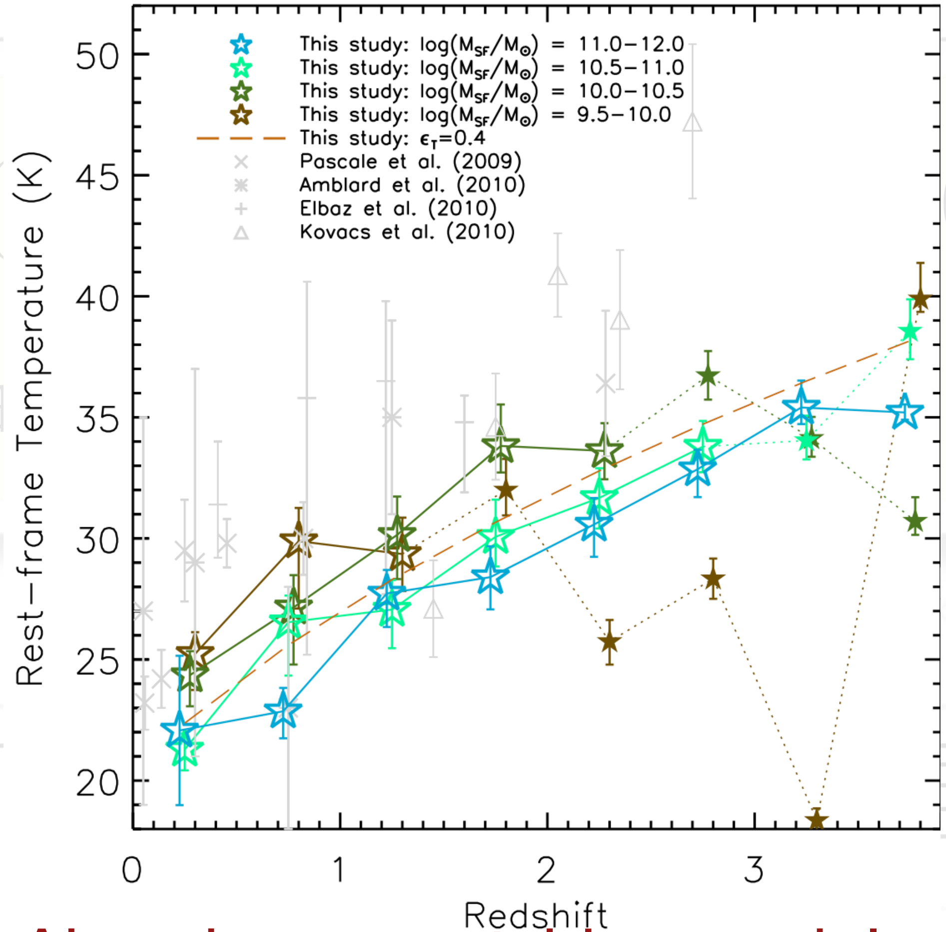
- Extension of Shang et al. (2012) Model
- Luminosity-Mass (L-M) Log-Normal Relationship
- Fit **all** auto- and cross-spectra, *and counts*, simultaneously
- Used a single (just cold) and double component (warm and cold) thermal SED, with and without evolution of Temperature with redshift

Halo Model: Lingyu Wang (Durham)

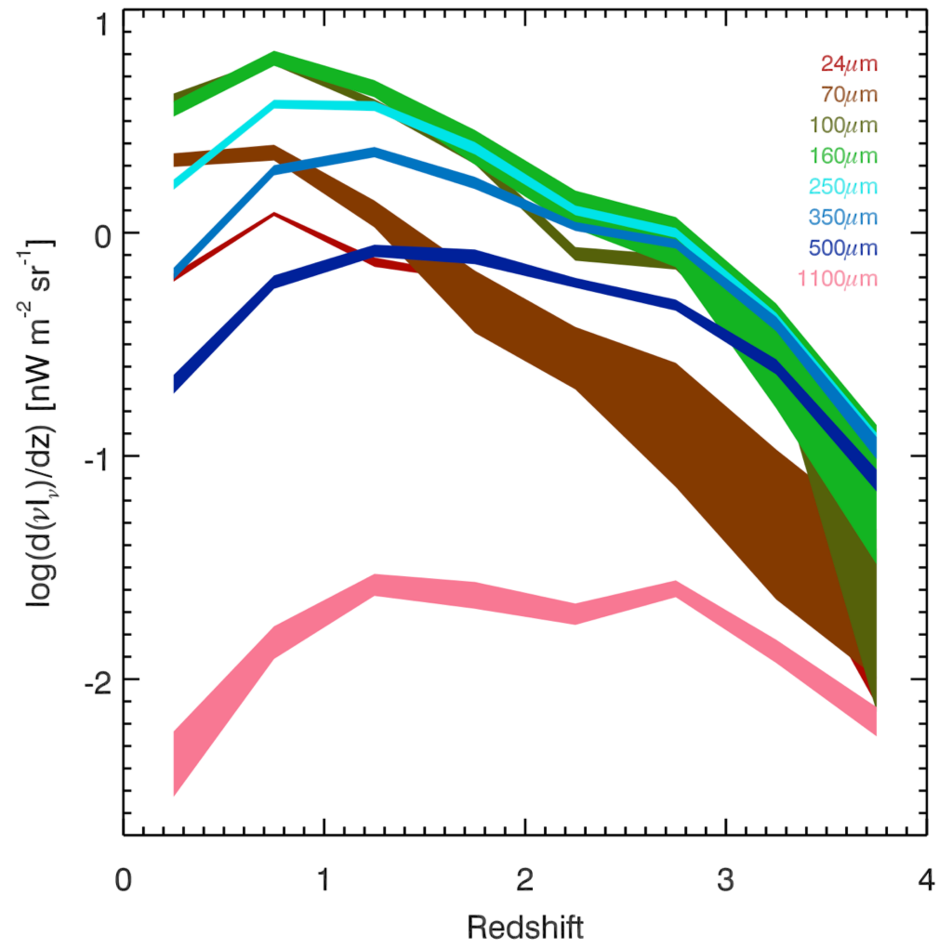


# From Stacking Results!

## Stacked Temperature




## Redshift distribution of flux



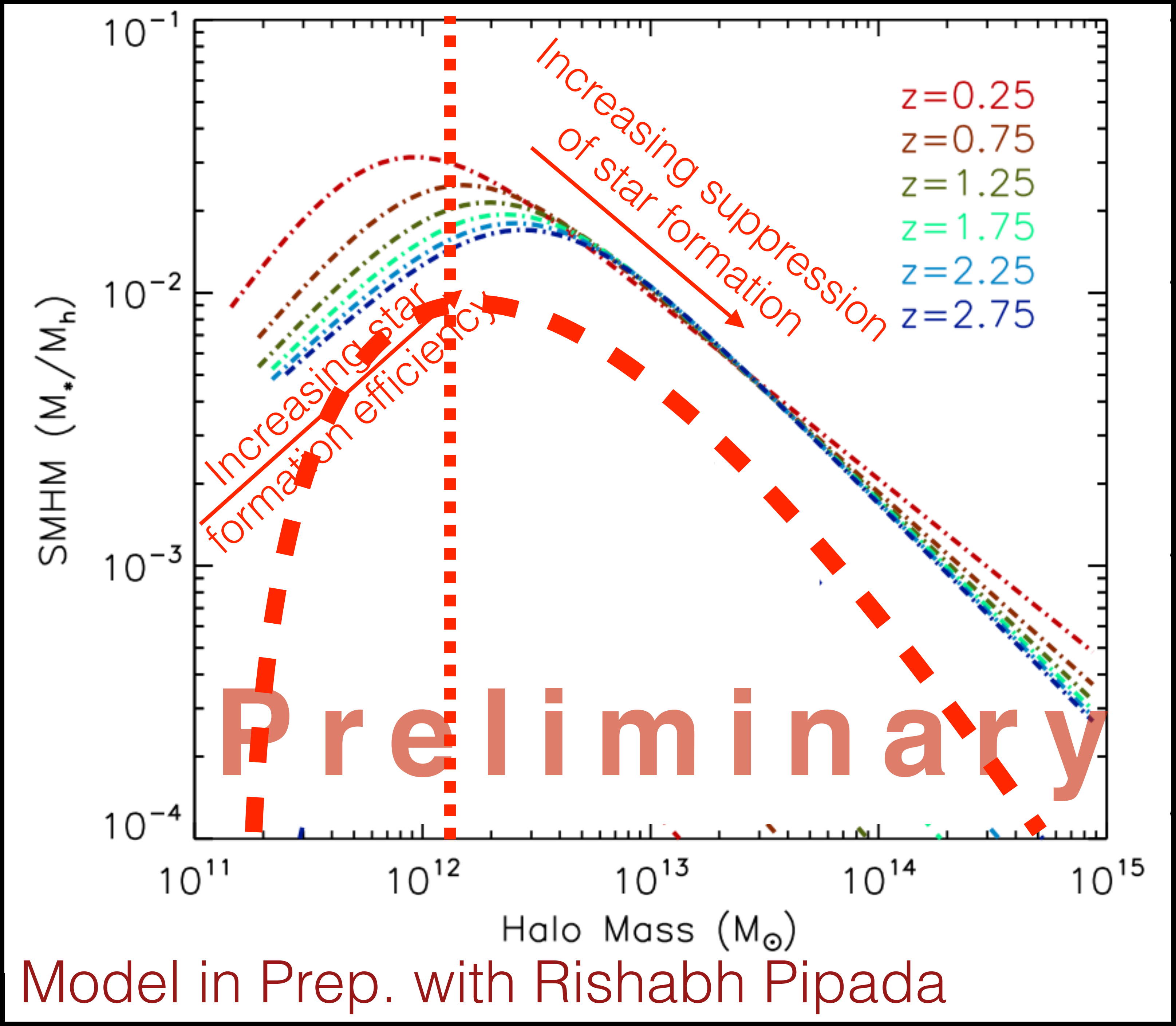

Abundance-matching model
with Rishabh Pipada in prep.

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

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

# Connecting SF to Stellar and Halo Mass

Can we use stacked infrared luminosities to understand the role of environment in the growth of stellar mass?




Halo Mass Function from Moster+(2012)

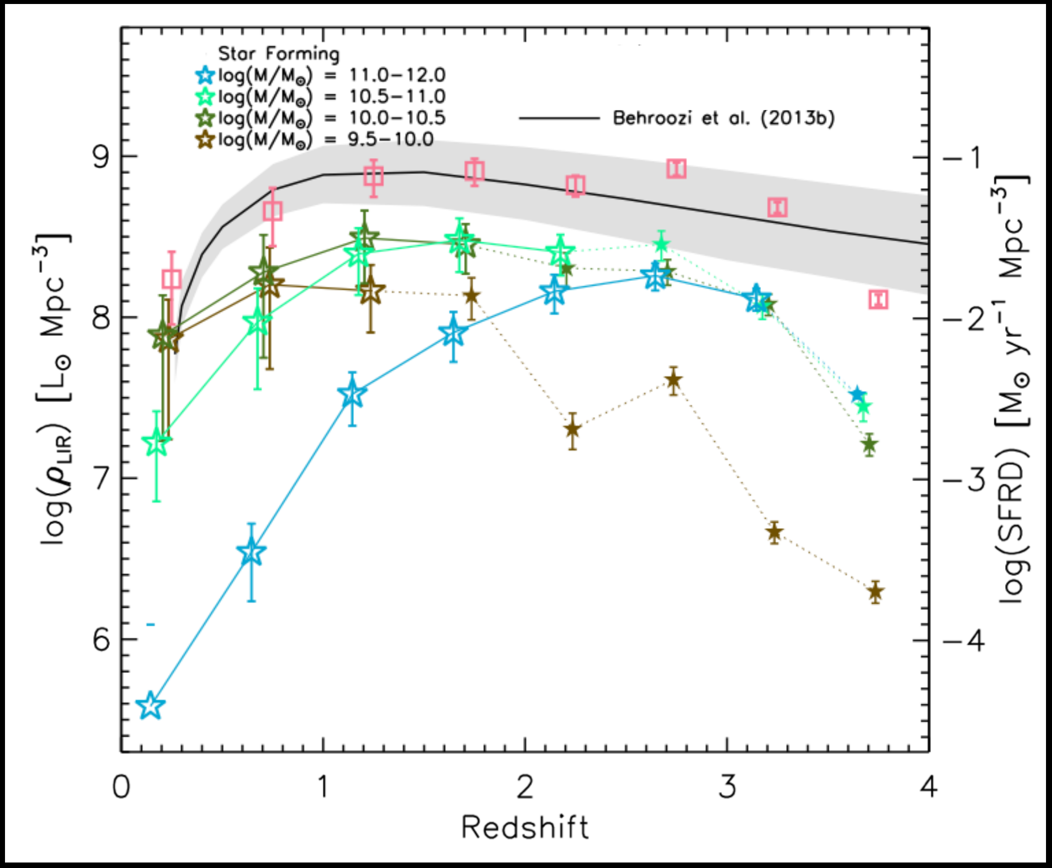
$L_{IR}(M_{stellar}, z)$ -> SFR from Viero+(2013b)

# Summary

## 1. History of Cosmic Star Formation

- The cosmic star formation rate density can be traced to high redshift, without having to correct for extinction, in the infrared.

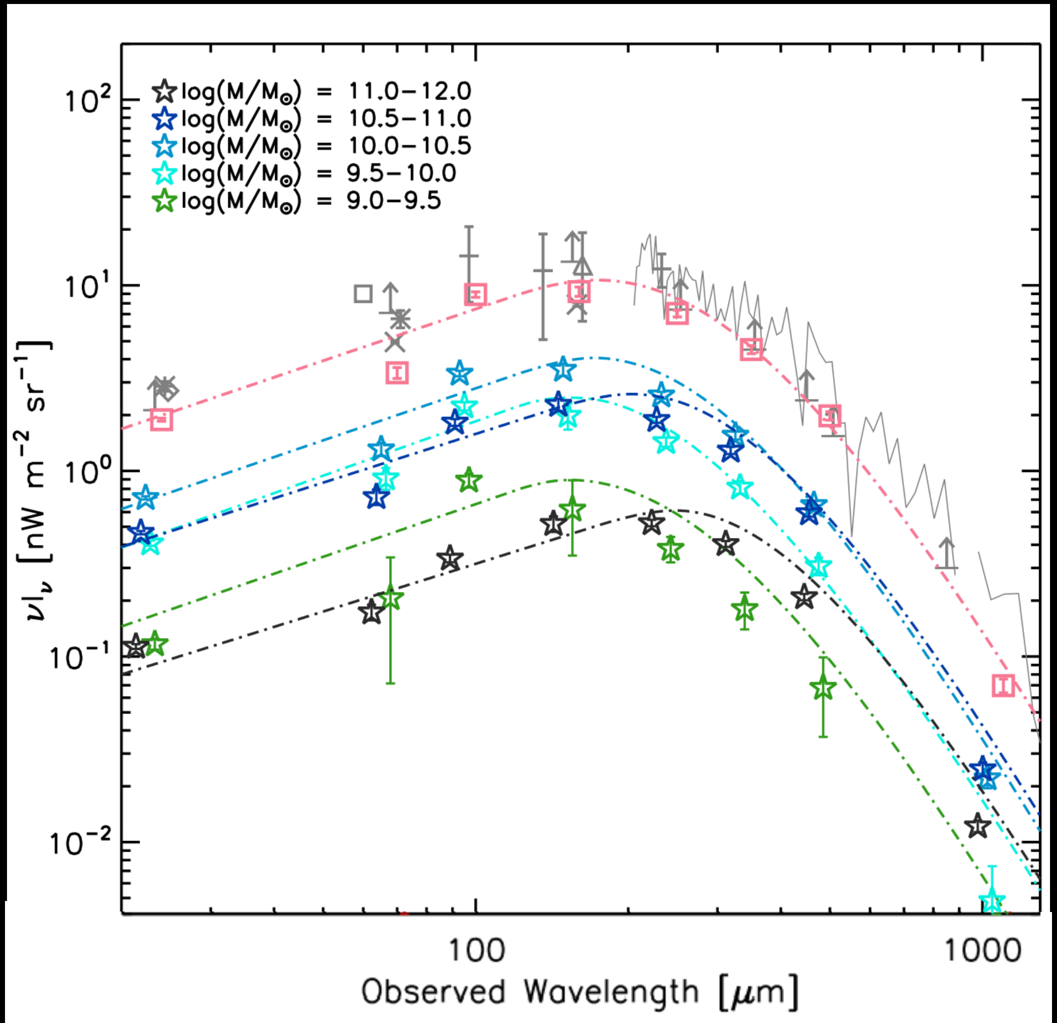
- Star formation is dominated by
  - ⋆ “normal” galaxies to z≈1
  - ⋆ LIRGS between z≈1 - 2 or 3
  - ⋆ ULIRGS at higher-z.



# Summary

## 2. Origin of the CIB

- At least ~70% of the Infrared Background originates from well known optical galaxies
- ~90% of that flux density from galaxies with stellar mass log(M/M☉)=10-11.

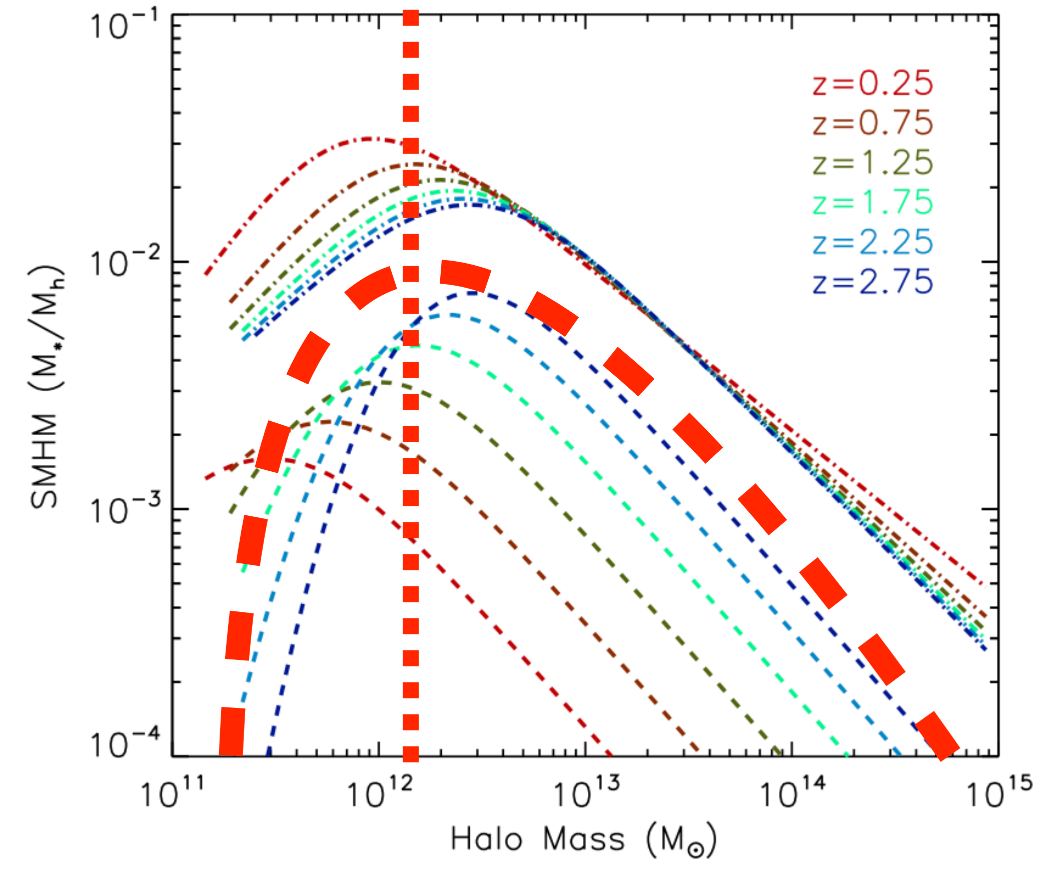


# Summary

## 3. Growth of Stellar Mass

- Halo masses of most efficient star-formation is
  - $\log(M/M_\odot) = 12.2 \pm 0.5$.

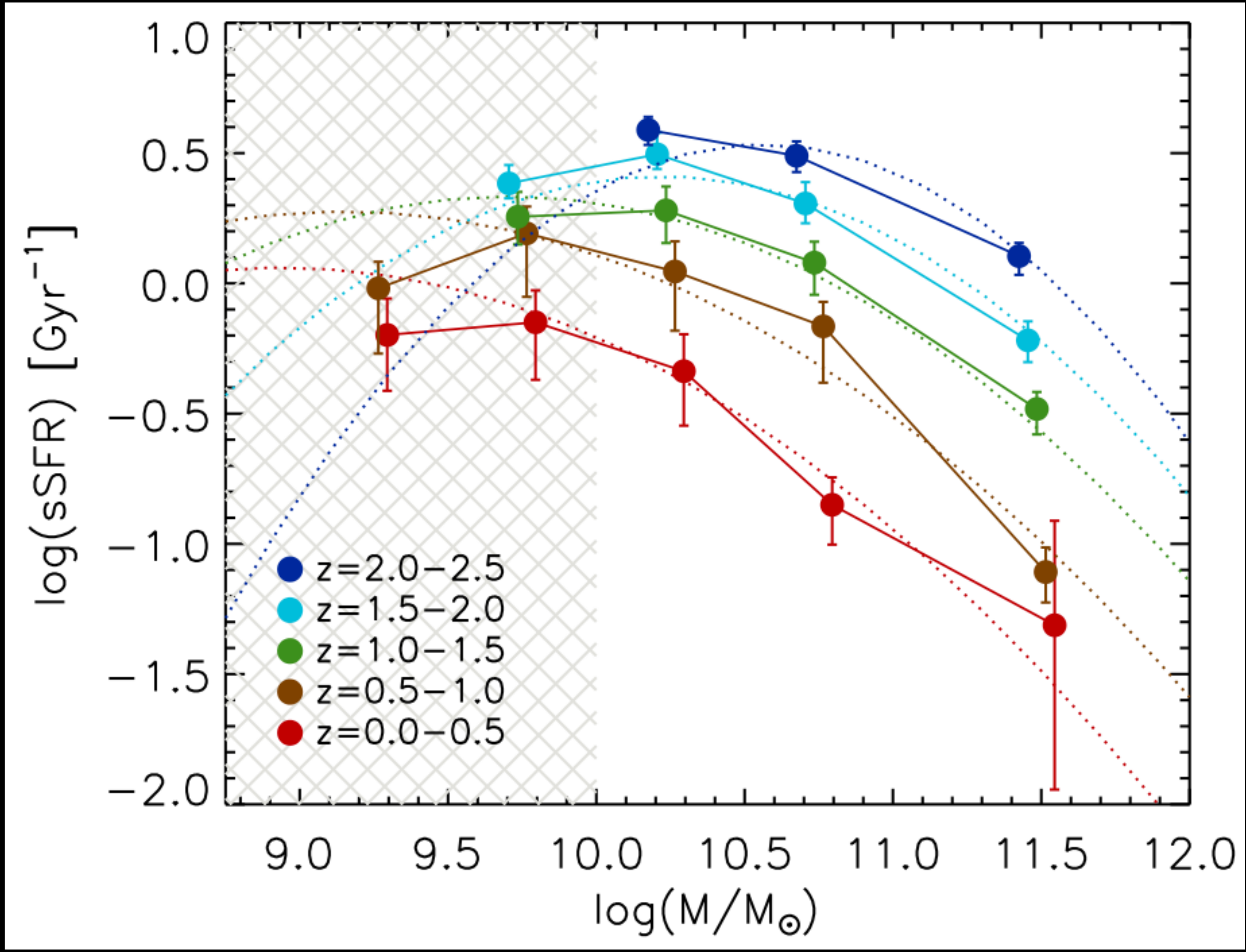
- Models to understand the growth of stellar mass and regulation of that growth are underway.



# Moving Forward

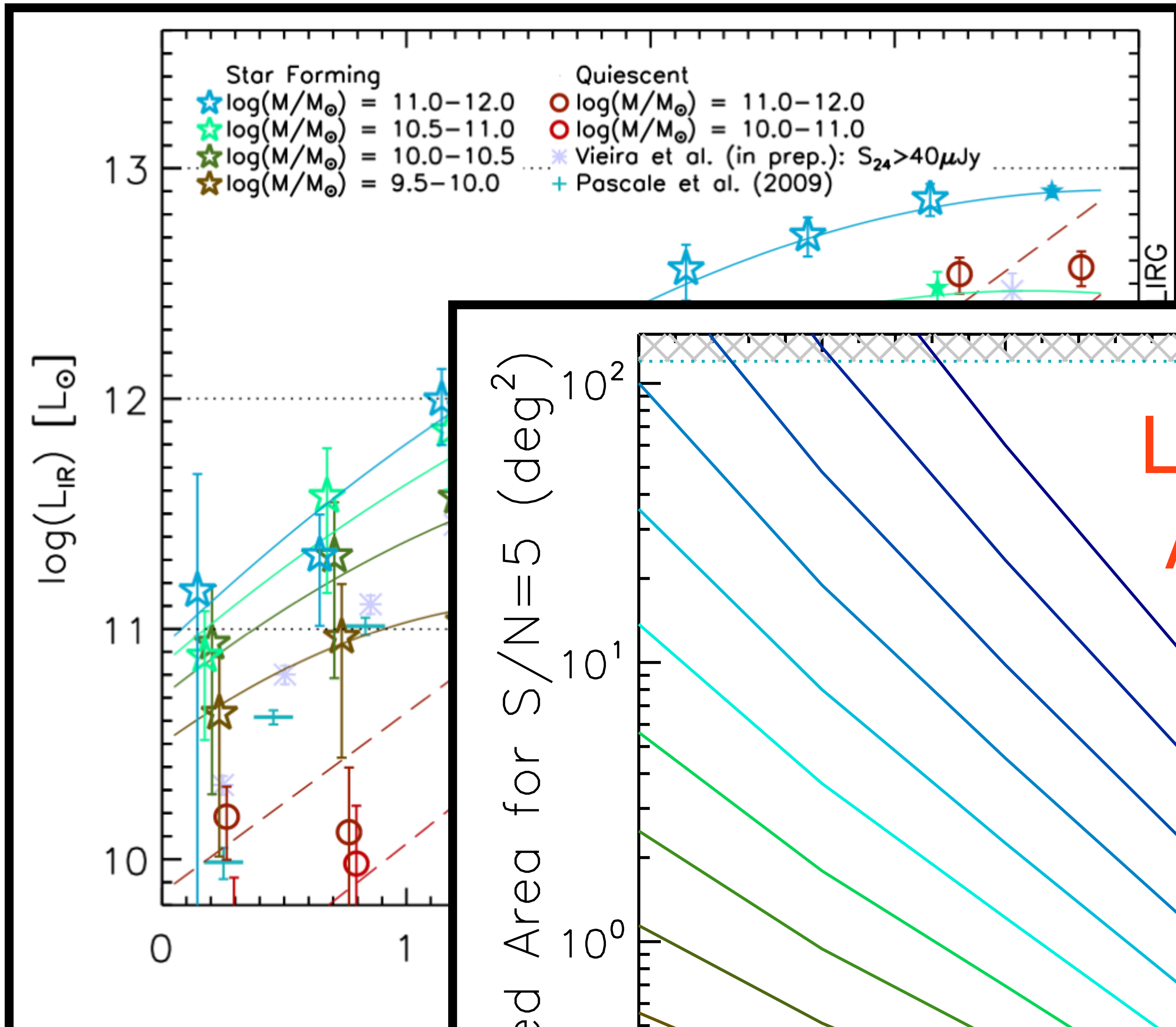
Galaxy Evolution models critically fail to match low mass galaxies at intermediate redshifts (e.g., Guo+ 2011, Weinmann+ 2011,2012)

They require accurate $L_{IR}$ & SFRs for this faint population, and that of their progenitors



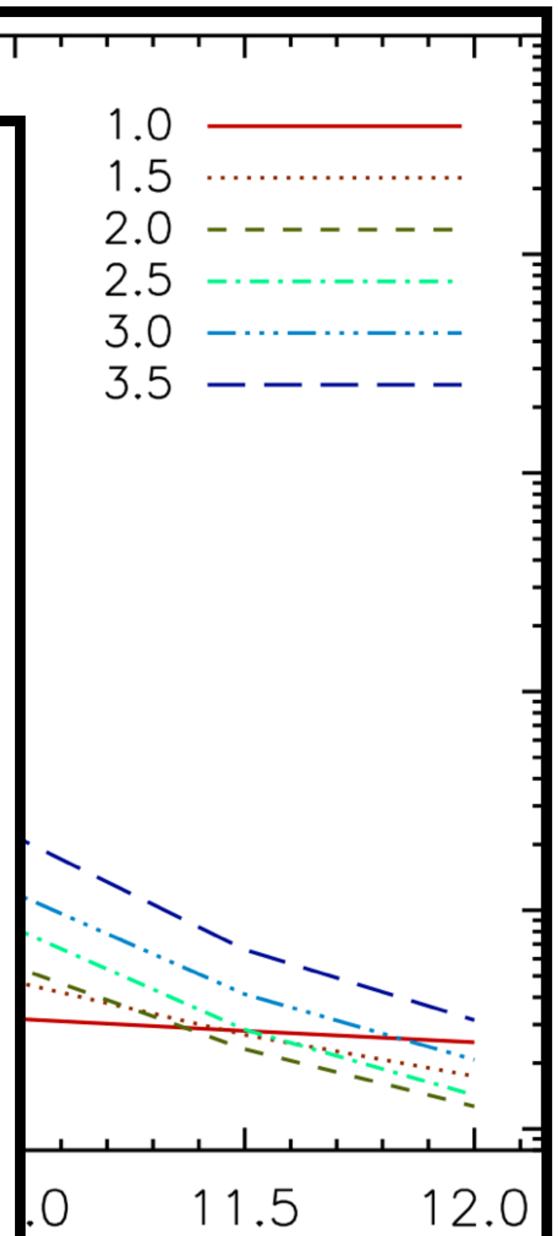

Arumugam, Viero, Quadri et al. (in prep.)

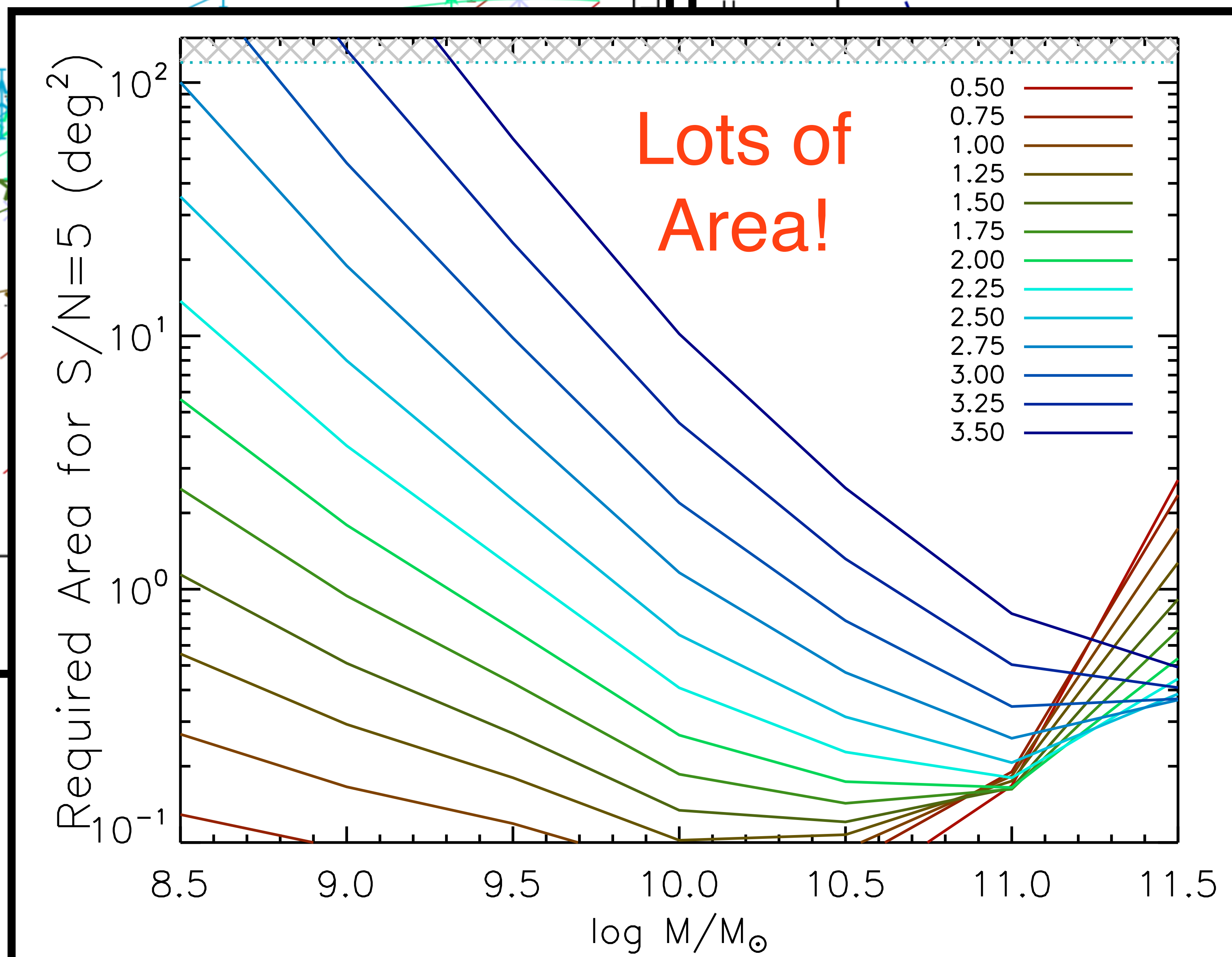
# Moving Forward



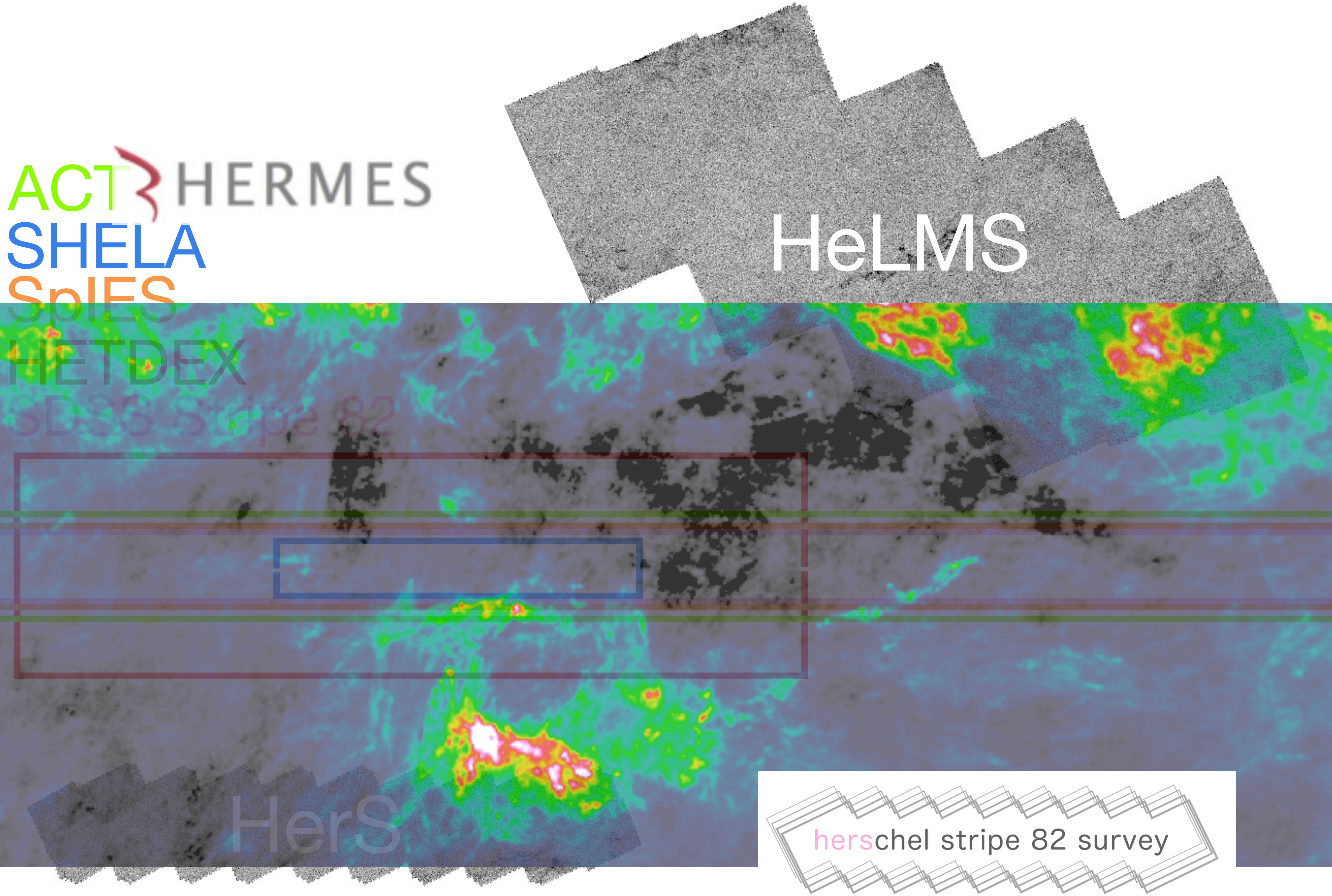

L-M*-z

Lots of sources to probe small masses

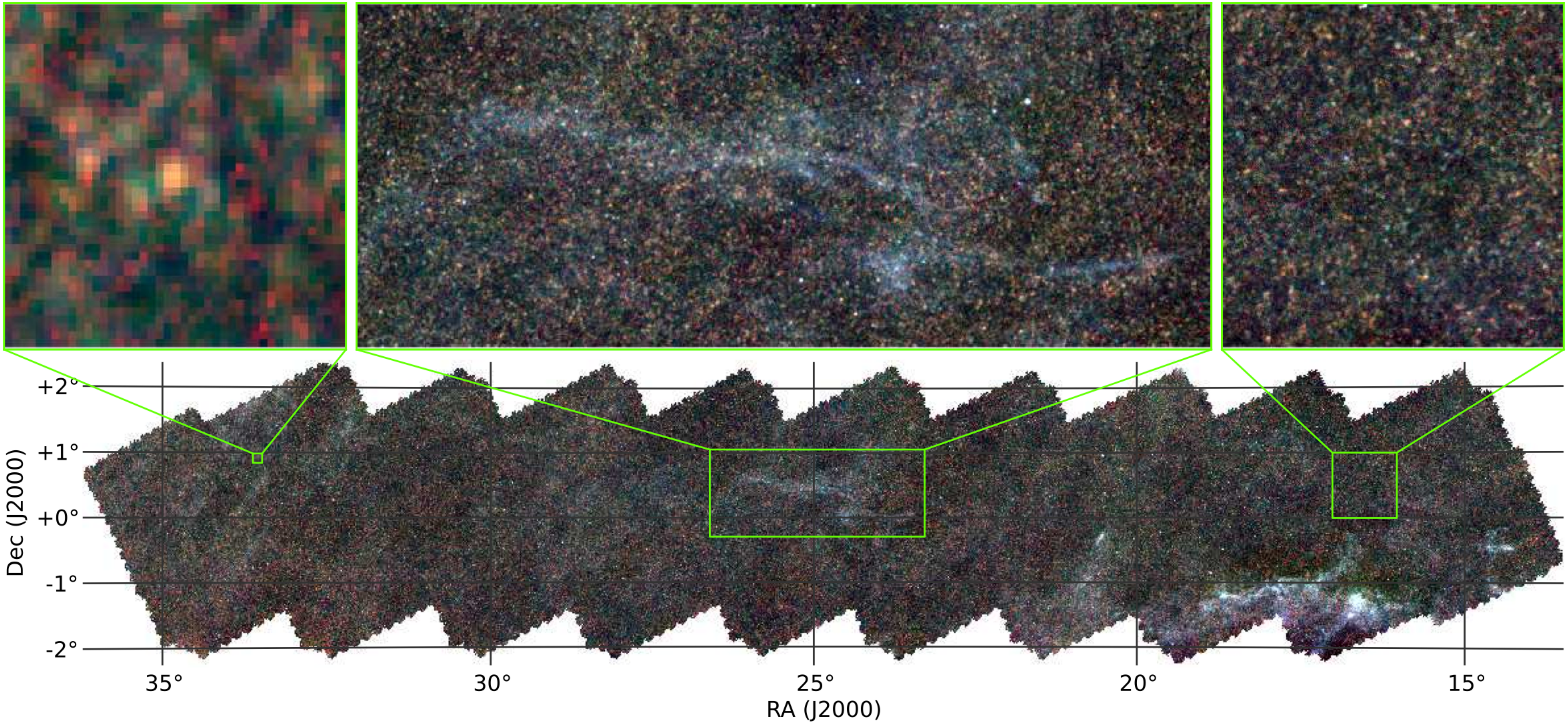



estimated using mass function of Muzzin et al. 2013



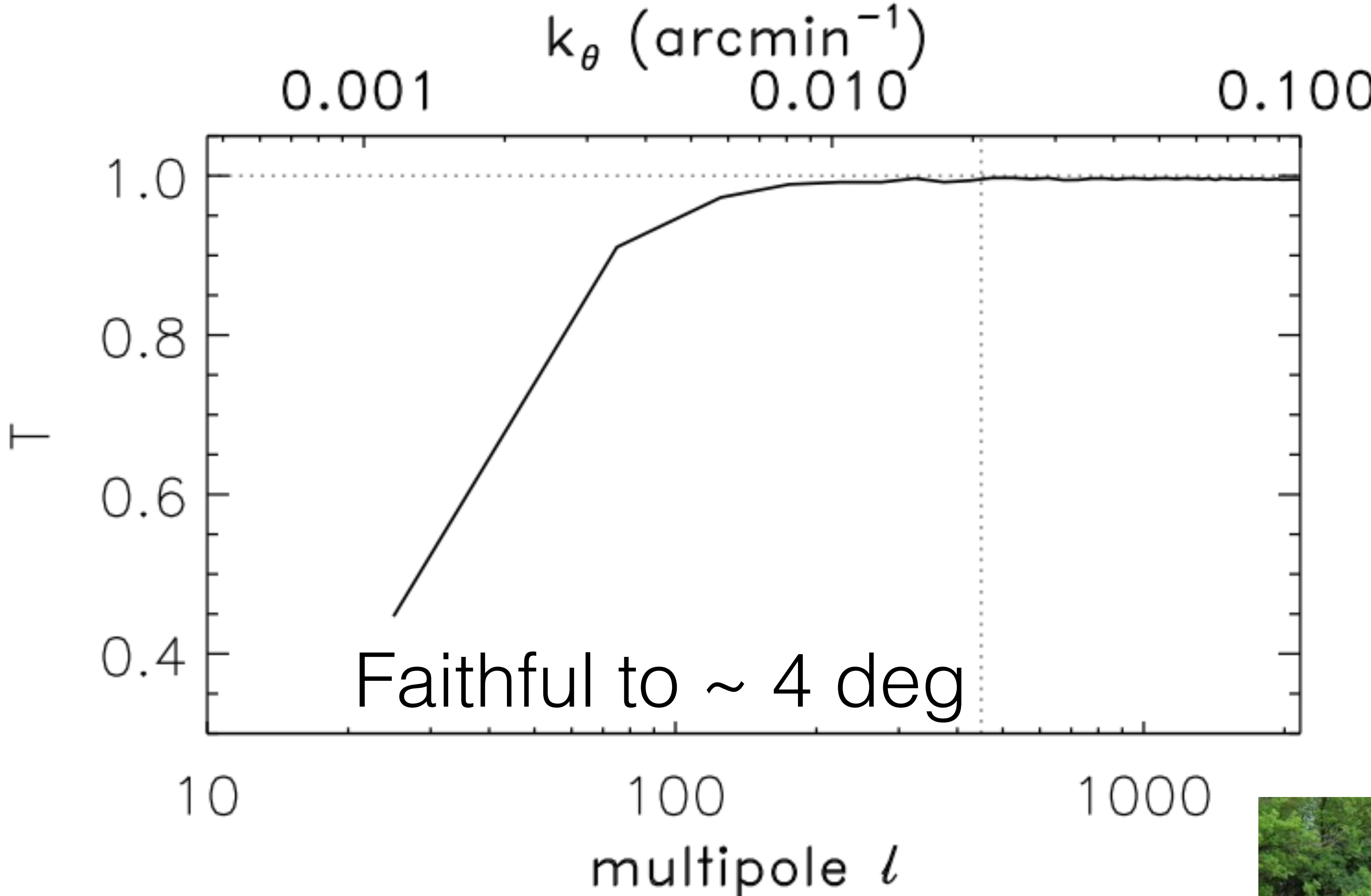
ACT
HERMES
SHELA
SpIES
HETDEX
SDSS Stripe 82
HeLMS
HerS
herschel stripe 82 survey




- HerS - 70 deg2 (~20 deg along S82)
- HeLMS - 280 deg2 (~25 deg along S82)

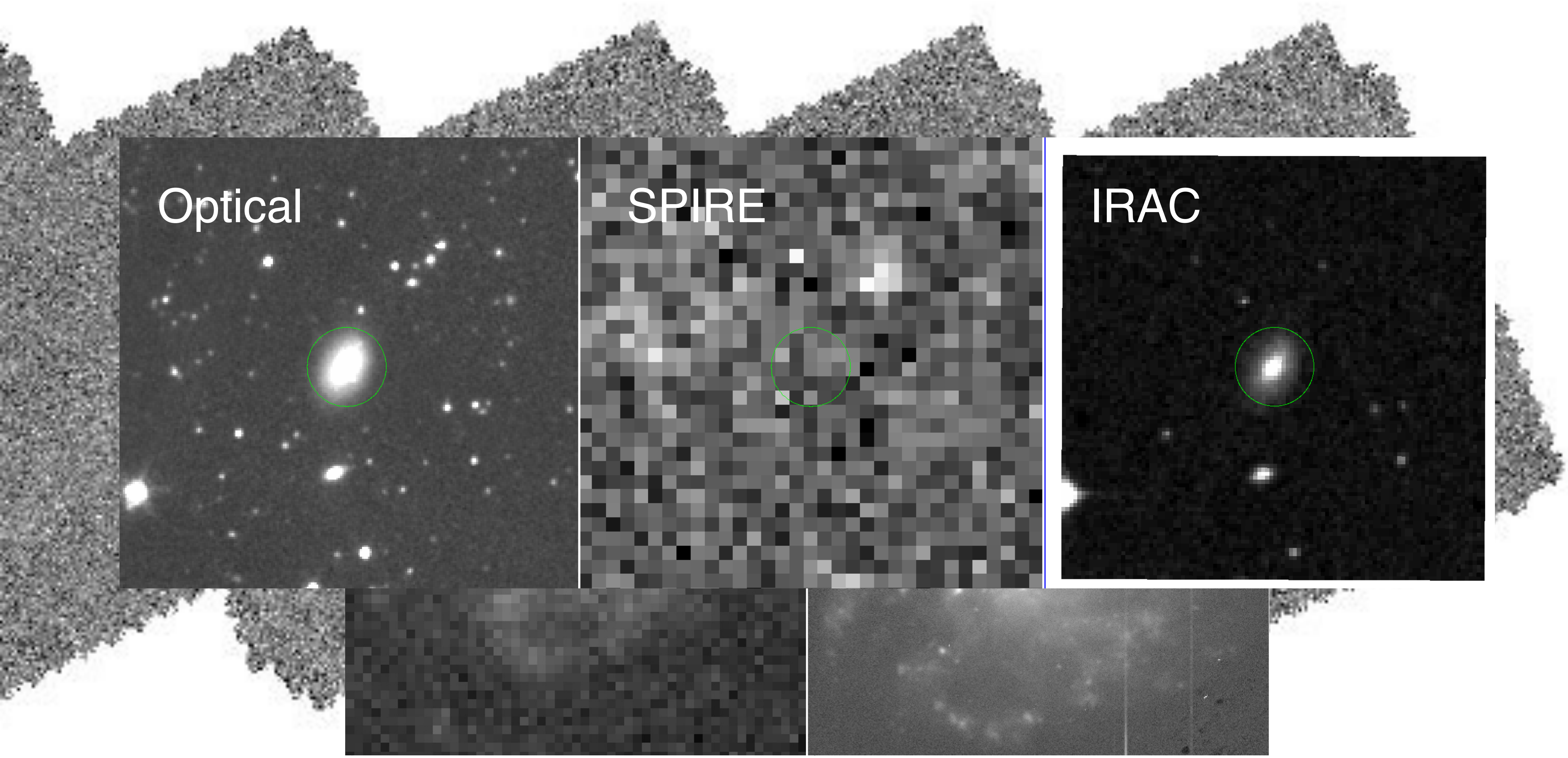
SANEPIC maps made by Viktoria Asboth (UBC) and the SMAP team.

# Transfer Function



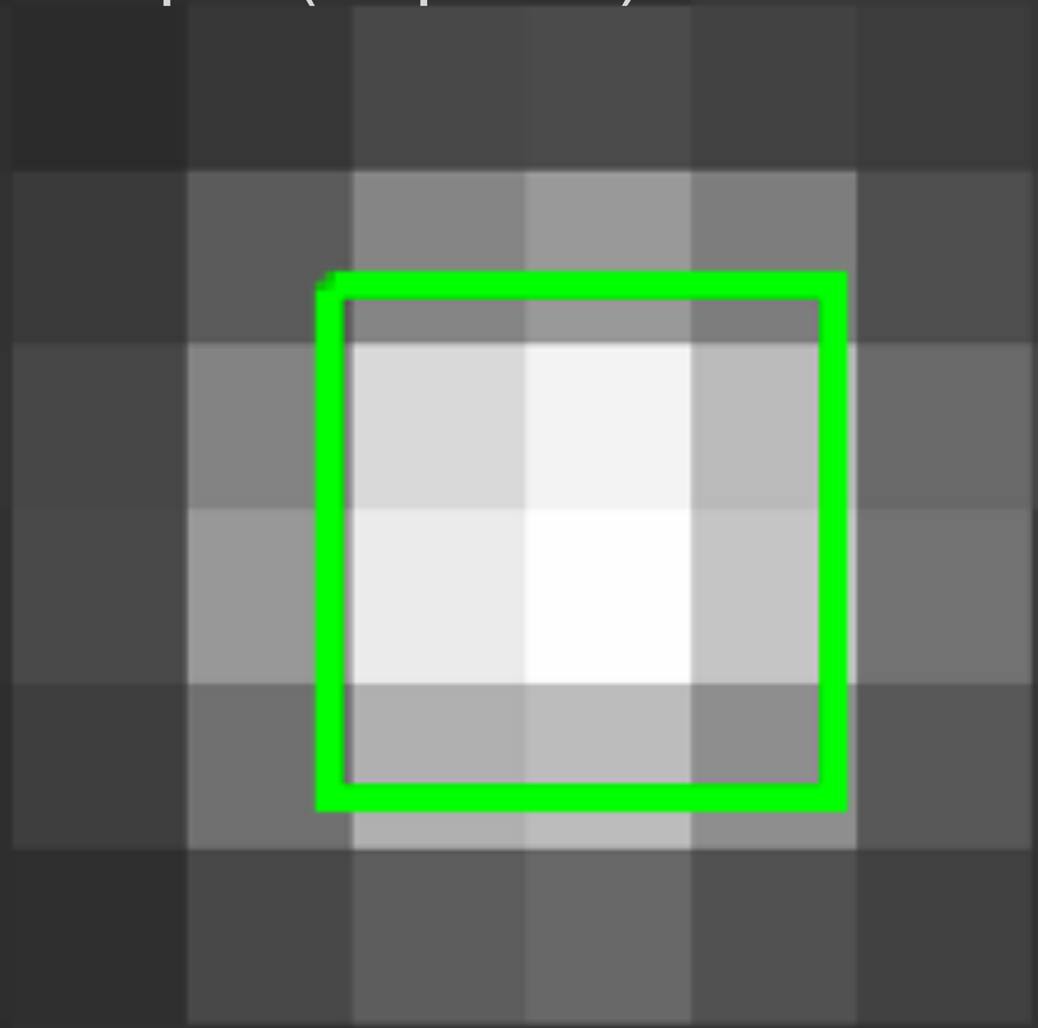

SANEPIC maps made by Viktoria Asboth (UBC) and the SMAP team.

# Local Galaxies

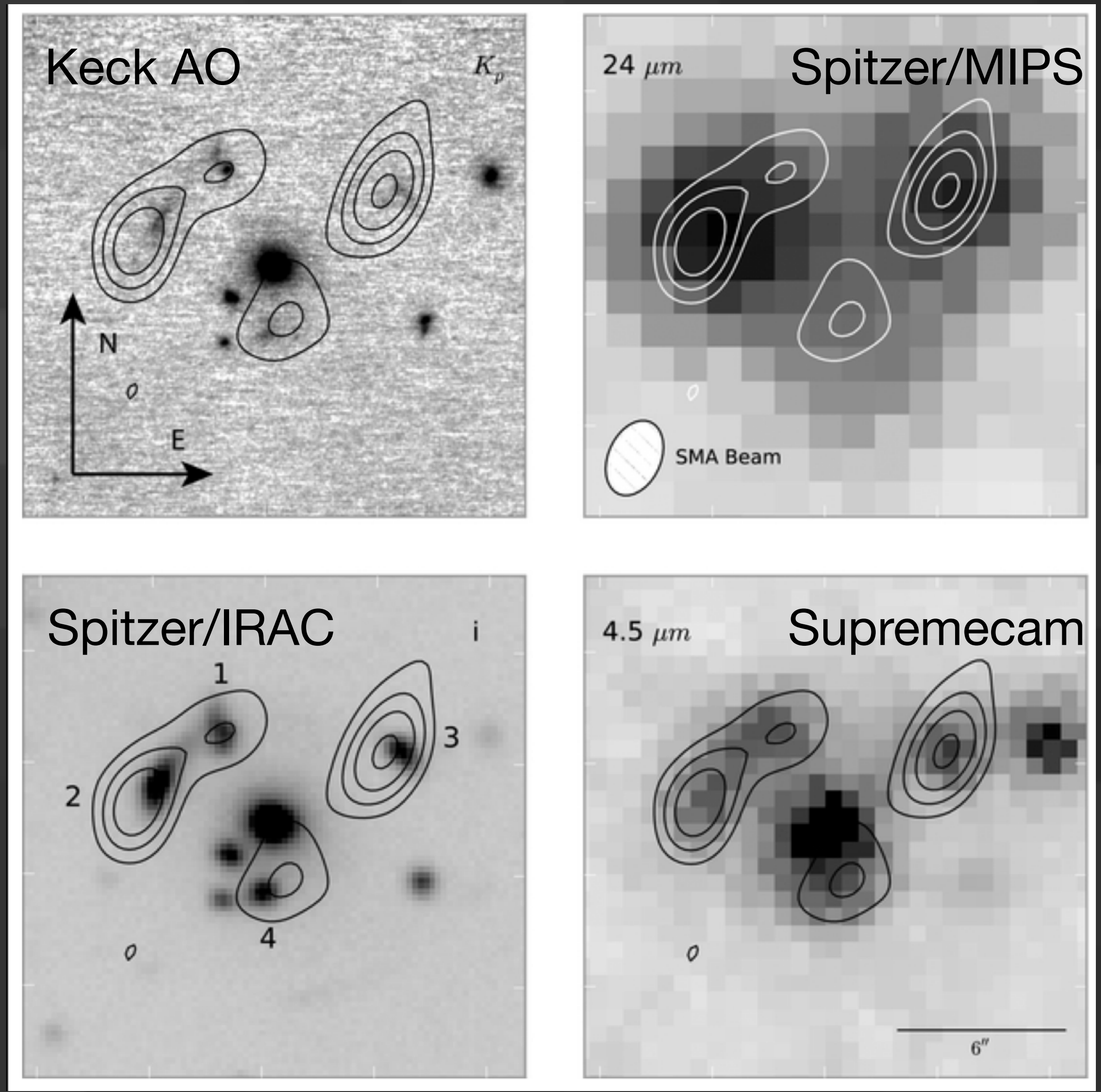


# Lensed Sources

SPIRE 250μm (6” pixels)

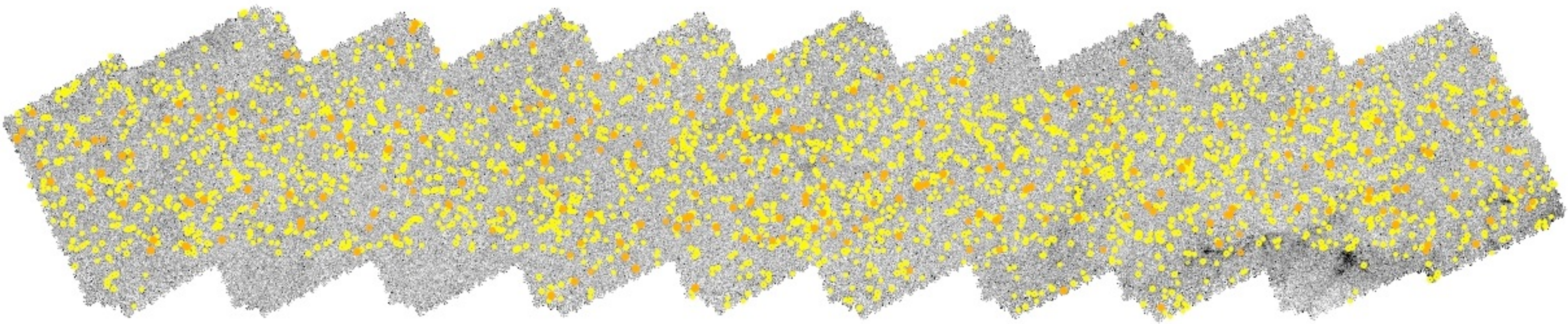


z=2.97 from spectroscopic follow-up

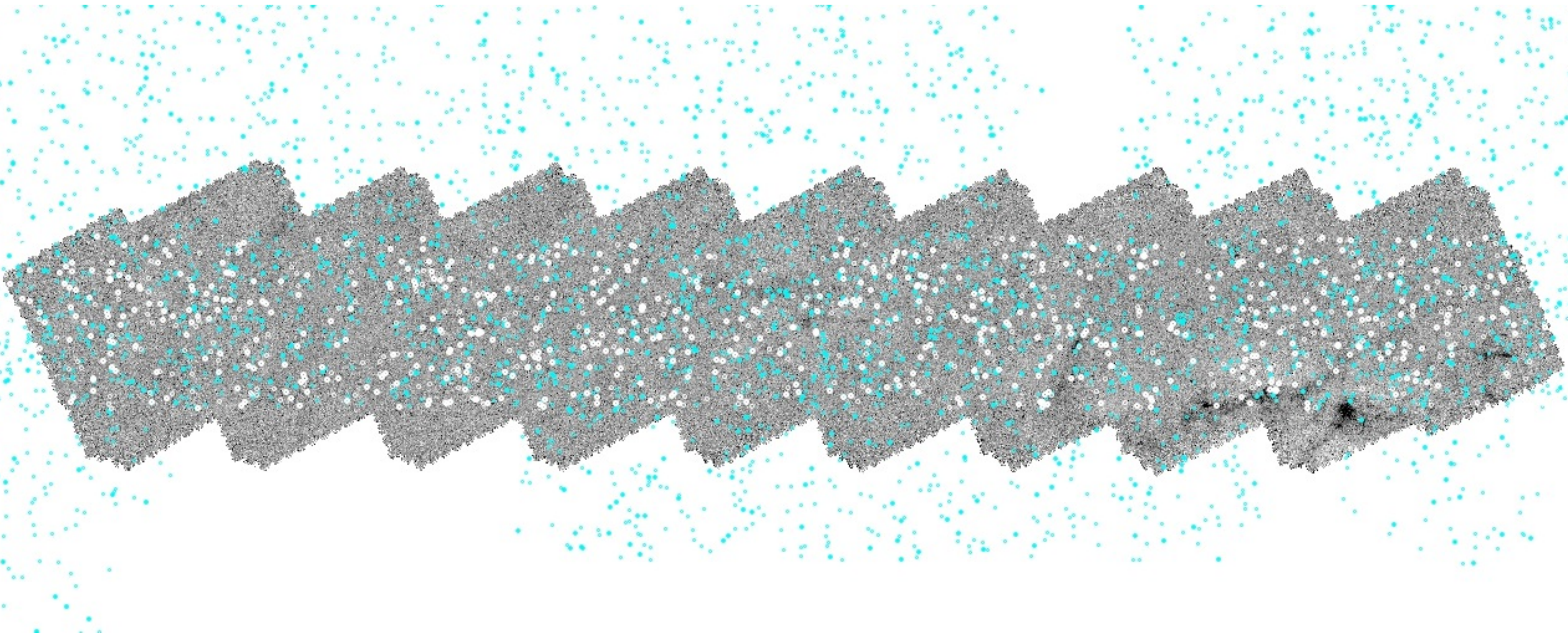



Contours From Submillimeter Array (SMA)

Conley et al. (2011)
also see: Vieira+ 2013, Gonzalez-Nuevo+ 2012, Wardlow+ 2012, Fu+ 2013

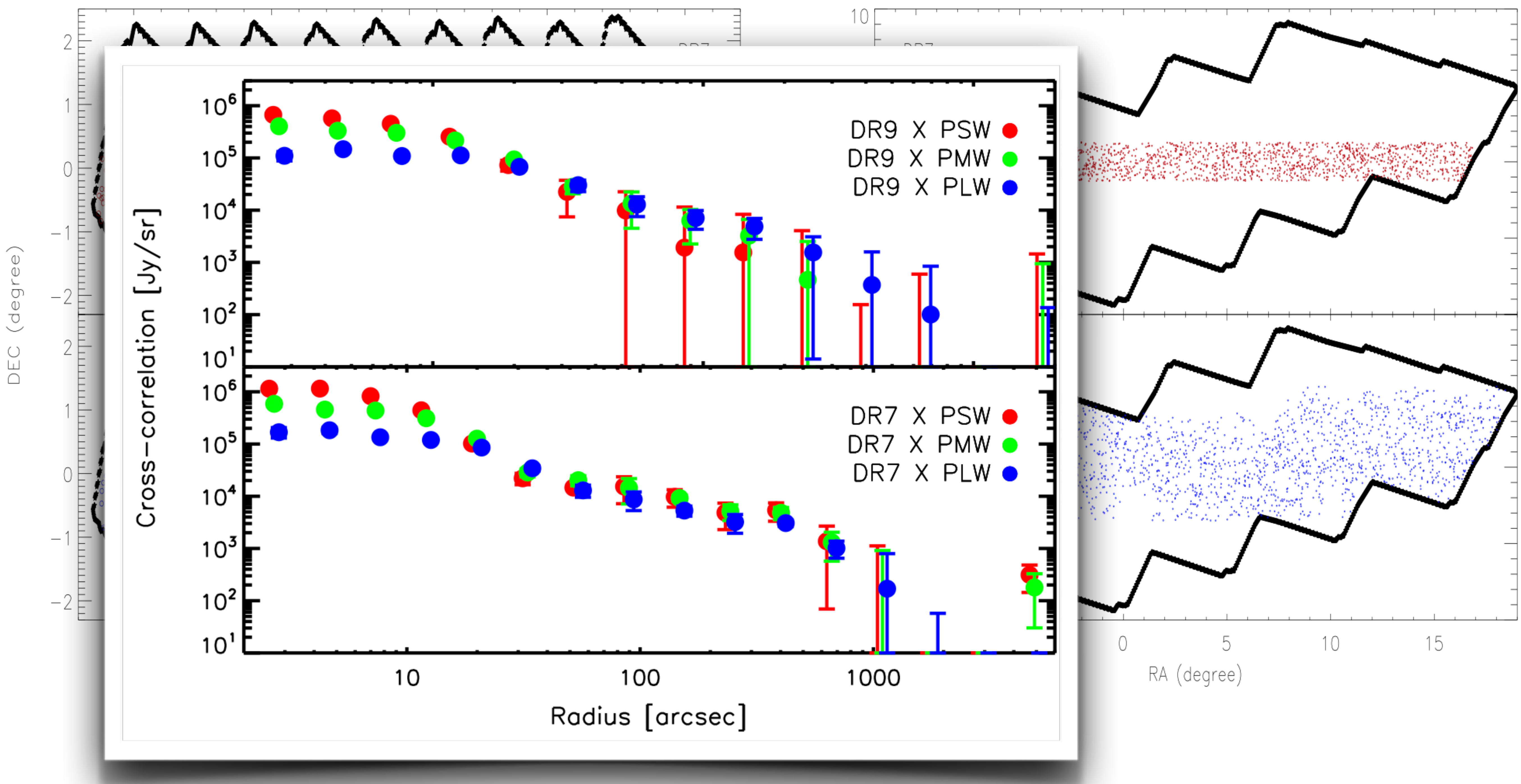


- BOSS QSOs
- DLAs



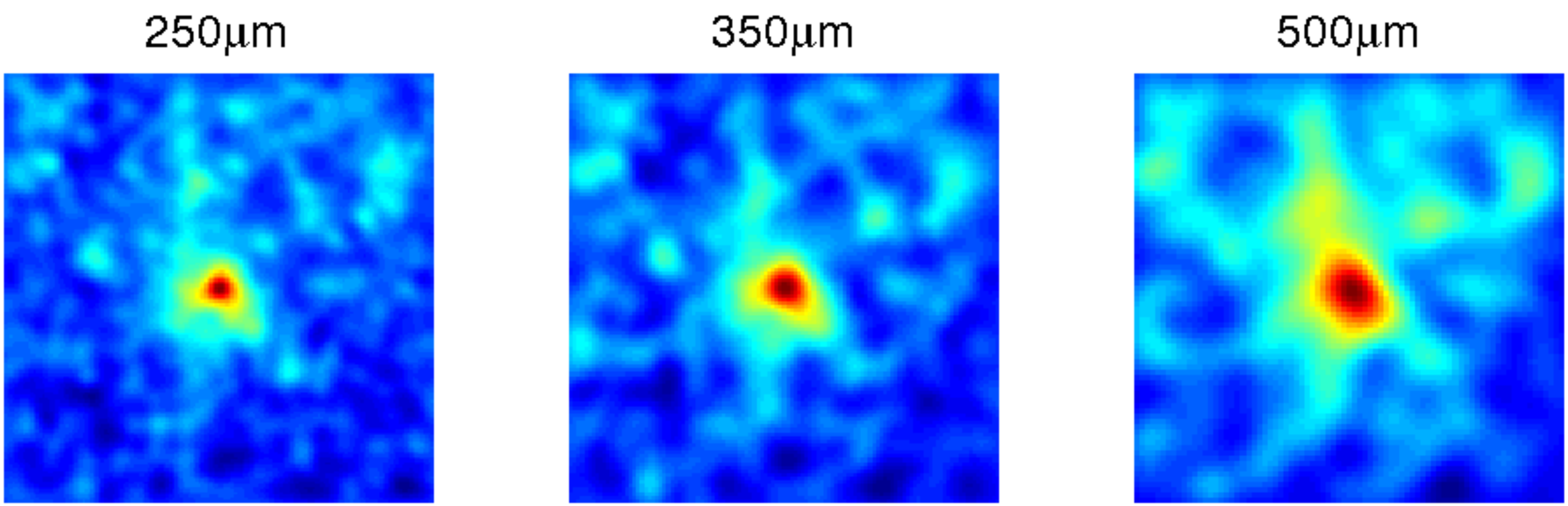
- Clusters (Geach et al. 2012)
- BOSS quasars

# X-Correlations w/ SDSS QSOs



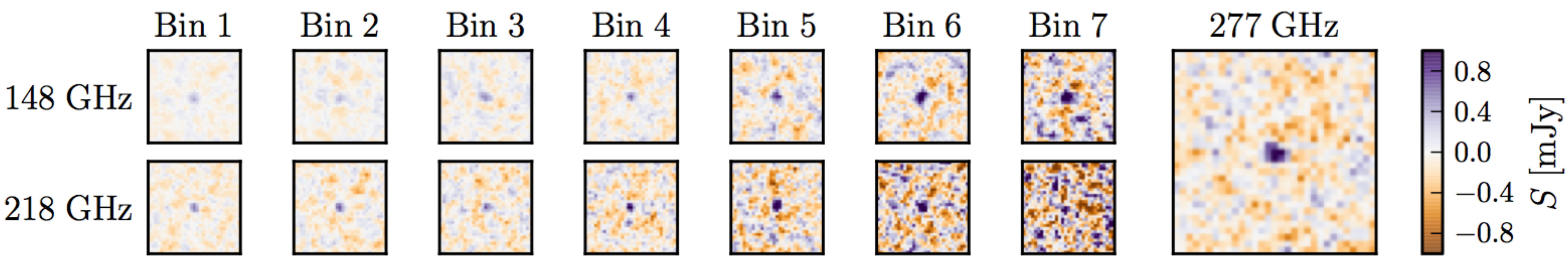

Wang et al. (in prep.)

# Cluster Stack




Phil Korngut using Rykoff et al. 2013 redMapper positions

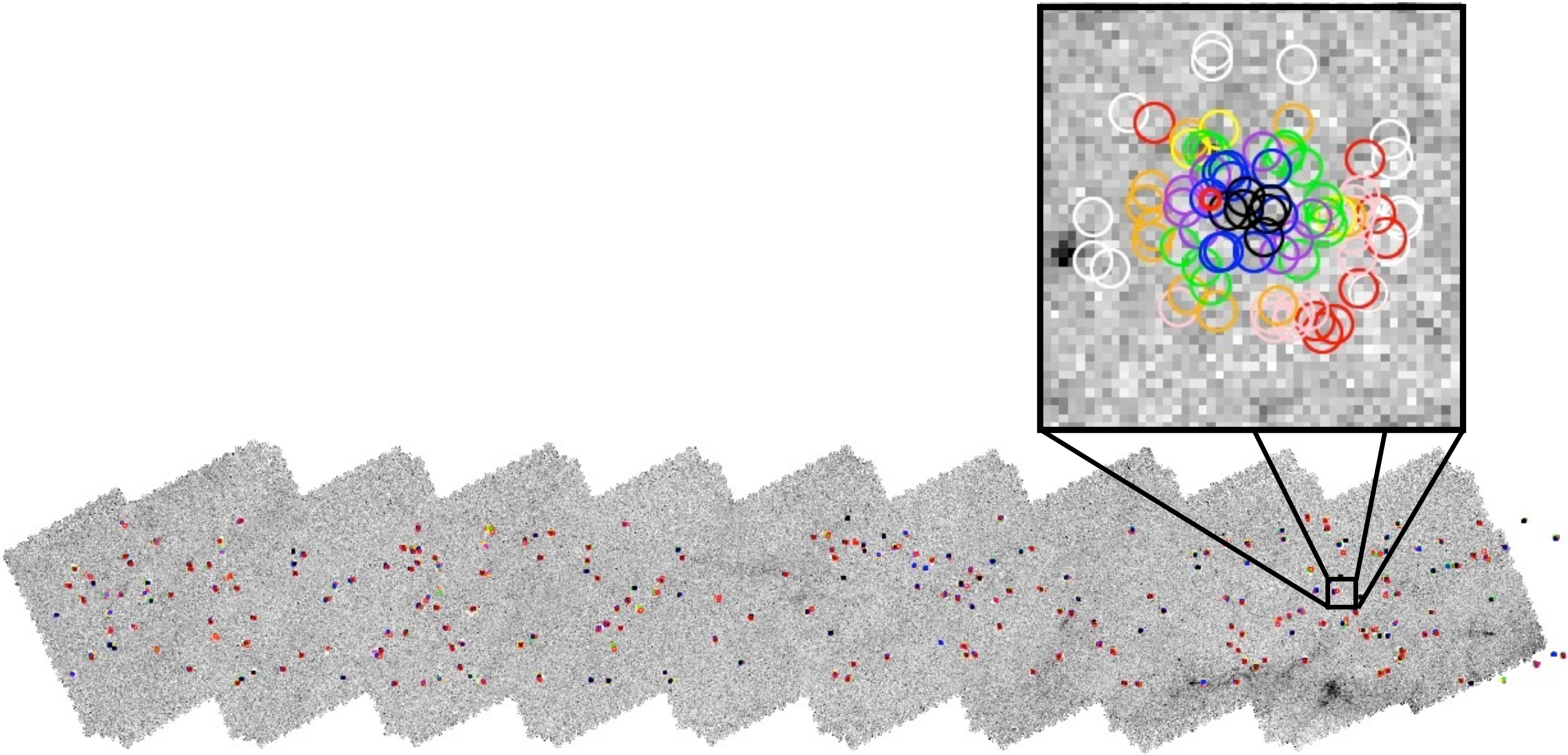
# HerS Submillimeter and ACT SZ detections in Radio Stacks




- Stacked ~4400 Radio galaxies in HerS/ACT
- Detection of SZ in $\log(M/M_\odot)$~13 halos

HeLMS/HerS x ACT

Gralla et al. 2013
arXiv:1310.8281



# Cluster Members

herschel stripe 82 survey

HERMES

Viero+ 2014
arXiv:1308.4399

Oliver+ 2012
arXiv:1203.2562


Find Maps/Catalogs at:

(available now!) http://www.astro.caltech.edu/hers

(coming in June) http://hedam.lam.fr/HerMES/

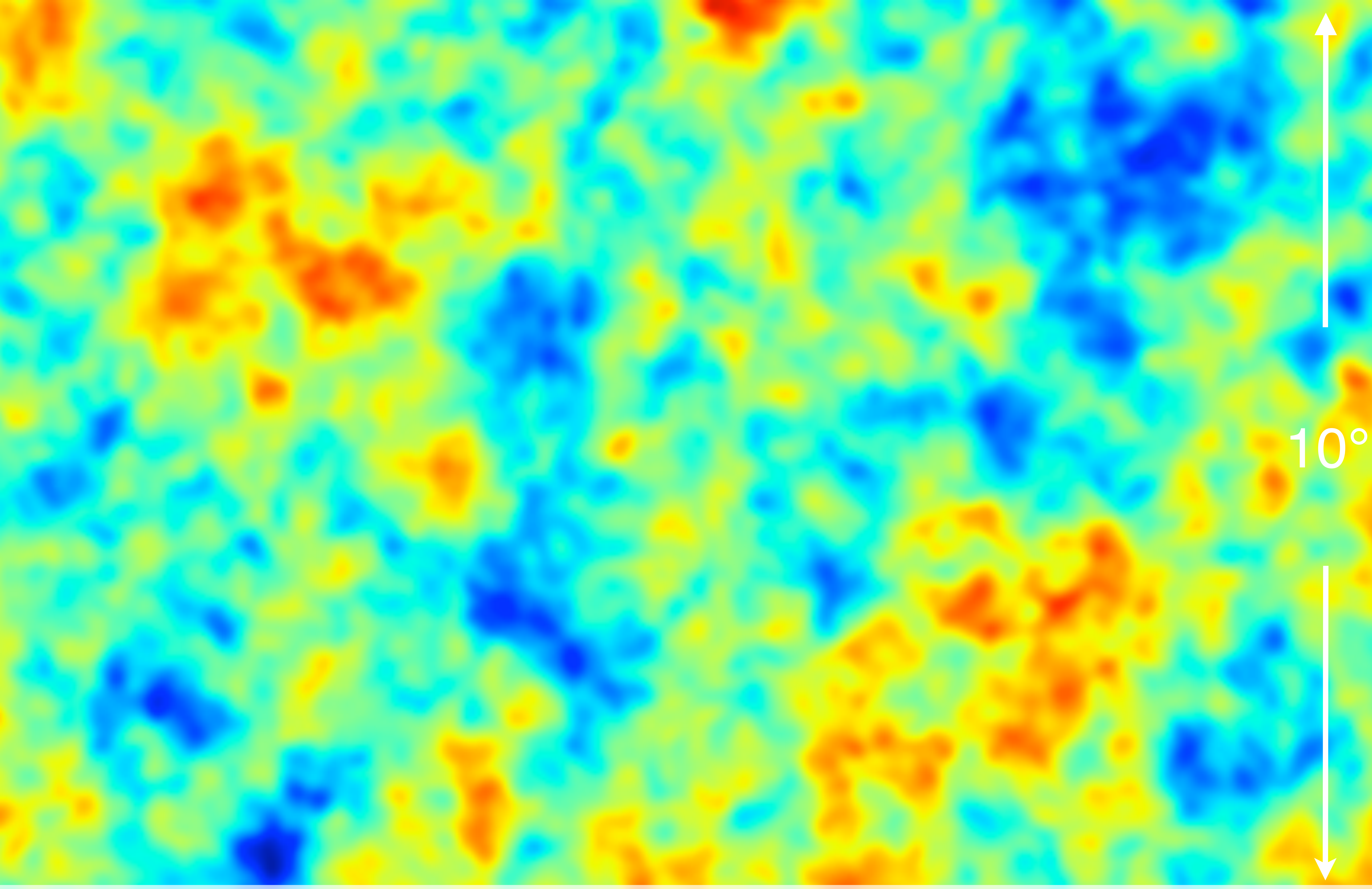
# More Fun with Cross Correlations! (time permitting!)

Dust emission correlates with other tracers of deep potential wells, e.g.,:

- quasars
- LRGs, radio galaxies
- clusters (and the SZ effect!)

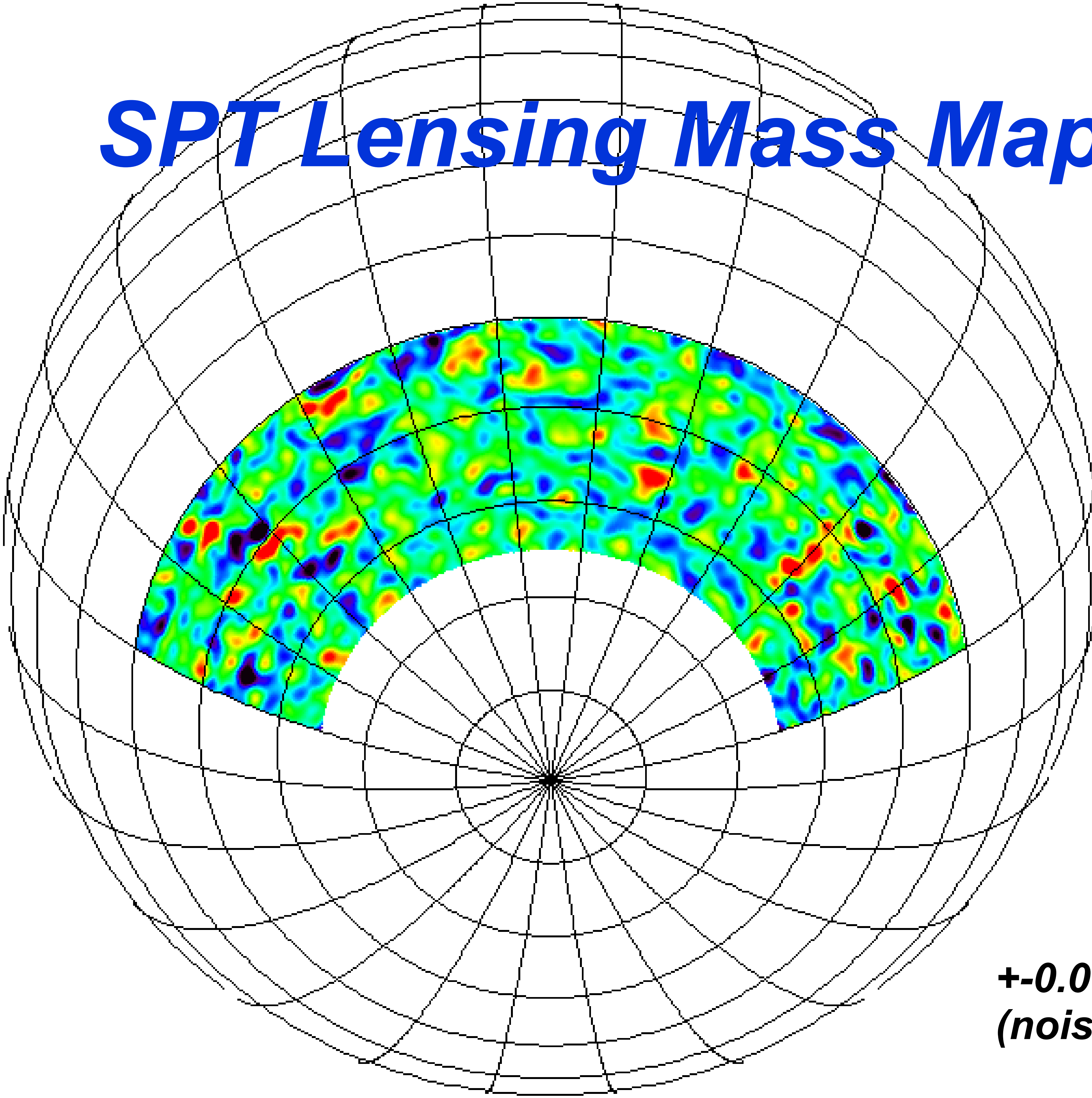
The CIB traces dark matter, thus should correlate with lensing, as traced by:

- CMB-lensing maps
- lensing B-modes
- weak-lensing maps



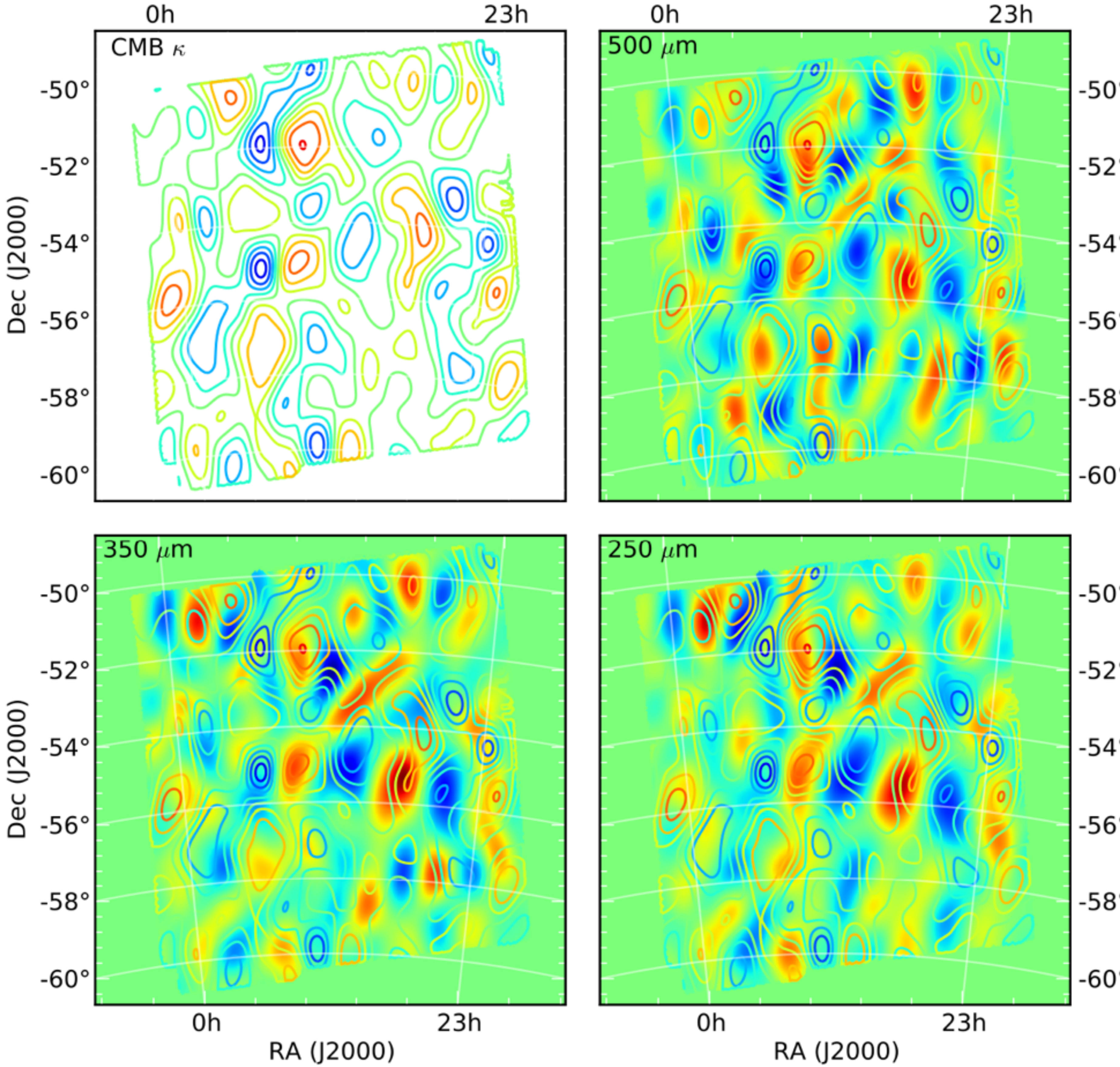

# Cross-Correlations with CMB Lensing

# SPT Lensing Mass Map



+-0.05 color bar
(noise ~0.01)

SPT X
SPIRE

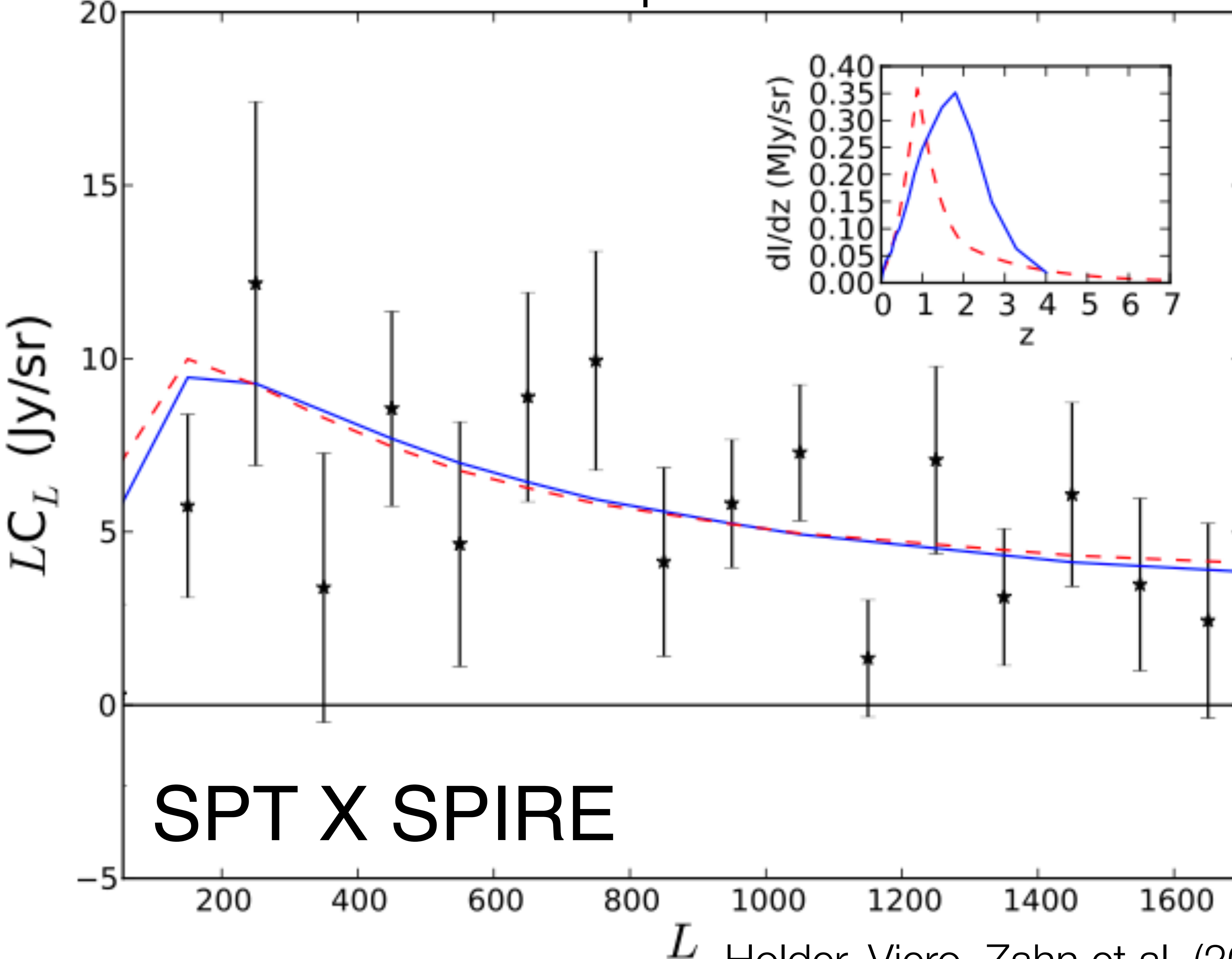



# Lensed CMB x CIB

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

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

$CMB_{lensed} x CIB_{500\mu m}$



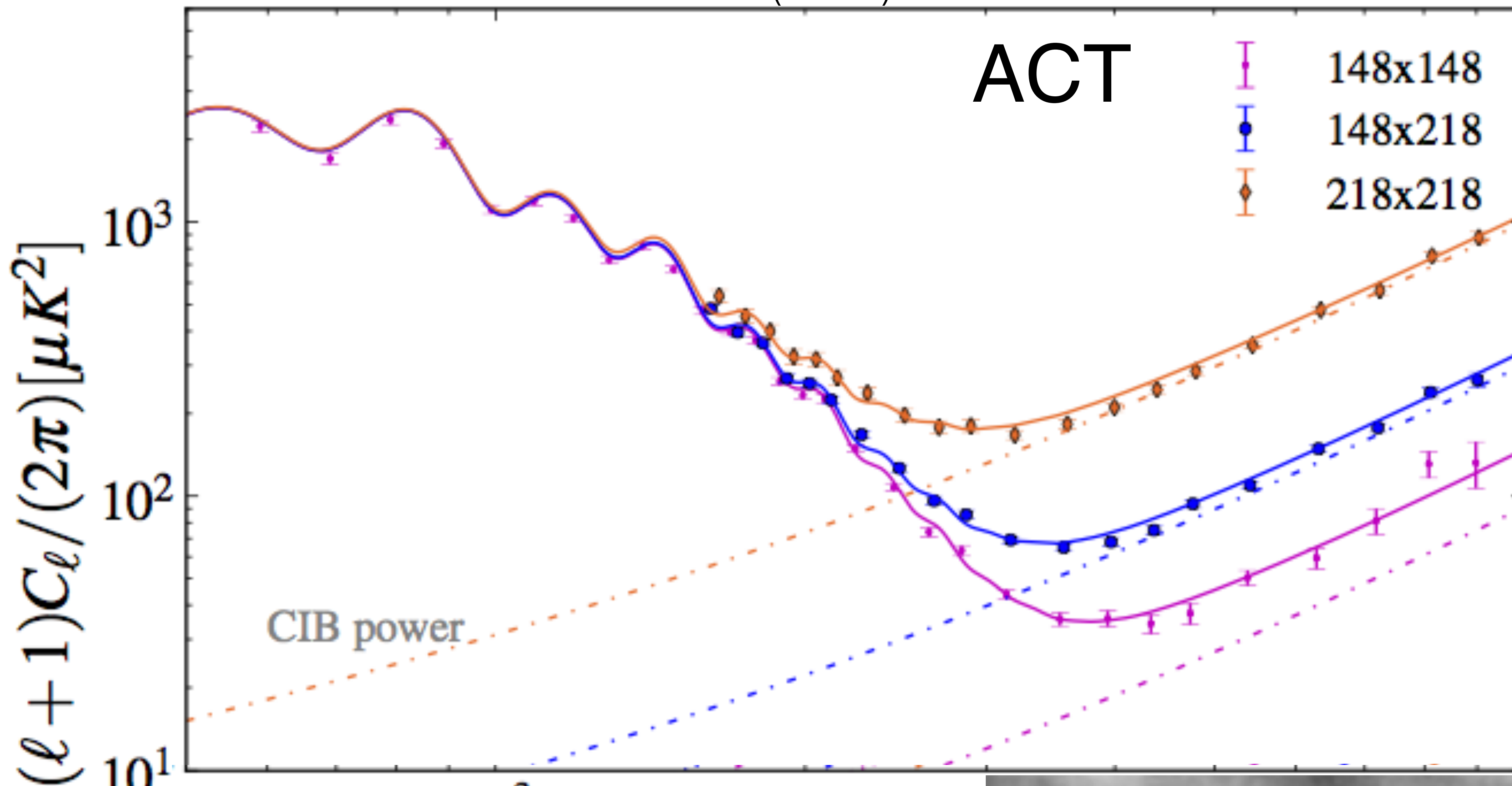

Holder, Viero, Zahn et al. (2013)
arXiv:1304.0446

# Measuring the CIB bias

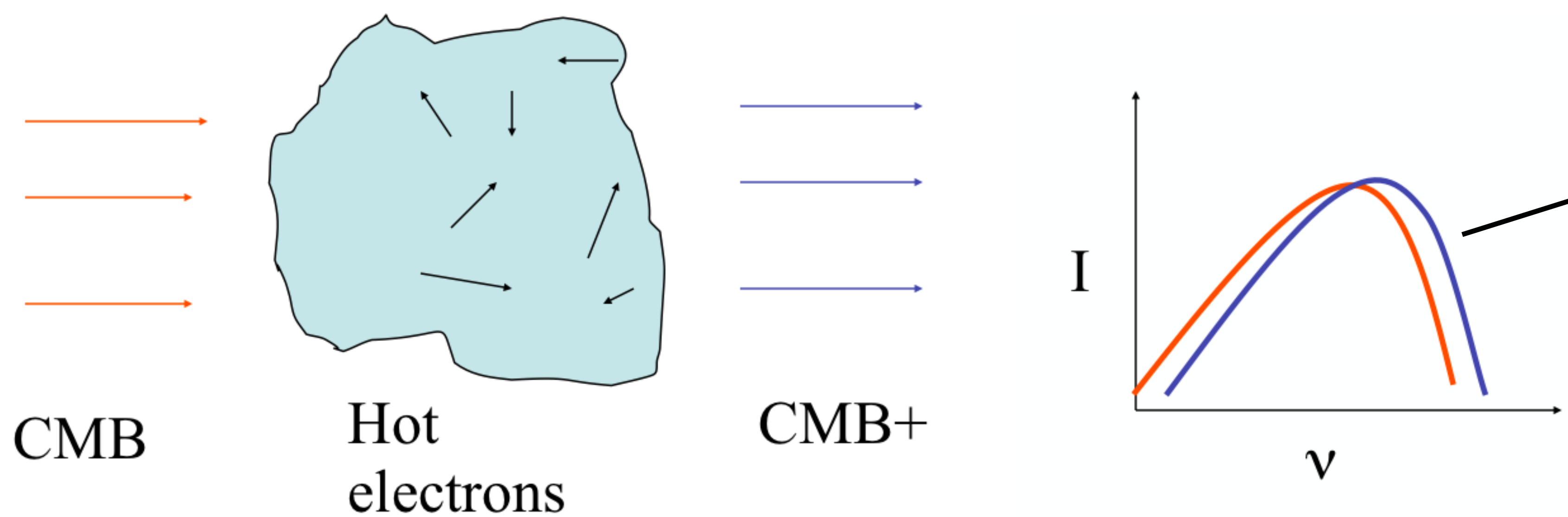
# CIB as CMB Foreground

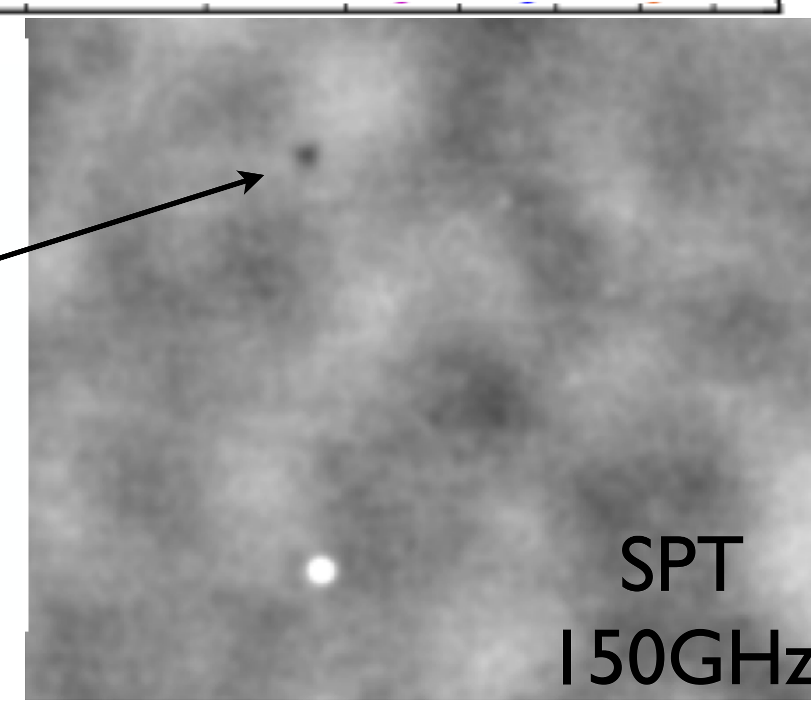
Dusty Galaxies a significant contaminant at 150 and 220 GHz

Sievers et al. (2013) arXiv: 1301.0824



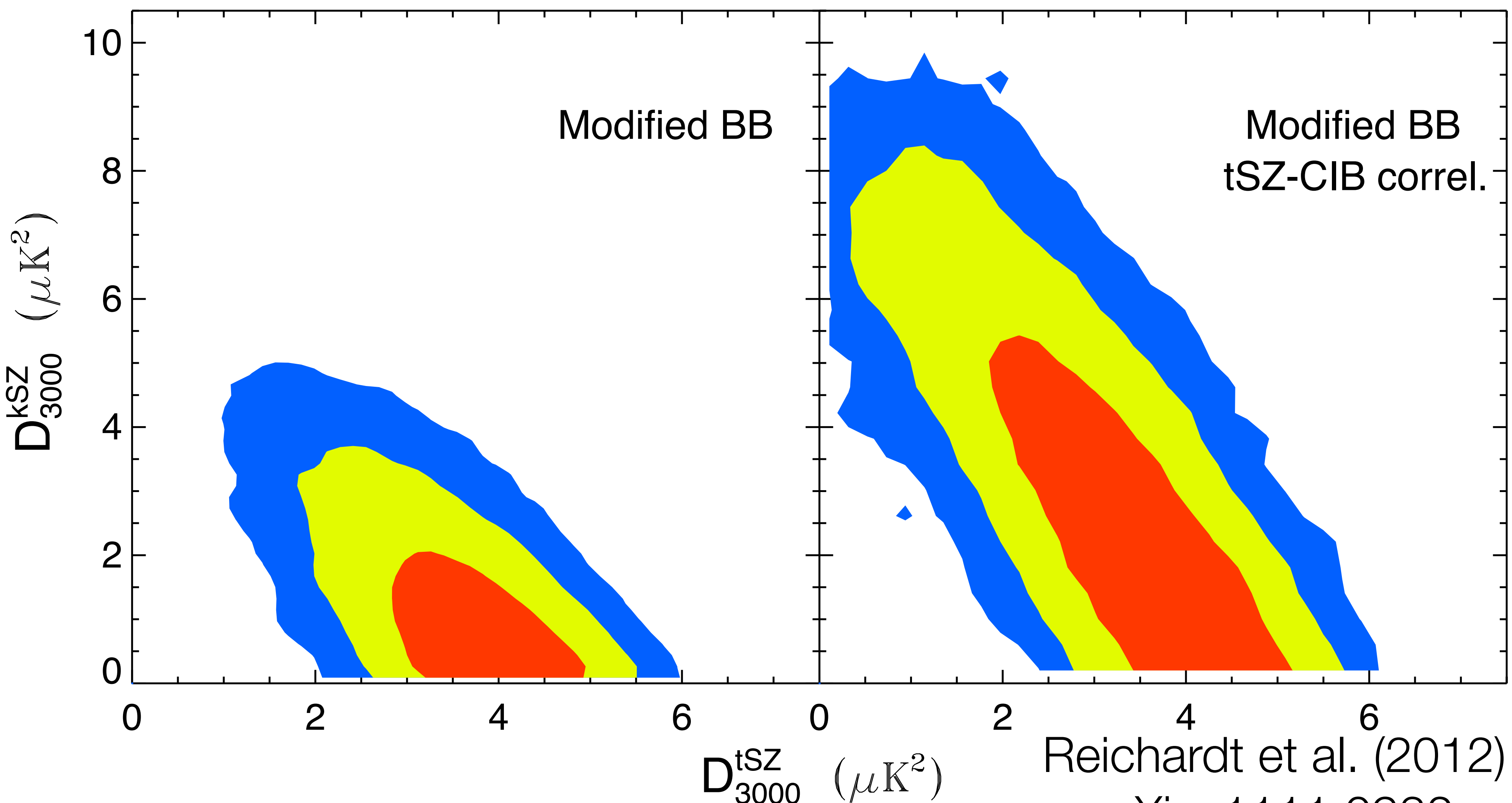

SZ effect distortion of CMB by Compton scattering in massive clusters



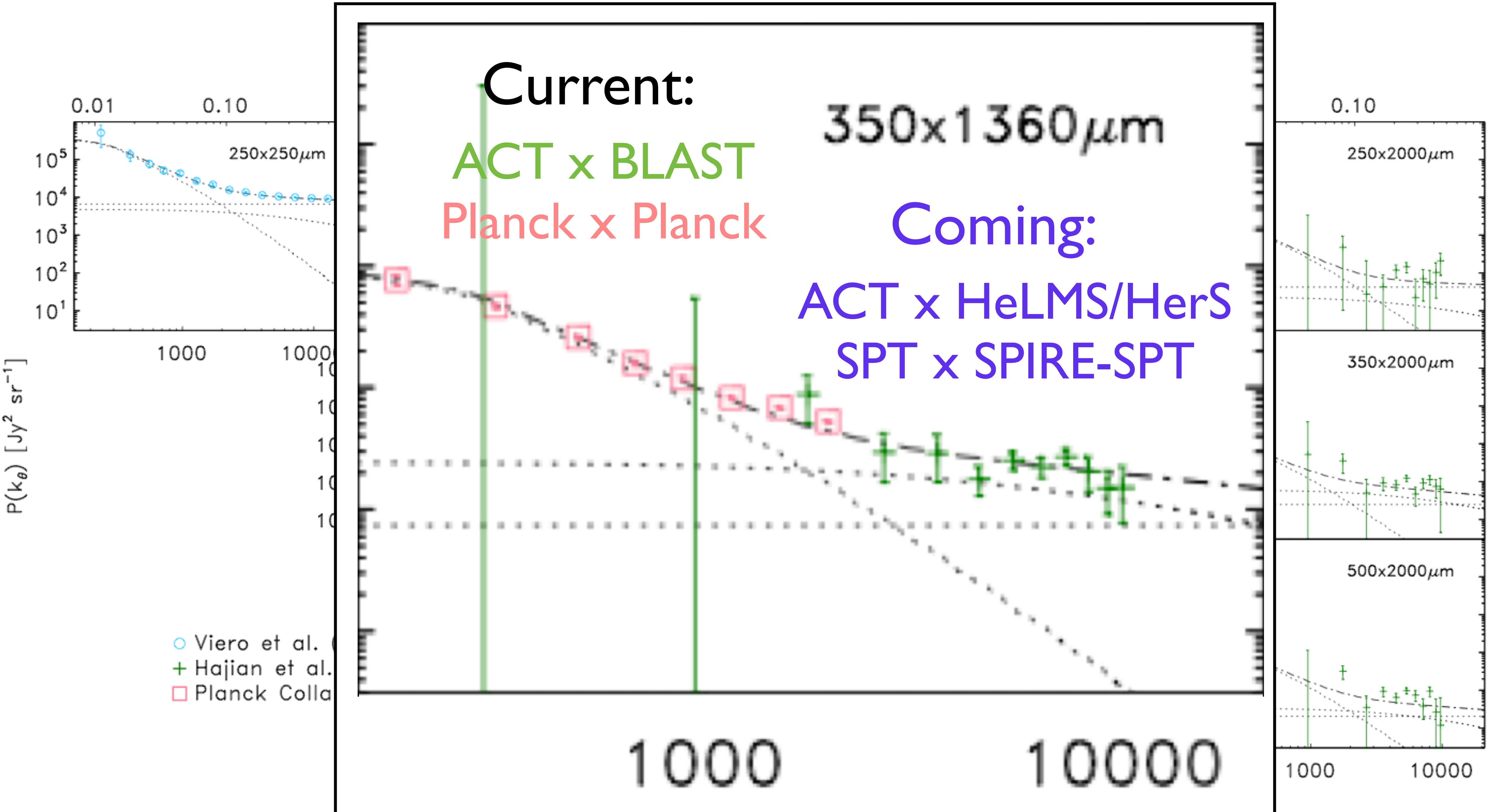



# thermal SZ-CIB correlation?

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

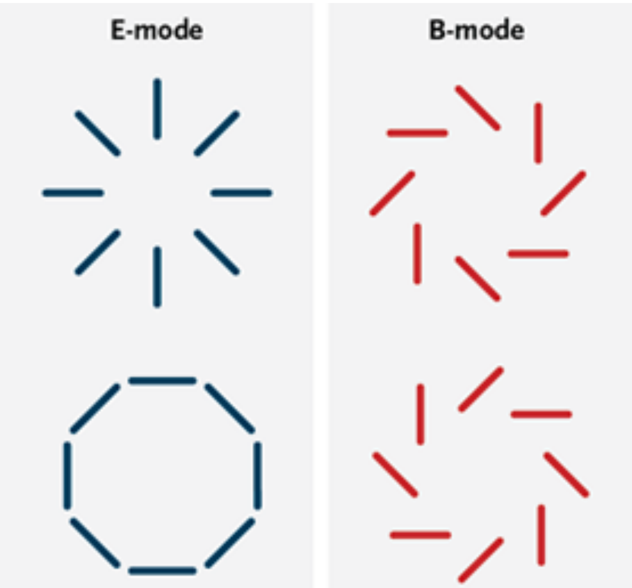


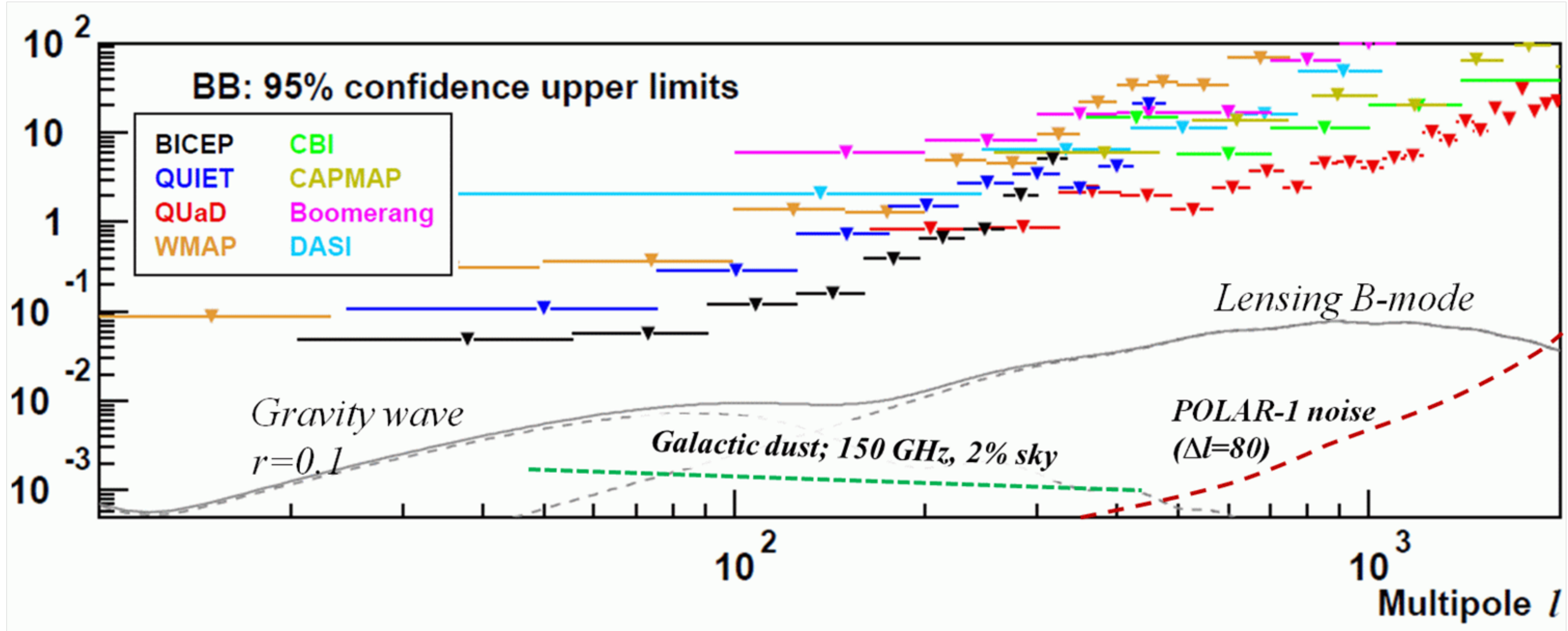

Reichardt et al. (2012)
arXiv: 1111.0932



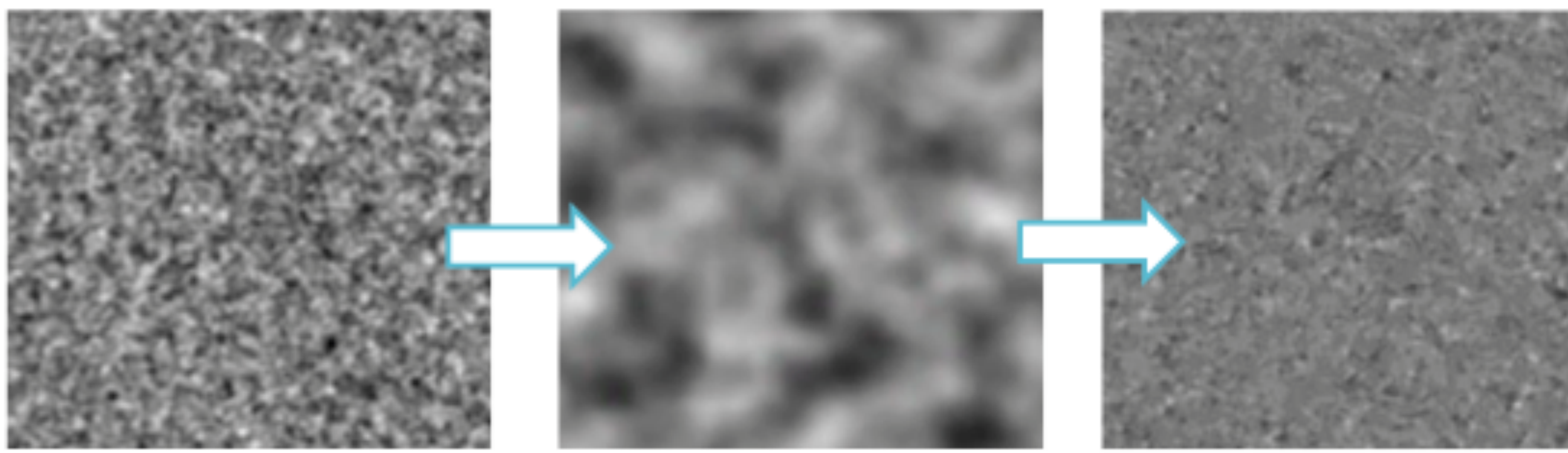

Green: Hajian, Viero et al. (2011)
Blue: Viero et al. (2013)
Red: Planck Collaboration (2013)

# Cross-Correlating CIB and CMB




- Lensing mixes E-modes into B-modes



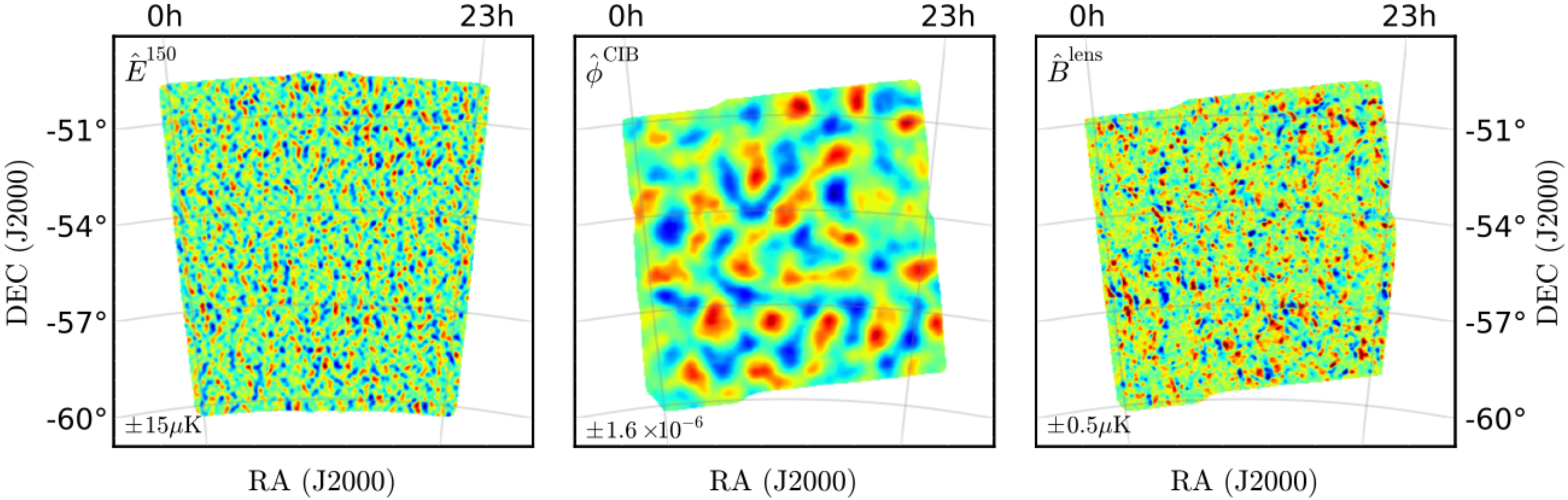
Gaussian E-mode background

Gravitational lens

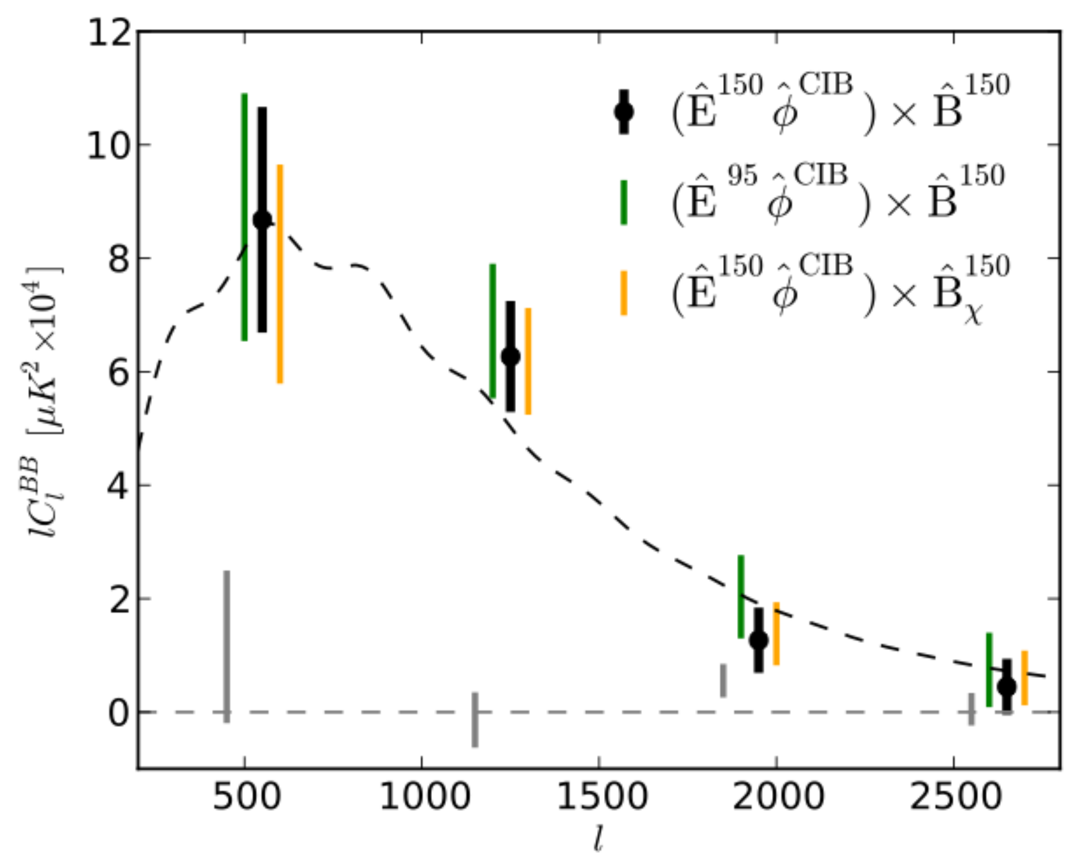
Lensing B-mode

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

# CMB Lensing B-modes




- 7.7σ detection of B-mode signal




# CMB Lensing B-modes

herschel stripe 82 survey

HERMES

Viero+ 2014
arXiv:1308.4399

Oliver+ 2012
arXiv:1203.2562


Find Maps/Catalogs at:

(available now!) http://www.astro.caltech.edu/hers

(coming in June) http://hedam.lam.fr/HerMES/