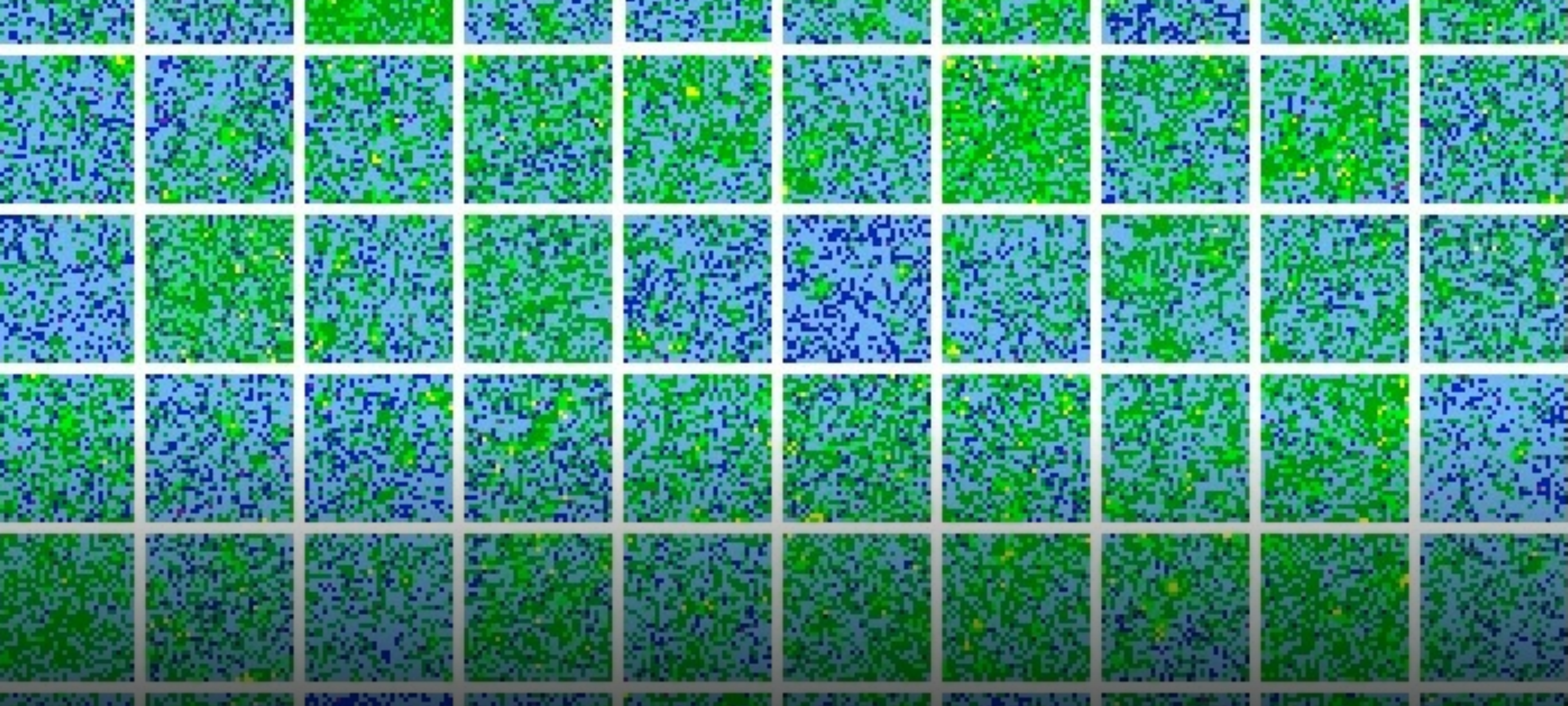




Dusty Galaxies, Blurry Backgrounds,
and how I learned to stop worrying about
and love statistical methods.

Marco Viero - Caltech

University of Wyoming - Colloquium

Students, I'm sorry I missed Lunch!!



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

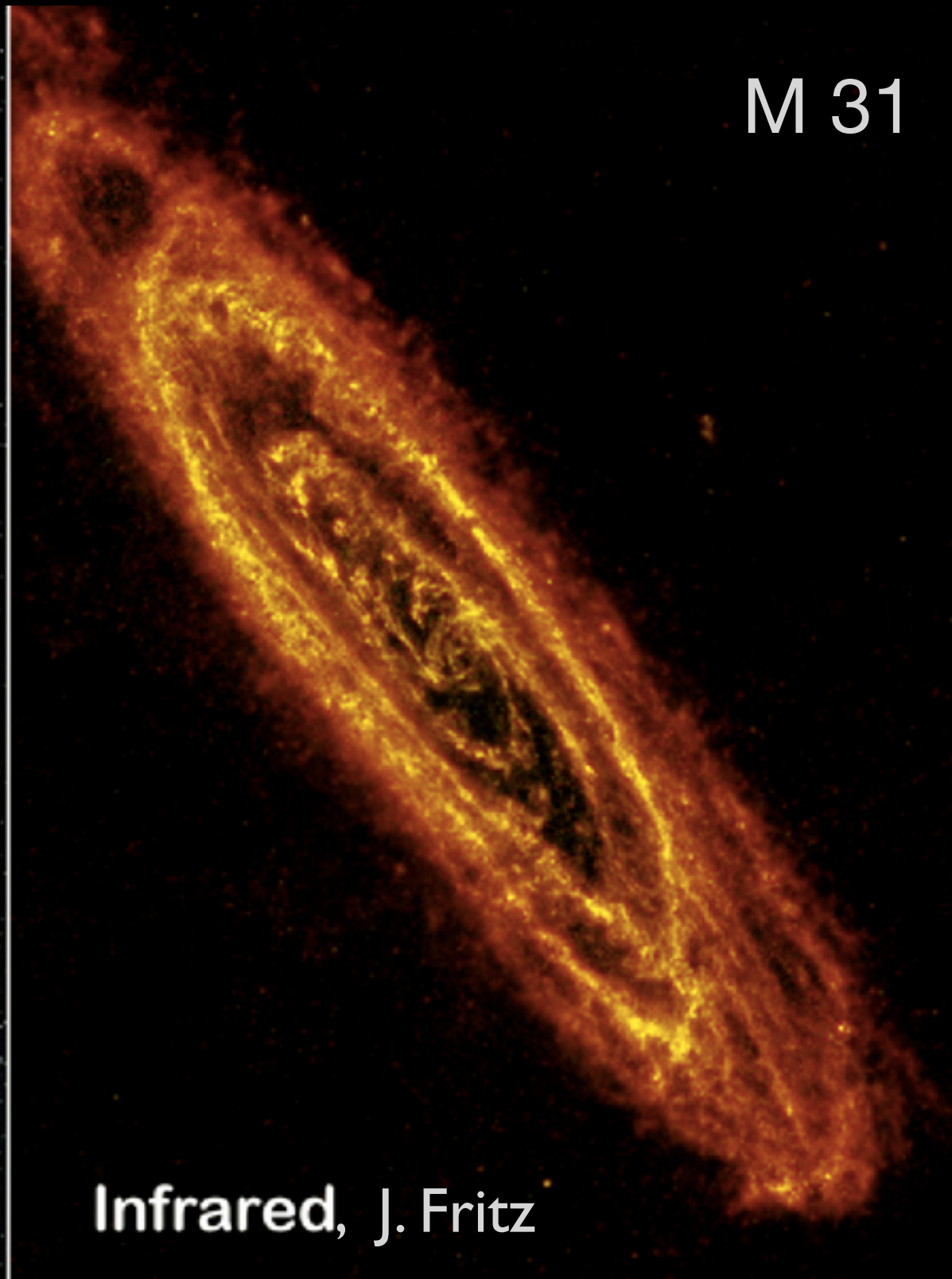
SMG = Submillimeter Galaxy

DSFG = Dusty Star-Forming Galaxy

FIR/submillimeter: dust warmed by stars



Optical, R. Gendle



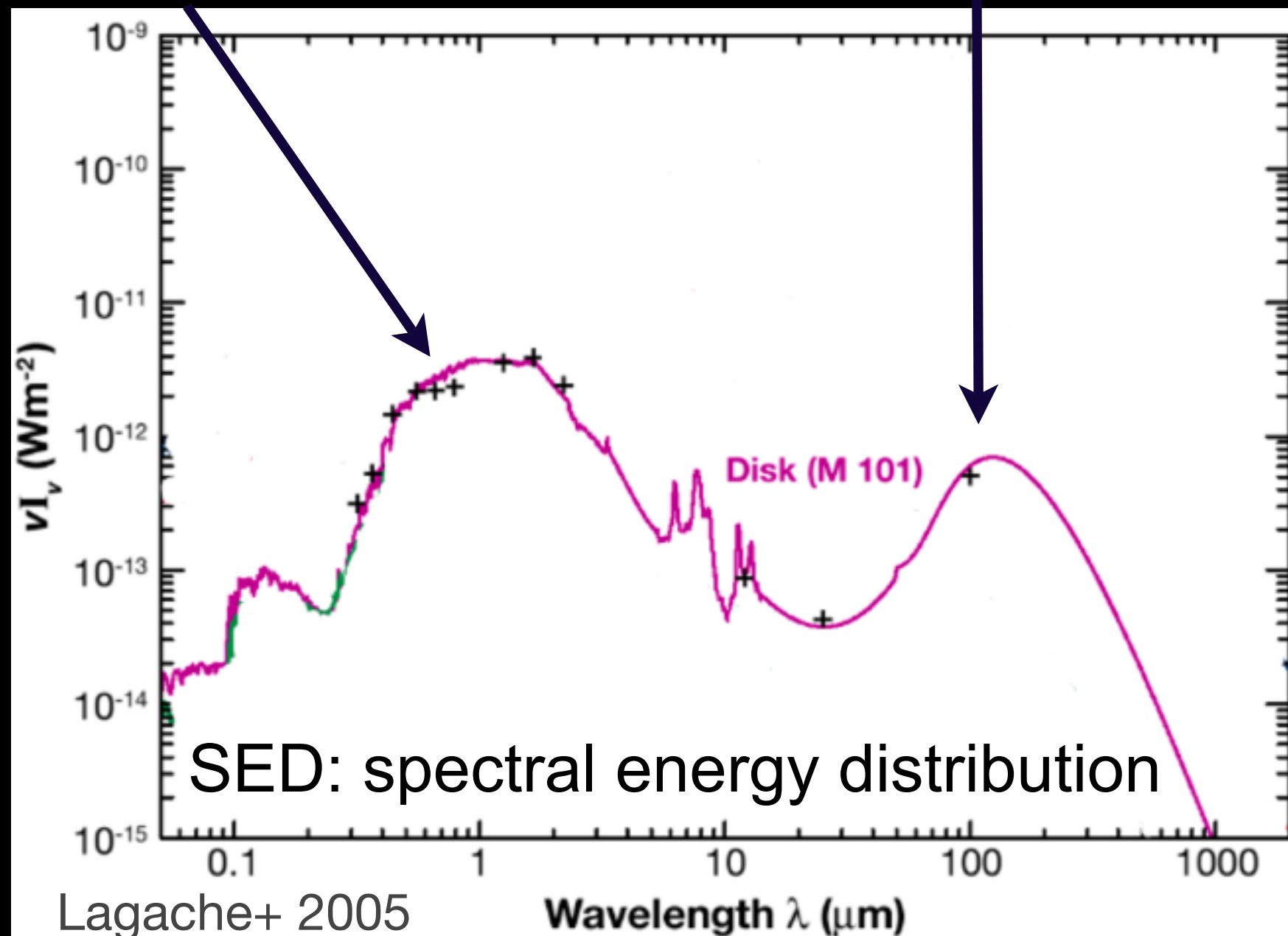
Infrared, J. Fritz

M 31

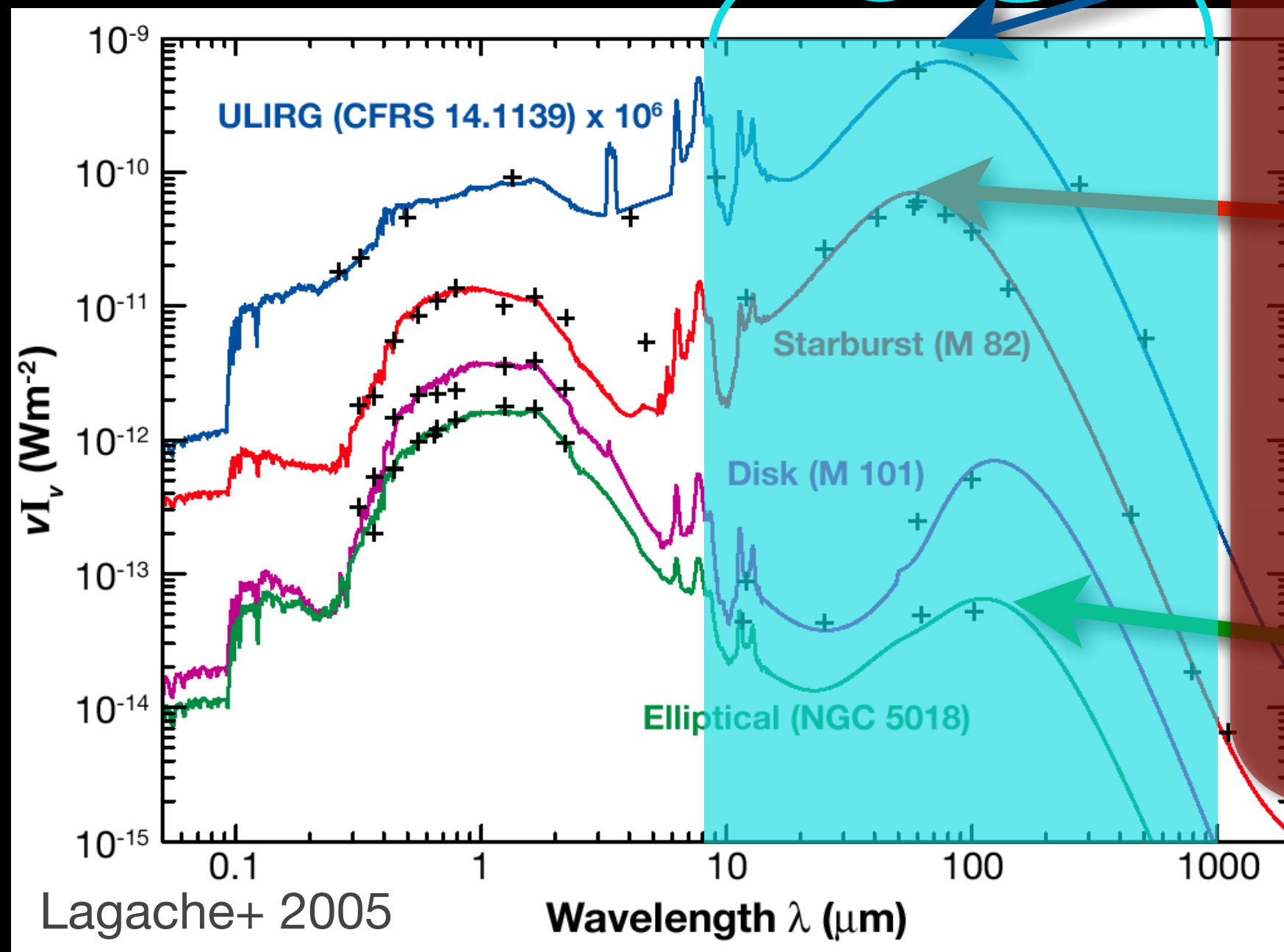
UV/Optical and FIR/submm SED

Dust re-emits in the FIR

Optical/UV Starlight absorbed by dust



UV/Optical and FIR/submm SED



Infrared Luminosity

$L_{\text{IR}} = \text{integral from}$
8 to 1000 μm

Star-formation rate

$\text{SFR} \propto L_{\text{IR}}$

ULIRGS:

$\log(L_{\text{IR}}/L_\odot) = 12-13$

$\text{SFR} \approx 100-1000 \text{ M}_\odot/\text{yr}$

LIRGS:

$\log(L_{\text{IR}}/L_\odot) = 11-12$

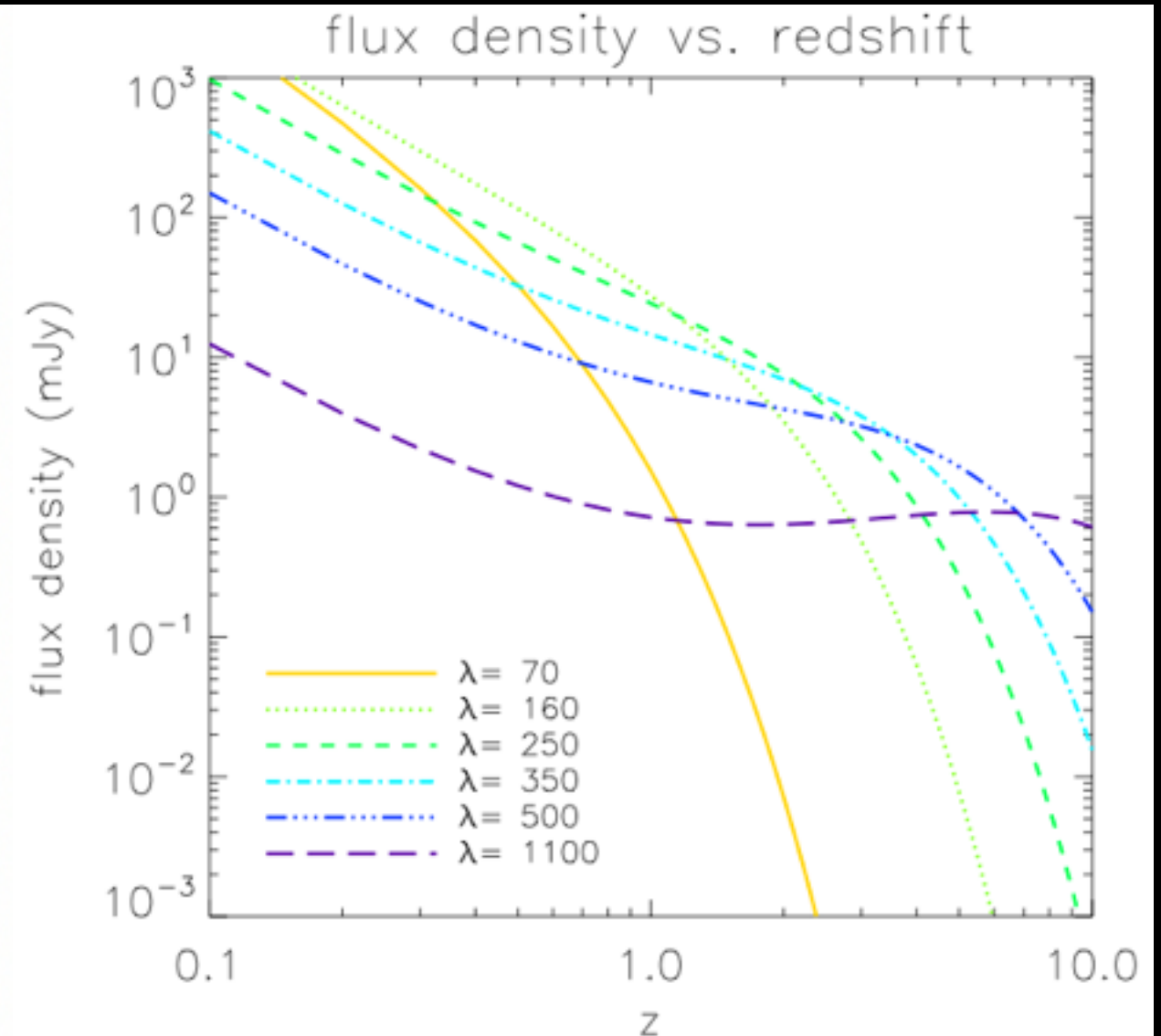
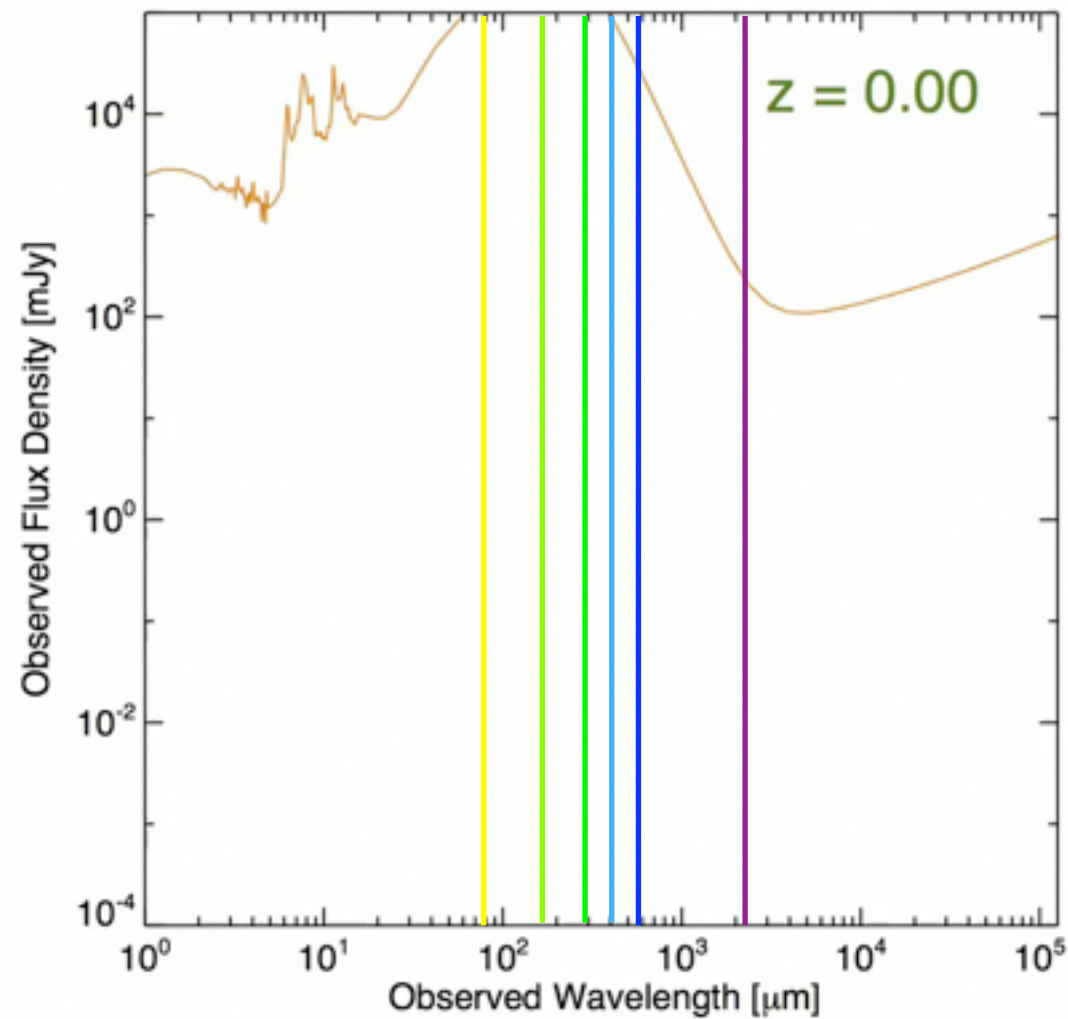
$\text{SFR} \approx 10-100 \text{ M}_\odot/\text{yr}$

sub-LIRGS (“normal”):

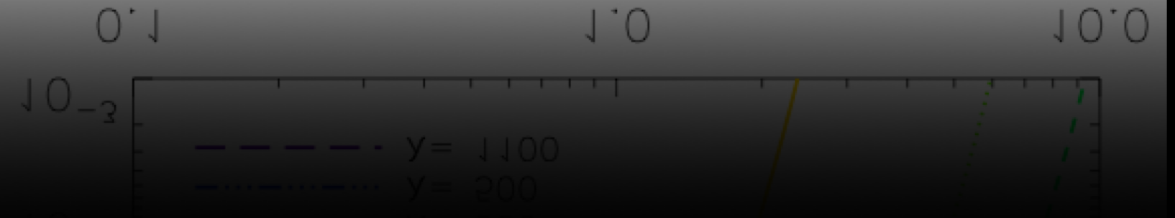
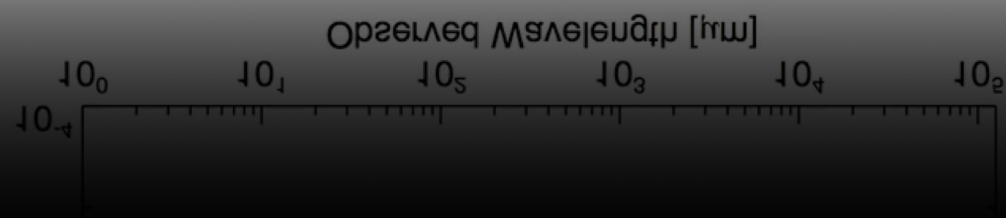
$\log(L_{\text{IR}}/L_\odot) < 11$

$\text{SFR} \lesssim 10 \text{ M}_\odot/\text{yr}$

Submillimeter: Window to High Redshift Star-Forming galaxies



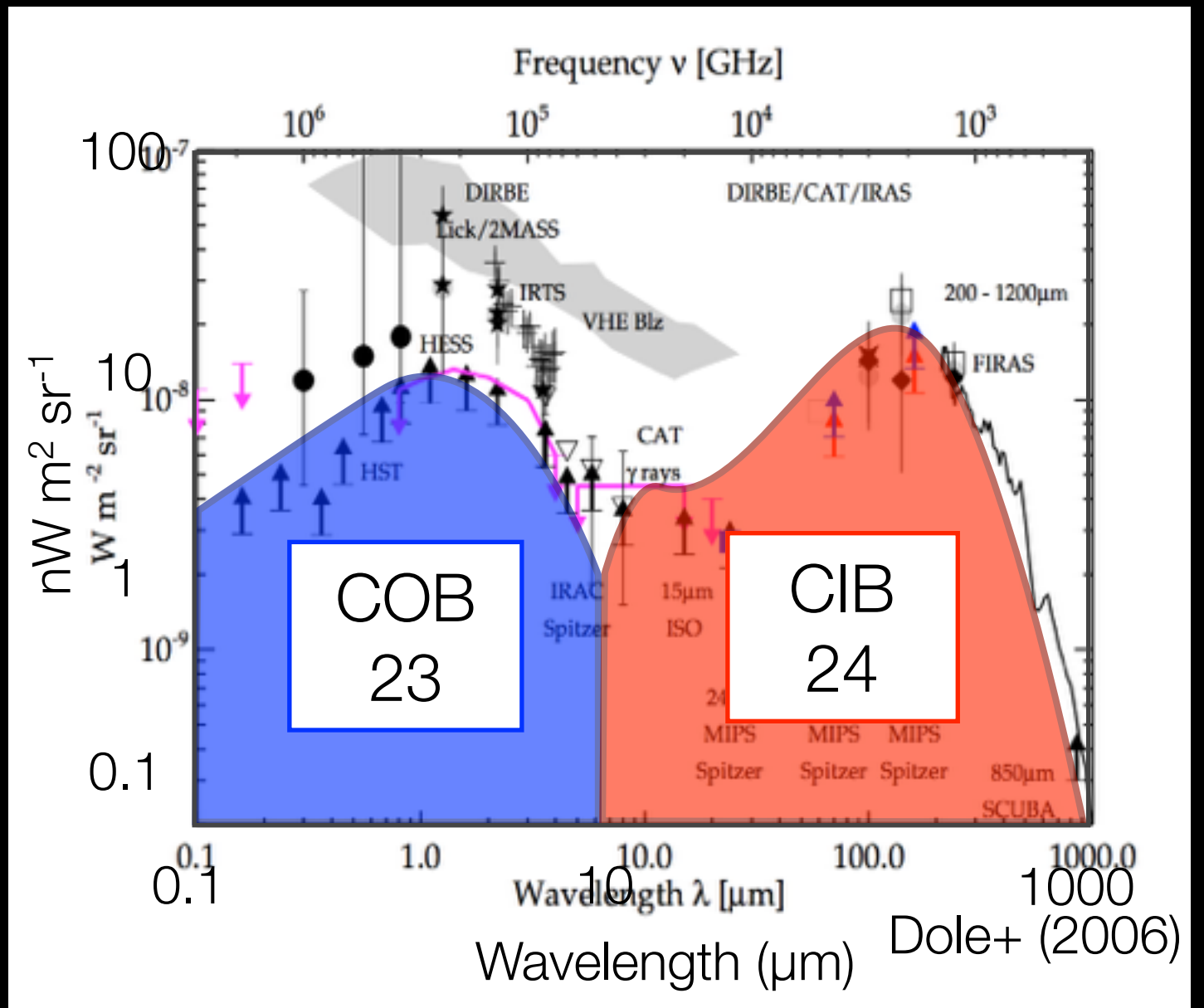
Caitlin Casey (UC Irvine)



Cosmic UV/Optical and FIR/submillimeter Backgrounds

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

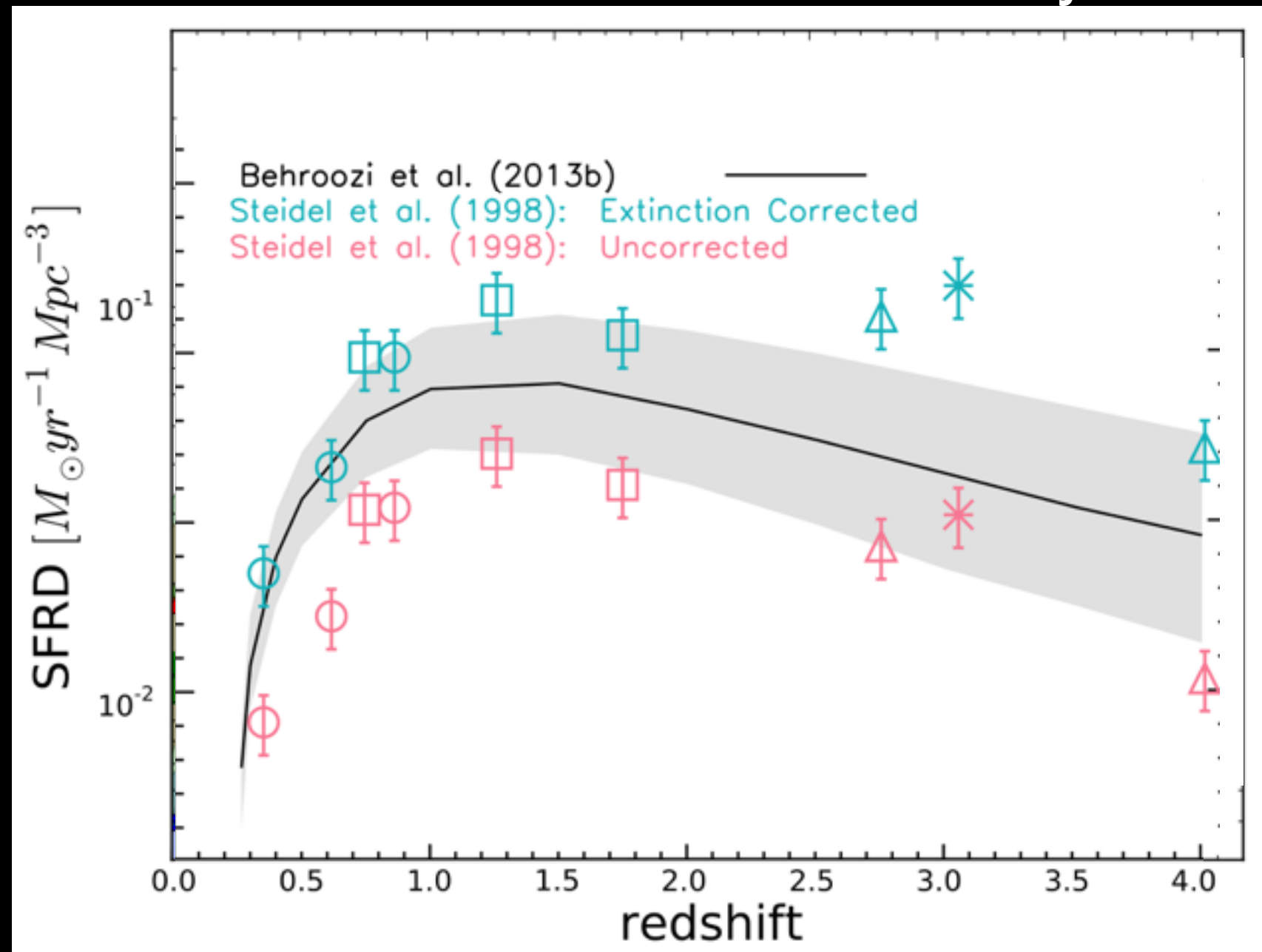
Can we understand the infrared component of galaxies in the same detail as the optical?



Motivation #1: History of Cosmic Star Formation

Star-Formation Rate Density

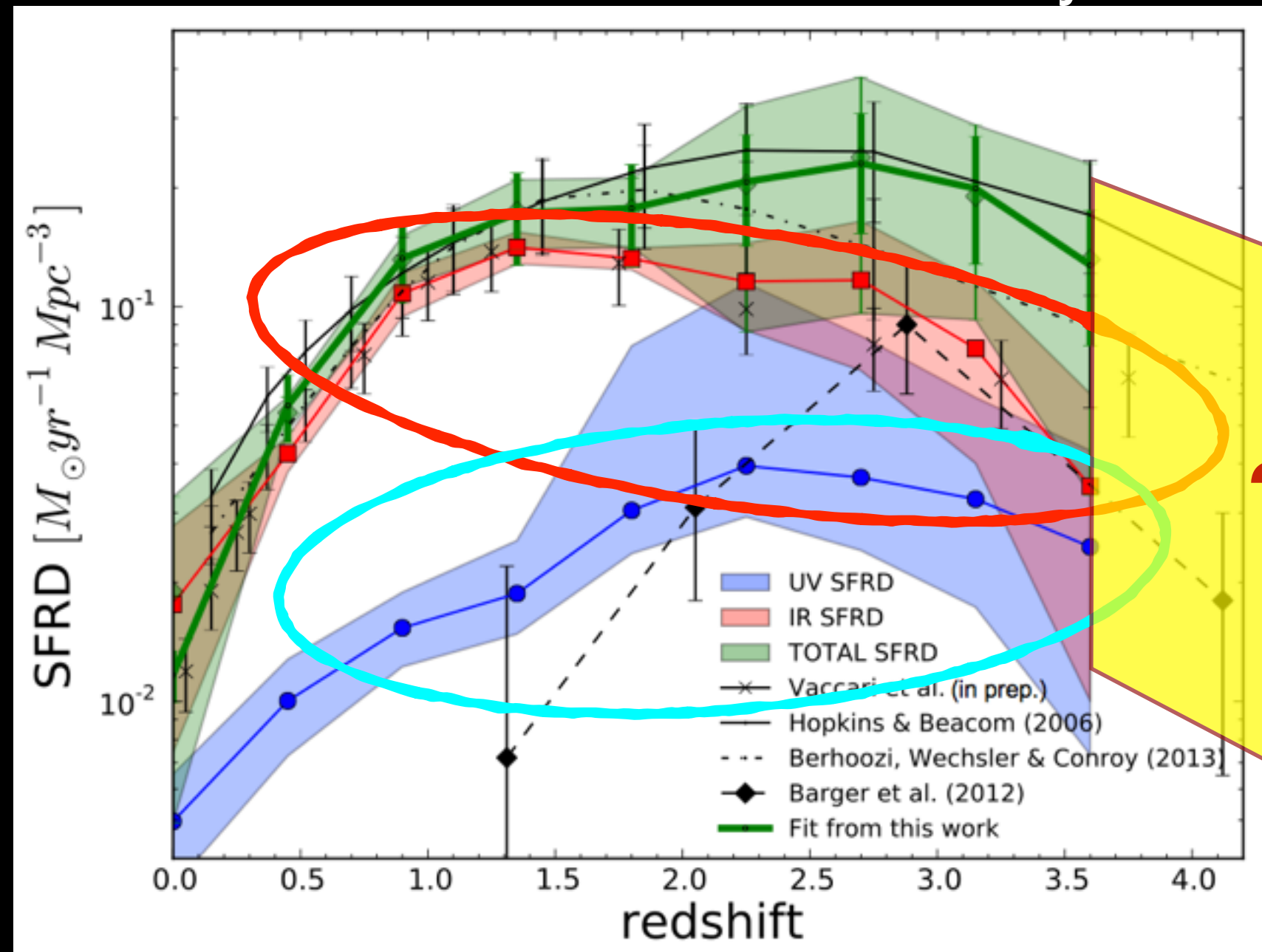
Traditional,
Lyman break
galaxy (i.e.,
UV-selected)
estimates need
to correct for
dust extinction



Motivation #1: History of Cosmic Star Formation

Star-Formation Rate Density

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



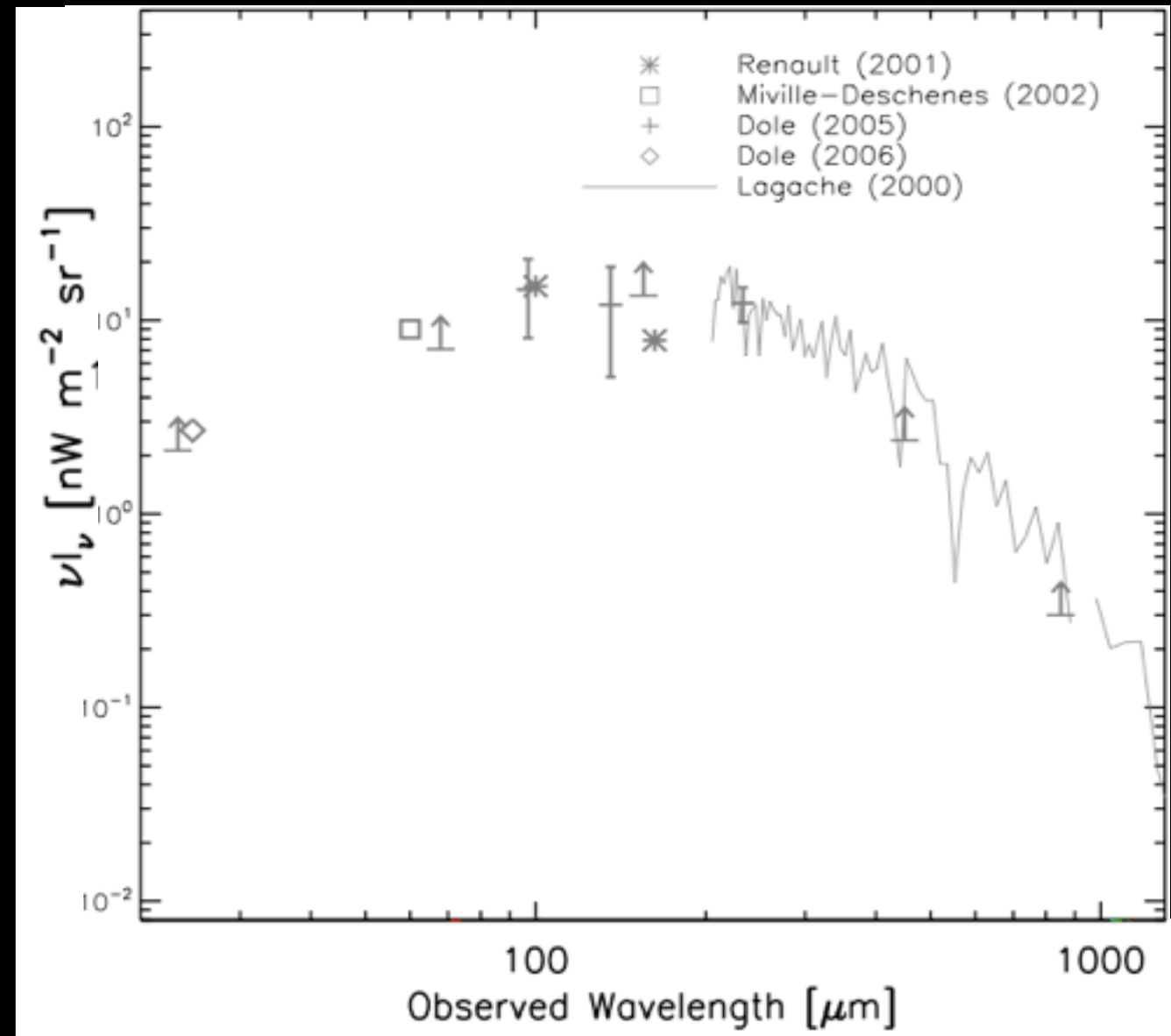
Burgarella+2013

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??

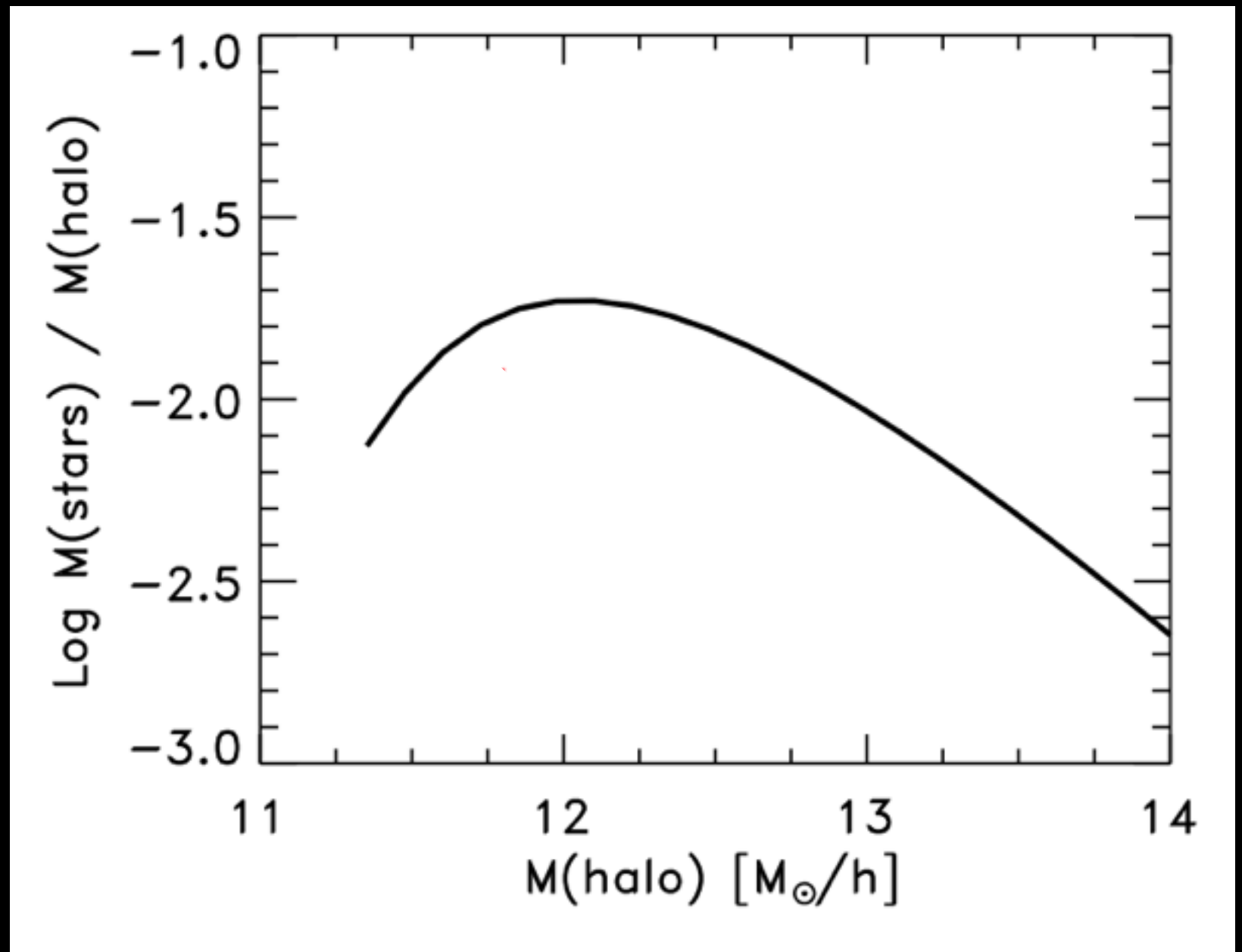


Motivation #3: Growth of Stellar Mass

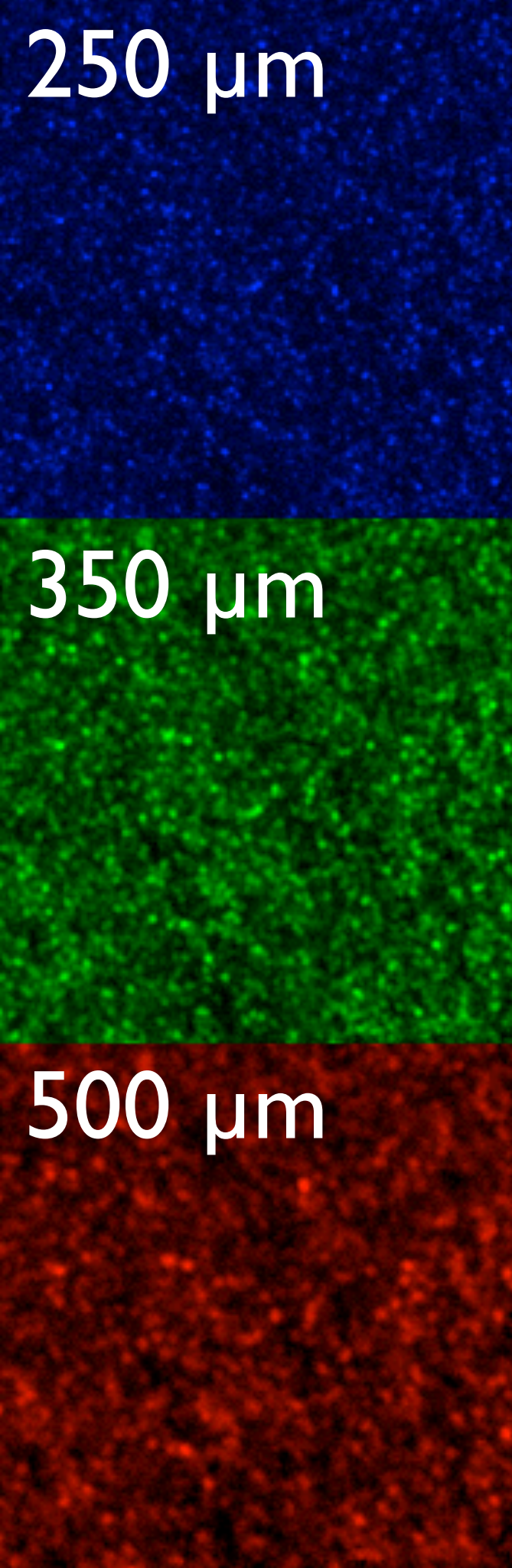
The stellar mass-halo mass (SM-HM) relation measures the efficiency in which galaxies form stars.

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)



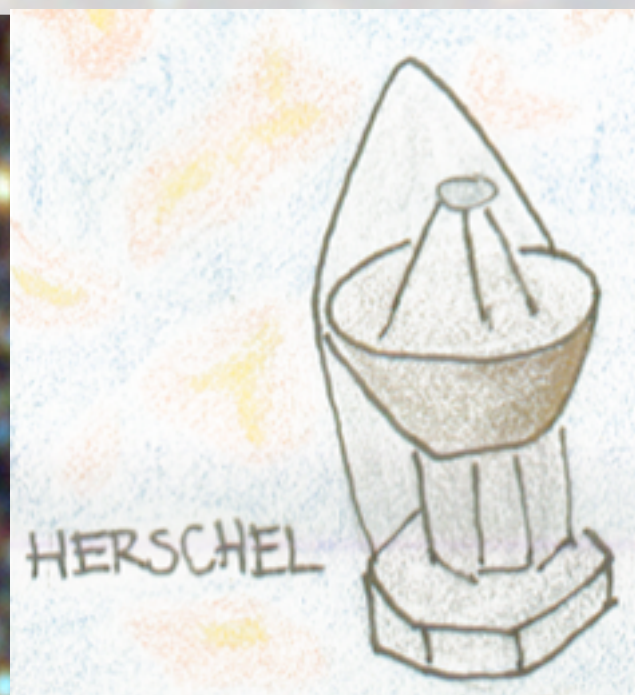
Herschel/SPIRE

PSF size
(FWHM)

250 μm - 16"

350 μm - 25"

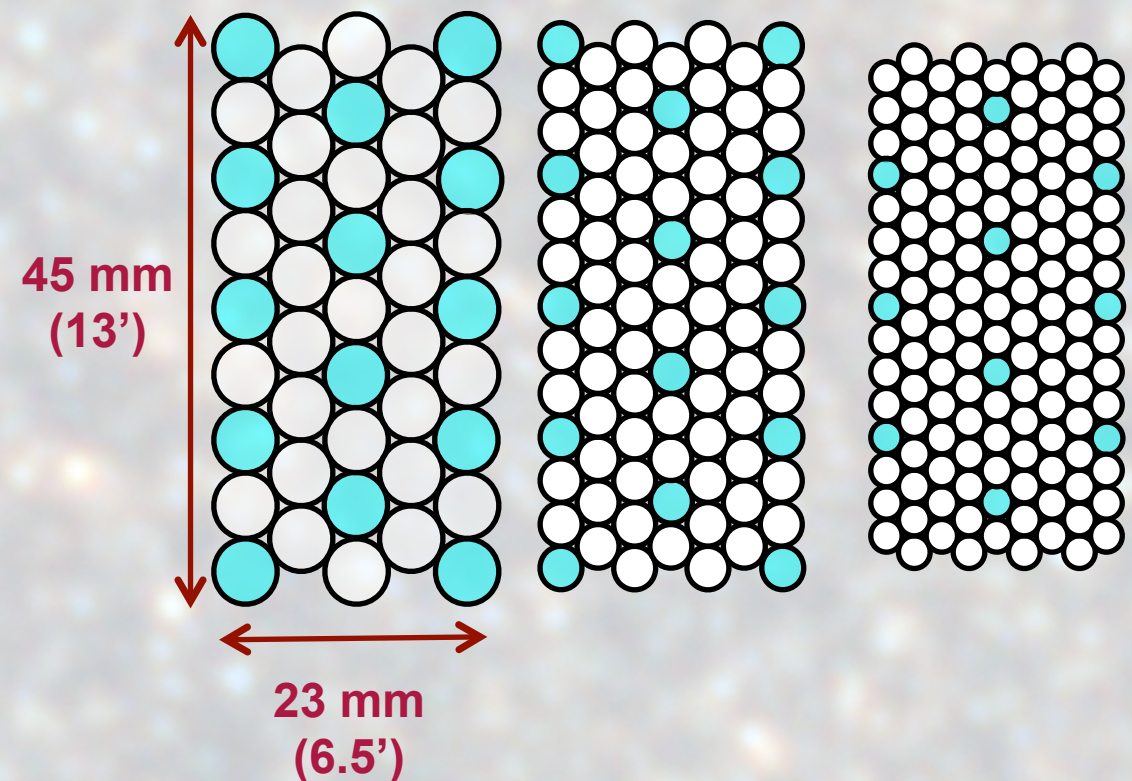
500 μm - 36"



500 μm
43 detectors

350 μm
88 detectors

250 μm
139 detectors

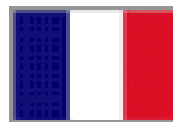
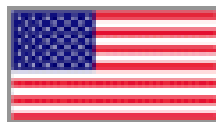


HerMES - Herschel Multi-tiered Extragalactic Survey

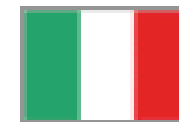
**To study the evolution of galaxies in the distant Universe
The biggest project on the Herschel Space Observatory
A European Space Agency mission**



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



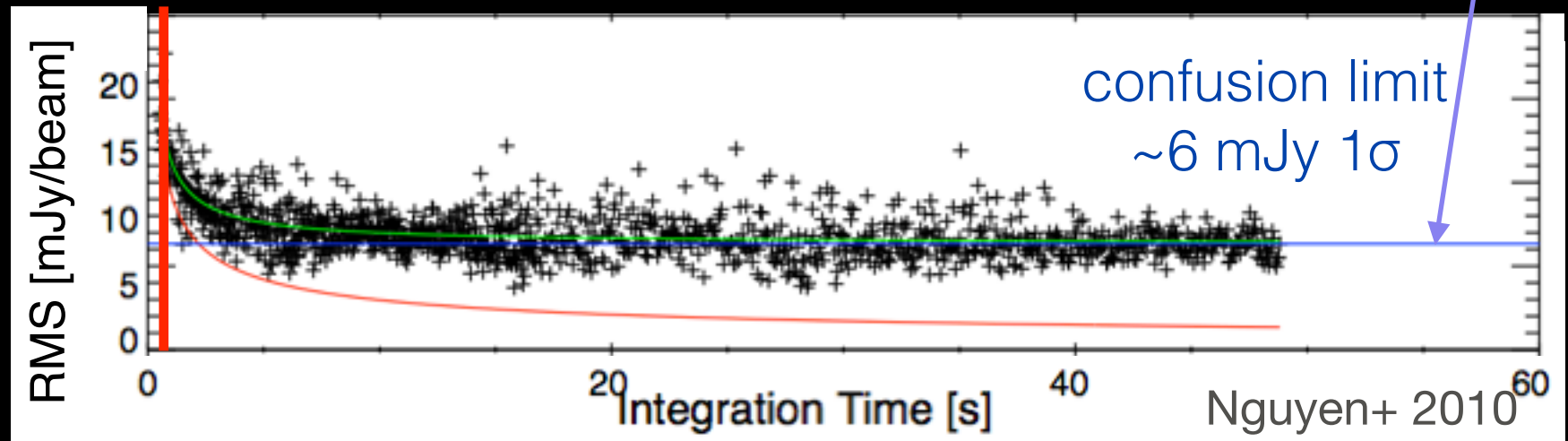
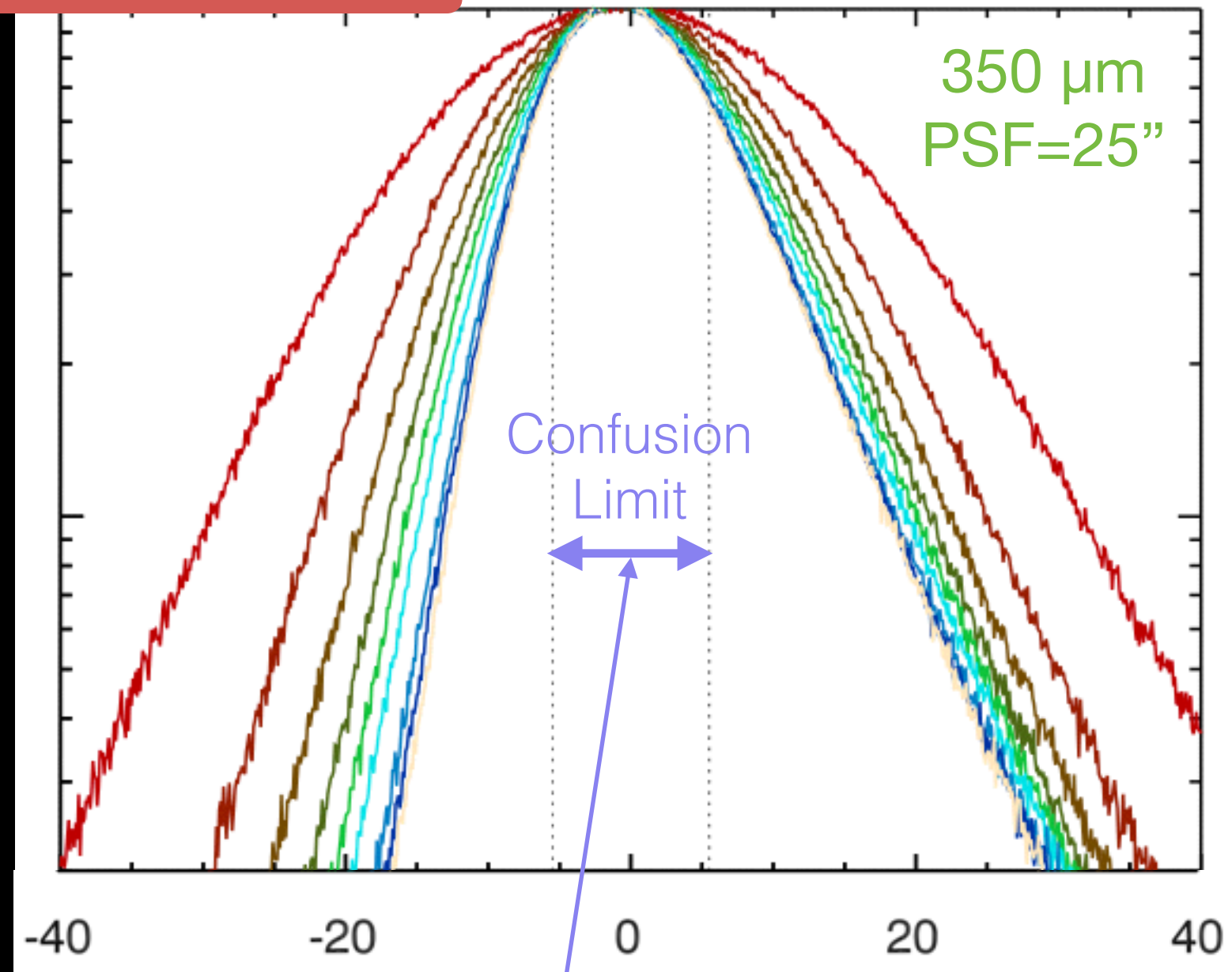
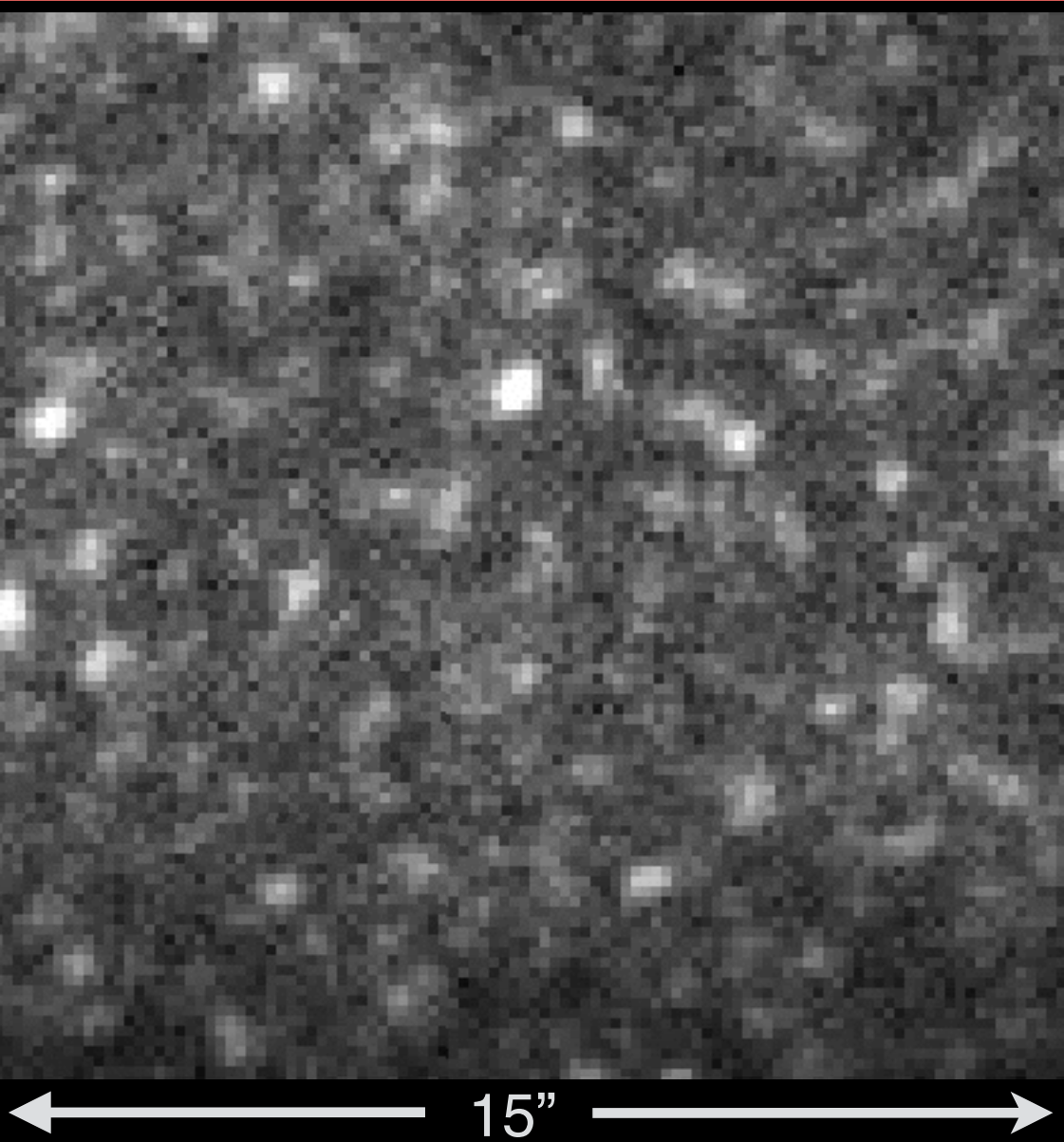
The Team

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

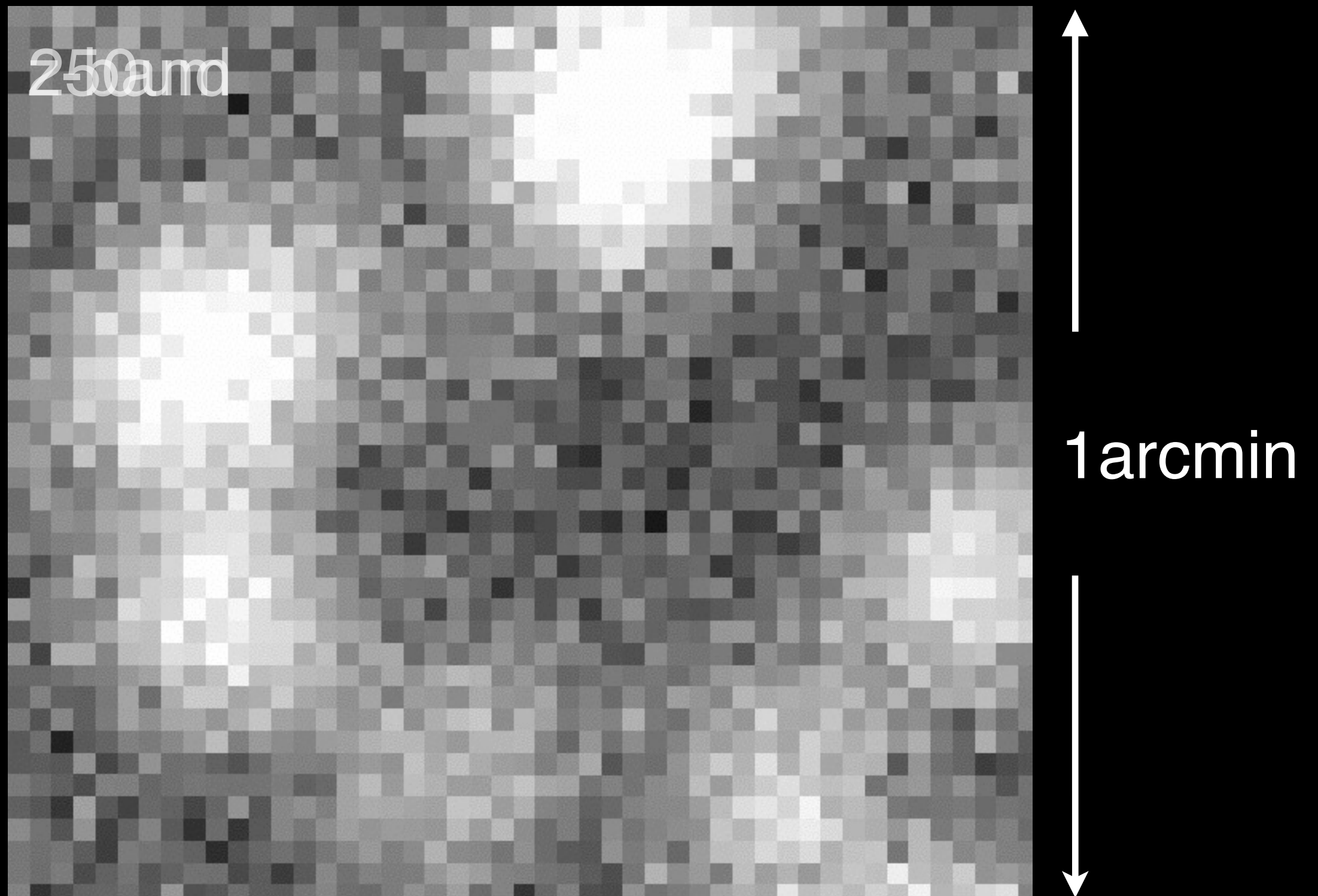
Faculty & Researchers PostDocs PhD Students

Plus engineers, instrument
builders, software developers etc.

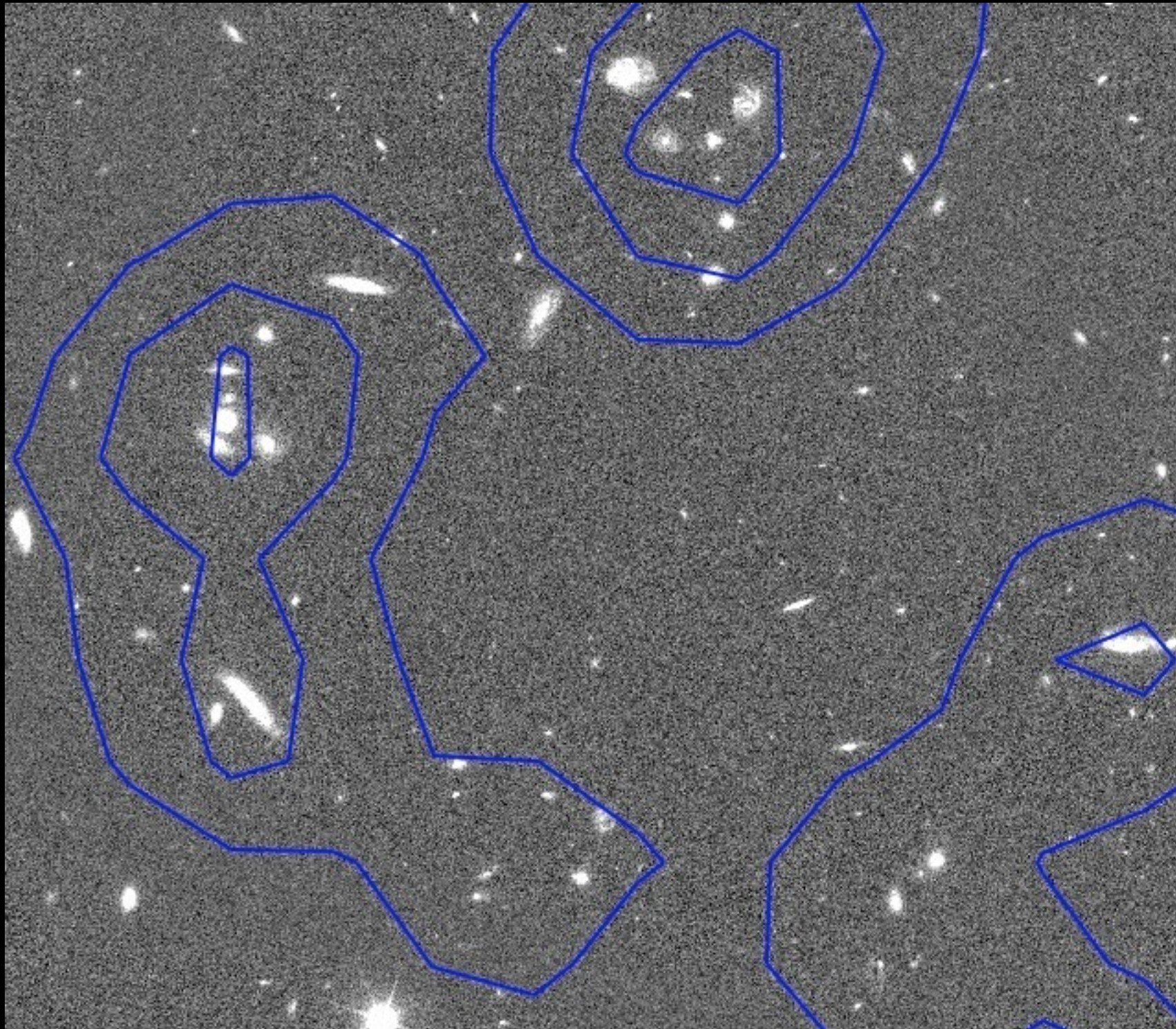
Confusion vs. Instrument Noise



Confusion Noise

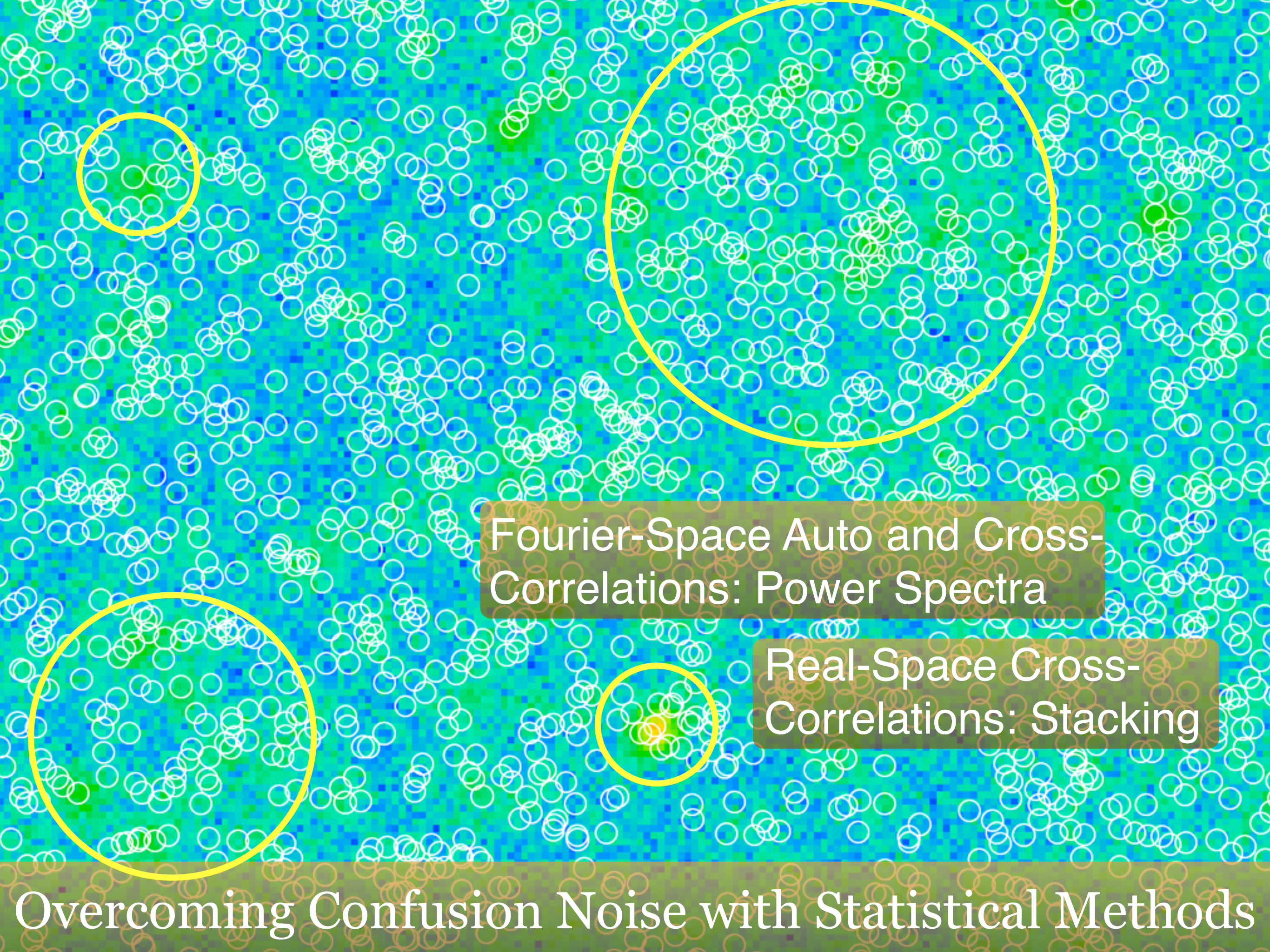


Confusion Noise



1 arcmin



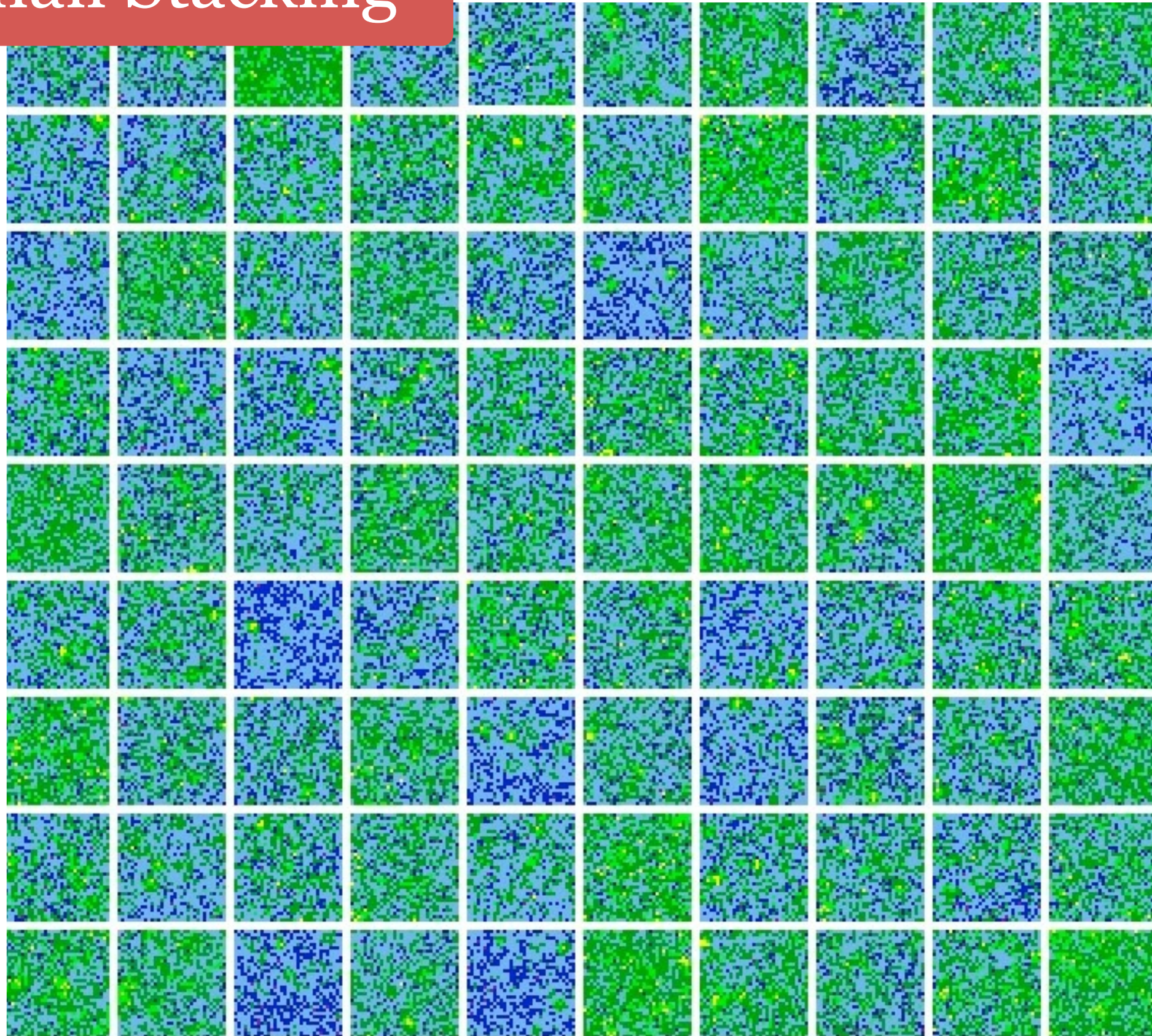


Fourier-Space Auto and Cross-
Correlations: Power Spectra

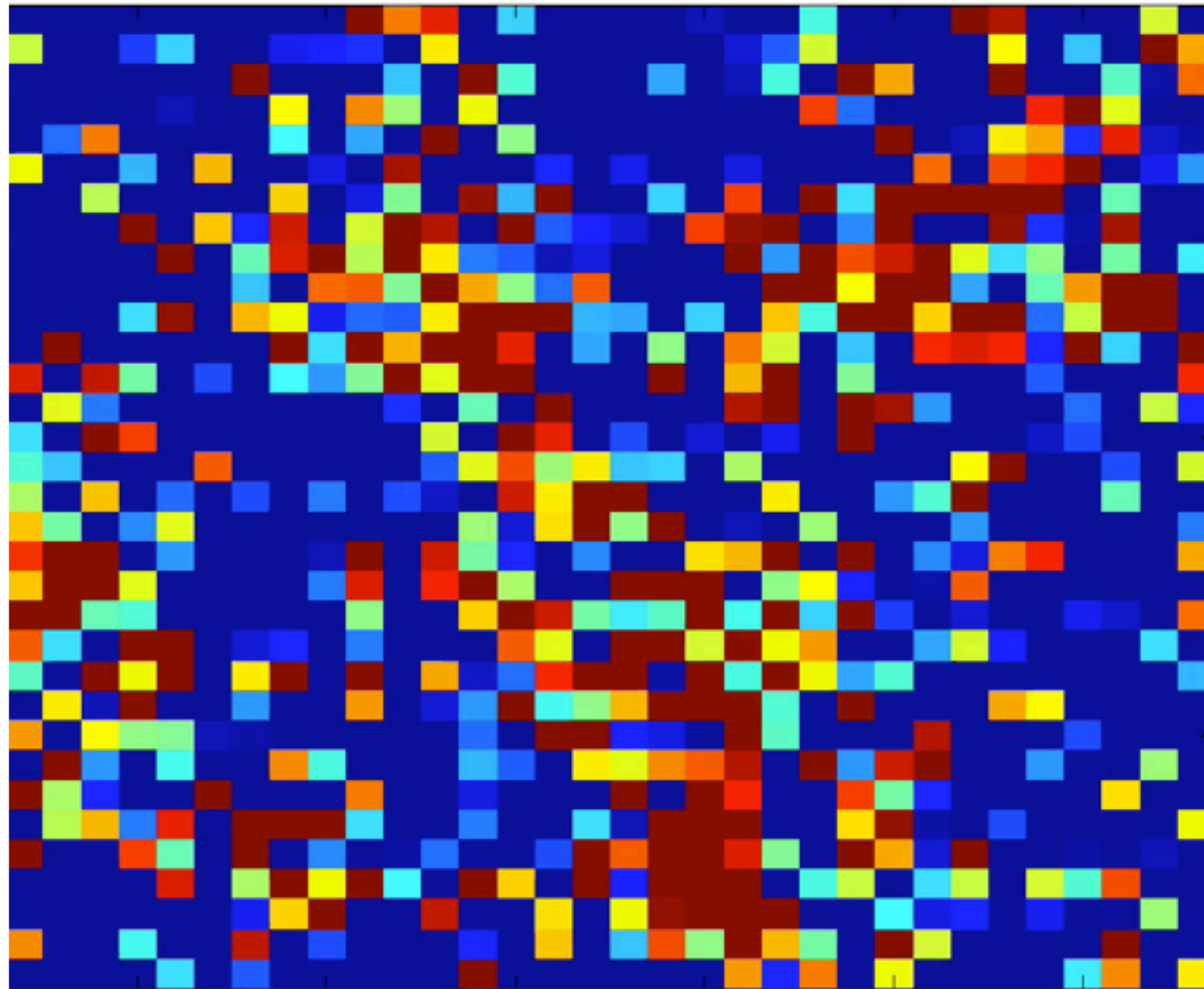
Real-Space Cross-
Correlations: Stacking

Overcoming Confusion Noise with Statistical Methods

Thumbnail Stacking



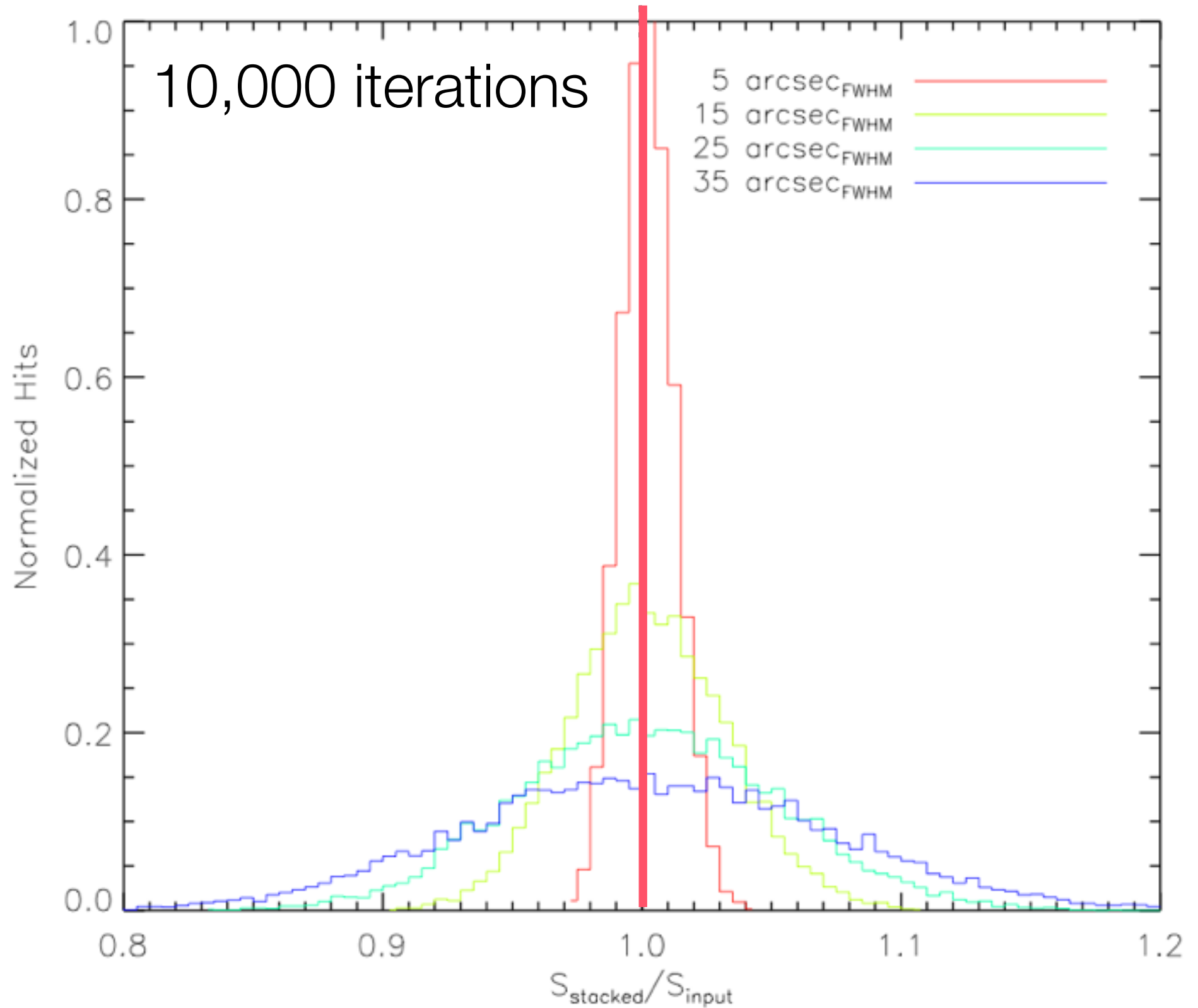
Thumbnail Stacking



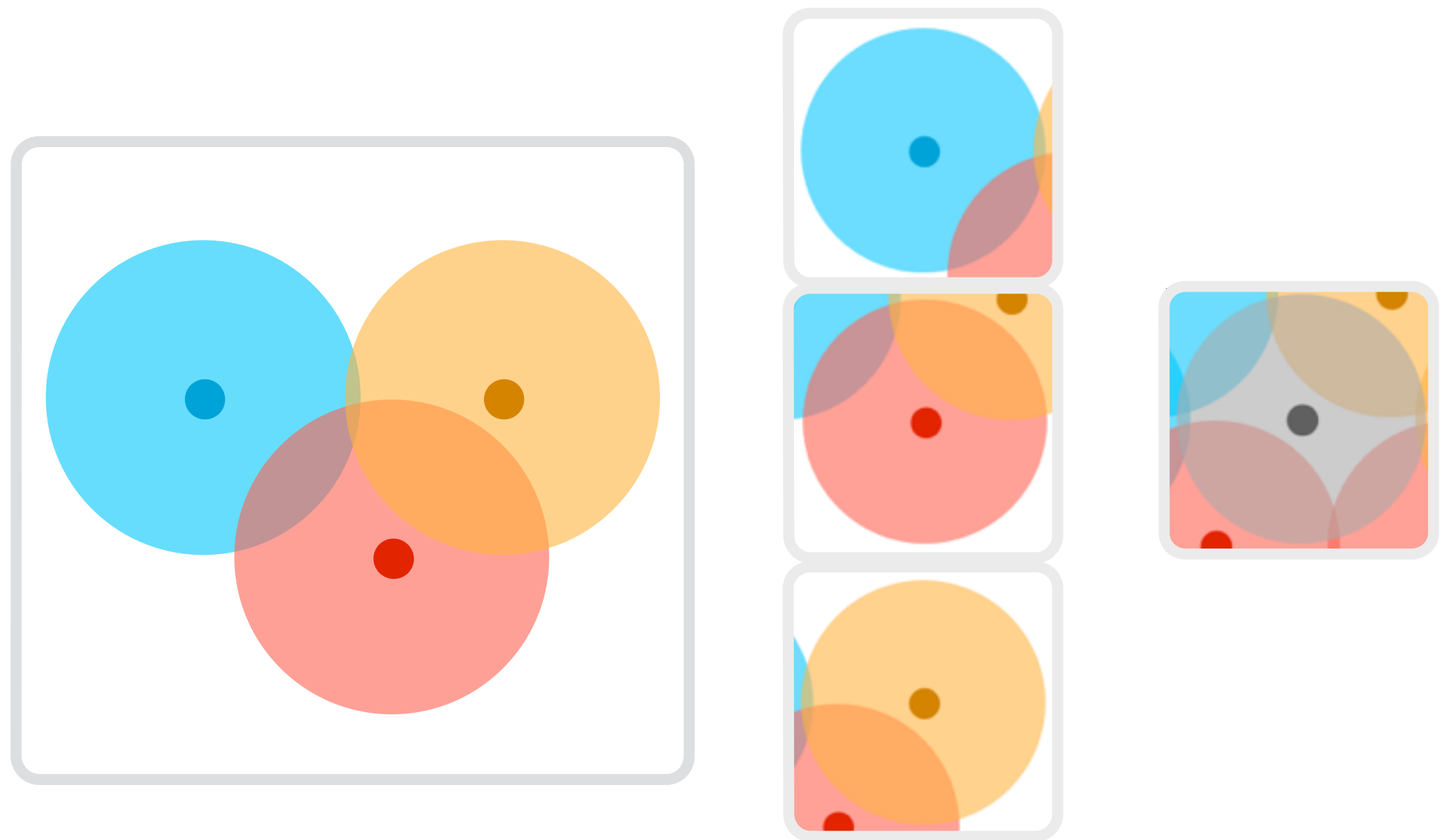
Phil Korngut (Caltech)

Uncorrelated Simulation

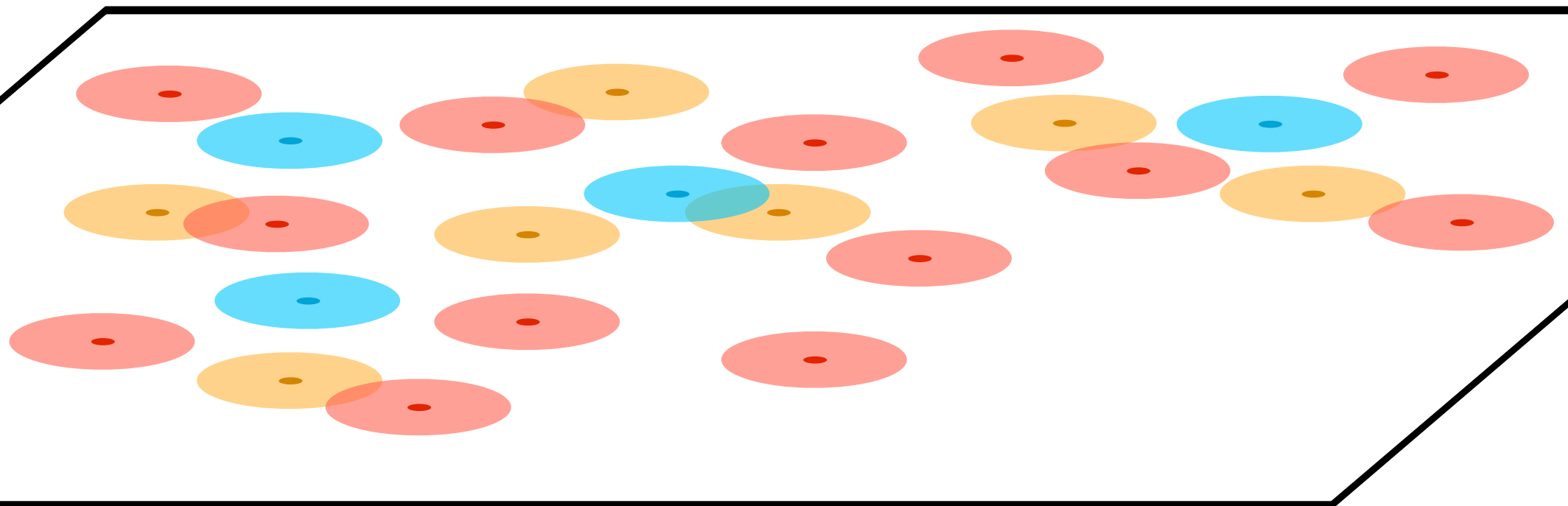
no bias



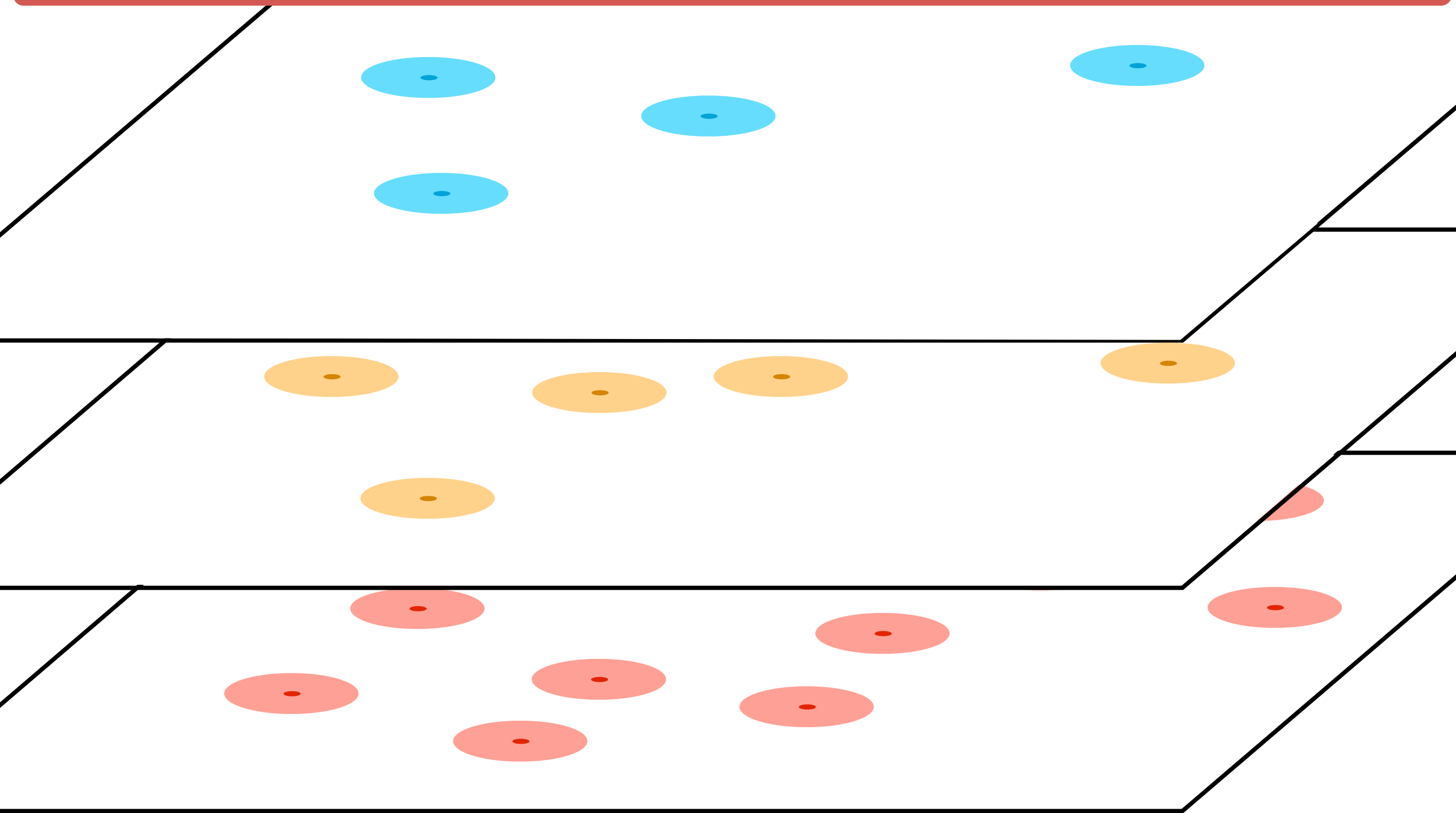
Correlation (clustering) Induced Bias



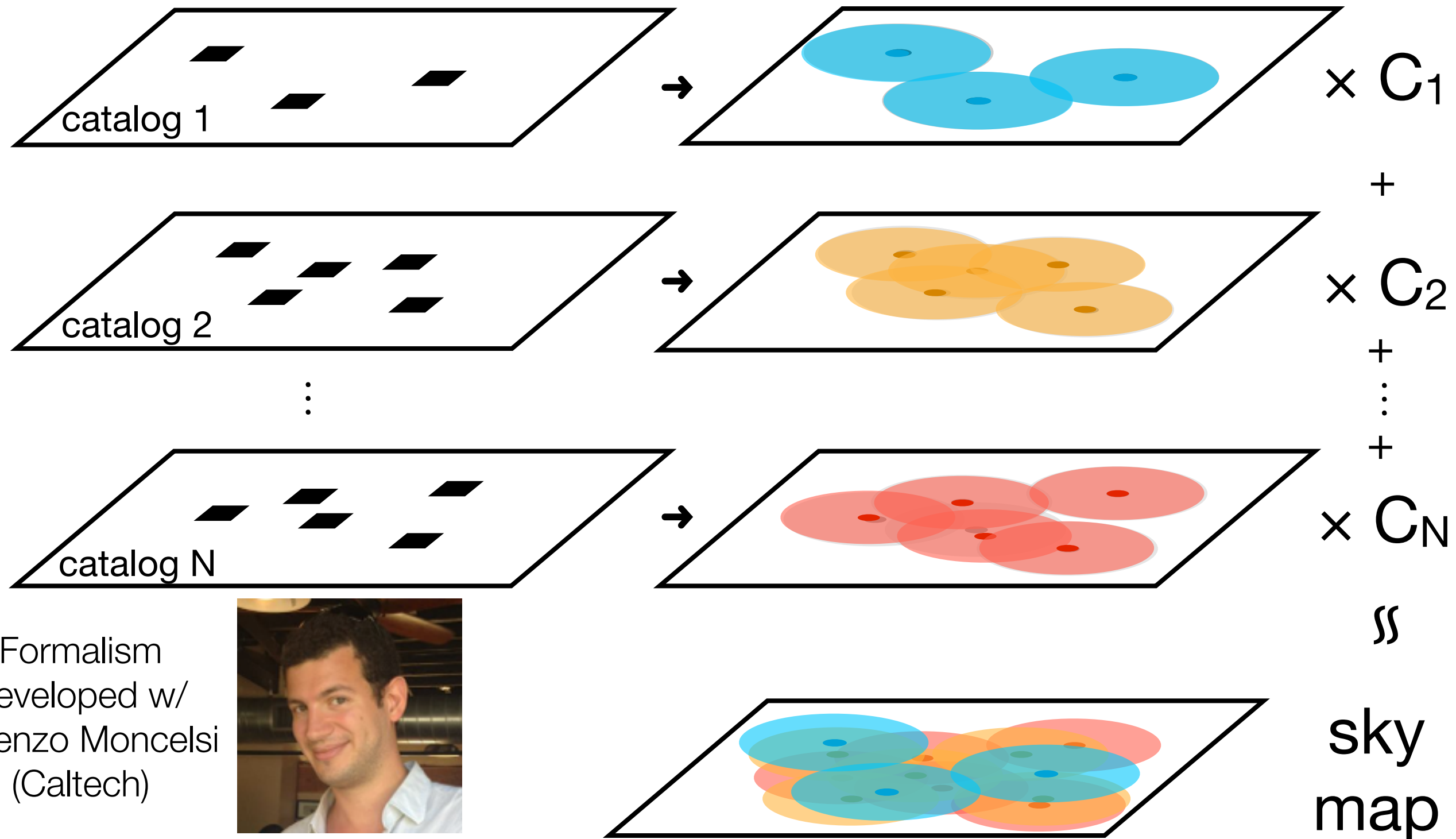
Correlation (clustering) Induced Bias



Correlation (clustering) Induced Bias

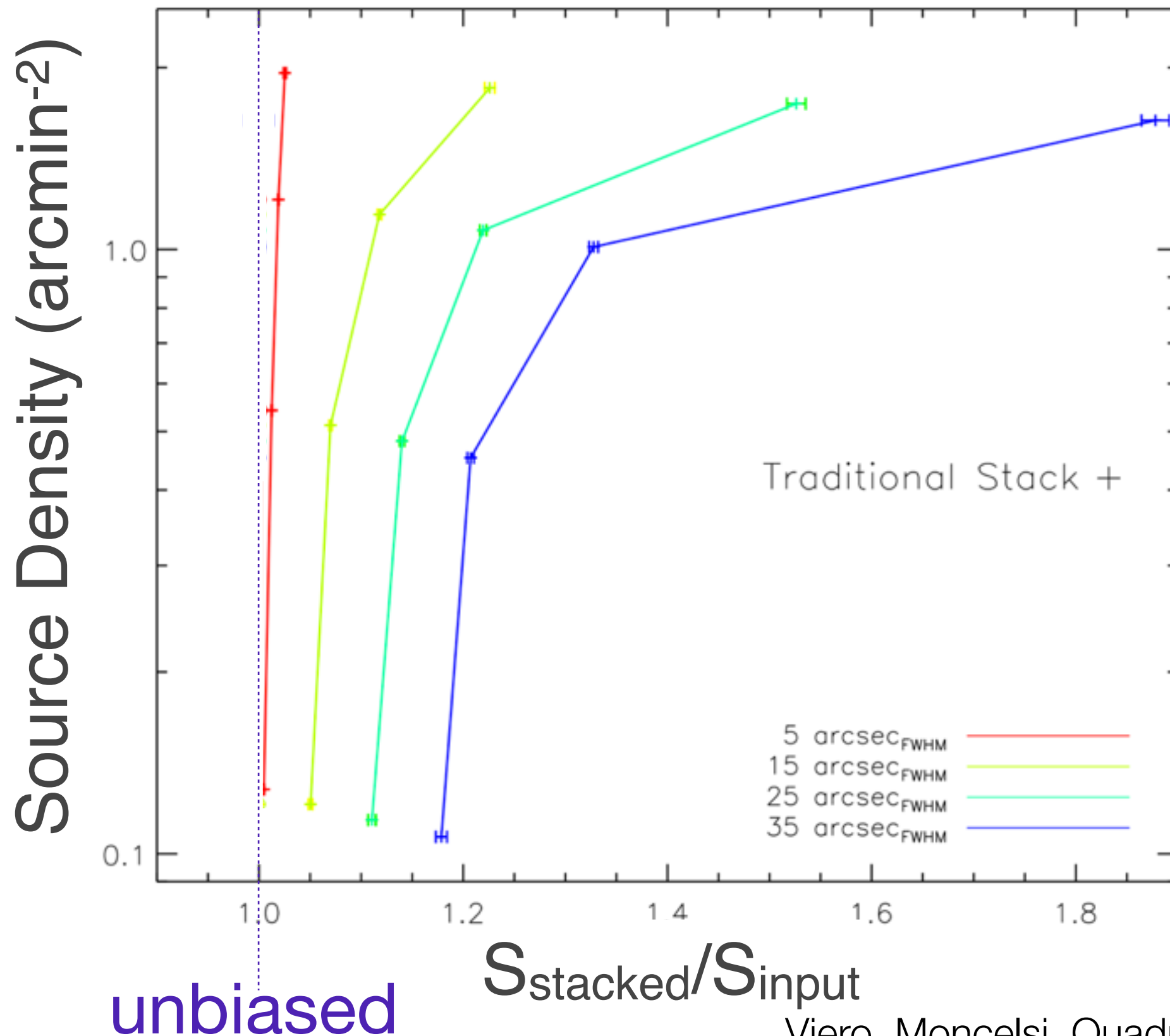


SIMSTACK: Simultaneous Stacking Algorithm



SIMSTACK code publicly available
see [arXiv:1304.0446](https://arxiv.org/abs/1304.0446)

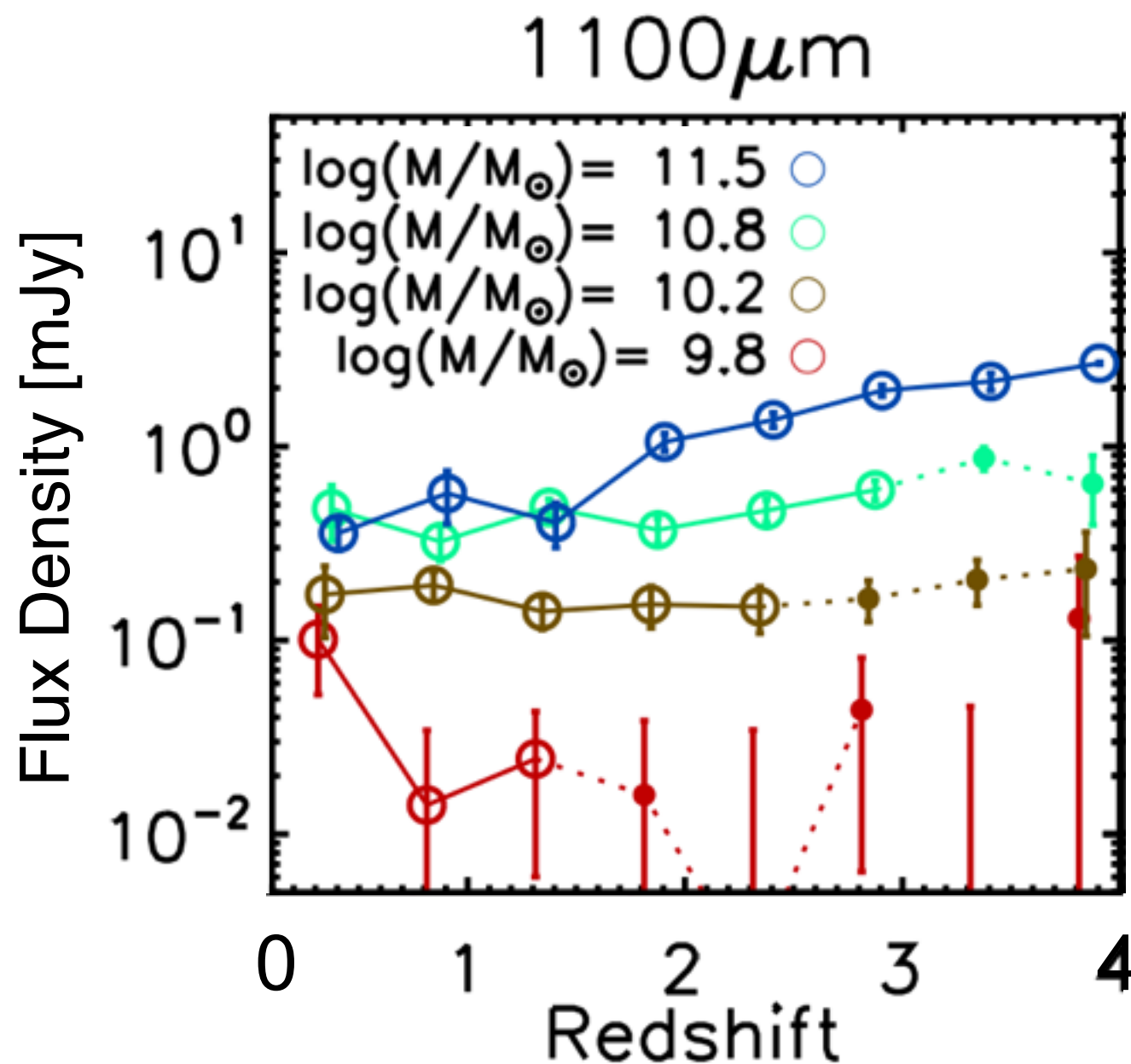
SIMSTACK: Simultaneous Stacking Algorithm



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.)

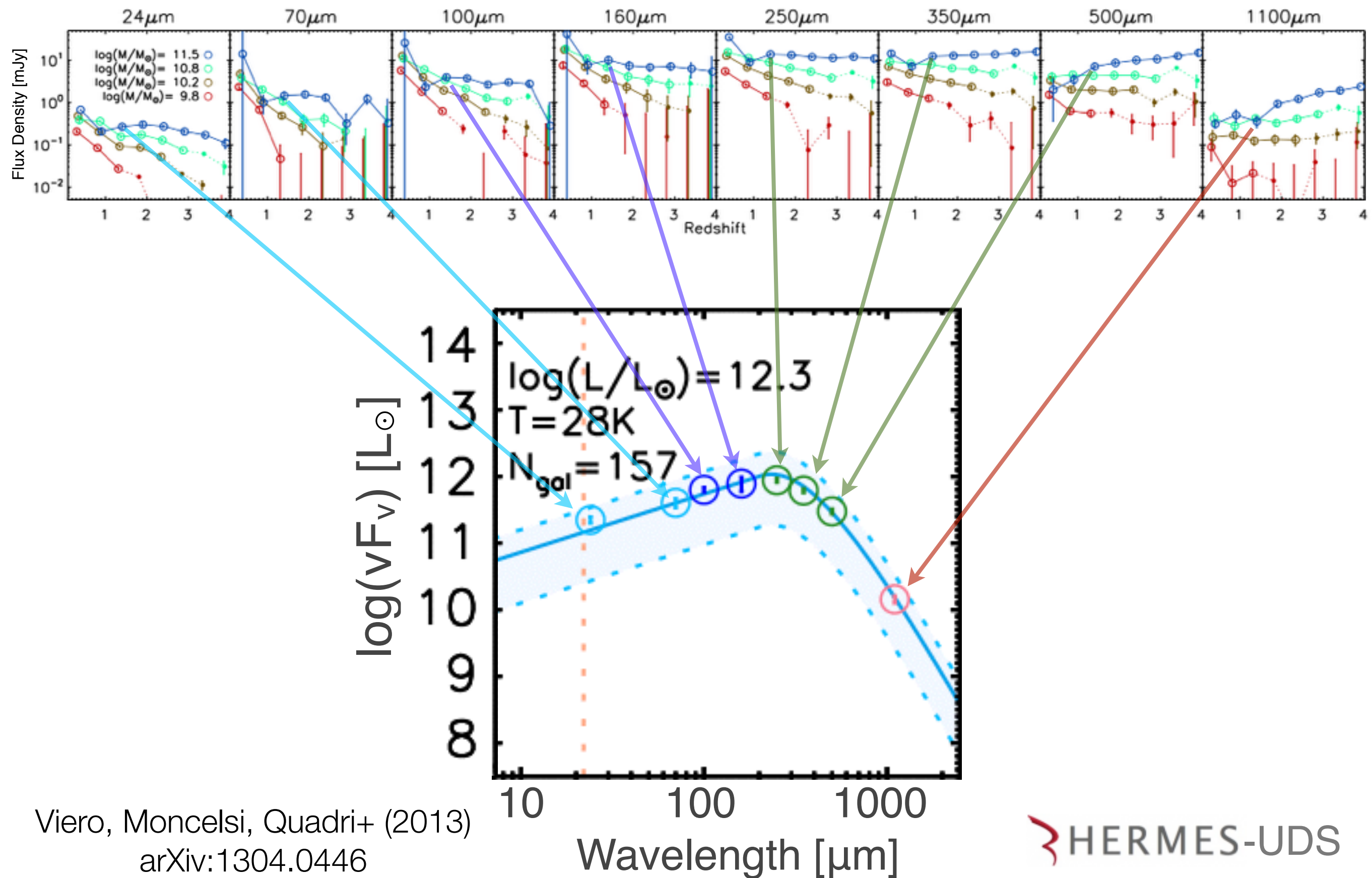
- UKIDSS/UDS [2/3 deg²]
- uBVRizJHK + IRAC ch1234
- K-band magnitude cut 24 AB
- 81,000 sources in ~0.63 deg²
- redshifts - EAZY (Brammer 2008)
- masses - FAST (Kriek 2009)

HERMES

maps (HerMES; Oliver et al. 2012)

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

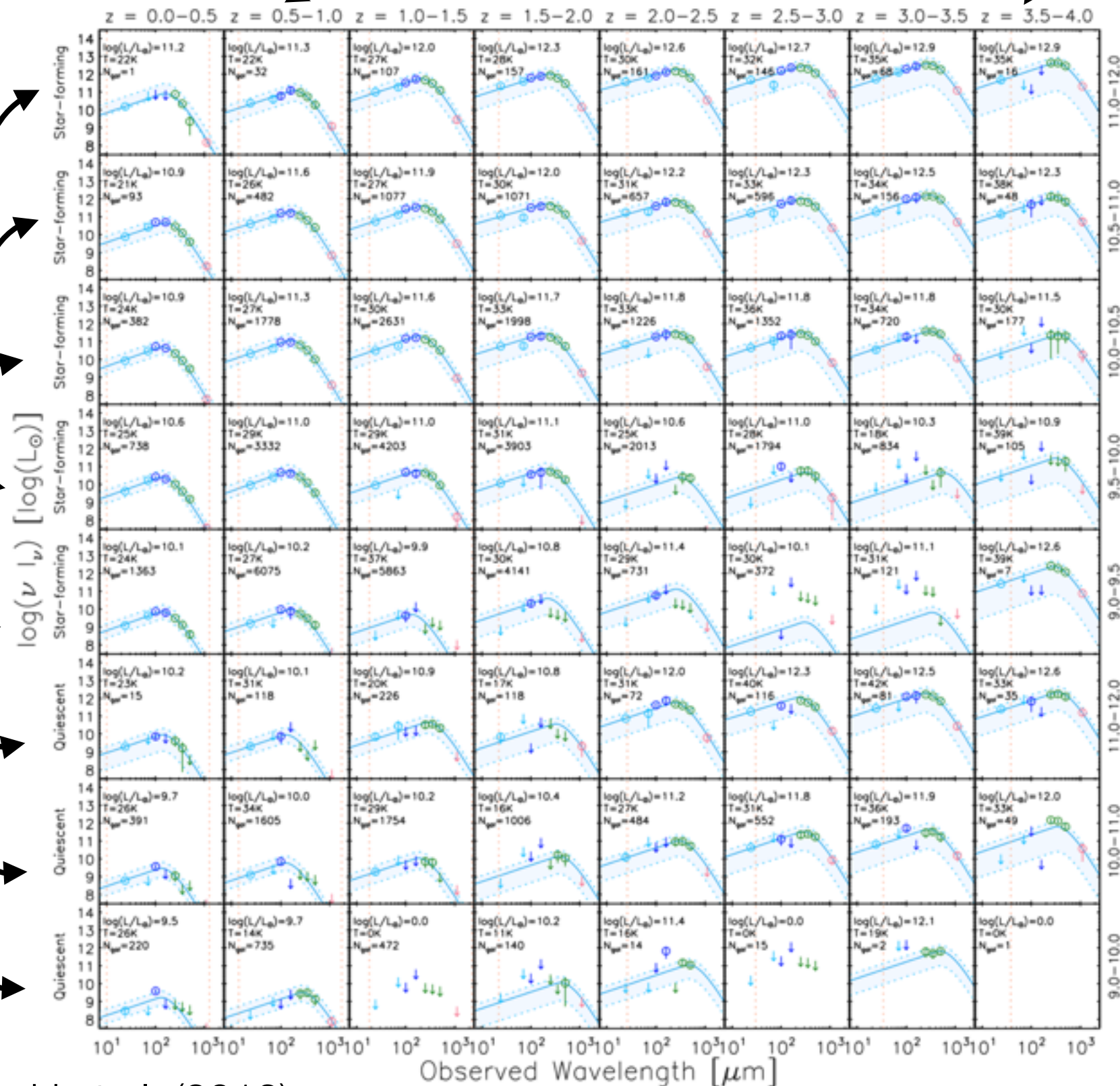
SIMSTACK of Galaxies by Stellar Mass and Redshift



SEDS

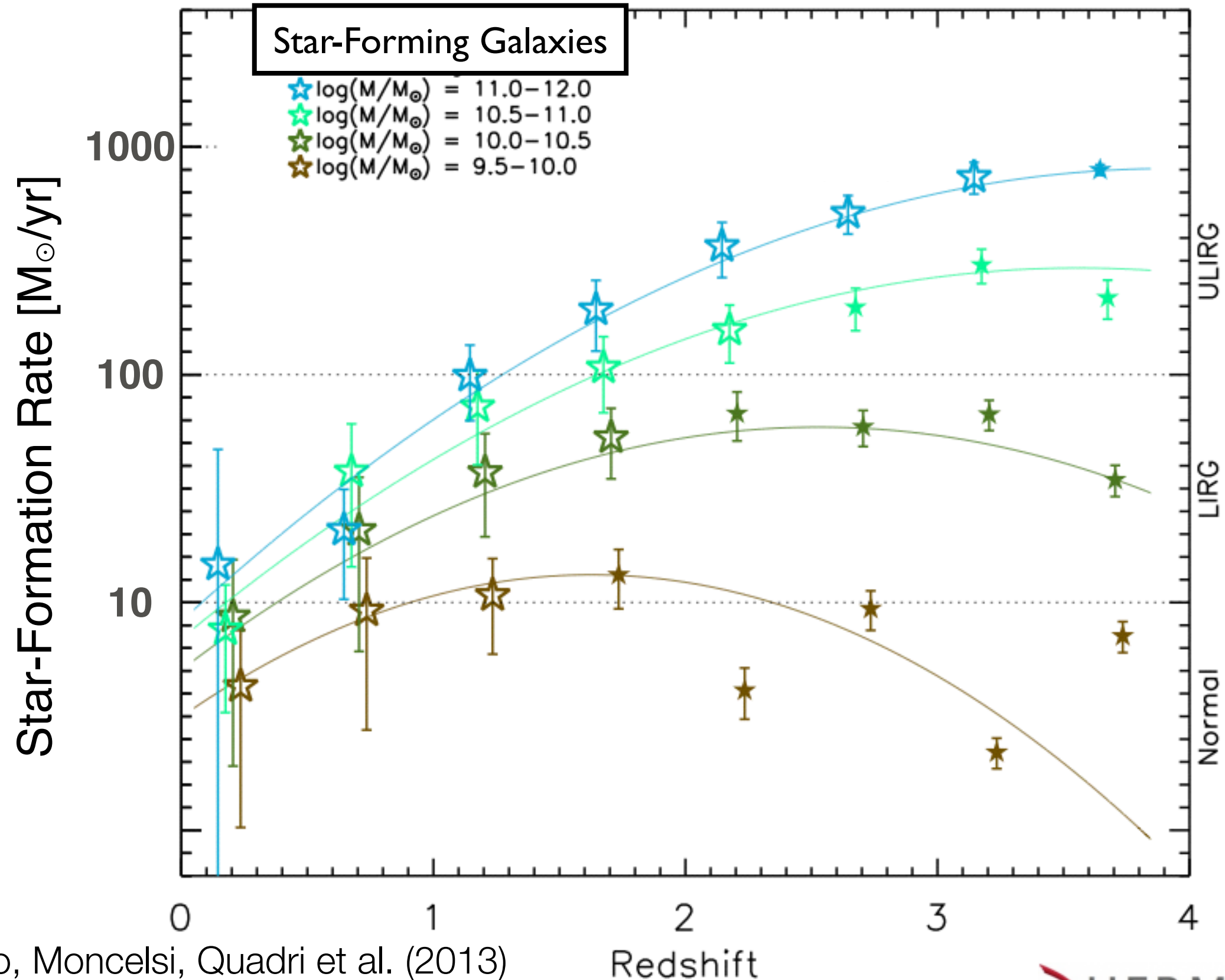
redshift
slices

stellar
mass
slices



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

Average Galaxy Infrared Luminosity by Stellar Mass and Redshift

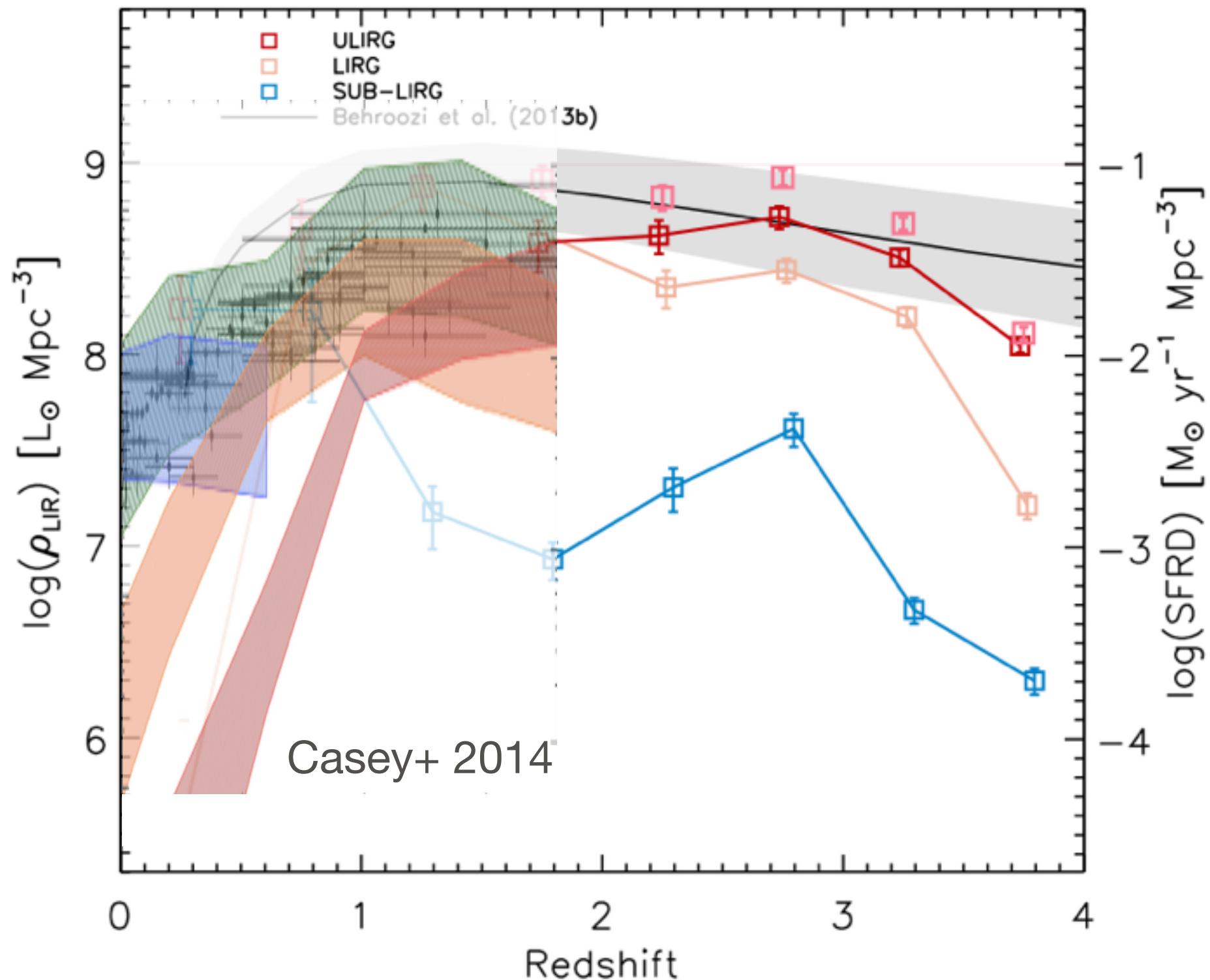


Viero, Moncelsi, Quadri et al. (2013)
arXiv:1304.0446

Motivation Recap

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

Stacked Infrared Luminosity Density

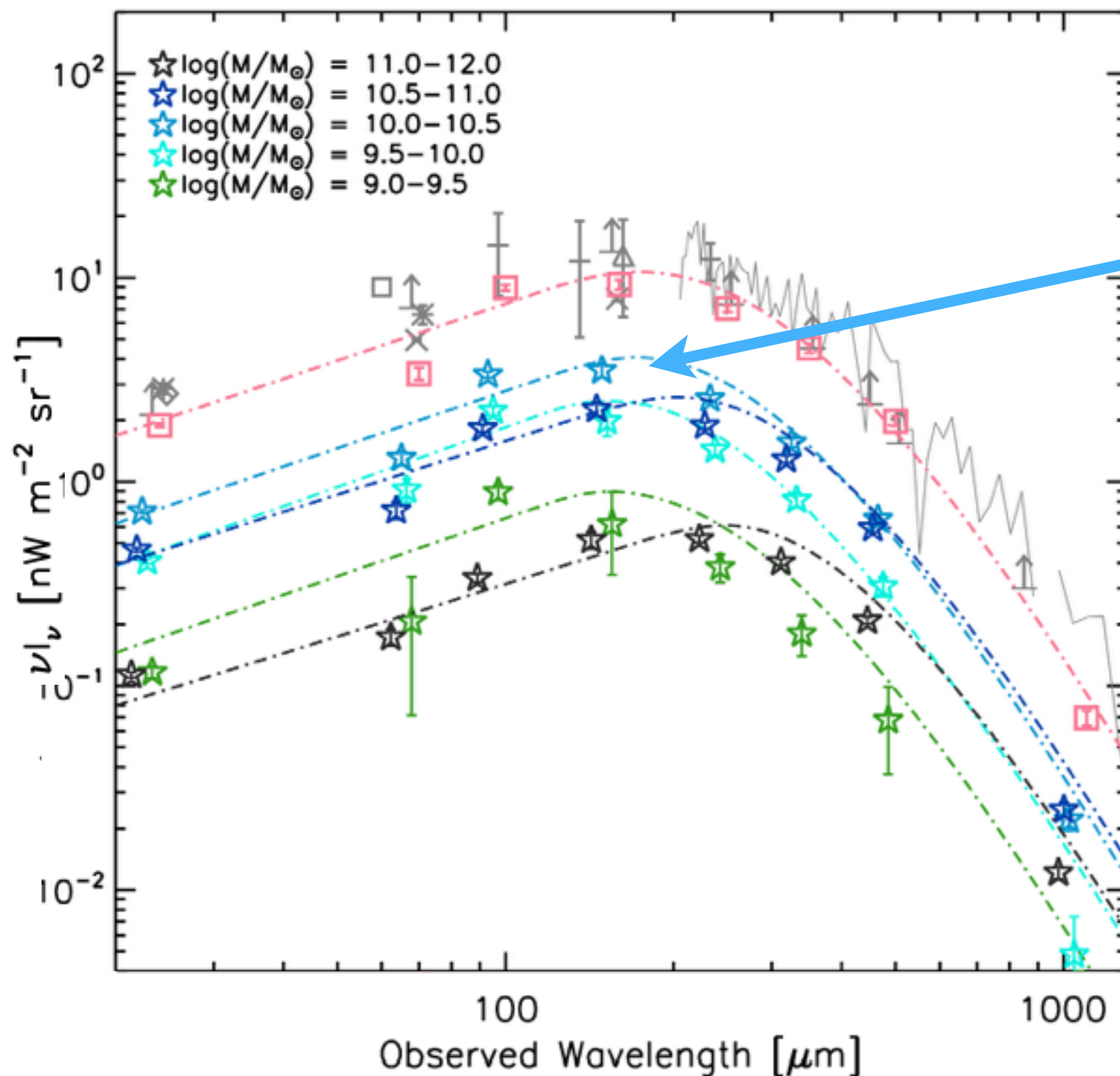


Viero, Monceli, Quadri et al. (2013)
arXiv:1304.0446

Motivation Recap

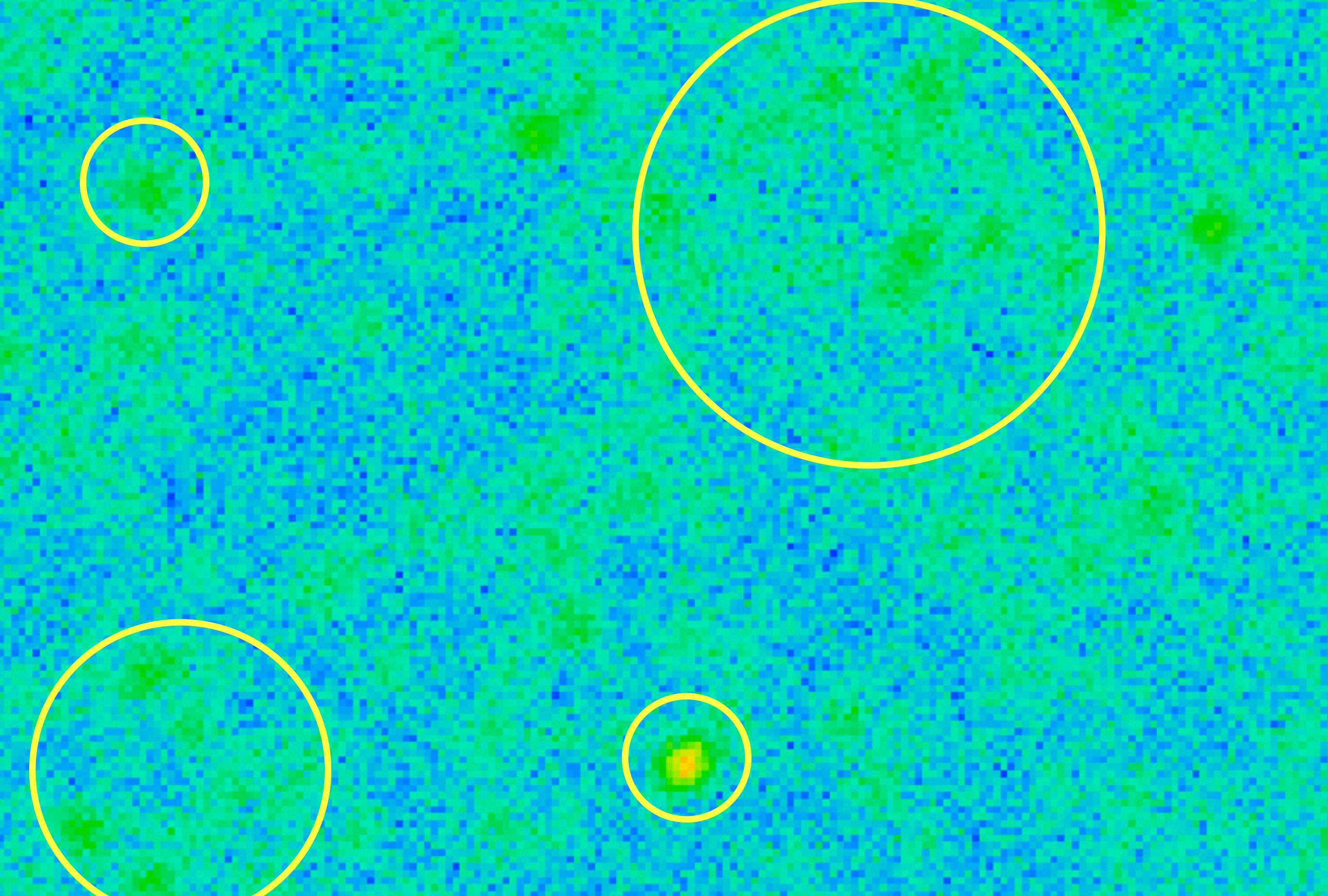
1. History of Cosmic Star Formation
2. Origin of the CIB
3. Growth of Stellar Mass

Stacked CIB



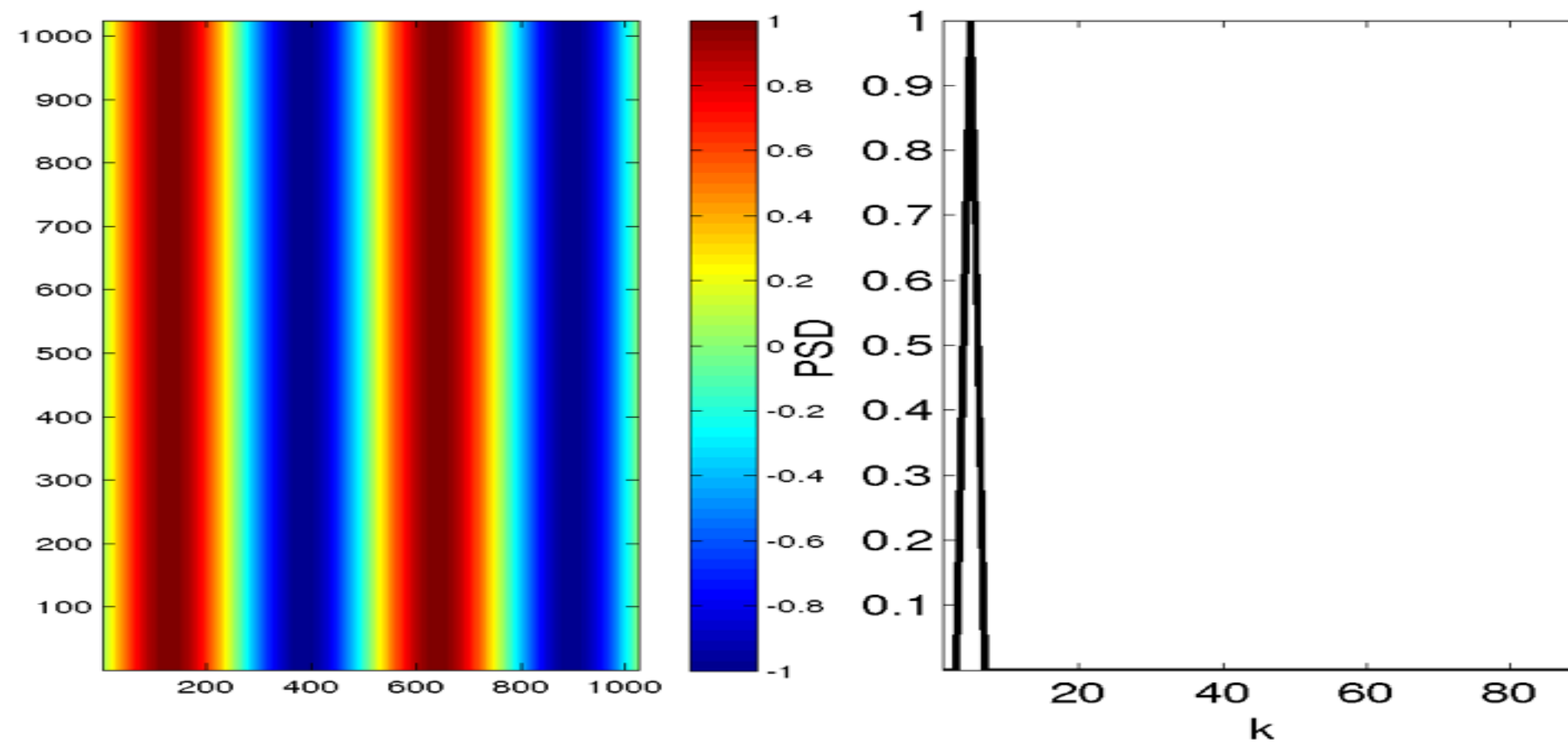
~70% at SPIRE
wavelengths

$\log(M/M_{\odot}) \sim 10-11$
i.e., $M \lesssim M^*$



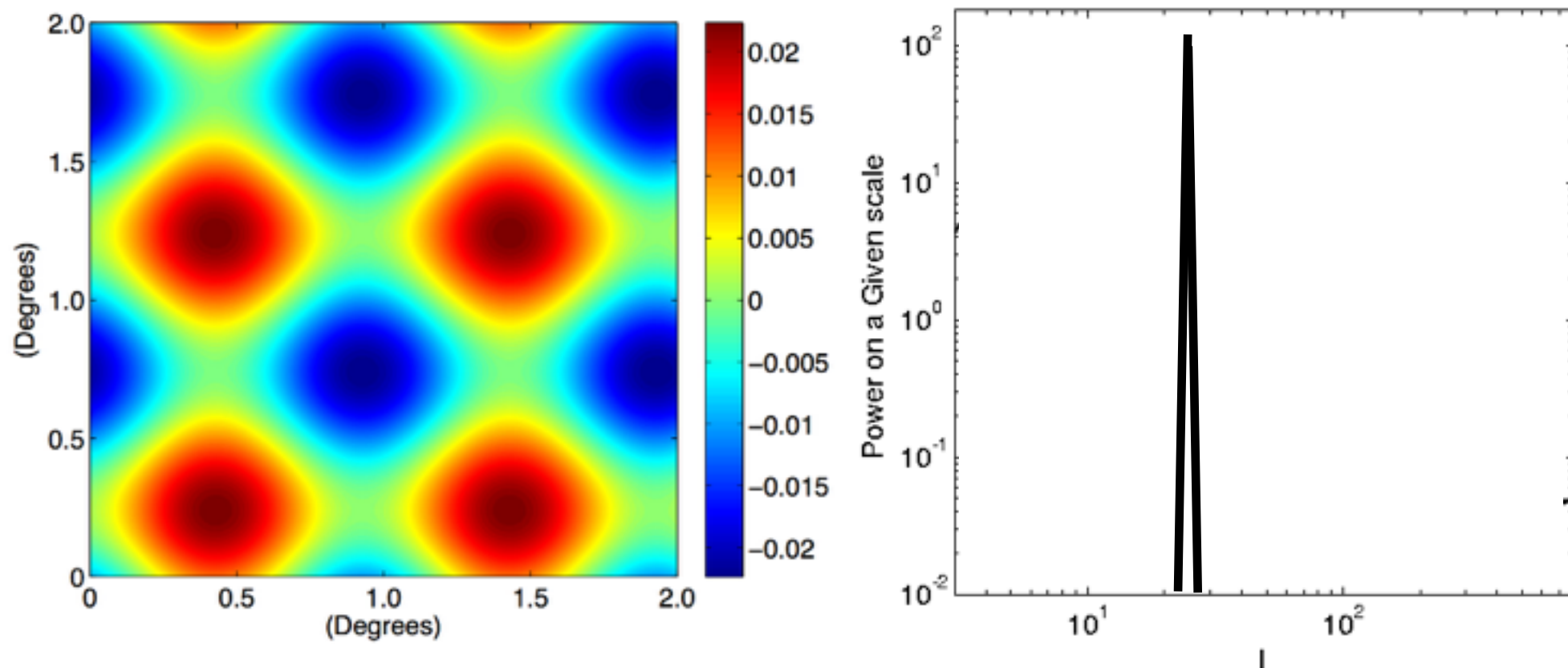
Power Spectrum of Background Fluctuations

Power Spectrum



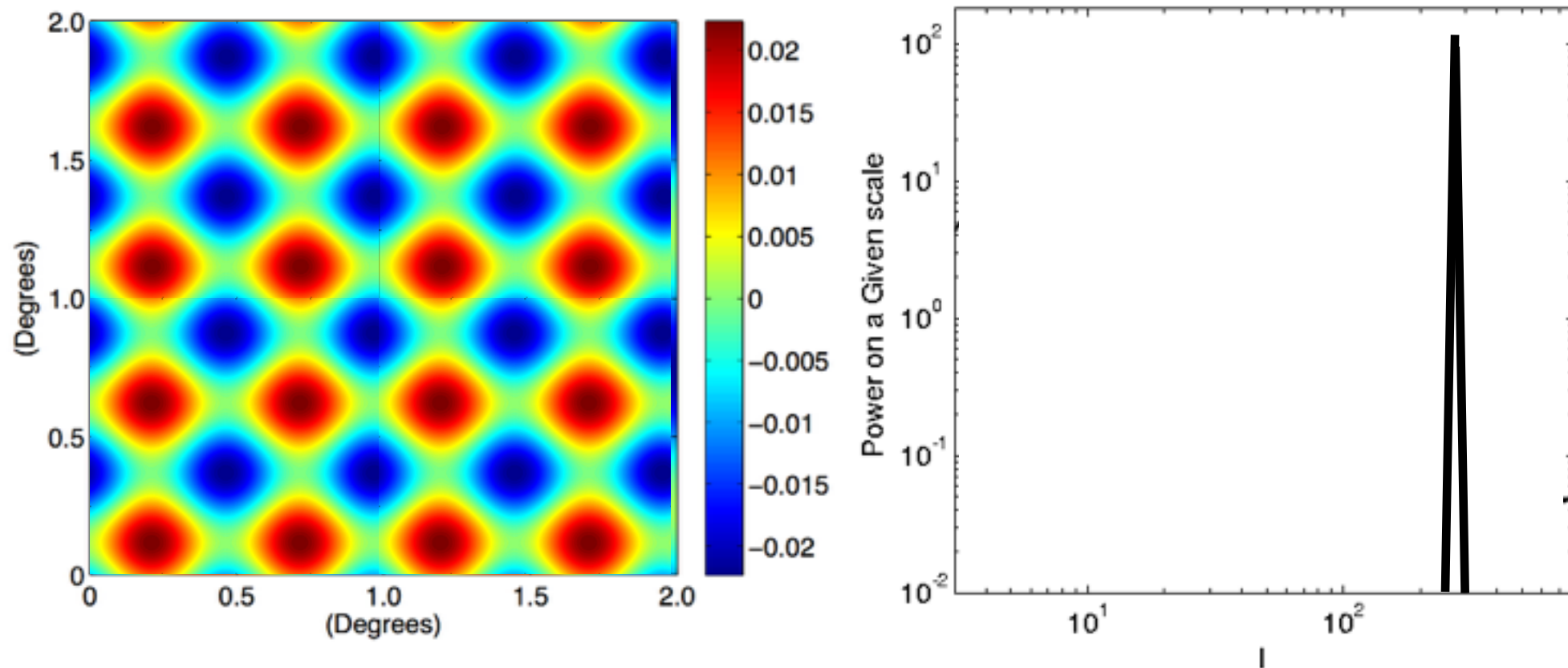
Phil Korngut (Caltech)

Power Spectrum



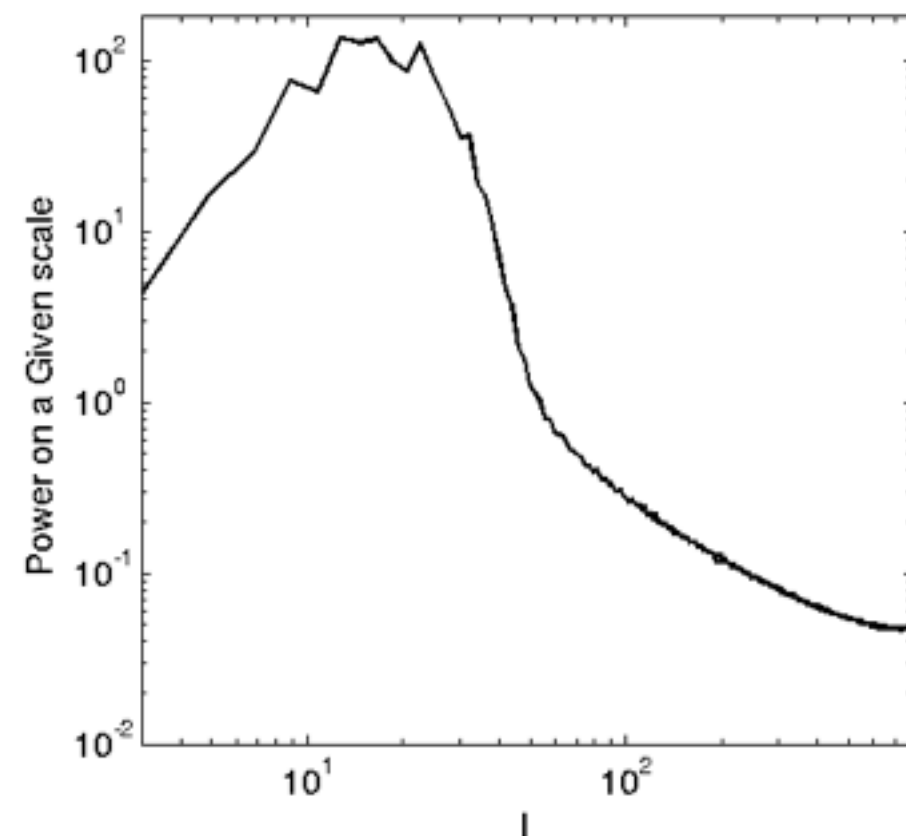
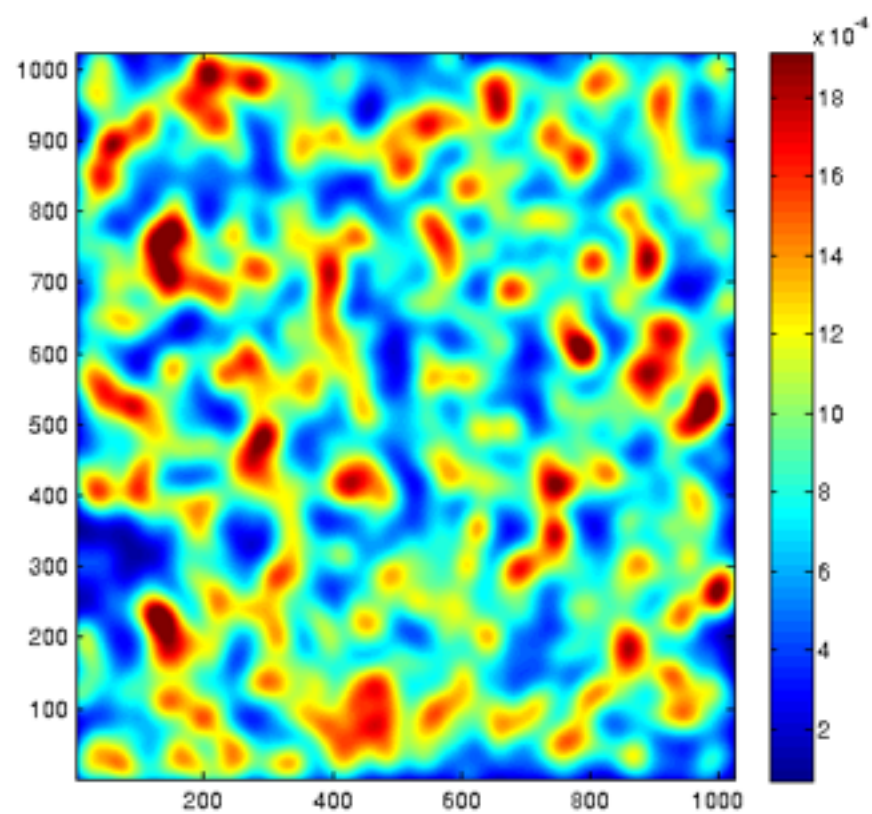
Phil Korngut (Caltech)

Power Spectrum



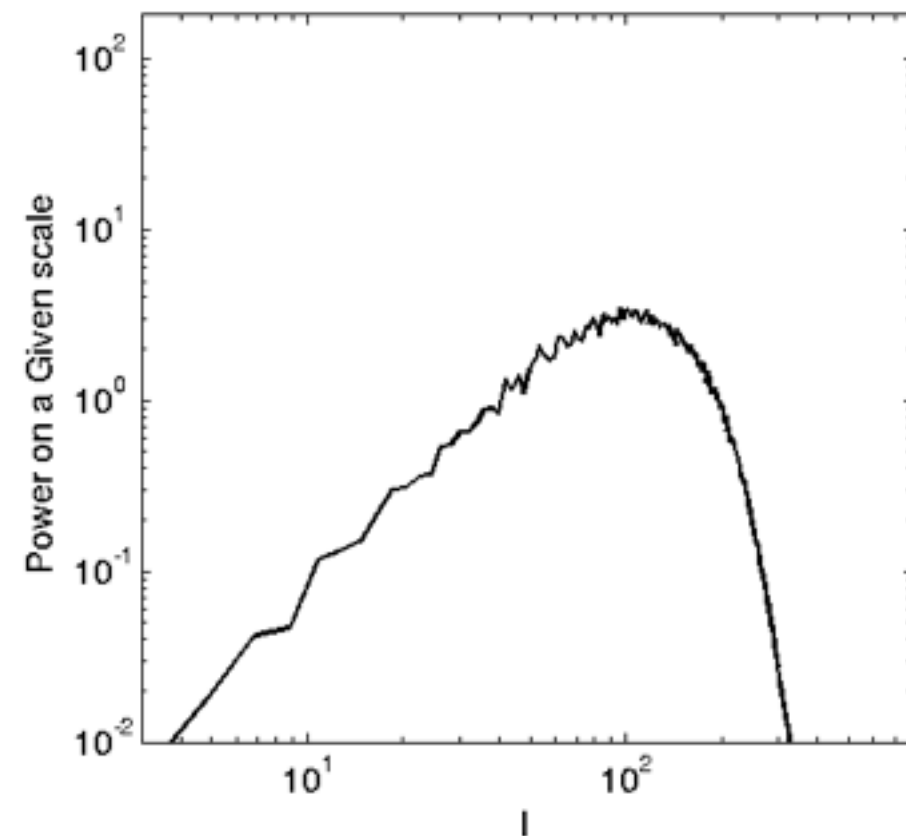
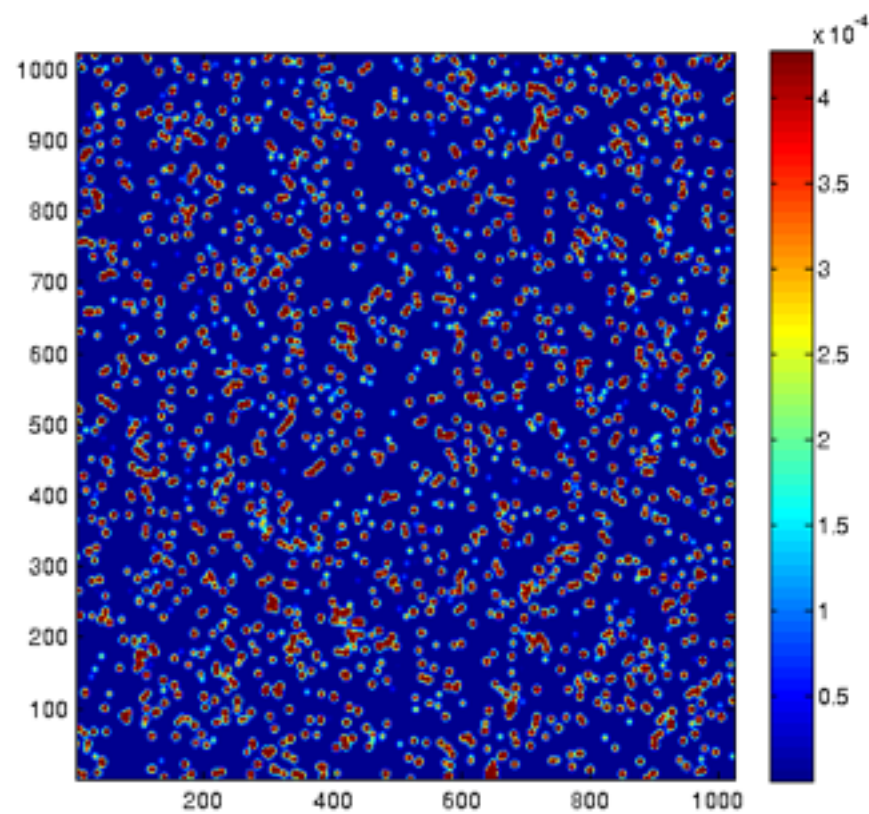
Phil Korngut (Caltech)

Power Spectrum



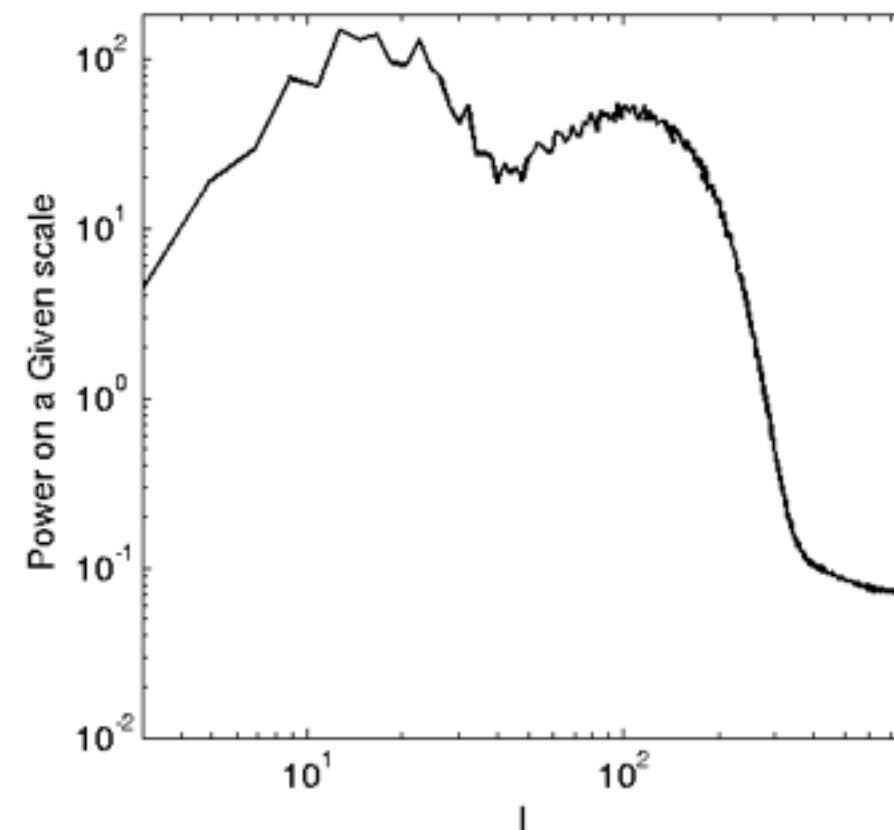
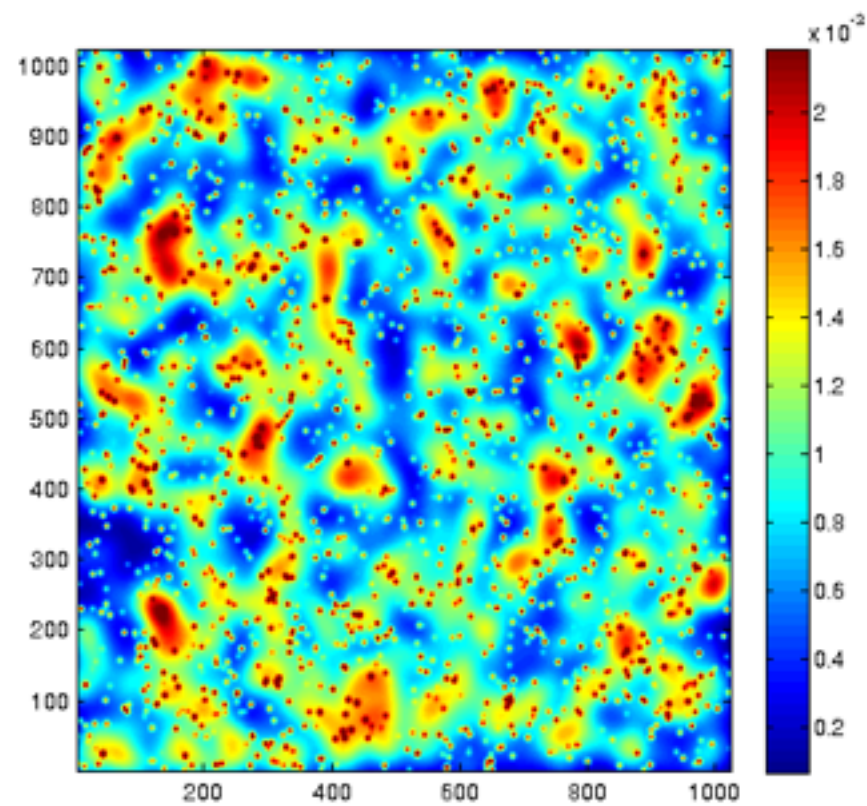
Phil Korngut (Caltech)

Power Spectrum



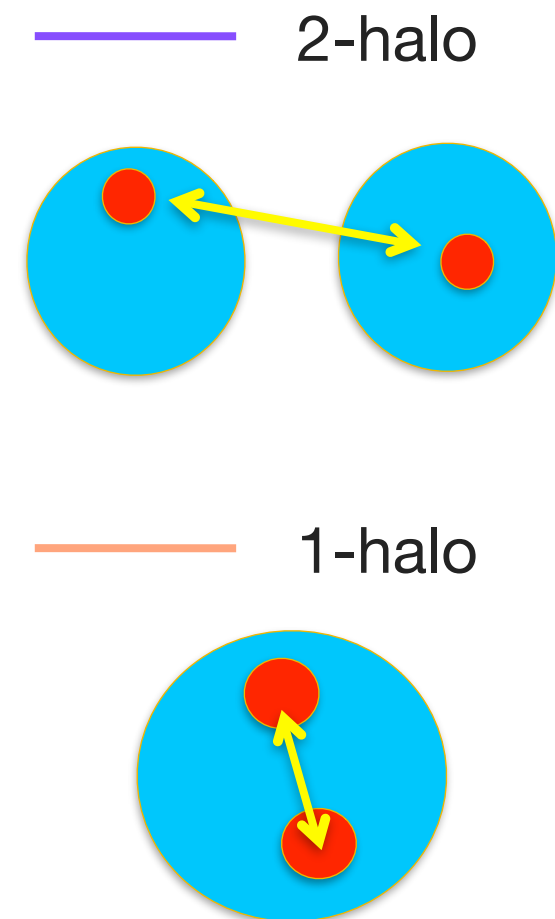
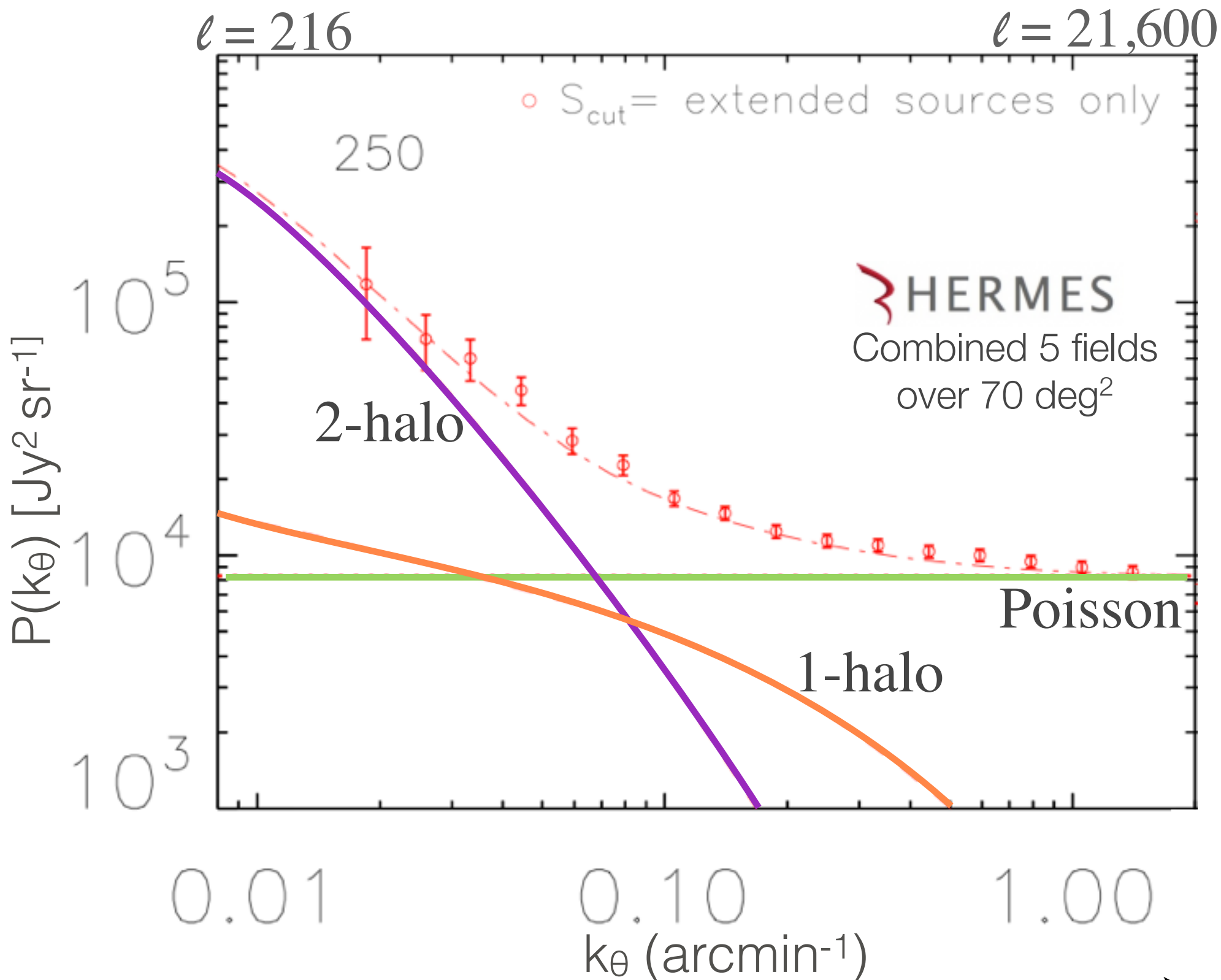
Phil Korngut (Caltech)

Power Spectrum



Phil Korngut (Caltech)

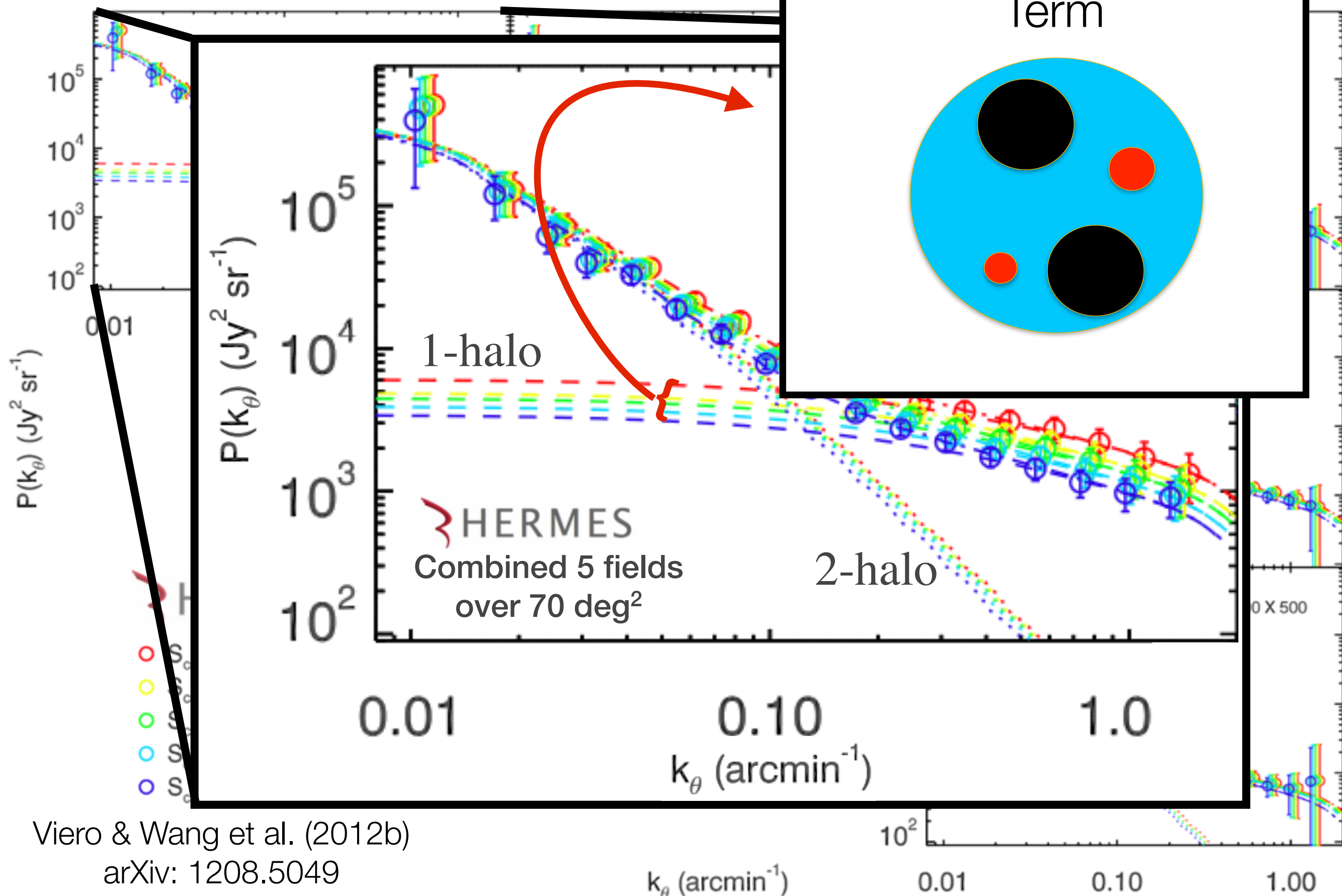
CIB Power Spectrum



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

Smaller Scales

CIB Power Spectrum



Viero & Wang et al. (2012b)

arXiv: 1208.5049

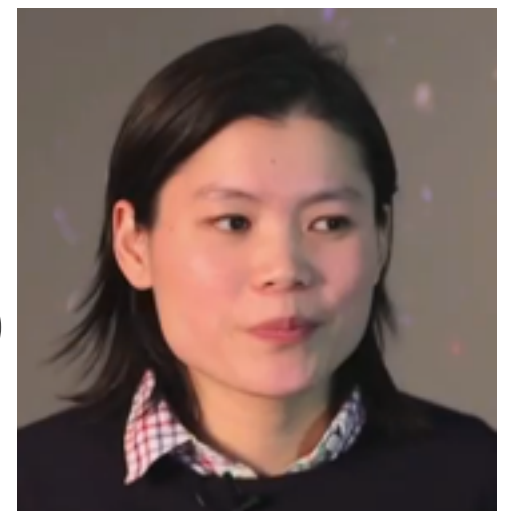
Motivation Recap

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

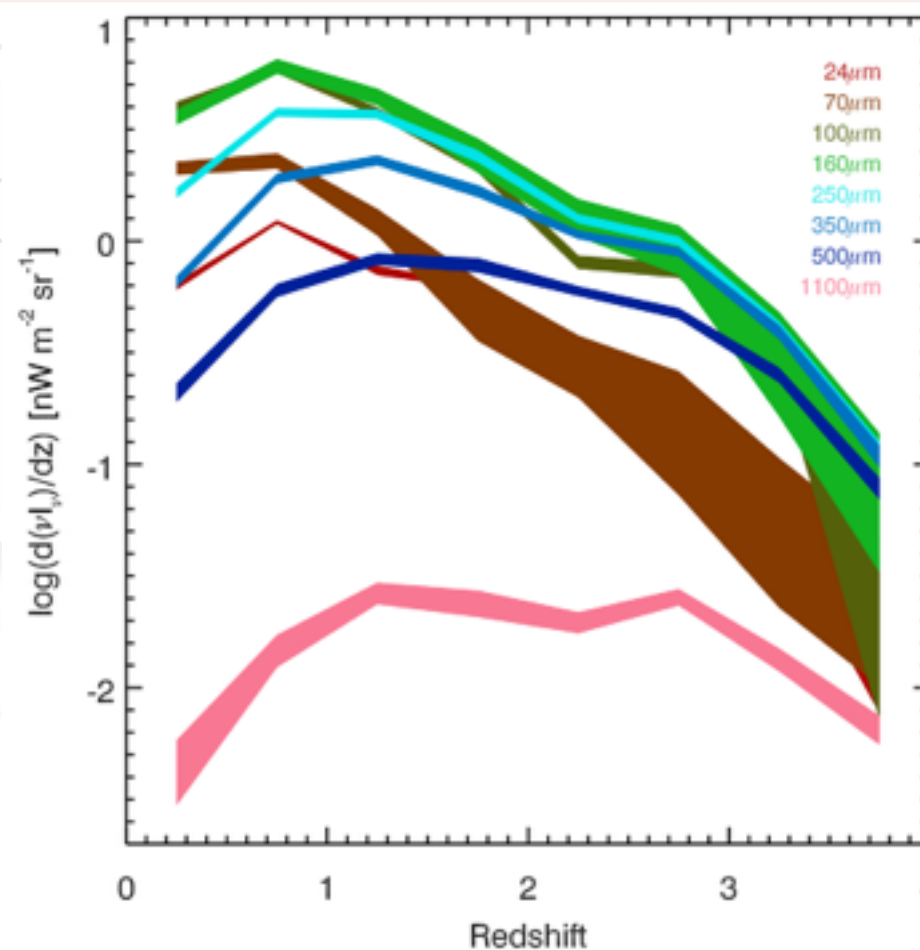
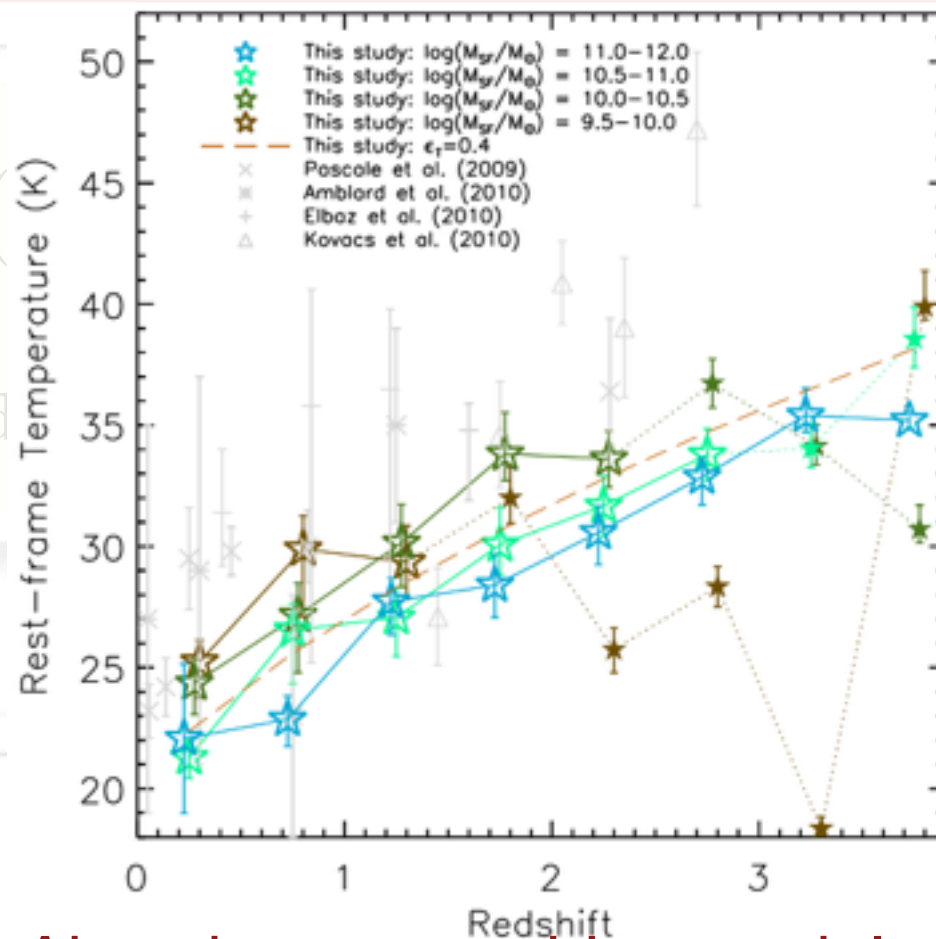
Halo Model: Lingyu Wang (Durham)



From Stacking Results!

Stacked Temperature

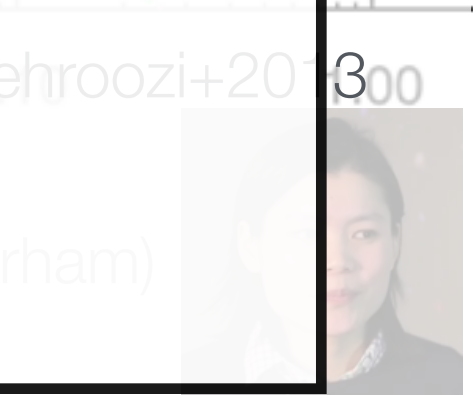
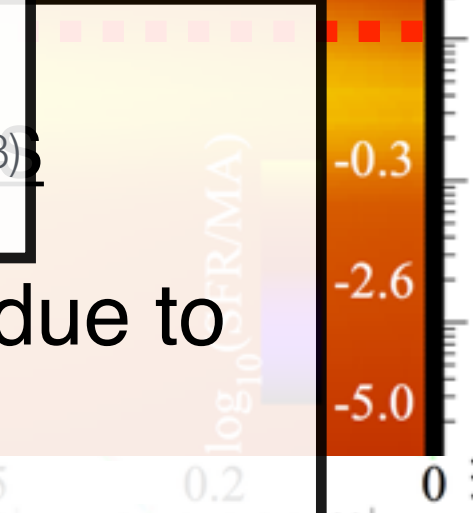
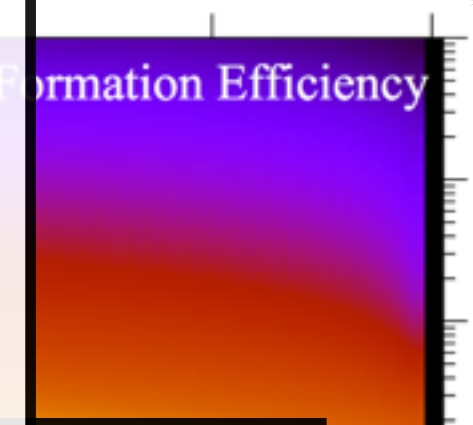
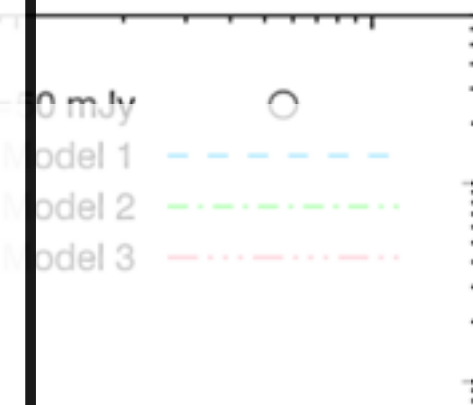
Redshift distribution of flux



Abundance-matching model
with Rishabh Pipada in prep.

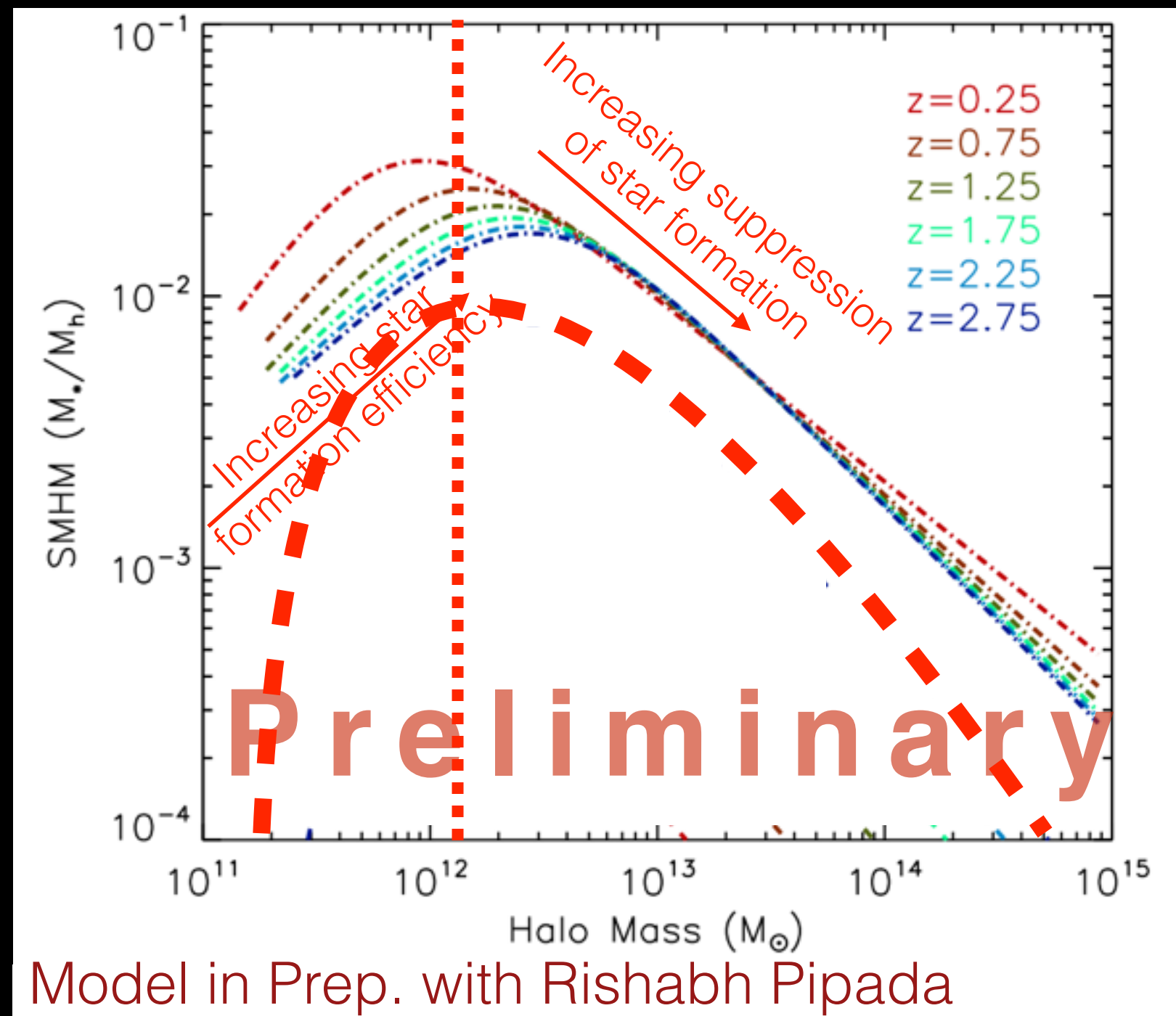
Viero, Monceli, Quadri et al. (2013)
arXiv:1304.0446

- Too many parameters; difficult to interpret due to degeneracies between:
 - Redshift distribution of intensities, dl/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?



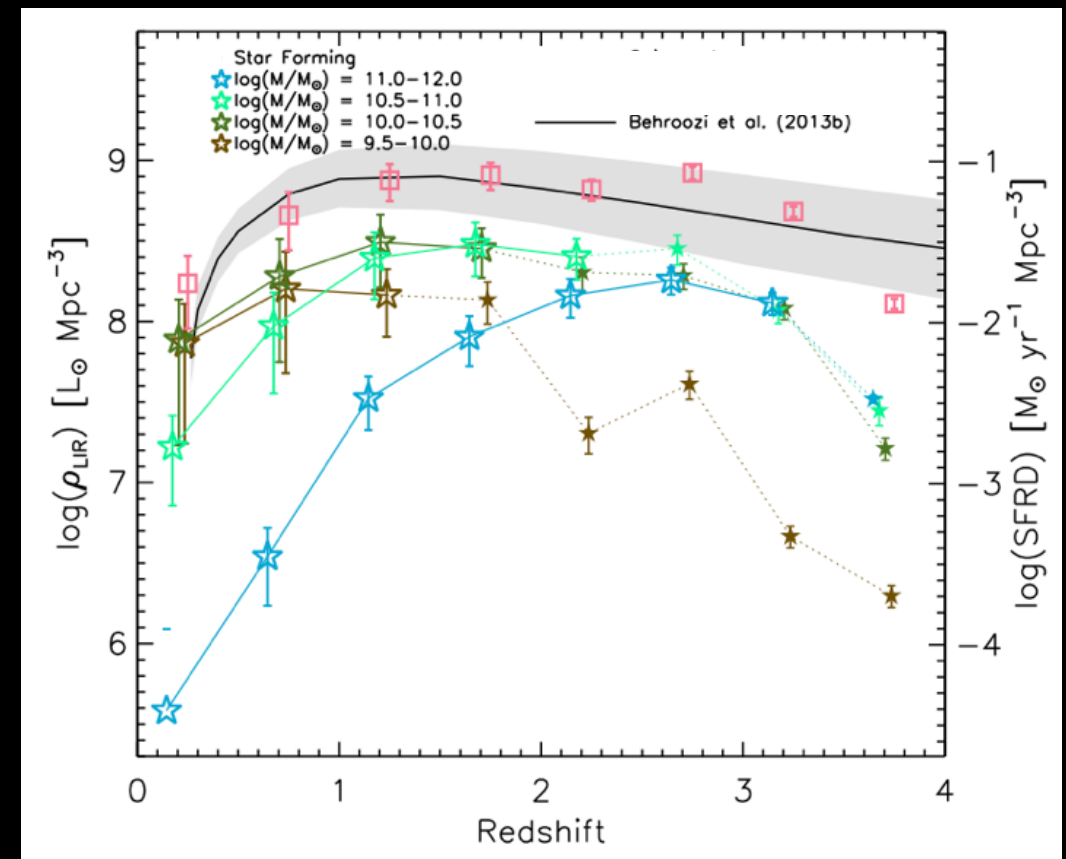
Halo Mass Function from Moster+(2012)

$L_{\text{IR}}(M_{\text{stellar}}, z) \rightarrow \text{SFR}$ from Viero+(2013b)

Summary

1. History of Cosmic Star Formation

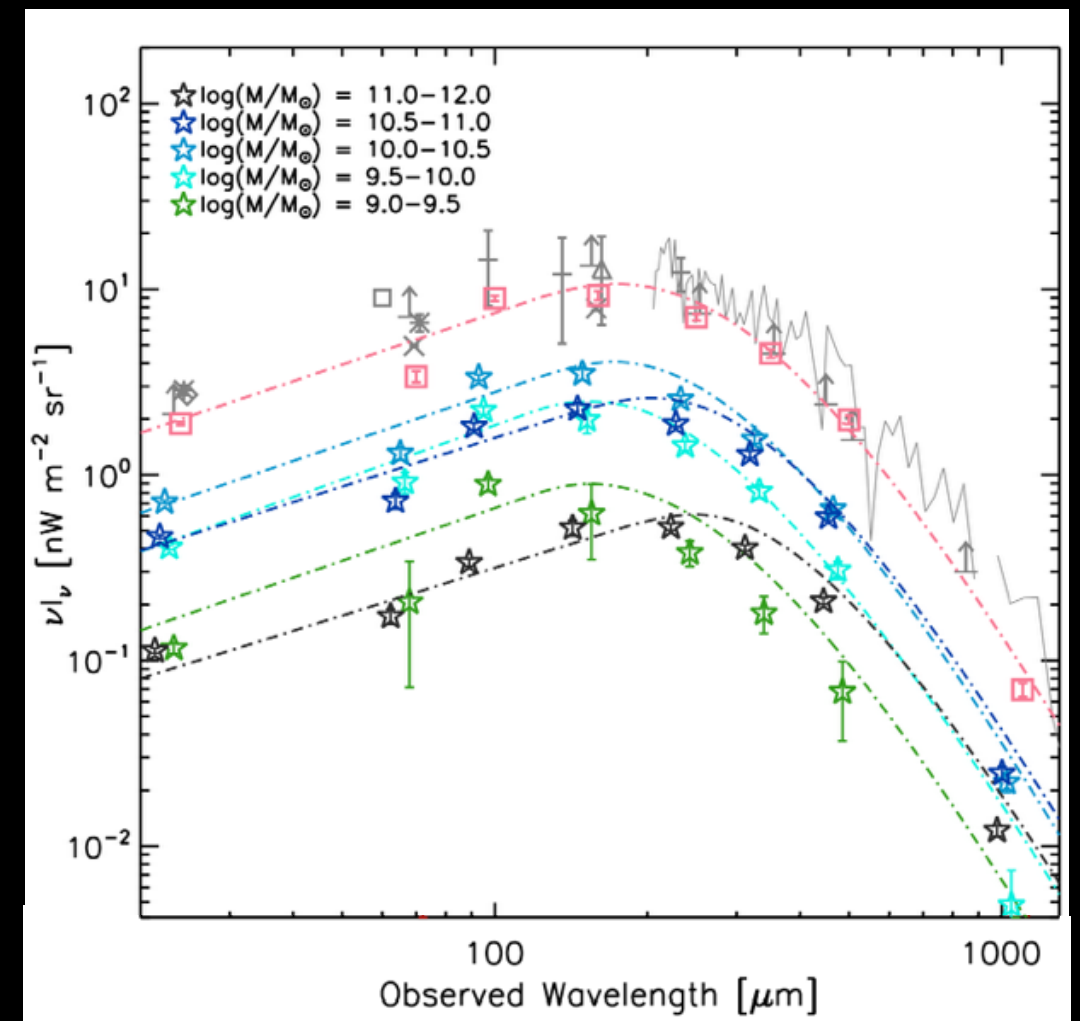
- The cosmic star formation rate density can be traced to high redshift, without having to correct for extinction, in the infrared.
- Star formation is dominated by
 - ★ “normal” galaxies to $z \approx 1$
 - ★ LIRGS between $z \approx 1 - 2$ or 3
 - ★ ULIRGS at higher- z .



Summary

2. Origin of the CIB

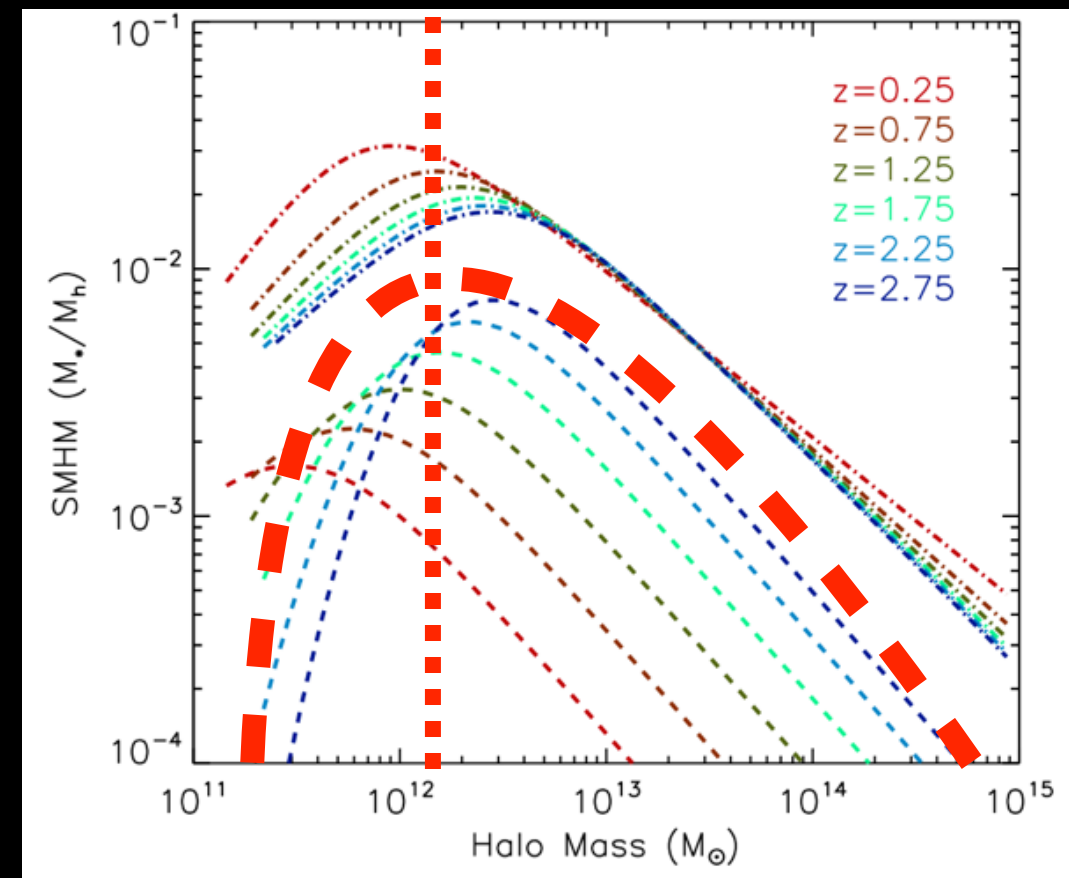
- At least $\sim 70\%$ of the Infrared Background originates from well known optical galaxies
- $\sim 90\%$ of that flux density from galaxies with stellar mass $\log(M/M_{\odot})=10-11$.



Summary

3. Growth of Stellar Mass

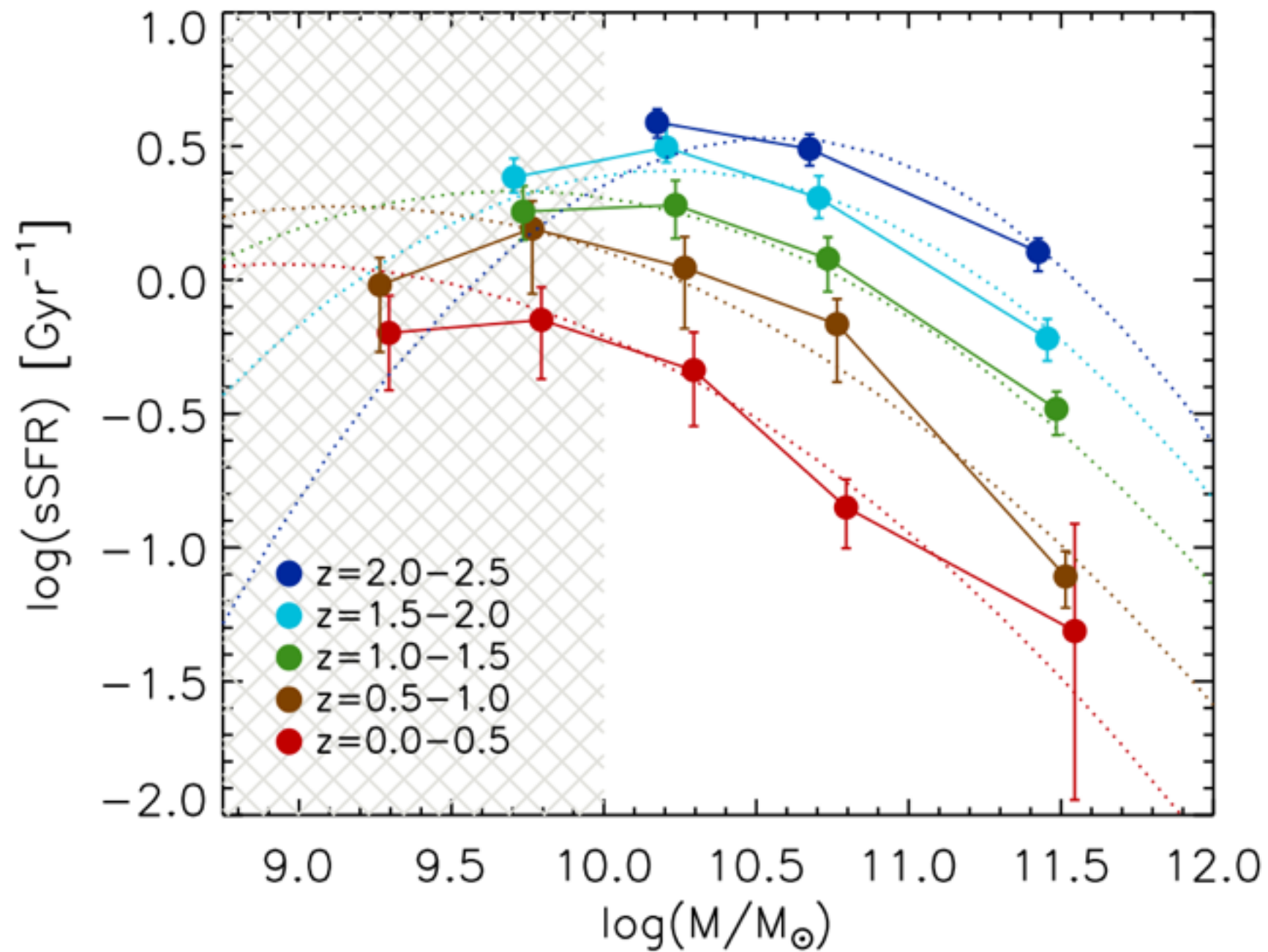
- Halo masses of most efficient star-formation is
 - $\log(M/M_{\odot})=12.2\pm0.5$.
- Models to understand the growth of stellar mass and regulation of that growth are underway.



Moving Forward

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

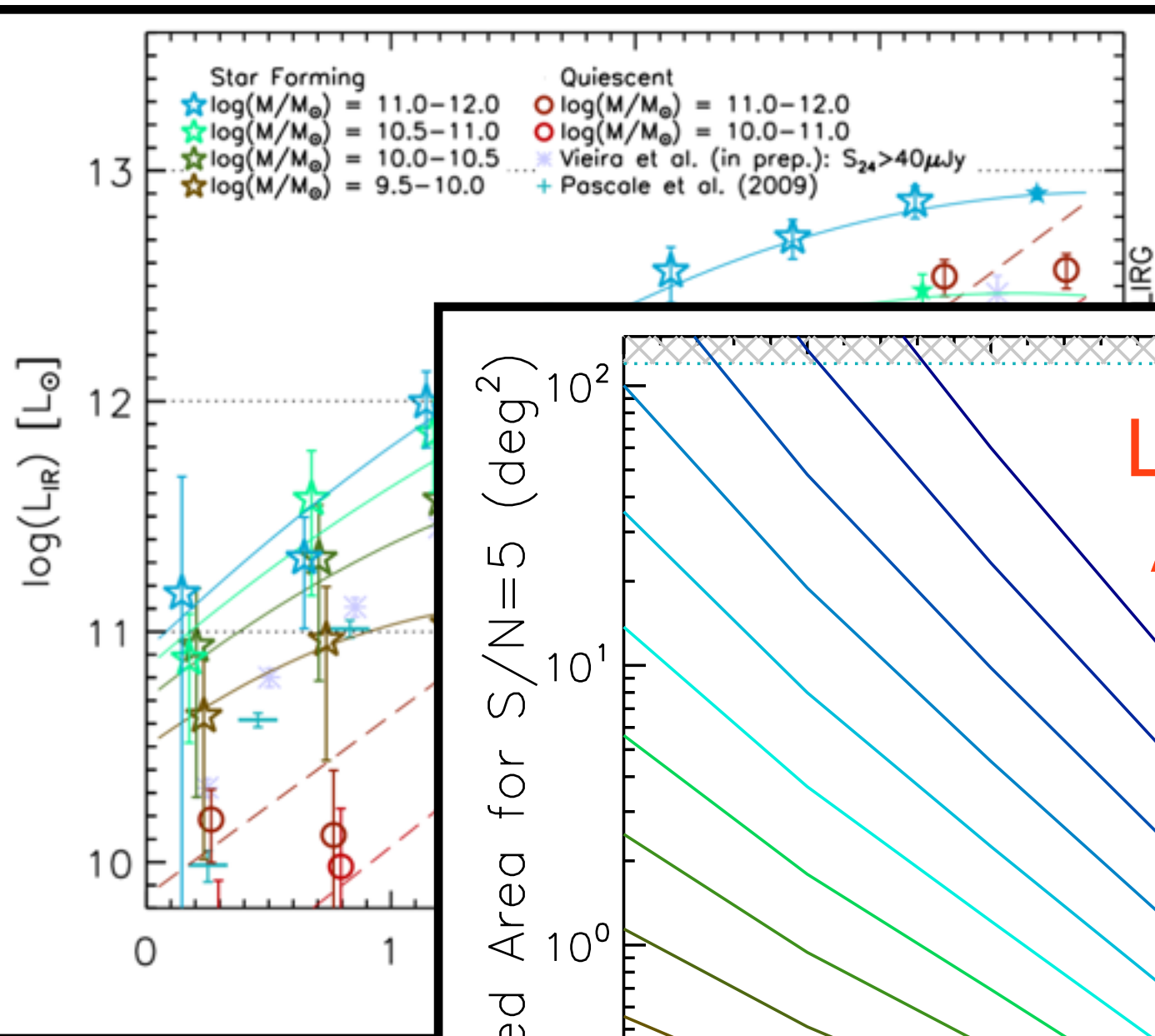
They require accurate L_{IR} & SFRs for this faint population, and that of their progenitors



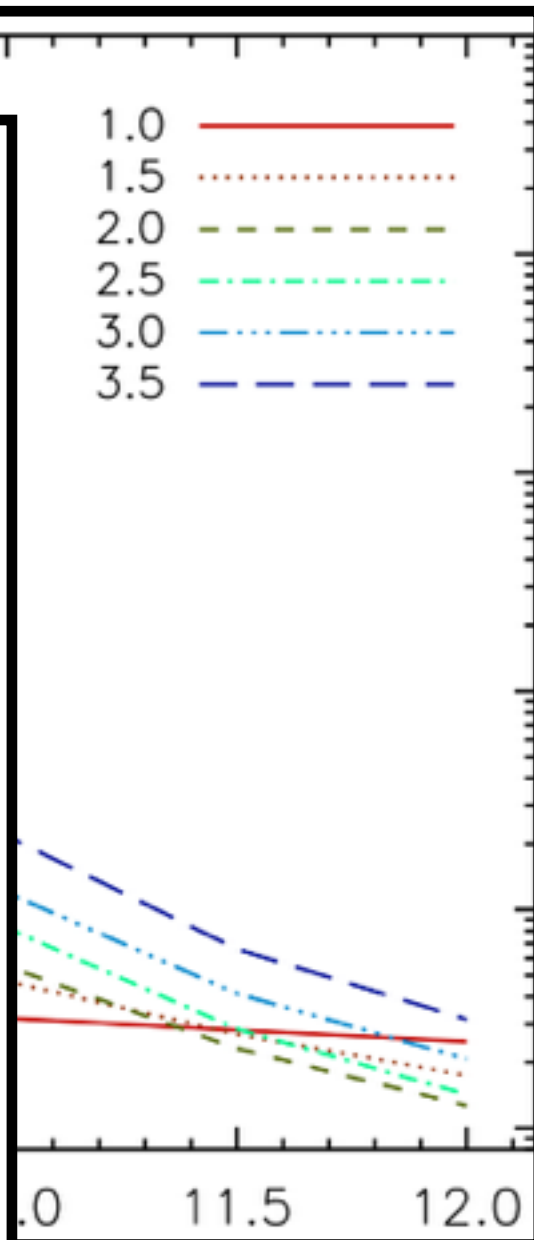
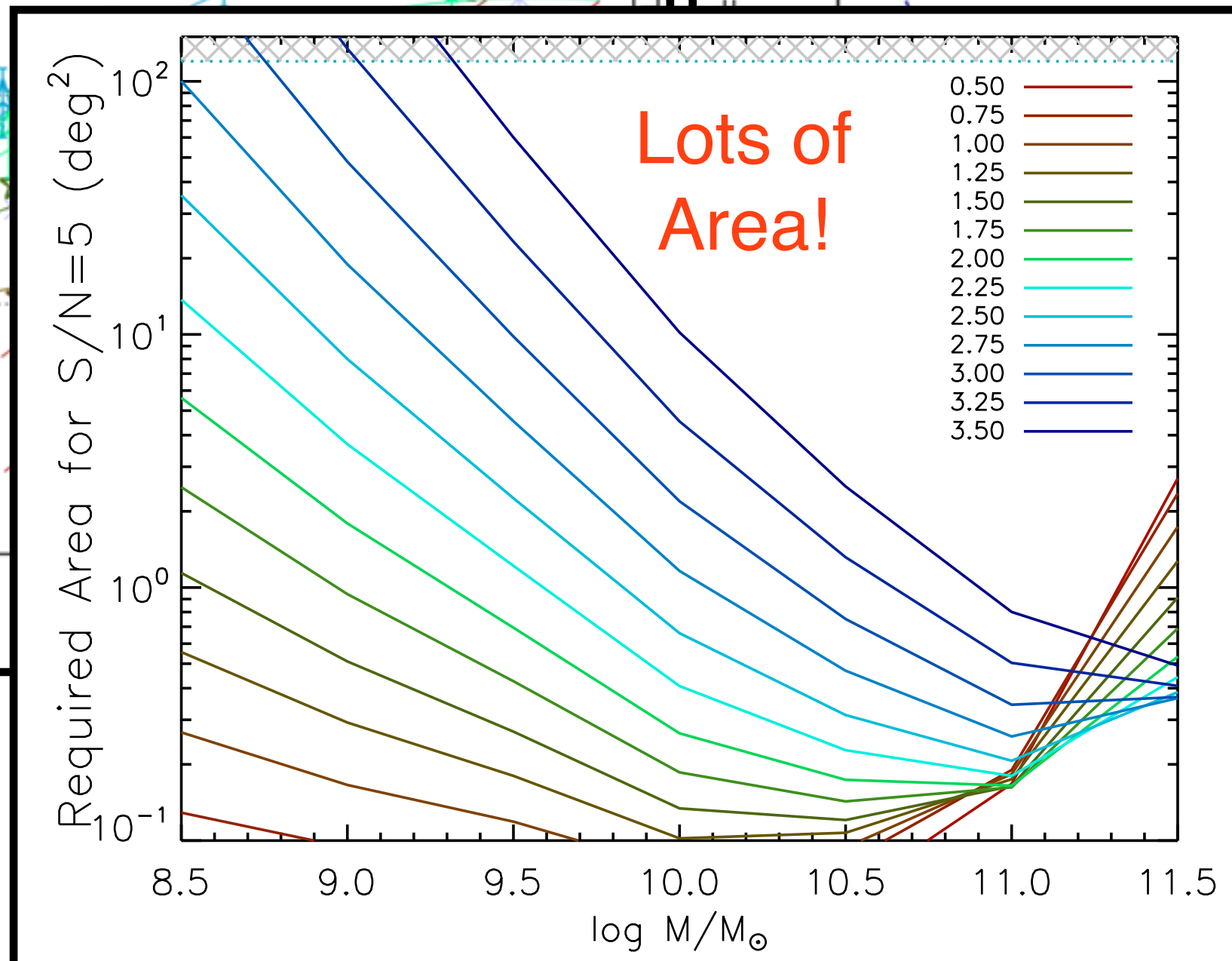
Arumugam, Viero, Quadri et al. (in prep.)

Moving Forward

Lots of sources to probe small masses



L-M*-z



estimated using mass function of Muzzin et al. 2013

ACT HERMES

SHELA

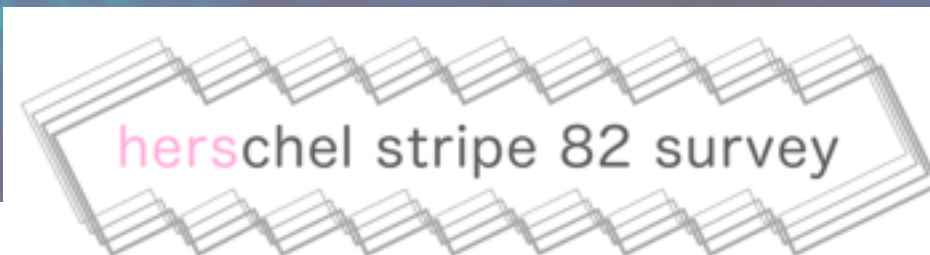
SpIES

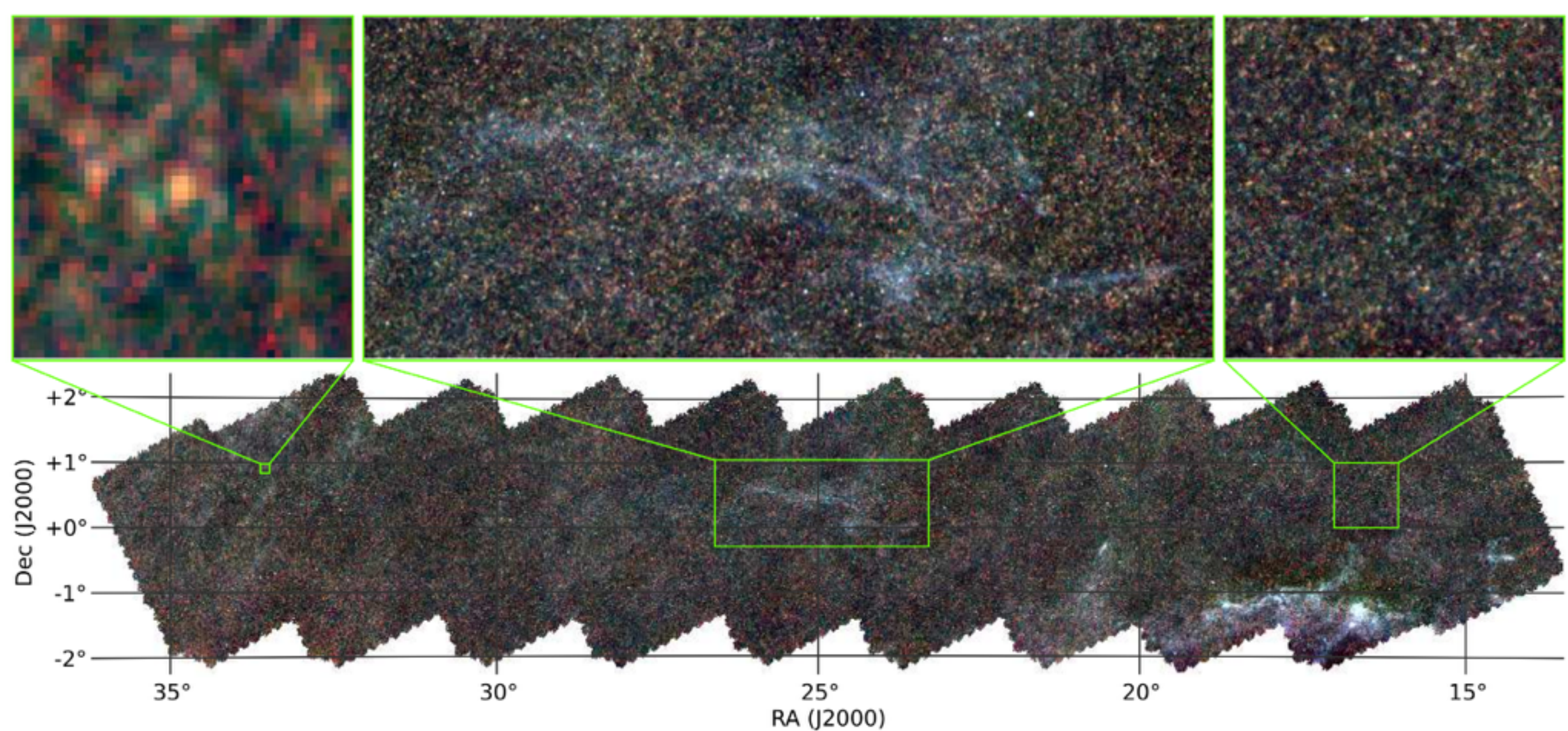
HETDEX

SDSS Stripe 82

HeLMS

HerS



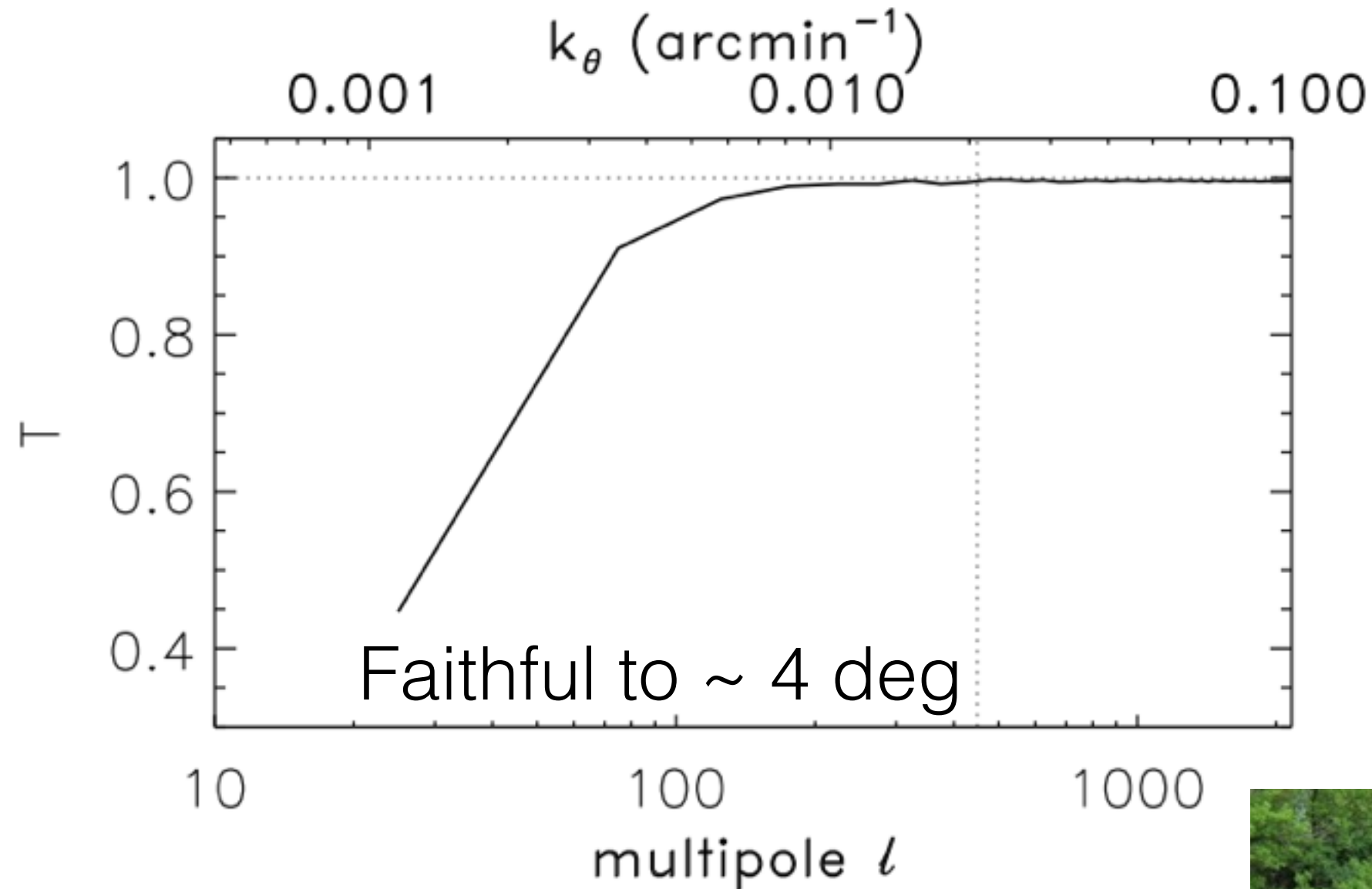


- HerS - 70 deg² (~20 deg along S82)
- HeLMS - 280 deg² (~25 deg along S82)

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



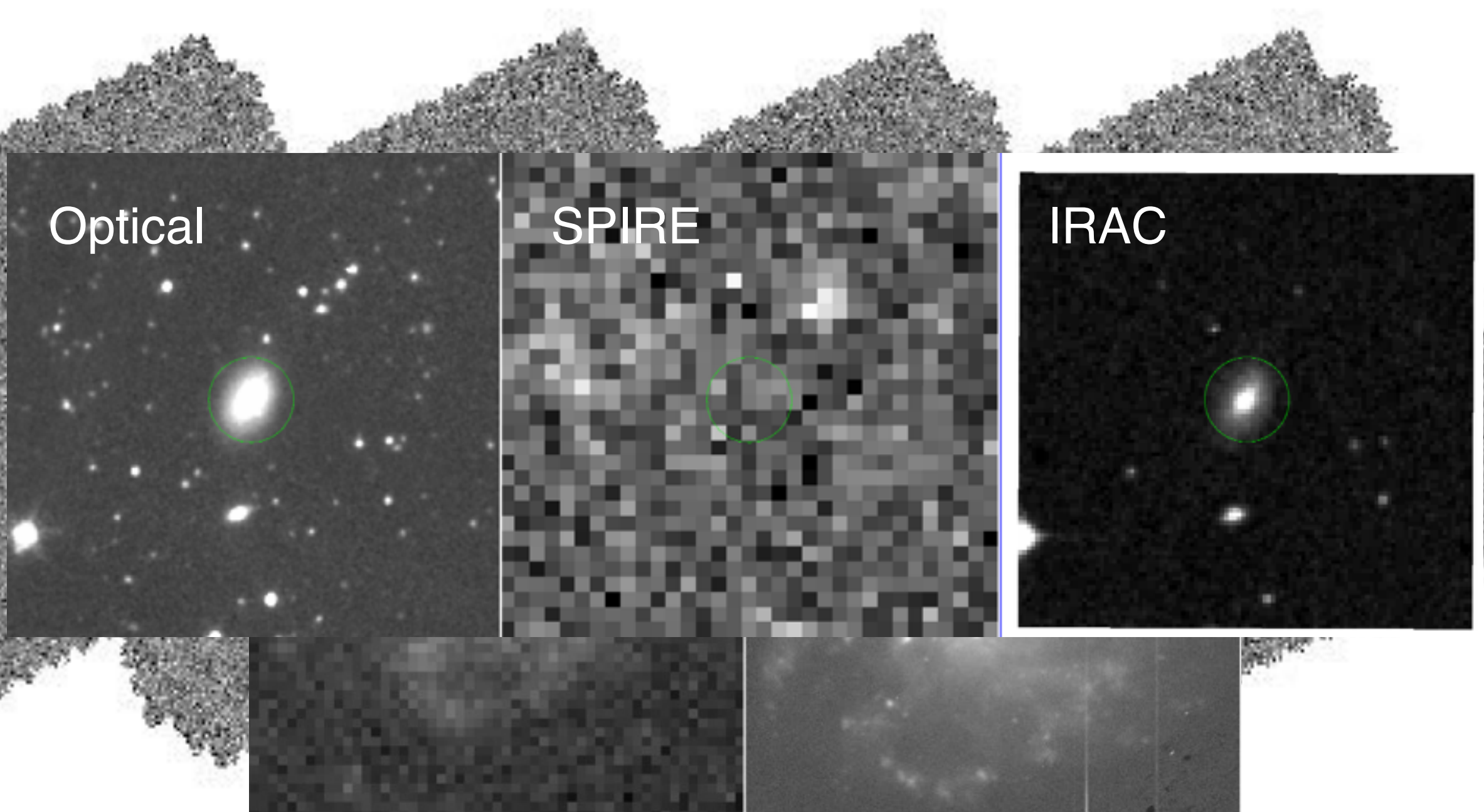
Transfer Function



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

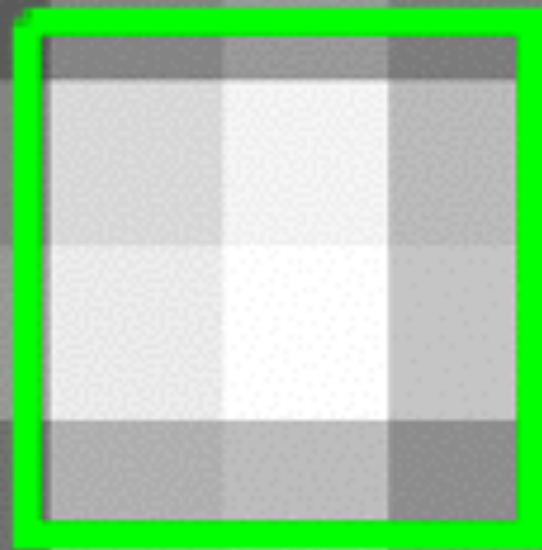


Local Galaxies

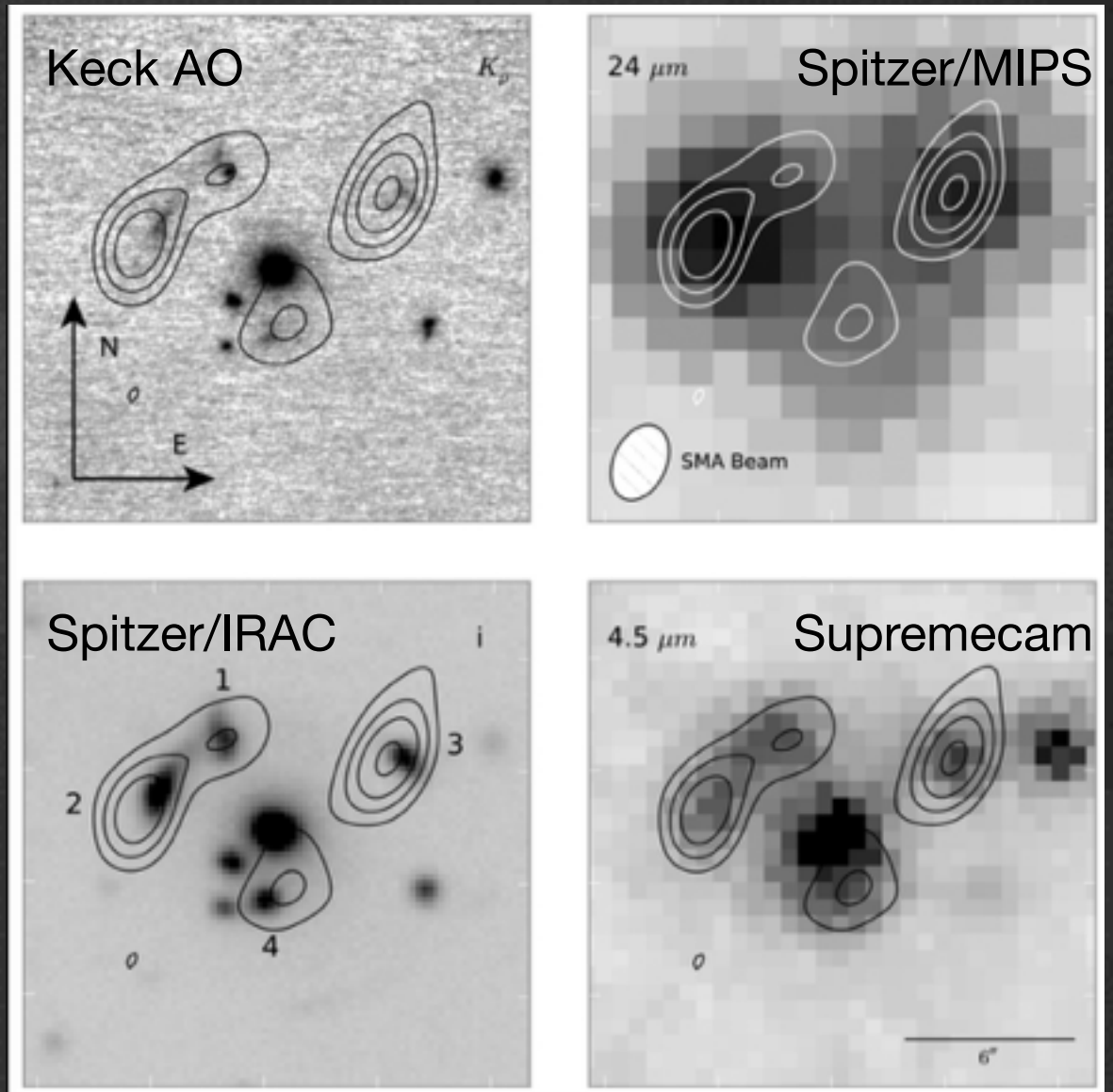


Lensed Sources

SPIRE 250 μ m (6" pixels)



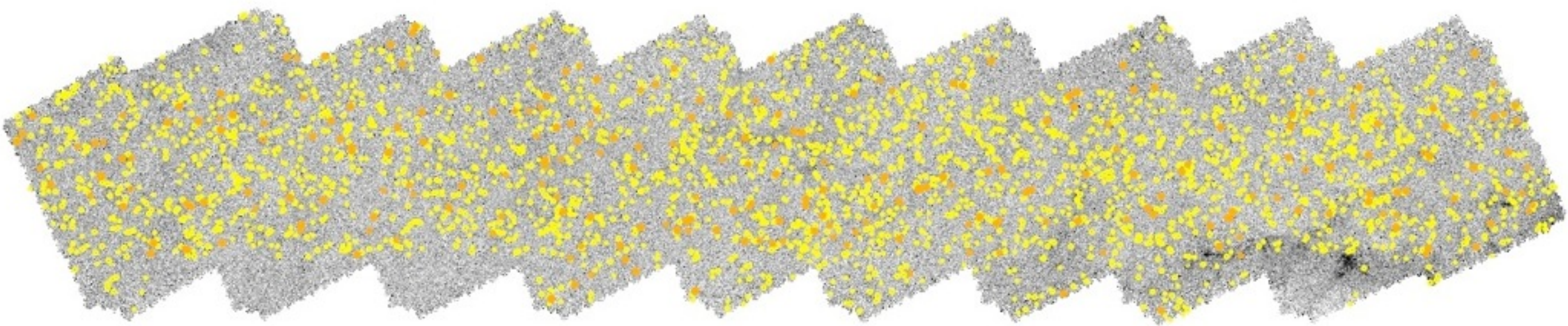
$z=2.97$ from spectroscopic follow-up



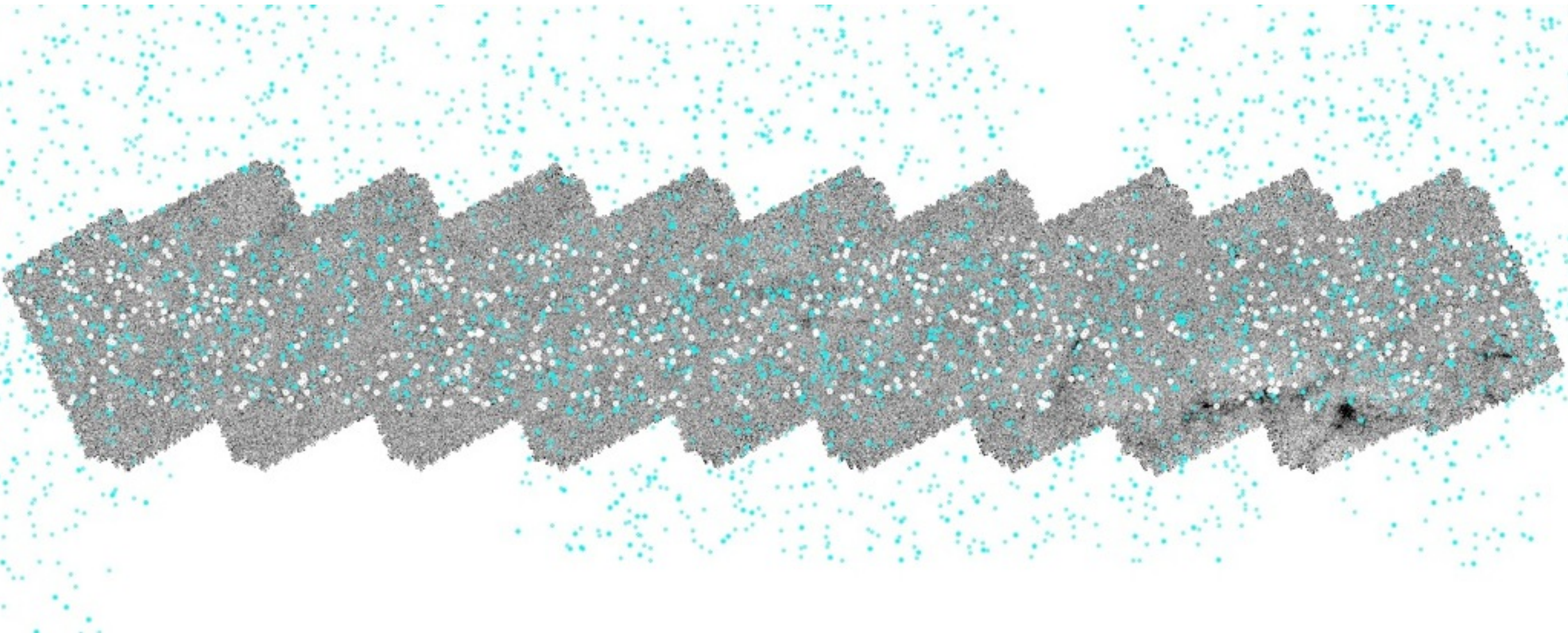
Contours From Submillimeter Array (SMA)

Conley et al. (2011)

also see: Vieira+ 2013, Gonzalez-Nuevo+ 2012, Wardlow+ 2012, Fu+ 2013

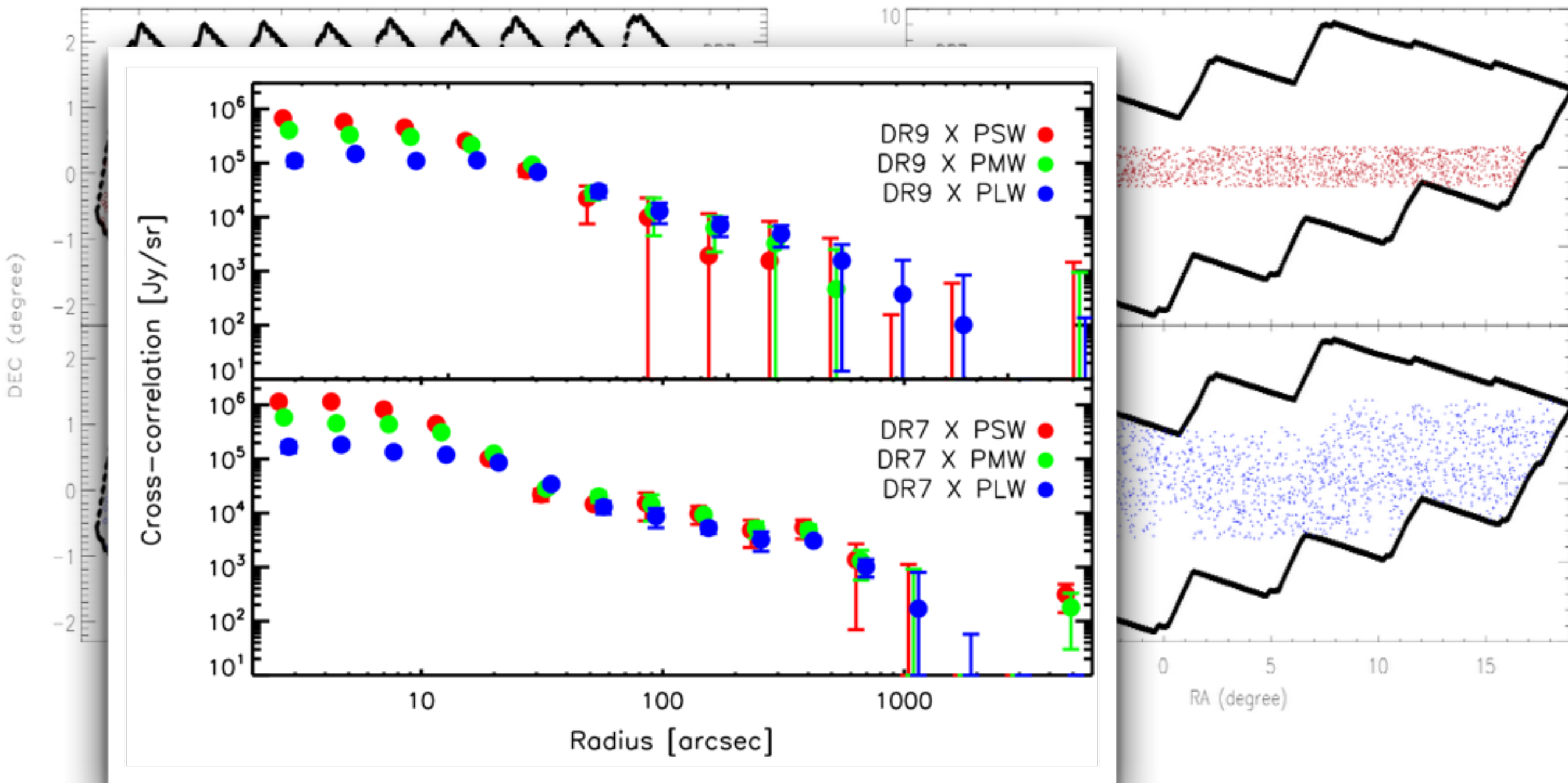


- BOSS QSOs
- DLAs



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

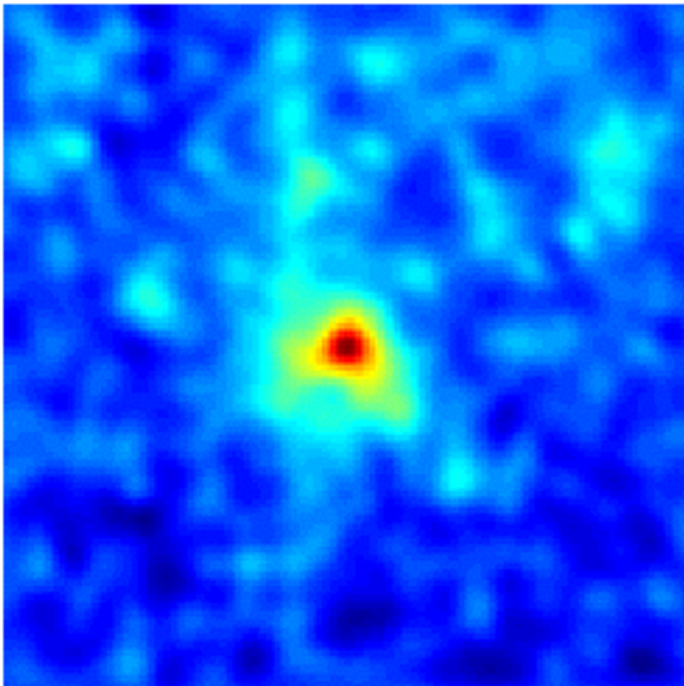
X-Correlations w/ SDSS QSOs



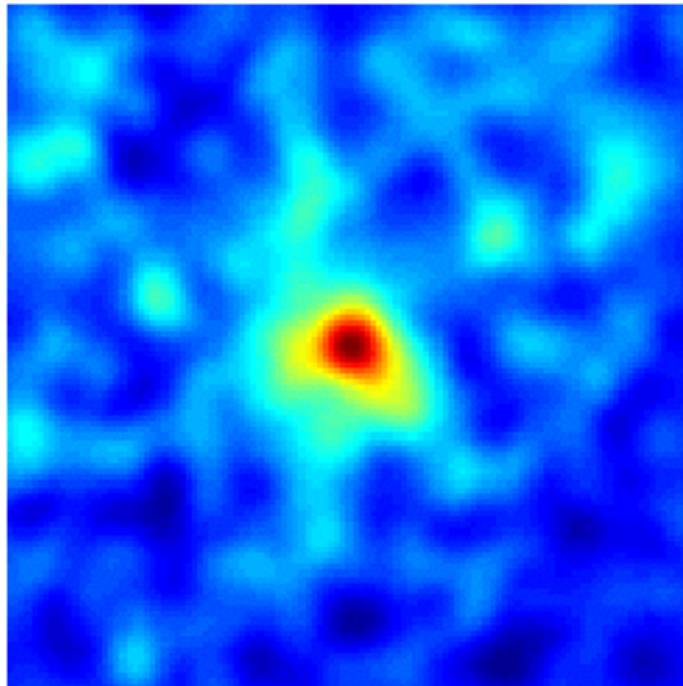
Wang et al. (in prep.)

Cluster Stack

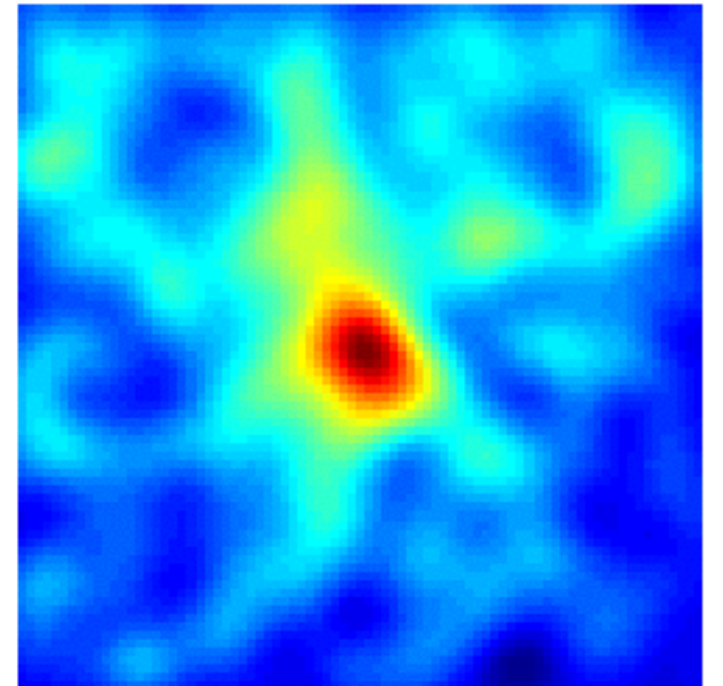
250 μ m



350 μ m

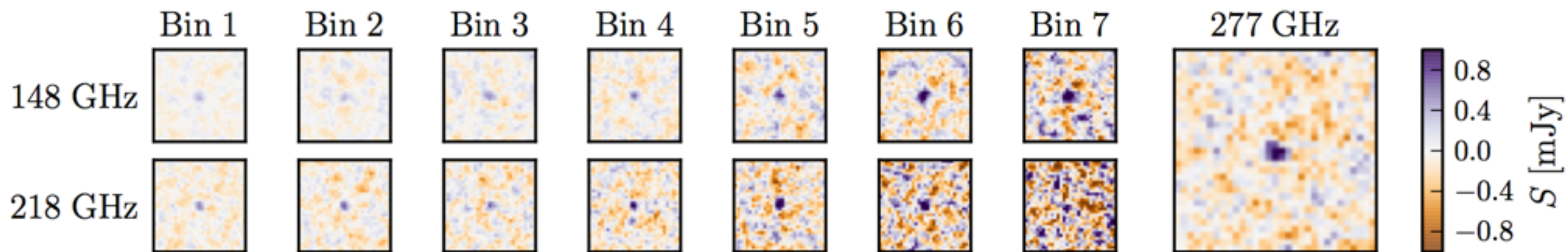


500 μ m



Phil Korngut using Rykoff et al. 2013 redMapper positions

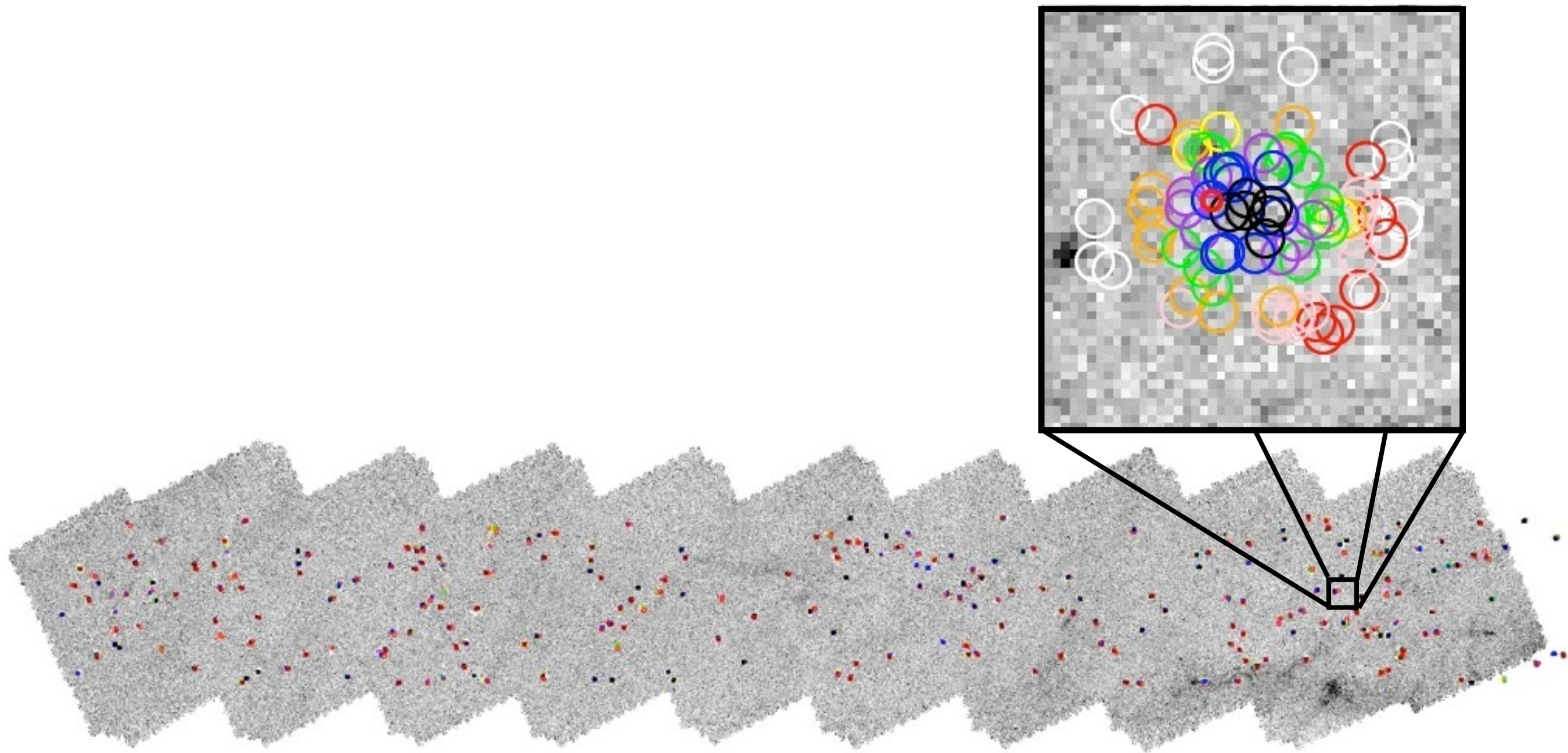
HerS Submillimeter and ACT SZ detections in Radio Stacks



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

HeLMS/HerS x ACT

Gralla et al. 2013
arXiv:1310.8281



Cluster Members



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/>

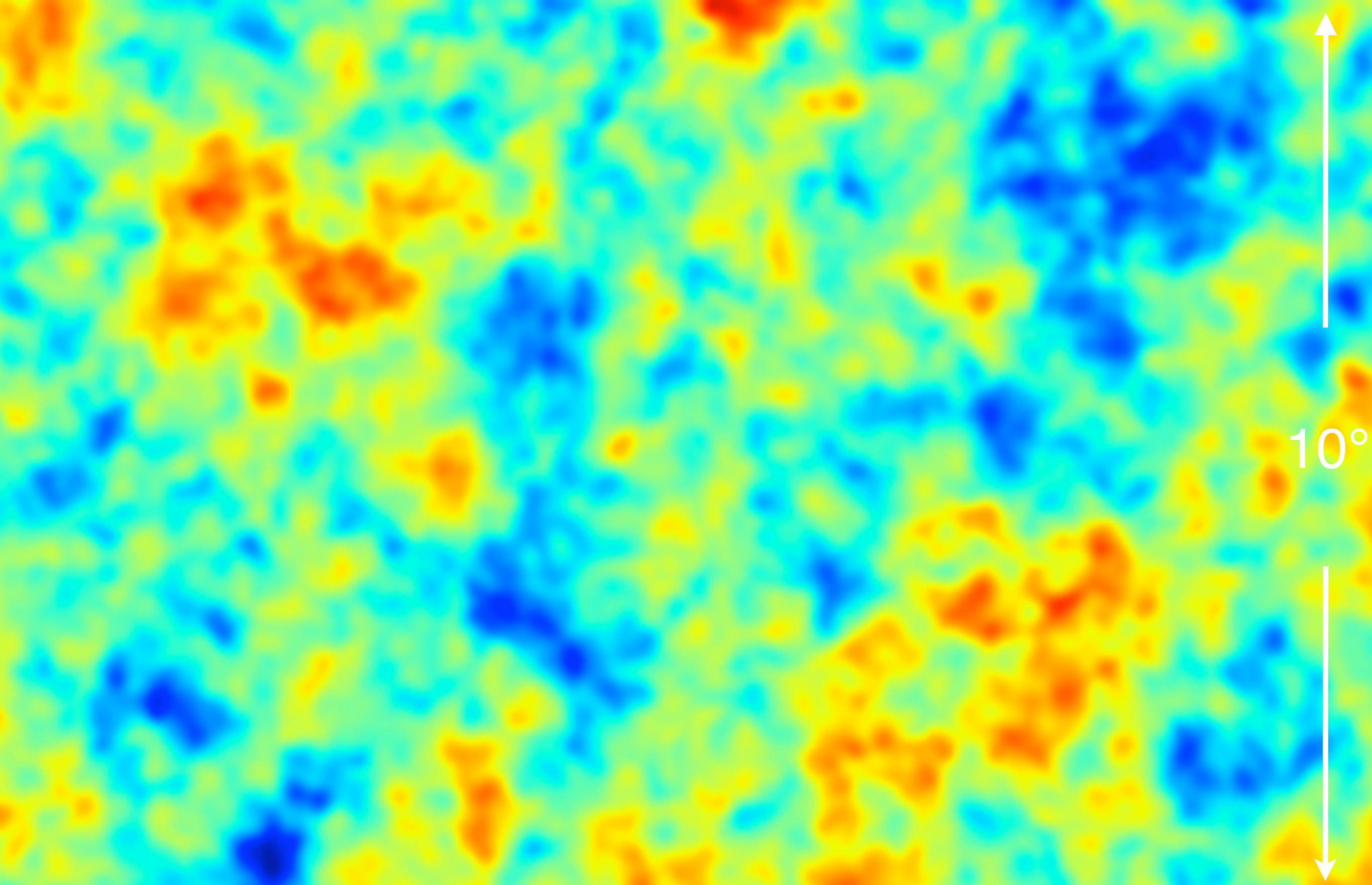
More Fun with Cross Correlations! (time permitting!)

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

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

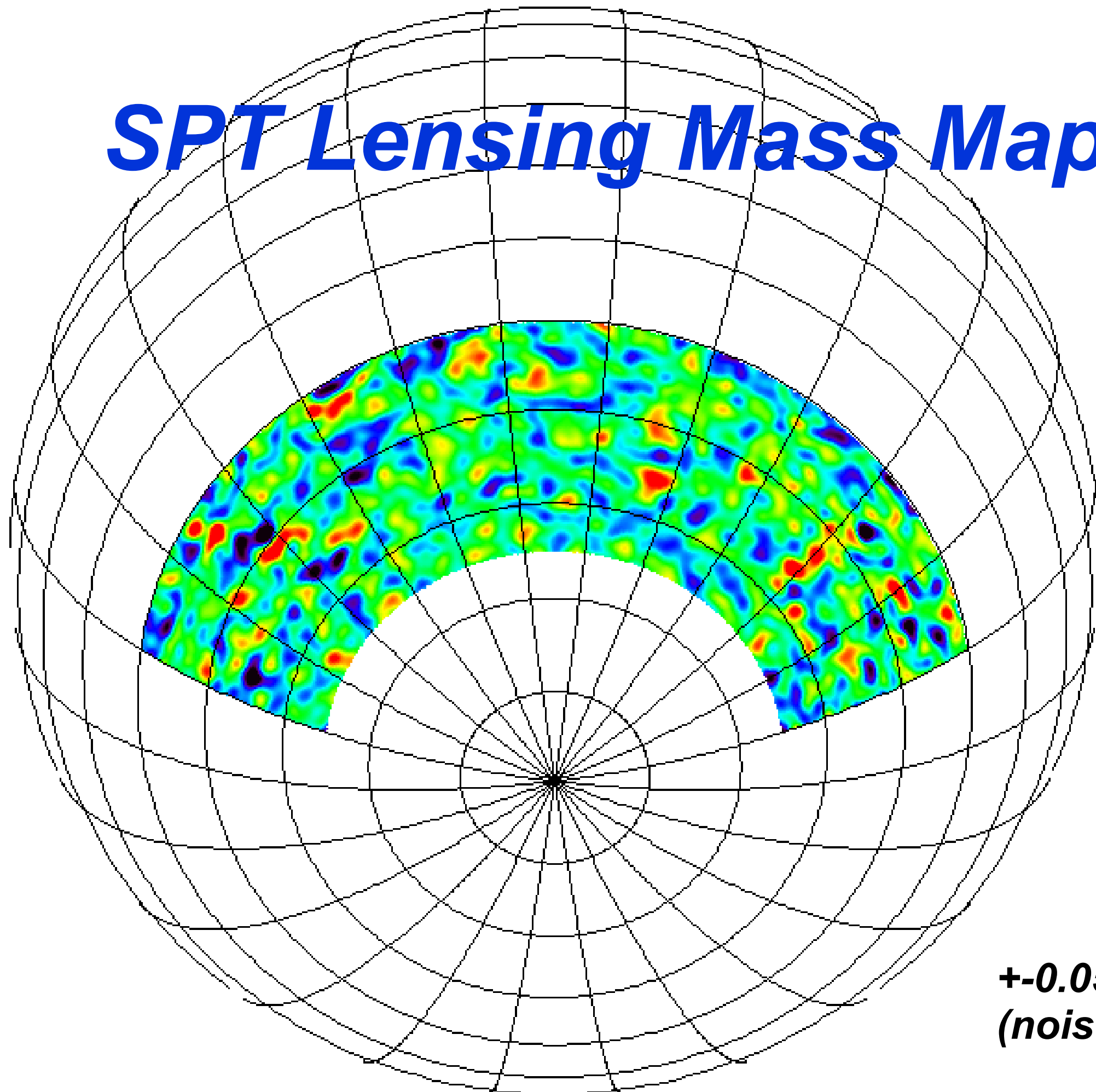
The CIB traces dark matter, thus should correlate with lensing, as traced by:

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



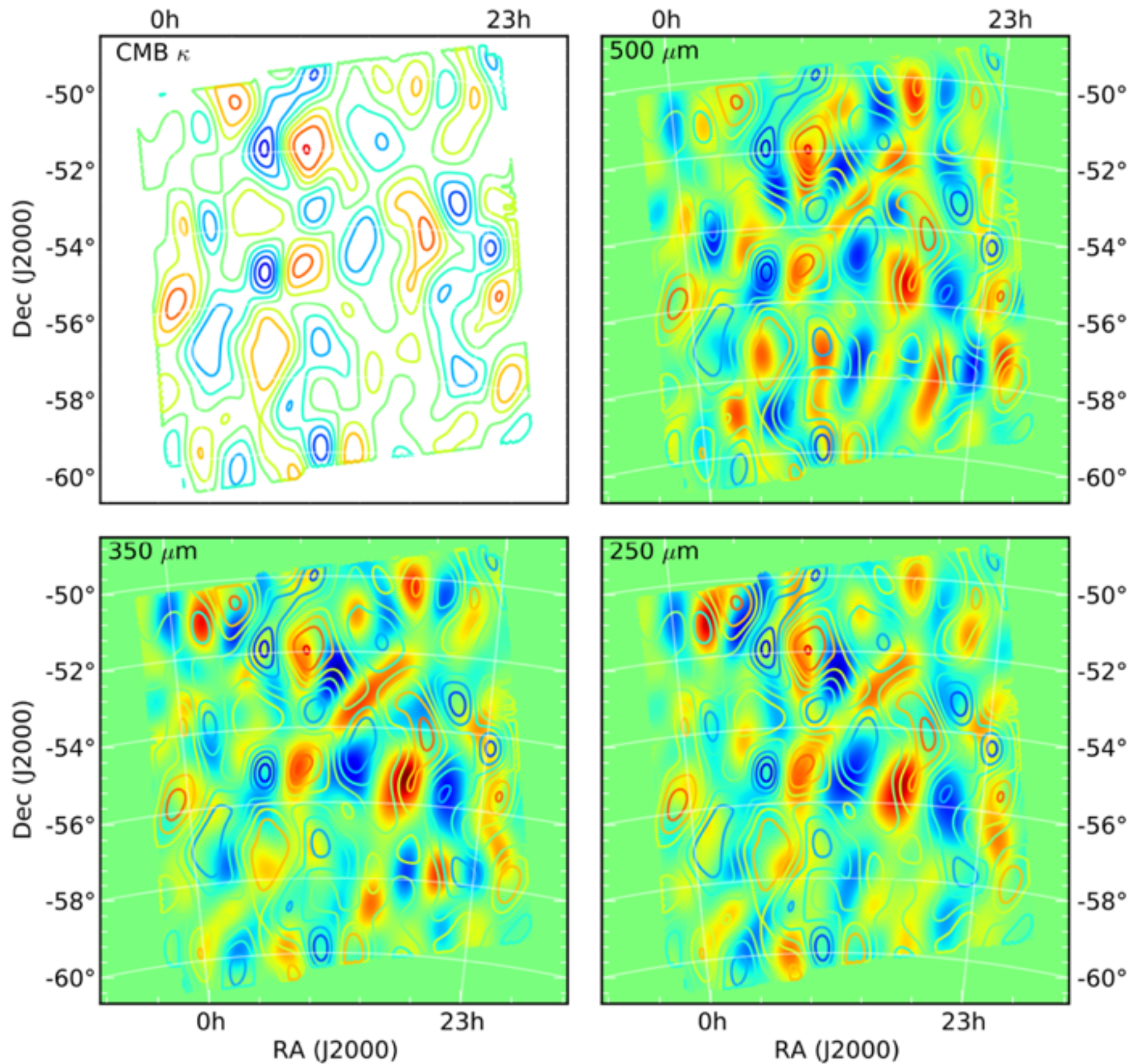
Cross-Correlations with CMB Lensing

SPT Lensing Mass Map



***± 0.05 color bar
(noise ~ 0.01)***

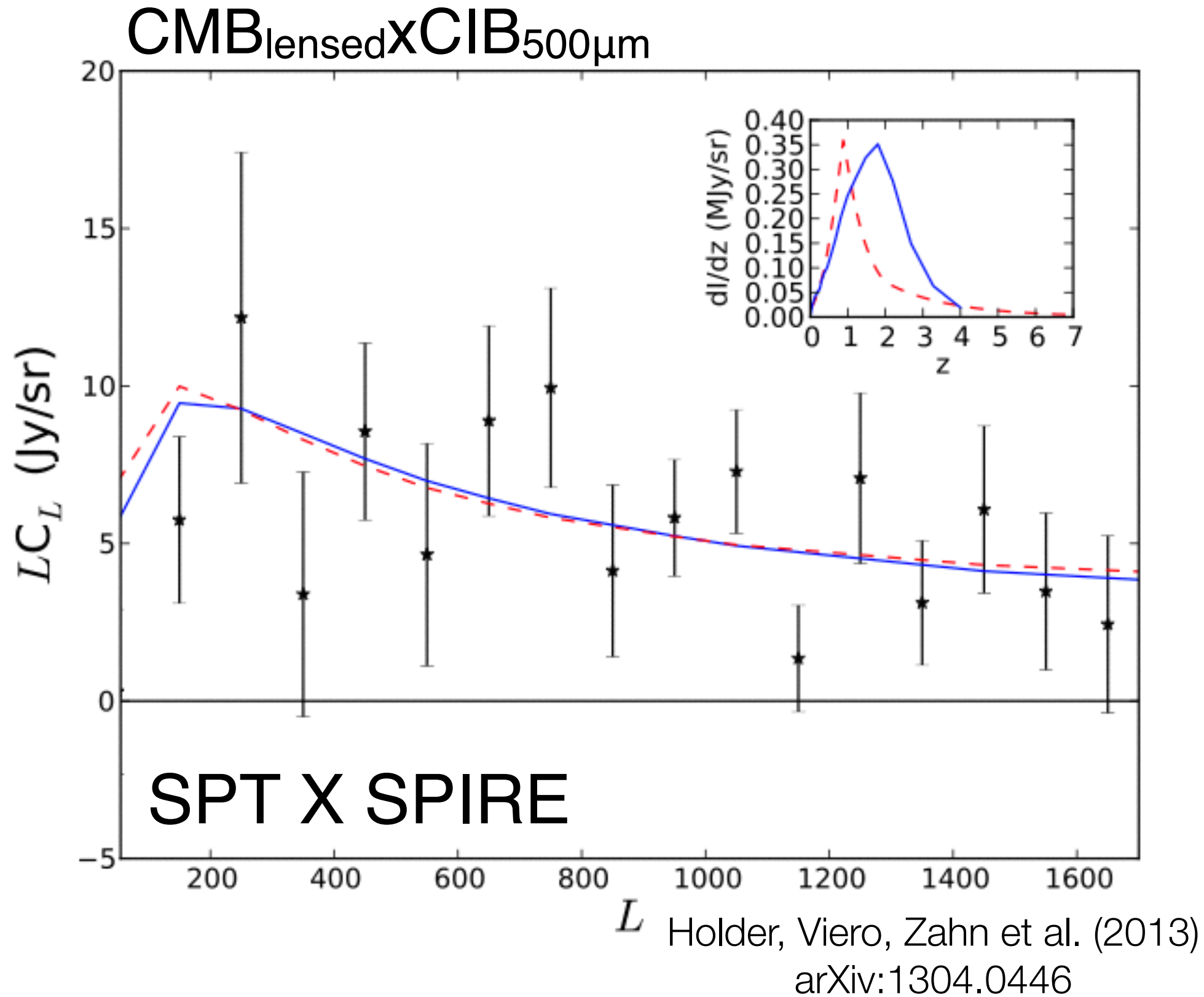
SPT X
SPIRE



Lensed CMB x CIB

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

- $6.7\text{--}8.8\sigma$ detection (Planck 42σ !)
- bias = 1.3-1.8, strongly model dependent

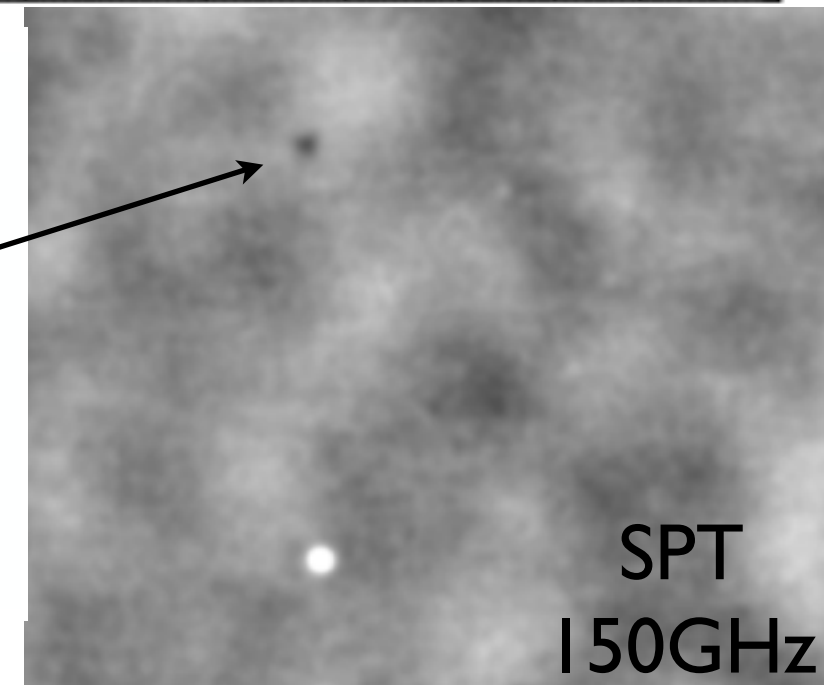
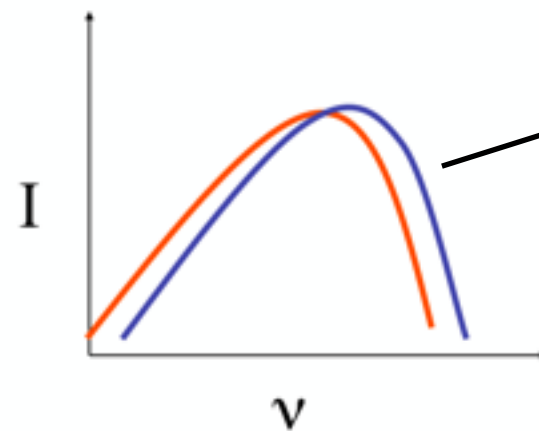
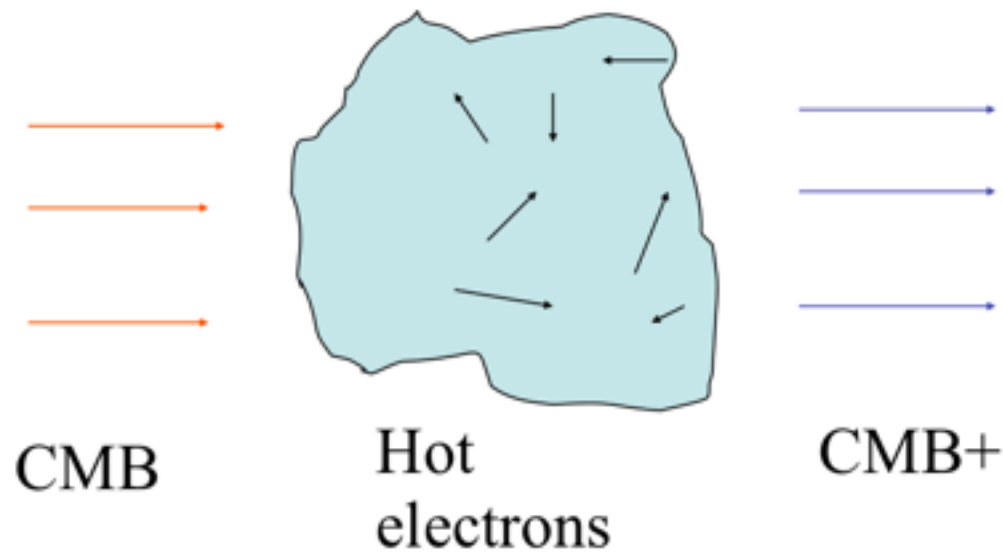
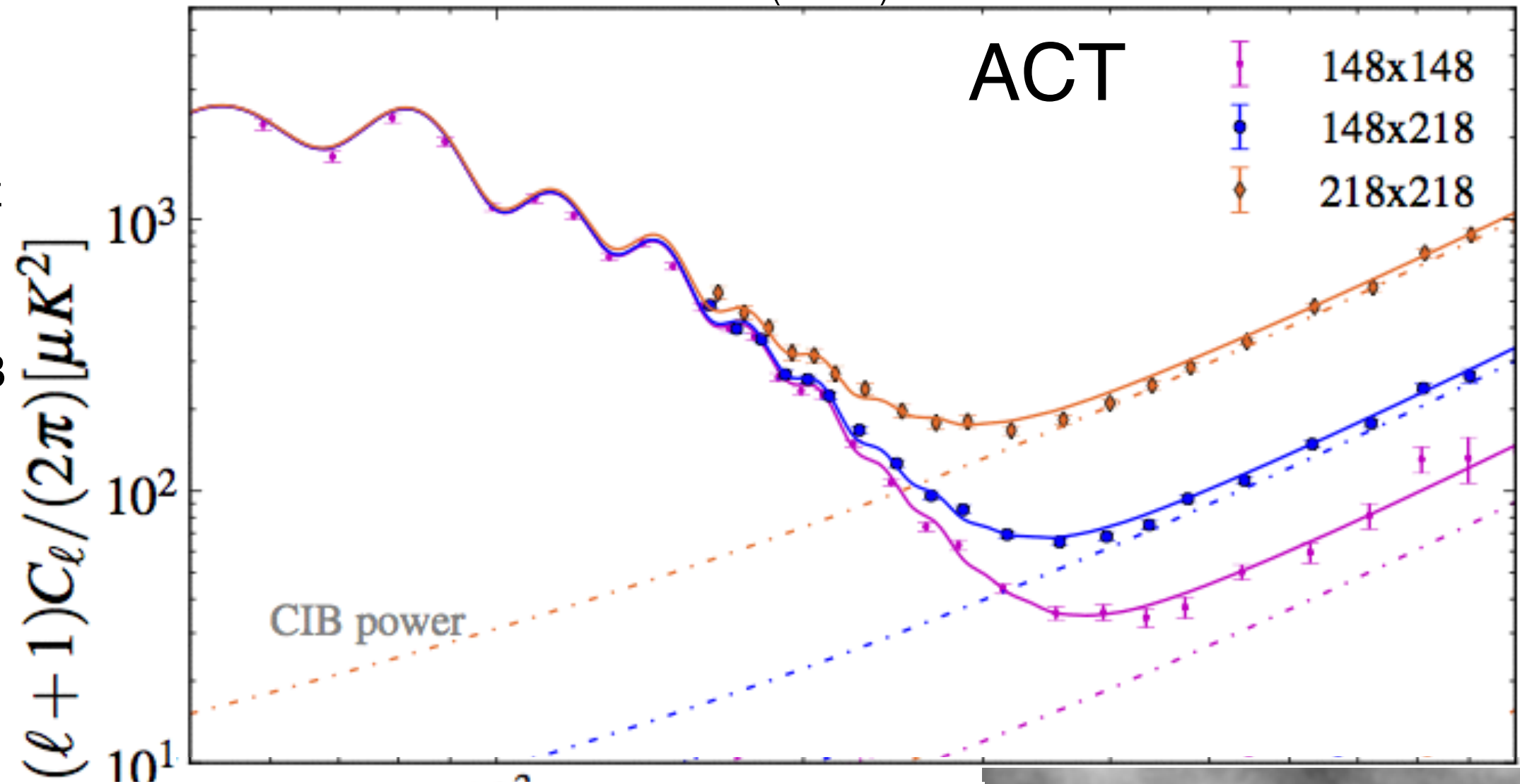


Measuring the CIB bias

Dusty Galaxies a significant contaminant at 150 and 220 GHz

SZ effect distortion of CMB by Compton scattering in massive clusters

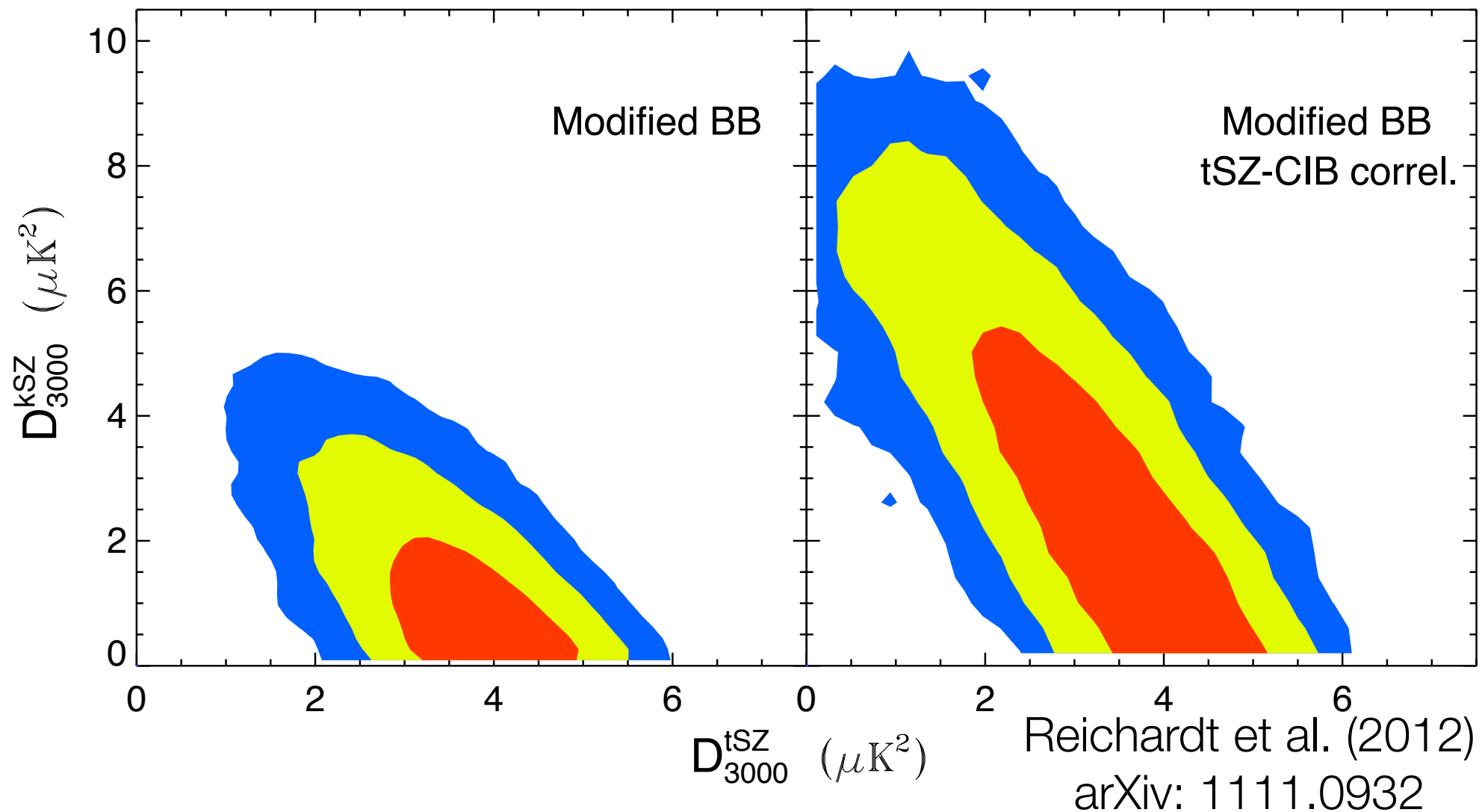
ACT

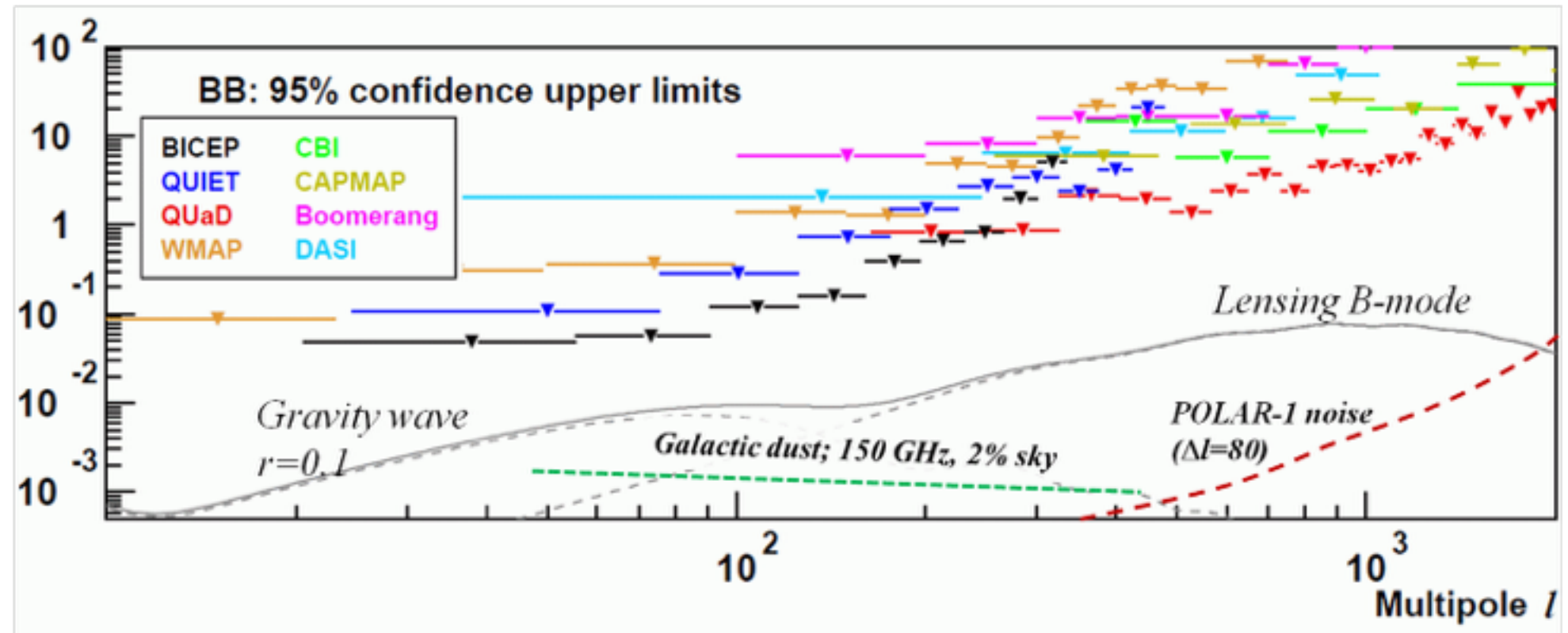
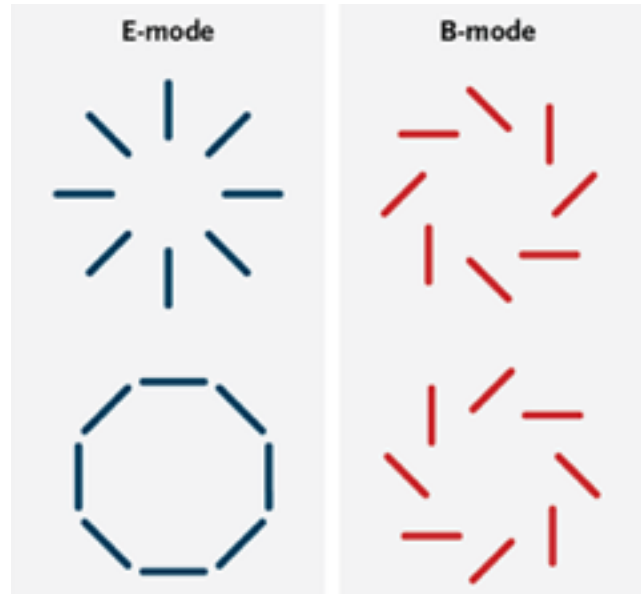


CIB as CMB Foreground

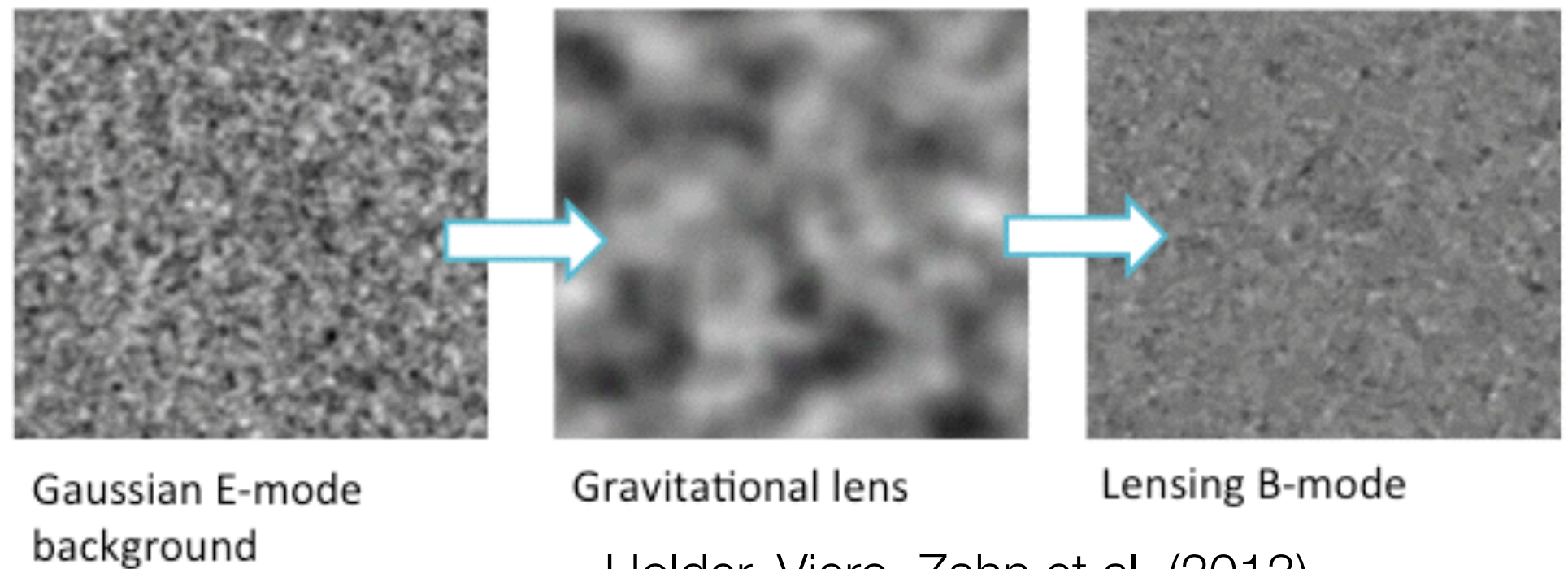
thermal SZ-CIB correlation?

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



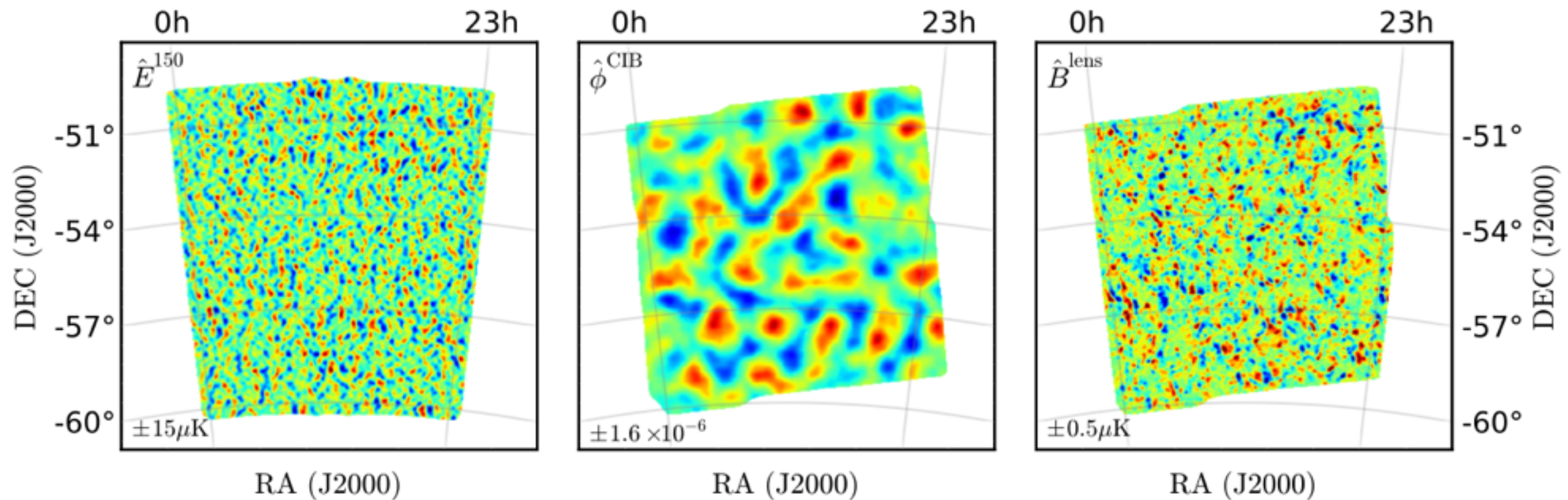


- Lensing mixes E-modes into B-modes

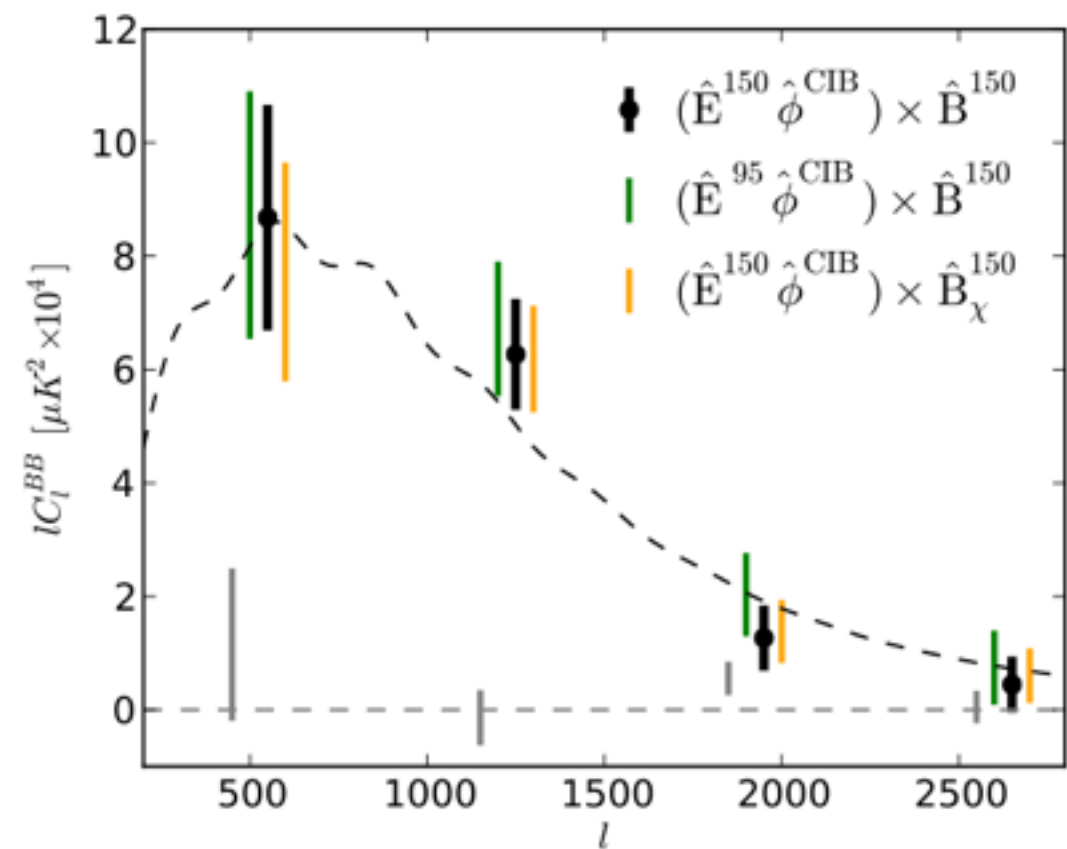


Holder, Viero, Zahn et al. (2013)
arXiv:1304.0446

CMB Lensing B-modes



- 7.7σ detection of B-mode signal



CMB Lensing B-modes



Viero+ 2014
arXiv:1308.4399



Oliver+ 2012
arXiv:1203.2562



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

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