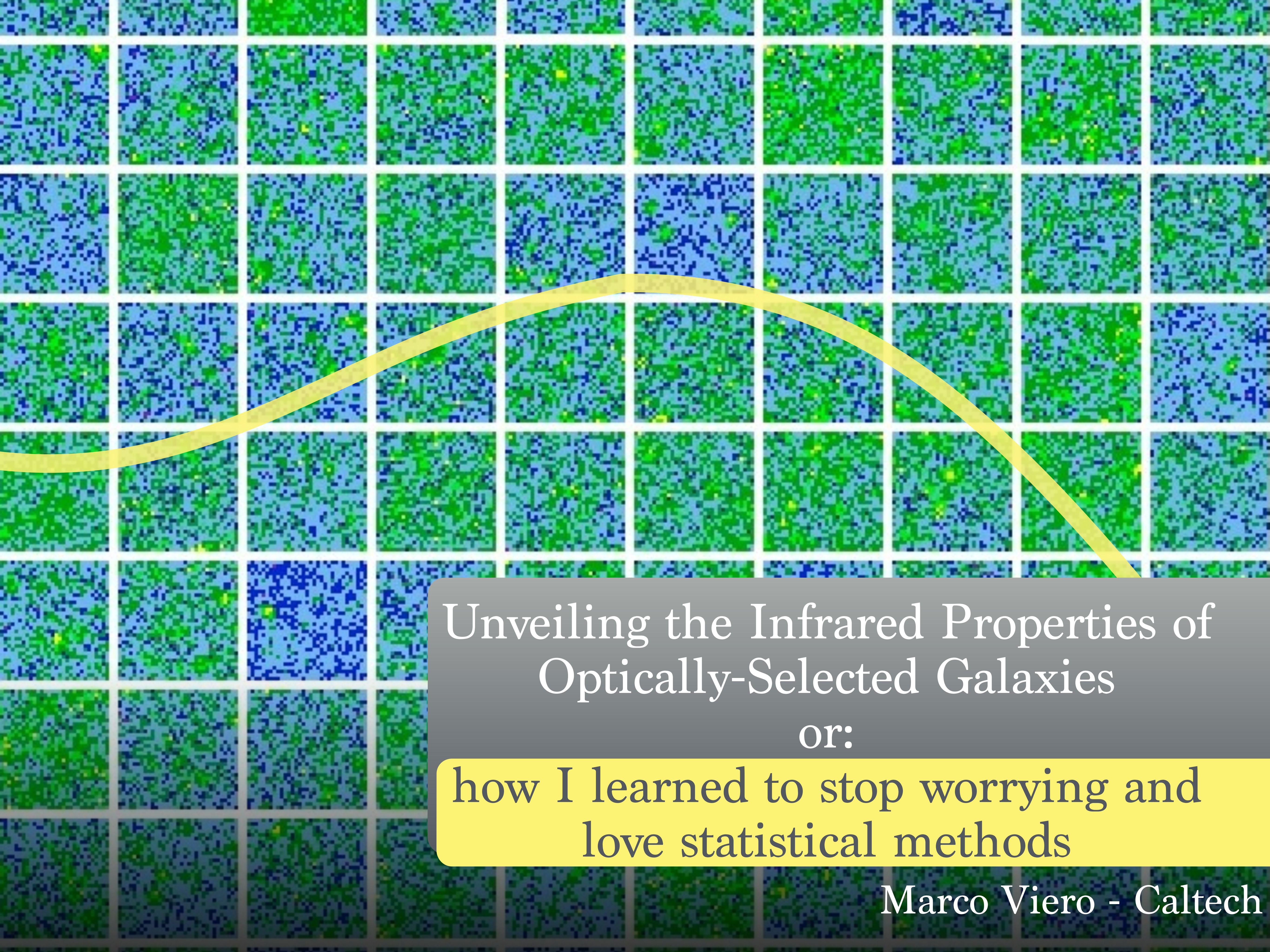


Unveiling the Infrared Properties of Optically-Selected Galaxies
or:
how I learned to stop worrying and love statistical methods

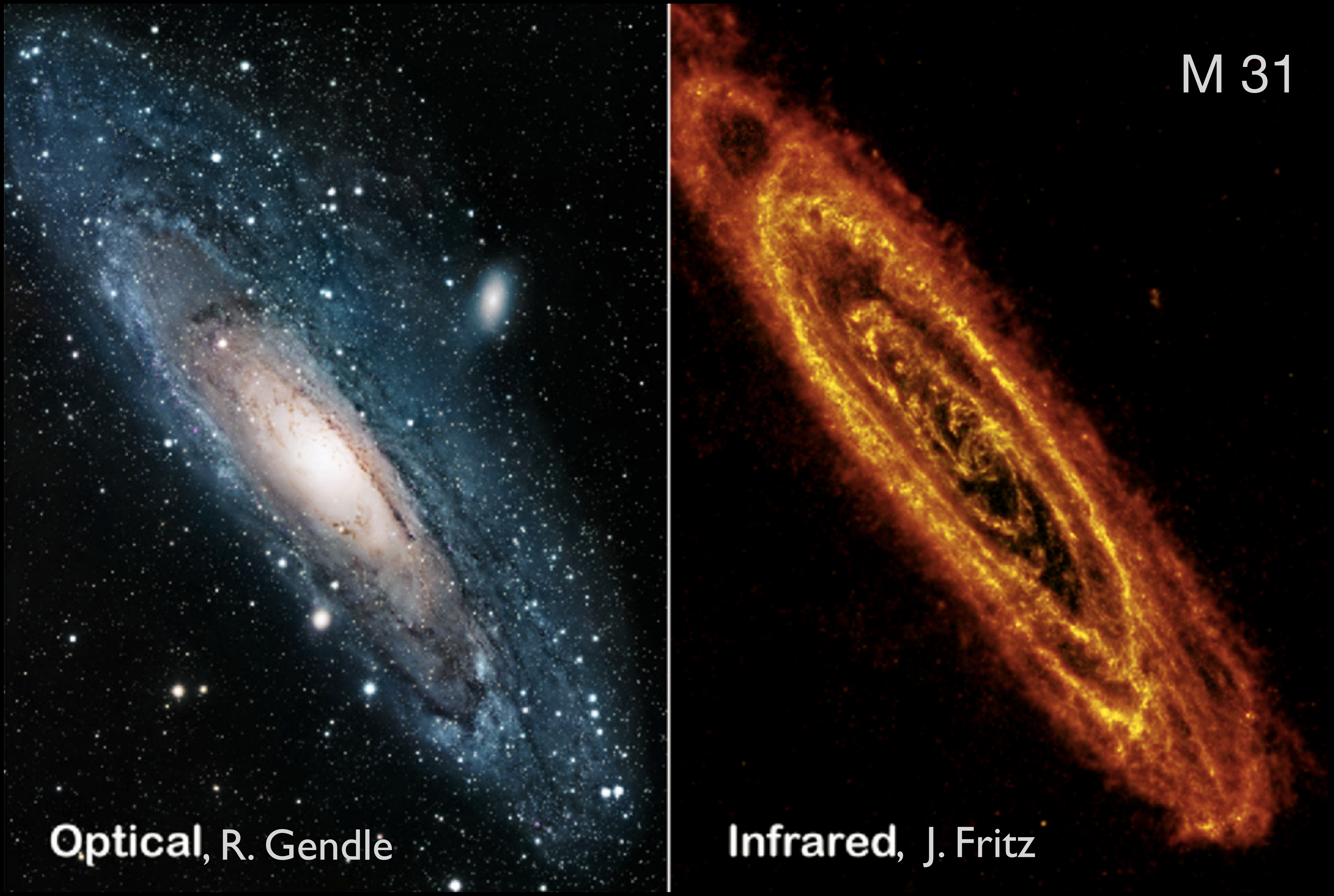
Marco Viero - Caltech

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 (namely, cross-correlations).
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

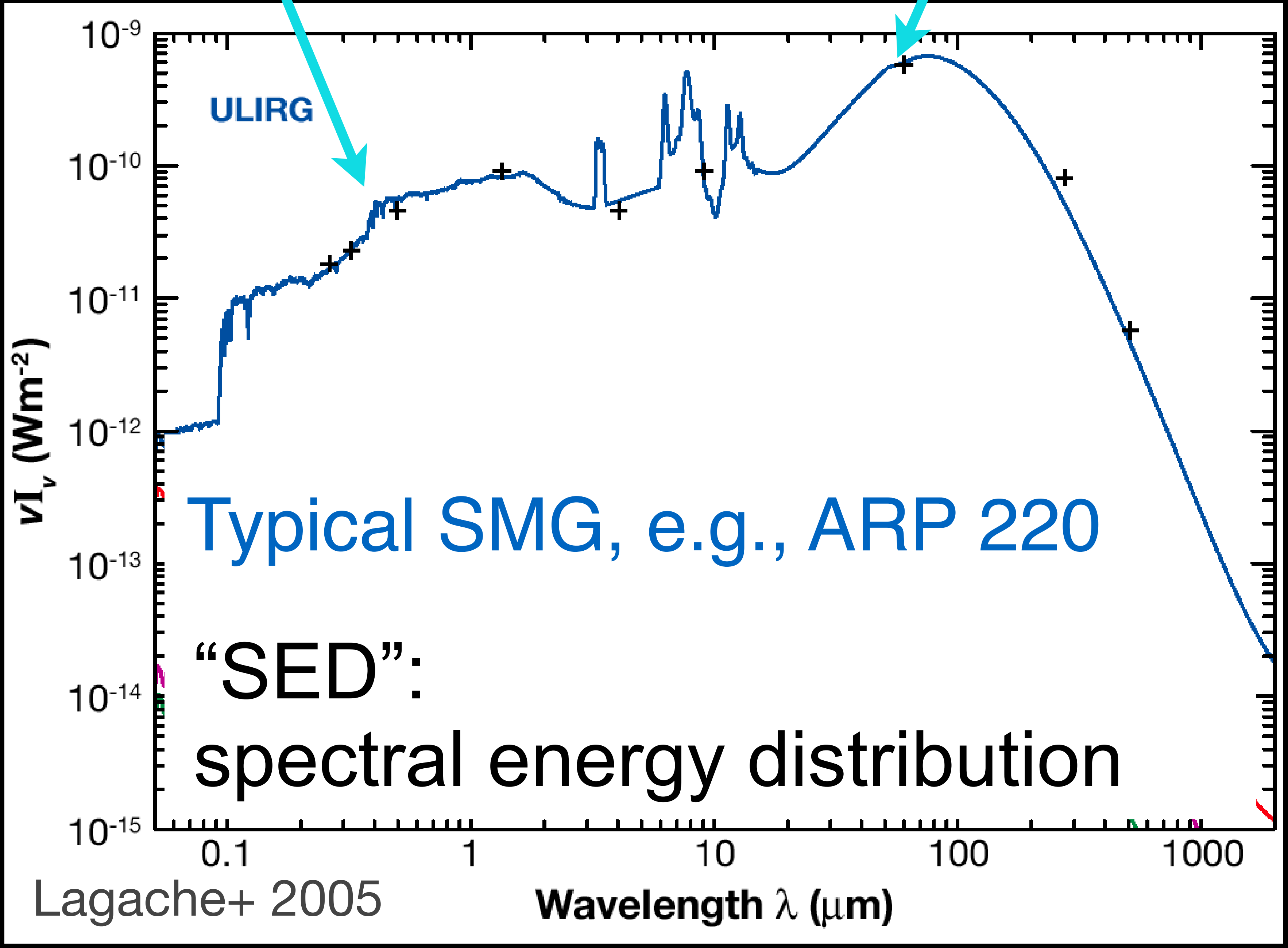
FIR/submillimeter: dust warmed by stars



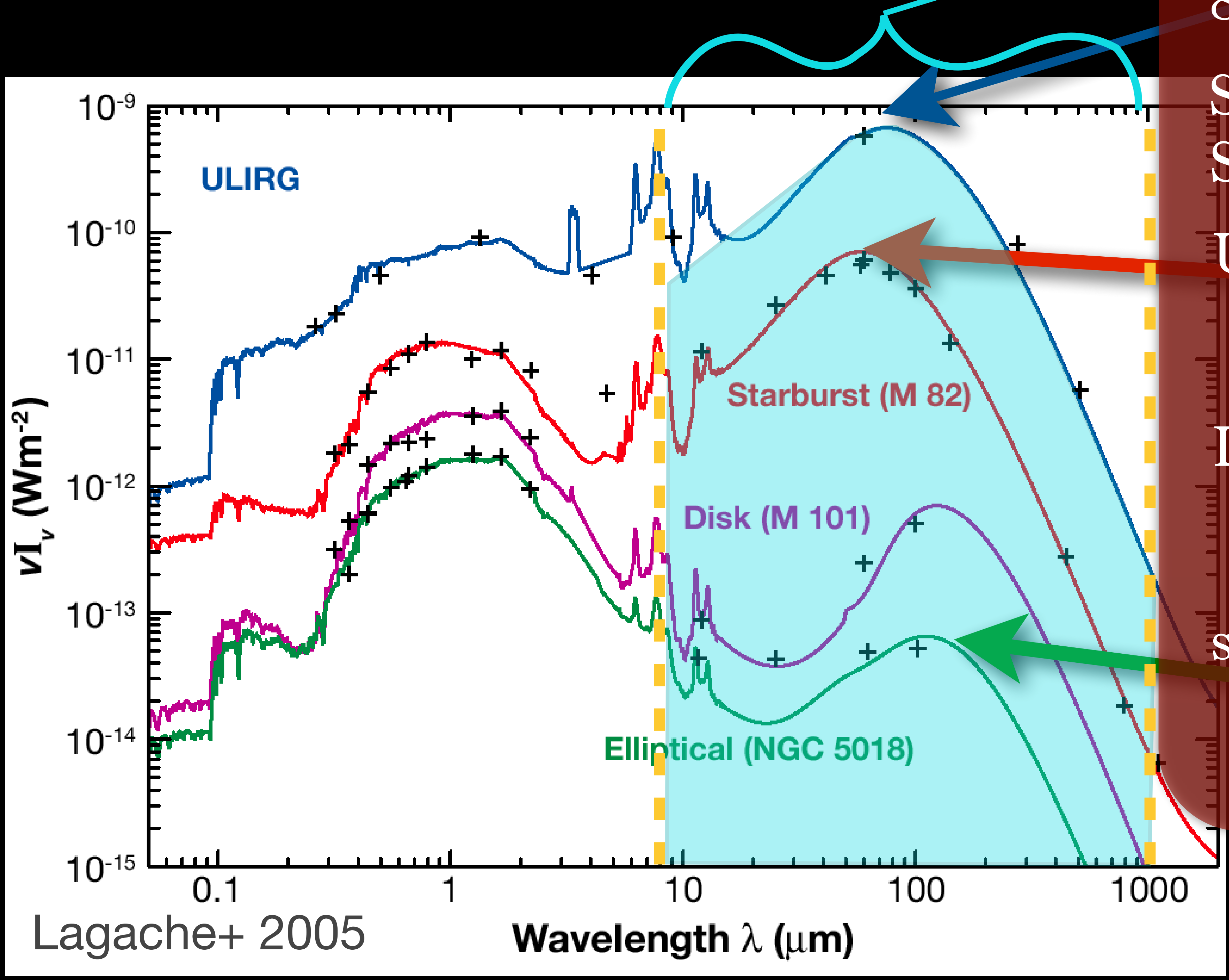
UV/Optical and FIR/submm SED

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

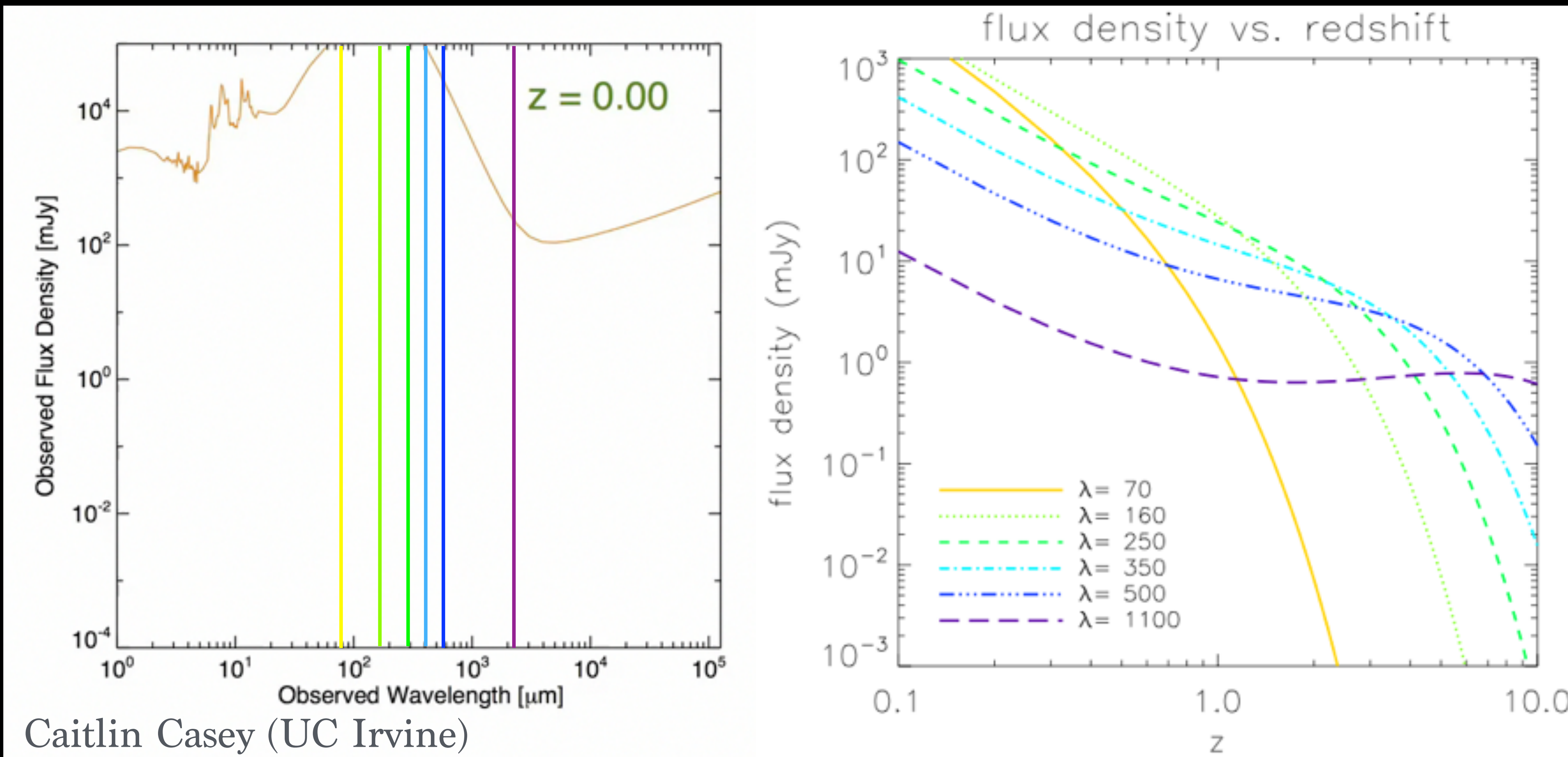
SFR ∝ L_{IR}

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

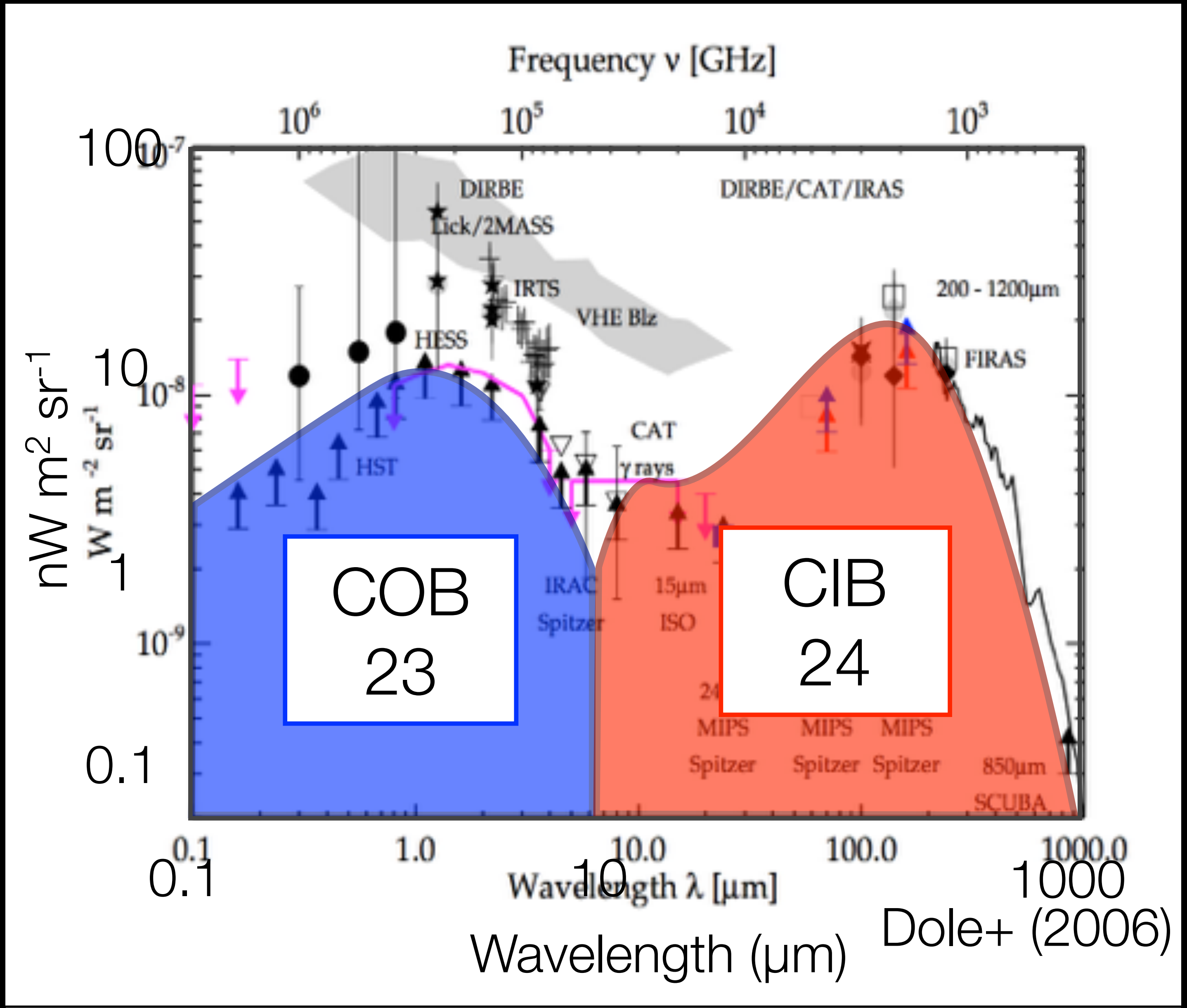


Caitlin Casey (UC Irvine)

Motivation #1: Origin of the Cosmic Infrared Background

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

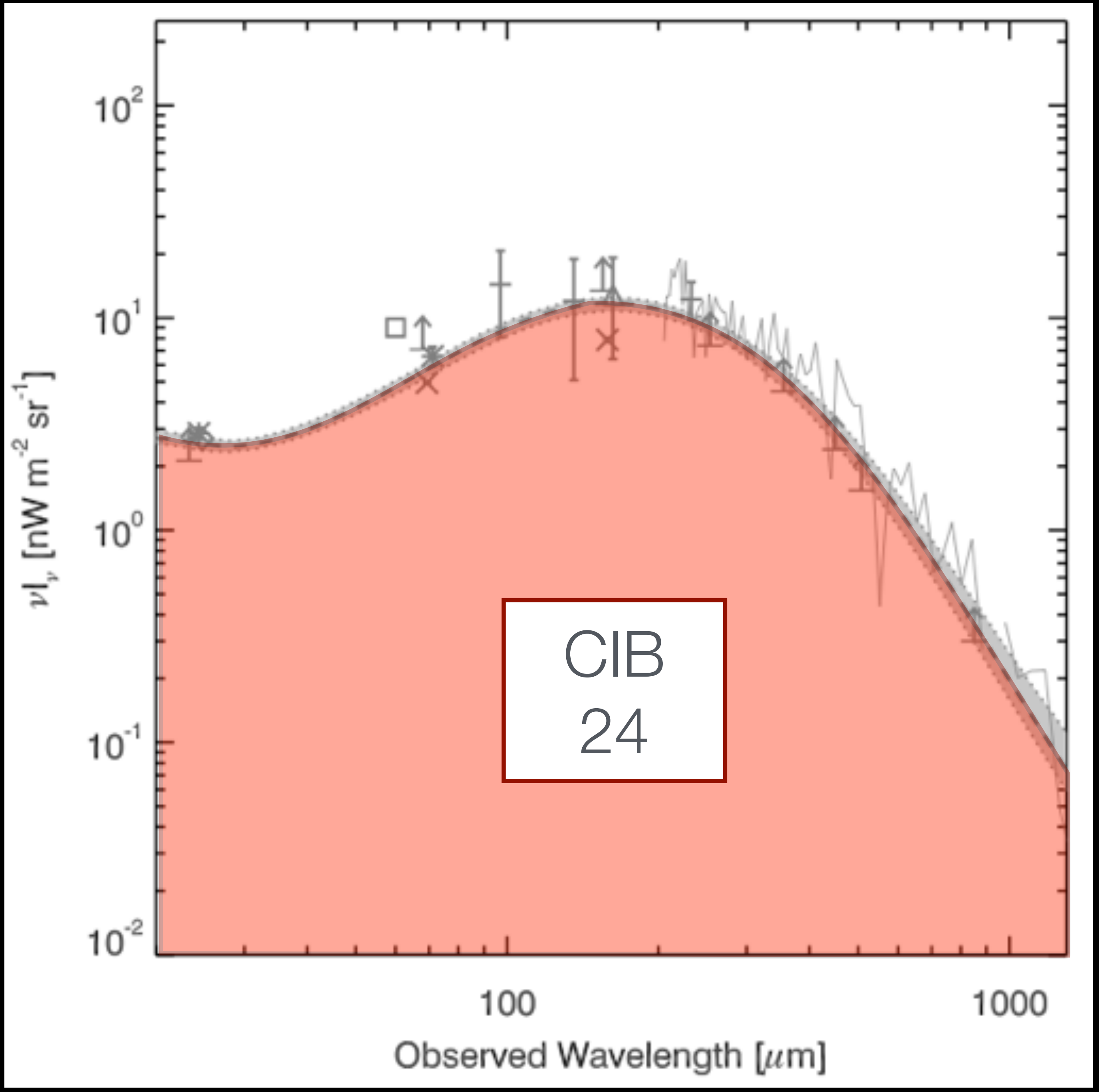
Can we understand the infrared component of galaxies in the same detail as the optical?



Motivation #1: Origin of the Cosmic Infrared Background

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

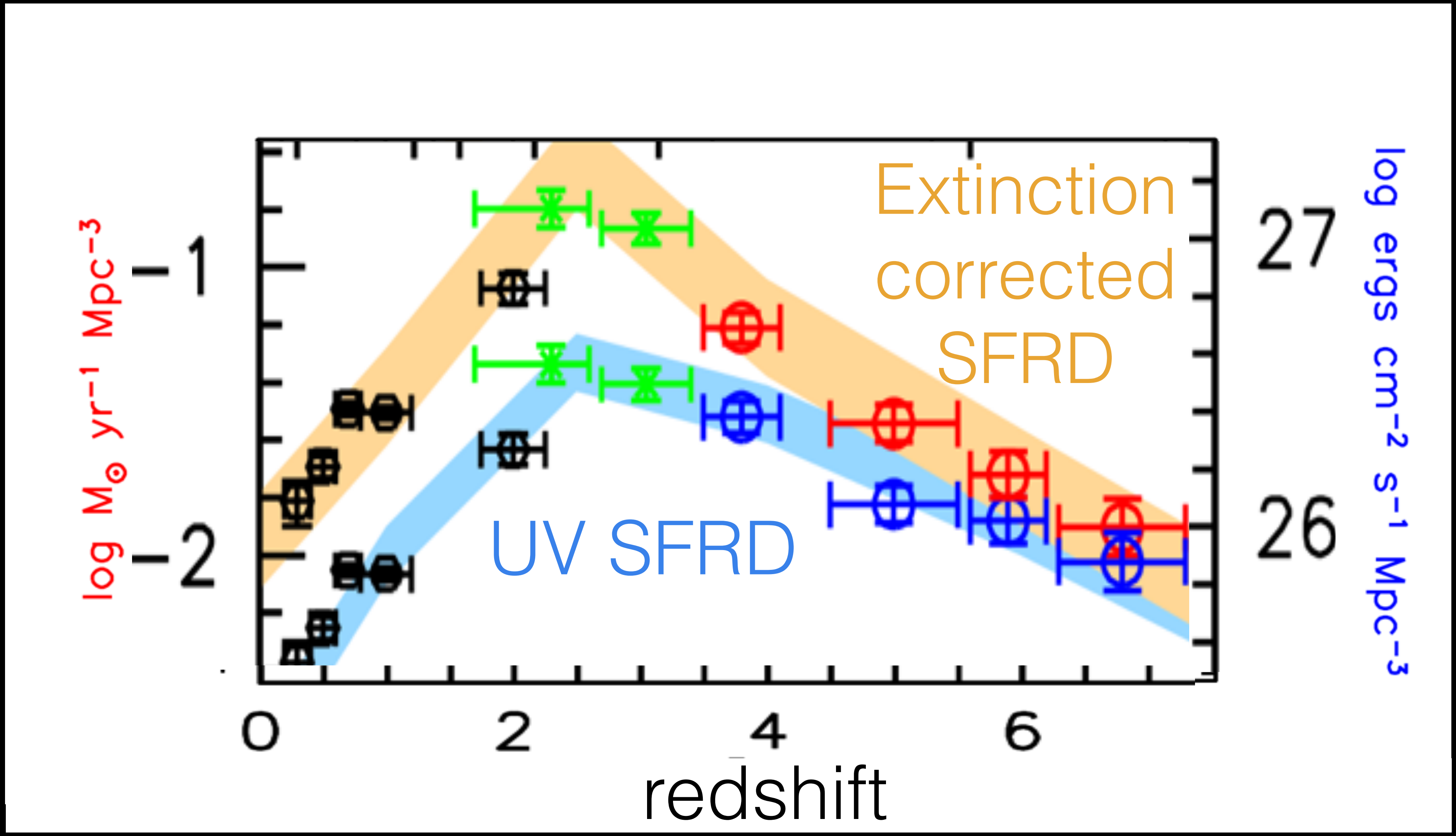
How does it break down? By Stellar Mass? Redshift? SMGs? DSFGs? AGN? Other??



Motivation #2: History of Cosmic Star Formation

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

Star-Formation Rate Density

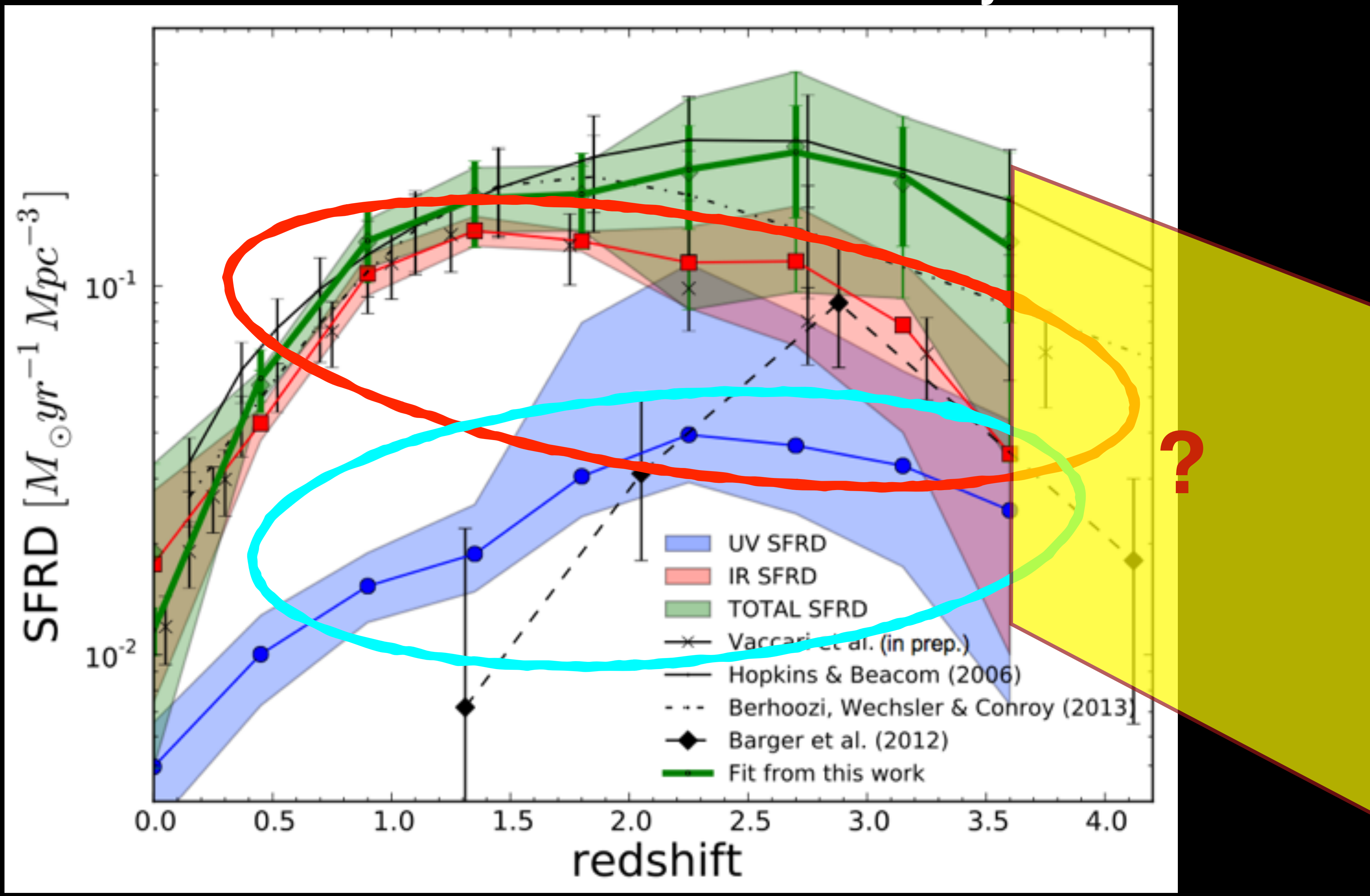


Bouwens+2009

Motivation #1: History of Cosmic Star Formation

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

Star-Formation Rate Density



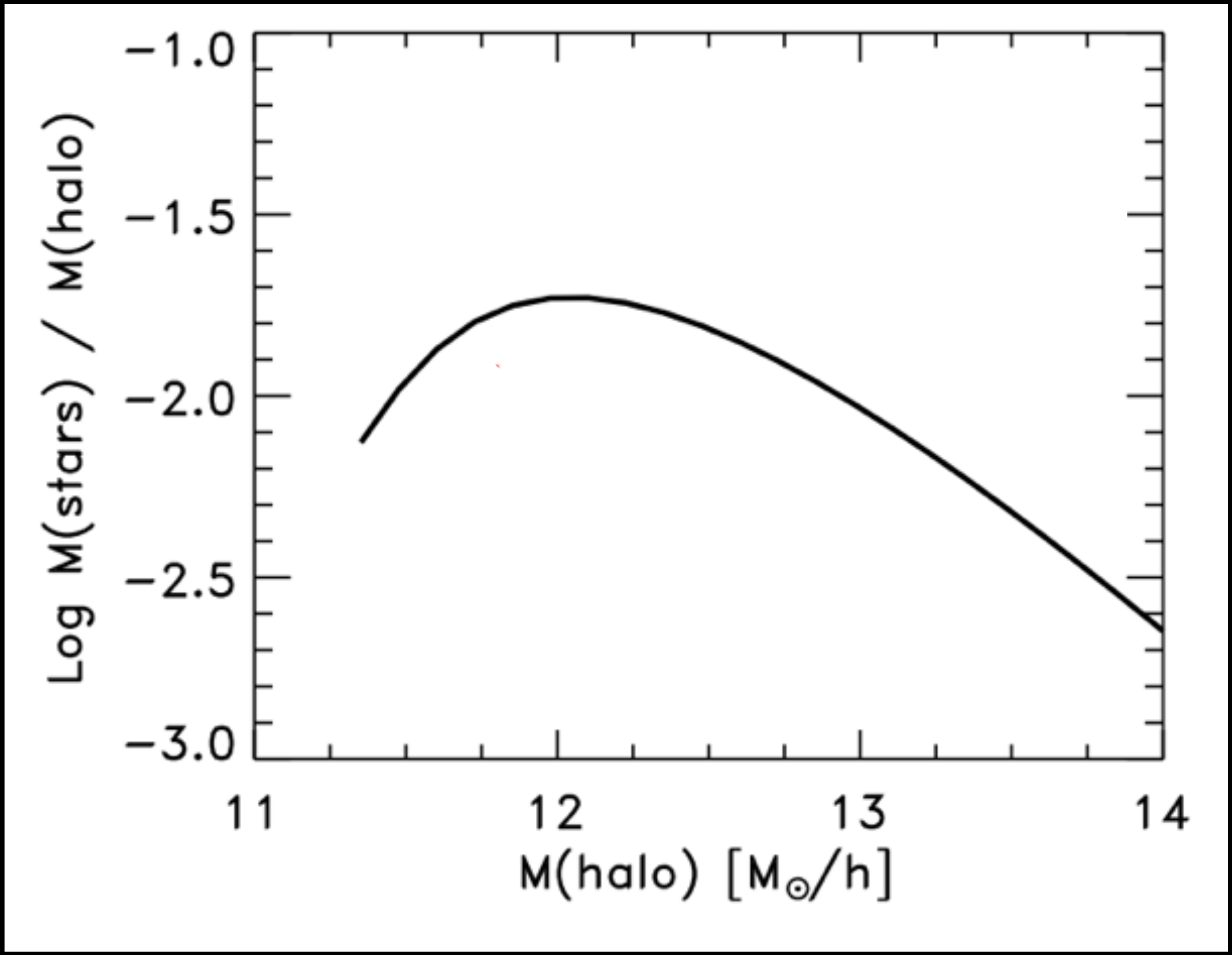
Burgarella+2013

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)

HERMES

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

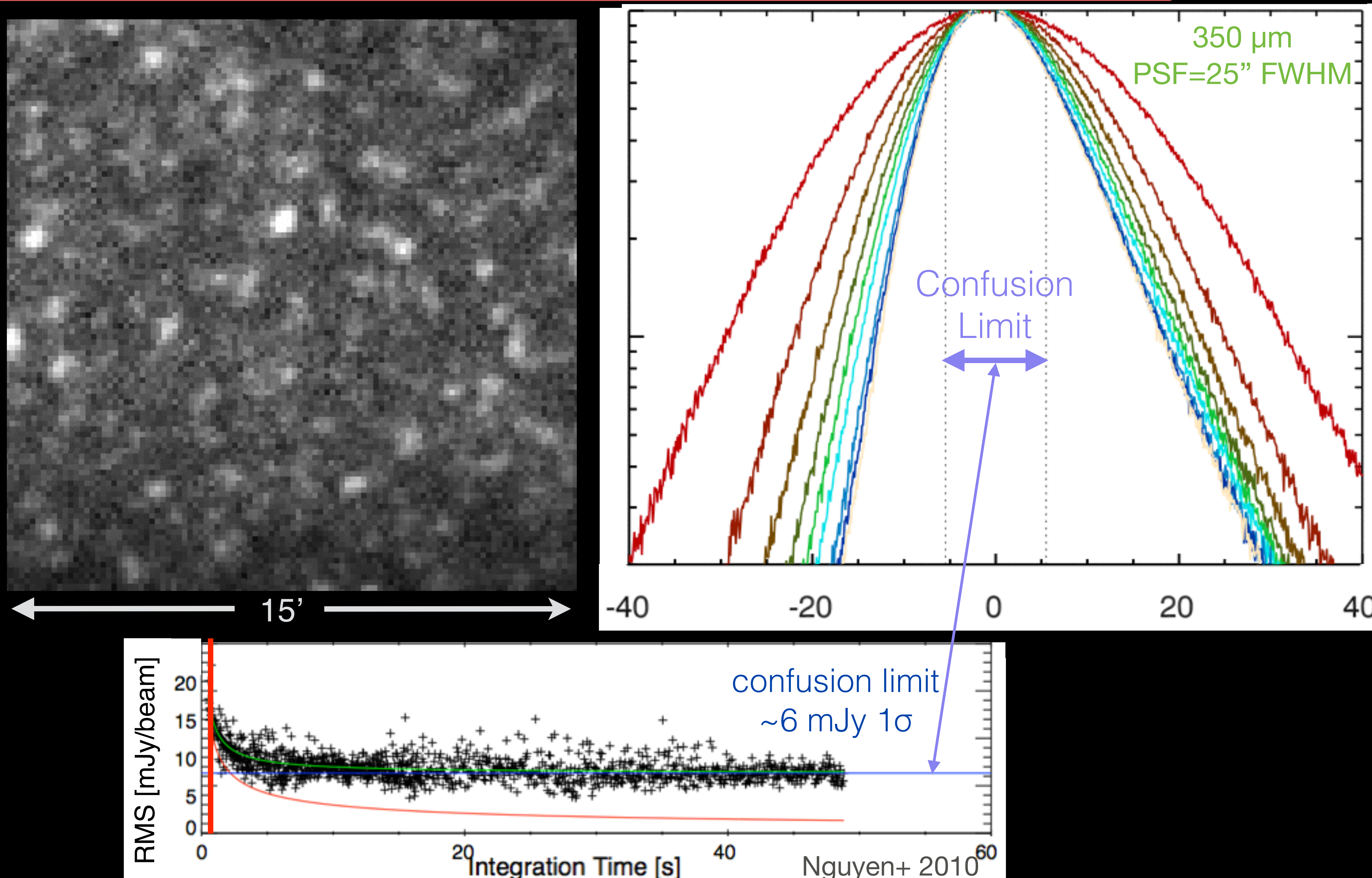
The Team

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

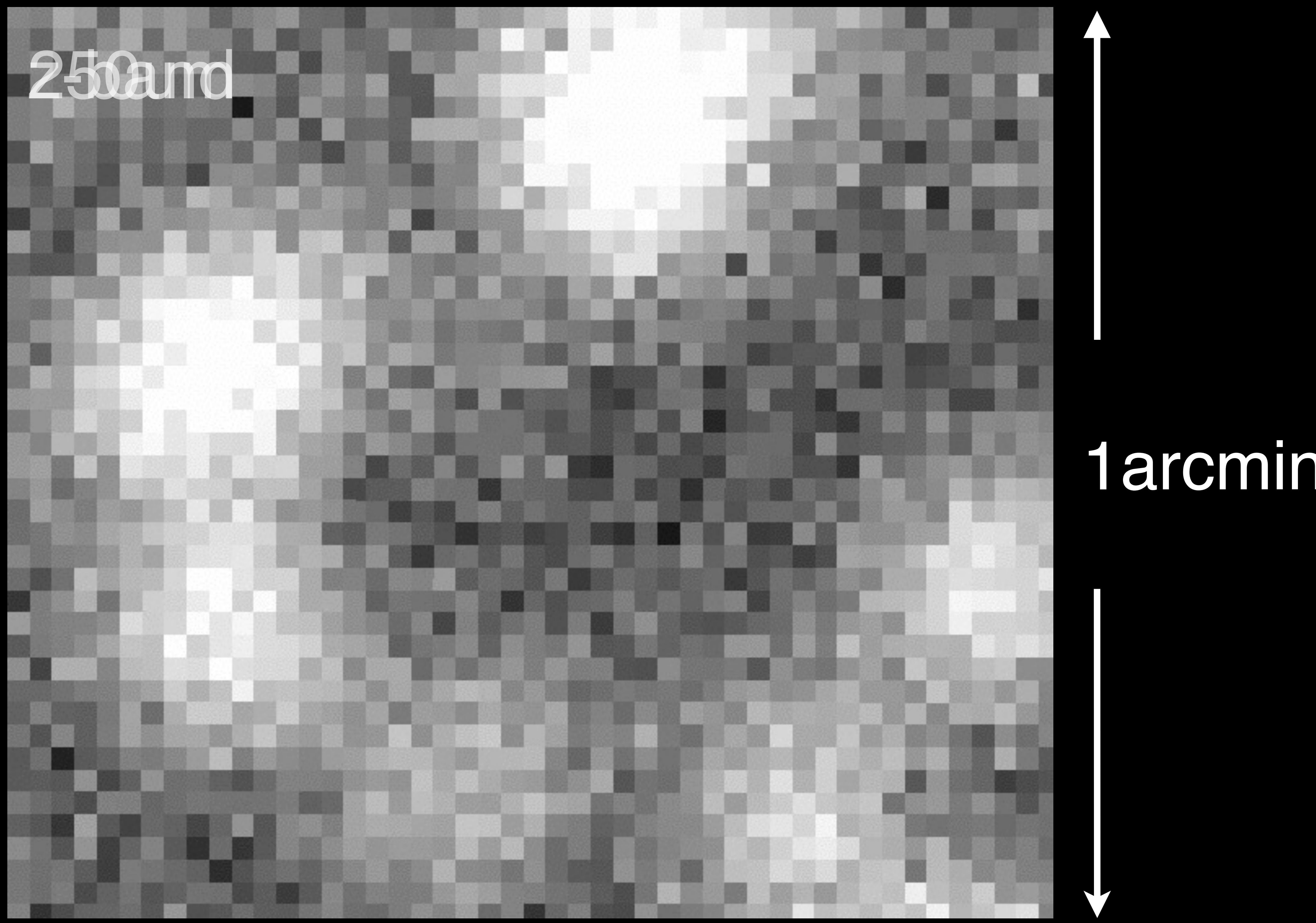
Faculty & Researchers PostDocs PhD Students

Plus engineers, instrument builders, software developers etc.

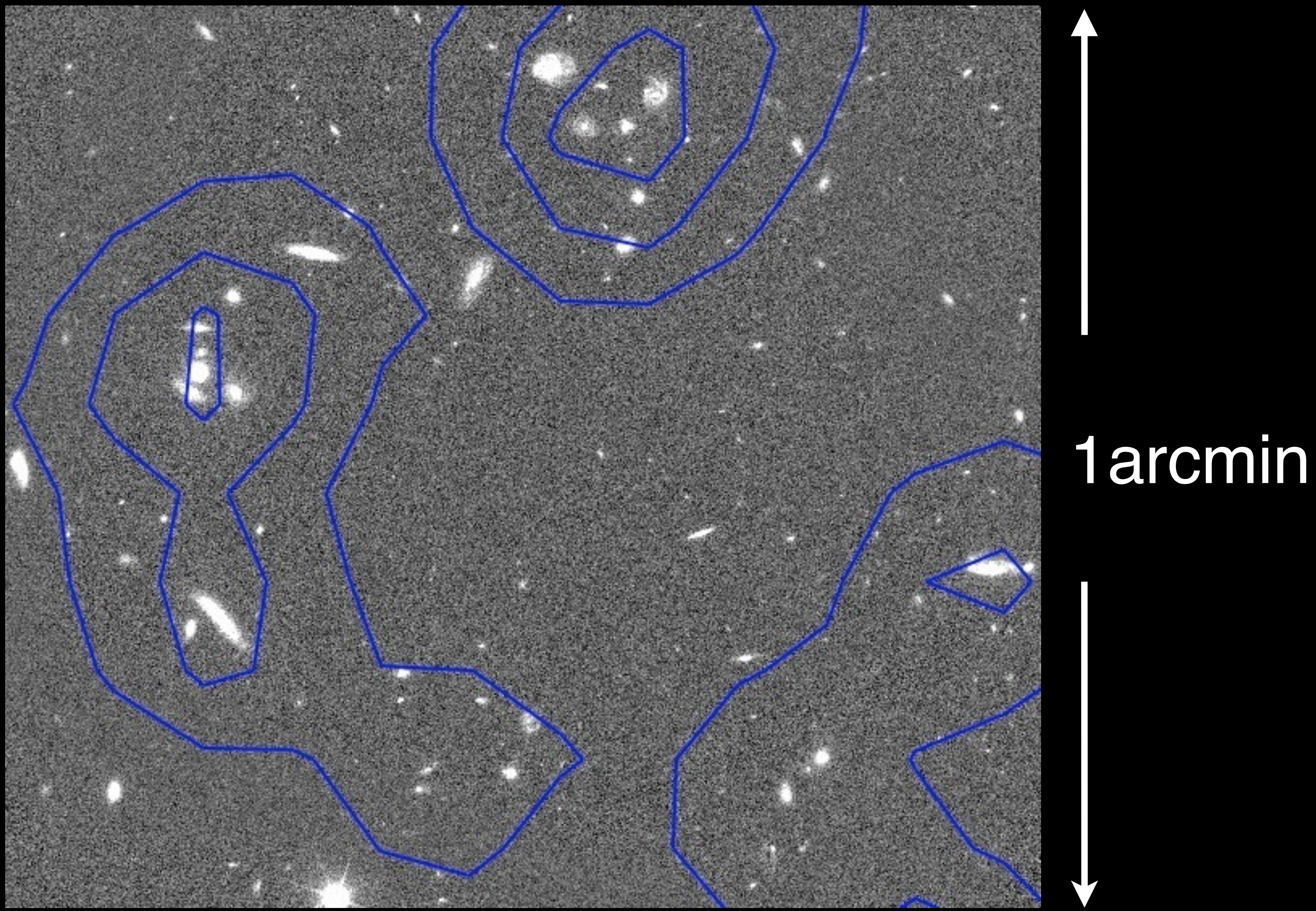
Instrument Noise and the Confusion Limit

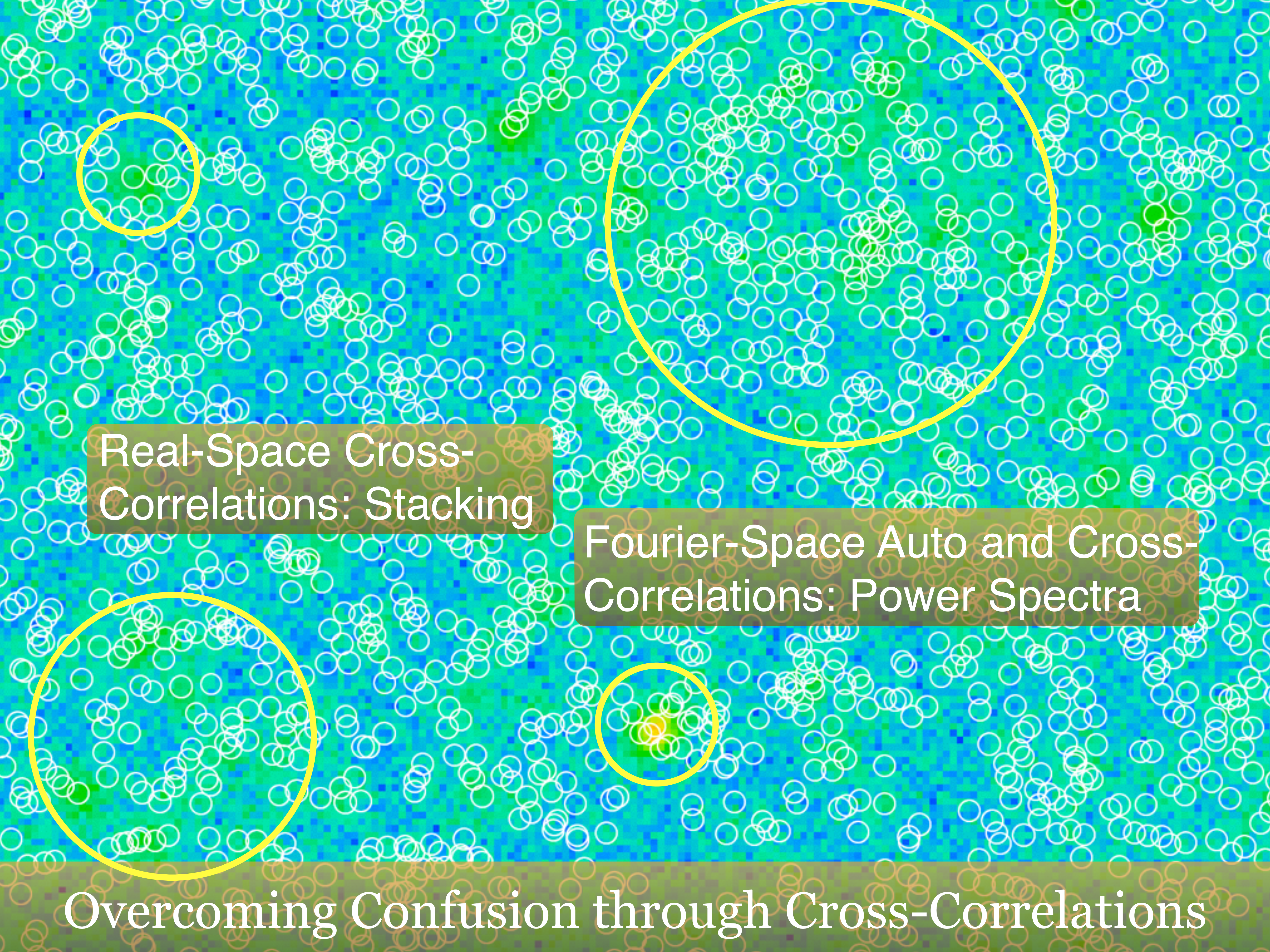


Source Confusion

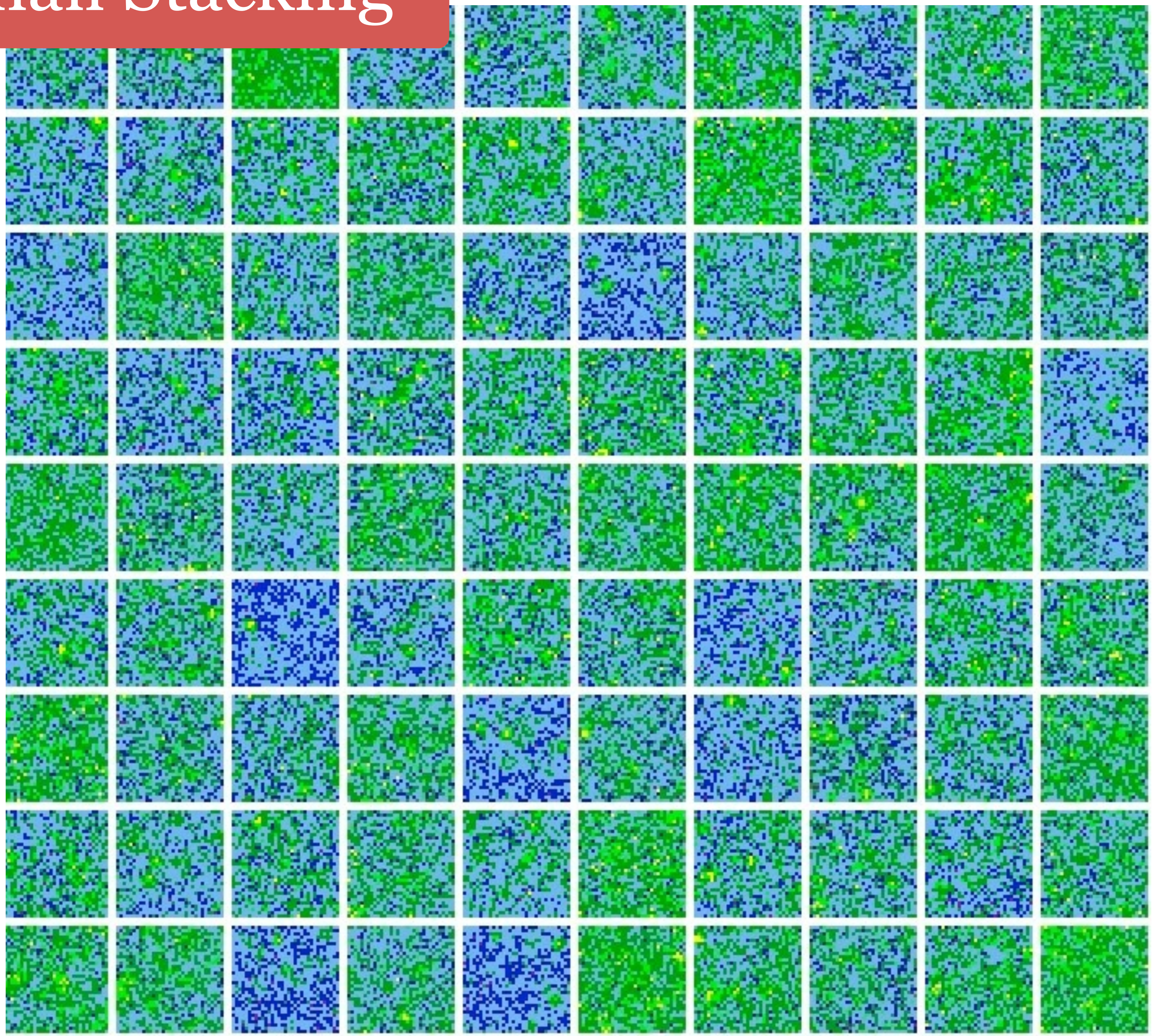


Source Confusion

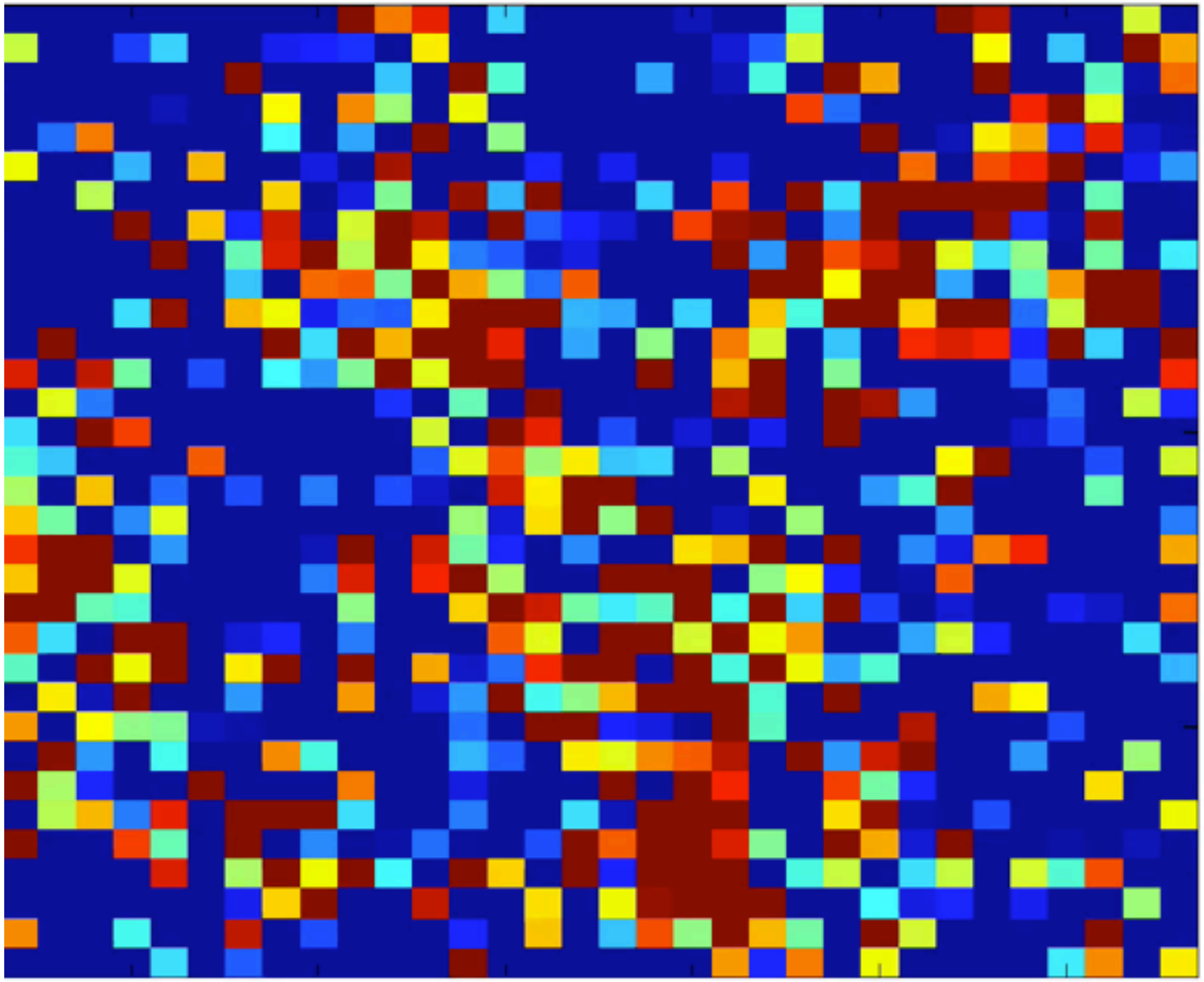



Real-Space Cross-Correlations: Stacking
Fourier-Space Auto and Cross-Correlations: Power Spectra
Overcoming Confusion through Cross-Correlations

Thumbnail Stacking

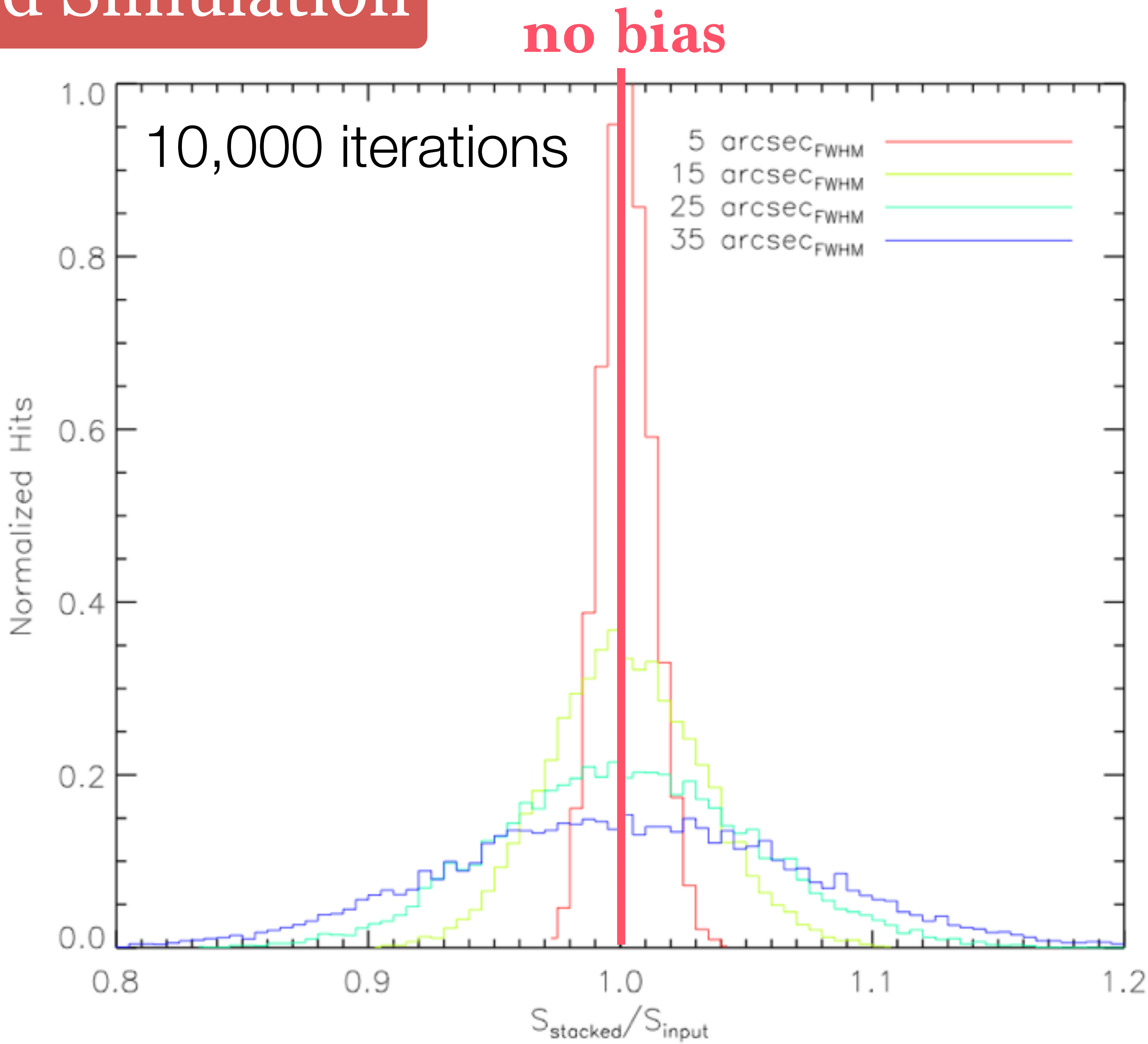


Thumbnail Stacking

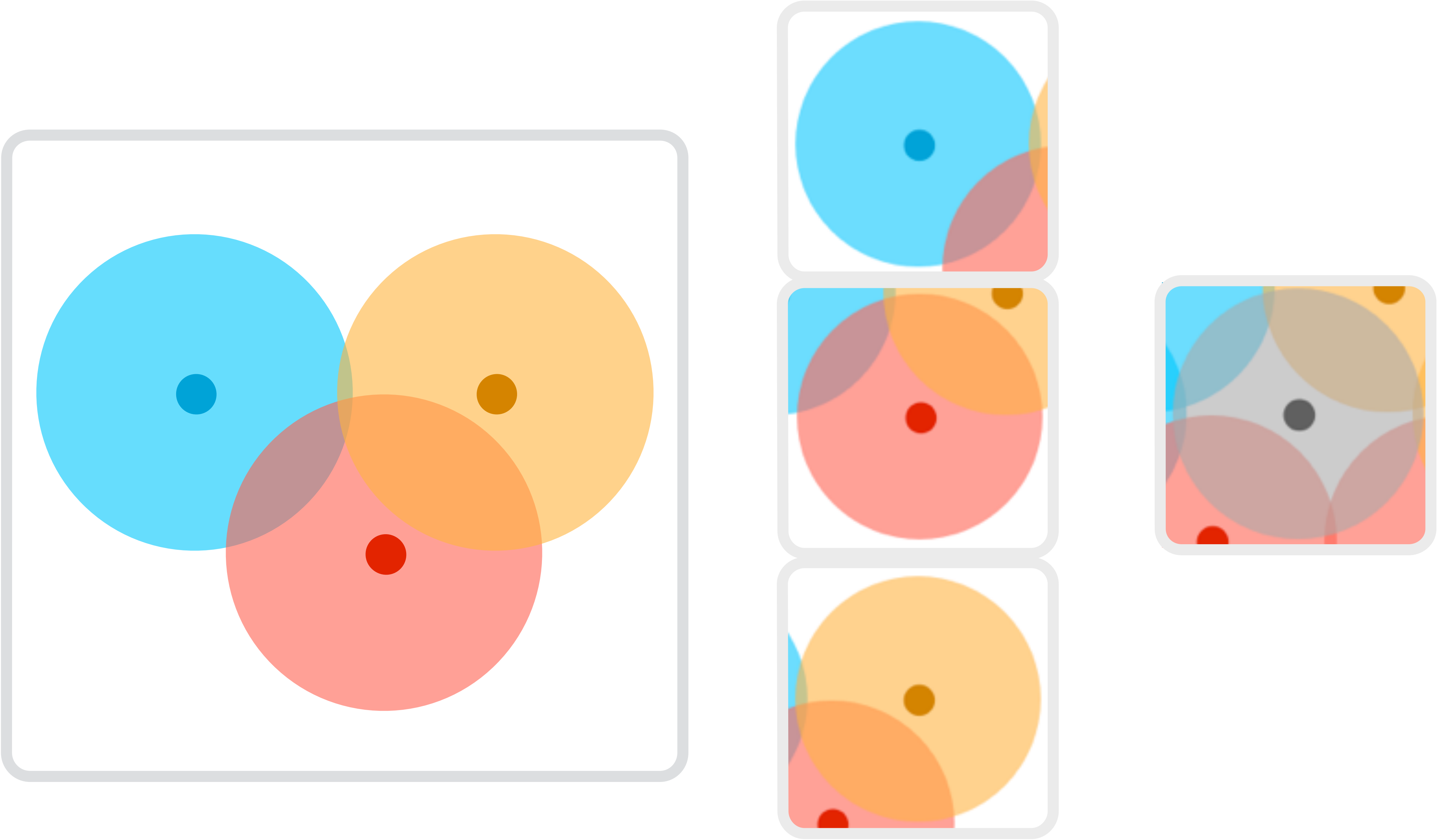


Phil Korngut (Caltech)

Uncorrelated Simulation



Correlation (clustering) Induced Bias

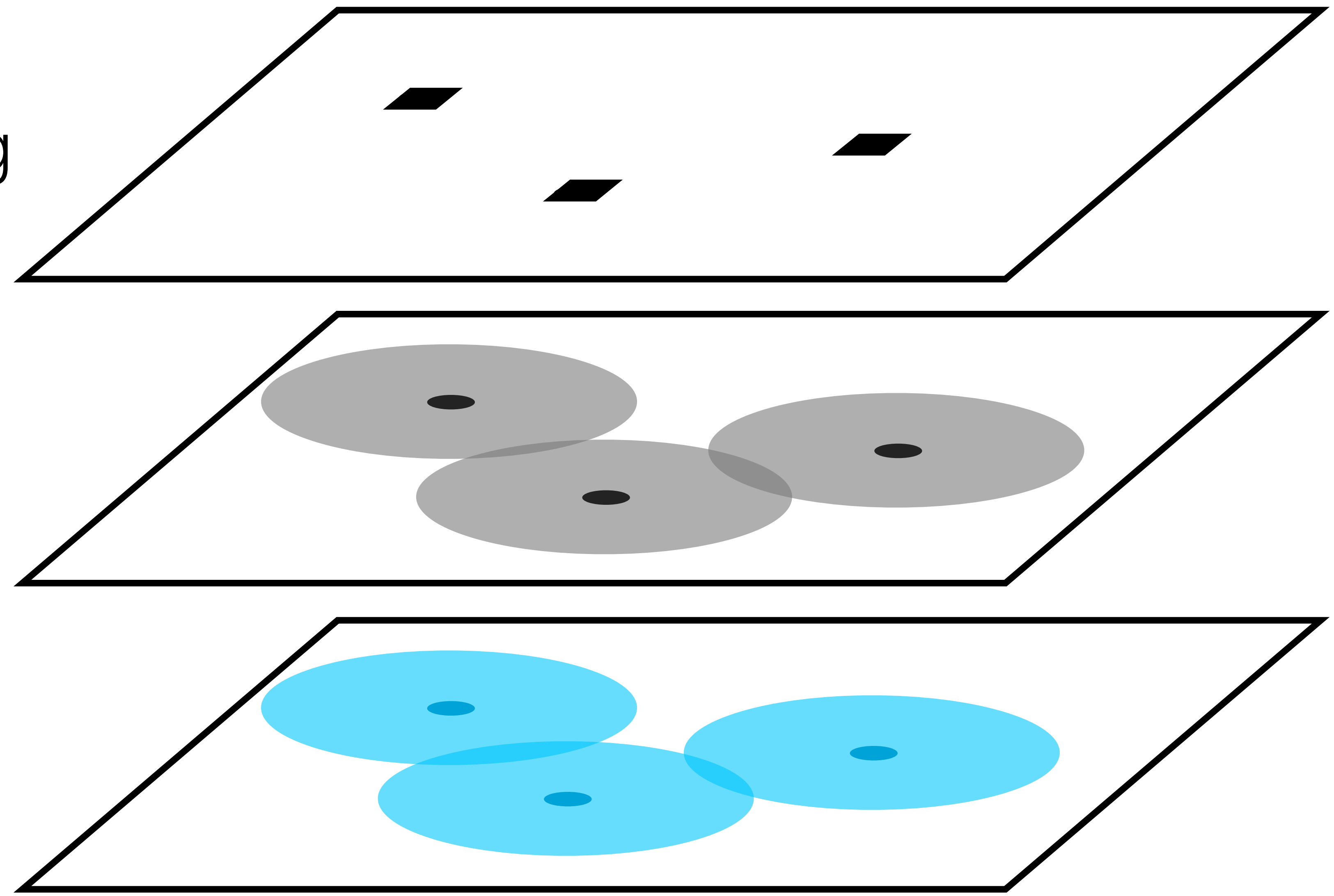


SIMSTACK: Simultaneous Stacking Algorithm

make hits map from catalog

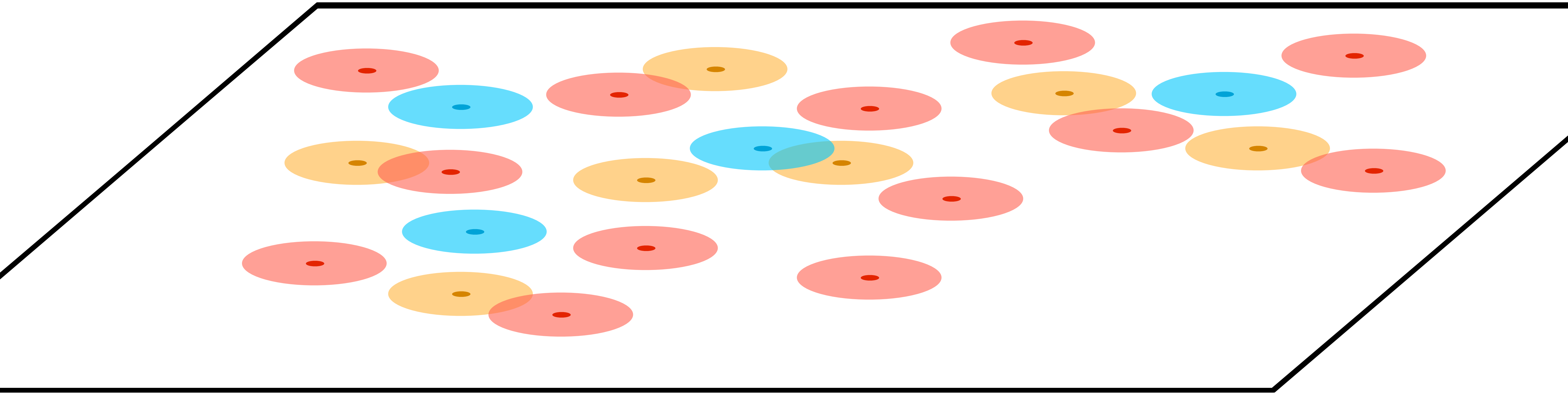
convolve with map p.s.f.

regress to find stacked flux

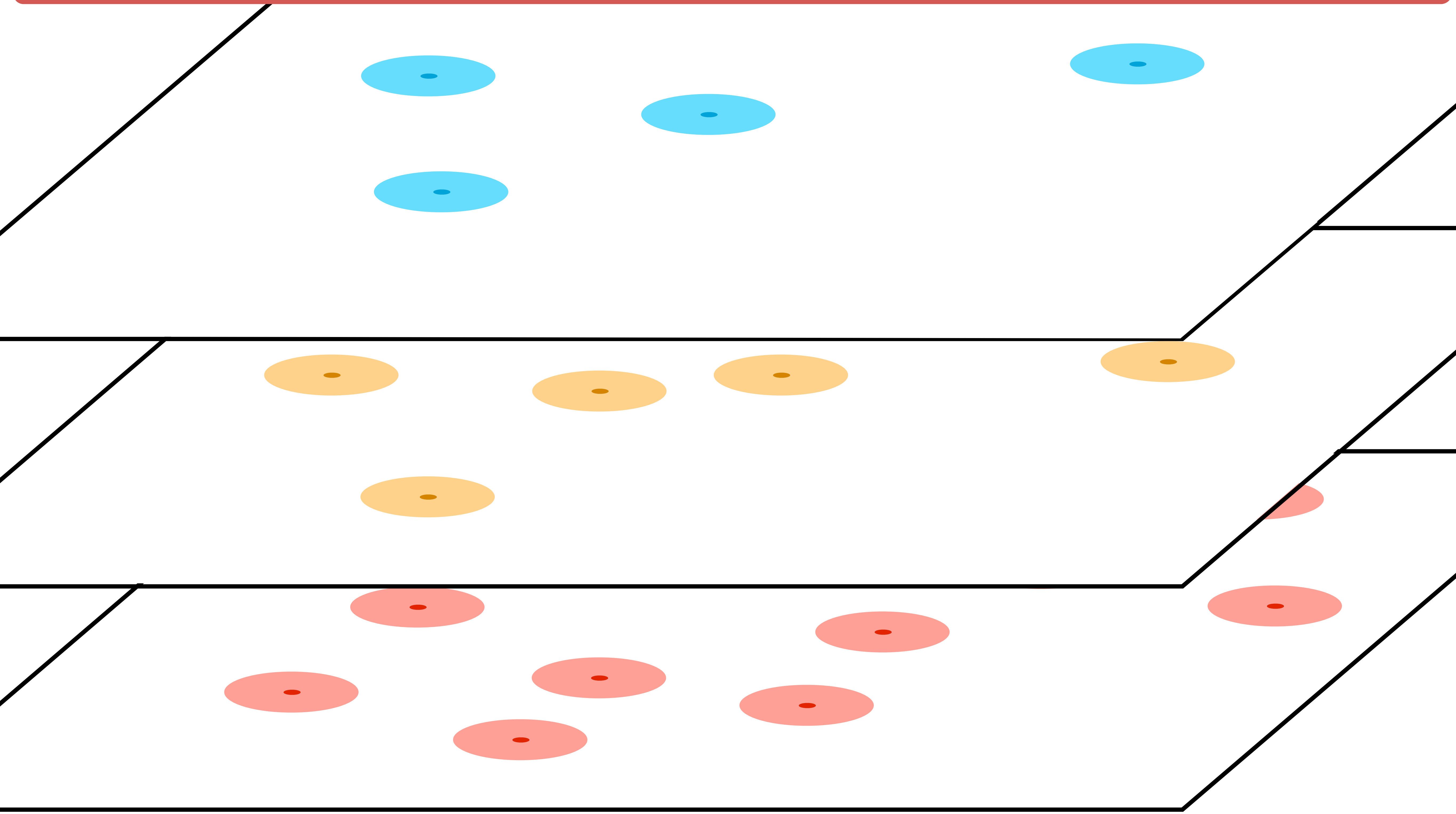


Formalism developed w/ Lorenzo Moncelsi (Caltech);
also see Kurczynski & Gawiser (2010), Roseboom et al. (2010)
SIMSTACK code publicly available in arXiv:1304.0446

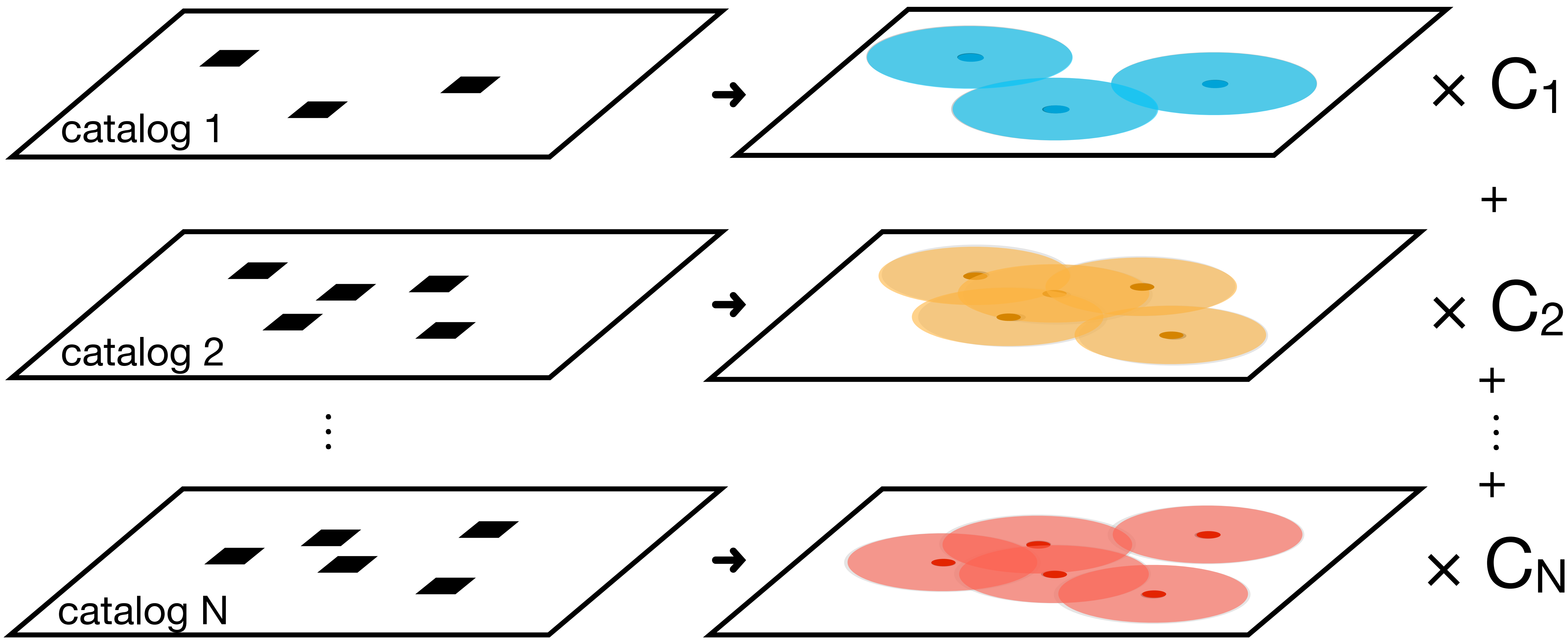
SIMSTACK: Simultaneous Stacking Algorithm

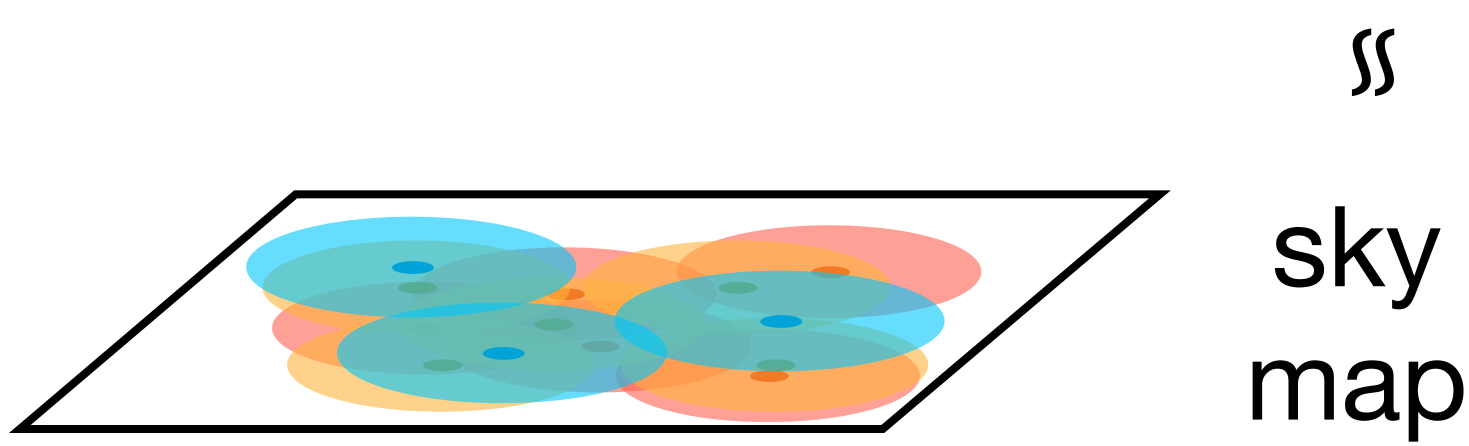


SIMSTACK: Simultaneous Stacking Algorithm



SIMSTACK: Simultaneous Stacking Algorithm

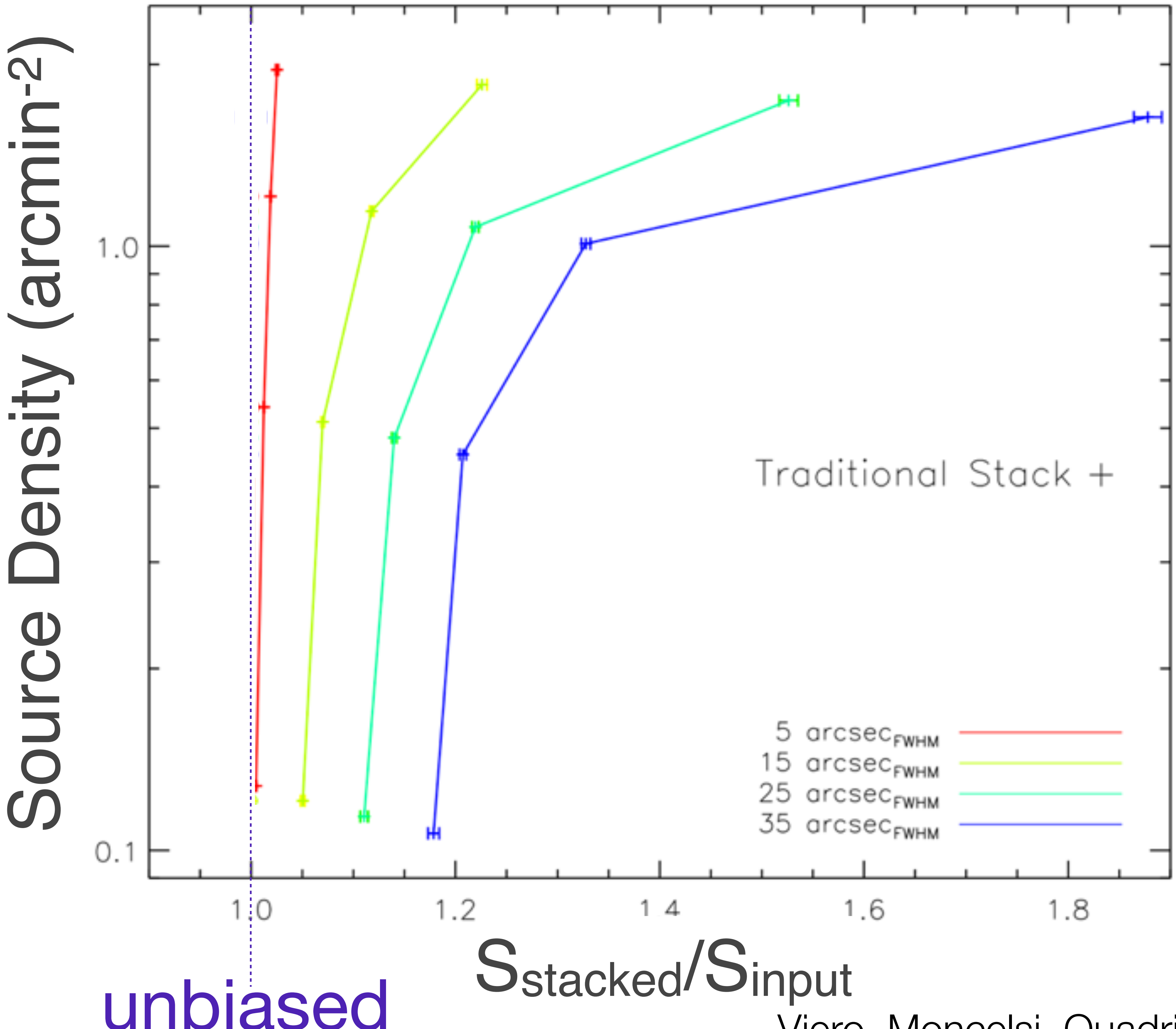




Formalism developed w/ Lorenzo Moncelsi (Caltech)

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

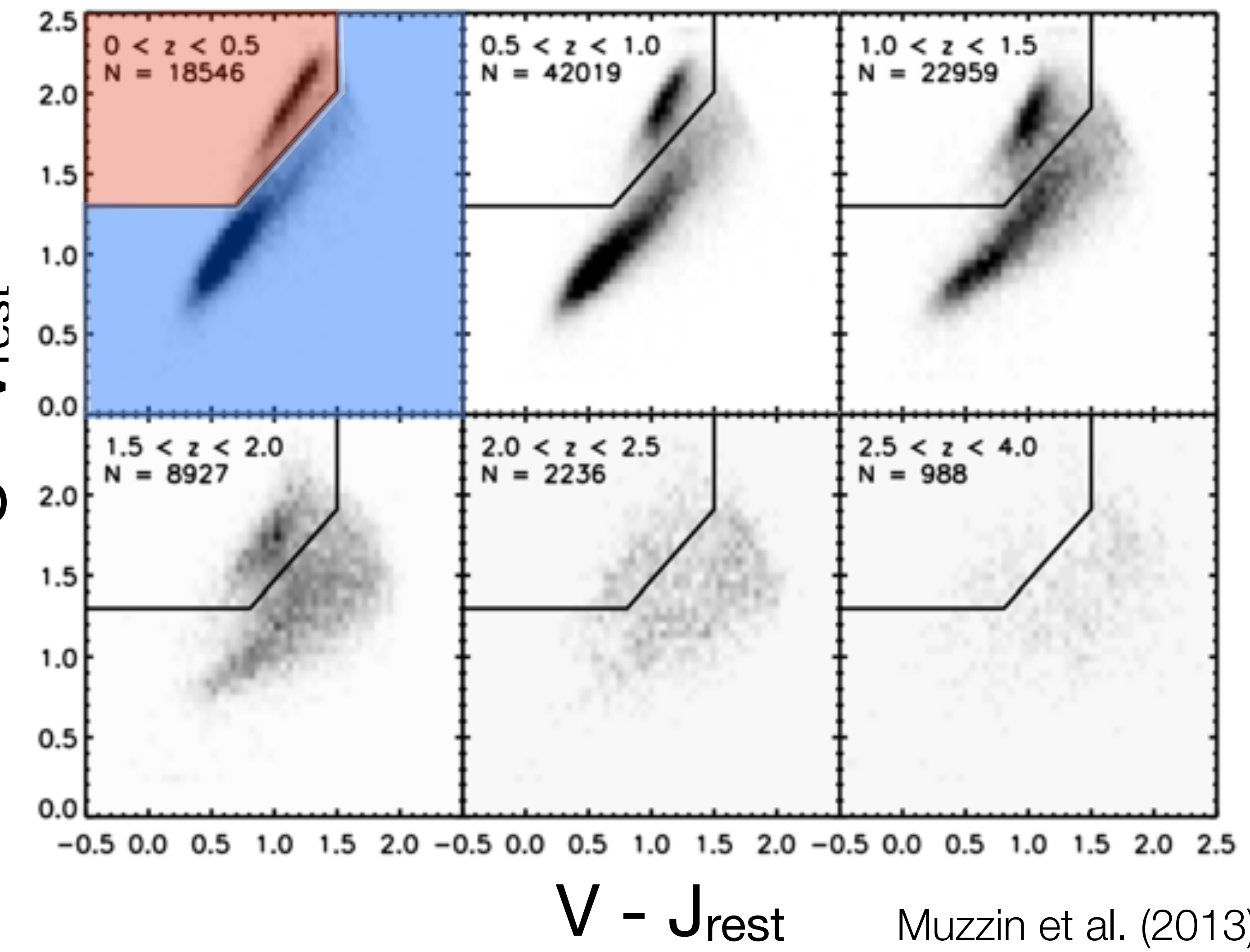
catalog (Williams & Quadri, in prep.)

- 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)

maps (HerMES; Oliver et al. 2012)

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

Separating Quiescent from Star-forming



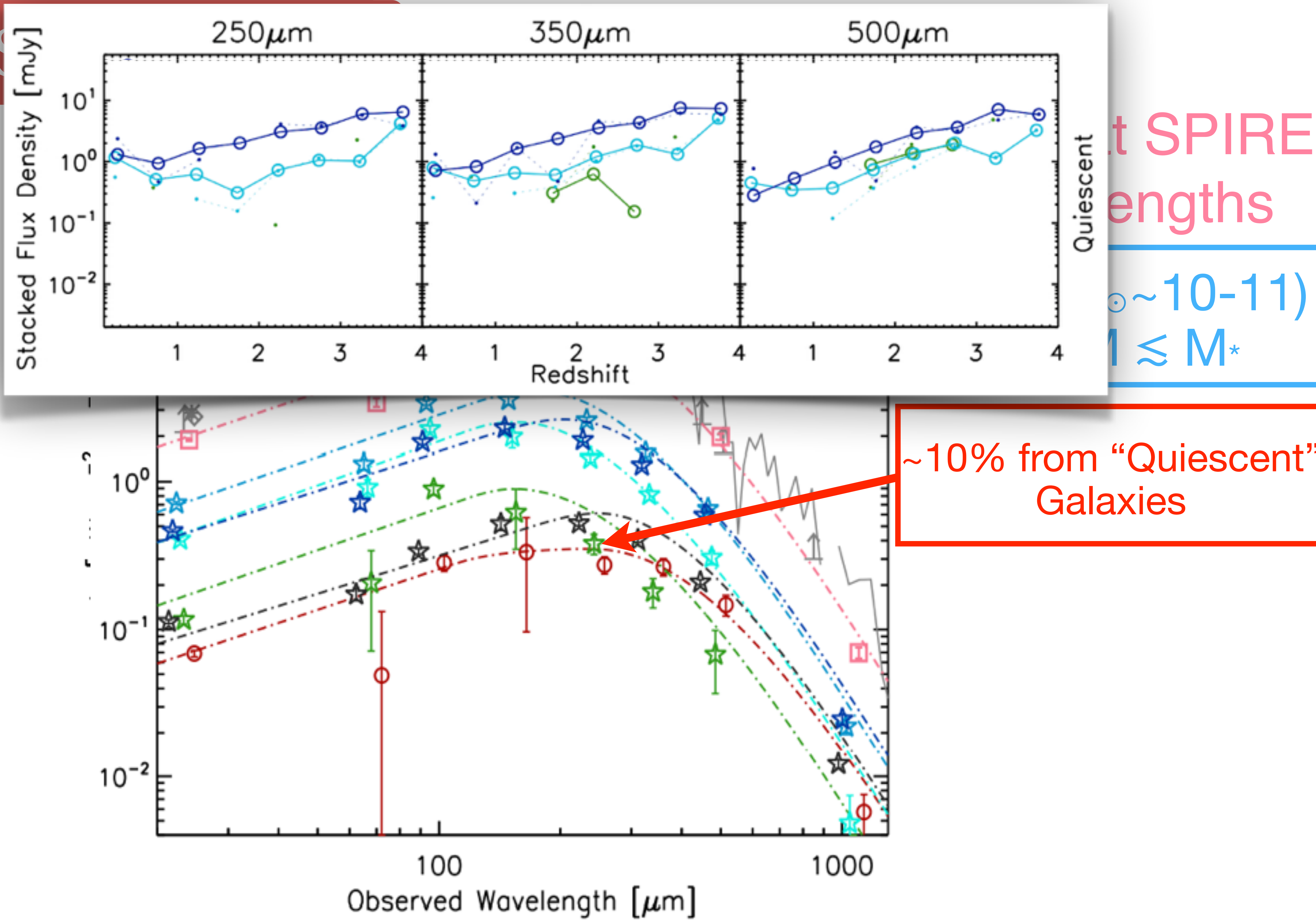
Muzzin et al. (2013)

Redshift

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

Motivation Recap

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



…t SPIRE
…engths
…⊙~10-11)
…M ≲ M*

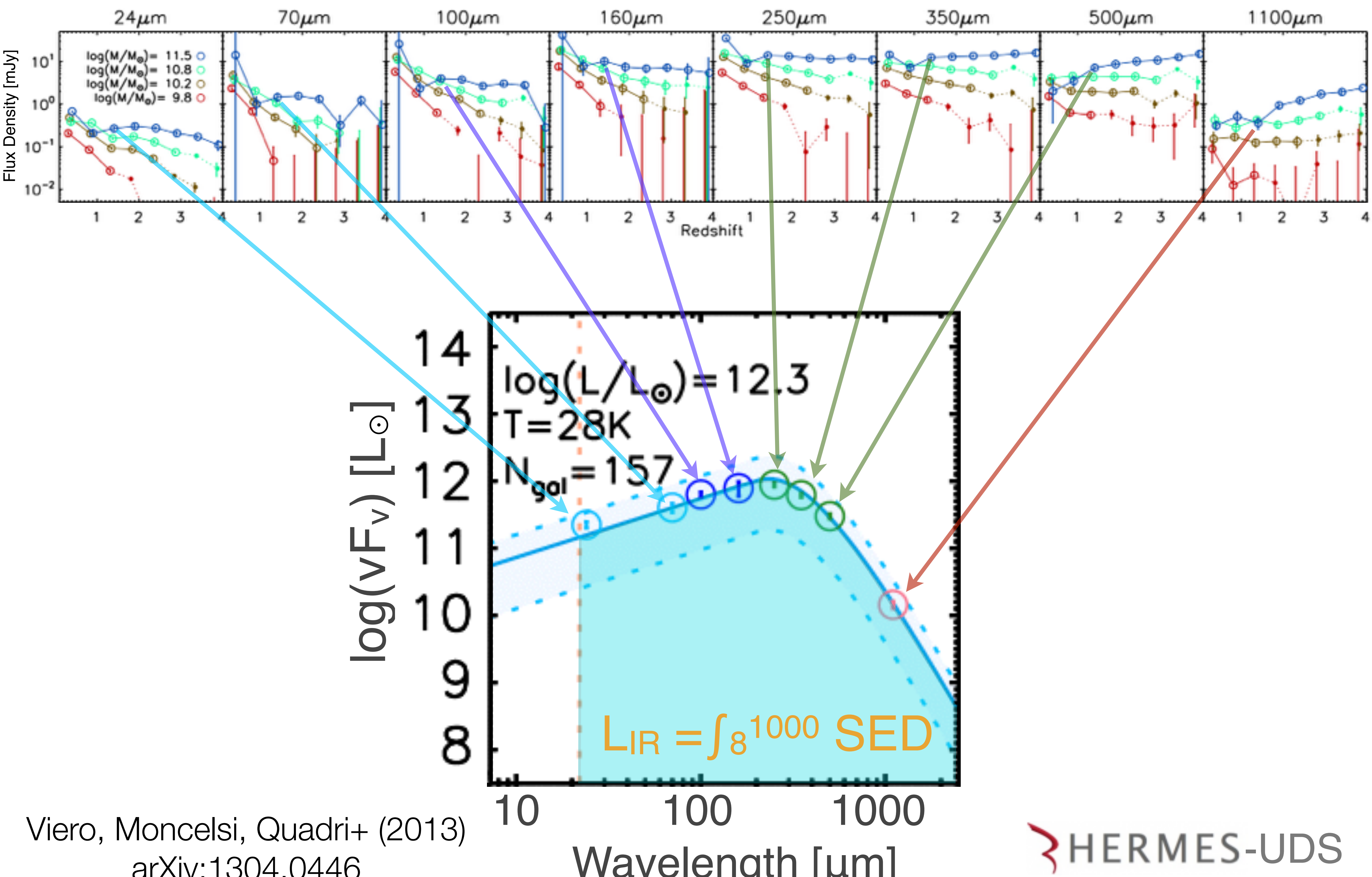
Viero, Moncelsi, Quadri et al. (2013)
arXiv:1304.0446

HERMES-UDS

Motivation Recap

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

SIMSTACK of Galaxies by Stellar Mass and Redshift



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

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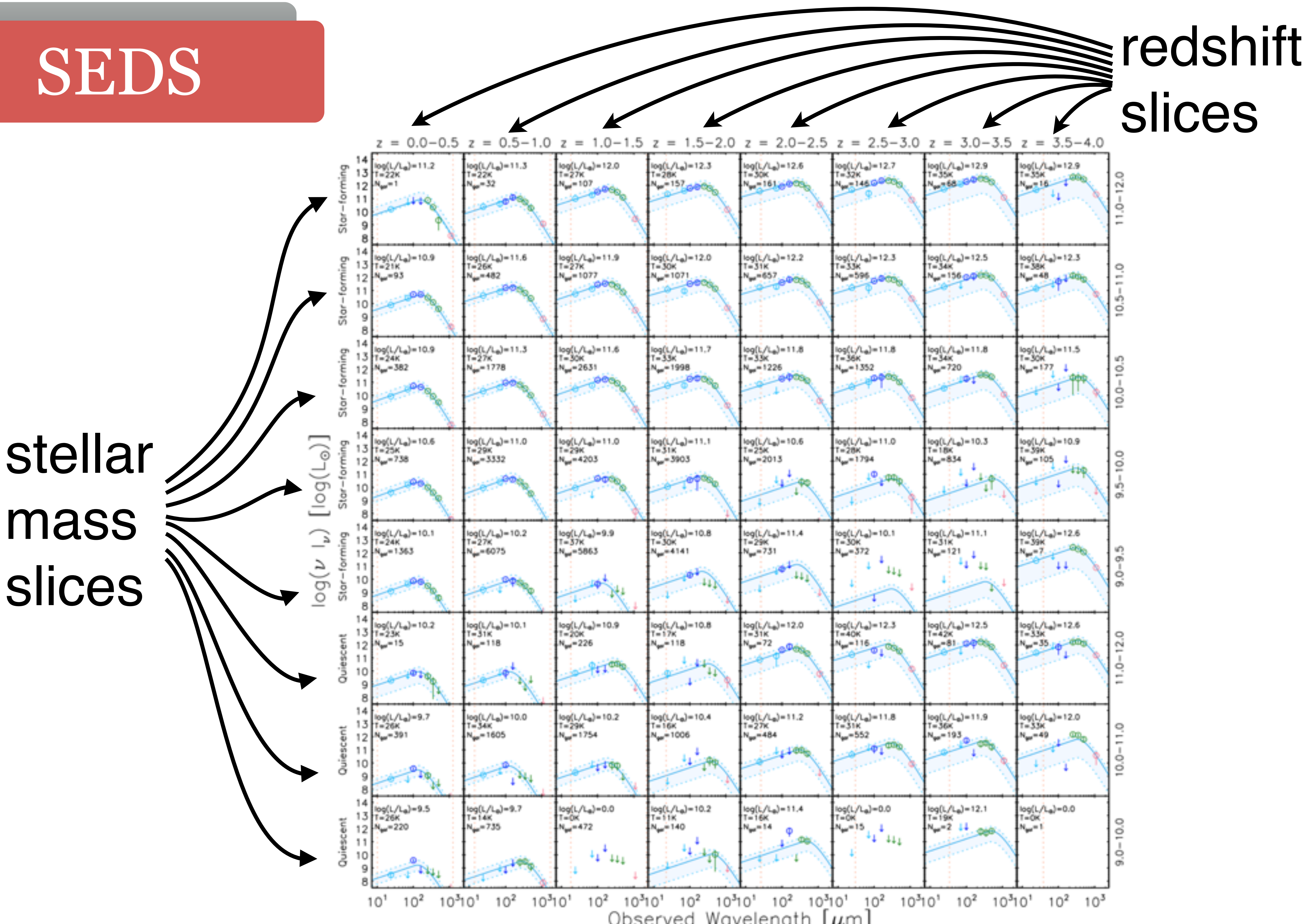
SEDS



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

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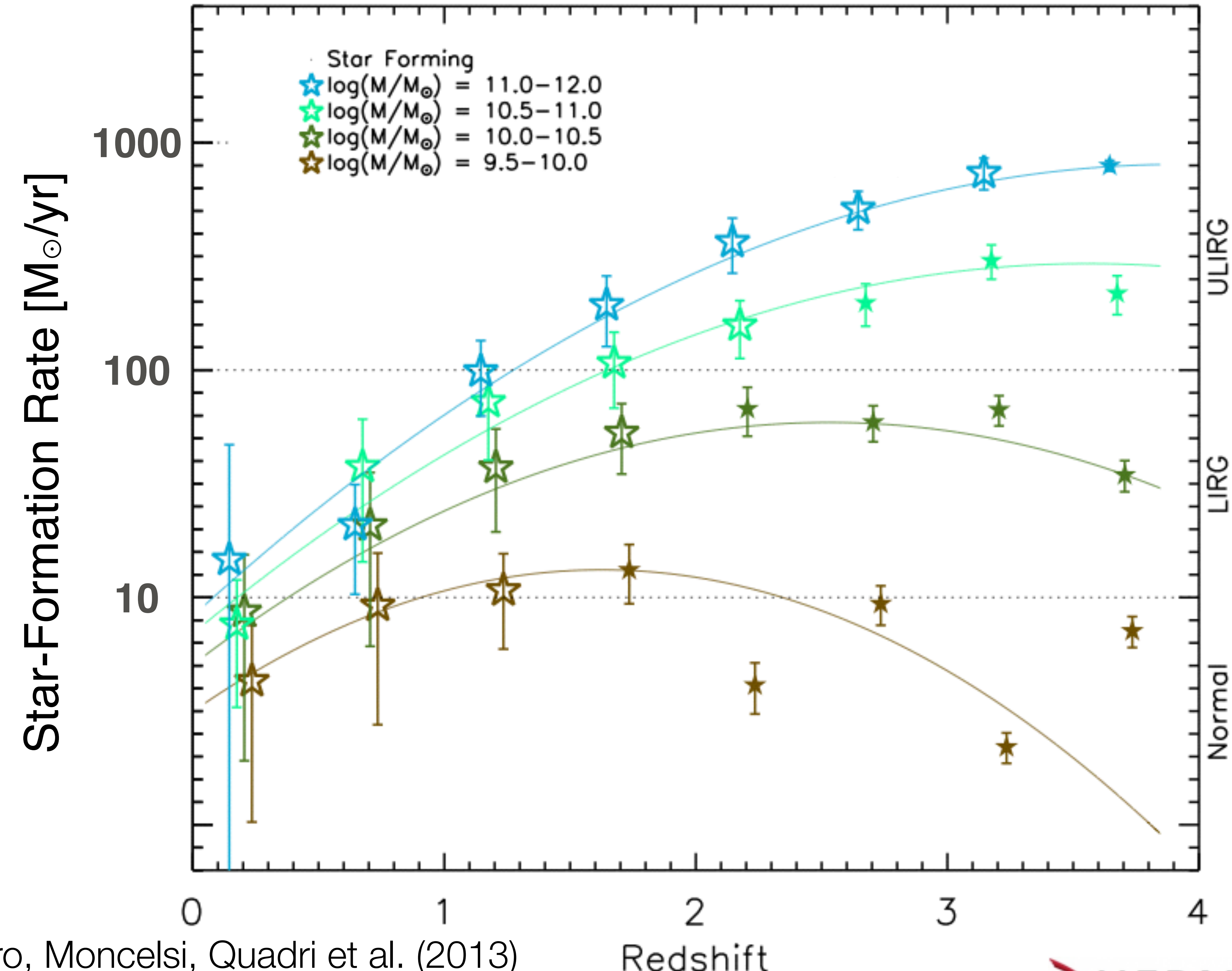
Average Galaxy Infrared Luminosity by Stellar Mass and Redshift



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

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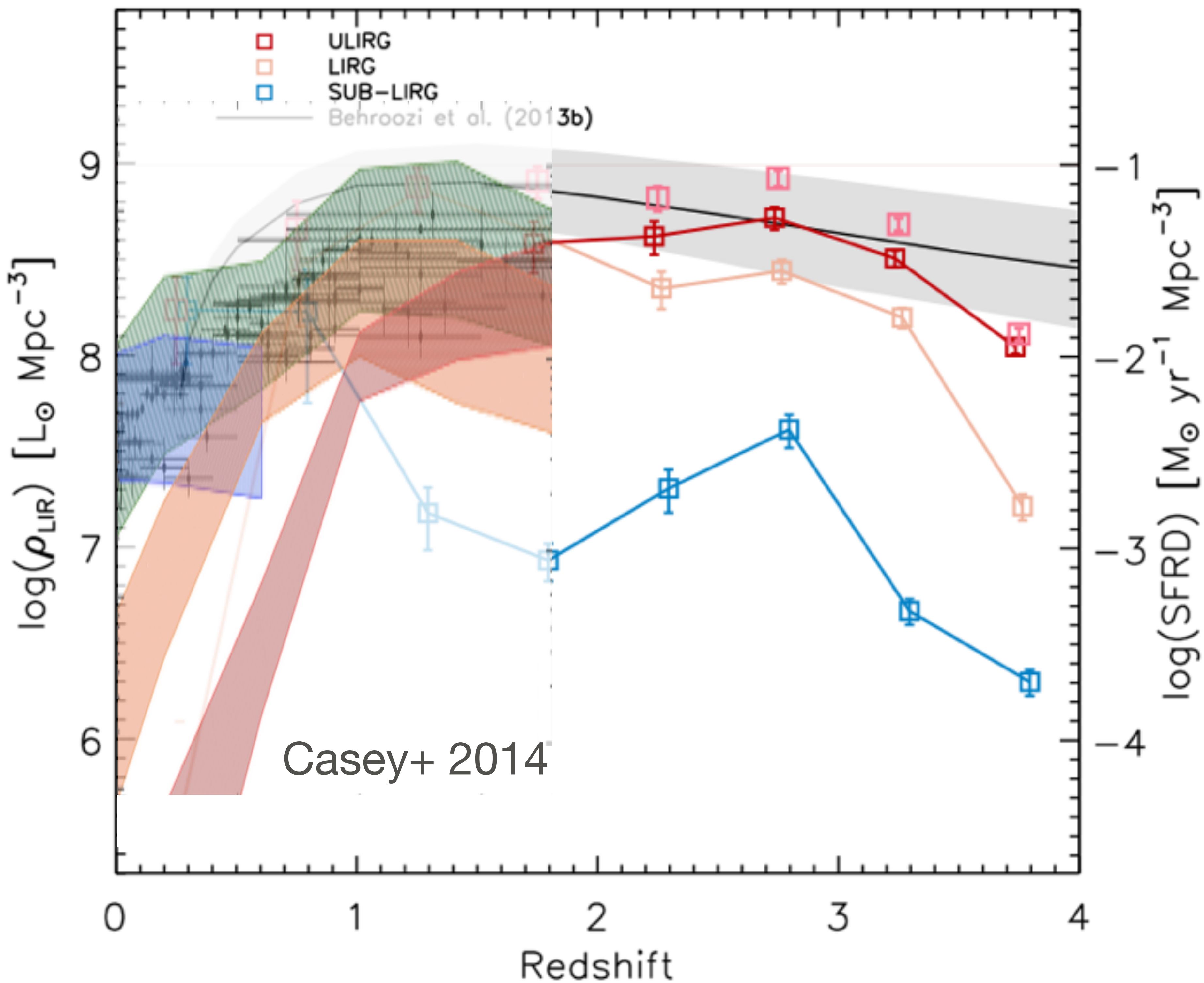
Stacked Infrared Luminosity Density



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

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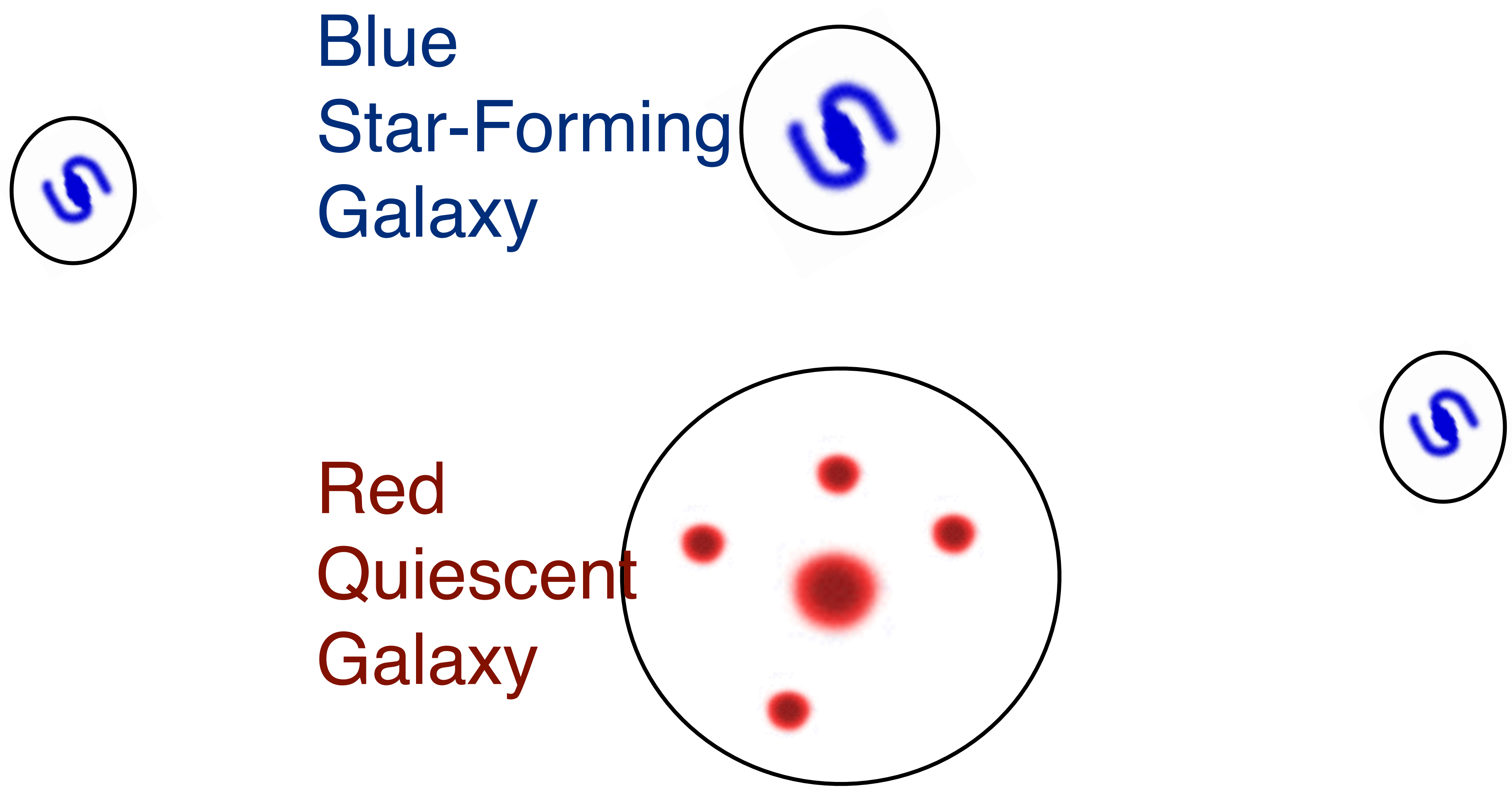
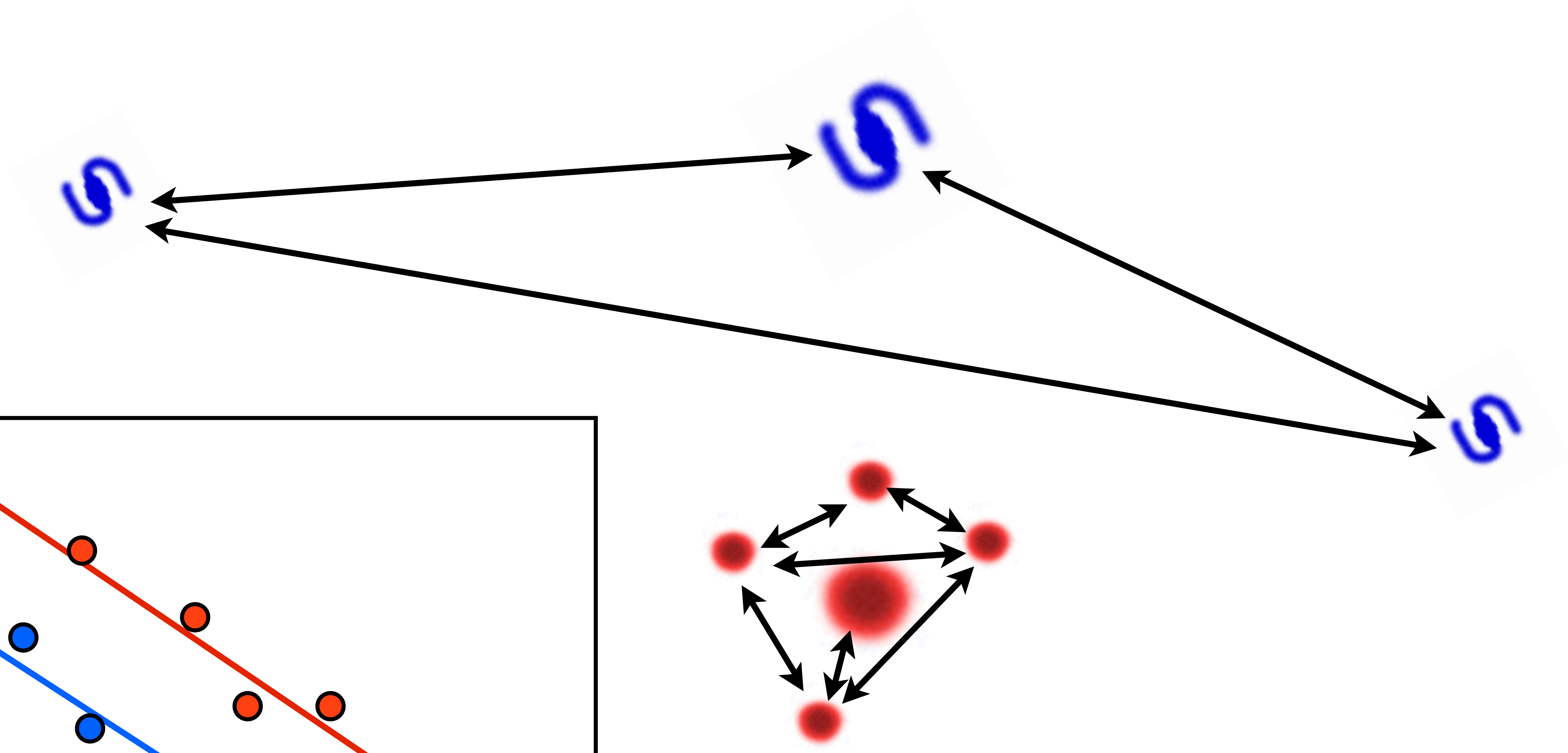
Motivation Recap

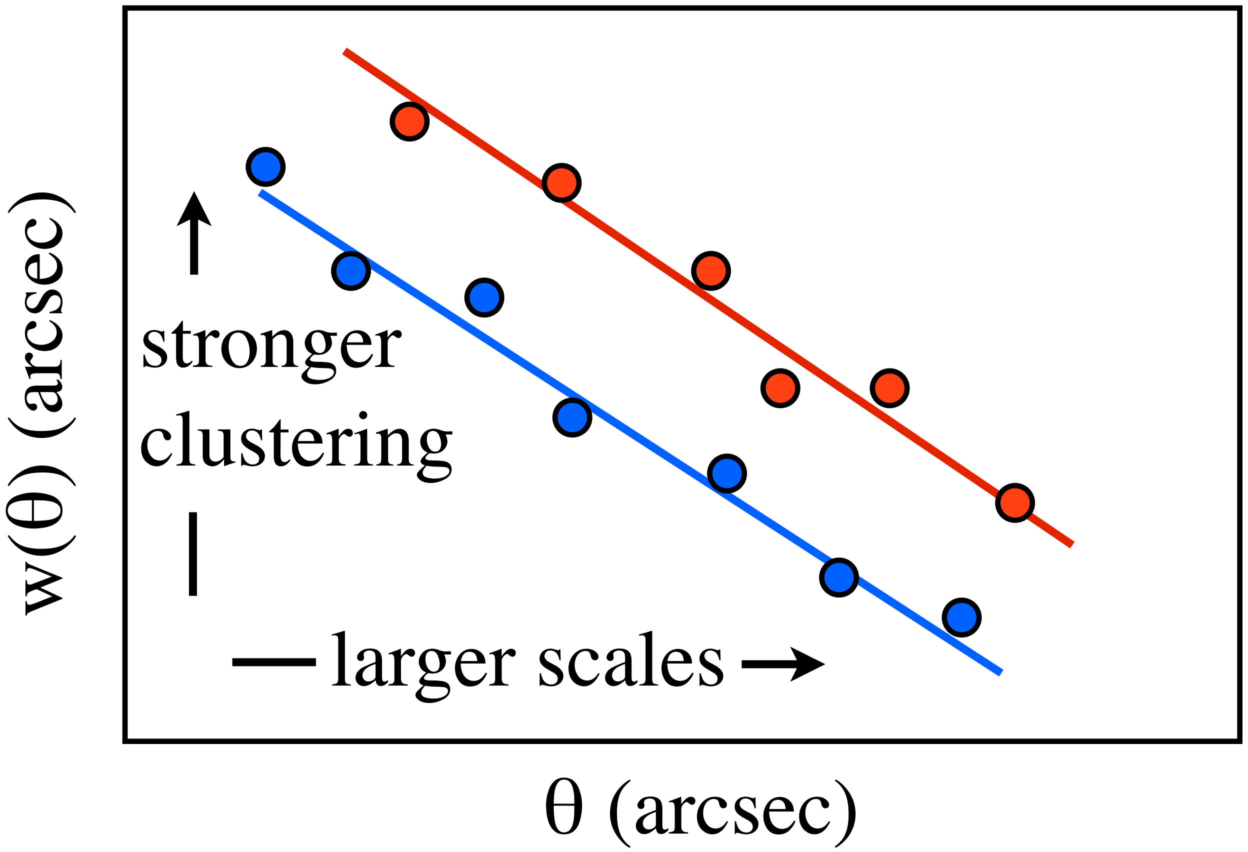
1. Origin of the CIB
2. History of Cosmic Star Formation
3. Growth of Stellar Mass

Galaxy Clustering and the Correlation Function

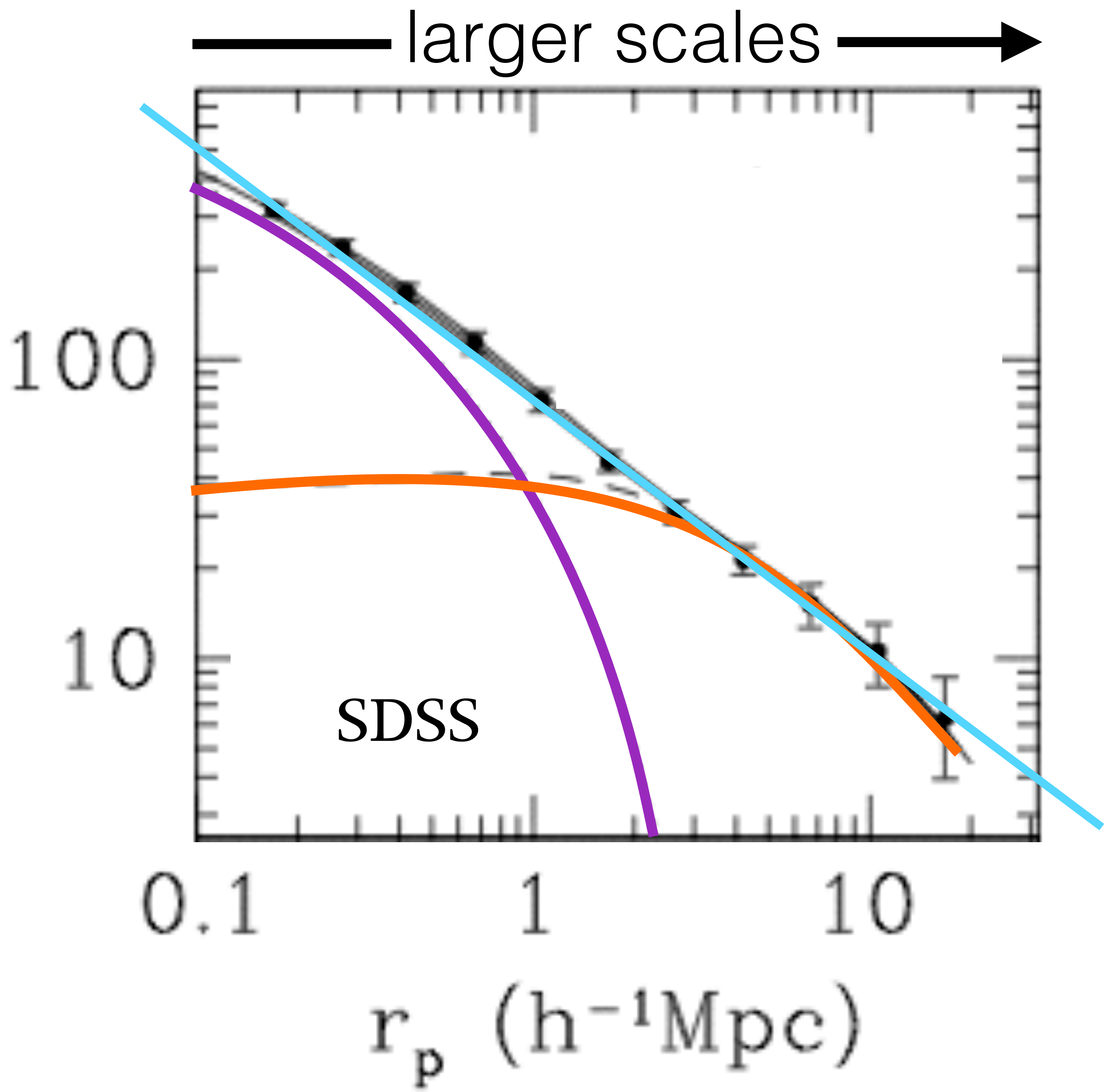


Galaxy Clustering and the Correlation Function

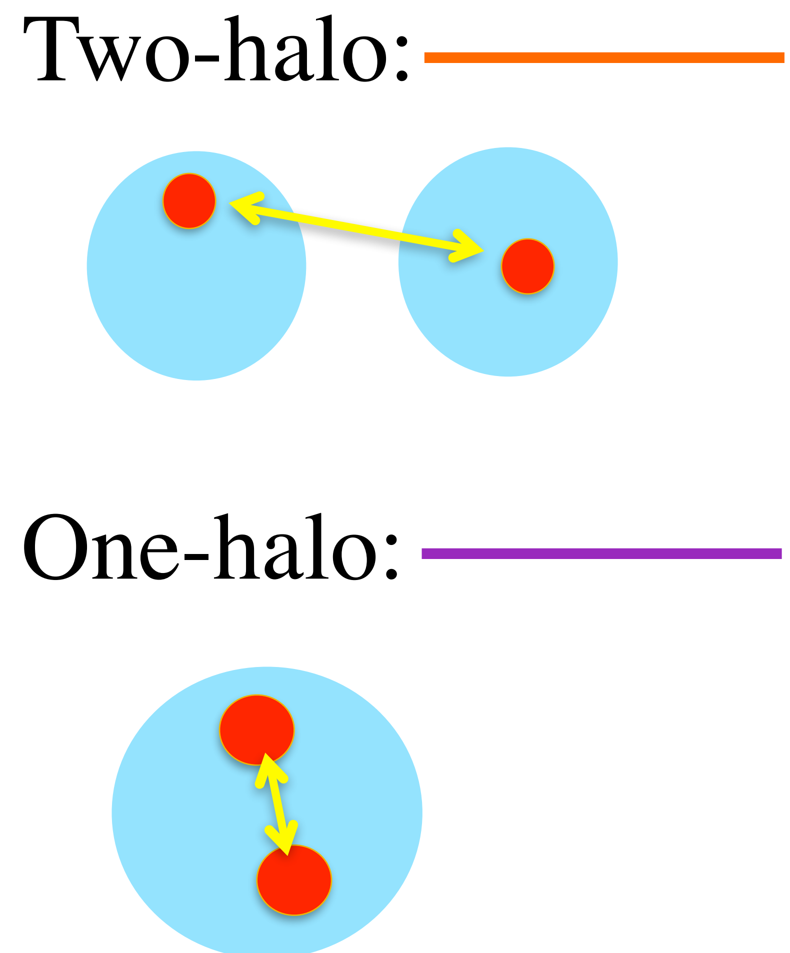




Galaxy Clustering and the Correlation Function

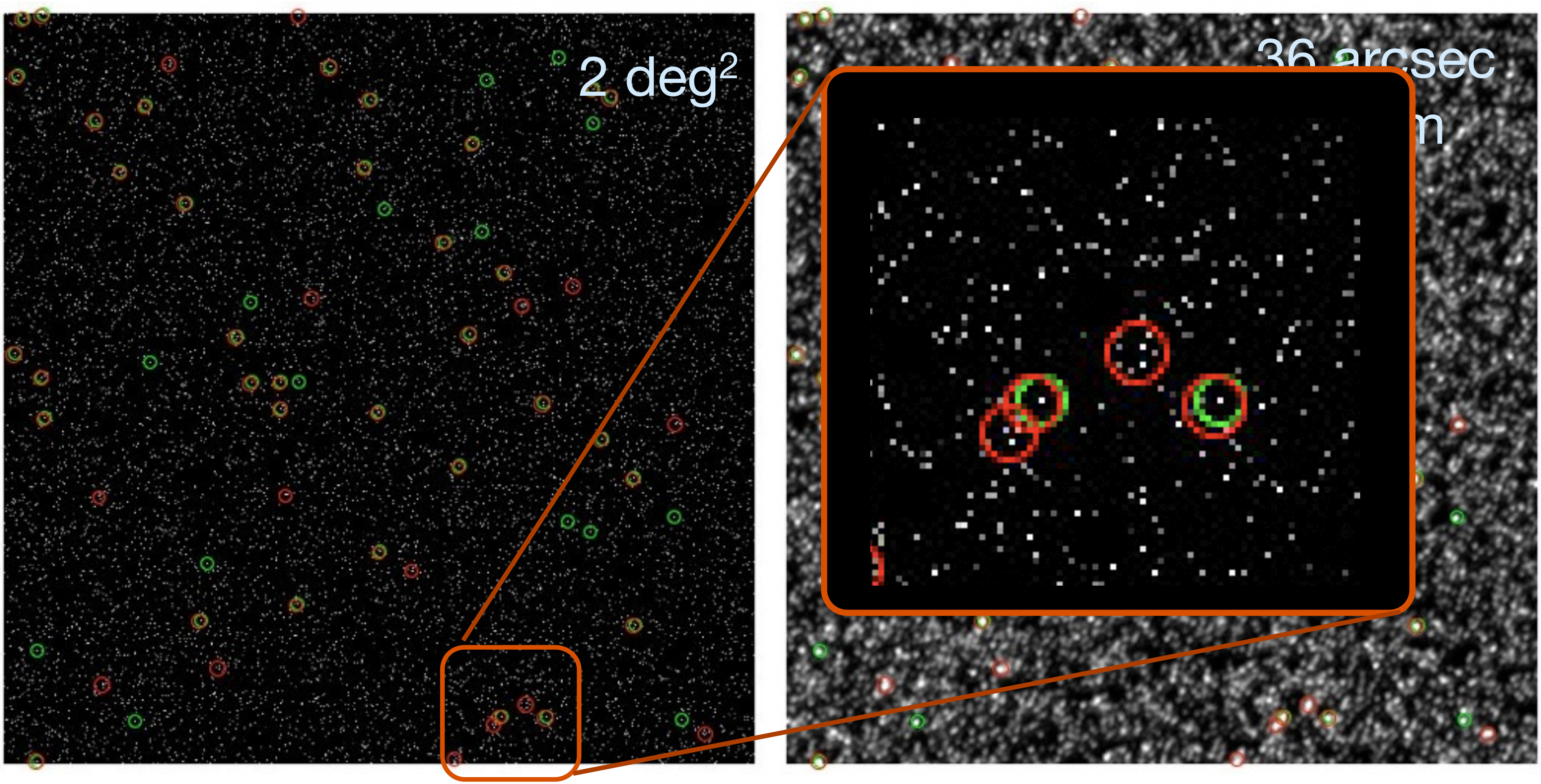


Zheng (2007)



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

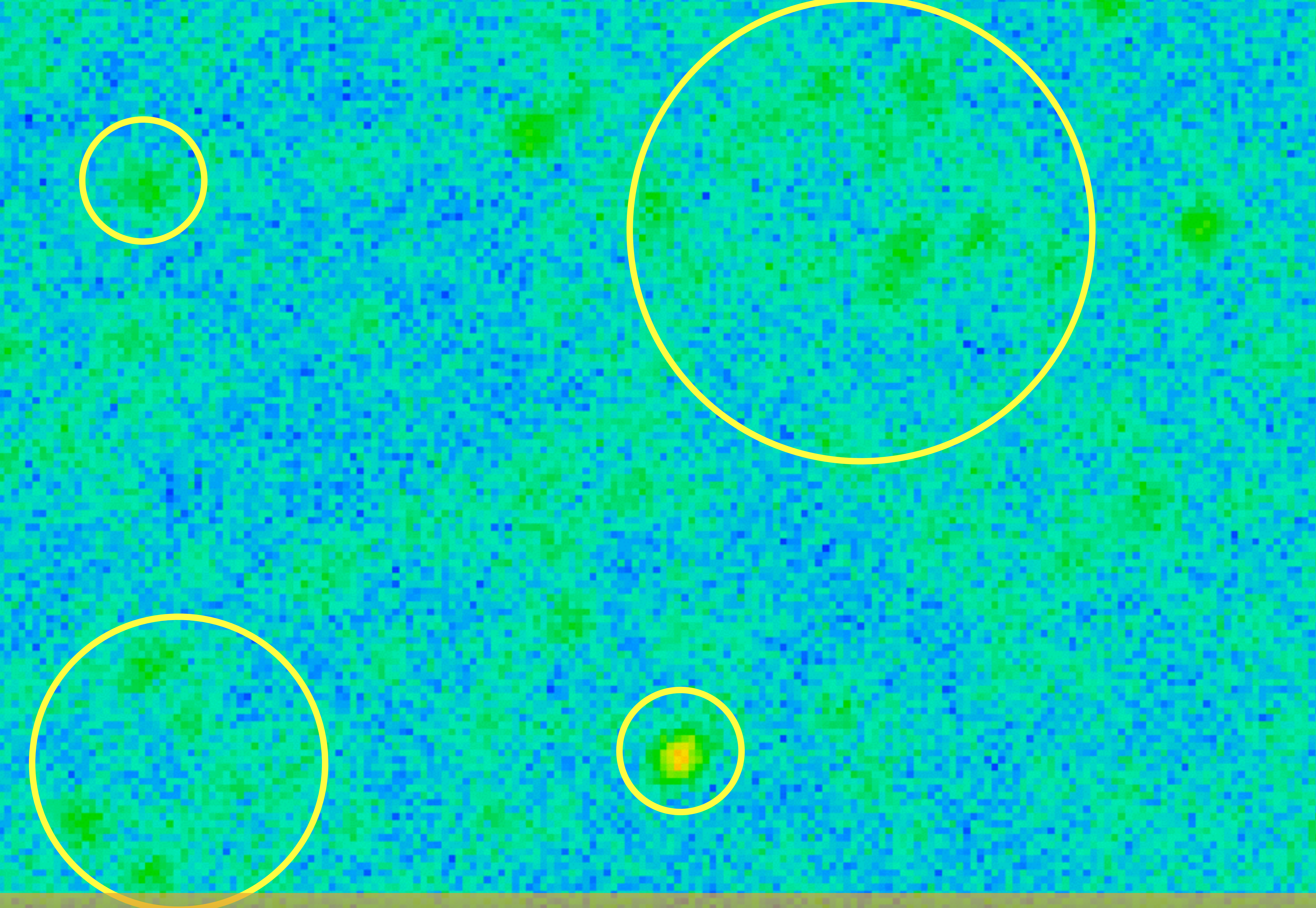
Galaxy Clustering and the Correlation Function



50 brightest placed

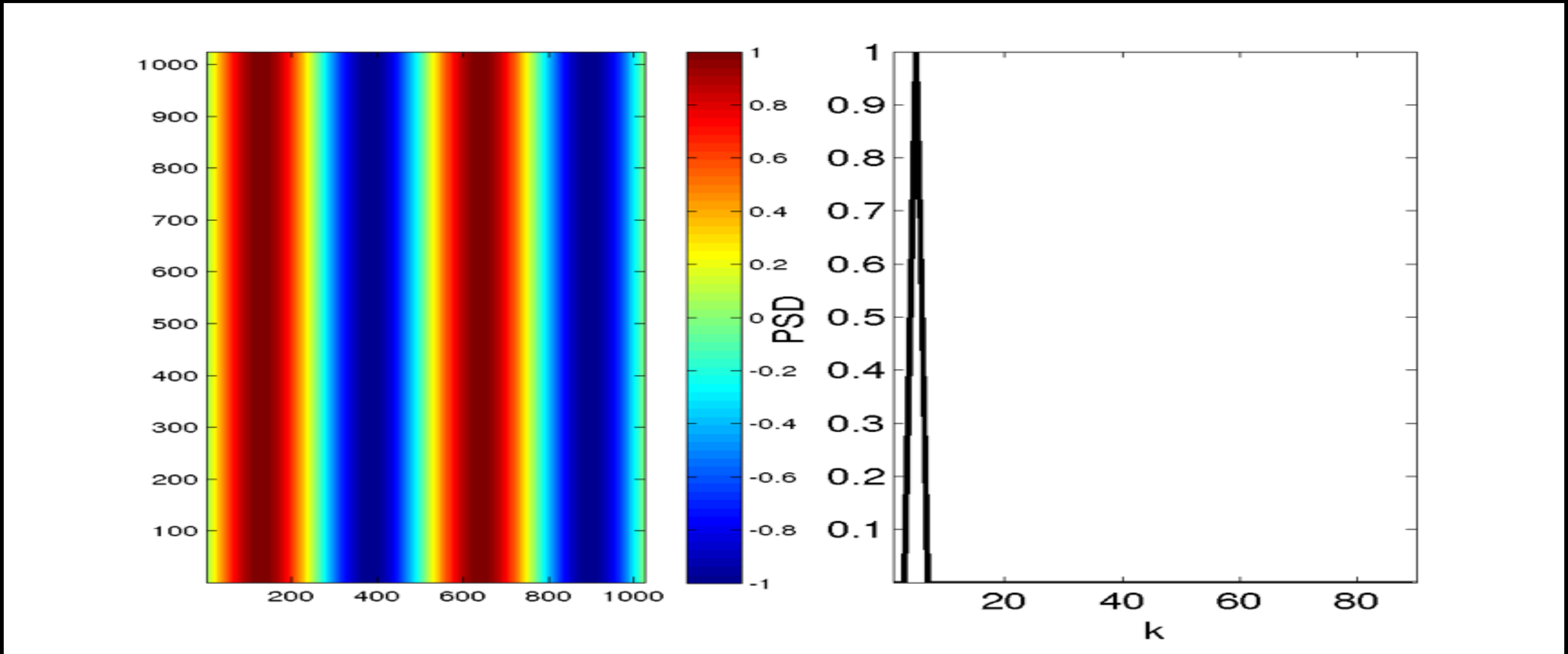
70% of the brightest recovered

50 brightest recovered



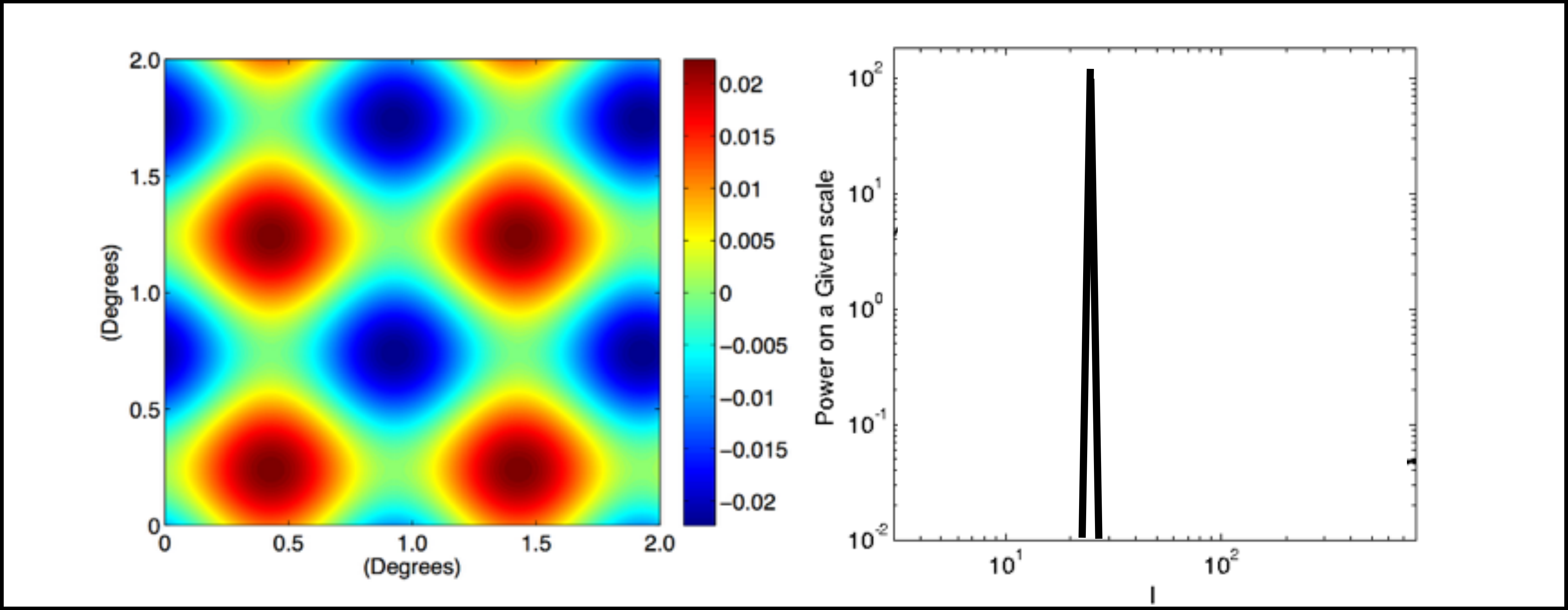
Power Spectrum of Background Fluctuations

Power Spectrum



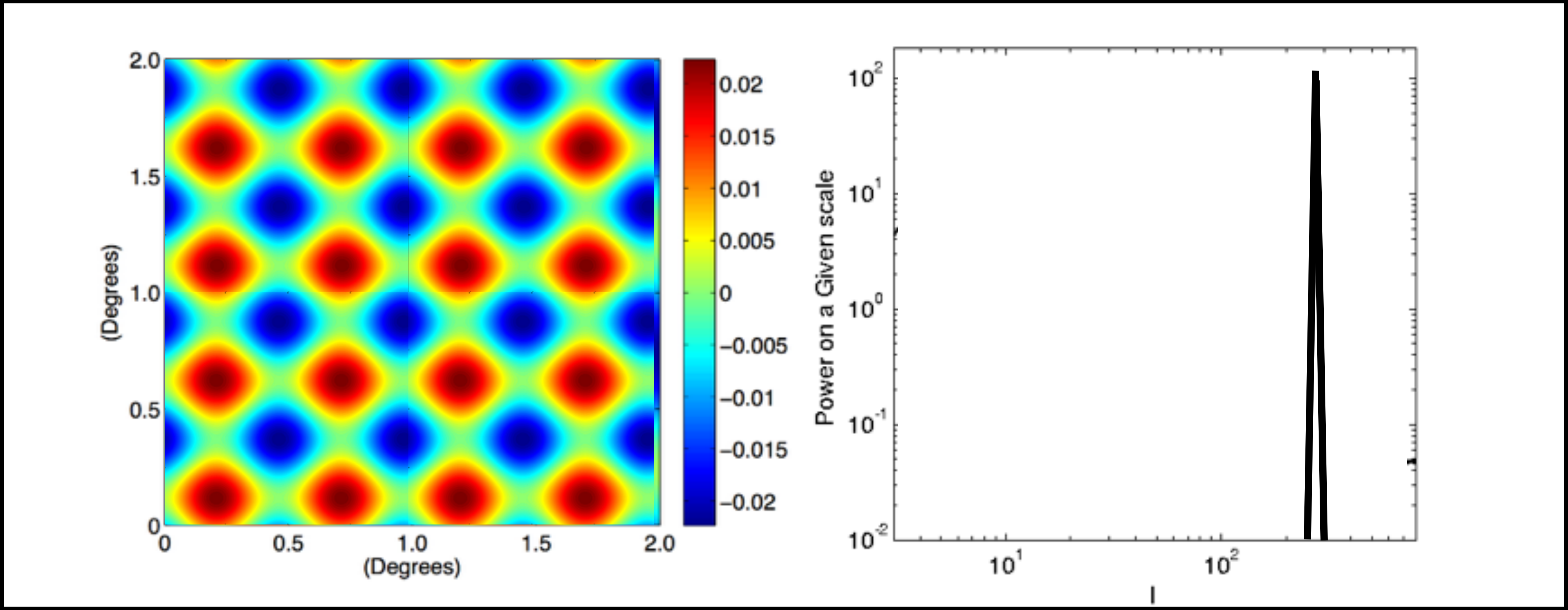
Phil Korngut (Caltech)

Power Spectrum



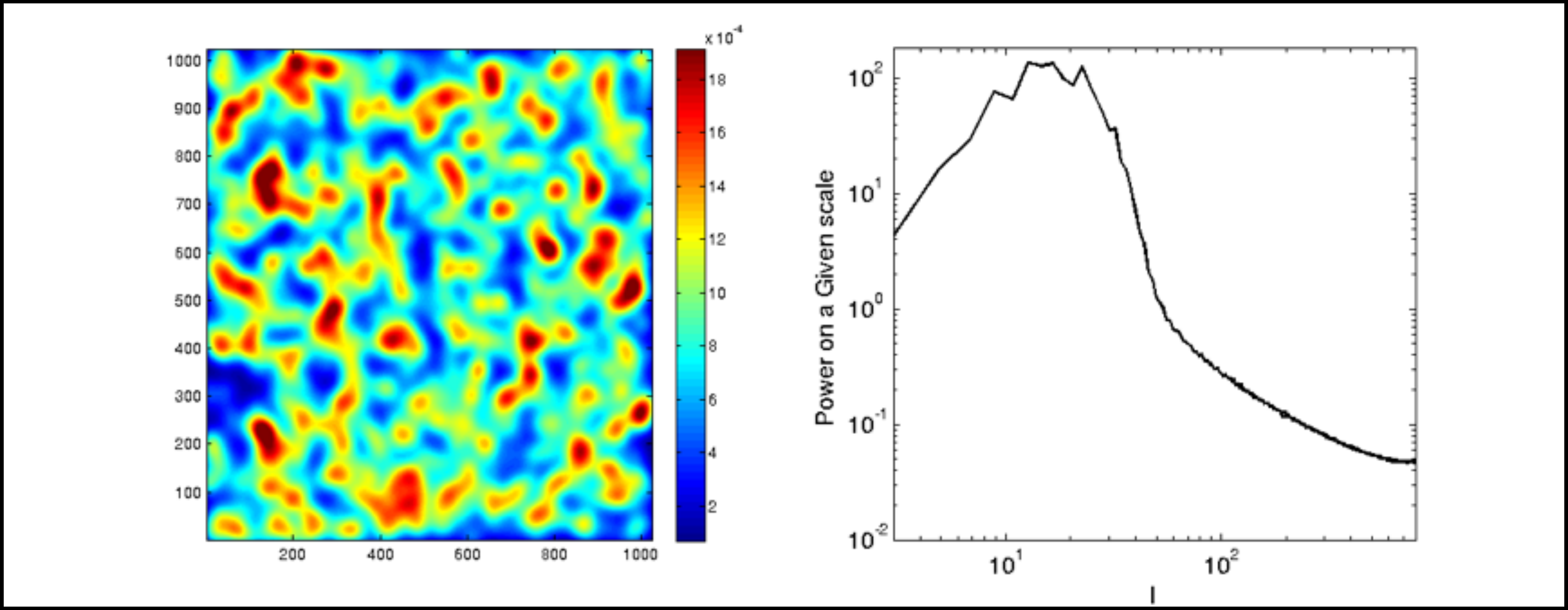
Phil Korngut (Caltech)

Power Spectrum



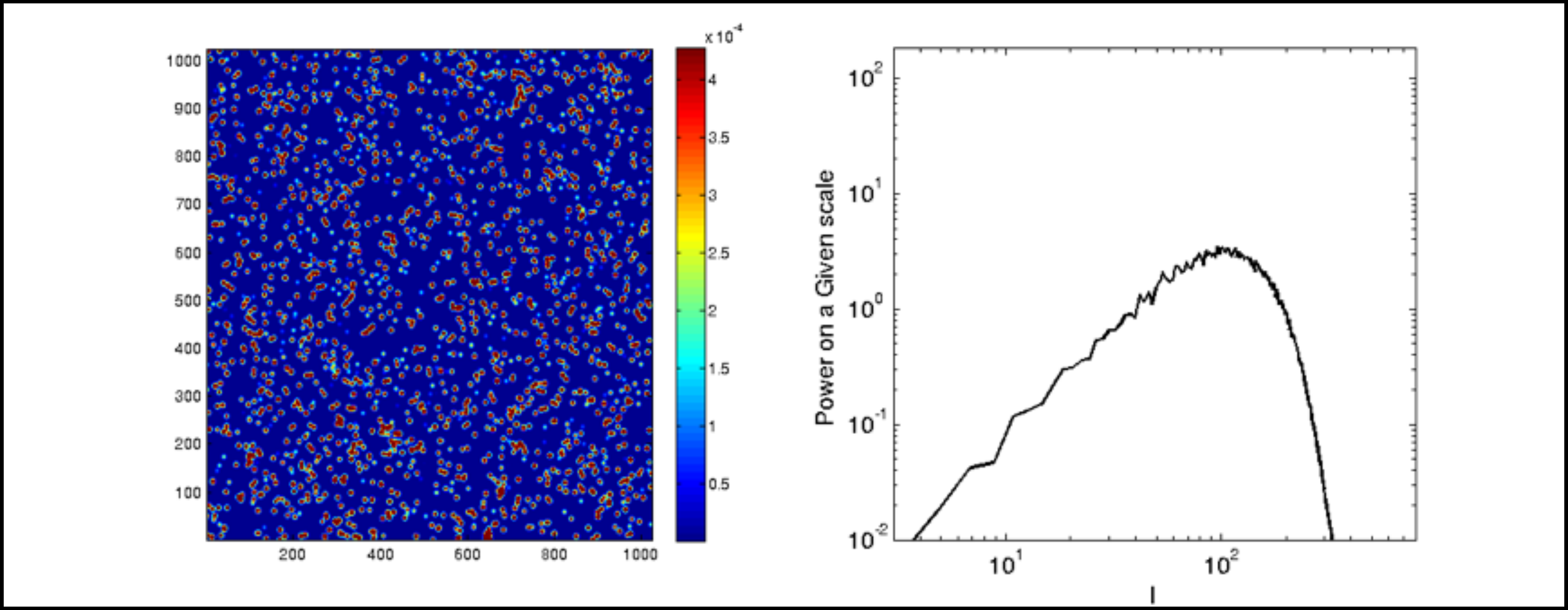
Phil Korngut (Caltech)

Power Spectrum



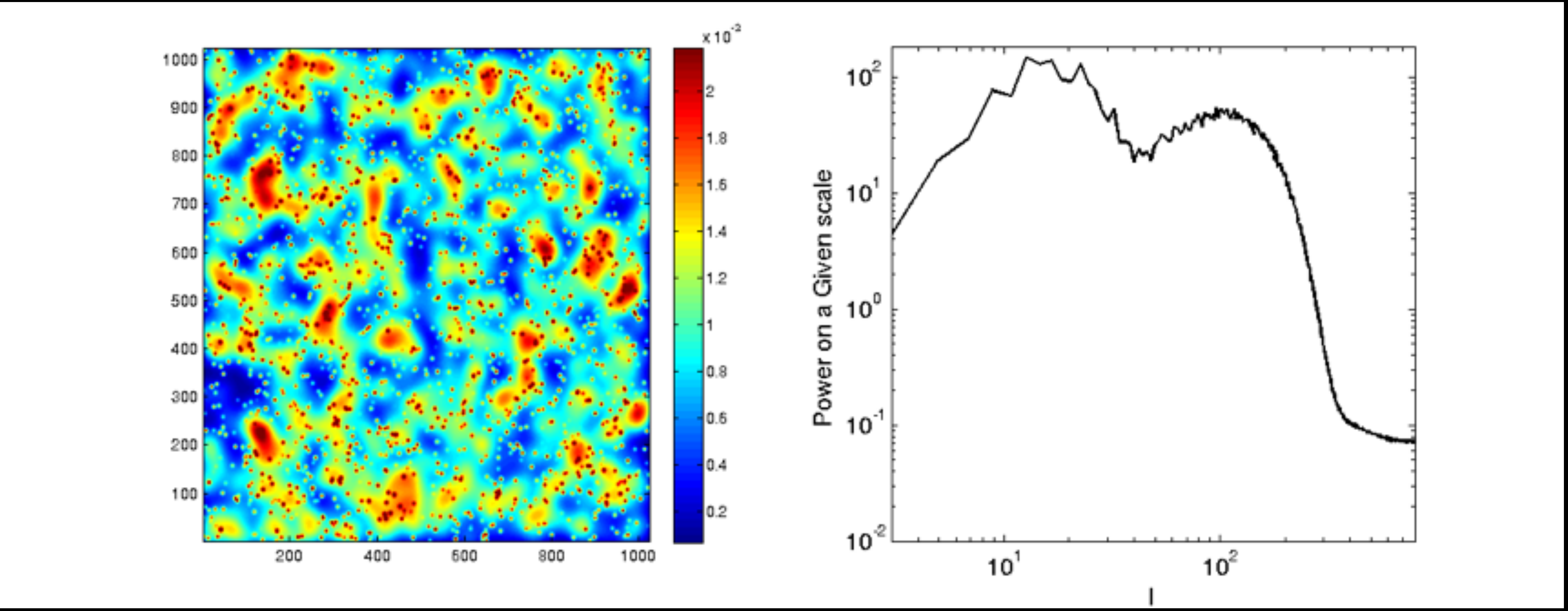
Phil Korngut (Caltech)

Power Spectrum



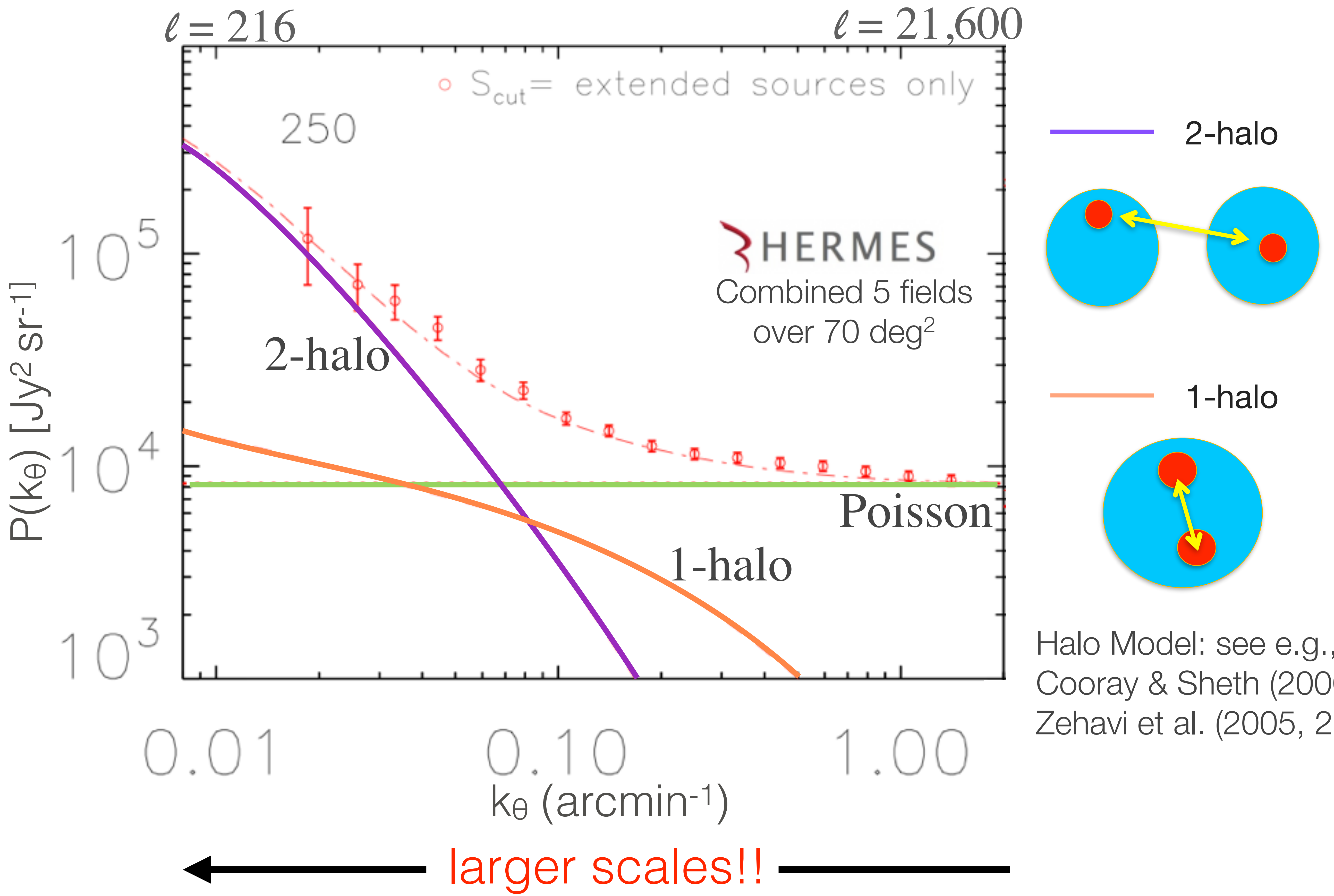
Phil Korngut (Caltech)

Power Spectrum



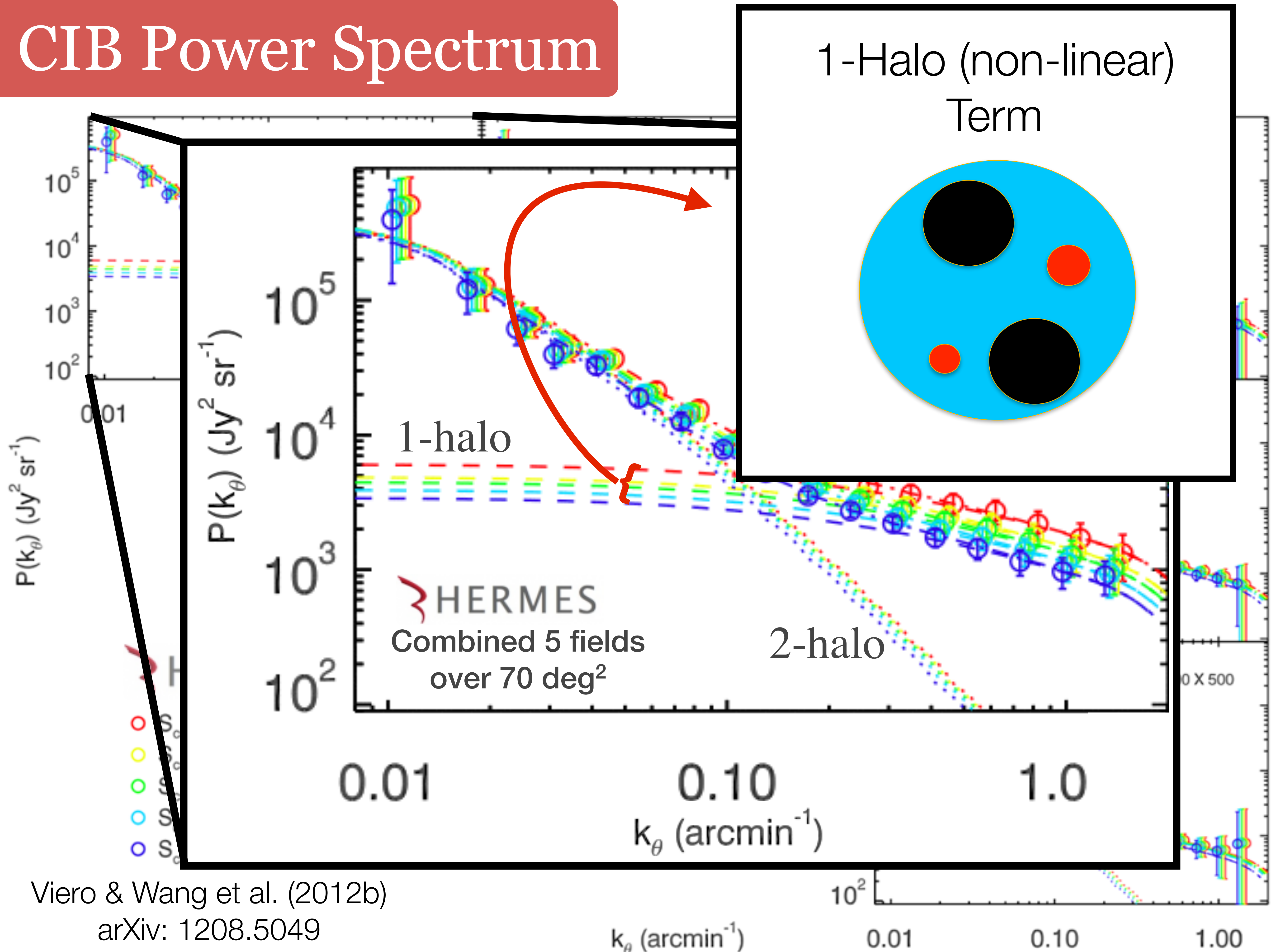
Phil Korngut (Caltech)

CIB Power Spectrum



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

CIB Power Spectrum



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

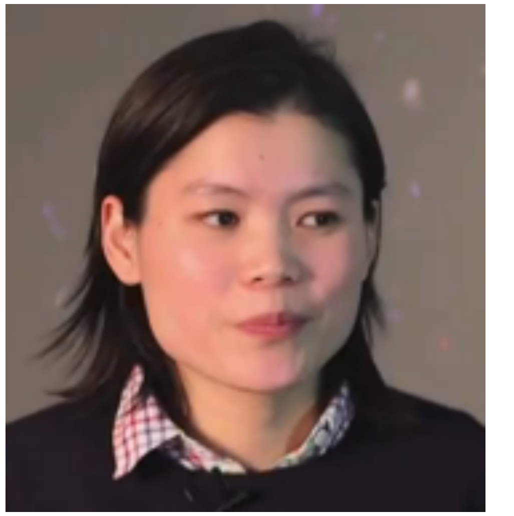
Motivation Recap

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

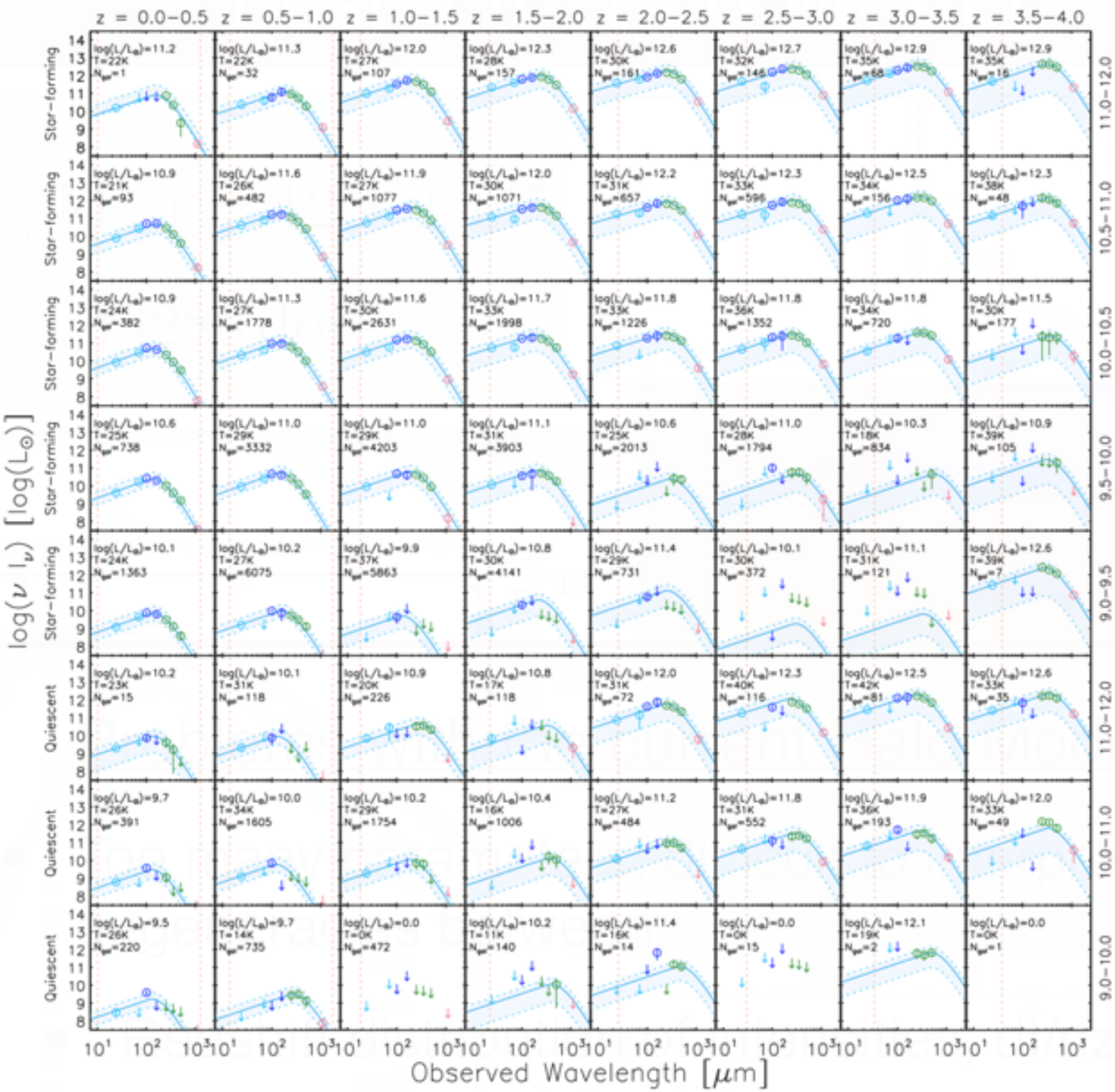
Halo Model (in a Nutshell)

- 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)



Stacking Results Can Help!

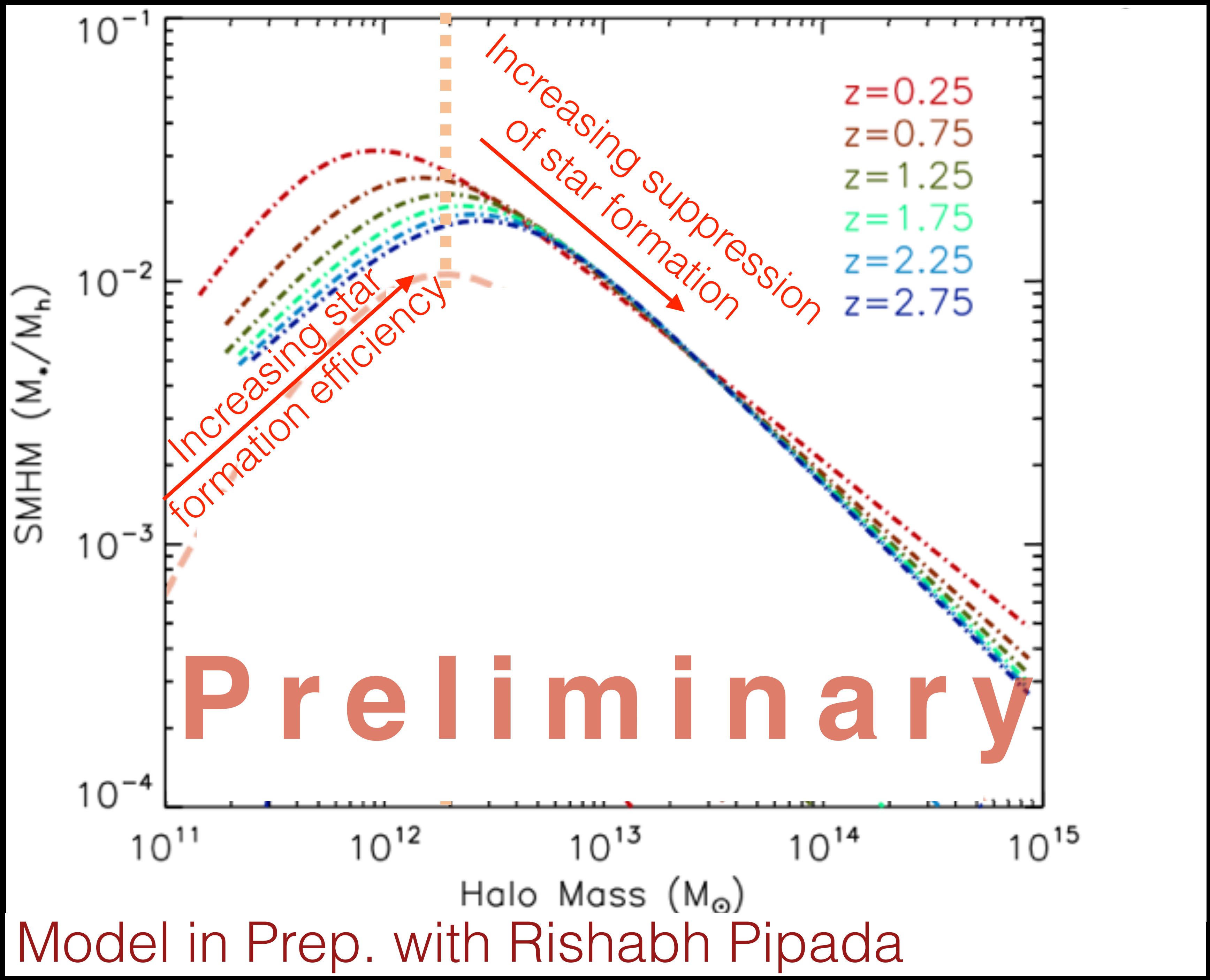


Abundance-matching model
with Rishabh Pipada in prep.

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

Connecting SF to Stellar and Halo Mass

Can we combine **stacked infrared luminosities** and **clustering measurements** to understand the role of environment in the growth of stellar mass?



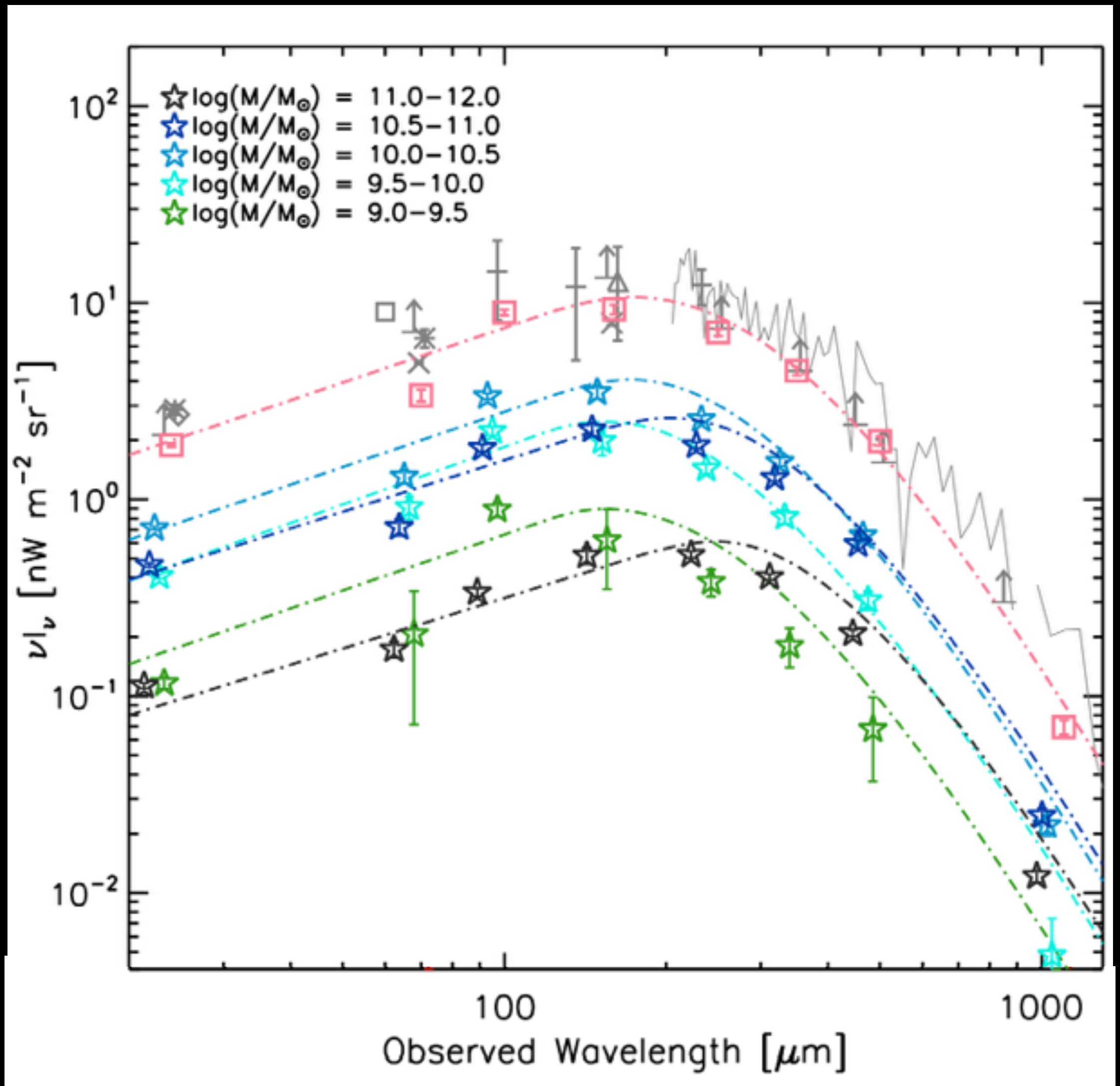
SM-HM Function from Moster+(2012)

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

Summary

1. 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…
- i.e., at or below M*, **not** what comes to mind when you think *submillimeter galaxy*

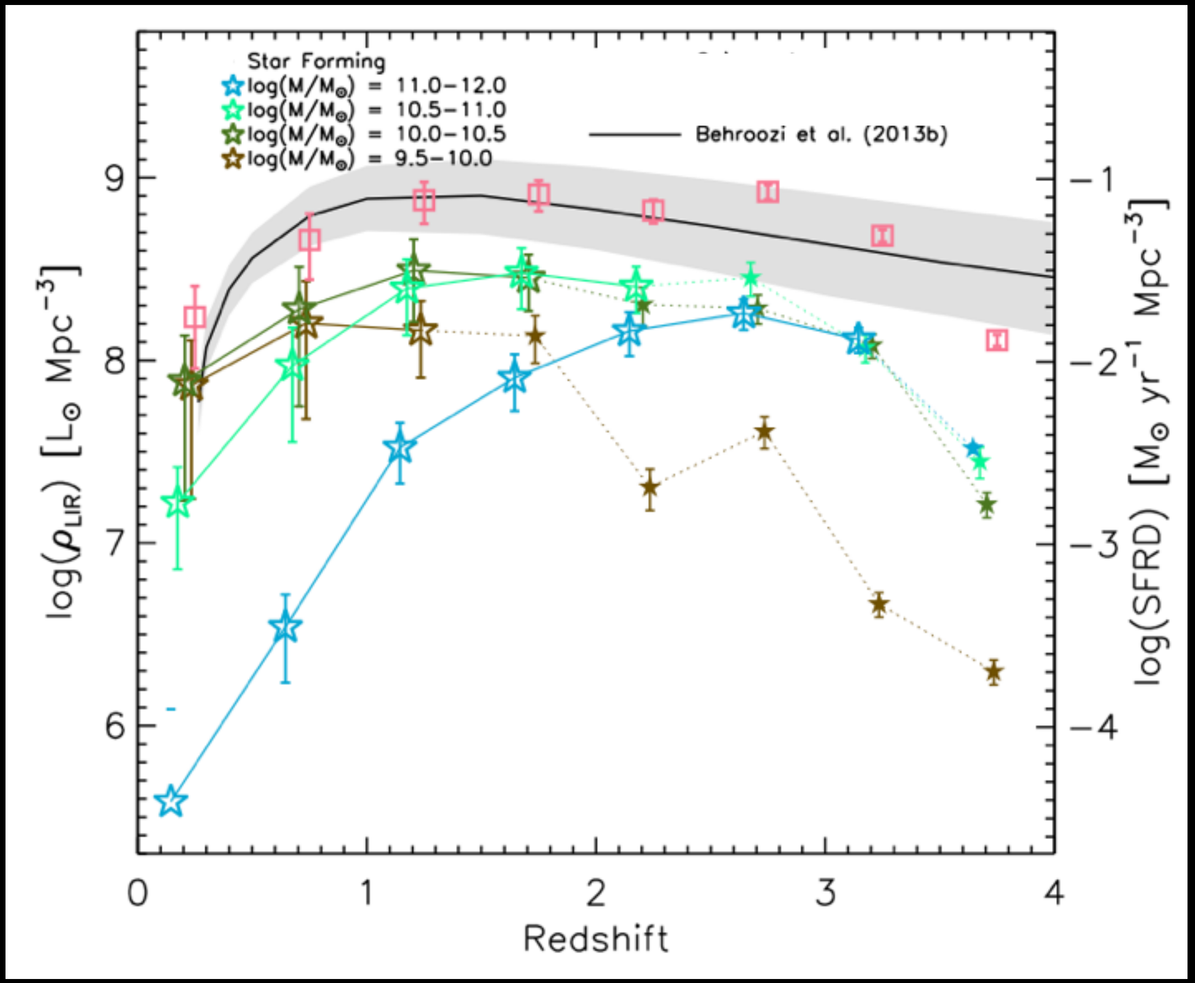


Summary

2. History of Cosmic Star Formation

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

- Star formation is dominated by galaxies with $\log(M_*/M_\odot)$ =
  - ⋆ < 10 at z < 1
  - ⋆ 10-11 at z ≈ 1-2
  - ⋆ > 11 at z > 2

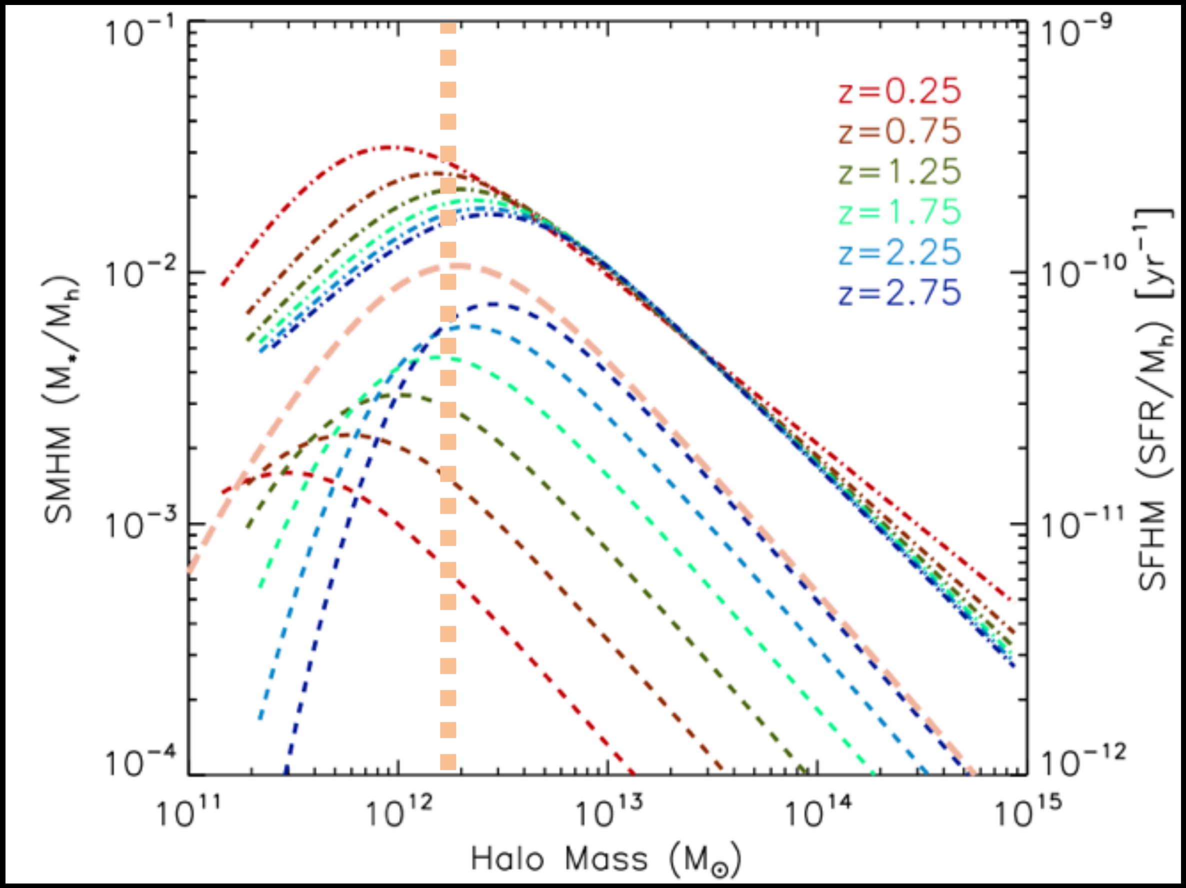


Summary

3. Growth of Stellar Mass

- Halo mass of most efficient star-formation is around
  $\log(M/M_\odot)=12.1\pm0.5$

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

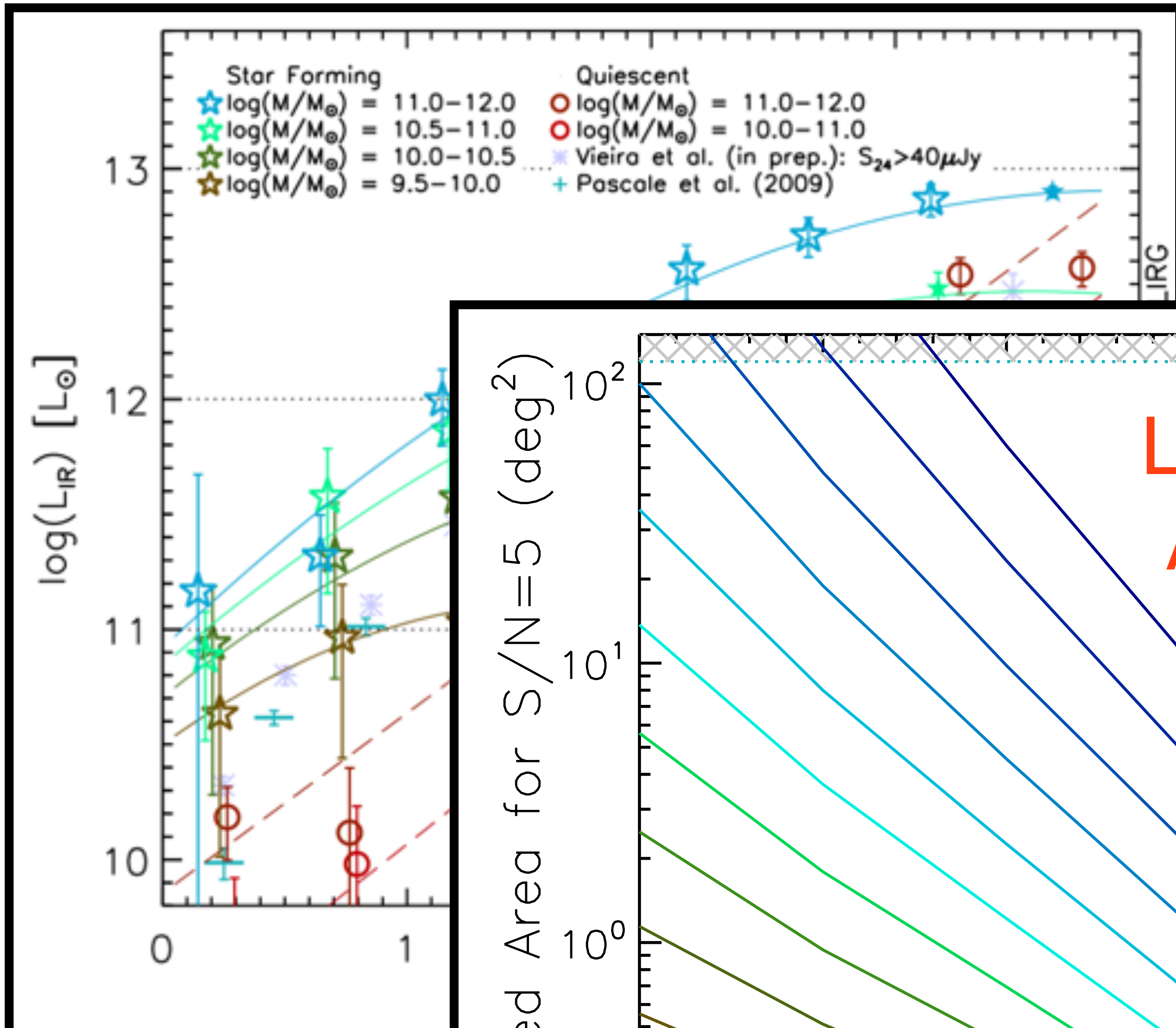


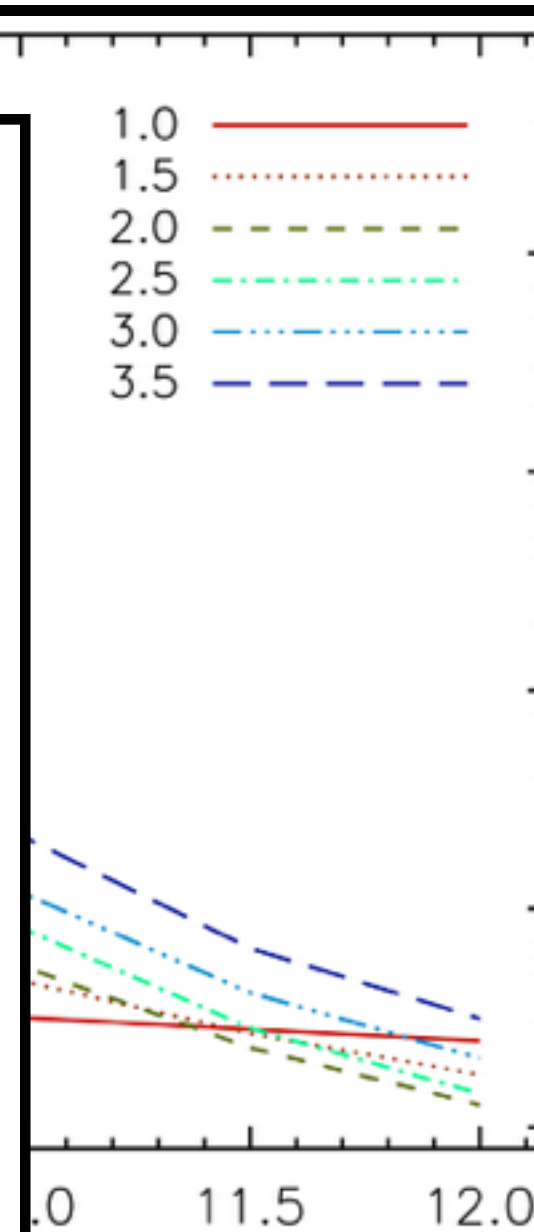
Summary

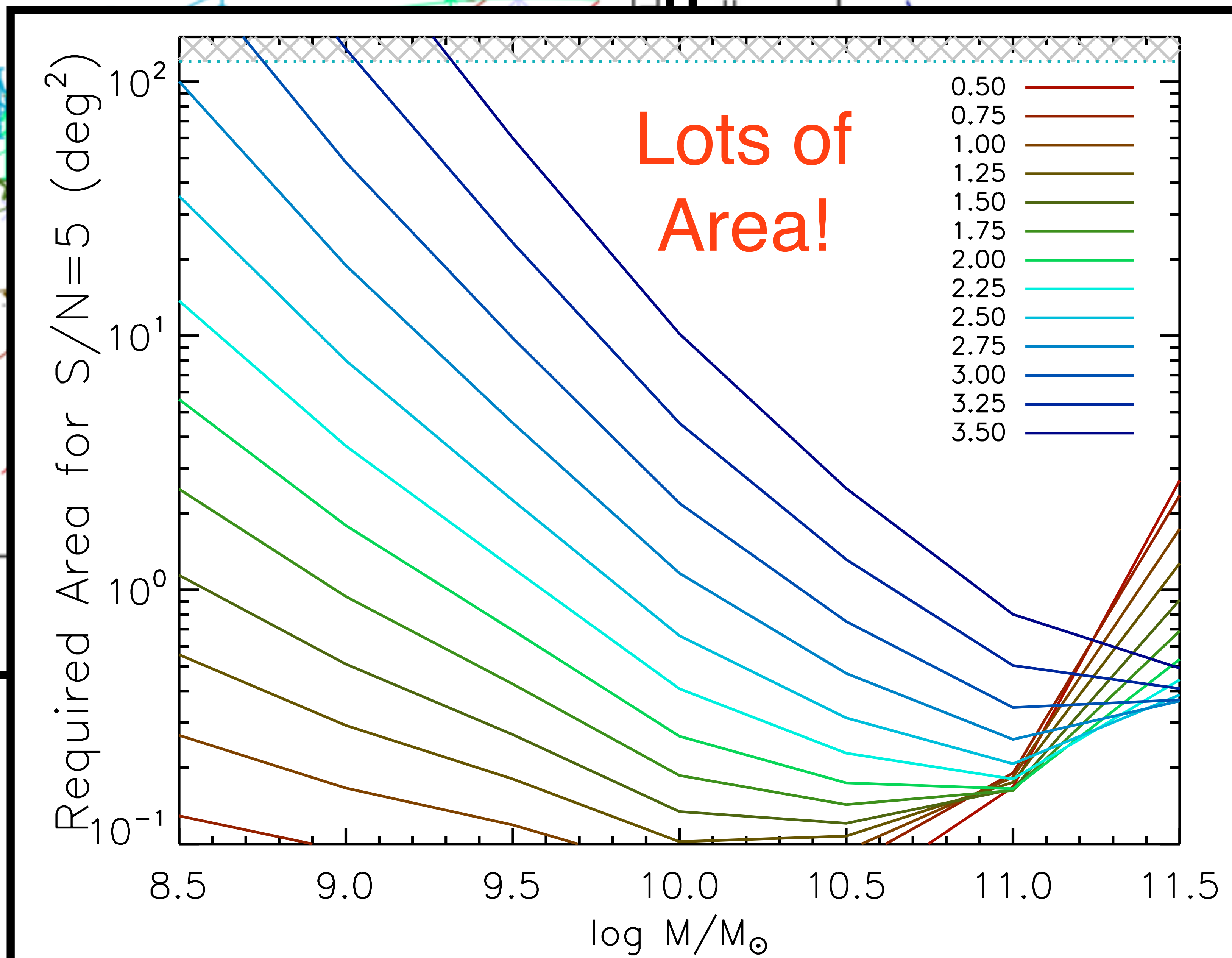
- Origin of the CIB
  - At least 70% of the CIB originates from known optical galaxies.
  - Most of that comes from galaxies with stellar mass $\log(M/M_{\odot})=10\text{-}11$, i.e., at or below M_*
- History of Cosmic Star Formation
  - Star formation is dominated by lower mass galaxies locally, LIRGs with $\log(M/M_{\odot})=10\text{-}11$ between z=1-2, and ULIRGS with $\log(M/M_{\odot})>11$ at higher z .
- Growth of Stellar Mass
  - Halo mass of most efficient star-formation is $\log(M/M_{\odot})=12.1\pm0.5$.
  - Models to understand the growth of stellar mass and regulation of that growth are underway.

Moving Forward

Lots of sources to probe small masses

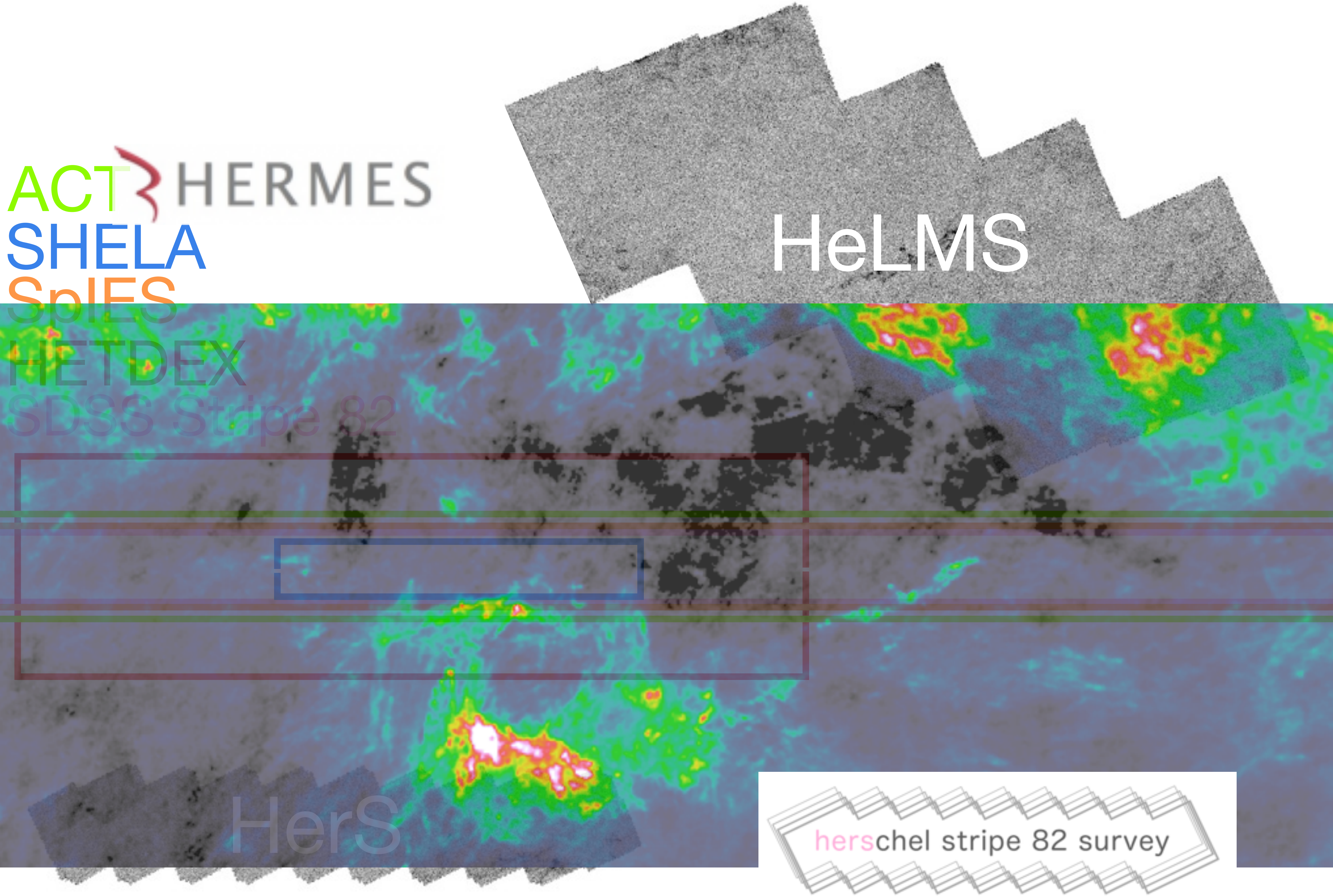


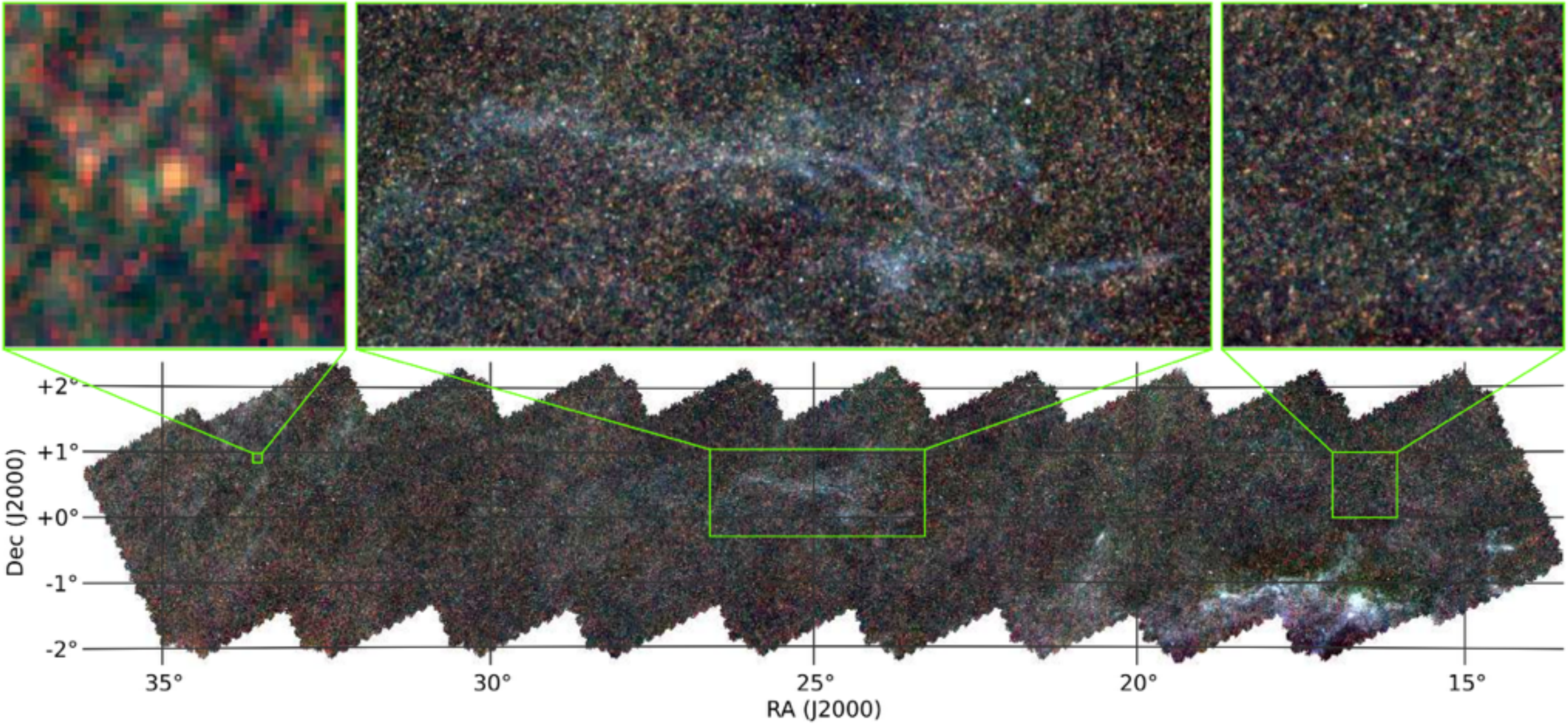




L-M*-z

estimated using mass function of Muzzin et al. 2013


ACT
HERMES
SHELA
SpIES
HETDEX
SDSS Stripe 82
HeLMS
HerS
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.

herschel stripe 82 survey

HERMES

Viero+ 2014
arXiv:1308.4399

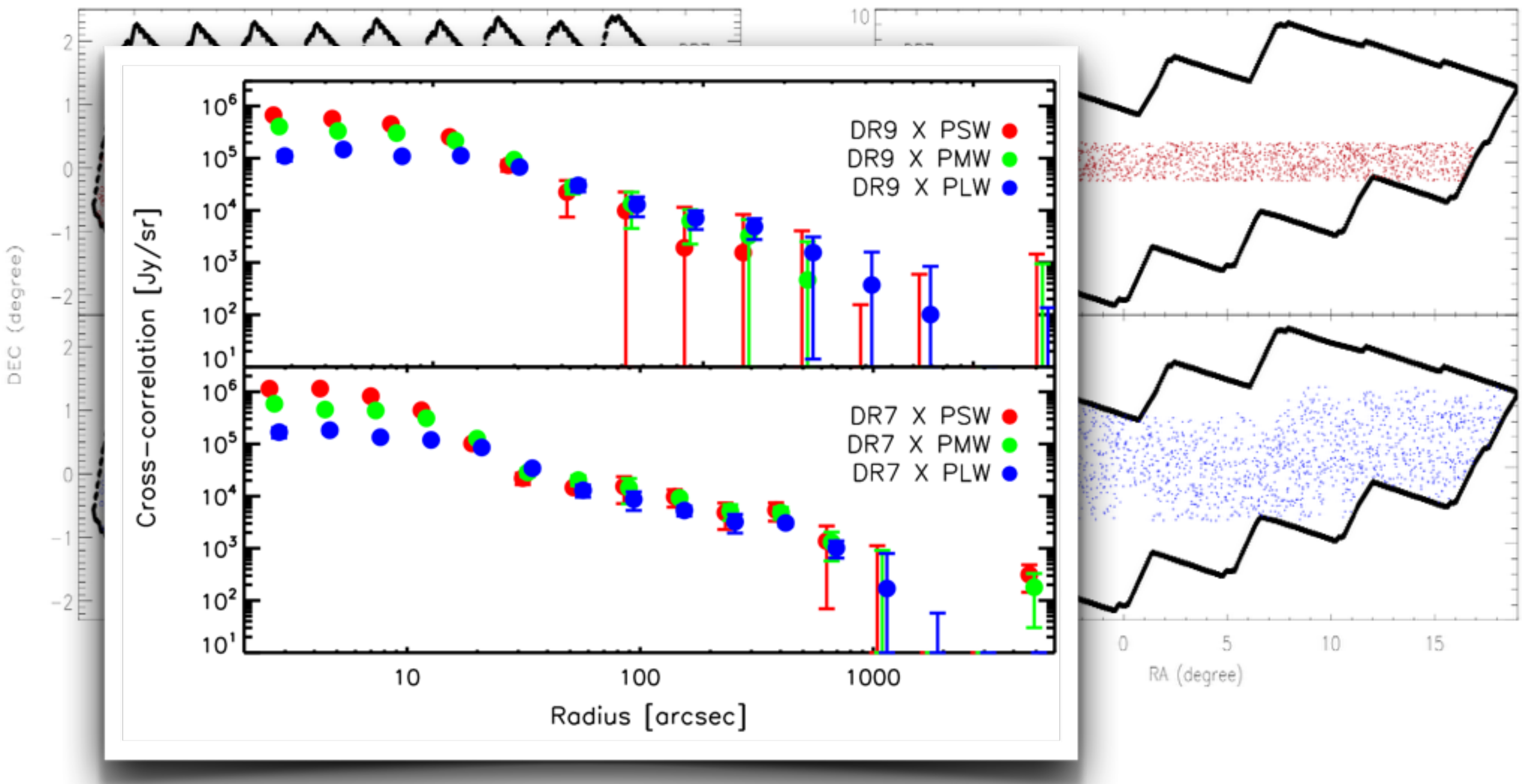
Oliver+ 2012
arXiv:1203.2562

Find Maps/Catalogs at:

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

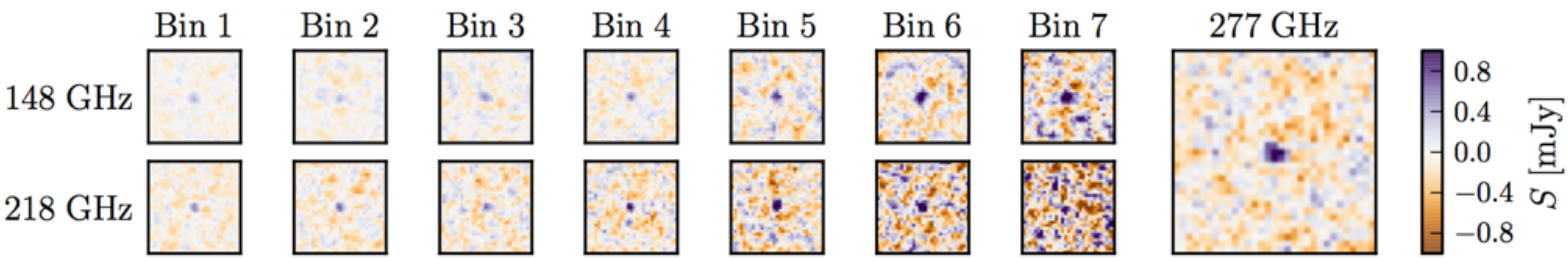
(coming in June) http://hedam.lam.fr/HerMES/

X-Correlations w/ SDSS QSOs



Wang et al. (in prep.)

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

herschel stripe 82 survey

HERMES

Viero+ 2014
arXiv:1308.4399

Oliver+ 2012
arXiv:1203.2562

Find Maps/Catalogs at:

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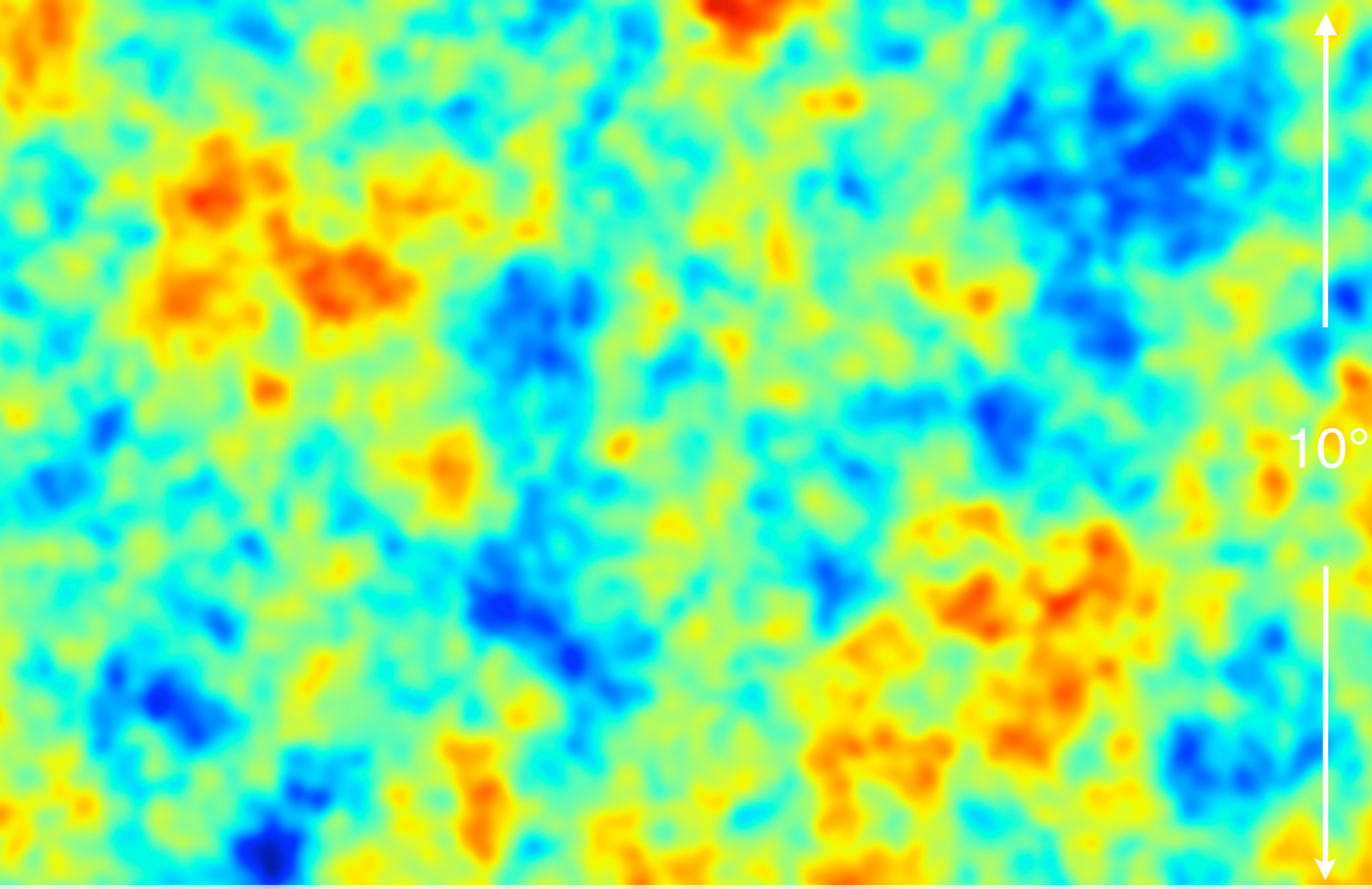
More Fun with Cross Correlations! (time permitting!)

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

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

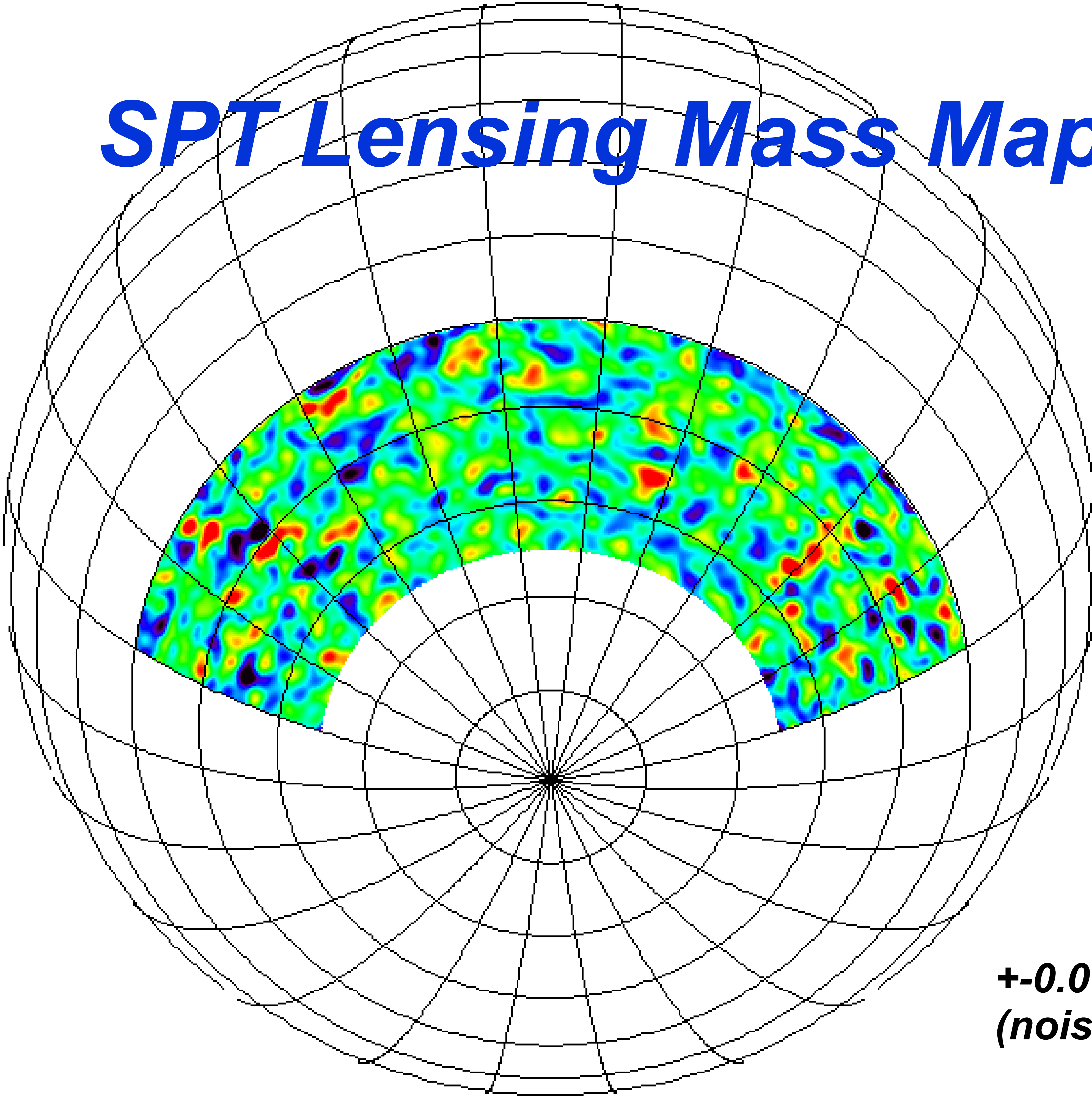
The CIB traces dark matter, thus should correlate with lensing, as traced by:

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



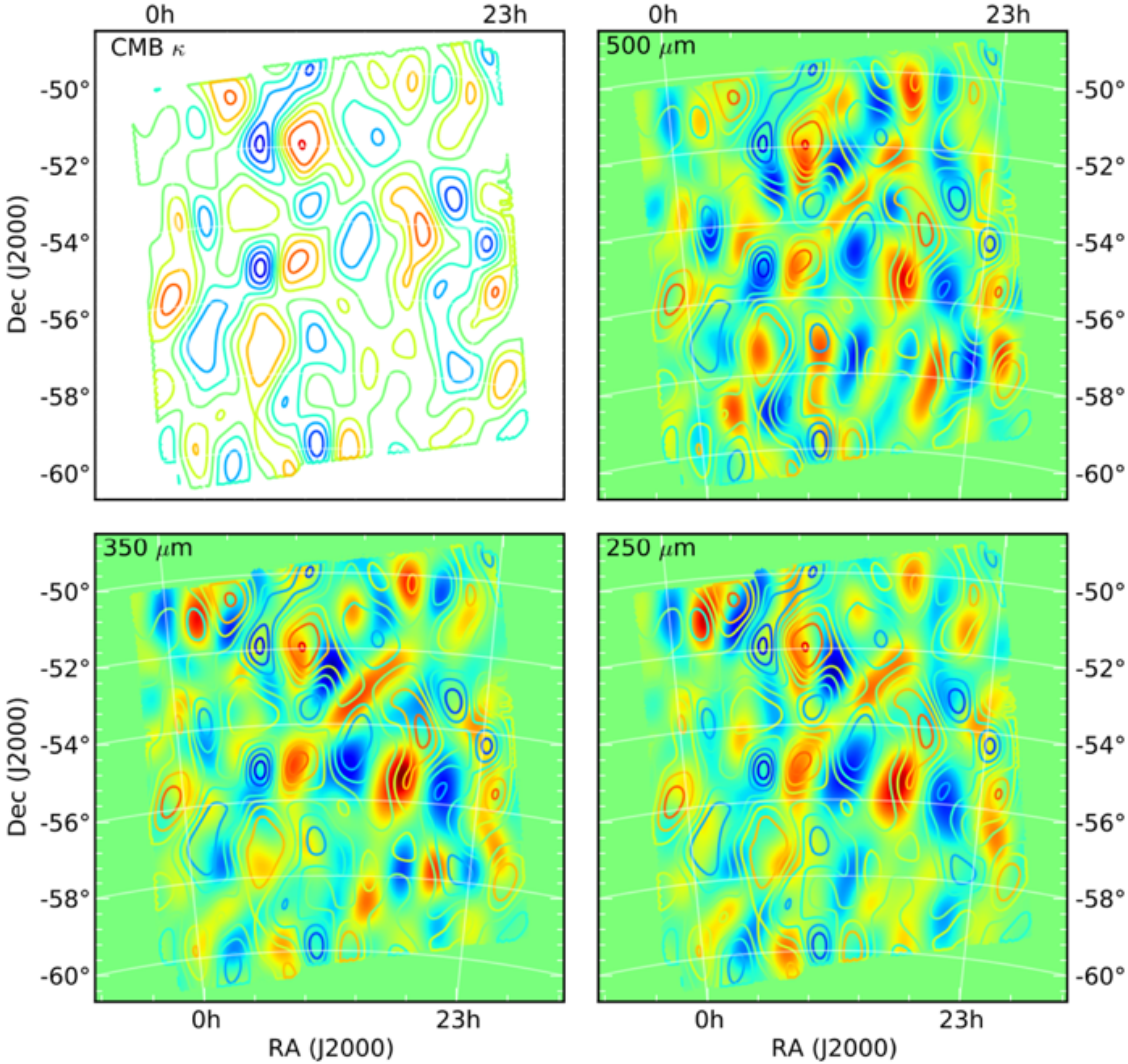
Cross-Correlations with CMB Lensing

SPT Lensing Mass Map



+-0.05 color bar
(noise ~0.01)

SPT X SPIRE



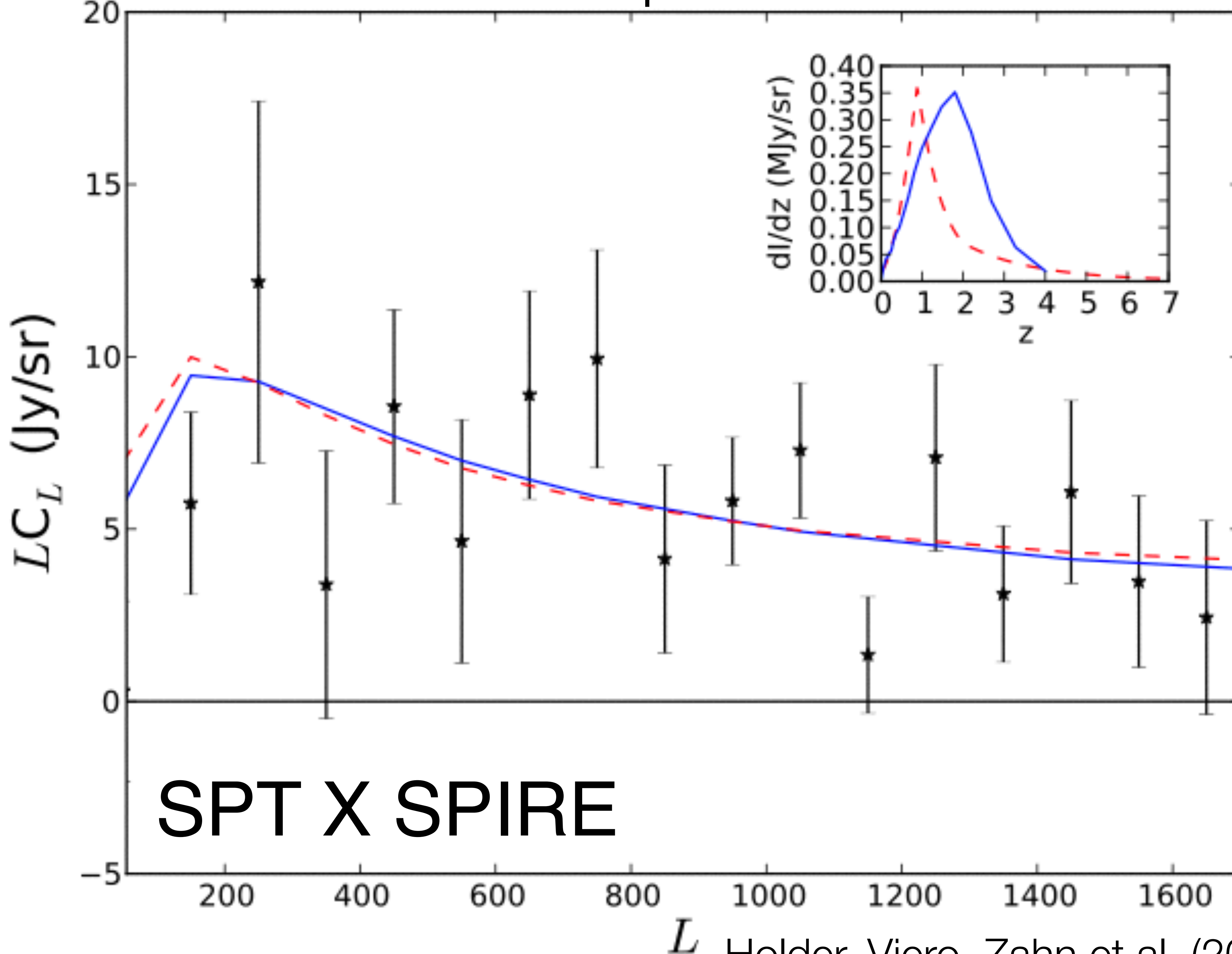
Lensed CMB x CIB

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

Measuring the CIB bias

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

CMB$_{lensed}$xCIB$_{500μm}$

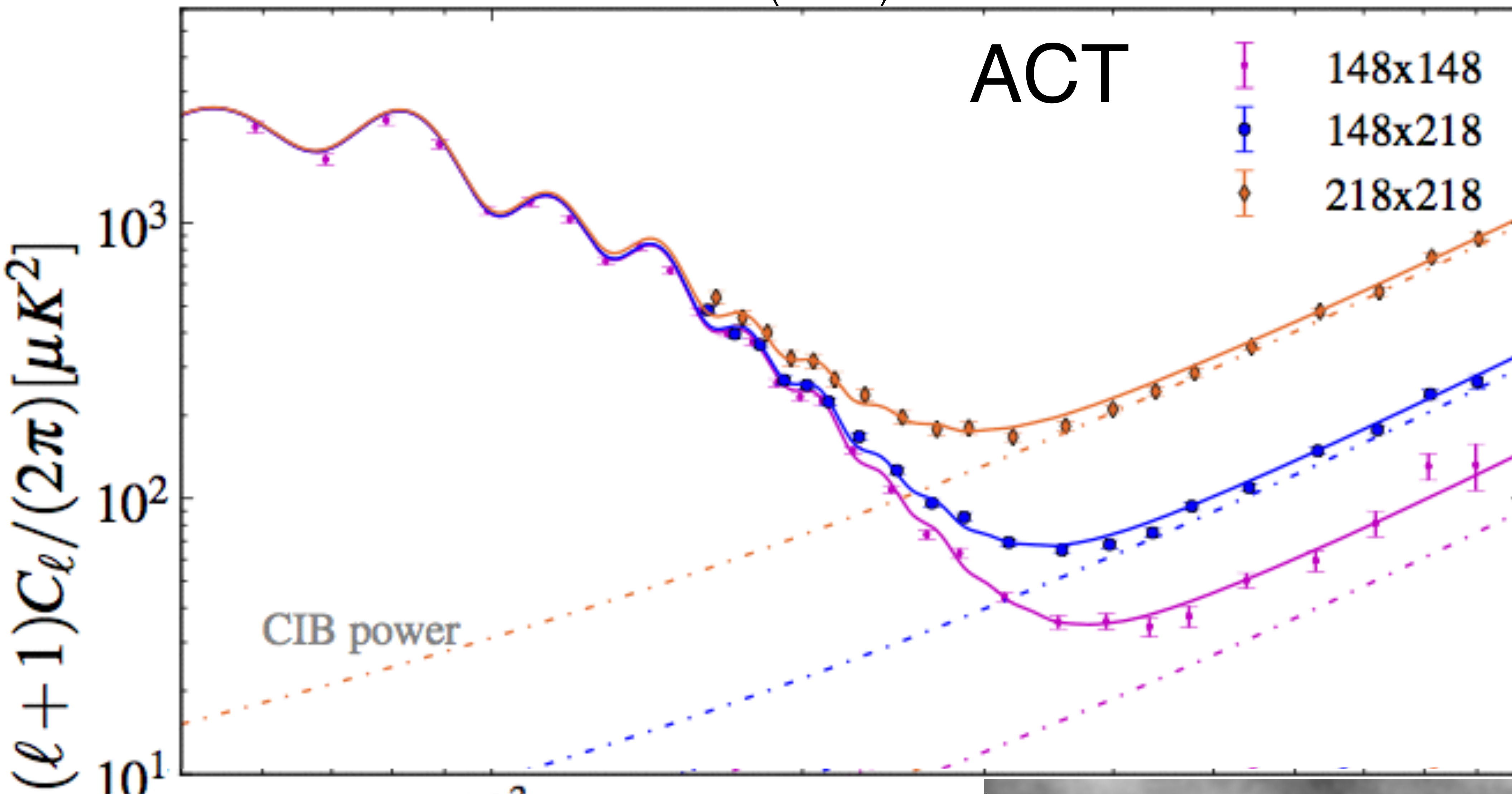


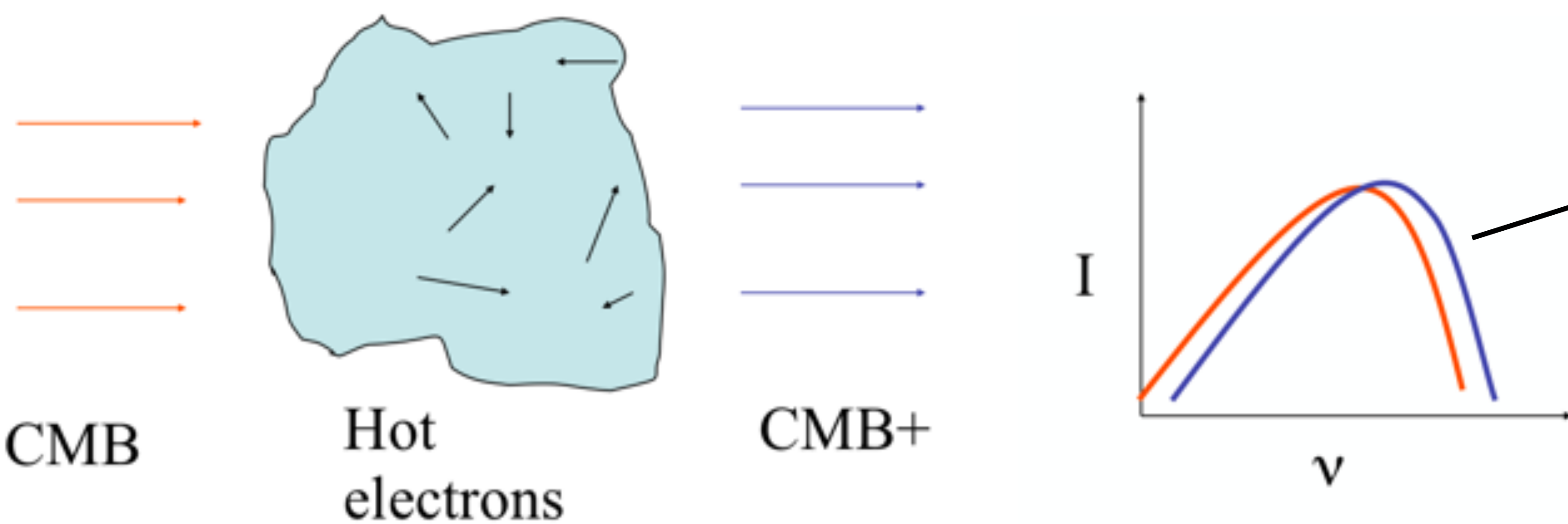
Holder, Viero, Zahn et al. (2013) arXiv:1304.0446

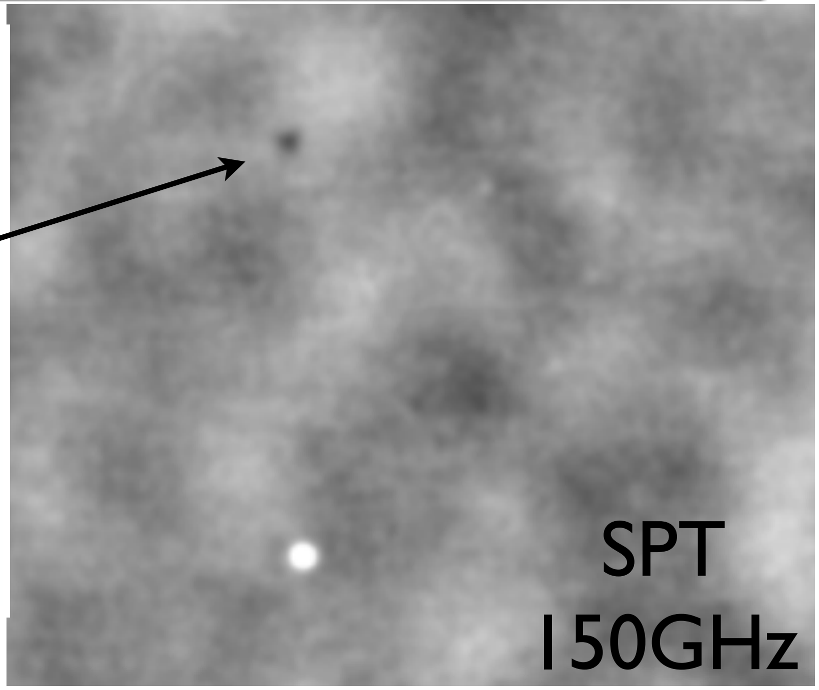
Dusty Galaxies a significant contaminant at 150 and 220 GHz

SZ effect distortion of CMB by Compton scattering in massive clusters

Sievers et al. (2013) arXiv: 1301.0824



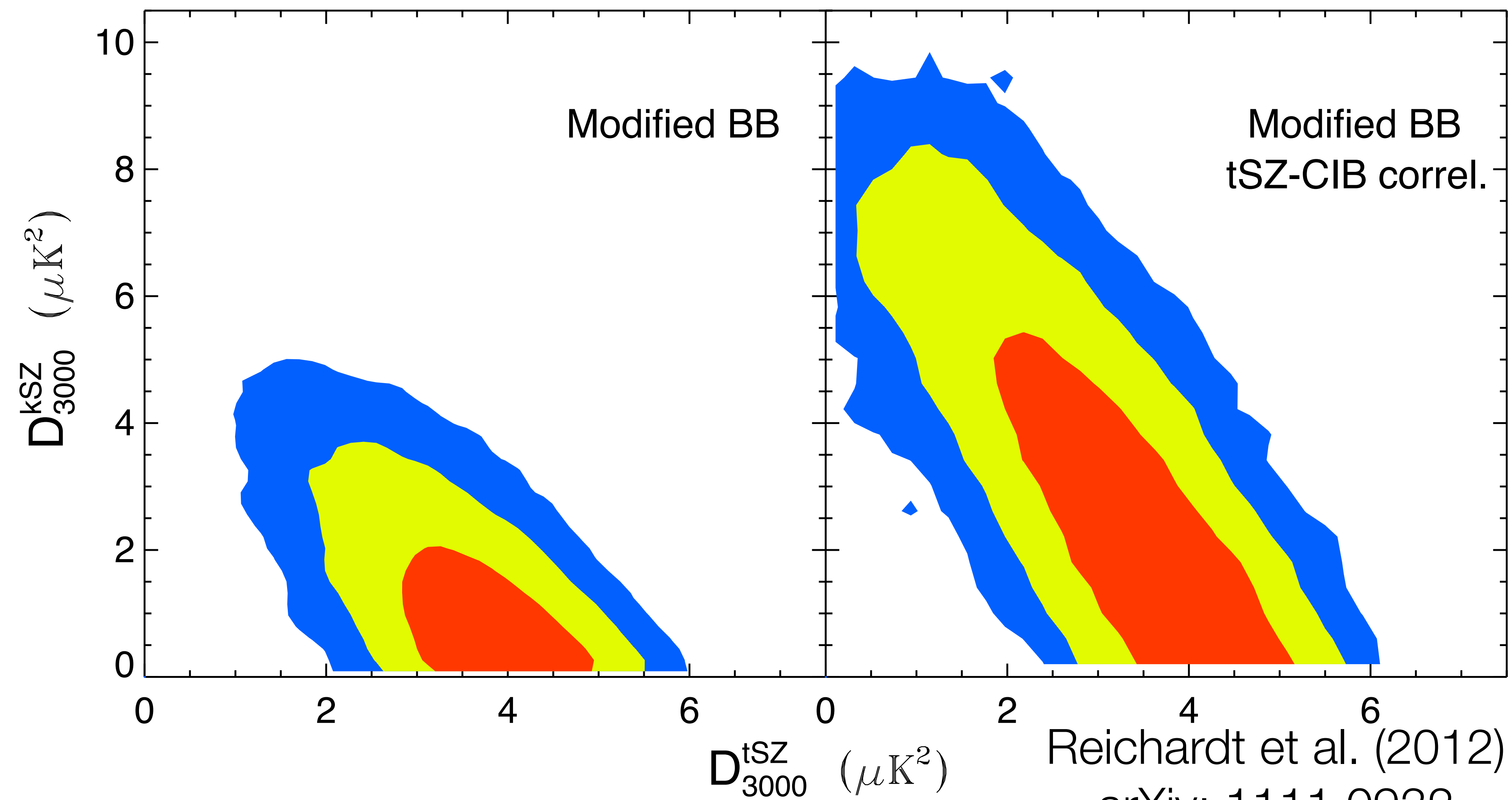




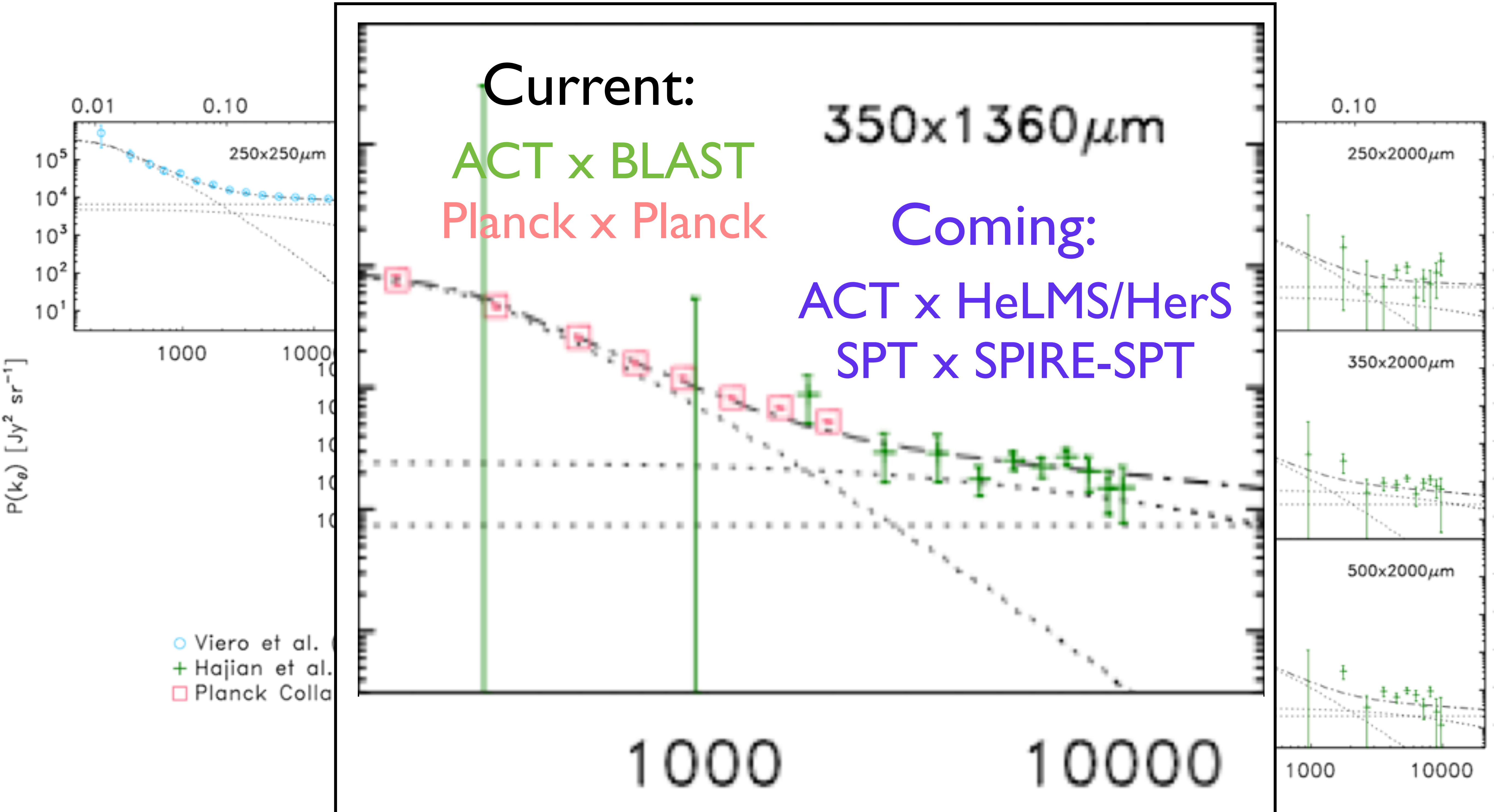
CIB as CMB Foreground

thermal SZ-CIB correlation?

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

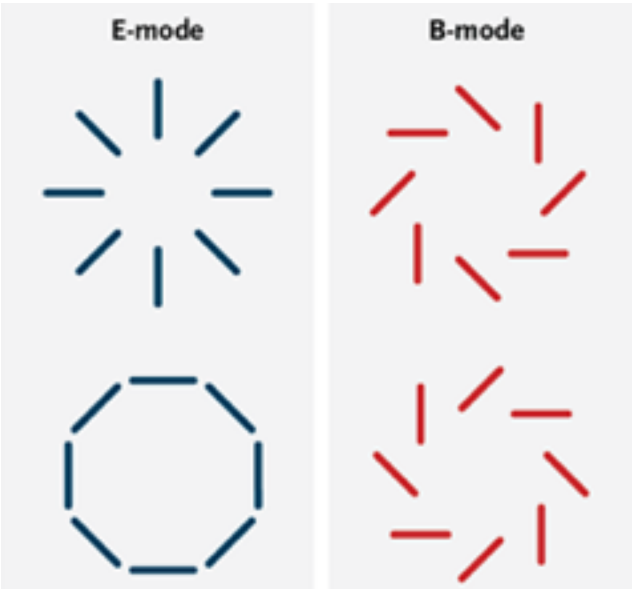


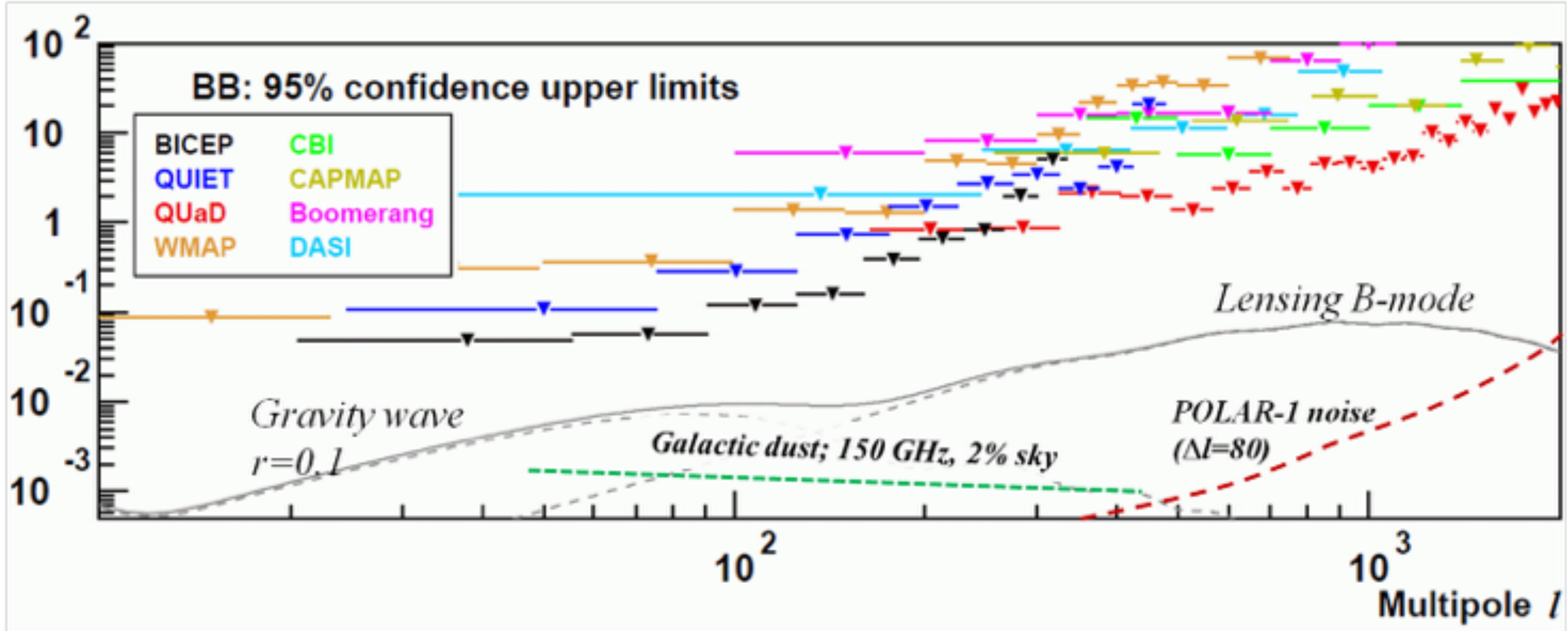
Reichardt et al. (2012)
arXiv: 1111.0932



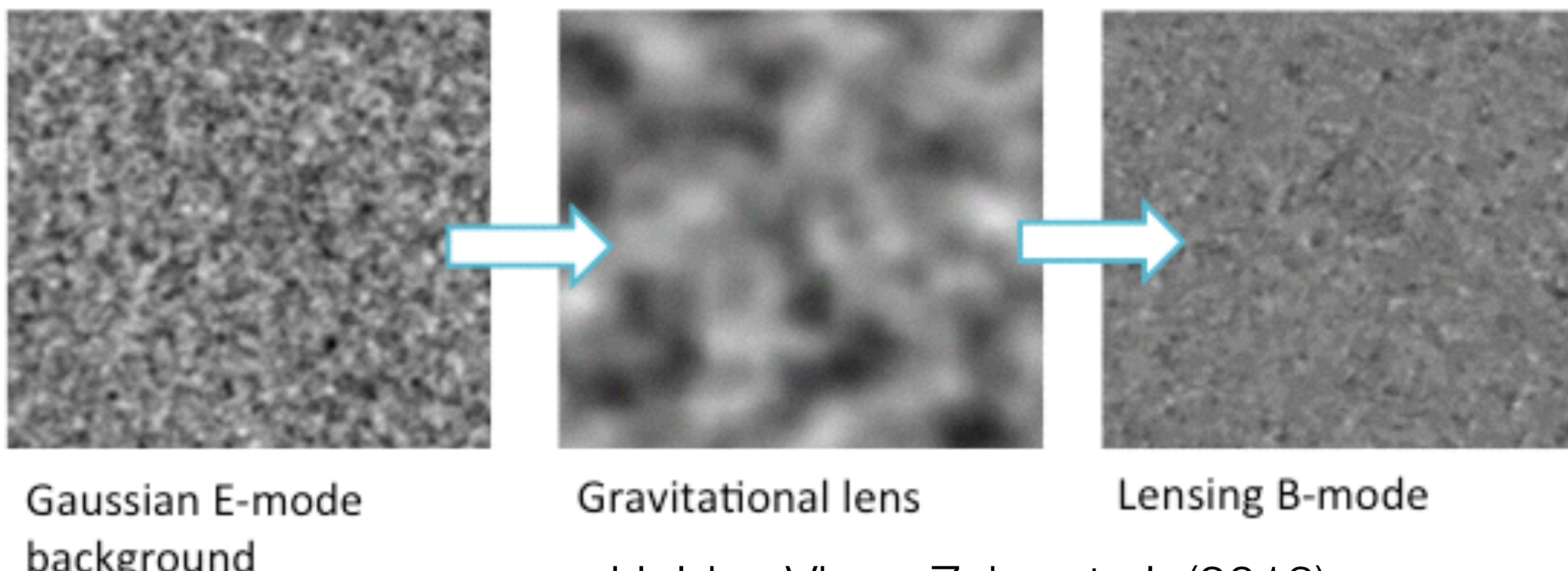
Green: Hajian, Viero et al. (2011)
Blue: Viero et al. (2013)
Red: Planck Collaboration (2013)

Cross-Correlating CIB and CMB



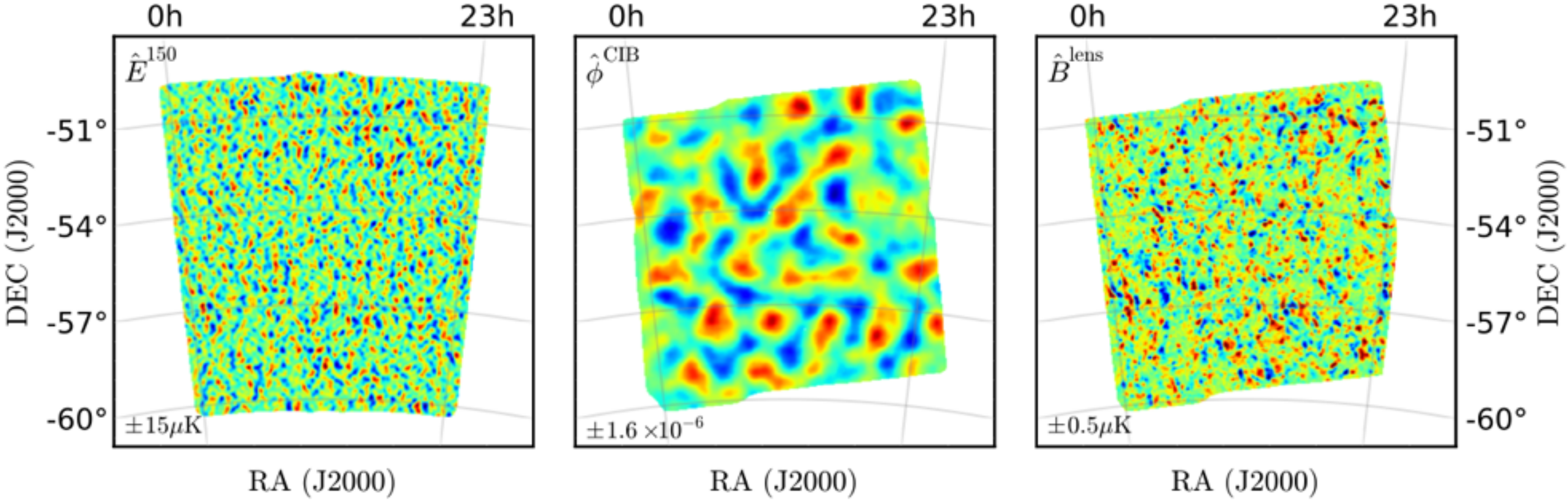


- Lensing mixes E-modes into B-modes

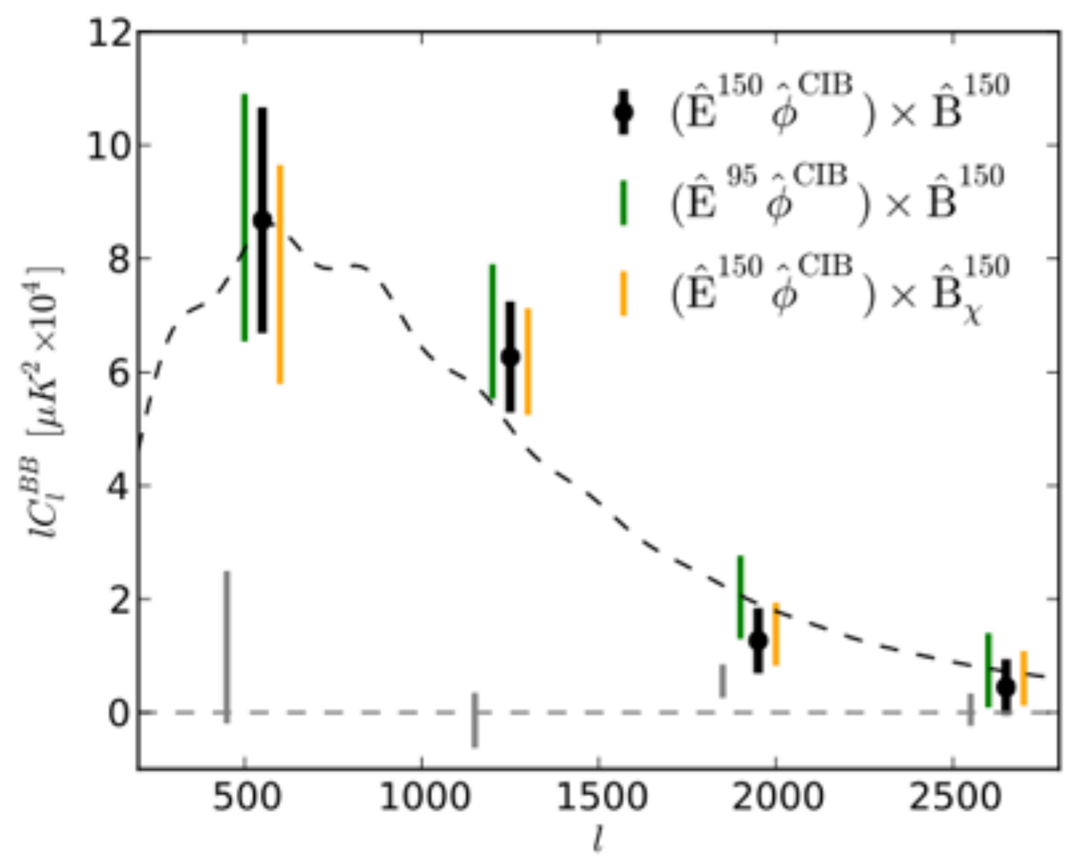


Holder, Viero, Zahn et al. (2013)
arXiv:1304.0446

CMB Lensing B-modes



- 7.7σ detection of B-mode signal



CMB Lensing B-modes

herschel stripe 82 survey

HERMES

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