# Seeing the (Infrared) Light

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w/
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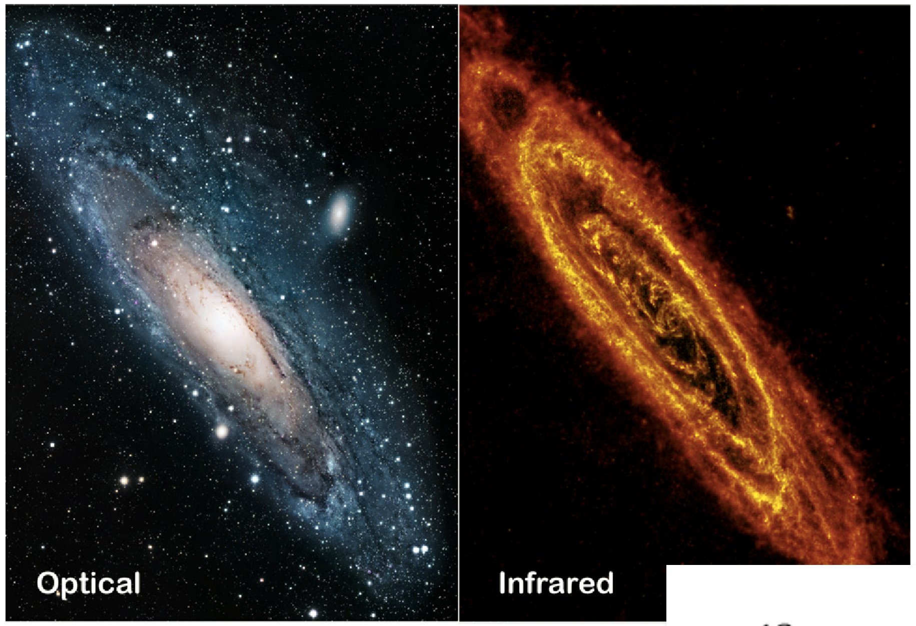
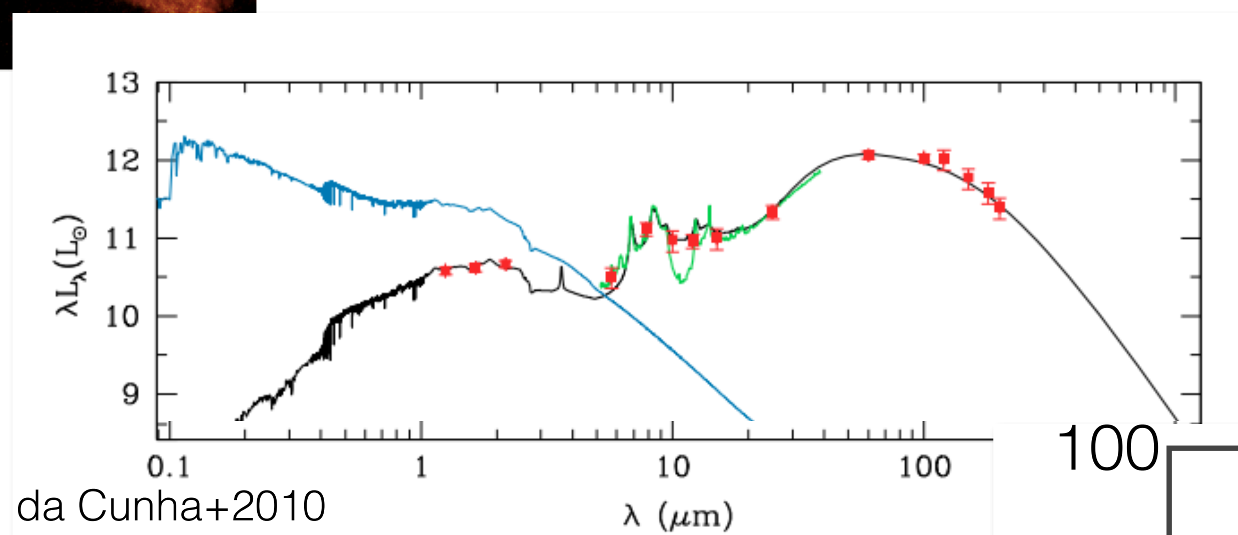
and the HerMES Collaboration

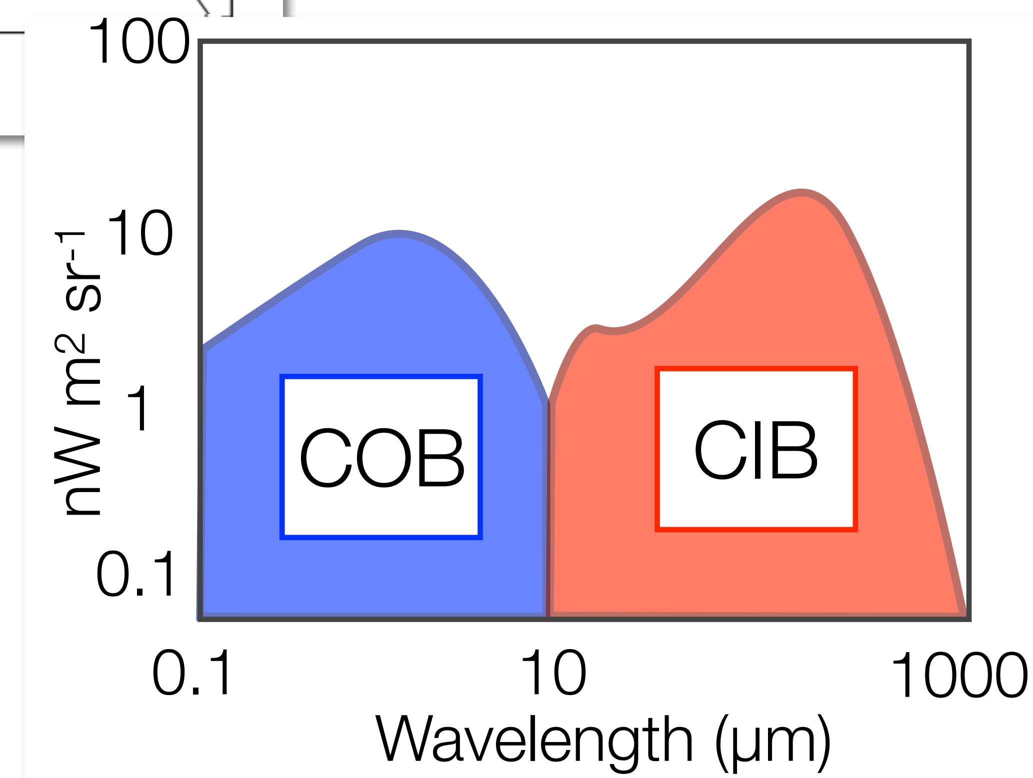
# Motivation




- Infrared/Submillimeter emission reprocessed starlight by dust
- IR/Submm traces star formation
- Half the emission is tied up in dust



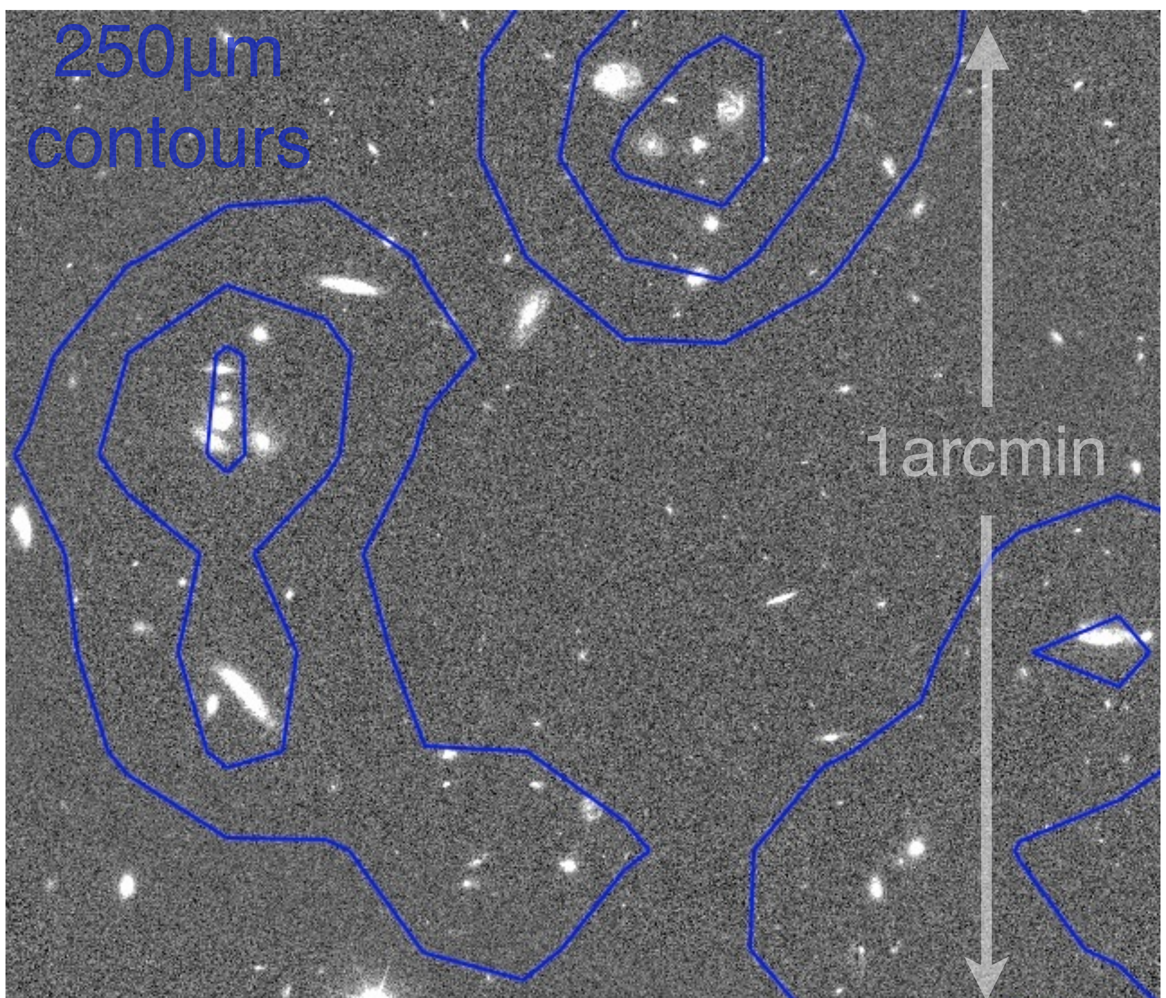
da Cunha+2010




- How do we reconcile COB and CIB?
- Want to know:
  - ➡which galaxies make up CIB?
  - ➡how much of the CIB is accounted for?
  - ➡what limits does this place on models?

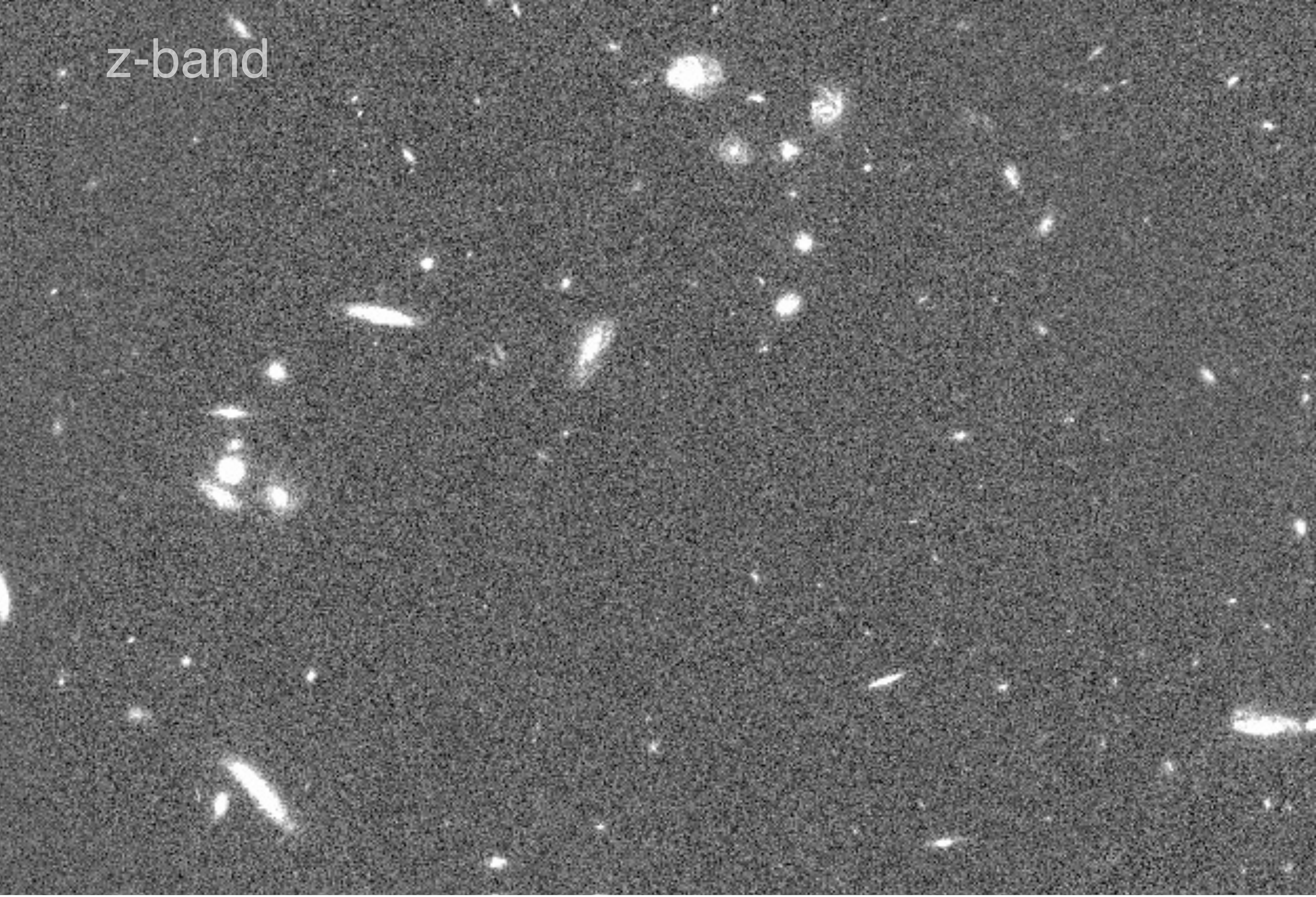
# *Herschel*/SPIRE

| Band | PSF size (FWHM) | Confusion Limit (5σ) |
|---|---|---|
| 250 μm: | 18” | 24.0 mJy |
| 350 μm: | 25” | 27.5 mJy |
| 500 μm: | 36” | 30.5 mJy |

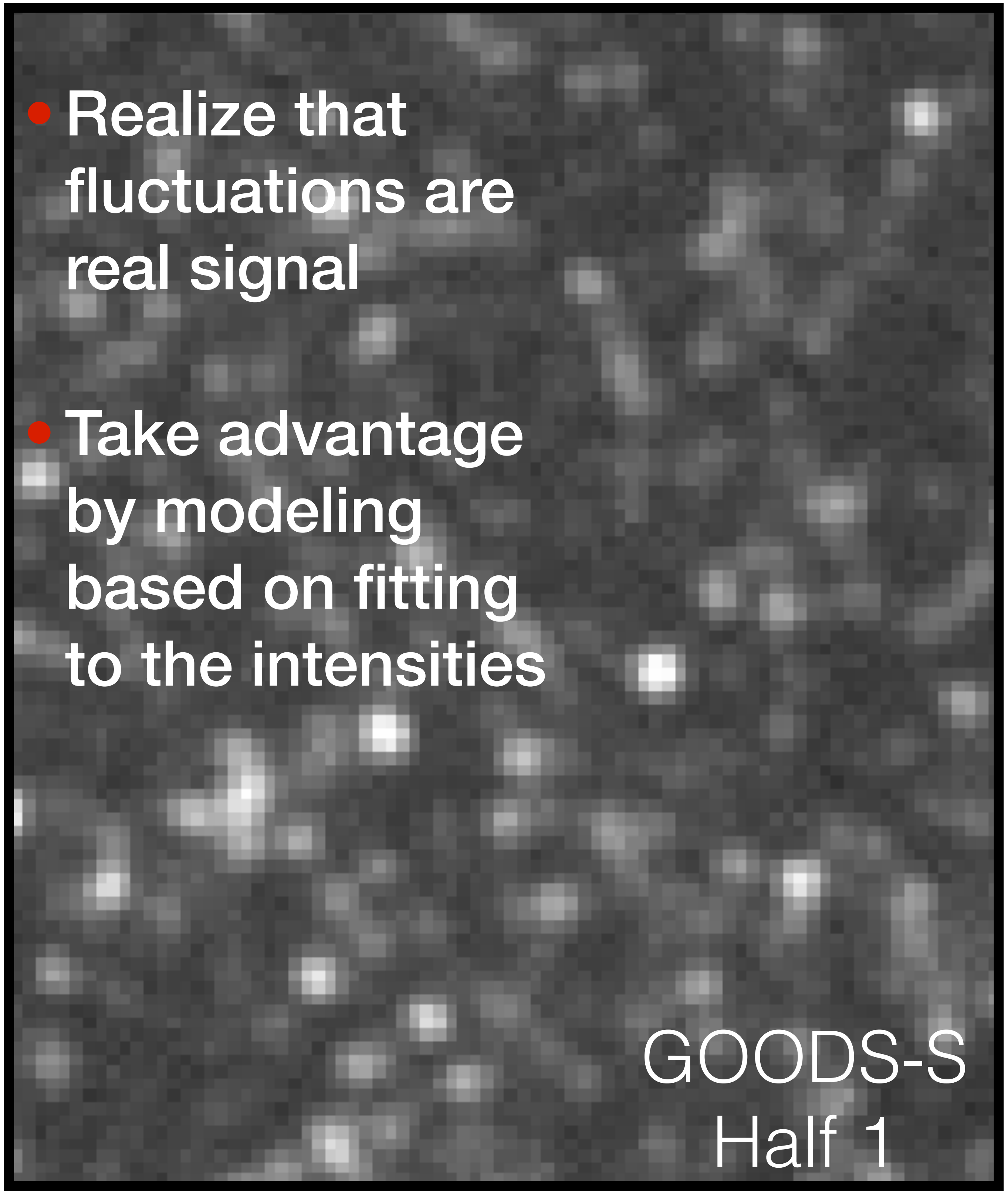


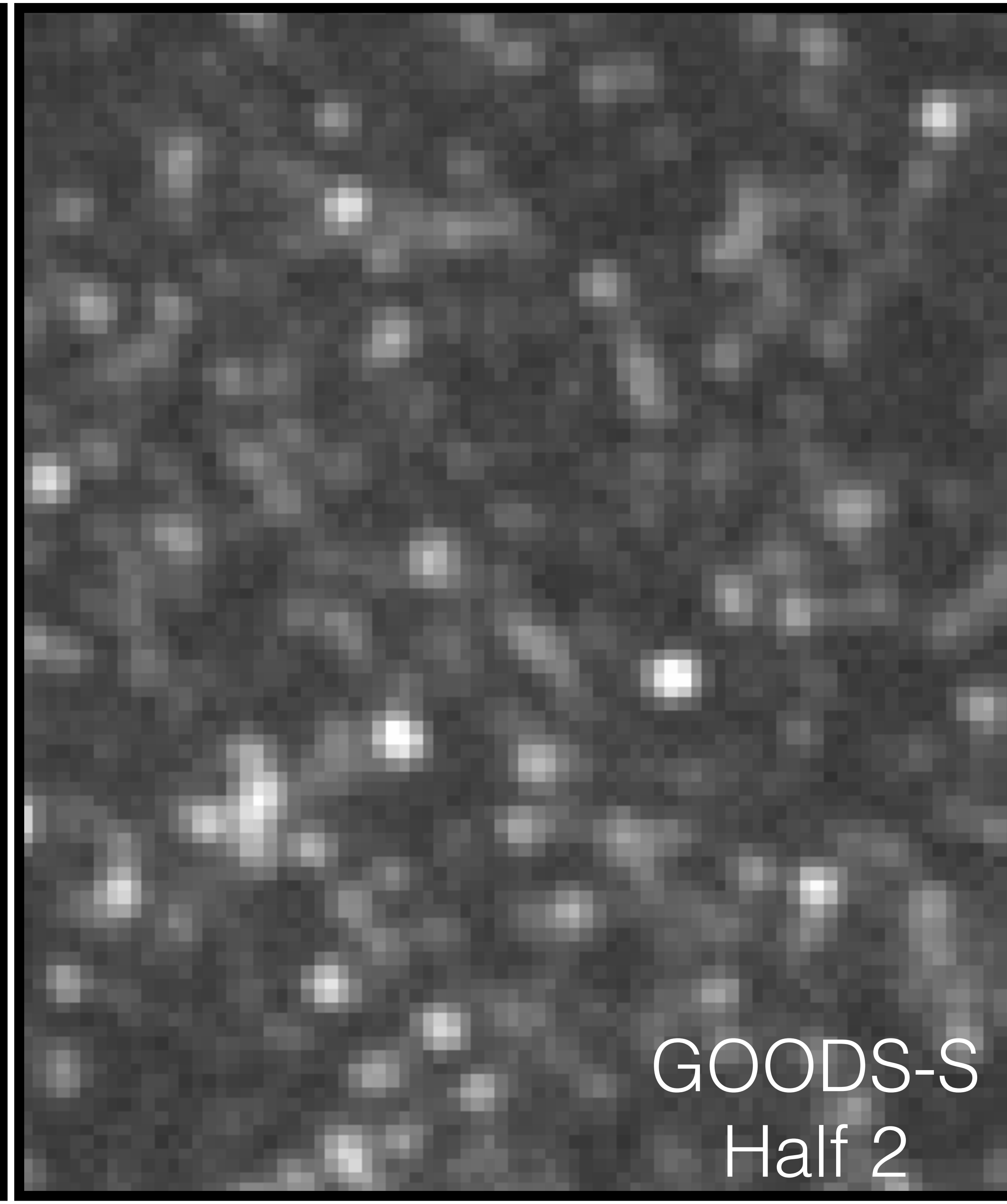


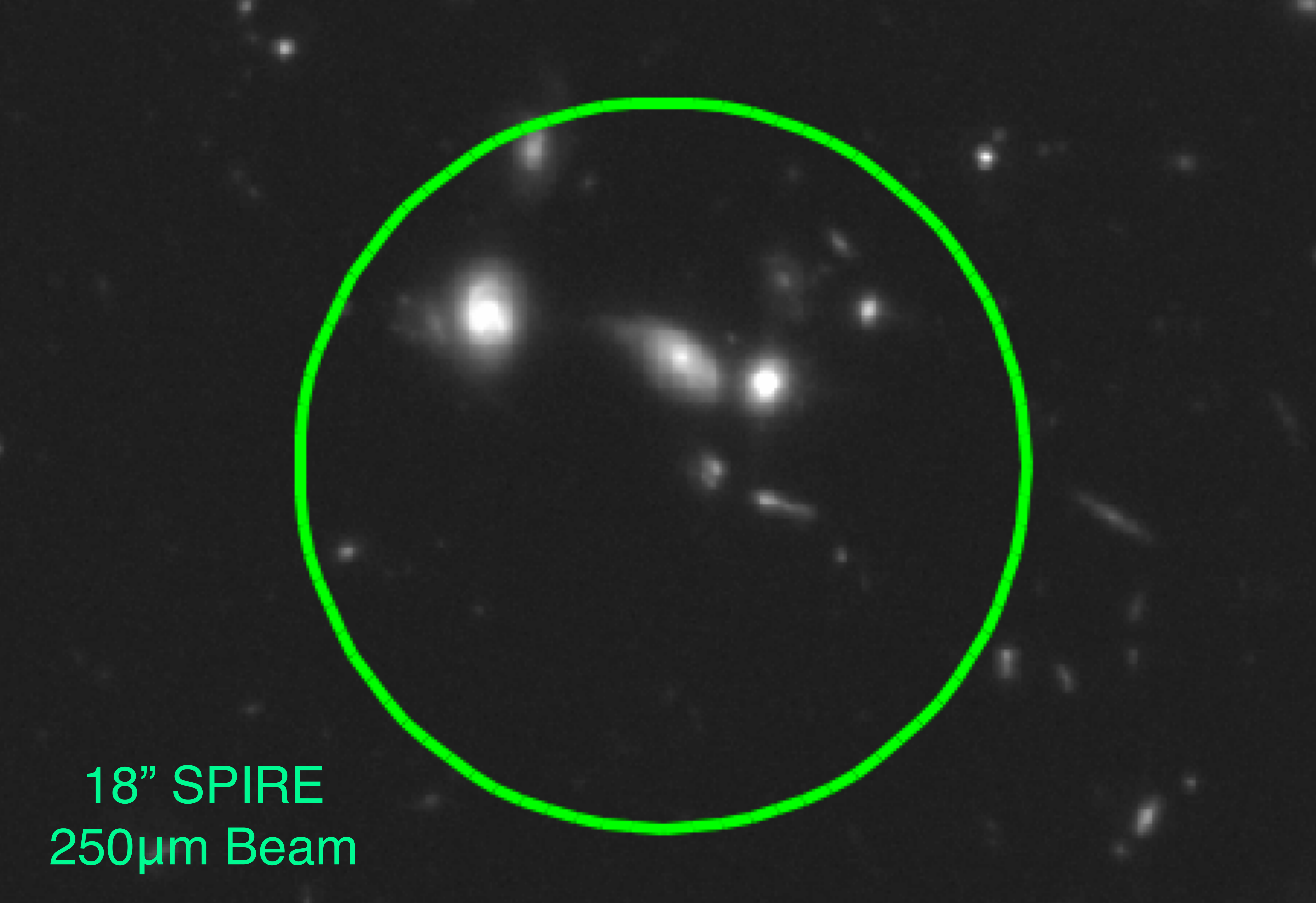
- < 1% of sources resolved at 5σ due to source confusion
- Strength is surveys, with ~1000 $deg^2$ observed

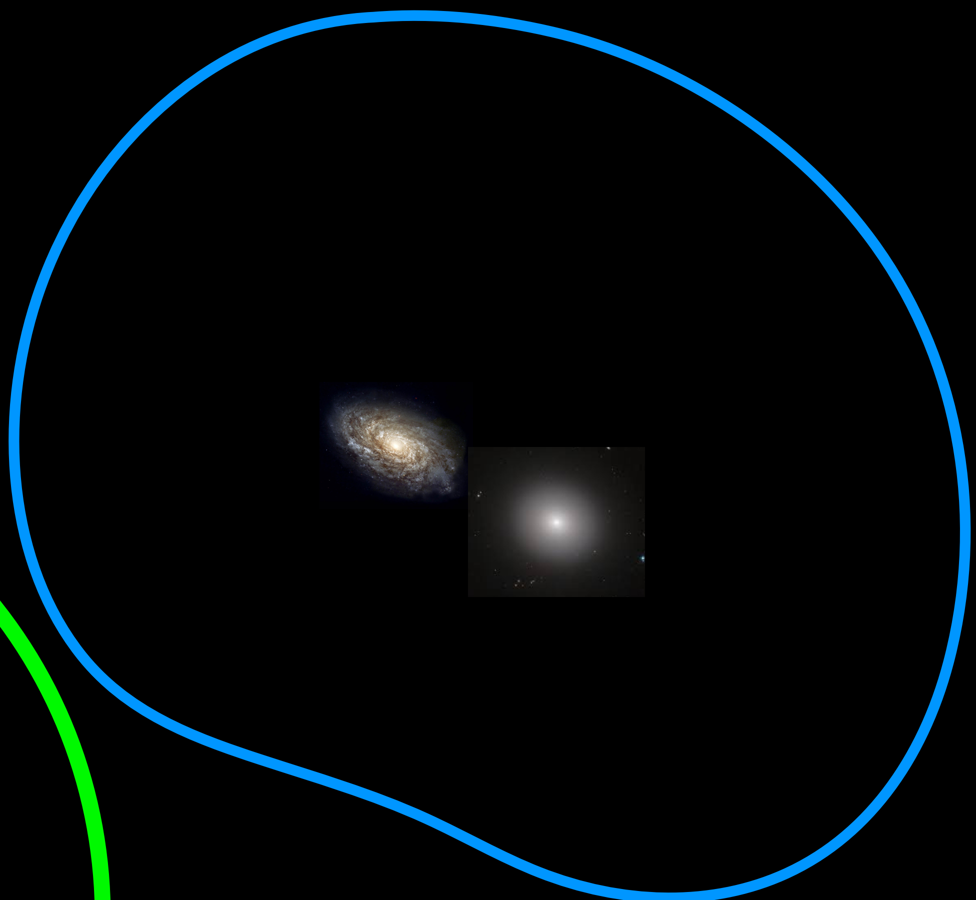

z-band

- Realize that fluctuations are real signal
- Take advantage by modeling based on fitting to the intensities



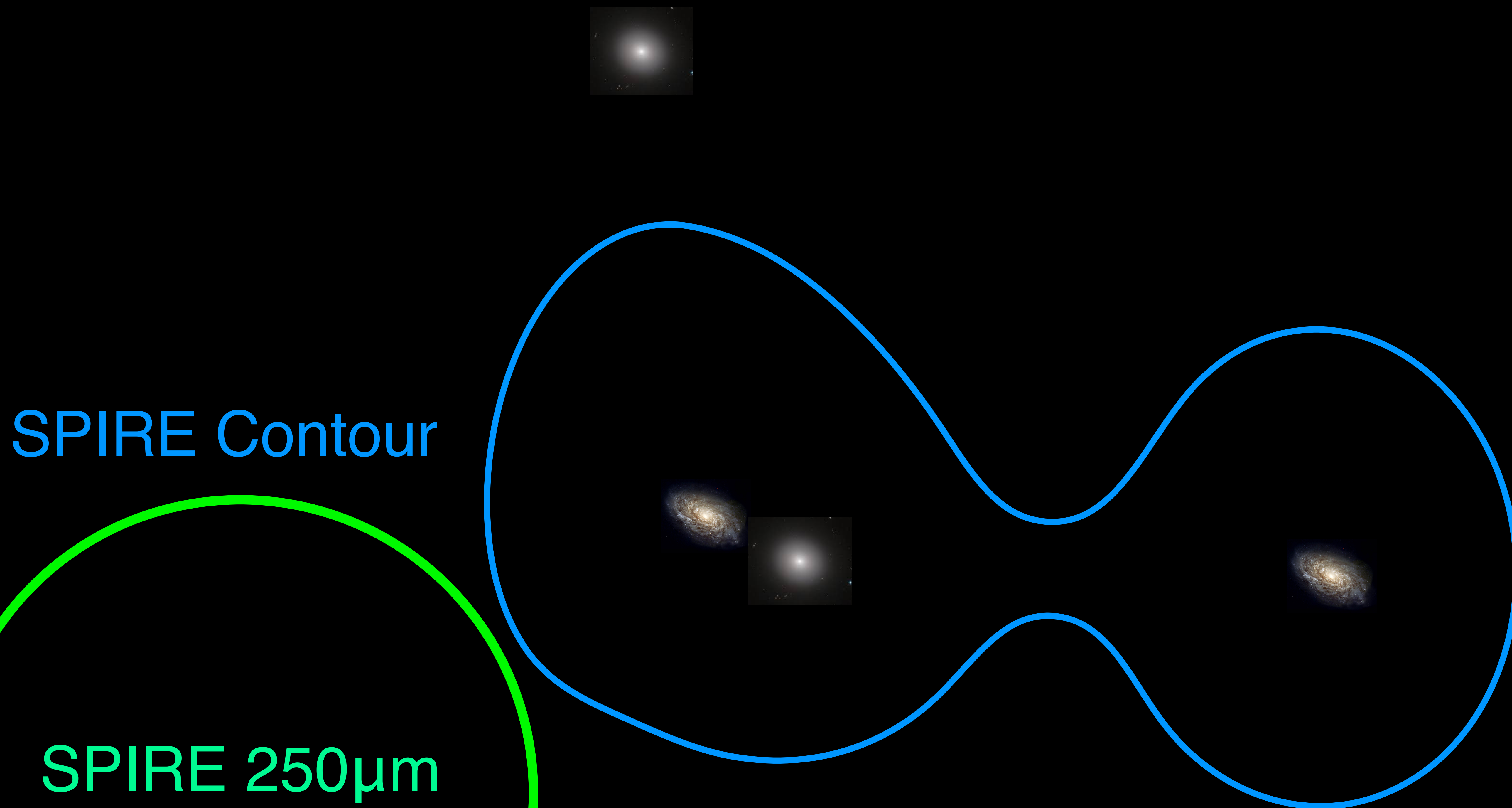




18” SPIRE
250µm Beam





- Difficult to attribute an individual submillimeter “source” to any single galaxy





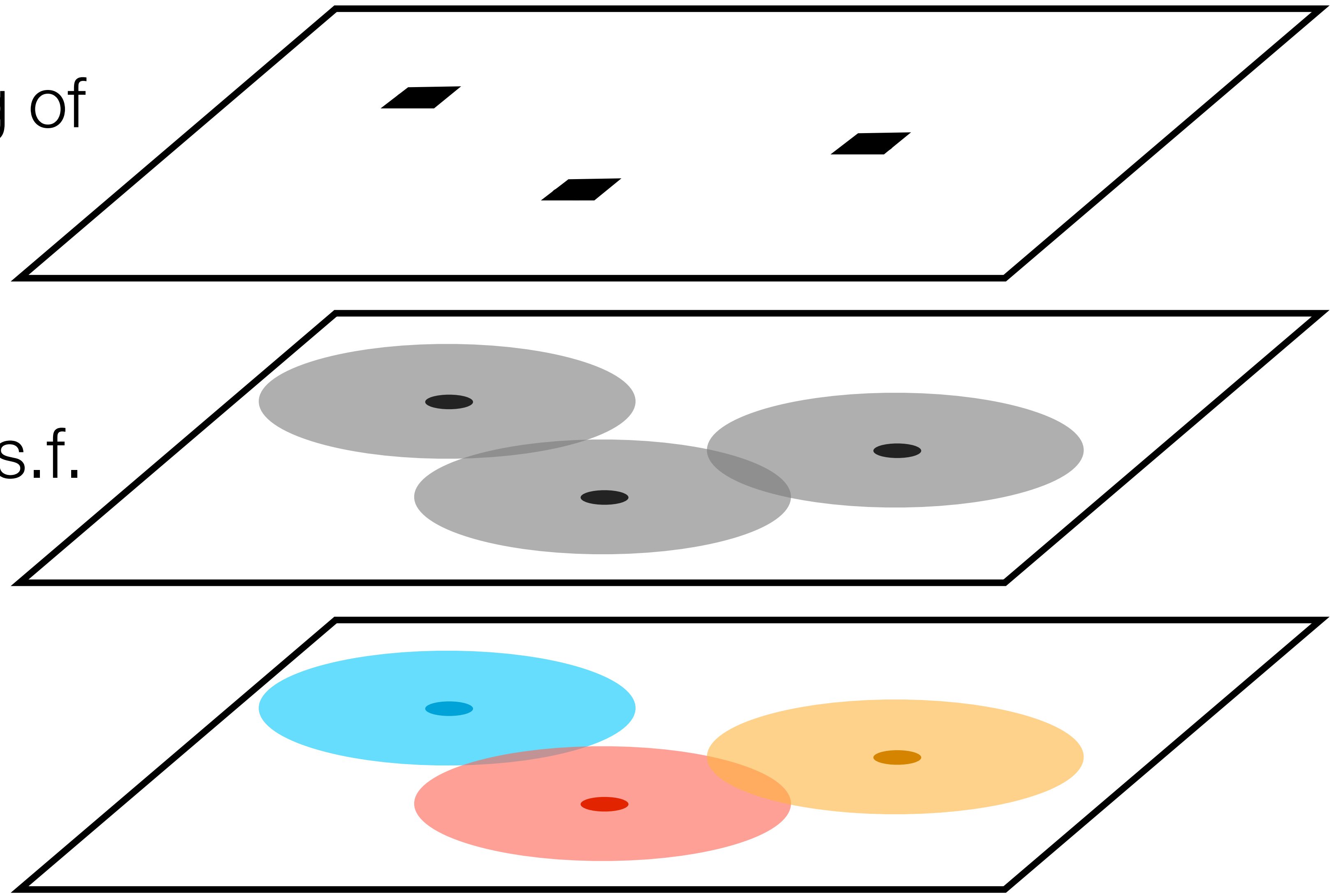
- Key is to identify galaxies with similar *physical* properties, and then rely on ***statistics*** *to fit* ***fluctuations***

# SIMSTACK: Synthetic Intensity Fitting Algorithm

make hits map from catalog of similar objects

convolve with instrument p.s.f.

regress to find *mean* flux density

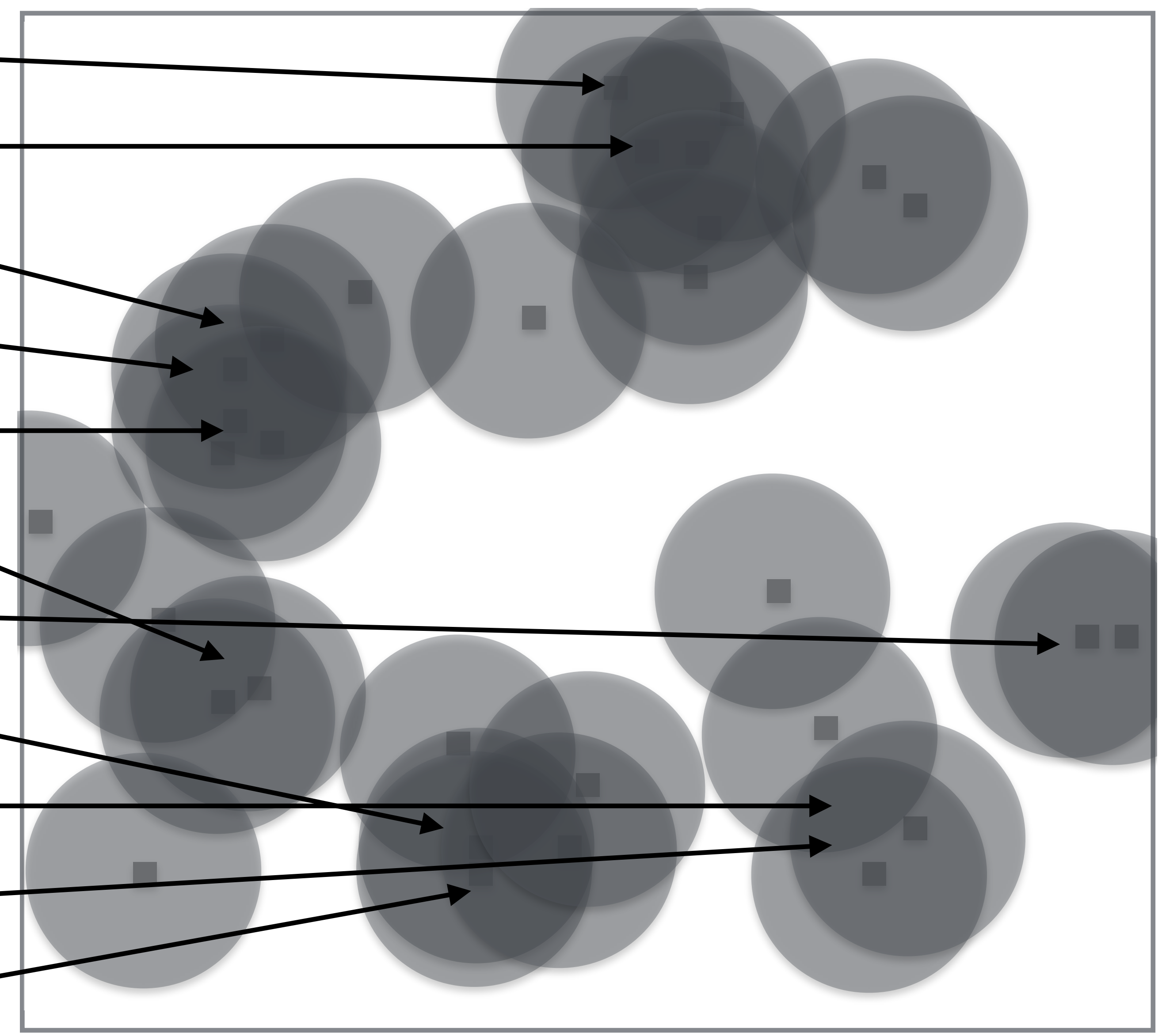


Formalism developed w/ Lorenzo Moncelsi (Caltech);
also see Kurczynski & Gawiser (2010), Roseboom et al. (2010)

**SIMSTACK code publicly available (see arXiv:1304.0446):**
**IDL (old) — https://web.stanford.edu/~viero/downloads.html**
**Python (under development!) — https://github.com/marcoviero/simstack**

# Simplest Intensity Fitting

| RA | DEC |
|---|---|
| 149.853 | 2.608 |
| 149.854 | 2.258 |
| 149.752 | 2.584 |
| 149.832 | 2.724 |
| 149.275 | 2.196 |
| 149.262 | 2.966 |
| 149.915 | 2.206 |
| 149.546 | 2.564 |
| 149.824 | 2.047 |
| 149.453 | 2.278 |
| 149.863 | 2.788 |
| … | … |
| … | … |



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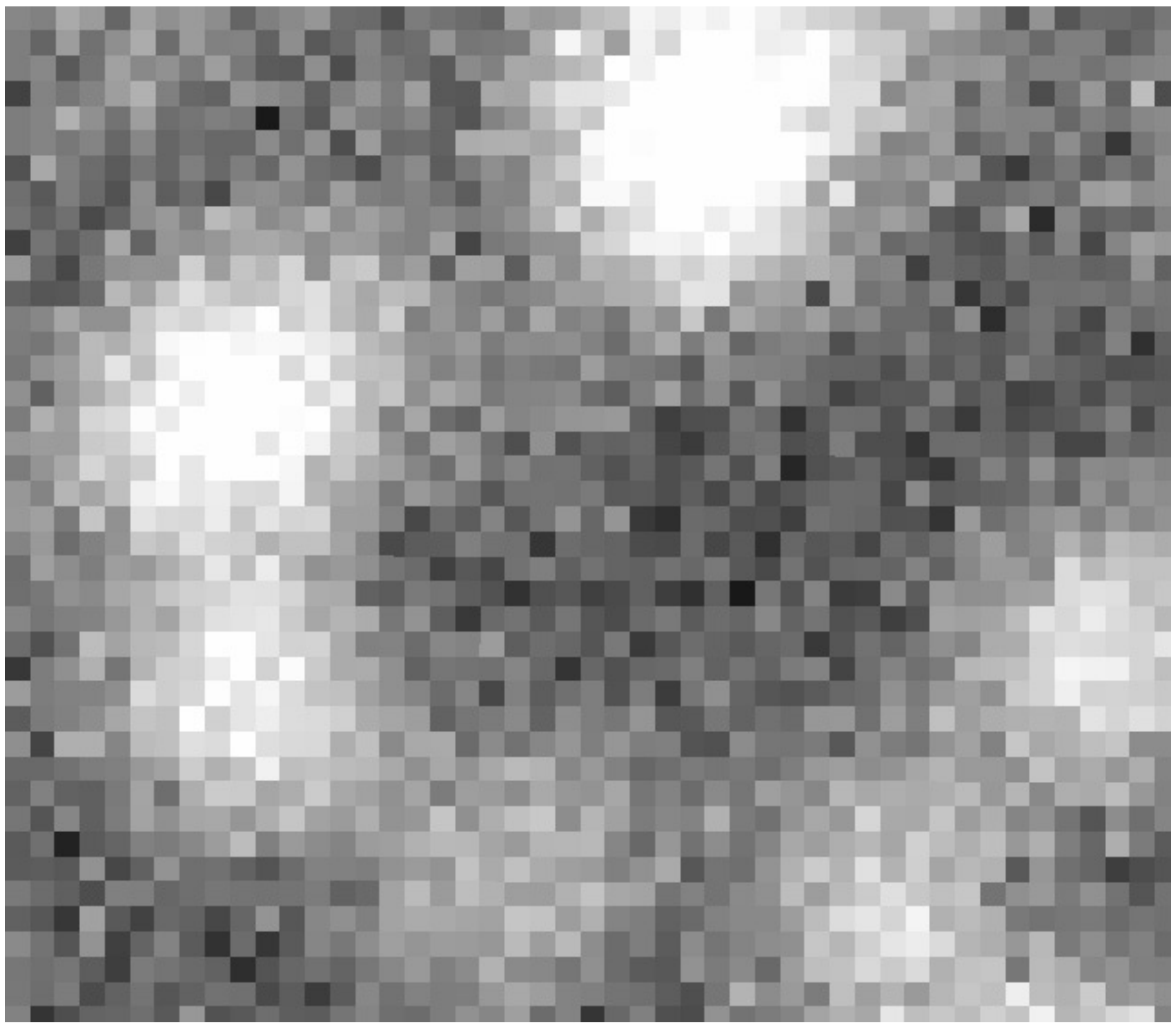
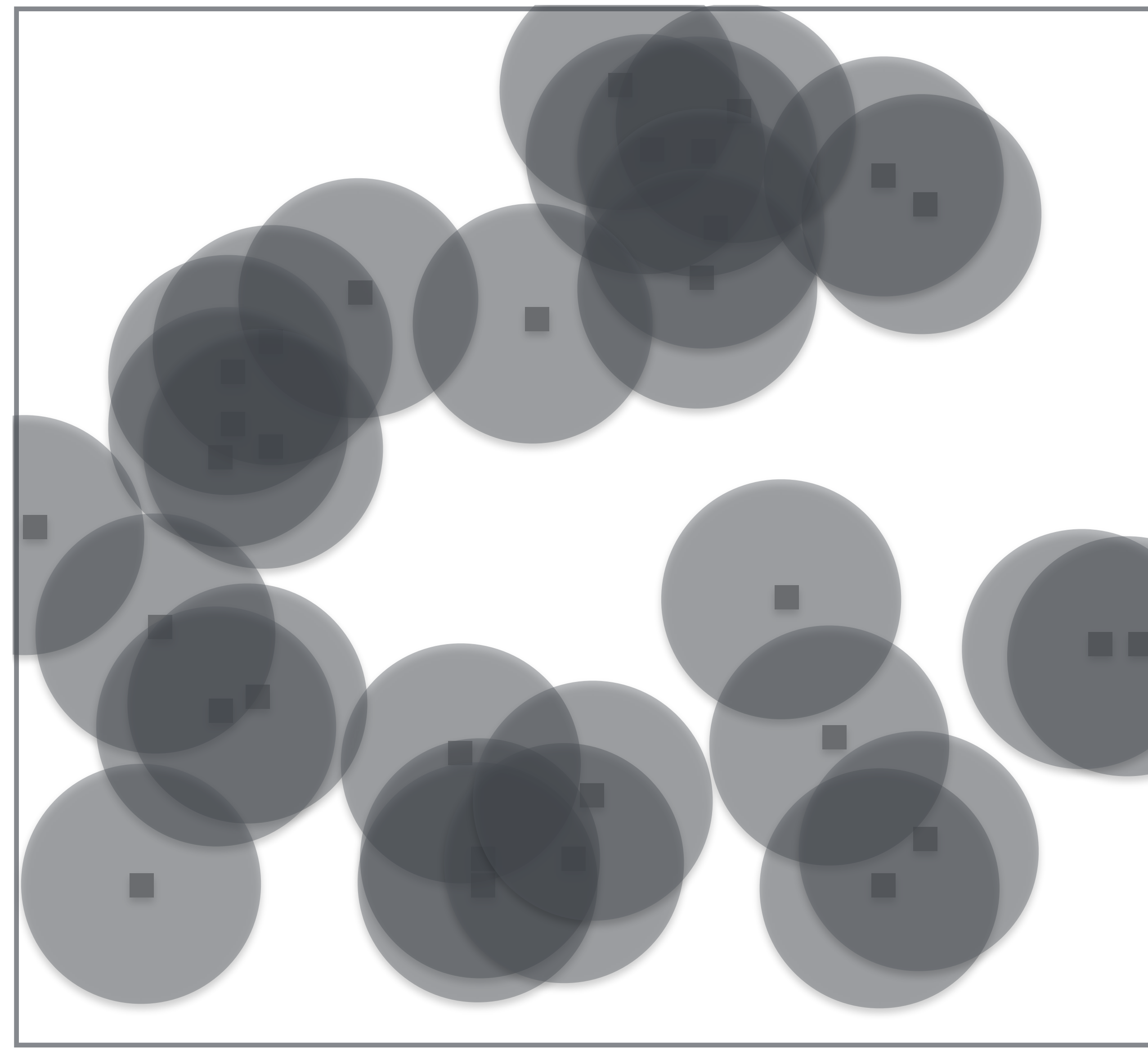
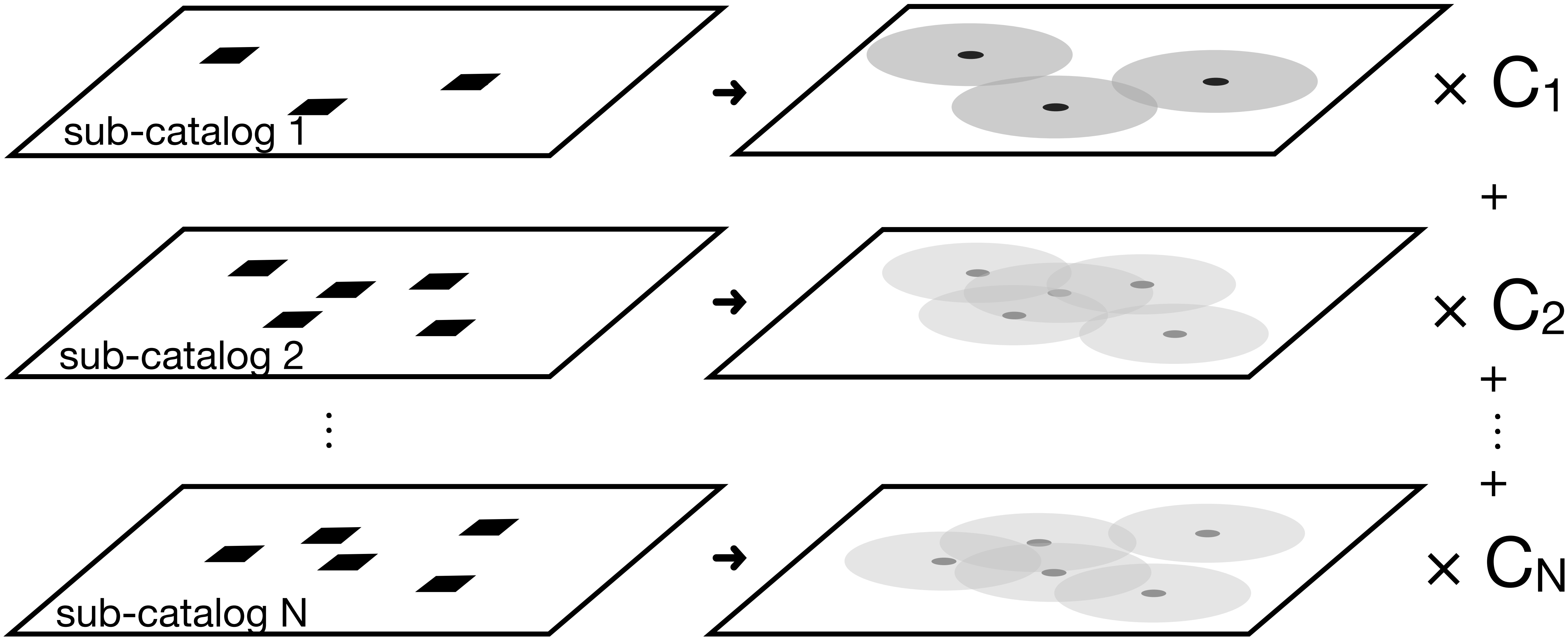
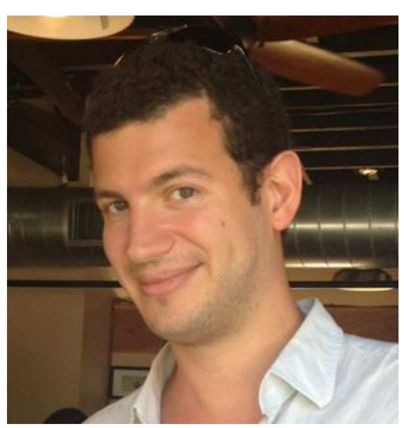


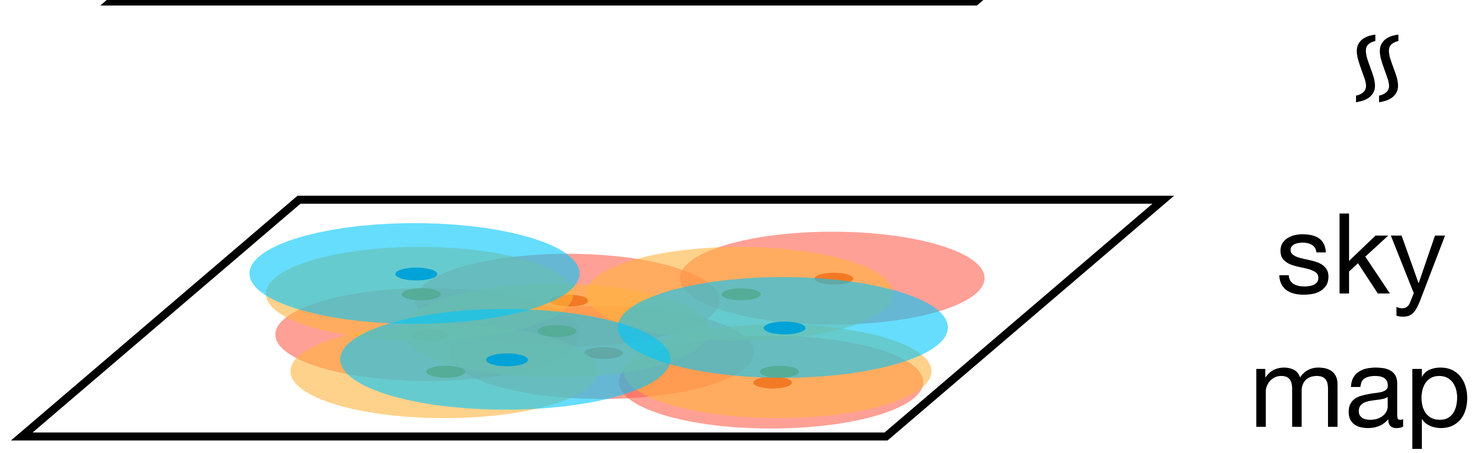


# SIMSTACK: Synthetic Intensity Fitting Algorithm




Formalism developed w/ Lorenzo Moncelsi (Caltech)

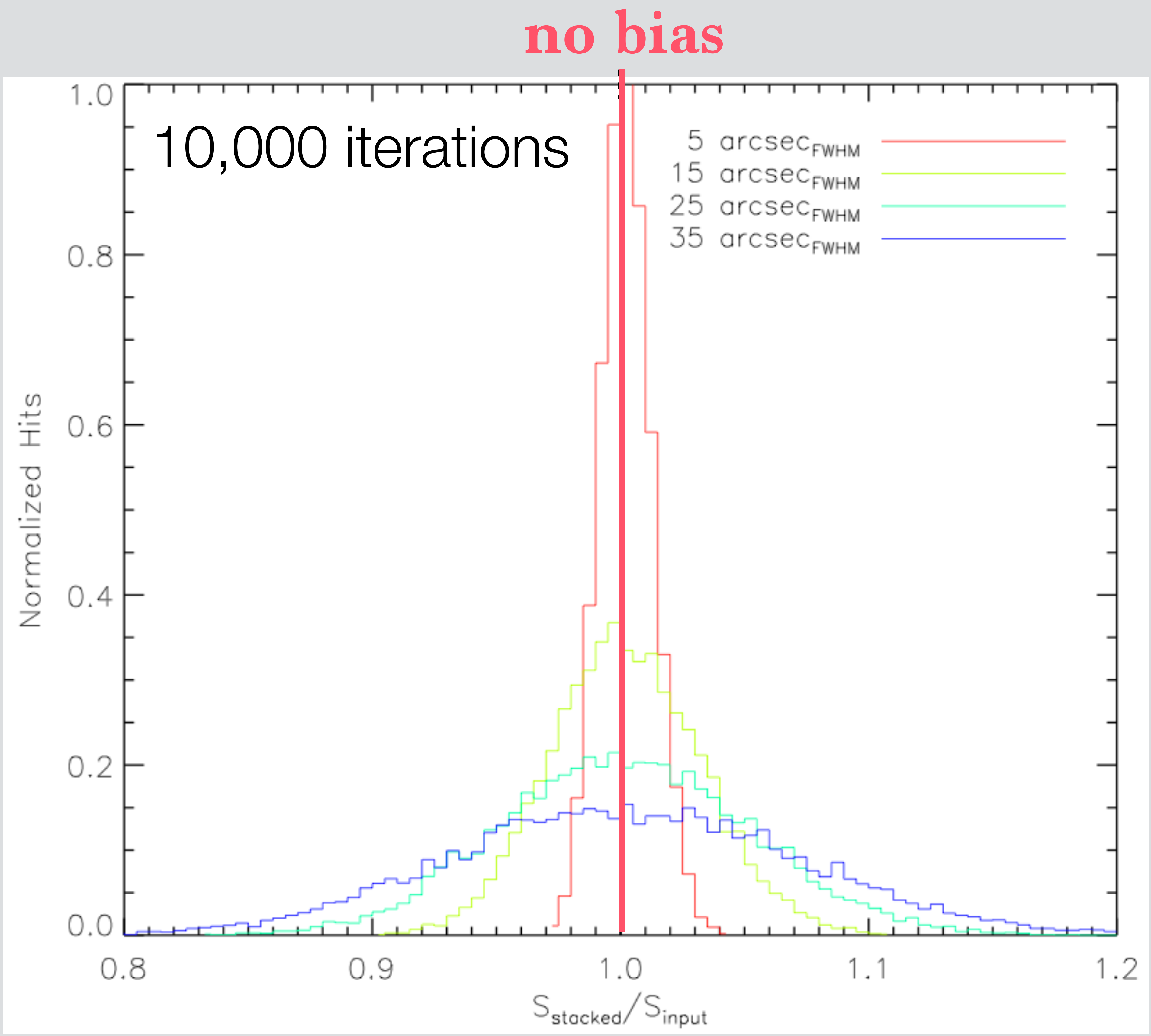





**SIMSTACK code publicly available (see arXiv:1304.0446):**
**IDL (old) — https://web.stanford.edu/~viero/downloads.html**
**Python (under development!) — https://github.com/marcoviero/simstack**

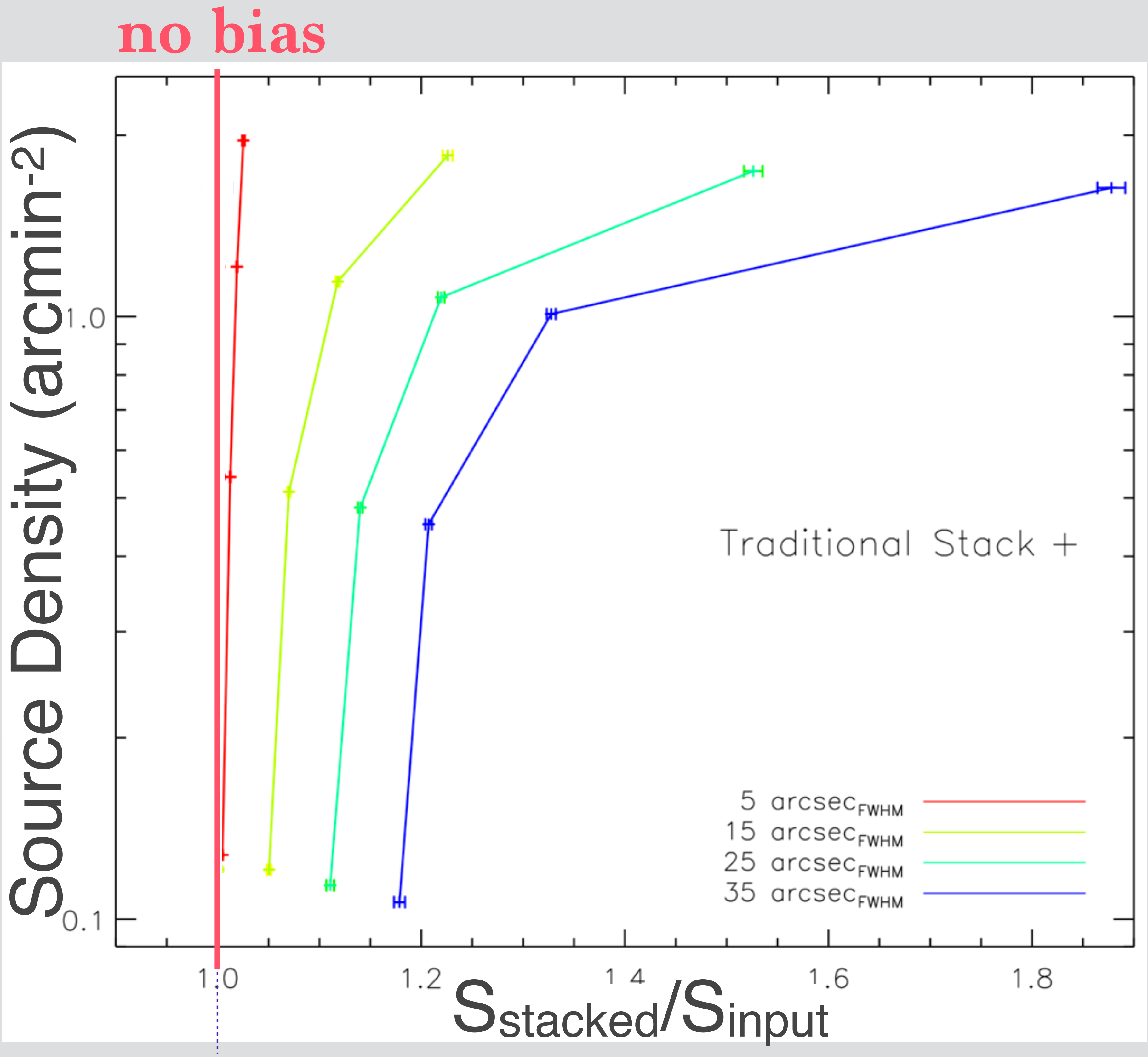
# Aside: Correlated vs. Uncorrelated Emission

- In a typical **thumbnail stack**, uncorrelated emission does not bias result, only adds noise



# Aside: Correlated vs. Uncorrelated Emission

- However *correlated* emission does bias a typical thumbnail stack, increasingly with increasing beam



Near-Infrared Selected Sources at z~1.5

**Take advantage of statistics**

Split catalog up into groups of *Similar Galaxies*

- ➡**Assumption** **is that galaxies with similar physical properties — described by their optical SEDs — will have similar infrared properties.**
- ➡**This is Key! Only works if this assumption holds.**

# The Measurement

# SIMSTACK: Measurement Data

## Catalogs

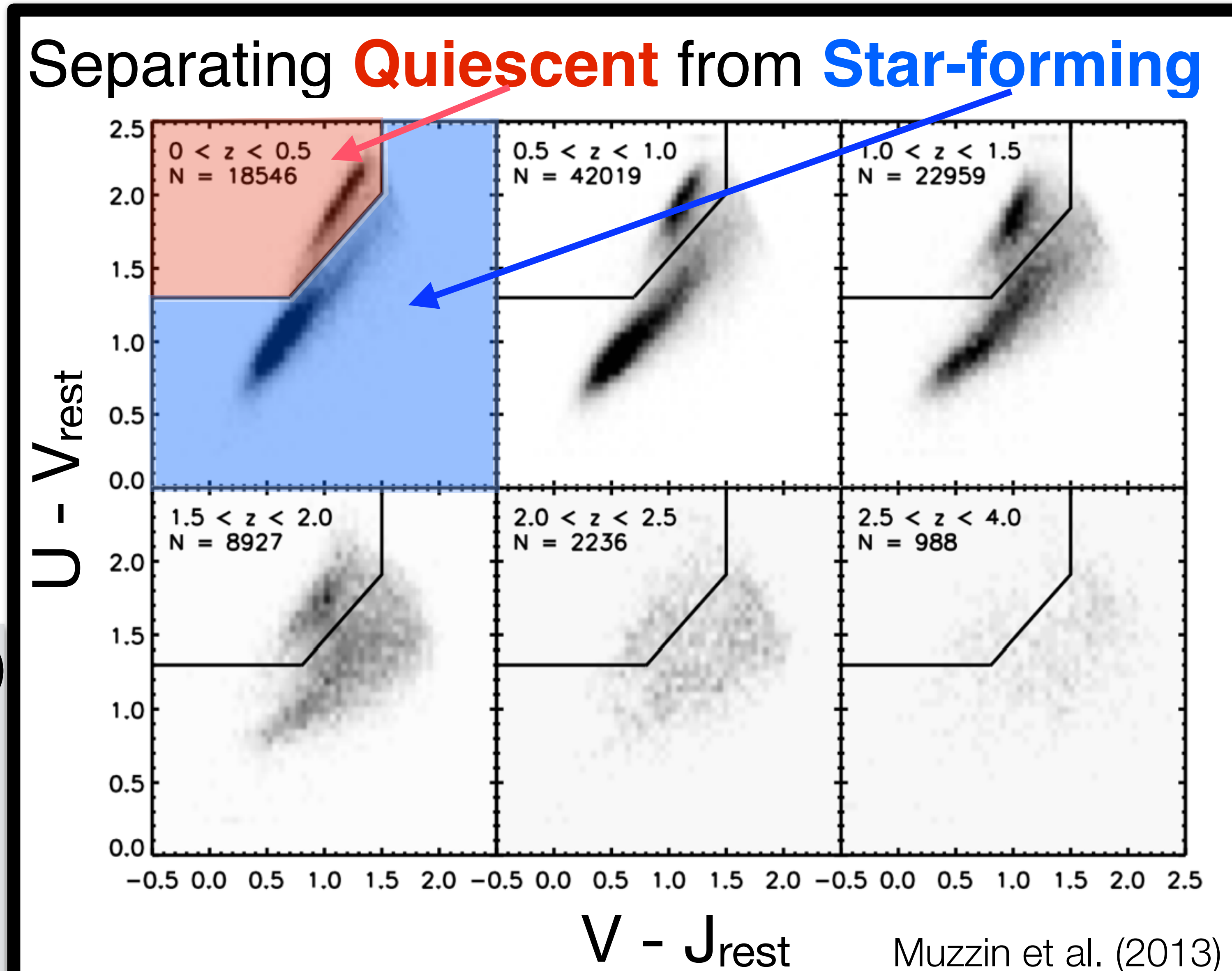
- UKIDSS/UDS [2/3 deg$^2$] / COSMOS [1.6 deg$^2$]

  uBVRizJHK + IRAC ch1234

  K-band cut 23.4 / 24 AB

  80,000 / 120,000 sources

- **Redshifts** - EAZY (Brammer 2008)
- **Masses** - FAST (Kriek 2009)
- **Colors** - UVJ (Williams 2009)



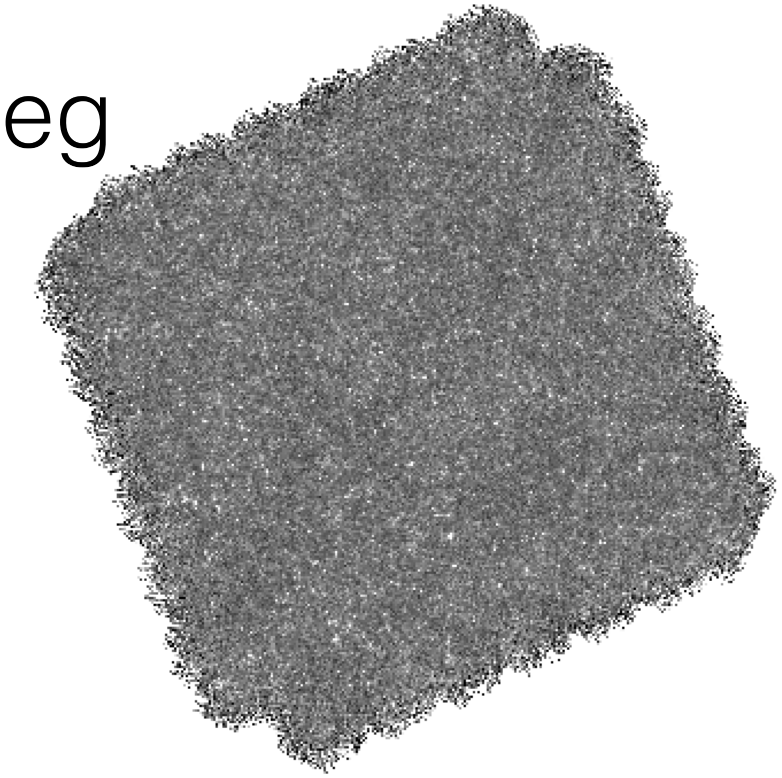

Muzzin et al. (2013)

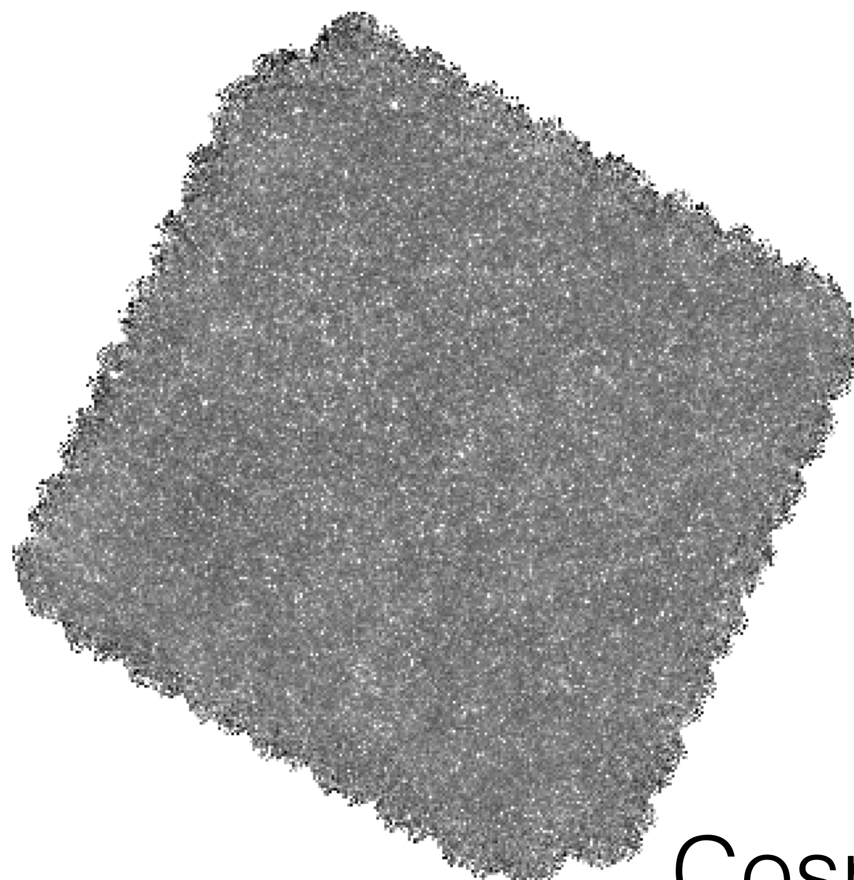
# SIMSTACK: Measurement Data

## Maps

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

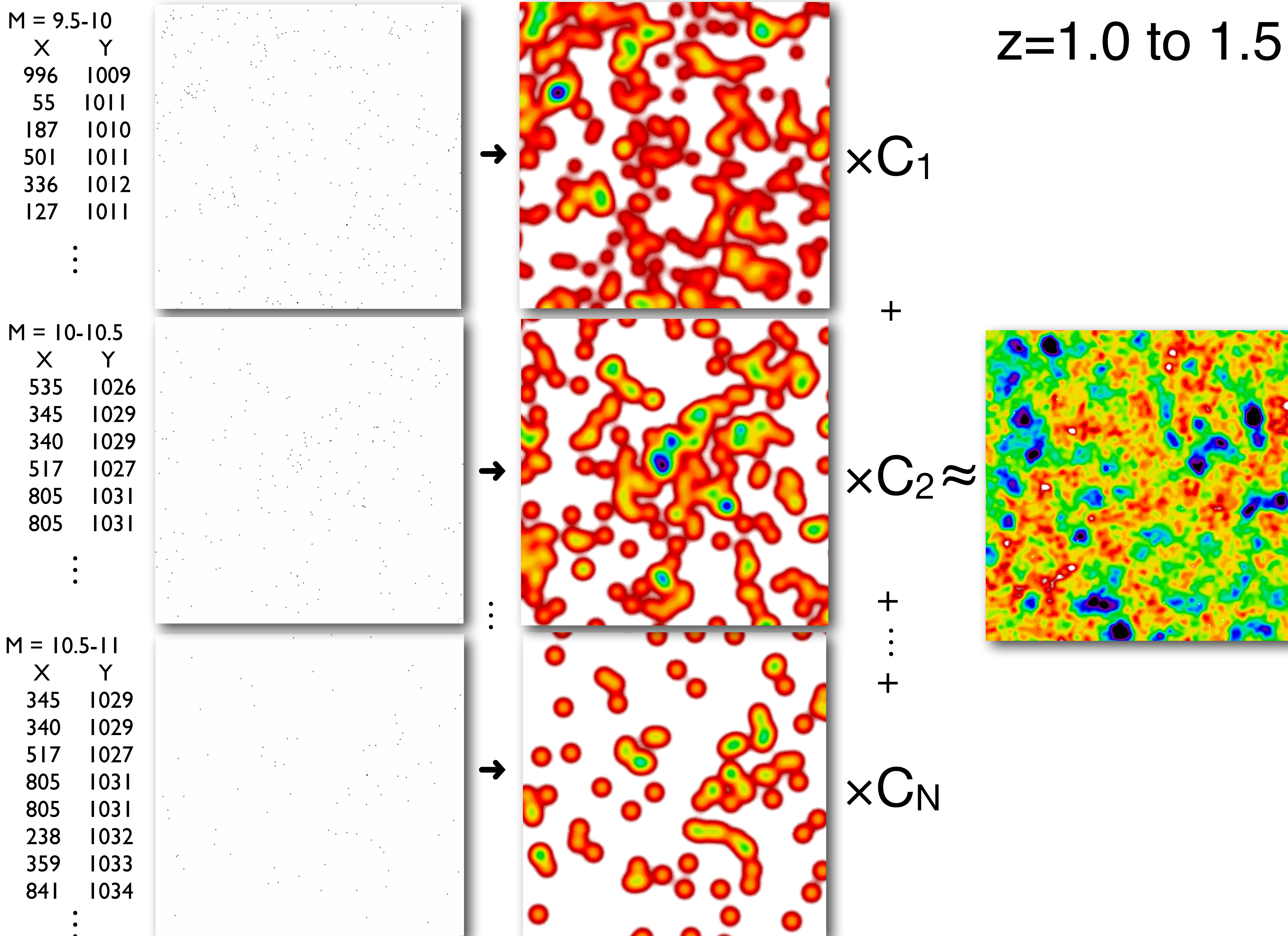
UDS - 1.4 x 1.4 deg





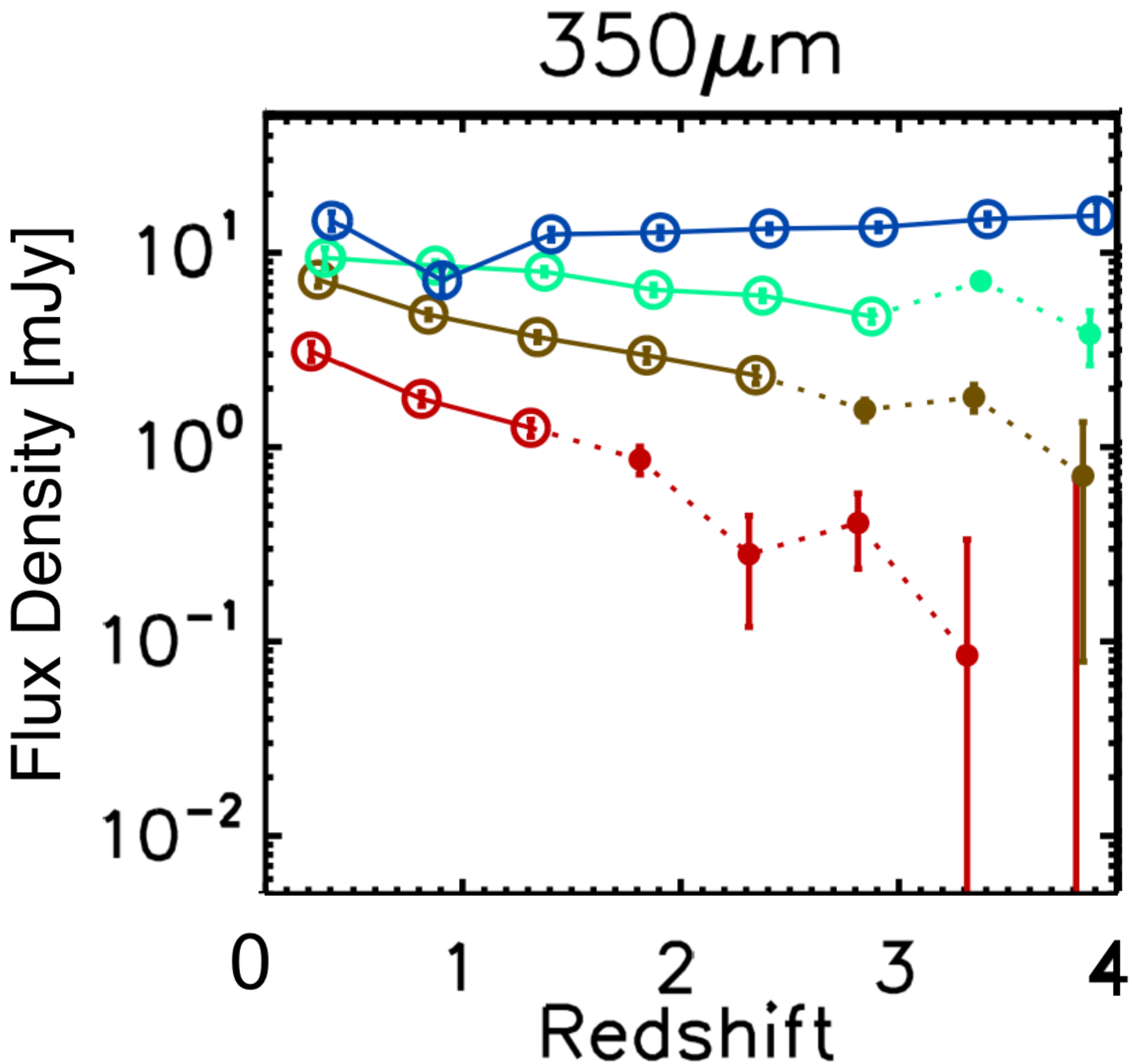
Cosmos - 1.8 x 1.8 deg

# z=1.0 to 1.5


M = 9.5-10
X Y
996 1009
55 1011
187 1010
501 1011
336 1012
127 1011
⋮
M = 10-10.5
X Y
535 1026
345 1029
340 1029
517 1027
805 1031
805 1031
⋮
M = 10.5-11
X Y
345 1029
340 1029
517 1027
805 1031
805 1031
238 1032
359 1033
841 1034
⋮
$\times C_1$
+
$\times C_2 \approx$
+
⋮
+
$\times C_N$

# SIMSTACK: Flux Densities (M,z)

HERMES



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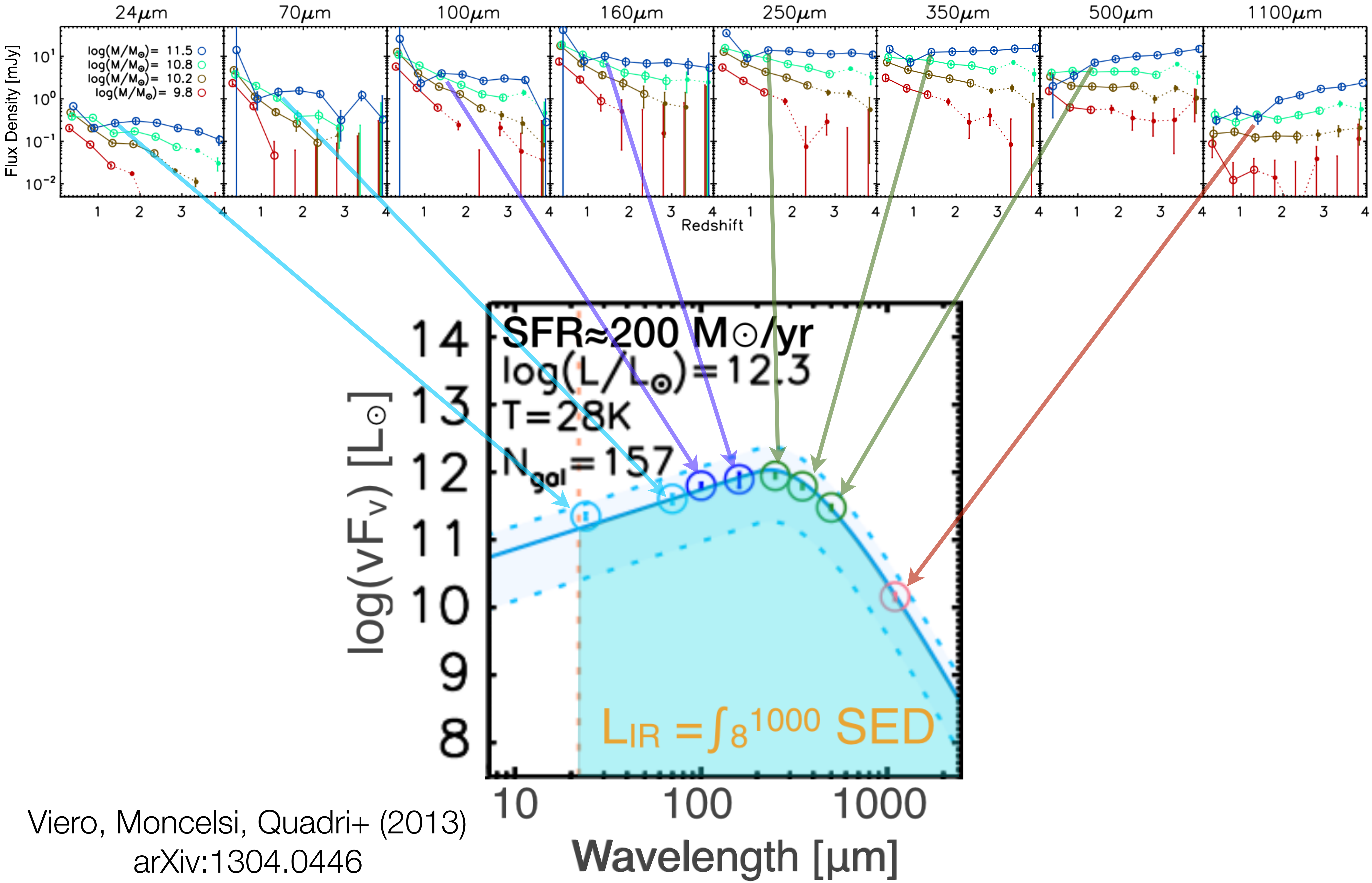
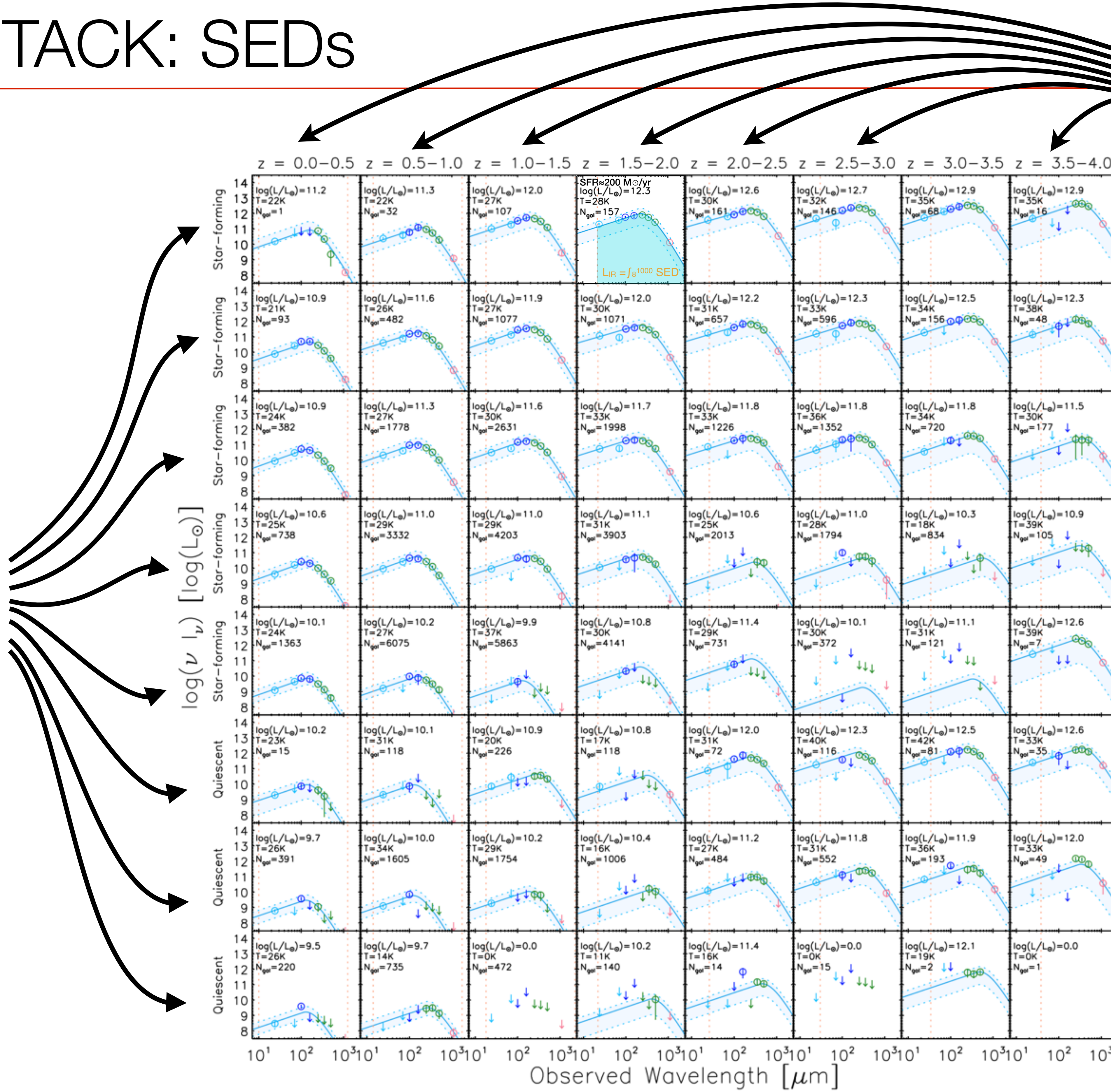



Viero, Moncelsi, Quadri+ (2013)
arXiv:1304.0446

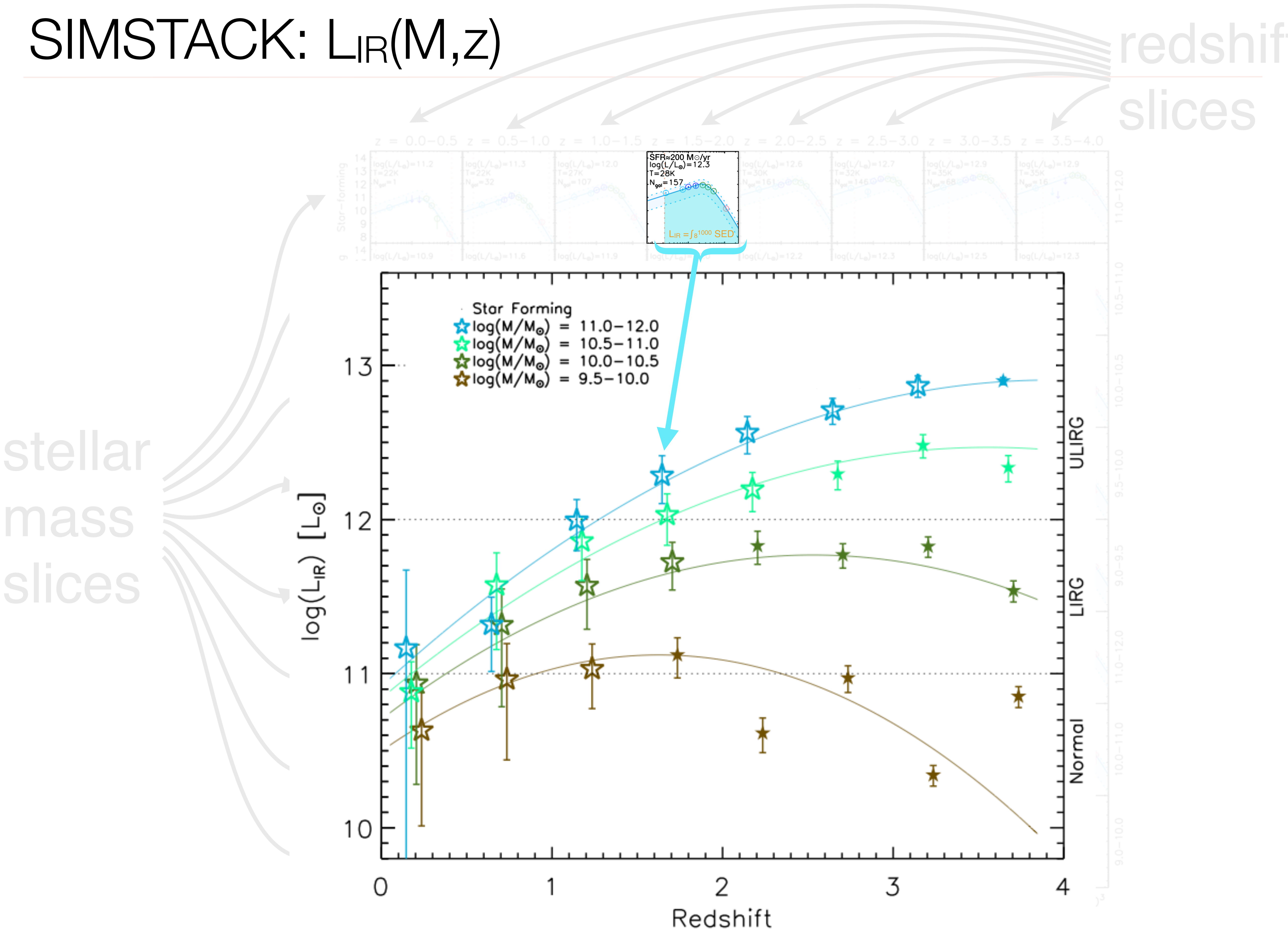
# SIMSTACK: SEDs

redshift slices

stellar mass slices



# SIMSTACK: $L_{IR}$(M,z)



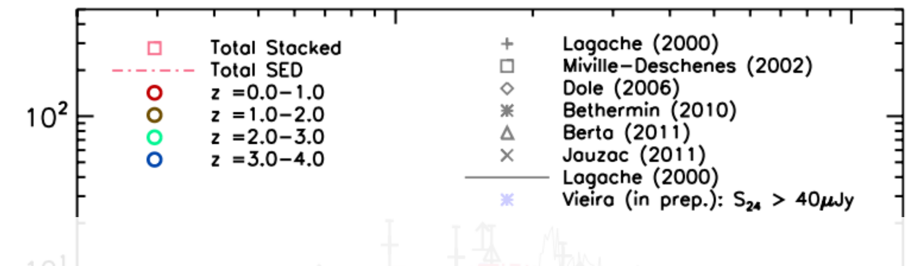
# CIB Breakdown

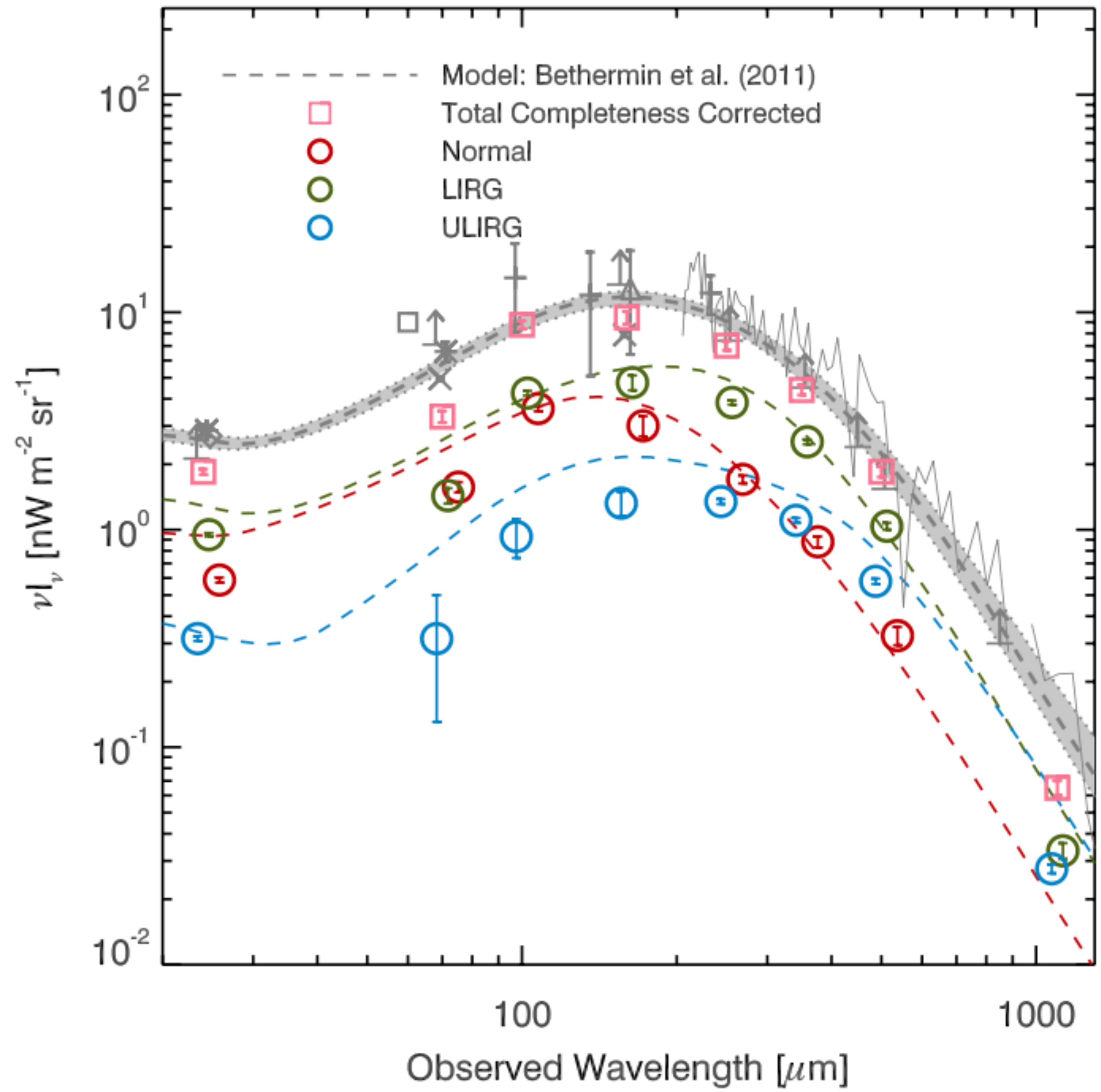
Split Sample by:

ULIRGS

LIRGS

Normal

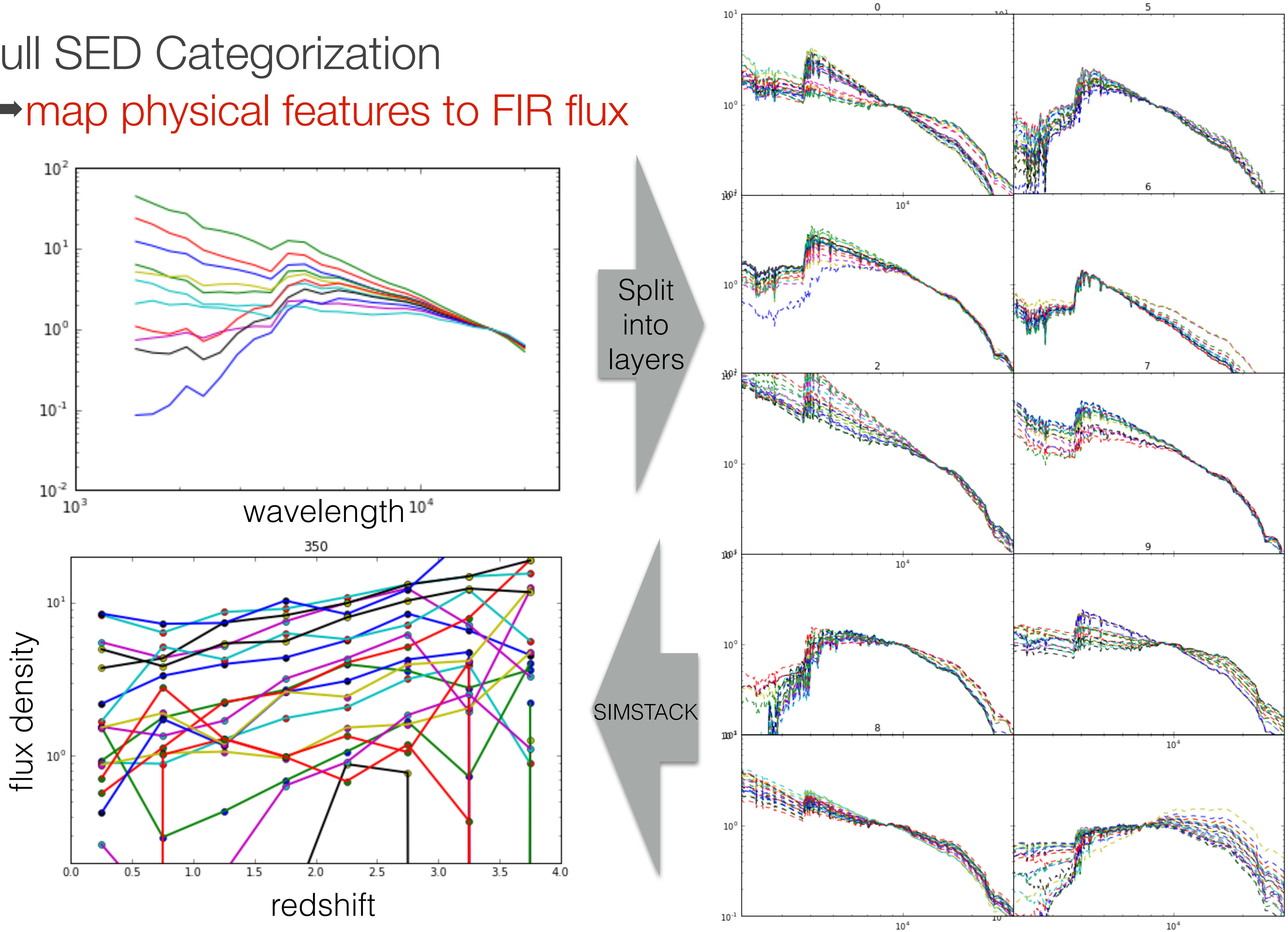


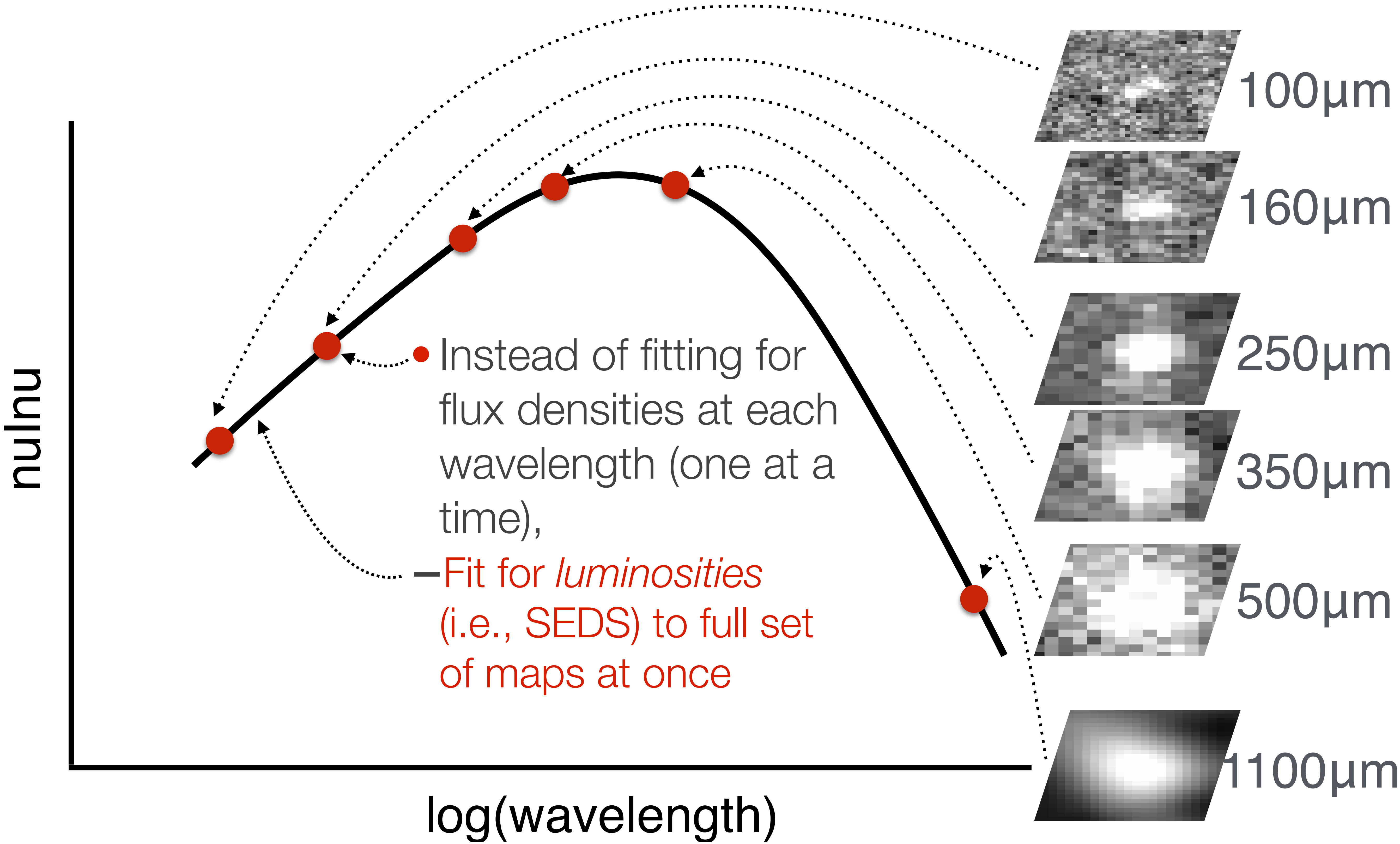

Viero, Moncelsi, Quadri et al. (2013)
arXiv:1304.0446

# SIMSTACK: Beyond Colour

- Full SED Categorization
  - ➡ map physical features to FIR flux



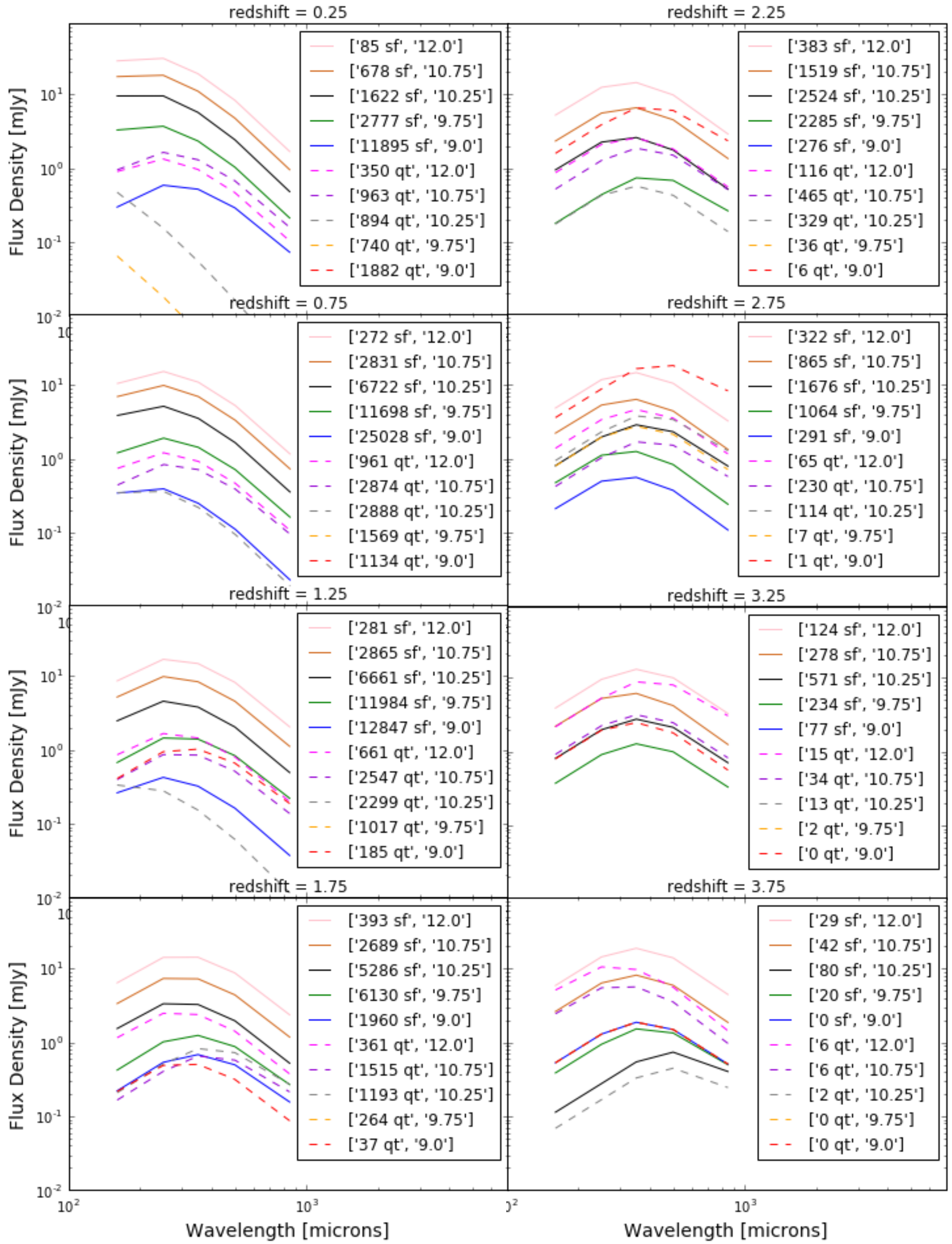
# SEDSTACK: Beyond Flux

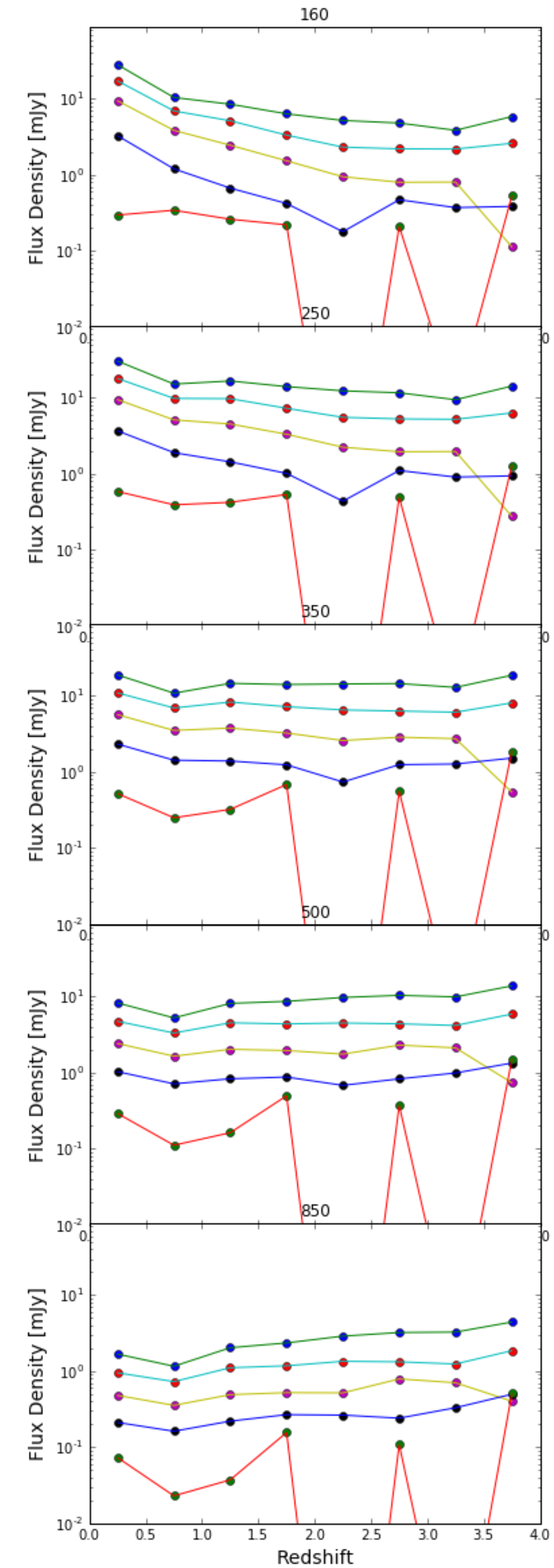



- Instead of fitting for flux densities at each wavelength (one at a time),
  - Fit for *luminosities* (i.e., SEDS) to full set of maps at once

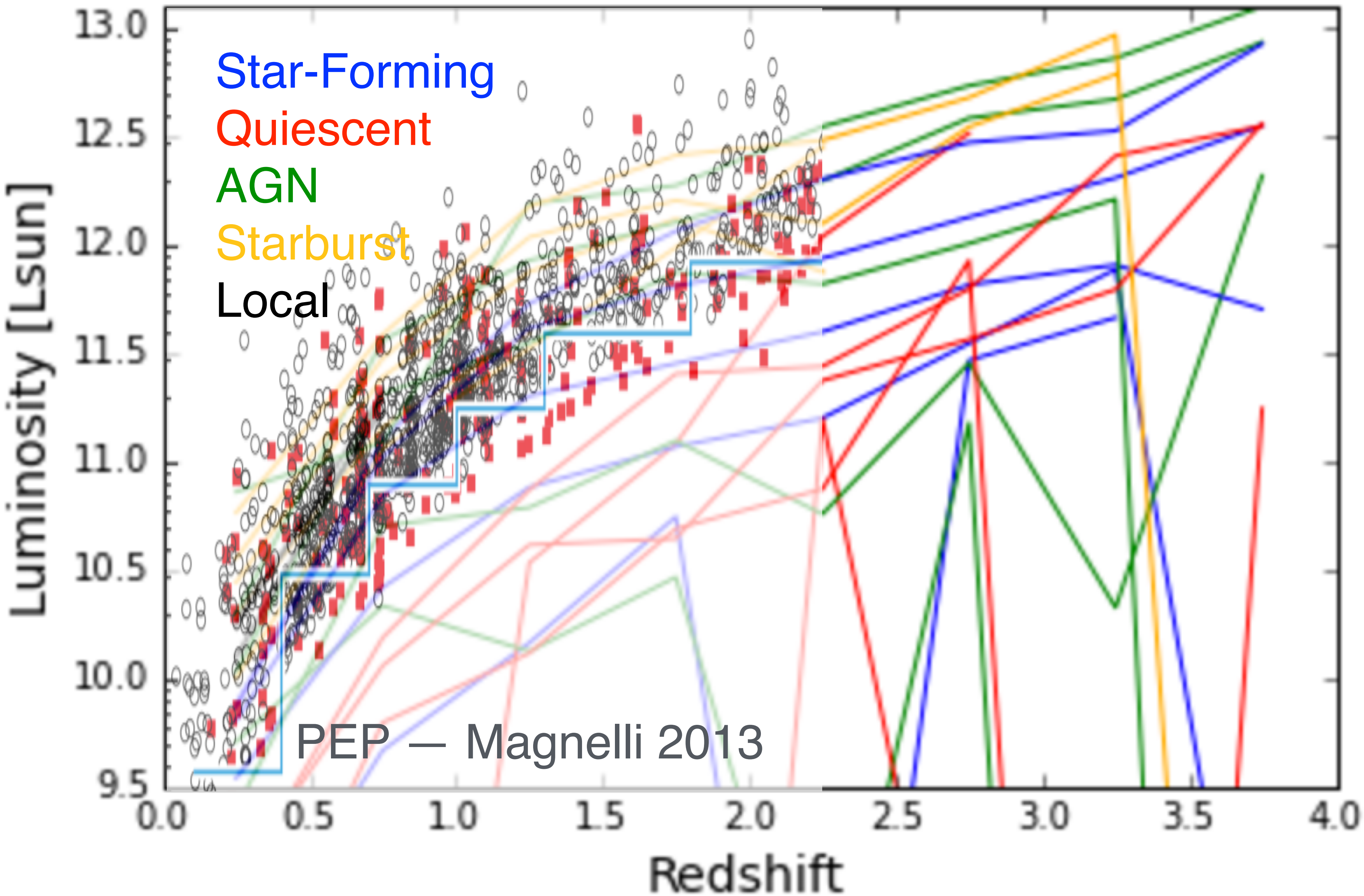
# SEDSTACK in z - M - QT/SF bins

- Advantages:
  - ➡ leverage high S/N components to better constrain faint-end



# SEDSTACK: Beyond Flux

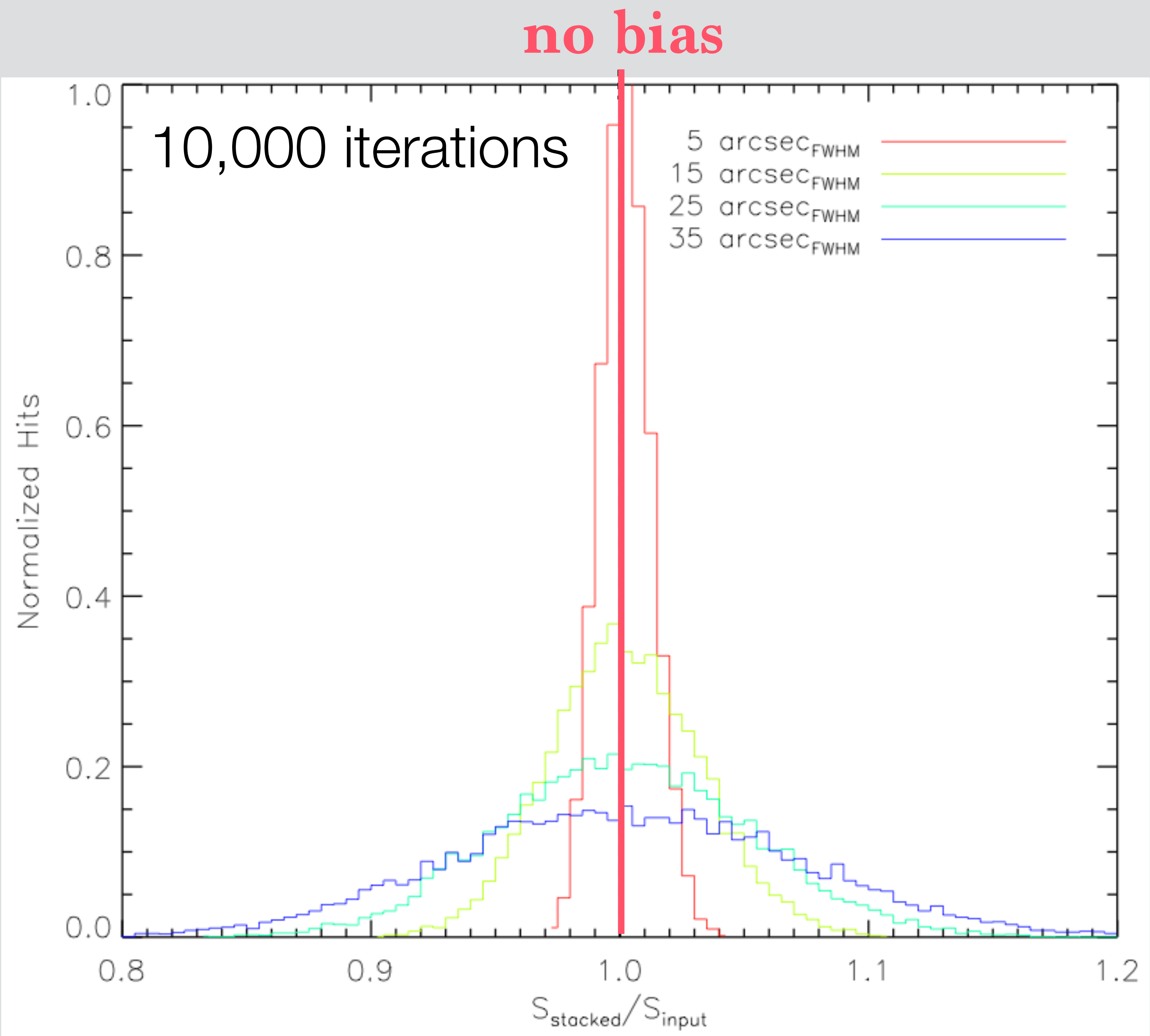



- SEDSTACK lets us explore more layers (e.g, here 25)
- Deeper than "The deepest Herschel-PACS far-infrared survey" Magnelli (2013)

So, 70% of CIB identified…
what about the rest?

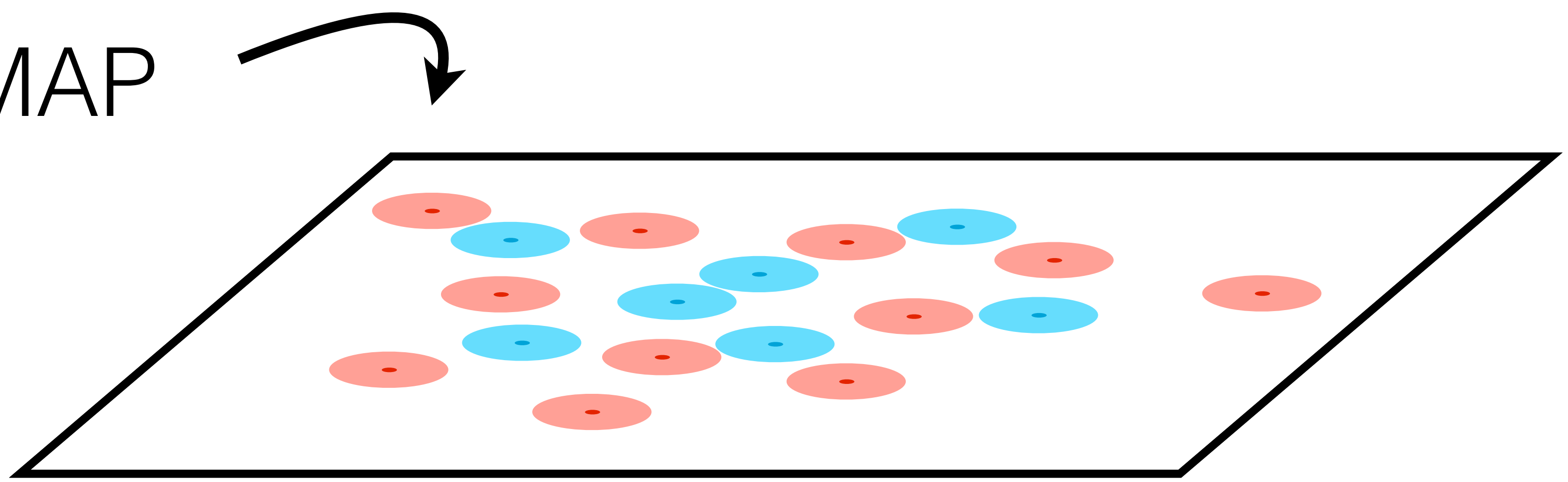
# Aside: Correlated vs. Uncorrelated Emission

- Uncorrelated emission does not bias result, only increases noise

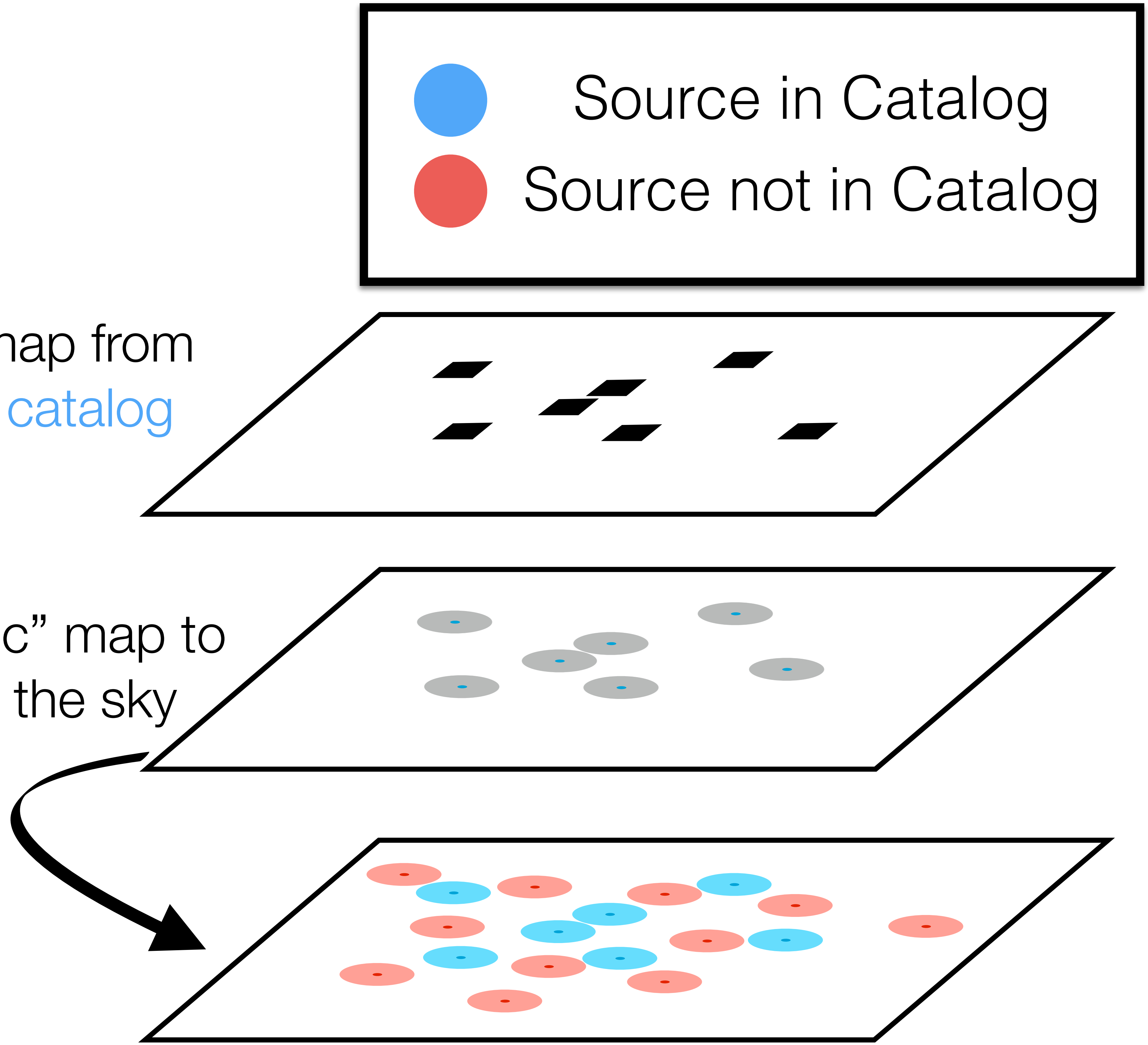


# A New Accounting of the CIB


Imagine this is a SKY MAP



# A New Accounting of the CIB

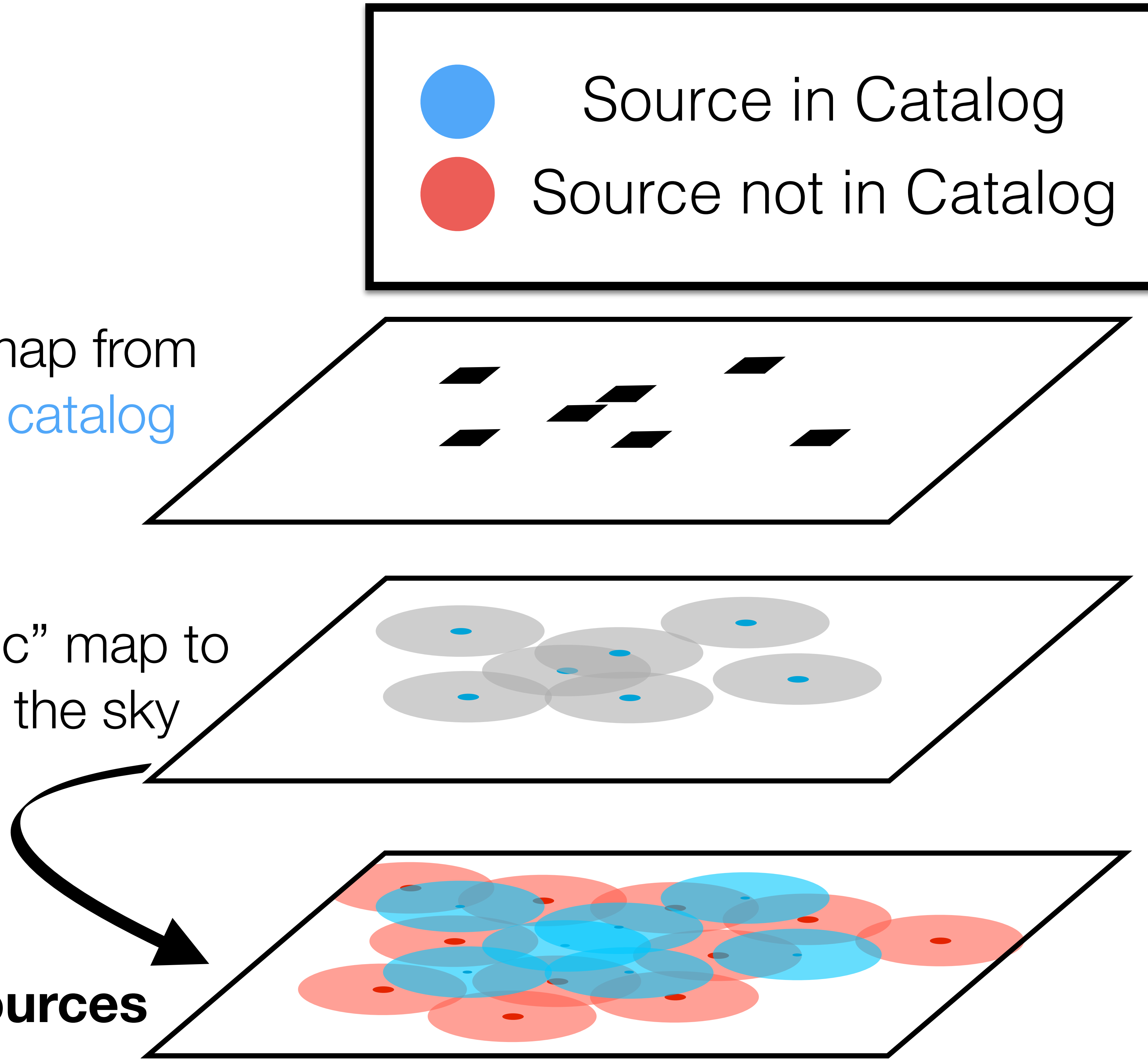



make synthetic “hits” map from positions of sources in catalog

fit “synthetic” map to the map of the sky

***Un*****biased if :**
**-beam is small**

# A New Accounting of the CIB




make synthetic "hits" map from positions of sources in catalog

fit "synthetic" map to the map of the sky

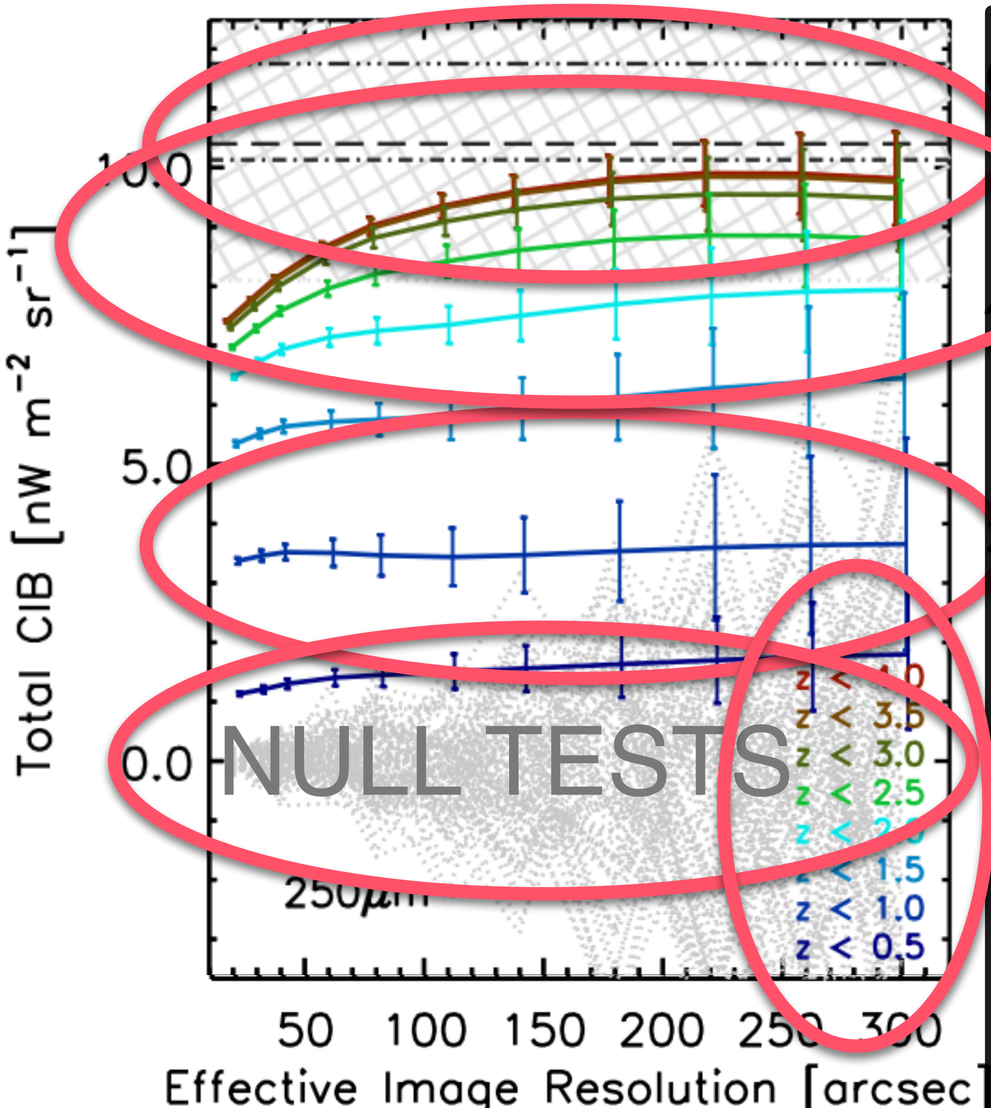
***Biased* if :**

**-beam is big**

**-missing a lot of sources**

# A New Accounting of the CIB

COBE: Fixsen 1998 -----------------




- x-axis increasing beam
- y-axis cumulative Intensity below z
- FIRAS Direct measurement ~30% errors
- Null tests on random positions
- Flat because Catalog is ~100% complete to log(M/Msun) = 9 - 11.5
- Nearly all of the CIB is accounted for by emission correlated with known, cataloged, galaxies. ***But is it necessarily originating from galaxies?***

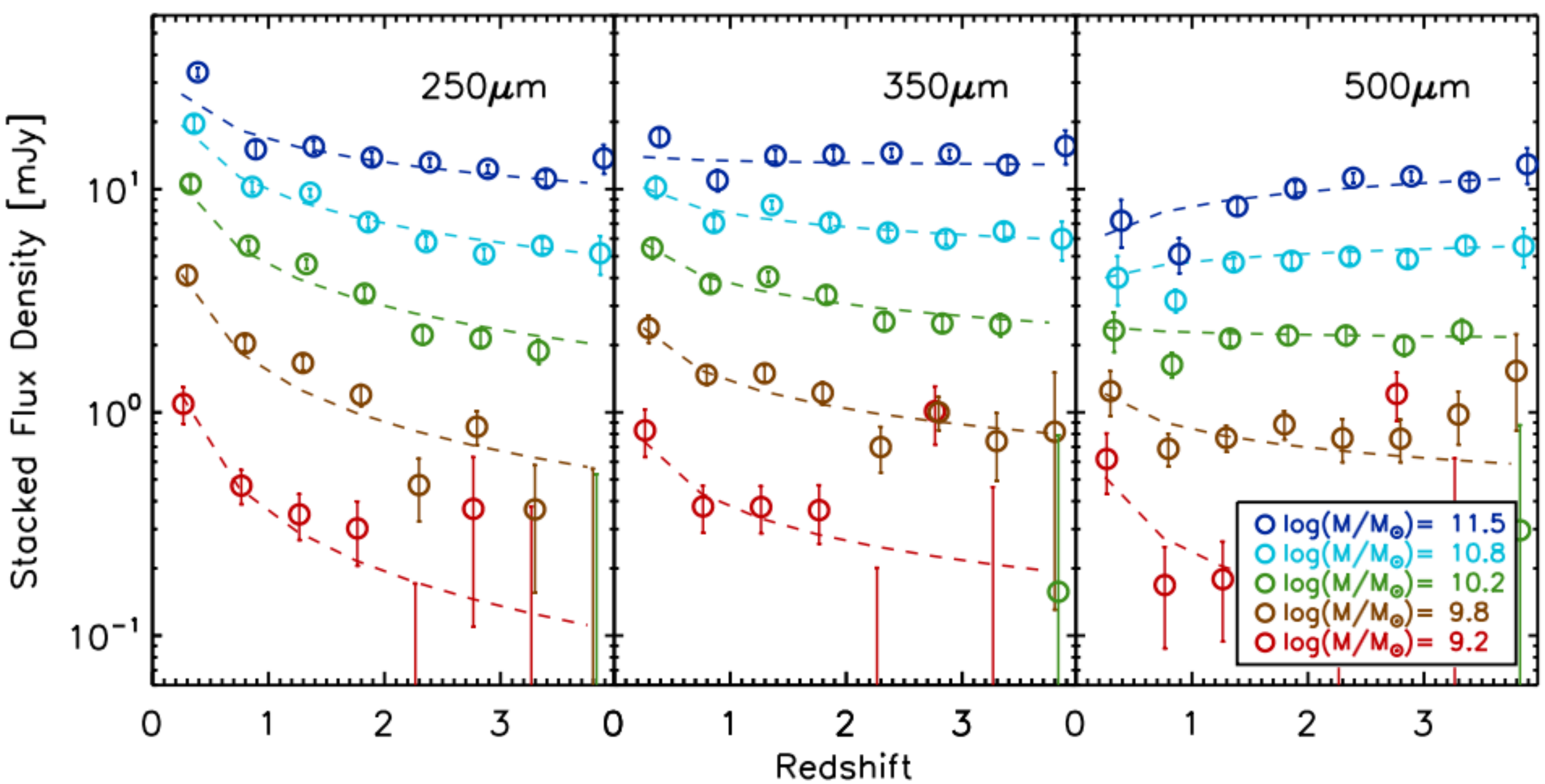
**Smooth with bigger beam** →

Viero, Moncelsi, Quadri et al. (2015)
arXiv:1505.06242

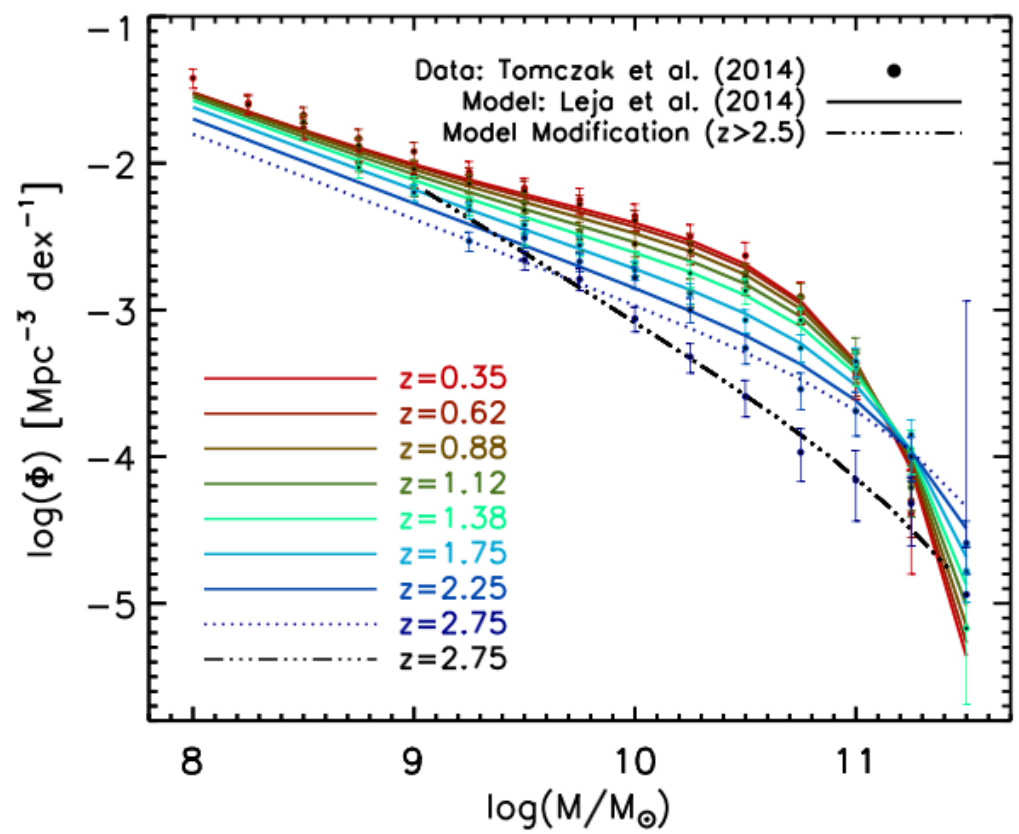
# A New Accounting of the CIB

HERMES

## Submillimeter Flux Densities



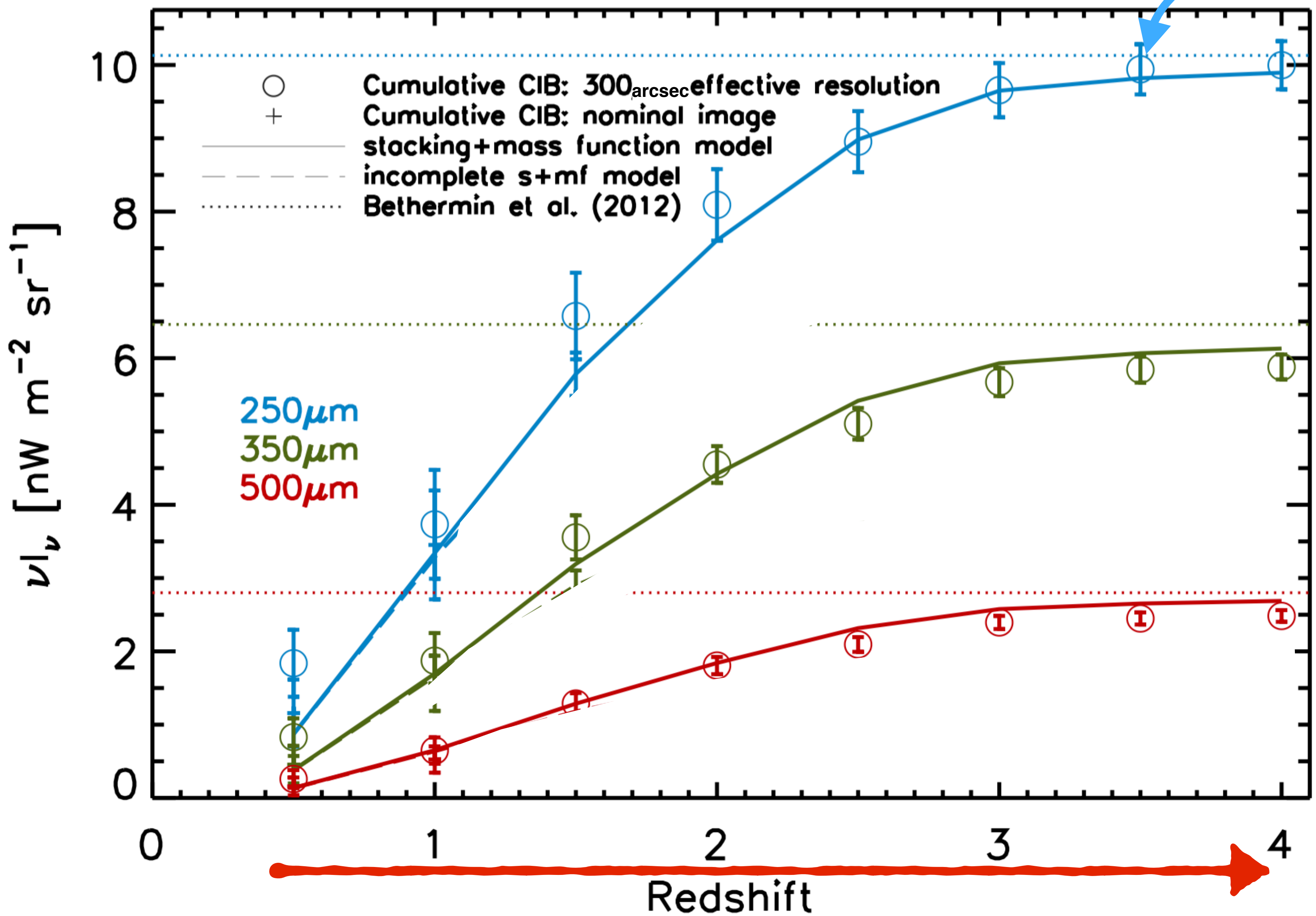

## Stellar Mass Functions

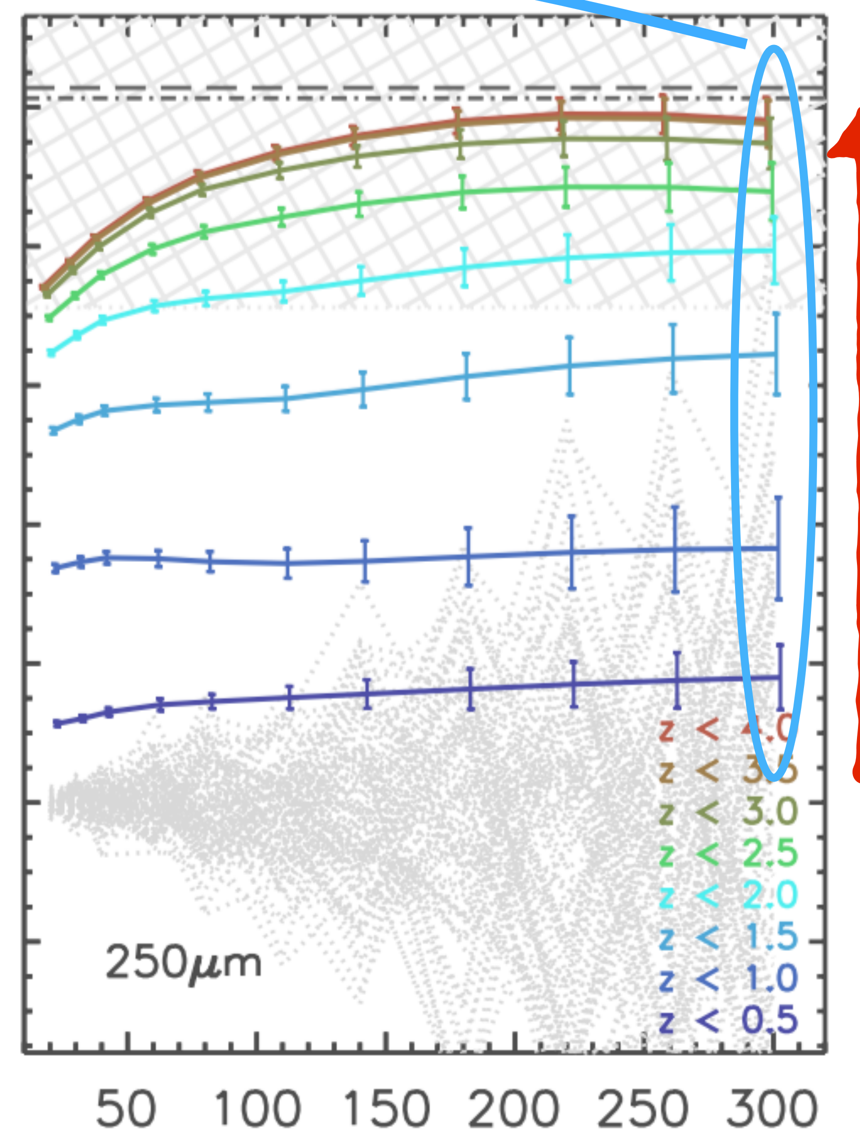



- Parametric fit to the (nominally) stacked flux densities (dashed lines)
- Parametric fit to the stellar mass functions from Leja et al. 2014 (solid lines)

# A New Accounting of the CIB

HERMES




Viero, Moncelsi, Quadri et al. (2015)
arXiv:1505.06242

- Circles/Solid lines: Model compared to total CIB after smoothing to 300 arcsec FWHM.

# A New Accounting of the CIB: Summary

HERMES

- Current Estimates of the total CIB can be explained by known galaxies, and their correlated companions, at z < 4
- This technique is not limited to submillimeter maps or CIB studies
  - ➡ as we push to higher redshifts, intensities will be powerful probes of first galaxies, which will be faint, numerous, and highly correlated

Viero, Moncelsi et al. (2015) — arXiv:1505.06242

THE ASTROPHYSICAL JOURNAL LETTERS, 809:L22 (6pp), 2015 August 20 doi:10.1088/2041-8205/809/2/L22


HERMES: CURRENT COSMIC INFRARED BACKGROUND ESTIMATES CAN BE EXPLAINED BY KNOWN GALAXIES AND THEIR FAINT COMPANIONS AT $z < 4$

M. P. VIERO[1,2], L. MONCELSI[2], R. F. QUADRI[3], M. BÉTHERMIN[4,5], J. BOCK[2,6], D. BURGARELLA[7], S. C. CHAPMAN[8], D. L. CLEMENTS[9], A. CONLEY[10], L. CONVERSI[11], S. DUIVENVOORDEN[12], J. S. DUNLOP[13], D. FARRAH[14], A. FRANCESCHINI[15], M. HALPERN[16], R. J. IVISON[13,17], G. LAGACHE[7], G. MAGDIS[18], L. MARCHETTI[15], J. ÁLVAREZ-MÁRQUEZ[7], G. MARSDEN[16], S. J. OLIVER[12], M. J. PAGE[19], I. PÉREZ-FOURNON[20,21], B. SCHULZ[2,22], DOUGLAS SCOTT[16], I. VALTCHANOV[11], J. D. VIEIRA[23,24], L. WANG[25,26], J. WARDLOW[27], AND M. ZEMCOV[2,6]

ABSTRACT

We report contributions to cosmic infrared background (CIB) intensities originating from known galaxies and their faint companions at submillimeter wavelengths. Using the publicly available UltraVISTA catalog and maps at 250, 350, and 500 $\mu$m from the *Herschel* Multi-tiered Extragalactic Survey, we perform a novel measurement that exploits the fact that uncataloged sources may bias stacked flux densities—particularly if the resolution of the image is poor—and intentionally smooth the images before stacking and summing intensities. By smoothing the maps we are capturing the contribution of faint (undetected in $K_S \sim 23.4$) sources that are physically associated, or *correlated*, with the detected sources. We find that the cumulative CIB increases with increased smoothing, reaching $9.82 \pm 0.78$, $5.77 \pm 0.43$ and $2.32 \pm 0.19$ nWm$^{-2}$ sr$^{-1}$ at 250, 350, and 500 $\mu$m at 300 arcsec FWHM. This corresponds to a fraction of the fiducial CIB of $0.94 \pm 0.23$, $1.07 \pm 0.31$, and $0.97 \pm 0.26$ at 250, 350, and 500 $\mu$m, where the uncertainties are dominated by those of the absolute CIB. We then propose, with a simple model combining parametric descriptions for stacked flux densities and stellar mass functions, that emission from galaxies with $\log(M/M_\odot) > 8.5$ can account for most of the measured total intensities and argue against contributions from extended, diffuse emission. Finally, we discuss prospects for future survey instruments to improve the estimates of the absolute CIB levels, and observe any potentially remaining emission at $z > 4$.

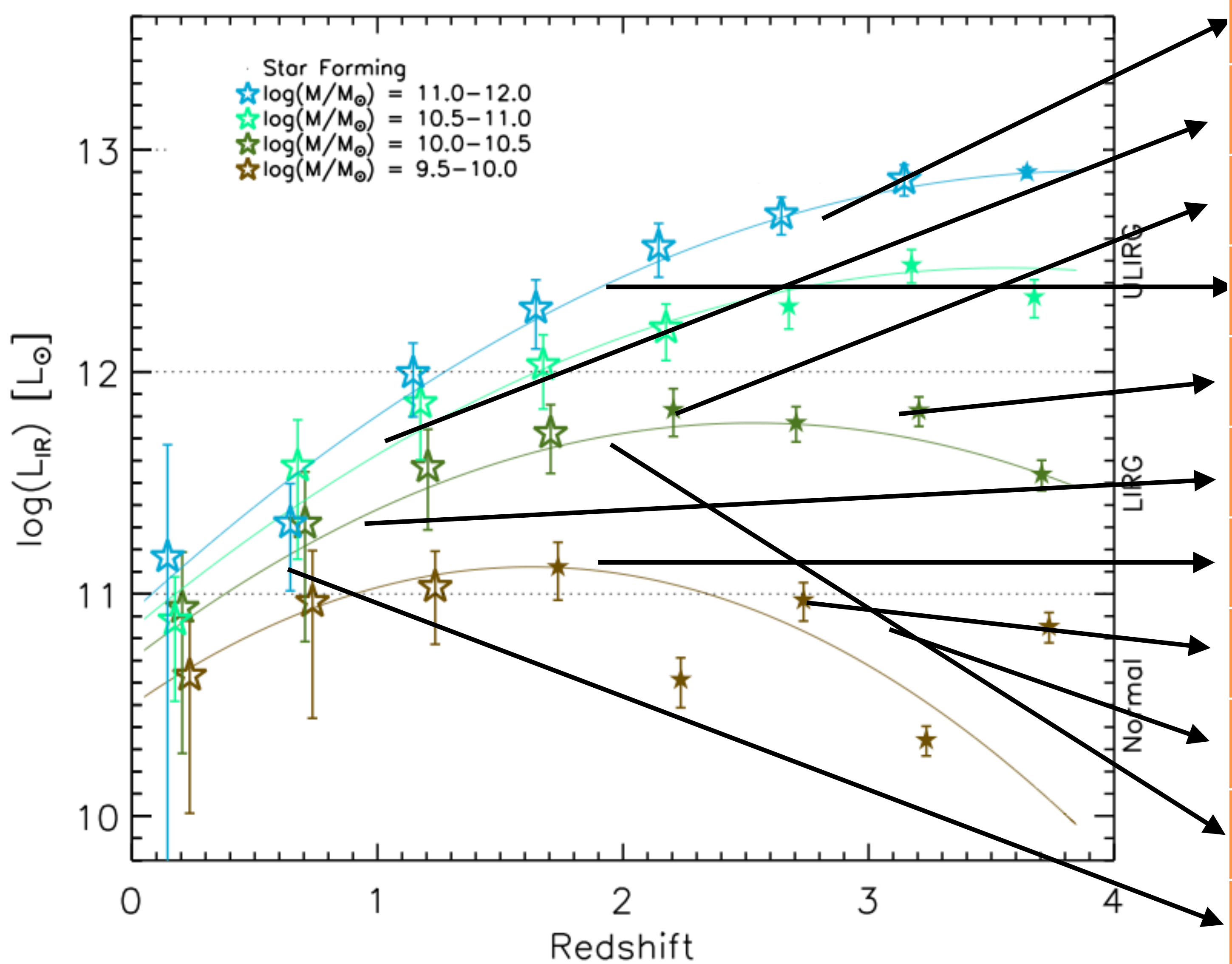
*Key words:* cosmology: observations – galaxies: evolution – infrared: galaxies – large-scale structure of universe – submillimeter: galaxies

1. INTRODUCTION

Of all the light that has been emitted by stars, about half has been absorbed by interstellar dust and thermally re-radiated at far-infrared to submillimeter wavelengths, appearing as a diffuse, extragalactic, cosmic infrared background spanning 1–1000 $\mu$m (CIB; Hauser & Dwek 2001; Dole et al. 2006). Statistically characterizing the sources responsible for this background is necessary to gain a full understanding of galaxy formation and cosmology, and thus remains an ongoing pursuit.

The CIB was first detected in spectroscopy with the Far Infrared Absolute Spectrophotometer (FIRAS; Puget et al. 1996; Mather et al. 1999). Observations of local starburst galaxies with *IRAS* (Soifer et al. 1984) showed that galaxies

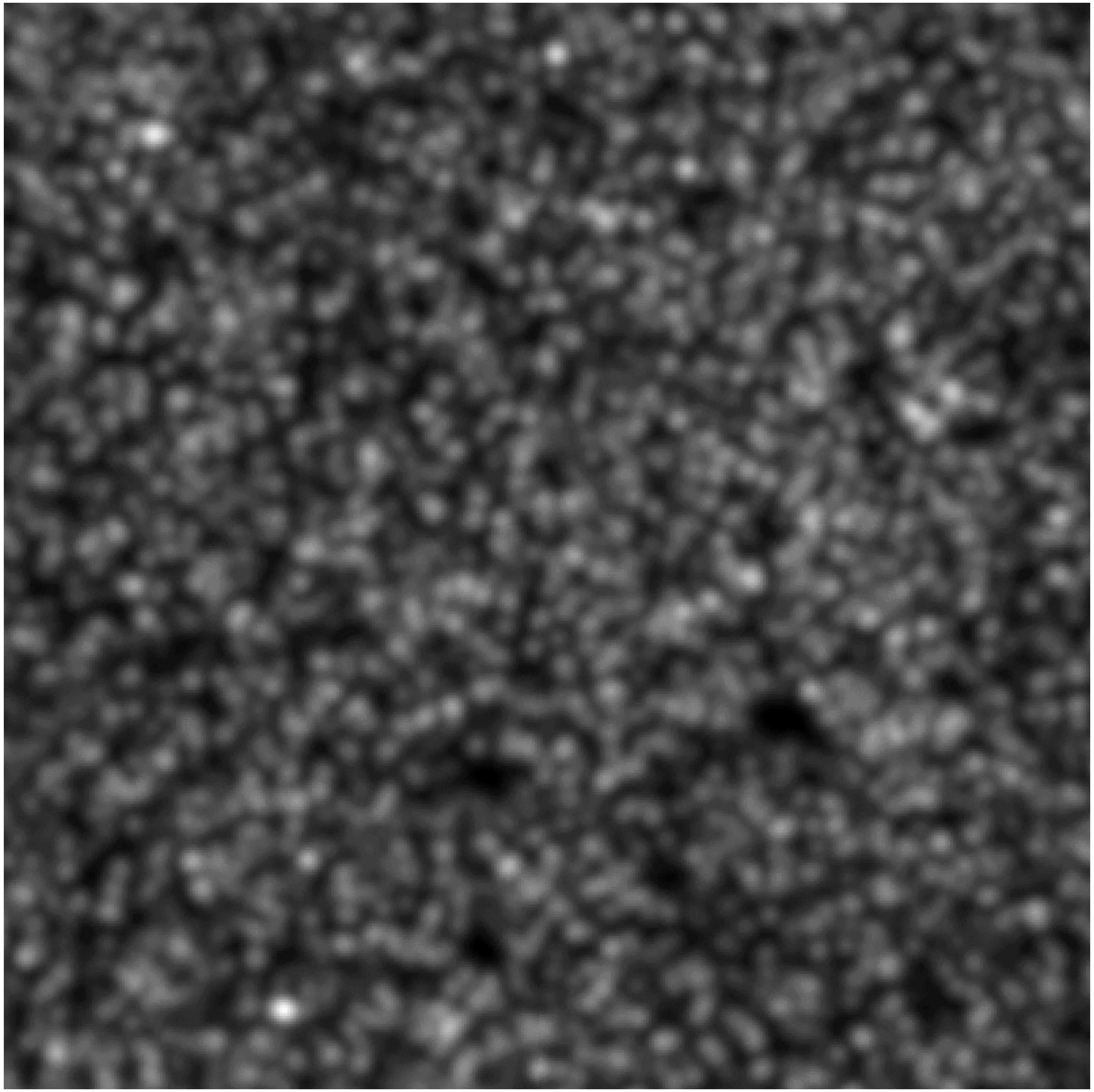
# SIMSTACK: coming full circle



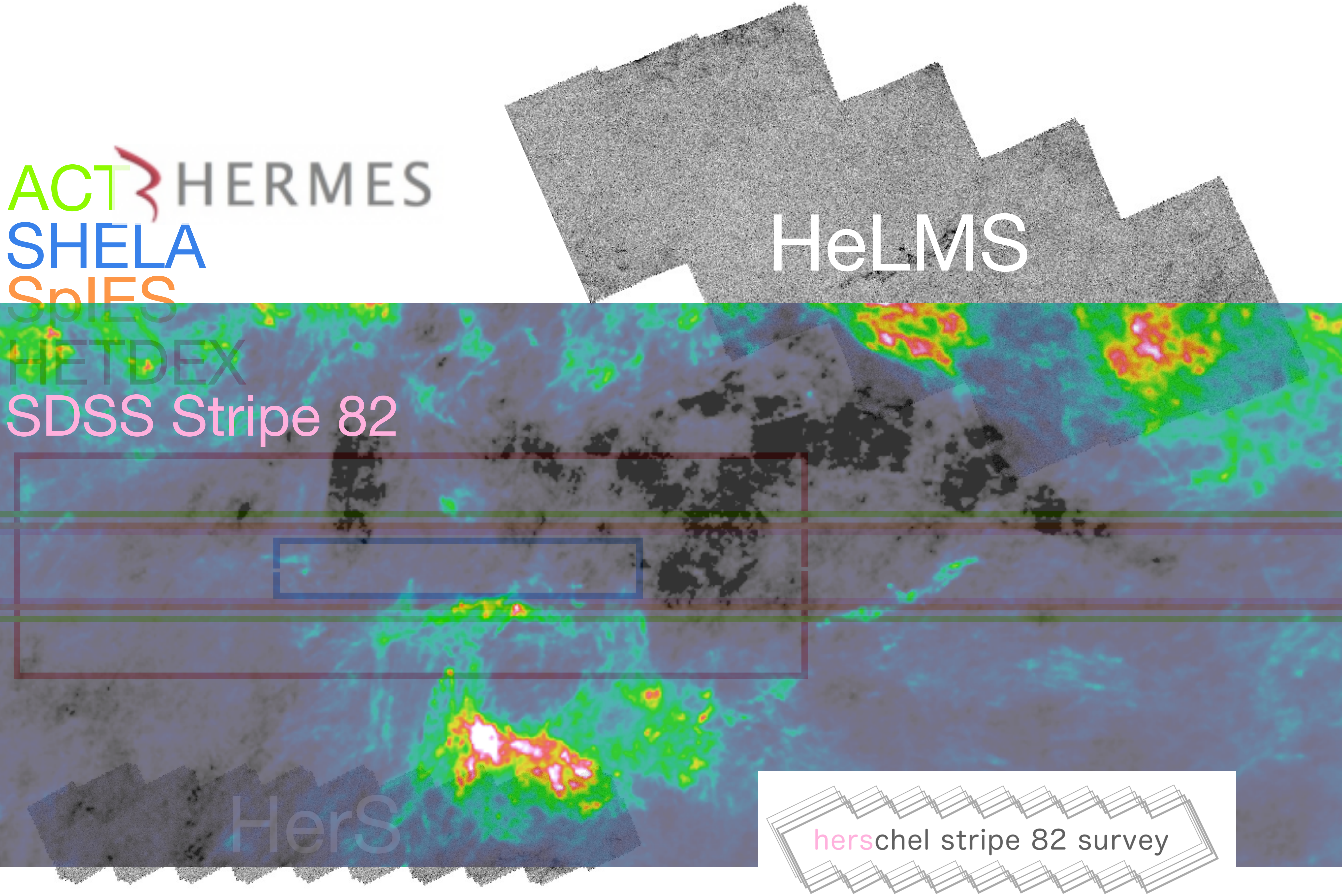

| Flux | RA | DEC |
|---|---|---|
| 41.4 | 149.853 | 2.608 |
| 3.5 | 149.854 | 2.258 |
| 4.4 | 149.752 | 2.584 |
| 16.7 | 149.832 | 2.724 |
| 22.5 | 149.275 | 2.196 |
| 3.6 | 149.262 | 2.966 |
| 5.8 | 149.915 | 2.206 |
| 3.1 | 149.546 | 2.564 |
| 2.3 | 149.824 | 2.047 |
| 4.0 | 149.453 | 2.278 |
| 2.1 | 149.863 | 2.788 |
| … | … | … |

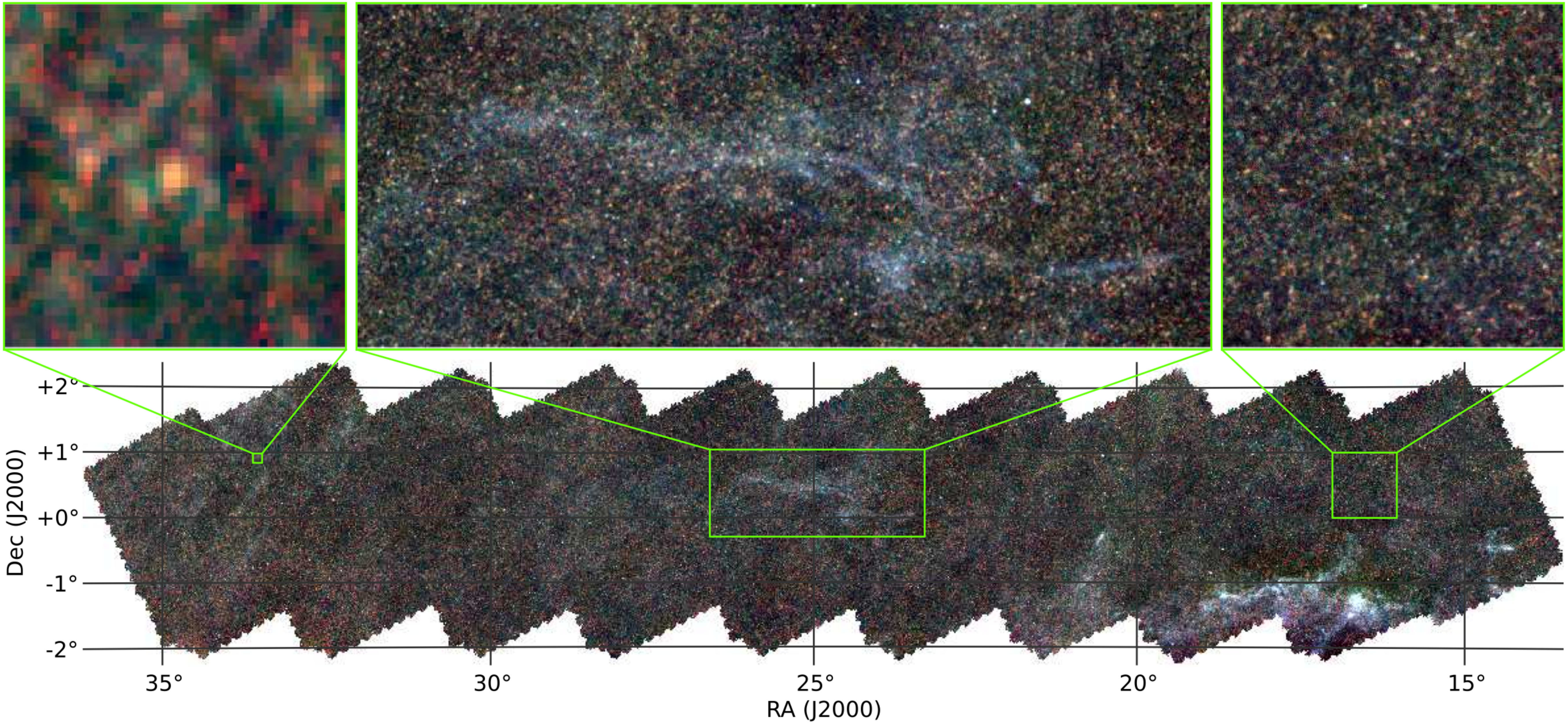
Viero, Moncelsi, Quadri et al. (2013)
arXiv:1304.0446

# SIMSTACK: coming full circle



| Flux | RA | DEC |
|---|---|---|
| 41.4 | 149.853 | 2.608 |
| 3.5 | 149.854 | 2.258 |
| 4.4 | 149.752 | 2.584 |
| 16.7 | 149.832 | 2.724 |
| 22.5 | 149.275 | 2.196 |
| 3.6 | 149.262 | 2.966 |
| 5.8 | 149.915 | 2.206 |
| 3.1 | 149.546 | 2.564 |
| 2.3 | 149.824 | 2.047 |
| 4.0 | 149.453 | 2.278 |
| 2.1 | 149.863 | 2.788 |
| … | … | … |


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:

HerS: http://www.astro.caltech.edu/hers

HeLMS: http://hedam.lam.fr/HerMES/

# Summary

- Intensities are the way of the future, and not limited to FIR
  - ➡as we push to higher redshifts, intensities will be powerful probes of galaxies that are faint, numerous, and highly correlated

- SIMSTACK/SEDSTACK works
  - ➡Splitting up of sample *needs improving*, but eventually will ideally:
    - map optical/NIR features into infrared emission
    - explain the scatter in the star-forming “main sequence”
    - identify true outliers
    - provide measurement-based guidance for IR galaxy models
    - clean foregrounds for very high-z work
  - ➡Python Code — https://github.com/marcoviero/simstack

- Large SPIRE surveys in the SDSS Stripe 82 publicly available:
  - ➡www.astro.caltech.edu/hers
  - ➡hedam.lam.fr/HerMES/