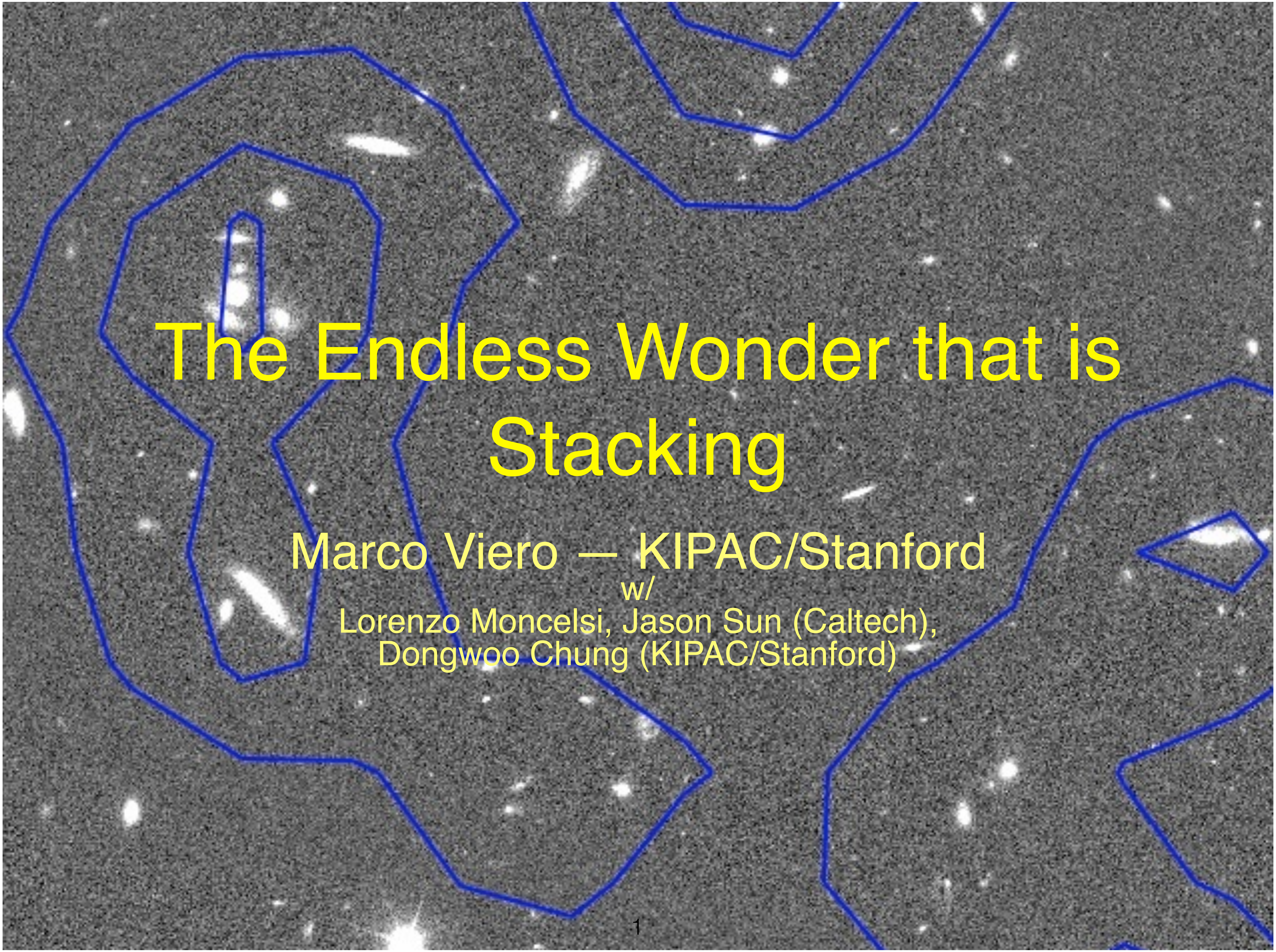


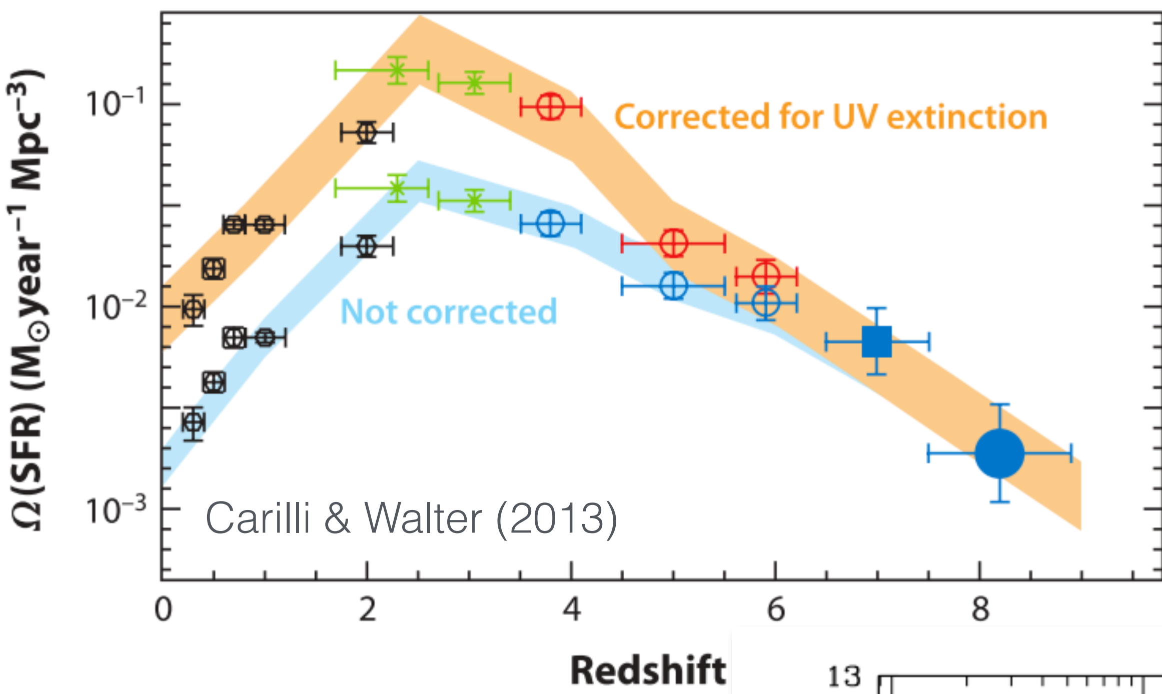
# The Endless Wonder that is Stacking

Marco Viero – KIPAC/Stanford
w/
Lorenzo Moncelsi, Jason Sun (Caltech),
Dongwoo Chung (KIPAC/Stanford)

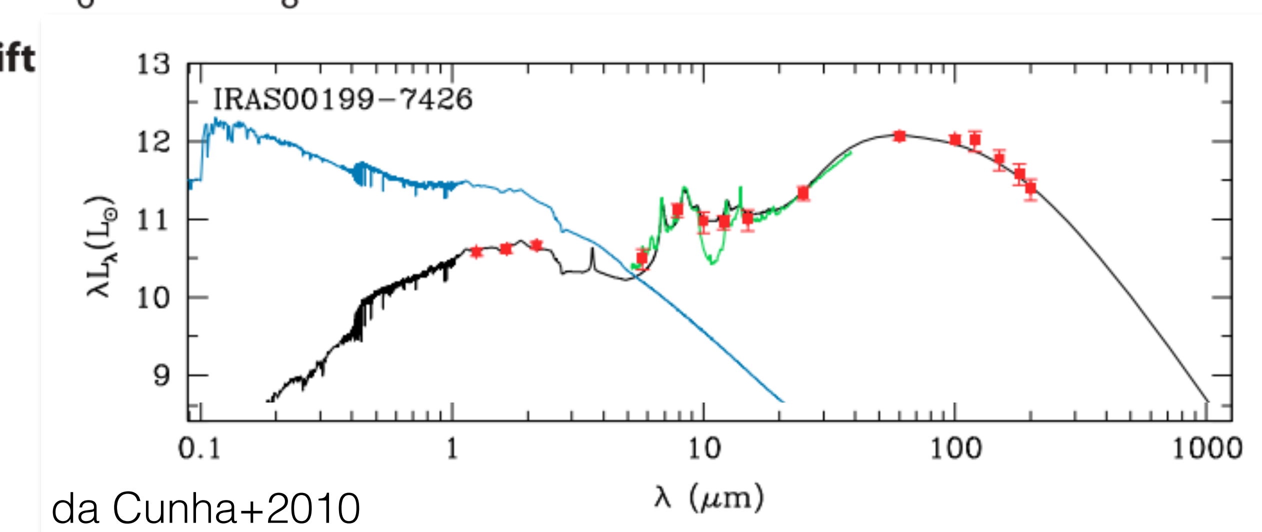
# Outline

- The CIB
- The challenge
- The solution
  - SIMSTACK code and how to use it.
- Some interesting results
- Some applications and Future work

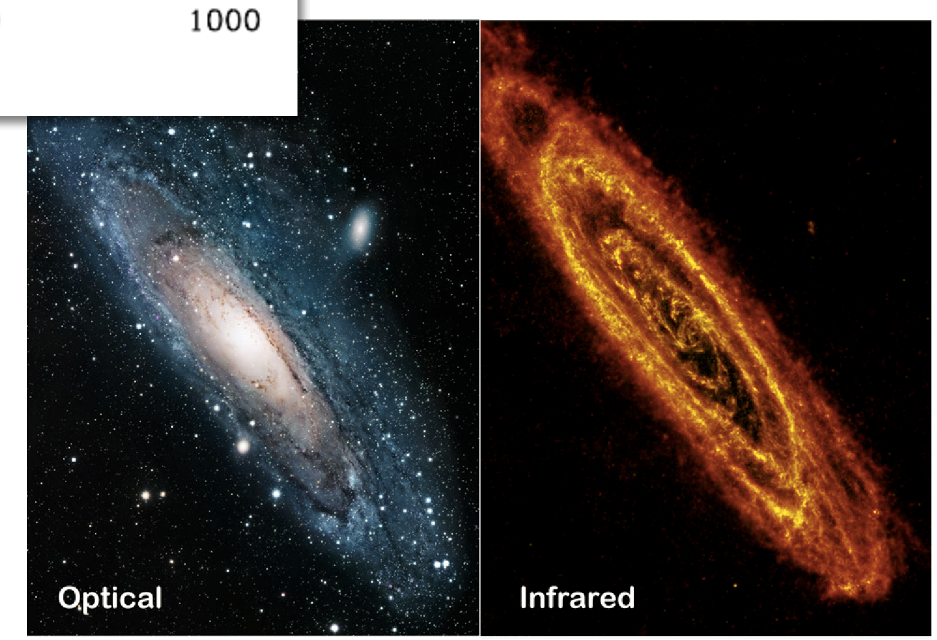
# Motivation — History of Star Formation




- Infrared/Submillimeter emission reprocessed starlight by dust.
- IR/Submm traces star formation.
- The CIB contains the integrated history of star formation.

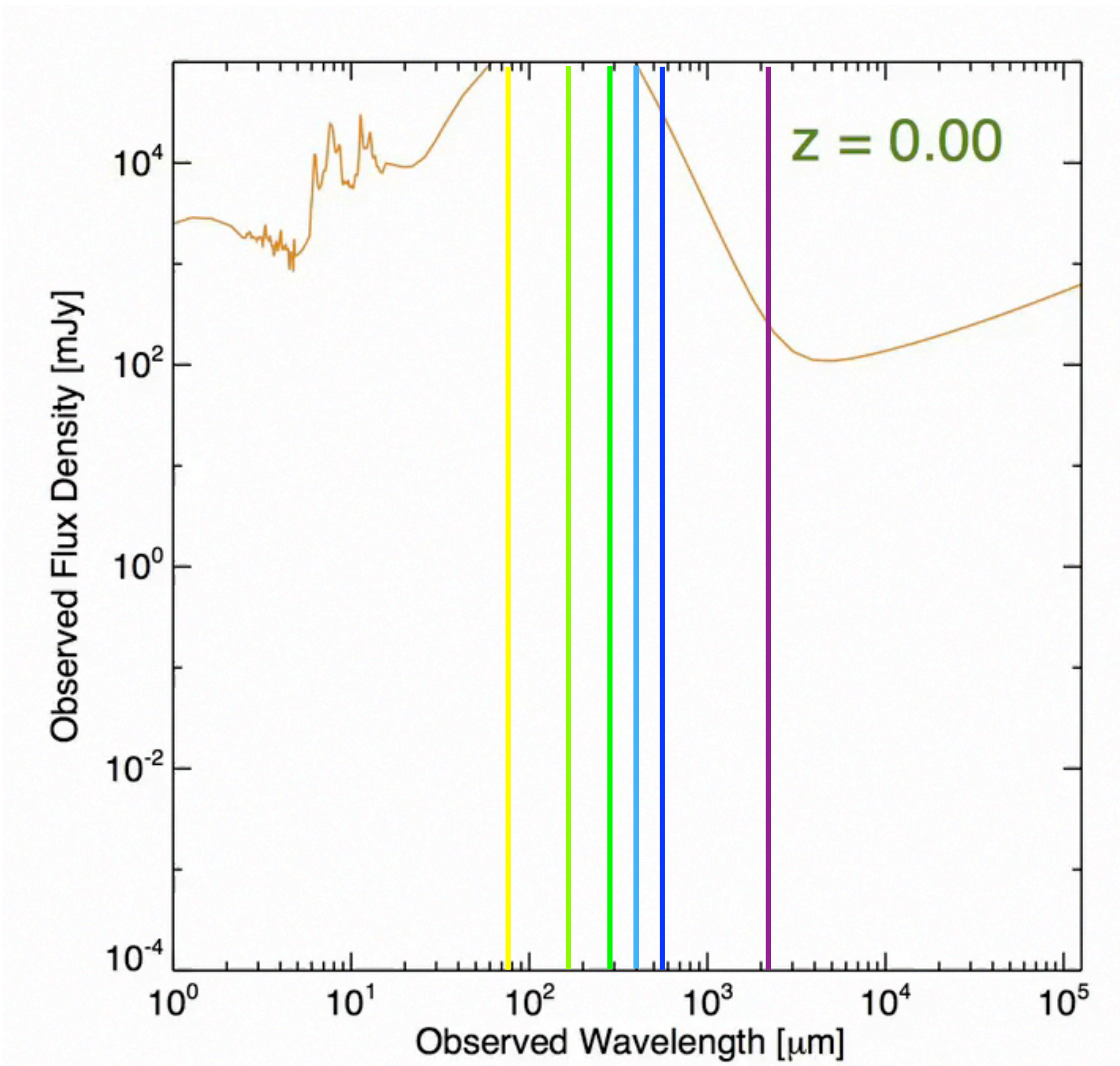



- Why not determine SFRs by observe the dust directly, rather than correcting UV?
- Missing population of dusty galaxies at high-z?
- Outliers?

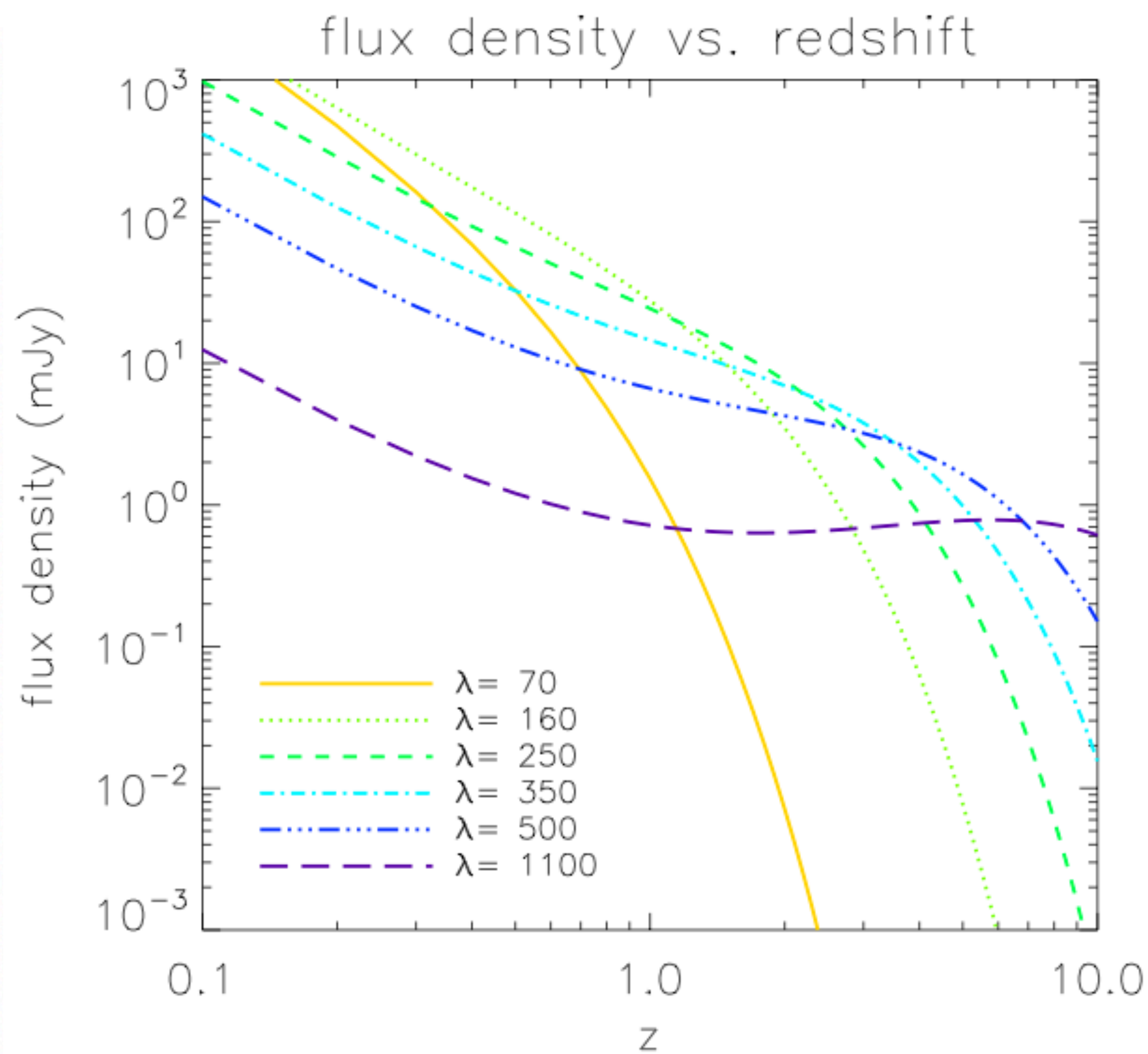


# Dusty Galaxies at High-z

- Negative K-correction means galaxies remain bright as z increases!

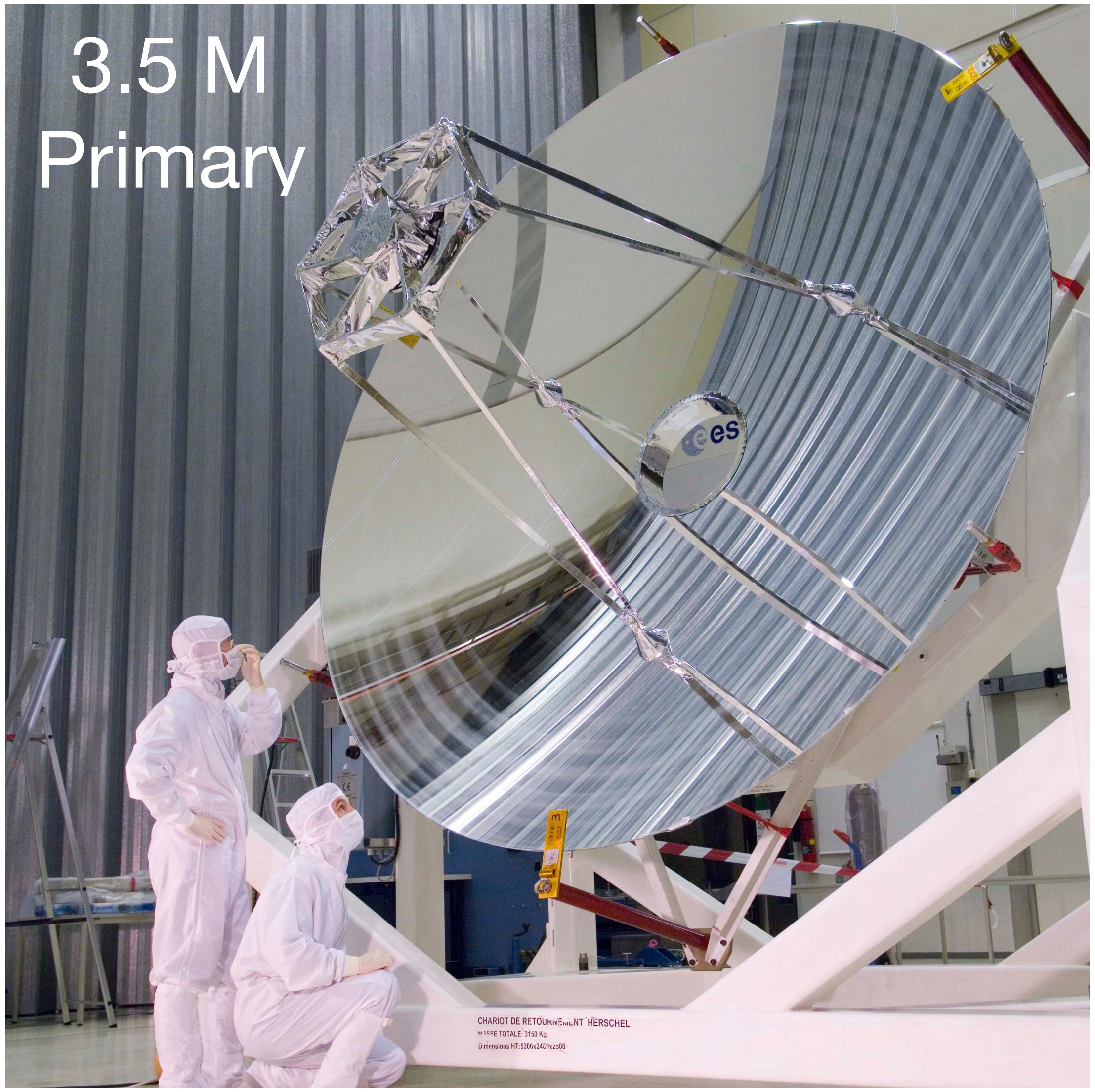


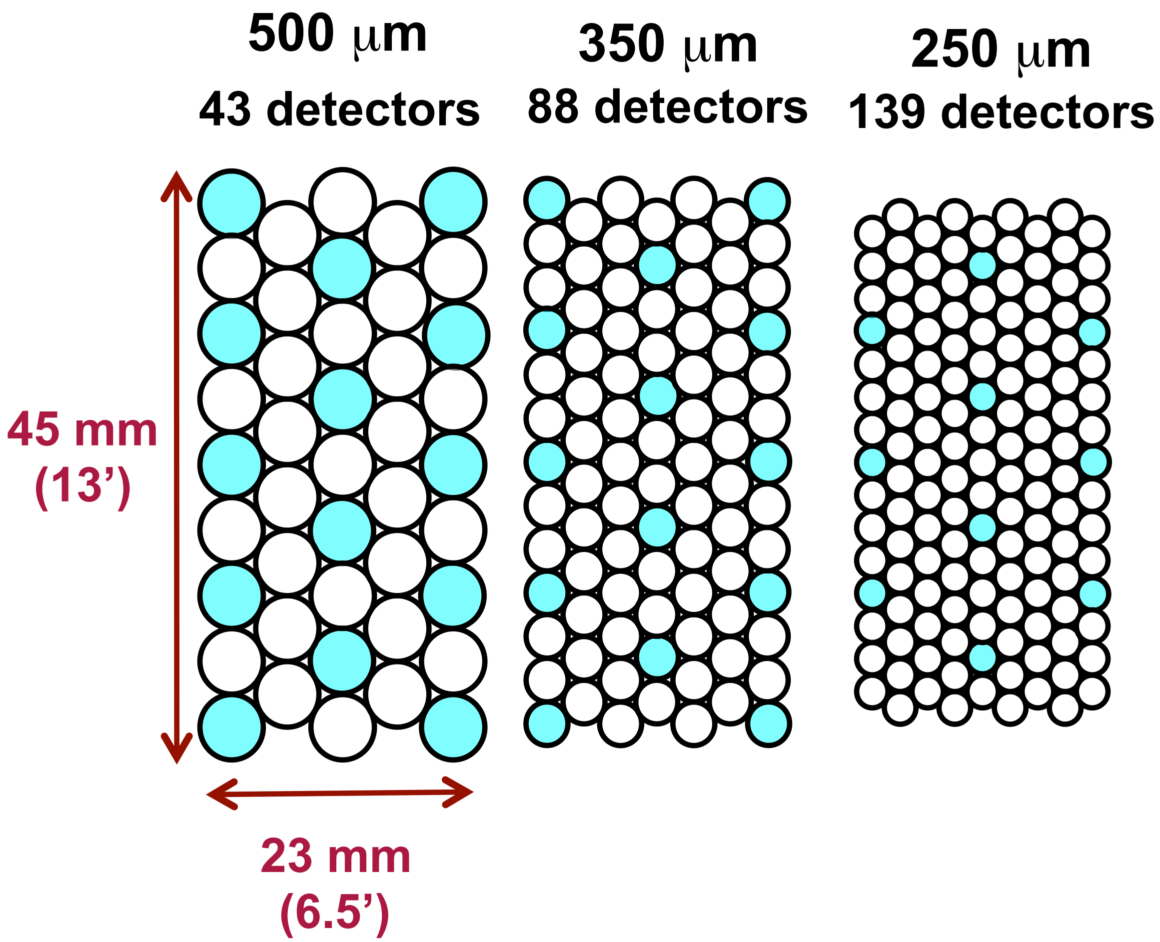

Animation credit — Caitlin Casey (UT Austin)



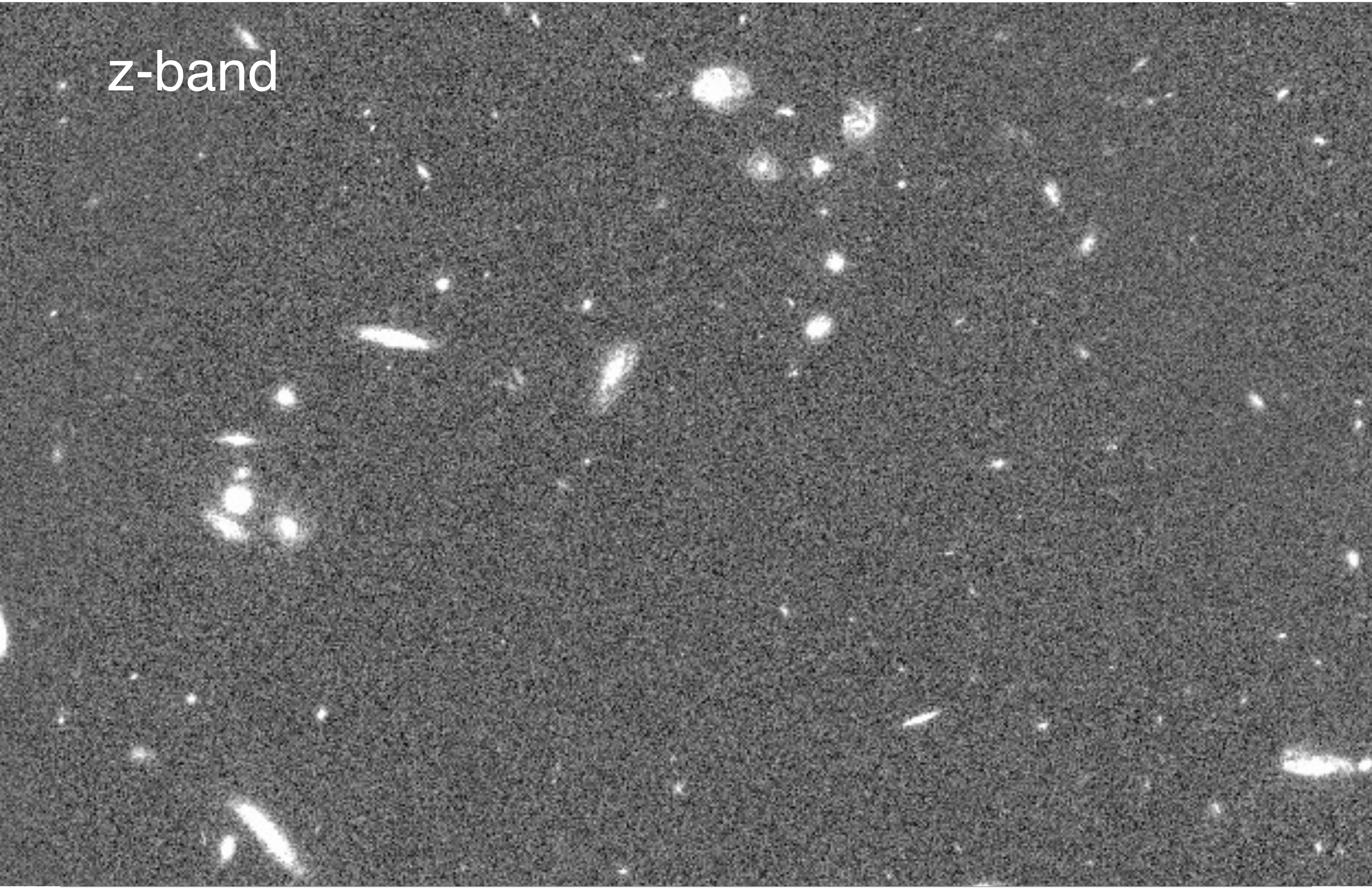
# *Herschel Space Observatory* — SPIRE

| 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 |



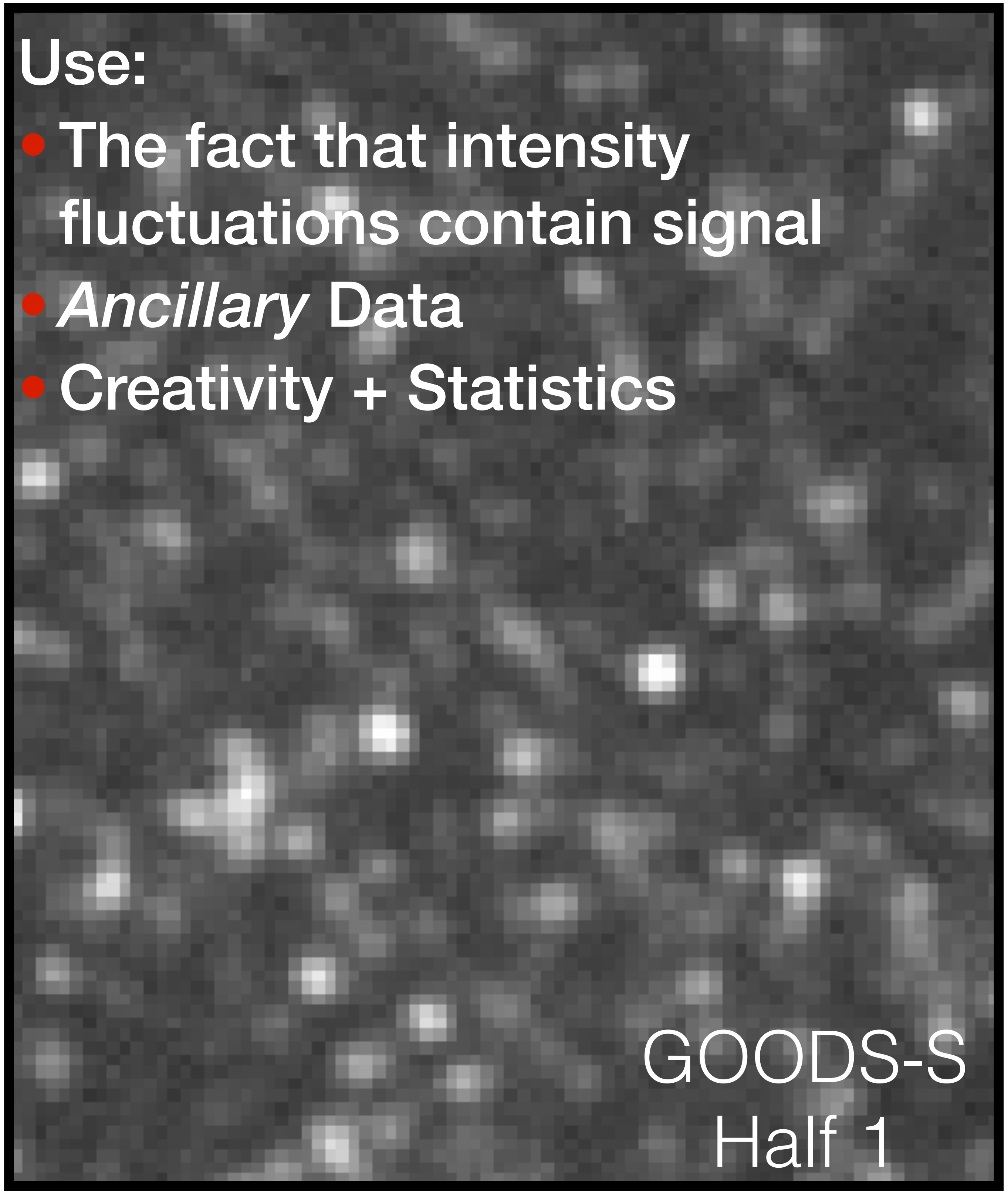
# Challenge — Source Confusion

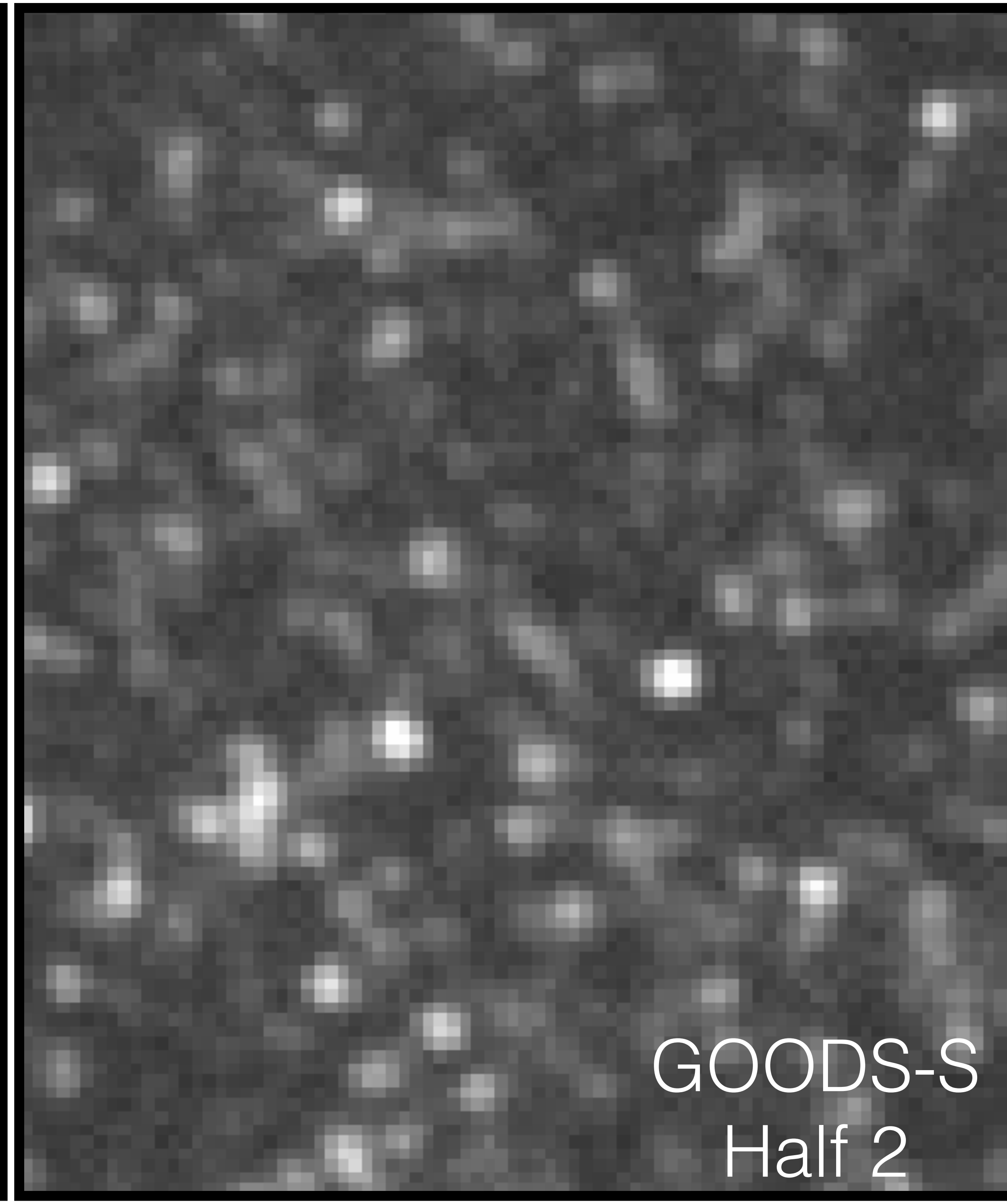


# Solution

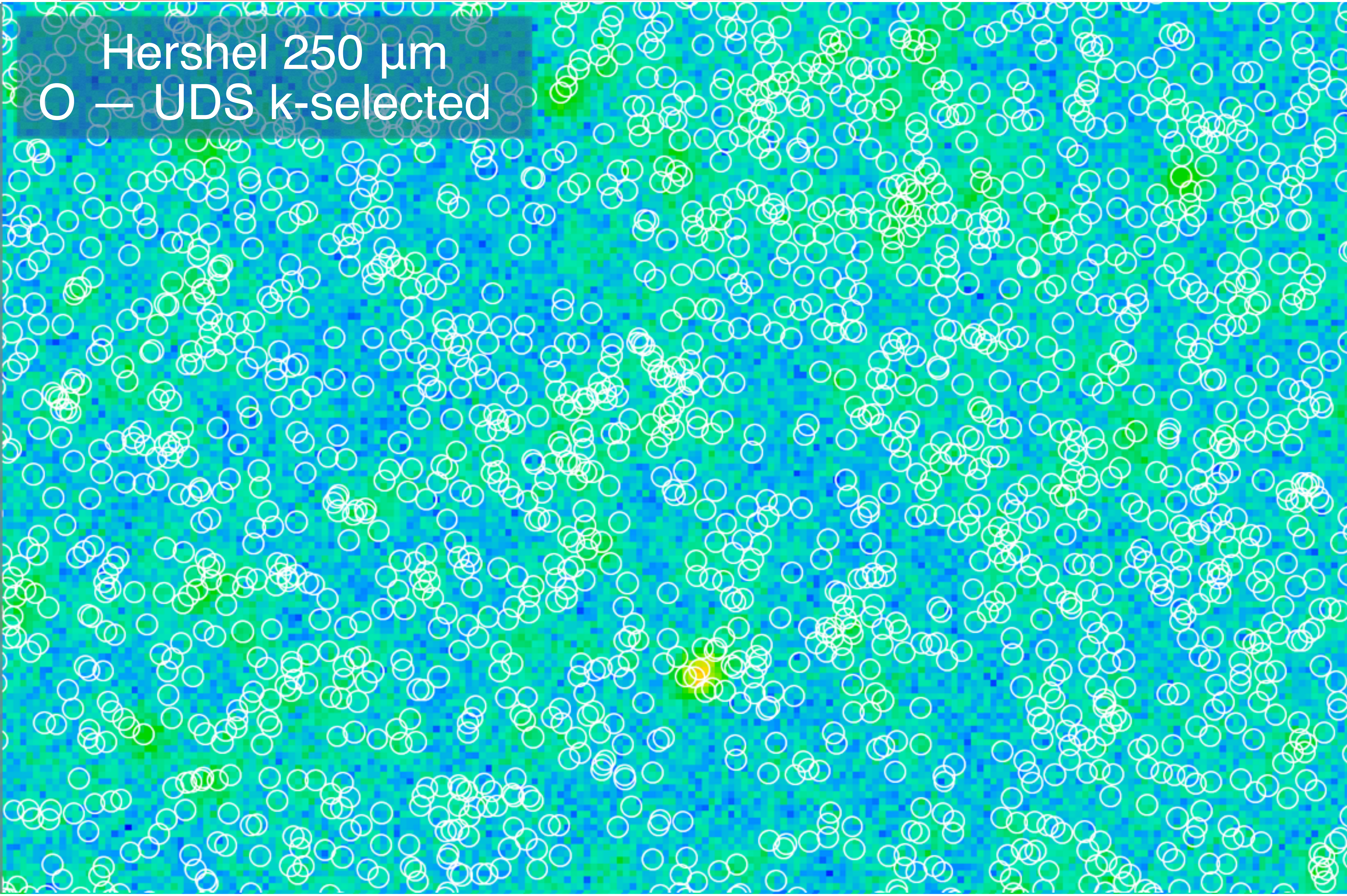
Use:

- The fact that intensity fluctuations contain signal
- *Ancillary* Data
- Creativity + Statistics



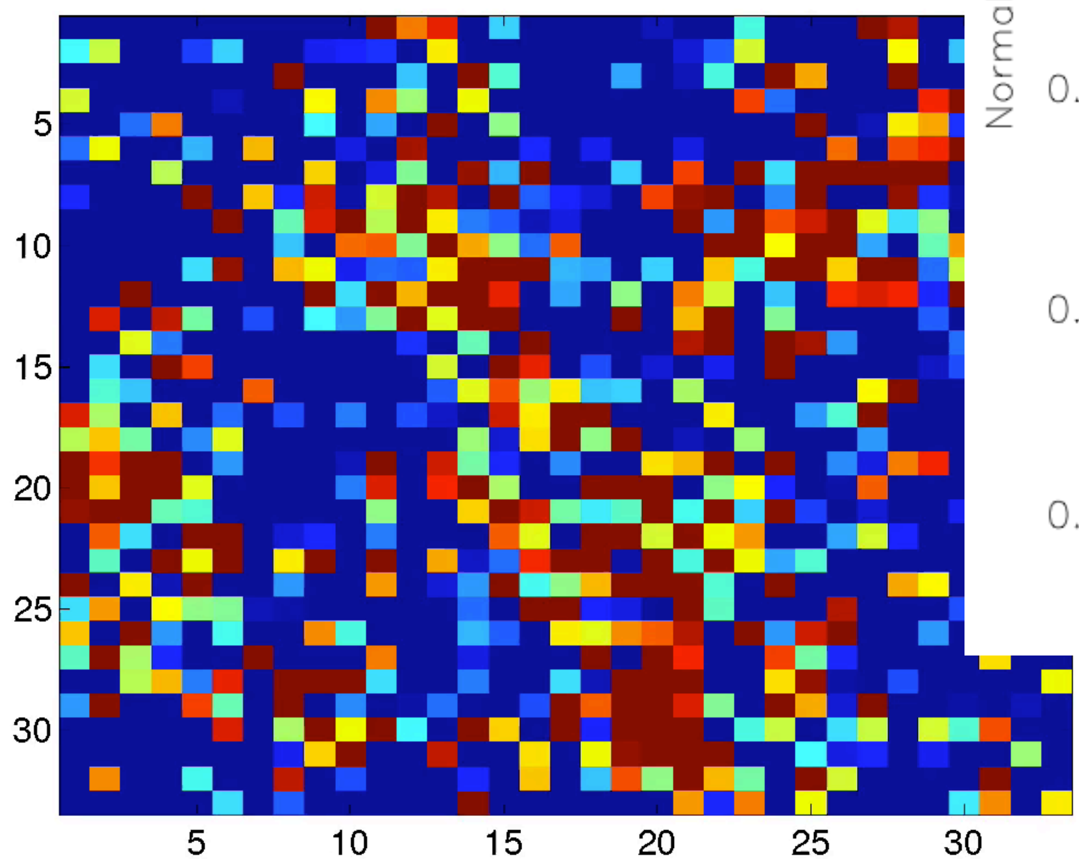



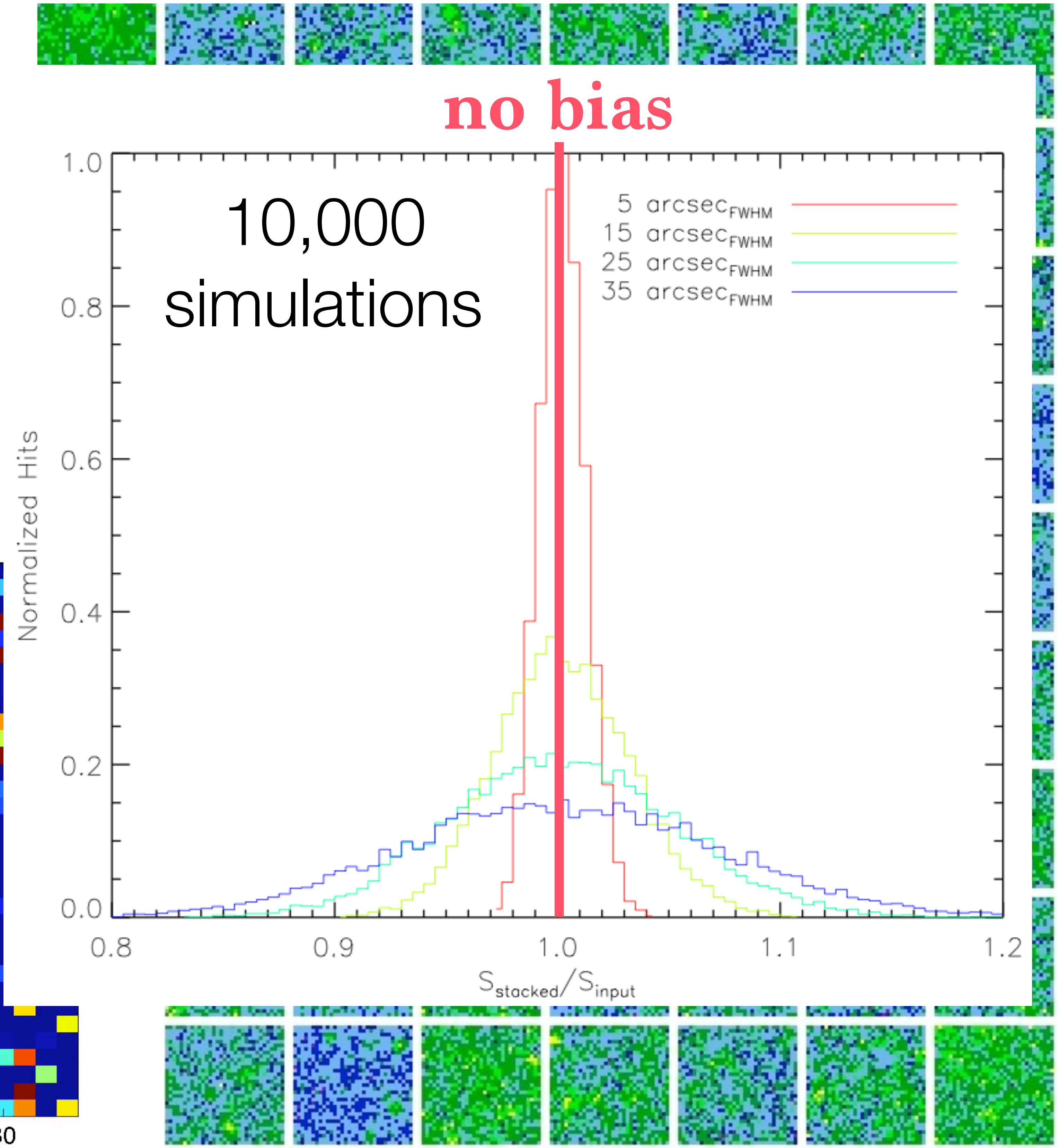
# Covariance of Catalog and Map (Stacking)



# Covariance of Catalog and Map (Stacking)

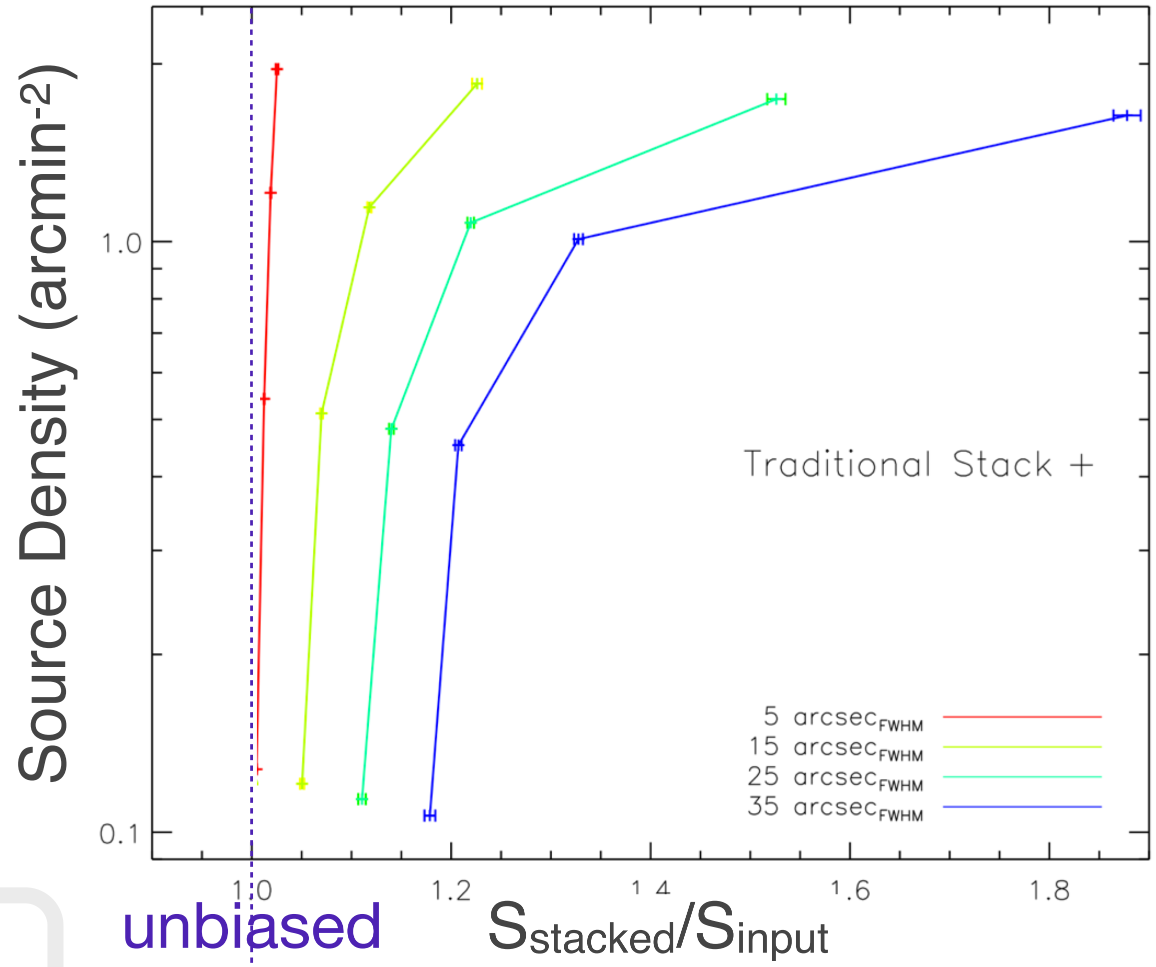
- Thumbnail stacking is equivalent to saying the off-diagonals of the covariance are zero.
  - ➡ same as saying objects are uncorrelated (i.e., not clustered.)

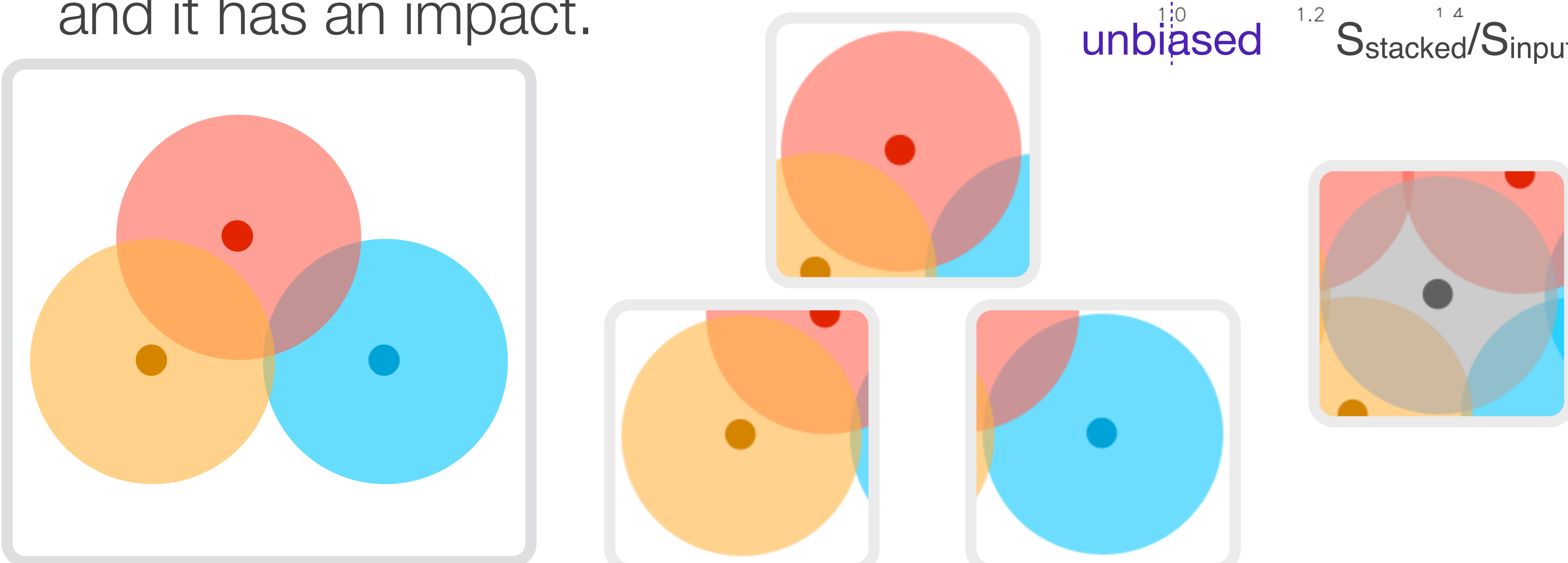


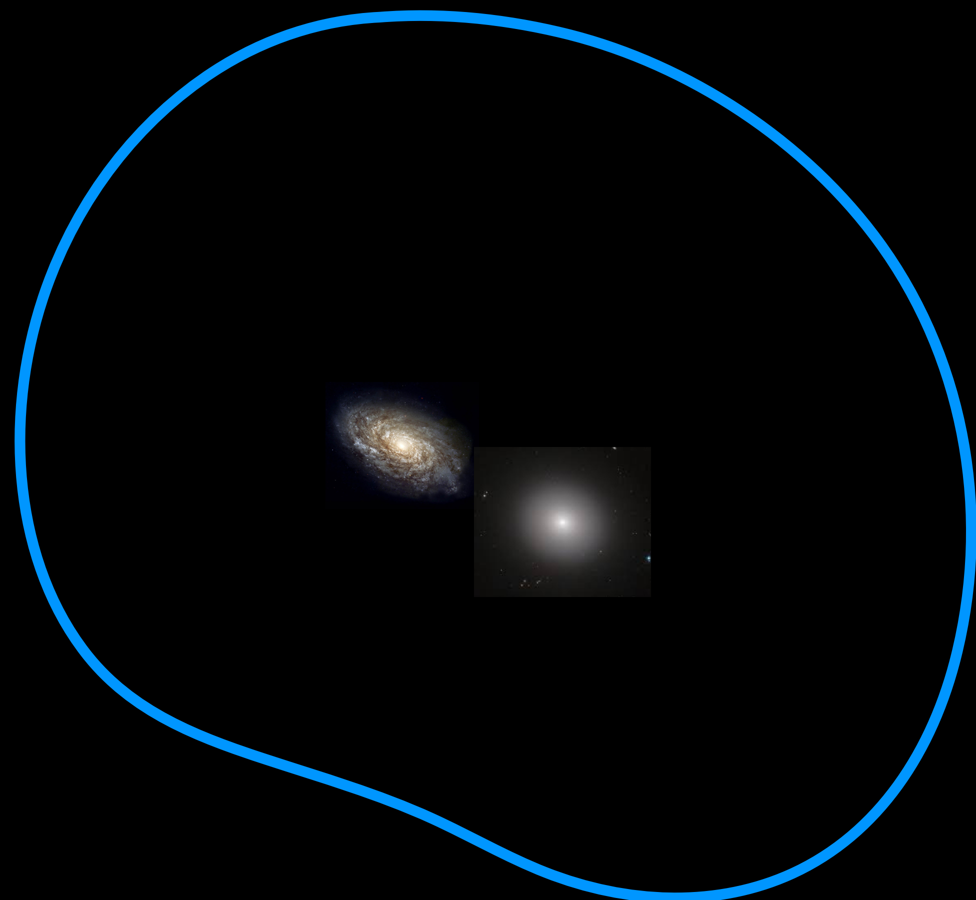
# Covariance of Catalog and Map (Stacking)

- Thumbnail stacking is equivalent to saying the off-diagonals of the covariance are zero.
  - ➡same as saying objects are uncorrelated (i.e., not clustered.)
- But galaxies are clustered, and it has an impact.

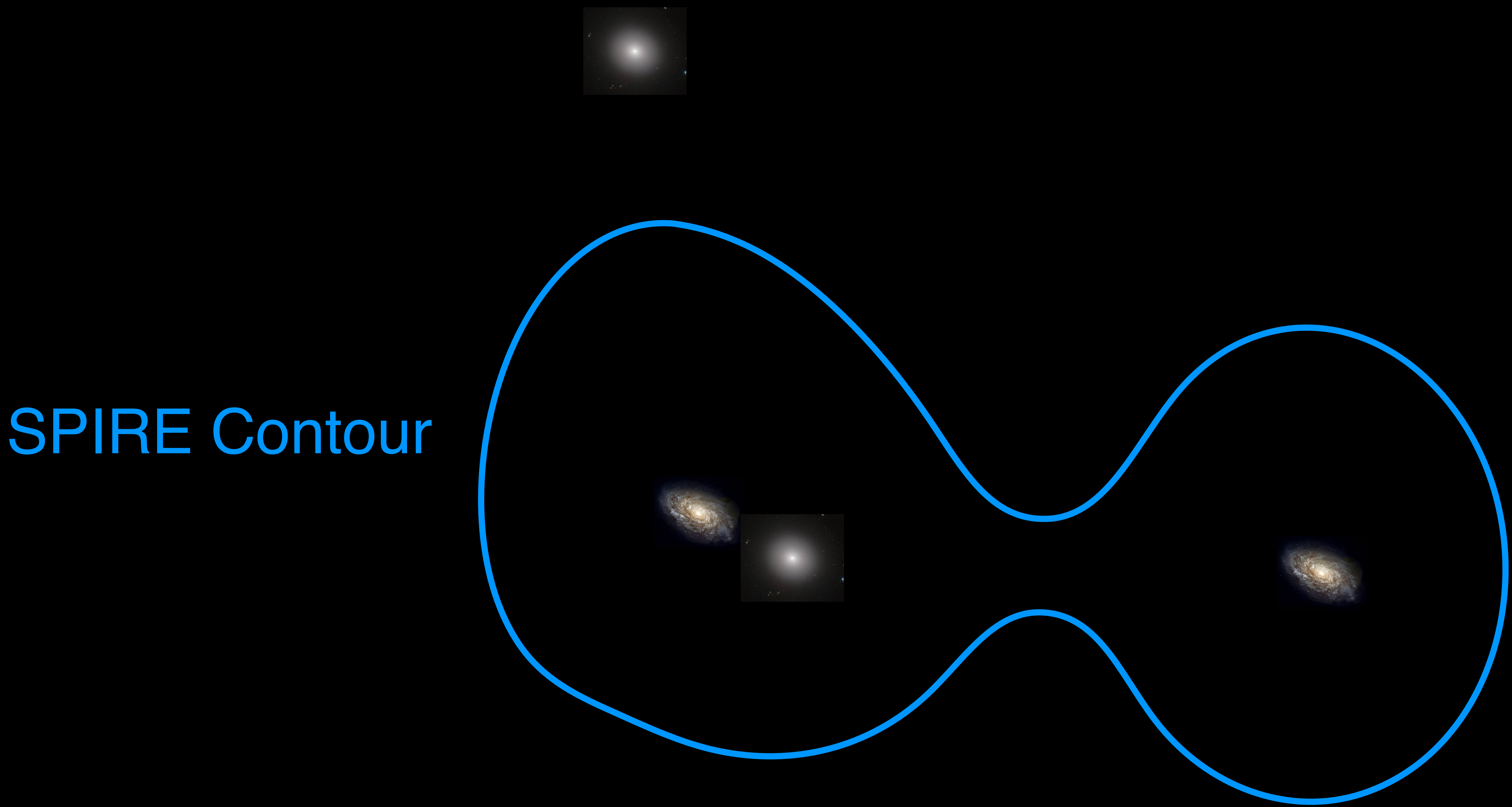


SPIRE Contour



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



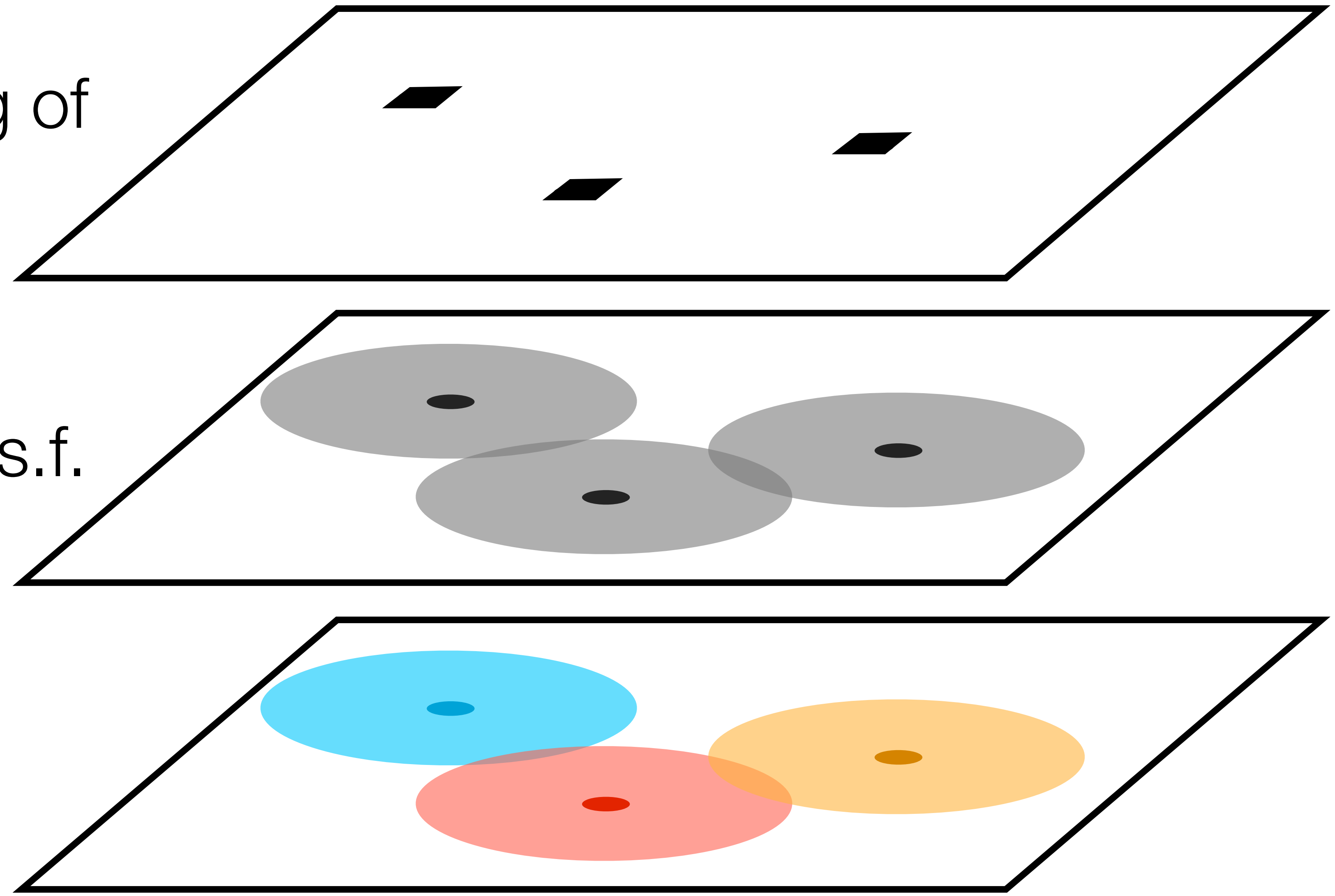

- Key is to identify galaxies with similar ***physical*** properties, and then rely on ***statistics to fit fluctuations***

# SIMSTACK: Simultaneous Stacking Algorithm

make hits map from catalog of similar objects

convolve with instrument p.s.f.

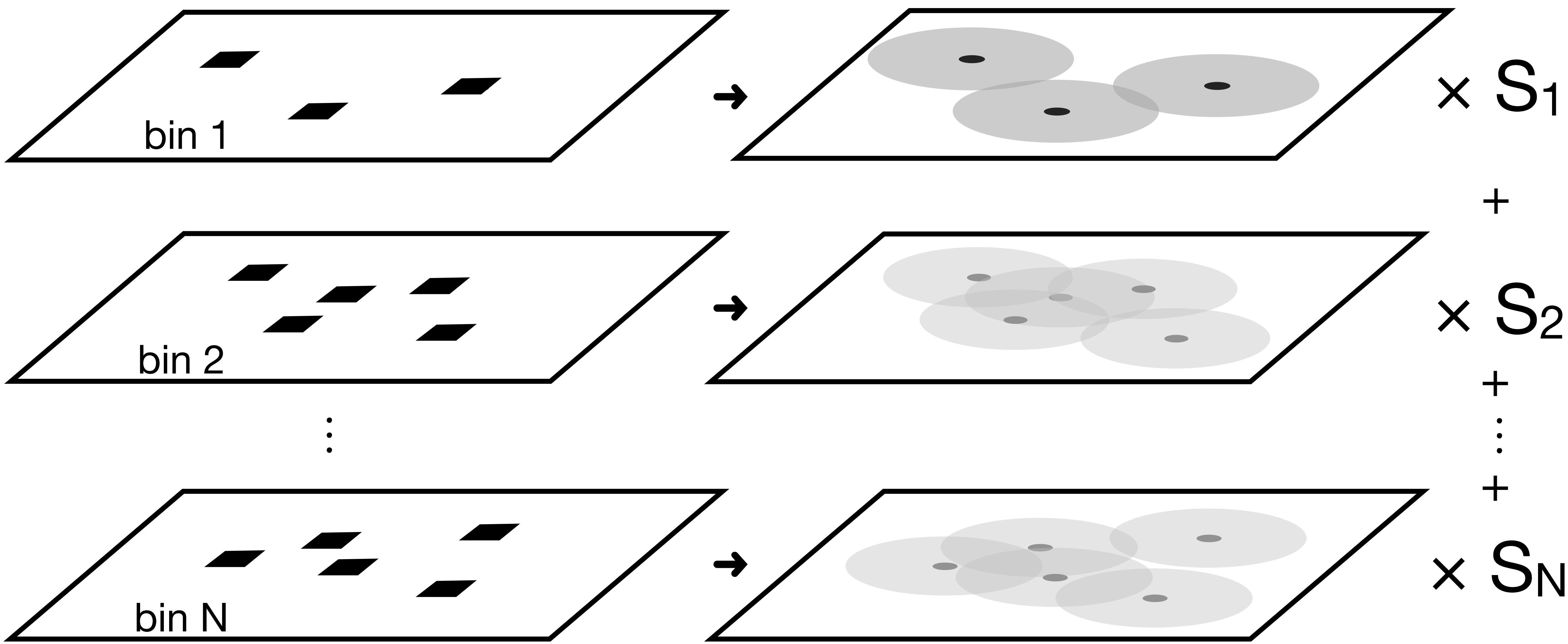
regress to find *mean* flux density, S

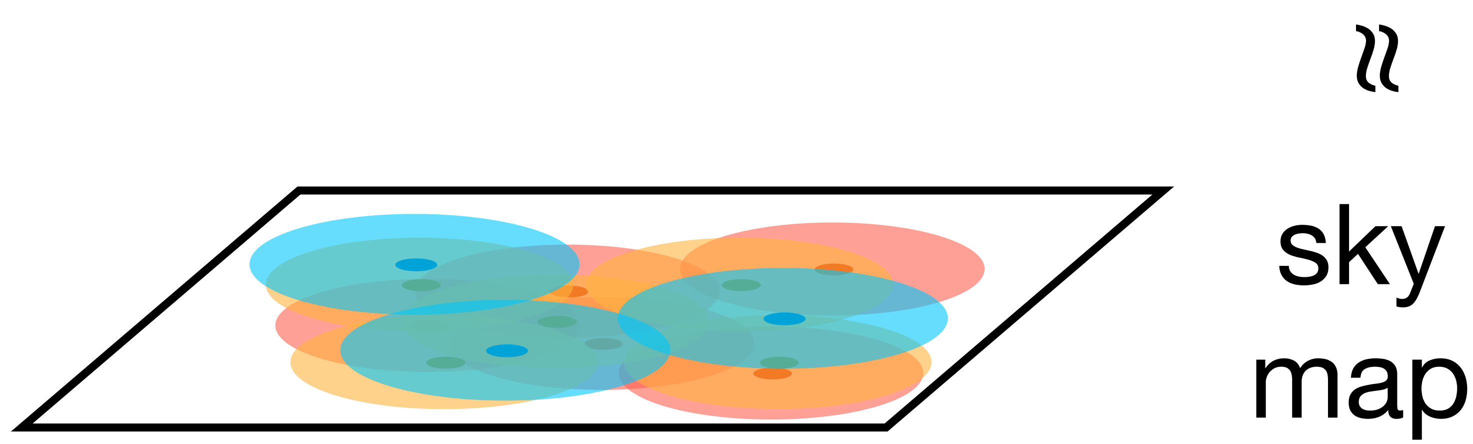


Formalism developed w/ Lorenzo Moncelsi (Caltech);
also see Kurczynski & Gawiser (2010), Roseboom et al. (2010)

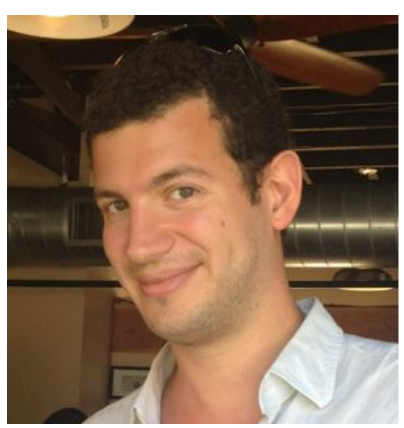
**SIMSTACK code publicly available (see arXiv:1304.0446):**
**IDL (old) — https://web.stanford.edu/~viero/downloads.html**
**Python — https://github.com/marcoviero/simstack**

# SIMSTACK: Simultaneous Stacking Algorithm




Formalism developed w/ Lorenzo Moncelsi (Caltech)



**SIMSTACK code publicly available (see arXiv:1304.0446):**
**Python — https://github.com/marcoviero/simstack**

# SIMSTACK: Measurement Data

## Catalogs

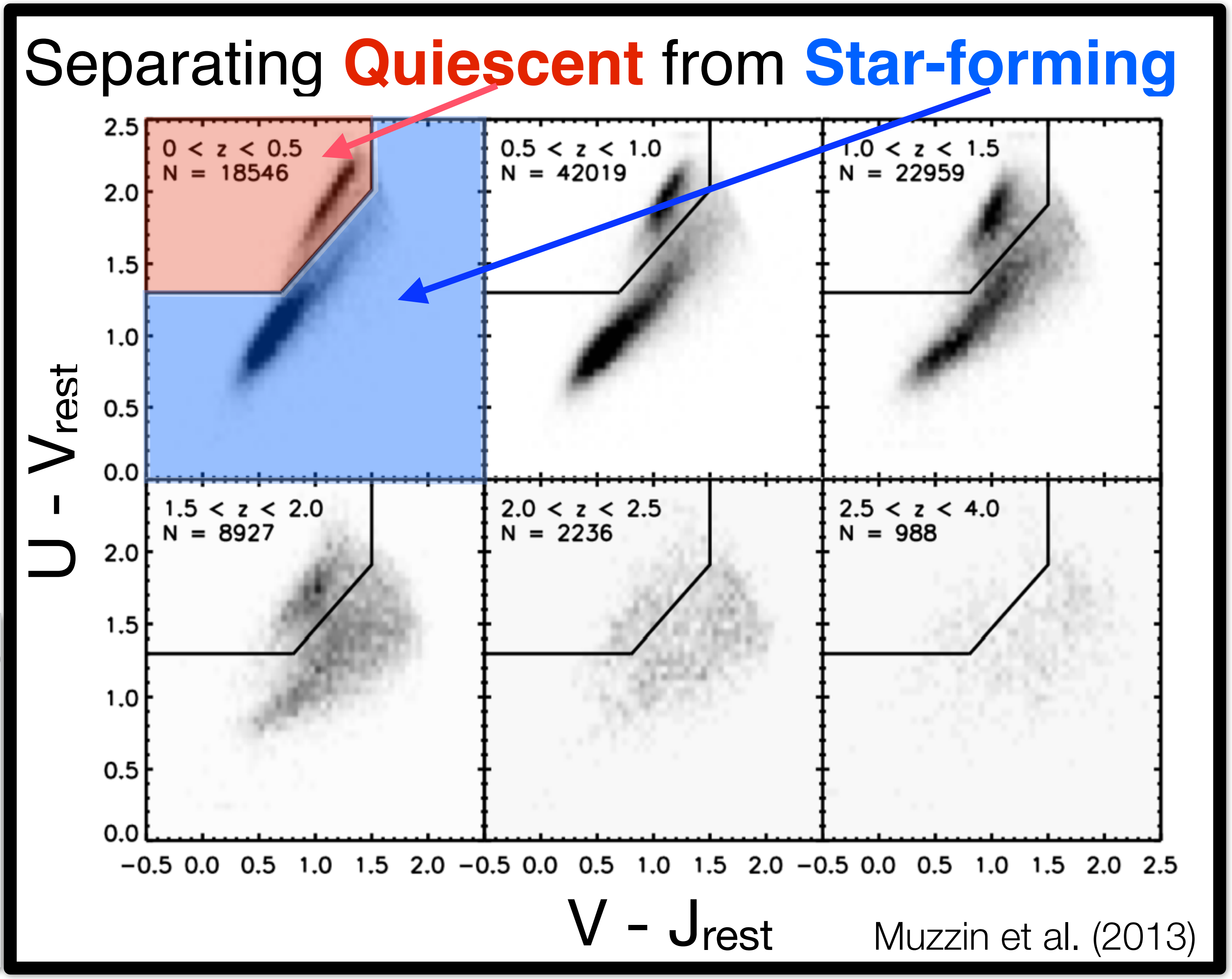
- UKIDSS/UDS [2/3 deg$^2$]  /  COSMOS [1.6 deg$^2$]

  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)

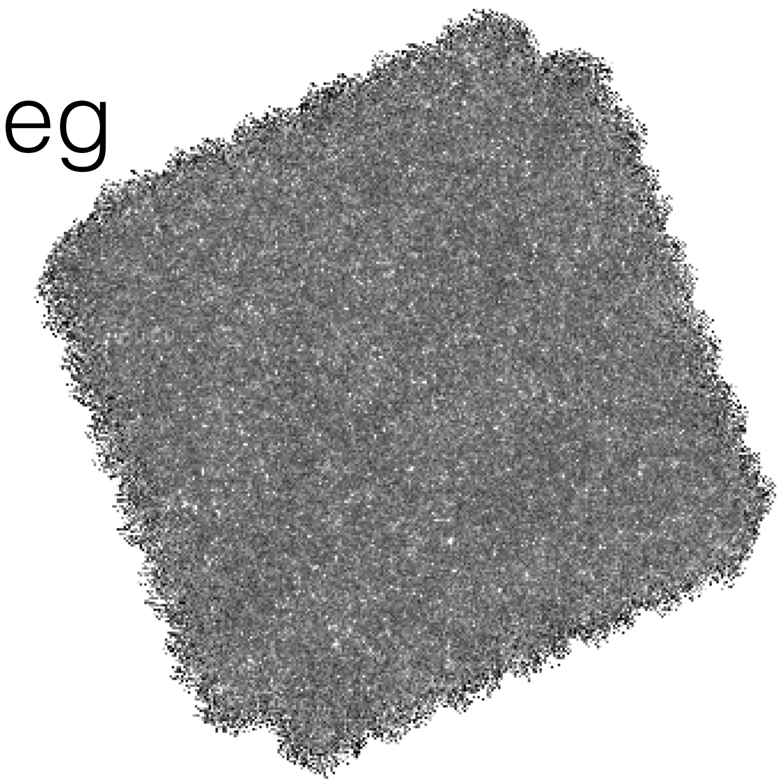


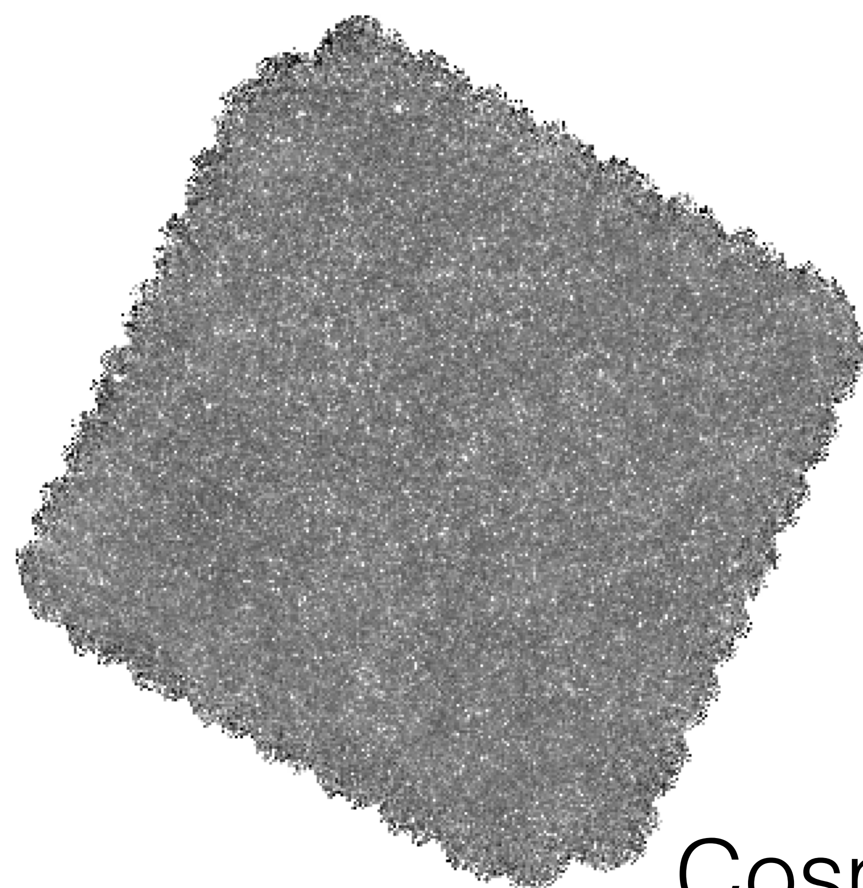
# SIMSTACK: Measurement Data

## Maps

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

UDS - 1.4 x 1.4 deg



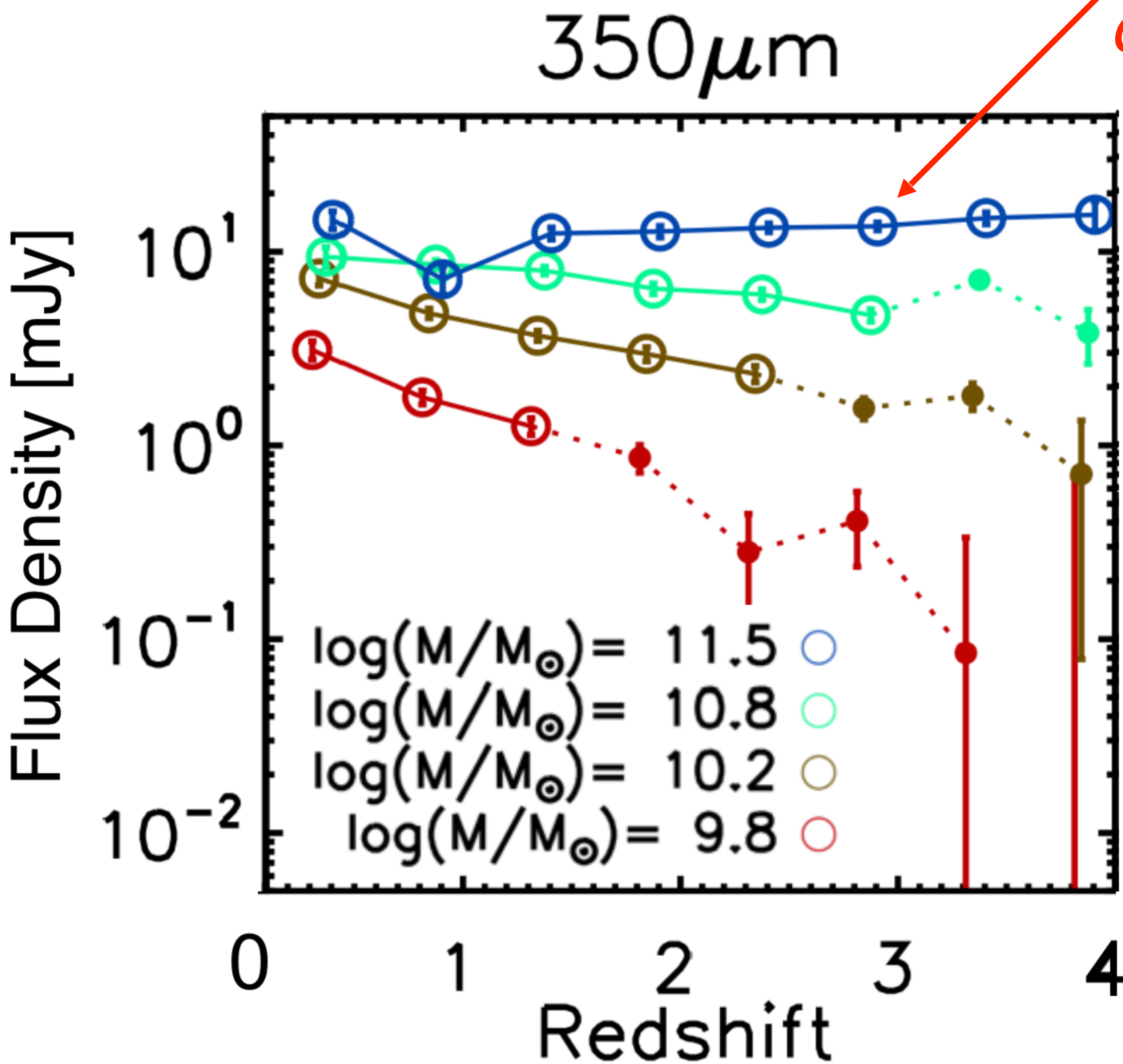


Cosmos - 1.8 x 1.8 deg

# SIMSTACK: Flux Densities (M,z)

HERMES

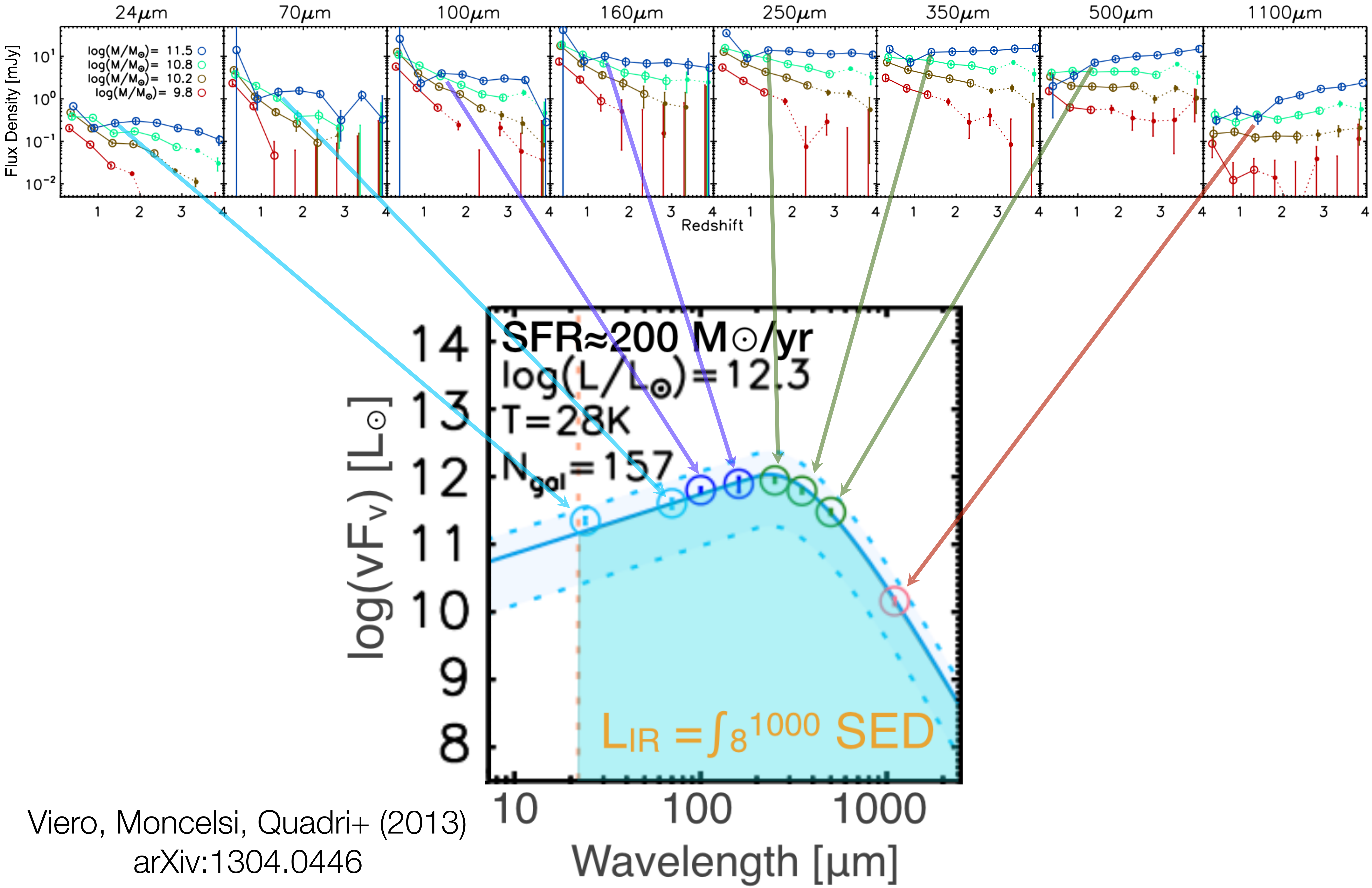
*Each circle one bin*




Data here:
UDS catalog
&
Herschel
SPIRE maps

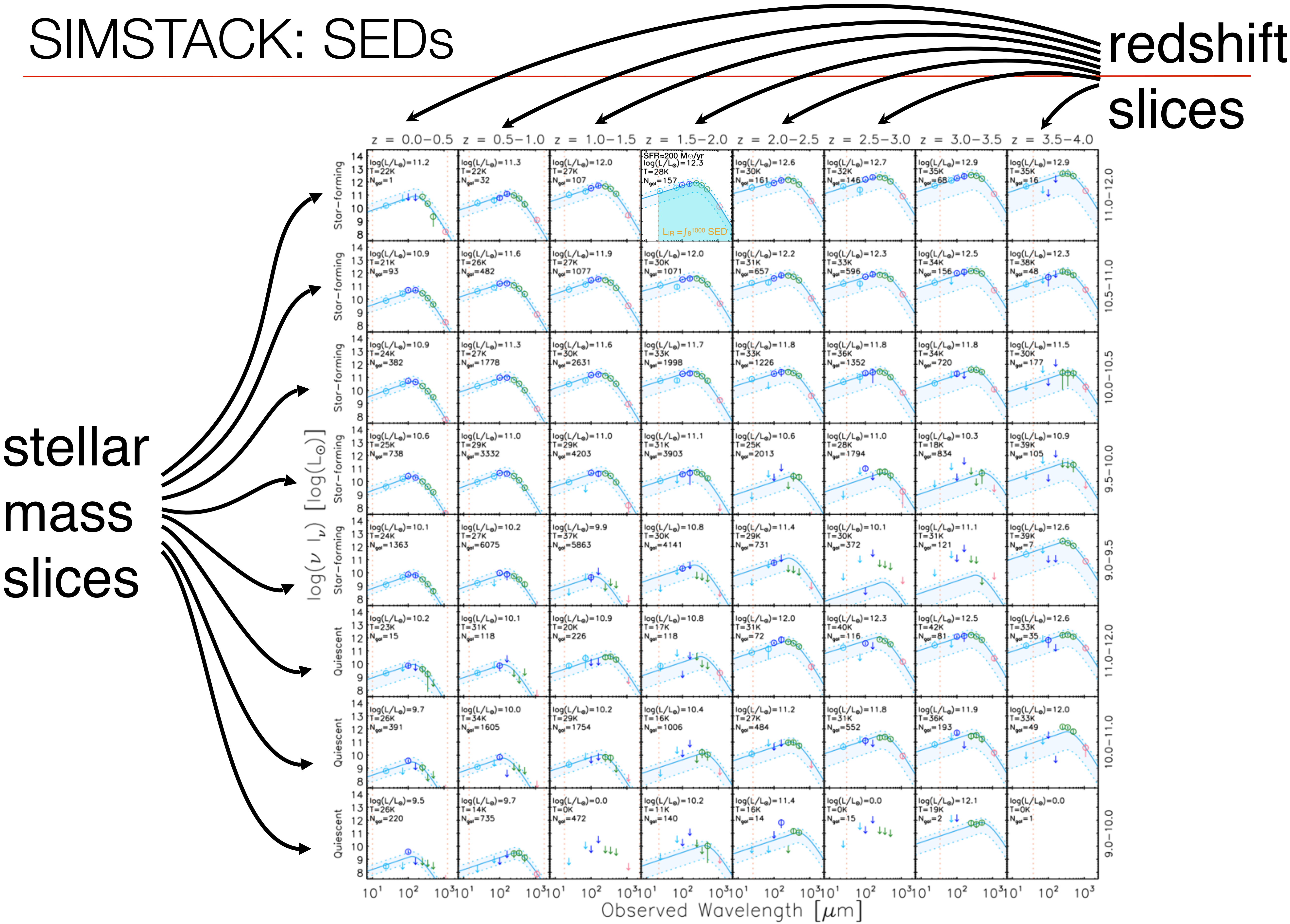
# SIMSTACK: SEDs

HERMES

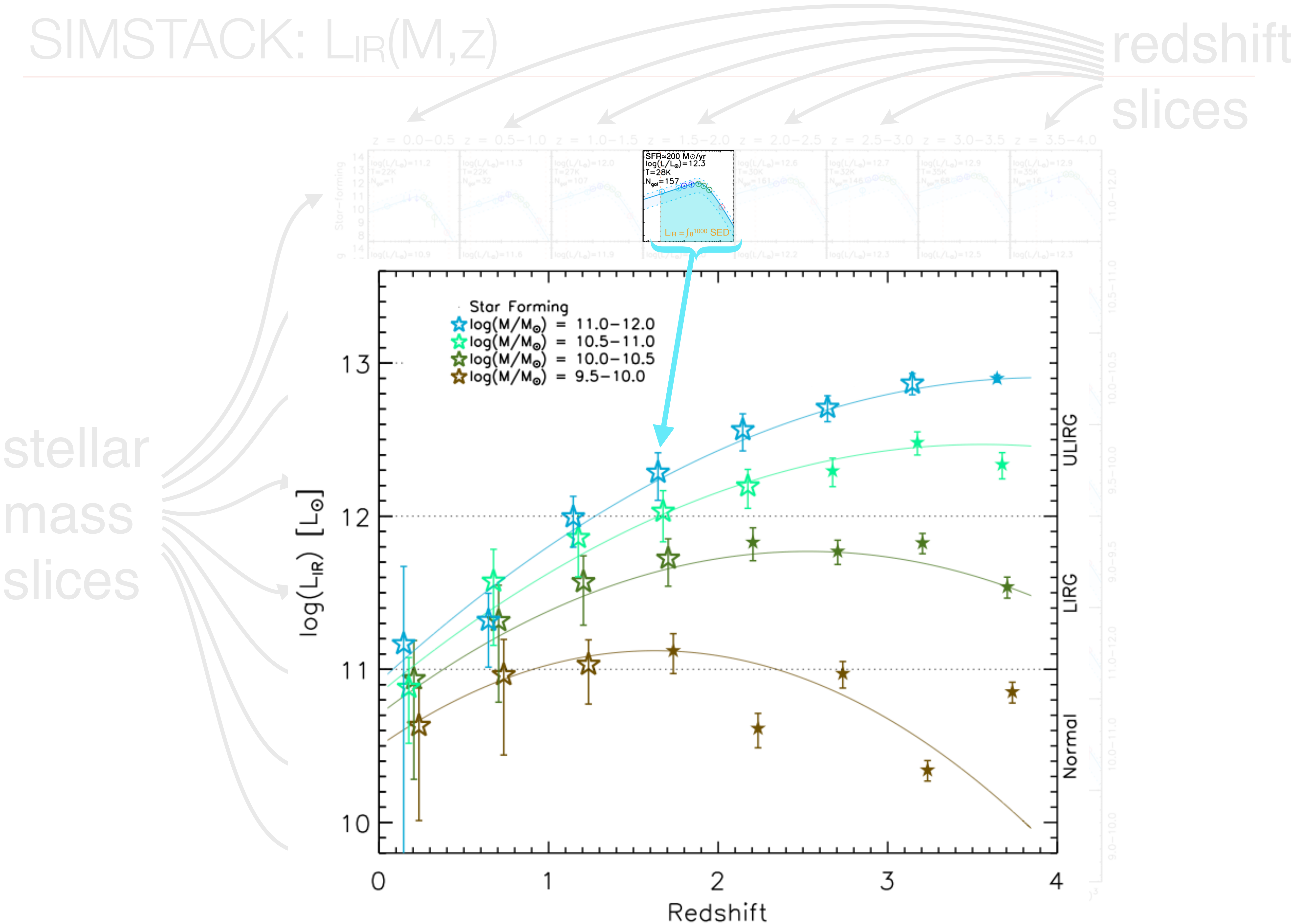



Viero, Moncelsi, Quadri+ (2013)
arXiv:1304.0446

# SIMSTACK: SEDs

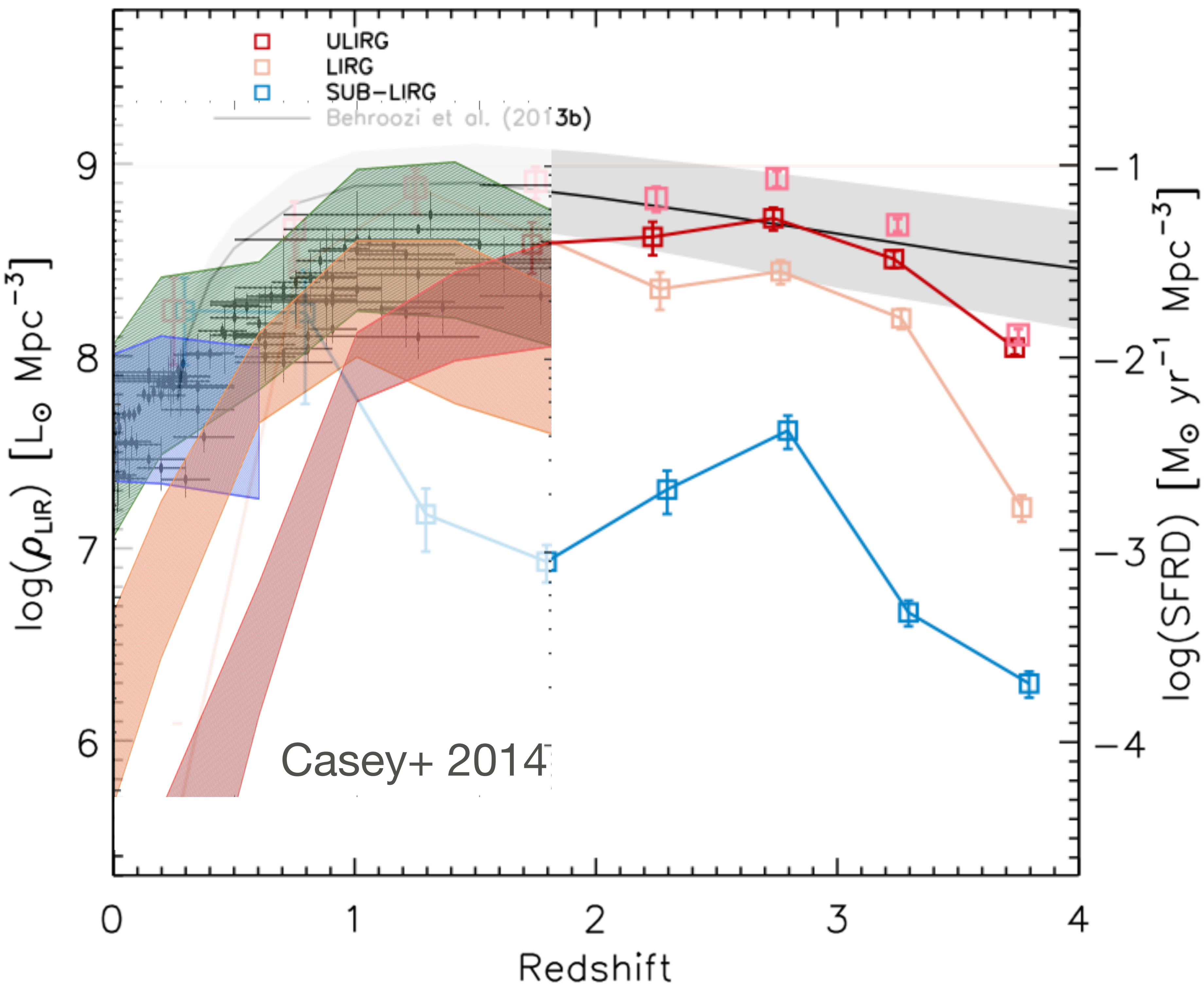


# SIMSTACK: $L_{IR}(M,z)$



# CIB Breakdown

- Broken down by Luminosity class
- In good agreement with previous estimates w. resolved sources.
  - ➡but to much higher redshift!
- Broken down by stellar mass see clear downsizing.



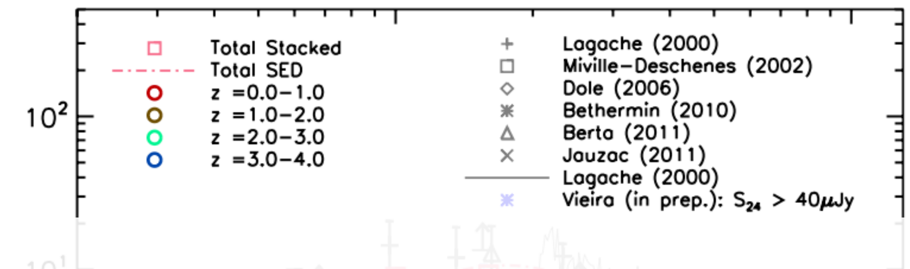
HERMES

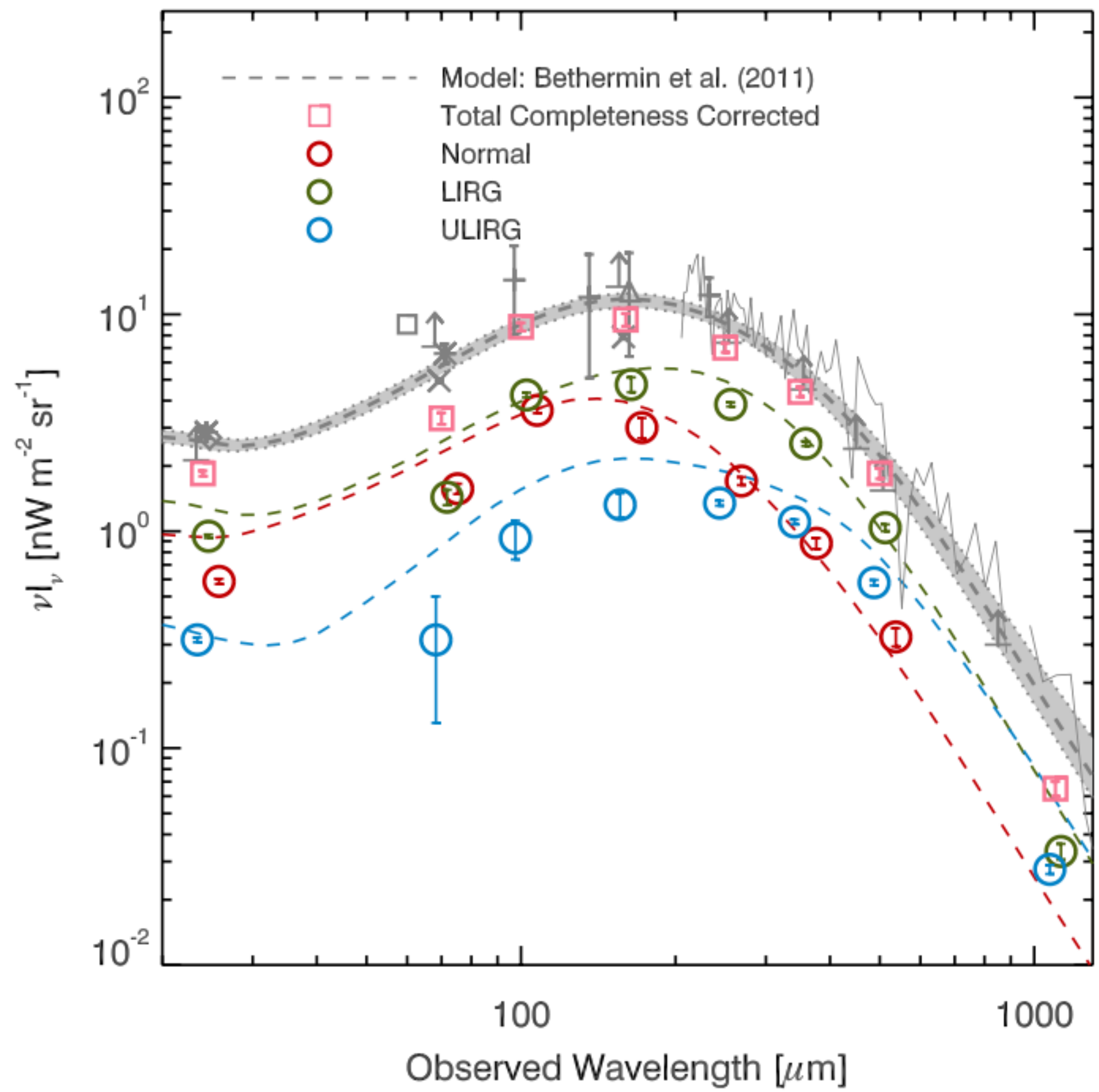
# Split Sample by:

ULIRGS

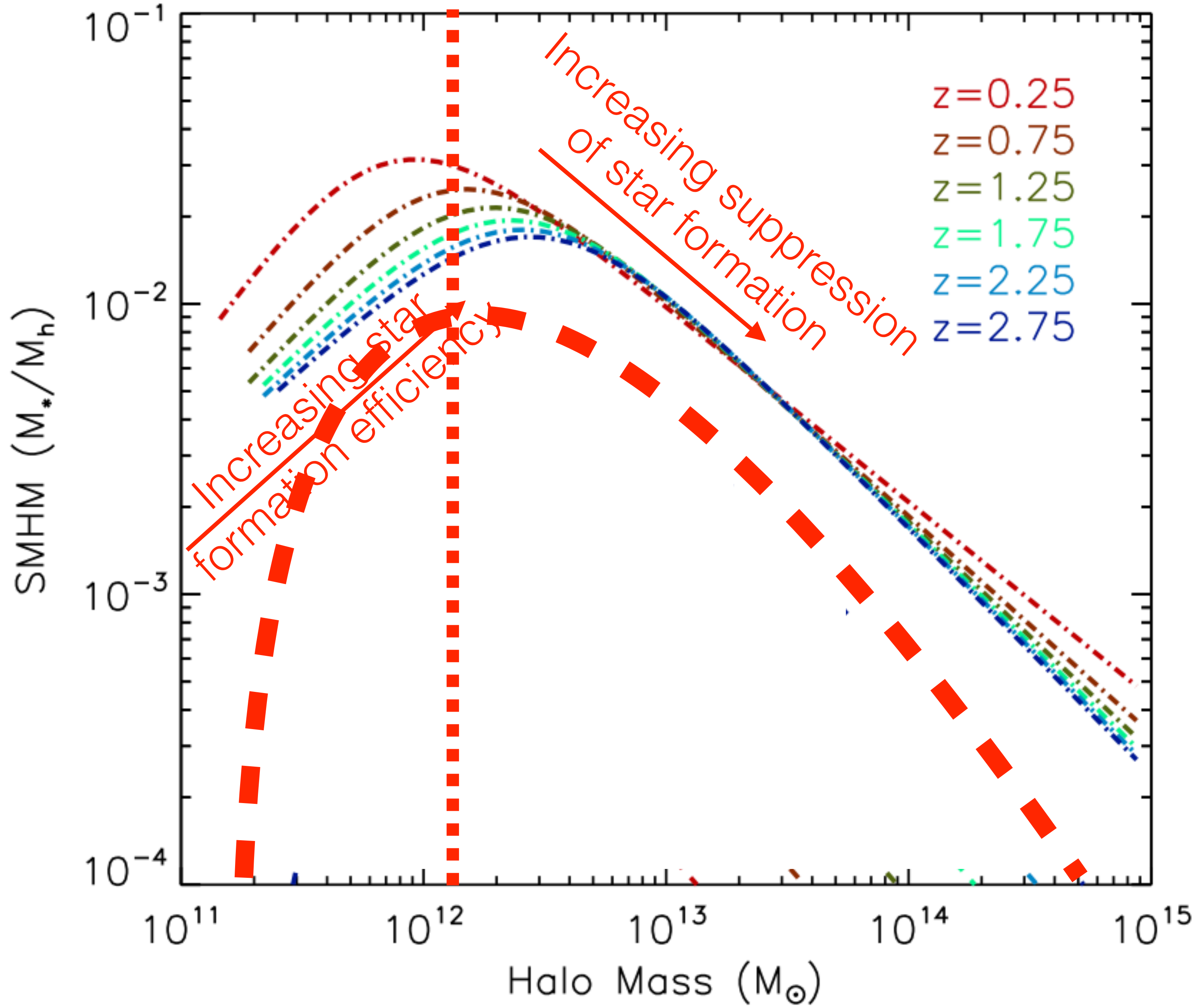
LIRGS

Normal




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




Halo/Stellar Mass Function from Moster+(2012)

# SIMSTACK is simple to use

- Define type of stack, and where everything is, **in config file**.
  - ➡ ./run_simstack_cmd_line.py config_file_name.cfg

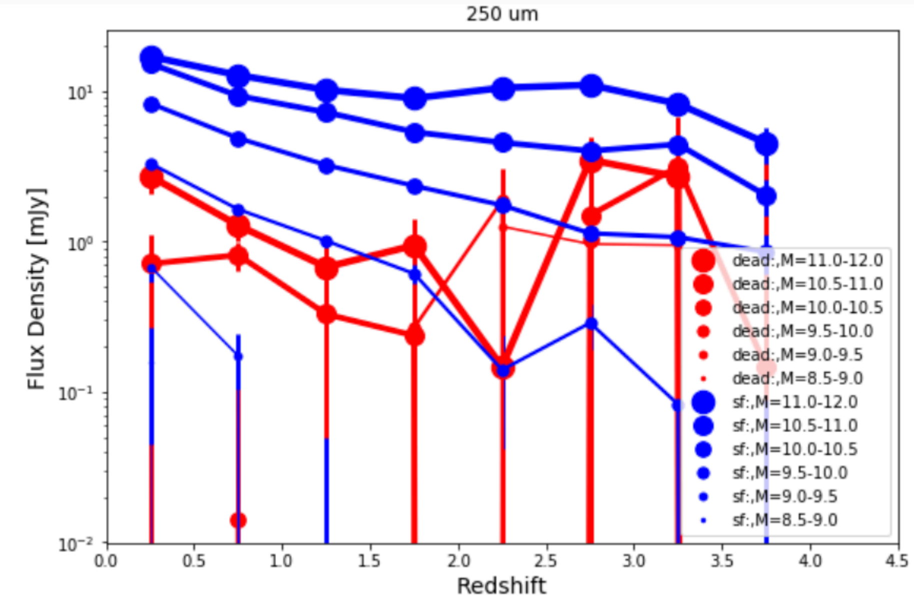
```
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; Example parameter file for simstack code
;
; Contact: Marco Viero (marco.viero@stanford.edu)
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
[general]
;populations chooses how the catalog is split into groups with like-properties
;classifying_scheme chooses how the catalog is split into groups with like-properties
;Options are: sf-qt ; general ; uvj ;
classification_scheme = general
bootstrap        = False 0 2 ; True/False, initial number, number of iterations
;Catalog specific names for redshift, stellar mass, RA, and DEC
zkey = PHOTOZ
mkey = MASS_MED
ra_key = ALPHA_J2000
dec_key = DELTA_J2000

[populations]
;Name_of_sub-population = index, [conditions]
;Here conditions are: feature, greater than, less than, equal to
;False when one of those does not apply
sf   = 1 CLASS False False 1
dead = 0 CLASS False False 0

[cosmology] ; Cosmology - Planck15
omega_m = 0.3075
omega_l = 0.6910
omega_k = 0.
h        = 0.6774

[io] ; Input/output
;output_folder will contain the directories:
; - simstack_fluxes
; - bootstrapped_fluxes
;If they don't exist the code will create them!
output_folder           = PICKLESPATH simstack/stacked_flux_densities/
flux_densities_filename = simstack_flux_densities
shortname               = uVista__Laigle_v1.1__sf-qt__z_bins_in_slices_test

[catalogs]
catalog_path = CATSPATH uVista/
catalog_file = COSMOS2015_Laigle+_Simplified_v1.1.csv

[binning]
optimal_binning = False ; Not yet working
bin_in_lookbackt= False ; Not yet working from command line, and requires NPpredict be installed
all_z_at_once   = False
;If binning in lookback time, redshift_nodes should be in Gyr from present day.
redshift_nodes  = 0.01 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0
mass_nodes      = 8.5 9.0 9.5 10.0 10.5 11.0 12.0
```

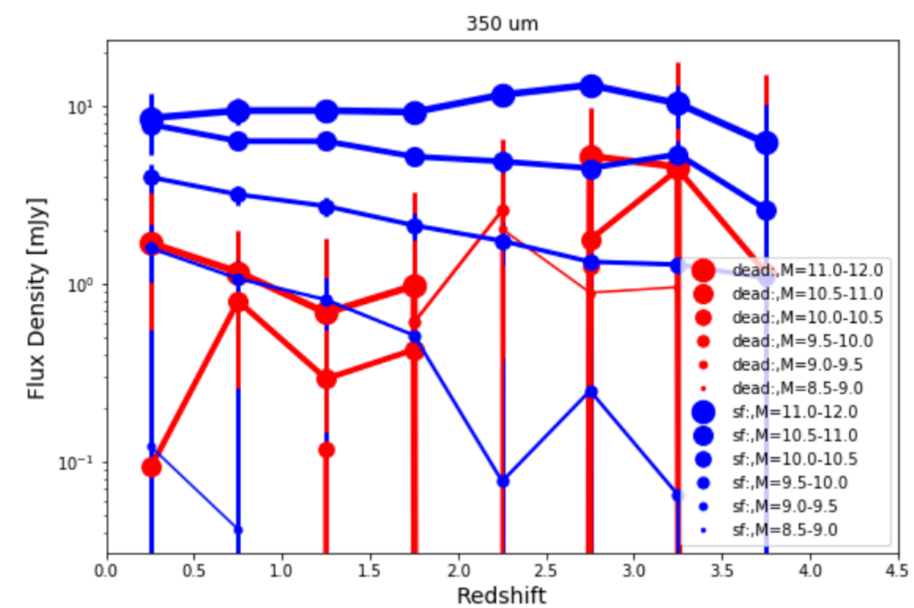
```
[maps_to_stack]
; True/False represents whether to stack them
mips_24    =  24.0 False
pacs_green = 100.0 False
pacs_red   = 160.0 False
spire_PSW  = 250.0 True
spire_PMW  = 350.0 False
spire_PLW  = 500.0 False
scuba_450  = 450.0 False
scuba_850  = 850.0 False

[map_path]
mips_24 = MAPSPATH /data/cutouts/
pacs_green = MAPSPATH /data/cutouts/
pacs_red = MAPSPATH /data/cutouts/
spire_PSW = MAPSPATH /data/cutouts/
spire_PMW = MAPSPATH /data/cutouts/
spire_PLW = MAPSPATH /data/cutouts/
scuba_450 = MAPSPATH /data/cutouts/
scuba_850 = MAPSPATH /data/cutouts/

[map_file]
; Maps need to be in Jy/beam.  If they are not, use second element in [beams] below to convert them.
mips_24    = mips_24_GO3_sci_10.cutout.fits
pacs_green = pep_COSMOS_green_Map.DR1.sci.cutout.fits
pacs_red   = pep_COSMOS_red_Map.DR1.sci.cutout.fits
spire_PSW  = cosmos-uvista-hipe12_itermap_10_iterations_6.0_arcsec_pixels_PSW.signal.cutout.fits
spire_PMW  = cosmos-uvista-hipe12_itermap_10_iterations_6.0_arcsec_pixels_PMW.signal.cutout.fits
spire_PLW  = cosmos-uvista-hipe12_itermap_10_iterations_6.0_arcsec_pixels_PLW.signal.cutout.fits
scuba_450  = map450_new_header.cutout.fits
scuba_850  = S2CLS_COSMOS_NMF_DR1_new_header.cutout.signal.fits

[noise_file]
; If fits file contains noisemap in second extension, has same name as signal map
mips_24    = mips_24_GO3_unc_10.cutout.fits
pacs_green = pep_COSMOS_green_Map.DR1.err.cutout.fits
pacs_red   = pep_COSMOS_red_Map.DR1.err.cutout.fits
spire_PSW  = cosmos-uvista-hipe12_itermap_10_iterations_6.0_arcsec_pixels_PSW.noise.cutout.fits
spire_PMW  = cosmos-uvista-hipe12_itermap_10_iterations_6.0_arcsec_pixels_PMW.noise.cutout.fits
spire_PLW  = cosmos-uvista-hipe12_itermap_10_iterations_6.0_arcsec_pixels_PLW.noise.cutout.fits
scuba_450  = map450_new_header_rms.cutout.fits
scuba_850  = S2CLS_COSMOS_NMF_DR1_new_header.cutout.noise.fits

[beams]
;1- PSF file path+names, or effective FWHM
;2- Beam area in sr.  Should be 1.0 if maps are in Jy/beam, otherwise actual effective area if Jy/sr
mips_24    = 6.32 1.55e-09
pacs_green = 6.7 2.0271e-09 ; MJy/sr to Jy/beam
pacs_red   = 11.2 4.6398e-09 ; MJy/sr to Jy/beam
spire_PSW  = 17.6 1.0
spire_PMW  = 23.9 1.0
spire_PLW  = 35.2 1.0
scuba_450  = 7.8 1.0
scuba_850  = 12.1 1.0
```

# SIMSTACK

- It will save stacked results in a folder you define.
- You can access the results with an iPython Notebook
  - [https://github.com/marcoviero/simstack/blob/master/notebooks/plot_simstack_output.ipynb](https://github.com/marcoviero/simstack/blob/master/notebooks/plot_simstack_output.ipynb)

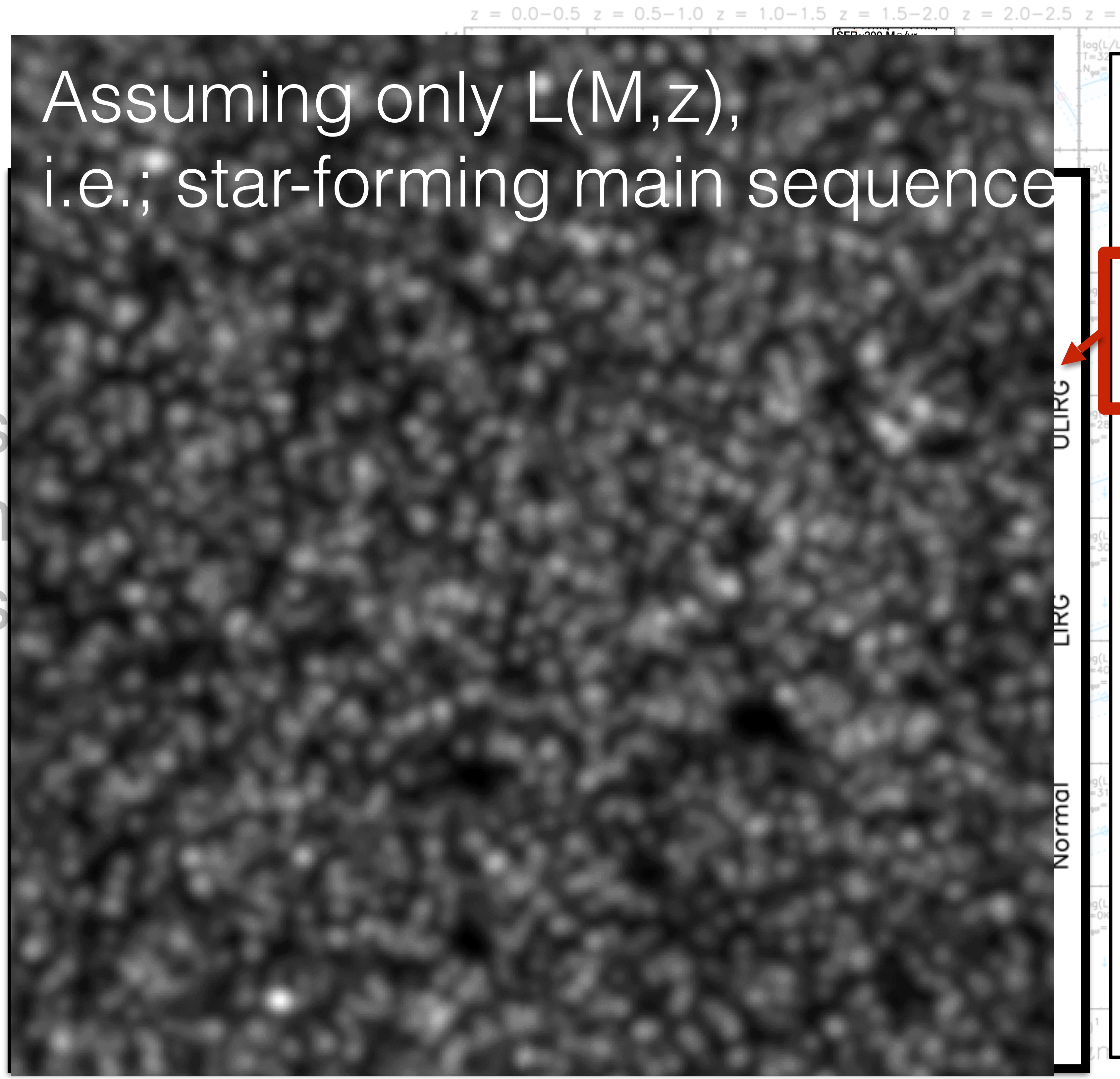
```
In [1]: import pdb
        import numpy as np
        import pandas as pd
        import os
        import pylab as plt
        from utils import clean_args
        from utils import clean_nans
        from utils import fast_sed
        from utils import fast_sed_fitter
        from utils import fast_Lir
        from utils import stagger_x
        from utils import subset_averages_from_ids
        from utils import main_sequence_s15
        from bincatalogs import Field_catalogs
        from astropy.cosmology import Planck15 as cosmo
        import astropy.units as u
        try:
            from simstack import PickledStacksReader, measure_cib
        except:
            from simstack.simstack import PickledStacksReader, measure_cib

        %matplotlib inline

In [2]: conv_luv_to_sfr = 2.17e-10
        conv_lir_to_sfr = 1.72e-10
        L_sun = 3.839e26 # W
        c = 299792458.0 # m/s
        a_nu_flux_to_mass = 6.7e19
        h = 6.62607004e-34 #m2 kg / s  #4.13e-15 #eV/s
        k = 1.38064852e-23 #m2 kg s-2 K-1 8.617e-5 #eV/K

In [3]: popcolor=['red','blue','green','orange','black','grey','chocolate','darkviolet','pink','magenta','dodgerblue','lavender

In [4]: path_pickles = os.environ['PICKLESPATH']
        path_maps    = os.environ['MAPSPATH']
        path_catalogs= os.environ['CATSPATH']

In [5]: #Location of the stacked parameter file
        shortname = 'uVista__Laigle_v1.1__sf-qt__z_bins_in_slices_test'
        path_config = path_pickles + '/simstack/stacked_flux_densities/simstack_fluxes/'+shortname+'/'
        file_config = 'example.cfg'
        if os.path.exists(path_config+file_config) == True:
            print path_config+file_config

        /data/pickles//simstack/stacked_flux_densities/simstack_fluxes/uVista__Laigle_v1.1__sf-qt__z_bins_in_slices_test/exam
        ple.cfg
```



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

redshift slices



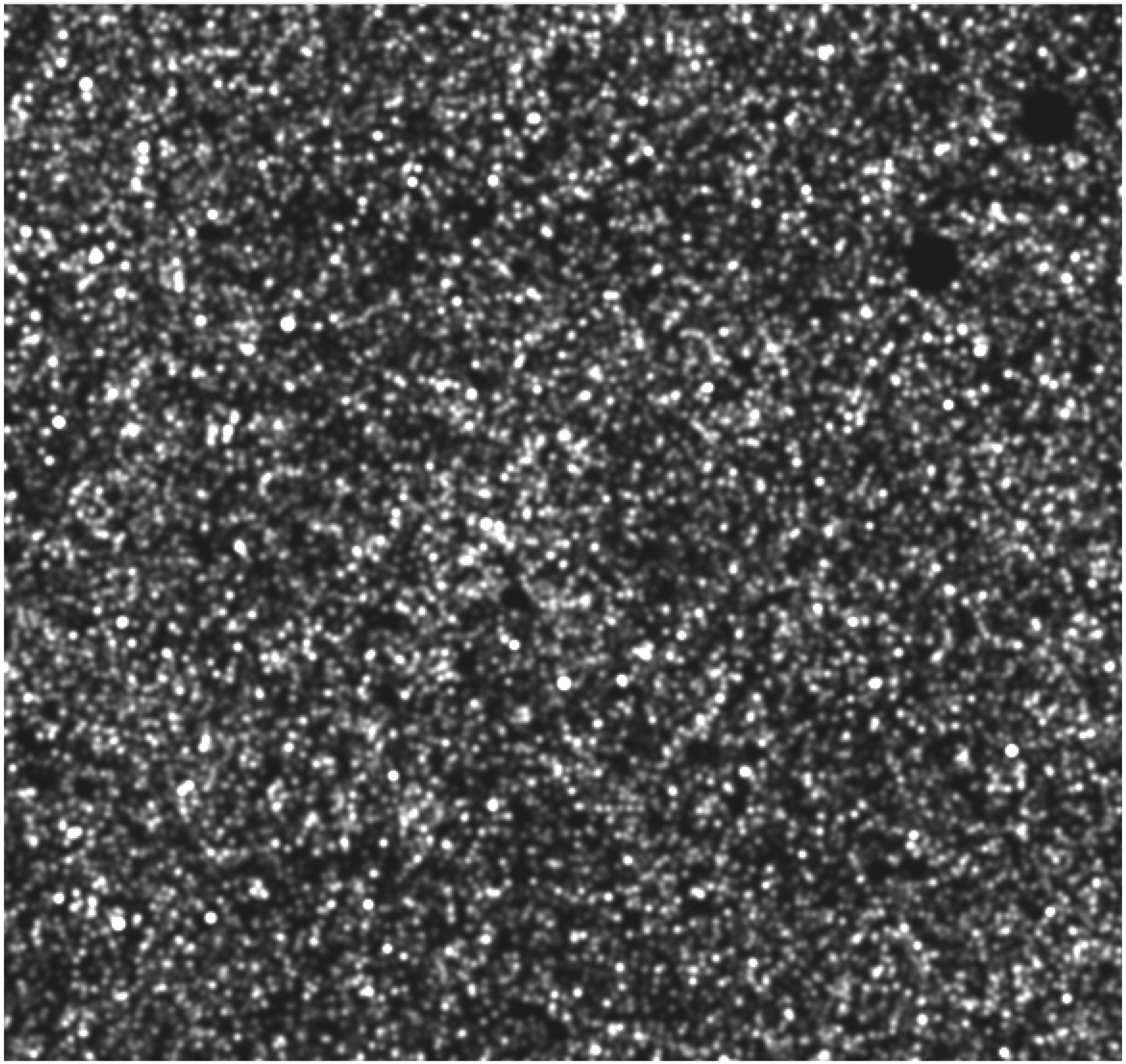

Assuming only L(M,z),
i.e.; star-forming main sequence

- Deep ancillary data can be fit with SED models, providing:
  - Stellar Mass
  - Redshift
  - Extinction/UV slope
  - AGN fraction
  - Age/Tau…

Each bin therefore has <M>,<z>, <Av>, $<F_{agn}>$, etc., which can be fit with function of form:

- $LIR = P(z)^{\alpha} P(M)^{\beta} P(Av)^{\gamma} \ldots$

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



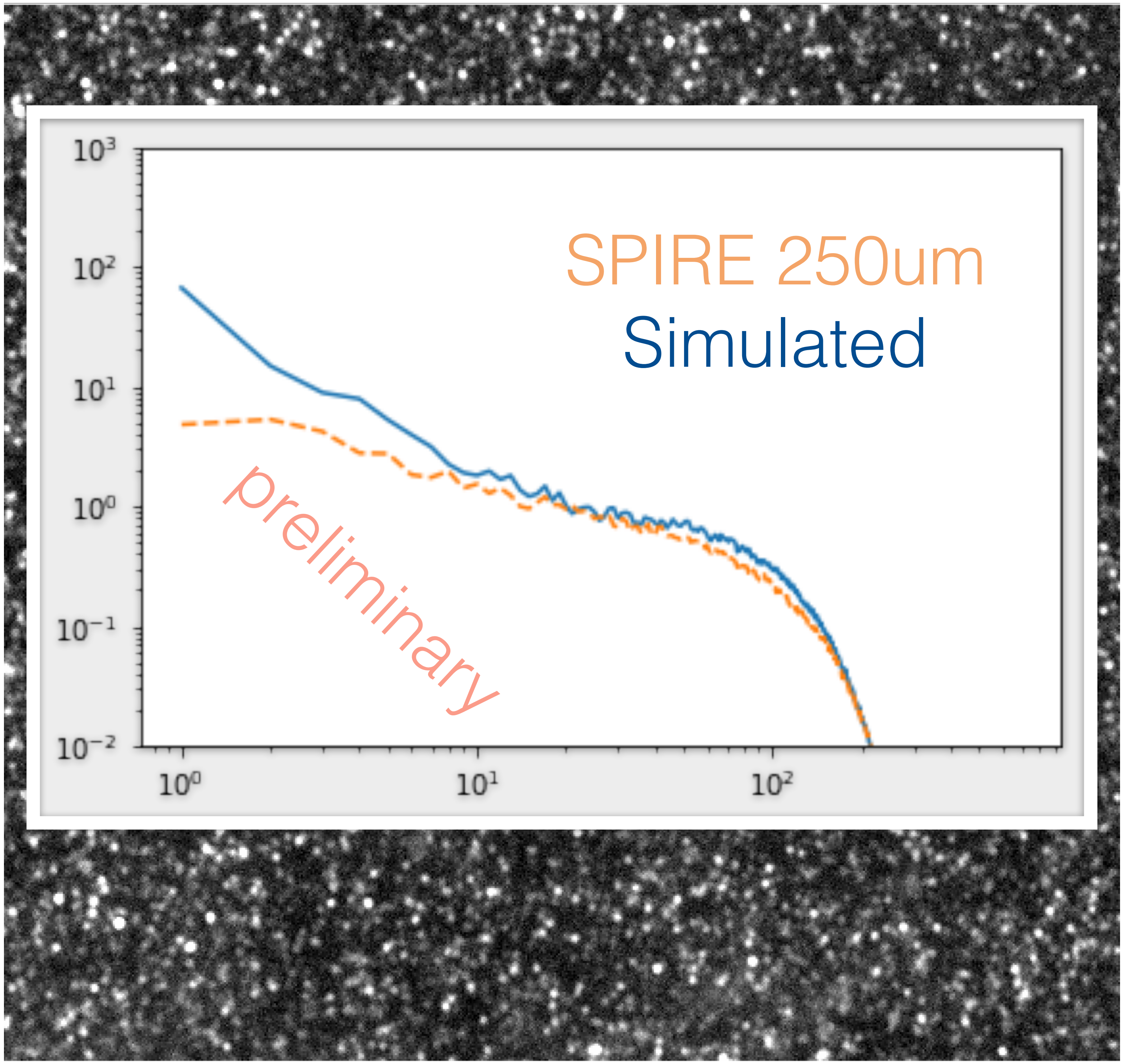
Fit can be improved by splitting the sample into finer subsamples, isolating e.g,;

- Star-forming/Quiescent
- AGN
- Starbursts

We find features most influential are, for 4 subsamples:

- $\log(LIR) = C + \alpha(z)\times\log(1+z) + \beta(z)\times\log(M) + \gamma(z)\times\log(Av) + \delta(z)\times\log(F_{agn})$

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



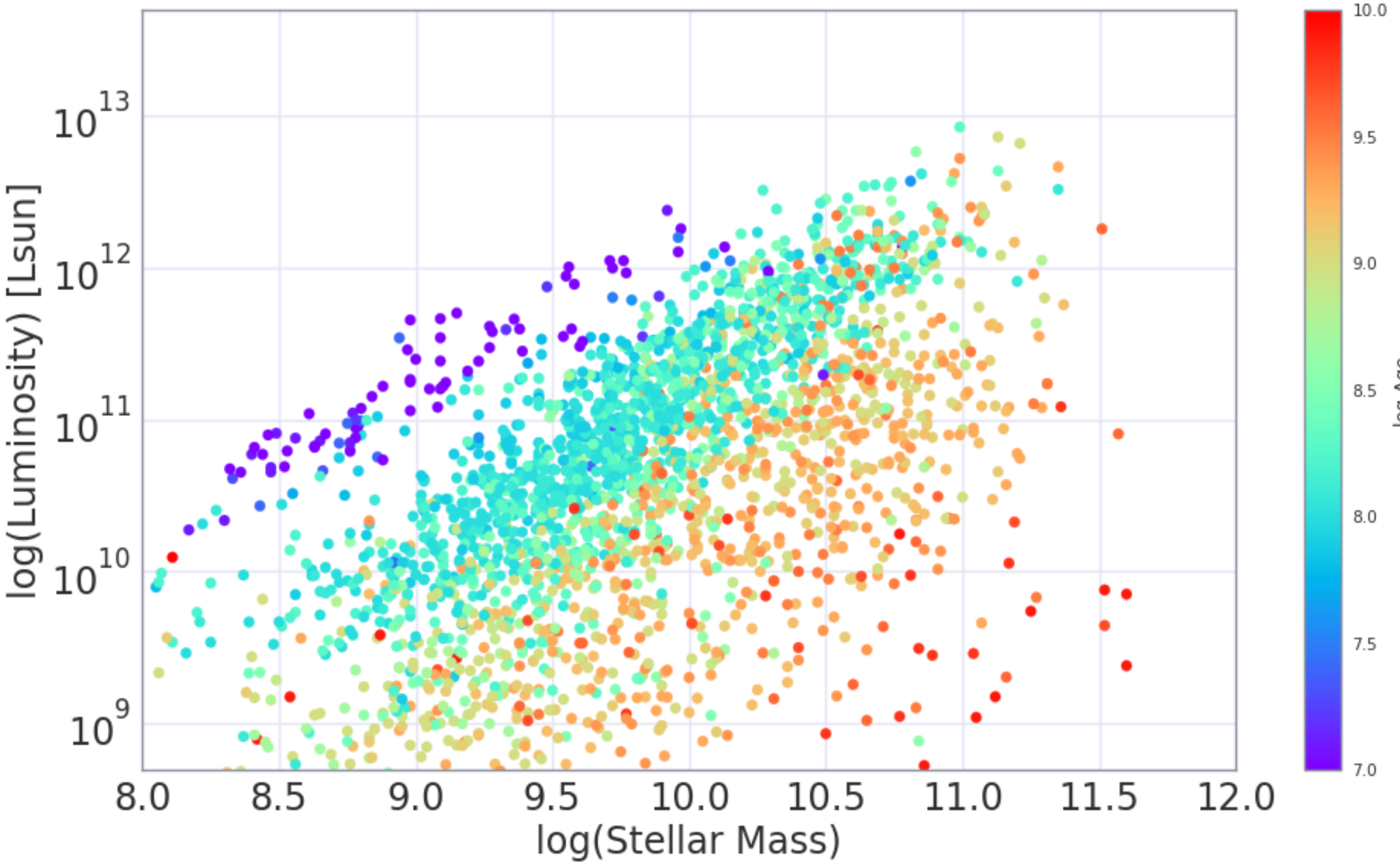

Fit can be improved by splitting the sample into finer subsamples, isolating e.g,;

- Star-forming/Quiescent
- AGN
- Starbursts

We find features most influential are, for 4 subsamples:

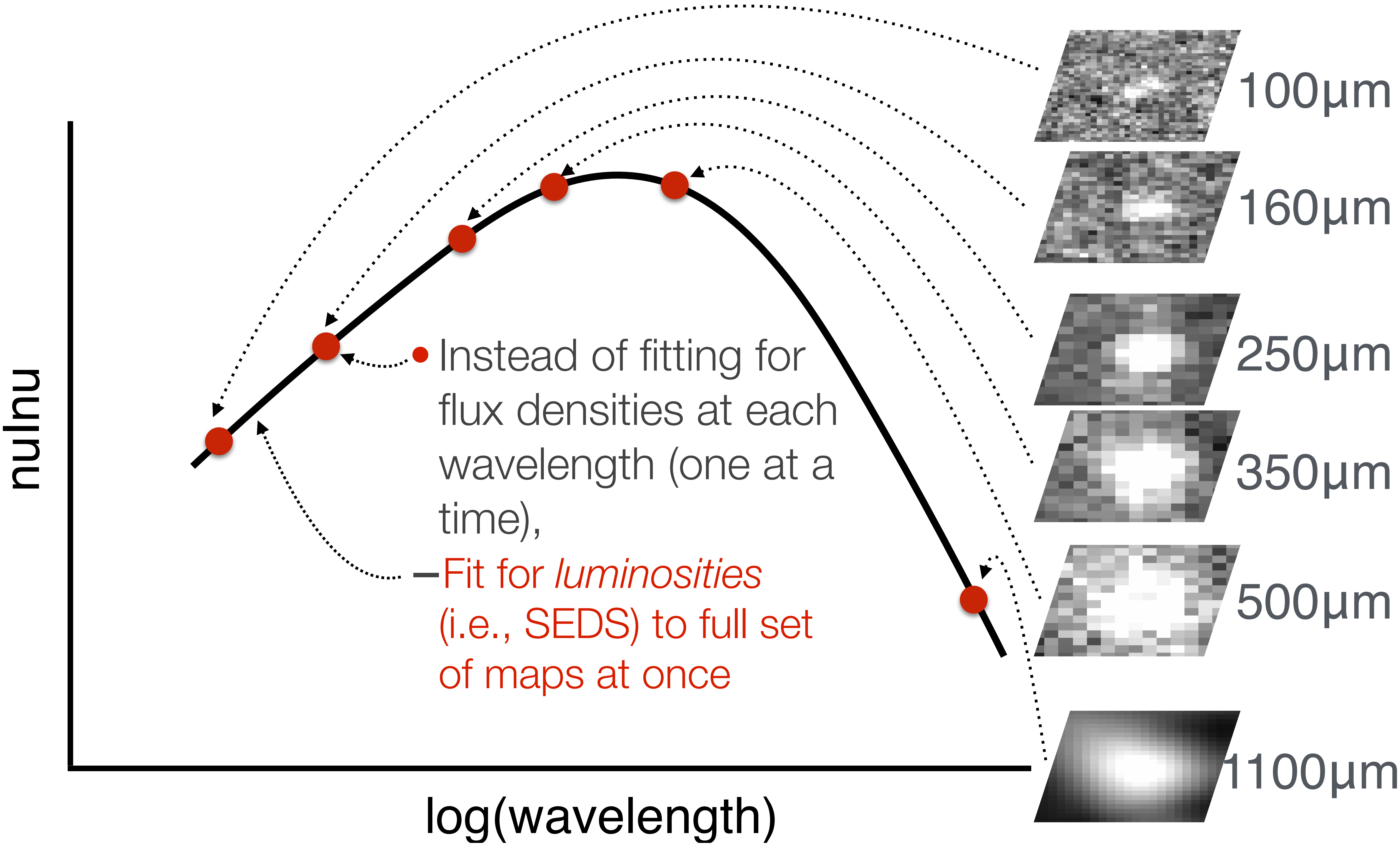
- log(LIR) = C+ $\alpha(z)\times\log(1+z)$ + $\beta(z)\times\log(M)$ + $\gamma(z)\times\log(Av)$ + $\delta(z)\times\log(F_{agn})$

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



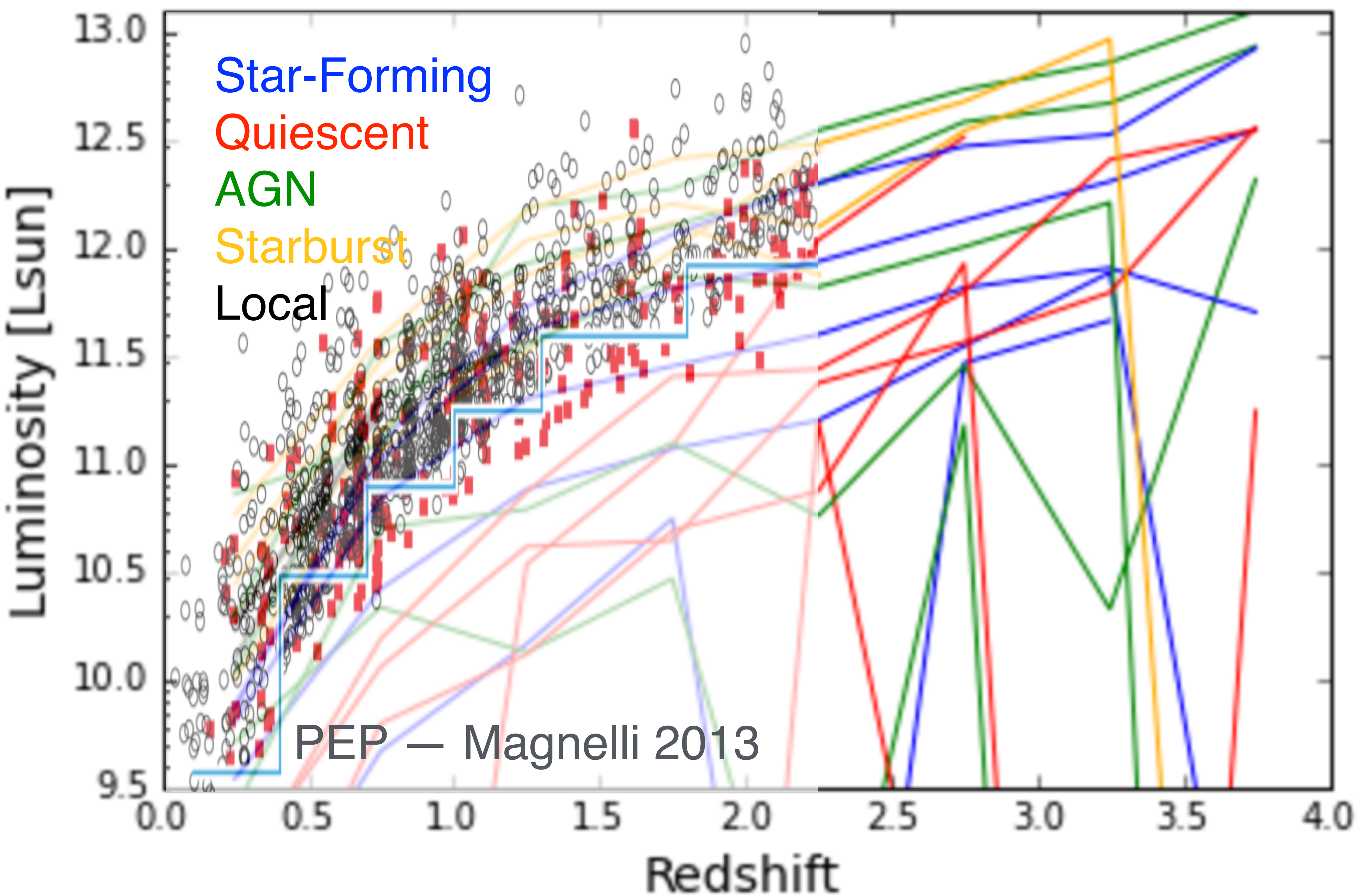

0

# SEDSTACK: Beyond Flux



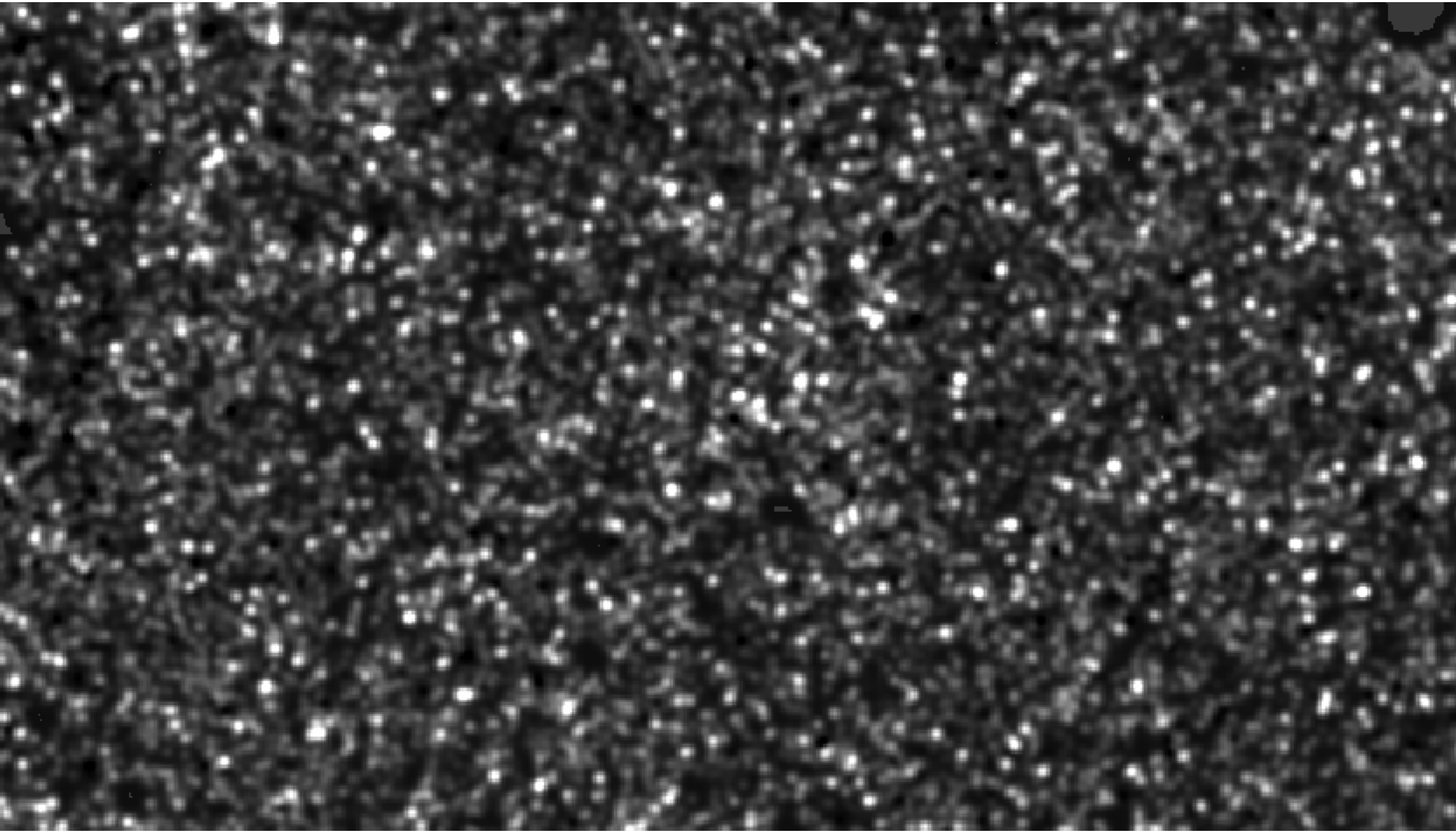

- Instead of fitting for flux densities at each wavelength (one at a time),
  - Fit for *luminosities* (i.e., SEDS) to full set of maps at once

# SEDSTACK: Beyond Flux




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

# And FLUCTFIT?



# Applications: CII/CO/CIB Modeling

et al. 2000; Rowan-

ass function, which Magnelli et al. 2012; hroozi et al. (2013a). a recent comprehen- MF for high-redshift cope of this paper. In

be absorbed into $\sigma_{SFR}$

*Luminosity*

minosity, we assume

$L_{CO}$ (units of $L_\odot$) is

$$L_{CO} = 4.9 \times 10^{-5} L_\odot \left( \frac{\nu_{CO,rest}}{115.27 \text{ GHz}} \right)^3 \left( \frac{L'_{CO}}{\text{K km s}^{-1} \text{pc}^2} \right) \quad (4)$$

## Tony Li et al. 2016

where $\nu_{CO,rest} = 115.27$ GHz is the rest-frame frequency of the CO transition.

To resummarize the model:

1. Halos → SFR: Get $\overline{\text{SFR}}(M, z)$ from the results of Behroozi et al. (2013a)
2. Add log-scatter, $\sigma_{SFR}$
3. SFR → $L_{IR}$: Get $L_{IR}$ from SFR $= \delta_{MF} \times 10^{-10} L_{IR}$
4. $L_{IR} \to L'_{CO}$: Get $L'_{CO}$ from $\log L_{IR} = \alpha \log L'_{CO} + \beta$
5. Add log-scatter, $\sigma_{L_{CO}}$

Not all halos the same (*assembly bias*): *Add scatter*. ← (2)

Not all galaxies star-forming: *Add scatter*. ← (5)

with fiducial parameter values:

$$\sigma_{SFR} = 0.3, \sigma_{L_{CO}} = 0.3,$$
$$\delta_{MF} = 1.0, \alpha = 1.37, \beta = -1.74.$$

Figure 2 shows the combined result of these steps, plotting the mean $L_{CO}(M_h)$ relation from our fiducial model, as well as the equivalent relation from previous studies. Notably, $L_{CO}$ in this model is not linear in $M$, a simplifying assumption that has

7 While this paper was under review, the values of ($\alpha$, $\beta$) in Dessauges-

# Applications: CII/CO/CIB Modeling

et al. 2000; Rowan-
ass function, which
Magnelli et al. 2012;
hroozi et al. (2013a).
a recent comprehen-
MF for high-redshift
cope of this paper. In
es quoted above, we
og $\delta_{MF} = 0.0 \pm 0.3$
prior's $\pm 3\sigma$ interval

be written as
explicitly accounts
as opposed to active
simplicity, we have
out Equation (1) due
be absorbed into $\sigma_{SFR}$

*Luminosity*

minosity, we assume

$L_{CO}$ (units of $L_\odot$) is

$$L_{CO} = 4.9 \times 10^{-5} L_\odot \left(\frac{\nu_{CO,rest}}{115.27\ \mathrm{GHz}}\right)^3 \left(\frac{L'_{CO}}{\mathrm{K\ km\ s^{-1}\ pc^2}}\right) \quad (4)$$

## Tony Li et al. 2016

where $\nu_{CO,rest} = 115.27$ GHz is the rest-frame frequency of the CO transition.

To resummarize the model:

1. Halos → ~~SFR~~: Get ~~$\overline{SFR}(M, z)$~~ from the results of Behroozi et al. (2013a)
2. ~~Add log-scatter, $\sigma_{SFR}$~~
3. ~~SFR → $L_{IR}$: Get $L_{IR}$ from SFR $= \delta_{MF} \times 10^{-10} L_{IR}$~~
4. $L_{IR} \to L'_{CO}$: Get $L'_{CO}$ from $\log L_{IR} = \alpha \log L'_{CO} + \beta$
5. ~~Add log-scatter, $\sigma_{L_{CO}}$~~

Stellar Mass – $M_*$

Use empirically derived $L_{IR}(z, M_*)$

with fiducial parameter values:

$$\sigma_{SFR} = 0.3,\ \sigma_{L_{CO}} = 0.3,$$
$$\delta_{MF} = 1.0,\ \alpha = 1.37,\ \beta = -1.74.$$

Figure 2 shows the combined result of these steps, plotting the mean $L_{CO}(M_h)$ relation from our fiducial model, as well as the equivalent relation from previous studies. Notably, $L_{CO}$ in this model is not linear in $M$, a simplifying assumption that has

[7] While this paper was under review, the values of ($\alpha$, $\beta$) in Dessauges-

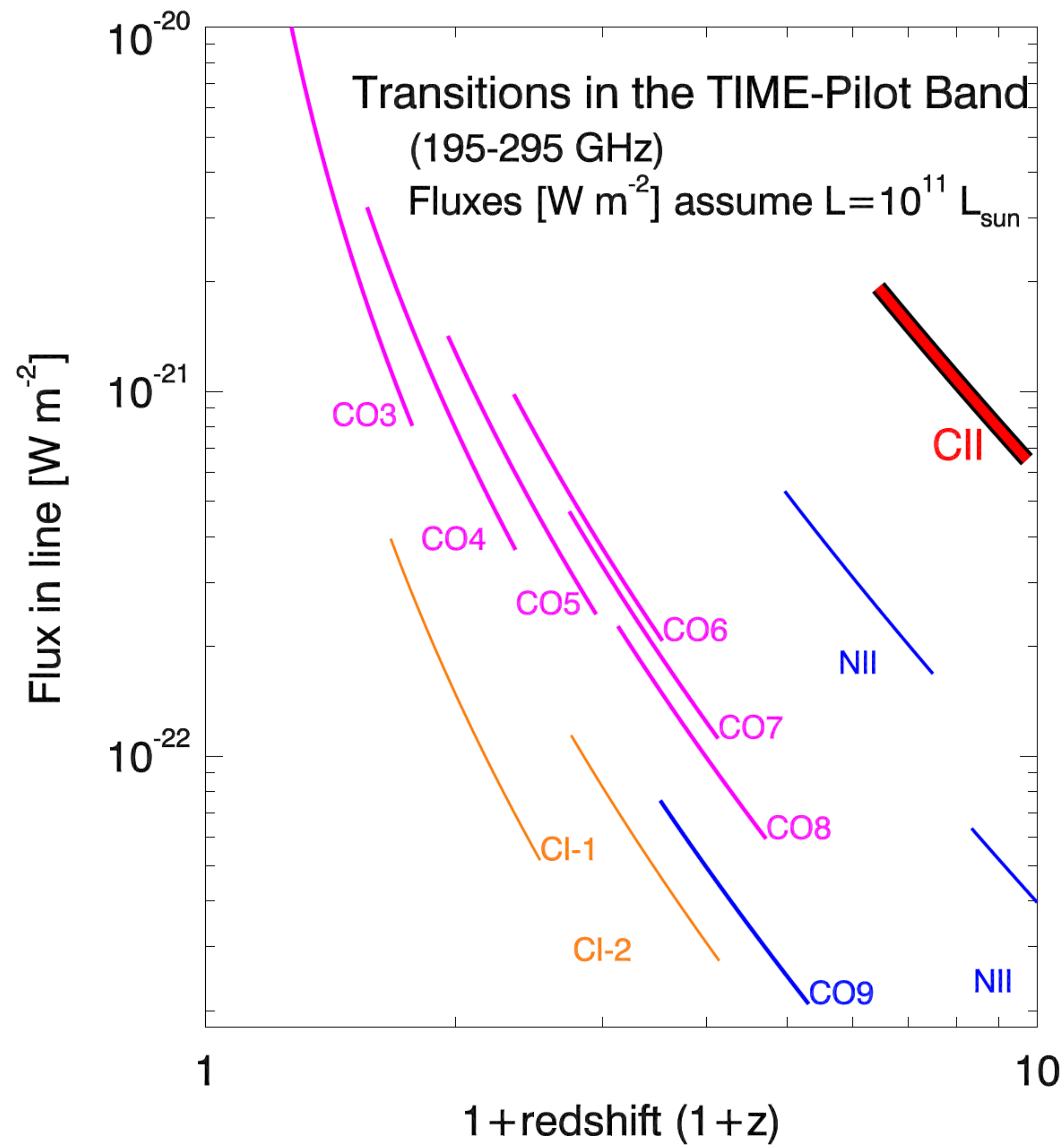
# Applications

- Signal
  - ➡ Connect to Halo properties (including assembly bias) to:
    - estimate CO levels,
    - construct covariances,
    - test different estimators (i.e., beyond power spectrum),
    - Details being discussed during this meeting!
  - ➡ Extend to other lines that correlate with thermal dust SED
    - CII, OII, OIII, NII
    - r.f. 850um as tracer of ISM Mass.

- Foregrounds
  - ➡ Predict CO contamination in CII data cubes (e.g, Sun and the TIME collaboration, 2017)

# Masking CO in CII line-intensity maps

- Targeting CII at z = 6-10 means separating signal from lower-z CO.
- In deep fields (e.g., COSMOS, UDS, GOODS), all potentially significant CO emitters (z=1-3) will be cataloged in the UV, optical, and NIR with great detail.
  - ➡ In these cases, we can construct an estimator for CO from optical predictors of the mean LIR.
  - ➡ How much variance is there from the mean, and how aggressively does masking need to be to play it safe?

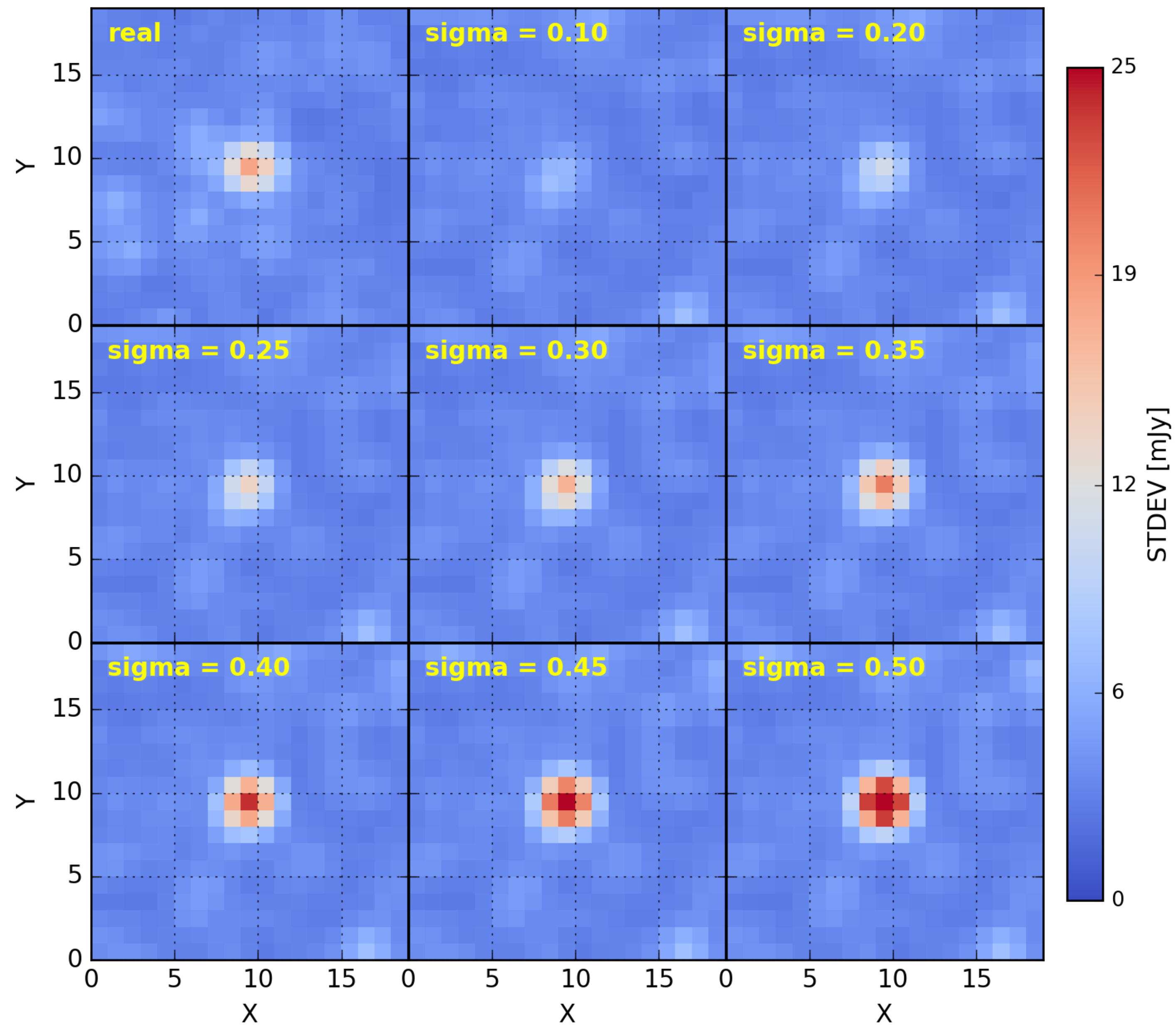


# Masking CO in CII data: Sun et al. 2017

Variance in the LIR estimator determined by comparing scatter in the difference map with simulations.

- Find sigma = 0.33

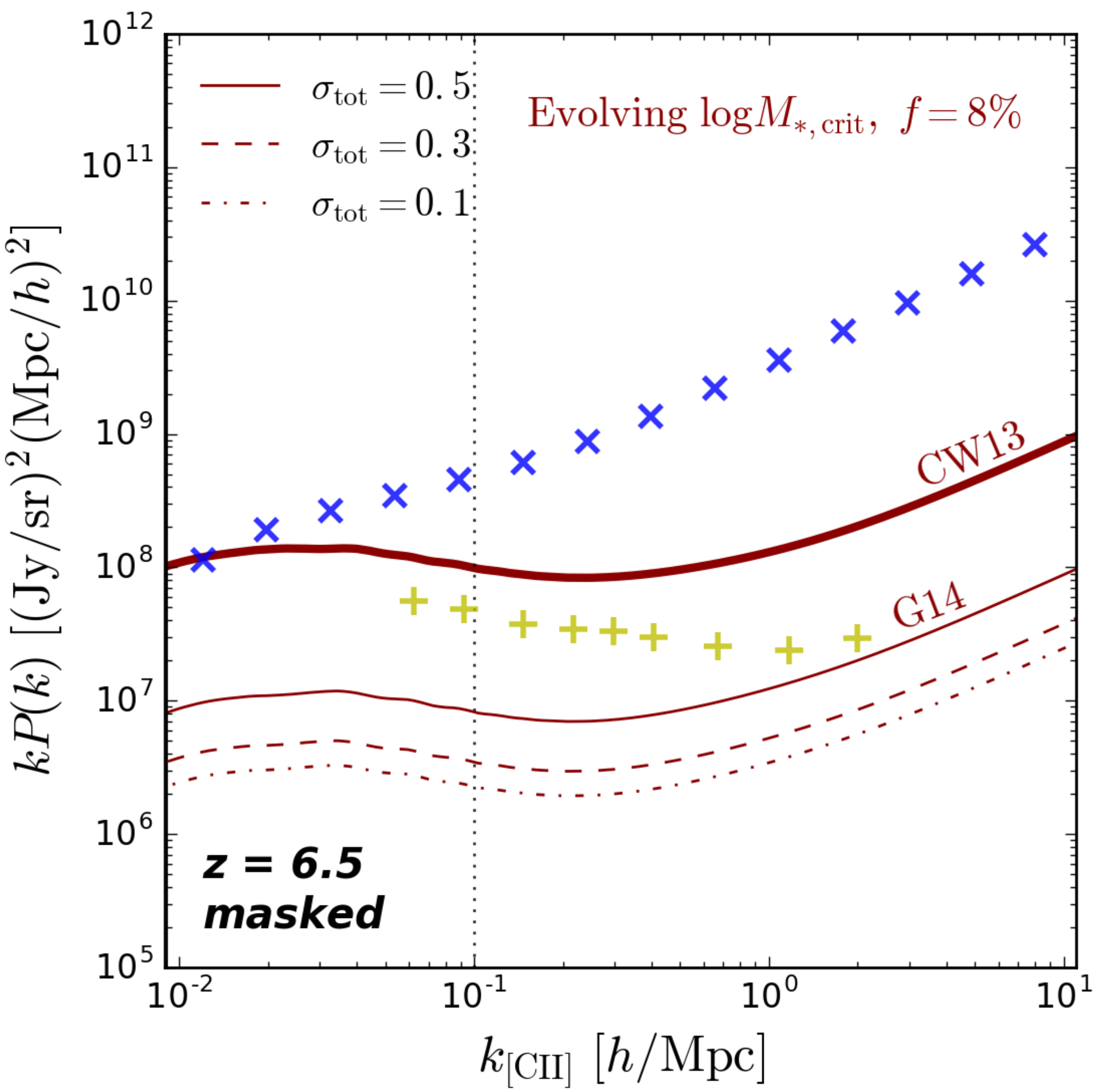

Guaocho (Jason) Sun

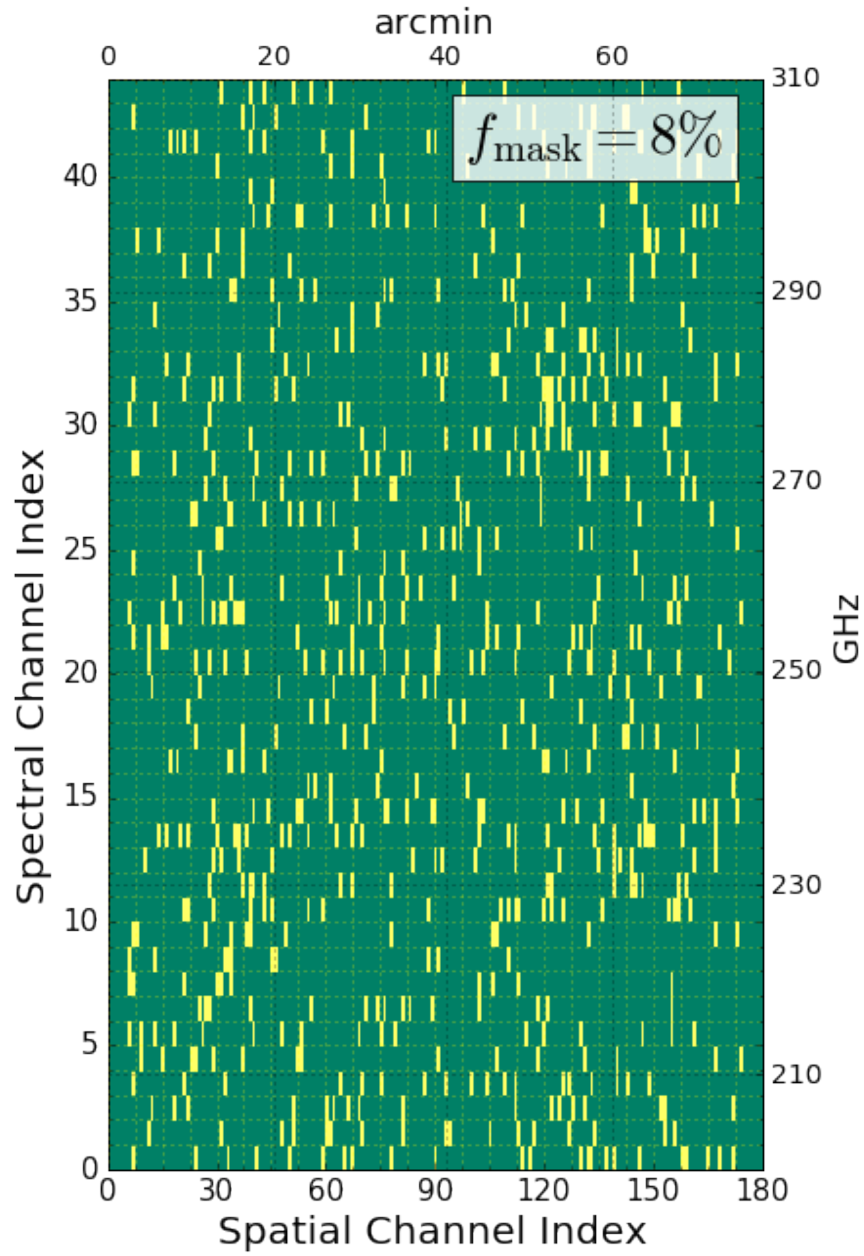



Lorenzo Moncelsi

Sun, Moncelsi, Viero & TIME collaboration 2017, arXiv:1610.10095

# Masking CO in CII data: Sun et al. 2017




Sun, Moncelsi, Viero & TIME collaboration 2017, arXiv:1610.10095

# Summary

- CIB continuum intensities are key to empirically connecting optical features of typical galaxies to their FIR/submm components
- Applications for this model include:
  - ➡Forecasting CO power for:
    - Survey design
    - Covariance construction
    - Testing Estimators
    - Measurement Interpretation

- SIMSTACK is easy to use, and available at:
  - ➡https://github.com/marcoviero/simstack