Tracing Dusty Star Forming Galaxies through Cosmic Time

Chapman, Aravena, Nikola, Magnelli, Riechers,
D.Scott, Hill, Bertoldi, Stacey, Herter, many others

Session Outline

- Introduction
- Herschel and SCUBA2 lessons / comparisons (SC)
- Path to science (MA)

Outline of products

Science Theme:

- **Star formation history (SFH) with DSFGs**

Science Goals:

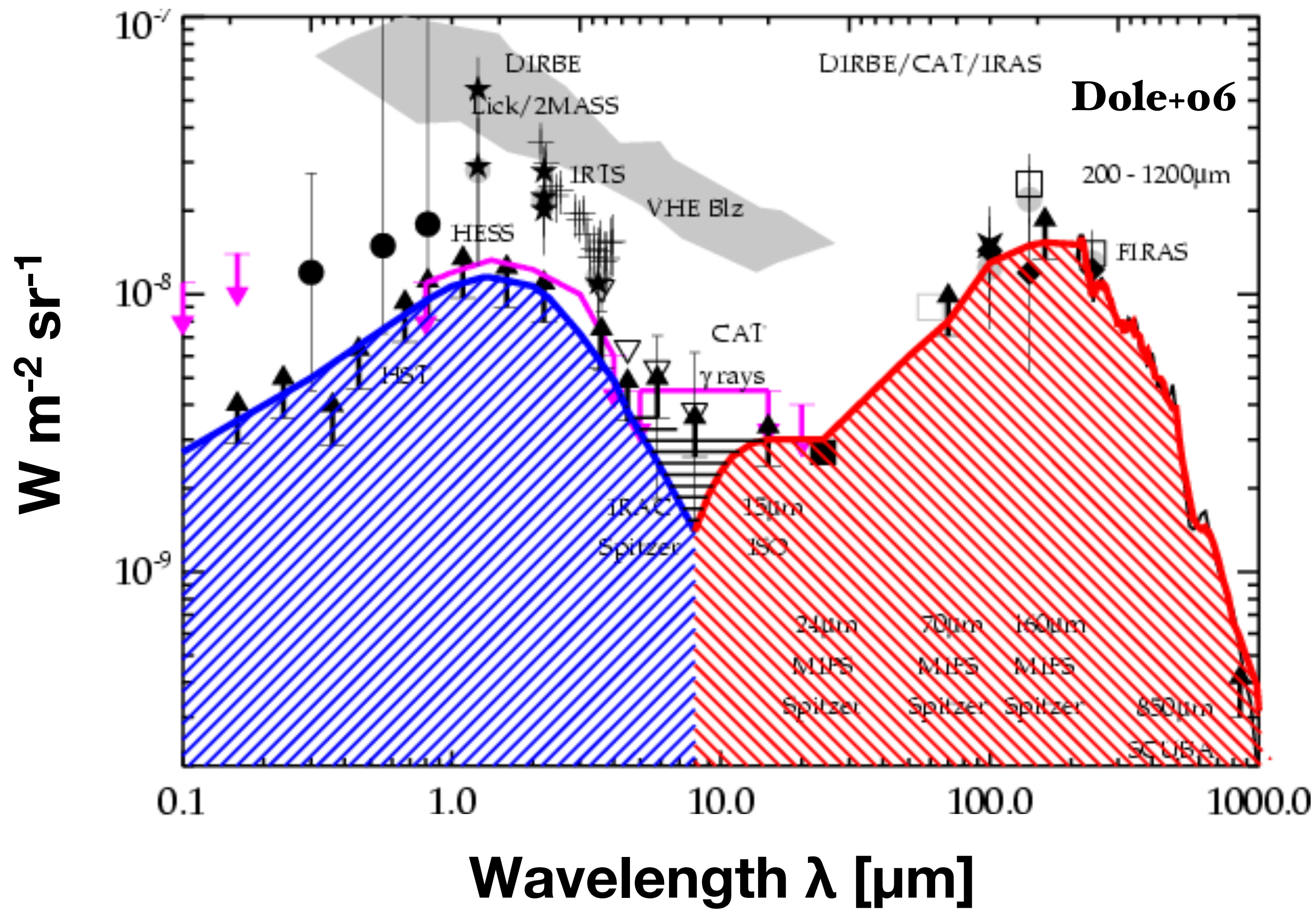
- **Resolving up to ~40% of the CIB at 350μm**
- **—> Robust constraints of the bright-end of the LF**
- **—> Impact of environment**
- **—> Role of dusty SF galaxies in the global galaxy evolution scenario**
- **—> Study of "exotic" galaxies**

First light science **50deg^2;** ***Baseline science*** **200deg^2 and** ***deep fields*****?**

Full Science >5000deg^2 (CCATp 350μm legacy)

Path to science

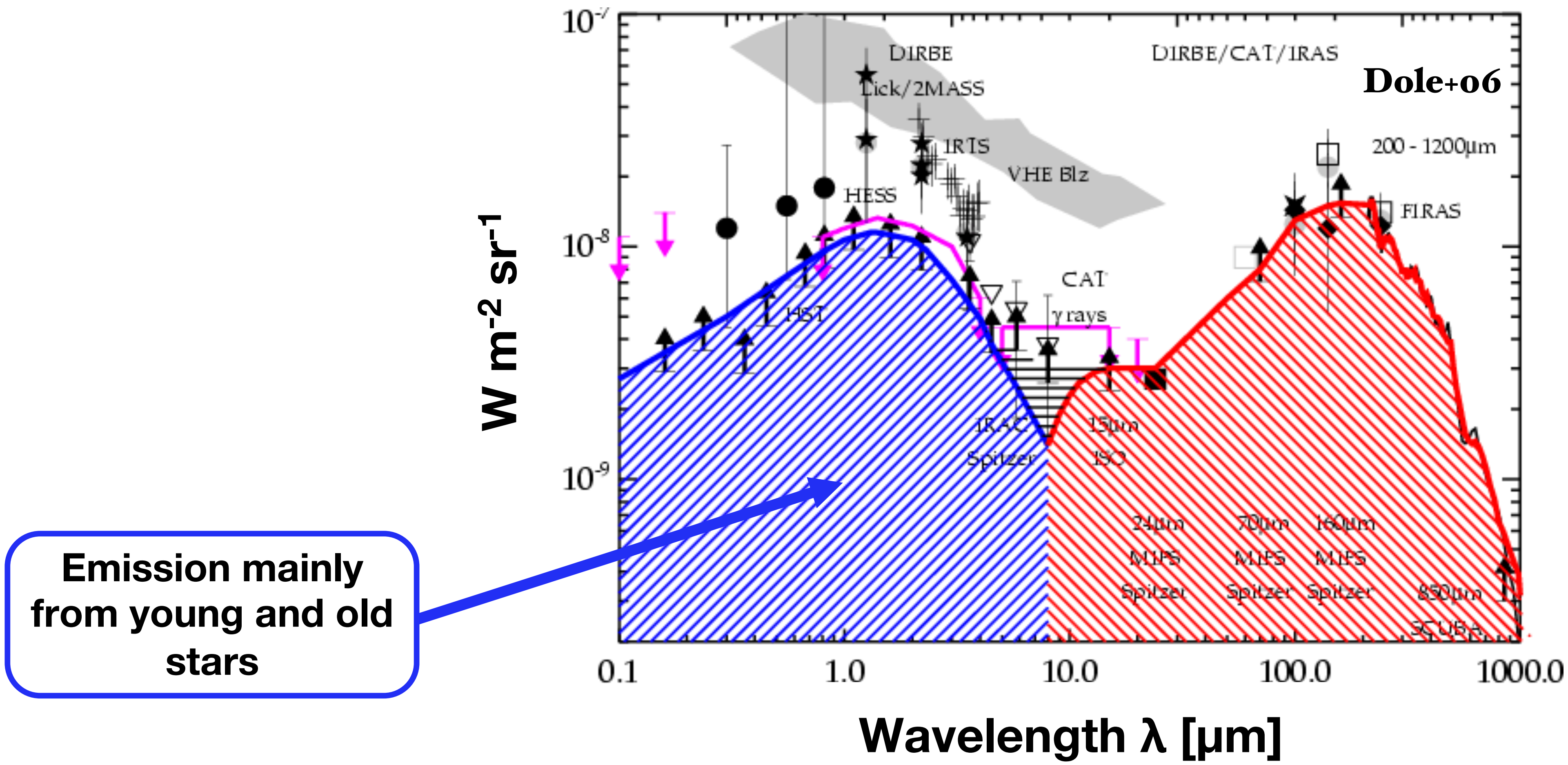
- **Observing requirements: 350μm to confusion limit (2.5mJy) ; plus other bands**
- **A submm map deeper (≳ x 2) and over a wider area (≳ x 5) than those obtained by the *Herschel Space Observatory* at >250μm**
- **A large and comprehensive sample of dusty SF galaxies (≳ 300,000) :**



The cosmic infrared background includes about half of the energy radiated by all galaxies at all wavelengths across cosmic time (e.g., Dole+06)

at z~0, L_{IR} ~1/3 L_{opt}

→ Strong evolution of the IR galaxy population with redshift



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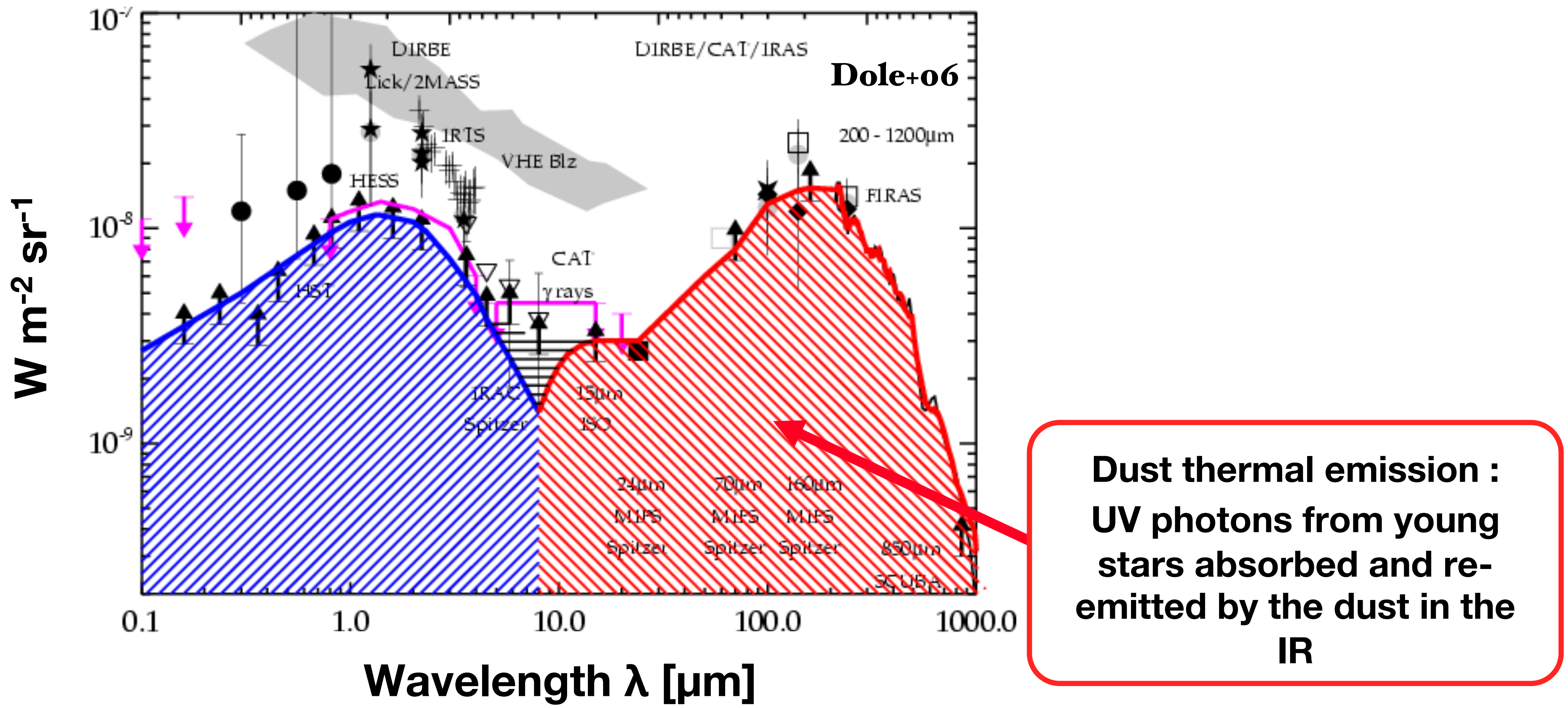

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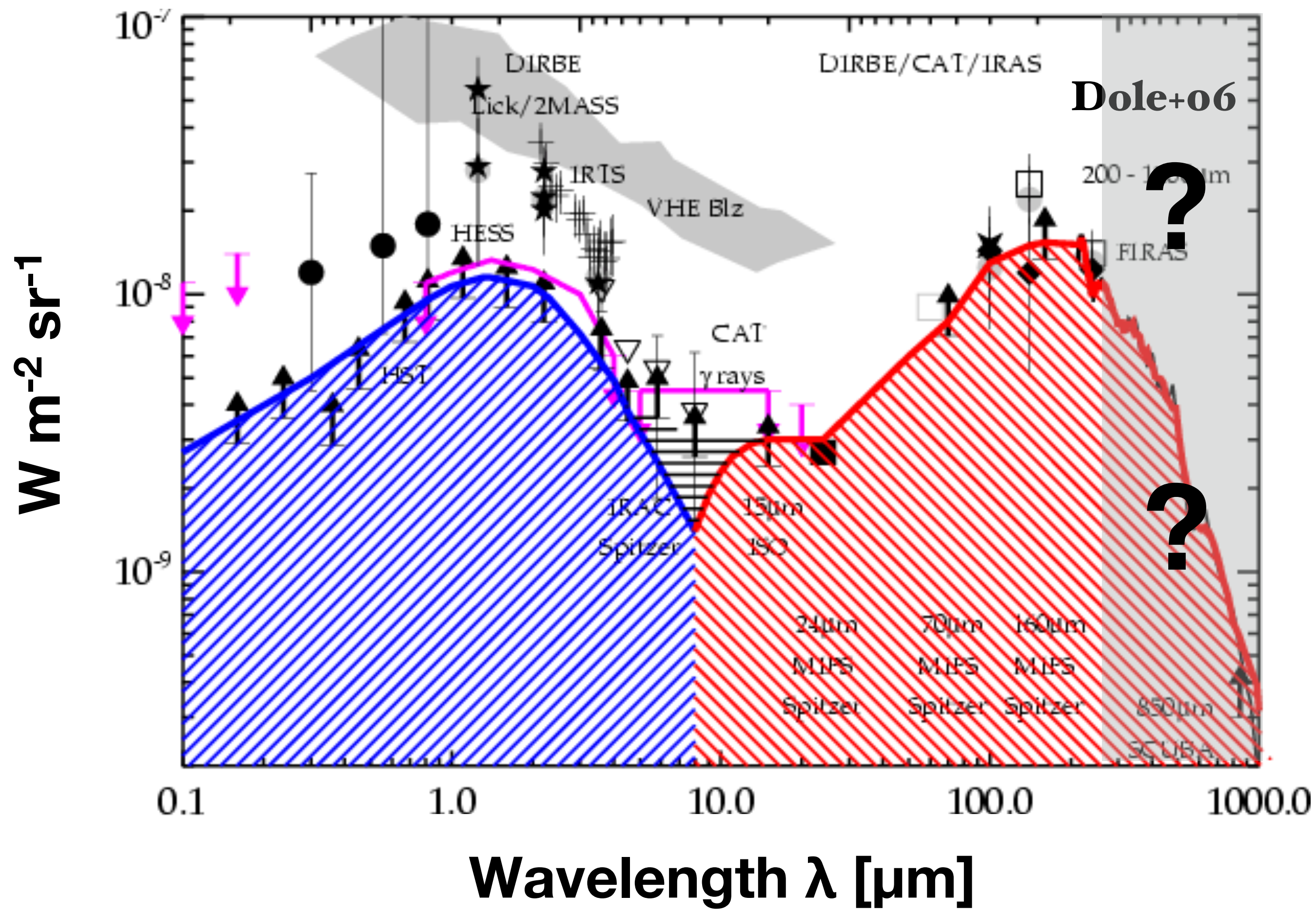
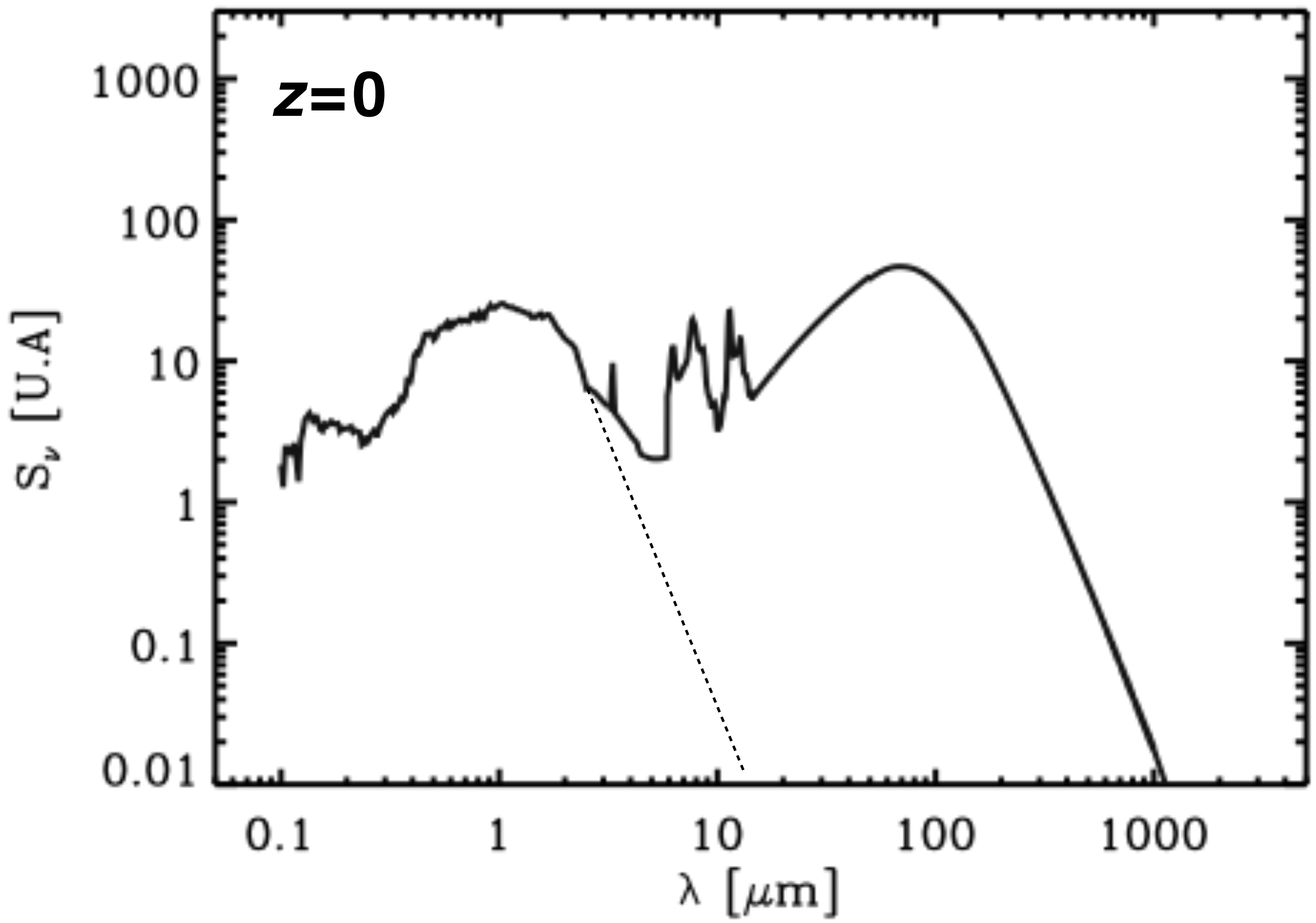


At λ > 250um, only ~15% of the CIB has been resolved into individual sources !!

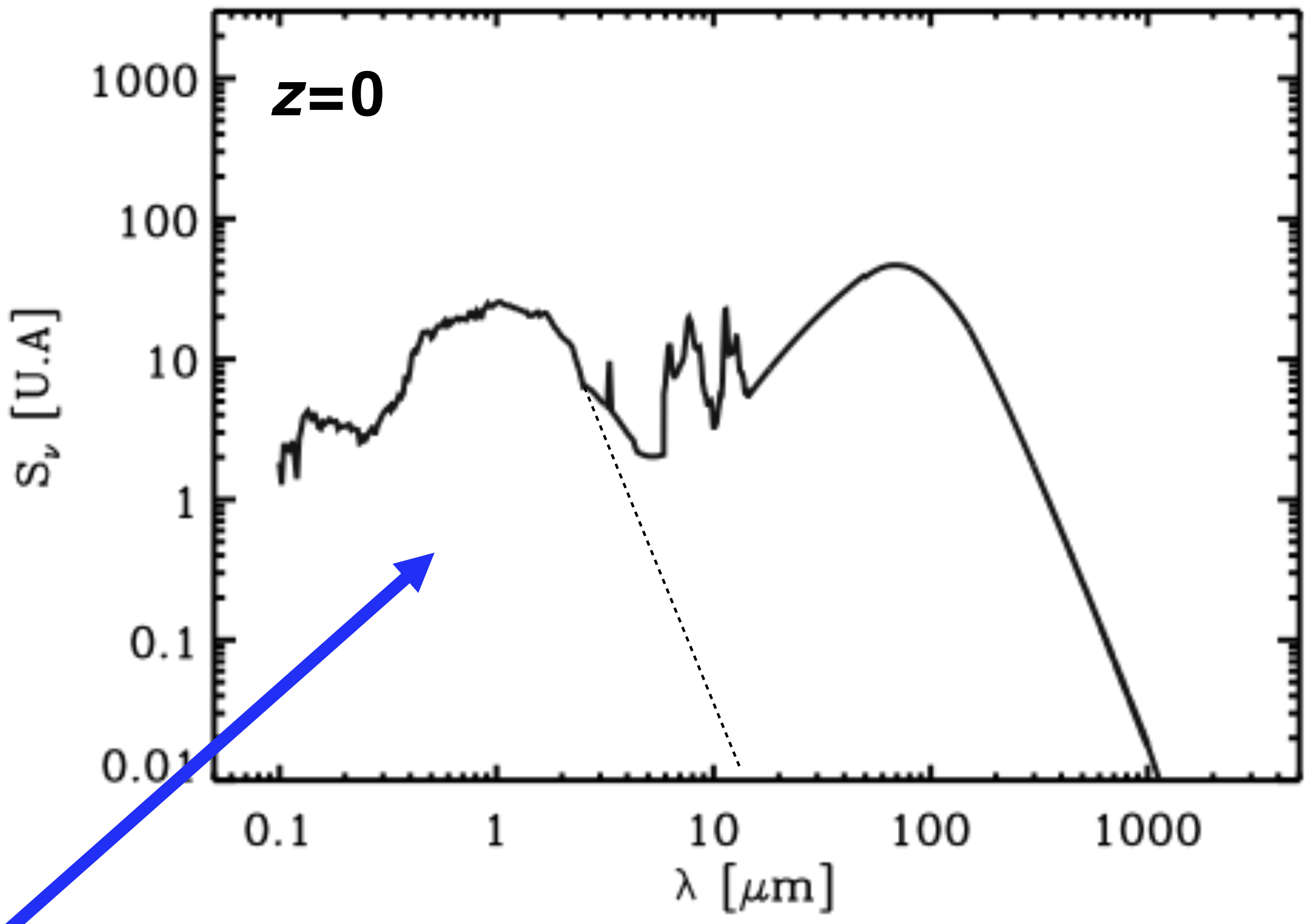
The cosmic infrared background includes about half of the energy radiated by all galaxies at all wavelengths across cosmic time (e.g., Dole+06)

at $z\sim0$, $L_{IR} \sim 1/3\ L_{opt}$

→ Strong evolution of the IR galaxy population with redshift



z=0
1000
100
10
1
0.1
0.01
S_ν [U.A]
0.1
1
10
100
1000
λ [μm]


z=0
1000
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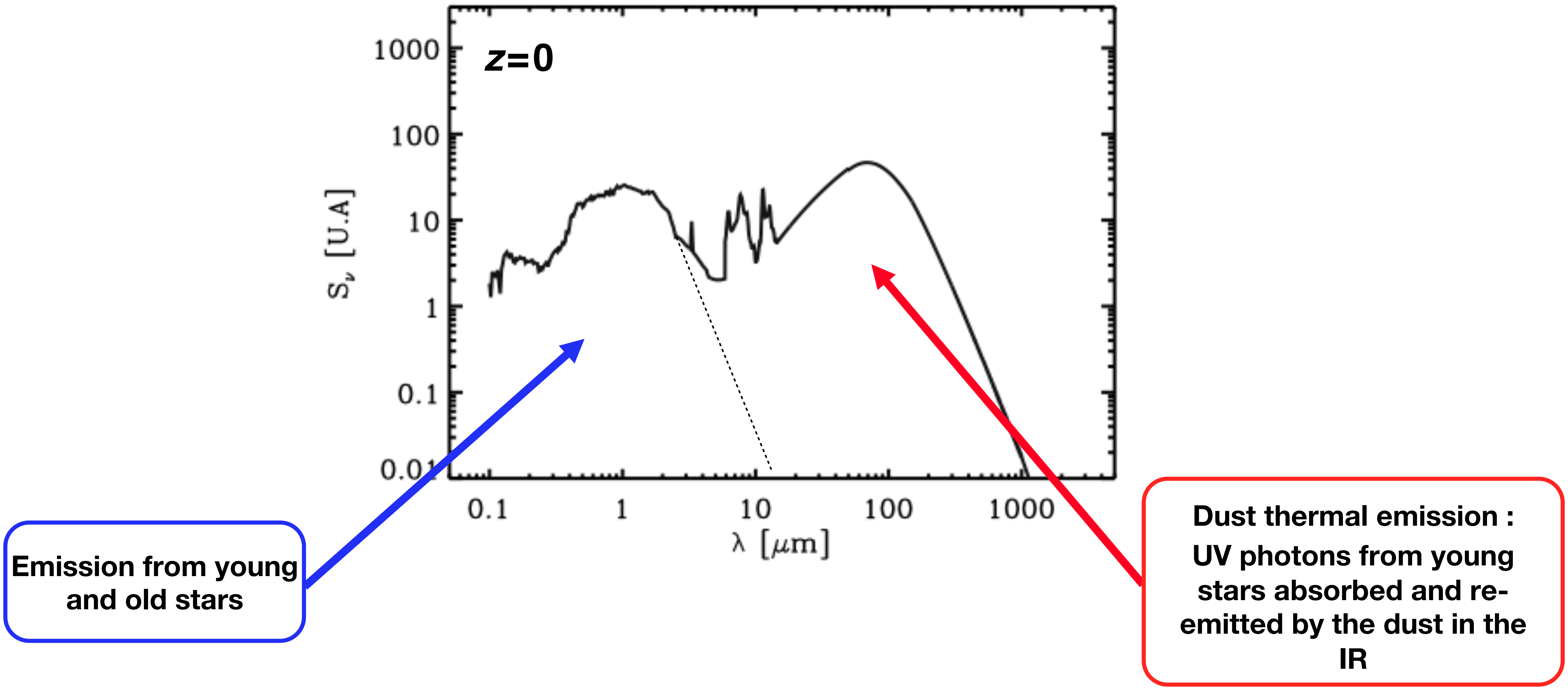
Emission from young
and old stars



z=0
1000
100
10
1
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S_ν [U.A]
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100
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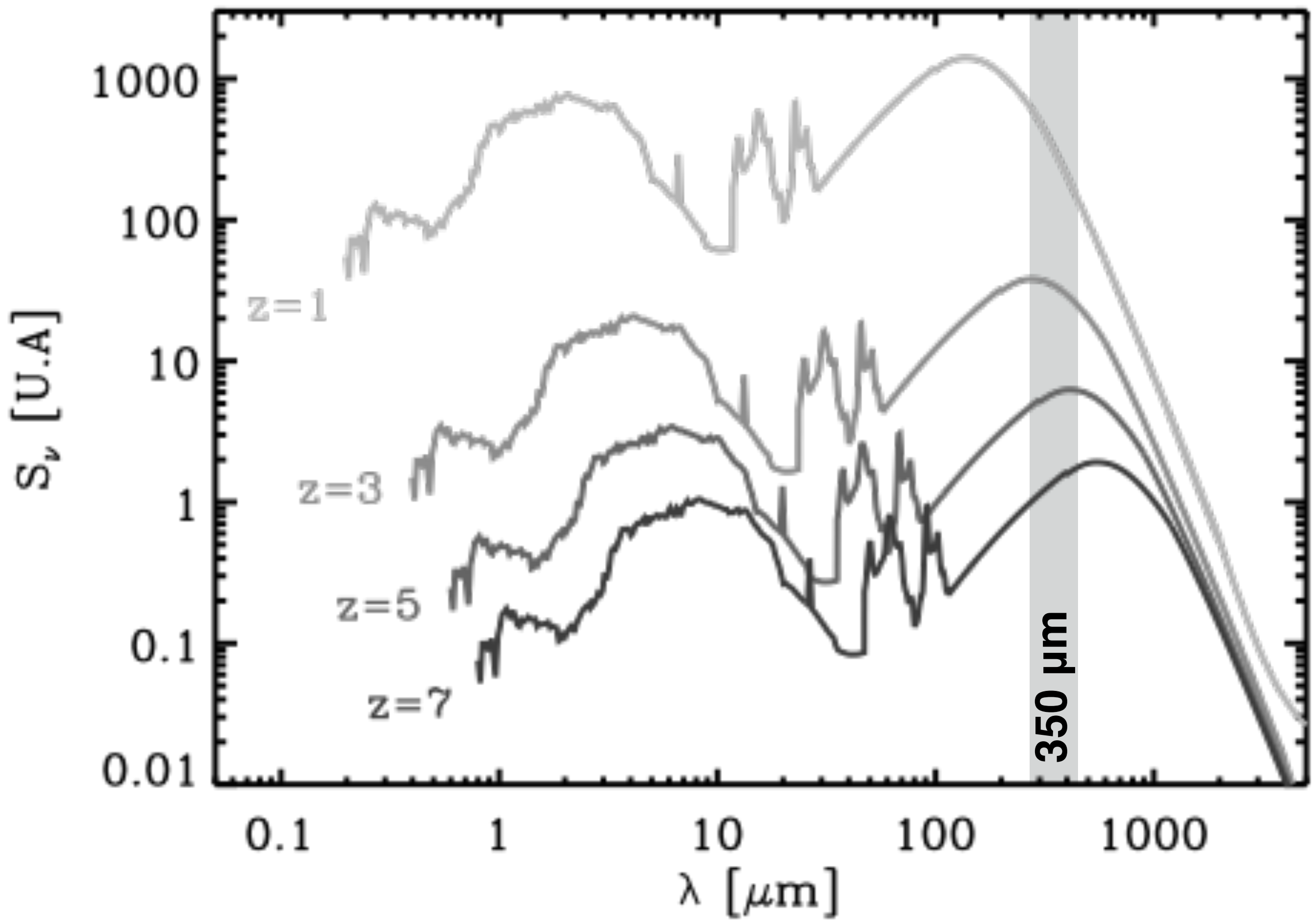
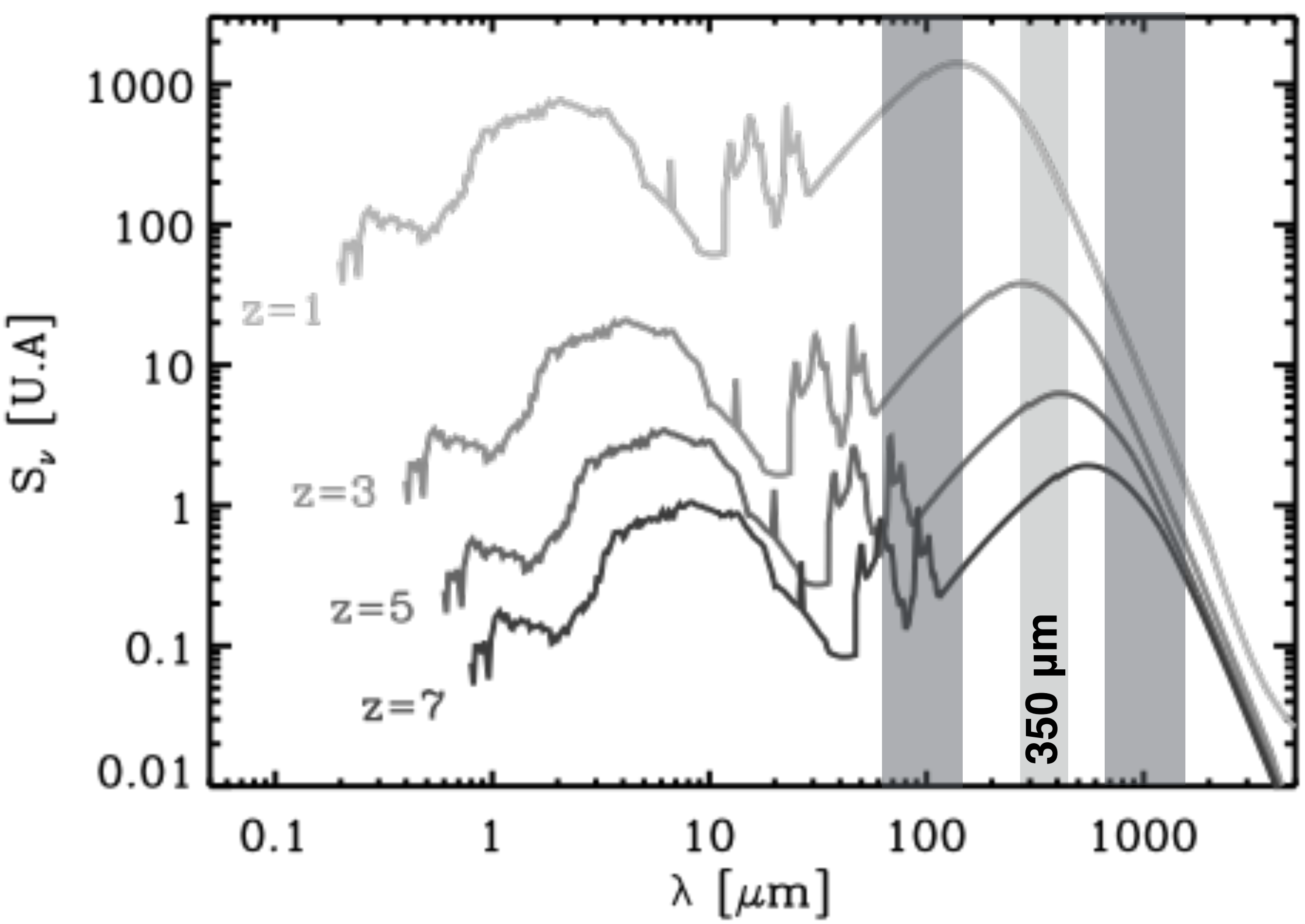
λ [μm]
Emission from young and old stars
Dust thermal emission :
UV photons from young stars absorbed and re-emitted by the dust in the IR

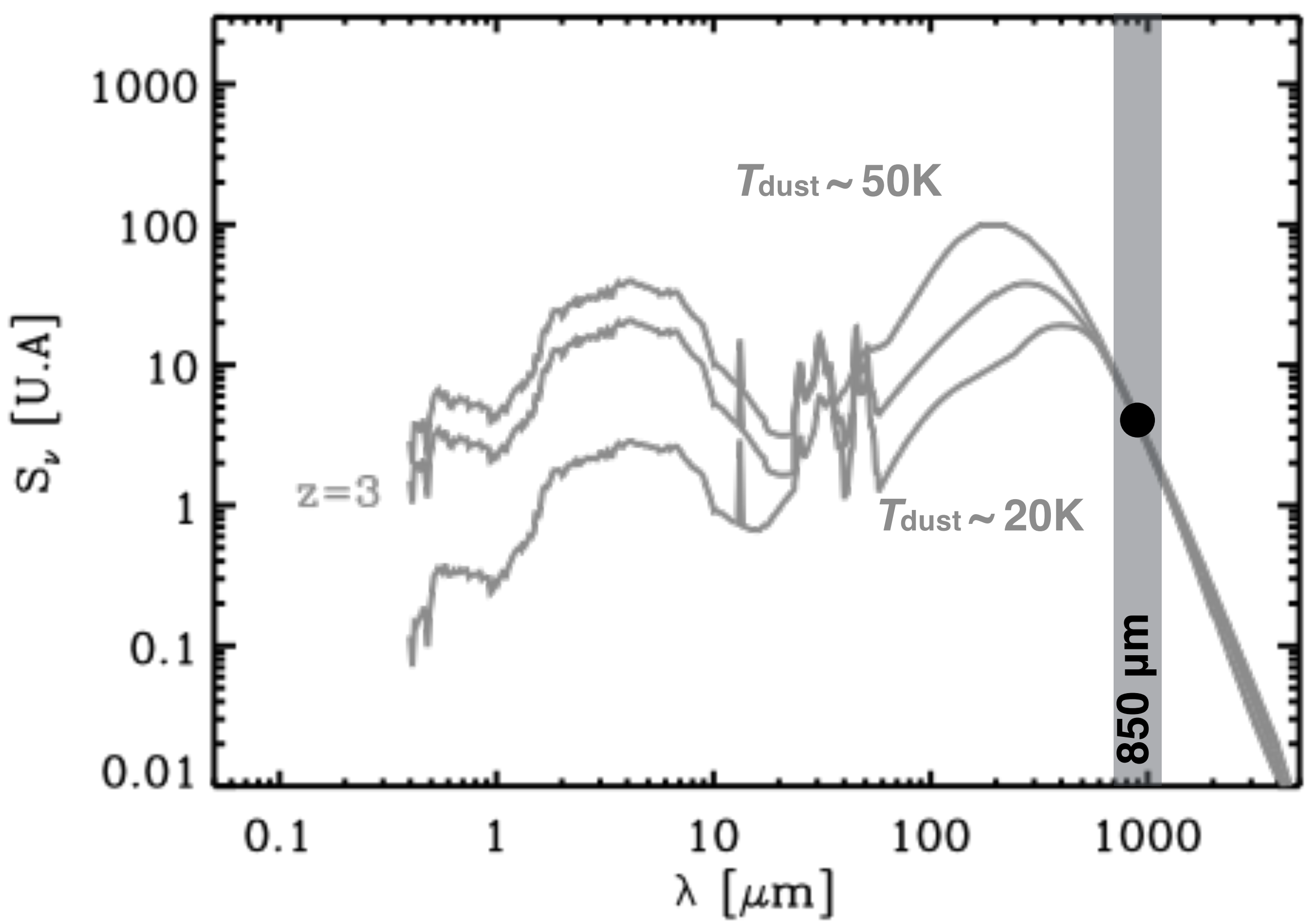


At $1 < z < 7$, the 350μm band probes the peak of the IR emission of galaxies

350μm flux densities are thus excellent proxies of the IR-luminosity and SFR_{IR} of high-z galaxies



1000
100
10
1
0.1
0.01
0.1
1
10
100
1000
S_ν [U.A]
λ [μm]
z=1
z=3
z=5
z=7
350 μm



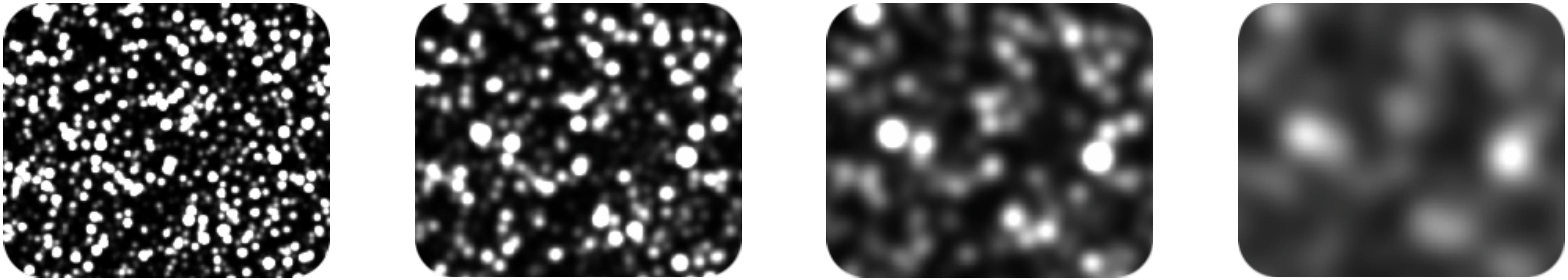
On the contrary, the ≳ 850μm bands probe the IR peak of galaxies only at z ≳ 5

≳ 850μm flux densities provide robust SFR_{IR} estimates only at z ≳ 5

BUT: 850um (and longer) is the key to finding the most distant galaxies!

Why did Herschel resolve only a small fraction of the CIB at 250μm< λ < 500μm ?

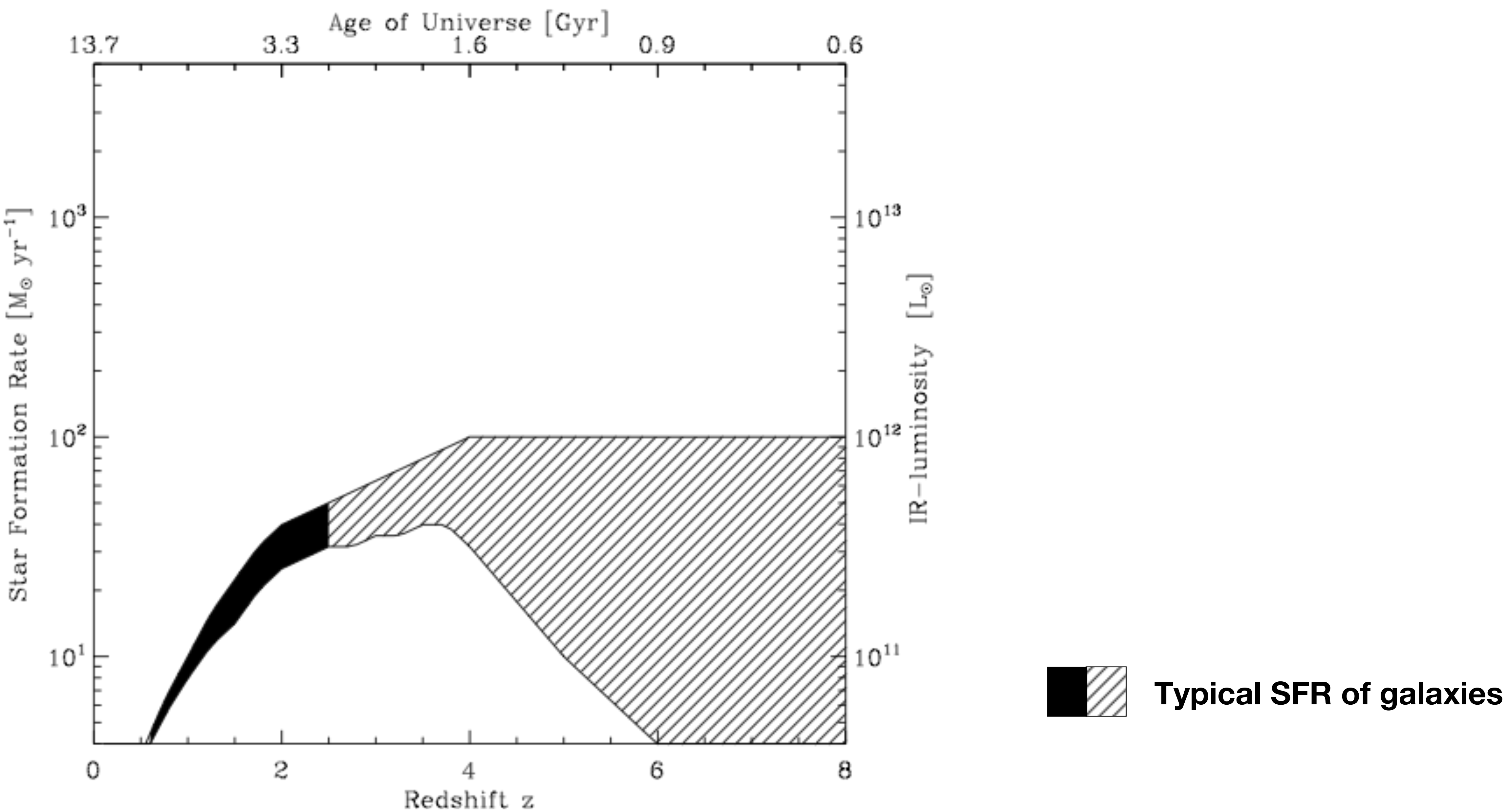
CONFUSION limit



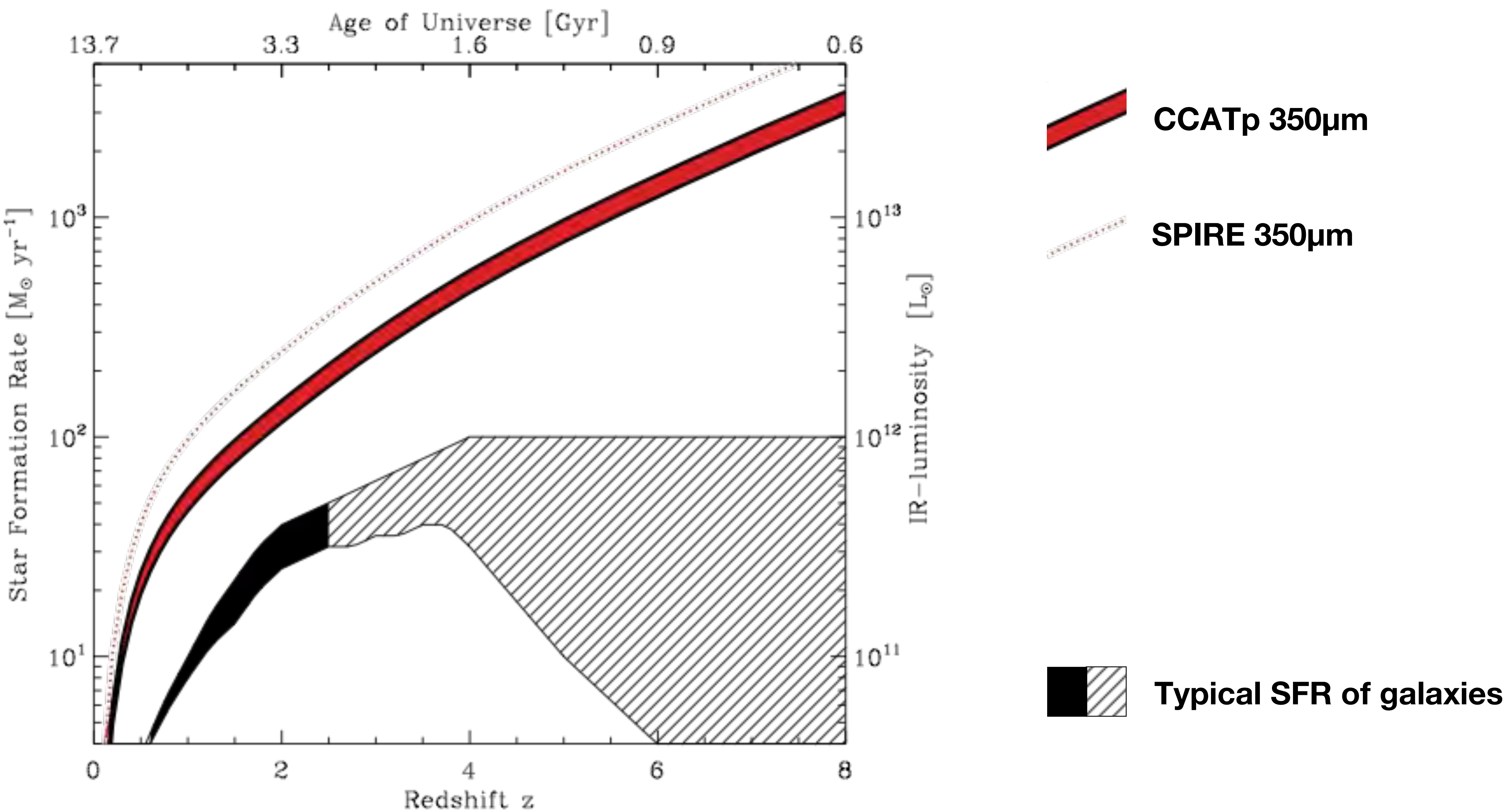
FWHM = x FWHM = 2x FWHM = 4x FWHM = 8x

CONFUSION ≣ NUMBER COUNT ⊗ FWHM
and
FWHM $\propto$ λ / D

—> increase D … difficulty to put large aperture telescope in space and difficulty to observe from the ground at these wavelengths because of the atmosphere



Age of Universe [Gyr]
13.7
3.3
1.6
0.9
0.6
Star Formation Rate [M☉ yr⁻¹]
10³
10²
10¹
IR−luminosity [L☉]
10¹³
10¹²
10¹¹
0
2
4
6
8
Redshift z
Typical SFR of galaxies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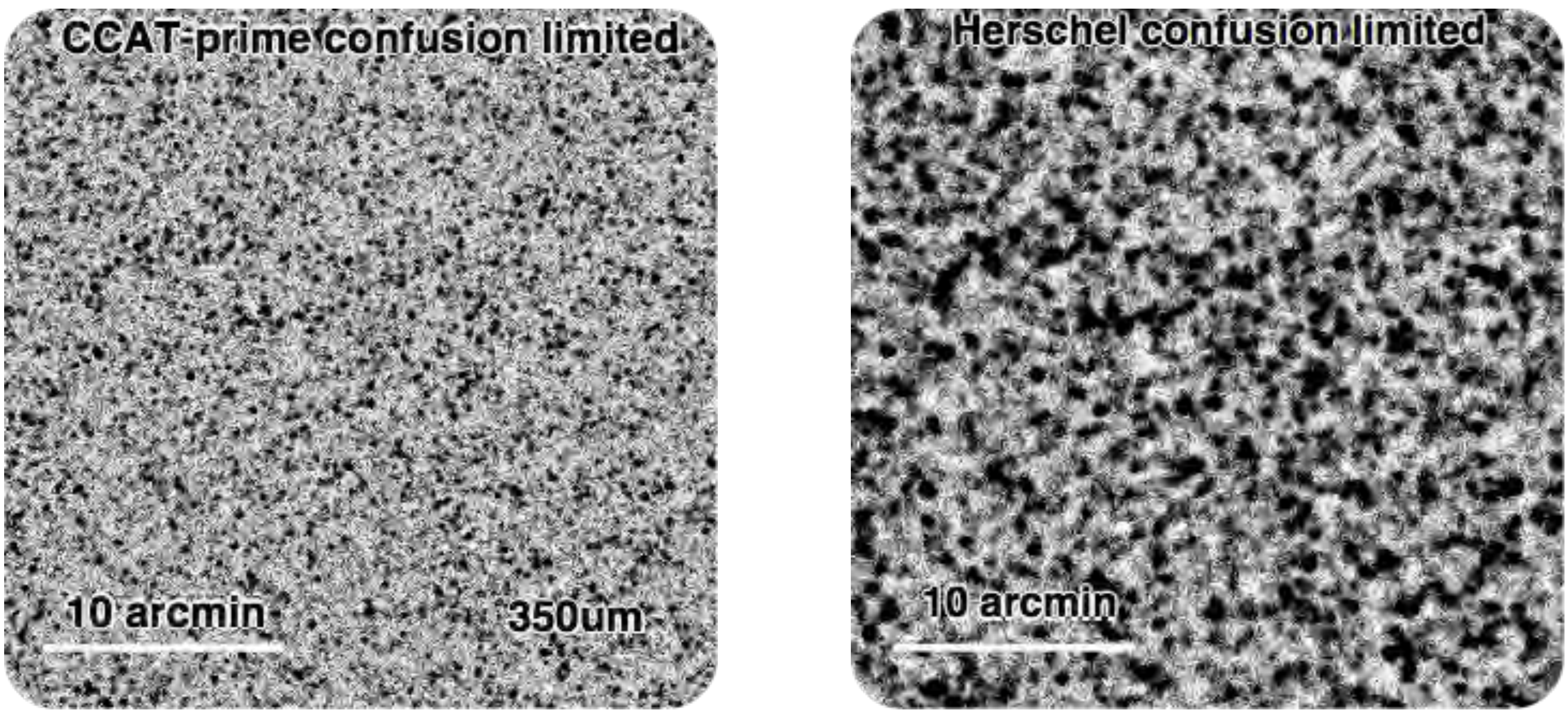
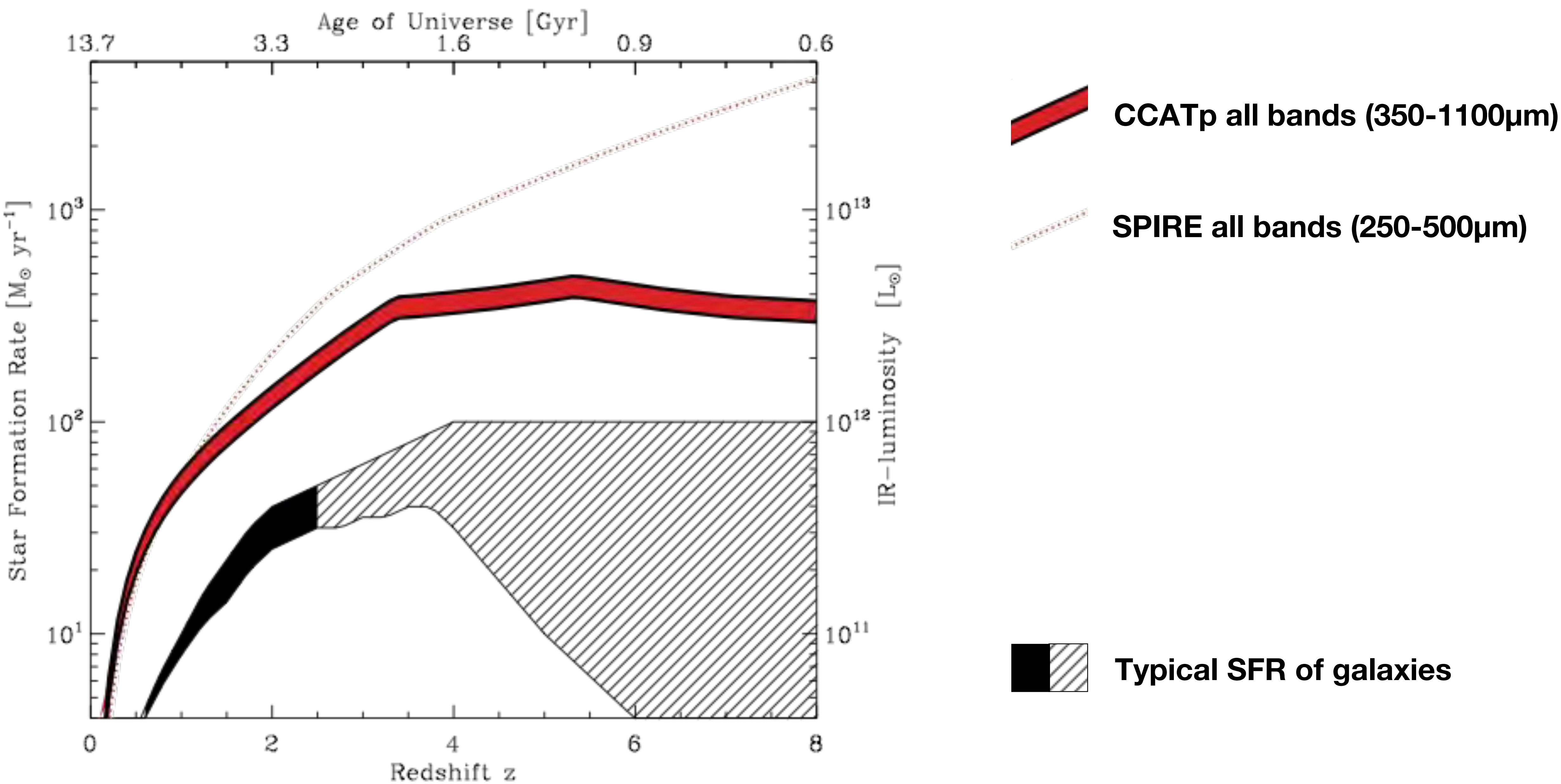
Redshift z
CCATp 350μm
SPIRE 350μm
Typical SFR of galaxies

Age of Universe [Gyr]



Redshift z



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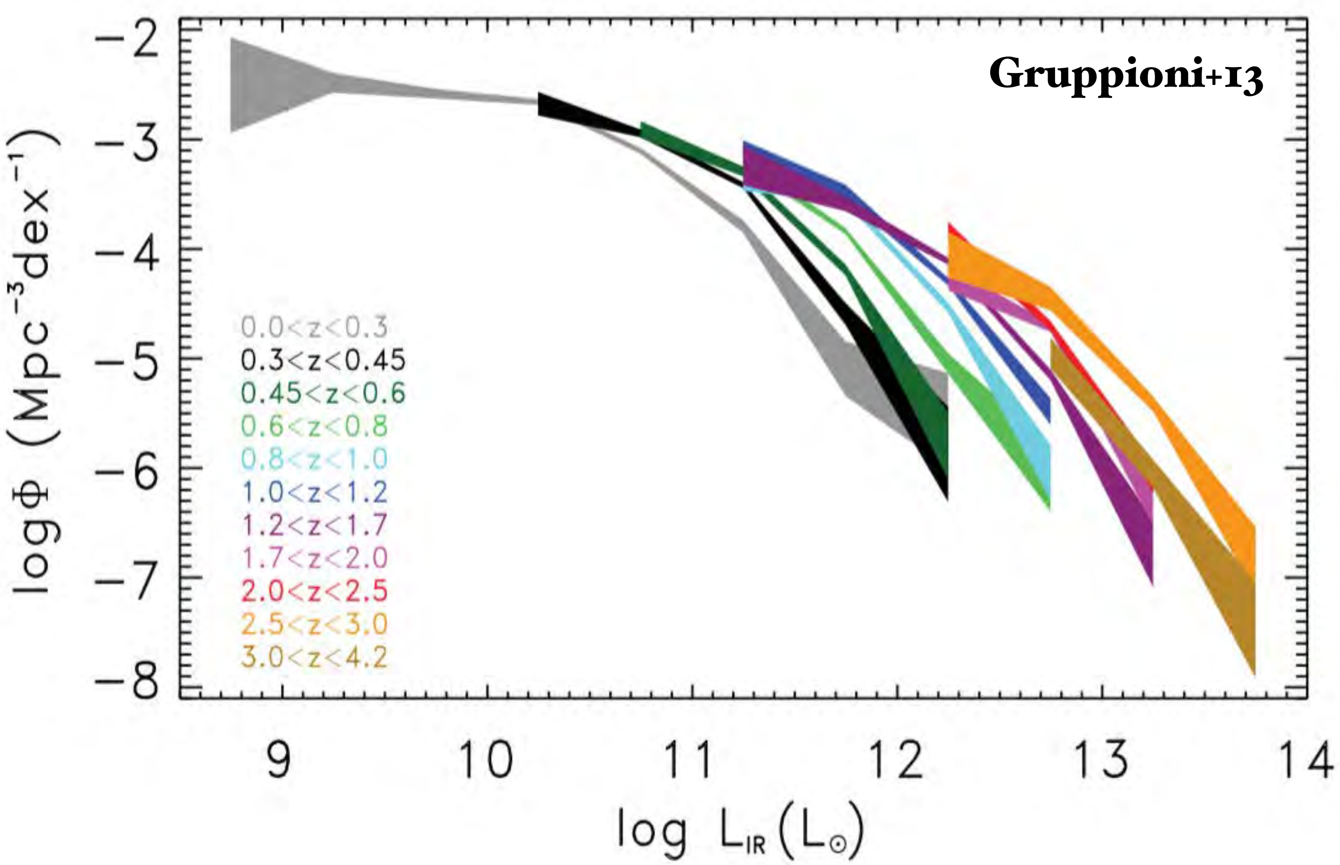
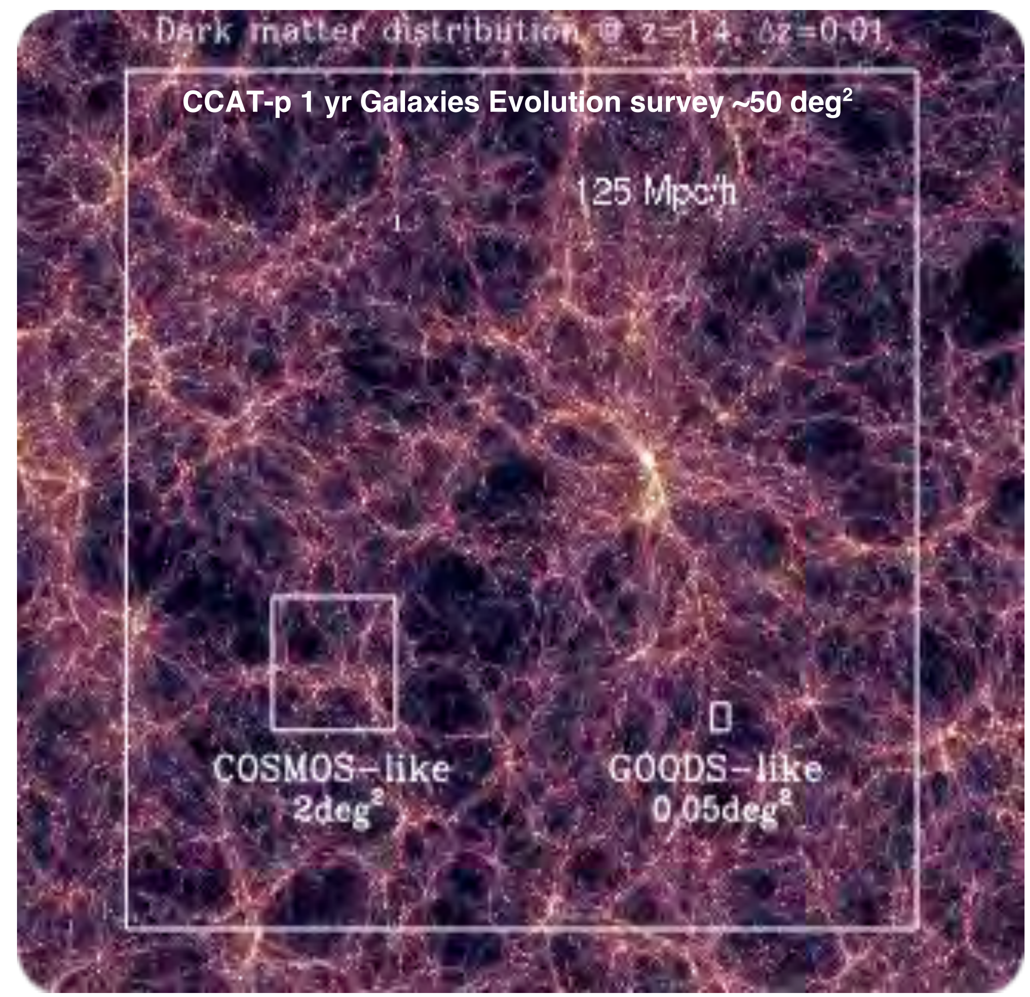
Redshift z
CCATp all bands (350-1100µm)
SPIRE all bands (250-500µm)
Typical SFR of galaxies

Age of Universe [Gyr]

The area of the survey matters also a lot …

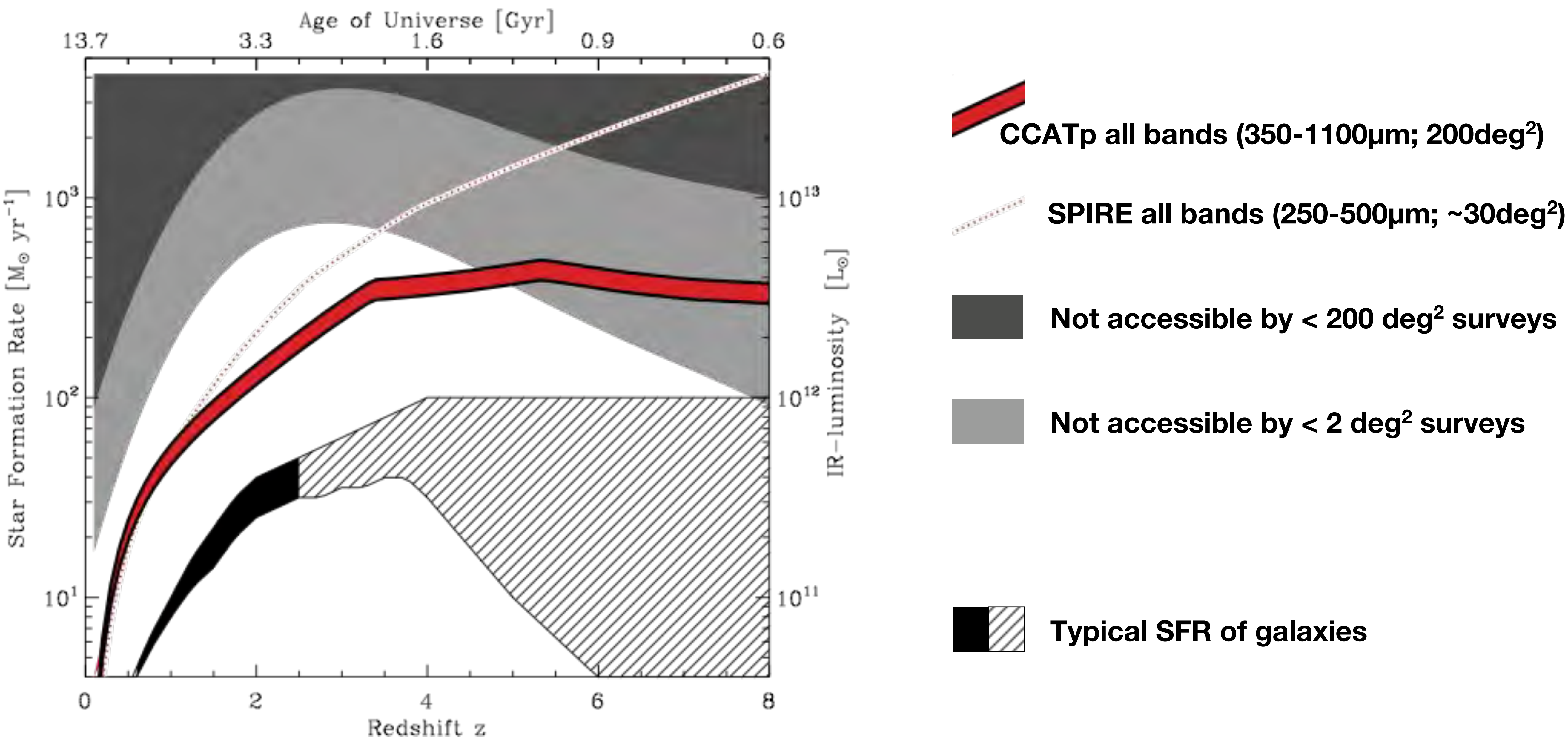




… to accurately probe the high-end of the LF

… to probe the impact of environment

Redshift z



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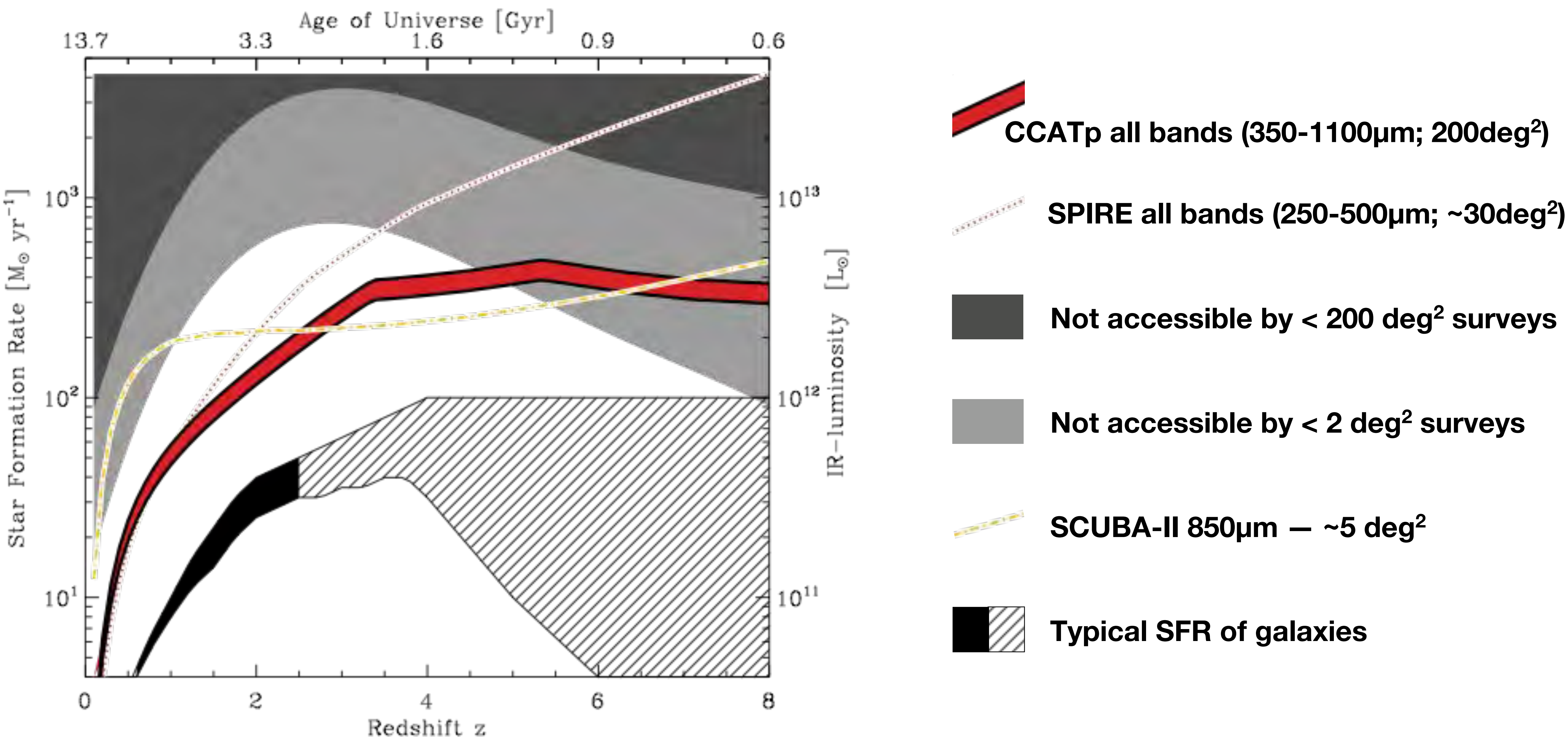
IR–luminosity [L⊙]
Redshift z
0
2
4
6
8
CCATp all bands (350-1100μm; 200deg²)
SPIRE all bands (250-500μm; ~30deg²)
Not accessible by < 200 deg² surveys
Not accessible by < 2 deg² surveys
Typical SFR of galaxies



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Redshift z
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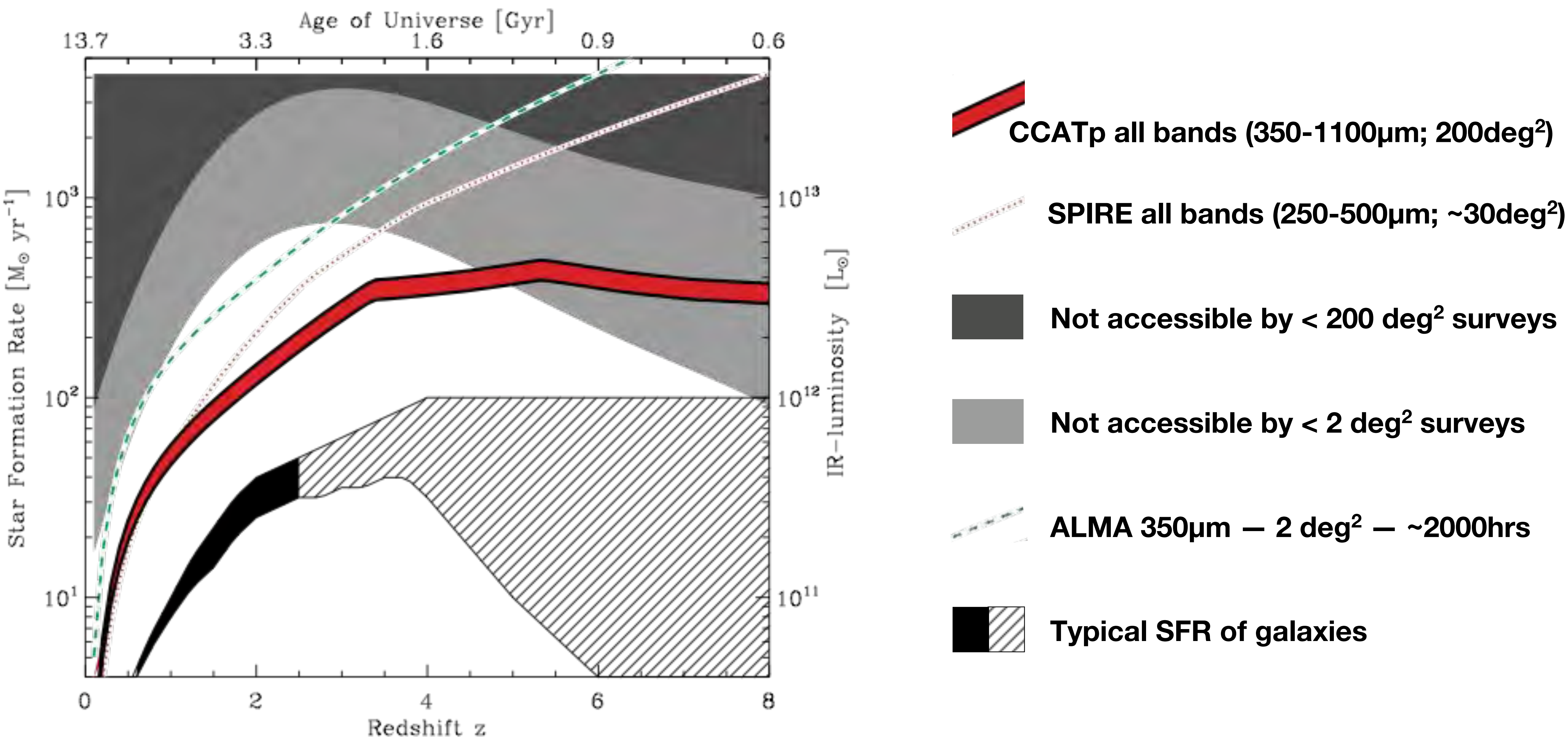
SCUBA-II 850µm — ~5 deg²
Typical SFR of galaxies



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Redshift z
CCATp all bands (350-1100μm; 200deg²)
SPIRE all bands (250-500μm; ~30deg²)
Not accessible by < 200 deg² surveys
Not accessible by < 2 deg² surveys
ALMA 350μm — 2 deg² — ~2000hrs
Typical SFR of galaxies

CCAT-p SFH survey will provide us with …

- A submm map deeper ($\gtrsim$ x 2) and over a wider area ($\gtrsim$ x 5) than those obtained by the *Herschel Space Observatory* at >250um
  —> Resolving up to ~40% of the CIB at 350μm

- A large and comprehensive sample of dusty SF galaxies ($\gtrsim$ 300,000) :
  —> Robust constraints of the bright-end of the LF
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The redshift of these galaxies will be obtained using :

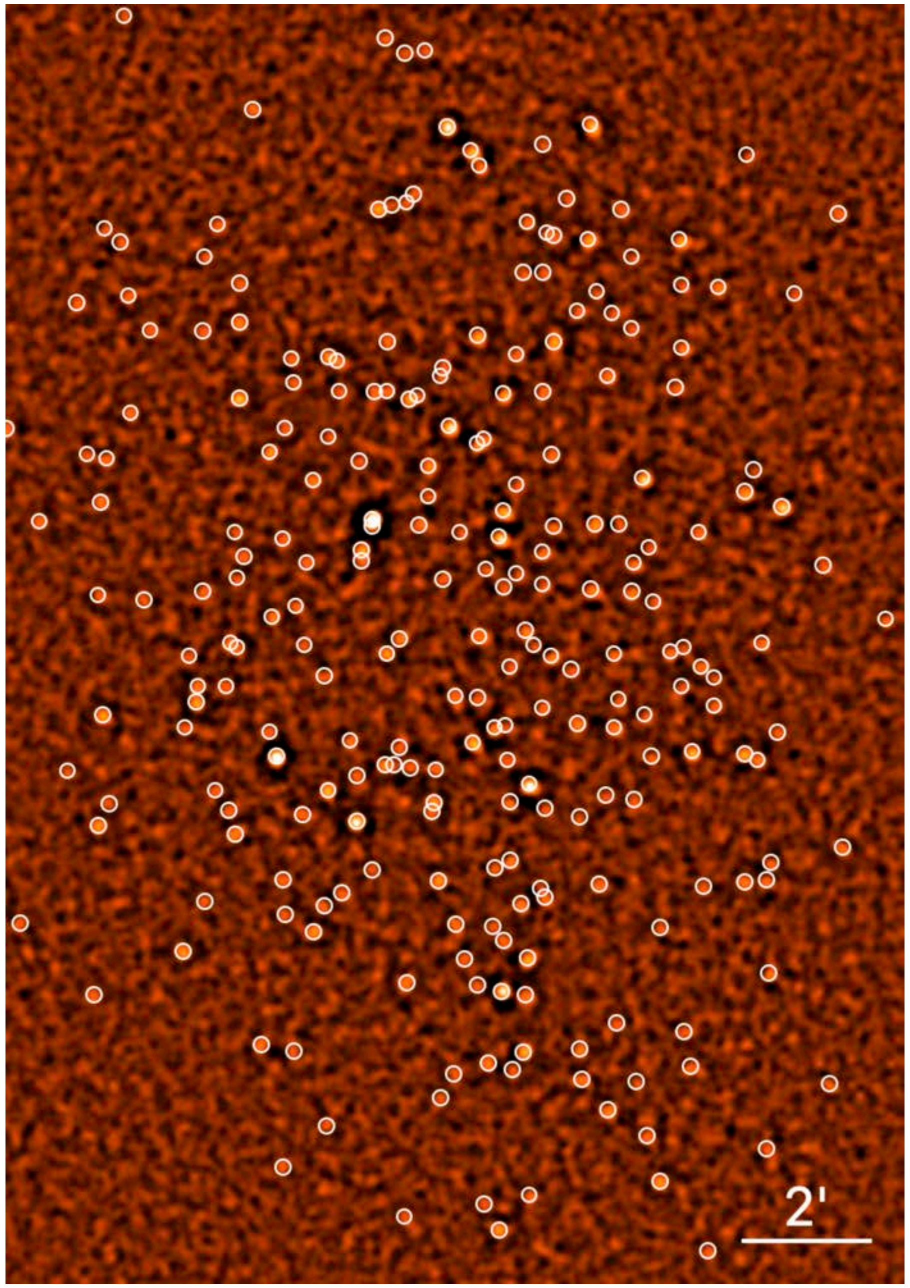
- *Multi-λ observations from P-CAM (FIR photometric redshift)*
- *[CII] and CO line detections from the P-Cam + Fabry-Perot interferometers*
- *Euclid Deep field*
- *ALMA follow-up*

JCMT-*STUDIES*

(SCUBA-2 Ultra -Deep Imaging EAO Survey)

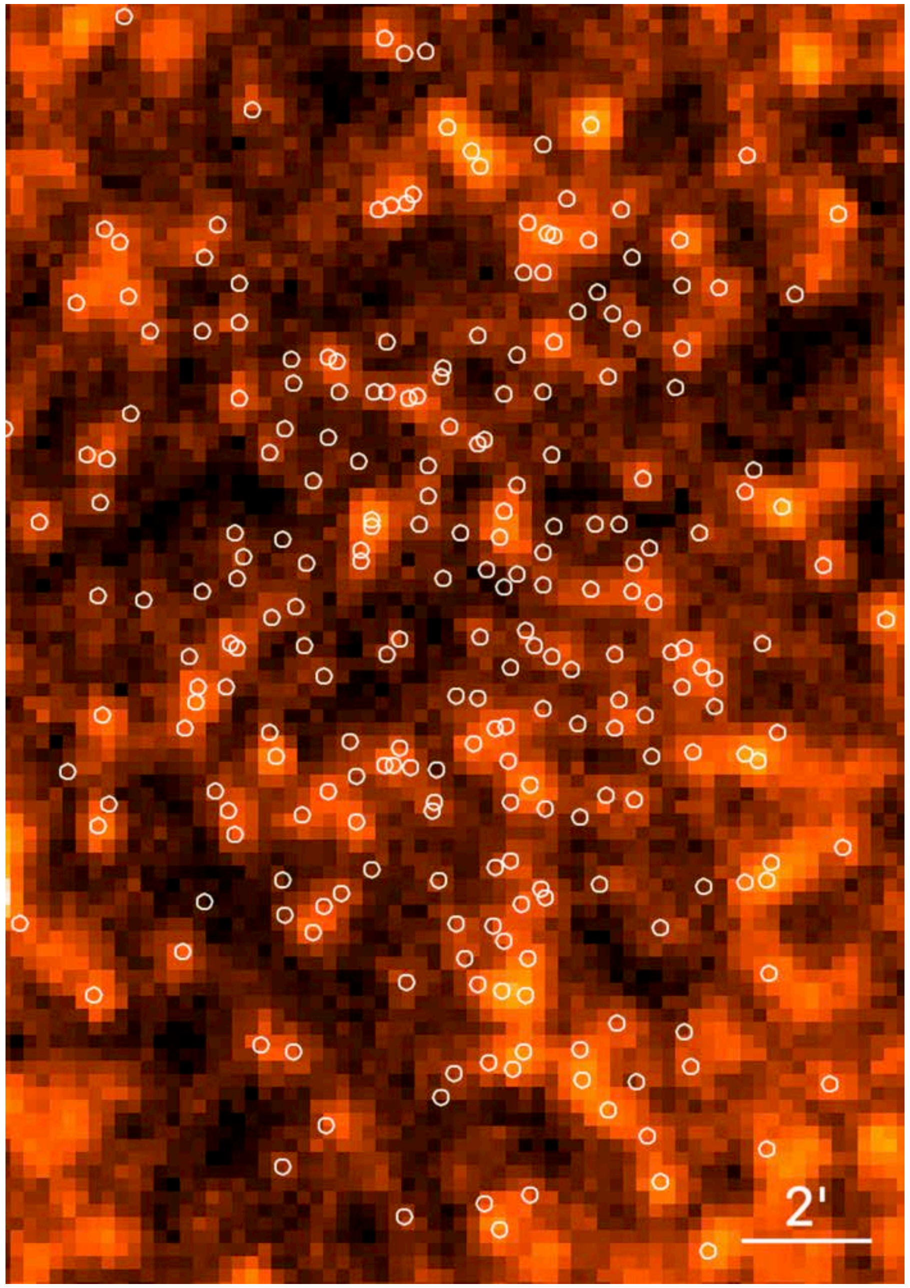
- EAO JCMT Large Program
  (Co-PIs: S. Chapman, I. Smail, H. Shim, T. Kodama, X. Zheng, **W.-H. Wang**)
- Two ultradeep 450 μm pointings, 8” beam:
  - STUDIES-COSMOS (**330 hr**, completed in 2020)
  - STUDIES-UDS (**320 hr**, 16% completion so far)
  both within the CANDELS region.
- carried out under the best submillimeter weather of Maunakea (!)
- **one Daisy pointing in each field.**
  (*D* = 3′ ultradeep core, *D* = 15′ deep outer region)
- $\sigma_{450\mu m}$ < 0.6 mJy in the ultradeep core, **≲ 3 mJy in entire map.**
  (comparable to CCATp)

Power of SCUBA-2 at 450 μm



STUDIES-COSMOS 450 μm

60% complete STUDIES (2018) + archival data

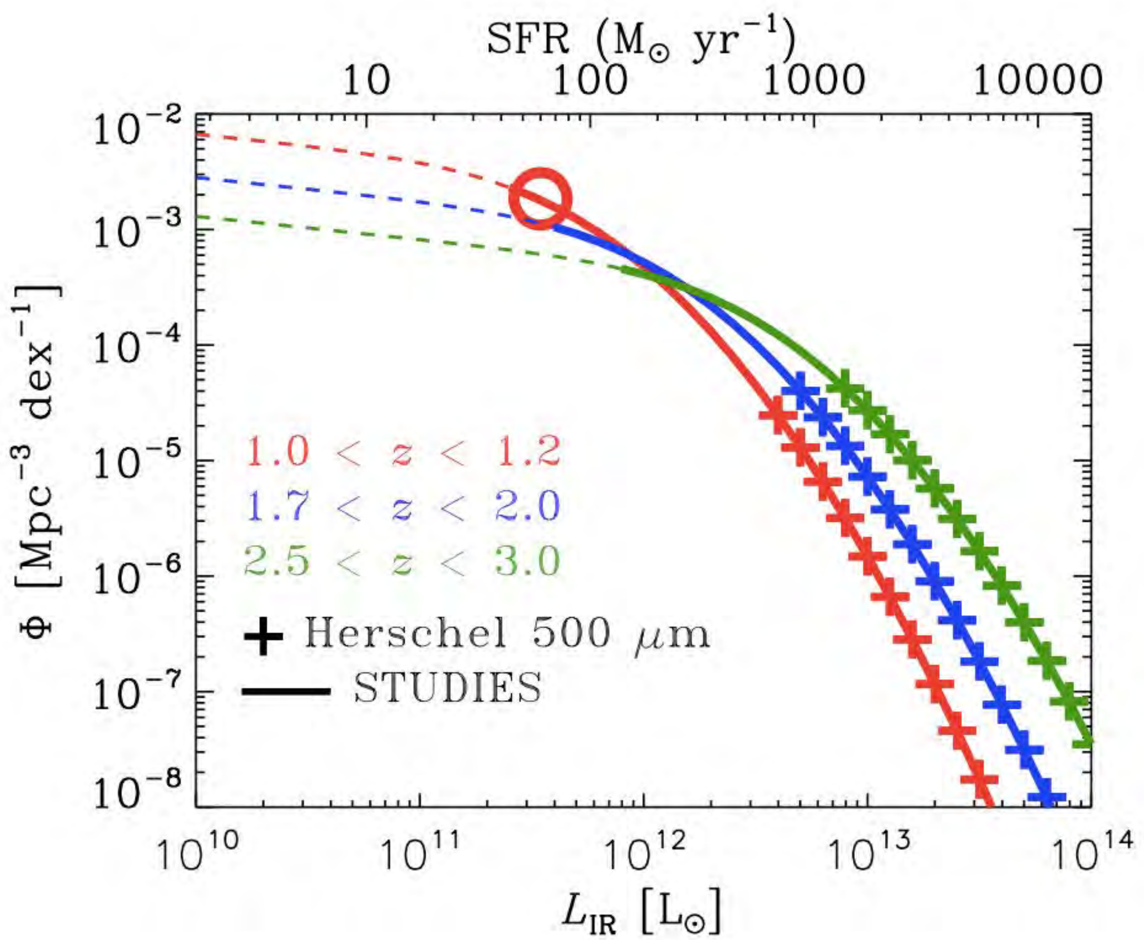


Herschel 500 μm

Circles: ~250 4σ SCUBA-2 sources

Goals of STUDIES

- To obtain confusion limited SCUBA-2 450 μm maps.
- Deepest ever FIR selected galaxy samples (10× deeper than Herschel SPIRE confusion limit),
  - overlap with the optically selected star-forming galaxies.
- To resolve the bulk of the cosmic IR background at 450 μm.
- To probe beyond the FIR L* up to z ~ 3.



2015 forecast of IR luminosity functions from STUDIES. Red cycle shows the size of typical error bars.

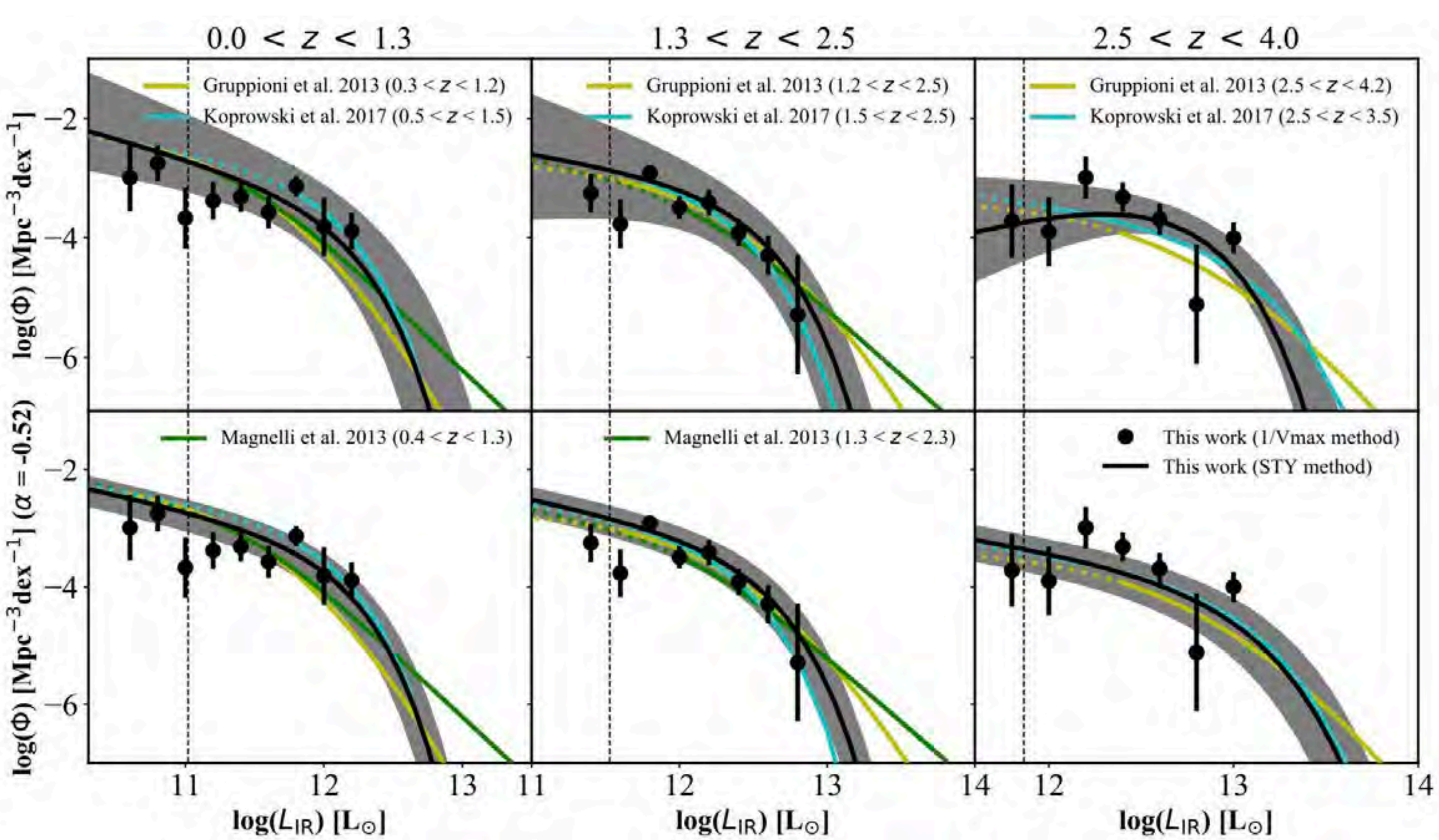
STUDIES Summary

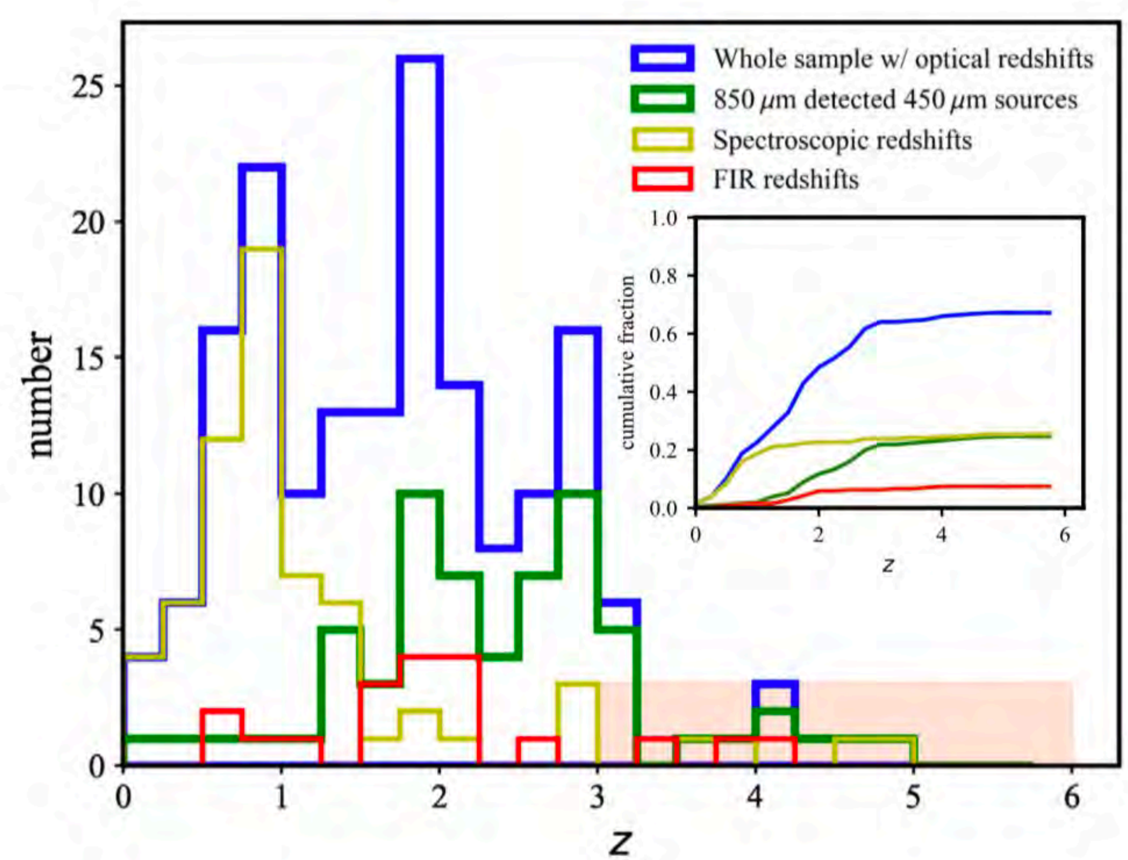
- Unprecedentedly "large" and deep 450 μm samples … provides examples of power of CCATp SFH science, *especially if we have some deep 'super-confusion' fields.*

- 450um "dropouts" have not yielded any useful science. Fields too small.

- Both rest-frame optical morphology and clustering are similar for SMGs and optically selected star-forming galaxies … Triggering mechanisms for dusty SMGs remain unclear.

- *Machine learning can be a powerful tool to overcome the narrow survey area at 450 μm.*

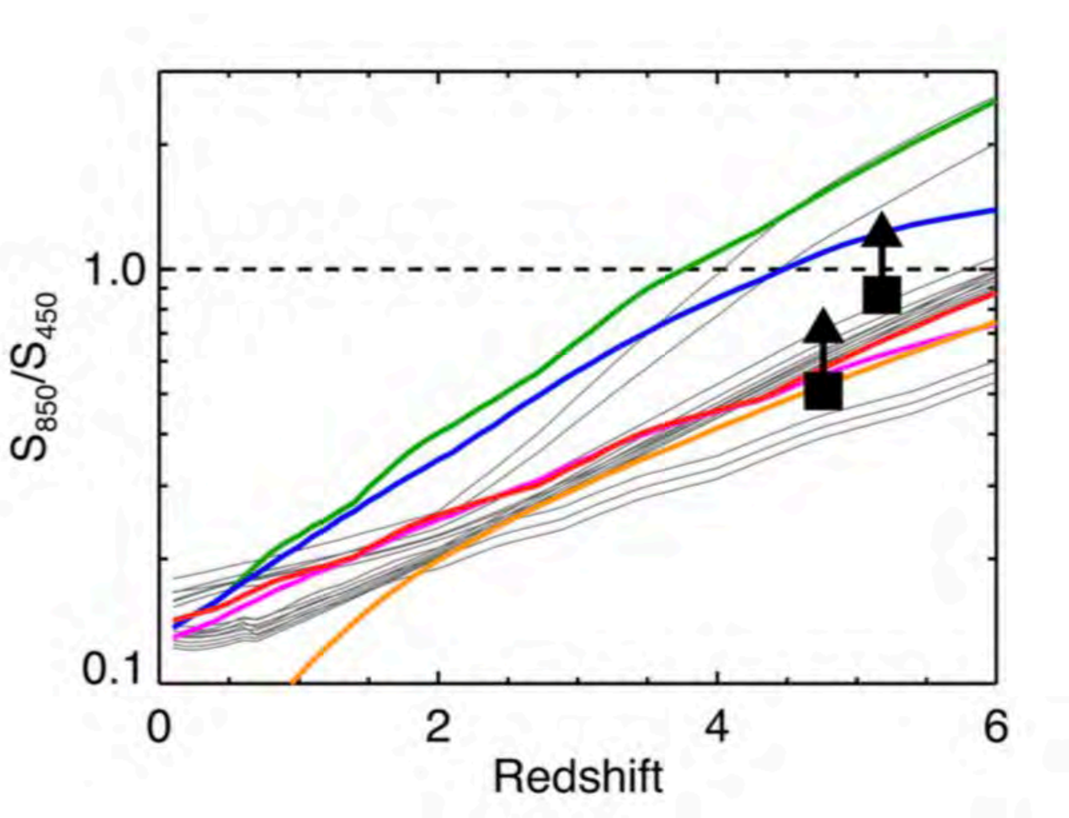


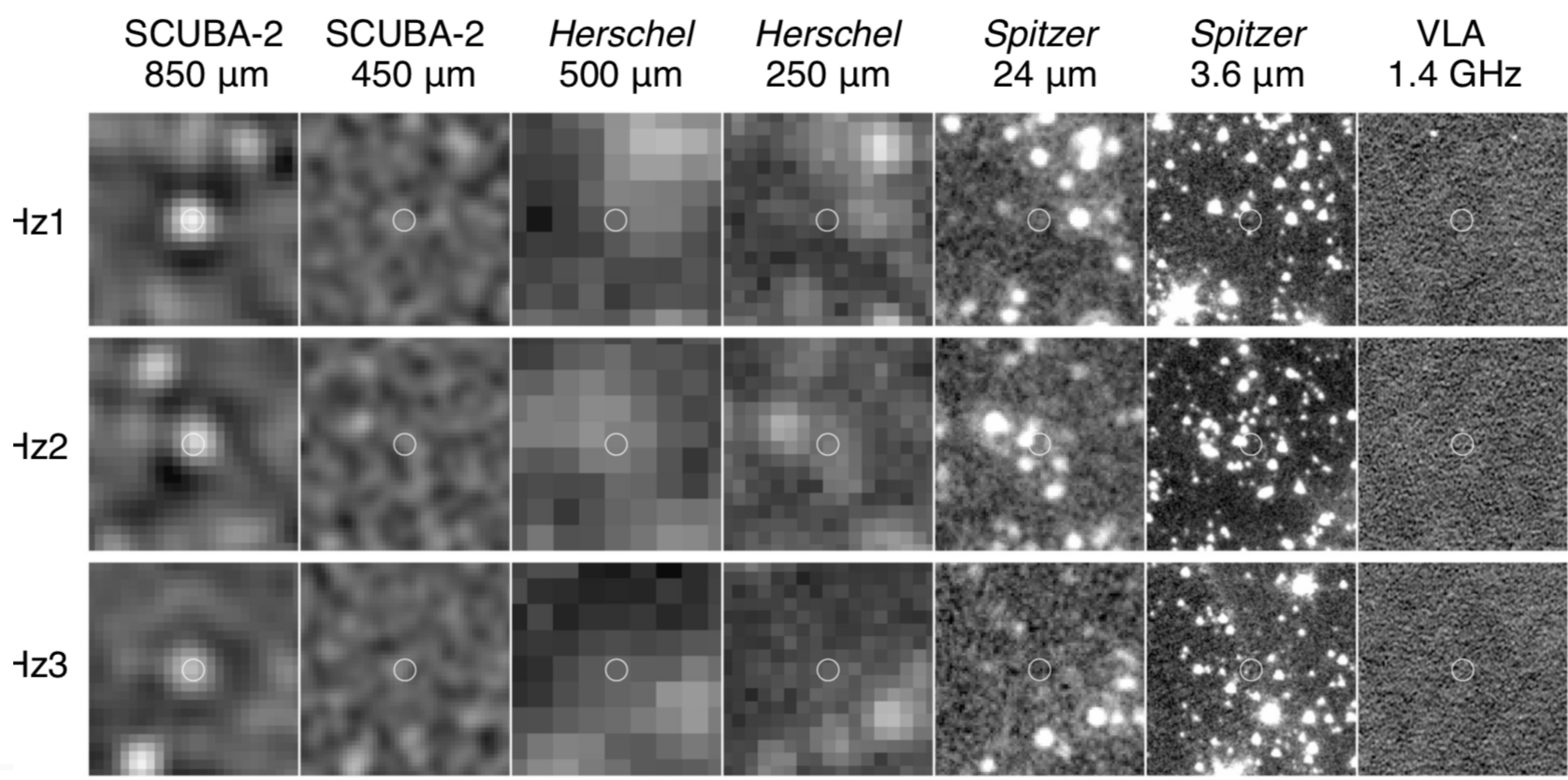


Lim et al. (2020a)

Highest z: 450um dropouts?

- **5 candidates were followed up by SMA: 1 was detected**
- **Few with large 850/450 flux ratios … seem all blended sources (hence biased 850 fluxes)**
- **There aren't many convincing high-z candidates**
  … survey areas too small?

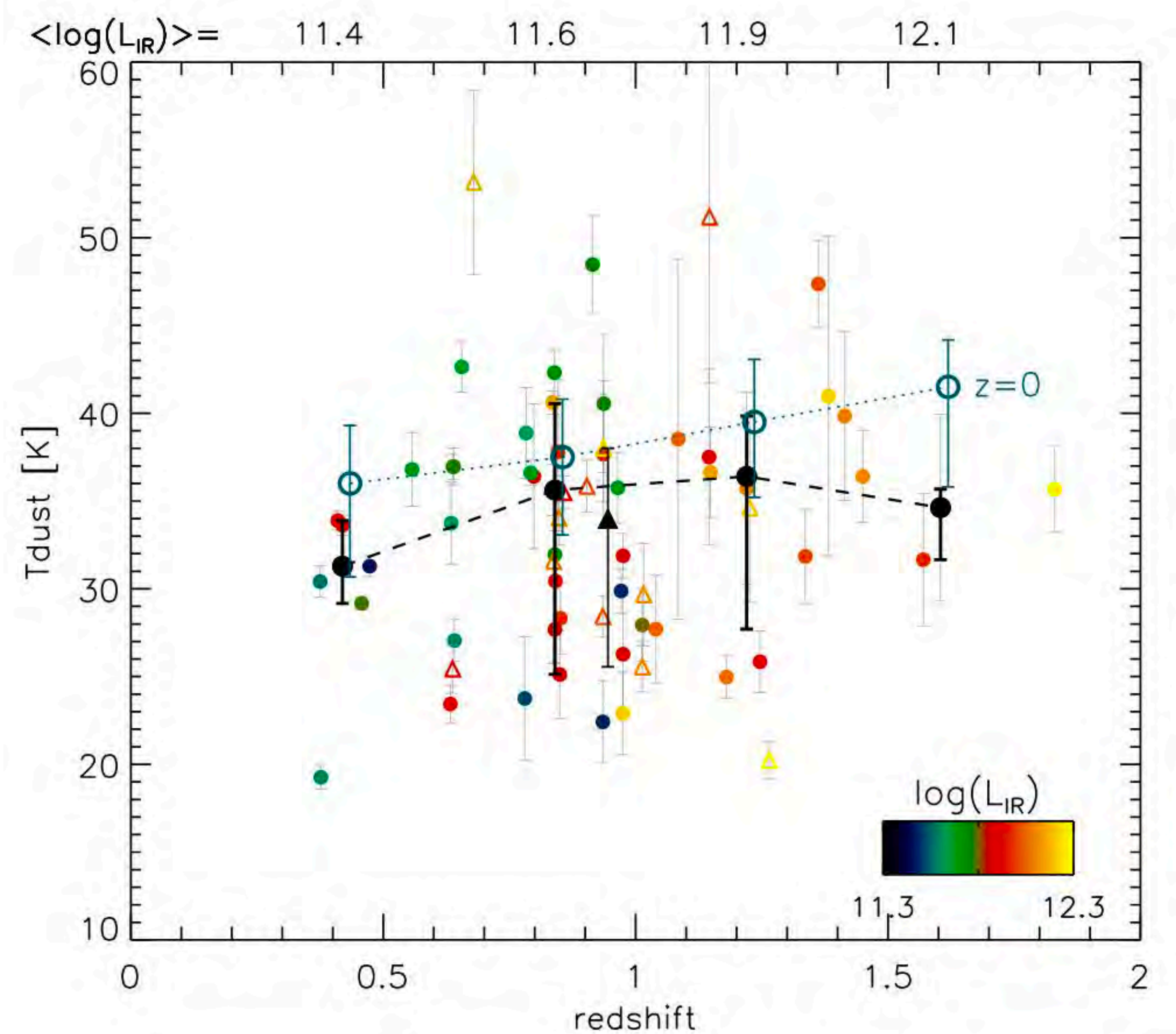




PCam350μm *Deep Field* and Super-confusion

- **Herschel SPIRE lesson … is it worth going deeper than confusion limit (1-σ 2.5mJy for CCATp 860GHz)?**
- **GOODS-N: measurements to 5-σ of 4.4mJy, 4.8mJy and 7.6mJy at 250μm, 350μm and 500μm (Elbaz+2010)**
- **below the SPIRE confusion limit 1-σ of 5.8mJy, 6.3mJy, 6.8mJy (Nguyen et al. 2010).**

- **limit is a spatially averaged statistical limit … considers galaxies homogeneously distributed in field and affected in the same way by close neighbors.**
- **Use higher spatial resolution at lower wavelengths (eg., IRAC or 24μm) …**
  flag galaxies more "isolated" …
  SPIRE flux densities more robust
- **But it's a 24μm-selected catalog!**



CCATp SFH needs Deep Fields

- 350 micron really is important – the best angular resolution with CCAT-Prime; we should take advantage of the superior telescope site: one or more deep ~5deg^2 fields, ECDFS and COSMOS

- survey fields are sort of selected; T.Herter White Paper has a table of fields.
  - G.Stacey showed this table with expected sensitivity goals for each of the planned surveys.
  - The SFH supposed to take advantage of all survey fields (DSFH, EoR, and CMB/SZ) selected.

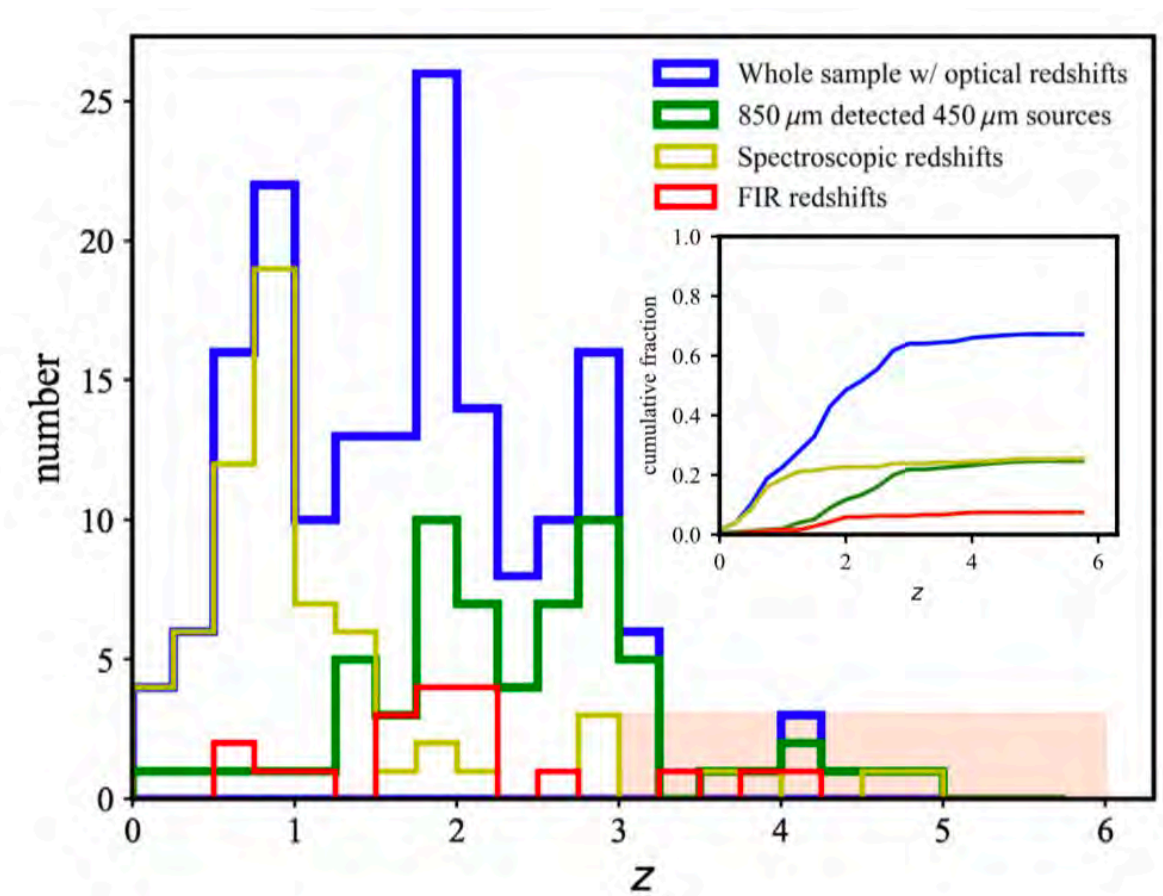
- T.Nikola: “it would require some pushing to change the survey fields and depths …
  This workshop is probably a good place to start pushing.”

The end

EXTRA SLIDES

STUDIES Recent Results

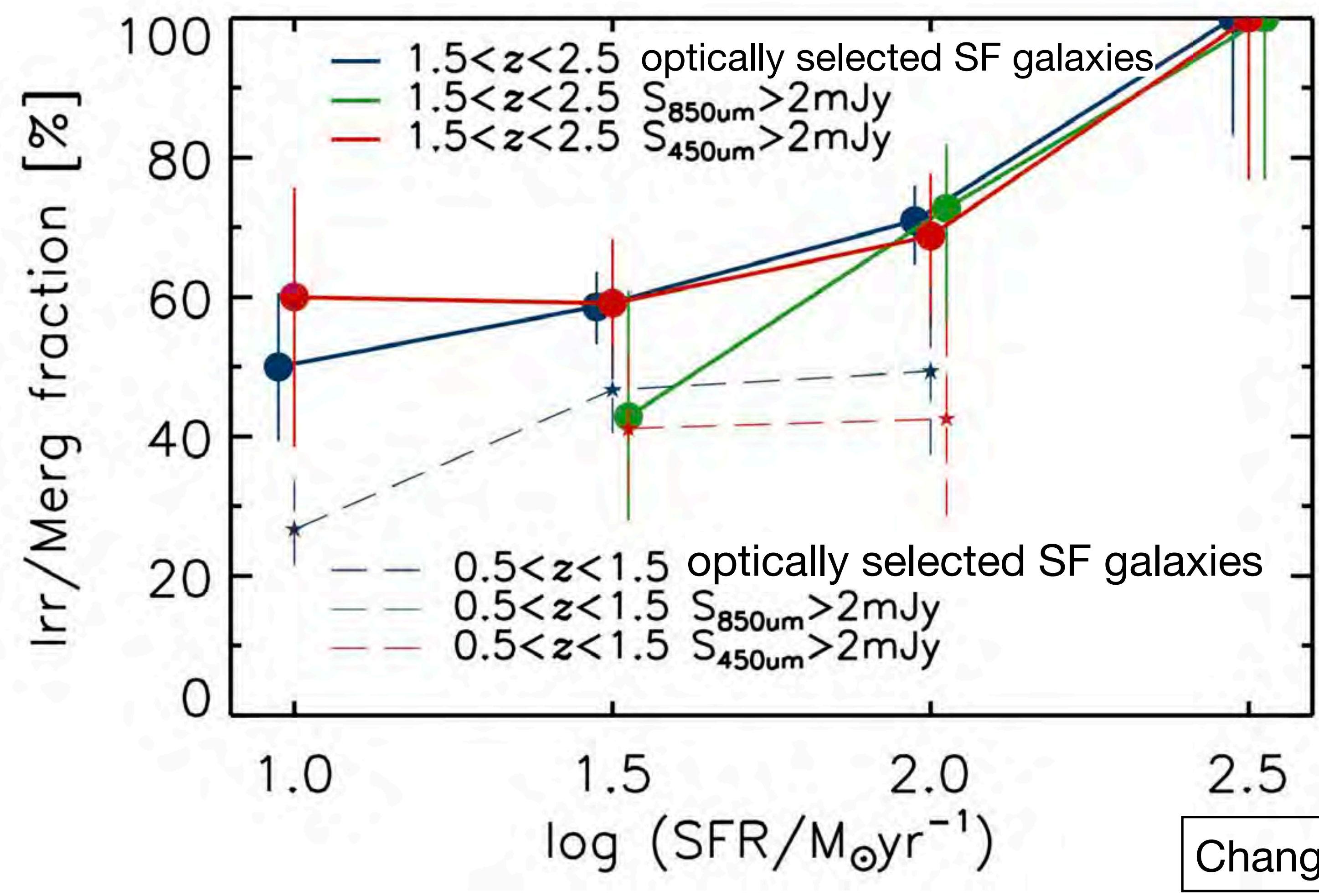
- Based on data taken until 2018 in COSMOS.
  - 184 hr from STUDIES in a DAISY pointing.
  - 188 hr from the archive (Casey et al. 2013; Geach et al. 2013), over a ~4× larger area.
- rms noise ~ 0.65 mJy in the deepest region.
- 256 sources with S/N > 4, of which 82% have counterparts at 3 GHz or 24 μm.
- z mostly between 0.5 and 3, median = 1.8, lower than the median of 850 μm samples (e.g., Chapman et al. 2003, 2005; Simpson et al. 2017).



Lim et al. (2020a)

Recent Results I

WFC3 Morphology of SMGs and Normal Galaxies

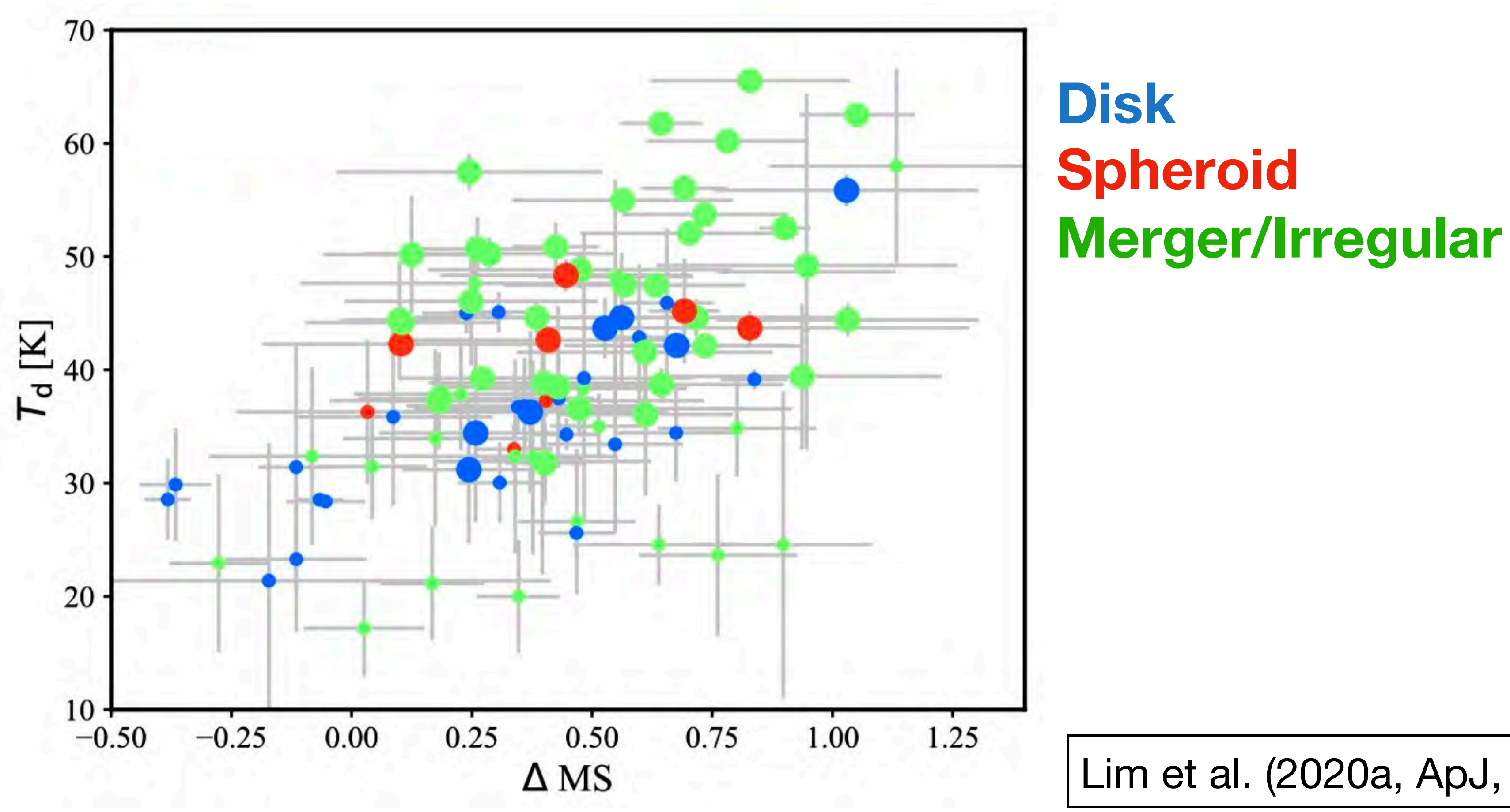


Chang et al. (2018, ApJ, 865, 103)

- merger/disturbed morphology positively correlates with SFR in all samples.
- optically selected star-forming galaxies and SFR-matched 450/850 μm selected SMGs behave similarly in merger fraction (and also in R_e and n).
- What exactly makes a star-forming galaxy an SMG?

Recent Results II

Morphology, Dust Temperature, and Offset from Main-sequence

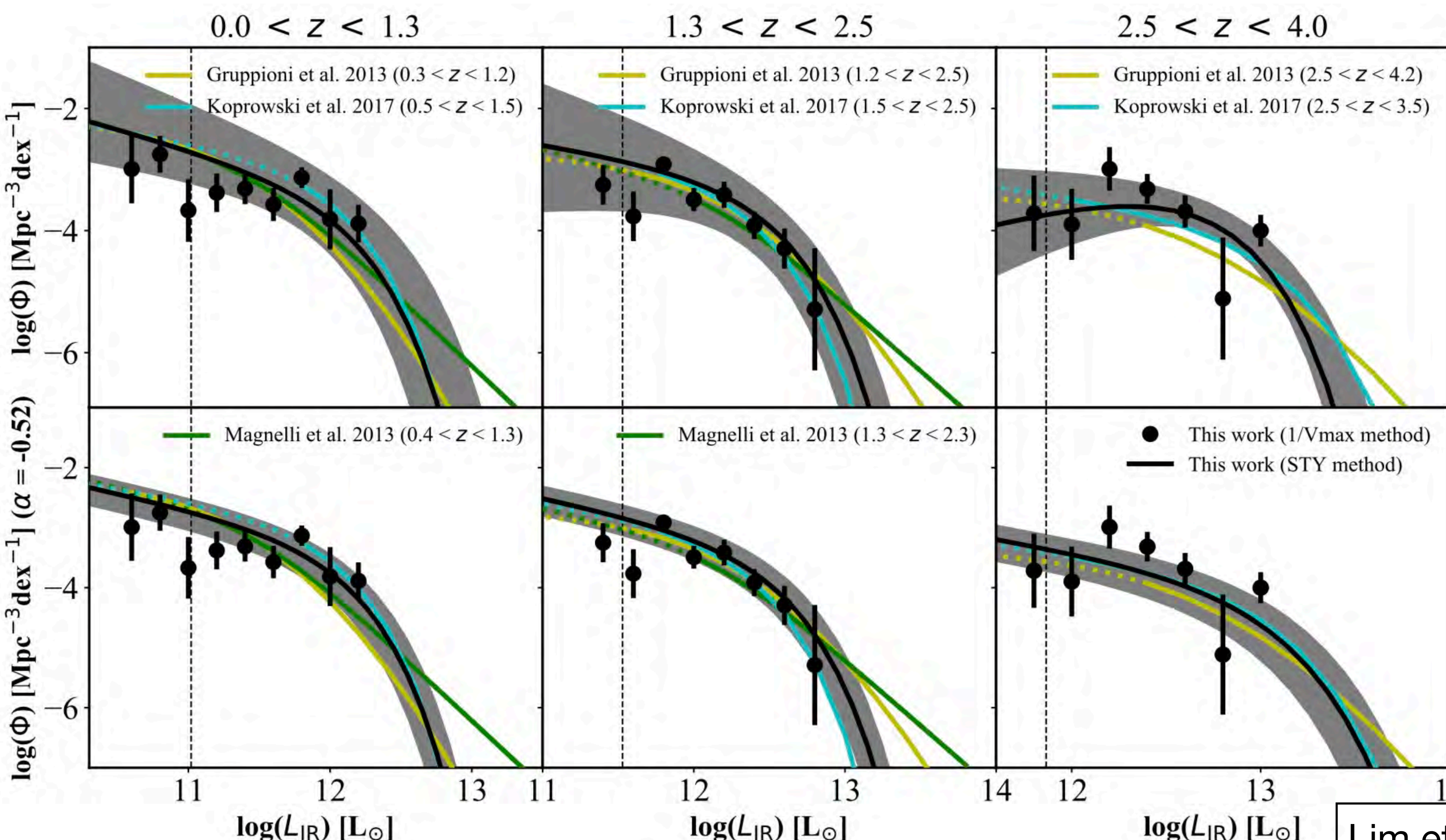


Lim et al. (2020a, ApJ, 8890, 80)

- T_d, merger morphology, and offset from main-sequence (ΔMS) positively correlate with each other.
- Consistent with some simulations (e.g., Hayward et al. 2011) where merger triggers starbursts in the nucleus regions and raises dust temperature.

Recent Results III

IR Luminosity Functions



Lim et al. (2020a, ApJ, 8890, 80)

- First FIR survey that can constrain the faint-end slopes of LF up to z ~ 2.5. (Herschel works typically assume faint-end slopes).
- Faint-end slope consistent with ALMA measurements (Dunlop et al. 2017).
- Complete STUDIES data in COSMOS and UDS should dramatically improve both the bright and faint ends.

Recent Results IV

Machine Learning Selection of SMG and Clustering

- Training sample:
  - 164 SMGs with $S_{450\mu m} > 4$ mJy in the ~40 arcmin^2 deep STUDIES-COSMOS region
  - 4705 field galaxies with $K_s < 24.5$ in the same region known to be non-SMGs.
- ML algorithm: XGBoost
- 13-band photometry included for training: $uBVrizJHK_s$[3.6][4.5][5.8][8.0]
- Goal: to select SMG candidates using the same set of photometry from the 1.6 deg^2 COSMOS field.

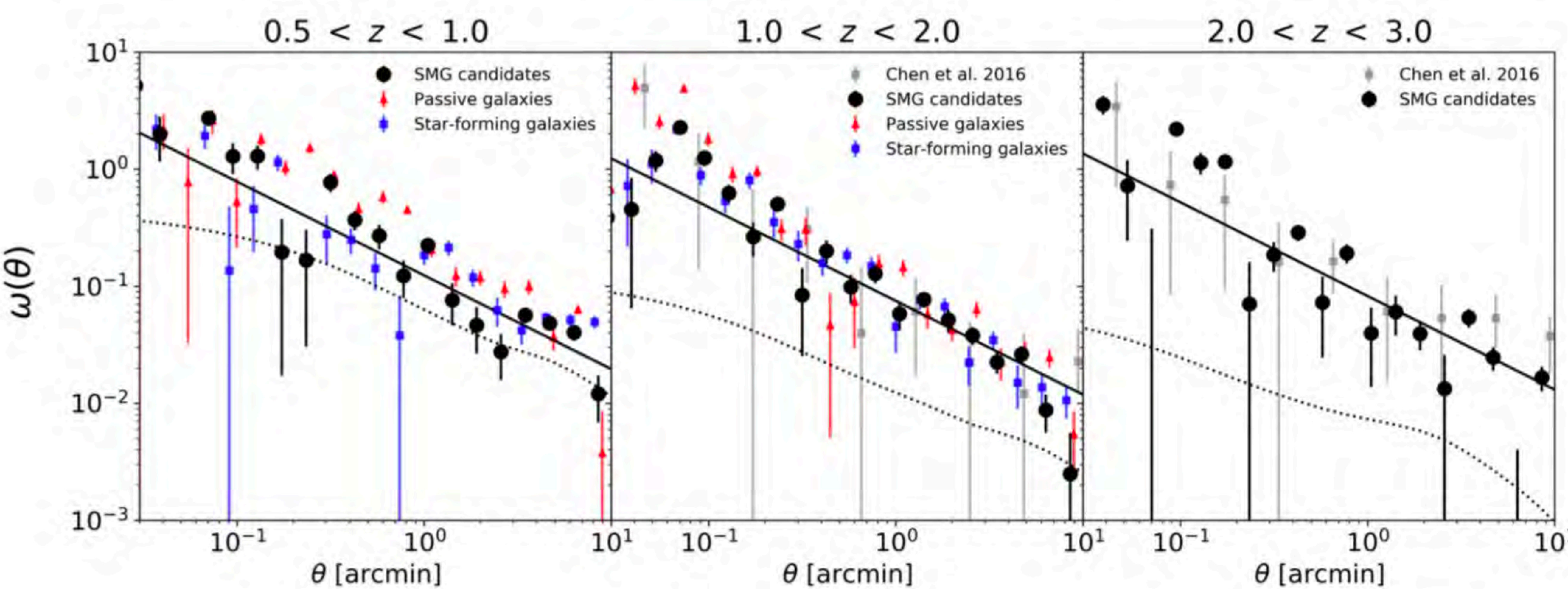
Recent Results IV

Machine Learning Selection of SMG and Clustering

- ML selection results:
  - 6182 SMG candidates from the entire COSMOS field. (Expected to find 6100, based on 450 μm counts)
  - 88% of the 6182 ML-selected candidates have 3 GHz or 24 μm counterparts
  - Sub-samples with ALMA observations have high selection completeness (76%) and accuracy (82).
  - ML-selected candidates show strong 450 μm stacked flux (5.3 ± 0.2 mJy) using the wide shallow 450 μm image from the S2COSMOS survey.

Recent Results IV

Machine Learning Selection of SMG and Clustering

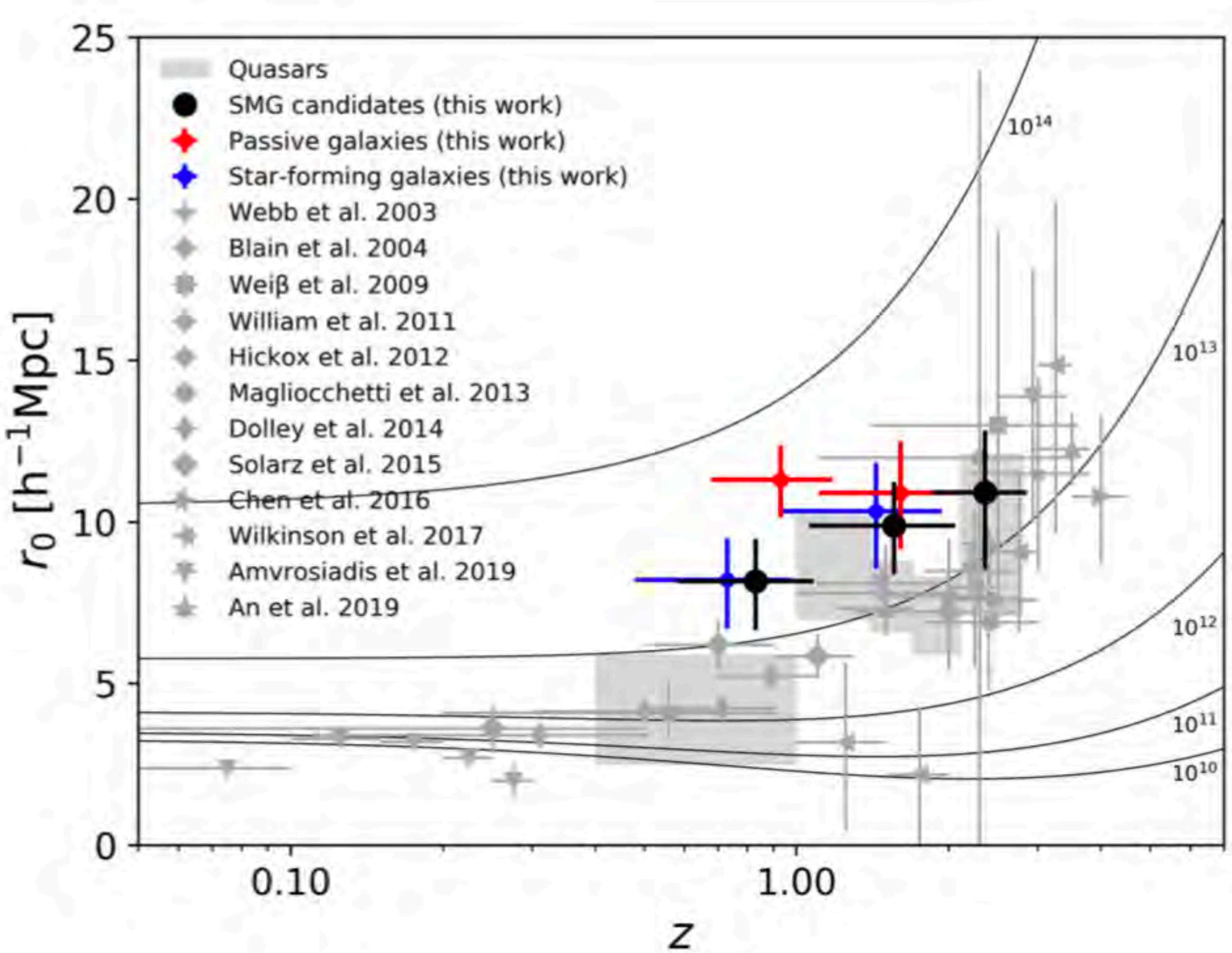


Lim et al. (2020b, ApJ submitted)

- Large sample from the ML selection in 1.6 deg^2 enables clustering analyses, and comparison with normal SF galaxies and passive galaxies.

Recent Results IV

Machine Learning Selection of SMG and Clustering

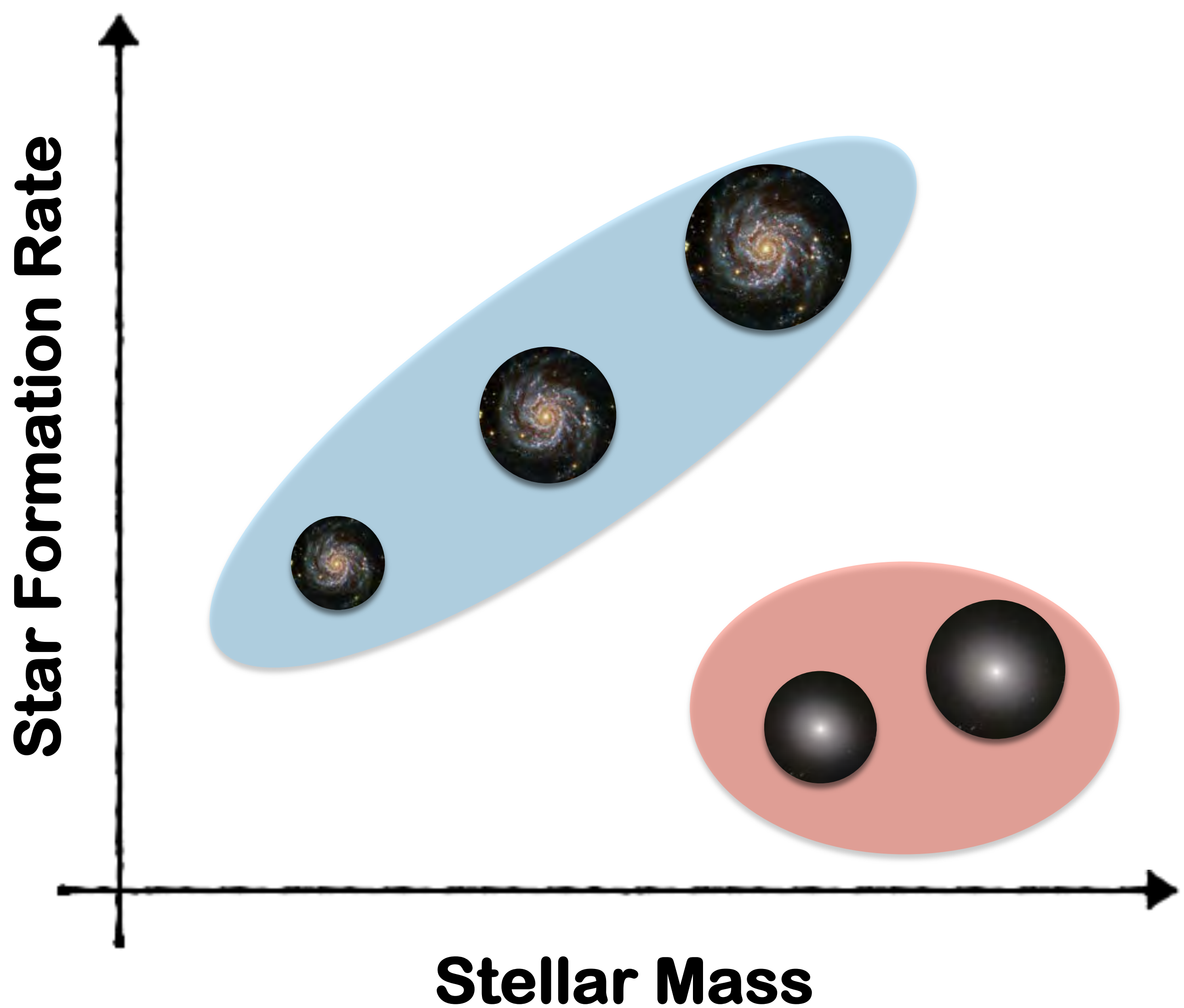


ML SMG candidates
M*-matched normal SF galaxies
M*-matched passive galaxies

Lim et al. (2020b, ApJ submitted)

- Halo mass ~ 2×10^{13} h^{-1} $M_\odot$ for ML SMG candidates, and no evolution from z = 0.5 to 3.
- No significant difference between SMGs and normal SF galaxies.
  (Yet another evidence against SMG being triggered by mergers, since merger should be more common in biased regions.)
- Passive galaxies are in more massive halos.

Why do we care about having a good statistic on this population of dusty highly star-forming galaxies ?



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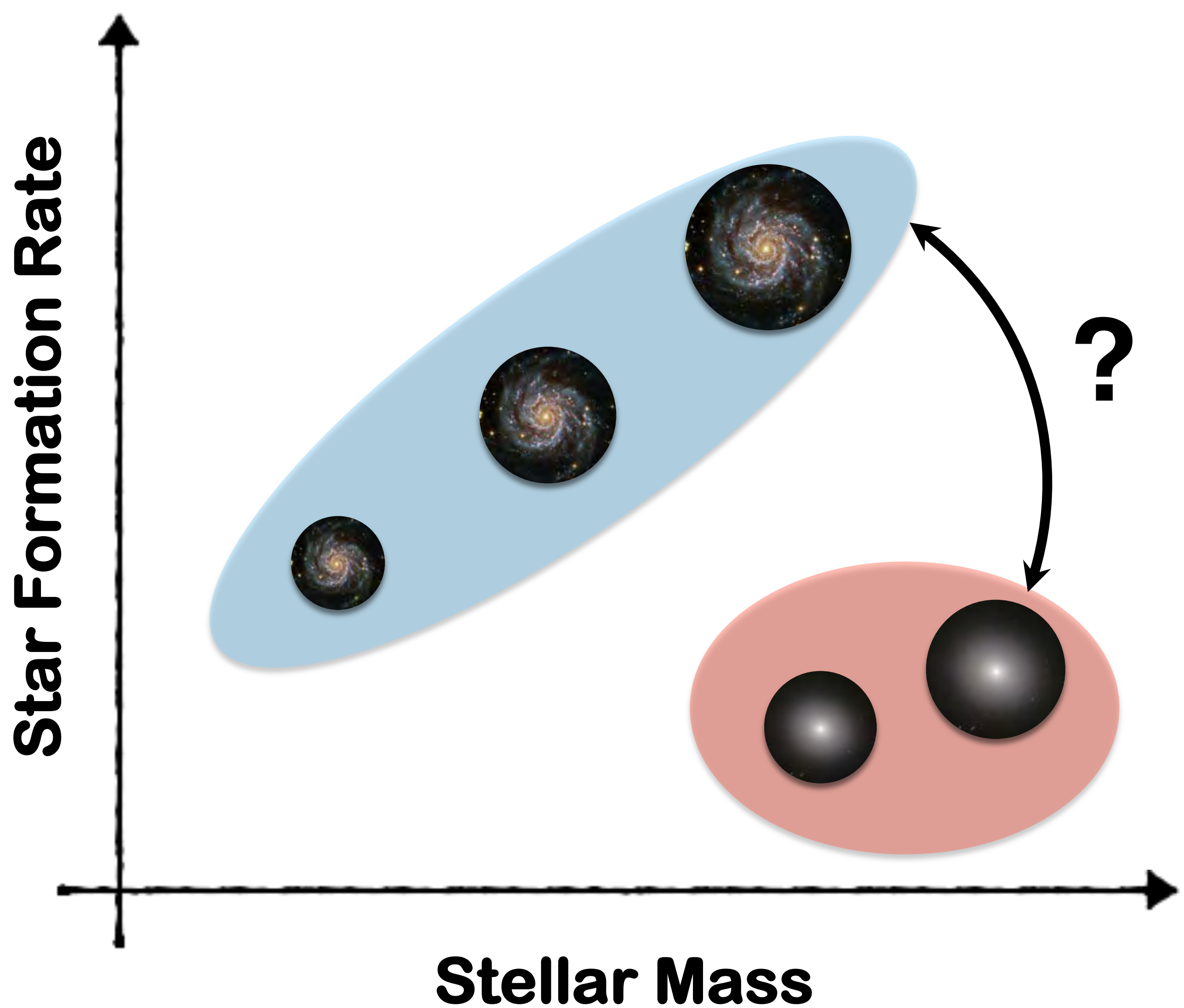

The origin of local "red" and "dead" ellipticals still remains unknown ...

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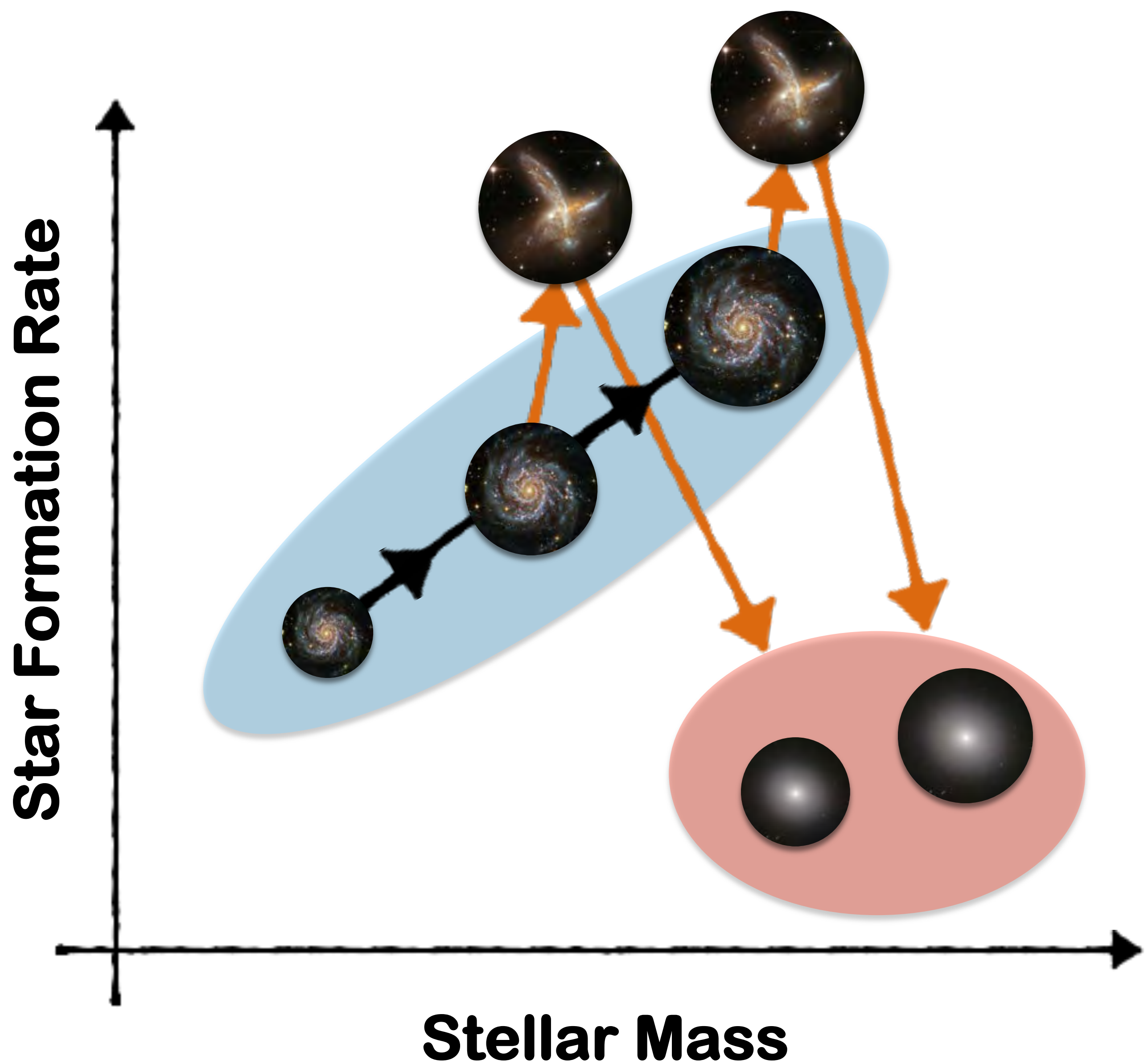

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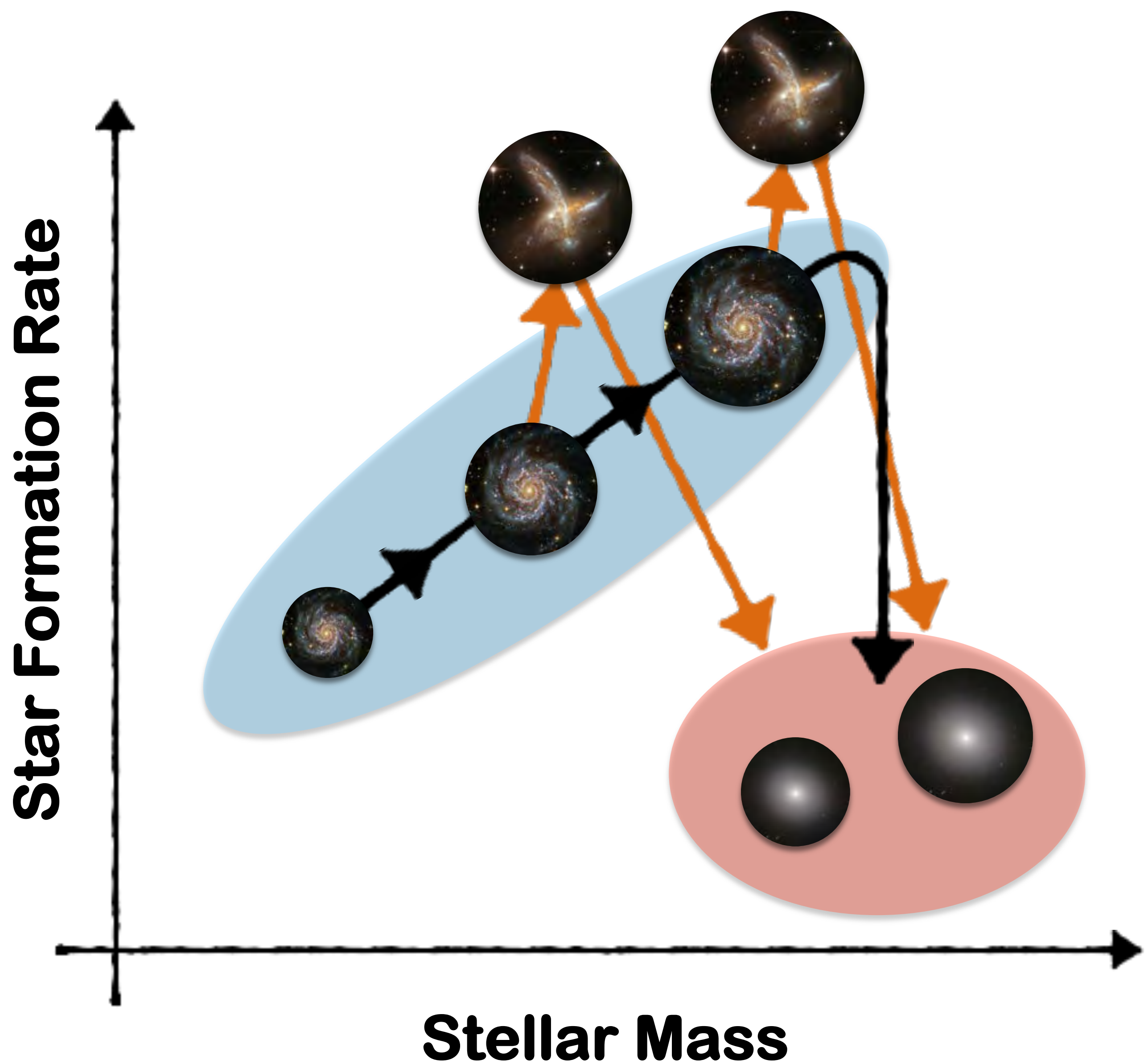

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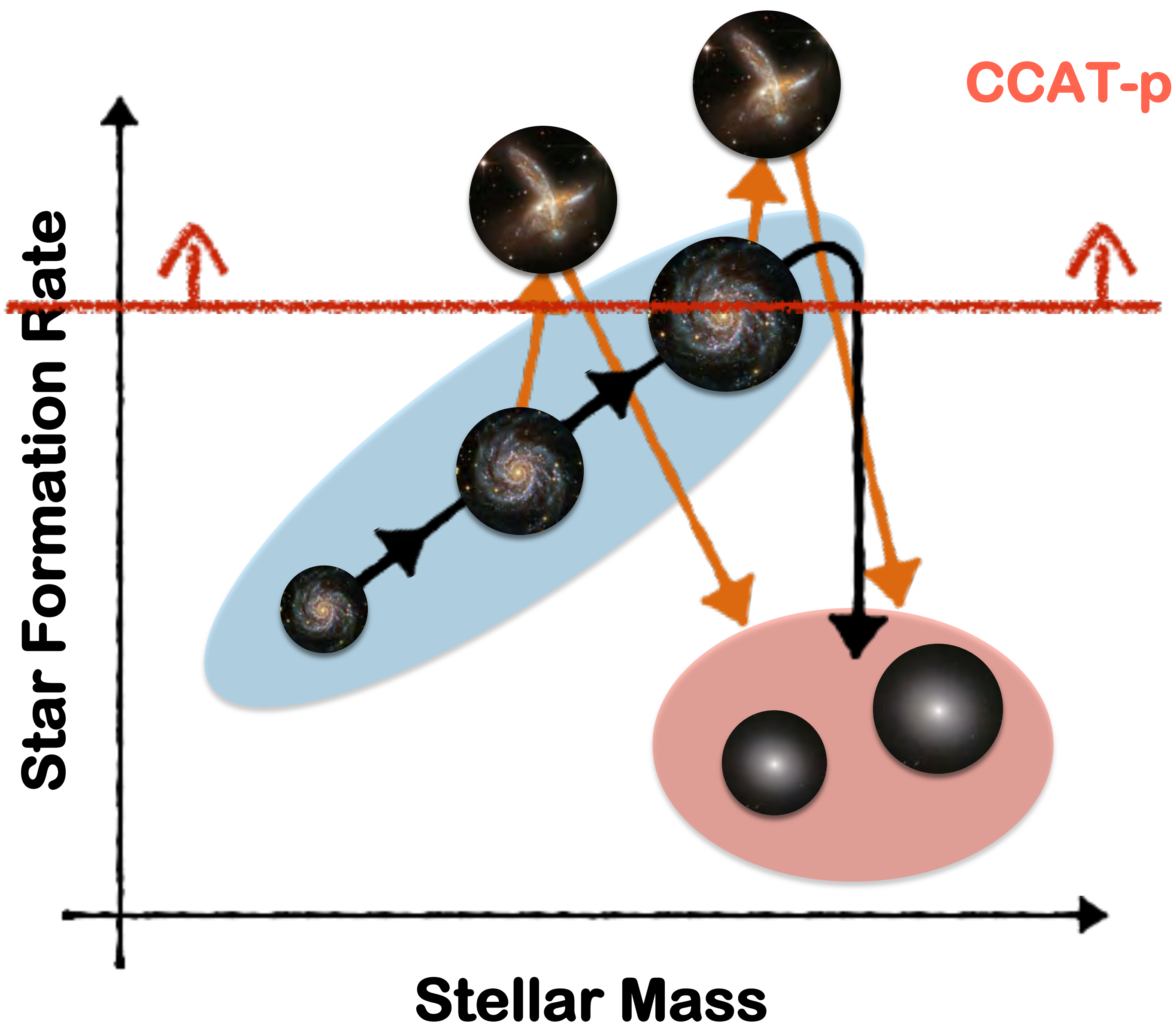

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CCAT-p will detect large samples of such galaxies, allowing us to understand the formation of local ellipticals

- ✓ **The CCAT-p SFH survey will be deeper and wider than those carried by the *Herschel Space Observatory,* resolving up to ~40% at > 250 µm**
- ✓ **For the first time, it will provide us with very large and comprehensive samples of dusty SF galaxies over cosmic time**
- ✓ **These samples will constrain the bright end of the LF and the impact of environment on the SF activity of galaxies**
- ✓ **These samples might provide us with the missing link between blue and red galaxies**

CCAT-p in a nutshell

- ✓ 6-m aperture submillimeter (submm) telescope
- ✓ Exceptional location at 5600-m on Cerro Chajnantor
- ✓ 11 μm rms surface accuracy allowing efficient operation at 350 μm
- ✓ P-Cam —> simultaneous observations at 350, 450, 740, 860μm and 1.1mm with each a ~1° FoV
- ✓ P-Cam + Fabry-Perot interferometer —> low (sub)millimeter spectrometer in all these bands

GEvo

(The CCAT-p Galaxies Evolution survey)

"Study of dusty star-forming galaxies with a survey going deeper and over a wider area than those carried by the Herschel Space Observatory at λ > 250 μm"

- ✓ 1st year - "science demonstration survey" —> ~ 50 deg^2 down to the confusion limit
- ✓ 4 years - "full survey" —> ~ 200 deg^2 down to the confusion limit