Scuba-2 Ultra Deep Imaging EAO Survey (STUDIES) : Multiple-wavelength properties and luminosity functions of 450-µm-selected galaxies

Speaker: Chen-Fatt Lim (ASIAA & NTU, Taiwan)

Collaborators: Wei-Hao Wang, Chian-Chou Chen
& STUDIES team (136 members from Canada, China, Korea, Japan, United Kingdom, Taiwan, etc)

JCMT User Meeting 2019 @ ASIAA, 6-8 November 2019

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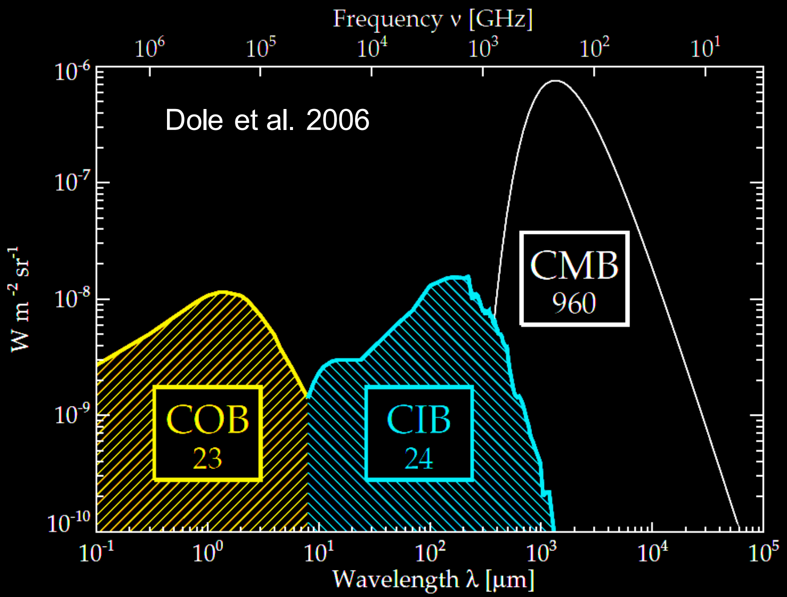
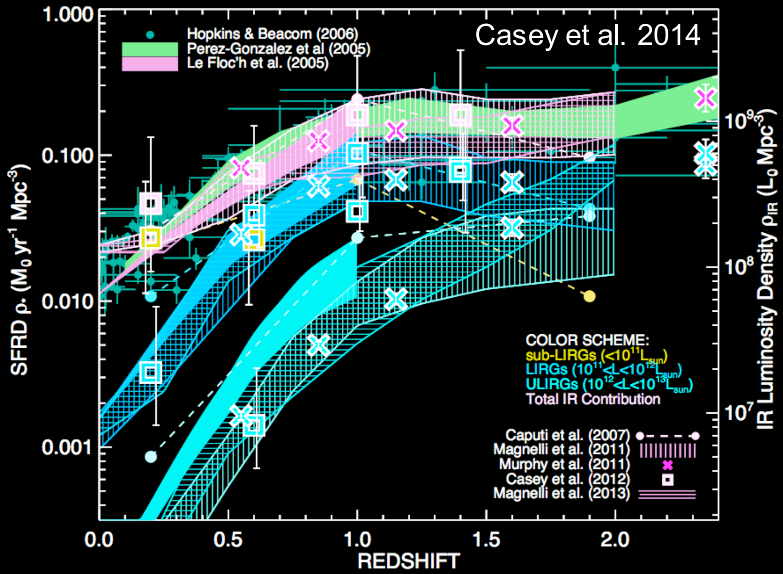
Why we need the far-infrared observations?

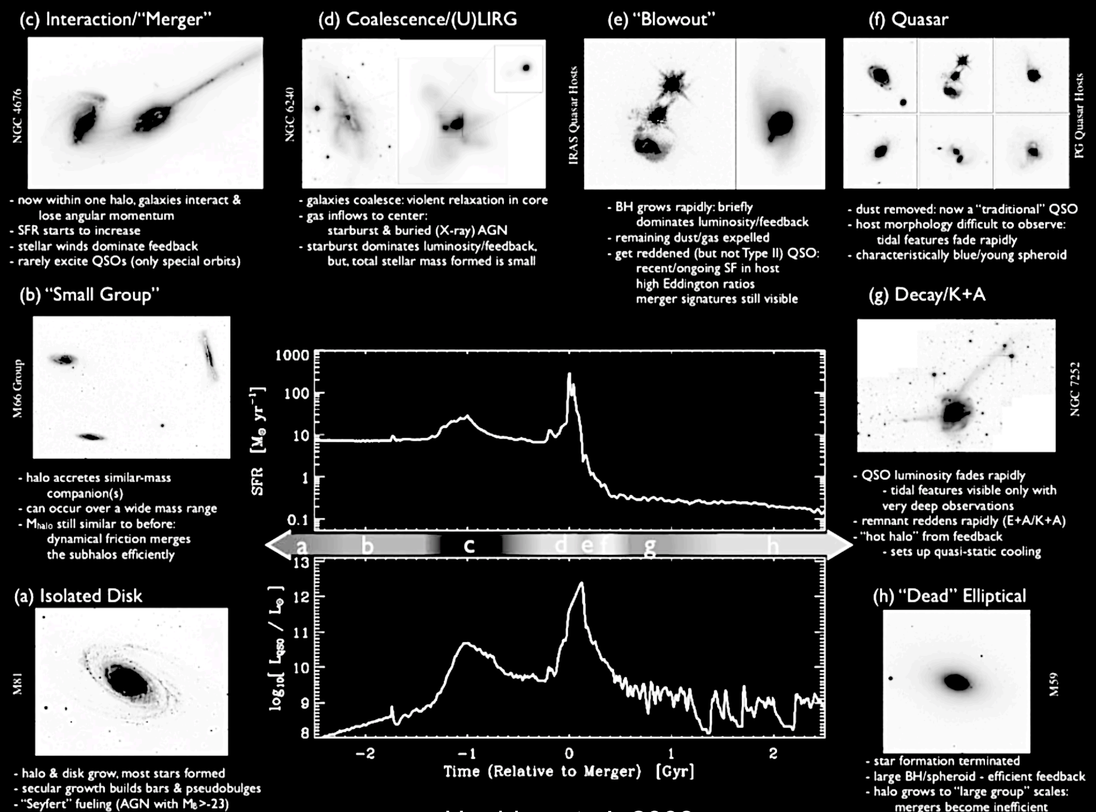
Introduction





- A comparable integrated radiative energy comes from IR-to-sub-mm and UV-to-optical wavelengths
- IR-luminous population plays a dominant role in cosmic star formation at $z > 1.5$, which is occupying the same epoch of the peak star-formation and AGN activities

What the sub-millimeter galaxies (SMGs) could be?



Hopkins et al. 2008

- From the low-z observations, the IR luminosity is correlated with high SFRs and galaxy mergers
- Dust particle re-radiates the light at IR/sub-mm during the starburst phase
- Starburst phase is believed to be short-lived (~200 Myr)
- Our understanding of this population is still incomplete, especially at faint and high-redshift ends
- We need a deep and huge sample size of IR/sub-mm selected galaxies

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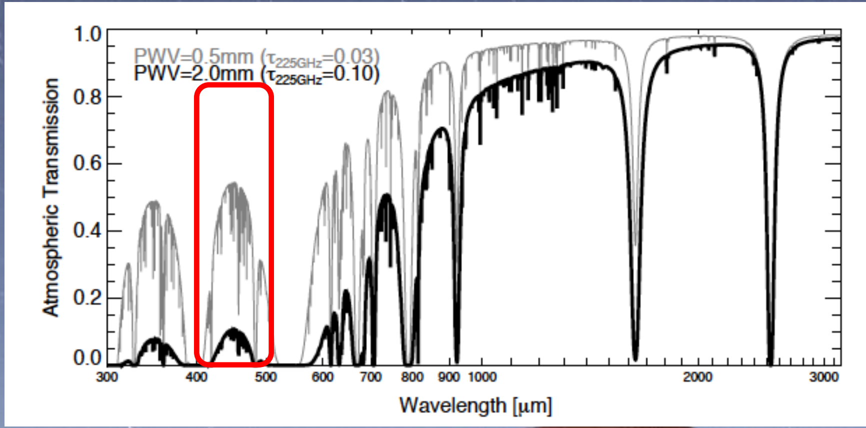
The James Clerk Maxwell Telescope (JCMT) – SCUBA-2

- Scanning 450- and 850-μm images simultaneously
- 7.9” and 15” spatial resolution at 450 μm and 850 μm
- 450-μm observations are sensitive to the water vapor



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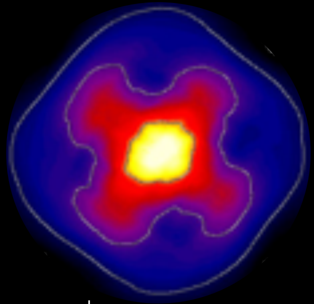
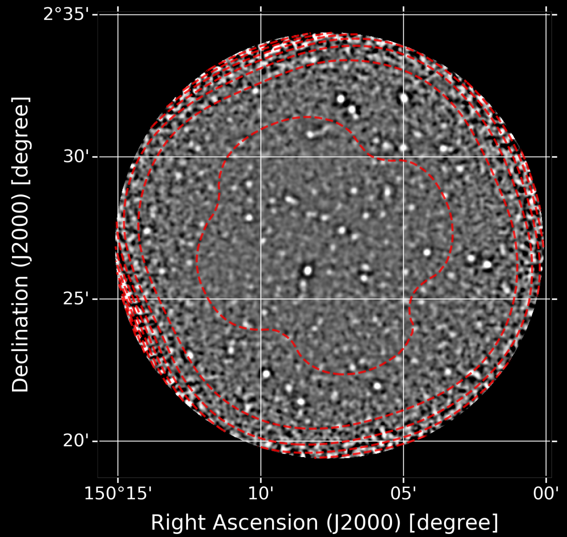
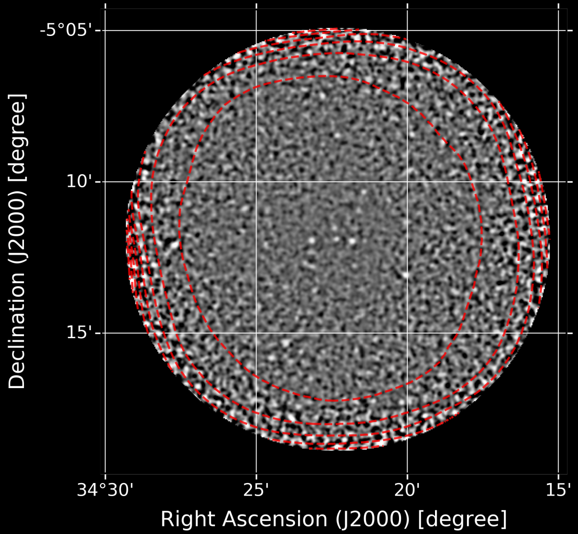
The SCUBA-2 Ultra Deep Imaging EAO Survey (STUDIES)

- An EAO JCMT Large Program (P.I. Wei-Hao Wang)
- A confusion limited 450-μm map; the deepest image ever in far-infrared
- Daisy scan mode (D ~ 3’ ultra-deep core; D ~ 10’ outer region)
- STUDIES:
  - STUDIES-COSMOS (330 hr, 2015-2019) [84% complete]
  - STUDIES-UDS (320 hr, 2017-2020) [14% complete]





σ_{450} ~ 0.6 mJy

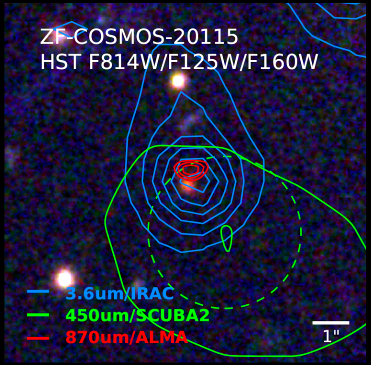


σ_{450} ~ 2.0 mJy

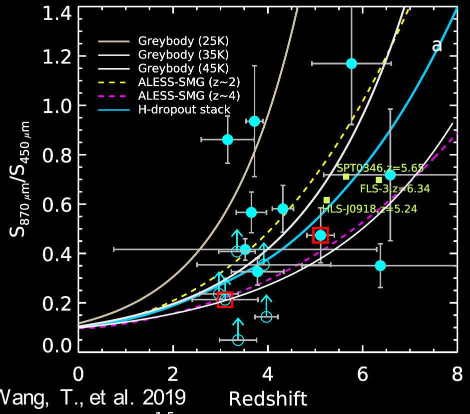
Previous publications

Scientific Progress

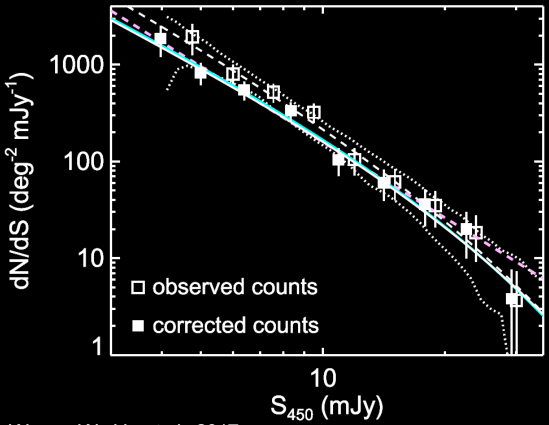
- Main publications
  - Wang, W.-H., et al., ApJ, 850, 37W (2017)
  - Chang, Y.-Y., et al., ApJ, 865, 103C (2018)
  - Lim, C.-F., et al. submitted to ApJ (2019)
- Publications using STUDIES data
  - Simpson, J. M., et al., ApJ, 844L, 10S (2017)
  - Aoyama, S., et al., MNRAS, 484, 1852A (2019)
  - Wang, T., et al., Nature, 572, 211 (2019)



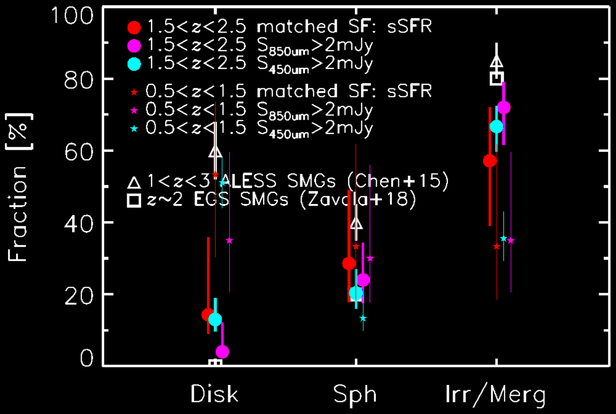
Simpson, J. M., et al. 2017



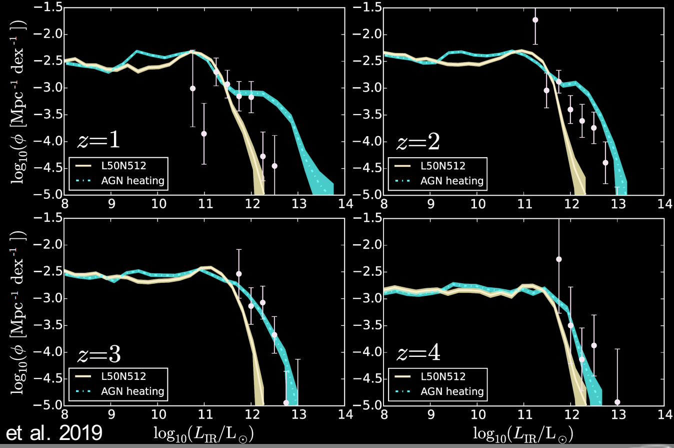
Wang, T., et al. 2019



Wang, W.-H., et al. 2017



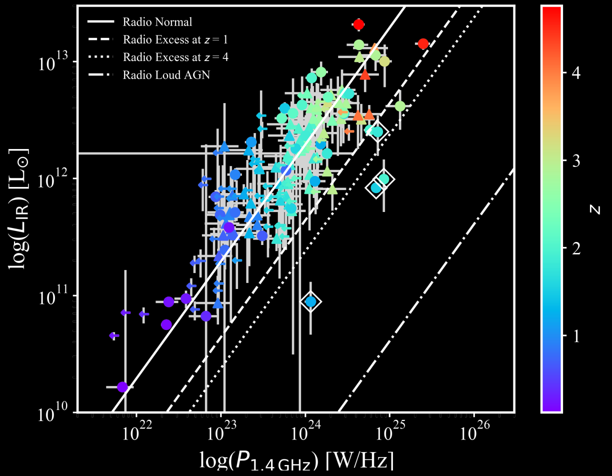
Chang, Y.-Y., et al. 2018

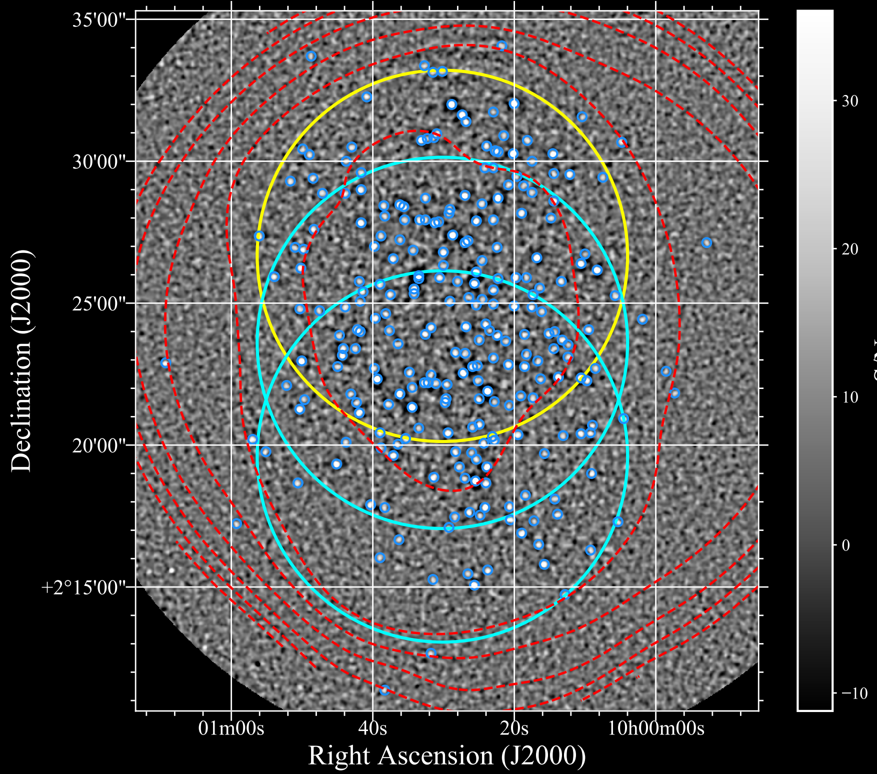


Aoyama, S., et al. 2019

Current results of STUDIES-COSMOS

- STUDIES (by March 2018; first released) + SCUBA-2 archival data from S2CLS (Geach+13,17) and Casey+13
- The r.m.s noise is ~ 0.65 mJy in the deepest region
- 256 sources with S/N ≥ 4
- 134 sources have VLA 3GHz; while 76 sources have MIPS 24-μm counterparts
- 192 (out of 210) sources have optical counterparts in the COSMOS field





C.-F., Lim et al. 2019 submitted to ApJ

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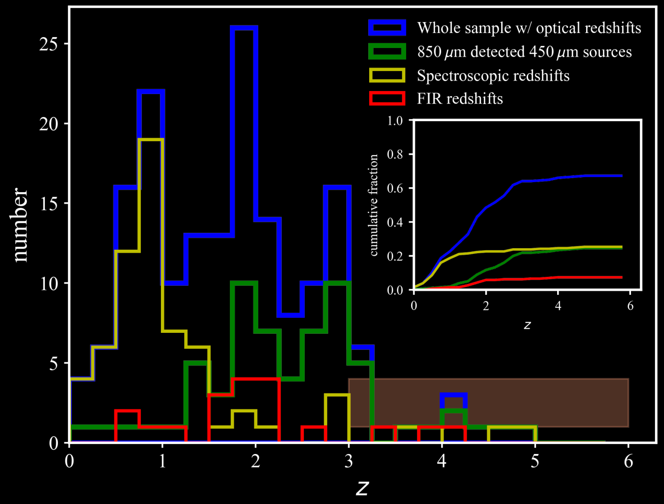
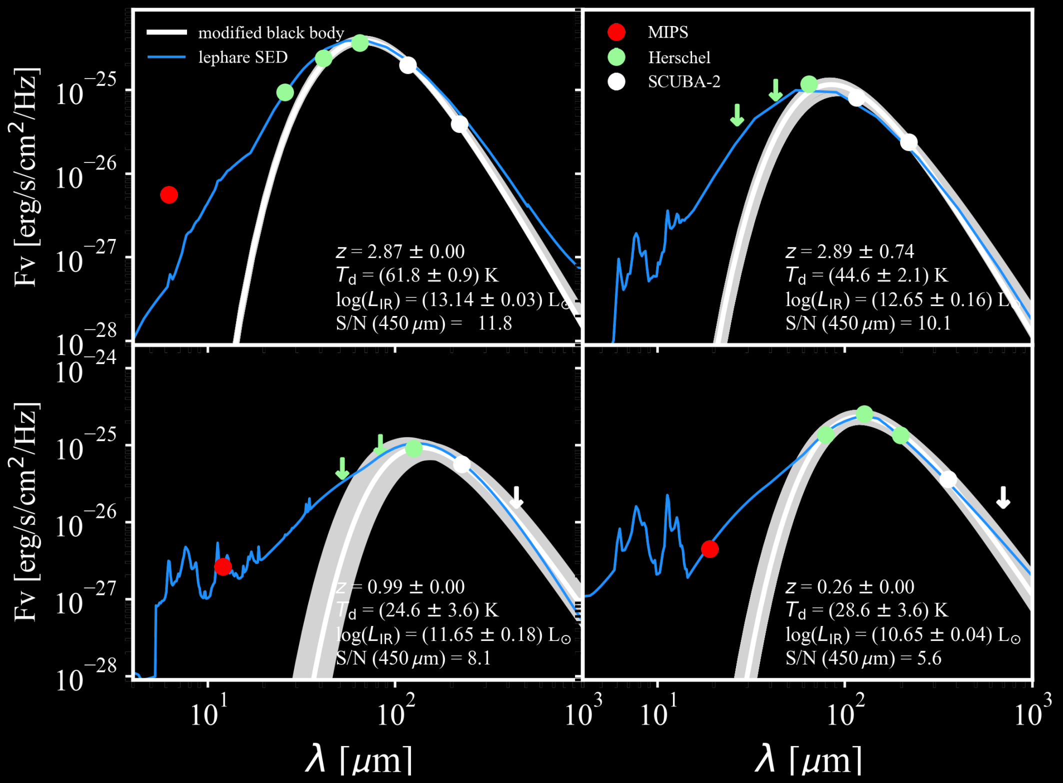
Physical properties of 450-μm sources

- COSMOS2015 catalog
  - $\langle z \rangle = 1.8 \pm 1.0$
  - $\langle \log(M_*) \rangle = 10.8 \pm 0.4\ M_\odot$
  - β_{UV} and L_{UV} (SFR_{UV})
- FIR wavebands
  - $\langle \log(L_{IR}) \rangle = 12.1 \pm 0.5\ L_\odot$ (SFR_{IR})
  - $\langle T_d \rangle = (38 \pm 10)$ K





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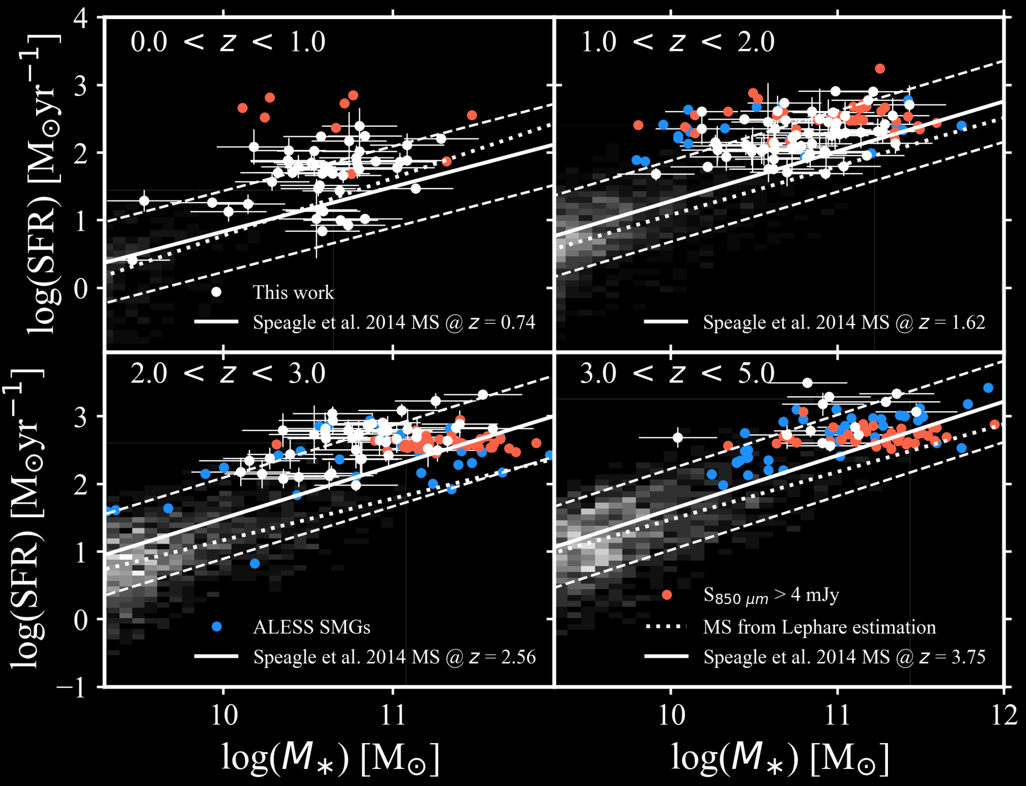
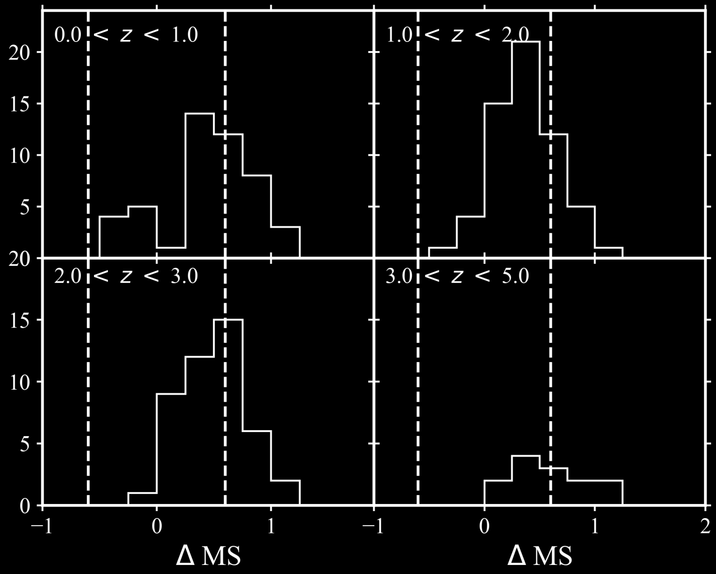
The Star-forming Main Sequence

C.-F., Lim et al. 2019 submitted to ApJ





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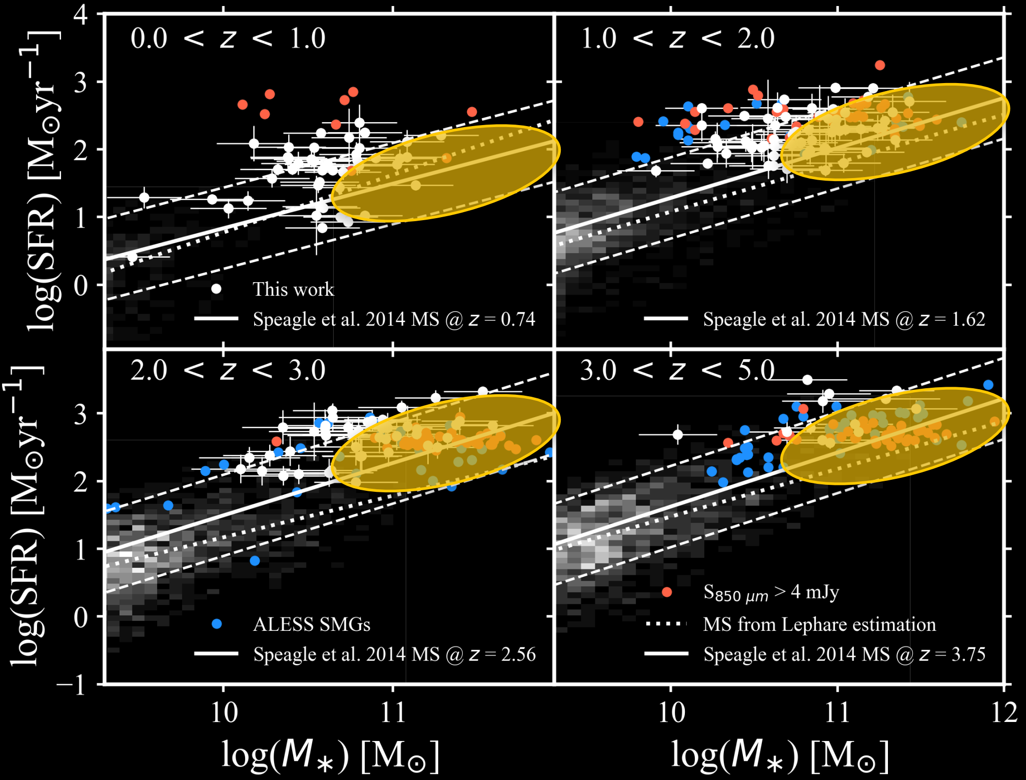
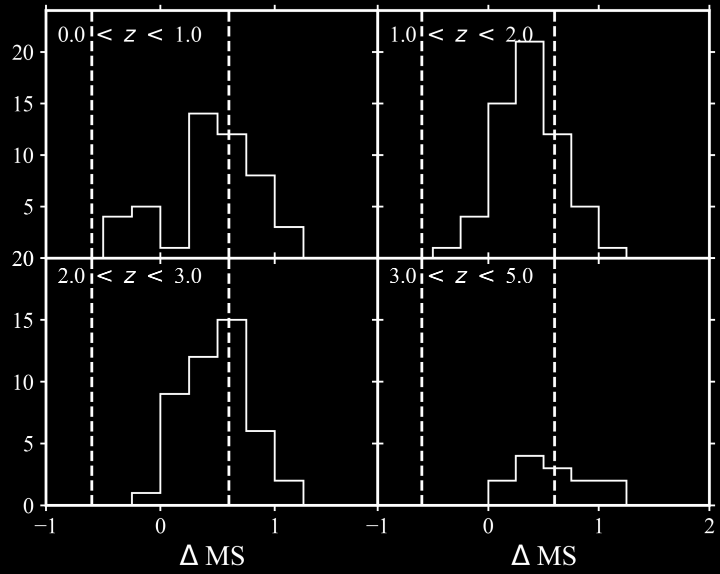


C.-F., Lim et al. 2019 submitted to ApJ



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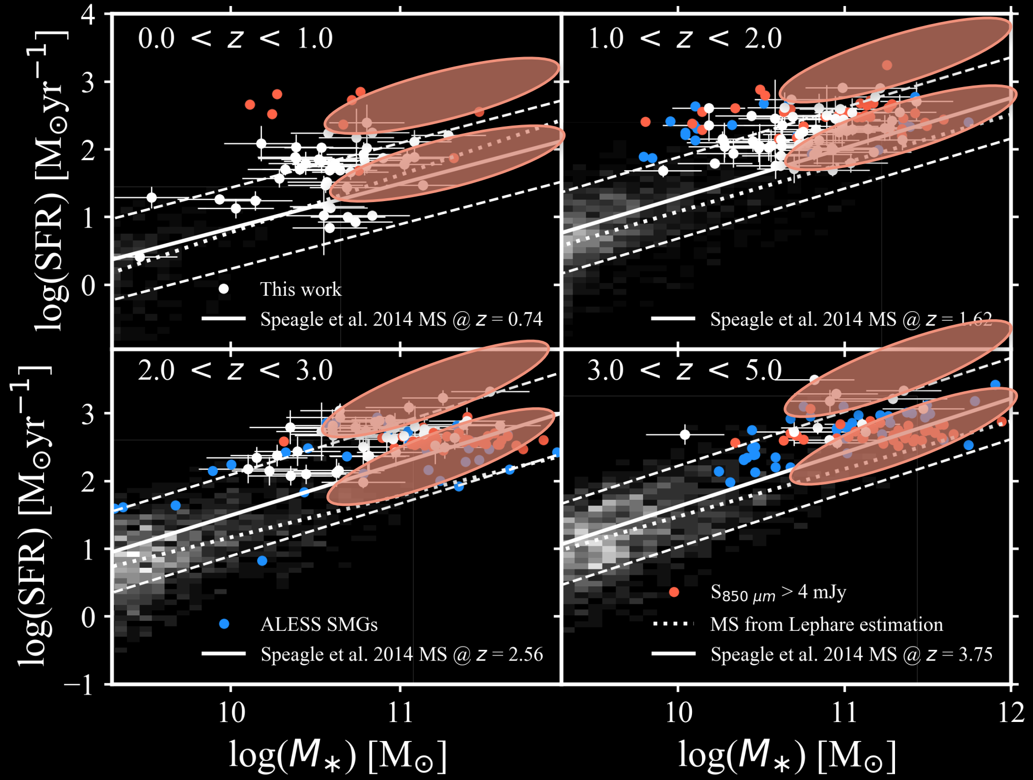

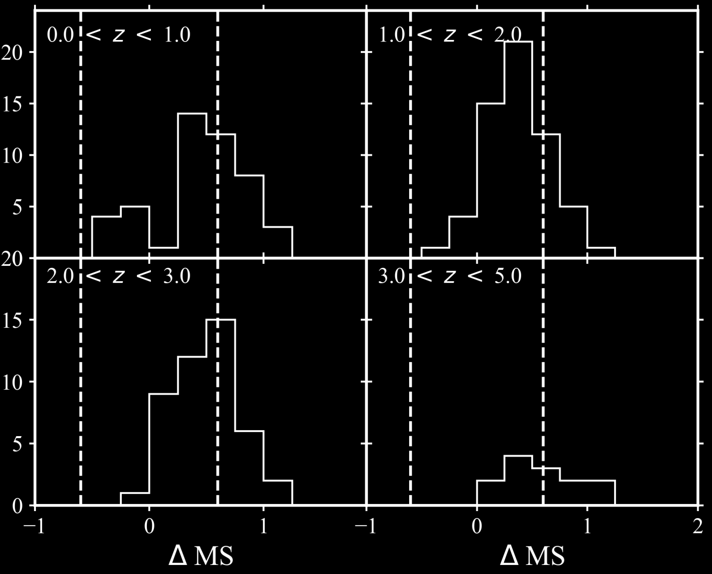

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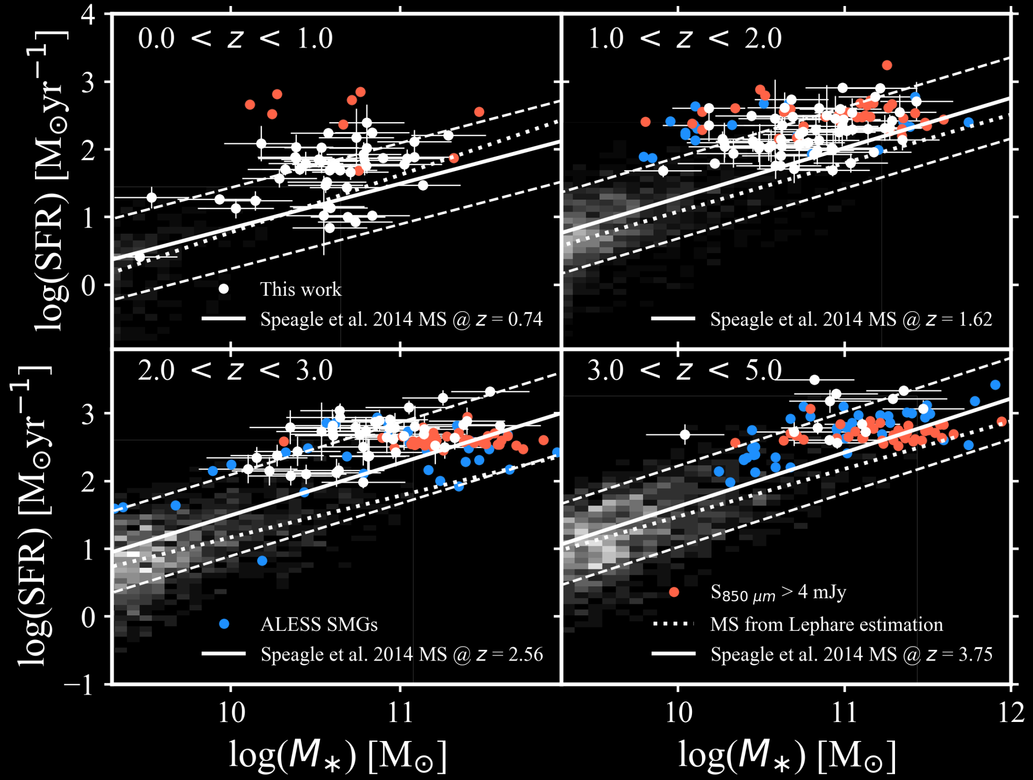

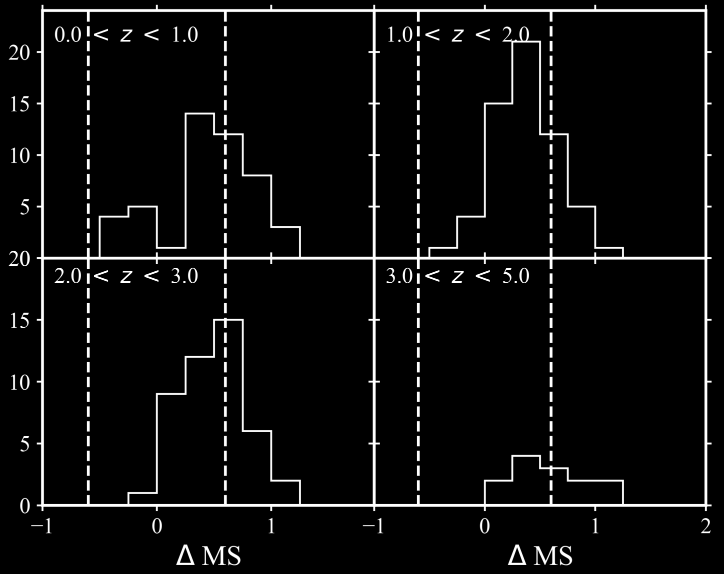

C.-F., Lim et al. 2019 submitted to ApJ

- 35% of our sample are classified as starburst galaxies ($\Delta MS \geqslant +0.6$ dex)
- An intermediate MS fraction between the two extremes (da Cunha+2015, Koprowski+16…)

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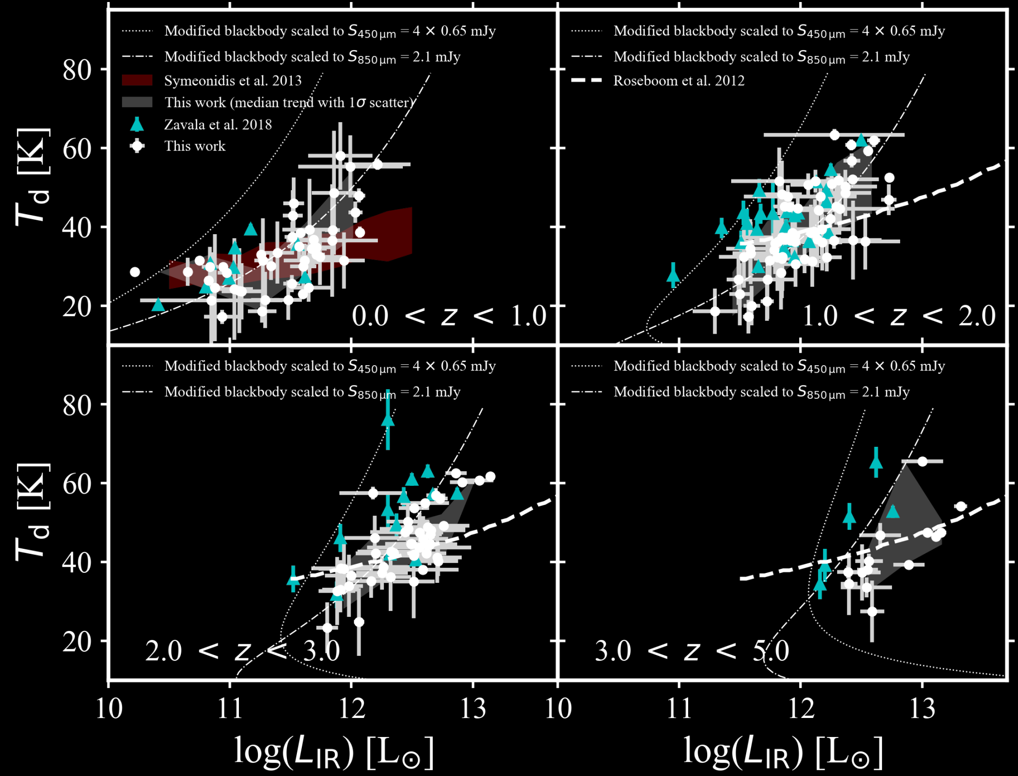
$T_d - L_{IR}$ relation



C.-F., Lim et al. 2019 submitted to ApJ

- Our galaxies overlap with the nearby (Symeonidis+13) and high-redshift (Rooseboom+12; Zavala+18) samples
- The emission from the majority of dust is in equilibrium
- Physical effect + selection effect
- 850-µm selection effect biases against the hotter population, while the 450-µm biases against cooler sources at high redshift
- Our sample provides a good representation of high-luminous ($L_{IR} > 10^{12}L_\odot$) population out to $z = 3$

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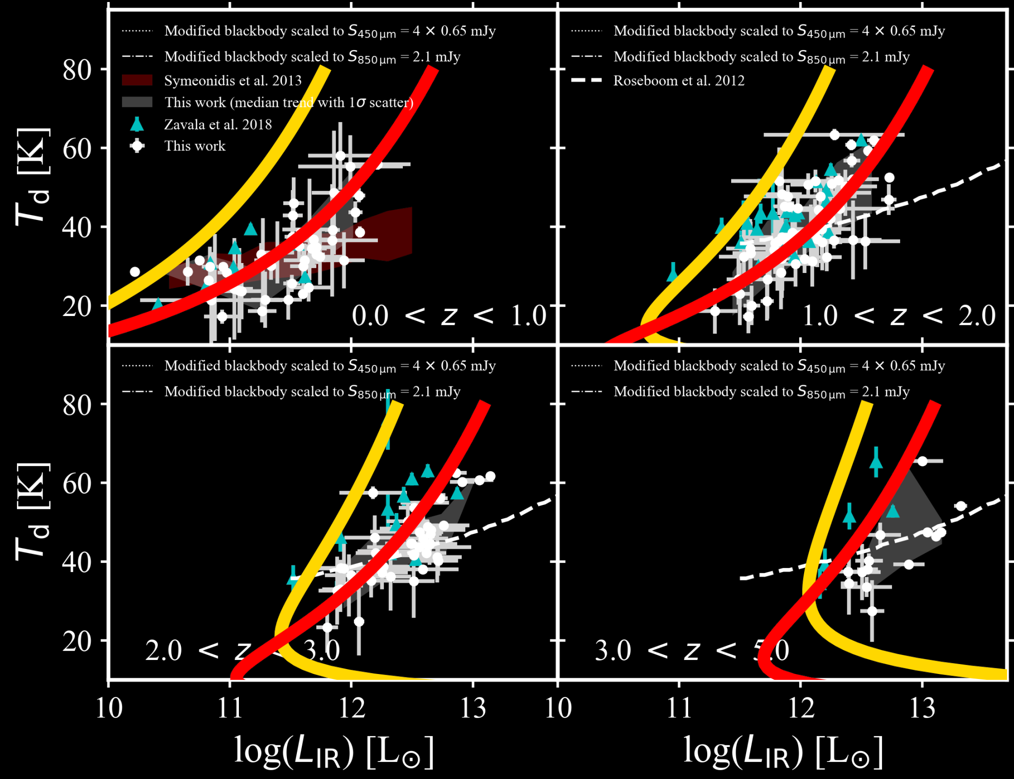

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450-µm detection limits

850-µm confusion limits

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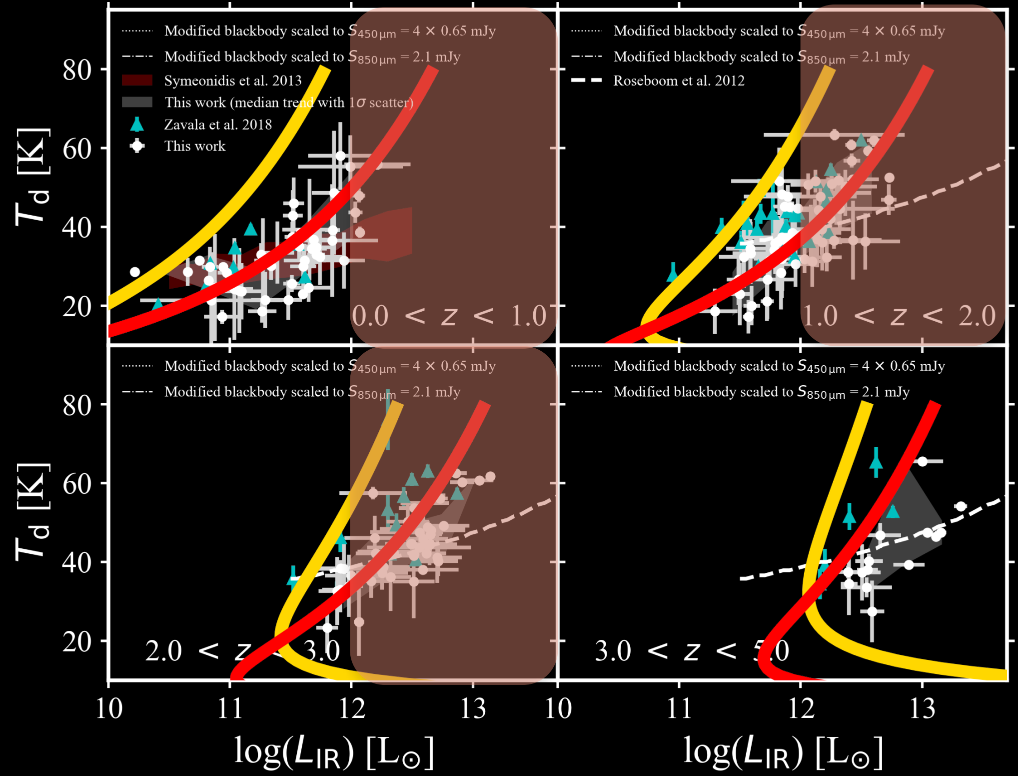

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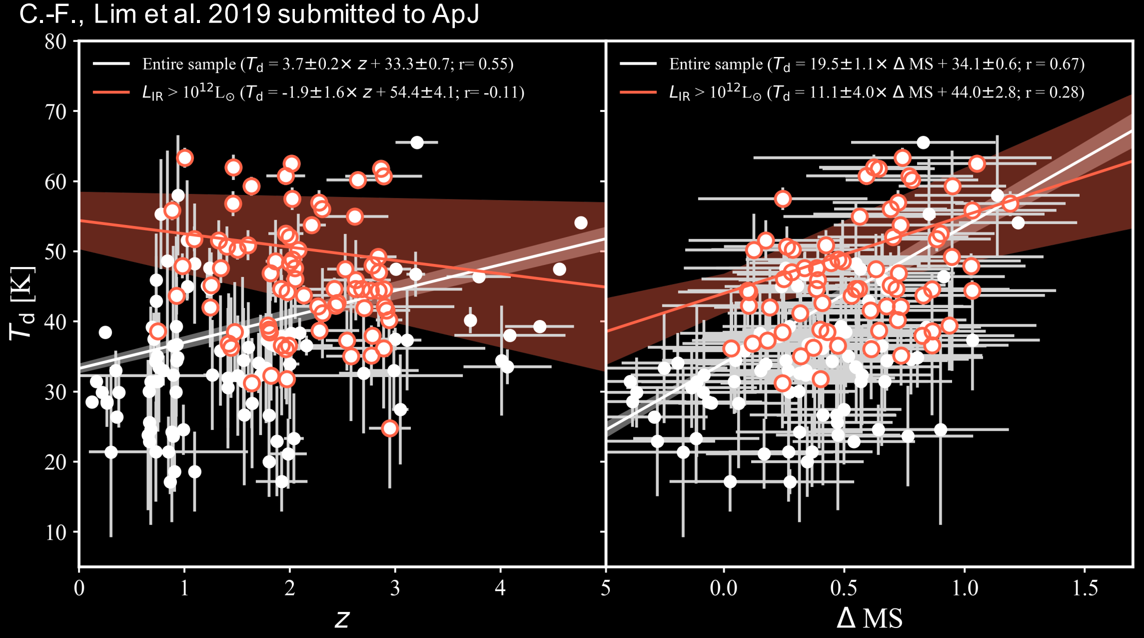
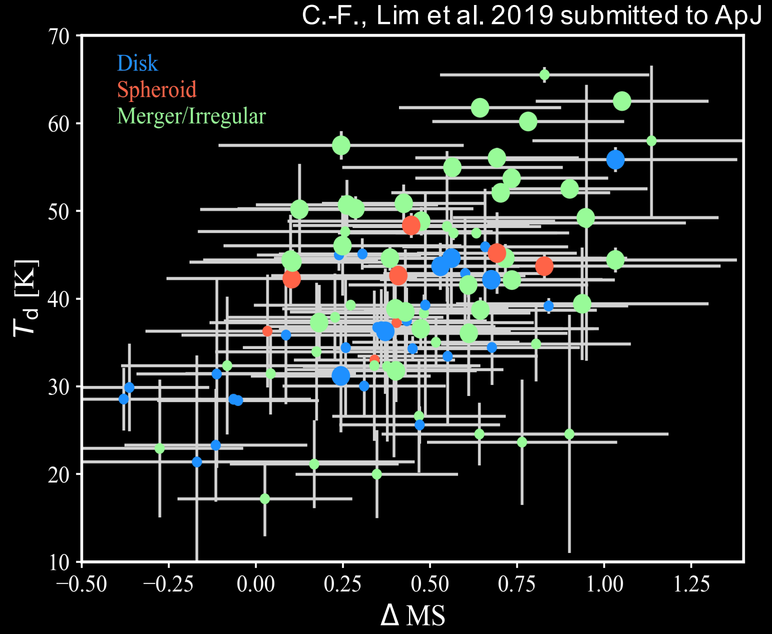
$T_d - z$ and $T_d - \Delta MS$ relations





- No evolution of T_d with z ($L_{IR} > 10^{12}L_\odot$ at $z < 3$)
- A moderate correlation between T_d and ΔMS
- Morphological classes (Chang+18): Mergers/irregulars are warmer; starbursts of SMGs are driven by mergers that lead to a sharp increase in T_d during the burst (e.g. Hayward+11; Cowley+17)

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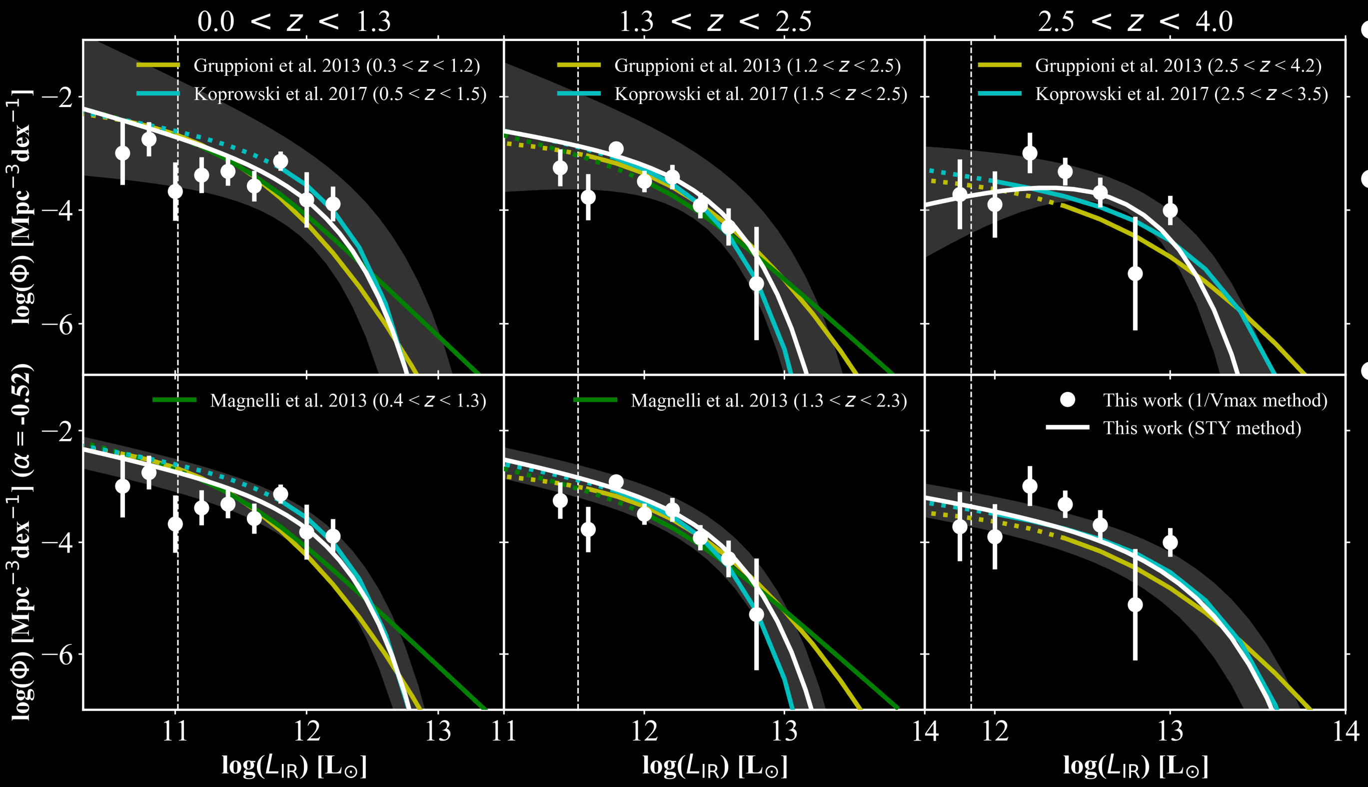
IR Luminosity Function



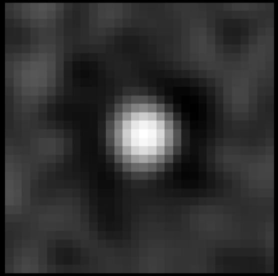
- We construct the IR-LFs with $1/V_{max}$ and likelihood methods (free- and fixed-α)
- At $z < 2.5$, our α (-0.6, -0.4) are consistent with the ALMA-based estimation (α = -0.4, Koprowski+17)
- The constraint in α (=-0.9) may be weak at $z > 2.5$

C.-F., Lim et al. 2019 submitted to ApJ

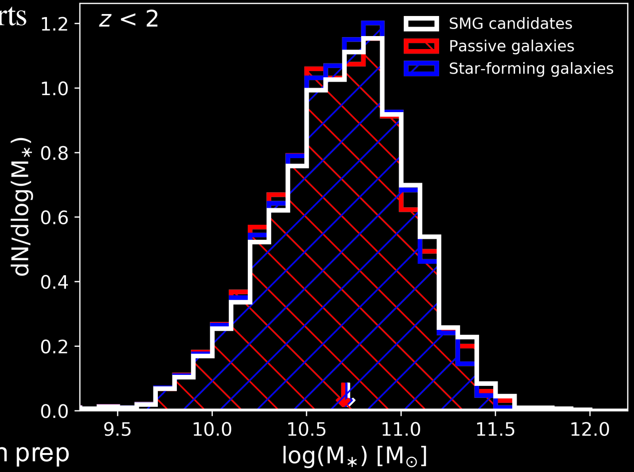
Machine Learning (Preliminary Results)

Future Prospect

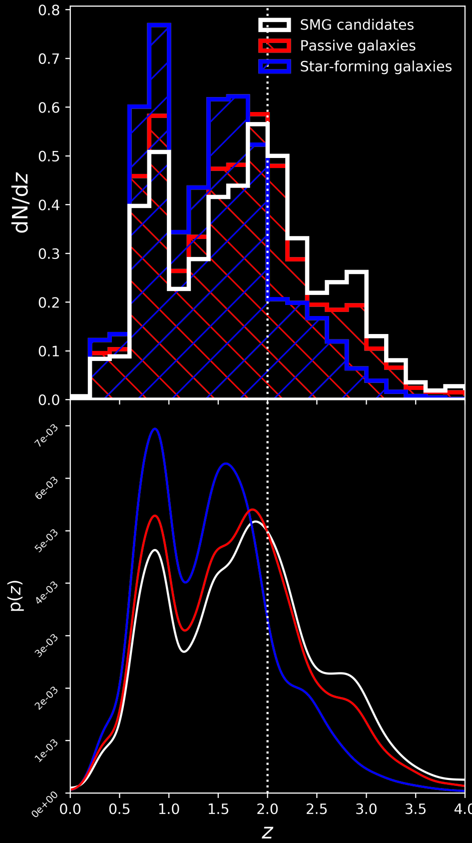
- Training dataset in Machine Learning (XGBoost):
  - 164 SMGs ($S_{450\,\mu m} \geqslant 4$ mJy + optical counterparts)
  - 4705 field galaxies reside within r.ms.(450) < 1 mJy region ($Ks < 24.5$)
- 78 color-colors from thirteen-band photometry ($uBV\ ri^{+}z^{++}JHKs$[3.6][4.5][5.8][8.0])
- 5620 SMG candidates in the COSMOS field (1.6 deg^2)
  - Expected finding number is 6111±1596
  - ~86 ± 1% have MIPS 24-µm /VLA counterparts
  - Stacked 450-µm flux = 4.9 ± 0.2 mJy
- Comparison samples ($z < 2$)
  - Passive galaxies
  - Star-forming galaxies



a shallower SCUBA-2 survey - S2COSMOS (Simpson+19)



C.-F., Lim et al. 2020 in prep



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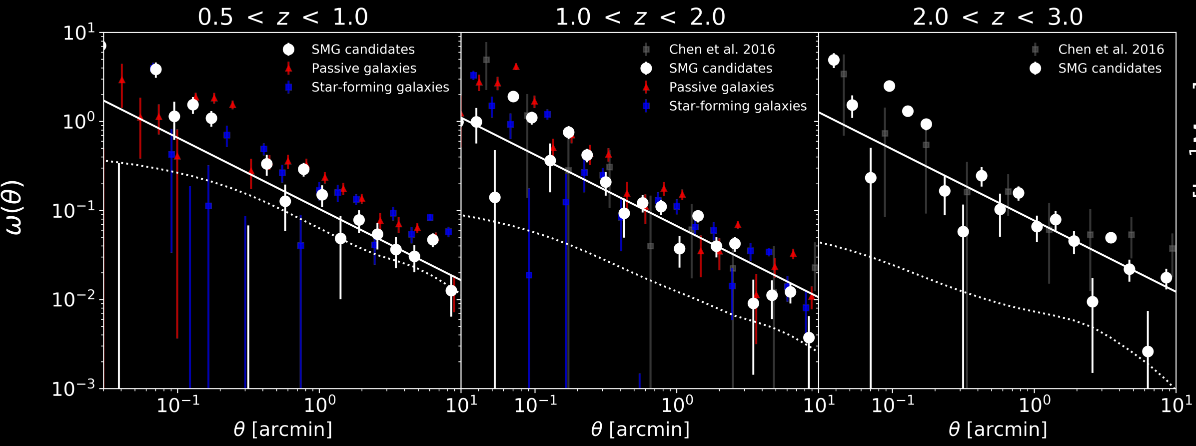
Clustering measurements (Preliminary Results)

- Auto-correlation technique in the SMG candidates and the comparison samples
- Constrain the dark matter halo masses and the clustering evolutions
- No evidence that clustering signals of SMGs have evolution with z (reside in the typical halo mass of ~ $10^{13} h^{-1} M_{\odot}$)
- Passive galaxies show stronger clustering signals
- No significant difference between the SMG candidates and star-forming galaxies (matched z and M_*)



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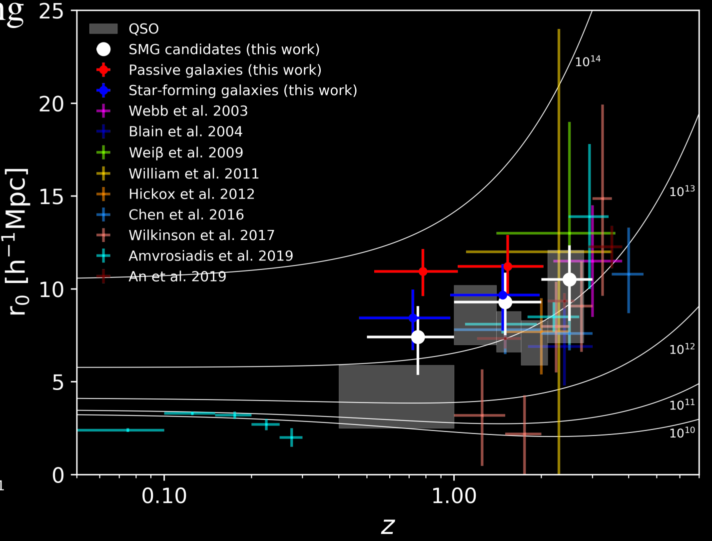

C.-F., Lim et al. 2020 in prep

Summary

Summary

- We constructed an extremely deep 450-μm image
- About 35% of our sample are classified as starburst galaxies
- Our sample provides a good representation of high-luminous population out to $z = 3$
- We find a moderate tendency between the T_d and ΔMS, which favors the scenario that the starbursts of SMGs are driven by merger activity
- No evidence that clustering signal of SMG has evolution with z
- No significant difference between the SMG and star-forming galaxies (matched z and M_*)

More and more exciting results will be published with complete STUDIES data !!!!

Thank you

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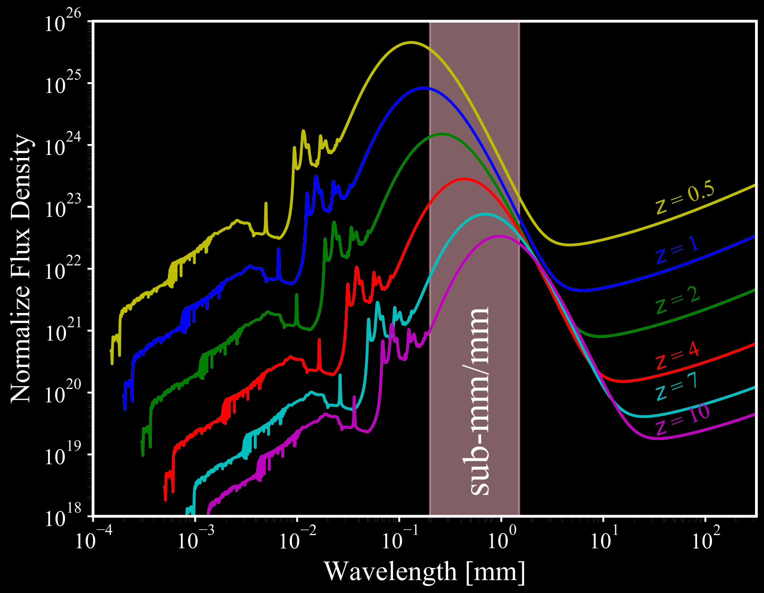
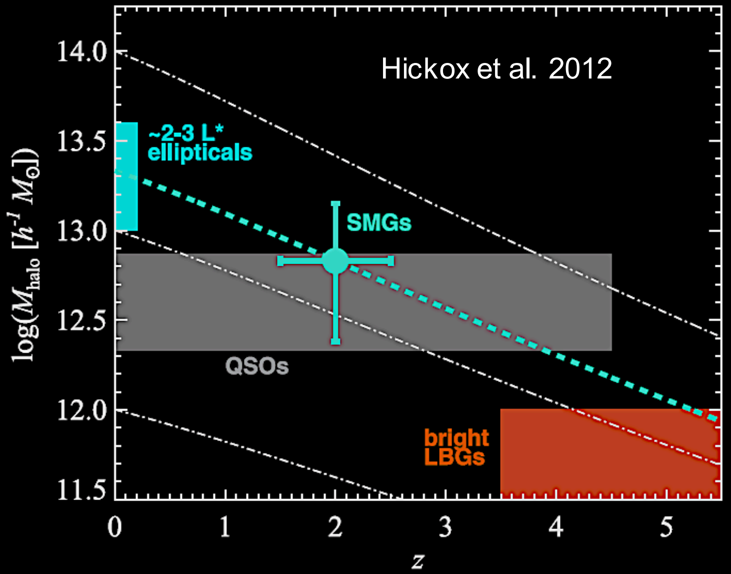
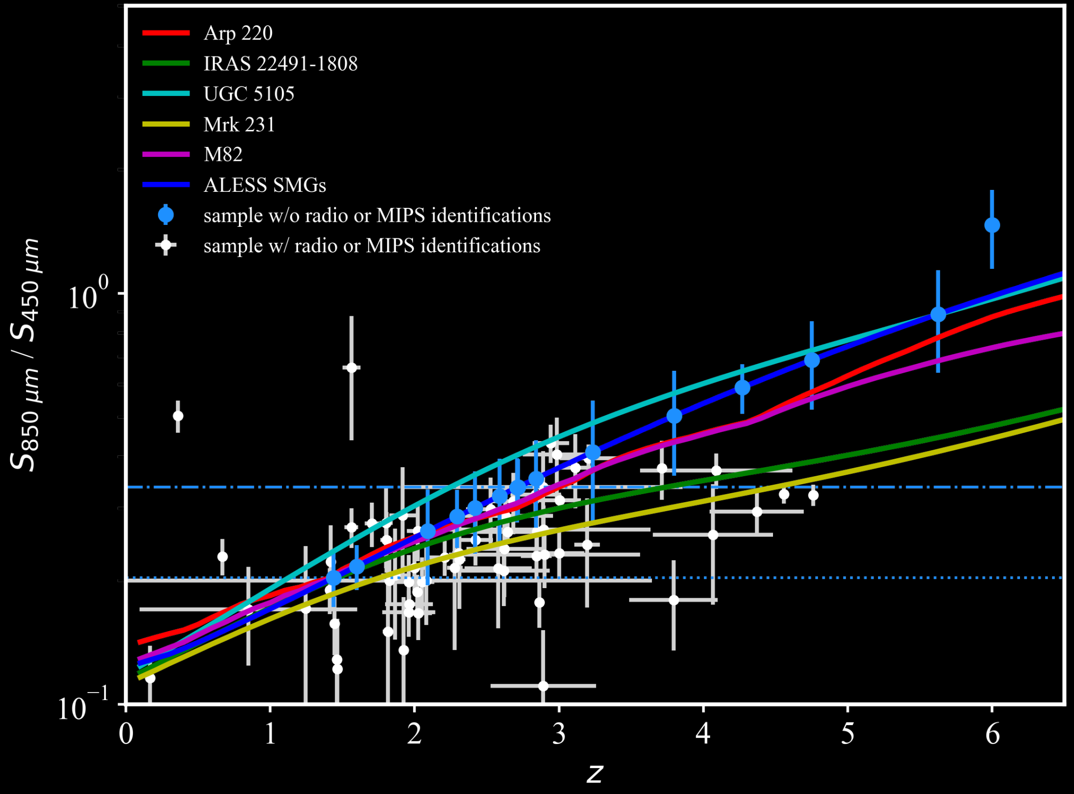
Sub-millimeter galaxies (SMGs)





- Typical SMGs have $L_{IR} > 10^{11} L_{\odot}$
- The negative K-correction leads us easy to detect the SMGs at high redshift
- The SMGs reside in haloes of mass > $10^{13} h^{-1} M_{\odot}$, which are believed to be the progenitors of massive systems (ellipticals) in the local Universe

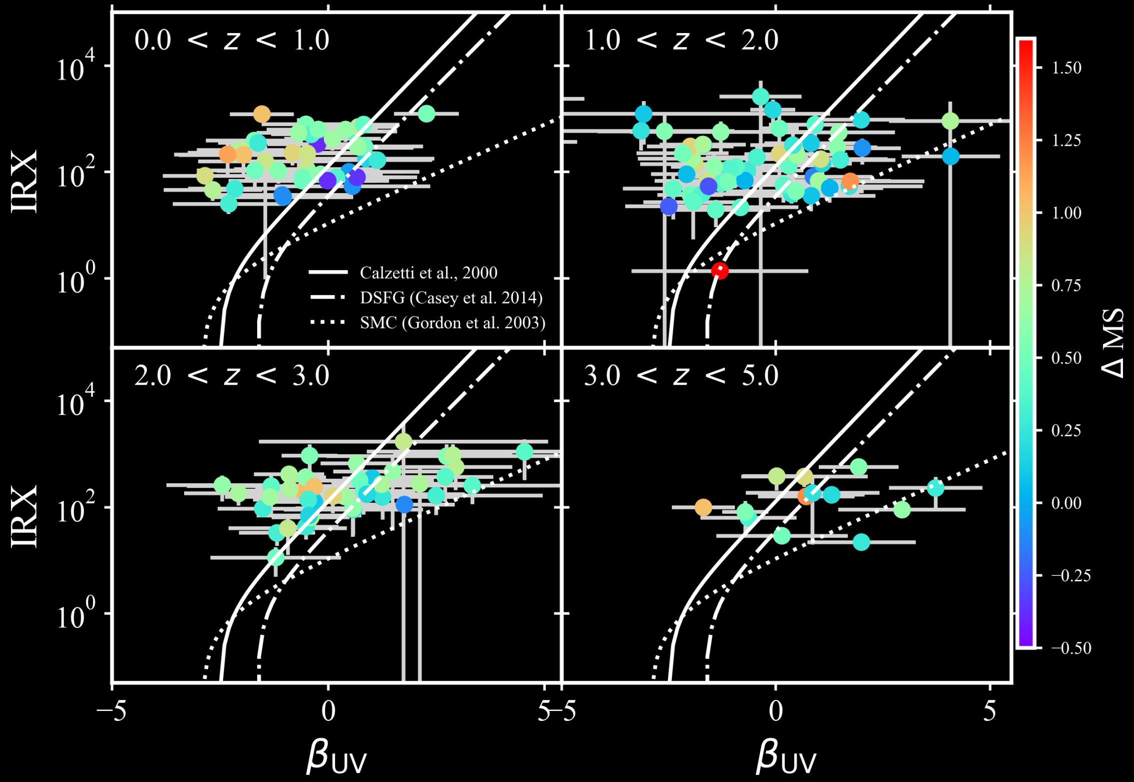
Unidentified sources



- The unidentified sources are consistent with being at high redshift

Dust Attenuation Correlation

C.-F., Lim et al. 2019 submitted to ApJ



- The L_{IR}/L_{UV}(IRX) and UV-slope (β_{UV}) can indicate the amount of dust attenuation
- 450-μm sources are on or above the local relations and span a wide range of IRX values (Howell+10; Casey+14)
- Most of our sources lie above the SMC relation (the limit of star-forming galaxies)

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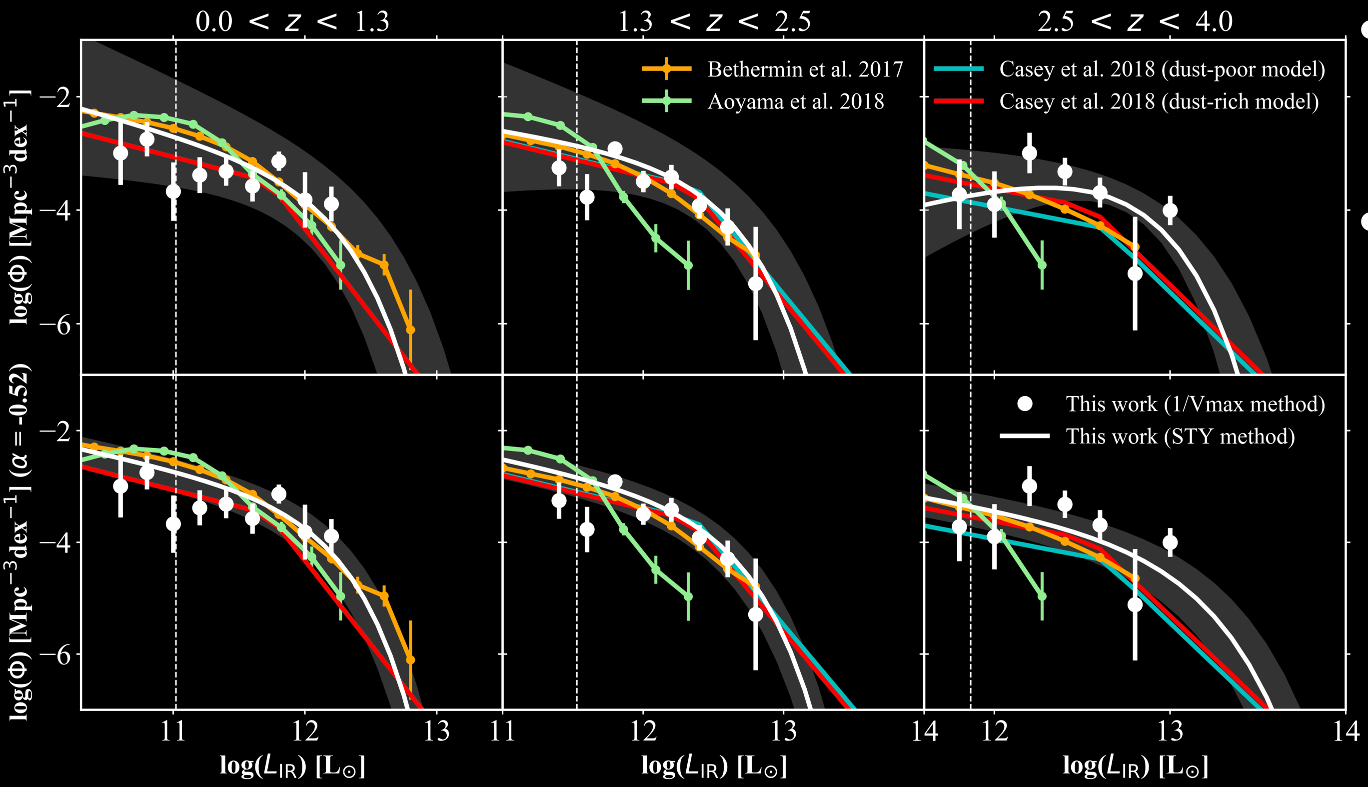
IR Luminosity Function (compared to models)



- The models and our observations start to diverge for high redshift bins (z >1.3 or z >2.5)
- The models require some ingredient that produces more IR-emitting galaxies at high redshift

C.-F., Lim et al. 2019 submitted to ApJ

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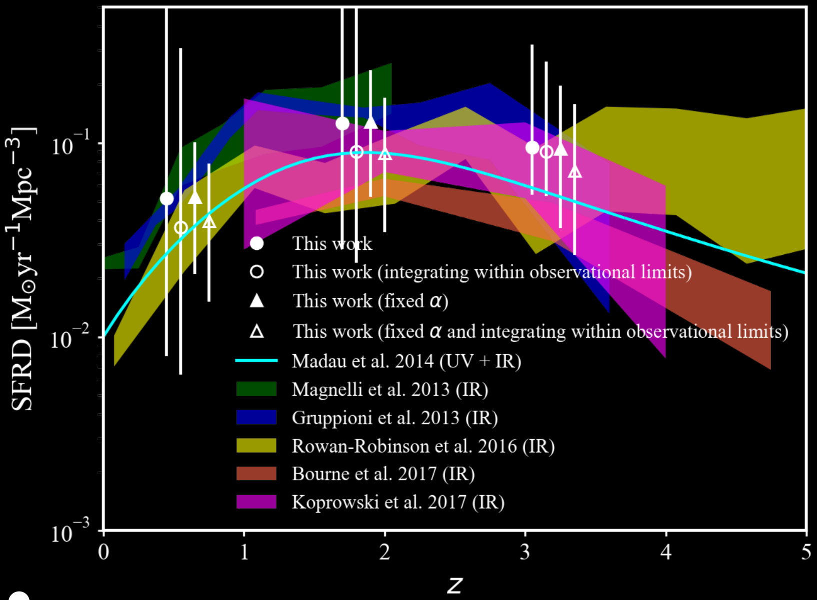
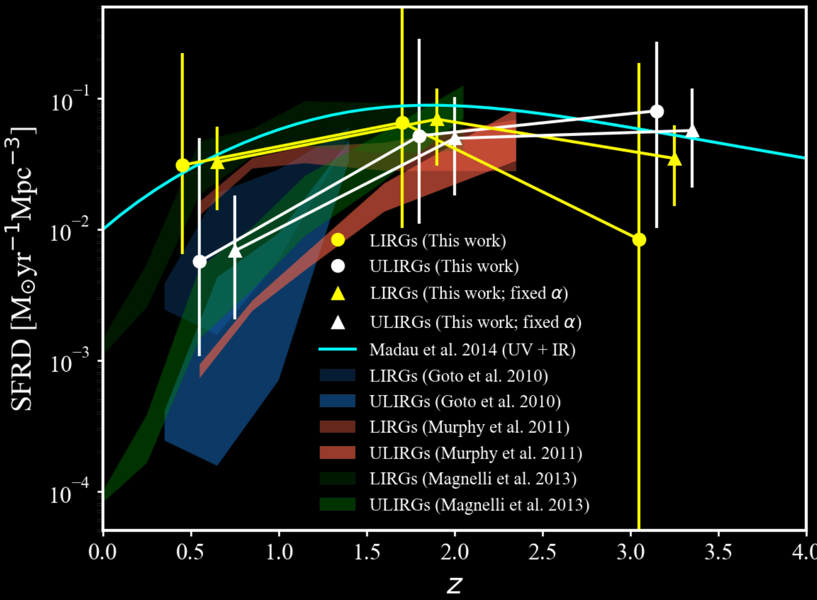
The evolution of obscured SFR density

C.-F., Lim et al. 2019 submitted to ApJ



C.-F., Lim et al. 2019 submitted to ApJ



- Given that the considerable uncertainties of all the measurements and ours, we conclude that our results are in broad agreement with all of the previous works
- The contribution of ULIRGs (L_{IR} = 10^{12}-10^{13} $L_{\odot}$) to SFRD rises from low redshift and plays a comparable role with LIRGs (L_{IR} = 10^{11}-10^{12} $L_{\odot}$) at $z > 2$

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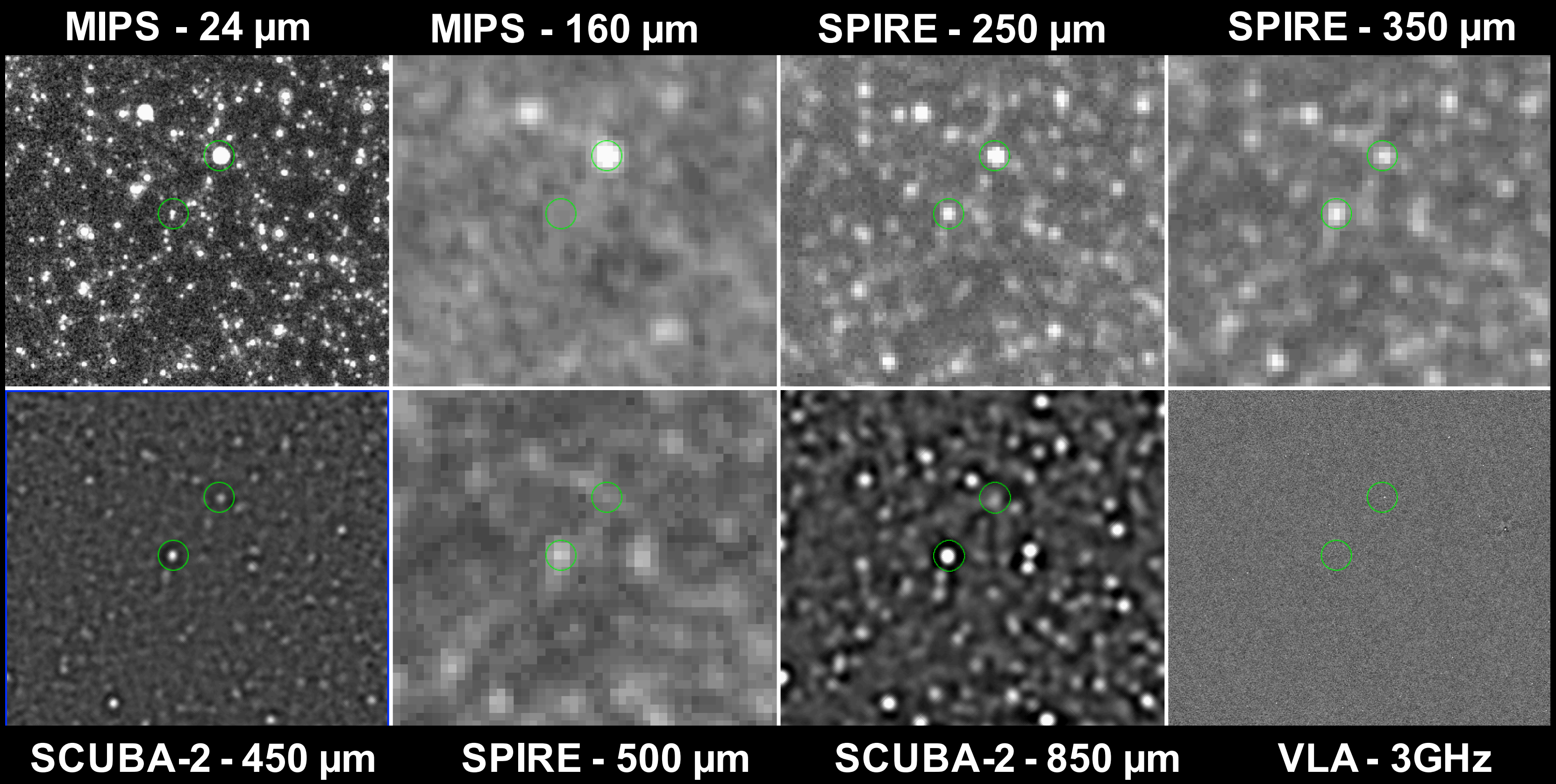
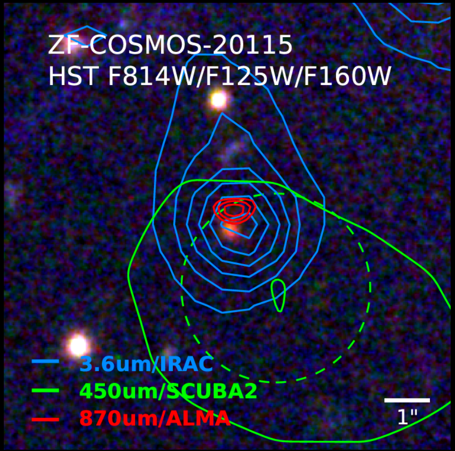
Cutoff Images

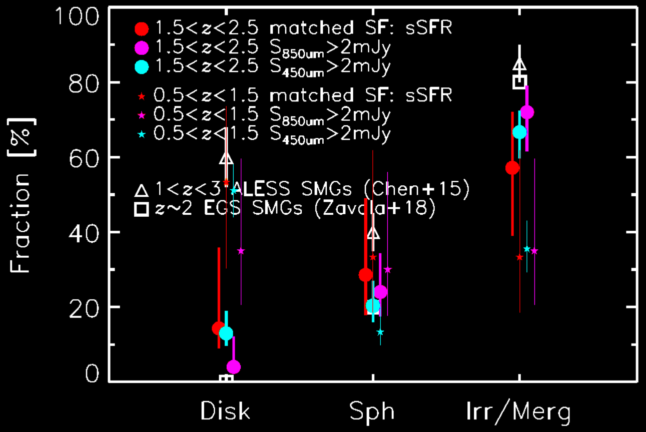


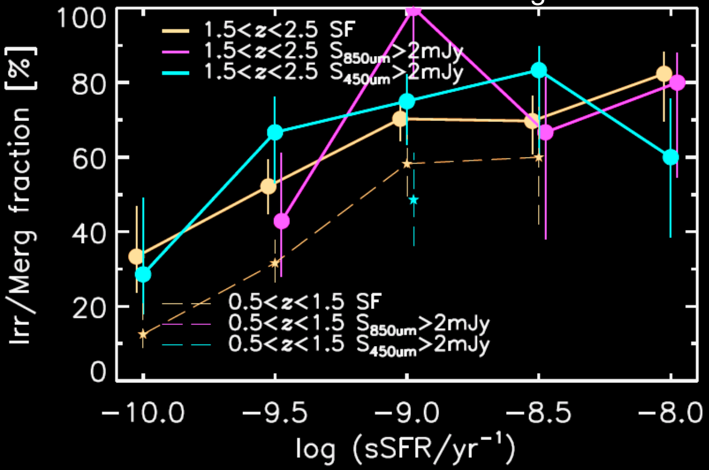
Previous publications

Simpson et al. 2017



Chang et al. 2018





- A proposed passive galaxy at $z = 3.717$
  - Red colors $(H - [4.5] > 4)$
  - High EW of Balmer absorption lines
- $L_{IR} = 9.2\times10^{11} L_\odot$ (SFR ~ $100 M_\odot\, yr^{-1}$)
- Ongoing merger event
- Remove the tension between observations and models of galaxy formation

- Compares our 450 μm SMGs with normal SF galaxies (*NUVrJ*)
- Both SMGs and the matched galaxies show high fractions (70%) of disturbed features, and the fractions depend on the SFRs.
- These suggests that their star formation activity is related to galaxy merging, and the stellar structures of SMGs are similar to those of star-forming galaxies.

Thank you

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Sub title