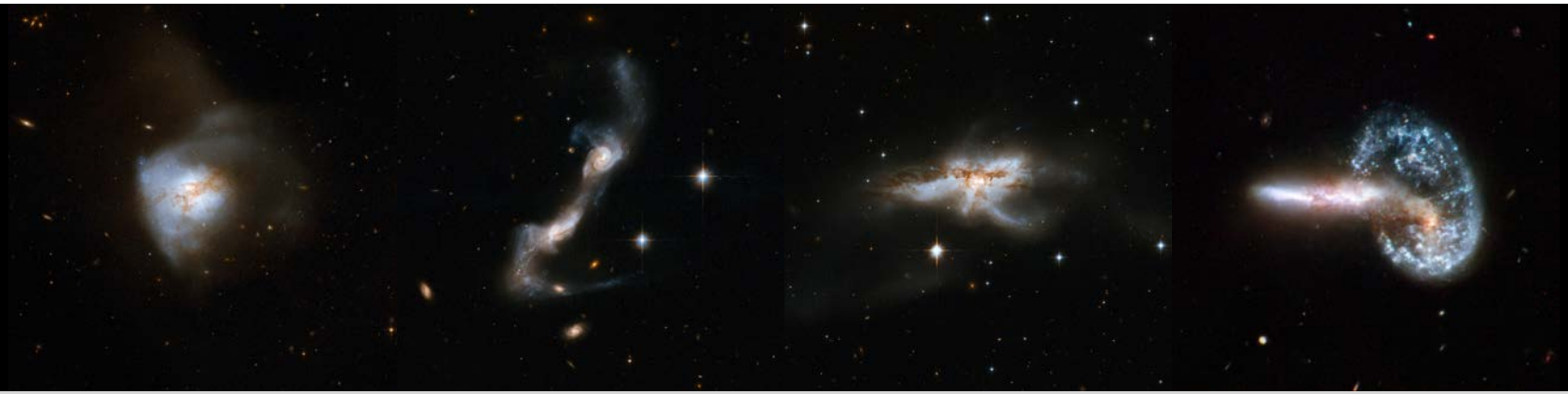

SEDs of Luminous Infrared Galaxies:

Herschel-GOALS: PACS and SPIRE imaging of the complete sample of local (U)LIRGs

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Institute for Astronomy
University of Hawaii at Manoa

J. Chu, **N. Lee**, K. Larson, **Vivian U.**, **J. Kartaltepe**, J. Mazzarella, A. Evans, J. Howell, J. Surace, L. Armus, **T. Diaz-Santos**, V. Charmandaris, K. Iwasawa, D.-C. Kim, C. Casey, T. Vavilkin, M. Dufault, J. Barnes, B. Chan, D. Frayer, S. Haan, H. Inami, C. Ishida, A. Petric, and the GOALS Team

The Universe Explored by Herschel – 18 October, 2013 ESA/ESTEC, Noordwijk

Outline

1. The GOALS Sample

2. The Multi-wavelength (U)LIRG Atlas

3. Herschel PACS+SPIRE photometry

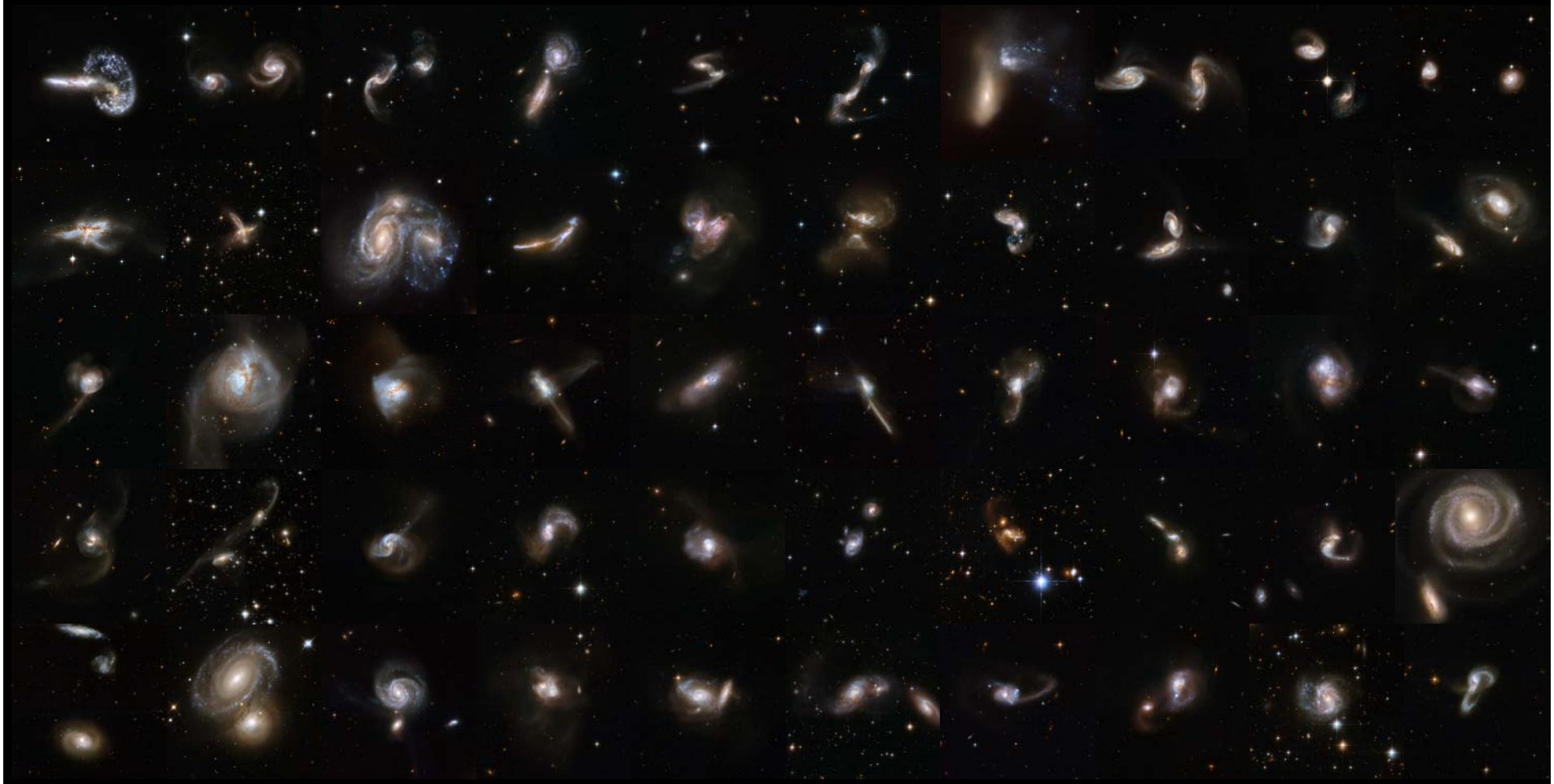
4. GOALS FIR SEDs (T_{dust}, M_{dust}, ….)

5. Comparison with high-redshift (U)LIRGs

P12 Diaz-Santos et al.
P28 Lu et al.

P26 Lee et al.
P23 Kartaltepe et al.

GOALS: The Great Observatories All-Sky LIRGs Survey (see Armus+09)



HST-ACS images of GOALS (U)LIRGs PI: Aaron Evans / Hubble Heritage Release

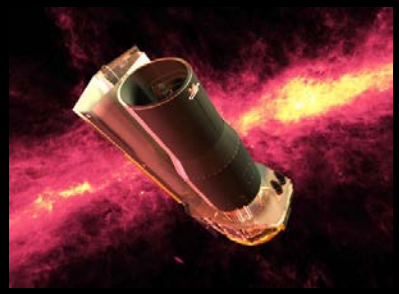
The Multi-wavelength GOALS Atlas

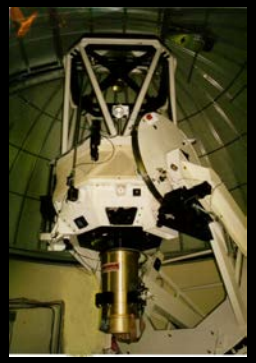
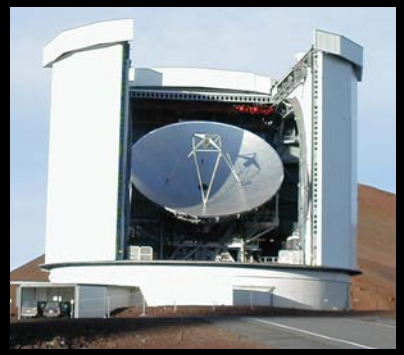
- Compilation of a complete, consistent photometry
- Determine global physical properties of galaxies
- Multi-wavelength SFR and AGN indicators
- Create benchmark for local (U)LIRGs to compare with high-z studies of (U)LIRGs

GOALS: X-ray to Radio SEDs

- **<u>203 objects</u>**: $L_{IR} > 10^{11.0} L_{\odot}$, (selected from the IRAS Revised Galaxy Survey, all sky, $S_{60} > 5.24$ Jy – Sanders+03)
- **<u>35-50 bands</u>**: from hard X-rays to 1.49 GHz

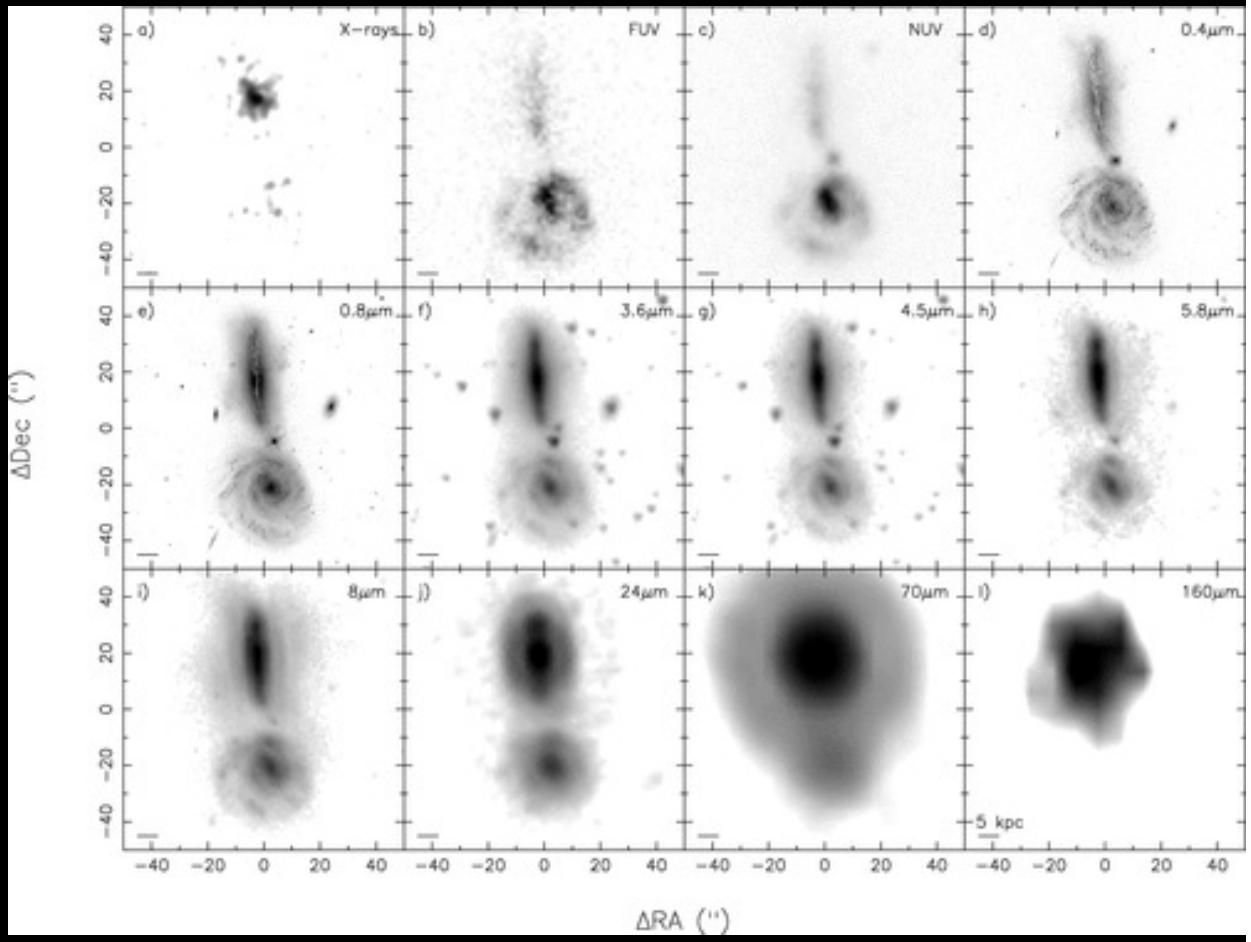



Mask Photometry

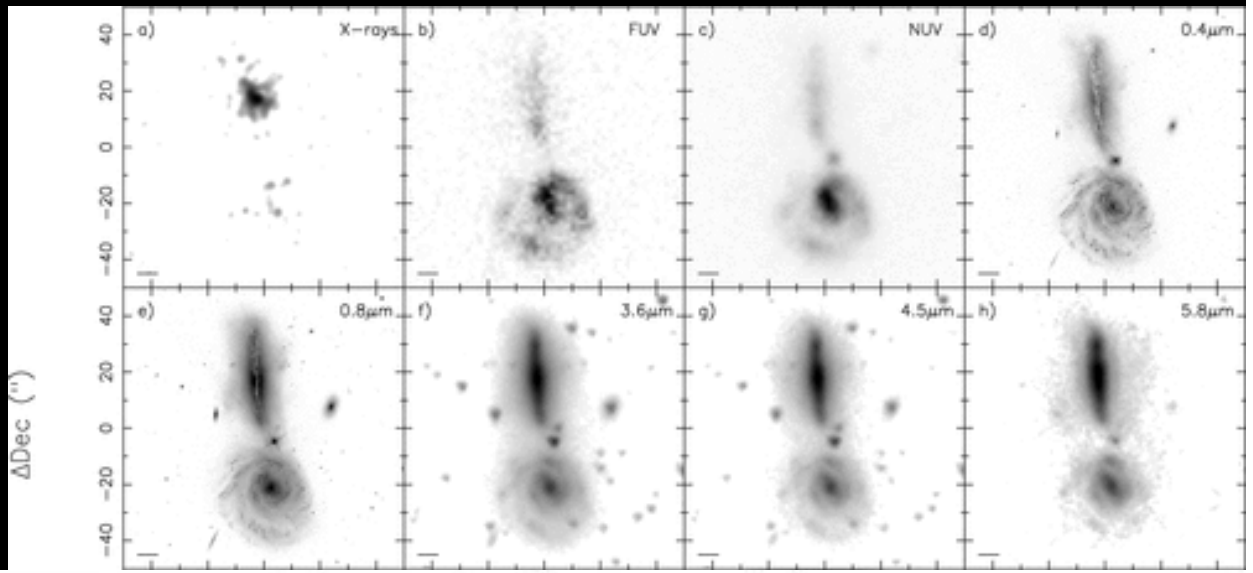
- Define masks for uniform "aperture"

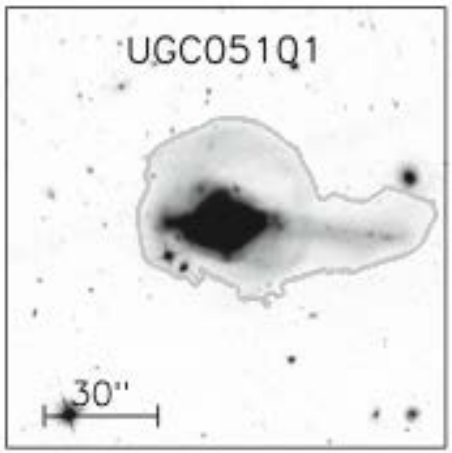


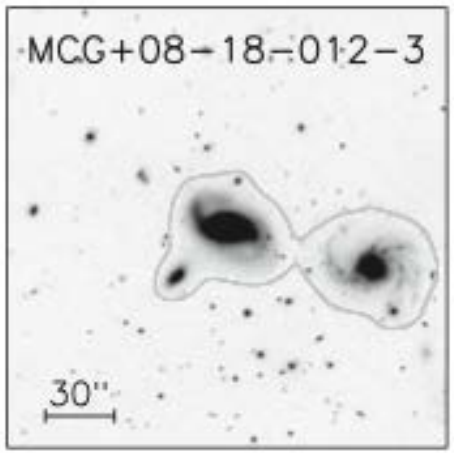
Arp 302 (Armus+ 2009, PASP, 121, 559)

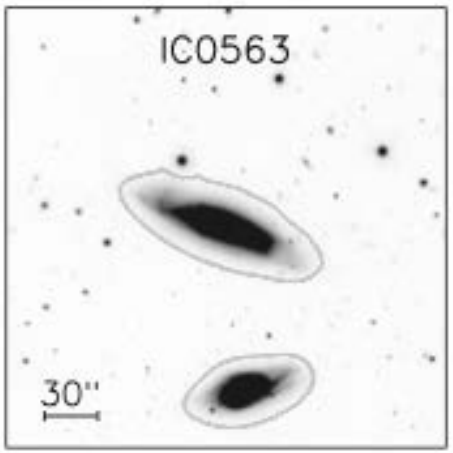
Mask Photometry

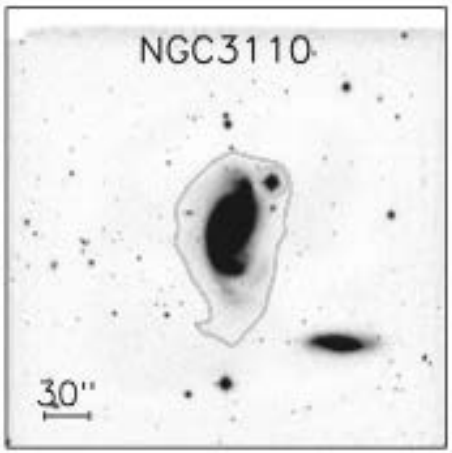
- Define masks for uniform "aperture"







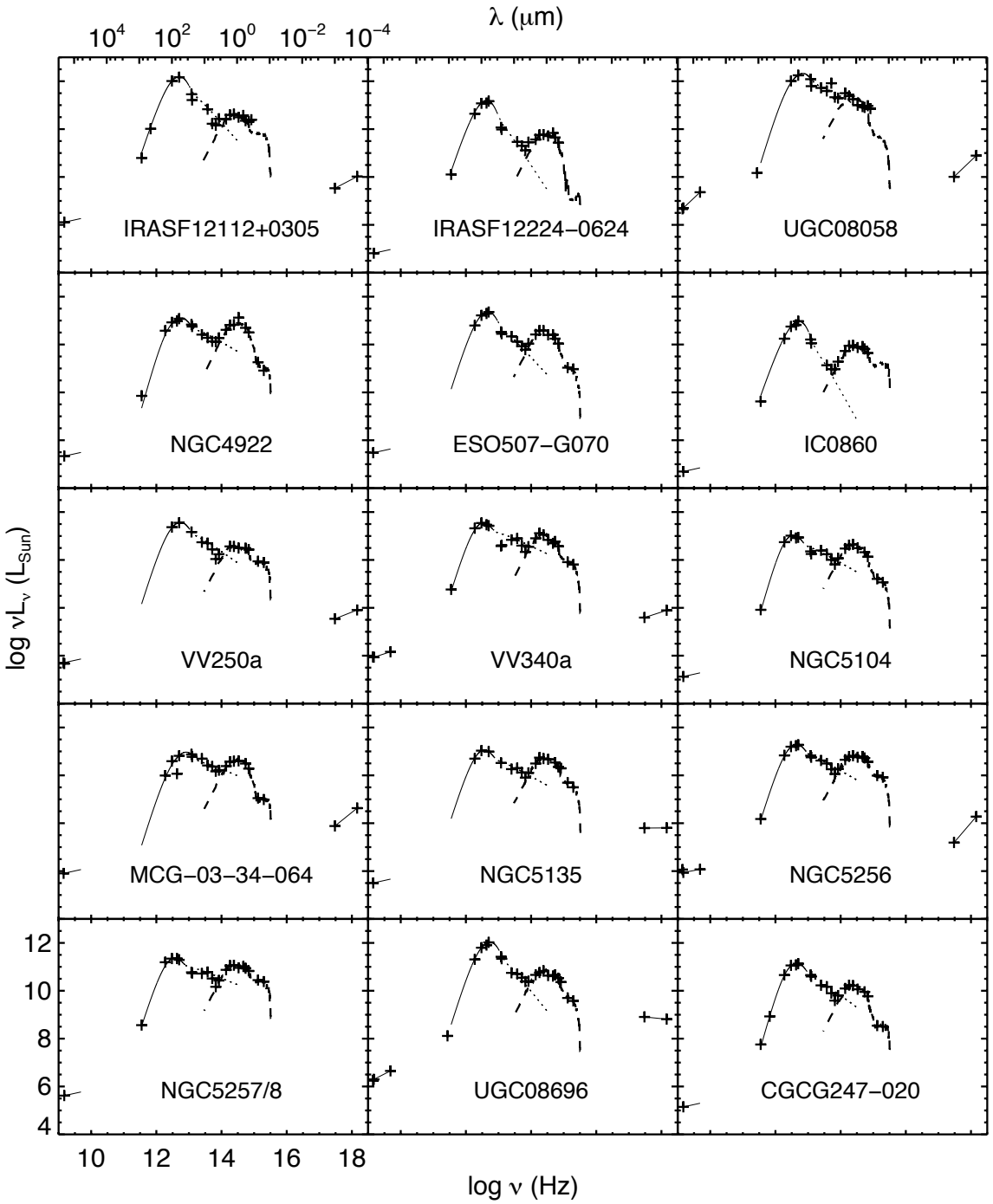




SED Sample

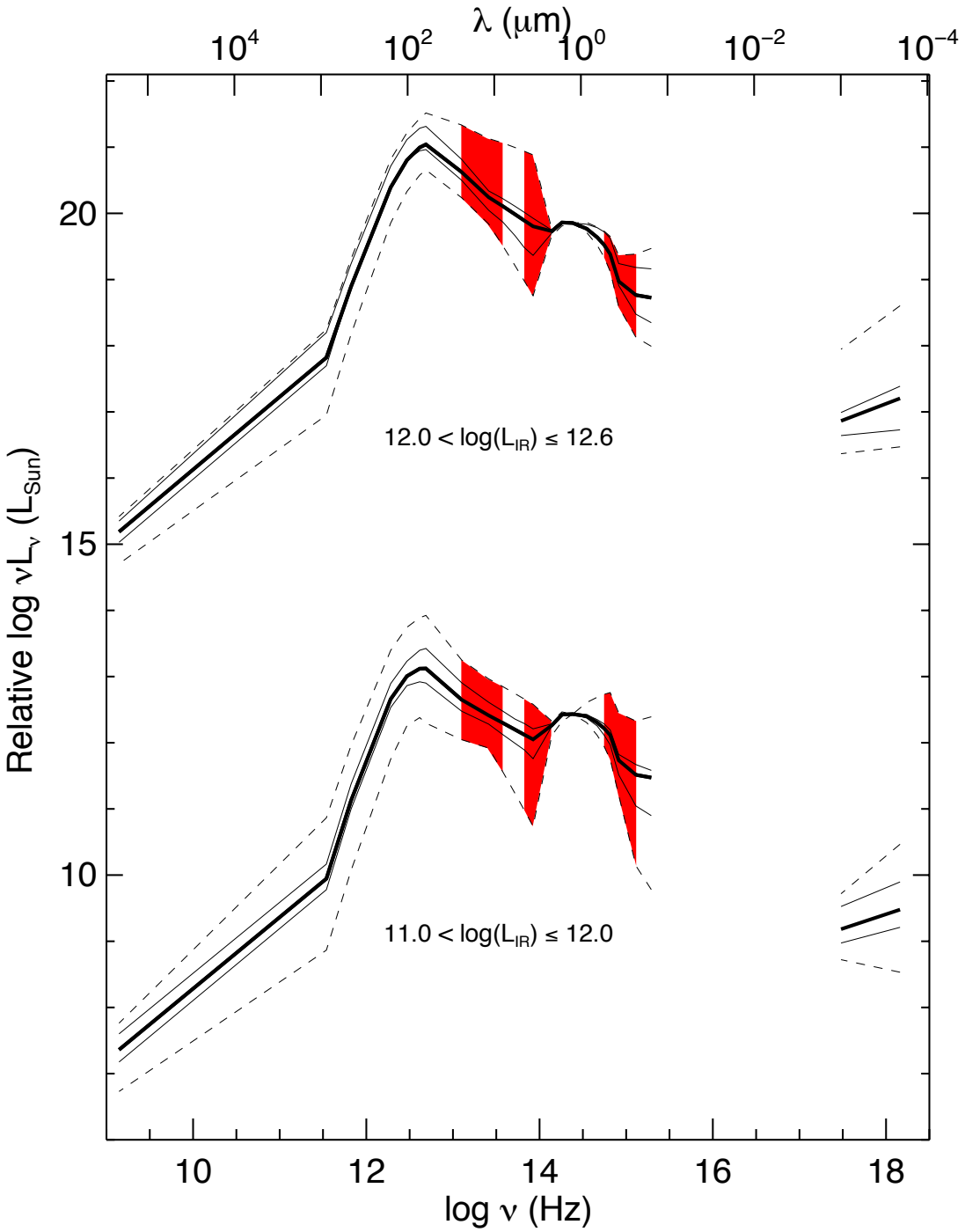
- 11 ULIRGs + 56 LIRGs

(Vivian U+12)

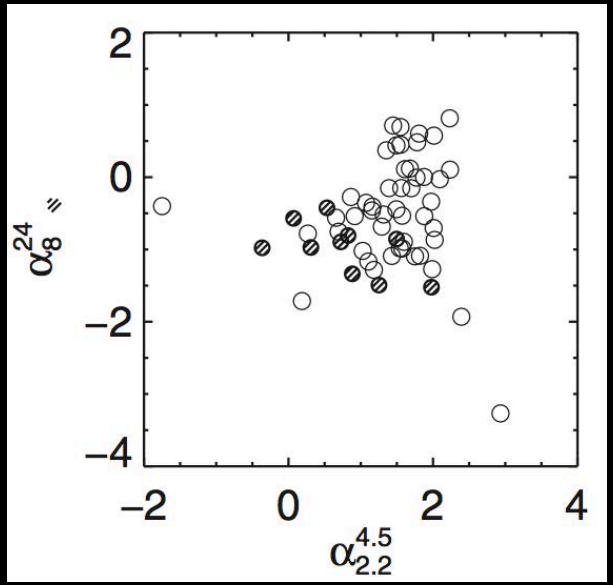


SED Variations

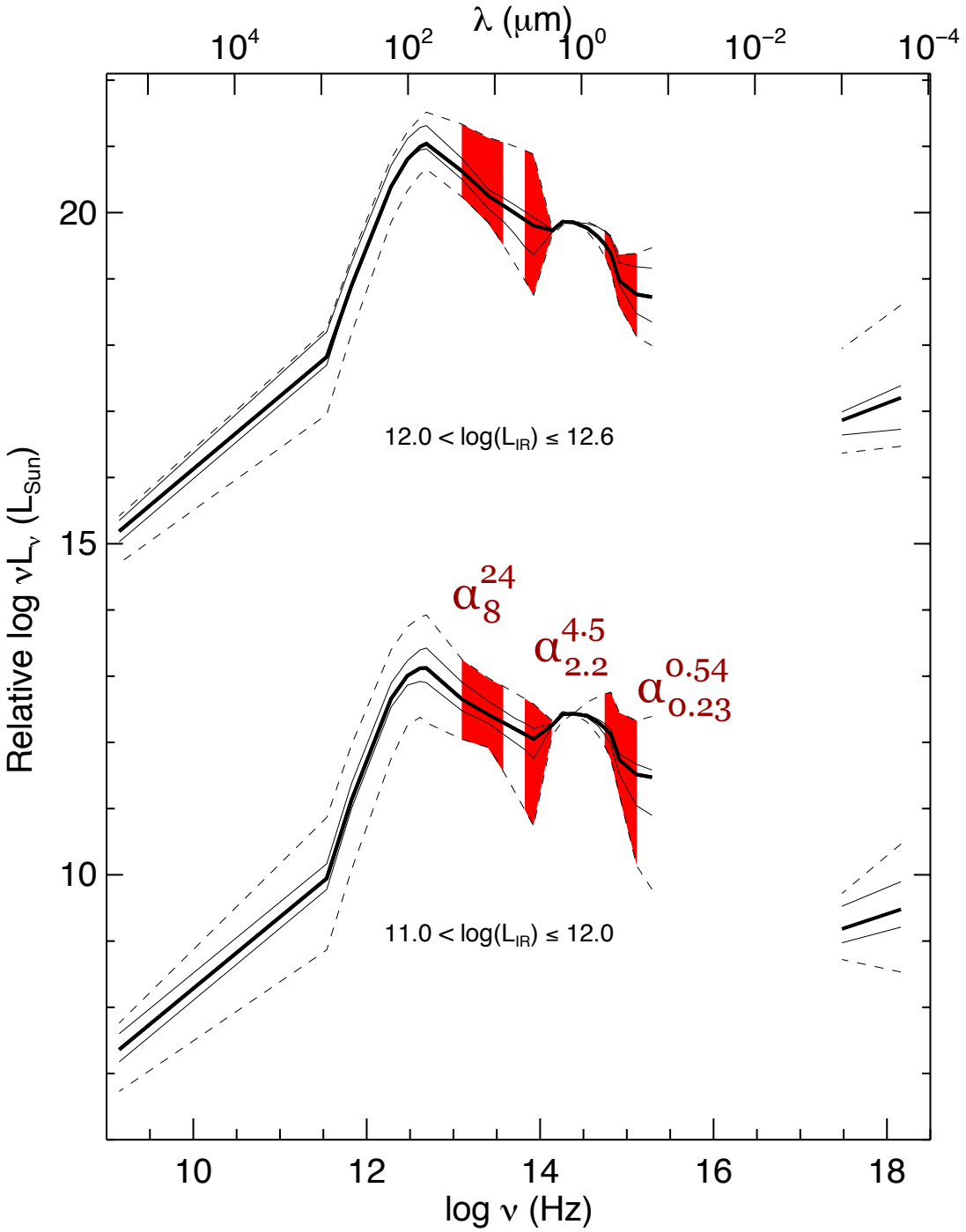
- 11 ULIRGs + 56 LIRGs
- e.g. Stellar-to-dust ratio: 1.2 dex for ULIRGs and 0.7 dex for LIRGs
- (Vivian U+12)



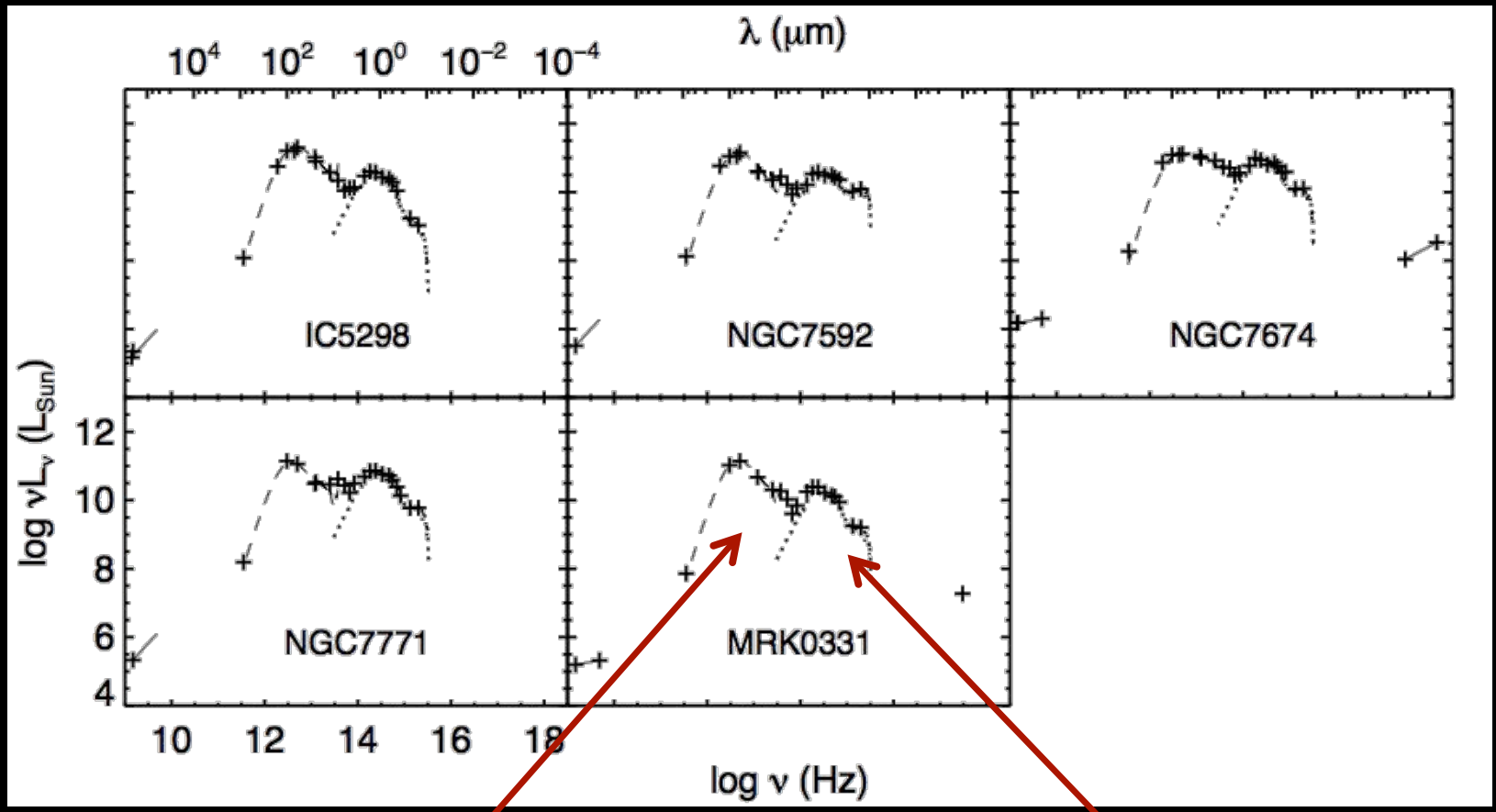
Spectral Indices



- ULIRGs: deeper trough at λ ~ 4-8μm, due to greater silicate dust absorption (U+12)



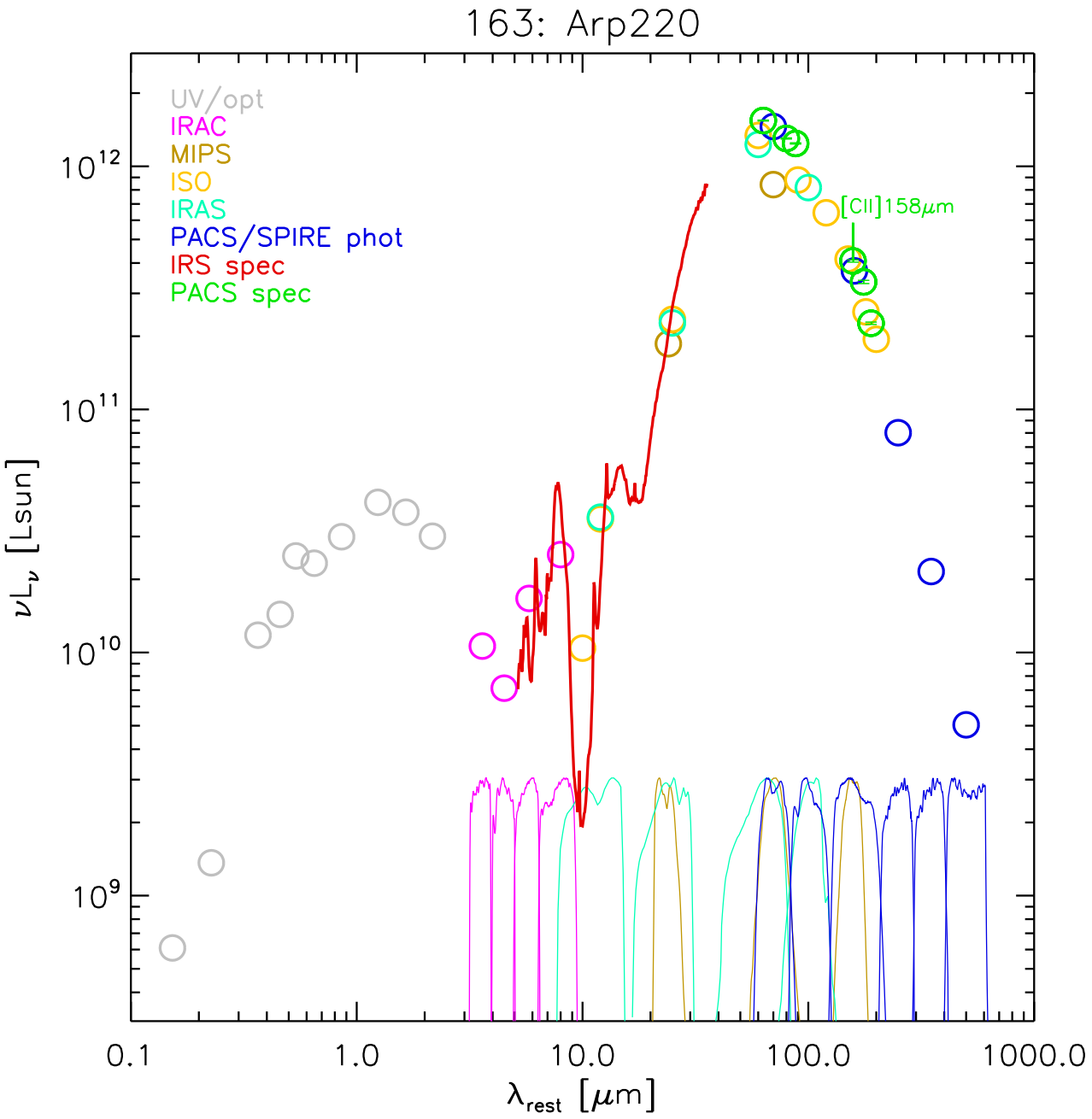
Fitting SEDs

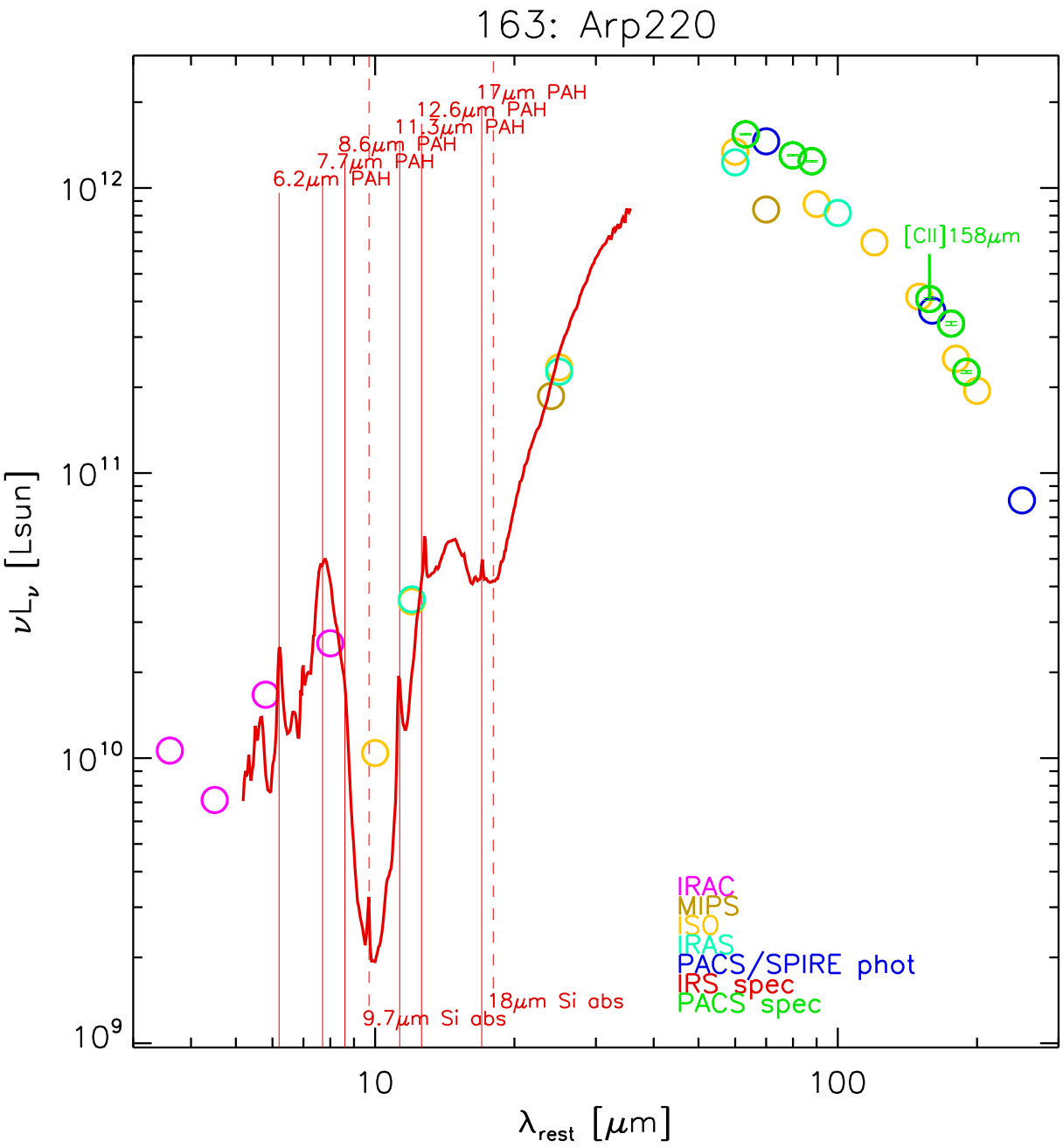


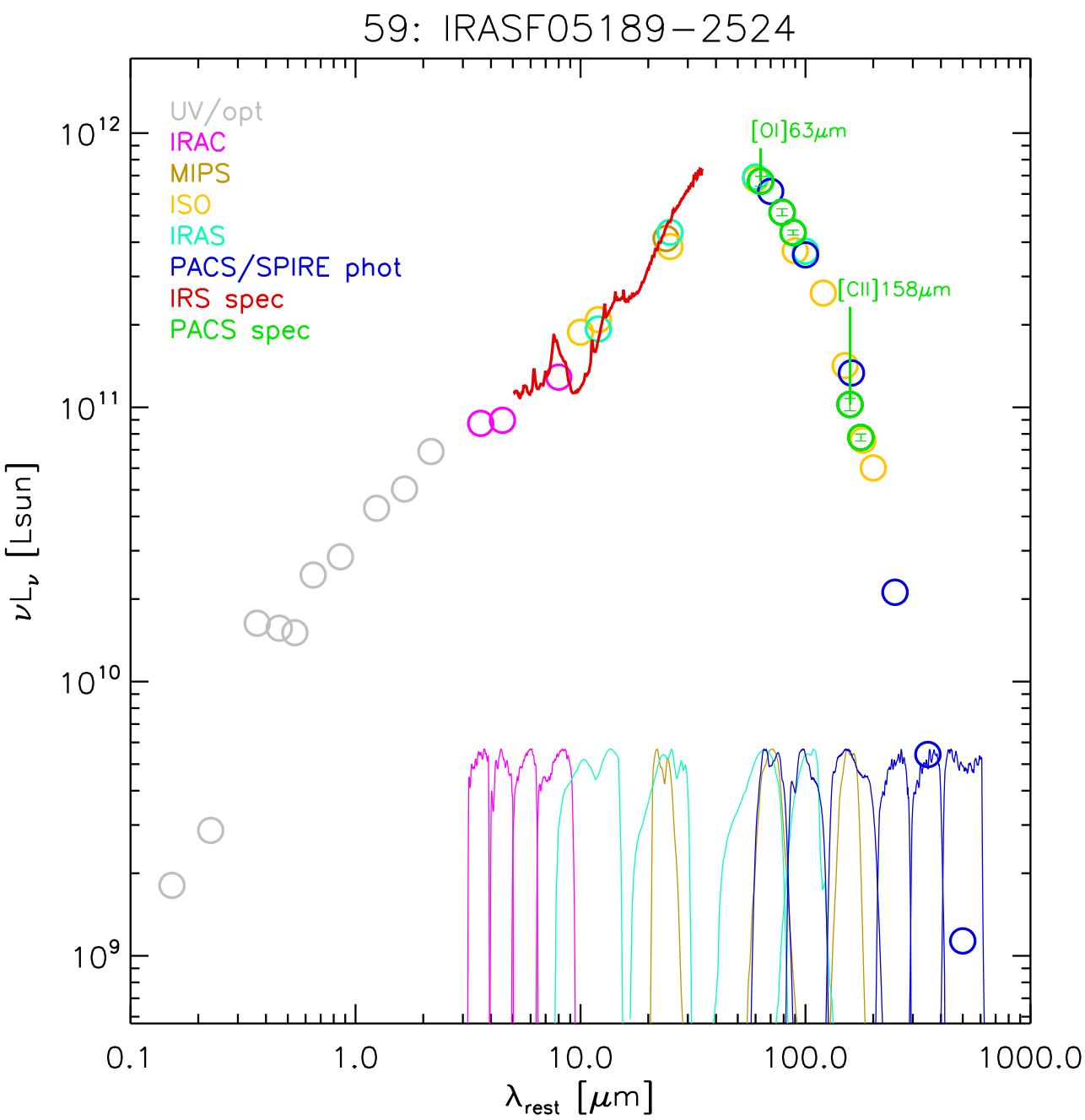
Modified blackbody
(L_{IR}, T_{dust}, M_{dust})

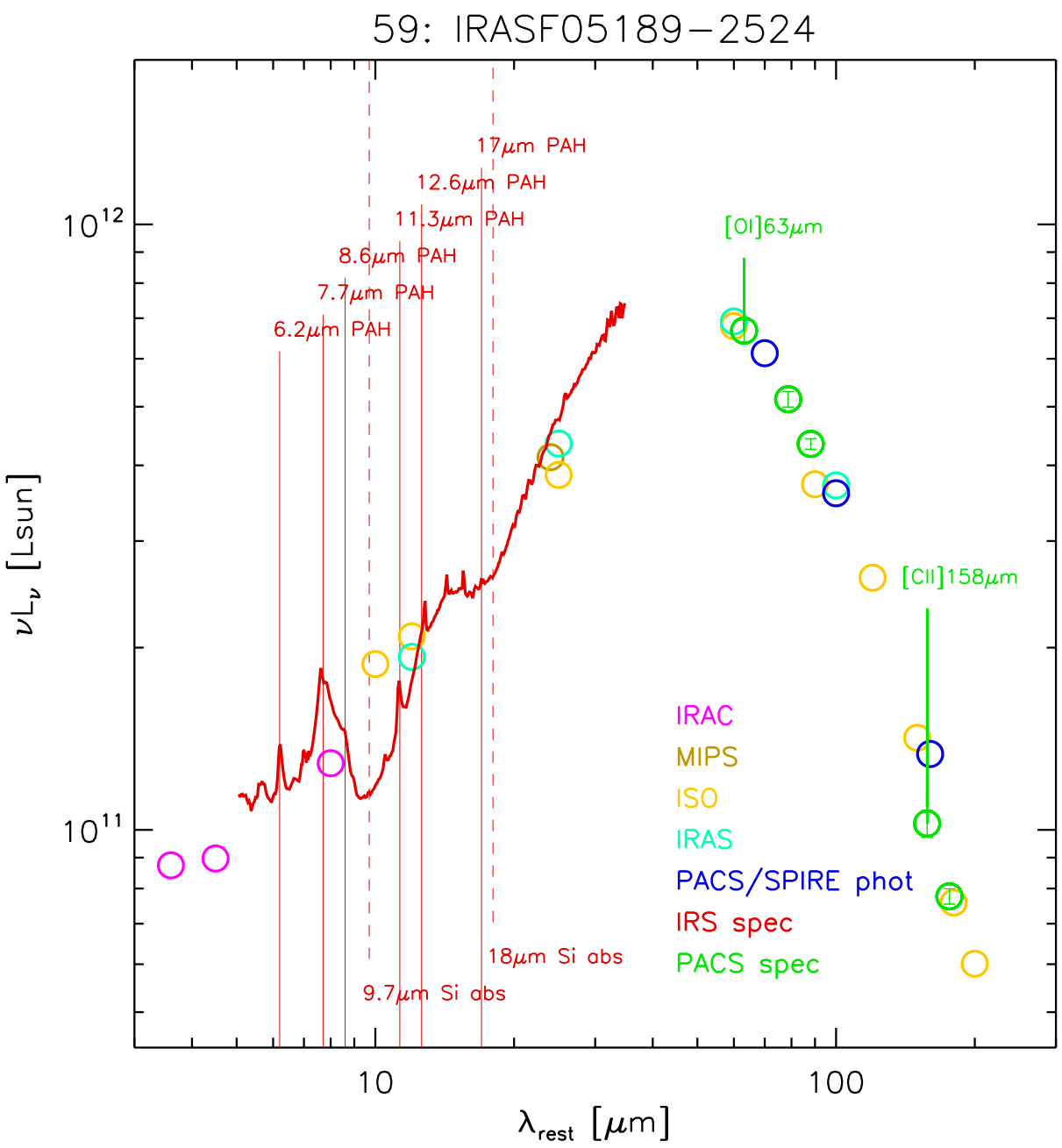
BC03 with Chabrier IMF
($M_{\star}$)

Herschel photometry




163: Arp220
17μm PAH
12.6μm PAH
11.3μm PAH
8.6μm PAH
7.7μm PAH
6.2μm PAH
[CII]158μm
9.7μm Si abs
18μm Si abs
IRAC
MIPS
ISO
IRAS
PACS/SPIRE phot
IRS spec
PACS spec
10^{12}
10^{11}
10^{10}
10^{9}
νL_ν [Lsun]
10
100
λ_{rest} [μm]


59: IRASF05189−2524
UV/opt
IRAC
MIPS
ISO
IRAS
PACS/SPIRE phot
IRS spec
PACS spec
[OI]63μm
[CII]158μm
10^{12}
10^{11}
10^{10}
10^{9}
νL_ν [Lsun]
0.1
1.0
10.0
100.0
1000.0
λ_{rest} [μm]


59: IRASF05189−2524
17μm PAH
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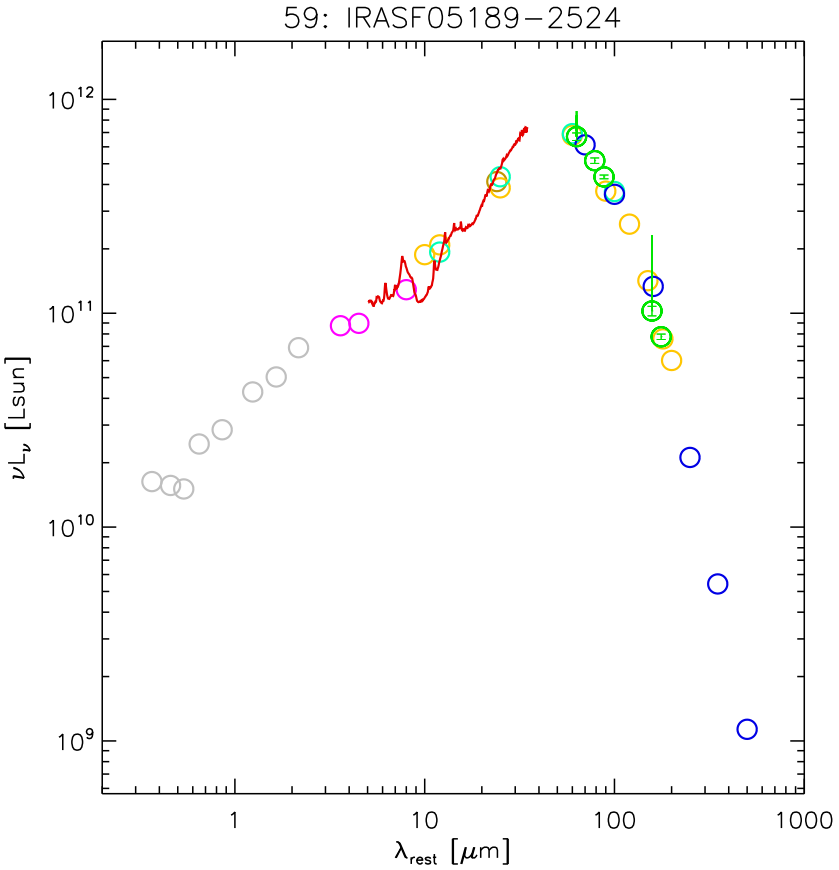
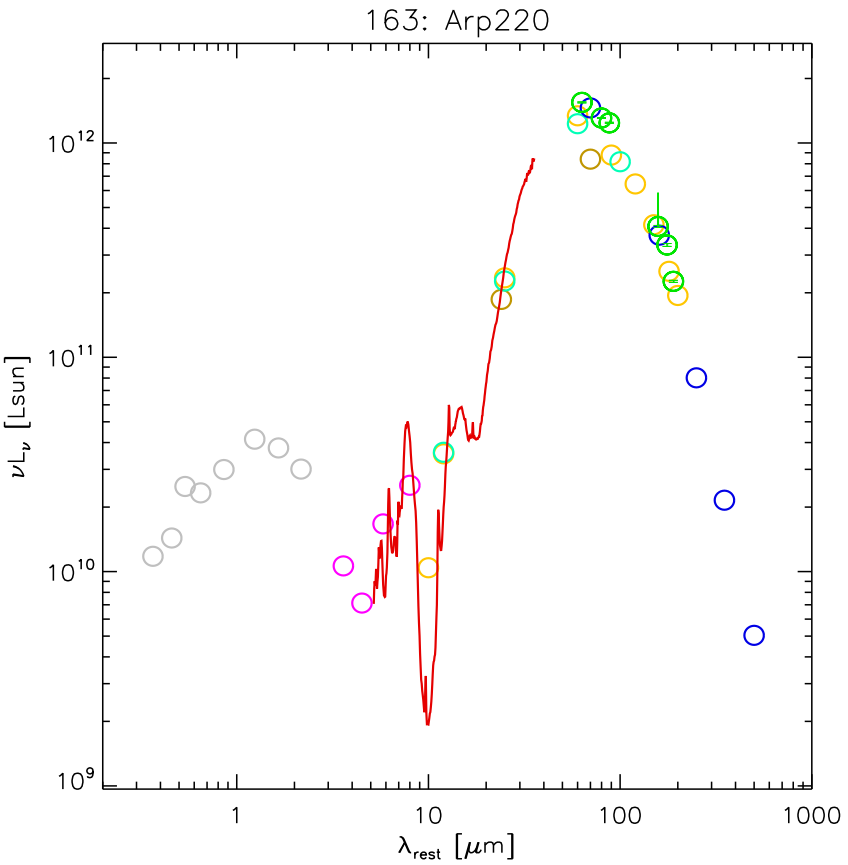
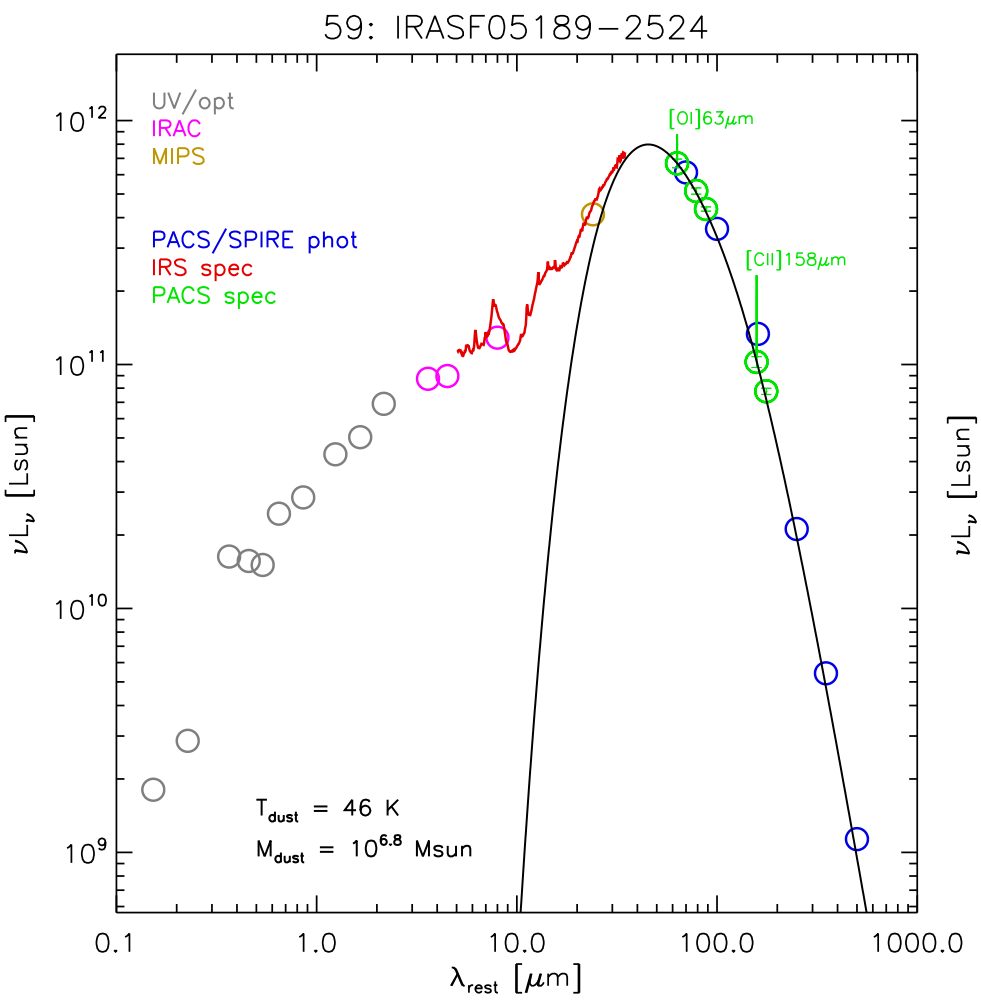
PACS/SPIRE phot
IRS spec
PACS spec
10^{12}
10^{11}
10
100
νL_ν [Lsun]
λ_{rest} [μm]

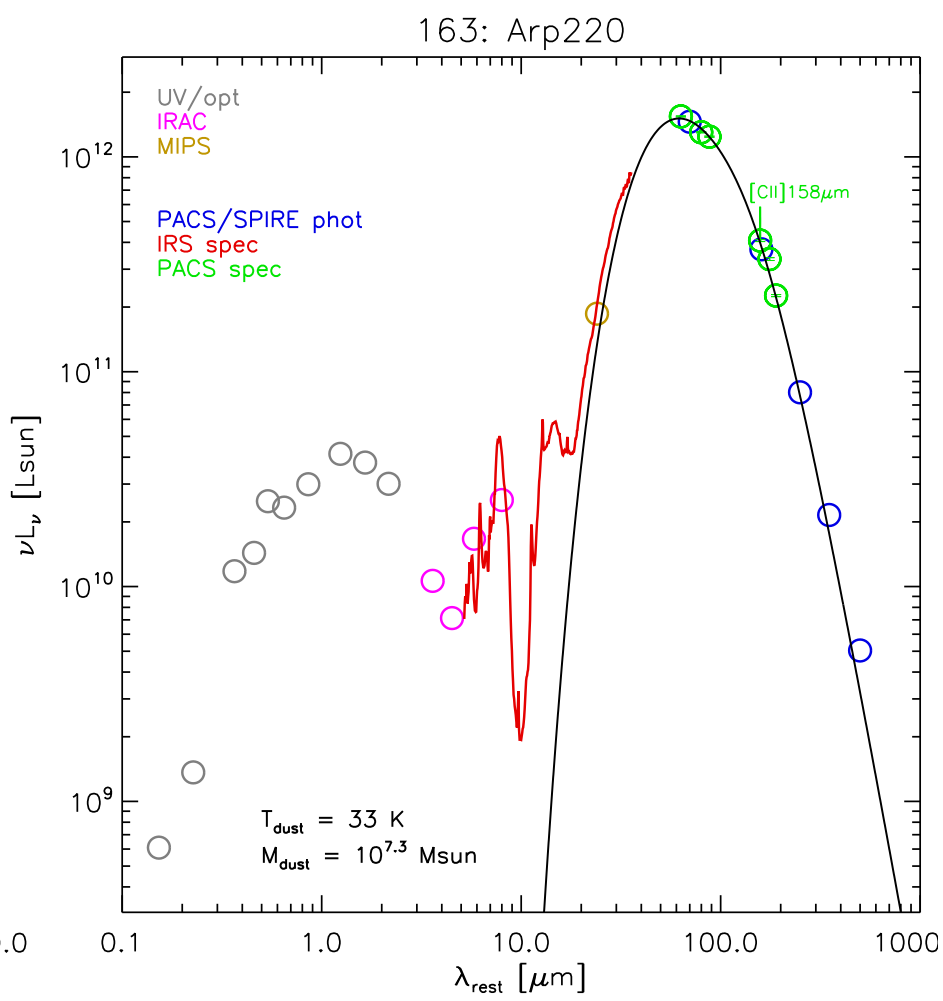


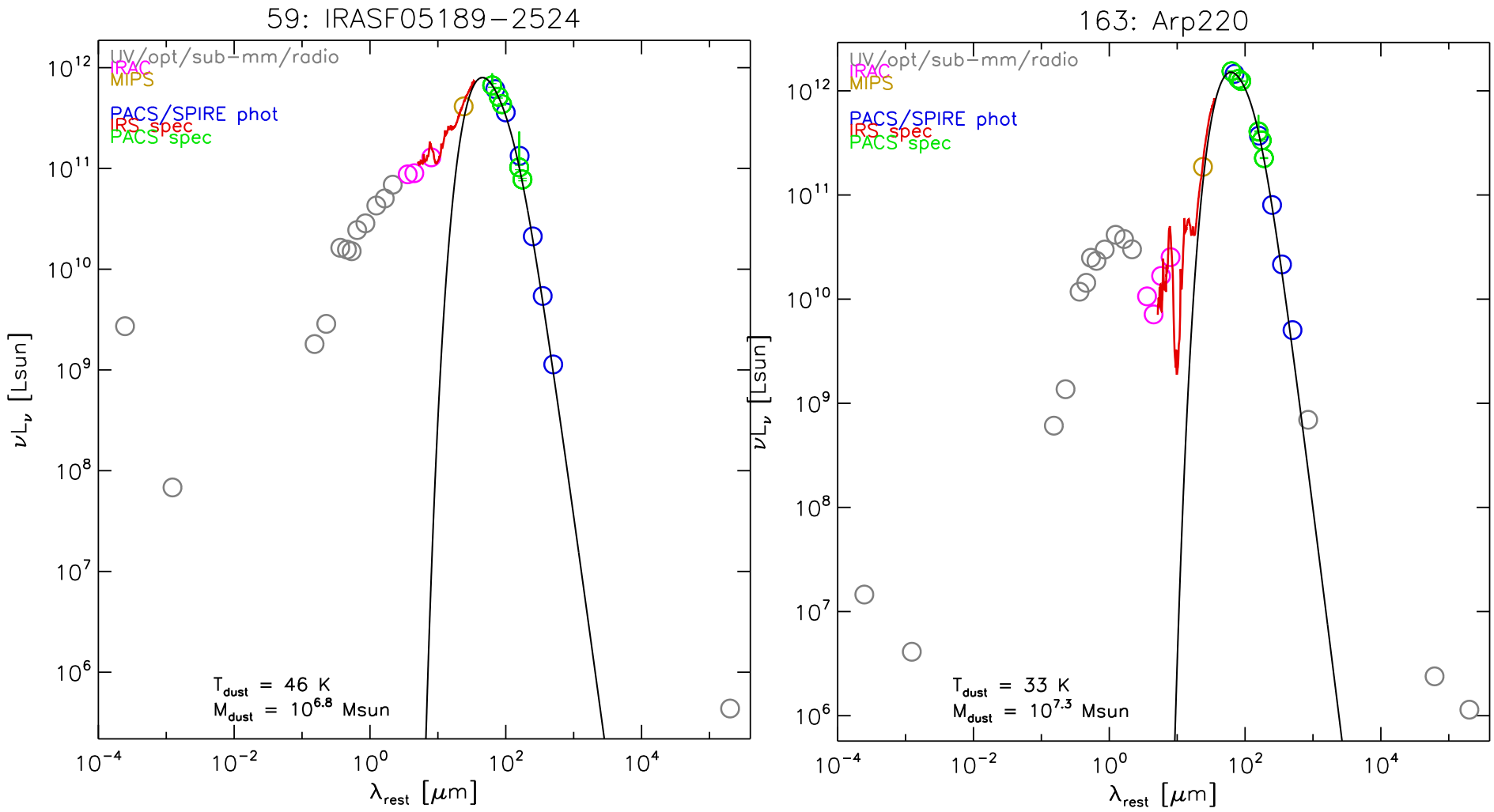


"warm" ULIRG $L_{IR} = 10^{12.18}\, L_{sun}$

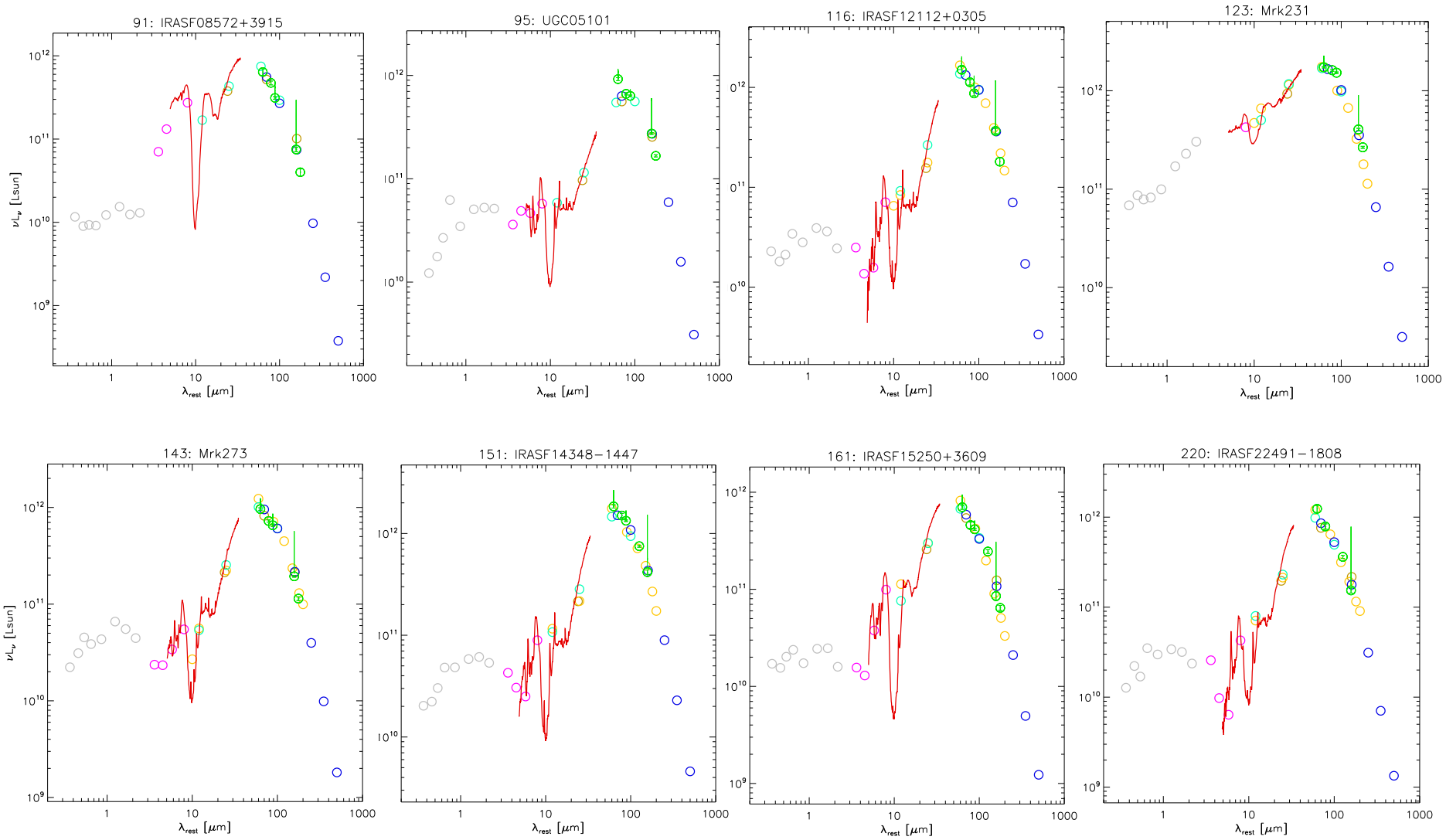
"cool" ULIRG $L_{IR} = 10^{12.21}\, L_{sun}$


59: IRASF05189−2524
UV/opt
IRAC
MIPS
PACS/SPIRE phot
IRS spec
PACS spec
[OI]63μm
[CII]158μm
T_dust = 46 K
M_dust = 10^6.8 Msun
νL_ν [Lsun]
λ_rest [μm]
10^12
10^11
10^10
10^9
0.1
1.0
10.0
100.0
1000.0


163: Arp220
UV/opt
IRAC
MIPS
PACS/SPIRE phot
IRS spec
PACS spec
[CII]158μm
T_dust = 33 K
M_dust = 10^7.3 Msun
νL_ν [Lsun]
λ_rest [μm]
10^12
10^11
10^10
10^9
0.1
1.0
10.0
100.0
1000


59: IRASF05189−2524
UV/opt/sub−mm/radio
IRAC
MIPS
PACS/SPIRE phot
IRS spec
PACS spec
T_{dust} = 46 K
M_{dust} = $10^{6.8}$ Msun
νL_ν [Lsun]
λ_{rest} [μm]
163: Arp220
UV/opt/sub−mm/radio
IRAC
MIPS
PACS/SPIRE phot
IRS spec
PACS spec
T_{dust} = 33 K
M_{dust} = $10^{7.3}$ Msun
νL_ν [Lsun]
λ_{rest} [μm]

SEDs for GOALS ULIRGs <– new Herschel data



Dust Properties

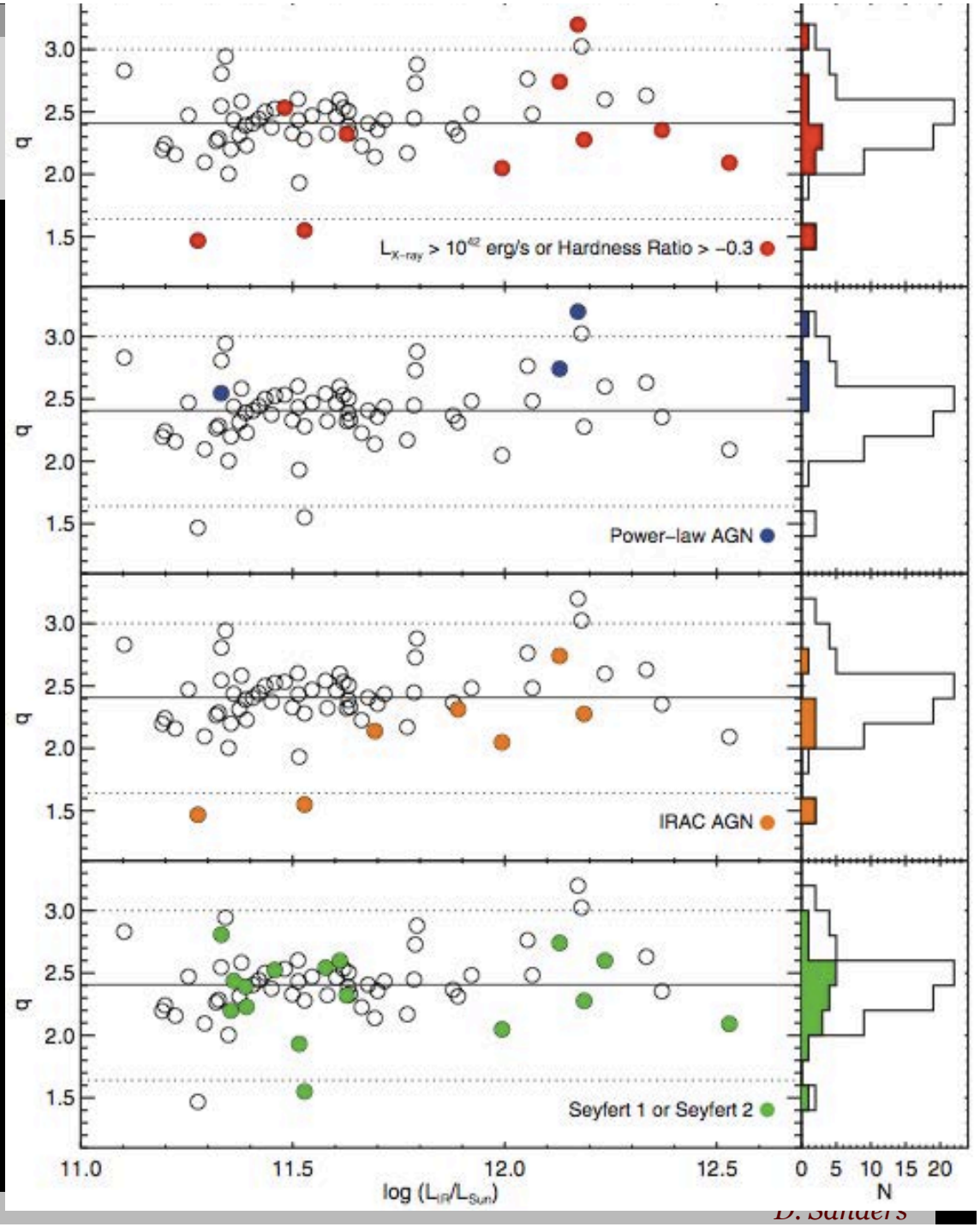
- Dust temperature: $\langle T_{dust} \rangle$ = 40.4 K (ULIRGs), 32.5 K (LIRGs)
  - ~3-8 K cooler than from Perault (1987), which often adopted a peak shortward of the true peak
  - Need Herschel PACS+SPIRE data points to constrain real peaks !
- Dust masses: $\langle M_{dust} \rangle = 10^{7.2}\ M_{\odot}$ (ULIRGs), $10^{7.4}\ M_{\odot}$ *(LIRGs)*
  - Computed from dust fit to Herschel data using Casey+11)
  - Adopted dust absorption coefficient of $\kappa_{850} = 0.15\ m^2\ kg^{-1}$

AGN Indicators

- Radio-infrared flux ratio criteria - radio-excess: $q < 1.64$ (Yun+ 01, Condon+ 91)
- X-ray AGN – Hardness Ratio HR > -0.3, $L_{HX} > 10^{42}$ erg/s (Iwasawa+ 11b; Ptak+ 03)
- Power-law AGN – $\log(\nu L_{4.5})$-$\log(\nu L_{2.2}) > 0$ (Alonso-Herrero+ 06, Donley+ 07)
- IRAC-color cuts (e.g. Donley+ 12)
- Optical emission line diagnostics (Veilleux+ 99)

AGN Indicators

- 60% of the ULIRGs + 25% of the LIRGs show AGN signatures
- Fraction of AGN hosts increases with L_{IR} (e.g. MIR slope, L_{HX})



Summary of Local (U)LIRGs

- Compilation of a complete, consistent photometry atlas
- Determine global physical properties
  - e.g. $\langle M_{\star} \rangle = 10^{10.79}\, M_{\odot,}$ $\langle T_{\rm dust} \rangle = 33$ K, $\langle M_{\rm dust} \rangle = 10^{7.3}\, M_{\odot}$
- Multiwavelength AGN indicators
  - AGN hosts: 60% of the ULIRGs, 25% of the LIRGs
- Create benchmark for local (U)LIRGs to compare to high-z studies

…what happens at high redshifts?

IR SEDs and Morphologies of Herschel Selected Galaxies at 0.3 < z < 3 in the COSMOS Field

P26.

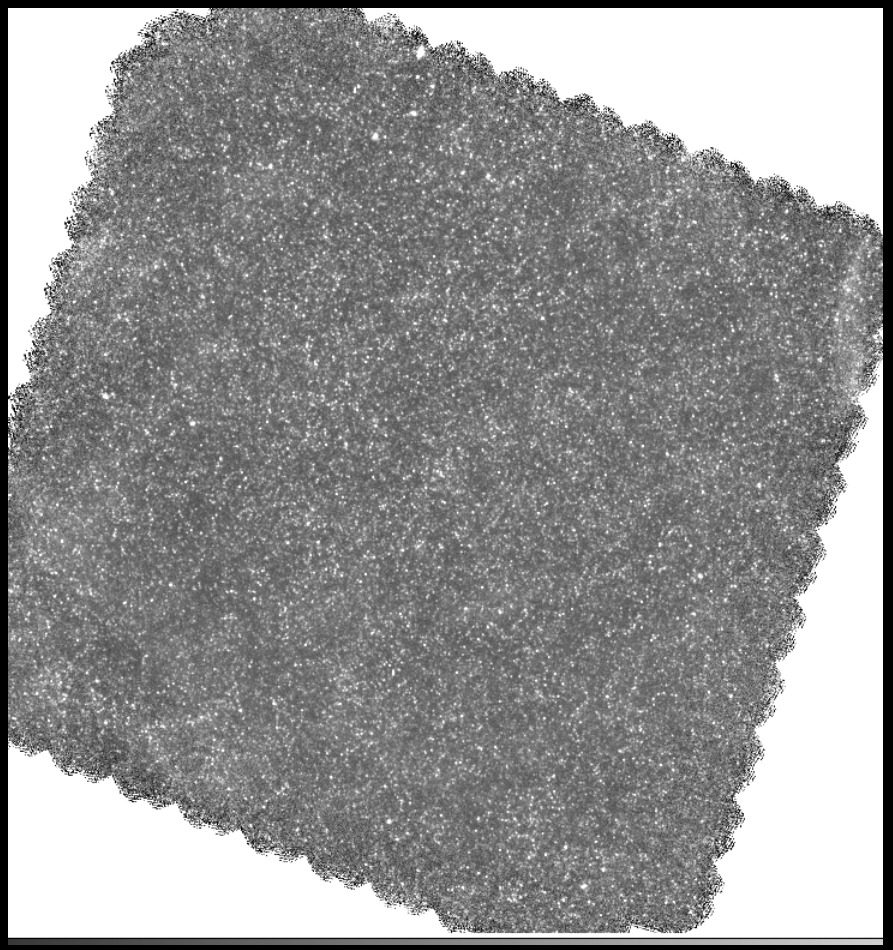
Nicholas Lee

Institute for Astronomy, Hawaii

With D. Sanders, C. Casey, C-L. Hung, Y. Li

COSMOS - A Wealth of Multi-Wavelength Data

- Using 24 um priors, extract Herschel sources with XID method (Roseboom+2010)
- Can match to the wealth of data available in COSMOS - optical & infrared photometry, stellar masses, photo-z's, etc.
- The Herschel PACS and SPIRE data allow us to directly measure the peak of infrared luminosity at restframe λ ~ 100 μm



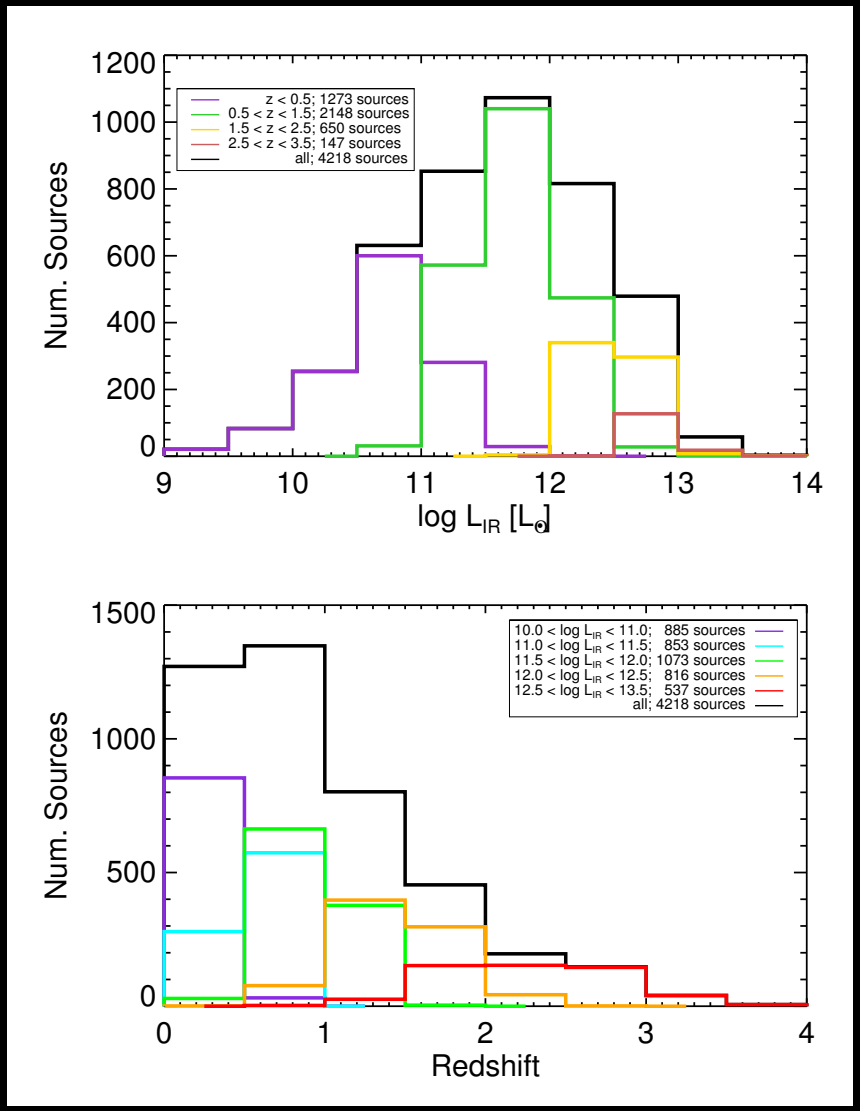
Infrared Luminosities

- Far-IR SEDs fit to a coupled greybody & powerlaw (see Casey, 2012)

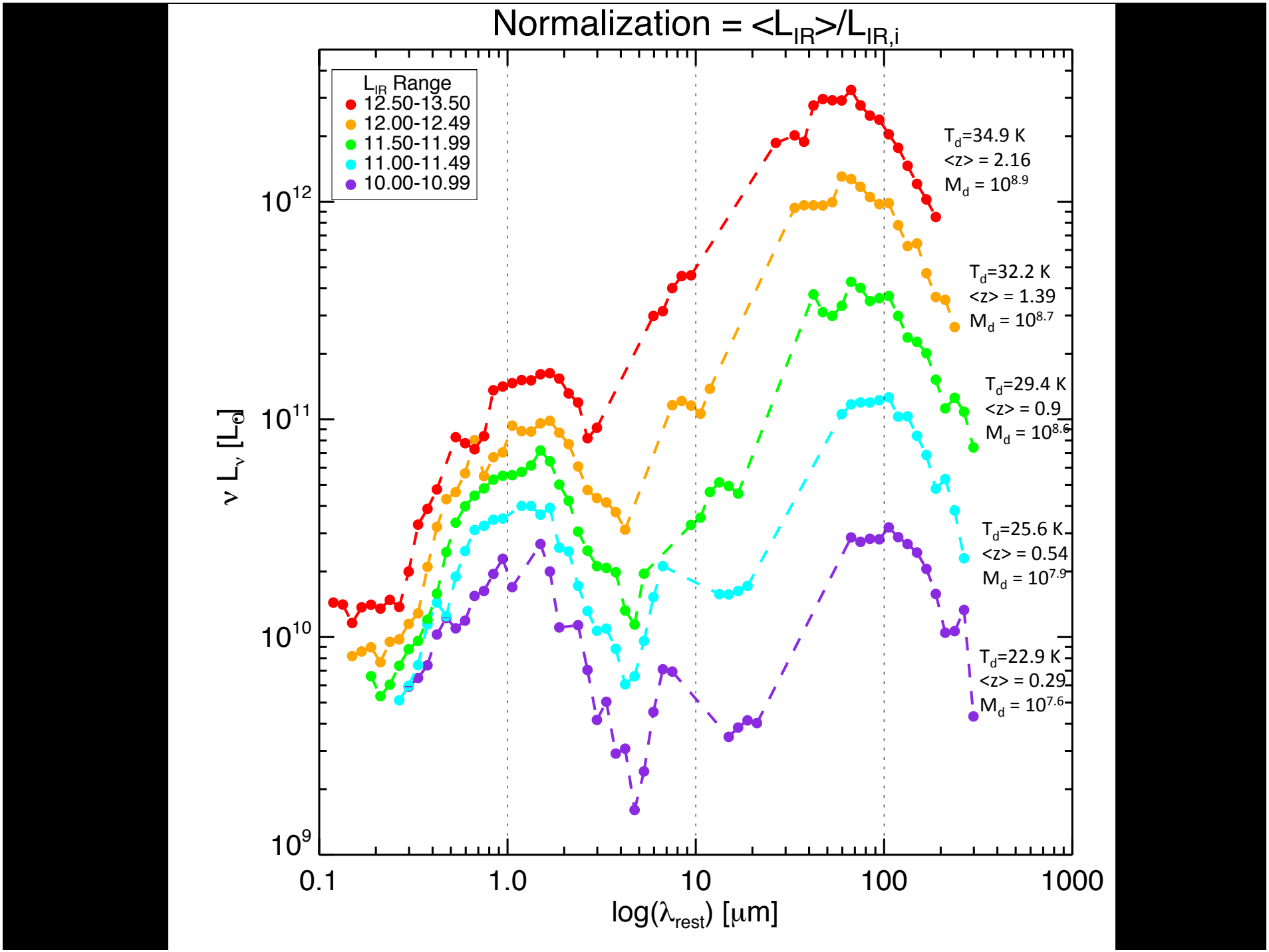
$$S(\lambda) = N_{\rm bb}\,\frac{(1-e^{-(\frac{\lambda_0}{\lambda})^{\beta}})(\frac{c}{\lambda})^3}{e^{hc/\lambda kT}-1} + N_{\rm pl}\,\lambda^{\alpha}\,e^{-(\frac{\lambda}{\lambda_c})^2}$$

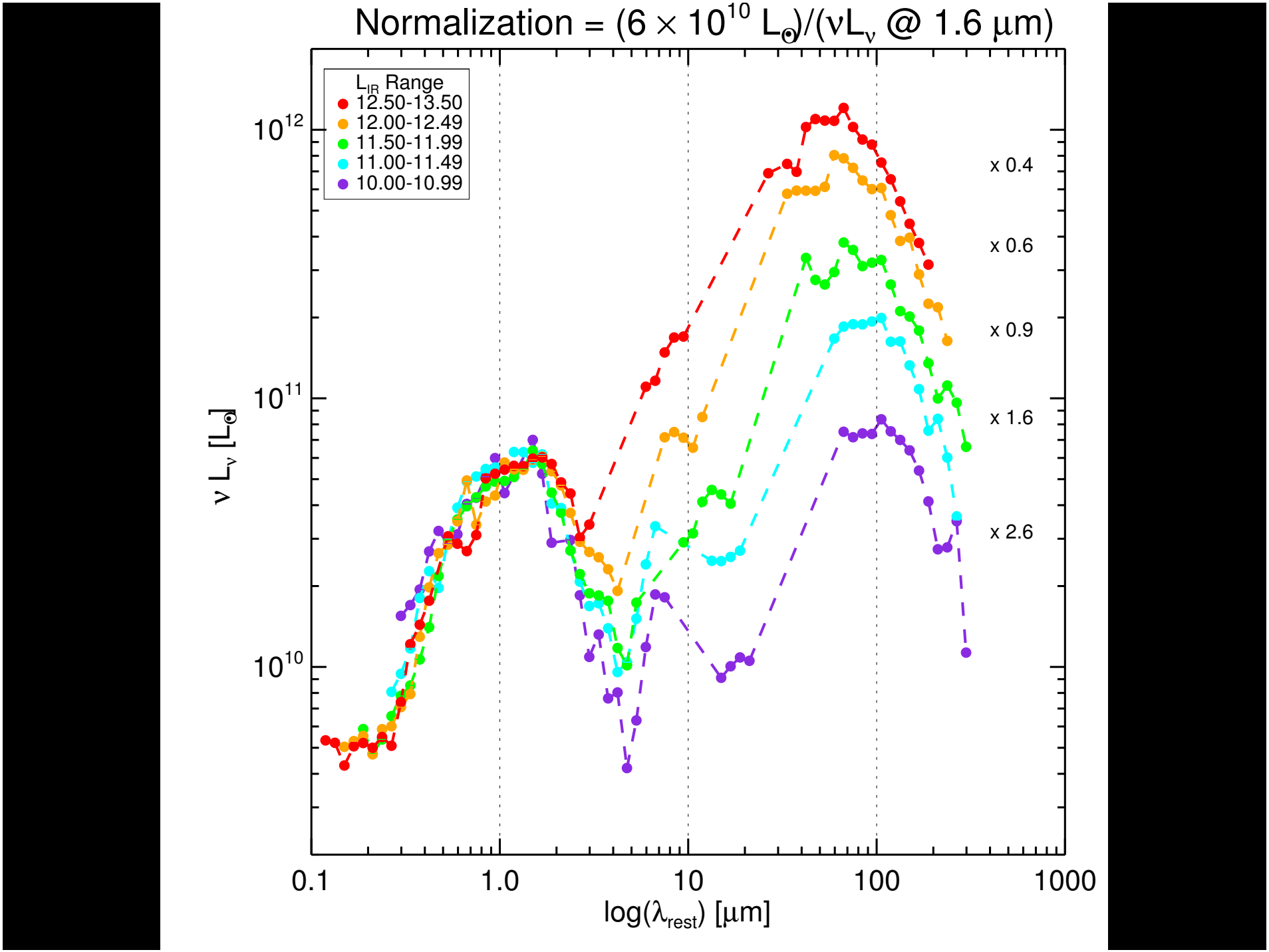
- Determine dust temperature ($T_{\rm d}$), IR luminosity ($L_{\rm IR}$ = L(8-1000 μm)), and dust mass ($M_{\rm dust}$)
- Free parameters: β, α, $N_{\rm bb}$, $T_{\rm dust}$
- Does not fit PAH features, but PAH contribution to $L_{\rm IR}$ is only ~5%

COSMOS Herschel sources



- Galaxies with at least 2 Herschel detections at >5σ
- Matched all sources to optical catalog via 24 μm and k-band counterparts.
- Total: 4218 sources


Normalization = <L_IR>/L_IR,i
L_IR Range
12.50-13.50
12.00-12.49
11.50-11.99
11.00-11.49
10.00-10.99
T_d=34.9 K
<z> = 2.16
M_d = 10^8.9
T_d=32.2 K
<z> = 1.39
M_d = 10^8.7
T_d=29.4 K
<z> = 0.9
M_d = 10^8.6
T_d=25.6 K
<z> = 0.54
M_d = 10^7.9
T_d=22.9 K
<z> = 0.29
M_d = 10^7.6
10^12
10^11
10^10
10^9
ν L_ν [L_⊙]
0.1
1.0
10
100
1000
log(λ_rest) [μm]


Normalization = (6 × 10^10 L⊙)/(νL_ν @ 1.6 μm)
L_IR Range
12.50-13.50
12.00-12.49
11.50-11.99
11.00-11.49
10.00-10.99
x 0.4
x 0.6
x 0.9
x 1.6
x 2.6
10^12
10^11
10^10
ν L_ν [L⊙]
0.1
1.0
10
100
1000
log(λ_rest) [μm]

Summary

1. **Herschel PACS+SPIRE photometry has been obtained for the complete sample of 203 GOALS objects. Data will be published separately and as part of a multi-wavelength ATLAS.**

2. **PACS+SPIRE photometry is well fit by a single temperature "cool-dust" mBB.**

3. **Dust temperature: $\langle T_{dust} \rangle$ = 40.4 K (ULIRGs), 33.2K (LIRGs)**
   $\langle M_{dust} \rangle = 10^{7.2} M_{\odot}$ (ULIRGs), $10^{7.4} M_{\odot}$ (LIRGs)

4. **IR SEDs of high-z (U)LIRGs appear to be well described by the mean and range of SEDs observed in GOALS**