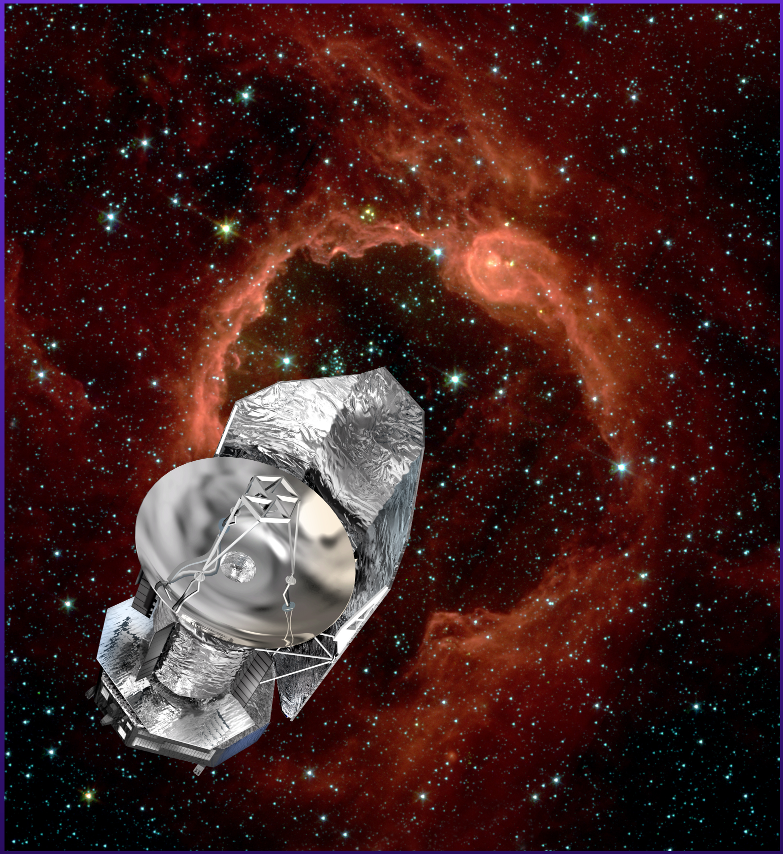
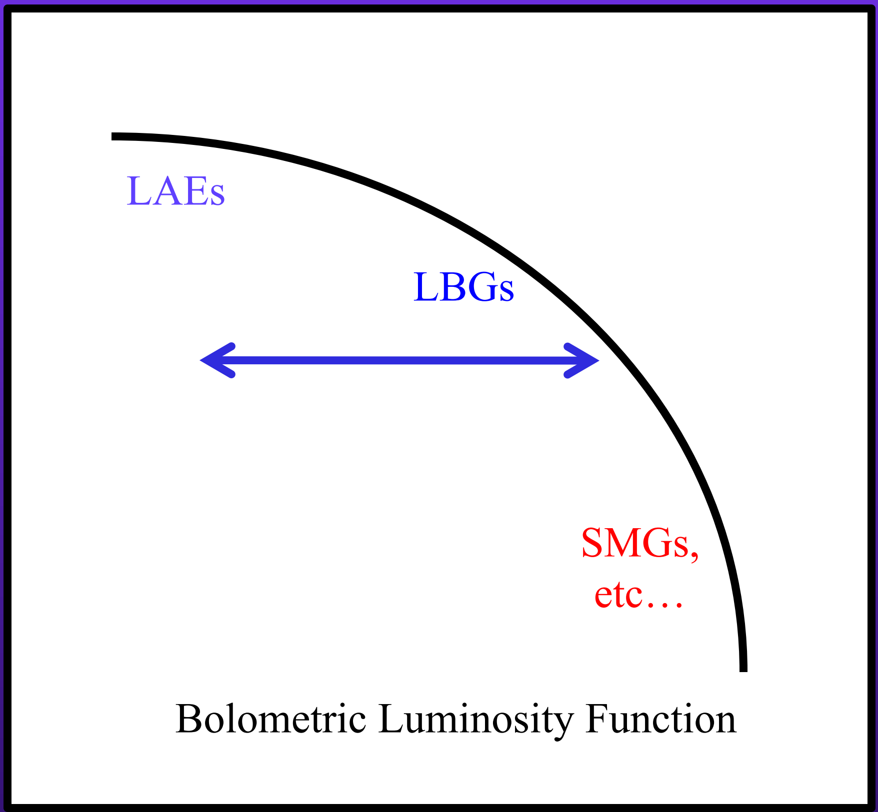
The Dust Properties of Typical Star-Forming Galaxies at High Redshift

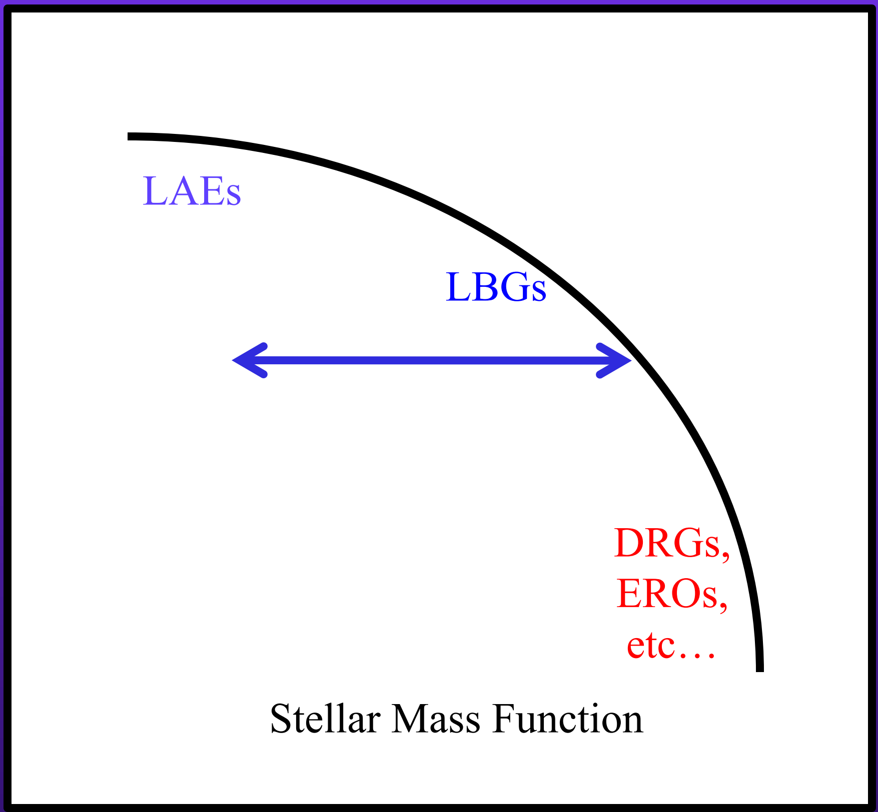
Naveen Reddy (UCR)



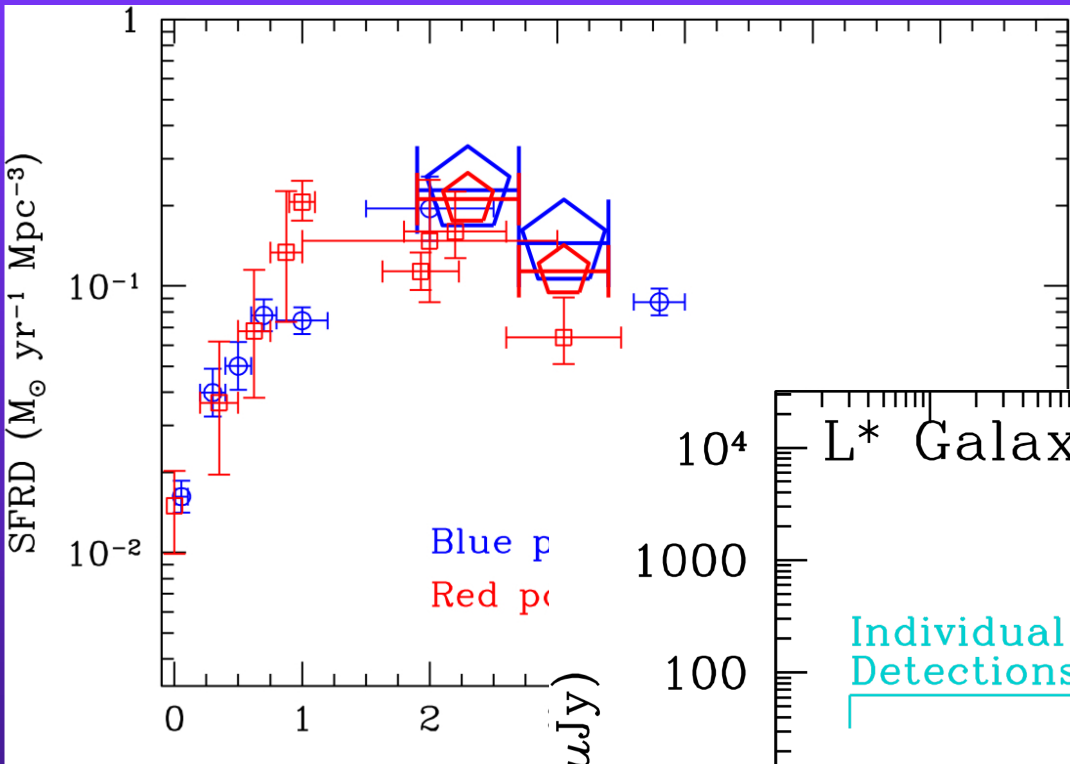
Through the Infrared Looking Glass, Pasadena, CA, 03 October 2011

Some Context: Demographics of z~2-3 Galaxies



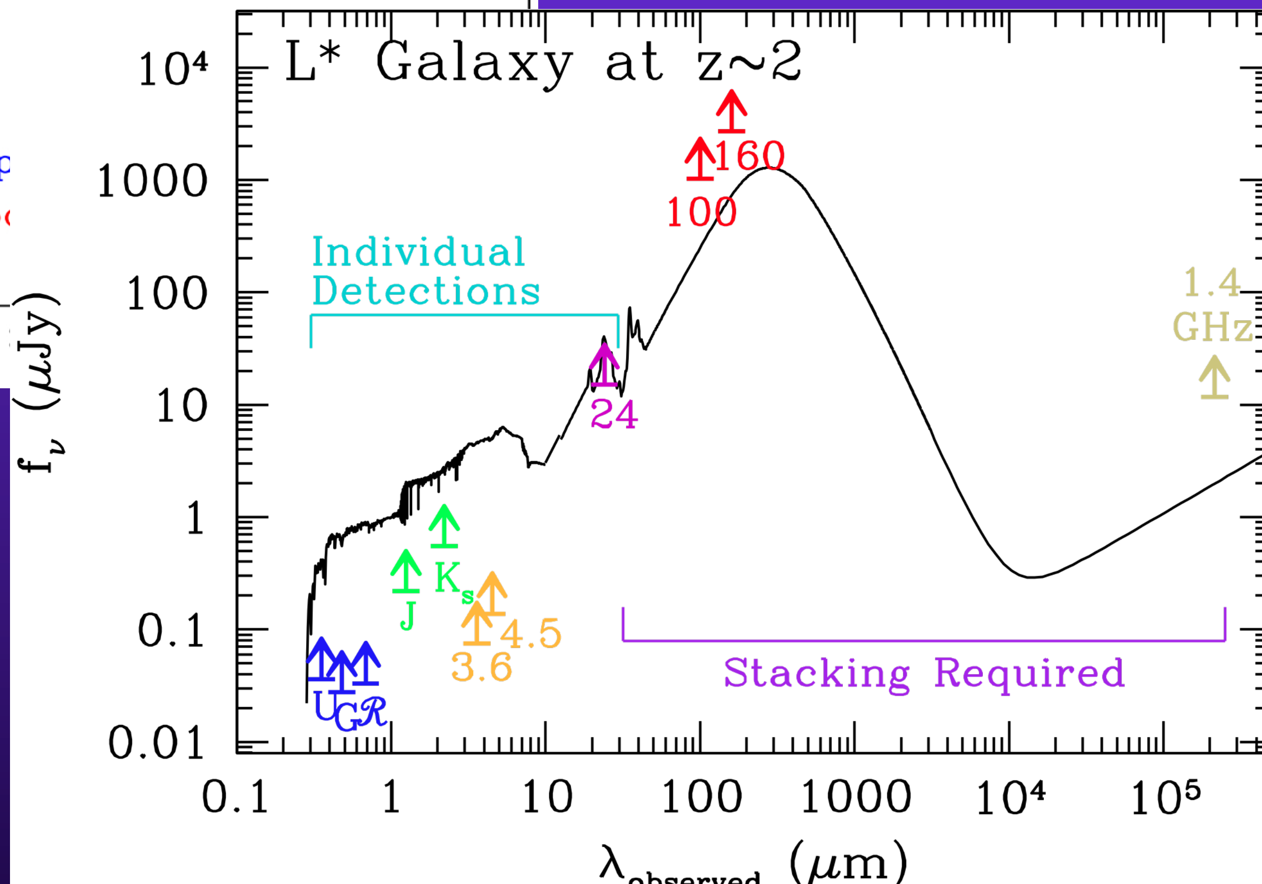


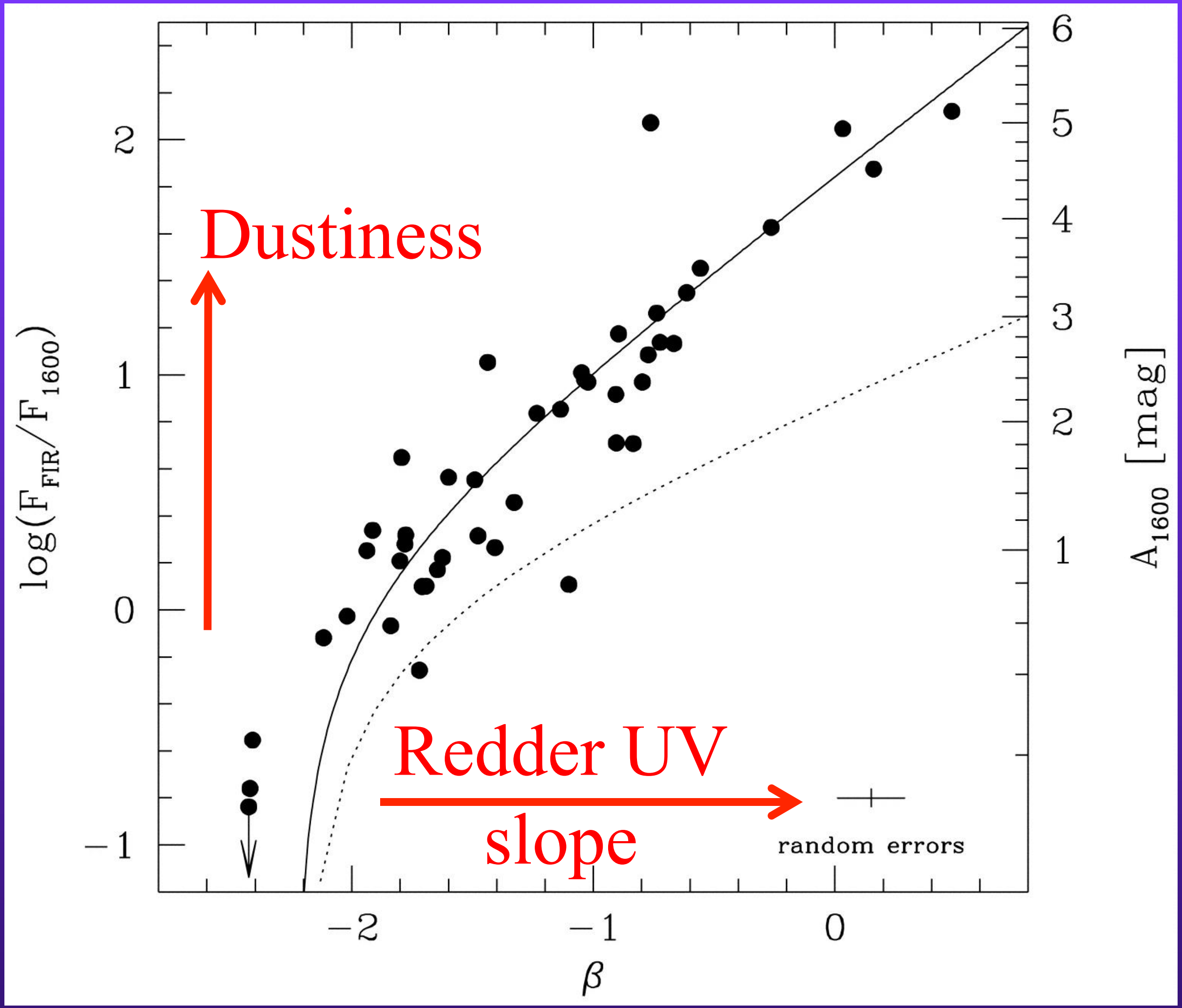
Motivations



Reddy et al 2008a

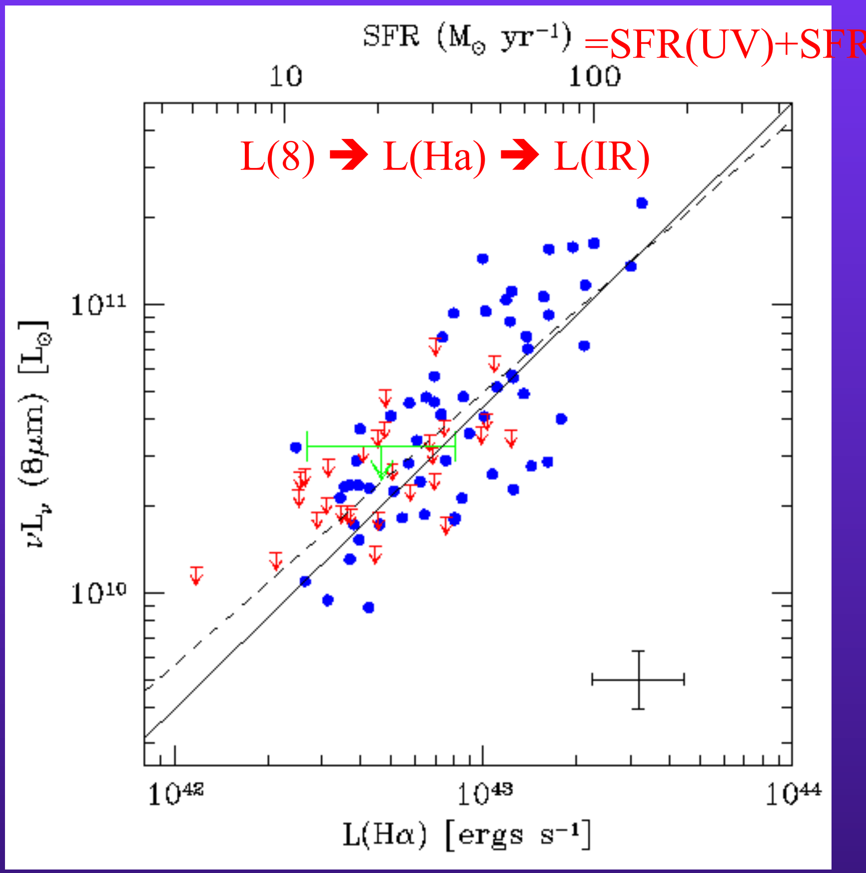
Inferring dust attenuation based on other indicators

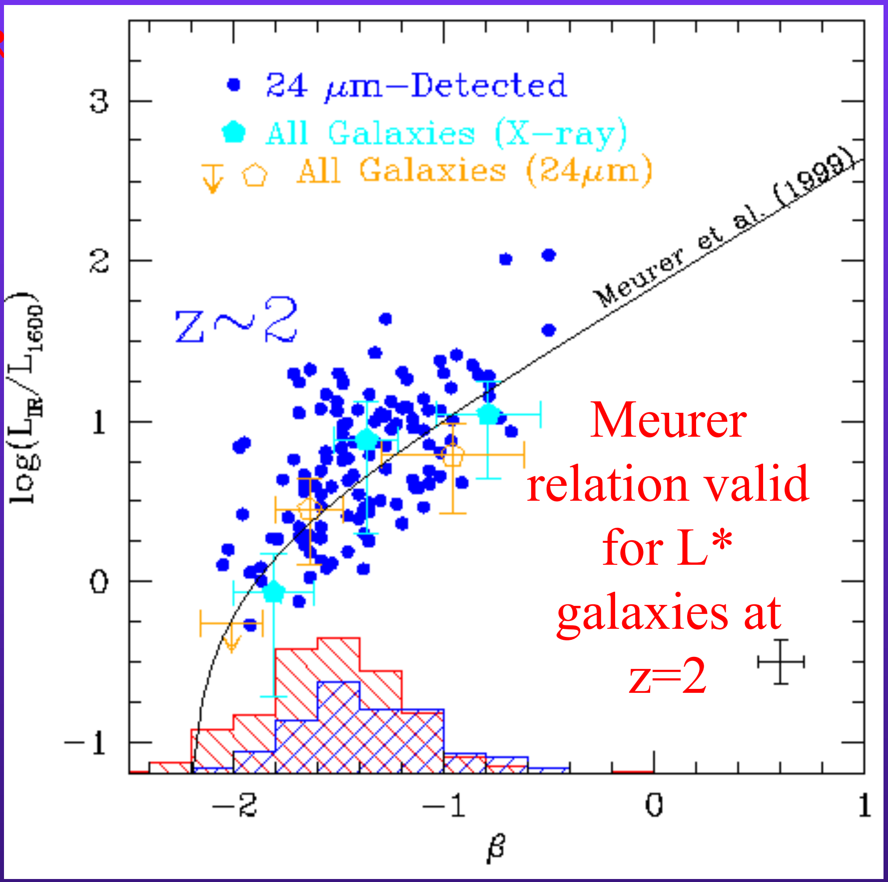




Meurer+99; Calzetti+00

Correlation between 8 micron and Hα

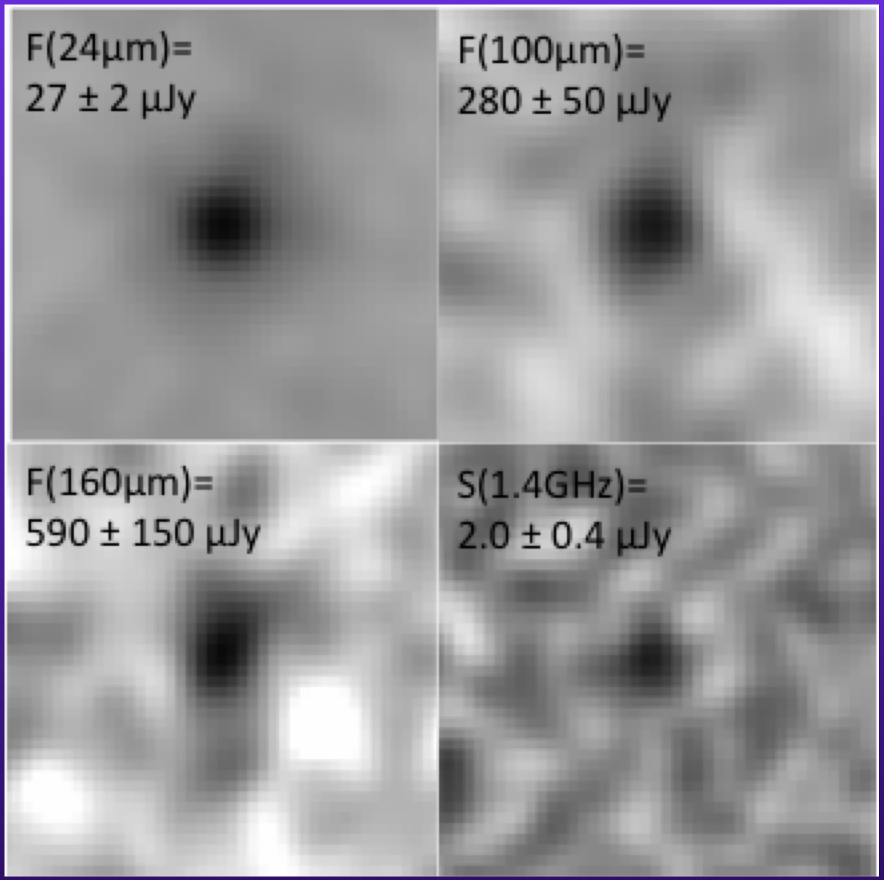




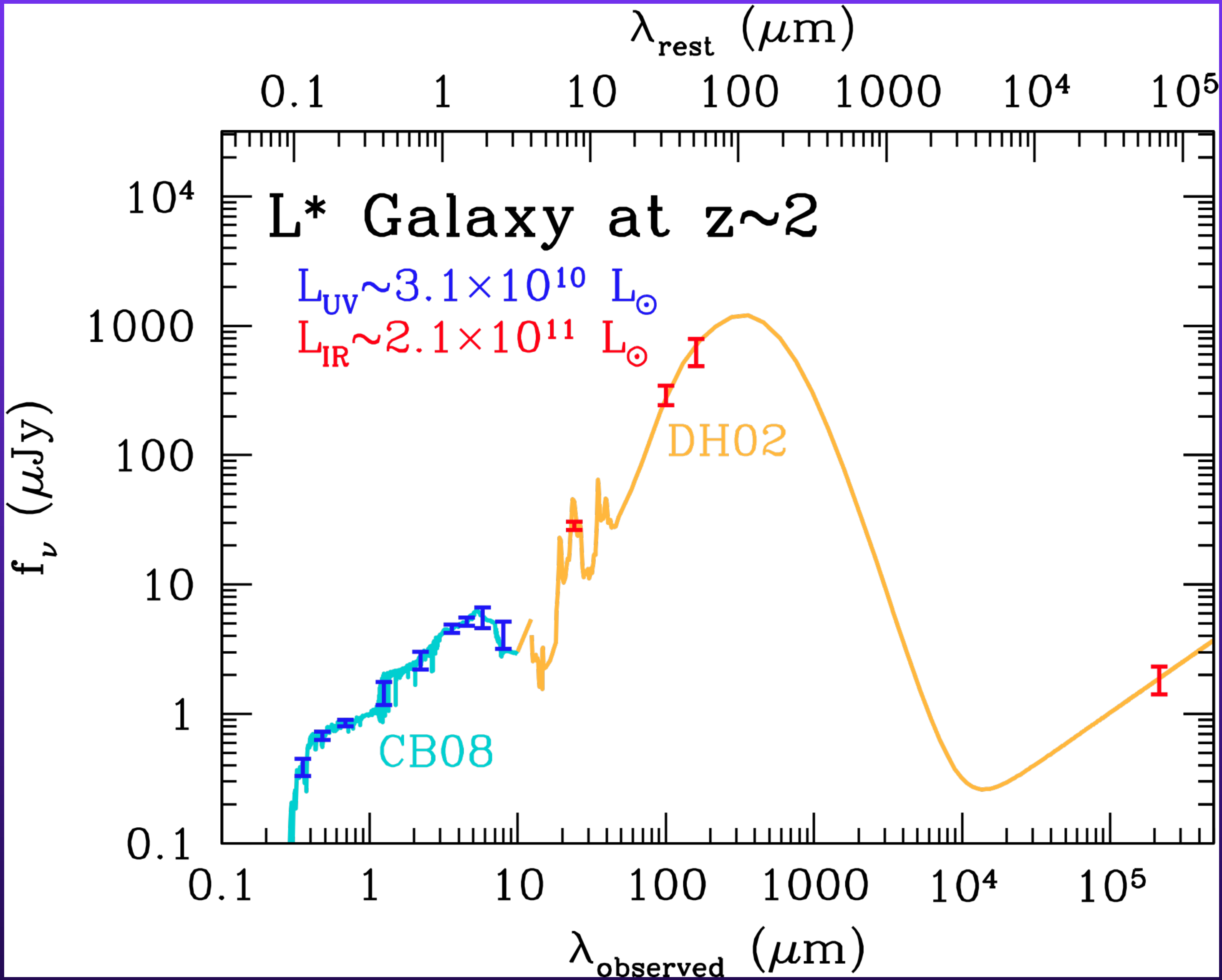
Remarkable similarity in ratio of small to large dust grain emission in galaxies over past 10 billion years

Herschel Stacking Method

- Stacked spectroscopically confirmed UV-selected galaxies at redshifts 1.5<z<2.6 in GOODS-North field
- Removed AGN based on presence of optical emission lines and/or power-law SED through the IRAC bands and very high 24 micron flux (>~100 μJy)



Median Dust SED of L*(UV) galaxy at z~2



Radio-IR correlation; Elbaz+11 templates, CE+01, DH+02, Rieke+09

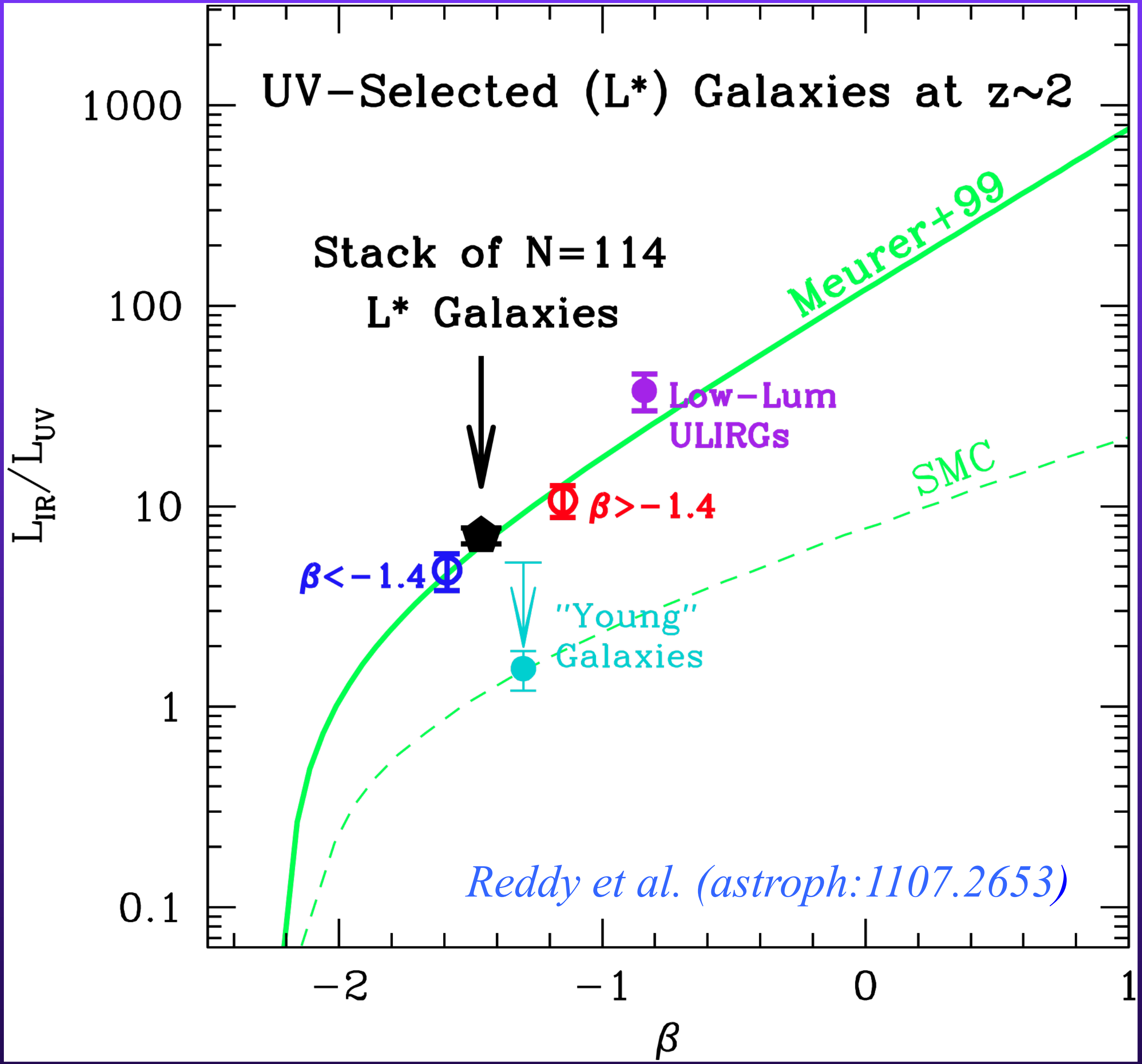
+

Different combinations of Spitzer / Herschel / VLA data

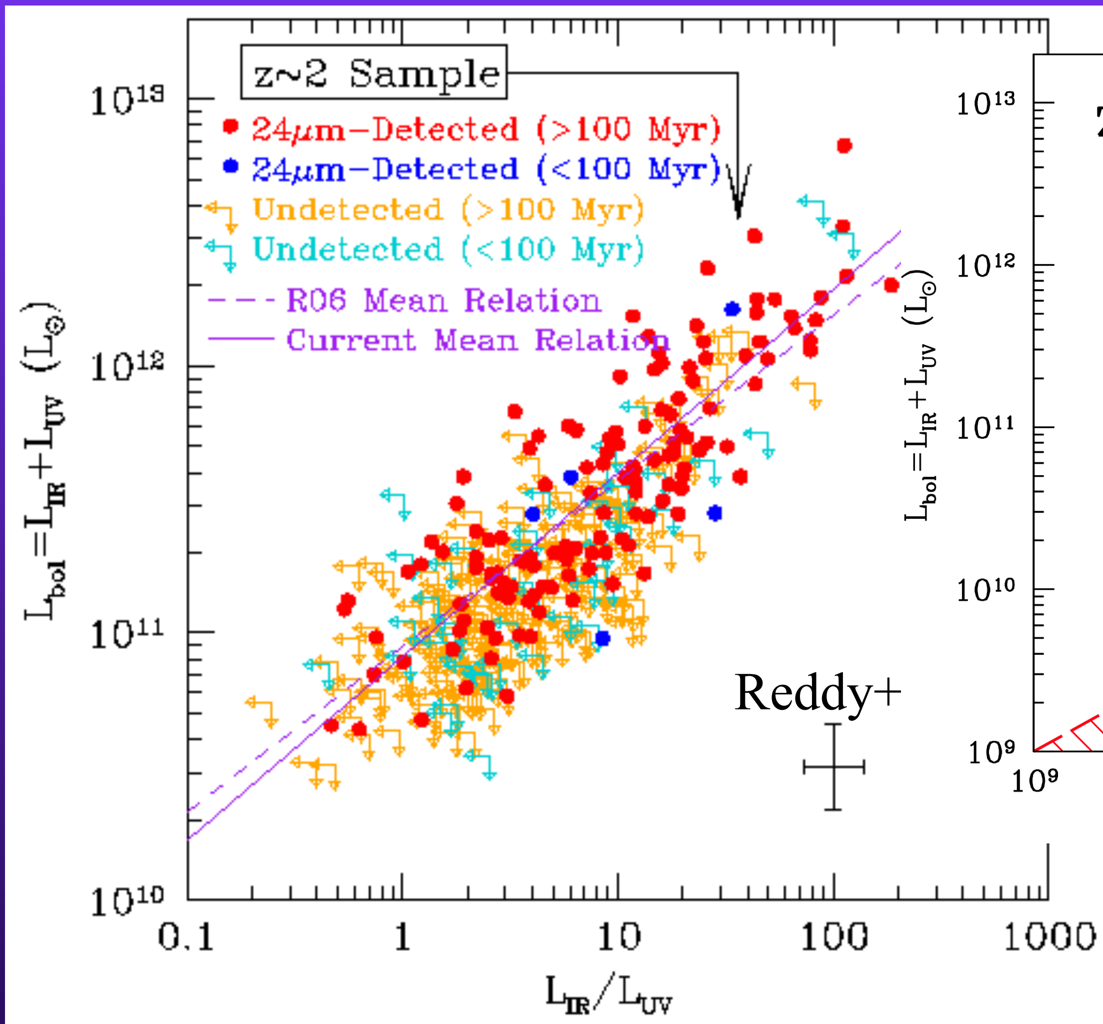
TABLE 1
Comparison of Infrared Luminosities (L_{IR}) [a]

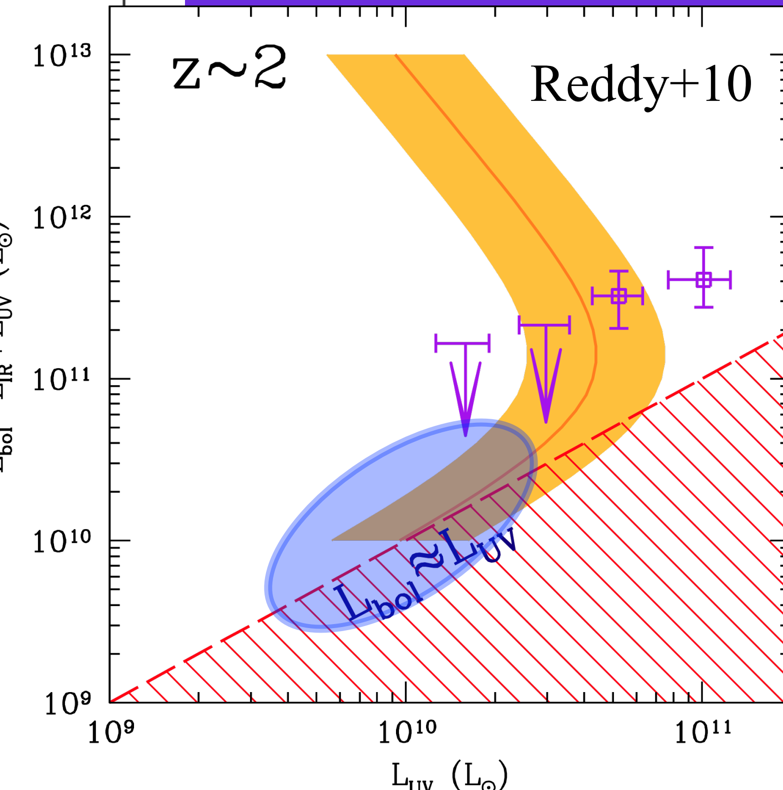
Template	λ, ν [b]	Sample A	Sample B	Sample C	Sample D	Sample E	Sample F
R10a [c]	24	2.0 ± 0.3	1.8 ± 0.1	1.2 ± 0.2	2.7 ± 0.2	15.7 ± 0.5	0.3 ± 0.1
Bell03 [d]	1.4	2.2 ± 0.5	2.2 ± 0.4	1.7 ± 0.6	2.9 ± 0.8	7.9 ± 1.7	$3\,\sigma$: < 3.0
Elbaz+11-MS Lum [e]	24	1.9 ± 0.2	1.6 ± 0.1	1.2 ± 0.1	2.2 ± 0.2	9.0 ± 0.3	0.5 ± 0.1
...	100	3.0 ± 0.4	2.9 ± 0.5	2.0 ± 0.6	3.8 ± 0.7	12.7 ± 1.4	$3\,\sigma$: < 2.8
...	160	3.0 ± 0.4	2.4 ± 0.6	2.1 ± 0.6	2.9 ± 0.9	11.1 ± 1.7	1.7 ± 1.1
...	100, 160	3.0 ± 0.3	2.7 ± 0.4	2.1 ± 0.4	3.5 ± 0.5	12.0 ± 1.0	$3\,\sigma$: < 2.8
...	24, 100, 160	2.3 ± 0.3	1.7 ± 0.2	1.3 ± 0.2	2.3 ± 0.3	9.2 ± 0.4	$3\,\sigma$: < 2.8
...	24, 100, 160, 1.4	2.3 ± 0.3	1.7 ± 0.2	1.3 ± 0.2	2.3 ± 0.3	9.2 ± 0.5	$3\,\sigma$: < 2.8
Elbaz+11-MS Lum-Eq Weight [f]	24, 100, 160, 1.4	3.0 ± 0.2	2.5 ± 0.2	2.1 ± 0.2	3.0 ± 0.2	11.3 ± 0.3	$3\,\sigma$: < 2.8
Elbaz+11-SB Lum [e]	24	3.7 ± 0.5	3.1 ± 0.2	2.3 ± 0.3	4.3 ± 0.4	17.7 ± 0.5	1.0 ± 0.2
...	100	2.4 ± 0.3	2.3 ± 0.4	1.6 ± 0.5	3.0 ± 0.5	10.0 ± 1.1	$3\,\sigma$: < 2.2
...	160	2.3 ± 0.3	1.9 ± 0.5	1.7 ± 0.5	2.3 ± 0.7	8.6 ± 1.3	1.3 ± 0.9
...	100, 160	2.4 ± 0.2	2.1 ± 0.3	1.6 ± 0.3	2.7 ± 0.4	9.4 ± 0.9	$3\,\sigma$: < 2.2
...	24, 100, 160	2.6 ± 0.3	2.7 ± 0.3	2.0 ± 0.3	3.6 ± 0.4	15.5 ± 0.7	$3\,\sigma$: < 2.2
...	24, 100, 160, 1.4	2.6 ± 0.4	2.6 ± 0.3	2.0 ± 0.4	3.5 ± 0.5	15.0 ± 0.8	$3\,\sigma$: < 2.2
Elbaz+11-SB Lum-Eq Weight [f]	24, 100, 160, 1.4	2.3 ± 0.2	2.0 ± 0.1	1.7 ± 0.2	2.4 ± 0.2	8.8 ± 0.2	$3\,\sigma$: < 2.2
CE01 Lum [e]	24	3.4 ± 0.4	2.6 ± 0.2	1.7 ± 0.2	4.1 ± 0.3	11.3 ± 1.2	0.4 ± 0.1
...	100	2.4 ± 0.3	2.3 ± 0.4	1.6 ± 0.5	3.1 ± 0.6	10.9 ± 1.2	$3\,\sigma$: < 2.3
...	160	2.2 ± 0.3	1.8 ± 0.4	1.5 ± 0.4	2.1 ± 0.6	7.9 ± 1.2	1.2 ± 0.8
...	100, 160	2.3 ± 0.3	2.0 ± 0.3	1.6 ± 0.3	2.7 ± 0.4	9.4 ± 0.9	$3\,\sigma$: < 2.3
...	24, 100, 160	2.4 ± 0.3	2.3 ± 0.3	1.6 ± 0.3	3.3 ± 0.4	12.3 ± 0.4	$3\,\sigma$: < 2.3
...	24, 100, 160, 1.4	2.4 ± 0.4	2.3 ± 0.3	1.6 ± 0.4	3.2 ± 0.4	12.1 ± 0.6	$3\,\sigma$: < 2.3
CE01 Lum-Eq Weight [f]	24, 100, 160, 1.4	2.2 ± 0.2	1.8 ± 0.1	1.5 ± 0.2	2.3 ± 0.2	8.2 ± 0.2	$3\,\sigma$: < 2.3
CE01 Col [g]	100, 160	2.1 ± 0.4	1.8 ± 0.6	2.1 ± 1.0	1.7 ± 0.6	7.9 ± 1.5	...
...	24, 100, 160	2.3 ± 0.6	2.2 ± 0.8	1.6 ± 0.9	3.0 ± 1.2	10.4 ± 2.3	...
CE01 Col-Eq Weight [h]	24, 100, 160, 1.4	2.4 ± 0.7	2.2 ± 0.8	1.6 ± 0.9	3.0 ± 1.2	12.1 ± 2.7	...
DH02 Lum [e]	24	3.0 ± 0.4	2.3 ± 0.2	1.7 ± 0.2	3.6 ± 0.3	21.5 ± 0.6	0.6 ± 0.1
...	100	2.1 ± 0.3	2.0 ± 0.4	1.5 ± 0.5	2.7 ± 0.5	7.8 ± 0.9	$3\,\sigma$: < 2.0
...	160	2.2 ± 0.3	1.8 ± 0.4	1.6 ± 0.4	2.1 ± 0.6	7.4 ± 1.2	1.3 ± 0.9
...	100, 160	2.1 ± 0.2	1.9 ± 0.2	1.5 ± 0.3	2.5 ± 0.4	7.7 ± 0.6	$3\,\sigma$: < 2.0
...	24, 100, 160	2.3 ± 0.3	2.2 ± 0.2	1.6 ± 0.2	3.0 ± 0.4	13.6 ± 0.7	$3\,\sigma$: < 2.0
...	24, 100, 160, 1.4	2.3 ± 0.3	2.2 ± 0.3	1.6 ± 0.3	3.0 ± 0.5	13.2 ± 0.8	$3\,\sigma$: < 2.0
DH02 Lum-Eq Weight [f]	24, 100, 160, 1.4	2.2 ± 0.2	1.8 ± 0.1	1.6 ± 0.2	2.2 ± 0.2	7.4 ± 0.2	$3\,\sigma$: < 2.0
DH02 Col [g]	100, 160	2.2 ± 0.4	1.5 ± 0.5	1.7 ± 0.7	1.7 ± 0.6	6.9 ± 1.3	...
...	24, 100, 160	2.4 ± 0.7	2.1 ± 0.7	1.5 ± 0.8	2.8 ± 1.1	10.5 ± 2.4	...
DH02 Col-Eq Weight [h]	24, 100, 160, 1.4	2.3 ± 0.6	2.2 ± 0.8	1.6 ± 0.9	3.6 ± 1.5	9.5 ± 2.2	...
Rieke+09 Lum [e]	24	5.0 ± 0.6	3.6 ± 0.3	2.0 ± 0.2	6.1 ± 0.5	46.1 ± 1.3	0.5 ± 0.1
...	100	2.5 ± 0.3	2.3 ± 0.4	1.8 ± 0.6	3.0 ± 0.5	8.2 ± 0.9	$3\,\sigma$: < 2.3
...	160	2.2 ± 0.3	1.9 ± 0.4	1.7 ± 0.5	2.1 ± 0.6	6.1 ± 0.9	1.4 ± 1.0
...	100, 160	2.3 ± 0.2	2.1 ± 0.2	1.7 ± 0.2	2.5 ± 0.3	7.1 ± 0.6	$3\,\sigma$: < 2.3
...	24, 100, 160	2.3 ± 0.2	2.3 ± 0.3	1.8 ± 0.3	3.1 ± 0.4	11.2 ± 0.7	$3\,\sigma$: < 2.3
...	24, 100, 160, 1.4	2.3 ± 0.3	2.3 ± 0.3	1.8 ± 0.4	3.0 ± 0.5	11.0 ± 0.9	$3\,\sigma$: < 2.3
Rieke+09 Lum-Eq Weight [f]	24, 100, 160, 1.4	2.2 ± 0.2	1.9 ± 0.1	1.7 ± 0.2	2.2 ± 0.2	6.3 ± 0.2	$3\,\sigma$: < 2.3
Rieke+09 Col [g]	100, 160	3.1 ± 0.6	2.8 ± 0.8	2.4 ± 1.3	3.6 ± 1.3	12.5 ± 2.7	...
...	24, 100, 160	2.7 ± 0.7	2.4 ± 0.8	1.8 ± 1.0	3.2 ± 1.3	11.9 ± 2.7	...
Rieke+09 Col-Eq Weight [h]	24, 100, 160, 1.4	2.6 ± 0.7	2.3 ± 0.8	1.8 ± 0.9	3.1 ± 1.2	12.1 ± 2.7	...

L(IR) similar

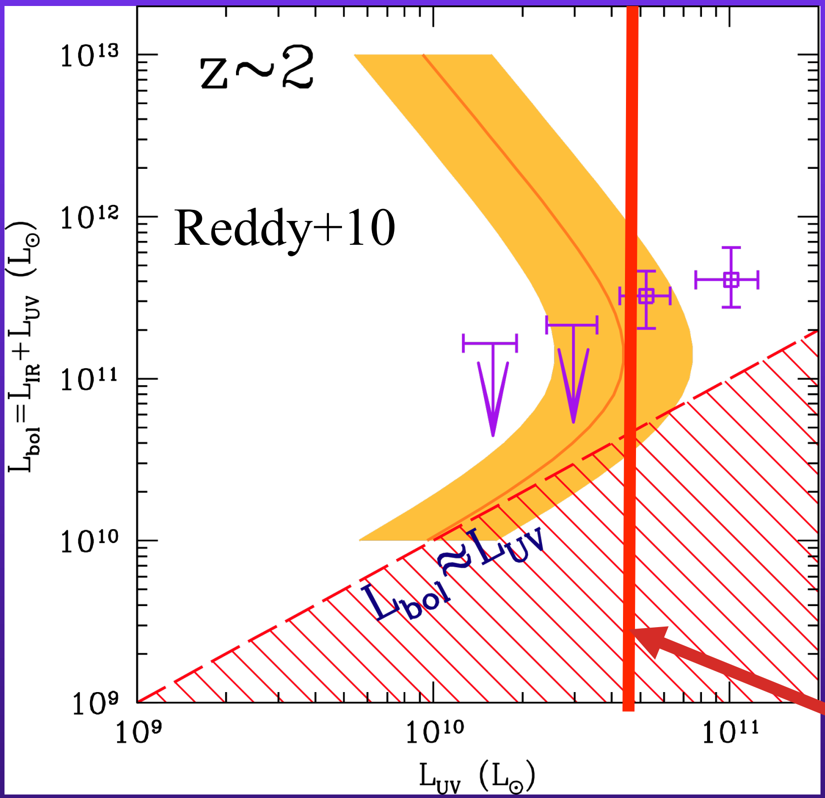

UV−Selected (L*) Galaxies at z~2
Stack of N=114
L* Galaxies
Meurer+99
Low−Lum
ULIRGs
SMC
β>−1.4
β<−1.4
"Young"
Galaxies
Reddy et al. (astroph:1107.2653)
1000
100
10
1
0.1
−2
−1
0
1
L_{IR}/L_{UV}
β

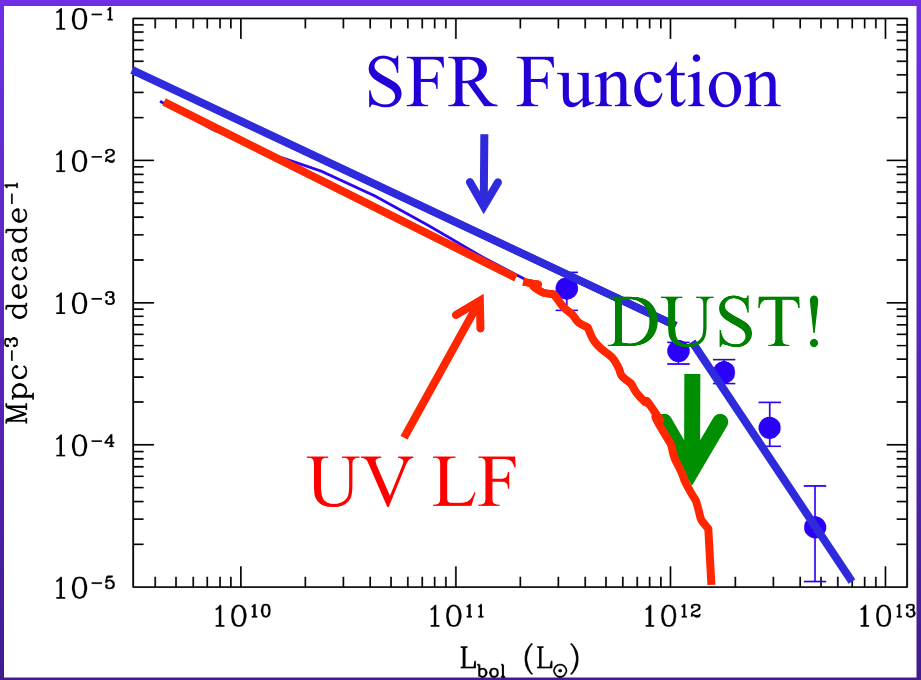
UV Faint Galaxies Are Less Bolometrically Luminous on Average…





Effect of Dust on the Galaxy Luminosity Function

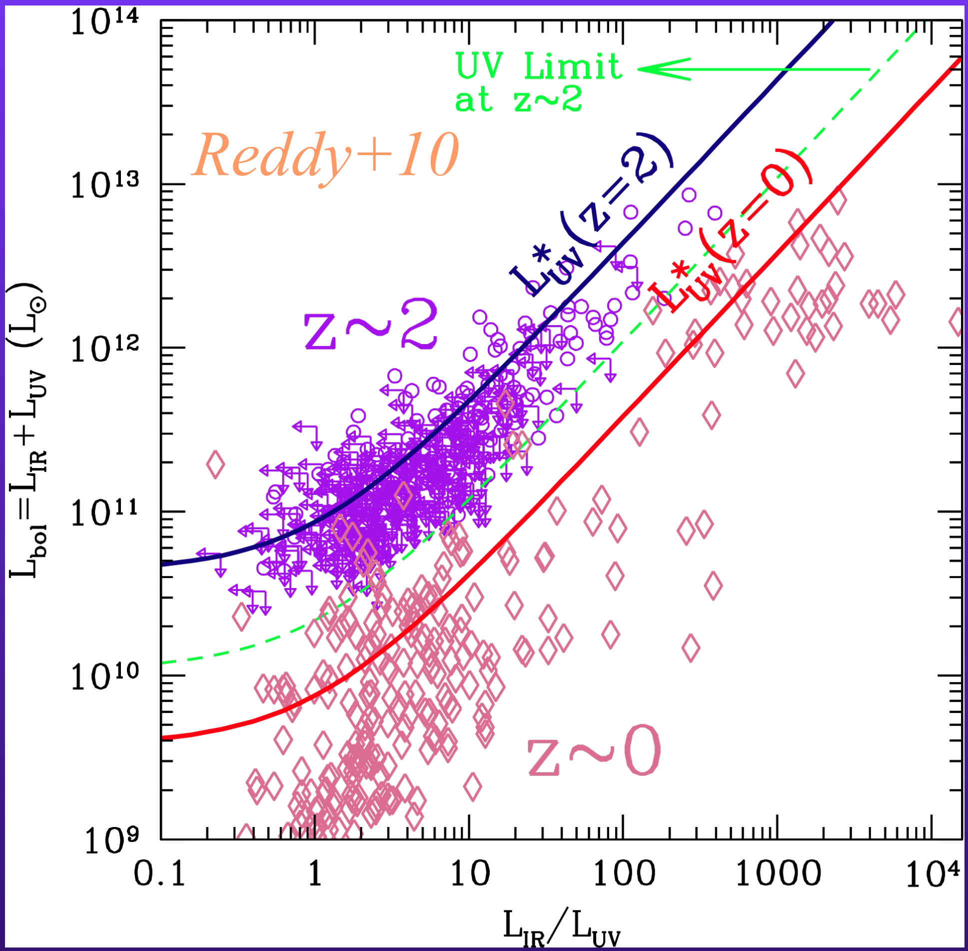




Saturation of UV
luminosity around
L*(UV)

Dust affects UV LF and therefore our interpretation of how it evolves with redshift

Redshift Evolution of Dust Extinction

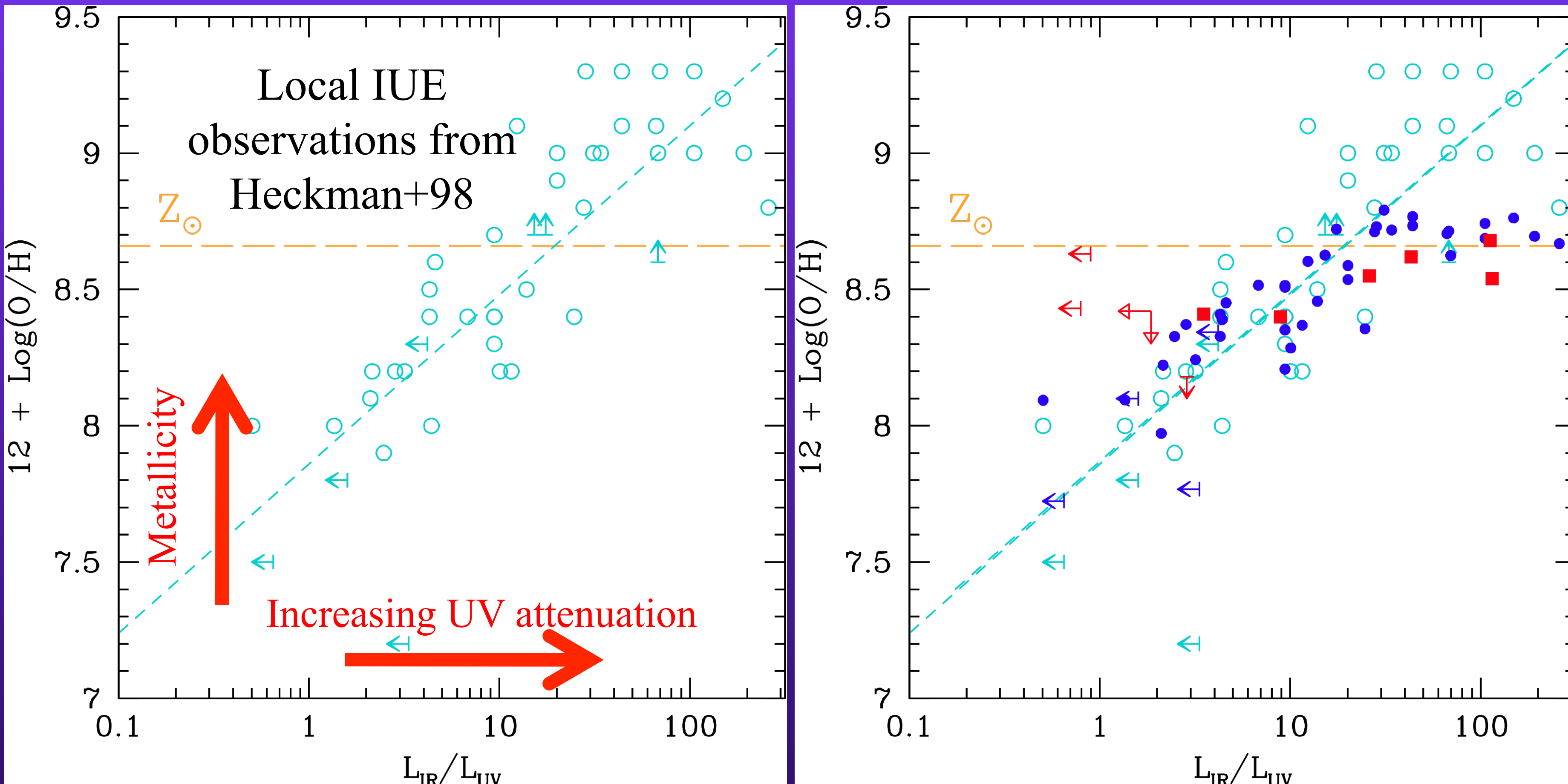


- Tight relation between L(bol) and dust
- At fixed L(bol), z~2 galaxies less dusty than z~0 galaxies
- Evolution in extinction per unit SFR due to increasing dust-to-gas ratio?

Reddy+10, Buat+08, Burgarella +08, Daddi+07, Zoran+06, Adelberger & Steidel 2000, Reddy +06, Wang & Heckman 96,

Z>>2 UV Dropout selections are likely to be more complete for high SFR galaxies (if they exist) than inferred from local observations

Physical Mechanism behind L(bol) vs. Dustiness Relation



Evolution of L(bol) vs. Dustiness relation directly tied to metallicity evolution

Conclusions

FOCUS: bring multi-wavelength information we have for high redshift galaxies into a coherent picture for the evolution of dust with galaxy luminosity and redshift:

- L* galaxies at z~2 are LIRGs (~2e10 Lsun)
- Dust attenuation of UV-bright galaxies ~4-5, similar to prediction from the UV slope
- Dust limits the maximum UV luminosity of star-forming galaxies, thus affecting the shape of the UV luminosity function
- Evolution of extinction per unit star formation rate, likely tied to a change in metallicity as galaxies age