GOODS-Herschel: The deepest view of the far-infrared skies

Mark Dickinson

NOAO

Congratulations to GOODS/CANDELS collaborator Adam Riess for his astonishing double Nobel prize!

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SCIENCE - SCITECH

Three Americans Share 2011 Nobel Peace Prize in Physics

Published October 04, 2011 | Associated Press

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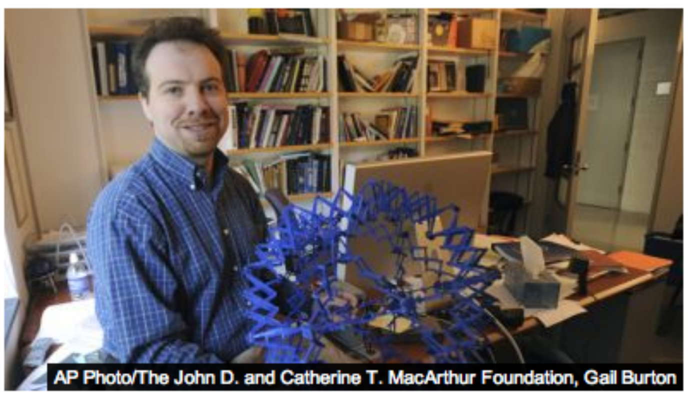


The Royal Swedish Academy of Sciences says American Saul Perlmutter, U.S.-Australian citizen Brian Schmidt and U.S. scientist Adam Riess (pictured here in 2008) share the 2011 Nobel Prize in physics. The trio were honored Tuesday, Oct. 4, 2011 "for the discovery of the acclerating expansion of the universe through observations of distant supernovae."

STOCKHOLM – Three U.S.-born scientists won the Nobel Prize in physics Tuesday for discovering that the universe is expanding at an accelerating pace, a stunning revelation that suggests the cosmos will eventually freeze to ice.

The Royal Swedish Academy of Sciences said American Saul Perlmutter would share the 10 million kronor ($1.5 million) award with U.S.-Australian Brian Schmidt and U.S. scientist Adam Riess. Working in two separate research teams during the 1990s -- Perlmutter in one and Schmidt and Riess in the other -- the scientists raced to map the universe's expansion by analyzing a particular type of supernovas, or exploding stars.

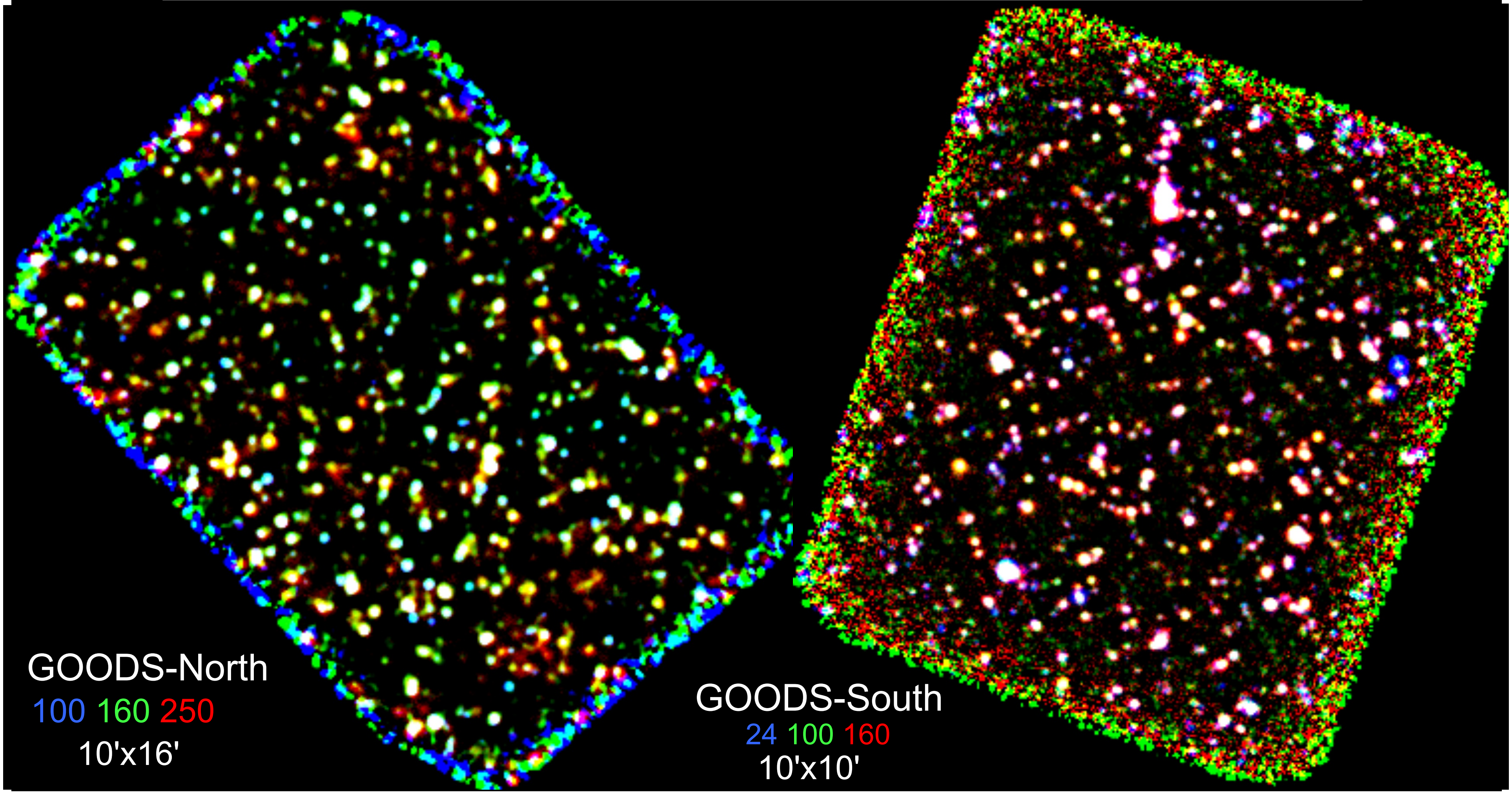
GOODS-Herschel (*Herschel Open Time Key Program*)

The Great Observatories Origins Deep Survey : far IR imaging with Herschel

Deepest images of the sky in the 2 GOODS fields :
1818 sources down to

1 mJy at 100 μm, 2.6 mJy@160μm, 5mJy@250μm, 8mJy@350μm, 10mJy@500μm

X	UV U B V I Z J H K	3.6μm 4.5μm 5.8μm 8μm	IRS16	MIPS24	radio
2x10^{-16}erg/s/cm^2	~28AB 22AB	~1μJy	50μJy	20μJy	12μJy



GOODS-Herschel: Daring to achieve the ordinary!

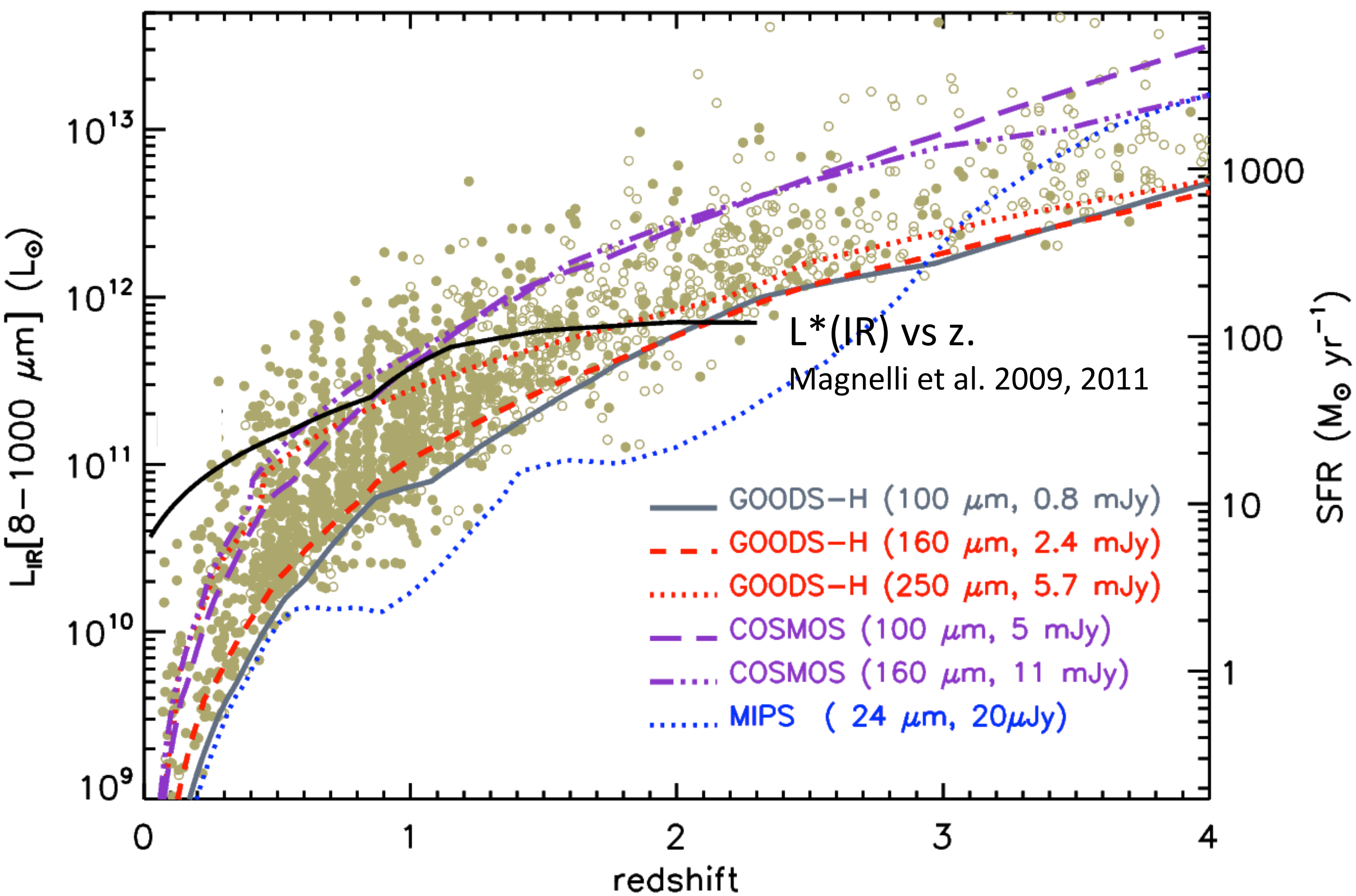
GOODS fields are unique for PACS and SPIRE 250μm data deep enough to detect ~L^*_{IR} galaxies at z ≈ 2

L^*_{IR} = 7 x 10^{11} Lo @ z≈2 (Magnelli et al. 2011)

Comparable data for both GOODS fields:

N: from GOODS-Herschel

S: from PEP, HerMES + GOODS-H



The GOODS-Herschel team

A&A 533, A119 (2011)
DOI: 10.1051/0004-6361/201117239

Astronomy & Astrophysics

GOODS–*Herschel*: an infrared main sequence for star-forming galaxies⋆

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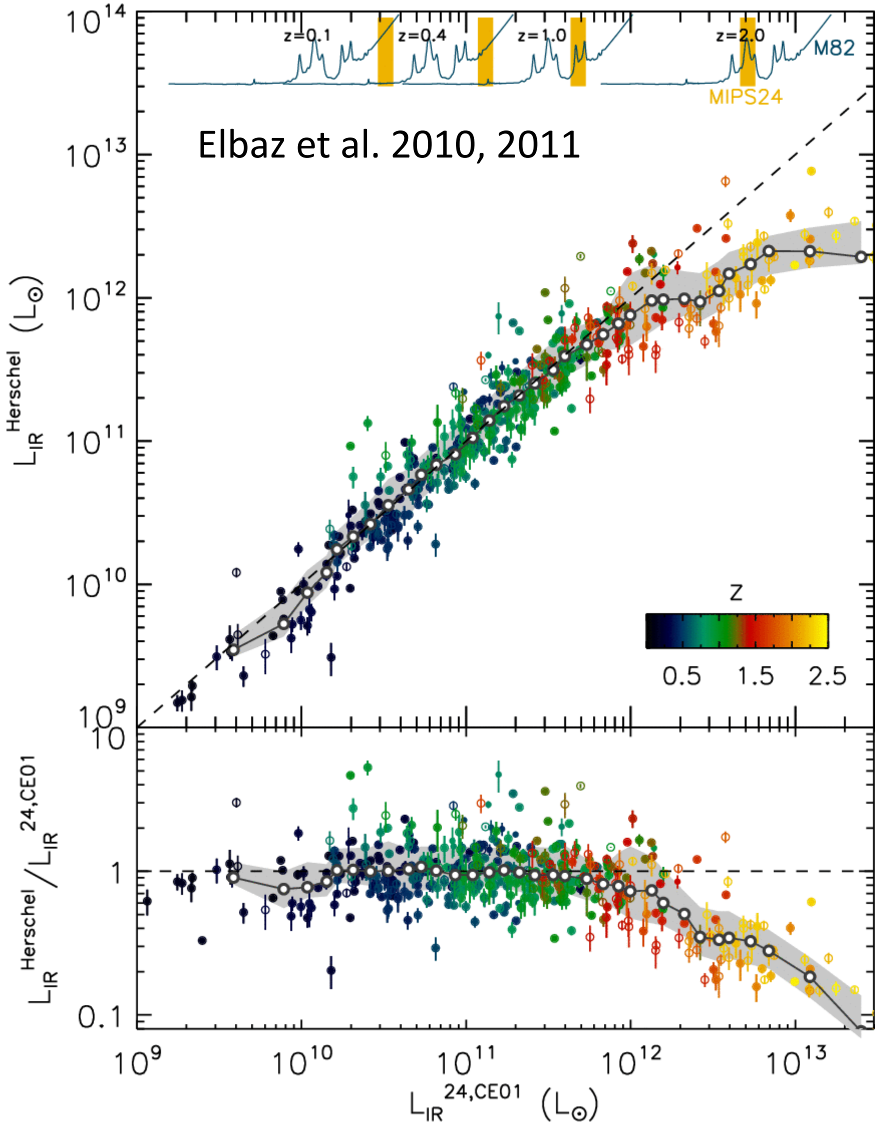
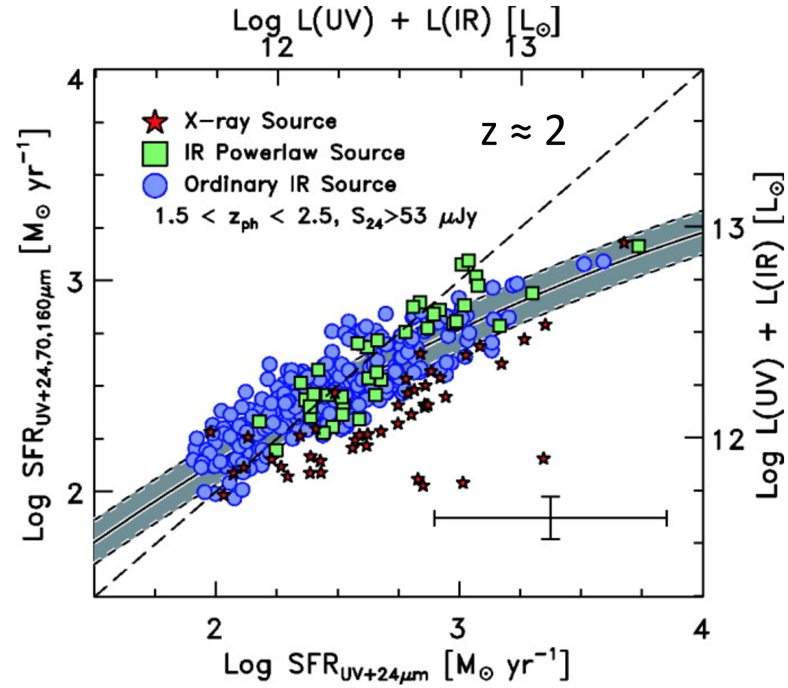
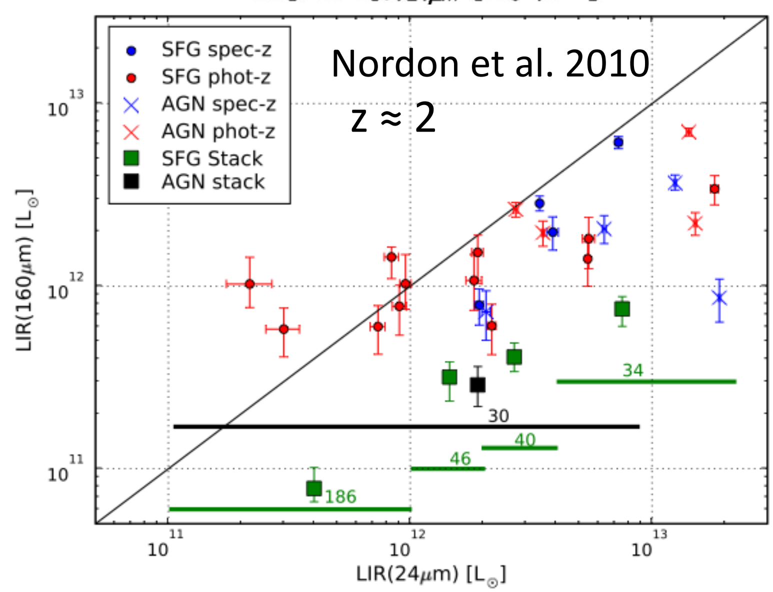
Does 24μm data overestimate L_{IR} at z ~ 2 ?

(aka the mid-IR excess problem)



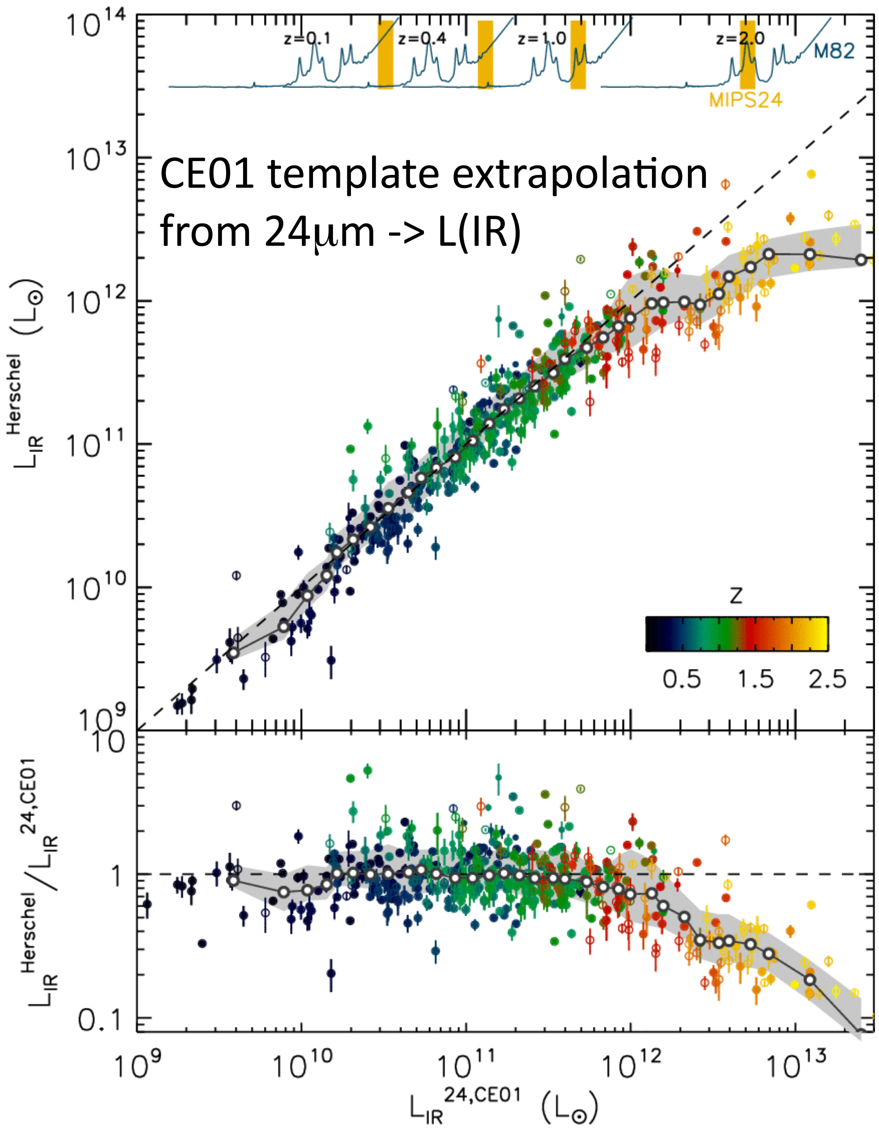
Pre-Herschel: Papovich et al. 2007, Daddi et al. 2007; Magnelli et al. 2009

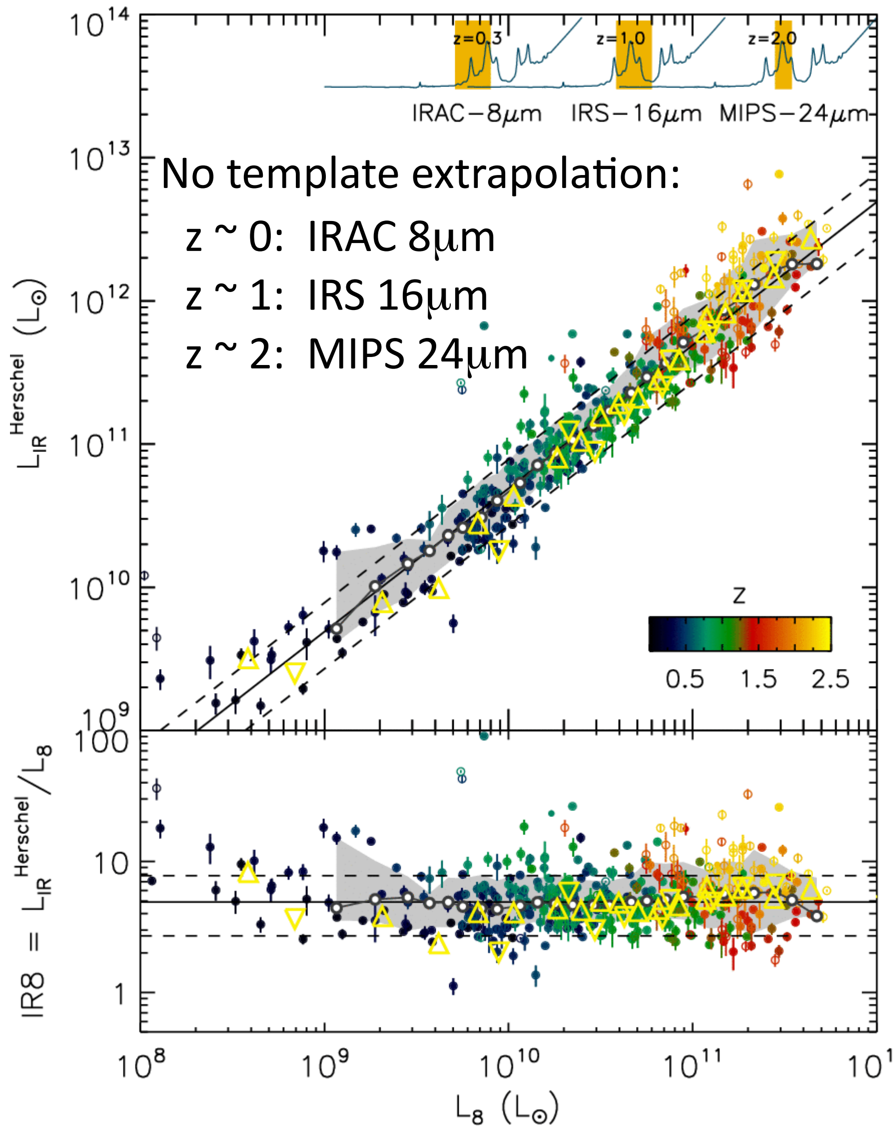




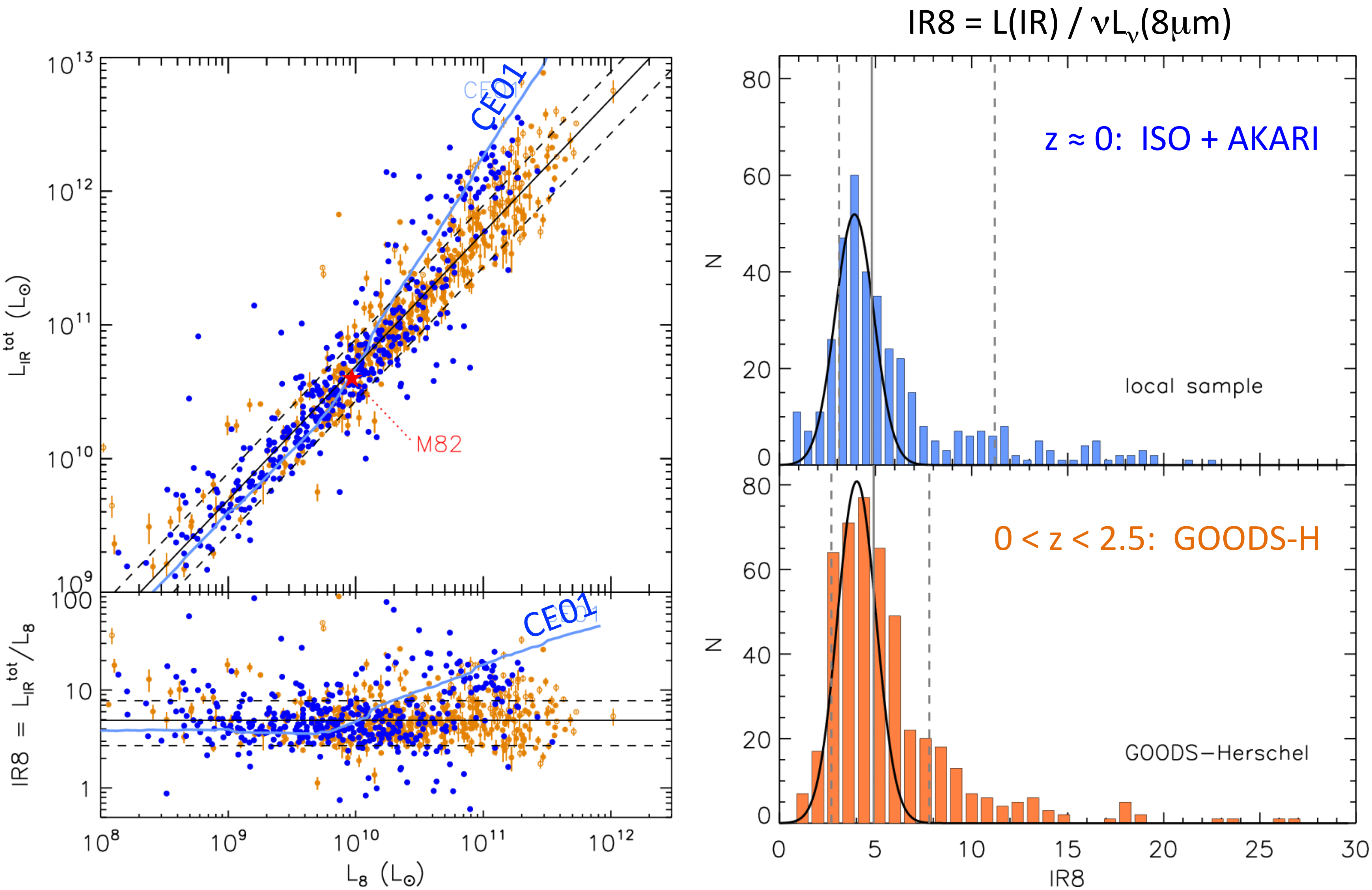
Focusing consistently on L(8μm) vs. L(IR) changes the picture

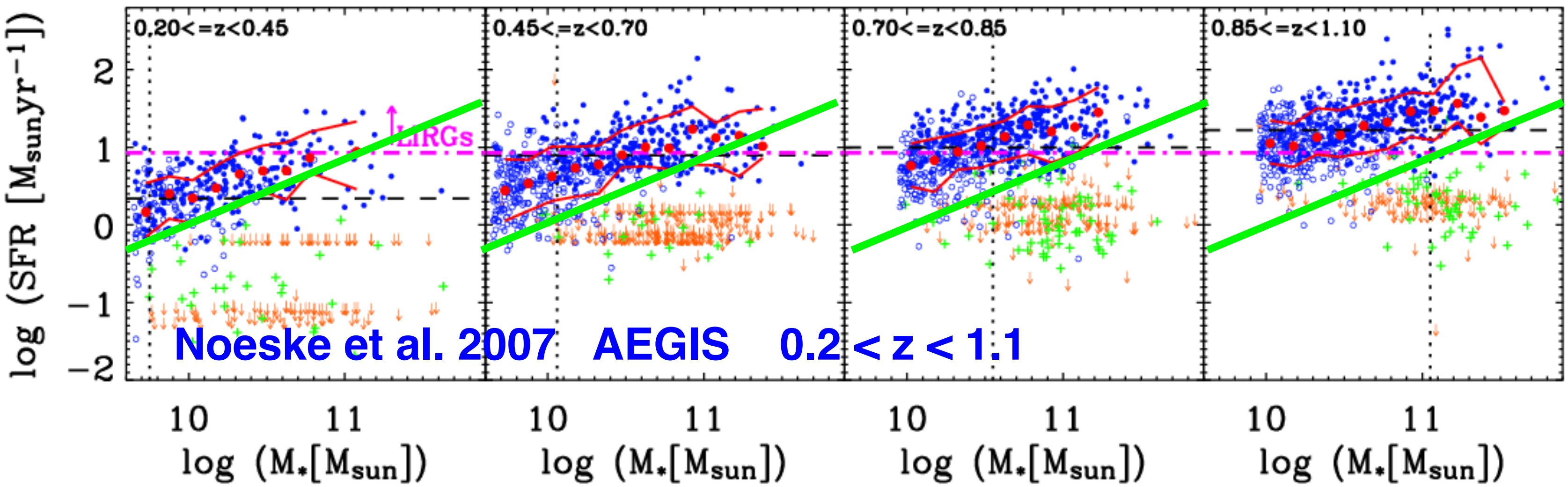
IR8 = L(IR) / νL_ν(8μm)

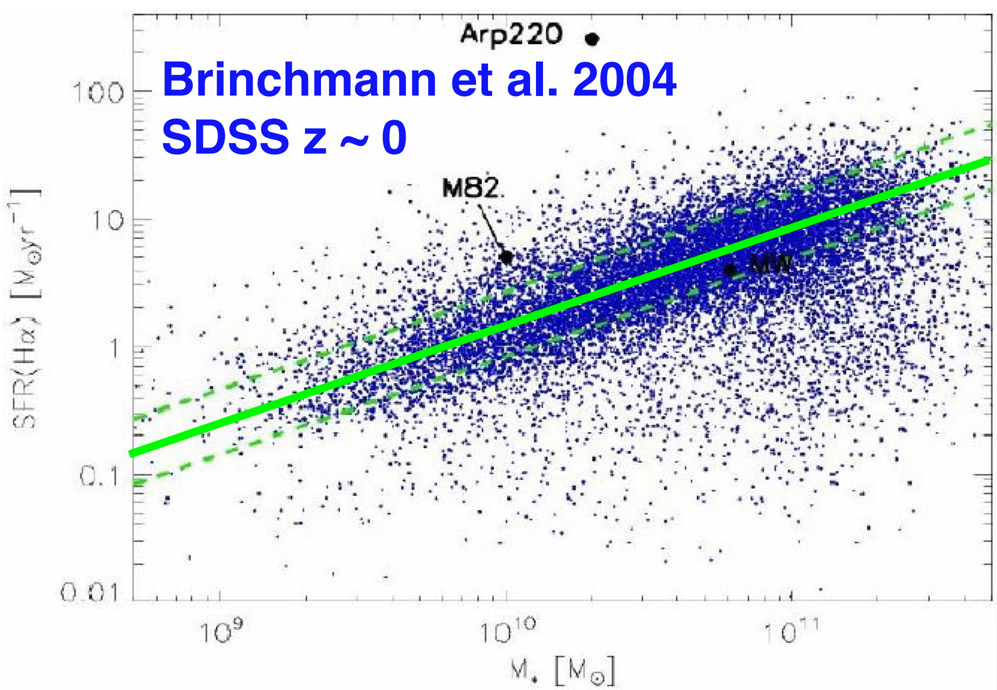


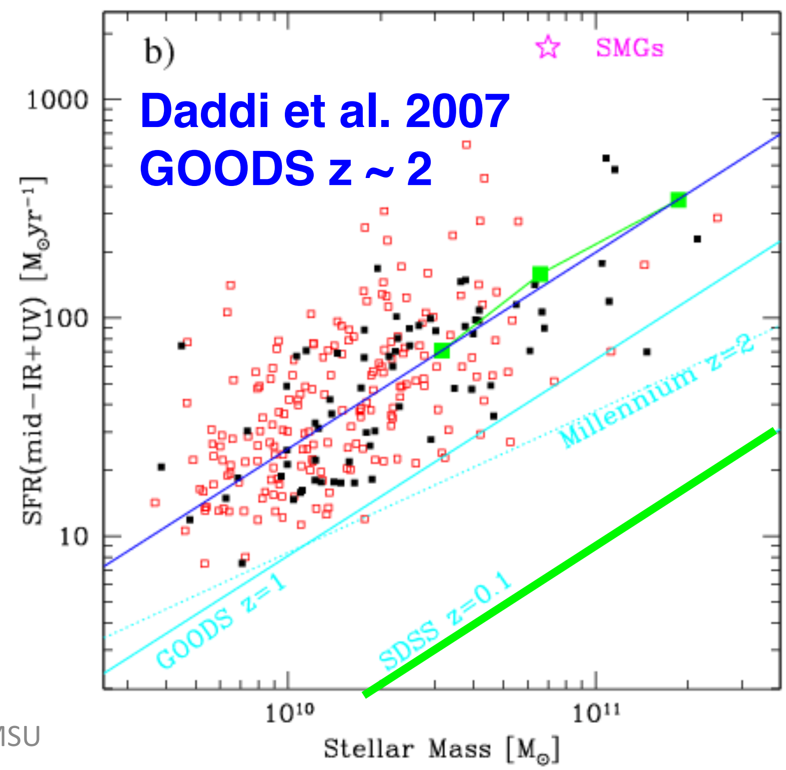


What are the high-IR8 galaxies?

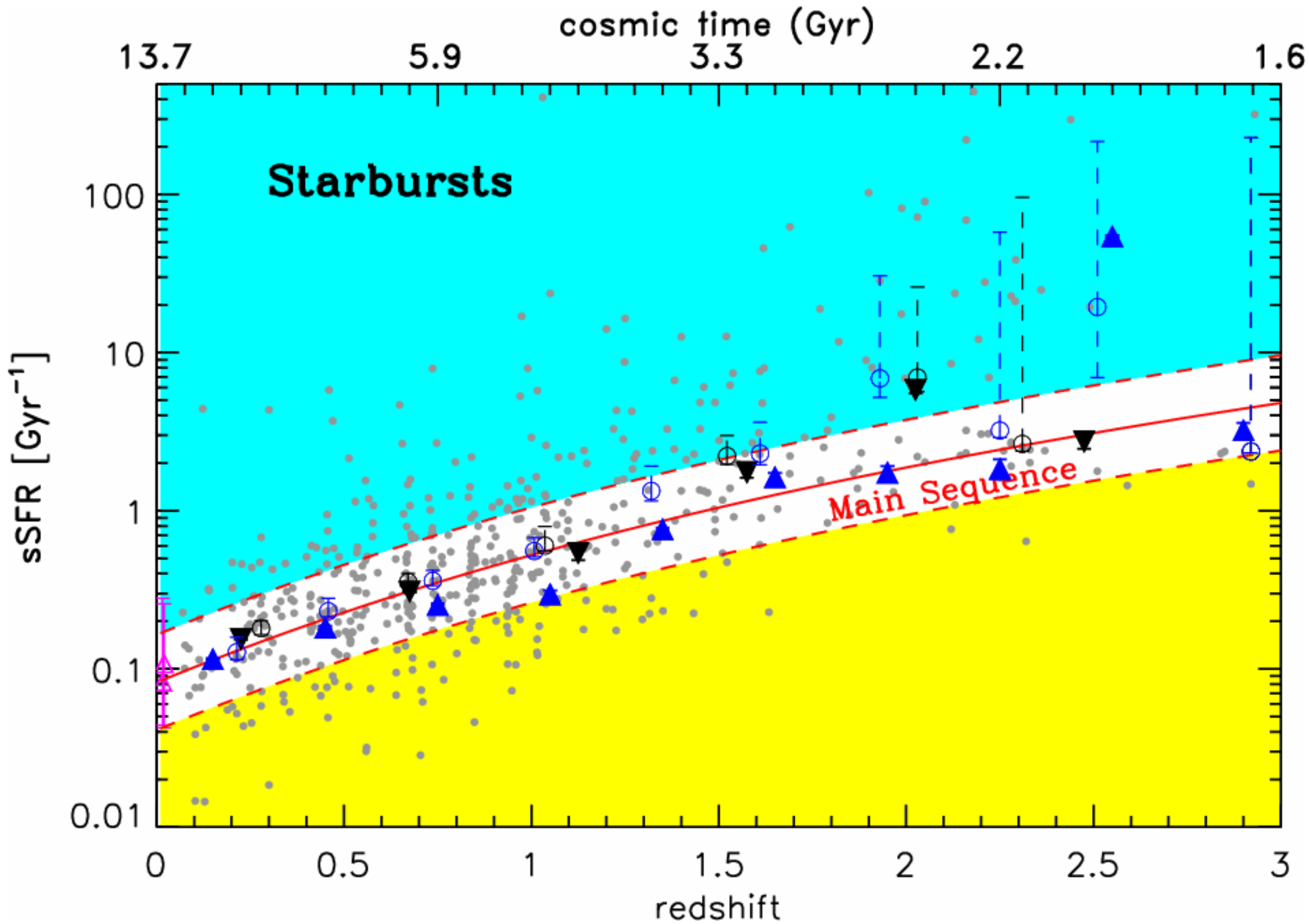



0.20<=z<0.45
0.45<=z<0.70
0.70<=z<0.85
0.85<=z<1.10
LIRGs
Noeske et al. 2007 AEGIS 0.2 < z < 1.1
log (SFR [Msun yr−1])
log (M*[Msun])


Arp220
Brinchmann et al. 2004
SDSS z ~ 0
M82
MW
SFR(Hα) [M⊙yr−1]
M* [M⊙]

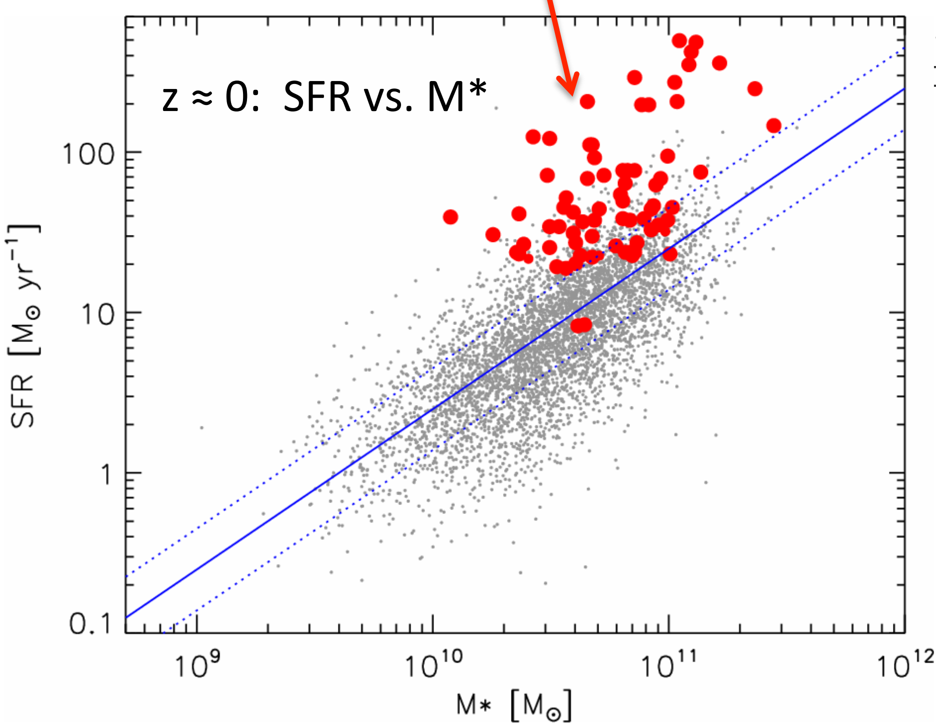

b)
SMGs
Daddi et al. 2007
GOODS z ~ 2
Millennium z=2
GOODS z=1
SDSS z=0.1
SFR(mid−IR+UV) [M⊙yr−1]
Stellar Mass [M⊙]

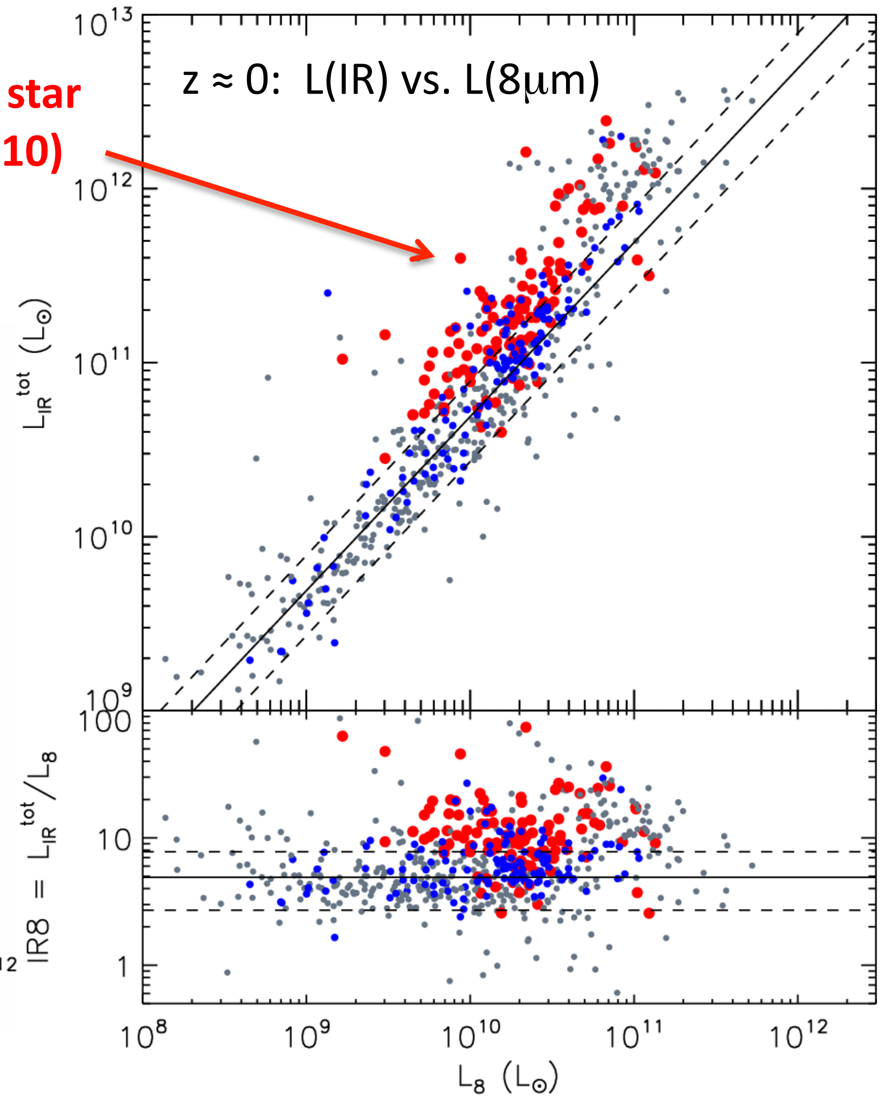
Redshift evolution of the specific SFR (SSFR)

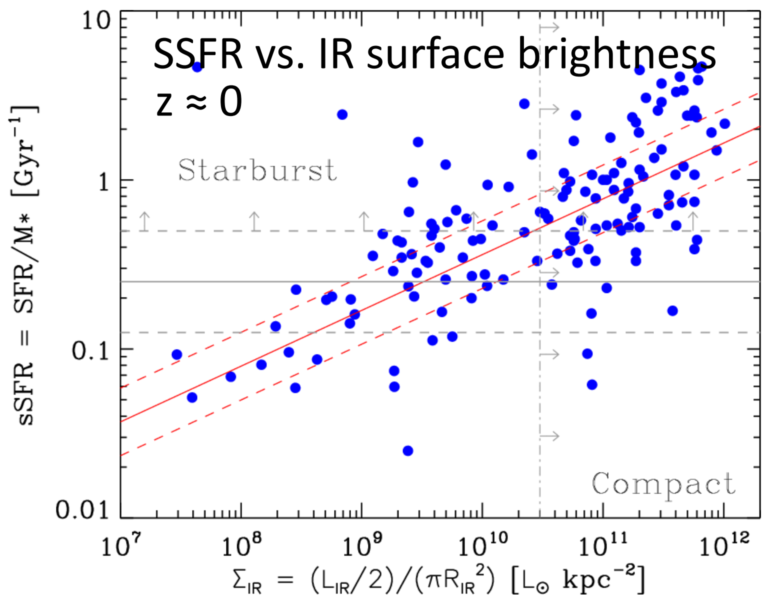


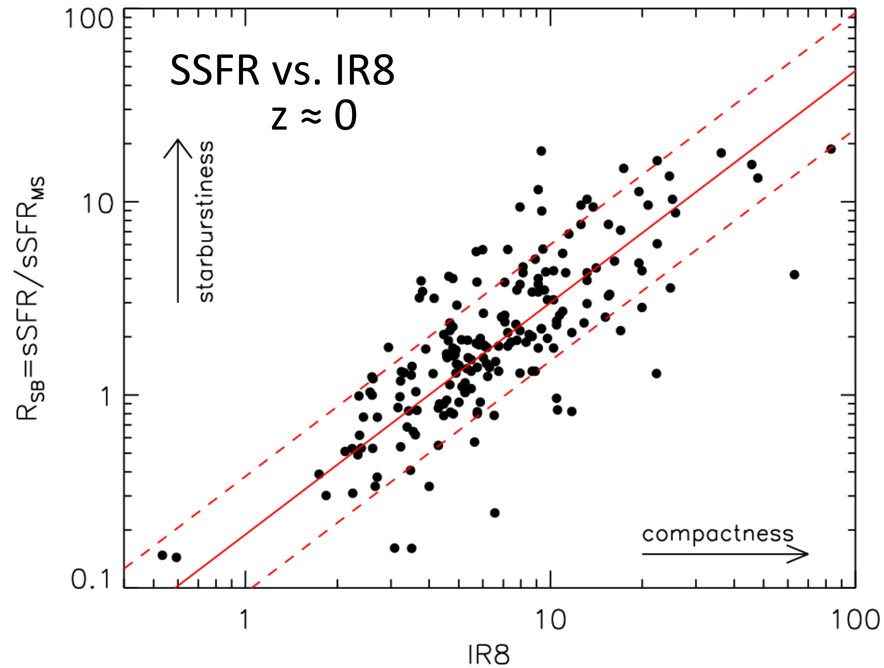
Starburst galaxies have high SFR surface density

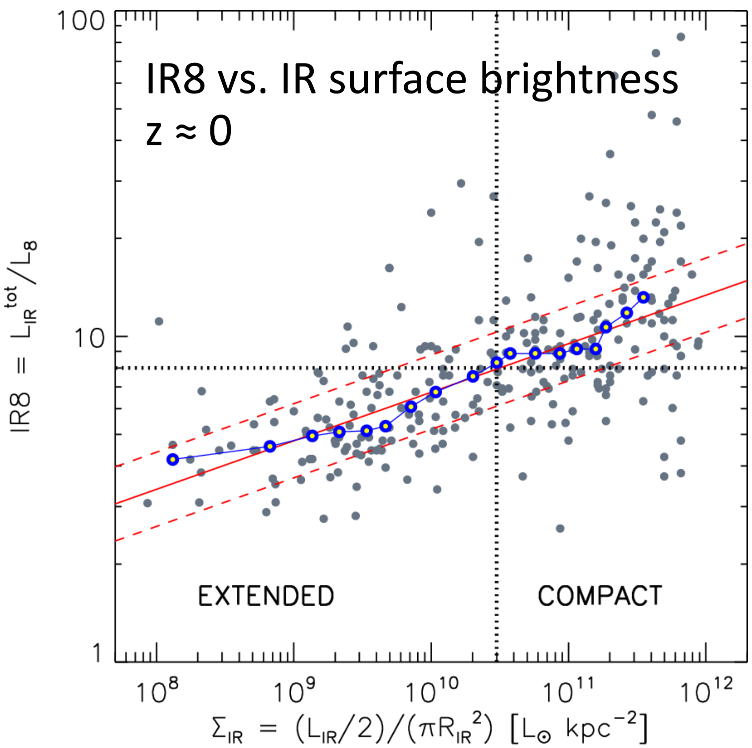
LIRGs with compact / high surface brightness star formation from GOALS (Díaz-Santos et al. 2010)

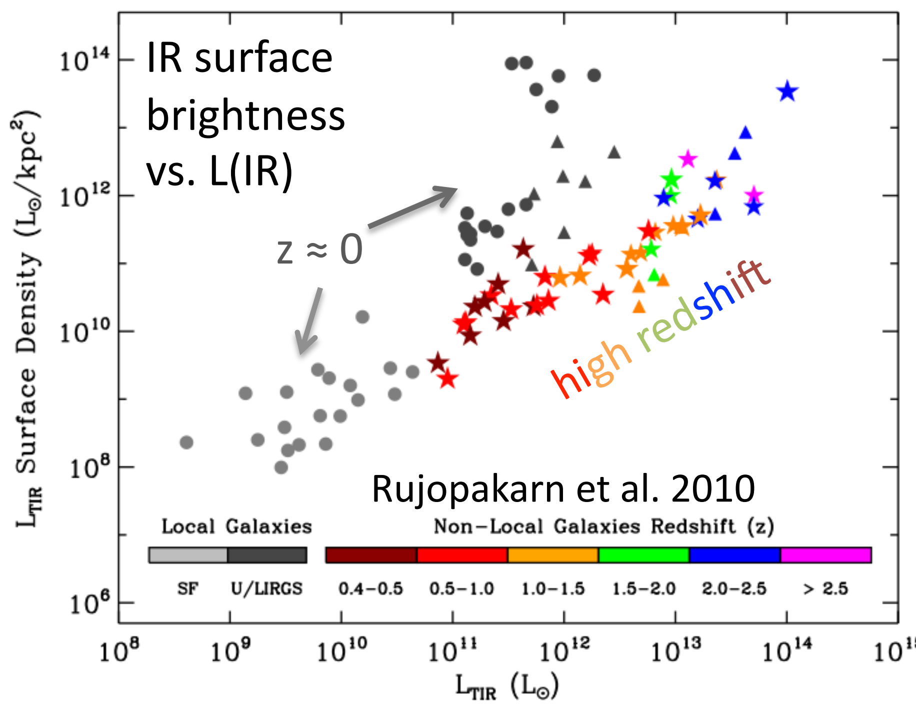





SSFR vs. IR surface brightness
z ≈ 0
Starburst
Compact
sSFR = SFR/M* [Gyr^{-1}]
10
1
0.1
0.01
10^7 10^8 10^9 10^{10} 10^{11} 10^{12}
Σ_{IR} = $(L_{IR}/2)/(\pi R_{IR}^2)$ [$L_\odot$ kpc^{-2}]

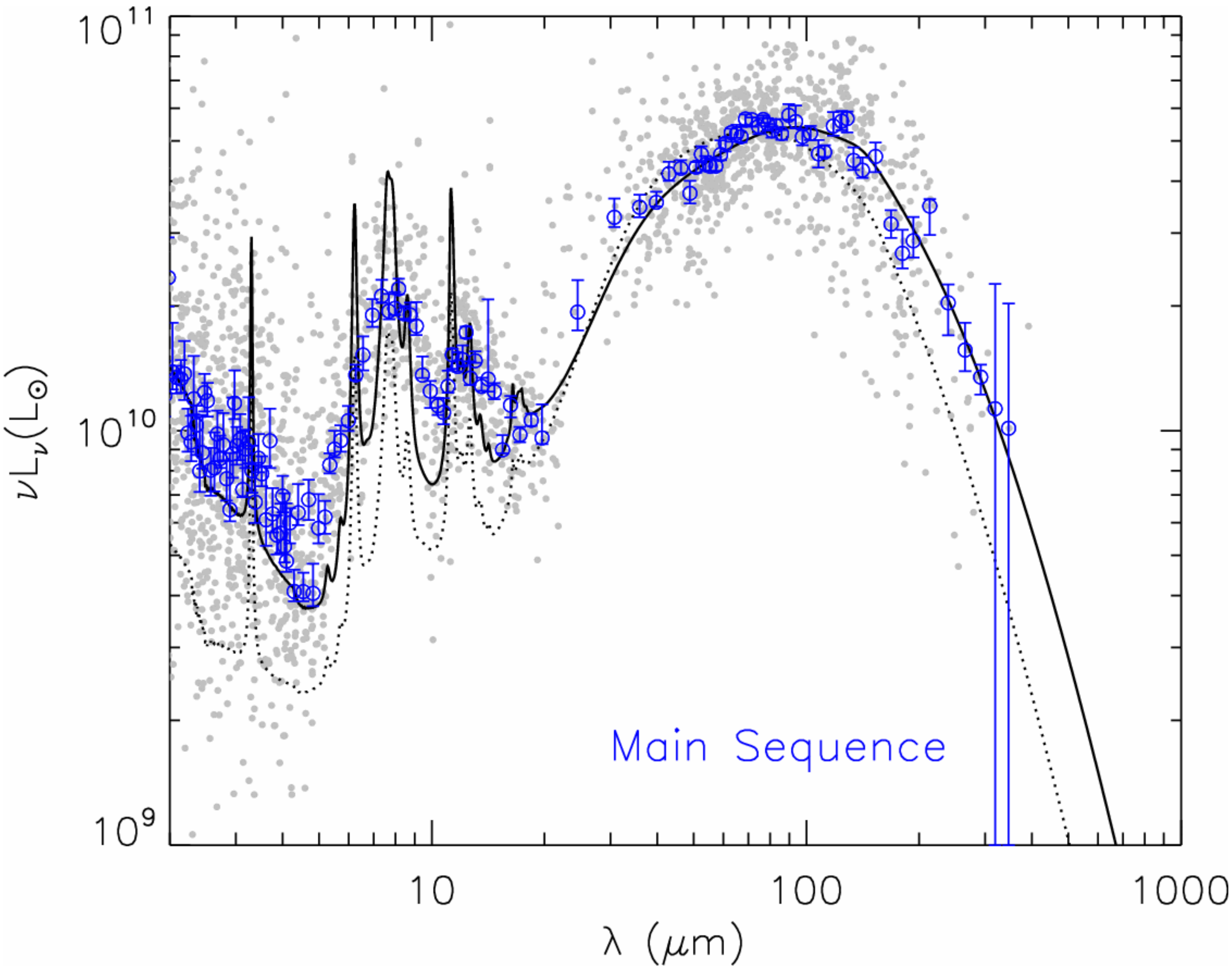

SSFR vs. IR8
z ≈ 0
starburstiness
compactness
R_{SB}=sSFR/sSFR$_{MS}$
100
10
1
0.1
1
10
100
IR8


IR8 vs. IR surface brightness
z ≈ 0
EXTENDED
COMPACT
IR8 = L_{IR}^{tot}/L_8
100
10
1
10^8 10^9 10^{10} 10^{11} 10^{12}
Σ_{IR} = $(L_{IR}/2)/(\pi R_{IR}^2)$ [$L_\odot$ kpc^{-2}]


IR surface brightness vs. L(IR)
z ≈ 0
high redshift
Rujopakarn et al. 2010
Local Galaxies
Non-Local Galaxies Redshift (z)
SF
U/LIRGS
0.4–0.5
0.5–1.0
1.0–1.5
1.5–2.0
2.0–2.5
> 2.5
L_{TIR} Surface Density ($L_\odot$/kpc^2)
10^{14}
10^{12}
10^{10}
10^8
10^6
10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15}
L_{TIR} ($L_\odot$)

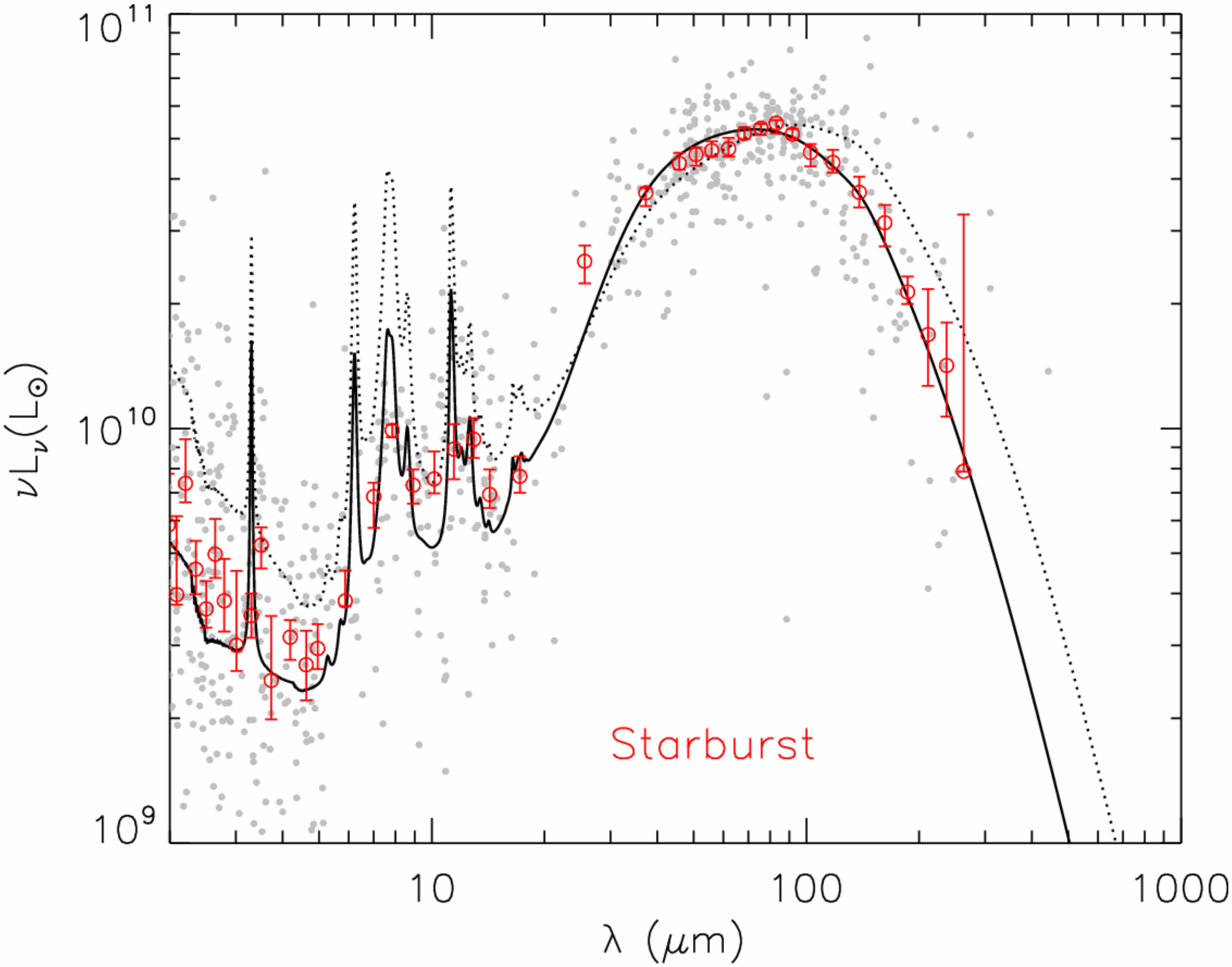
New IR templates from GOODS-H

Constructed by shifting normalized GOODS-H photometry to the rest frame



New IR templates from GOODS-H

Constructed by shifting normalized GOODS-H photometry to the rest frame

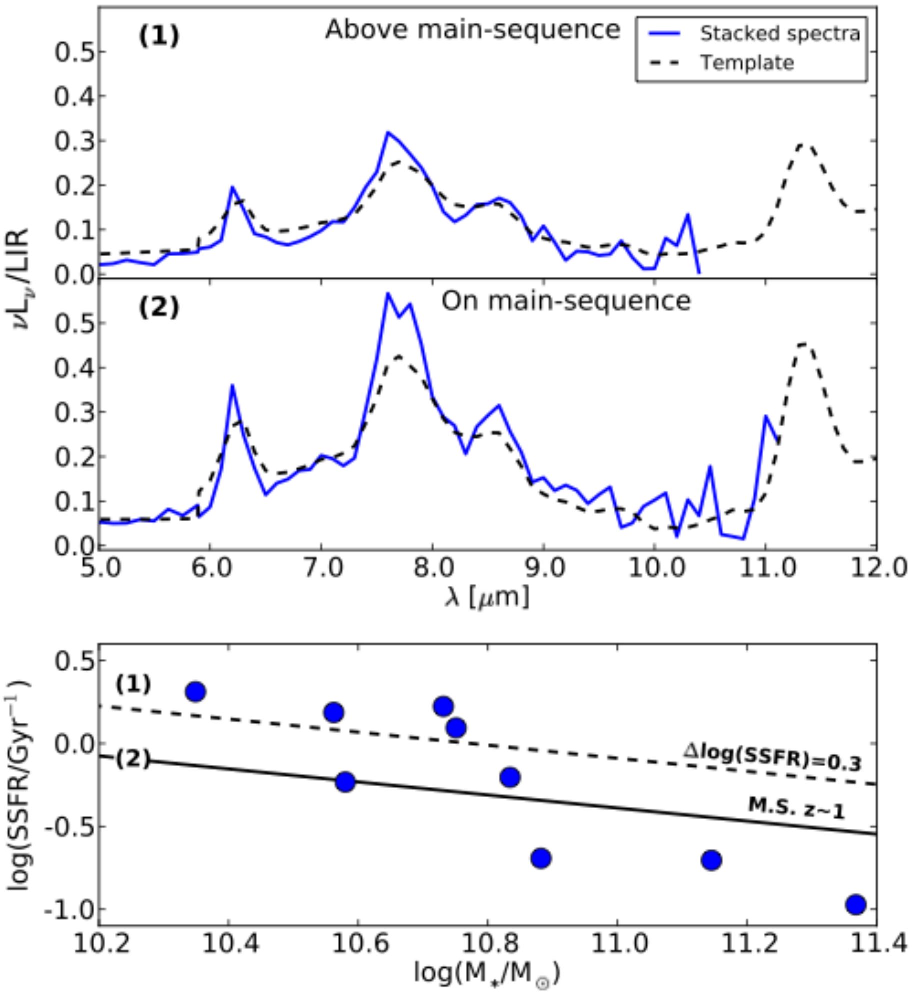


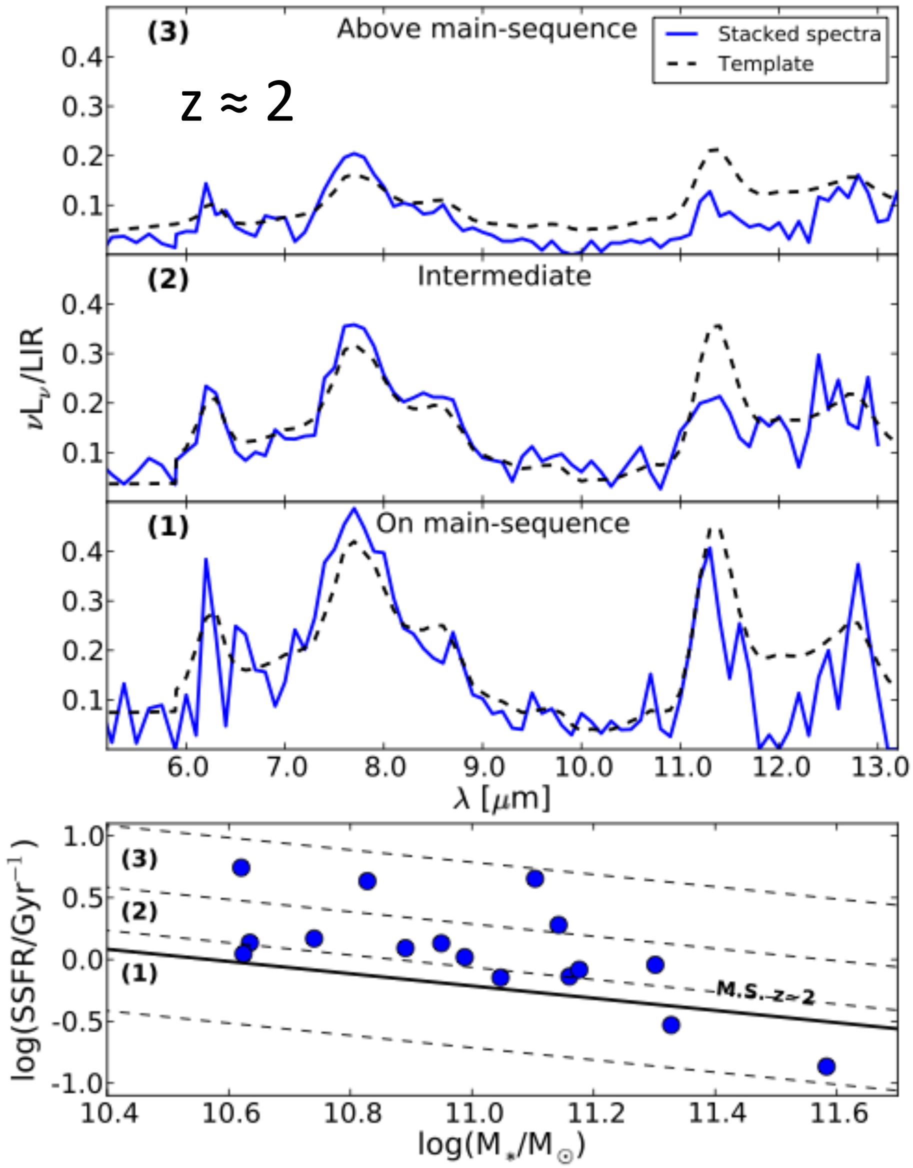
Stronger PAH emission on the MS

Nordon et al. 2011; spectra from Fadda et al. 2010

See also:
Rigby et al. 2008 – lensed LIRGs
Pope et al. 2008 – SMGs

z ≈ 1





To recap:

- Infrared compactness, IR8, and SSFR all correlate
- The MS vs. SB distinction occurs at all redshifts
- z ≈ 0: ULIRGs are universally starbursts
- z ≈ 2: ULIRGs are frequently (but not always) MS
- Applying local ULIRG (= SB) templates to high-z MS galaxies leads to an overestimate of L(IR)
- L(IR) and SFR at z ~ 2 *cannot* be universally derived from 24μm data alone without knowledge of "starburstiness" (= SFR compactness, SSFR, or IR8)
- True far-IR data (e.g., from Herschel) are essential for a full picture of z~2 star formation (at least on a galaxy-by-galaxy basis)
- The physical cause behind the MS/SB distinction at high-z is not yet clearly established
  - We might assume mergers and there is evidence (see Jeyhan Kartaltepe's talk) but not a 1:1 correlation (e.g., the MS includes many apparently merging/ interacting galaxies)

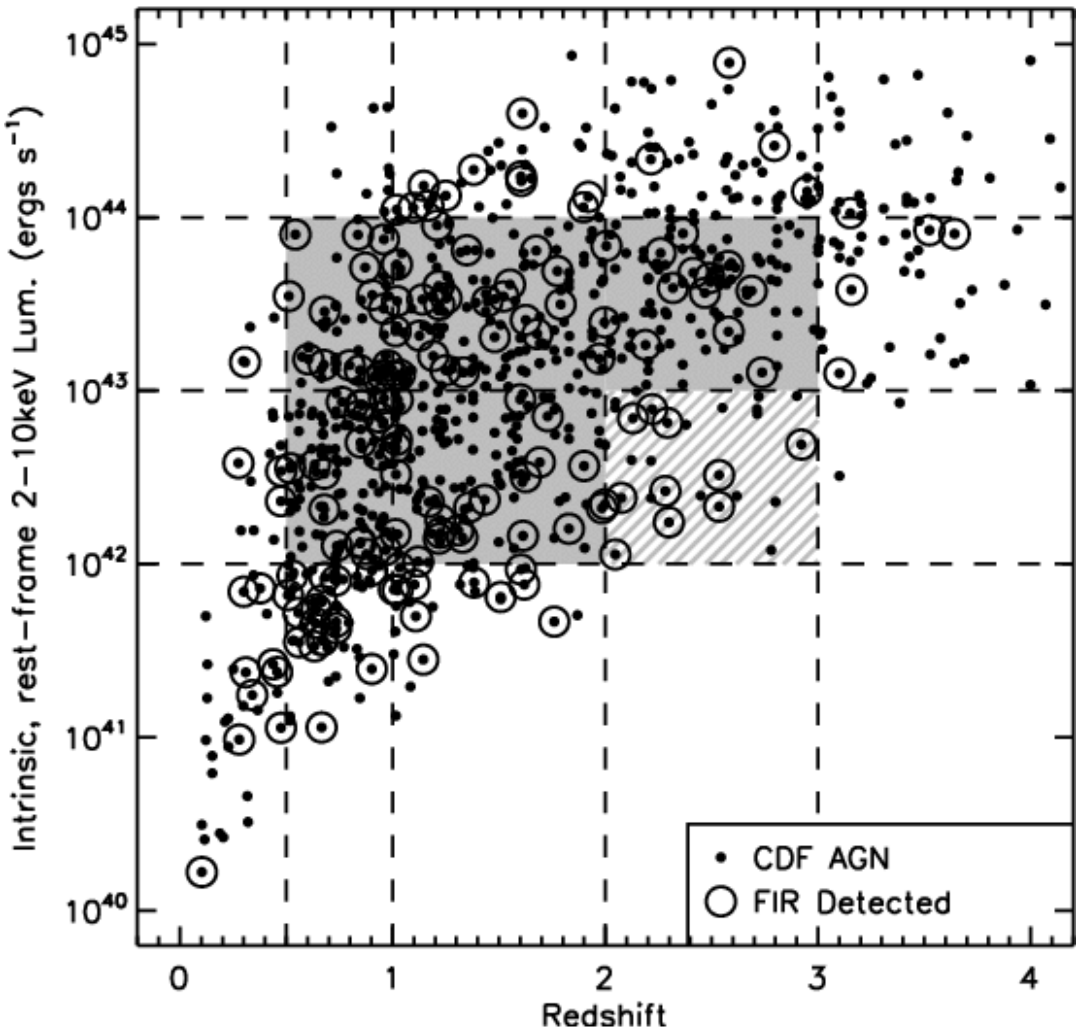
J. Mullaney et al. 2011

Star formation in AGN host galaxies

2-4 Msec Chandra Deep Field data permits selection of moderately luminous AGN over wide ranges in L_X and z.

GOODS-H PACS data lets us study the FIR luminosities and SFRs of the AGN hosts.

Several studies (including this work) show that the FIR luminosity is usually dominated by star formation, not the AGN. (A few likely AGN-dominated sources are excluded here.)

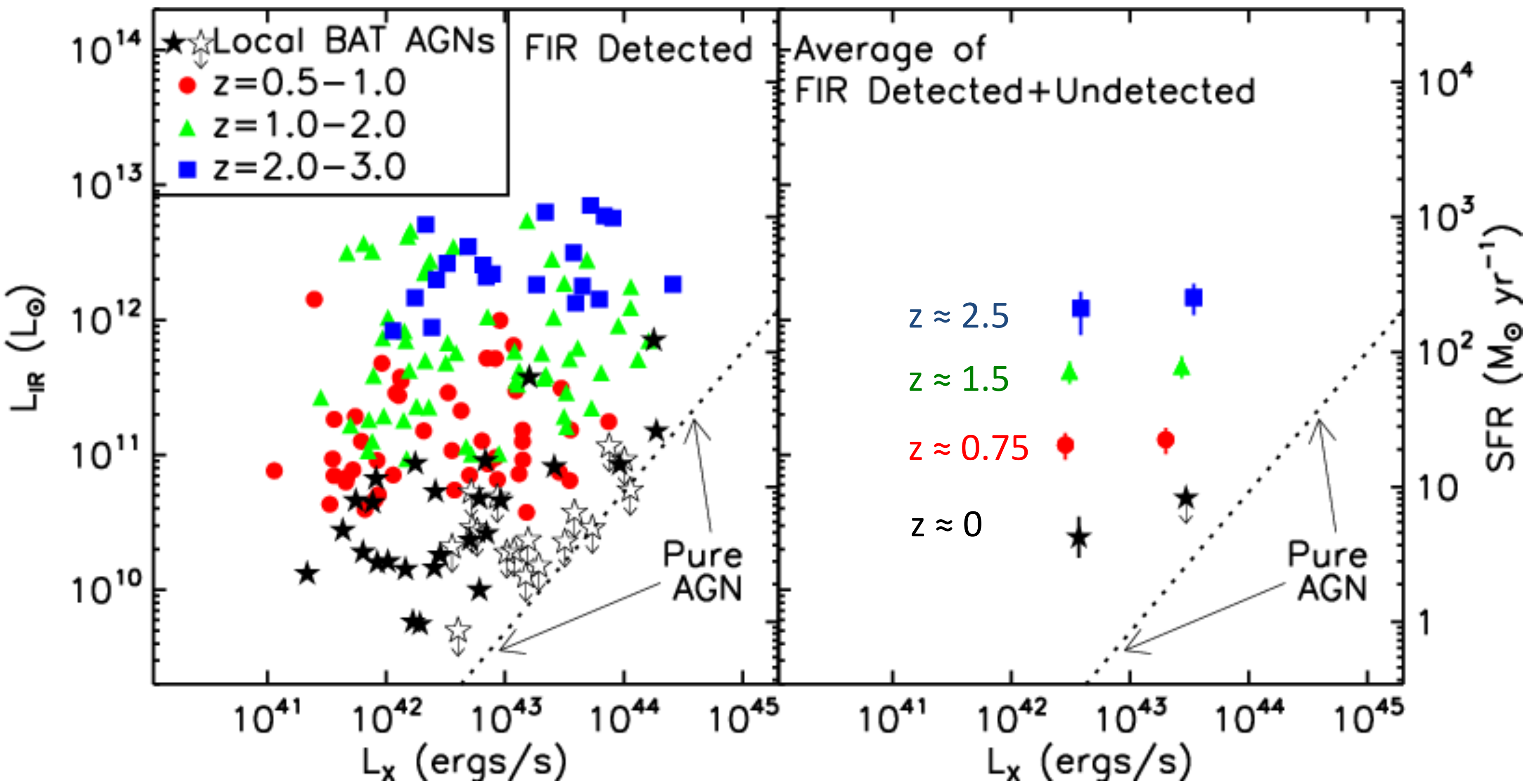


Mullaney et al. 2011

Accretion luminosity vs. star formation

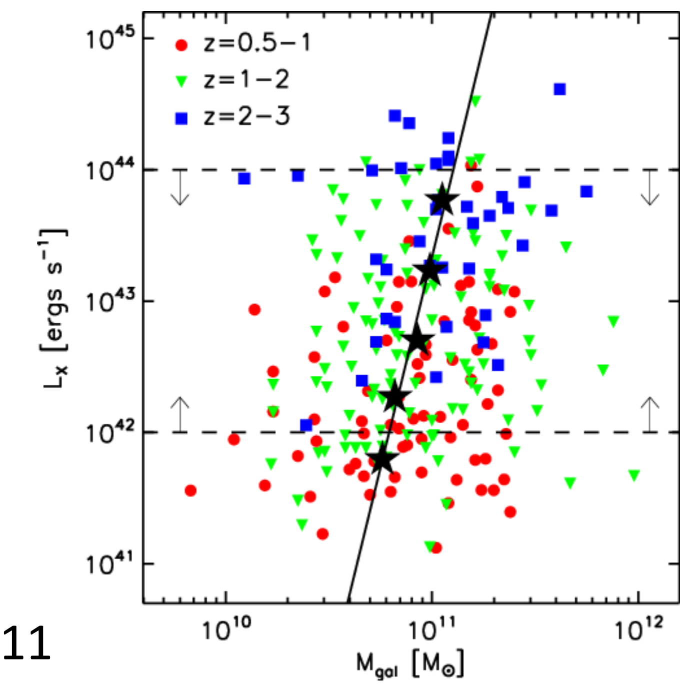
No correlation between L_X and L_{IR}, but a strong trend in L_{IR} vs. z at fixed L_X

See also: Mullaney et al. 2010, Lutz et al. 2010, Shao et al. 2010

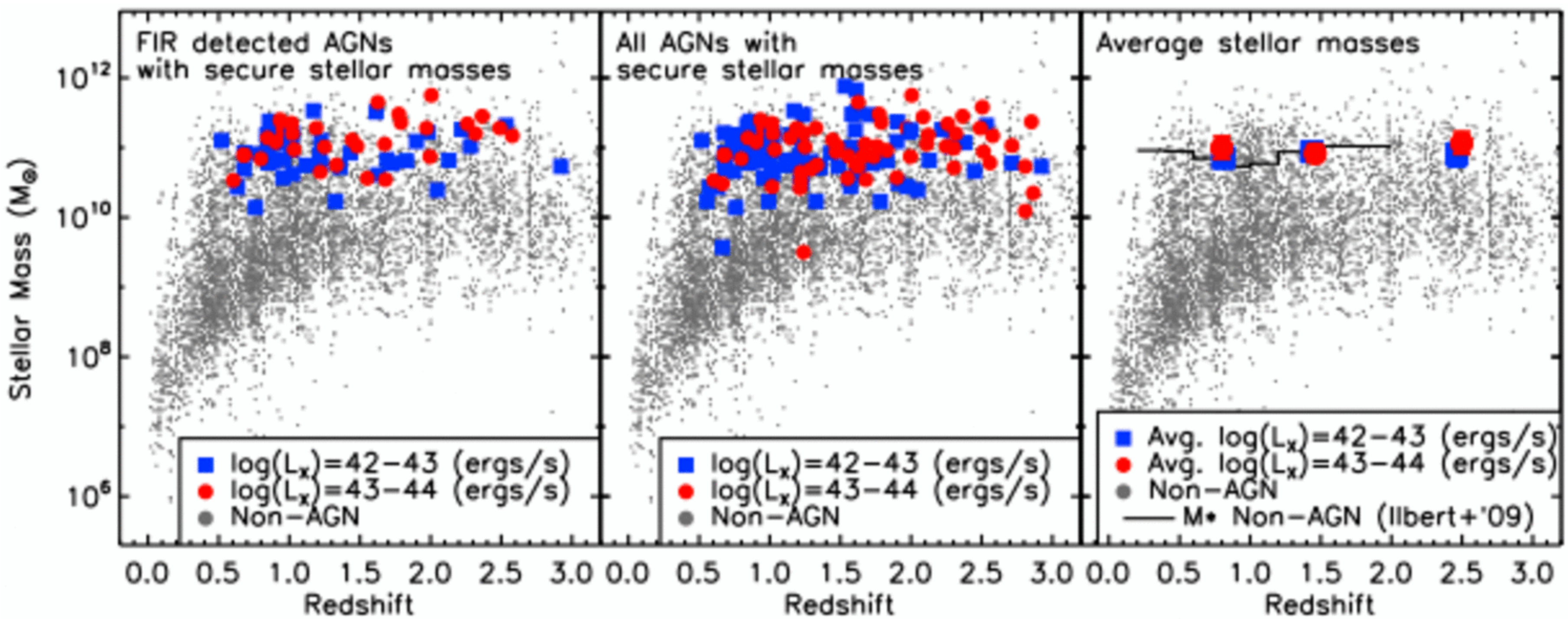


AGN live in massive host galaxies

Only a weak correlation between M* and L_X and no trend with redshift



Mullaney et al. 2011

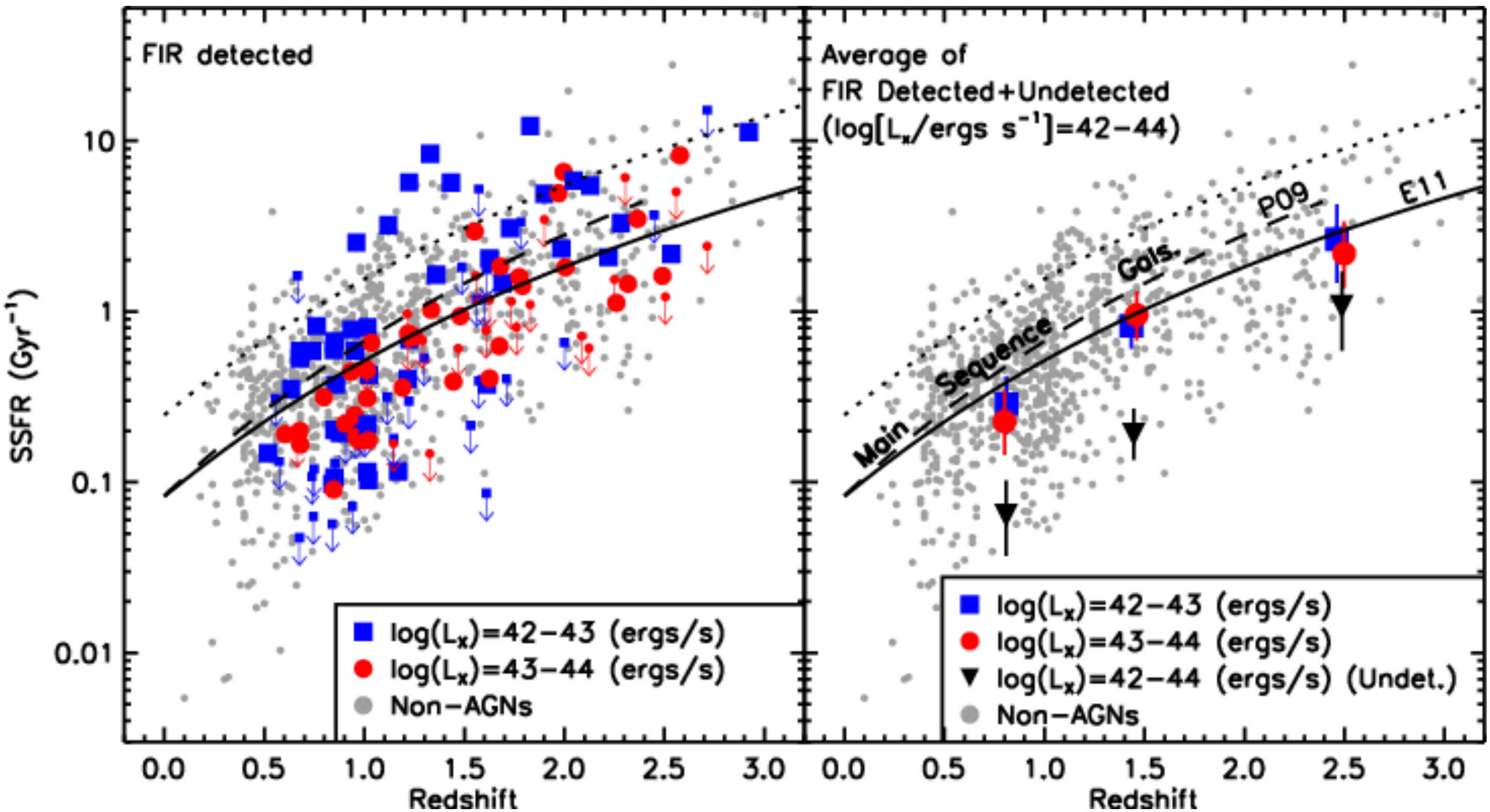


Mullaney et al. 2011

AGN live mostly in main sequence galaxies

~80% in MS hosts; 15+/- 7% quiescent; < 10% in starbursts (SSFR > 3x $SSFR_{MS}$)

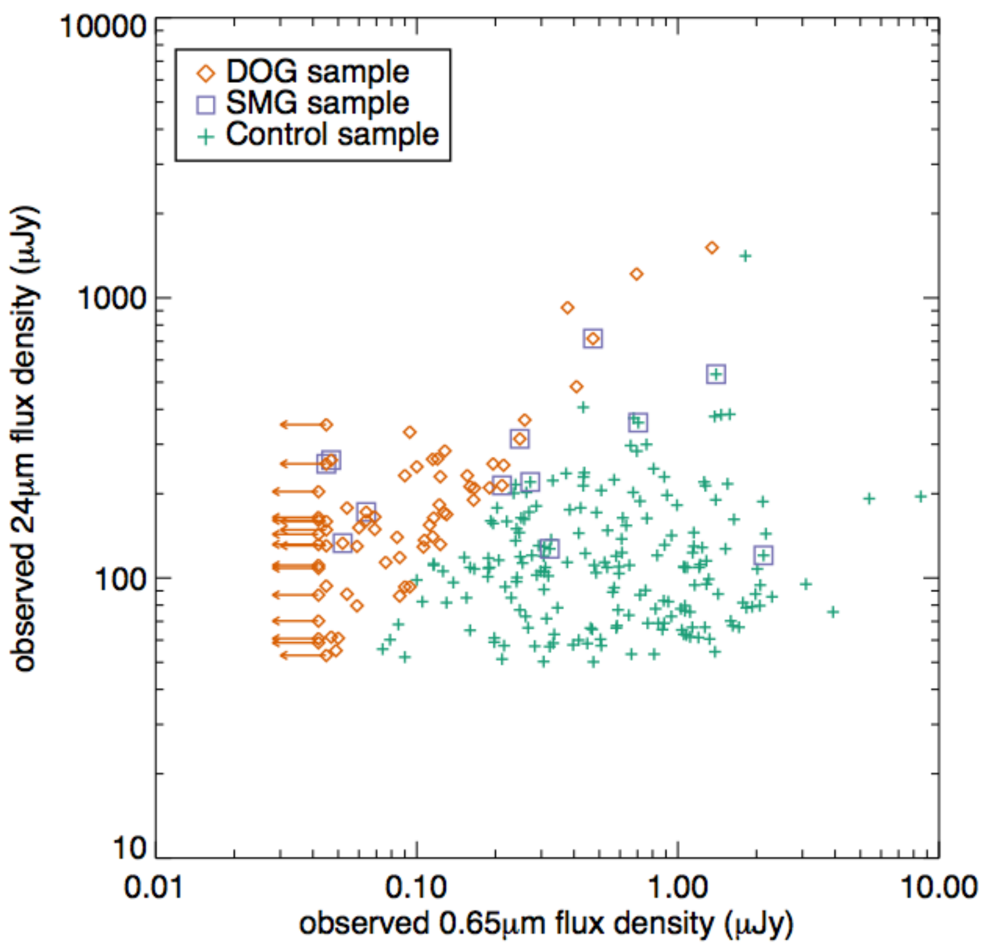
Suggests that AGN are fuelled by “secular” processes that also fuel SF, and not mainly by mergers. See also morphological arguments: Grogin et al. 2005; Cisternas et al. 2011, Kocevski et al. 2011

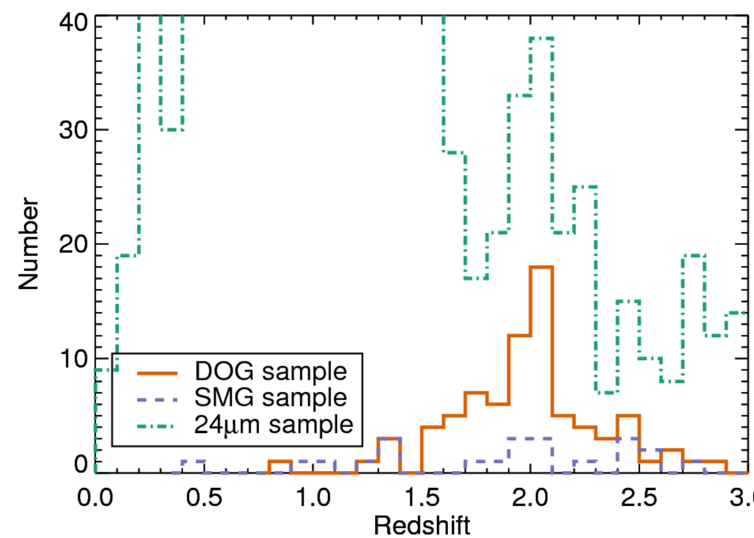


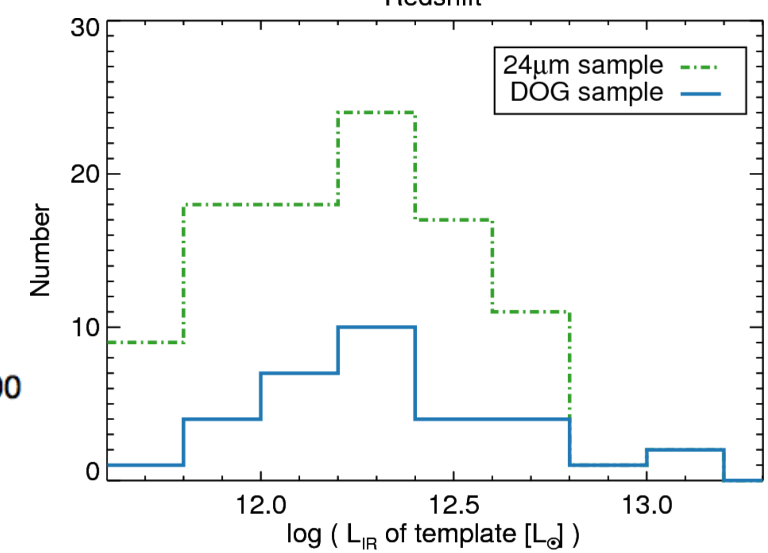
GOODs DOGs

Penner et al. 2011

Dust-Obscured Galaxies: F24/F(R) > 1000 (Dey et al. 2008; J. Melbourne's talk)







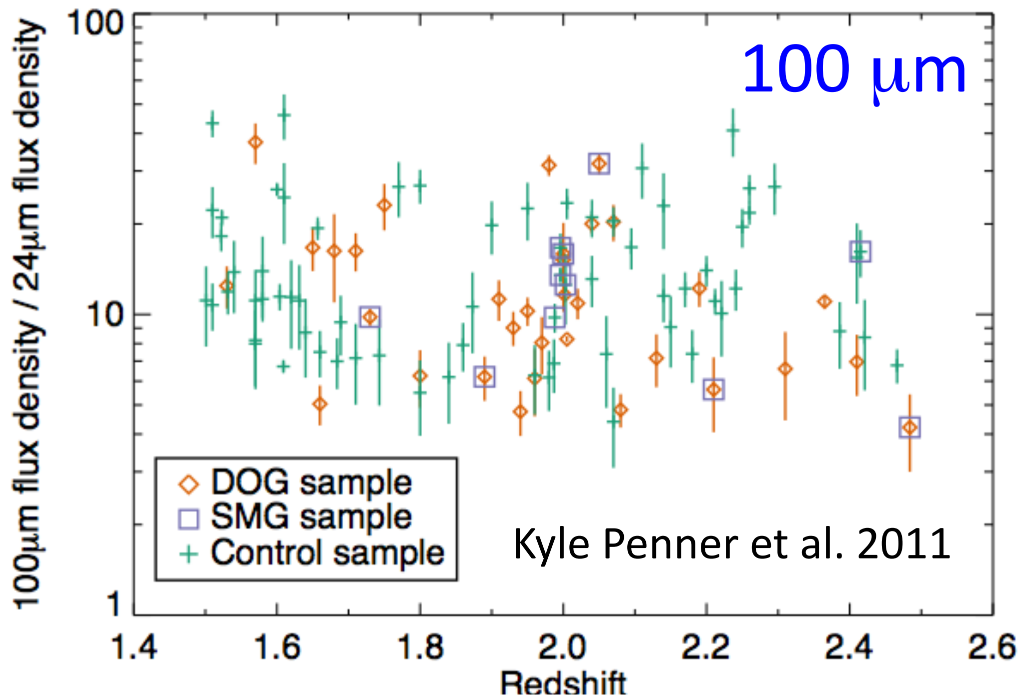
Are DOGs unusually bright in the mid-IR, or unusually faint in the UV?

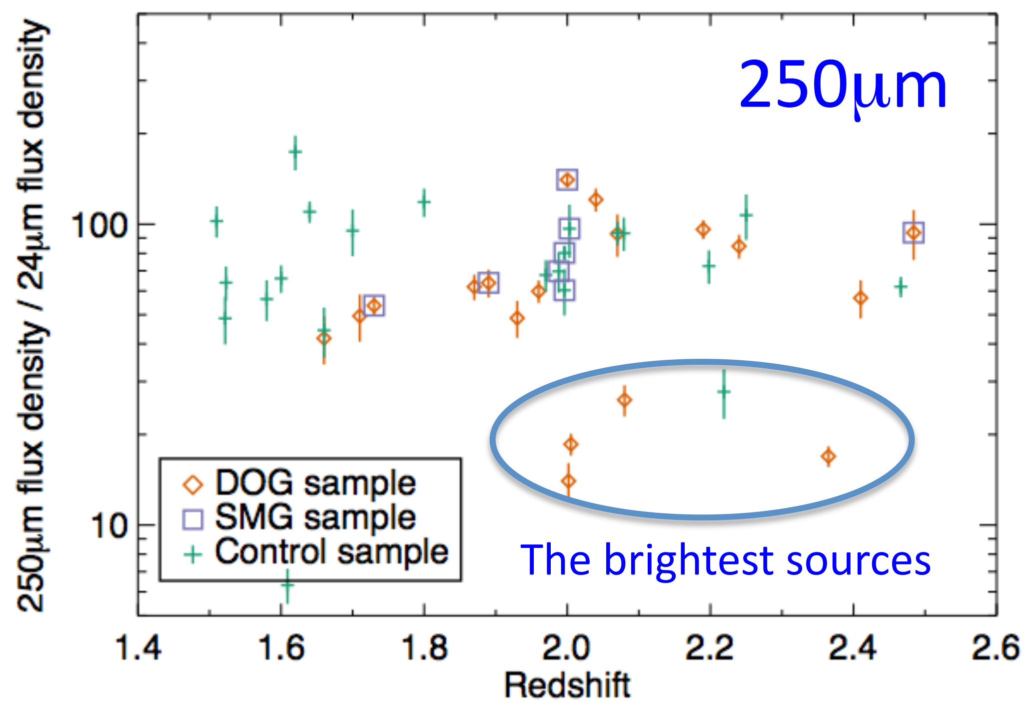
Mainly the latter:

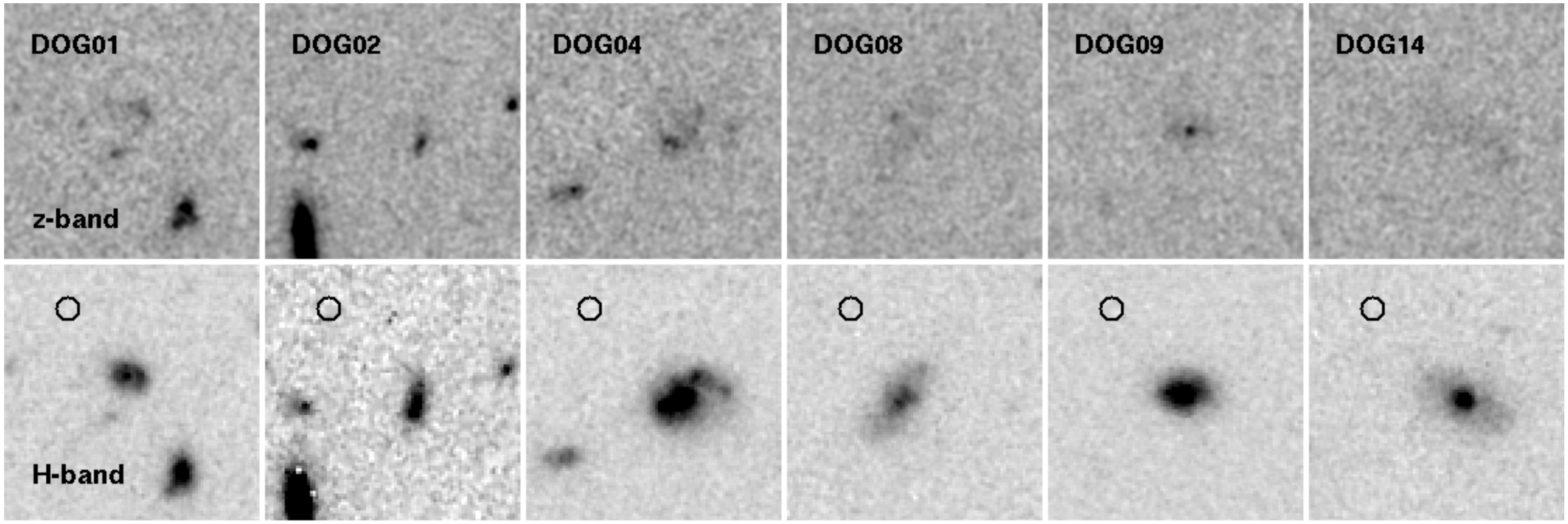
Far-IR / 24μm ratios are indistinguishable for DOGs and non-DOGs

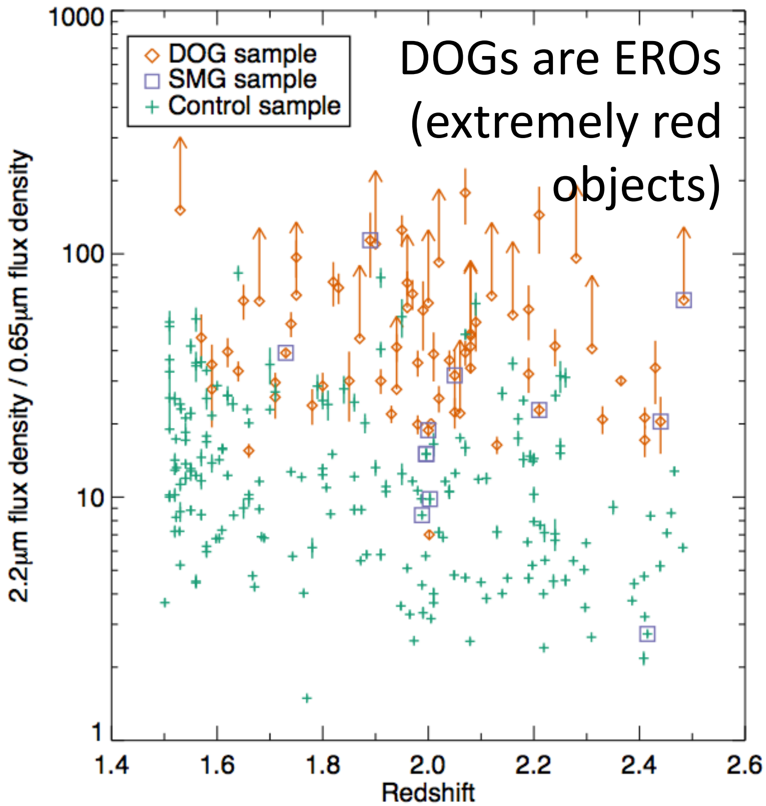
(Conclusion is statistically robust when non-detections are taken into account with survival analysis.)

The few brightest 24μm sources do show lower S250/S24, probably indicating excess mid-MIR emission – likely AGN (see J. Melbourne's "power-law dogs")



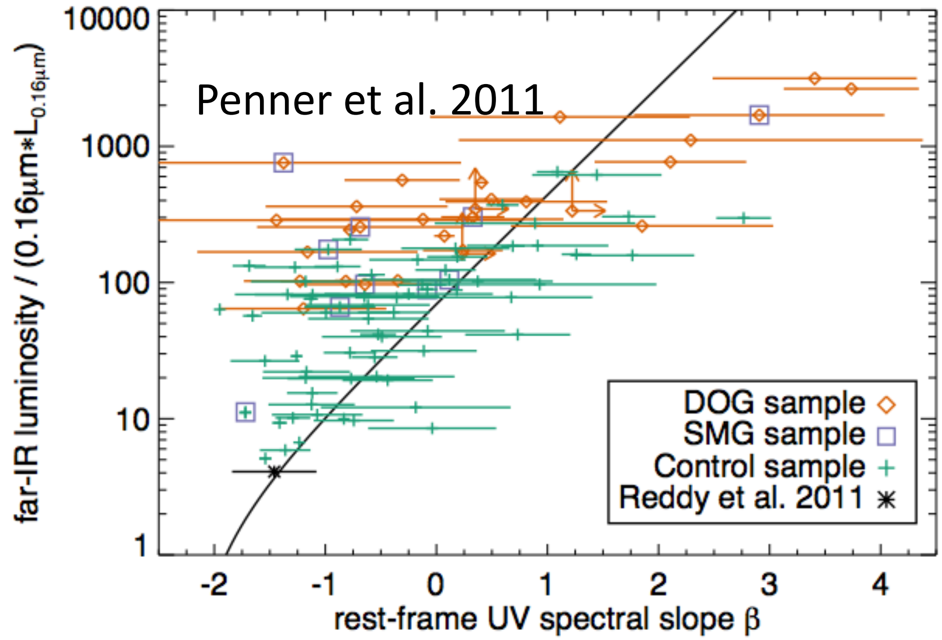


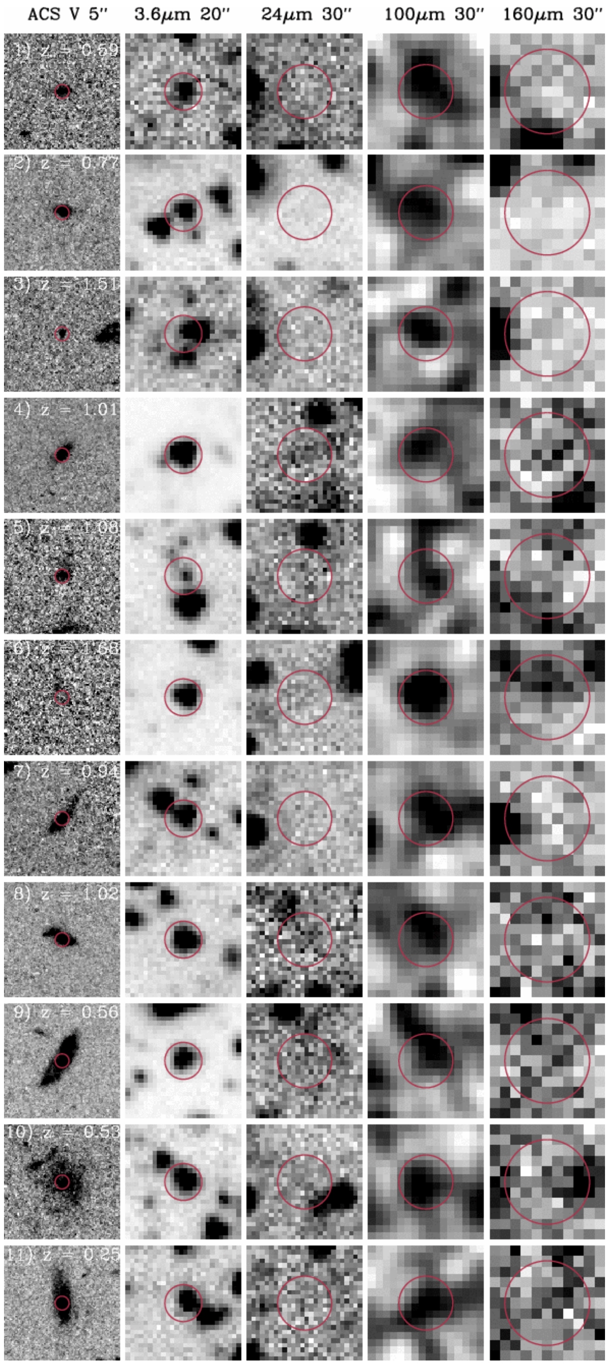


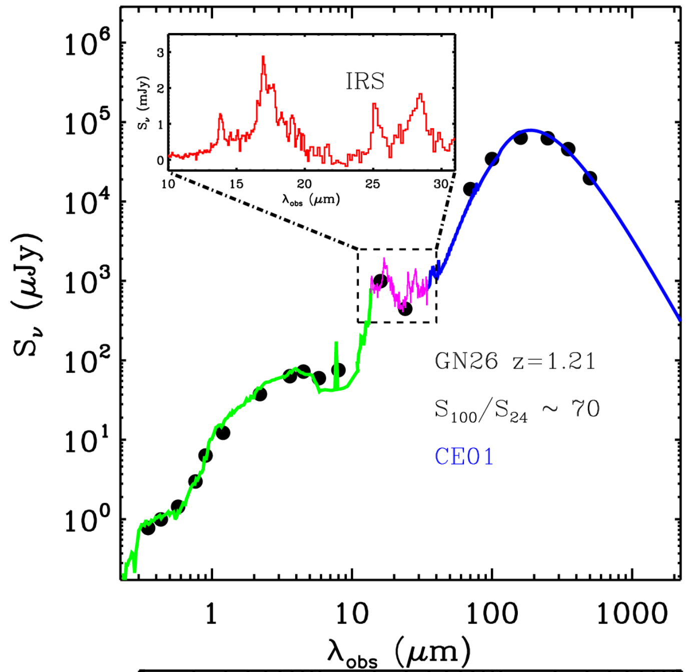


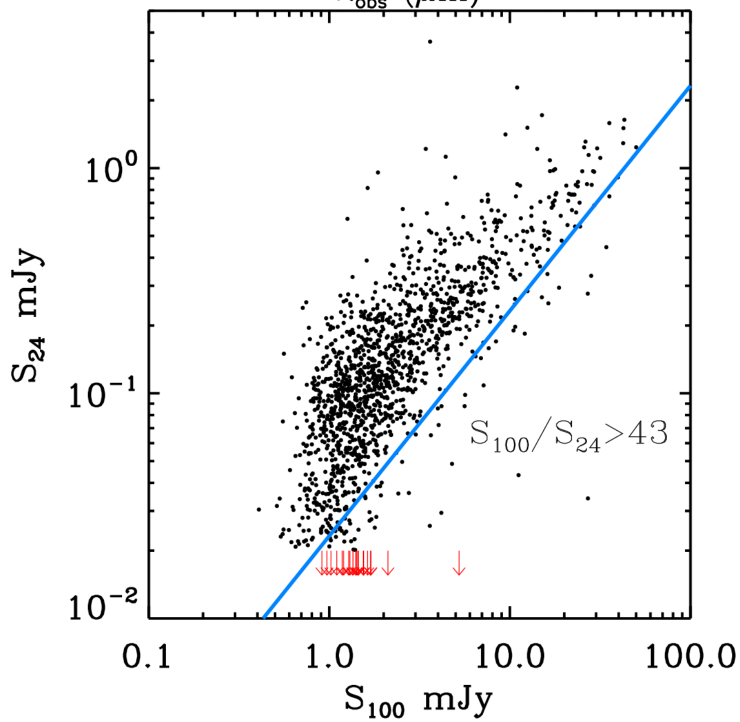
UV slopes are very hard to measure for UV-invisible galaxies…

But: DOGs are not all wildly off IRX-β









24μm "dropouts"

Magdis et al. 2011a

Detected in PACS,
< 20 μJy at 24μm

Faintest members of a population with $S_{100} / S_{24} > 43$

Mainly found at z≈1.3 and z≈0.4 – presumably due to 9.7 and 18 μm silicate absorption

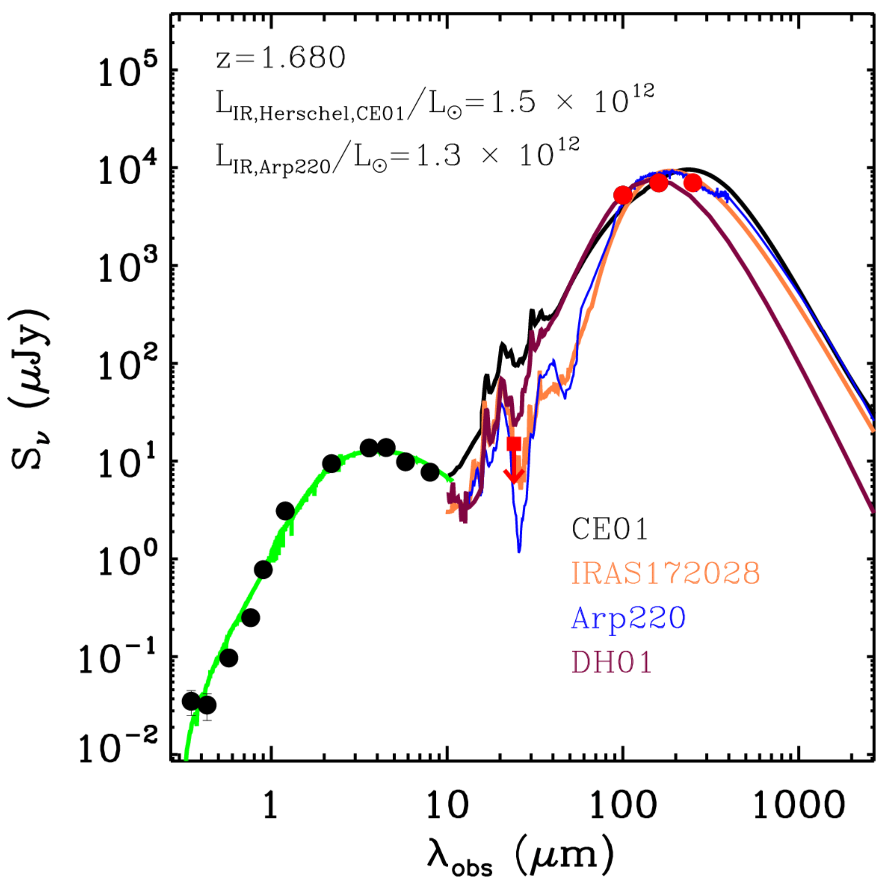
These are 8-16% of (U) LIRGs at 1 < z < 2.

True "dropouts" are rare in GOODS – 1-2% of 24μm sources at z > 1

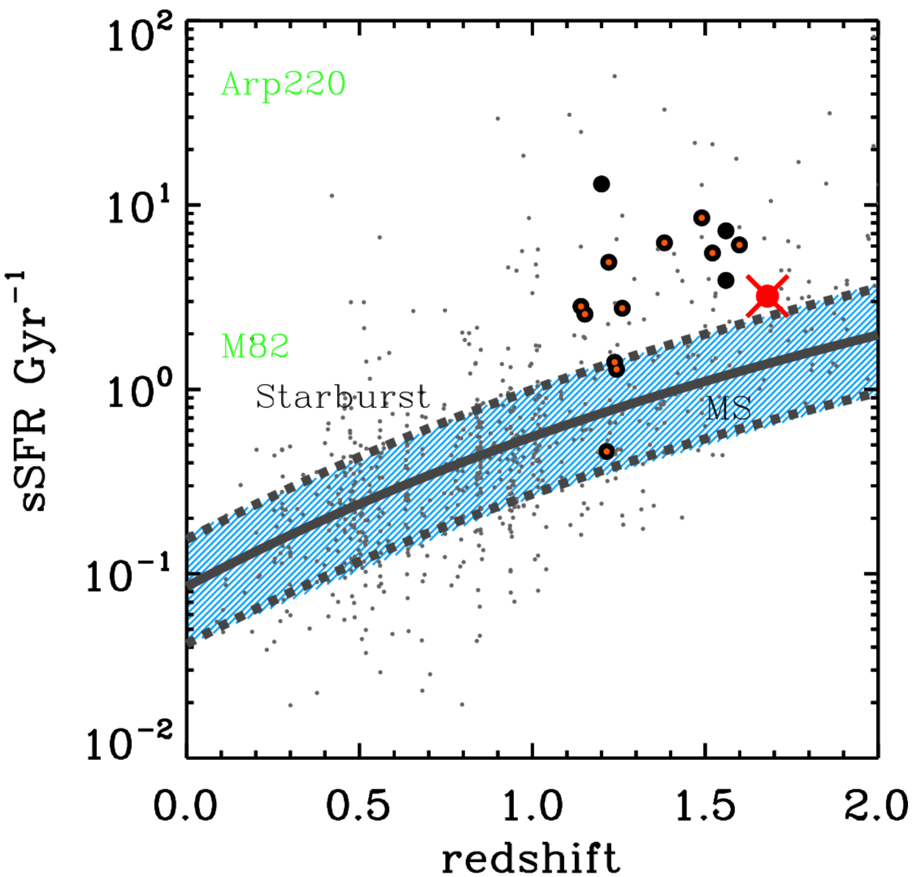
Silicate absorbed sources are mainly starbursts

Magdis et al. 2011a

Bona fide z ≈ 1.7 ULIRG missed in GOODS 24μm



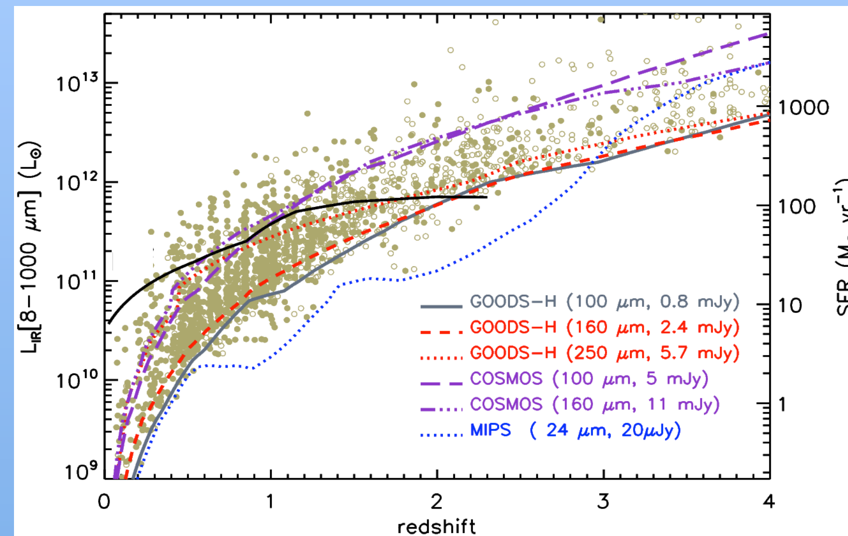
High-S100/S24 sources mostly lie well above the main sequence at z > 1

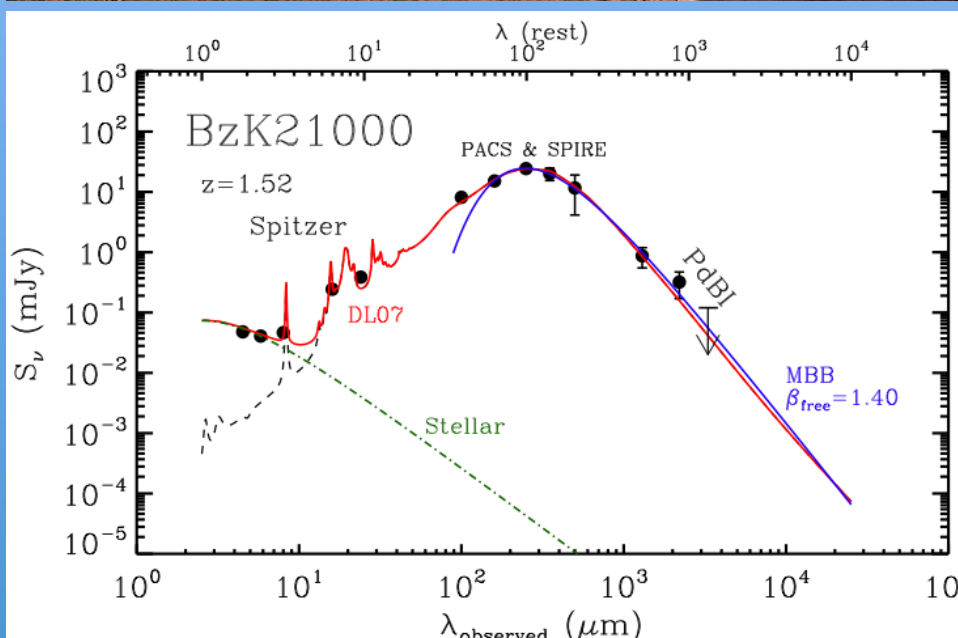


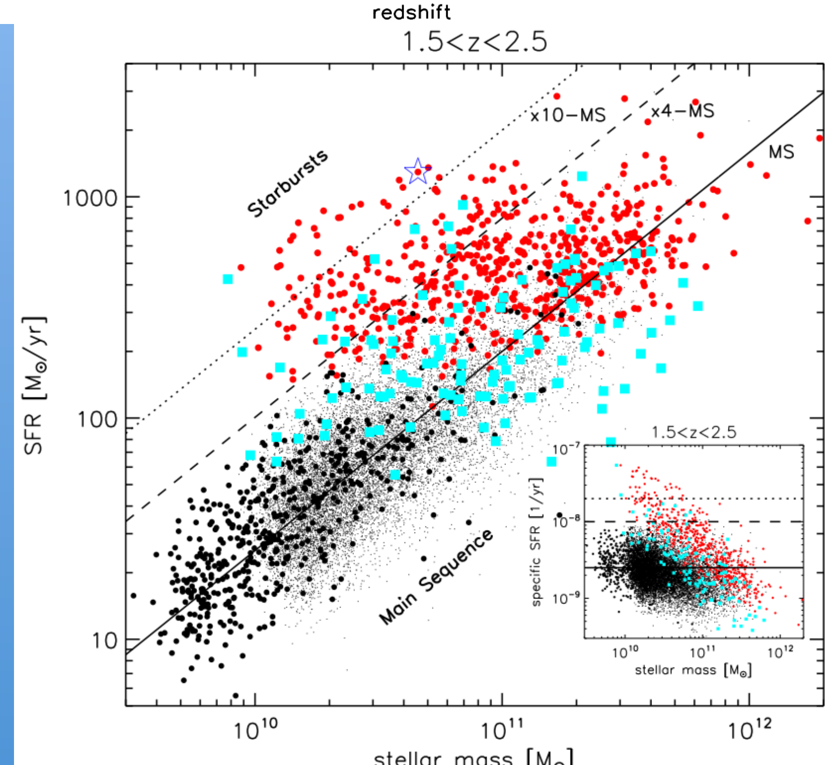
Summary

- Herschel has enhanced our understanding of the main sequence / starburst paradigm at high redshift
- There is an "infrared main sequence", where the SED shape (especially mid-IR/far-IR ratio) correlates with the specific star formation rate and with star formation surface density
- ULIRGs at $z \approx 0$ are all starbursts; ULIRGs at $z \approx 2$ can be MS
- Mis-application of local starburst SED templates to high-z MS galaxies leads to the "mid-IR excess" problem
- AGN reside mainly in massive (~10^{11} M_o) galaxies on or slightly below the main sequence, whose SFRs evolve with redshift like those of other MS galaxies
- DOGs are dusty
- Silicate-dropouts exist, are fairly rare, and are mainly starburst galaxies

We will miss Herschel when it's gone…

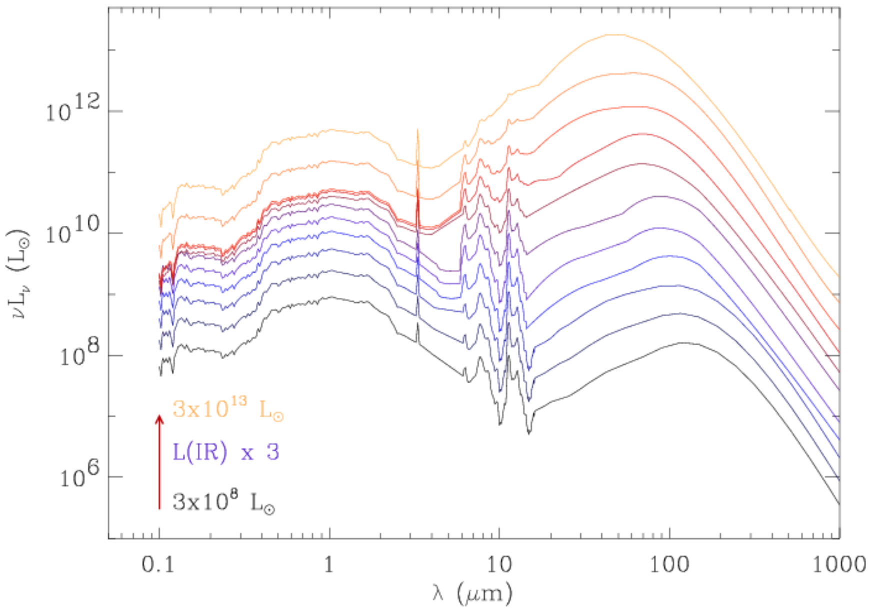


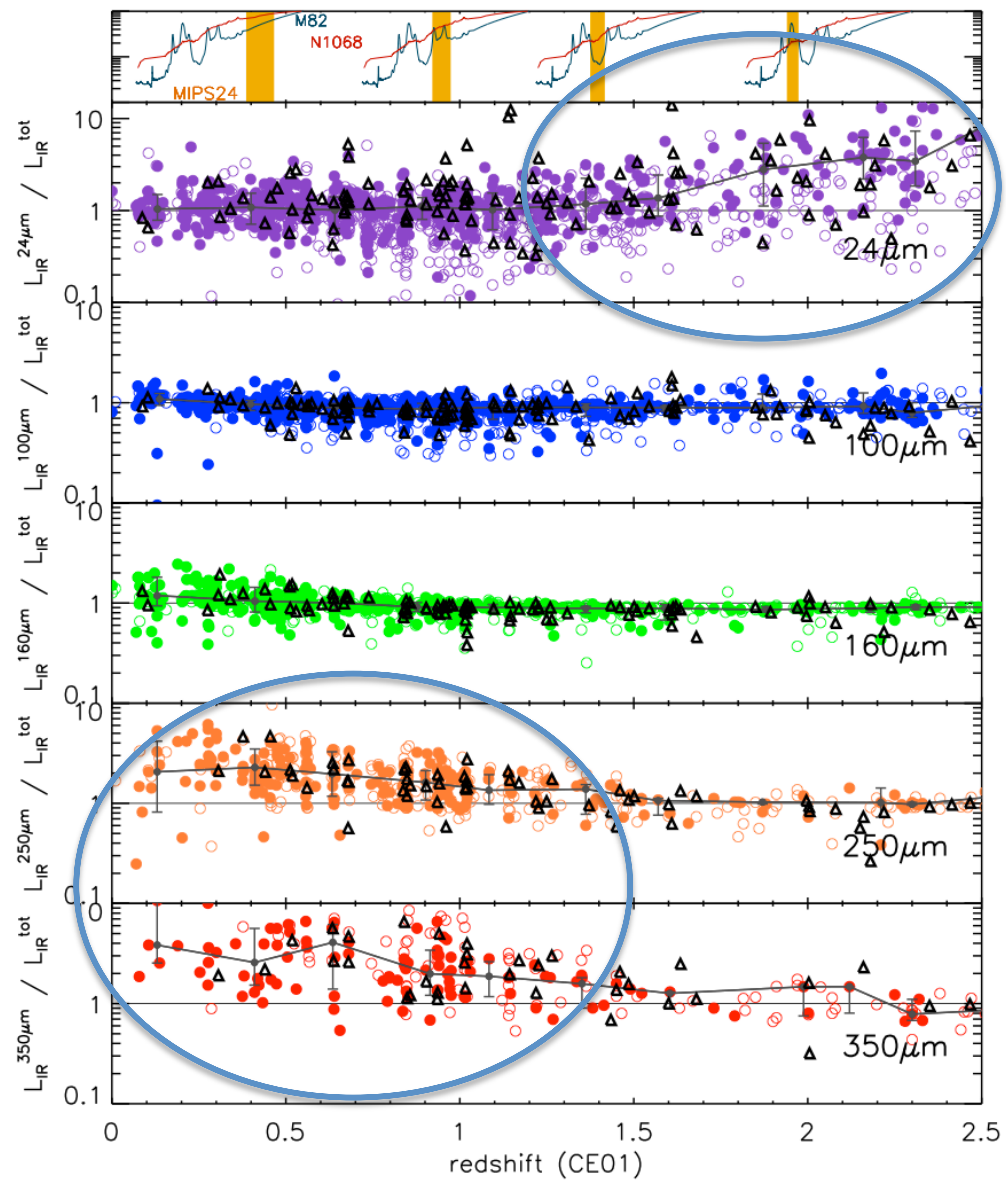




Extra slides

Improving bolometric corrections for star-forming galaxies





CE01 library:

- 24μm over-predicts L_{IR} at z > 1.3 (the "MIR-excess" problem)
- SPIRE over-predicts L_{IR} at z < 1.3 (not enough cold dust in CE01 templates)

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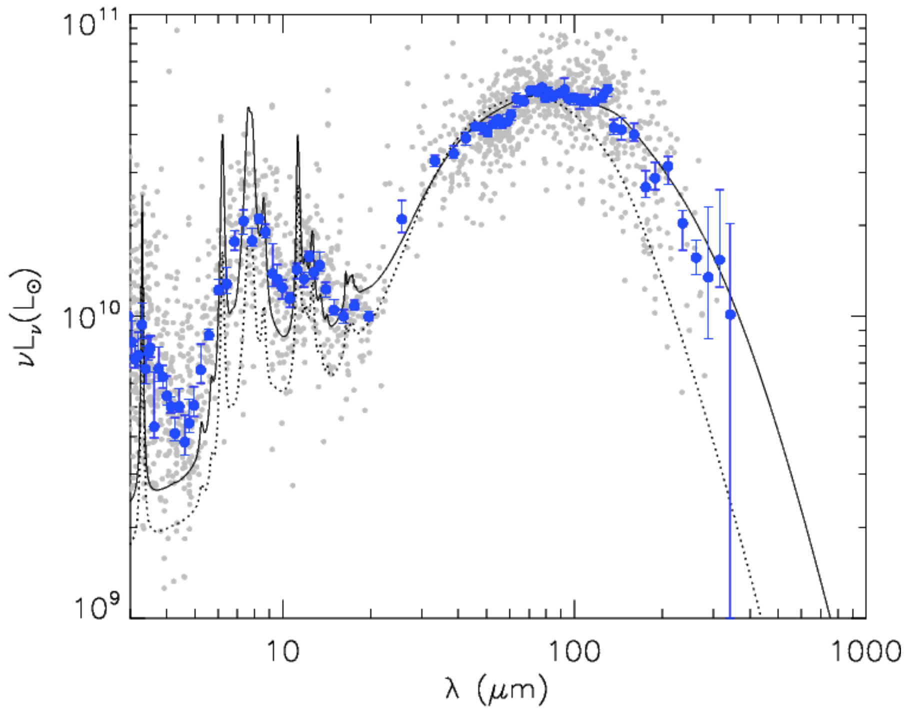
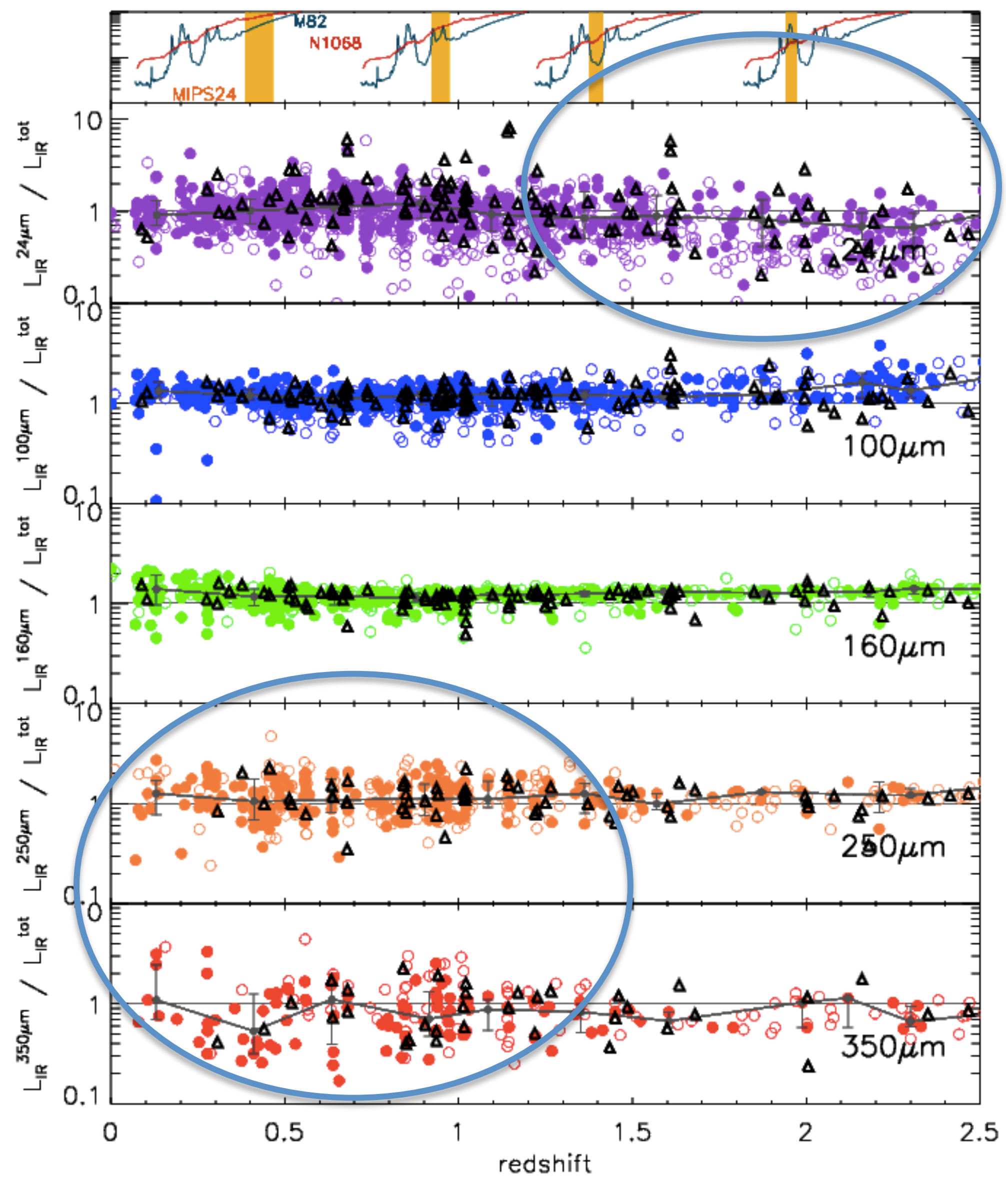
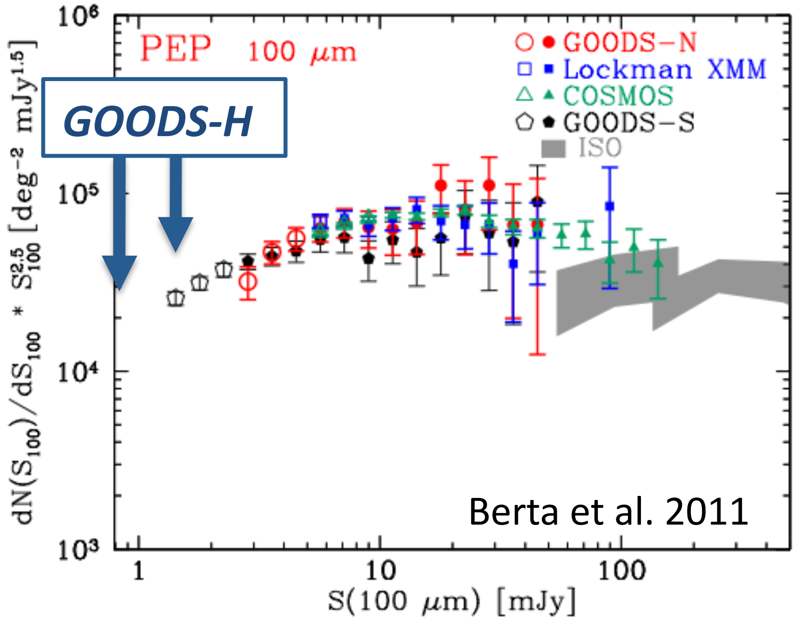
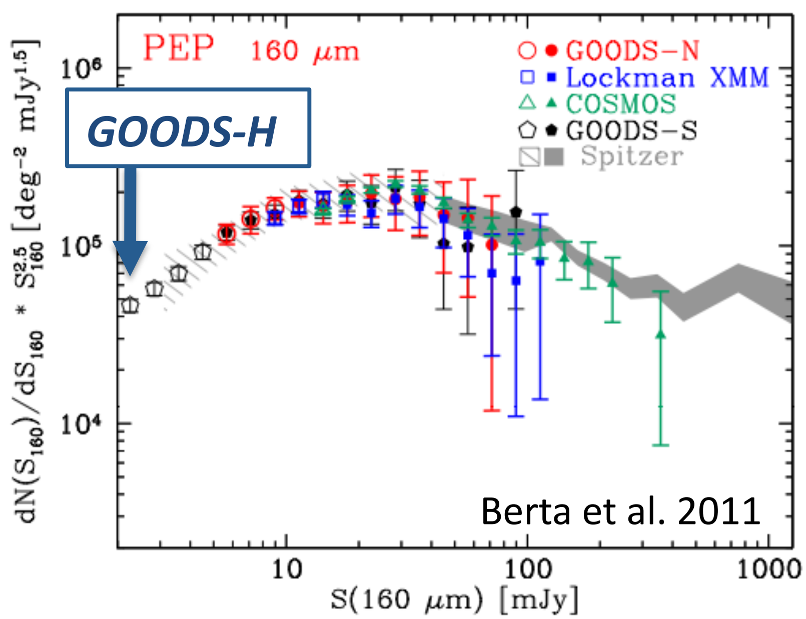


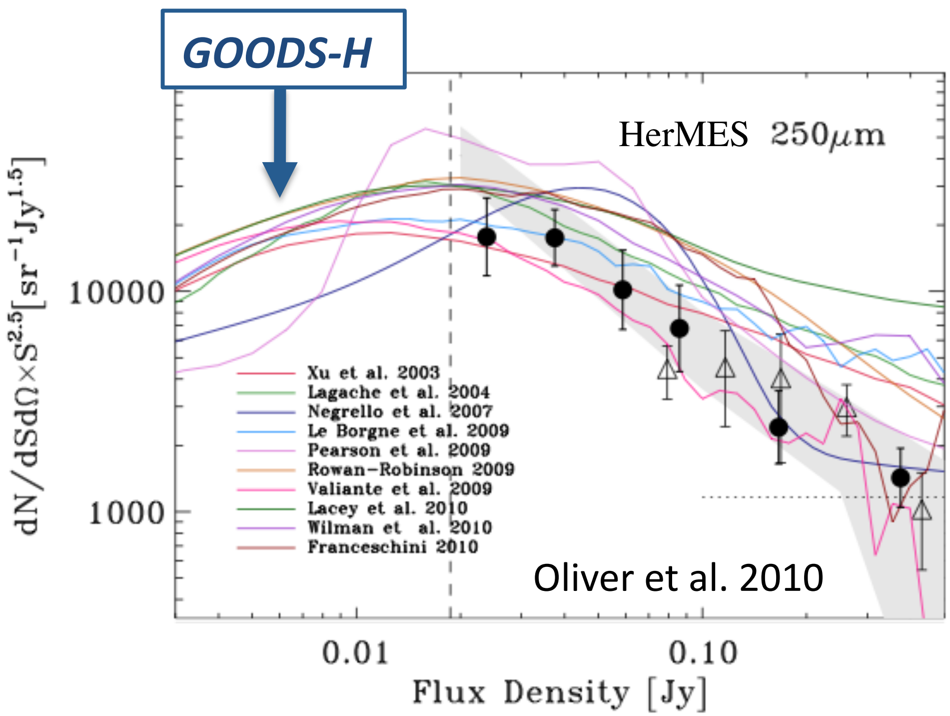


Elbaz+2011 main sequence SED (single template for all galaxies):

- Fixes the “MIR-excess” at high z (although it will underestimate L_{IR} for starbursts)
- More cold dust fixes L_{IR} from SPIRE at low z







GOODS-H: Daring to achieve the ordinary!