In and Out the main sequence of star-forming galaxies at z=2

Giulia Rodighiero (Universita' di Padova)

On behalf of the PEP Team

BOLOGNA – 12 April 2012

COSMOS 24 100 160 μm

The Main Sequence at Low and High Redshift

The Outliers:

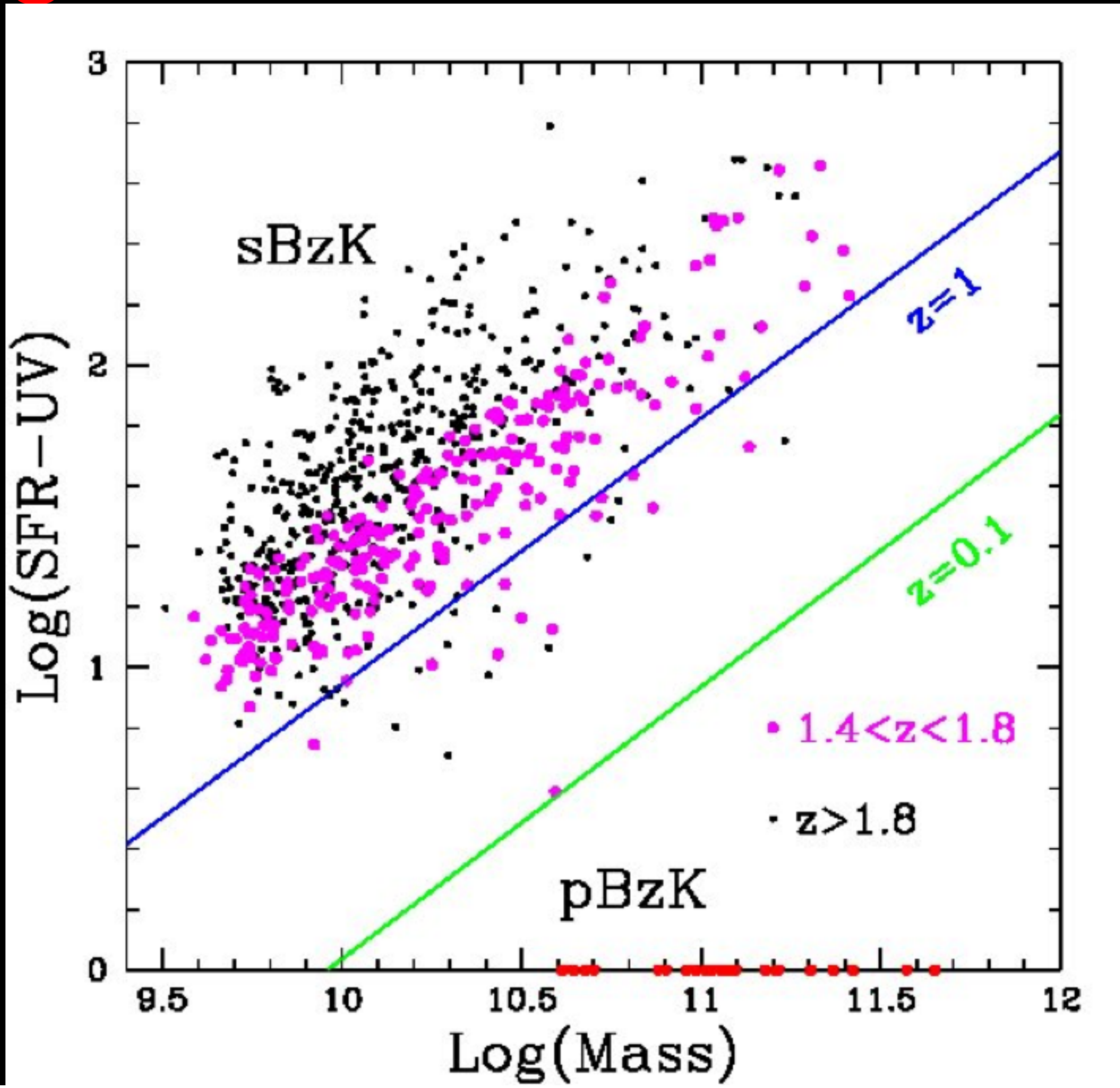
- red starbursting galaxies
- red & dead (quenched) galaxies

Herschel looking at COSMOS & GOODS fields

The relative role of starbursts and quasi-steady SFR in the mass growth of galaxies

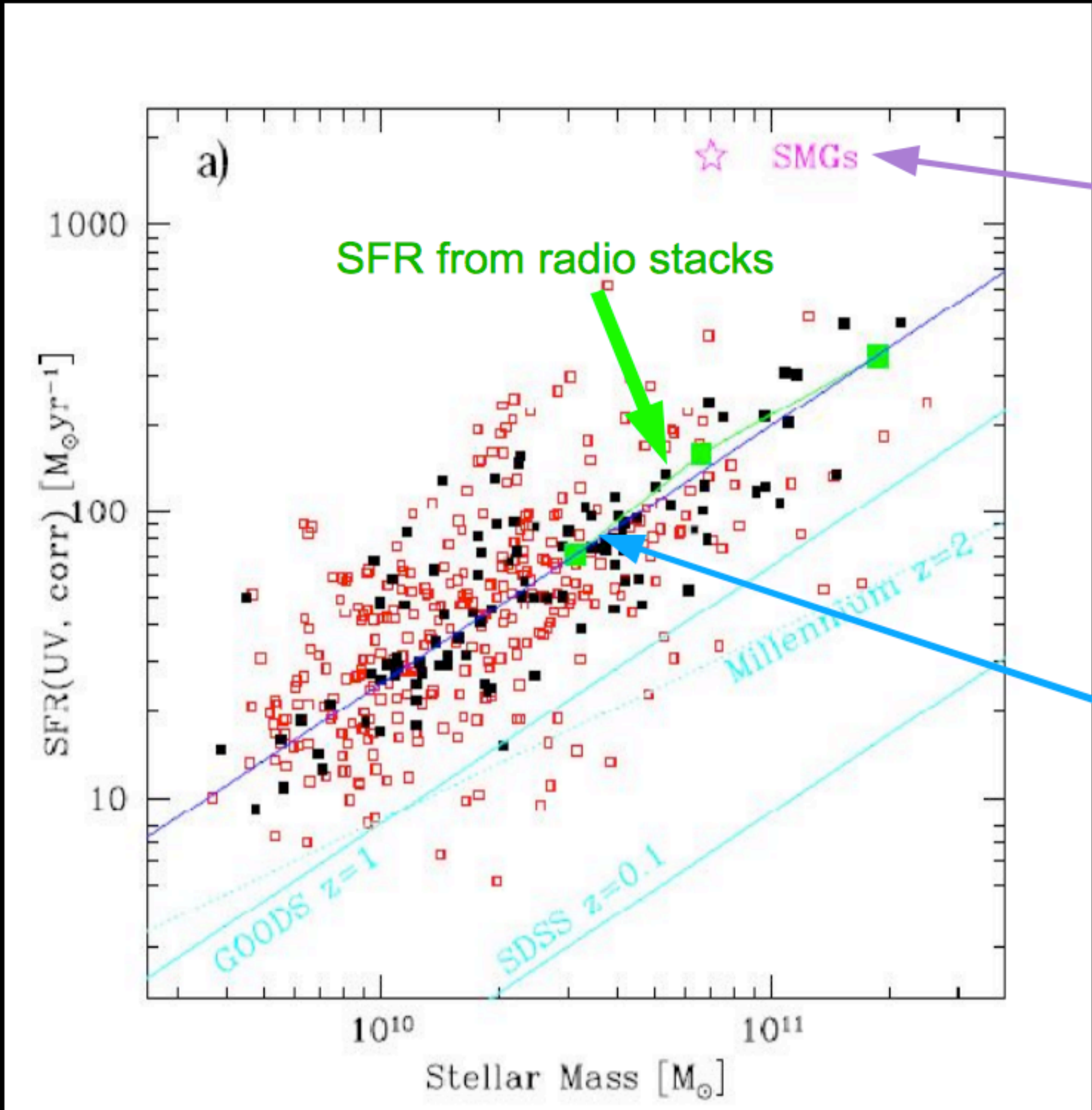
Other PEP results

The Main Sequence of Star-forming galaxies at 1.4 < z < 2.5



Alvio Renzini

Starbursts or just high SFR at z~2?



SMGs may be the real, major-merger driven, starburst galaxies

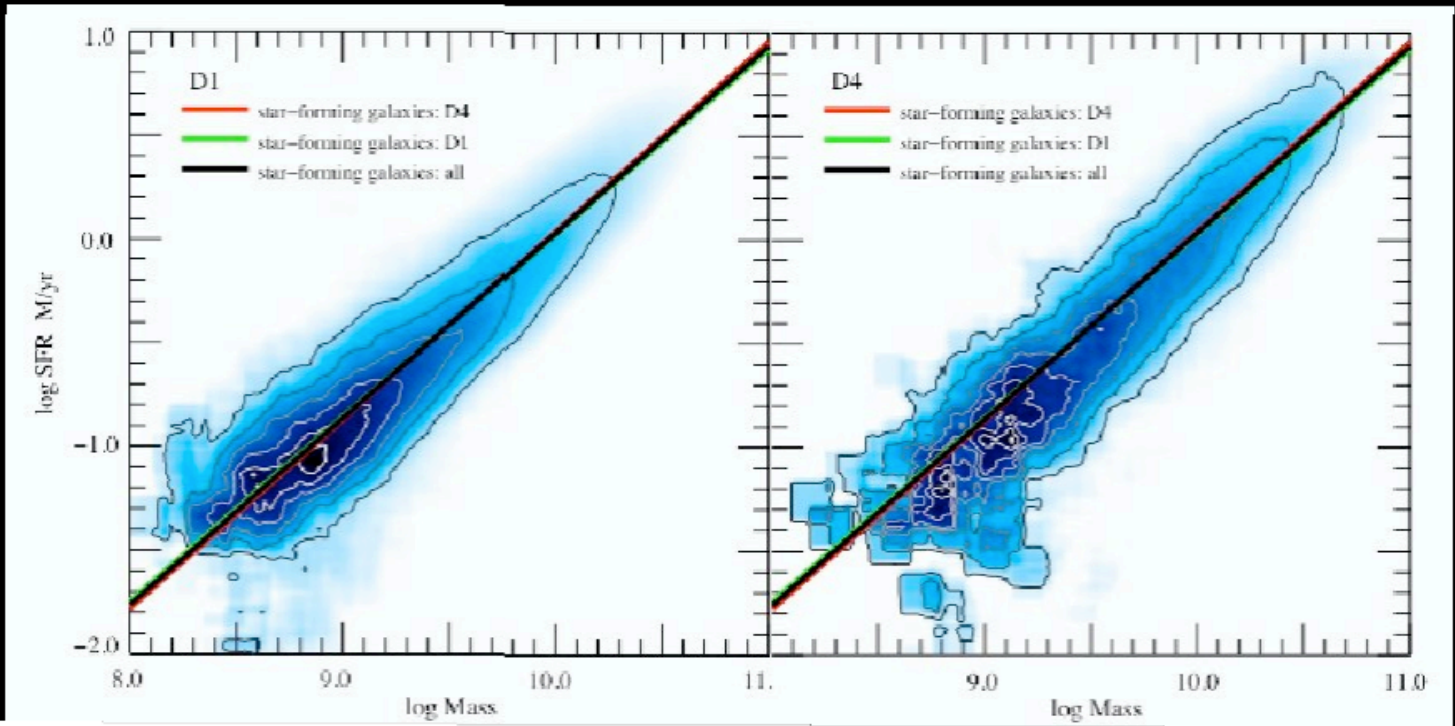
SFR $\propto$ ~$M^{0.9+/-0.1}$ with very small dispersion!!

No starbursting galaxies!

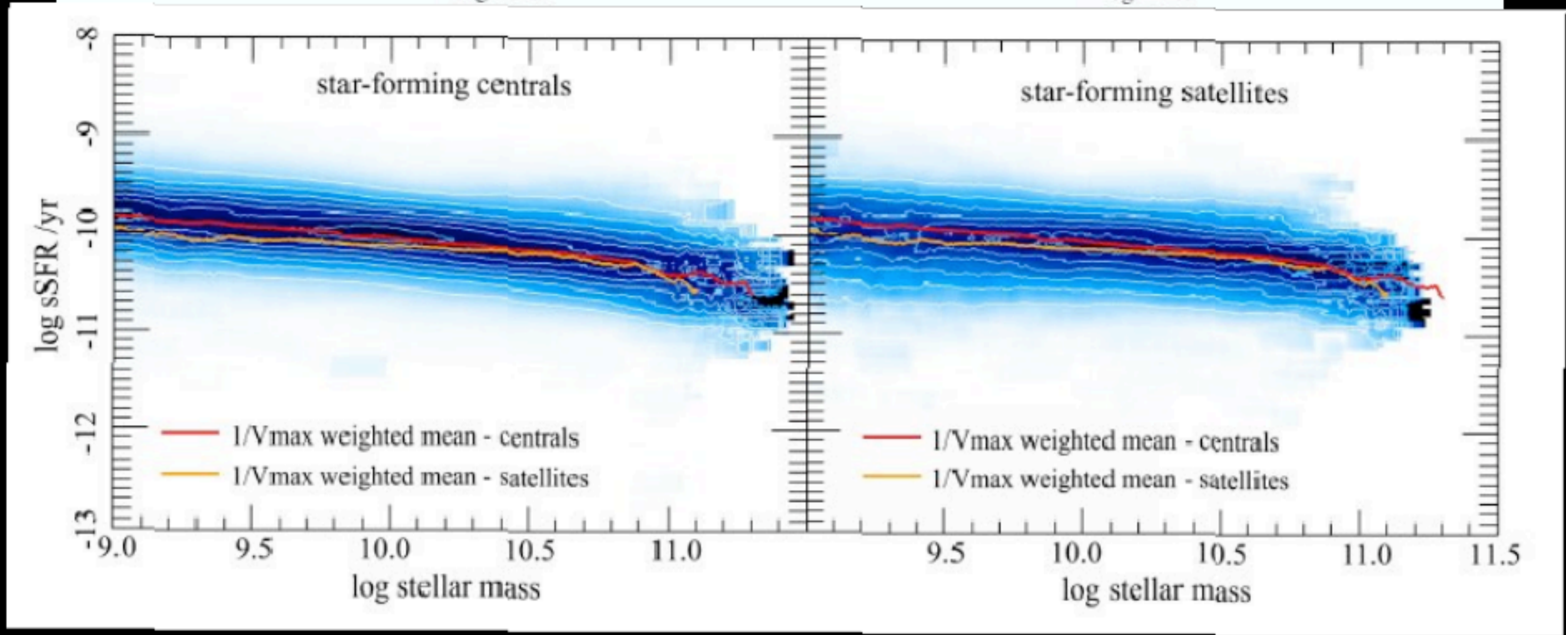
just galaxies with high SFR, continuously fed by cold-stream accretion!

GOODS-S Field: Daddi et al. 2007

The SFR-M* relation in the local Universe



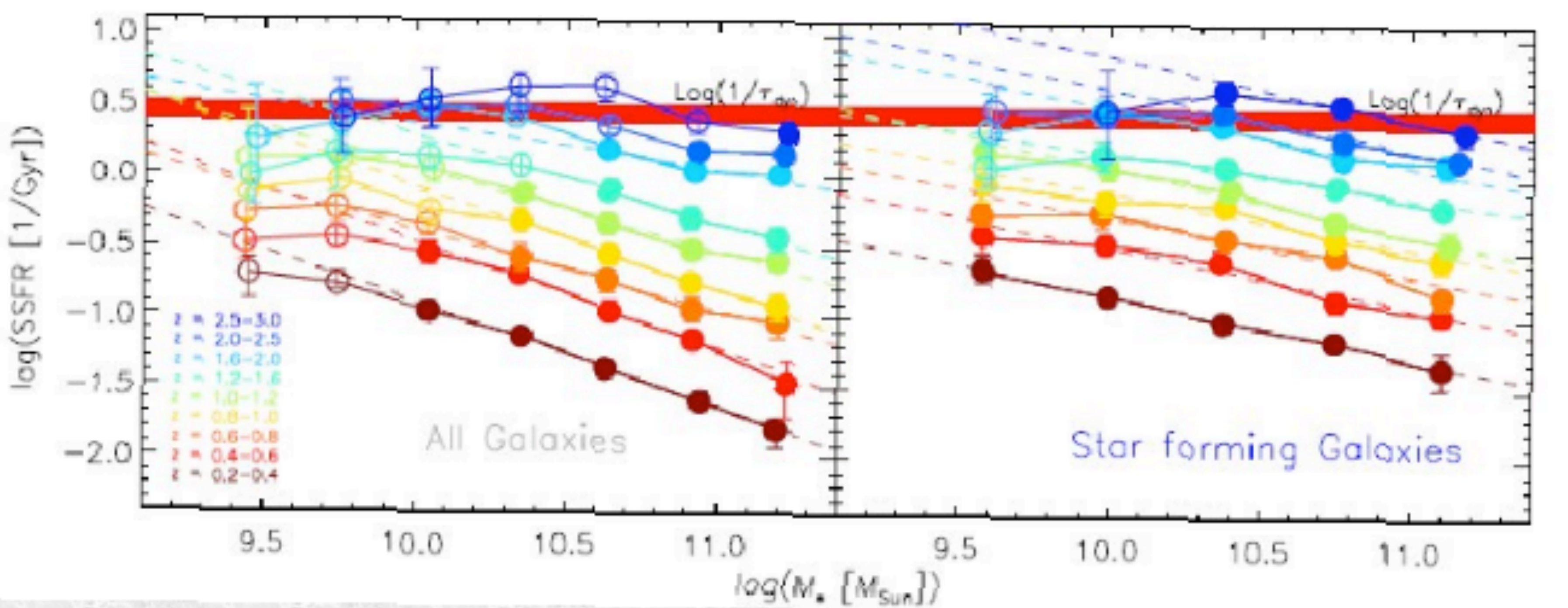
From SDSS data, SFR from Hα, Peng et al (2010)



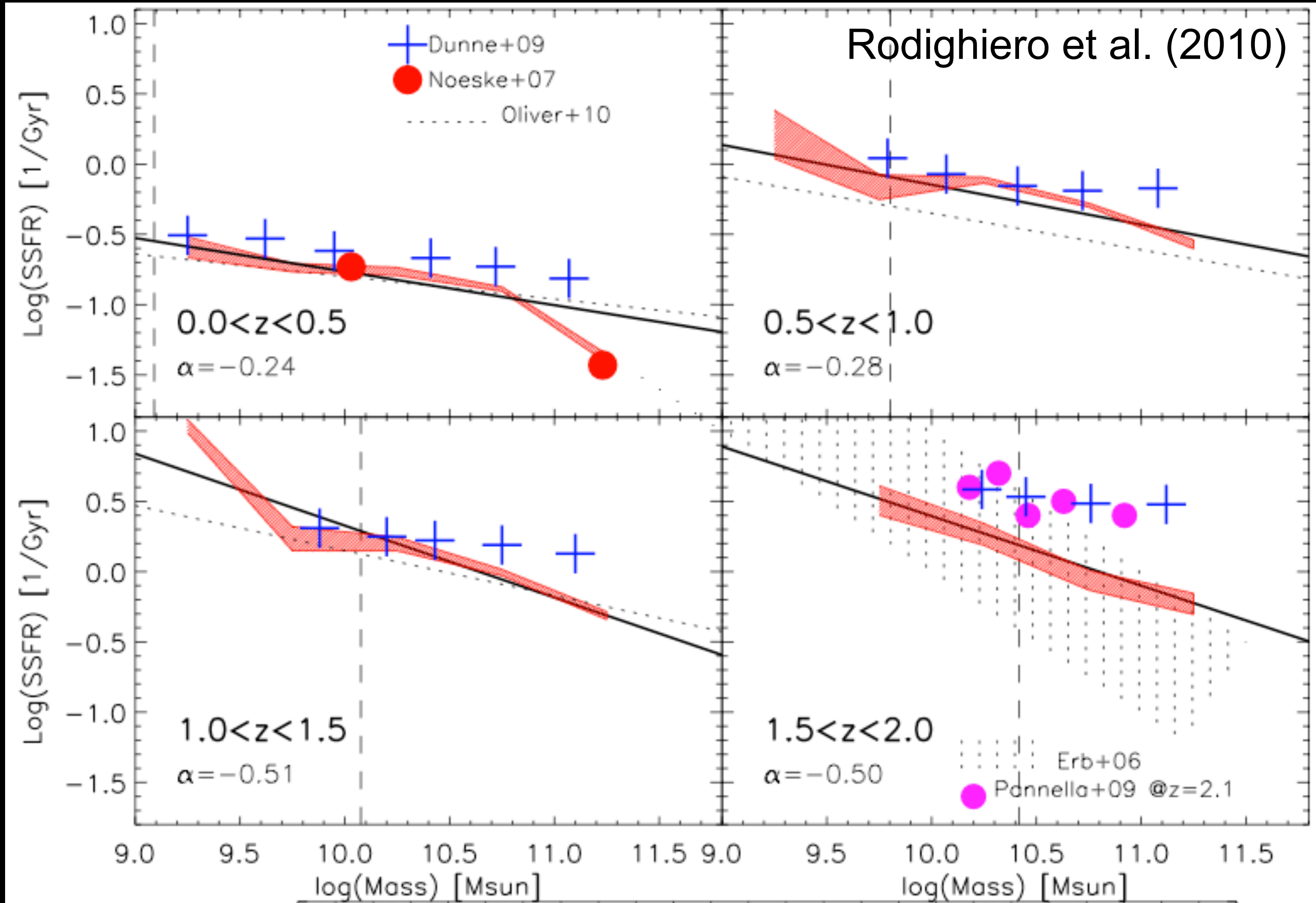
Peng et al. (2011)

A Caveat: not all measurements of the SSFR agree …

Another estimate of the SSFR from stacked radio data, Karim et al. (2011)



STACKING analysis on PACS maps



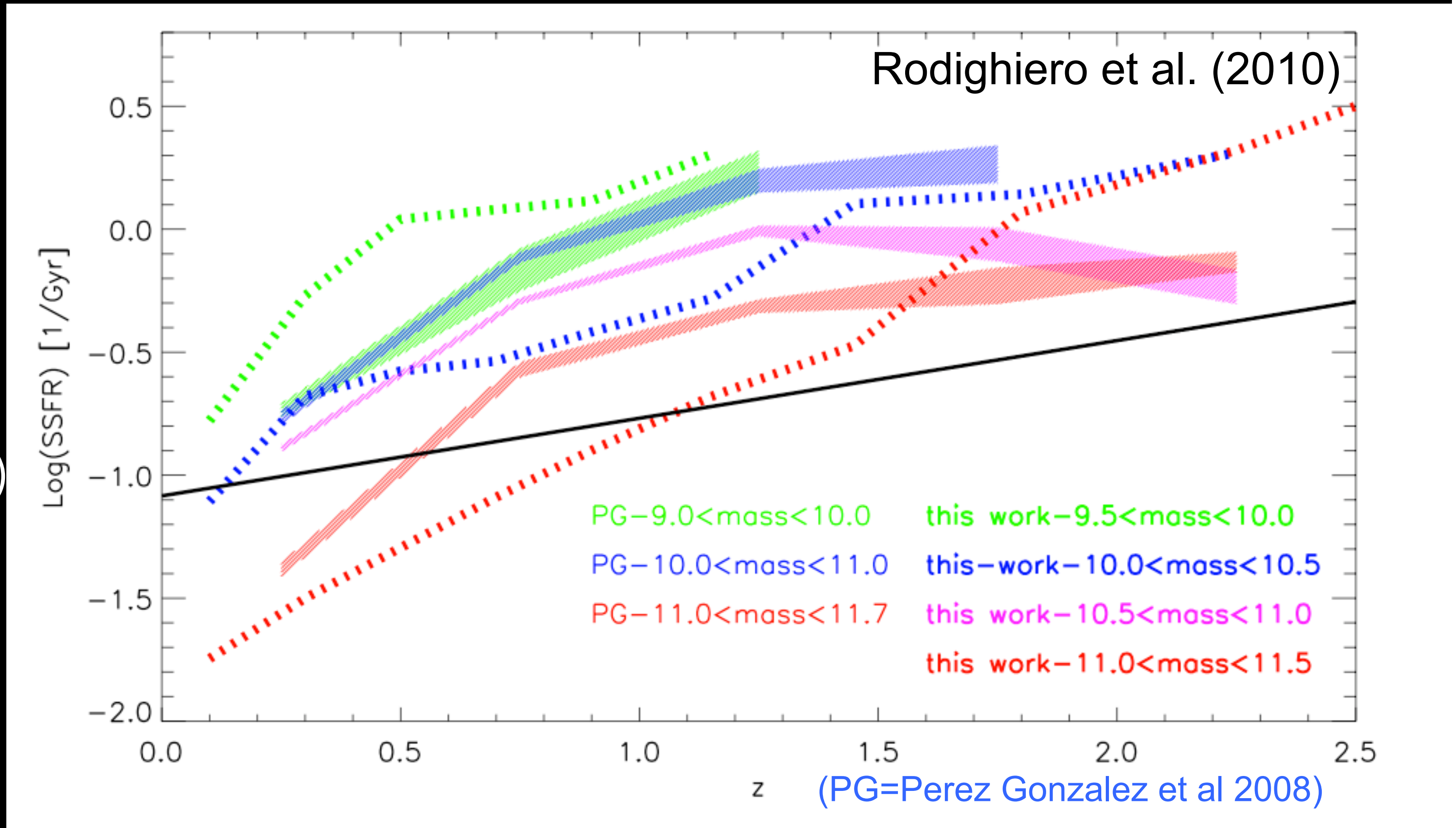
The slope of the Herschel SSFR-mass relation becomes steeper with redshift.

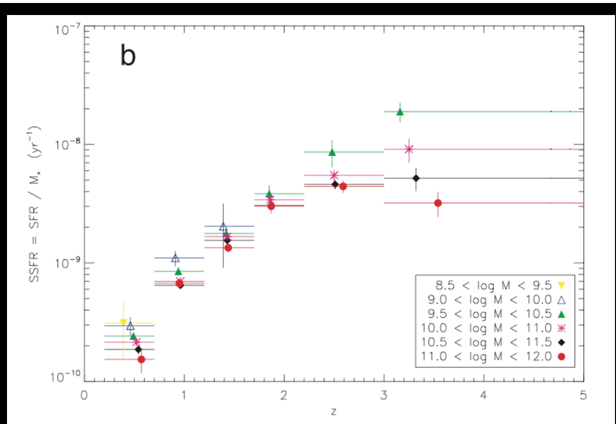
At z<1, our results are in broad agreement with those based on radio-stacking that found almost flat relations up to z~2 (Dunne et al. 2009, Pannella et al. 2009), while at z>1 our relation evolves toward stronger dependencies.

Combining far-IR detection and no-detections: STACKING analysis on PACS maps

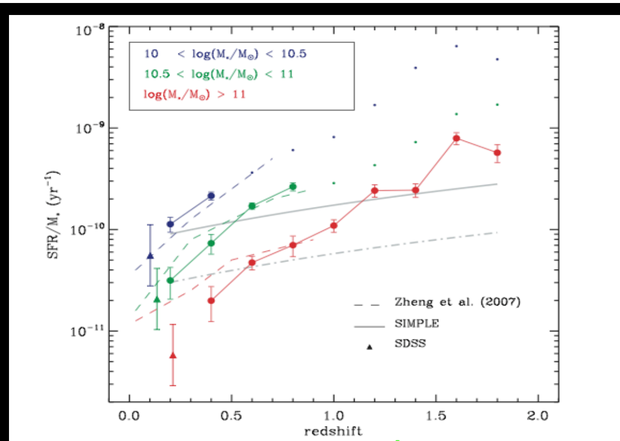
The higher the masses, the lower the sSFR at all z

Flattening above z~1.5 for log(mass) >10.5





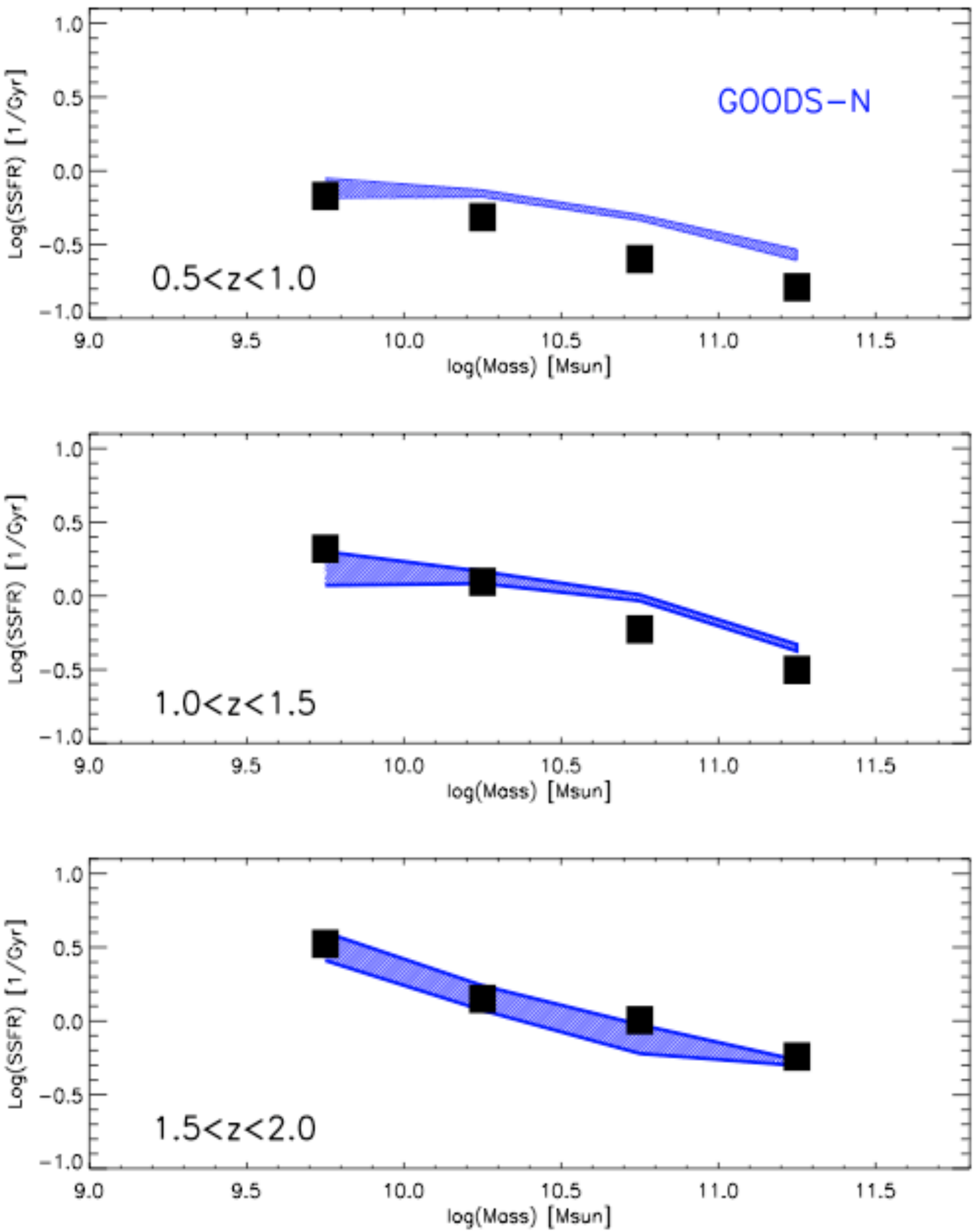
Dunne et al. 2009 – radio stacking



Damen et al. 2009

RADIO vs FAR-IR: good agreement when using the same parent catalog for stacking!

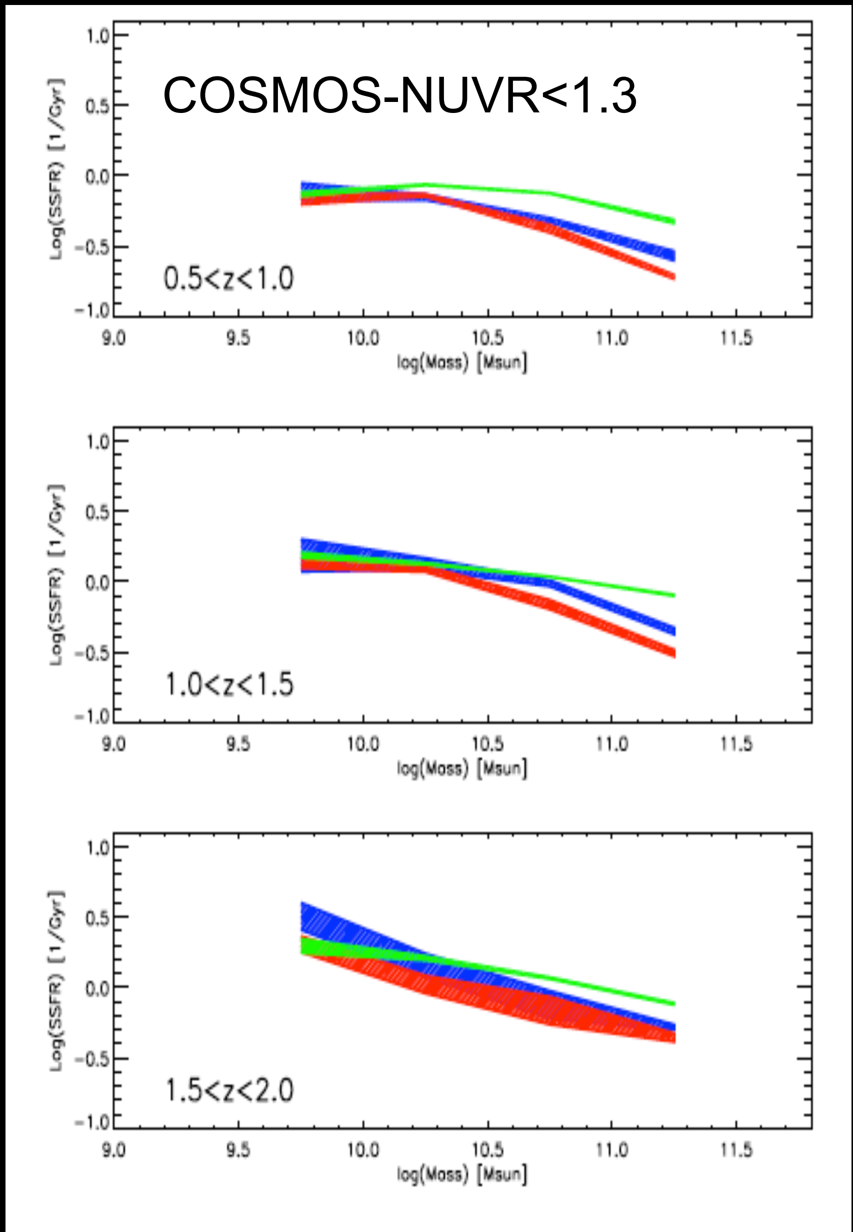
radio analysis by P. Ciliegi



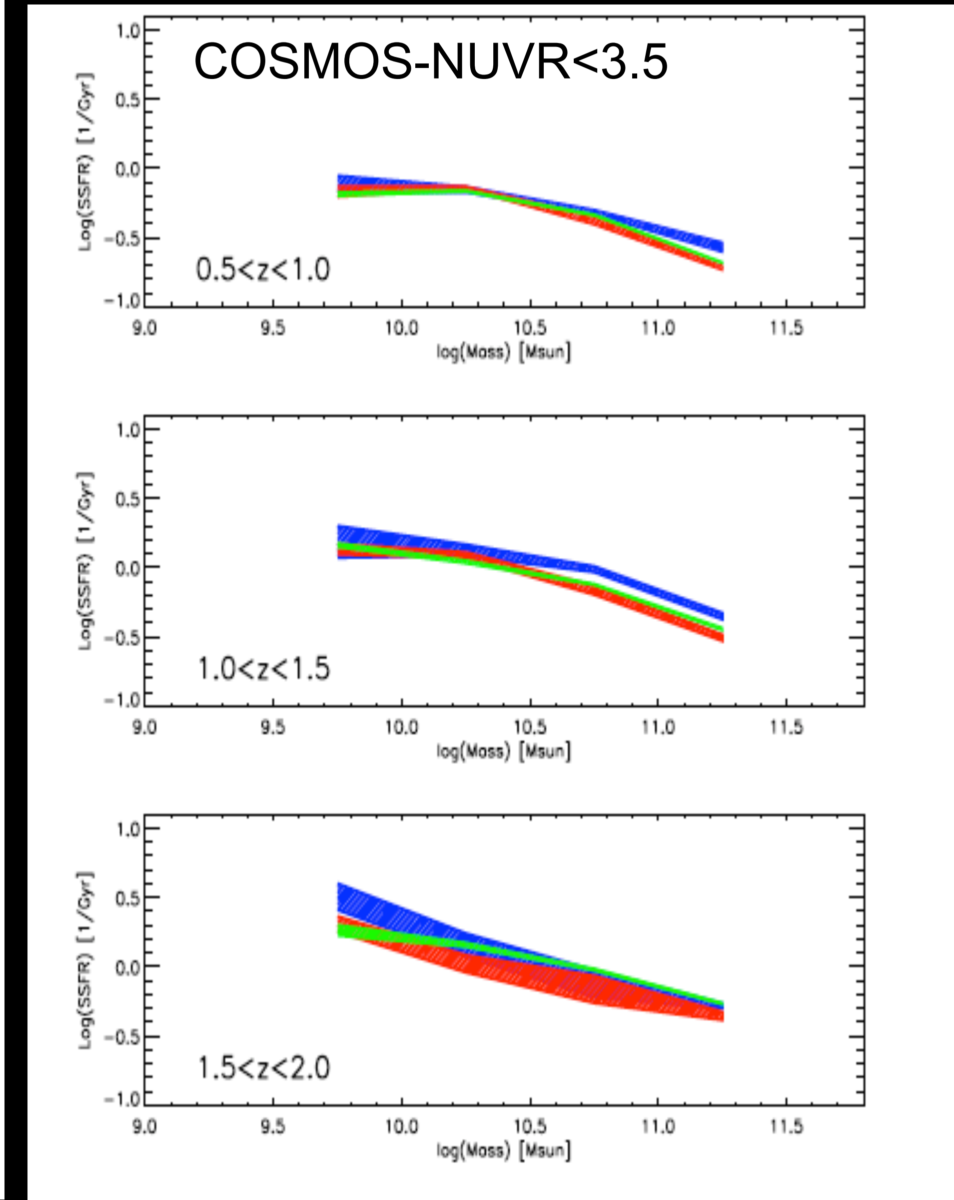
Rodighiero et al. (in prep)

Cosmic variance + Selection techniques

GOODS-N
GOODS-S
COSMOS

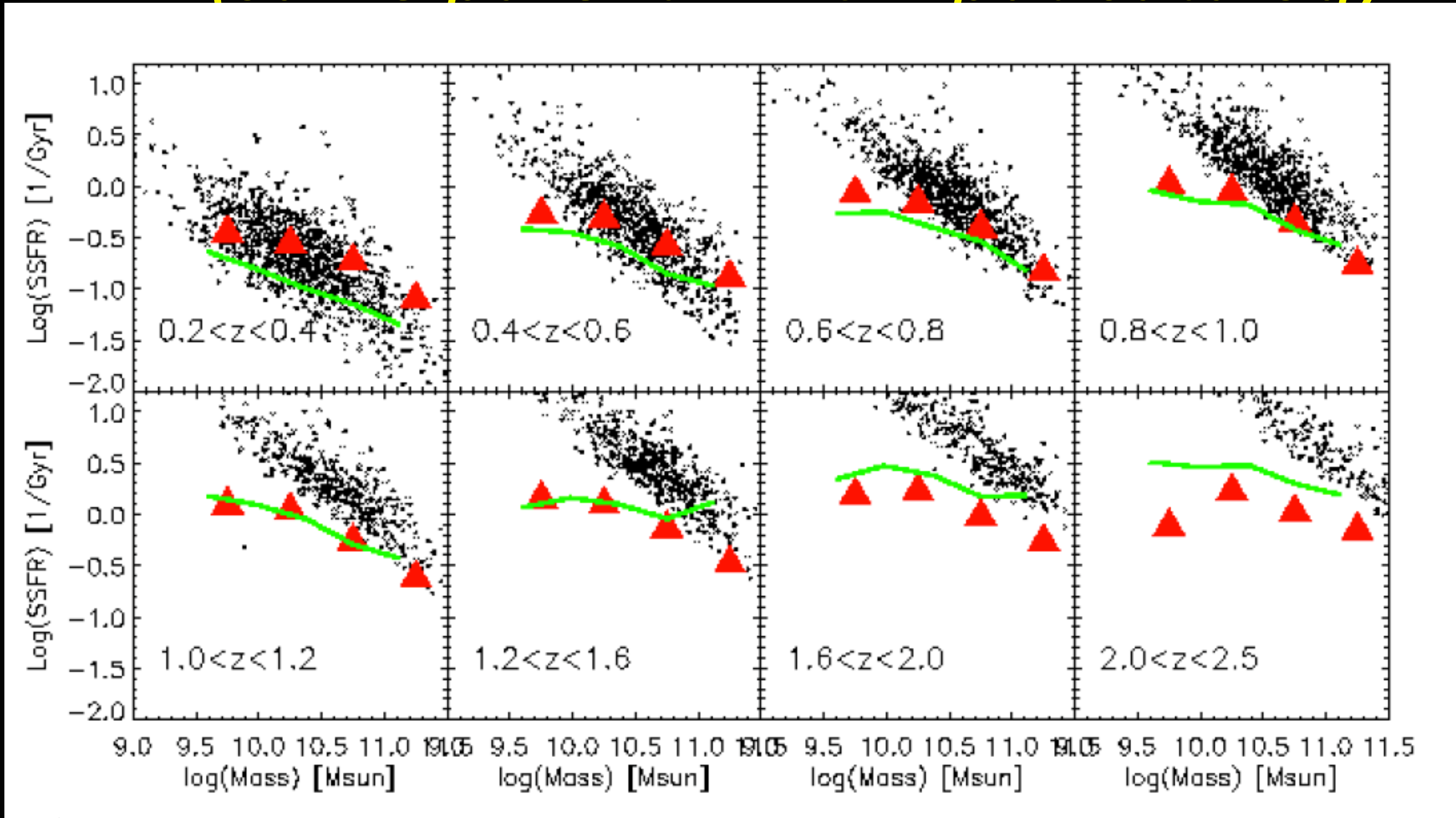


High activity gals (Ilbert criterium)



Intermediate activity gals (Ilbert criterium)

RADIO vs PACS stacking in COSMOS (same parent IRAC input catalog)



PACS stacking

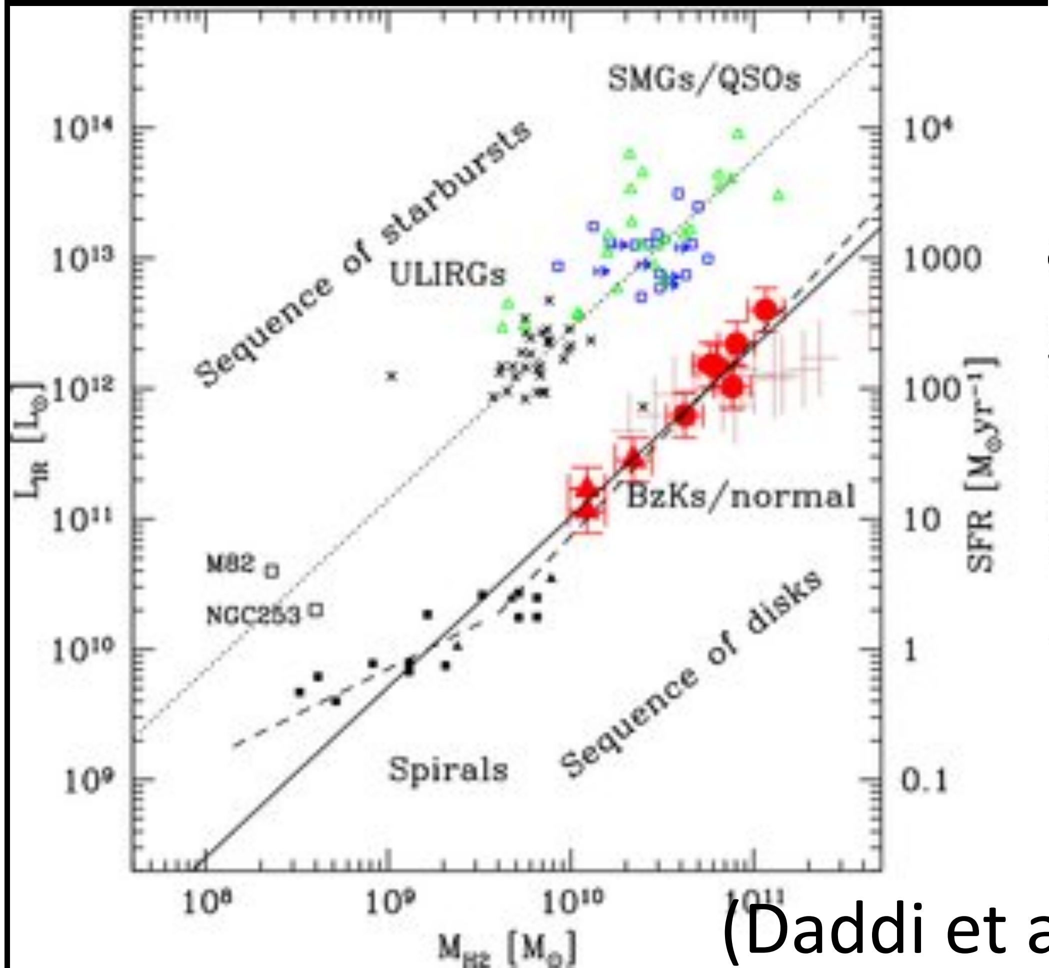
RADIO stacking

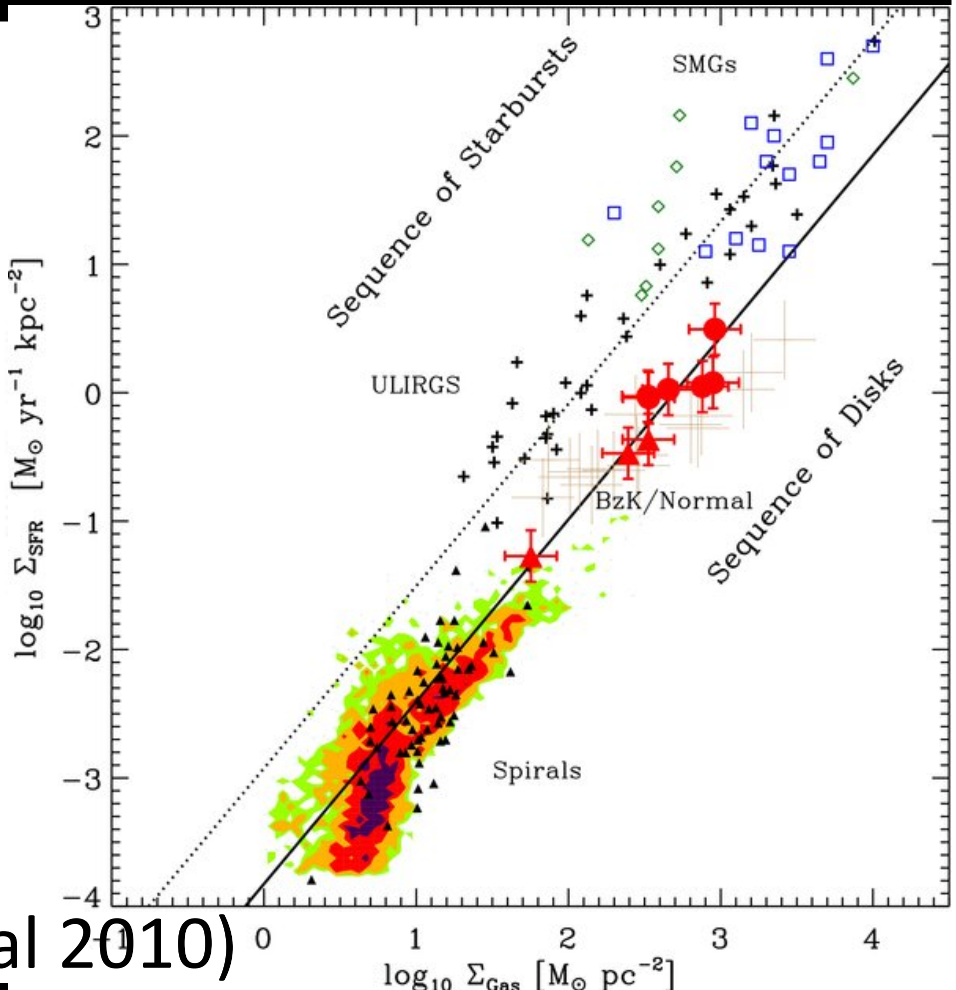
In collaboration with A. Karim & M. Sargent

So… SSFR-mass slope depends on selection (wavelength, flux level, stacking accuracy…):

better to look only at real detections !!!!!!!!

Two regimes of star formation: quasi-steady **on** *the main sequence, starbursts* **off** *of it*





(Daddi et al 2010)

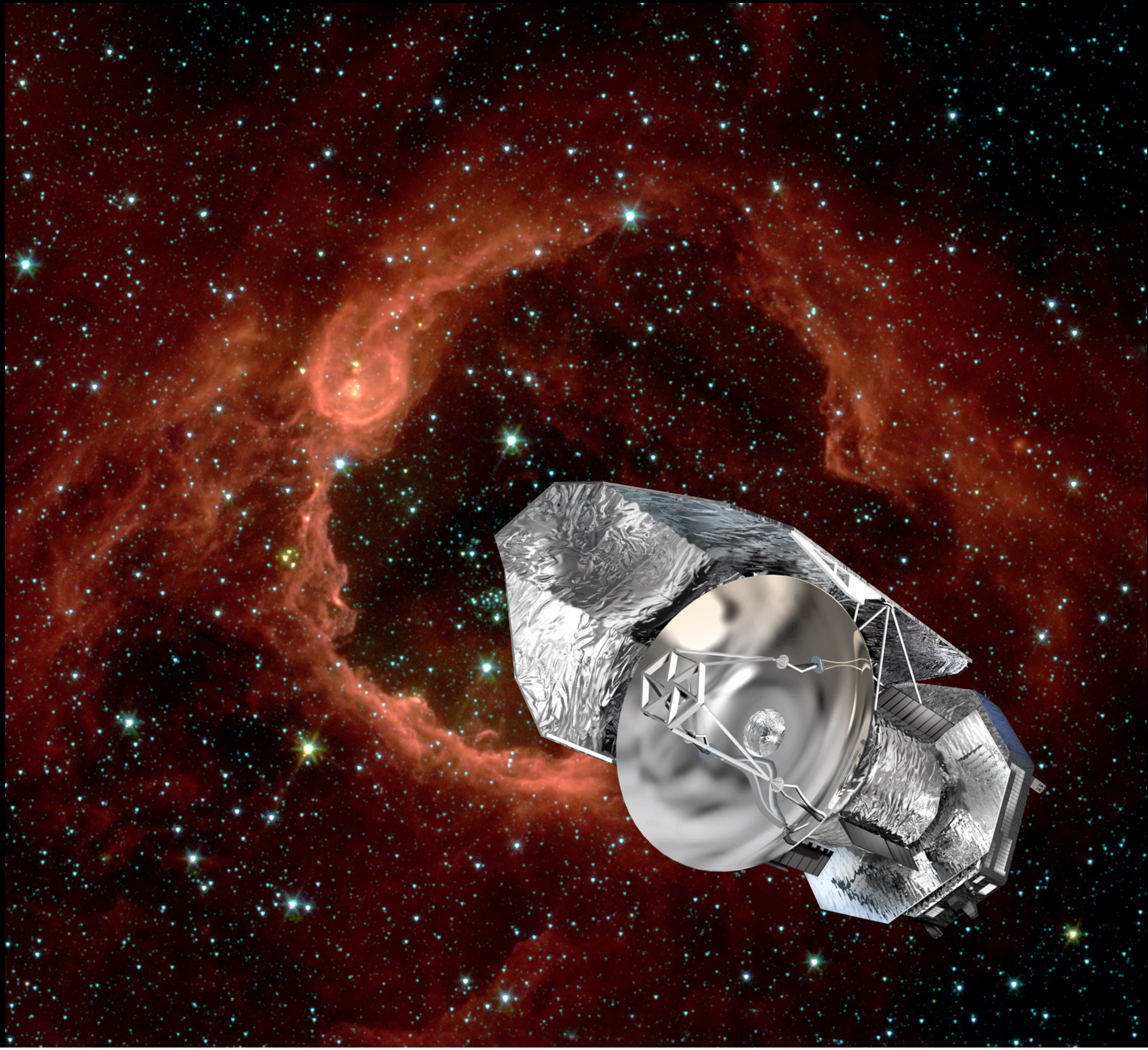
Two regimes of star formation: quasi-steady **on** *the main sequence, starbursts* **off** *of it*

Two Critical Questions:

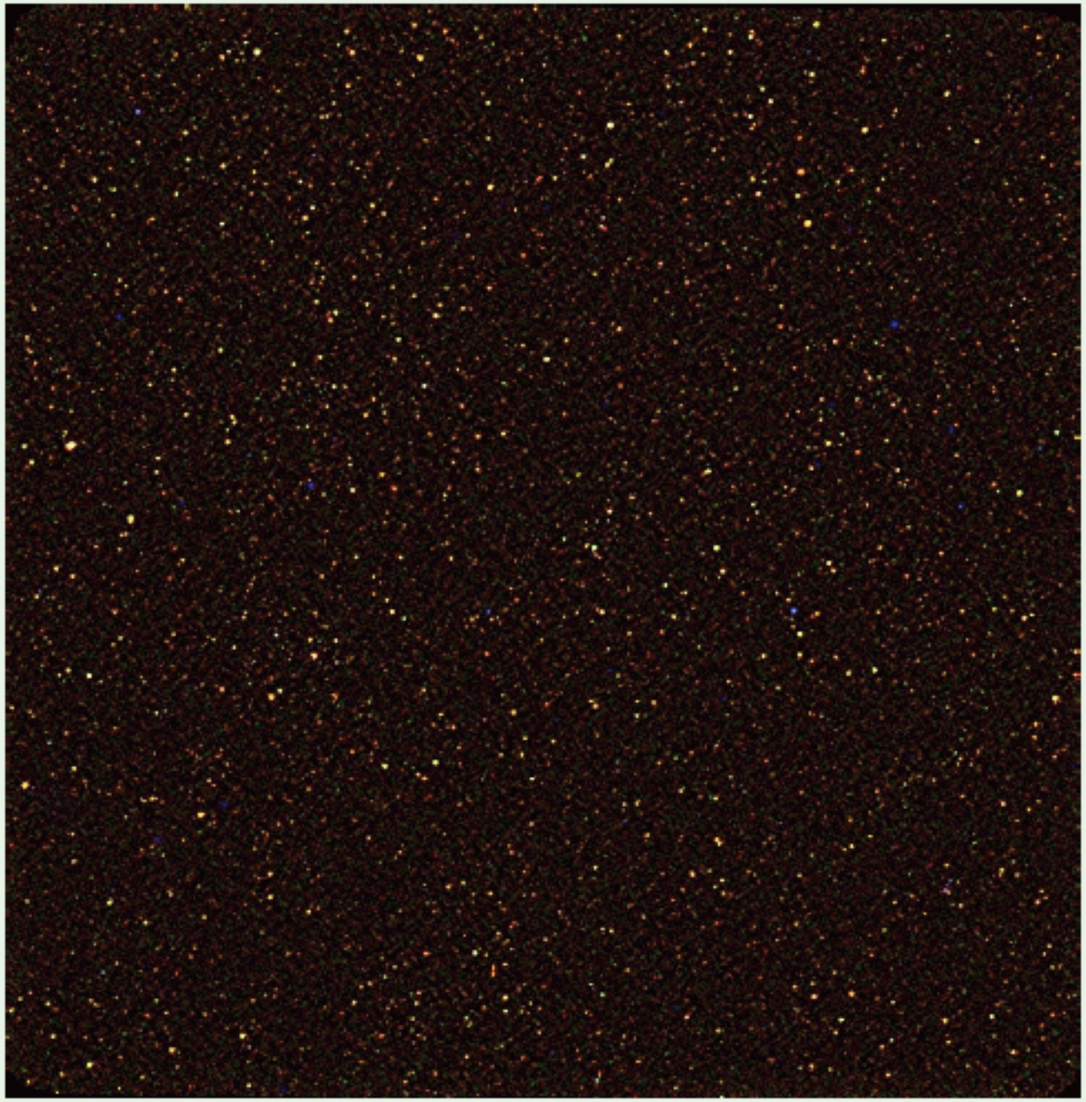
Q1: what is the relative number of main sequence and starburst galaxies?

Q2: what is their relative contribution to the global, cosmic star formation rate density?

Answering with HERSCHEL/PACS observations over the GOODS & COSMOS fields

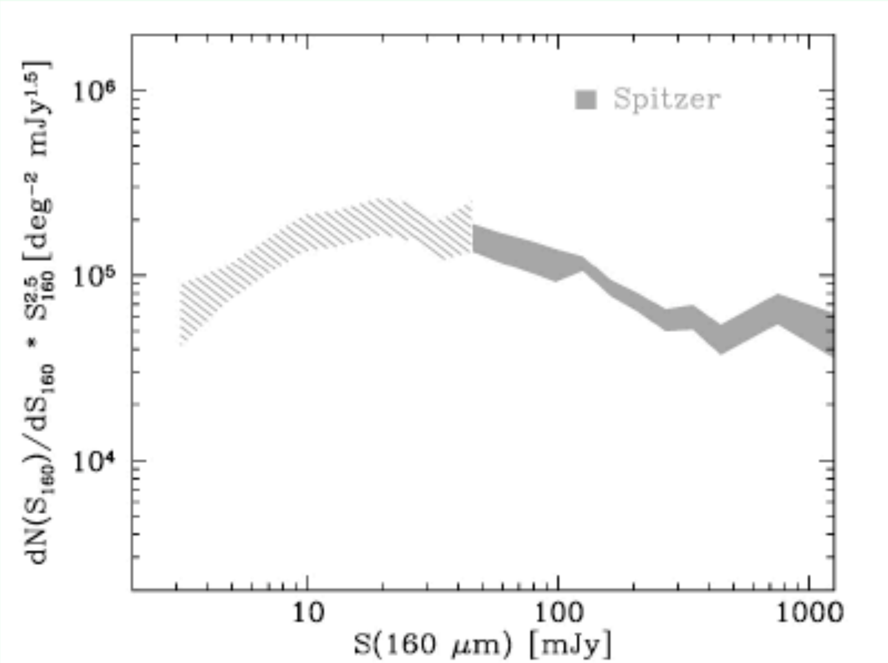


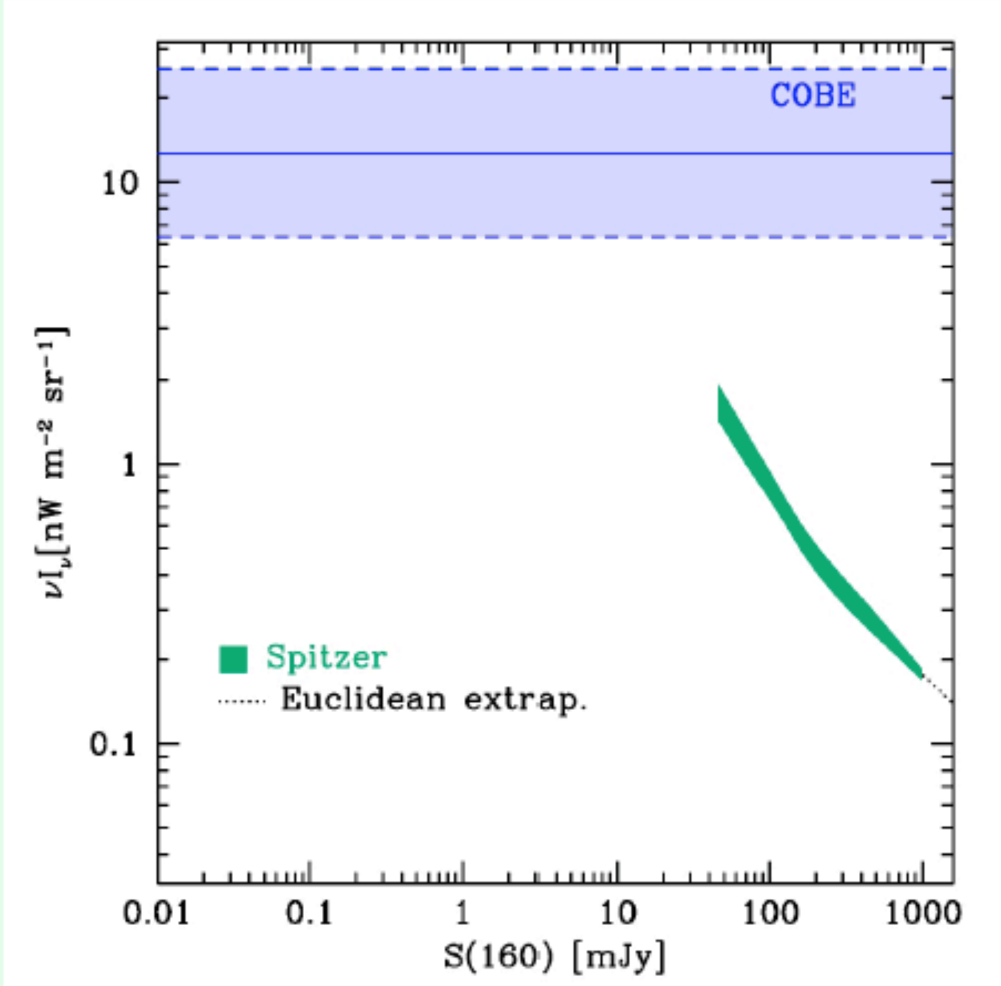
PACS Evolutionary Probe



GOODS-S/N Lockman EGS ECDFS COSMOS
+ 10 Lensing Clusters + 2 z~1 clusters

What did we know?

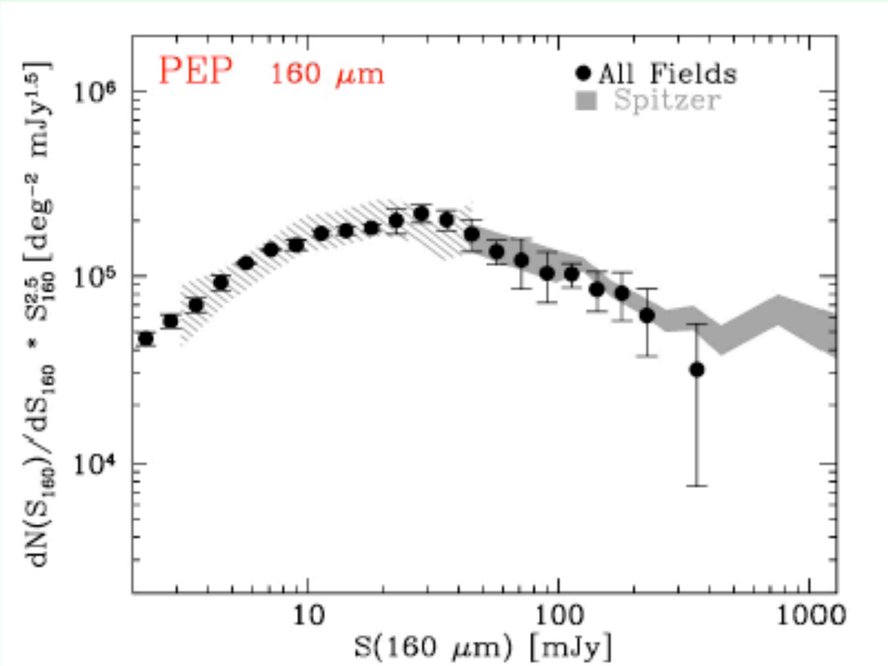


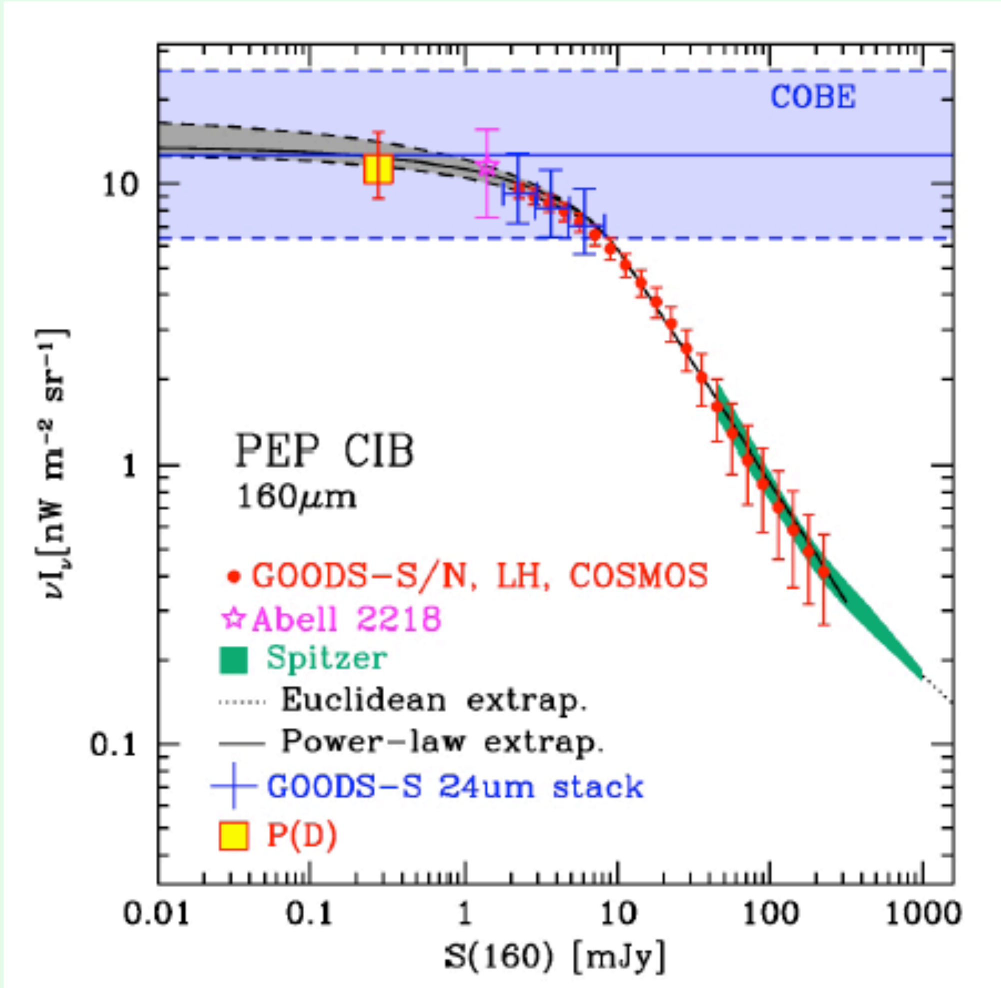


Based on Bethermin et al. (2010) data

Berta et al. (2011)

What do we know now!



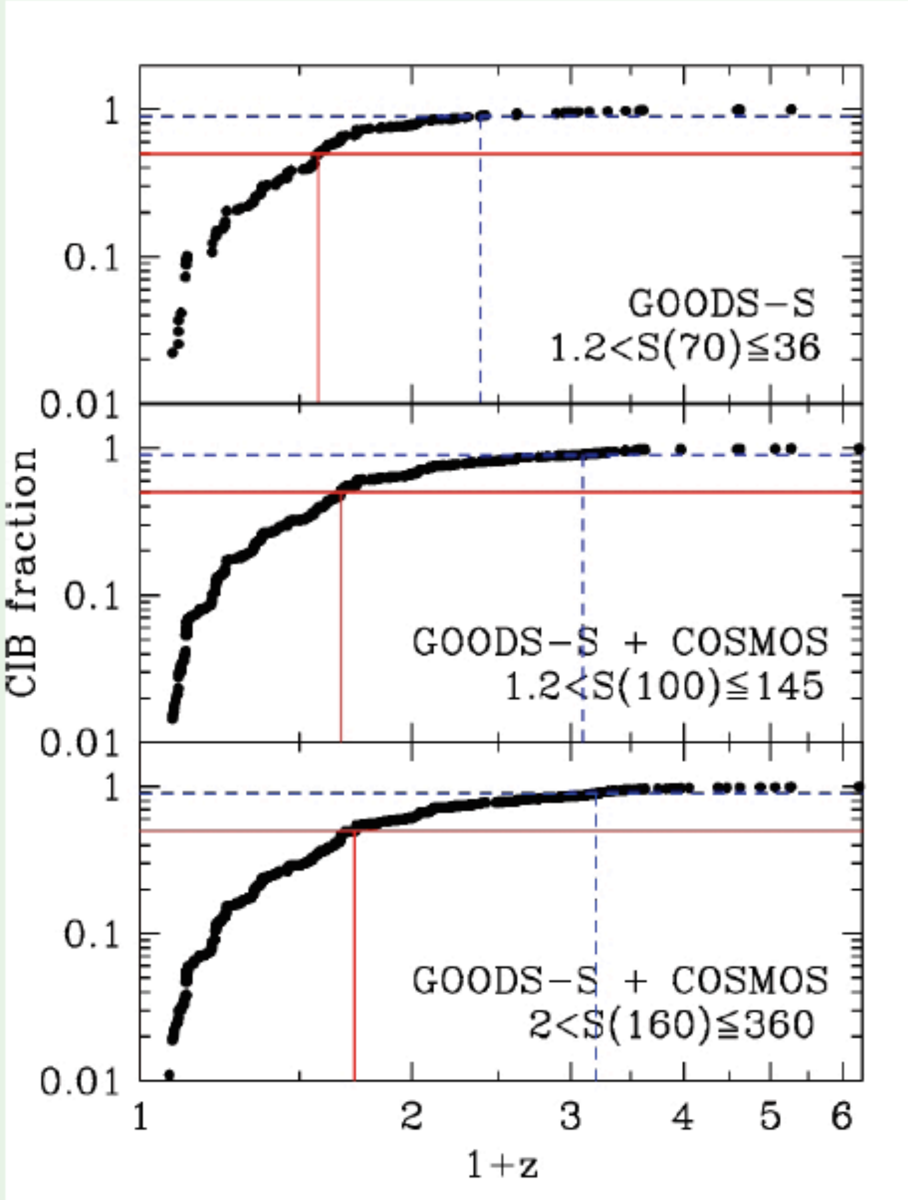


10 times deeper!

Resolved CIB:	P(D):
~55% @ 100μm	~60%
~70% @ 160μm	~82%

Berta et al. (2011)

Redshift and Luminosity



Resolved CIB

z ≤ 0.5	95% in normal glxs
0.5 < z ≤ 1.0	>90% in LIRGs
1.0 < z ≤ 2.0	50% in ULIRGs
z>2	88% in ULIRGs

Globally, ~50% of the CIB resolved in the three PACS bands was produced by LIRGs.

Berta et al. (2011)

HERSCHEL/PACS observations over the GOODS & COSMOS FIELDS

Rodighiero et al. (2011)

Data-set required to fully sample the stellar mass – SFR plane:

1. PACS 100µm and 160µm shallow source catalogs with extraction based on 24µm prior positions + IRAC-selected source catalog from Ilbert et al. (2010)

2. PACS 70, 100 and 160µm deep catalog in GOODS-S + multiwavelength photometry, spec & photo-z

3. BzK COSMOS catalog (Daddi/McCracken)

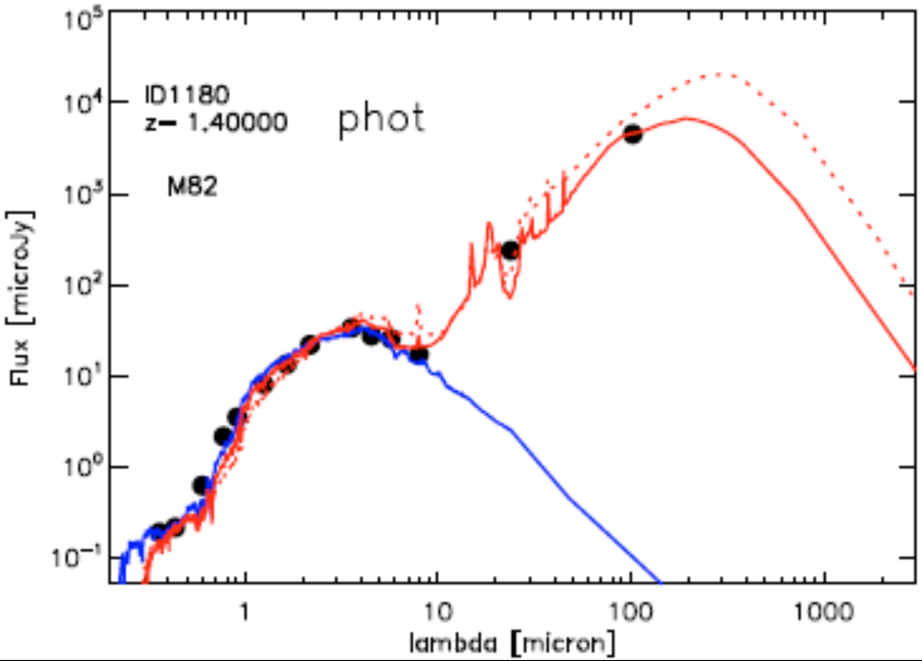
4. BzK GOODS-S catalog (Daddi et al. 2007)

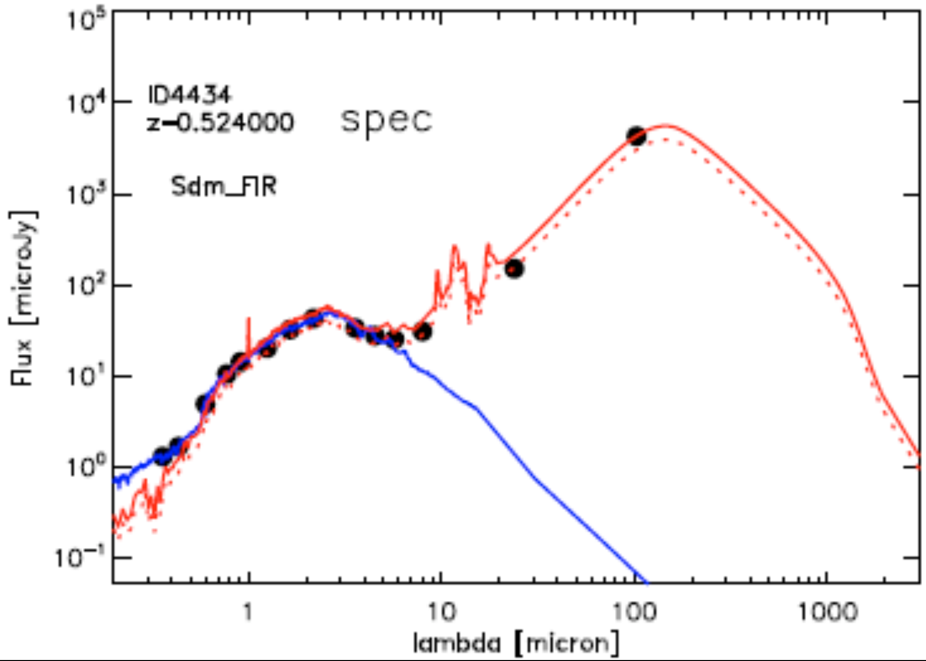
SFR:

derived from SED fitting to the complete UV-to-PACS observed photometry and converting the bolometric emission ([8-1000]μm) with the Kennicutt et al. (1998) relation (inclusion of unobscured SF does not affect the results).

STELLAR MASSES:

classical SED fitting to the UV-to-IRAC (5.8μm) with Bruzual & Charlot models

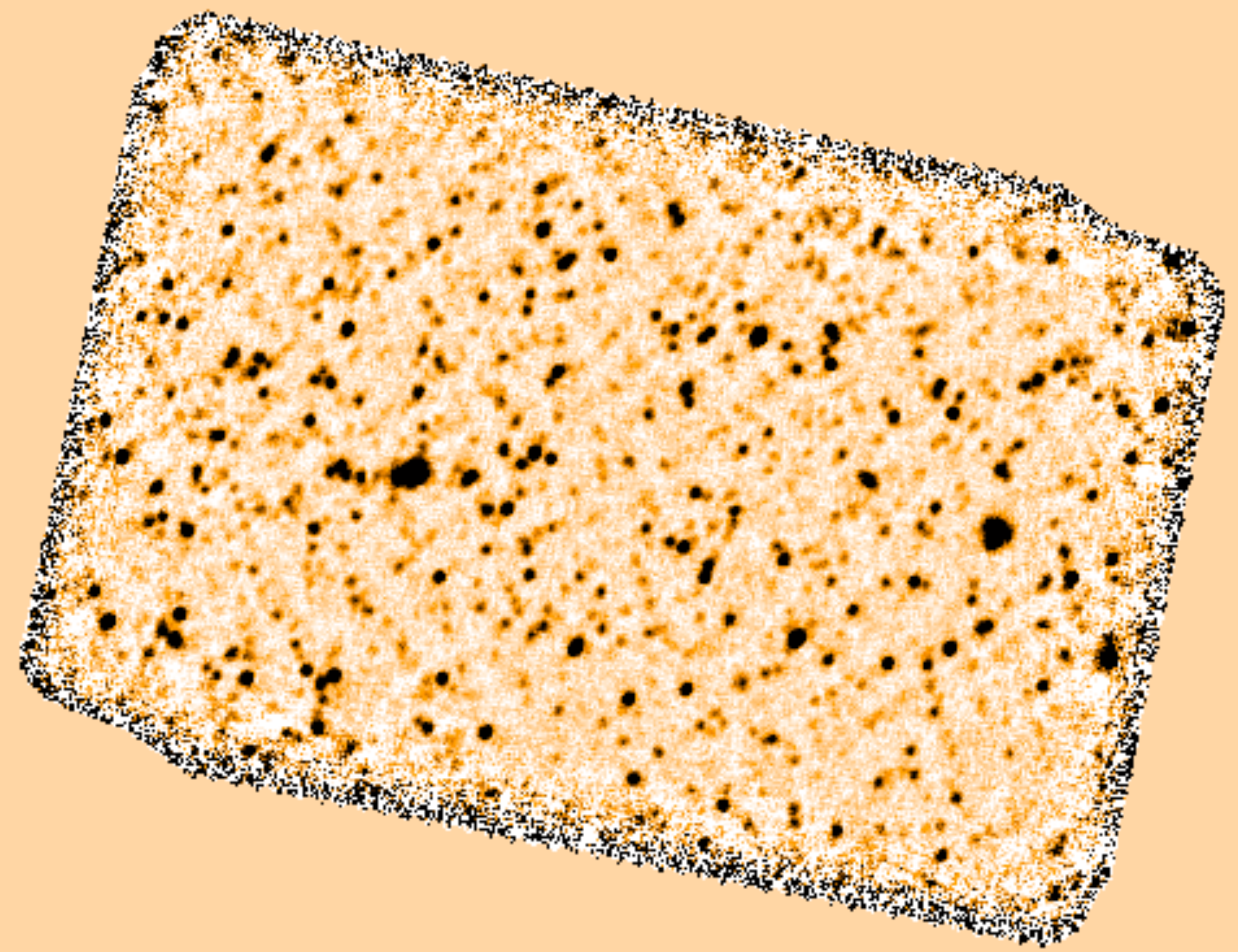




The PEP- GOODS South

(Lutz et al. 2011)

~21'x14'

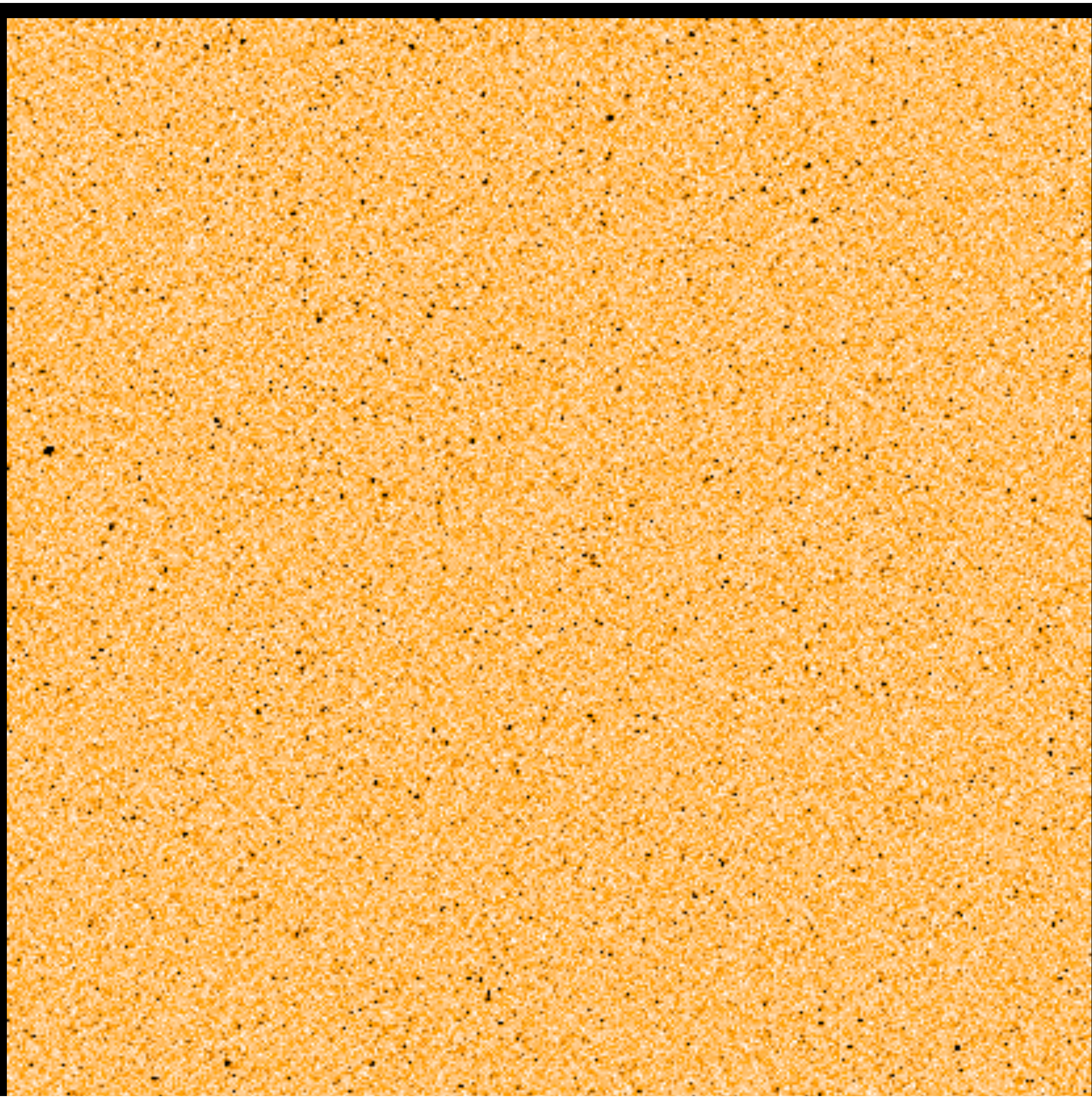


Field & band	F(3σ) mJy	N ≥ 3σ	F(5σ) mJy	N ≥ 5σ	Completeness 3σ	f(spur) 3σ	Completeness 5σ	f(spur) 5σ
GOODS-S 70	∼ 1.0	361	∼ 1.8	189	0.32	0.21	0.84	0.00
GOODS-S 100	∼ 1.1	787	∼ 1.9	424	0.21	0.28	0.64	0.04
GOODS-S 160	∼ 2.0	874	∼ 3.3	531	0.14	0.51	0.52	0.10

Table 4: Statistics of GOODS-S catalogs extracted using position priors at 24μm.

The PEP-COSMOS

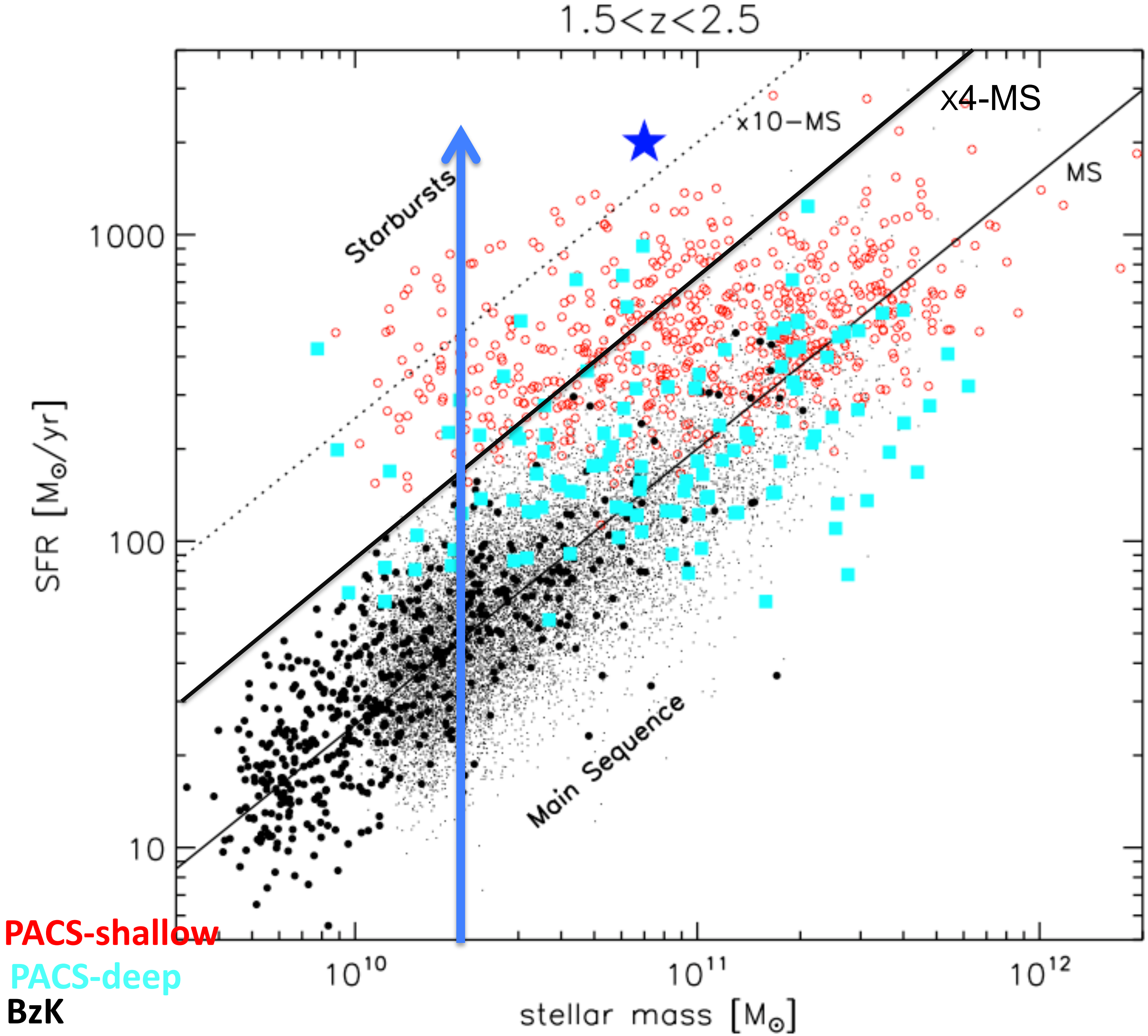
~2 square degrees



Field & band	F(3σ) mJy	$N \geq 3\sigma$	F(5σ) mJy	$N \geq 5\sigma$	Completeness 3σ	f(spur) 3σ	Completeness 5σ	f(spur) 5σ
COSMOS 100	~ 5.0	5368	~ 8.0	2999	0.43	0.58	0.90	0.09
COSMOS 160	~ 11.0	4649	~ 18.0	2159	0.29	0.48	0.84	0.09

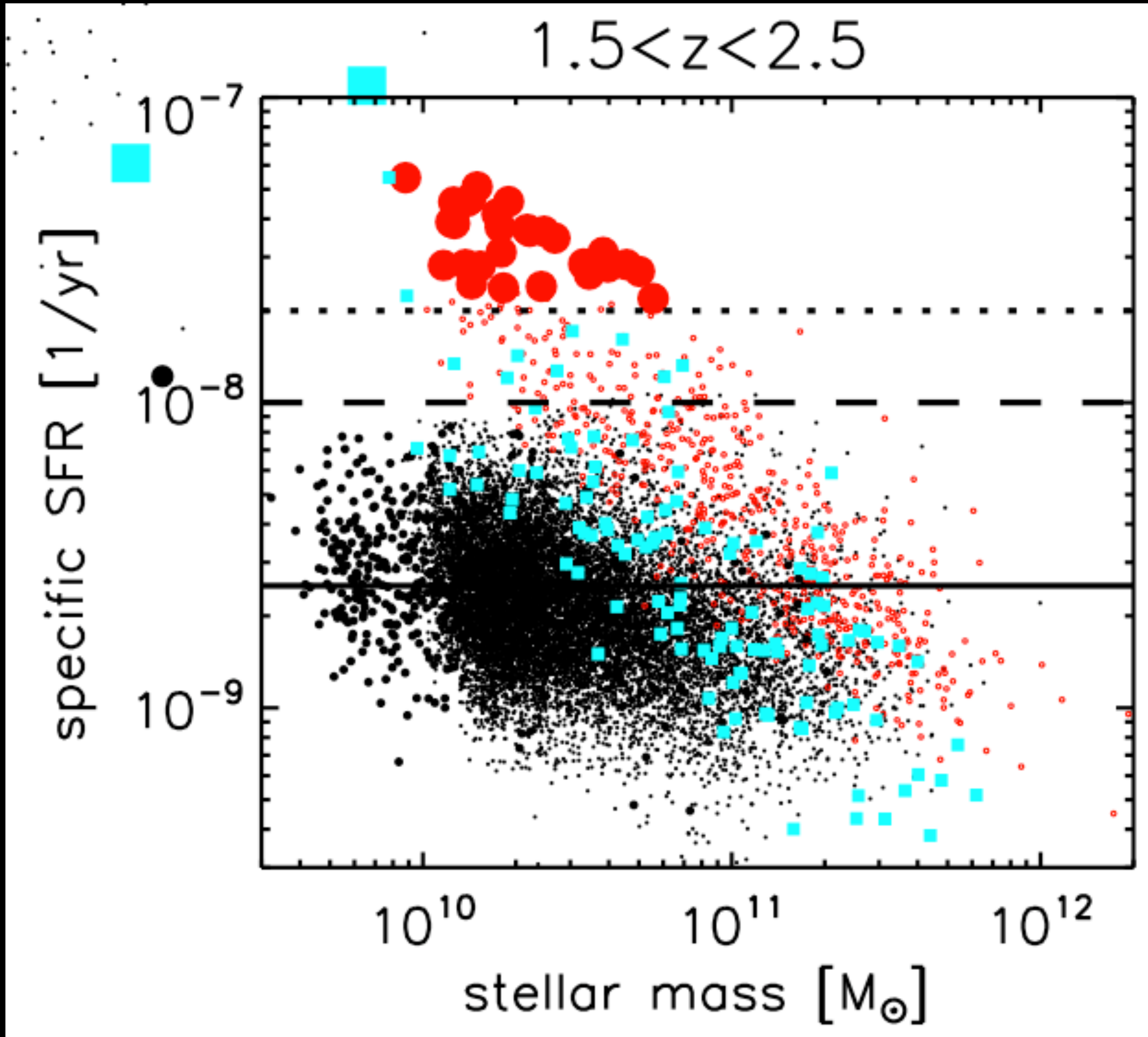
Table 3: Statistics of COSMOS catalogs extracted using position priors at 24μm.

Populating the mass-SFR plane

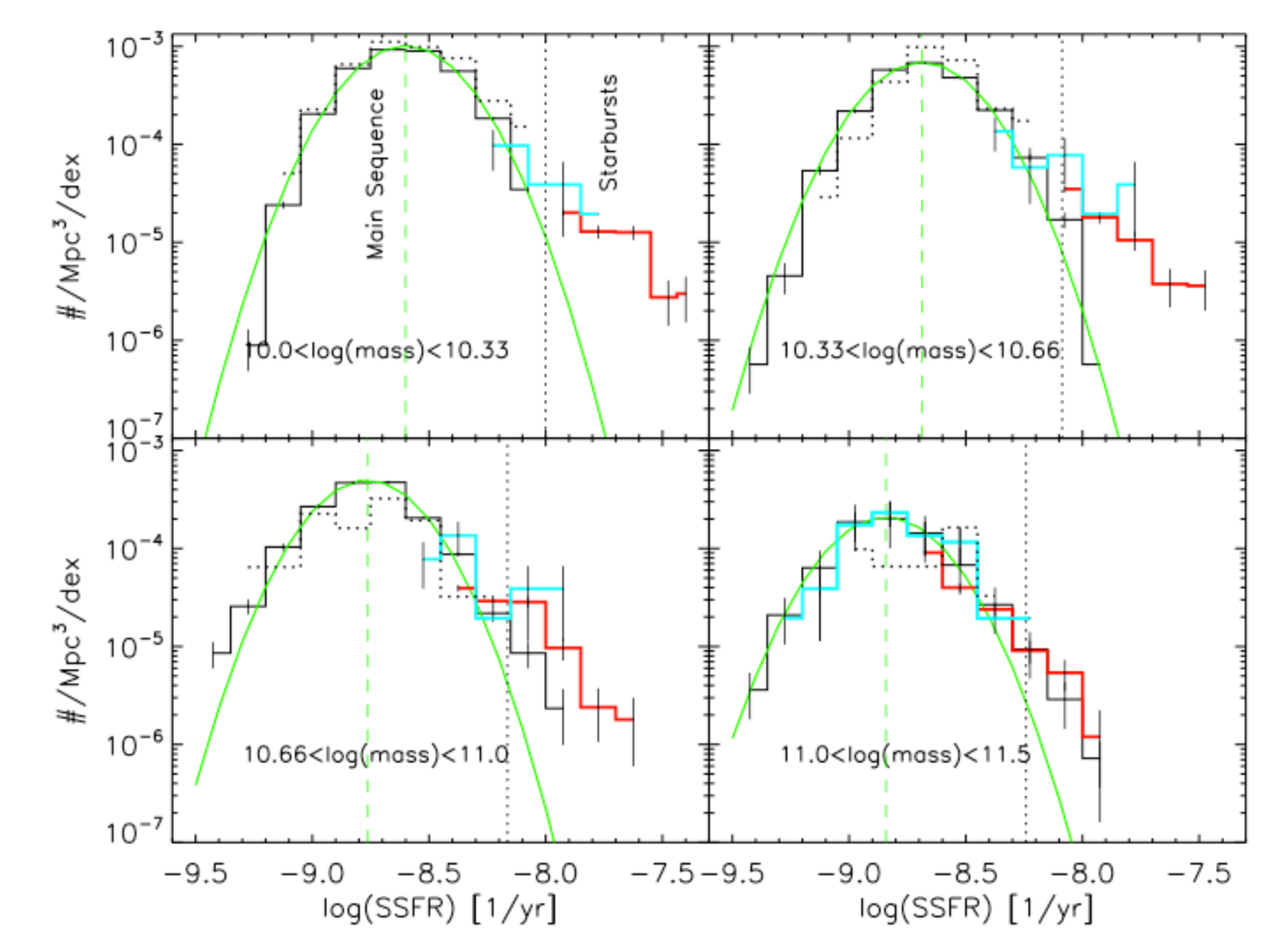


1.5<z<2.5
x4-MS
x10−MS
MS
Starbursts
Main Sequence
SFR [M⊙/yr]
stellar mass [M⊙]
1000
100
10
10^10
10^11
10^12
PACS-shallow
PACS-deep
BzK

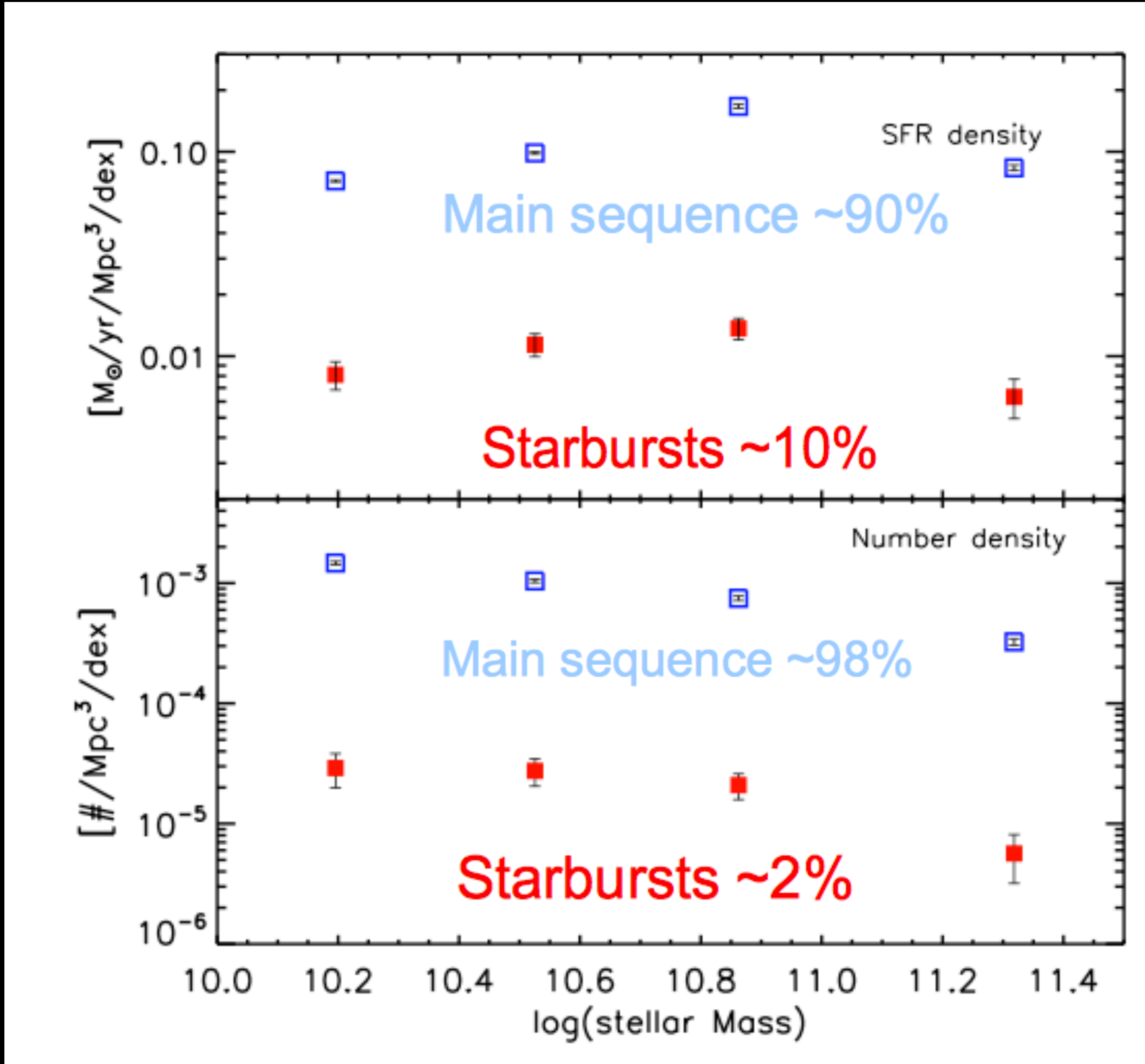
Same but in Specific-SFR



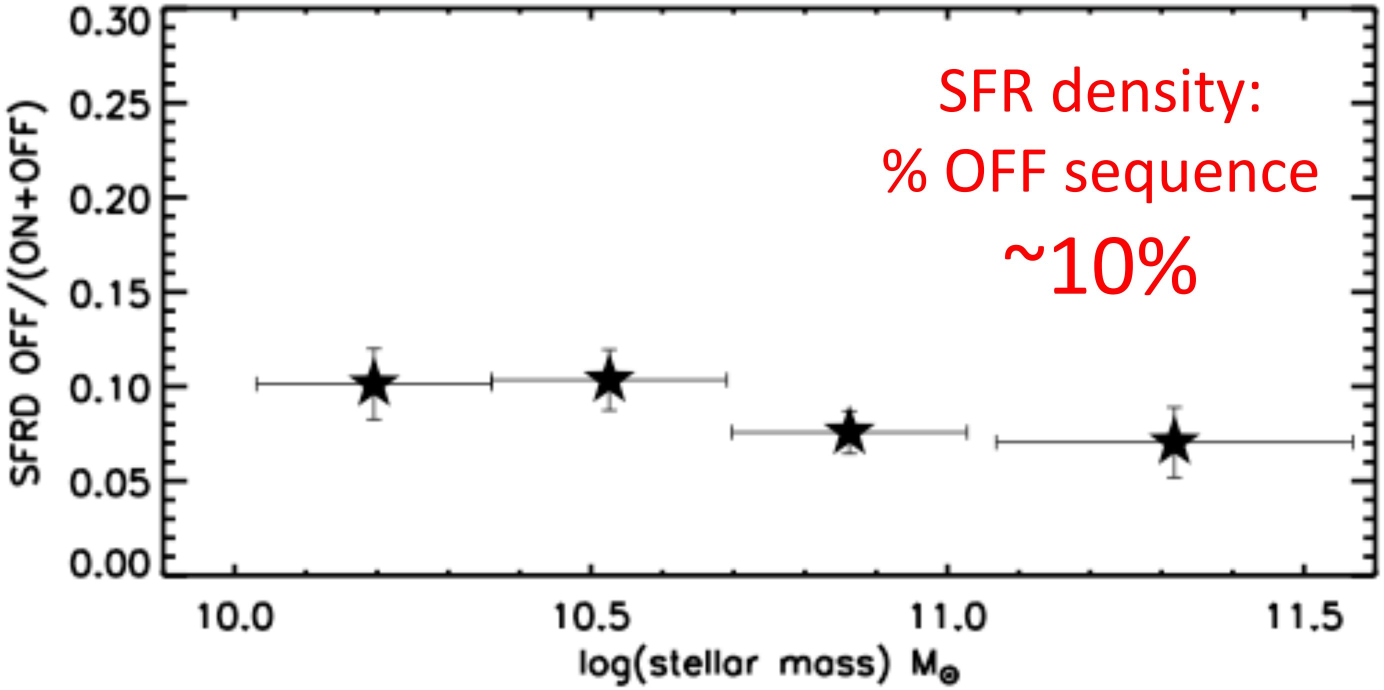
Number densities as a function of mass and SSFR bins:



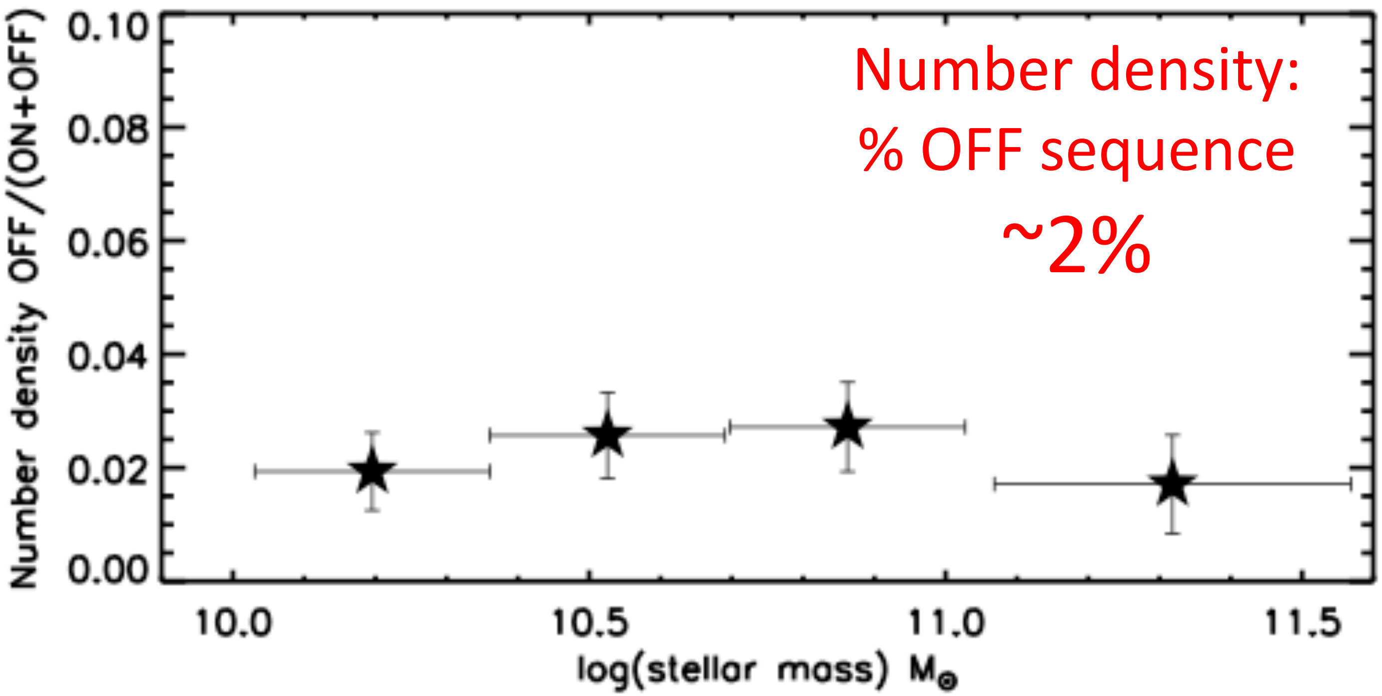
SFR density & Number density: ON and OFF sequence



SFR density



Number density



DUTY CYCLE ON/OFF the MAIN SEQUENCE

With only ~2% of the massive galaxies being OFF the main sequence, on average each galaxy spends 20 Myr in the starburst mode.

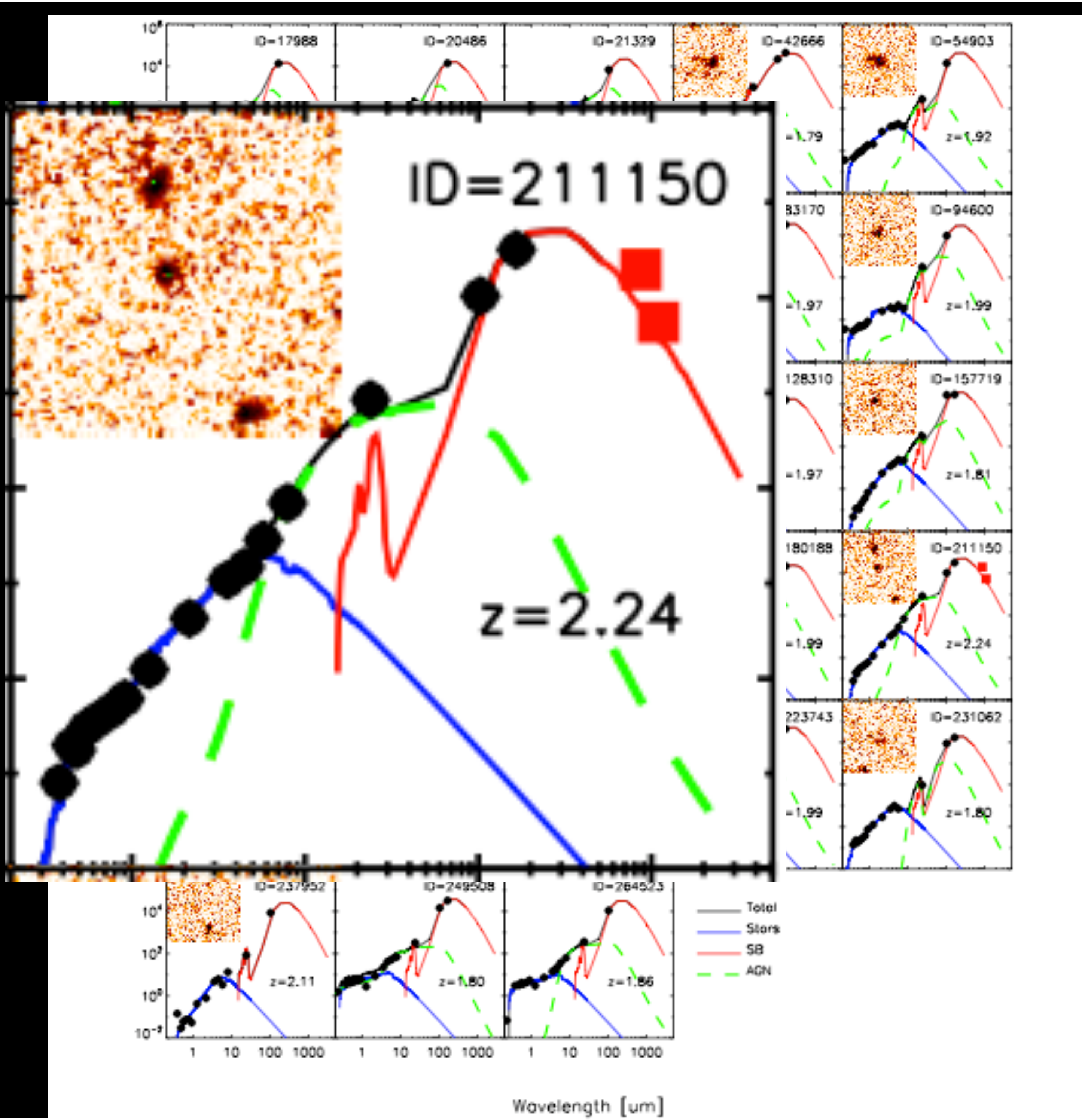
This is actually much shorter than both the gas depletion timescale (~0.5 Gyr) and the dynamical time in starburst galaxies (~50-200 Myr, Daddi et al. 2010; Genzel et al. 2010).

Not all galaxies may experience a (merger-driven) starburst during these ~2 Gyr of cosmic time interval.

The most SB sources:
SMGs brothers

Dominated by SFR

Obscured AGN present
but does never dominate
the bolometric far-IR emission



MAIN CONCLUSION

TESTING THE STARBURST-MERGER PARADIGM

The merger-enhanced SFR phase[illegible] relatively unimportant for the stellar ma[illegible]wth of z ~ 2 galaxies, and probably so a[illegible]dshifts given that z ~ 2 is known to be [illegible] prime time' for SMGs (Chapman et al. 2[illegible]

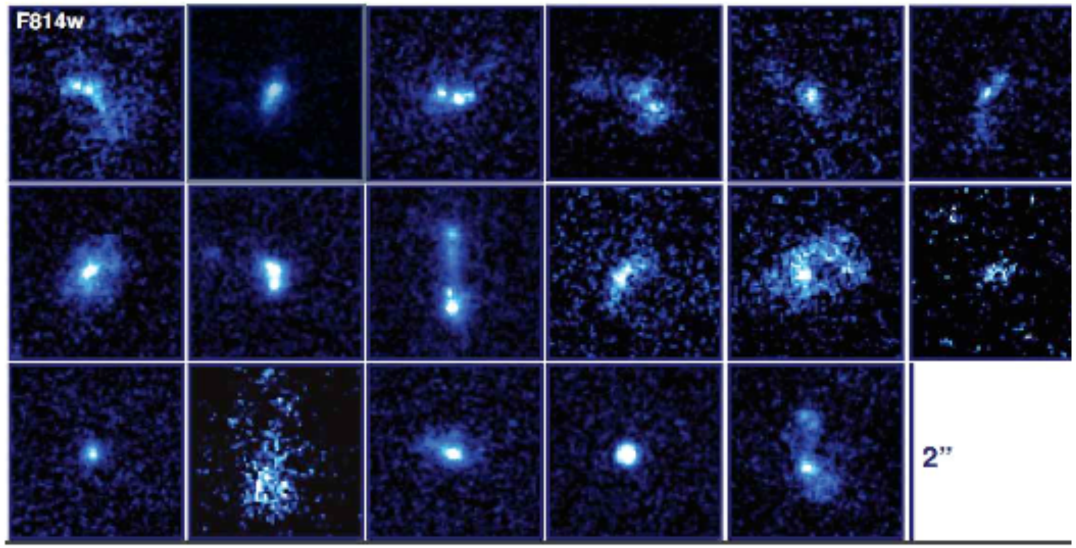
Still, goi[illegible]ugh a merging-driven starburst phase ma[illegible]star-forming galaxies into passive ellipt[illegible]cals.

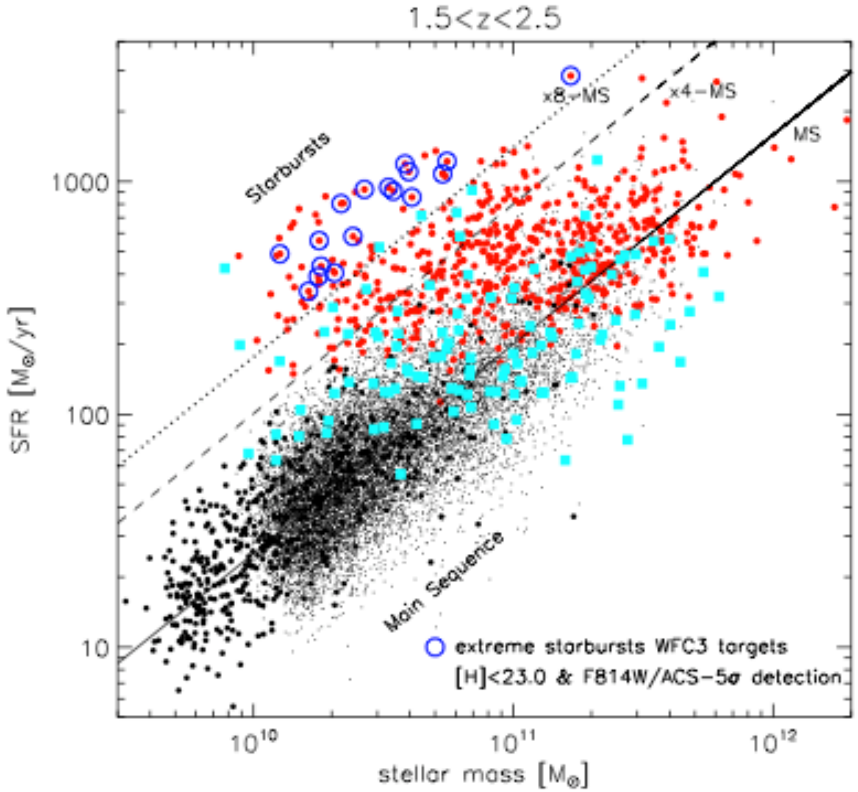
Follow-up campaign of extreme off-sequence Herschel sources at z=2 (1)

Hubble Space Telescope | Cycle 20 GO Proposal | **778**

The rest-frame optical view of Herschel starbursts at z~2: the role of major mergers in forcing galaxies out of steady-state

Principal Investigator: Dr. Giulia Rodighiero





P.I. G. Rodighiero

Follow-up campaign of extreme off-sequence Herschel sources at z=2 (2)

IRAM
300, rue de la Piscine
38406 ST. MARTIN d'HERES (France)
Fax: (33/0) 476 42 54 69

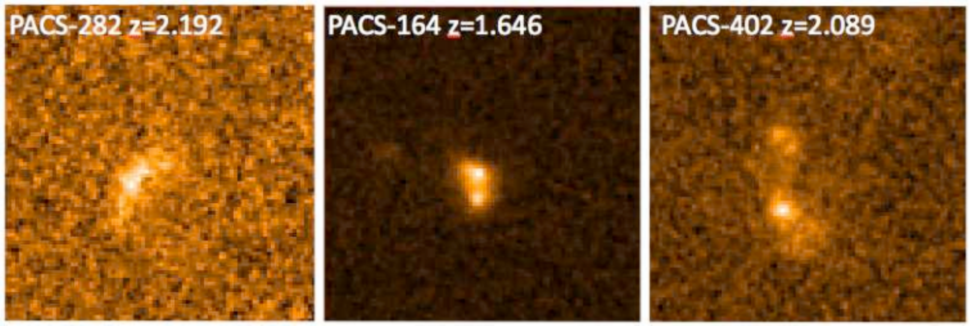
For IRAM use
Registration N°:
Date:

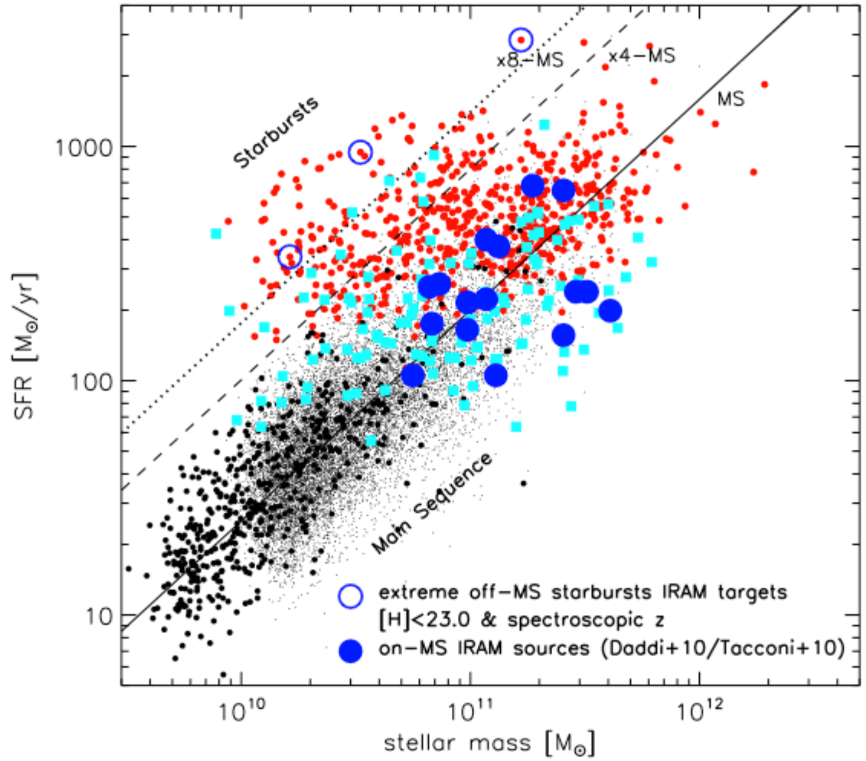
PROPOSAL FOR INTERFEROMETER

Deadline: 15 Mar 2012 Period: 01 Jun 2012 — 30 Nov 2012

TITLE

Herschel Extreme Starbursts at Redshift ∼ 2





P.I. G. Rodighiero

Follow-up campaign of extreme off-sequence Herschel sources at z=2 (3)

EUROPEAN SOUTHERN OBSERVATORY

Organisation Européenne pour des Recherches Astronomiques dans l'Hémisphère Austral
Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

OBSERVING PROGRAMMES OFFICE • Karl-Schwarzschild-Straße 2 • D-85748 Garching bei München • e-mail: opo@eso.org • Tel.: +49-89-32 00 64 73

APPLICATION FOR OBSERVING TIME PERIOD: **90A**

Important Notice:

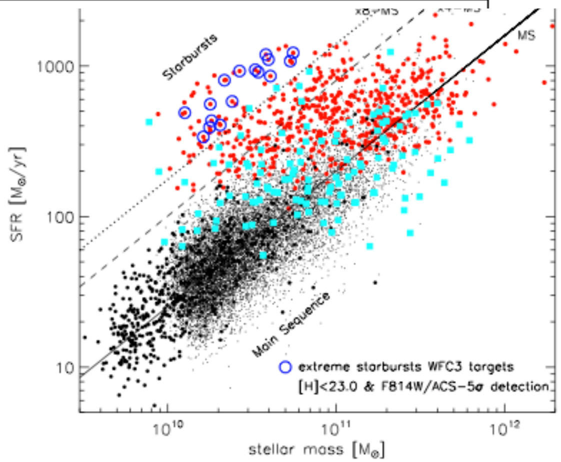
By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of CoIs and the agreement to act according to the ESO policy and regulations, should observing time be granted

1. Title Category: **A–1**

Xshooter spectroscopy of Herschel extreme-starburst galaxies at $z \approx 2$

[redacted]

P.I. M. Carollo



Follow-up campaign of extreme off-sequence Herschel sources at z=2 (4)

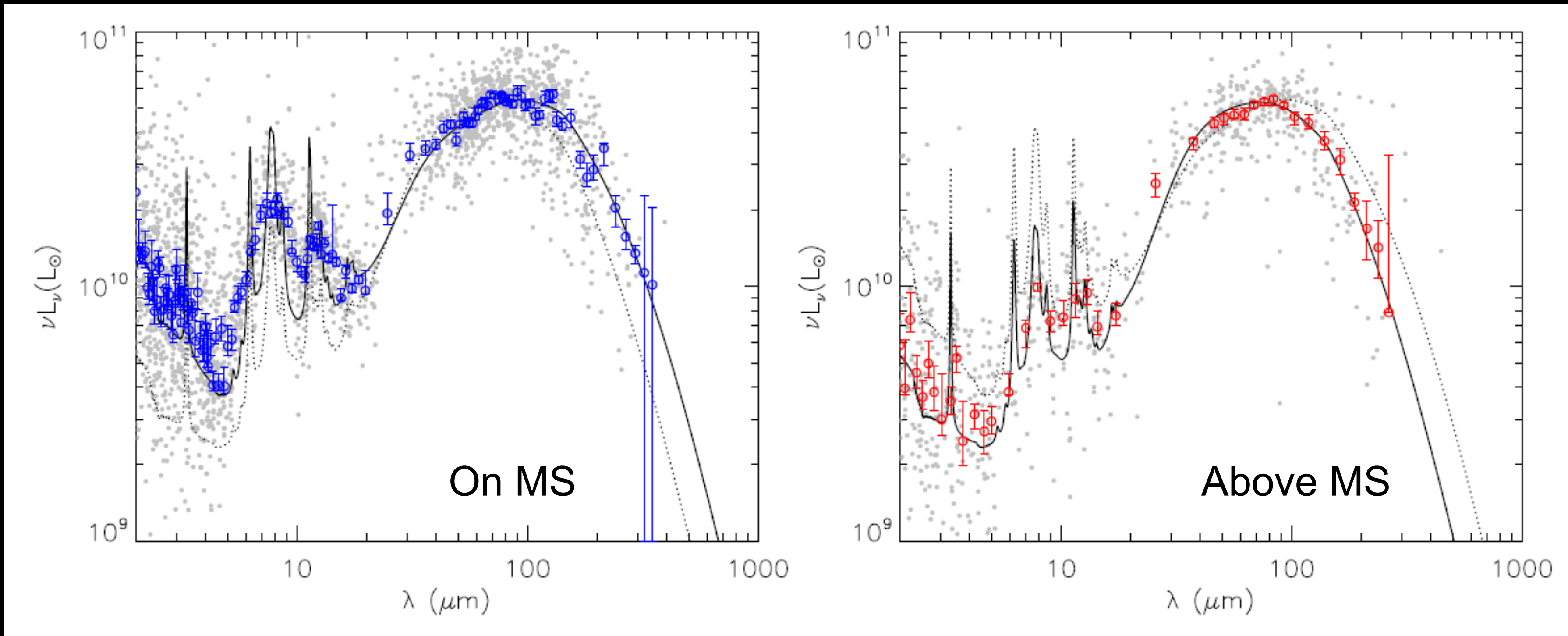
Upcoming:

TNG/NICS spectroscopy (+ G. Cresci)

ALMA

ESO/SINFONI dynamics

Average SEDs for high-z galaxies on and above MS

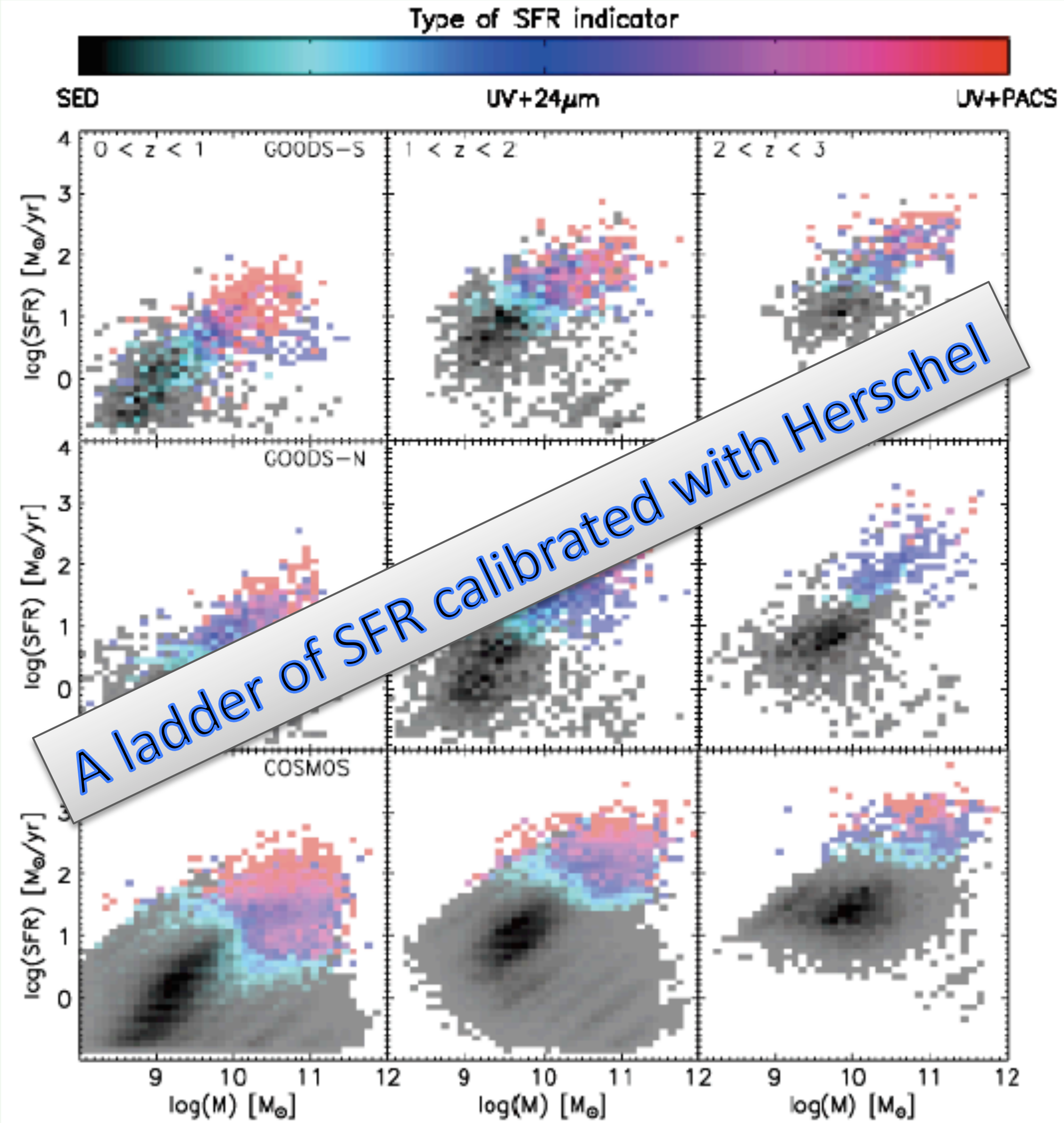


High PAH/FIR, cold FIR

Low PAH/FIR, warm FIR

Elbaz+11 1105.2537 (GOODS-Herschel KP)

Probing the Main Sequence



Wuyts et al. (2011a)

SF mode along the MS (data)

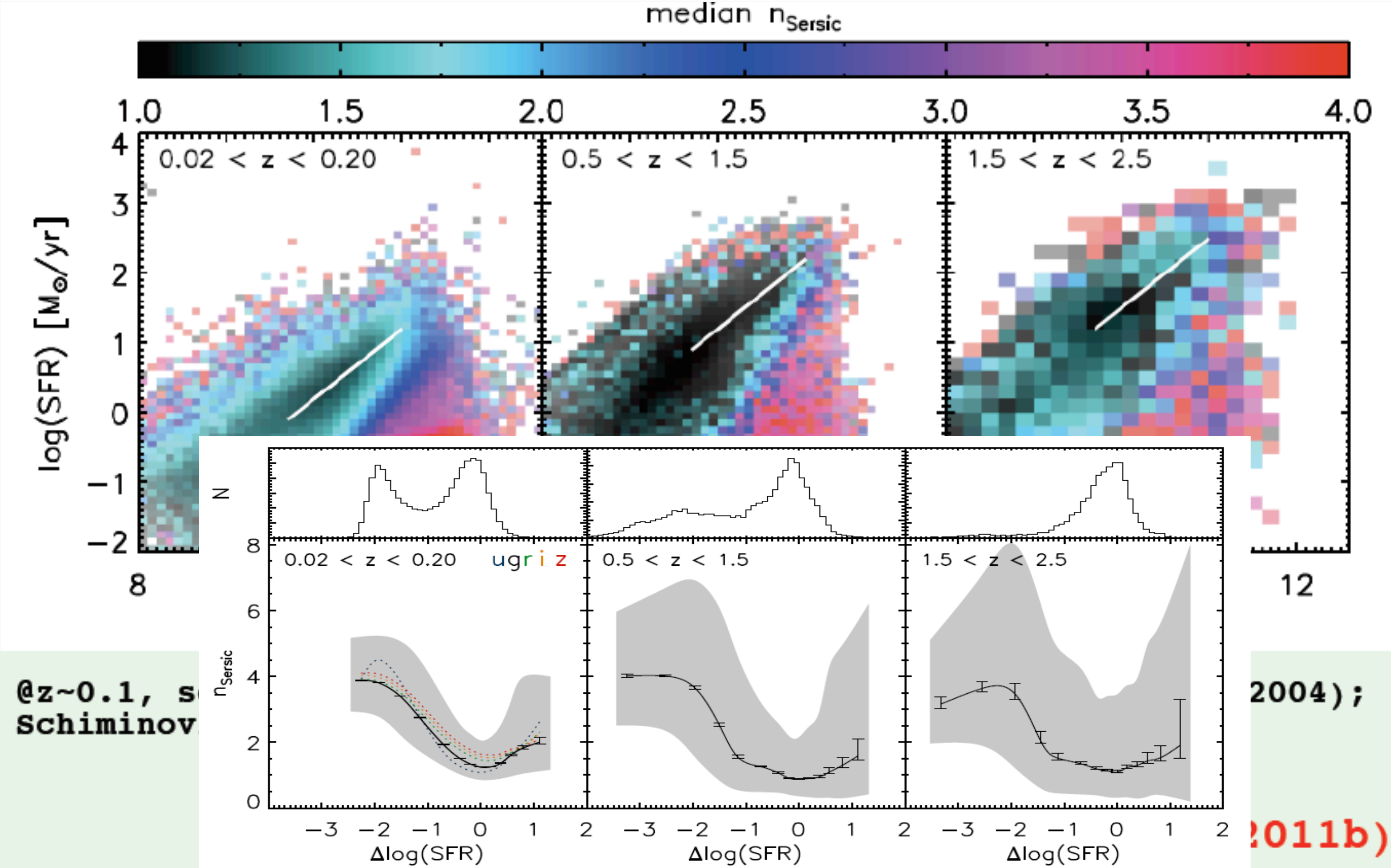
- SDSS DR7, GALEX DR5
  SFRs & Masses from MPA-JHU
  sizes & Sersic indices from NYVAGC
- COSMOS
  HST/ACS I_{814}, Herschel/PACS 100, 160μm, Spitzer/MIPS 24μm
- UDS
  WFC3 H_{160}, Spitzer/MIPS 24μm
- GOODS-N
  HST/ACS z_{850}, Herschel/PACS 100, 160μm, Spitzer/MIPS 24μm
- GOODS-S
  HST/ACS B_{435}, V_{606}, i_{775}, z_{850}, HST/WFC3 Y_{098}, J_{125}, H_{160}, Herschel/PACS 70, 100, 160μm, Spitzer/MIPS 24μm

- 639.924 galaxies @ z ~ 0.1
- 97.250 galaxies @ z ~ 1
- 24.456 galaxies @ z ~ 2

Photometric redshifts with EAZY (Brammer et al. 2008)
Stellar masses with FAST (Kriek et al. 2009)
SFRs from UV+PACS / UV+MIPS / SFR_{SED} (Wuyts et al. 2011)
Structural parameters with GALFIT (Peng et al. 2010)

Wuyts et al. (2011b)

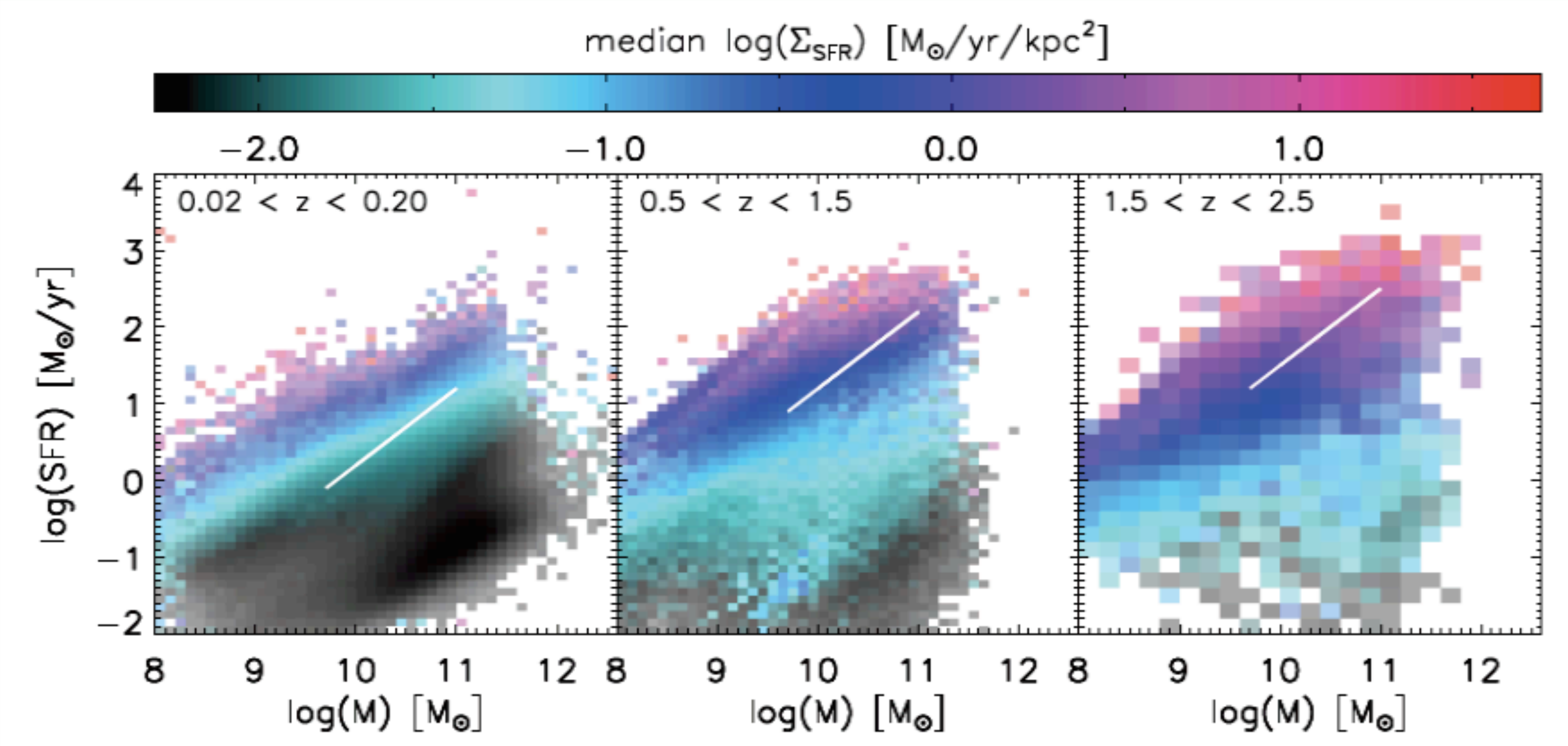
Morphologies on and off the main sequence



@z~0.1, s… 2004);
Schiminov…

…2011b)

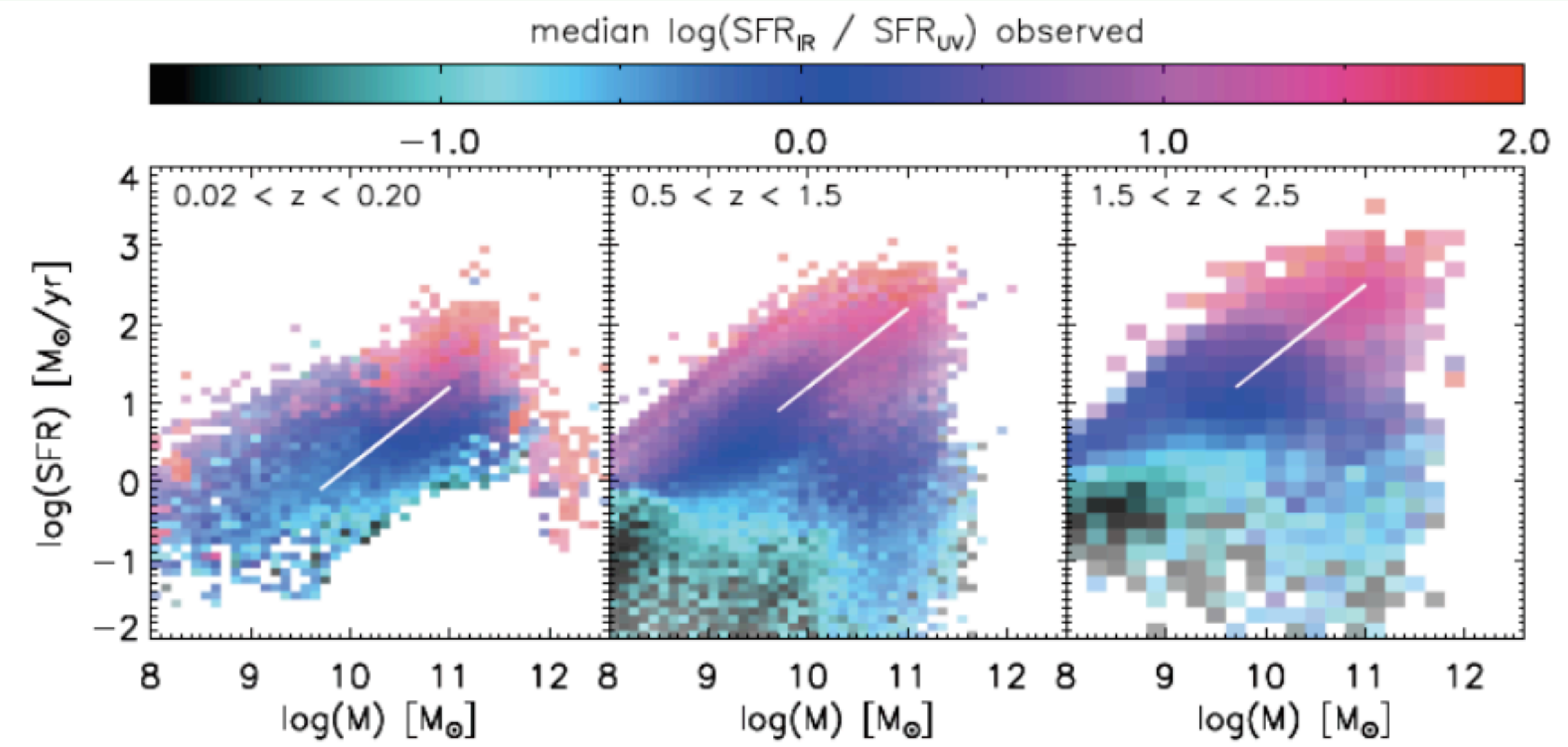
SFR surface density



See also Schiminovich et al. (2007), Elbaz et al. (2011)

Wuyts et al. (2011b)

SFR_{IR} vs. SFR_{UV}



See e.g. also Heckman et al. (1998), Reddy et al. (2010)

Wuyts et al. (2011b)

Putting all tiles together

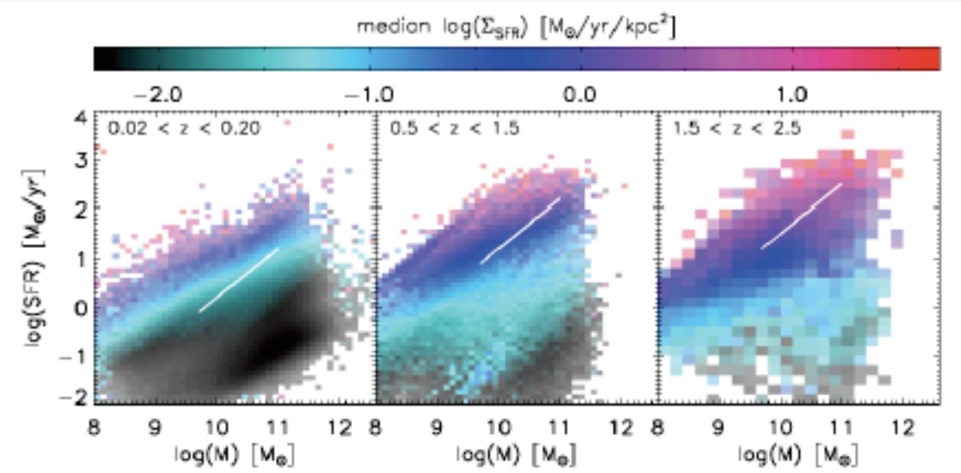
- $\Sigma_{SFR} \xrightarrow{①} \Sigma_{gas} \xrightarrow{②} \Sigma_{metal} \xrightarrow{③} \tau \xrightarrow{④} SFR_{IR}/SFR_{UV}$

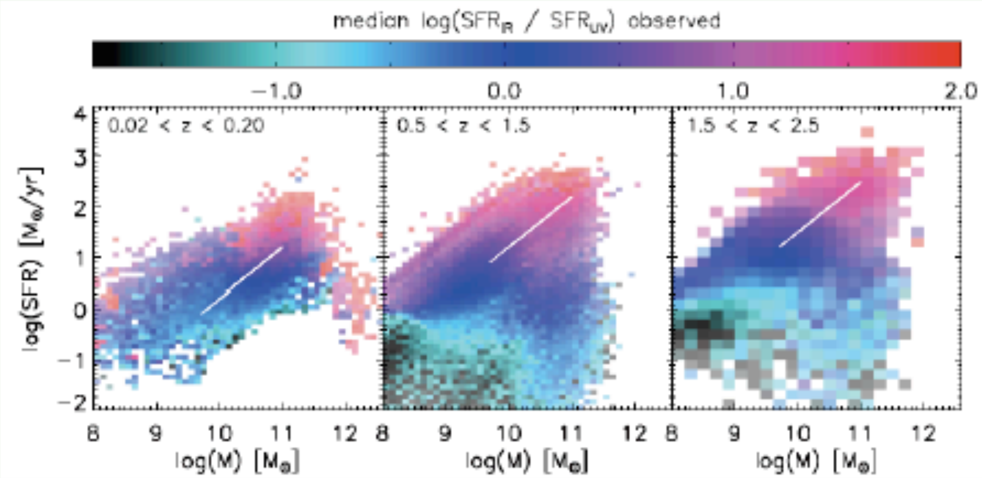
① Kennicutt-Schmidt relation (Kennicutt 1998; Genzel et al. 2010)

② Mass-SFR-Metallicity relation Z(M,SFR) (Mannucci et al. 2010)

③ $(Z/Z_{sun}) * [N_H/A_V]_{Milky\ Way}$ (Bohlin et al. 1978)

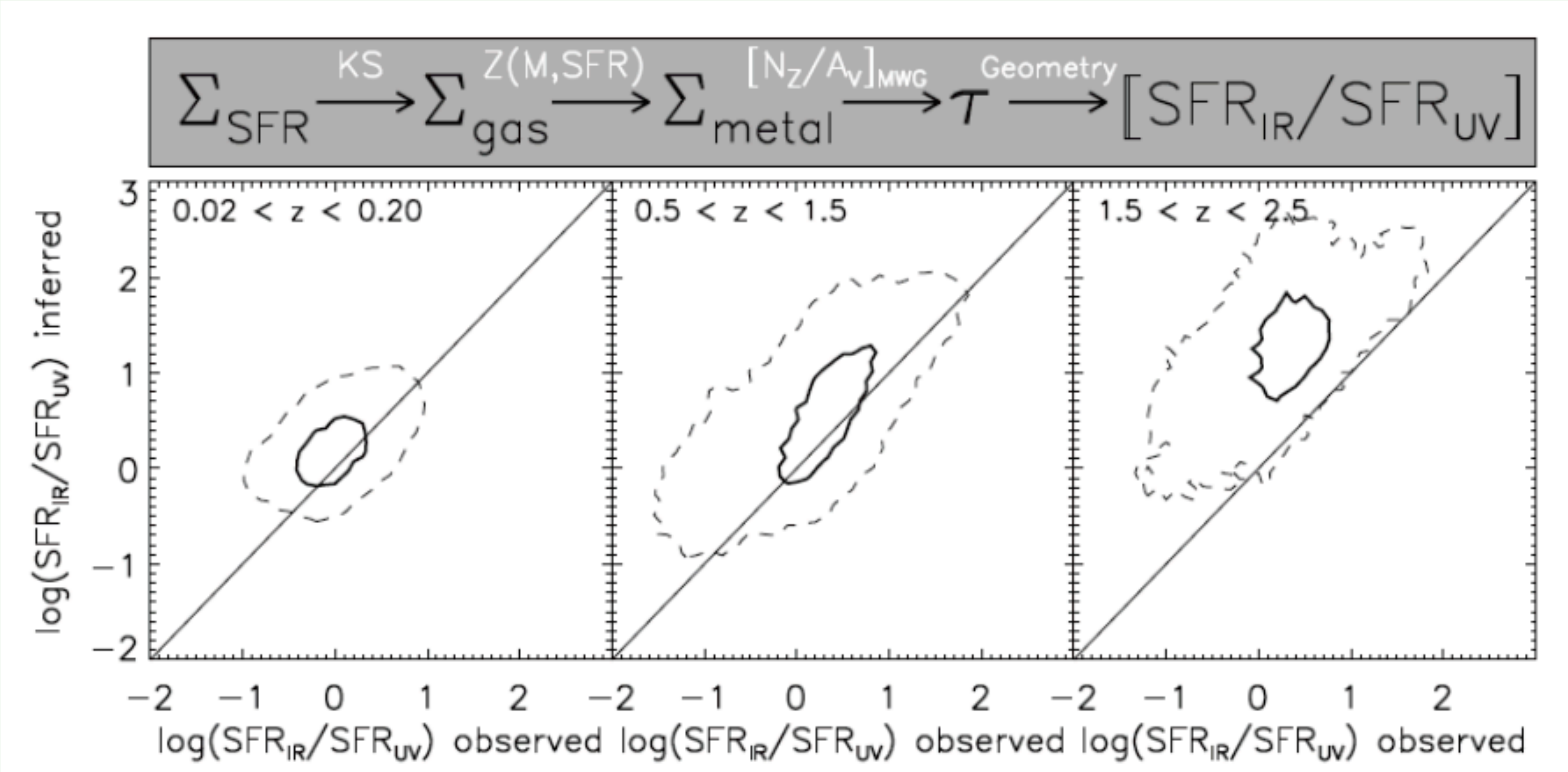
④ Mixed geometry $L_{att} = L_{int}(1 - e^{-\tau})/\tau$ (Forster Schreiber et al. 2001)





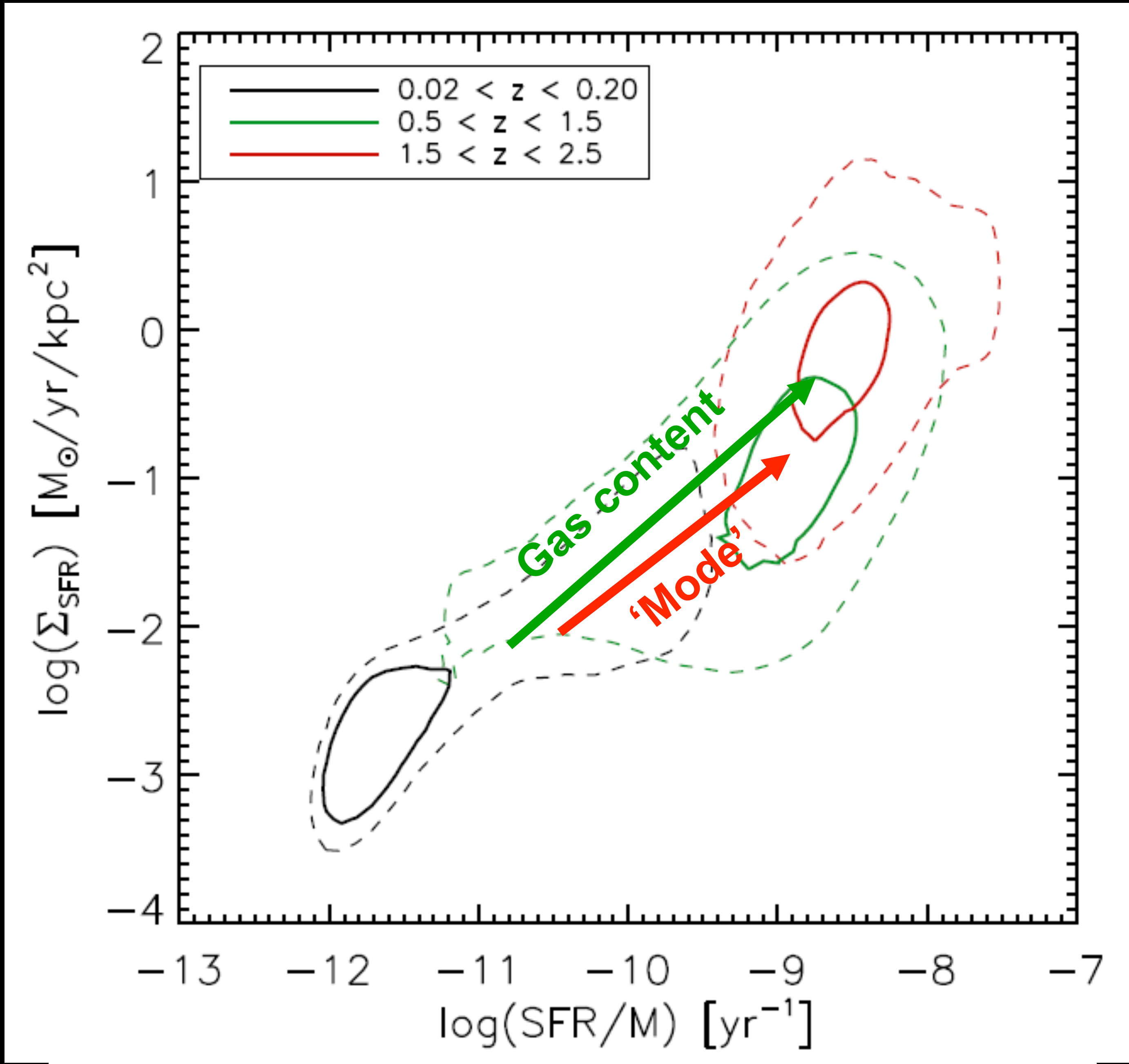
Wuyts et al. (2011b)

Putting all tiles together



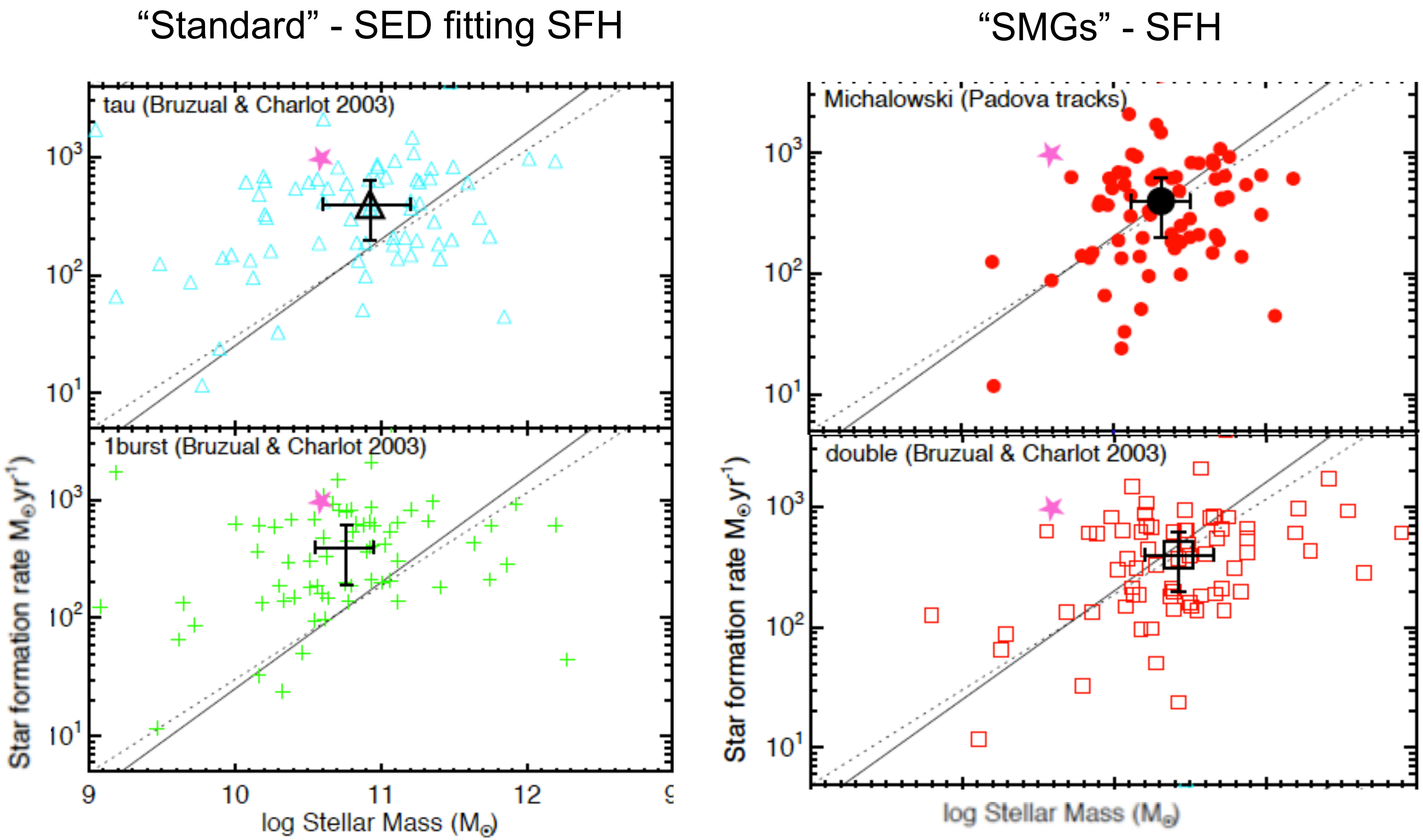
Wuyts et al. (2011b)

Sizes and star formation densities

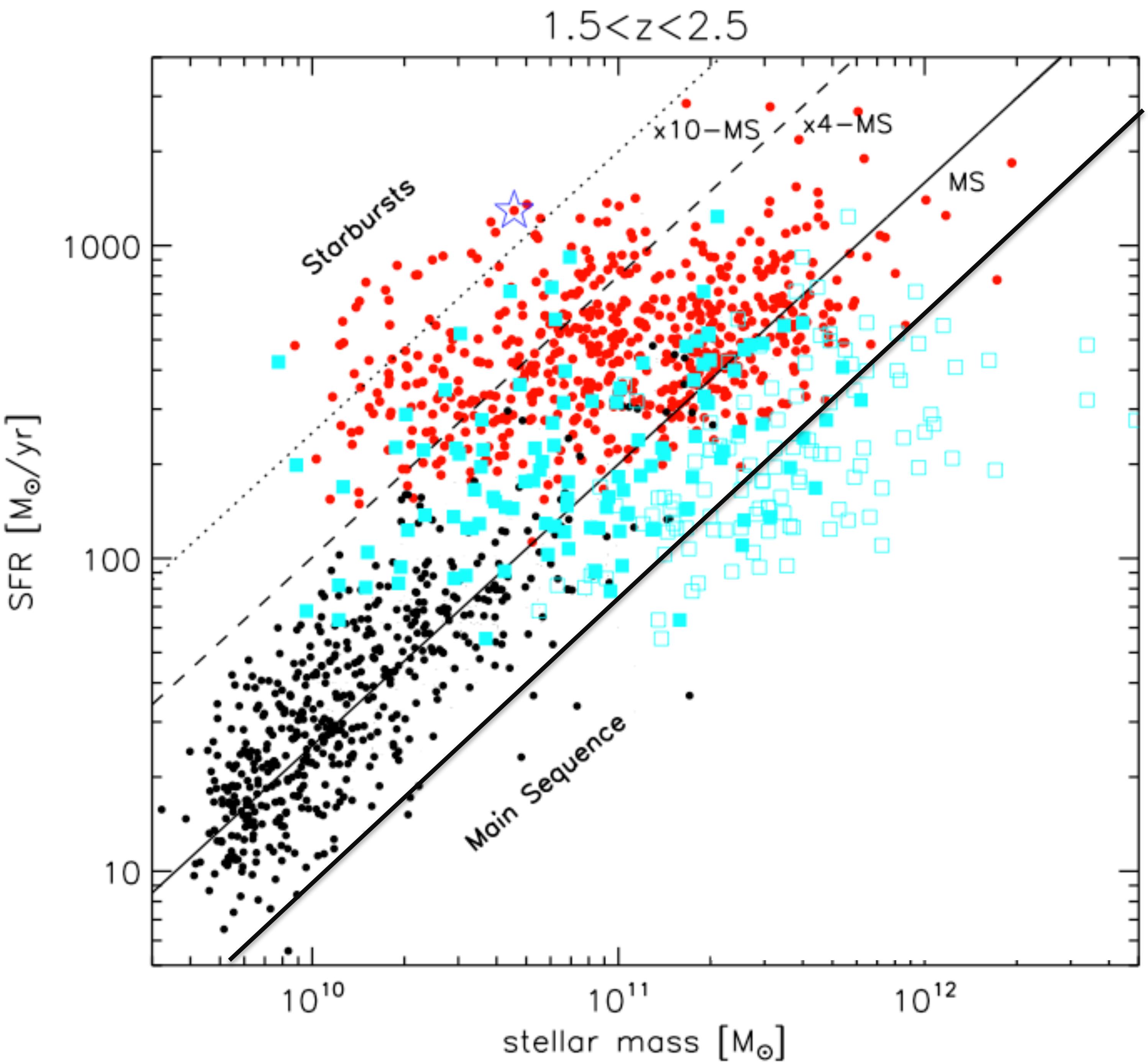


SMG stellar masses: open debate underestimated by a factor up to 3?

Michalowski et al. (2011)
Cirasuolo et al. (2010)

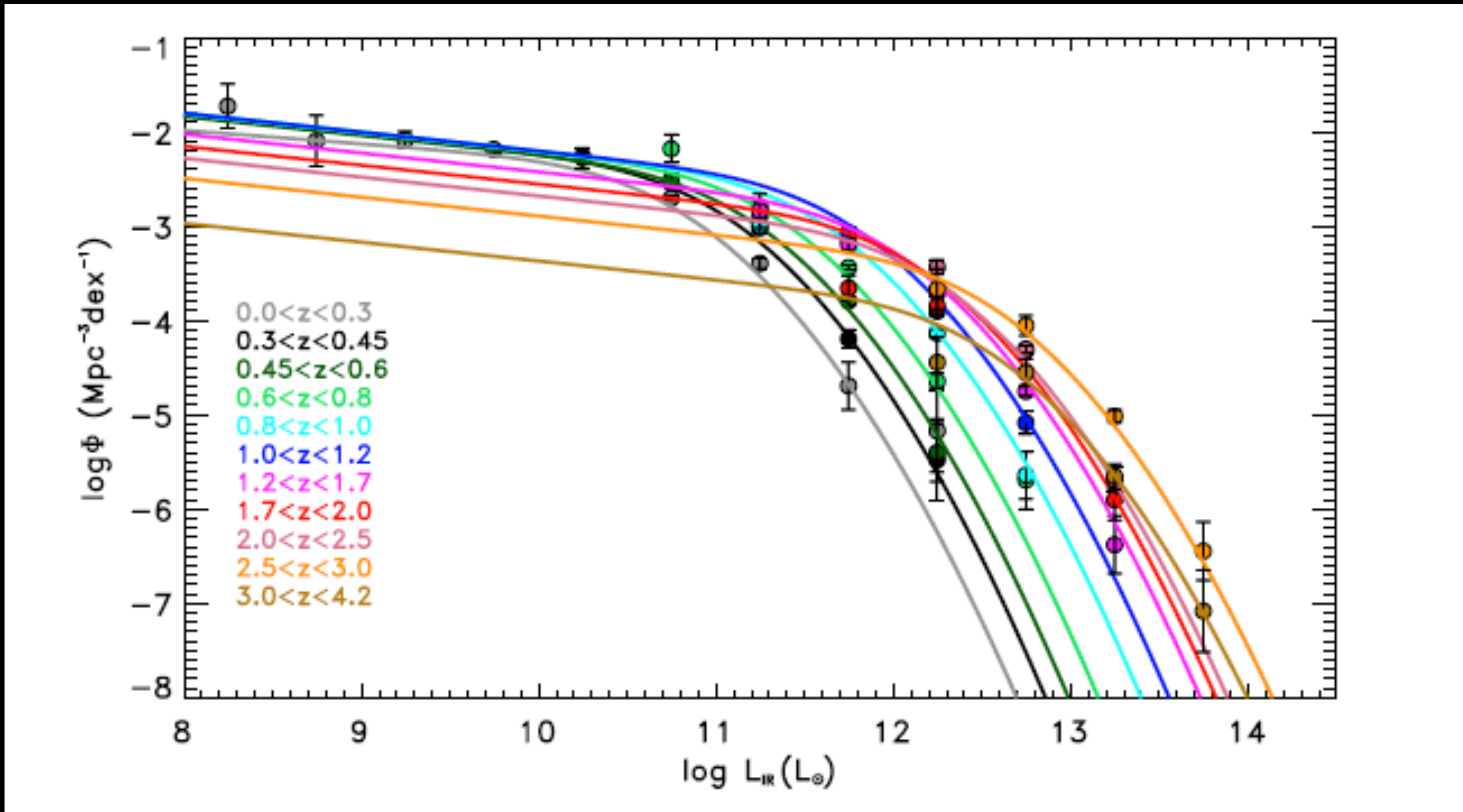


A double component SFH shifts all the MS at higher masses (~x3)!!



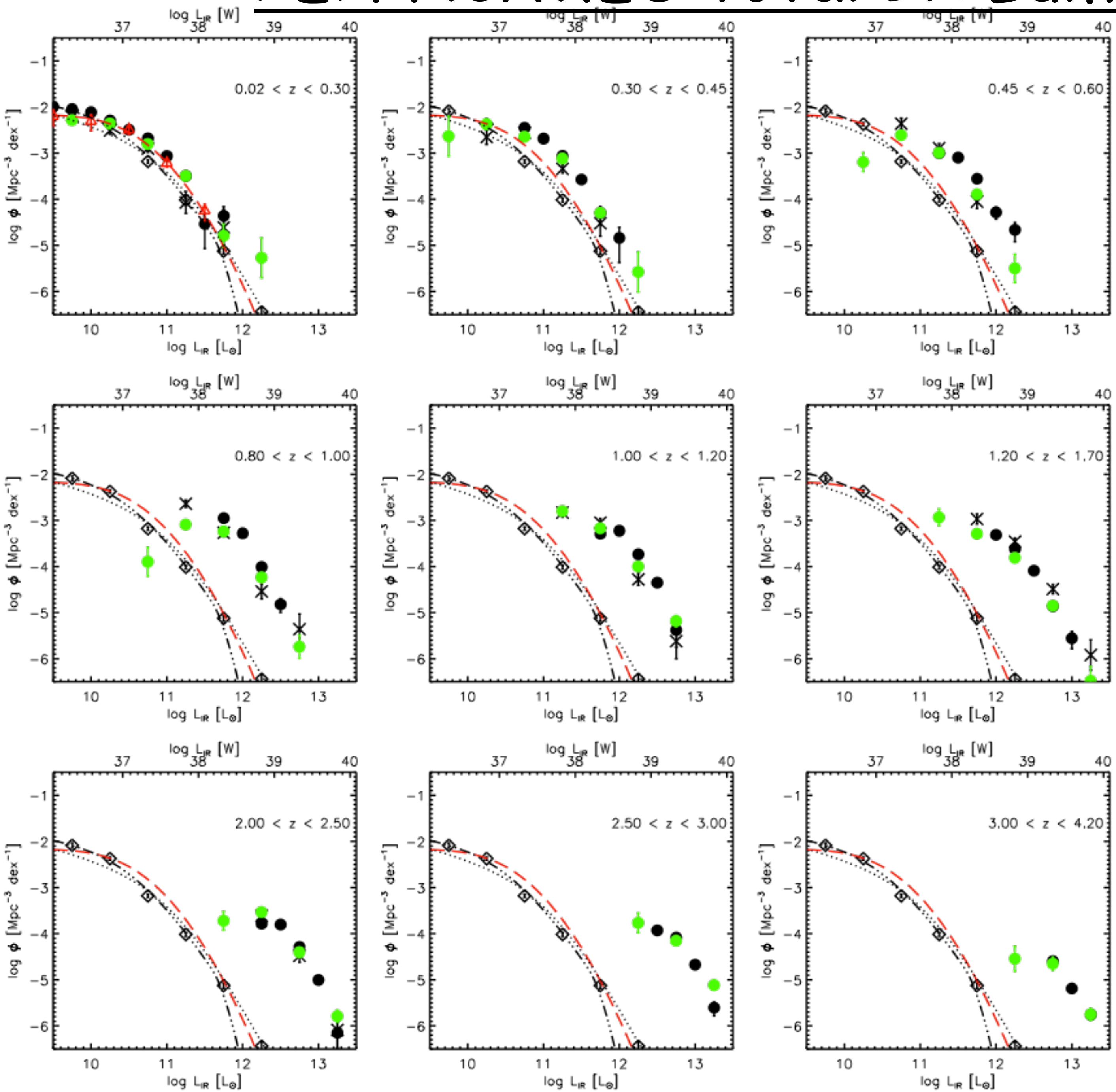
Double component masses by M. Cirasuolo

The Herschel PEP/HerMES LF up to z~4



Gruppioni et al. (2012)

PEP/HerMES total IR Luminosity



IR Bolometric LF(z)

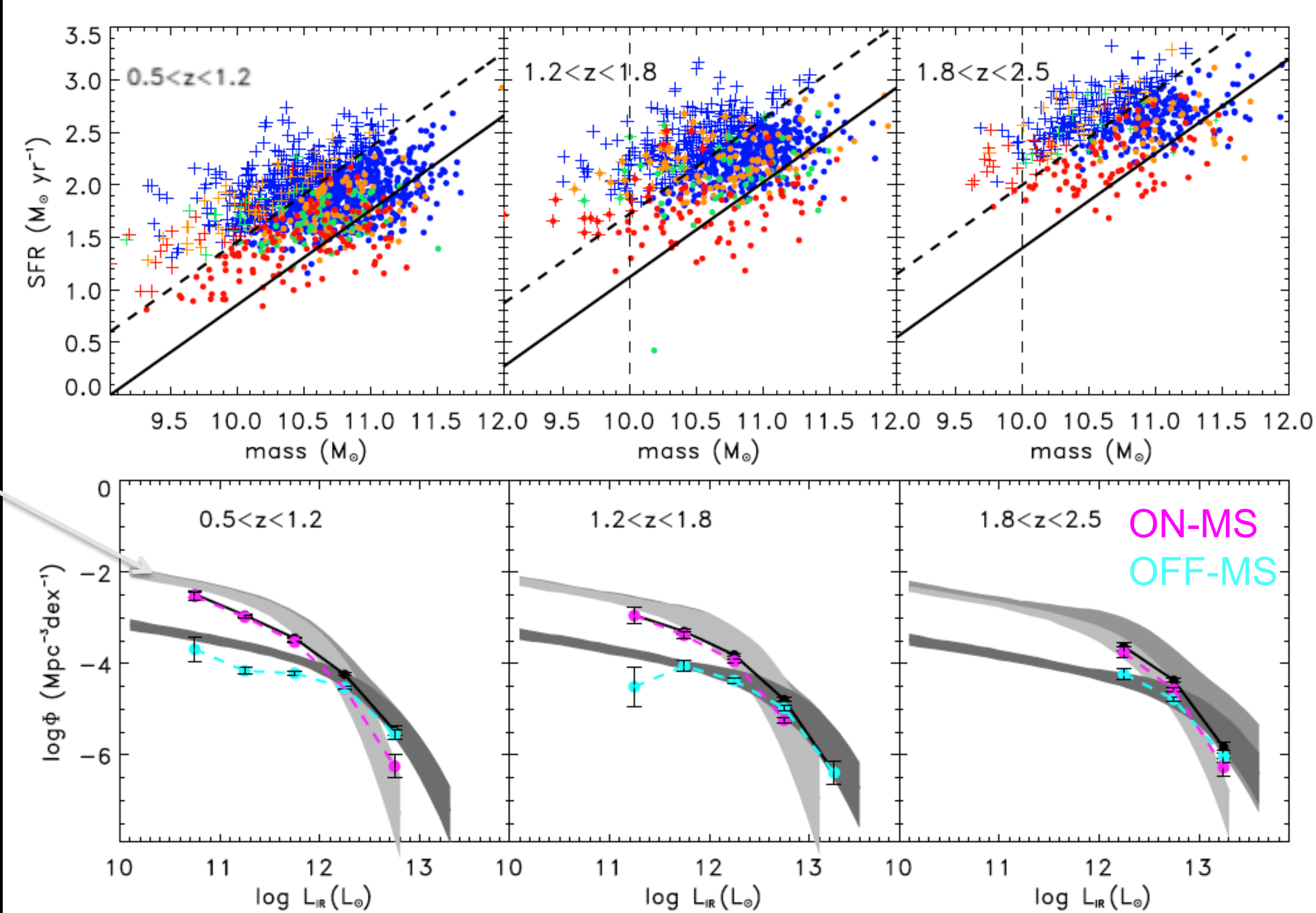
Vaccari et al. in prep (SPIRE samples)

Gruppioni et al. in prep (PACS Blind Samples)

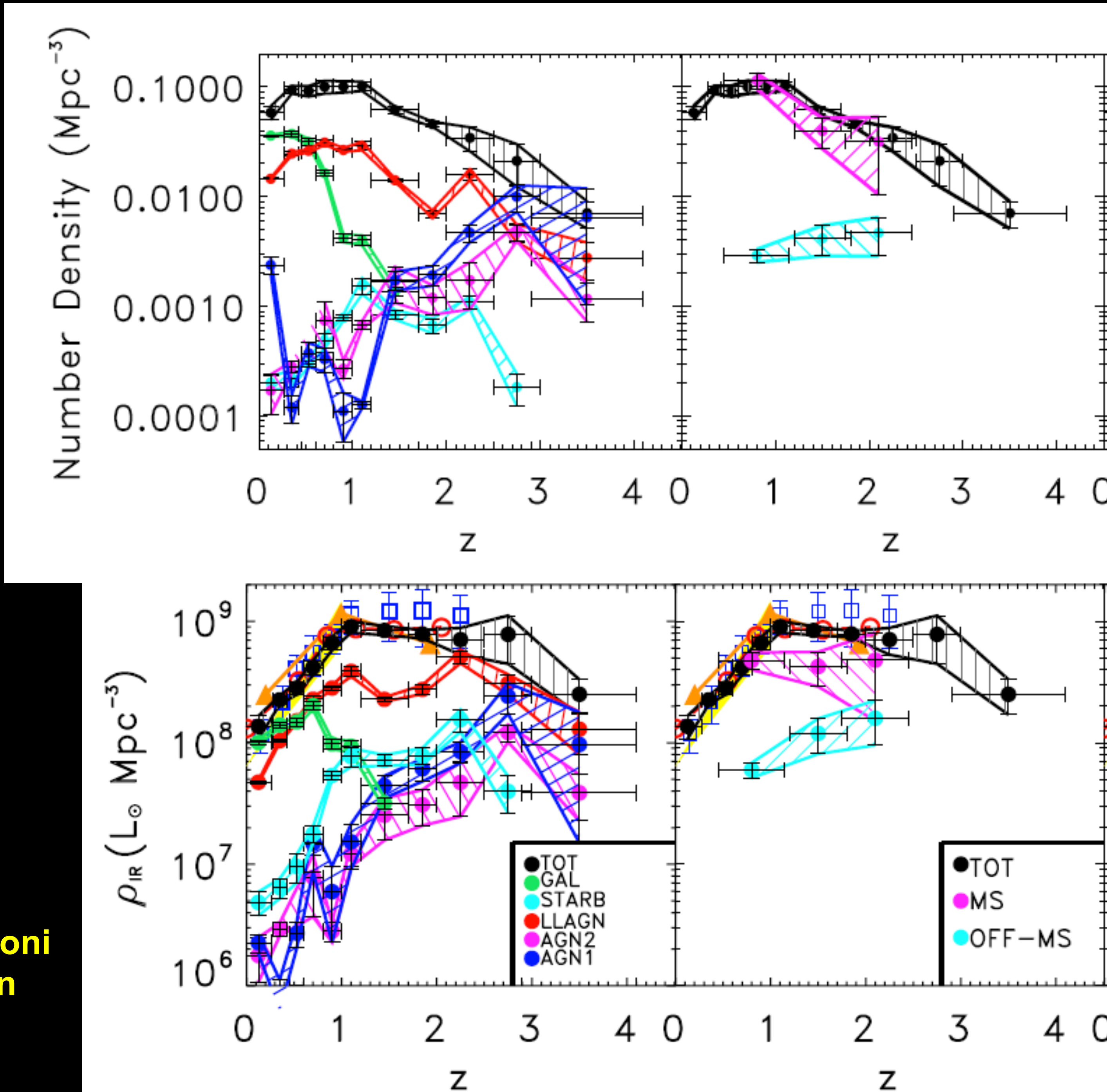
ON- and OFF-main sequence Luminosity functions

Computation of stellar masses and SFR with MAGPHYS (energy-balance, Da Cunha et a. 2008) of PACS/COSMOS-GOODS-ECDFS sources

Predictions from Sargent et al. 2012



Gruppioni et al. (in prep.)

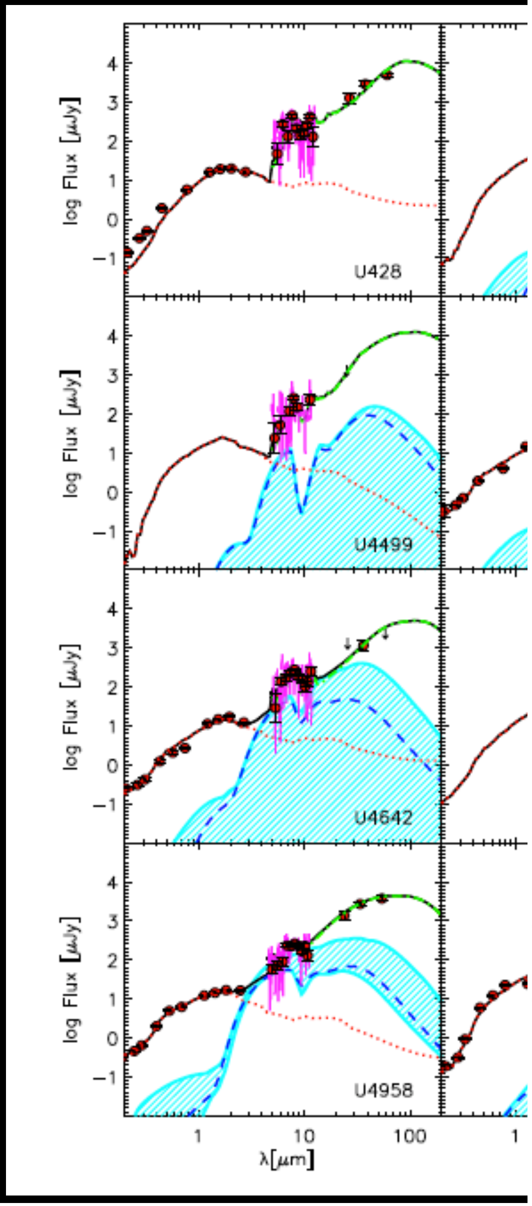


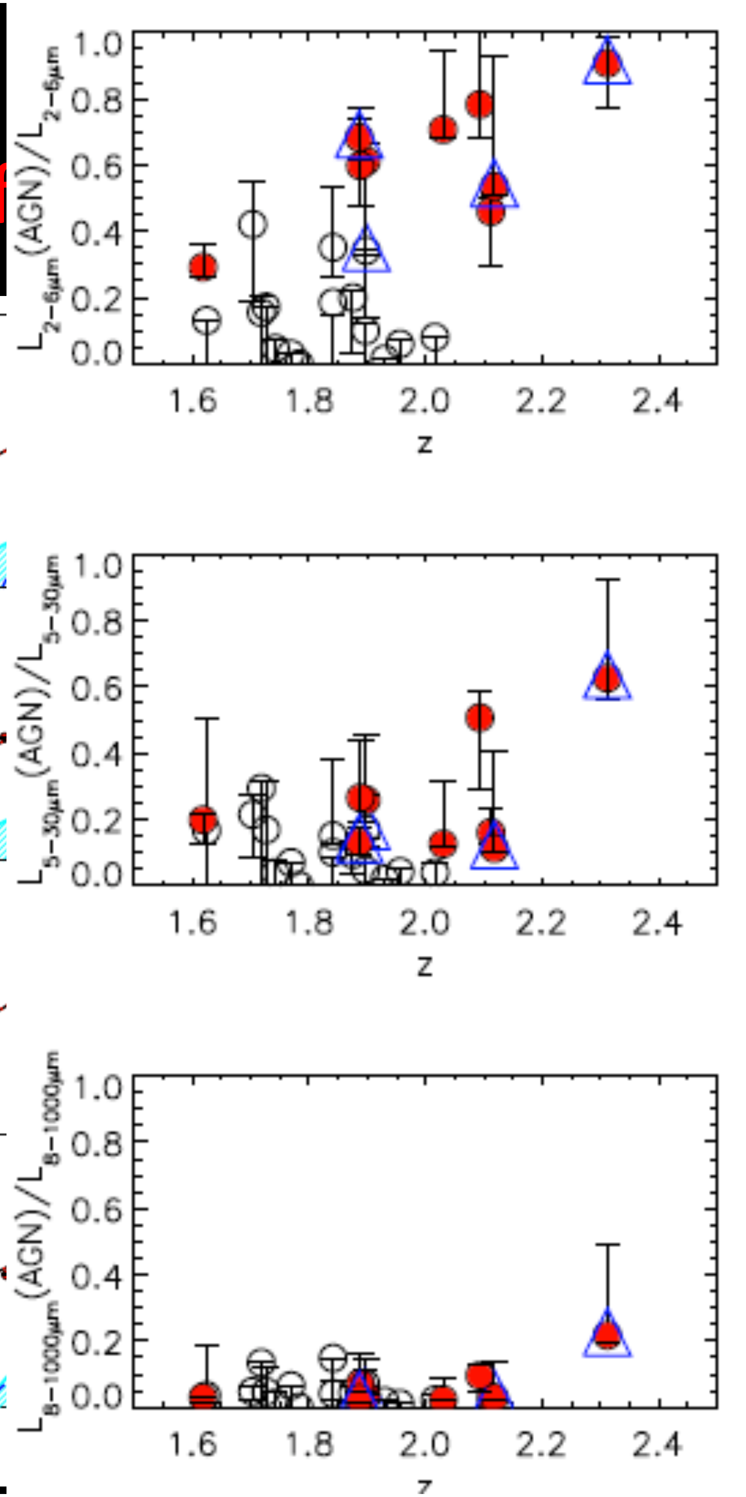
Number density

SFR density

Gruppioni et al. (in prep.)

The AGN co galaxies at z~2
f ing

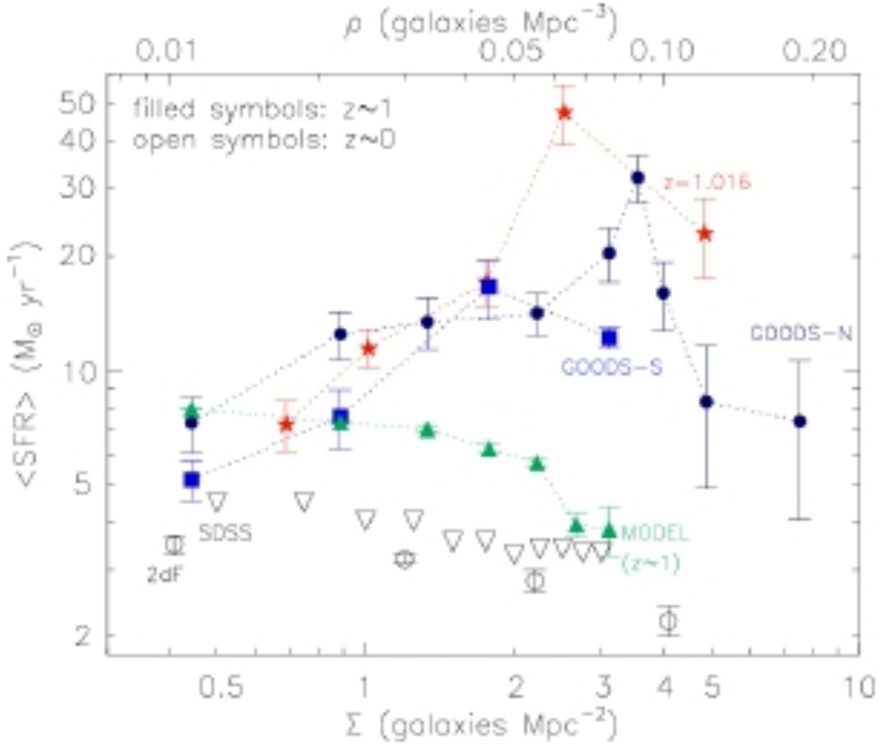


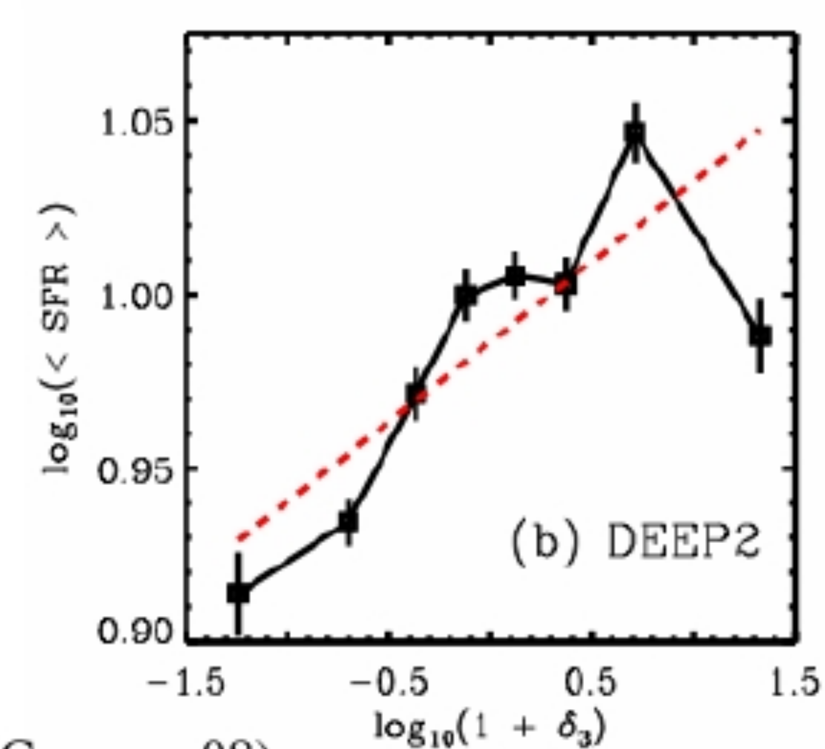


AGN component is present in 35% of the sample but its contribution to the 8-1000µm emission accounts for only ~5% of the total IR energy budget

Pozzi et al. (2012)

The SFR-density relation at @ redshift ~1





(Elbaz+07,Cooper+08)

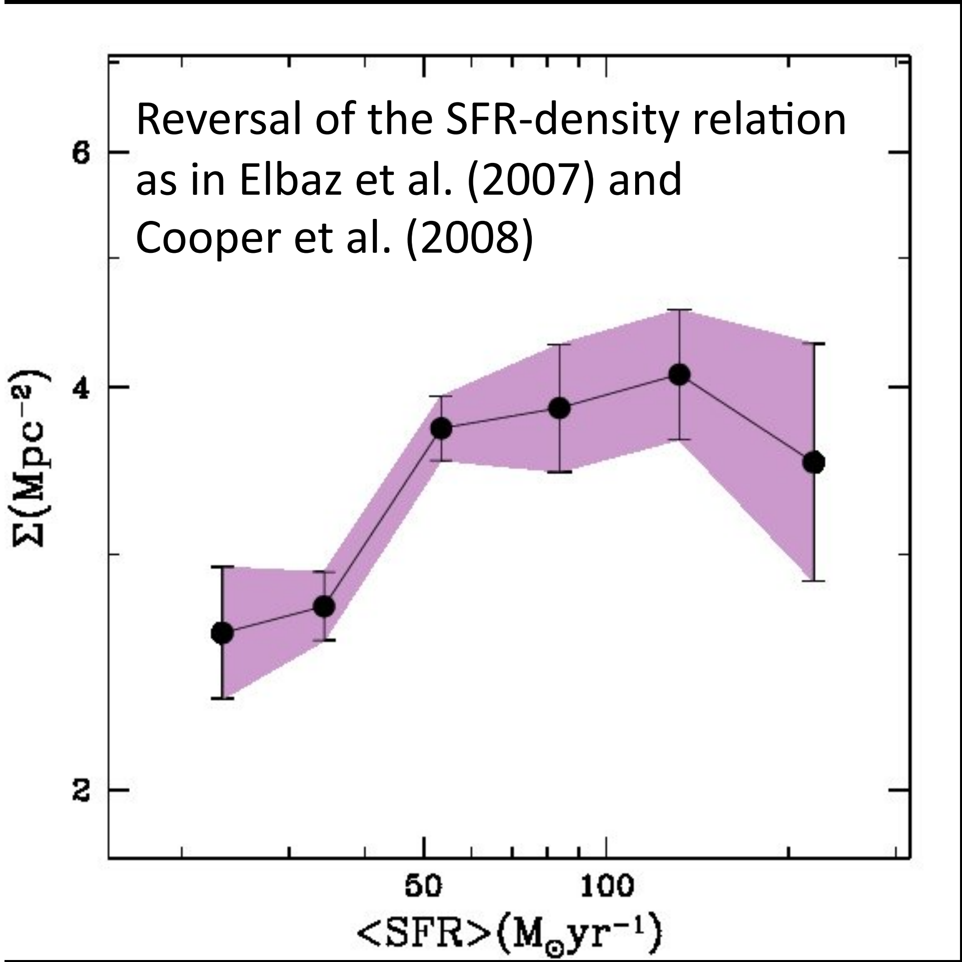
SFR based on MIPS 24 μm

SFR based on [OII] emission

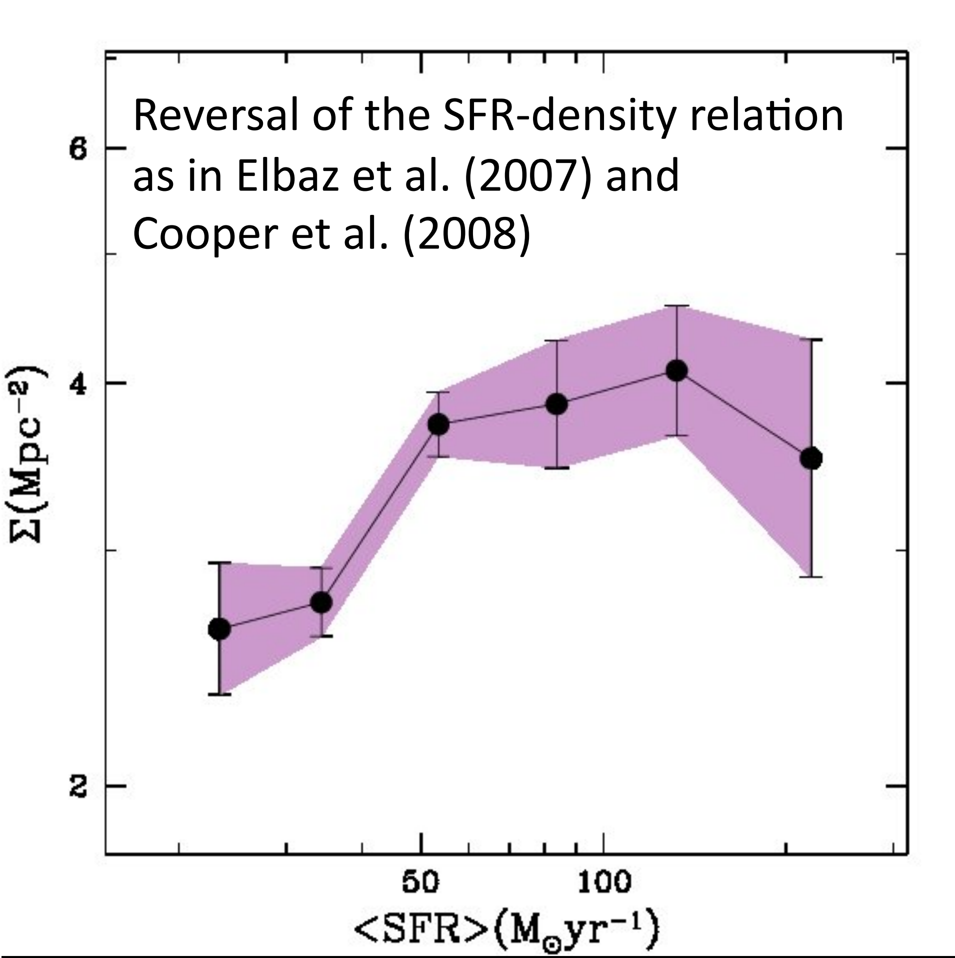
The SFR-density relation at z~1

(Popesso et al. 2010)

...when the galaxy formation process is still going on



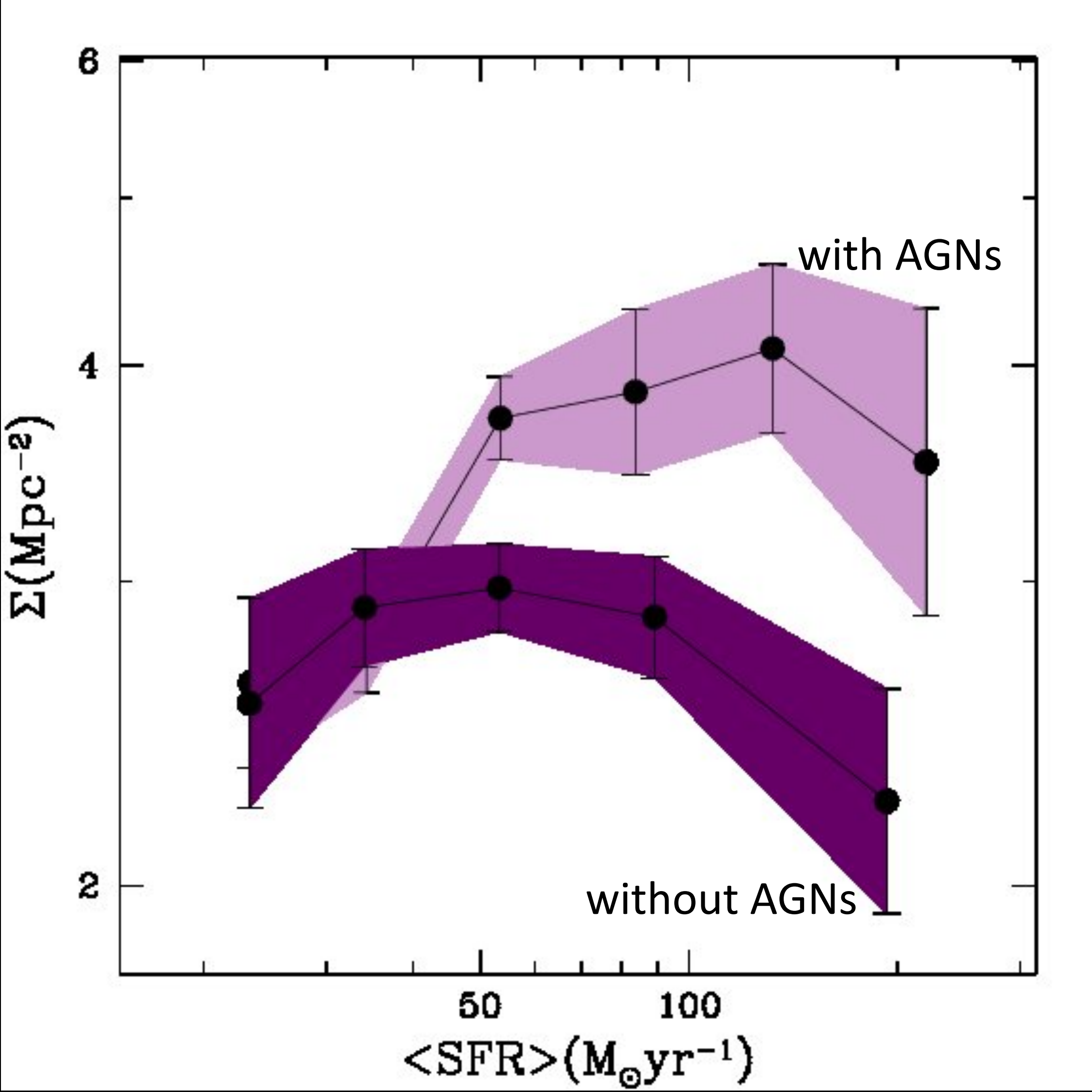
The SFR-density relation at z~1



What is the reversal due to?

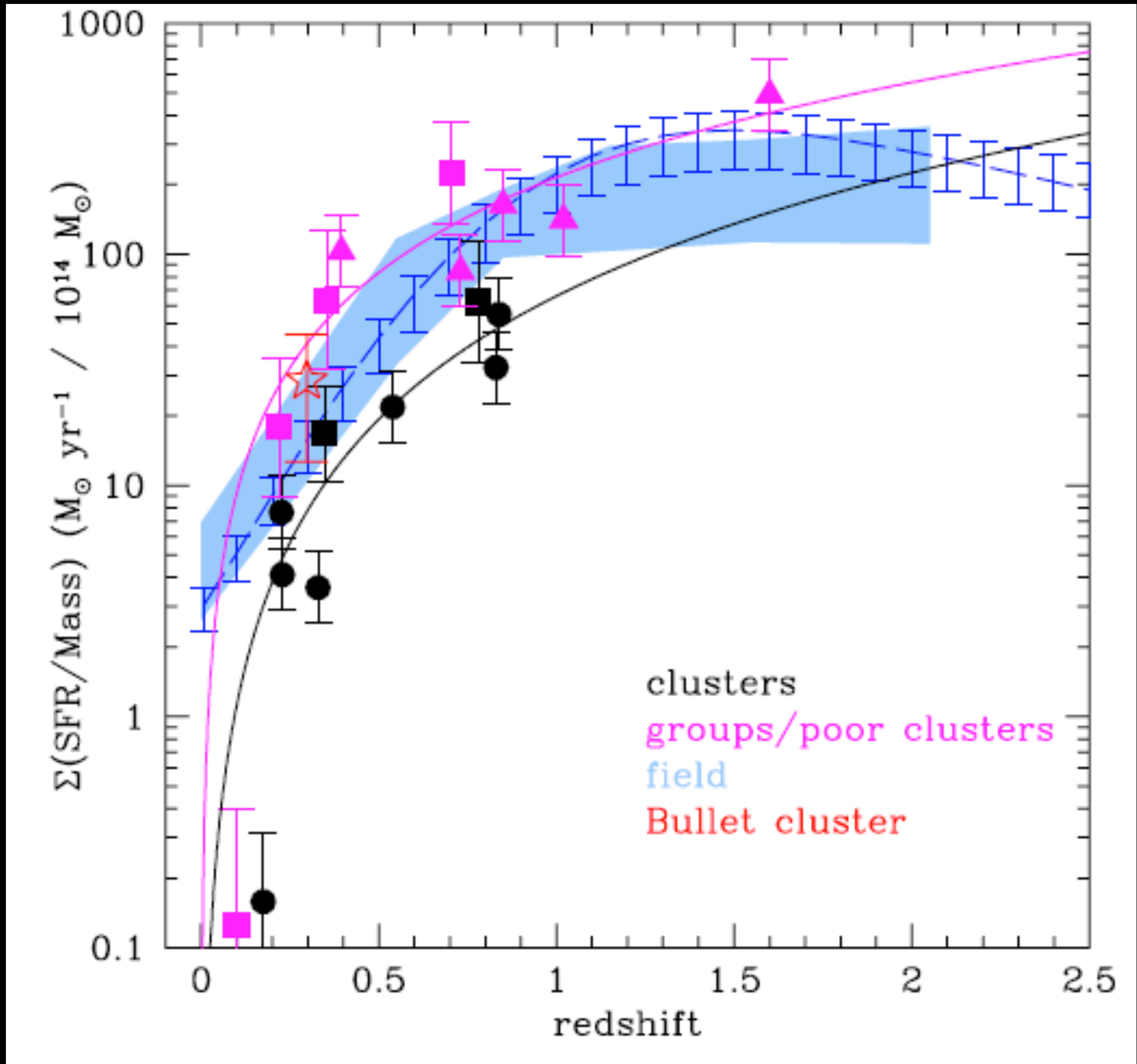
- mass segregation?
- morphology segregation?
- AGN?

The AGN root?



- Reversal of the SFR-density relation @ z~1 due to AGN contribution

The evolution of the SF activity per halo mass with redshift



Popesso et al. (2011)

Summary

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Michael Wetzstein
Eckhard Wieprecht

- ✓ PEP resolves 55% (70%) of the CIB at 100 (160) micron.
- ✓ Herschel/PEP provides a new, continuous calibration of SFR tracers (SFR ladder).
- ✓ Hubble sequence in place since z~2.5.
- ✓ Different structure and mode of SF in high-SFR tail.
- ✓ Compact quiescent galaxies descendants of high-SFR outliers?
- ✓ Majority of star formation at high-z takes place on the MS.