Star formation at intermediate redshift

• what is the redshift by which half of the stars that we see today were formed ?

(Peebles 1988, *The epoch of galaxy formation*)

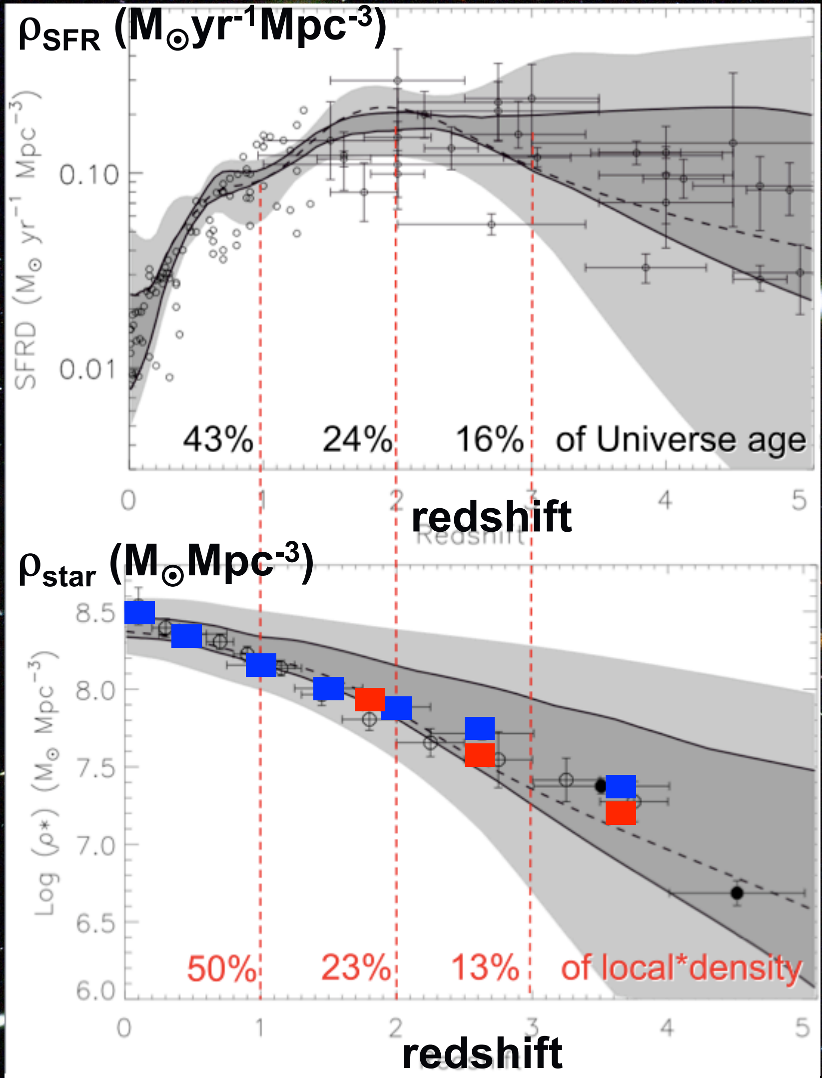
z	0 – 2.5	2.5 – 5	5 - ∞
votes in 1988	28	54	4

0.5 – 2.5 intermediate redshift

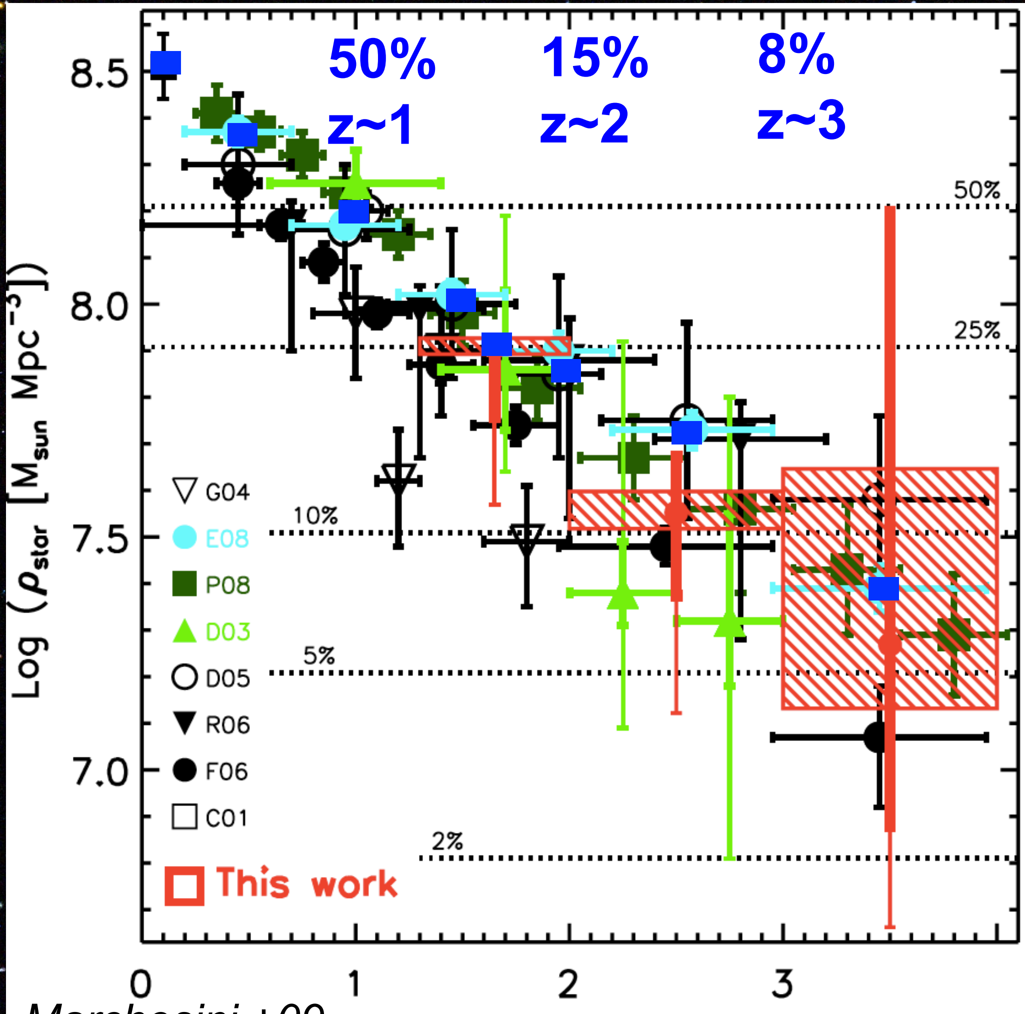
David Elbaz

Star formation at intermediate redshift

- broad consensus on the evolution of the stellar mass density
- broad consensus between integral of SFR density and M* density with time !



Le Borgne, Elbaz, Ocvirk, Pichon 10



Marchesini +09

Star formation at intermediate redshift

• what is the redshift by which half of the stars that we see today were formed ?

(Peebles 1988, *The epoch of galaxy formation*)

z	0 – 2.5	2.5 – 5	5 - ∞
votes in 1988	28	54	4
	~85 %	**~15%**	**<5% (% age after recombination)**

0.5 – 2.5 intermediate redshift

• have we really improved our knowledge of the actual SFR of galaxies ?

(dust extinction, IMF, timescale of star formation)

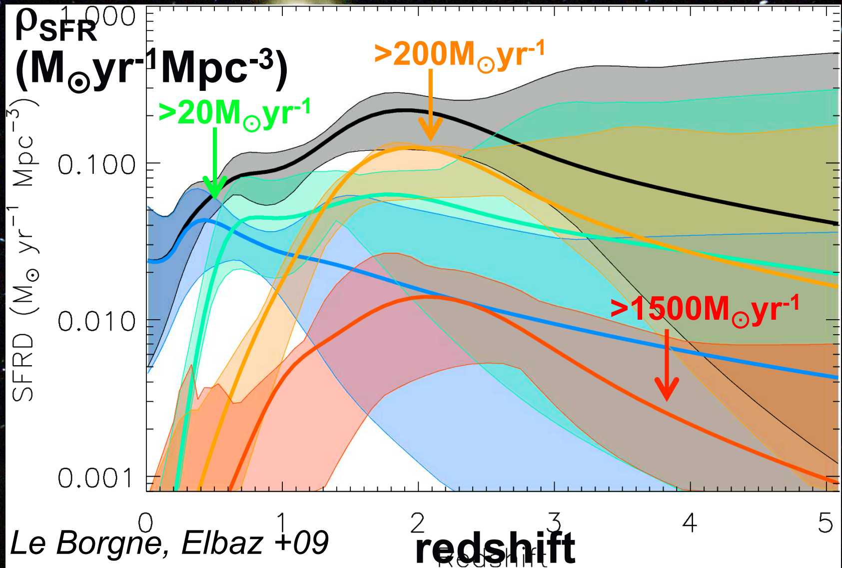
• assuming that we know when the bulk of present-day stars formed

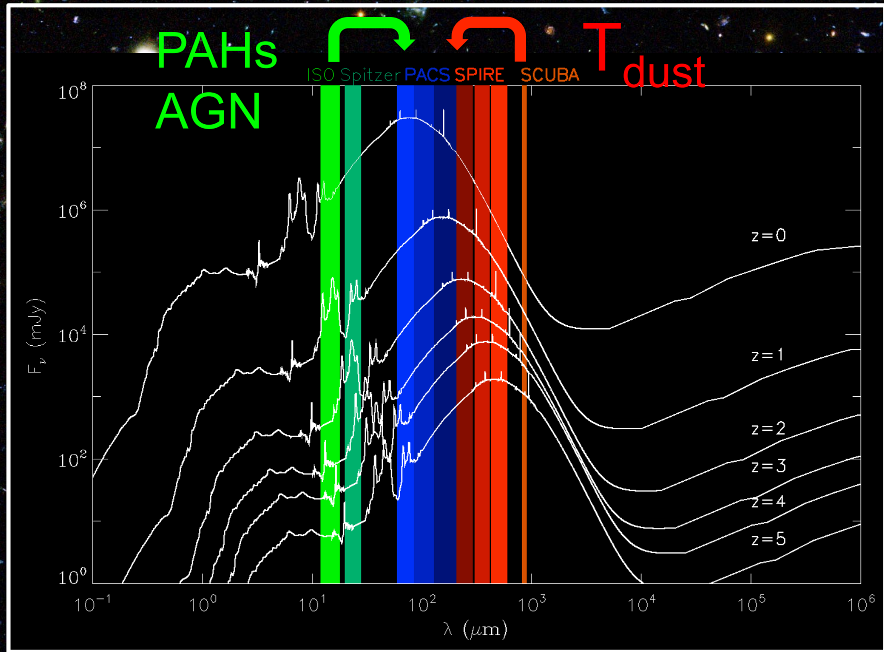
did they form in a violent/starburst mode or in a more normal/disk-like more ?

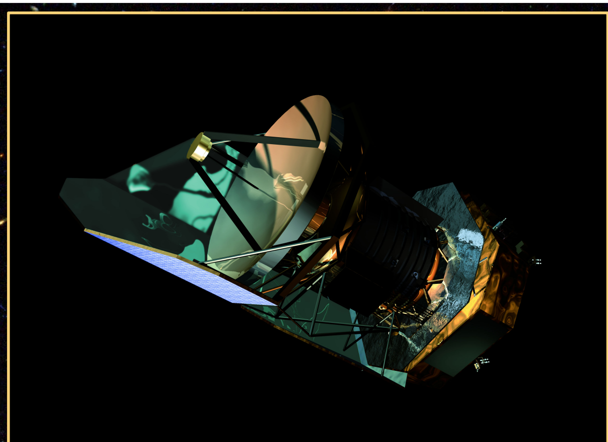
David Elbaz

Star formation at intermediate redshift

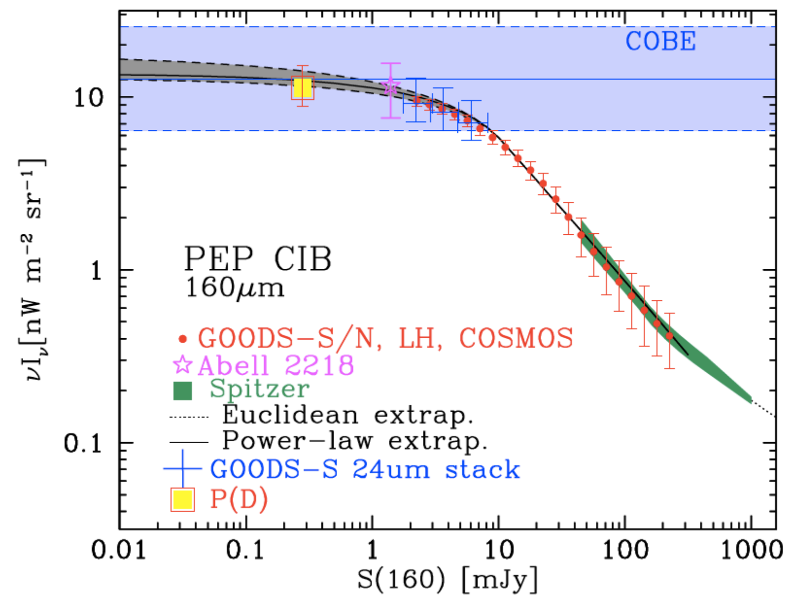
- broad consensus on the evolution of the stellar mass density
- broad consensus between integral of SFR density and M* density with time !
- star formation at the scale of individual galaxies follows simple scaling laws
- (U)LIRGs dominate the cosmic SFR density at z>0.5 ! but interpolations are uncertain...







Resolving and slicing the CIRB: ~75% resolved at 160μm, z<2 dominate



Bkg /sources:

PEP: Berta +11

(~35% @ 70μm)

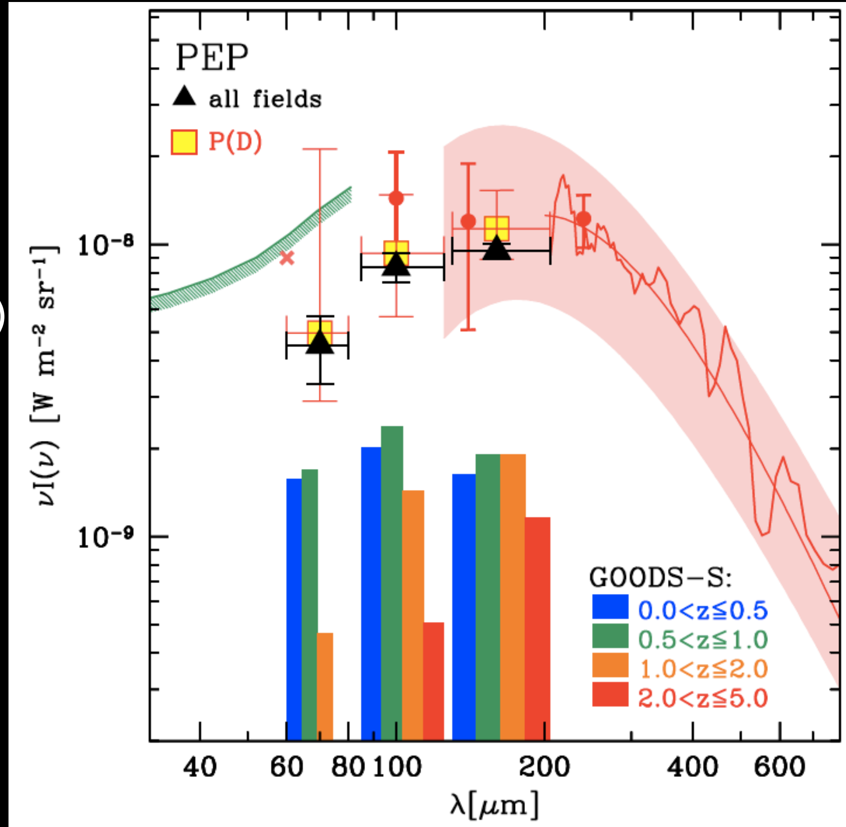
~58% @ 100μm

8.35 nWm^{-2}sr^{-1}

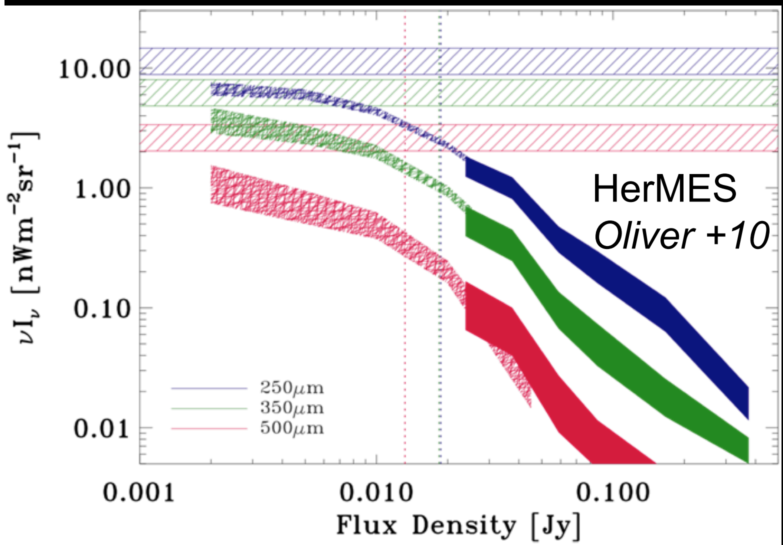
~74% @ 160μm

9.48 nWm^{-2}sr^{-1}

→ 89% P(D)



Berta +10, 11



HerMES: Oliver +10

Individual src P(D) statistics

15% @ 250μm → 64 %

10% @ 350μm → 60 %

6% @ 500μm → 43 %

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

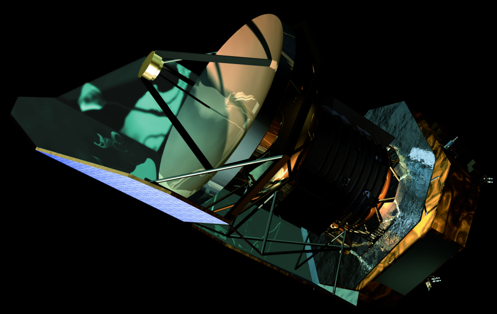
X	UV U B V I Z	J H K	3.6µm 4.5µm 5.8µm 8µm	IRS16	MIPS24	radio
2×10^{-16} erg/s/cm²	~28AB	22AB	~1µJy	50µJy	20µJy	12µJy

David Elbaz
Mark Dickinson
Bruno Altieri
Herve Aussel
Daniela Coia
Emanuele Daddi
Helmut Dannerbauer
Ho-Seong Hwang
Jeyhan Kartaltepe
Roger Leiton
Georgios Magdis
Benjamin Magnelli
Paola Popesso
Ivan Valtchanov
David Alexander
Alexandre Beelen
Matthieu Bethermin
Mark Brodwin
Veronique Buat
Dennis Burgarella
Daniela Calzetti
Catherine Cesarsky
Pierre Chanial
Stephane Charlot
Vass. Charmandaris
Ranga-Ram Chary
Kalliopi Dasyra
Herve Dole
Peter Eisenhardt
Harry Ferguson
N.Forster-Schreiber
David Frayer
René Gastaud
Mauro Giavalisco
Roberto Gilli
Elodie Giovannoli
Dan Hanisch
Sebastien Heinis
Kuang-Han Huang
Minh Huynh
Rob Ivison
Stephanie Juneau
Anton Koekemoer
Damien Le Borgne
Emeric Le Floc'h
Dieter Lutz
Glenn Morrison
James Mullaney
Eric Murphy
Maurilio Pannella
Casey Papovich
Kyle Penner
Alexandra Pope
Naveen Reddy
Samir Salim
Douglas Scott
Hyunjin Shim
Christian Surace
Harry Teplitz
Grant Wilson
Min Yun
+ Tanio Diaz-Santos, Lee Armus, Joe Mazzarella

Collaborators (60): *Fr, US, G, UK, Gr, It, Can, ESO, ESA*

362.6 hours (100µm & 160µm PACS + 31h SPIRE)

Herschel: 350 cm



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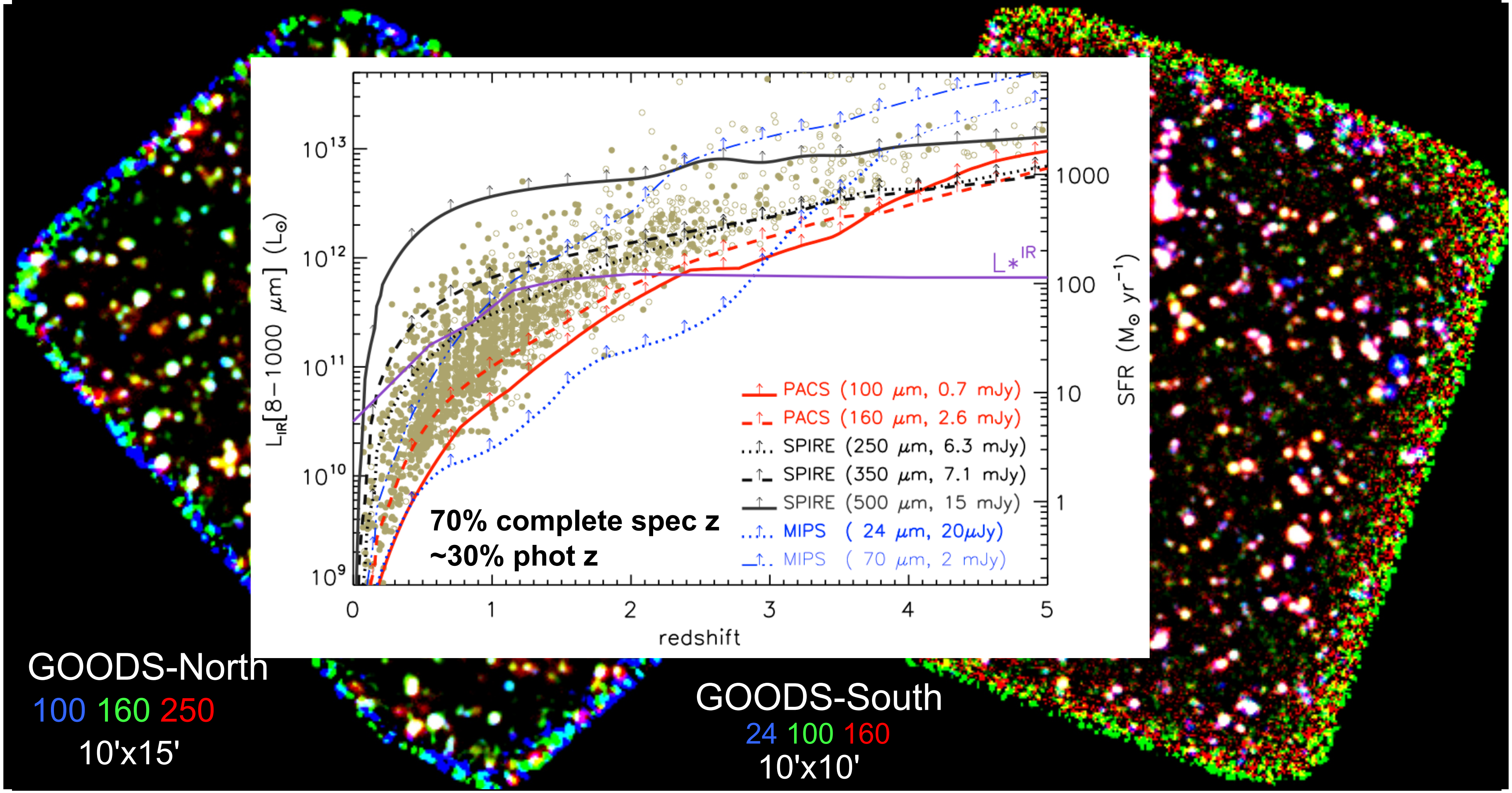
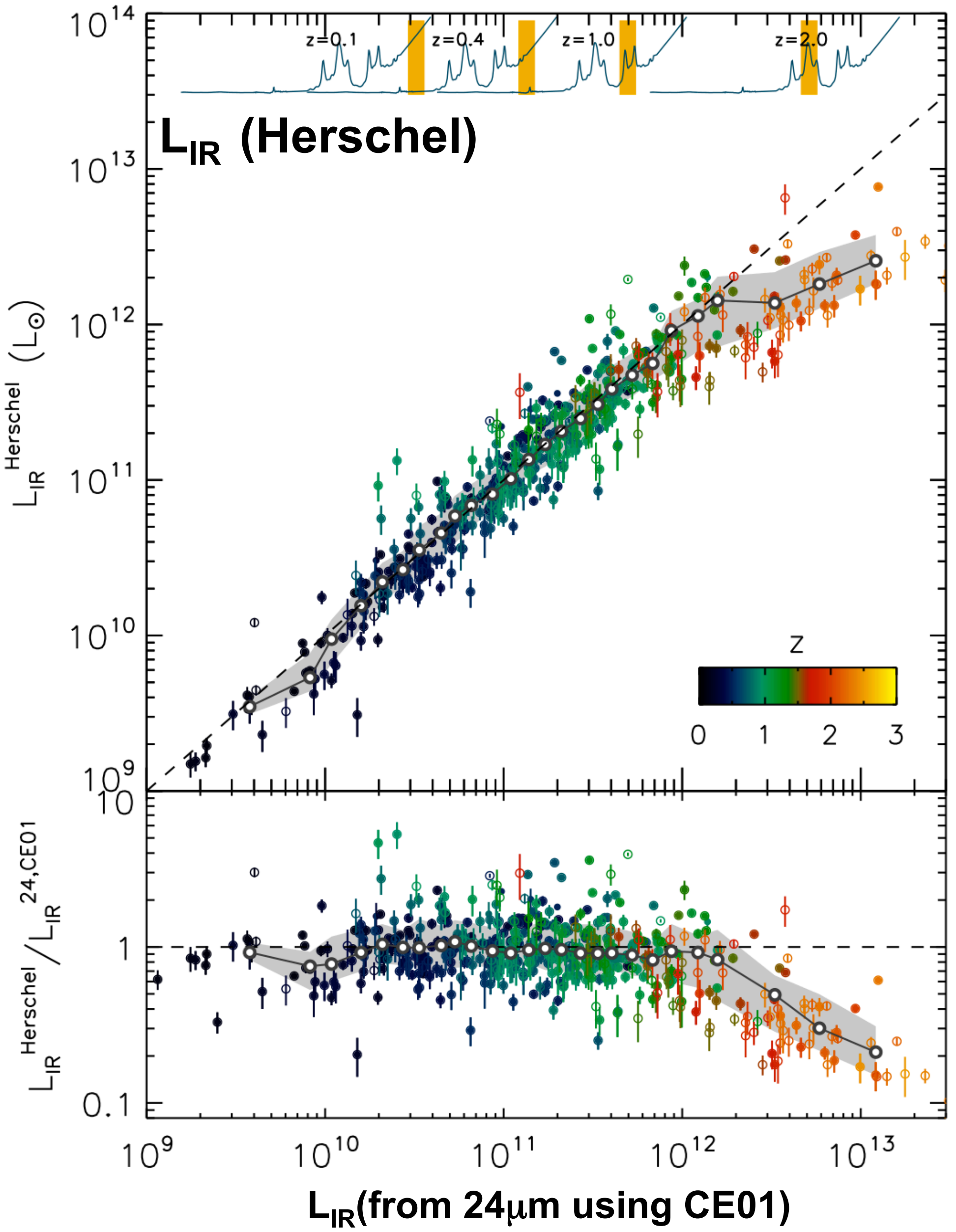
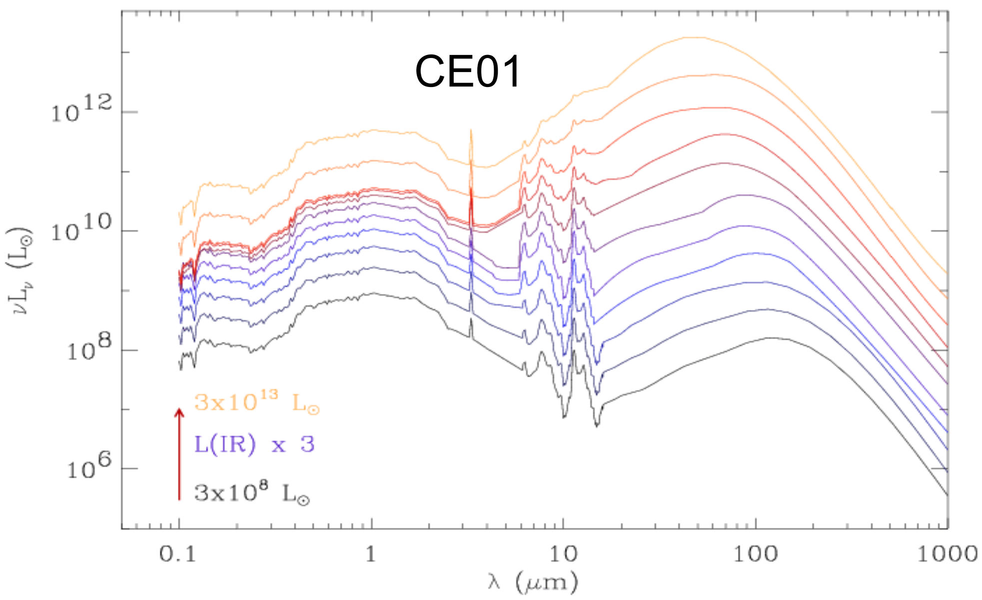
2×10^{-16}erg/s/cm²	~28AB 22AB	~1μJy	50μJy	20μJy	12μJy



The mid-IR excess problem... SED evolution/AGN/k-correction ?...

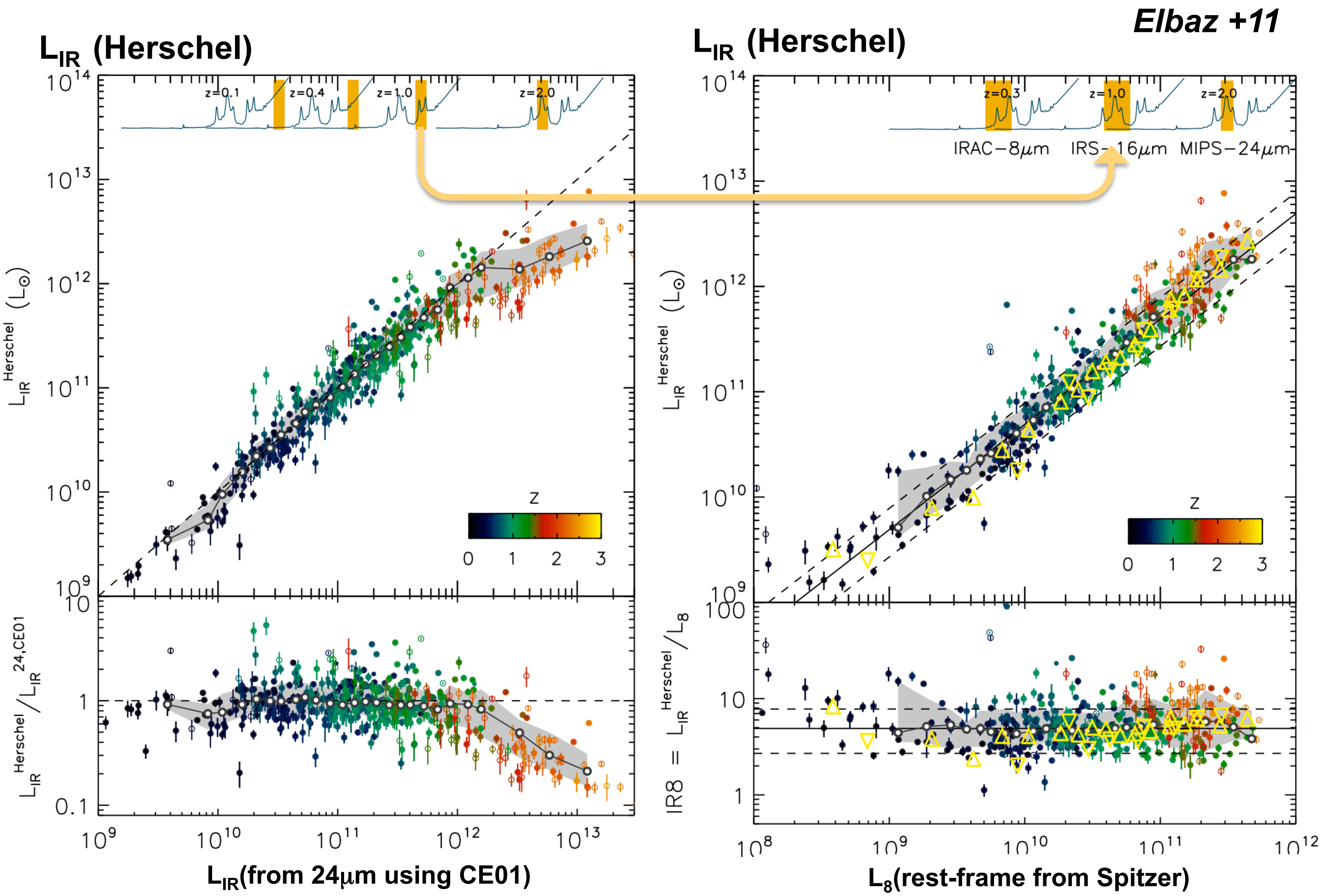


- mir and far IR consistent with local SEDs (Chary & Elbaz 01) up to z~1.5 (blue, green dots)
- at z>1.5: "mid-IR excess" (Daddi +07, Papovich +07) (orange, red dots)

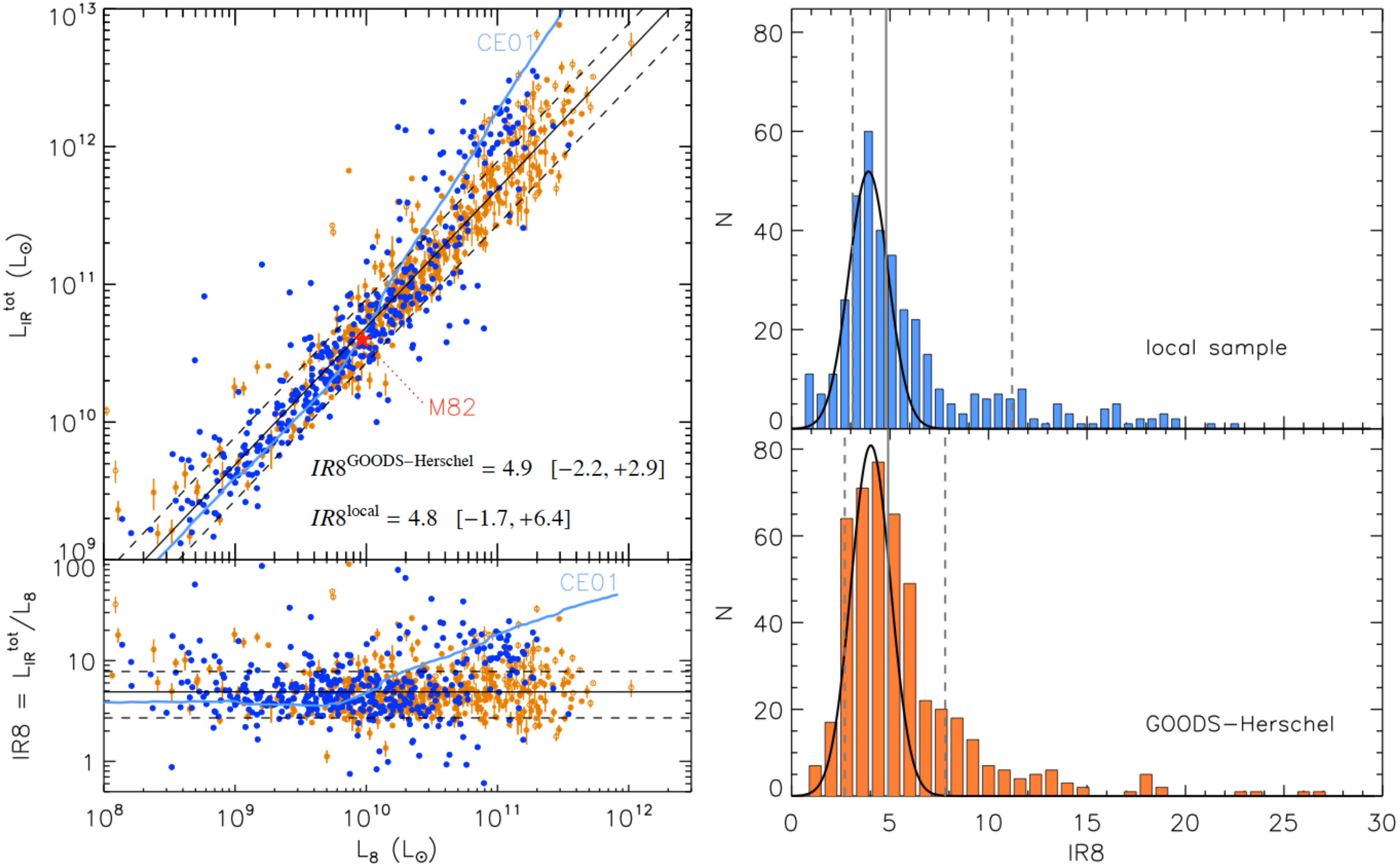


Elbaz +10, 11, Nordon +10

The mid-IR excess problem... SED evolution/AGN/k-correction ?...



IR main sequence : 2 modes of star formation ?

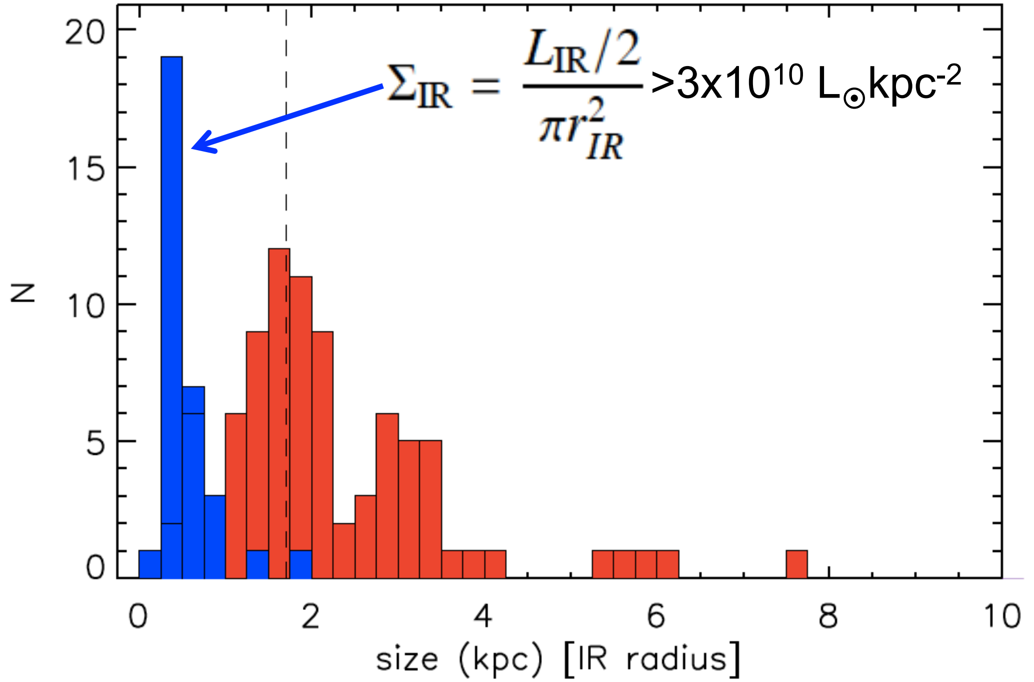


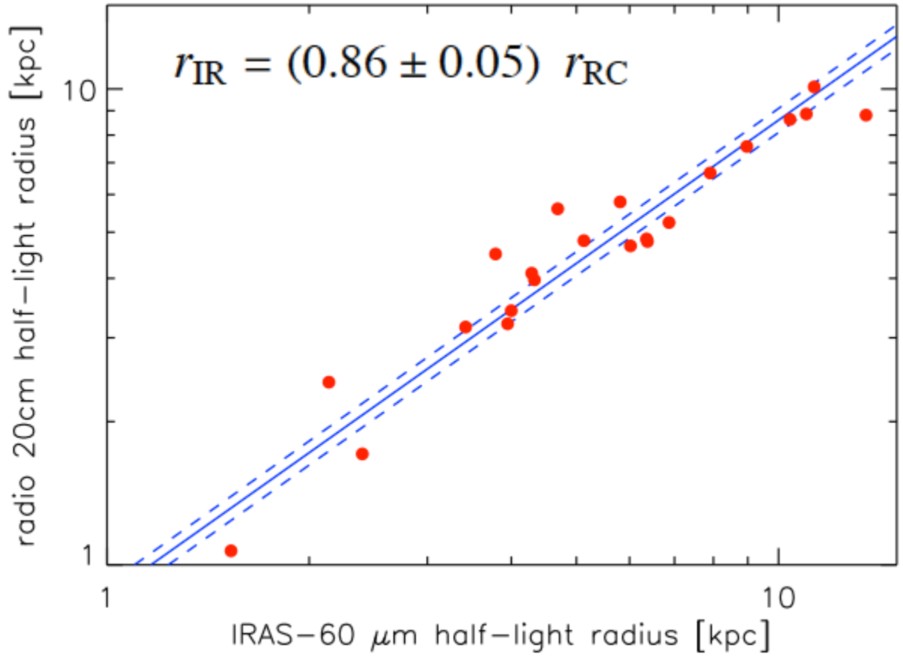
$IR8^{local}$(center Gaussian) = 3.9 [σ = 1.25]

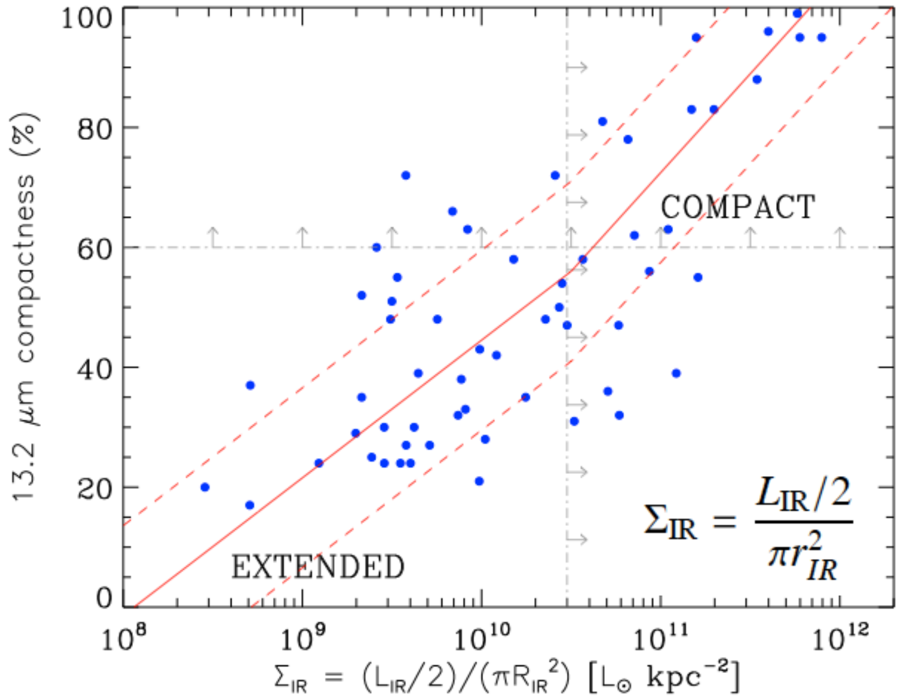
$IR8^{GOODS-Herschel}$(center Gaussian) = 4.0 [σ = 1.6]

Elbaz +11

IR main sequence : the role of SF compactness



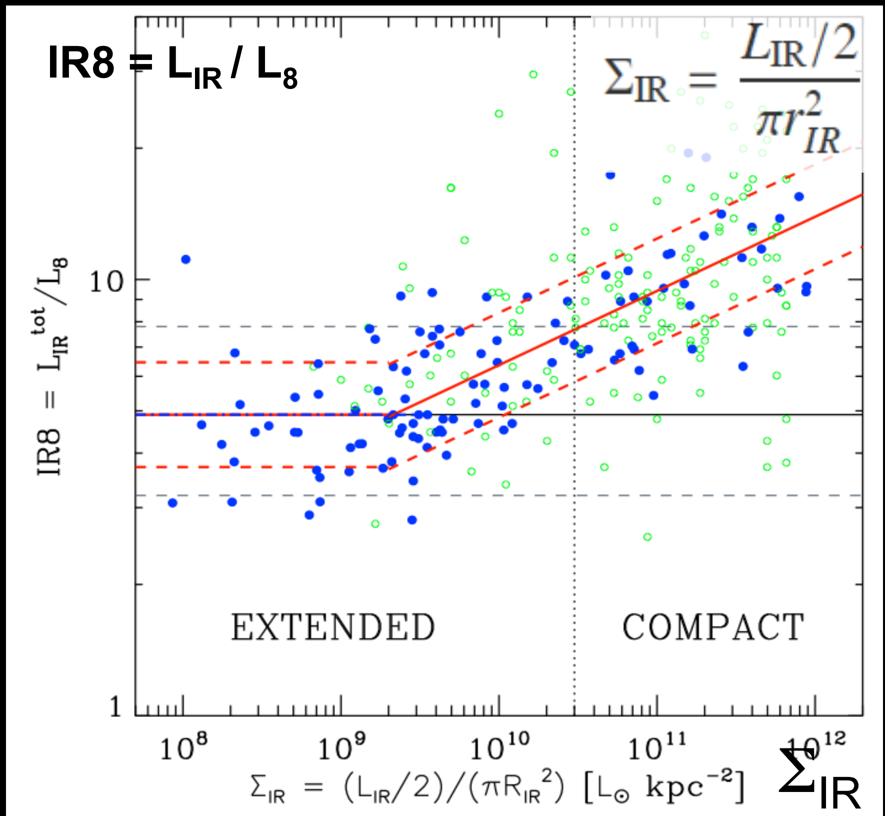


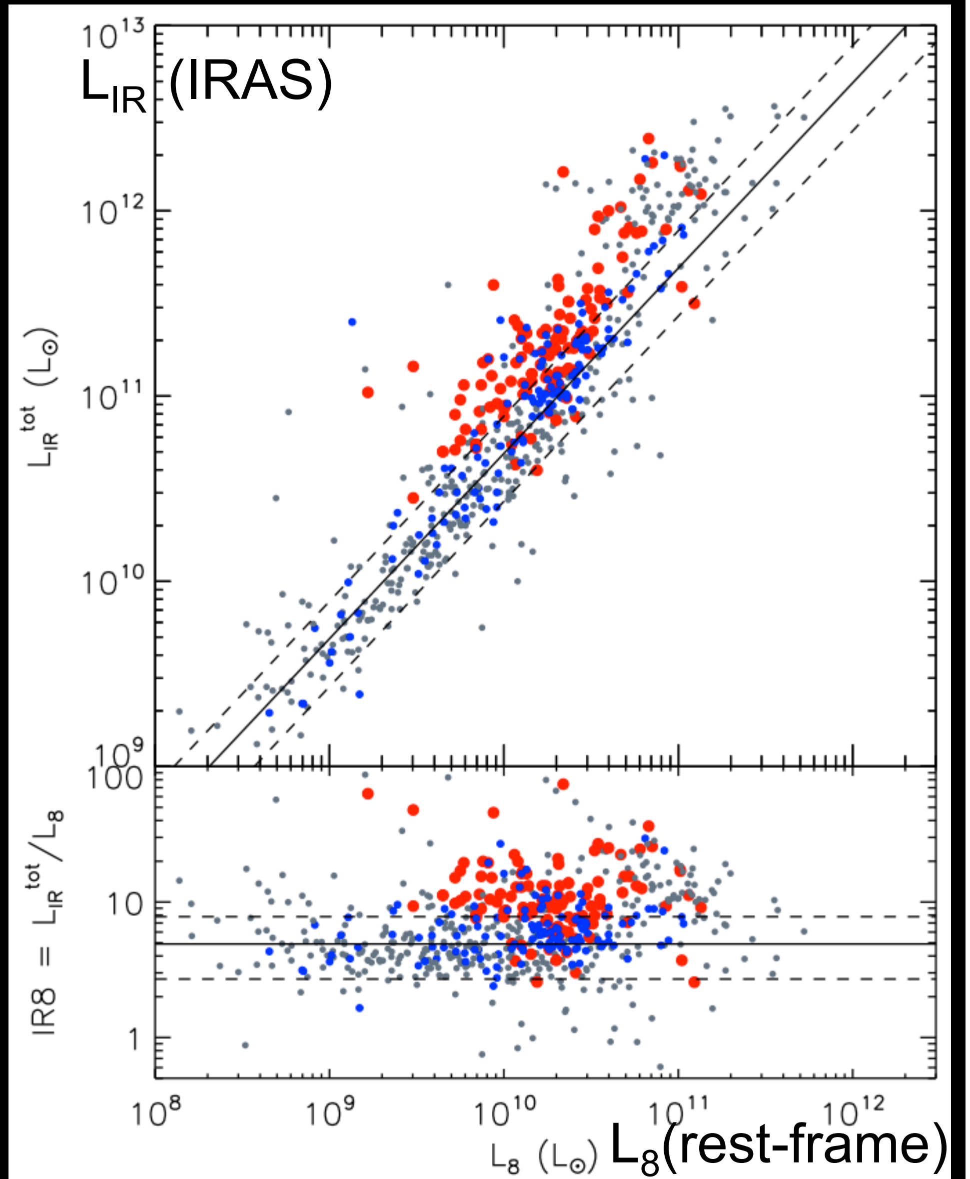


- radio size NVSS & FIRST 20cm: 1" ~ 0.5 kpc res°
- 13.2μm compactness : 3.6" ~ 1.7 kpc resolution Spitzer-IRS spectroscopy (spatial profile along slit) & IRAC-8μm imaging (Diaz-Santos +10)

Elbaz +11

IR main sequence : the role of SF compactness





$$IR8 = 5.0, \quad \text{for } \Sigma_{IR} < 3 \times 10^9 L_\odot \text{kpc}^{-2}$$

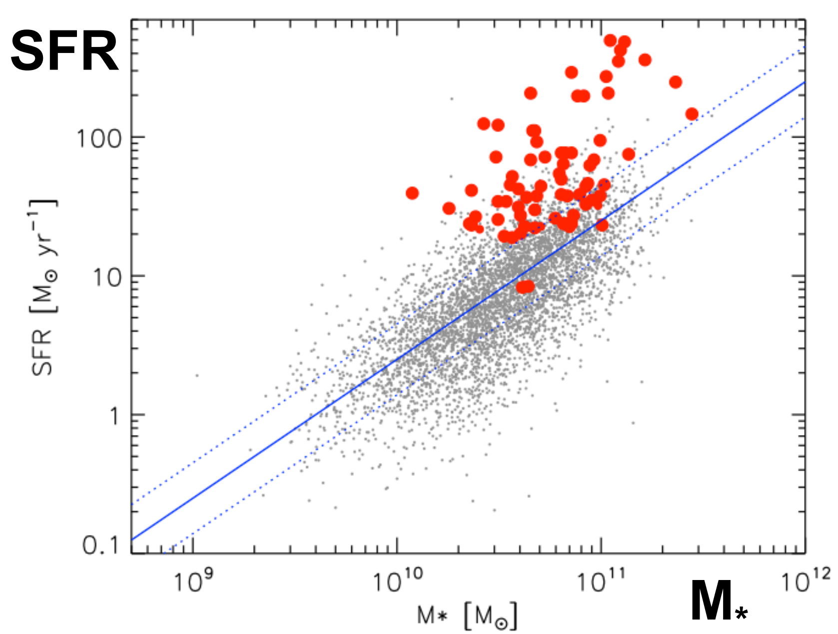
$$IR8 = 0.127 \times (\Sigma_{IR}/L_\odot \text{kpc}^{-2})^{0.17}, \quad \text{for } \Sigma_{IR} > 3 \times 10^9 L_\odot \text{kpc}^{-2}$$

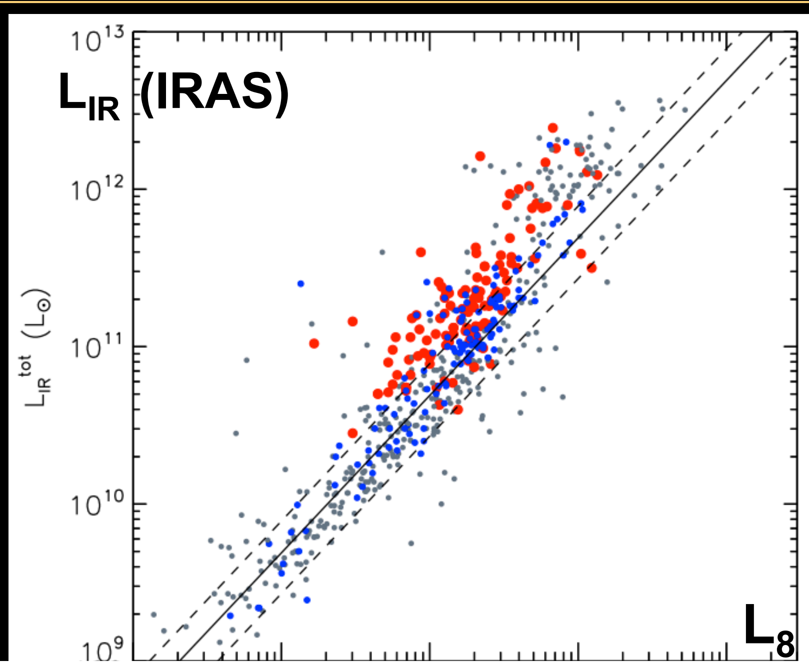
Local

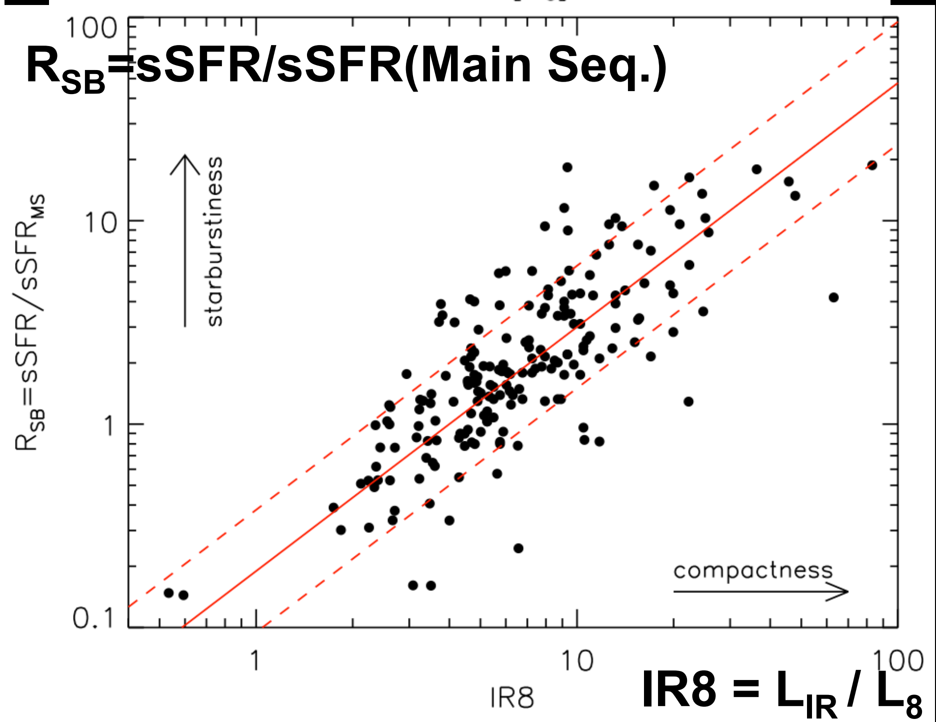
Elbaz +11

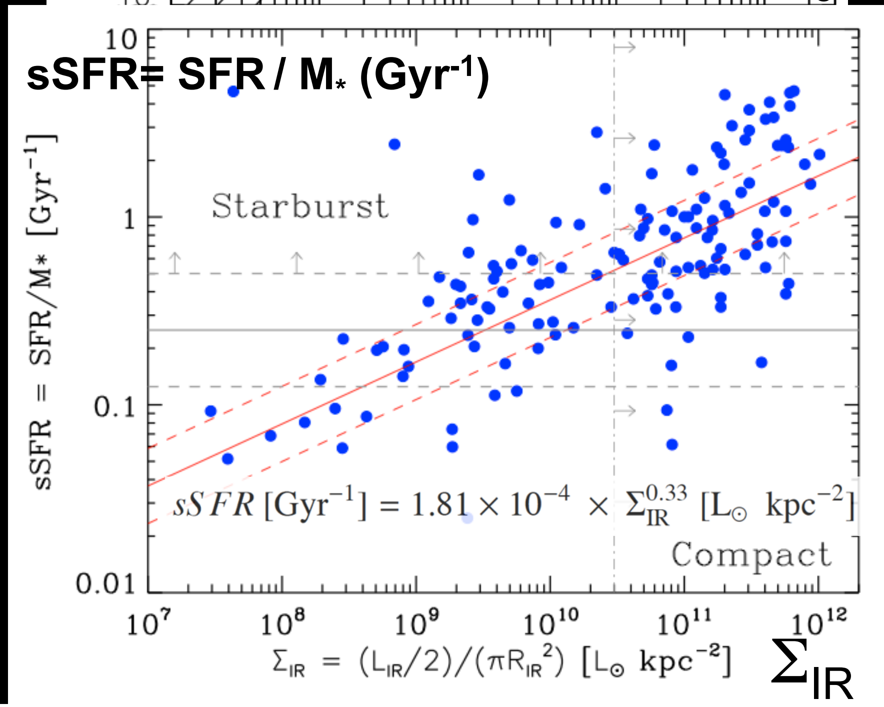
Galaxies with an excess in IR8, IR surface brightness and sSFR are the same !

→ high IR8 ~ compact starbursts

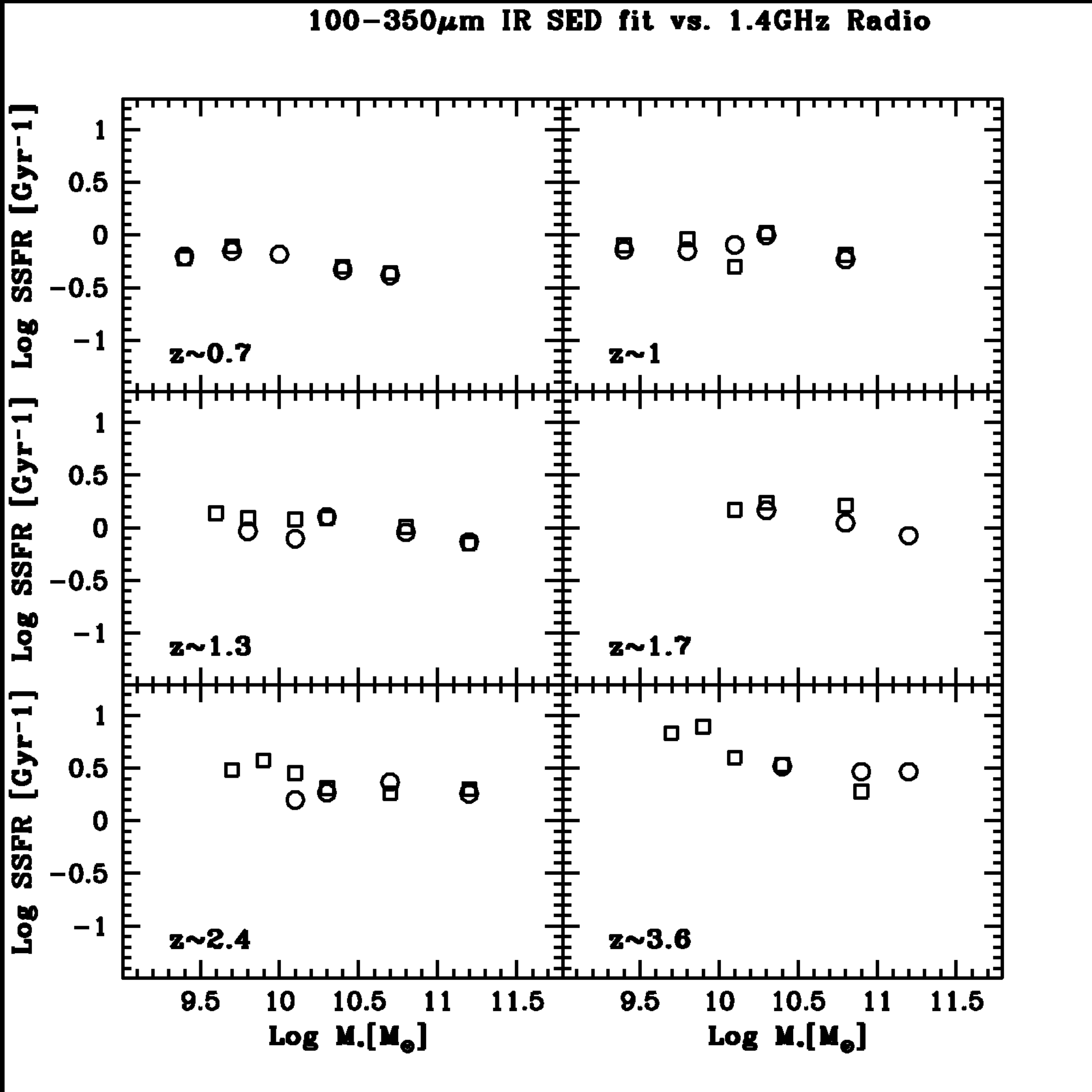


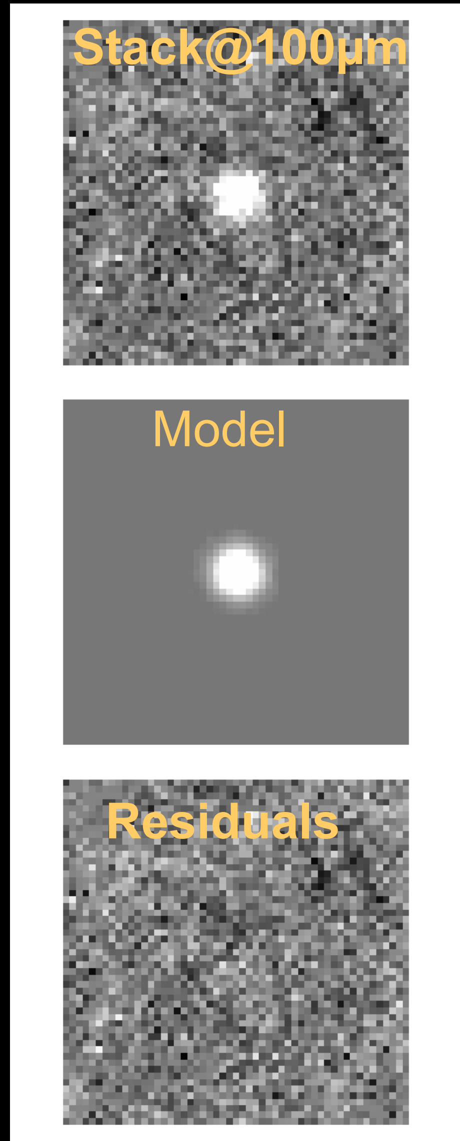






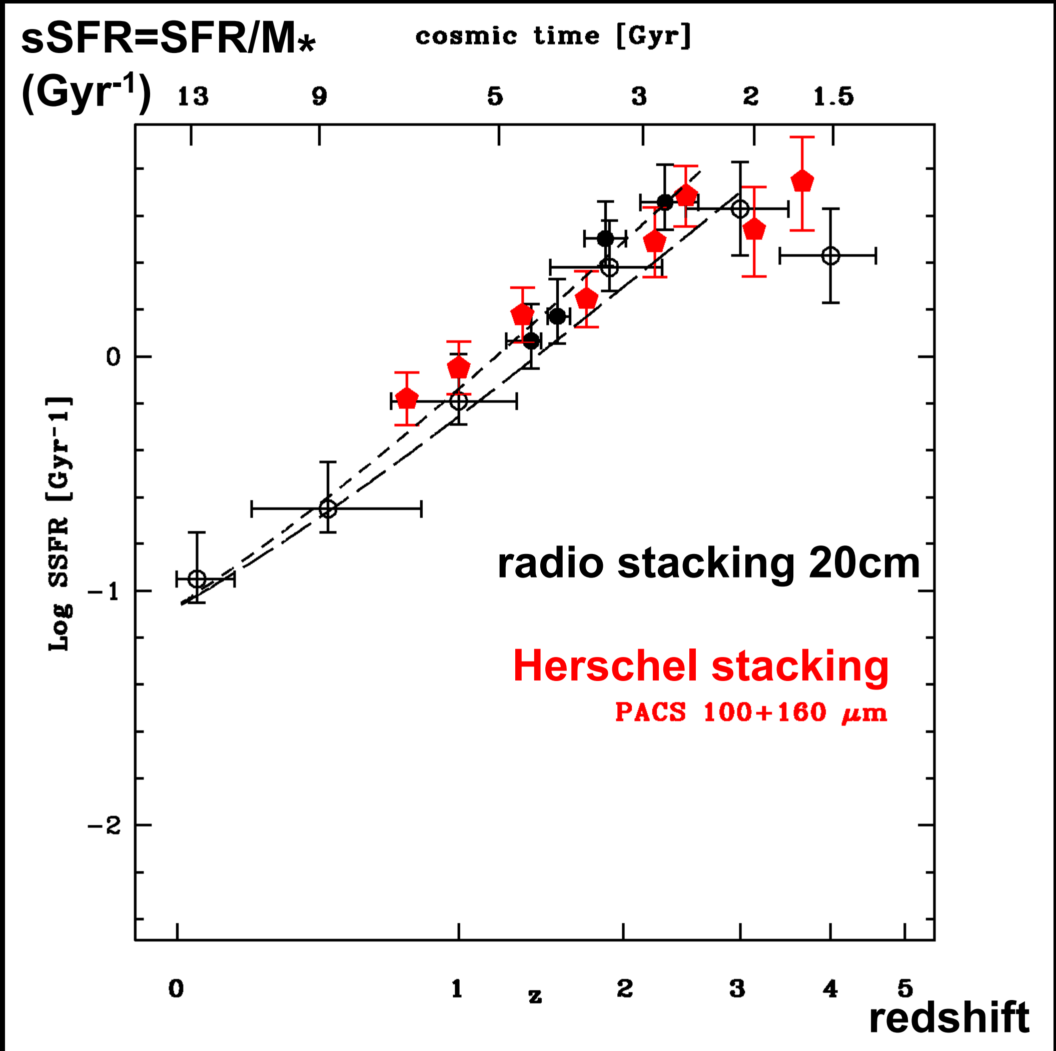
Evolution of sSFR = SFR/M* with redshift and M*





Pannella +11 (in prep.)

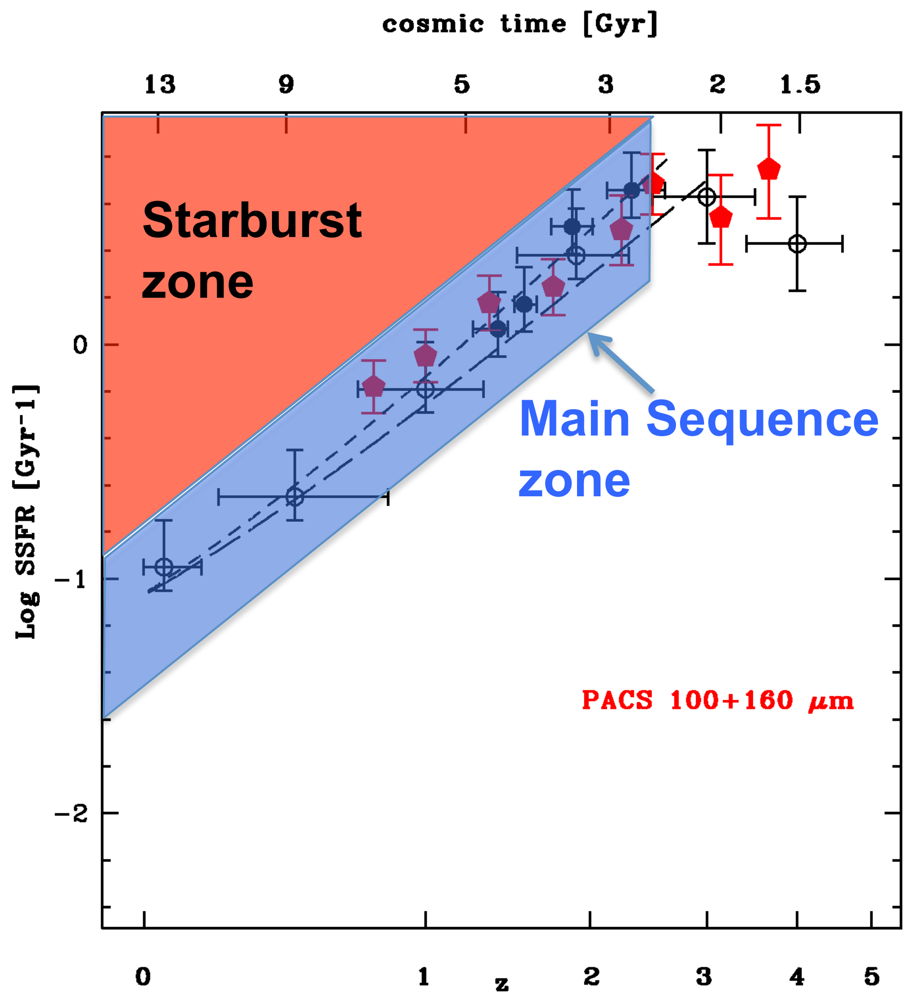
Evolution of the sFR (=SFR/M*) with cosmic time, redshift

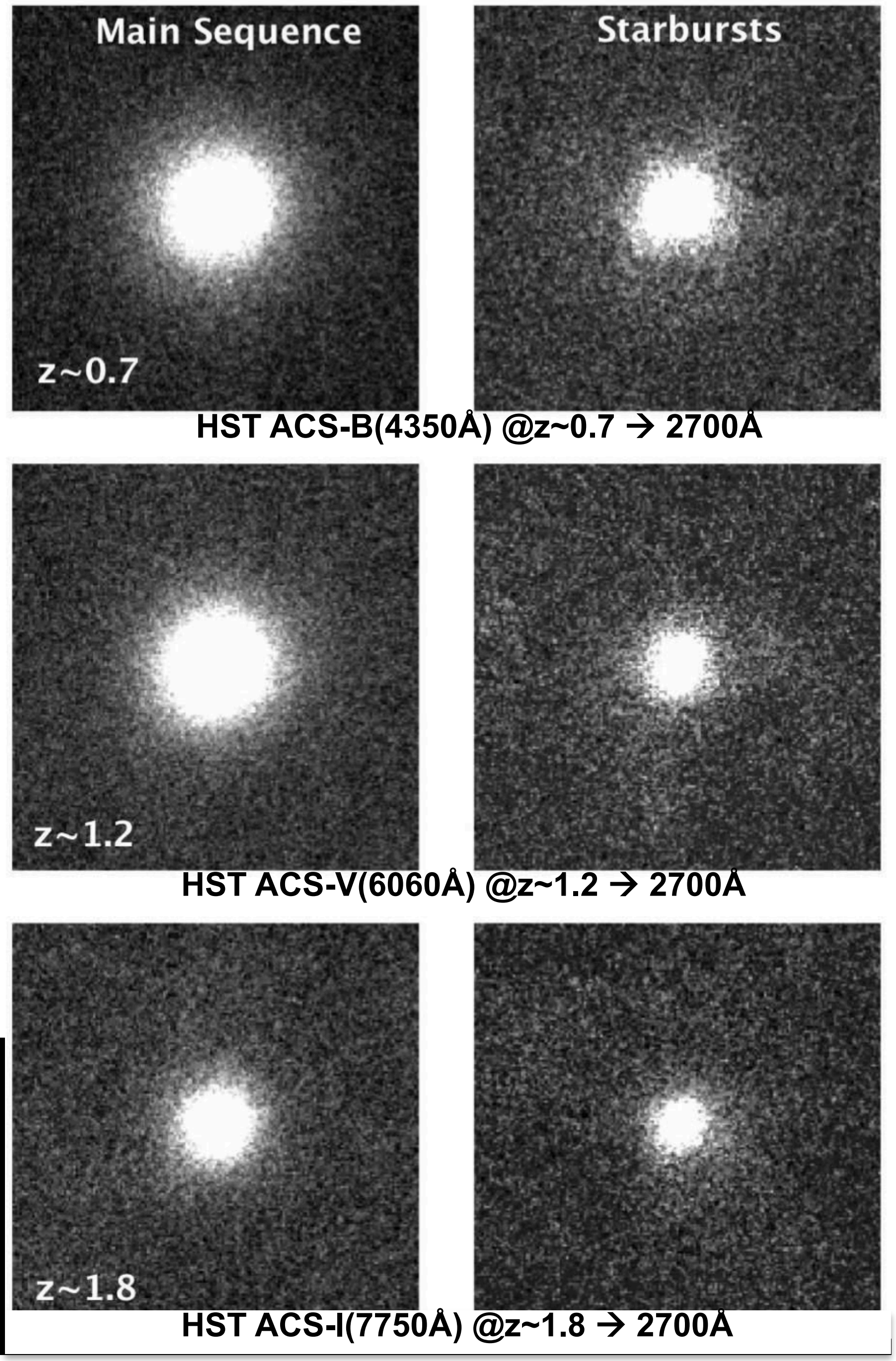


Pannella +11 (in prep.)

- consistent with radio stacking
- flattening at sSFR ~ 4 Gyr^{-1} around z~2-3 (doubling M* timescale ~250 Myr)
- peak sSFR at z~ 2.5

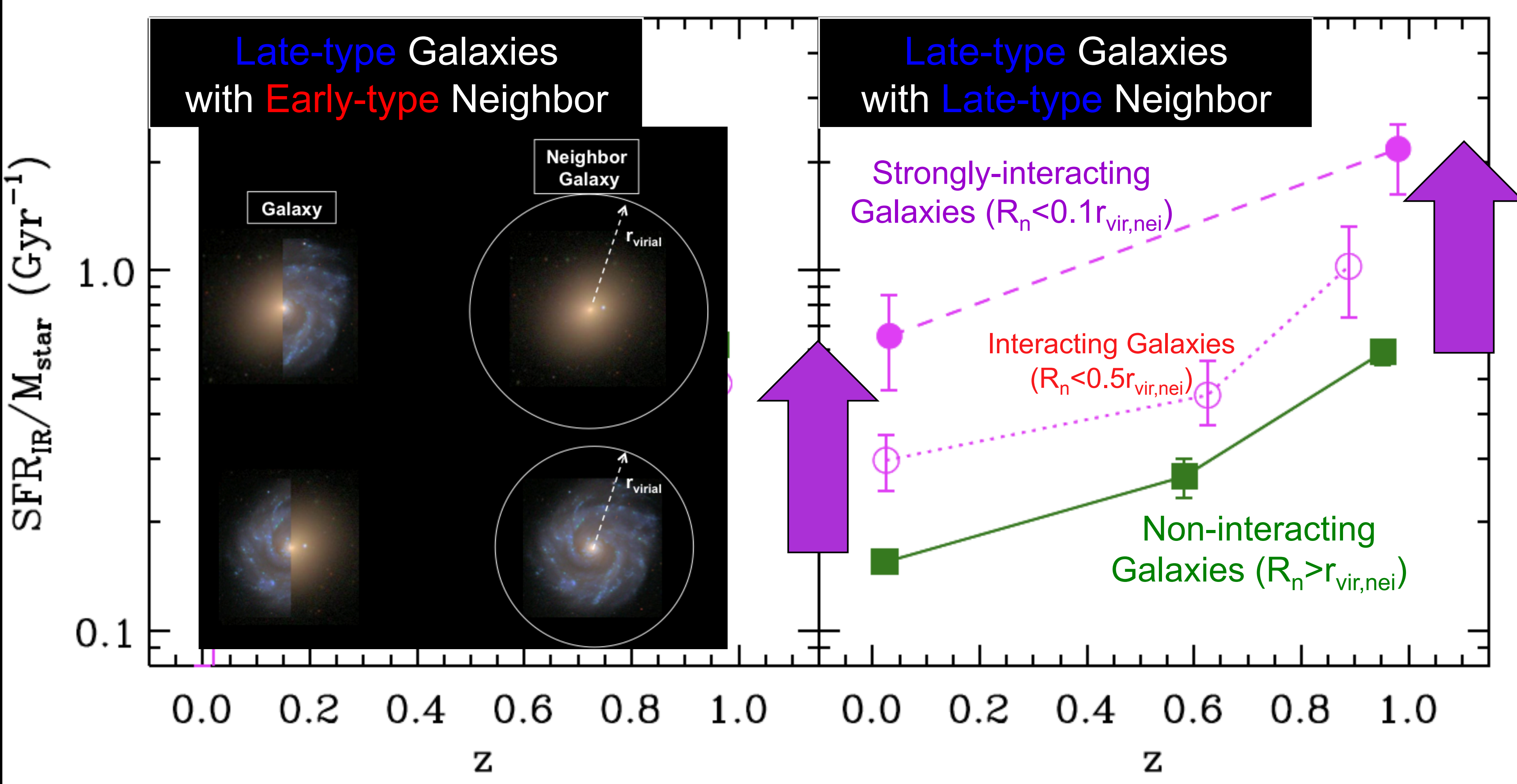
Star formation compactness of Main Sequence vs Starburst galaxies





Redshift	Main Sequence	Starburst	
		$R_{SB}>2$	$R_{SB}>3$
0.7	5.2 kpc	3.9 kpc	2.5 kpc
1.2	4.4 kpc	3.3 kpc	2.5 kpc
1.8	3.0 kpc	2.5 kpc	2.0 kpc

Increased sSFR in Galaxy-Galaxy interactions



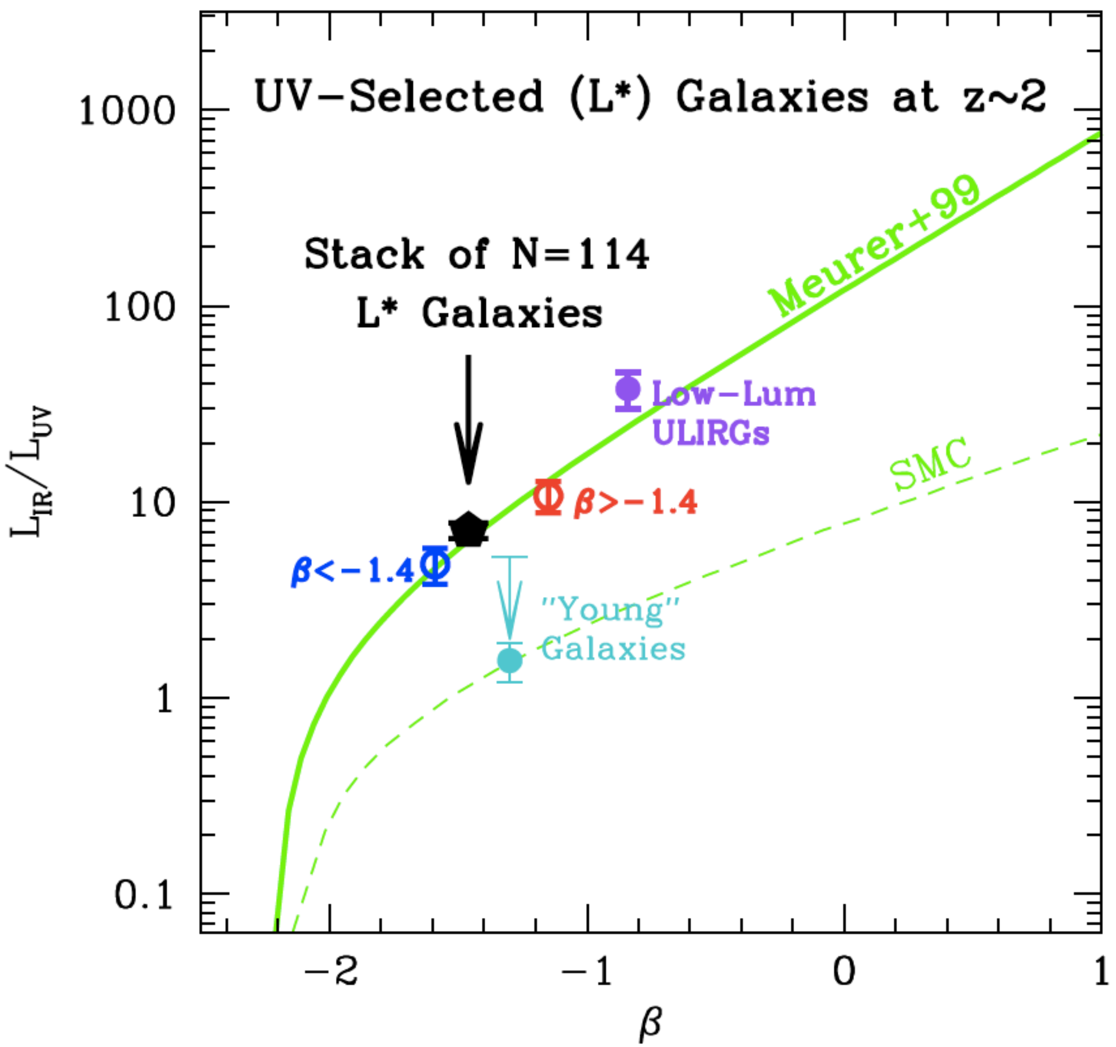
sSFRs increase by factor of ~4

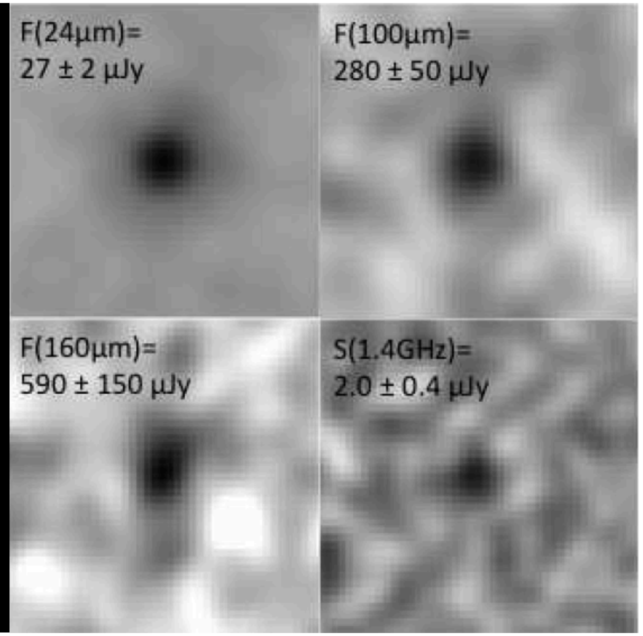
1) only when late-type galaxies interact with late-type galaxies

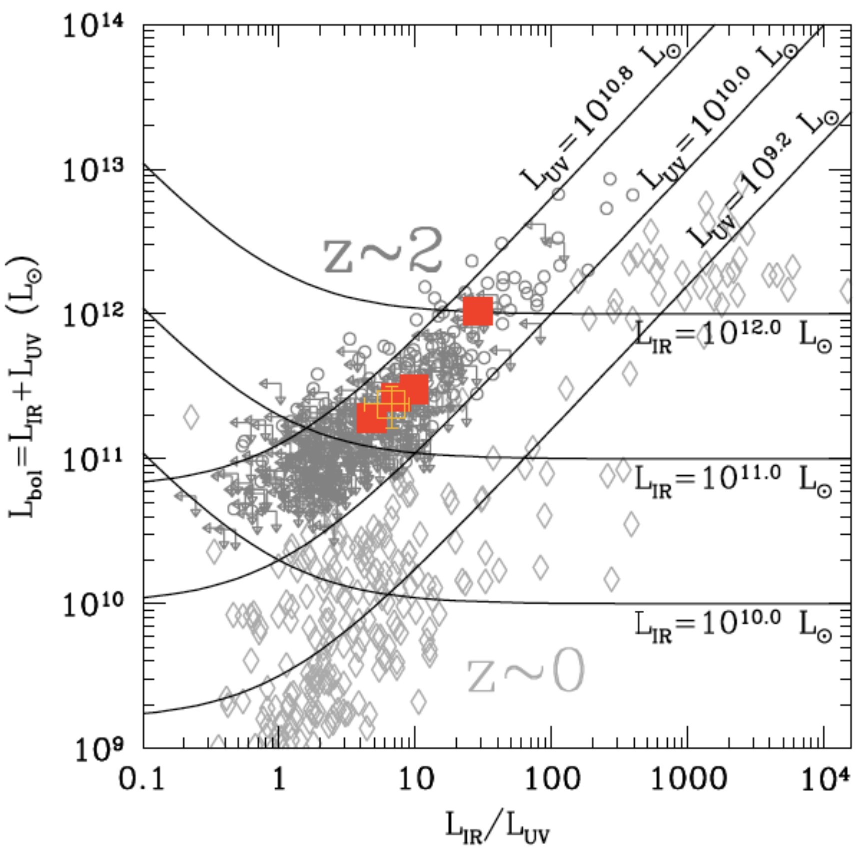
2) for all redshift bins at 0<z<1.1

Hwang +11

Dust attenuation of typical SF galaxies at z~2

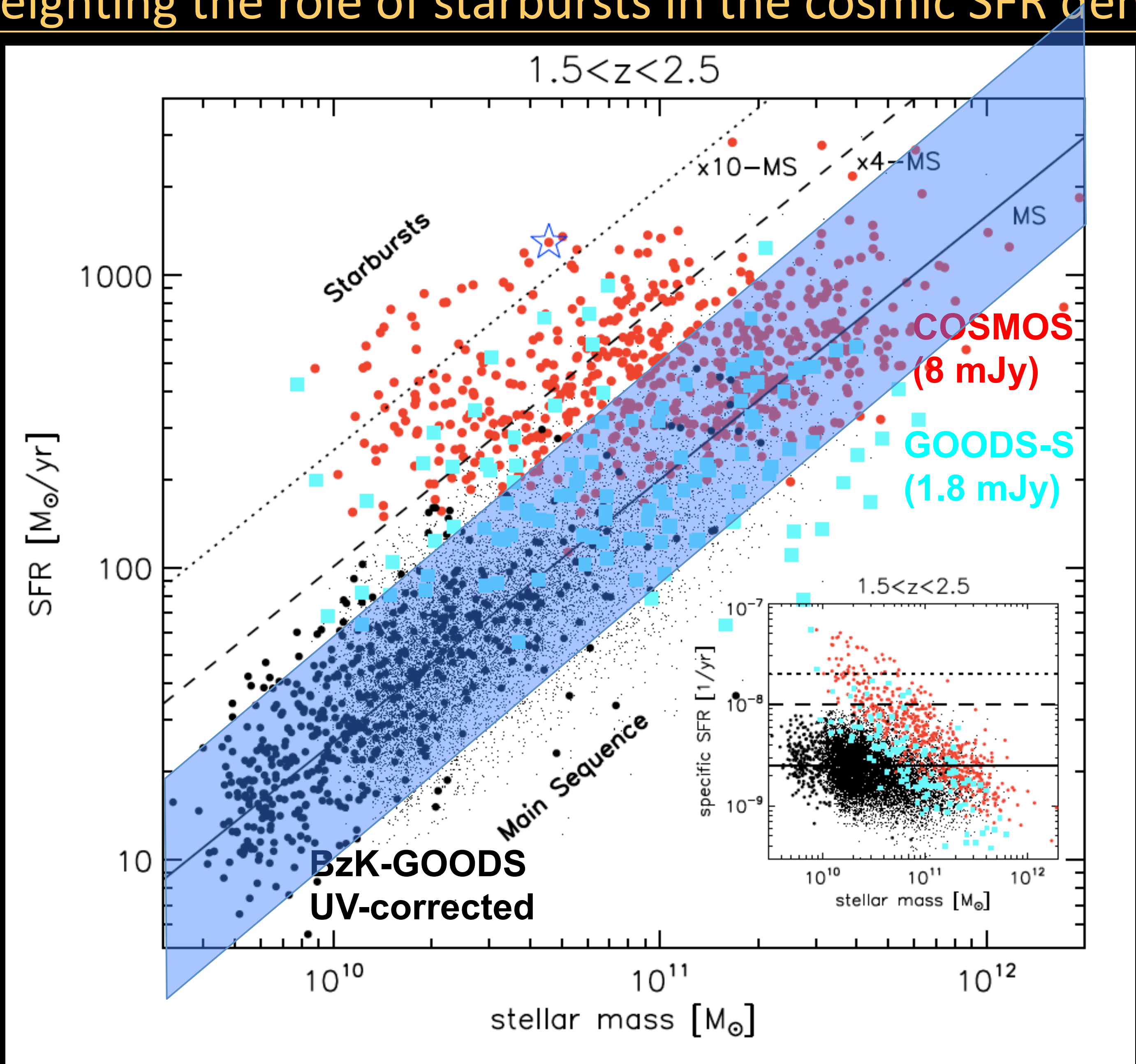






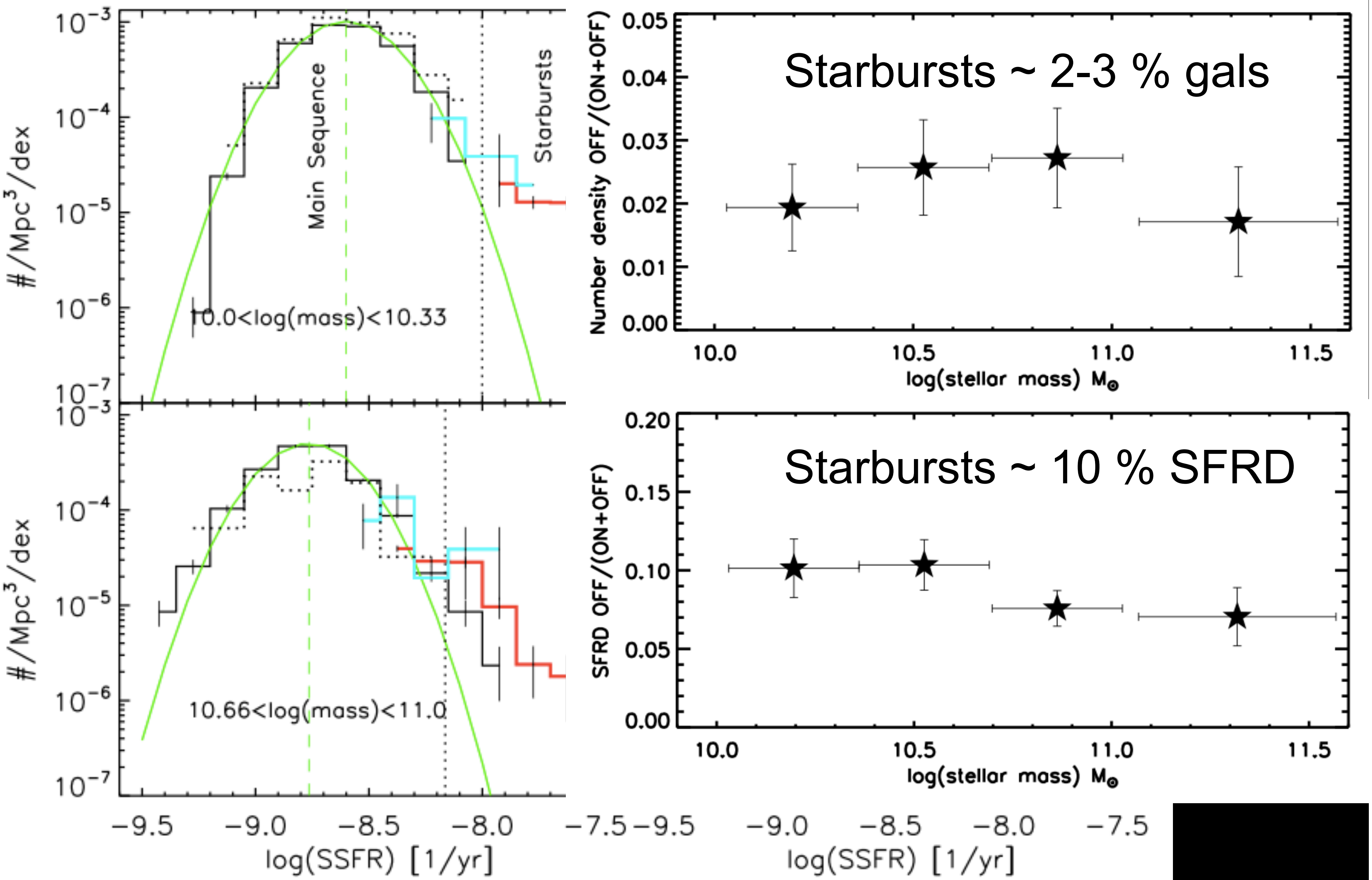
Reddy +11, TBS

Weighting the role of starbursts in the cosmic SFR density



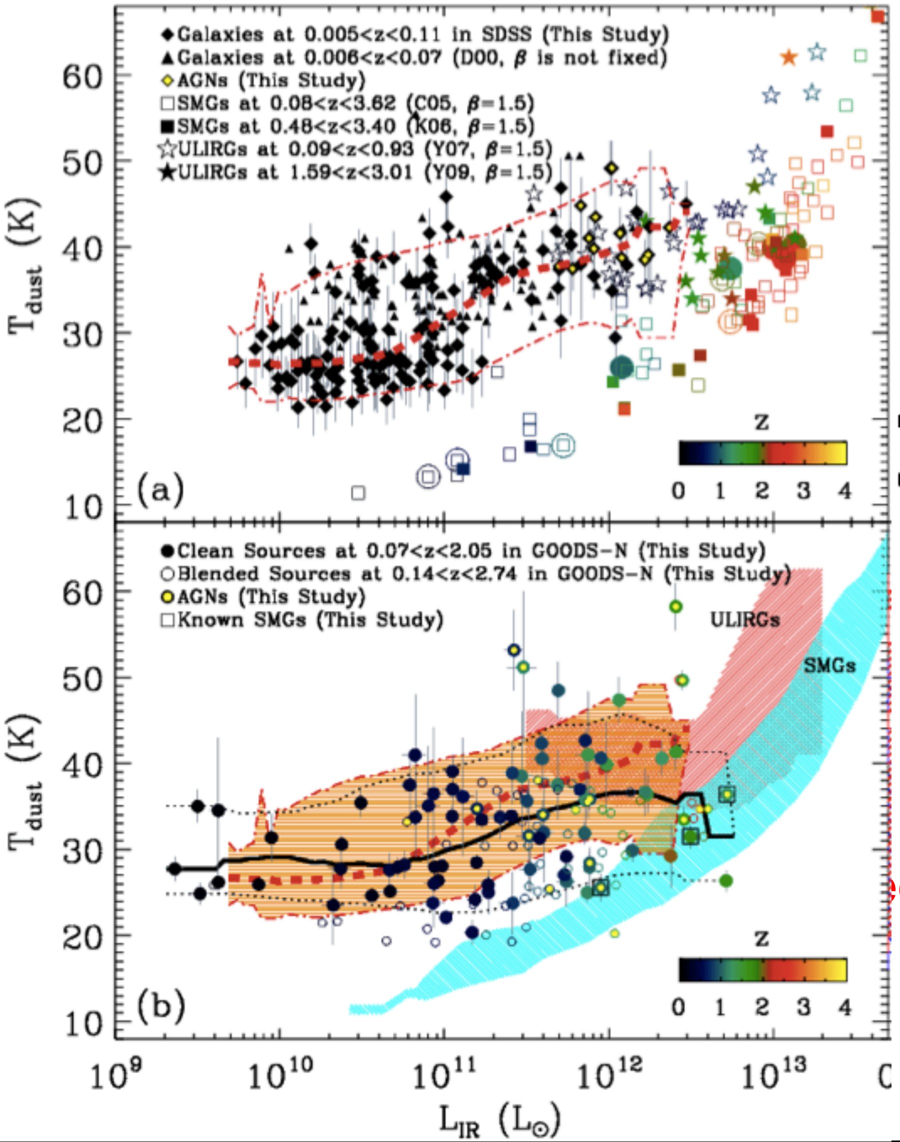
Rodighiero +11 (PEP, submitted)

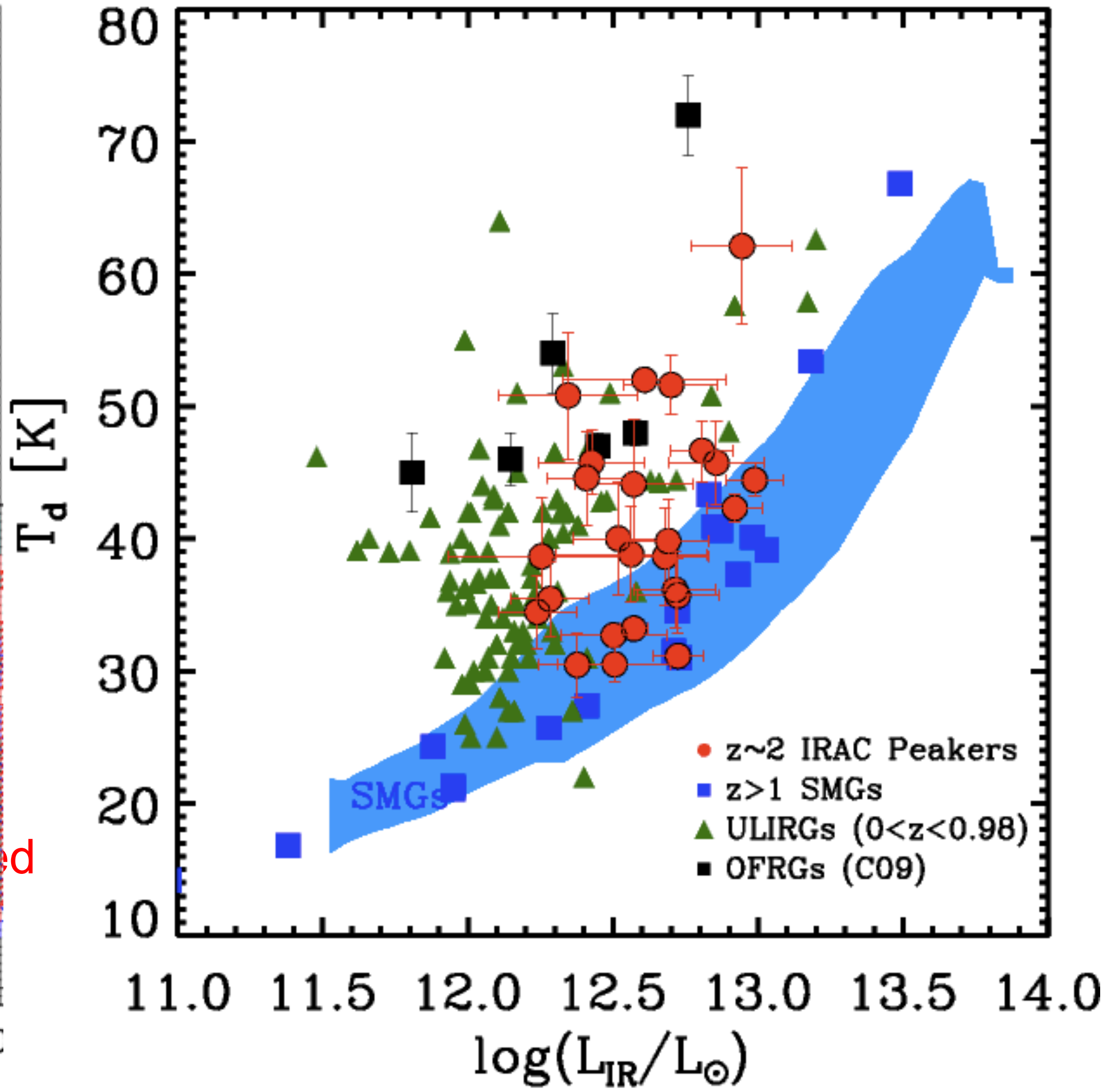
Weighting the role of starbursts in the cosmic SFR density



Rodighiero +11 (PEP, submitted)

Do we see any evidence for an evolution of Tdust ?

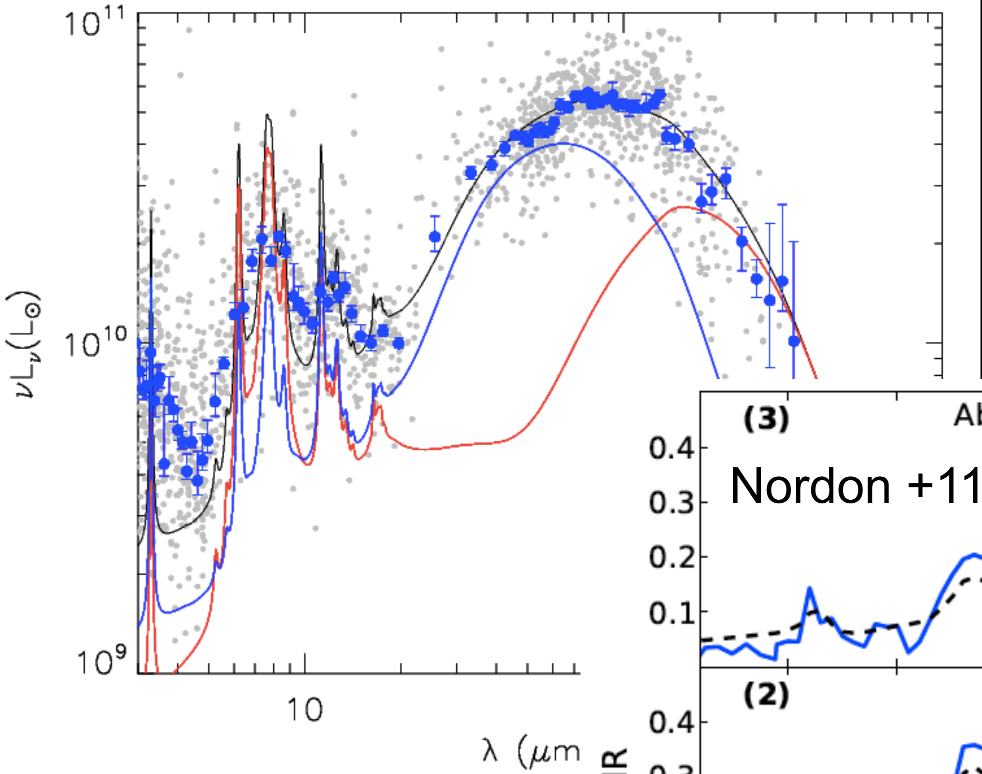




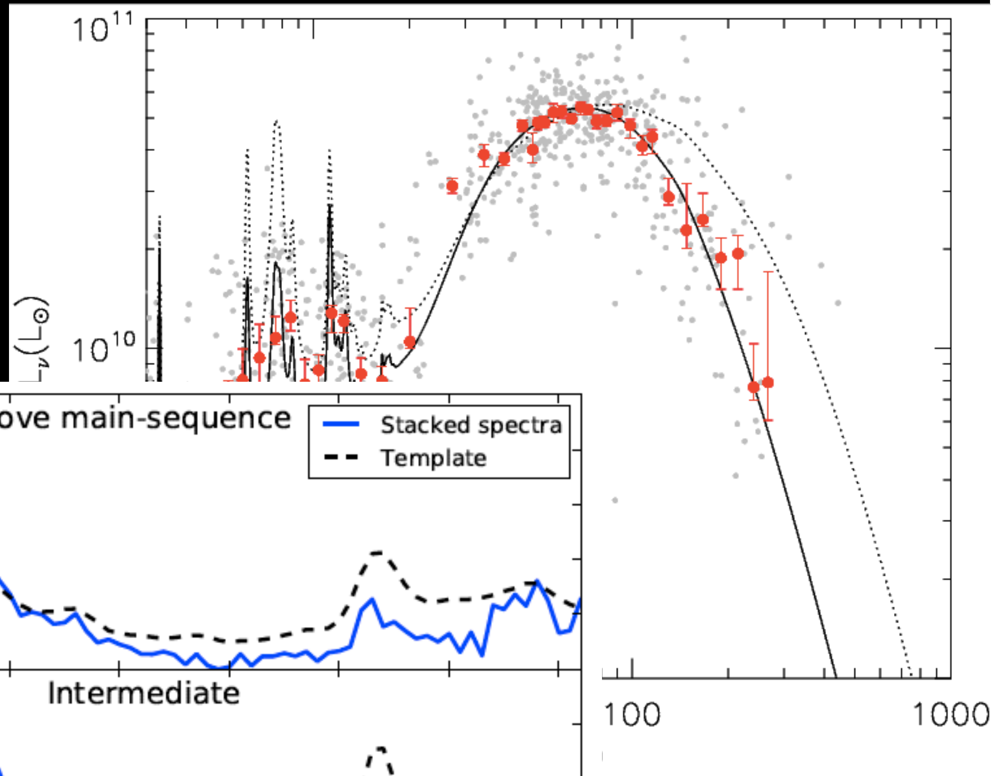
Hwang, Elbaz +10 *Magdis, Elbaz +10, Magnelli +10, Chapman +10*

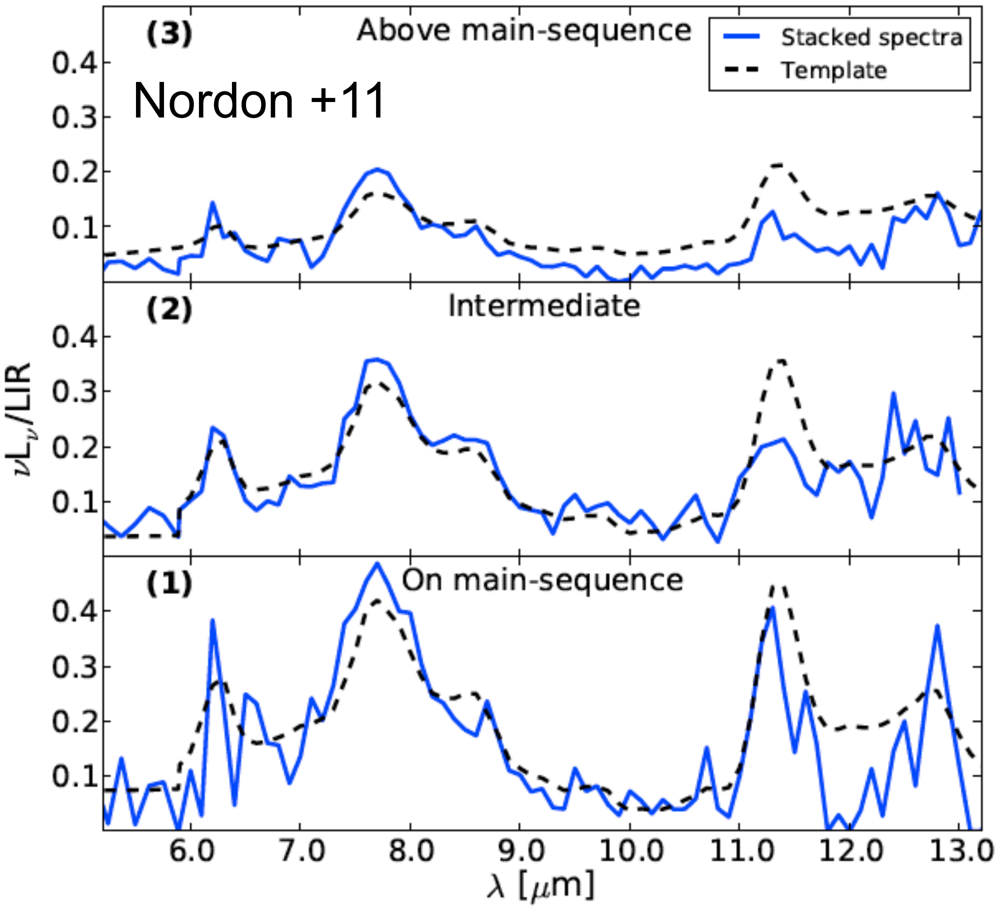
Proto-typical IR SED of Main Sequence and Starburst galaxies

Main Sequence



Starburst (high IR8, sSFR)





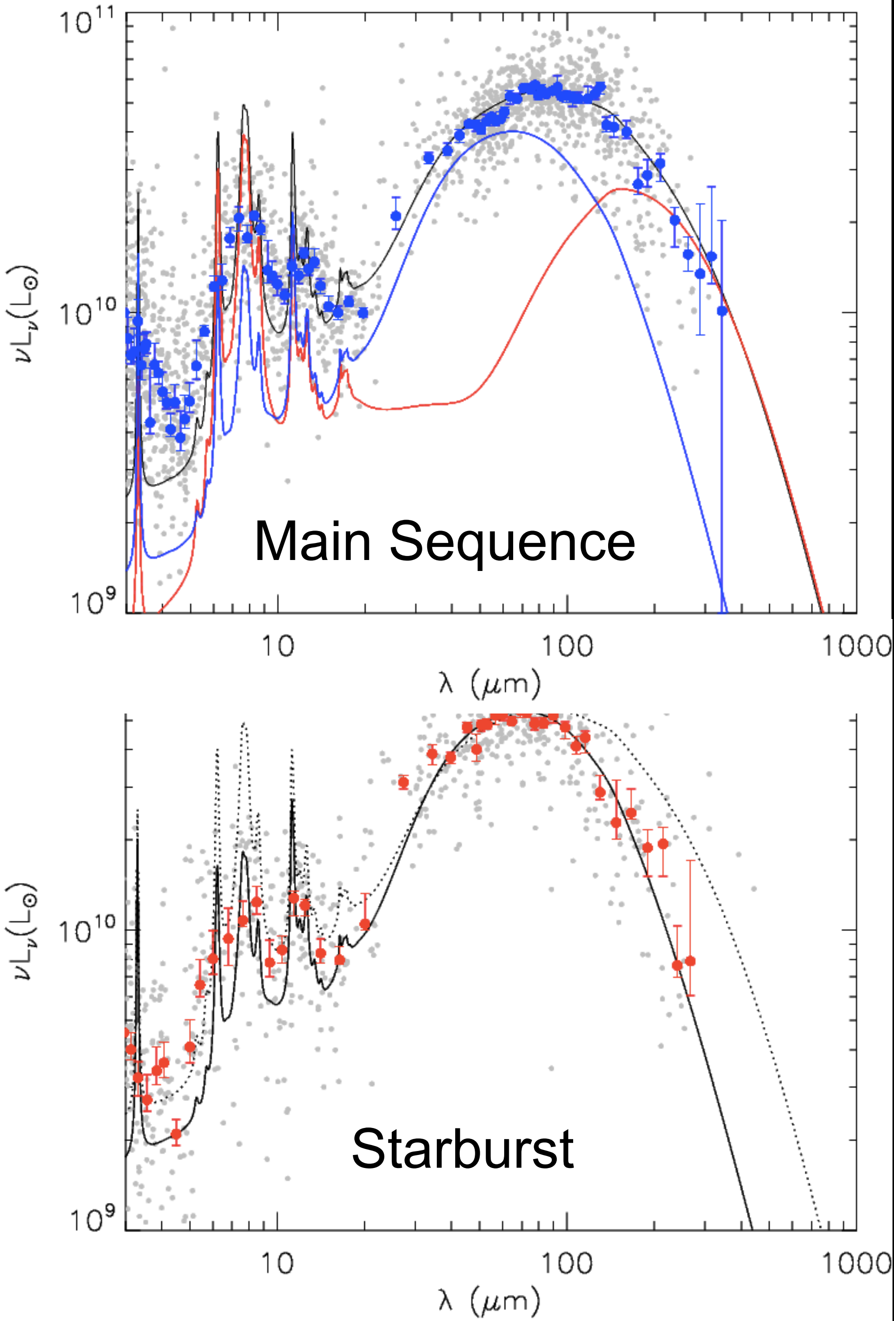
Main Sequence : broad far-IR
strong PAH features, ISM= 38

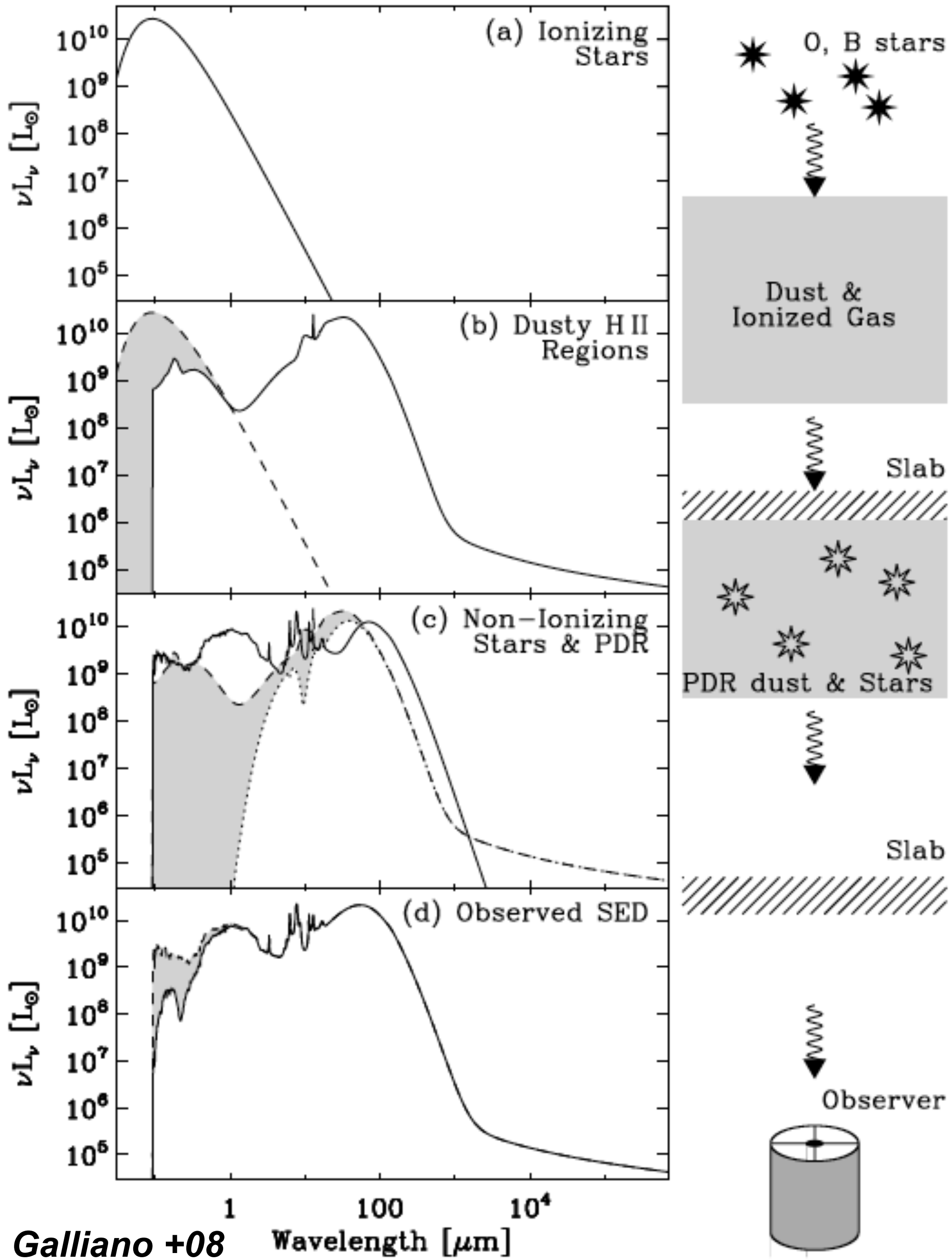
Model fit: 2
Range of du
T_{dust}(ISM)~

mp 45 – 50 K,
%, SF= 100 % SED

Elbaz +11

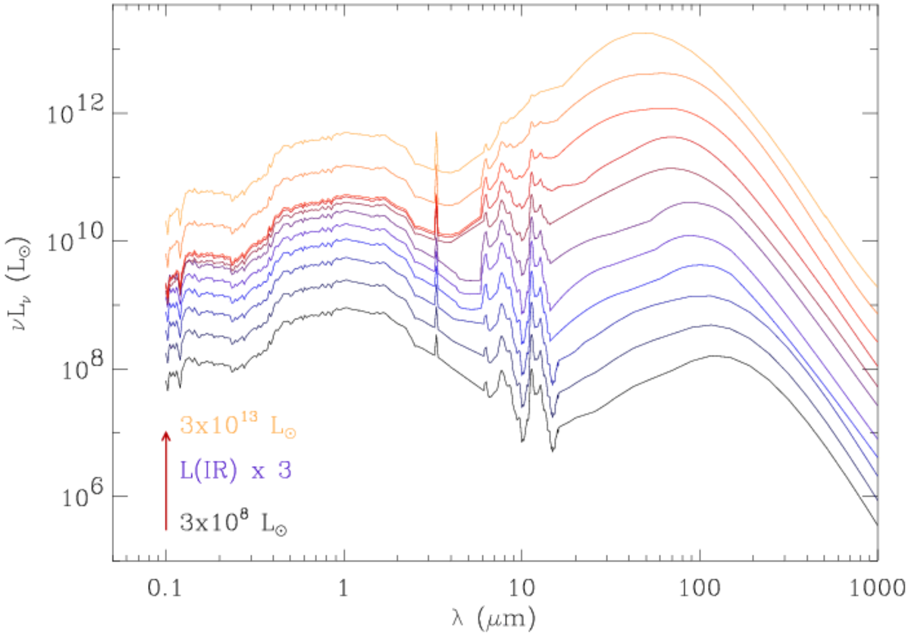
IR8=L_{IR}/L_8 as a tracer of star formation geometry (→ mergers)

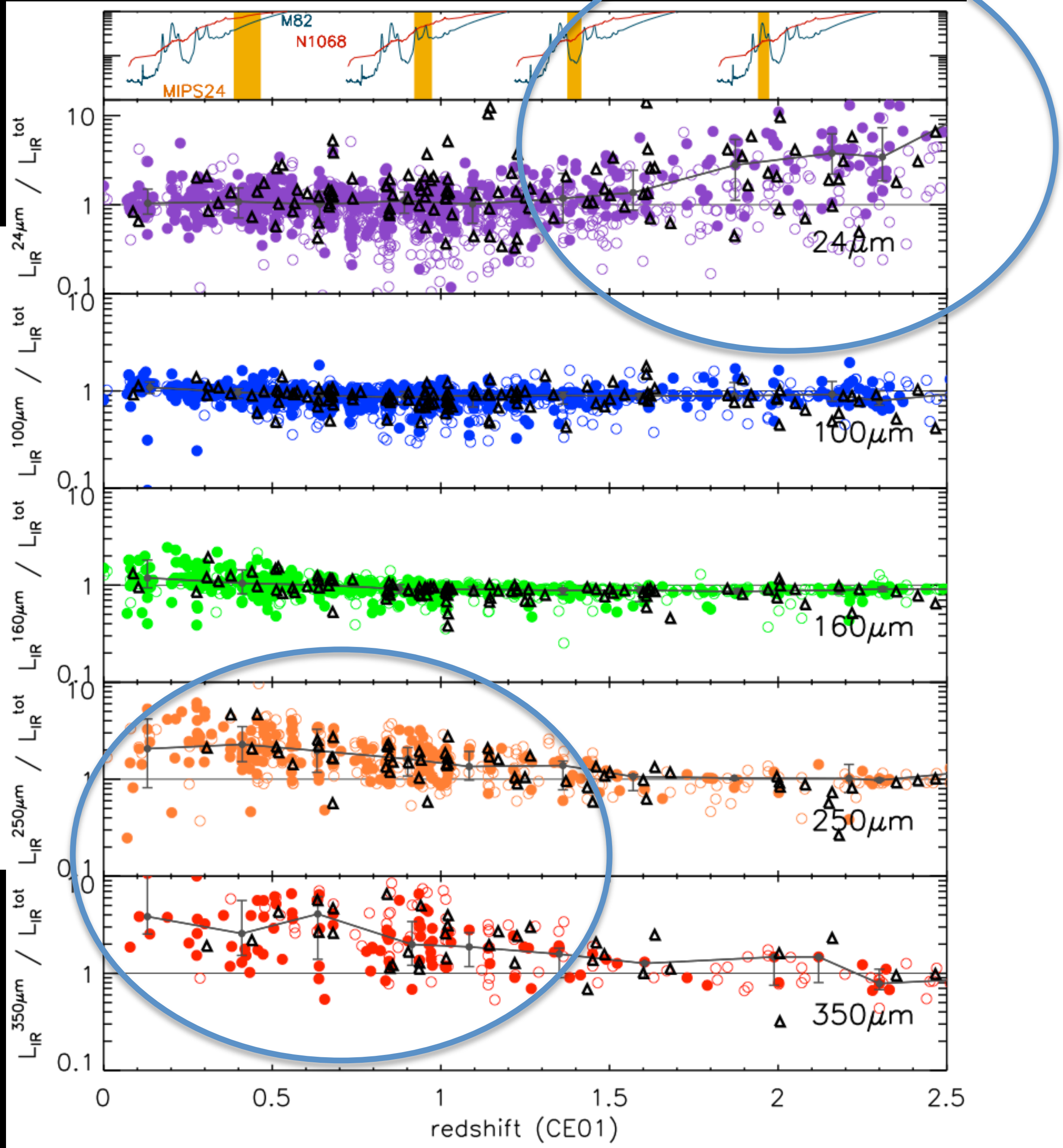




Galliano +08

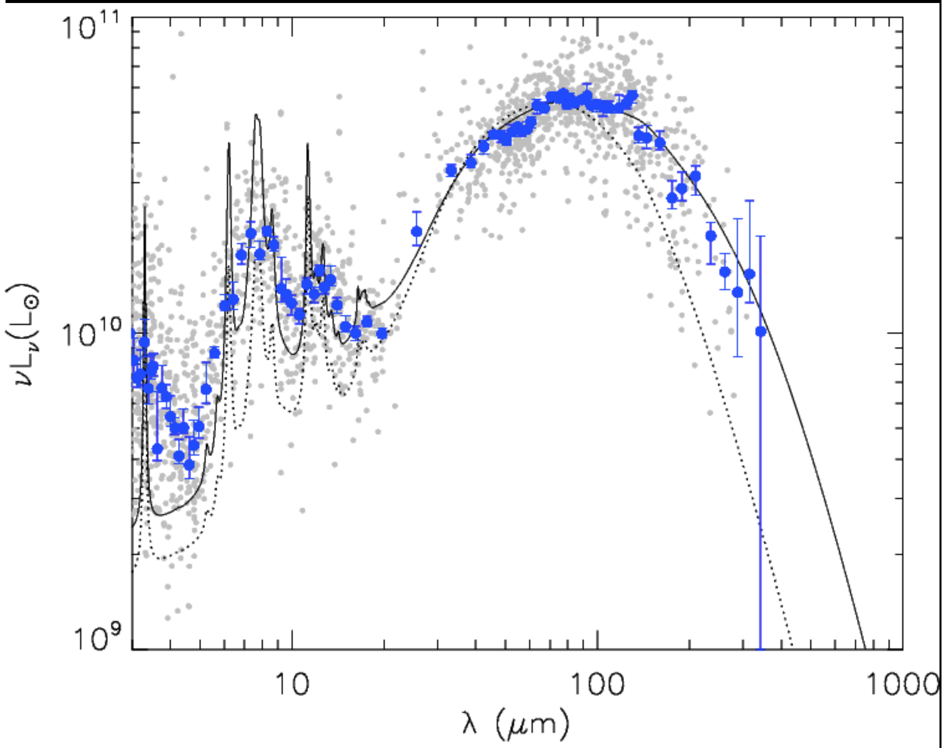
Improving the bolometric correction for SF galaxies

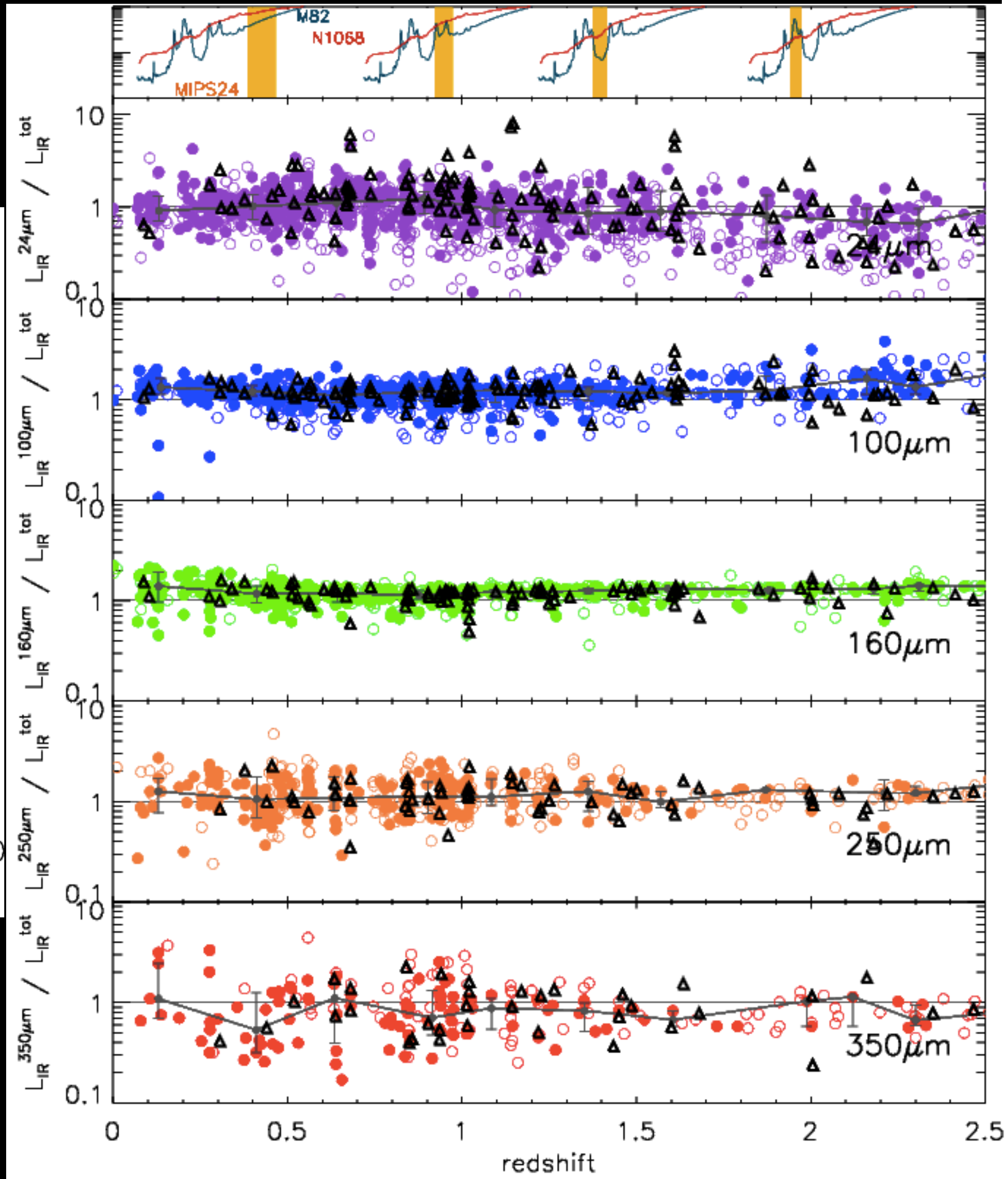




CE01 library of template IR SEDs

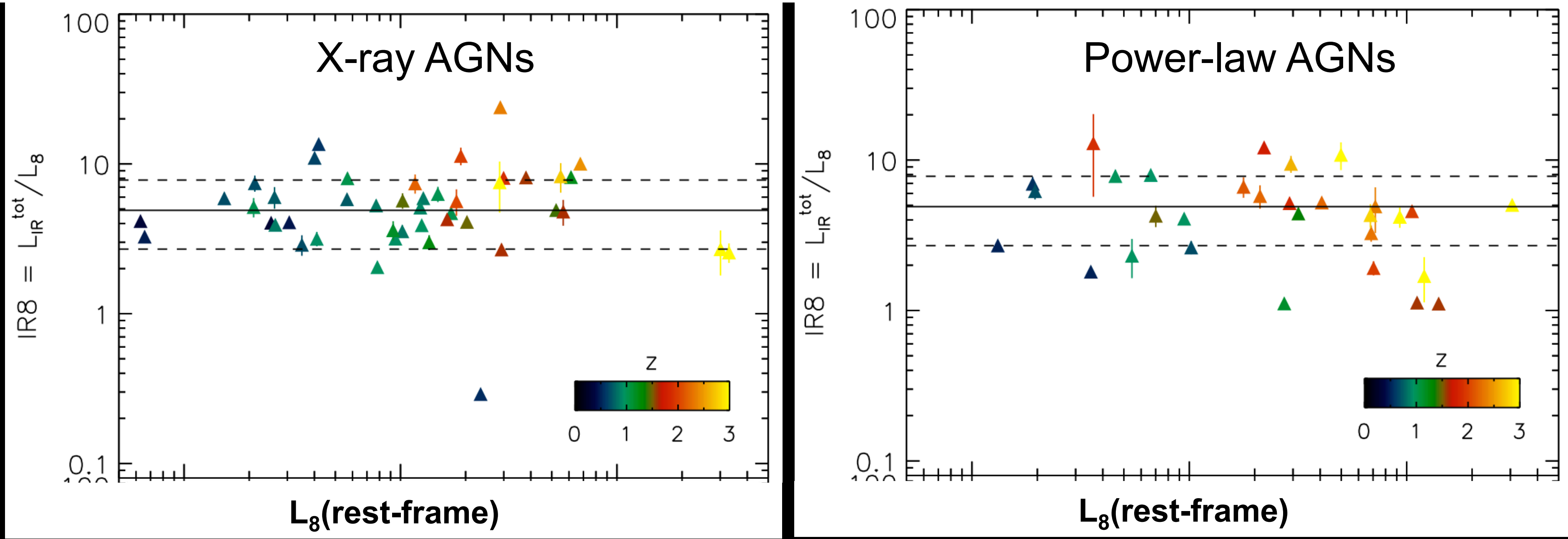
Improving the bolometric correction for SF galaxies



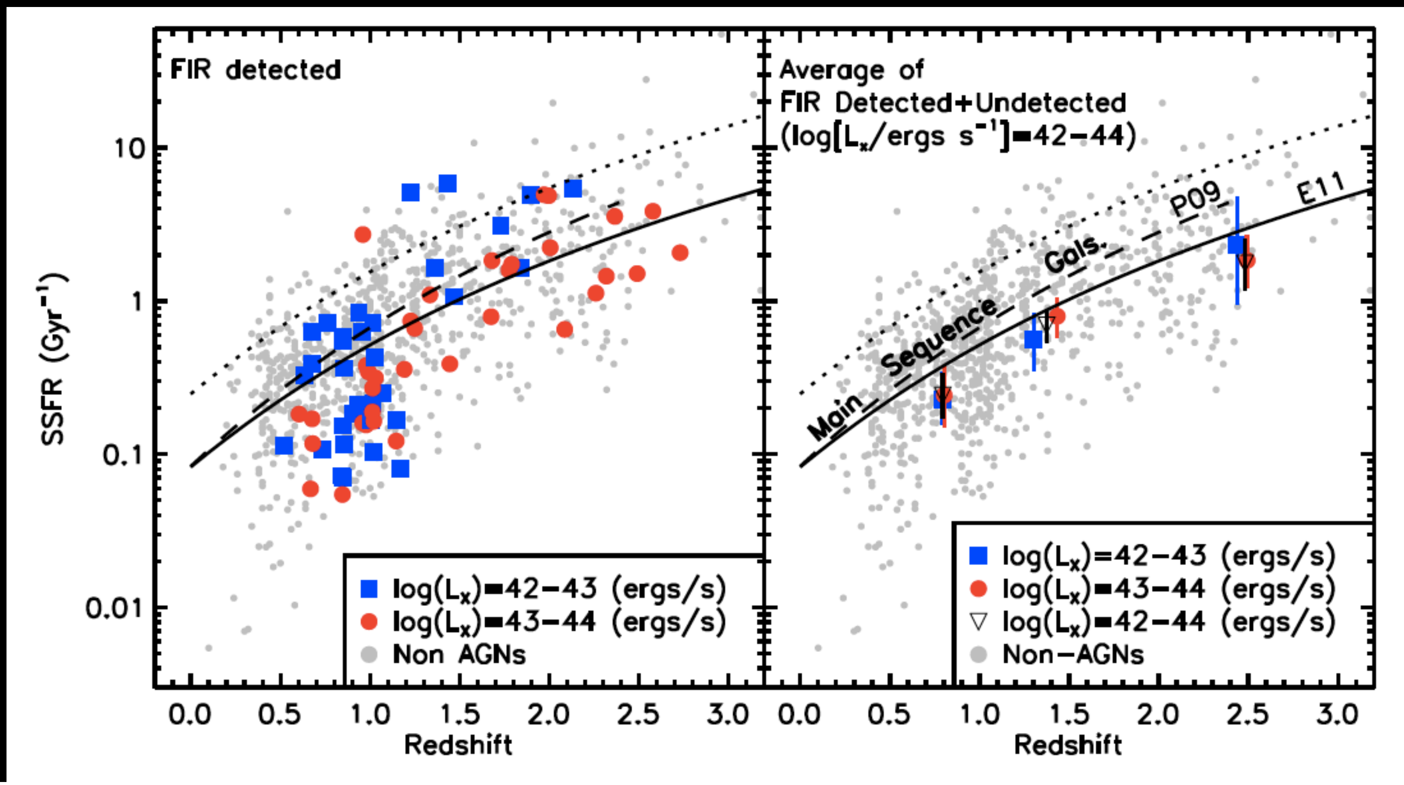


Unique IR SED for all galaxies:
main sequence

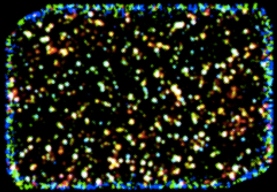
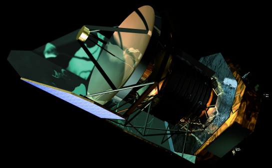
Elbaz +11



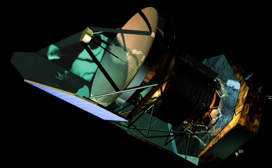
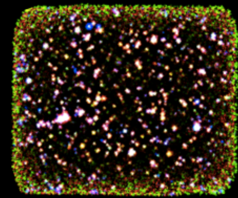
Elbaz +11



Mullaney +11

Conclusions

• Distant (U)LIRGs = normal star-forming galaxies + large Mgas, long-lasting (Gyrs)

• IR8= L_{IR}/L_8 universal among star-forming galaxies → geometry of SF regions

• High IR8 values for compact starbursts with high SFR / M* (mergers)

• Main Sequence galaxies (disk-like) dominate the cosmic SFR density at all redshifts !

→ The fall in cosmic SFR driven by the decrease in gas mass not merger rate

• Starbursts= mergers between late-types, ~10% of cosmic SFR density

• IR SED for MS and SB galaxies → bolometric correction

→ LIRG = SB at z~0 but MS at z~1 if $M^*>5\times10^{10}\ M_\odot$ (ULIRG@z=2 , $M^*>2\times10^{11}\ M_\odot$)

• IR dominated by star formation in AGNs ($L_X<10^{42\text{-}44}$ erg s^{-1})

Star formation at intermediate redshift

• what is the redshift by which half of the stars that we see today were formed ?

(Peebles 1988, *The epoch of galaxy formation*)

z	0 – 2.5	2.5 – 5	5 - ∞
votes in 1988	28	54	4
	~85 %	**~15%**	**<5% (% age after recombination)**

• have we really improved our knowledge of the actual SFR of galaxies ?

(dust extinction, IMF, timescale of star formation)

YES NO YES and NO

• assuming that we know when the bulk of present-day stars formed

did they form in a violent/starburst mode or in a more normal/disk-like more ?

Starburst mode not dominant , long duty-cycle dominates

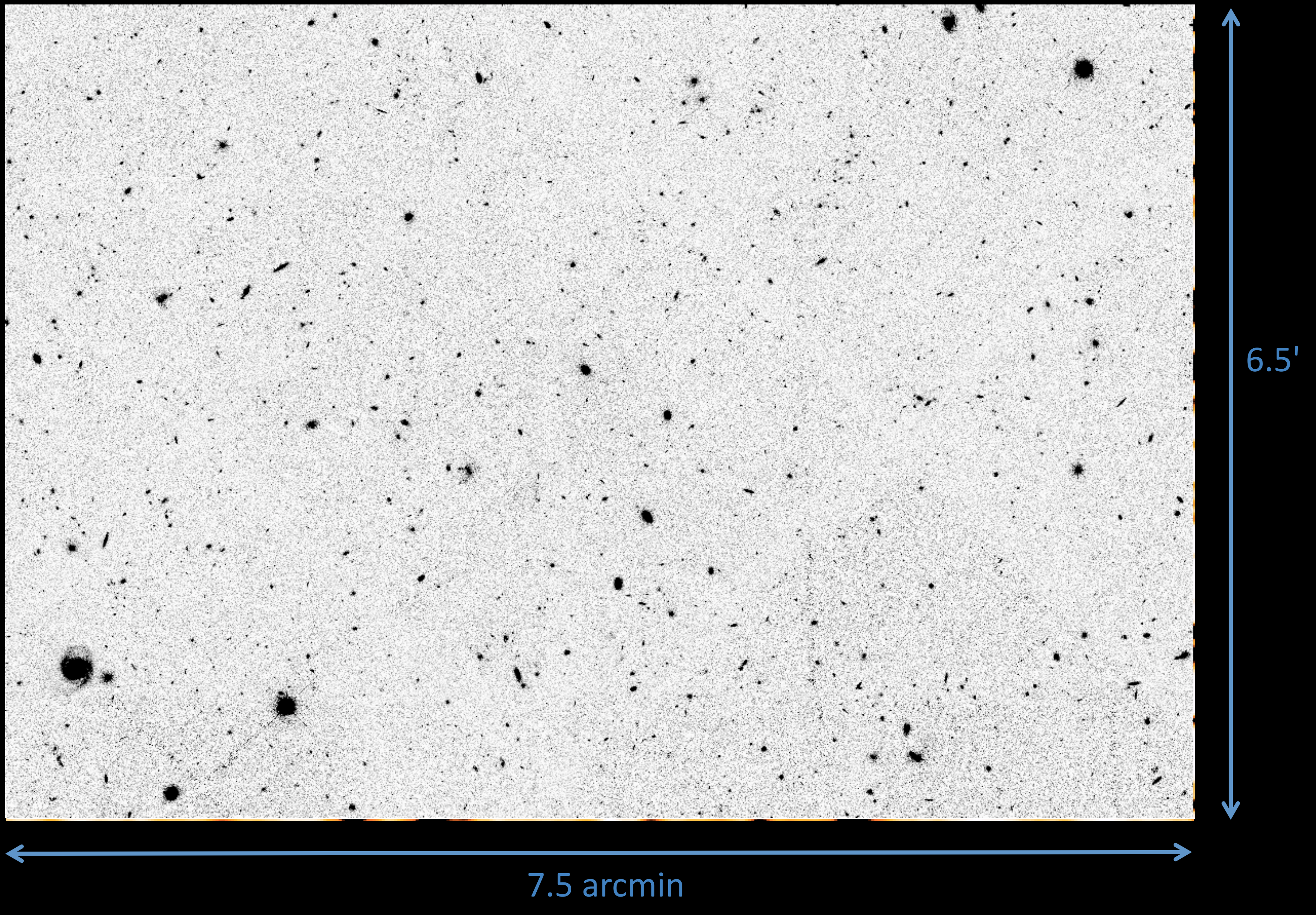
Maybe none of the two → infall driven star formation + dynamical instabilities ?

→ but no observational evidence of cold flows and outflows are ubiquitous...

The power of multi-wavelength imaging against confusion

500um 350um 250um 160um 100um 24um 3.6um 0.8um

7.5' x 6.5' zoom on the GOODS-North field (10' x 15')



Does the environment play a minor role in the star formation history of galaxies ?

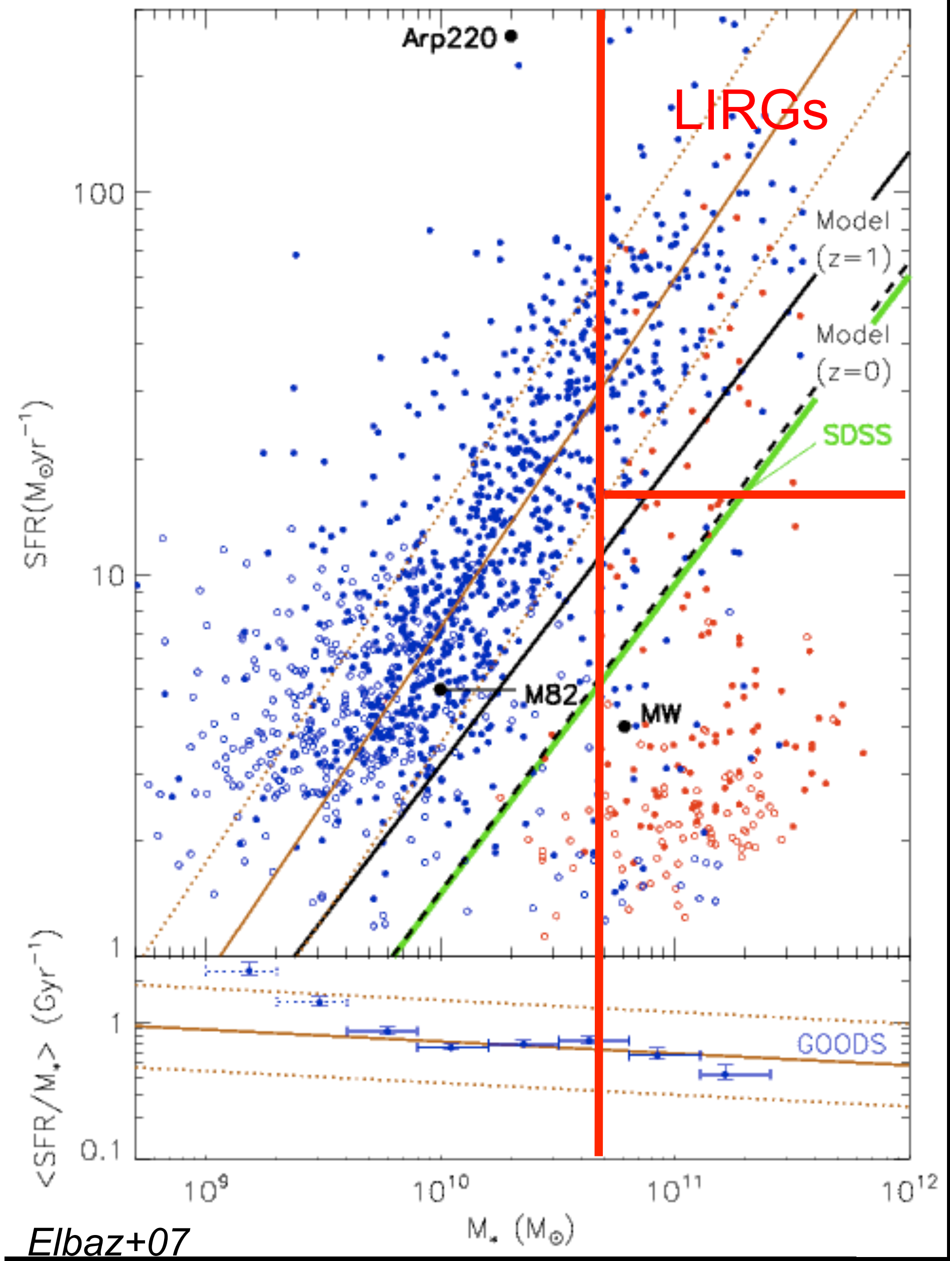
Galaxies in dense environments are redder, *deader*, fater than in the field
→ is it an effect of the environment or a selection effect ?

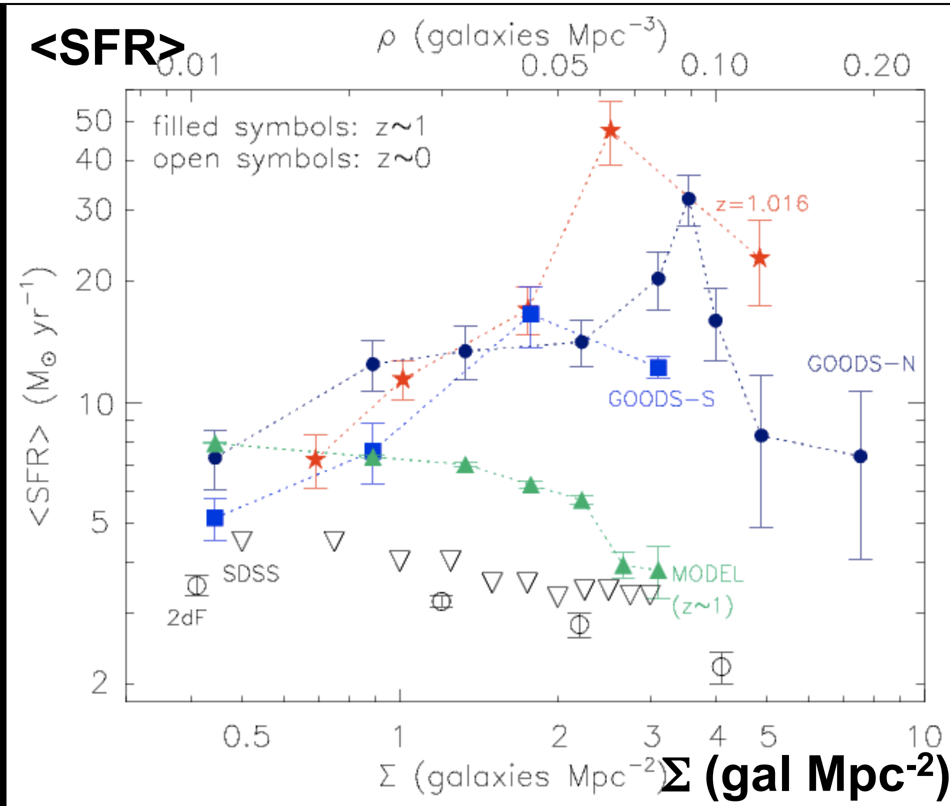
the fraction of ill people is larger in hospitals than outside
→ do hospitals make people sick or do diseased persons go to hospitals ?

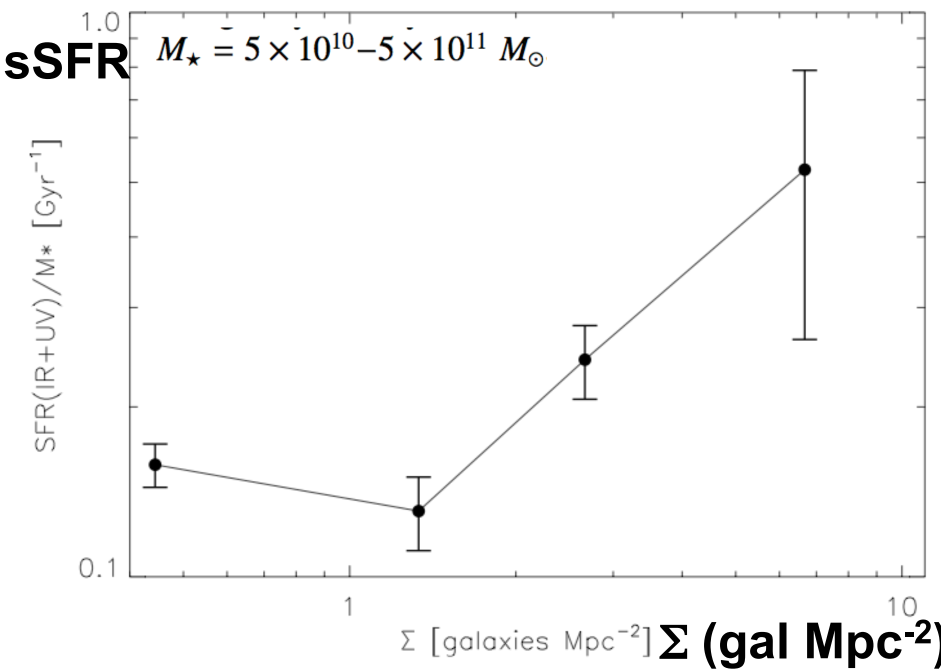
= the H - effect

=

Reversal of SFR – density & SFR – M* relation: is M* or density the key parameter ?





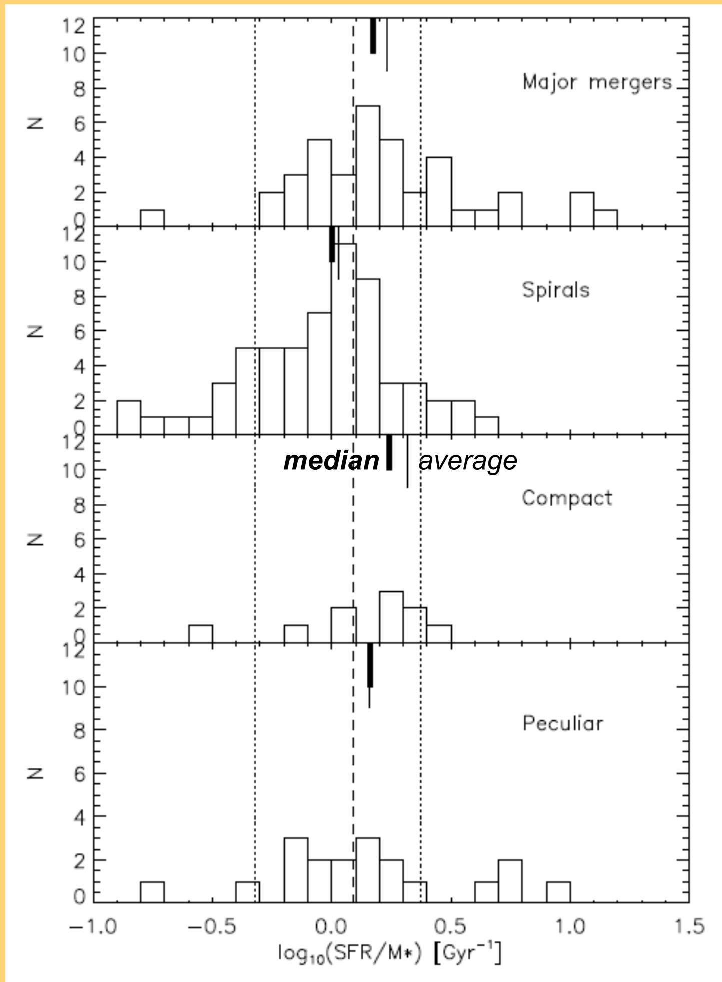


What is causing the reversal ? Major mergers ?

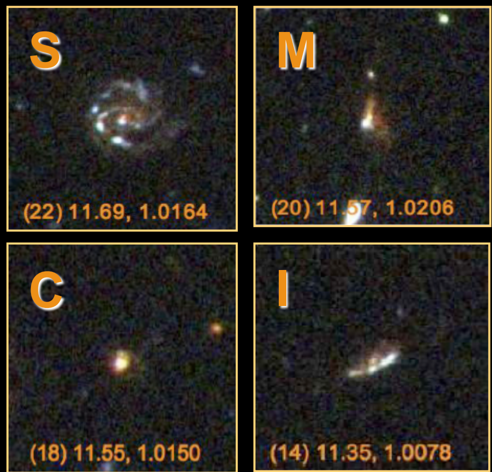
Morphology of 36 LIRGs at z=0.8±0.4 show only a minority of obvious major mergers (Zheng+04)

Elbaz +07: complete sample of 140 LIRGs from GOODS-N [S_{24}>25 μJy at 24 μm]

	z~0 Ishida 04	z~0.7 Bell 05	z~1 Elbaz 07
Spiral (S)	26 %	51 %	46 %
Merger (M)	41%+33% +close pair	26 %	31 %
Compact (C)	-	10 %	9 %
Irregular (I)	-	13 %	14 %
interactions		26-39 %	30-45 %



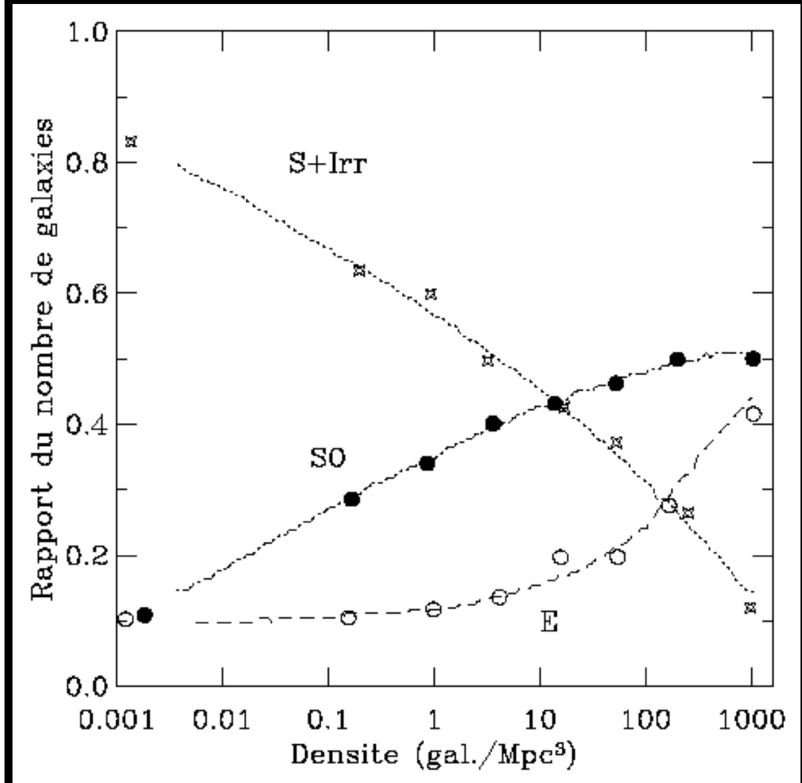
The role of major mergers is not dominant in LIRGs @ z~1



(see also Melbourne, Koo & Le Floc'h 2005)

sSFR(mergers) ~ sSFR(isolated) x 1.5-1.7 consistent with Lin et al. (2007; x 1.9) DEEP2

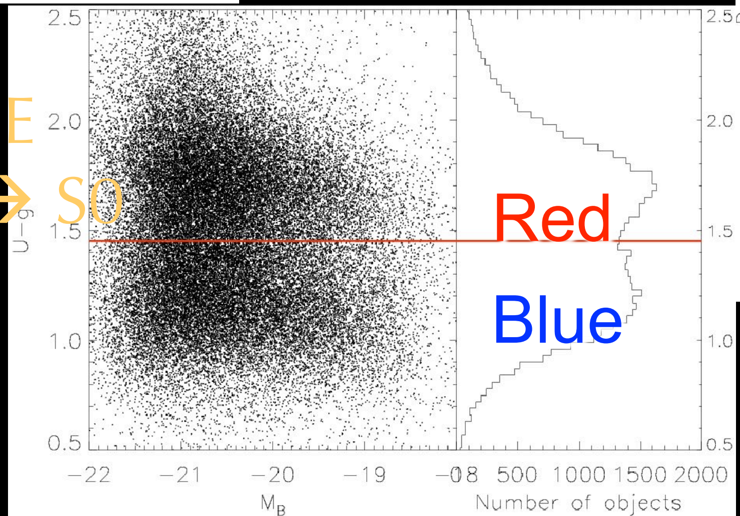
Does the environment play a minor role in the star formation history of galaxies ?

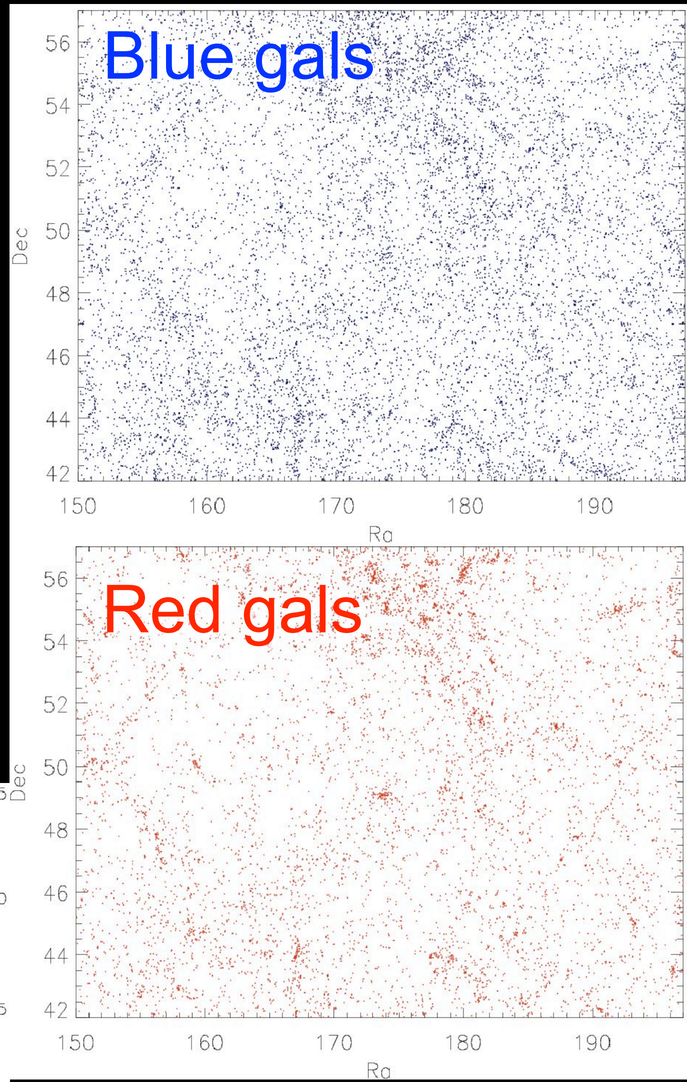


Dressler 1980

interactions: Sp → E

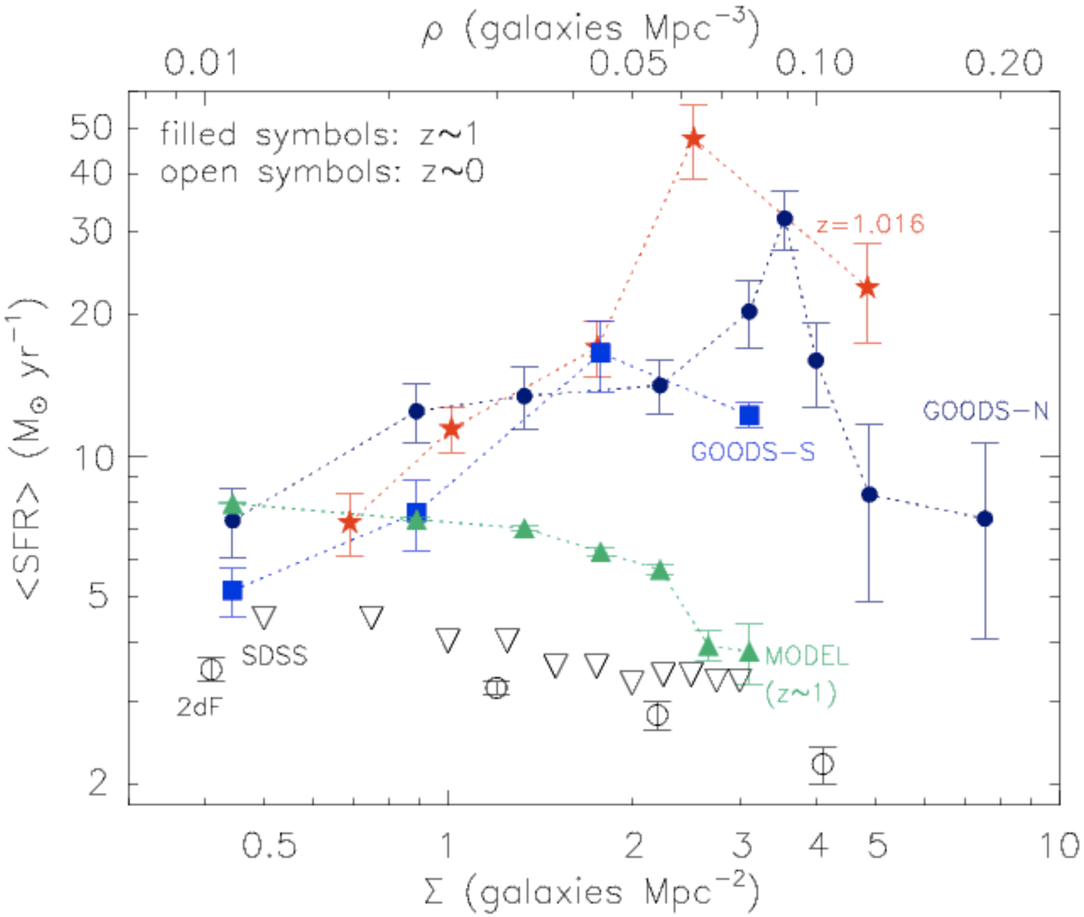
Ram pressure: Sp → S0

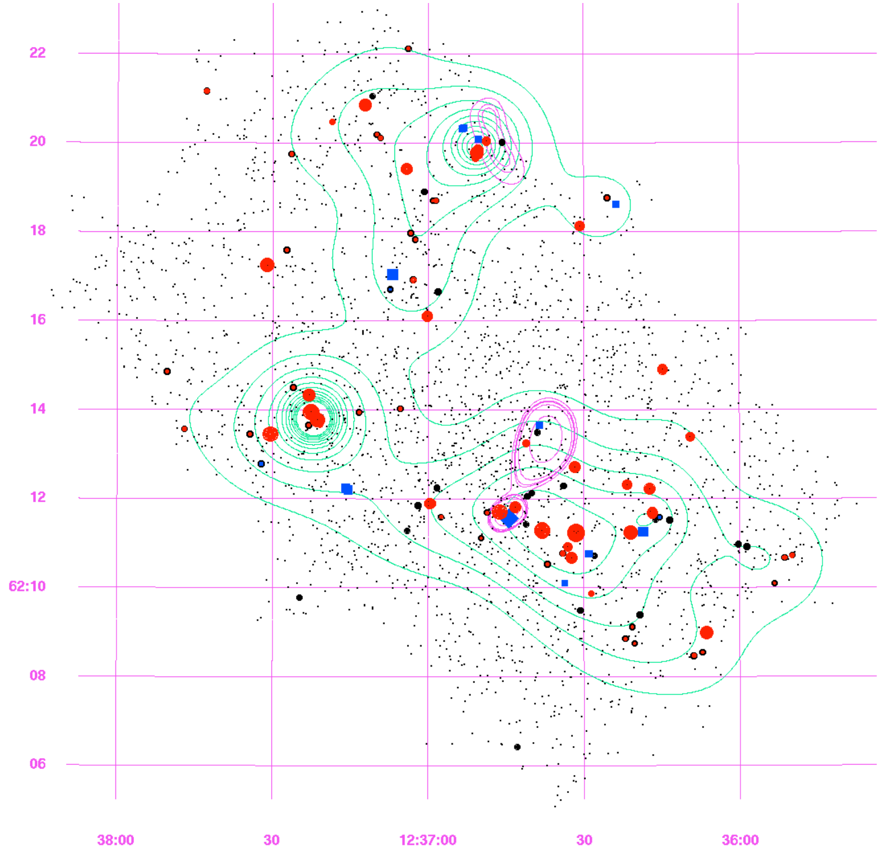


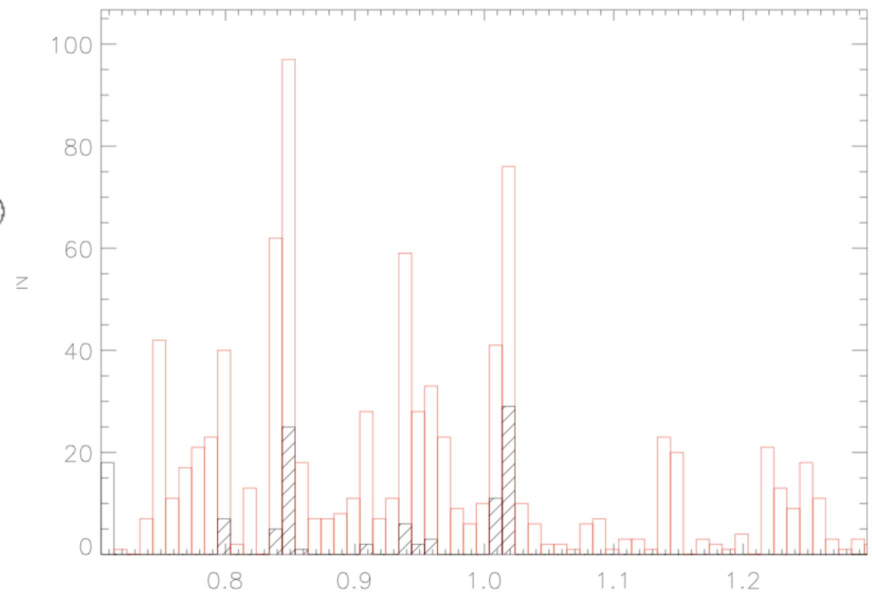


Elbaz +07

The star formation - galaxy density relation is reversed at z~1
(Elbaz et al. 2007)







The reversal is dominantly produced in the major z-peaks