

The main sequence from stars to galaxies

Questions

- Is the SFR – M_{\star} scaling-law or “main sequence” of star forming galaxies probing the bulk of the formation of present-day stars ?
- Can we learn information on micro (pc-scale) and/or macro (Mpc-scale) physics ?
 - self-regulation vs infall
- Does the main sequence reflect a true “universality” of star-formation ?
 - role of starbursts and mergers

David Elbaz (CEA Saclay)

Corentin Schreiber, Maurilio Pannella, Tao Wang, Xinwen Shu, Roger Leiton,
 Mark Dickinson, Hanae Inami, Benjamin Magnelli, Matthieu Béthermin, Mark Sargent, Dieter Lutz
 & GOODS-Herschel/CANDELS-Herschel teams



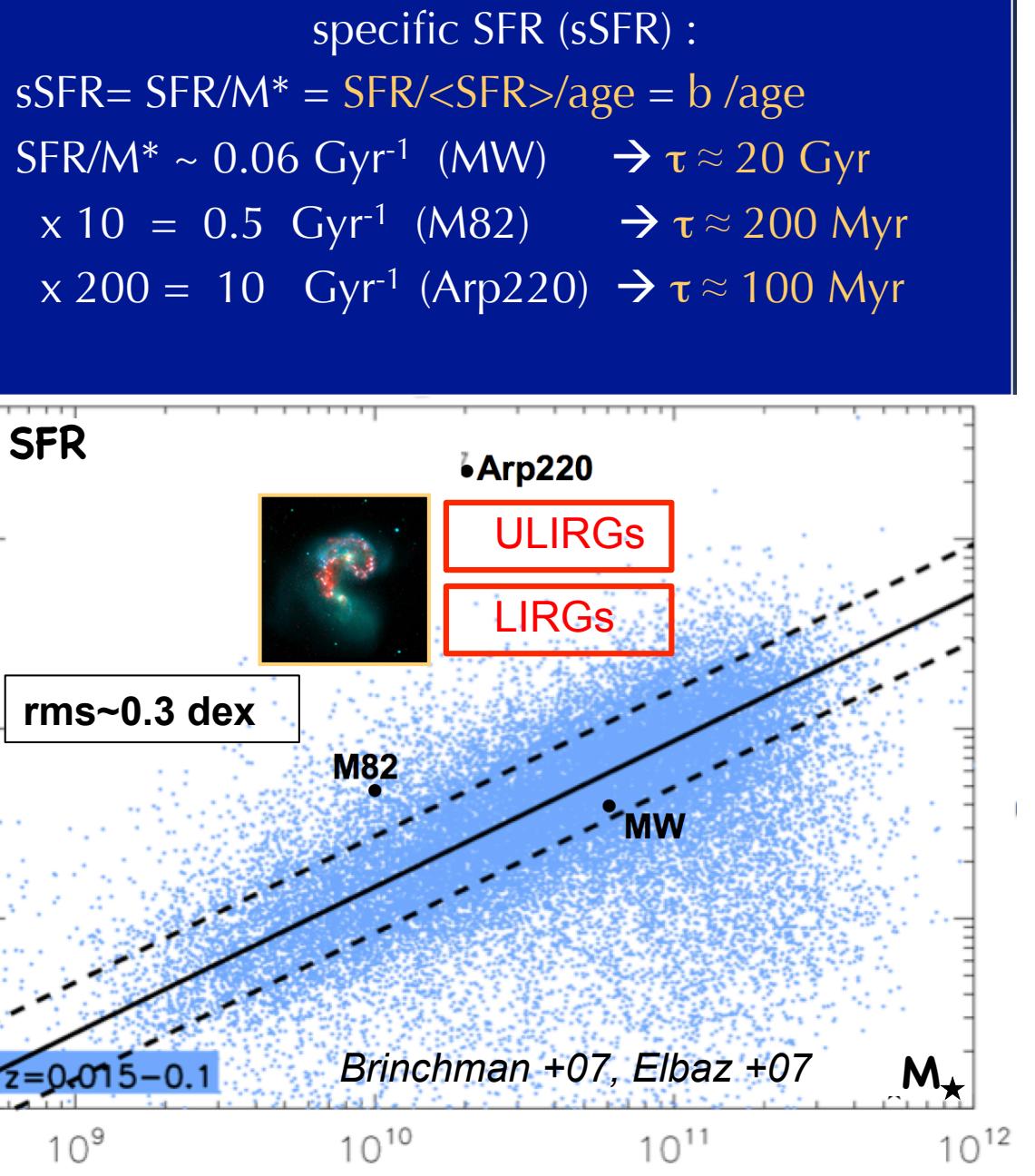
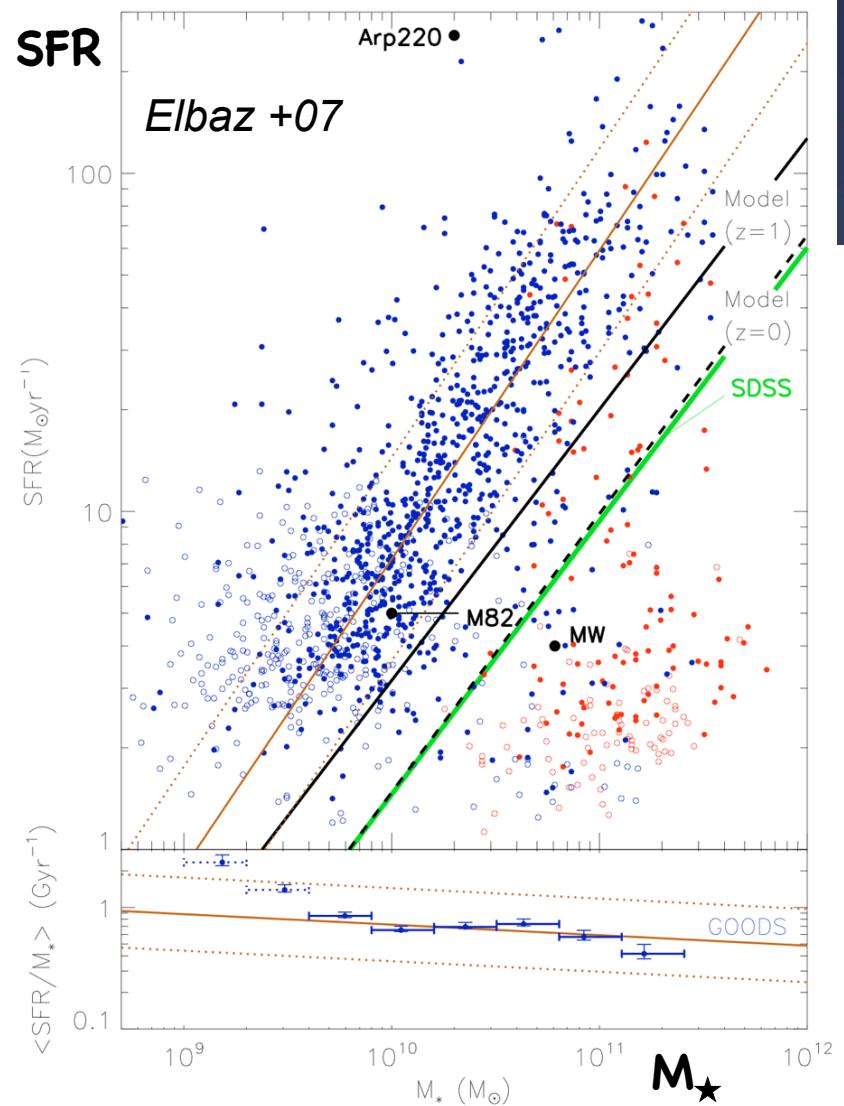
David Elbaz

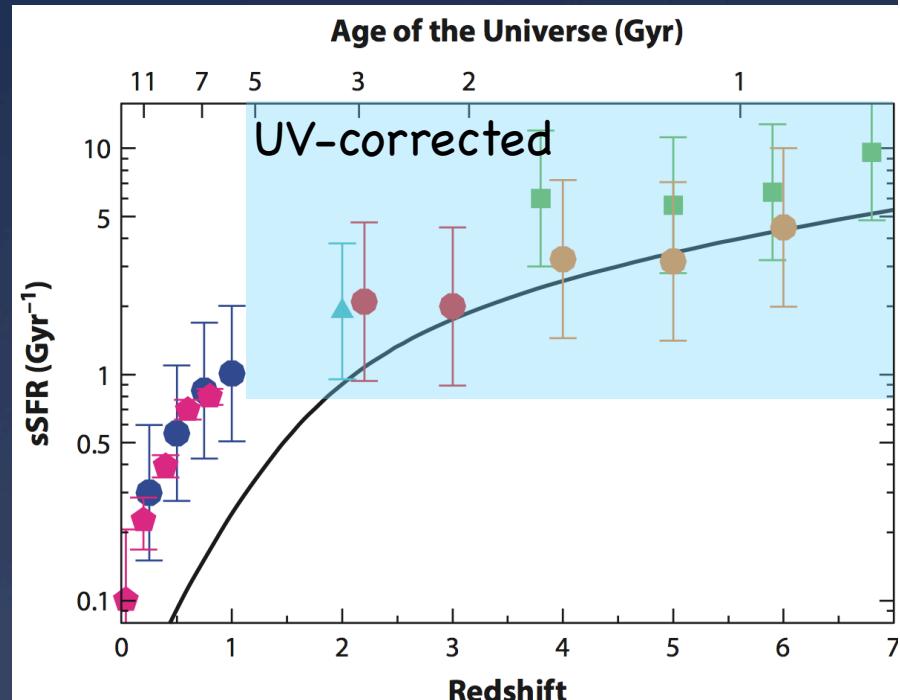
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The main sequence from stars to galaxies



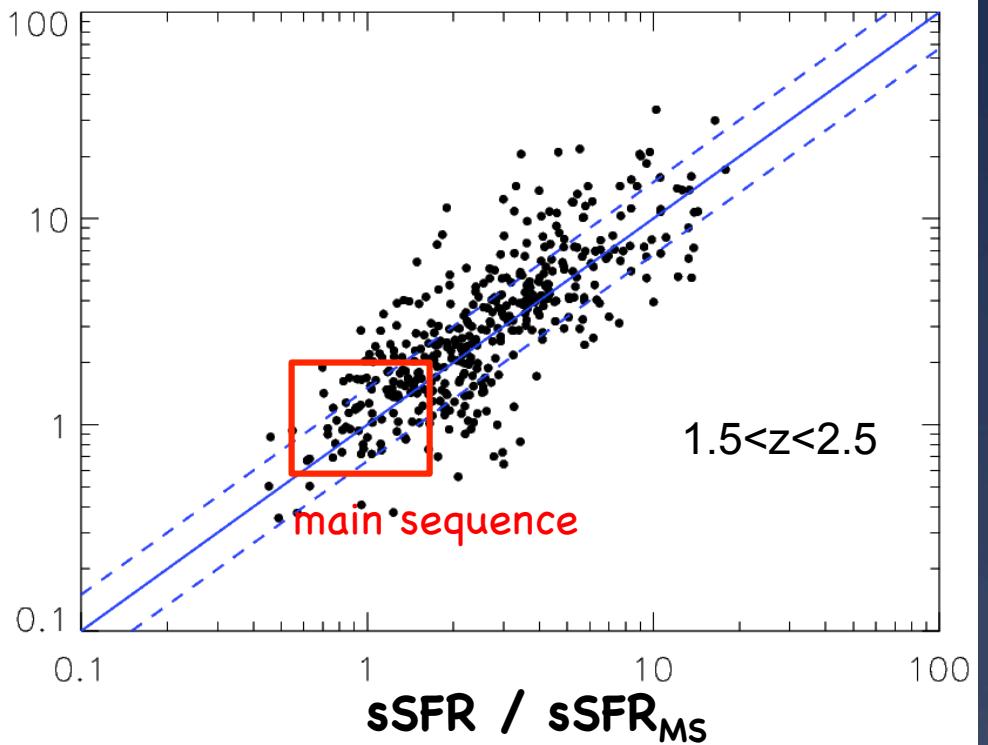
The main sequence of star forming galaxies





Compilation from Madau & Dickinson 2014

SFR(IR) / SFR(UV,corrected)



$$SFR_{IR} = SFR_{UV} \times \text{starburstiness}$$

$$\text{starburstiness} = (sSFR / sSFR_{MS})$$



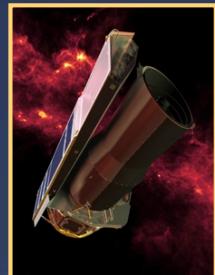
IRAS 1985
57 cm
41" fwhm

100
 μm



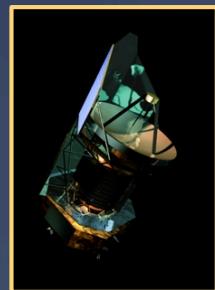
ISO 1995
60 cm

100 μm

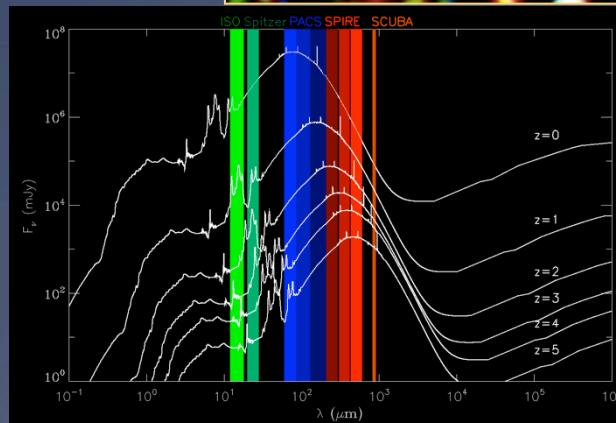


Spitzer 2003
85 cm

100 μm



Herschel 2009
350 cm
FWHM
100 μm =6.7 arcsec



GOODS + CANDELS-Herschel
- robust SFR
- $M_{\text{dust}} \rightarrow M_{\text{gas}} \rightarrow \text{SFE}$
- SED: T_{dust} , FIR/MIR
→ signature of mergers/SEDS
galaxies

NOAO Deep Wide Field Survey

$z = 2$

1 degree = 90 Mpc

cf Schreiber & Inami talks

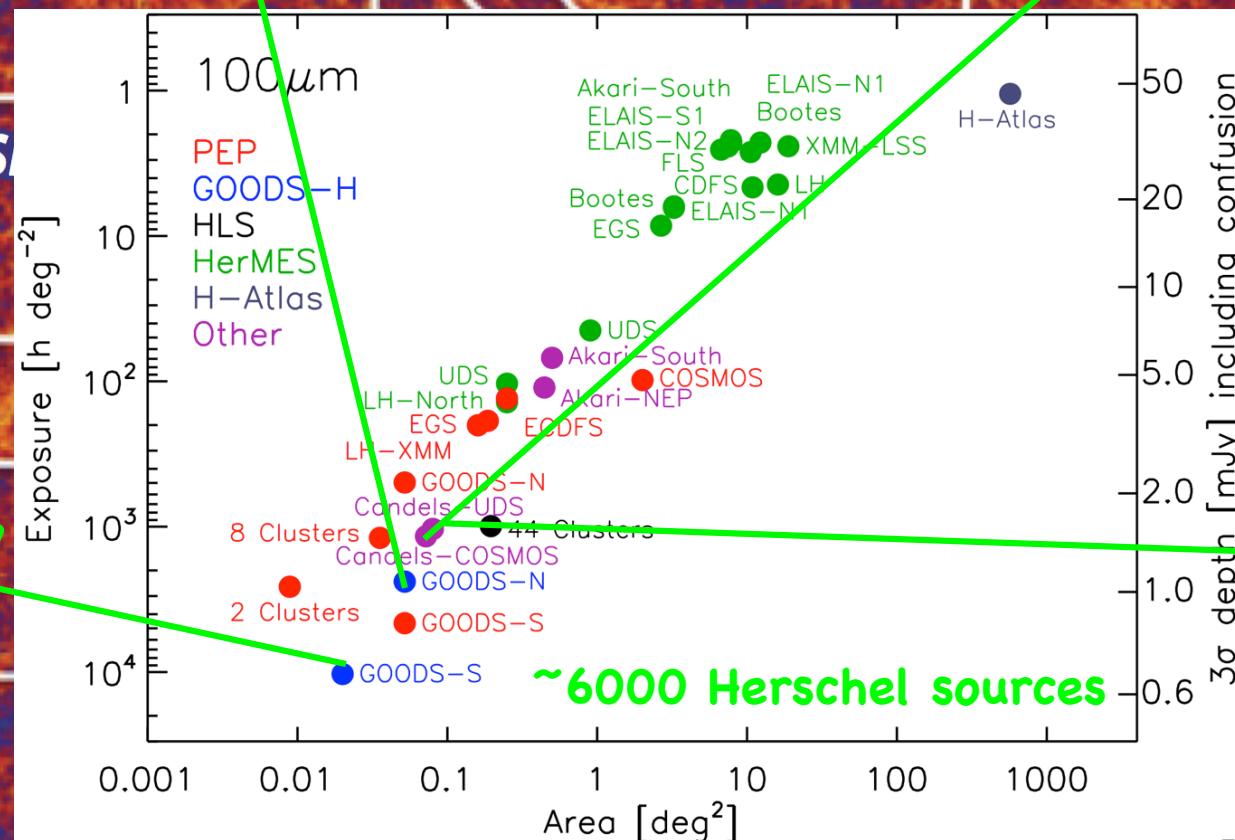
GOODS-H
PI Elbaz

CANDELS-H
PI Dickinson

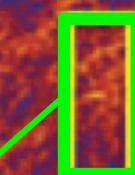
COSMOS

GOODS-N
HDF-N

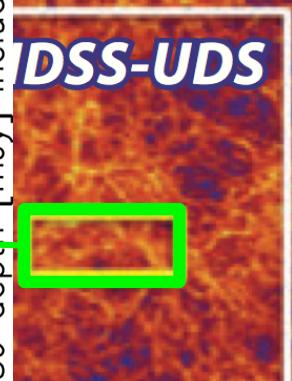
S



DSS-UDS



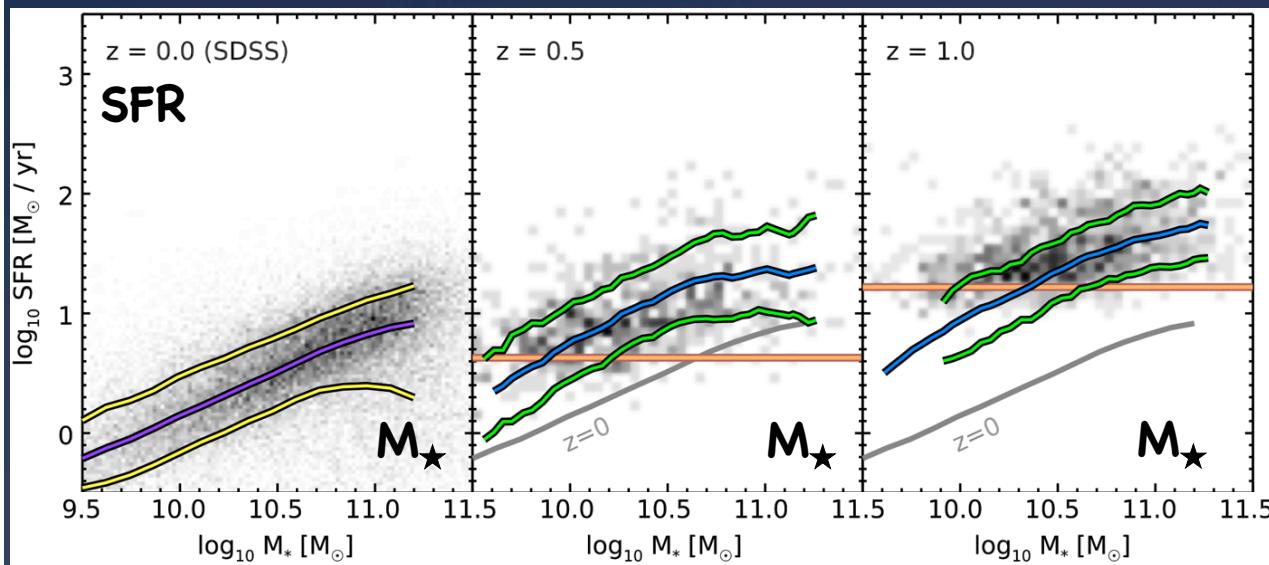
3 σ depth [mJy] including confusion



SFR – M_{\star} : the *Herschel* view on the main sequence

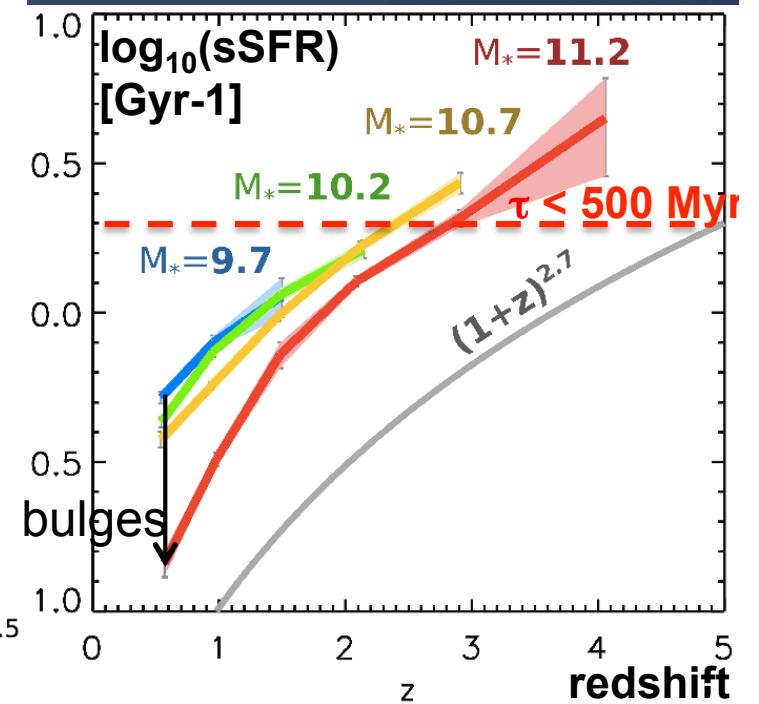
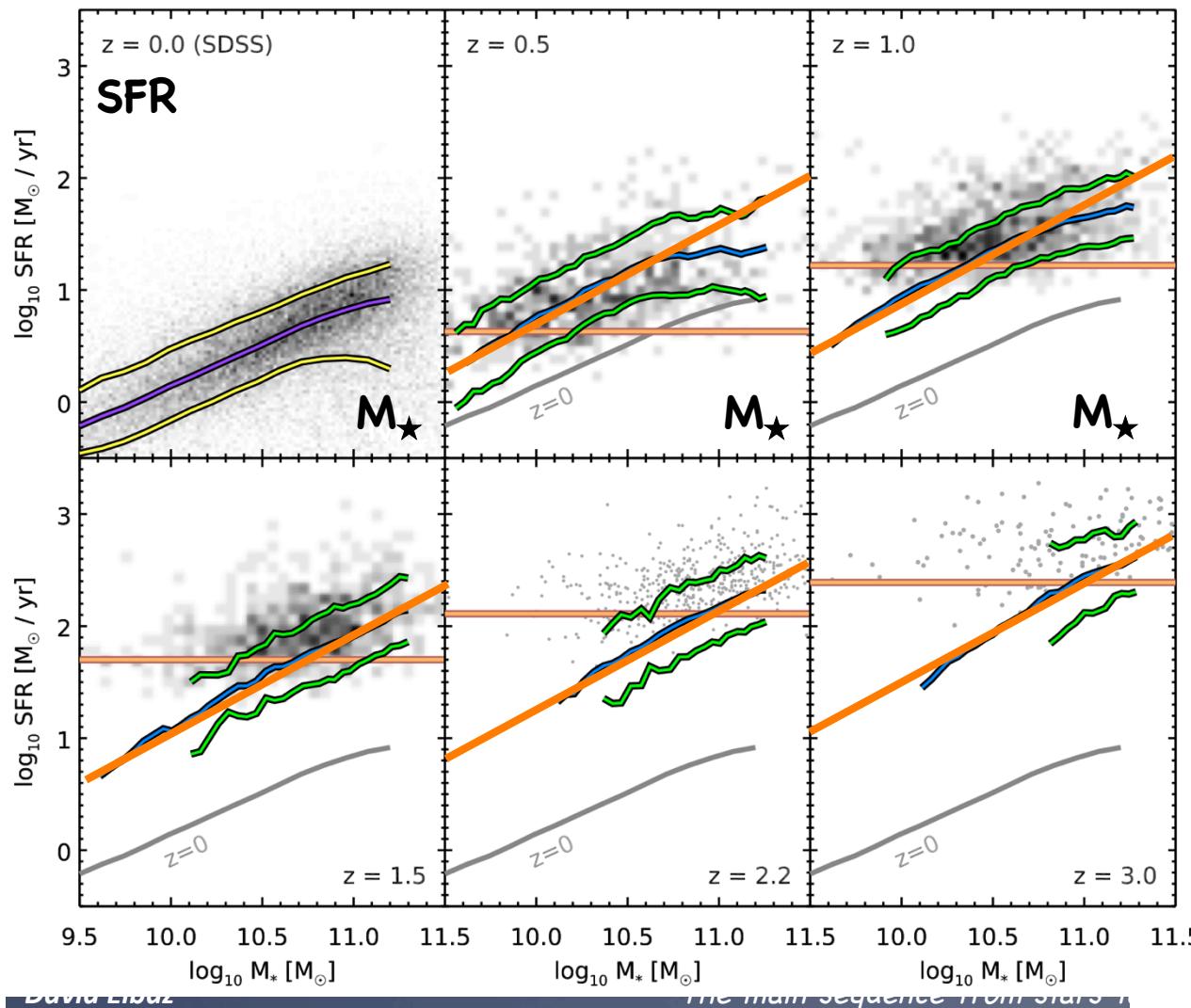
to avoid issues with IR selection : mass selected sample
WFC3 + nearly complete in z_{phot} & z_{spec}

Schreiber +2014



SFR – M_{\star} : the *Herschel* view on the main sequence

- SFR – M_{\star} main sequence in place over at least 90% of the Universe age
- rms ~ 0.3 dex of MS \rightarrow universality of SF \rightarrow self-regulation ? (cf P.Padoan)
- linear slope of $\log(\text{SFR}) - \log(M_{\star})$ \rightarrow sSFR universal at any given epoch
- break of the slope \rightarrow evidence for bulge formation \rightarrow slow “quenching of SF”



The enigma of star formation in the Milky Way



Interstellar Gas and Star Creation

By

SIDNEY VAN DEN BERGH

(Eingegangen am 29. Juni 1957)

*If no external supply is available, the gaz
in the solar vicinity will be exhausted about
700 million years from now*

$\text{SFR(MW)} \sim 7,5 \text{ M}_\odot \text{yr}^{-1}$

(Diehl *et al.* 2006 Nature)

Molecular gas (H_2): 10^9 M_\odot

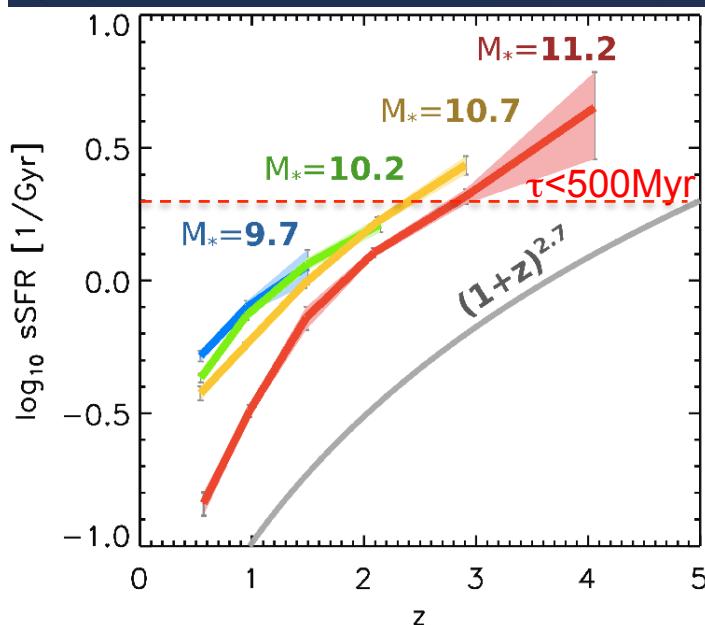
Neutral gas (HI): $5 \times 10^9 \text{ M}_\odot$

- | | |
|---|------------------------|
| → Gas refilled (e.g. infall, return gas fraction) | = Van den Bergh (1957) |
| → SFR reduced with reduced gas content: $\text{SFR} \sim \rho_{\text{gas}}$ | = Schmidt (1959) |

The MS is probably the best evidence for the need of infall

A $M_\star = 5 \times 10^{10} M_\odot$ galaxy at $z \sim 2$ has $M_{\text{gas}} \sim 5 \times 10^{10} M_\odot$

On the MS its $\text{SFR} \sim 90 M_\odot \text{yr}^{-1}$ \rightarrow gas exhausted in < 500 Myr

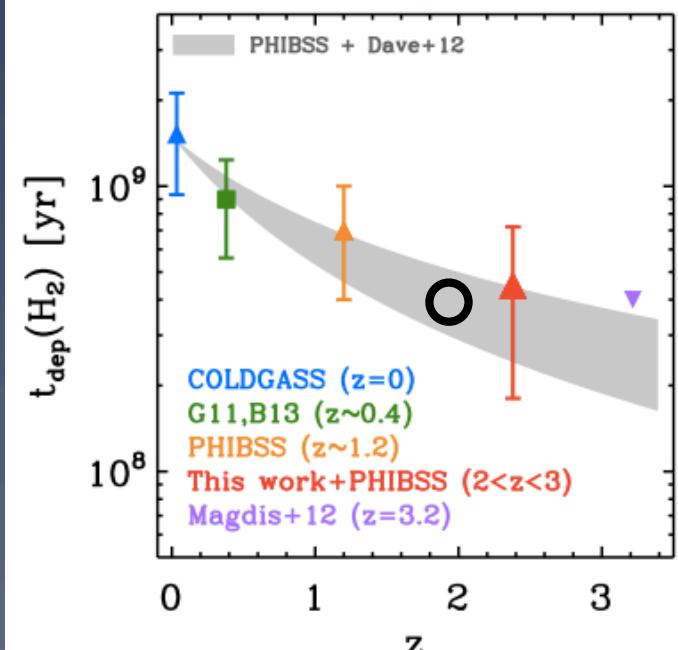
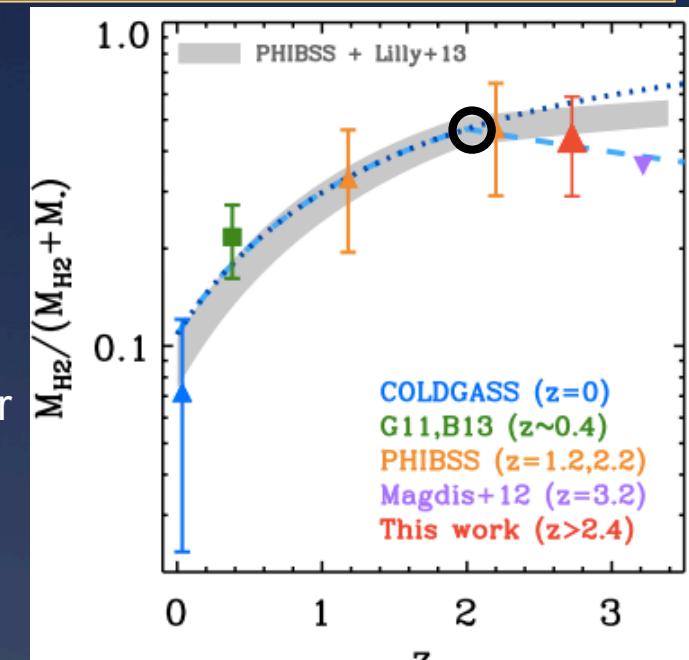


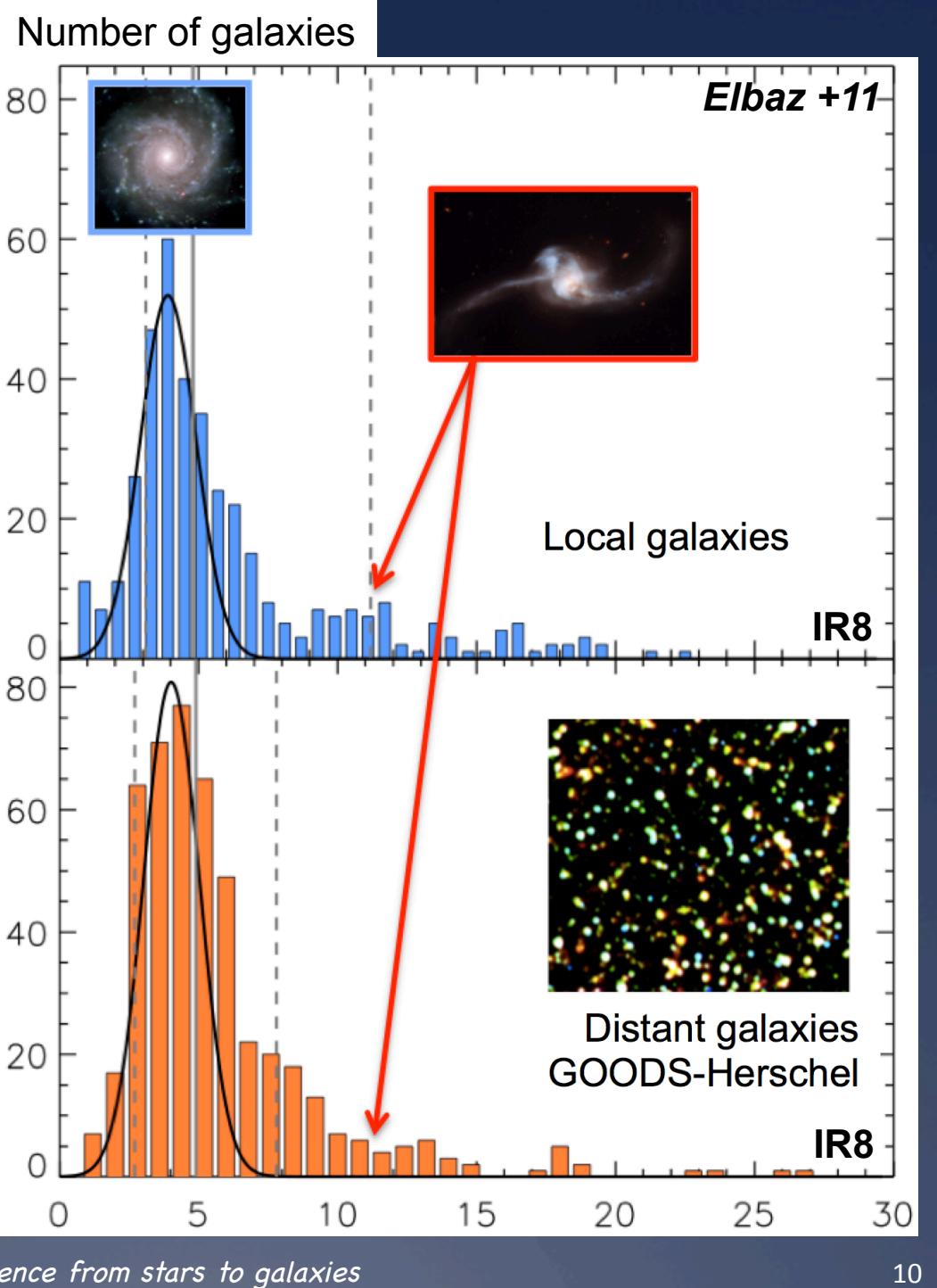
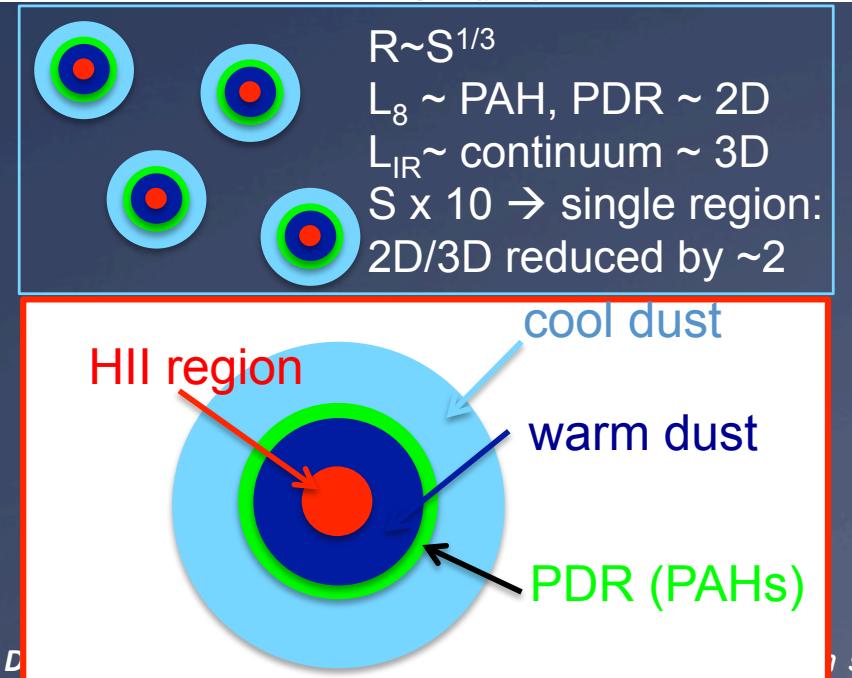
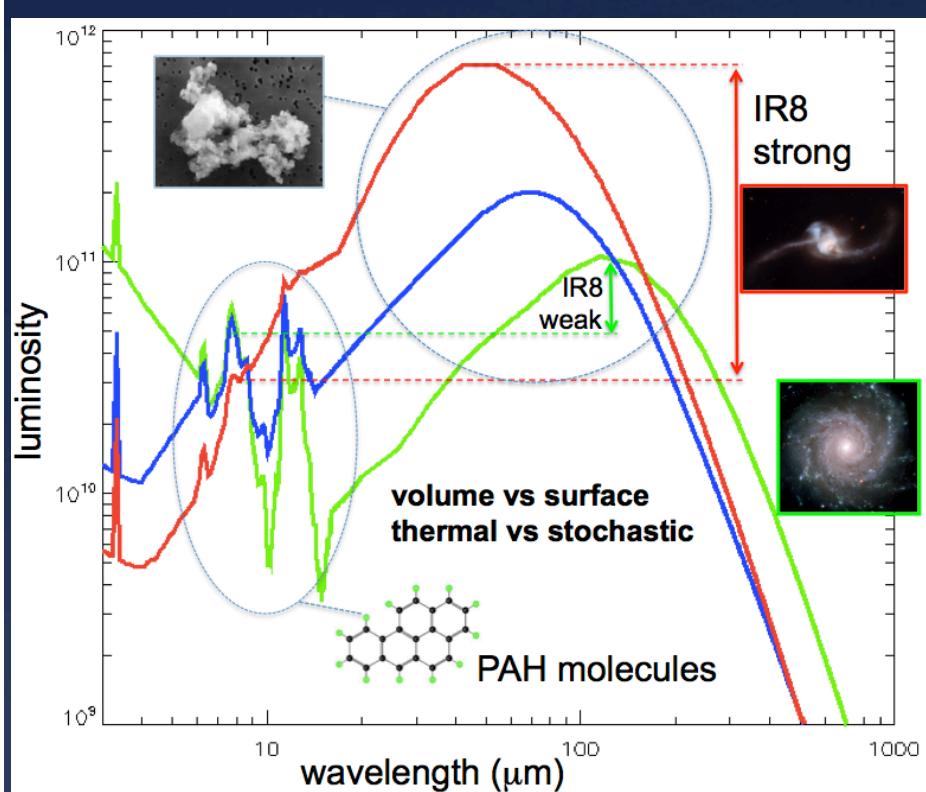
$500 \text{Myr} = \text{time } z=2.2 \text{ and } 1.9 !$

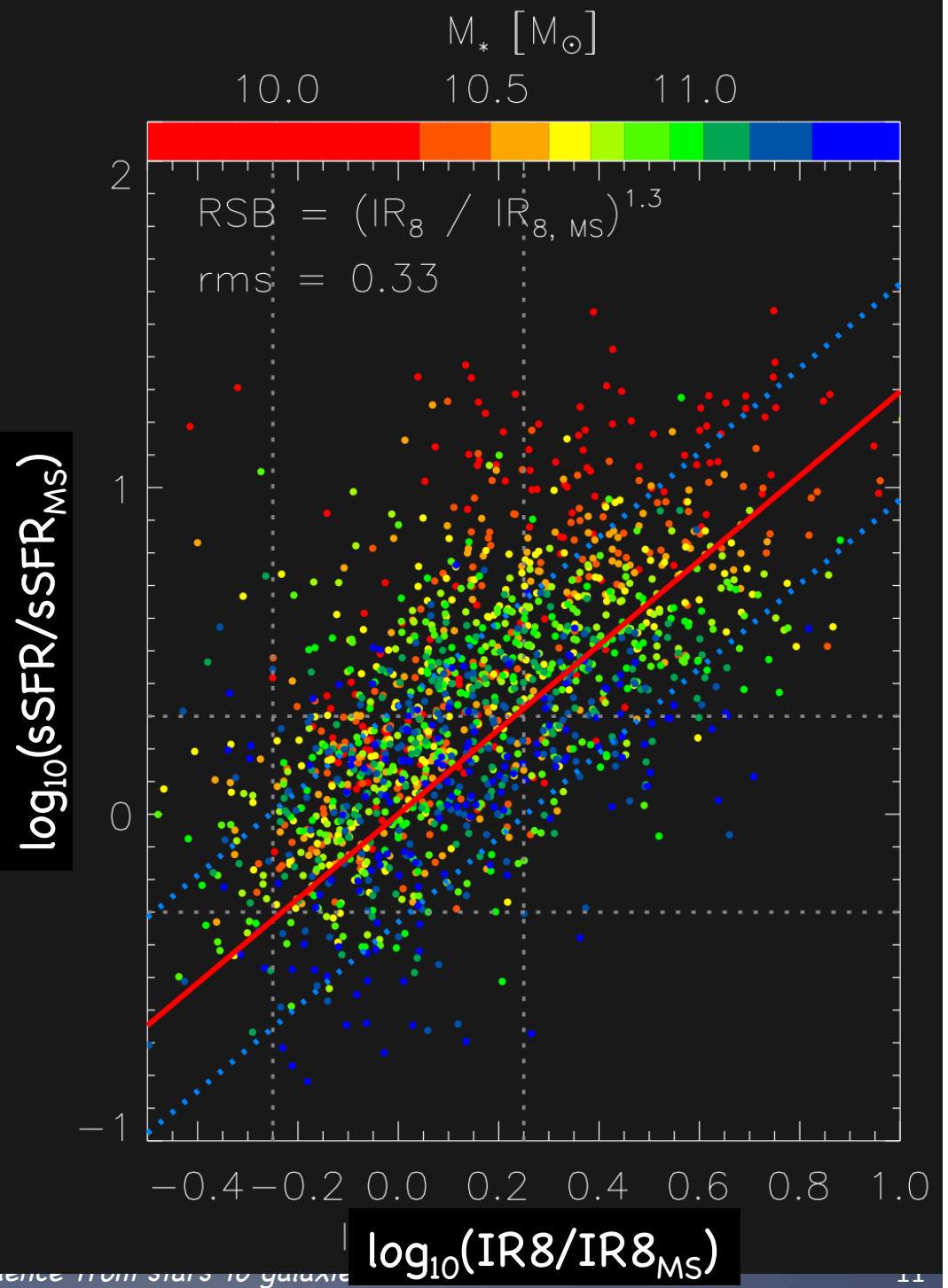
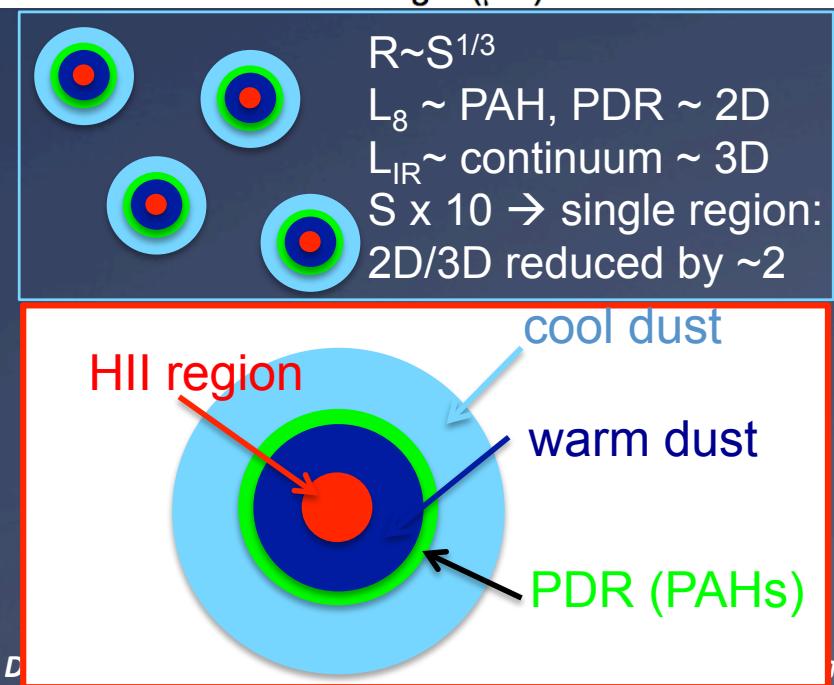
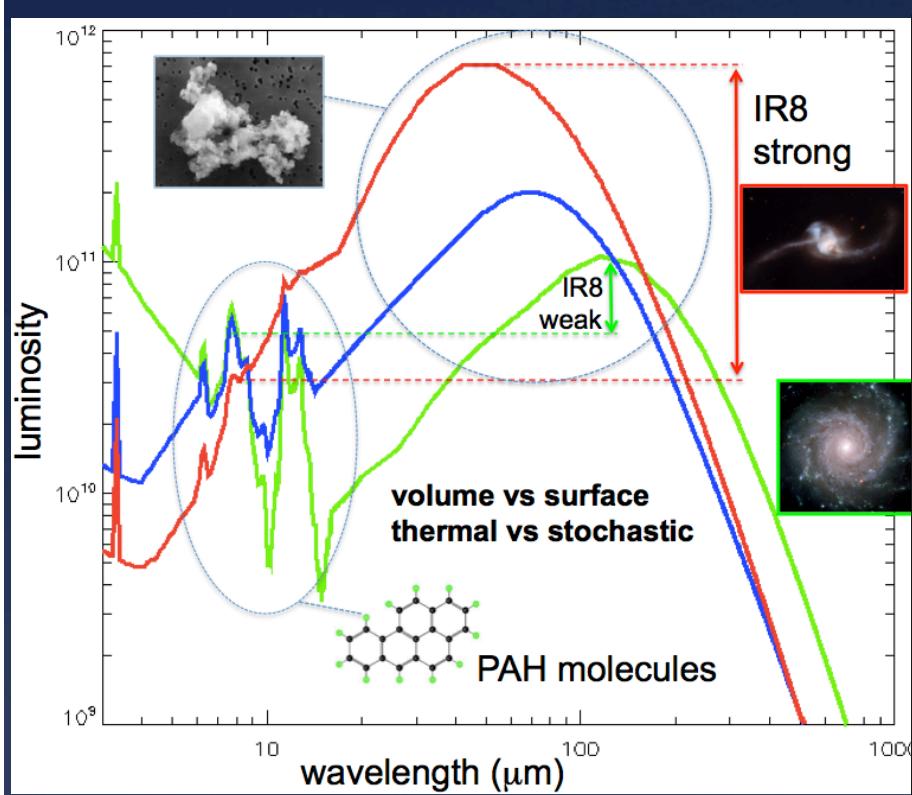
But >70% galaxies in MS
in this z range $\Rightarrow \tau_{\text{dep}} > 500 \text{Myr}$

\Rightarrow Longer duty cycle
 \Rightarrow evidence for infall !

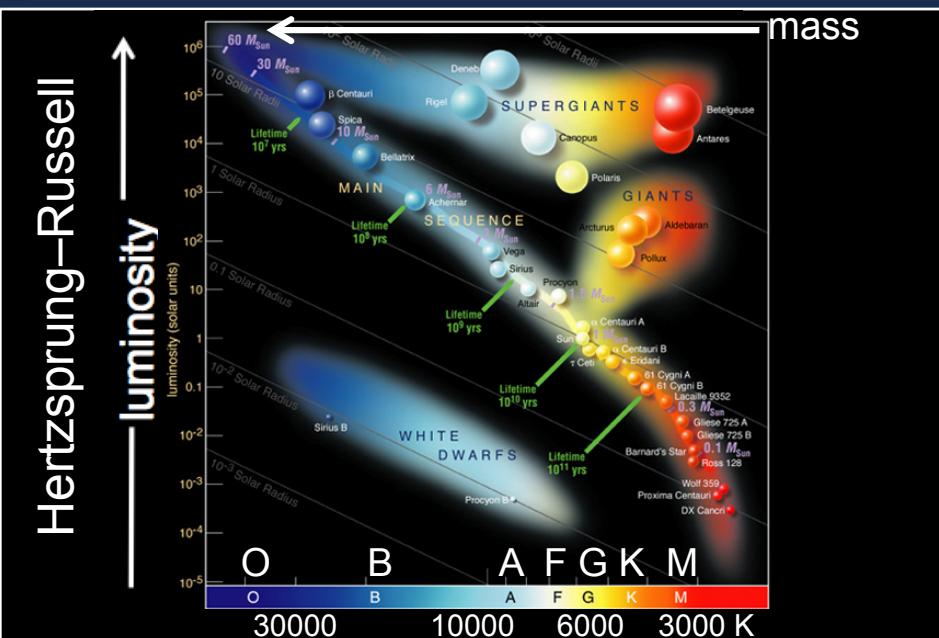
Saintonge +13







Analogy between the stellar and galactic main sequences



Stars spend most of their life on the MS

Massive stars die first

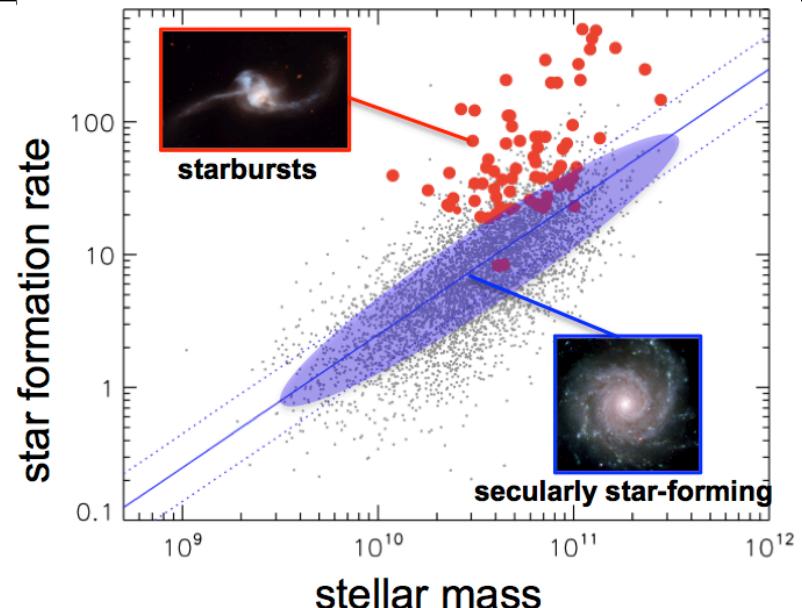
Stars have stellar winds

Stars spend a short fraction of their life in a more luminous phase (giants, AGB)

Universal efficiency of light production :
 $0.007 \Delta m c^2 \rightarrow \text{light}$

The most massive stars produce black holes that kill them

Dying stars = 10^9 times more luminous



Galaxies spend most of their life on the MS

Massive galaxies die first

Galaxies have galactic winds

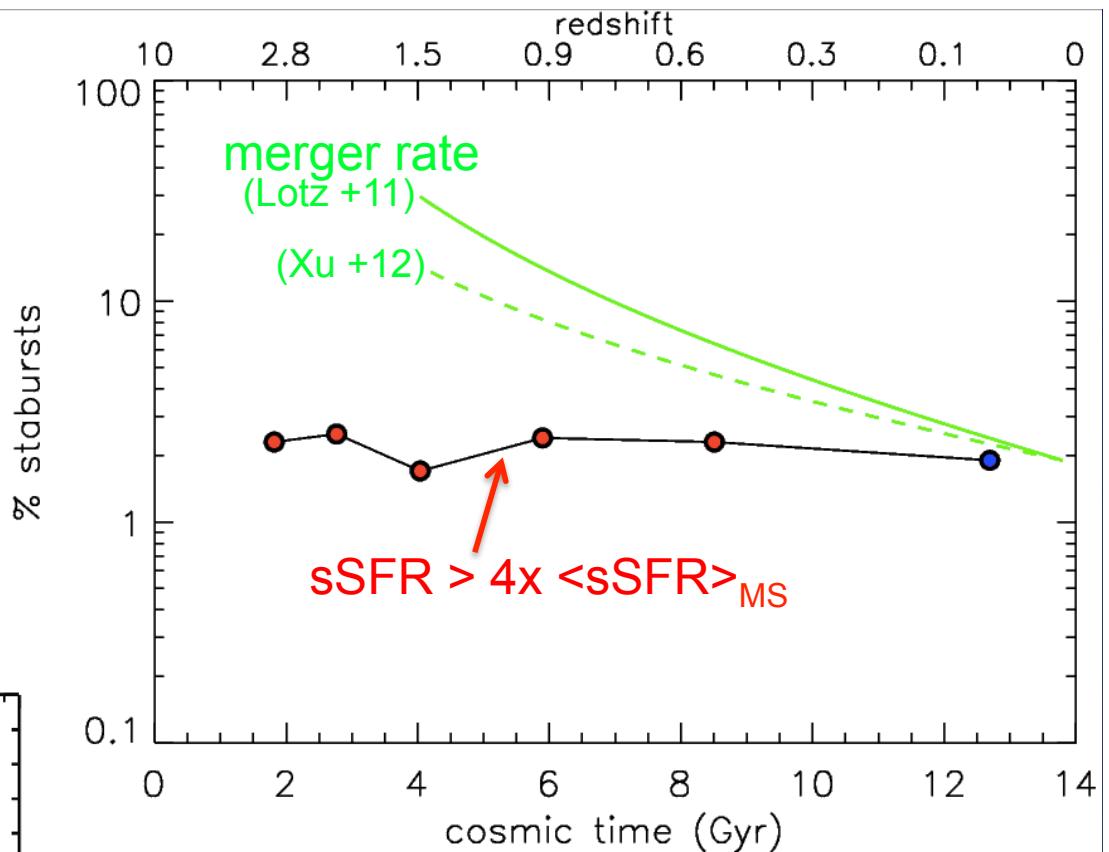
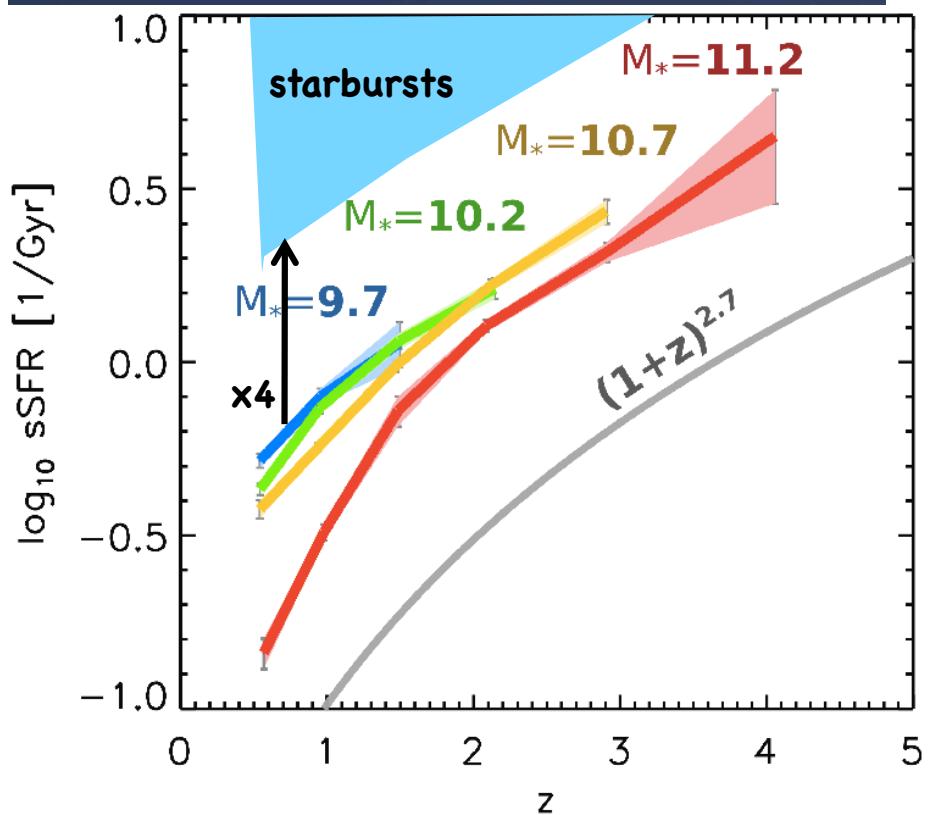
Galaxies spend a short fraction of their life in a more luminous starburst phase

Universal efficiency of light production :
 $SFR = 4 \times 10^8 M_{\text{dense}}$

The most massive galaxies produce black holes that kill them (?)

Dying galaxies more luminous ? (starbursts ?)

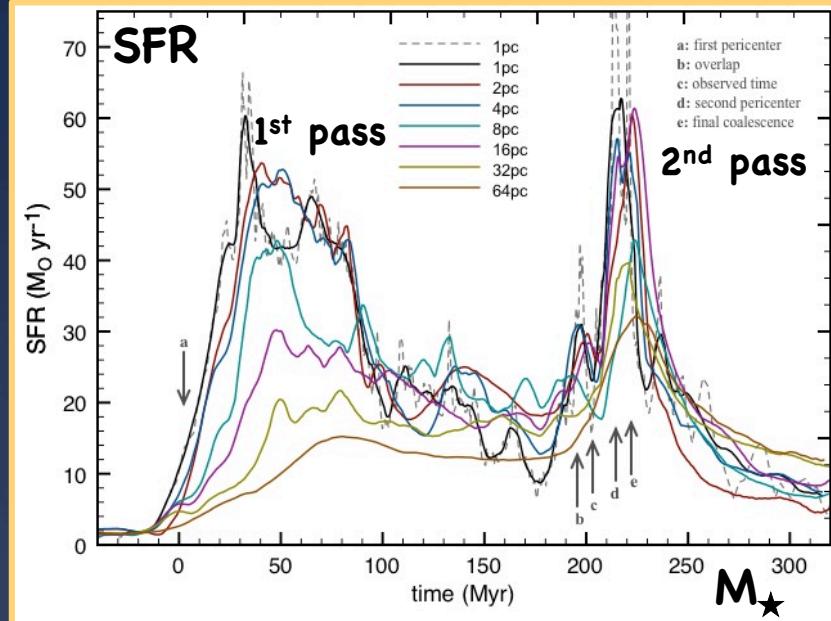
Redshift evolution of the % of starbursts



No evidence for a change of starburst %
with $z \rightarrow$ self-regulation vs mergers ?

Merger-driven starbursts in local vs distant galaxies

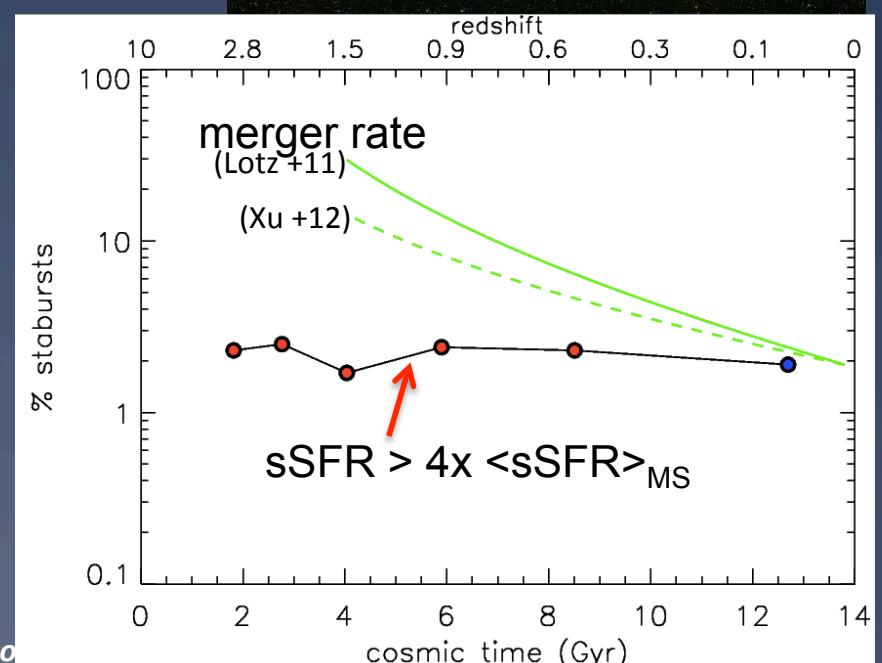
In low gas fraction local galaxies : turbulence ~ 5 km/s
merger \rightarrow compressive turbulence $\rightarrow \sim 50$ km/s \rightarrow strong SFR



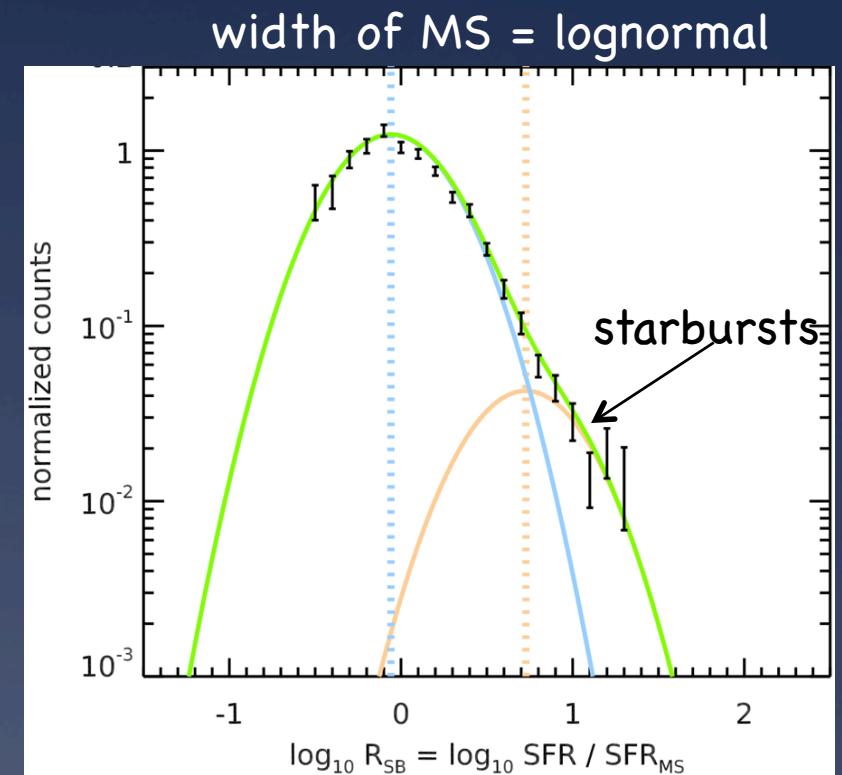
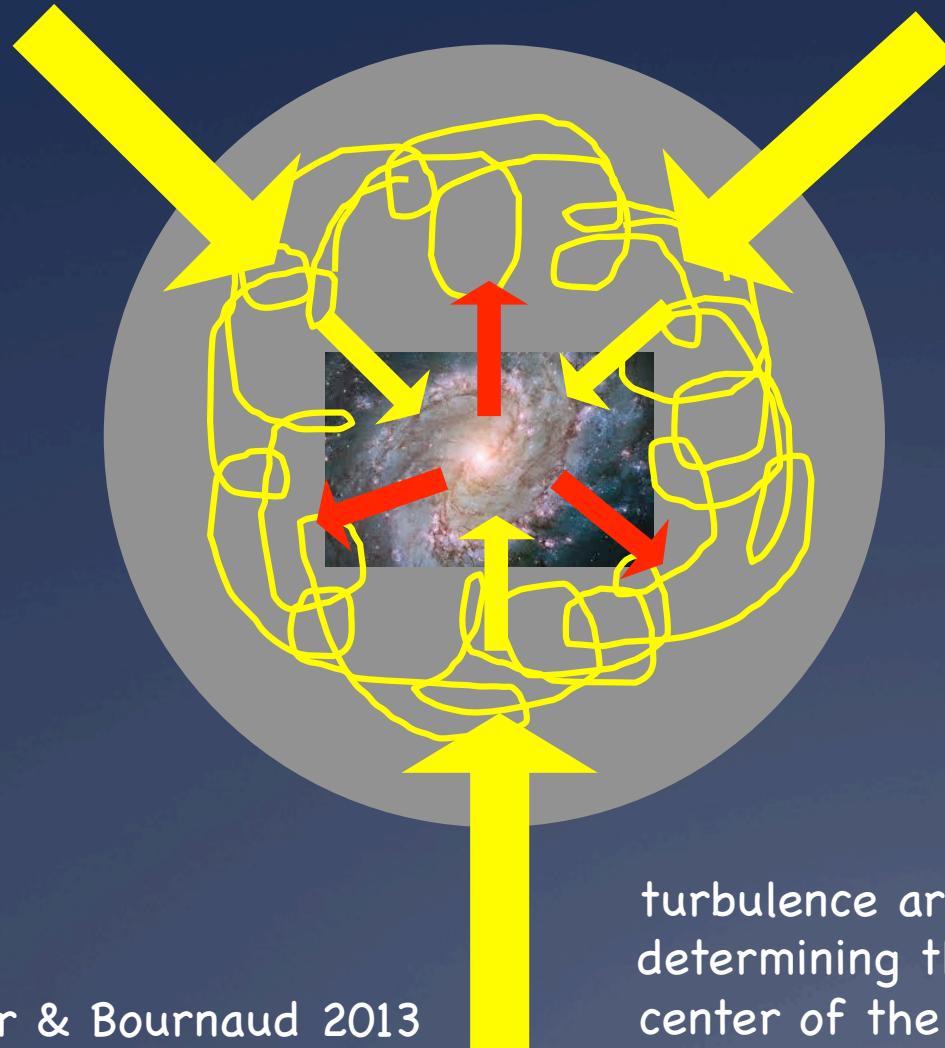
Renaud+2014
Bournaud+2015



In high gas fraction distant galaxies ($z \sim 2$, 40-50%):
turbulence already at ~ 50 km/s
 \rightarrow relative impact of compressive turbulence
induced by merger = minor
(see Perret, Renaud, Bournaud +2014)

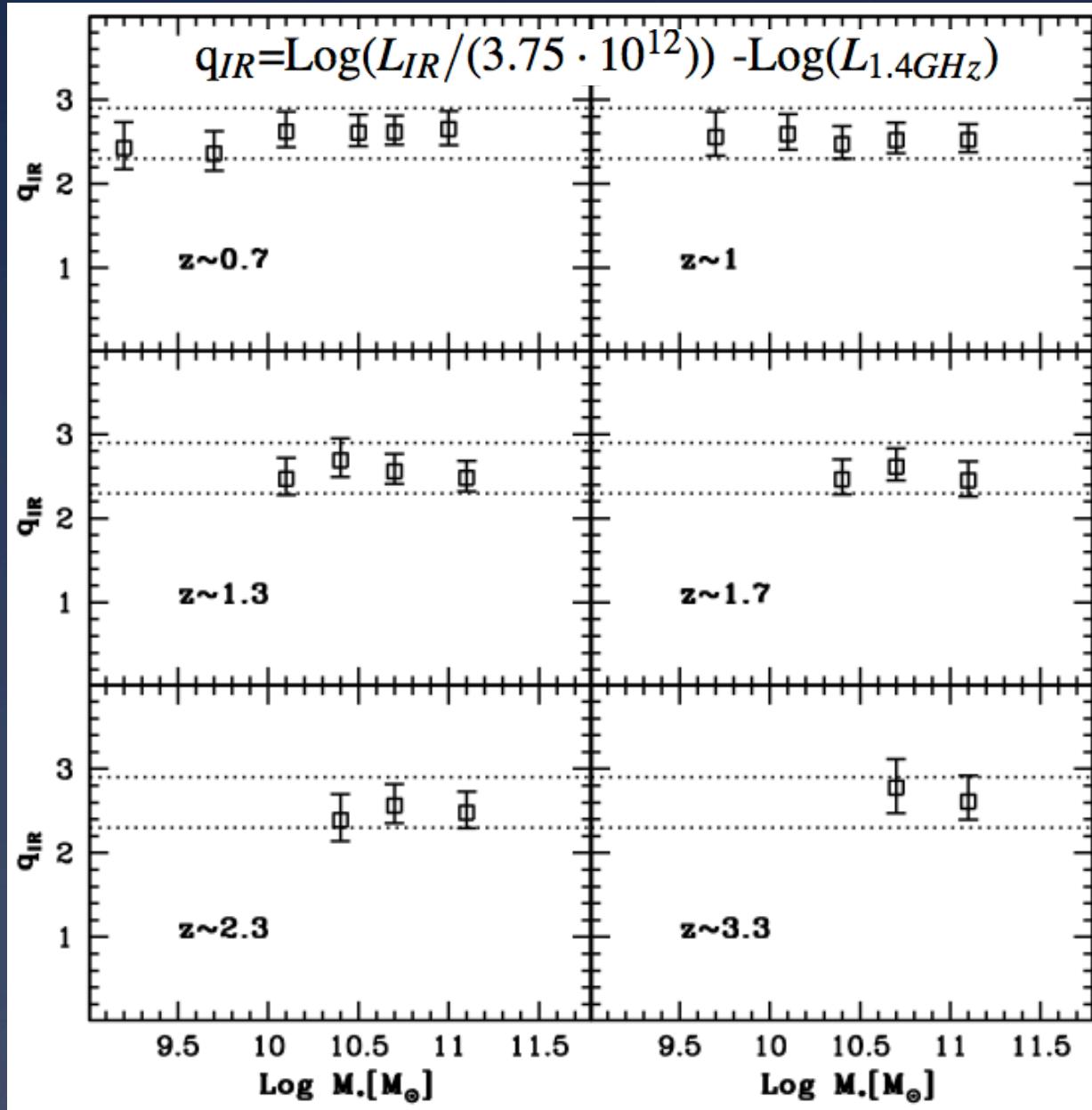


Let's extend the small/large scale analogy further :
is turbulence responsible for the shape of the width of the MS ?



turbulence around the galaxy → lognormal law
determining the fraction of « dense gas » in the
center of the halo, i.e. the fraction of gas
penetrating the galaxy

Radio – IR correlation : robustness of L_{IR} as a SFR indicator



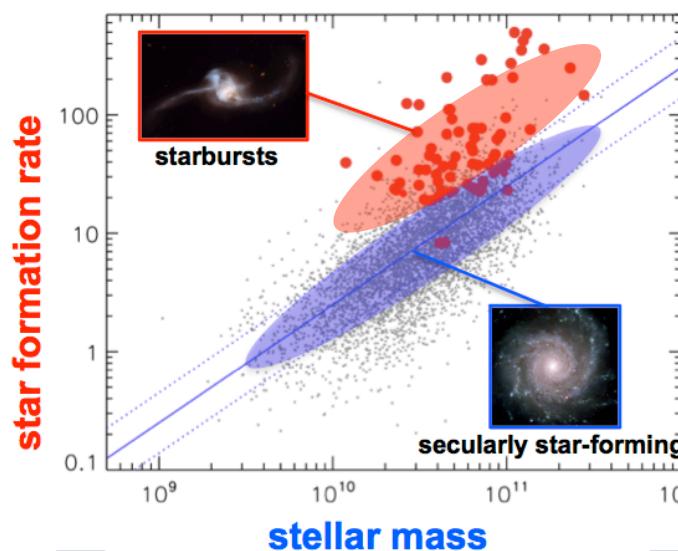
Timescale of FIR: 100 Myr
Timescale of radio: 10 Myr

Both SFR tracers agree independently of \neq timescales

Pannella +14
See also Ivison +10, Magnelli +12;
Casey +12, Strazzullo +10,
Del Moro +13

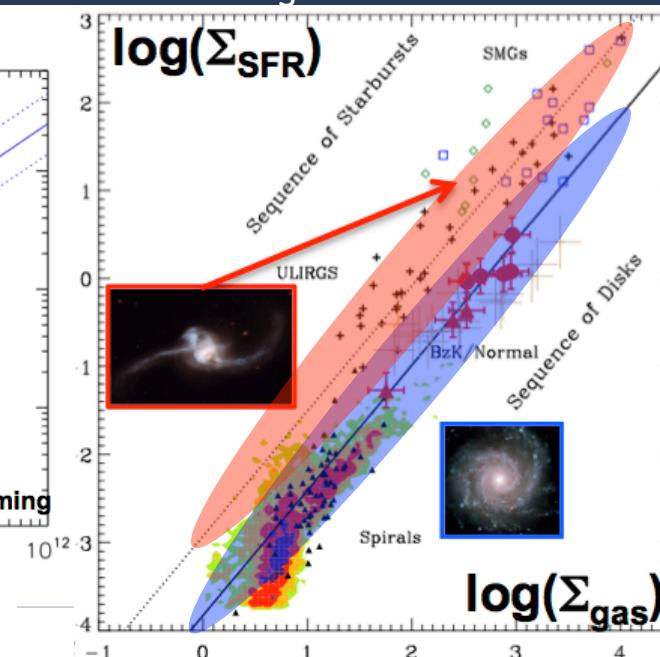
The main sequence paradigm

SFR- M_{\star} : "starburstiness"



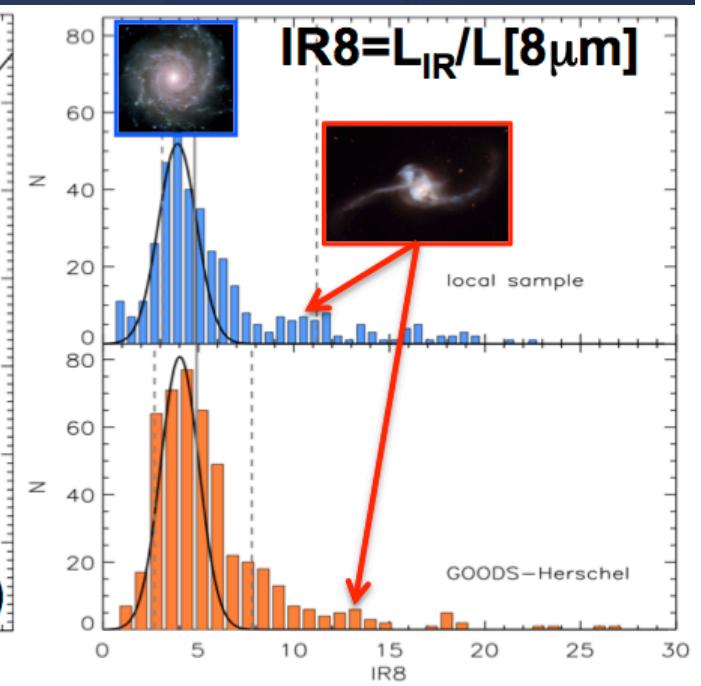
Elbaz +07, Daddi +07, Noeske +07 ...

SFR- M_{gas} : efficiency



Daddi, Elbaz +10, Genzel +10

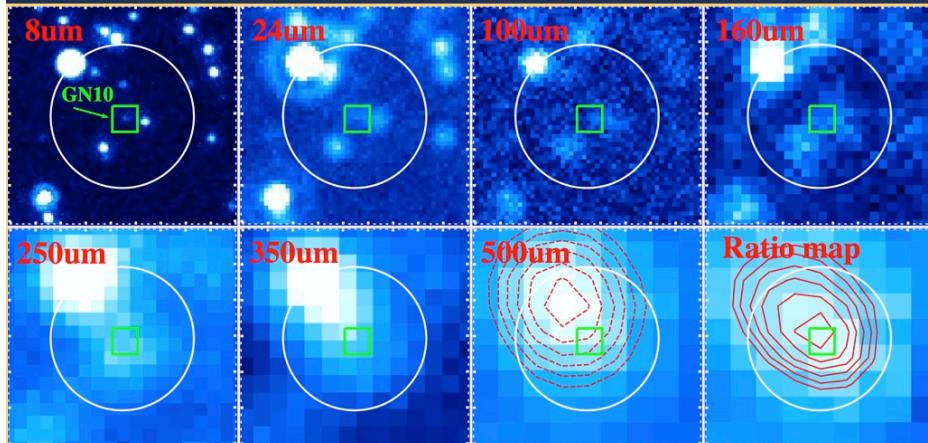
SFR – dust: compactness



Elbaz +11

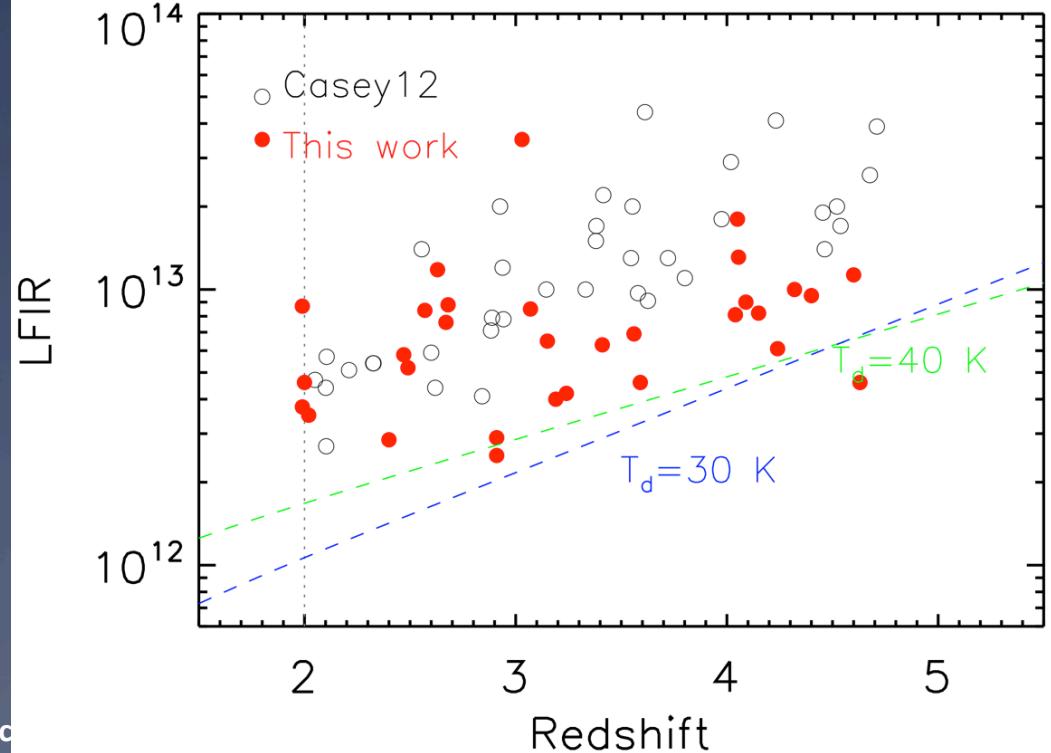
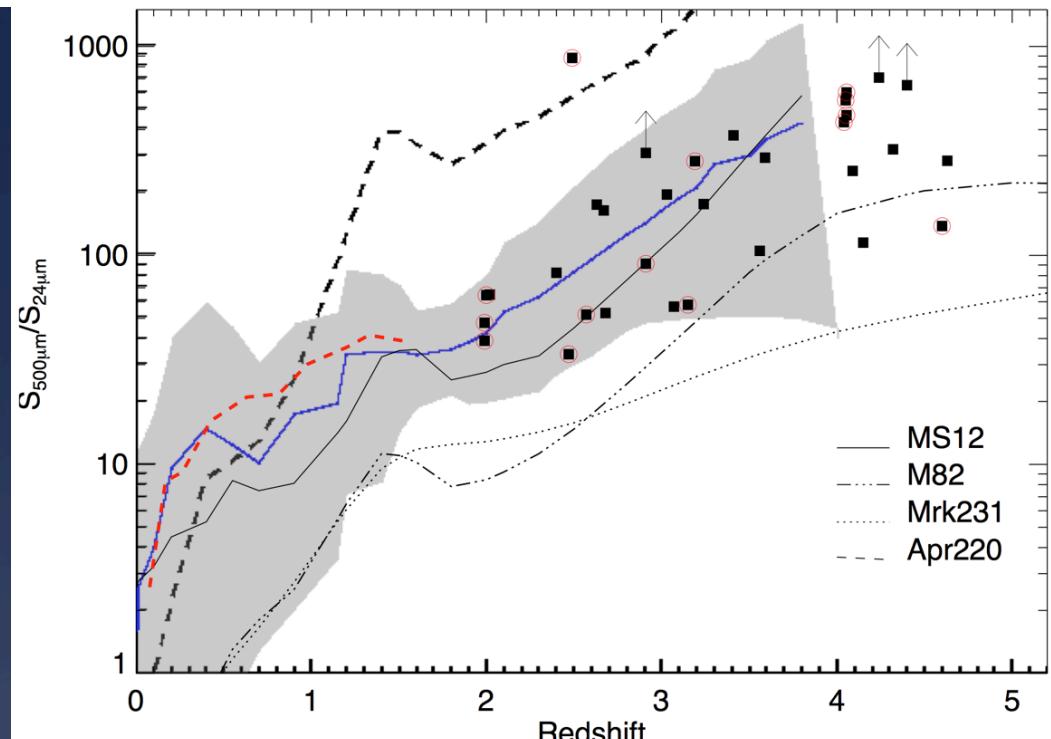
Taking advantage of the IR MS to « deconfuse » Herschel

Shu et al. (2014, TBS, see poster)



Identification of a $z=4.05$ galaxy (GN10, Daddi et al. 2009) based on the “color deconfusion”: $500\mu\text{m}$ flux was wrongly associated to a nearby source

31 candidate $z>2$ in GOODS-N 150'2





Conclusions

- A $\text{SFR} - M_{\star}$ main sequence of star forming galaxies has been in place over at least 90% of the Universe age
- Gas content of galaxies not enough to maintain such SF more than ~ 500 Myr \rightarrow probably the best evidence for the need for infall at all epochs.
- The small $\text{rms} \sim 0.3$ dex of the MS \Rightarrow universality of SF : 68% of galaxies have the same SFR at given M^* \rightarrow self-regulation ? (cf P.Padoan)
- The linear slope of $\log(\text{SFR}) - \log(M_{\star})$ \rightarrow sSFR universal at any given epoch
- The break of the slope (initially interpreted as evidence for a sublinear slope) is probably evidence for bulge formation in the MS \rightarrow slow “quenching of SF”
- The fraction of outliers with high sSFR, i.e. starbursts, is small and does not vary with redshift \rightarrow can be explained if relative impact of mergers is compressive turbulence whose relative role on highly turbulent gas rich distant galaxies is small.