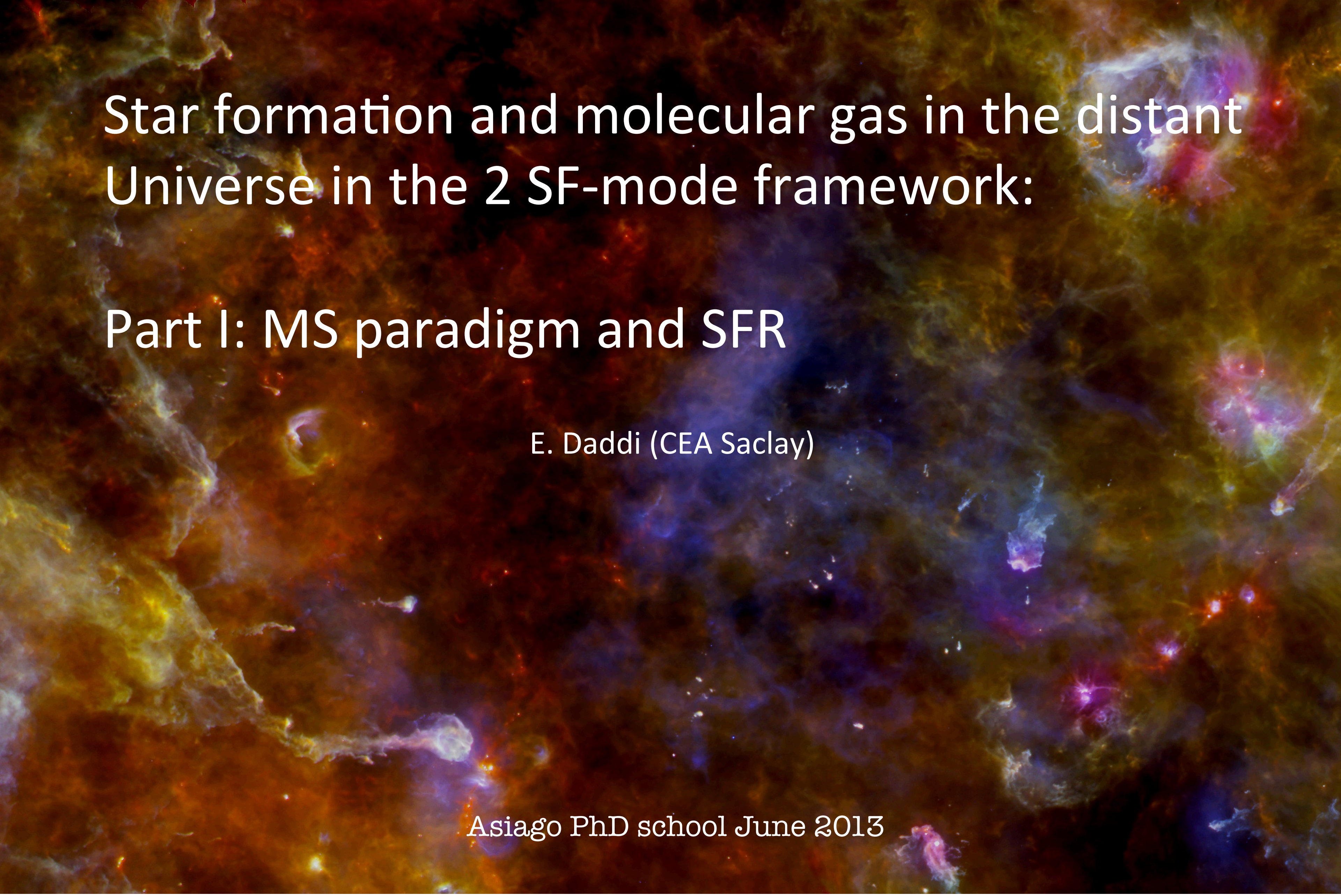


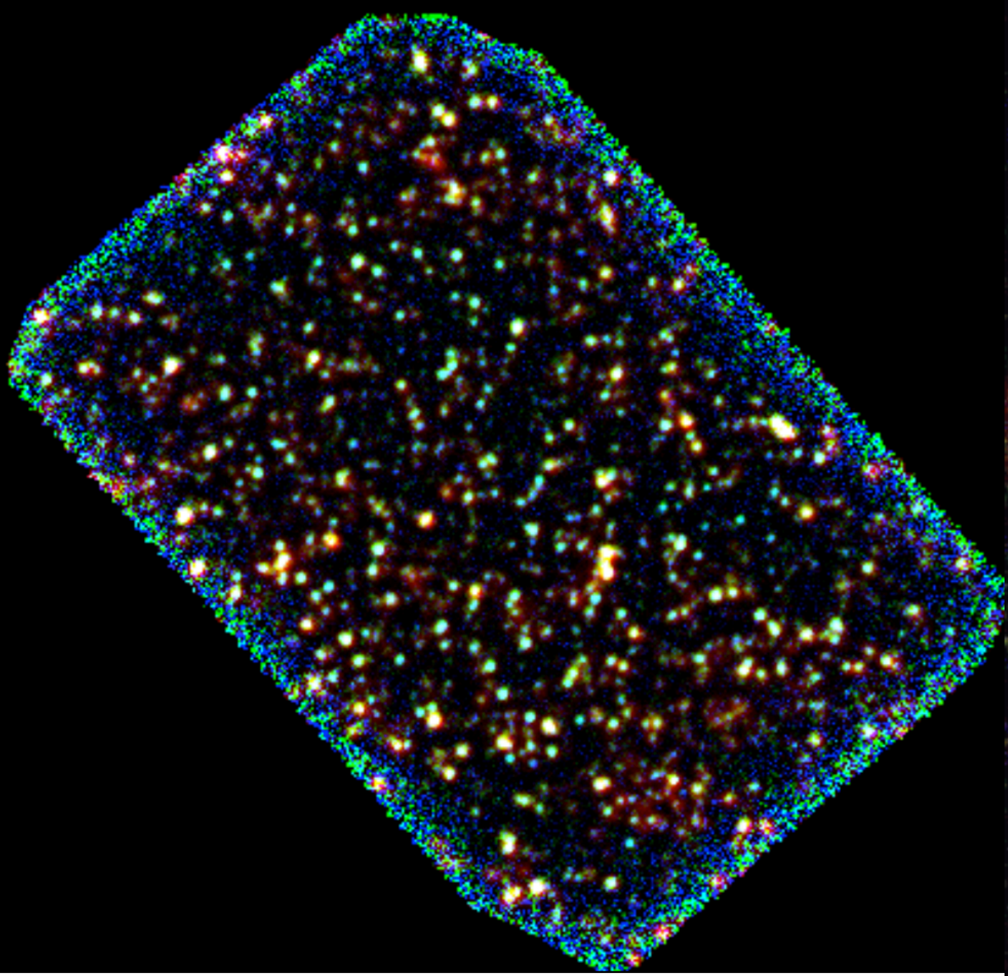
# Star formation and molecular gas in the distant Universe in the 2 SF-mode framework:

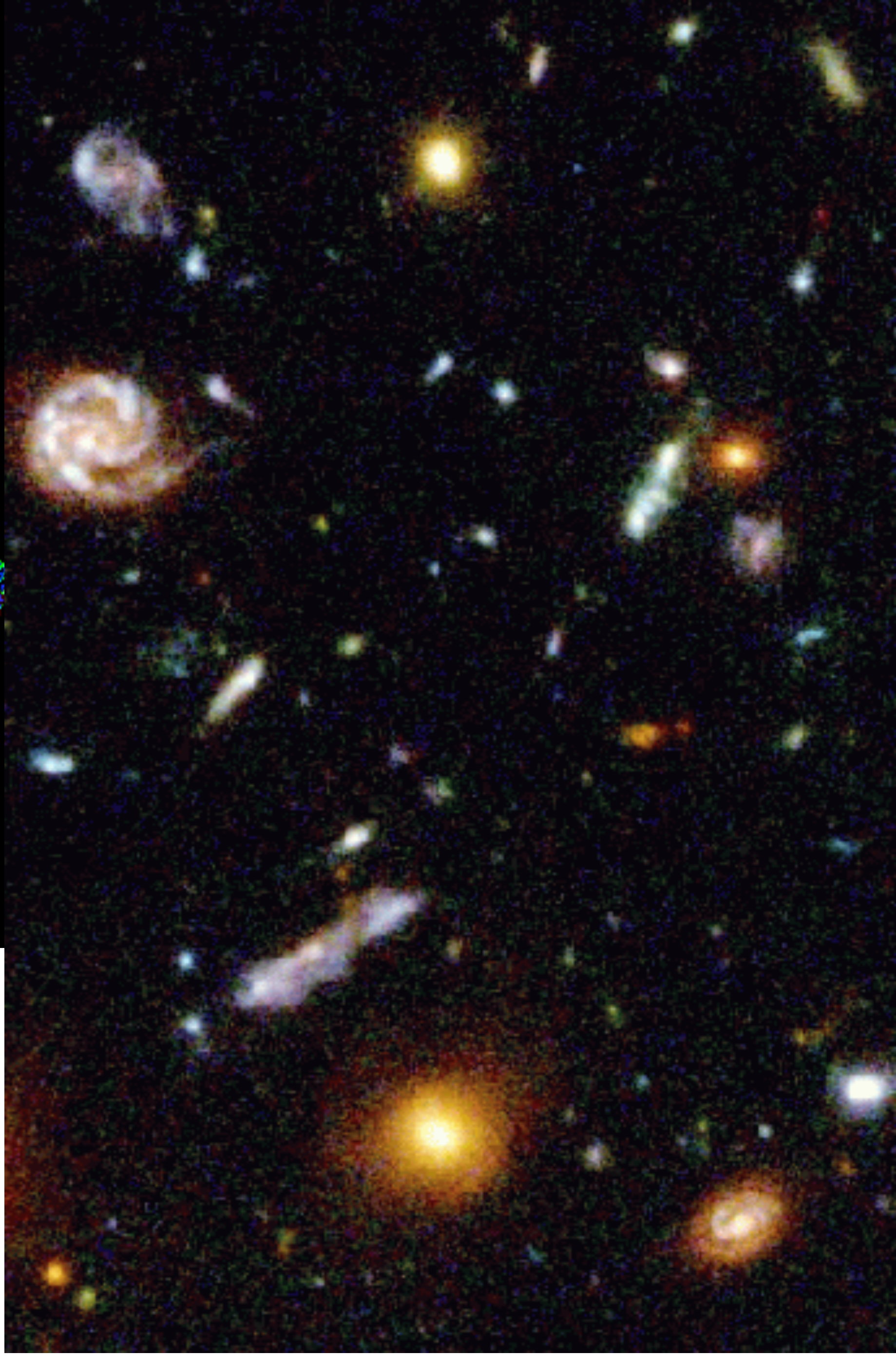
# Part I: MS paradigm and SFR

E. Daddi (CEA Saclay)

Asiago PhD school June 2013

European Research Council

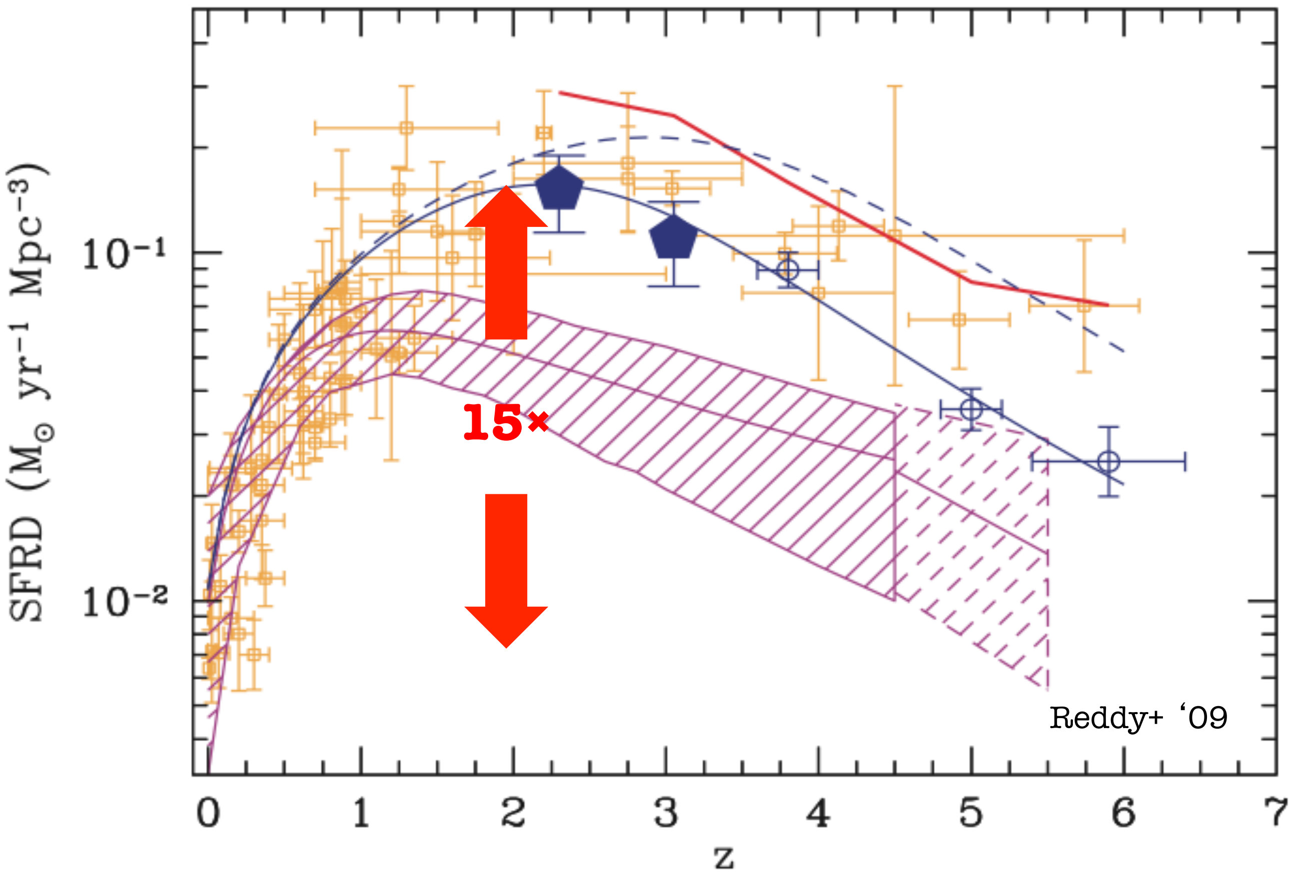




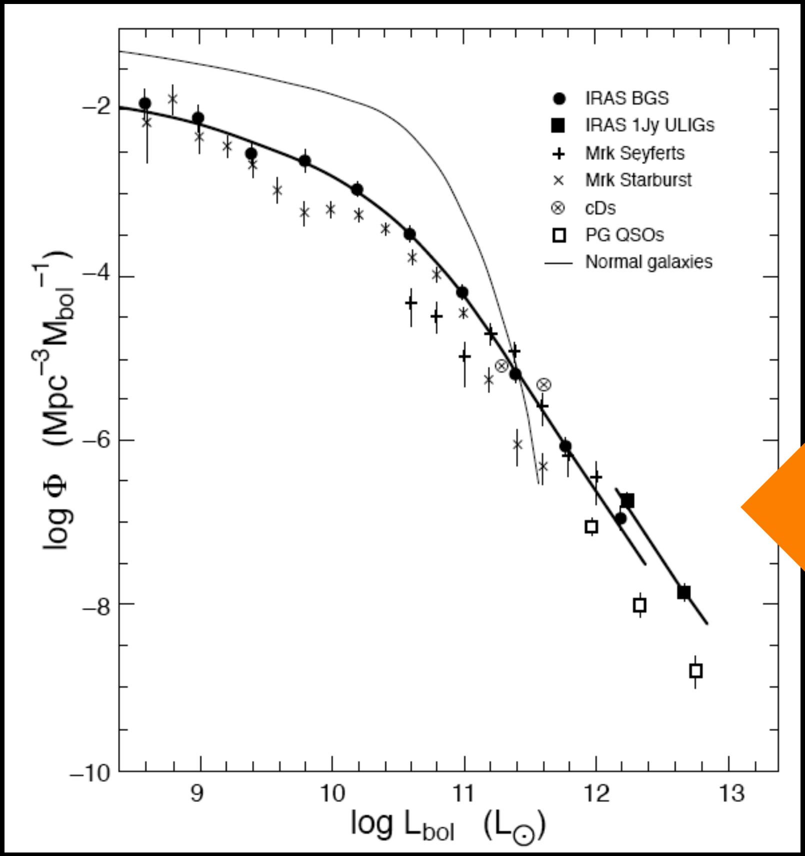
Complex observables

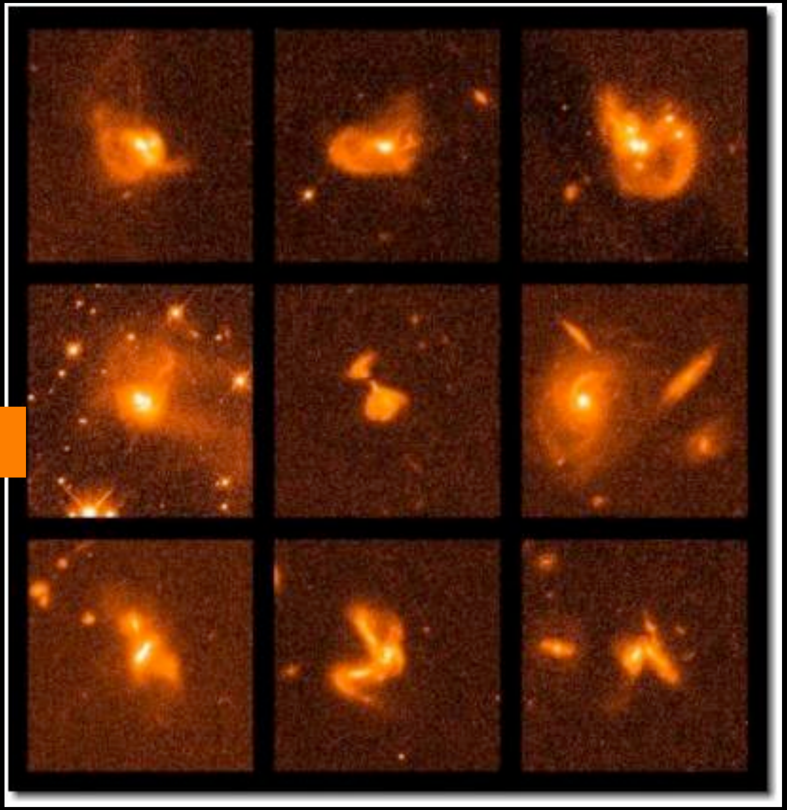
# Cosmic star formation history – when?

The cosmic *SFRD increases approx. 15-fold* over $0 < z < 2$, then probably declines at higher redshifts (e.g. Hopkins+ '04, Reddy+ '09, Bouwens+ '11).



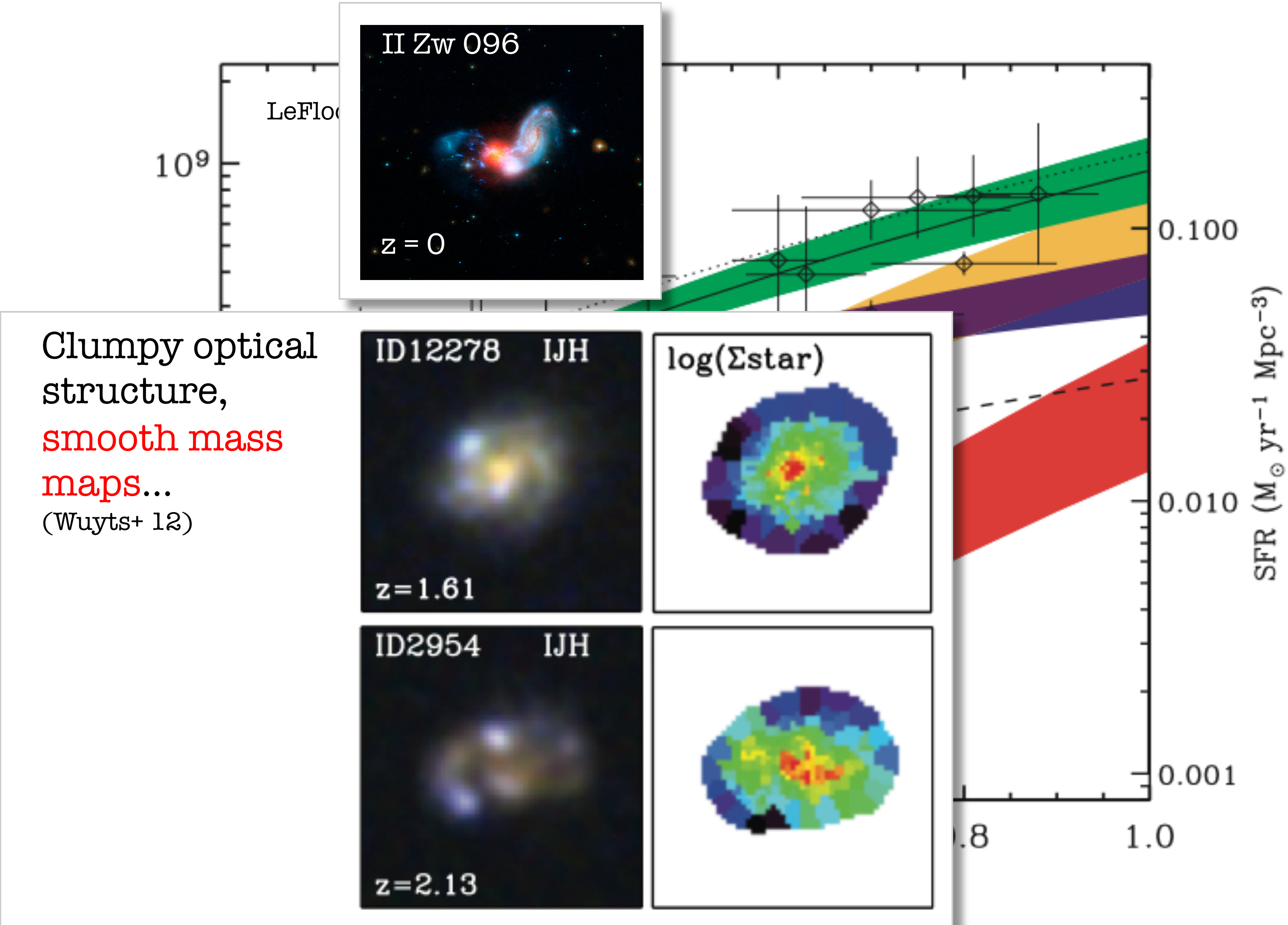
# At low-z, most luminous galaxies (ULIRGs) are mergers (bolometric LIR and SFR are equivalent)



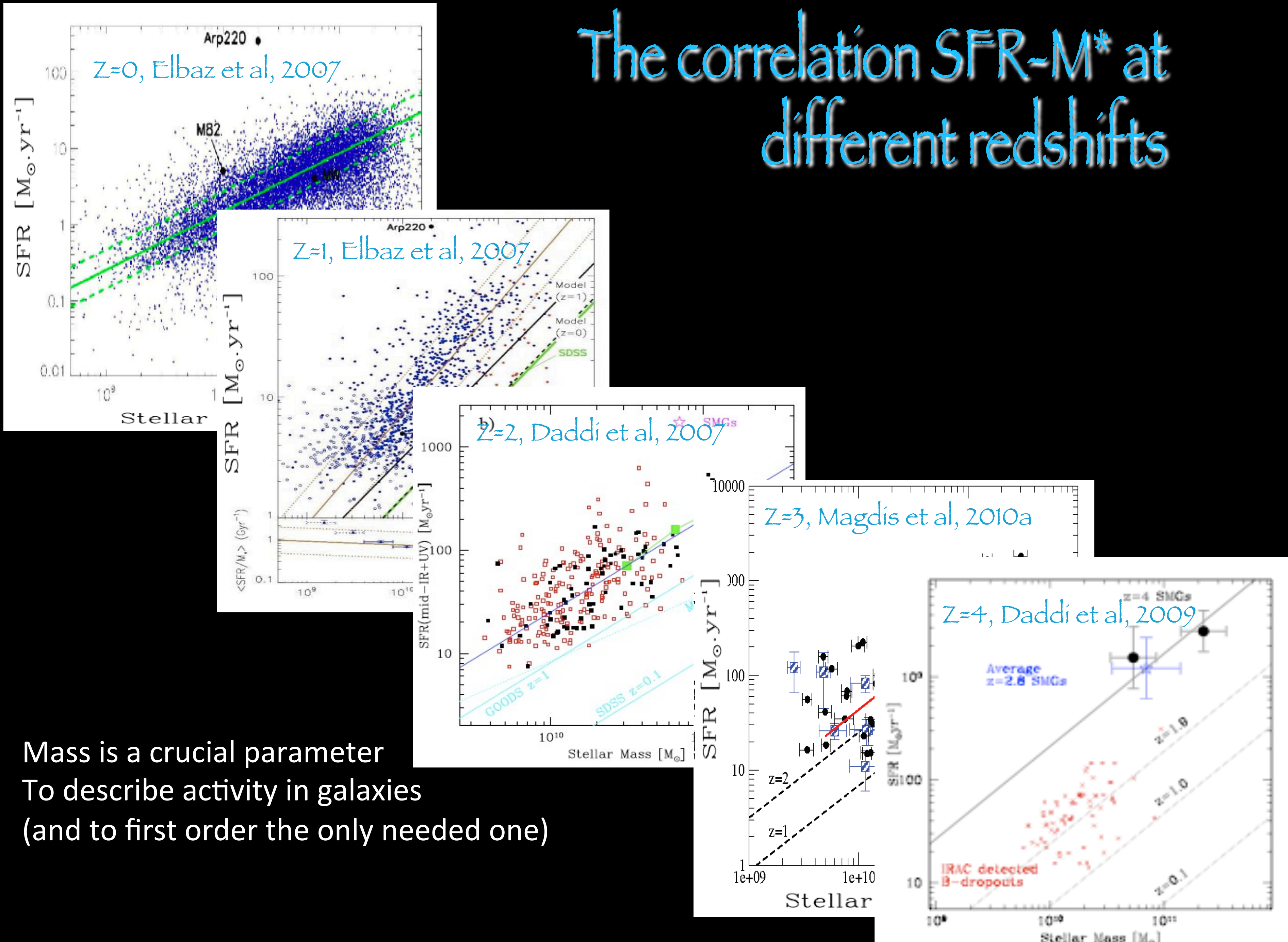



Rare overall but dominate LF at highest luminosities

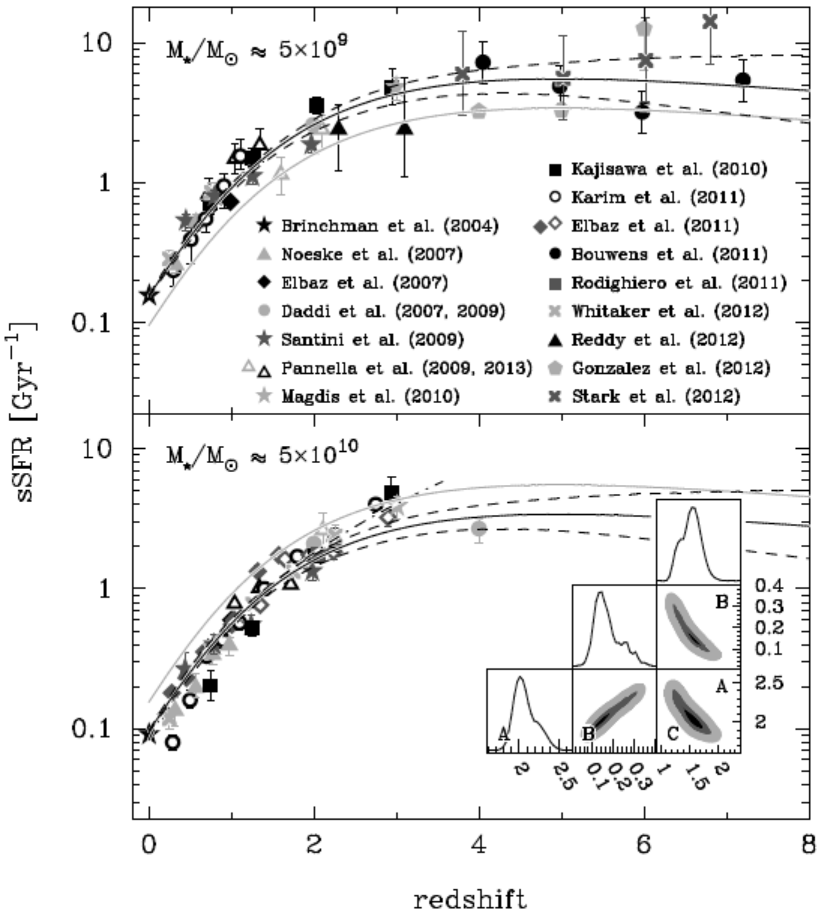
# Cosmic star formation history – which driver?



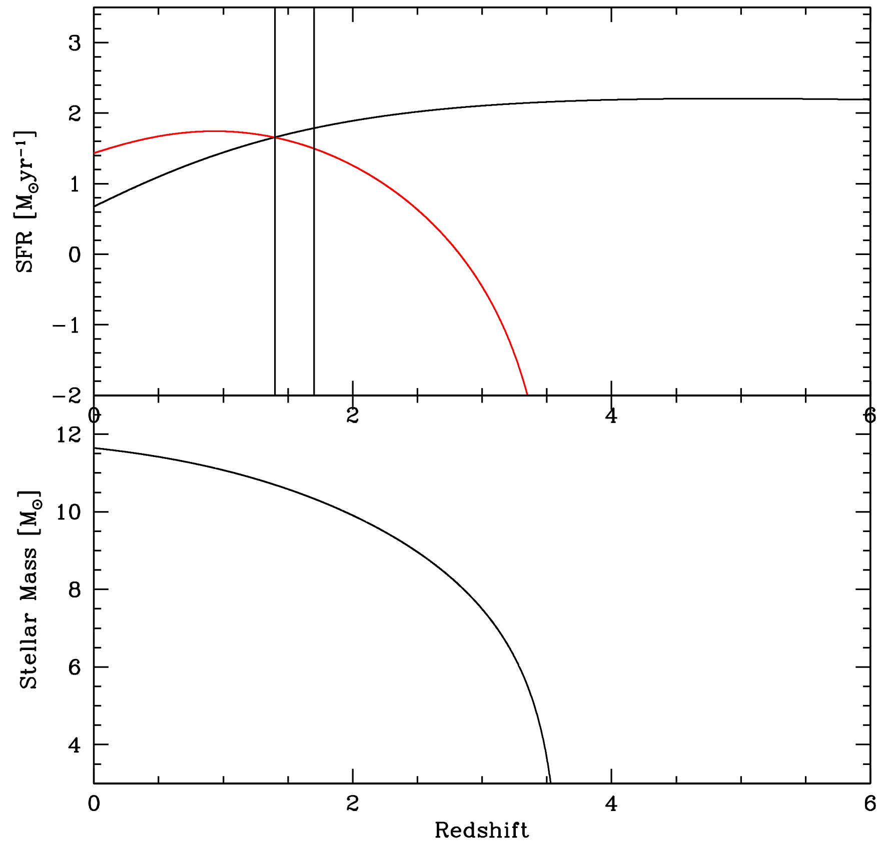
# The correlation SFR-M* at different redshifts




Mass is a crucial parameter
To describe activity in galaxies
(and to first order the only needed one)




sSFR history of the Universe




SFR history of a single galaxy and mass growth

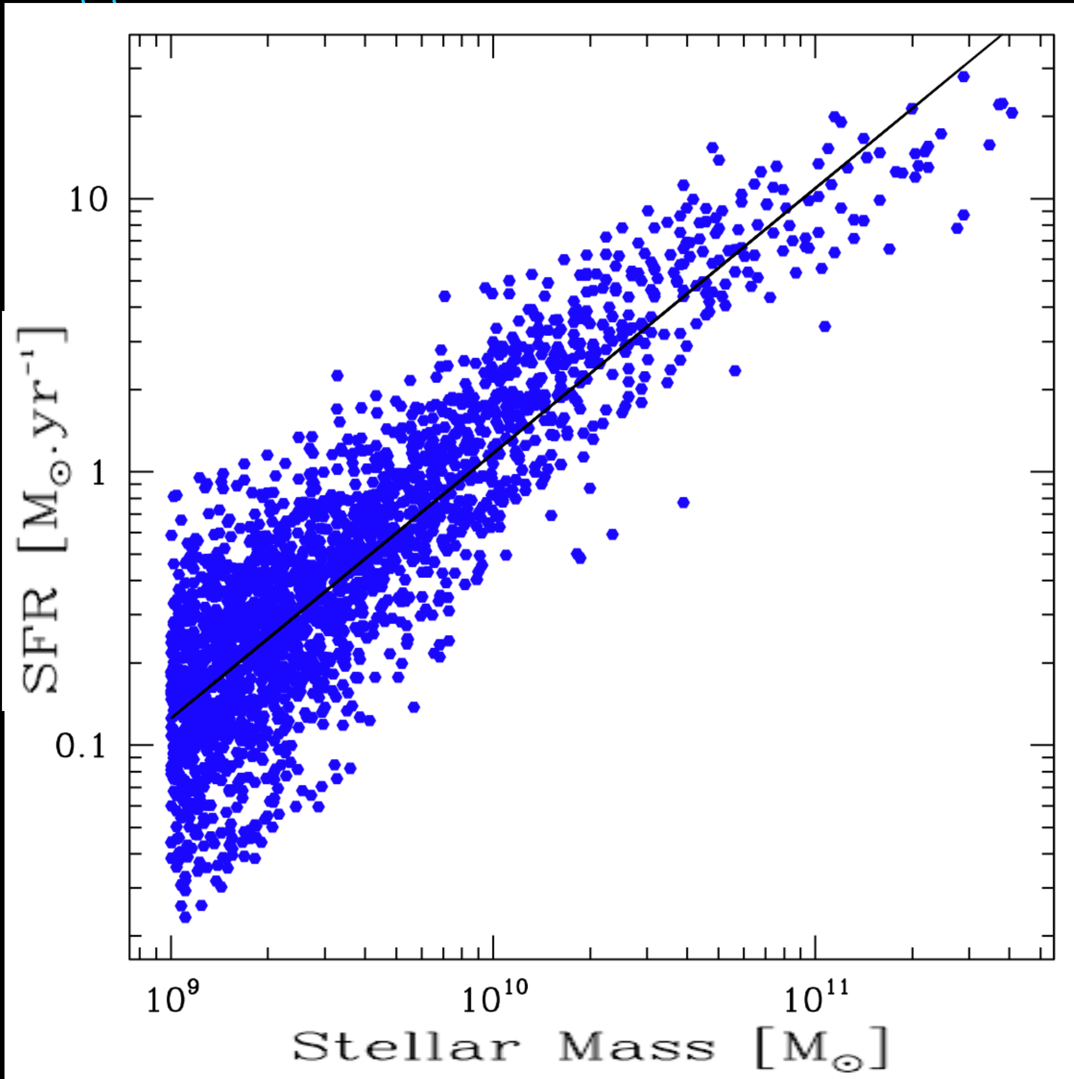
x2 dispersion in Main Sequence of SF galaxies → SF Histories are homogeneous

# Comparaison to simulations

- Scatter 0.26dex

Comparable to observations for disks

Oppenheimer and Davé, 2006 at z~1



Why the models predict a SFR propto M relation ?

Because it comes from the behaviour of the underlying DM
(Dekel et al 2013 in preparation)

### 3.2 Toy Model: Accretion

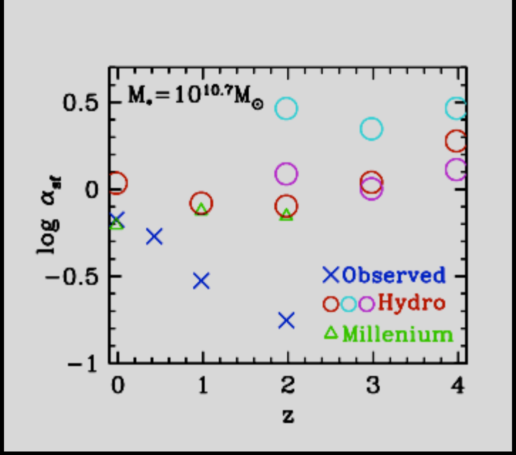
The average specific accretion rate of mass into halos of mass $M$ at $z$ can be approximated by an expression of the form

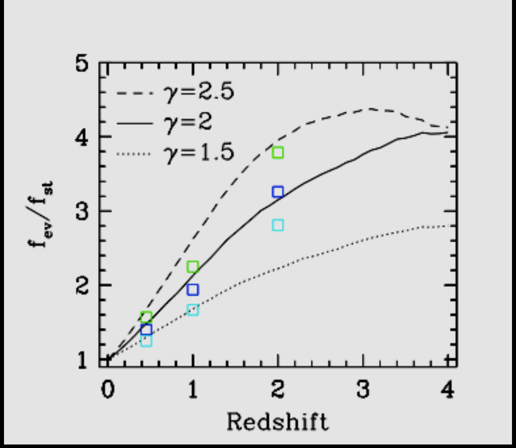
$$\frac{\dot{M}}{M} \simeq s M_{12}^{\beta} (1+z)^{\mu} \,. \tag{6}$$

In the EdS regime, $\mu \rightarrow 5/2$. As reported in §A, with $\beta = 0.14$ and the appropriate value of the normalization factor $s$, this approximation for the average of $M(z)$ was found to be good to better than 5% for $z > 1$ (it becomes an underestimate of $\sim 20\%$ at $z = 0$).

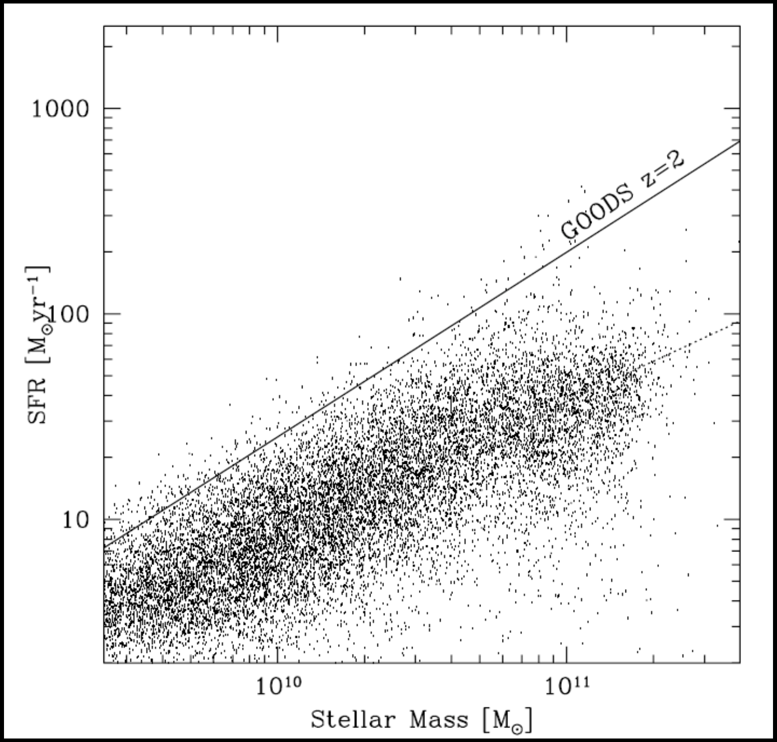
SFR-mass correlations were predicted by models before observations
But the rapid rise of LIR of galaxies up to z=2 is a problem for models

Dave 2007 ($\alpha$ = doubling time/$t_H$)




Kitzbichler & White2007

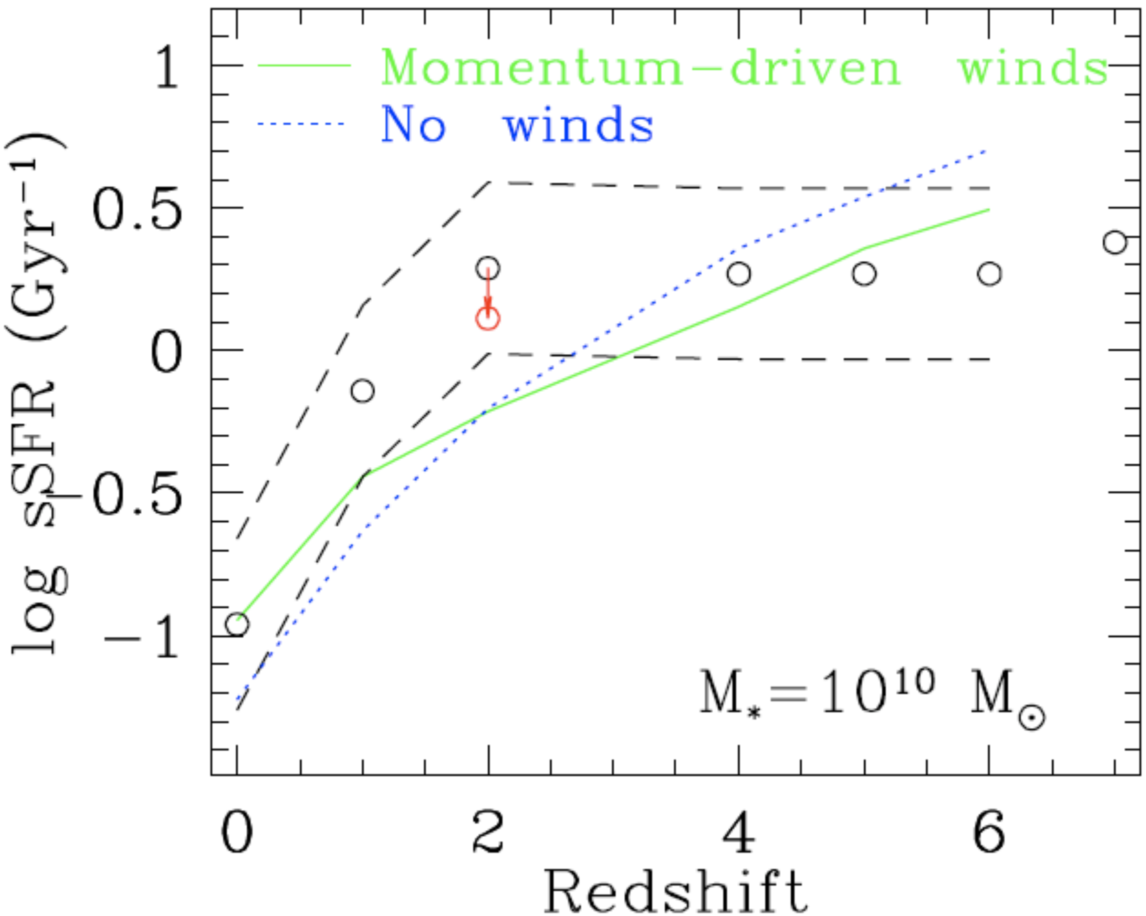



Requires a rapidly evolving IMF (see also Baugh 2005, etc)

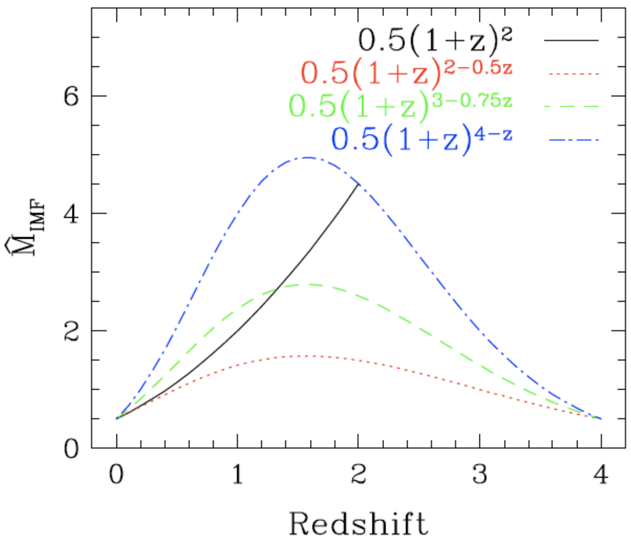
→the stars that made the IR background left nothing behind ?

→ test this issue with Mass-Function growth

# The puzzling cosmological evolution of SSFR



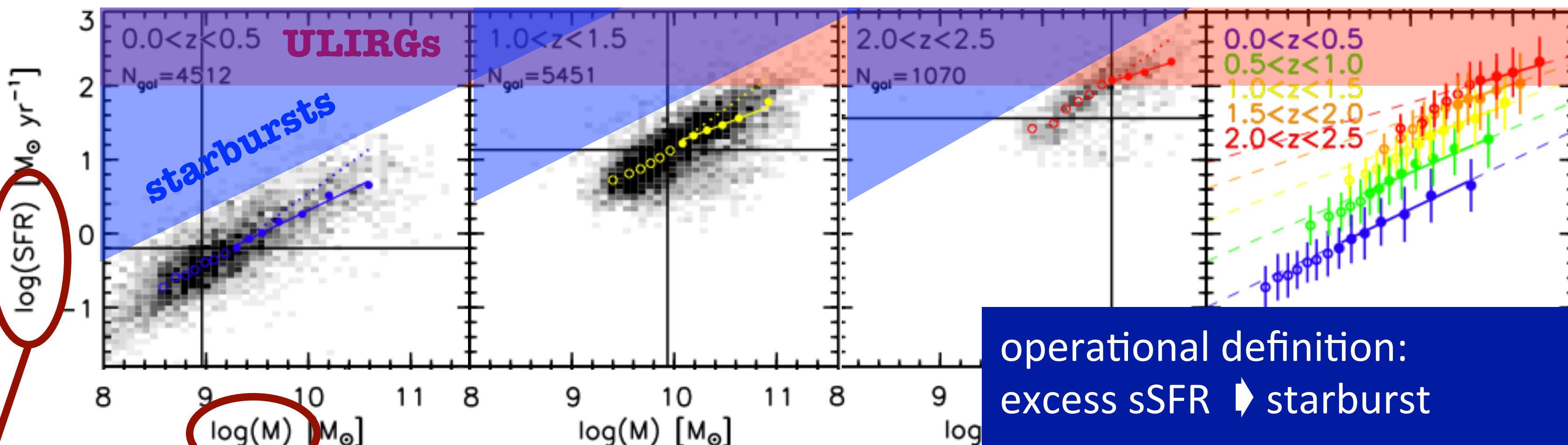

Dave et al 2010




Dekel et al. model: can do the rise to z=2, but cannot go down!

# Normal star-forming galaxies at high redshift (I)

MS at $z < 2.5$, apparent homogeneity of star-formation histories:



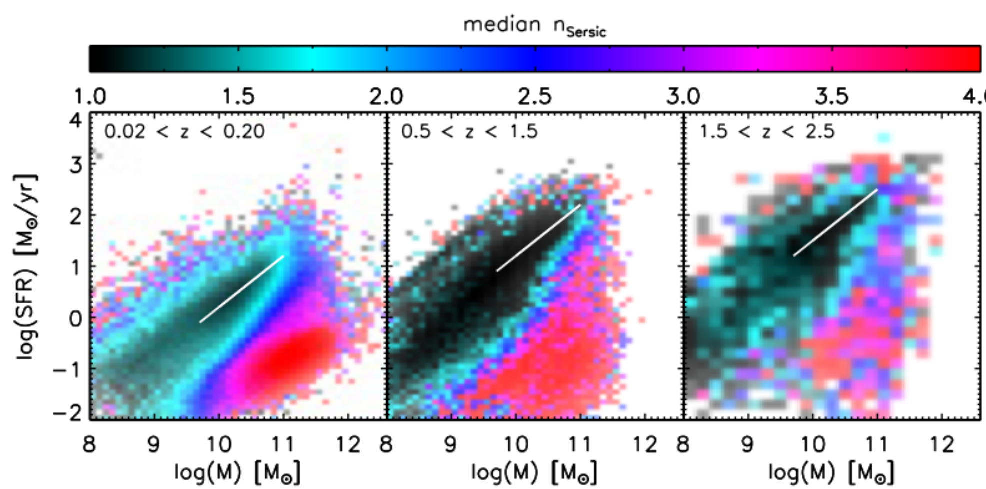

operational definition:
excess sSFR ➧ starburst

integral of past SFR

current SFR

sSFR the other crucial parameter
→ SF mode

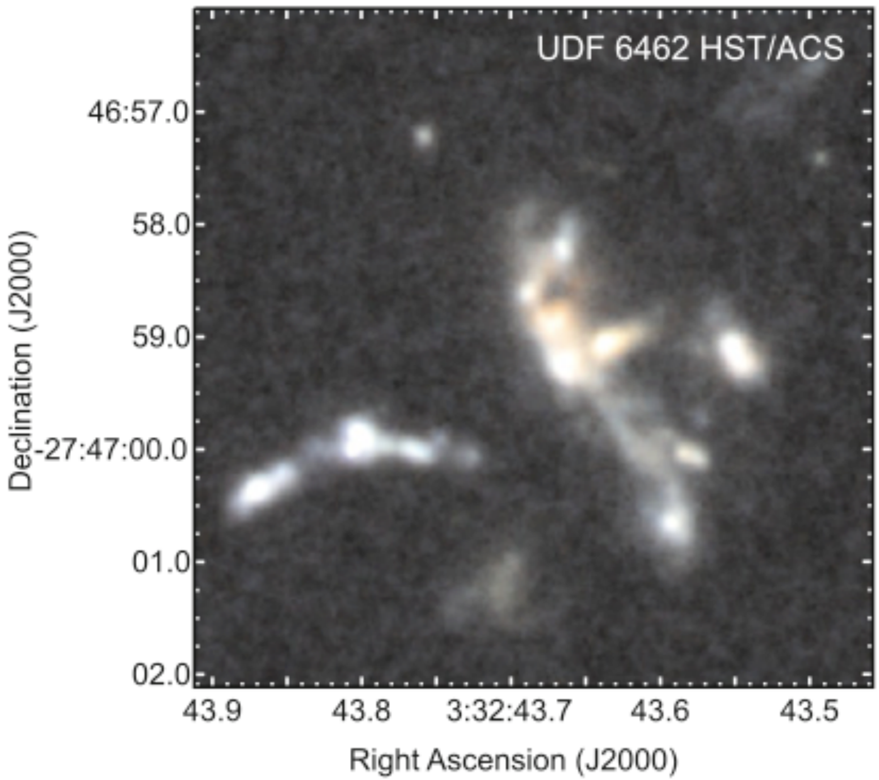
A sequence of exponential disks... (Wuyts+ '11; Salmi+ `12)



## Observational differences: Locally ULIRGs (mergers) vs spiral galaxies (disks)

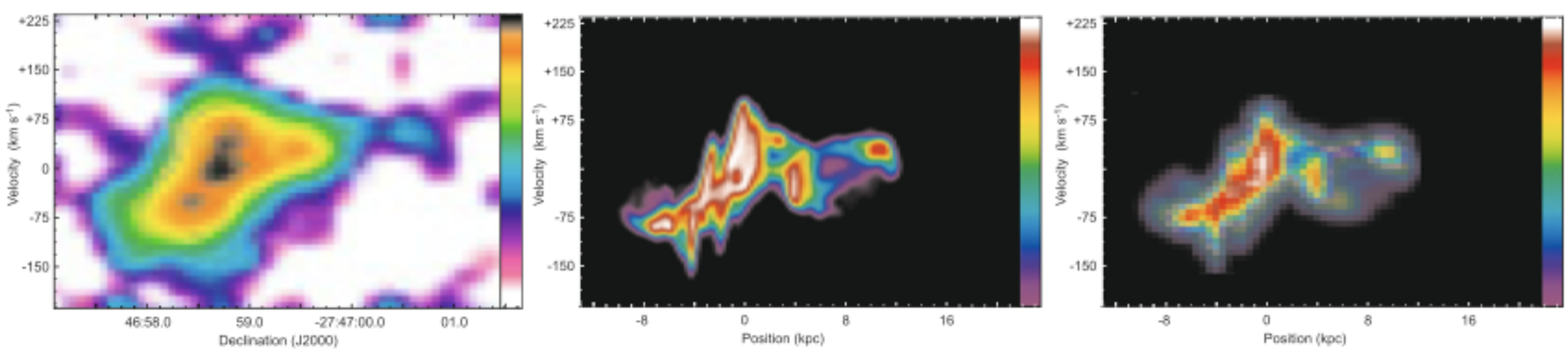
1) SSFR is higher in ULIRGs
2) (Dust temperature higher in ULIRGs)
3) ULIRGs are optically thick
4) ULIRGs are dynamically hot
5) Star formation efficiency SFR/LCO higher too
6) LCO/Mgas (conversion factor) higher
7) Excitation of CO emission higher

Here, one can apply the knowledge derived from studies of the local universe to understand the properties of galaxies at higher redshift.




Clumpy galaxies are
not necessarily mergers,
might be extremely rich
gas galaxies

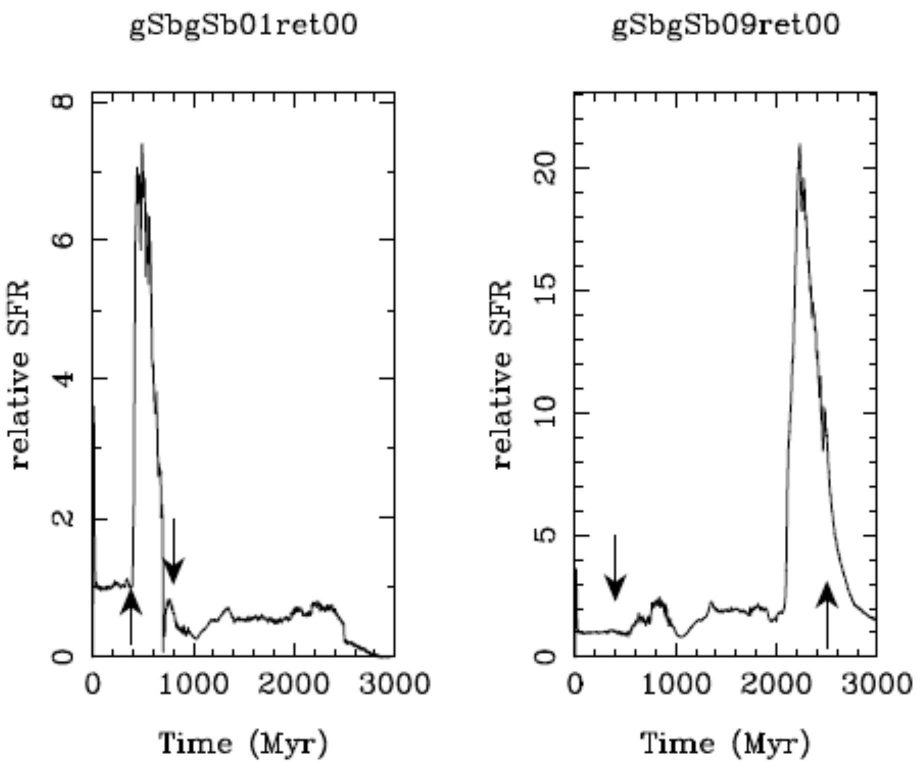
Bournaud, Daddi, et al 2008
z=1.57 BzK galaxy
UDF skywalker




See also works of Elmegreen et al., Genzel et al SINS spectroscopy

Framework: there are 2 ‘major’ SF modes for galaxy buildup: a ‘secular’/’ normal’ and a ‘starburst’

Definition (operational): starburst are the ‘excess SFR’ high-gas-density phase that *can* happen during mergers (or other events)



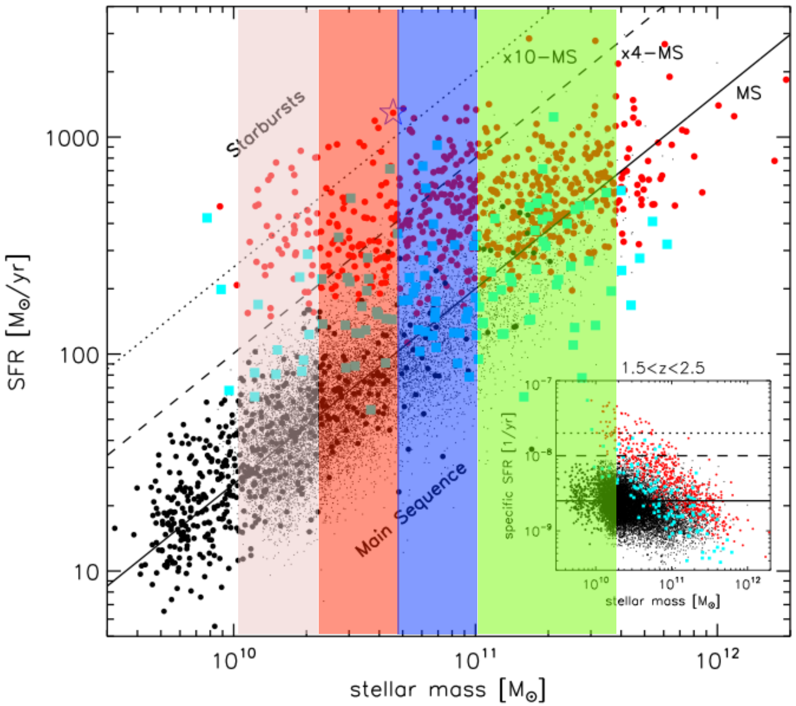

Di Matteo et al 2008
Martig & Bournaud 2008

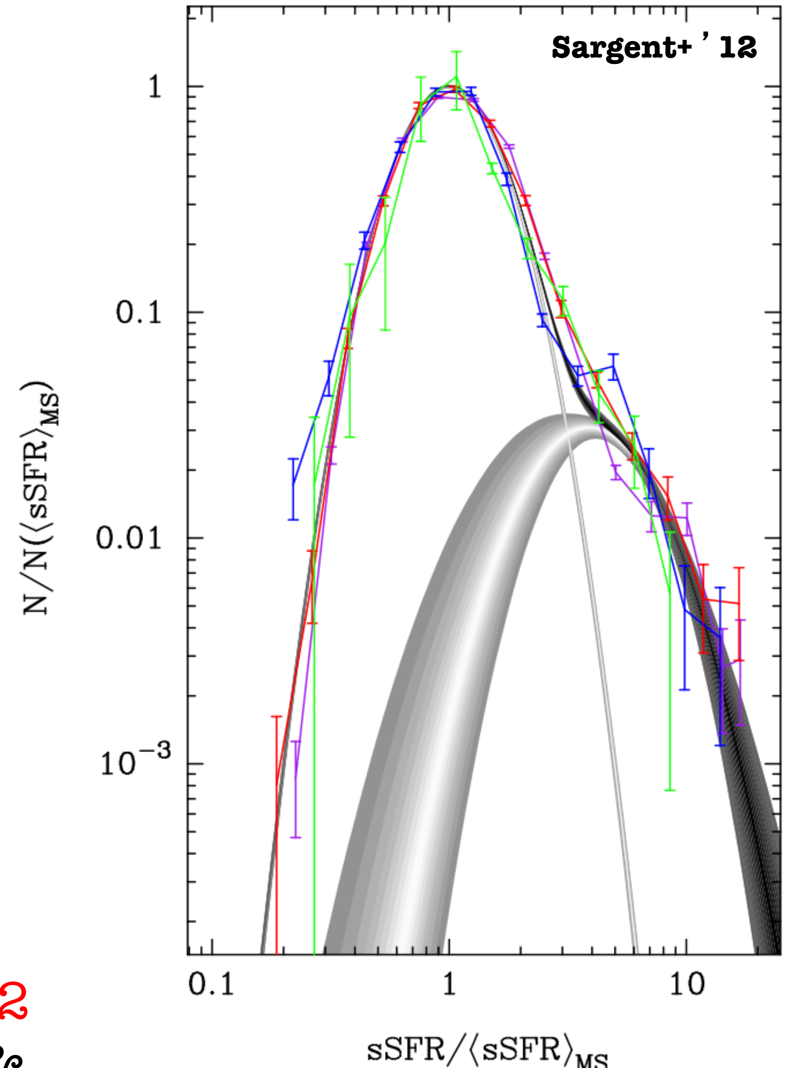
(Mihos & Hernquist 90’s)

- But does not happen in all mergers
- Even in mergers excess phase is short
- And in principle might be triggered by other instabilities ?

# Counting starbursts: the 2-SFM decomposition…

Distribution of (*massive*) star-forming galaxies at 1.5 < z < 2.5 w.r.t (s)SFR & $M_\star$ (Rodighiero+ '11):




Mass-invariant decomposition into 2 log-normal distributions ('normal' & starbursting galaxies, resp.).
(notice no MS in FIR selected samples )

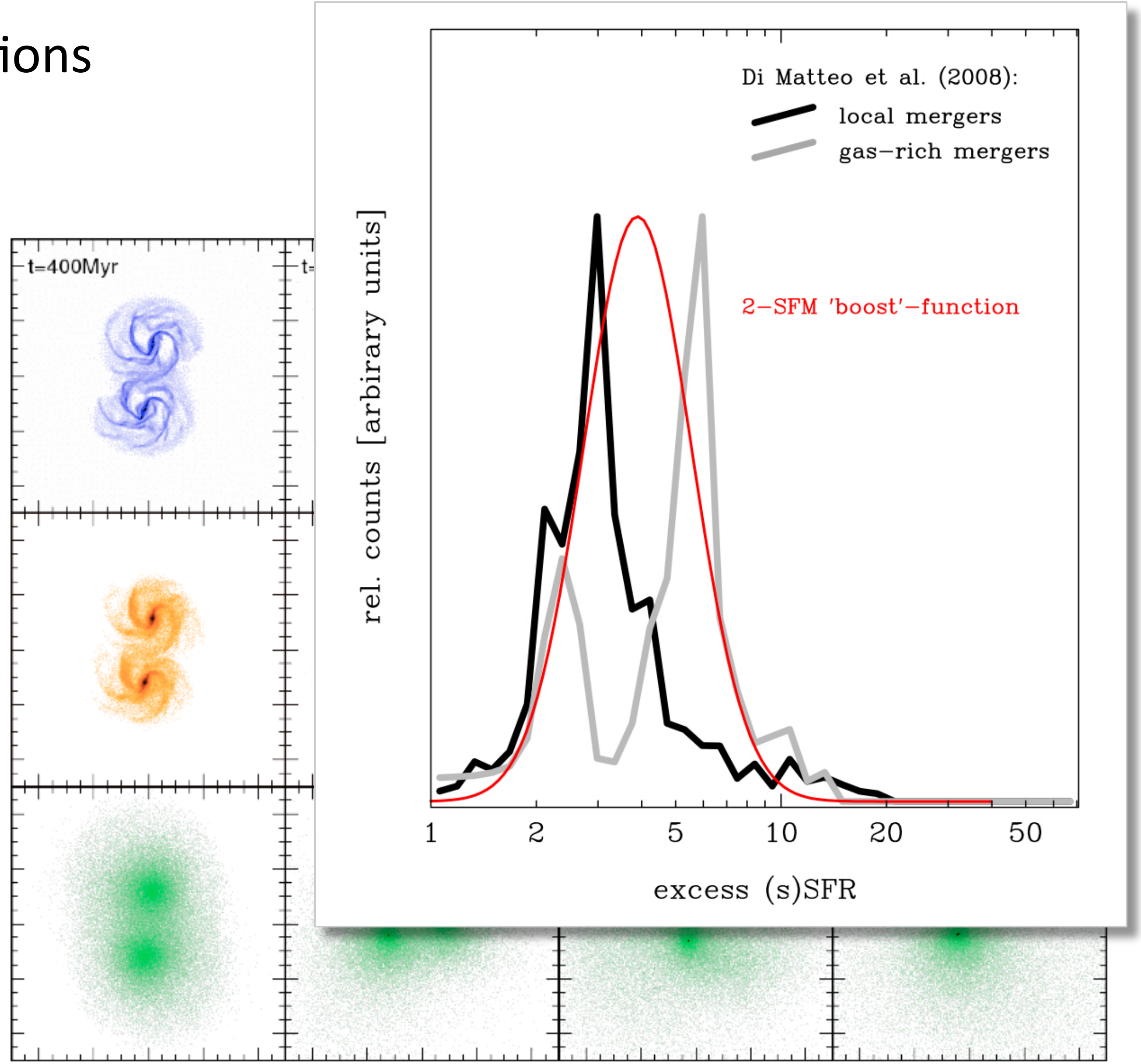
# Merger-simulations

Di Matteo+ ’07:
*retrograde* merger
of 2 Sbc galaxies
at $z$=0

gas ➽

stars ➽

dark matter ➽



# Cause(s) & effect: Interpreting the decomposition…

A snapshop at z ~ 2, prior to measuring (s)SFR distributions…

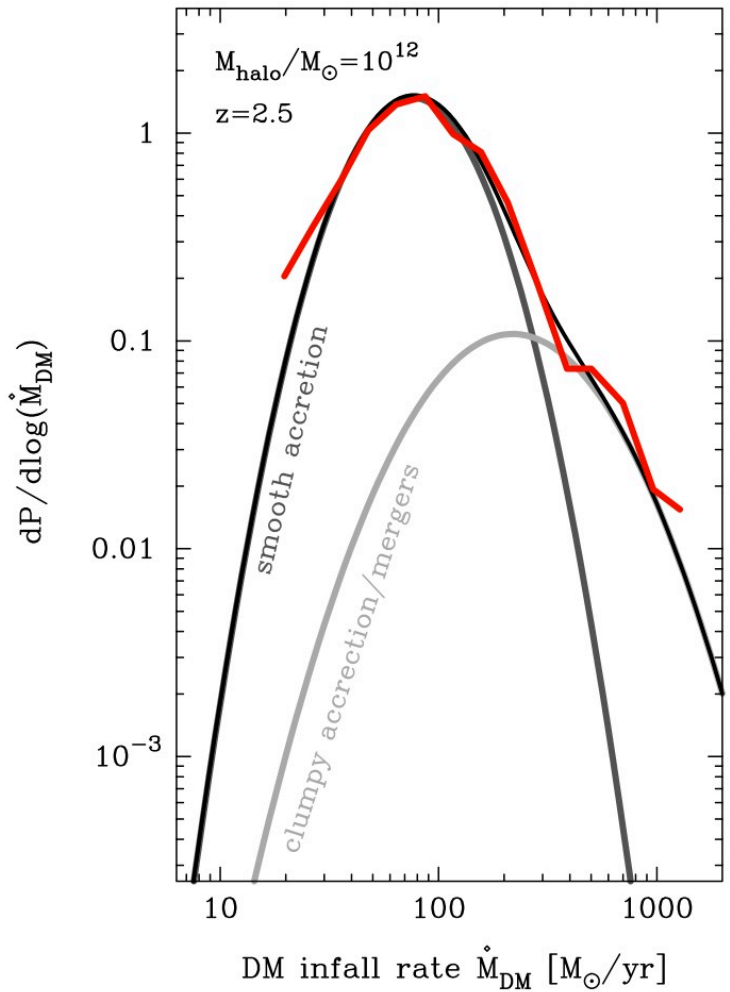
Dark matter accretion spectrum in cosmological simulations (Dekel+ '09; Goerdt+, in prep.):

- smooth accretion

  ➽ ***main-sequence activity?***

- clumpy accretion with major mergers in high-$\dot{M}_{DM}$ tail

  ➽ ***starbursts?***

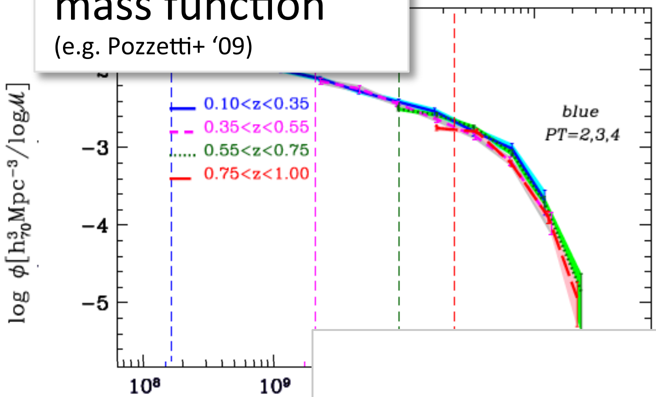


# The ‘2-SFM’ framework – bare necessities

1)

mass function

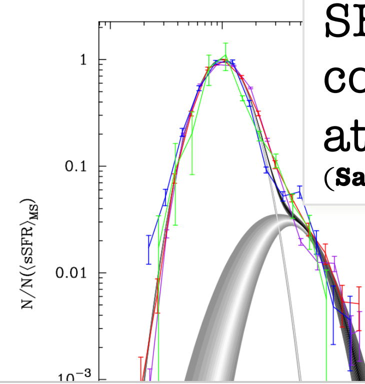
(e.g. Pozzetti+ ‘09)




2)

SB+MS de-composition at fixed $M_\star$

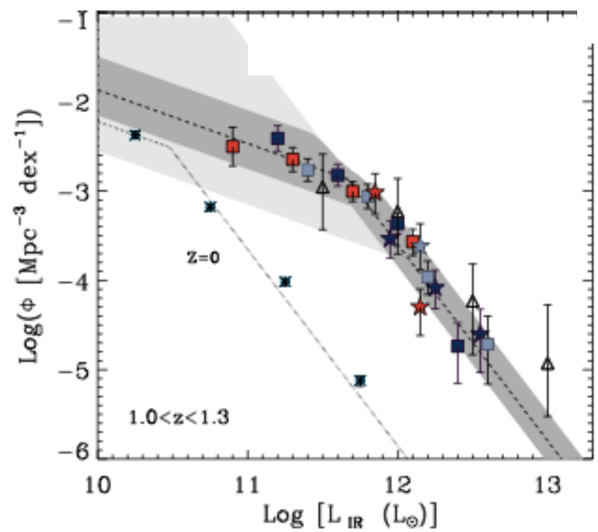
(**Sargent**+ ‘12)




SFR-distribution…

… or IR luminosity function (LF)

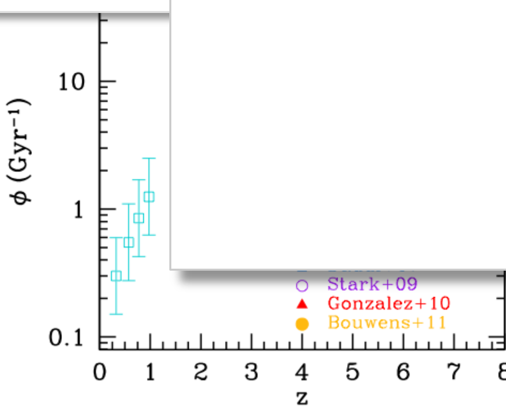
(e.g. Magnelli+ ‘09)




3)

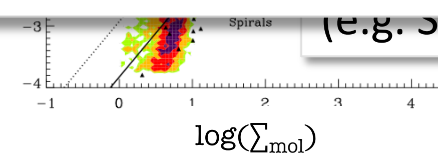
sSFR evolution

(e.g. Reddy+ ‘12)

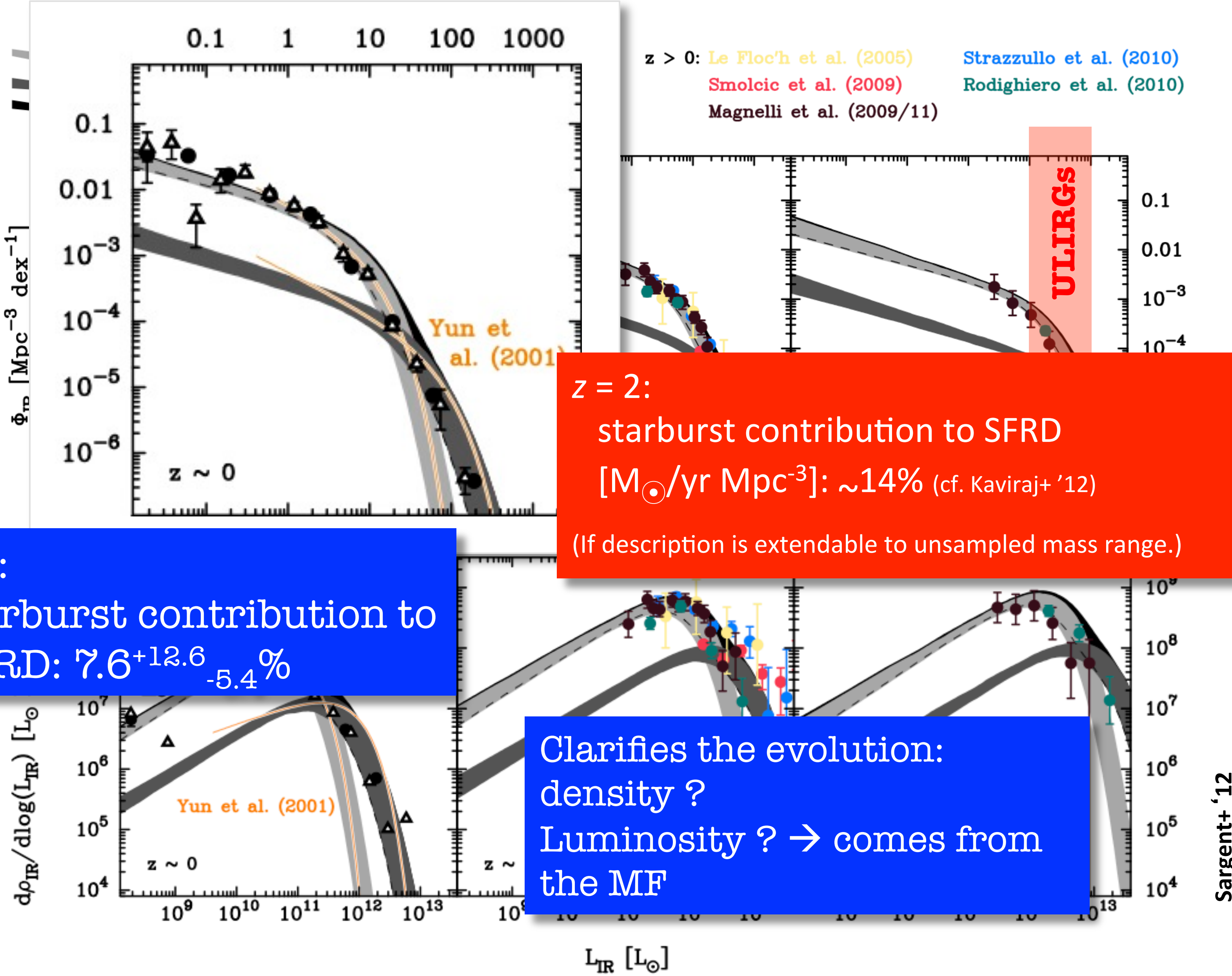



FE

(e.g. S-K law)



# IR LF: 2-SFM predictions vs. observations



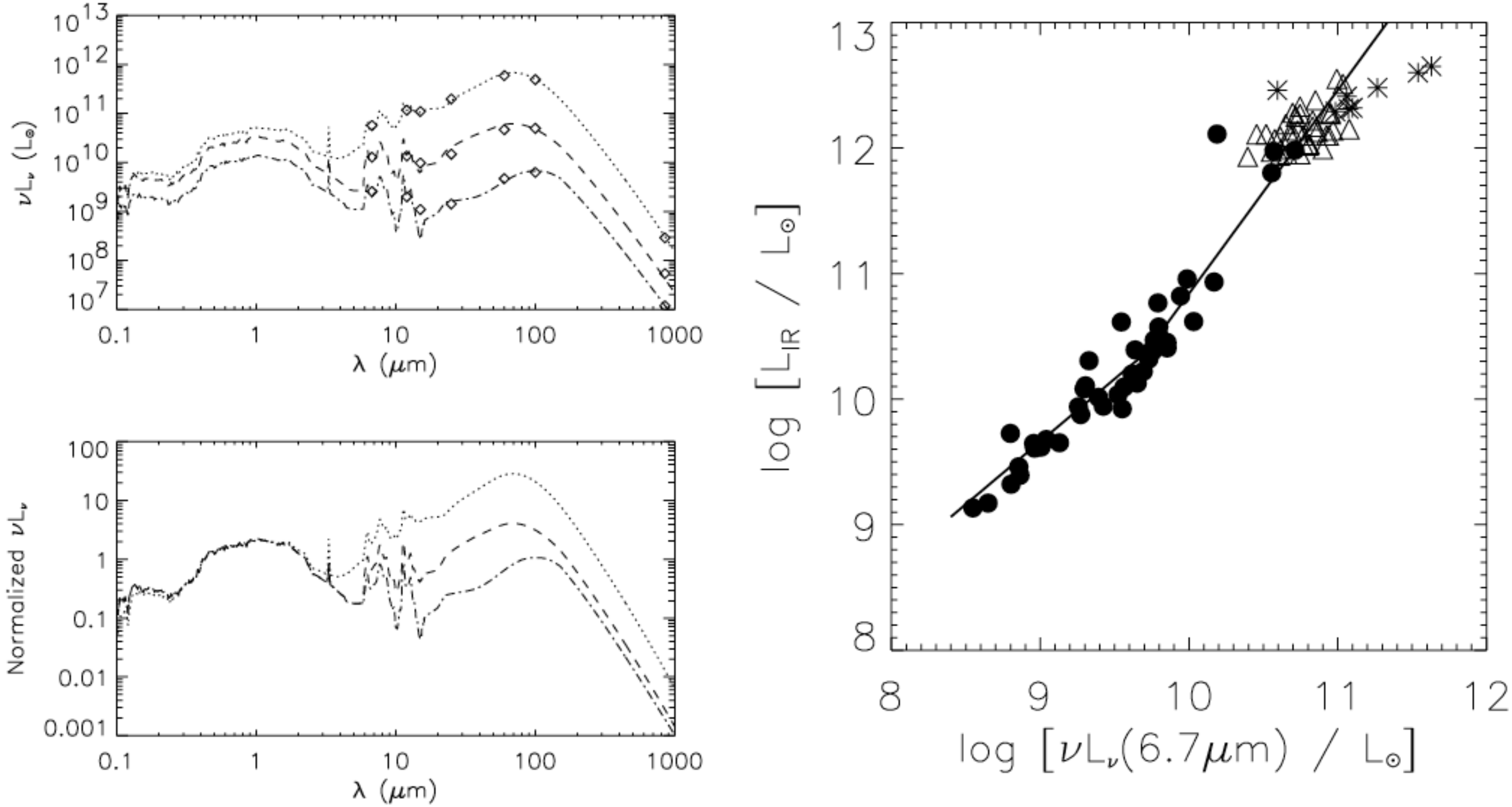

*z* = 2:
starburst contribution to SFRD [$M_\odot$/yr Mpc$^{-3}$]: ~14% (cf. Kaviraj+ '12)

(If description is extendable to unsampled mass range.)

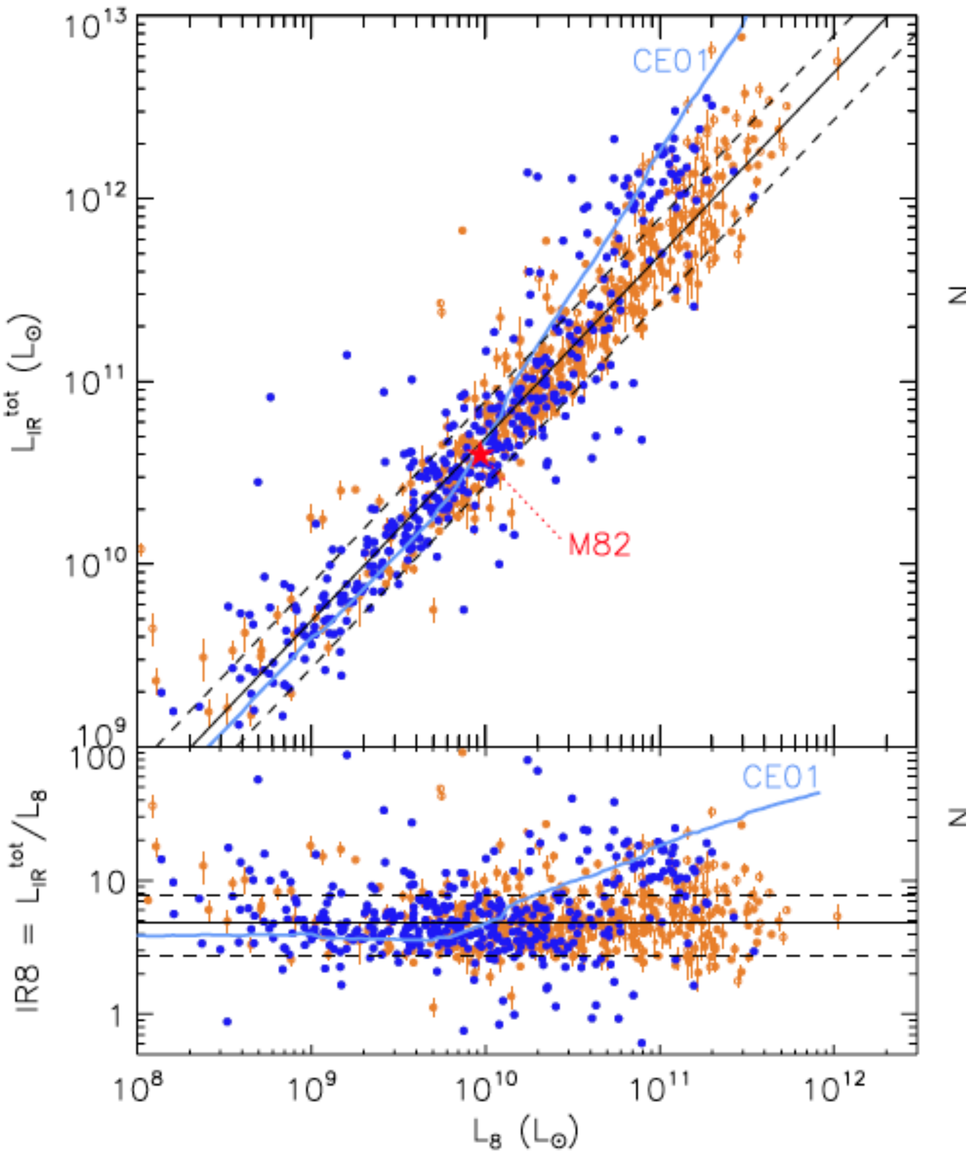
*z* = 0:
starburst contribution to SFRD: $7.6^{+12.6}_{-5.4}$%

Clarifies the evolution:
density ?
Luminosity ? → comes from the MF

Infrared- spectral energy distributions:
Old view: luminosity-dependent LIR SEDs




Chary & Elbaz 2001



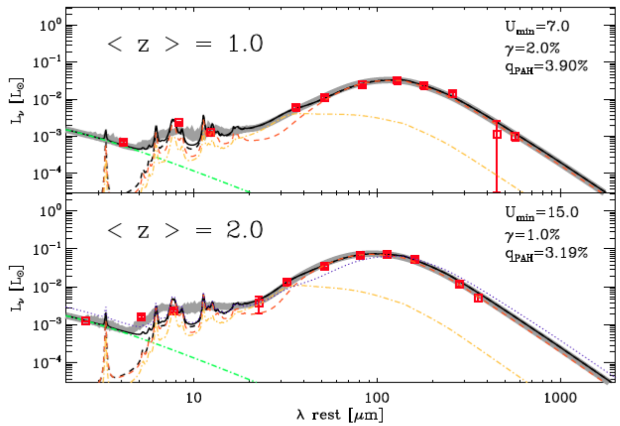

IR shape from mid-IR to
IR-bolometric is actually invariant,
But starbursts are different

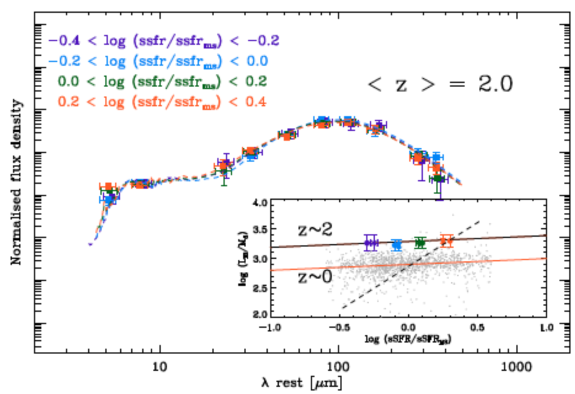
→ IR8 also defines MS galaxies

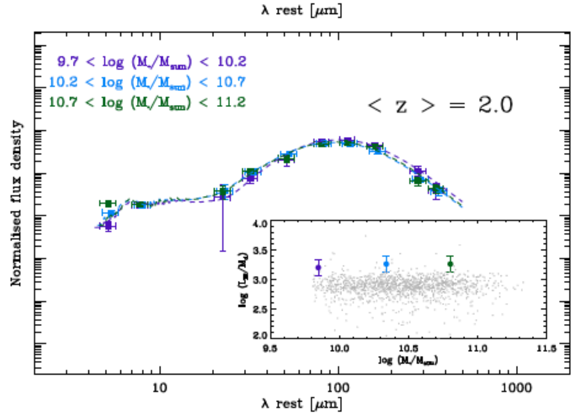
Elbaz et al 2011

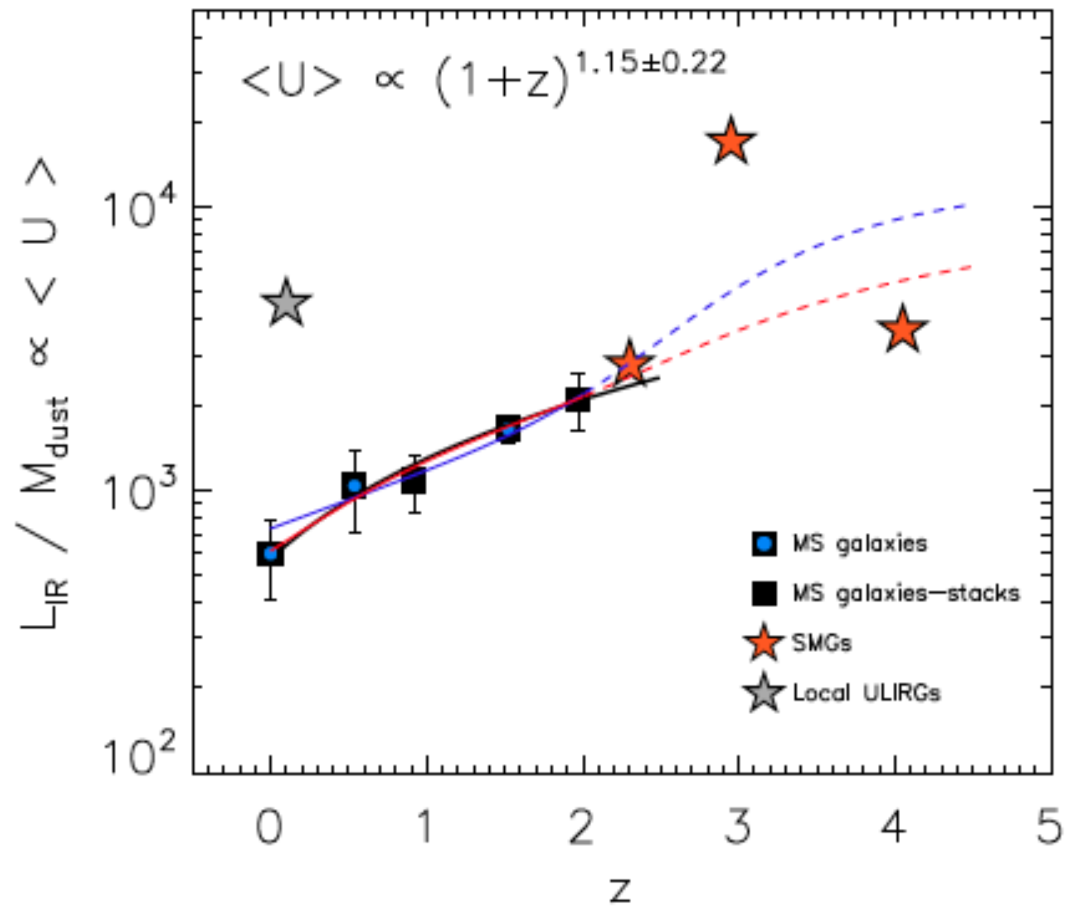
SEDs, Mdust … and Mgas (Magdis et al 2012)
Spitzer+Herschel(PACS/SPIRE)+Laboca+AzTEC

U ~ LIR/Md ~ SFE/Z



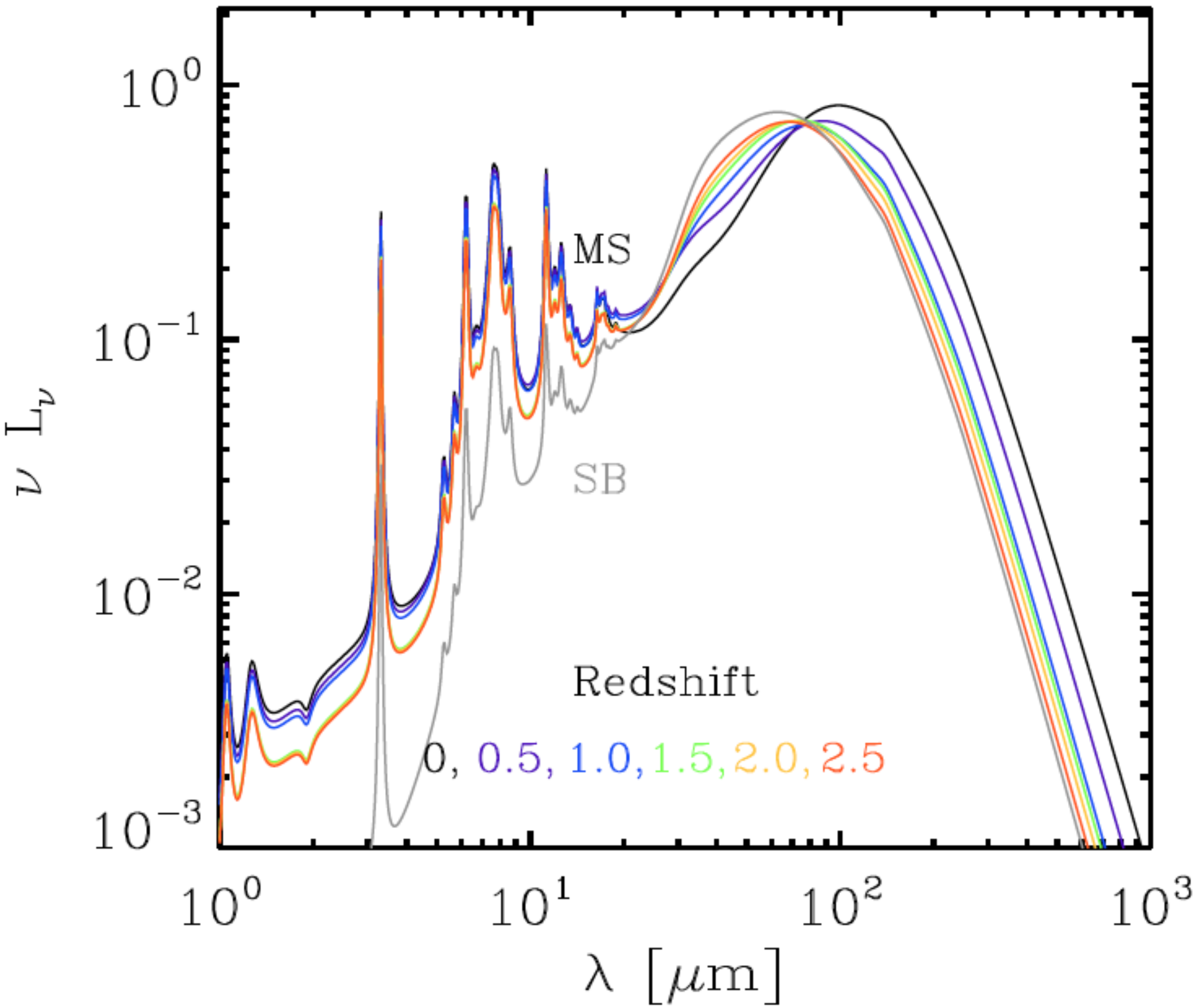



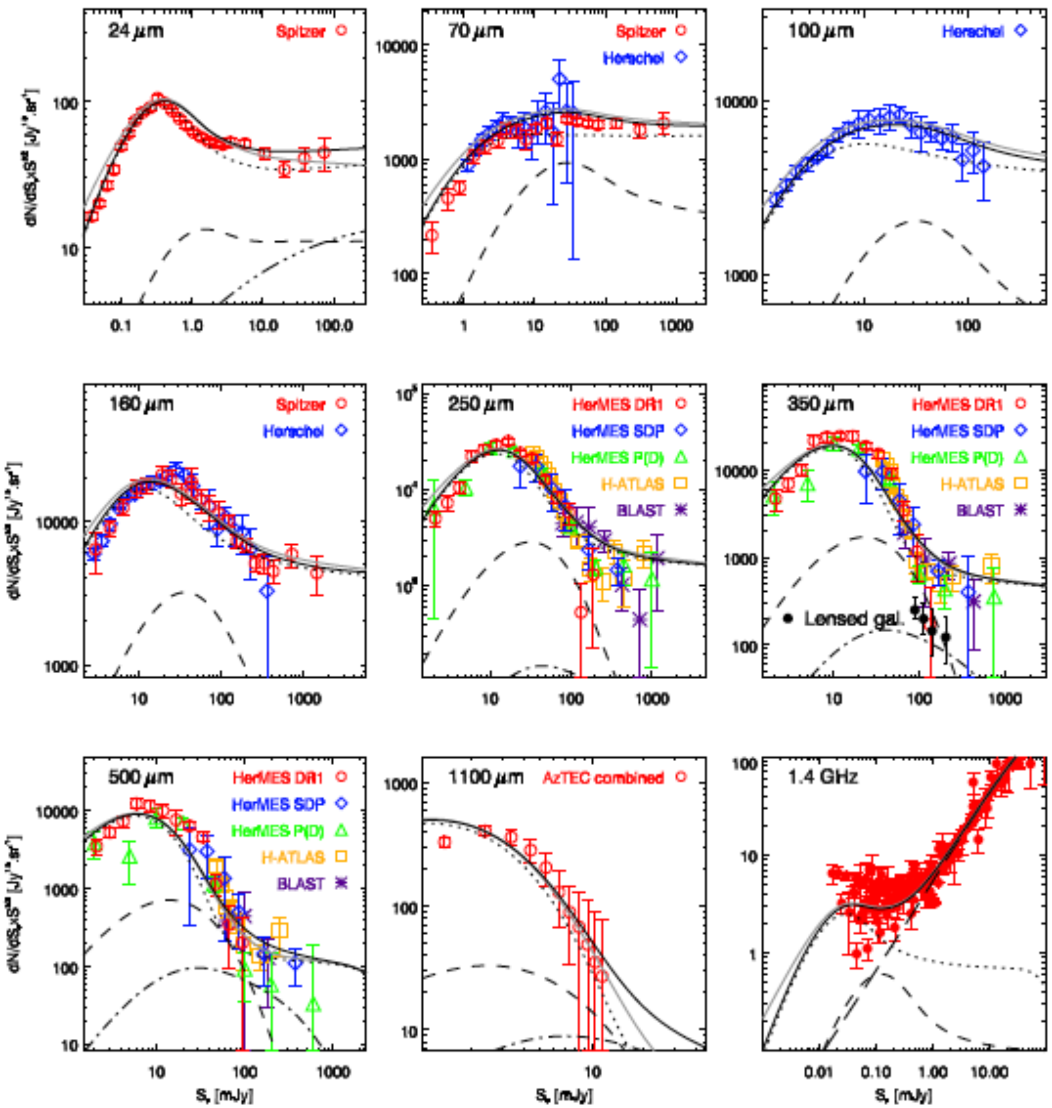

z~2 MS galaxies are warmer than z=0 MS galaxies
But they can be ULIRGs,  colder than z=0 ULIRGs
→ If you do cosmic evolution of "something" need to care what you are looking at (notice SBs are more luminous)

New redshift-dependent template SEDs for MS galaxies (Magdis et al 2012)

Only <U>==T is evolving



# A parameter-less prediction of IR galaxy counts (Bethermin et al 2012)

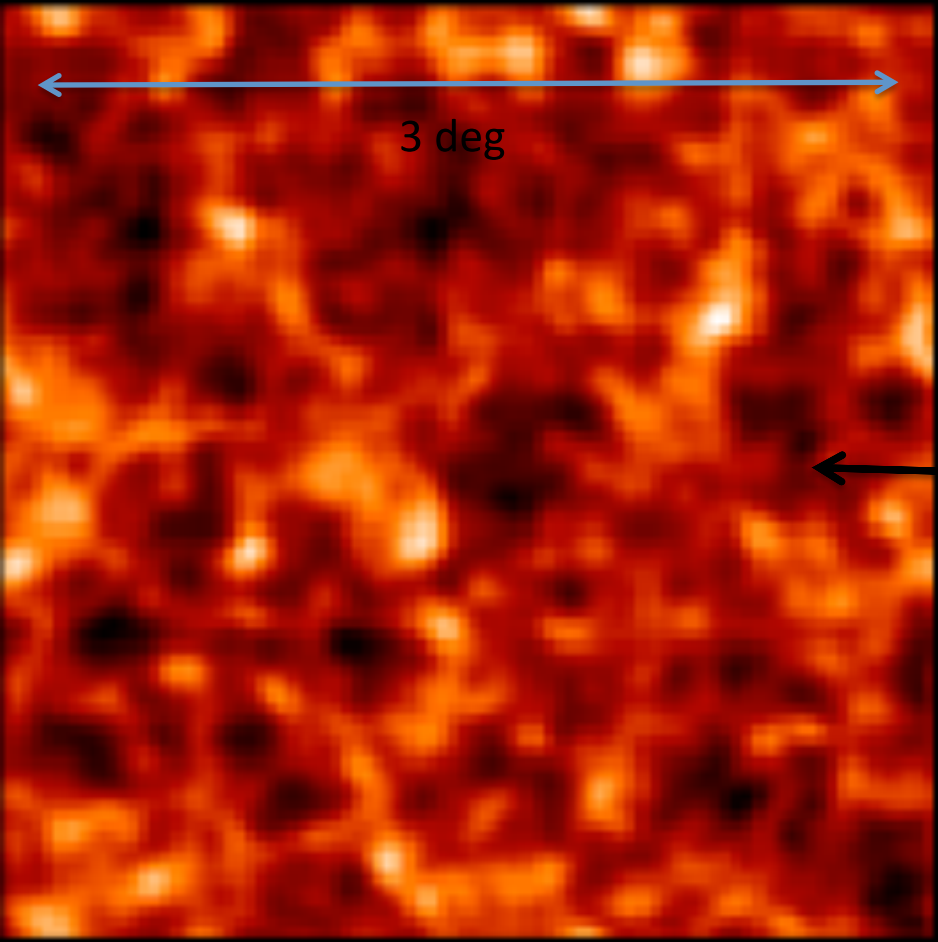



No free parameters here,
Only using external constraints

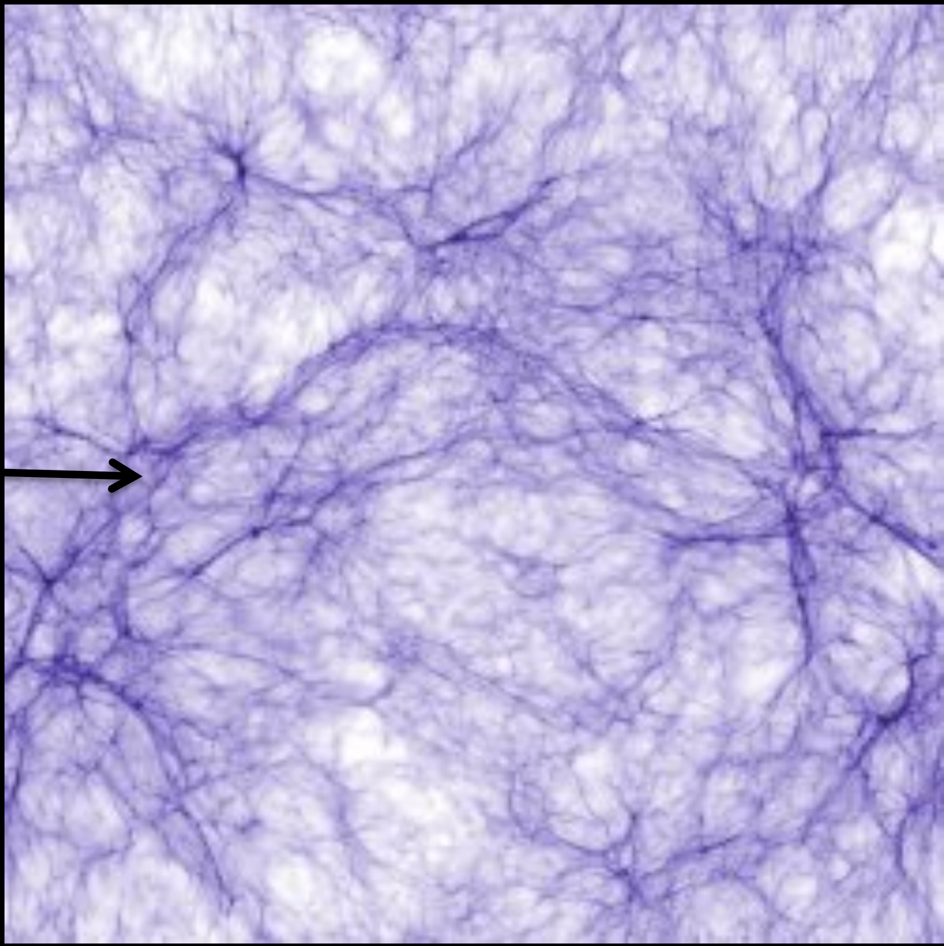
LFs (MS vs SB)
SEDs
+AGN, lensing

Notice how even at 1.1mm at bright fluxes, SBs do not dominate in this model (not a strong conclusion as it depends on not well constrained SEDs)

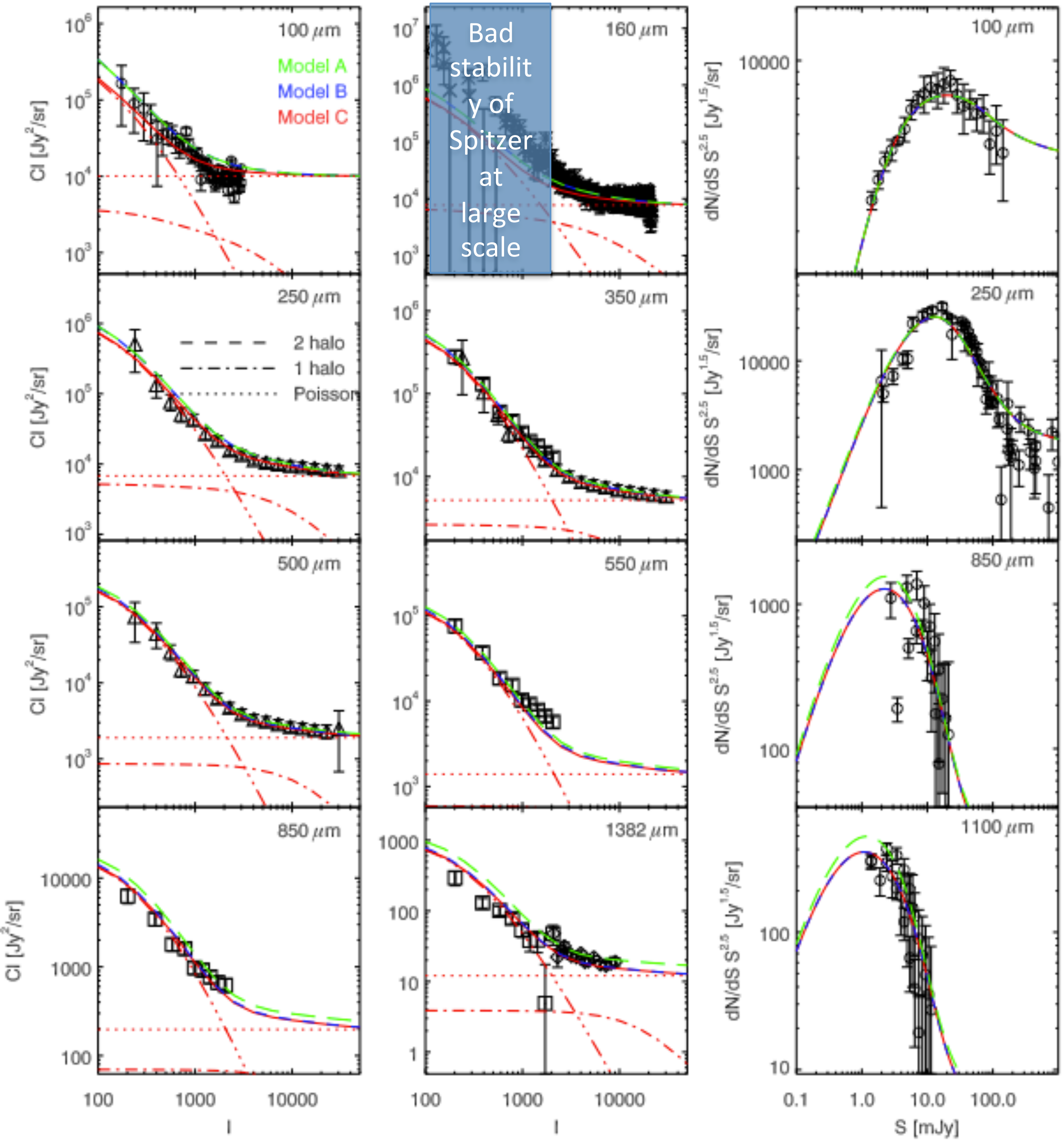
# FLUCTUATION OF THE COSMIC INFRARED BACKGROUND




Fluctuations of the cosmic infrared background (Planck collaboration et al.)



Simulation of large scale structures (Pichon, Teyssier)




# ANISOTROPIES OF THE CIB

**Model A:**
Fiducial model

**Model B:**
Lowest density, high sSFR

**Model C:**
Lowest density, high, sSFR +no star-formation around passive central galaxies

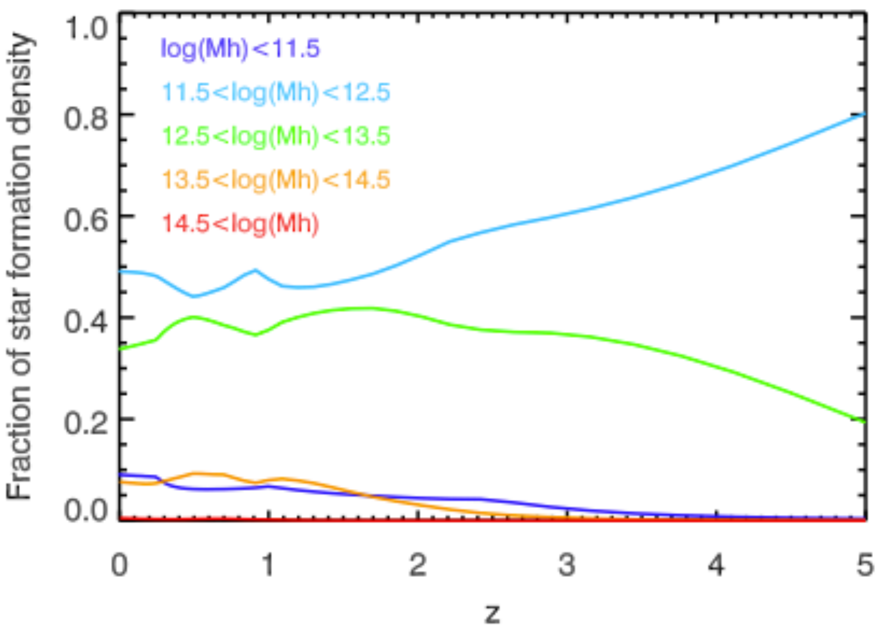
Check also with SPIRE cross power spectra, ACTxSPIRE, Planck CIBxlensing, clustering of PACS detected sources

CIB power spectrum and galaxy counts (Bethermin+13)

# STAR FORMATION HISTORY and HOST halos

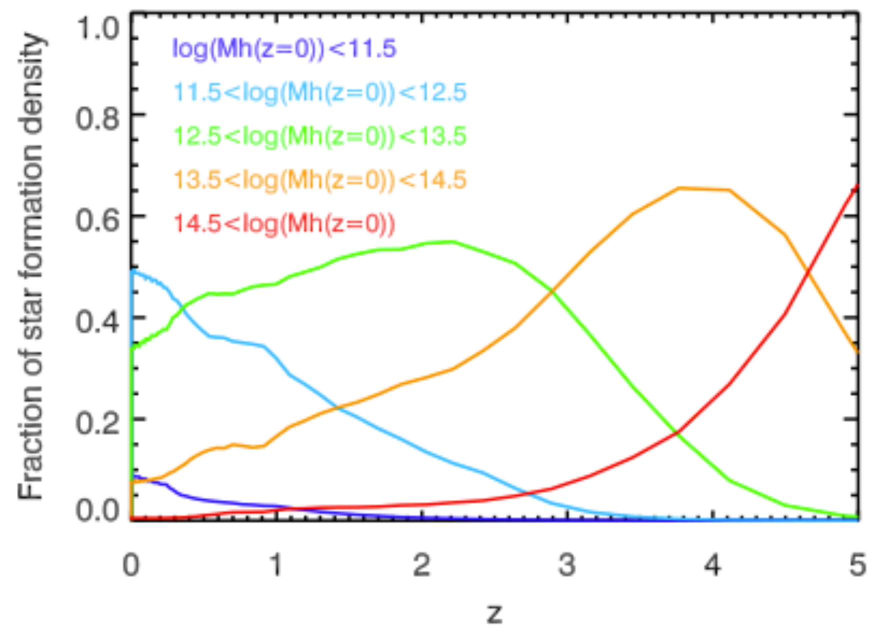
IF YOU WANT TO SEE AN UNIVERSALITY:

Instantaneous halo mass




IF YOU WANT TO SEE A DOWNSIZING:

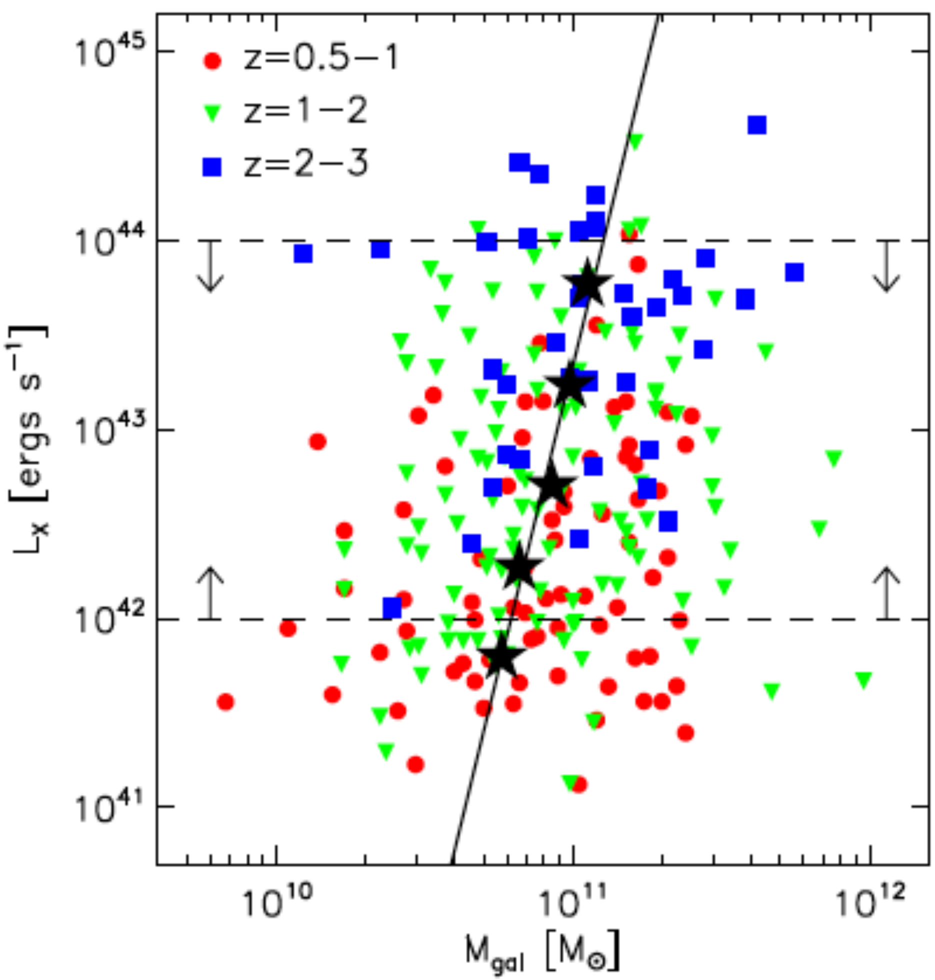
mass at z=0




Relative contribution of various halo masses as a function of redshift (Bethermin+13)

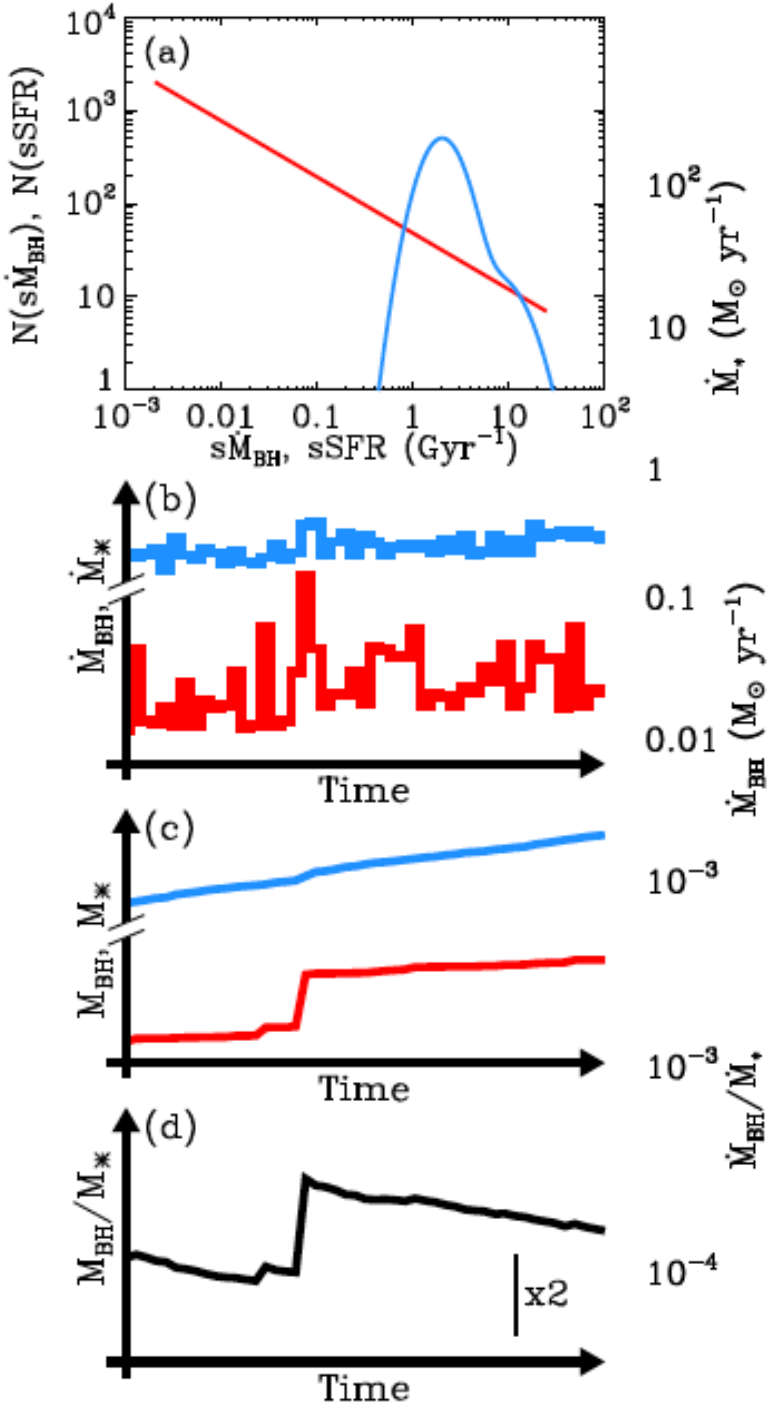
SFR → building stellar mass
Lx → BH accretion rate → Building BH mass

MBH versus M* correlation locally, the processes must be related




Is there an analogous of the M*/SFR correlation for BHs ?

Mullaney et al 2012a:
Apparently not




# AGN evolution

Doing ensemble averages (→ time averages)
The picture clears up for AGNs

Mullaney et al 2012b

Strongly suggest that BH and galaxy do grow
Together, and MBH/Mgalaxy is ~constant at the
Same ratio of today through formation epoch

←
There is a Main Sequence also for AGNs!
(when eliminating short-time fluctuations)

Level is ~ Magorrian

Gas reservoir regulating both SFR/AGN activity

# Summary

The Main Sequence (MS) paradigm

Rising star formation histories and homogeneity

Starbursts as outliers to MS, merging powered (?)

Relation to theory (positive and negative)

2 star formation mode framework

double Gaussian decomposition of sSFR, mass and redshift invariant

IR/radio counts prediction (no parameter)

CIB power spectrum prediction (no parameter)

Dust temperature/SED evolution for MS and SBs

The hidden AGN Main Sequence

# Star formation and molecular gas in the distant Universe in the 2 SF-mode framework:

# Part II: gas content and ALMA

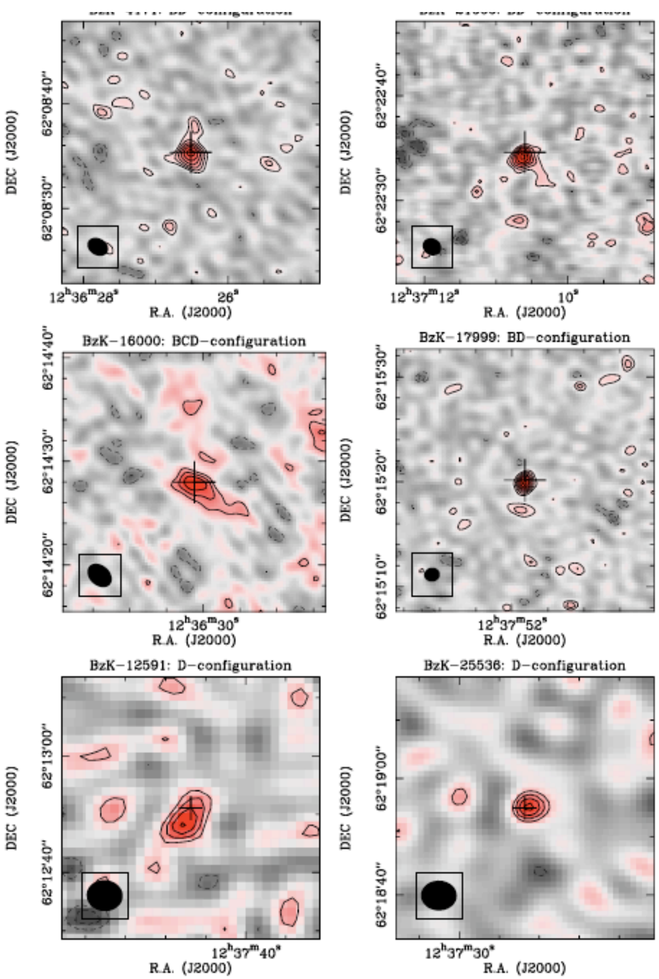
E. Daddi (CEA Saclay)

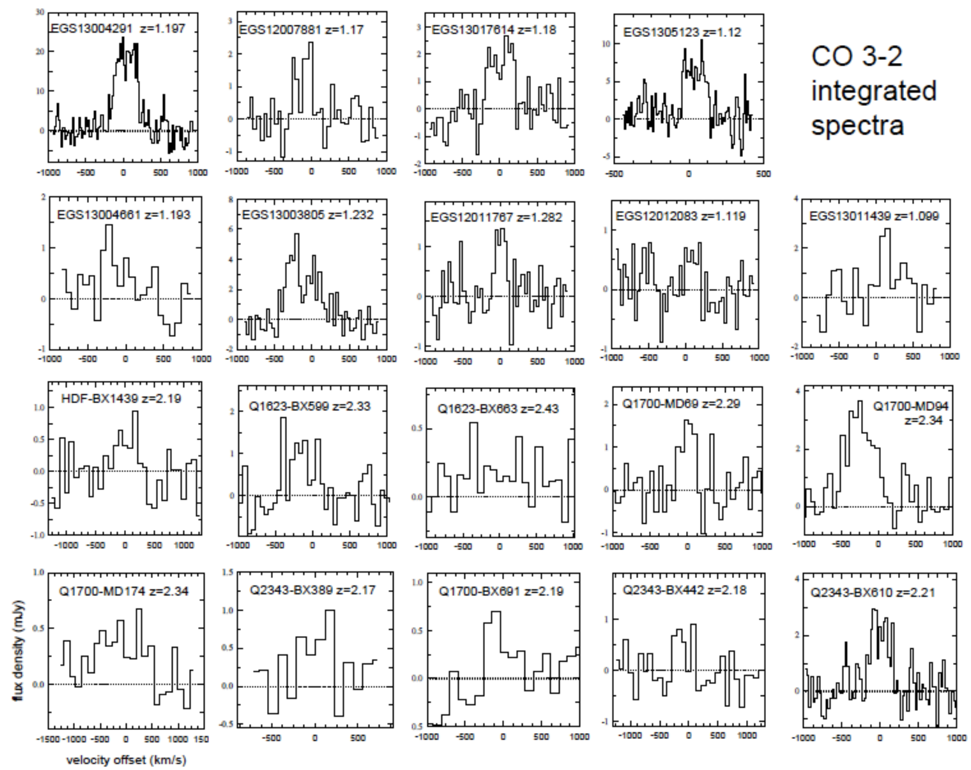
Asiago PhD school June 2013

European Research Council

Irfu cea

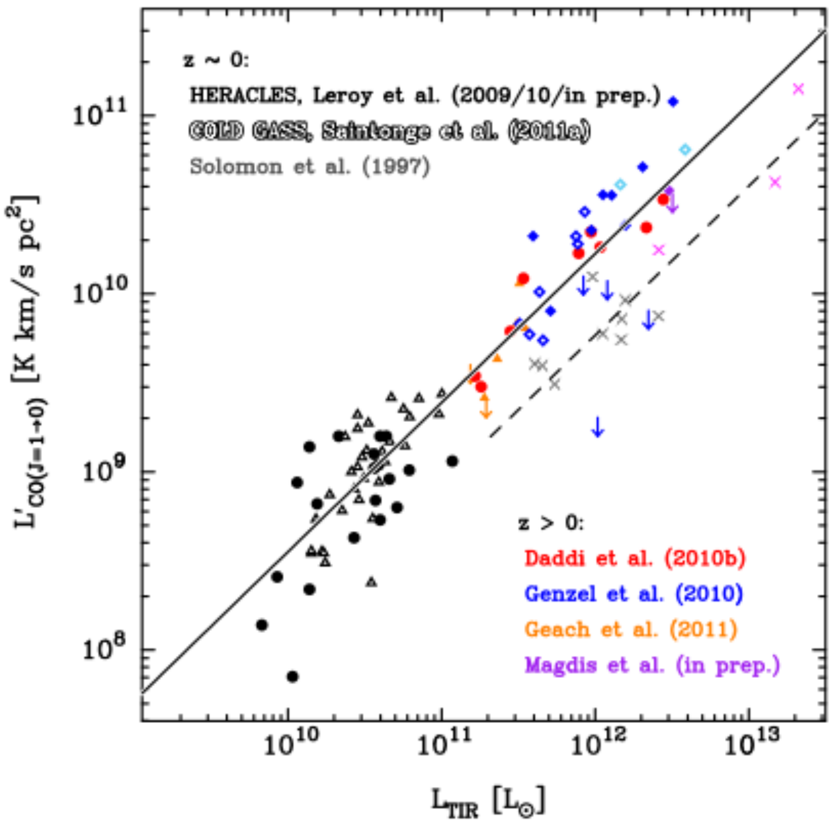
Since 2008: routine detection of CO emission lines inside normal (massive) galaxies (near-IR selected, UV/optically selected), opened up the way to study their gas content over 0.5<z<2.5

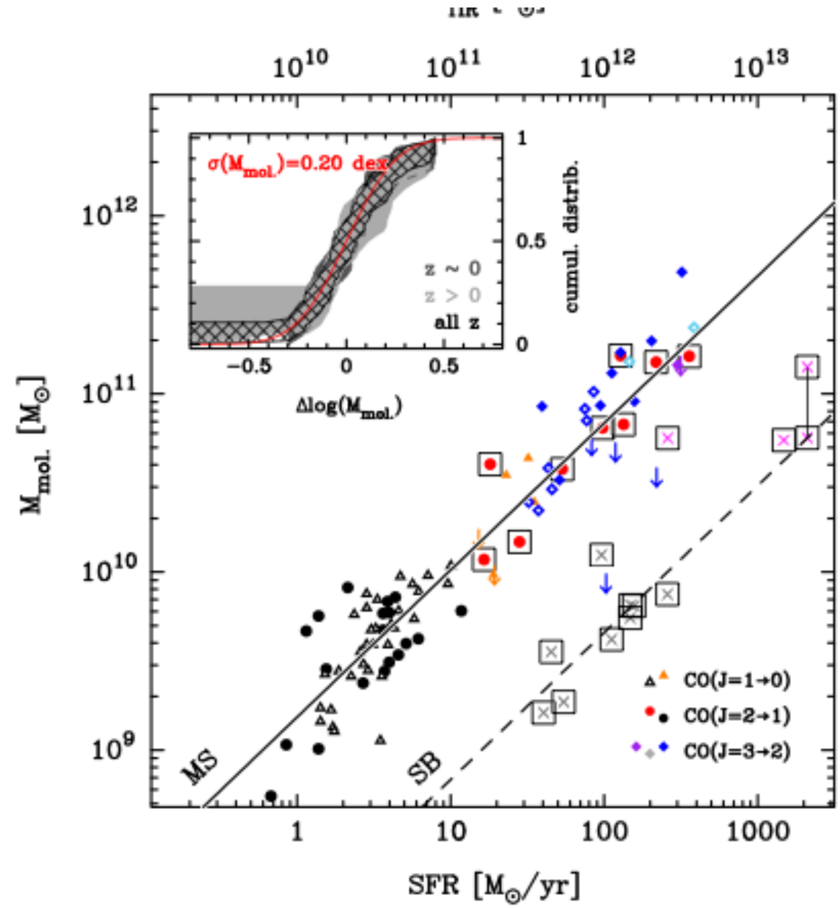



Daddi et al 2008; 2010; Tacconi et al 2010; 2012 Geach et al 2011; Combes et al 2012; etc

Tight correlations of LIR/SFR with CO and Mgas
(Daddi et al 2008; 2010ab; Tacconi et al 2010; Genzel et al 2010)
Sargent et al 2012, in preparation




X3 offset from *observables only*

X10 offset, dense gas fraction

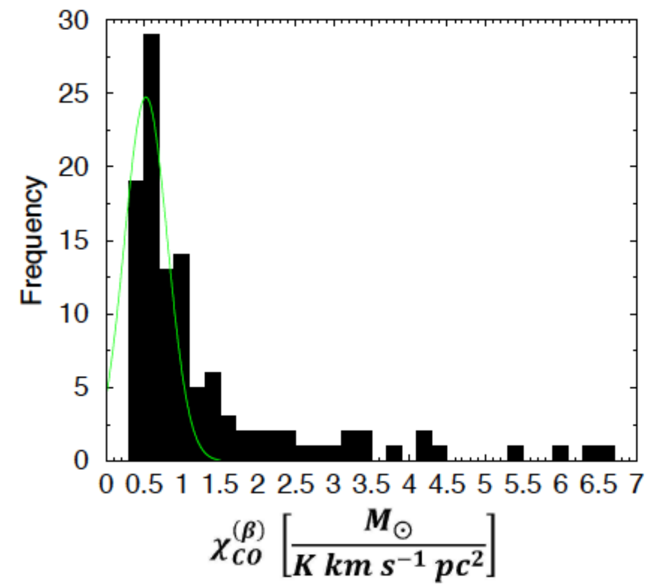
Doubling time for MS galaxies >~0.5Gyr, gas accretion rate high
Duty cycle high, MS narrow

# CO to H2 conversion factor, (or how much gas ? “”The gas IMF or M/L problem””)

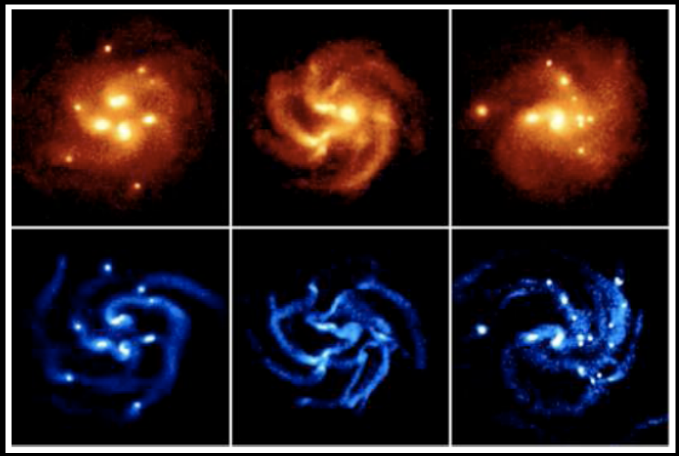
Massive z~2 galaxies are LIRGs/ULIRGs.
Locally, ULIRGs vs spirals differentiation in alphaCO

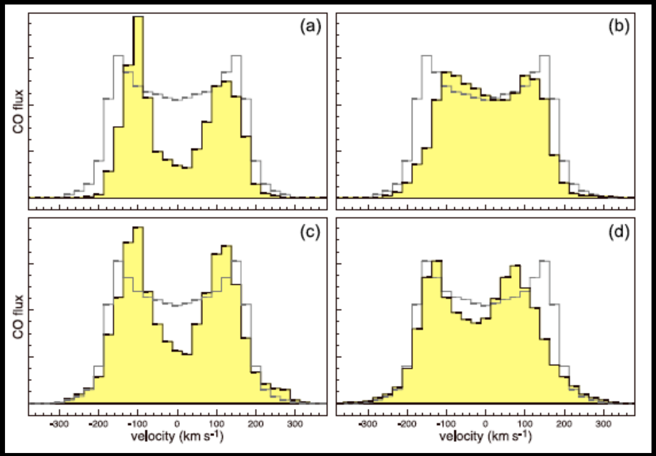
→ **In reality MS/SB differentiation ?**

z=0 LIRGs/ULIRGs
Papadopoulos et al 2012

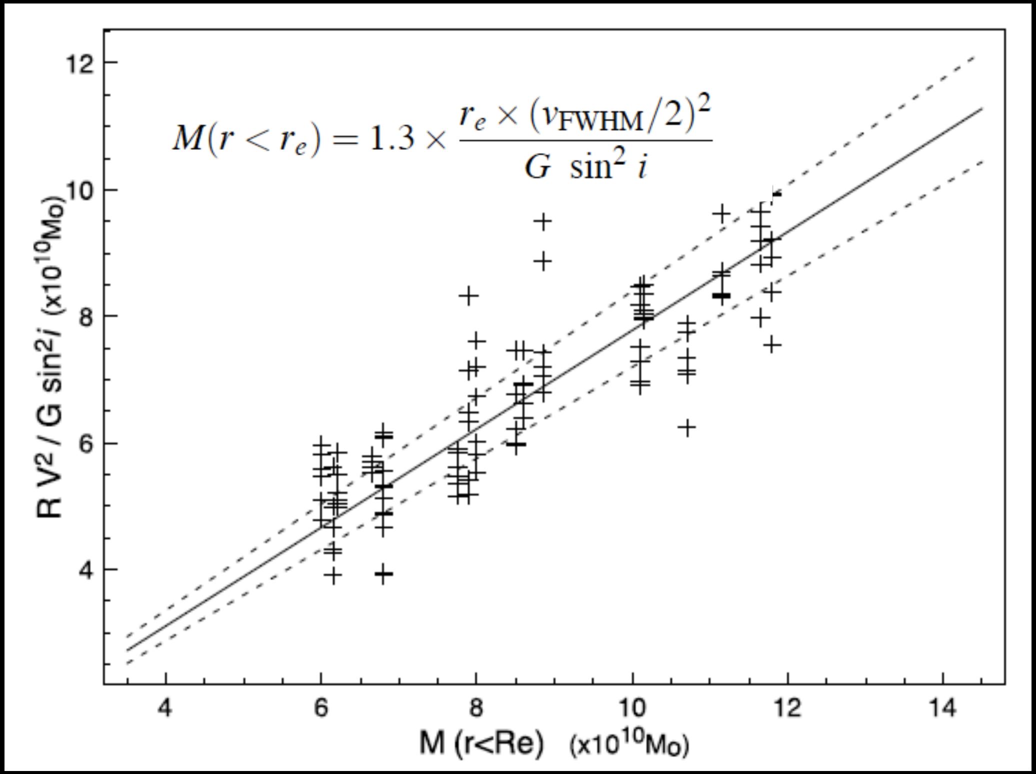


# Calibrating Mdyn estimate through clumpy disks simulations






Bournaud
Elmegreen
Elmegreen
2007

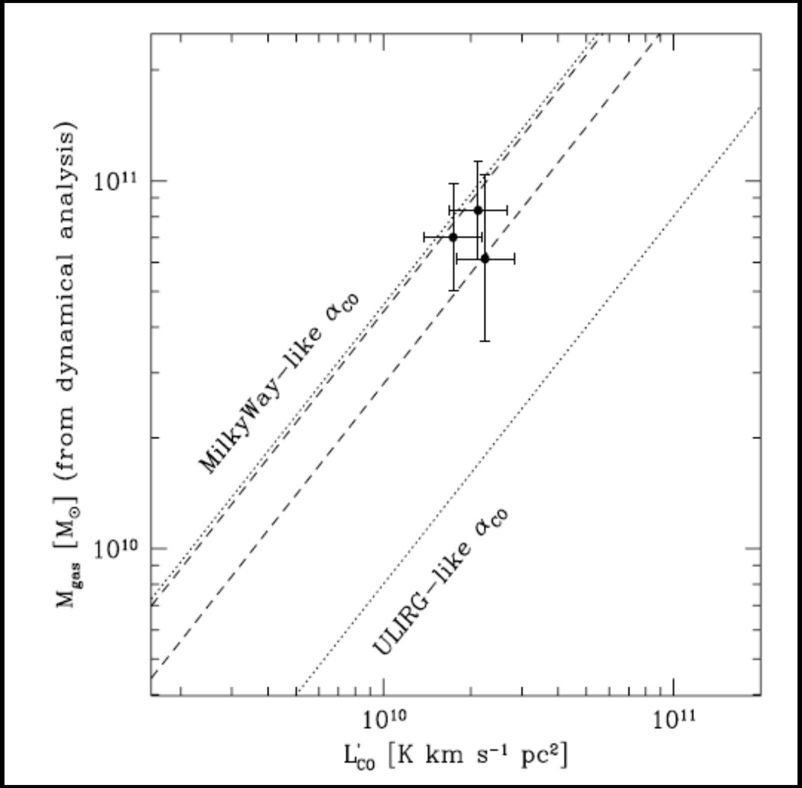



We ‘observed’ the models as the real data

$r_e$/sin i through Sersic fits
$v_{FWHM}$ (2-gaussian fits)

Account for dispersion 12%

High $a_{CO}$ conversion factor    (3.6 +- 0.8)
(assuming 25% of dark matter)




To get back to ‘0.8’
(ULIRGs value)

- Dark matter ~60%

- $M_{stars}$ x3 larger

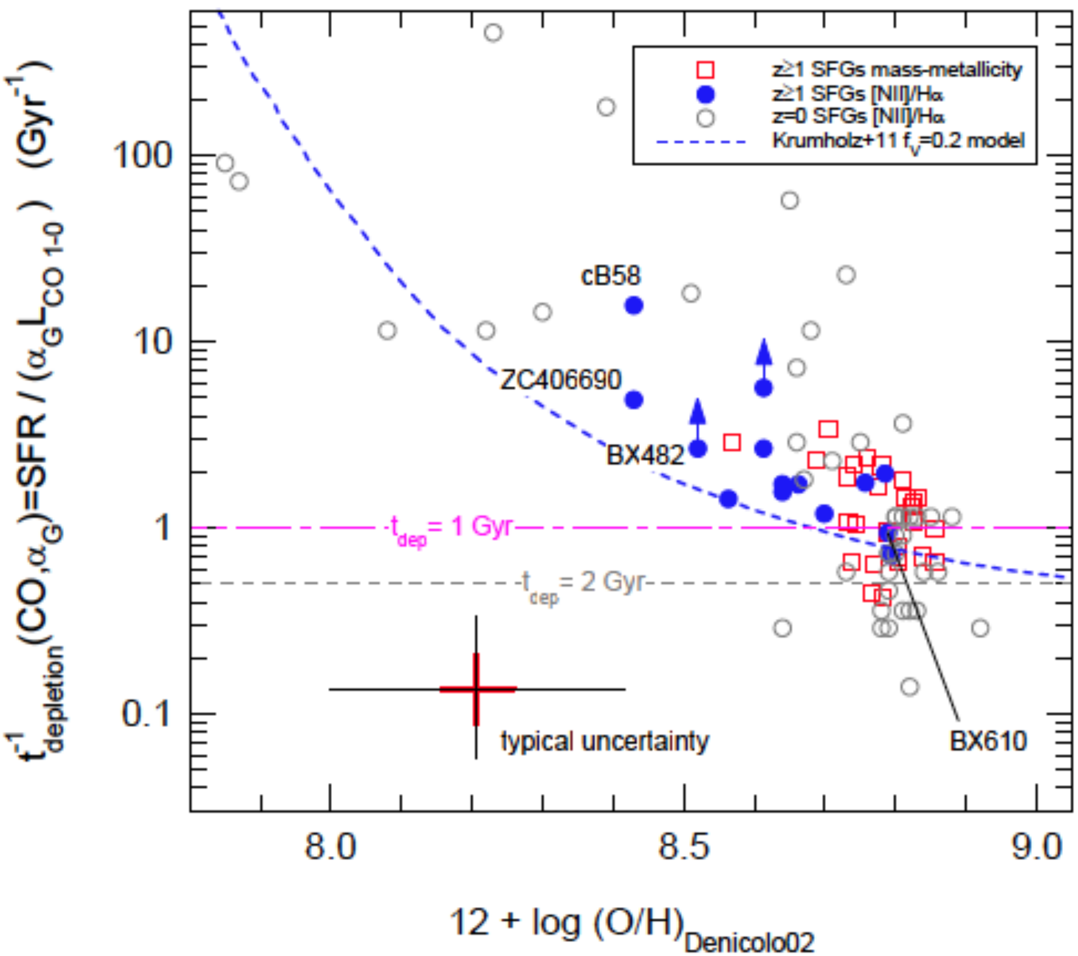
- ‘Bournaud’ factor down to 0.7 (1.3) (i.e., velocity overest.)

Daddi et al 2010

Based on Bournaud et al 2007 clumpy disk models

SFR/L'CO scales with metallicity as in local galaxies

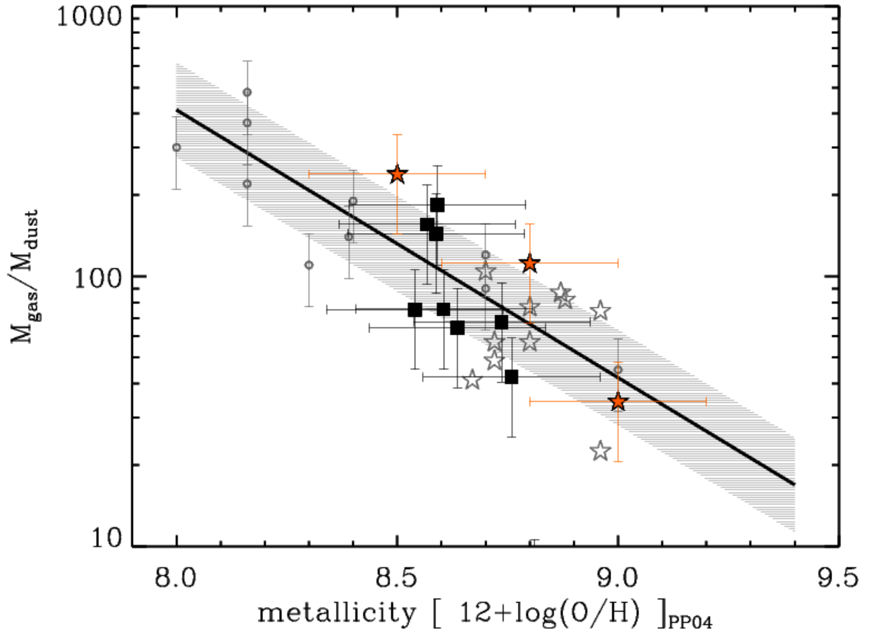
Genzel et al 2011

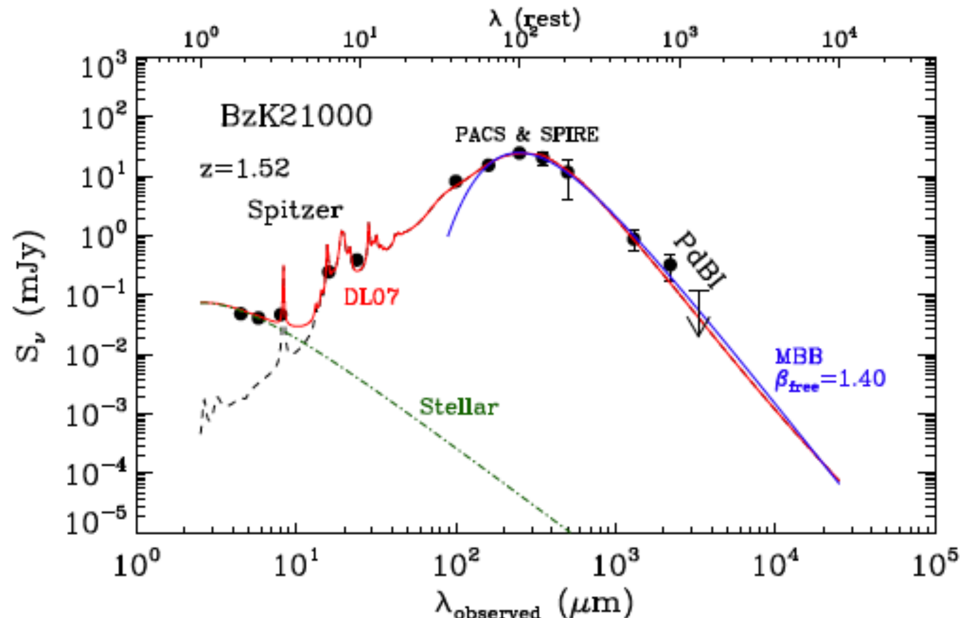



Supports idea that alpha_CO Scales with metallicity as in Local galaxies.

But tells nothing about the normalization

A powerful way to constrain Mgas is through Mdust, as Mdust ~ 0.5*Z*Mgas




Data from Leroy et al 2010; daCunha et al 2010
Magdis et al 2012 → agree with high aCO values
For MS galaxies

Magdis et al 2011; 2012
(Draine and Li 2007 models)
See also Magnelli et al 2012

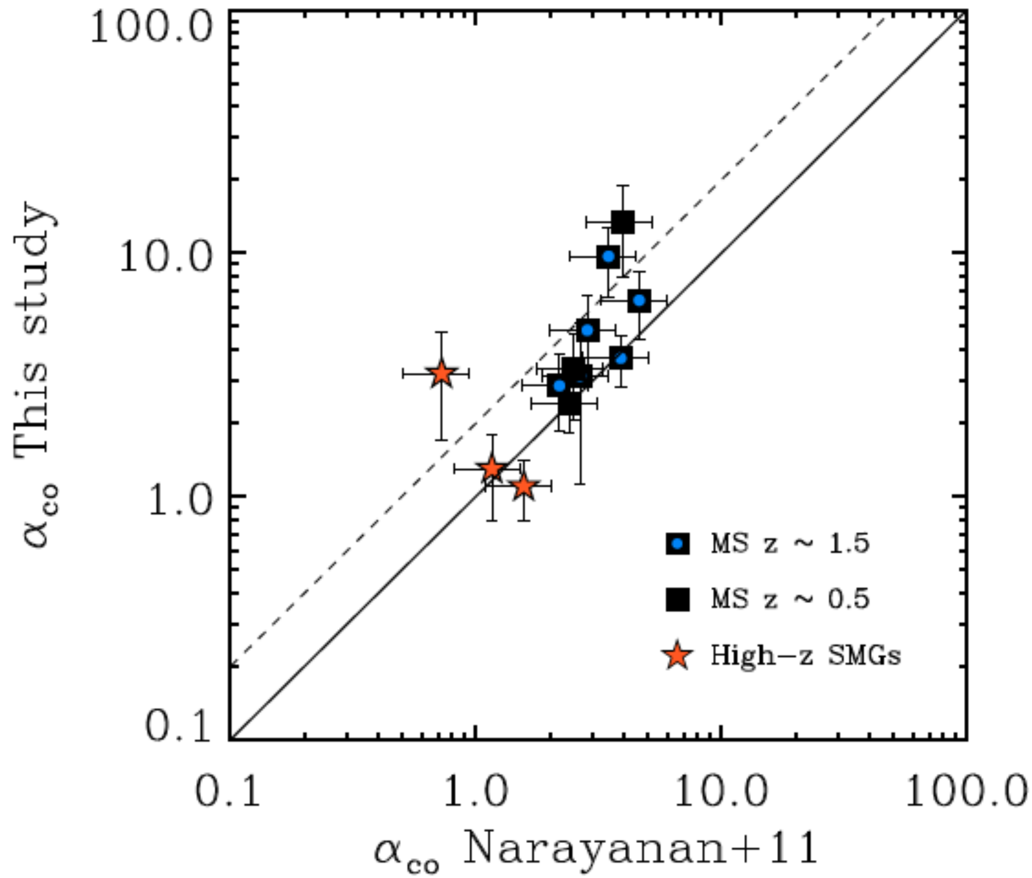
<U> ~ LIR/Mdust ~ $T^{4+\beta}$ ~ SFR/(Z*Mgas) ~ SFE/Z (Magdis+ `12)

From the IR SED shape, modulo metallicity, one can get to SFE!

In fact at z=0 U(ULIRGs)/U(massive spirals) ~ 10 just like SFE

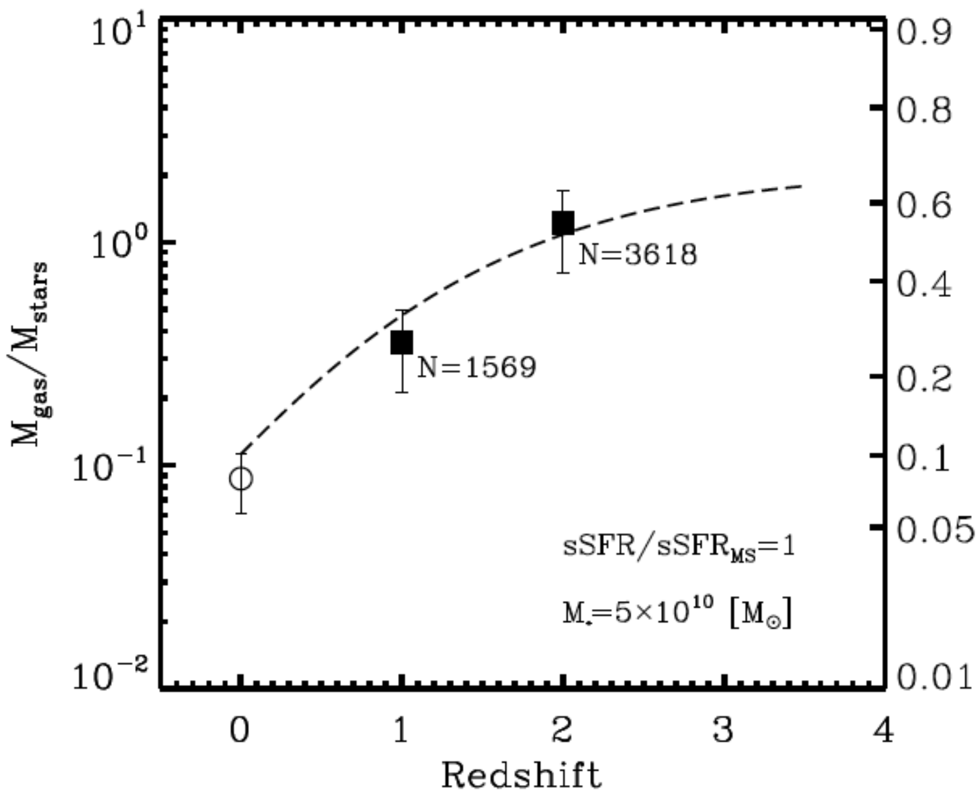
→ Confirm aco(Z) local trend and thus exploitation of CO observations
→ Get Mgas independently on CO/ALMA whatever, and on gigantic samples

Theory based a_CO, depending on L'CO and size in addition to metallicity (Narayanan et al 2011) → seems to be consistent with the rest, only x2 bias

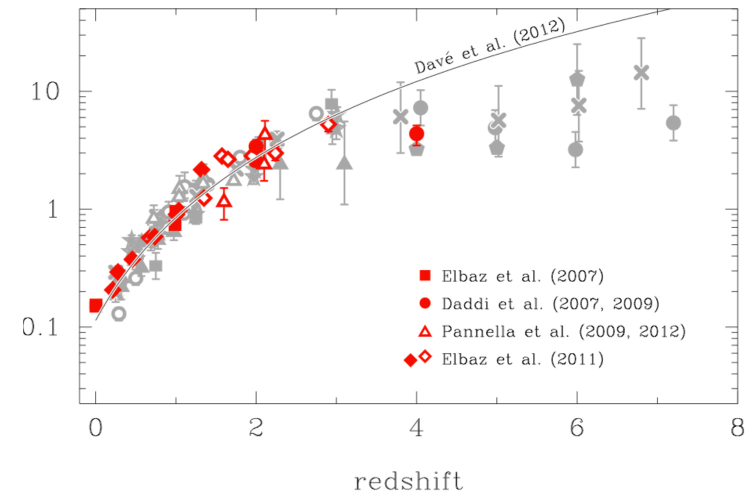



Magdis et al 2012

Gas fractions in MS galaxies rising sharply from z=0 to 2 from 5% to 50%
(Daddi et al 2008; 2010; Tacconi et al 2010; Geach et al 2011; etc)




Magdis et al 2012b



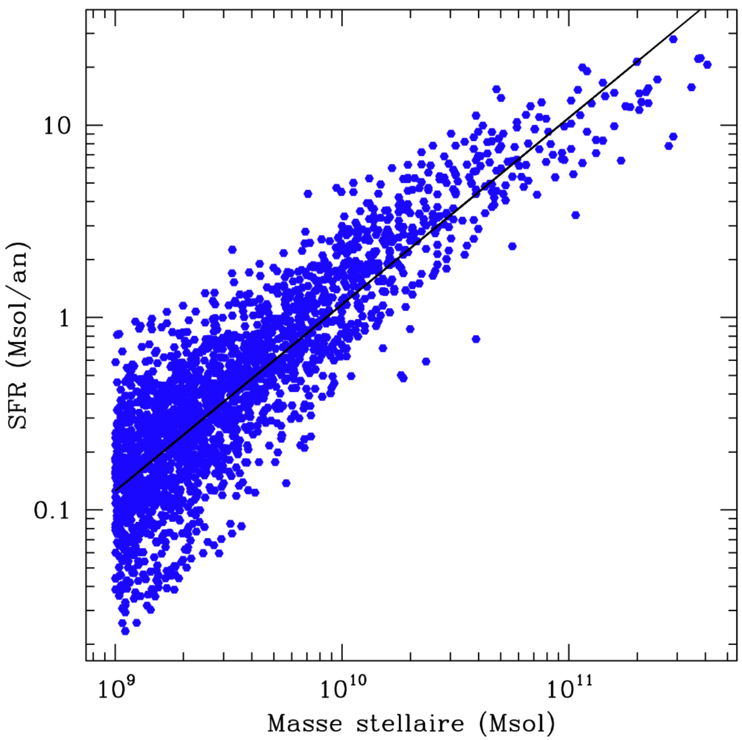

Fgas increase fully explains the sSFR increase of MS
No need to alter the IMF, or invoke anomalous SFE to account for the high SFRs z~2

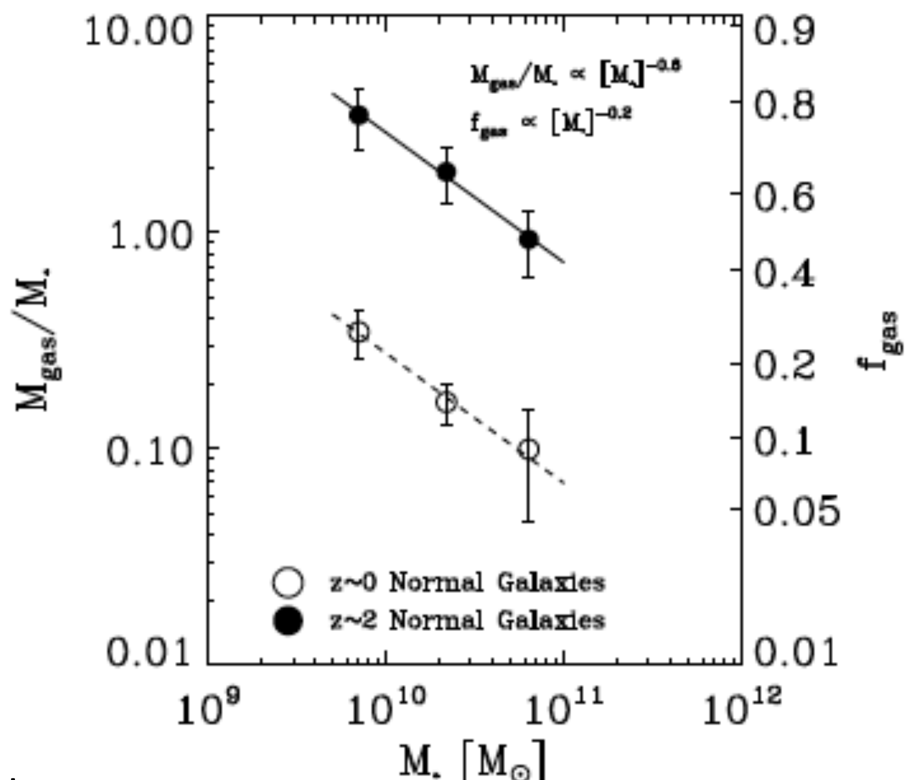
z>=2 massive galaxies are gas dominated, very different beasts from z=0 spirals

But fgas is not a single number quantity at a given z

As the SFR and M* rise along the MS, the gas fraction decreases (Magdis et al 2012)

Simple consequence of SF law slope, MS slopes<1

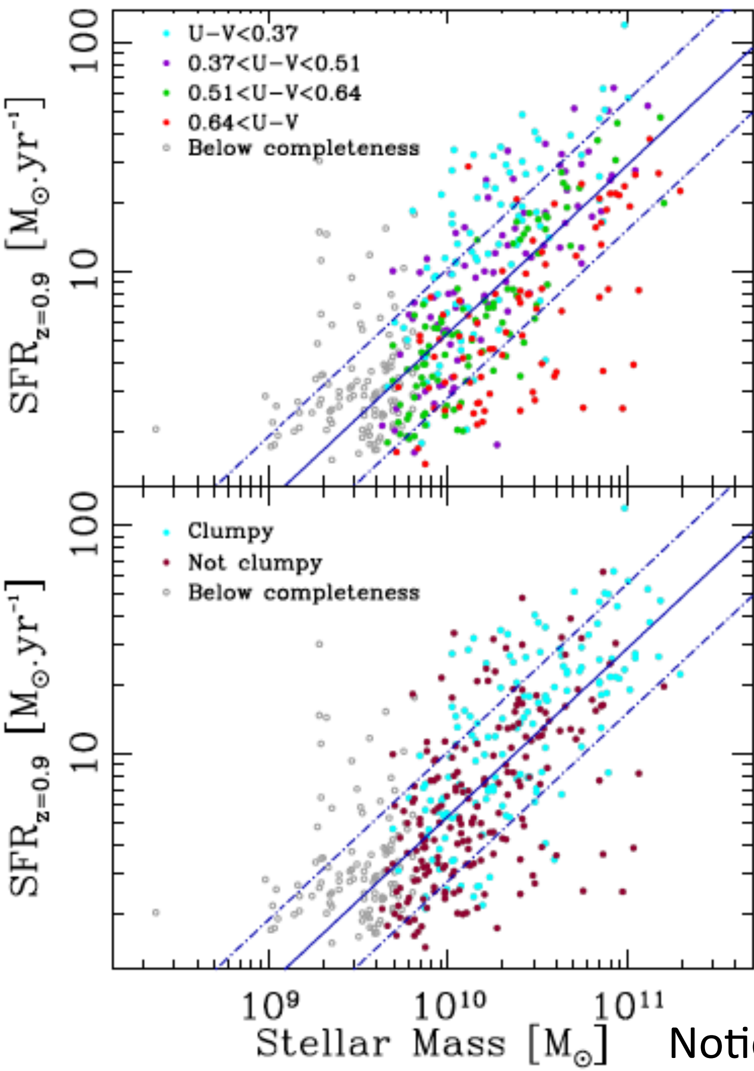



Magdis et al 2012

The bathtub is loosing water…

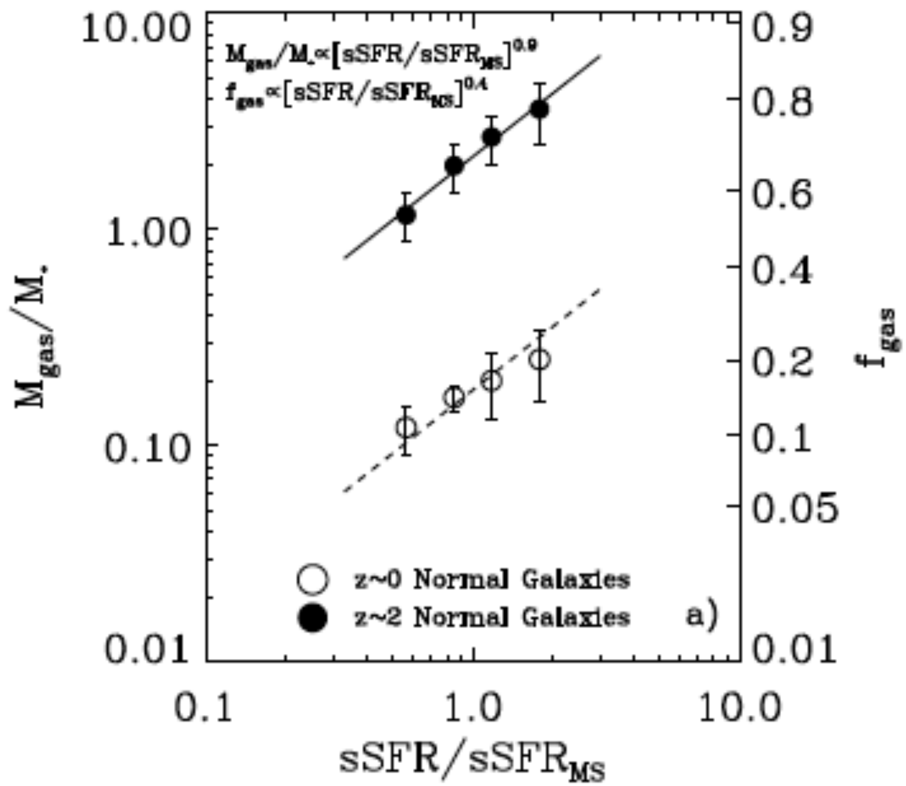
Salmi et al 2012




Why the MS is thick ?

1) Fgas driven ?
2) SFE driven ?

→ Fgas is the answer (Magdis et al 2012)



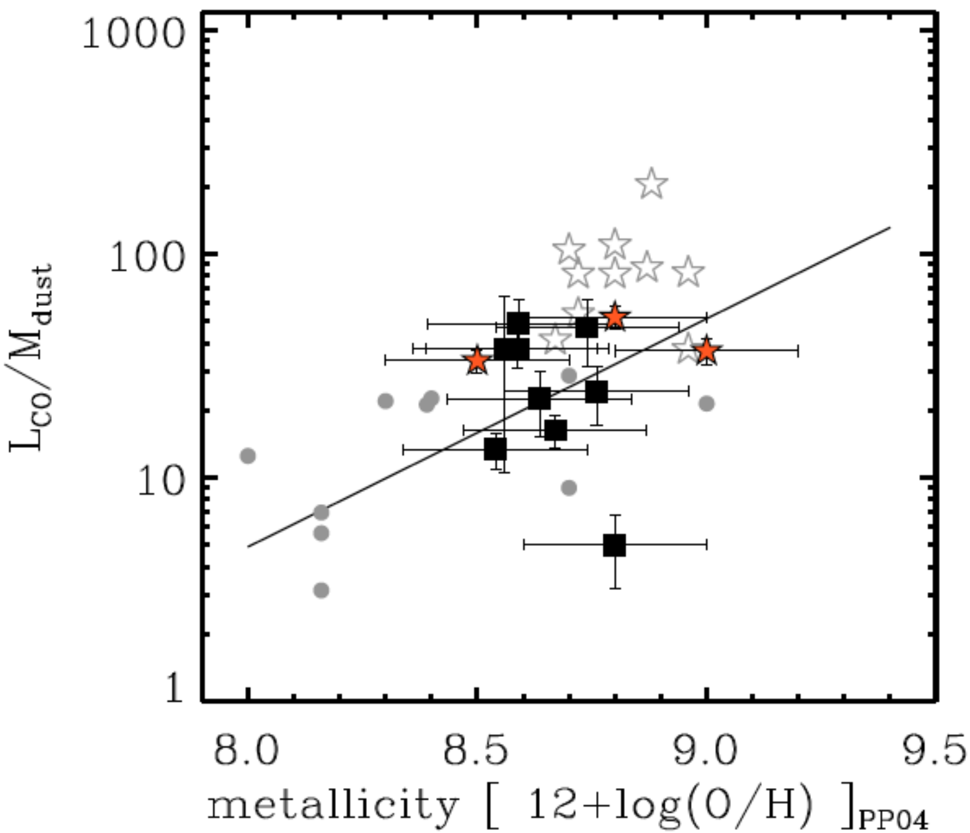

Notice that SFR feels f_dense, not fgas (e.g., Daddi+2010)

→ Must mean fluctuations are long lived >10^8yrs

(also time needed to reflect color variations)

A few word of caution on our 'alternative' method to Mgas:

- Could G/D vs Z behave much differently than at lower-z ? (unlikely, as high metal % in dust)
- Could the Z estimates for high redshift be biased ? (possibly, but mass-Z very weak trend)
- Is the Mgas H2 or HI too ? (likely H2 dominated at high-z)
- Draine and Lee models appropriate ? (hopefully!)

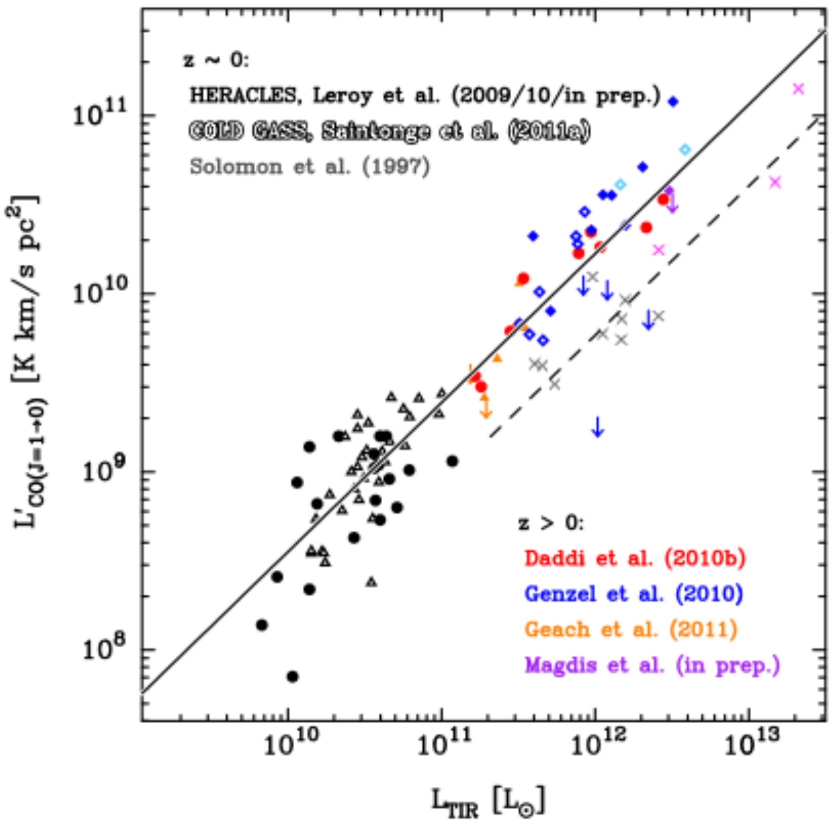


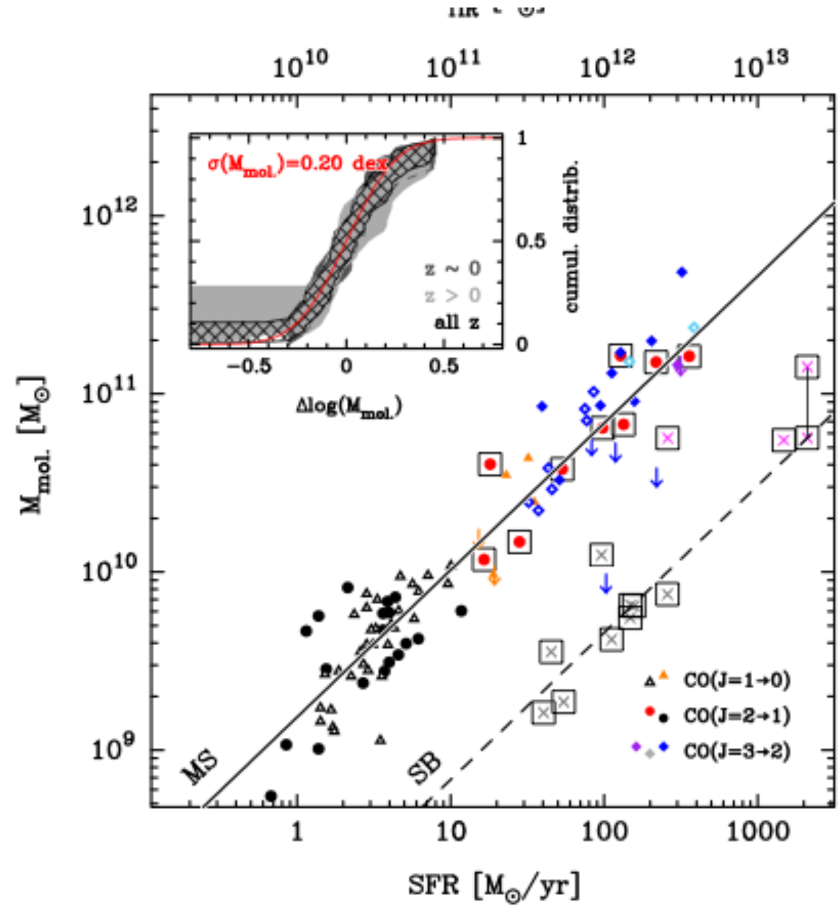

Lco/Mdust is similar at low
And high-z.

This is why our Mdust→Mgas
Exercise agrees with estimates
From L'CO when using local
Trends for aco

But they are independent.
and G/D can only overestimate
Gas moderately (we assume
50% metals into dust already)

Tight correlations of LIR/SFR with CO and Mgas
(Daddi et al 2008; 2010ab; Tacconi et al 2010; Genzel et al 2010)
Sargent et al 2012, in preparation



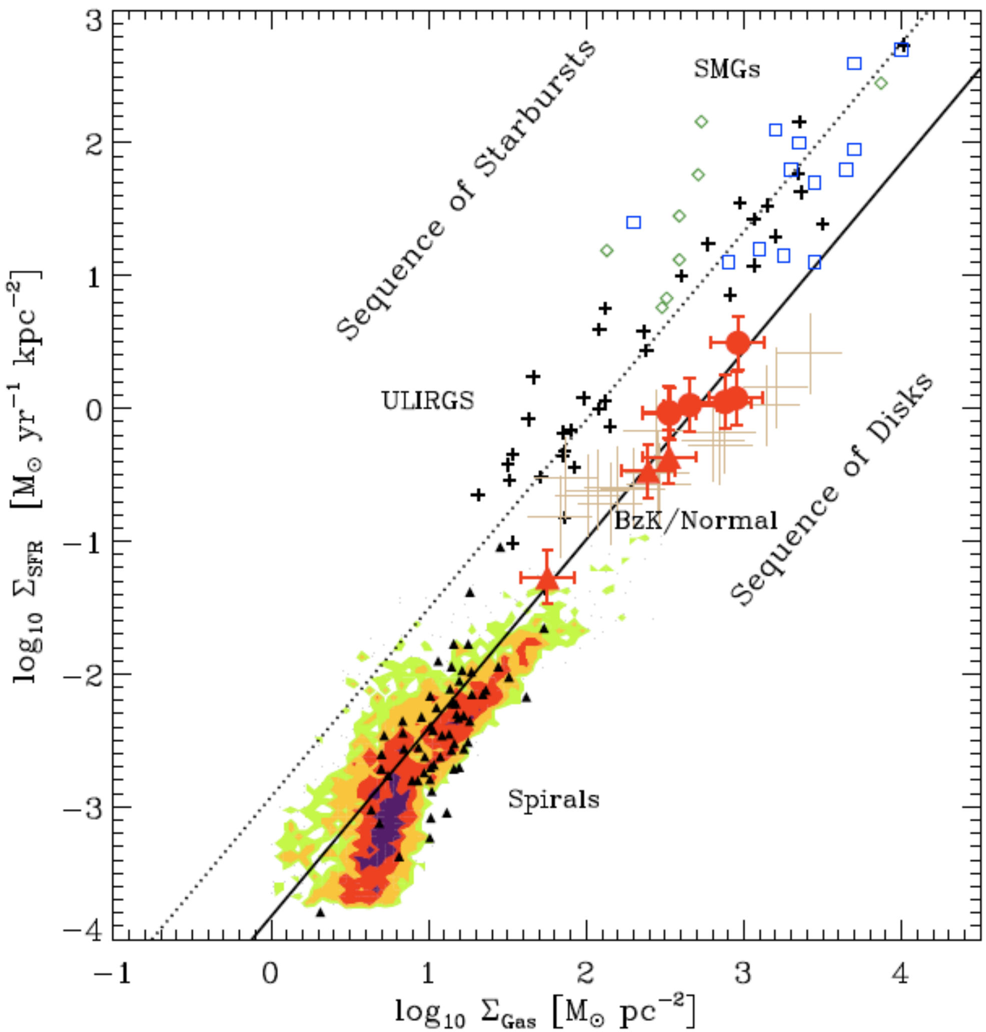

X3 offset from *observables only*

X10 offset, dense gas fraction

Doubling time for MS galaxies >~0.5Gyr, gas accretion rate high
Duty cycle high, MS narrow

Failure of classical Kennicutt law to account for z~1.5-2 normal galaxies

Something that could not be learned from low-z observations alone



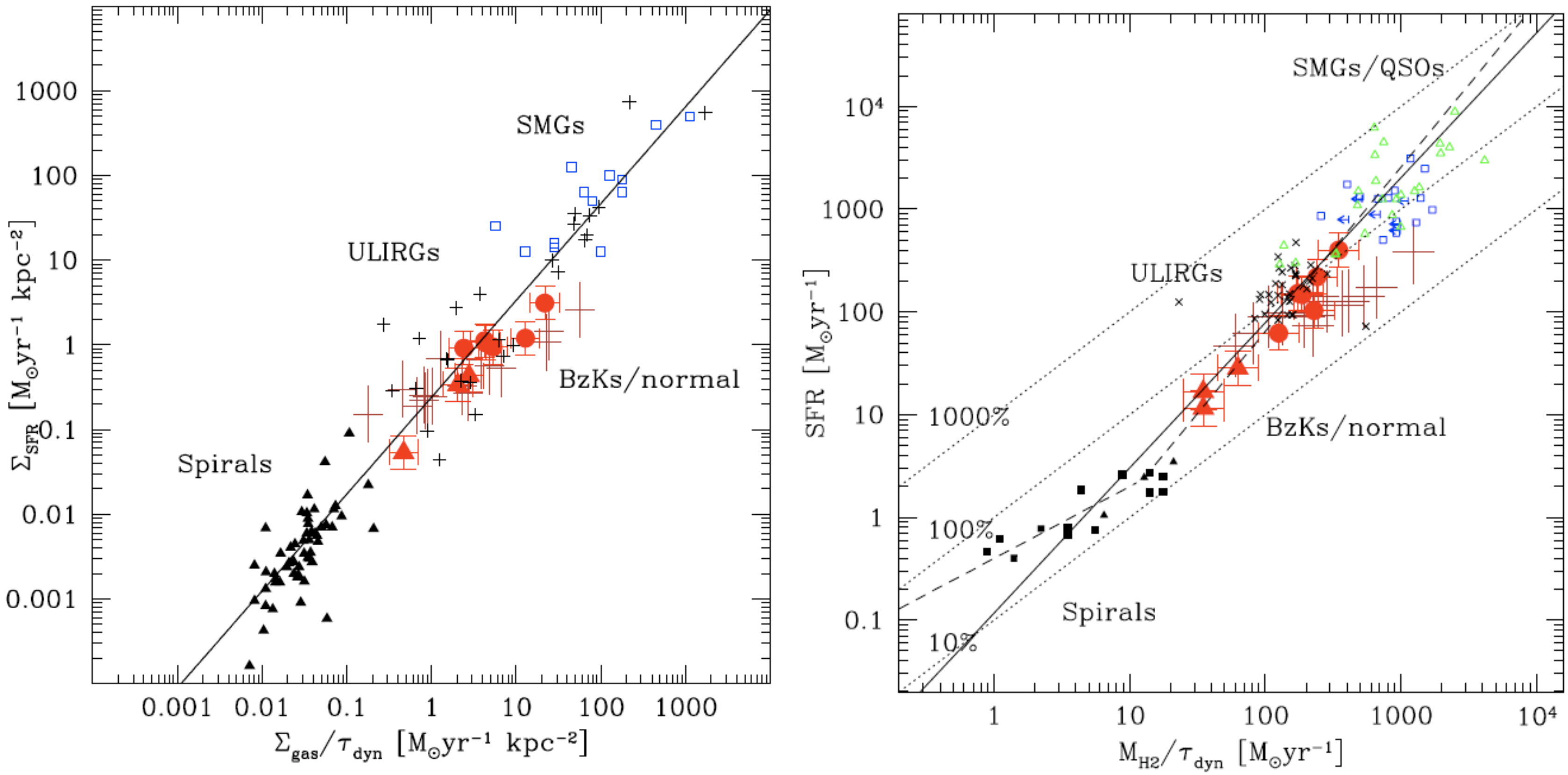

Normal (main sequence) Galaxies behave very Differently from SBs

BzKs have ~10 times lower Sigma_SFR than ULIRGs/SMGs

Daddi et al 2010b
see also Genzel et al 2010

Main (controversial) result of the new observations of gas in normal distant galaxies

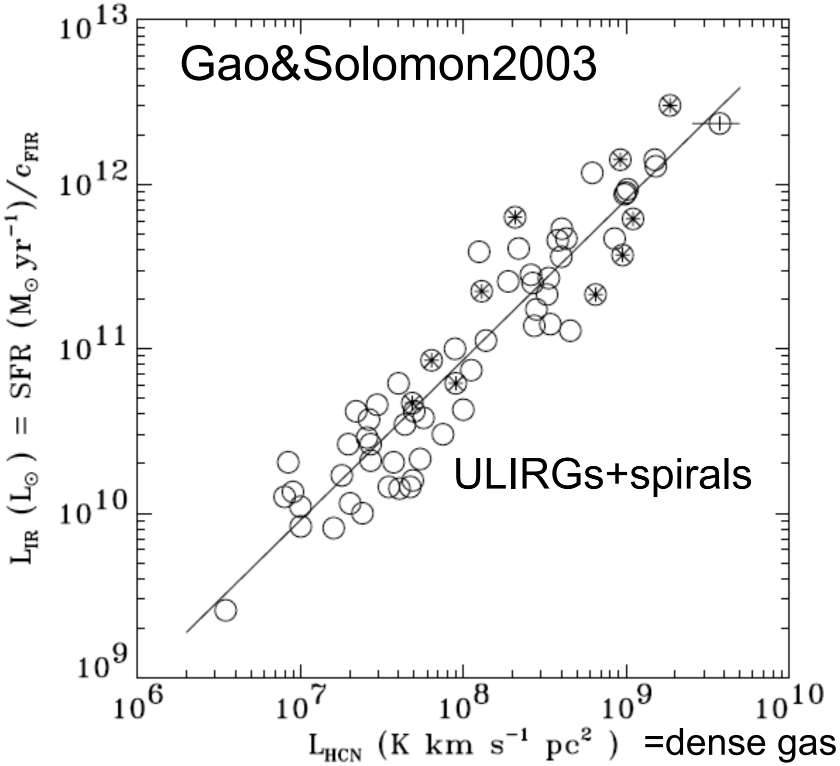
When considering the dynamical (rotation time)
Silk 97; Elmegreen 2002; Krumholz et al 2009; 2011; K98

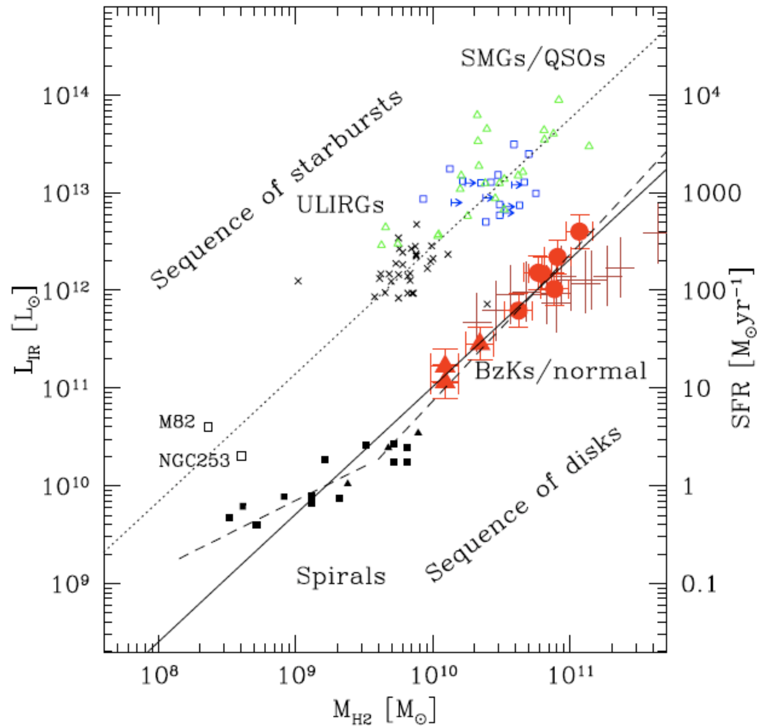



Both disks/starbursts fall back to a single law
→ tau_gas vs tau_dyn relation is unique

Krumholz et al → volumetric SF law must be used, including free fall time

# The different 'modes' seem to relate to dense gas fraction (Daddi et al 2010b)



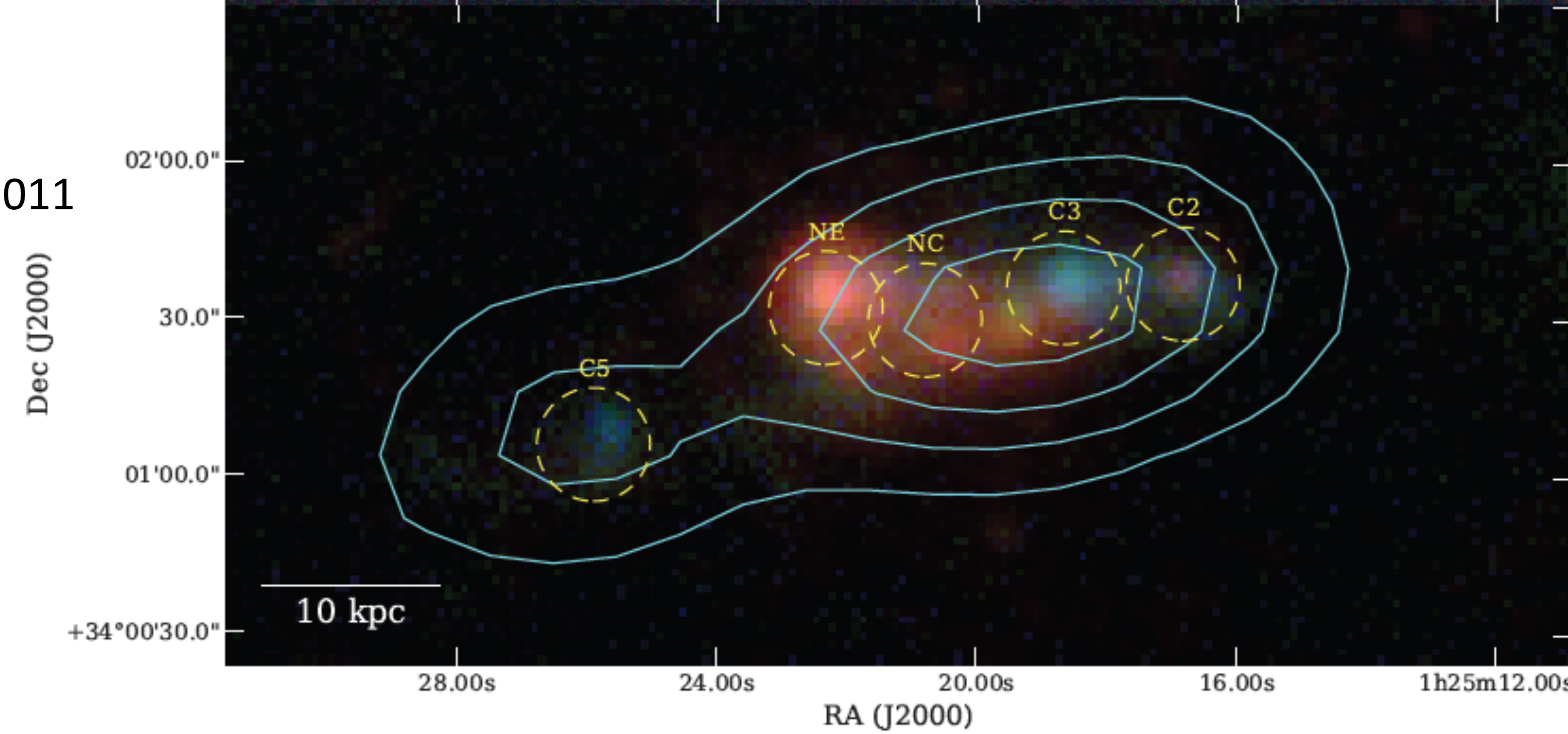



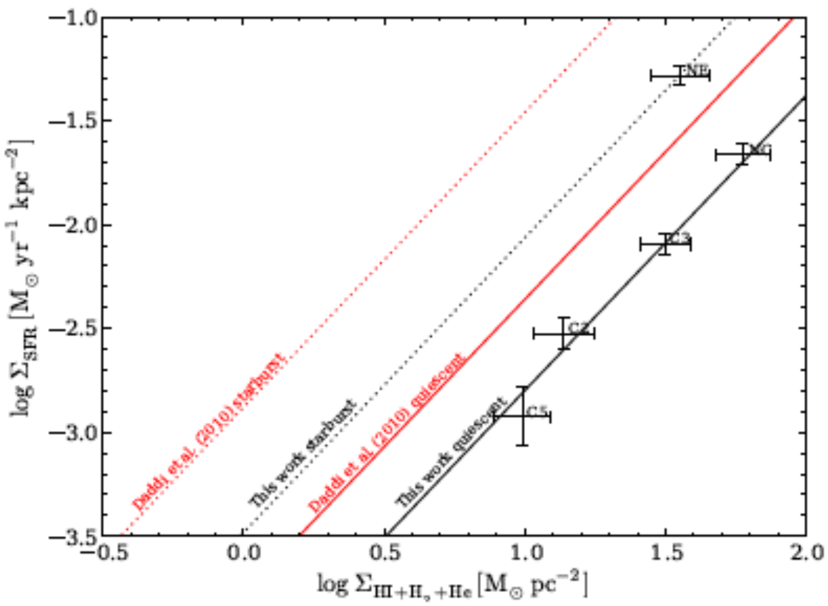

Bimodal trend for total $H_2$, single linear trend for most dense $H_2$

→Different behaviour for the fraction of dense gas in disks/SBs

→ playing with IMF would leave at least 1 bimodality

Arp158
Boquien et al 2011

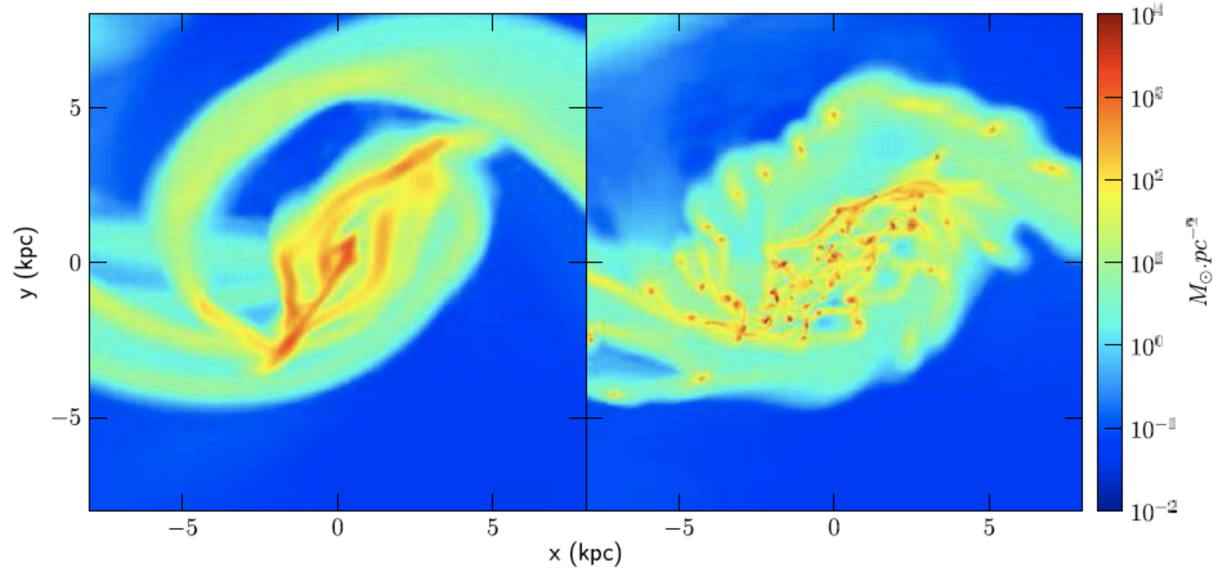


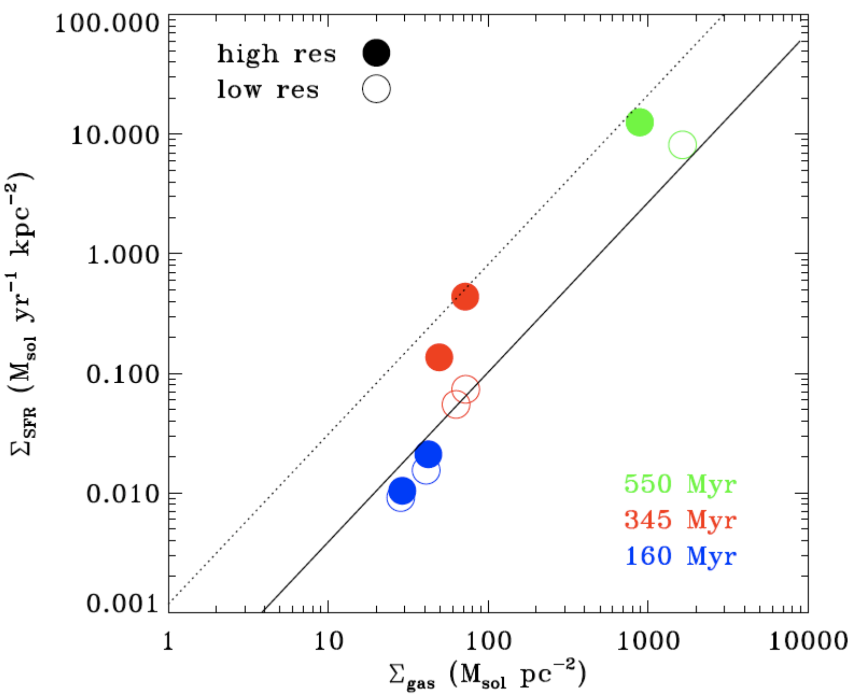




Two modes seen inside a single galaxy

Numerical simulations might reproduce this

(Teyssier, Chapon & Bournaud, 2010)



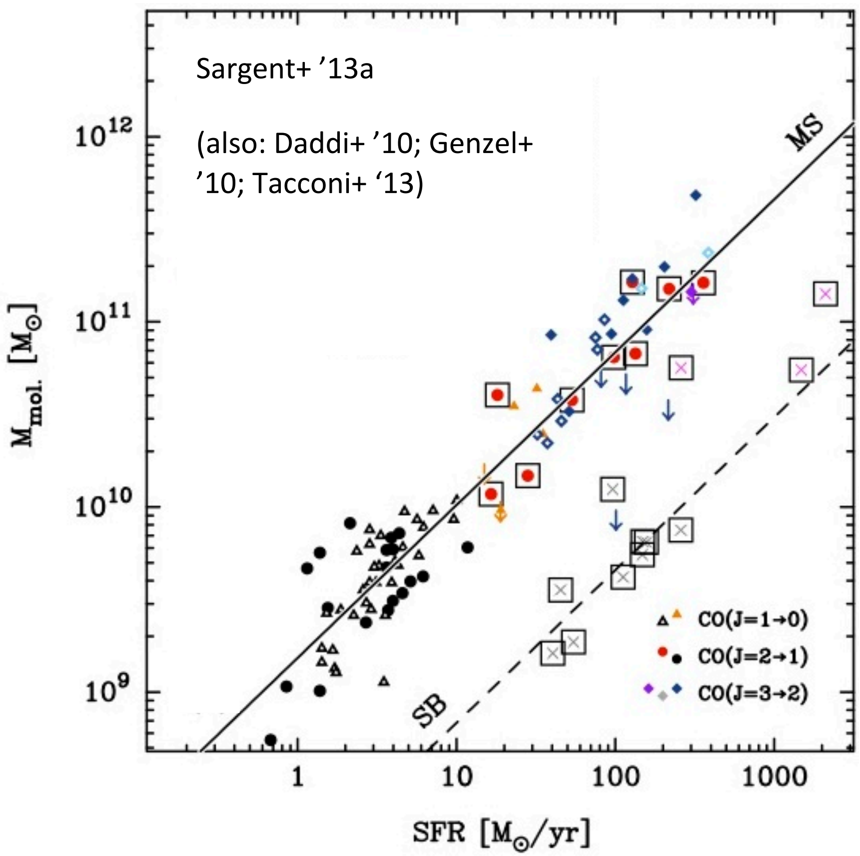

Seen at very high spatial resolution
A unique local 3D SF law

Merger phase has x10 increased SFE
In 2D or 1D
(mainly because of geometry and averaging effects)

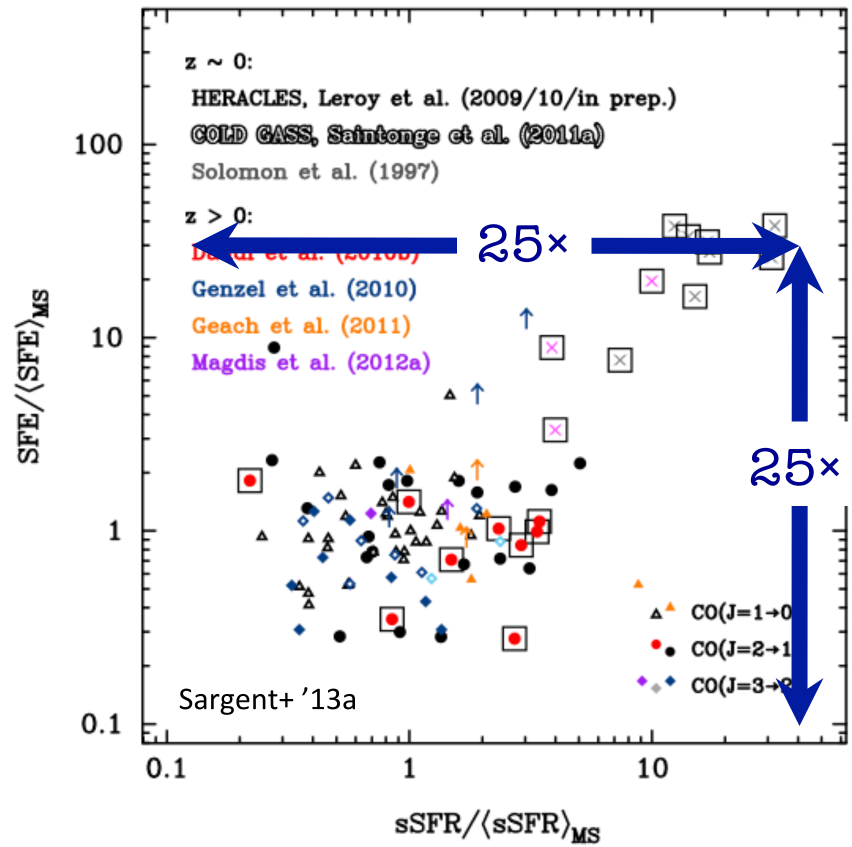
*But this 'merger' does not show the single central concentration one would expect?*

# 2 Star formation modes: Schmidt-Kennicutt plane

Integrated Schmidt-Kennicutt law for main seq. galaxies - tight and slightly non-linear:

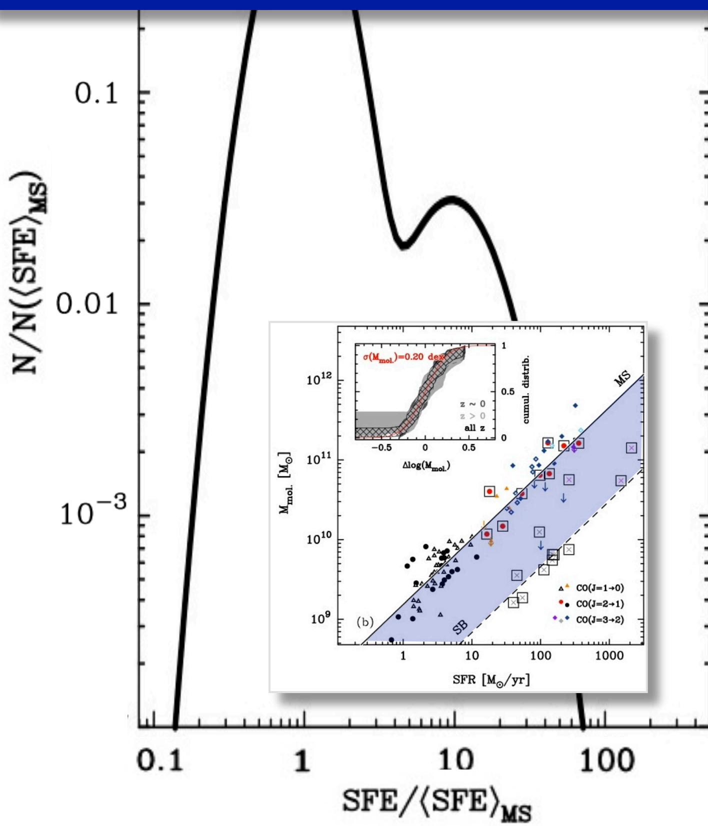


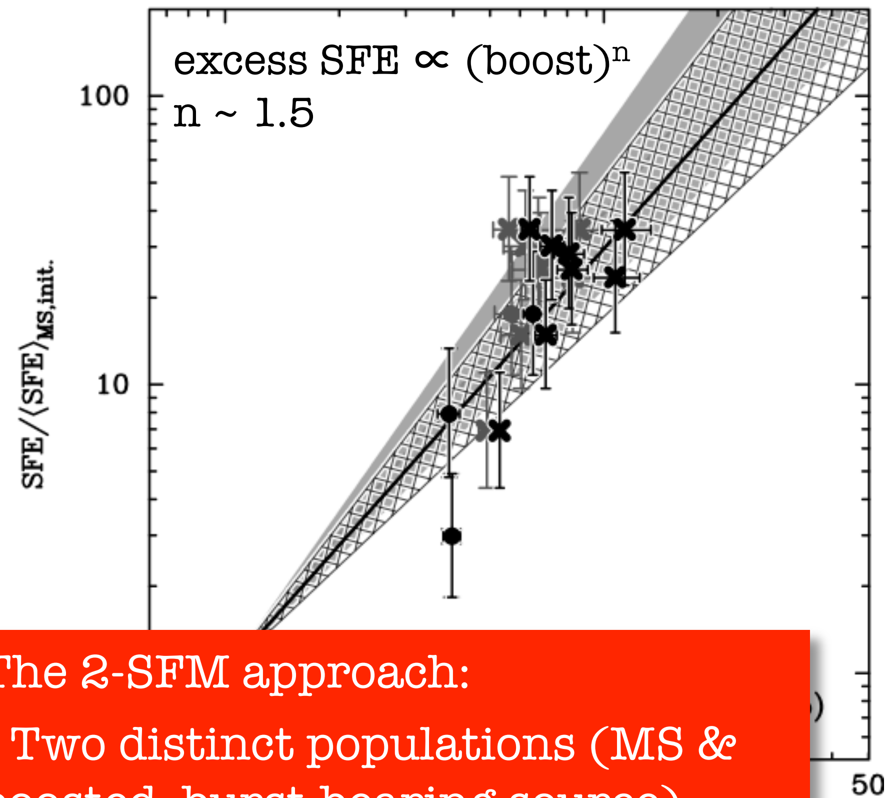

SFE-excess vs. sSFR-offset (relative to main seq. average)



# 2 Star formation modes: Schmidt-Kennicutt plane II

Within the 2-SFM framework, a dichotomy in the S-K plane **naturally arises** due to the **non-linear relation between SFE & SFR in starbursts**.




The 2-SFM approach:

- Two distinct populations (MS & boosted, burst-bearing source)
- A continuum of physical properties (e.g. SFE, $X_{CO}$) for starbursts, *depending on magnitude of boost*

**No discrete bimodality!**

# Merger simulations II

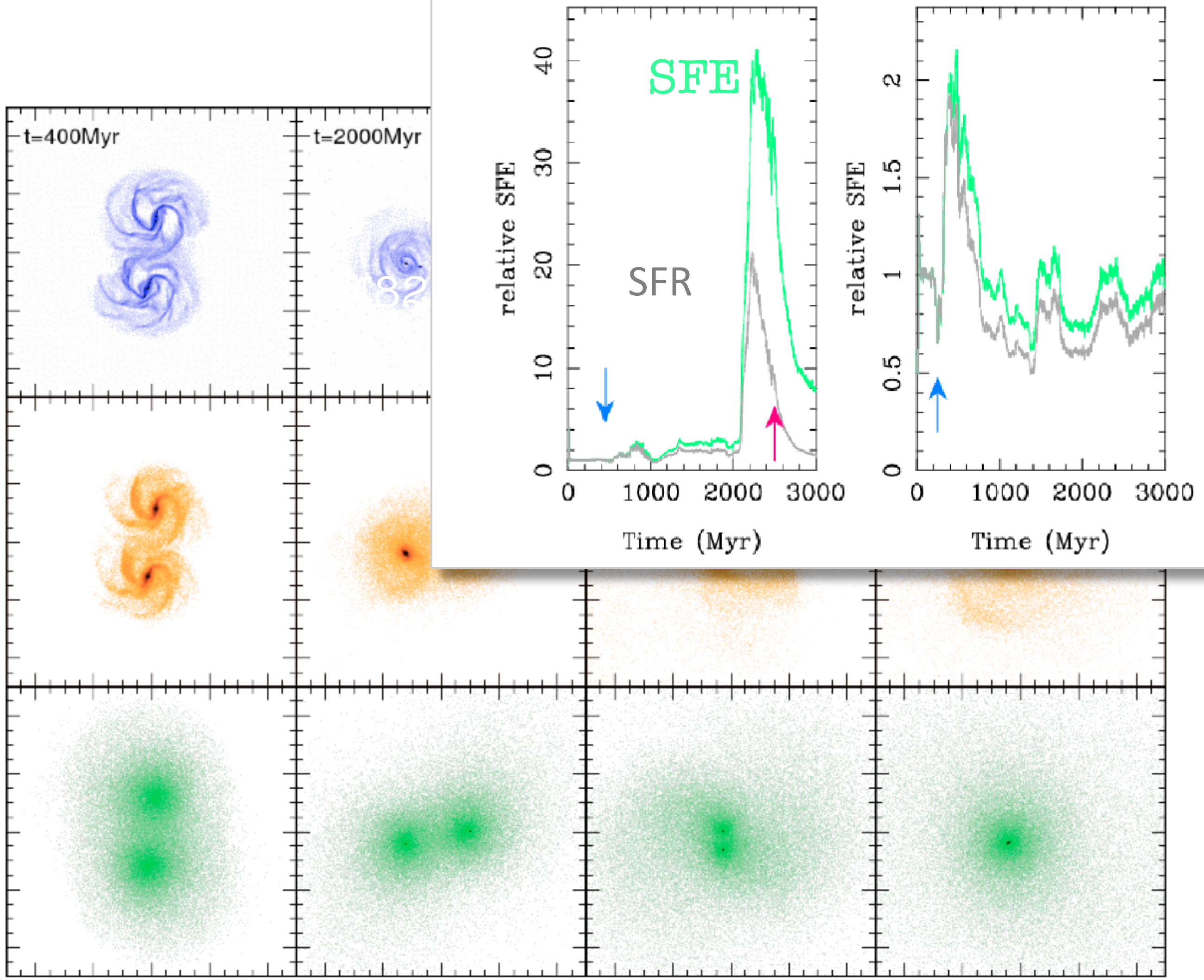
Di Matteo+ ’07:
*retrograde* merger
of 2 Sbc galaxies
at $z$=0

gas ➽

stars ➽

dark matter ➽

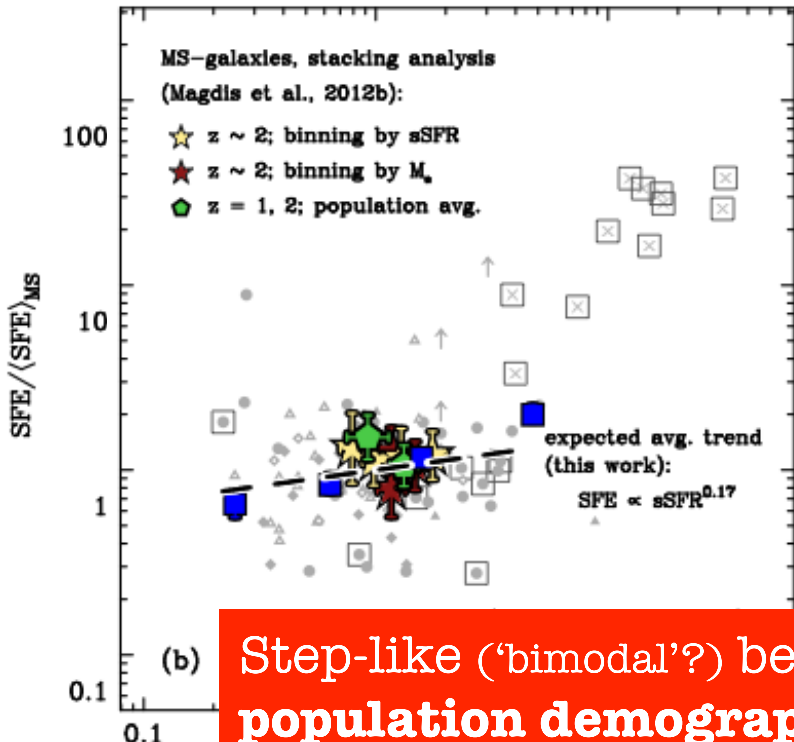
SFR & SFE response in a
di Matteo+ ’07 merger… & … a fly-by:



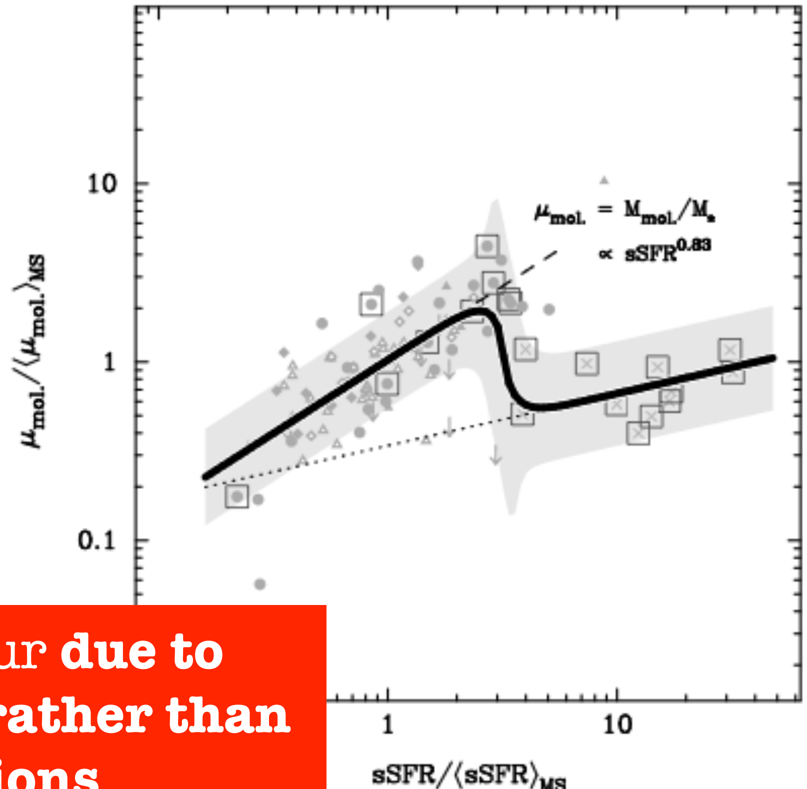
# SFE- & $f_{gas}$-variations in the SFR-$M_\star$ plane

redshift-invariant (for $M_\star/M_\odot > 10^{10}$) due to re-normalization

SFE vs. sSFR-offset from main seq.




$f_{gas}$ vs. sSFR-offset from main seq.
($\mu = M(H_2)/M_\star$)

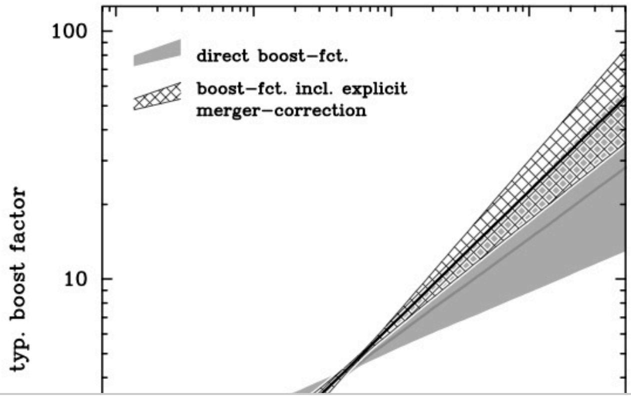



Step-like ('bimodal'?) behaviour **due to population demographics rather than dichotomy of scaling relations**

**At step**: predict *enhanced dispersion* due to population mix

# The former life of starbursts

*Statistical link* to past:
sSFR-excess vs. (s)SFR-boost relation




Toy model: SFR proceeds on much shorter time scales than gas can be accreted:

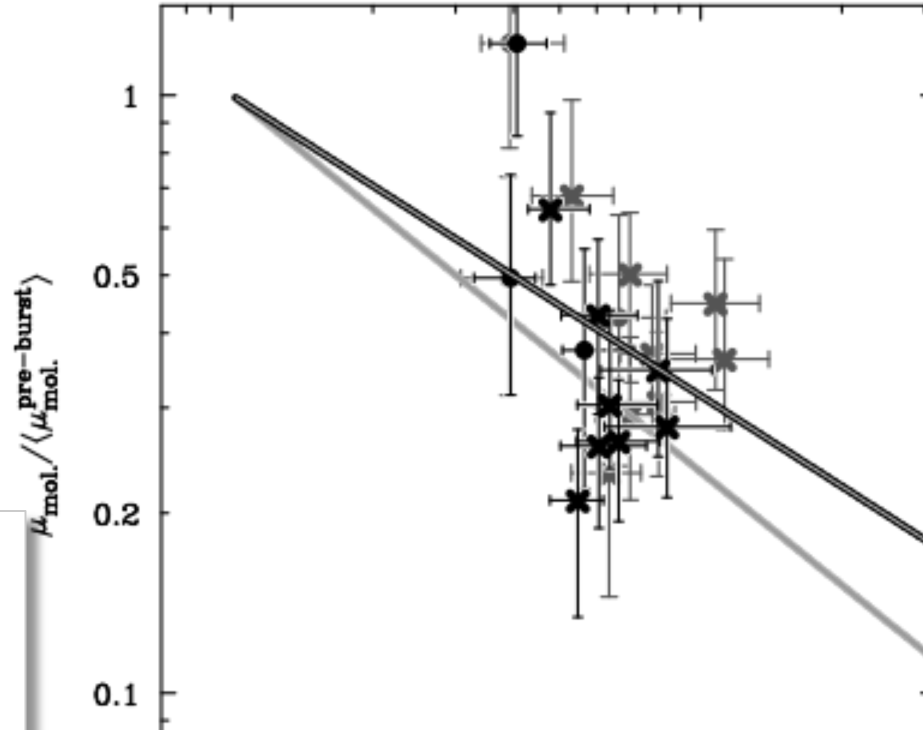
$$M_{\star} \rightarrow M_{\star,\, pre\text{-}burst} + SFR \times t^{merger}$$

$$M_{gas} \rightarrow M_{gas,\, pre\text{-}burst} - SFR \times t^{merger}$$

$$\frac{f_{\mathrm{mol.}}}{f_{\mathrm{mol.}}^{\mathrm{pre-burst}}} = \left(1 + (\mathrm{boost})^{\gamma_{\mathrm{SFE}}} \frac{t_{1/2}^{\mathrm{merger}}}{\tau^{\mathrm{pre-burst}}}\right)^{-1}$$

~0.6, i.e. $\mu/\mu^{\text{pre-burst}}$ ~ 0.4

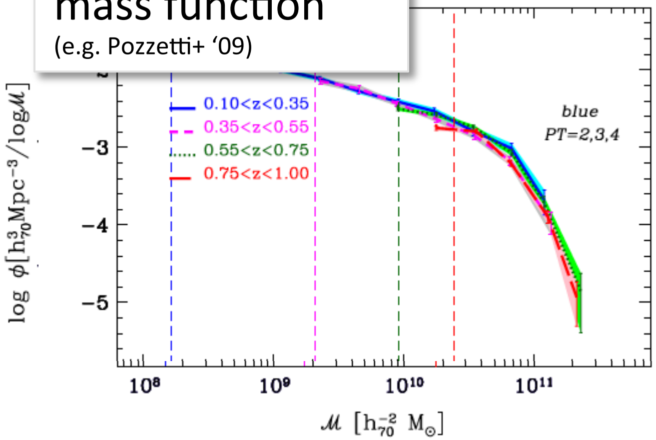
Sargent+ '13a



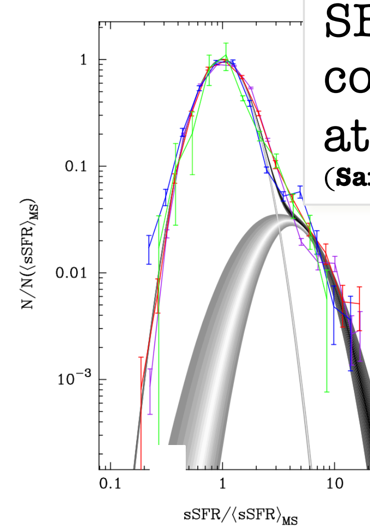

The gas fractions in sSFR-excess srcs. (starbursts) are in agreement with those expected based on merger simulations.

# The ‘2-SFM’ framework – bare necessities

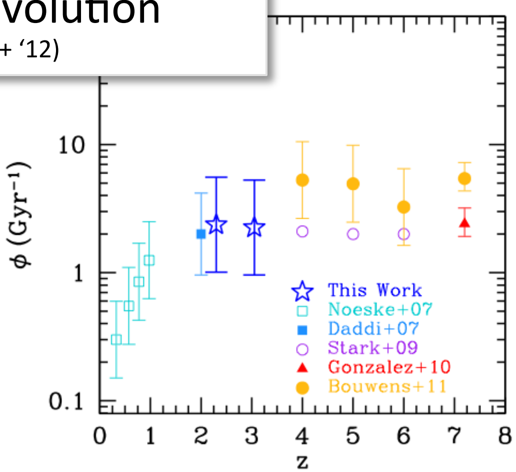
1) mass function
(e.g. Pozzetti+ ‘09)



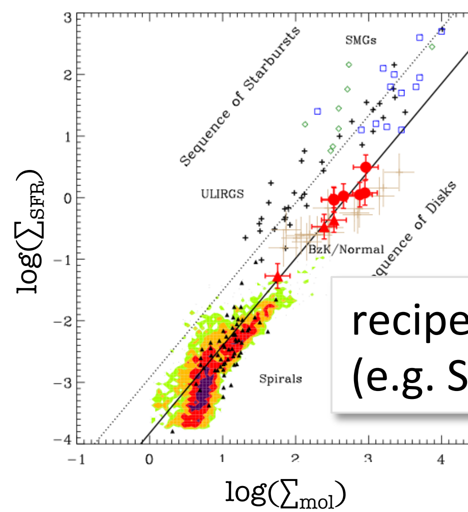

2) SB+MS de-composition at fixed $M_\star$
(**Sargent**+ ‘12)




3) sSFR evolution
(e.g. Reddy+ ‘12)

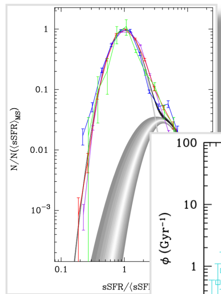



4) recipes for SFE
(e.g. S-K law)

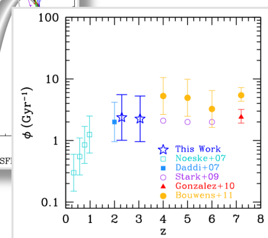


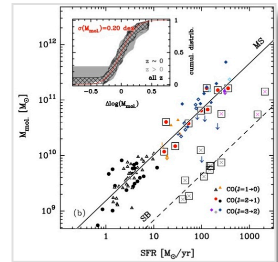
# Stellar mass fct. ➡ SFR distribution ➡ $H_2$ distribution

(s)SFR-distrib.
at fixed mass:



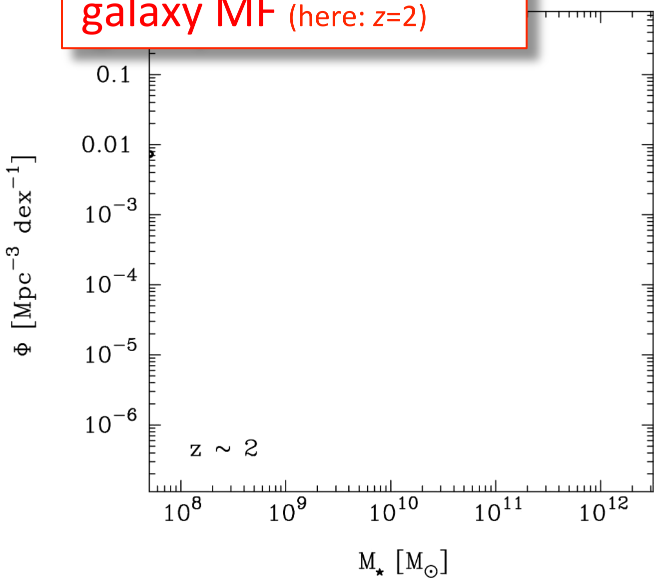

sSFR-evolution
of main-seq.:

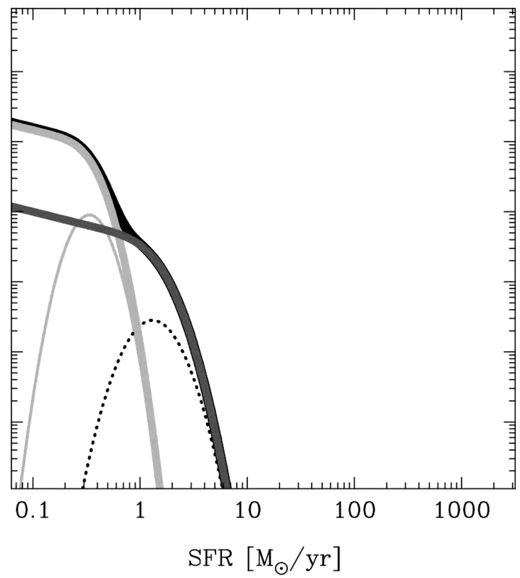



SFE-recipes for normal
& starburst galaxies
(Schmidt-Kennicutt rel.)

star-forming
galaxy MF (here: *z*=2)



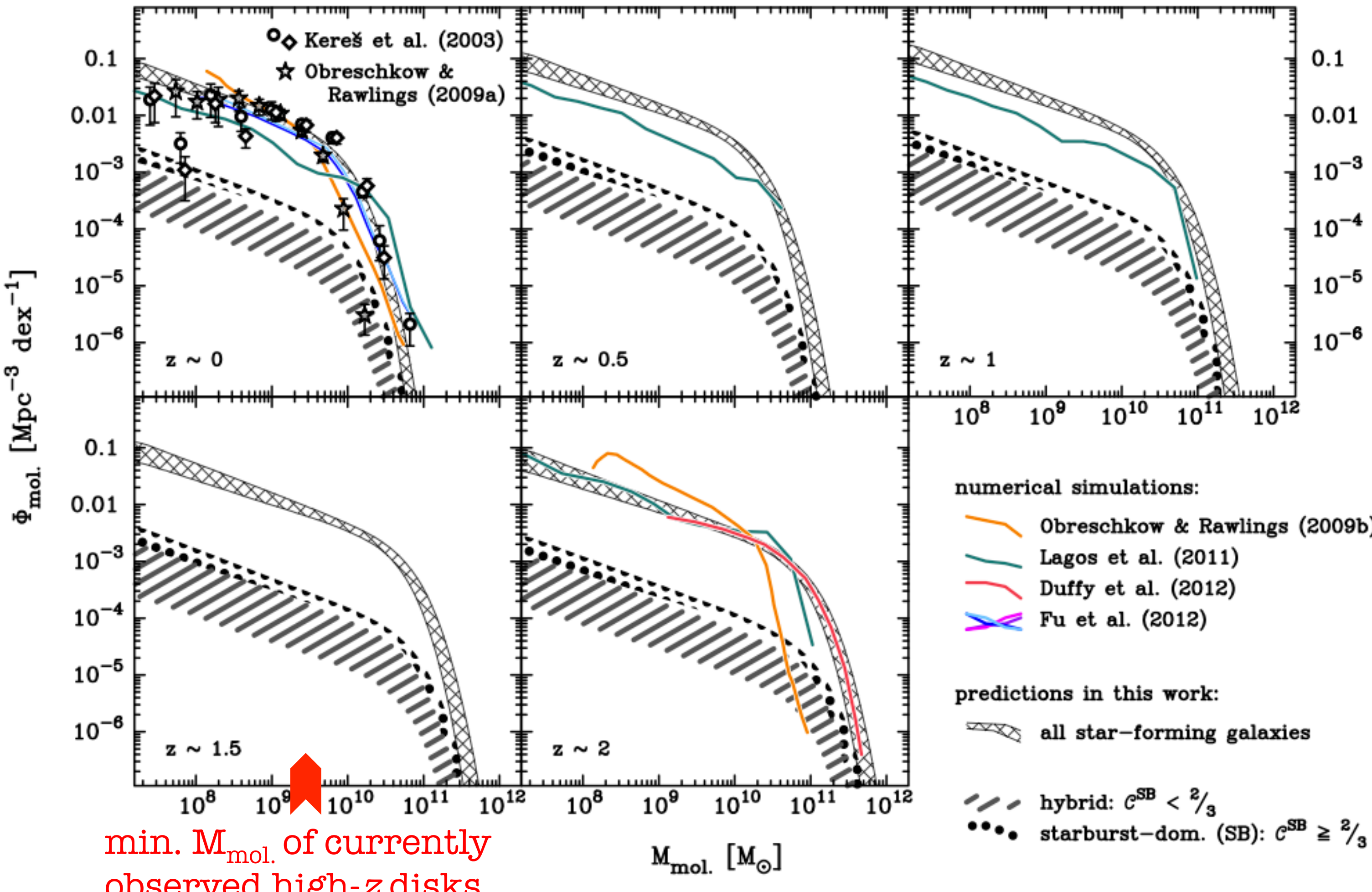




SFR distribution

# The molecular gas mass function ($z < 2.5$)

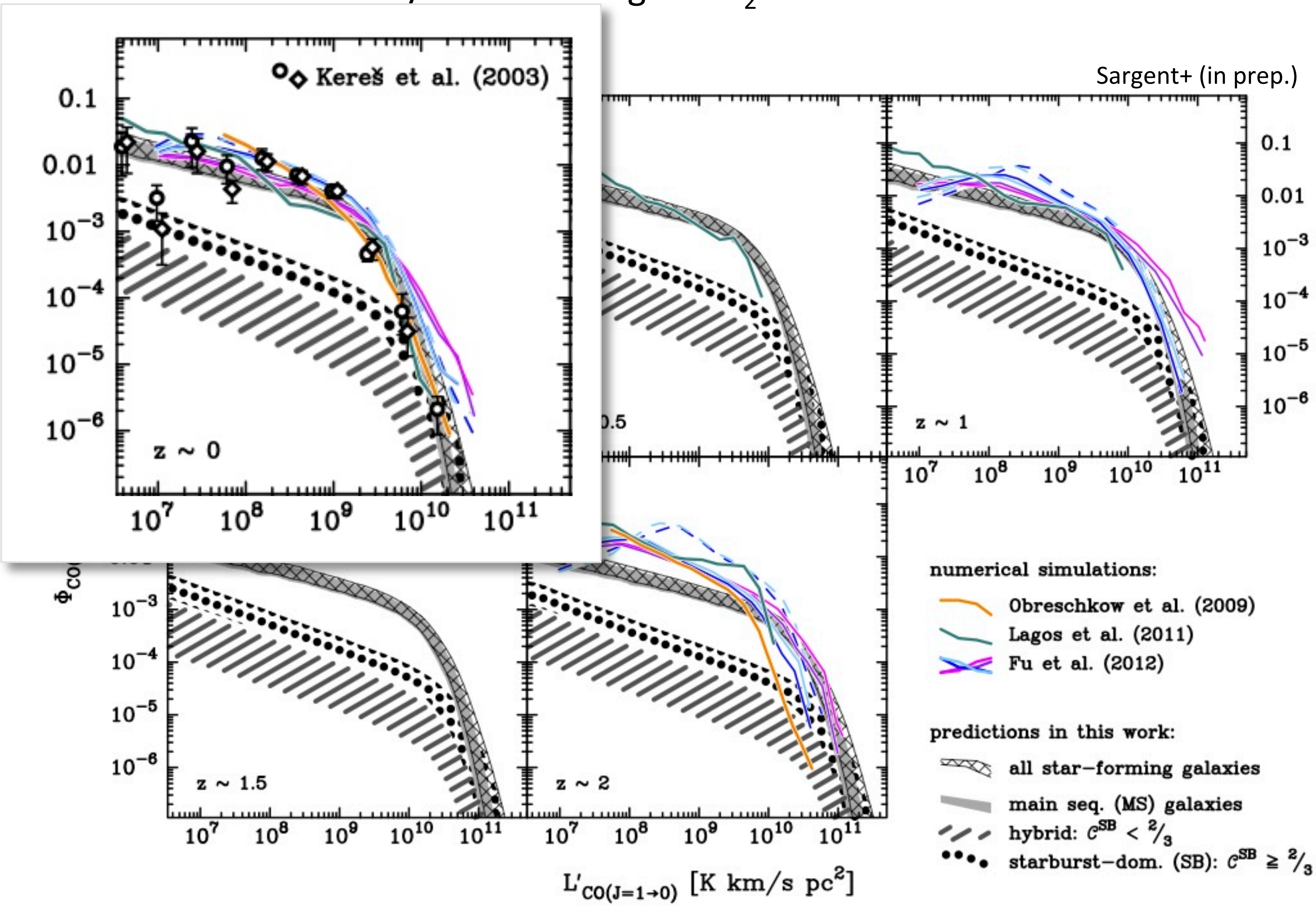
*Indirect measurements!* (Currently we only have ~40 high-*z* (public) mol. gas mass measurements in main-seq. galaxies)

Sargent+ '13b



# The CO($J$ =1-0) luminosity function

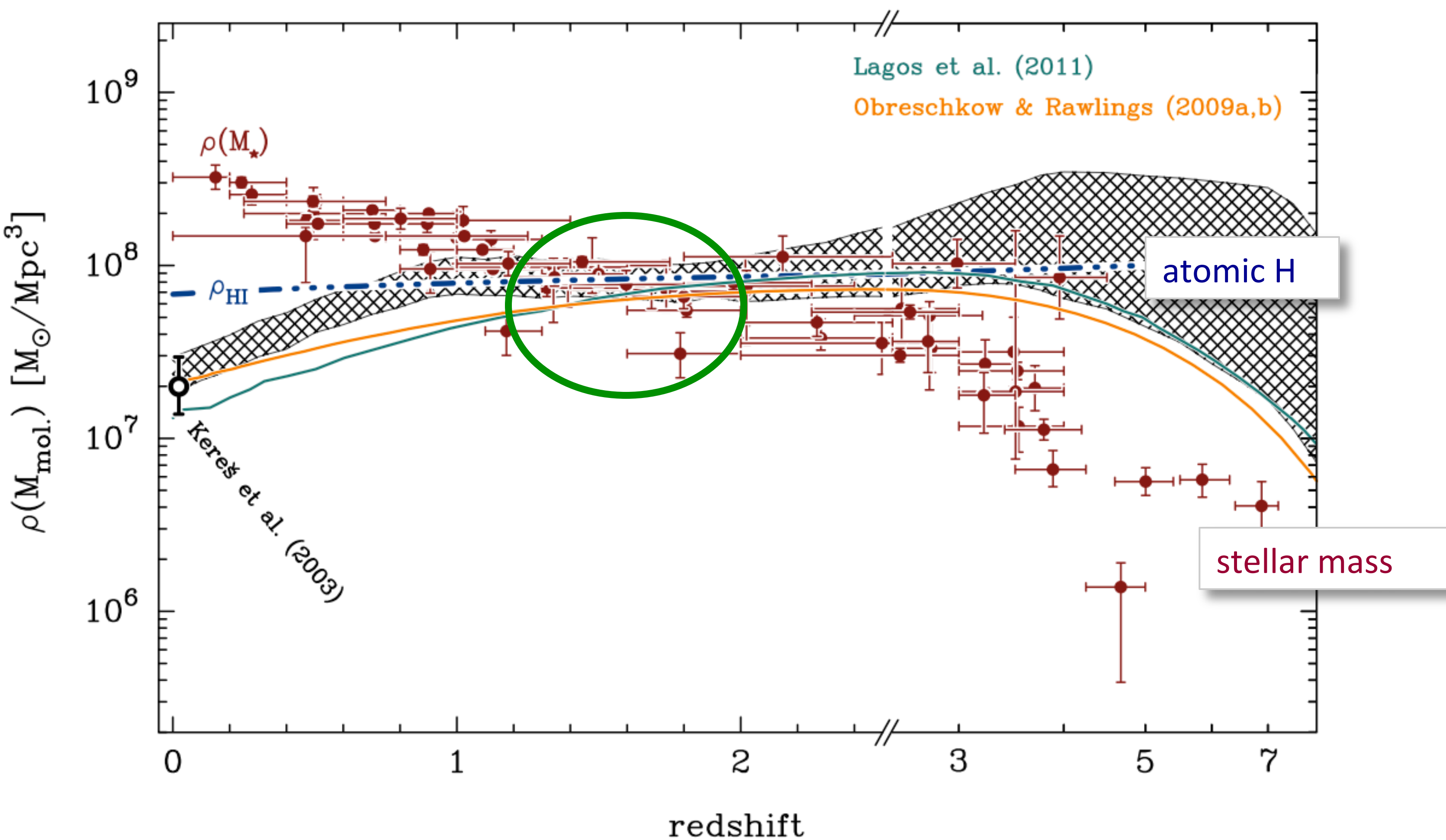
... or: the observational key to recovering the $H_2$ mass function

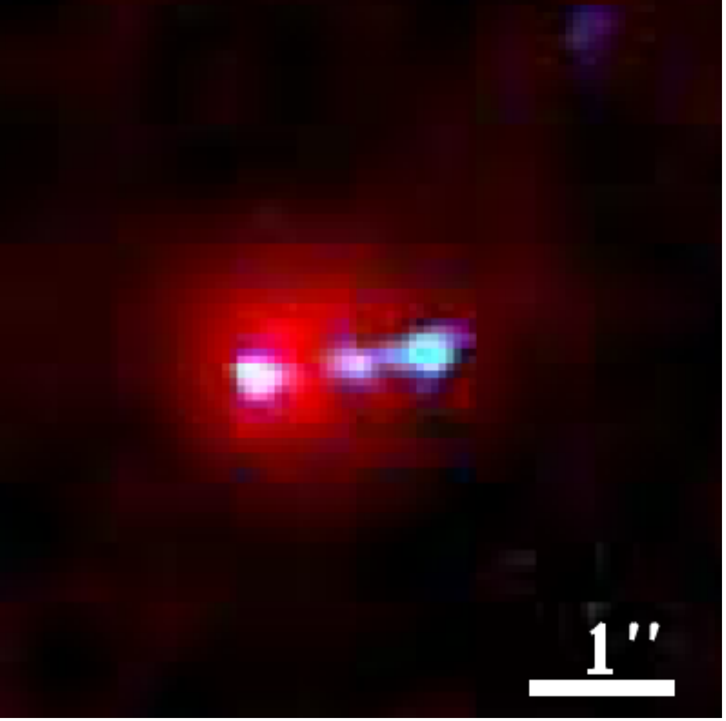


# Cosmic evolution of $H_2$-reservoirs

Ne
m
(
(
g

Sargent+ (in prep.)






Vanishing CII and continuum due to low-Z ?

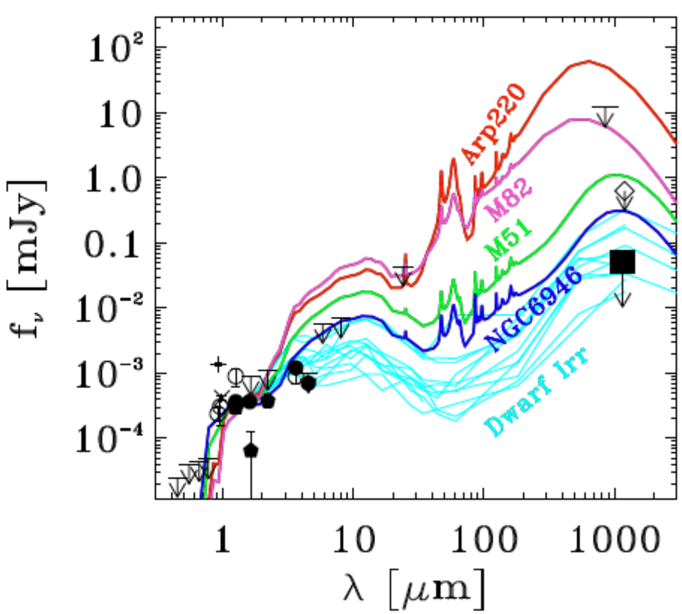
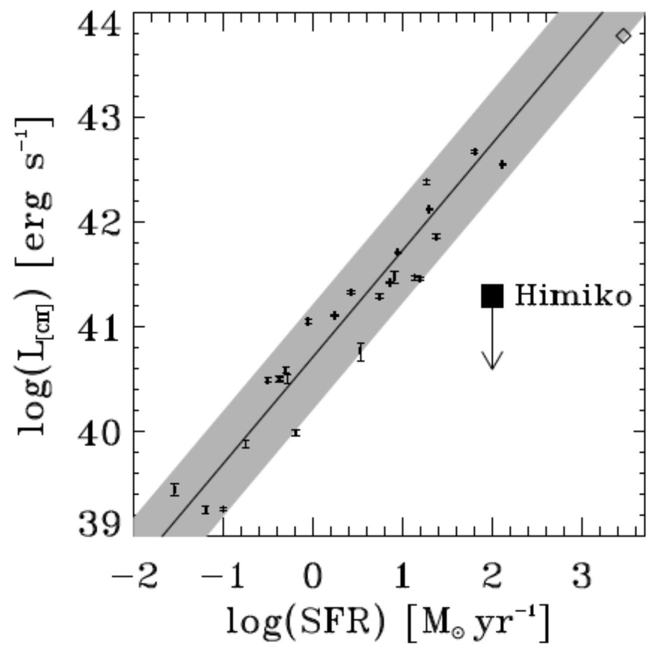



FIG. 5.— The optical to far-infrared SED of Himiko in the



# Summary

Gas in MS galaxies in the distant Universe

- From CO (alphaCO problem)
- From Mdust
- Dependence of fgas on z, sSFR, stellar mass

Bimodal behaviour in the KS plane (SF law)

- interpretation
- models

SF efficiency and fgas for starbursts

2-SFM predictions for the gas

- MF, LF
- gas madau plot

The puzzle of high-z low-Z Universe

"Cosmological Simulation in Galaxy Formation"