The different star formation modes during cosmic time

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Outline

Intro: the nature of star formation at low and high-z

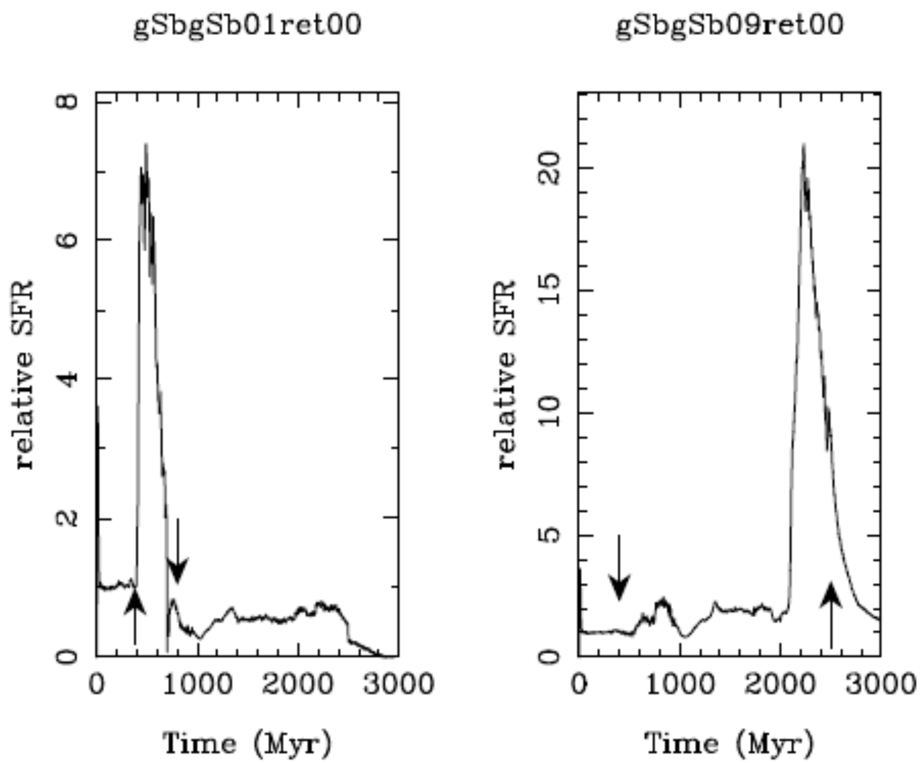
Mass-SFR correlation, molecular gas observations, star formation laws, comparison to theory

New/recent results: the bimodal view of galaxy activity
(quiescent vs starburst)

1. Conversion factor CO → H2, constraints through Mdust (Magdis et al 2011 and in preparation)
2. Statistical contribution of starbursts vs MS (Rodighiero et al. 2011)
3. From stellar mass to luminosity functions, a self consistent approach (Sargent, Bethermin, et al 2012)
4. H2 mass functions and global density versus redshift (Sargent et al. in preparation)

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)

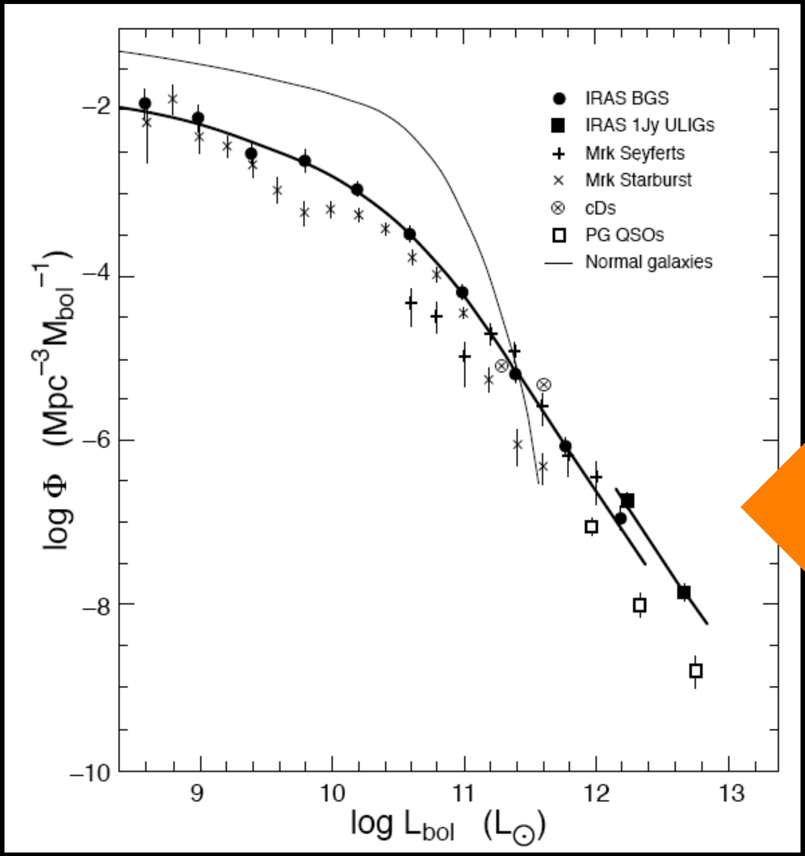


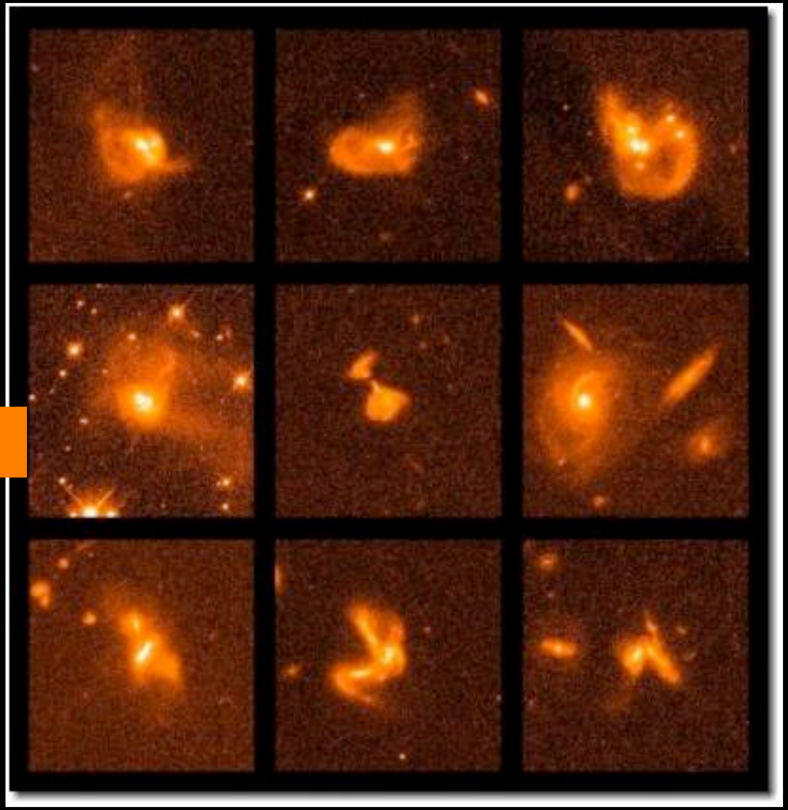
Di Matteo et al 2008
Martig & Bournaud 2008

(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 ?

At low-z, most luminous galaxies (ULIRGs) are mergers





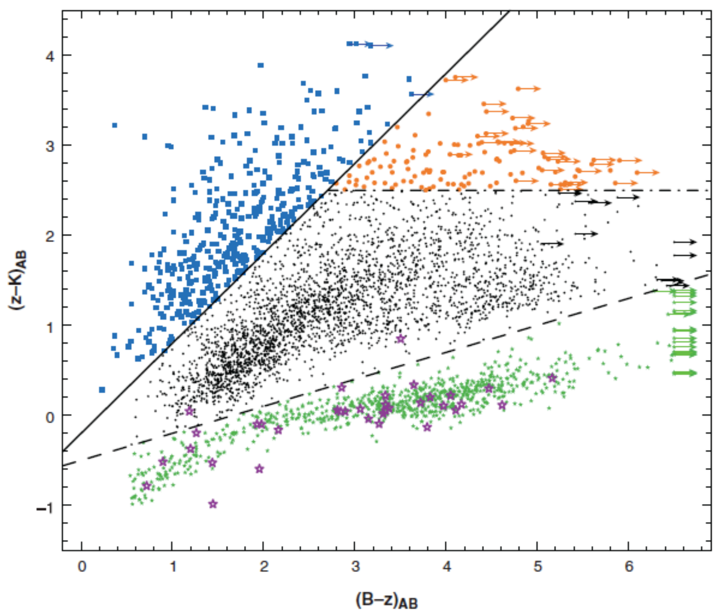
Observational differences: Locally ULIRGs (mergers) vs spiral galaxies (disks)

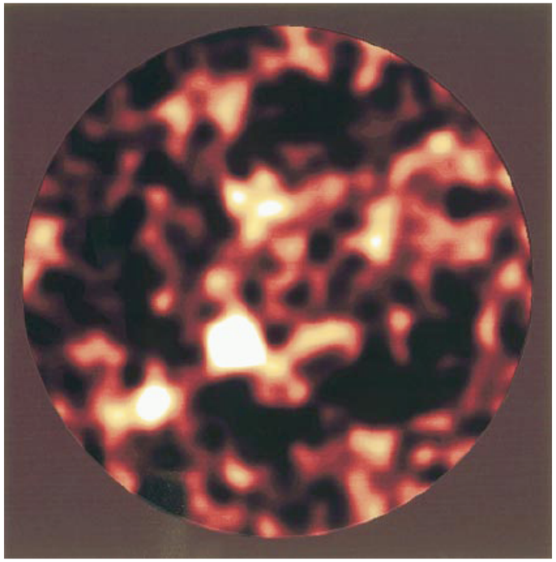
1) SSFR is higher in ULIRGs
2) (Dust temperature higher in ULIRGs)
3) ULIRGs are optically thick
4) ULIRGs are dynamically hot
5) Star formation efficiency SFR/LCO higher too
6) LCO/Mgas (conversion factor) higher
7) Excitation of CO emission higher

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

Is there something analog at high-z ? And in any case, we cannot Forget about this duality when studying high-z galaxies

BzK vs SMG share analogy between SDSS vs ULIRGs selection

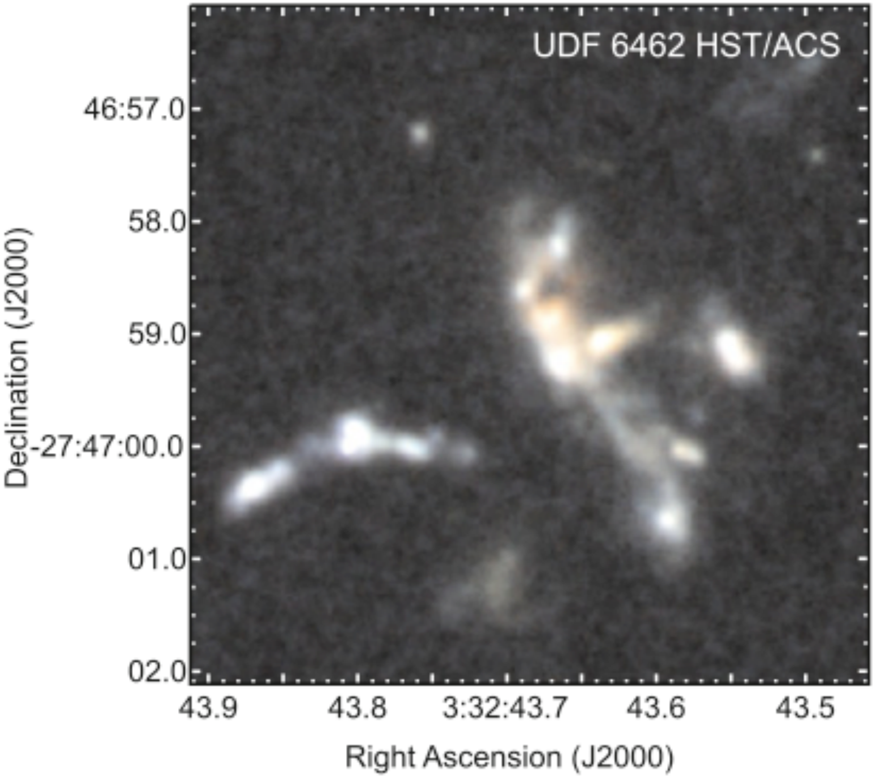




But beware:

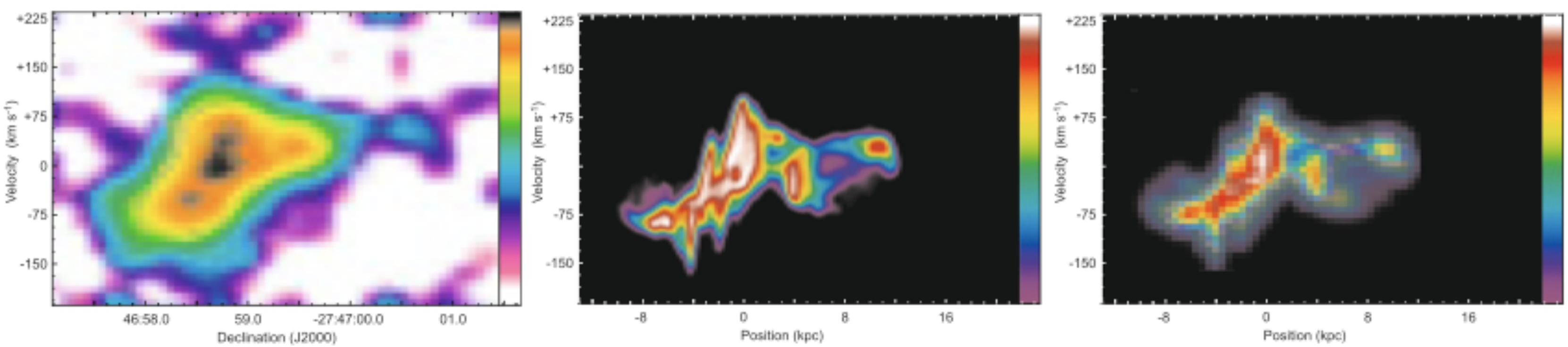
1) Lots of SMGs have BzK colors (although some are unseen)
2) Some BzKs can reach huge luminosities also UV-estimated

(i.e., they are often ULIRGs themselves)



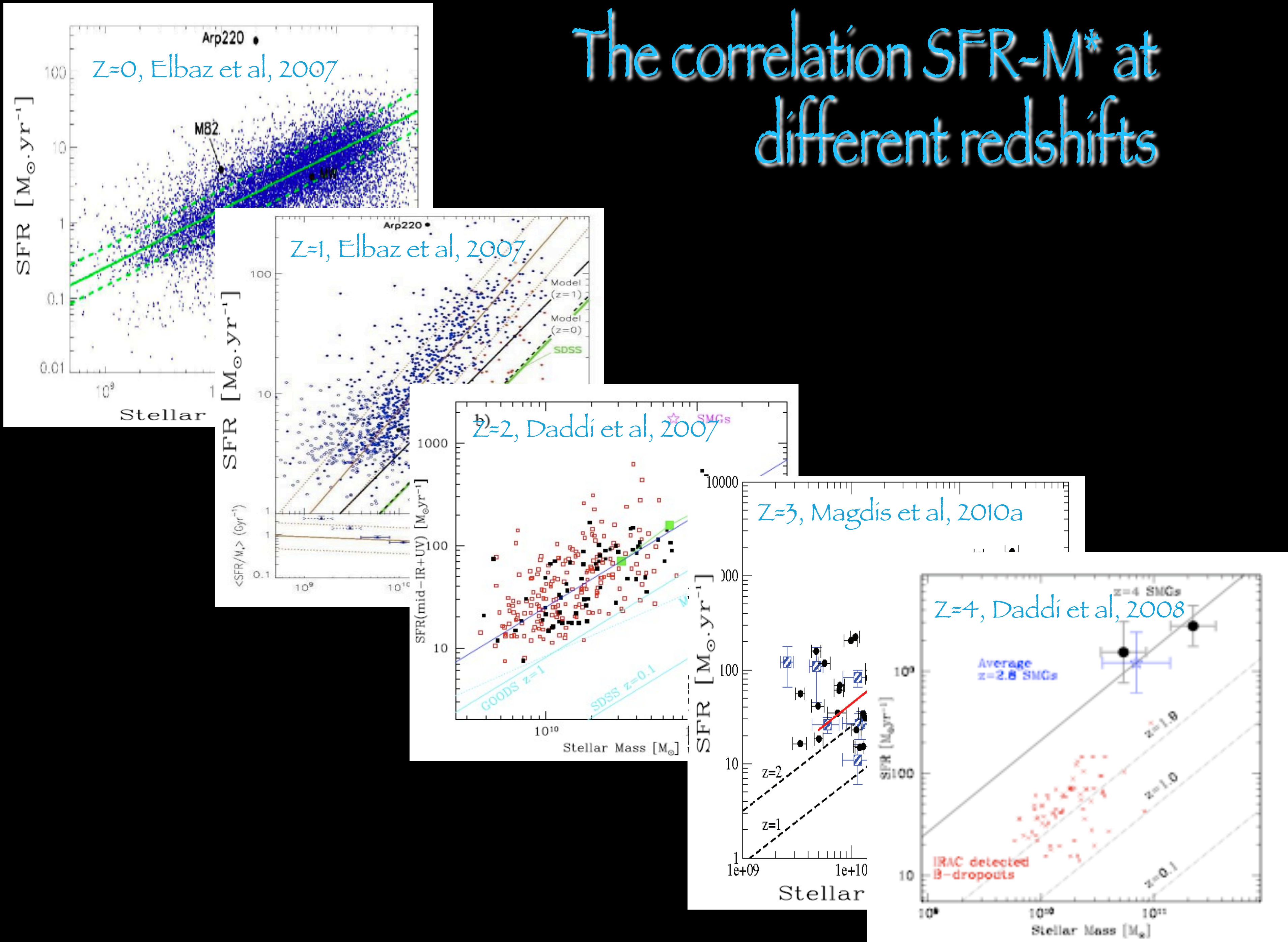
Clumpy galaxies are
not necessarily mergers,
might be extremely rich
gas galaxies

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



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

The correlation SFR-M* at different redshifts



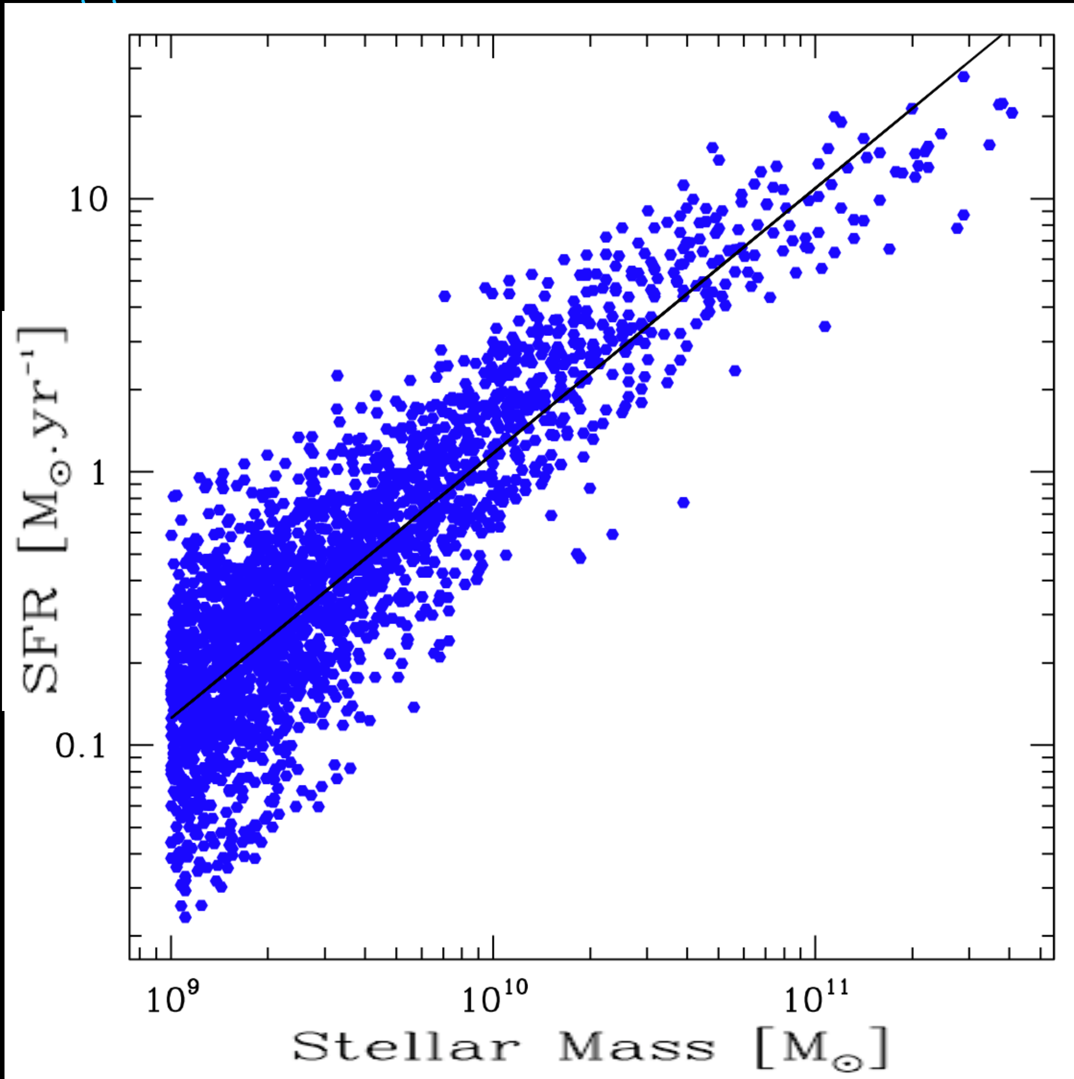
Comparaison to simulations

- Scatter 0.26dex

Comparable to observations for disks

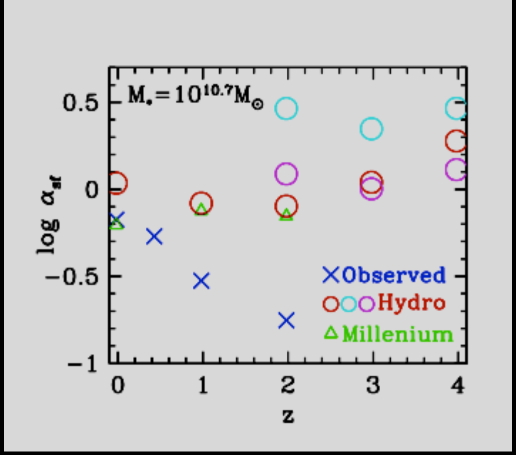
But simulations miss the SF ETG component

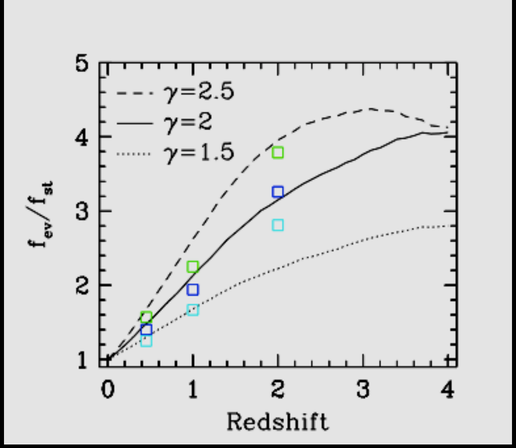
Oppenheimer and Davé, 2006 at z~1



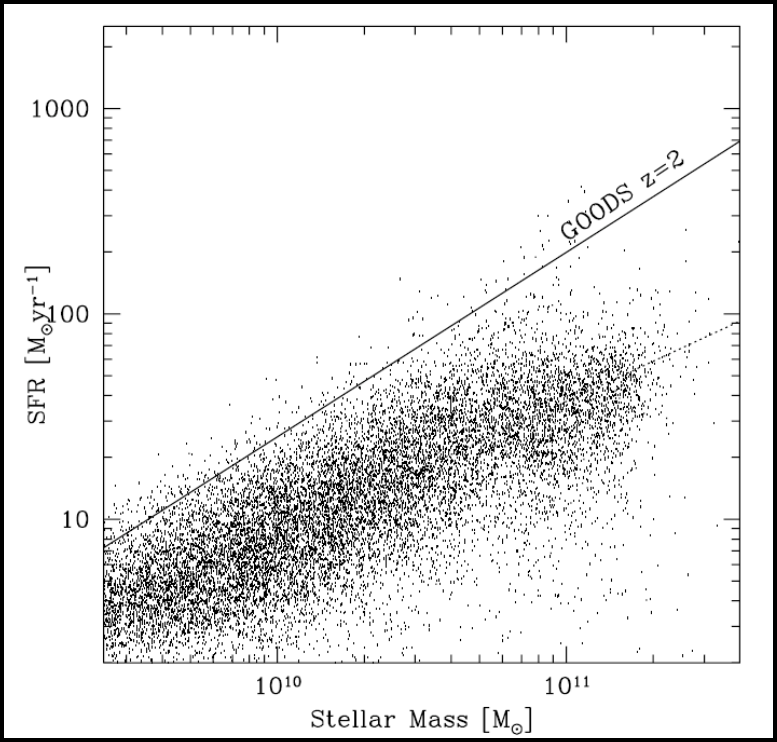
SFR-mass correlations were predicted by models before observations
But the rapid rise of LIR of galaxies up to z=2 is a problem for models

Dave 2007 (α = doubling time/t_H)





Kitzbichler & White2007

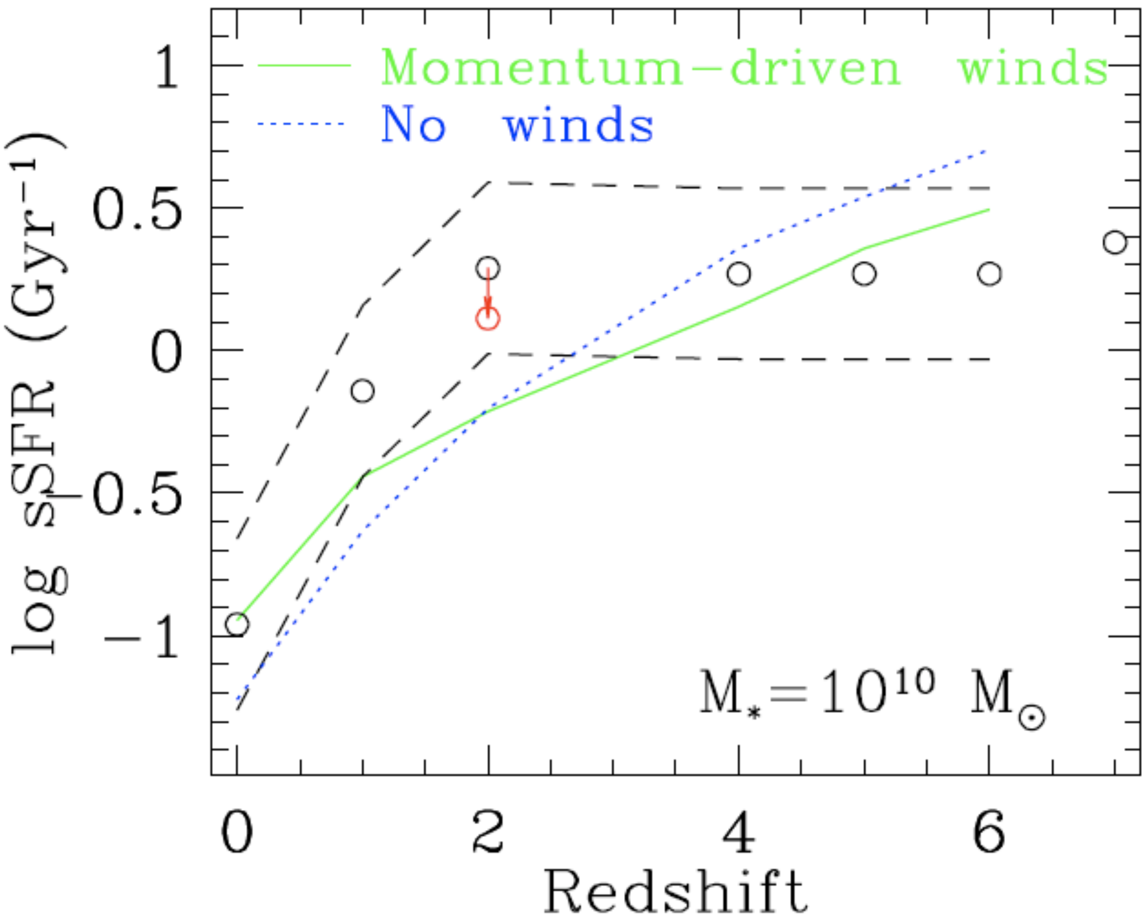


Requires a rapidly evolving IMF (see also Baugh 2005, etc)

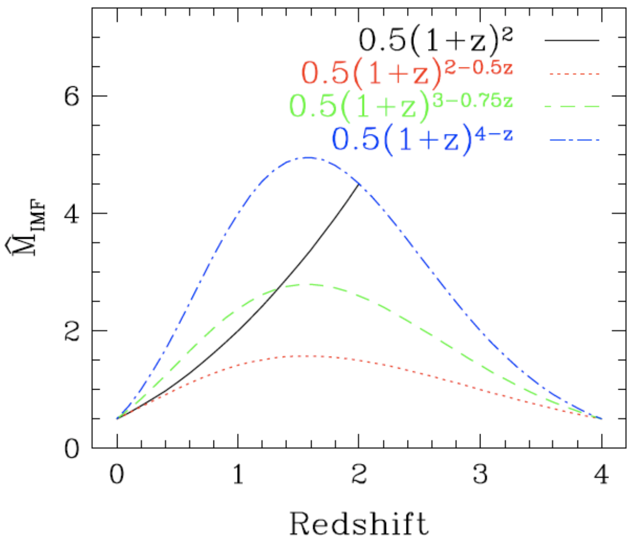
→the stars that made the IR background left nothing behind ?

→ test this issue with Mass-Function growth

The puzzling cosmological evolution of SSFR



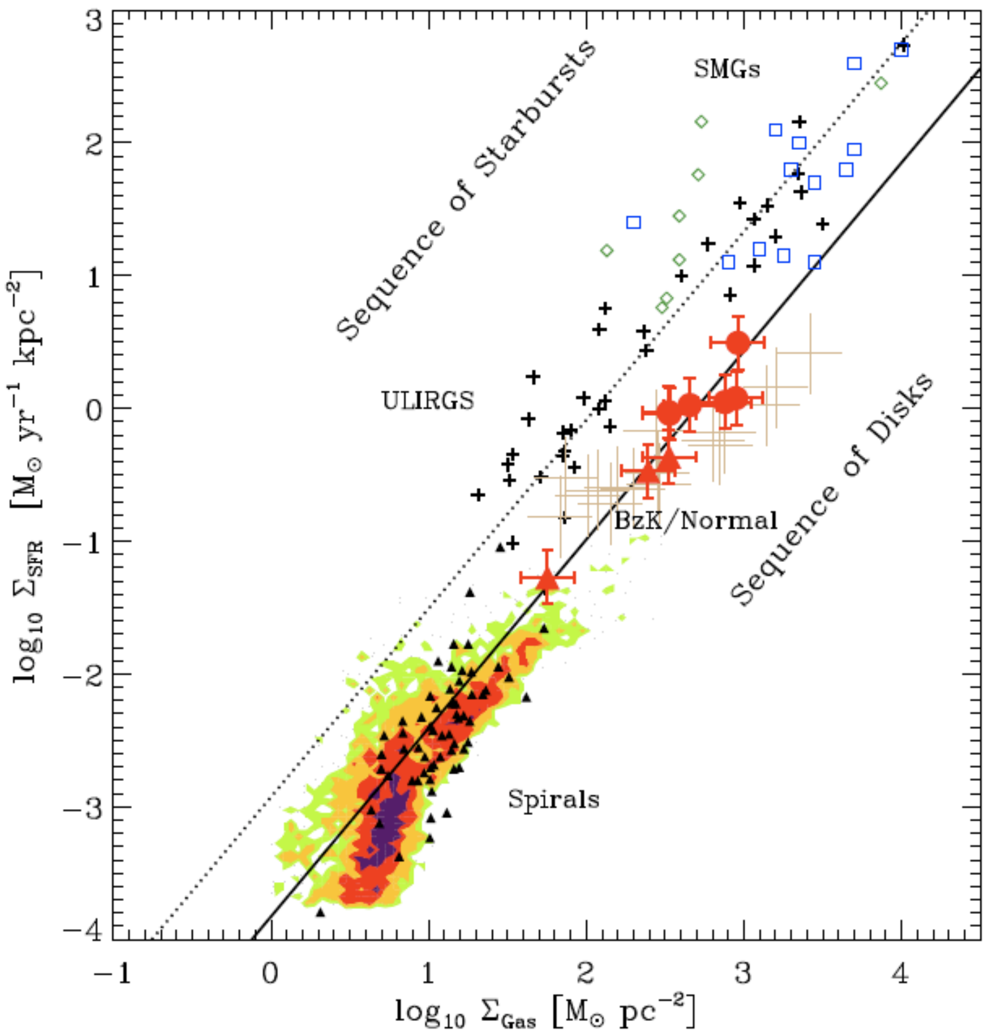
Dave et al 2010



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

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



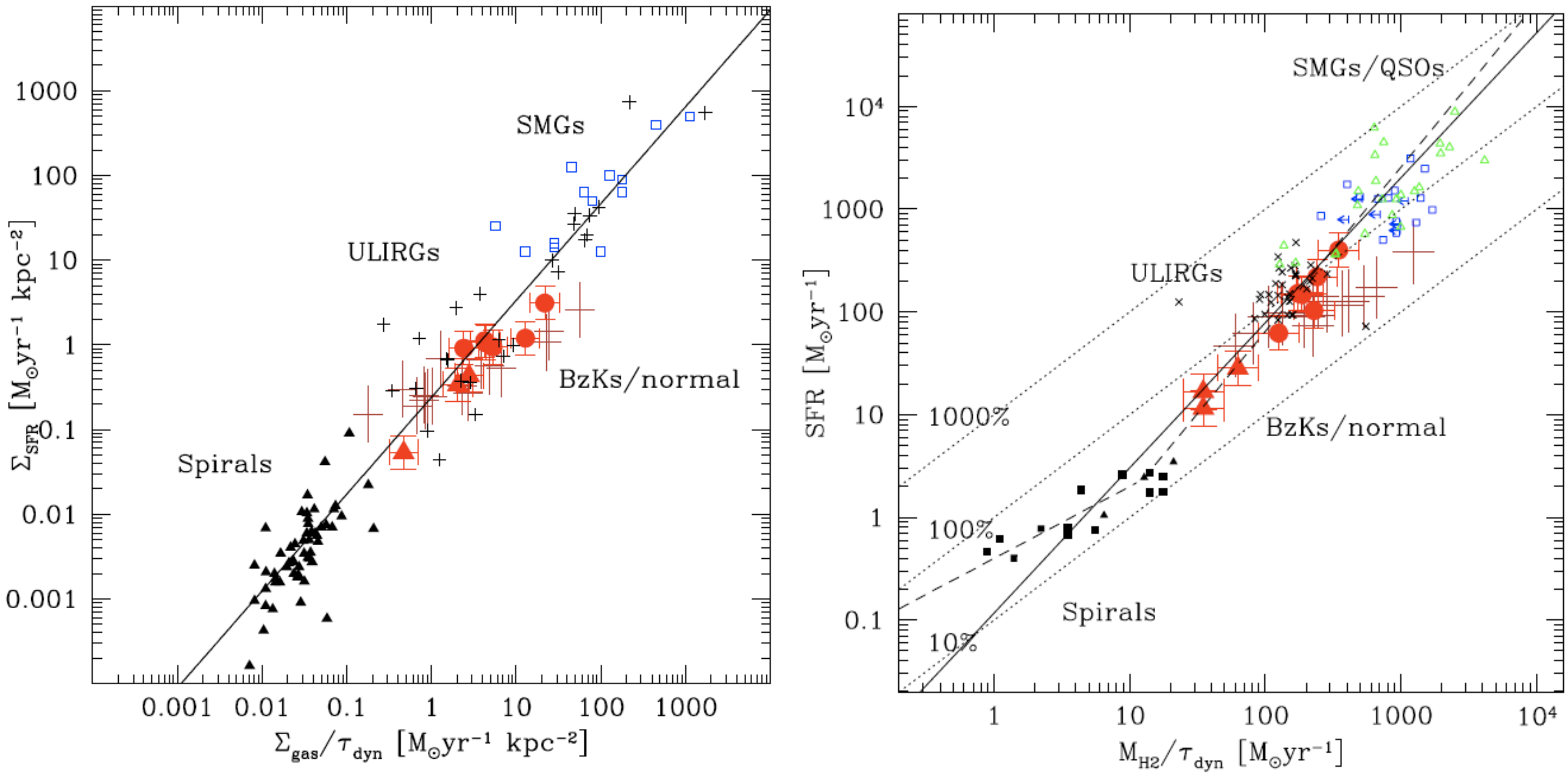
Normal (main sequence) Galaxies behave very Differently from SBs

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

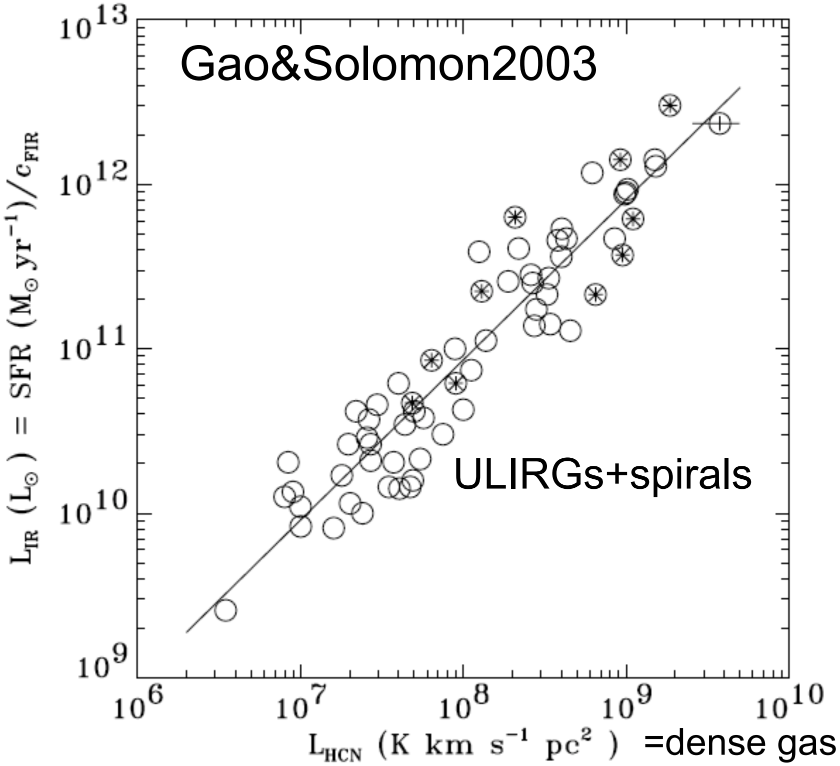
When considering the dynamical (rotation time)
Silk 97; Elmegreen 2002; Krumholz et al 2009; 2011; K98

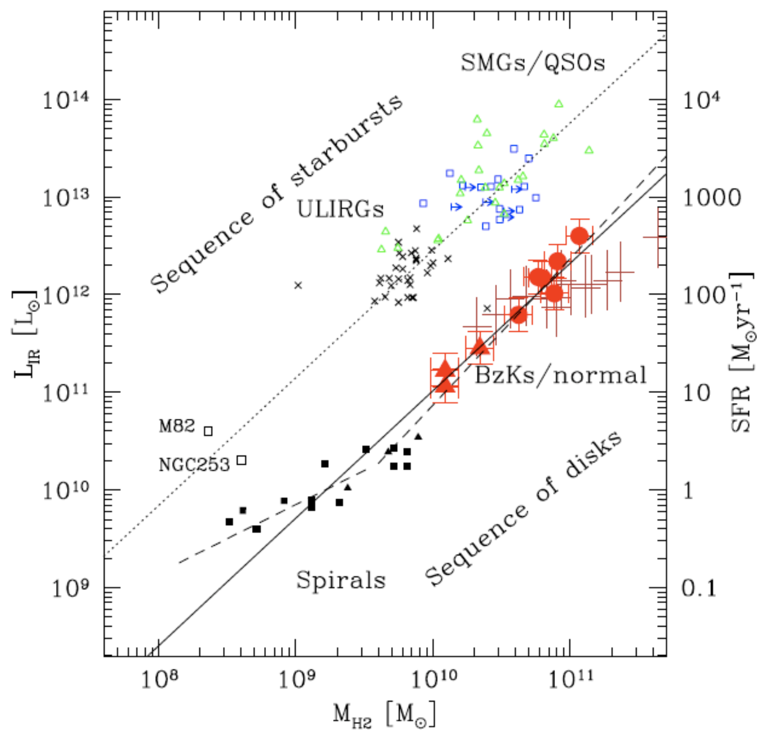


Both disks/starbursts fall back to a single law
→ tau_gas vs tau_dyn relation is unique

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

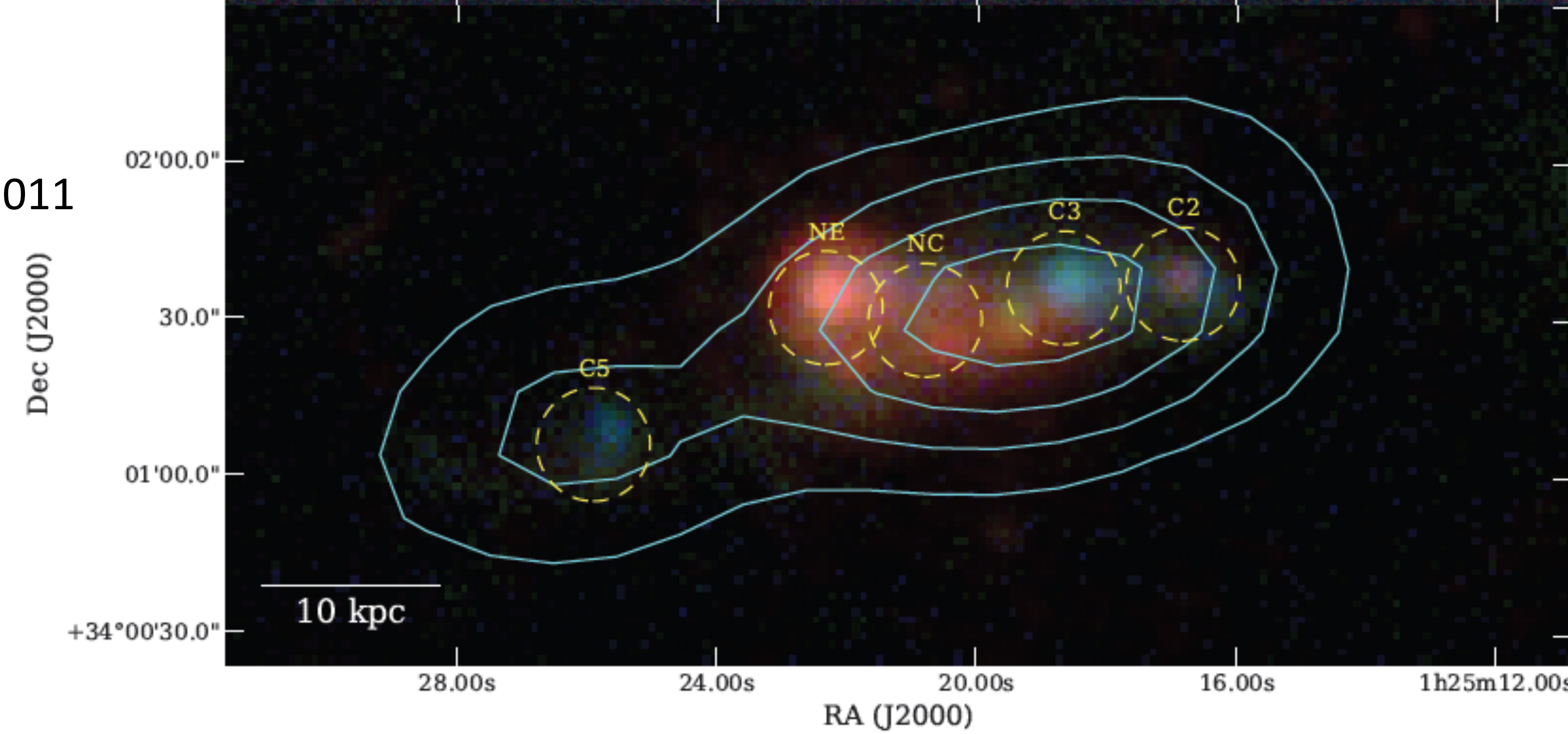
The different 'modes' seem to relate to dense gas fraction (Daddi et al 2010b)

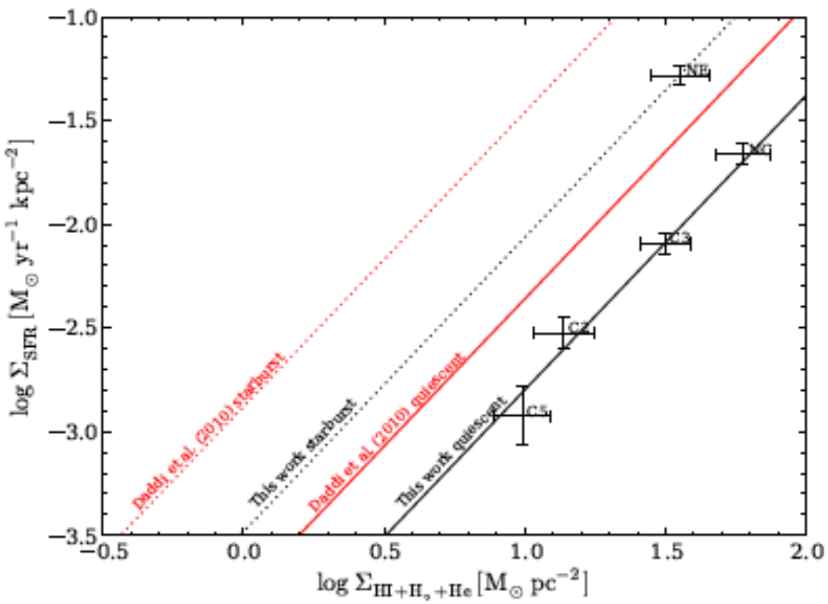




Bimodal trend for total H_2, single linear trend for most dense H_2
→Different behaviour for the fraction of dense gas in disks/SBs
→ playing with IMF would leave at least 1 bimodality

Arp158
Boquien et al 2011

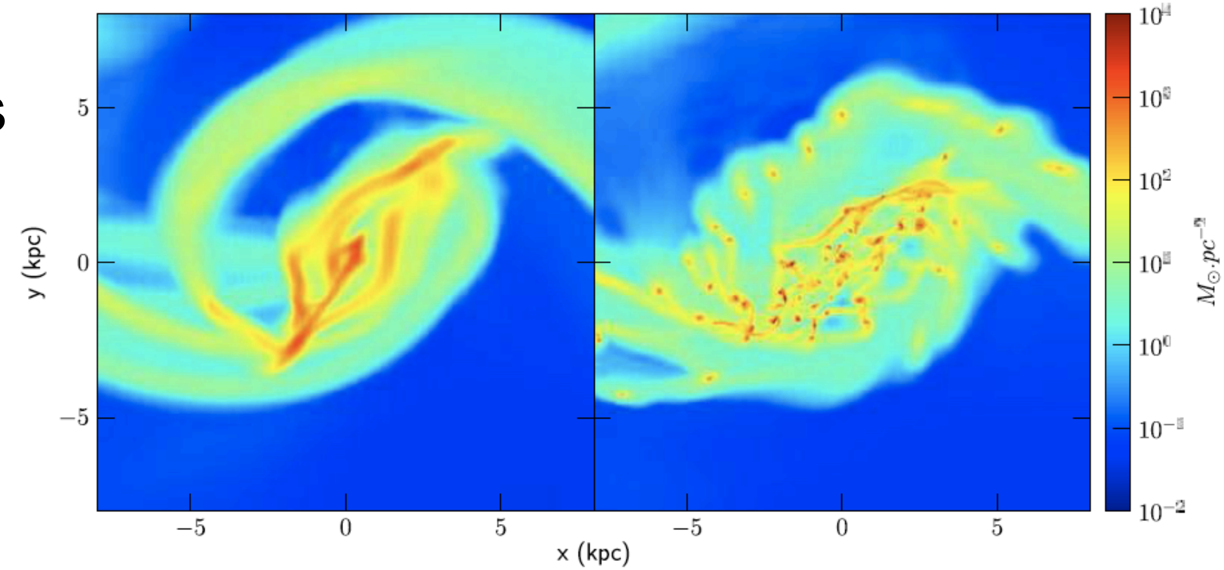


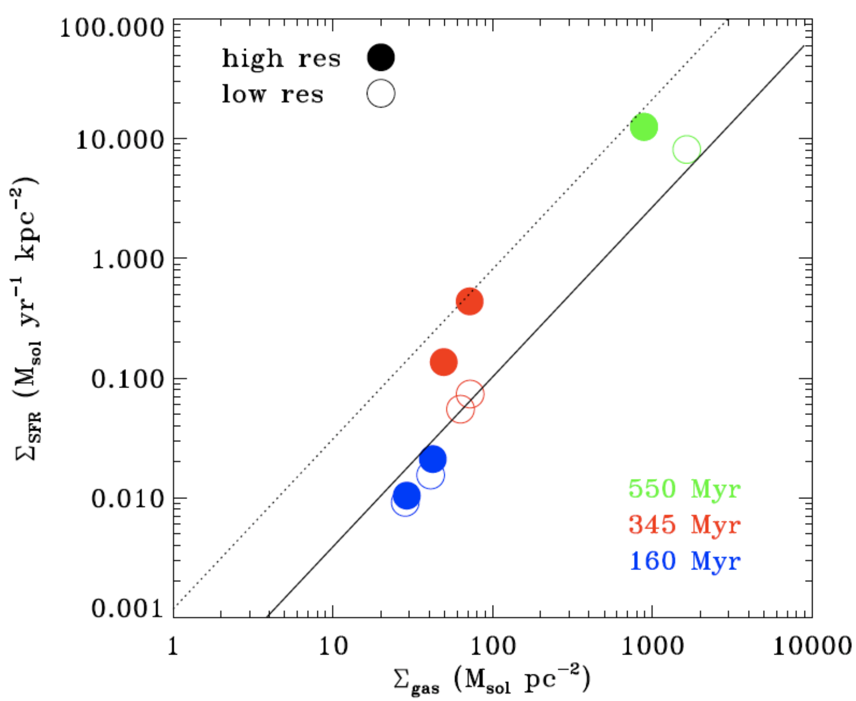


Two modes seen inside a single galaxy

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)

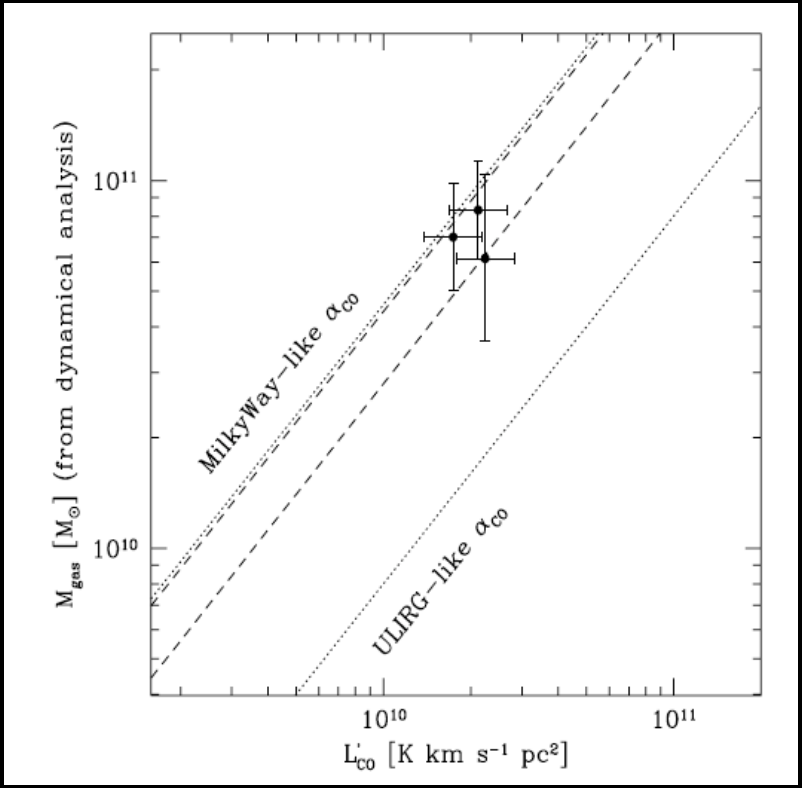
But this 'merger' does not show the single central concentration one would expect?

Two important problems:

1) CO to H2 conversion factors at high z. What they are ?
Different in SBs and MS galaxies ?
<u>This is totally fundamental for physical interpretation</u>
(are we fooling ourselves in believing z~2 massive galaxies are 50% gas ?)

2) Are SMGs all SBs (Engel/Tacconi et al) ? Or ~none (Dunlop et al) ?
Can we find starbursts at high-z to study this bimodality ?

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



To get back to '0.8' (ULIRGs value)

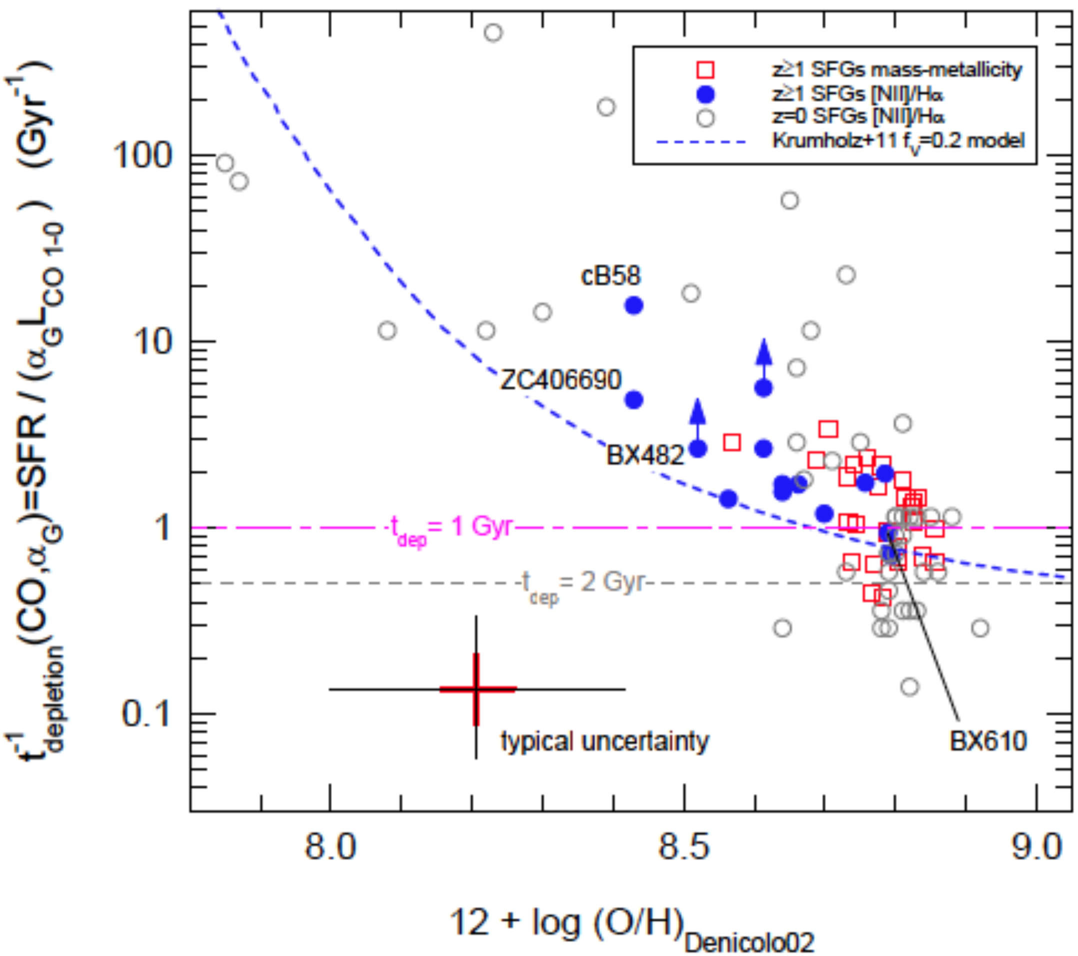
- Dark matter ~60%
- M_{stars} x3 larger
- 'Bournaud' factor down to 0.7 (1.3) (i.e., velocity overest.)

Daddi et al 2010

Based on Bournaud et al 2007 clumpy disk models
See also Narayanan et al results from theory

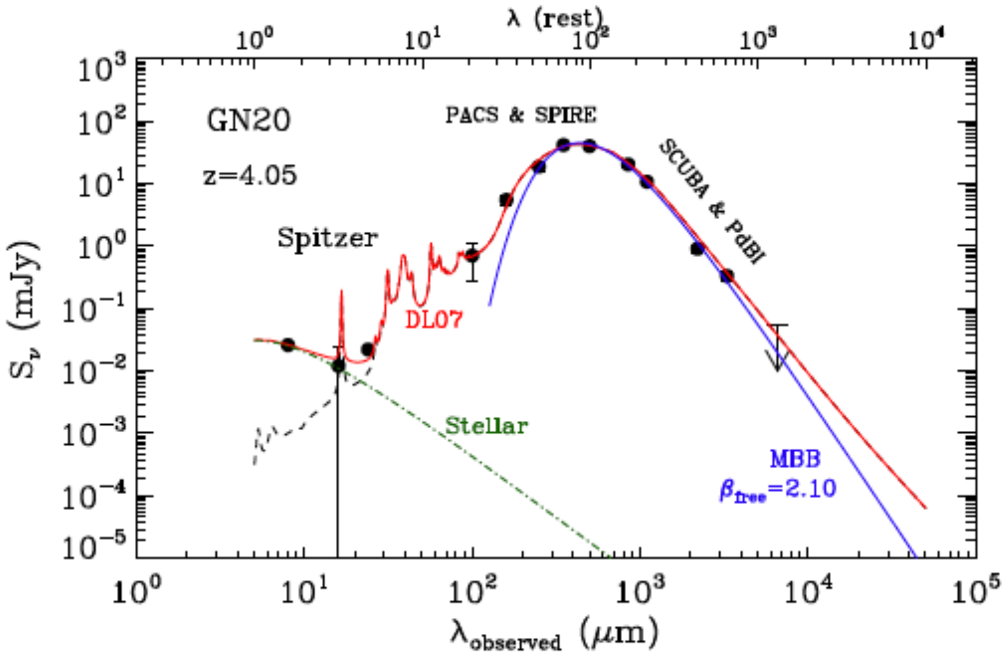
SFR/L'CO scales with metallicity as in local galaxies

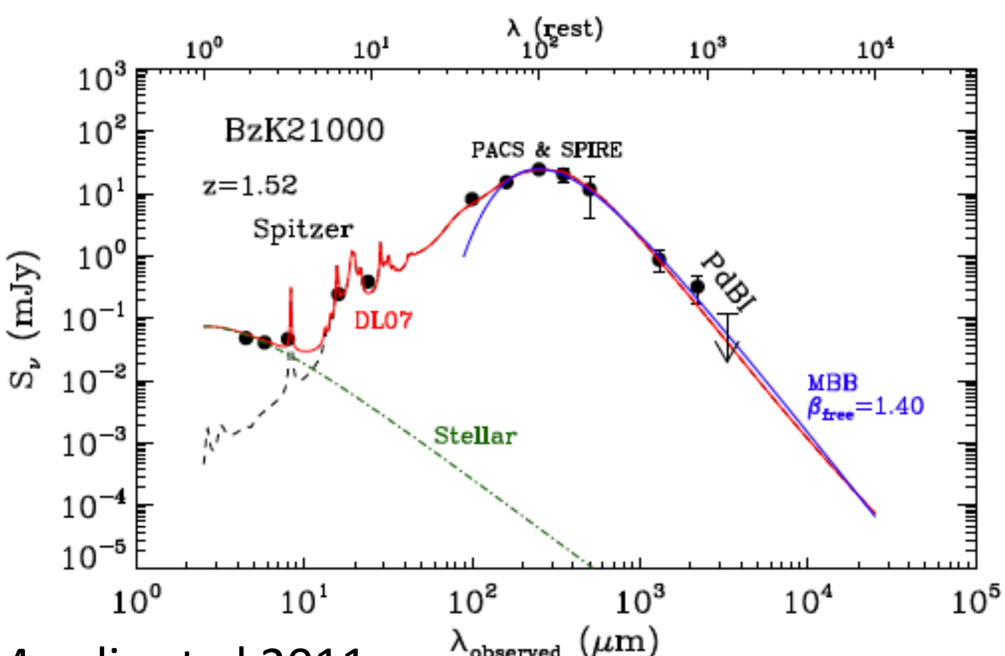
Genzel et al 2011



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

But tells nothing about the normalization





Magdis et al 2011

A way to constrain a_CO in the local Universe is through Mdust measurement (and prior knowledge of what Dust/Gas should be)

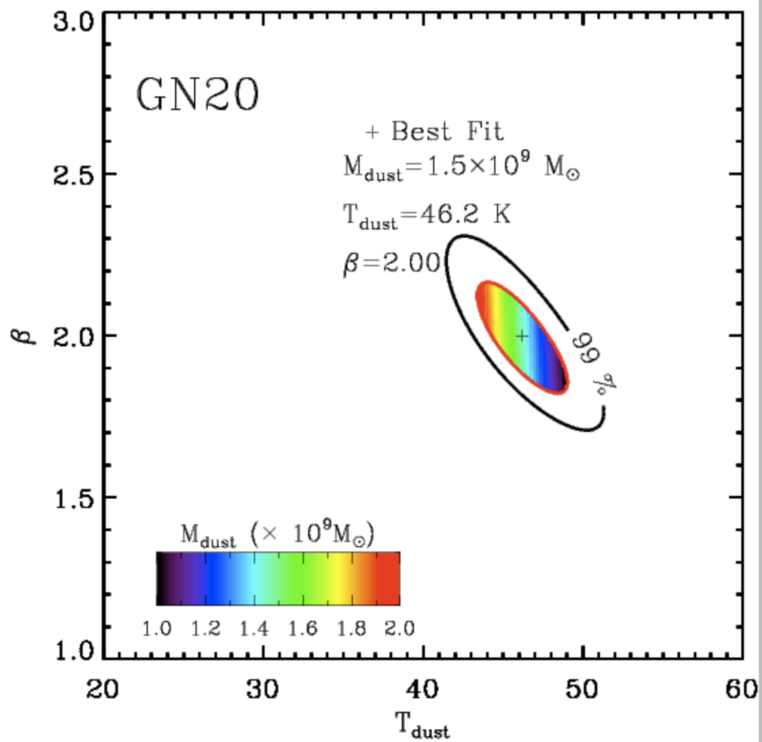
We had lots of IRAM observations to look at multiple CO transitions, and continuum as a byproduct (hard and expensive to get)

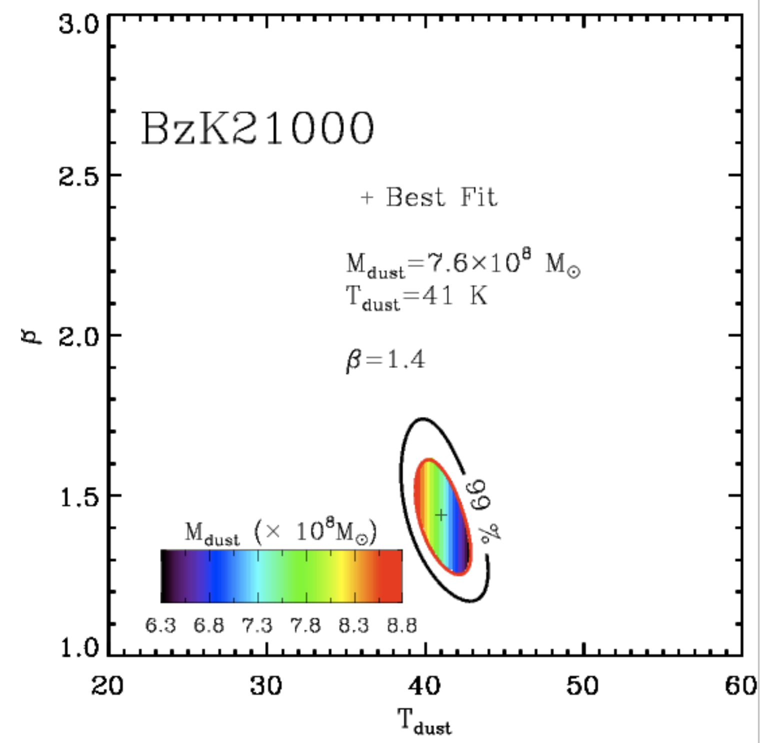
→ This will change dramatically with ALMA

Modeling approach:
- Full suite of Draine and Lee 2007 Models
- MBB with free T and beta

Parameter constraints from MBB models

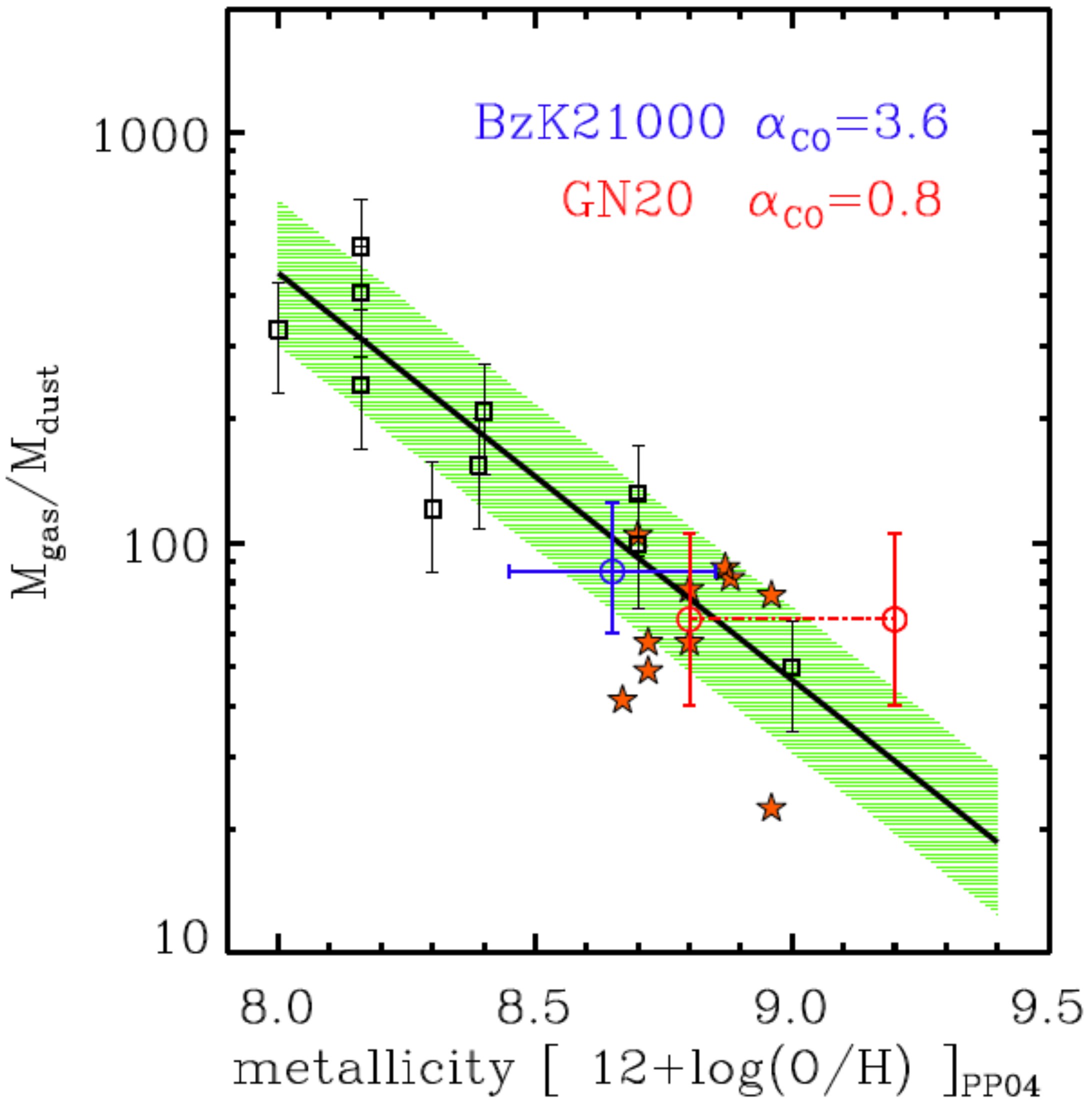
Magdis et al 2011





Different beta for MS vs starbursts ? Consistent with Elbaz et al 2011

Using the standard assumption for alpha_CO → they lie on the G/D relation

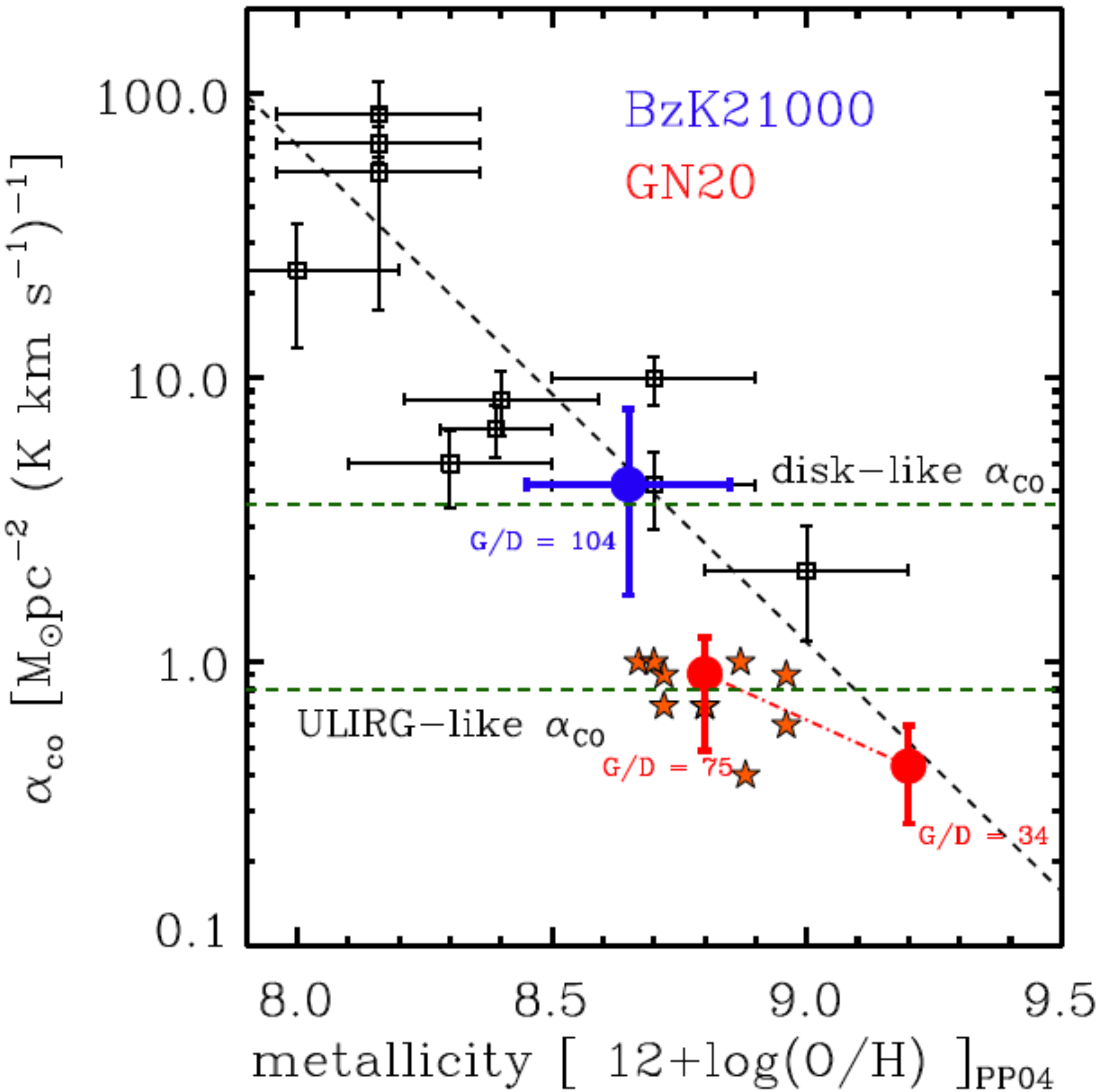


Local group spirals
(Leroy et al 2010)

ULIRGs
(Downes and Solomon 1998)

Magdis et al 2011

Trusting the G/D trend → get estimates for alpha_CO



Notice that it is very hard
To overestimate much Mgas
Hence alpha_CO
Because G/D > 1/Z

And the local relation has
G/D~2/Z

GN20 vs BzK21000 → normal vs starburst

Systematic difference in Mdust/LCO, Mdust/LIR
(similar Mdust/Mstar as expected, see da Cunha et al 2010)

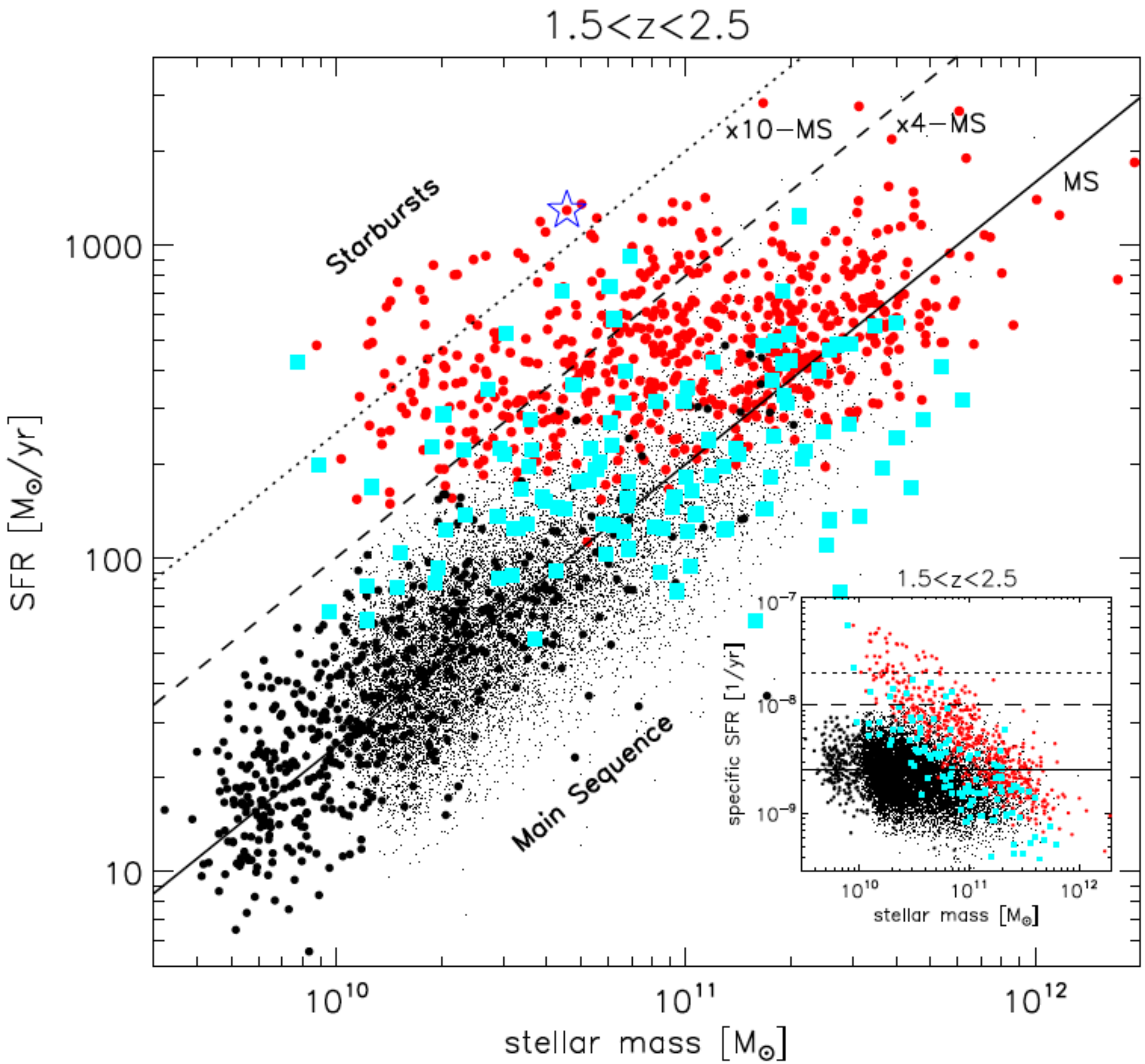
→ High sSFR in GN20 because SFR has been 'enhanced' (merger ?)

From D/G ratios trends → get alpha_CO much different in the two
→ Higher SFE=SFR/Mgas in GN20 by 5-10 (and prop shorter t_gas)
→ Confirm the much different locations in the KS plane

Of course, we would like to do this with >>2 galaxies

A few more are becoming available (IRAM/EVLA?).
Alma will probably change this field too

What is the statistical importance of SB galaxies ? *Typical answer: ~50%*

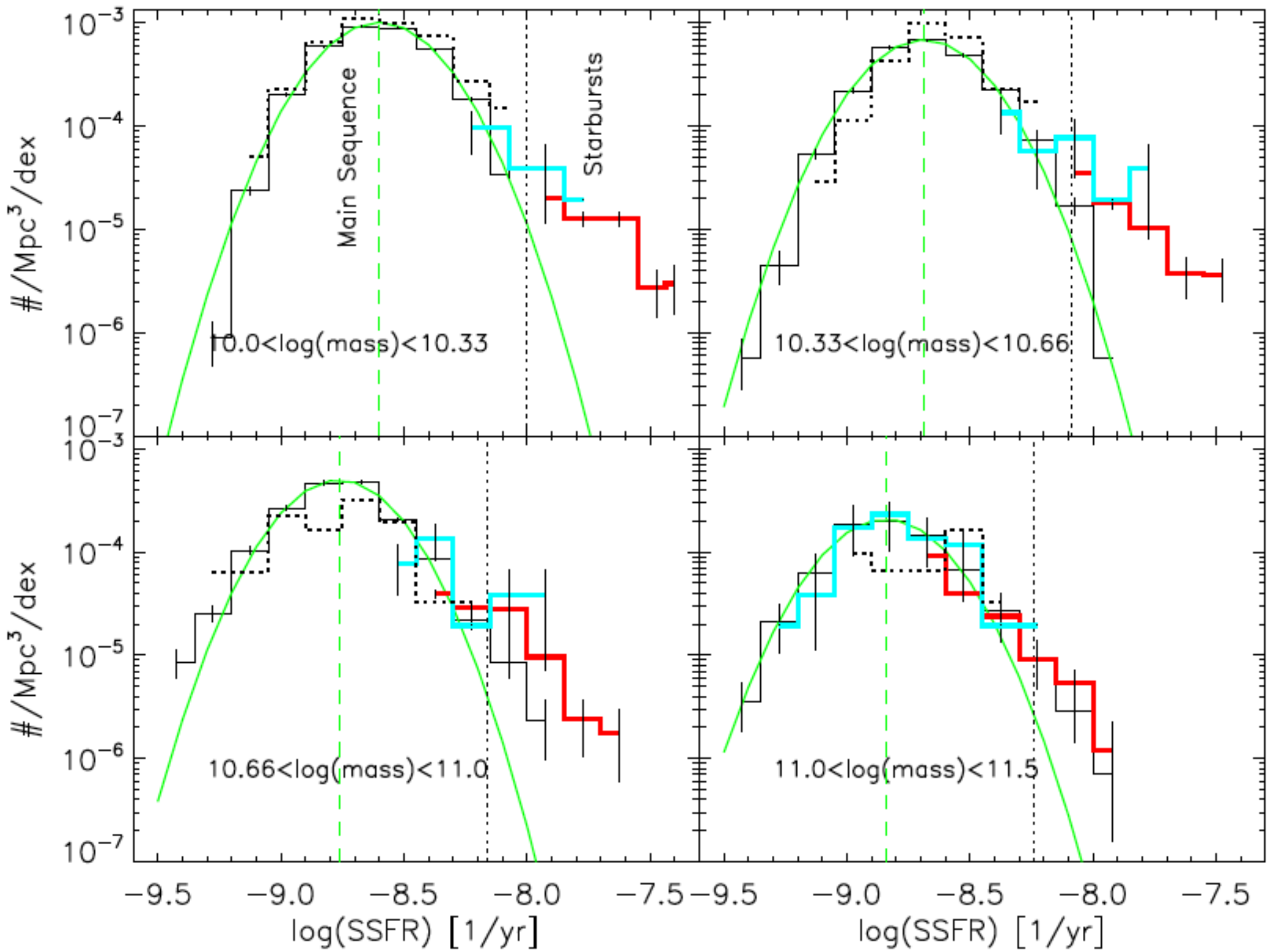


COSMOS PACS data
From PEP
(and also GOODS-S)

Near-IR galaxies
From BzK samples,
UV-corrected SFRs

Rodighiero et al. 2011

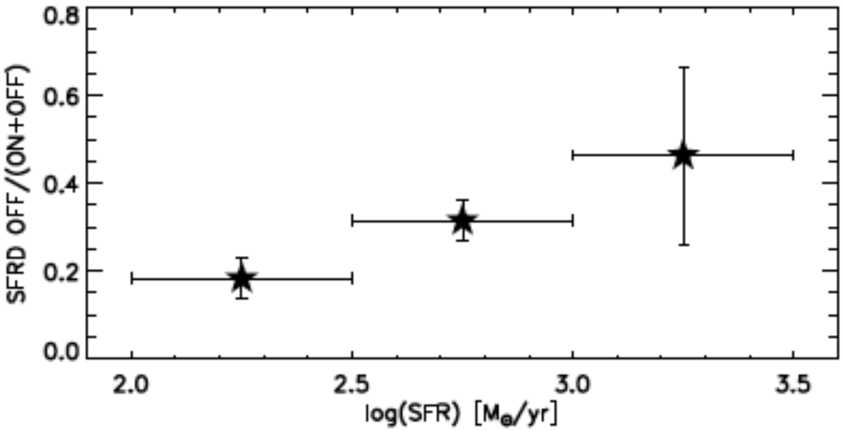
No main sequence see if using Herschel data alone (SFR-selection)



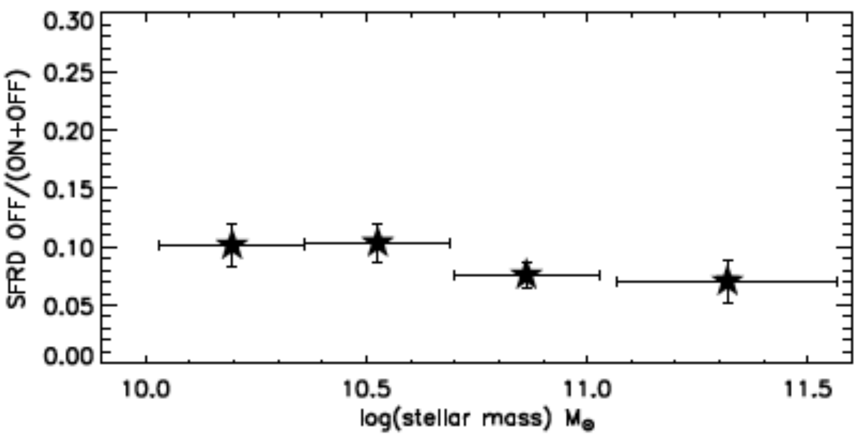
Notice very good agreement between UV and Herschel at the high mass bin

Threshold between MS and SB is objectively defined: 0.6 dex (2.5 sigma of the distribution) Notice that SBs will be present also below the threshold, but becoming overwhelmed by Normal galaxies. Also, they would be objects with minor modification of their SFRs

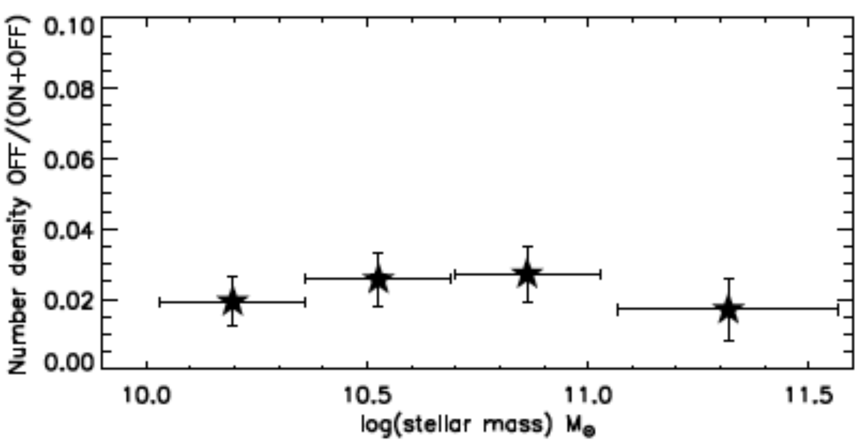
SB: objects with SFR enhanced on average by x4 over what they should heve, given M*



FIR selection (dust)
→ SMGs/Herschel galaxies are mixed bags (might explain similarities sometimes found with BzKs e.g. in excitation, SFE)
→ Need different approach tu build appropriate sample of starbursts



SFRD contribution of SBs only ~10% (mergers not so important for star form.)

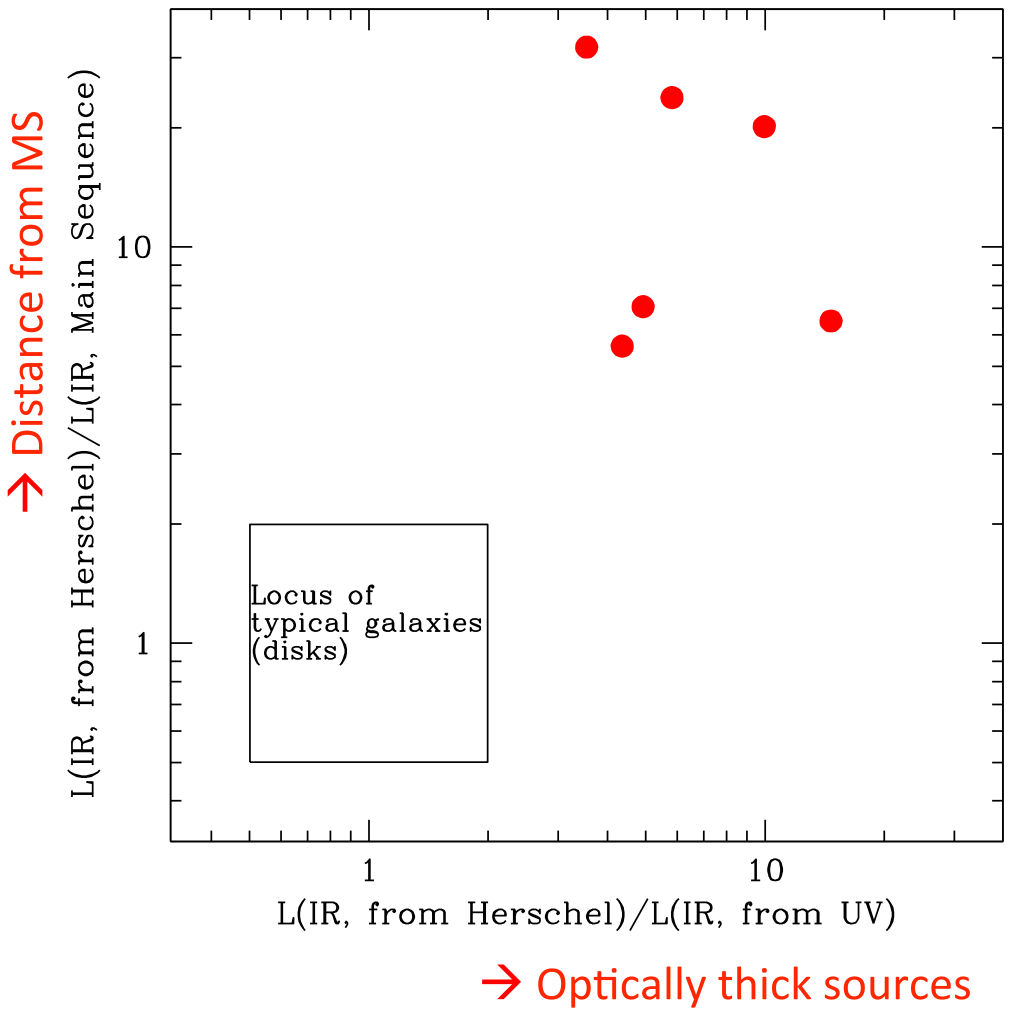


Near-IR selection (stars)
→ You must be very (un)lucky to pick up a SBs there (2% chance)

SB duty cycle ~20Myr
Much shorter than ~200Myr typical merger duration (refer only to SFR nnhancement >4)

MS outliers: are they mergers ?

HGOODS objects with sSFR x4 excess <u>and measured zspec</u>



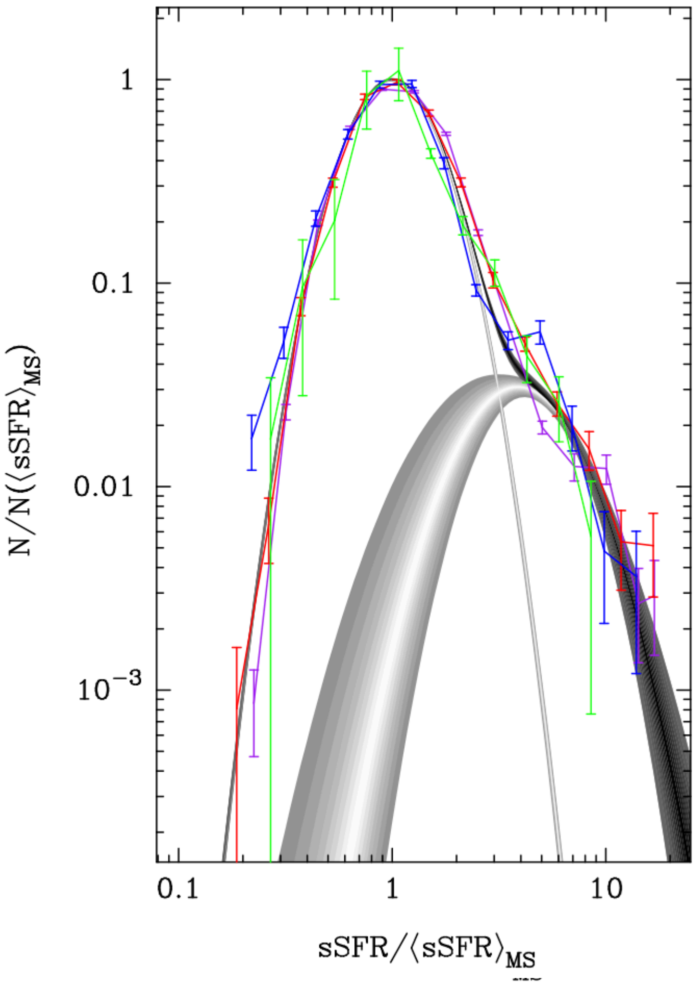
For all cases the UV SFR fails (optically thick)

UV underestimate similar to excess sSFR

Most likely they are indeed 'Dense' mergers

(Main sequence + starburst) decomposition

Sargent et al 2012 in press



Starburst contribution to SFRD [M_{sun}/yr Mpc^{-3}]: ~16%

(under some assumptions…!)

Star-forming galaxies: important properties @ z < 2

Sargent et al 2012 in press

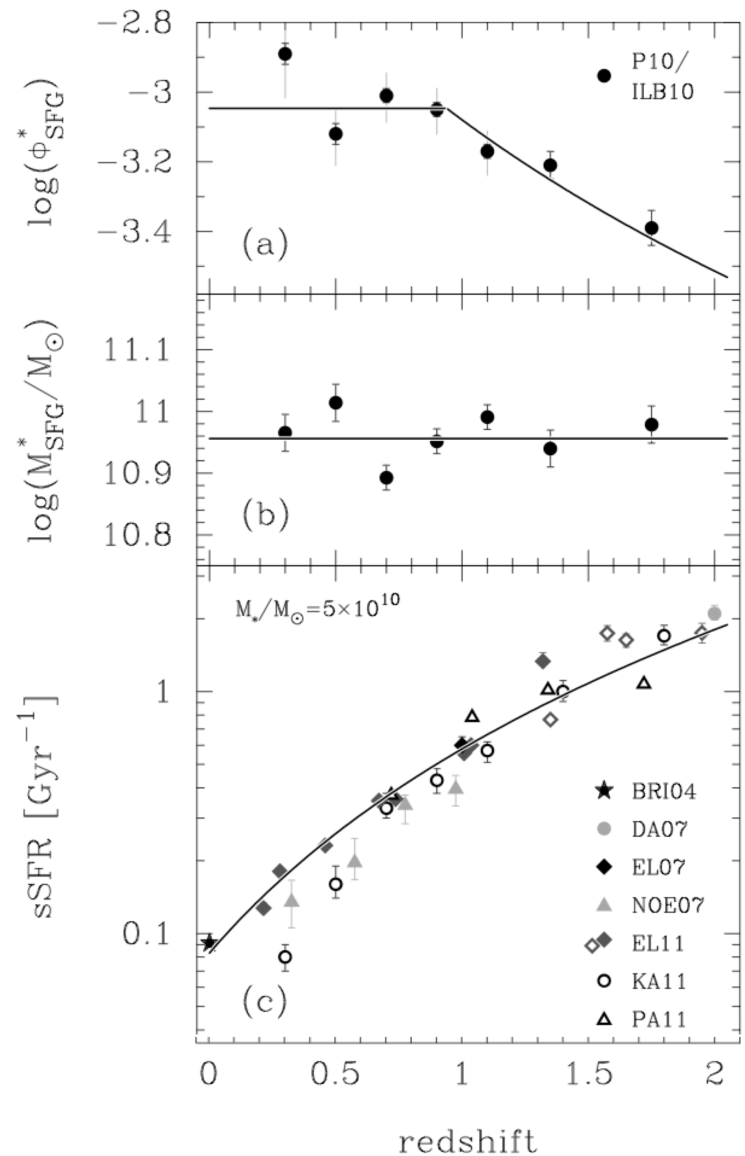
Evolution of stellar mass function of star-forming galaxies:

- constant M*
- Φ * constant to z = 1; then declining

(e.g. Bundy+ '06, Borch+ '06, Bell+ '07, Perez-Gonzalez+ '08, Pozzetti+09, Ilbert+ '10, Brammer+ '11)

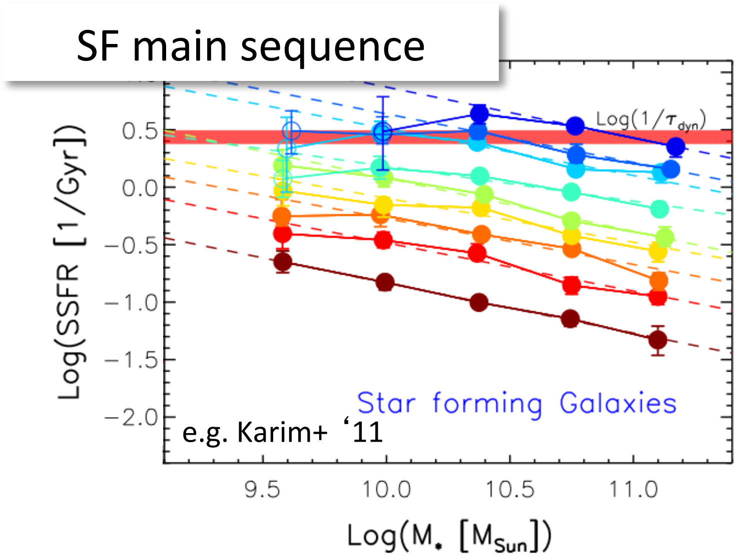
Evolution of specific SFR (=SFR/$M_{\star}$) for main sequence galaxies

(e.g. Brinchmann+ '04, Daddi+ '07, Elbaz+ '07, Noeske+ '07, Pannella+ '09, Damen+ '09, Pozzetti+09, Karim+ '11, etc.)



A simple recipe….

Sargent et al 2012
in press



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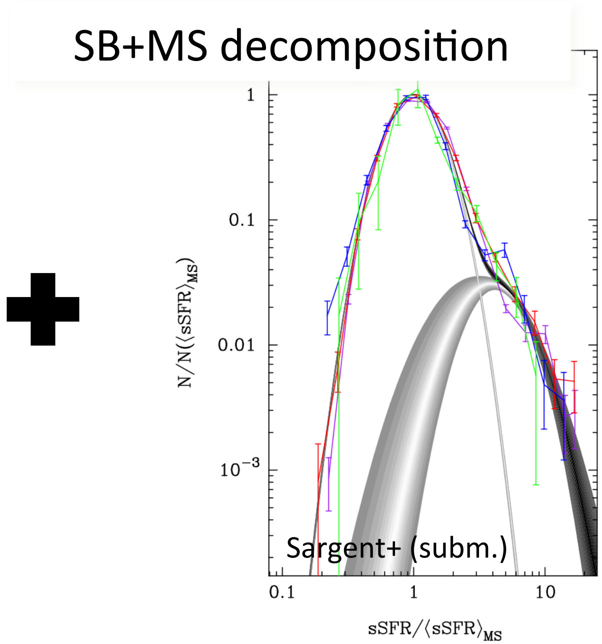

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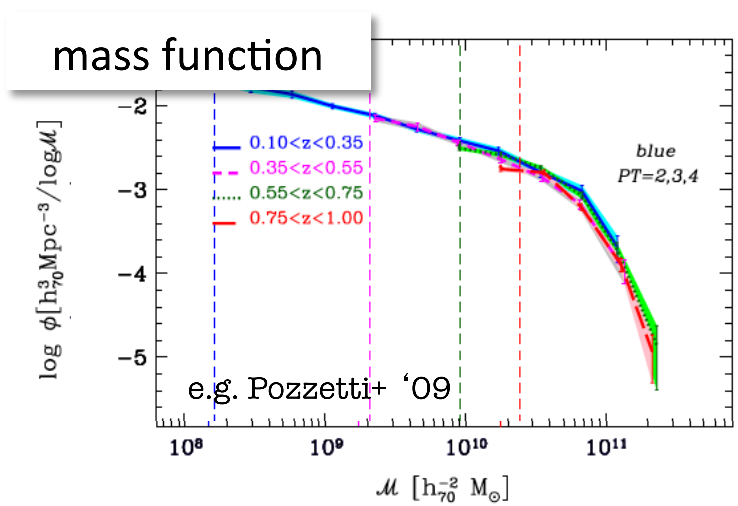

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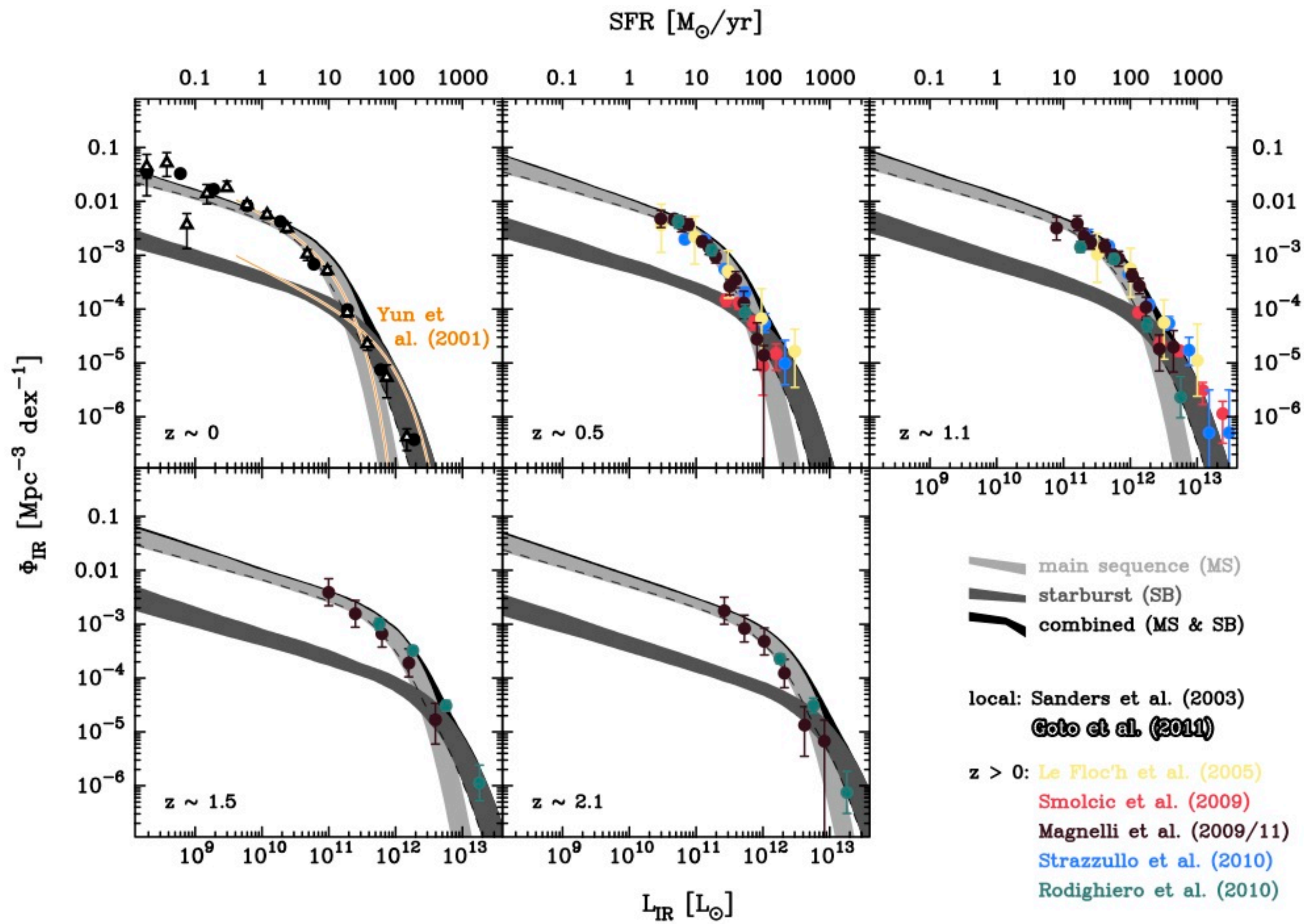
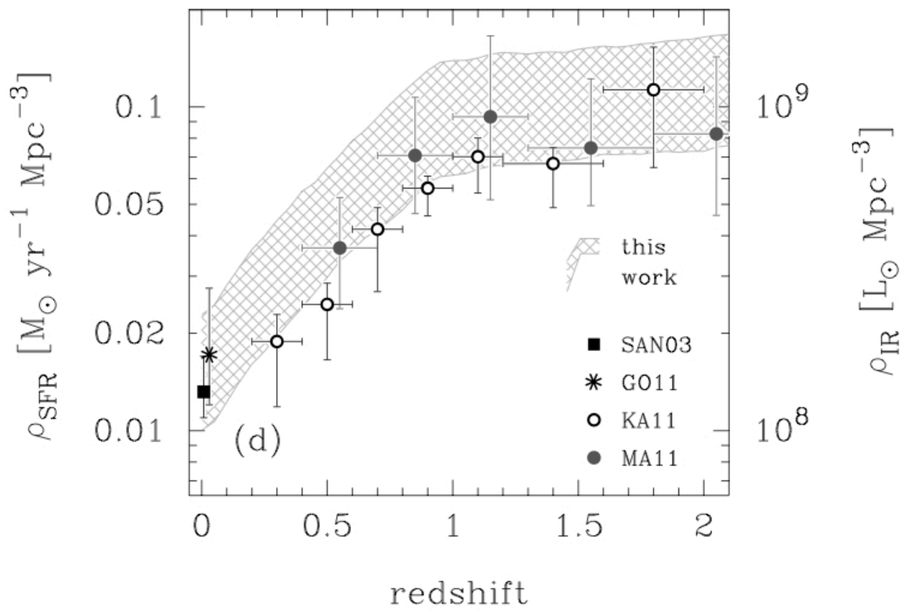
IR luminosity function: prediction vs. observations

Sargent et al 2012
in press



Predicted SFRD & cross-over scale

Sargent et al 2012
in press



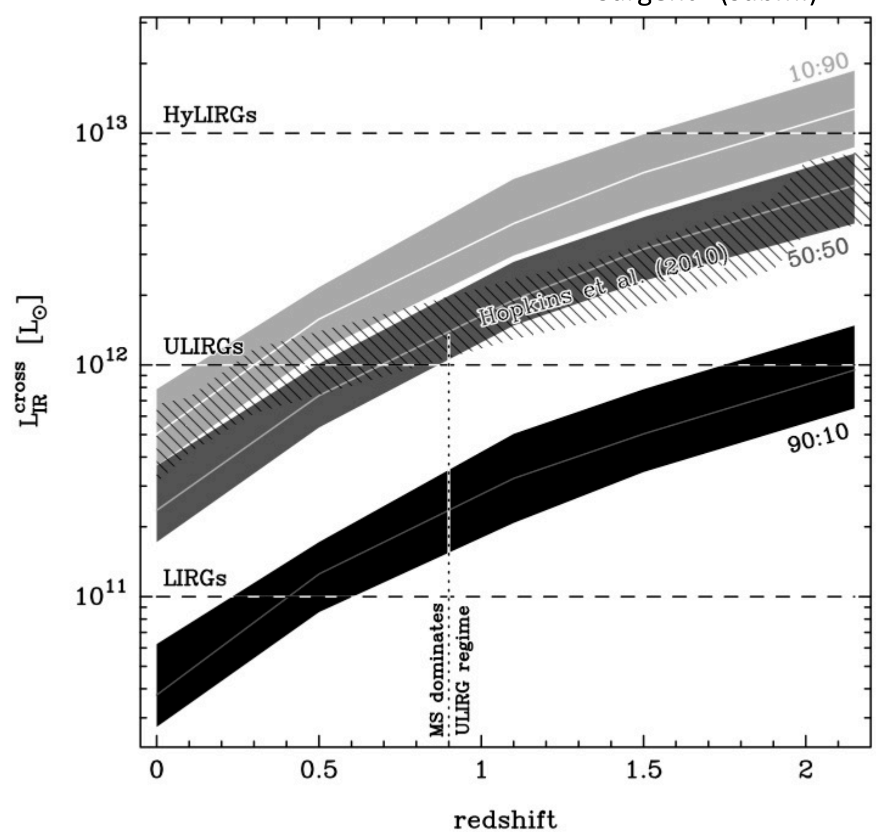
Cosmic star formation history reproduced

Starbursts *dominate* IR LF at

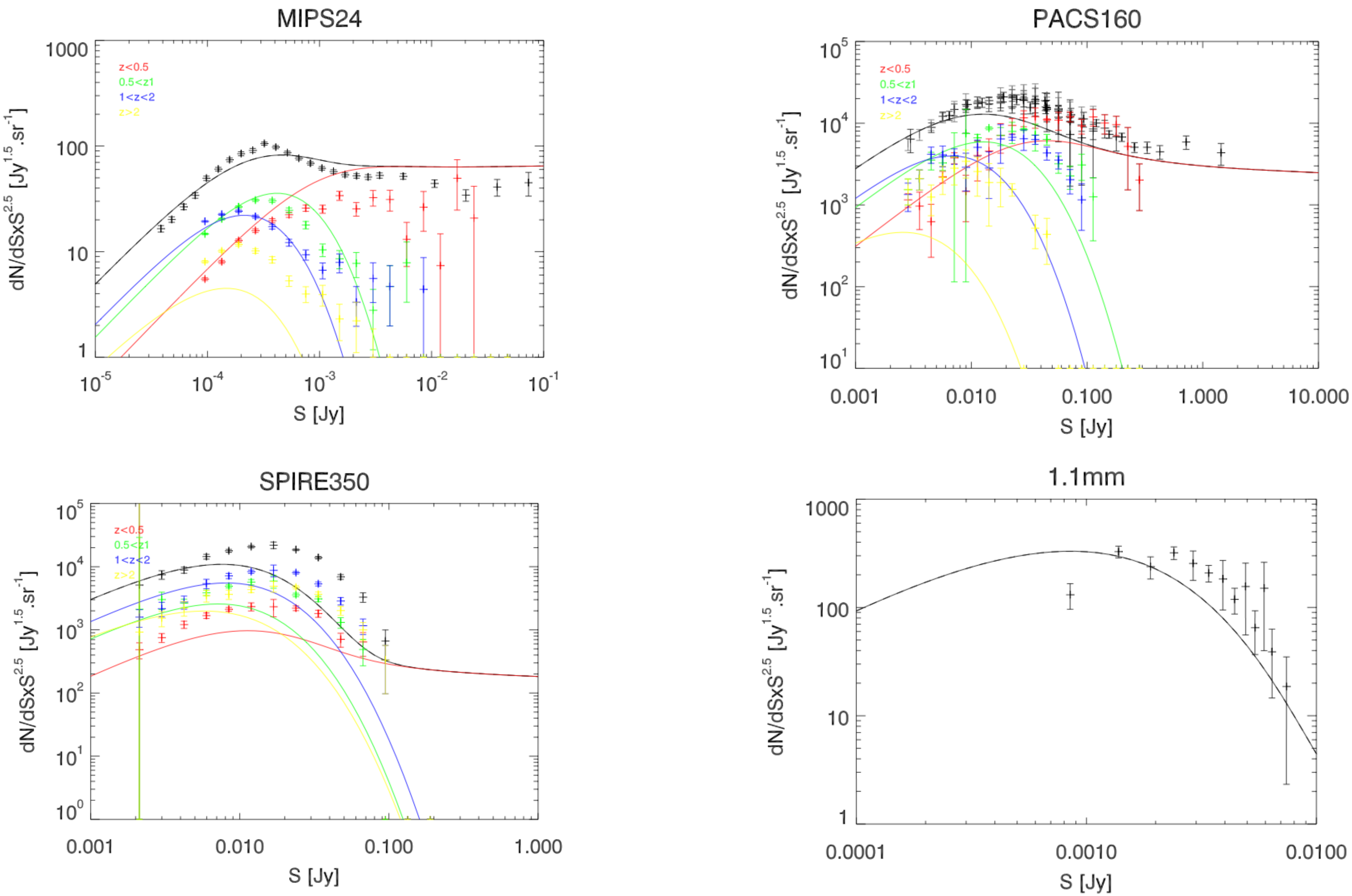
- z = 0: $\log(L_{IR}/L_{sun}) > 11.35$
- z = 2: $\log(L_{IR}/L_{sun}) > 12.7$

Selection by L_{IR} selects different populations at different redshifts!

Sargent+ (subm.)

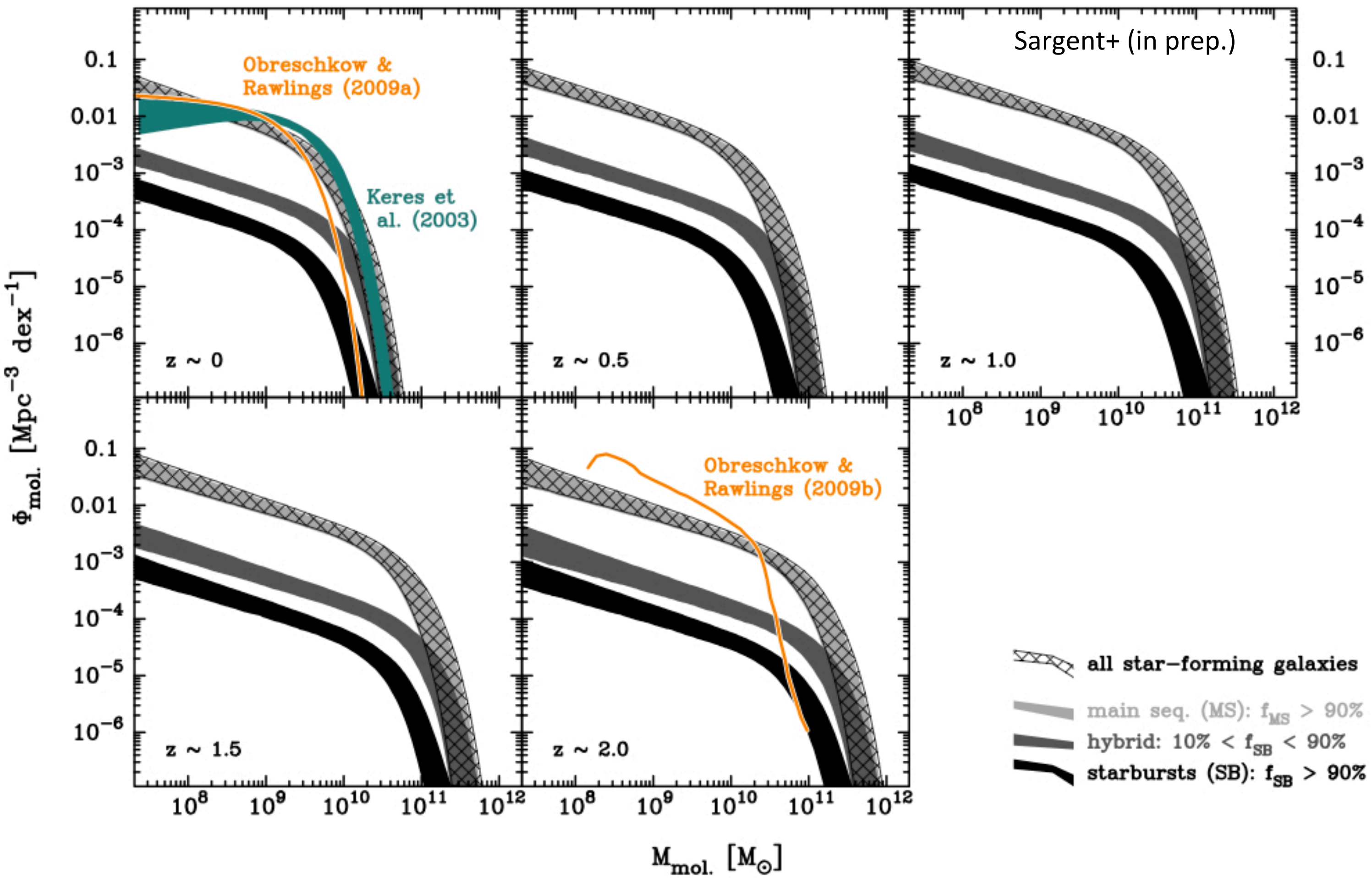


A powerful tool to predict observables: counts (Bethermin et al 2012, in preparation)



Molecular gas mass functions (Sargent et al 2012 in preparation) Based on Mgas-LIR SF laws

Predictions! (Currently we only have ~30 high-z mol. gas mass measurements in main-seq. galaxies)

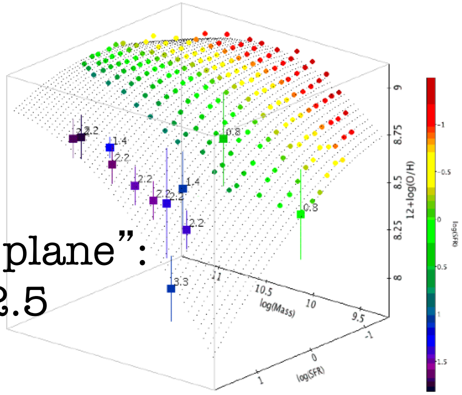


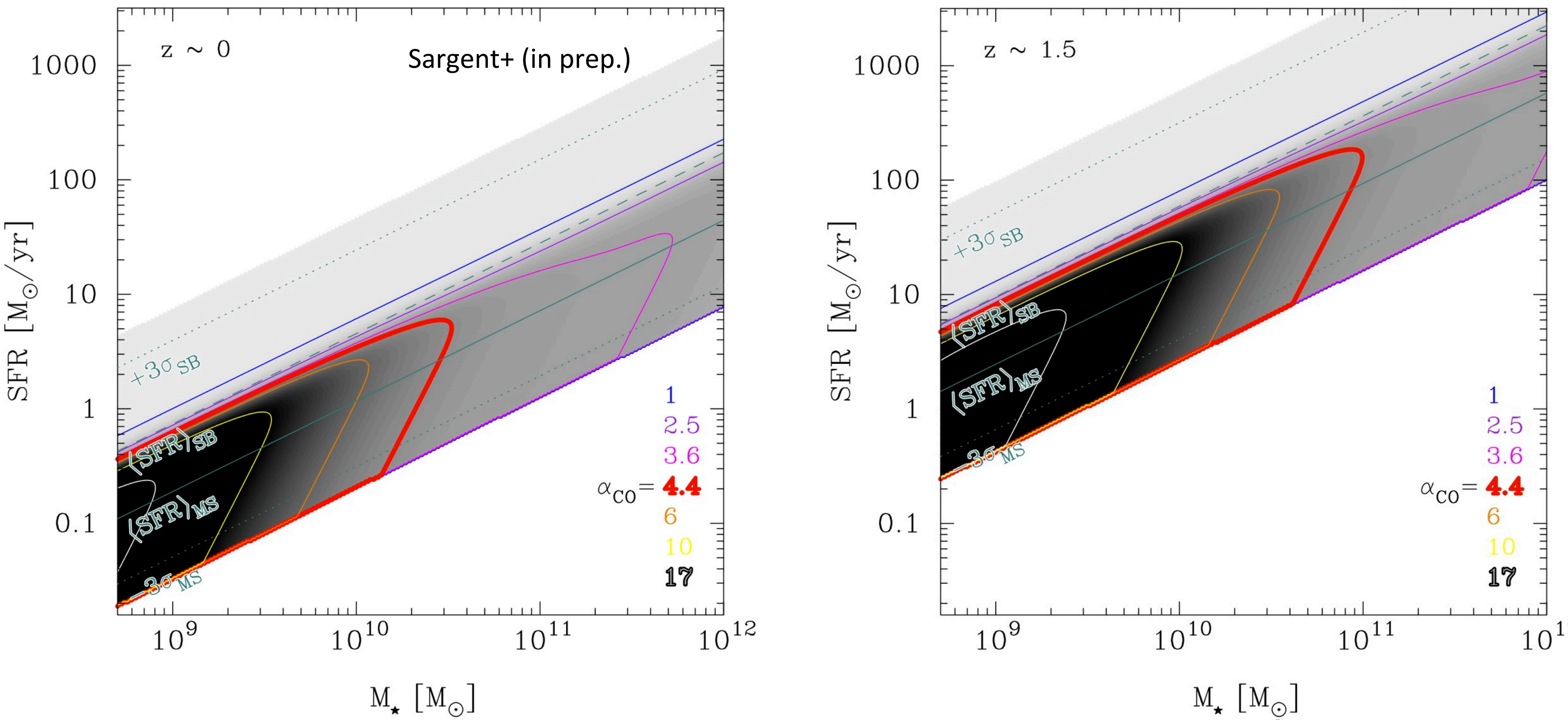
X_{CO}, α_{CO} …

Rule of thumb:

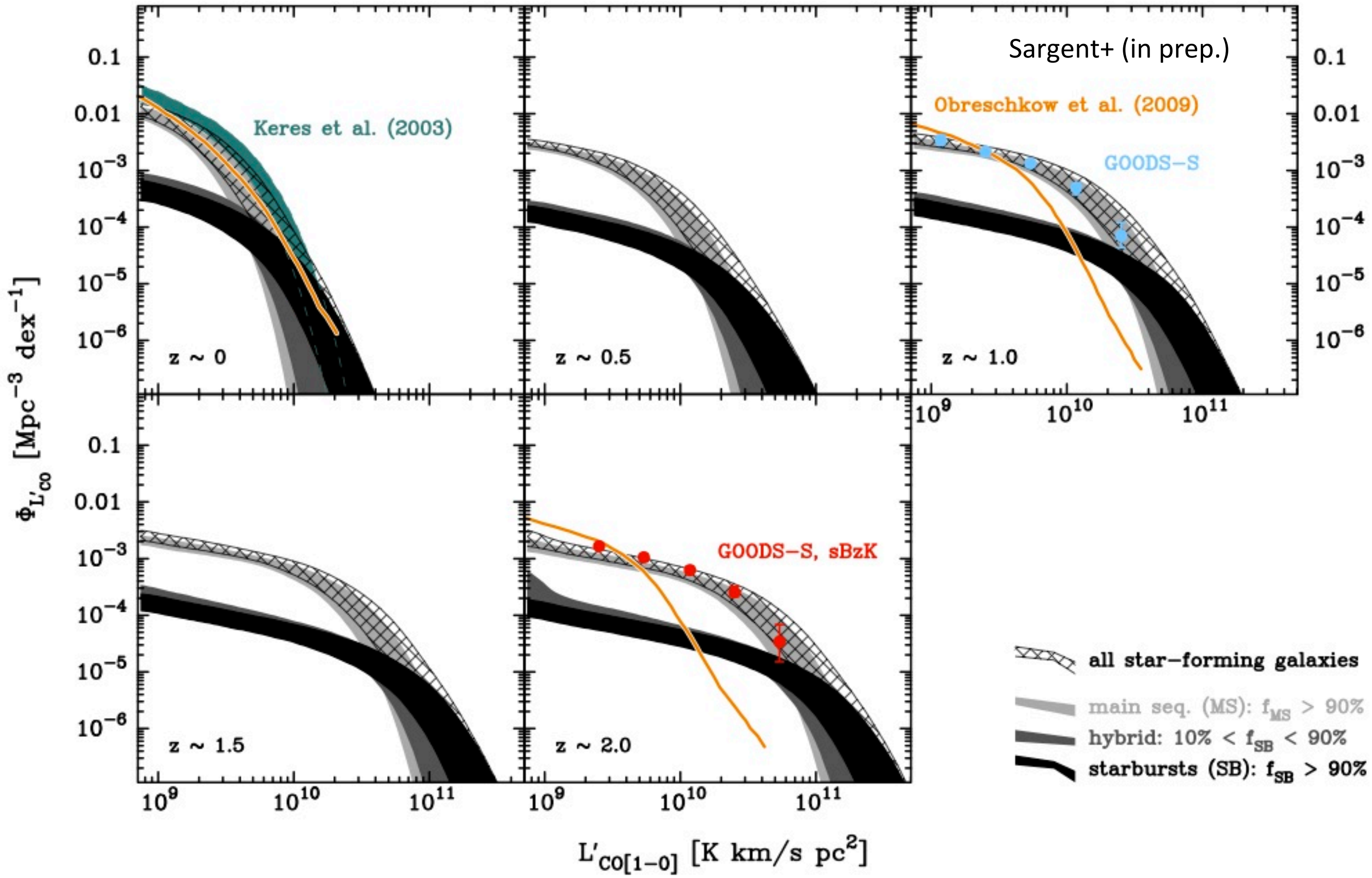
- MS: α_{CO} = 4
- SB: α_{CO} = 1

Mannucci+ ’ 10
“fundamental metallicity plane”:
Z(SFR, $M_\star$) out to z ~ 2.5

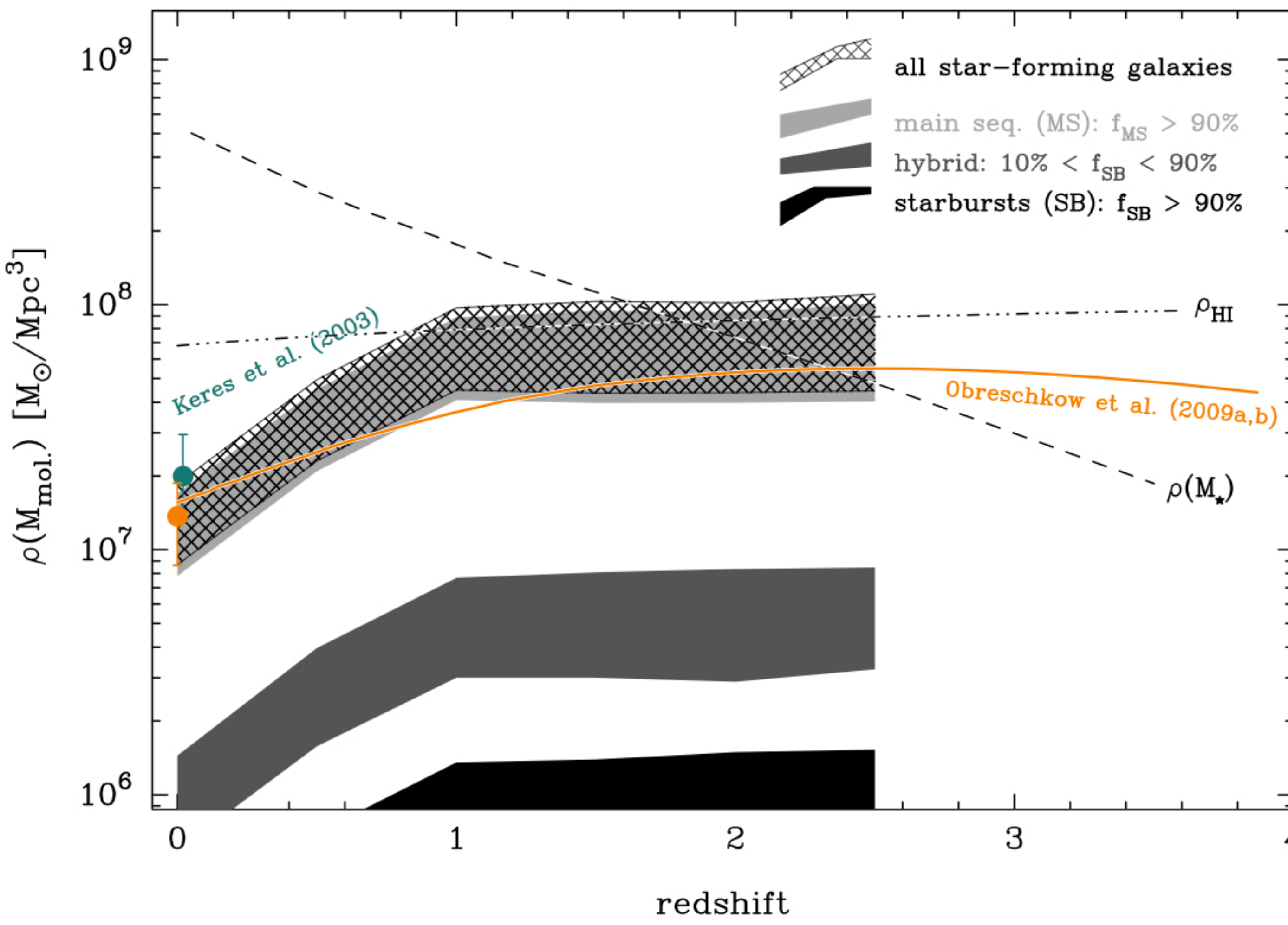




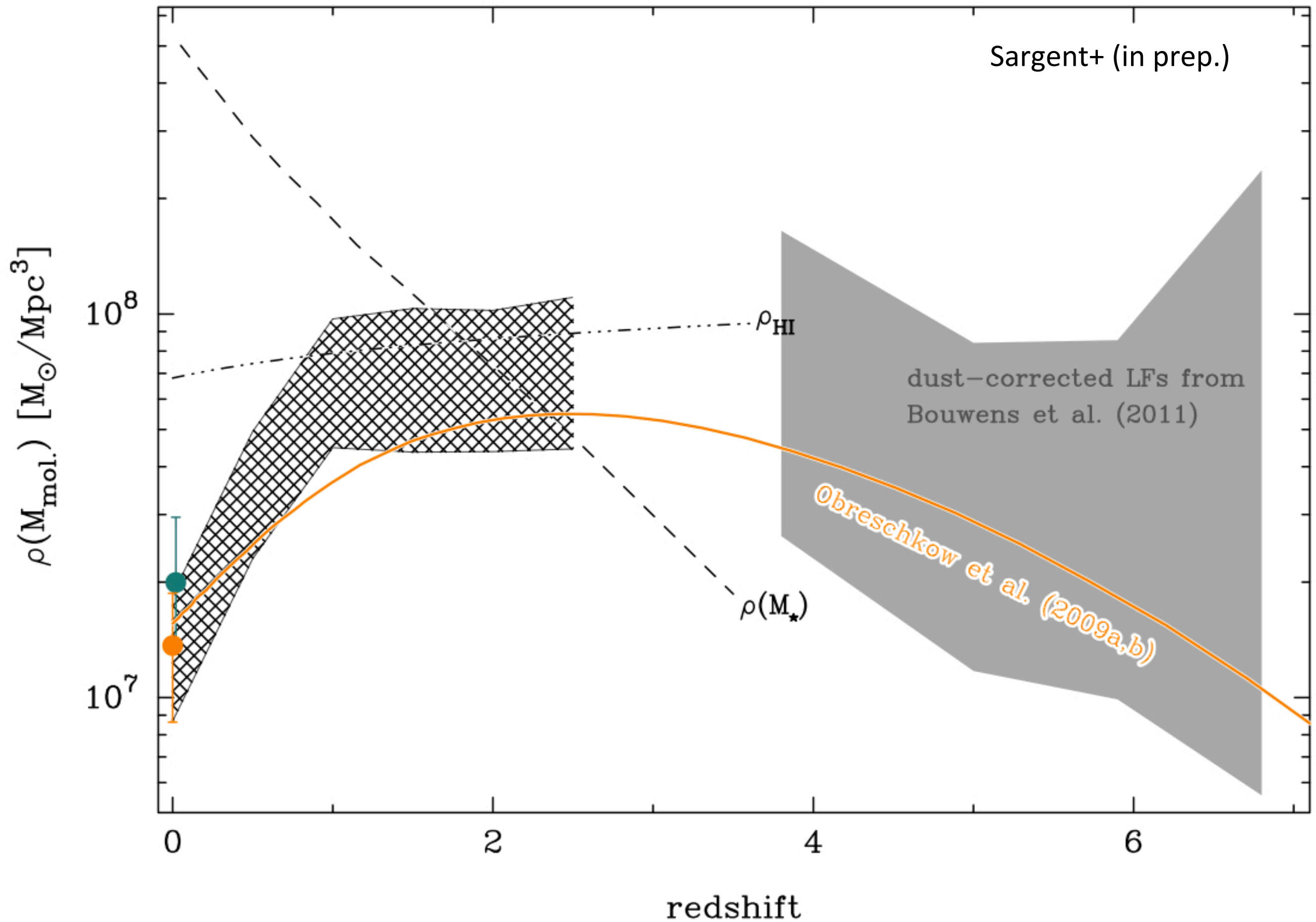
CO[1-0] luminosity functions – or: more predictions



Cosmic evolution of H_2-reservoirs



An indicative cosmic dense gas history & …
… *THE END*



Conclusions:

- When observing IR galaxies it is crucial to know if you are observing
a normal galaxy or a merger/starburst, to interpret the observables in term of physical properties

- SMGs and/or luminous Herschel galaxies are mixed bags of disks/SBs
- Near-IR/optical galaxies are almost all main sequence

- Herschel+mm (IRAM/ALMA) very powerful Mdust machine
- Mdust, T/beta, alpha_CO seem to believe as reasonably expected
(differences substantial between MS and SBs)
- Very little SFRD in the MS outliers ~10% (not an important mode
for the built up of stars)

- Mgas extrapolations: big rise of cosmic H2 density to z=1, flat afterwards
(problematic for gas accretion understanding, need confirmation)