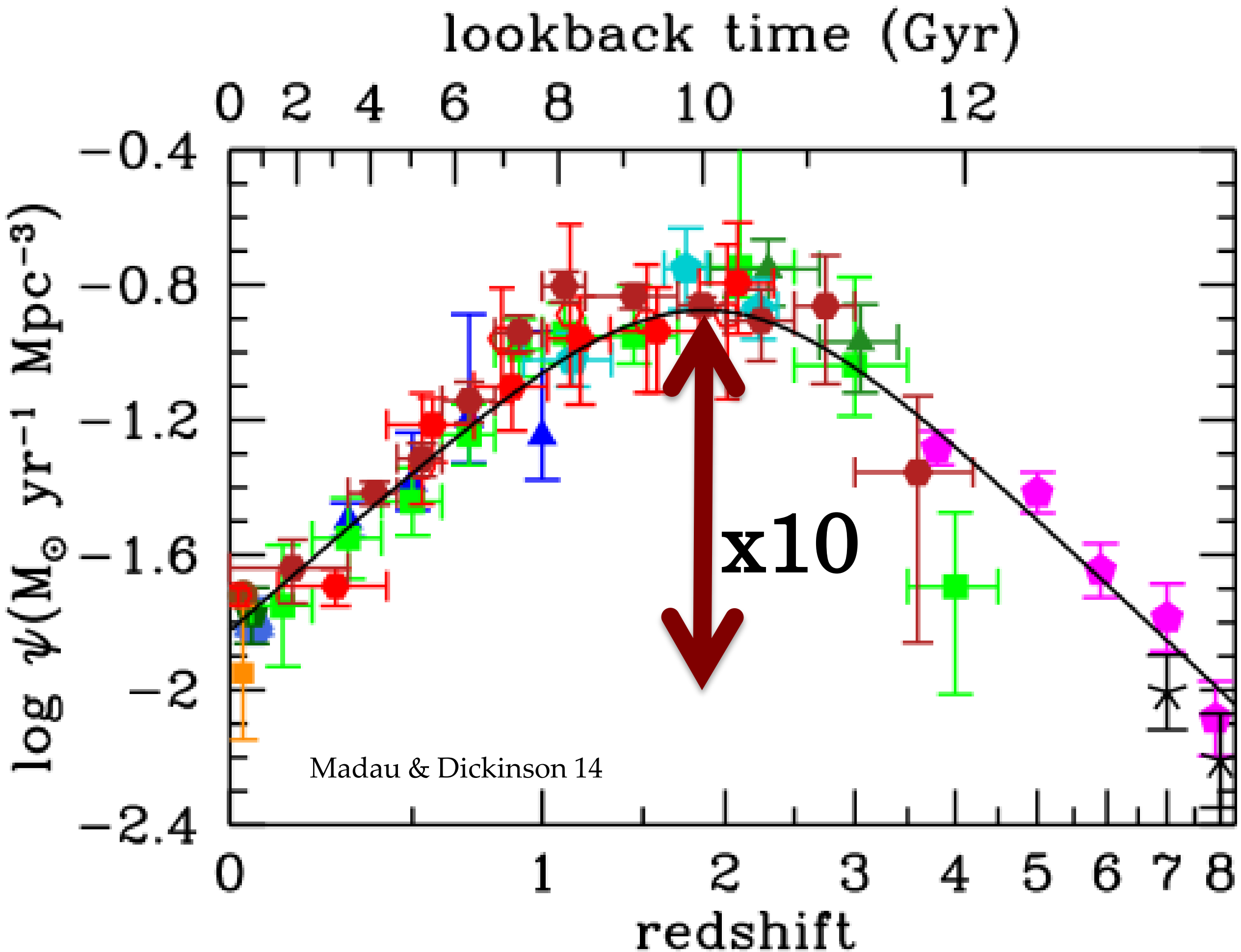
UNIVERSITY OF OXFORD

The Evolving ISM of Star Forming Galaxies Over the Last 10 Billion Years

Georgios Magdis

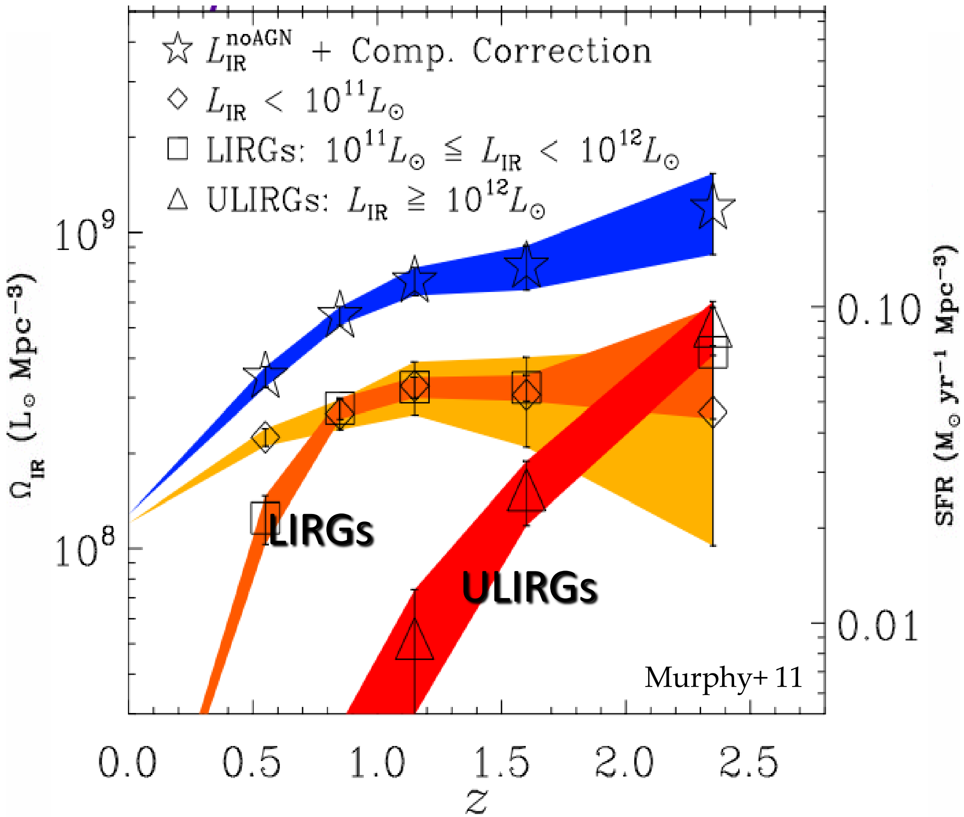
Cosmic Star Formation History

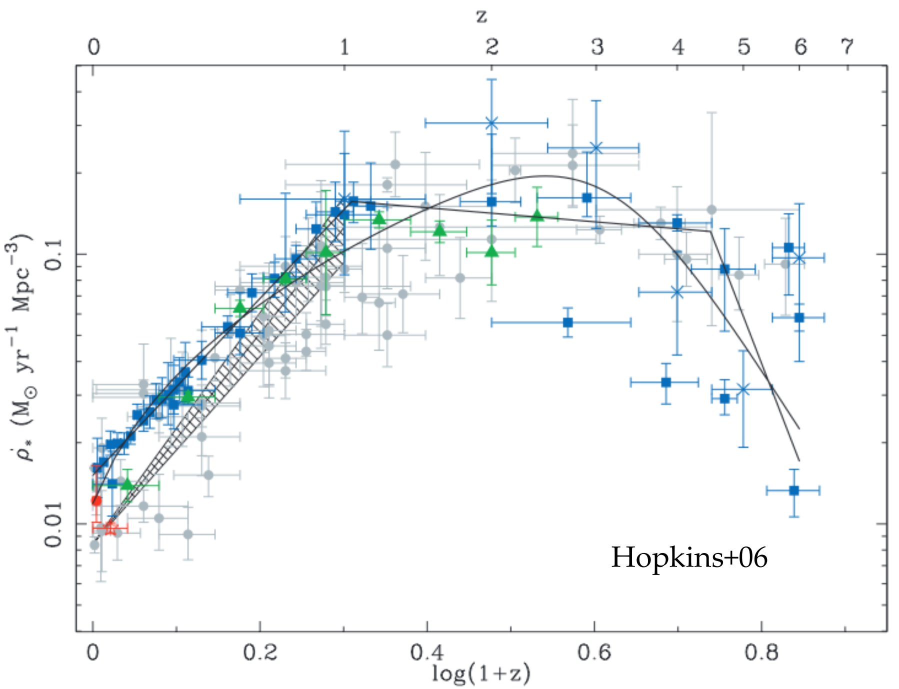


Mergers? Major? Minor?
(e.g. Somerville+2001, Conselice+2008)

Secular processes? Gas infall rates?
(Keres+2005, Bower+2006, Dekel+2009)

Number density of (U)LIRGs





- Rare in the local universe
- Number Density x 1000 (from z=0 to z=2)
- ULIRGs+LIRGs= 70% of SFRD

Star formation shifts towards massive galaxies with high SFR

Two major modes of star formation

Steady, long lasting mode:

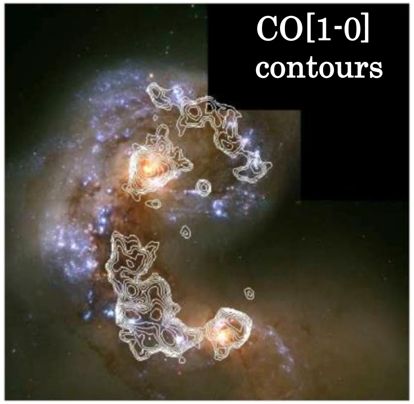
Most SF galaxies @ z=0
moderate SFR: 1-3 M/yr
moderate SFE: 5 L/M
low sSFR ~ 0.1 Gyr^{-1}
Long τ_{dep} ~ 1 Gyr
Extended star forming regions

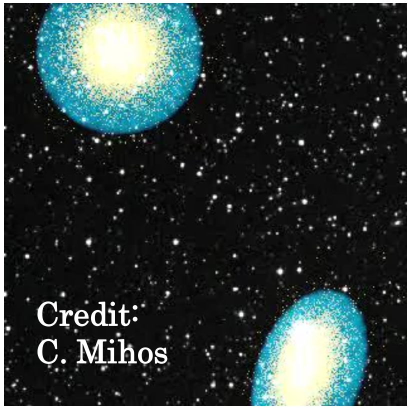
Local disks / normal galaxies

Starburst, short-lived mode:

Rare
high SFR > 10 M/yr
high SFE > 100 L/M
High sSFR > 1 Gyr^{-1}
Short τ_{dep} < 100Myrs
Compact star formation: 2Kpc

Major Mergers / Interactions / Local ULIRGs



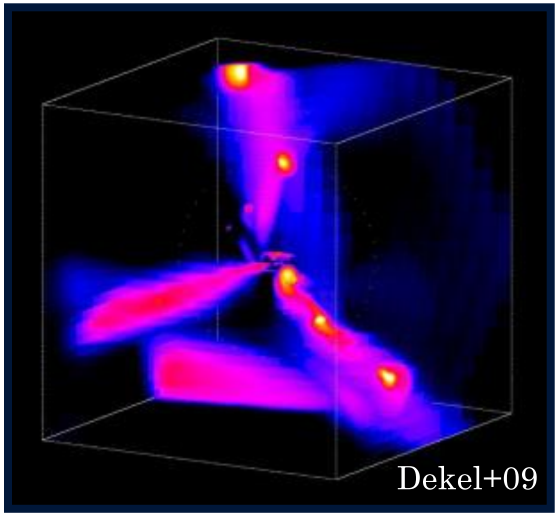


An alternative to mergers

- The high SFR of in the local Universe are driven by mergers
- Rapid increase of SFR in galaxies from z=0 to z=1
- Higher SFR in early Universe → more frequent mergers

High-z star forming galaxies → similar to local ULIRGs

OR



Higher SFR → More available gas

Continuous accretion of gas from the cosmic web. Natural route for maintaining the high gas surface densities and star formation rates

(e.g. Keres+05; Dekel +09; Bournaud & Elmegreen 09).

High-z star forming galaxies → similar to normal galaxies

Questions

What is the dominant mode of star formation in Universe ?

What are the processes that regulate galactic scale star formation ?

Is there a universal star formation law ?

What drives the decline of the SFRD from z=2 to the present day ?

Scaling Laws

Over the last 10 Billion Years (the majority) of star forming galaxies appear to obey the following (among others) relations :

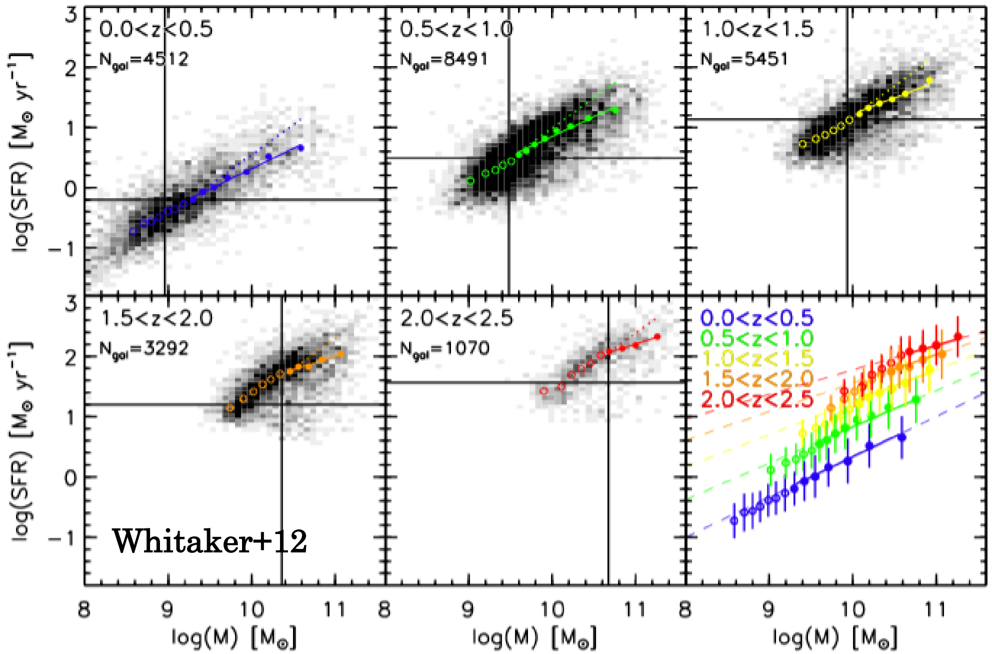
1. SFR – M_* (Main Sequence)
2. L_{IR} – L_{CII}
3. SFR (or L_{IR}) – M_{gas} (SF law)

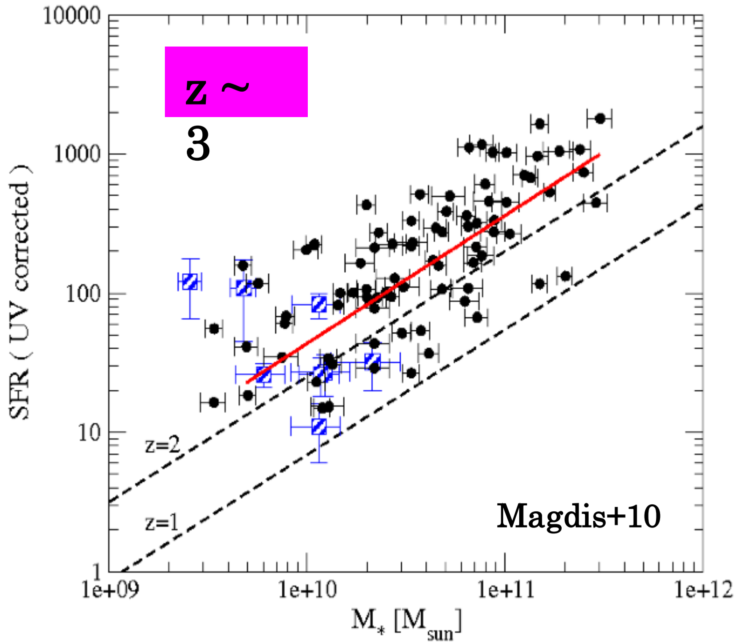
They mirror the process of star formation though cosmic time

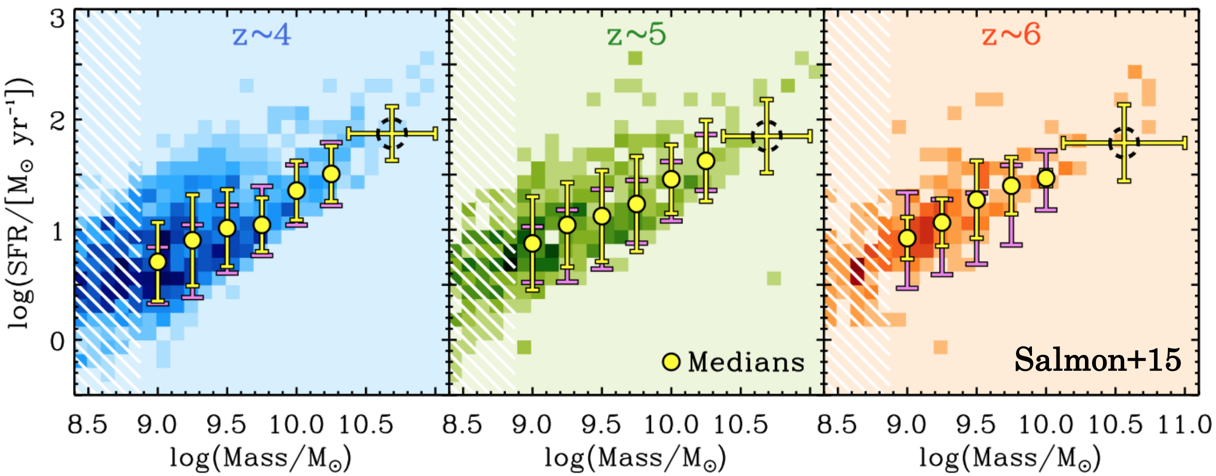
SFR – M_*

(Main Sequence)

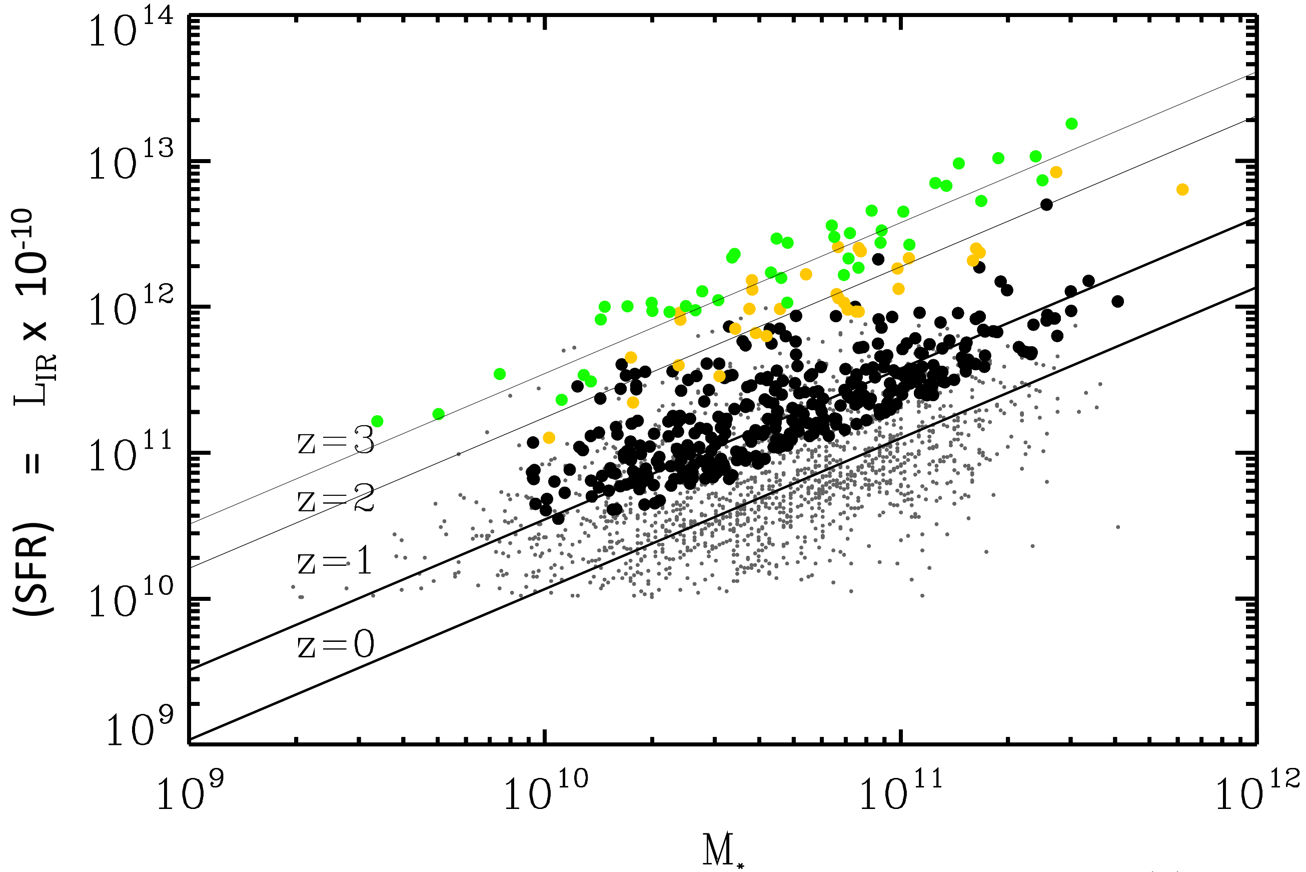
SFR-M* relation







SFR-M*

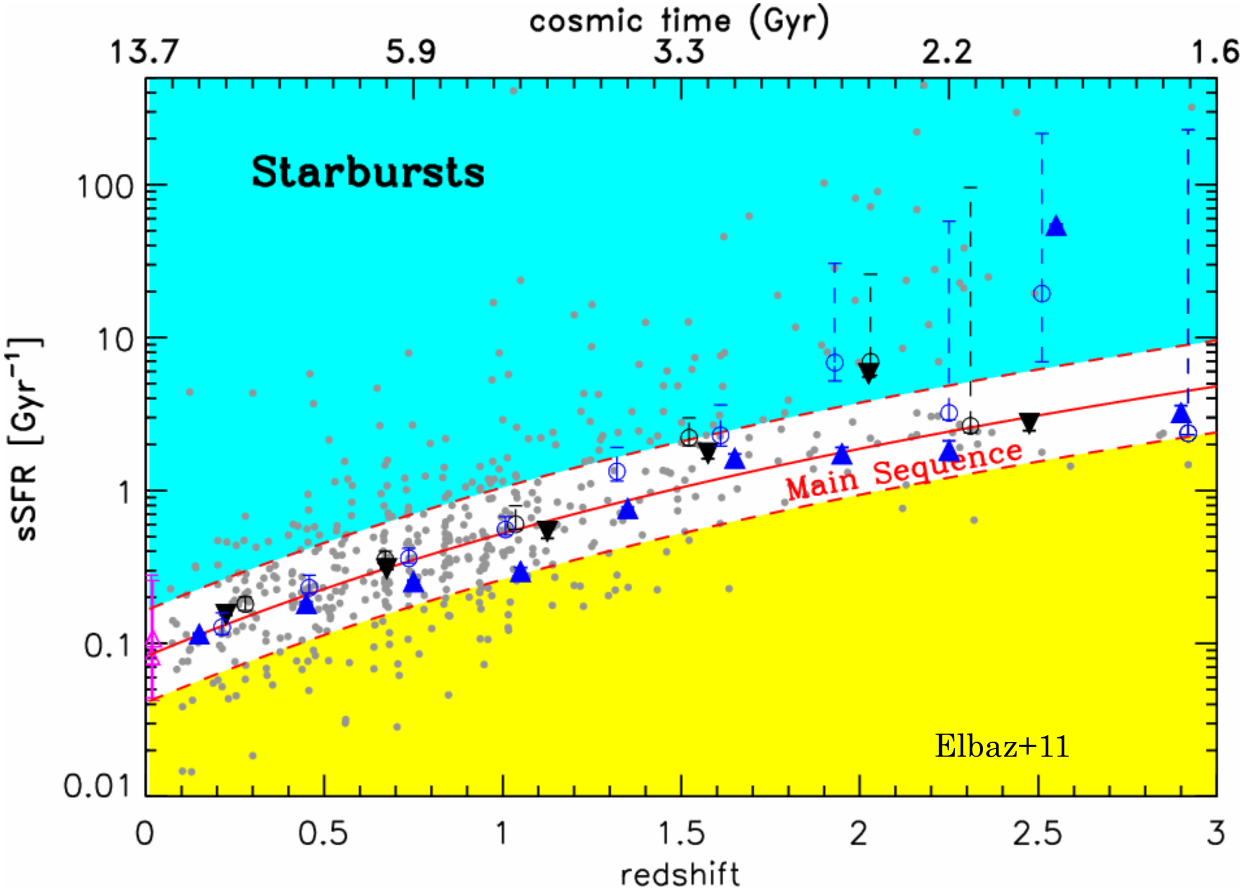


- The normalization factor increases with redshift: $sSFR(z) = sSFR_{z=0} * (1+z)^a$
- $SFR \sim M^{\beta}_{*}$, with β constant at all redshifts
- Small and constant scatter (0.3dex) at all redshifts

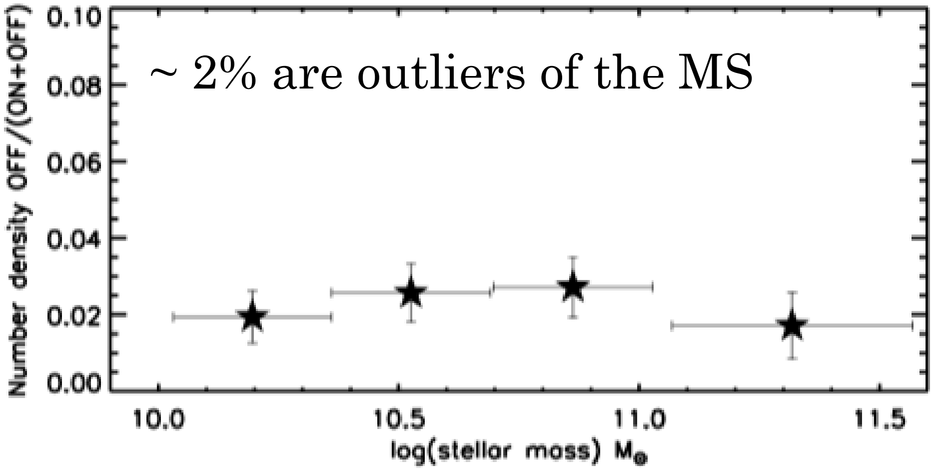
SFR-M*

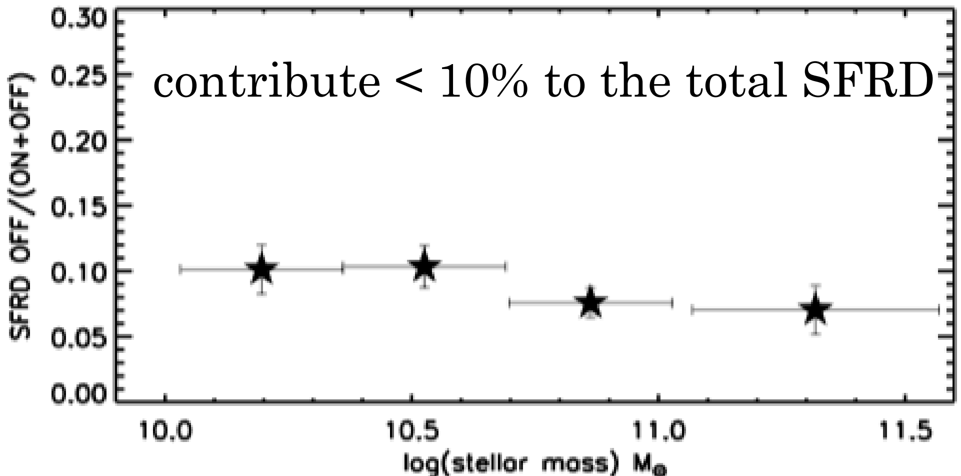
$$SFR(z,M) \sim F(z) \times M_*^{\beta}$$

$$sSFR(z,M) = sSFR_{z=0} * (1+z)^{\alpha} * (M_*/M_{ref})^{\beta}$$

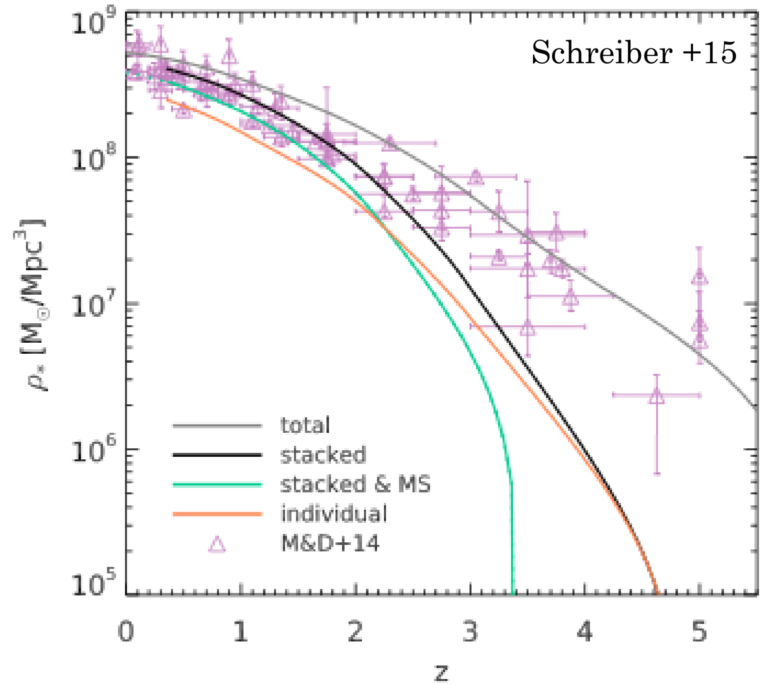


Main Sequence of star formation

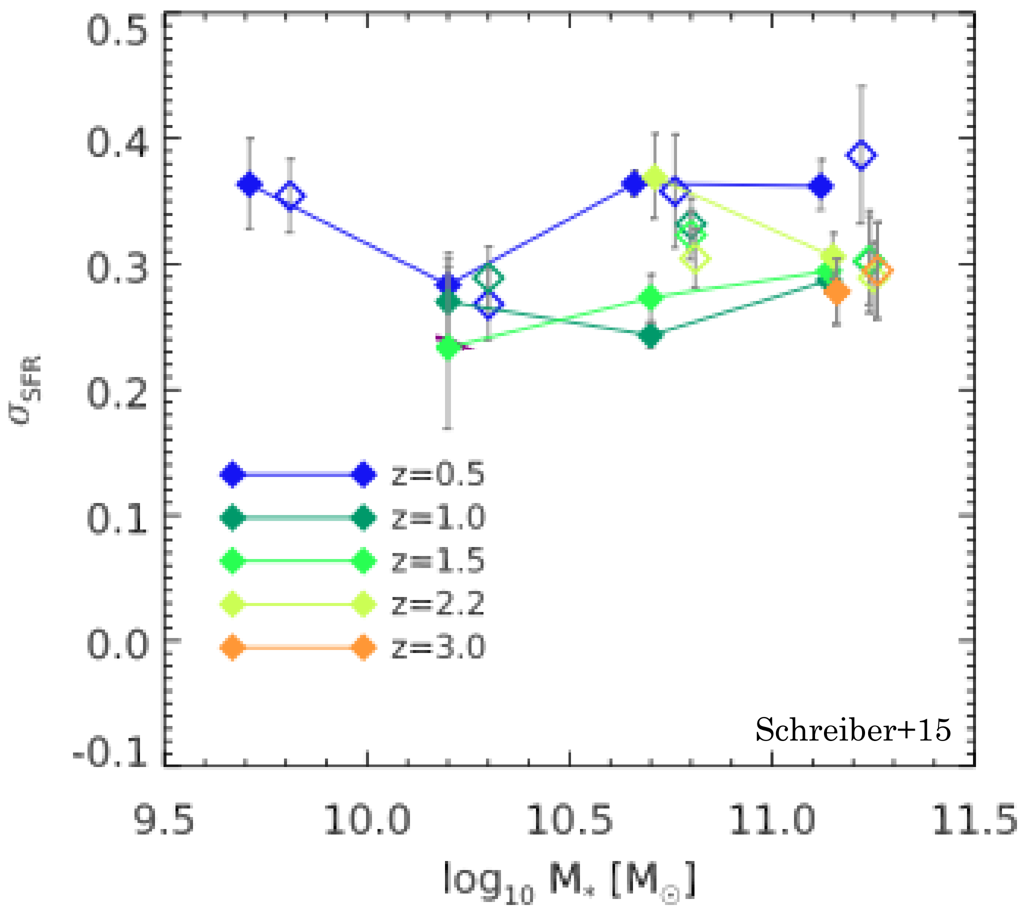




Rodighiero+11



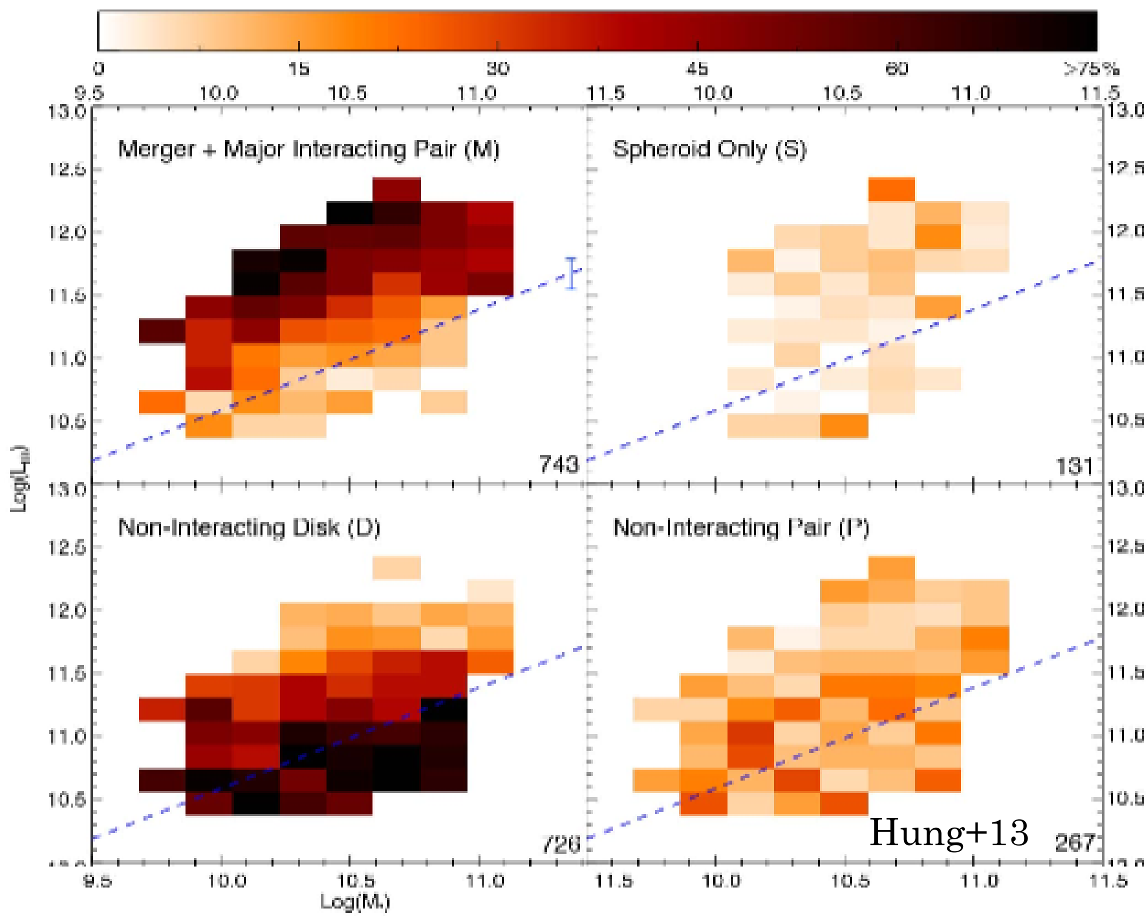
At least 70% of the present stars were formed in the main sequence



Scatter of the MS remains small (0.3dex) and rather constant at all redshifts and stellar masses

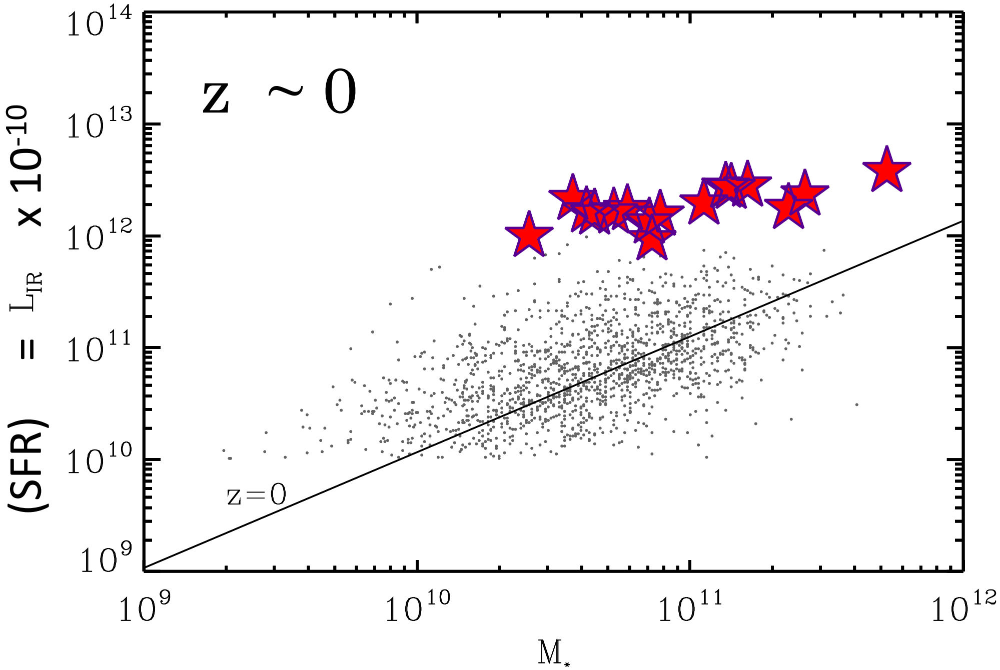
- Contraints on the stochastic nature of merger induced star formation (e.g. Noeske+07)
- Large degree of uniformity in the star formation history of the galaxies

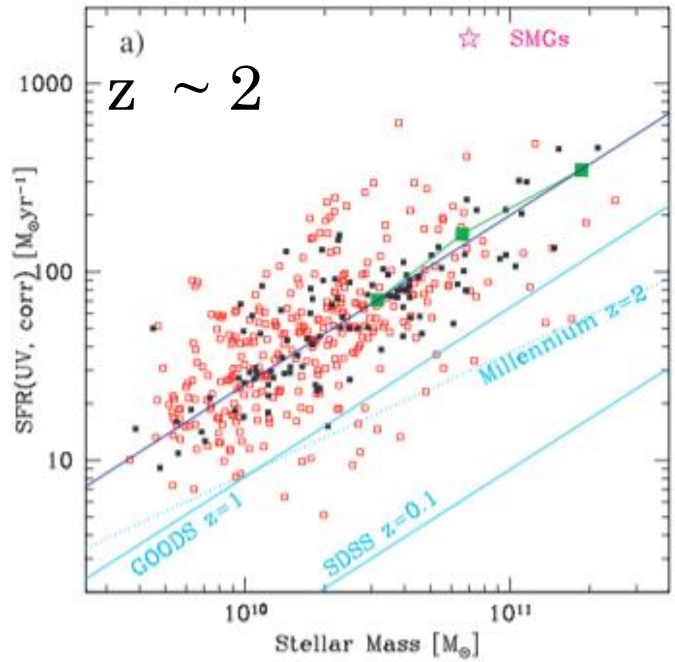
<z> ~ 0.7



Fraction of mergers increases as we move away from the MS

SFR-M*





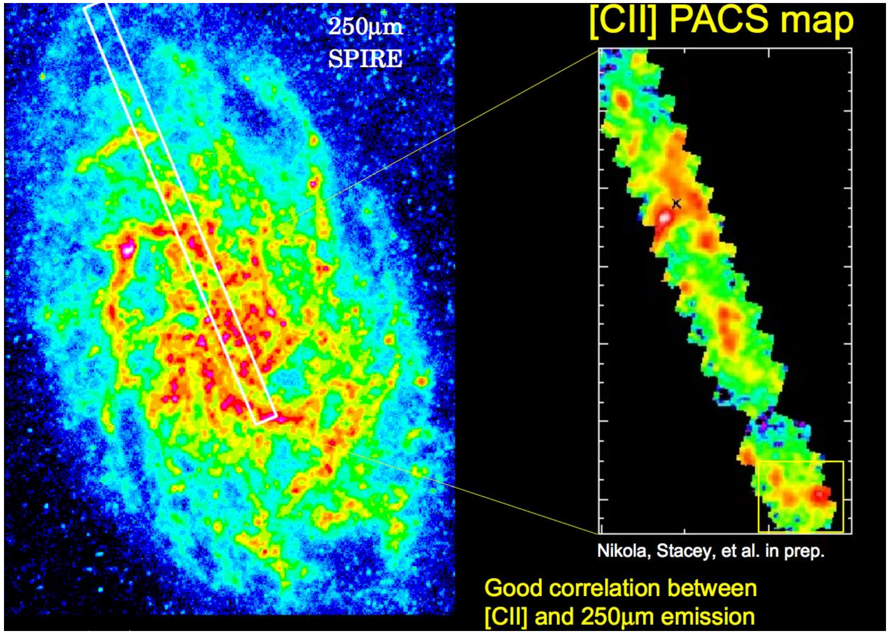
Local ULIRGs are strong outliers from MS

Majority of high-z ULIRGs follow the MS

Indication that SF in distant ULIRGs is not driven by stochastic starbursts, but have a different mode of star formation

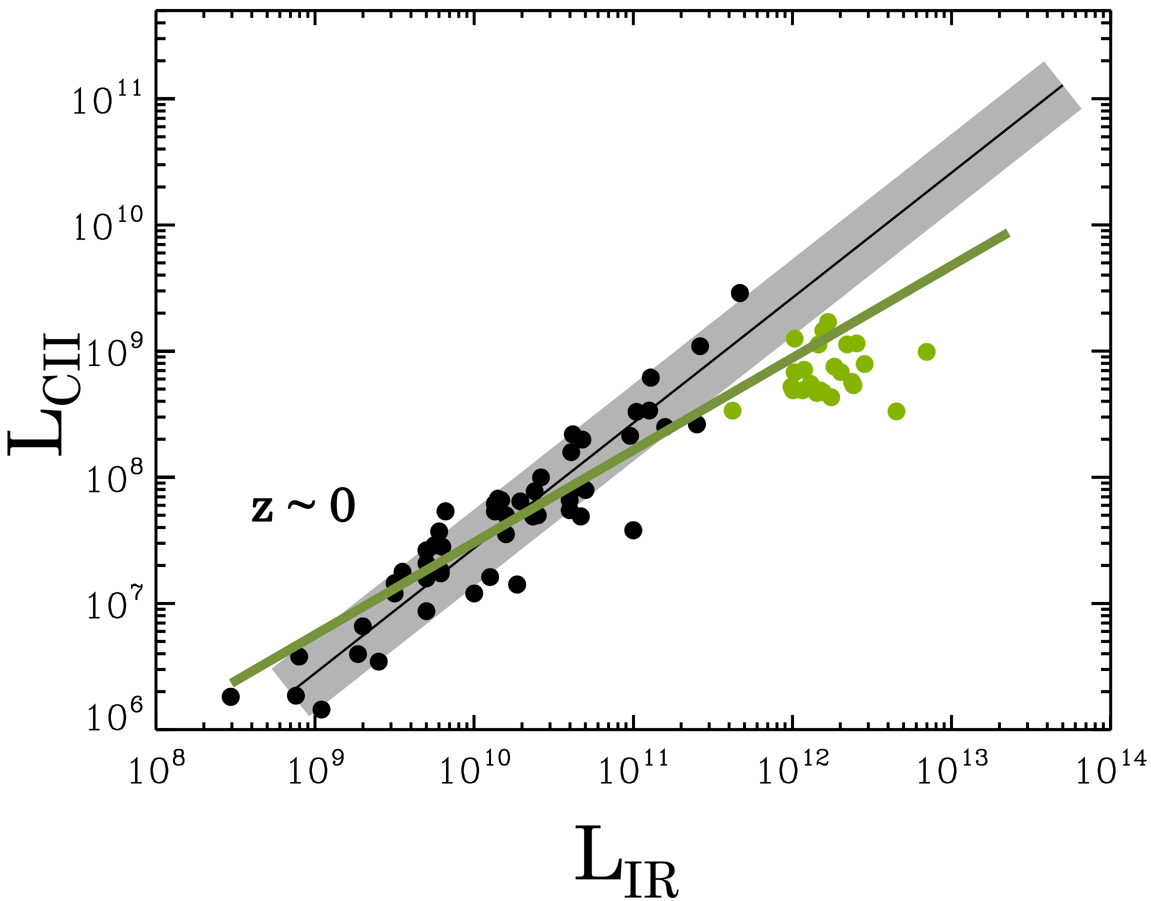
$$L_{IR} - L_{CII}$$

[CII] Emission



- [CII] 158µm is one of the strongest ISM cooling lines (T~90K)
- Accounts for 0.1-1% of the L_{IR}
- One of the most powerful spectroscopic tracers of the ionized & neutral components of the ISM
- Tracer of Star Formation Rate (?)

$L_{CII} - L_{IR}$ correlation



Local Galaxies ($L_{IR} < 10^{11} L_{\odot}$)

Almost linear correlation

e.g. Malhotra+97,+01, Herrero-Camus+14,

Local ULIRGs - CII deficit

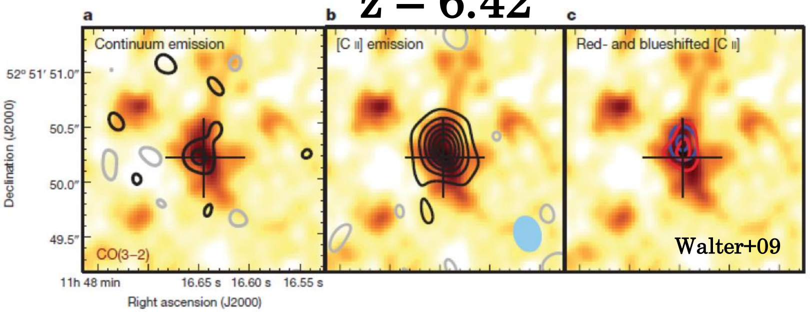
e.g. Luhman+03, Garcia-Carpio+11, Farrah+2013, Diaz-Santos+2013

Origin of the deficit:

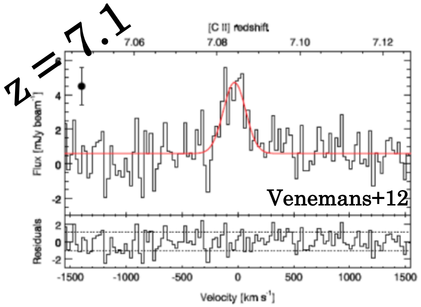
- AGN contamination → excess L_{IR} with respect to L_{CII}
- Stronger interstellar radiation fields (U) → increased dust to gas opacity
- n_H densities > n_{crit}, → recombination of C+ to C
- Self absorption

[CII] at high-z

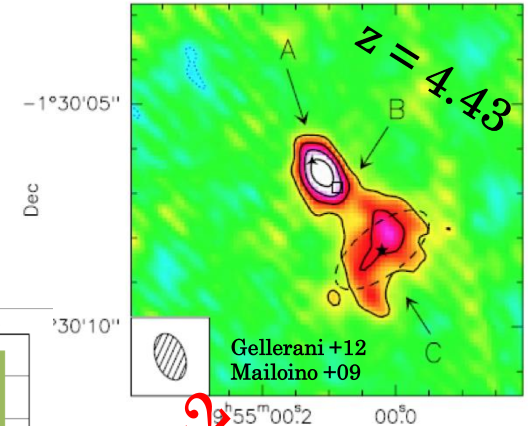
z = 6.42



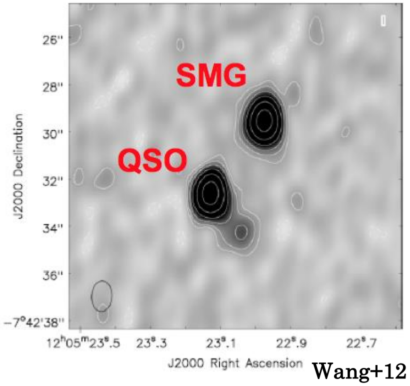
z = 7.1

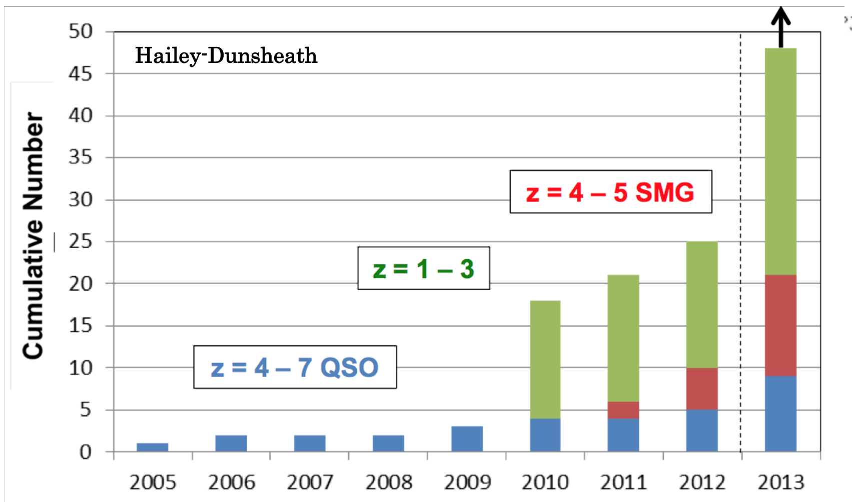


z = 4.43

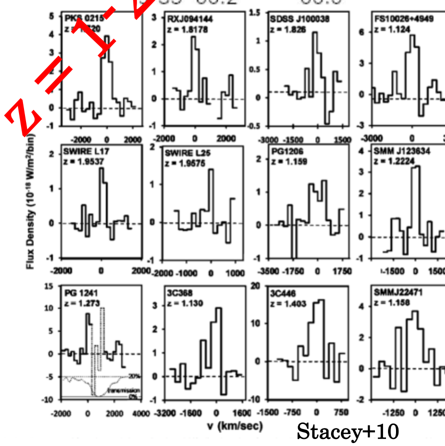


z = 4.69

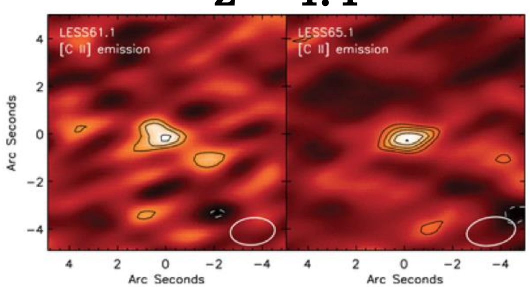




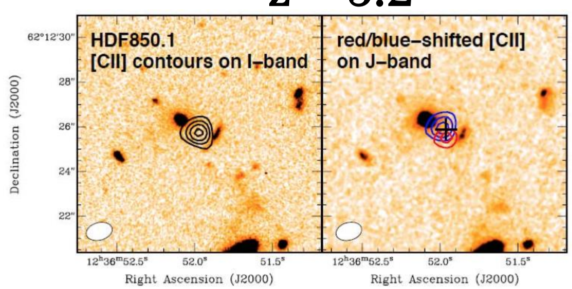
z = 1-2



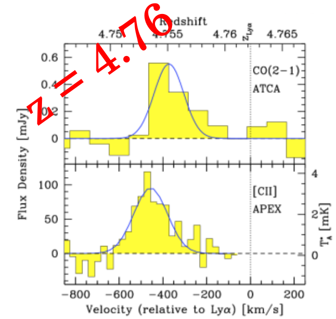
z = 4.4



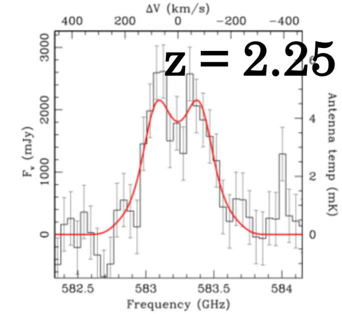
z = 5.2



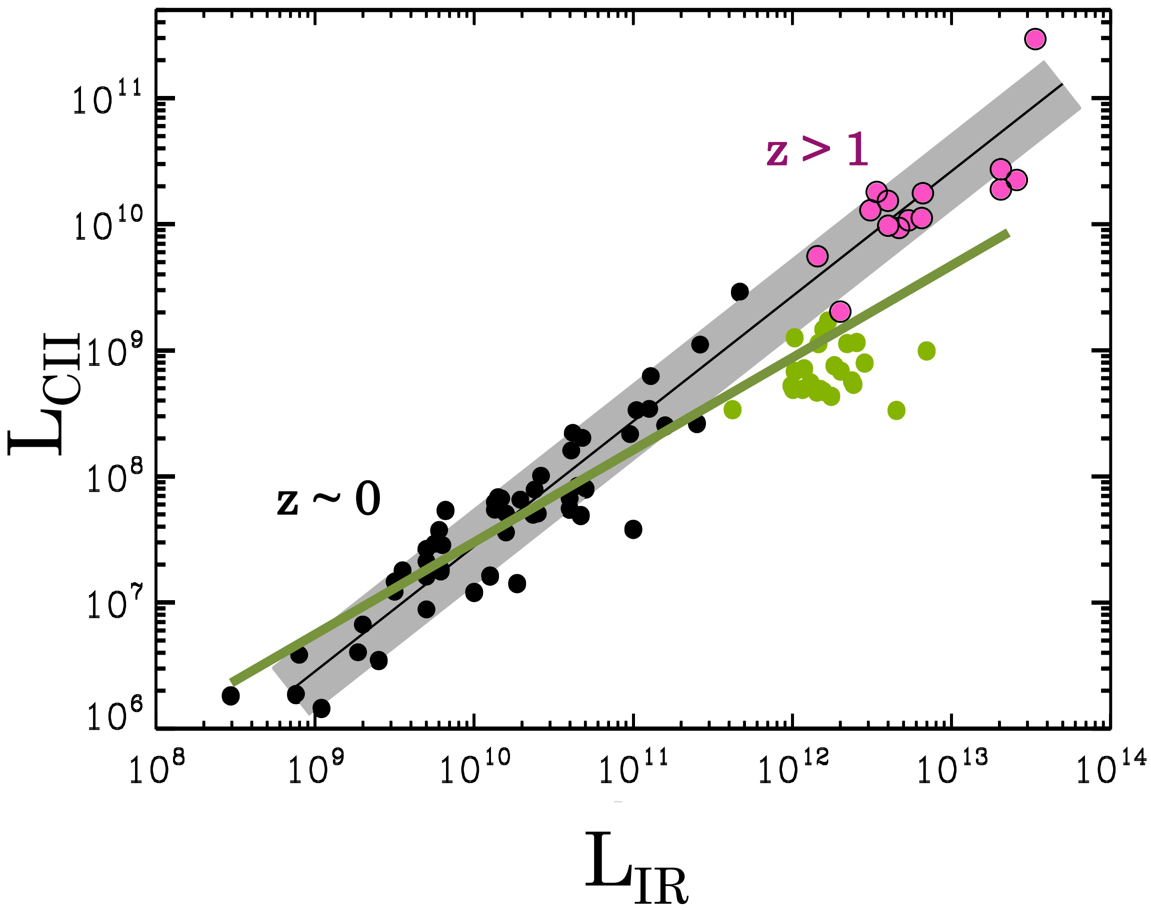
z = 4.76



z = 2.25



L_{CII} – L_{IR} correlation



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Almost linear correlation

e.g. Malhotra+97,+01, Herrero-Camus+14,

Local ULIRGs – CII deficit

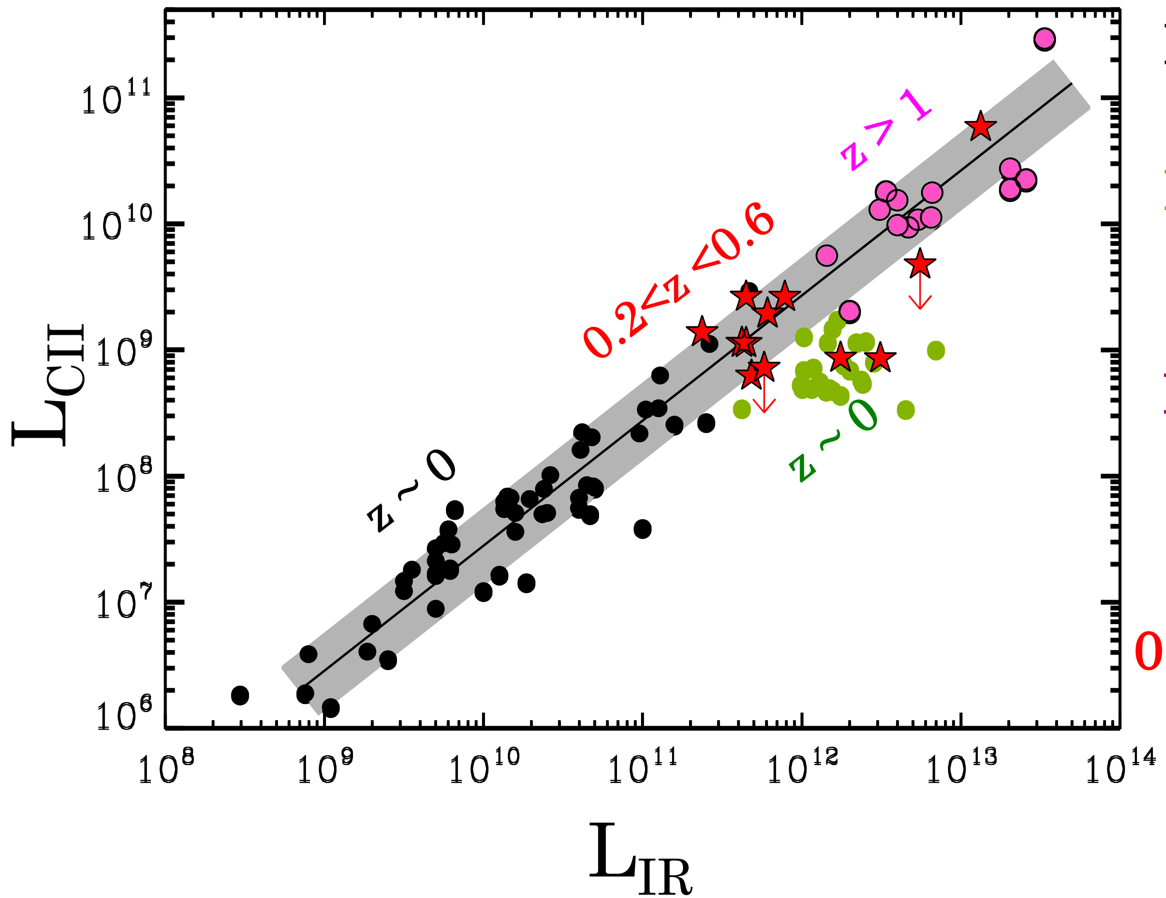
e.g. Luhman+03, Garcia-Carpio+11, Farrah+2013, Diaz-Santos+2013

High-z ULIRGs - ~~CII deficit~~

e.g.Iviison+2010, Hailey-Dunsheath+10, Stacey+10, Valtchanov+11

- A large fraction high-z ULIRGs behave like local normal galaxies
- Strong evolution of their [CII] emission

$L_{CII} - L_{IR}$ correlation



Local Galaxies

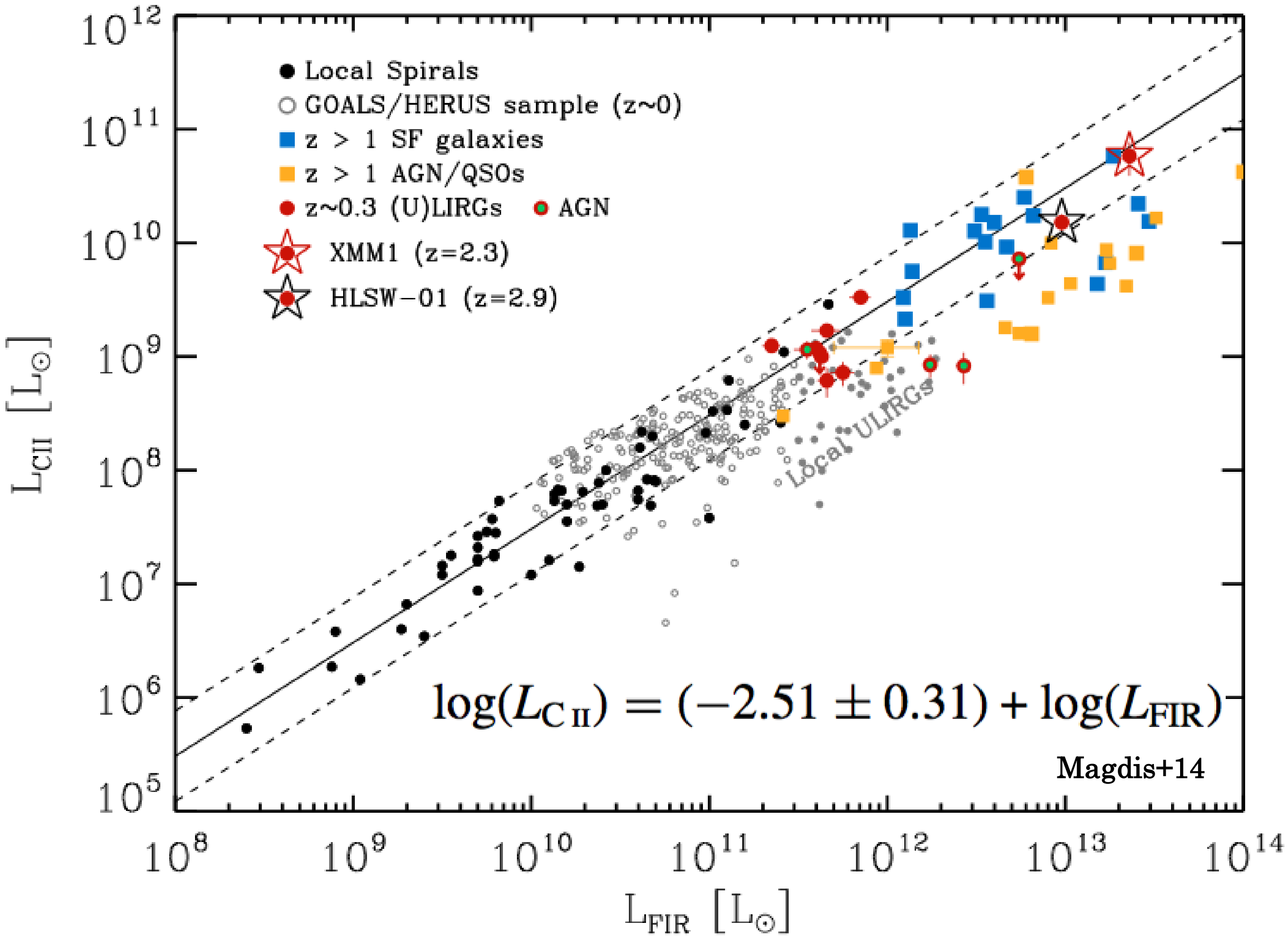
Local ULIRGs – CII deficit

High-z ULIRGs - CII deficit

0.2<z<0.6 ULIRGs - CII deficit

- Evolution already at place @z~0.3-0.4

$L_{CII} - L_{IR}$

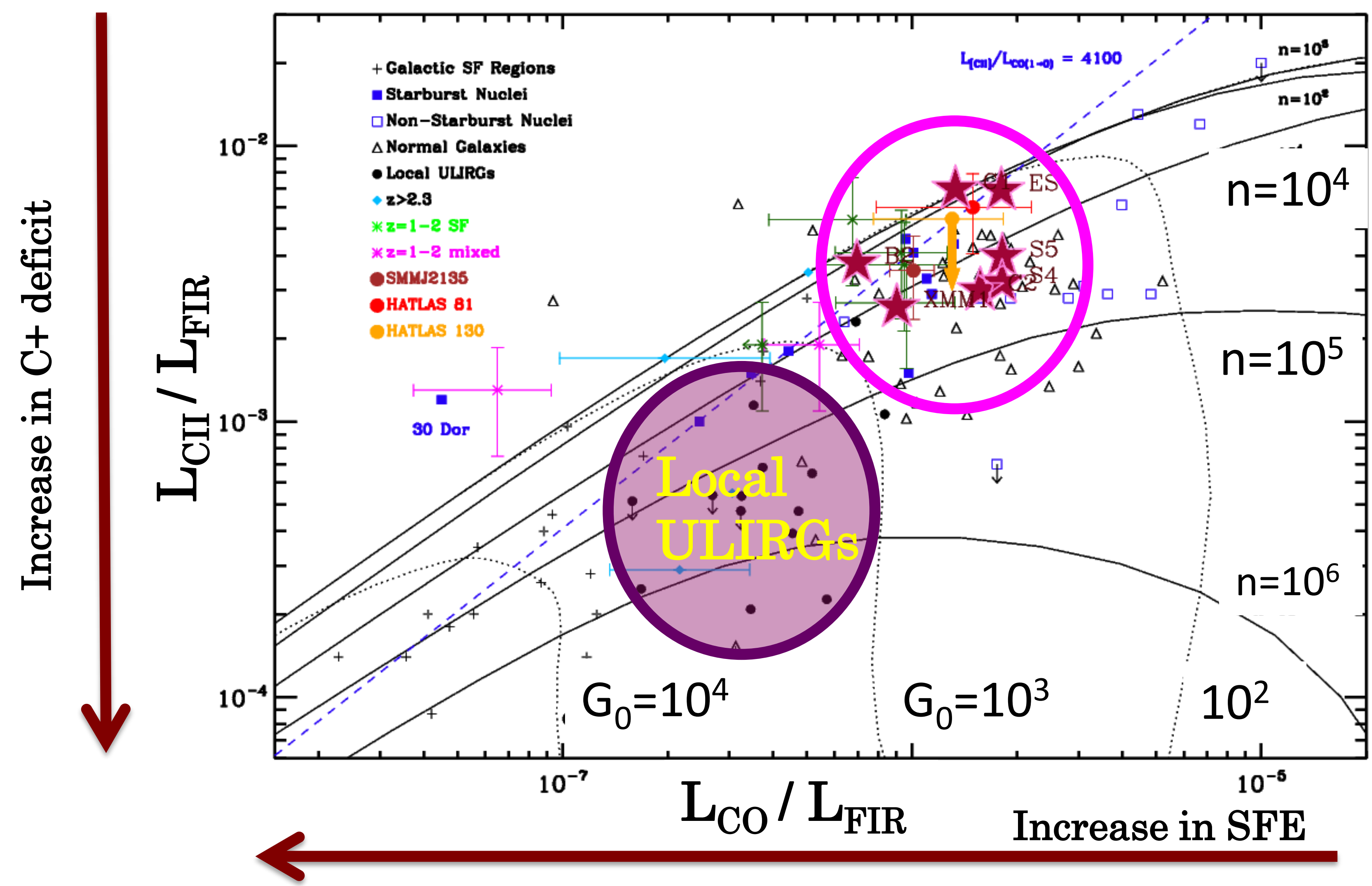


The majority of galaxies at all redshifts follow a universal L_{CII}–L_{IR} relation

Local ULIRGs and QSO's appear [CII] deficient.

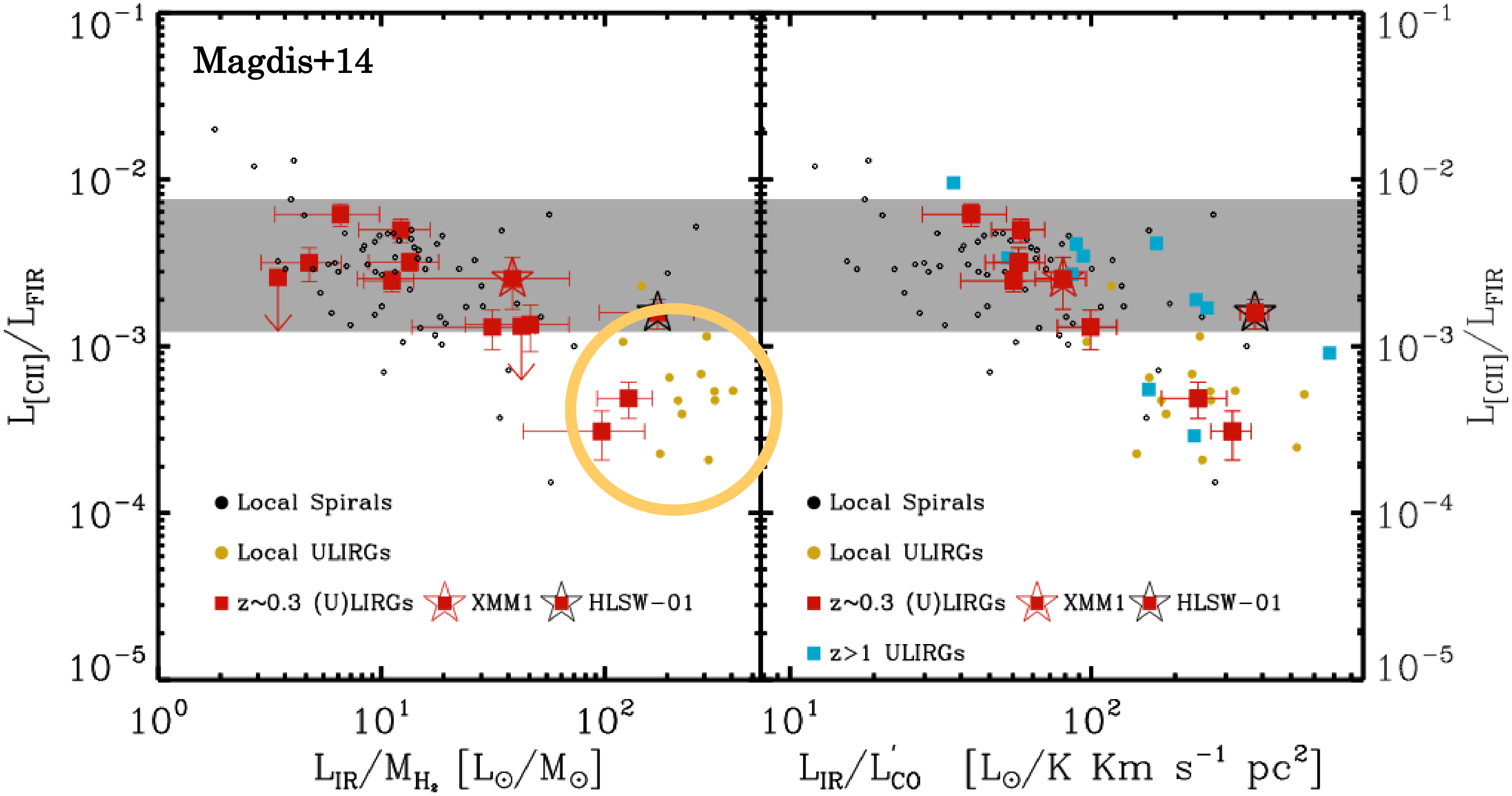
PDR fitting of [CII],CO, L_{IR}

Rigopoulou+14



Softer radiation fields

L_{CII}/L_{IR} vs SFE



[CII] deficit pronounced for sources with high SFE =SFR/M_{H2}

Different S-K law?

$\mathbf{SFR - M_{H2}}$

How to measure M_{H2}

H_2 is not observable under typical conditions

We have to rely on CO

$$M_{H2} = \alpha_{CO} \times I_{CO}$$

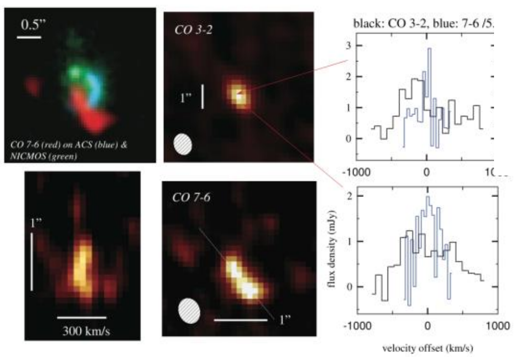
α_{CO} ~ 4-10 for local normal galaxies

α_{CO} ~ 0.8 for local ULIRGs

But what is the appropriate value at high-z ?

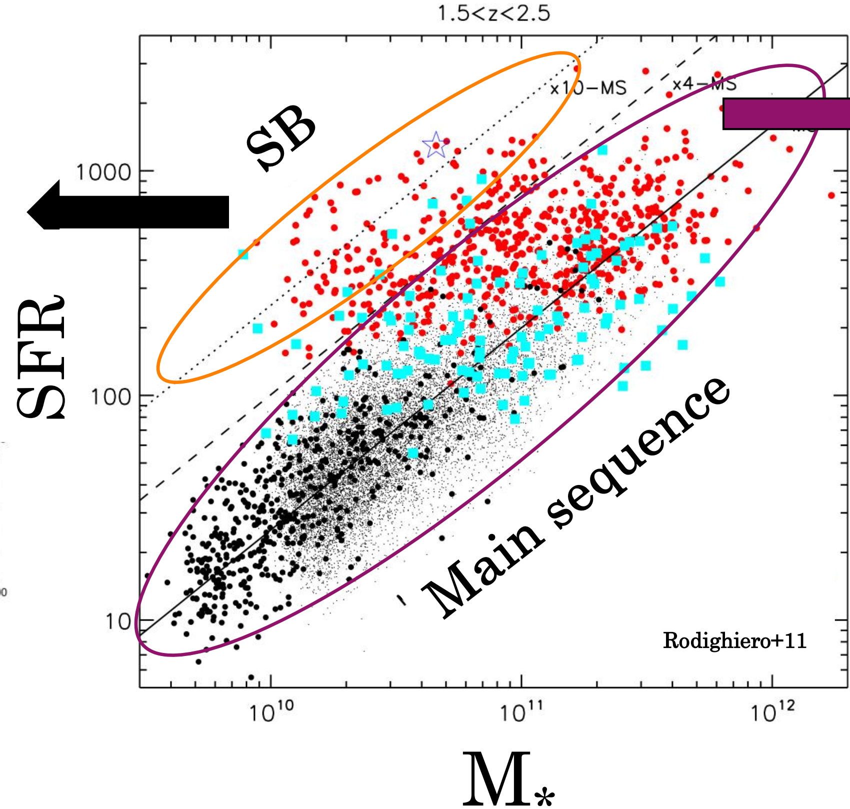
α_{CO} ; Dynamical Approach

Starbursts

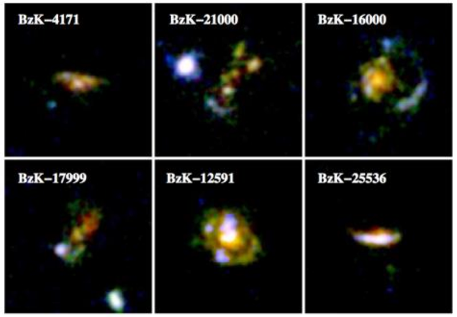


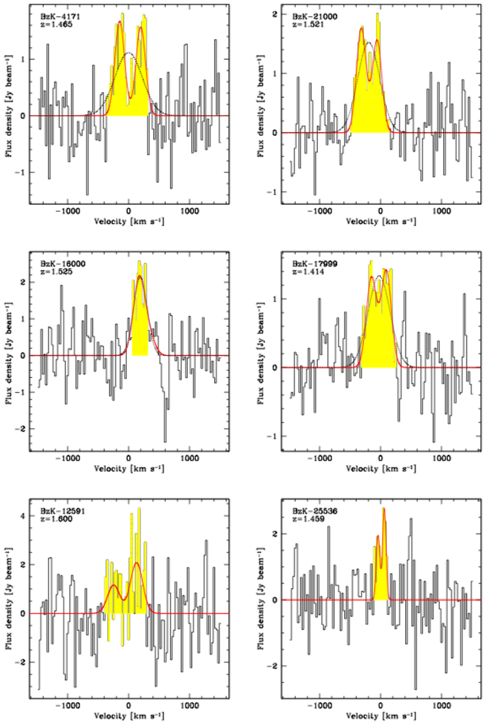
Tacconi+08

$\alpha_{CO} \sim 0.8$
Like local ULIRGs



Main sequence





Daddi+10

$\alpha_{CO} \sim 4.0$
Like local spirals

Validate and generalize the result with independent methods

α_{CO} ; Gas to Dust Mass Ratio Approach

$$\delta_{GDR} = (\Sigma_{HI} + \alpha_{CO} I_{CO}) \,/\, \Sigma_D$$

observables

At high-z, $M_{HI} + M_{H2} \approx M_{H2}$

(e.g. Obrewskow+10)

$$\alpha_{CO} = (\Sigma_D \times \delta_{GDR}) \,/\, I_{CO}$$

Gas to Dust Mass Ratio Approach

$$\alpha_{CO} = (\Sigma_D \times \delta_{GDR}) / I_{CO}$$

↓

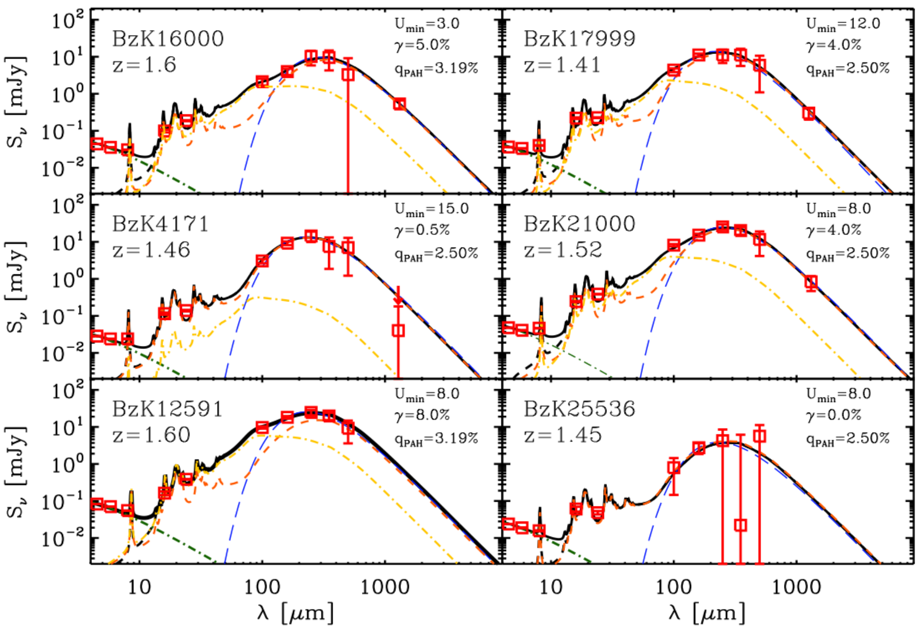
IRAM, ALMA, etc

Gas to Dust Mass Ratio Approach

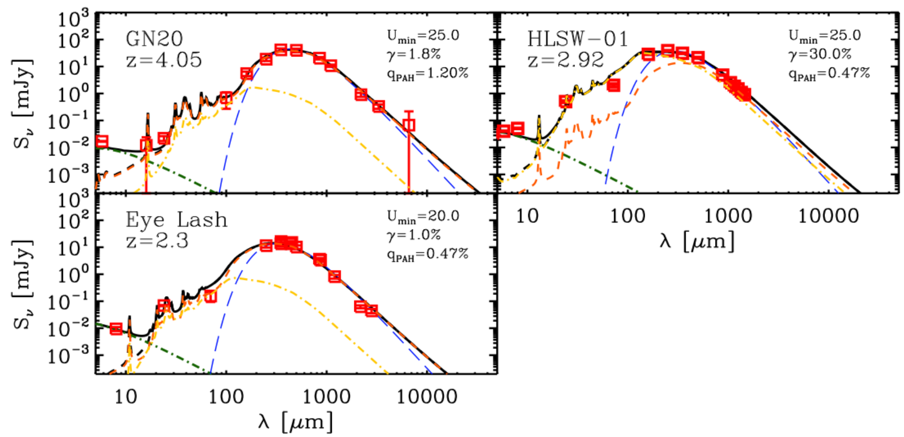
$$\alpha_{CO} = (\Sigma_D \times \delta_{GDR}) / I_{CO} \qquad (\Sigma_D = M_{dust})$$

Herschel + Ground based (sub)mm

Main sequence z~0.5-2.5



SMGs

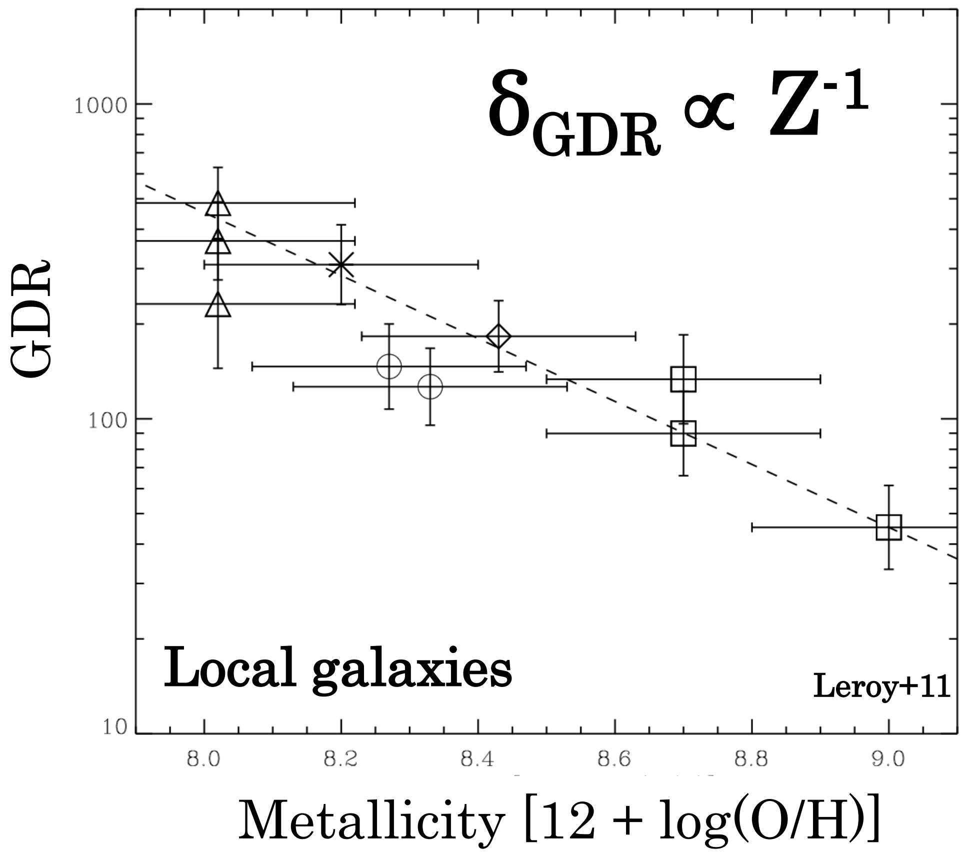


Magdis+11,12b

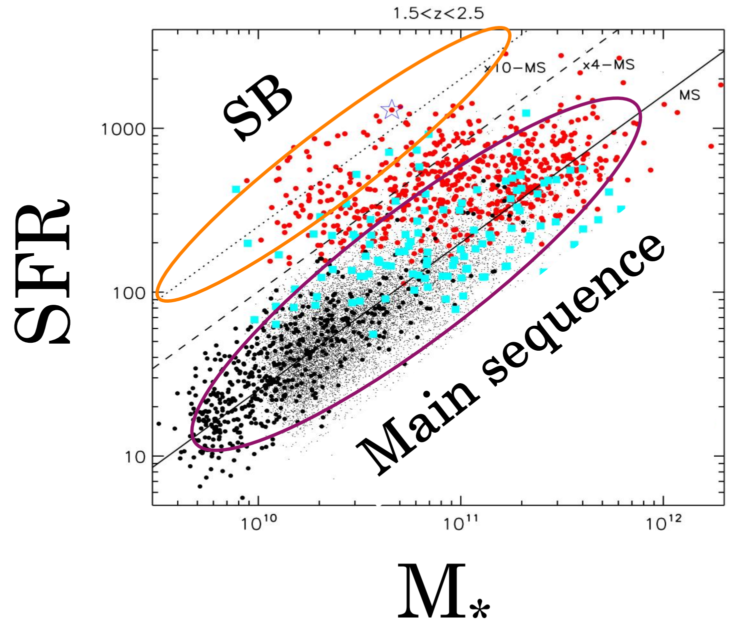
Based on GOODS-Herschel data

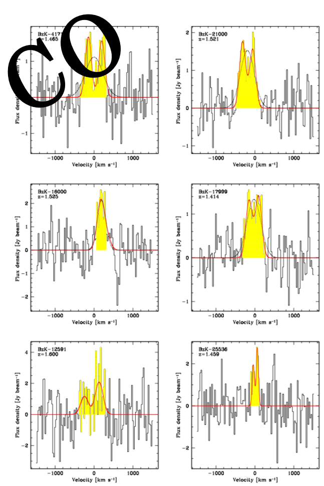
Dust to Gas Mass Ratio Approach

$$\alpha_{CO} = (\Sigma_D \times \delta_{GDR}) / I_{CO}$$



Dust to Gas Mass Ratio Approach





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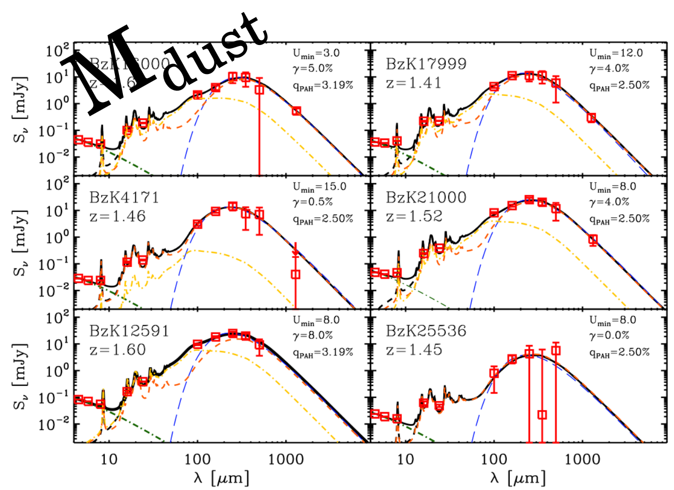

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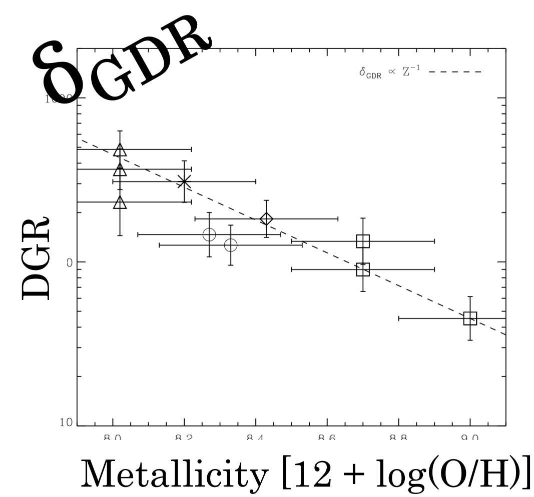
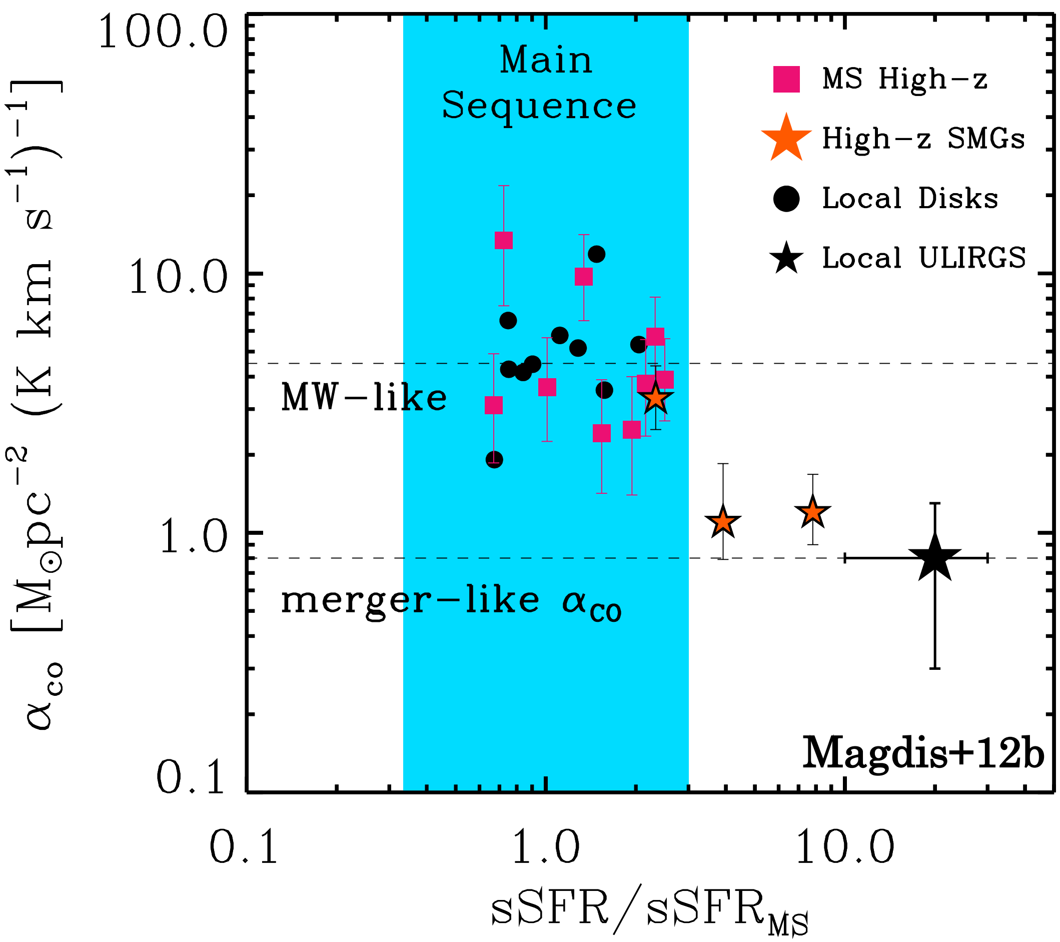
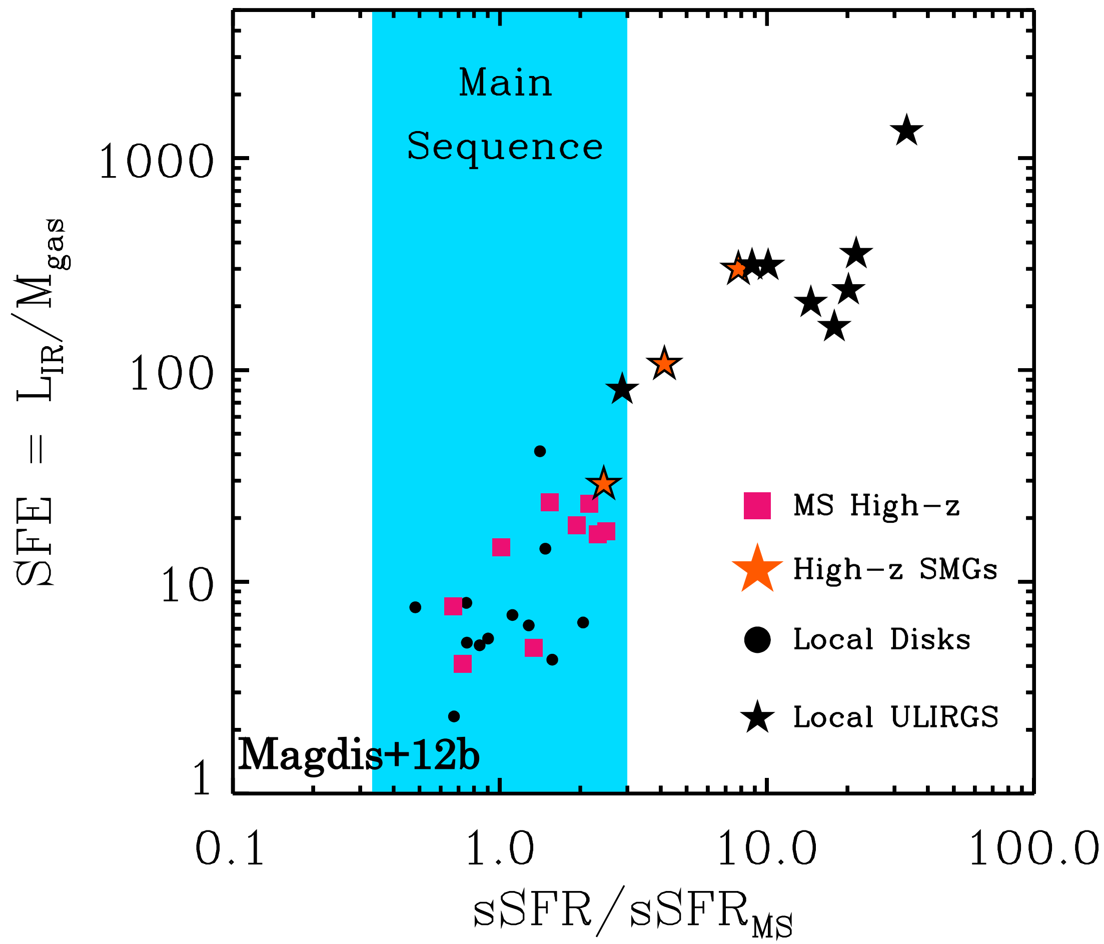




High-z Main Sequence (even if ULIRG like L_{IR})

$< \alpha_{CO} > \sim 4.5$

Agreement with dynamical Approach and semi analytical models (e.g. Narayanan+11)



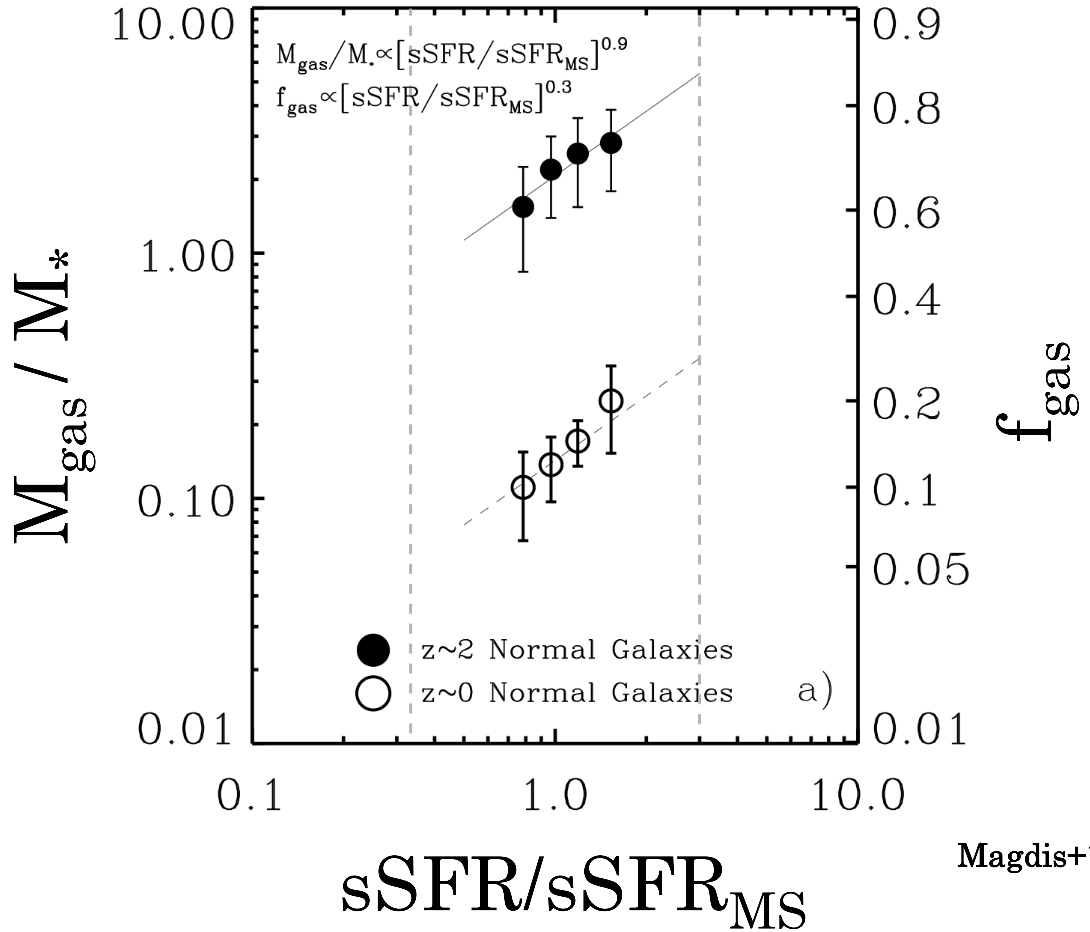
High-z Main Sequence (even if ULIRG like L_{IR})

SFE ~ 15 $L_\odot/M_\odot$

τ_{dep} ~ 0.7 Gyrs
x10 than local ULIRGs

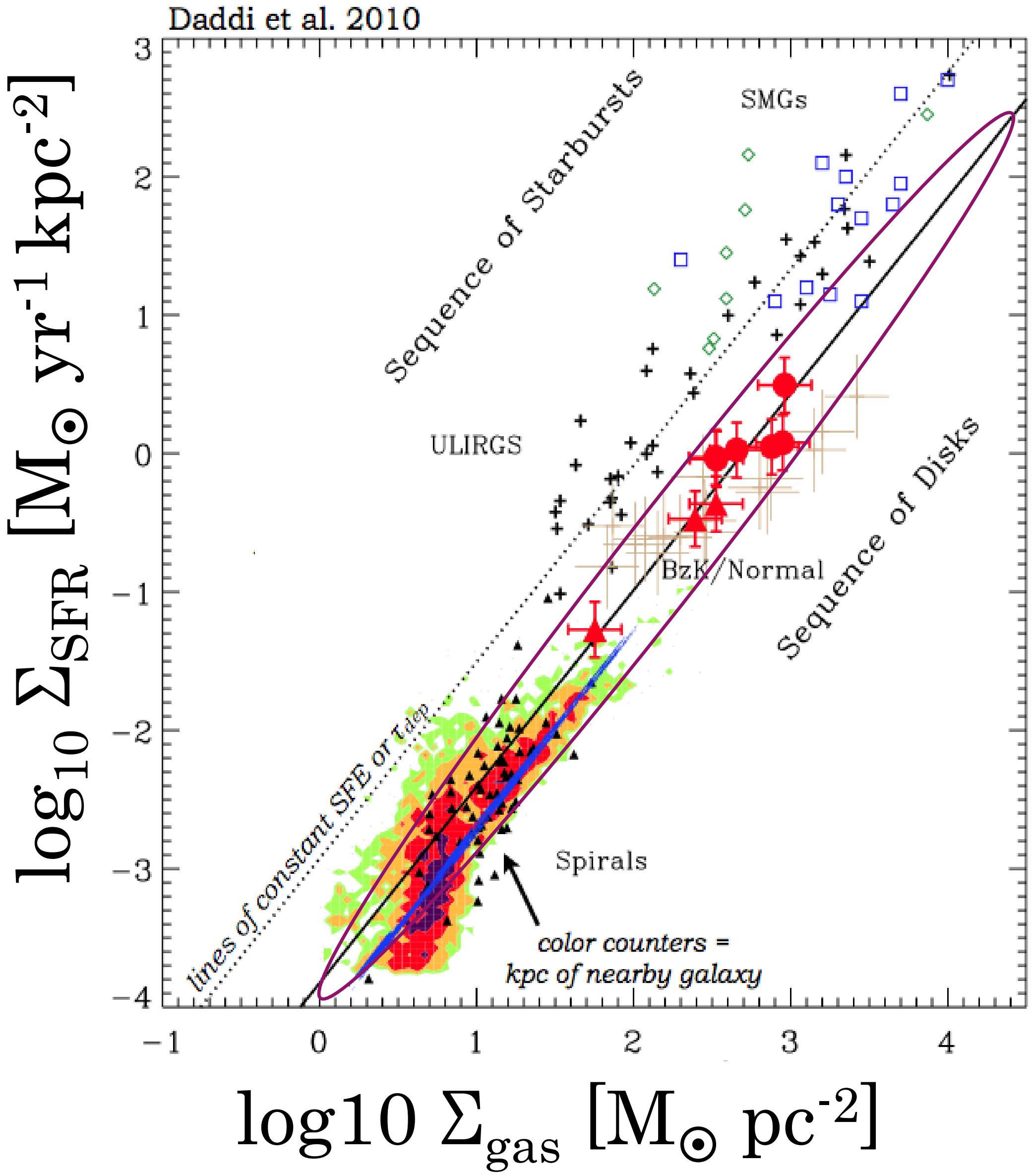
Dissecting the MS

Thickness of SFR-M_* → Variations of f_{gas}

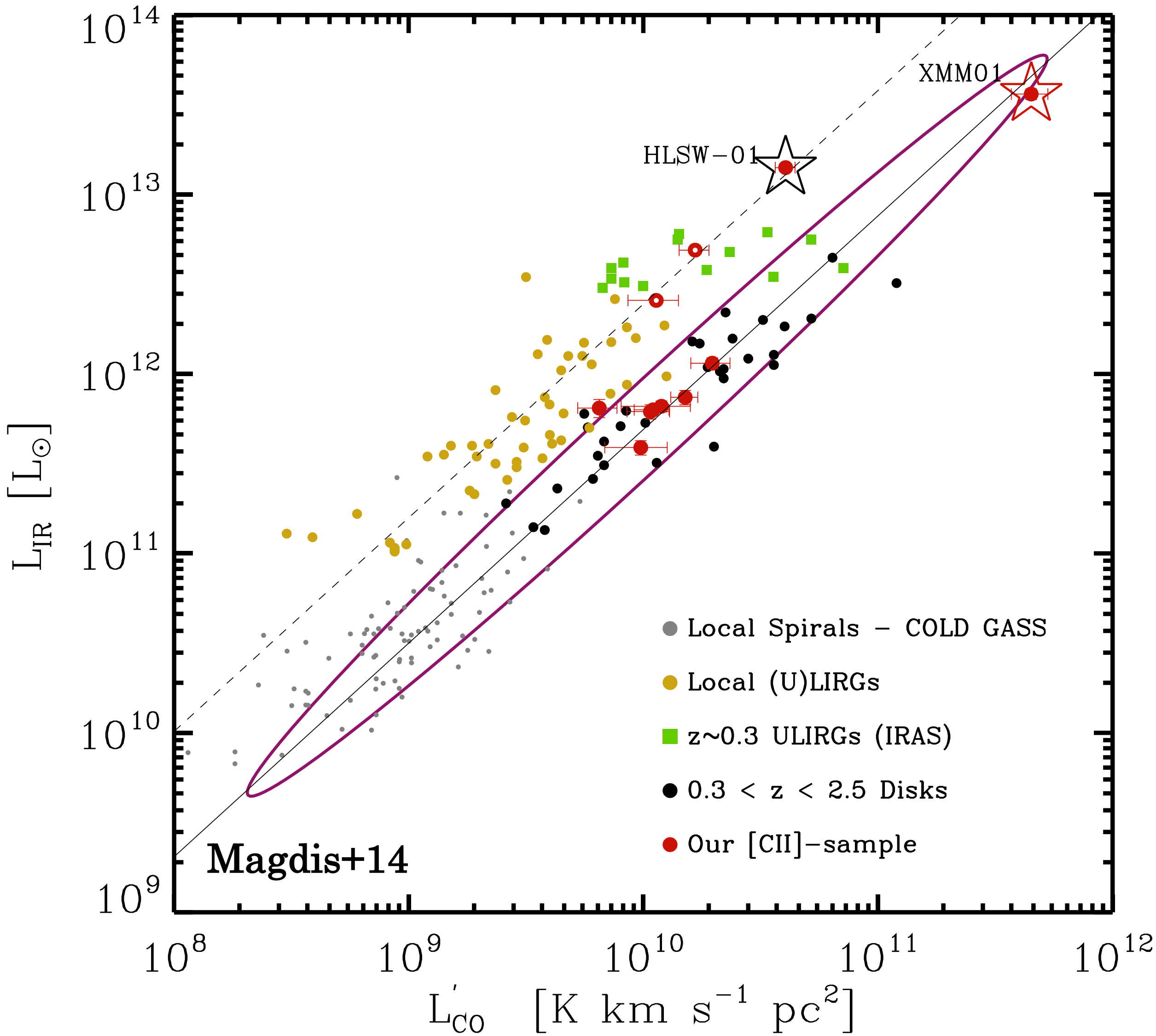


Magdis+12b

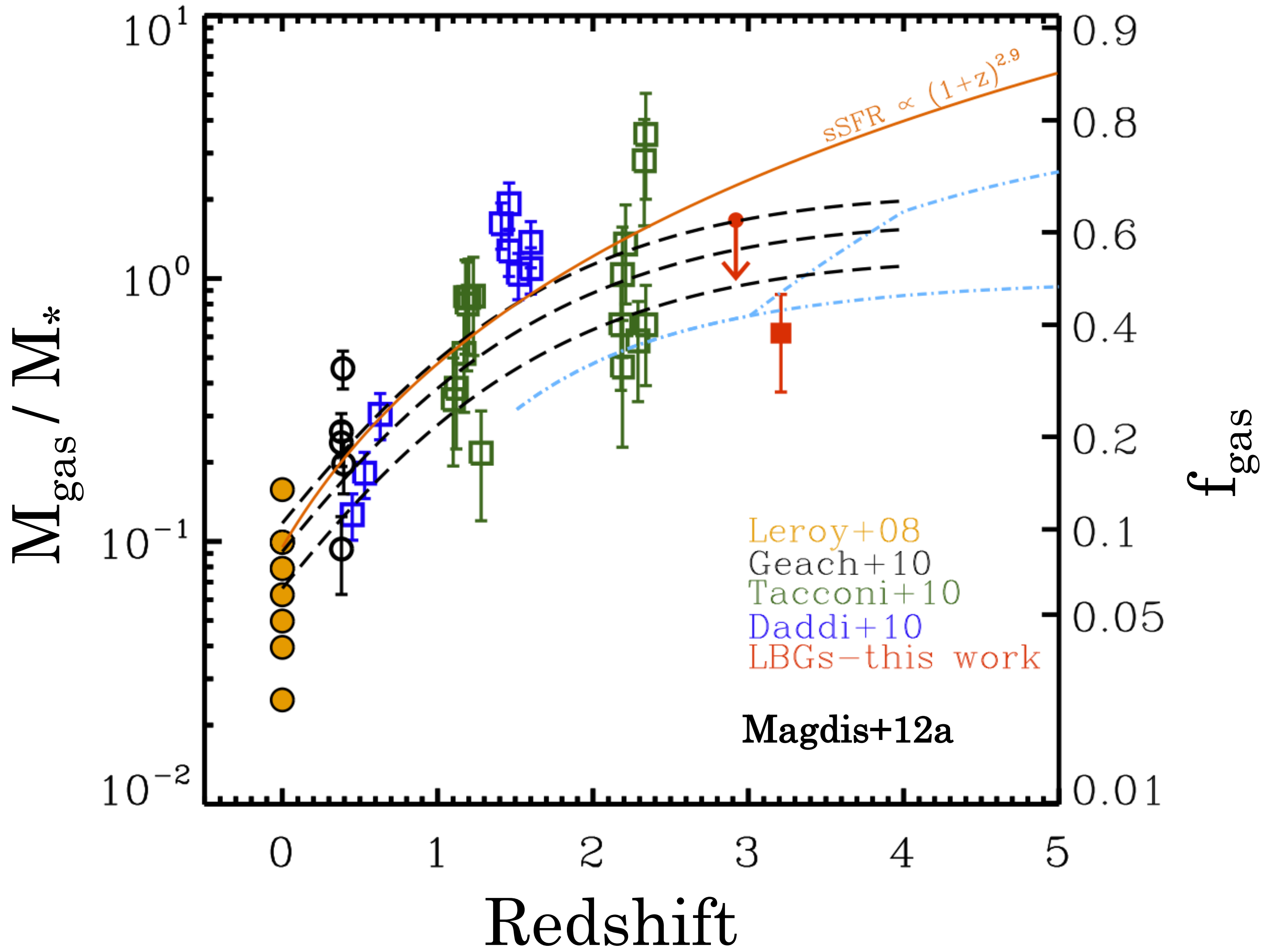
Star formation Law



Star formation Law

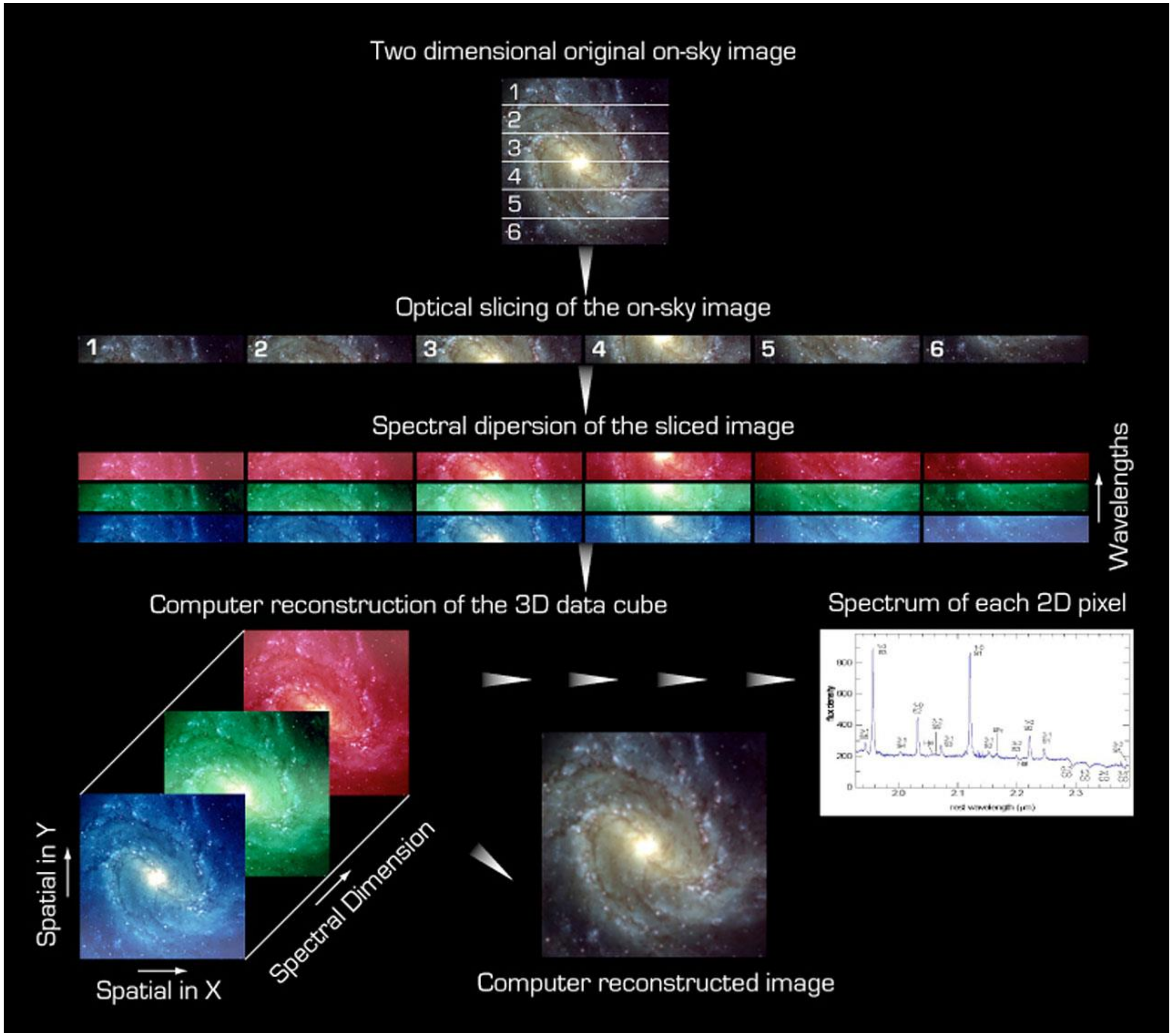


Evolution of Gas Fraction

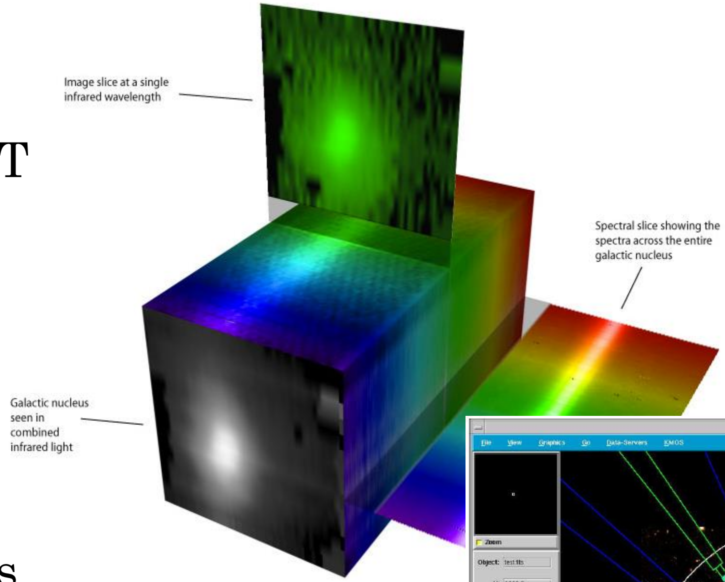


Kinematics across the MS

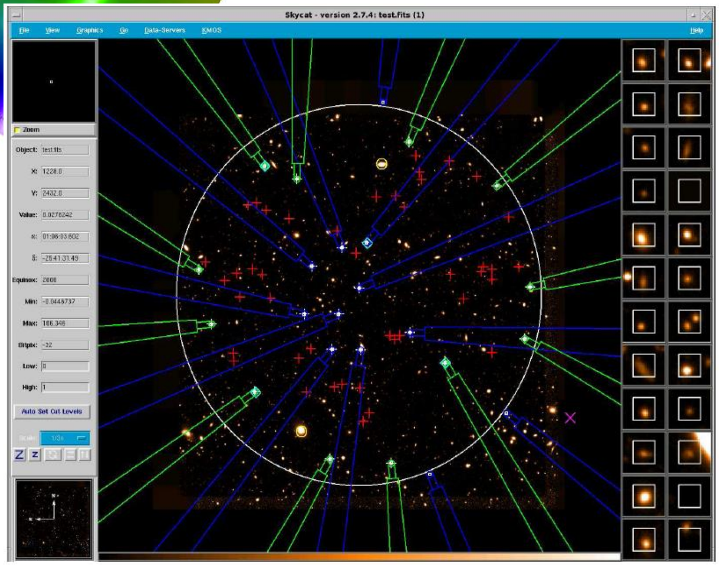
Integral Field Spectroscopy



KMOS



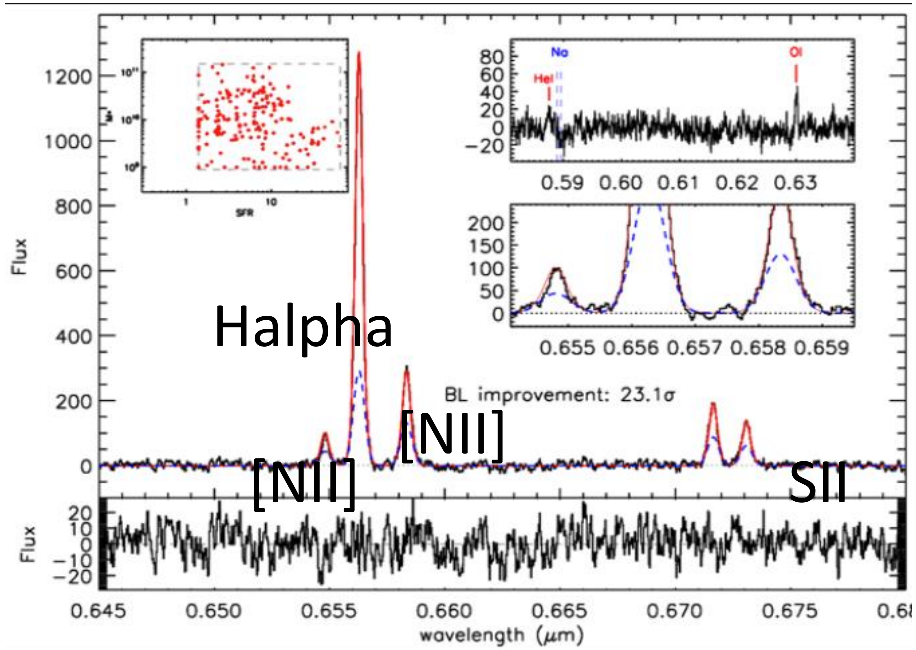
- KMOS: multi object IFU on VLT
- R~3500 spectroscopy at 0.8-2.5μm - zYJHK bands
- 7.2arcmin patrol field
- 24 robotic pickoff arms, with a 2.8”×2.8” FoV sampled at 0.2 arcsec
- IFUs are consolidated in groups of 8
- each set feeds one of 3 identical spectrographs
- Status: Observations began Autumn 2013



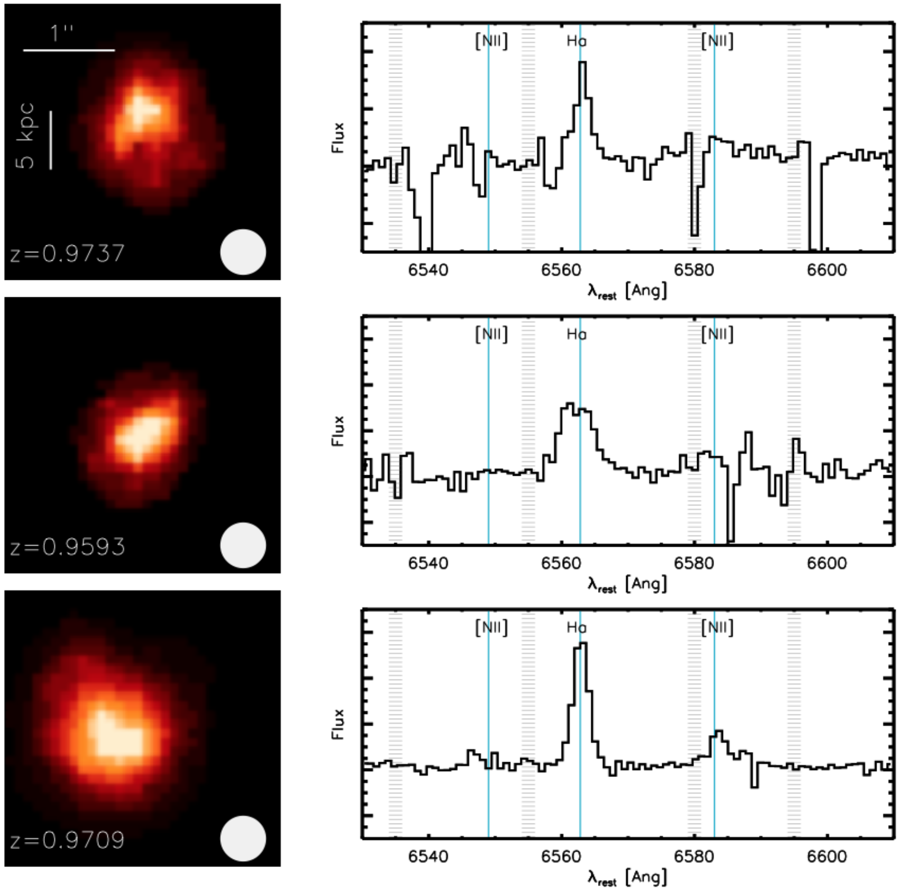
KROSS

KMOS REDSHIFT ONE SPECTROSCOPIC SURVEY

- KROSS - 30 Night Durham and Oxford KMOS GTO collaboration
- Up to 1000 resolved Hα observations of mass selected typical 'Main Sequence' star forming galaxies at $0.7 < z < 1.2$
- Mass selection K_{AB}=22.5 (logM ~ 9-9.5)
- Fields : UDS,COSMOS, ECDFS, SSA22
  - ~600 galaxies so far
  - 95% Ha detection rate
  - 80% resolved
  - 40% [NII] detection rate



1000 hours stack of all P92 targets

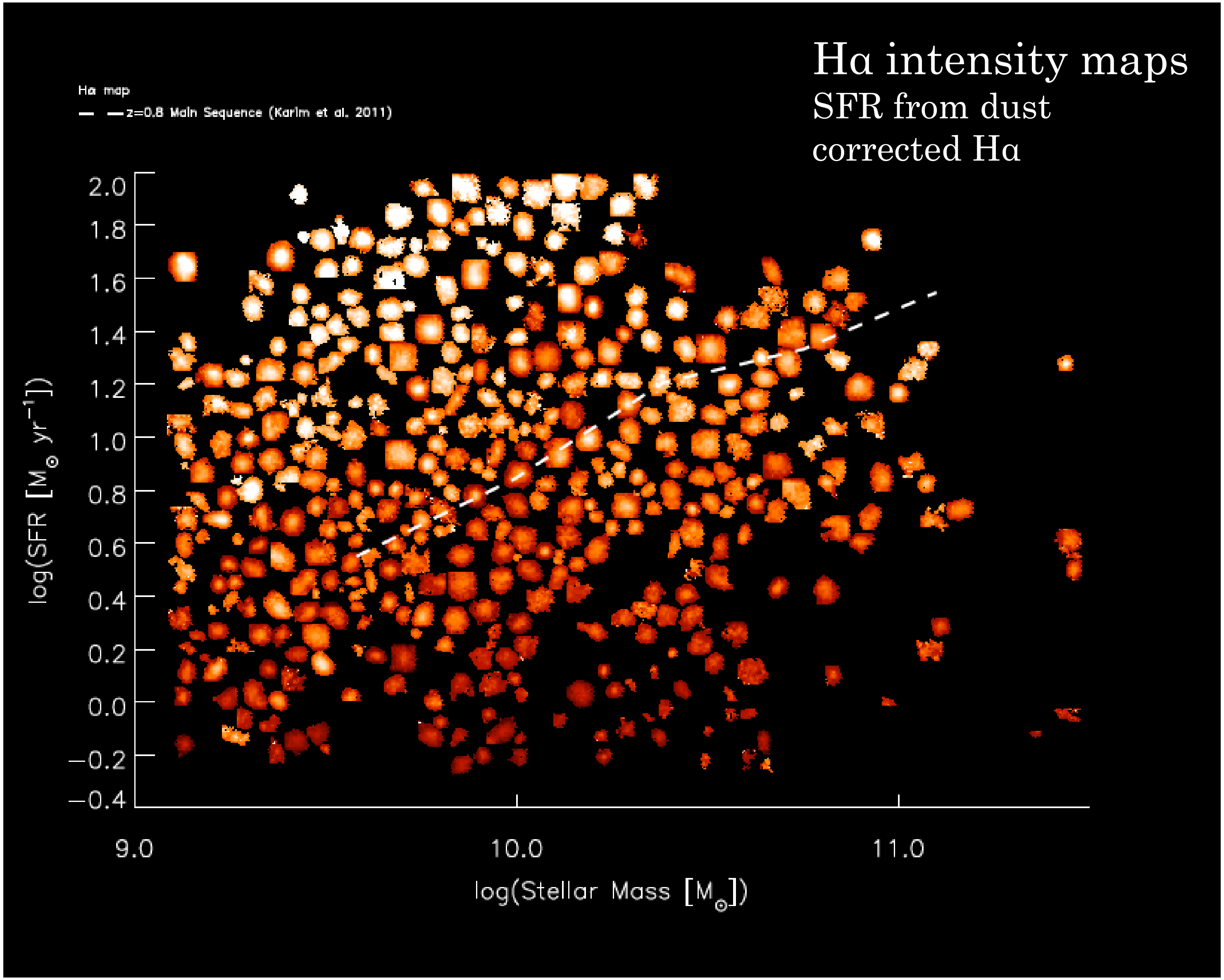


Detection of Hα line → SFR

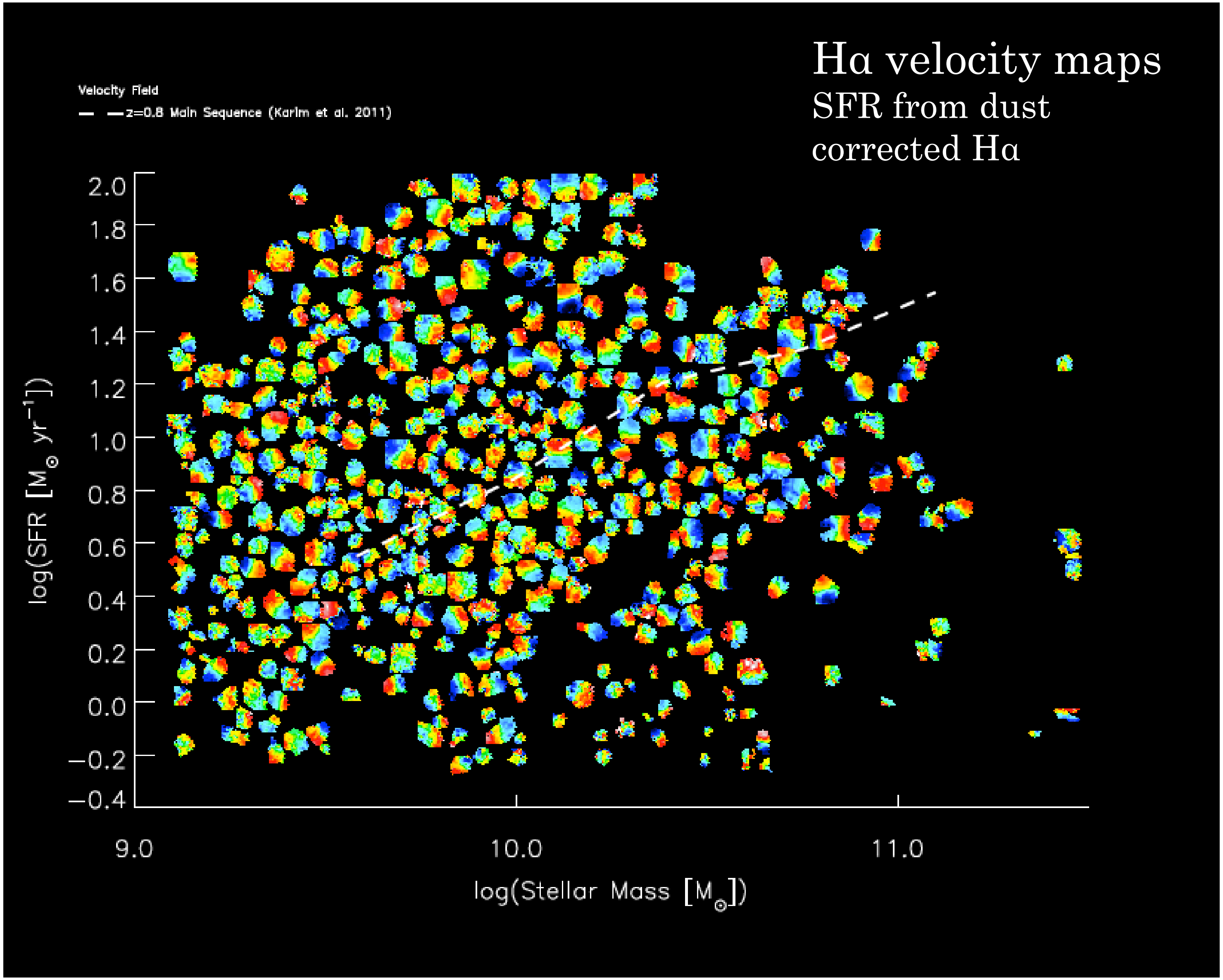
Spatially resolved sources → Measure $r_{H\alpha}$

Sources with [NII] and Hα → metallicity

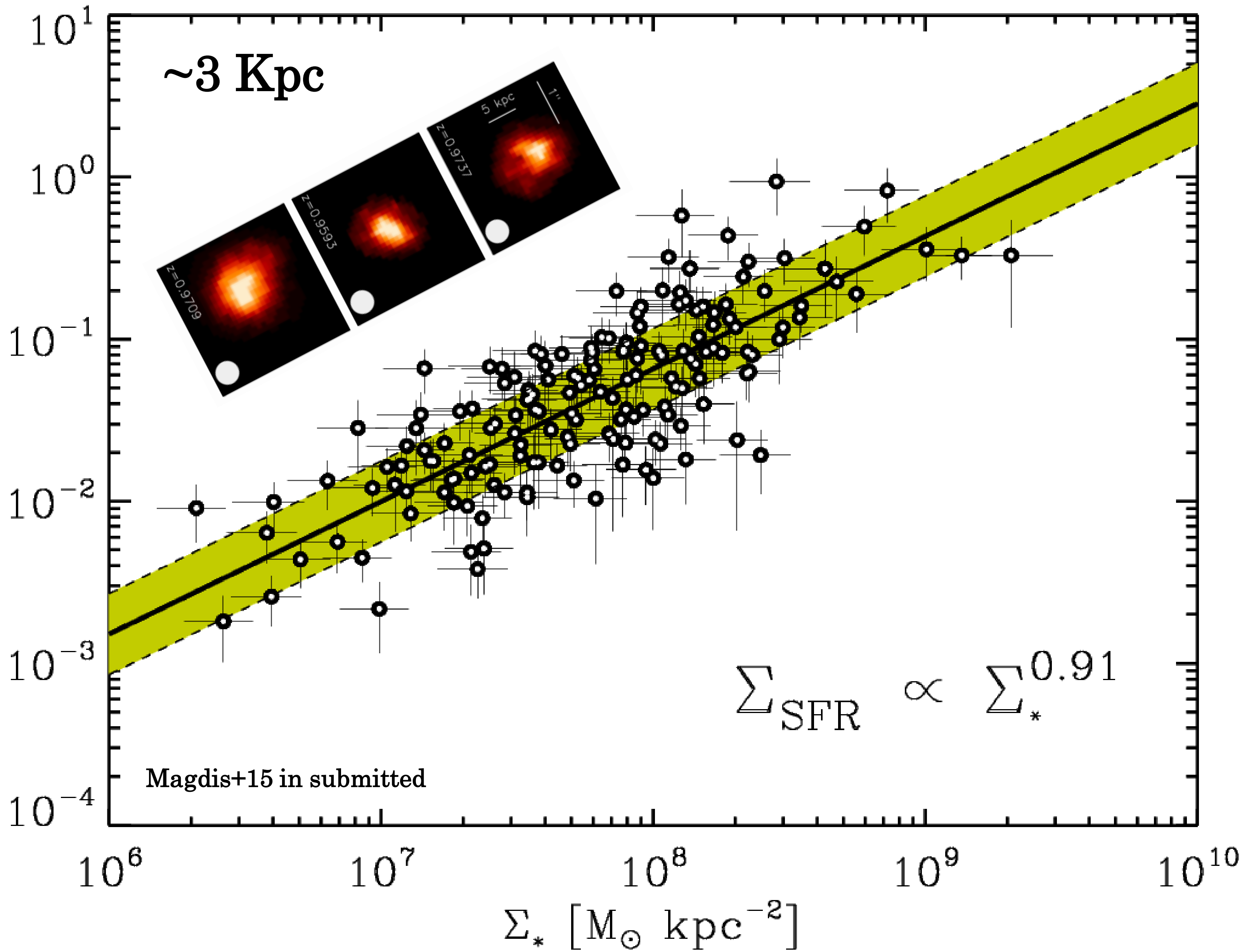
KROSS Main-Sequence at z~1



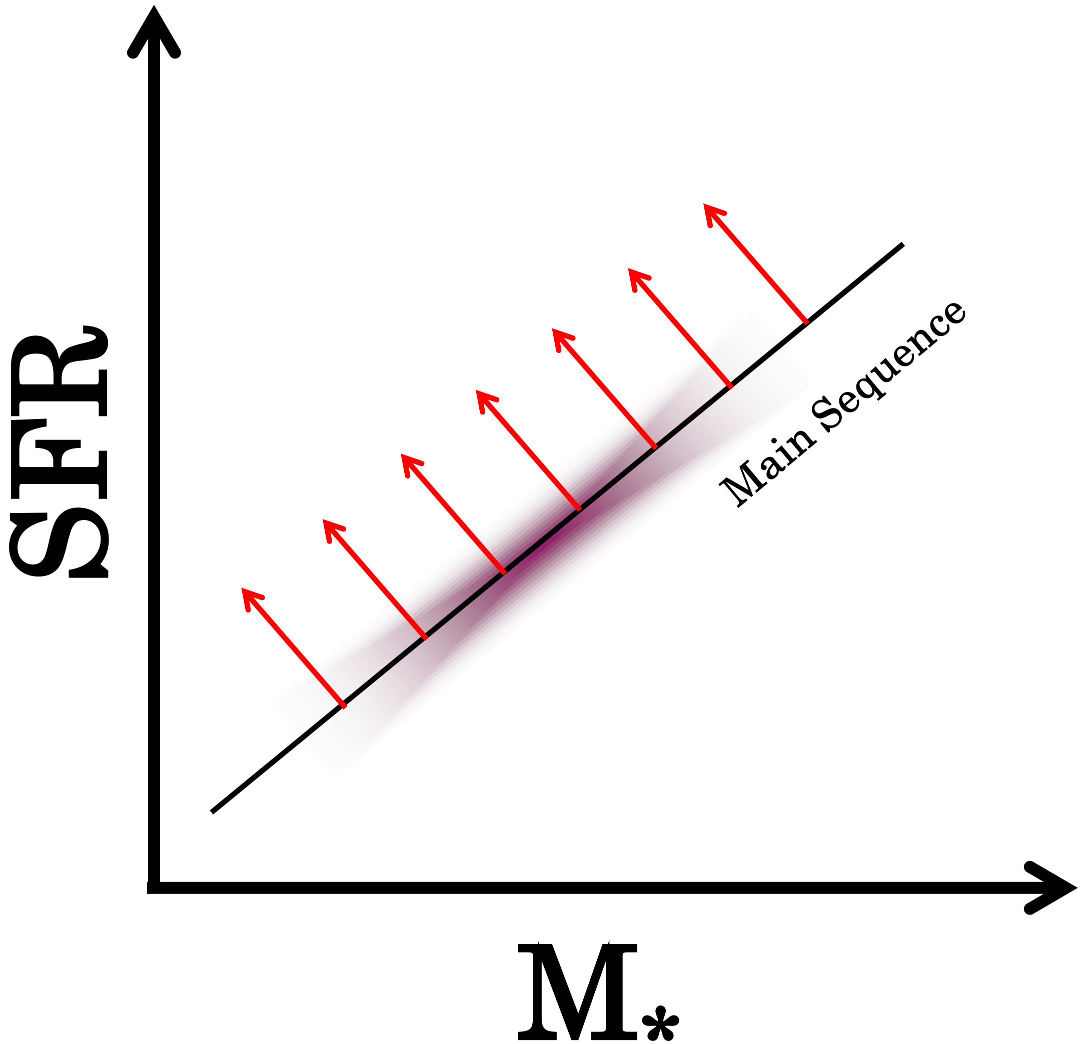
KROSS Main-Sequence at z~1



Resolved MS


~3 Kpc
z=0.9709
z=0.9593
z=0.9737
5 kpc
1"
Magdis+15 in submitted
$\Sigma_{SFR} \propto \Sigma_*^{0.91}$
Σ_{SFR} [$M_\odot$ yr^{-1} kpc^{-2}]
Σ_* [$M_\odot$ kpc^{-2}]
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^6
10^7
10^8
10^9
10^{10}

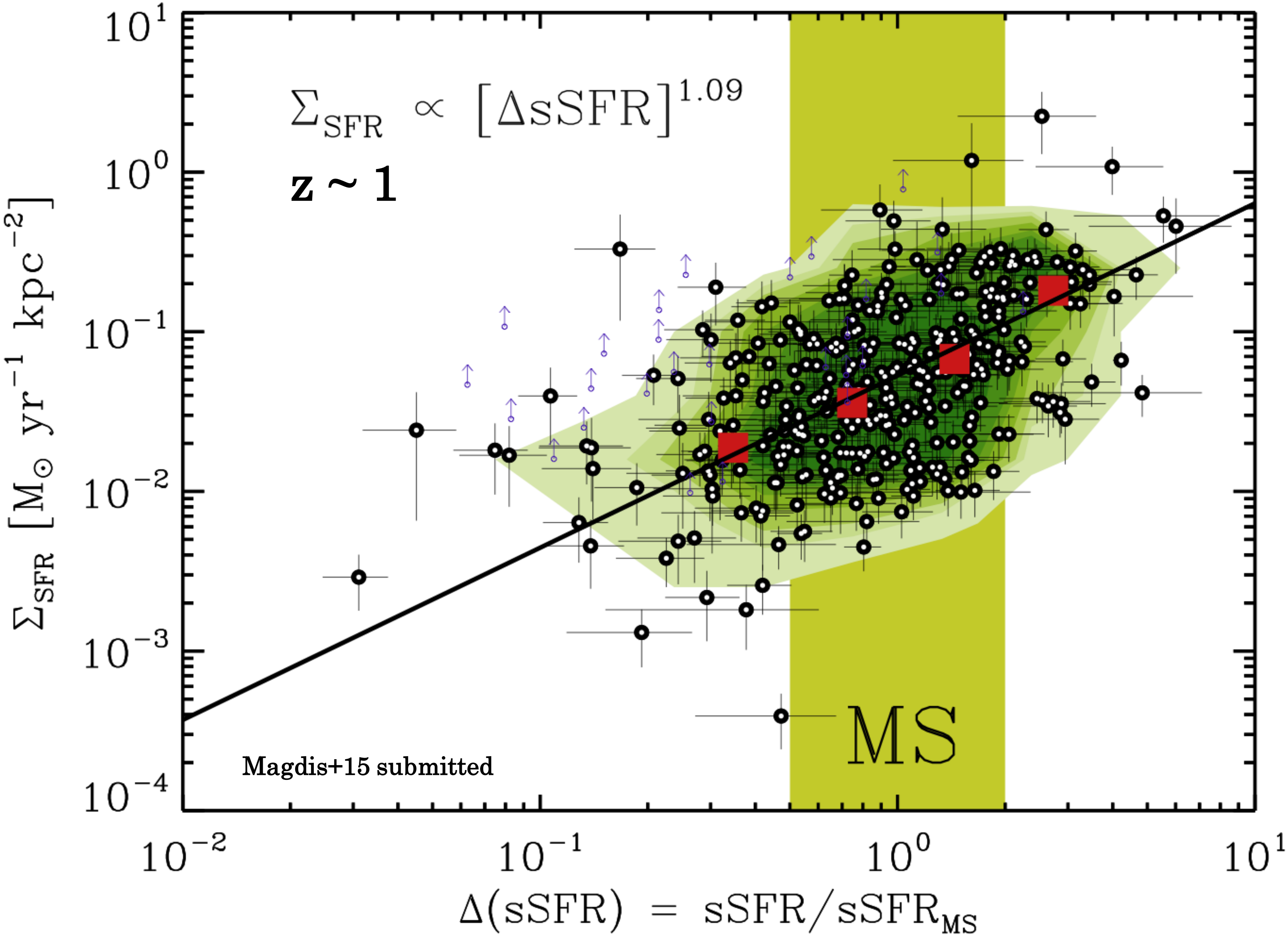
A paradigm



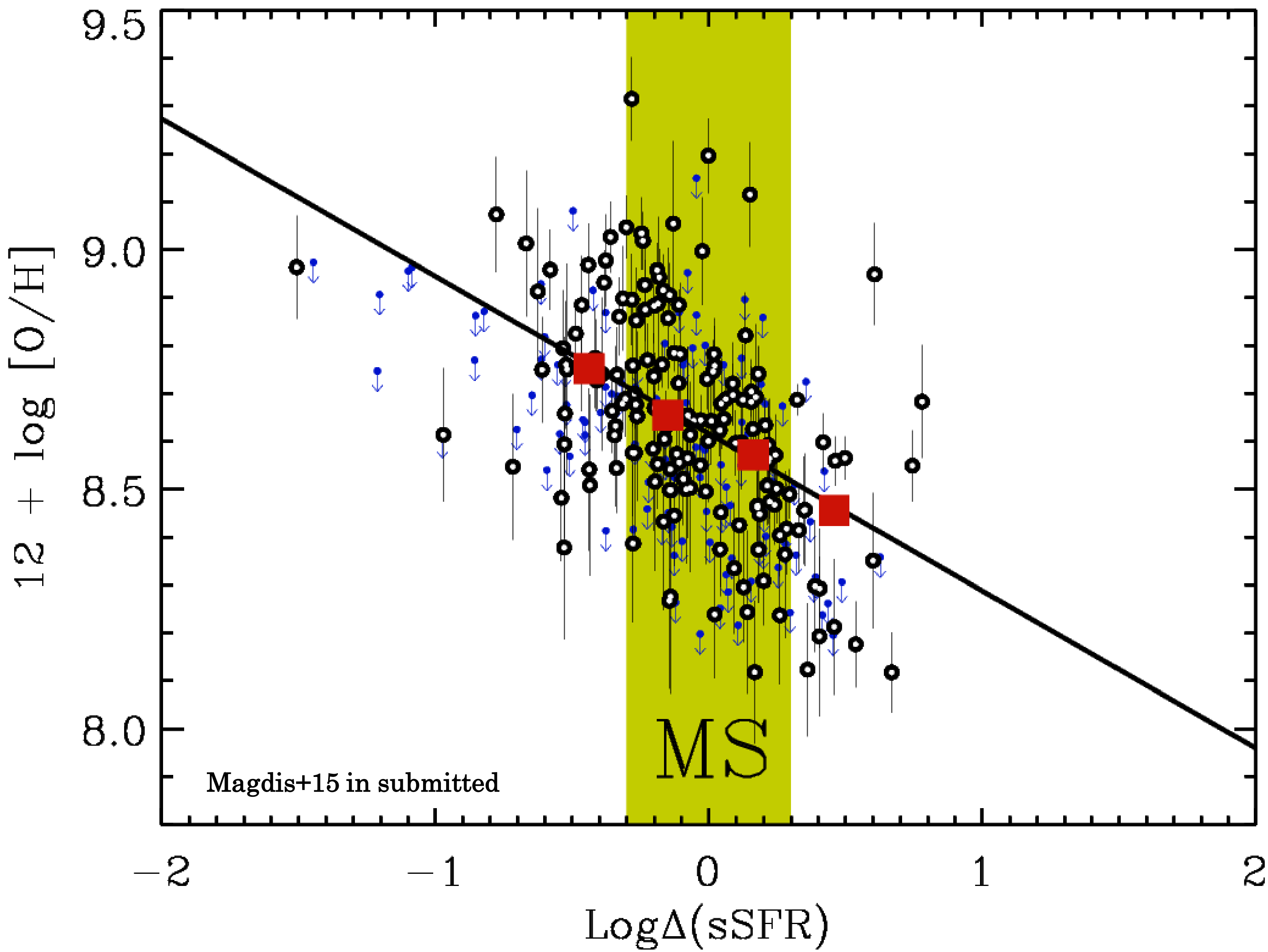
Moving away from MS

- **Higher SFE = SFR/Mgas** (e.g., Tacconi+08, Daddi+10, Magdis+12)
- **Lower τ_{dep}**
- **Weaker PAHs feature** (e.g. Elbaz+11, Nordon+12)
- **Lower L_{IR}/L_{CII}** (e.g., Garcia-Carpio+10, Diaz Santos+13, Magdis+14)
- **Higher Td** (e.g., Magdis+12b, Magnelli+14)
- **Increasing fraction of mergers** (e.g, Stott+12, Huing+13)
- **More compact star-formation ?**(e.g., Elbaz+11, Diaz-Santos+11,Martinez-Galarza+14)

SFR Density vs sSFR



Metallicity vs sSFR



Summary

1. Strong evolution in the star formation activity of ULIRGs, even @ z~0.4, as traced by CII, CO observations and Ha kinematics.
1. The properties of the galaxies are not tied to L_{IR}
1. Herschel data can provide the tools for Mgas estimates.
1. The thickness of the SFR-M_* is primarily driven by fgas variations.
1. Unique SF law for normal galaxies.

Galaxy growth was driven by driven by steady and smooth mode of star formation activity.

Special thanks to my close collaborators:

D. Rigopoulou – M. Bureau – N. Thatte (Univ. Oxford)
D. Elbaz – E. Daddi (CEA)
M. Dickinson (NOAO)
J-S. Huang (CfA,CAS)
M. Bethermin (ESO)
M. Sargent – S. Oliver (Univ. Sussex)
M. Griffin (Cardiff)
R. Maiolino (Univ. Cambridge)
V. Charmandaris (Athens Observatory)

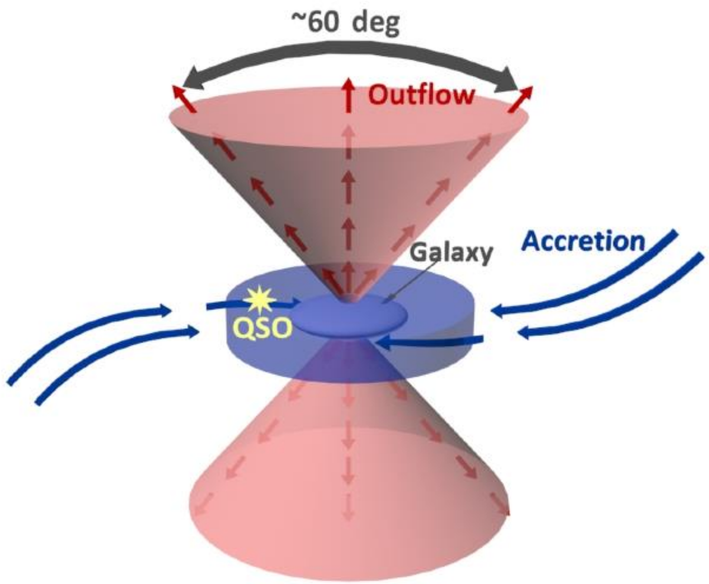
GOODS & PEP & HerMES

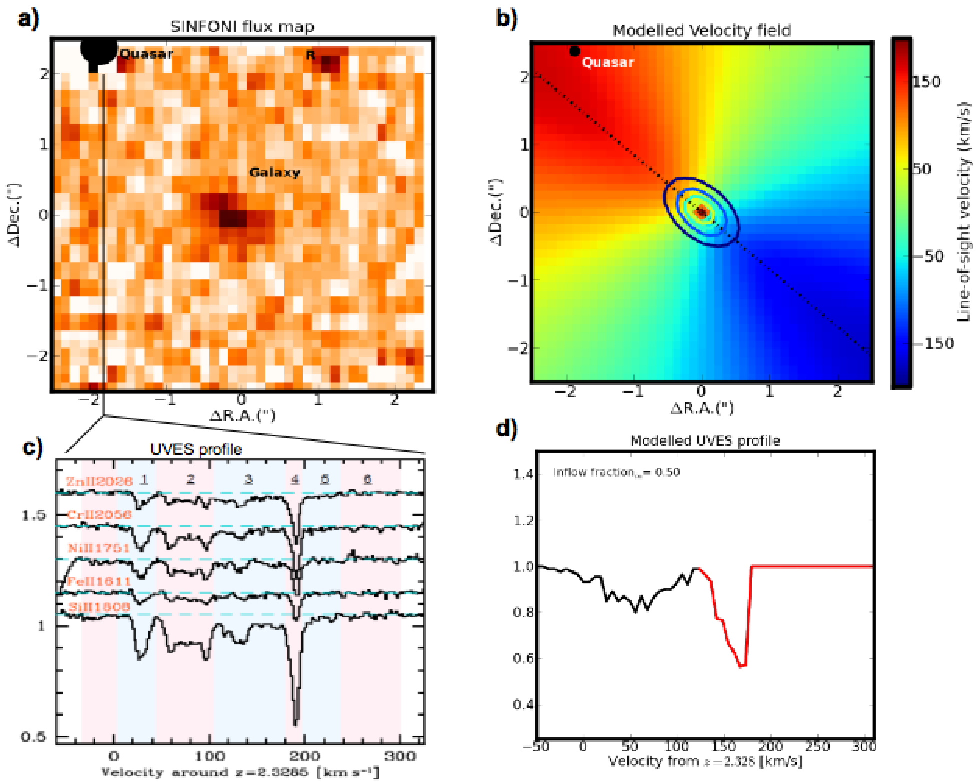
Thank you!

Future Directions

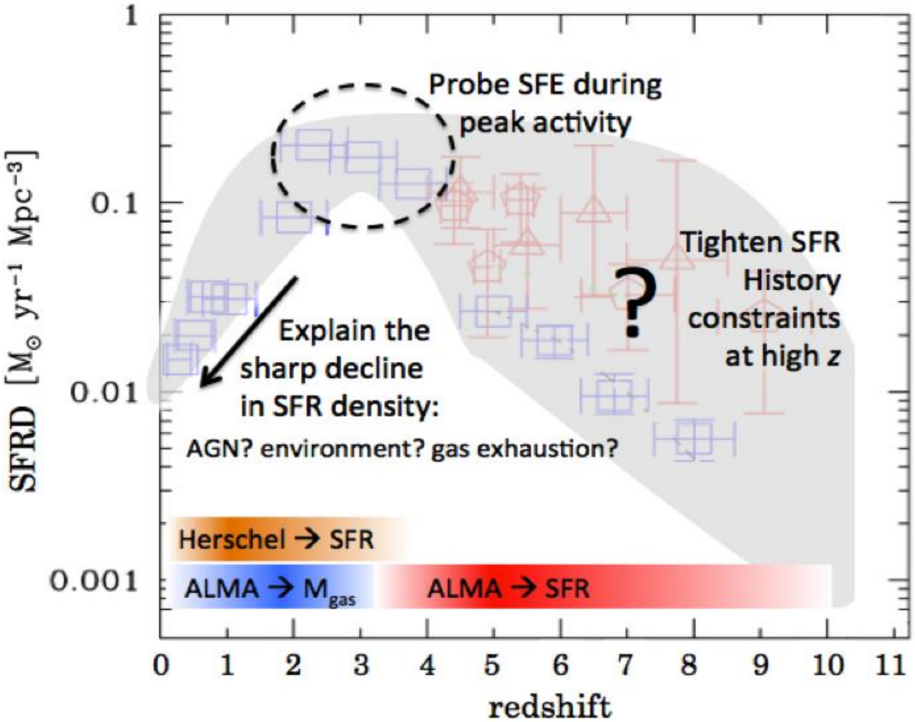
Where are the cold flows?

First evidence at high-z? Bouche+13



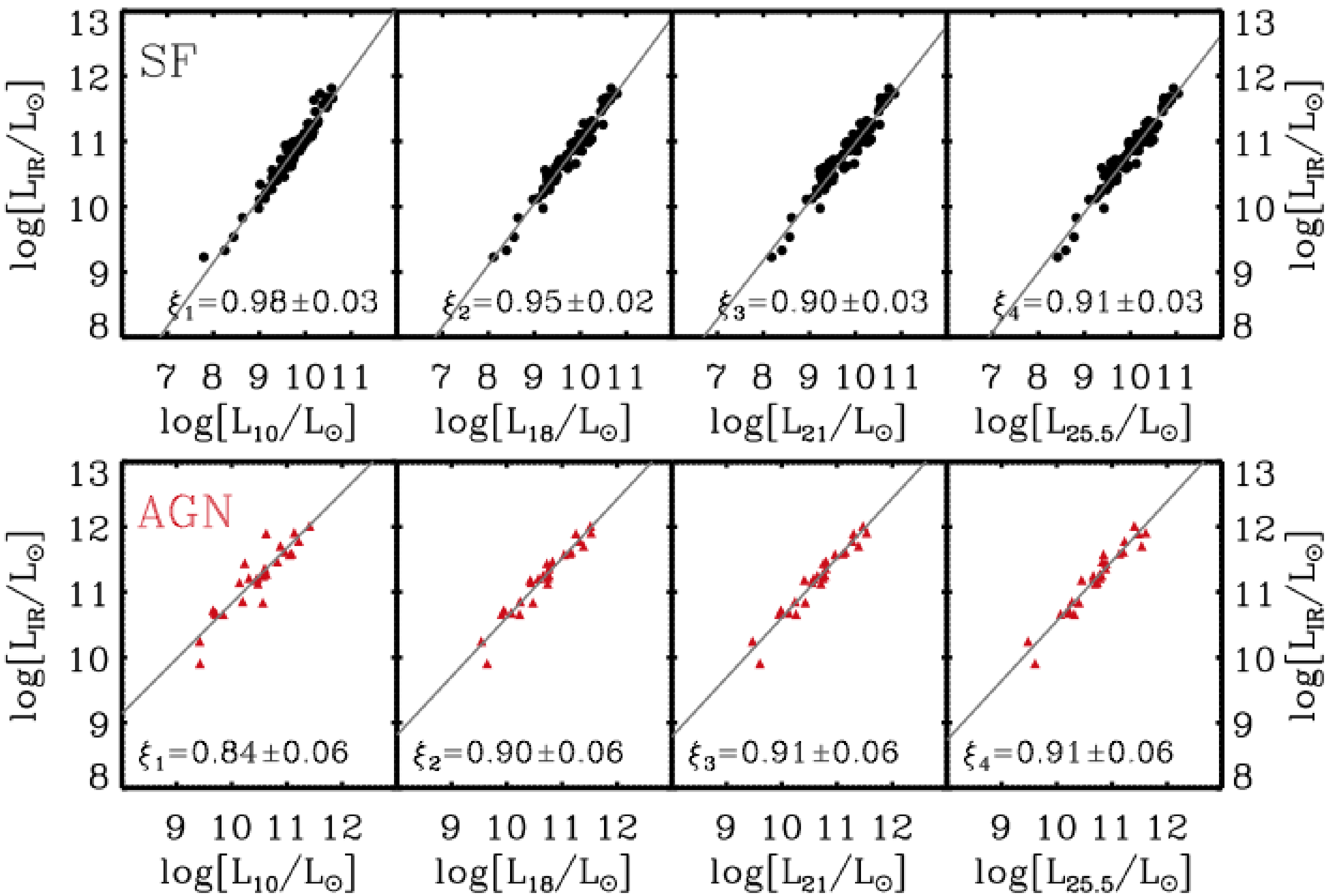


Herschel, ALMA, JWST synergy: Dusty universe at z>2



1) investigate whether LBGs really contribute most to the cosmic SFR density in its "rising phase" at z>2, or whether we have missed a significant dusty population
2) trace the evolution of the specific star formation rate at z>2, which is a matter of great controversy between current observations and theoretical models and observations
3) test the recently proposed scenario of a bimodal Kennicutt-Schmidt law, by applying the Magdis et al. (2011,2012b) method to derive the molecular gas mass of the galaxies
4) establish whether galactic-scale gas reservoirs are the necessary link between the observed co-evolution of AGN and star formation

JWST-MIRI



Magdis+13

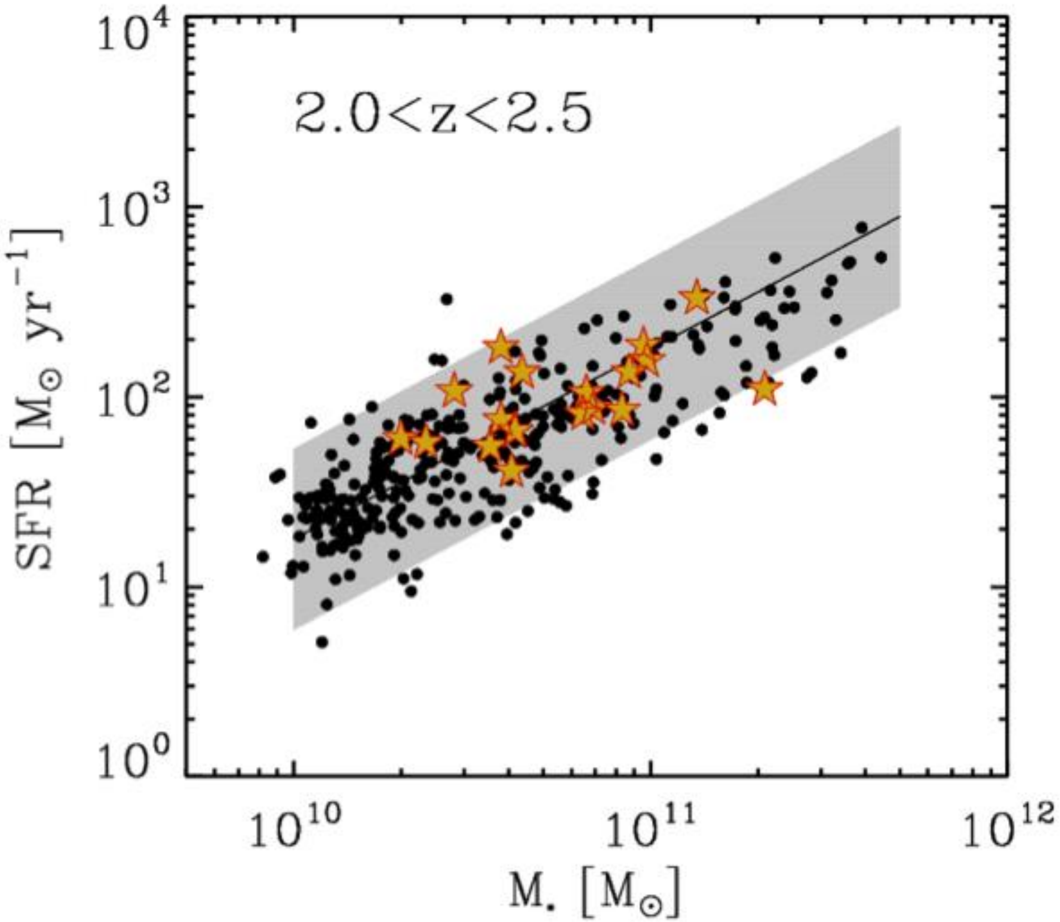
Kinematics at z > 2

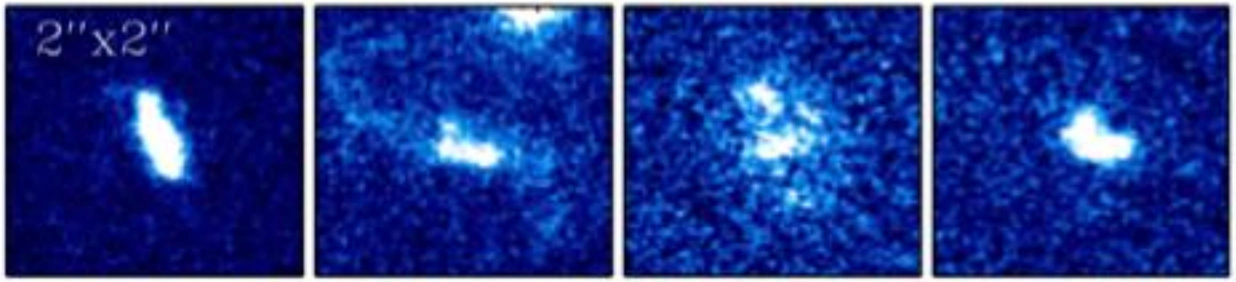
1 KMOS night so far (PI Magdis)

Target ~20 Herschel selected (i.e. ULIRGs) star forming galaxies at z ~ 2 - 2.50

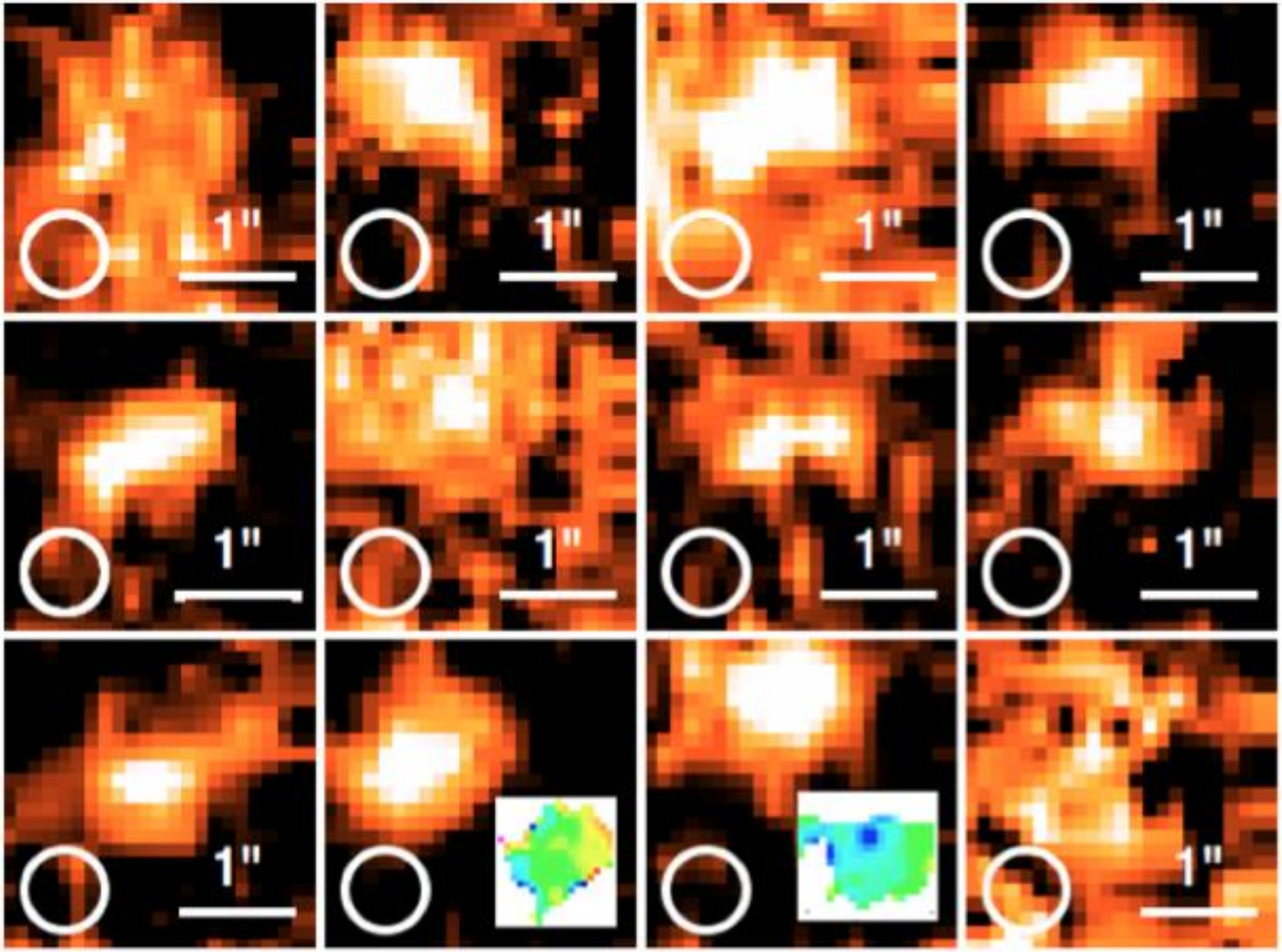
Much harder (seeing limited observations)

8h per pointing

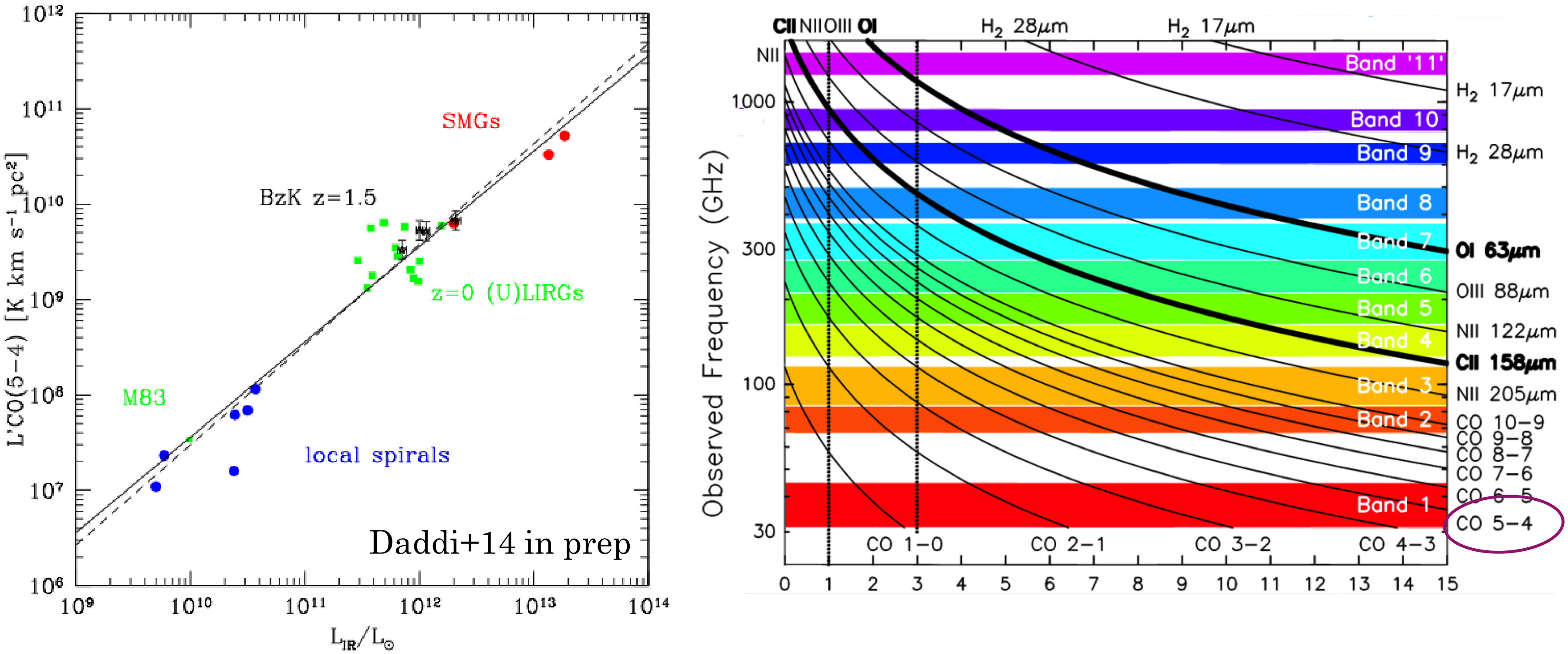




First results – Ha Maps



A systematic CO[5-4] survey at various redshifts with ALMA



SPICA-SAFARI

1) Deep extragalactic surveys at λ < 100μm

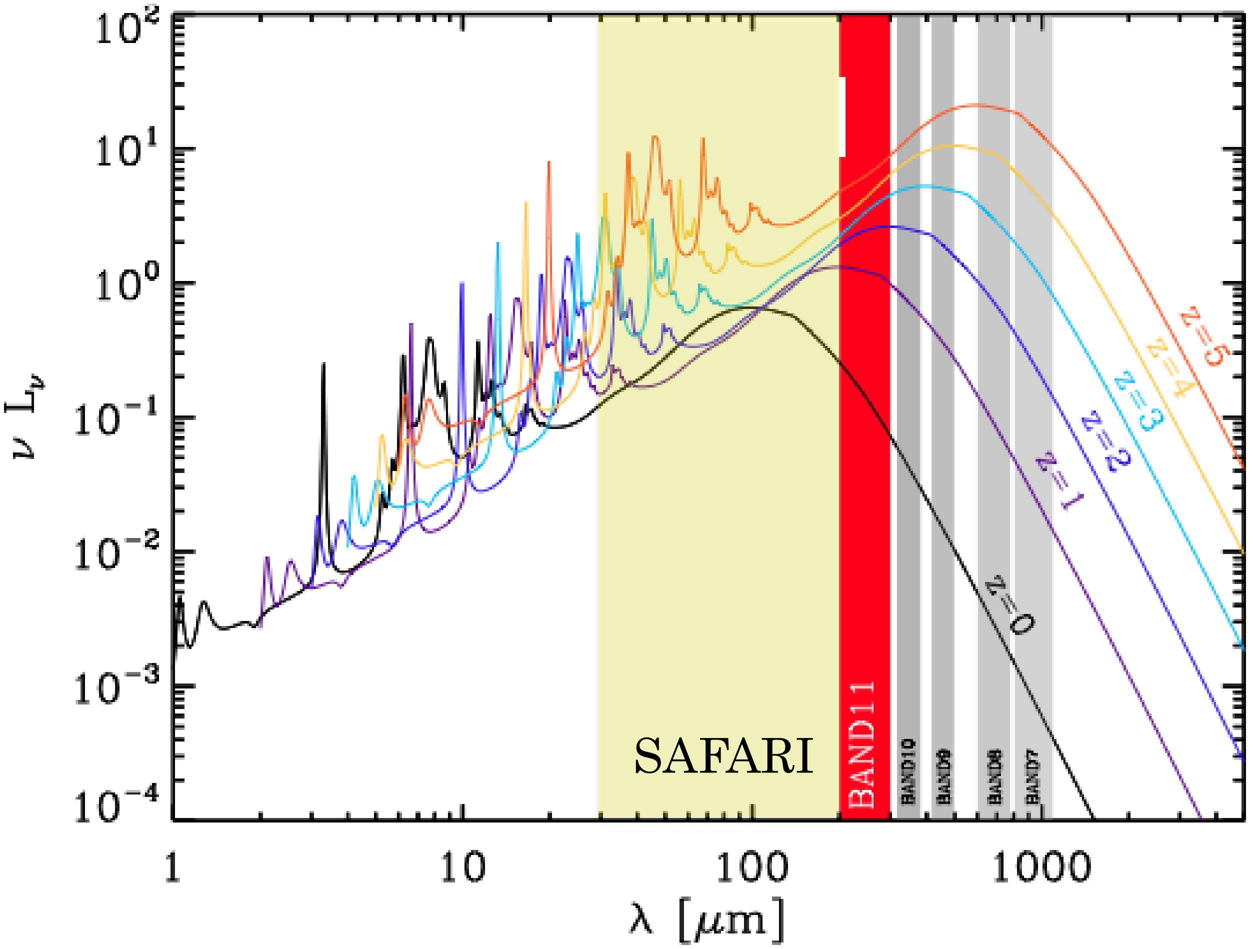
- AGN/SF decomposition
- Extend MS to higher redshifts and lower SFR

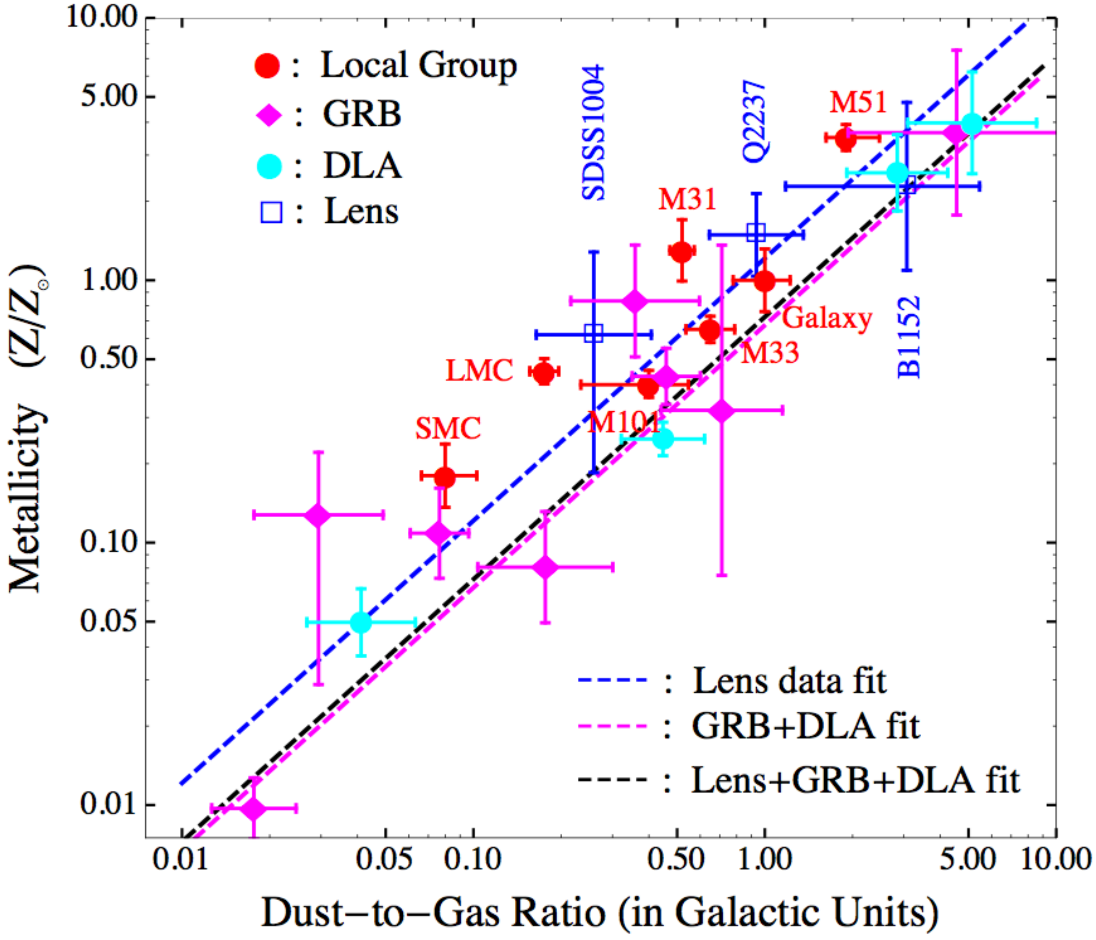
2) mid-IR line surveys

- Trace H_2 (17 and 28μm) for z= 0.5 to 9
- Break confusion at λ > 100μm

ALMA BAND11

Complement the gap between ALMA band 10 (λ>500μm) and SAFARI (λ<210μm)




Local Group
GRB
DLA
Lens
SDSS1004
Q2237
M51
M31
Galaxy
M33
B1152
LMC
SMC
M101
Lens data fit
GRB+DLA fit
Lens+GRB+DLA fit
Metallicity (Z/Z$_\odot$)
Dust−to−Gas Ratio (in Galactic Units)
10.00
5.00
1.00
0.50
0.10
0.05
0.01
0.01
0.05
0.10
0.50
1.00
5.00
10.00