# Exploring the HI-metallicity-SFR-galaxy mass connection with CALIFA


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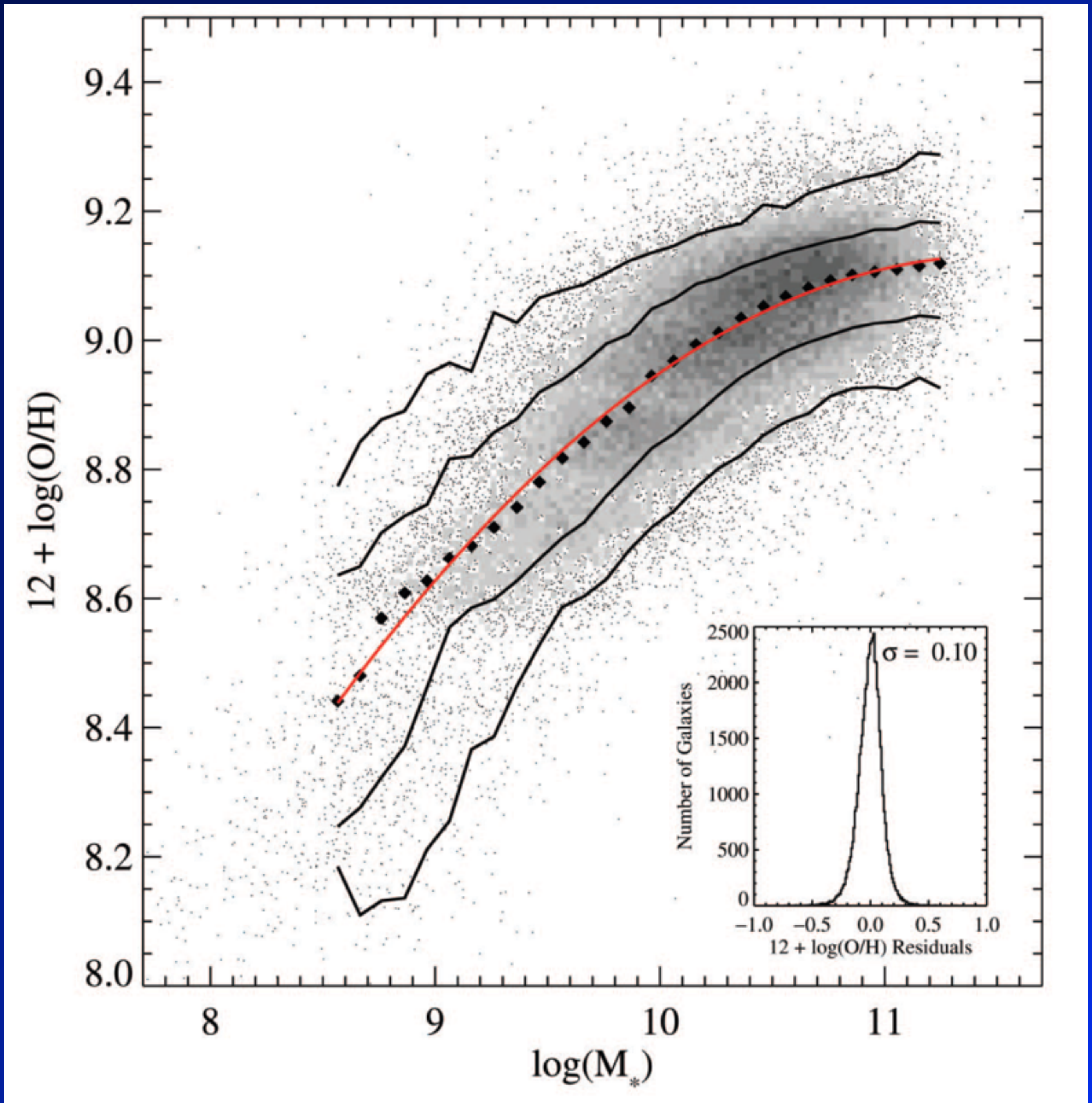
# Understanding galaxy assemble and evolution is challenging


**Scaling relationships try to help...**

**(...but we need a multiwavelength approach)**

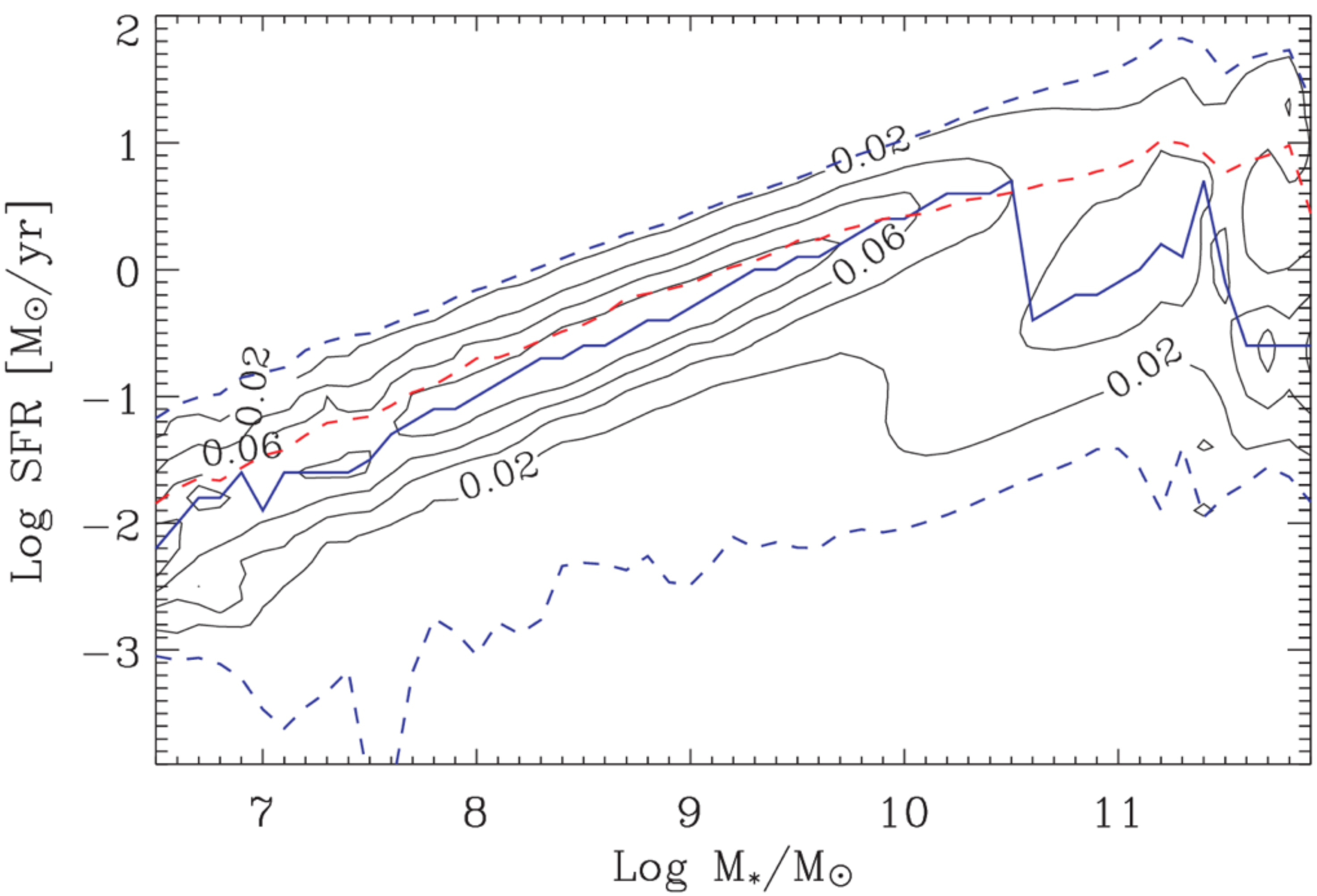
# Mass-metallicity (M-Z) relation for star-forming galaxies

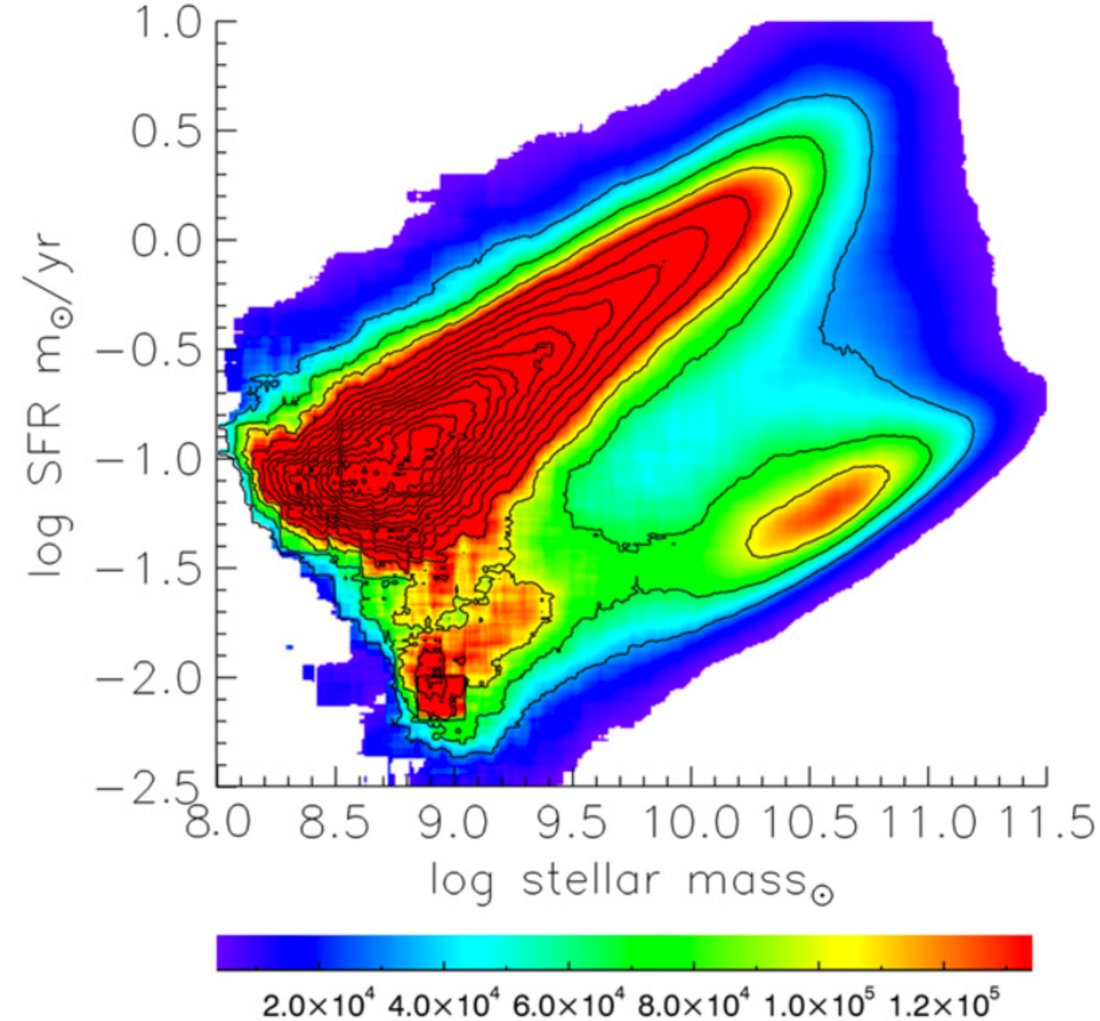
- Already seen by Lequeux et al. (1979), Kinman & Davison (1981) (both in BCDGs), Rubin et al. (1984) (spiral galaxies), Skillman et al. (1992), among others, plot by Tremonti et al. (2004)
- **Physical Mechanisms:**
  1. The loss of enriched gas by outflows (Tremonti et al. 2004; Kobayashi et al. 2007)
  2. The accretion of pristine gas by inflows (Finlator & Davé 2008)
  3. Variations of the initial mass function with galaxy mass (Köppen et al. 2007)
  4. Selective star-formation efficiency or downsizing (Brooks et al. 2007; Ellison et al. 2008; Calura et al. 2009; Vale Asari et al. 2009)
  5. Or a combination of them.




In brief: or it is a **evolutionary sequence** (more massive galaxies have processed a larger fraction of their raw material) or a **mass-retention sequence** (more massive galaxies retain a larger fraction of their processed material), or **both**.

# SFR-Mass (SFR-M) relation for star-forming galaxies

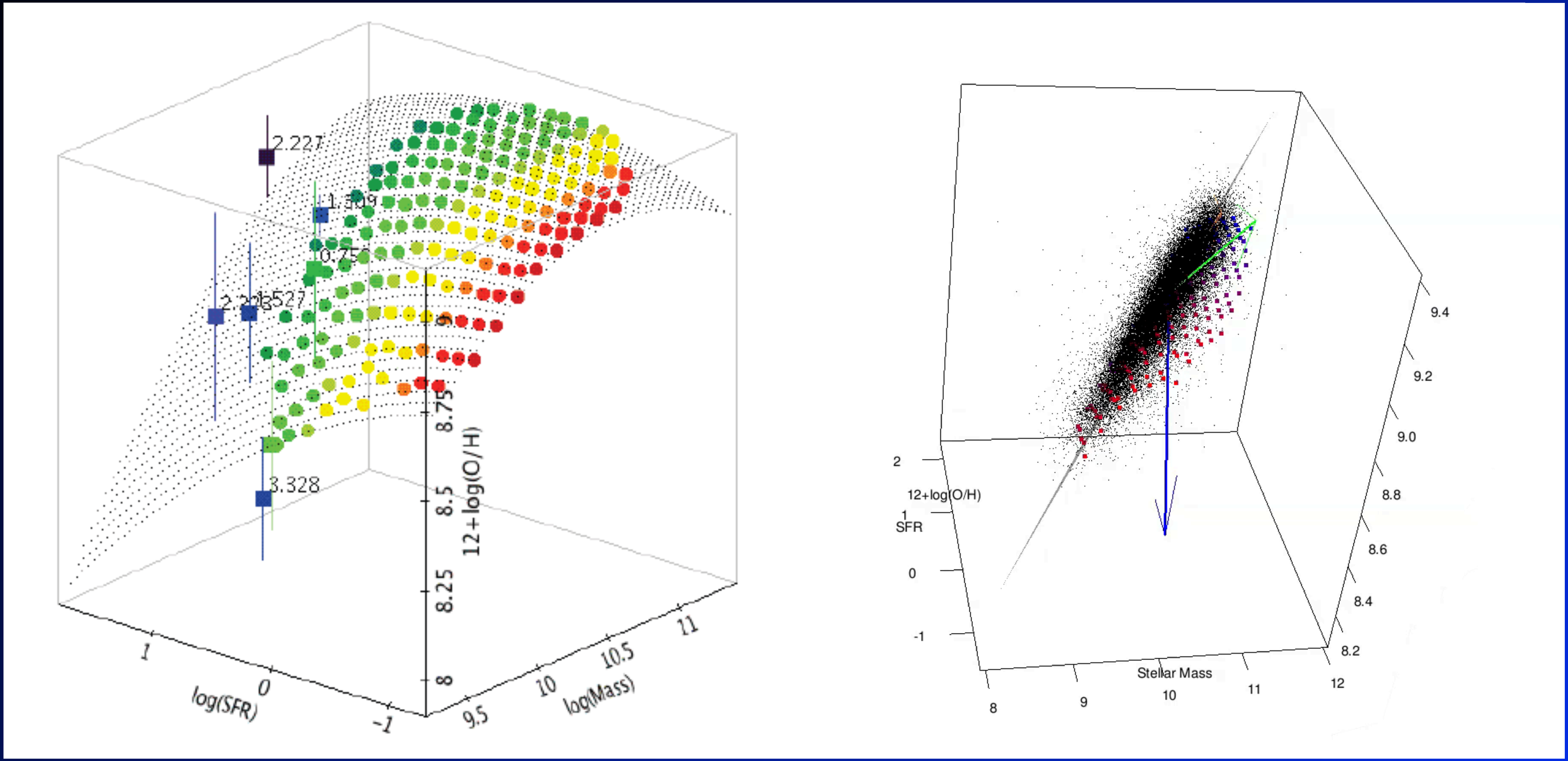



**See details in Brinchmann et al. (2004), plotted, *"Main sequence of SF galaxies"*, 1 s scatter ~ 0.2 dex also Salim et al. 2005, Noeske et al. 2007; Daddi et al. 2007; Elbaz et al. 2007; Rodighiero et al. 2010; Wuyts et al. 2011; Salim & Lee 2012; Renzini & Peng 2015 (plotted)**

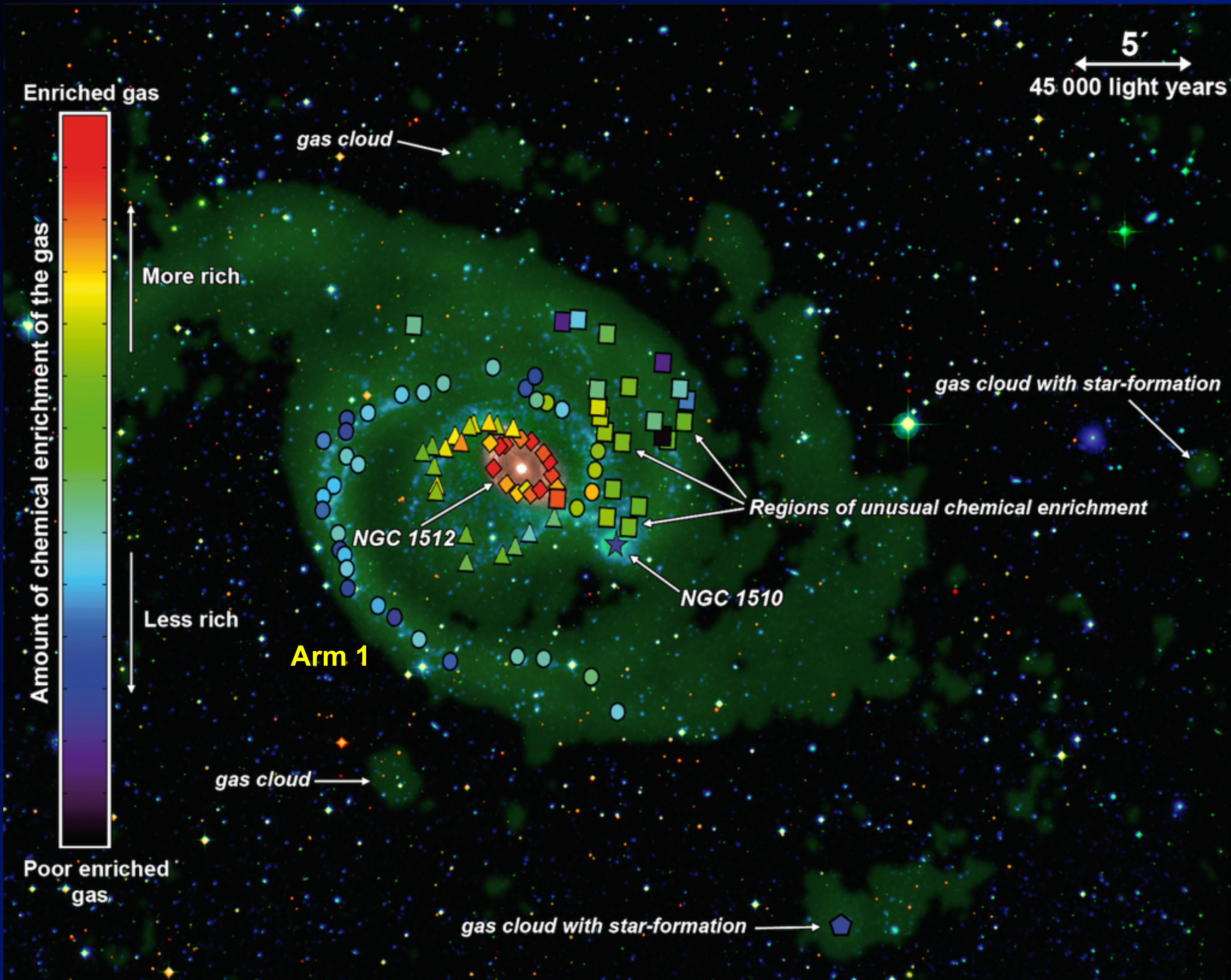
**Also in CALIFA: Catalán-Torrecilla et al. 2015; Cano-Díaz et al. (submitted) & SAMI: Ho et al. 2016**

# The M - Z - SFR relation




- Explored by Ellison et al. (2008)
- Lara-López et al. 2010b, A&A, 521, 53L ***"Fundamental Plane"***
- *Mannucci et al. (2010), "Fundamental Metallicity Relation" (FMR),* *O/H = f ( $M_{star}$ , SFR )*
- Lara-López, López-Sánchez & Hopkins, 2013, ApJ : **PCA analysis,** **Stellar Mass = f ( O/H and SFR )**
- Lara-López, Hopkins, López-Sánchez et al. 2013a,b (SDSS+GAMA)

# But for understanding galaxy evolution we also need gas!




FUV+NUV (blue) + H I map (green) + R (green) + J (red) + MIR (NGC 1512, luminosity)

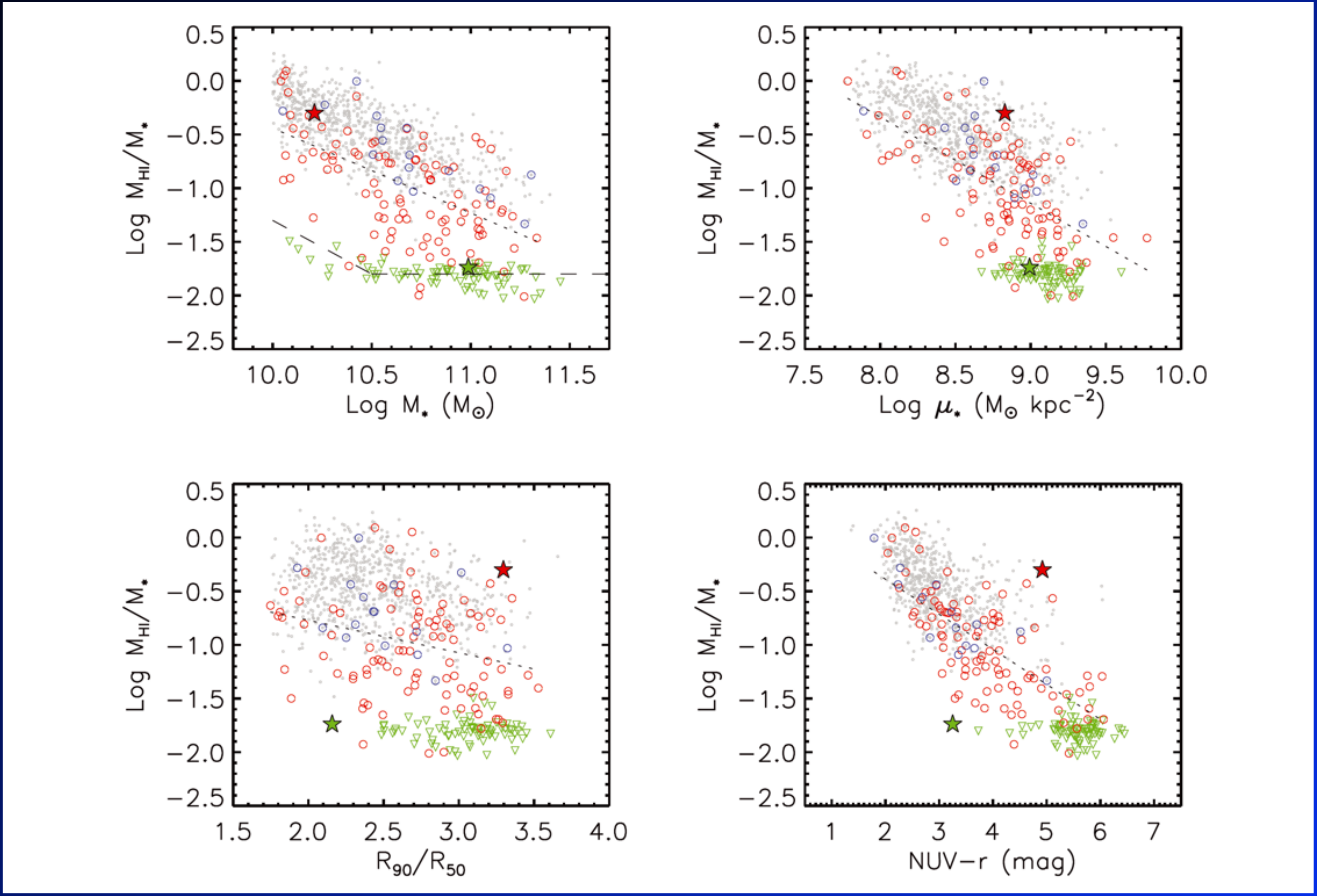
## NGC 1512/1510

- ATCA observ. 7 arrays, 3.11 days
- Huge amount of neutral gas!
- Two extended spiral arms
- Two TDG candidates?
- XUV disk, SFR given bu FUV
- O/H & more studied in 136 unique SF regions using 2dF/AAOmega @ AAT data
  - Radial & azymuthal O/H gradients

Koribalski & López-Sánchez 2009, MNRAS

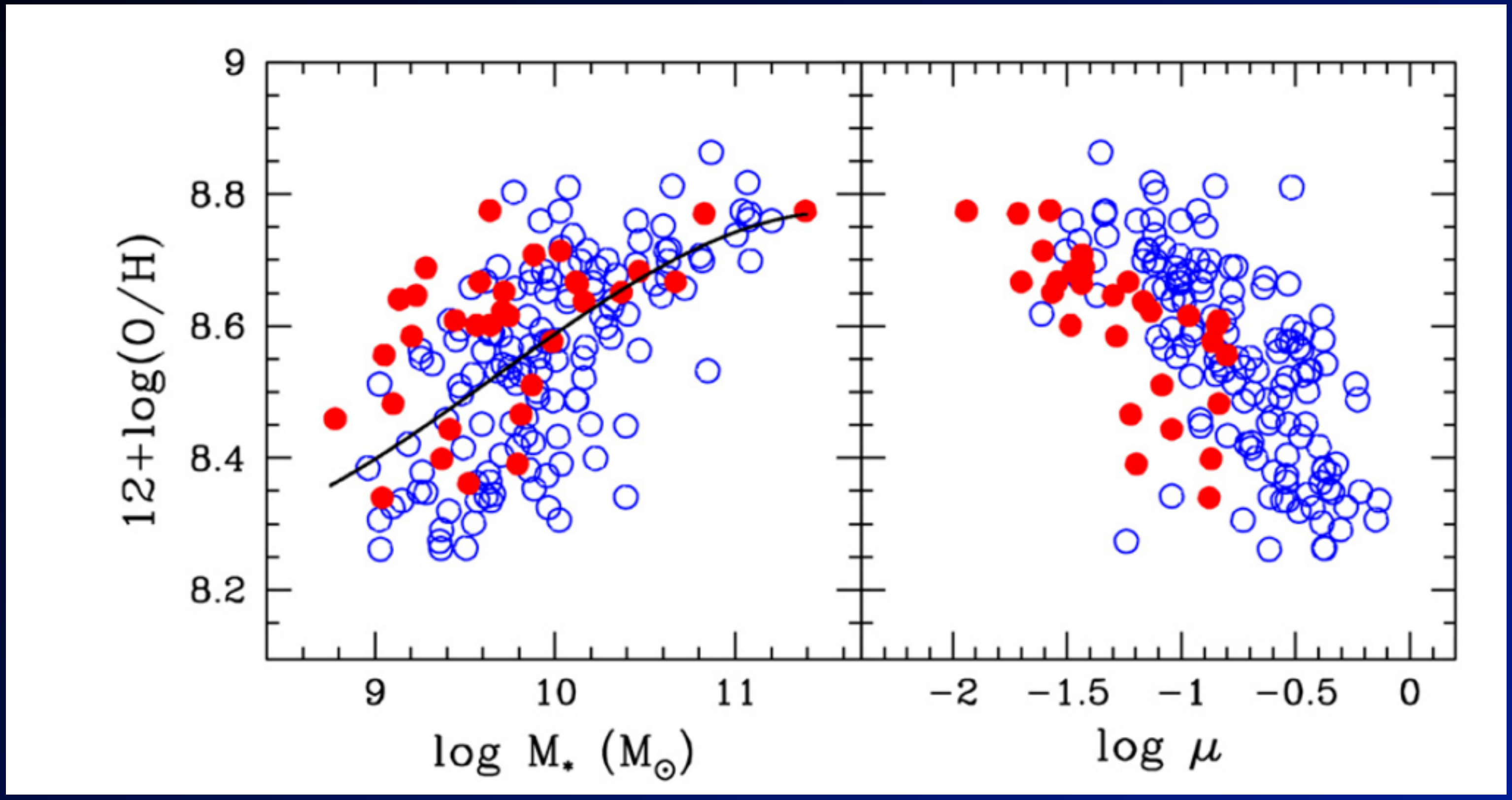
López-Sánchez et al. 2015, MNRAS, 450, 3381

# Stellar mass - gas fraction relations




See details in Catinella et al. (2010), plotted, *gas fraction anticorrelates with $M_{stars}$*
Saintonge+ 2011, Cortese+ 2011; Boselli+ 2014a,b; Bothwell+ 2013,2014; Hughes+ 2013, Rafieferantsoa+15

# Metallicity - gas fraction relations



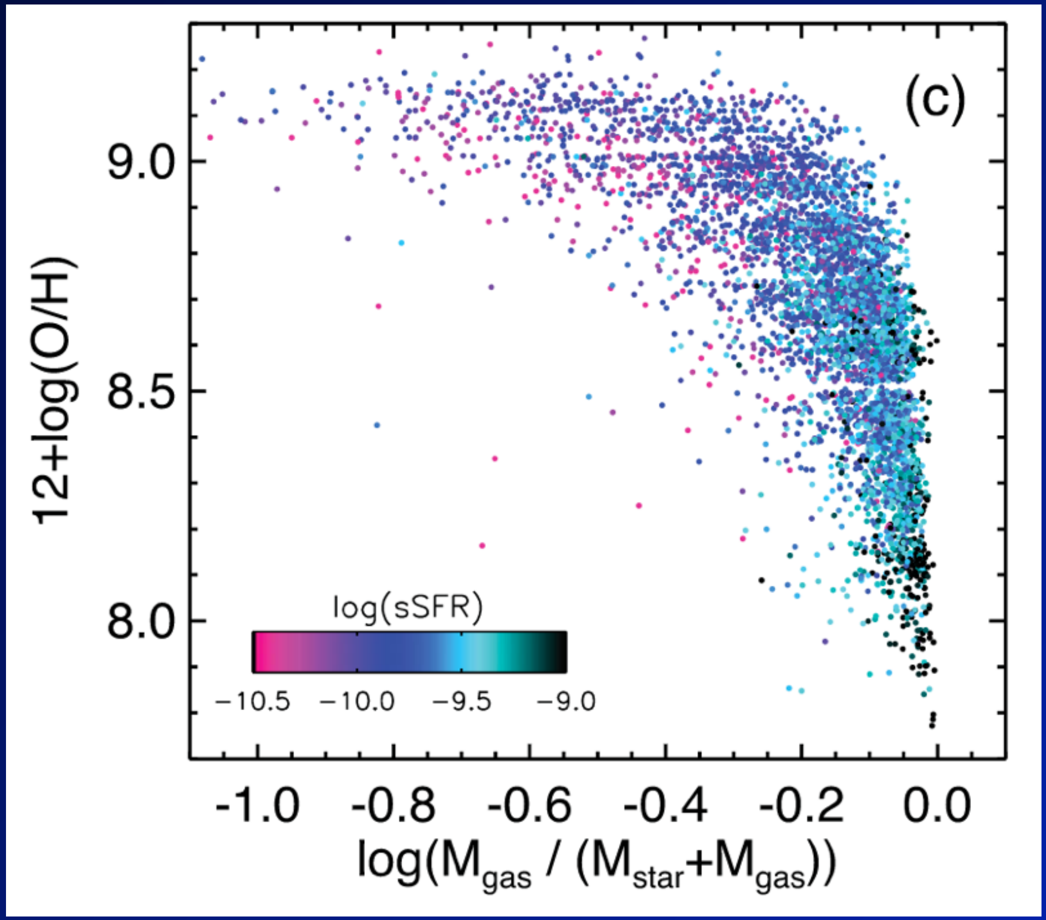

Hughes et al. 2013, A&A, 550, 115

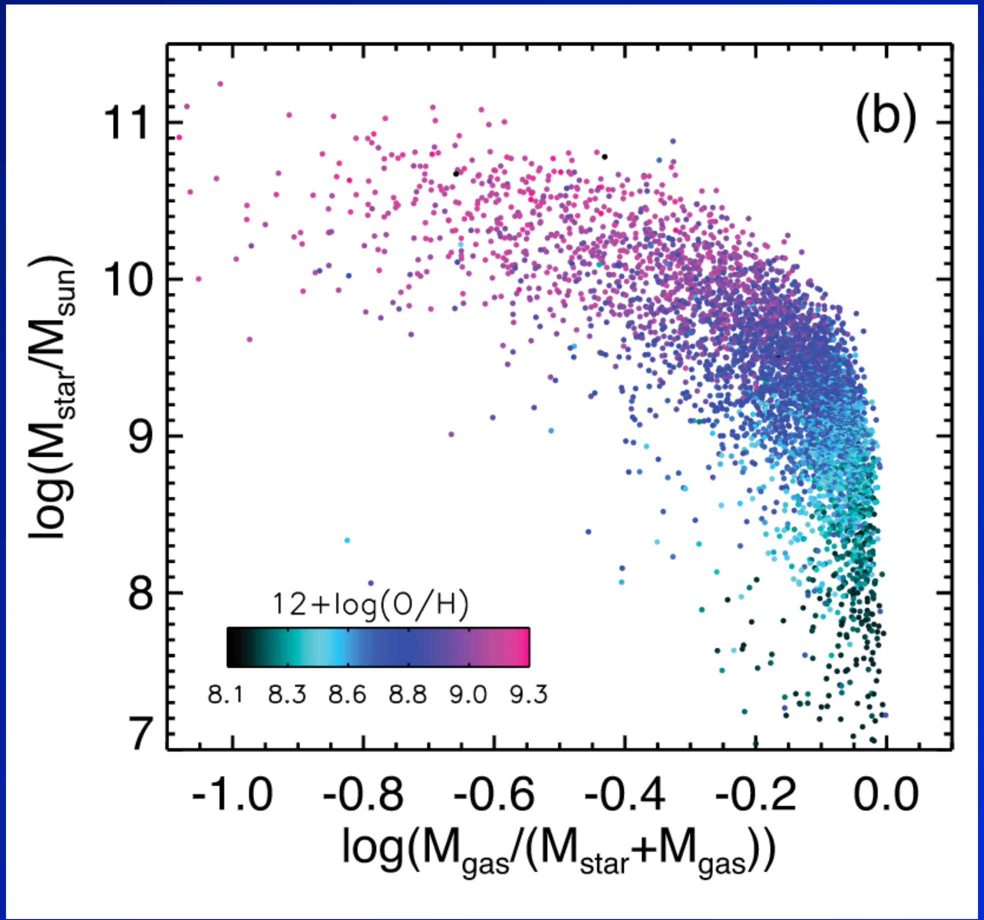
$M_{bar} = M_{star} + M_{gas}$

$M_{gas} = 1.34\ M_{HI}$

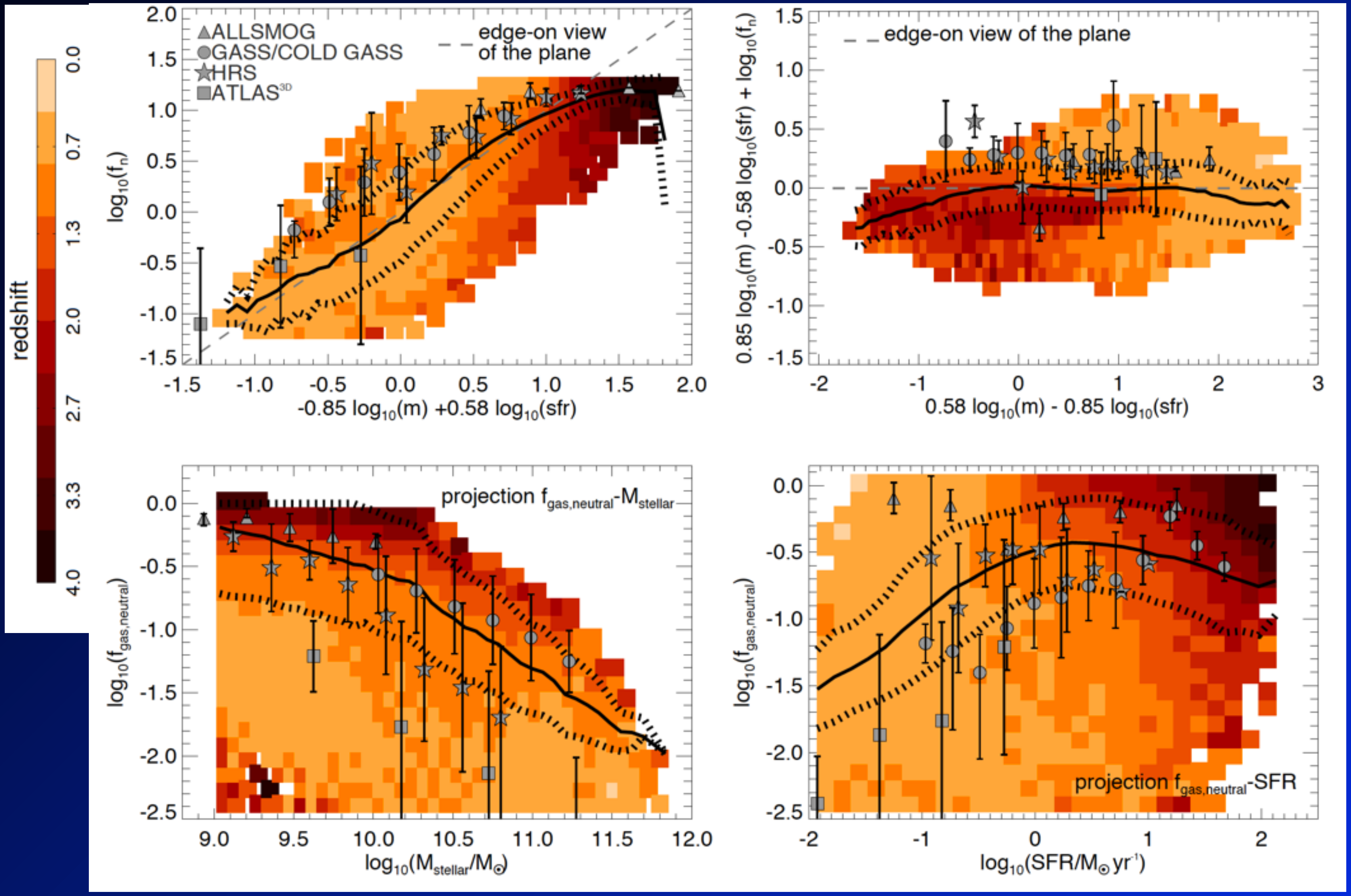
$\mu = M_{gas} / M_{bar}$ : gas mass to baryonic mass ratio

Lara-López, Hopkins, López-Sánchez et al. 2013, MNRAS, 433, L35



# Predictions by hydrodynamical simulations



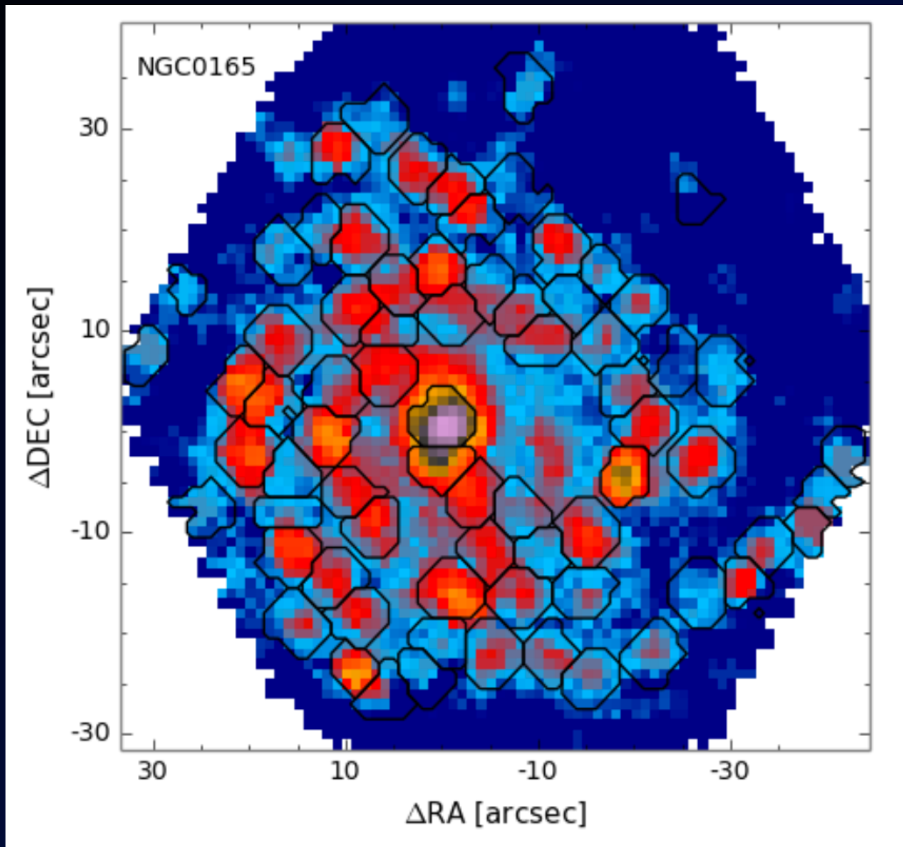

Using EAGLE (Schaye et al. 2015; Crain et al. 2015) hydrodynamical simulations by Lagos et al. 2015a,b

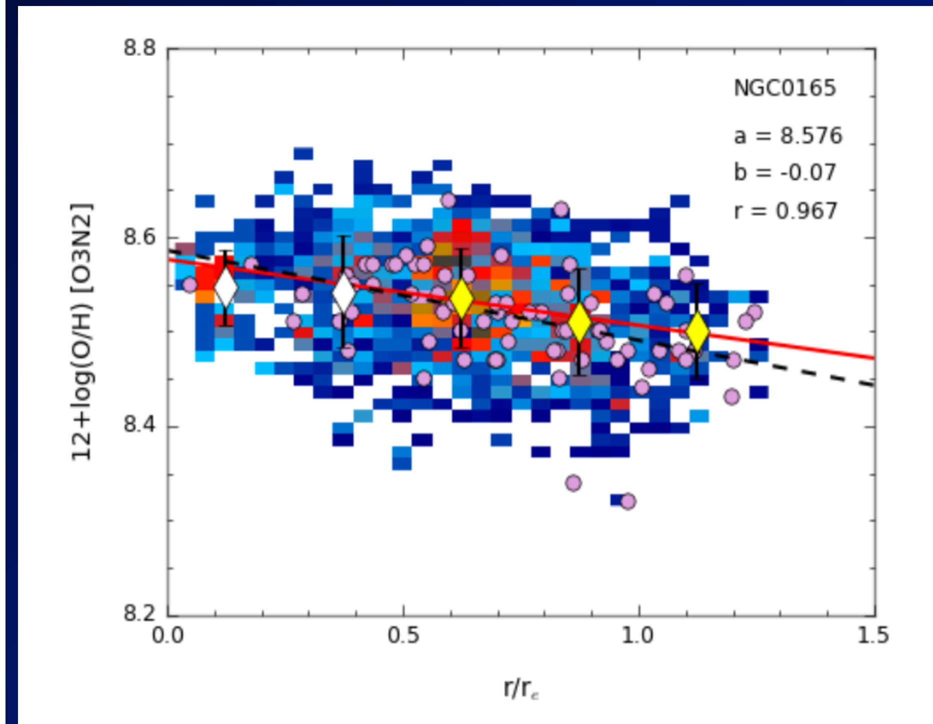
Lagos et al. 2015b: Use PCA to define a "Fundamental Plane of Star-Formation" Ms, SFR, Mgas/Mstar (55%)

The Z - Ms - SFR - Mgas/Mstar appears in second component (24%)

SFR consequence of inflows & outflows of gas

# Determining oxygen abundances with CALIFA



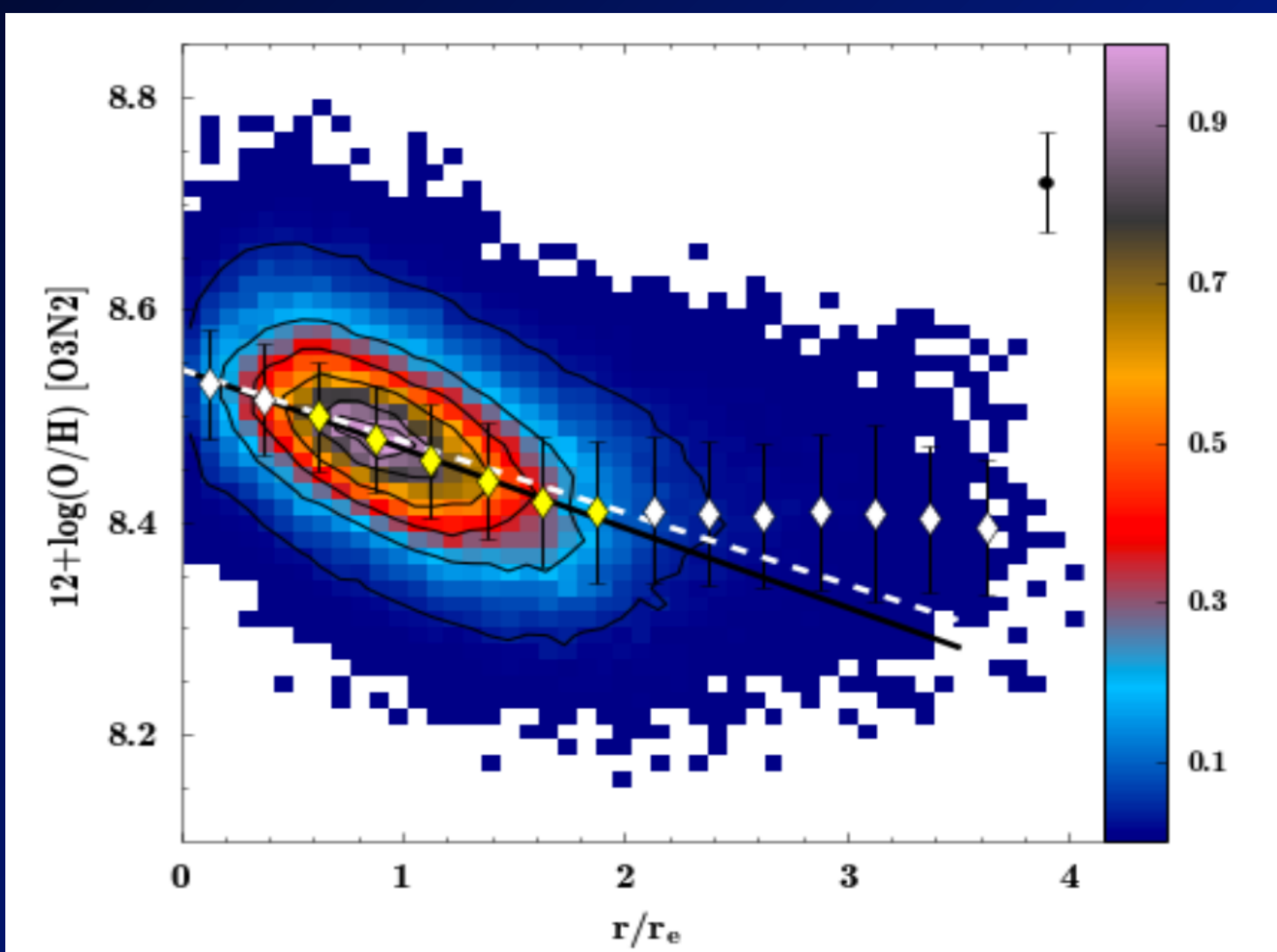

+300 galaxies, +9000 HII regions

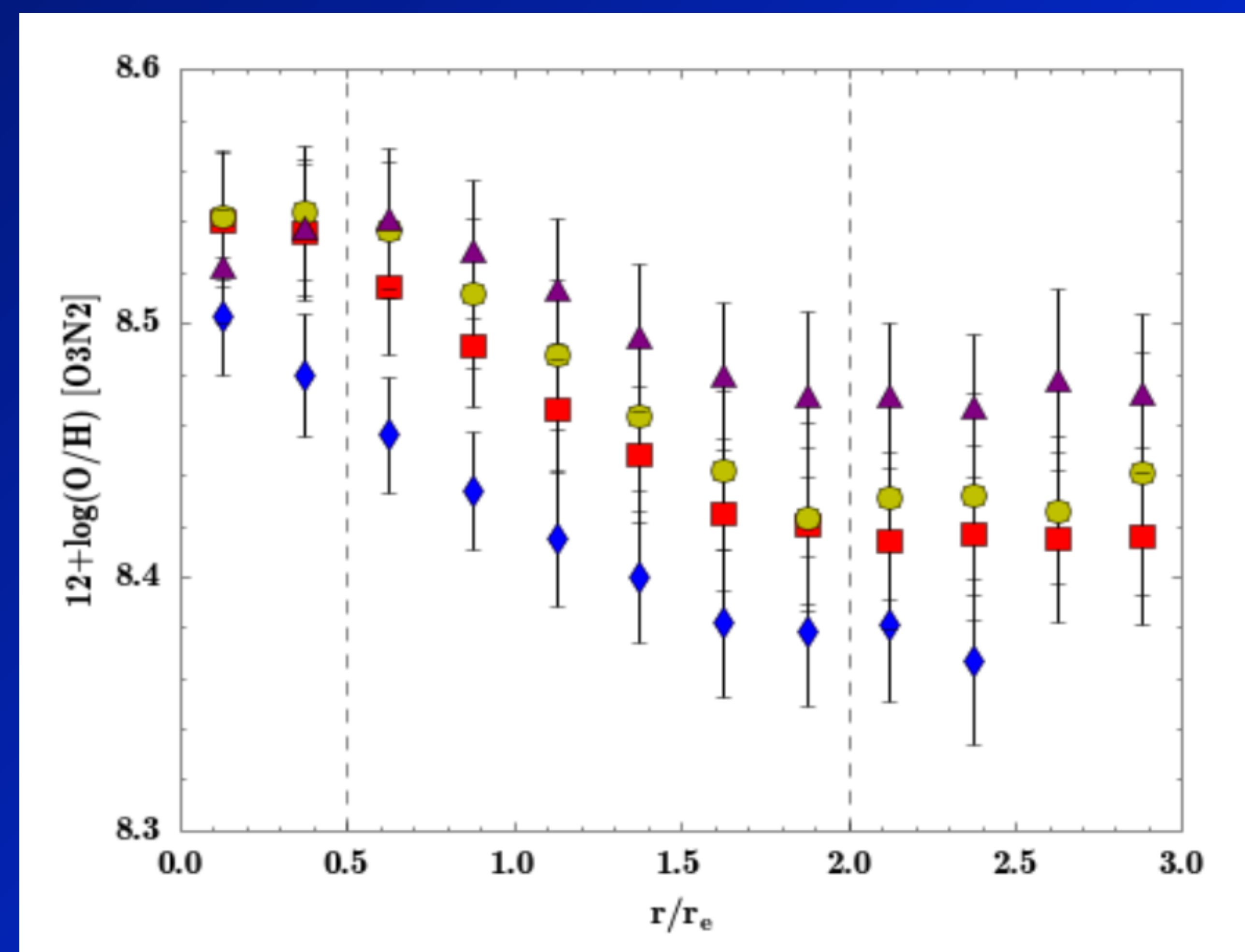
Using O3N2 & Marino et al. (2013)

Common O/H gradient
alpha = -0.07 dex/Re
standard deviation ~0.05 dex/Re

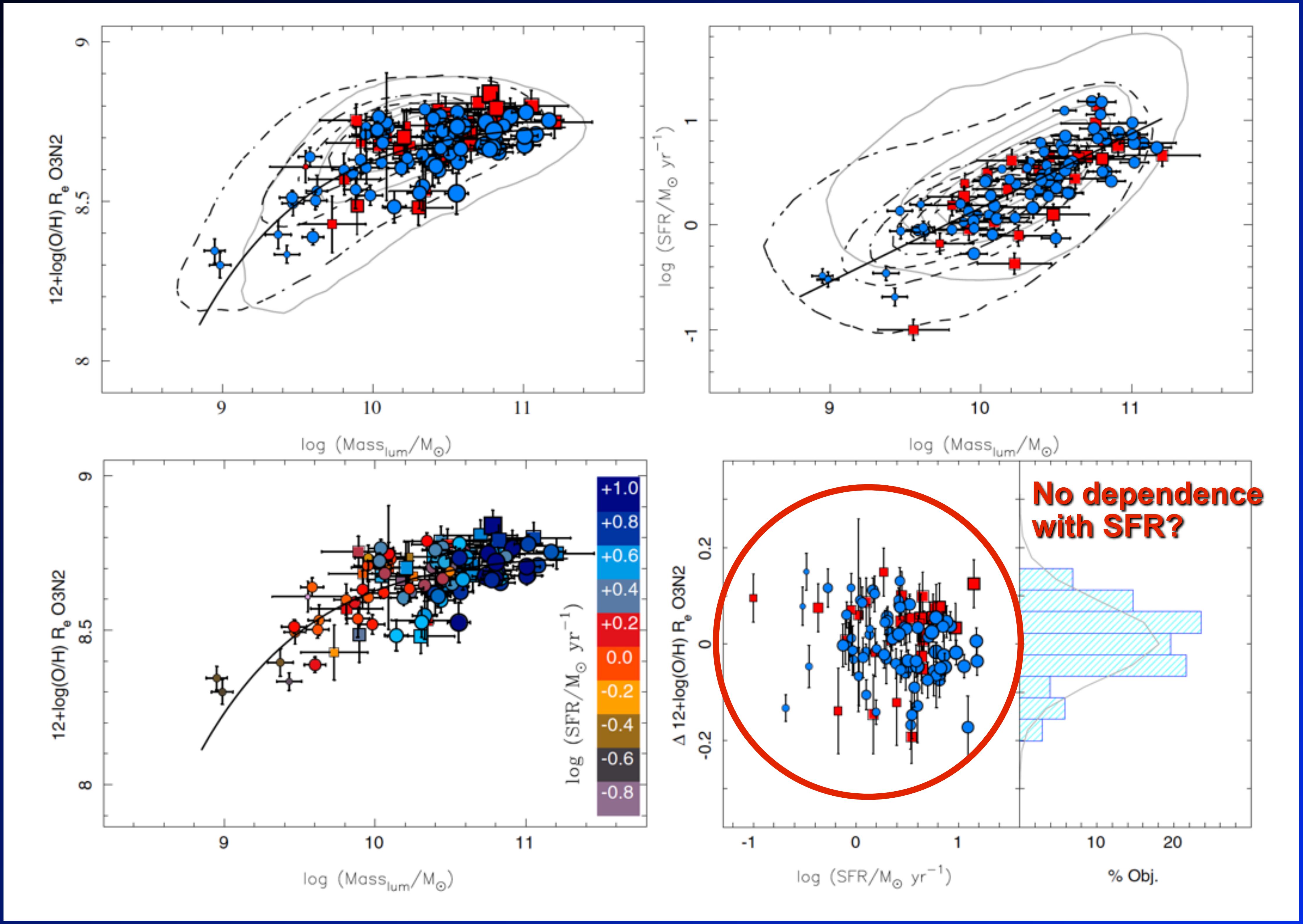
Sánchez et al. (2012a, 2014), Sánchez-Menguiano et al. (2016)

Also a common N/O gradient
Pérez-Montero et al. submitted



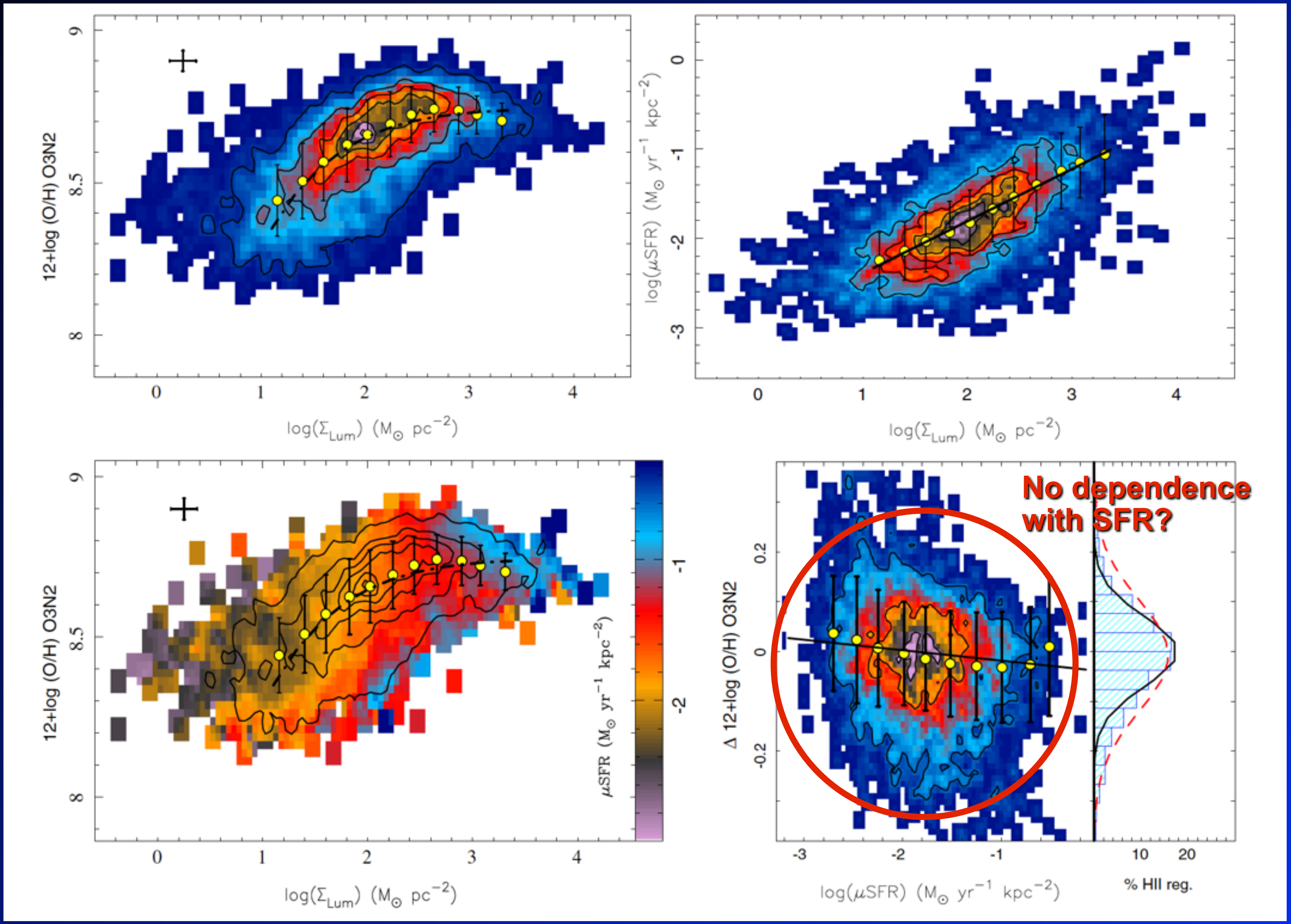



# GLOBAL Mass-Metallicity-SFR relations using CALIFA




Sánchez et al. (2013), Pérez-Montero et al. (2016)

# LOCAL Mass-Metallicity-SFR relations using CALIFA




Rosales-Ortega et al. (2012), Sánchez et al. (2013)

# Adding the HI data to the CALIFA survey

- Use literature to compile HI (single-dish) data of CALIFA galaxies
  - So far only **374 / 450 galaxies with HI**
    - ➡ Springob et al 2005: **232 / 374**
      - ✓ Corrected for self-absorption
    - ➡ Huchtmeier & Richter 1989: **57 / 374**
    - ➡ Theureau et al. 1998: **24 / 374**
  - **Heterogenous HI** data from literature, sometimes no errors
  - And **368 / 450 with HI and O/H**
- Build a database with O/H, Ms, Mg, Mbar, Mg/Ms, SFR, alpha...
- We only measure the **atomic neutral** gas

$$M_{gas} = 1.34\ M_{HI} = M_{atomic}$$

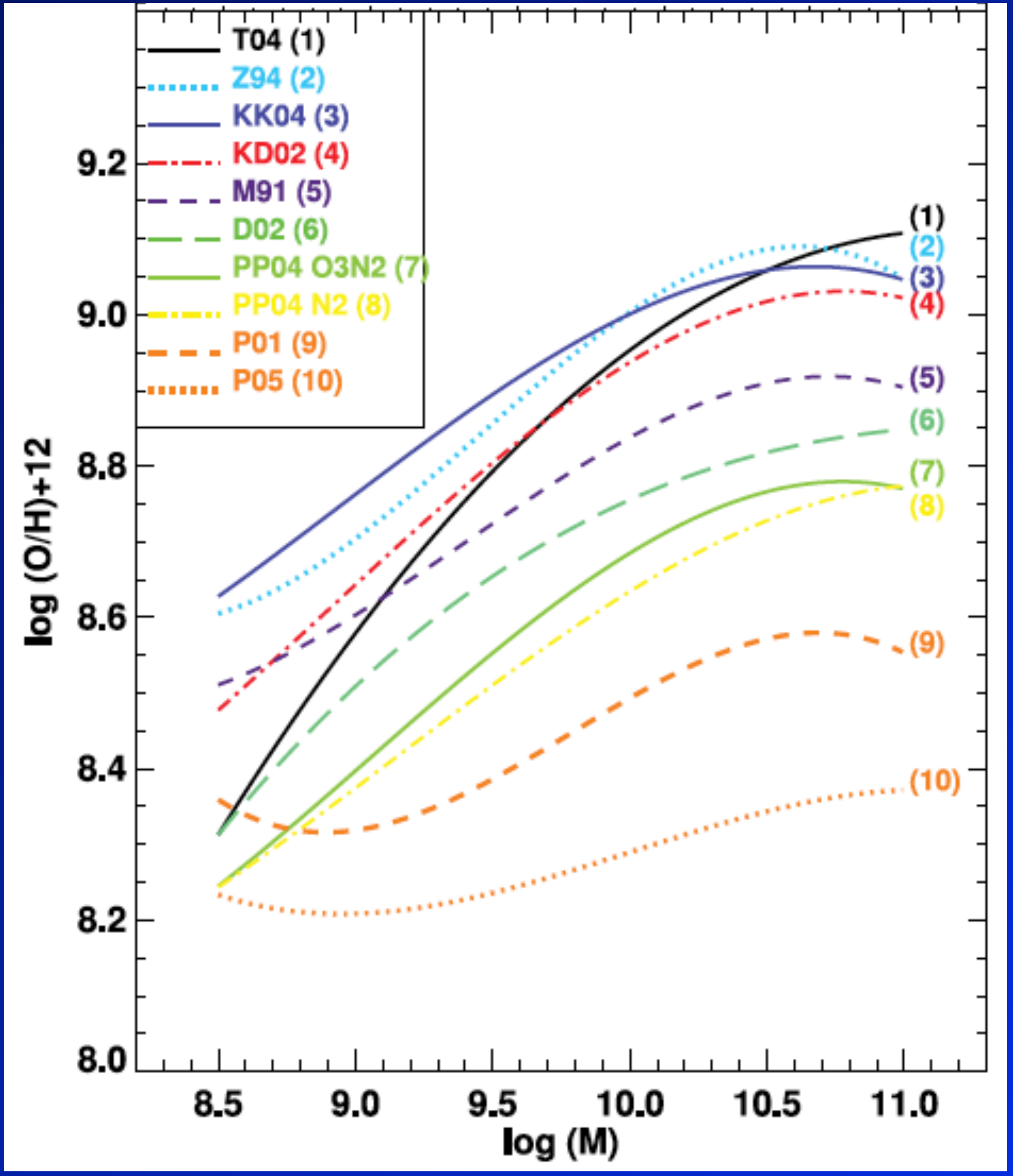
$$M_{neutral} = M_{atomic} + M_{molecular}$$

  - **Missing the molecular neutral** gas $H_2$
    - ★ Contribution of $M_{molecular}$ is expected important at high $M_{stars}$

| Num | Name | OH | lMs | lMg | lMb | lgs | lSFR | lSSFR |
|---|---|---|---|---|---|---|---|---|
| 1 | 2MASXJ01331766+1319567 | 8.40 | 9.49 | 9.48 | 9.78 | -0.01 | 0.85 | -8.64 |
| 2 | ARP118 | 8.46 | 11.61 | 10.09 | 11.62 | -1.51 | 1.01 | -10.60 |
| 3 | ARP220 | 8.54 | 10.86 | 10.58 | 11.04 | -0.28 | 1.88 | -8.98 |
| 4 | ESO539-G014 | 8.38 | 9.52 | 10.18 | 10.27 | 0.66 | -1.01 | -10.53 |
| 5 | ESO540-G003 | 8.46 | 10.08 | 10.15 | 10.42 | 0.07 | -0.25 | -10.33 |
| 6 | IC0159 | 8.41 | 10.09 | 9.62 | 10.22 | -0.48 | 0.10 | -9.99 |
| 7 | IC0208 | 8.54 | 10.14 | 9.57 | 10.24 | -0.57 | -0.52 | -10.65 |
| 8 | IC0307 | 8.53 | 10.93 | 9.96 | 10.97 | -0.97 | 0.29 | -10.64 |
| 9 | IC0480 | 8.48 | 10.22 | 10.00 | 10.43 | -0.22 | 0.07 | -10.15 |
| 10 | IC0485 | 8.51 | 10.92 | 9.97 | 10.97 | -0.95 | 0.72 | -10.20 |
| 11 | IC0674 | 8.50 | 10.87 | 10.10 | 10.94 | -0.77 | -0.07 | -10.94 |
| 12 | IC0776 | 8.31 | 9.31 | 9.57 | 9.76 | 0.26 | -0.54 | -9.85 |
| 13 | IC0851 | 8.37 | 8.92 | 9.51 | 9.61 | 0.59 | -1.13 | -10.05 |
| 14 | IC0944 | 8.53 | 11.10 | 10.01 | 11.13 | -1.08 | 0.31 | -10.78 |
| 15 | IC0995 | 8.37 | 9.63 | 9.58 | 9.91 | -0.06 | -0.59 | -10.23 |
| 16 | IC1078 | 8.55 | 10.78 | 9.79 | 10.83 | -0.99 | 0.26 | -10.52 |
| 17 | IC1151 | 8.42 | 9.84 | 9.71 | 10.08 | -0.13 | -0.26 | -10.10 |
| 18 | IC1256 | 8.56 | 10.51 | 10.16 | 10.67 | -0.35 | 0.17 | -10.34 |
| 19 | IC1528 | 8.53 | 10.38 | 10.17 | 10.59 | -0.21 | 0.15 | -10.24 |
| 20 | IC1683 | 8.56 | 10.57 | 9.16 | 10.59 | -1.41 | 0.44 | -10.14 |
| 21 | IC1755 | 8.55 | 10.88 | 10.03 | 10.94 | -0.85 | -0.27 | -11.15 |
| 22 | IC2095 | 8.28 | 8.86 | 9.05 | 9.27 | 0.19 | -0.88 | -9.74 |
| 23 | IC2098 | 8.50 | 9.97 | 9.80 | 10.20 | -0.17 | -0.77 | -10.74 |
| 24 | IC2101 | 8.49 | 10.36 | 10.09 | 10.55 | -0.27 | 0.20 | -10.16 |
| 25 | IC2247 | 8.51 | 10.51 | 9.85 | 10.59 | 0.66 | 0.08 | -10.43 |

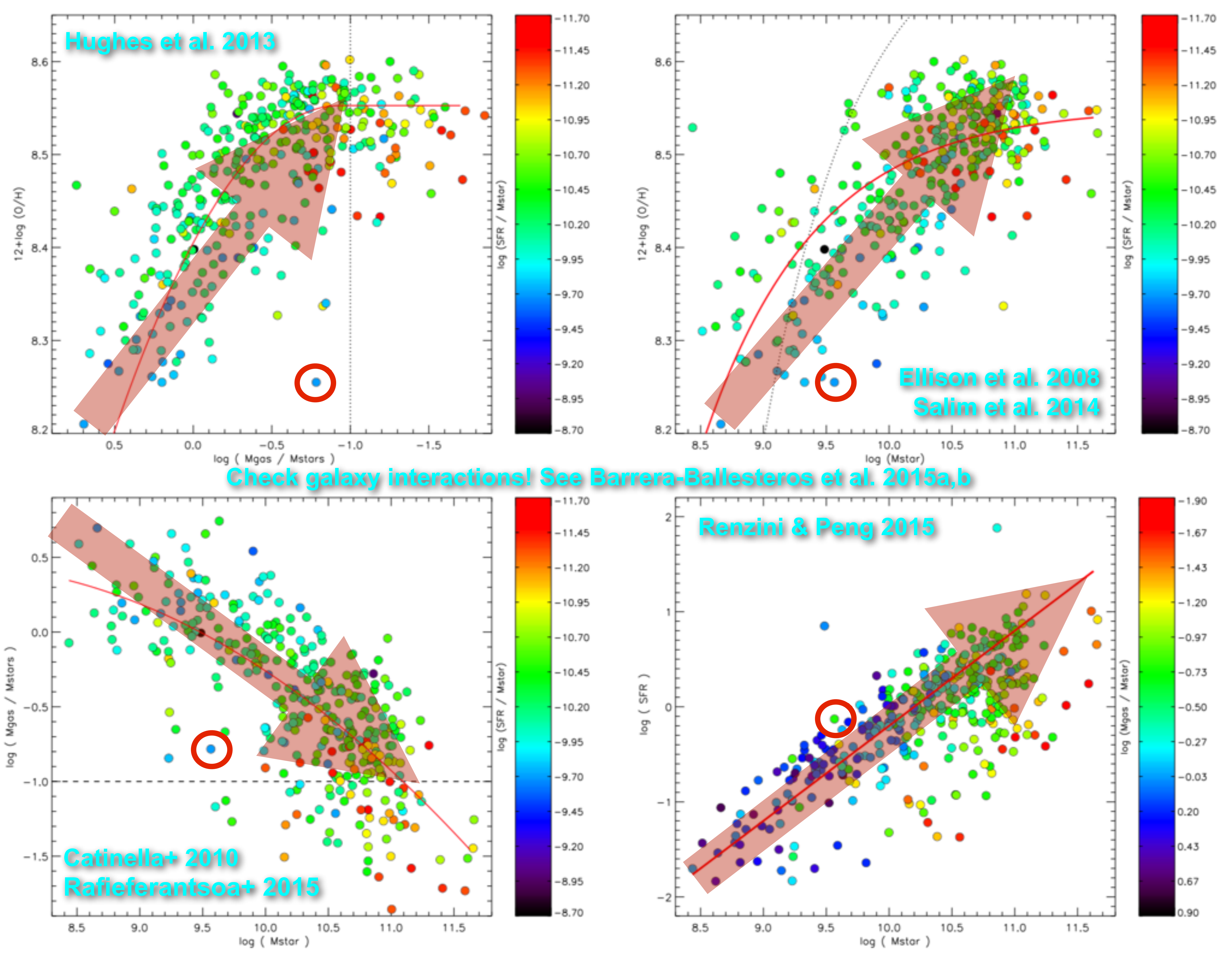
# Precautions & biases

- We assume as **(O/H)$_{Re}$** as **representative of metallicity**
- The problem of the **ABSOLUTE O/H scale**
  - CALIFA uses empirical calibrations based on **Te-method** & **Marino et al. (2013)**, with ***max* [ 12 + log(O/H) ] ~ 8.65**
  - Similar results using **ONS method** (Sánchez et al. 2015,2016) or **HII-Chi-MISTRY** (Pérez-Montero 2014;Pérez-Montero et al. sub)
    - ★ Using **Kewley & Dopita** photoionization models (SDSS, GAMA, SAMI) ***max* [ 12 + log(O/H) ] ~ 9.15**
    - ★ See **Kewley & Ellison 2008, Moustakas et al. 2010, López-Sánchez & Esteban 2010b, López-Sánchez, Dopita, Kewley et al. 2013**
  - Using stars, CALIFA data show **( Z / H )$_{< 2 Gyr}$ ~ (O/H)$_{M13}$** see **González Delgado (2015, 2016)**
  - In Milky Way, ***max* [ 12 + log(O/H) ] ~ 8.6 using Te & CEL**
    **Esteban et al 2004, 2005, 2009, 2015, García-Rojas et al. 2006, 2007**
  - New photoionization models **reproduce O/H** given by Te-scale (e.g. Dors et al. 2011; Morisset et al. submitted)




**Kewley & Ellison 2008**

- **IMF** variations
  - See **Lyubenova et al. (submitted)**
  - For computing $M_{stars}$ and SFR the IMF is slightly different (see **Sánchez et al. 2016a**, Pipe3D paper II)


Hughes et al. 2013
12+log (O/H)
log ( Mgas / Mstars )
log (SFR / Mstar)
Ellison et al. 2008
Salim et al. 2014
log (Mstar)
Check galaxy interactions! See Barrera-Ballesteros et al. 2015a,b
log ( Mgas / Mstars )
log ( Mstar )
Catinella+ 2010
Rafieferantsoa+ 2015
Renzini & Peng 2015
log ( SFR )
log (Mgas / Mstar)

# PCA Analysis: Relating Ms - Z - Mg/Ms - SFR

**Covariance Matrix:**

| | log(Ms) x | 12+log(O/H) y | log(Mg/Ms) z | log (SFR) w |
|---|---|---|---|---|
| x | 1.000 | 0.739 | -0.722 | -0.760 |
| y | | 1.000 | -0.660 | 0.489 |
| z | | | 1.000 | -0.409 |
| w | | | | 1.000 |

➡ **C1 relates everything! (but Lagos et al. 2015b)**

➡ **C2 related to Schmidt-Kennicutt law?**

C1 = **0.558** x + **0.500** y - **0.482** z + 0.454 w

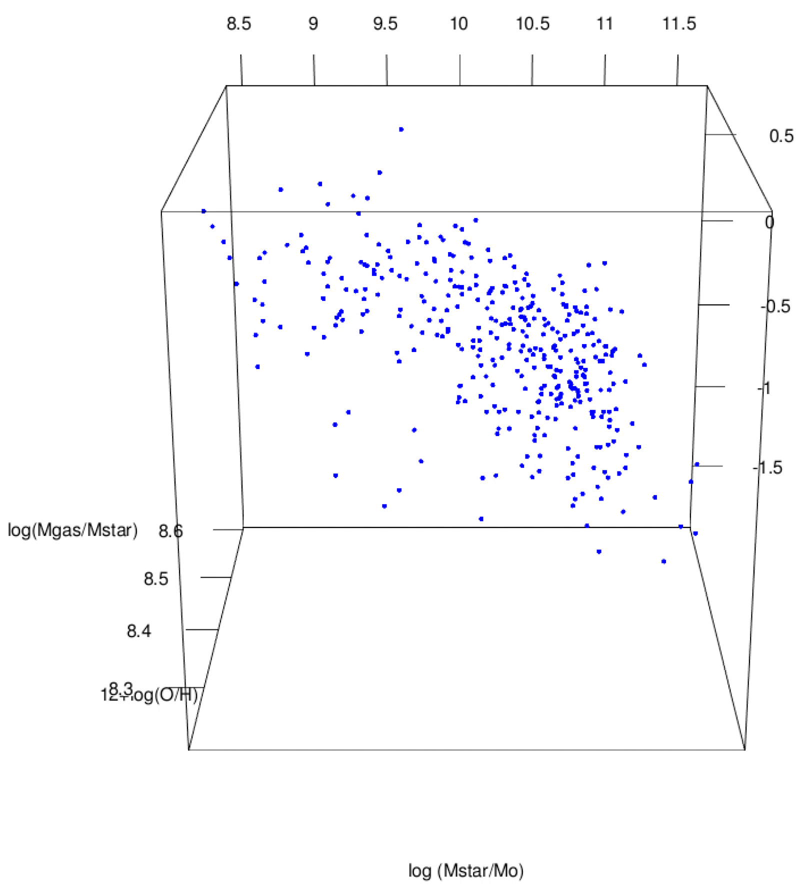
C2 = -0.135 x + 0.325 y - **0.540** z - **0.764** w

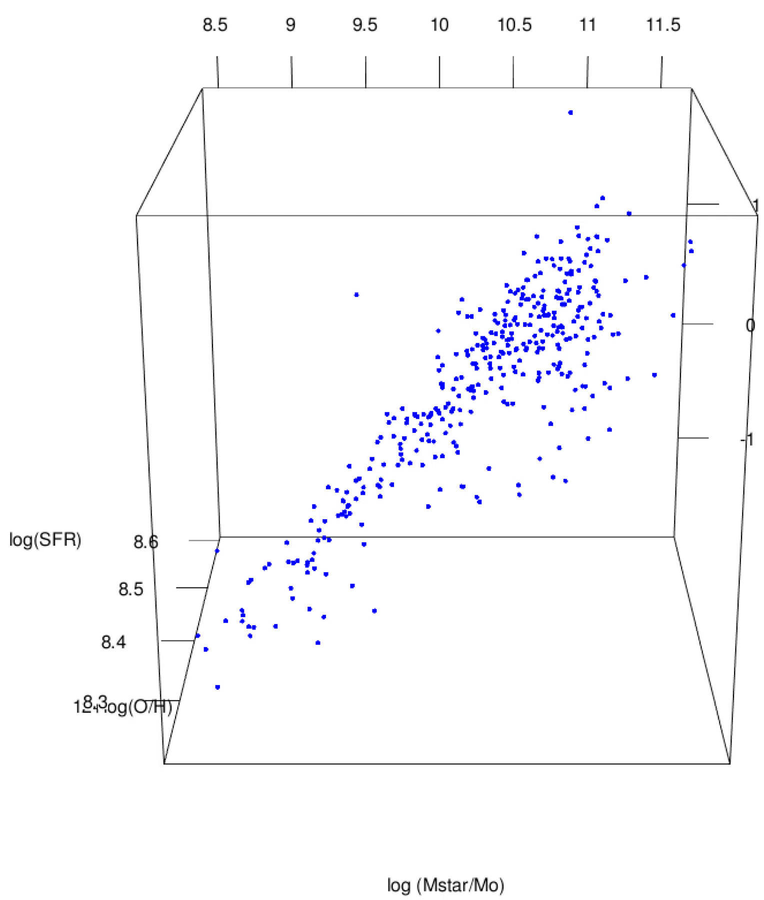
C3 = -0.089 x - **0.776** y - **0.617** z + 0.090 w

C4 = **0.814** x - 0.204 y - 0.308 z - 0.448 w

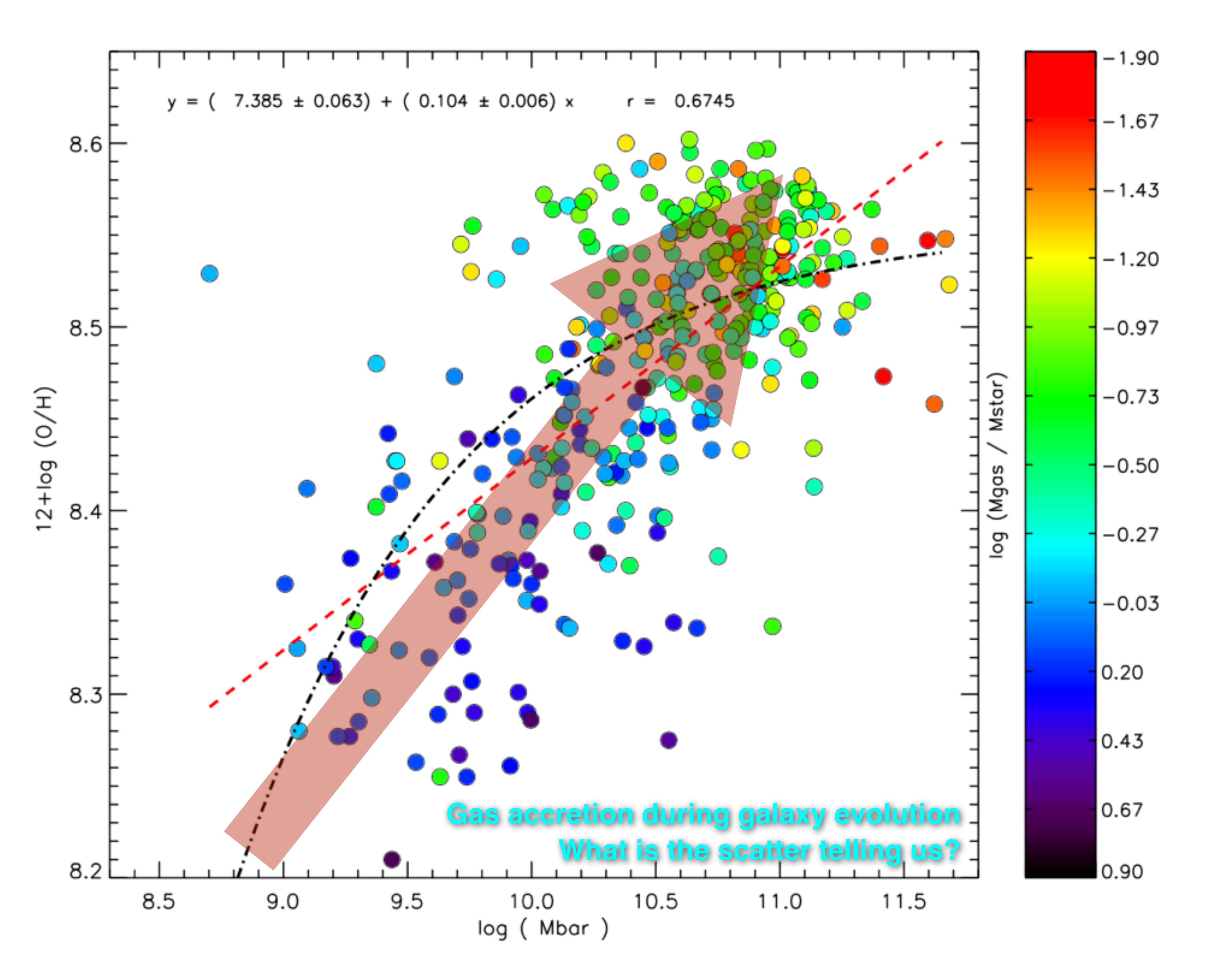
**Importance of components:**

| | C1 | C2 | C3 | C4 |
|---|---|---|---|---|
| Standard deviation | 1.704 | 0.798 | 0.578 | 0.351 |
| Proportion of Variance | 0.73 | 0.16 | 0.084 | 0.031 |
| Cumulative Proportion | 0.73 | **0.89** | 0.97 | 1.000 |

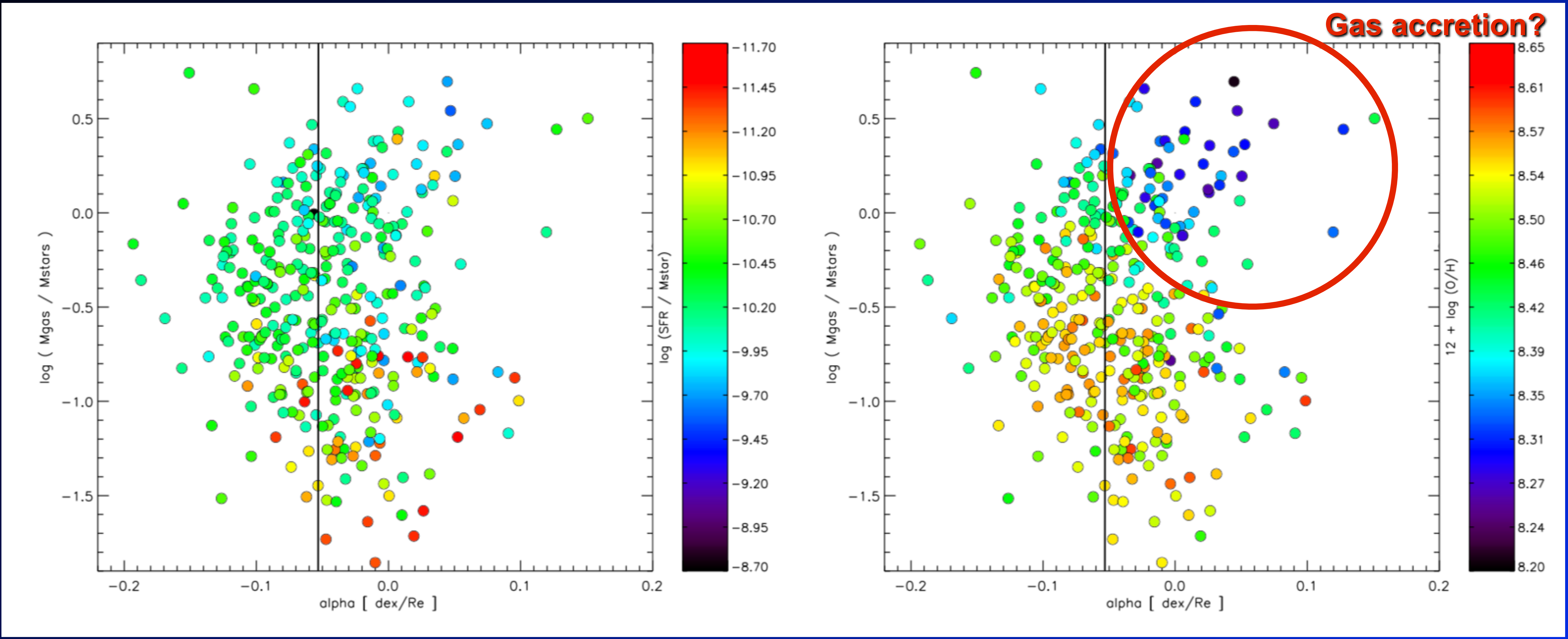


# A baryonic mass-metallicity relation

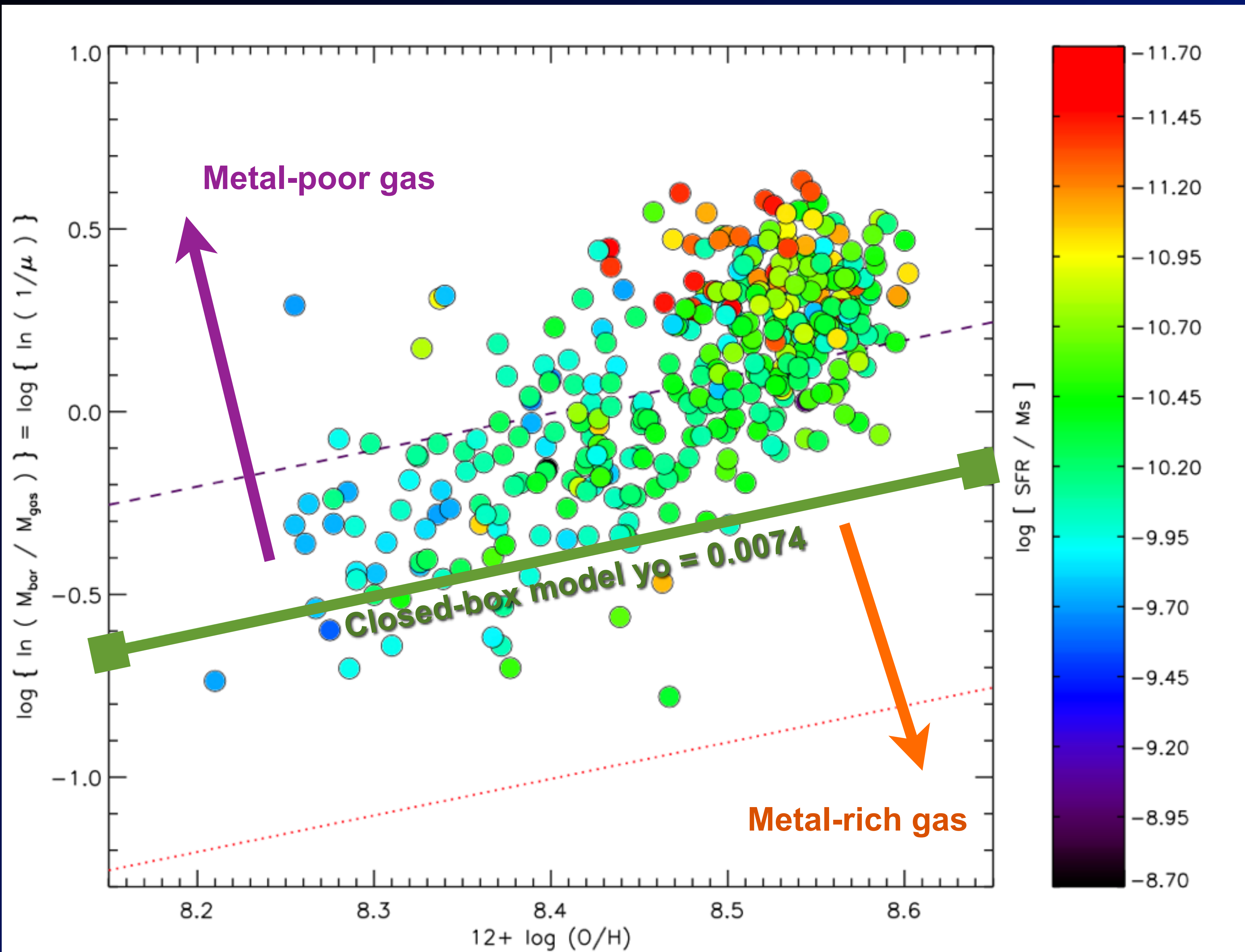


# Comparison Mgas/Mstar with the slope of oxygen gradients




Slope alpha [dex/Re] by Sánchez-Menguiano et al. (2016), Sánchez et al. (in prep)

# Chemical enrichment and galaxy evolution




"Easy" closed-box model:

$$Z_O = y_O \ln(1/\mu),$$

$Z_O$ : oxygen mass fraction

$y_O$ : stellar yield by mass

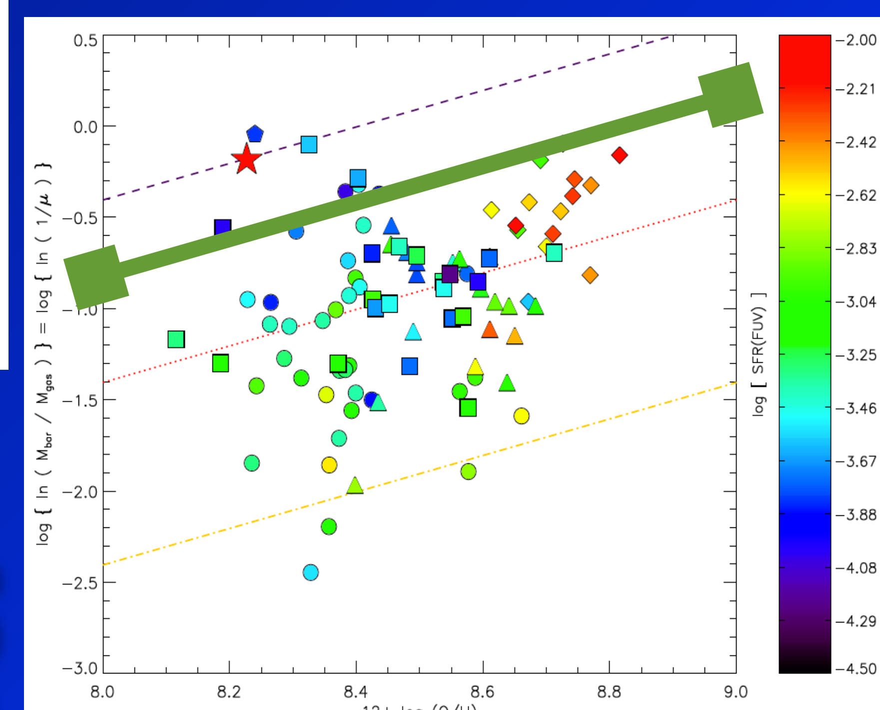
$\mu = M_{gas} / M_{bar}$ : gas mass to baryonic mass ratio

$y_O$ : 0.0074: theoretical yield of O expected for stars with rotation following Meynet & Maeder (2002) models

High-mass (high-Z) galaxies tend to have metal-poor gas

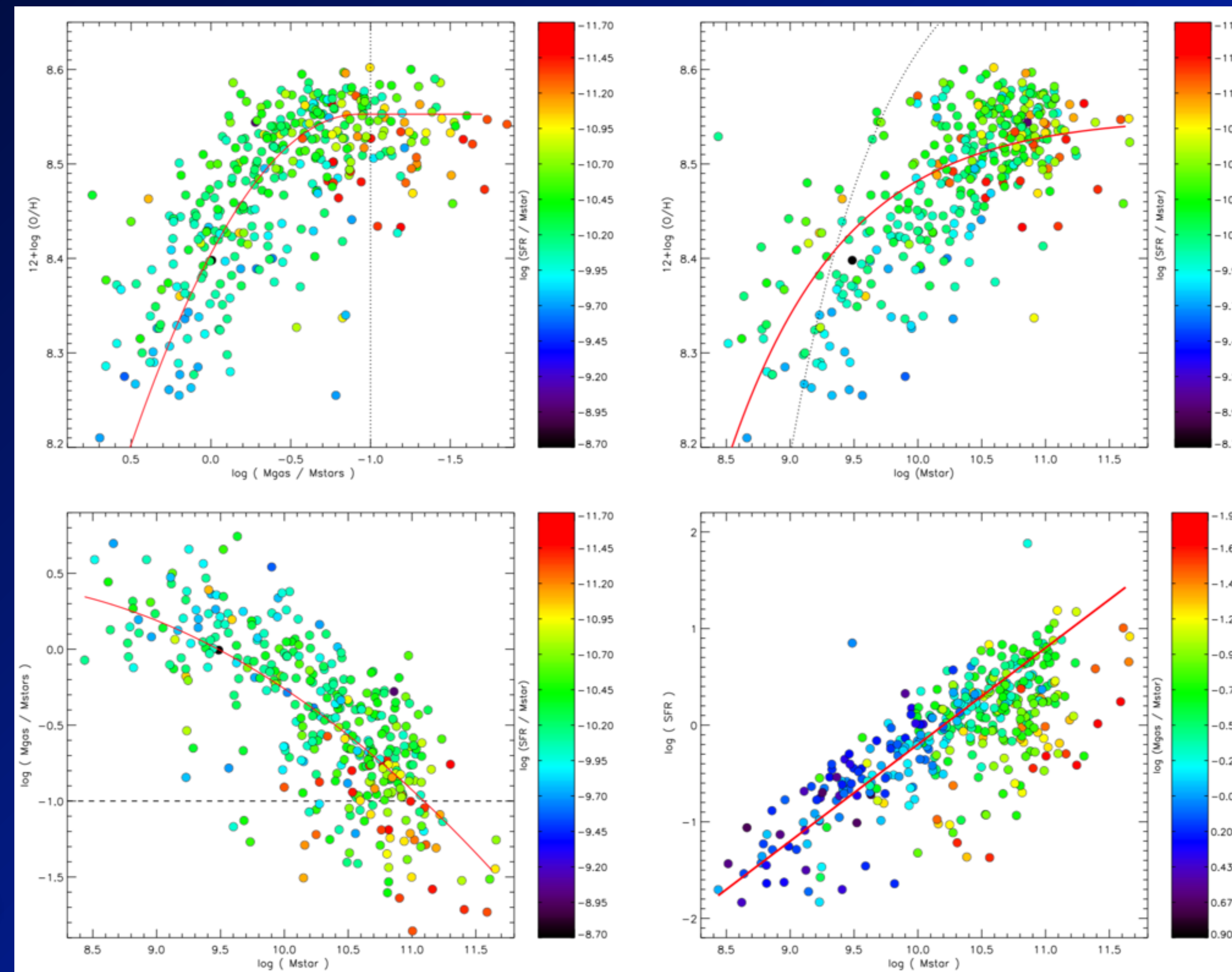
Low-mass (low-Z) galaxies tend to have metal-rich gas

➡ Metal enriched mass-loss during galaxy evolution, later accreted in dwarf SF galaxies & galaxies outskirsts (flattening of O/H gradients)




Regions in NGC 1512, López-Sánchez et al. 2015, MNRAS, 450, 3381

# Conclusions




- Be aware of **biases** using strong-line methods to derive **metallicity**
  - Metallicity is an **INTENSIVE** property
- Studying the **mass-metallicity-SFR relations** to get better understanding of galaxy formation and evolution.
  - The **neutral gas** plays a role !
- Compiling the HI data from literature:
  - Data for **368 / 450 with HI and O/H**
  - We define relations with **Mg/Ms**
  - **PCA** analysis suggests a **Ms-O/H-Mg/Ms** relation (**C1**), but see **Lagos et al. 2015b**, with a **Mg/Ms-SFR** relation (**C2**)
  - We define a **Baryonic Mass-Z relation**
  - We study the **chemical enrichment** of galaxies
    - **Flattening/invert slopes = gas accretion**
    - **Metal enriched mass-loss during galaxy evolution, later accreted in dwarf SF galaxies & galaxies outskirsts (flattening of O/H gradients)**

- **Next step 1:** Add more data points! The **full CALIFA** sample + others (López-Sánchez 2010, Hughes et al. 2013, GAMA+GASS, SAMI+HI, in the future **TAIPAN+WALLABY**)
- **Next step 2:** Add **molecular gas!** (CO data please!!) Also other parametres: interacting, N/O, dust ...
- **Next step 3:** compare with predictions given by models to constrain galaxy evolution (Mollá et al., Lagos et al. 2015, and more)