The "enigma" of metal-poor starbursts

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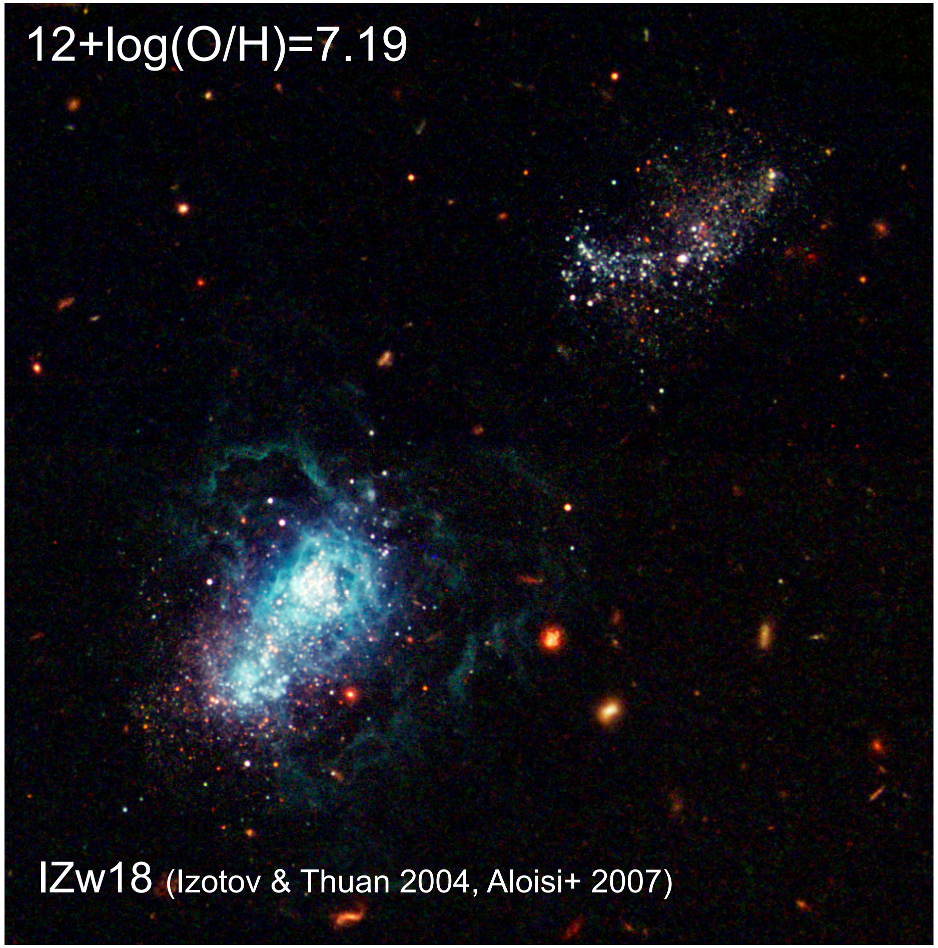
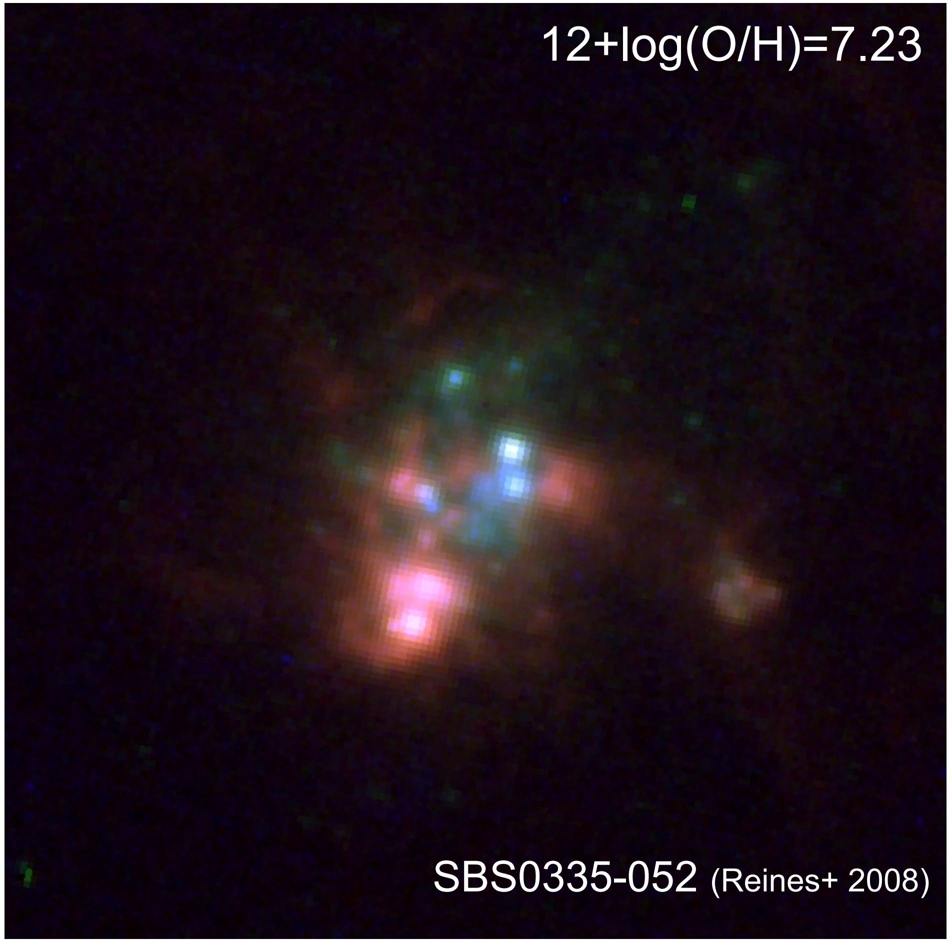


M_*~7e5 $M_\odot$, 1150 O stars, SFR ~ 0.1 $M_\odot yr^{-1}$,



M_*~6e6 $M_\odot$, 9400 O stars, SFR ~ 1 $M_\odot yr^{-1}$

How does metallicity govern star formation?

✓ Compile a sample of ~1000 galaxies spanning a wide range of redshift, M_*, SFR, and with adequate representation at low metallicities.

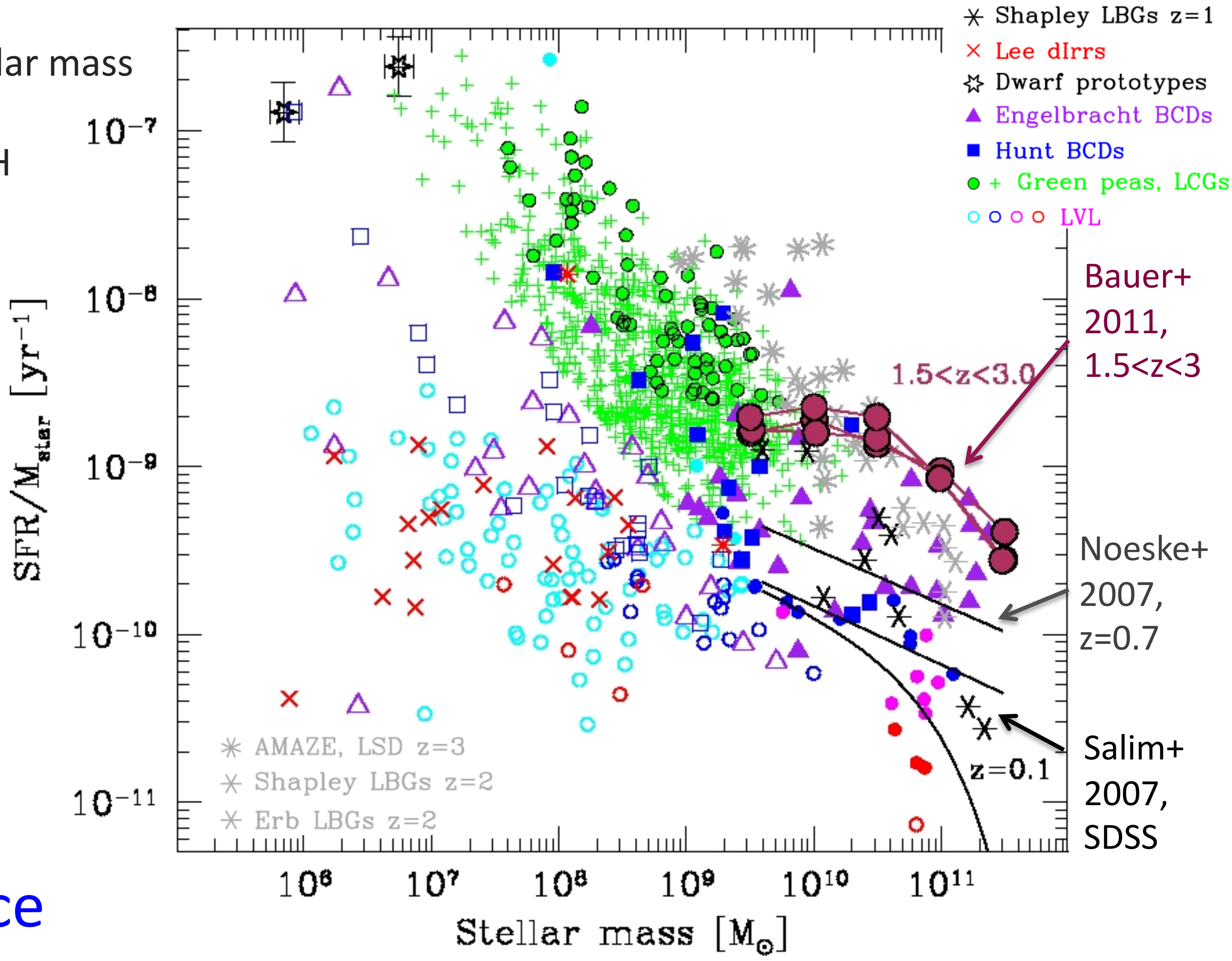
✓ Examine observed scaling relations of O/H, SFR, M_* : SFR vs. O/H, star formation “Main Sequence” (SFMS), mass-metallicity relation (MZR).

Some BCDs and Luminous Compact Galaxies in the Local Universe are outliers from the scaling relations in the same way as Lyman-Break Galaxies (LBGs) at redshift 1-3: too high SFR for their mass, and too massive for their low metallicity.

✓Develop models with different initial conditions (size, density, mass) which predict the scaling relations, independently of metallicity (and independently of redshift).

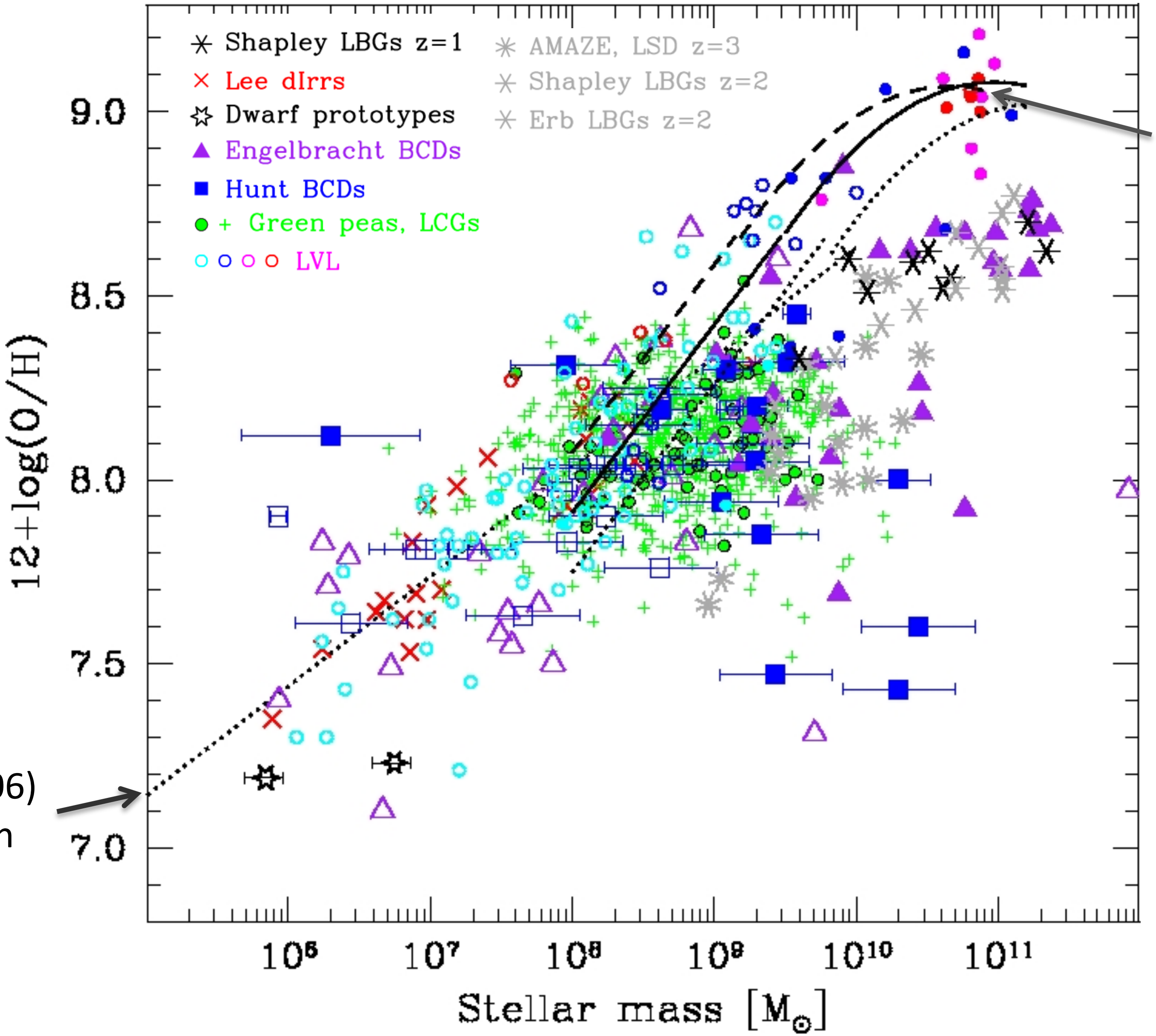
High dynamic range makes a difference

≈10^5 in stellar mass
≈10^6 in SFR
≈100 in O/H



SF Main Sequence

Mass-metallicity relation (MZR)

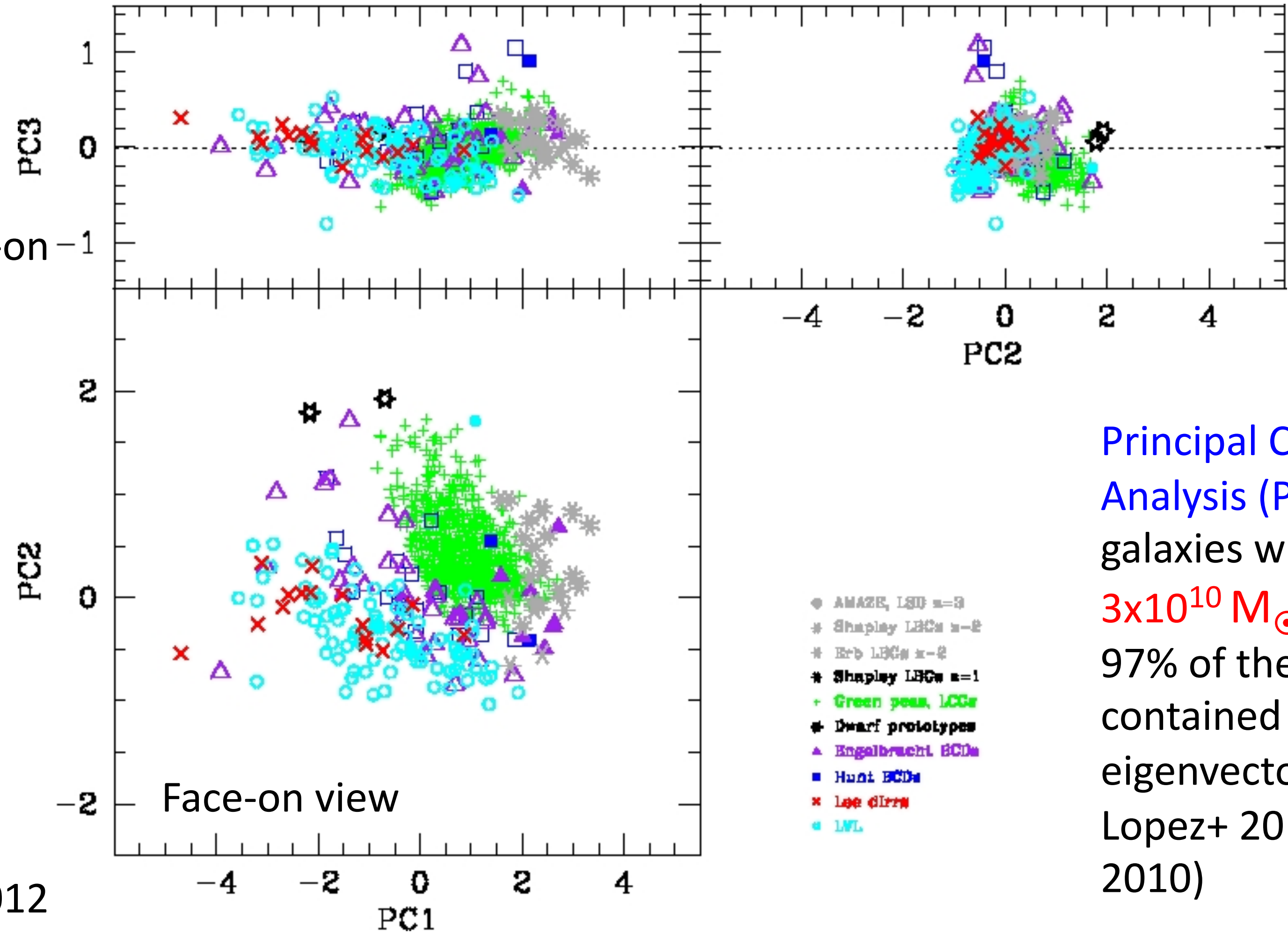


Fundamental Metallicity Relation makes MZR adjustments with SFR = 0.1, 1, 10 $M_\odot$ yr^{-1} (Mannucci+ 2010, 2011)

Lee+ (2006) regression

A Fundamental Plane of M_{star}, SFR, and O/H

Edge-on



Edge-on

Hunt+ 2012

Principal Component Analysis (PCA) on galaxies with $M_{*} \leq 3 \times 10^{10}\ M_{\odot}$ shows that 97% of the variation is contained in the first two eigenvectors (cf Lara-Lopez+ 2010, Mannucci+ 2010)

Figure 4. Different projections using the 3 PCs found by the PCA. Galaxies are coded as shown in the lower right (empty) panel. The top left and right panels show the orthogonal "edge-on" views of the plane; the bottom panel shows the plane face-on. $x_1 = 12+\log(\mathrm{O/H}) - \langle 12+\log(\mathrm{O/H})\rangle$, $x_2 = \log(SFR) - \langle\log(SFR)\rangle$ ($M_{\odot}\ \mathrm{yr}^{-1}$), and $x_3 = \log(M_{\rm star}) - \langle\log(M_{\rm star})\rangle$ ($M_{\odot}$). $\langle 12+\log(\mathrm{O/H})\rangle = 8.063$; $\langle\log(SFR)\rangle =$ -0.594; $\langle\log(M_{\rm star})\rangle = 8.476$. PC1 $=$ $0.12\,x_1 + 0.75\,x_2 + 0.65\,x_3$; PC2 $=$ $-0.31\,x_1 - 0.65\,x_2 - 0.69\,x_3$; PC3 $=$ $-0.94\,x_1 - 0.11\,x_2 + 0.31\,x_3$. The axes are expanded in the top panels to exaggerate the variations in PC3, relative to the much larger dynamic ranges in PC1 and PC2

The bottom line

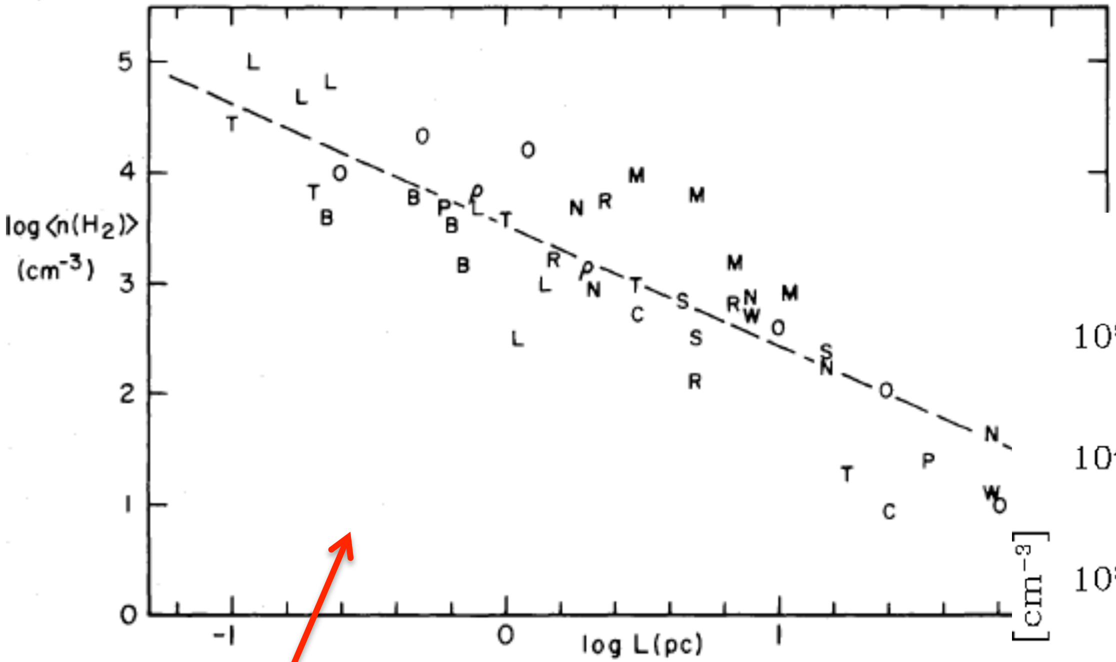
Galaxies with $M_{star} \leq 3x10^{10}\ M_{\odot}$ behave similarly (in SFR-M_{star}-O/H space) at all redshifts.

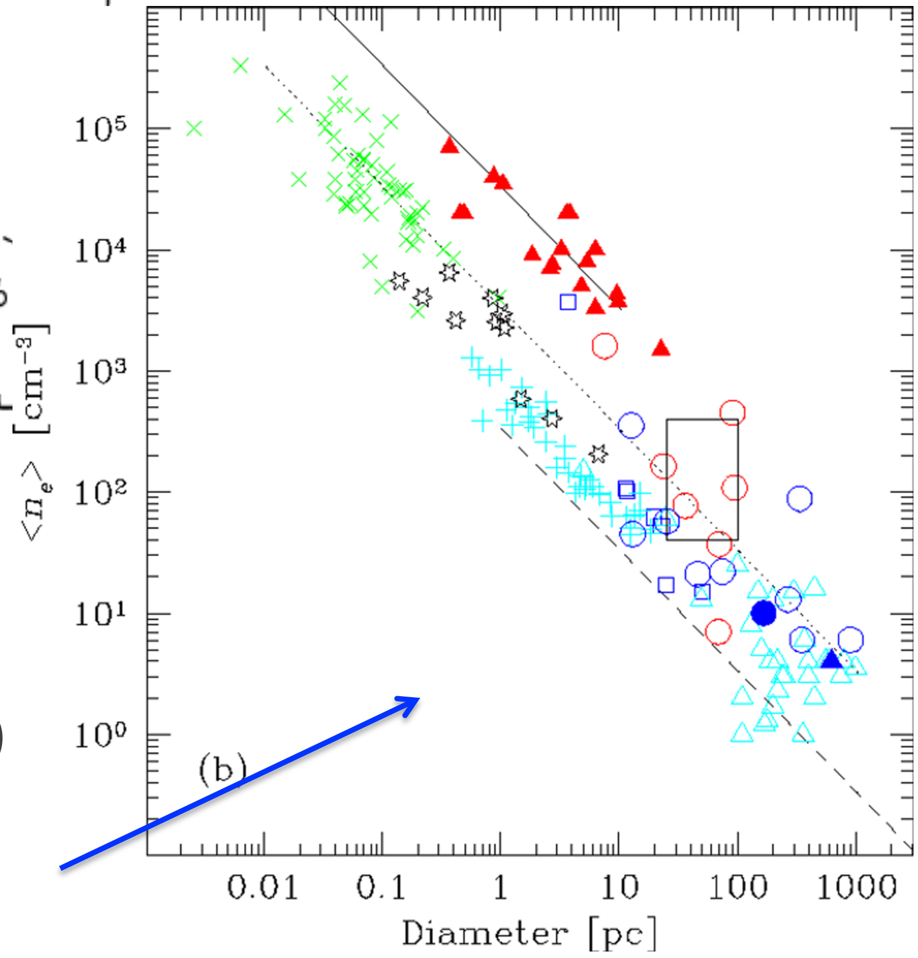
The existence of a FP that spans redshifts ≤ 3 implies that the SFMS and MZR do not really change with redshift, but rather that the galaxy populations that define them change with z.

The "evolution" in the scaling relations is apparently a result of selecting the galaxies which are most common at a particular redshift.

Why?

“Active” star formation in compact, dense regions





Like molecular clouds (Larson 1980), size and density also inversely correlated in Galactic and extragalactic HII regions (BCDs)

(taken from Hunt & Hirashita 2009: lines correspond to τ with varying dust filling factor).

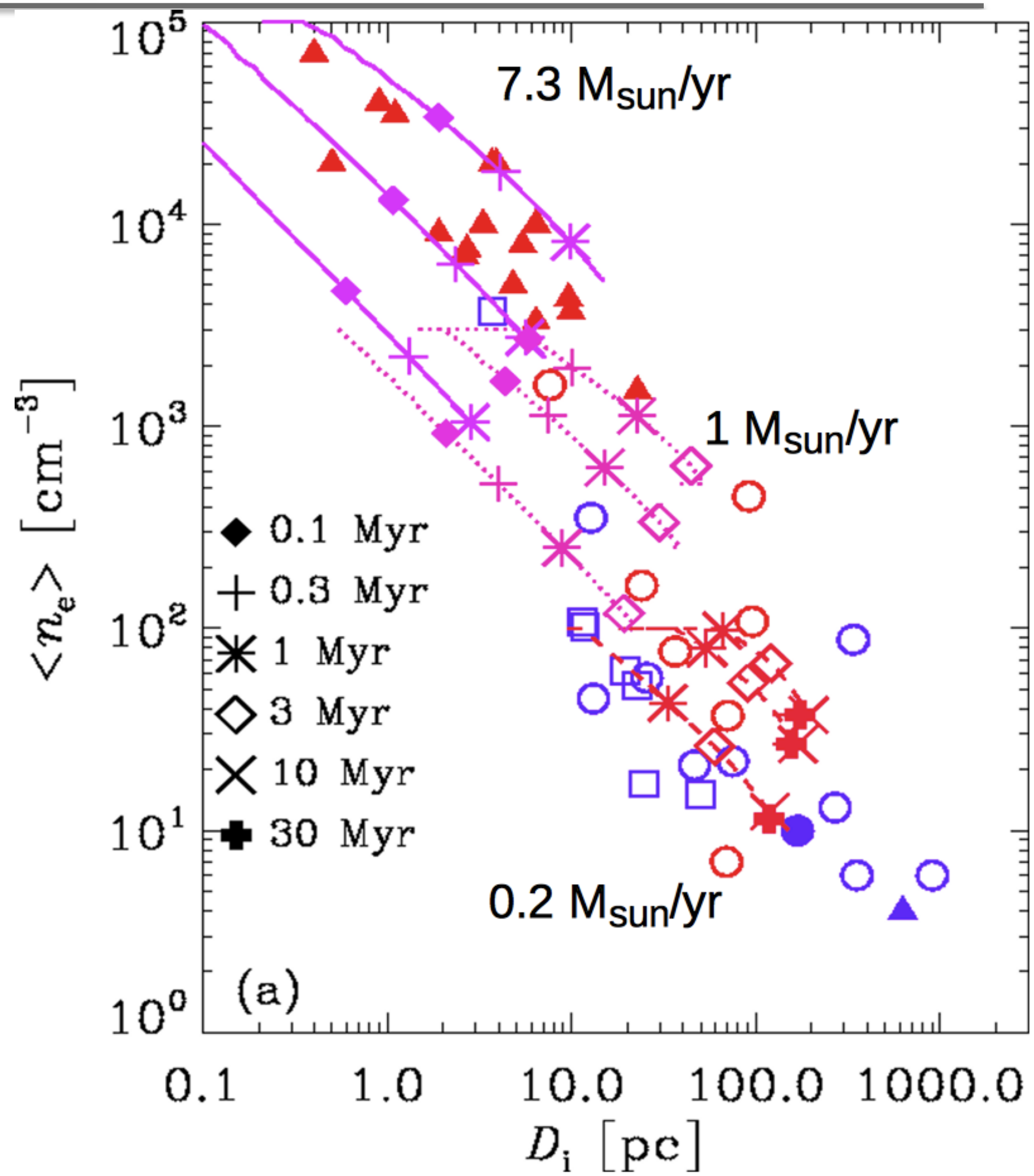
Evolving HII region models for size-density relation

One-zone models which consider HII region expansion, gas consumption, and *dust intermixed with ionized gas can be divided into two basic regimes:*

Dense + compact ("active")

Diffuse ("passive")

Hunt & Hirashita (2009), although see Dopita+ (2006) for an alternative explanation of the size-density relation that involves radiation pressure compression of ionized gas front



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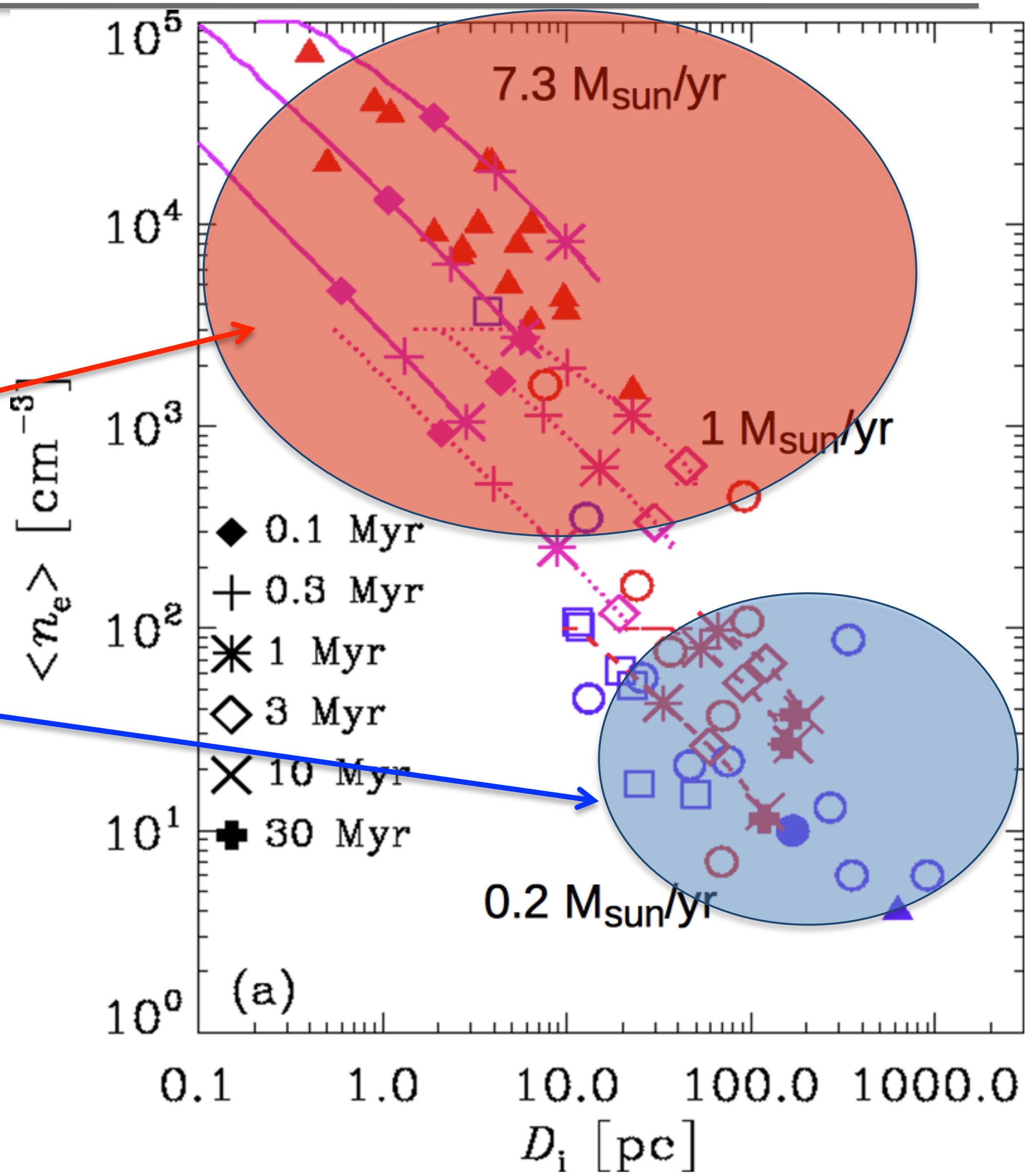

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Timescales and initial conditions

Active SF episodes (occurring in compact, dense regions) have higher surface densities (gas, SFR, stellar mass, …) and evolve over shorter timescales than…

…Passive SF episodes (in more diffuse, tenuous regions) which have lower surface densities and much longer evolutionary times.

Active/passive SF modes are independent of metallicity. SFR, IR luminosity can vary by a factors of 50-100 or so at a given abundance. Metal-poor starbursts do exist!

Starbursts deviate from the MS and MZR main trends which are instead defined by equilibrium-mode (passive) galaxies. Starbursts (active mode) evolve more quickly than quiescent star-forming galaxies (passive mode), and are more frequent at high redshift. Mergers or something else also?

Can initial conditions alone explain the deviations from the MS and MZR?

Our tools

- Semi-analytical chemical evolution models:

  MICE (Multiphase Interstellar medium Chemical Evolution) models (adapted from Galli+ 1998, Magrini+2007)
- One-zone model: with a single galactic component and without infall or outflow processes. No radial variations.
- Model follows the evolution of the baryonic components:
  - ✓ diffuse gas (g)
  - ✓ molecular clouds (c)
  - ✓ stars (s)
  - ✓ stellar remnants (r)
- At t = 0 all the mass of the galaxy is in the form of g. Then the conversion processes
  - ✓ g ➔ c ➔ s ➔ r + g
  - ✓ s(massive) 🡻 c (massive stars disrupt molecular clouds)
- Transform the gas into the other baryonic components
  - ✓ with the condition: $F_g + F_c + F_s + F_r = 1$ (closed box)

How a galaxy evolves (30 different ways)

→The radius is computed at t=0 with the assumption of uniform density (evolution at constant volume): $R_{gal} = 3\ M_{gal}/(4\pi\rho_0)^{1/3}$

→Two densities ρ_0 for the diffuse gas: 1 cm^{-3} (*spiral-type, slowly evolving*) and 400 cm^{-3} (*proto elliptical-type, rapidly evolving*)

→ Three densities for the molecular clouds:

- ✓ *diffuse* clouds $n_{H2} = 10^3\ cm^{-3}$
- ✓ *compact* clouds $n_{H2} = 5x10^4\ cm^{-3}$
- ✓ *hyper-dense* clouds $n_{H2} = 10^6\ cm^{-3}$

→ Five galaxy masses: 10^7 to $10^{11}\ M_\odot$

→ Scaling the models: chemical downsizing

SFR and cloud formation rate depend on the galaxy and on cloud density:

- ✓ Cloud formation: $\propto M_{gal}^{1/3}$ (scaling with size)
- ✓ Star formation: $\propto M_{gal}^{1/3} n_{mc}^{1/2}$ (scaling with cloud free-fall time)

Results: O/H, SFR, M_*

Two representative masses: 10^8, 10^{11} $M_\odot$

Rapidly evolving: red, magenta; slowly evolving: blue, green

Different molecular cloud densities shown as solid, dashed, dotted curves

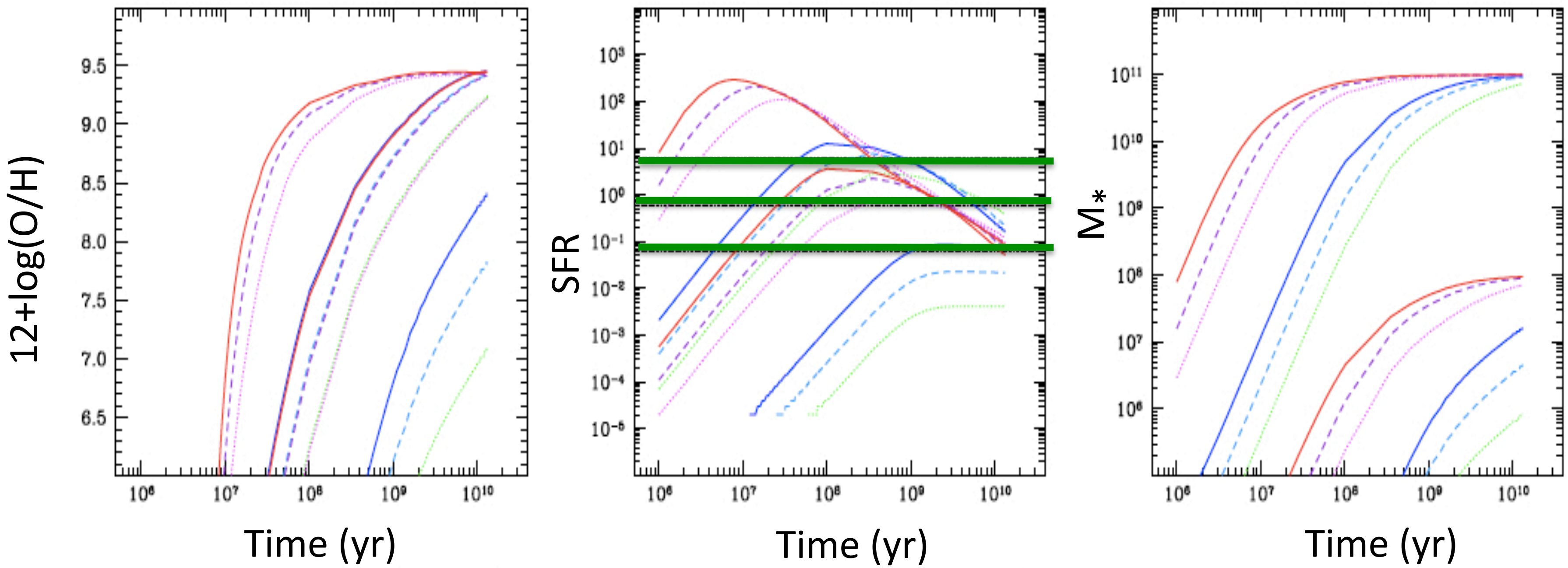
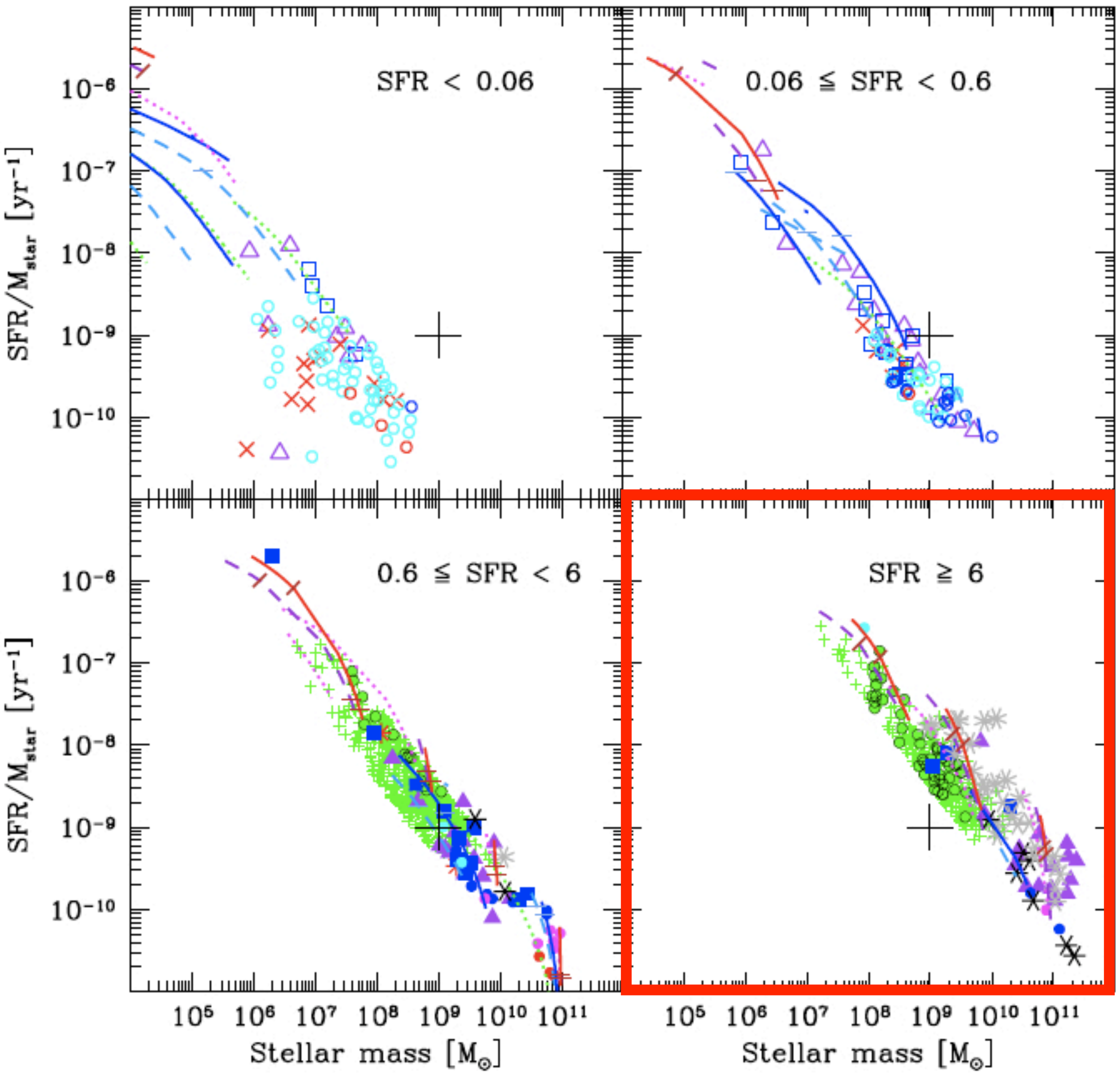


Figure 2. Predictions of O/H (left panel), SFR (middle panel), and $M_{\rm star}$ (right panel) vs. time in the MICE models. Models of two representative galaxies, $10^8\,M_\odot$ and $10^{11}\,M_\odot$, are coded by line type and color. The diffuse, compact, and hyper-dense cases for elliptical galaxies are shown as dotted (magenta) lines, dashed (dark violet) lines, and solid (red) lines, respectively. The different initial cloud masses can be easily distinguished in the models. Spiral galaxies are shown as dotted (green) lines, dashed (light blue) lines, and solid (blue) lines, respectively, for the diffuse, compact, and hyper-dense cases. In the middle panel, dotted horizontal lines show the four SFR regimes considered here: SFR $\leqslant 0.06\,M_\odot\,{\rm yr}^{-1}$, $0.06 <$ SFR $\leqslant 0.6\,M_\odot\,{\rm yr}^{-1}$, $0.6 <$ SFR $\leqslant 6\,M_\odot\,{\rm yr}^{-1}$, and SFR $\geqslant 6\,M_\odot\,{\rm yr}^{-1}$.

Magrini+ 2012

The Main Sequence (SFMS)

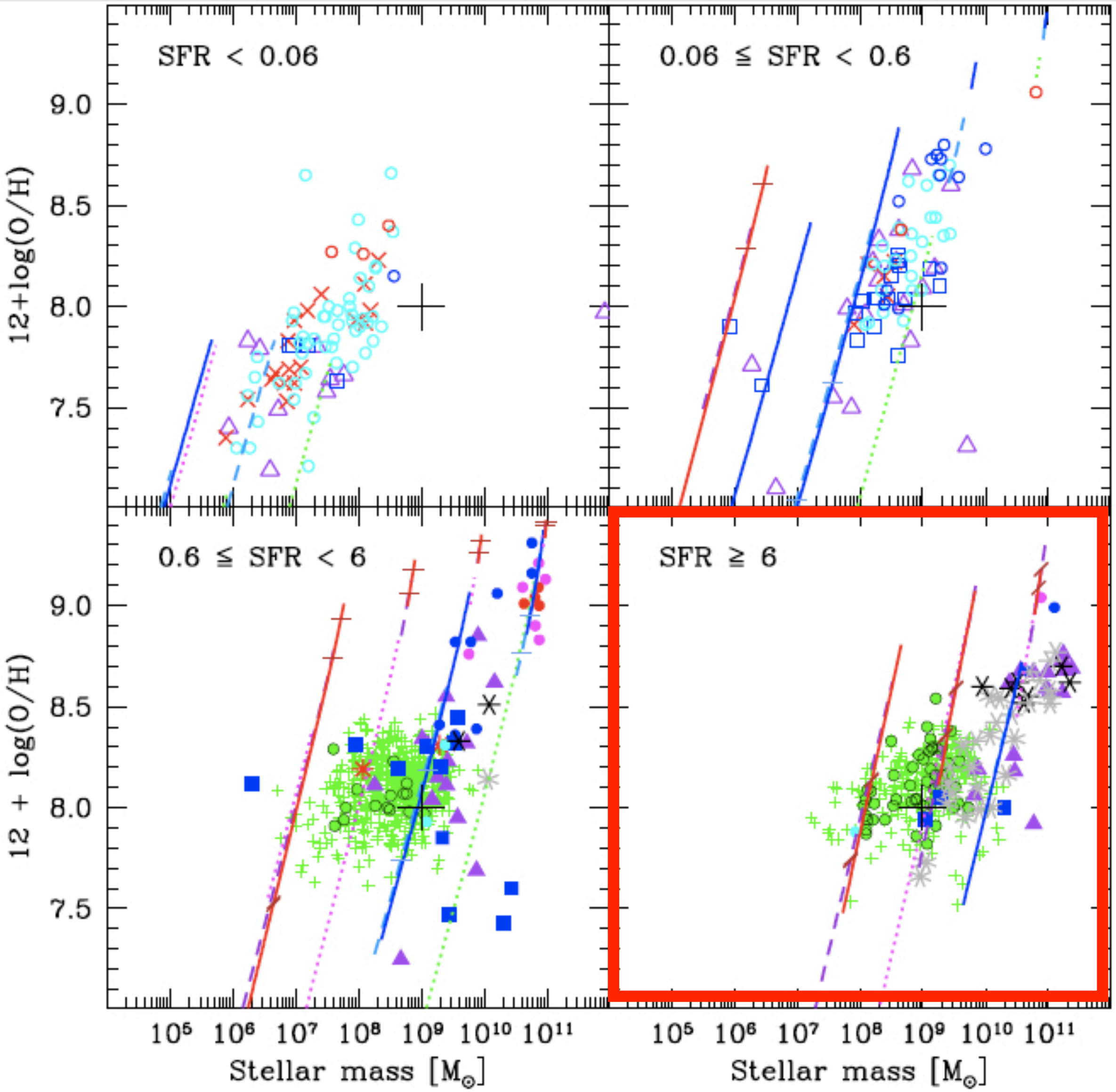


- Many LCGs and Green Peas at z~0.3, and some BCDs at z~ 0, are coincident with the LBGs in the AMAZE and LSD samples at z~3.

- Systems in early stages of their evolution, and with high SFR.

- *There are local galaxy populations which mimic the properties of galaxies at high redshift*

The Mass-Metallicity relation (MZR)



- Extreme starbursts require rapidly evolving models at young ages < ~200-300Myr
- Evolutionary tracks of rapidly evolving *active* galaxies

What are the **drivers** of the *active* and *passive* modes of star formation?

We can successfully predict scaling relations (even the outliers) using models without inflow/outflow. In our modelling the different modes of star formation are driven by:

- Intrinsic characteristics in terms of size of the galaxies and/or density of their star forming regions

- Their evolutionary age (time from the last main SF episode), i.e., the timescale of their SF history

- Not by metallicity, which turns out to be a consequence

(Metal-poor) starbursts (active mode), locally and at high redshift, apparently share common characteristics which shape their evolution and thus define the scaling relations.