INAF ISTITUTO NAZIONALE DI ASTROFISICA
OSSERVATORIO ASTROFISICO DI ARCETRI

UNIVERSITÀ DEGLI STUDI FIRENZE

Lecture VII: Insights into galaxy evolution from stellar population and gas scaling relations

Astrophysics of Galaxies 2019-2020

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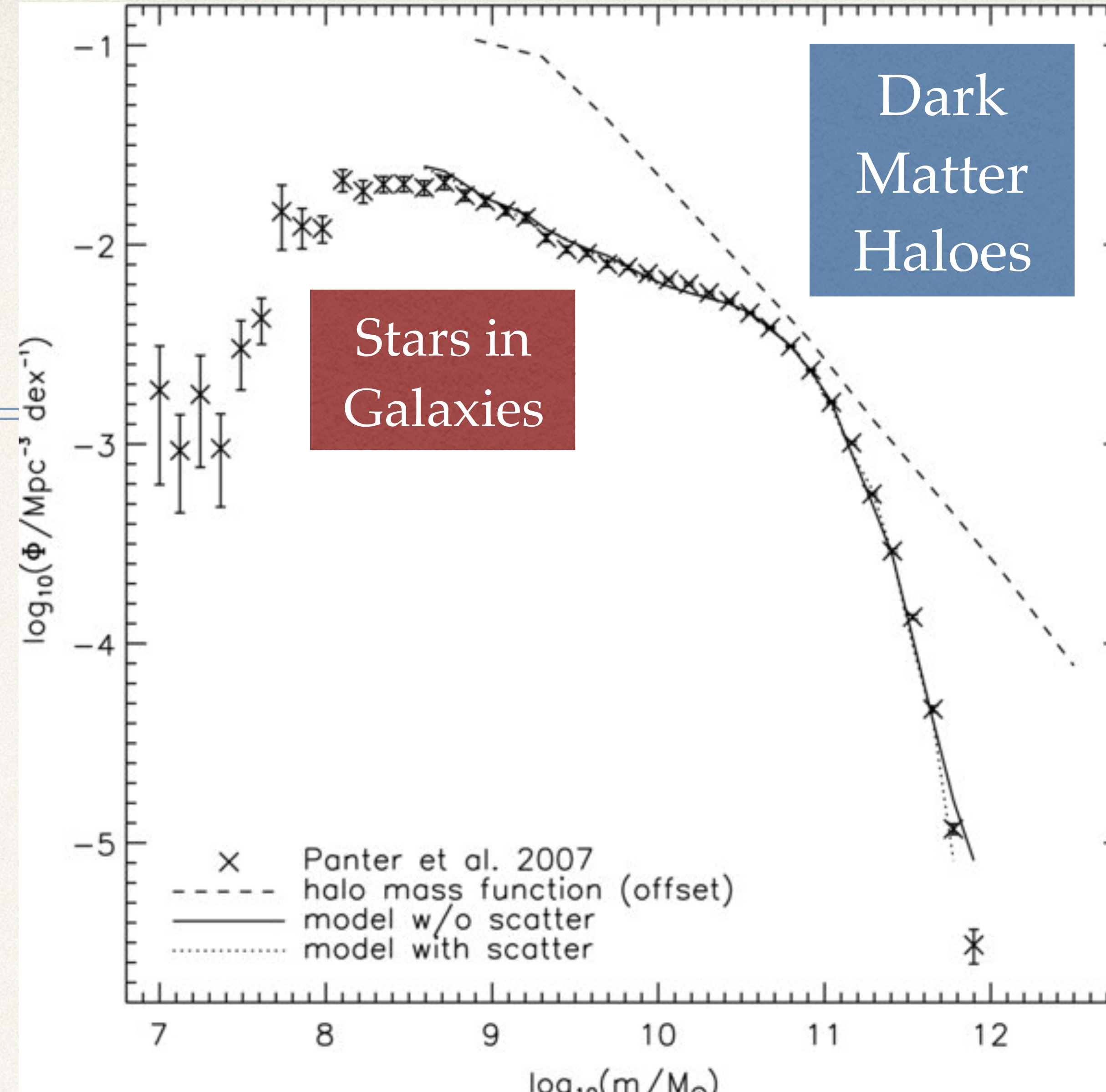
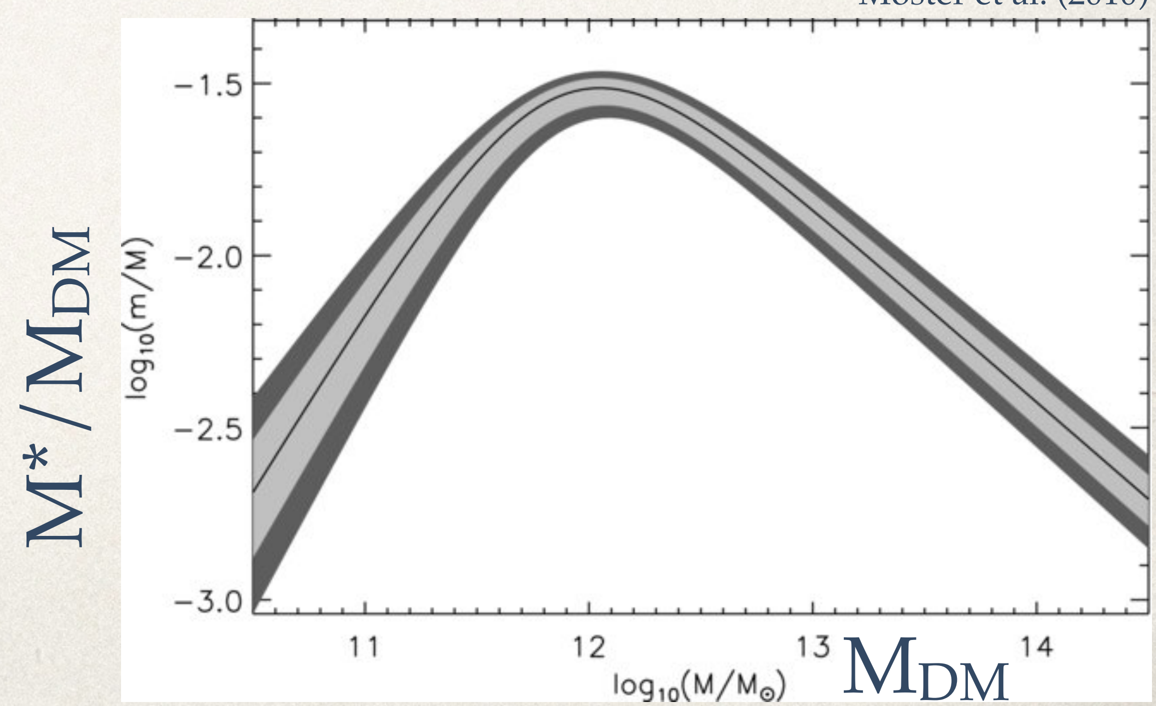
The *Problem*

- The galaxy formation paradigm asserts that galaxies form inside dark matter halos
- Yet the mass functions of DM and stars do not match!
- Efficiency of galaxy formation is suppressed at low and high masses —> feedback???



Moster et al. (2010)



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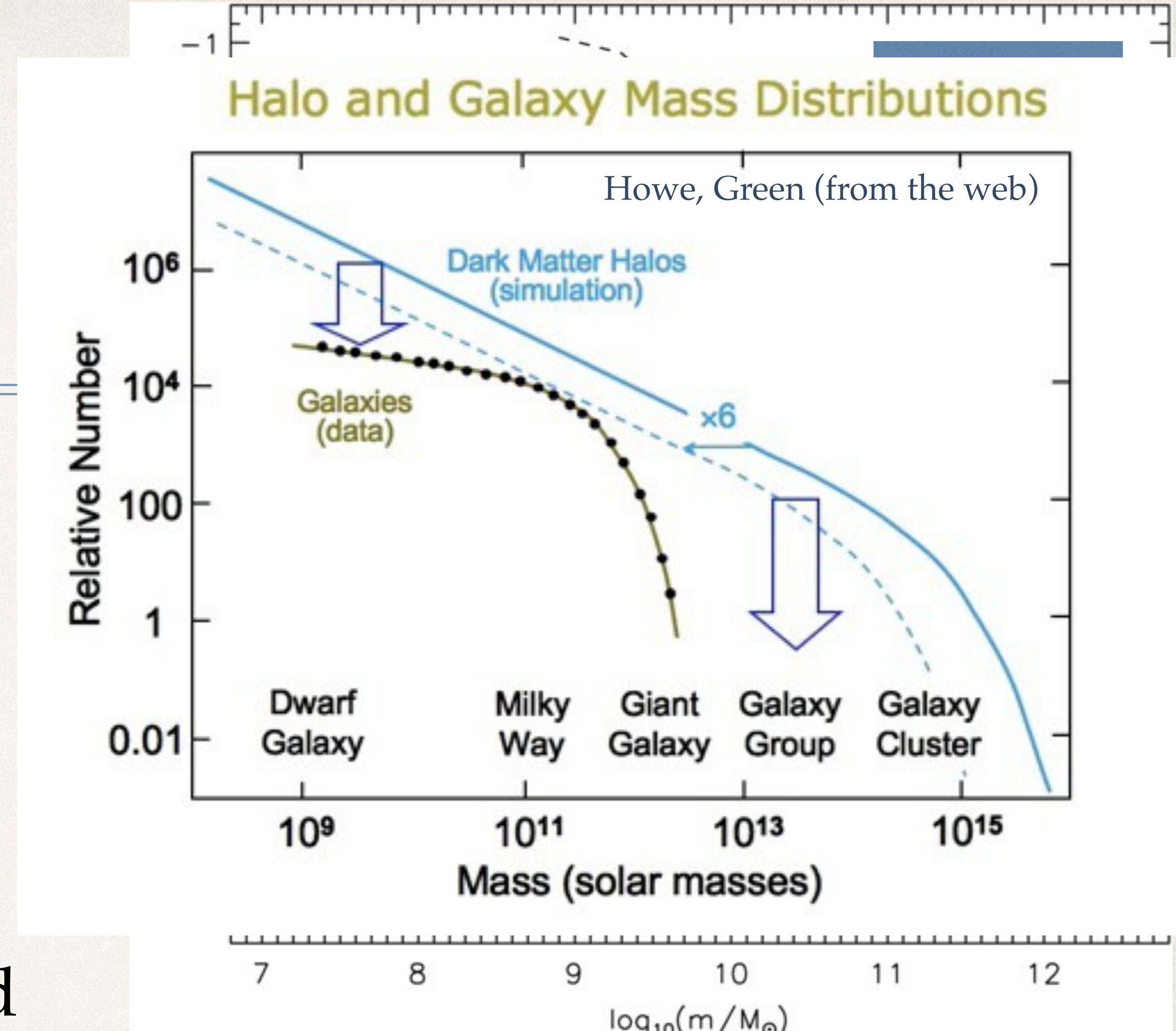

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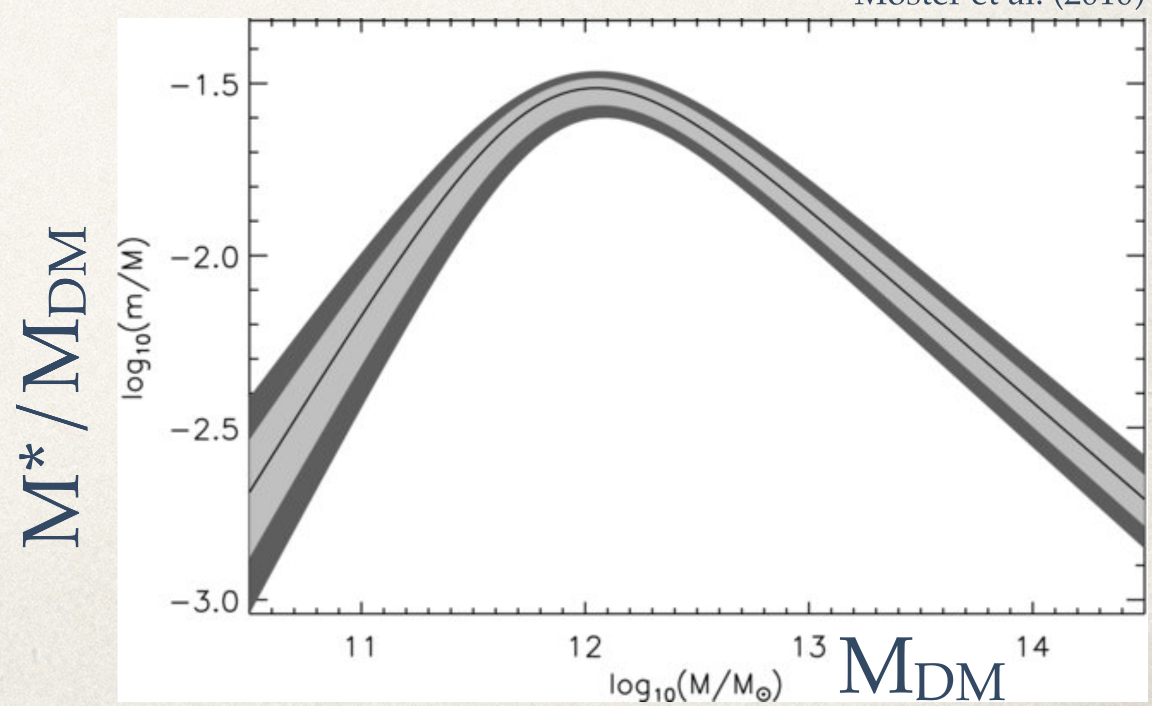
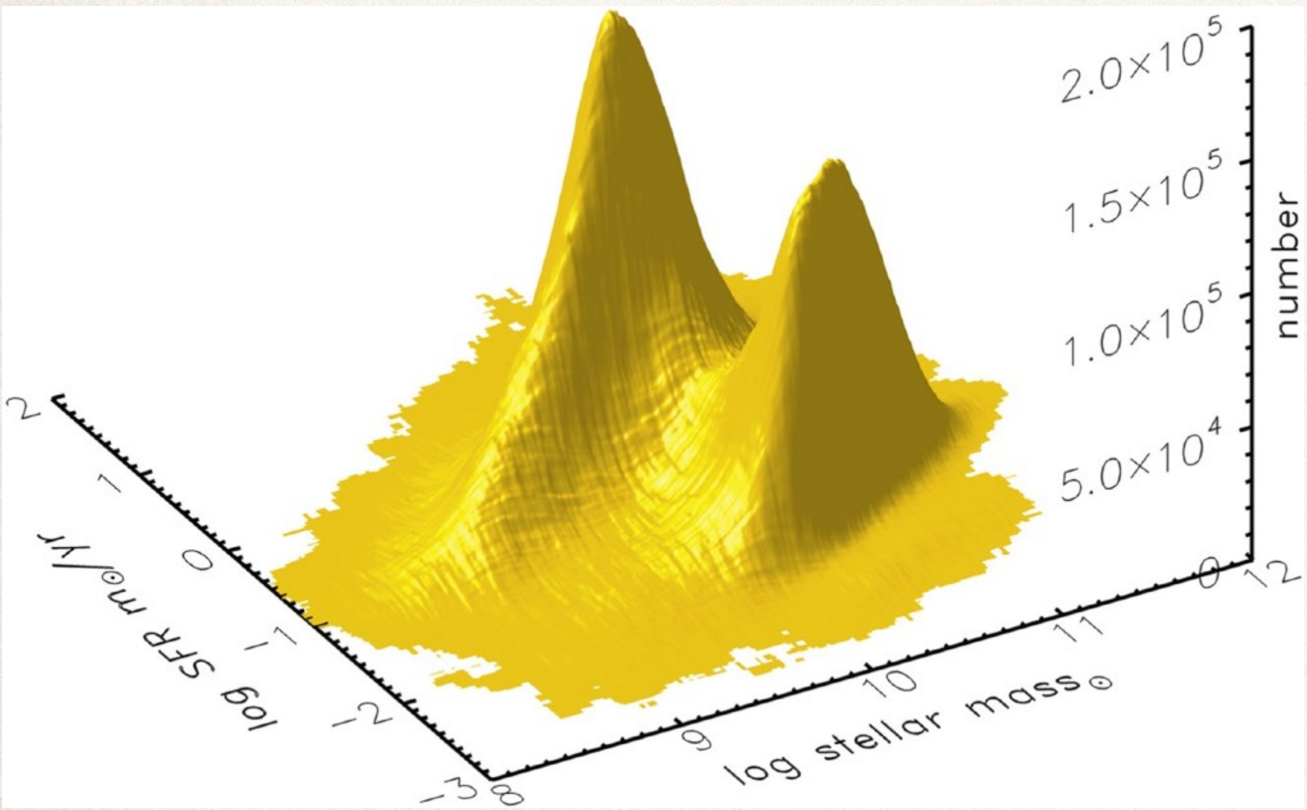
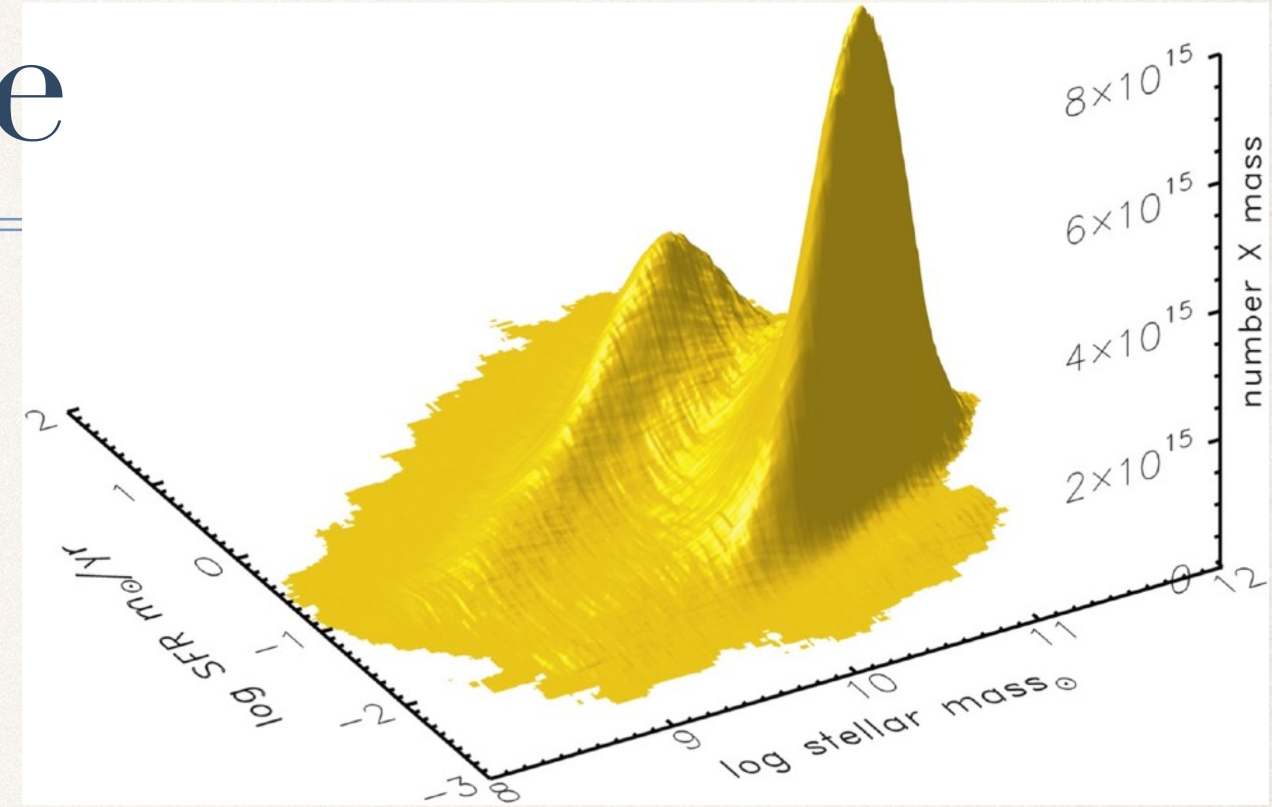
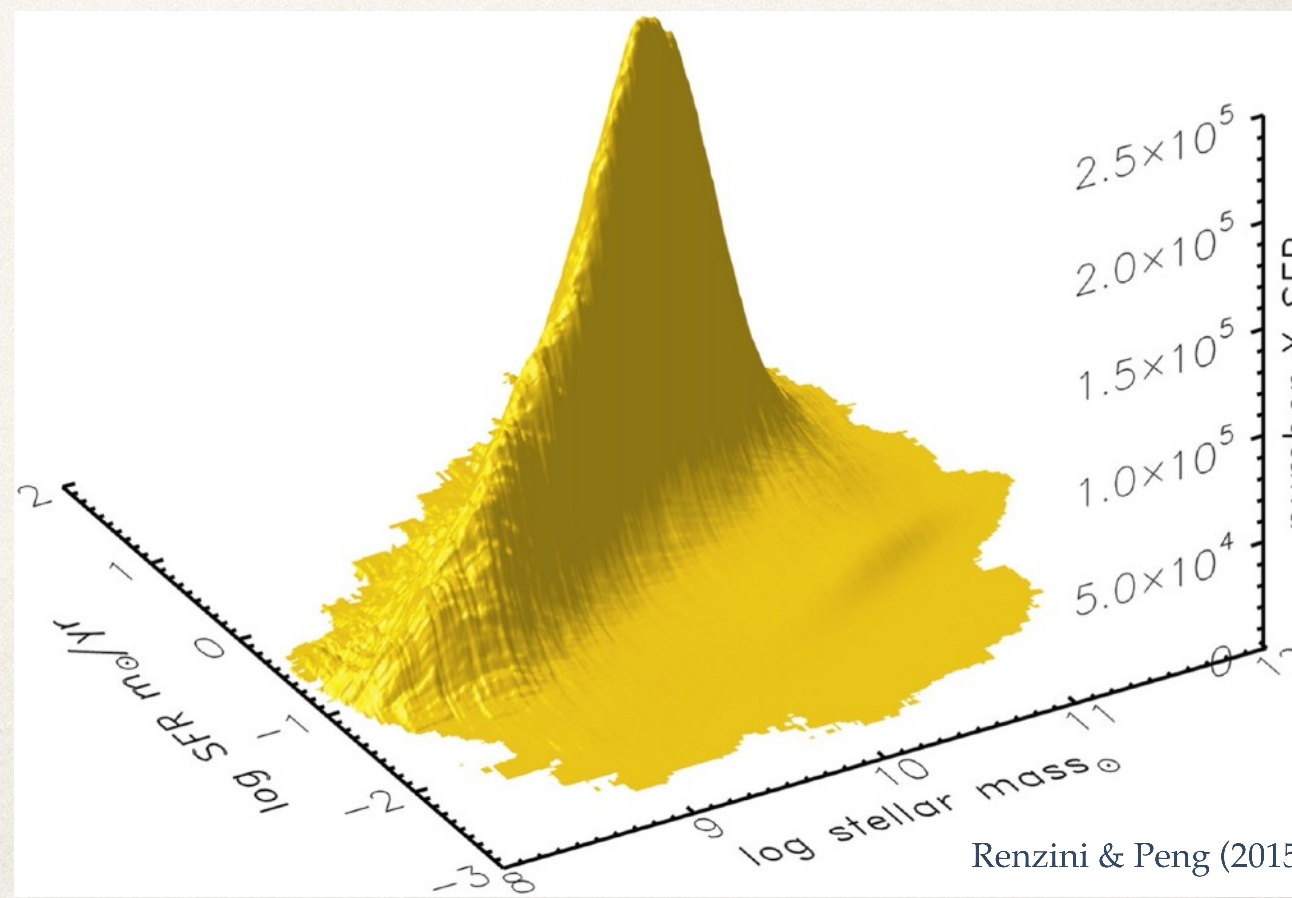


The SFR-Mass relation and the SF Main Sequence





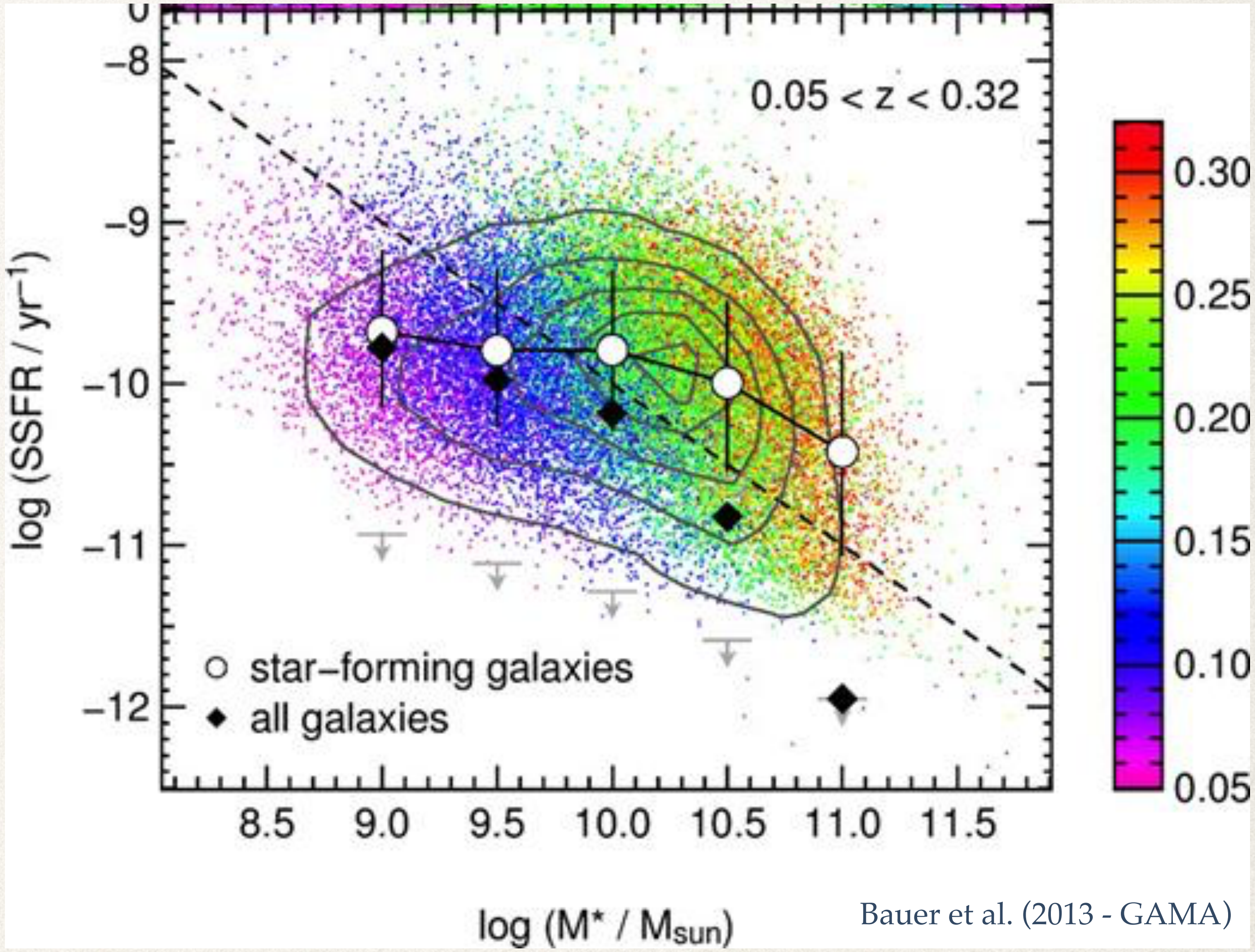
~240,000 SDSS galaxies:
0.02 < z < 0.085



Renzini & Peng (2015)

sSFR vs Stellar Mass

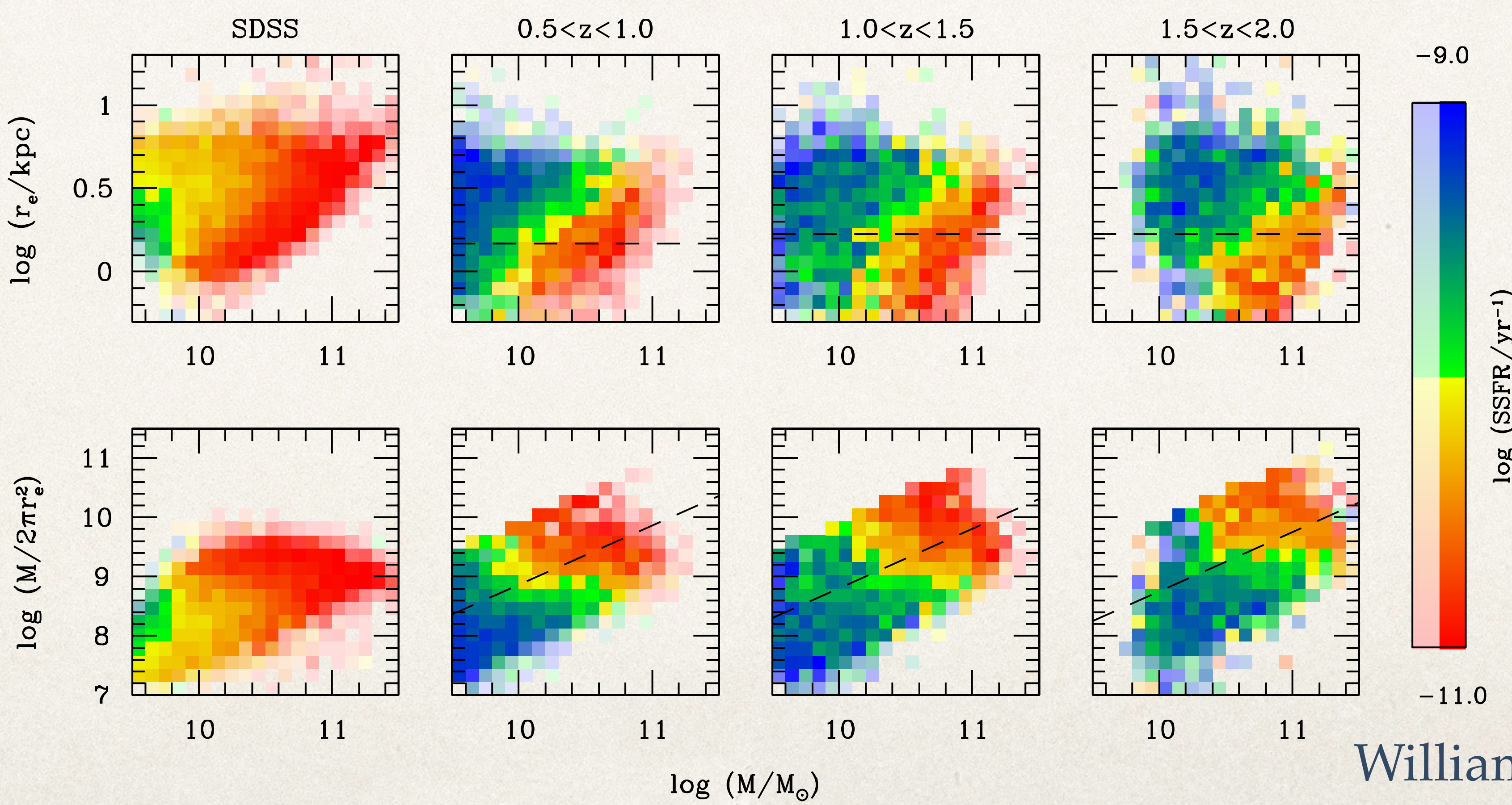
- ***Star-forming galaxies*** have roughly constant sSFR, with a hint for down-bending at the highest masses
- If ***ALL galaxies*** are considered, a strong trend emerges



Bauer et al. (2013 - GAMA)

Stellar mass (surface density) vs sSFR

- Stellar mass (causally?) determines sSFR at all z up to 2
- Surface mass density appears even better correlated
- What causes what?
  - dynamically hot systems have troubles forming stars?
  - or massive systems are so because they have been very efficient in using up their gas in the past?



Williams et al. (2010)

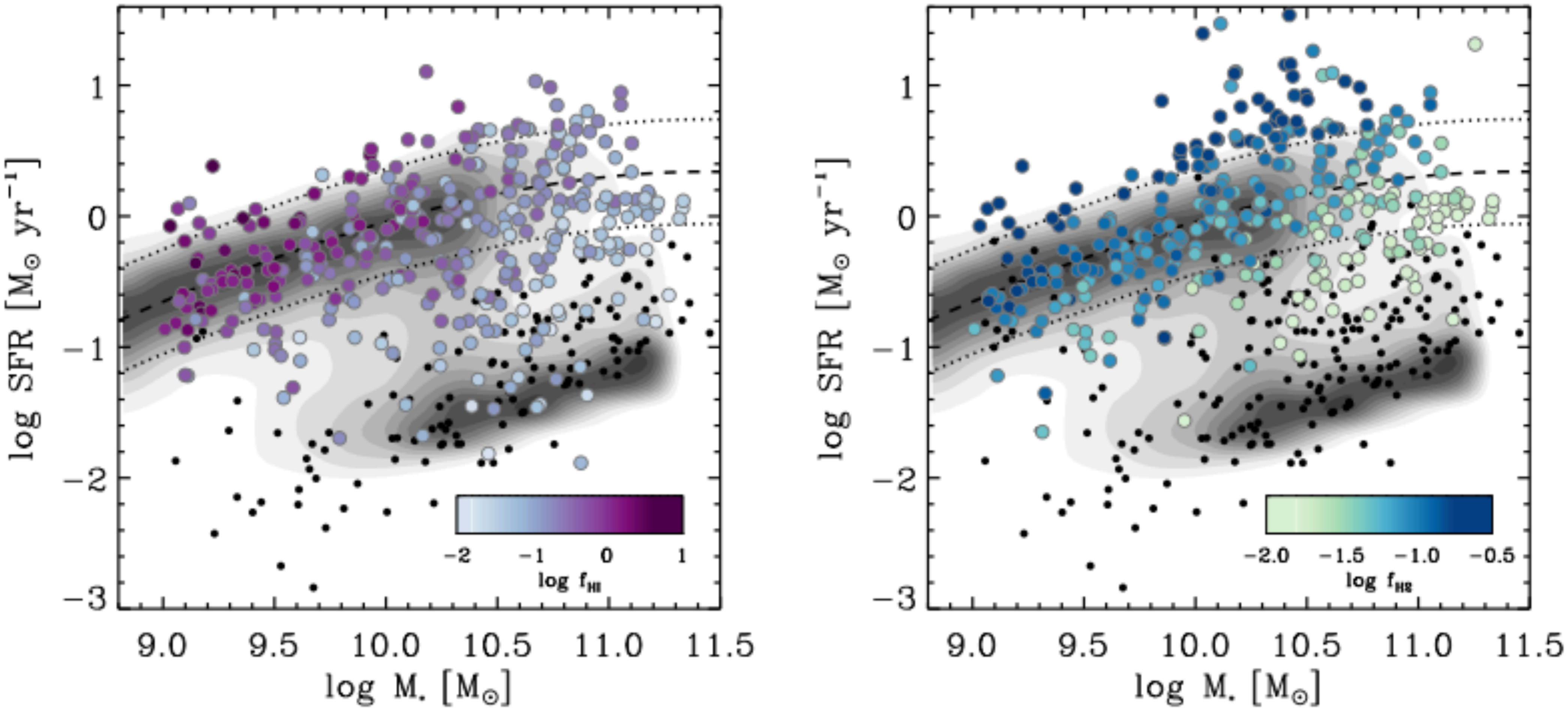
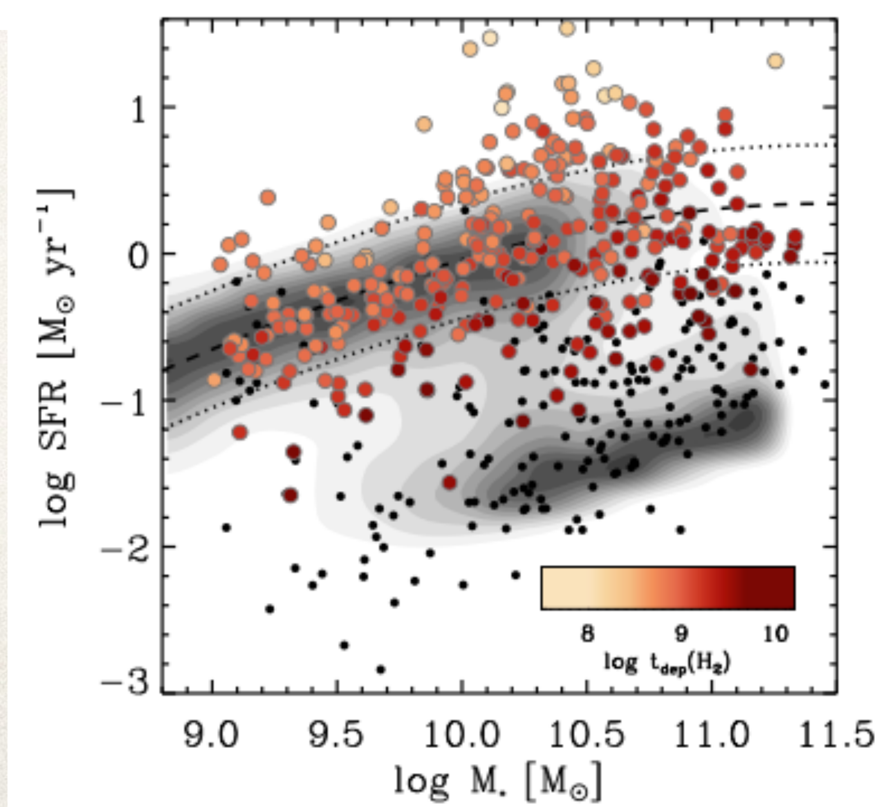


Figure 7. Distribution of the xCOLD GASS sample in the SFR-M_* plane, color-coded by atomic gas mass fraction (left) and molecular gas mass fraction (right). The smaller black symbols are galaxies un-detected in the HI and CO(1-0) line, respectively. The grayscale contours show the overall SDSS population. The dashed and dotted lines indicate the position of the main sequence and the ±0.4dex scatter around this relation, respectively.

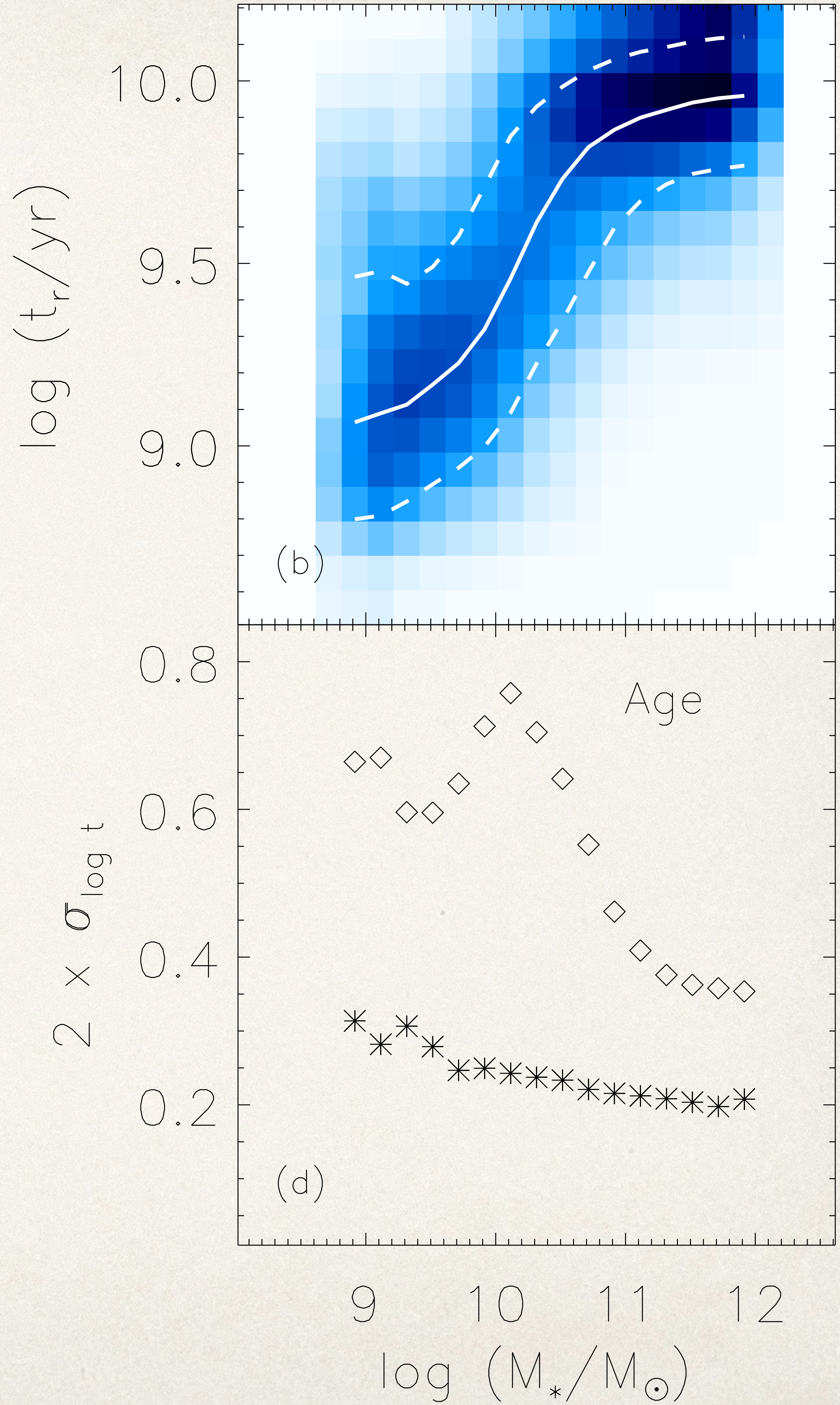
Saintonge et al. (2017)



Age-M* relation

- Massive galaxies all have SFH peaked in the past ~10 Gyr
- Smaller masses, smaller ages, but much more scatter
- Transition at between 10^{10} and $10^{10.5}$ $M_{\odot}$

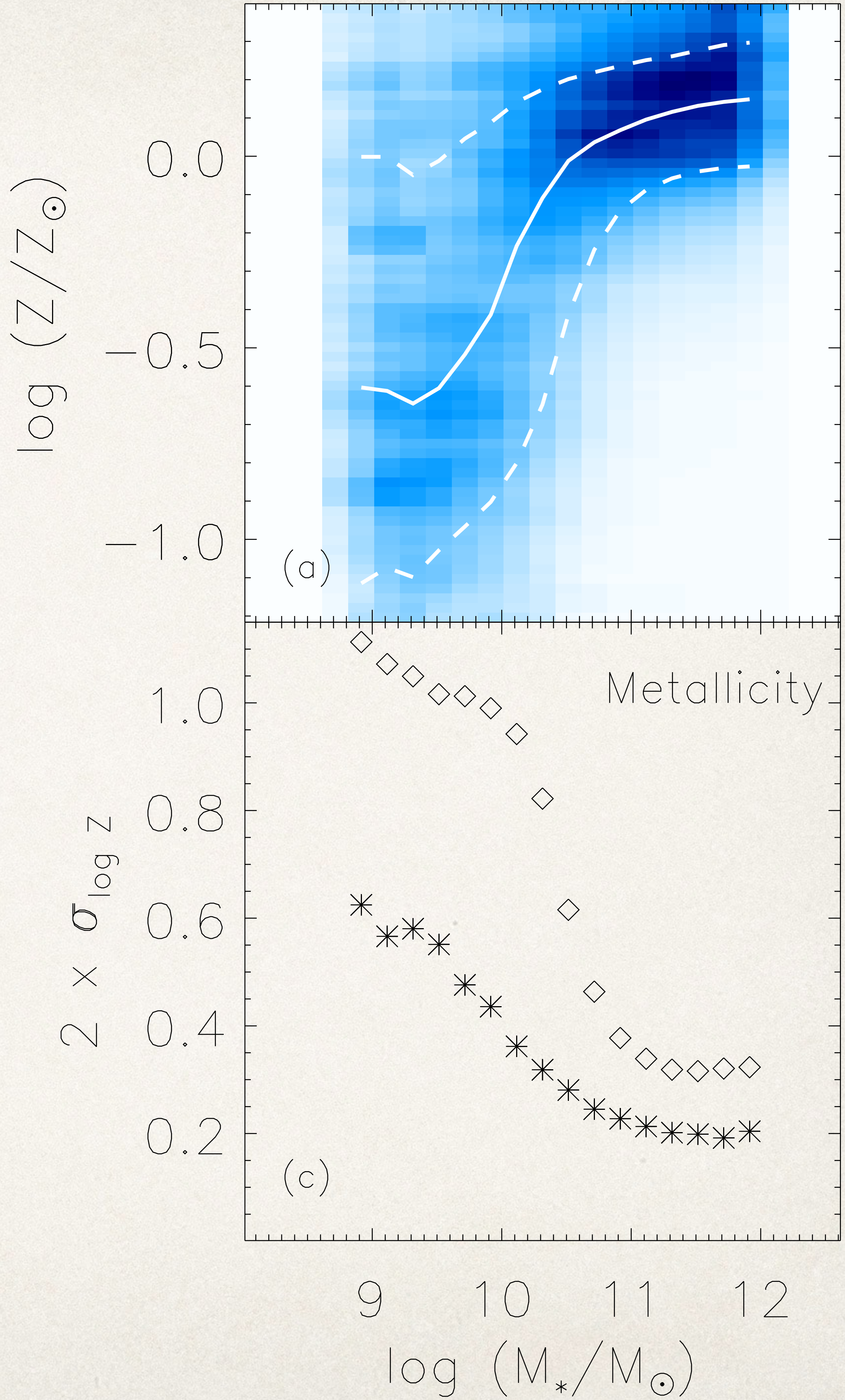
Gallazzi et al. (2005)



Stellar Z-M* relation

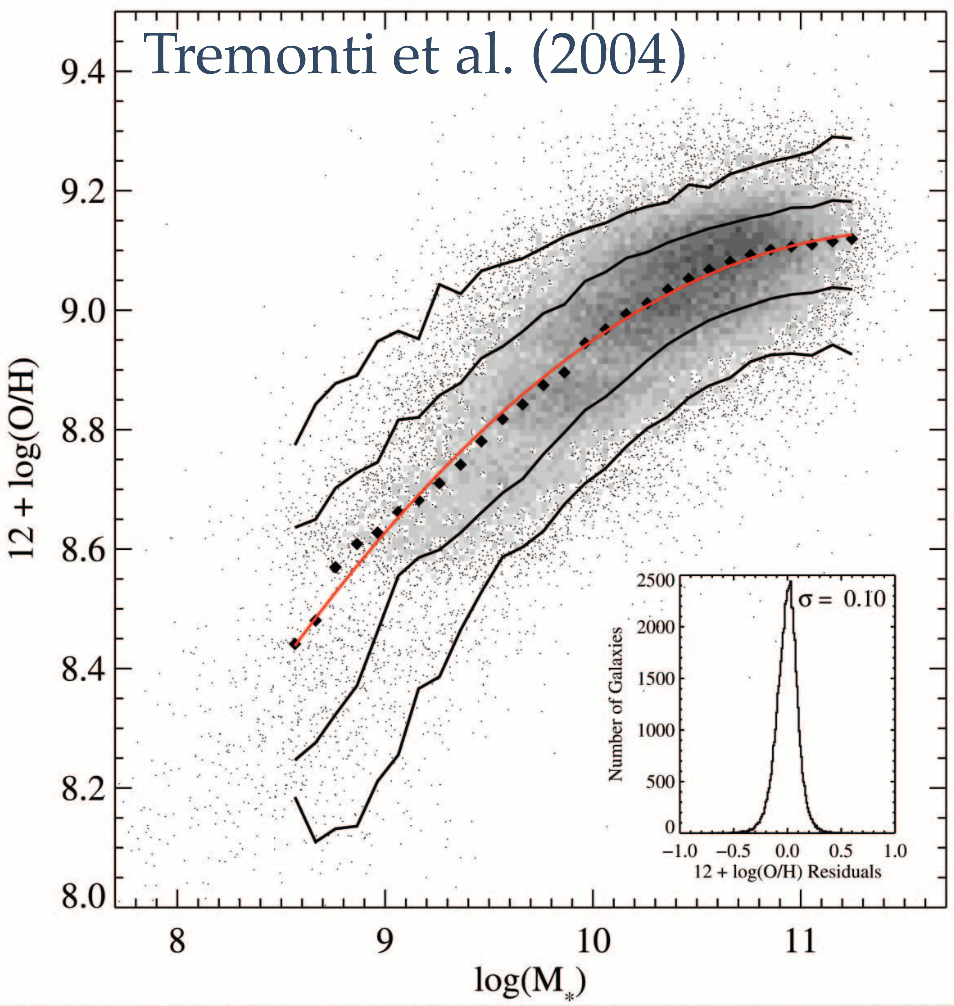
- Massive galaxies all have high Z
- Transition at between 10^{10} and $10^{10.5}$ $M_{\odot}$
- Smaller masses, very large scatter, preferred low Z: evidence for winds? or for delayed chemical evolution?
- ~mirror Z_{gas} relation

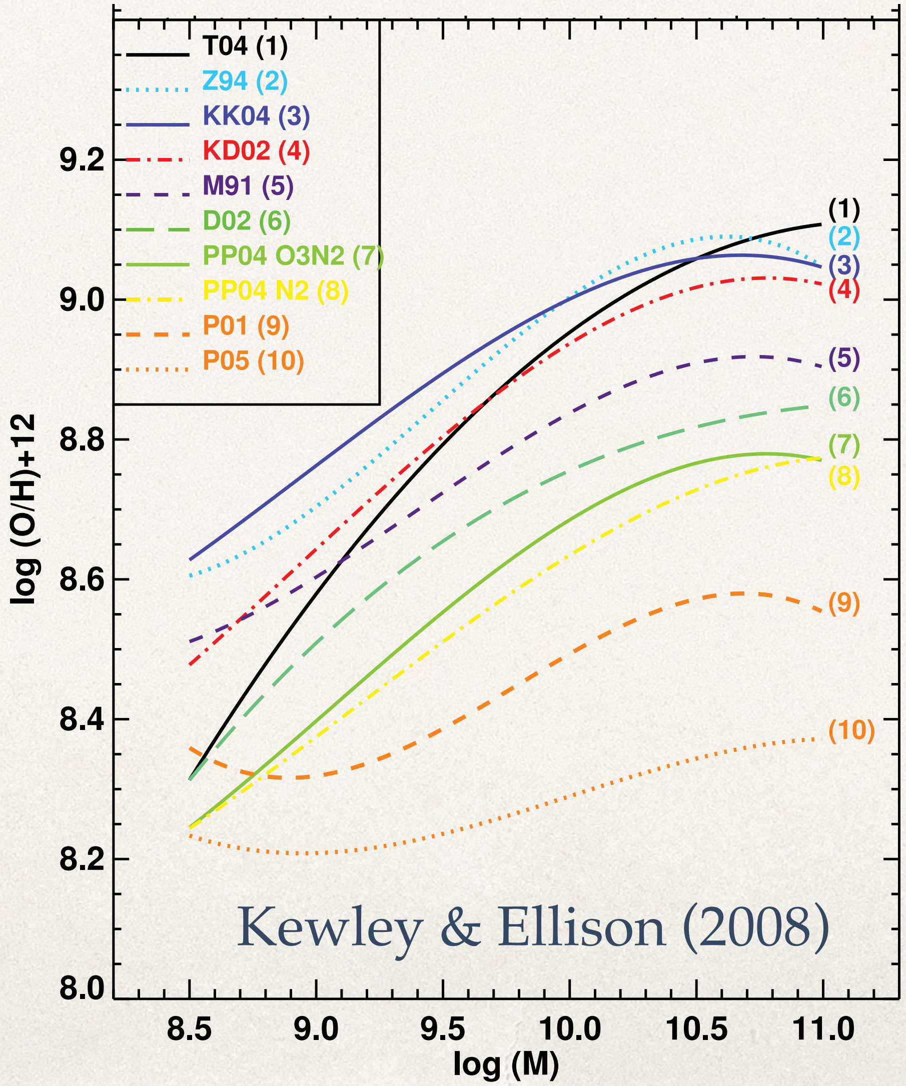
Gallazzi et al. (2005)



Stellar Mass-Metallicity (gas)

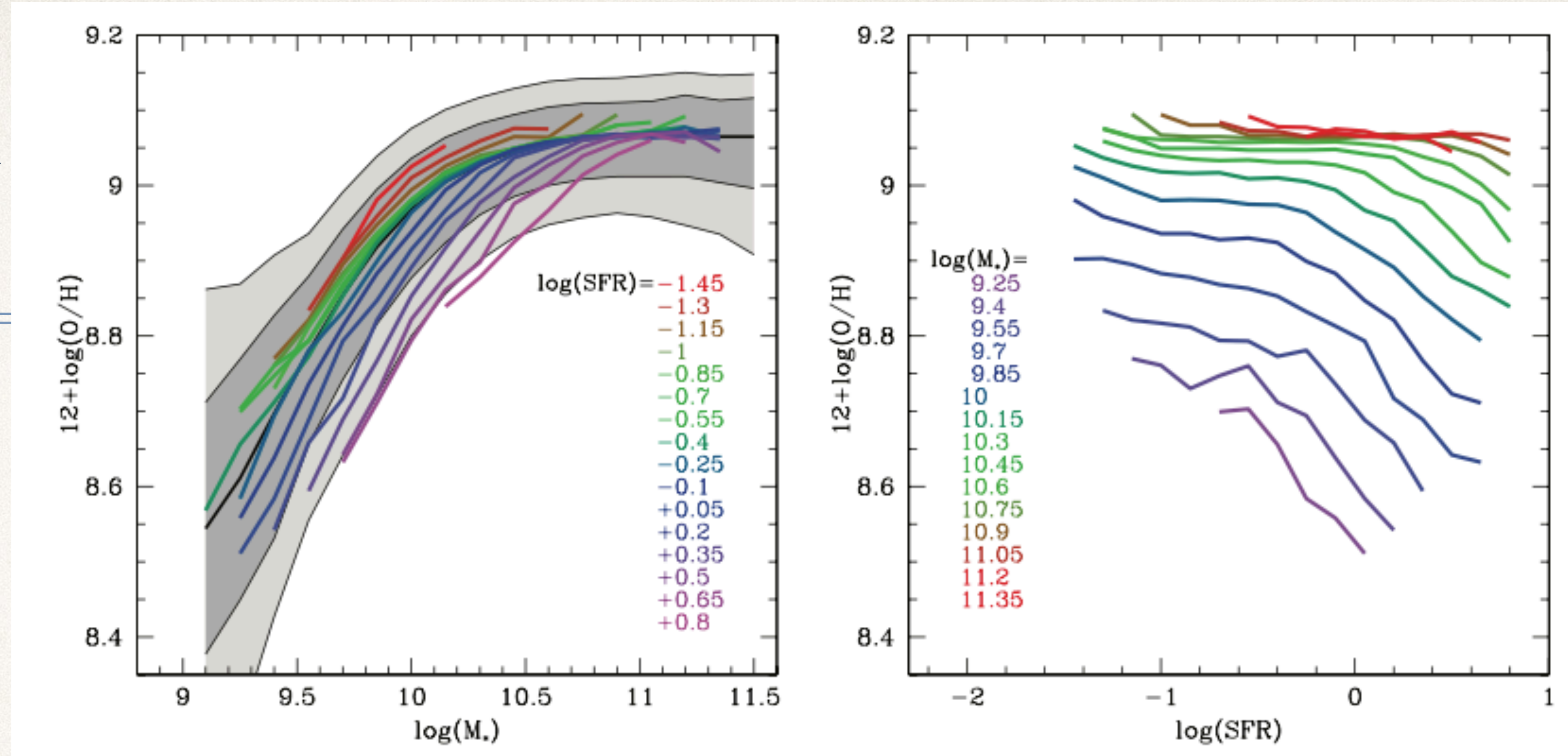
- Degree of chemodynamical evolution is relat
- More massive galaxies are more mature?
- Evidence for metal-loaded outflows?





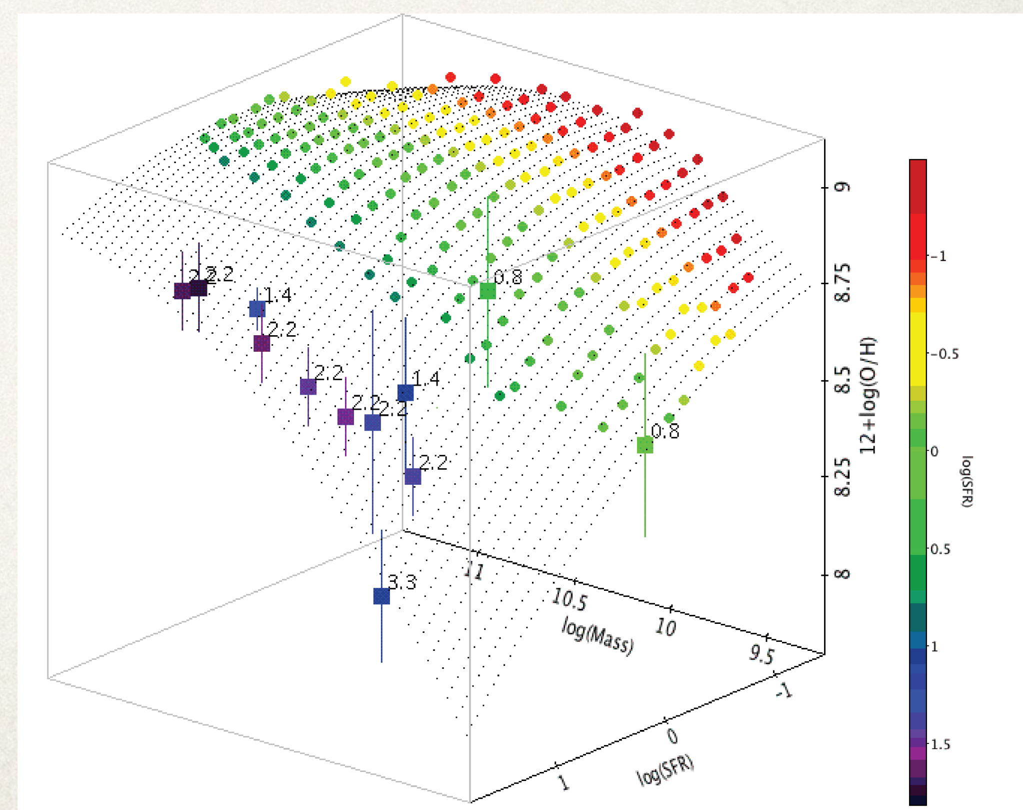
Mannucci et al. (2010)

The FMR



The fundamental metallicity relation

- A manifold in the SFR-Mass-Metallicity space
- Combines mass-Z relation with Mass-(s)SFR
- Connection via metal “dilution” and Schmidt-Kennicutt law?
- Evidence for feedback?
- Still some debate…
(e.g. Barrera-Ballesteros et al. 2017, also Sánchez et al. 2017)



Chemical evolution: some basic theoretical notions

- Definitions:

Mass in gas $M_g(t)$

Mass in stars $M_*(t)$

Mass of metals in gas $M_{m,gas}(t)$

Metallicity of the gas $Z_{gas}(t) \equiv \frac{M_{m,gas}(t)}{M_g(t)}$

Stellar yield $y \equiv \frac{M_{\text{produced metals}}}{M_{*(\text{living+remnants})}}$

Vincenzo et al. (2015)

	Stellar yields: Nomoto et al. (2013)											
Z	R	y_O	y_Z	R	y_O	y_Z	R	y_O	y_Z	R	y_O	y_Z
Z(Sun)=0.02	IMF: Salpeter (1955)			IMF: Chabrier (2003)			IMF: Kroupa et al. (1993)			IMF: Kroupa (2001)		
0.0	0.261	0.021	0.043	0.403	0.044	0.087	0.244	0.011	0.024	0.380	0.040	0.079
1.0×10^{-3}	0.293	0.018	0.026	0.450	0.038	0.055	0.291	0.009	0.014	0.424	0.034	0.050
5.0×10^{-3}	0.300	0.016	0.025	0.459	0.034	0.052	0.300	0.008	0.013	0.433	0.030	0.047
1.0×10^{-2}	0.302	0.015	0.024	0.463	0.032	0.051	0.303	0.008	0.013	0.436	0.029	0.046
2.0×10^{-2}	0.305	0.014	0.023	0.466	0.030	0.049	0.307	0.007	0.012	0.439	0.027	0.044
5.0×10^{-2}	0.304	0.017	0.023	0.466	0.036	0.049	0.307	0.009	0.012	0.439	0.032	0.044

Chemical evolution: some basic theoretical notions

- Just math:

$$\frac{\mathrm{d}Z_{\mathrm{gas}}}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}\,\frac{M_{m,gas}(t)}{M_g(t)} =$$

$$= \frac{1}{M_g(t)}\,\frac{dM_{m,gas}(t)}{dt} - \frac{M_{m,gas}(t)}{M_g^2(t)}\,\frac{dM_g(t)}{dt} =$$

$$= \frac{1}{M_g(t)}\left(\frac{dM_{m,gas}(t)}{dt} - Z_{gas}(t)\frac{dM_g(t)}{dt}\right)$$

Chemical evolution: some basic theoretical notions

- ***Instantaneous recycling approximation (IRA)***: metals are produced by stellar evolution and incorporated in the ISM instantaneously

$$\frac{dM_{m,gas}}{dt} = y\frac{dM_*}{dt} - Z_{gas}(t)\frac{dM_*}{dt} = \frac{dM_*}{dt}\left(y - Z_{gas}(t)\right)$$

Chemical evolution: some basic theoretical notions

- ***The closed-box hypothesis***: no gas is allowed to enter or escape the system
- From mass conservation: $$\frac{dM_*}{dt} = -\frac{dM_{gas}}{dt}$$
- $$\frac{dZ_{gas}}{dt} = \frac{1}{M_g(t)}\left(\frac{dM_{m,gas}(t)}{dt} - Z_{gas}(t)\frac{dM_g(t)}{dt}\right)$$
  $$\frac{dM_{m,gas}}{dt} = \frac{dM_*}{dt}(y - Z_{gas}(t))$$ IRA
  $$\frac{dM_*}{dt} = -\frac{dM_{gas}}{dt}$$ closed box

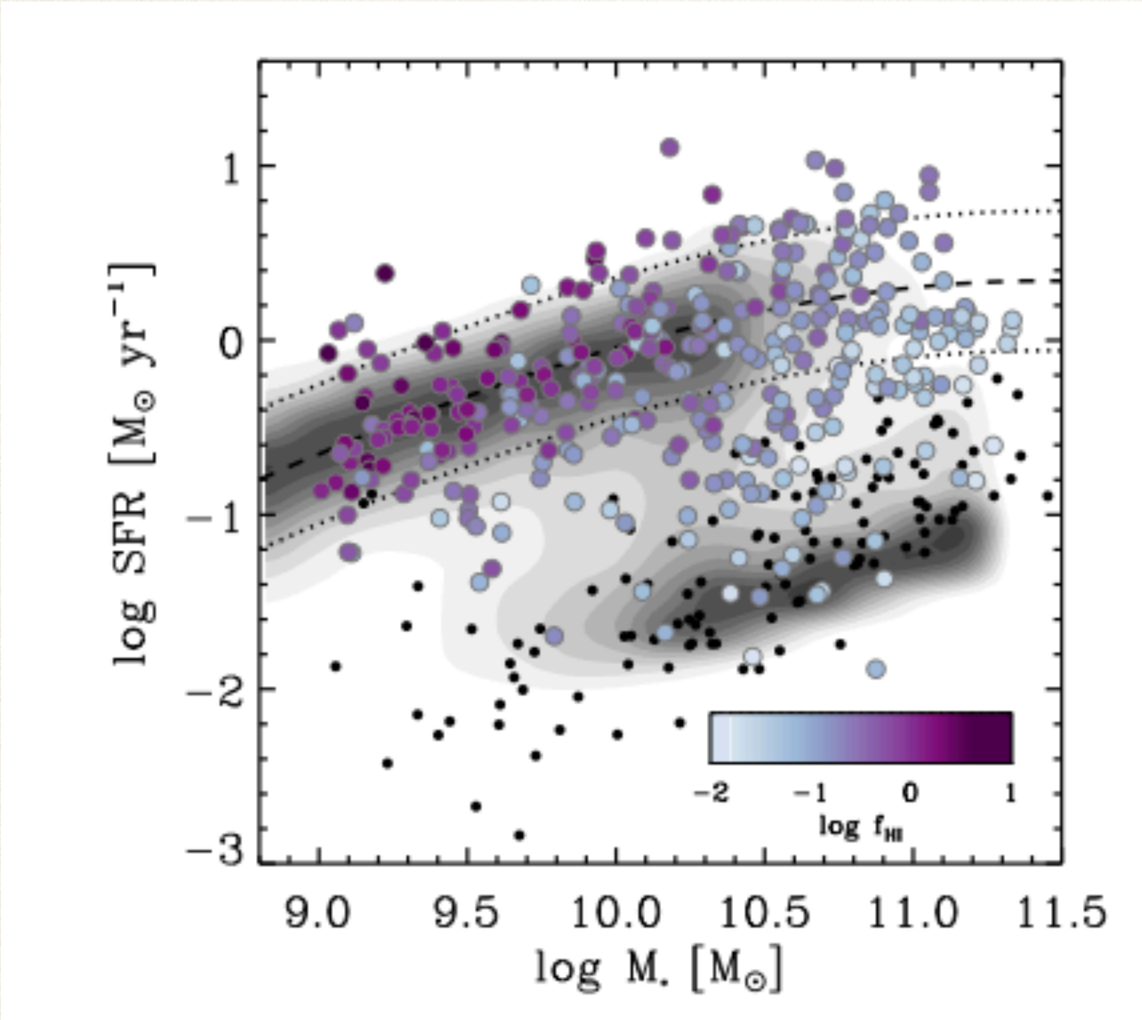
$$\frac{dZ_{gas}}{dt} = \frac{-y}{M_g(t)}\frac{dM_g(t)}{dt} = -y\frac{d\ ln(M_g(t))}{dt}$$

Chemical evolution: evolution of Z_{gas} in the closed-box

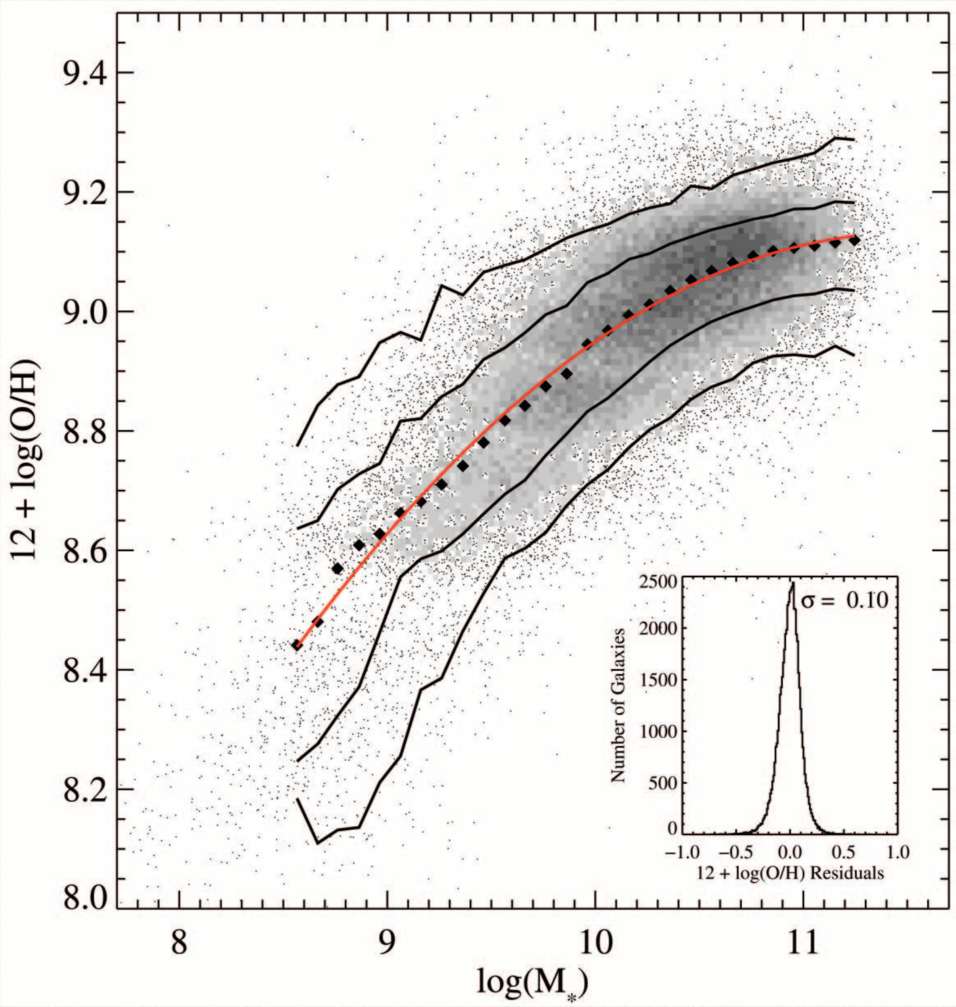
- integrating the last equation $$\frac{dZ_{gas}}{dt} = -y \frac{d \ ln(M_g(t))}{dt}$$

  we obtain: $$Z_{gas}(t) = Z_{gas}(t_0) - y \, ln\left(\frac{M_g(t)}{M_{g,0}}\right)$$

- As time goes by and gas is consumed, Z_{gas} diverges logarithmically
- As $M_{g,0}$ is the total (baryonic) mass of this idealised galaxy, the equation predicts a dependence of Z_{gas} on the gas fraction



Saintonge et al. (2017)



Tremonti et al. (2004)

- Incomplete chemical evolution: higher gas fraction implies lower metallicity
- Qualitative explanation — quantitatively???
- Are metal-loaded outflows needed??

Stellar metallicities in the closed-box model

- Cumulative metallicity distribution of stellar mass:

$$M_*(Z<Z(t)) = M_g(t) - M_{g,0} = M_{g,0}\left(1 - e^{-\frac{Z(t)-Z(t_0)}{y}}\right)$$

- By differentiating wrt to Z one obtains the differential distribution:

$$\frac{dM_*}{dZ}(Z) \propto e^{-\frac{Z-Z(t_0)}{y}}$$

- This can be used to derive the mass-weighted stellar metallicity:

$$<Z> = \frac{\int_{Z(t_0)}^{Z(t)} dZ\, Z e^{-\frac{Z-Z(t_0)}{y}}}{\int_{Z(t_0)}^{Z(t)} dZ\, e^{-\frac{Z-Z(t_0)}{y}}}$$

Stellar metallicities in the closed-box model

- With the change of variable $x=Z/y$:

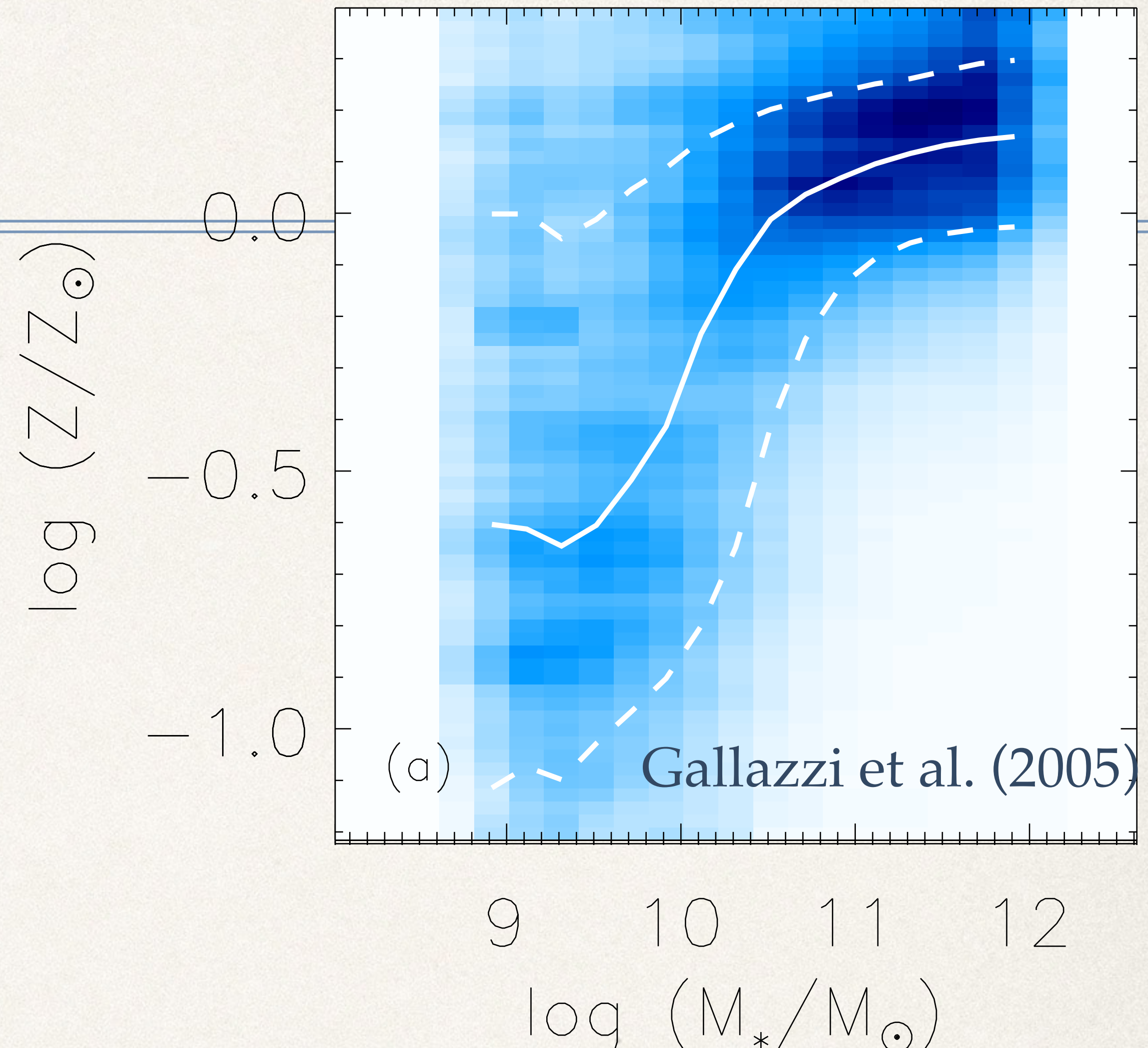
$$<Z>=\frac{y^2 e^{\frac{Z(t_0)}{y}} \int_{Z(t_0)/y}^{Z(t)/y} dx\, x\, e^{-x}}{y e^{\frac{Z(t_0)}{y}} \int_{Z(t_0)/y}^{Z(t)/y} dx\, e^{-x}} = y \frac{\int_{Z(t_0)/y}^{Z(t)/y} dx\, x\, e^{-x}}{\int_{Z(t_0)/y}^{Z(t)/y} dx\, e^{-x}}$$

- In the limit of $Z(t_0) \ll y$ and with t such that $M_g(t) \ll M_g(0)$, the integration limits can be replaced with $[0,\infty)$ and

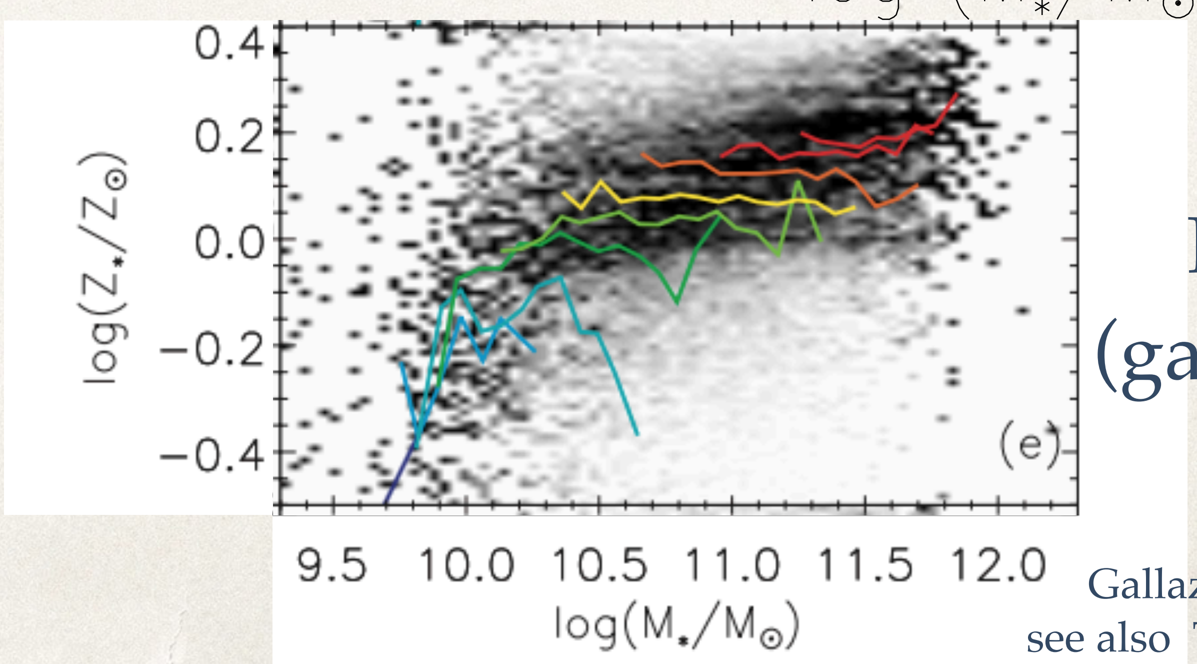
  $$<Z^*>=y$$

- In a closed-box starting from ~0 metallicity the average stellar metallicity approaches the yield as long as the gas is consumed

How to interpret the Z*-M* relation?



- Galaxies less massive than $10^{10.5}$ are definitely below the yield:
  - far from gas consumption? Certainly not all of them
  - Metals lost due to outflows?
  - Metallicity diluted by inflows?



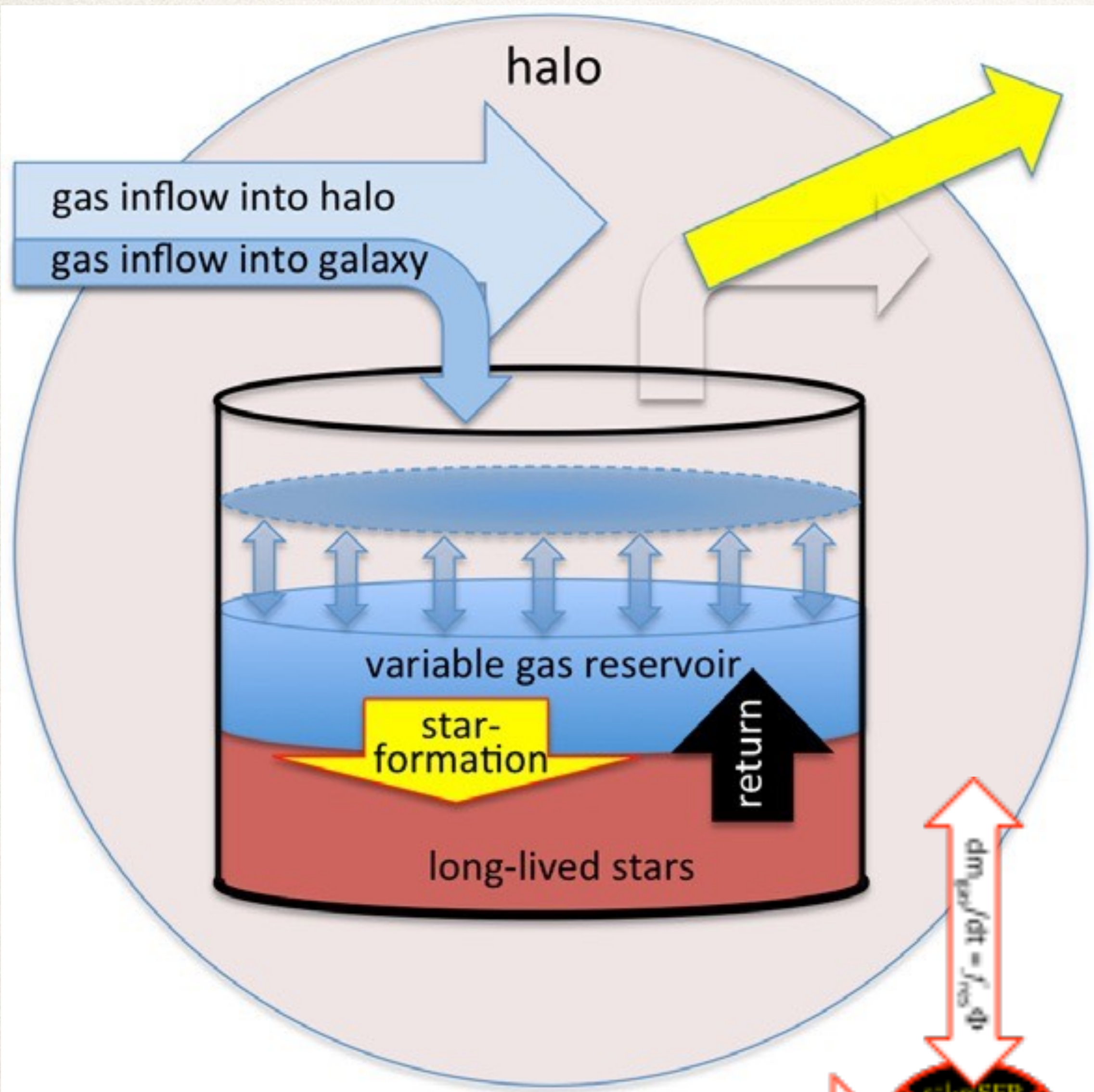
ETGs (gas poor!)

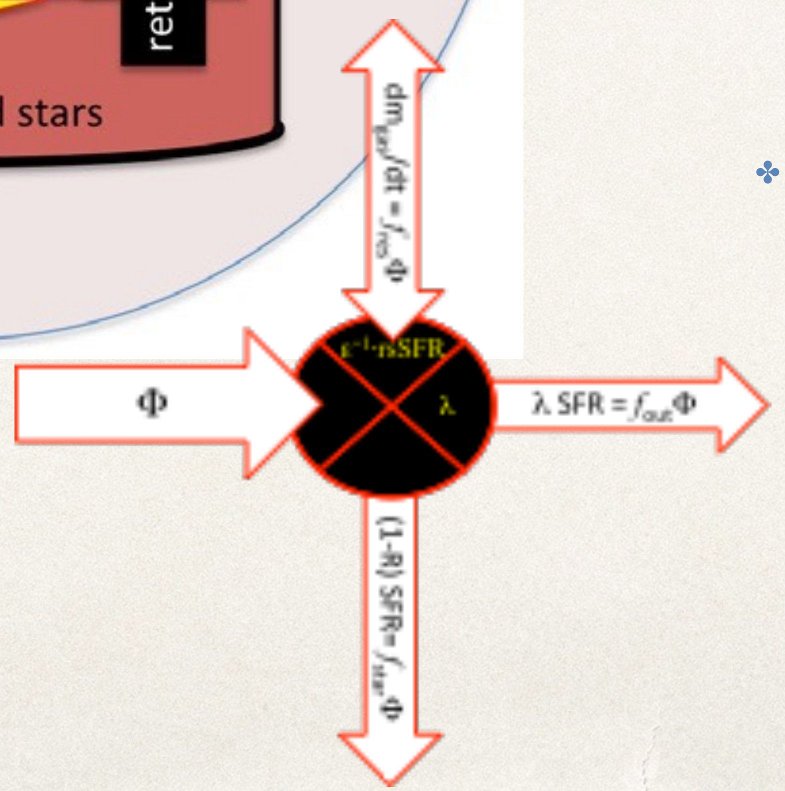
Gallazzi et al. (2006), see also Trager et al. (2000)

Departures from closed-box: what do we learn from them?

- Delayed chemical enrichment
- Inflows: galaxies do not originate from a monolithic collapse
- Outflows (—> feedback): (metal enriched) gas is expelled from galaxies due to
    - winds powered by Supernovae and in general by the radiation of the most luminous stars
    - Active Galactic Nuclei

A simple picture





Lilly et al. (2013)

- Explains/recovers
  - relations between halo mass and stellar mass
  - mass-SFR-Z relations
  - redshift evolution of these relations
- Ingredients
  - efficiency of conversion of gas in the reservoir into stars lambda
  - mass loading factor: fraction of gas reservoir ejected in/outside the halo

Spatially resolved relations:

are global relations set by the local physics (alone)?

M*-SFR

Integrated

Spatially resolved

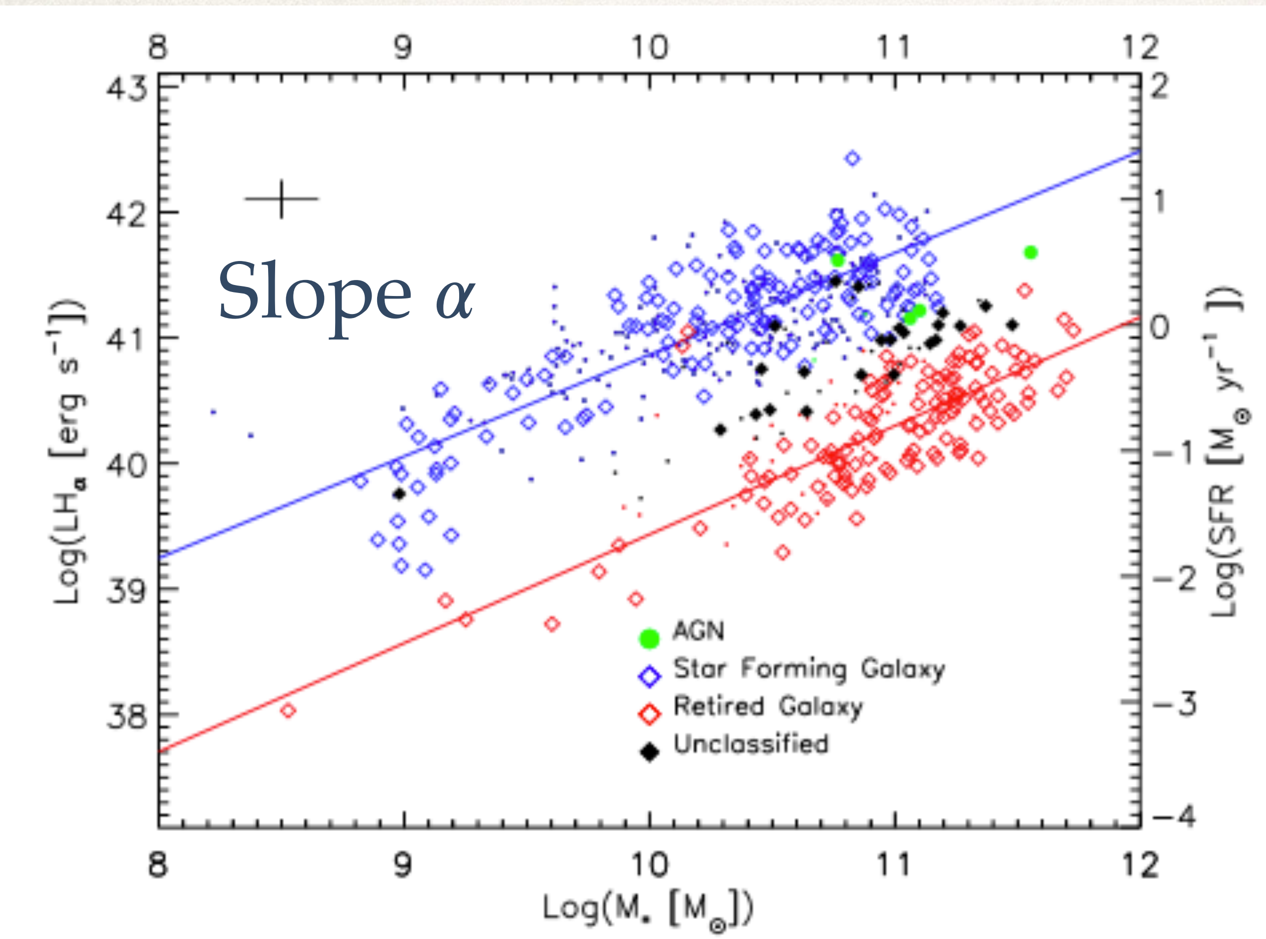


Figure 1. Integrated M_* vs. SFR relation for the CALIFA sample. Green symbols represent galaxies that lie above the Kewley limit (KL) and whose Hα equivalent widths (EWs) are >6 Å, i.e., are galaxies whose ionization emission is dominated by the AGN activity. Blue symbols represent galaxies below the KL and with EW(Hα) > 6 Å, and that have inclinations < 60°, i.e., that lie in the star formation main sequence (SFMS). Red symbols represent galaxies with EW(Hα) < 3 Å, i.e., that lie in a retired galaxies sequence (RGS).

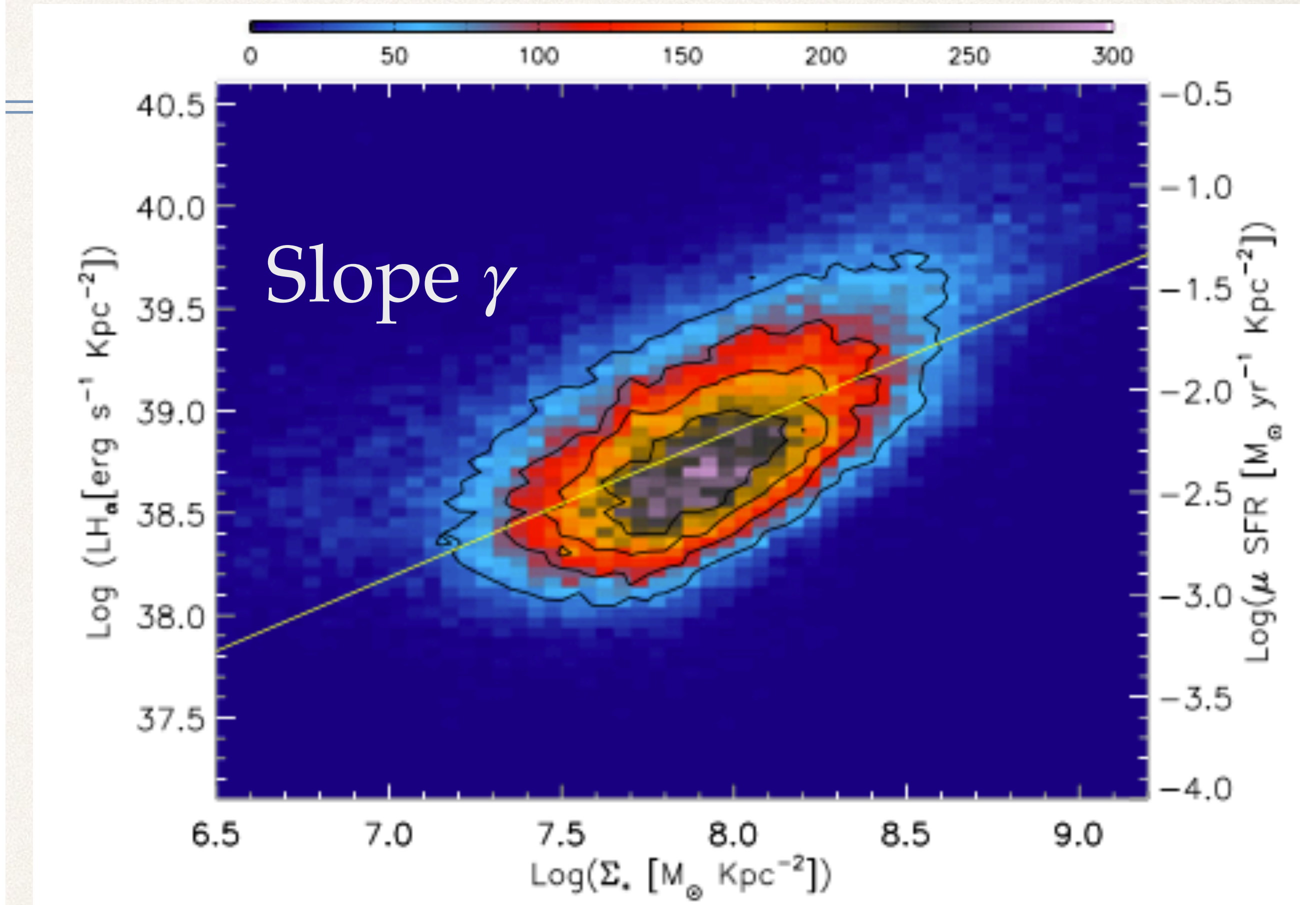
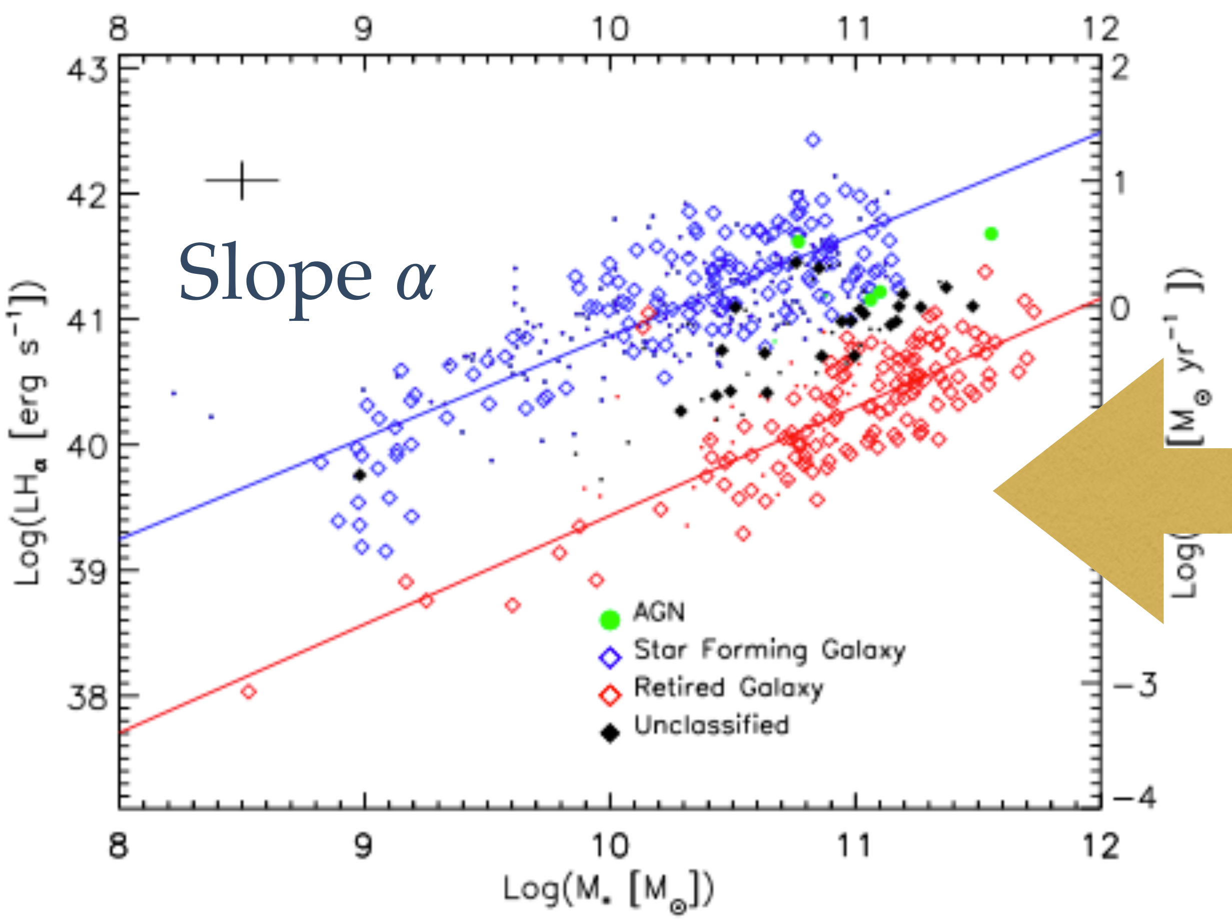


Figure 2. Spatially resolved SFMS relation for the CALIFA sample that holds for scales in the range of 0.5–1.5 kpc. Colors in the plot represent the amount of data points presented in this study. The outermost contour holds within itself 80% of the total data presented in the plot. Further contours hold 60%, 40%, and 20% of the total amount of data in the plot. Yellow line represents the linear fitting to the spatially resolved SFMS relation using the 80% of the data (see Table 1 for further details of the linear fitting).

Cano-Díaz et al. (2016)

M*-SFR

Integrated



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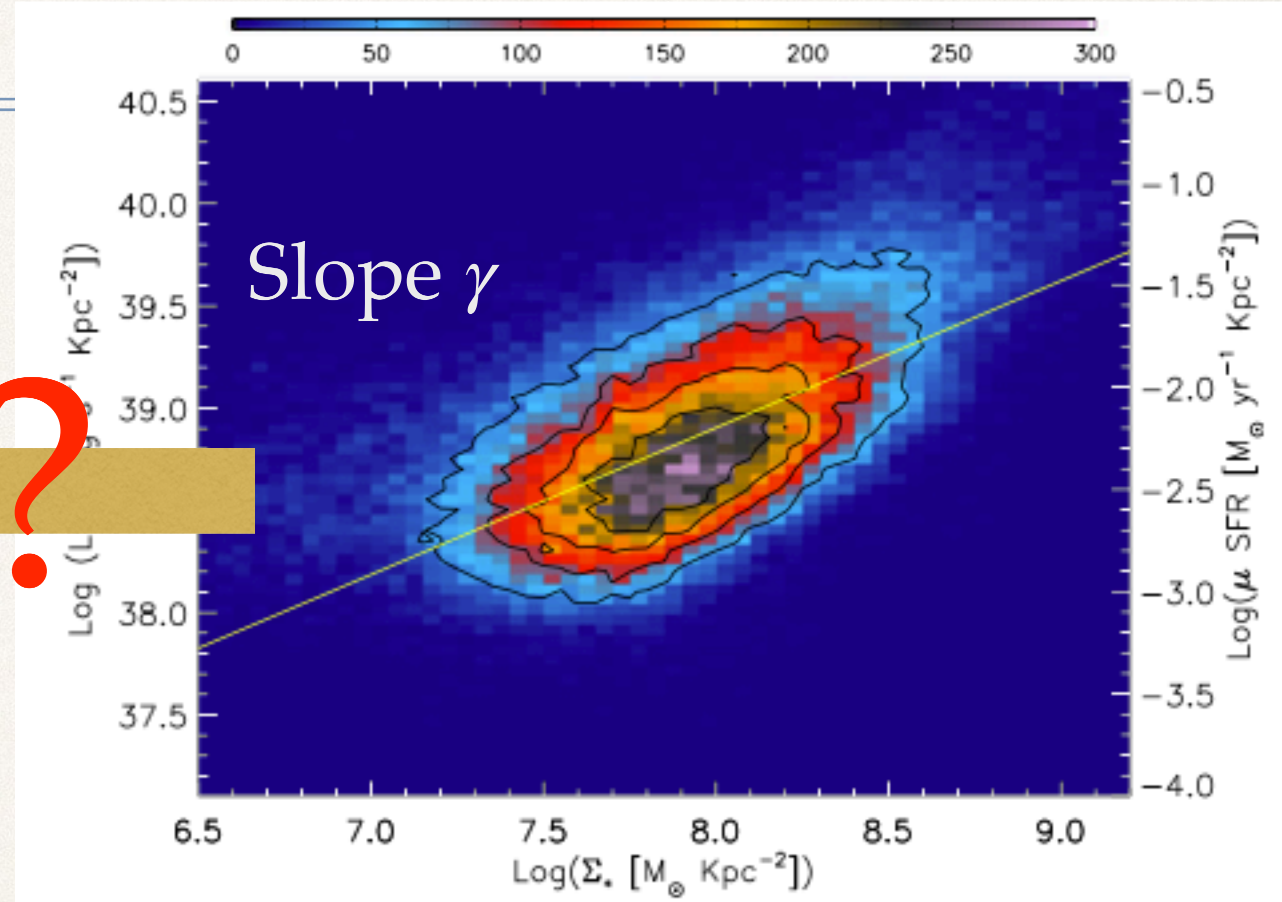
Spatially resolved



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$M_* \propto \Sigma_h R_h^2$

$\Sigma_h \propto M_*^\beta,\ \beta \sim 0.5 \implies$

$\mu_{SFR} \propto \Sigma_*^\gamma,\ \gamma \sim 0.7$

$$\psi \propto \mu_{SFR} R^2 \propto \mu_{SFR}\frac{M_*}{\Sigma_*} \propto \Sigma_*^{\gamma-1} M_* \propto M_*^{\beta(\gamma-1)+1}$$

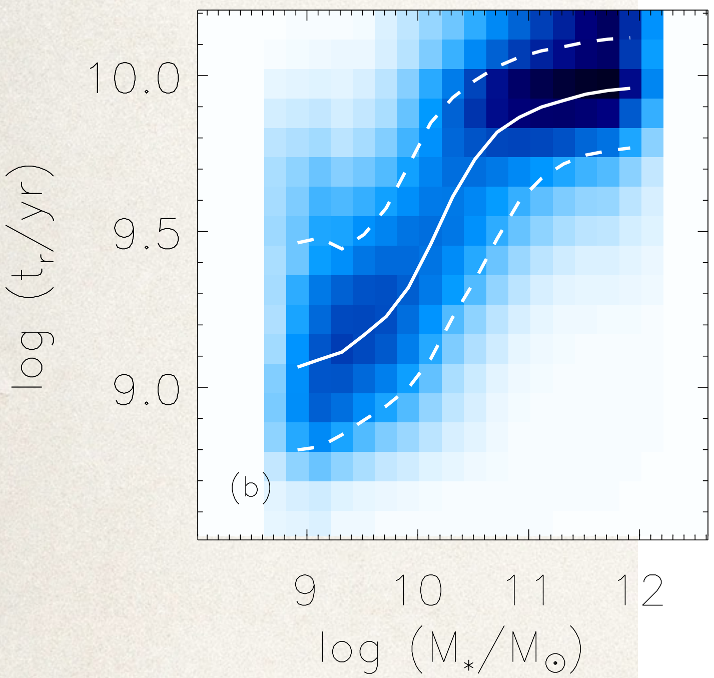
$$\beta(\gamma-1)+1 \sim 0.5(0.7-1)+1 = 0.85$$

$\Rightarrow \psi \propto M_*^\alpha, \alpha \sim 0.85\text{–}1$

Cano-Díaz et al. (2016)

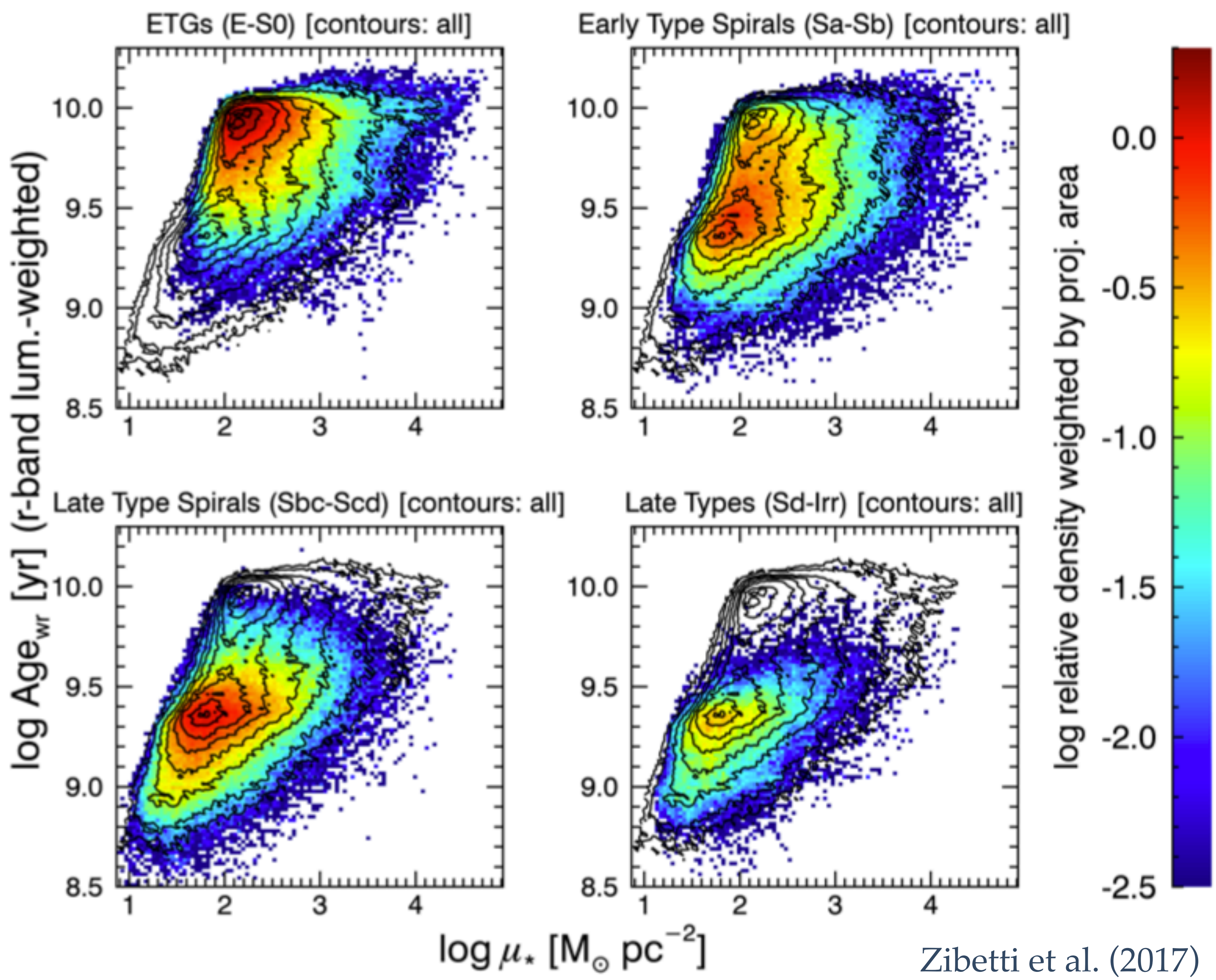
M*-age

Integrated



Gallazzi et al. (2005)

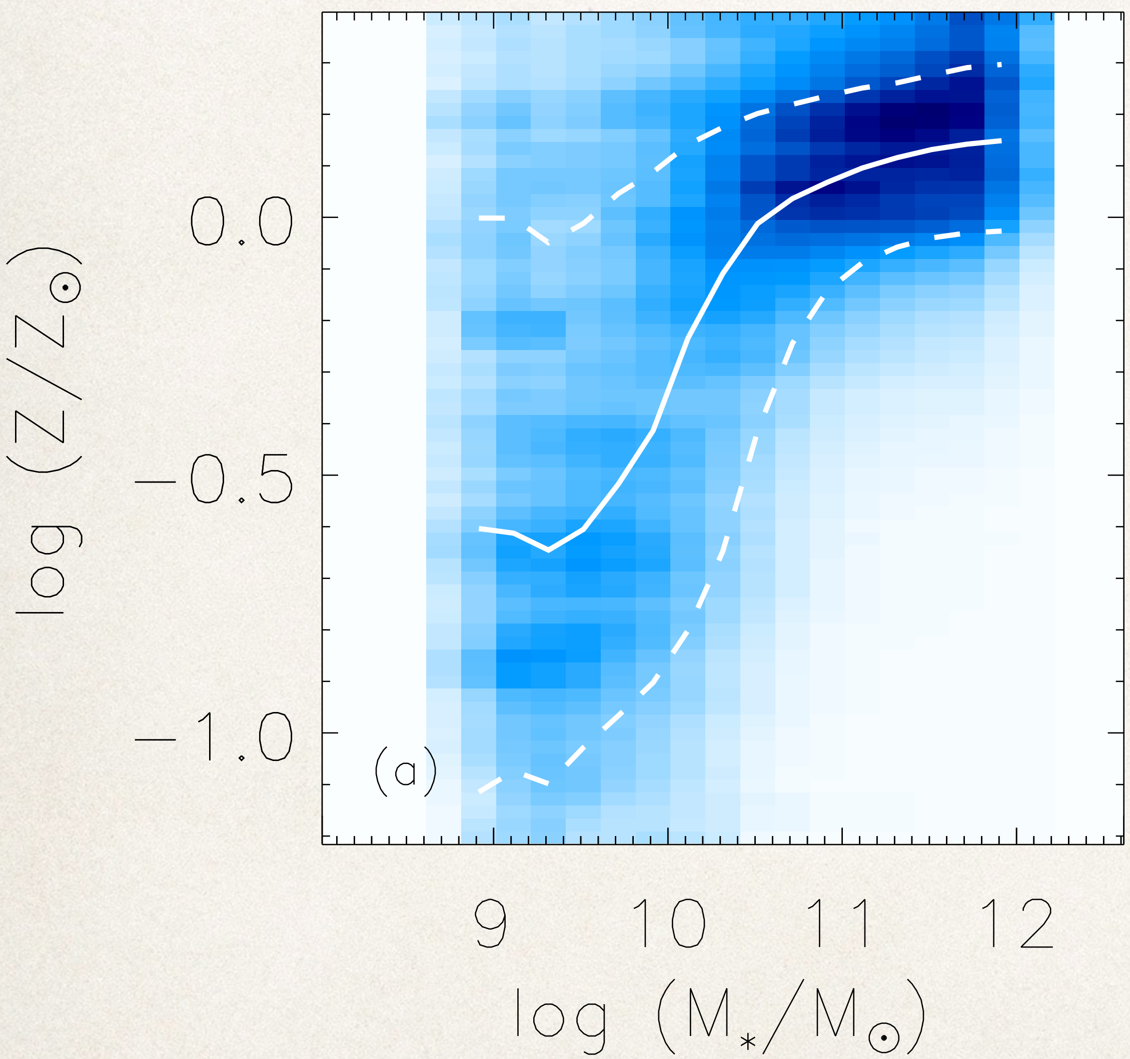
Spatially resolved



Zibetti et al. (2017)

M*-Z*

Integrated



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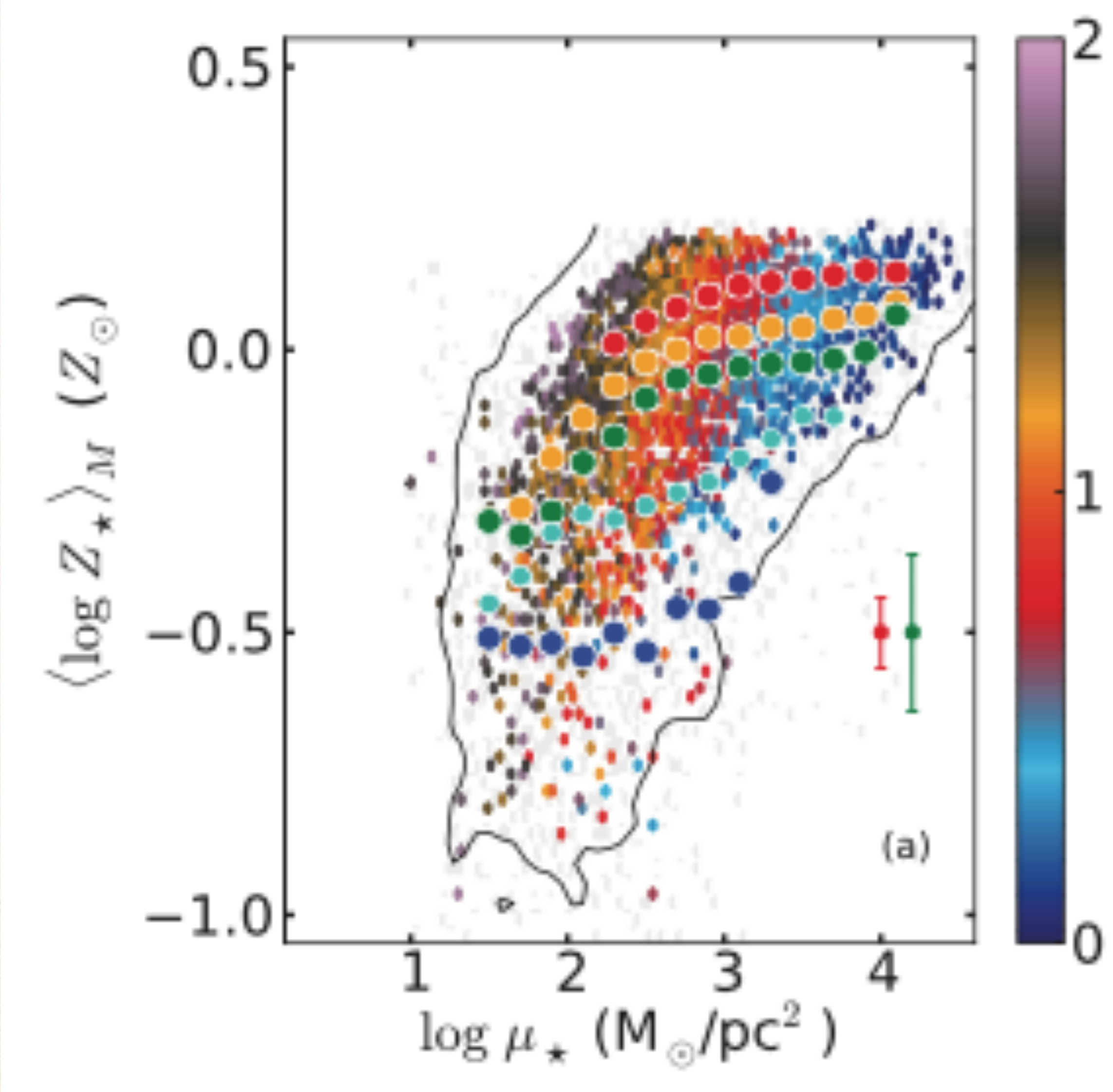
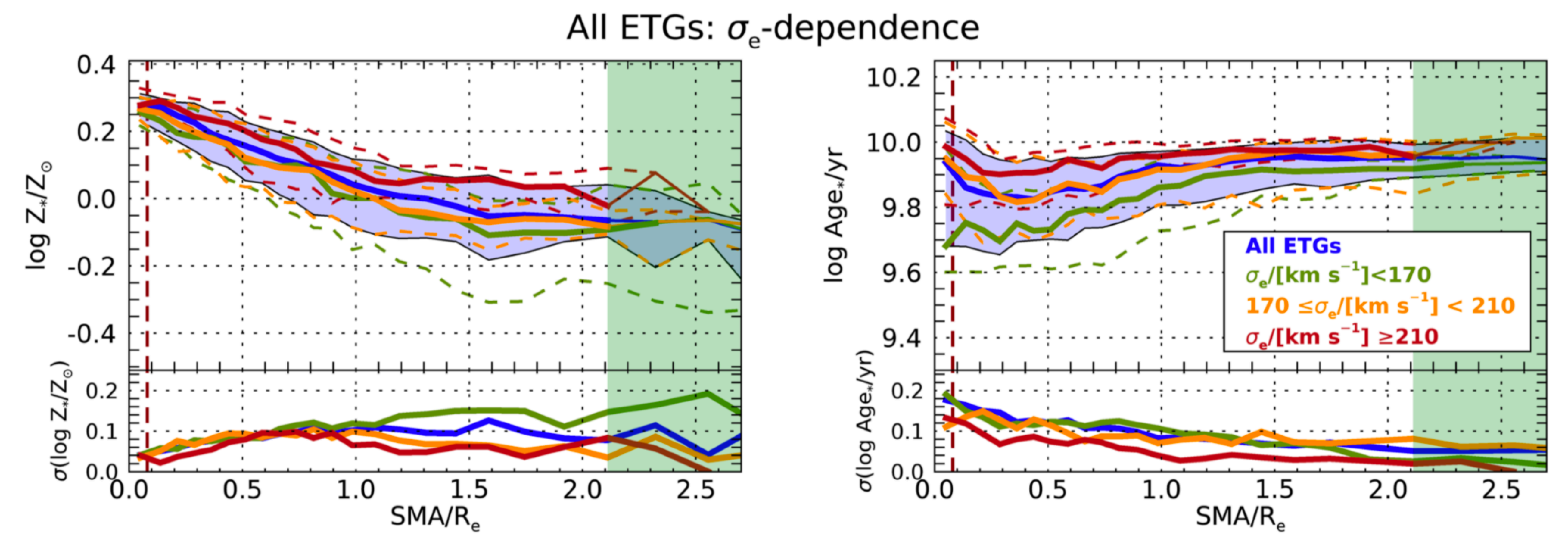


Gonzalez Delgado et al. (2014)

Stellar populations in ETGs

~1 kpc spatially resolved regions
from CALIFA



Zibetti et al. (2019)

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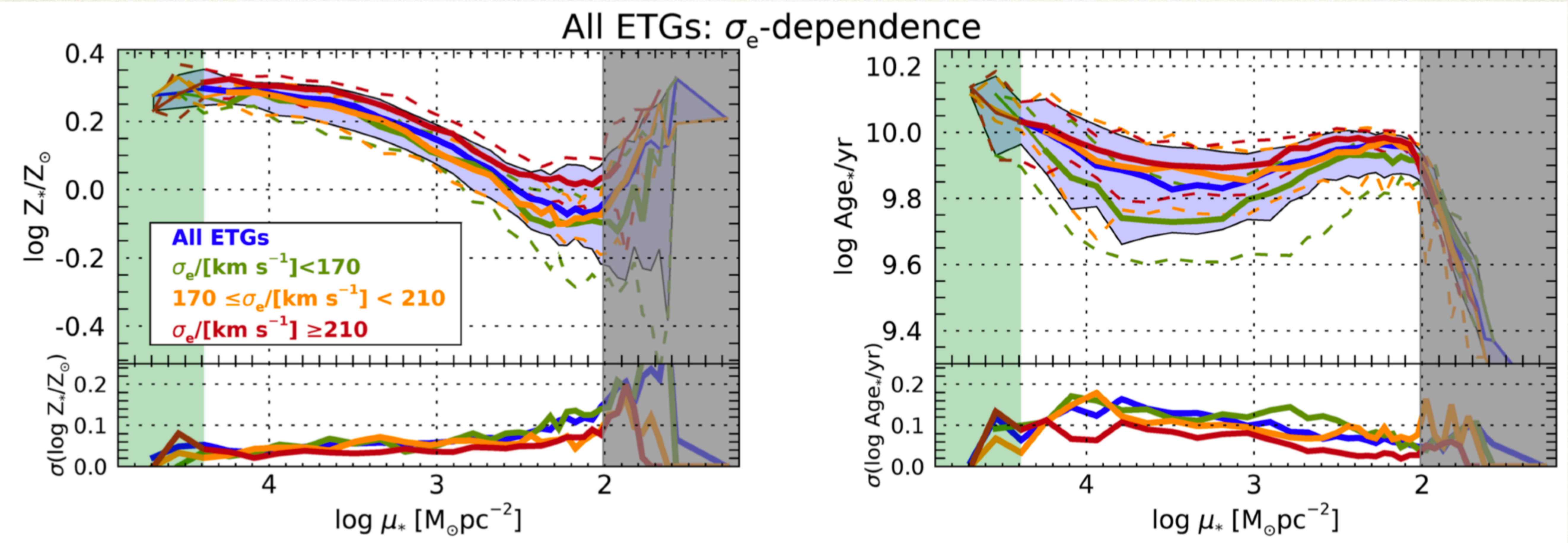

Zibetti et al. (2019)

Spatially resolved relations: are global relations set by the local physics (alone)?

- No simple answer: local and global cannot be disentangled
- Also, galaxies are not static nor stationary systems: what does a current local property tell us about the past and the evolutionary history?
- So, what and how do we learn them?
  - play with models, introduce physical prescriptions which depend on local and global properties to different degrees
  - challenge models with more and more detailed observations