The Chemical Evolution of Star-Forming Galaxies

Gas, Dust and Star-Formation
Chania, Crete, Greece
May 25, 2015

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Harvard-Smithsonian Center for Astrophysics

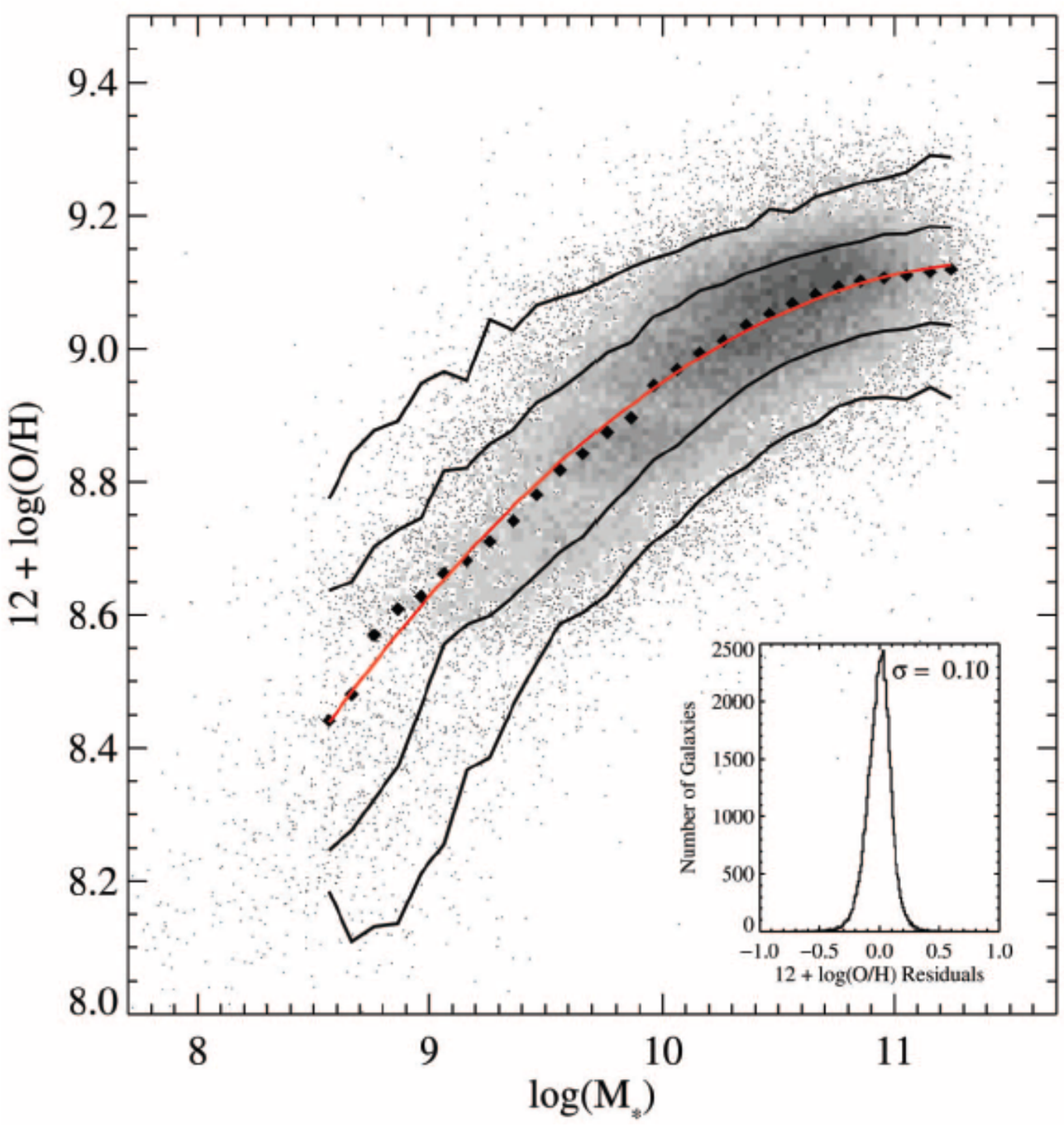
Metallicity, Star-Formation and Gas Flows

Gas-Phase Oxygen Abundance

$Z = 12 + \log(O/H)$

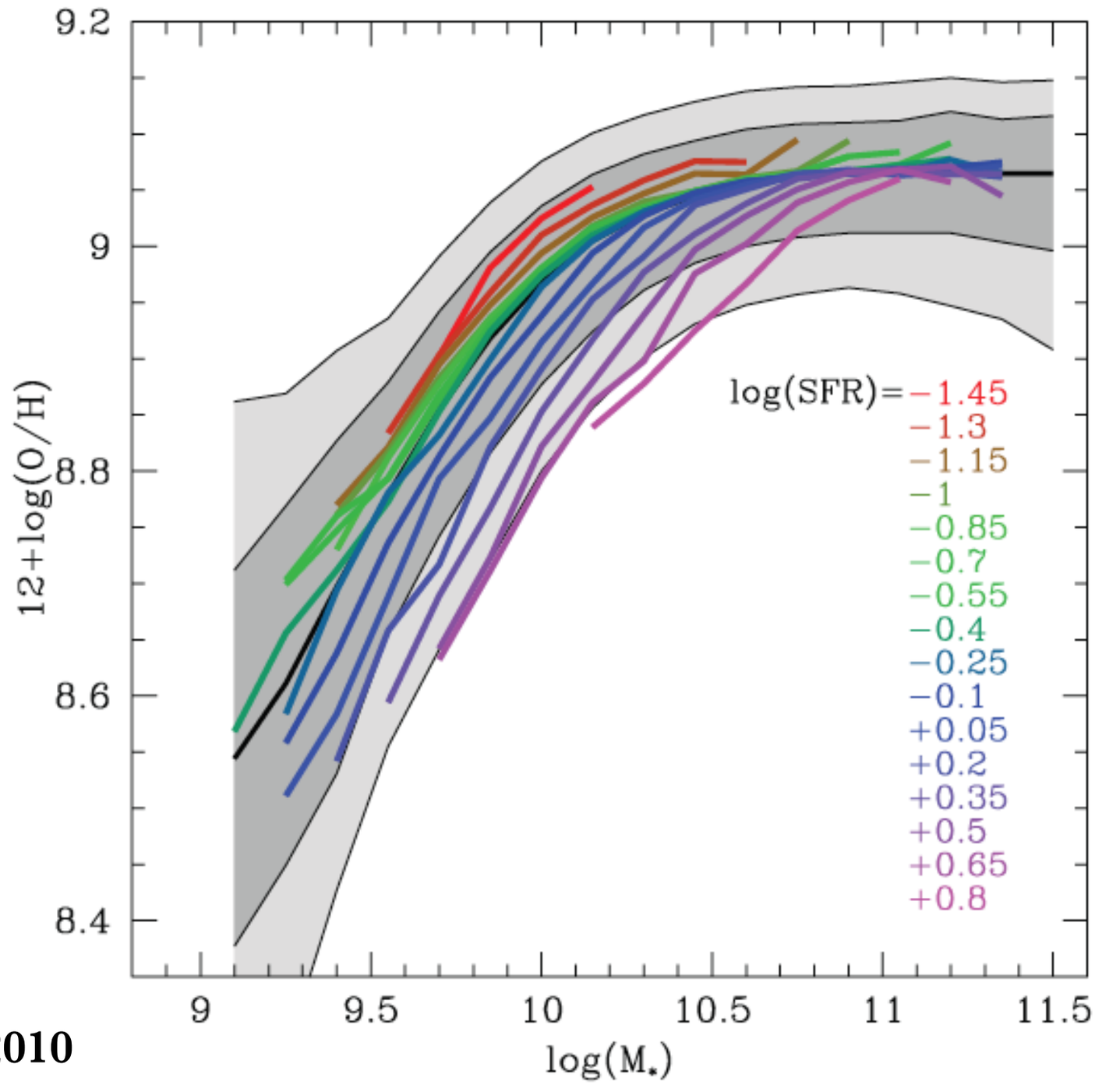
	Star-Formation	Inflows	Outflows
ΔZ	↑	↓	?

The Mass-Metallicity Relation



TREMONTI+, 2004

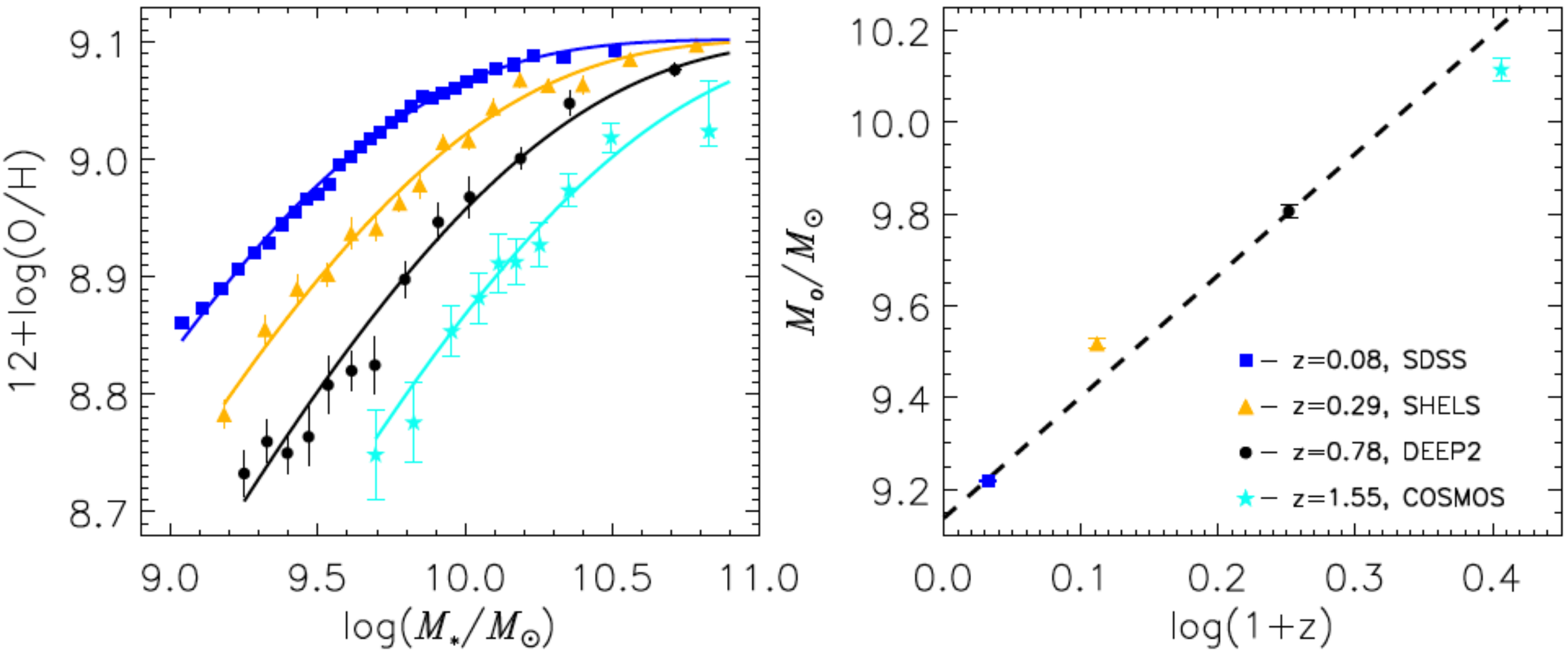
The Stellar Mass, Metallicity and SFR Relation



MANNUCCI+, 2010

Evolution of the Mass-Metallicity Relation

$$12 + \log(O/H) = Z_o + \log\left[1 - \exp\left(-\left[\frac{M_*}{M_o}\right]^{\gamma}\right)\right]$$



ZAHID+, 2014B

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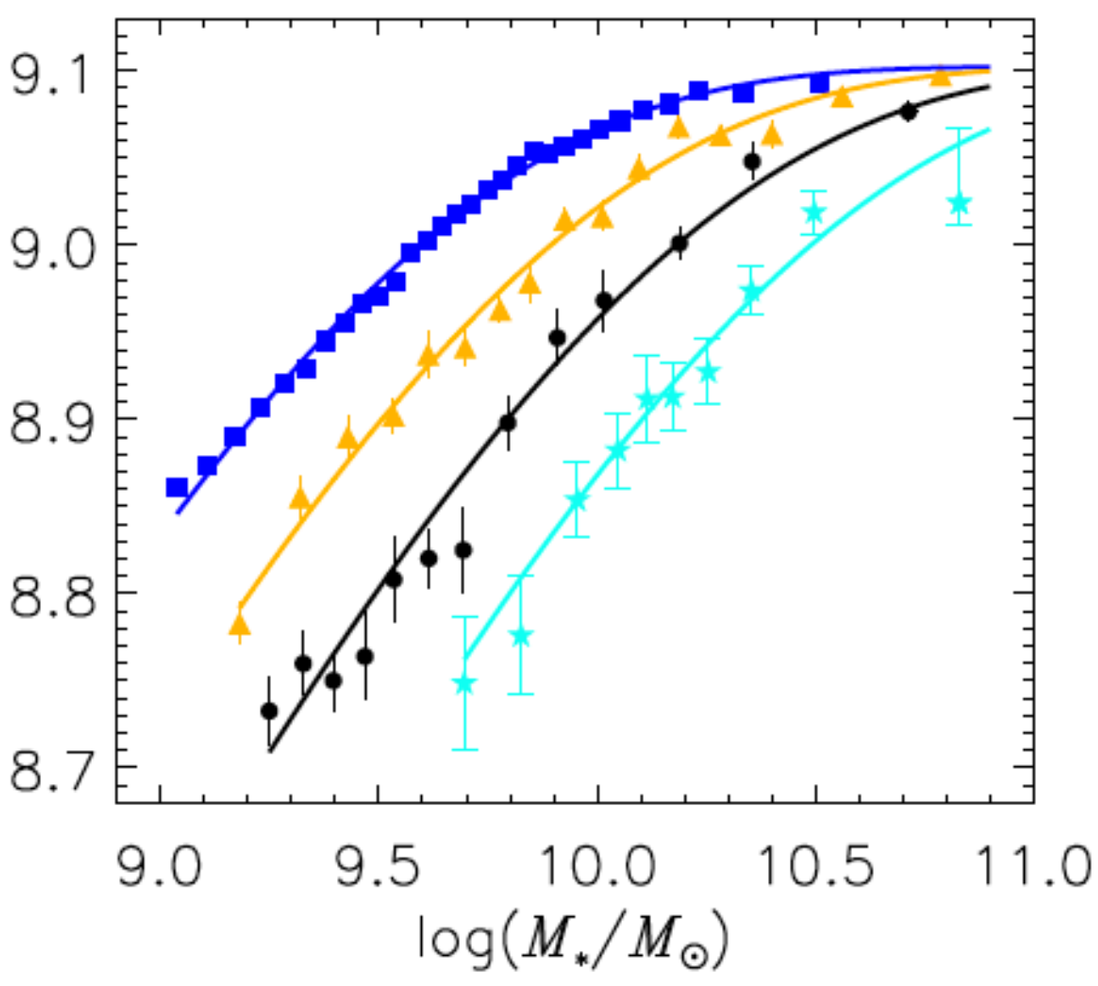

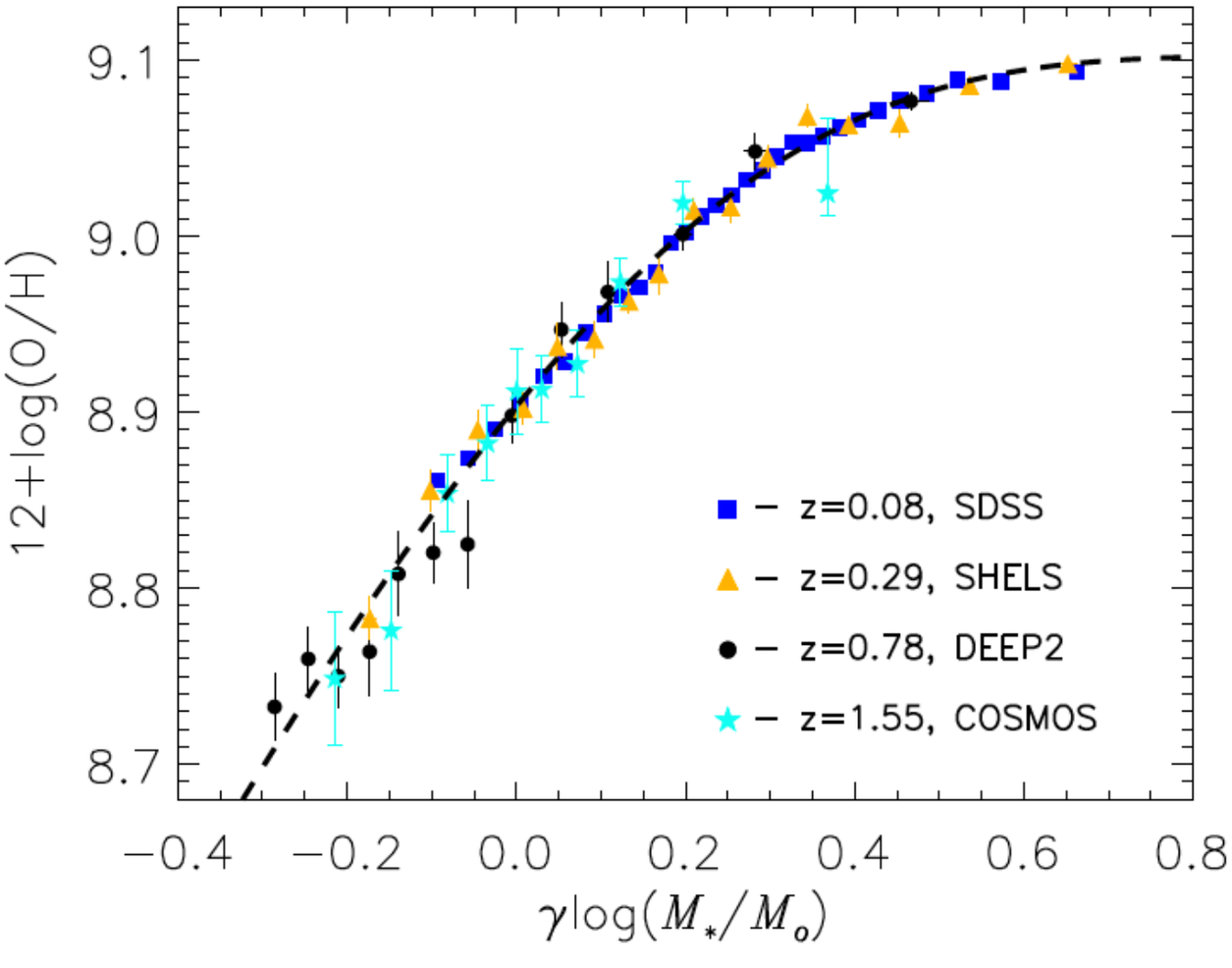

ZAHID+, 2014B

The Key Question:
What do the parameters mean physically?

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$$\gamma = 0.513 \pm 0.009$$

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$$Z_o = 9.102 \pm 0.002$$

$$\gamma = 0.513 \pm 0.009$$

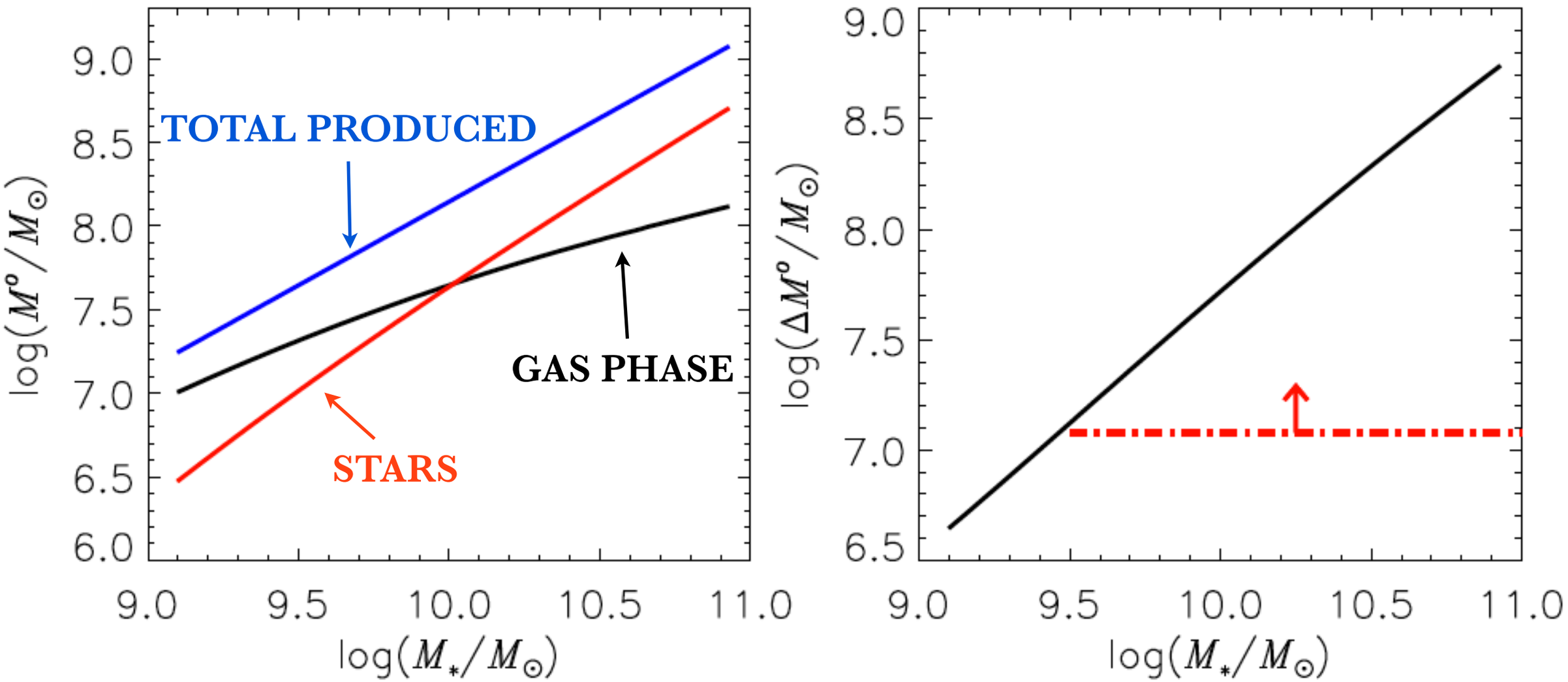
$$\log(M_o/M_\odot) = (9.138 \pm 0.003) + (2.64 \pm 0.05)\log(1+z)$$

Analytical Model of Galactic Chemical Evolution

$$\frac{dZ}{dM_*} = \frac{d}{dM_*}\left(\frac{M_z}{M_g}\right) = \frac{1}{M_g}\left(\frac{dM_z}{dM_*} - Z\frac{dM_g}{dM_*}\right)$$

The Impact of Outflows

$$\Delta M^o = M_T^o - M_g^o - M_*^o$$



$$\Delta M^o \propto M_*$$

ZAHID+, 2012B

Analytical Model of Galactic Chemical Evolution

$$\frac{dZ}{dM_*} = \frac{d}{dM_*}\left(\frac{M_z}{M_g}\right) = \frac{1}{M_g}\left(\frac{dM_z}{dM_*} - Z\frac{dM_g}{dM_*}\right)$$

ASSUME:

1) $M_g = GM_*^g$
2) $M_{z,out} \propto M_*$
3) $\mathrm{Star-formation\ fueled\ by\ inflow}$

Analytical Model of Galactic Chemical Evolution

SOLUTION TO ANALYTICAL MODEL:

$$12 + \log(O/H) = \log\left(\frac{Y_N}{1-R}\right) + \log\left[1 - \exp\left(-\frac{M_*}{M_g}\right)\right]$$

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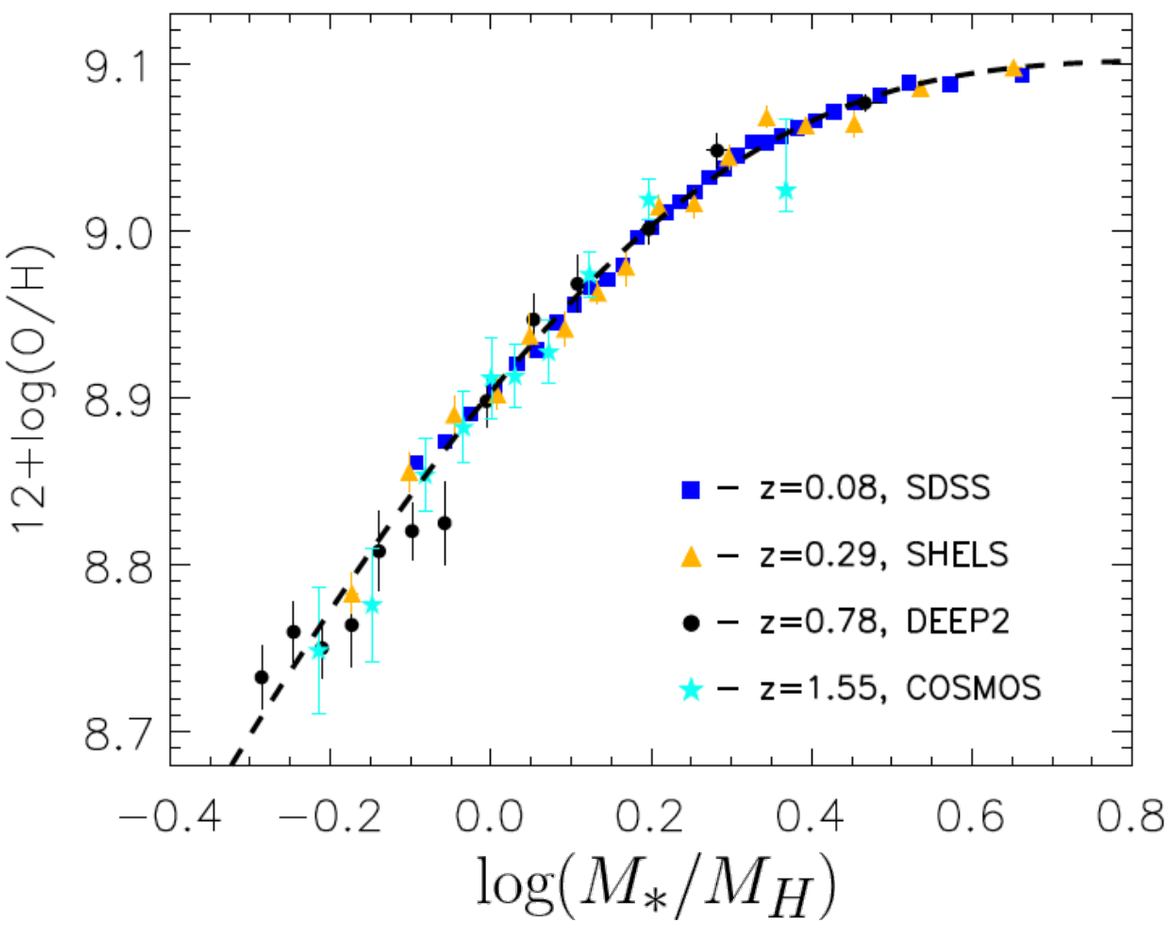
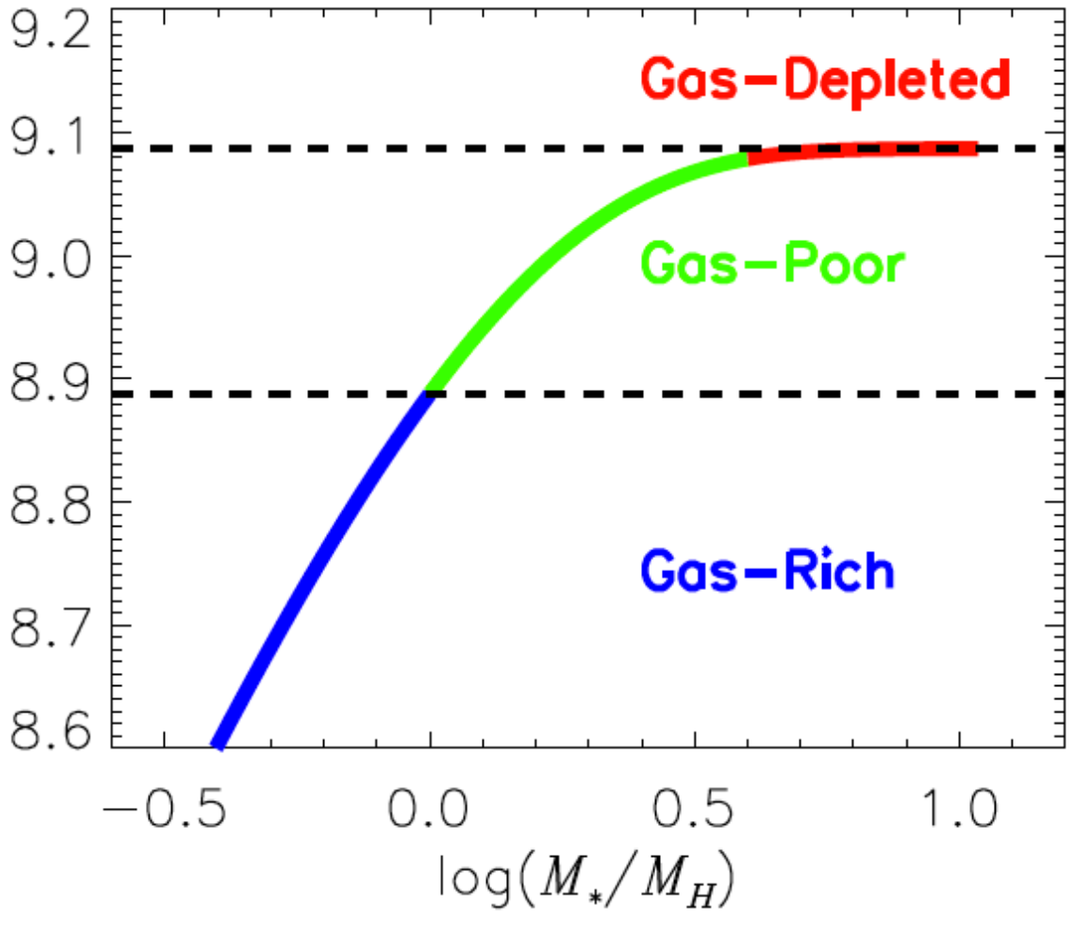
$$M_g = G M_*^g$$
$$\gamma = 1 - g$$
$$M_o = G^{1/\gamma}$$

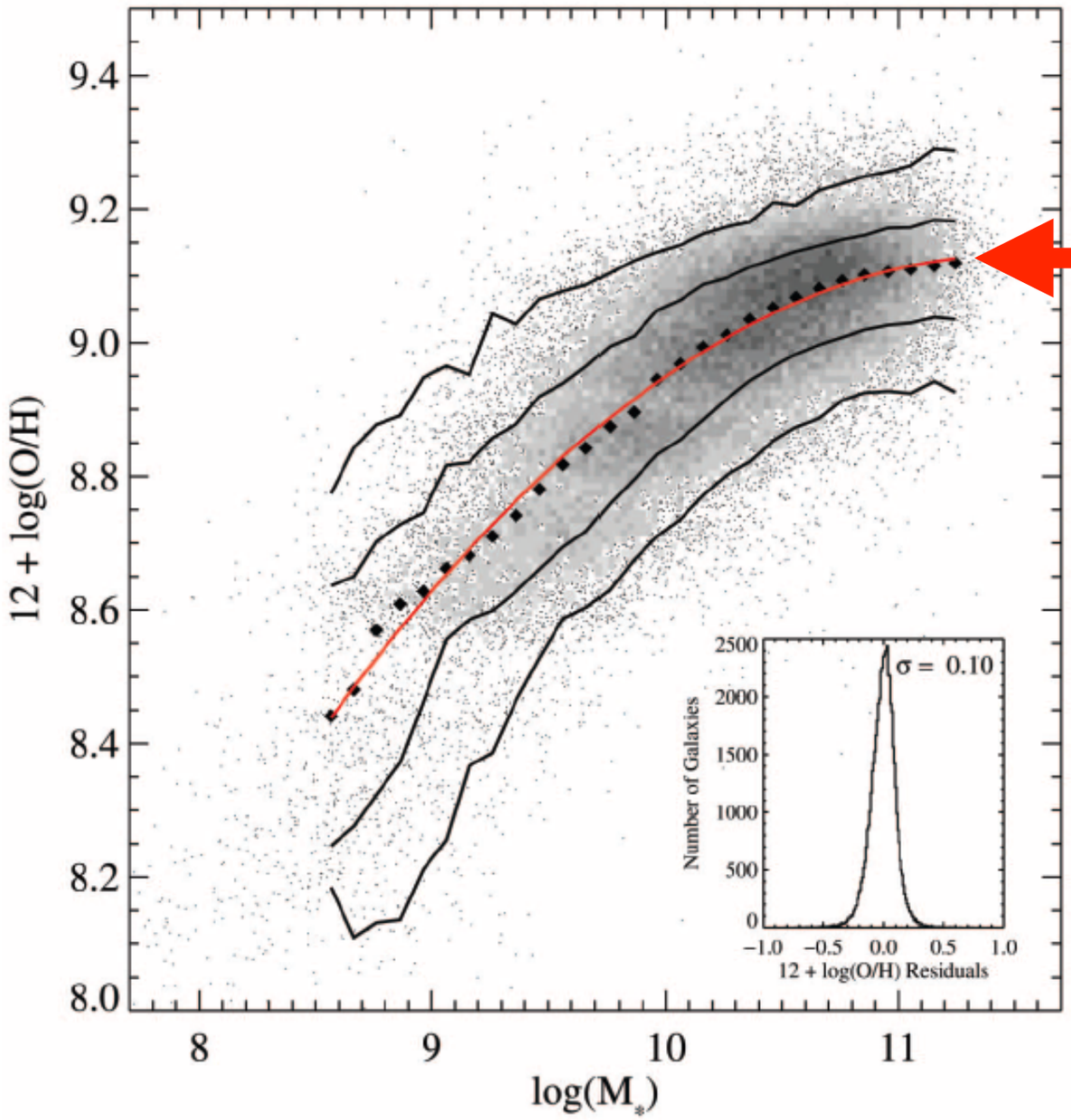
The Universal Metallicity Relation

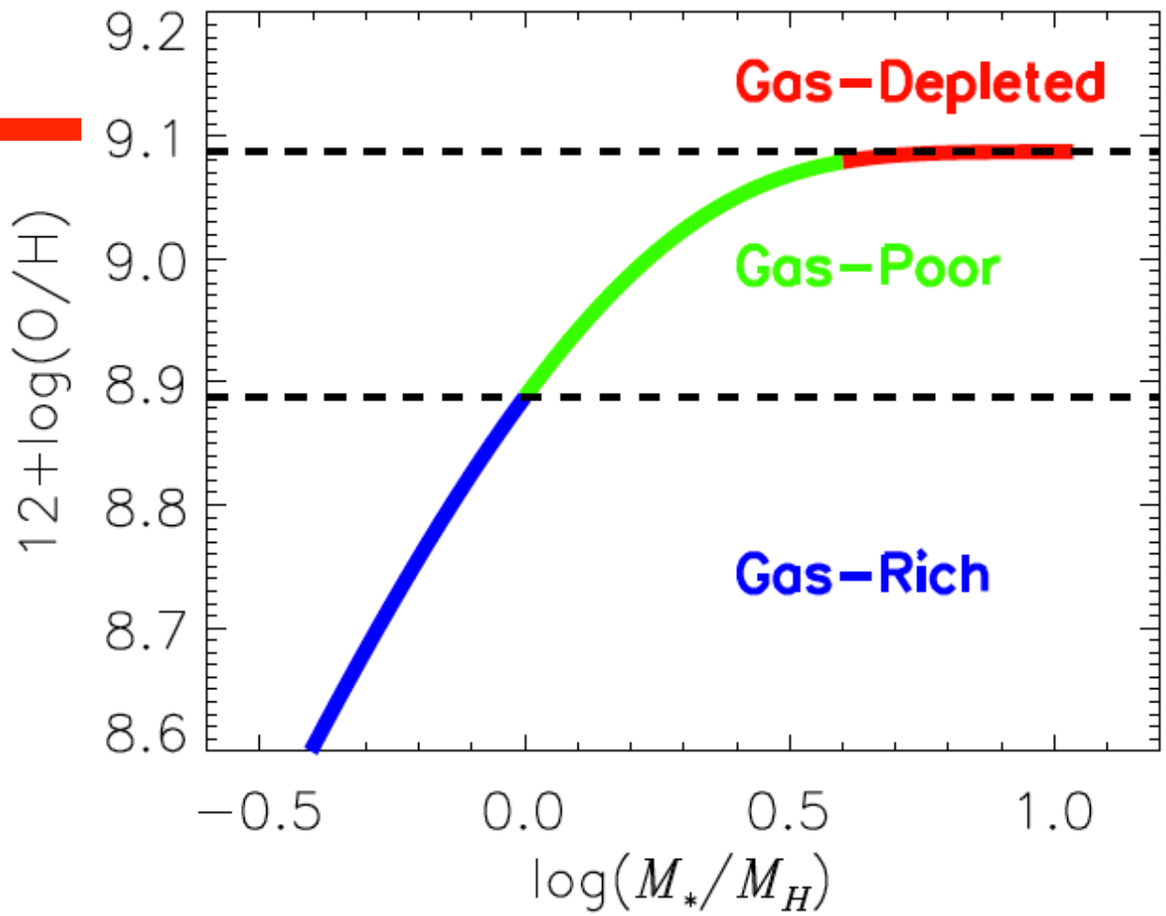




ZAHID+, 2014B

The Origin of the Mass-Metallicity Relation





ZAHID+, 2014B

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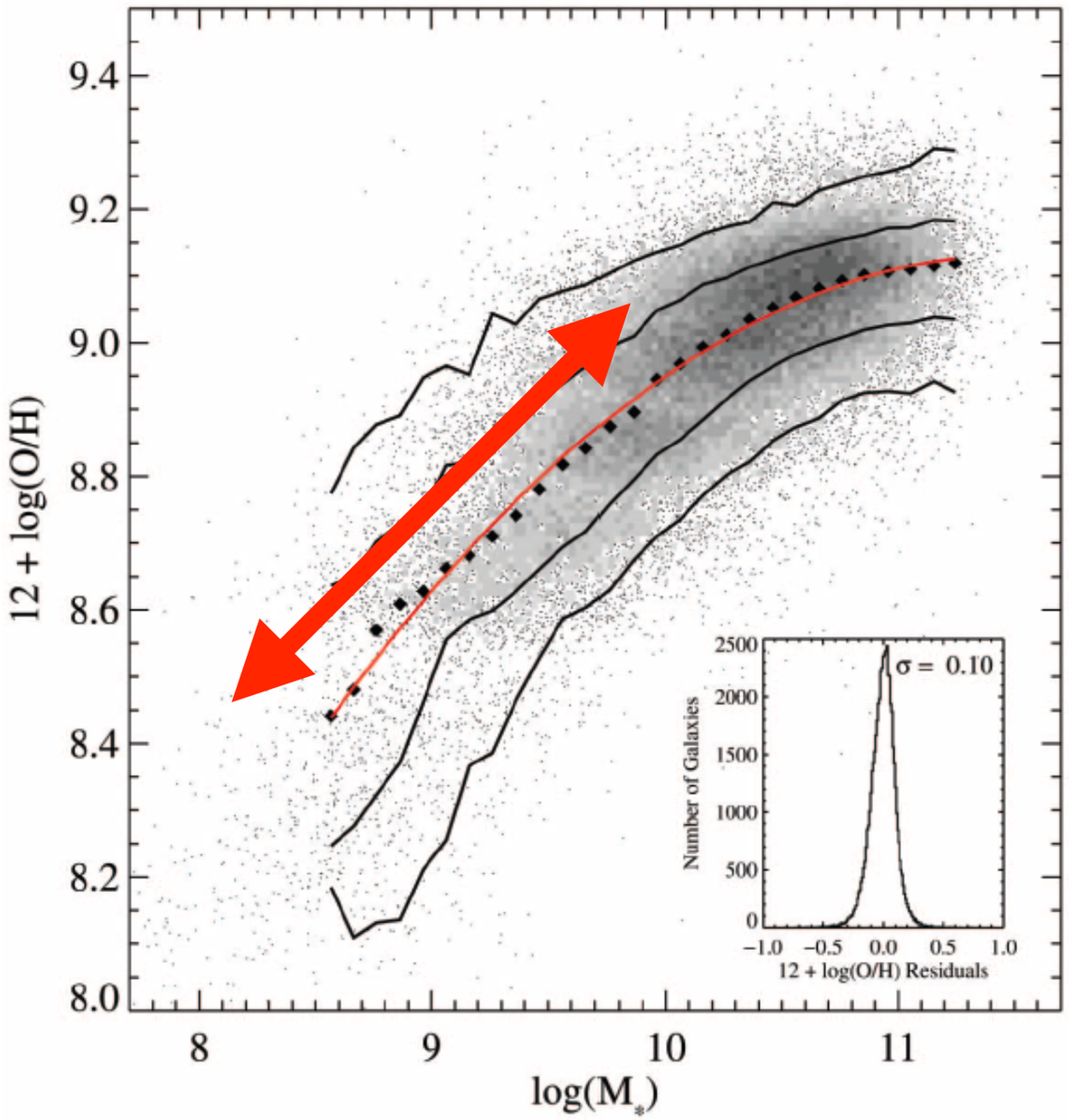

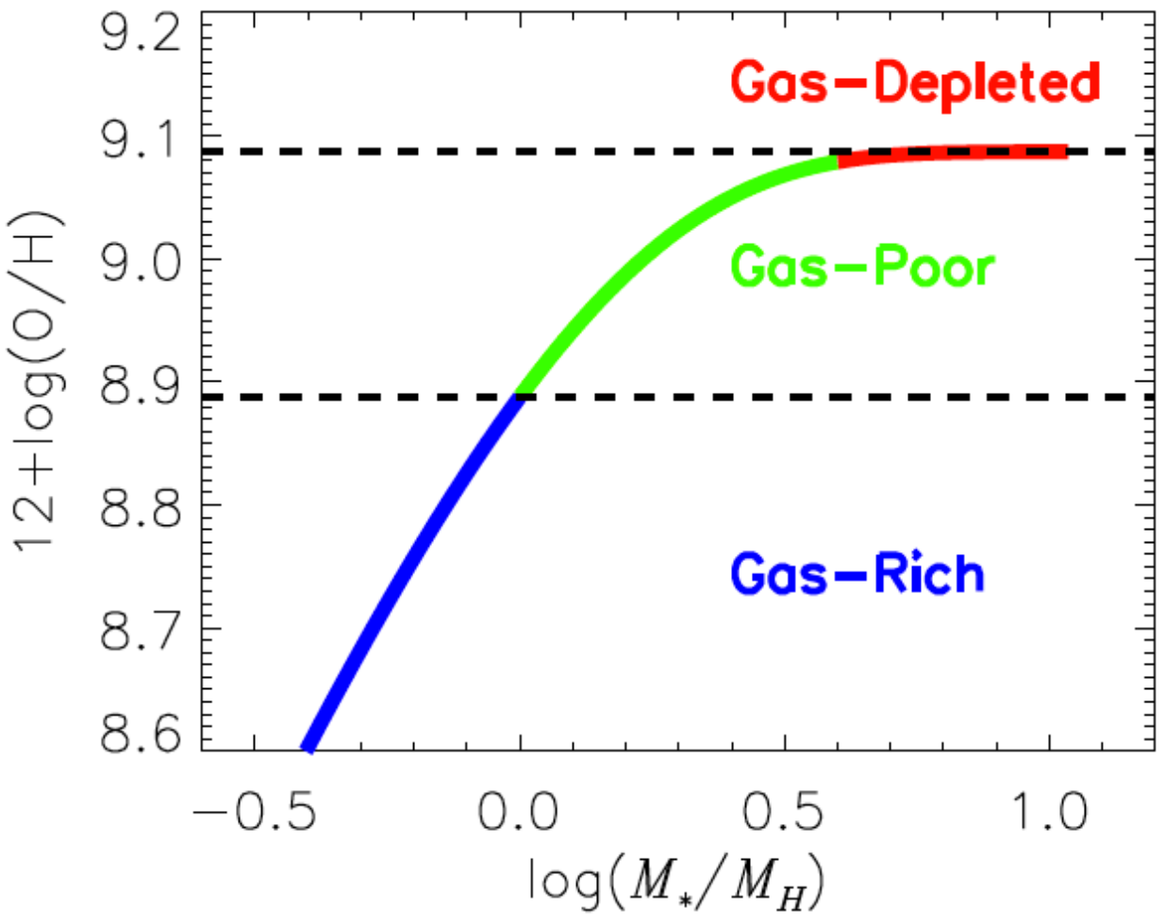

ZAHID+, 2014B

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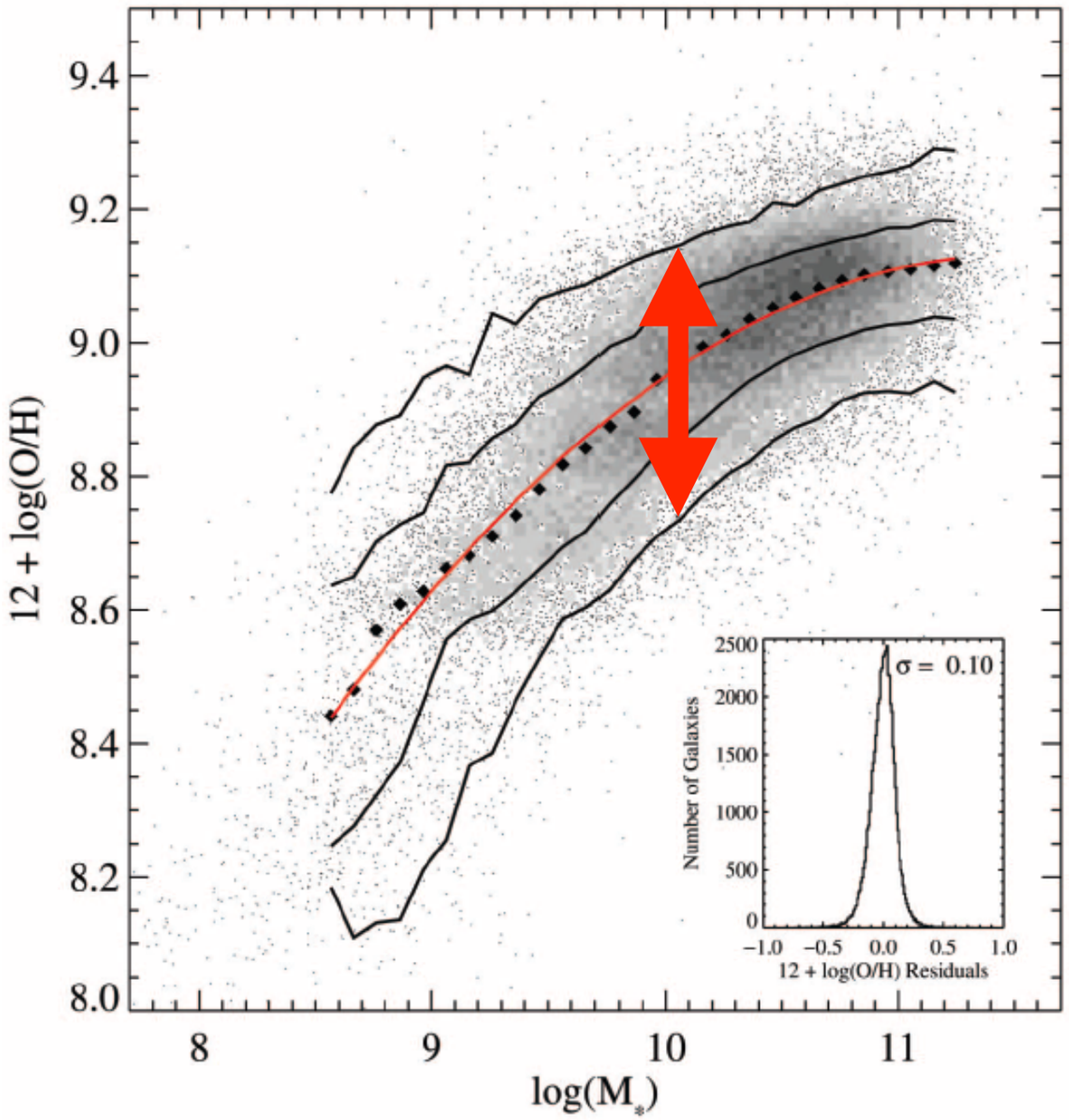

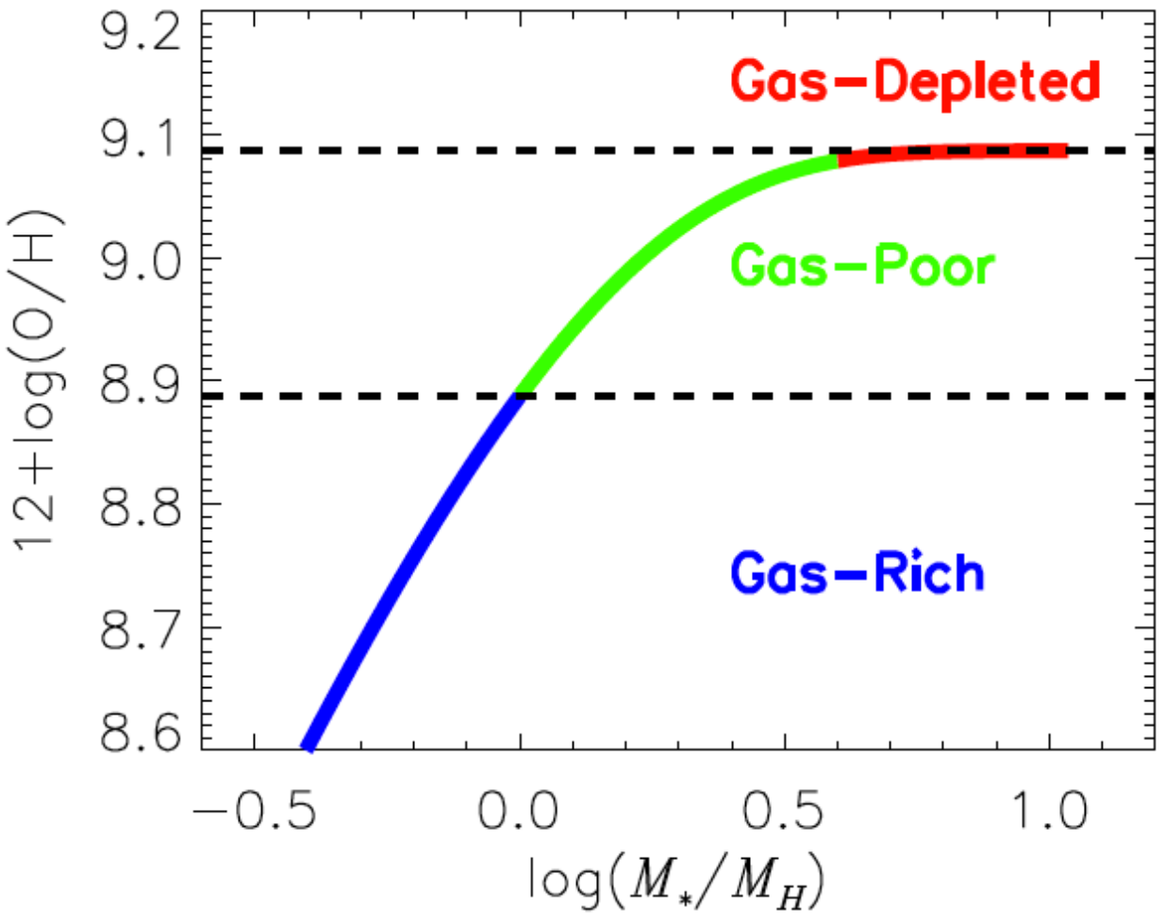

ZAHID+, 2014B

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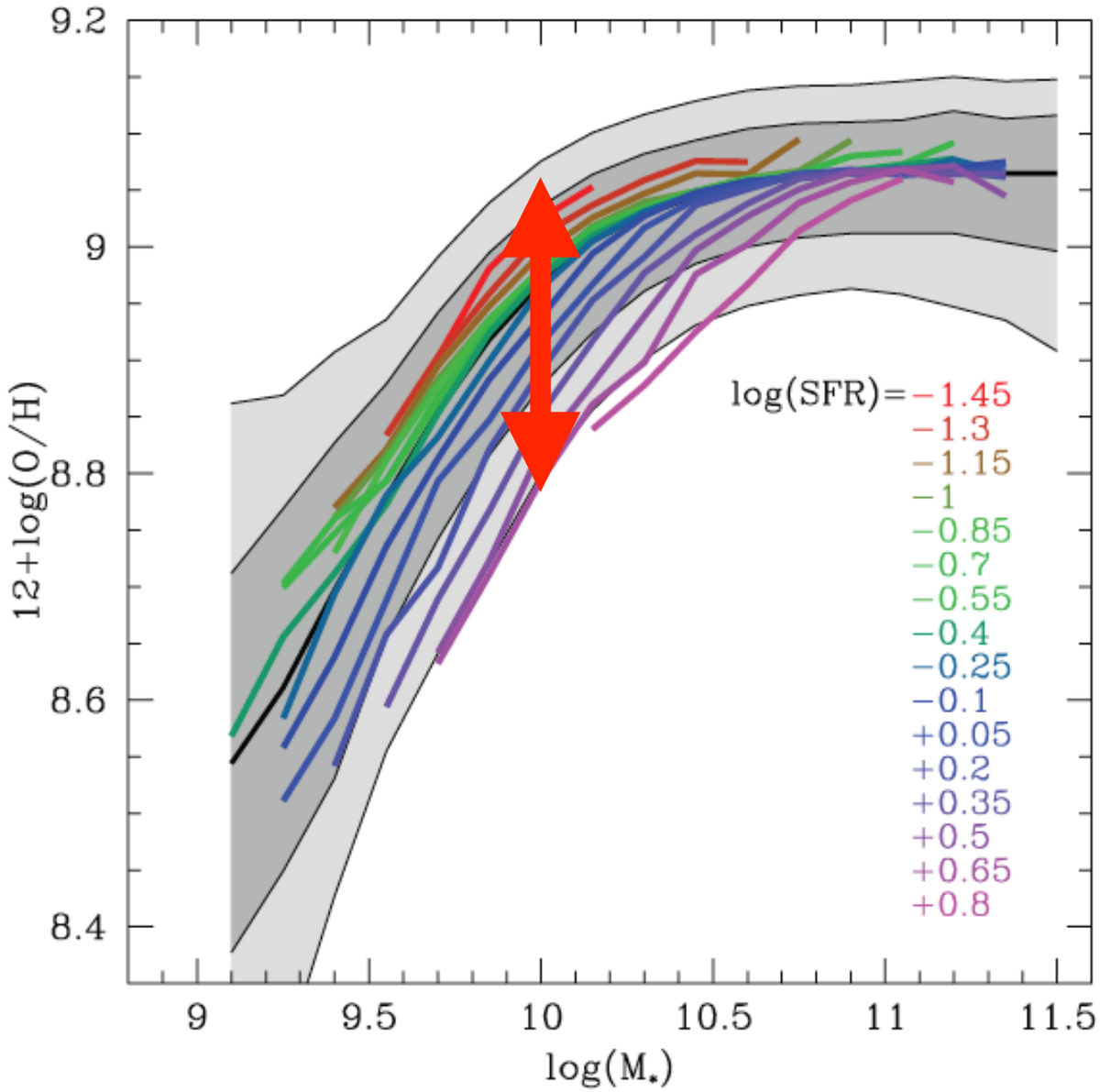
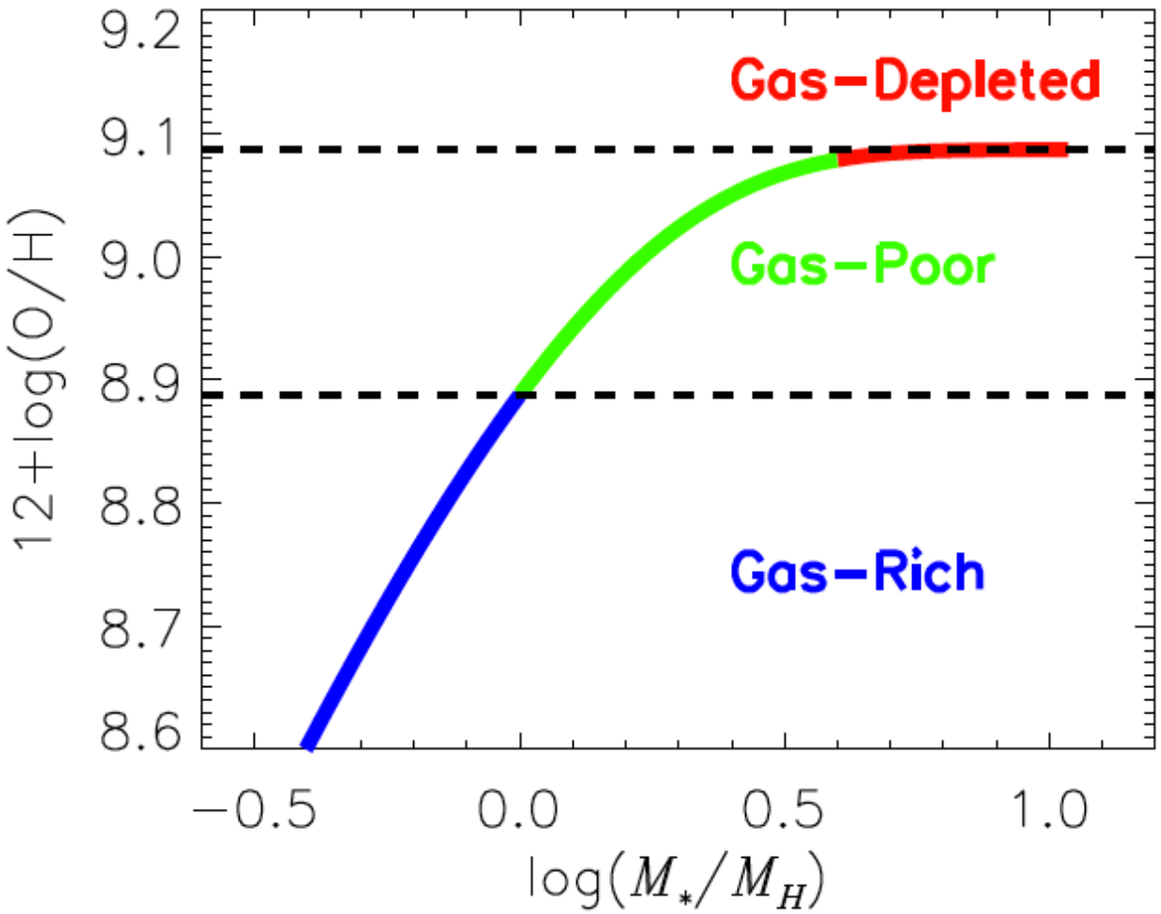
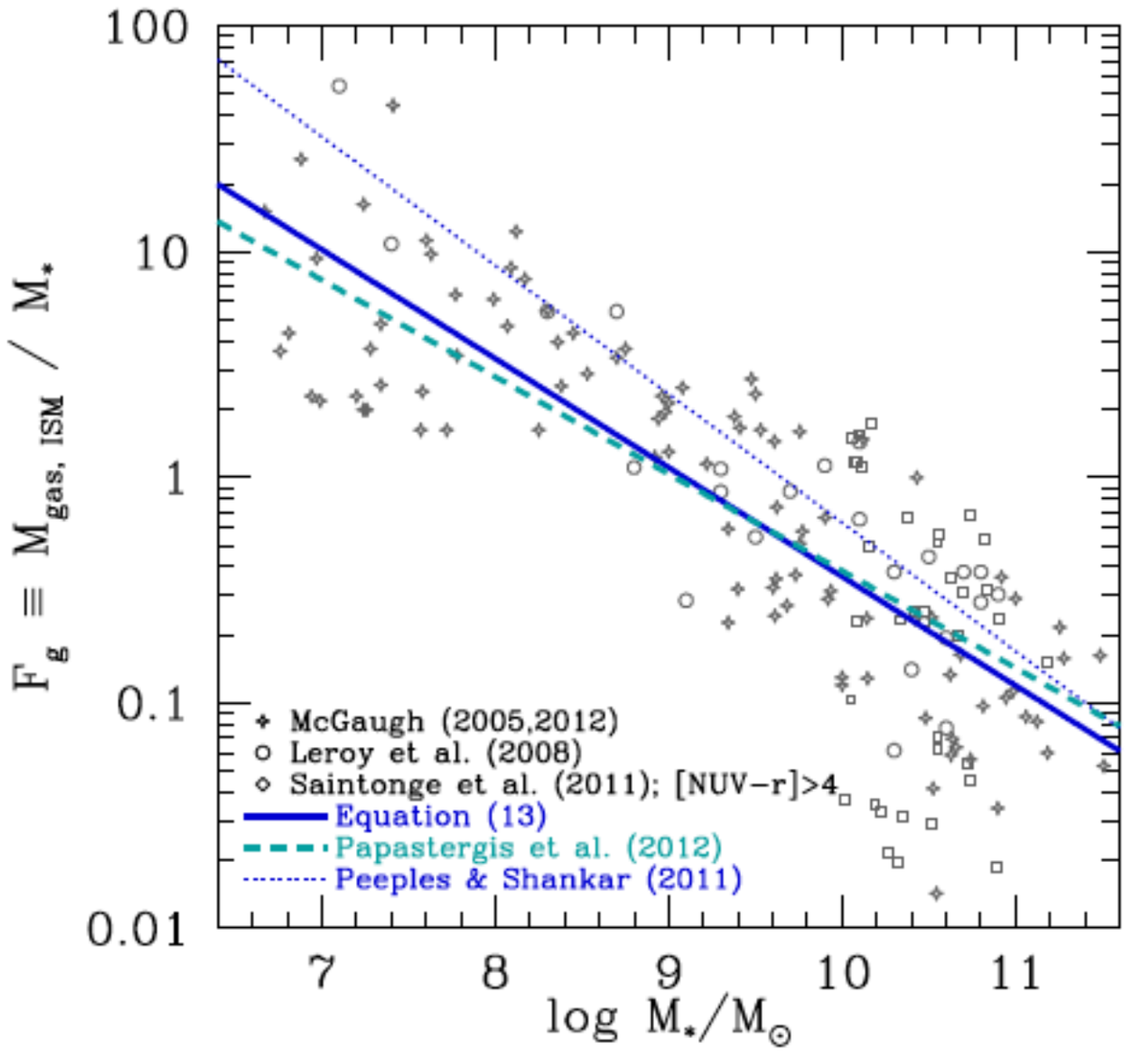




ZAHID+, 2014B

The Observed Gas Mass - Stellar Mass Relation



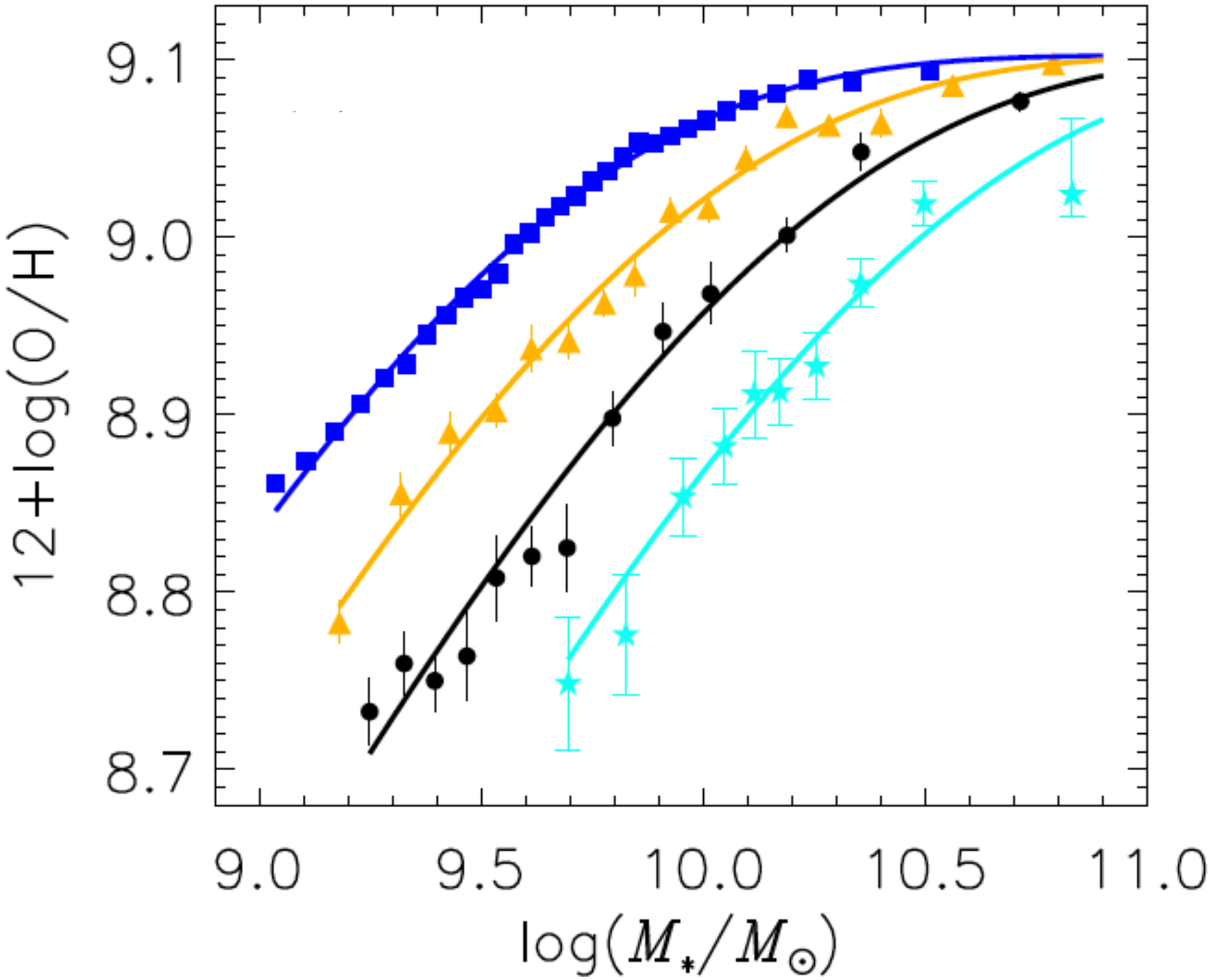
$$\frac{M_g}{M_*} \propto M_*^{-0.5}$$

$$M_g \propto M_*^{0.5}$$

$$\gamma = 1 - g = 0.5$$

PEEPLES+, 2014

The Evolution of the Mass-Metallicity Relation



ZAHID+, 2014B

Model Predicts Cosmological Evolution of Gas

AVERAGE GAS MASS

$$M_g(M_*, z) = 3.87 \times 10^9 \, (1+z)^{1.35} \left(\frac{M_*}{10^{10} M_\odot} \right)^{0.49} \quad [M_\odot]$$

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1) Gas mass has weak dependence on redshift

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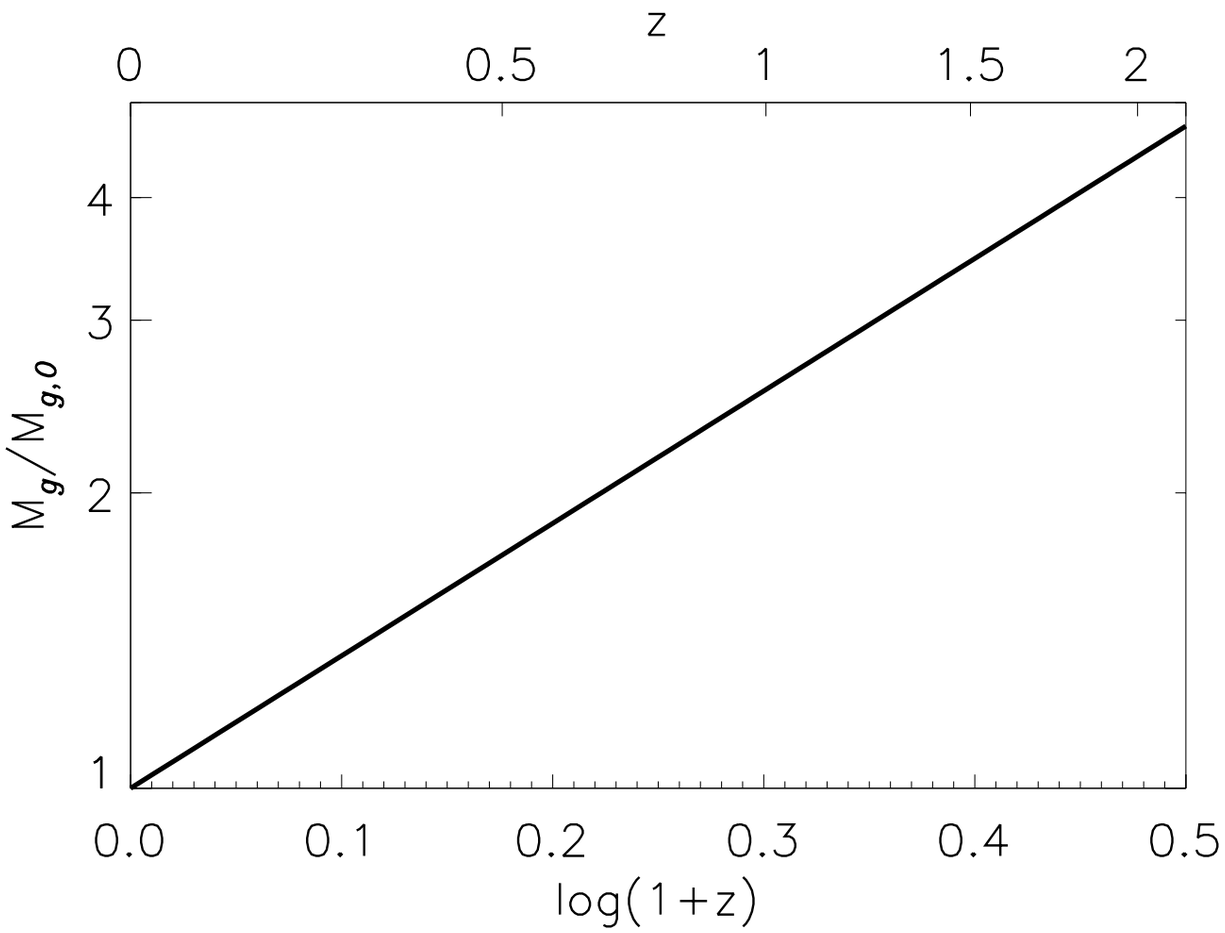
1) Gas mass has weak dependence on redshift

2) Slope of gas mass - stellar mass relation independent of redshift out to z ~ 1.5

Model Predicts Star-Formation Efficiency Increases



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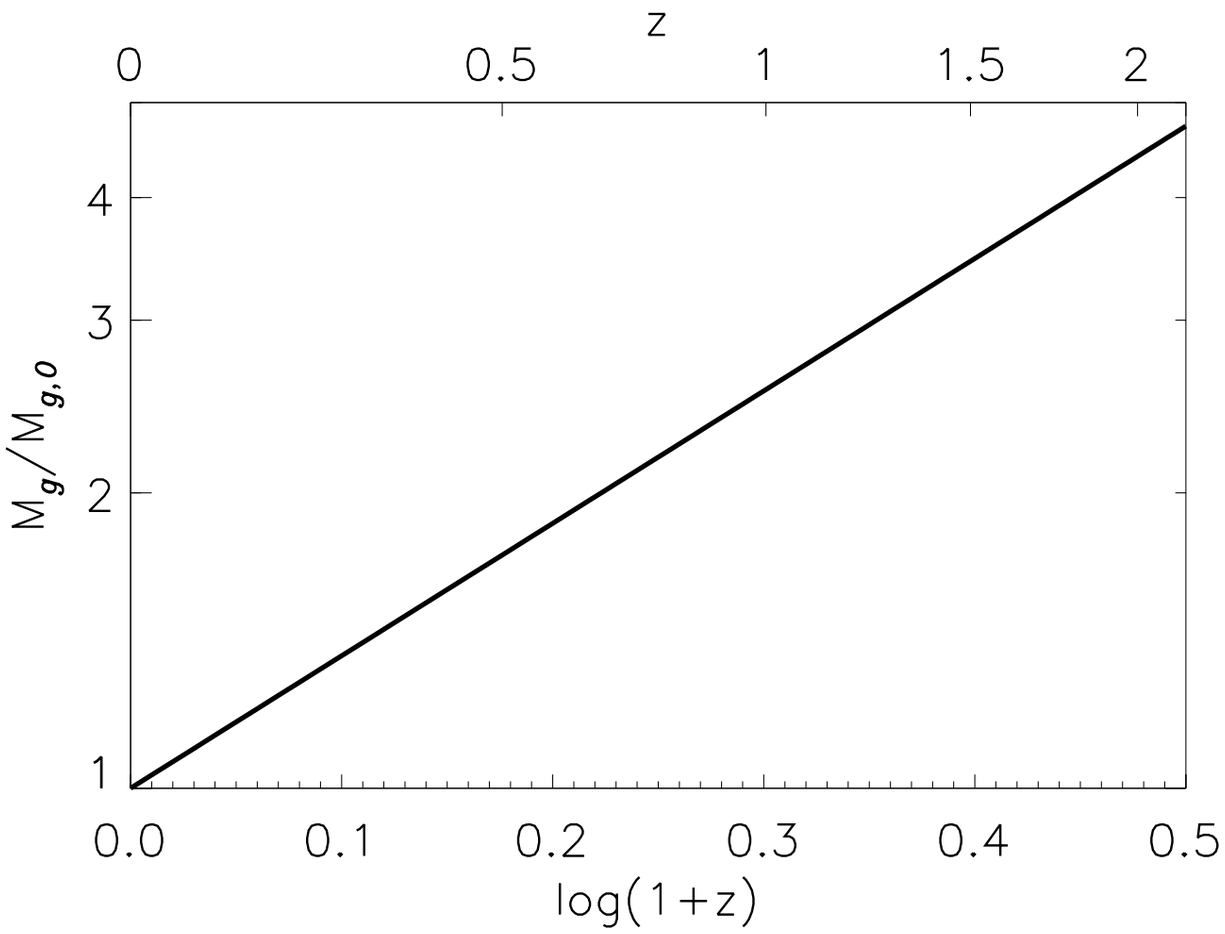

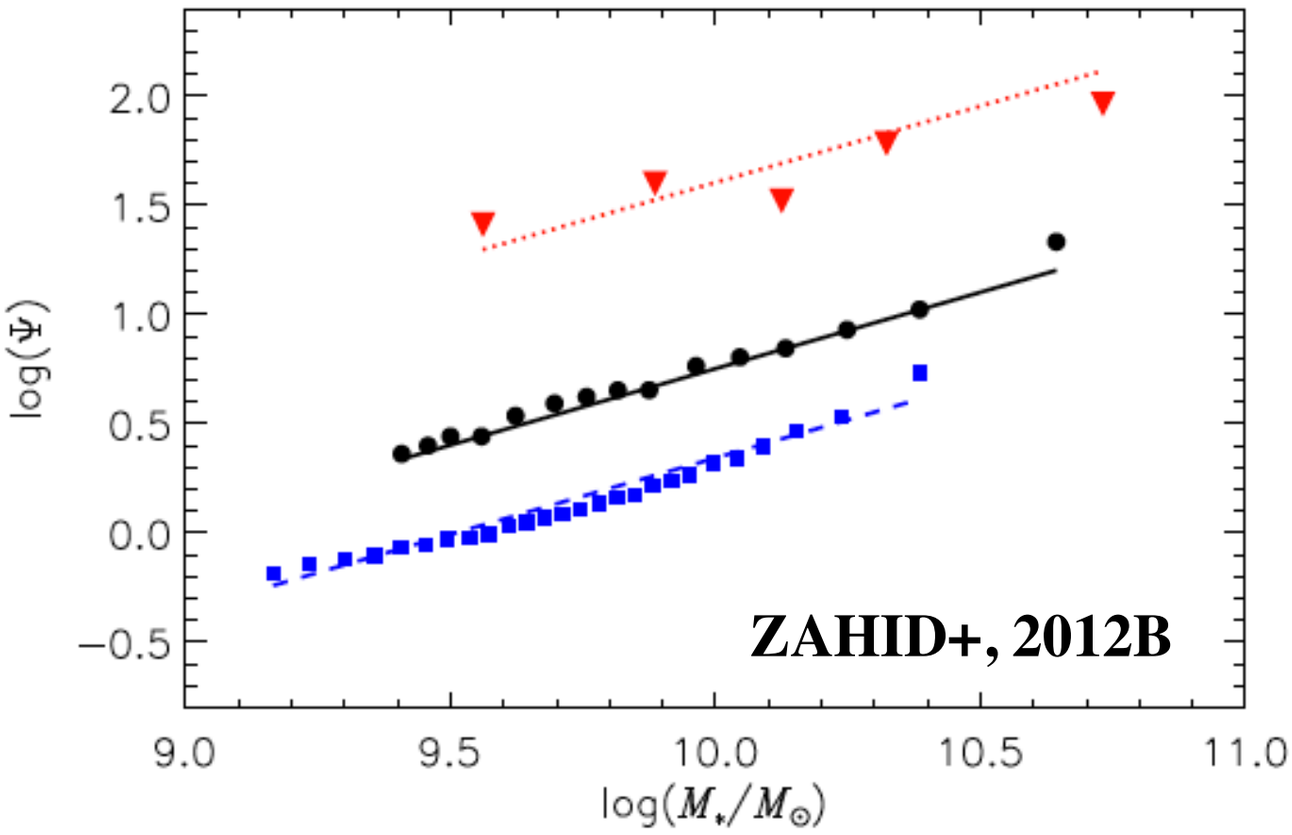

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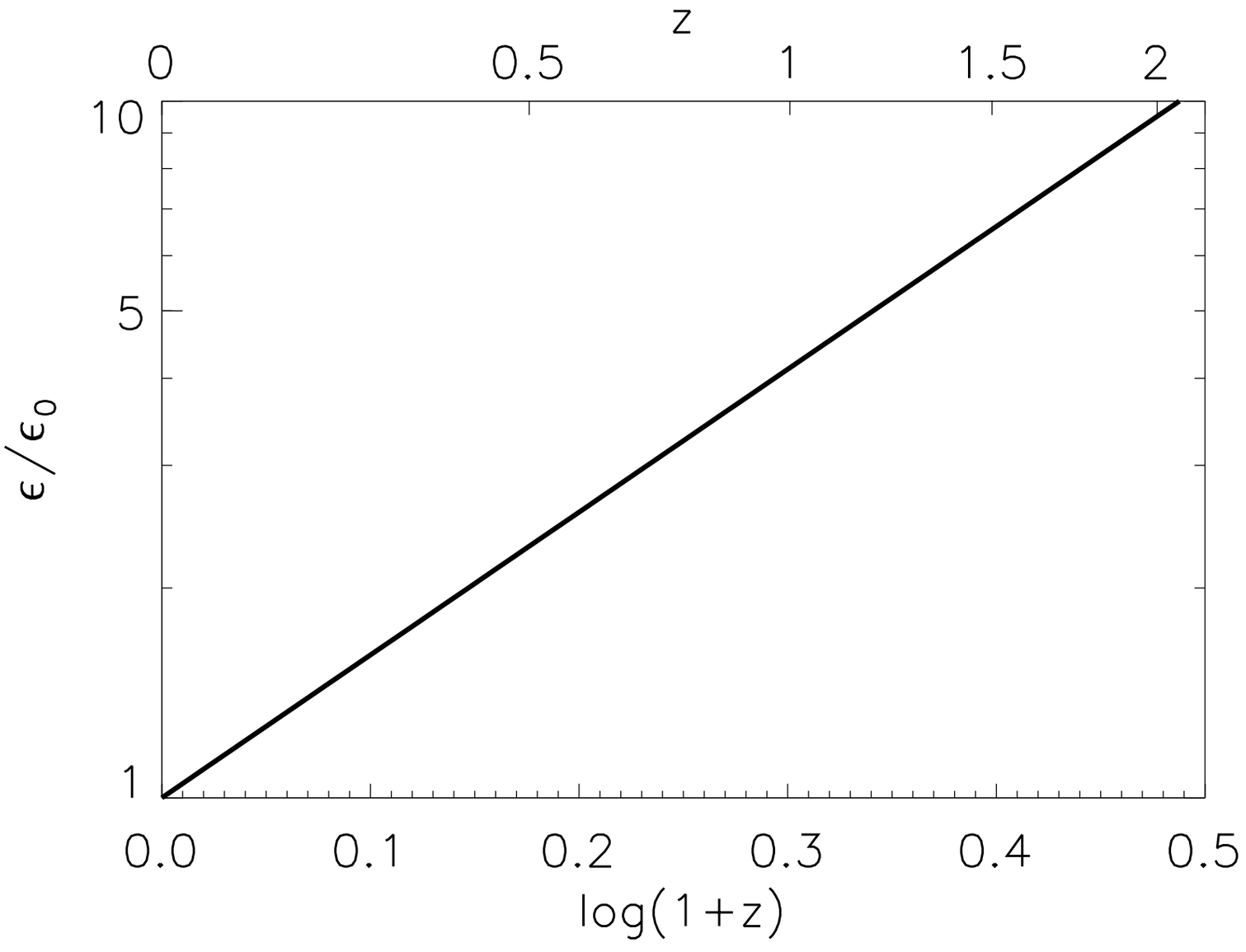


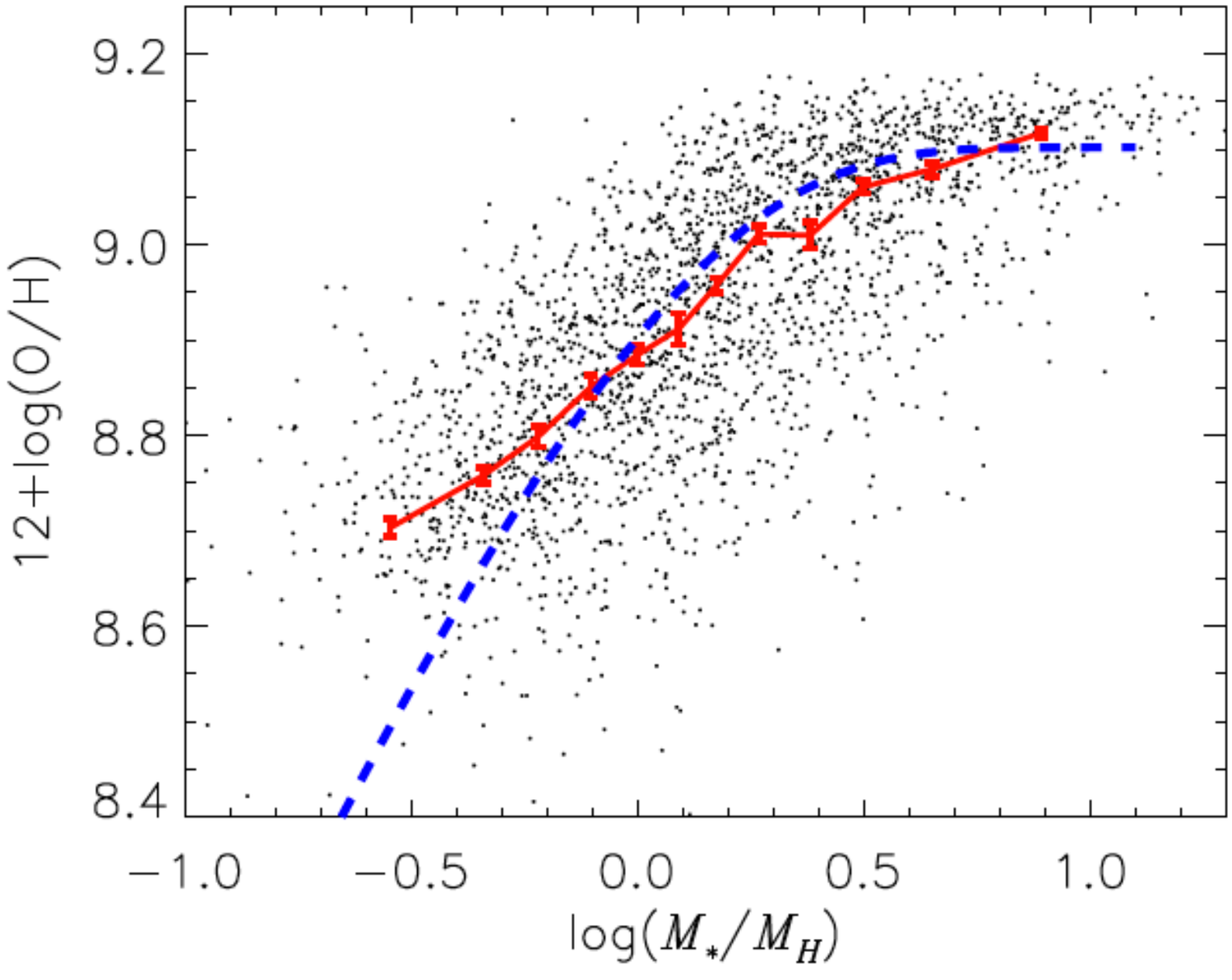
$$\epsilon = \frac{SFR}{M_g} \quad [\mathrm{yr}^{-1}]$$

THE UNIVERSAL RELATION OF GALACTIC CHEMICAL EVOLUTION: THE ORIGIN OF THE MASS–METALLICITY RELATION

H. Jabran Zahid[1,2], Gabriel I. Dima[1], Rolf-Peter Kudritzki[1], Lisa J. Kewley[3], Margaret J. Geller[2], Ho Seong Hwang[2], John D. Silverman[4], and Daichi Kashino[5]

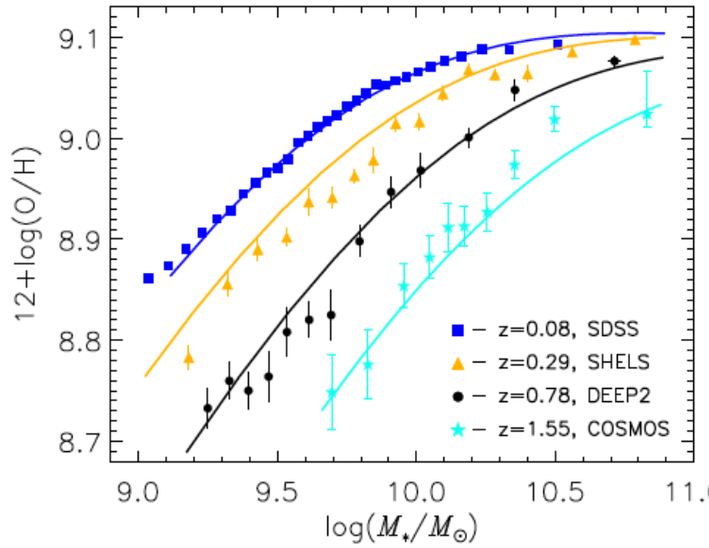
THE ASTROPHYSICAL JOURNAL, 791, 130
ARXIV:1404.7526

The Universal Metallicity Relation in Local Galaxies



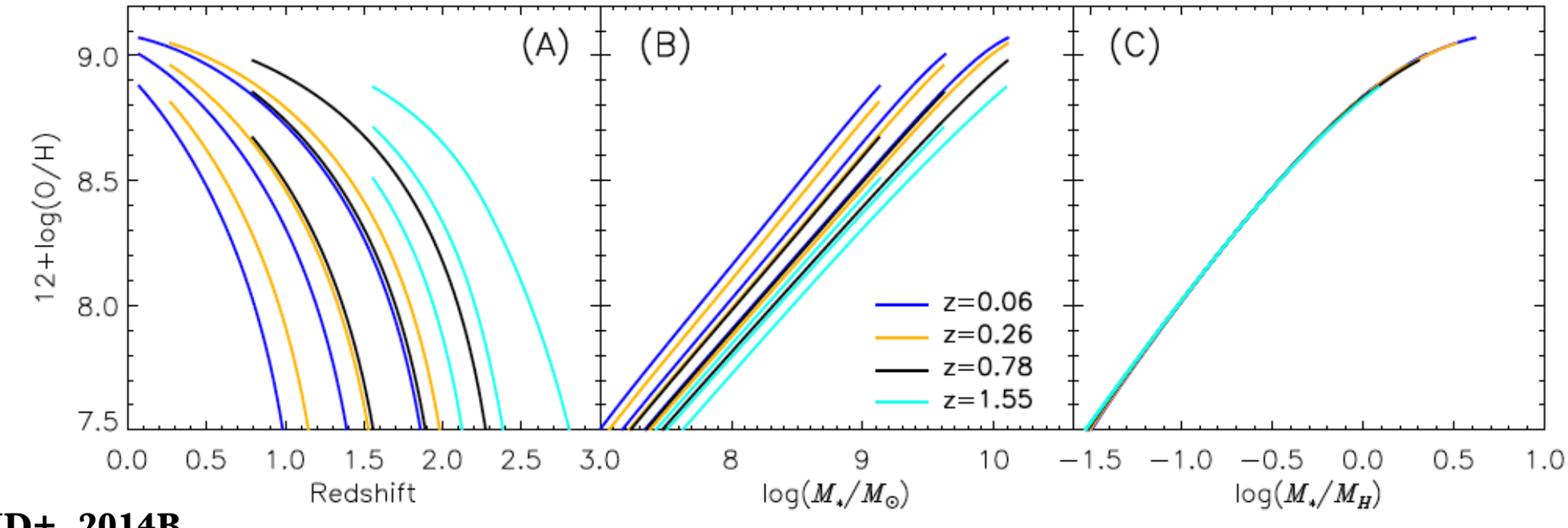
ZAHID+, 2014B

NUMERICAL MODELING OF CHEMICAL EVOLUTION



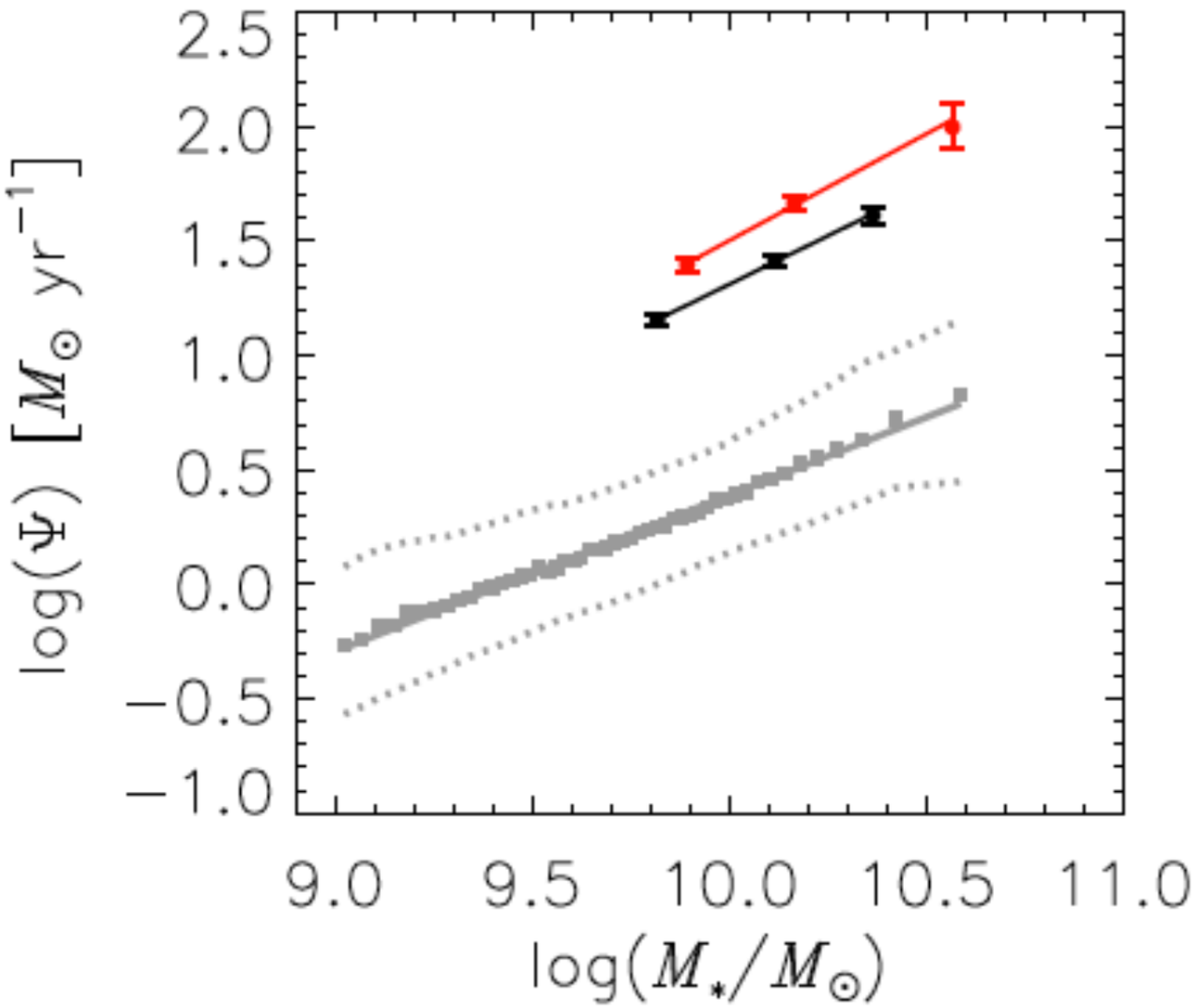
NUMERICALLY SOLVE

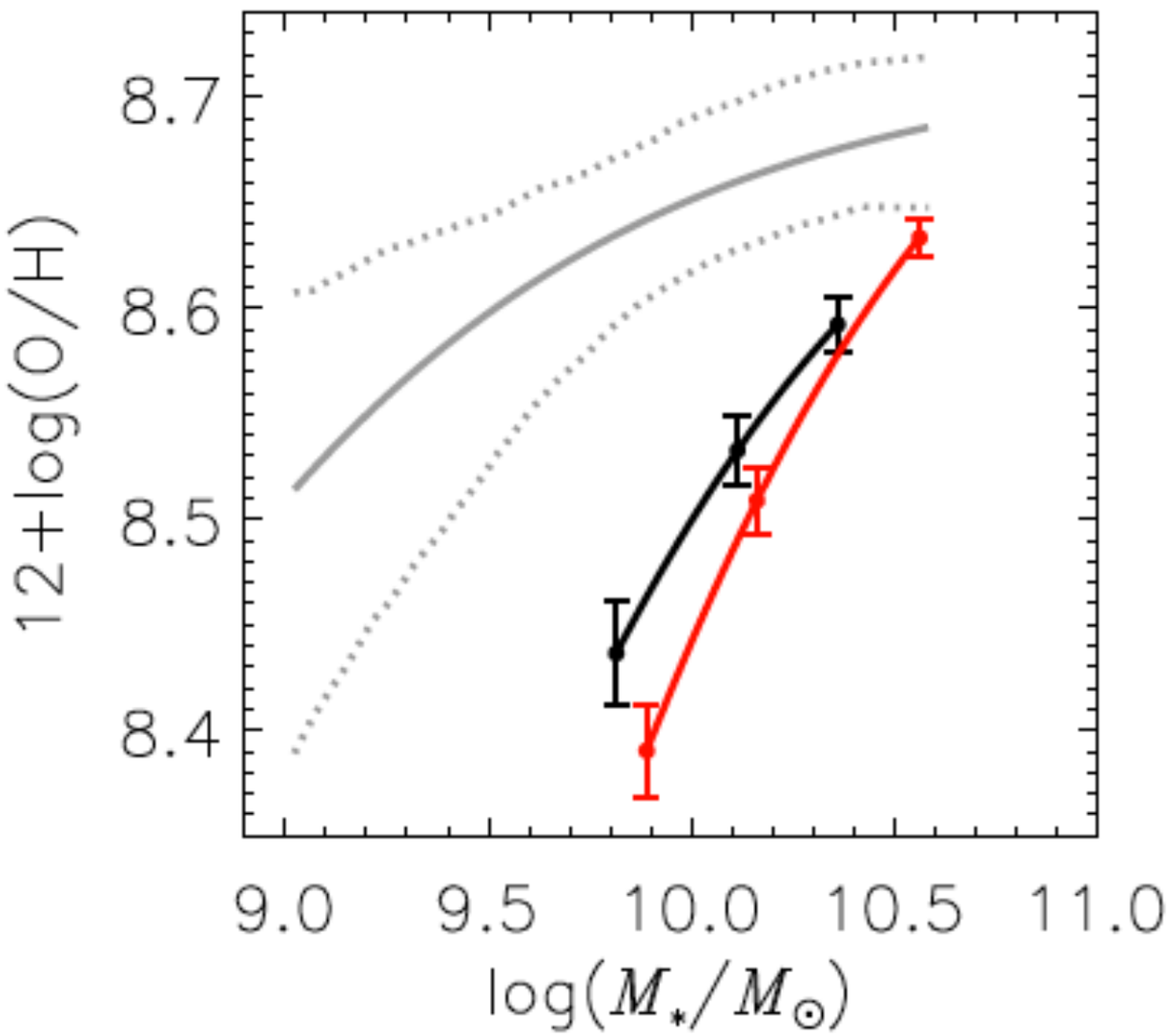
$$\frac{\mathrm{d}Z}{\mathrm{d}M_*} = \frac{\mathrm{d}}{\mathrm{d}M_*}\left(\frac{M_z}{M_g}\right) = \frac{1}{M_g}\left(\frac{\mathrm{d}M_z}{\mathrm{d}M_*} - Z\frac{\mathrm{d}M_g}{\mathrm{d}M_*}\right)$$



ZAHID+, 2014B

The Stellar Mass, Metallicity and SFR Relation





ZAHID+, 2014C

ANALYTICAL MODEL OF GALACTIC CHEMICAL EVOLUTION

$$\frac{\mathrm{d}Z}{\mathrm{d}M_*} = \frac{\mathrm{d}}{\mathrm{d}M_*}\left(\frac{M_z}{M_g}\right) = \frac{1}{M_g}\left(\frac{\mathrm{d}M_z}{\mathrm{d}M_*} - Z\frac{\mathrm{d}M_g}{\mathrm{d}M_*}\right)$$

$$\frac{\mathrm{d}M_z}{\mathrm{d}M_*} > Z\frac{\mathrm{d}M_g}{\mathrm{d}M_*}$$

$$\frac{\mathrm{d}Z}{\mathrm{d}M_*} \approx \frac{1}{M_g}\frac{\mathrm{d}M_z}{\mathrm{d}M_*}$$

$$\mathrm{d}M_z = Y\mathrm{d}M_* - Z\mathrm{d}M_* + RZ\mathrm{d}M_* + Z_i\mathrm{d}M_i - Z_w\mathrm{d}M_w.$$

$$\frac{\mathrm{d}M_z}{\mathrm{d}M_*} = Y - Z(1-R) + Z_i\frac{\mathrm{d}M_i}{\mathrm{d}M_*} - Z_w\frac{\mathrm{d}M_w}{\mathrm{d}M_*}$$

$$\zeta \equiv Z_w\frac{\mathrm{d}M_w}{\mathrm{d}M_*} - Z_i\frac{\mathrm{d}M_i}{\mathrm{d}M_*} \qquad \int_0^{M_*} \zeta\mathrm{d}M'_* \propto M_*$$

$$Y_N \equiv Y - \zeta \qquad \frac{\mathrm{d}Z}{\mathrm{d}M_*} \approx \frac{Y_N - Z(1-R)}{M_g}$$

ANALYTICAL MODEL OF GALACTIC CHEMICAL EVOLUTION

$$\frac{\mathrm{d}Z}{\mathrm{d}M_*} \approx \frac{Y_N - Z(1-R)}{M_g}$$

$$M_g = GM_*^g$$

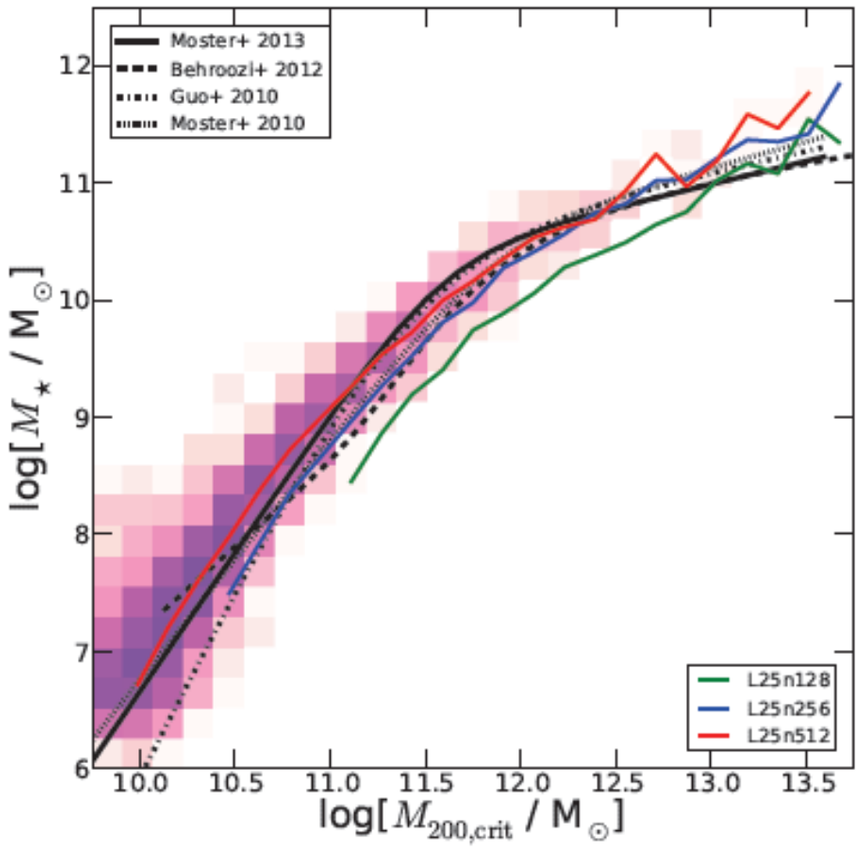
$$Z(M_*) = \frac{Y_N}{1-R}\left[1 - \exp\left(-\left[\frac{1-R}{1-g}\right]\frac{M_*}{M_g}\right)\right]$$

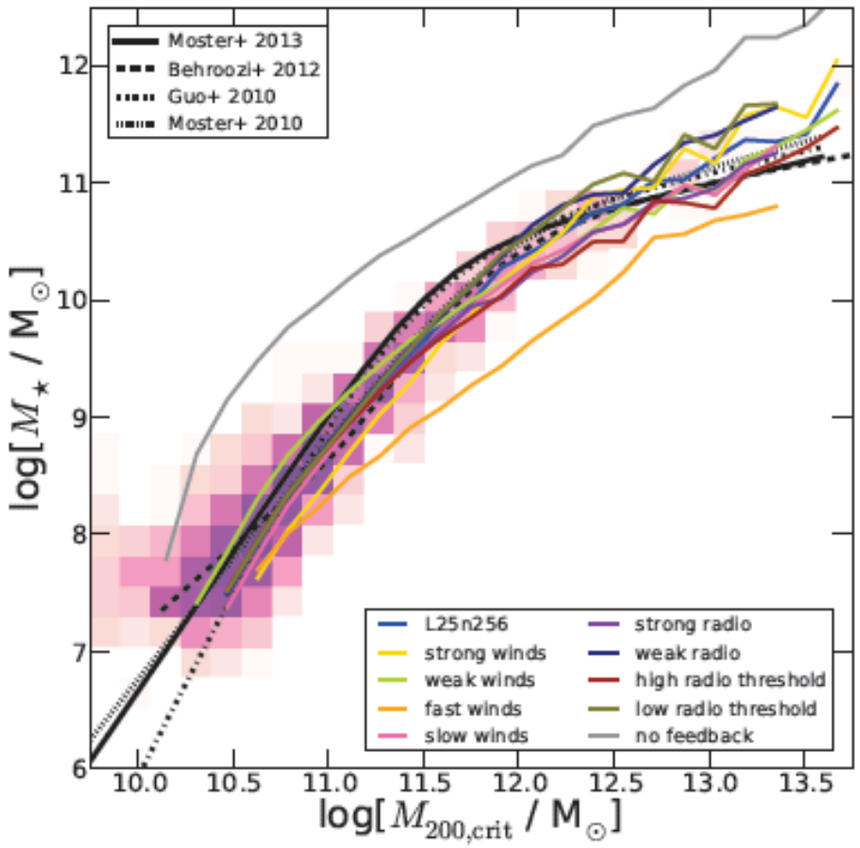
$$12 + \log(O/H) = Z_o + \log\left[1 - \exp\left(-\left[\frac{M_*}{M_o}\right]^\gamma\right)\right]$$

$$Z_o = \log\left(\frac{Y_N}{1-R}\right) \qquad \frac{1-R}{1-g}\left(\frac{M_*}{M_g}\right) \approx \frac{M_*}{M_g} \approx \left(\frac{M_*}{M_o}\right)^\gamma \qquad \left(\frac{M_*}{M_o}\right)^\gamma \approx \frac{M_*^{1-g}}{G}$$

COSMOLOGICAL CONNECTION

VOGELSBERGER+, 2013





$$M_h \propto M_*^{1/2}$$
$$M_g \propto M_*^{1/2}$$

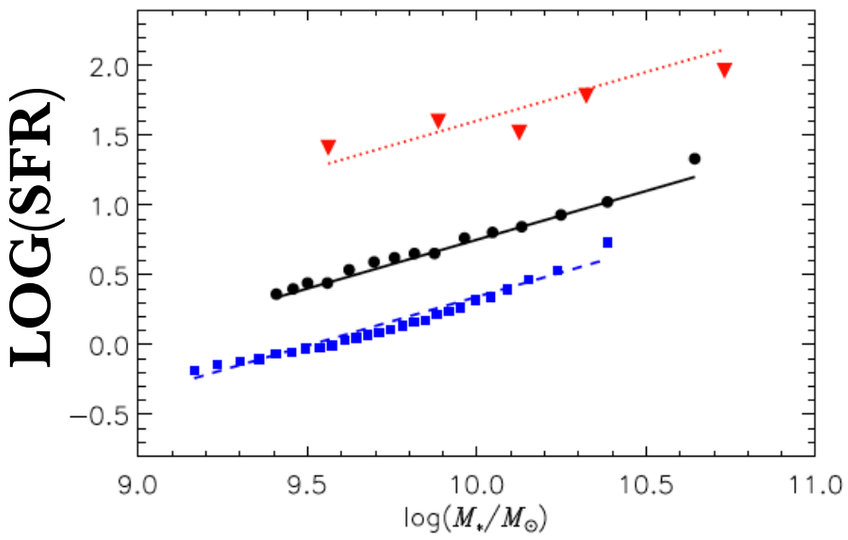
$$\frac{M_g}{M_h} \propto C$$

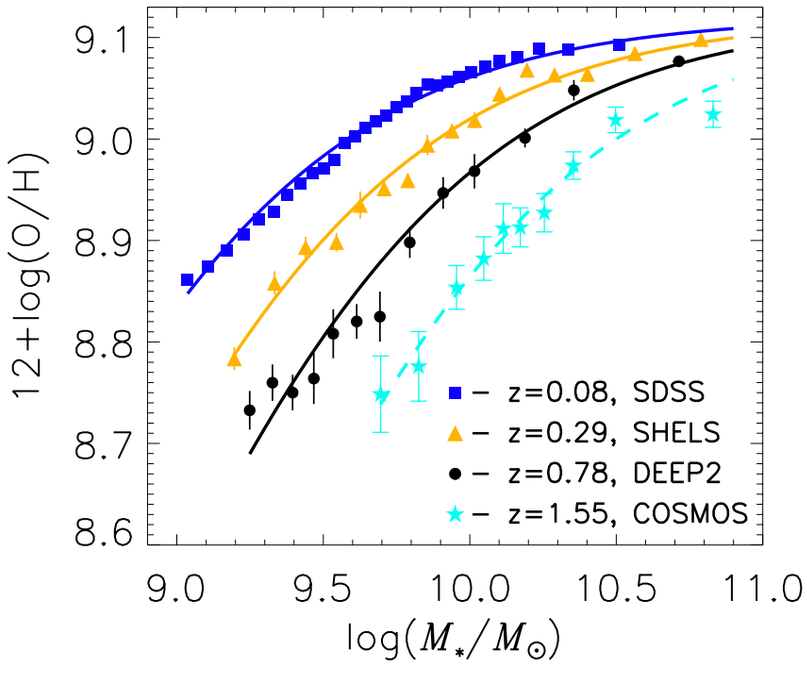
ALSO SEE:

BEHROOZI+, 2013

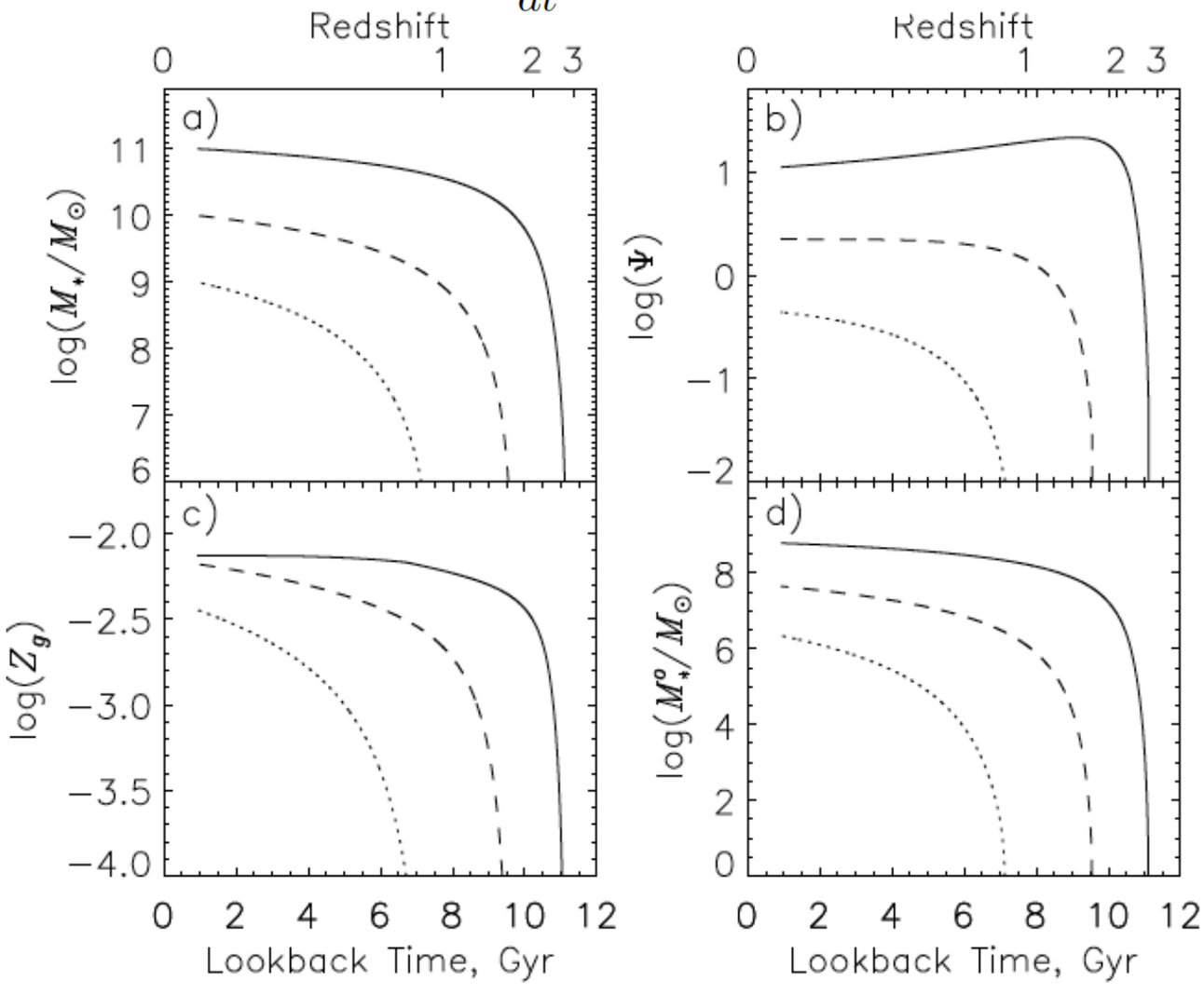
LEAUTHAUD+, 2012

OXYGEN IN STARS



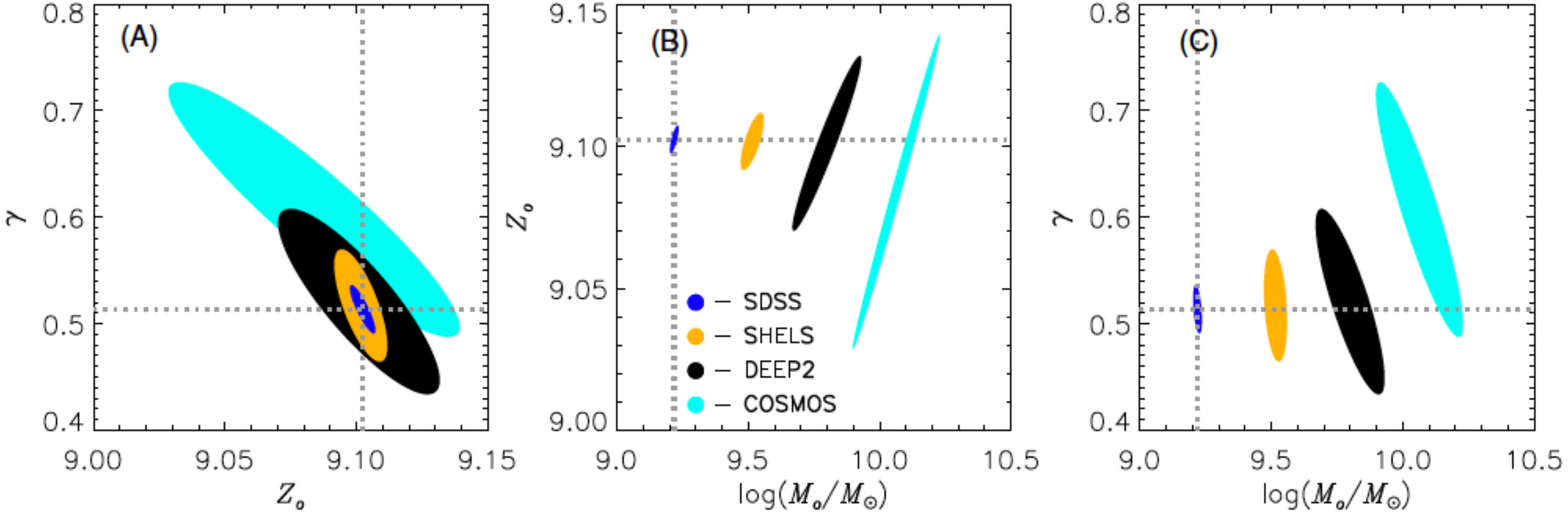


$$\frac{dM_*^o}{dt} = (1-R)\, Z_g\, \Psi$$

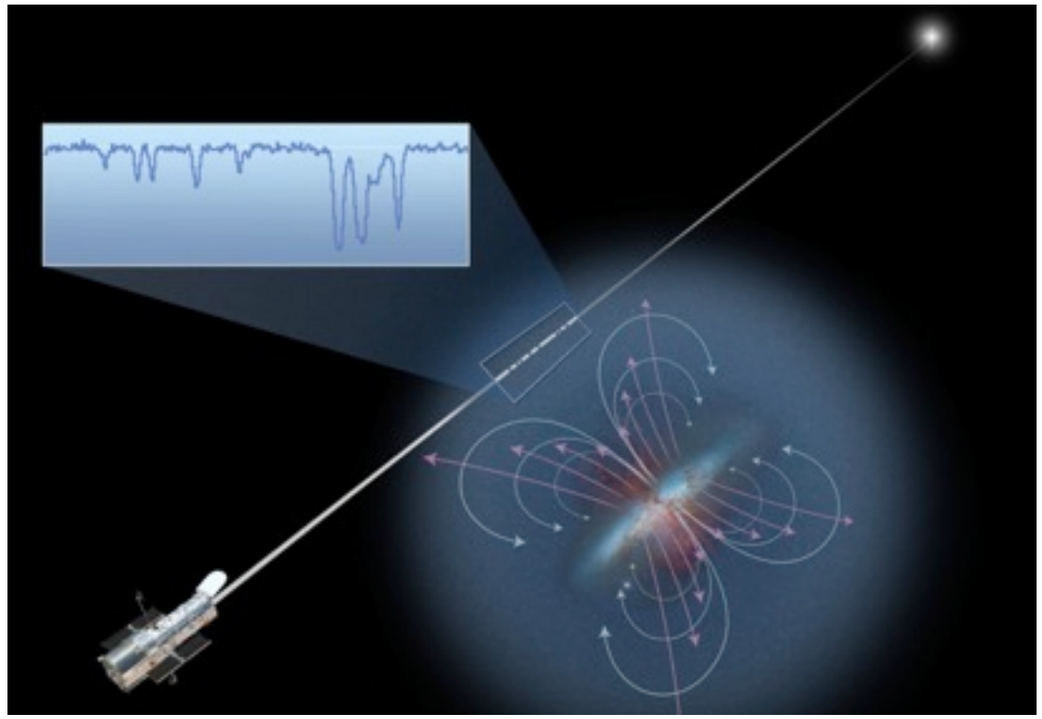


ZAHID+, 2012B

Covariance Among Fit Parameters

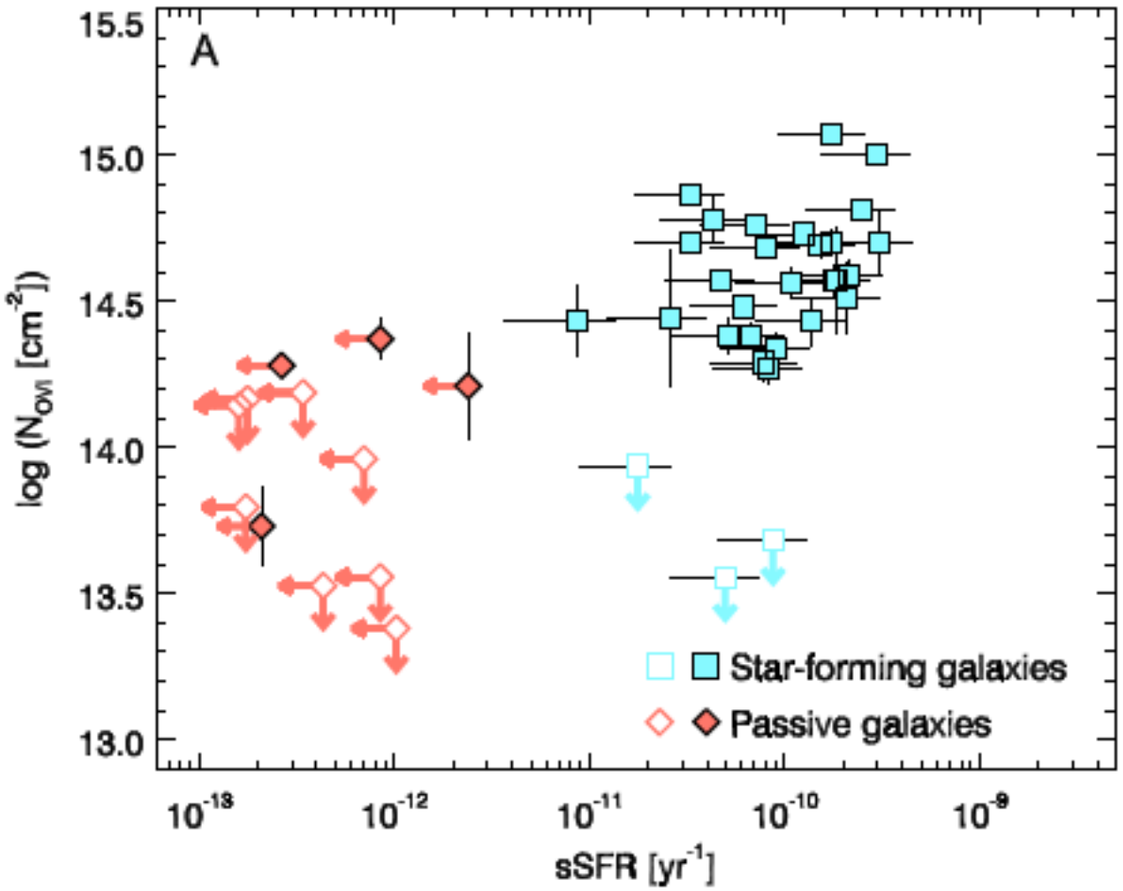


OUTFLOWS IN STAR-FORMING GALAXIES

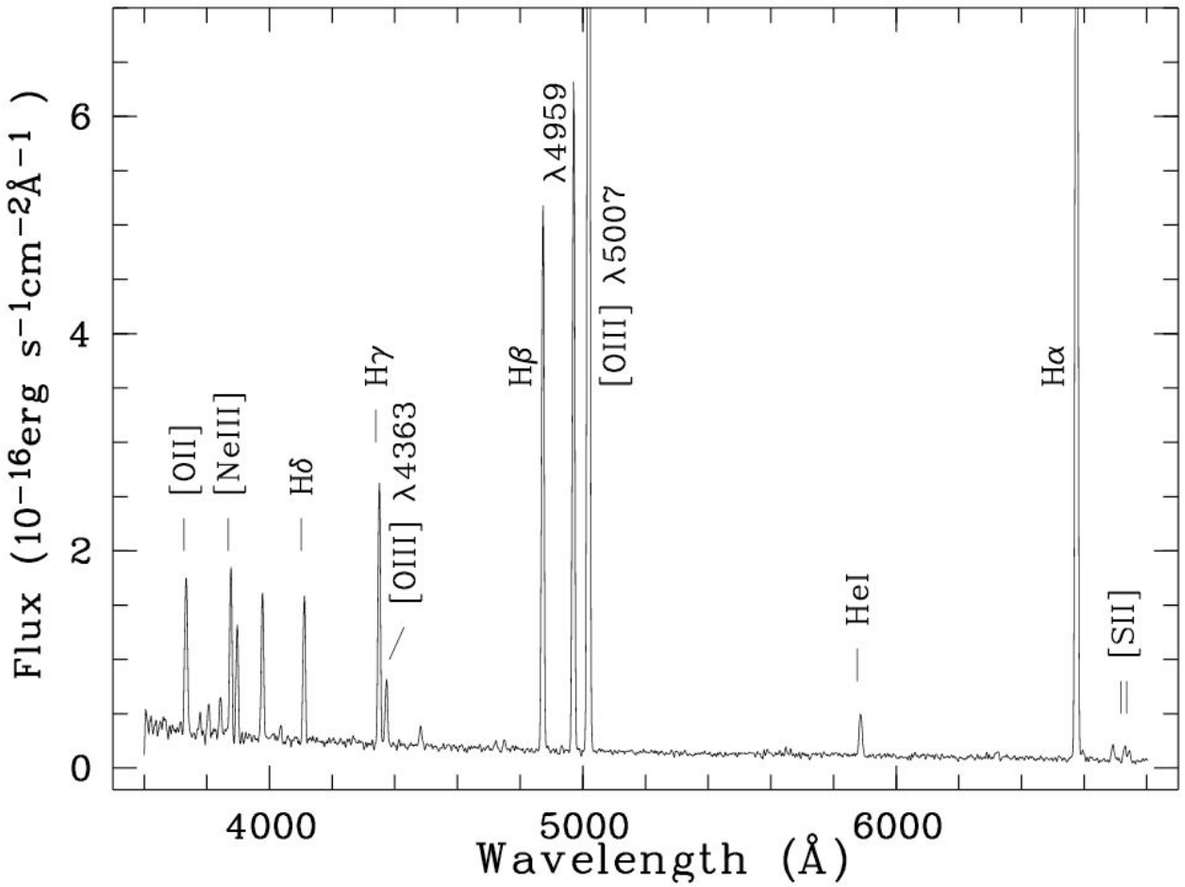


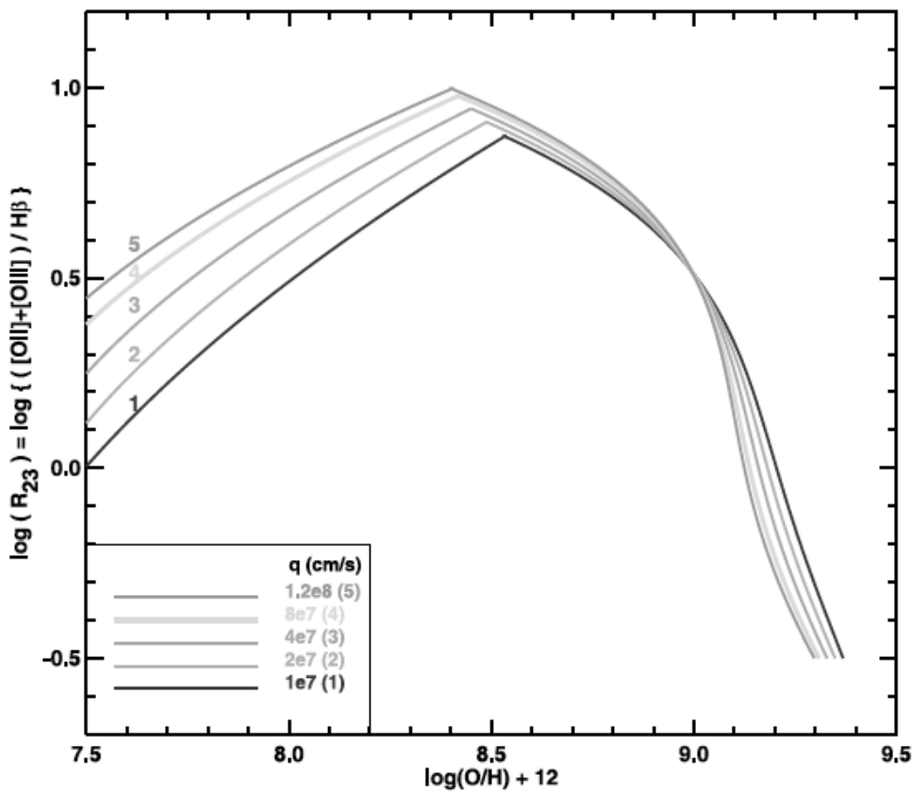
Credit: STScI, J. Werk

Tumlinson+, 2011



HOW TO MEASURE METALLICITY





Kobulnicky & Kewley, 2004