A Census of Oxygen in Local Star-Forming Galaxies

Mapping Oxygen in the Universe
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Inventory of Oxygen

- Total oxygen produced:

  observed property

$$\frac{dM_T^o}{dz} = P_o\,\Psi$$

$$M_T^o(z > z_i) = P_o \int_{z_i}^{z} \Psi(z')\,dz'$$

$$M_T^o = P_o\,\frac{M_*}{1-R}$$

- Oxygen in the gas-phase:

  observed property

$$Z_g = M_g^o / M_g$$

$$M_g^o = Z_g\,M_g$$

- Oxygen in stars:

  need history of SFR and metallicity

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

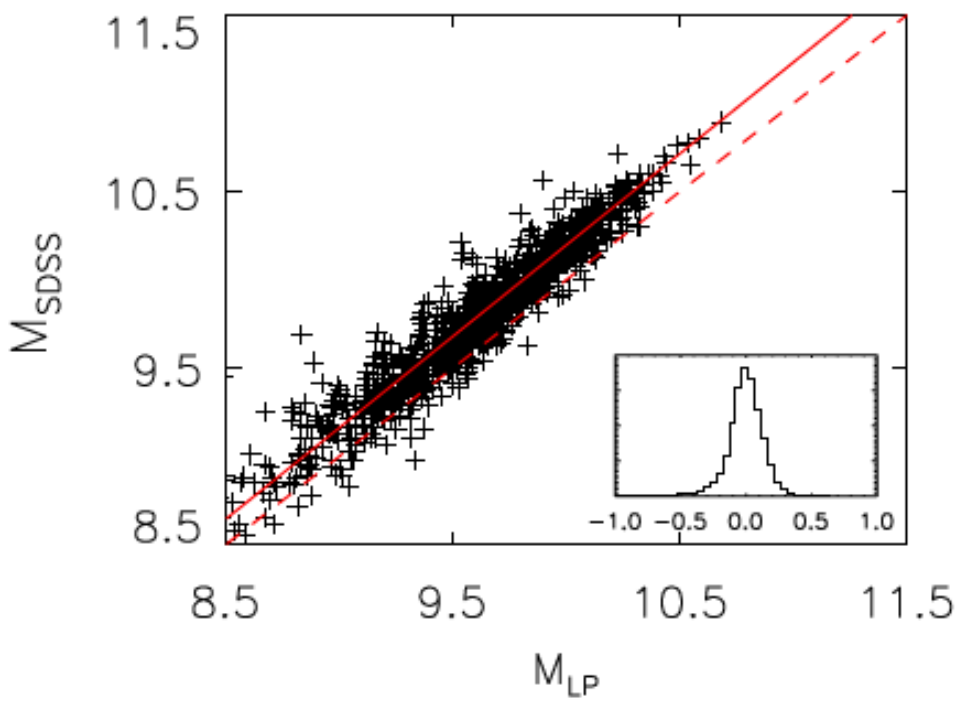
$$M_*^o(z > z_i) = (1-R) \int_{z_i}^{z} Z_g(z')\,\Psi(z')\,dz'$$

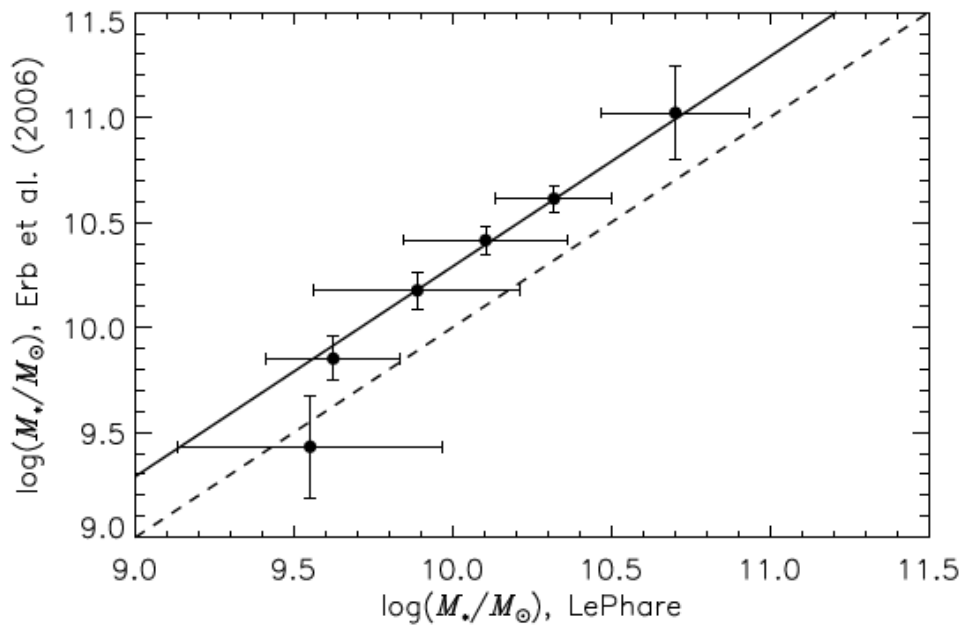
The Data

- **We make accurate relative measurements of stellar mass, SFR and metallicity (crucial)**
- Three samples of star-forming galaxies at z = [0.07, 0.78, 2.26]
- z = 0.07: ~20,000 galaxies in SDSS (Zahid+ 2011)
- z = 0.78: 1348 galaxies from DEEP2 (Zahid+ 2011)
- z = 2.26: 89 UV color selected galaxies binned into 6 mass bins (Erb+ 2006)

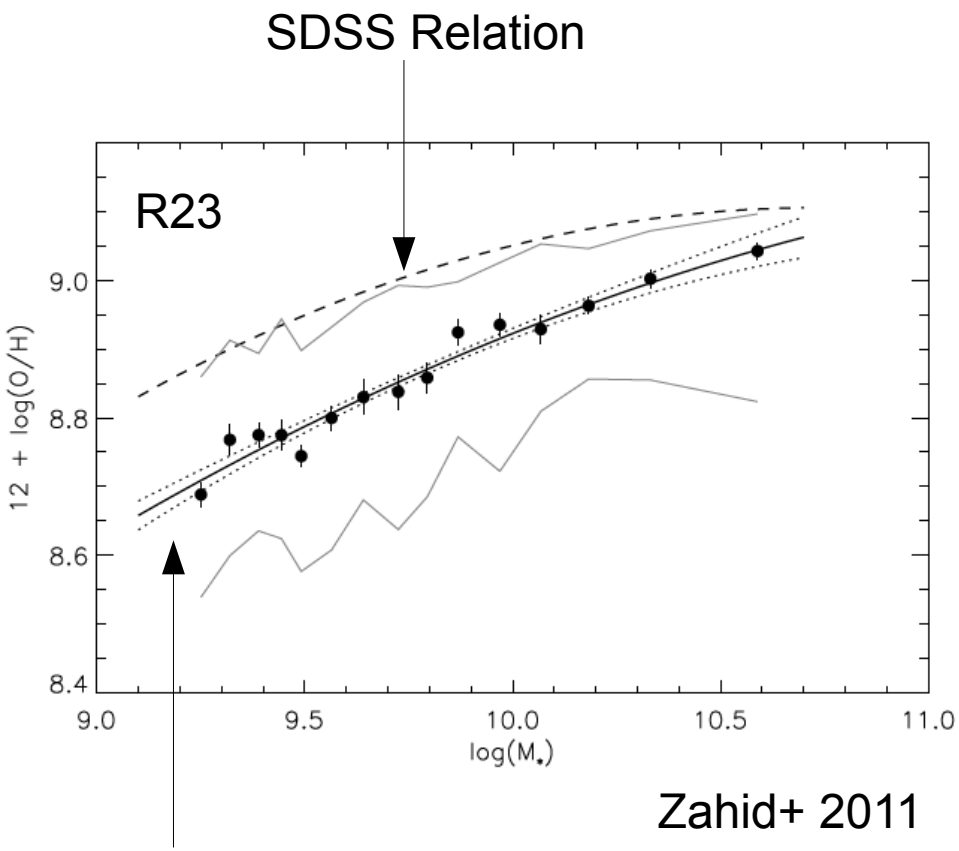
Stellar Masses

Determine M/L ratio from SED fits to photometry, scale to observed luminosity to get stellar mass



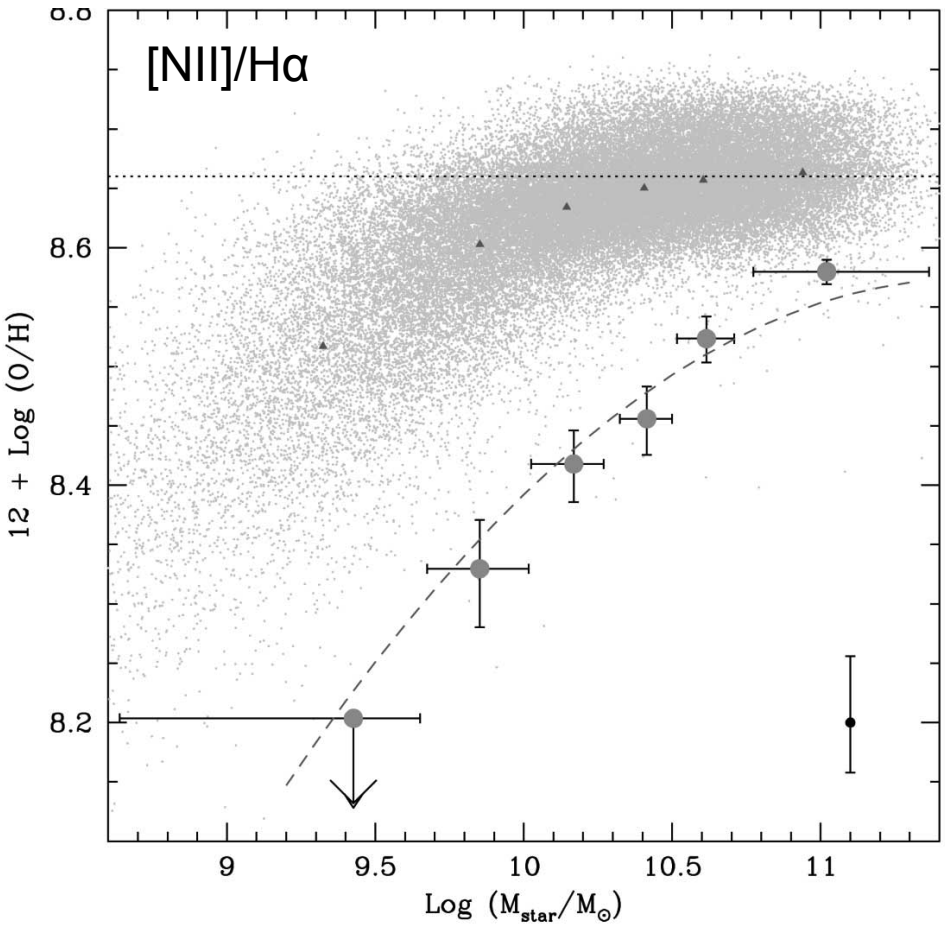


Metallicities I



Zahid+ 2011

DEEP2 Relation



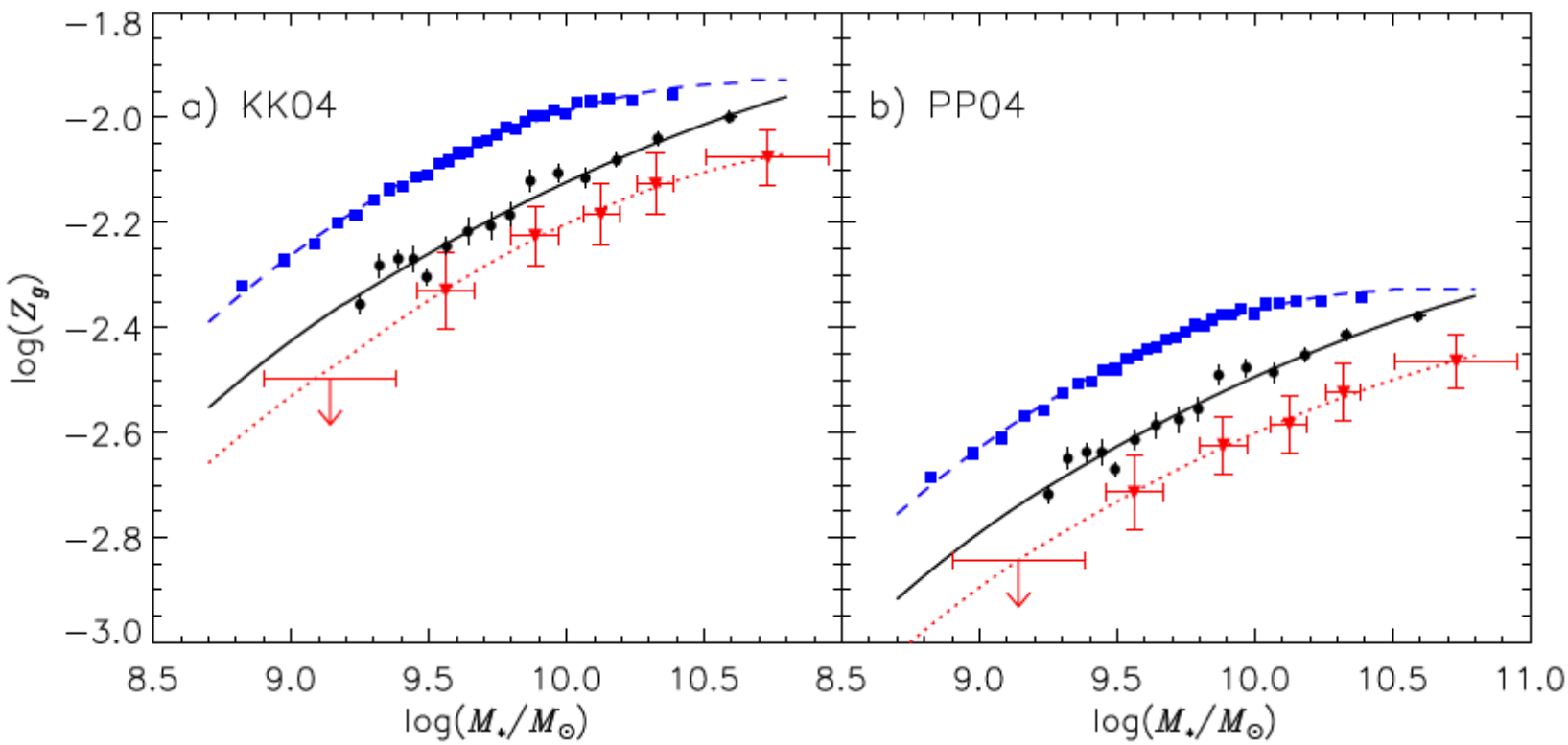
Erb+ 2006

Metallicities II

Convert to mass abundance

$$\log(Z_g) = 12 + \log(\mathrm{O/H}) - 12 - \log\left(\frac{M_O/M_H}{X M_H + Y M_{He}}\right)$$

$$= \log(\mathrm{O/H}) - \log\left(\frac{15.999/1.0079}{0.75 \cdot 1.0079 + 0.25 \cdot 4.0026}\right)$$



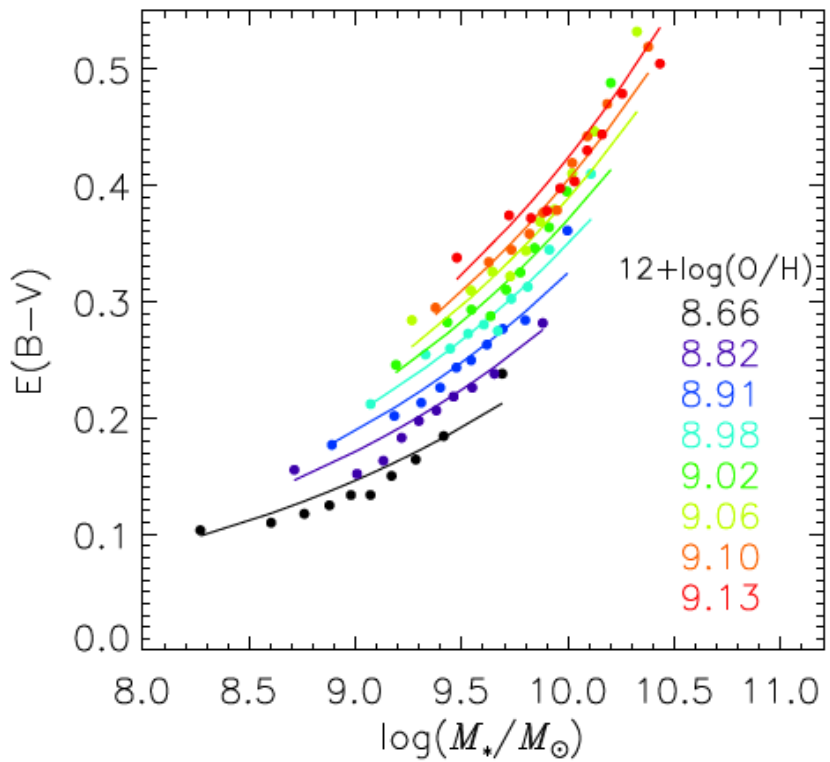
Convert to common diagnostic using Kewley & Ellison 2008 conversion constants. We adopt **average** of the two diagnostics.

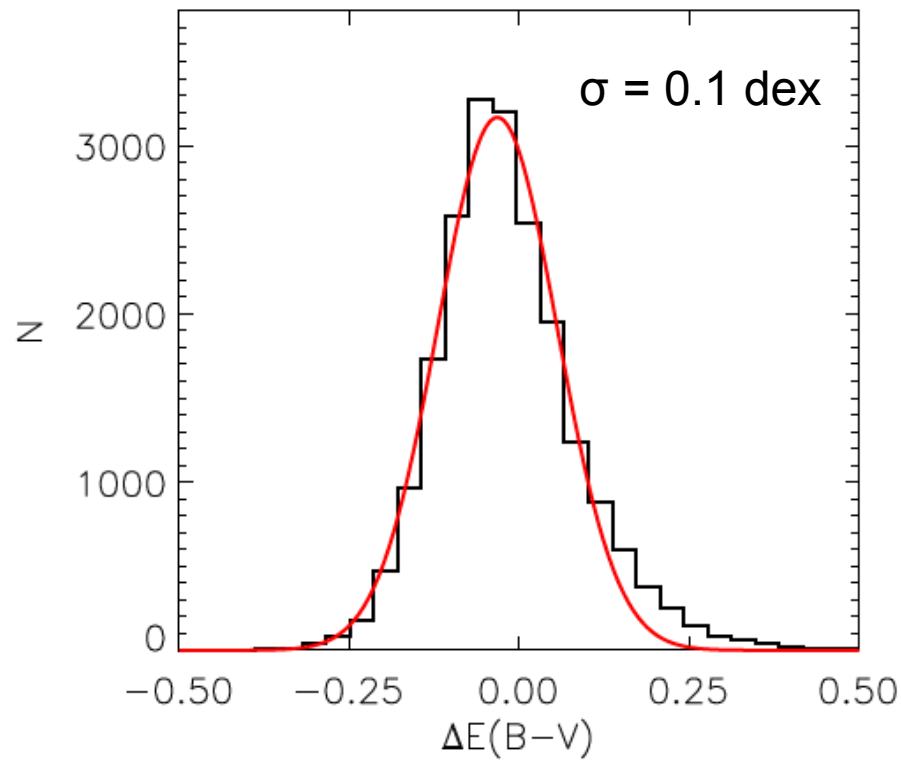
SFR I

- Balmer emission originating in HII regions act as proxy for number of ionizing photons
- Ionizing photons produced by mass, short-lived stars - assuming IMF gives SFR
- For SDSS adopt DR7 aperture and extinction corrected SFR (Brinchmann+ 2004, Salim+ 2007)
- For DEEP2 use Hβ fluxes calibrated using photometry and extinction correction inferred from local data
- For Erb+ 2006 sample use Hα luminosity with extinction correction from local data

SFR II: Extinction Correction

E(B-V) determined from SDSS sample from Balmer decrement and Cardelli+1989 extinction law.





$$\mathrm{E(B-V)} = (0.11 + 0.29 Z^{0.79}) \times M^{0.25}$$

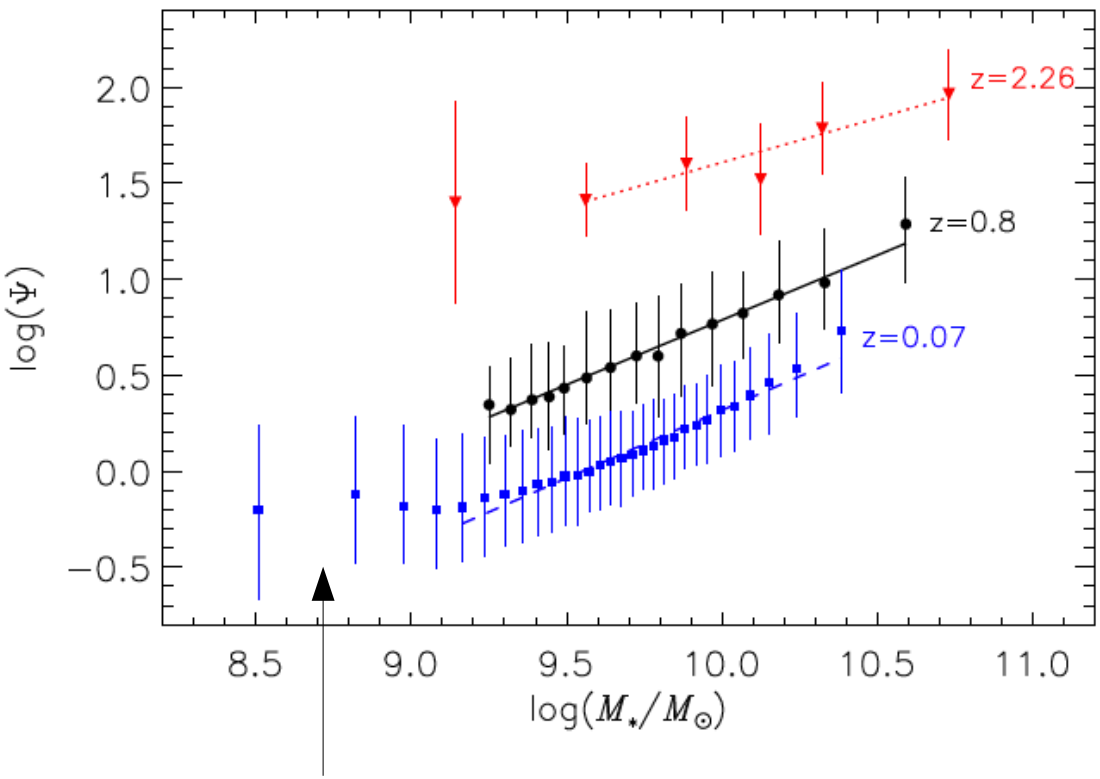
$$Z = 10^{(12+\log(\mathrm{O/H})-8)}$$

$$M = M_*/10^{10}$$

See also: Garn & Best, 2010
Sobral+ 2011
Xiao+ 2012

The Main-Sequence Relation I

- A tight relation exists between stellar mass and SFR
- The slope and scatter are constant and overall normalization increases with redshift (Noeke+ 2007, Salim+2007, Elbaz+2007, Daddi+2007, Pannella+2009)
- We observe this in our three samples



Flattening due to incompleteness

$$\log(\mathrm{SFR}) = \delta + \gamma \cdot [\log(M_*/M_\odot) - 10]$$

Sample	redshift	δ	γ
SDSS	0.07	0.317 ± 0.003	0.71 ± 0.01
DEEP2	0.78	0.800 ± 0.009	0.69 ± 0.02
E06	2.26	1.636 ± 0.028	0.49 ± 0.07

Parameterization of SFR

Separate variables in parameterization

$$\Psi(M_*, z) = \psi_o(z) \cdot f(M_*)$$

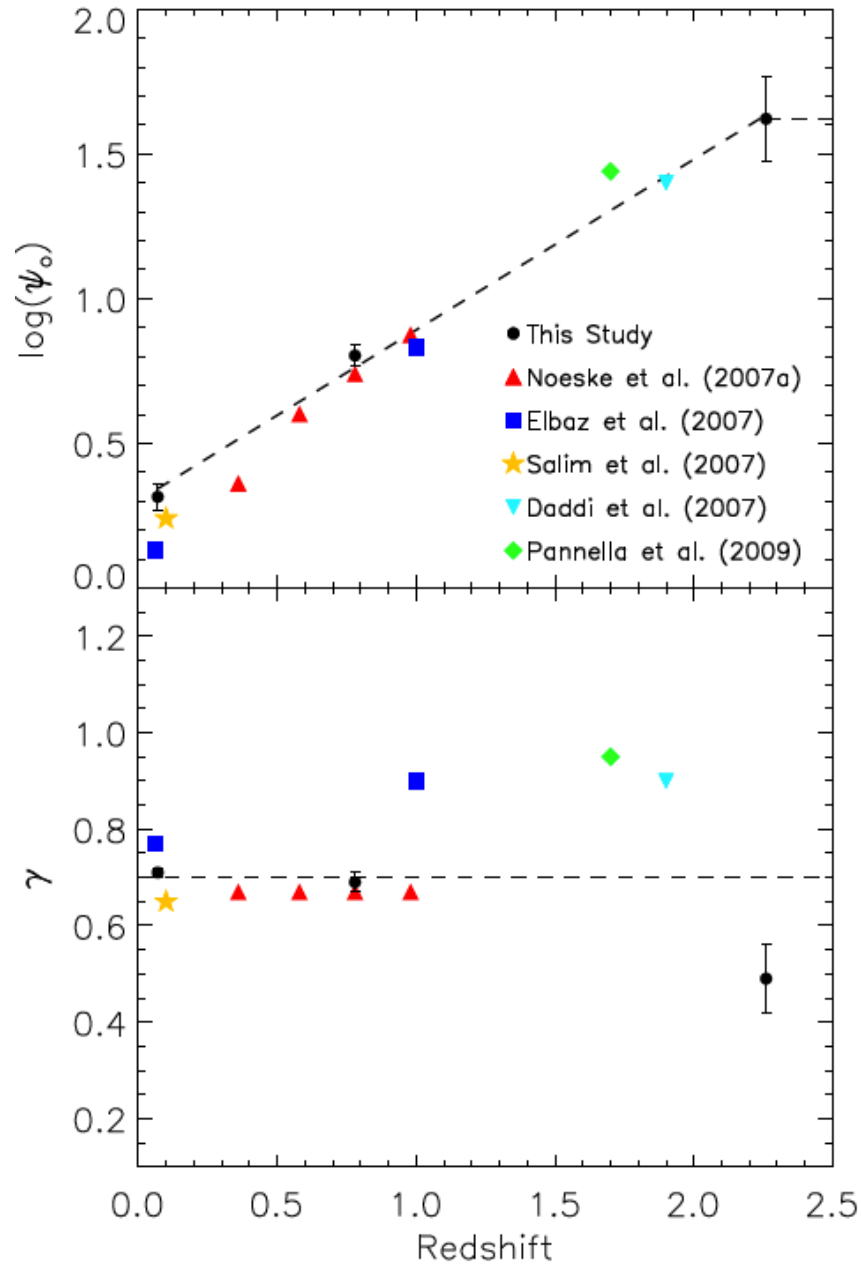
$$\psi_o(z) = \alpha \cdot \exp(\beta z)$$

$$f(M_*) = (M_*/10^{10} M_\odot)^\gamma$$

Fit to the data

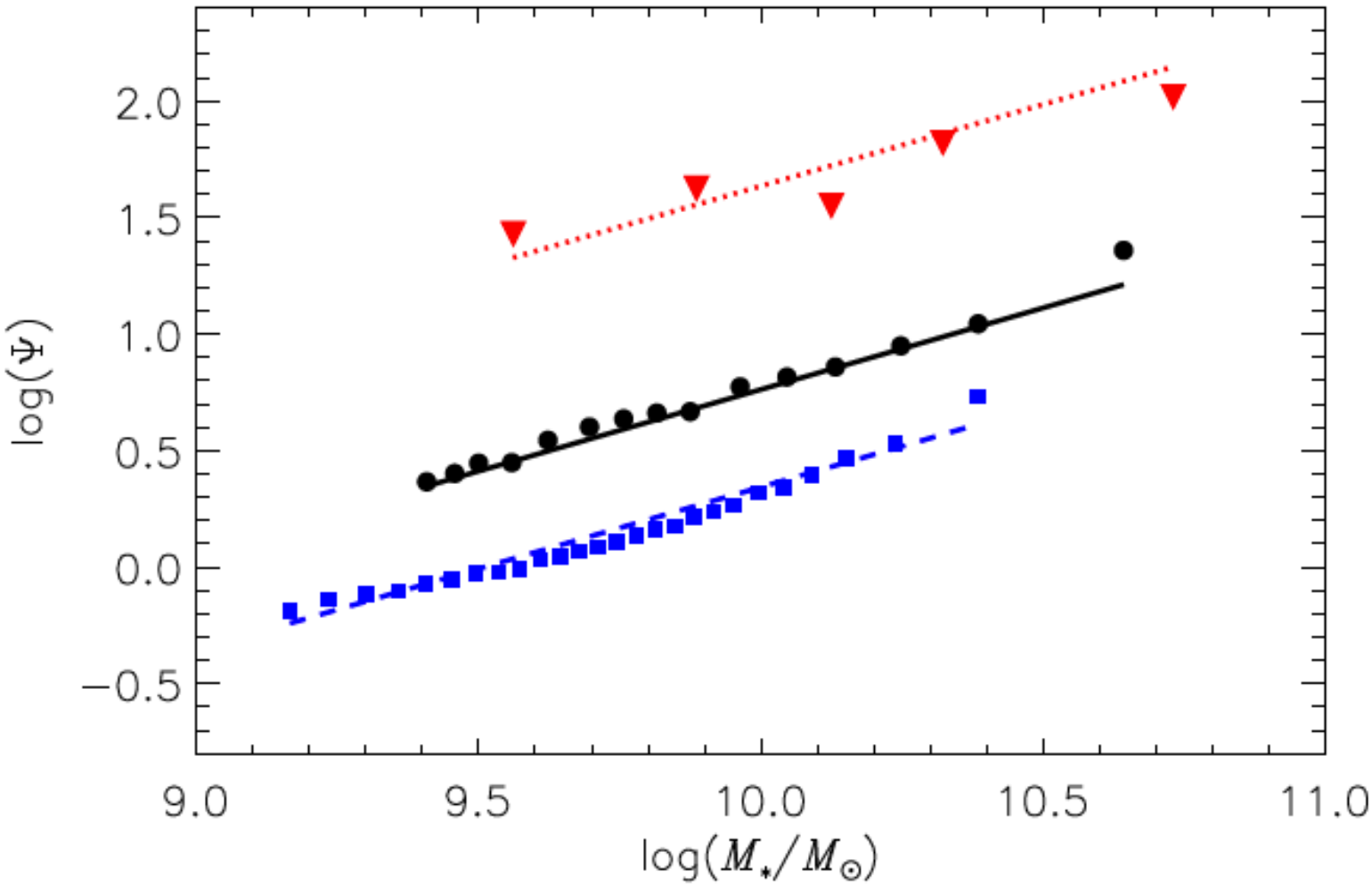
$$\Psi(M_*, z) = 2.00 \cdot \exp(1.33z) \left(\frac{M_*}{10^{10}}\right)^{0.7}$$

$$[M_\odot \, \mathrm{yr}^{-1}]$$



Fit to our data, results agrees remarkably well with values in the literature. Extinction correction works well.

Main Sequence Relation II



$$\Psi(M_*, z) = 2.00 \cdot \exp(1.33z) \left(\frac{M_*}{10^{10}}\right)^{0.7} [M_\odot\,\mathrm{yr}^{-1}]$$

The Star Formation History

$$\Psi(M_*, z) = 2.00 \cdot \exp(1.33z) \left(\frac{M_*}{10^{10}}\right)^{0.7} [M_\odot \, \mathrm{yr}^{-1}]$$

$$\frac{dM_*}{dz} = (1 - R)\,\Psi$$

$$M_*(z) = M_{*,i} + (1 - R) \int_{z_i}^{z} \Psi(M_*,\, z')\, dz'$$

- The mass of galaxy in local universe is only dependent on formation redshift (see Noeske+ 2007, Leitner 2012)
- Here we assume R is constant, carry out analysis with time dependent mass return, does not change results
- Gives us a way to identify local star-forming galaxies with their progenitors
- **Does not apply to individual galaxies, only works in a statistical sense**

Census of Oxygen I: Total Oxygen Production

$$M_T^o = P_o \frac{M_*}{1 - R}$$

Total amount of oxygen produced depends only on the total amount of star formation and the oxygen yield

Census of Oxygen II: Oxygen in the Gas-Phase

Compiled by Peeples & Shankar 2011 (McGaugh 2005, Leroy+2008, Garcia-Appadoo+2009)

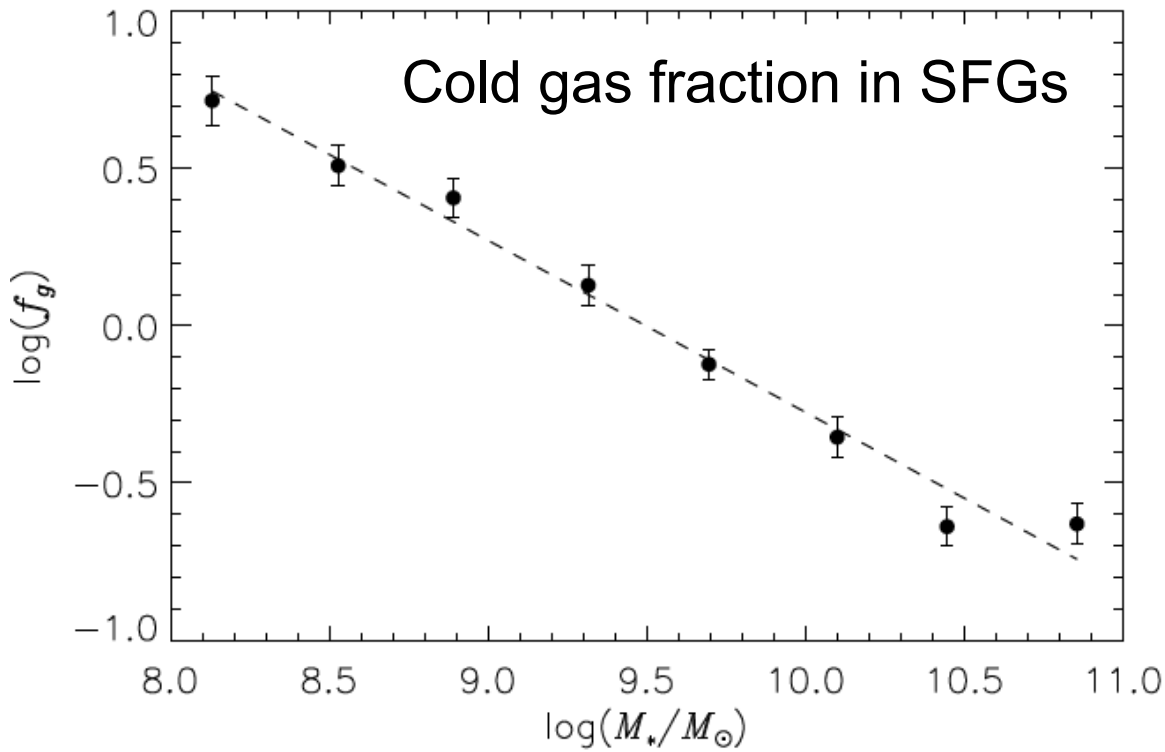
Oxygen in gas-phase determined from local MZ relation and gas fraction

$$M_g^o = Z_g M_g$$

$$f_g = M_g / M_*$$

$$M_g = f_g M_*$$

$$M_g^o = Z_g f_g M_*$$



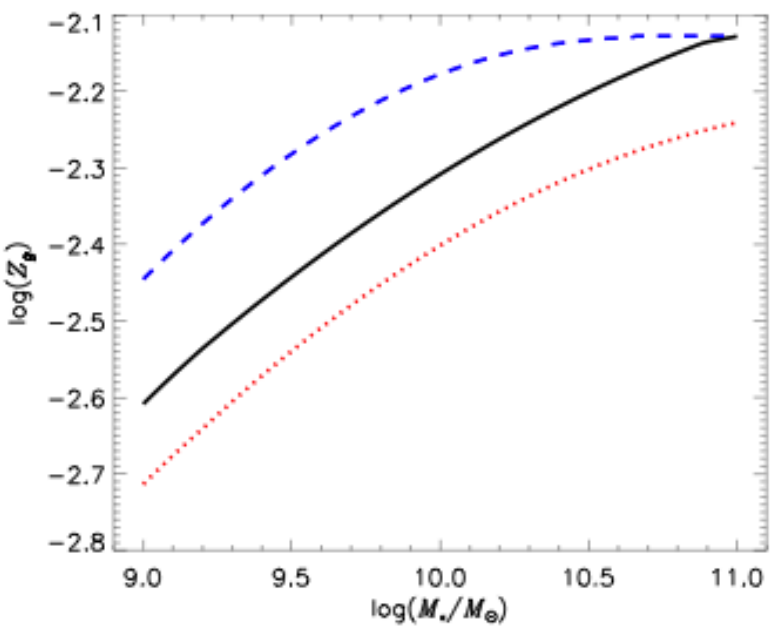
$$\log(f_g) = (-0.28 \pm 0.03) - (0.55 \pm 0.03) \cdot [\log(M_*/M_\odot) - 10]$$

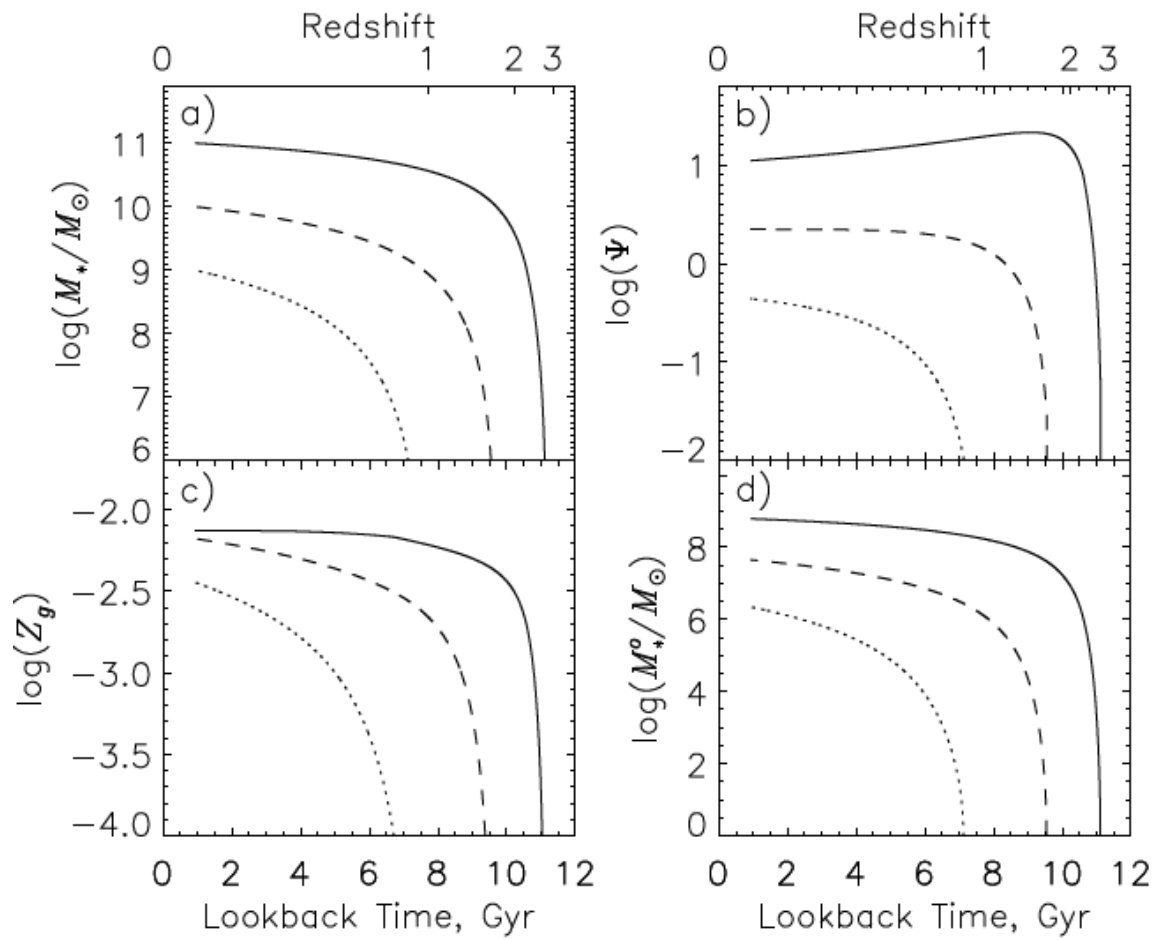
Add 0.1 dex for ionized gas

Census of Oxygen III: Oxygen Locked Up in Stars

$$M_*^o(z > z_i) = (1 - R) \int_{z_i}^{z} Z_g(z') \cdot \Psi(z')\, dz'$$

Interpolate metallicity in mass and redshift in order to determine chemical evolution history

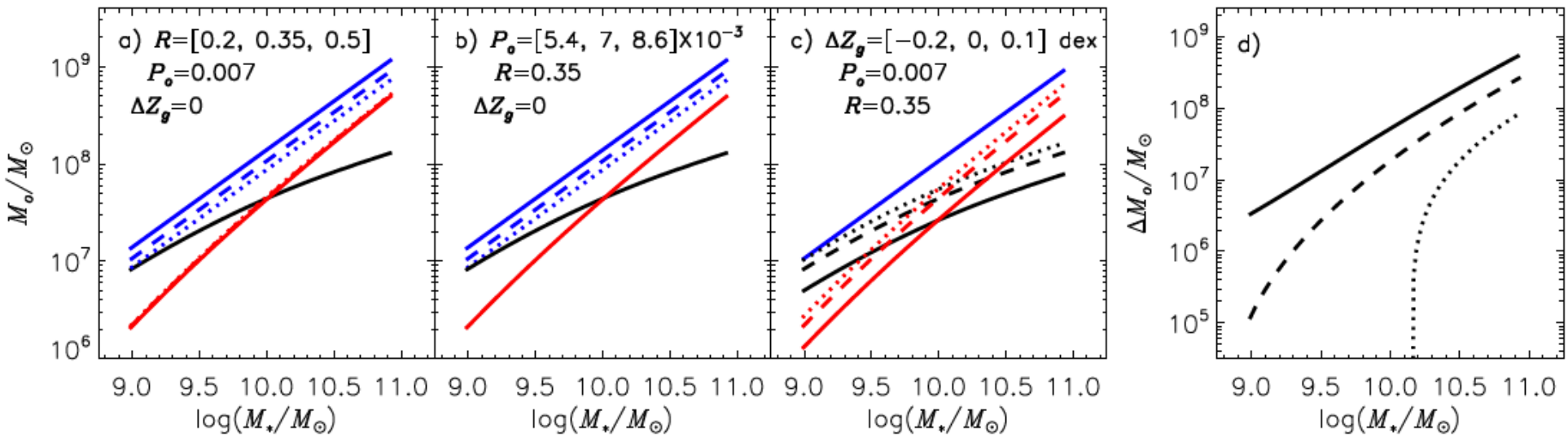




Results: An Oxygen Deficit

3 free parameters in model:

R - the return fraction
P_o - the oxygen yield
ΔZ_g - absolute calibration of metallicity

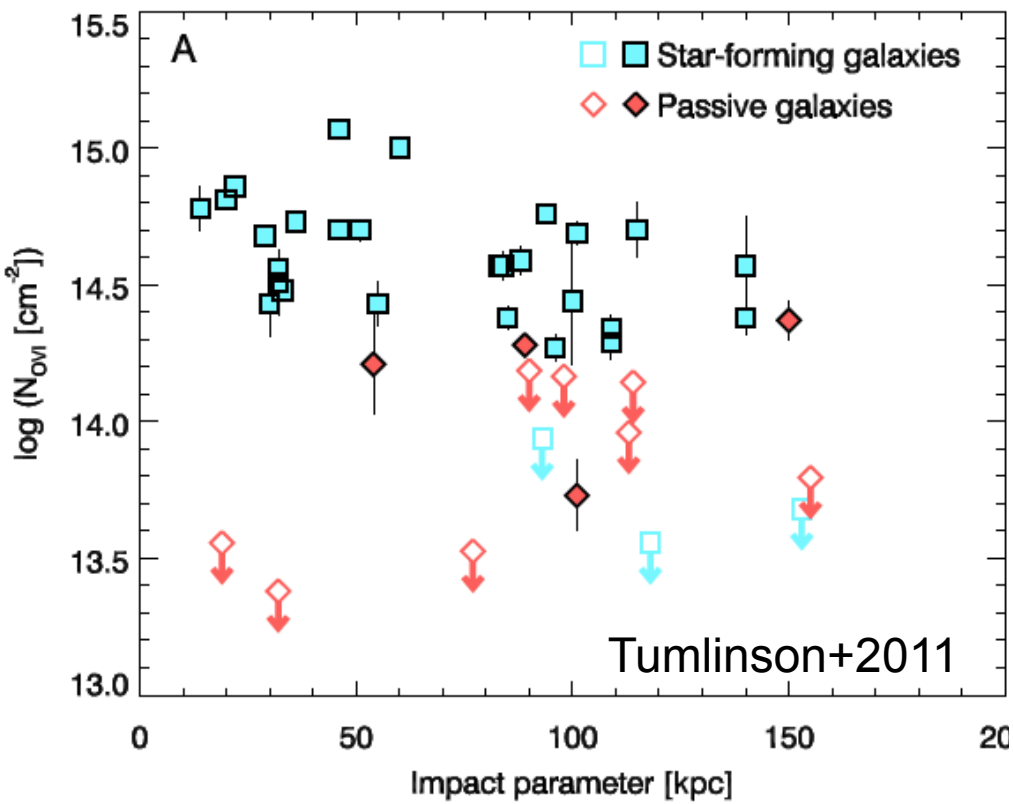


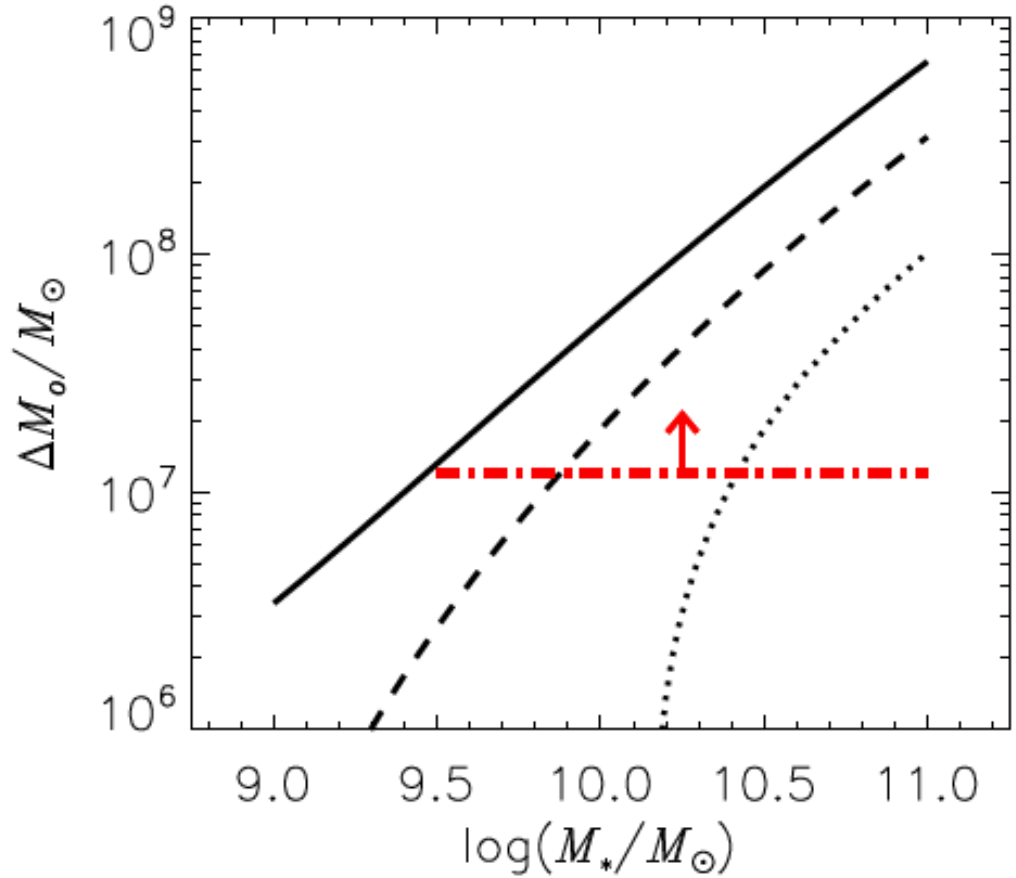
Blue is total amount of oxygen produced
Black is amount of oxygen in the gas-phase
Red is amount of oxygen in stars

Define oxygen deficit as: $\Delta M^o = M_T^o - M_g^o - M_*^o$

Results only depend on $\Delta Z_g(1-R)/P_o$

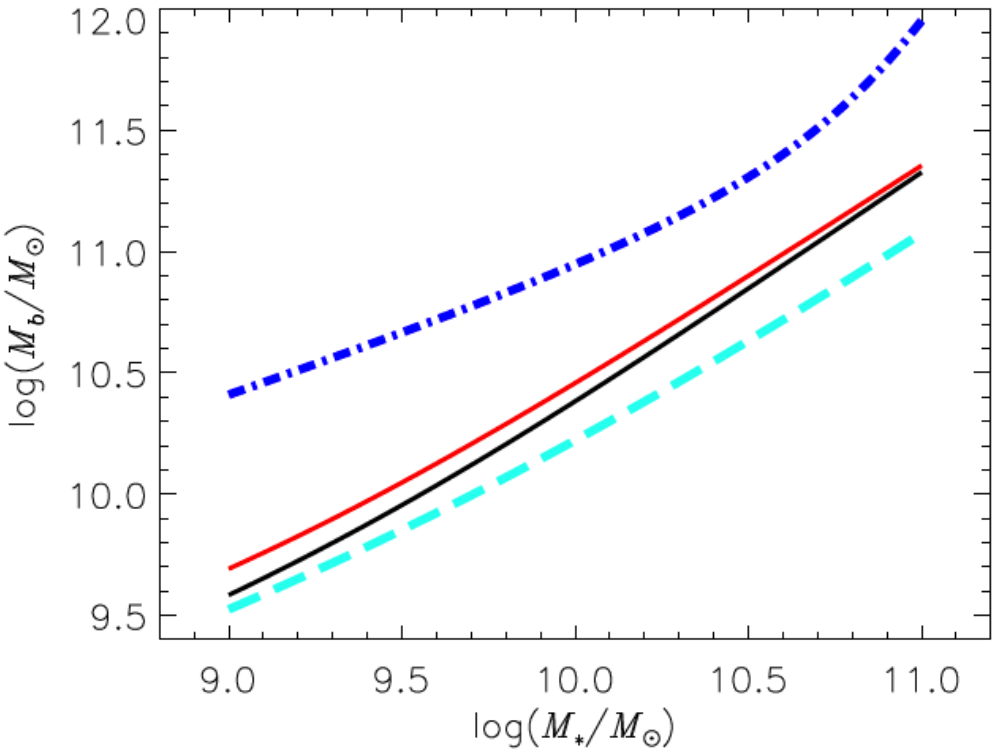
Oxygen in Halos of SFGs

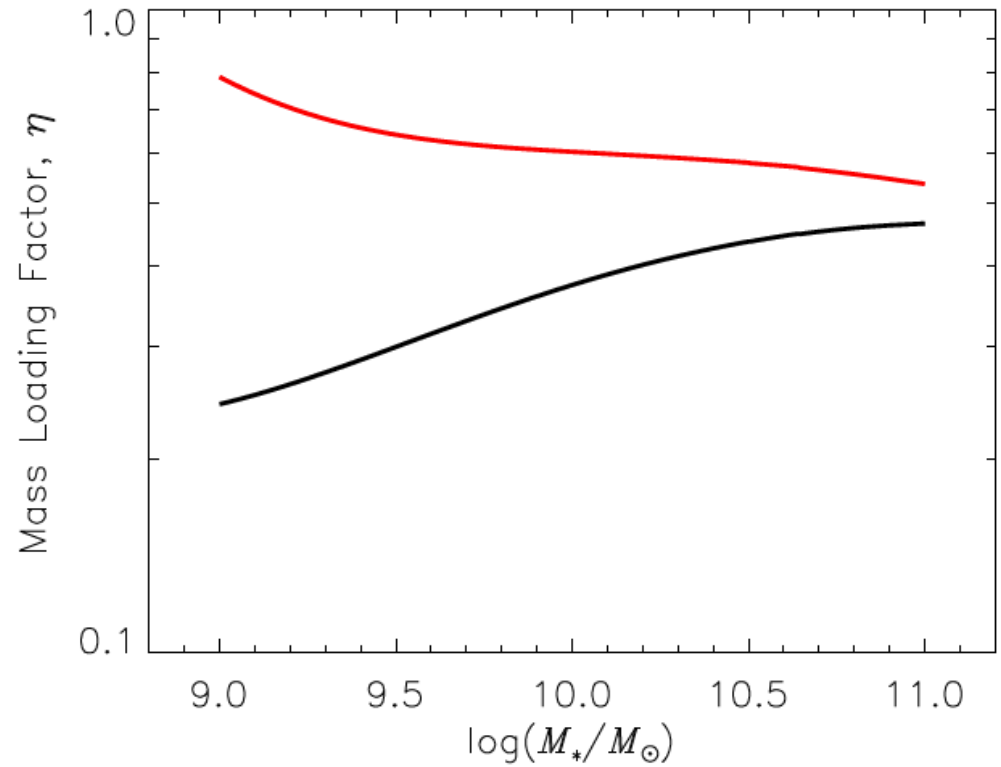




Tumlinson+2011 estimate >$10^7 M_\odot$ oxygen in halos of star-forming galaxies

Baryonic Mass Loss





Enriched outflow

$$\Delta M_b = \frac{M_T^o - M_g^o - M_*^o}{P_o} = \frac{\Delta M_o}{P_o}$$

Uniform outflow

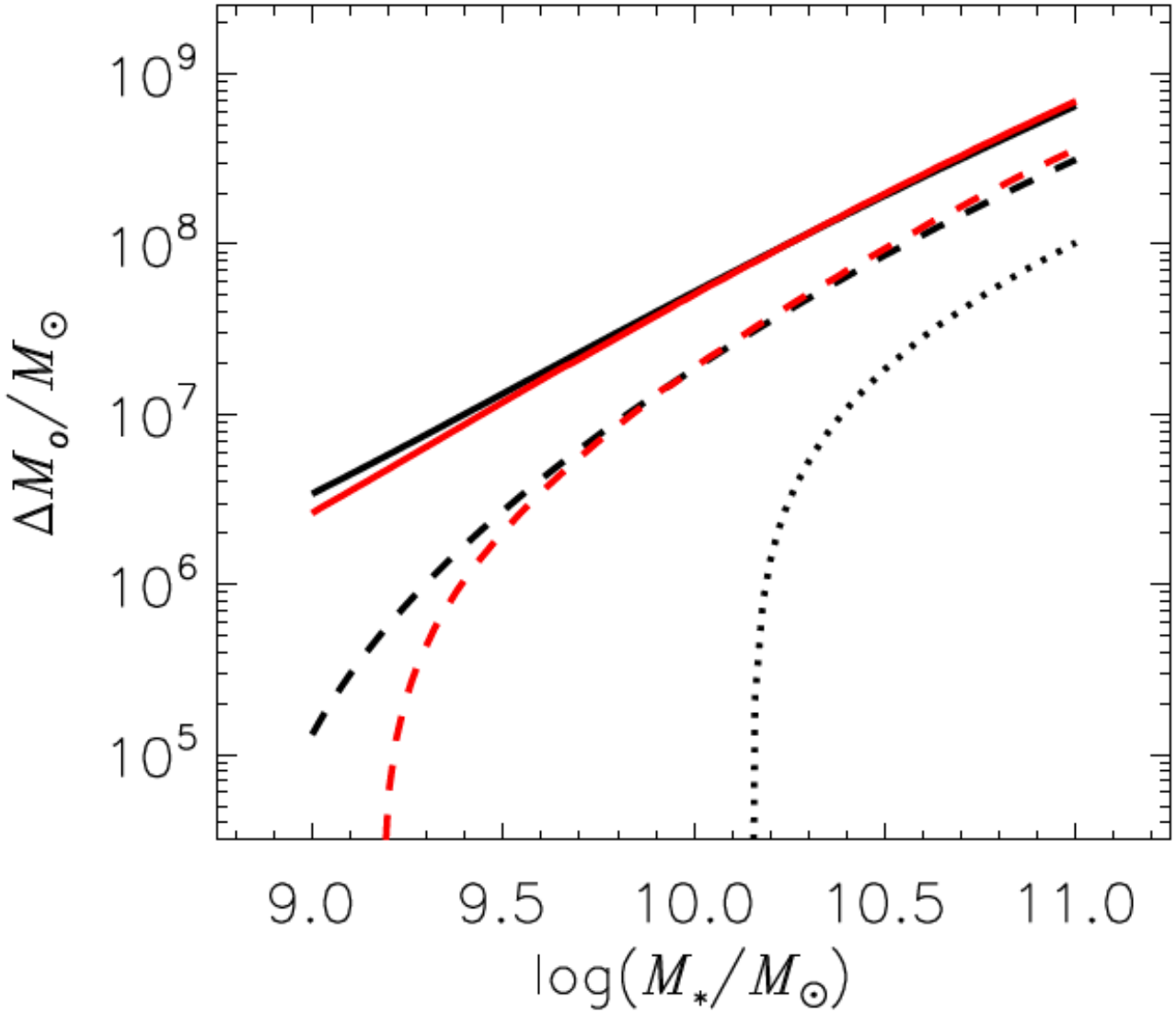
$$\Delta M_{b\psi} = \frac{\Delta M_o}{Z_\psi} \qquad Z_\psi = \frac{\int_{z_i}^{z} \Psi Z_g dz}{\int_{z_i}^{z} \Psi dz}$$

Average Mass-Loading

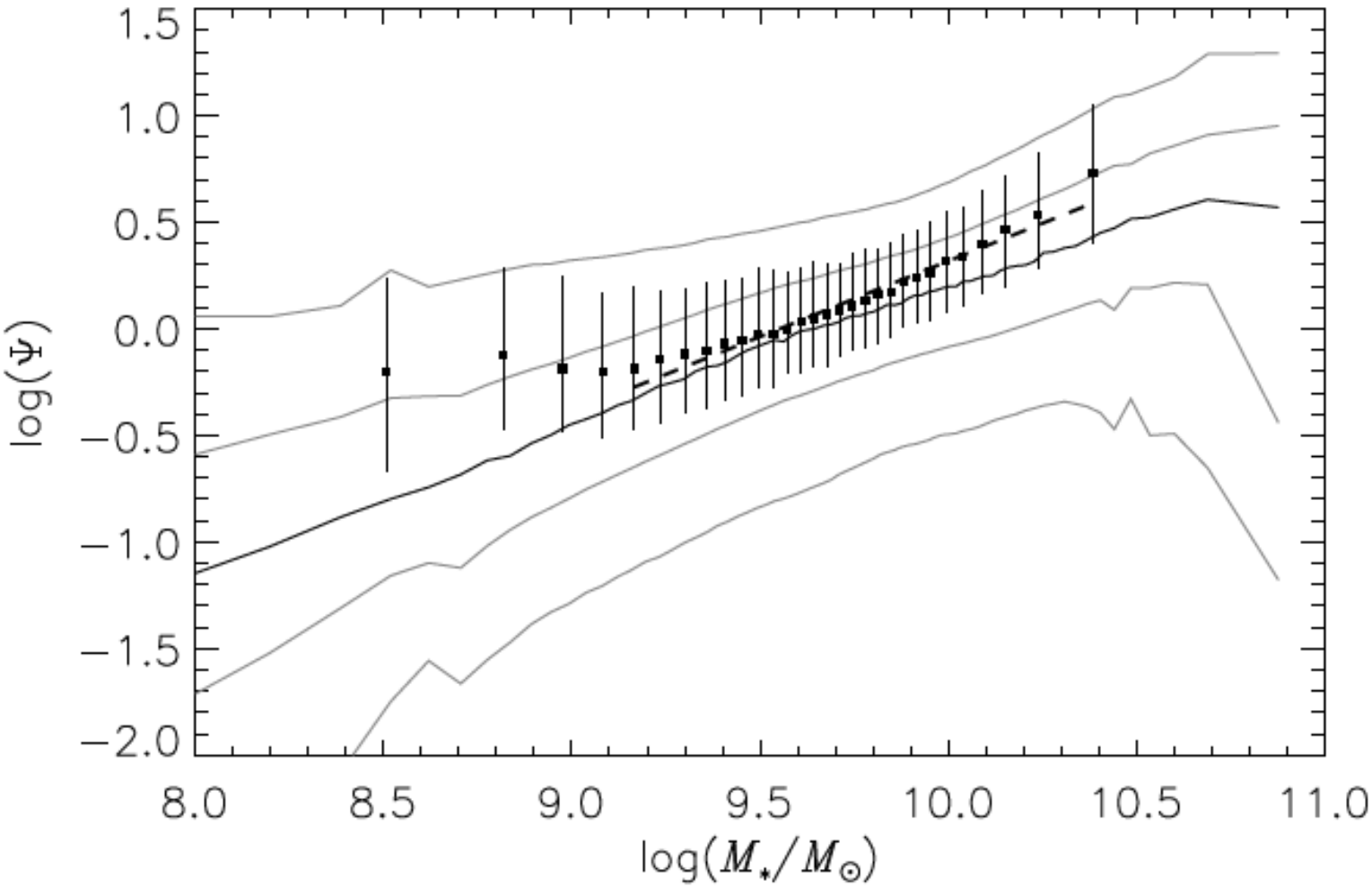
$$\eta = \frac{\Delta M_b}{M_*/(1-R)}$$

Conclusions

- First self-consistent, empirical model census study of oxygen
- Mass loss a ubiquitous process in star-forming galaxies, scaling favors a momentum driven wind
- Has important impact for origin of MZ relation
- Amount of oxygen found in CGM consistent with oxygen deficit
- Mass loss from galaxies can only account for a fraction of missing baryons
- Absolute calibration of abundance scale and stronger constraints on oxygen yield are crucial for rigorous quantitative analysis



$$\dot{M}_R(t) = \int_0^t \Psi(t')\dot{f}_{mr}(t-t')dt'$$


1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
log(Ψ)
8.0
8.5
9.0
9.5
10.0
10.5
11.0
log(M*/M⊙)