Decoding Galactic Chemical Evolution with Gas-phase and Stellar Abundances

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Ohio State

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YCAA Seminar

in collaboration with

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Mass—Metallicity Relation:

- gas-phase abundances of galaxies as a function of stellar mass (and SFR)

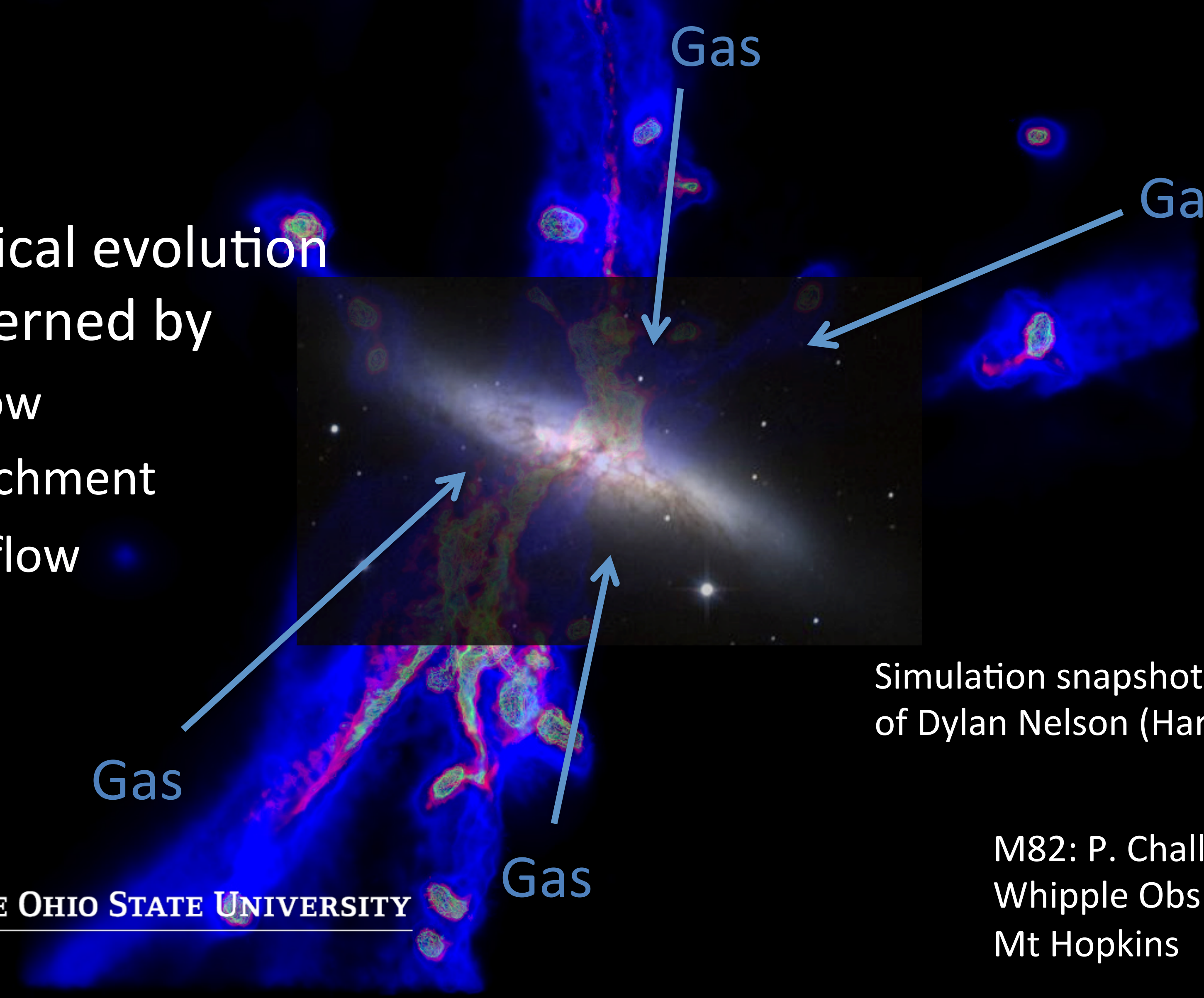
Principal Component Abundance Analysis (PCAA):

- use PCA to characterize patterns in the abundances of Milky Way stars

Pristine Gas Inflow from IGM

Chemical evolution is governed by

- Inflow
- Enrichment
- Outflow



Simulation snapshot courtesy of Dylan Nelson (Harvard)

M82: P. Challis, Whipple Obs. Mt Hopkins

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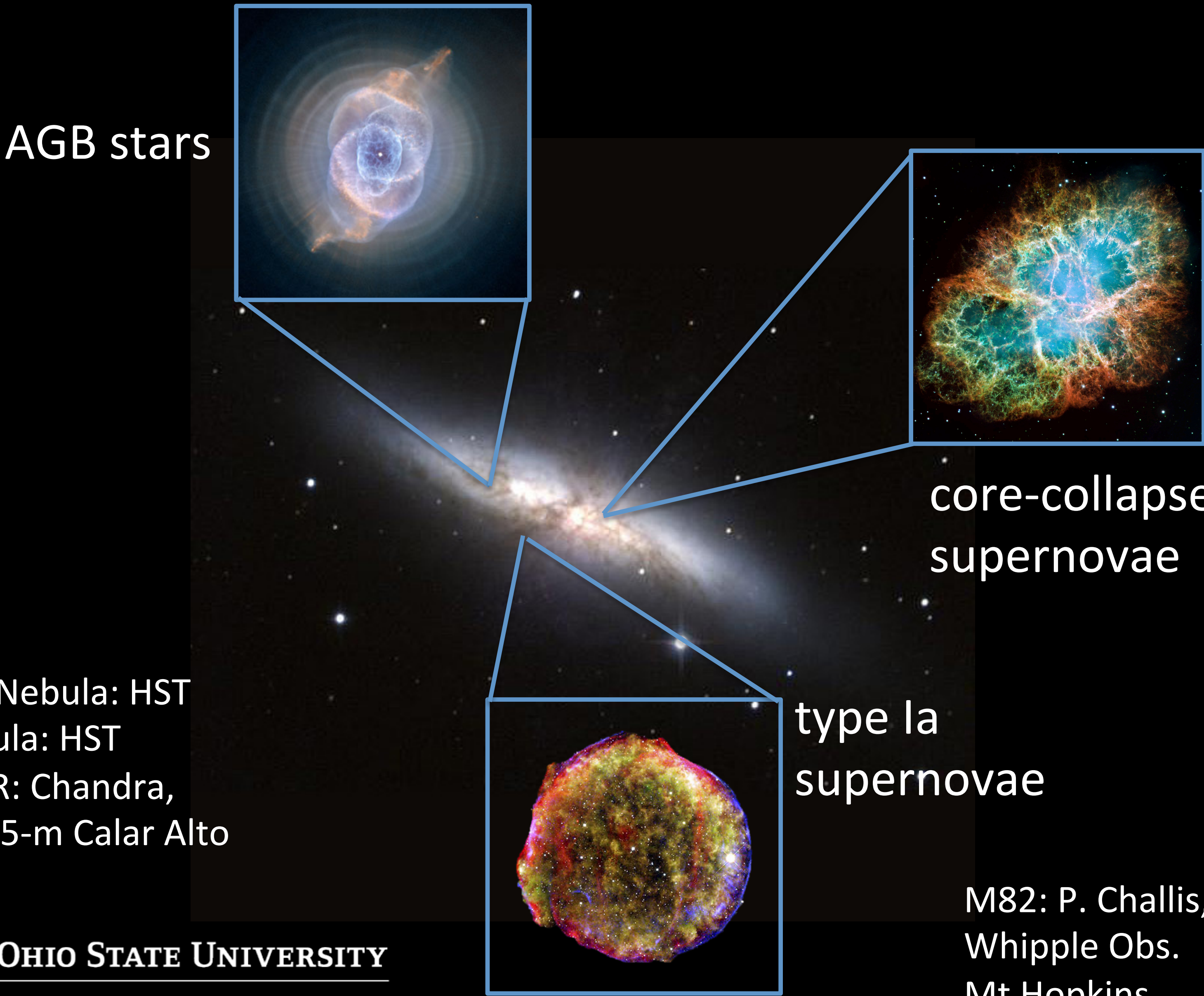
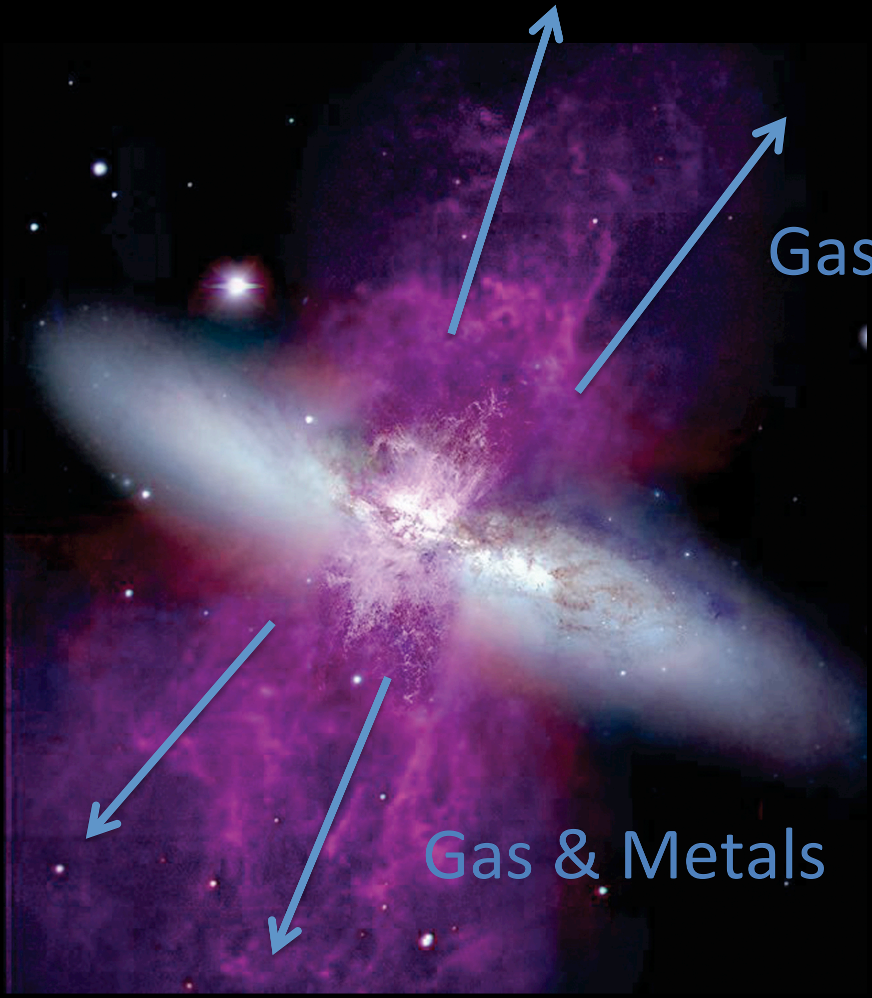
Metal Production in Stars



Cat's Eye Nebula: HST
Crab Nebula: HST
Tycho SNR: Chandra, Spitzer, 3.5-m Calar Alto

M82: P. Challis, Whipple Obs. Mt Hopkins

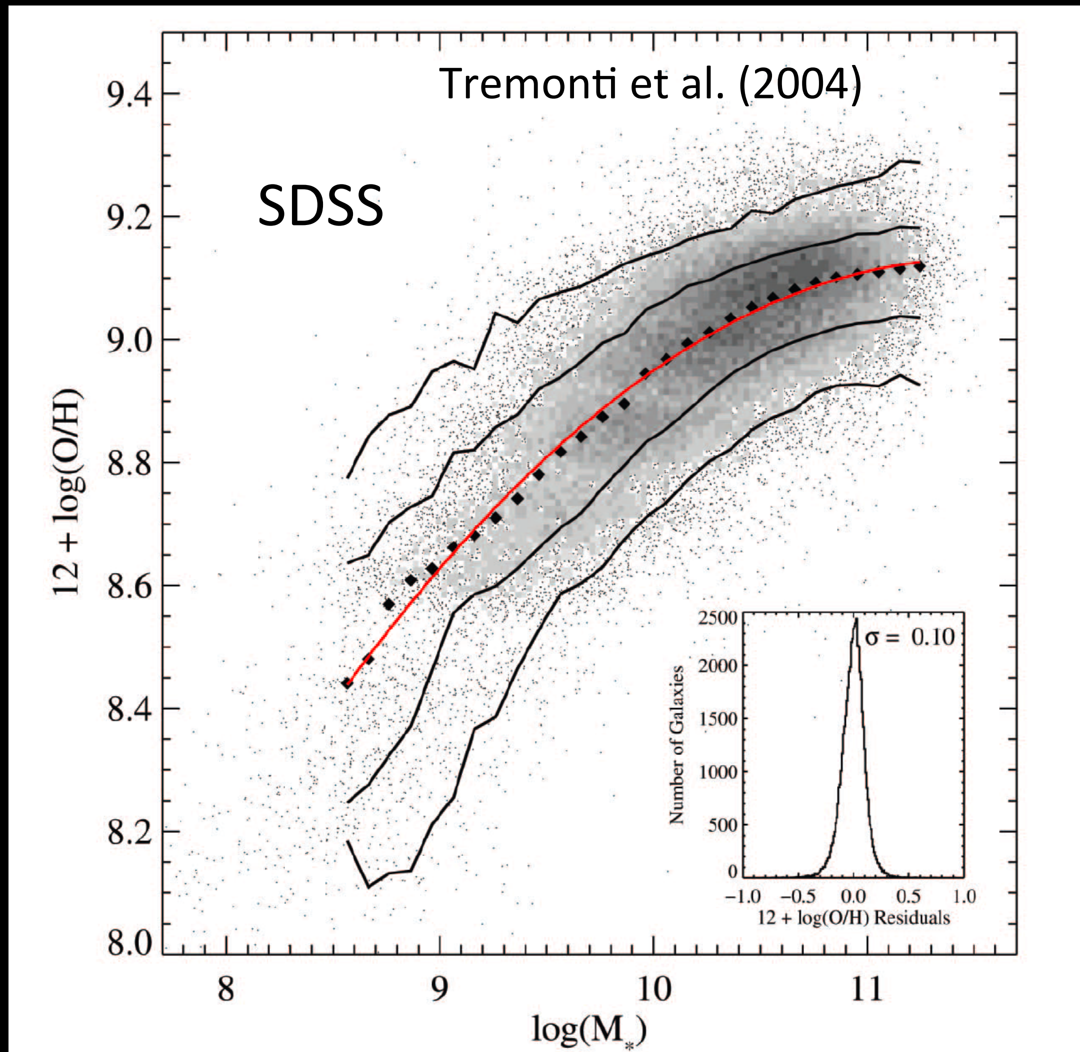
Metal Ejection in Galactic Winds



M82: WIYN telescope & HST (Hα → purple)

Mass—Metallicity Relation

Gas-phase Oxygen Abundance



oxygen → ½ of metal abundance & bright optical emission lines

gas-phase → recent enrichment history

Stellar Mass

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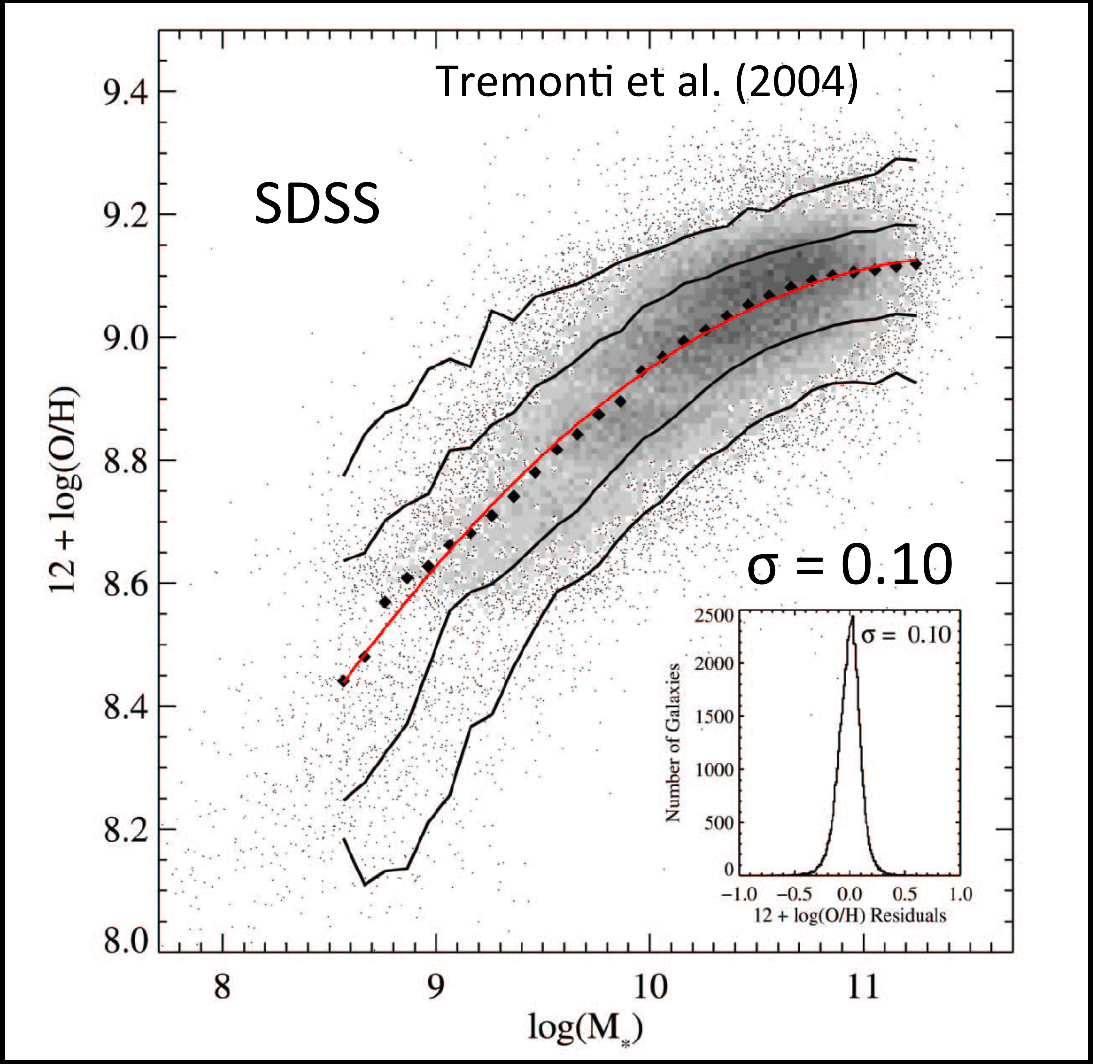
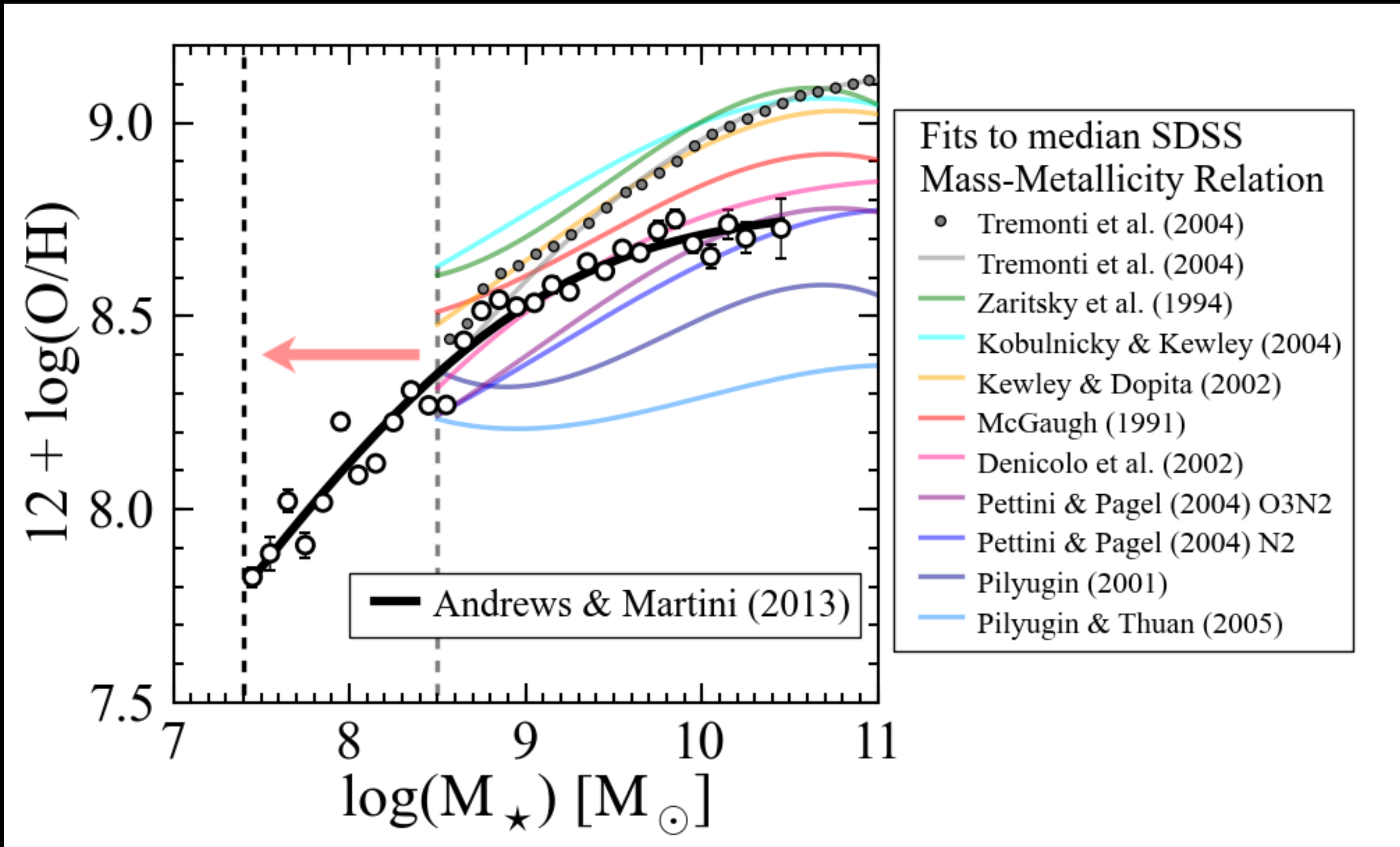
Mass—Metallicity Relation



Features:

- normalization
- low mass slope
- turnover mass
- scatter
- evolution

Direct Method Mass—Metallicity Relation



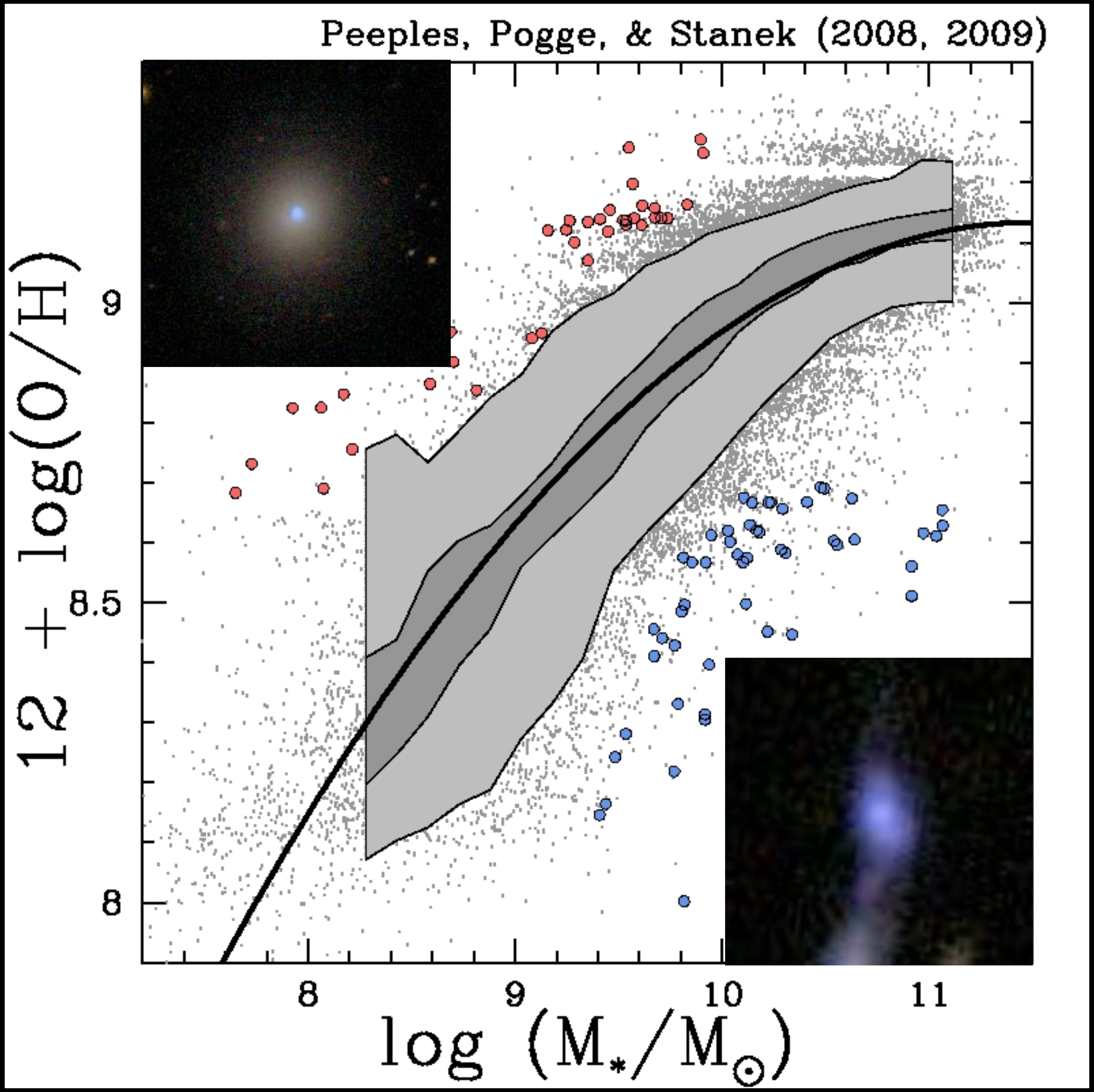
Fits from Kewley & Ellison (2008)

Outliers from the Mass—Metallicity Relation

Observations:

scatter in Mass—Metallicity correlated:

- lower SFR → higher O/H
- higher SFR → lower O/H



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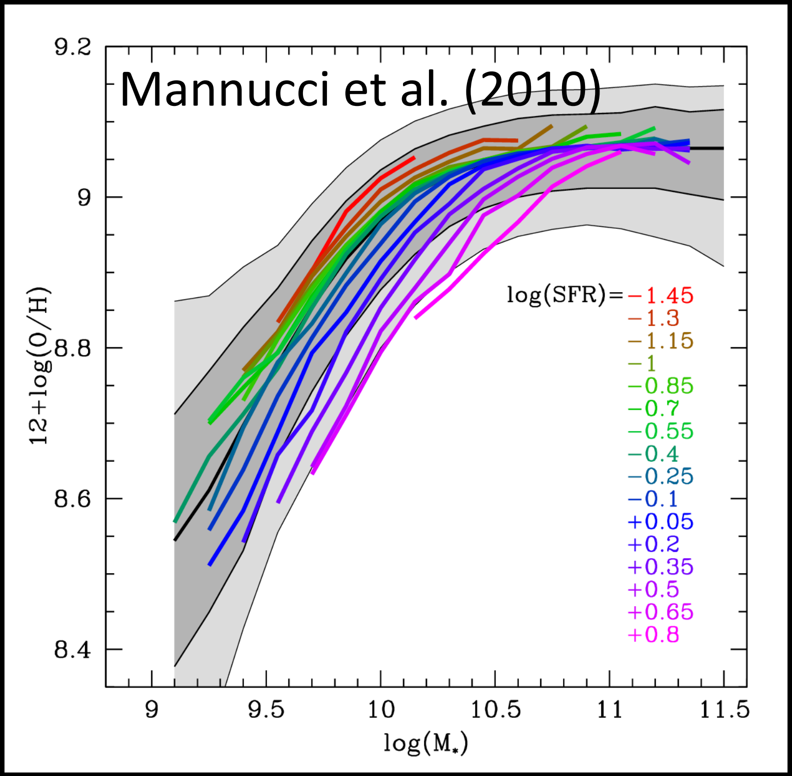
slide courtesy of Molly Peeples

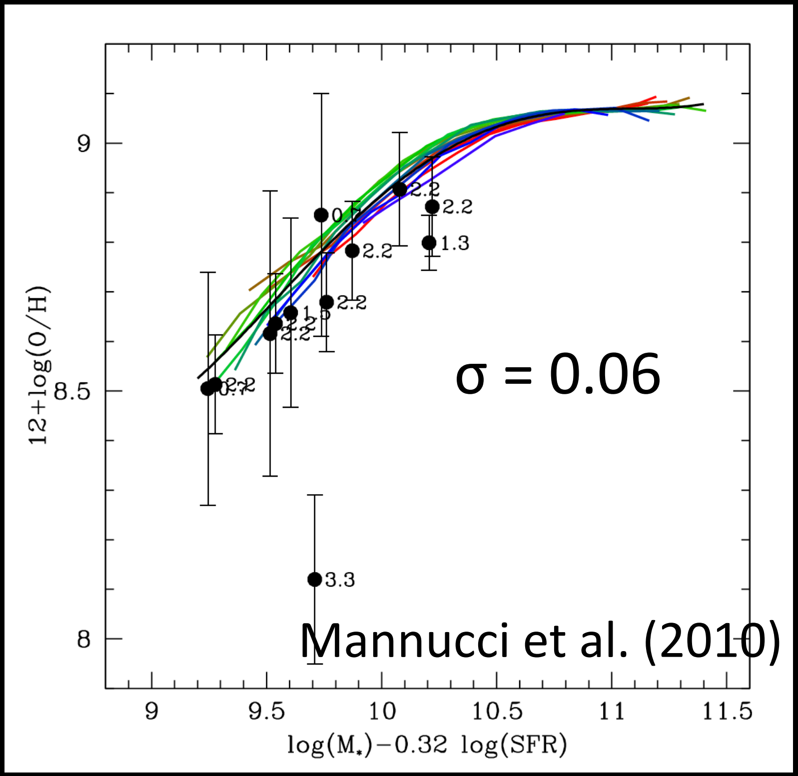
Mass—Metallicity—SFR Relation

Fundamental Metallicity Relation

12 + log(O/H)



→



Stellar Mass

$\log(M_\star) - 0.32 \log(\mathrm{SFR})$

Mass—Metallicity—SFR relation:

- less scatter
- no evolution out to z ~ 2.5

$$\mu_\alpha = \log(\mathrm{M}_*) - \alpha \log(\mathrm{SFR})$$

Mannucci et al. (2010): α = 0.32

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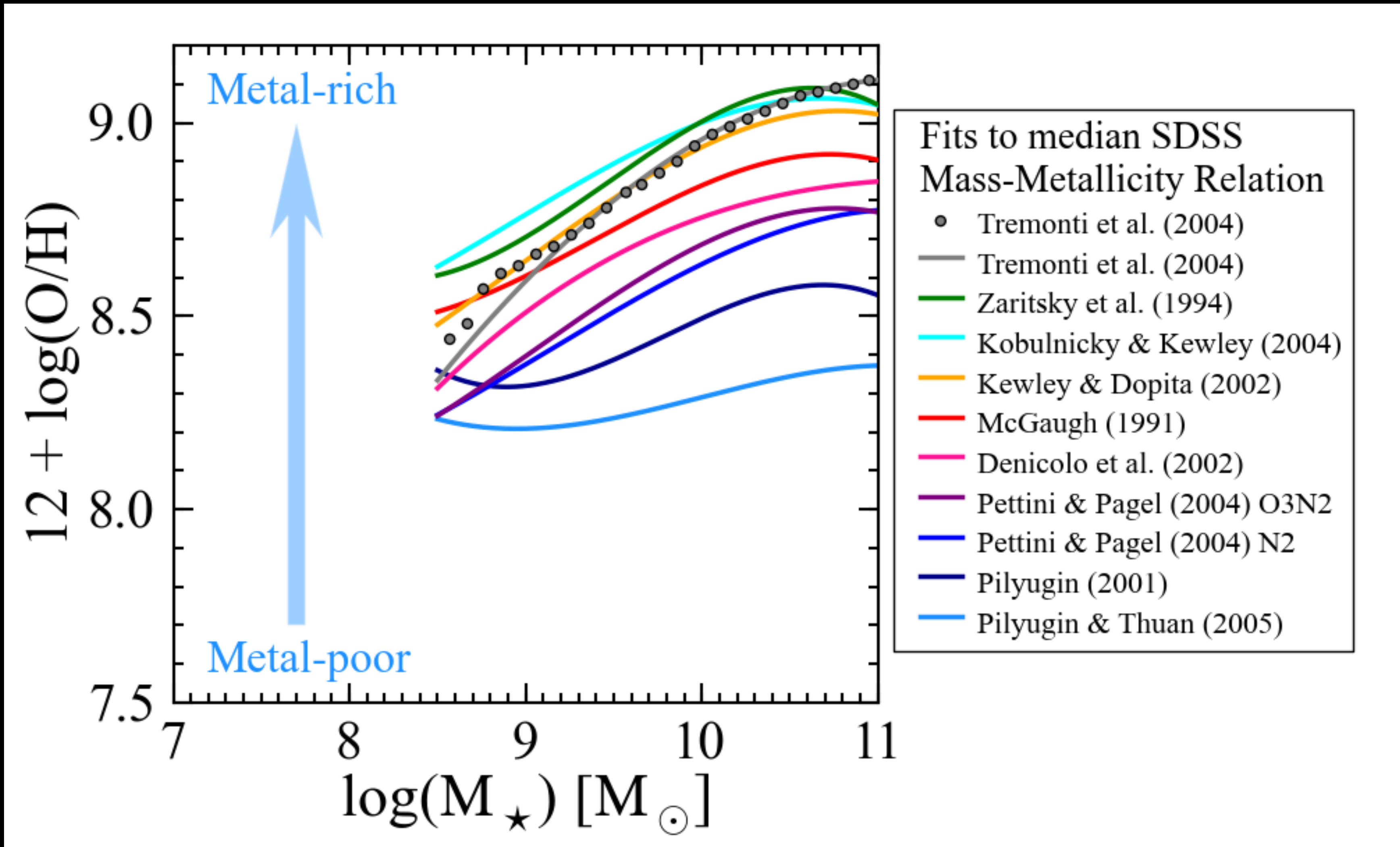
see also Lara-López et al. (2010)

Strong line metallicity determinations suffer from large systematic uncertainties.



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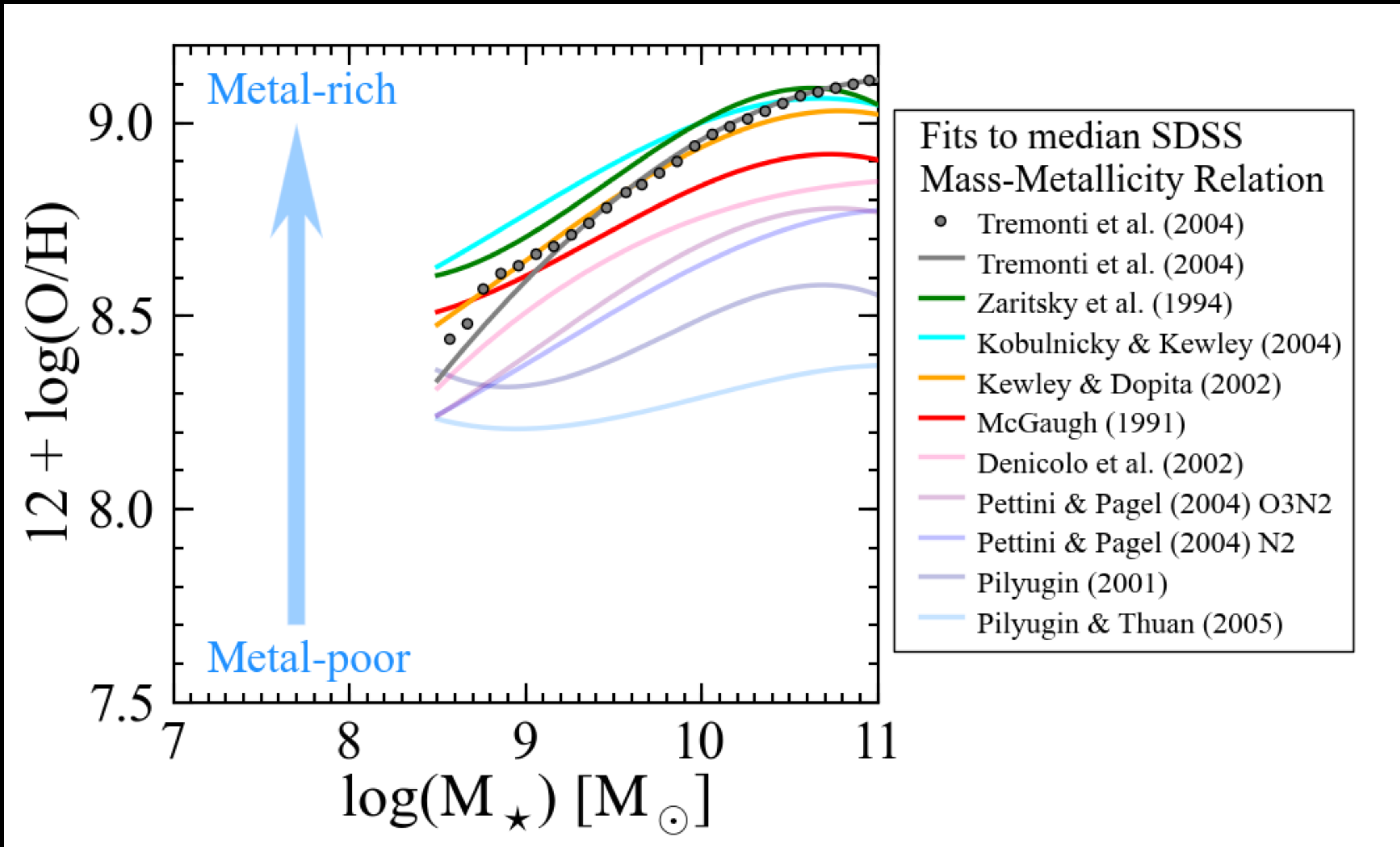
Fits from Kewley & Ellison (2008)

Theoretical Calibrations



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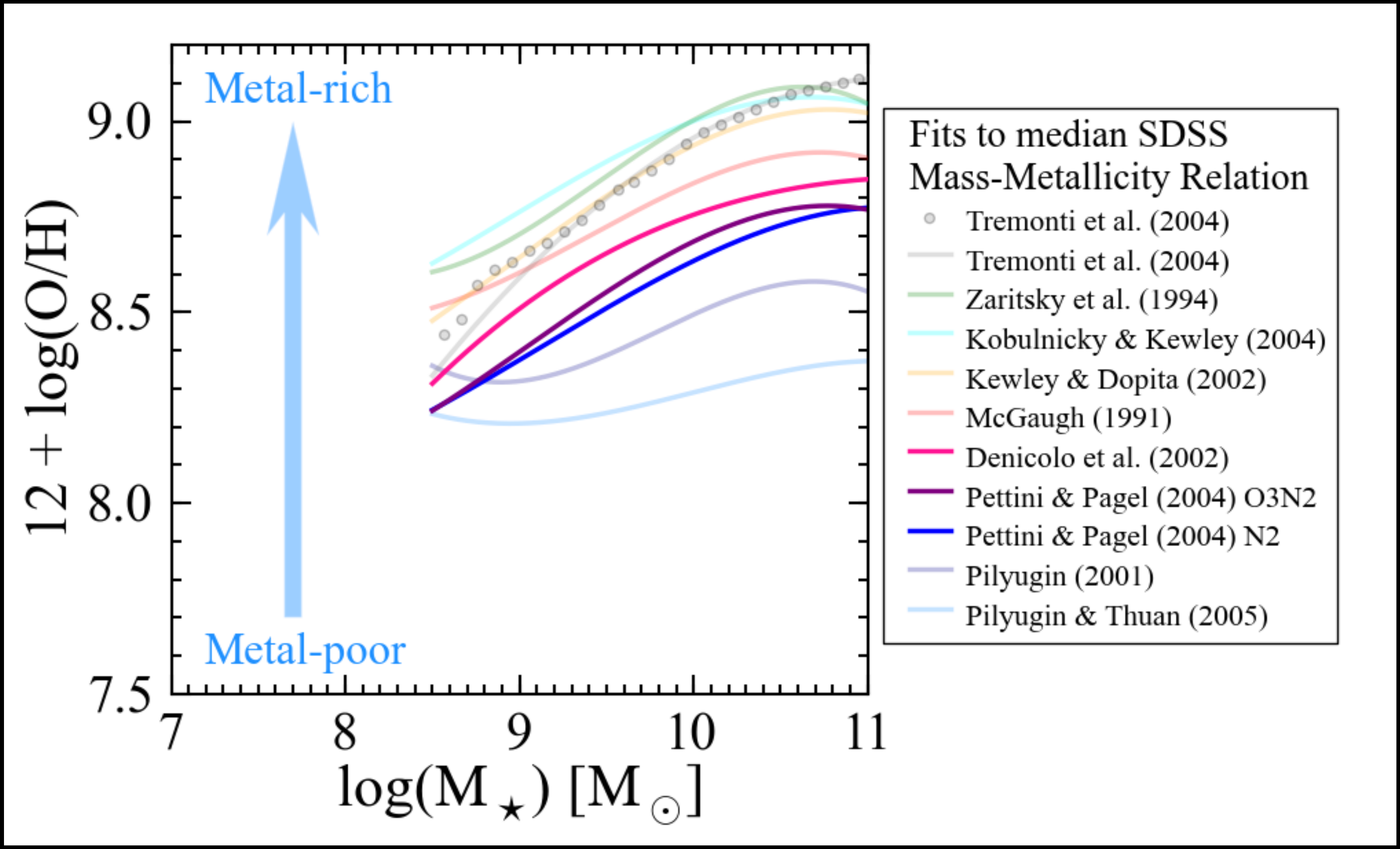
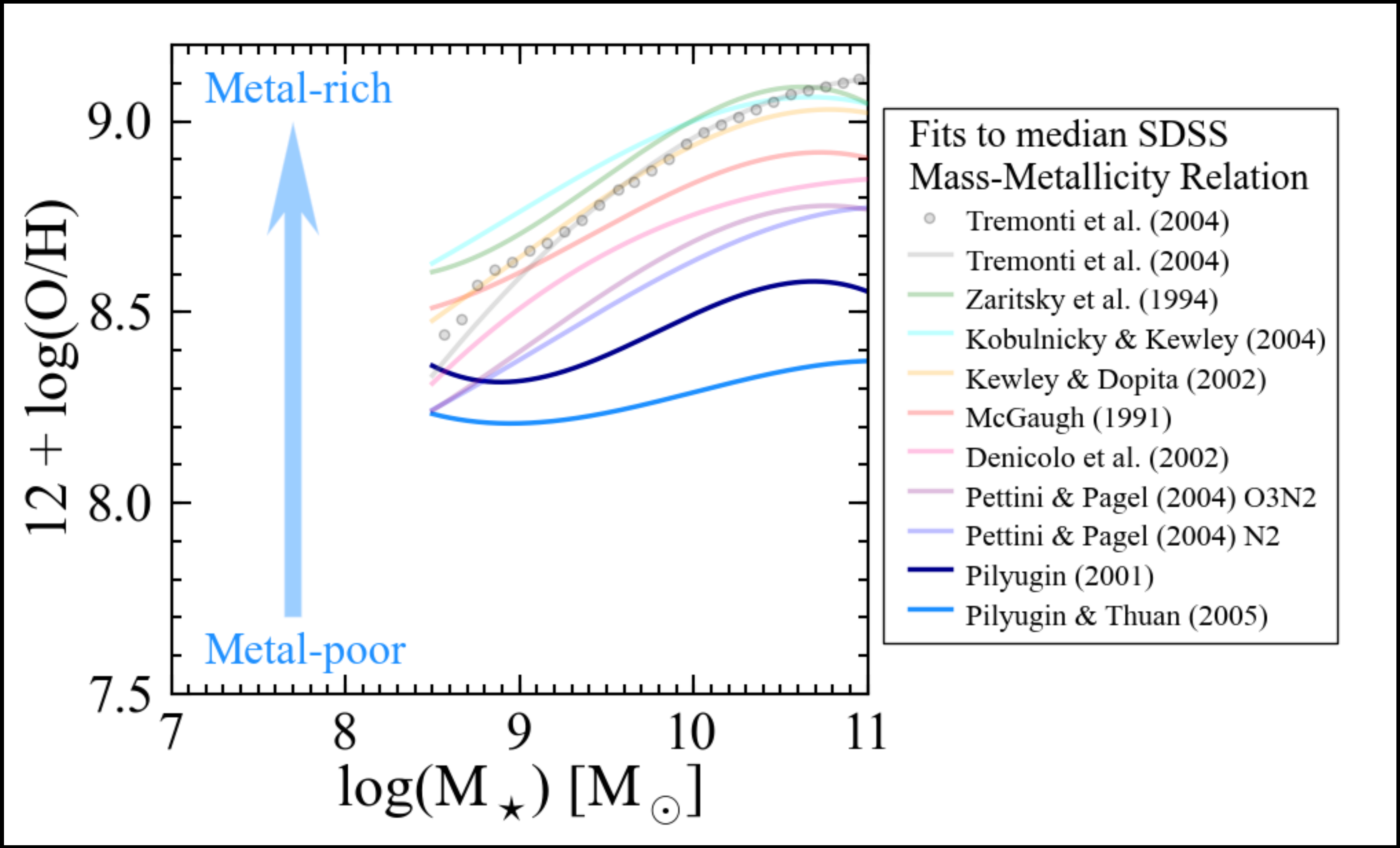
Fits from Kewley & Ellison (2008)

Semi-Empirical Calibrations



Fits from Kewley & Ellison (2008)

Empirical Calibrations



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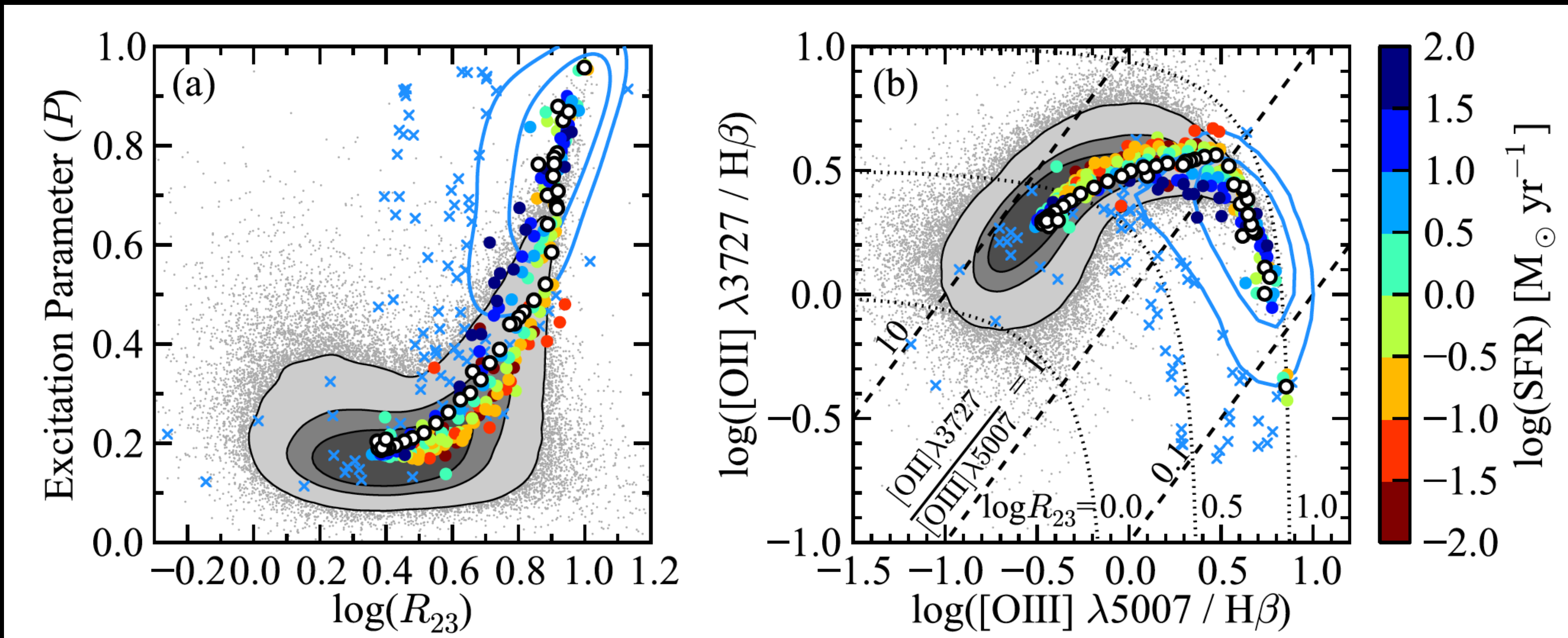
Fits from Kewley & Ellison (2008)

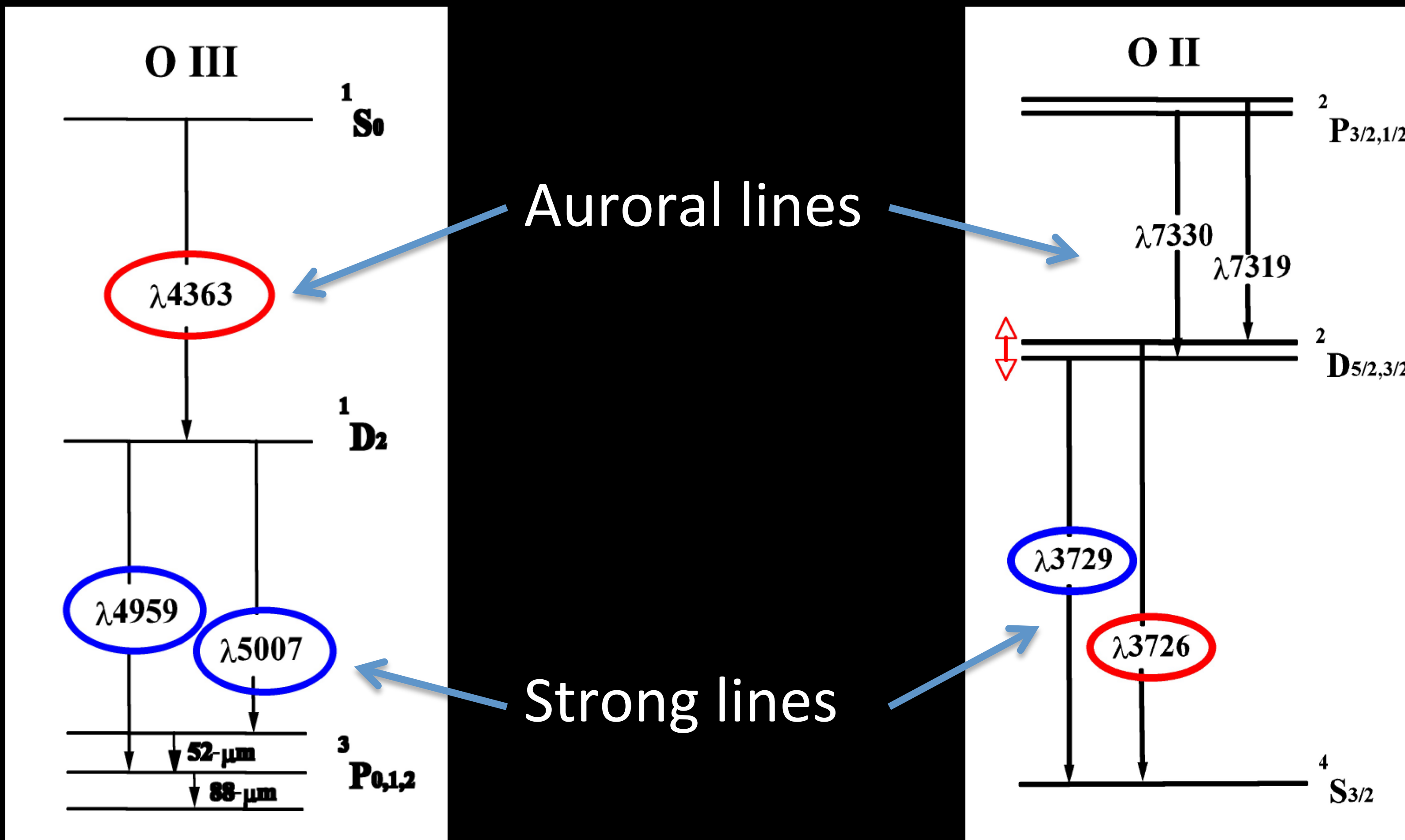
Excitation Parameter vs. R23



Andrews & Martini (2013)

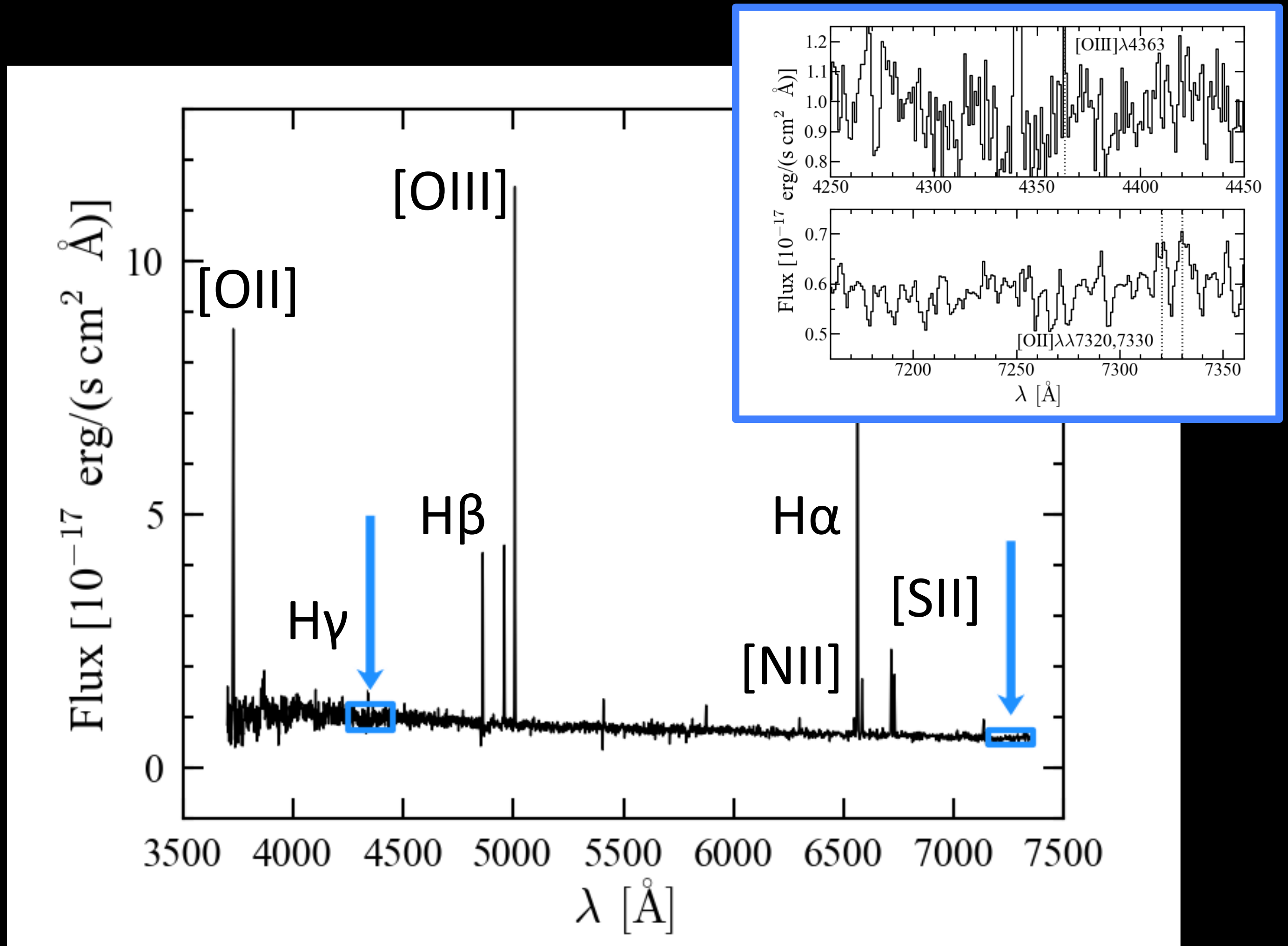
- Empirical calibrations are based on high excitation, low metallicity HII regions
- The stacks probe low excitation parameters and high metallicites, like the overall galaxy population.

Auroral Lines: Temperature-sensitive



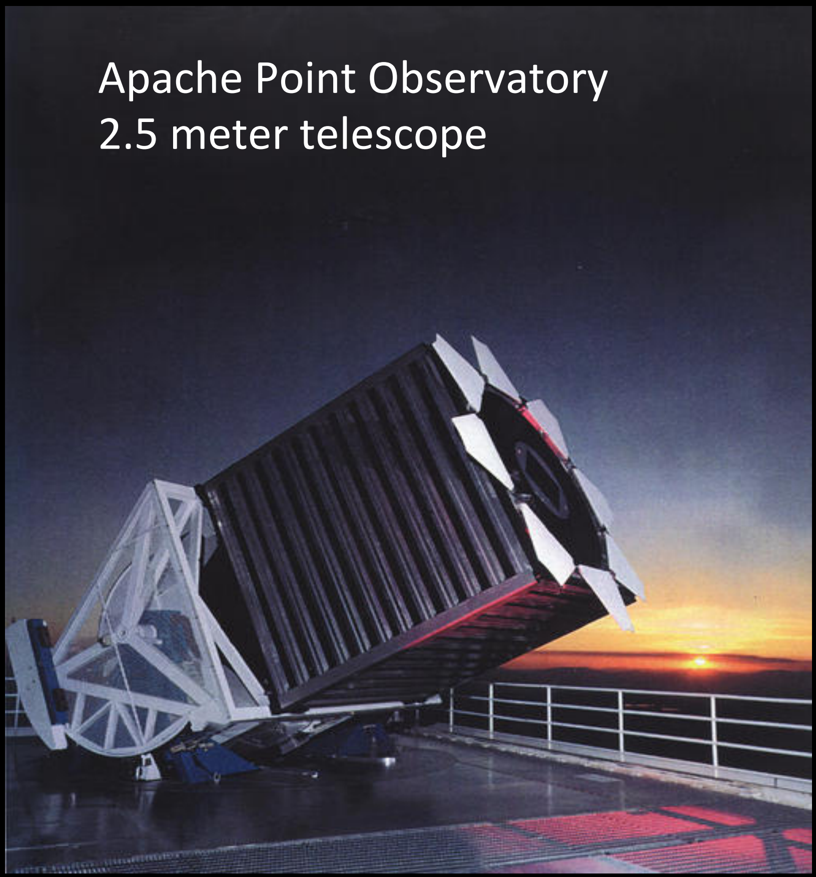
M. Westmoquette

The auroral lines are very weak



SDSS

York et al. (2000)
Strauss et al. (2002)
Abazajian et al. (2009)


Apache Point Observatory
2.5 meter telescope

Stacked ~200,000 star-forming galaxies to reduce the random fluctuations due to noise, which allows the auroral lines to be detected

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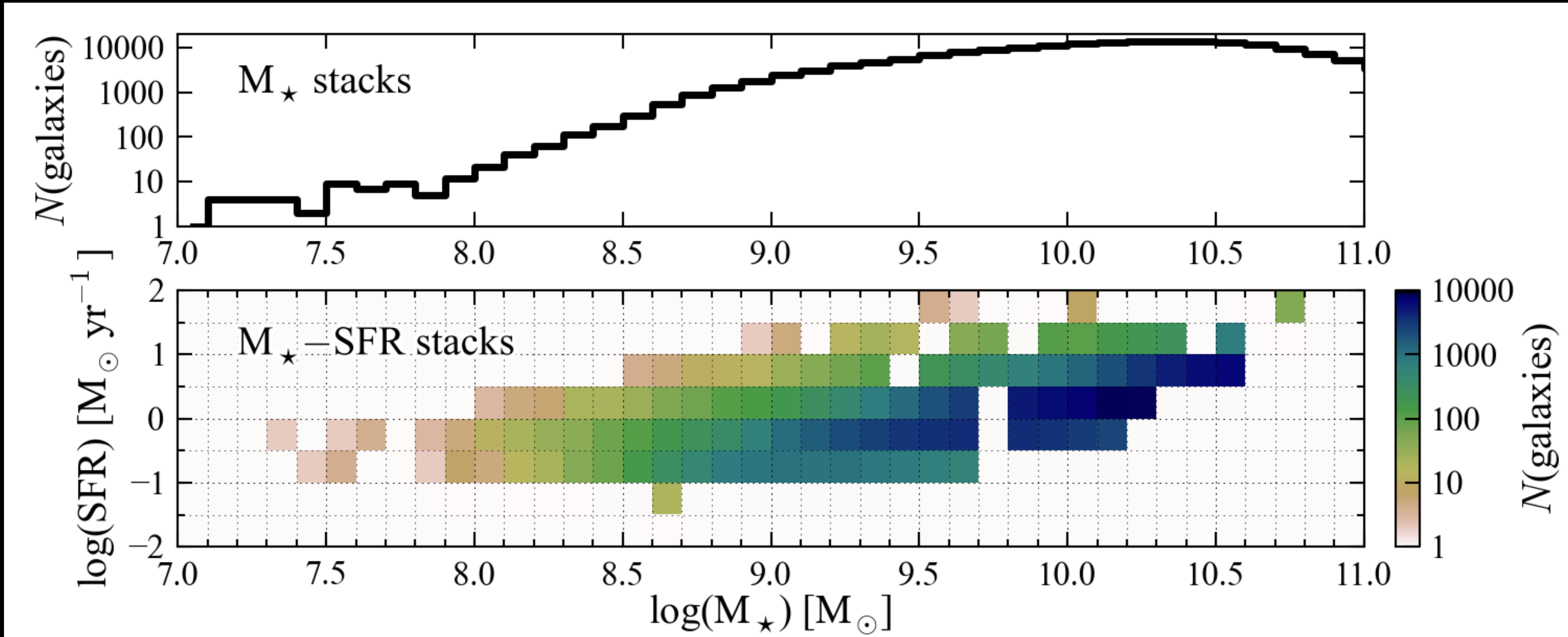
Bins in Stellar Mass and SFR



We stacked in bins of

- 0.1 dex in $M_\star$
- 0.1 dex in $M_\star$ and 0.5 dex in SFR

mass → metallicity

$M_\star$ → Kauffmann et al. (2003)

SFR → Brinchmann et al. (2004), Salim et al. (2007)

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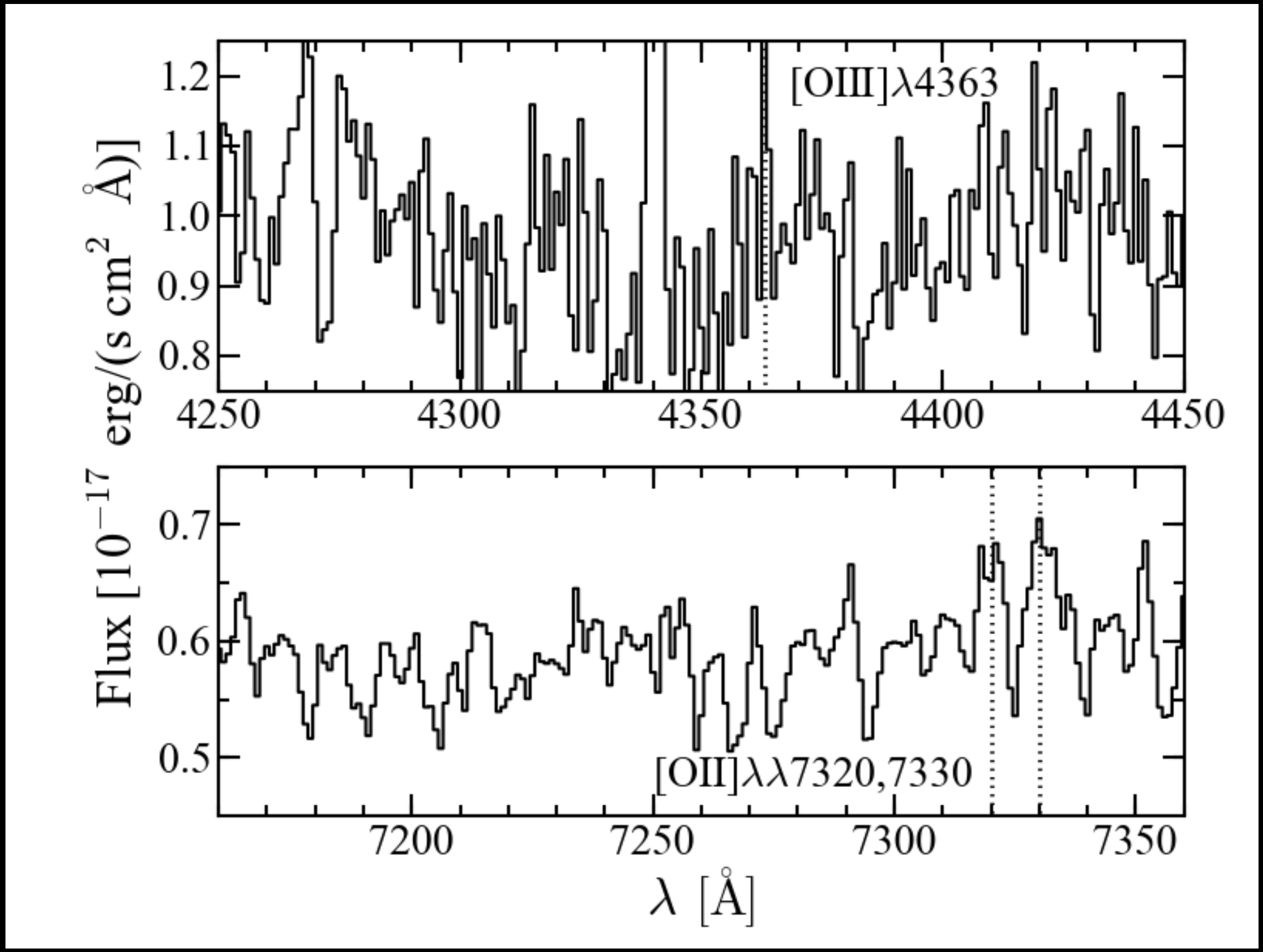
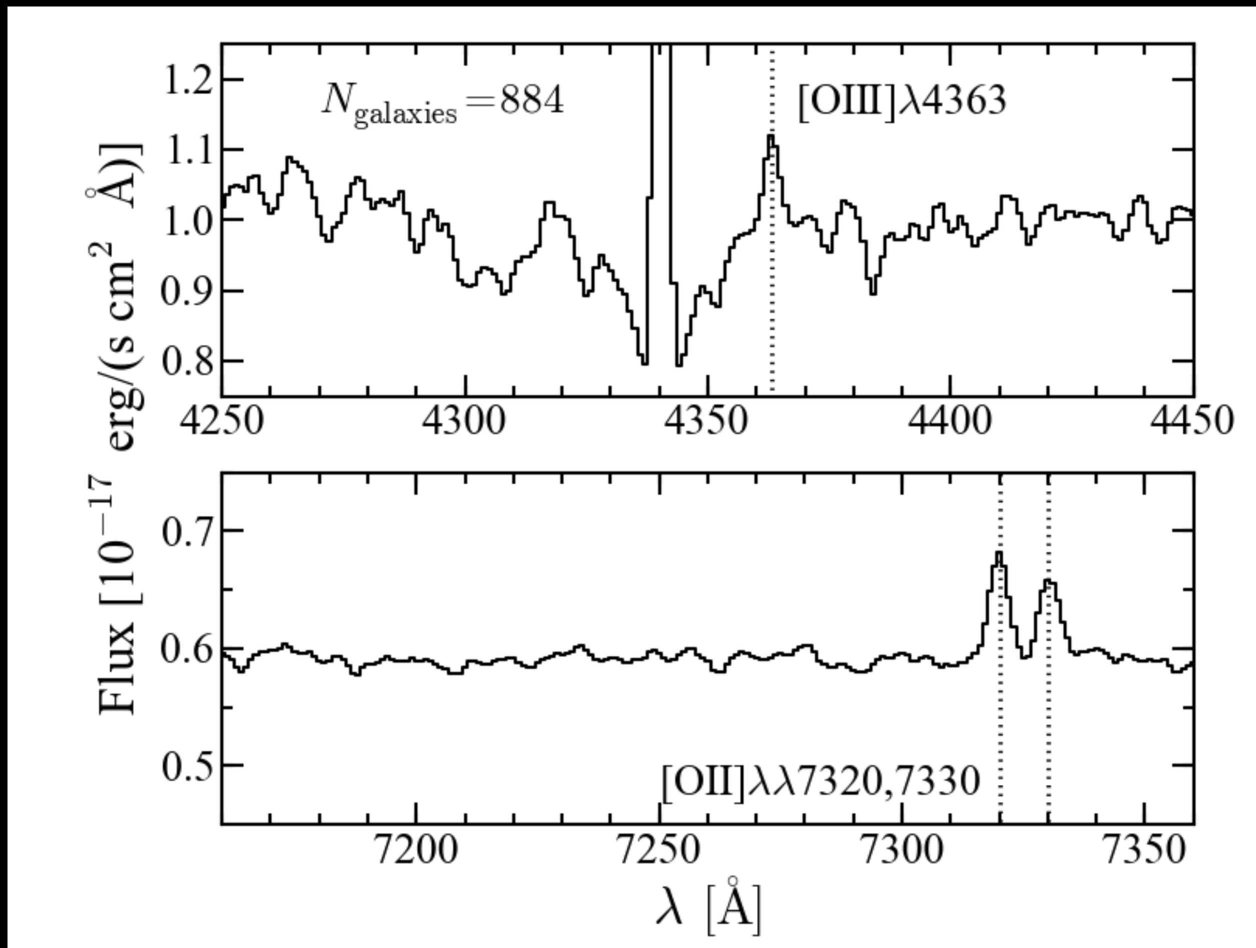
Auroral Lines of a Single Galaxy

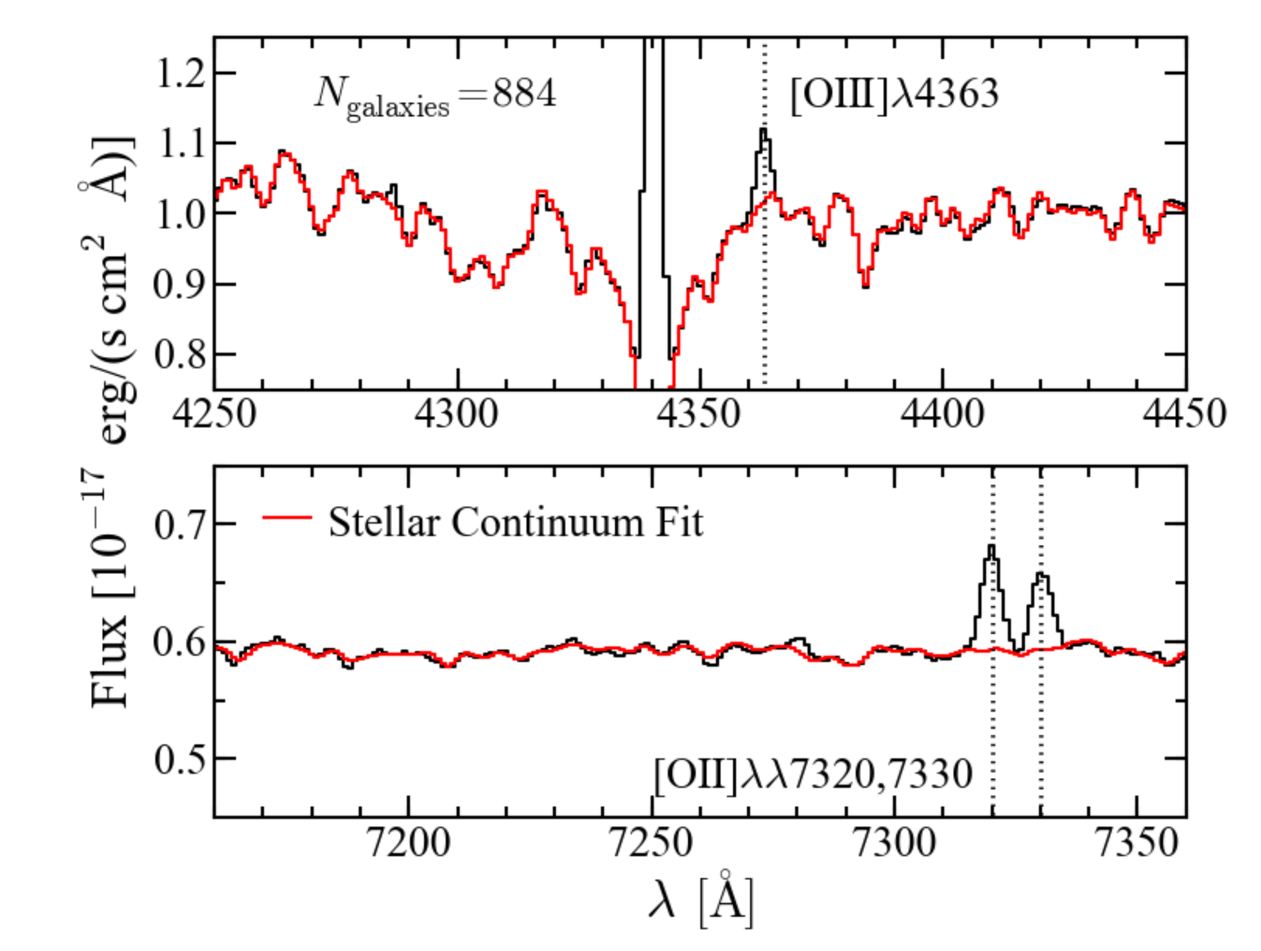


Stack of Galaxies



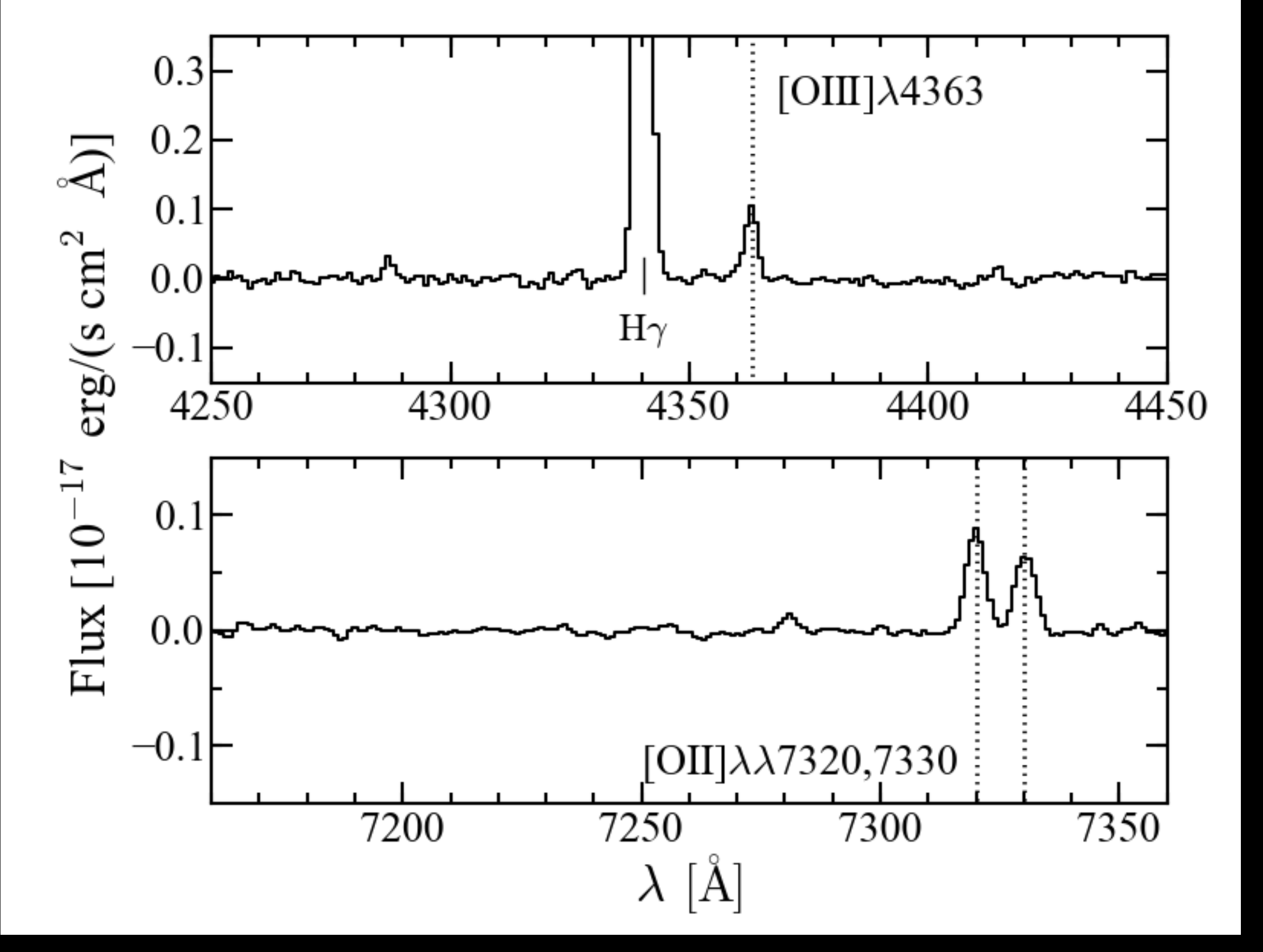
stellar absorption lines

Fit the Underlying Stellar Spectrum

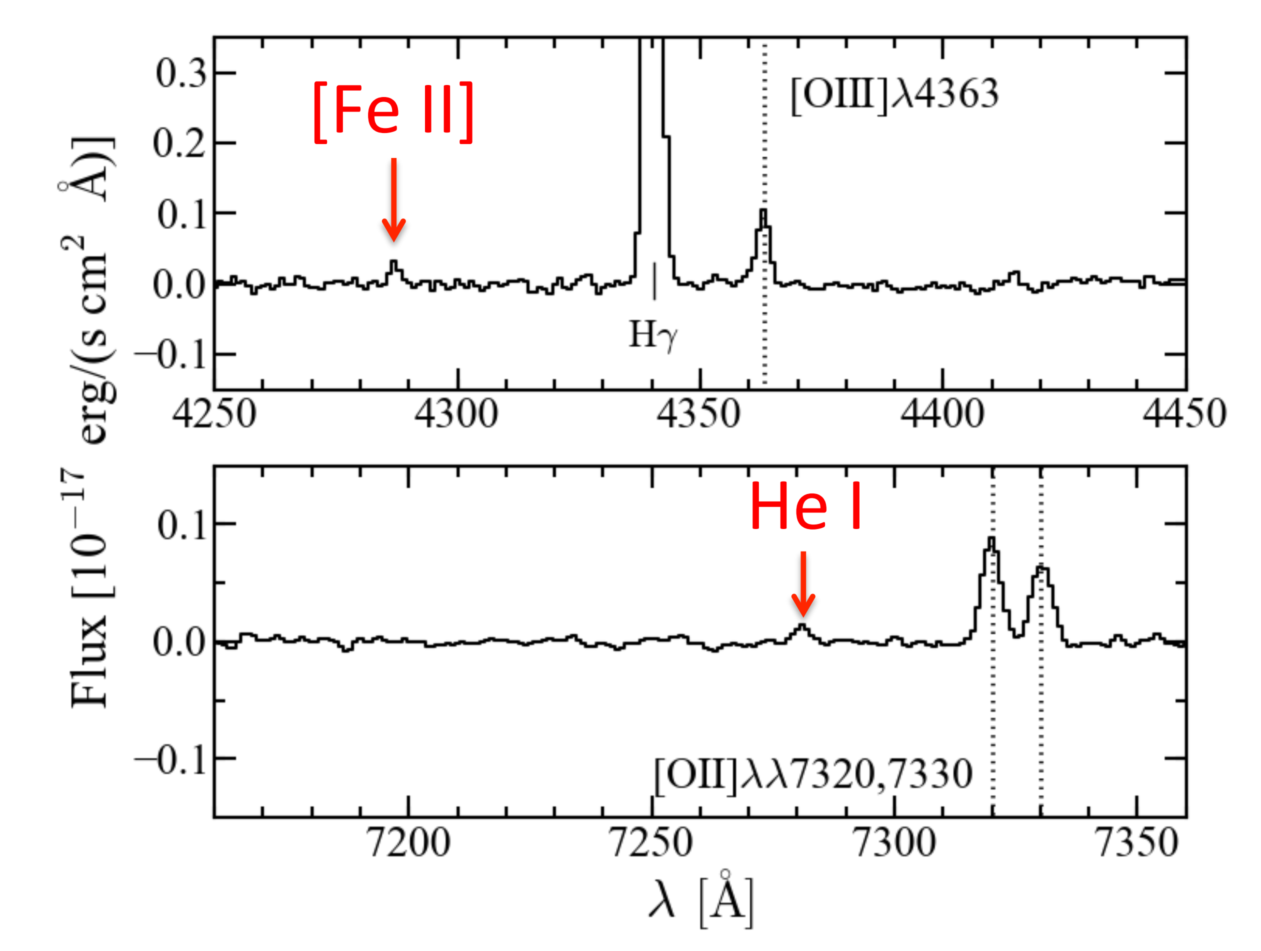


Stellar continuum fit with STARLIGHT stellar synthesis code (Cid Fernandes et al. 2005)

Final Spectrum



Final Spectrum



Direct Method

limiting factor

$$\frac{\text{Auroral Line}}{\text{Strong Line}}$$

↓

$$\frac{\text{Strong Line}}{\text{H}\beta} + \text{Temperature}$$

↓

Ionic Abundance

$$\frac{\text{[OIII] } \lambda 4363}{\text{[OIII] } \lambda\lambda 4959,\ 5007}$$

↓

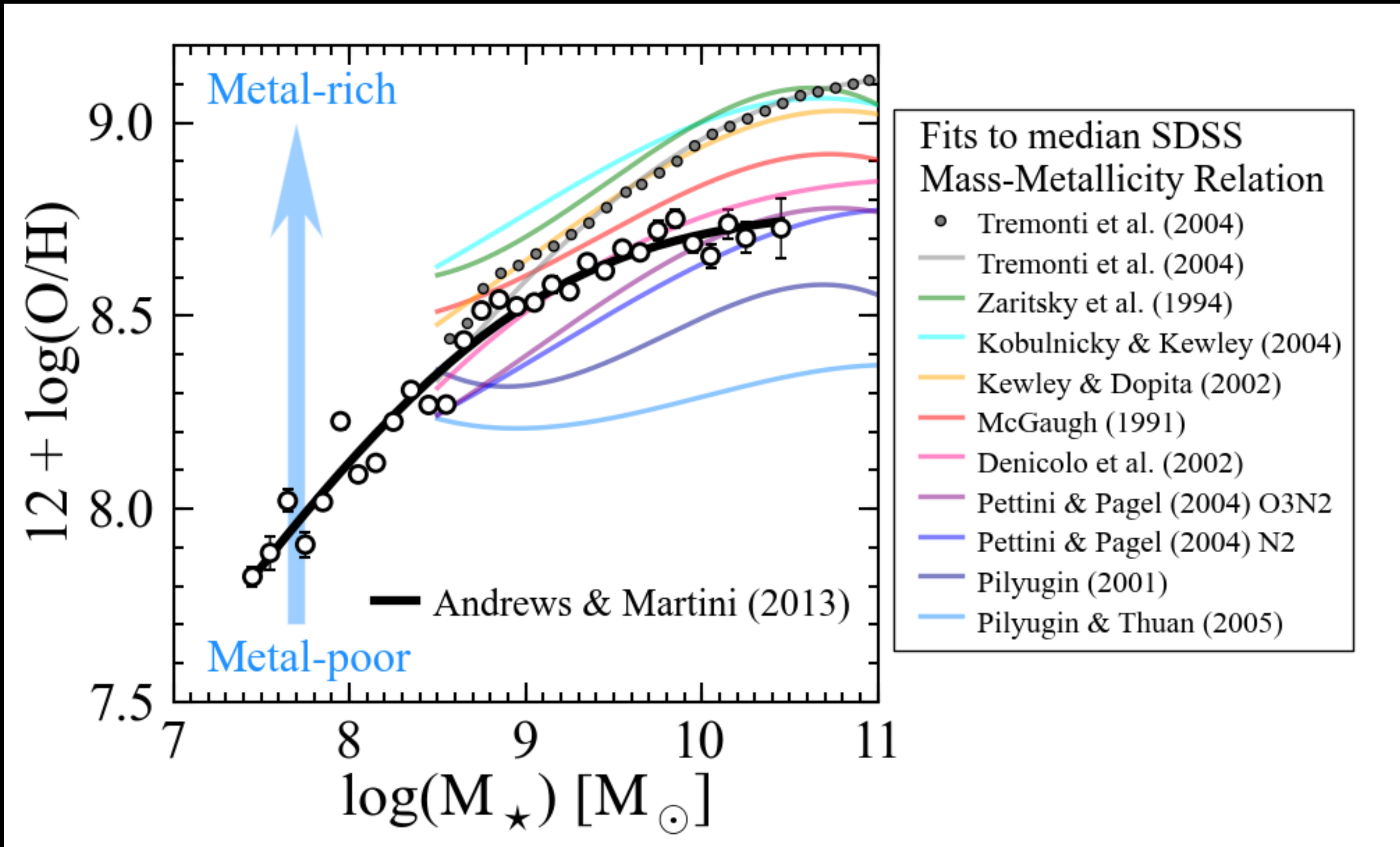
$$\frac{\text{[OIII] } \lambda\lambda 4959,\ 5007}{\text{H}\beta} + \text{Te[OIII]}$$

↓

$$\frac{\text{O++}}{\text{H}}$$

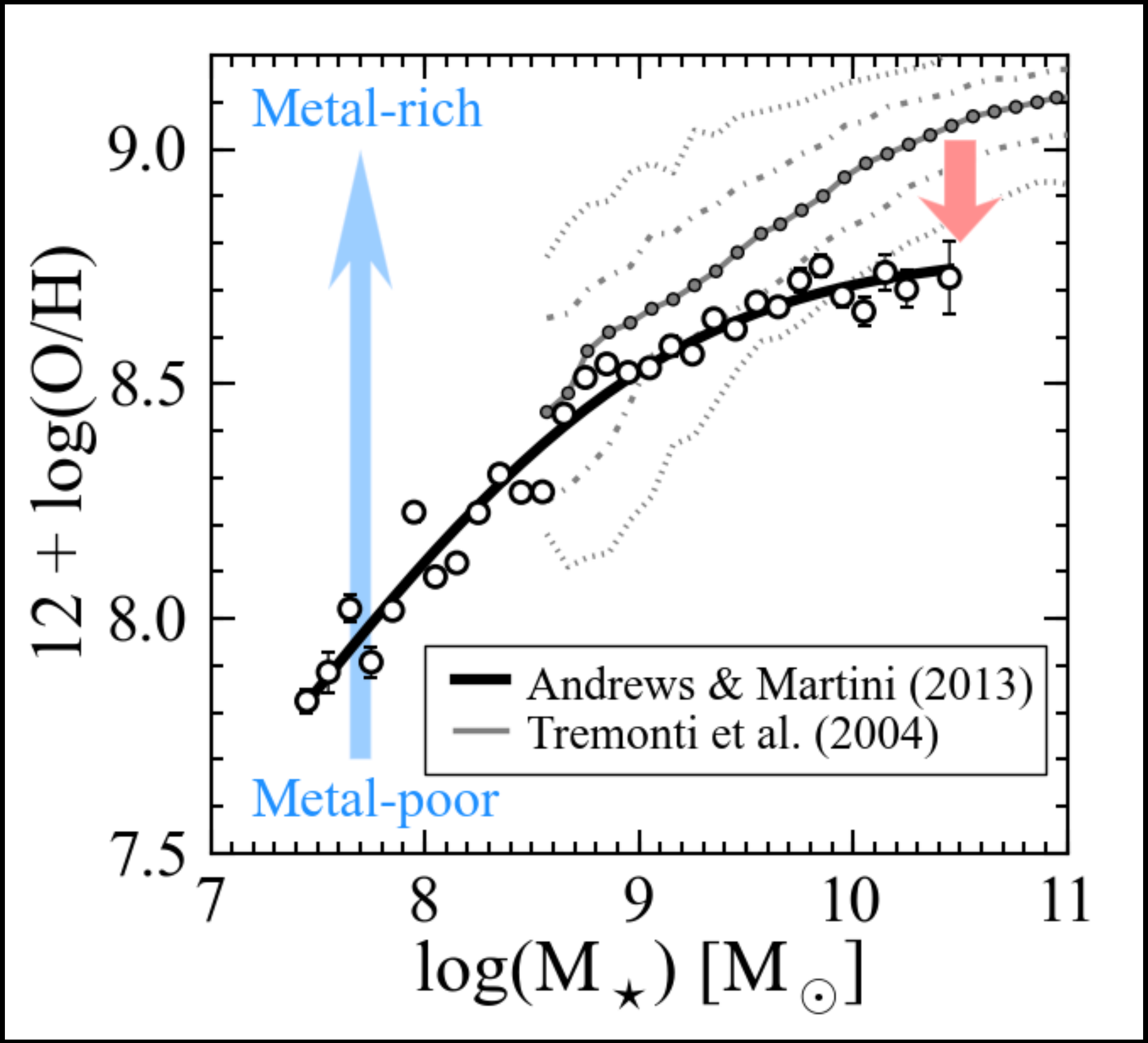
Metallicity: $\frac{\text{O}}{\text{H}} = \frac{\text{O+}}{\text{H}} + \frac{\text{O++}}{\text{H}}$ (Repeat for O+)

Direct Method Mass—Metallicity Relation



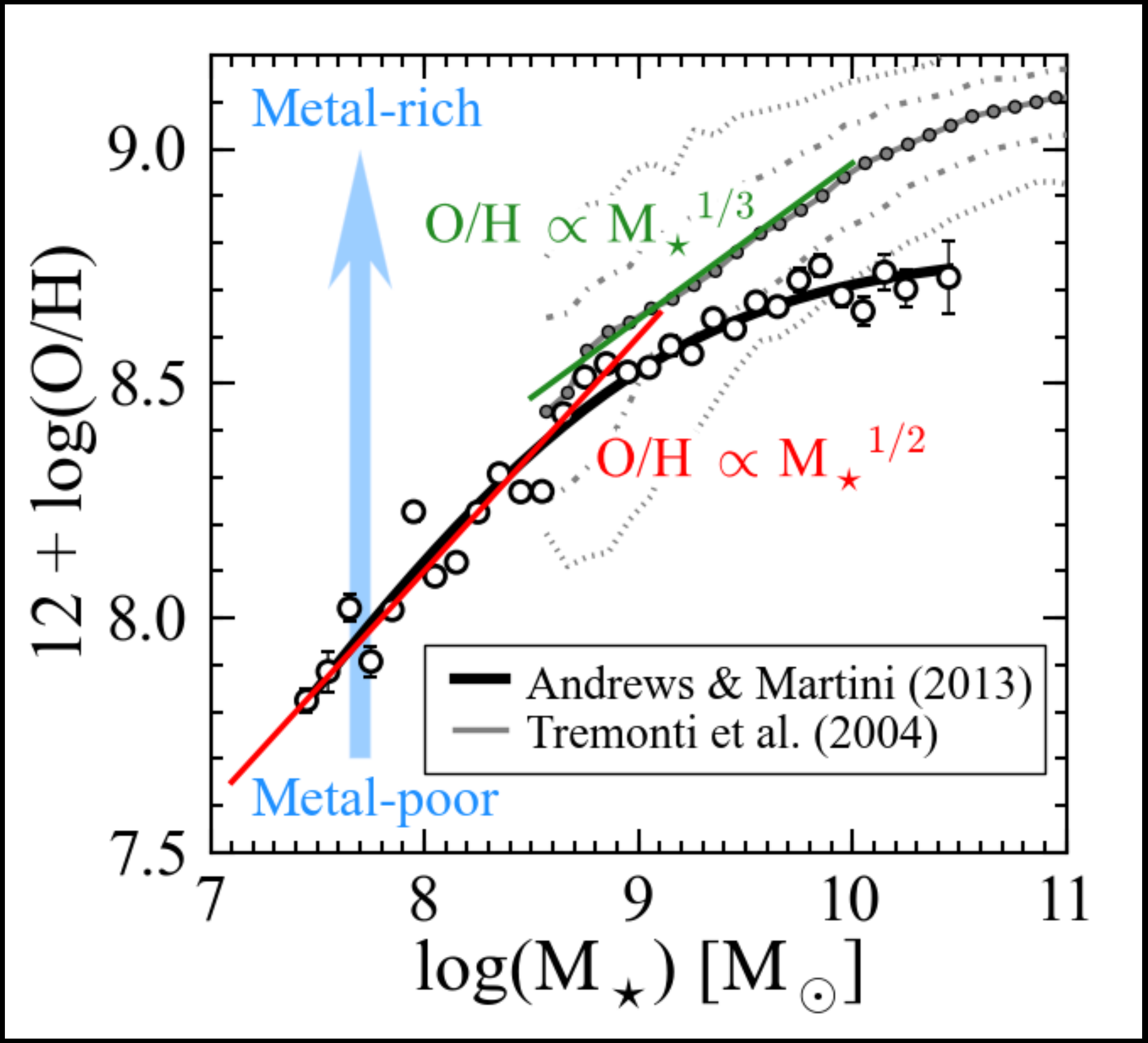
Fits from Kewley & Ellison (2008)

Normalization



Galactic winds are efficient at ejecting metals…

Low Mass Slope



…especially in low mass galaxies.

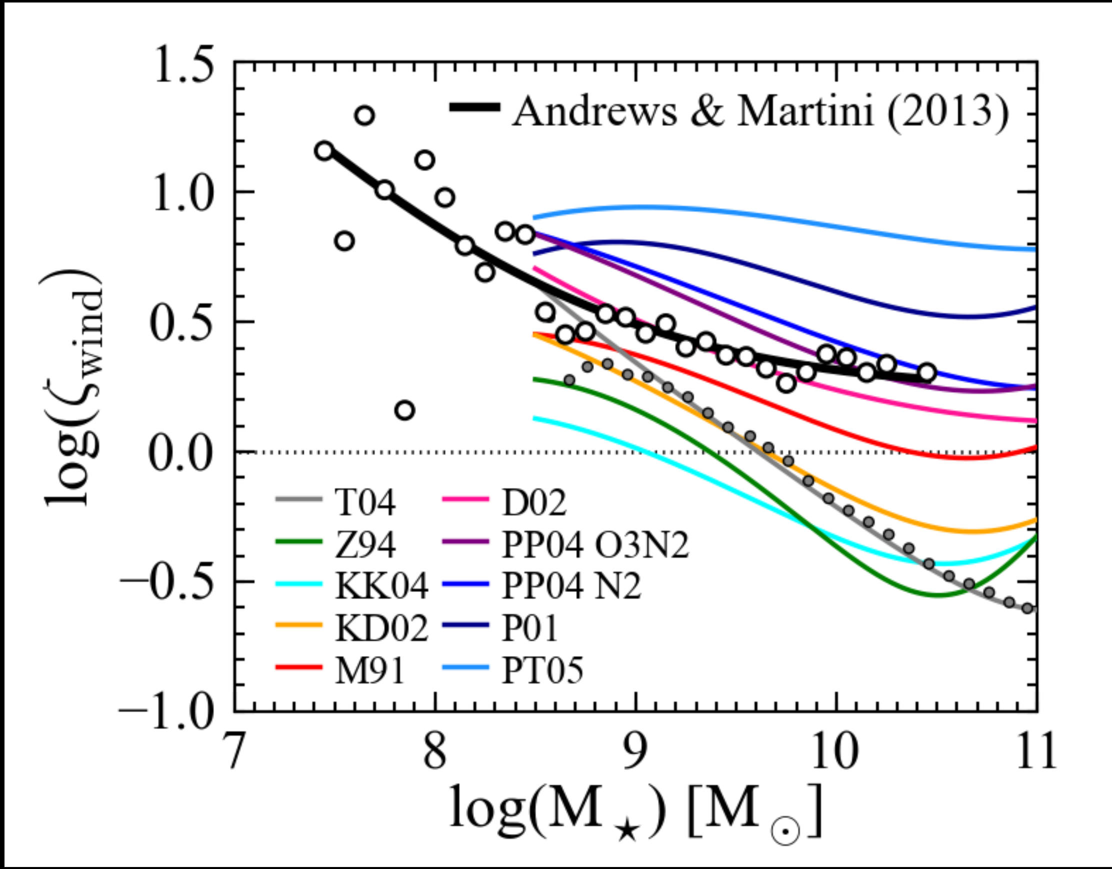
Metal Ejection Efficiency

Metallicity-weighted mass-loading factor

↓

$$\zeta_{\rm wind} = \left(\frac{Z_{\rm wind}}{Z_{\rm ISM}}\right)\left(\frac{\dot{M}_{\rm wind}}{\rm SFR}\right)$$

Peeples & Shankar (2011)



Transform the Mass—Metallicity Relation into the metal ejection efficiency as a function of $M_\star$

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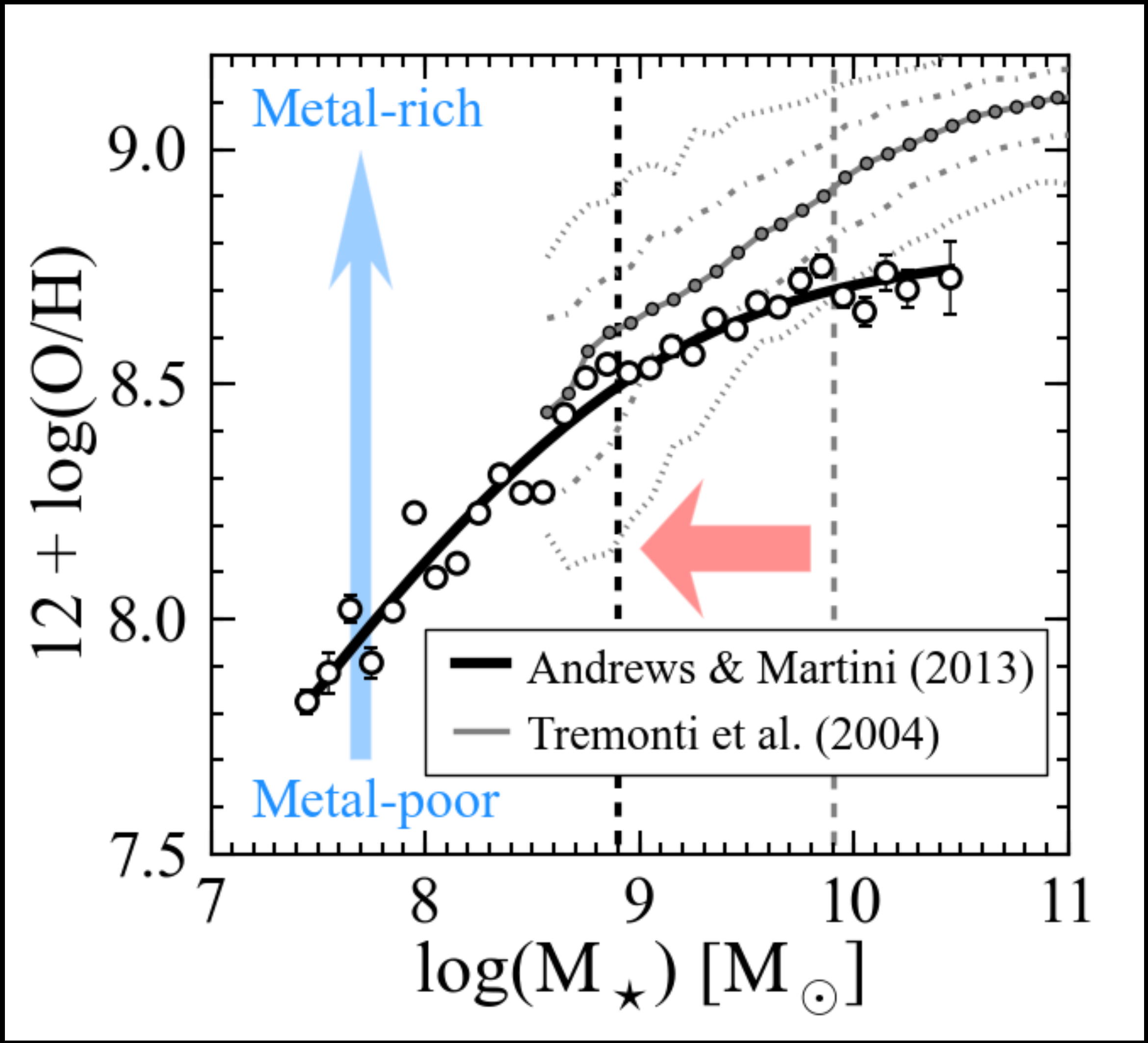
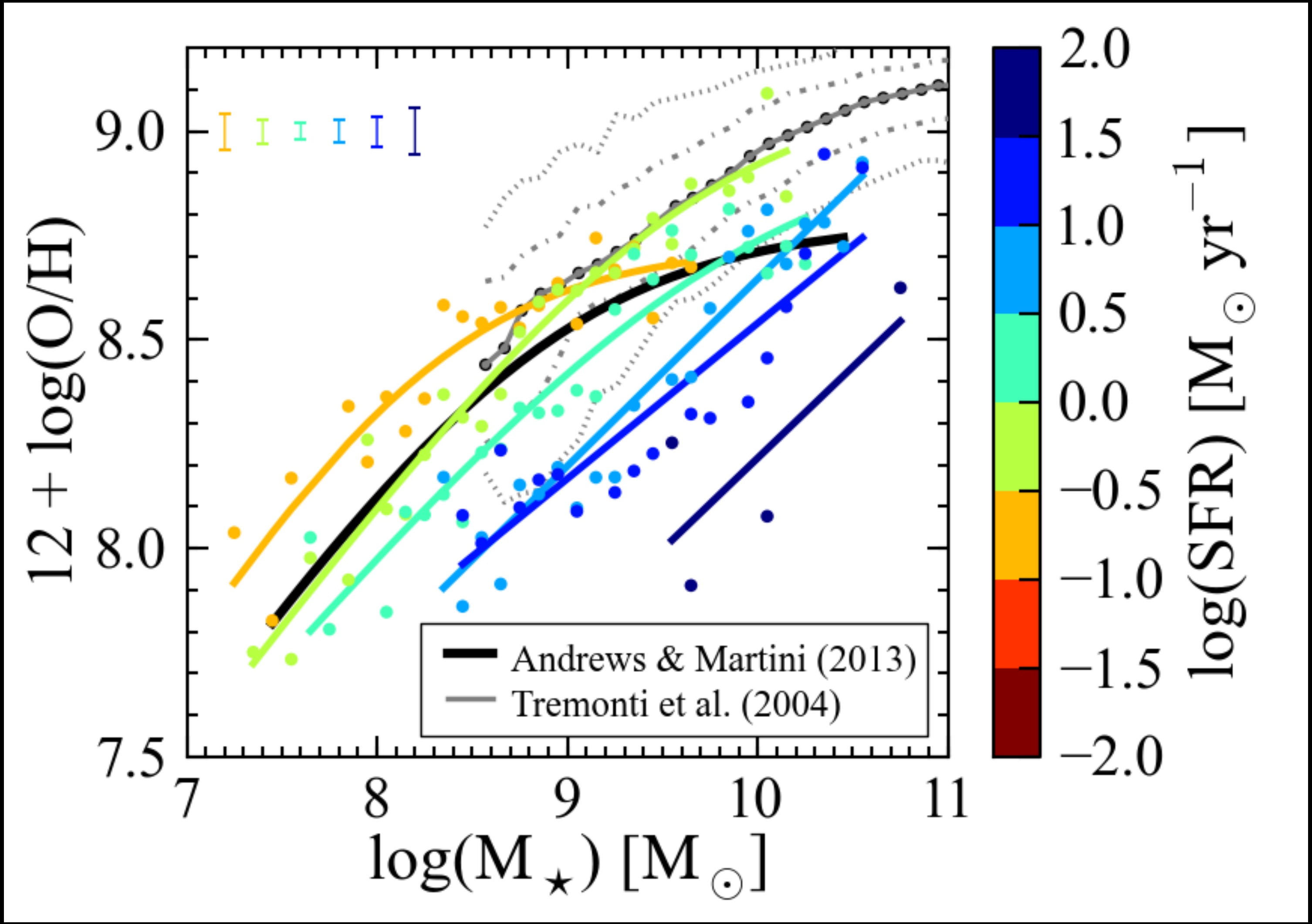
Turnover Mass

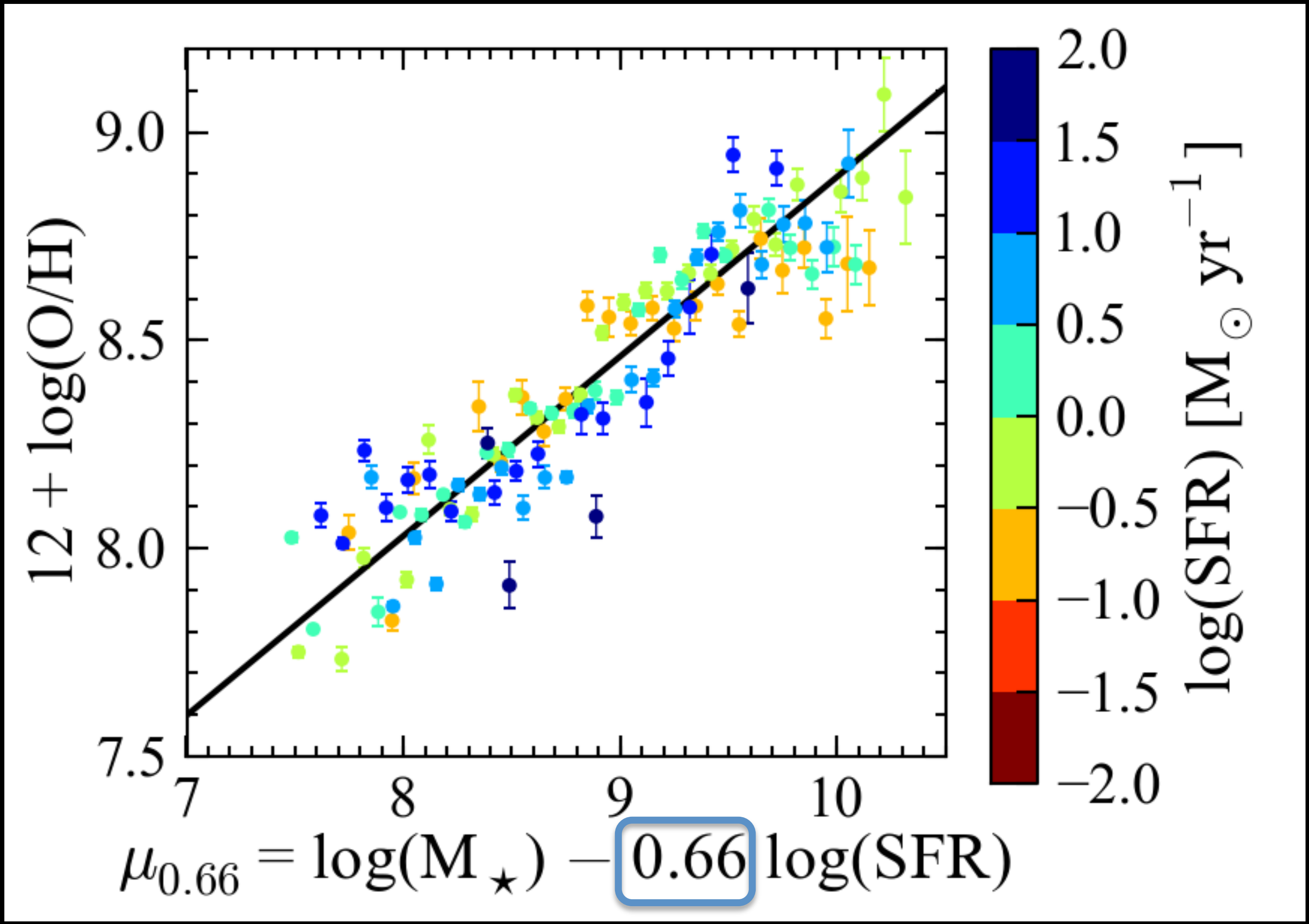


Low turnover caused by strong SFR-dependence

SFR-dependence of the Mass--Metallicity Relation



Direct Method Fundamental Metallicity Relation



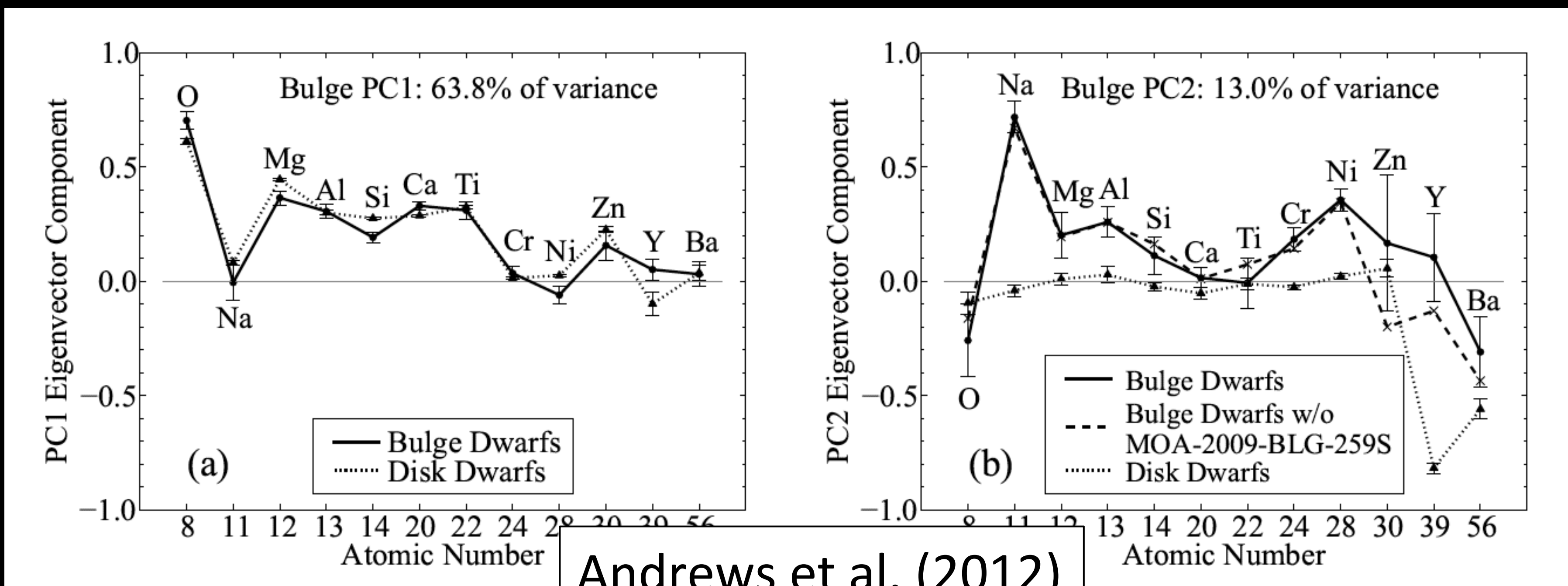
Mannucci et al. (2010): α = 0.32

Stellar Abundances

- Detailed record of a galaxy's enrichment history
- Multi-element abundances → differential enrichment
- combine with asteroseismic ages and dynamical information (enrichment as a function of time and location)

Principal Component Abundance Analysis

- PCAA finds the correlated patterns of elements that explain the strongest variations within the data.
- Dimensionality?
- How does chemical evolution proceed?
- Classify stellar populations?



Andrews et al. (2012)

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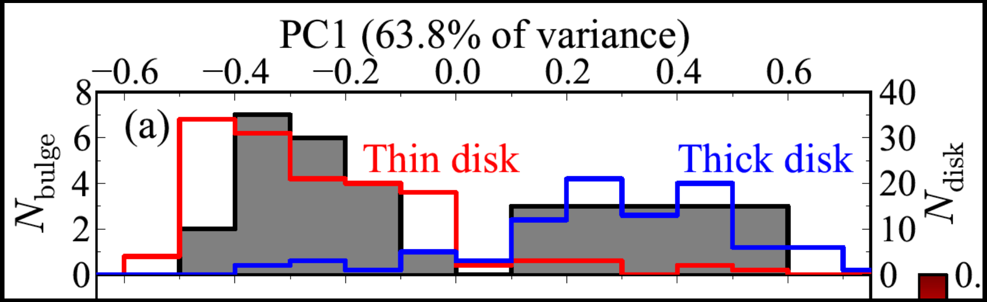
Microlensed Bulge Dwarfs:
35 stars x 12 elements

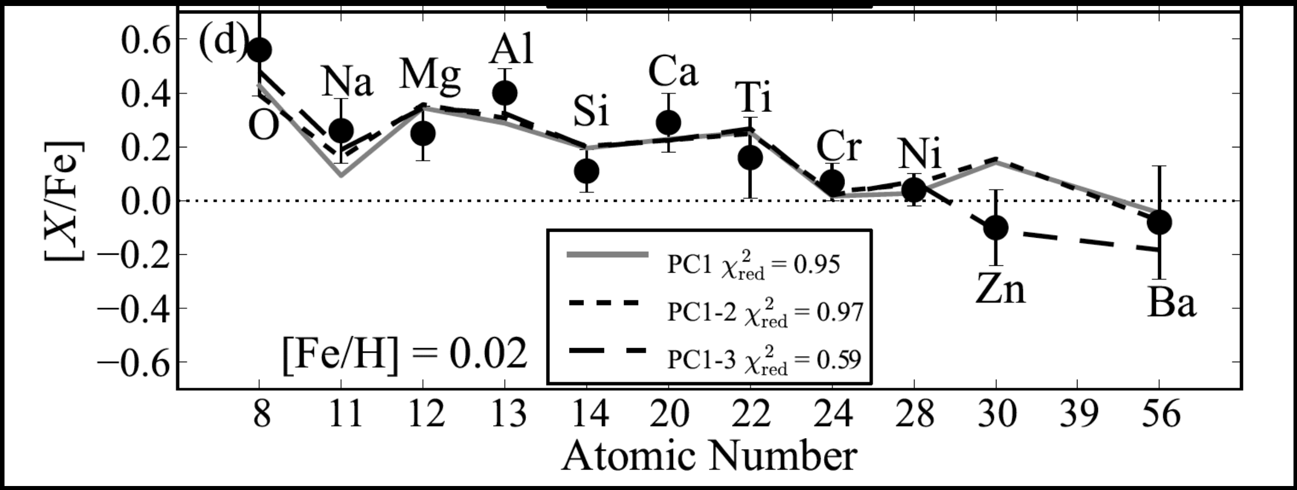
PCAA of Microlensed Bulge Dwarfs

bimodality in [Fe/H] is recovered in PC1



Andrews et al. (2012)

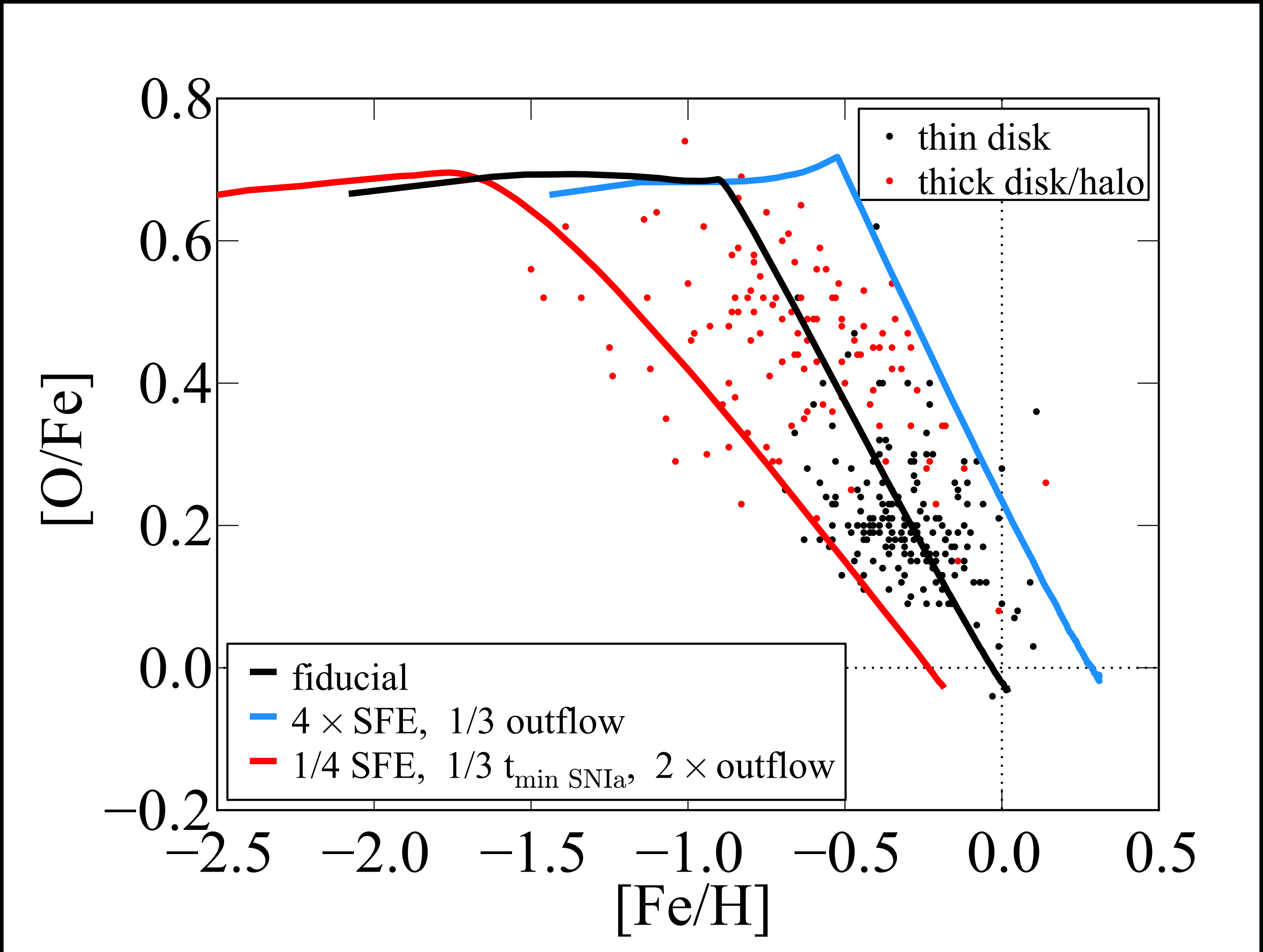
χ^2-fitting of principal components to abundance patterns



Andrews et al. (2012)

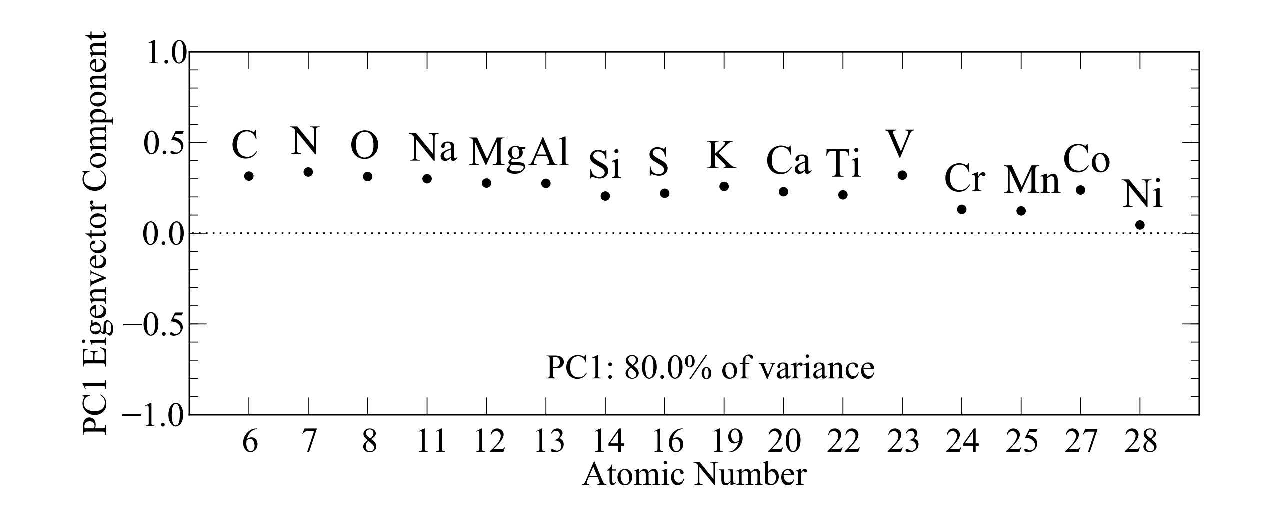
The Ohio State University

PCAA of Chemical Evolution Models

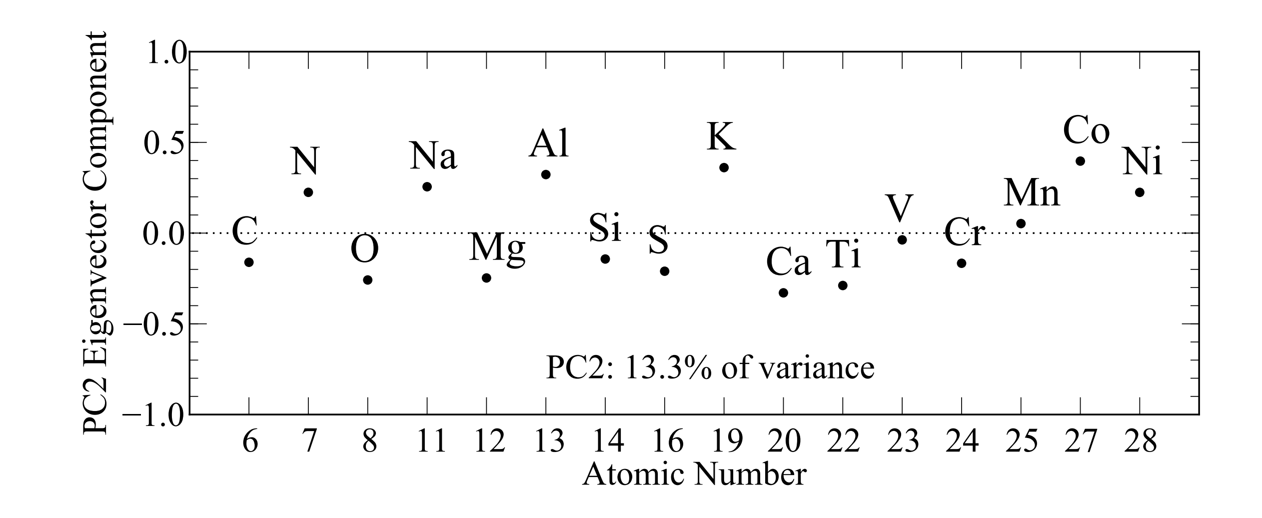


PCAA of Chemical Evolution Models

PC1



PC2



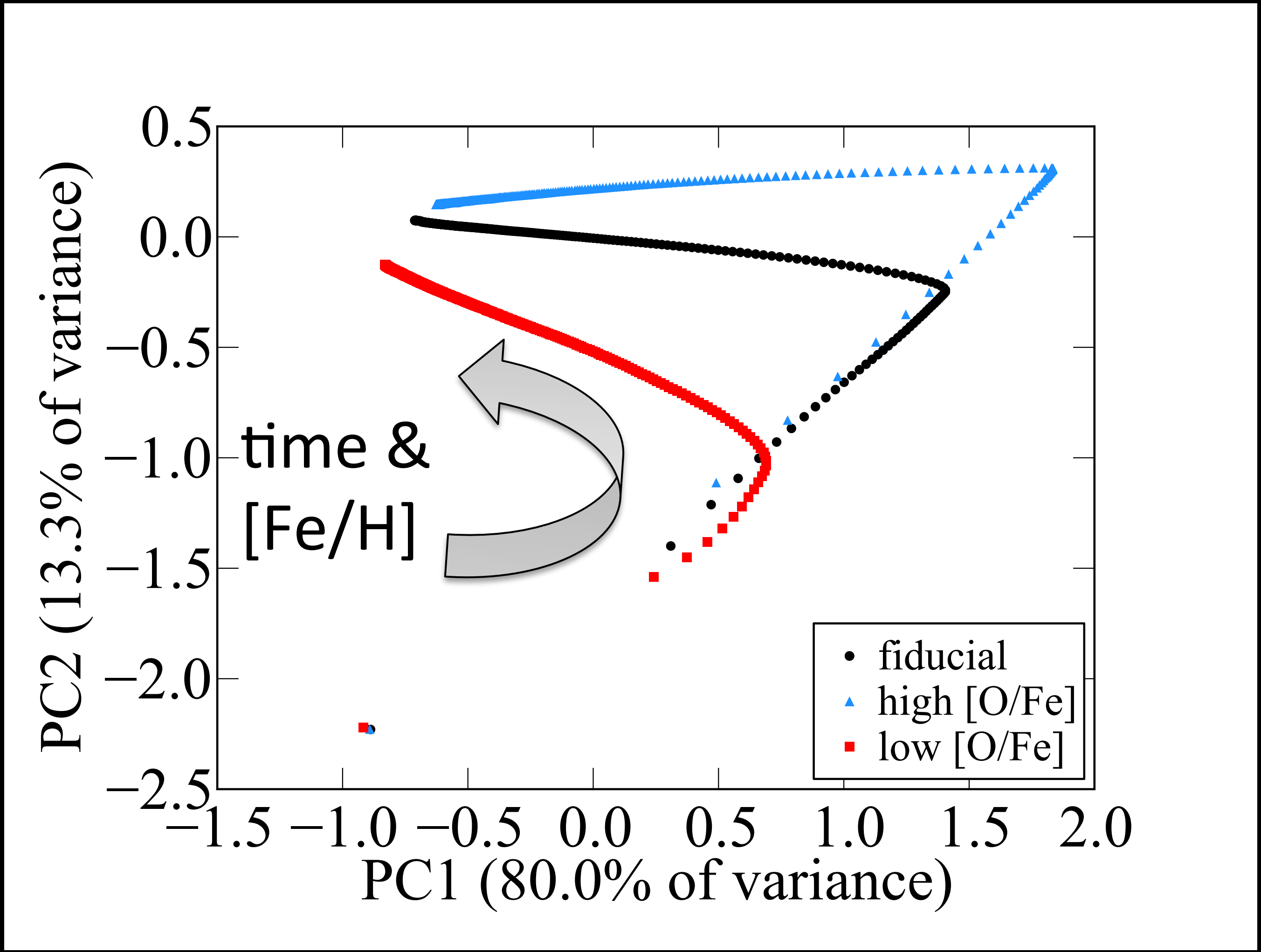
PCAA of Chemical Evolution Models

↑

Metallicity-dependent elements

Metallicity-independent elements

↓



All elements →

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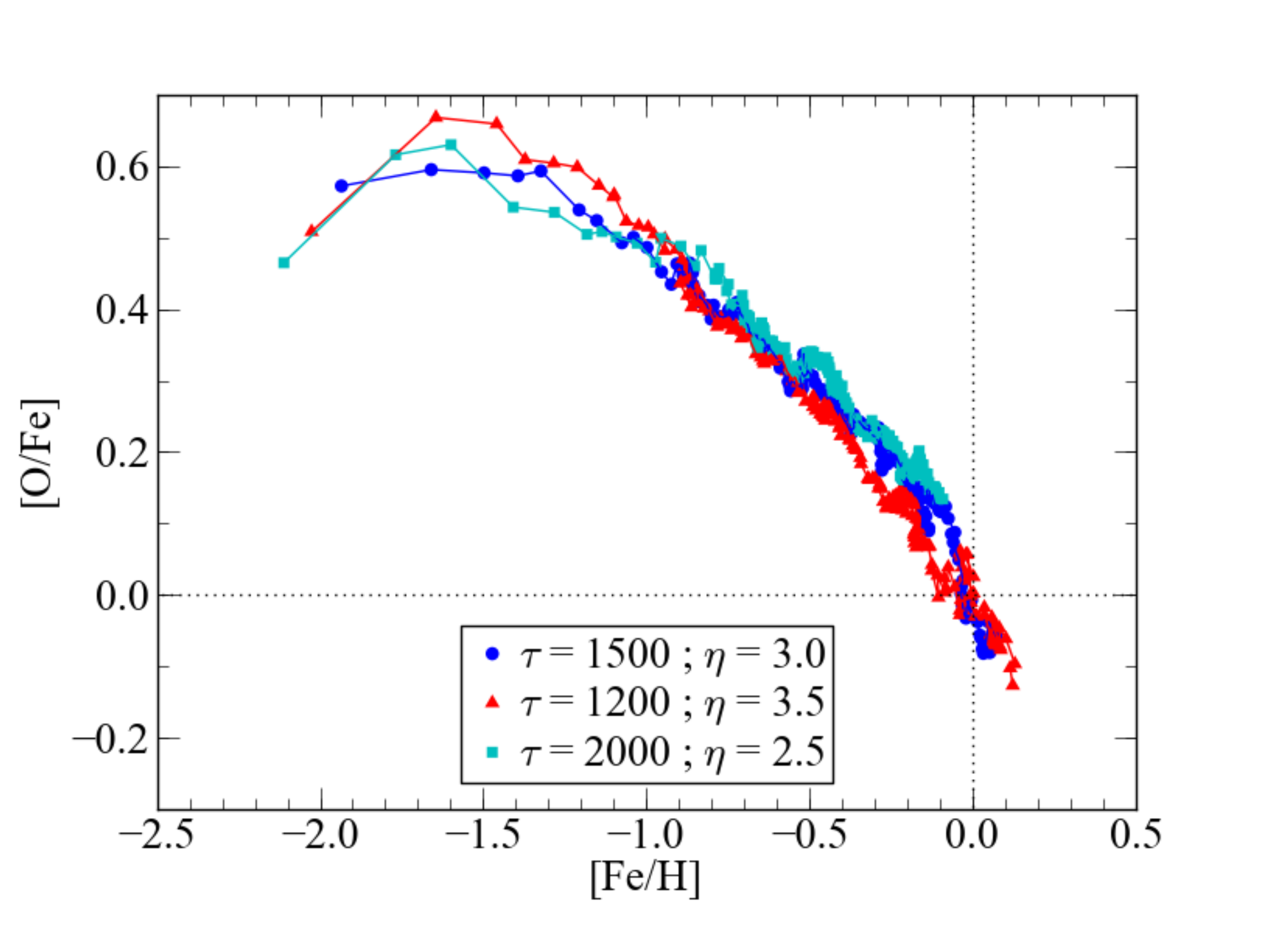
PCAA Applications

1. Microlensed Bulge Dwarfs
2. Microlensed Bulge Giants
3. CEMP stars
4. Chemical evolution model
5. Schönrich & Binney (2009) chemo-dynamical model
6. APOGEE: ~100,000 stars x 16 elements

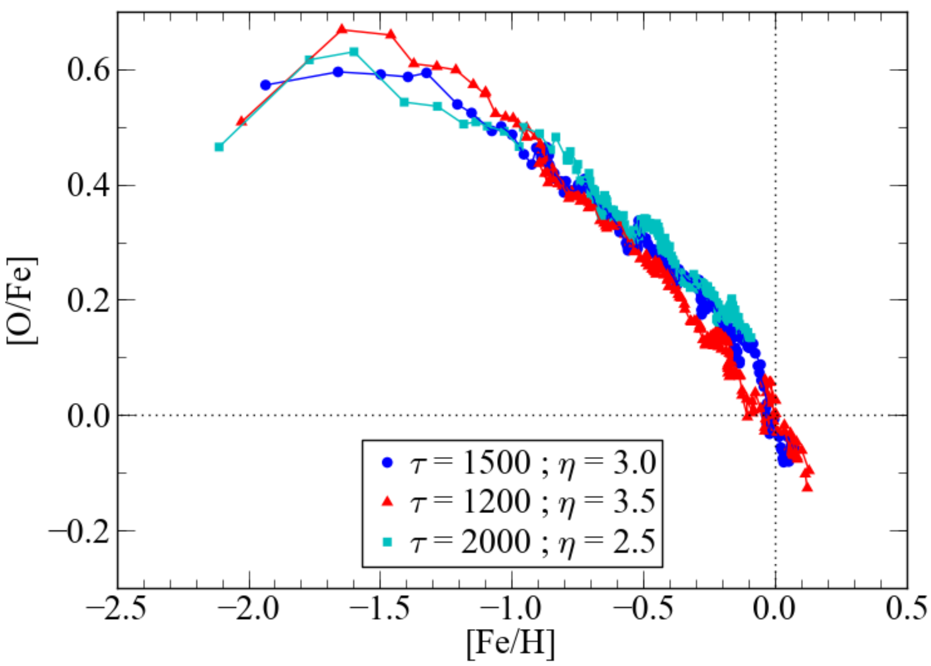
Summary

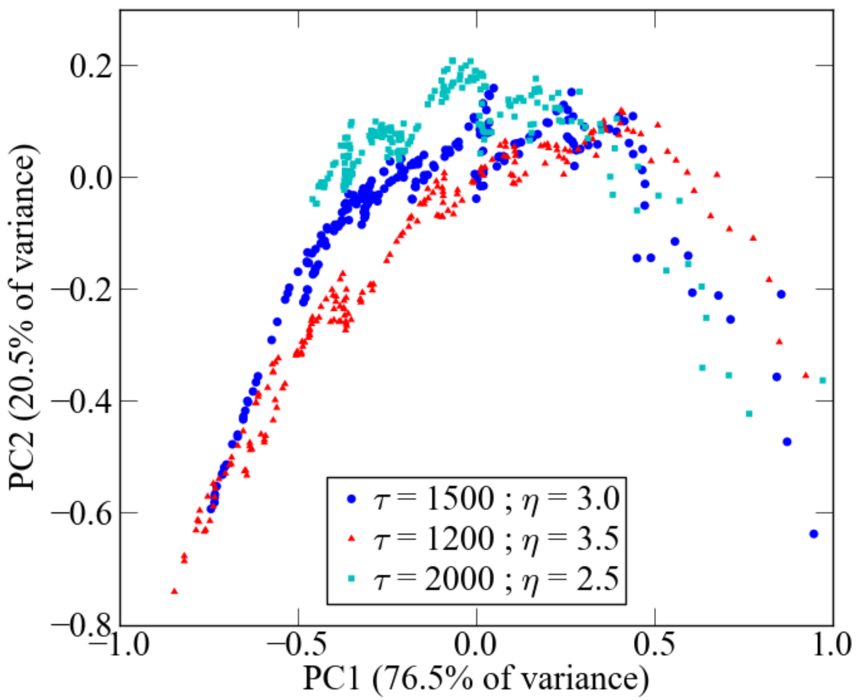
- stacked SDSS galaxy spectra to measure metallicities with the direct method, which relies on weaker but more reliable lines
- direct method Mass—Metallicity relation
  - extends to low mass
  - strong SFR-dependence
- Principal Component Abundance Analysis of existing stellar abundance data sets and chemical evolution models with a future application to APOGEE data

Classification with PCAA

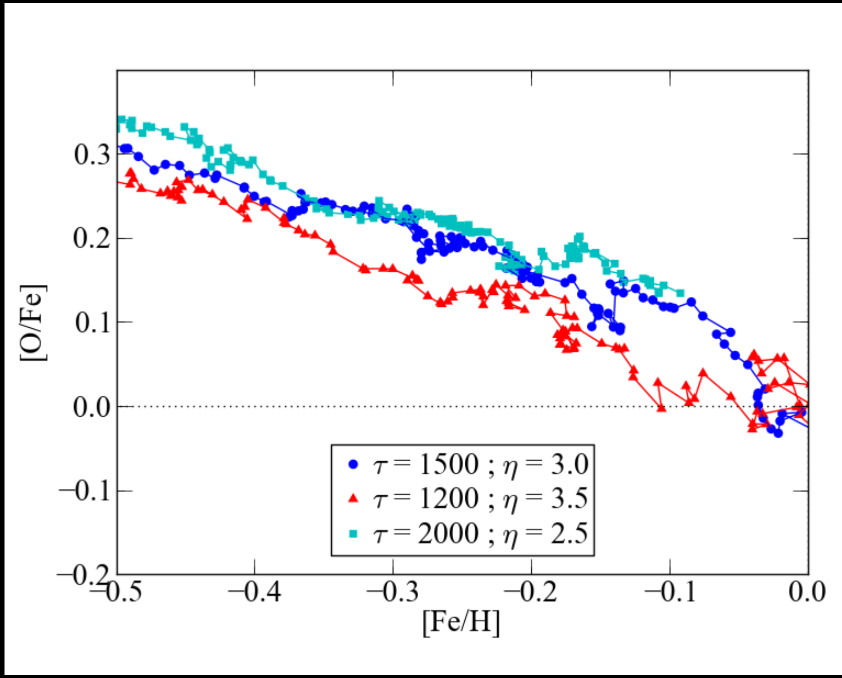


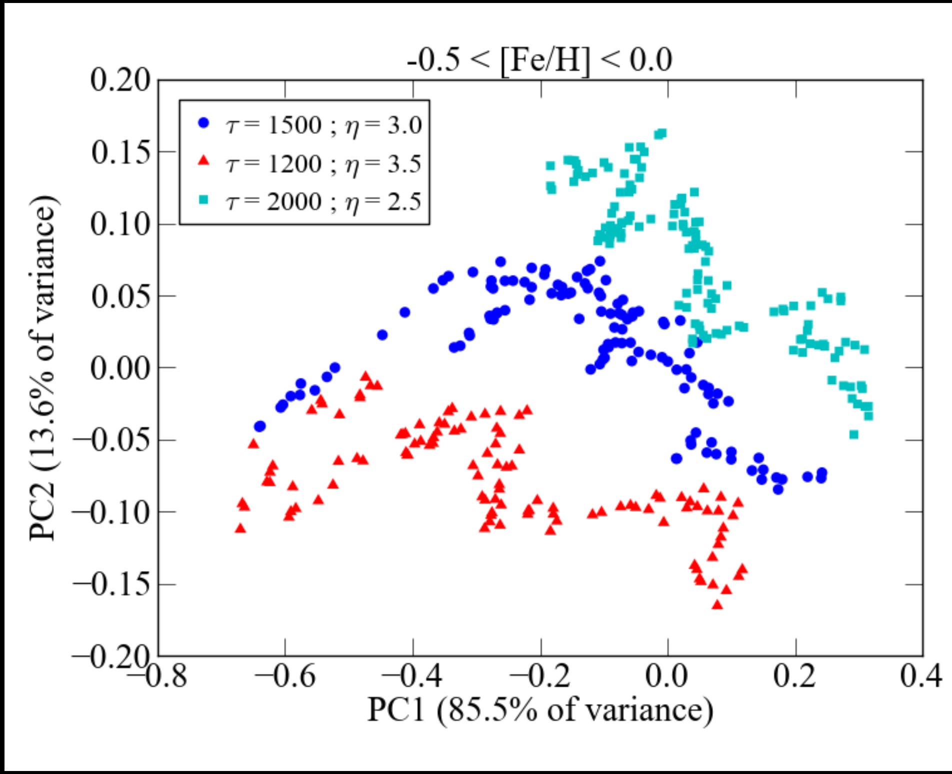
Classification with PCAA





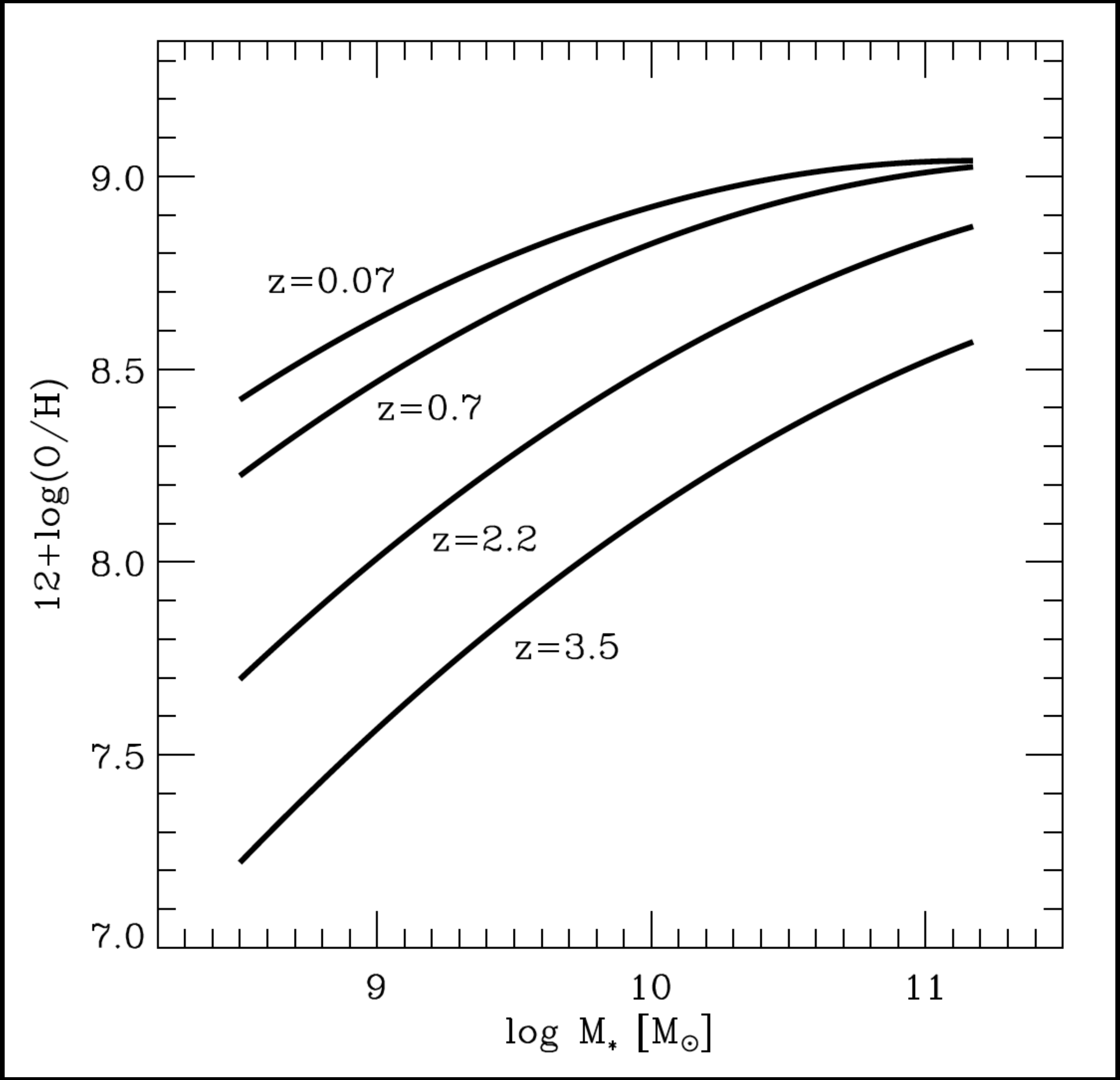
Classification with PCAA





Evolution of the Mass—Metallicity Relation

12+log(O/H)



Stellar Mass

Maiolino et al. (2008)

Sample Selection

- Remove AGN according to BPT diagram (Baldwin et al. 1981; Kauffmann et al. 2003)
- $0.027 < z < 0.25$
  - both [OII] λ3727 and [OII] λλ7320, 7330
- Same signal-to-noise ratio cuts as Tremonti et al. (2004):
  - Hβ, Hα, [NII] λ6583 > 5σ
  - [OIII] λ5007 > 3σ or log([NII] λ6583 / Hα) < -0.4

Final Sample

- ~200,000 star-forming galaxies
- $M_\star$ → Kauffmann et al. (2003)
- SFR → Brinchmann et al. (2004), Salim et al. (2007)

Direct Method

limiting factor

$$\frac{[\text{OIII}]\ \lambda 4363}{[\text{OIII}]\ \lambda\lambda 4959,\ 5007}$$

↓

$$\frac{[\text{OIII}]\ \lambda\lambda 4959,\ 5007}{\text{H}\beta} + \text{Te}[\text{OIII}]$$

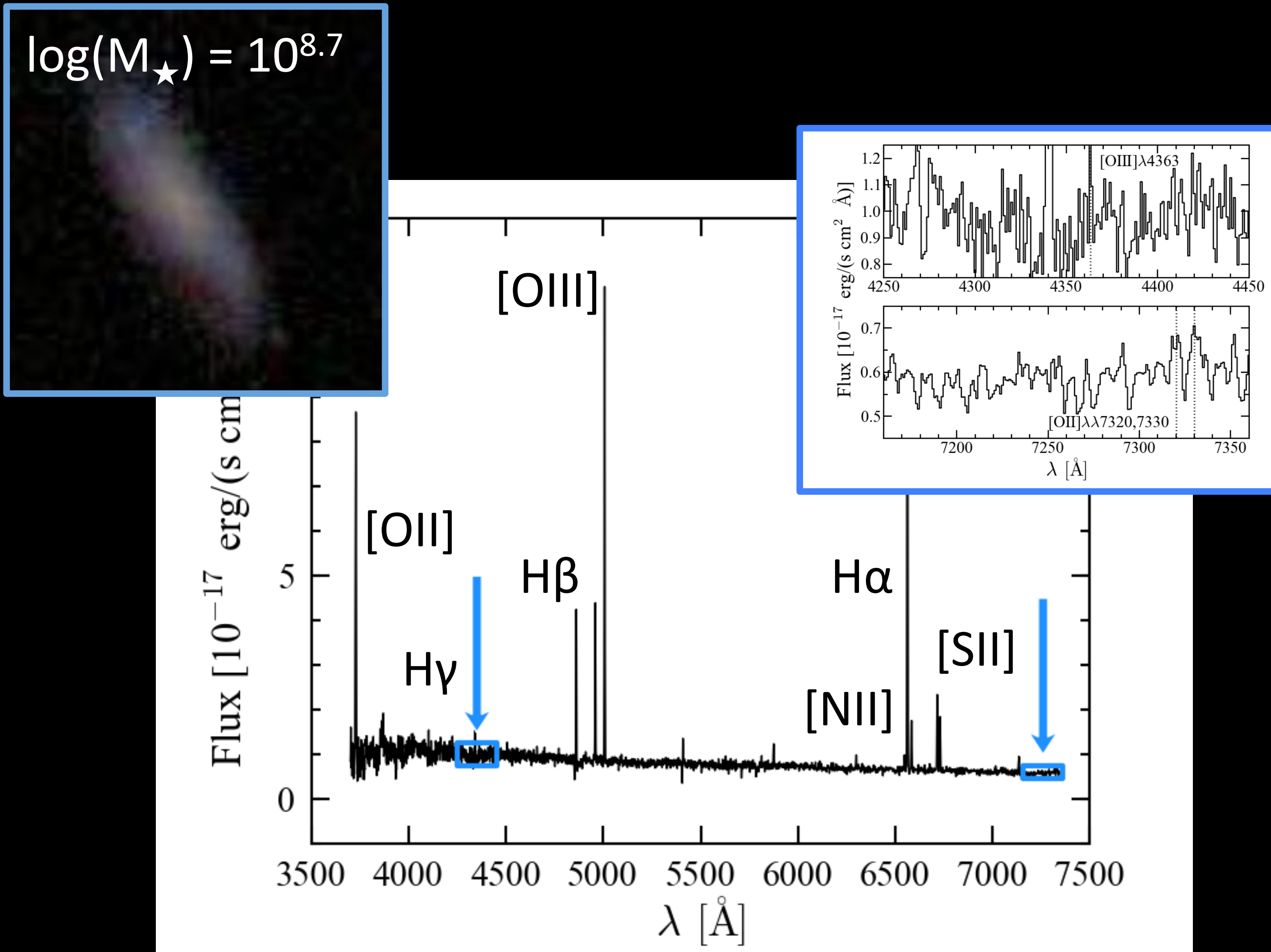
↓

$$\frac{\text{O}^{++}}{\text{H}}$$

↓

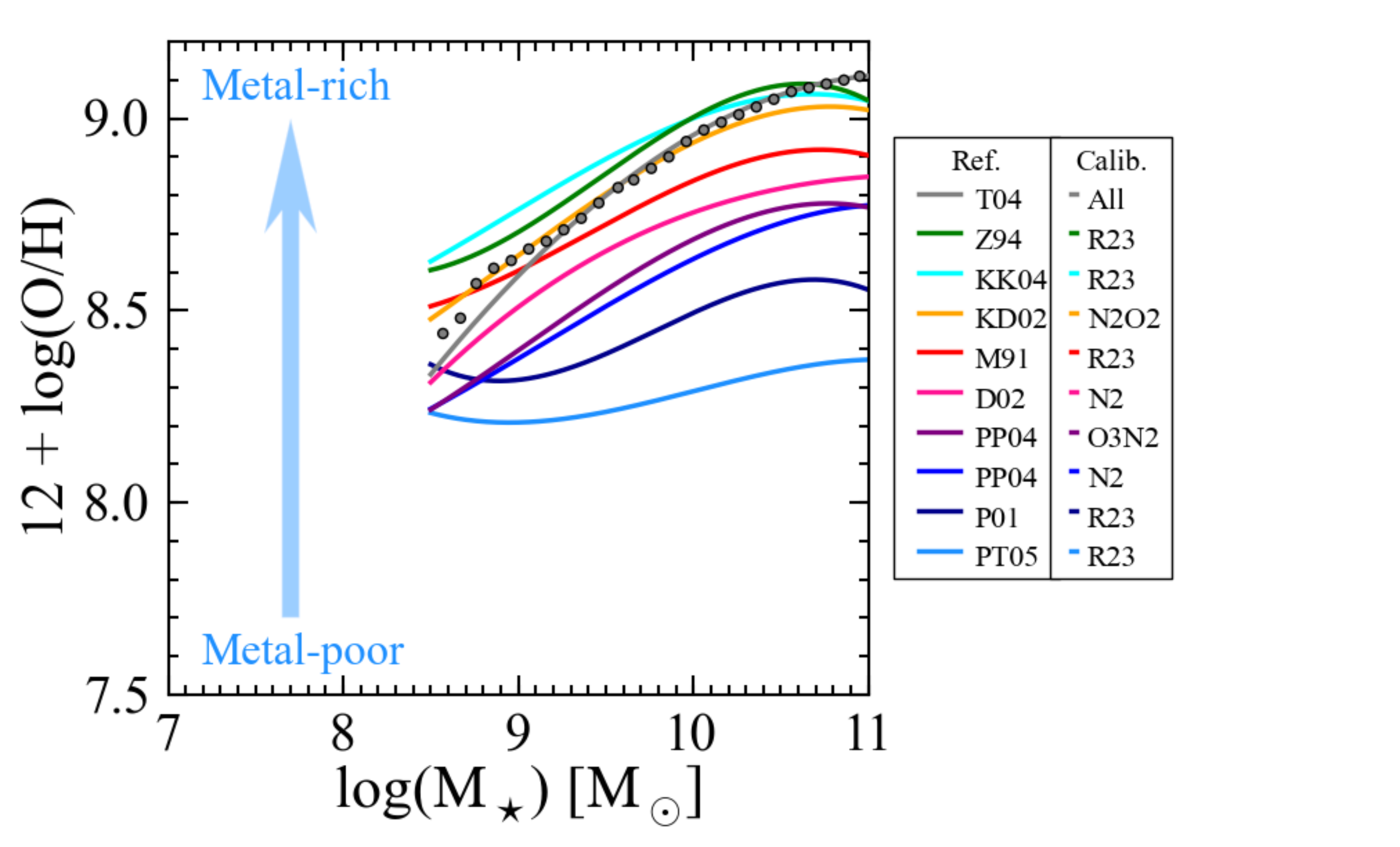
Metallicity: $$\frac{\text{O}}{\text{H}} = \frac{\text{O}^{+}}{\text{H}} + \frac{\text{O}^{++}}{\text{H}}$$

(Repeat for O+)



log(M★) = 10^8.7
[OIII]
[OII]
Hβ
Hα
Hγ
[SII]
[NII]
Flux [10^−17 erg/(s cm
0
5
3500
4000
4500
5000
5500
6000
6500
7000
7500
λ [Å]
[OIII]λ4363
[OII]λλ7320,7330
Flux [10^−17 erg/(s cm^2 Å)]
1.2
1.1
1.0
0.9
0.8
4250
4300
4350
4400
4450
0.7
0.6
0.5
7200
7250
7300
7350
λ [Å]

Strong Line Indicators

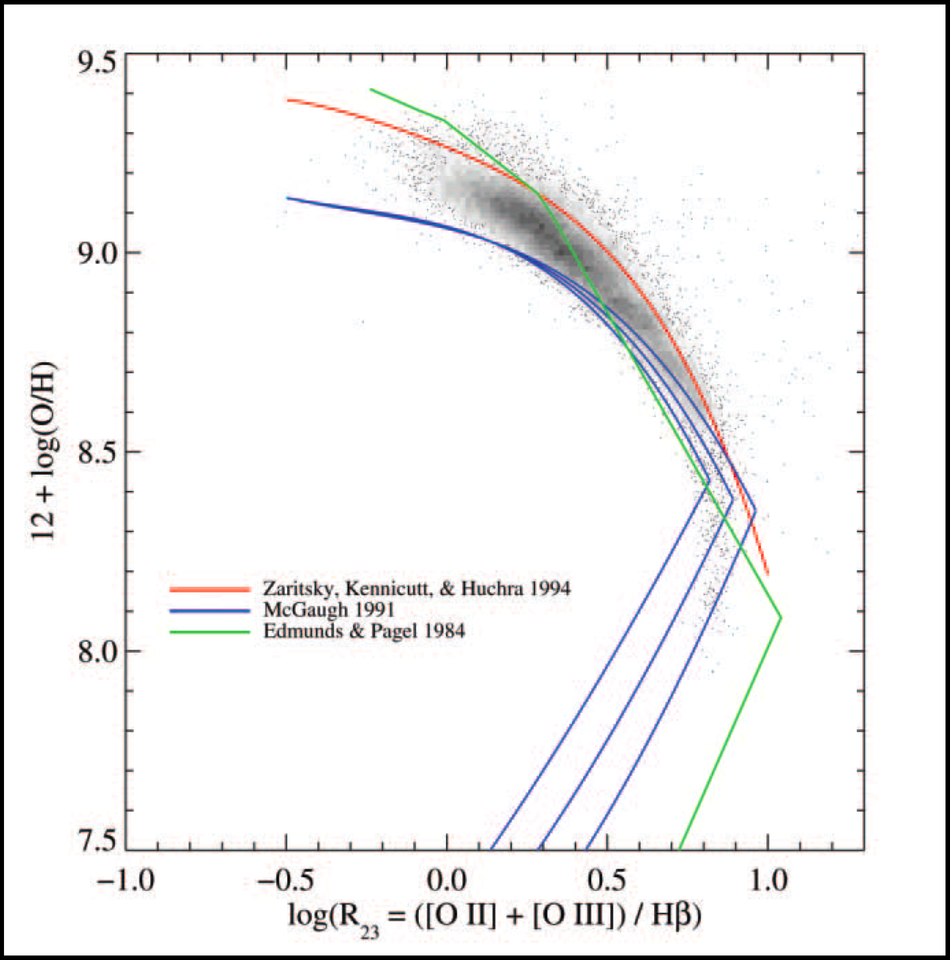


Fits from Kewley & Ellison (2008)

Strong Line Indicators

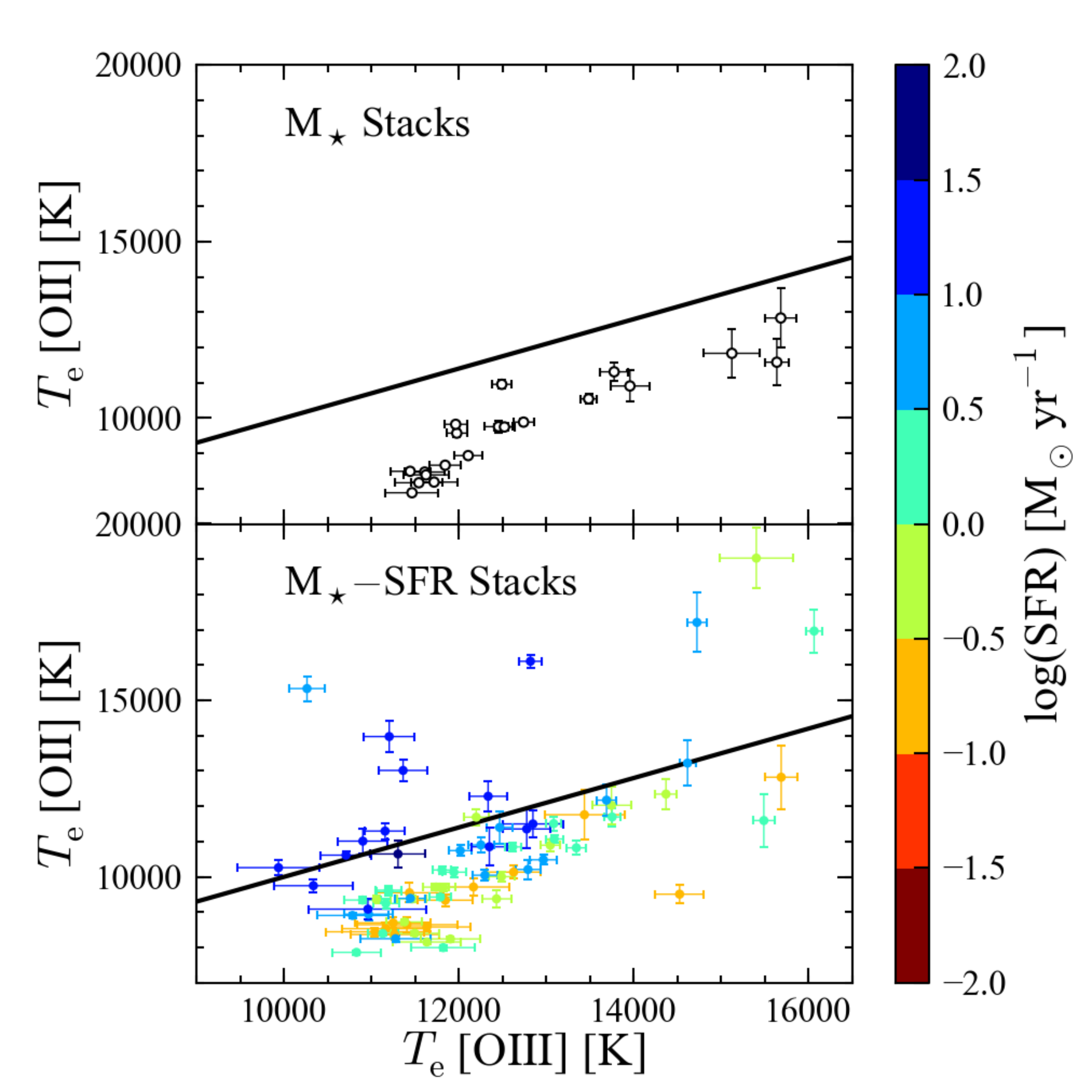
- R23 = ([OII] λ3727 + [OIII] λλ4959, 5007) / Hβ
- N2O2 = [NII] λ6583 / [OII] λ3727
- N2 = [NII] λ6583 / Hα
- O3N2 = ([OIII] λ5007) / Hβ) /
  ([NII] λ6583 / Hα)

R23 is double-valued



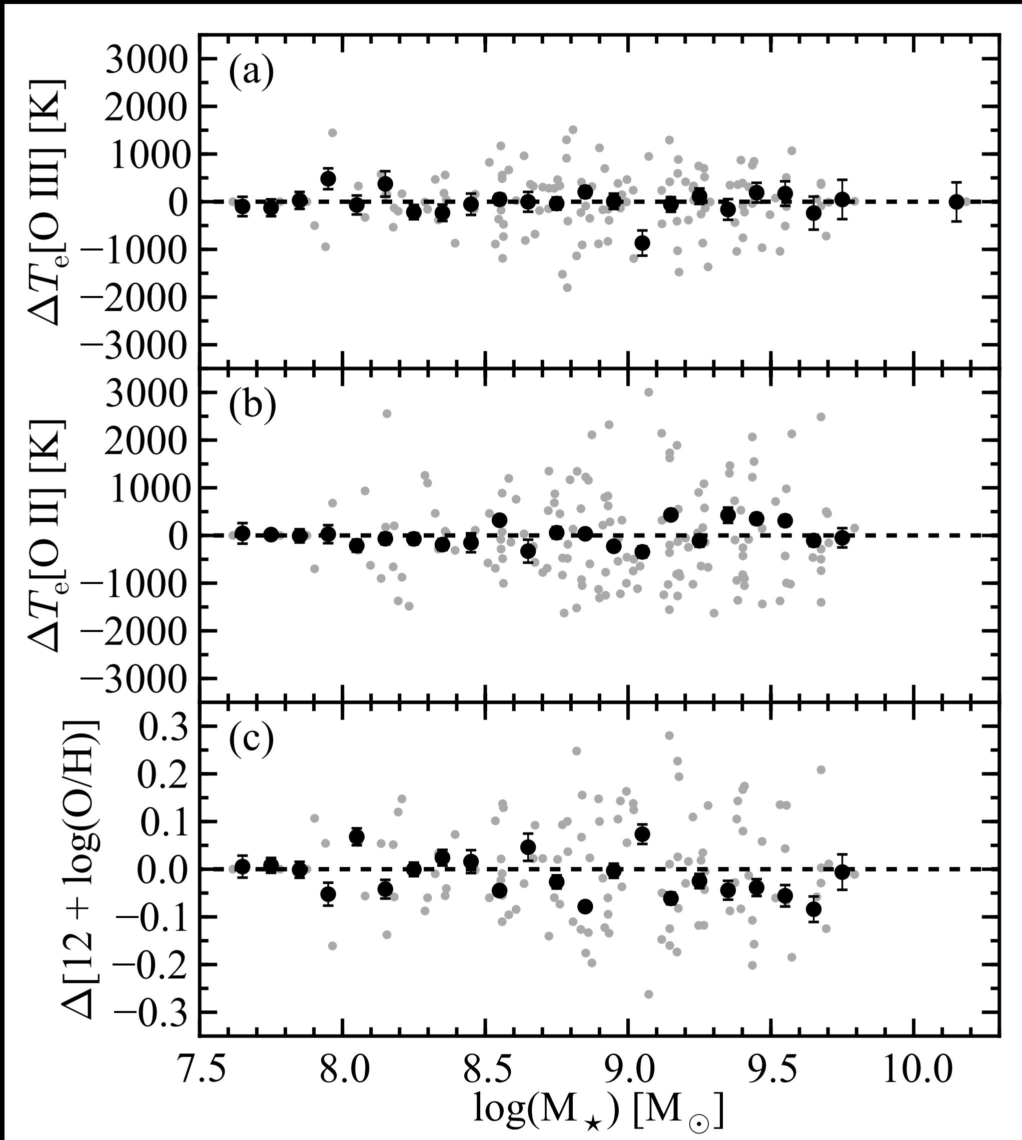
Tremonti et al. (2004)

Electron Temperatures



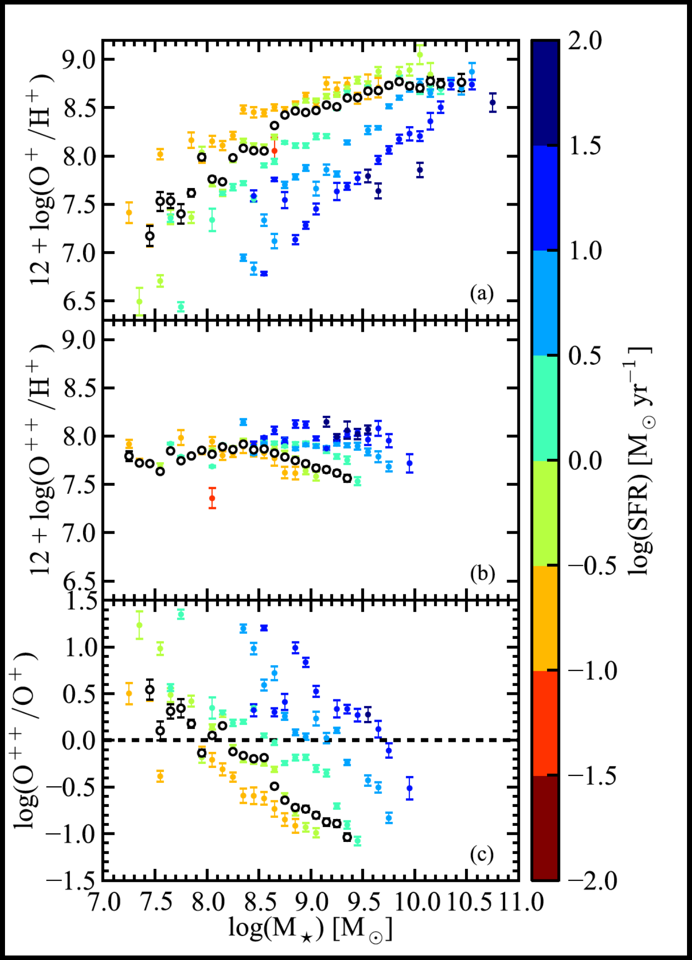
Black line:
Te[OII]—Te[OIII] relation
(Garnett 1992)

Stacks of Galaxies with Detectable Auroral Lines

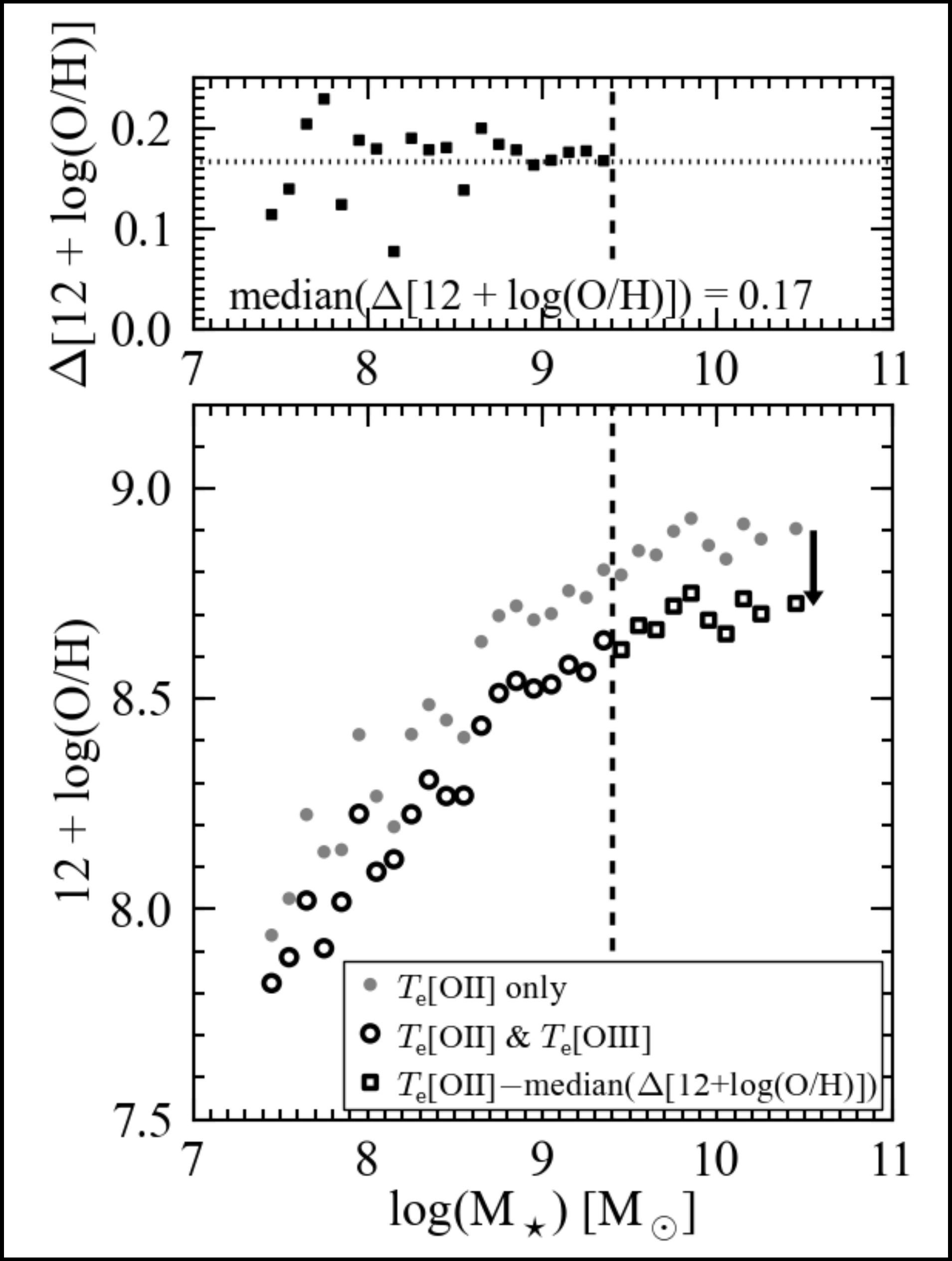


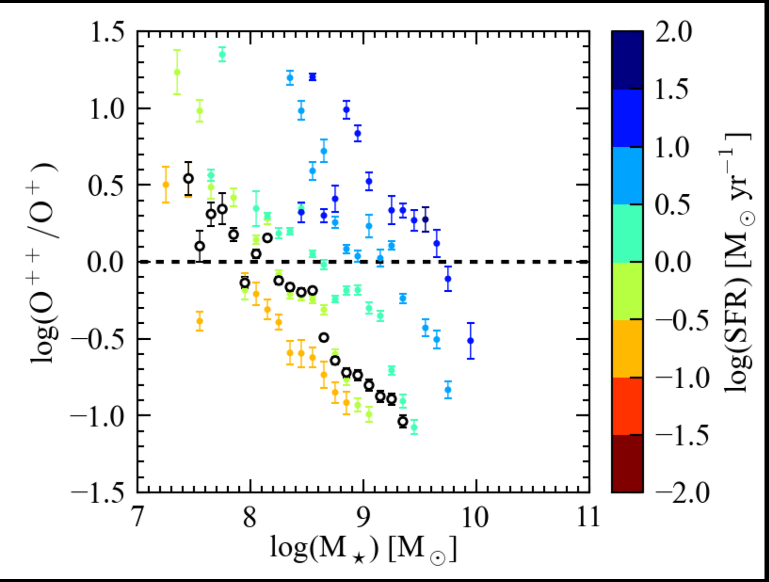
Pilyugin et al. (2010): 181 SDSS galaxies with [OIII] λ4363 and [OII] λλ7320, 7330

Dashed line: residual from median of galaxies in each stack


12 + log(O$^+$/H$^+$)
12 + log(O^{++}/H$^+$)
log(O^{++}/O$^+$)
(a)
(b)
(c)
log(M$_\star$) [M$_\odot$]
log(SFR) [M$_\odot$ yr^{-1}]

Accounting for undetected [OIII] λ4363





Asymptotic Logarithmic Fit

$$12 + \log(\mathrm{O/H}) = 12 + \log(\mathrm{O/H})_{\mathrm{asm}} - \log\left(1 + \left(\frac{M_{\mathrm{TO}}}{M_\star}\right)^{\gamma}\right)$$

- Polynomial fits can cause unphysical trends when extrapolated
- Physical justification for a turnover and asymptotic behavior at high mass

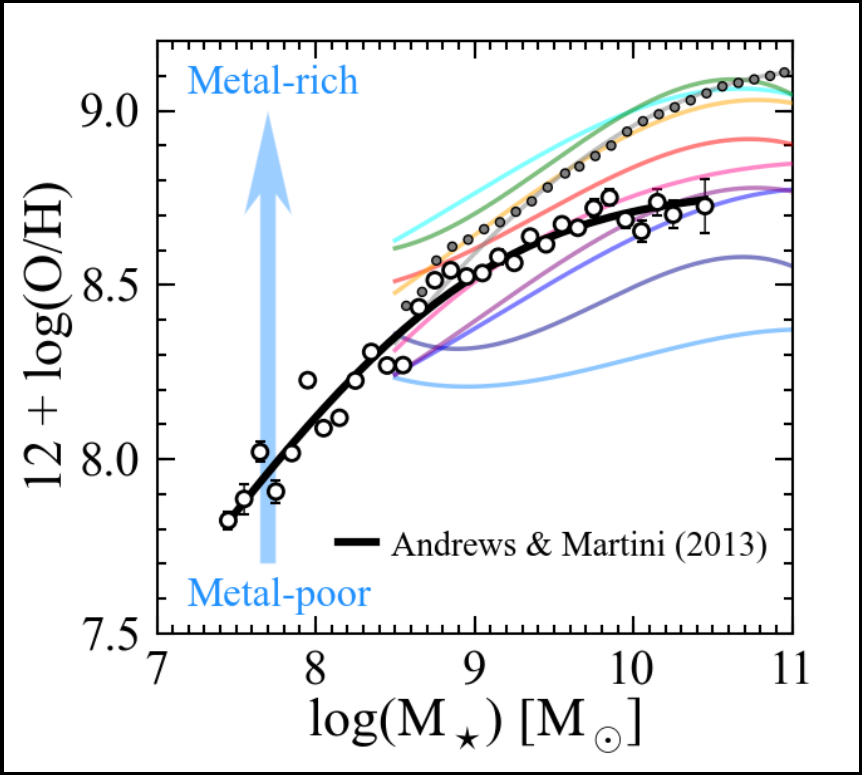
Metal Ejection Efficiency

Peeples & Shankar (2011)

Metallicity-weighted mass-loading factor

↓

$$\zeta_{\rm wind} = \left(\frac{Z_{\rm wind}}{Z_{\rm ISM}}\right)\left(\frac{\dot{M}_{\rm wind}}{\rm SFR}\right)$$



Transform the Mass—Metallicity Relation into the metal ejection efficiency as a function of $M_\star$

Metal Ejection Efficiency

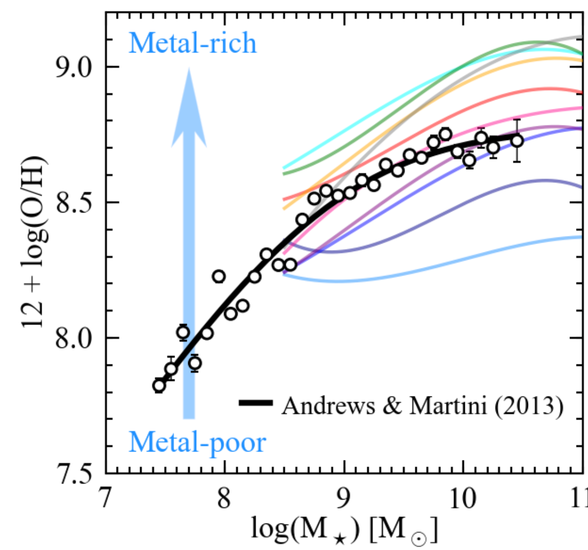
"Metallicity-weighted mass-loading factor"

Peeples & Shankar (2011)

$$\zeta_{\rm wind} = \left(\frac{Z_{\rm wind}}{Z_{\rm ISM}}\right)\left(\frac{\dot{M}_{\rm wind}}{\rm SFR}\right)$$

$$\zeta_{\rm wind} = \frac{y}{Z_{\rm ISM}} - 1 - (\alpha F_{\rm gas})$$

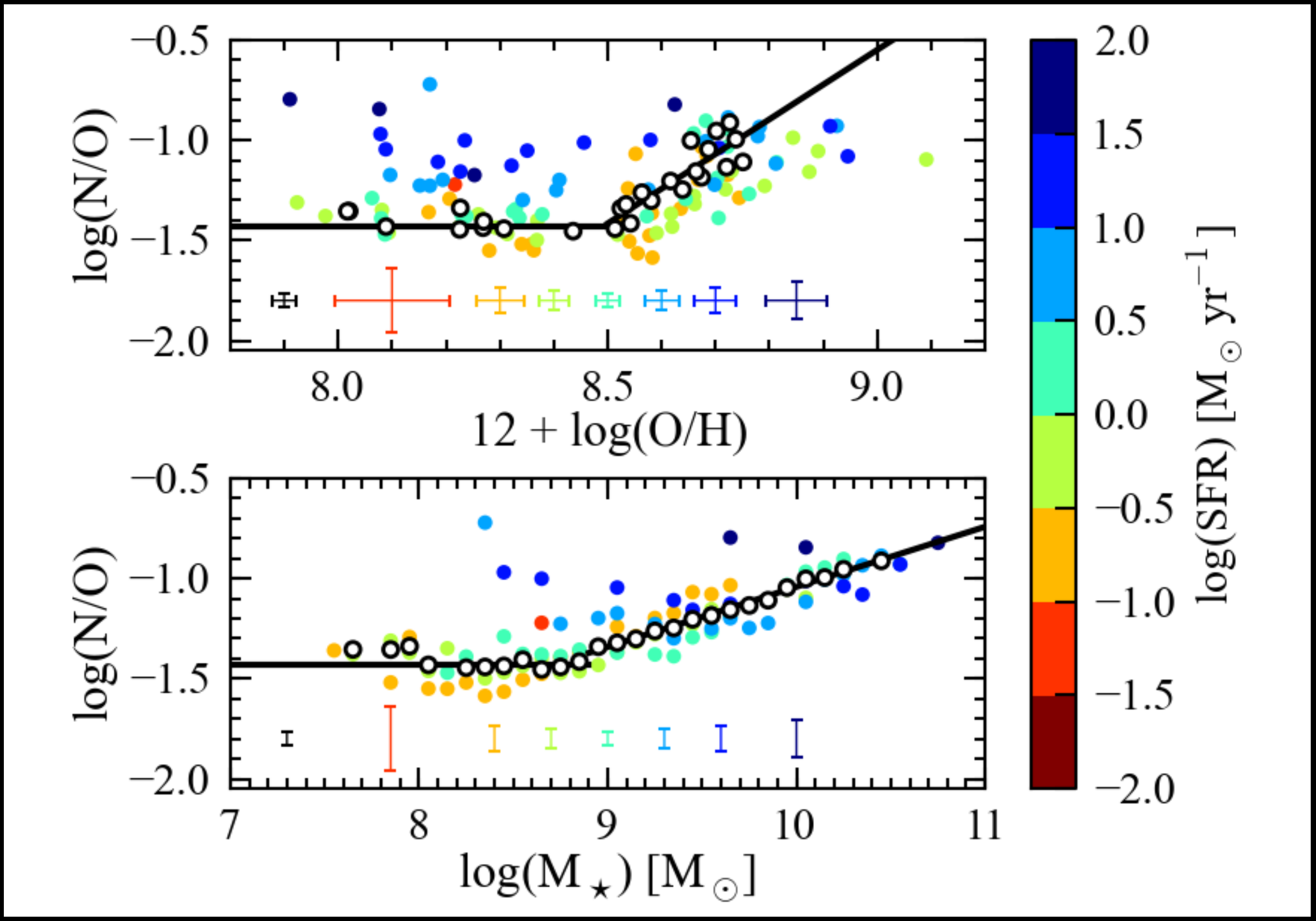
- nucleosynthetic yield: $y = 0.015$
- α ~ order unity (different from α in the fundamental metallicity relation)
- $F_{gas} = M_{gas}/M_\star$



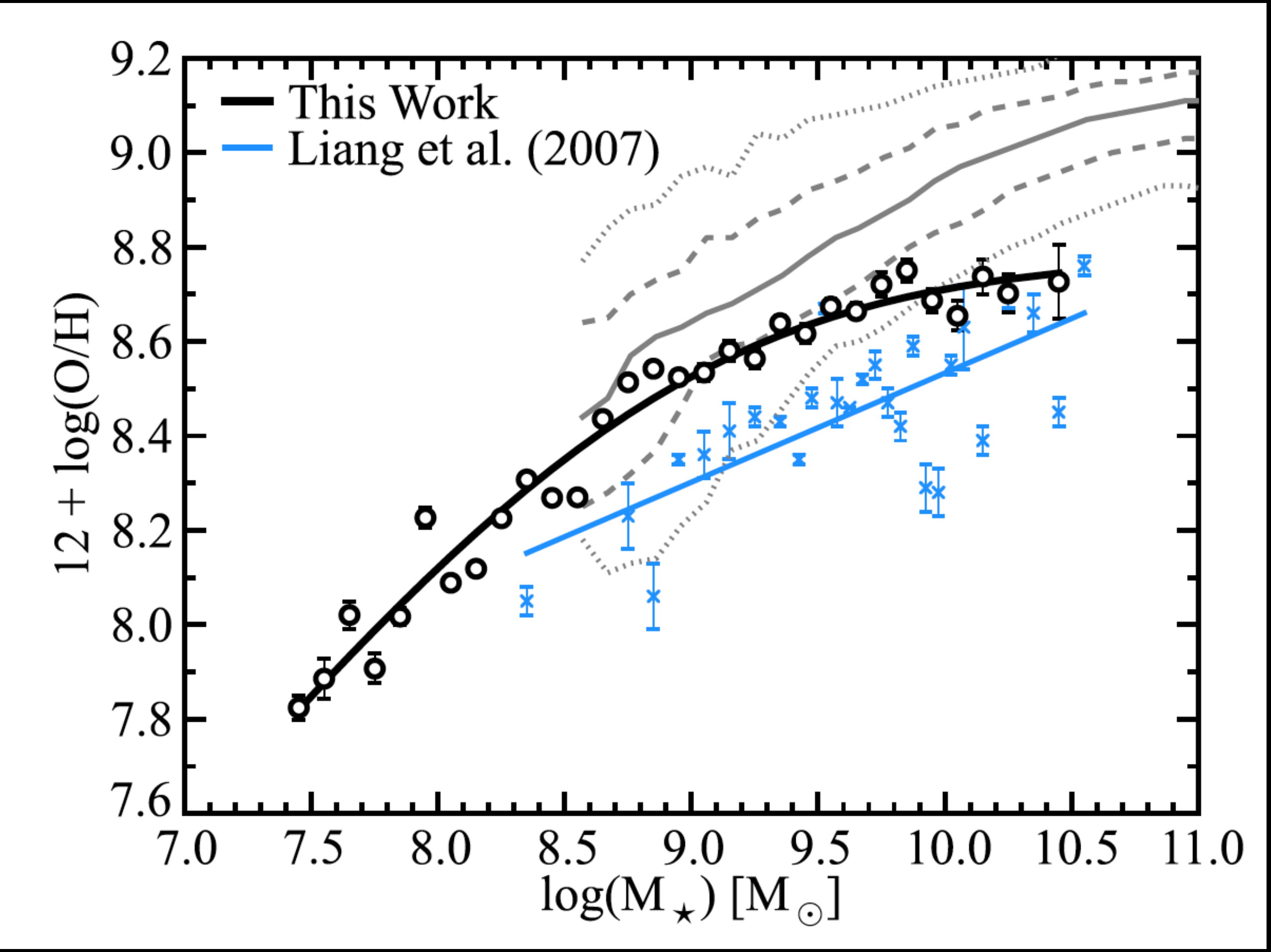
Fits from Kewley & Ellison (2008)

Transform the Mass—Metallicity Relation into the metal ejection efficiency as a function of $M_\star$

N/O



−0.5
−1.0
−1.5
−2.0
log(N/O)
8.0
8.5
9.0
12 + log(O/H)
−0.5
−1.0
−1.5
−2.0
log(N/O)
7
8
9
10
11
log(M⋆) [M⊙]
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
log(SFR) [M⊙ yr−1]

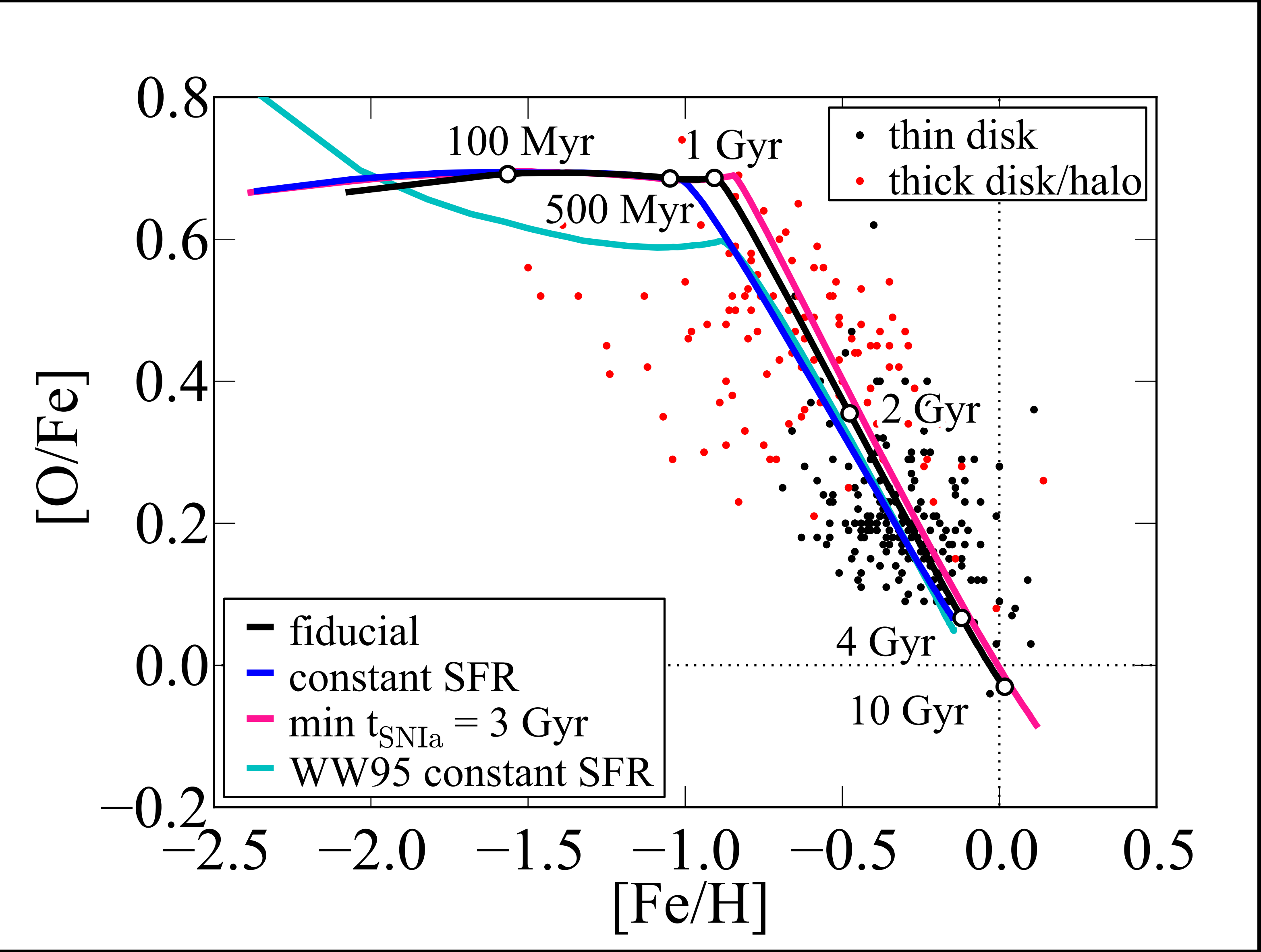


This Work
Liang et al. (2007)
12 + log(O/H)
log(M$_\star$) [M$_\odot$]
9.2
9.0
8.8
8.6
8.4
8.2
8.0
7.8
7.6
7.0
7.5
8.0
8.5
9.0
9.5
10.0
10.5
11.0

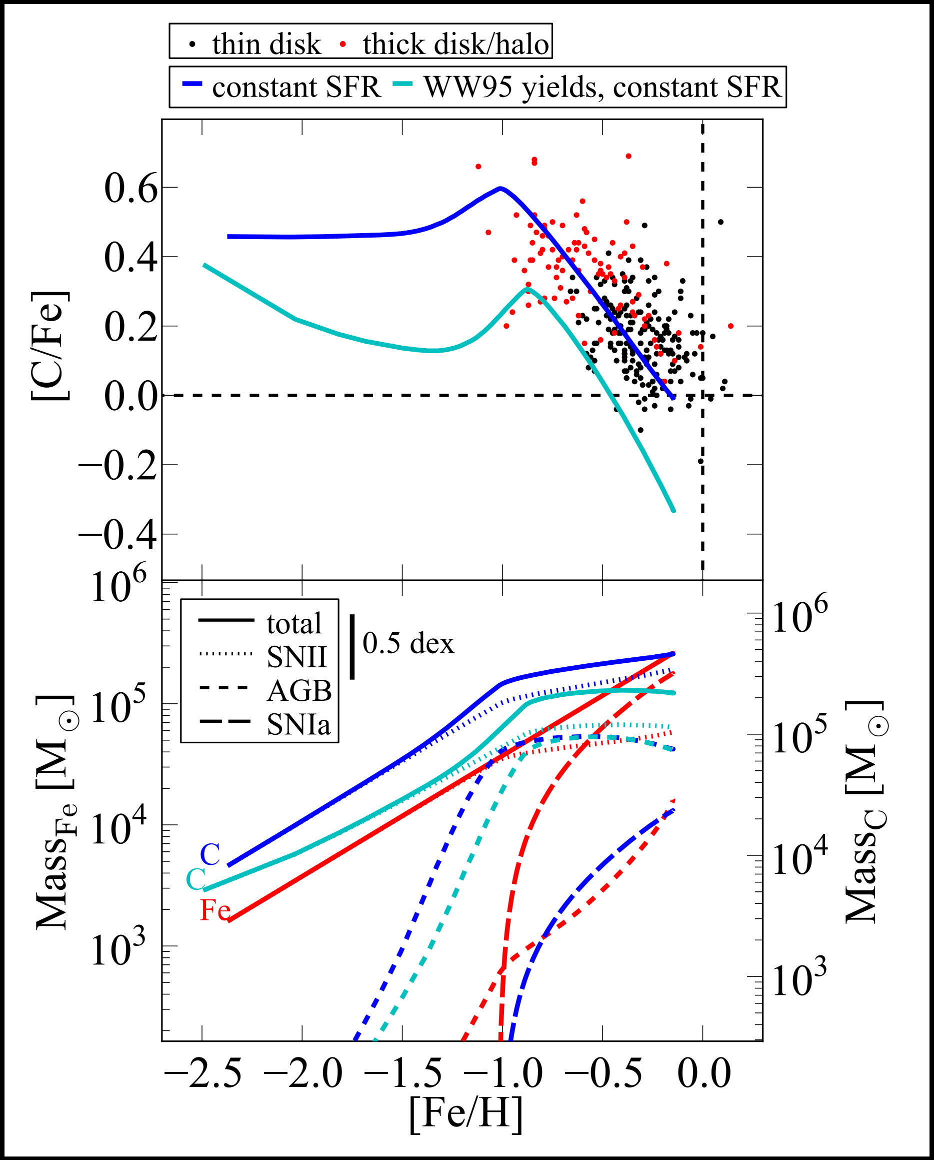
Outlook

- Kevin Croxall et al. (in prep.) Herschel measurements of FIR fine-structure lines
- High-z direct method metallicity measurements (plus stellar masses and SFRs) of high redshift galaxies

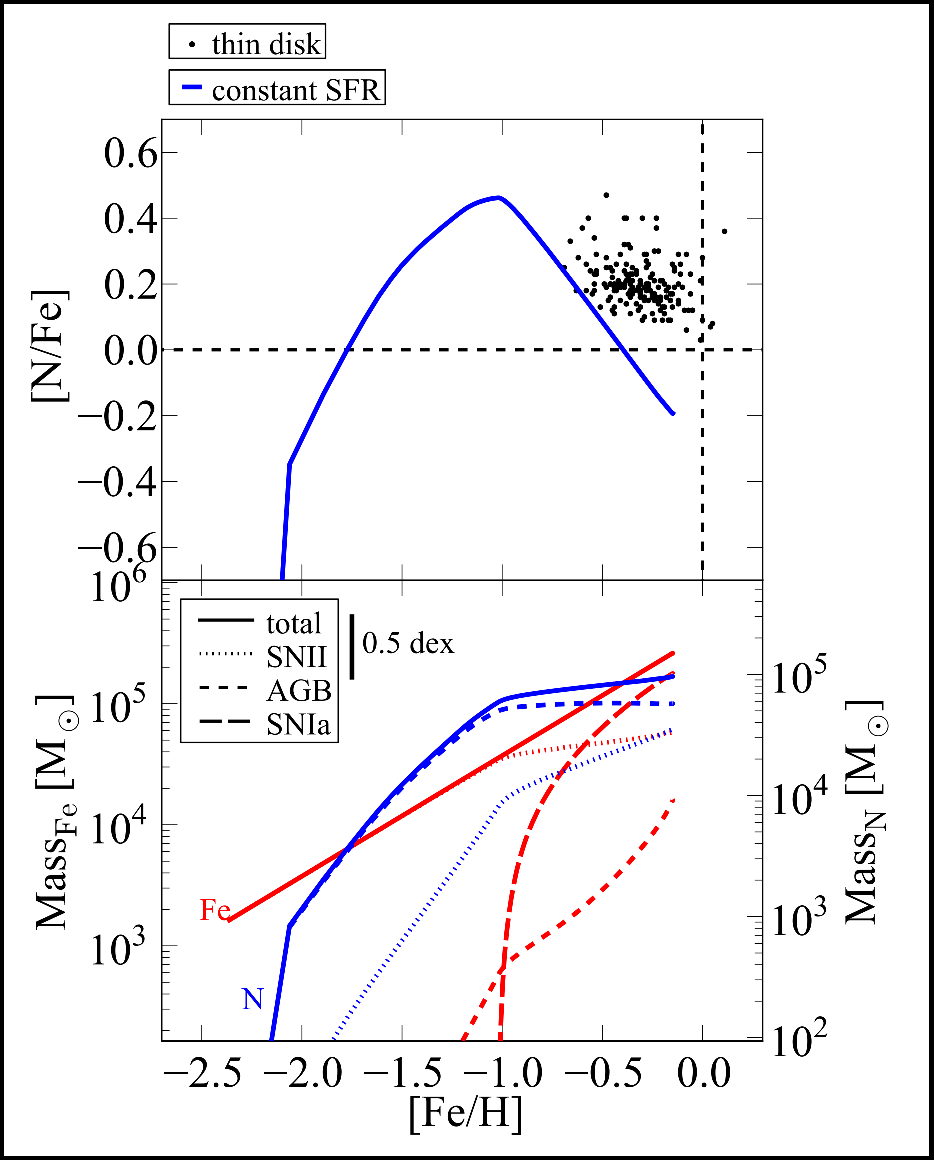
Chemical Evolution Models



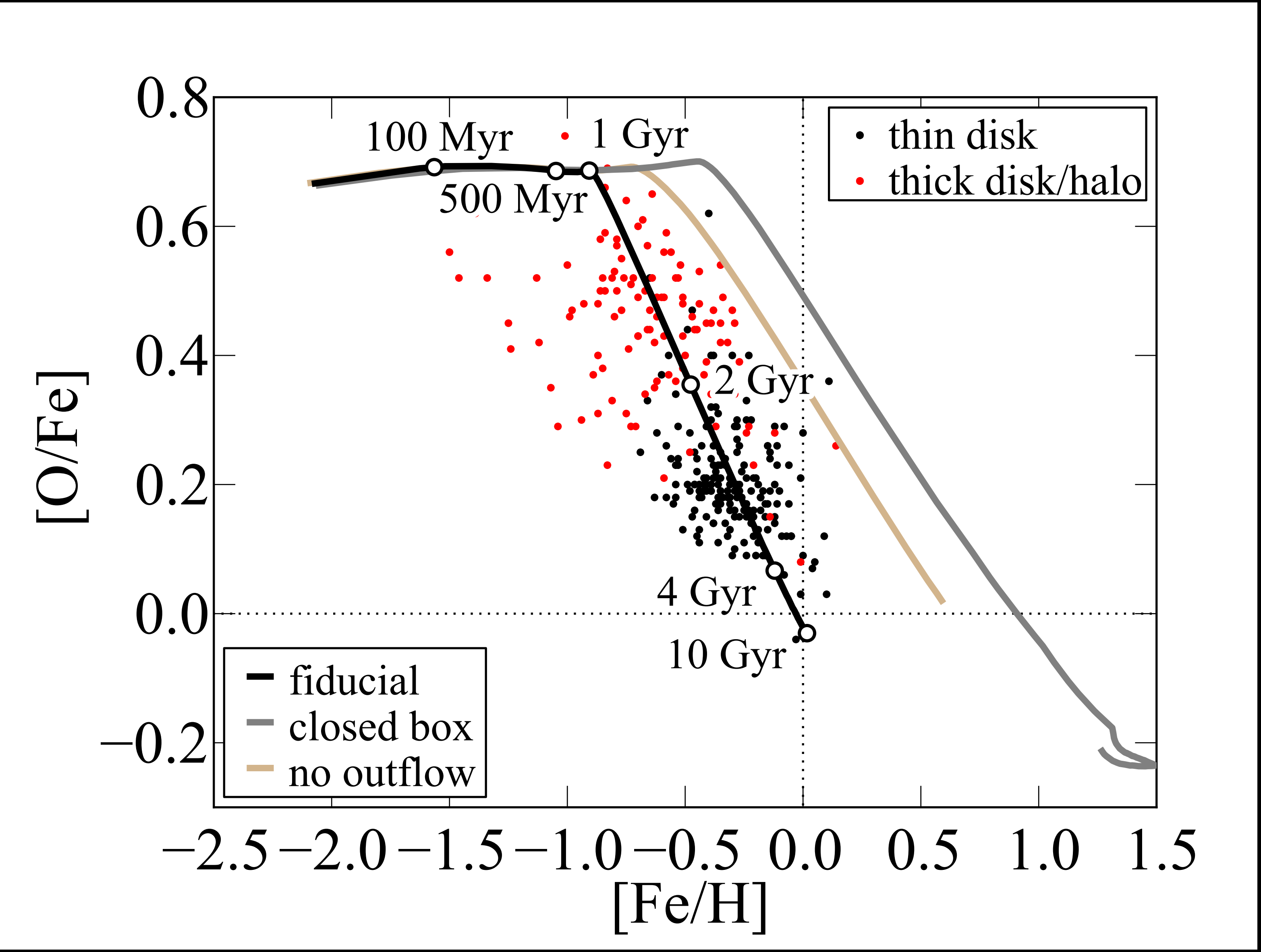
Chemical Evolution Models



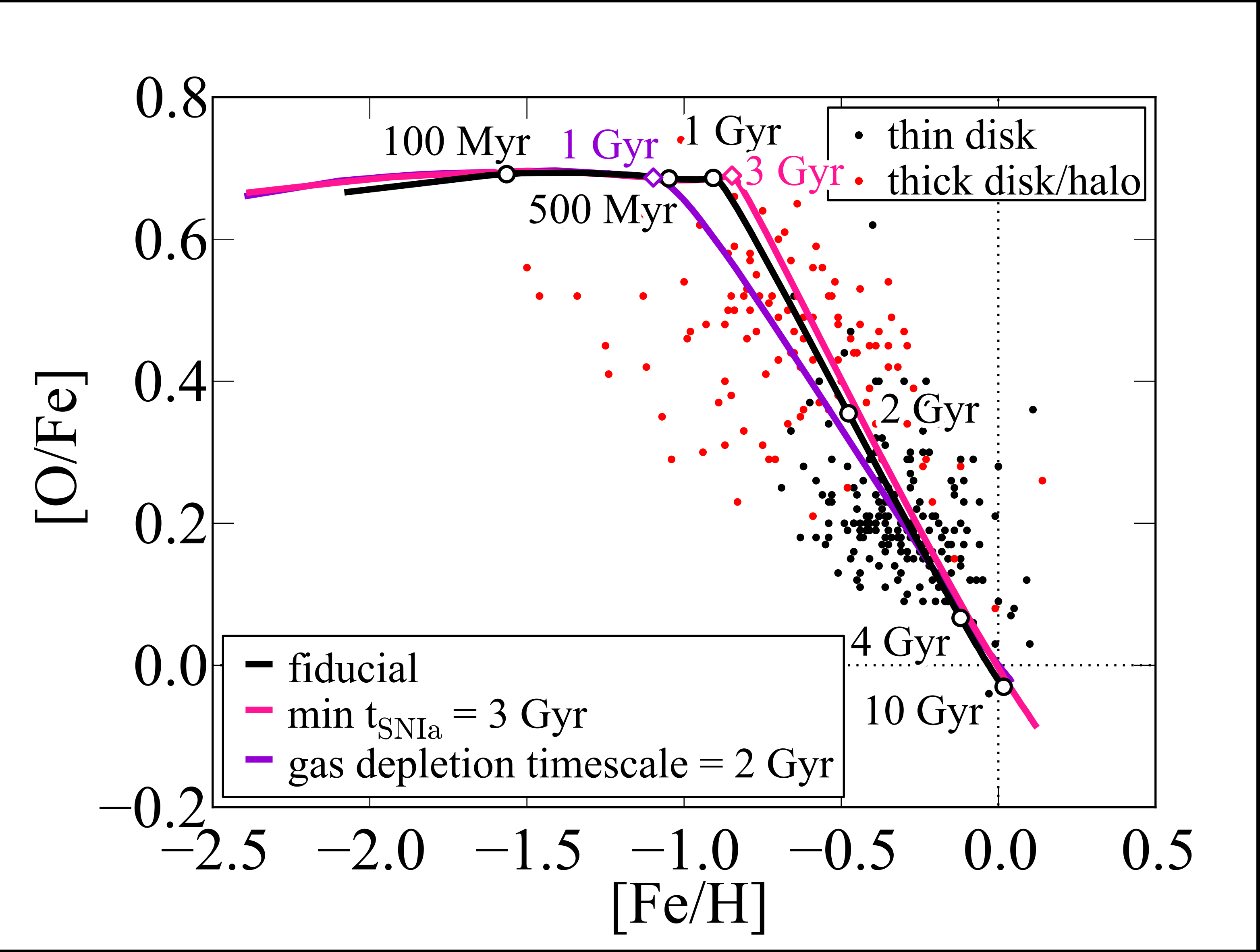
Chemical Evolution Models



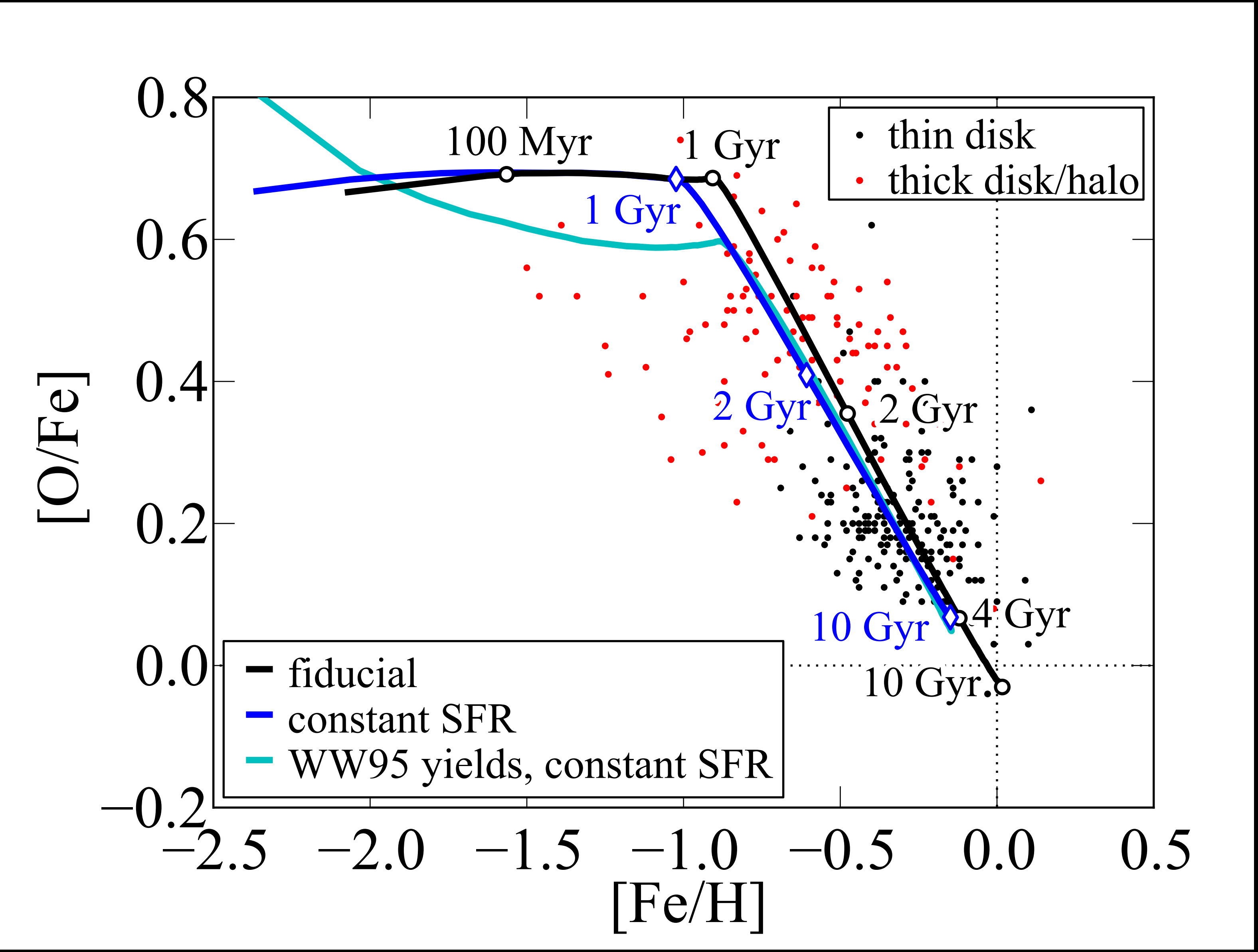
Chemical Evolution Models



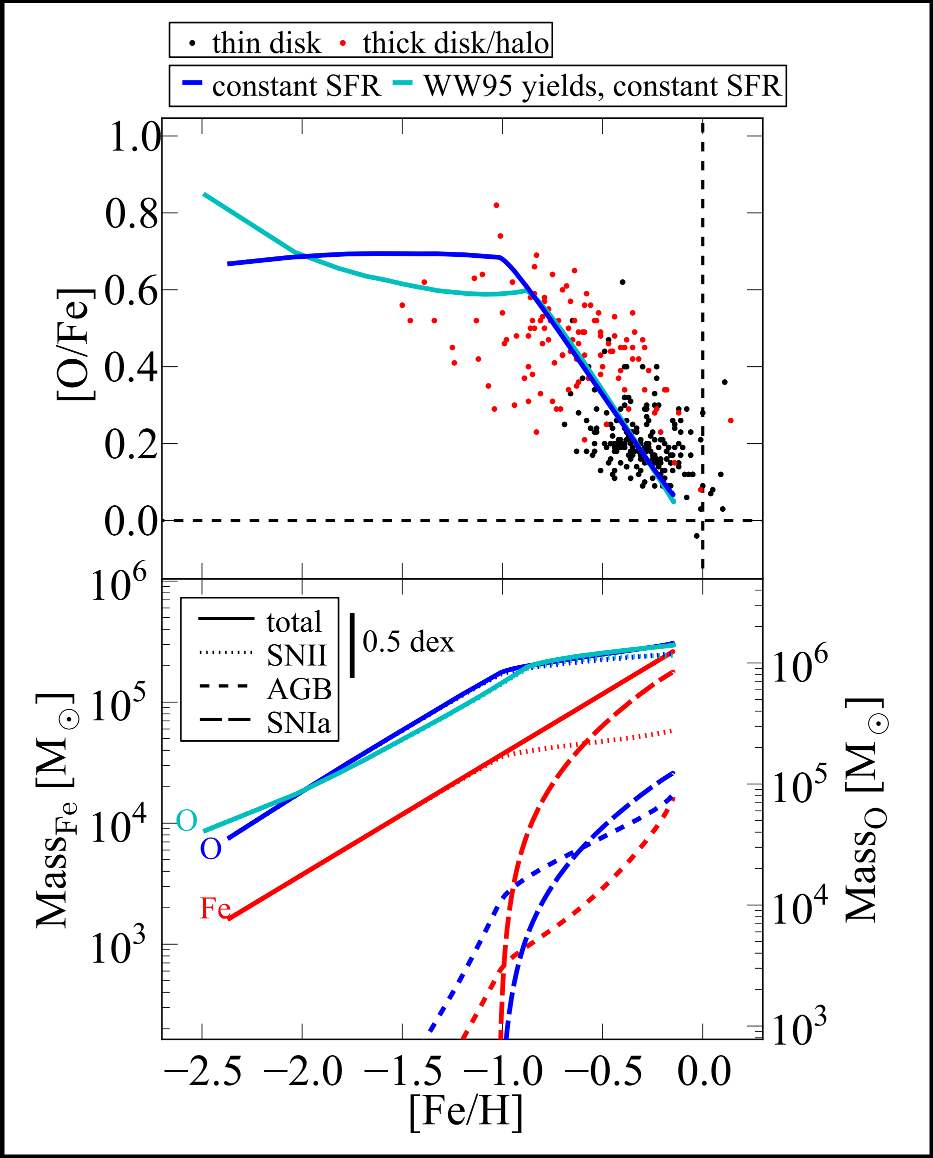
Chemical Evolution Models



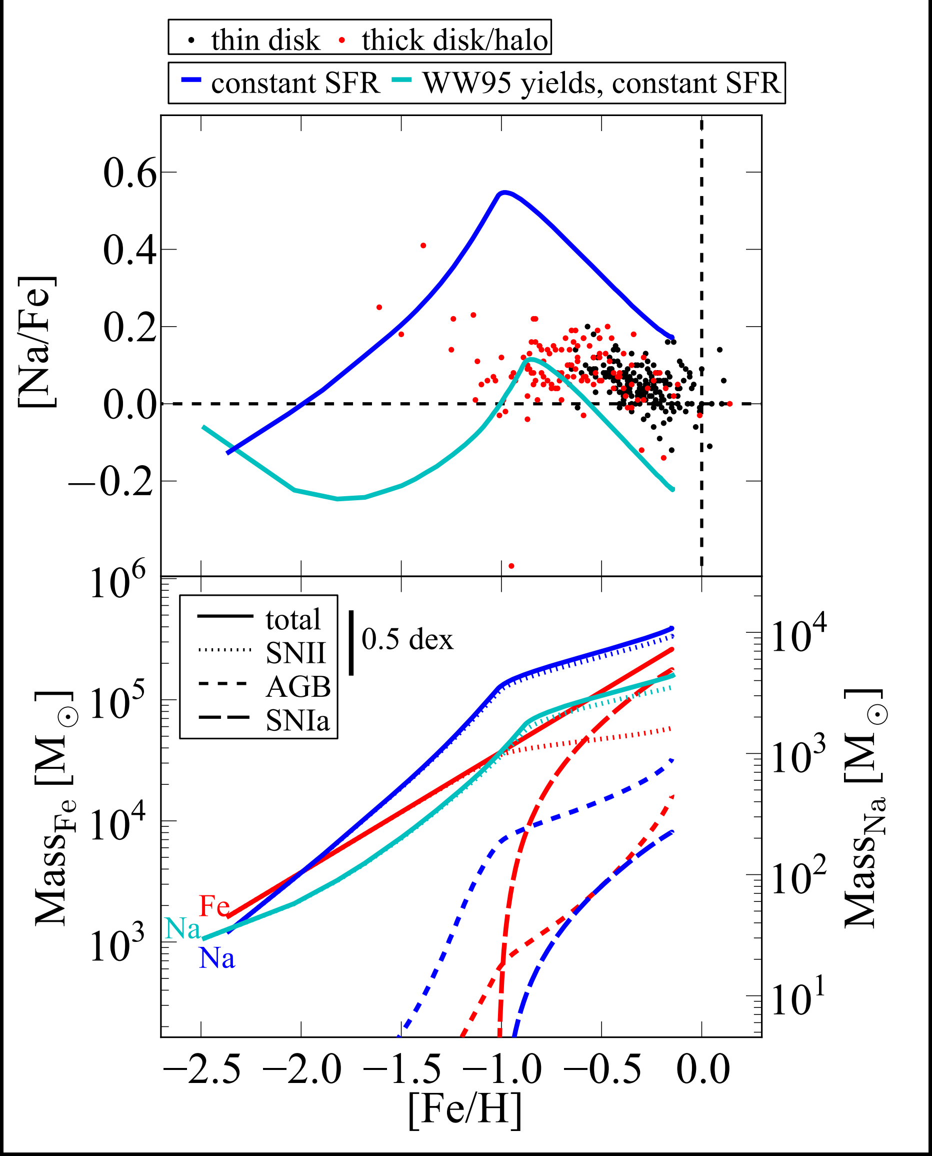
Chemical Evolution Models



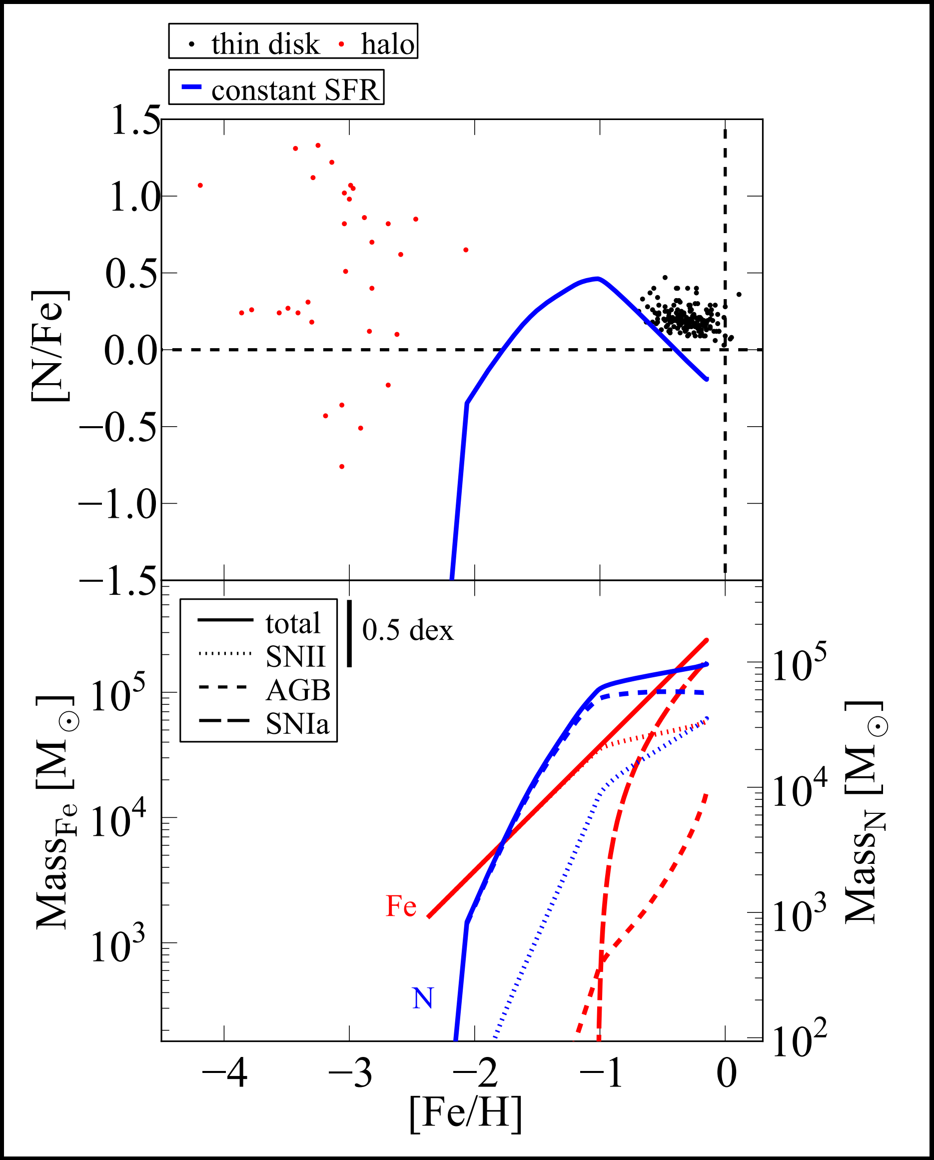
Chemical Evolution Models



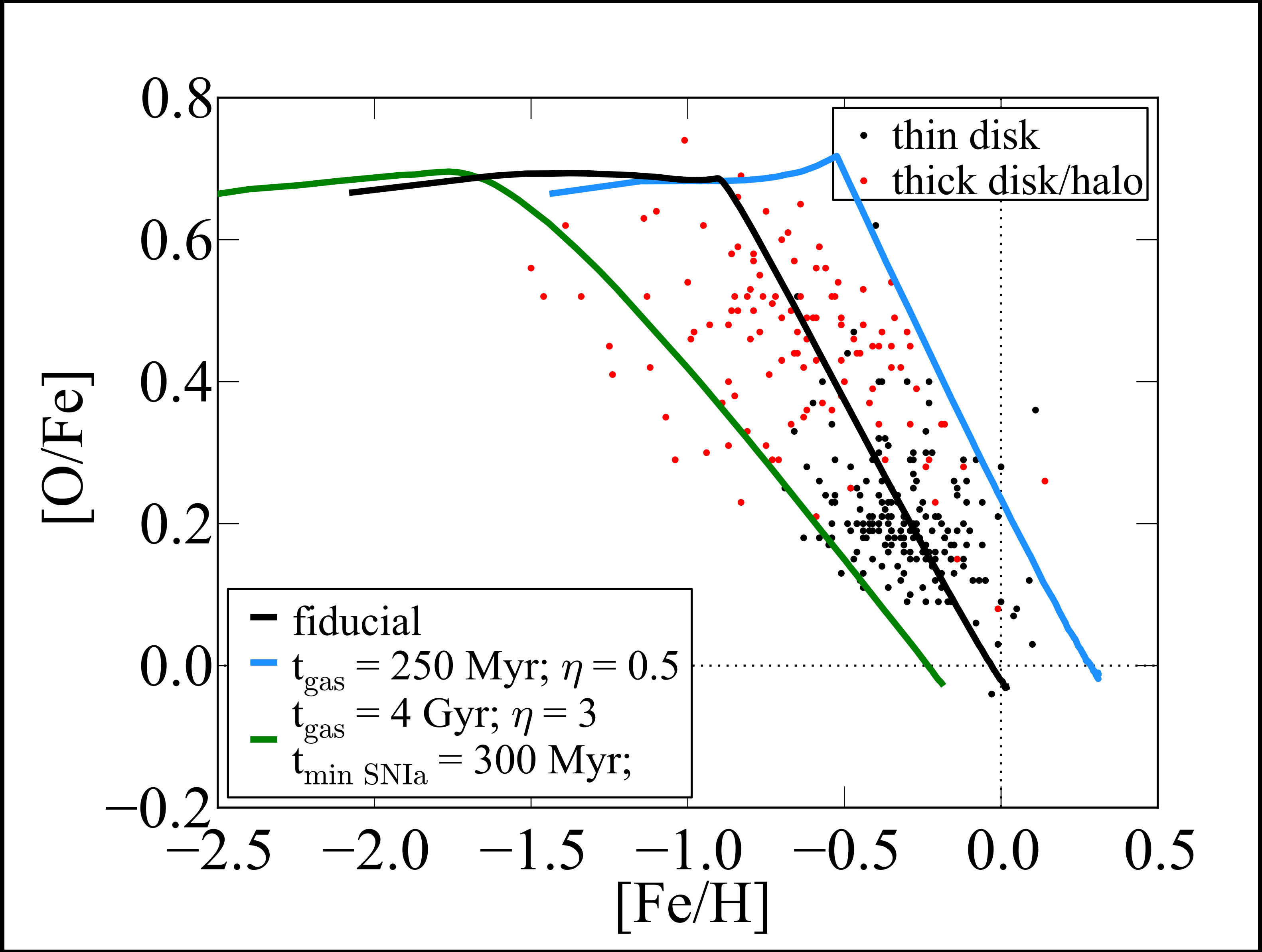
Chemical Evolution Models



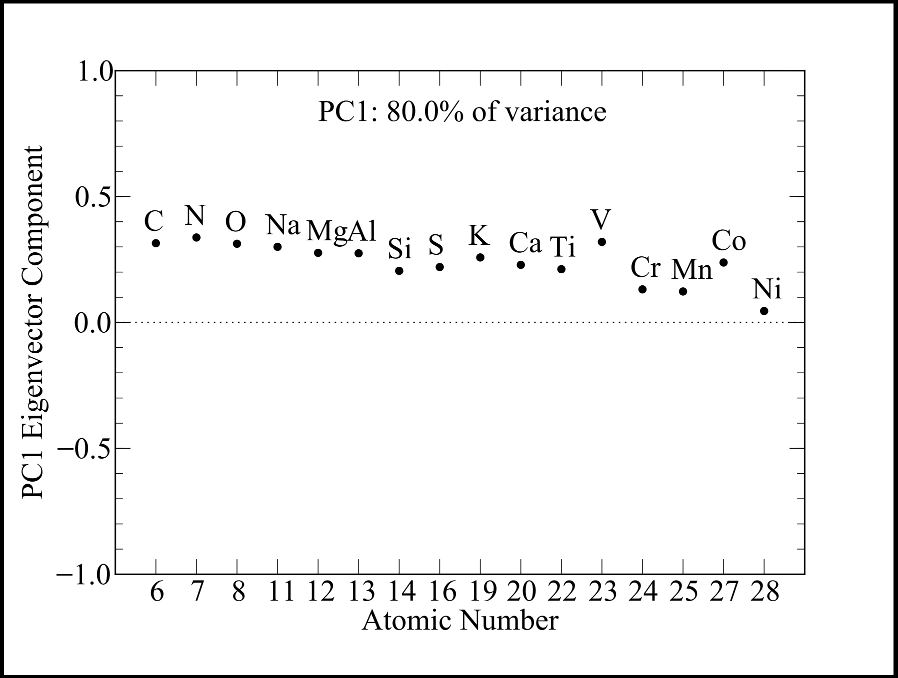
Chemical Evolution Models

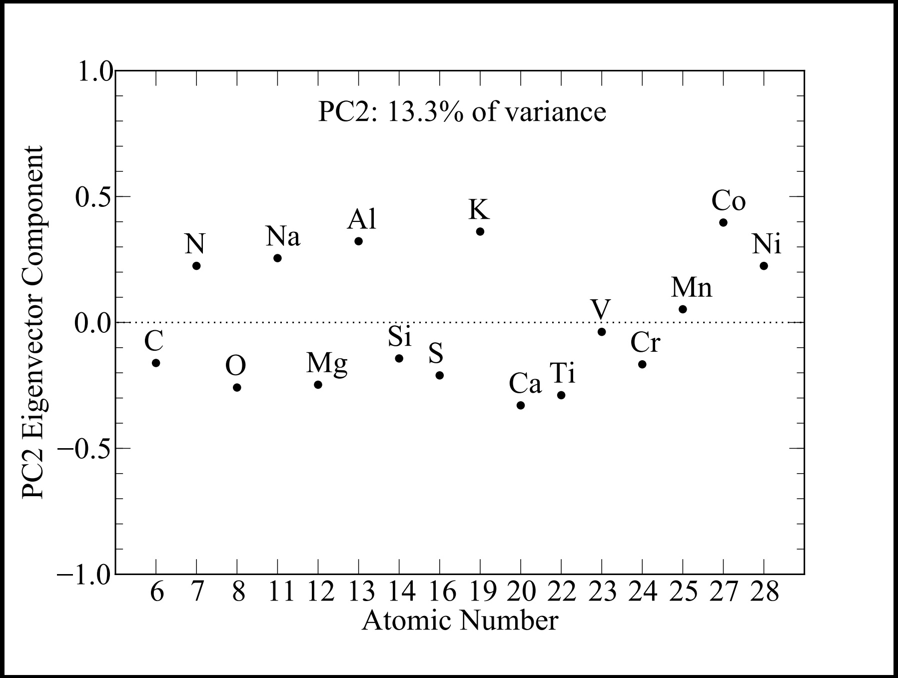


PCAA of Chemical Evolution Models



PCAA of Chemical Evolution Models





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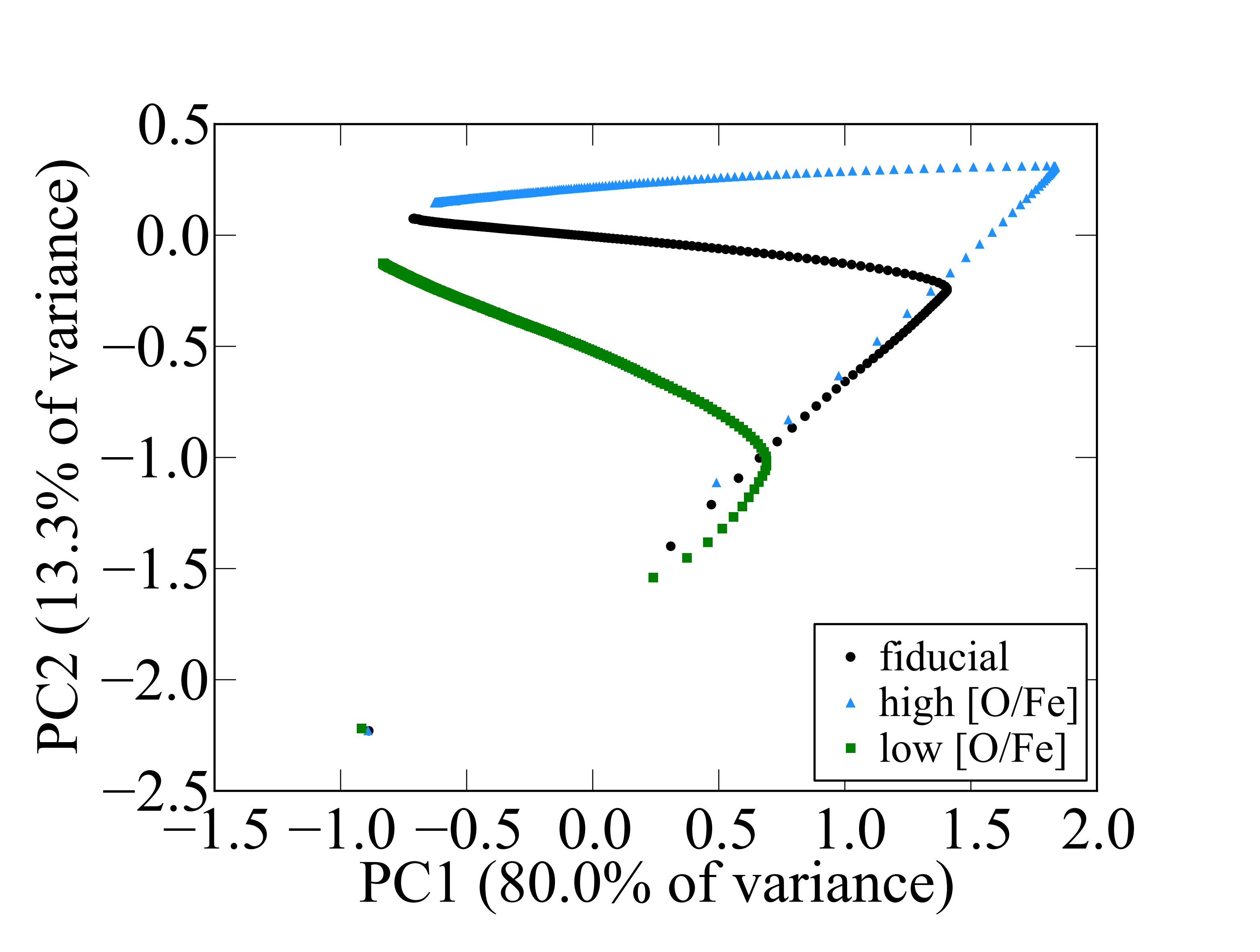
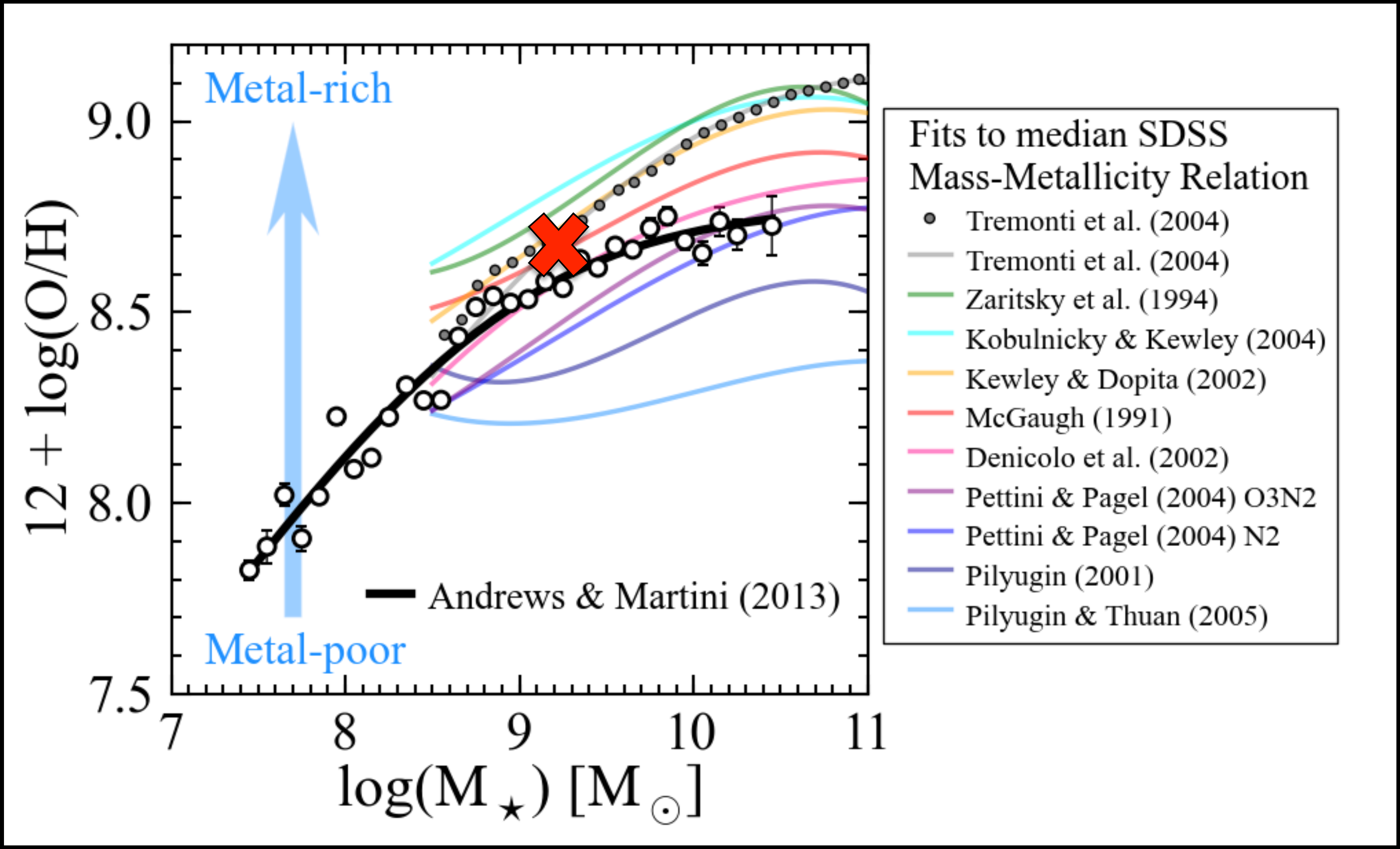


Direct Method Mass—Metallicity Relation



Fits from Kewley & Ellison (2008)