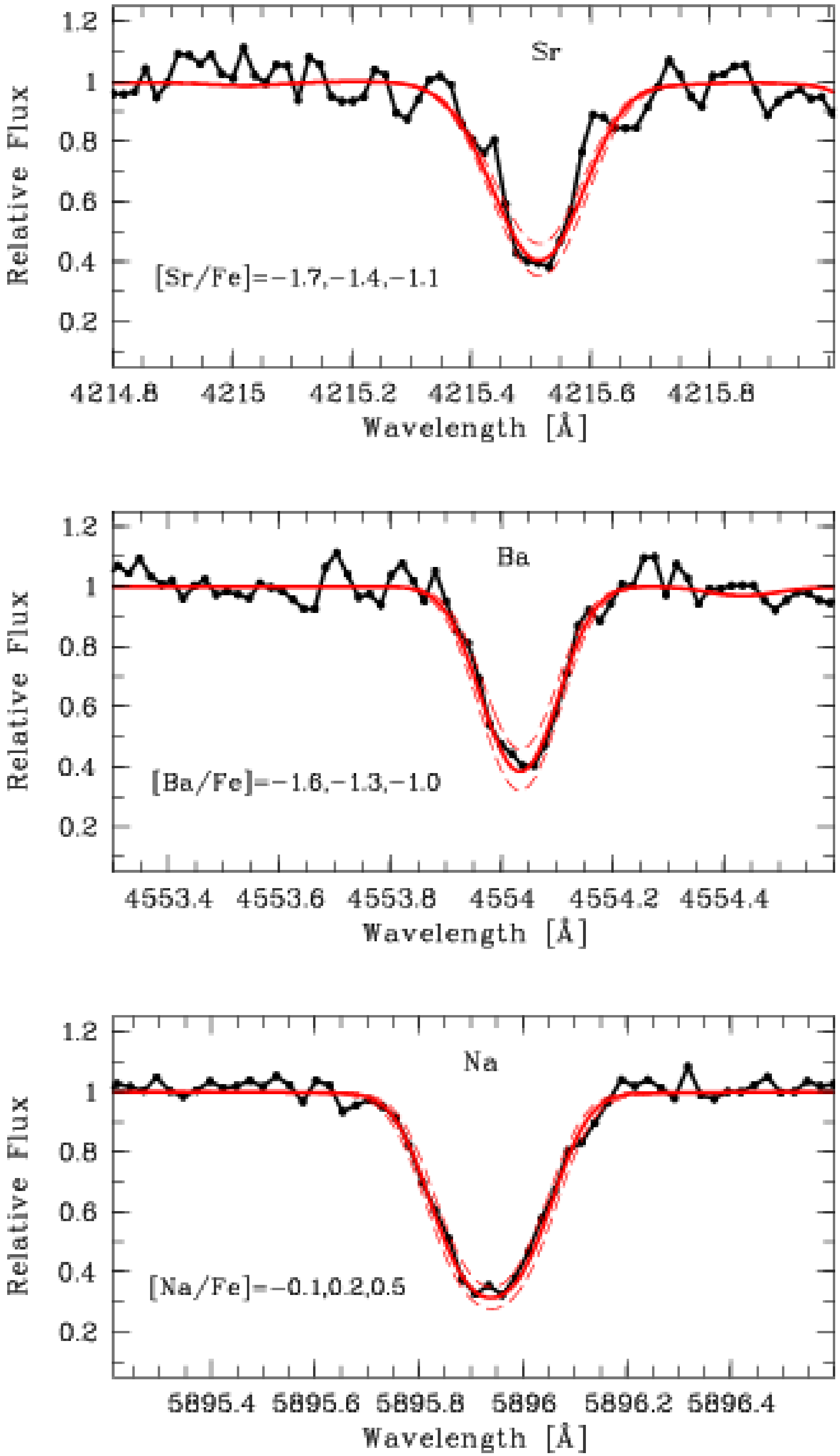
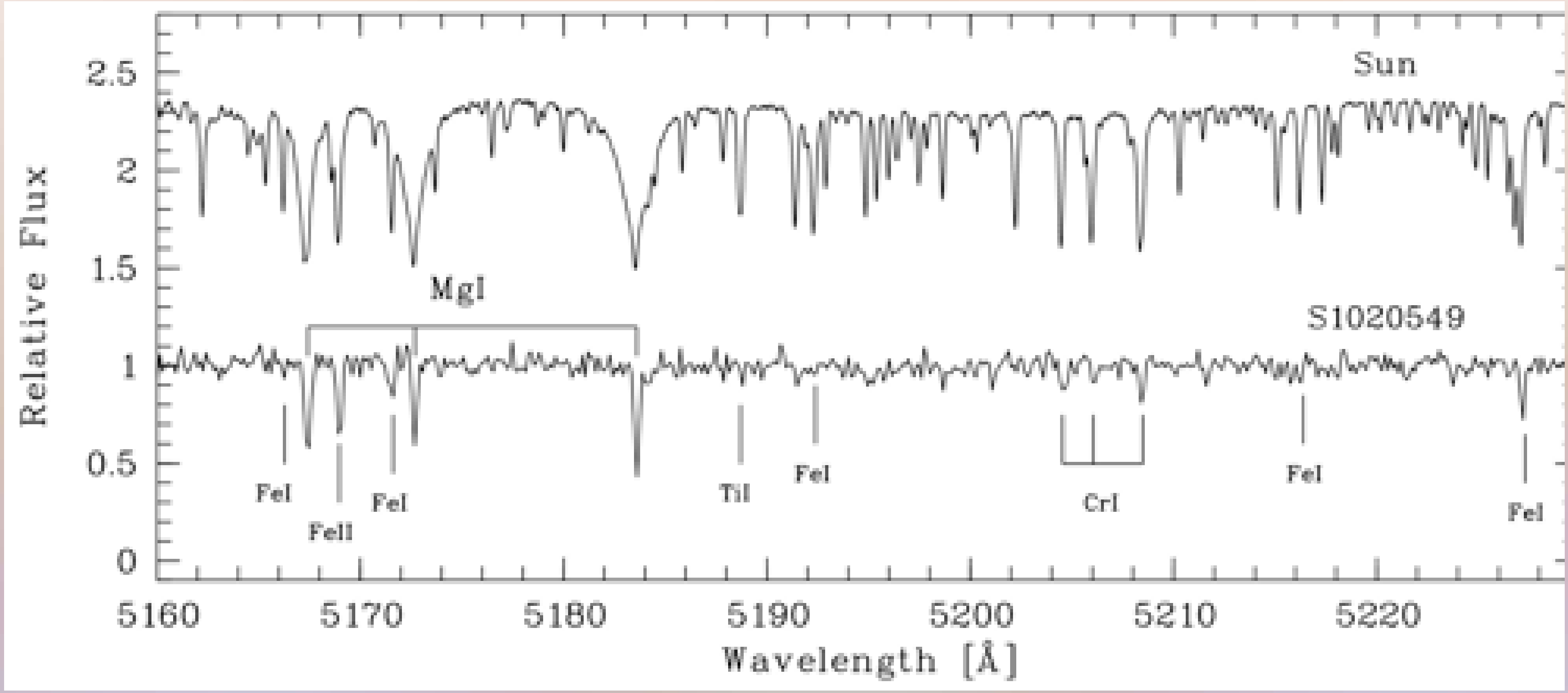
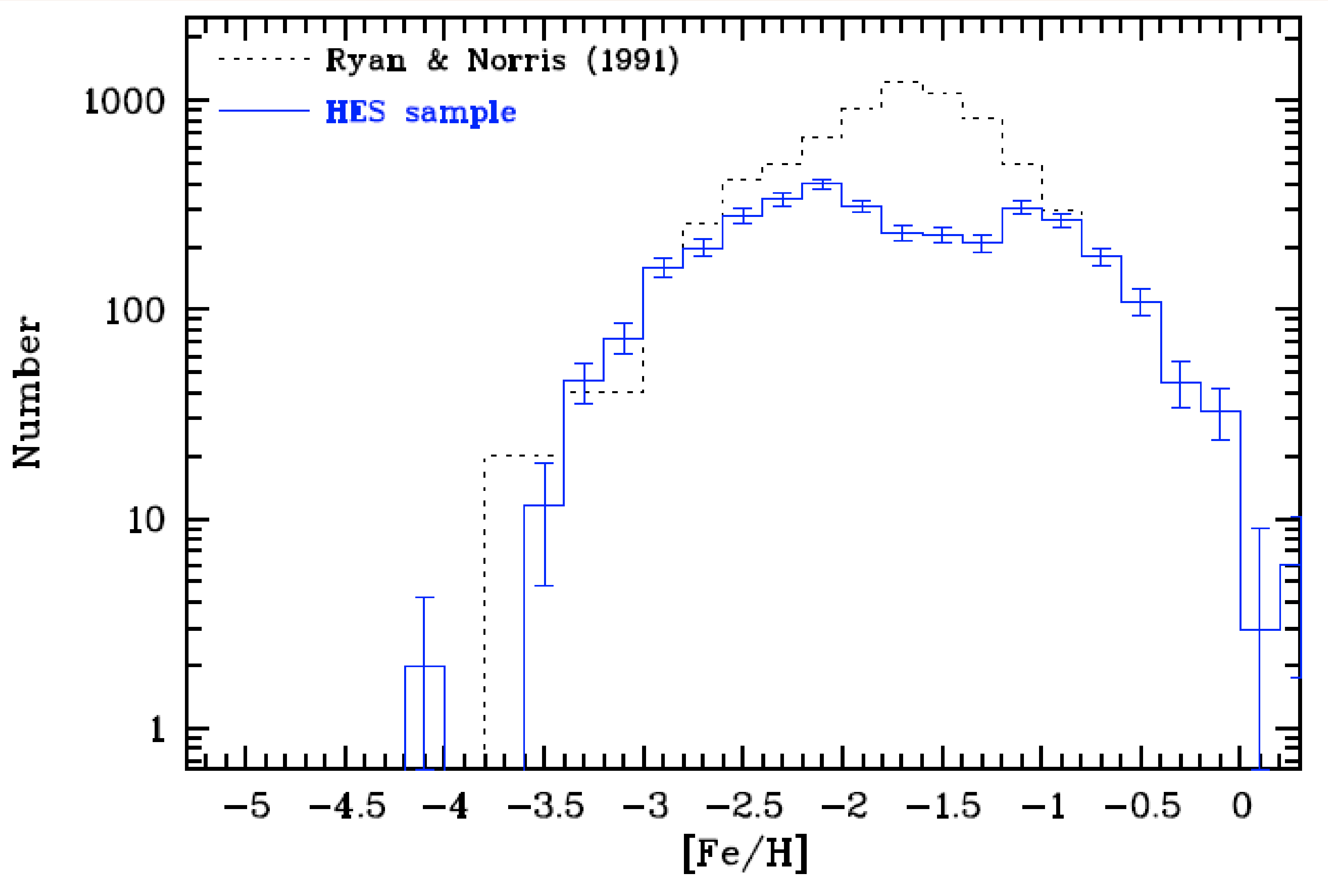
Chemical Evolution: Measurements in the Galaxy and Beyond

- Measuring abundances in
  - Stars
  - Galaxies (integrated light spectroscopy)
  - HII regions
  - DLAs


Sr
[Sr/Fe]=−1.7,−1.4,−1.1
Relative Flux
Wavelength [Å]
Ba
[Ba/Fe]=−1.6,−1.3,−1.0
Relative Flux
Wavelength [Å]
Na
[Na/Fe]=−0.1,0.2,0.5
Relative Flux
Wavelength [Å]

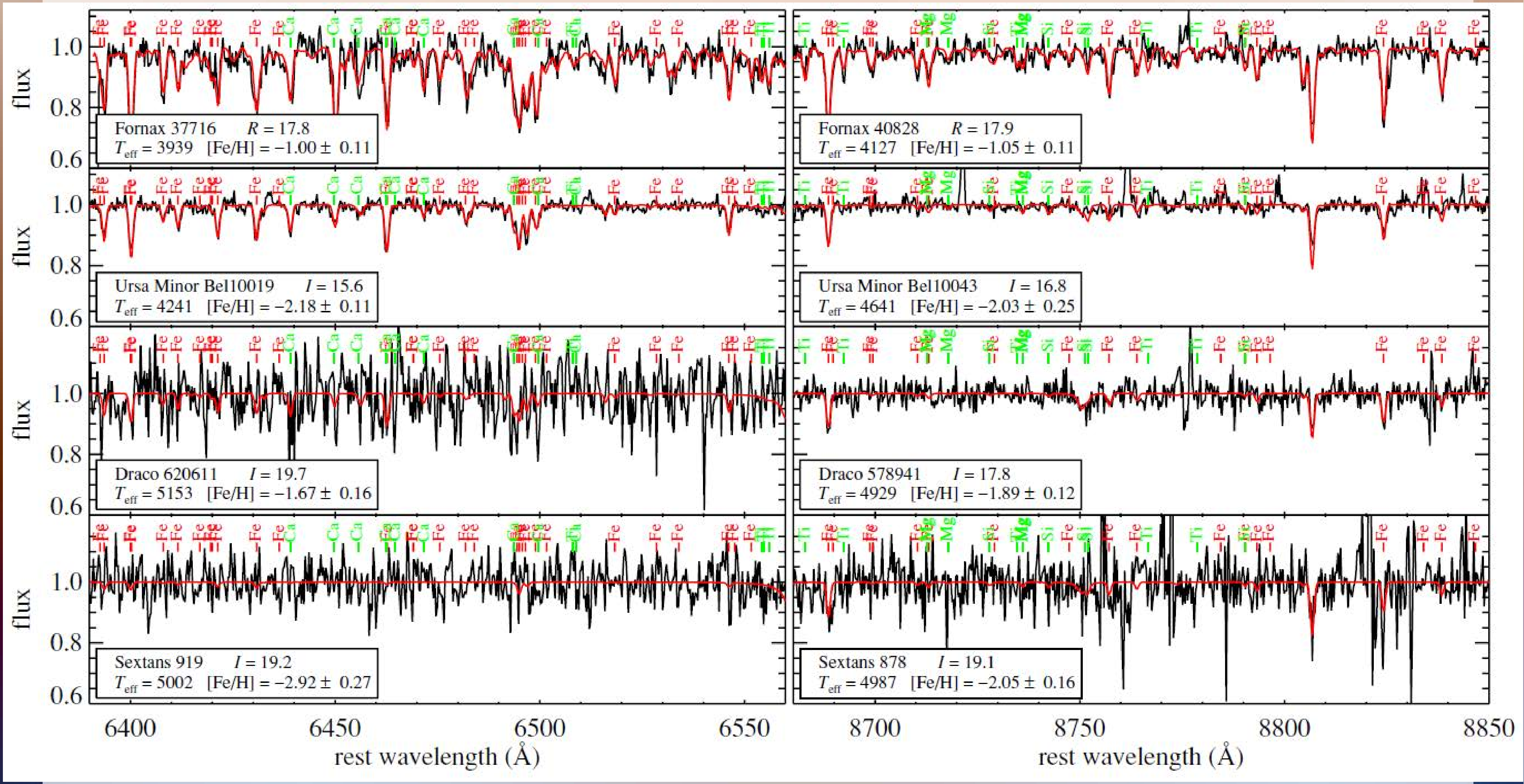

Sun
S1020549
MgI
FeI
FeII
FeI
TiI
FeI
CrI
FeI
FeI
Relative Flux
Wavelength [Å]
0
0.5
1
1.5
2
2.5
5160
5170
5180
5190
5200
5210
5220

Metallicity distribution function



Schörck et al. 2009, A&A, 507, 817

Medium-resolution spectroscopy



Kirby et al. 2010, ApJS, 191, 352

The Astronomical Journal, 144:4 (36pp), 2012 July doi:10.1088/0004-6256/144/1/4

THE OBSERVED PROPERTIES OF DWARF GALAXIES IN AND AROUND THE LOCAL GROUP

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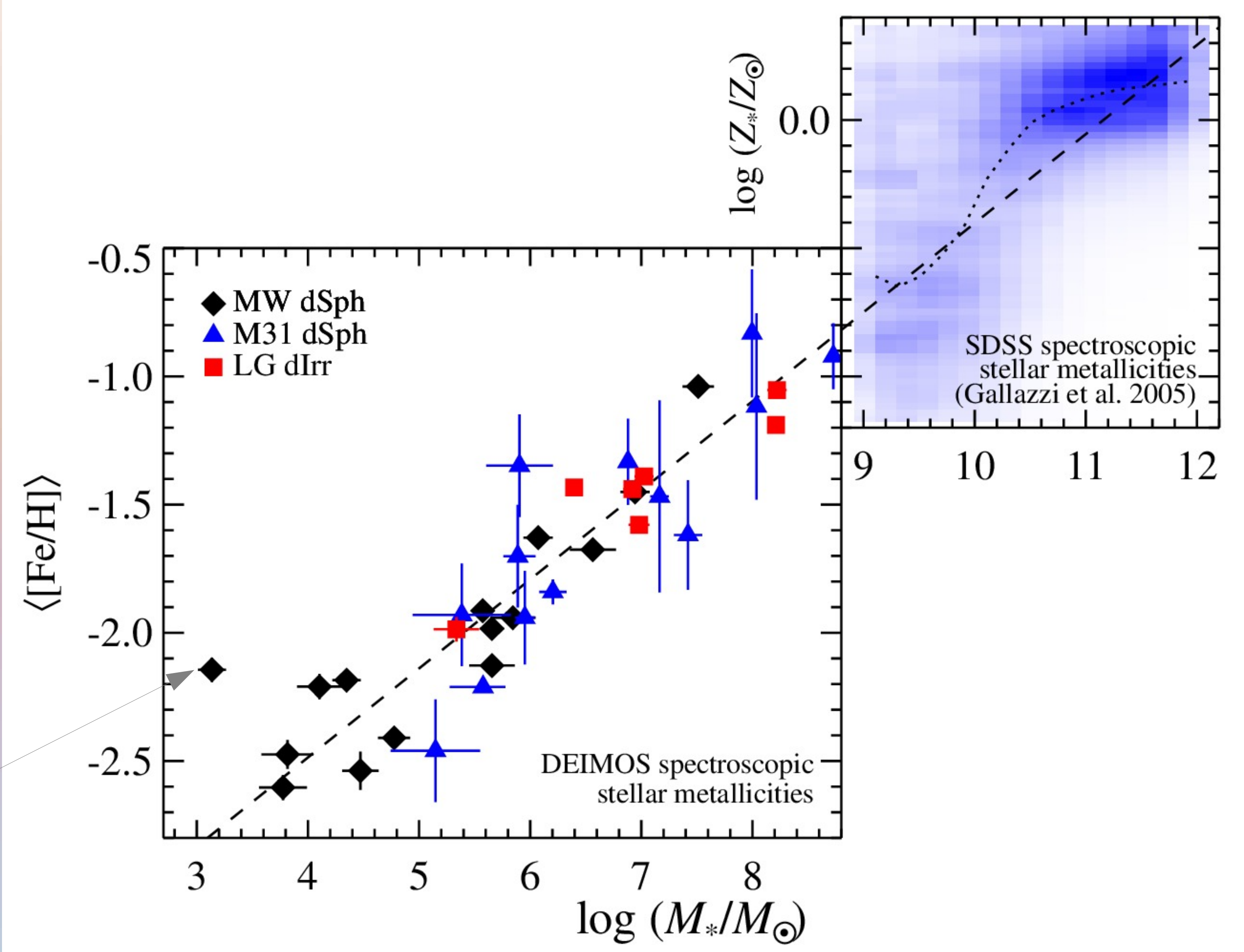
"classic" reference: Mateo 1998 ARA&A 36 435

Table 1
Basic Information

(1) Galaxy	(2) Other Names	(3)	(4)	(5) R.A. J2000	(6) Decl. J2000
			The MW sub-group (in order of distance from the MW)		
The Galaxy	The MW	G	S(B)bc	$17^h45^m40^s.0$	$-29^d00^m28^s$
Canis Major		G	????	$07^h12^m35^s.0$	$-27^d40^m00^s$
Sagittarius dSph		G	dSph	$18^h55^m19^s.5$	$-30^d32^m43^s$
Segue (I)		G	dSph	$10^h07^m04^s.0$	$+16^d04^m55^s$
Ursa Major II		G	dSph	$08^h51^m30^s.0$	$+63^d07^m48^s$
Bootes II		G	dSph	$13^h58^m00^s.0$	$+12^d51^m00^s$
Segue II		G	dSph	$02^h19^m16^s.0$	$+20^d10^m31^s$
Willman 1	SDSS J1049+5103	G	dSph	$10^h49^m21^s.0$	$+51^d03^m00^s$
Coma Berenices		G	dSph	$12^h26^m59^s.0$	$+23^d54^m15^s$
Bootes III		G	dSph?	$13^h57^m12^s.0$	$+26^d48^m00^s$
LMC	Nubecula Major	G	Irr	$05^h23^m34^s.5$	$-69^d45^m22^s$
SMC	Nubecula Minor	G	dIrr	$00^h52^m44^s.8$	$-72^d49^m43^s$
	NGC 292				
Bootes (I)		G	dSph	$14^h00^m06^s.0$	$+14^d30^m00^s$
Draco	UGC 10822	G	dSph	$17^h20^m12^s.4$	$+57^d54^m55^s$
	DDO 208				
Ursa Minor	UGC 9749	G	dSph	$15^h09^m08^s.5$	$+67^d13^m21^s$
	DDO 199				
Sculptor		G	dSph	$01^h00^m09^s.4$	$-33^d42^m33^s$
Sextans (I)		G	dSph	$10^h13^m03^s.0$	$-01^d36^m53^s$
Ursa Major (I)		G	dSph	$10^h34^m52^s.8$	$+51^d55^m12^s$
Carina		G	dSph	$06^h41^m36^s.7$	$-50^d57^m58^s$
Hercules		G	dSph	$16^h31^m02^s.0$	$+12^d47^m30^s$
Fornax		G	dSph	$02^h39^m59^s.3$	$-34^d26^m57^s$
Leo IV		G	dSph	$11^h32^m57^s.0$	$-00^d32^m00^s$
Canes Venatici II	SDSS J1257+3419	G	dSph	$12^h57^m10^s.0$	$+34^d19^m15^s$
Leo V		G	dSph	$11^h31^m09^s.6$	$+02^d13^m12^s$
Pisces II		G	dSph	$22^h58^m31^s.0$	$+05^d57^m09^s$
Canes Venatici (I)		G	dSph	$13^h28^m03^s.5$	$+33^d33^m21^s$
Leo II	Leo B	G	dSph	$11^h13^m28^s.8$	$+22^d09^m06^s$
	UGC 6253				
	DDO 93				
Leo I	UGC 5470	G/L	dSph	$10^h08^m28^s.1$	$+12^d18^m23^s$
	DDO 74				
	Regulus Dwarf				

Mass-metallicity relation (in stars)



Segue 2
Kirby et al. 2013, ApJ, 770, 16

Kirby et al. 2013, ApJ, 779, 102

Applying GCE models to data

Closed/Leaky Box ("Pristine") Model:

$$\frac{dN}{d[\mathrm{Fe/H}]} \propto \left(10^{[\mathrm{Fe/H}]}\right) \exp\left(-\frac{10^{[\mathrm{Fe/H}]}}{p}\right) . \qquad (2)$$

Pre-Enriched Model:

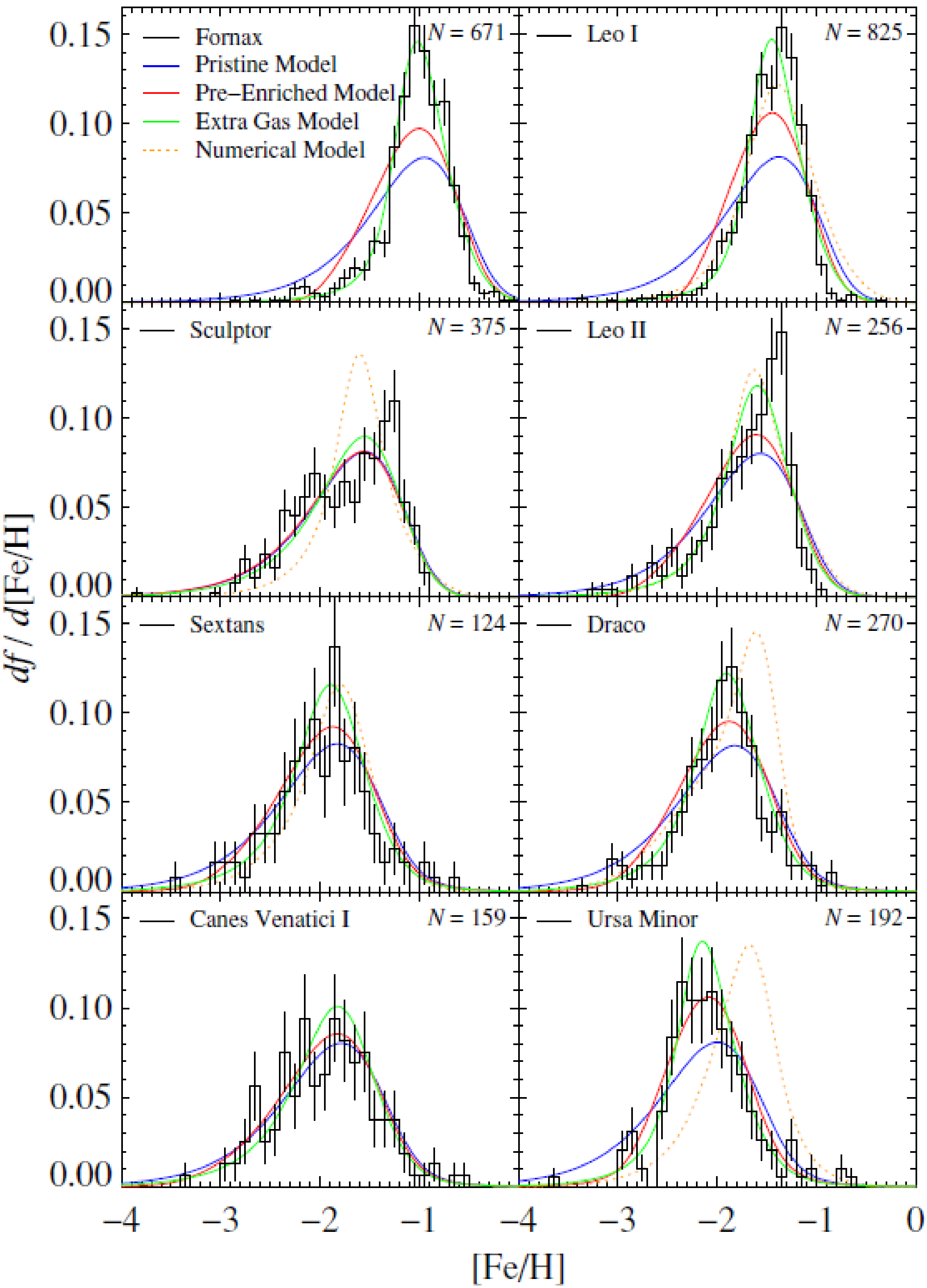
$$\frac{dN}{d[\mathrm{Fe/H}]} \propto \left(10^{[\mathrm{Fe/H}]} - 10^{[\mathrm{Fe/H}]_0}\right) \exp\left(-\frac{10^{[\mathrm{Fe/H}]}}{p}\right) , \qquad (1)$$

"Extra Gas" or "Infall" Model:

$$g(s) = \left(1 - \frac{s}{M}\right)\left(1 + s - \frac{s}{M}\right) , \qquad (3)$$

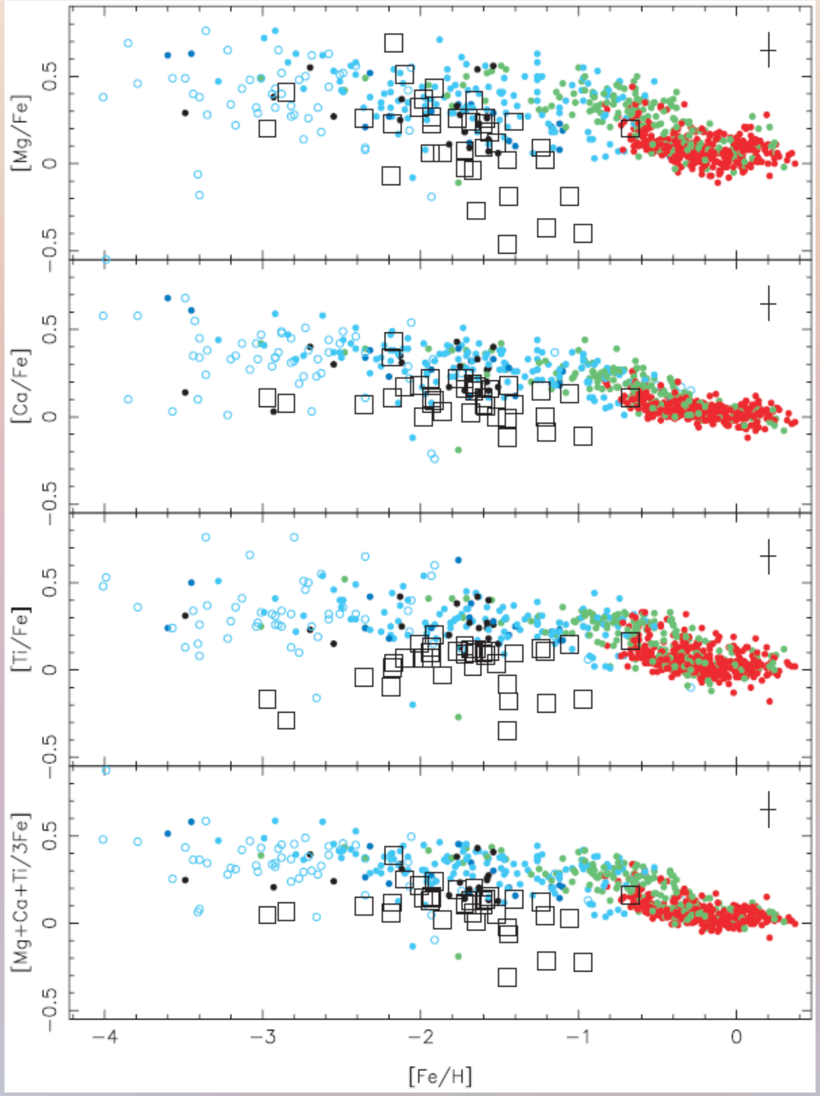
$$[\mathrm{Fe/H}](s) = \log\left\{ p \left(\frac{M}{1 + s - \frac{s}{M}}\right)^2 \times \left[\ln\frac{1}{1 - \frac{s}{M}} - \frac{s}{M}\left(1 - \frac{1}{M}\right)\right]\right\} \qquad (4)$$

$$\frac{dN}{d[\mathrm{Fe/H}]} \propto \frac{10^{[\mathrm{Fe/H}]}}{p} \frac{1 + s\left(1 - \frac{1}{M}\right)}{\left(1 - \frac{s}{M}\right)^{-1} - 2\left(1 - \frac{1}{M}\right) \times 10^{[\mathrm{Fe/H}]}/p} . \qquad (5)$$



Kirby et al. 2011, ApJ, 727, 78

Galactic archaeology in dwarf galaxy



Venn et al. 2004, AJ, 128, 1177 (360+ citations)

Numerical models for dwarf galaxies

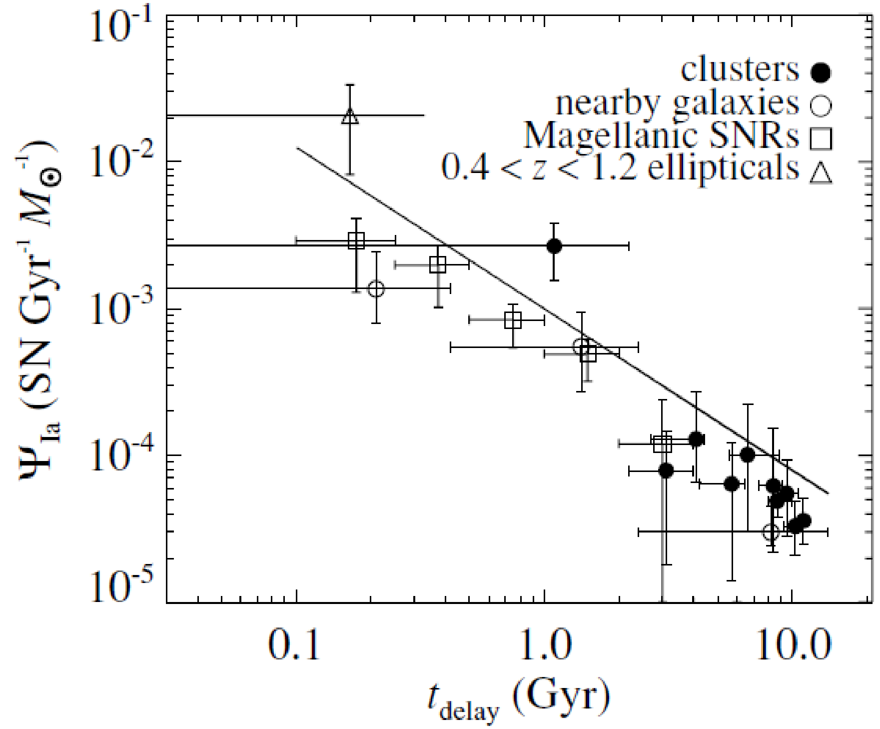
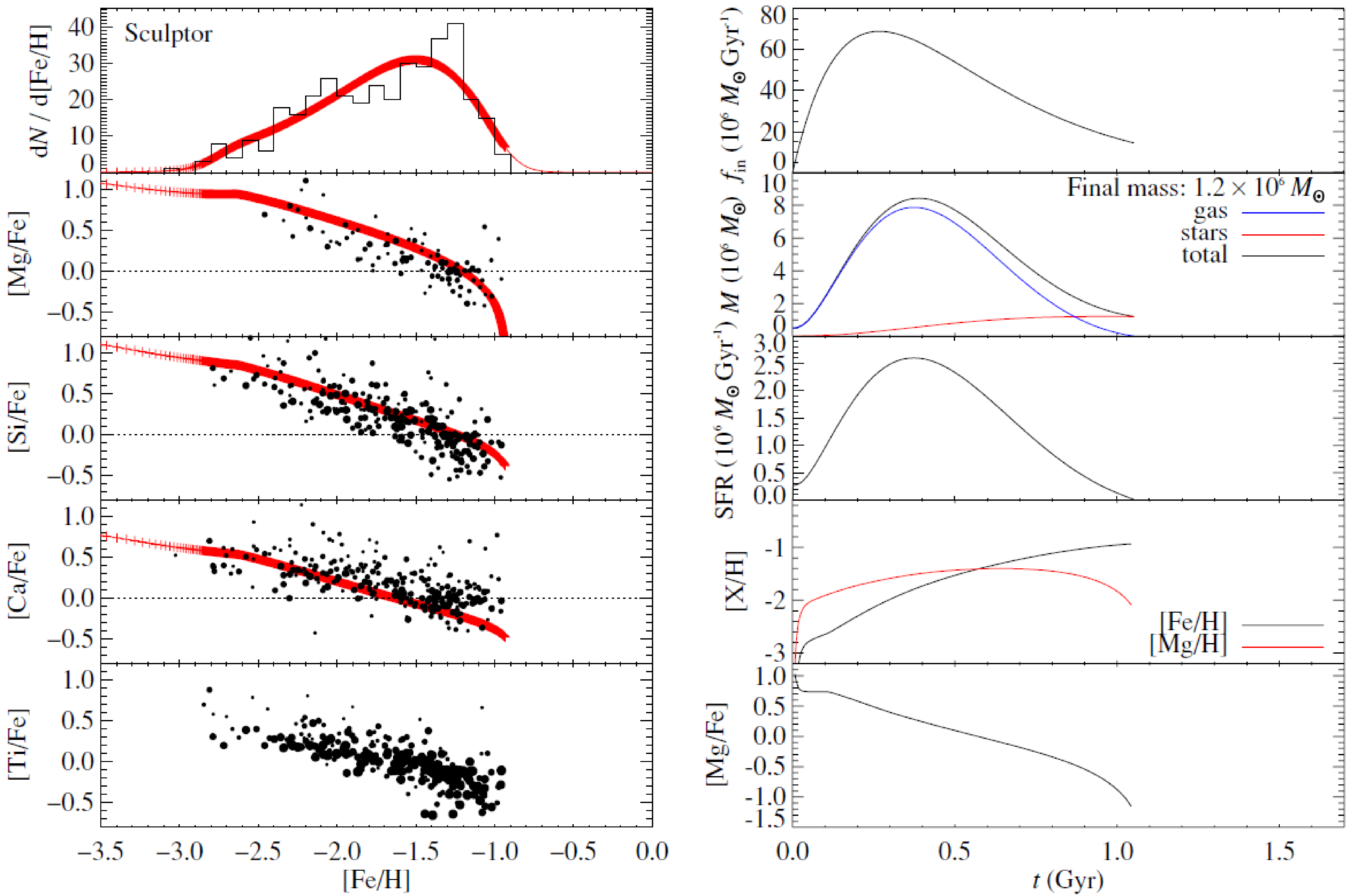


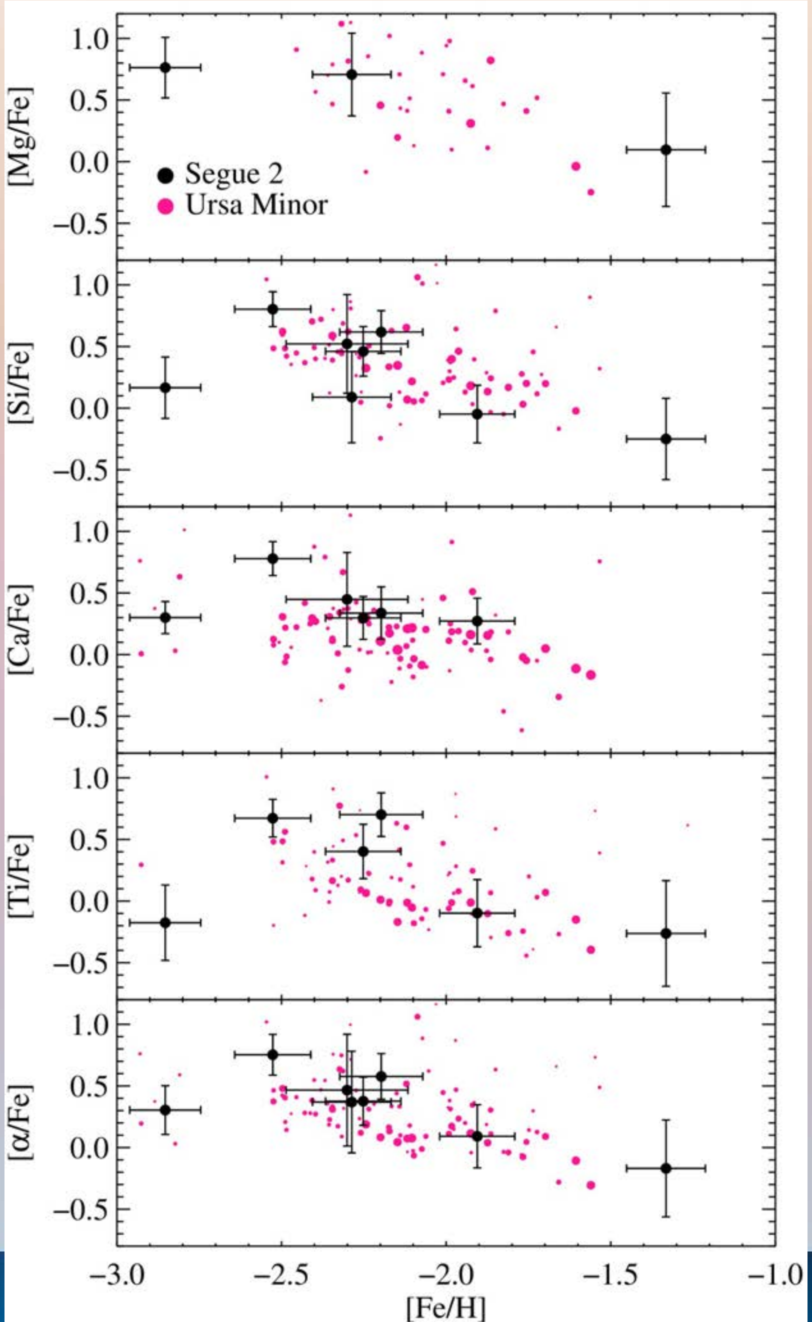
Figure 1. Type Ia SN DTD, as measured by Maoz et al. (2010). The data come from a variety of star formation environments, given in the figure legend. Equation (9) gives the expression for this function. Compare this figure to Maoz et al.'s Figure 2.

Maoz et al. 2010, ApJ, 722, 1879



Kirby et al. 2011, ApJ, 727, 79

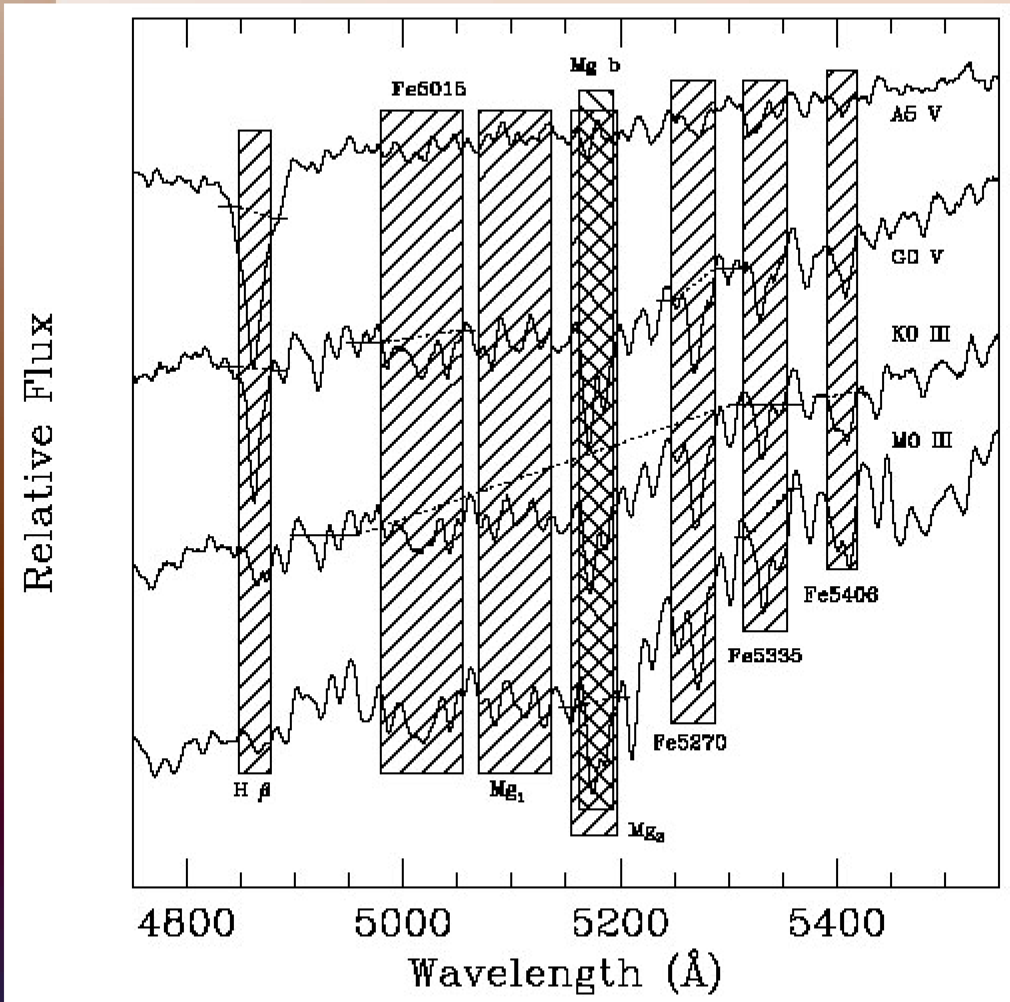
When is a galaxy not a galaxy?

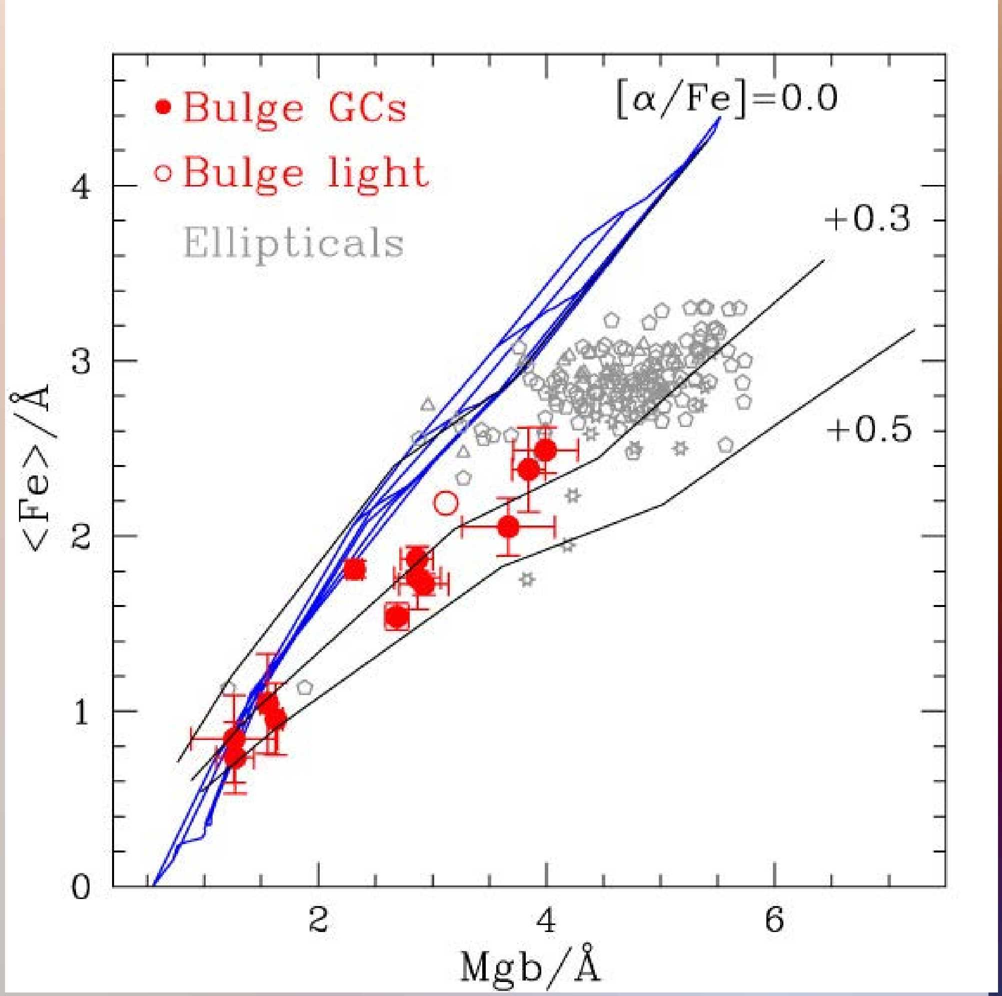


Kirby et al. 2011, ApJ, 770, 16

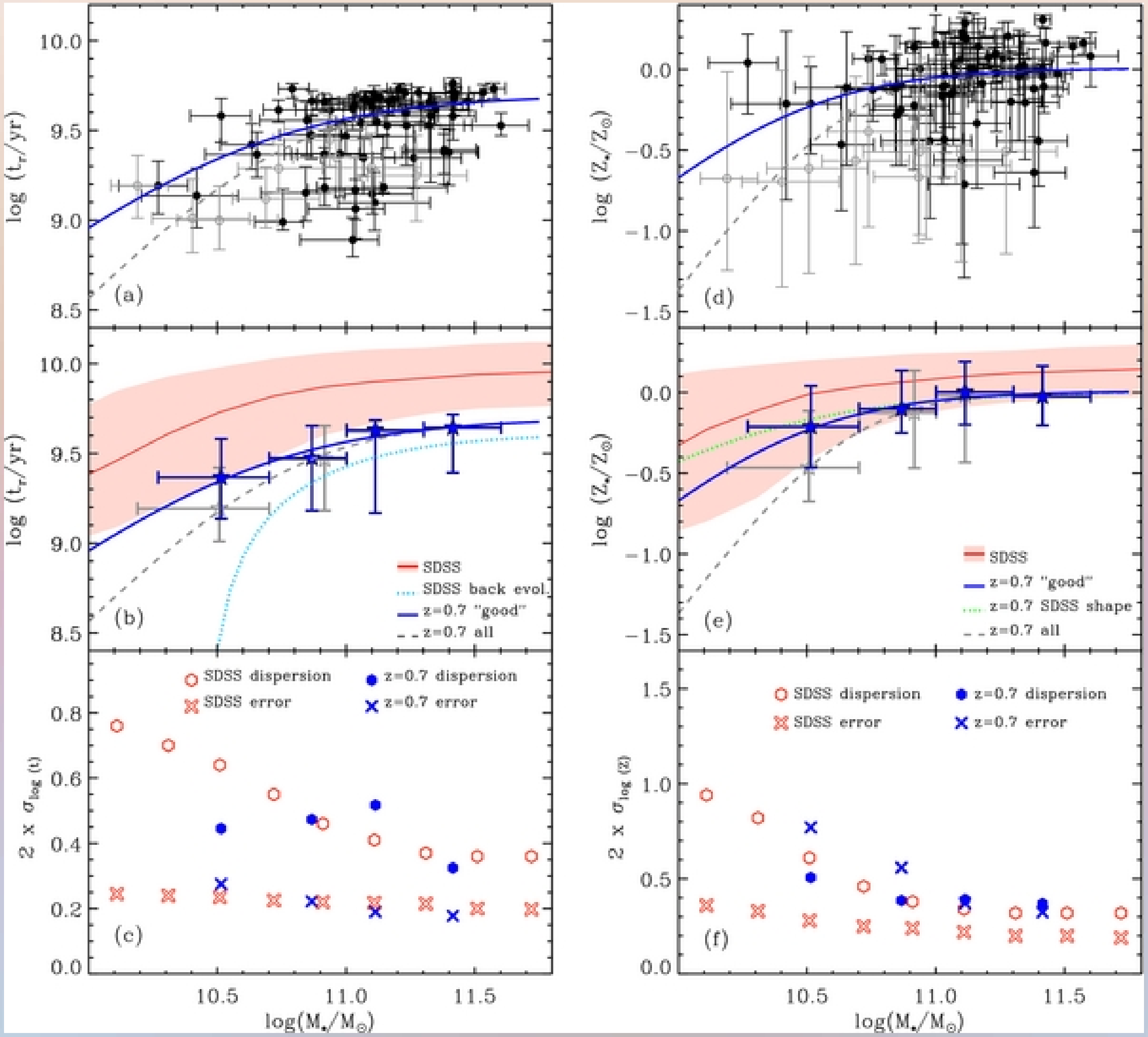
Whole galaxies: Integrated light spectroscopy

Lick Indices



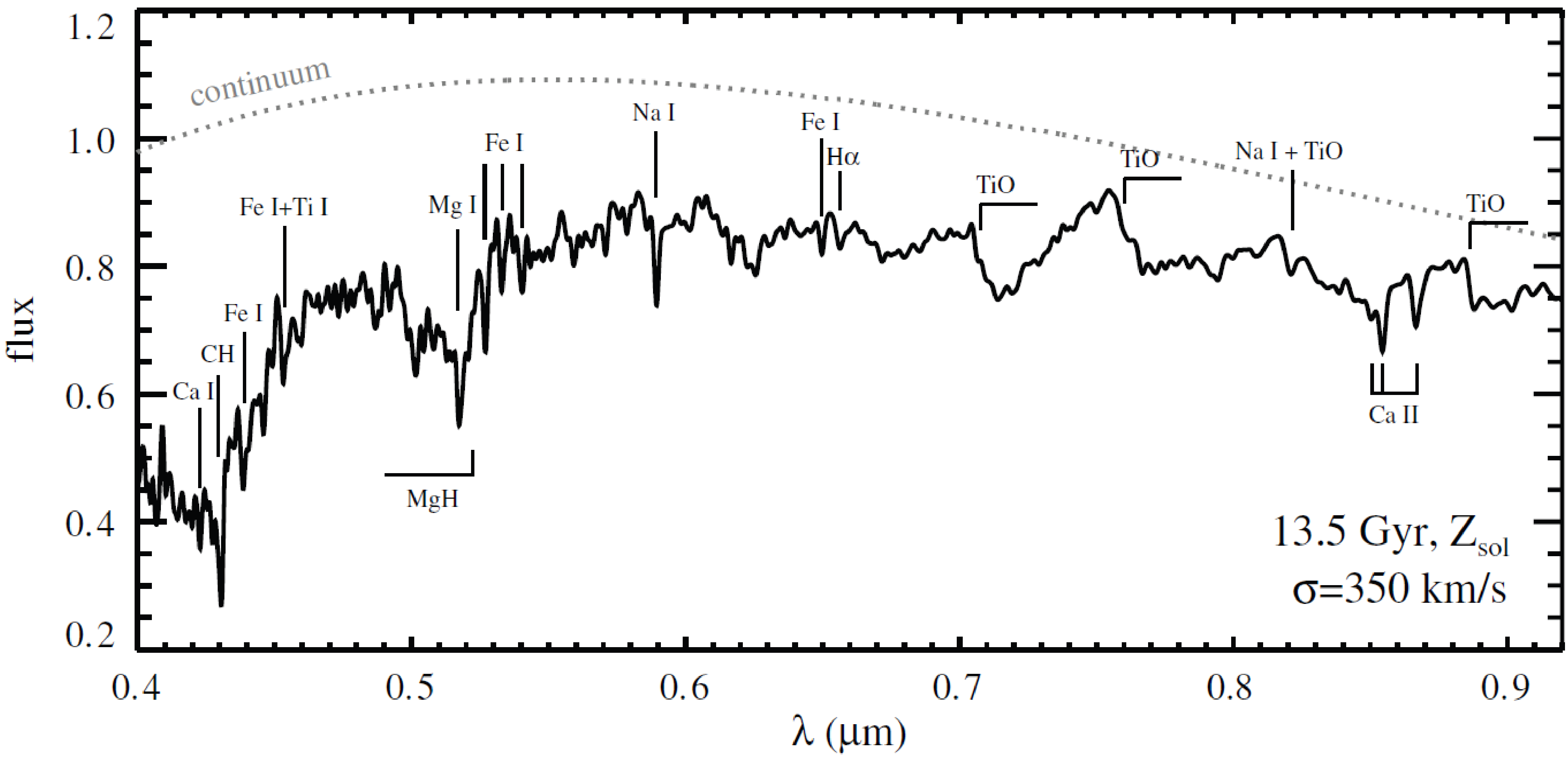


Mass-metallicity relation (still in stars)

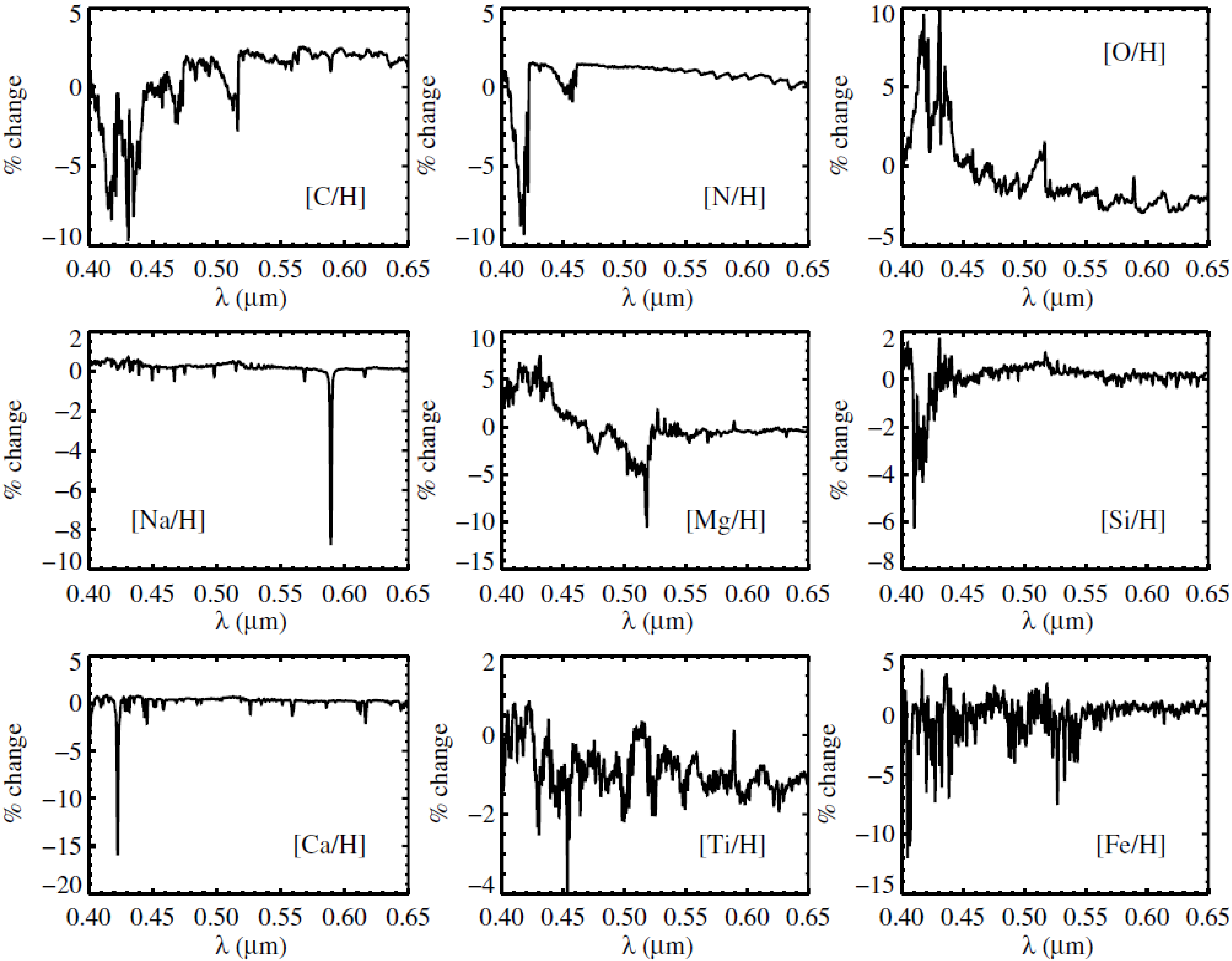


Gallazzi et al. 2014, ApJ, 788, 1

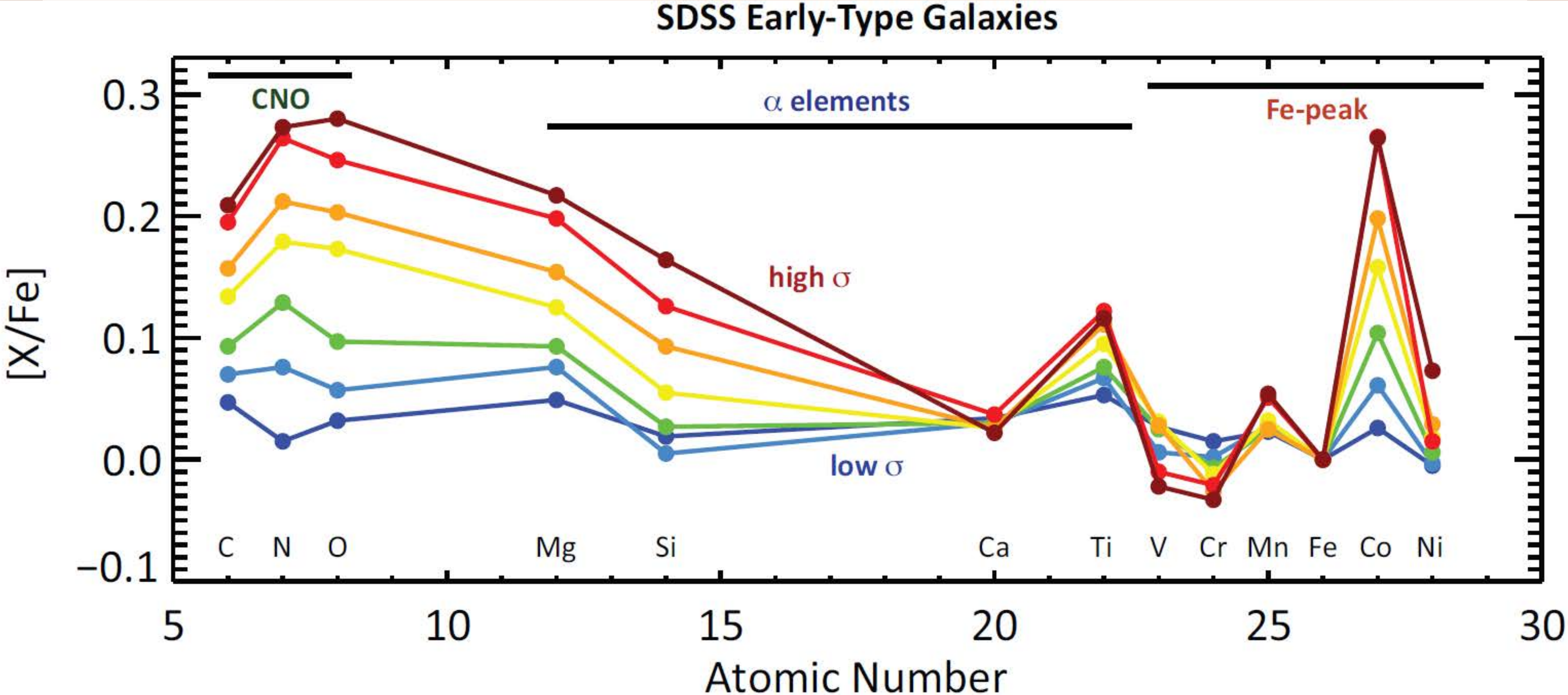
Full spectrum synthesis + fitting



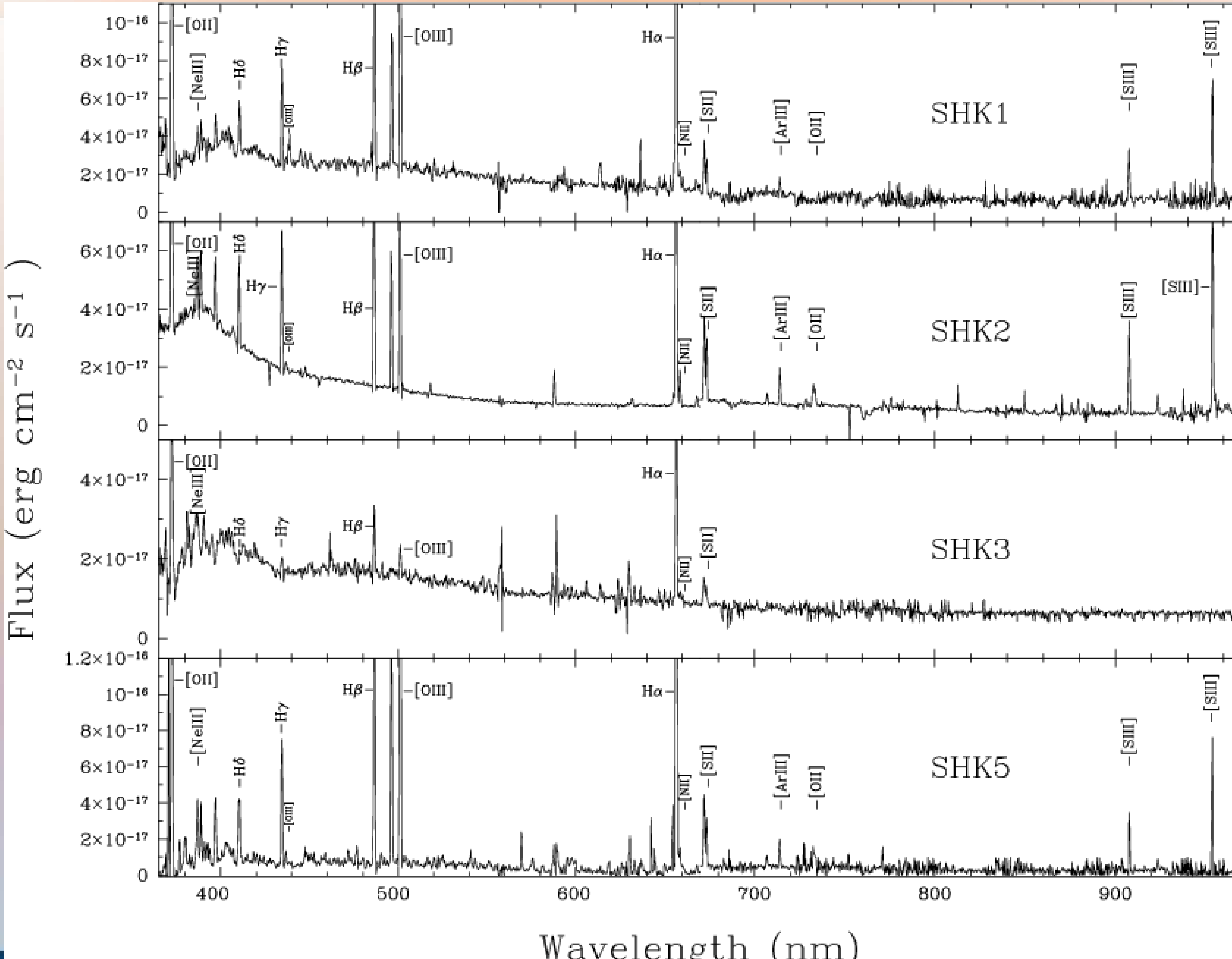
Conroy et al. 2014, ApJ, 780, 33



[C/H]
[N/H]
[O/H]
[Na/H]
[Mg/H]
[Si/H]
[Ca/H]
[Ti/H]
[Fe/H]
% change
λ (μm)

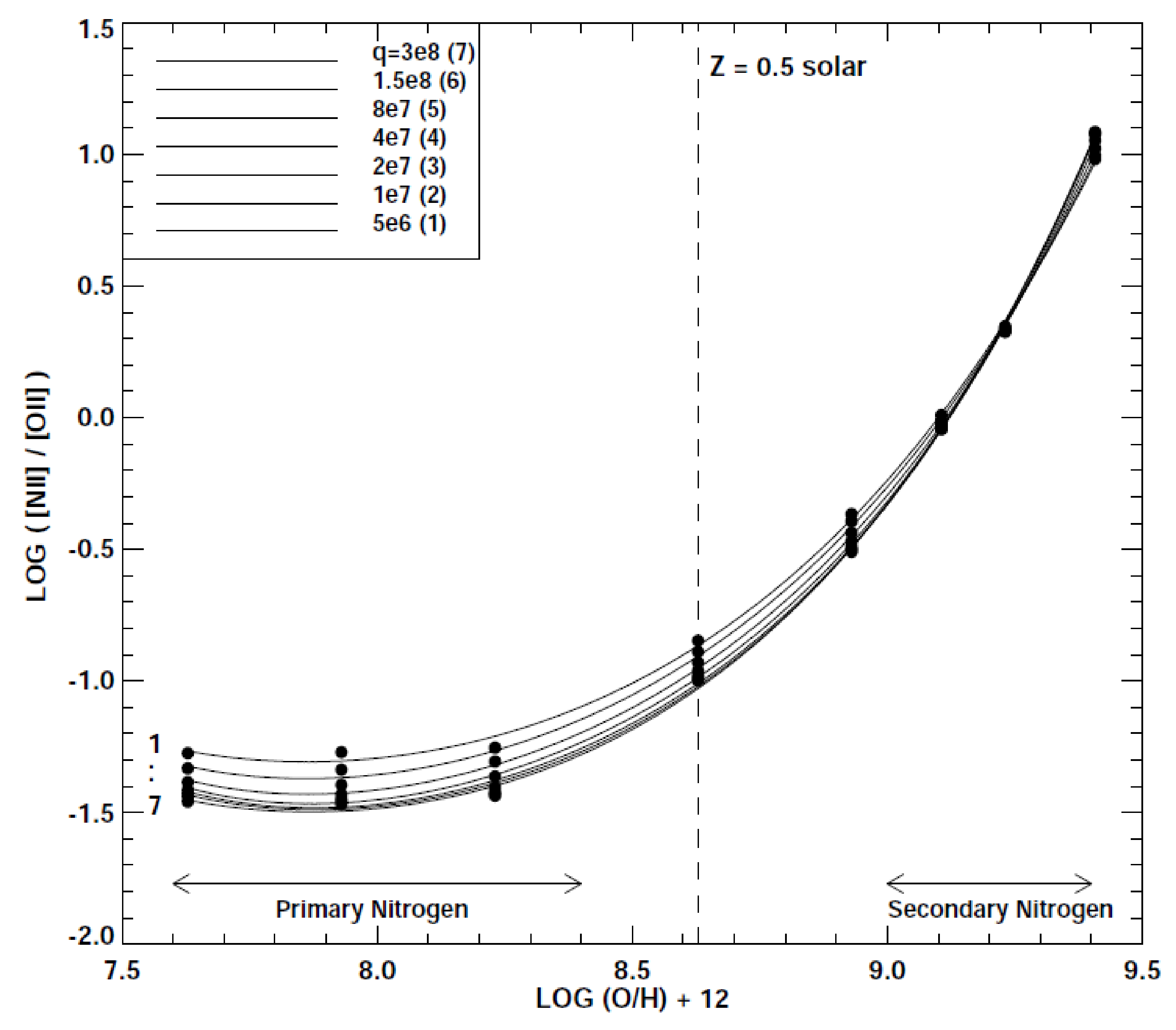


SDSS Early-Type Galaxies
CNO
α elements
Fe-peak
high σ
low σ
[X/Fe]
0.3
0.2
0.1
0.0
−0.1
C N O Mg Si Ca Ti V Cr Mn Fe Co Ni
5 10 15 20 25 30
Atomic Number



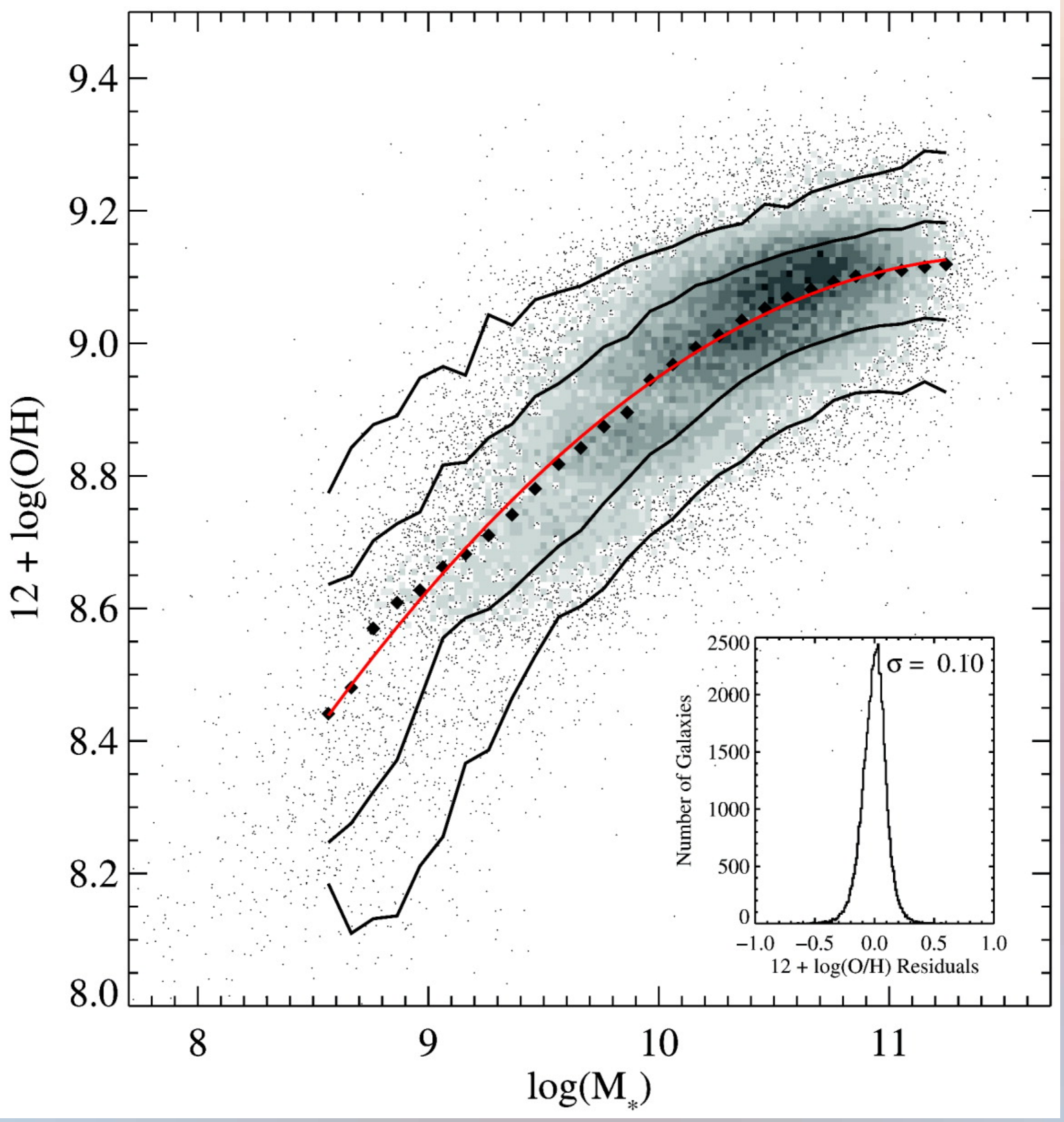
SHK1
SHK2
SHK3
SHK5
[OII]
[NeIII]
Hδ
Hγ
[OIII]
Hβ
Hα
[NII]
[SII]
[ArIII]
[SIII]
Flux (erg cm⁻² s⁻¹)
Wavelength (nm)
400
500
600
700
800
900

Emission lines in HII regions



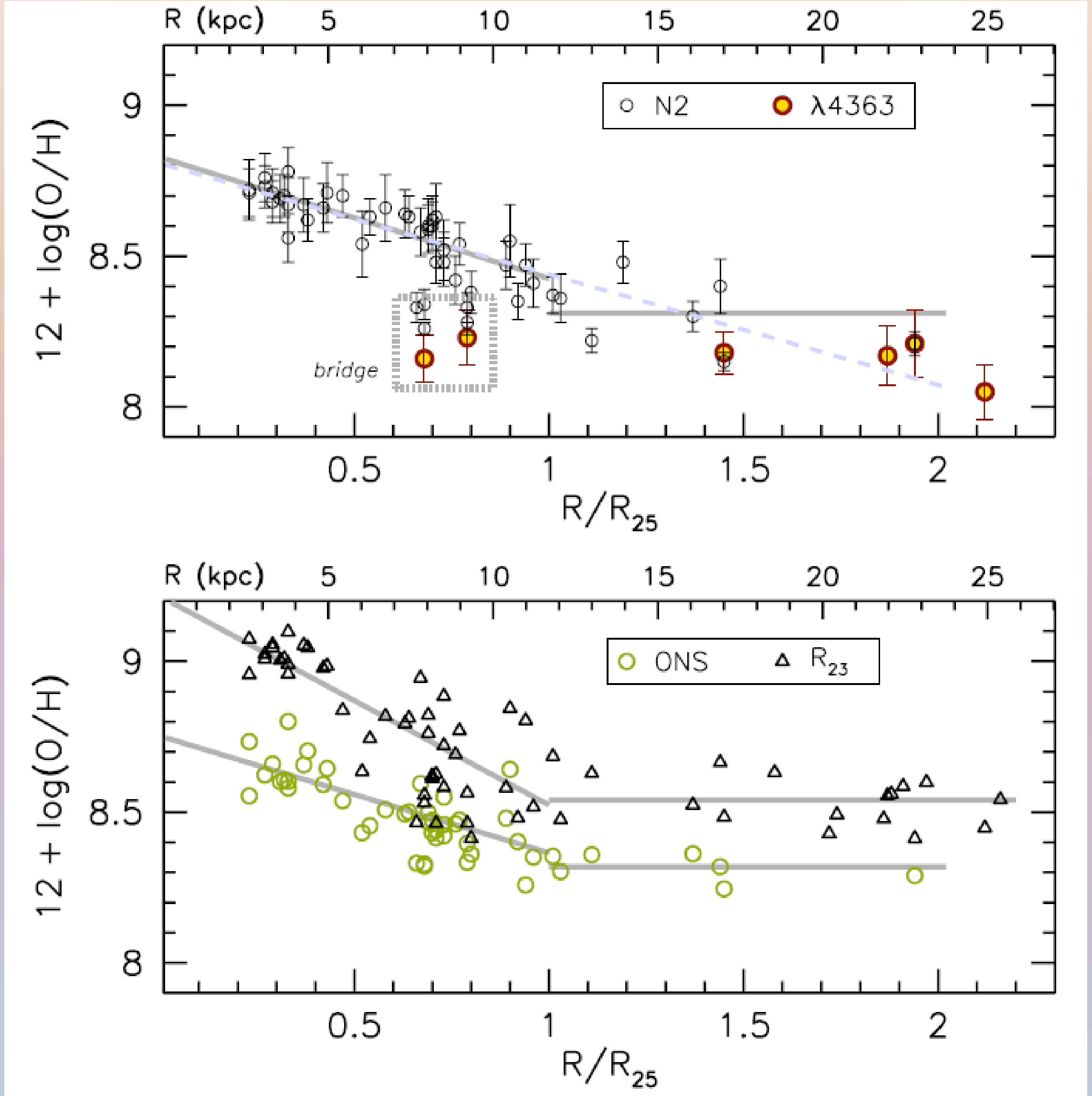
Kewley & Dopita 2002, ApJS, 142, 35 (~500 citations)

Mass-metallicity relation (in gas)

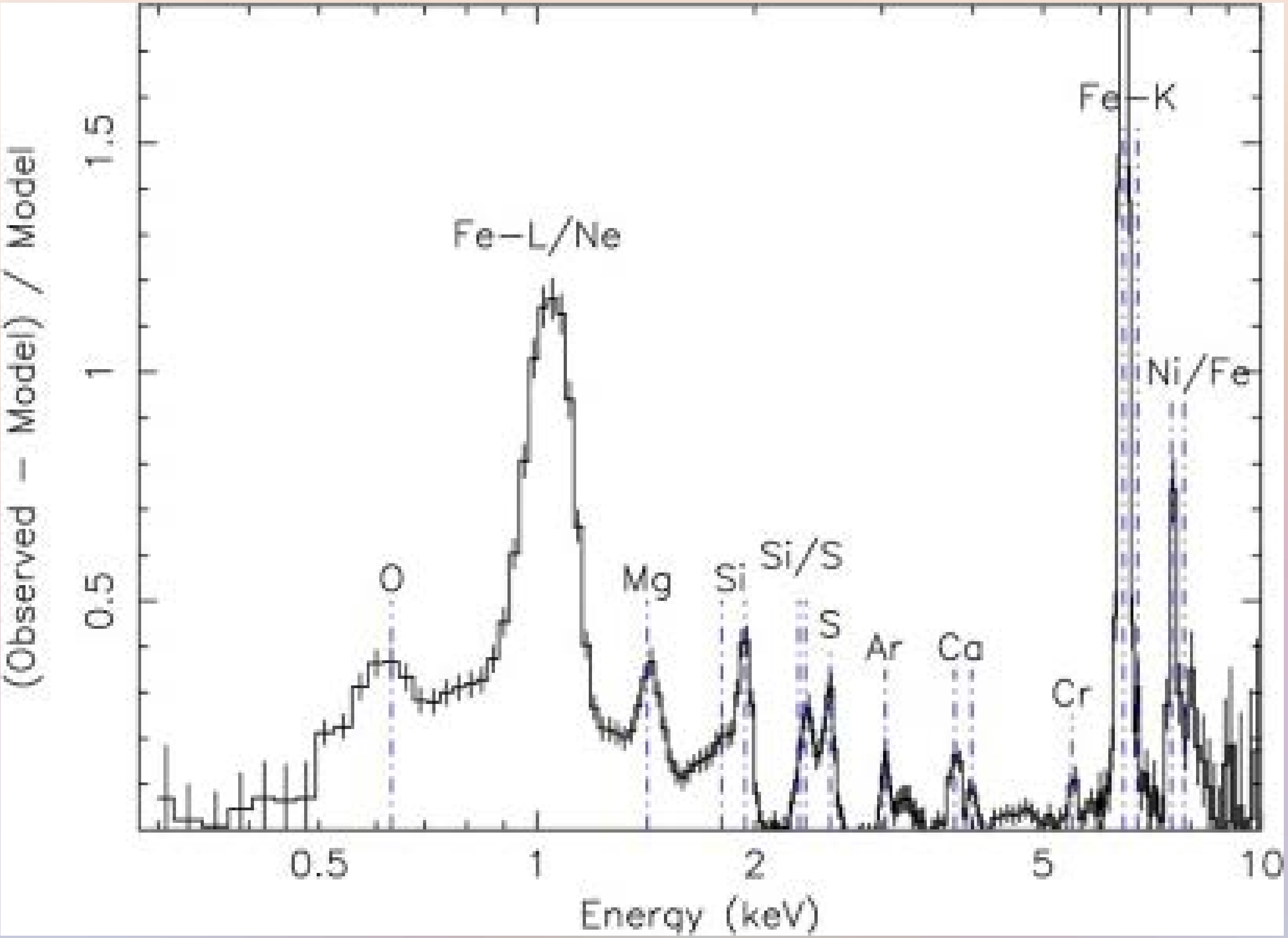


Tremonti et al. 2004, ApJ, 613, 898 (1300+ citations)

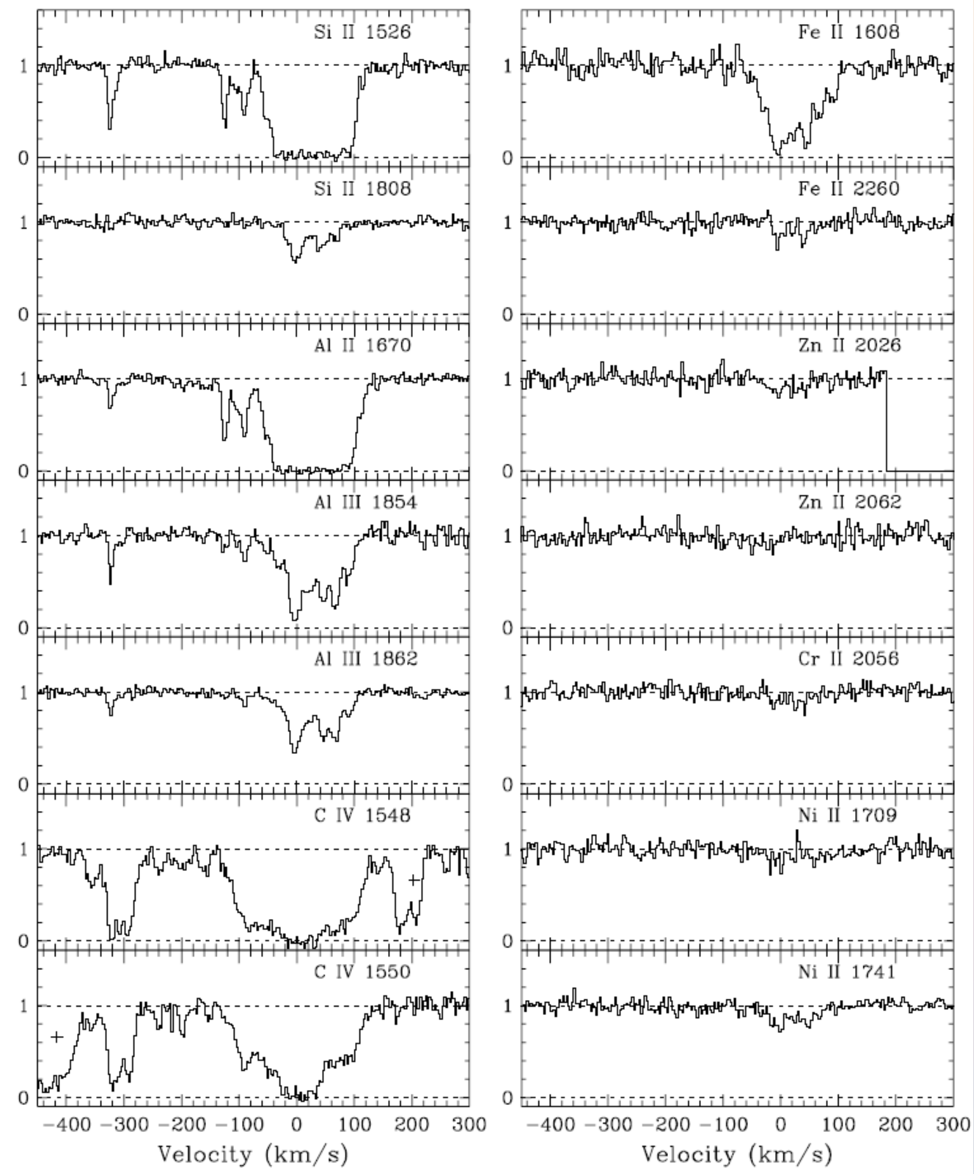
HII region abundance gradients in disks



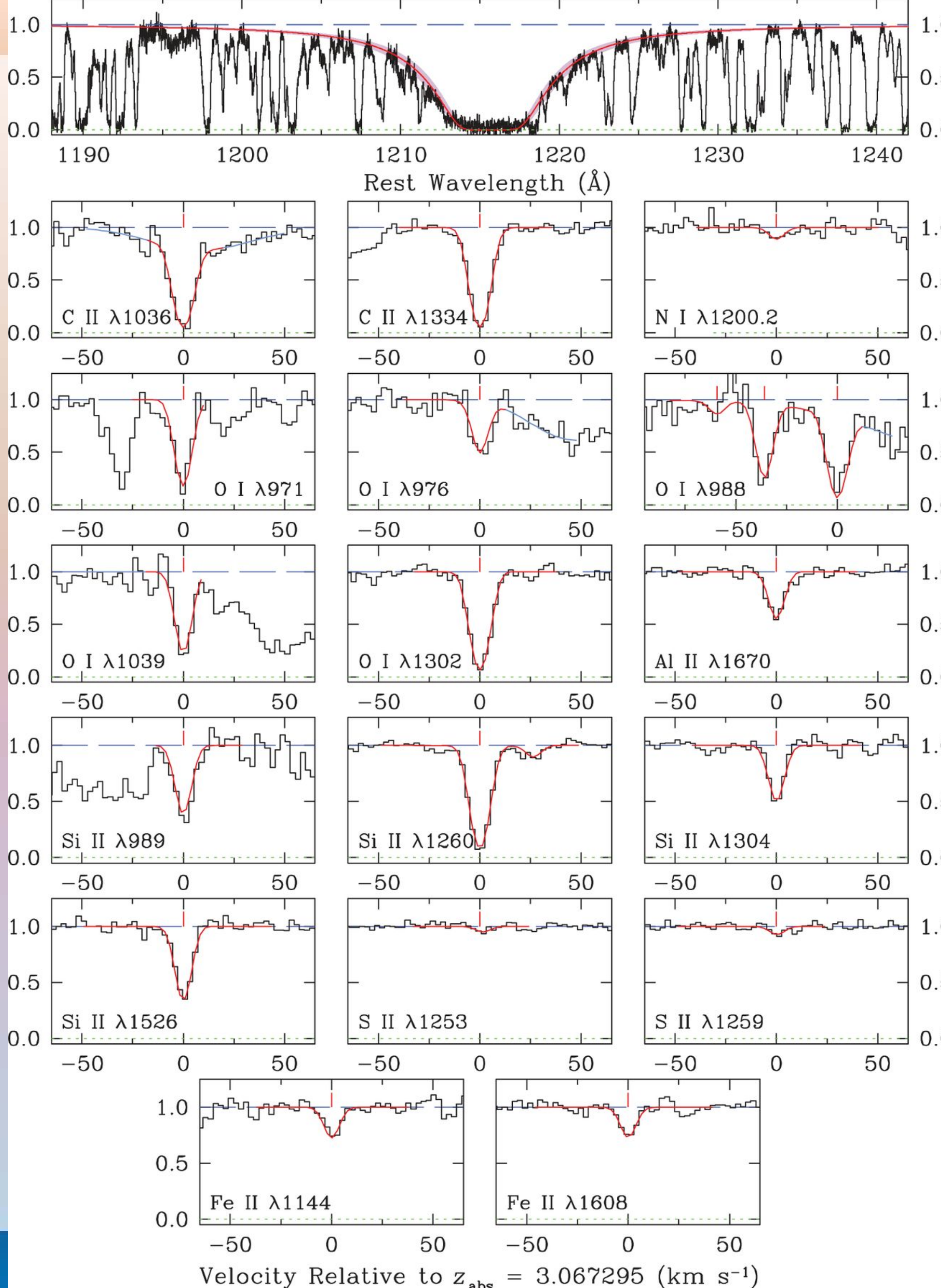
Bresolin, Kennicutt, & Ryan-Weber 2012, ApJ, 750, 122


Fe−K
Fe−L/Ne
Ni/Fe
O
Mg
Si
Si/S
S
Ar
Ca
Cr
(Observed − Model) / Model
0.5
1
1.5
0.5
1
2
5
10
Energy (keV)

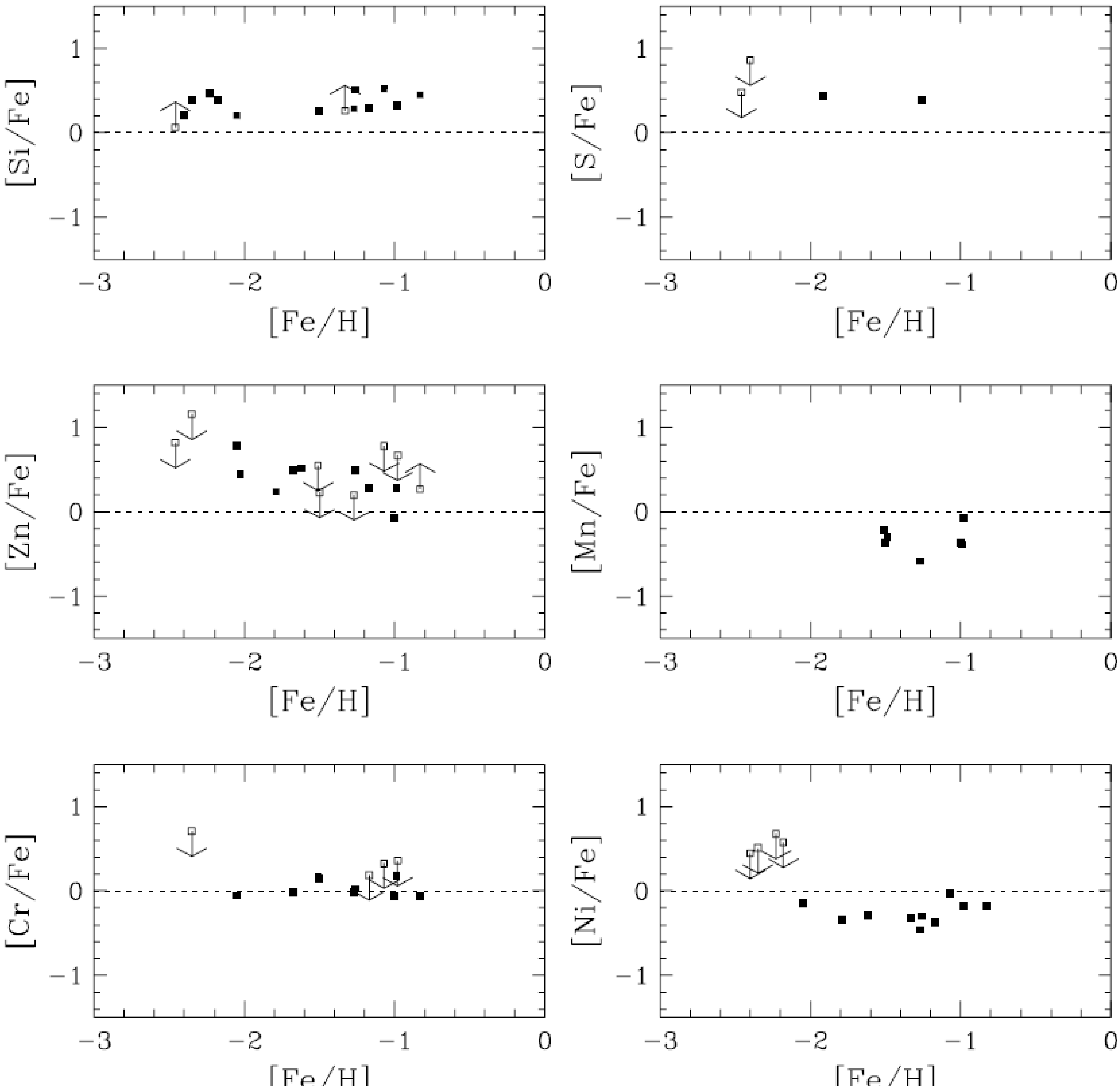
Abundances in DLAs



Lu et al. 1996, ApJS, 107, 475 (~400 citations)



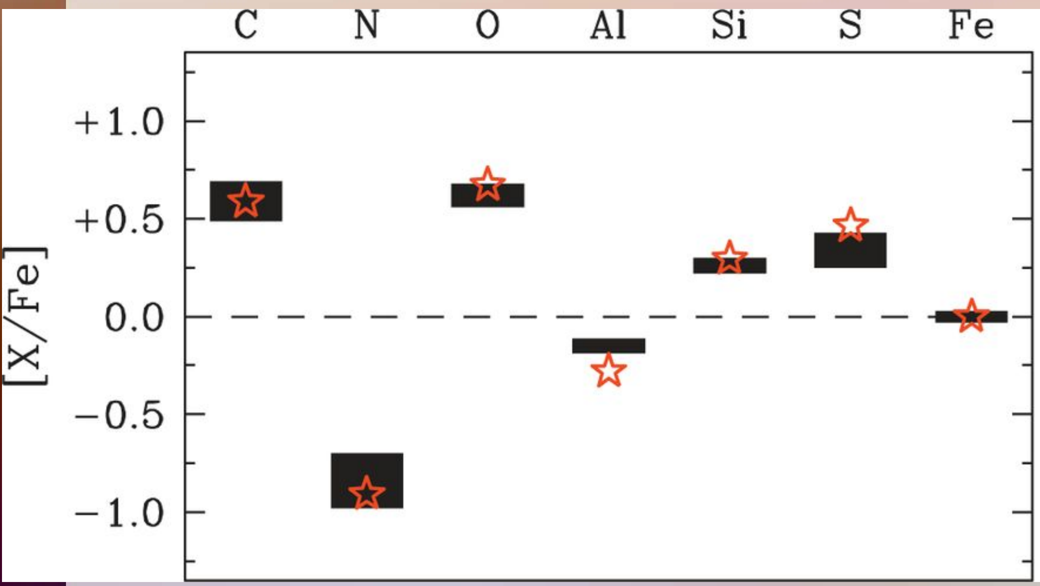
Cooke, Pettini, & Murphy 2012, MNRAS, 425, 327



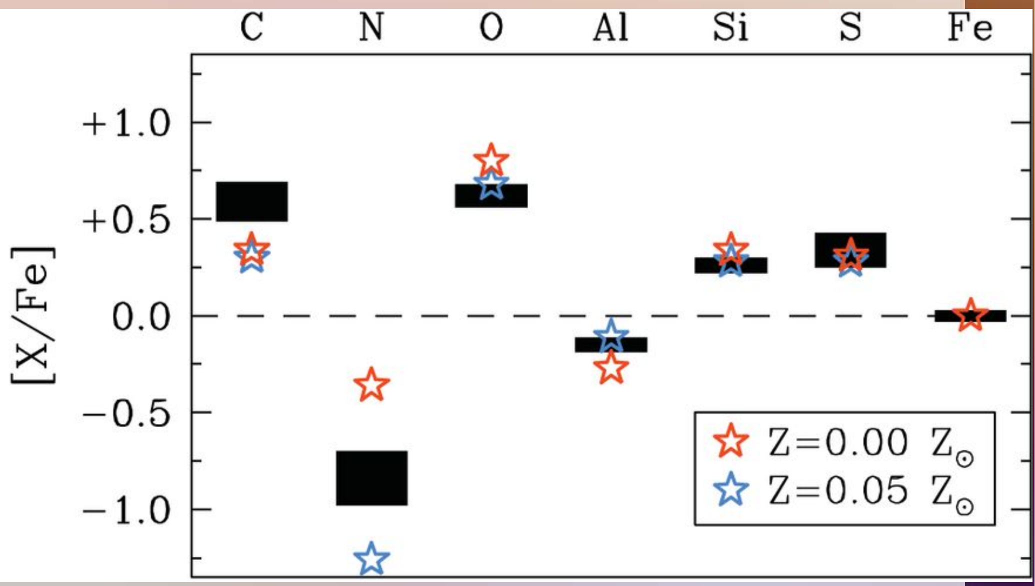
Lu et al. 1996, ApJS, 107, 475

Pop III nucleosynthesis and DLAs

Pop III

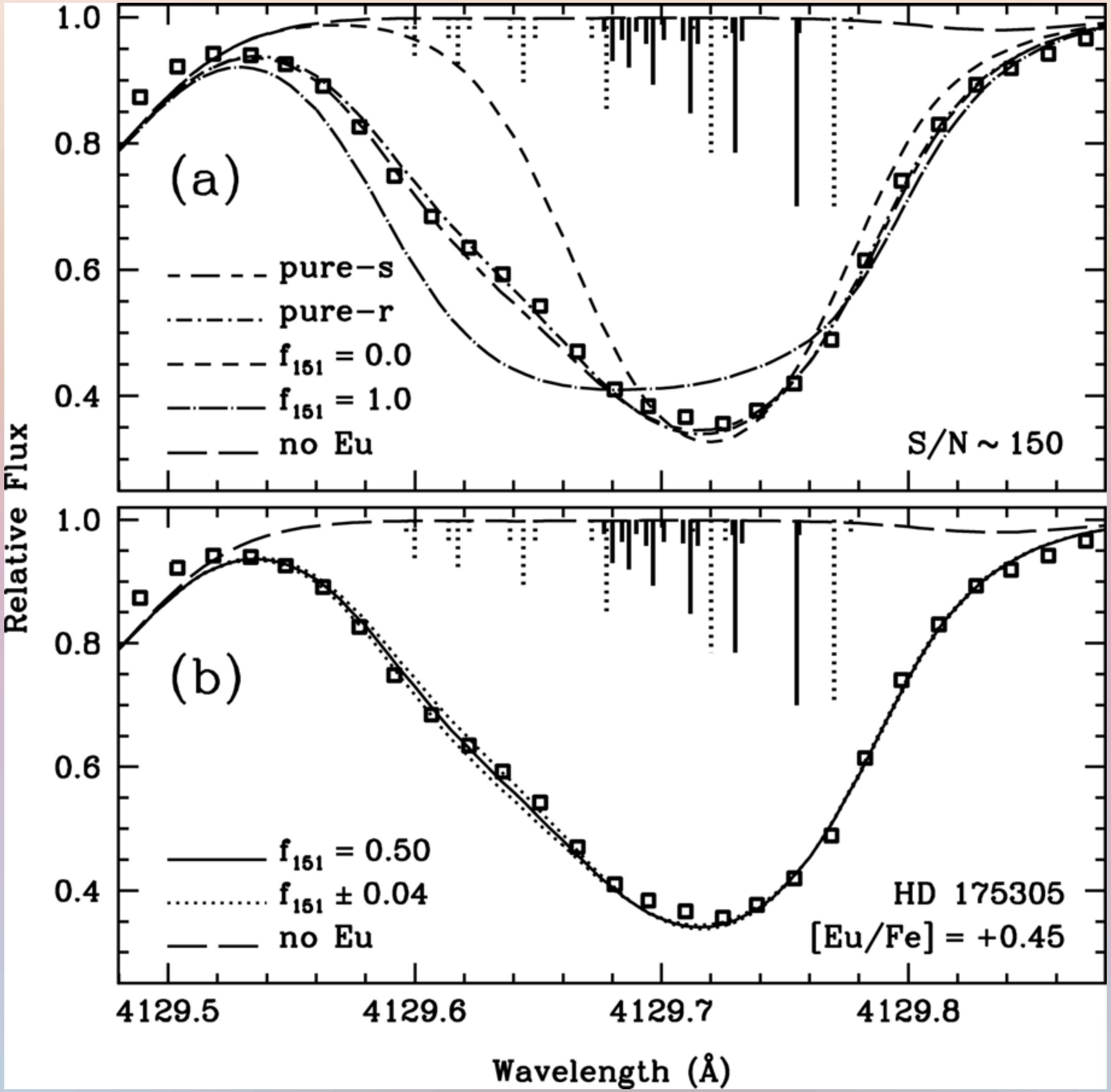


Pop II



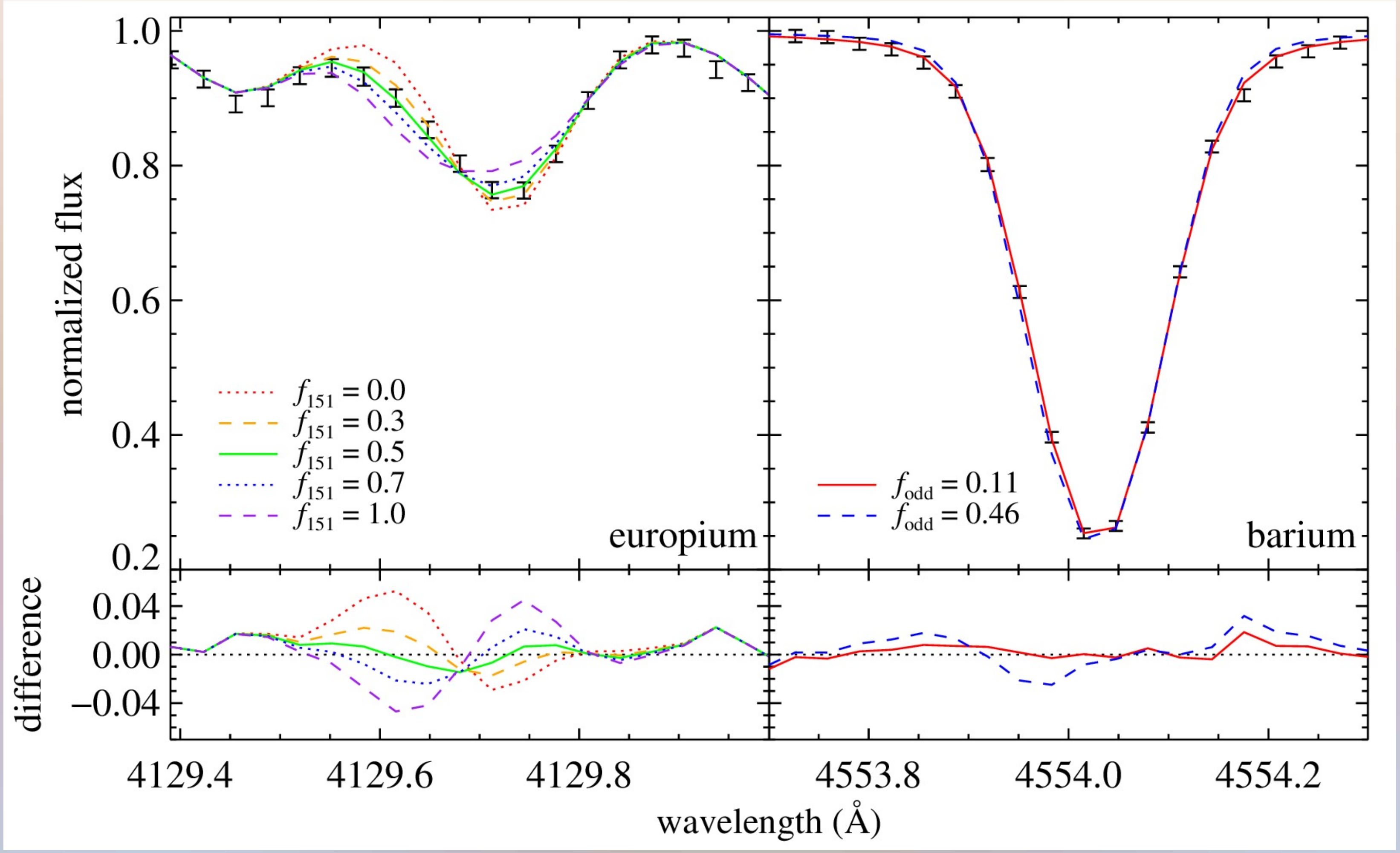
Cooke, Pettini, & Murphy 2012, MNRAS, 425, 327

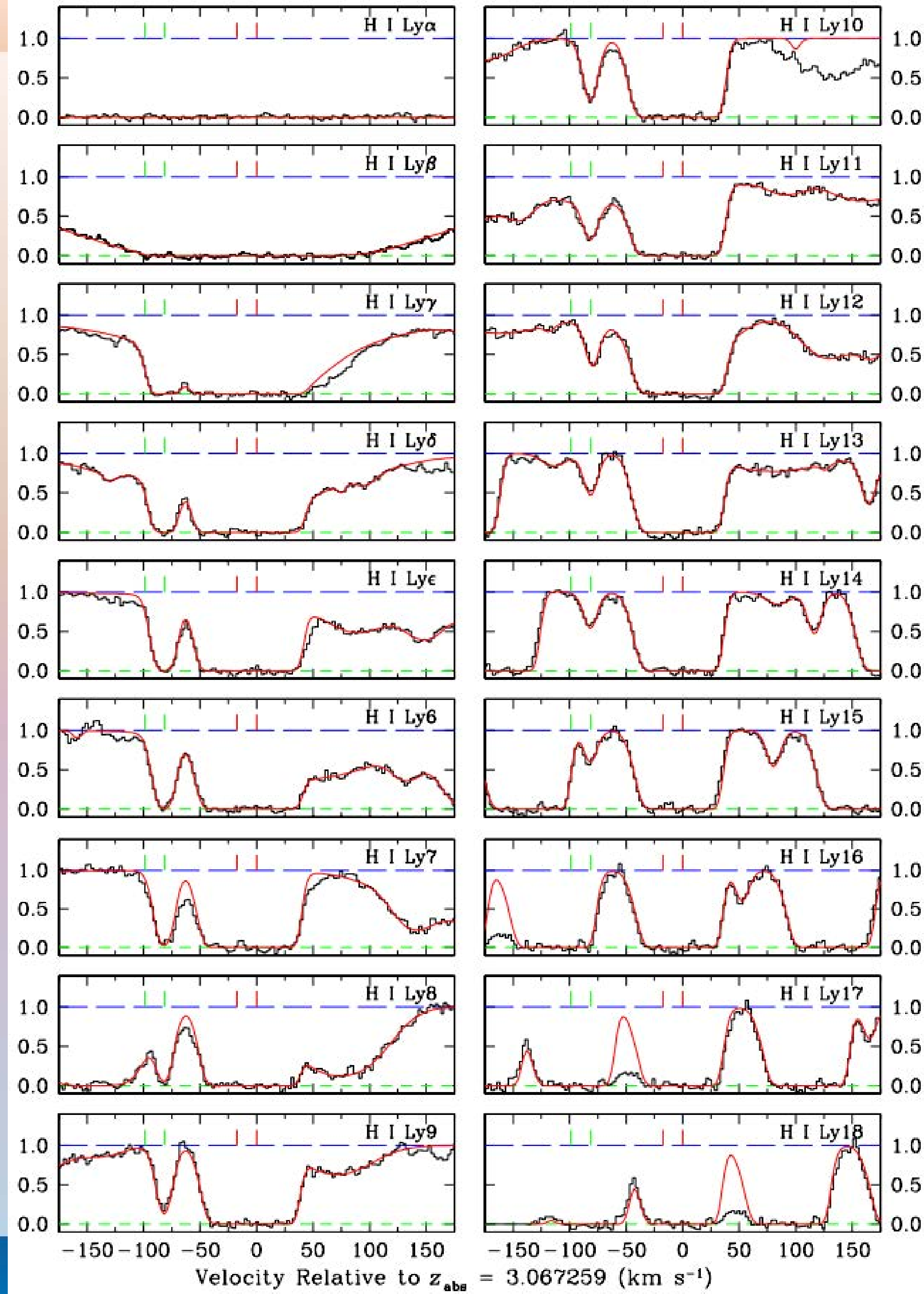
Stellar isotopes



Roederer et al. 2008, ApJ, 675, 723

Stellar isotopes





Cooke et al. 2014, ApJ, 781, 31