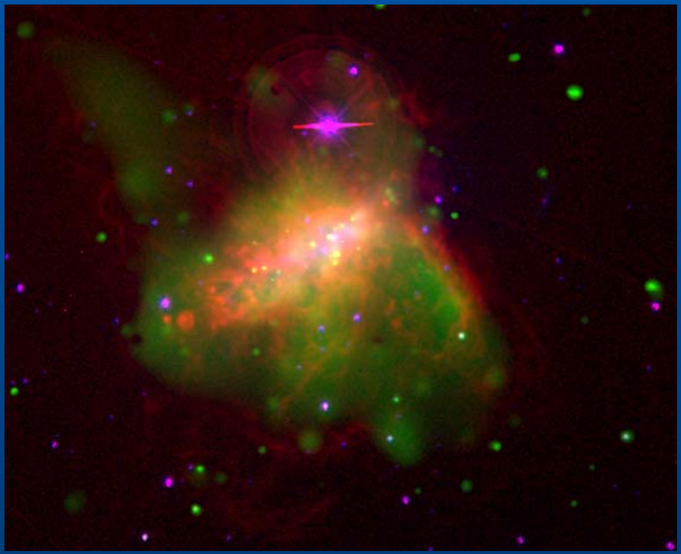
Metals in the Universe

R. Kennicutt (U. Arizona)

Observational Highlights

- Local Constraints
  - zeropoints, yields, diagnostics
  - global trends
  - metal ejection, global budgets
- Evolution of Metal Abundances
- General Conclusions



Origin and Evolution of the Elements, ed. A. McWilliam, M. Rauch (Carnegie Series, Vol 4), in press

Overview: Metals as Evolutionary Probes

- observed abundances trace a convolution of several evolutionary parameters and processes: SF history, IMF, heavy element yields, mixing, metal ejection, accretion, infall histories
- metallicity and its evolution can be measured for most major baryonic components
- metals provide fossil tracer of high-mass star formation
- abundance ratios provide nuclear clocks for key galaxy/star formation processes

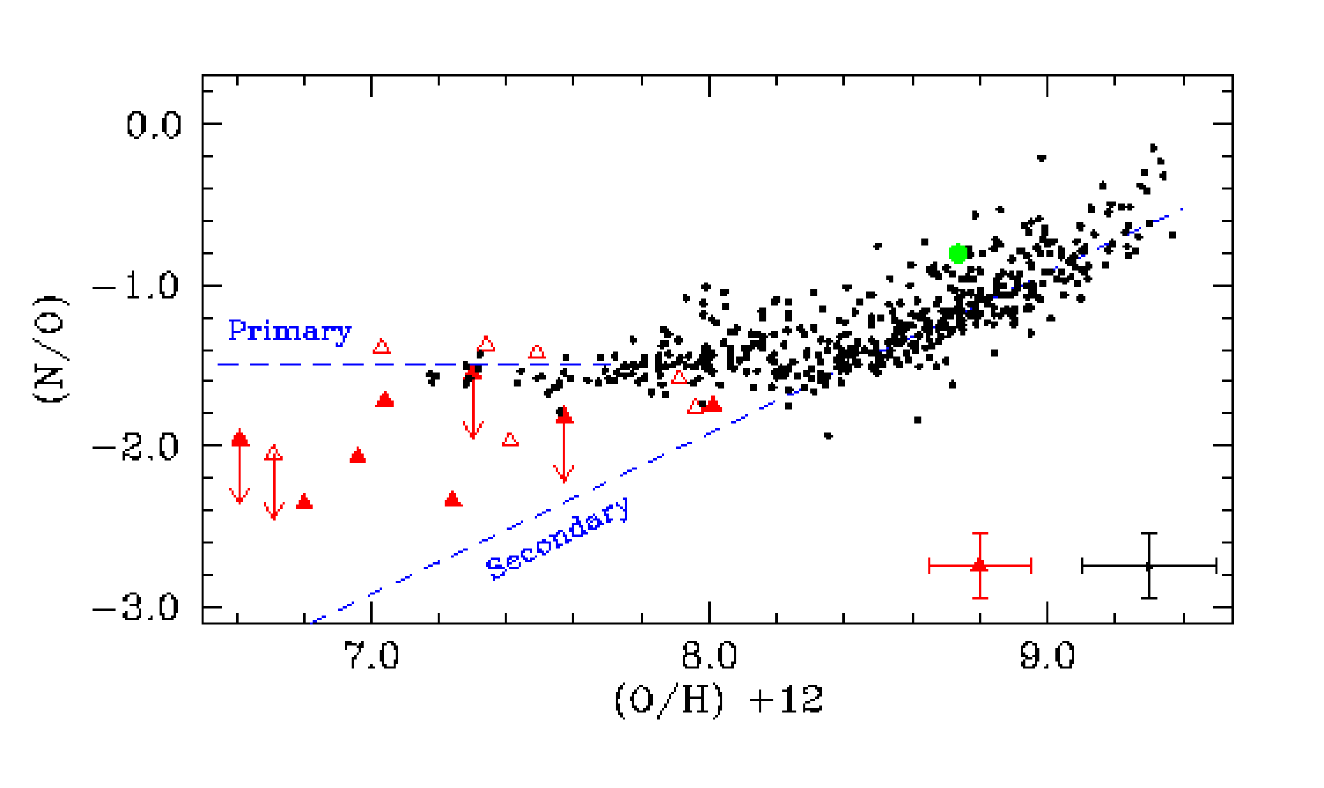
Foundation: Local Abundances

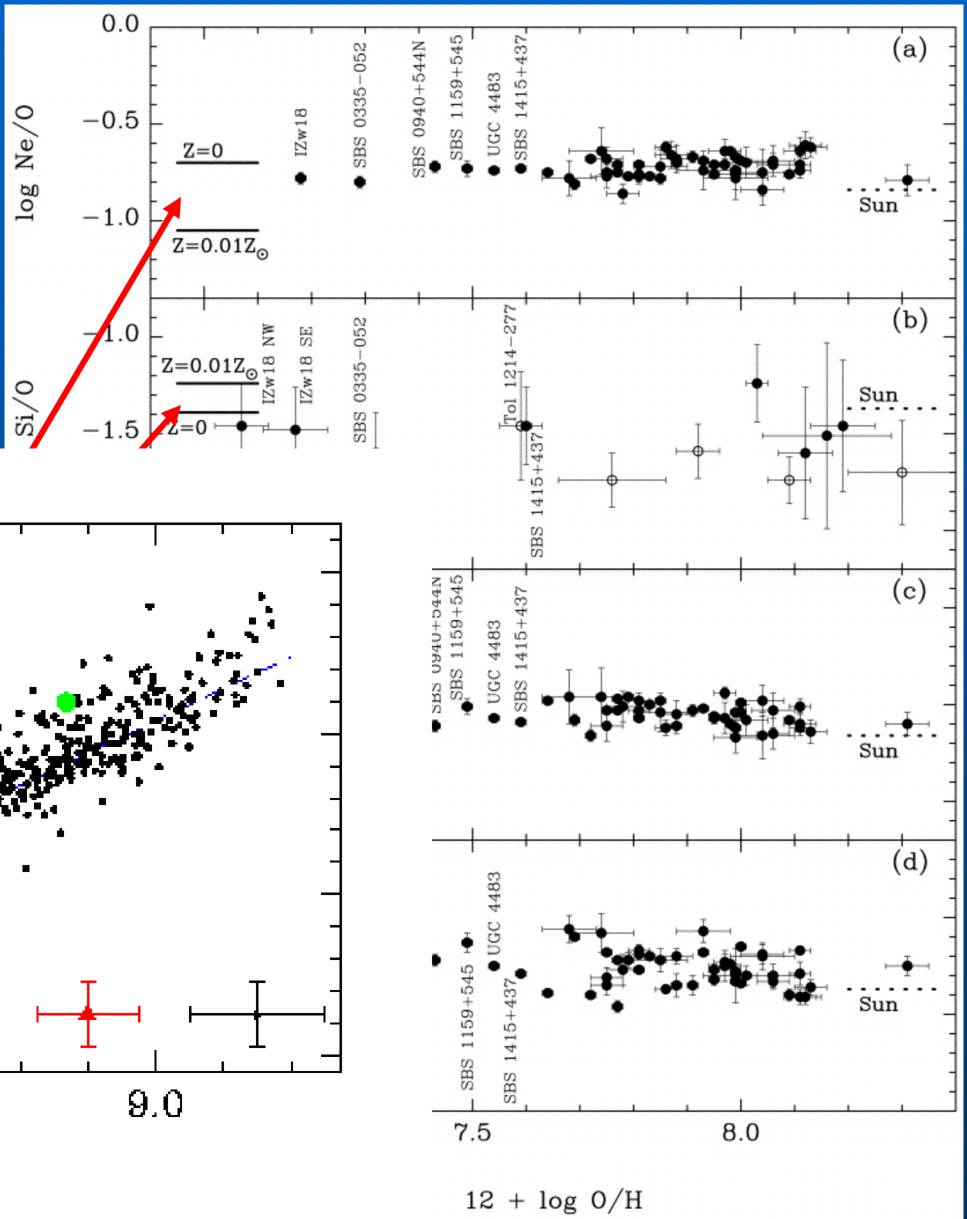
- Inconsistency between local solar vs nebular vs absorption line ISM abundances now resolved
  - solar oxygen abundance reduced downward to log O/H = -3.3 (Allende-Prieto et al 2001; Holweger 2001,)
  - T_e-based HII region abundances and HST/FUSE absorption line data give consistent local log O/H = -3.5 (Deharveng et al 2000; Meyer et al 1998; Moos et al 2002)
- Behavior of gas-phase heavy-element ratios consistent with theoretical expectations
  - absolute yields show rough agreement
- Improved metallicity diagnostics for lookback studies
  - 6-10m telescopes provide robust T_e-based HII region abundances to $Z > Z_o$ and faint low-Z HII regions
  - HST, FUSE UV spectra for range of Z, reddening, etc

Total metal yield:

y ~ 1/42 = 0.024

("Salpeter" IMF)

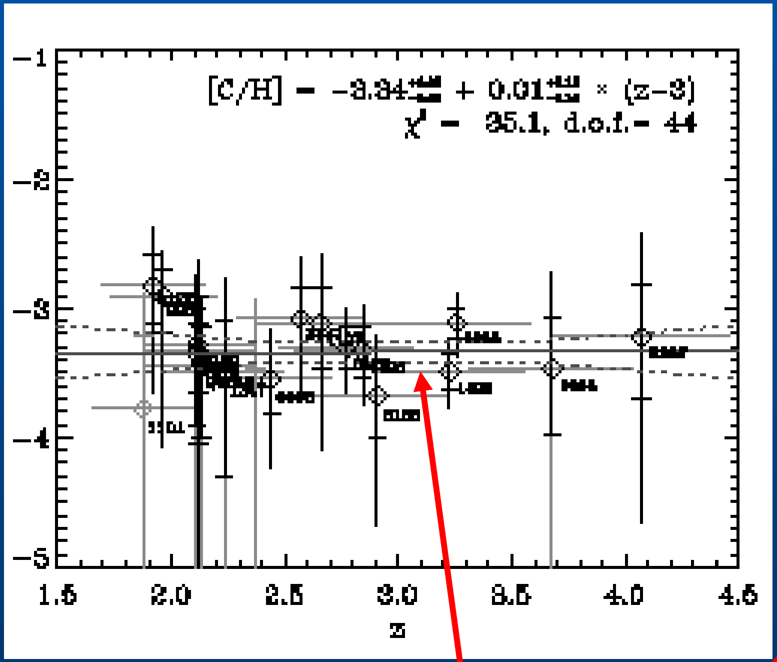


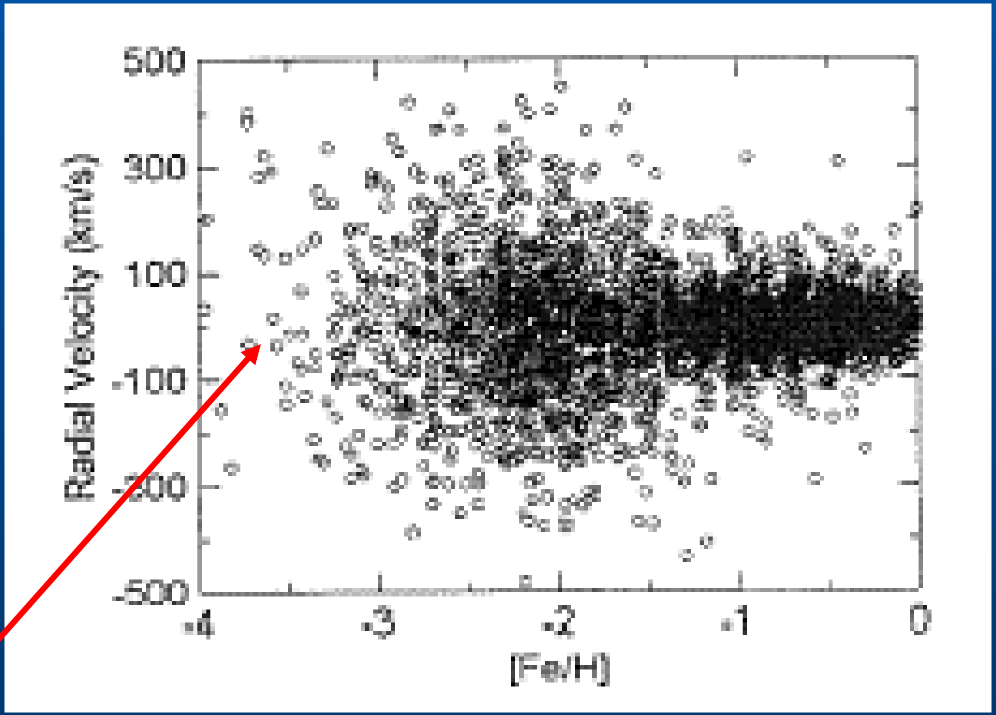


Pettini et al 2002, A&A, 391, 21

Izotov, Thuan 1999, ApJ, 511, 639

- the "Pop III" floor in the Galactic halo now seen at [Fe/H] ~ -4
  - rare "fossil" stars also found (e.g., HE0107-5240, [Fe/H] = -5.3)
  - otherwise halo Z distribution consistent with closed box model
- local observations restrict variability in IMF

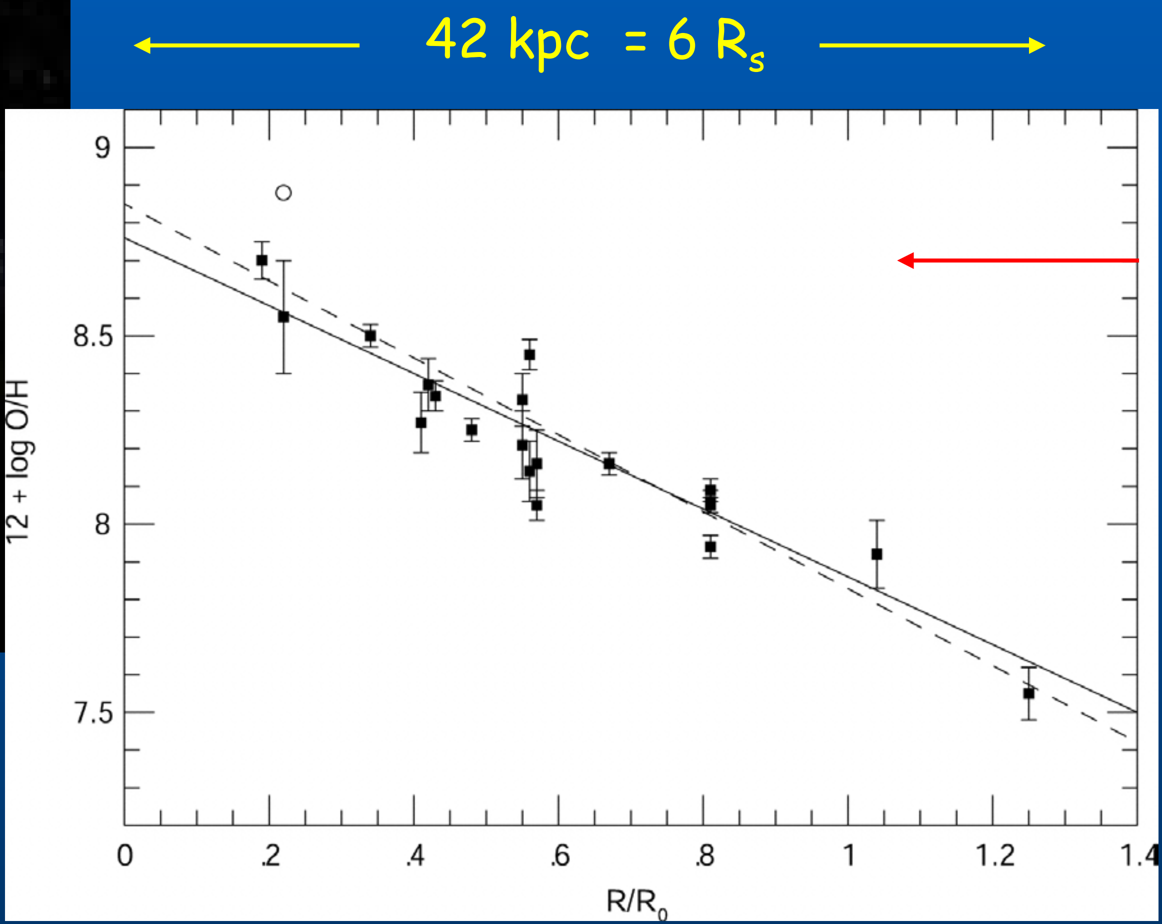




[Z/H] ~ -3.5

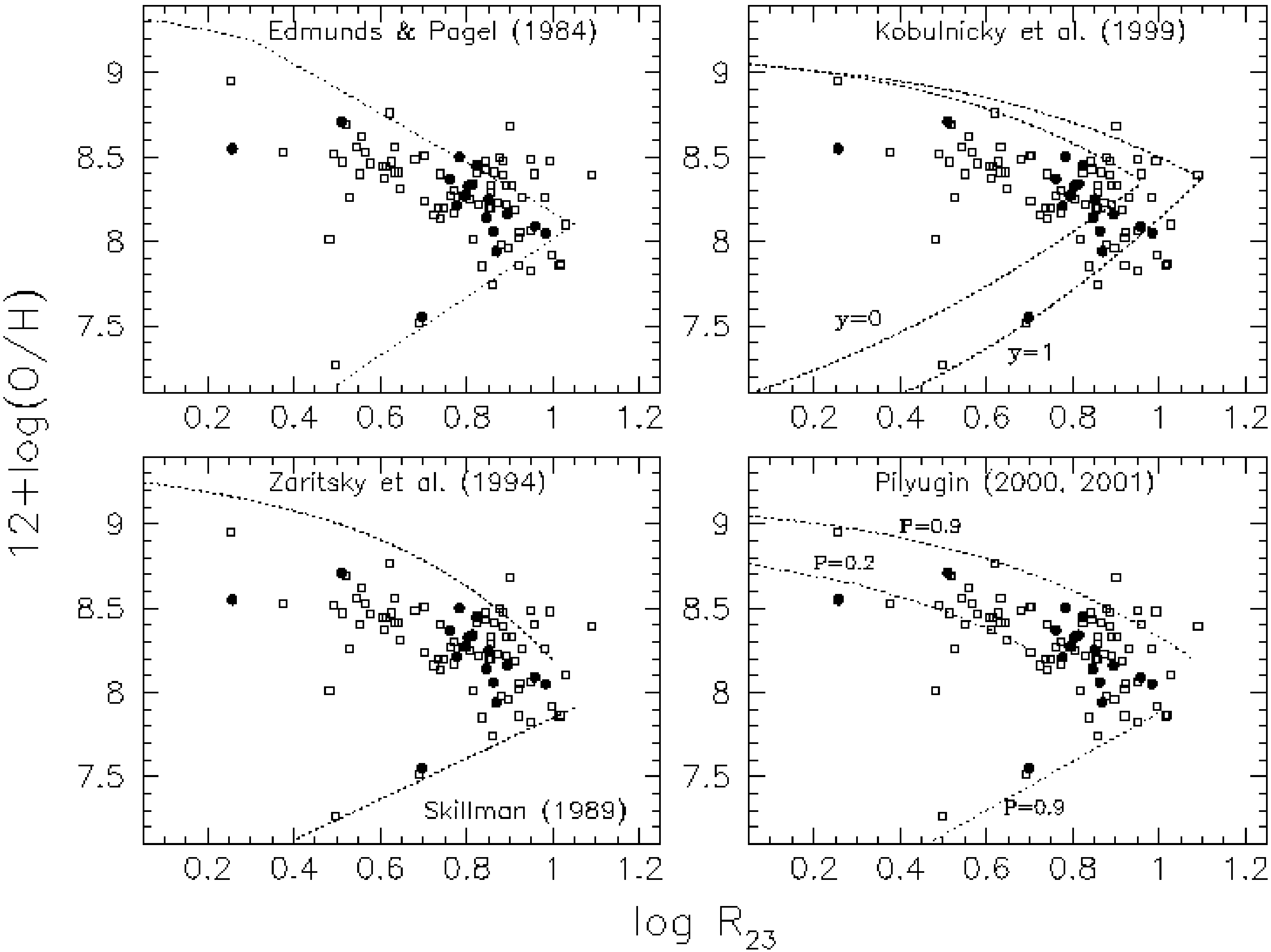
Beers 1999, Ap Sp Sc, 265, 105

e.g., M101

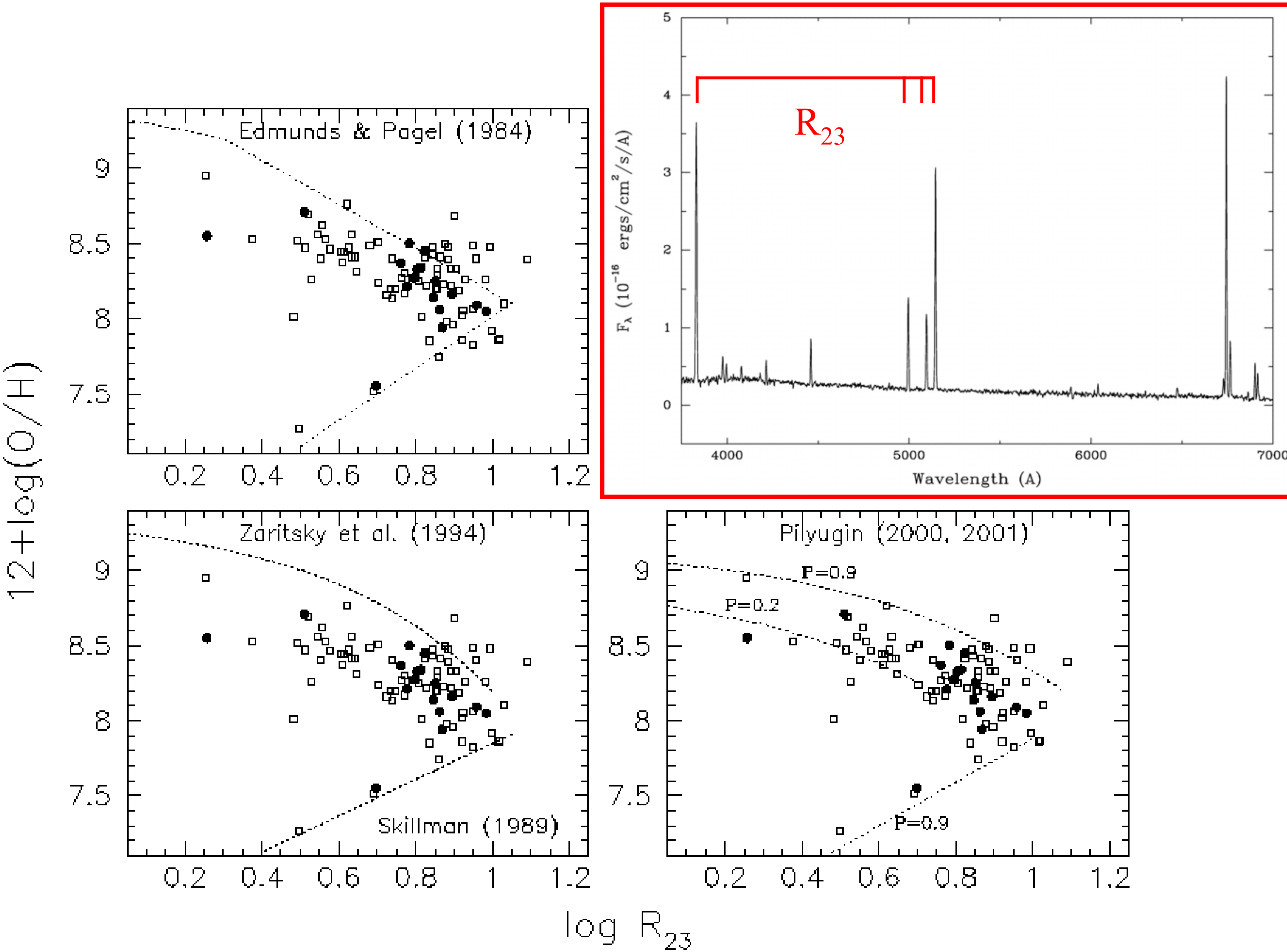


GALEX UV image!!

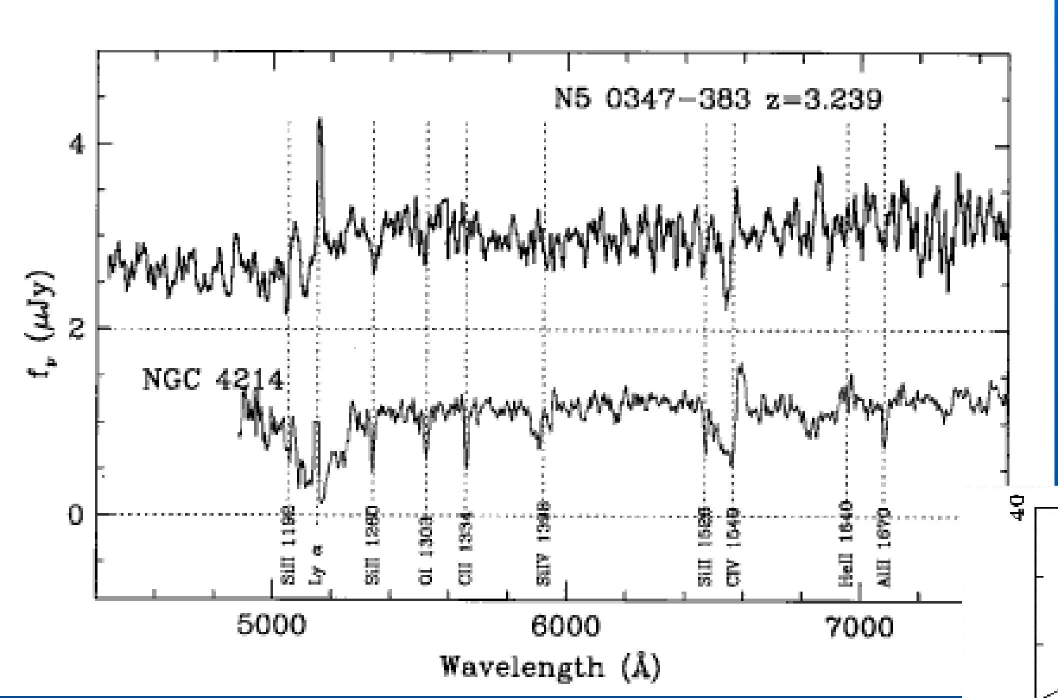
Kennicutt, Bresolin, Garnett 2003, ApJ, 591, 801



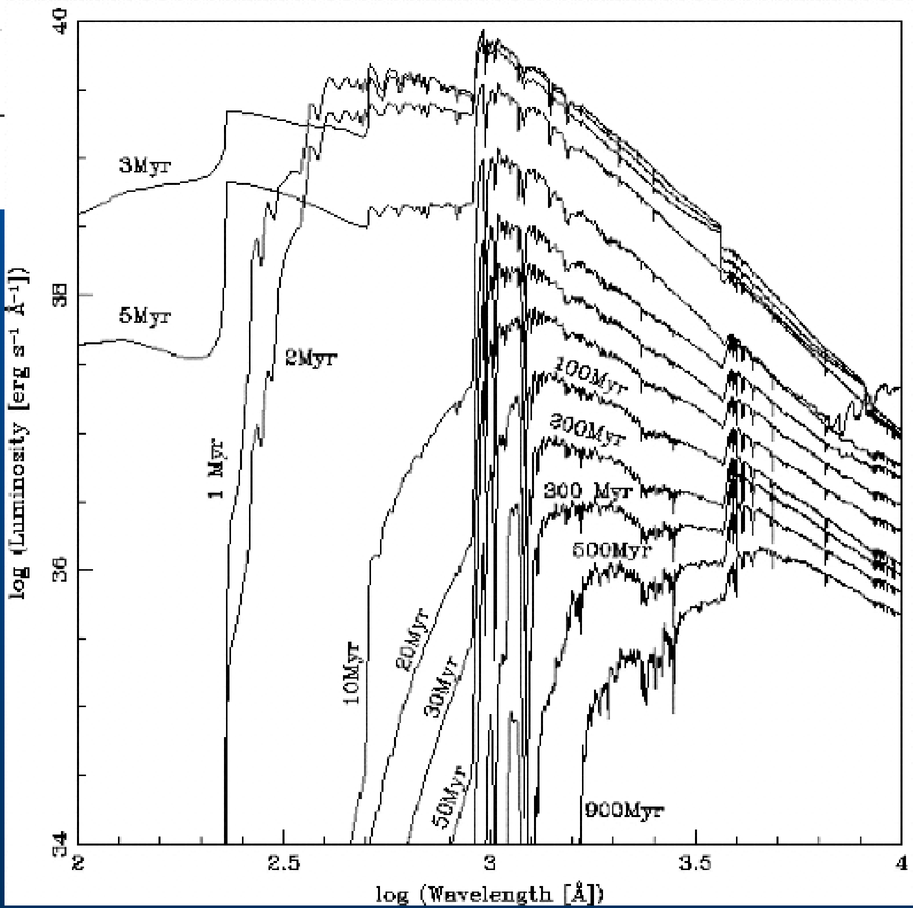
Kennicutt et al 2003, ApJ, 591, 801



Kennicutt et al 2003, ApJ, 591, 801

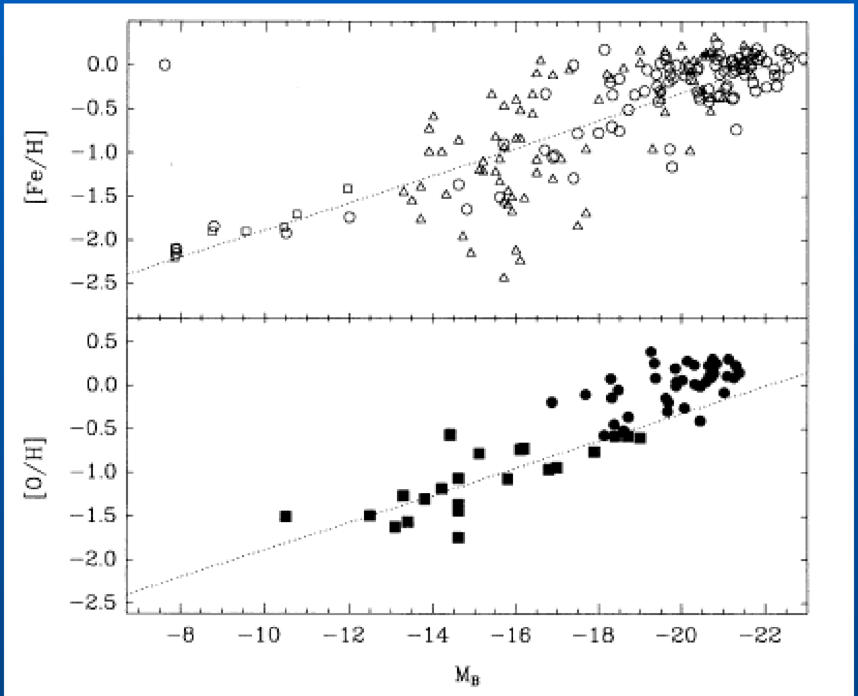


Steidel et al. 1996,
ApJ, 462, L17

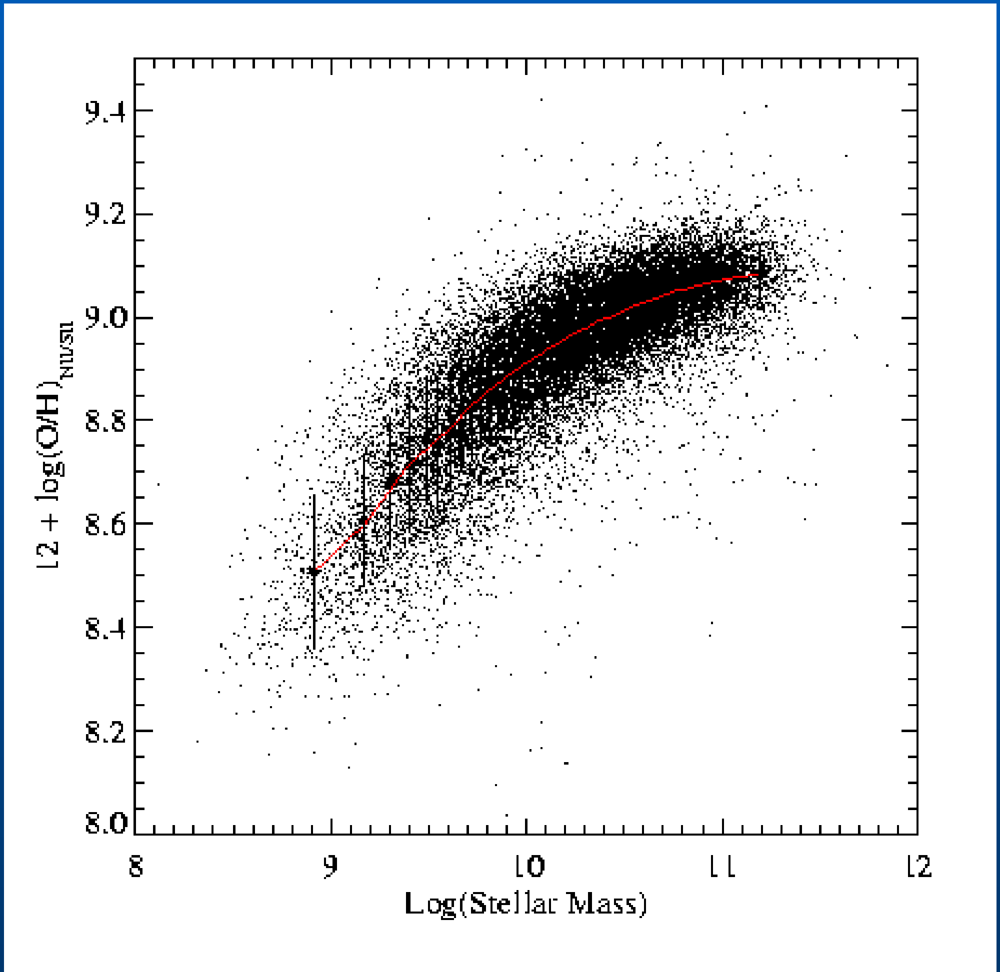


Leitherer et al. 1999, ApJS, 123, 3
"Starburst99"

- Local galactic mass-metallicity relation



Zaritsky et al. 1994, ApJ, 420, 87



C. Tremonti 2003, PhD thesis

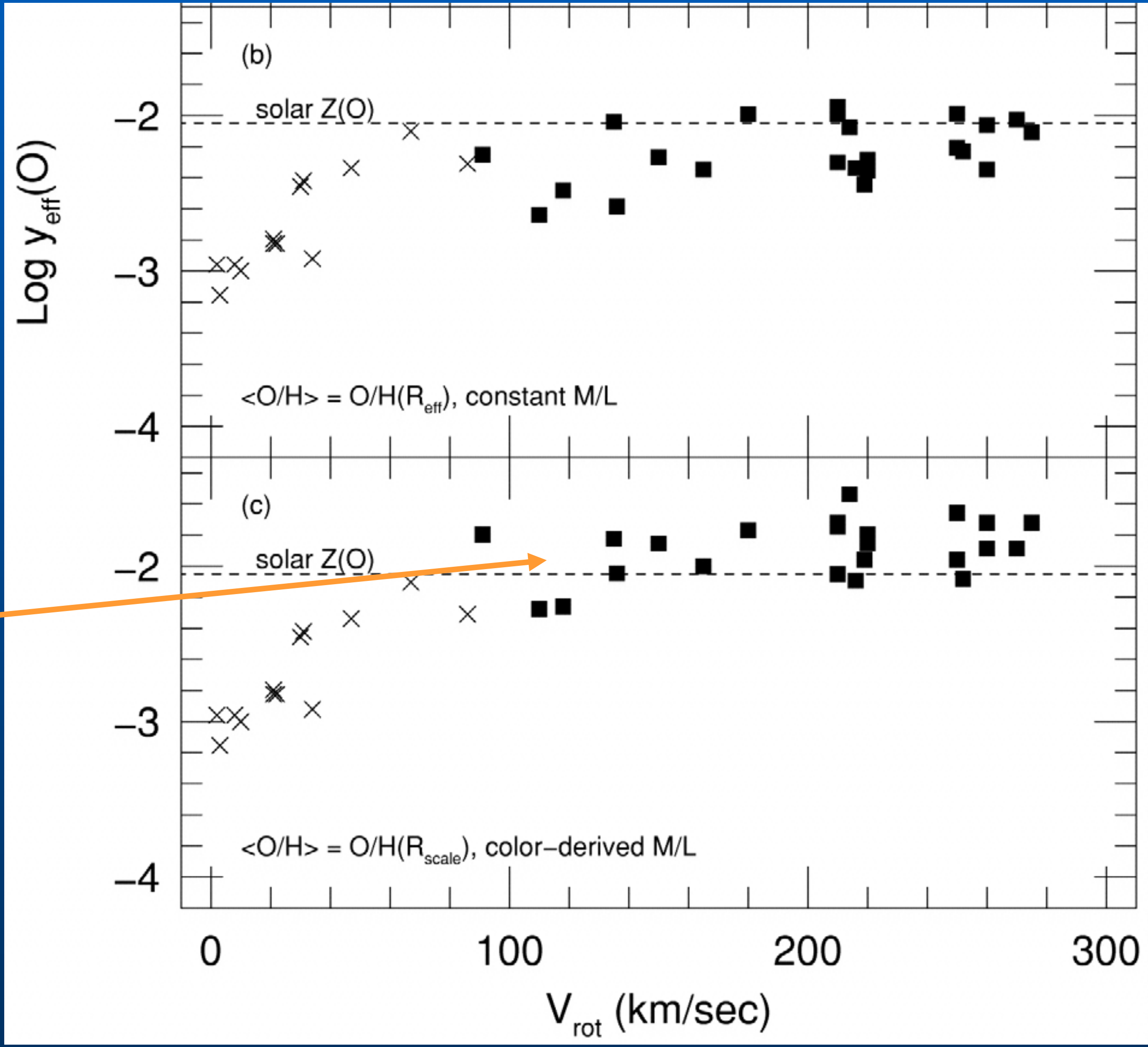
effective yield

$Z_{cb} = y \ln (1/\mu_{gas})$ (gas fraction $\mu_{gas} = M_g/(M^* + M_g)$)

$y_{eff} = -Z_{obs}/\ln \mu_{gas}$

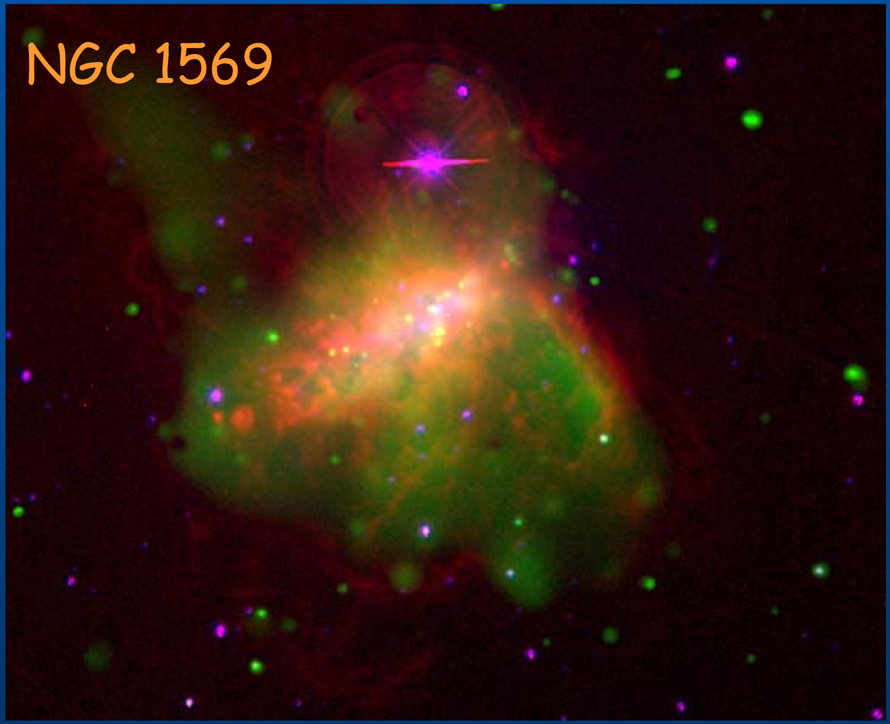
$y_{eff} = y\, Z_{obs}/Z_{cb}$

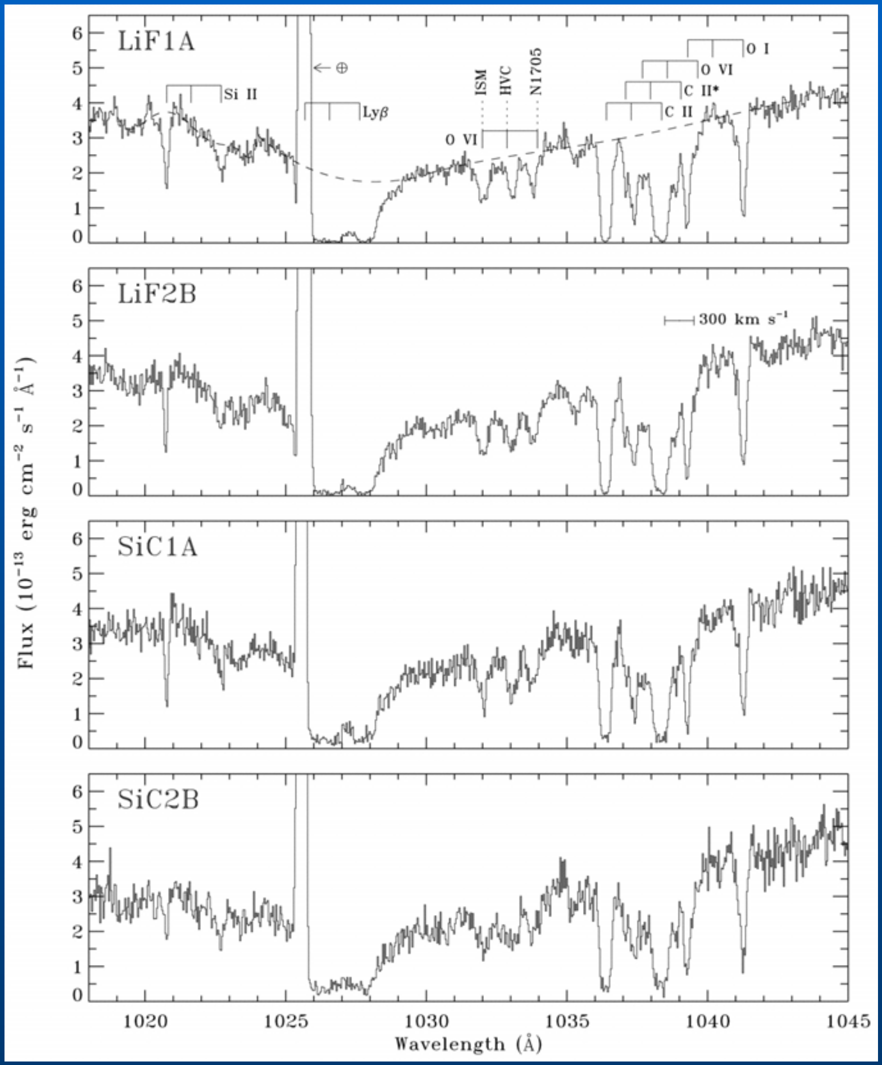
turnover at
$V_c \sim 100$- 150 km/sec
($L \sim 0.1\, L^*$)



Garnett 2002, ApJ, 581, 1019

- direct evidence from CXO and FUSE for metal ejection from starburst dwarfs

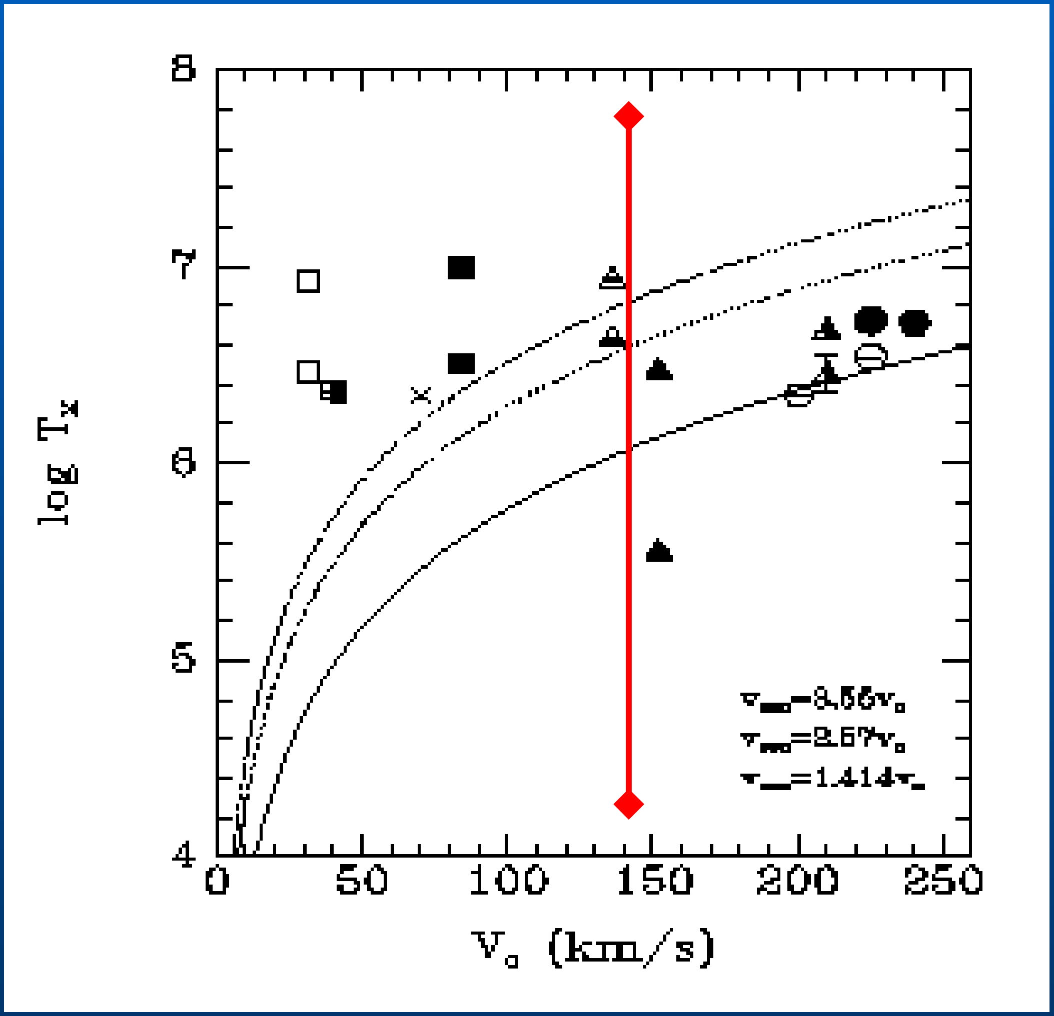


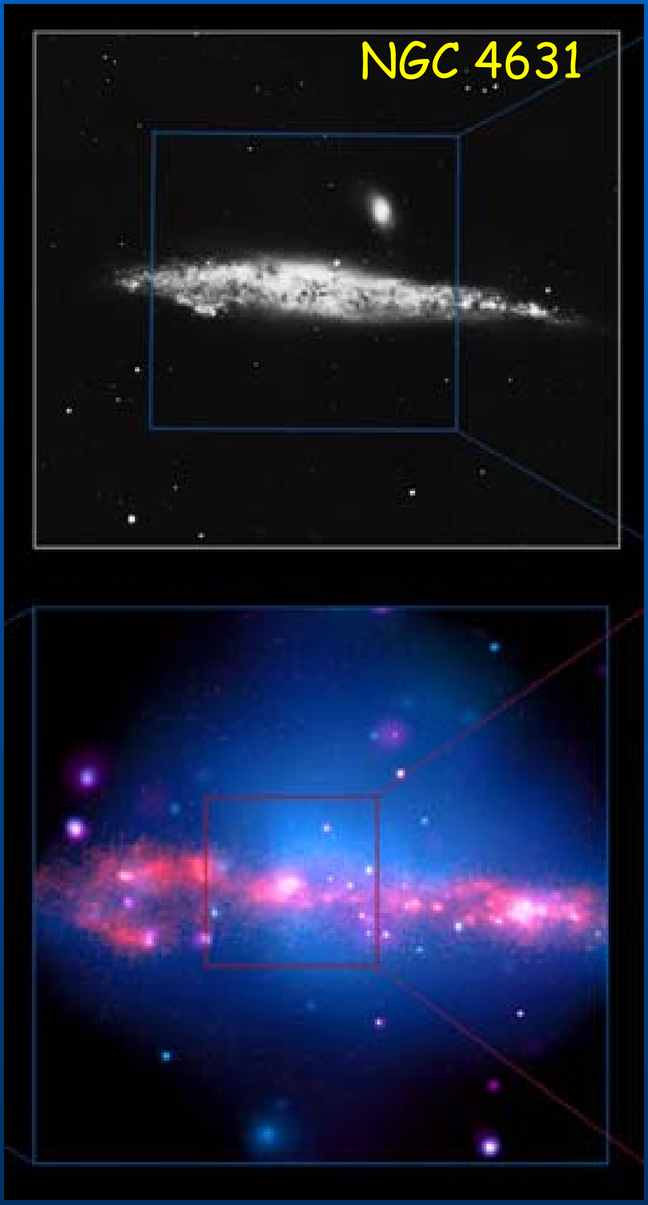


Martin et al 2002, ApJ 574, 663

Heckman et al 2001, ApJ, 554, 1021

- metal-enriched winds can escape for $V_c < 150$ km/sec

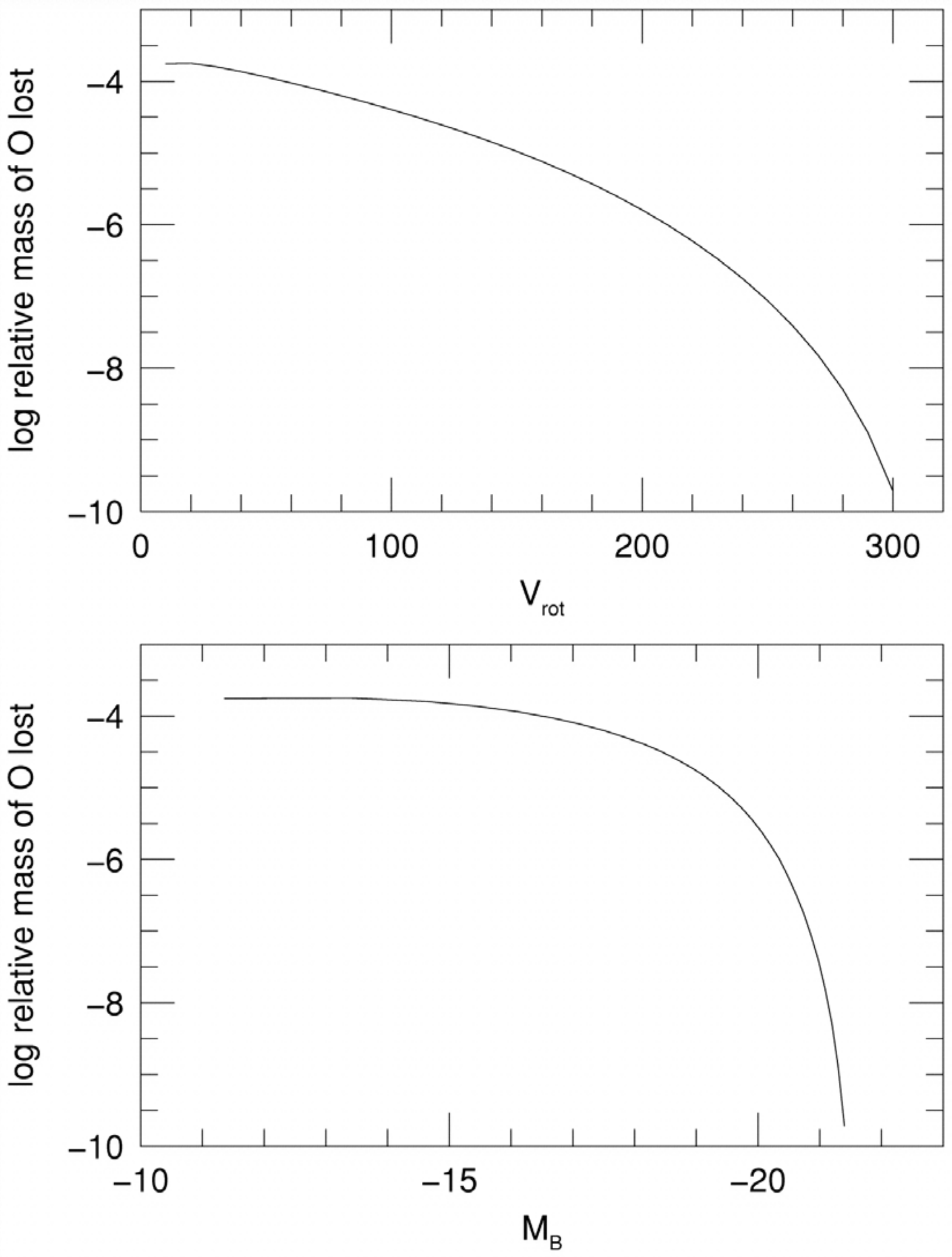




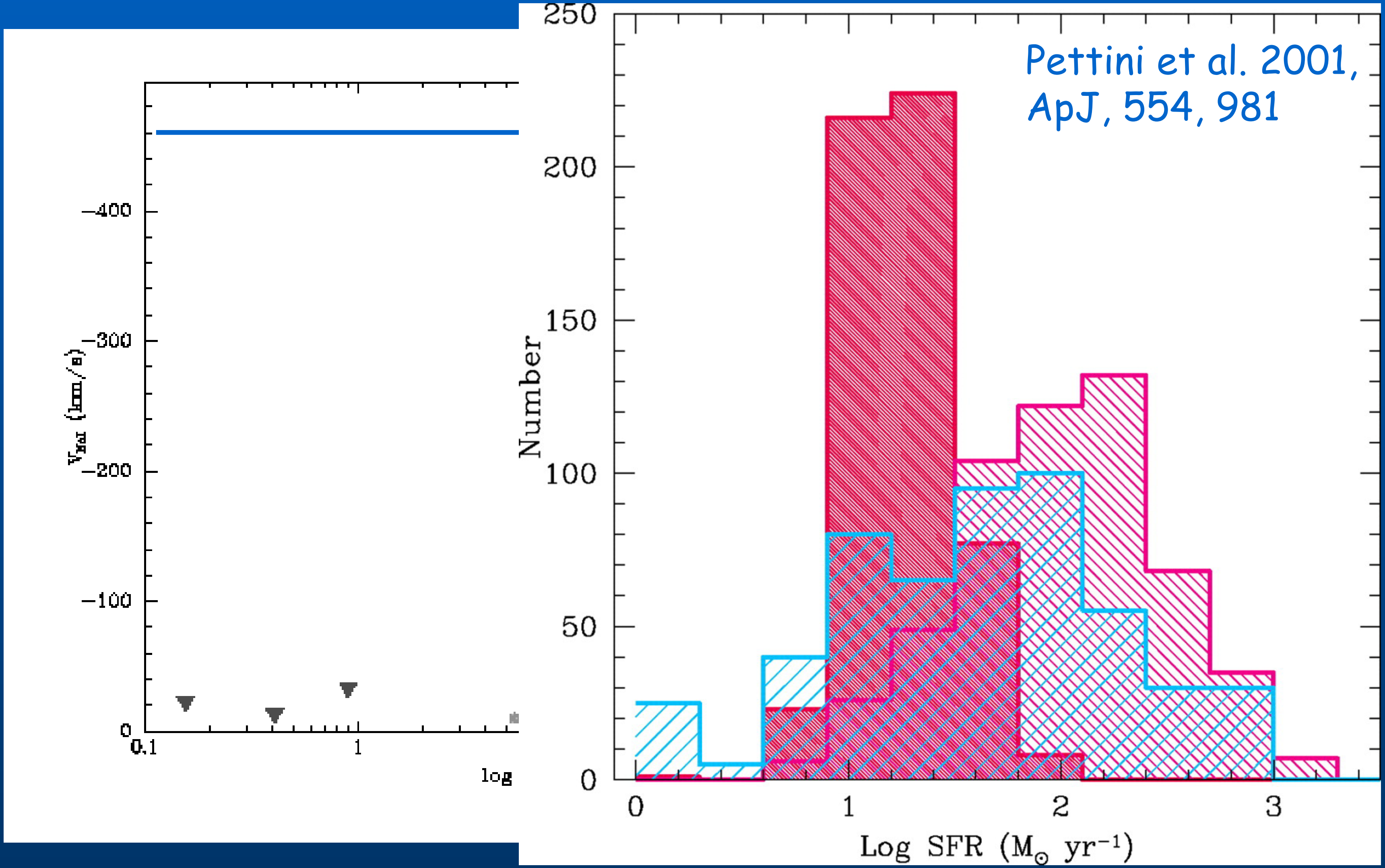
Martin 2003, Carnegie Symp.

- implications:
  - most present-day IGM enrichment is from low-mass galaxies
  - large fraction of total metals retained in disks

Garnett 2002, ApJ, 581, 1019



superwinds provide mechanism for metal ejection in luminous starburst galaxies



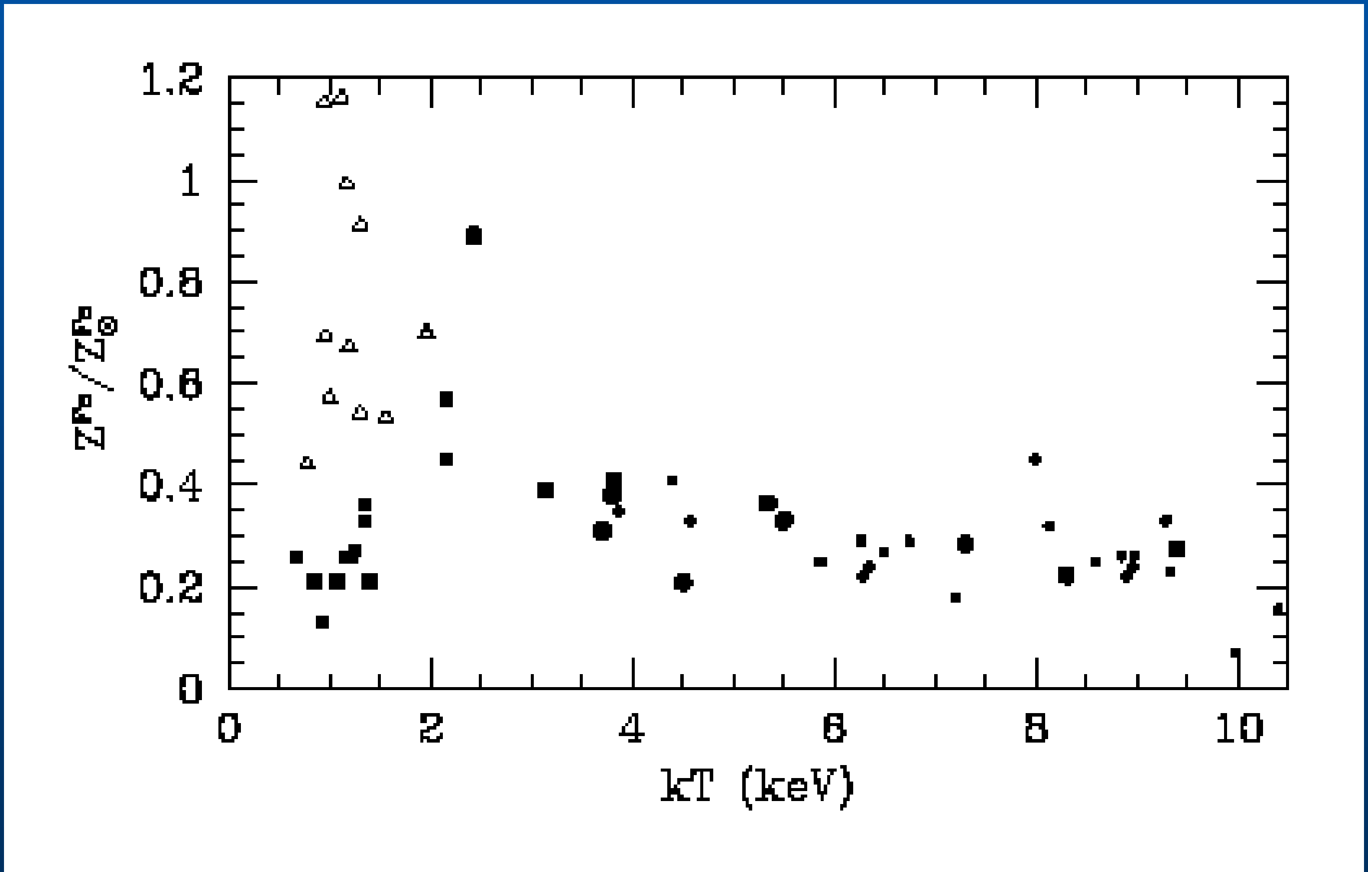
Martin & Armus 2003, in preparation

- Global Metals Budget (z = 0)
  - Pagel 2002, ASP Conf Ser 253, p. 489
  - Lilly, Carollo, Stockton 2002, astro-ph/0209243
  - Pettini 2002, astro-ph/0303272

Table 1. Inventory of nucleosynthetic products in the Universe

Component	baryons(ρ/ρ_c)	$Z/Z_\odot$)	metals(ρ/ρ_c)
Accesible heavy element components			
Spheroid stellar atmospheres	$0.004h_{70}^{-1}$	1.0	$7\times10^{-5}h_{70}^{-1}$
Disk stellar atmospheres	$0.0015h_{70}^{-1}$	1.0	$3\times10^{-5}h_{70}^{-1}$
Hot cluster gas	$0.0025h_{70}^{-1.5}$	0.3	$1.6\times10^{-5}h_{70}^{-1.5}$
Warm group/field gas	$0.02h_{70}^{-1.5}$?	$\lesssim 0.3$?	$\lesssim 1.2\times10^{-4}h_{70}^{-1.5}$?
Sum	$\sim 0.028h_{70}^{-1}$		$1.2-2.4\times10^{-4}h_{70}^{-1}$
Inaccessible components			
^{4}He in stellar cores		all ^{4}He	$\sim 0.8\times10^{-4}h_{70}^{-1}$

- cluster ICM abundances imply high global metal yield (~3 Z_o!), with 2/3 of baryons in ICM
- if rich clusters are fair samples of universe, where are most of the metals in the field?
  - ICM of groups? locked in disks? hot halos, coronae?



Renzini 2003, Carnegie Conf

TABLE 3

CENSUS OF METALS AT $z = 2.5$[a]

Component	Ω[b]	Z[c]	Ω_Z[d]
Observed:			
DLAs	0.0025	0.07	0.002
Lyα Forest	0.05 – 0.06	0.003	0.002 – 0.003
Lyman Break Galaxies	?	0.3	> 0.0002
Predicted:			
All Baryons (BBNS)	0.088		
Metals synthesised in Lyman Break Galaxies			0.035

[a] All entries are for $H_0 = 50$ km s^{-1} Mpc^{-1}; $\Omega_M = 1$, $\Omega_\Lambda = 0$.

[b] In units of the closure density $\rho_{crit} = 3.1 \times 10^{11} h^2 M_\odot$ Mpc^{-3}.

[c] In units of solar metallicity (0.0189 by mass).

[d] In units of $\Omega_{Z_\odot} = \Omega_{baryons} \times Z_\odot = 1.7 \times 10^{-3}$.

Pettini et al 2003, astro-ph/0303272

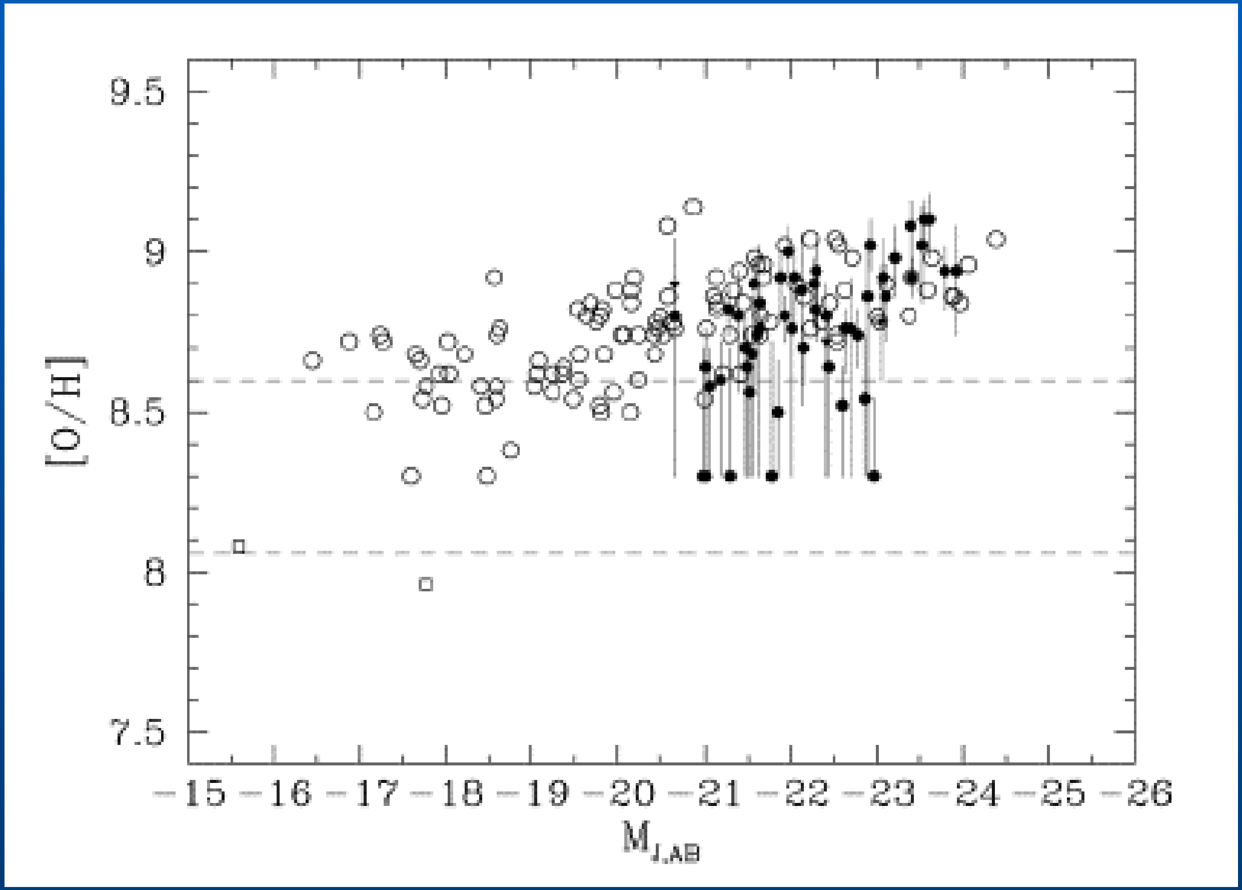
Metallicity Evolution

- Galaxies
  - emission-line diagnostics (ionized gas)
    - $z = 0 - 3$
  - UV resonance lines (hot stars, ISM)
    - $z = 1 - 3$
  - quasar, AGN emission lines
    - $z = 0 - 6.4$

- IGM
  - quasar absorption lines (IGM)
    - $z \sim 1 - 4$ (DLAs)
    - $z \sim 2 - 4$ (Ly-a forest)
  - X-ray abundances (cluster ICM)
    - $z \sim 0 - 1$

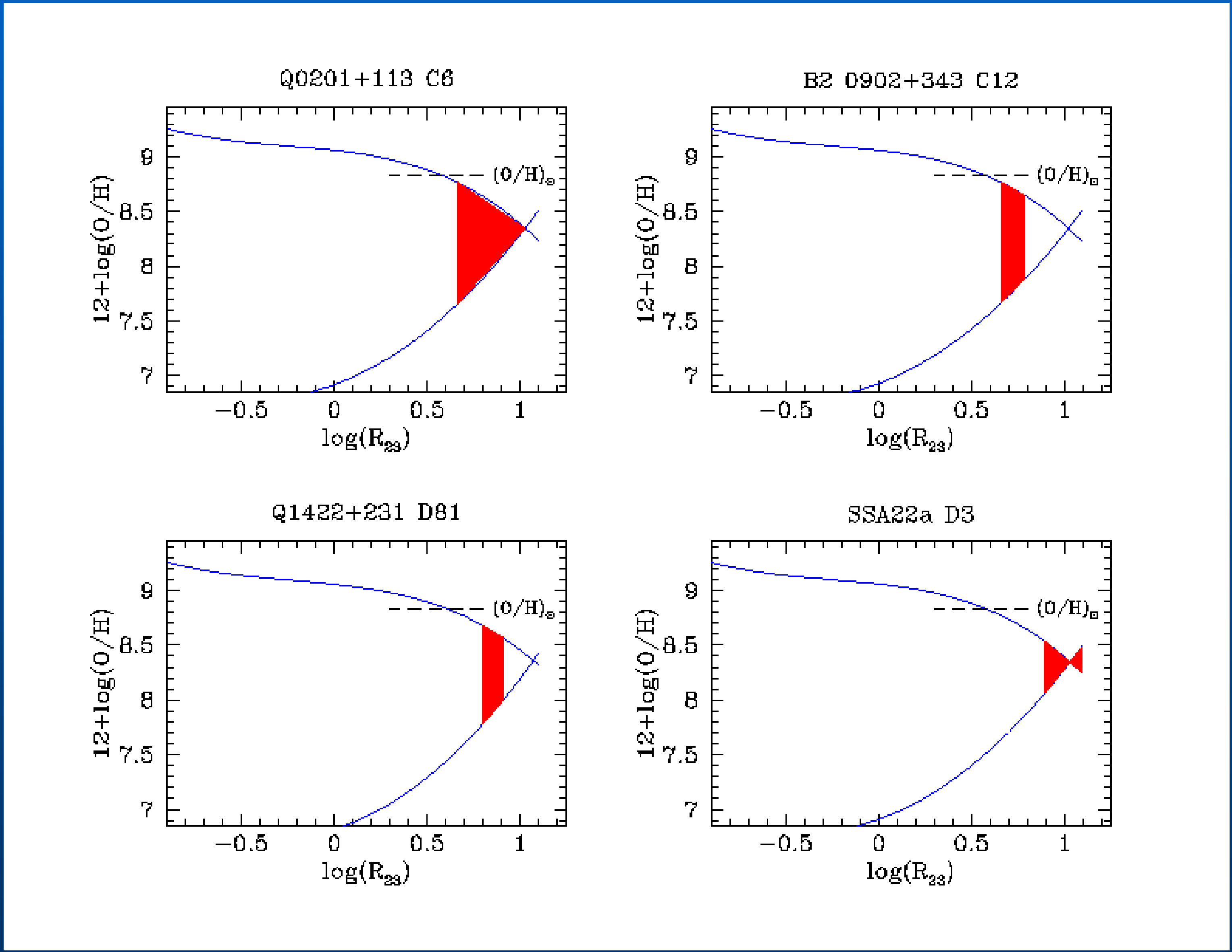
Lilly, Carollo, Stockton 2003, ApJ, in press (astro-ph/0307300)

- 66 CFRS galaxies, z = 0.47 - 0.92



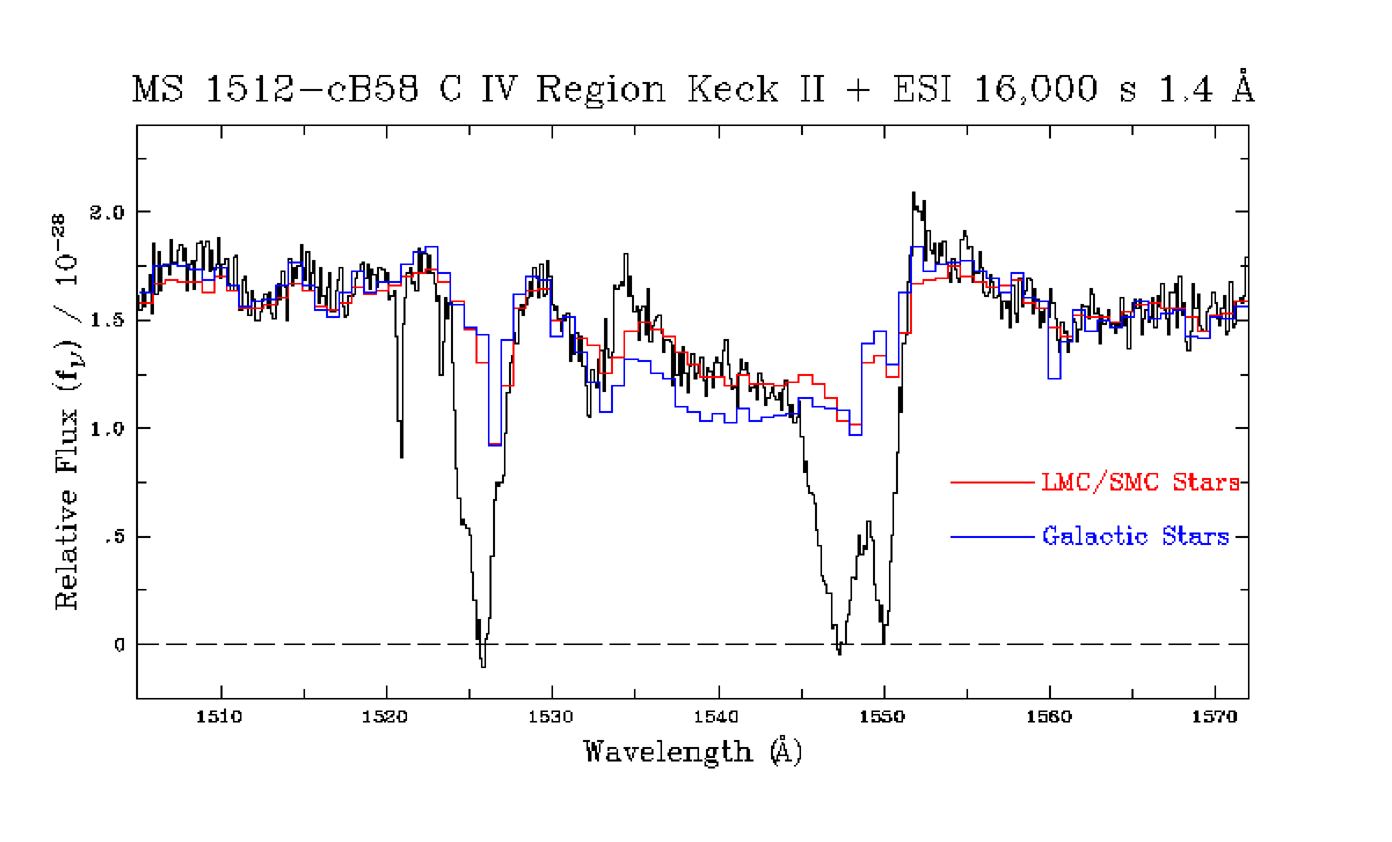
cf. Kobulnicky, Zaritsky 1999, ApJ, 511, 118
Hammer et al. 2001, ApJ, 550, 570
Contini et al. 2002, MNRAS, 330, 75
Kobulnicky et al. 2003, ApJ submitted

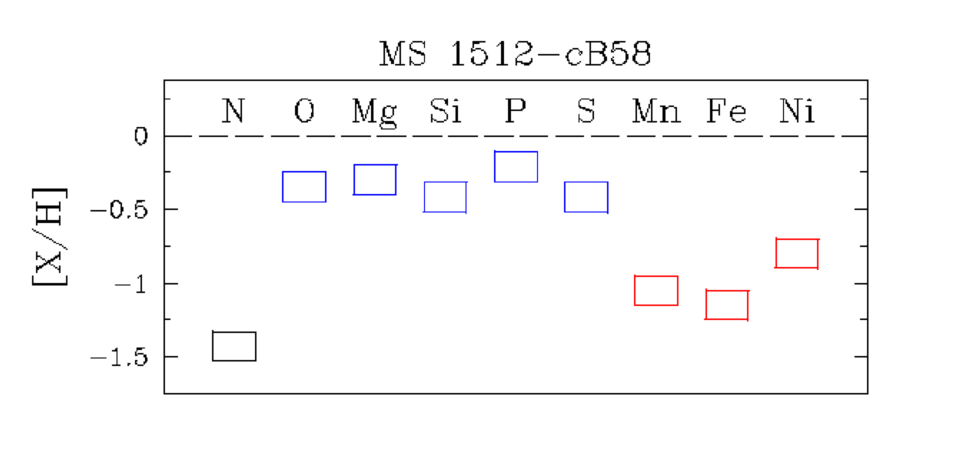
Lyman-break galaxies (z~3)



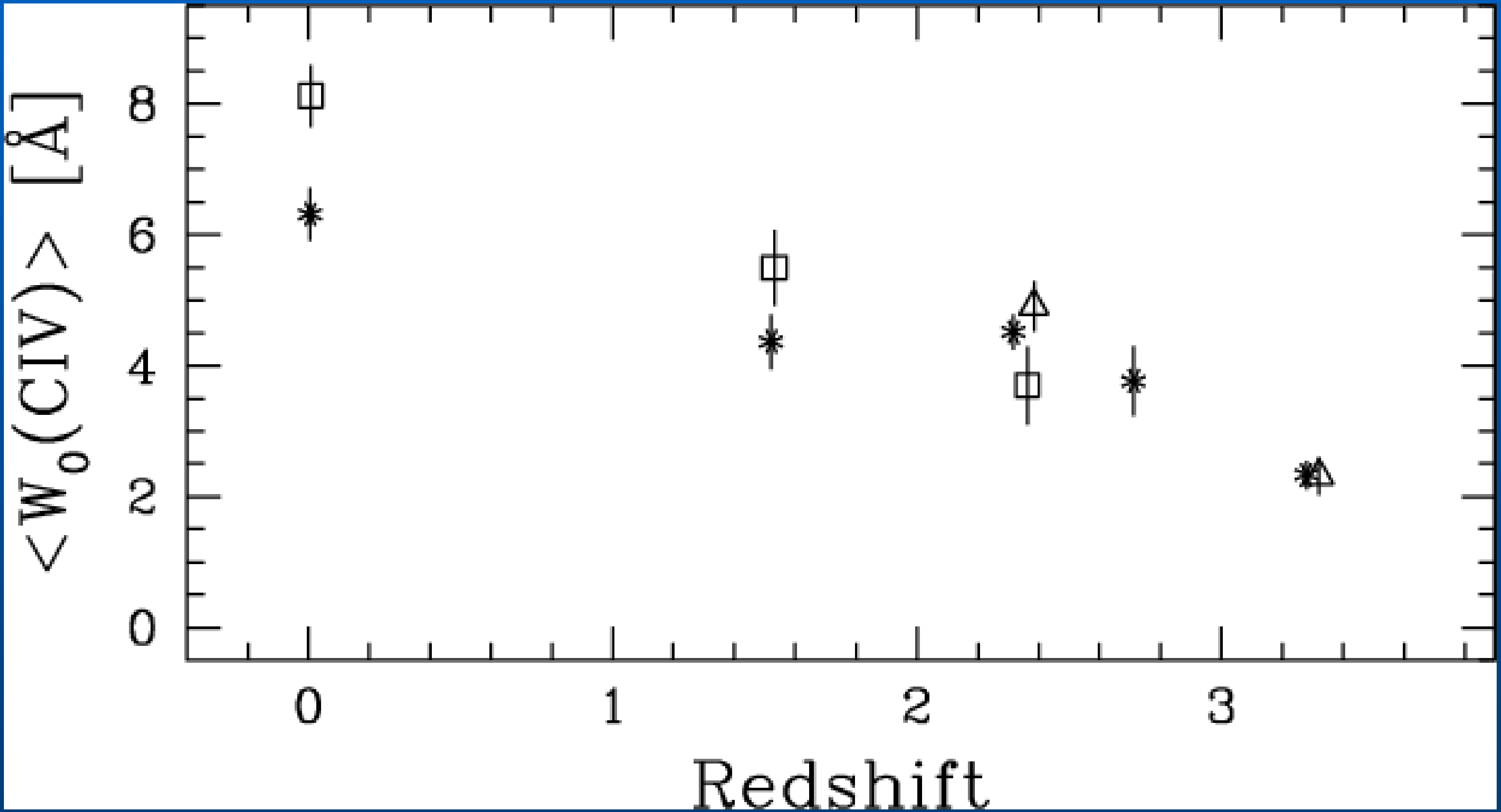
Pettini et al. 2001, ApJ, 554, 981

stellar abundances

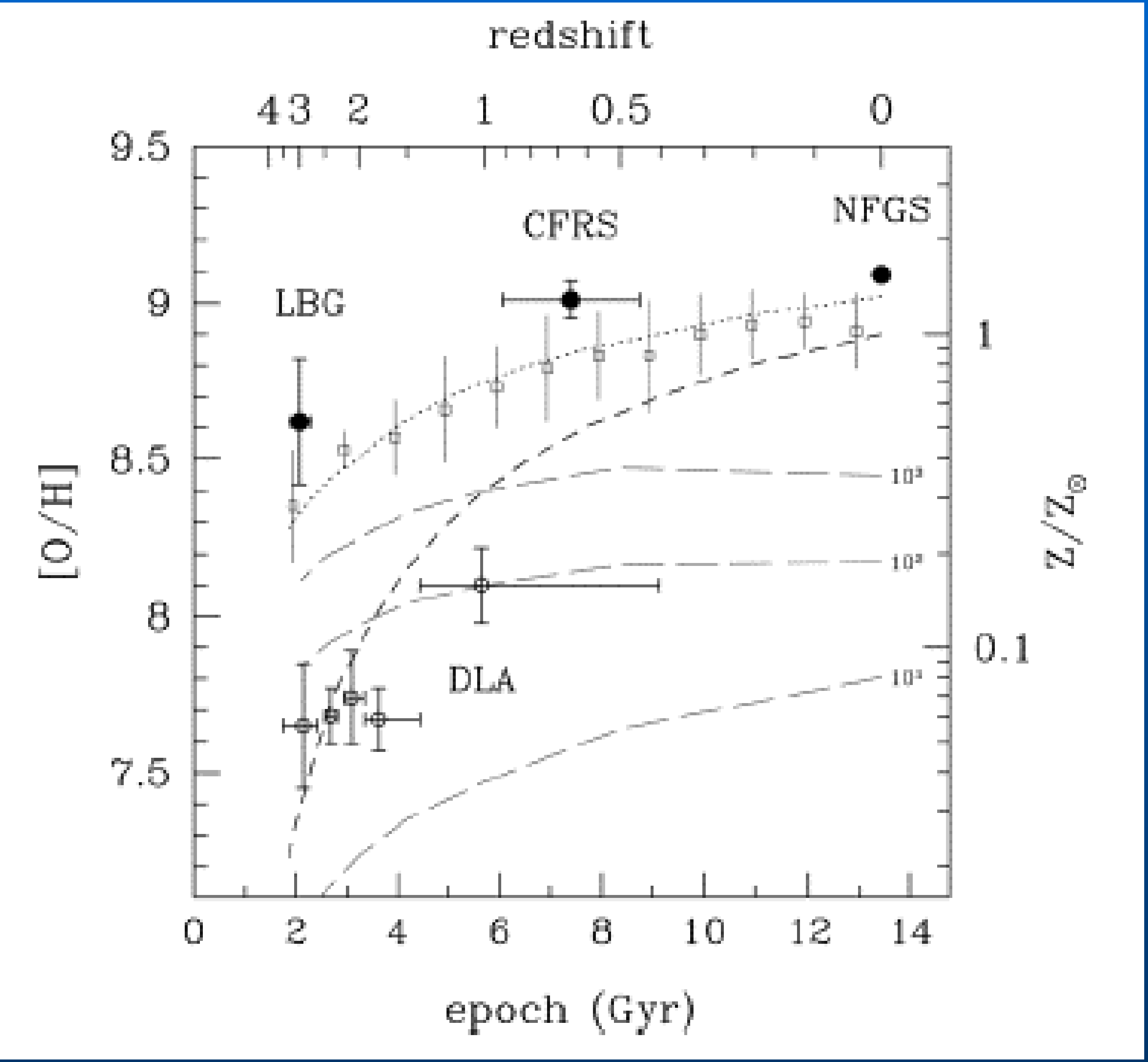




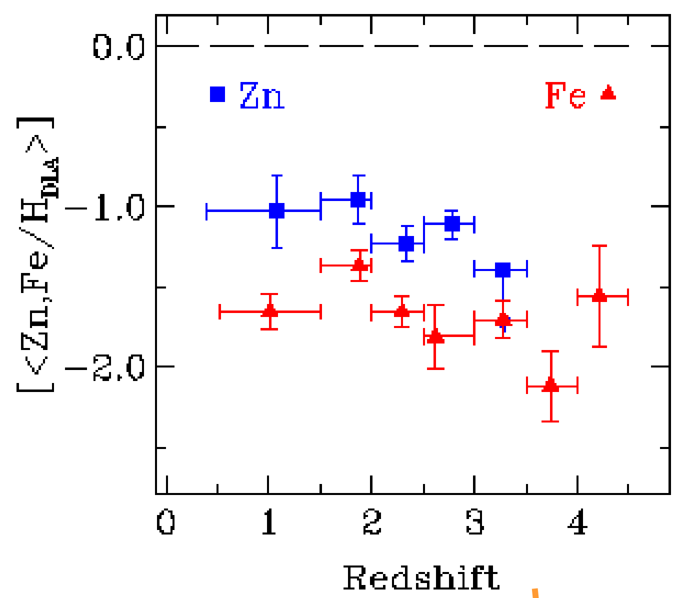
Pettini et al. 2002, ApJ, 569, 742
Mehlert et al. 2002, A&A, 393, 809
Shapley et al. 2003, ApJ, 588, 65
Savaglio et al. 2003, ApJ, submitted



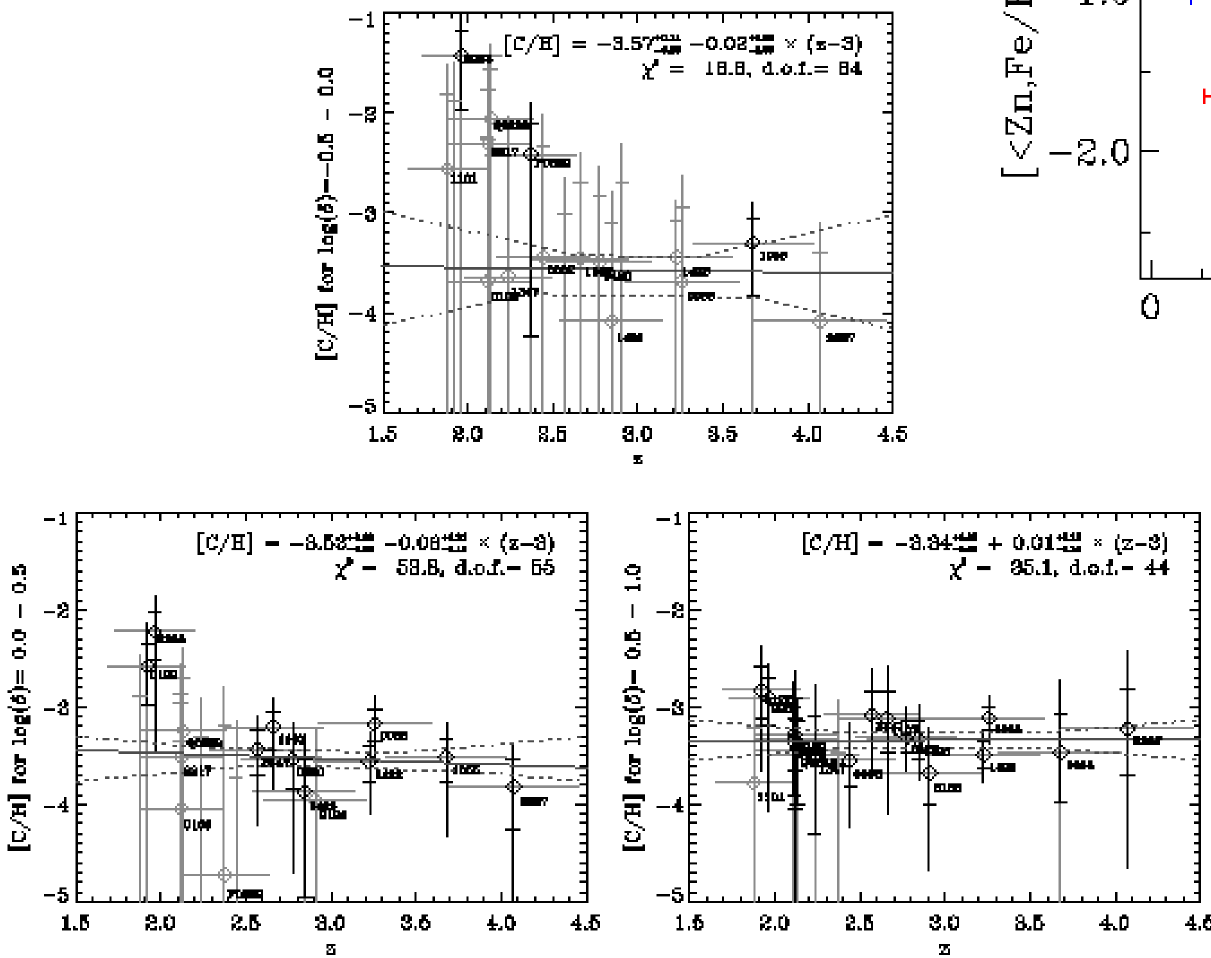
Mehlert al. 2002, *A&A*, 393, 809



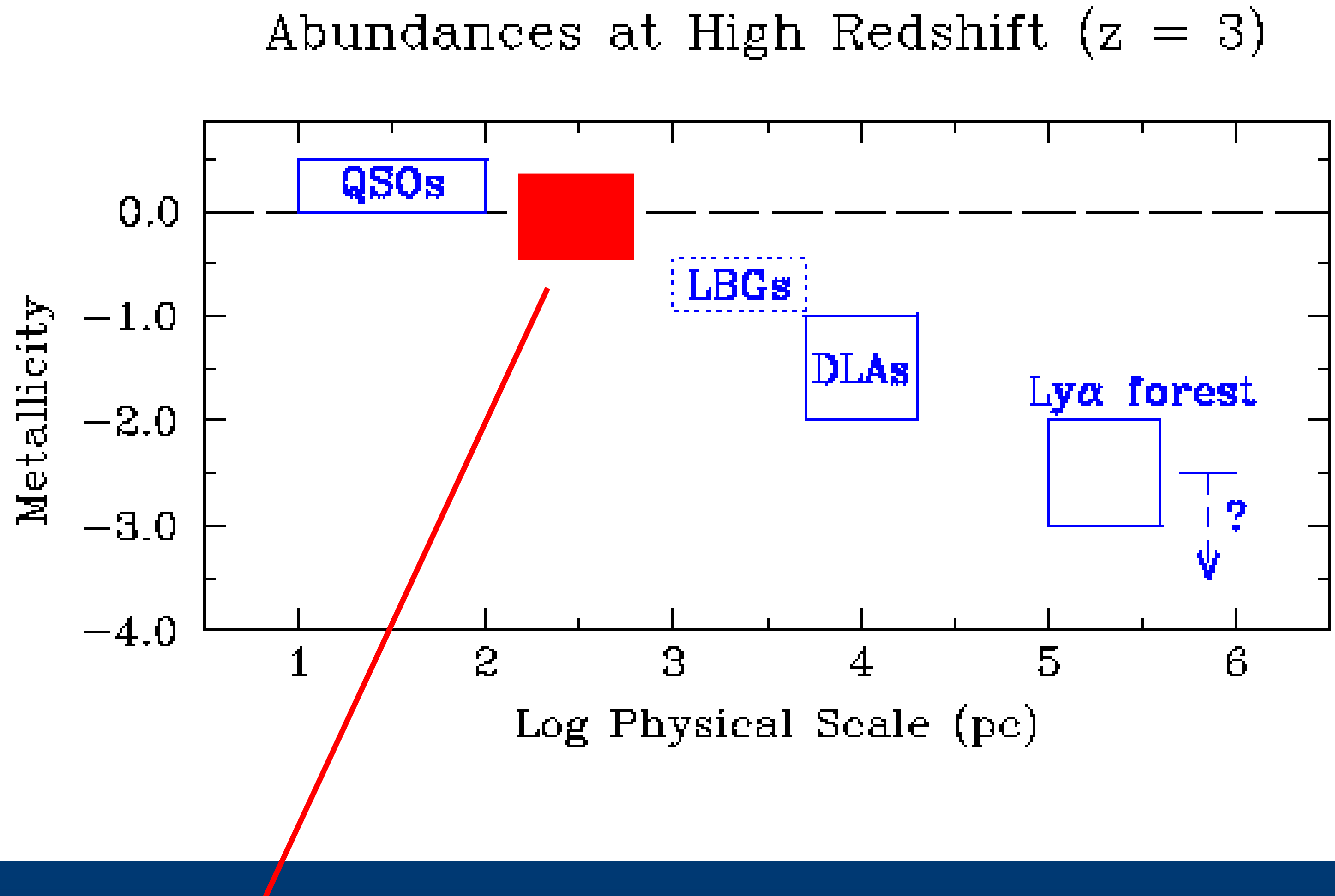
Lilly, Carollo, Stockton 2003, ApJ, in press (astro-ph/0307300)



Pettini 2003, astro-ph/0303272



Schaye et al. 2003, ApJ, in press (astro-ph/0306469)



submm sources??

Pettini 2002, astro-ph/0303272

Metallicity Evolution: Results

- clear evidence seen for chemical evolution of luminous galaxies over $z = 0 \rightarrow 3$
  - evolution seen in gas-phase and stellar abundances
  - roughly consistent with evolution in stellar birthrate
- evolution of IGM abundances is much weaker (possibly negligible) over accessible redshift ranges
  - bulk of metals unaccounted for at $z = 2$-3; $z = 0$??
- abundance floor $[Z/H] < -3$, roughly consistent with threshold in halo star Z distribution
- local abundances are correlated with local density (potential well depth), within and between galaxies
  - metal segregation already strongly in place by $z = 3$-4
  - role of observational selection??

- Future Attractions:
  (JWST, CELT/GMST/TMT/ELT/OWL…)