Elemental Abundances as Tracers of Star Formation

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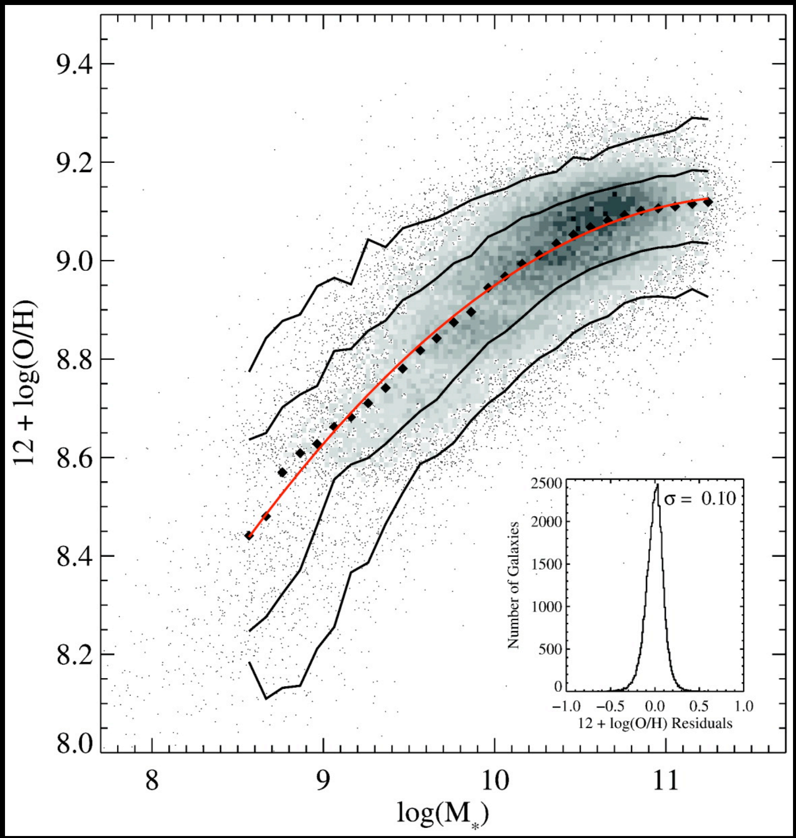


(Tremonti+04)

Plan

- **Basics of chemical evolution**
- **Simple closed-, leaky-, accreting-box models**
- **Applications:**
  - **Milky Way bulge and disk**
  - **Local star-forming galaxies**
  - **Local starburst galaxies**
  - **Distant galaxies**
  - **Distant quasars**

Relevant Review

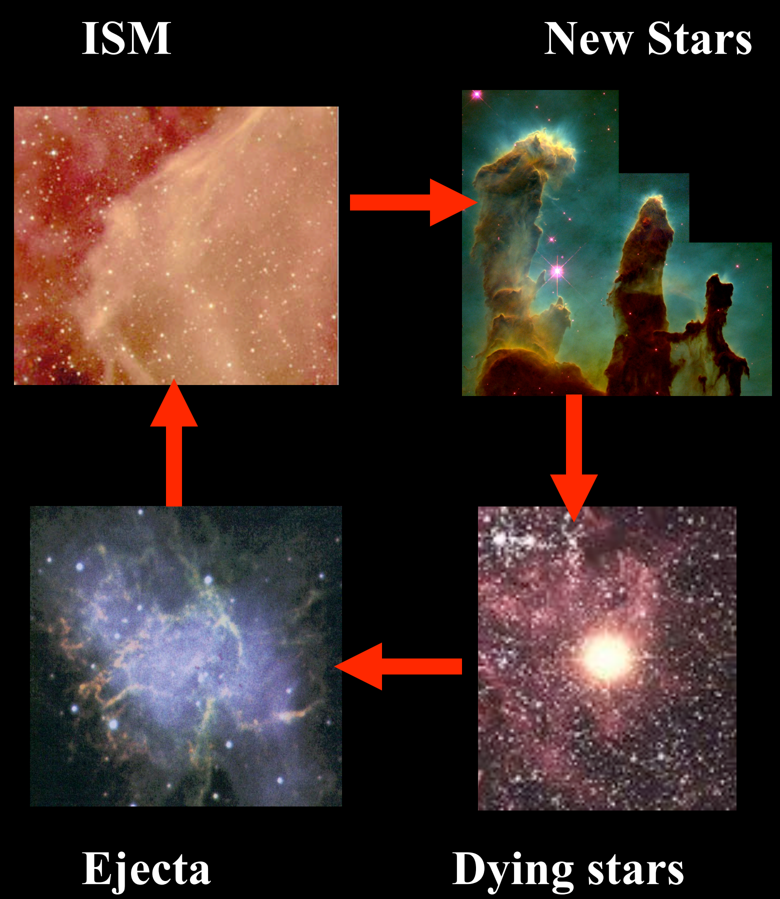
- Tinsley 1980, Fund. Of Cosmic Physics, 5, 287-388
- Binney & Tremaine 1987, Galactic Dynamics, Sections 9.2 & 9.3
- Binney & Merrifield 1998, Galactic Astronomy, Section 5.3
- Veilleux 2008, arXiv:0807.3904

Basics of Chemical Evolution

- *H and He were present very early on in the Universe, while all metals (except for a very small fraction of Li) were produced through nucleosynthesis in stars*
- *The fraction by mass of heavy elements is denoted by Z*
  - *The Sun's abundance* $Z_{sun} \sim 0.02$
  - *Most metal poor stars in the Milky Way have* $Z < 10^{-4} Z_{sun}$

Cycle of GAS and STARS in Galaxies

- *Gas is transformed into stars*
- *Each star burns H and He in its nucleus and produces heavy elements*
- *These elements are partially returned into the interstellar gas at the end of the star's life*
  - *Through winds and supernovae explosions*
  - *Some fraction of the metals are locked into the remnant of the star*



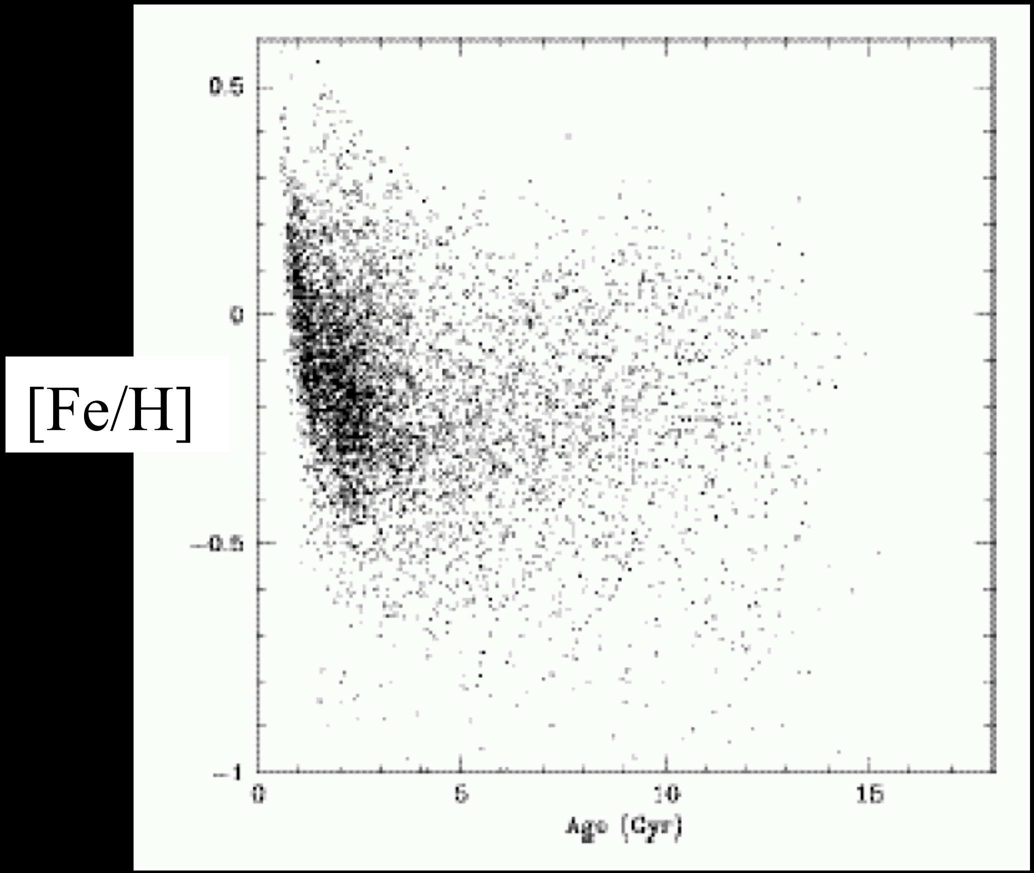
This implies that the chemical abundance of the gas in a star-forming galaxy should evolve with time

Chemical Evolution

- *The metal abundance of the gas, and of subsequent generations of stars, should increase with time*
  - *If there is no gas infall from the outside or selective loss of metals to the outside*
- *The evolution of chemical element abundances in a galaxy provides a clock for galactic aging*
- *Expect a relation between the ages and metal abundances of stars*
  - *On average, older stars contain less iron than younger stars*
  - *This is partially the case for the Solar neighborhood*

Chemical Evolution

- **Clear age-metallicity relation for nearby disk stars, but a lot of scatter for old ages**



(Nordstrom et al. 2005)

Simple Models

(e.g., Tinsley 1980, Fund. Of Cosmic Physics, 5, 287-388)

- *One-Zone, Closed Box*
  - *Galaxy's gas is well-mixed*
  - *No infall, no outflow*
  - $M_{tot} = M_{gas} + M_{star} \equiv M_g + M_s = M_{baryons}$ = *constant*
  - $M_h \equiv$ *mass of heavy elements in gas* $= Z_g M_g = Z M_g$
- *Instantaneous recycling approximation:*
  - *The (high-mass) stars return their nucleosynthetic products rapidly (much faster than the time to form a significant fraction of the stars)*
  - $dM_s' \equiv$ *total mass made into stars*
  - $dM_s'' \equiv$ *amount of mass instantaneously returned to ISM (from SNe, etc; enriched with metals)*
  - $dM_s \equiv dM_s' - dM_s''$ = *net matter turned into stars*
  - $y \equiv$ *yield of heavy elements (made instantaneously)*
  - *So* $y\, dM_s \equiv$ *mass of heavy elements returned to ISM*

Rough results for single generation

- *Only stars more massive than ~ 8 M_{sun} make heavies (SNe)*
- *dM_s" / dM_s ~ 0.20 = fraction of mass returned to ISM*
- *y ~ 0.01 (depends on stellar evolution and Initial Mass Function ≡ IMF)*
- *Z(shed gas) = (heavies shed) / (mass shed) = y dM_s / dM_s"*

  = 0.01/0.2 = 0.05

  (compared with Z_{sun} ~ 0.02)

One-zone, closed box model

- *Mass conservation implies:* $dM_g + dM_s = 0$ *(1)*
- *Net change in metal content of the gas:*
  - $dM_h = y\, dM_s - Z\, dM_s$
  - $dM_h = (y - Z)\, dM_s$ *(2)*
- *Change in* Z
  - *Since* $dM_g = -\, dM_s$ *and* $Z = M_h / M_g$
  - $dZ = dM_h / M_g - M_h\, dM_g / M_g^2$
    $= (y - Z) dM_s / M_g + (M_h/M_g)(dM_s/M_g) = y\, dM_s / M_g$
  - $dZ/dt = -\, y\, (dM_g/dt) / M_g$
- *Assuming* y *= constant (i.e. independent of time and Z):*

$$Z(t) = Z(0) - y \ln [\, M_g(t) / M_g(0)] = Z(0) - y \ln \mu(t)$$

where μ *= gas (mass) fraction* $\equiv M_g(t) / M_g(0) = M_g(t) / M_t$

- *The metallicity of the gas grows with time, as new stars are formed and the gas is consumed*

Metallicity Distribution of the Stars

- *The mass of the stars that have a metallicity less than $Z(t)$ is*

$$M_s[< Z(t)] = M_s(t) = M_g(0) - M_g(t)$$

or

$$M_s[< Z(t)] = M_g(0) * [1 - e^{-(Z(t)-Z(0))/y}]$$

- *When all the gas has been consumed, the mass of stars with metallicity Z, $Z + dZ$ is*

$$dM_s(Z) \propto e^{-(Z-Z(0))/y}\, dZ$$

Bulge of Milky Way

- **A closed box model reproduces well the metallicity distribution of stars in the bulge of our Galaxy**

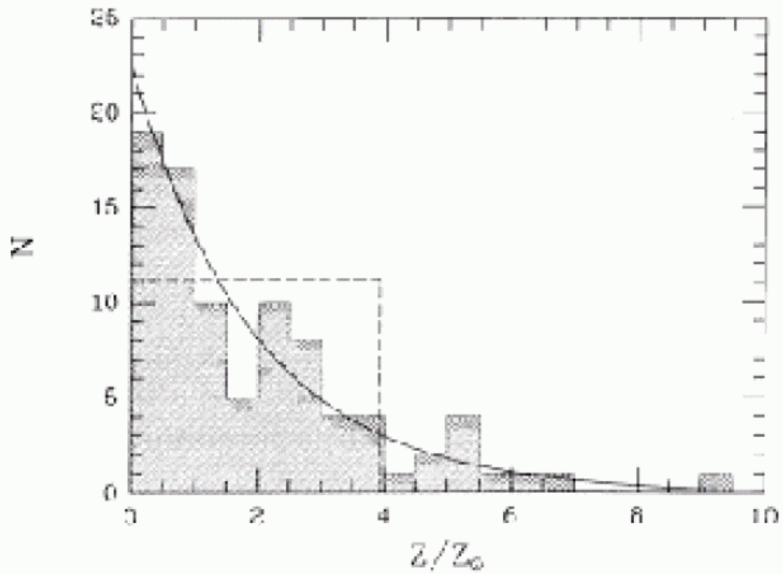


FIG. 8.—Differential abundance distribution of bulge giants compared to two limiting cases of the simple model of chemical evolation. *Solid line*: simple "closed box" model with complete gas consumption; $\langle z \rangle = 2.0z/z_{\odot}$. *Dashed line*: Simple model, in the limiting case where a small fraction of the initial volume of gas is converted to stars, the remainder being lost from the system.

(Rich 1990)

Disk of Milky Way

- *We derive the yield y from observations*

$$Z(today) \sim Z(0) - y \ln [M_g(today) / M_g(0)]$$

- *The average metal content of the gas in the disk near the Sun is $Z \sim 0.7\ Z_{sun}$*
- *The initial mass of gas $M_g(0) = M_s(today) + M_g(today)$ where $M_s(today) \sim 40\ M_{sun}/pc^2$ and $M_g(today) \sim 10\ M_{sun}/pc^2$*
- *Assuming that $Z(0) = 0$, we derive $y \sim 0.43\ Z_{sun}$*

Expected number of metal-poor stars

- *Compute the mass in stars with $Z < 0.25\, Z_{sun}$ compared to the mass in stars with the current metallicity of the gas:*

$$M_s(< 0.25\, Z_{sun}) / M_s(< 0.7\, Z_{sun}) = [1 - e^{-0.25\, Z_{sun}/y}]/[1 - e^{-0.7\, Z_{sun}/y}]$$
$$\sim 0.54$$

- *Half of all stars in the disk near the Sun should have $Z < 0.25\, Z_{sun}$*
- *However, only 2% of the F-G (old) dwarf stars in the solar neighborhood have such metallicity*
- *This discrepancy is known as the "G-dwarf problem"*

- *Possible solutions:*
  1. *Pre-enrichment in the gas: $Z(0) \sim 0.15\, Z_{sun}$*
  2. *Outflow (leaky-box model)*
  3. *Infall (accreting-box model)*

Leaky-Box Model

- *If there is an outflow of processed material, g(t), the conservation of mass (Eq. 1) becomes*

$$dM_g/dt + dM_s/dt + g(t) = 0$$

- *And the rate of change in the metal content of the gas mass (Eq. 2) now becomes*

$$dM_h/dt = y\, dM_s/dt - Z\, dM_s/dt - Zg$$

- *Example: Assume that the rate at which the gas flows out of the box is proportional to the star formation rate:*
  - $g(t) = c\, dM_s/dt$ (c is a constant; c = 0.01 - 5)
  - As before $dZ/dt = y/M_g(t) * dM_s/dt$
  - Where $dM_s/dt = -1/(1+c)\, dM_g/dt$
  - So $dZ/dt = -y/(1+c) * 1/M_g * dM_g/dt$
  - Integrating this equation, we get $Z(t) = Z(0) - y/(1+c) * \ln[M_g(t)/M_g(0)]$
  - The only effect of an outflow is to reduce the yield to an effective yield = $y/(1+c)$

Accreting-Box Model

- *Example: Accretion of pristine (metal-free) gas to the box*
- *Since the gas accreted is pristine, Eq (2) is still valid: the mass of heavy elements produced in a SF episode is*

  $dM_h/dt = (y - Z)\, dM_s / dt$
- *However, Eq. (1) for the conservation of mass in the box becomes:*

  $dM_g/dt = - dM_s/dt + f(t)$
- *Consider the simple case in which the mass in gas in the box is constant. This implies then*

  $dZ/dt = 1/M_g * [(y - Z)\, dM_s/dt - Z\, dM_g/dt] = 1/M_g * [(y - Z)\, dM_s/dt]$

Accreting-Box Model

- *Integrating and assuming that* $Z(0) = 0$

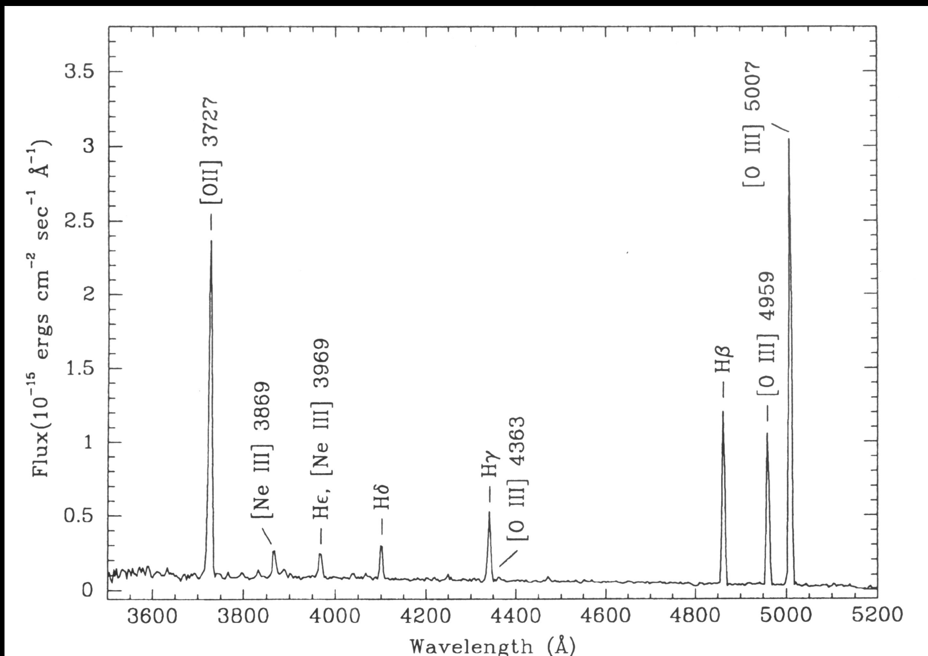
  $Z = y\,[1 - e^{-M_s/M_g}]$

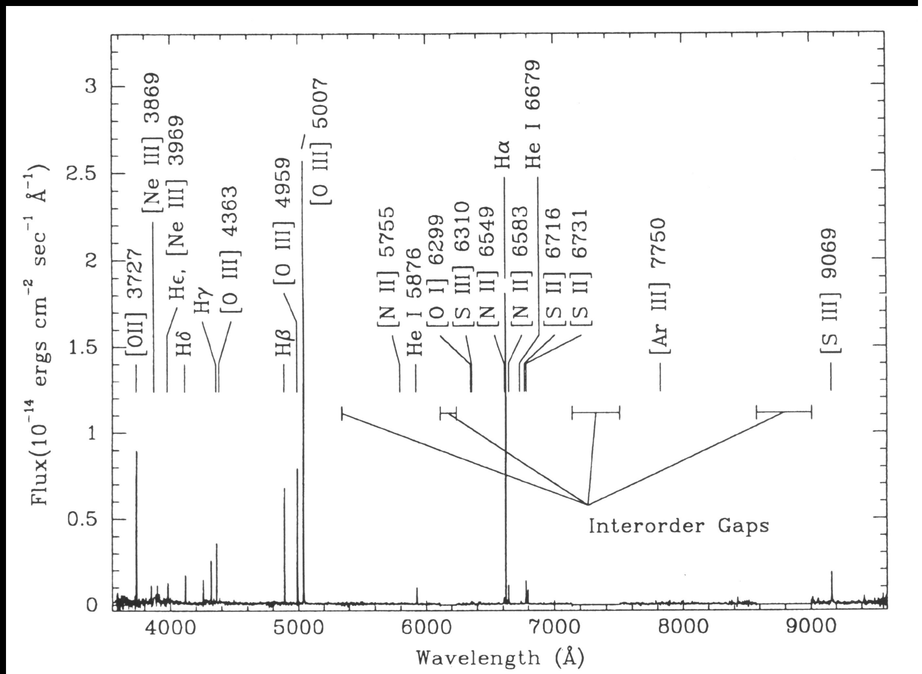
- *Therefore when* $M_s \gg M_g$*, the metallicity* $Z \sim y$
- *The mass in stars that are more metal-poor than* Z *is*

  $M_s(< Z) = -M_g \ln(1 - Z/y)$

- *In this case, for* $M_g \sim 10\ M_{sun}/pc^2$ *and* $M_s \sim 40\ M_{sun}/pc^2$*, and for* $Z = 0.7\ Z_{sun}$*, then* $y \sim 0.71\ Z_{sun}$*. Thus the fraction of stars more metal-poor than 0.25* Z_{sun} *is* $M(<0.25)/M(<0.7) \sim 10\%$*, in much better agreement with the observations of the solar neighborhood*

Measurements of Oxygen Abundance in Gas Phase

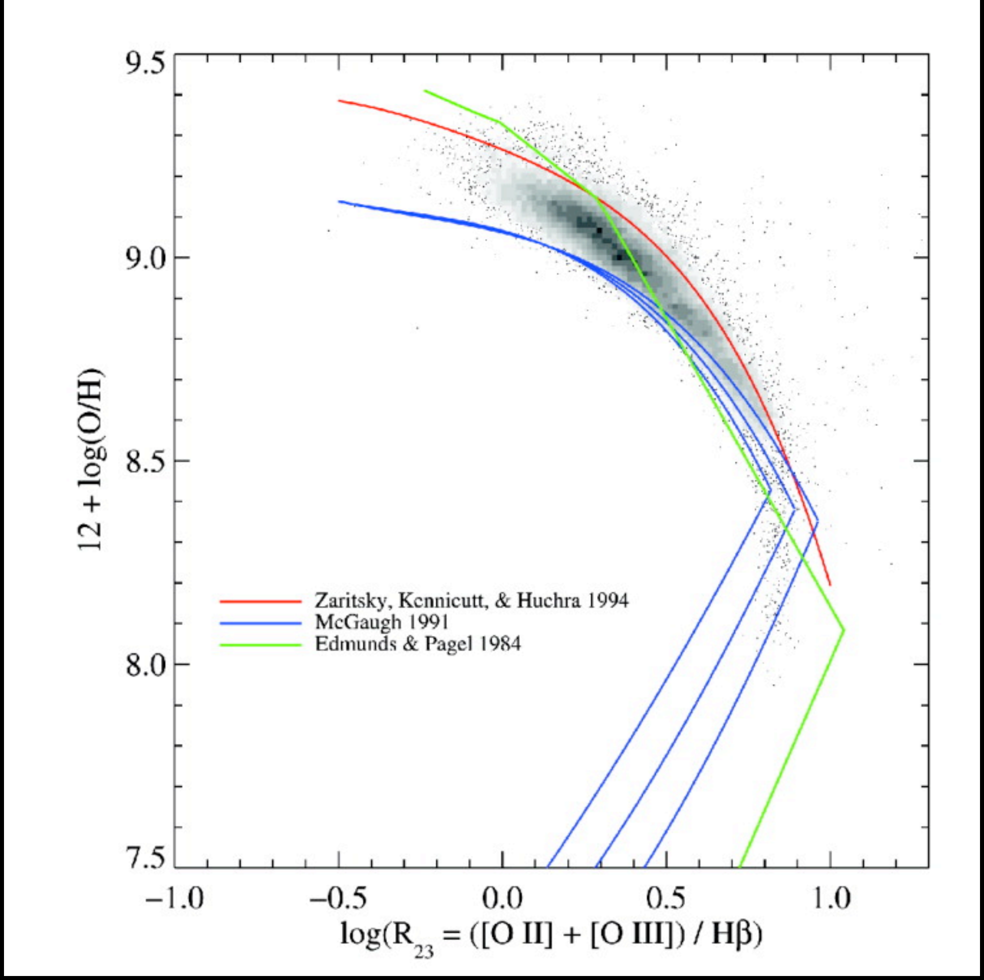




$$O/H = O^{o}/H + O^{+}/H + O^{++}/H + \ldots$$

Measurements of Oxygen Abundance in Gas Phase

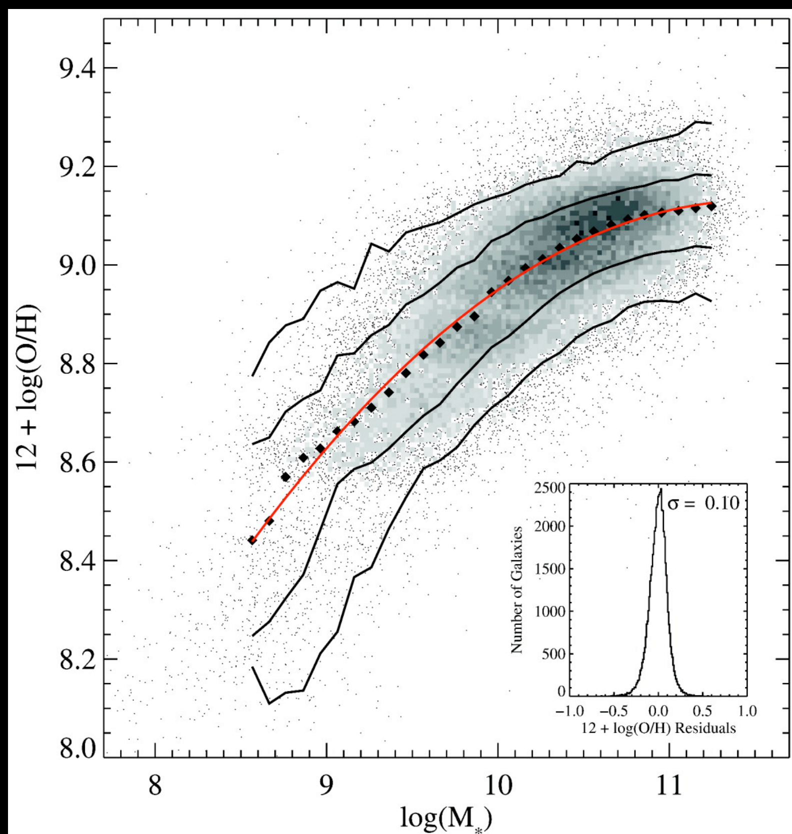
(strong line method)

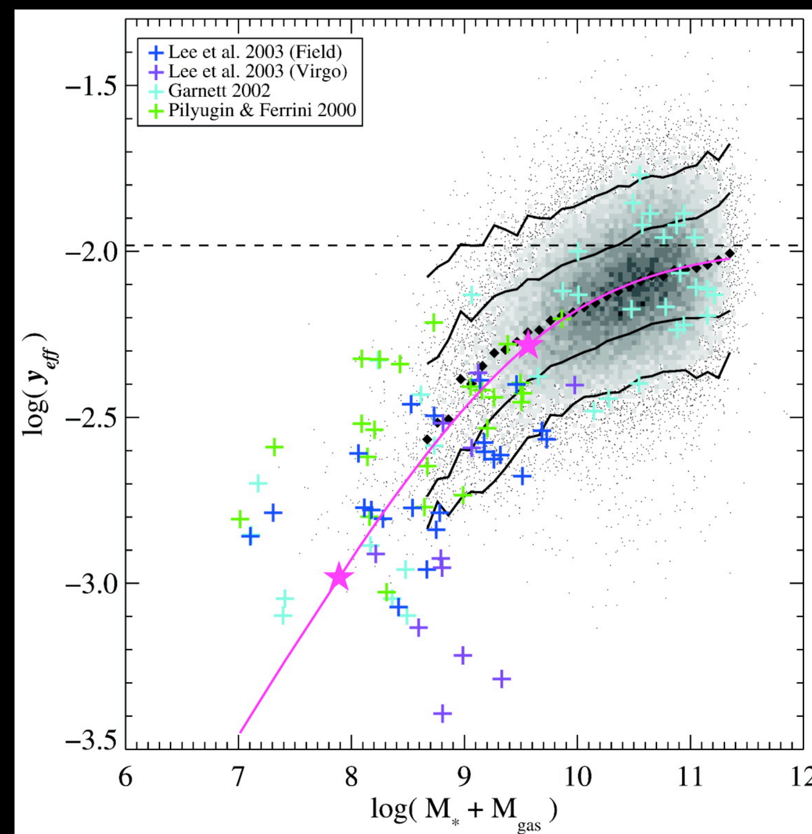


(Tremonti+04)

Local Star-Forming Galaxies

- **Mass-metallicity relation of galaxies favors leaky-box models:**
  → $y_{eff} = 1/(1+c)\,y$ → winds are more efficient at removing metals from shallower galaxy potential wells ($V_{rot} < 150$ km s^{-1})

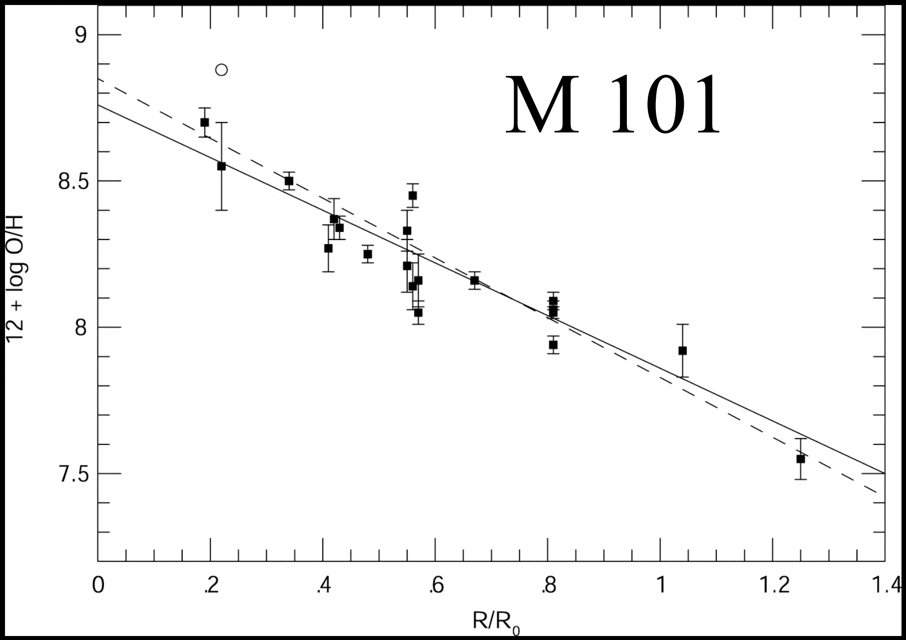




(e.g., Garnett+02; Tremonti+04; Kauffmann+03)

Local Star-forming Galaxies

- **Metallicity-radius relation of galaxies favors leaky-box models on a *local* scale**

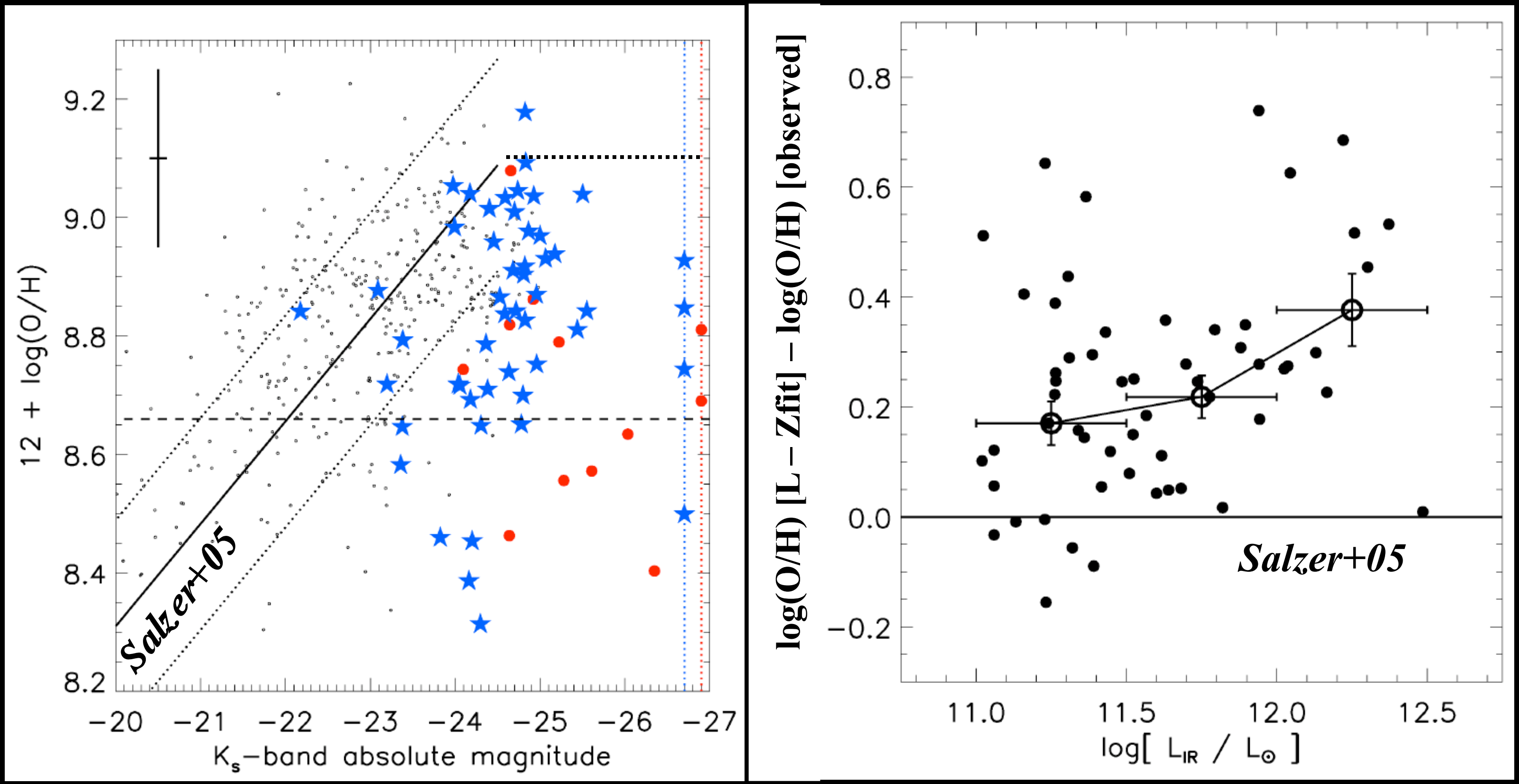


(Kennicutt+03; see also Zaritsky+94)

Local Powerful Starbursts

(Rupke, SV, & Baker 2008)

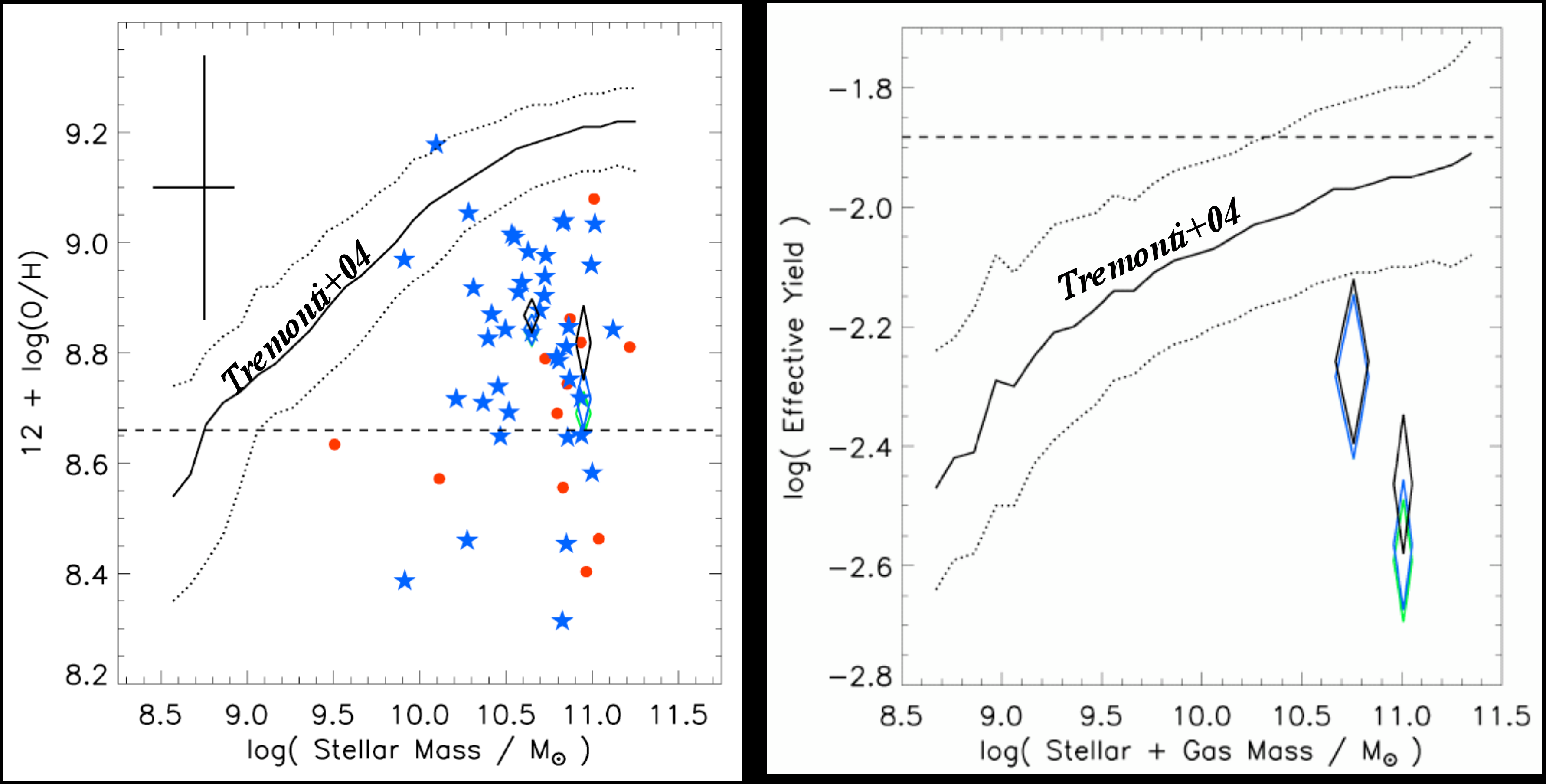
- Local U/LIRGs lie below the local *[O/H]* - L_{Host} relation
- The effect increases with increasing L_{IR} (~ starburst strength)
- "Dilution" by merger-induced gas inflows *(e.g., Iono+04; Naab+06)*



Local Powerful Starbursts

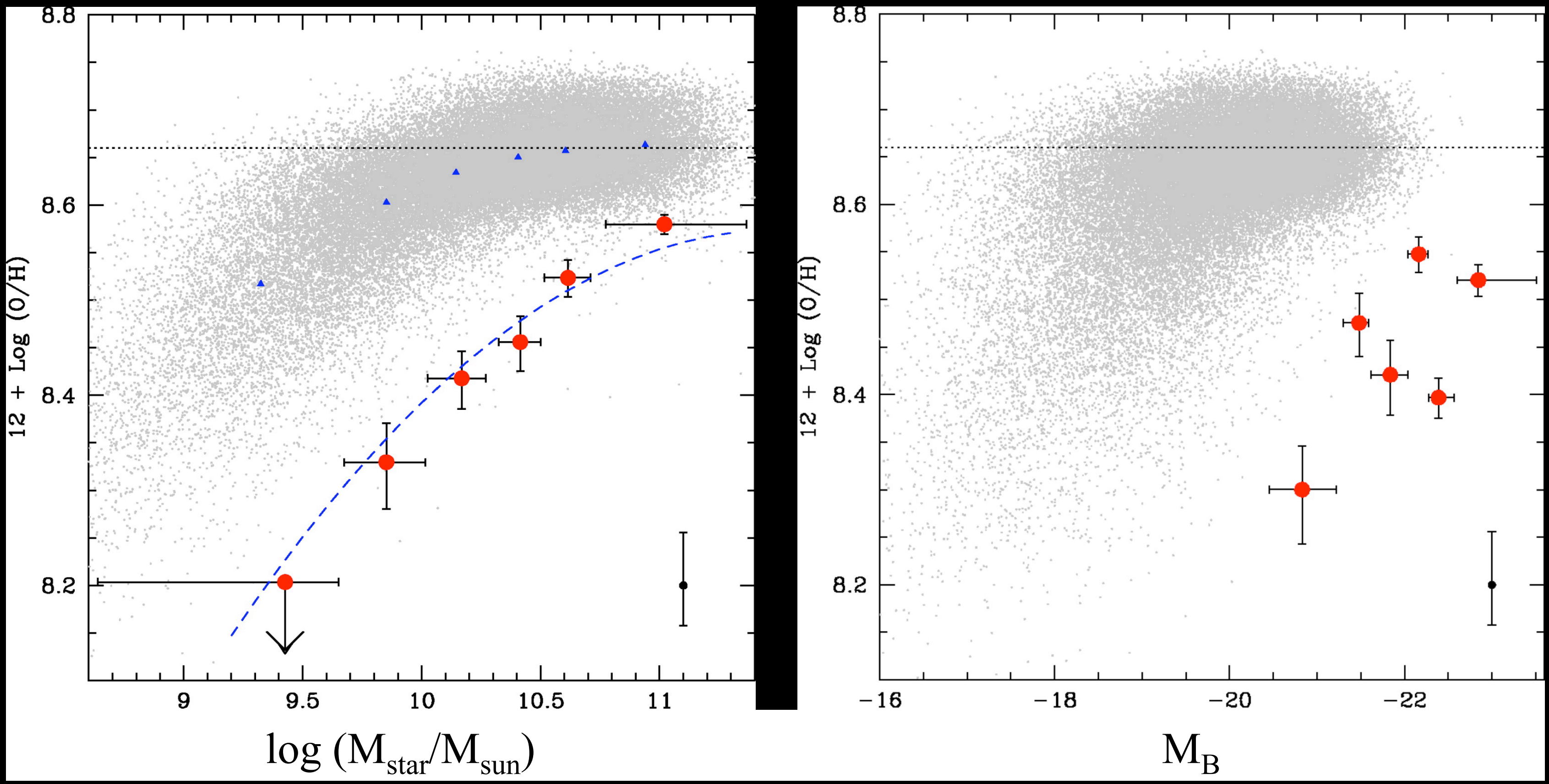
(Rupke, SV, & Baker 2008)

- **Merger-induced gas inflow lowers *[O/H]* and effective yield of local U/LIRGs below the SDSS values**



Distant Star-Forming Galaxies

- Mass-metallicity relation of high-z galaxies fall below that of local galaxies → Evolution???

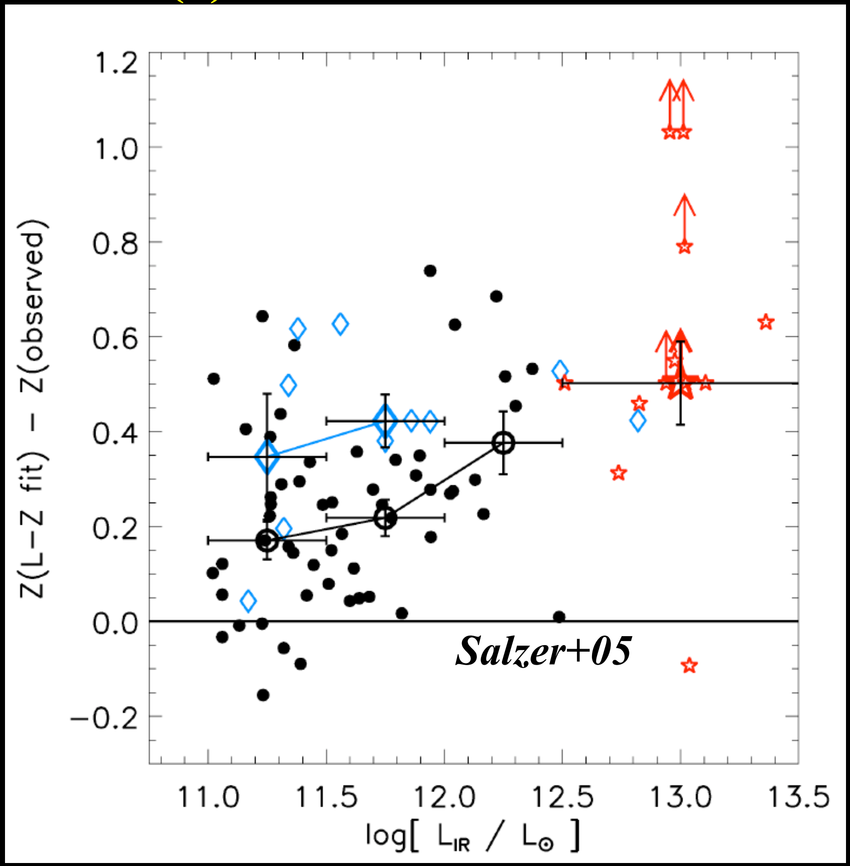


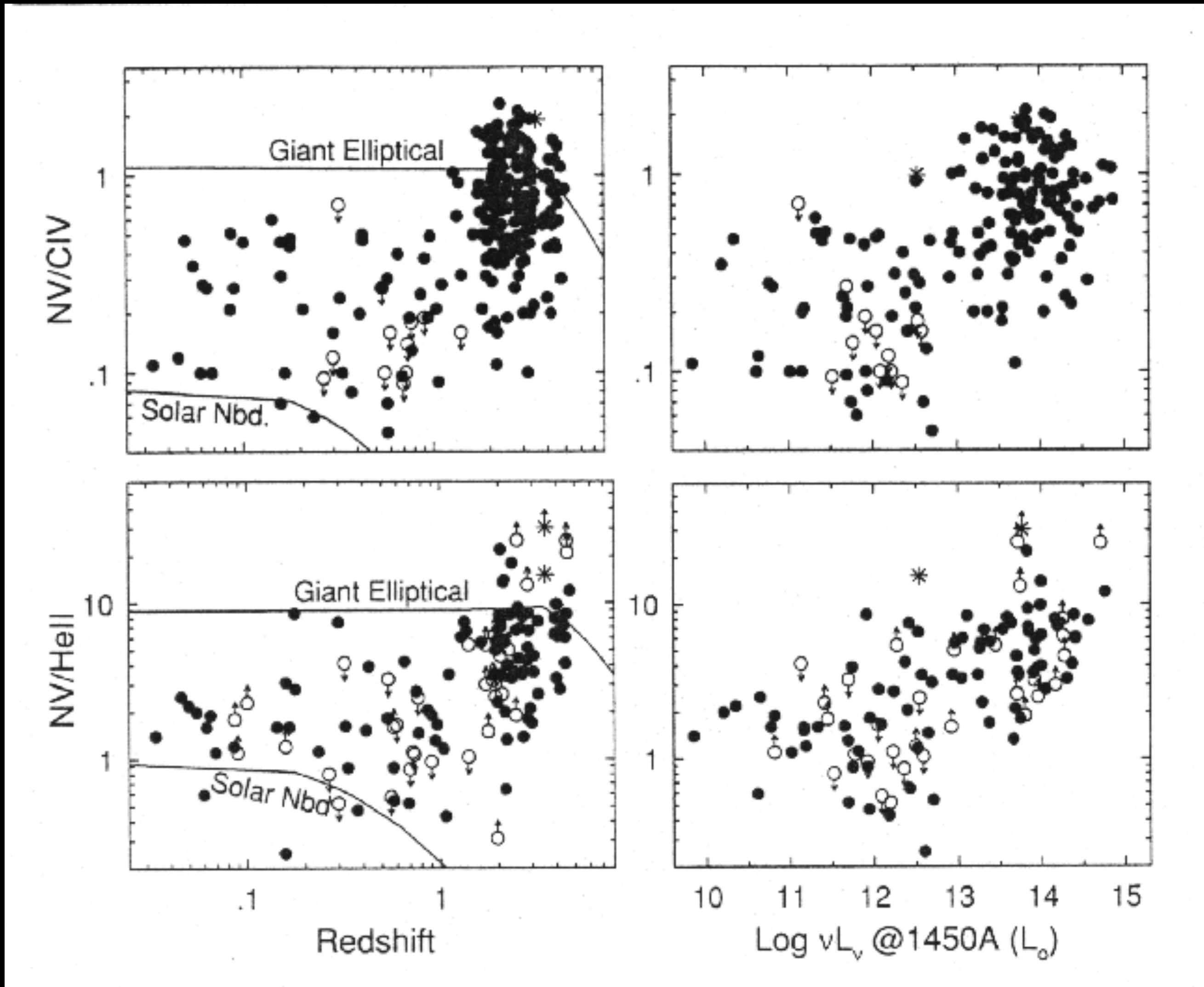
(Erb et al. 2006)

Metallicity Evolution in Powerful Starbursts

(Rupke, SV, & Baker 2008)

- *[O/H]* in LIRGs increases by ~0.2 dex from *z* ~ 0.6 to *z* ~ 0.1
- Modest if any evolution from *z* ~ 2 SMGs to *z* ~ 0.5 ULIRGs to *z* ~ 0.1 ULIRGs (?)

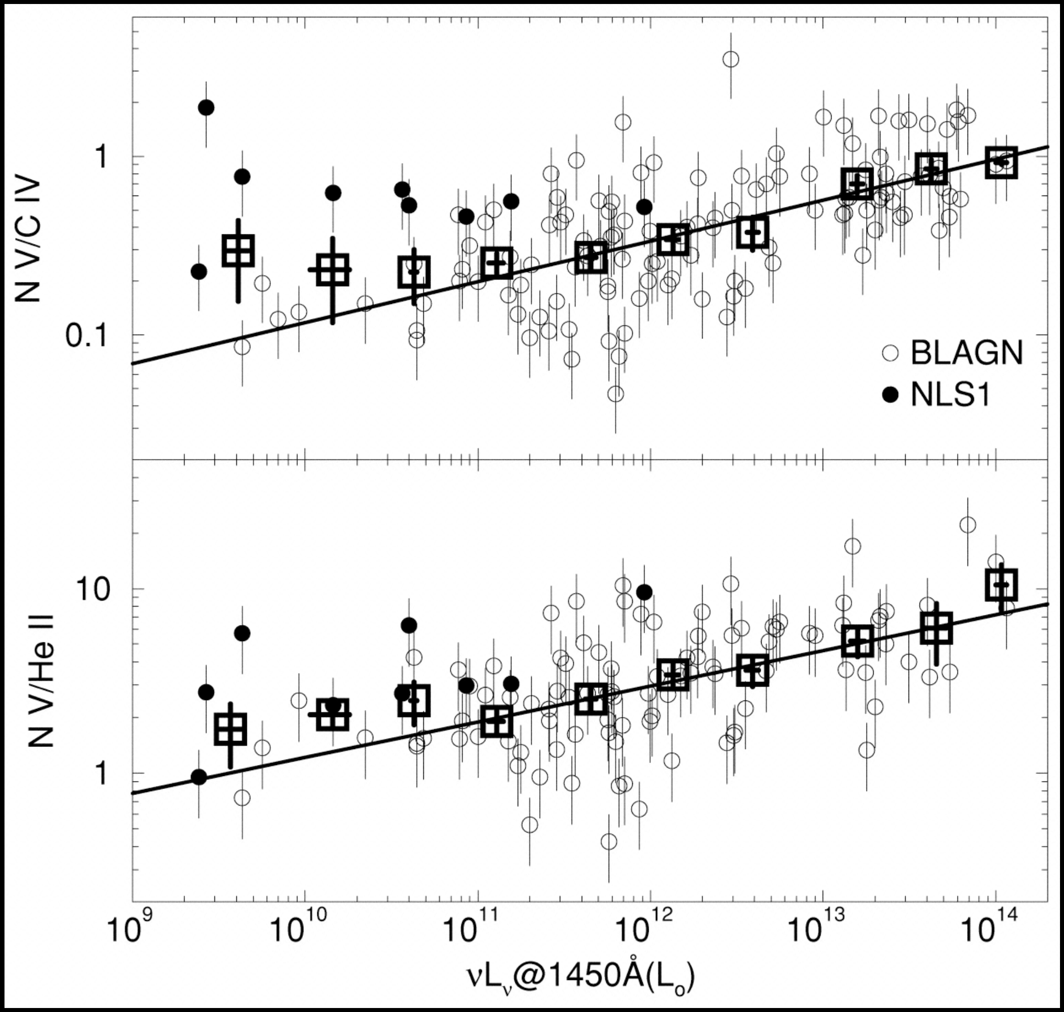




Metallicity in QSOs

(Hamann & Ferland 1999)

- **Apparent metallicity-luminosity trend in QSOs**
  - → **Mass-metallicity correlation among their host galaxies** ???



Metallicity in NLS1s

(Shemmer & Netzer 2002)

- **Apparent metallicity-luminosity trend in AGNs**
  - → **Mass-accretion rate relation**???

Summary

- *Simple closed-box model works well for bulge of Milky Way*
- *Outflow and/or accretion is needed to explain*
  - *Metallicity distribution of stars in Milky Way disk*
  - *Mass-metallicity relation of local star-forming galaxies*
  - *Metallicity-radius relation in disk galaxies*
  - *Merger-induced starburst galaxies*
  - *Mass-metallicity relation in distant star-forming galaxies*
  - *Distant quasars*