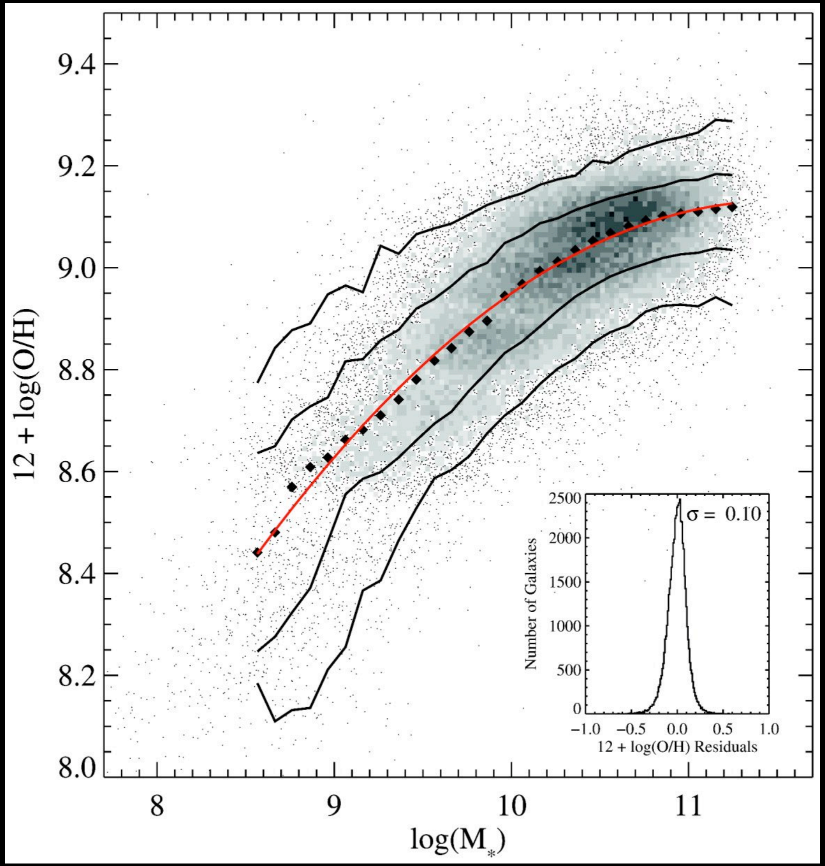
Lecture #4: Elemental Abundances as Tracers of Star Formation

S. Veilleux (U. Maryland)



(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

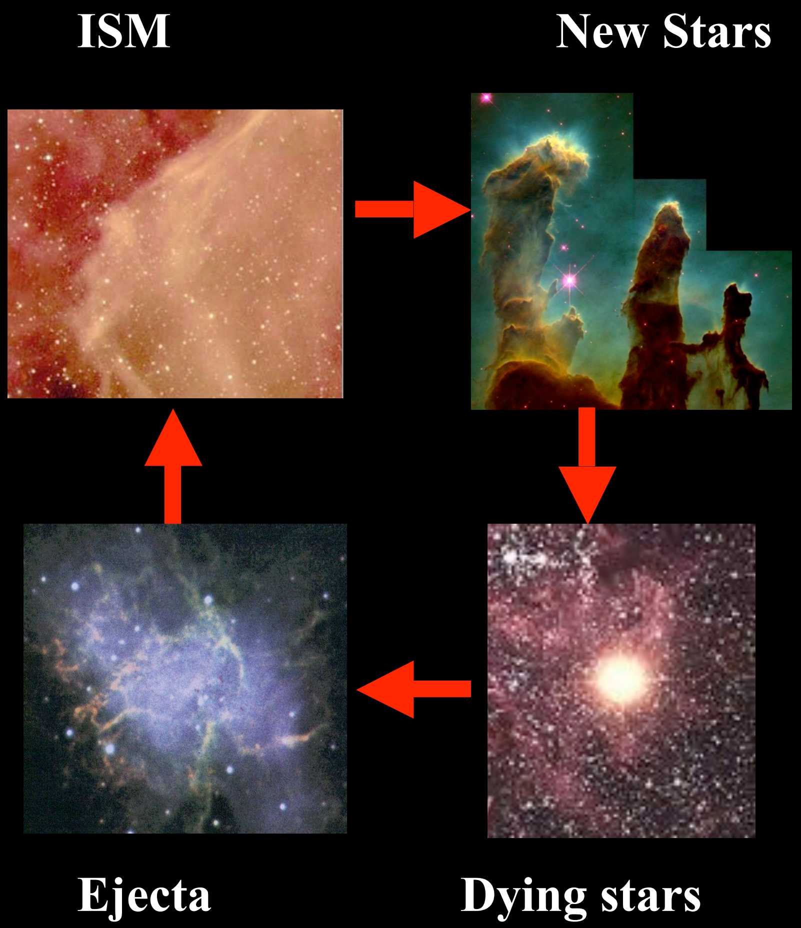
- Tinsley 1980, Fund. Of Cosmic Physics, 5, 287-388
- Binney & Tremaine 1987, Galactic Dynamics, Sections 9.2 & 9.3
- Binney & Merrifield 1998, Galactic Astronomy, Section 5.3

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



ISM

New Stars

Dying stars

Ejecta

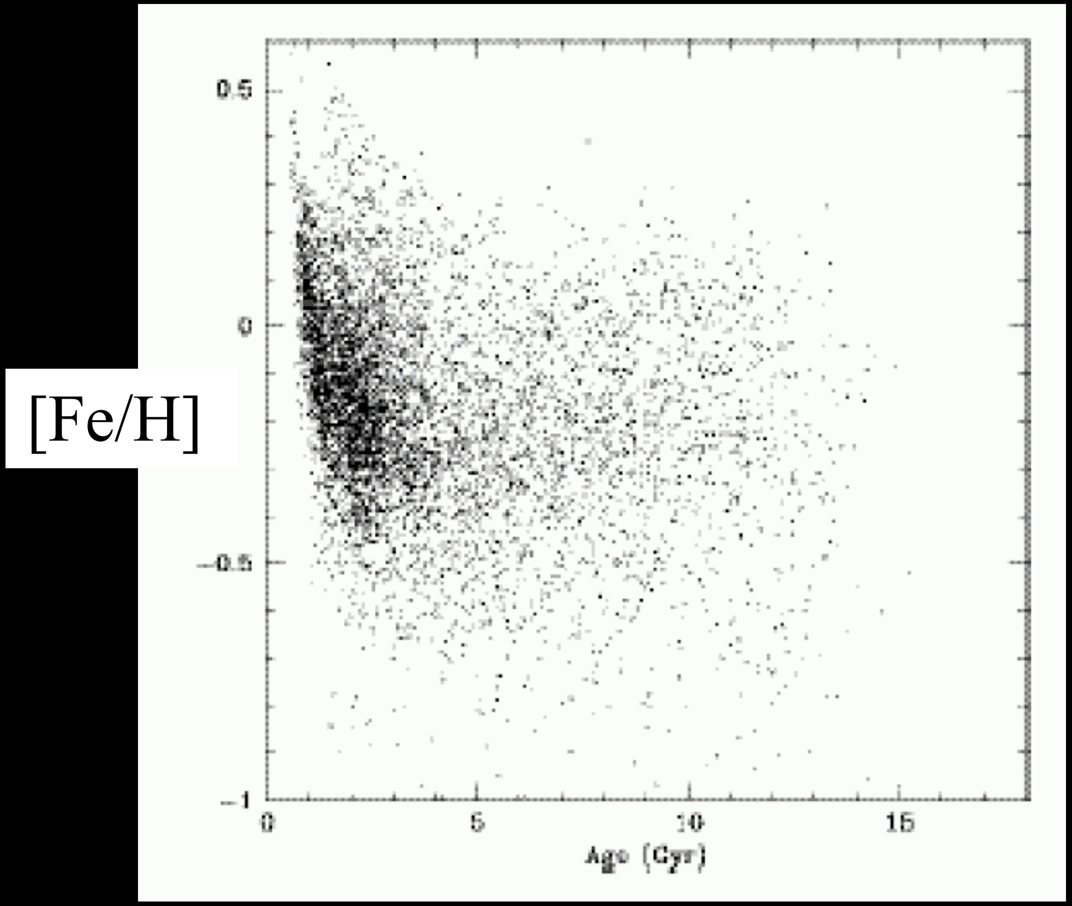
This implies that the chemical abundance of the gas in a star-forming galaxy should evolve with time

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

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)
- $dM_s'' / dM_s \sim 0.20$ = fraction of mass returned to ISM
- $y \sim 0.01$ (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 $Z_{sun} \sim 0.02$)

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):

$$\boxed{\begin{aligned} Z(t) &= Z(0) - y \ln [\, M_g(t) / M_g(0)] \\ &= Z(0) - y \ln \mu(t) \end{aligned}}$$

where μ = gas (mass) fraction ≡ $M_g(t) / M_g(0) = M_g(t) / M_t$

- 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**

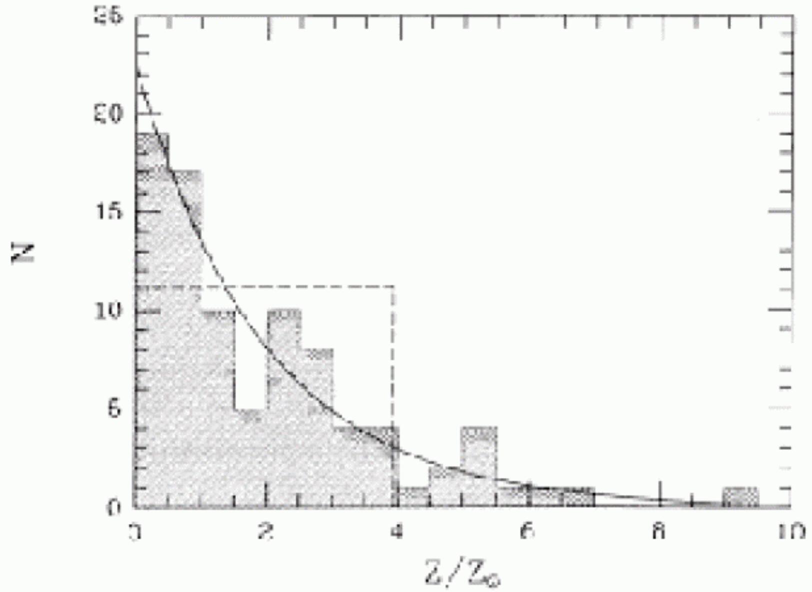


FIG. 8.—Differential abundance distribution of bulge giants compared to two limiting cases of the simple model of chemical evolation. *Solid line:* simple "closed box" model with complete gas consumption; $\langle z \rangle = 2.0 z_\odot$. *Dashed line:* Simple model, in the limiting case where a small 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

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

- 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 $M_g(0) = M_s(\mathrm{today}) + M_g(\mathrm{today})$ where $M_s(\mathrm{today}) \sim 40\ M_{sun}/\mathrm{pc}^2$ and $M_g(\mathrm{today}) \sim 10\ M_{sun}/\mathrm{pc}^2$
- 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 (Lecture #3)

- 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; Lecture #3: 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 $\boxed{Z(t) = Z(0) - y /(1+c) * \ln[M_g(t) /M_g(0)]}$
  - 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 $Z(0) = 0$

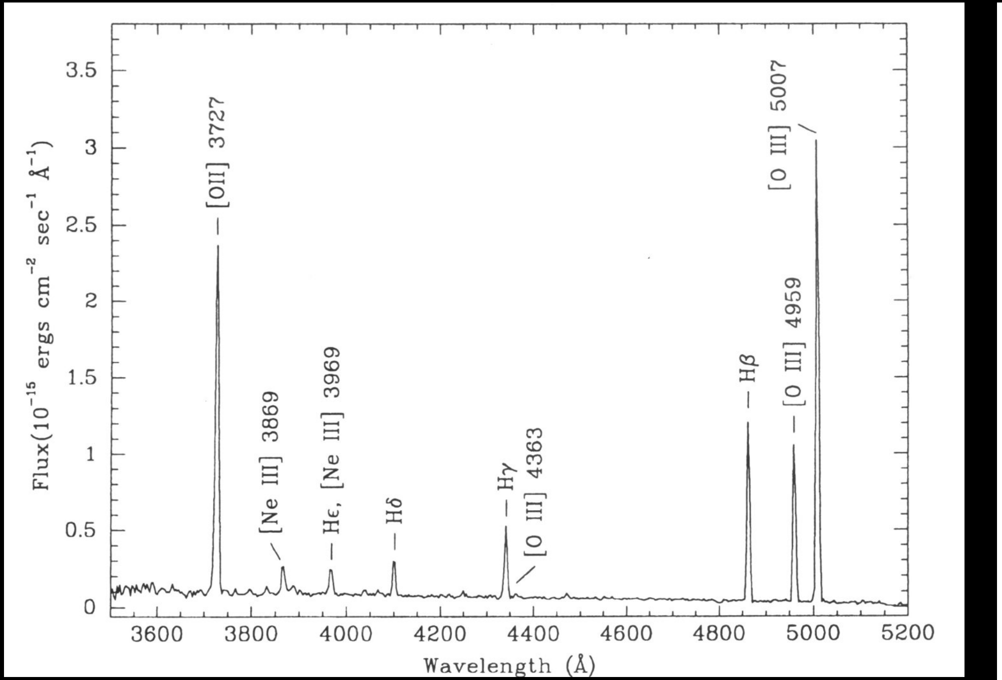
  $$Z = y\,[1 - e^{-M_s/M_g}]$$

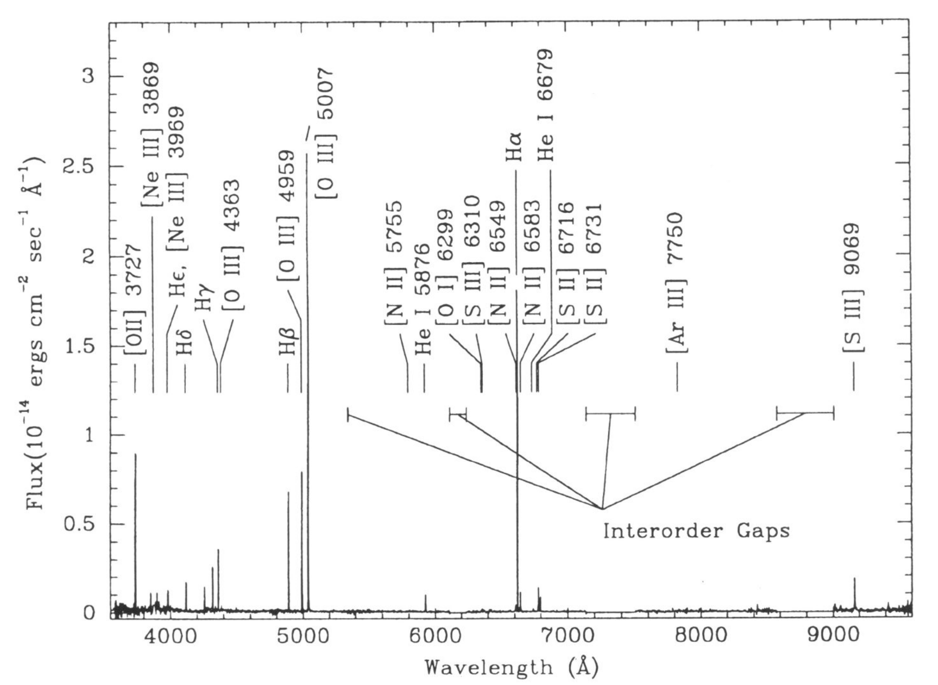
- Therefore when $M_s >> M_g$, the metallicity $Z \sim y$
- The mass in stars that are more metal-poor than Z is

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

- 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

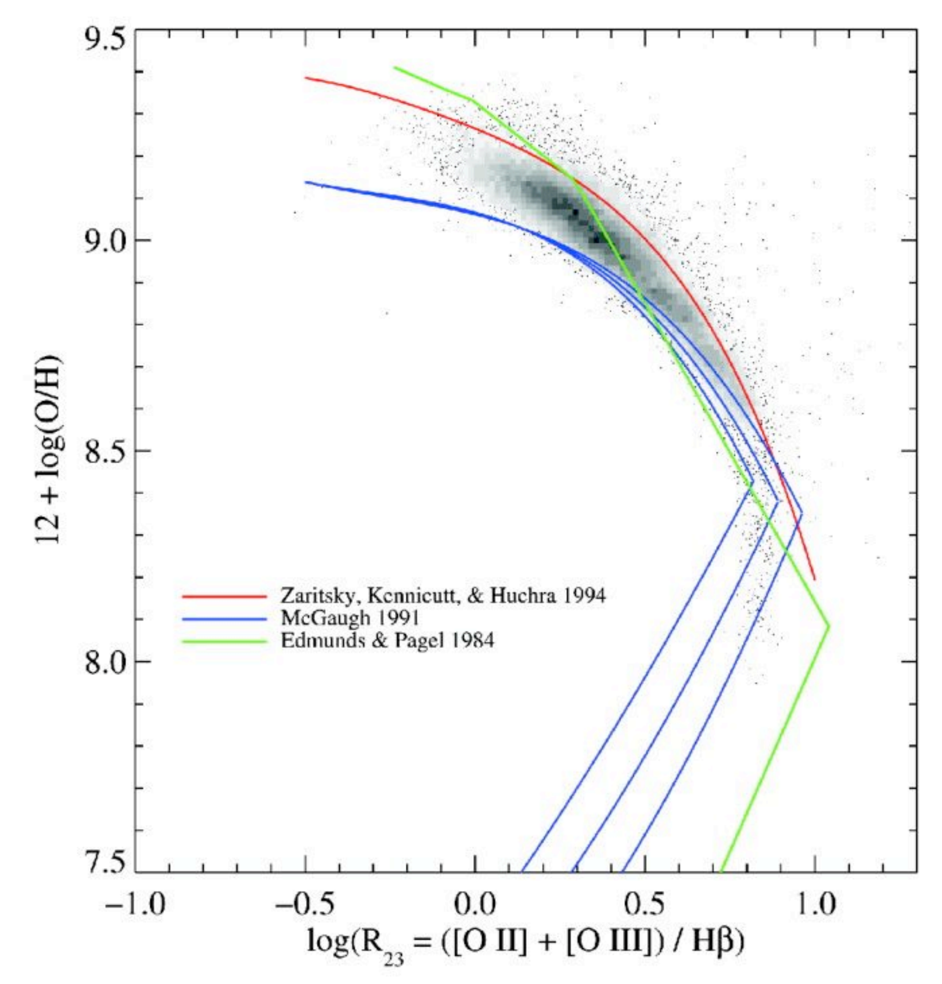




$$O/H = O^{o}/H + O^{+}/H + O^{++}/H + \ldots$$

Measurements of Oxygen Abundance in Gas Phase

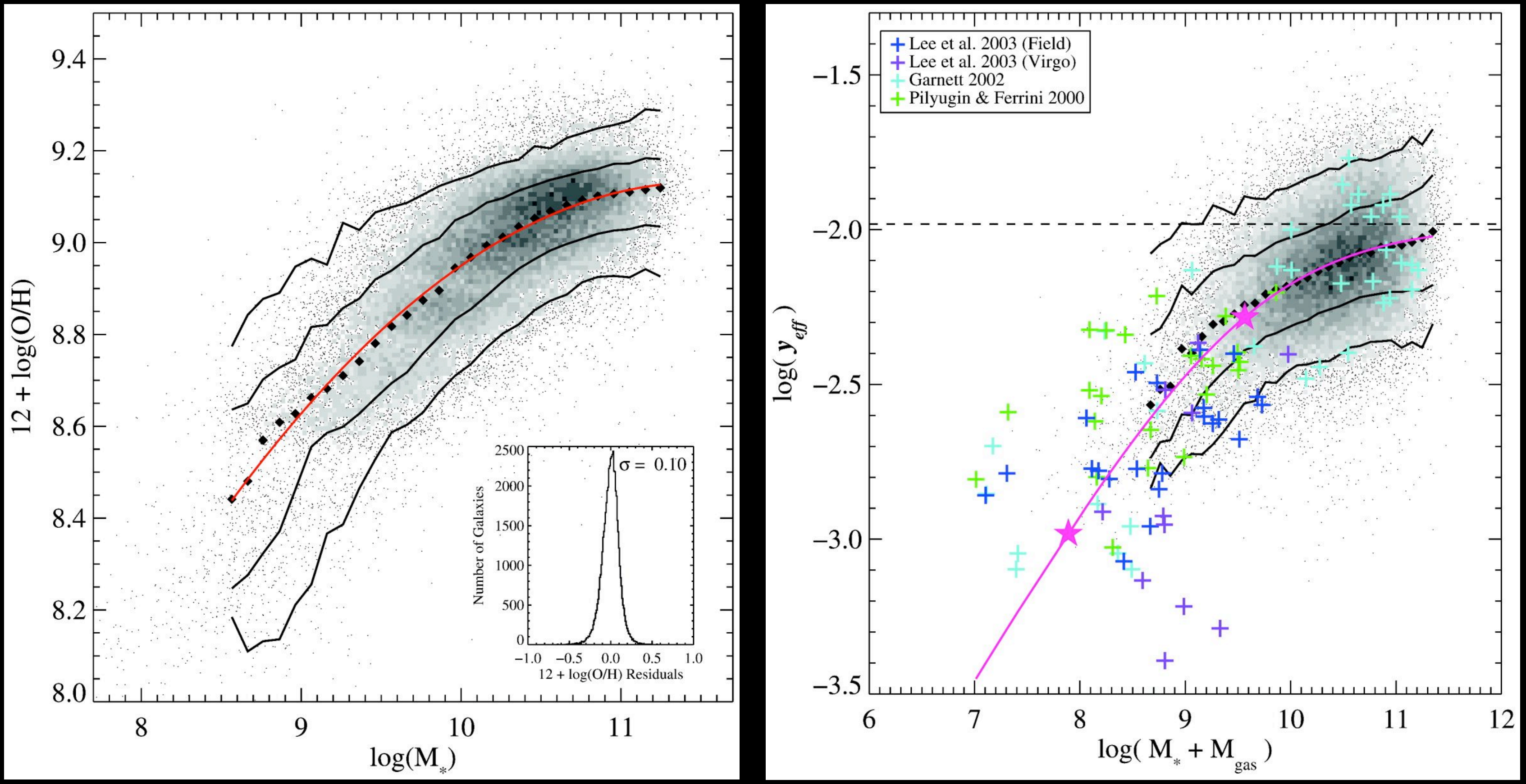
(strong line method)



(Tremonti+04)

Local Star-Forming Galaxies

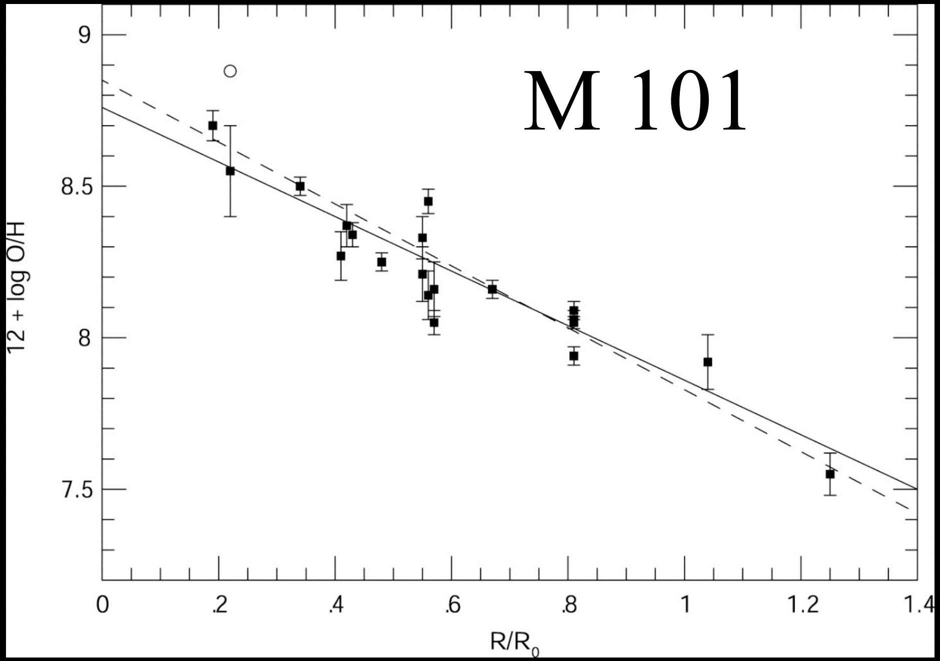
- Mass-metallicity relation of galaxies favors leaky-box models: → $y_{eff} = 1/(1+c)\ y$ → winds are more efficient at removing metals from shallower galaxy potential wells ($V_{rot} < 150$ km s^{-1})



(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**

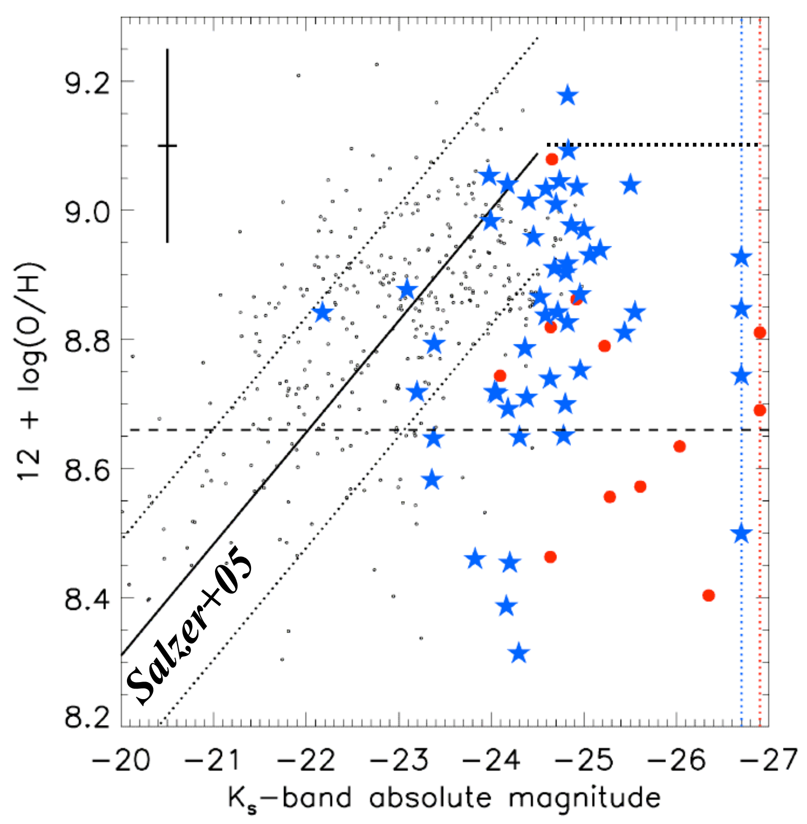


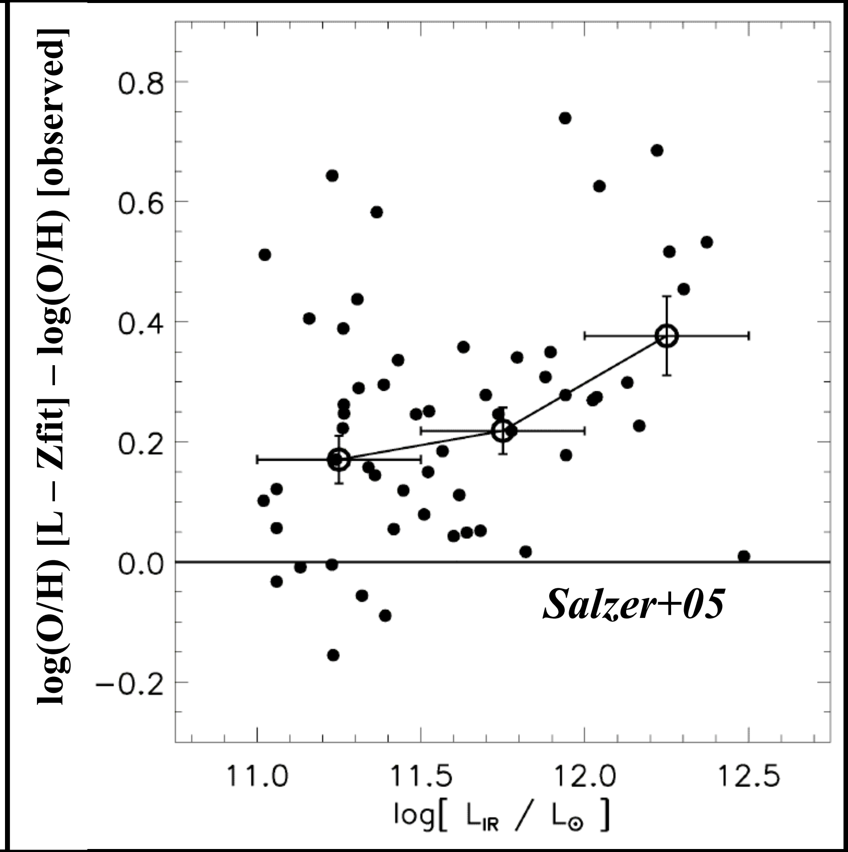
(Kennicutt+03; see also Zaritsky+94)

Local Powerful Starbursts

(Rupke, SV, & Baker 2007, astro-ph/0708.1766)

- **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)***

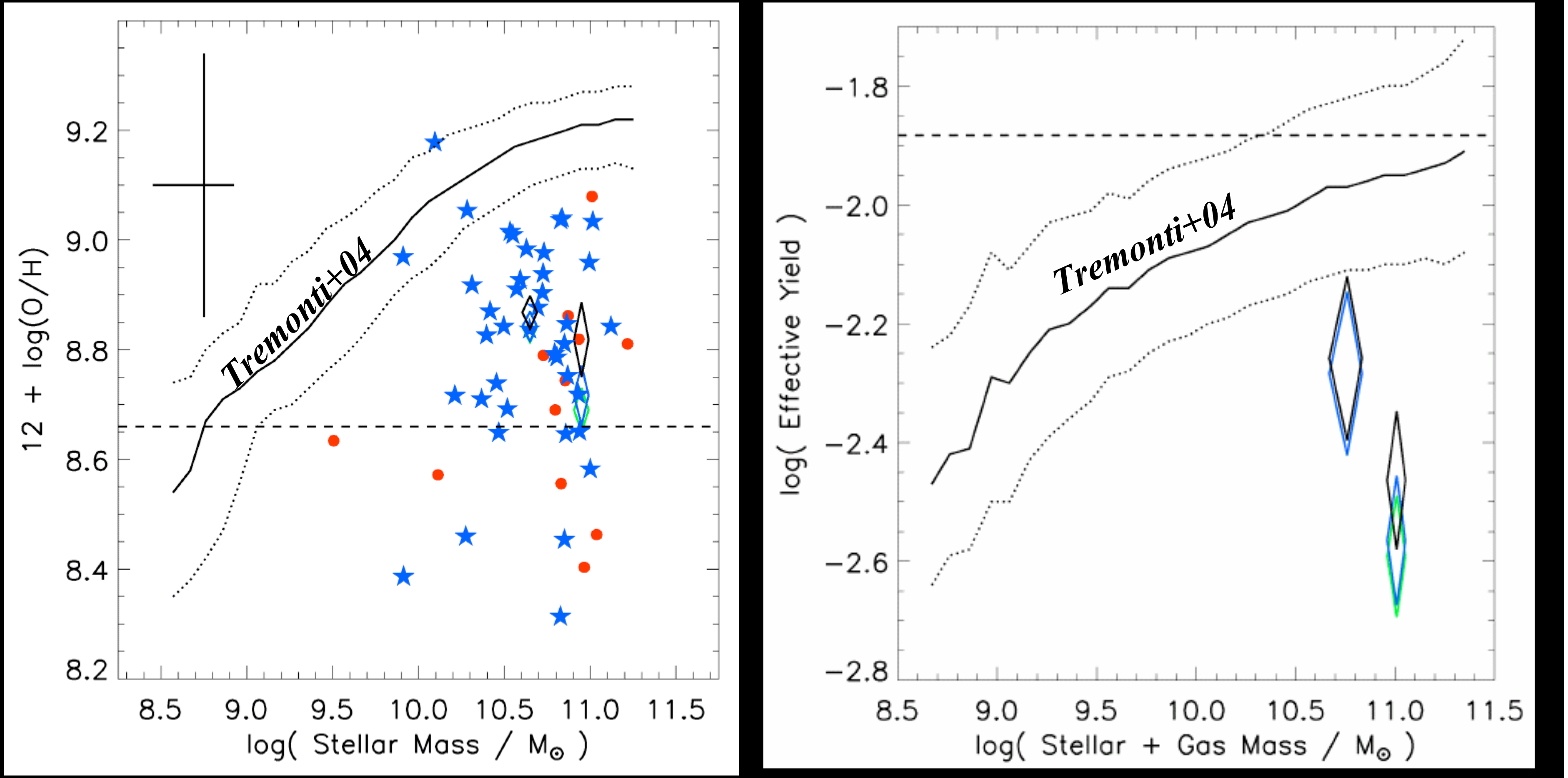




Local Powerful Starbursts

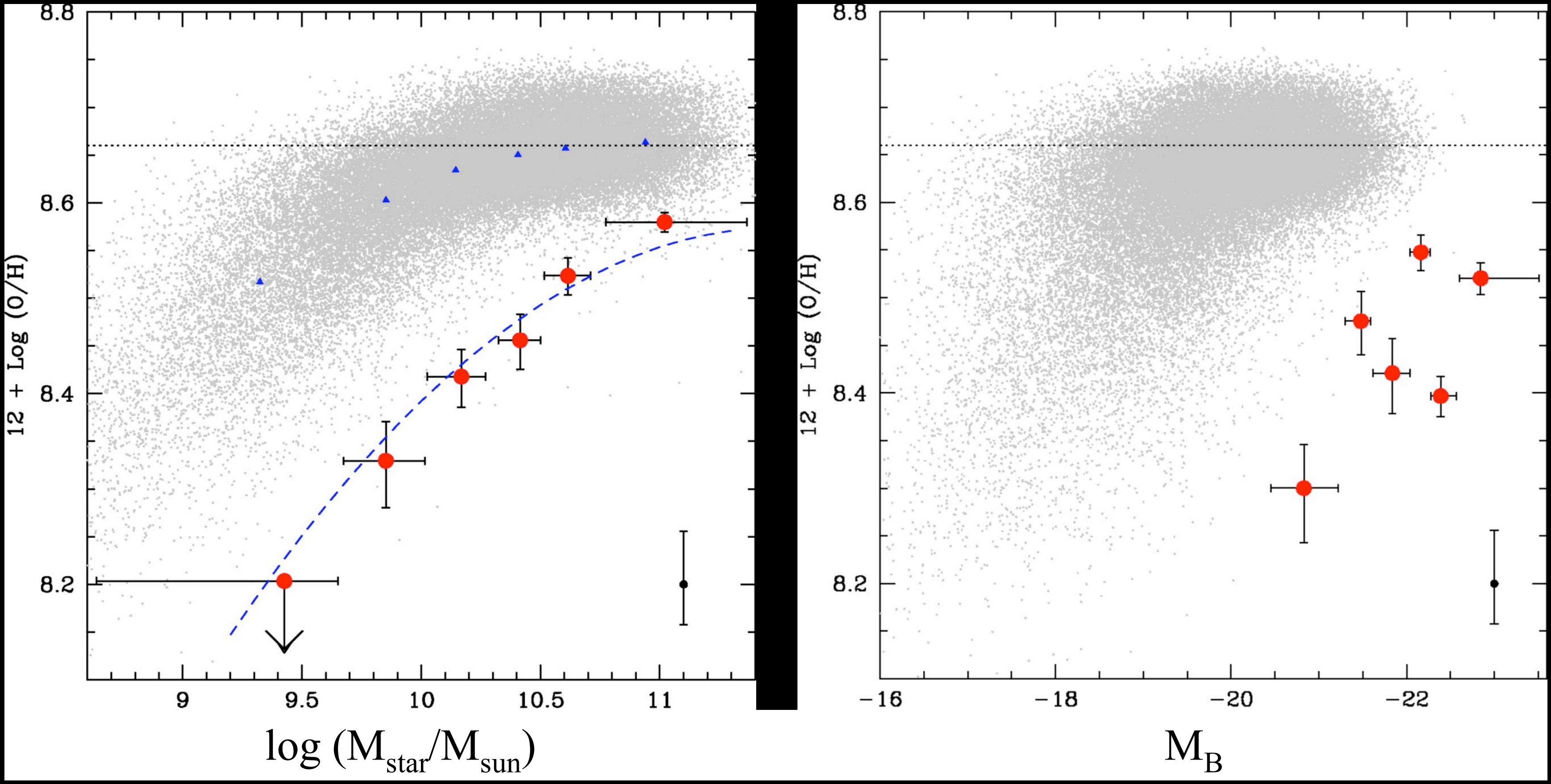
(Rupke, SV, & Baker 2007, astro-ph/0708.1766)

- **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???

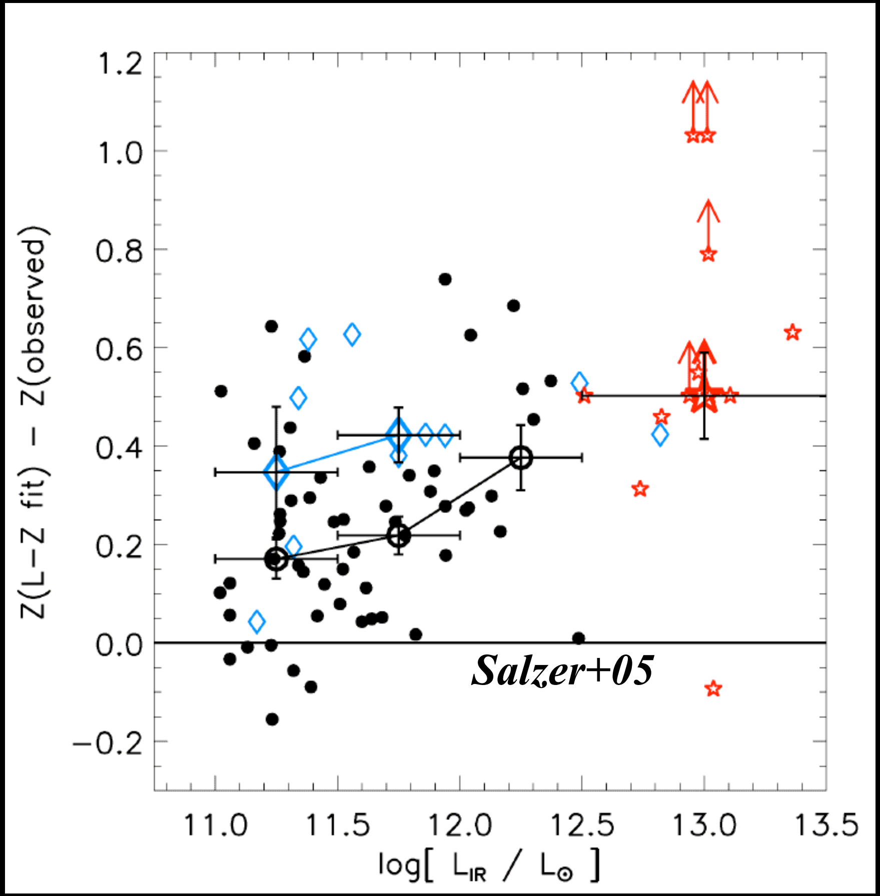


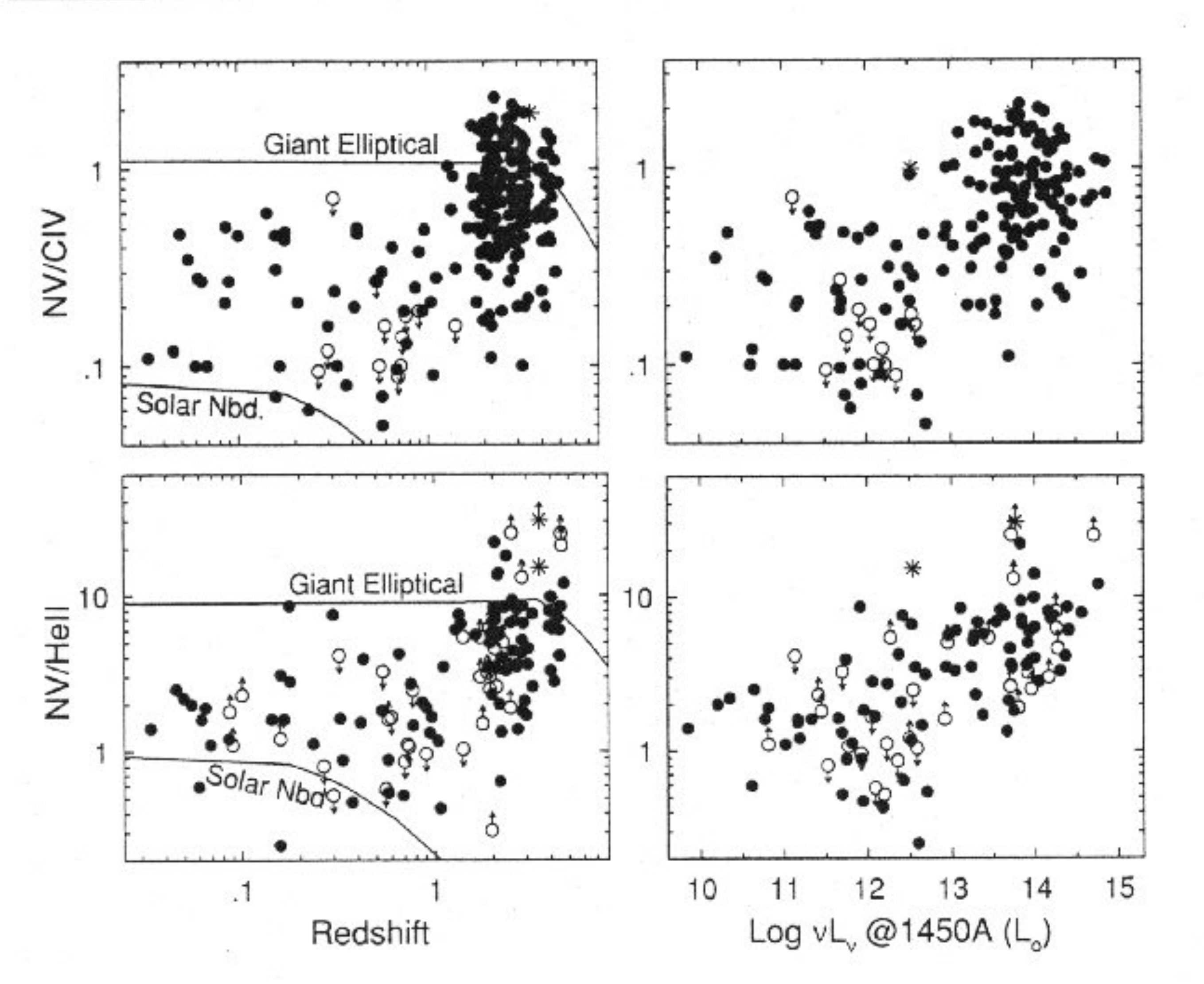
(Erb et al. 2006)

Metallicity Evolution in Powerful Starbursts

(Rupke, SV, & Baker 2007, astro-ph/0708.1766)

- *[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 (?)



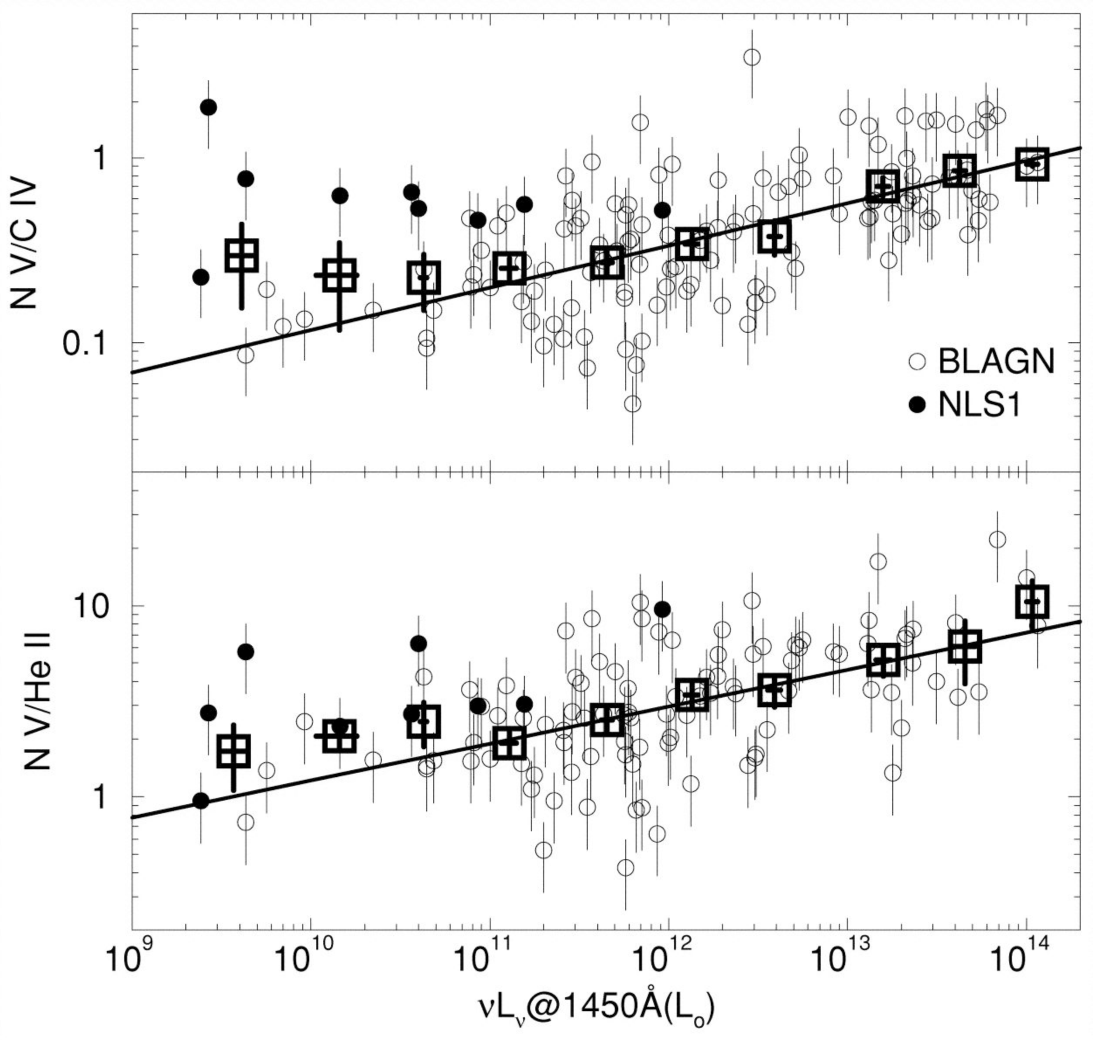


Metallicity in QSOs

(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