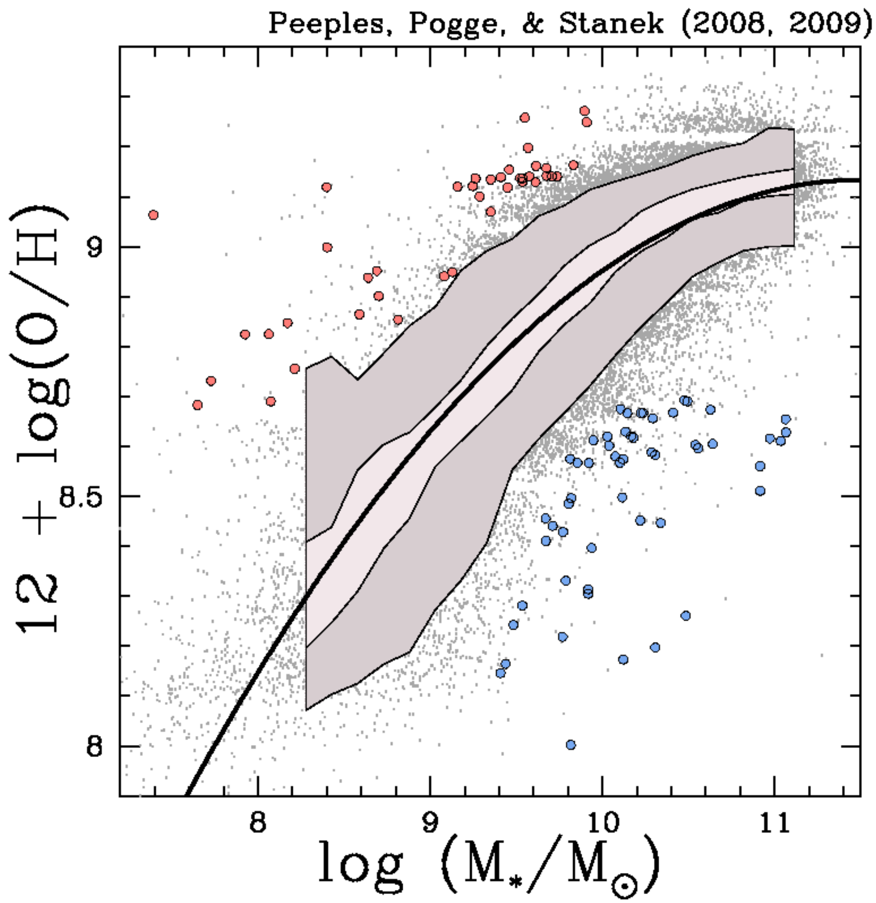
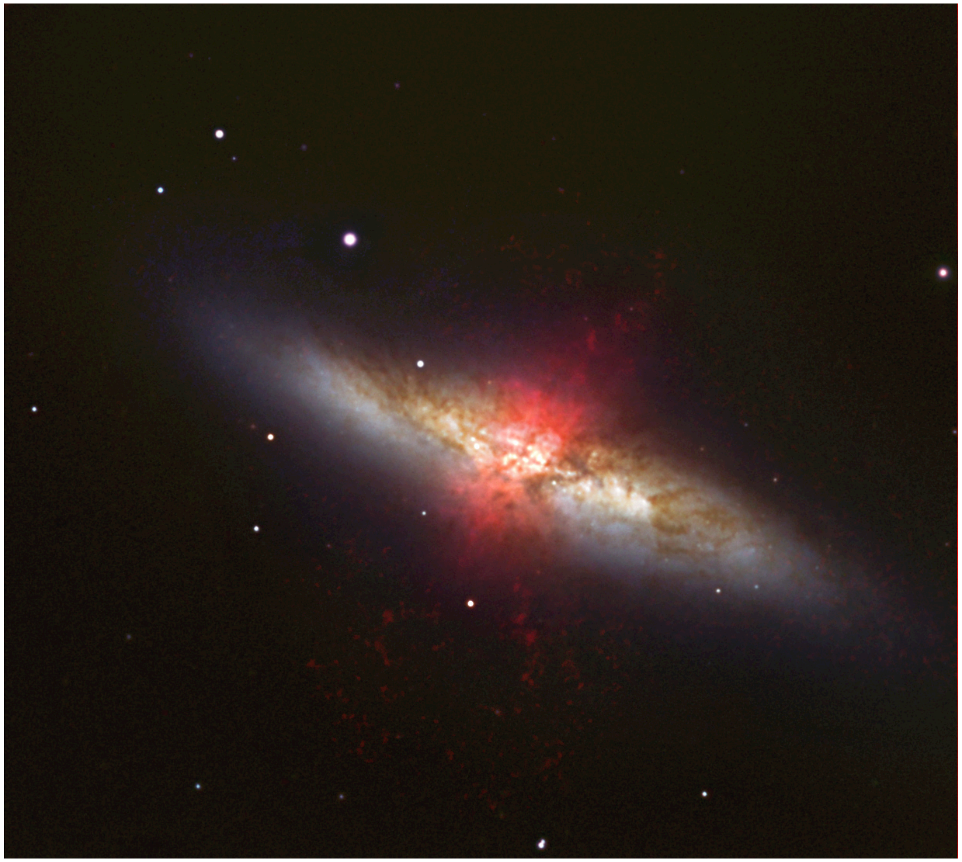
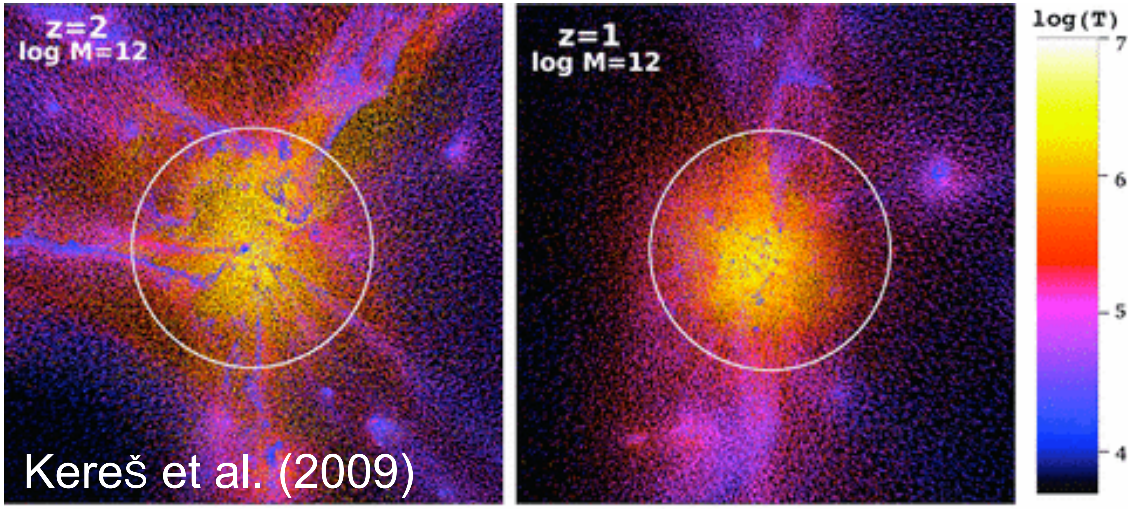
Balancing Gas Dilution and Outflows: The Mass-Metallicity Relation at z=0

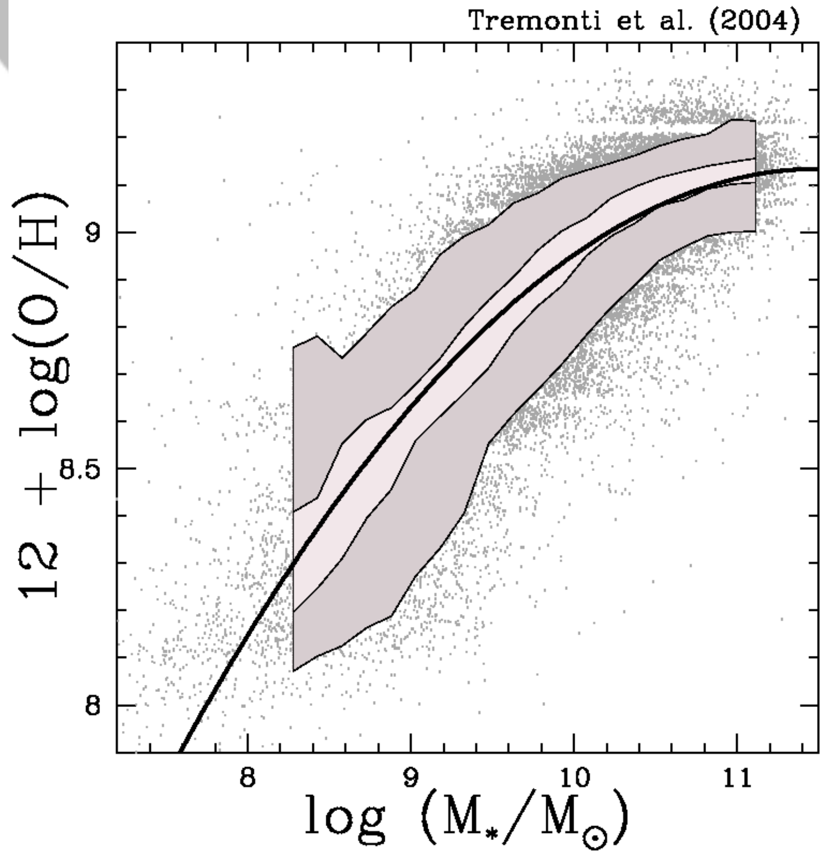
Molly Peeples (Ohio State)

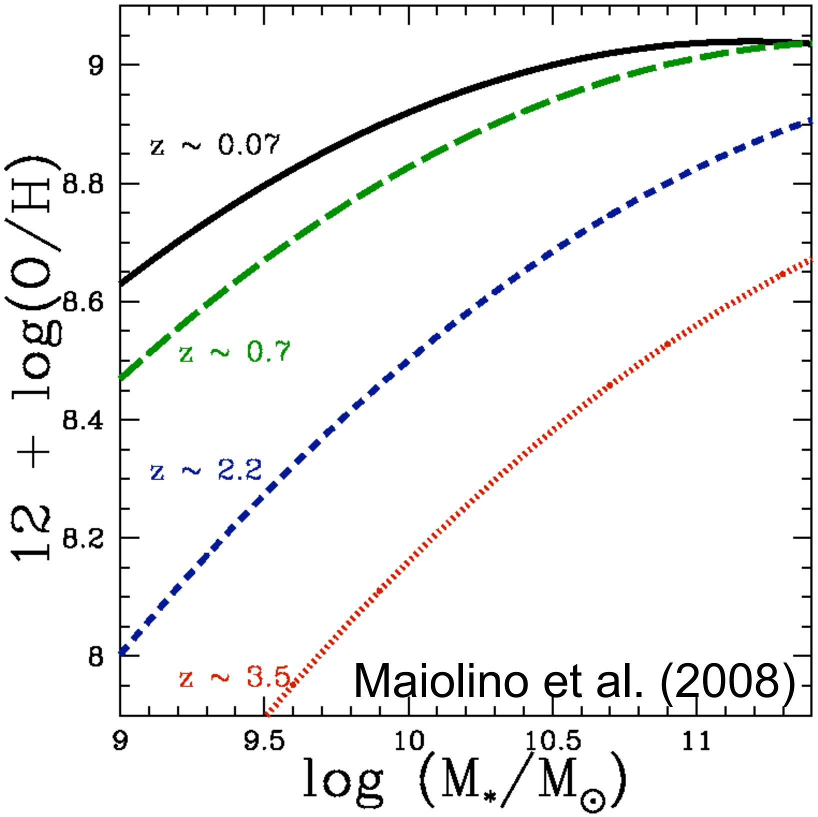
November 3, 2009 at Berkeley

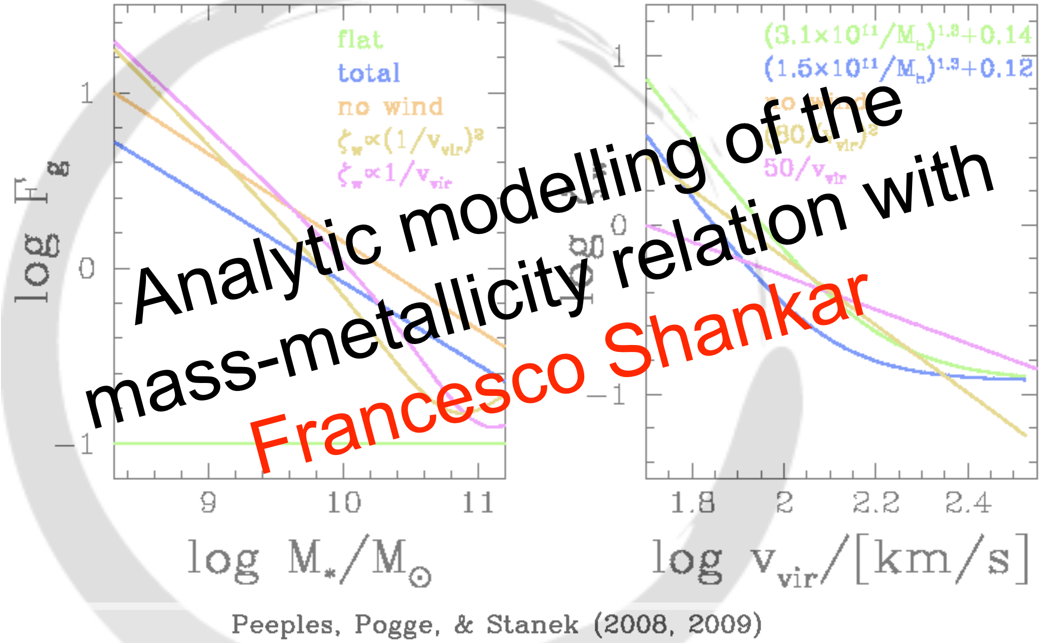




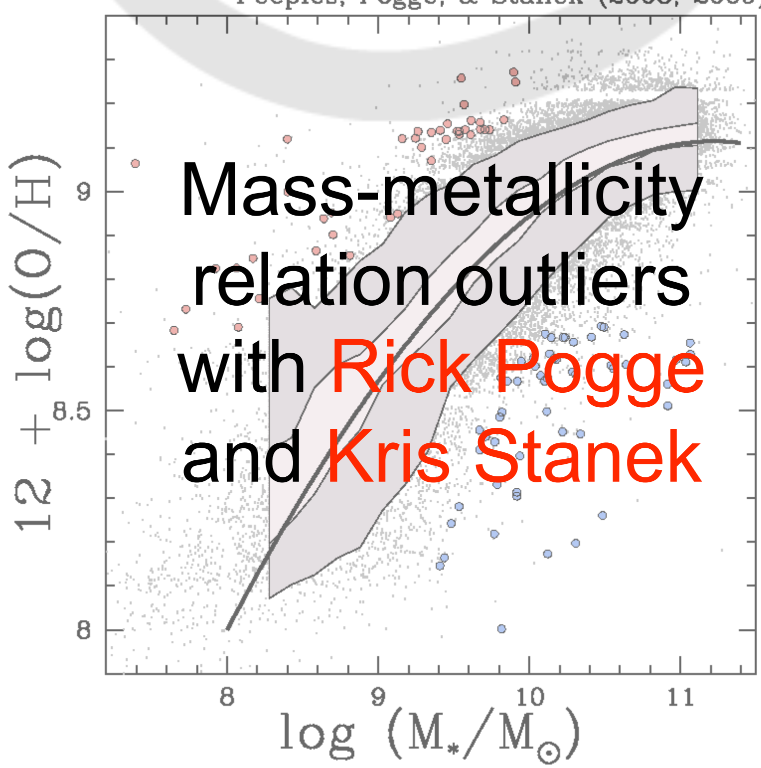

z=2
log M=12
z=1
log M=12
log(T)
7
6
5
4
Kereš et al. (2009)


Tremonti et al. (2004)
12 + log(O/H)
log (M*/M⊙)
8
8.5
9
8
9
10
11


z ~ 0.07
z ~ 0.7
z ~ 2.2
z ~ 3.5
Maiolino et al. (2008)
12 + log(O/H)
log (M*/M⊙)
8
8.2
8.4
8.6
8.8
9
9
9.5
10
10.5
11



Analytic modelling of the mass-metallicity relation with Francesco Shankar

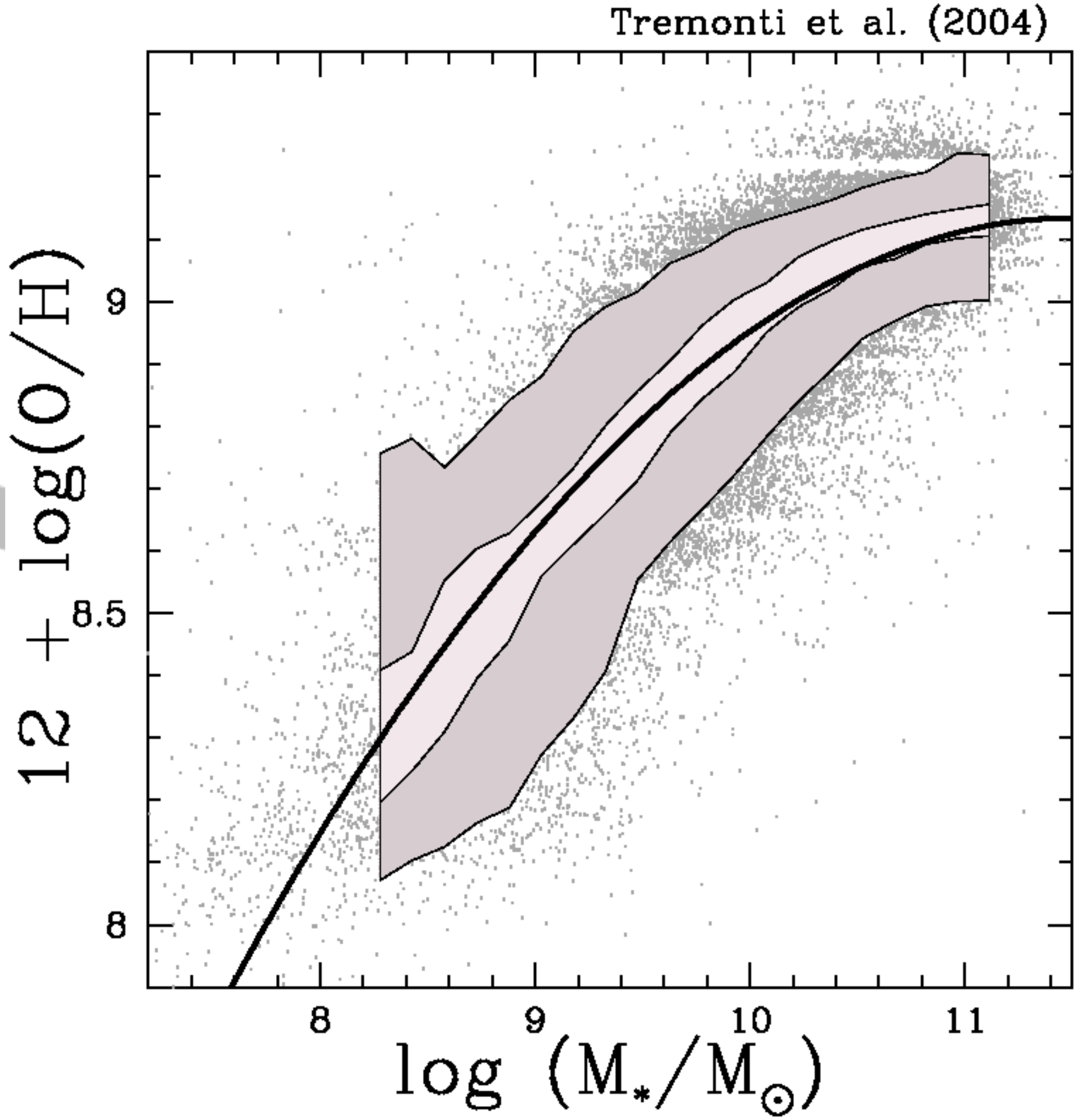


Mass-metallicity relation outliers with Rick Pogge and Kris Stanek

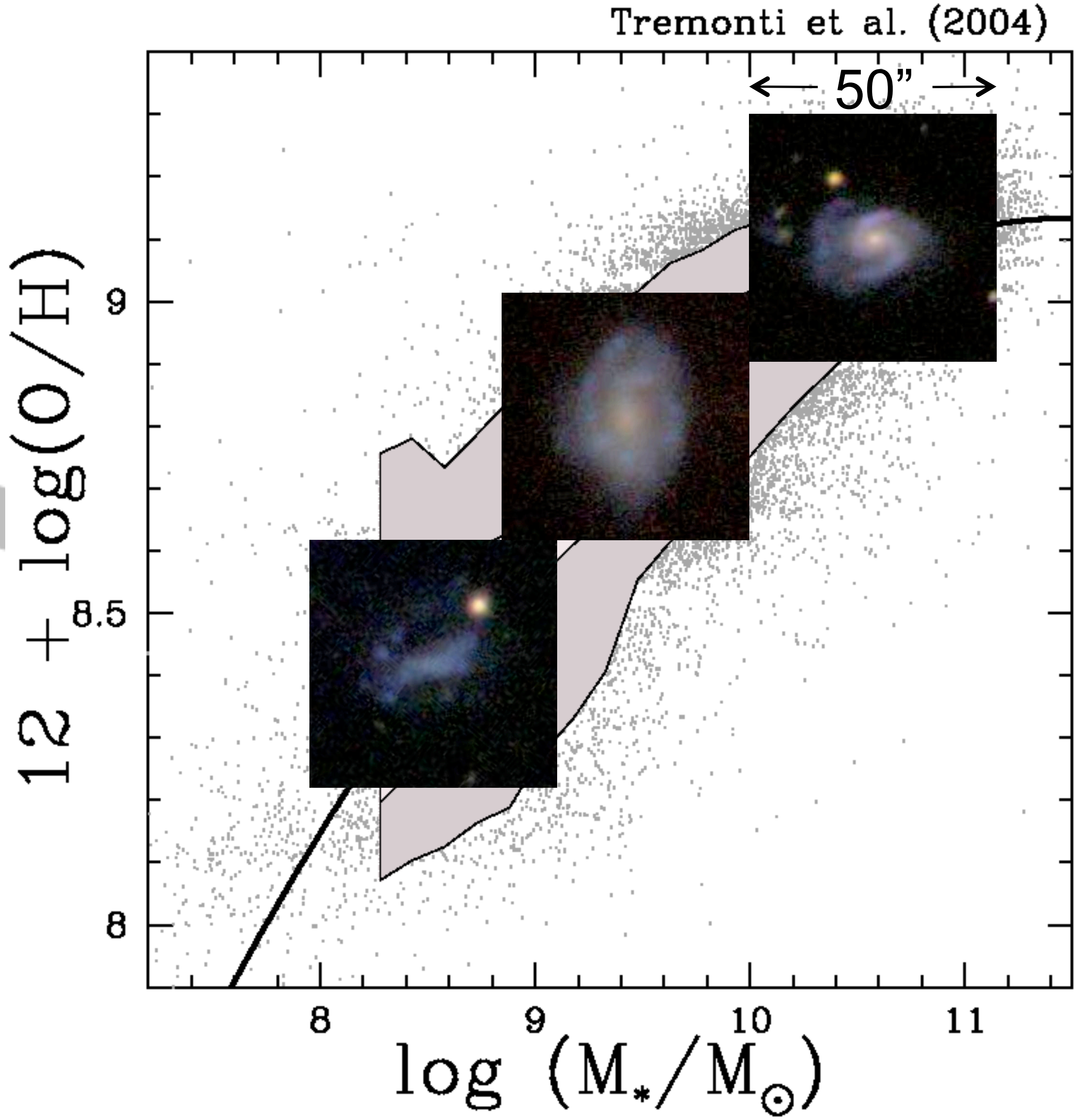
SPH work with
David Weinberg,
Romeel Davé,
Mark Fardal,
Neal Katz,
Dusan Kereš,
Ben Oppenheimer

with lots of discussions with David Weinberg and Todd Thompson

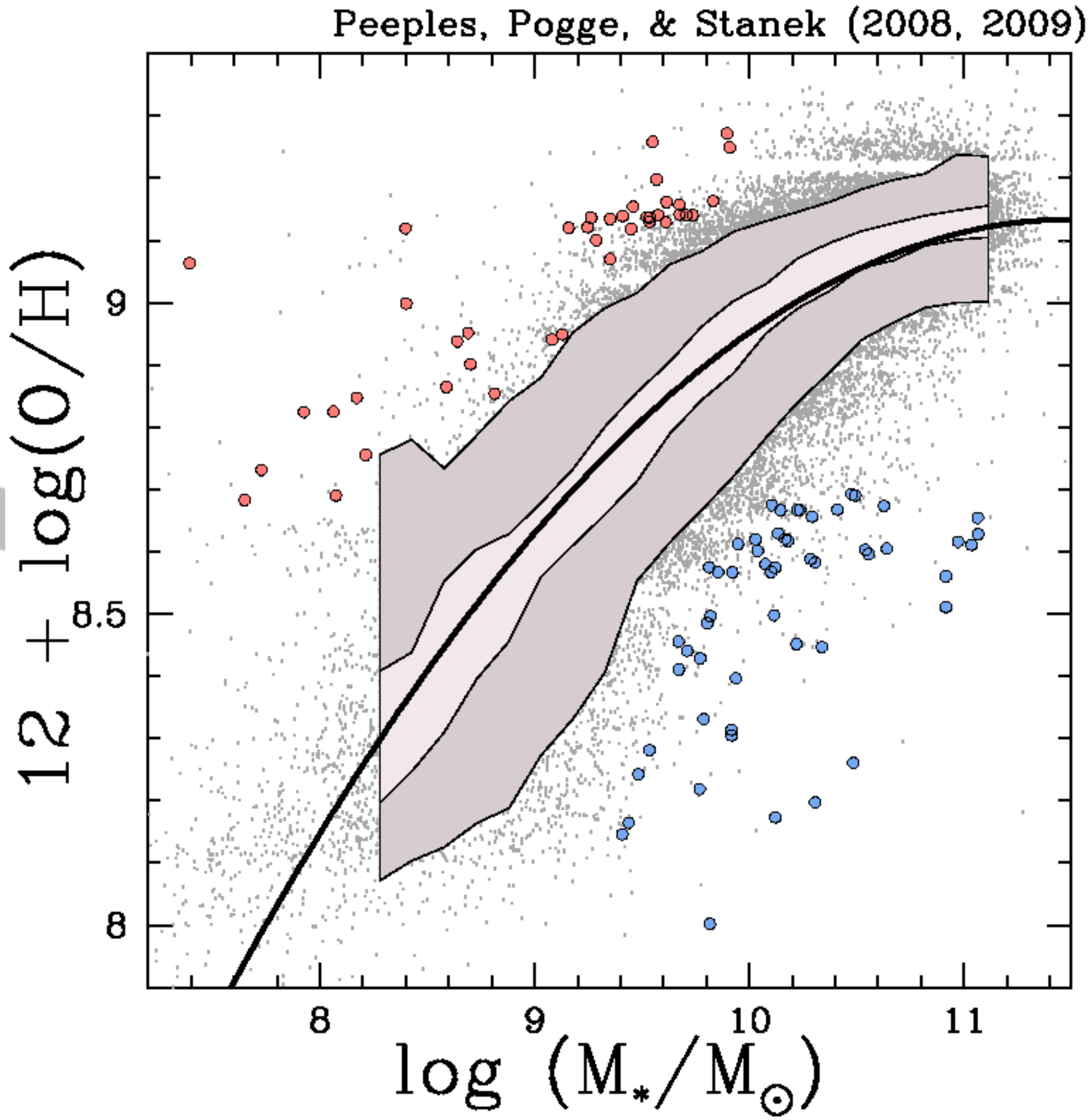
The Mass-Metallicity Relation



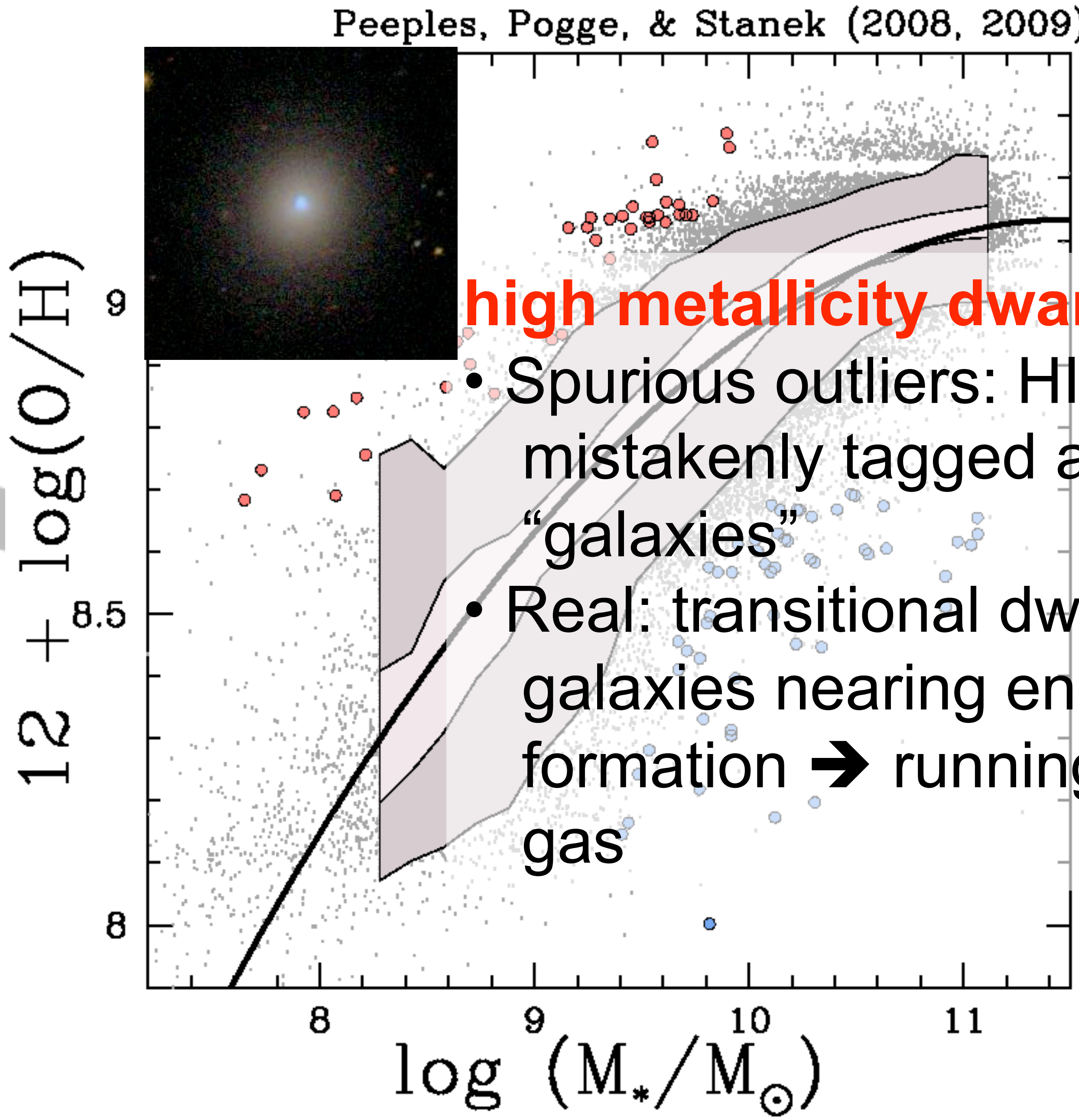
The Mass-Metallicity Relation



Outliers from the Mass-Metallicity Relation



Outliers from the Mass-Metallicity Relation



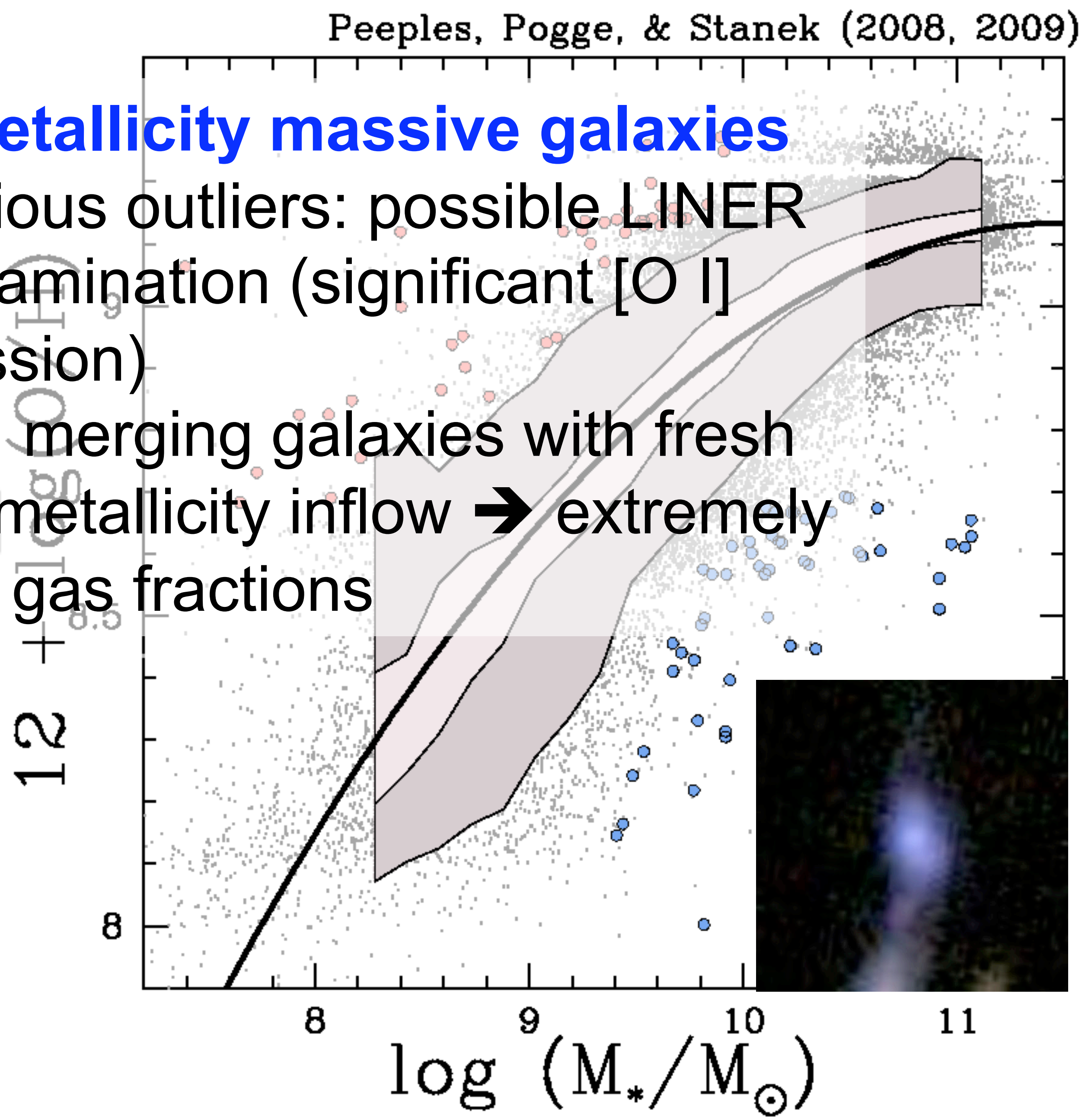
high metallicity dwarf galaxies

- Spurious outliers: HII regions mistakenly tagged as "galaxies"
- Real: transitional dwarf galaxies nearing end of star formation ➔ running out of gas

Outliers from the Mass-Metallicity Relation

low metallicity massive galaxies

- Spurious outliers: possible LINER contamination (significant [O I] emission)
- Real: merging galaxies with fresh low-metallicity inflow ➔ extremely high gas fractions



Outliers from the Mass-Metallicity Relation: Basic results

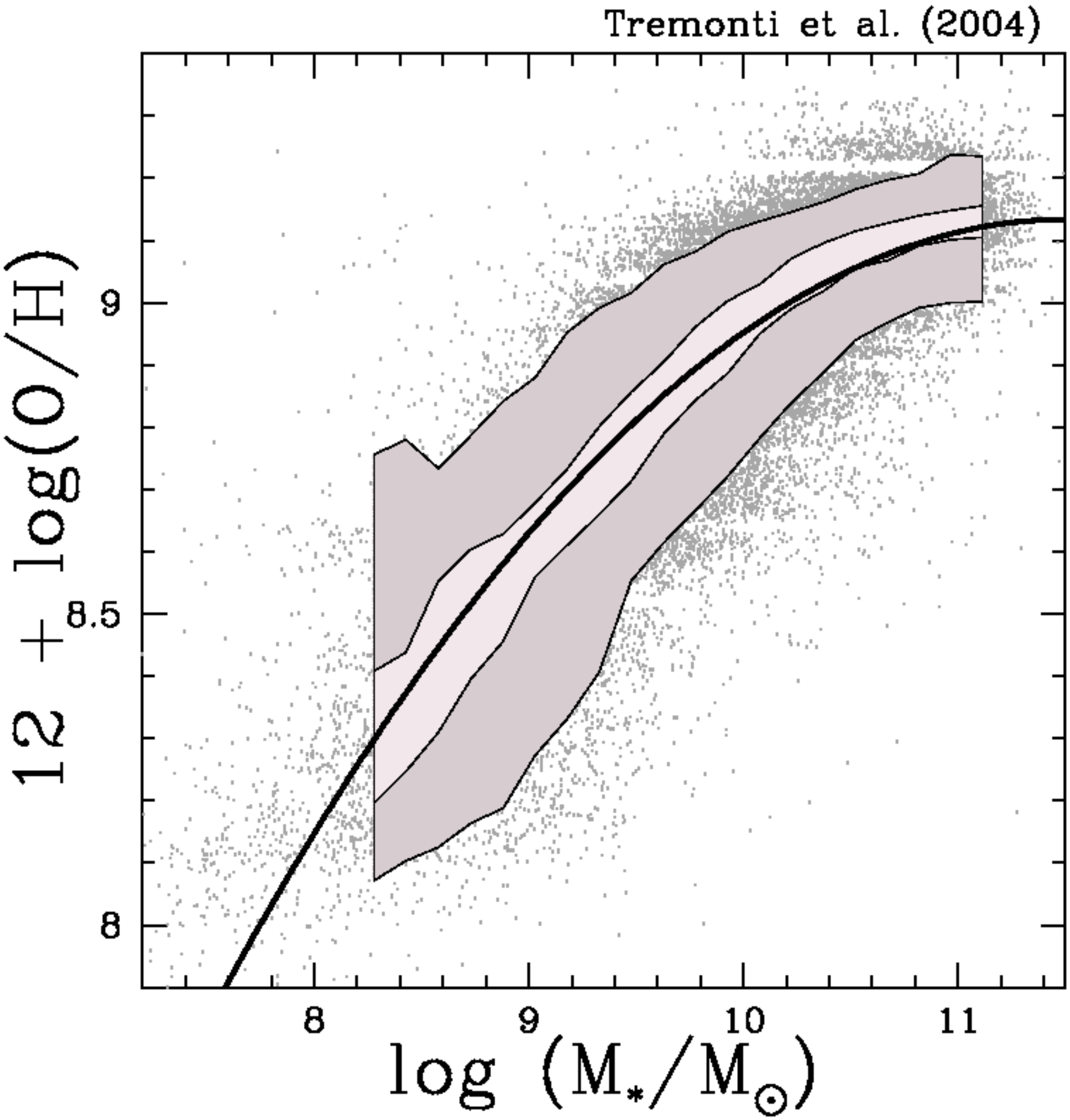
- Extreme outliers from the mass-metallicity relation exist; indications are that they have extreme gas fractions (for their masses)

- **High metallicity dwarf galaxies** are “dying” galaxies; relatively low gas fractions

- **Low metallicity massive galaxies** are merging galaxies; relatively high gas fractions

- Galaxies spend short fractions of their lives dying or crashing together

The Mass-Metallicity Relation



Combine ingredients for mass-metallicity relation...

Metals formed by supernovae

+ Metals locked up in stars

+ Gas dilutes the metals

+ Metals lost through outflows

= mass-metallicity relation?

Combine ingredients for mass-metallicity relation...

Metals formed by supernovae
+ Metals locked up in stars

} theory (SNII & IMF)

+ Gas dilutes the metals → observations

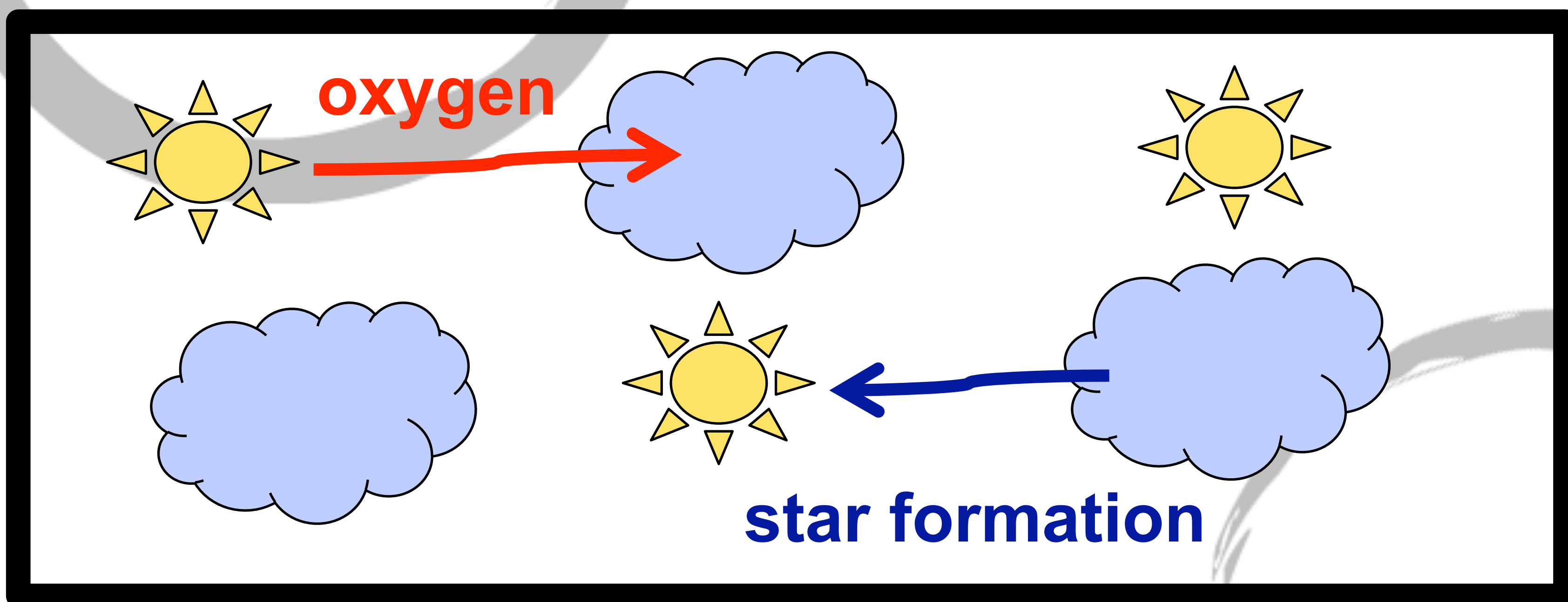
+ Metals lost through outflows → theory

≠ mass-metallicity relation !! → observations

Case 1: No winds

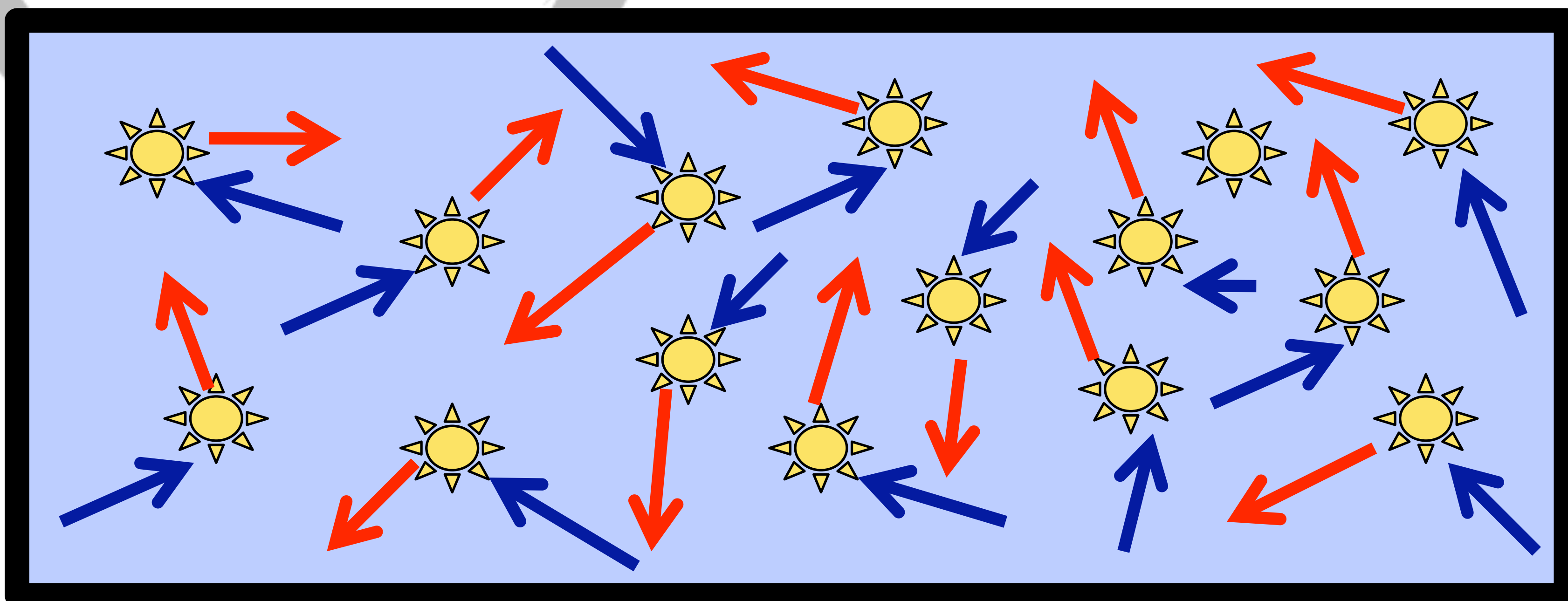
A Model Galaxy: what are the sources and sinks for ~~metals~~ oxygen?

stars form from galaxy's gas reservoir (ISM)



rate of metal production = $\boxed{\text{metals from star deaths}}$ − $\boxed{\text{metals locked in stars}}$

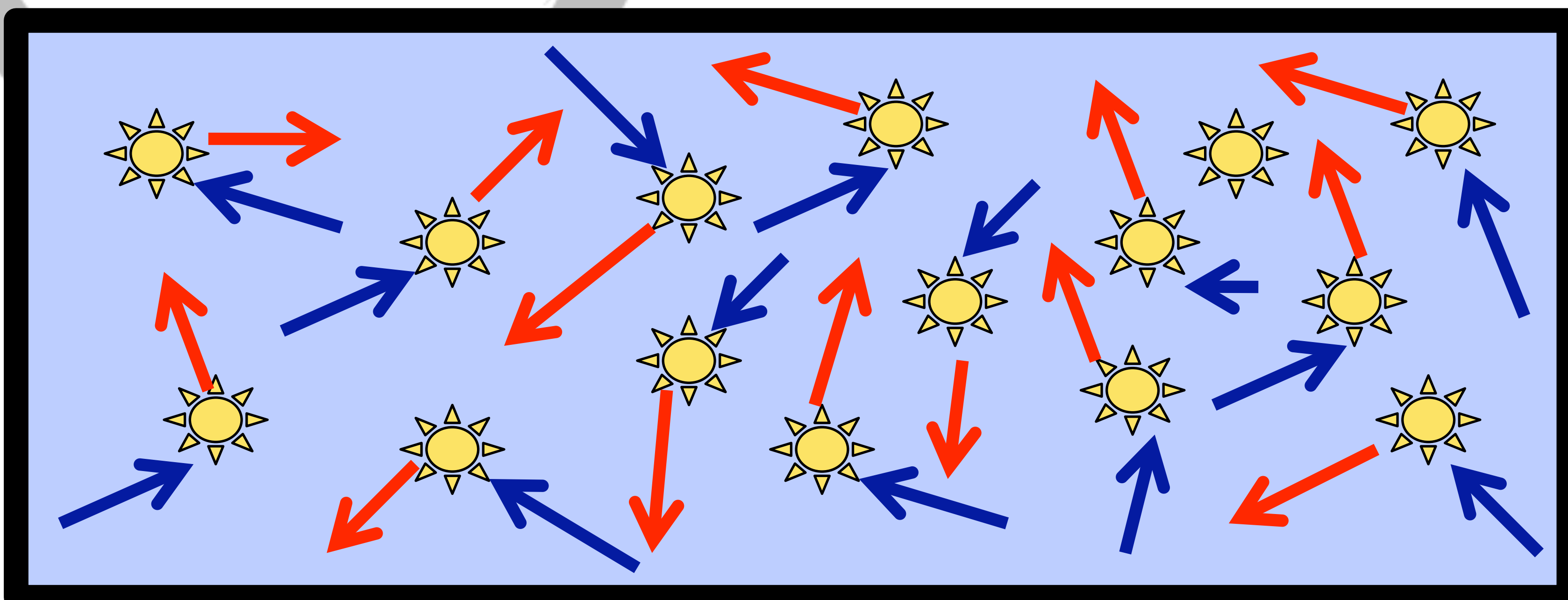
stars form from ISM gas…



…oxygen produced by Type II SNe (young stars; traces star formation)

$$\dot{M}_Z = \boxed{Z_{ej}\dot{M}_{recy}} - \boxed{Z_g\dot{M}_{SFR}}$$

stars form from ISM gas…

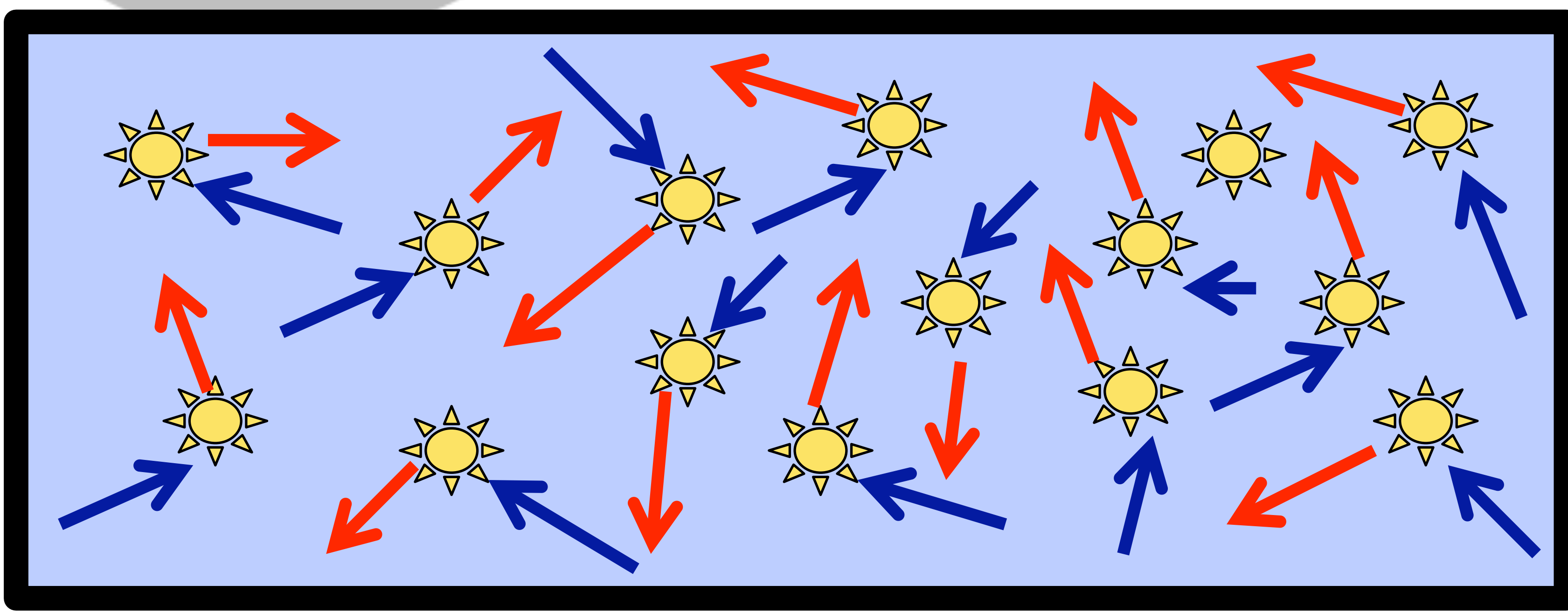


…oxygen produced by Type II SNe (young stars; traces star formation)

$$\dot{M}_Z = \boxed{Z_{ej}\dot{M}_{recy}} - \boxed{Z_g \dot{M}_{SFR}}$$

$$\boxed{y = Z_{ej}\frac{\dot{M}_{recy}}{\dot{M}_{SFR}}} \Rightarrow \dot{M}_Z = \dot{M}_{SFR}(\underline{y} - Z_g)$$

nucleosynthetic yield



Theory space ➔ observation space

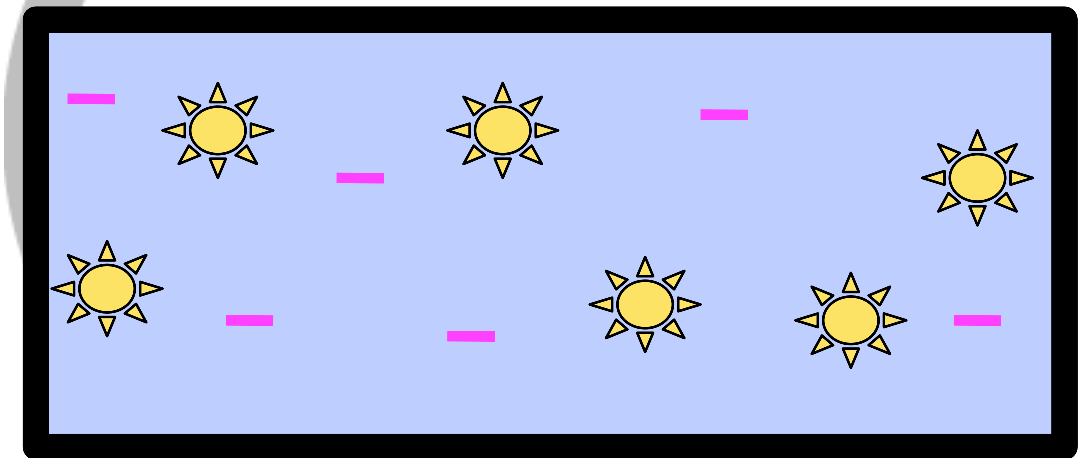
$$\dot{M}_Z = \dot{M}_{SFR}(y - Z_g)$$

want **integrated** metallicities and masses
➔ eliminate time dependence

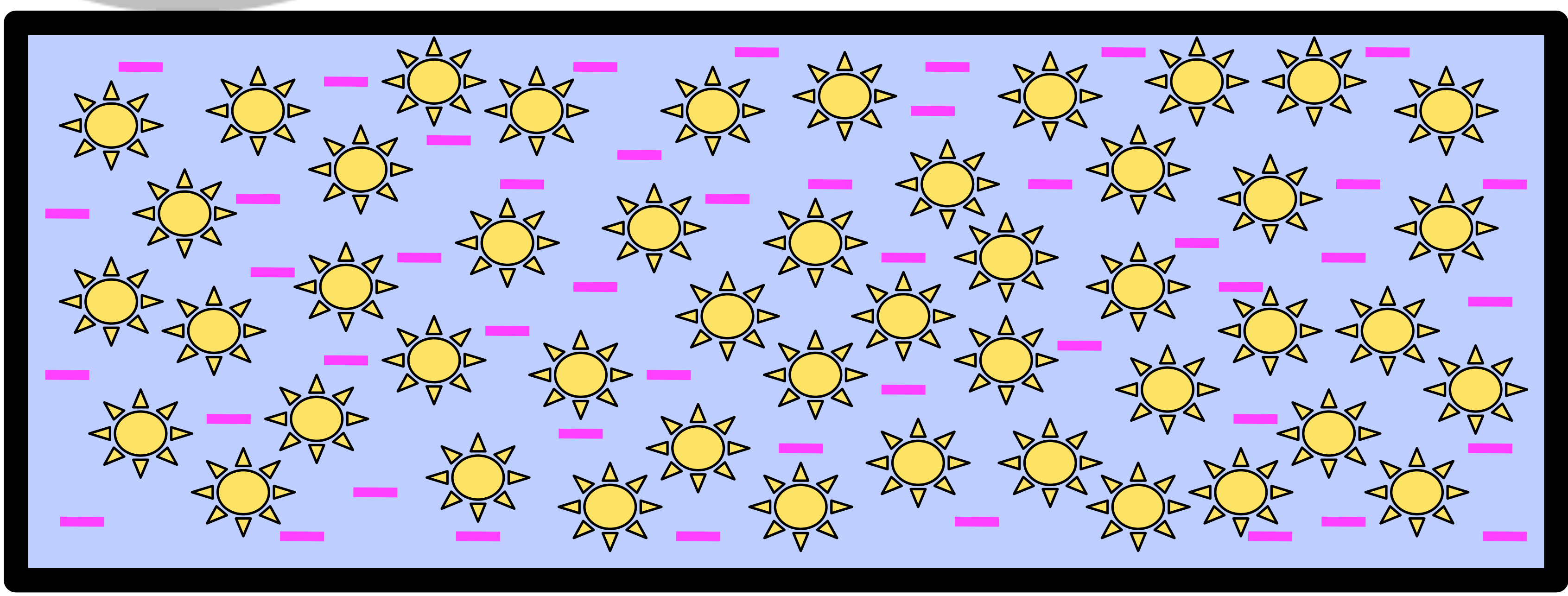
$$\frac{dM_Z}{dM_*} = \frac{1}{1 - f_{recy}} \frac{\dot{M}_Z}{\dot{M}_{SFR}} = \frac{y - Z_g}{1 - f_{recy}}$$

measure [# oxygen]/[# hydrogen];
model $Z_g = M_Z/M_g$

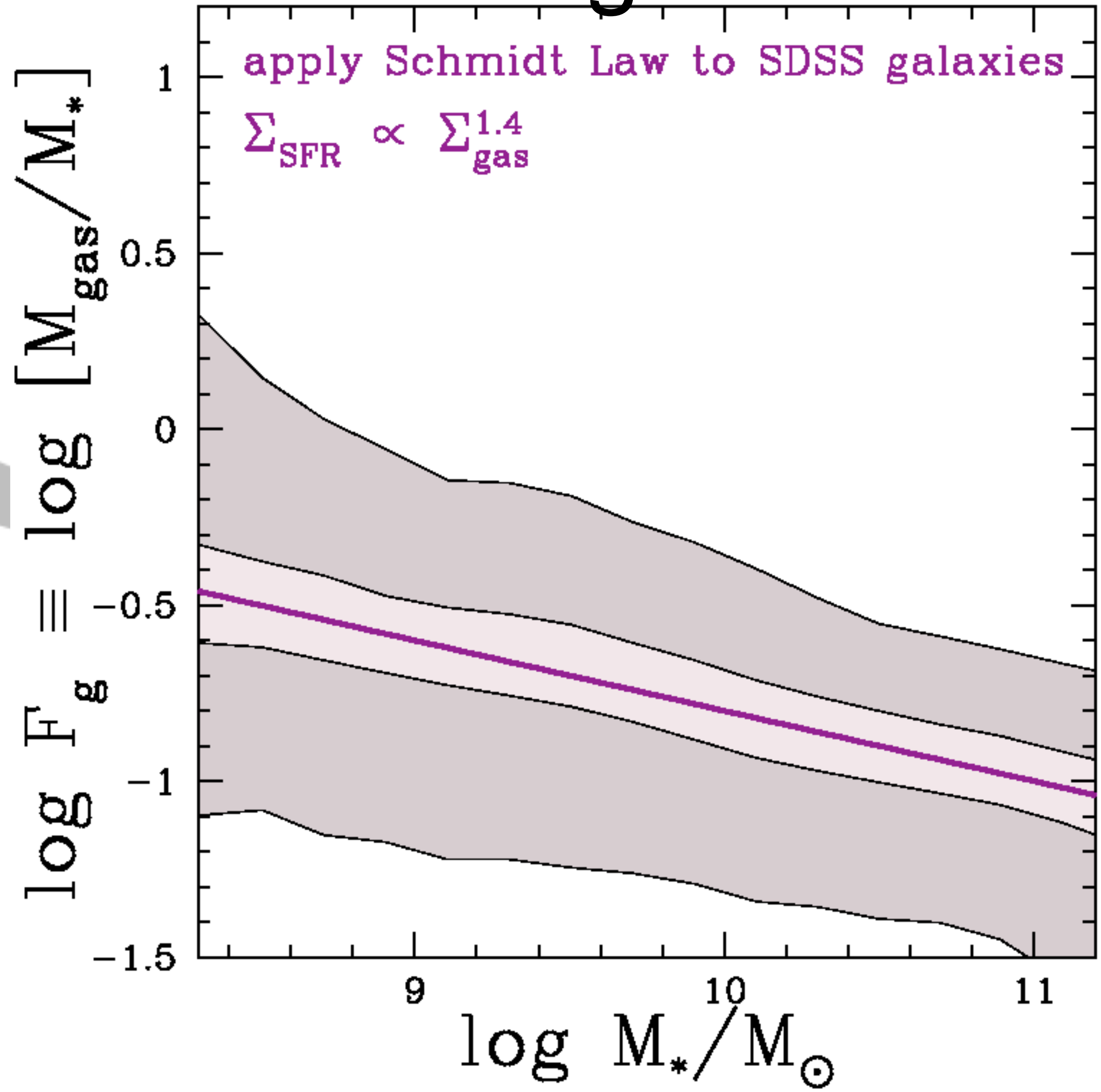
Gas dilutes metals



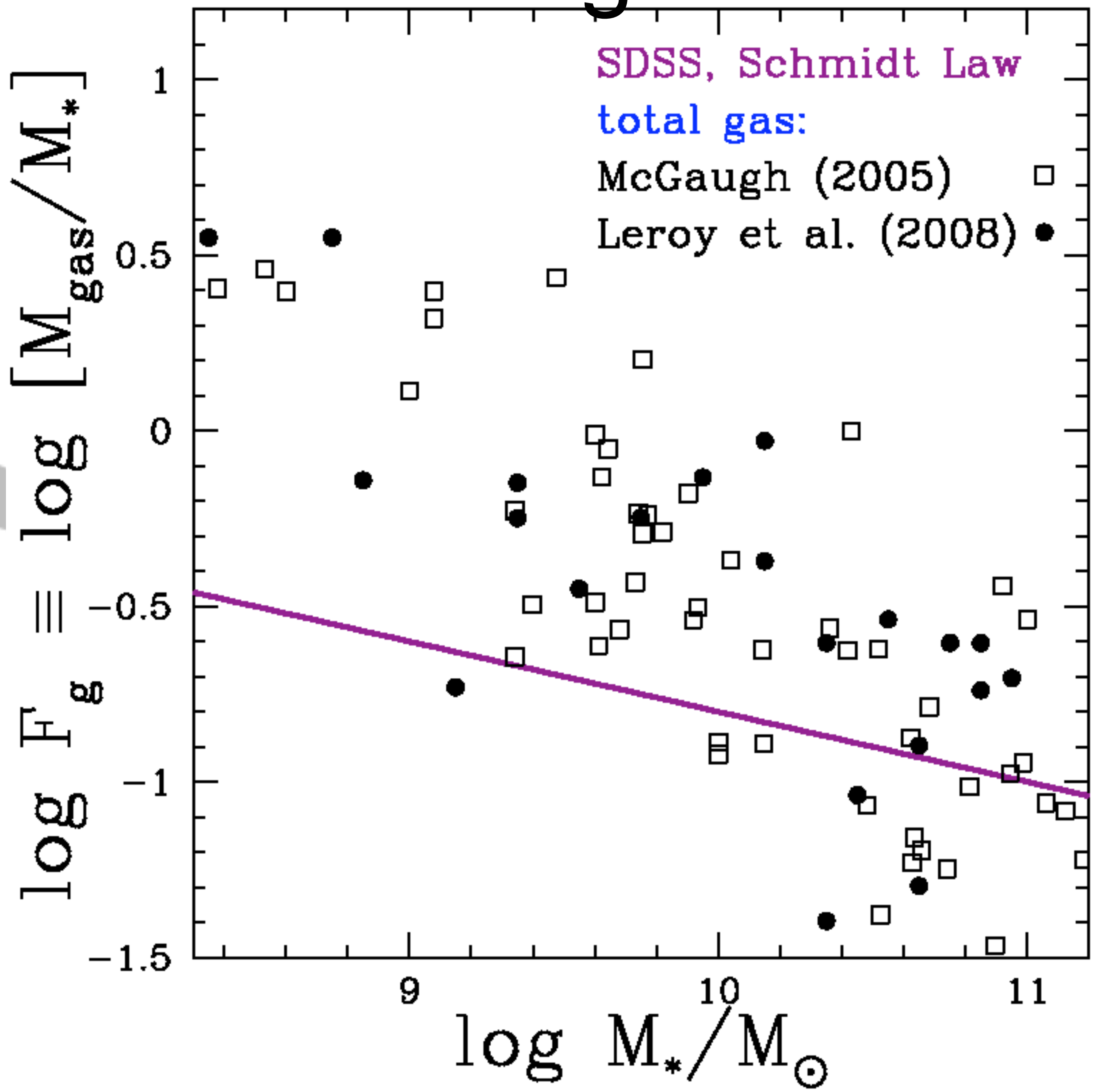
generally: galaxies with more stars have less gas (fractionally)
➔ same metals/stars, lower metallicity

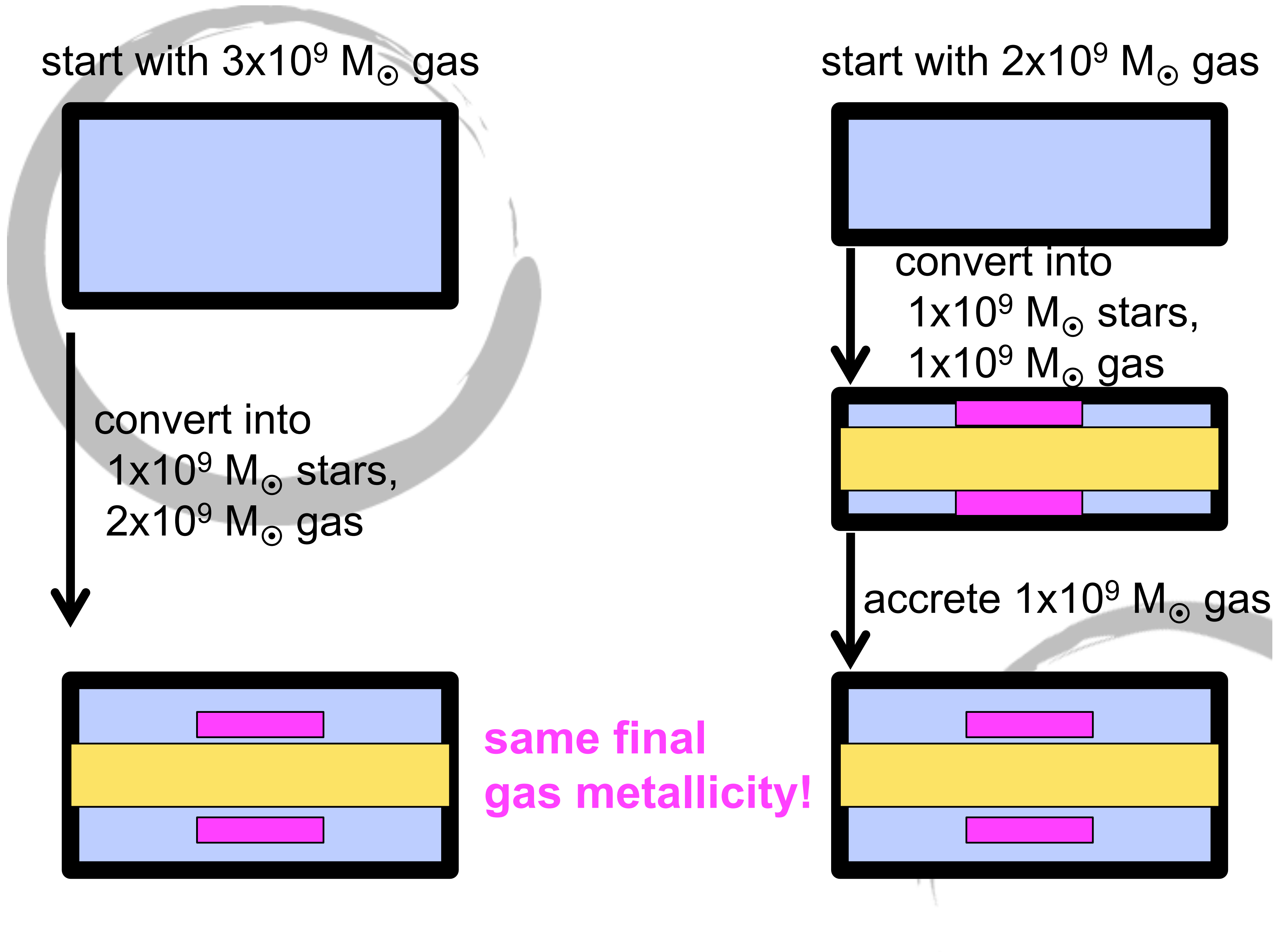


Gas dilution: gas fractions

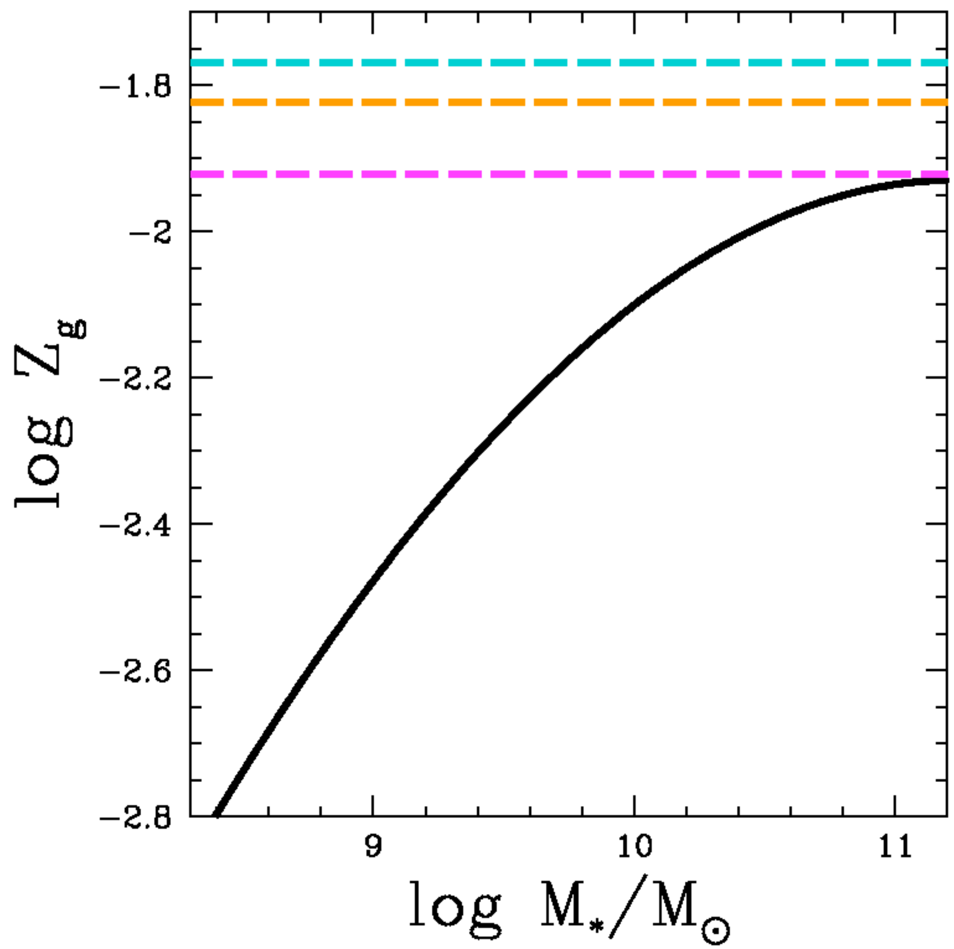


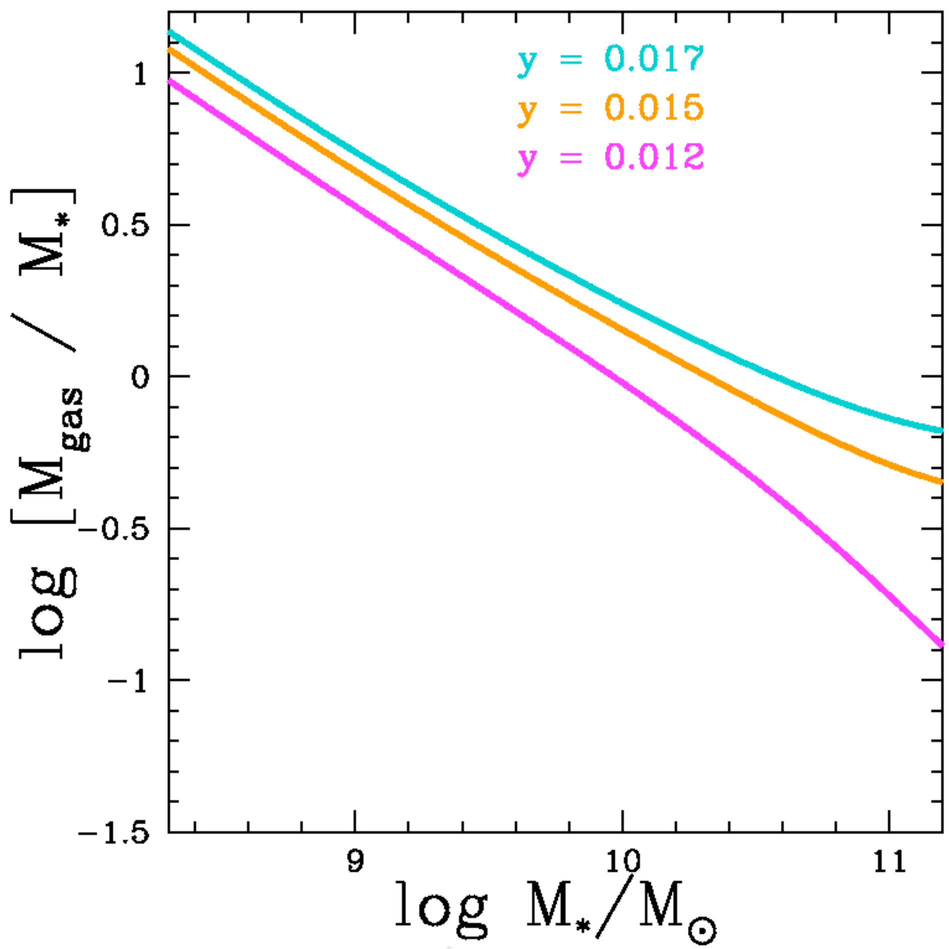
Gas dilution: gas fractions



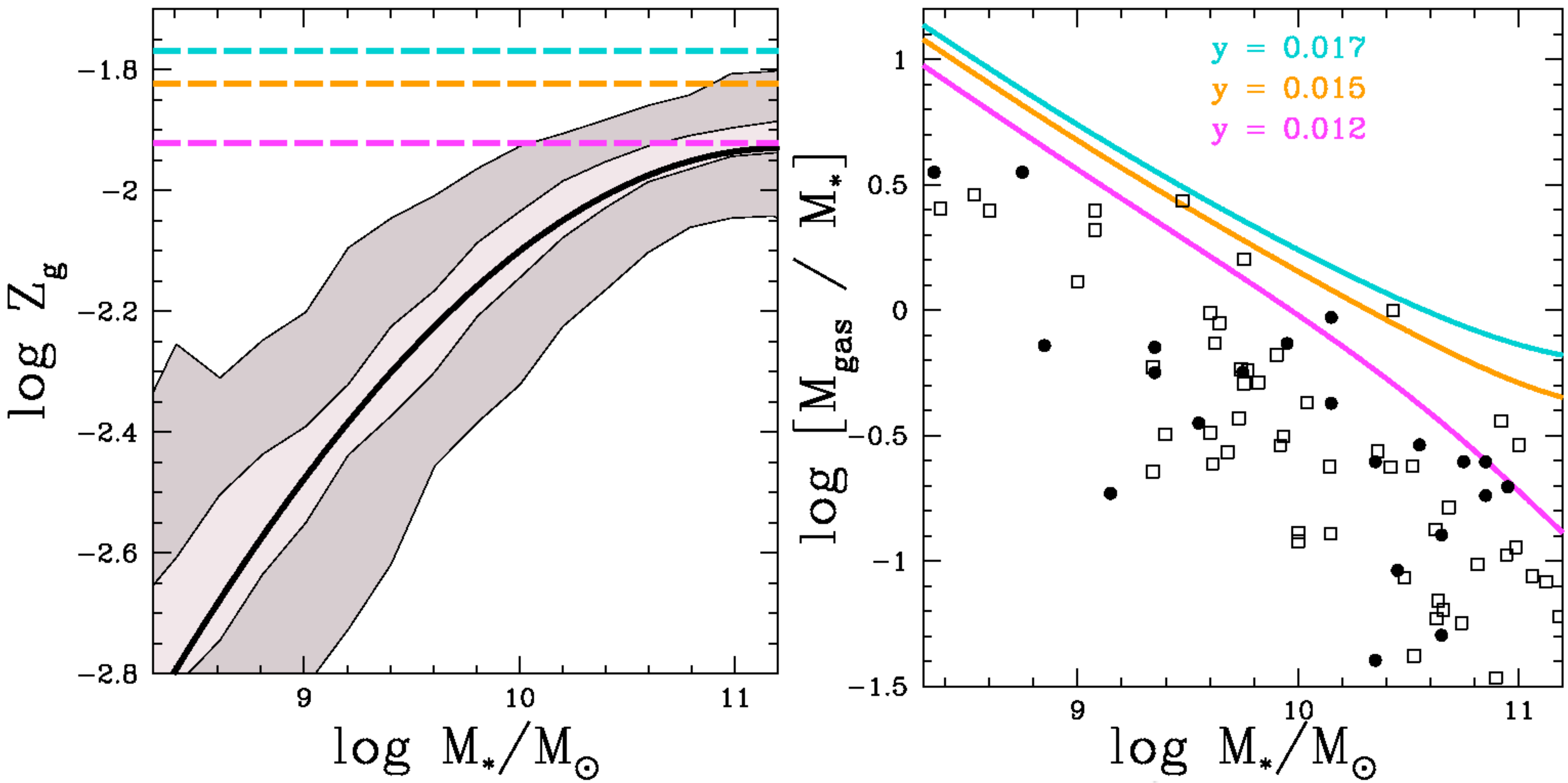

start with $3 \times 10^9 M_\odot$ gas
convert into
$1 \times 10^9 M_\odot$ stars,
$2 \times 10^9 M_\odot$ gas
start with $2 \times 10^9 M_\odot$ gas
convert into
$1 \times 10^9 M_\odot$ stars,
$1 \times 10^9 M_\odot$ gas
accrete $1 \times 10^9 M_\odot$ gas
same final
gas metallicity!

Gas dilution: gas fractions

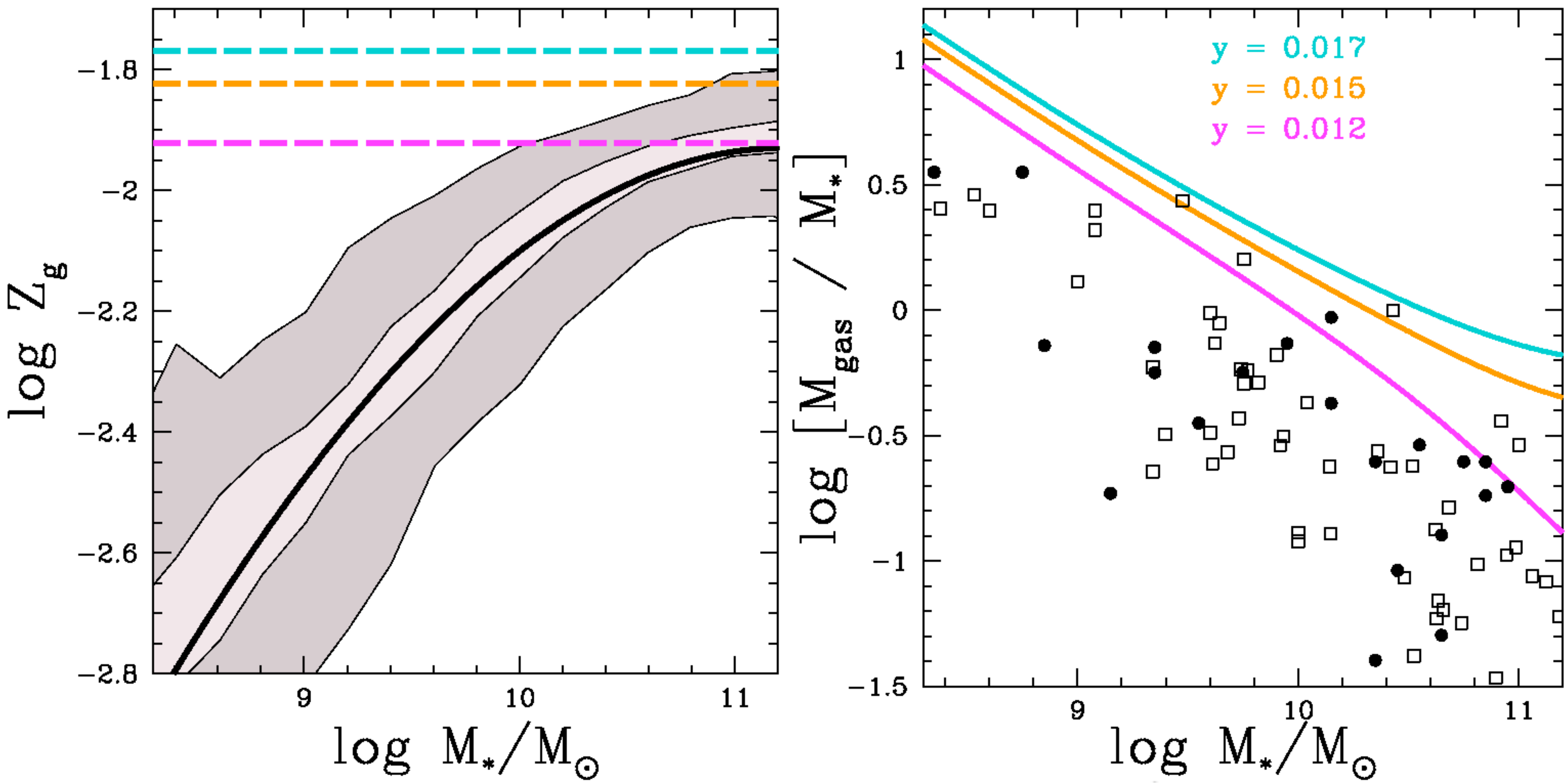




Gas dilution: gas fractions



Gas dilution: NOT ENOUGH

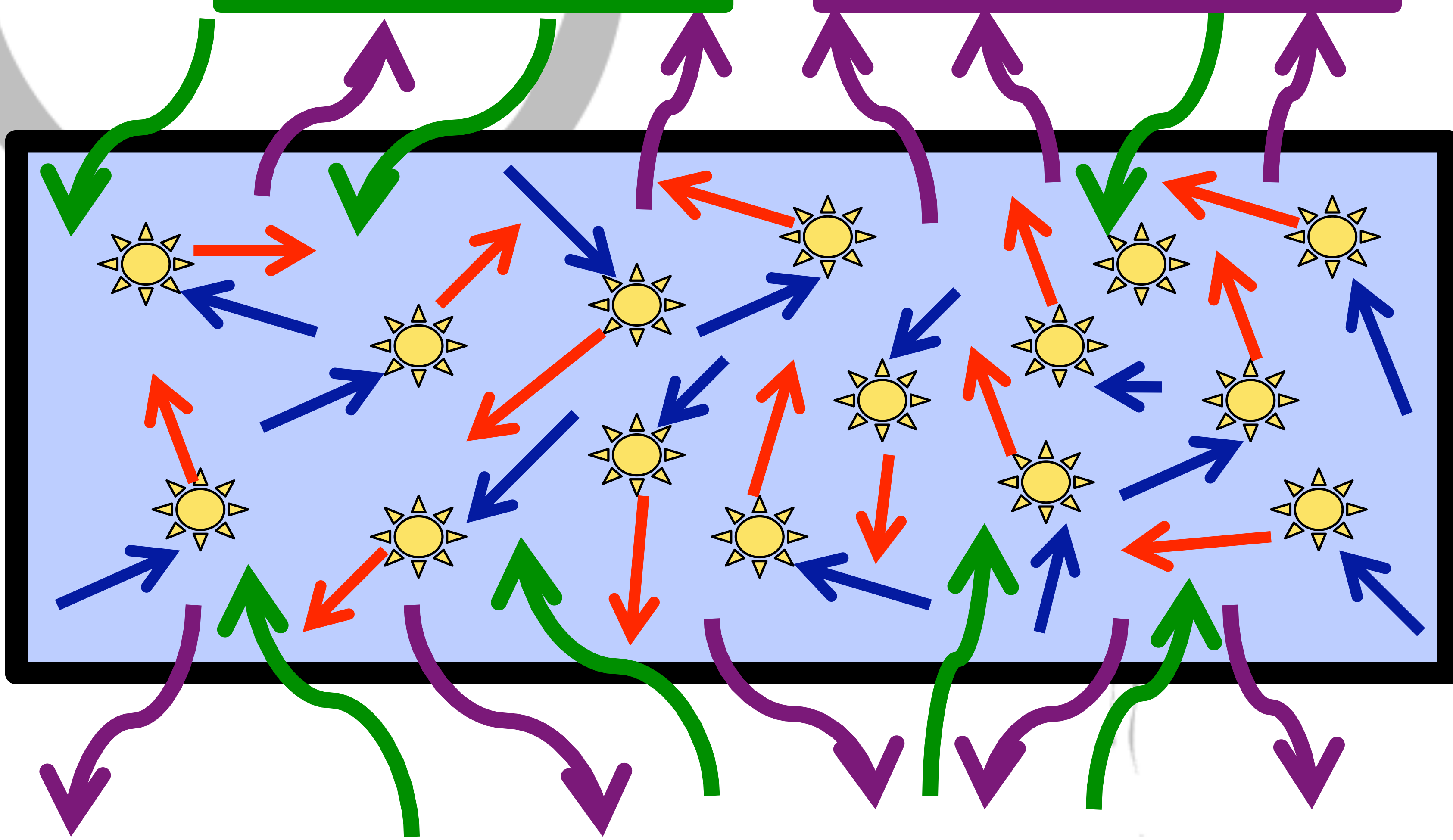


Case 2: With outflows

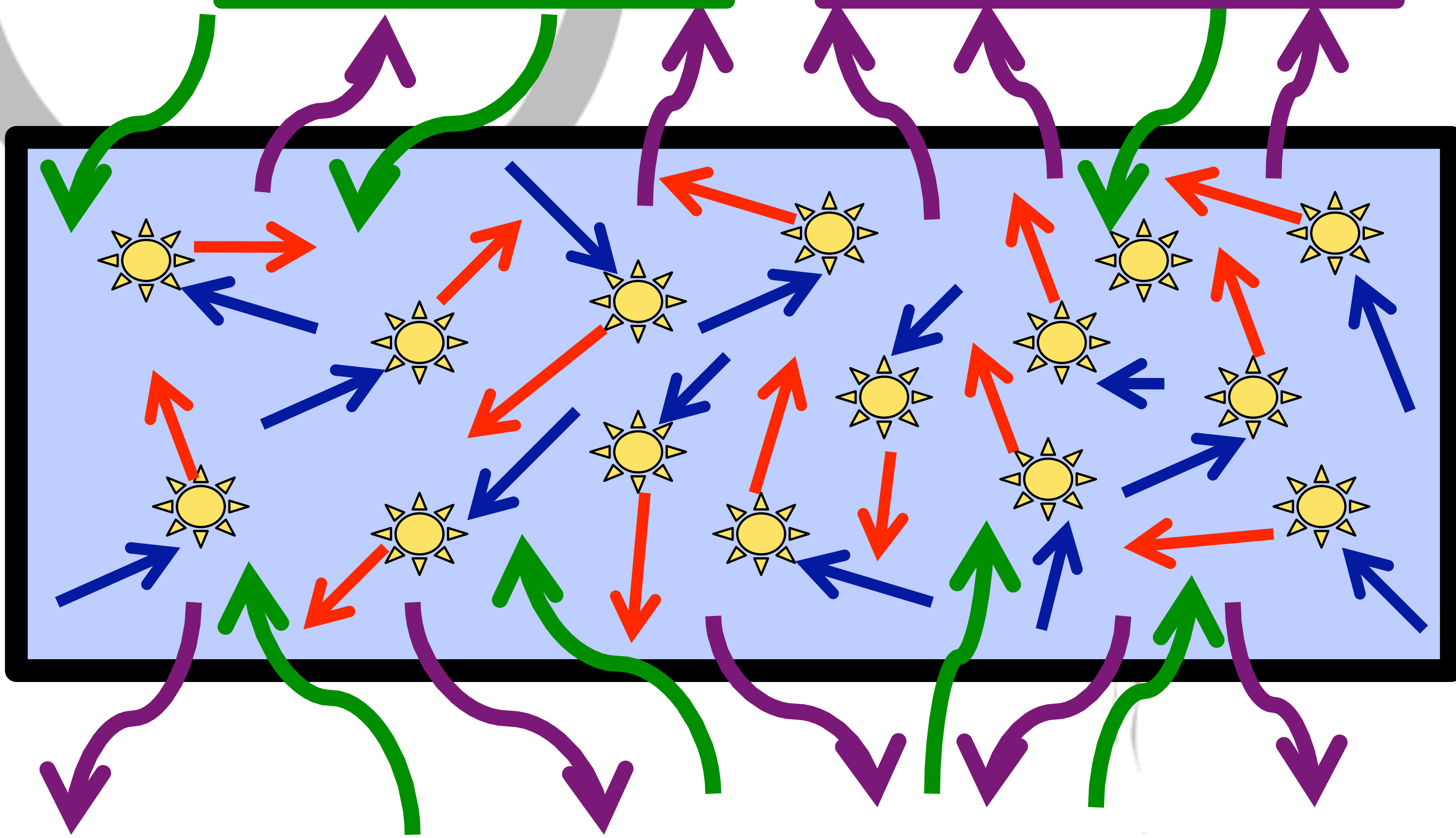
some relevant wind properties:

- efficiency η_w=[mass outflow rate]/[SFR]
- metallicity Z_{wind} (potentially $>Z_g$)
- velocity v_{wind}

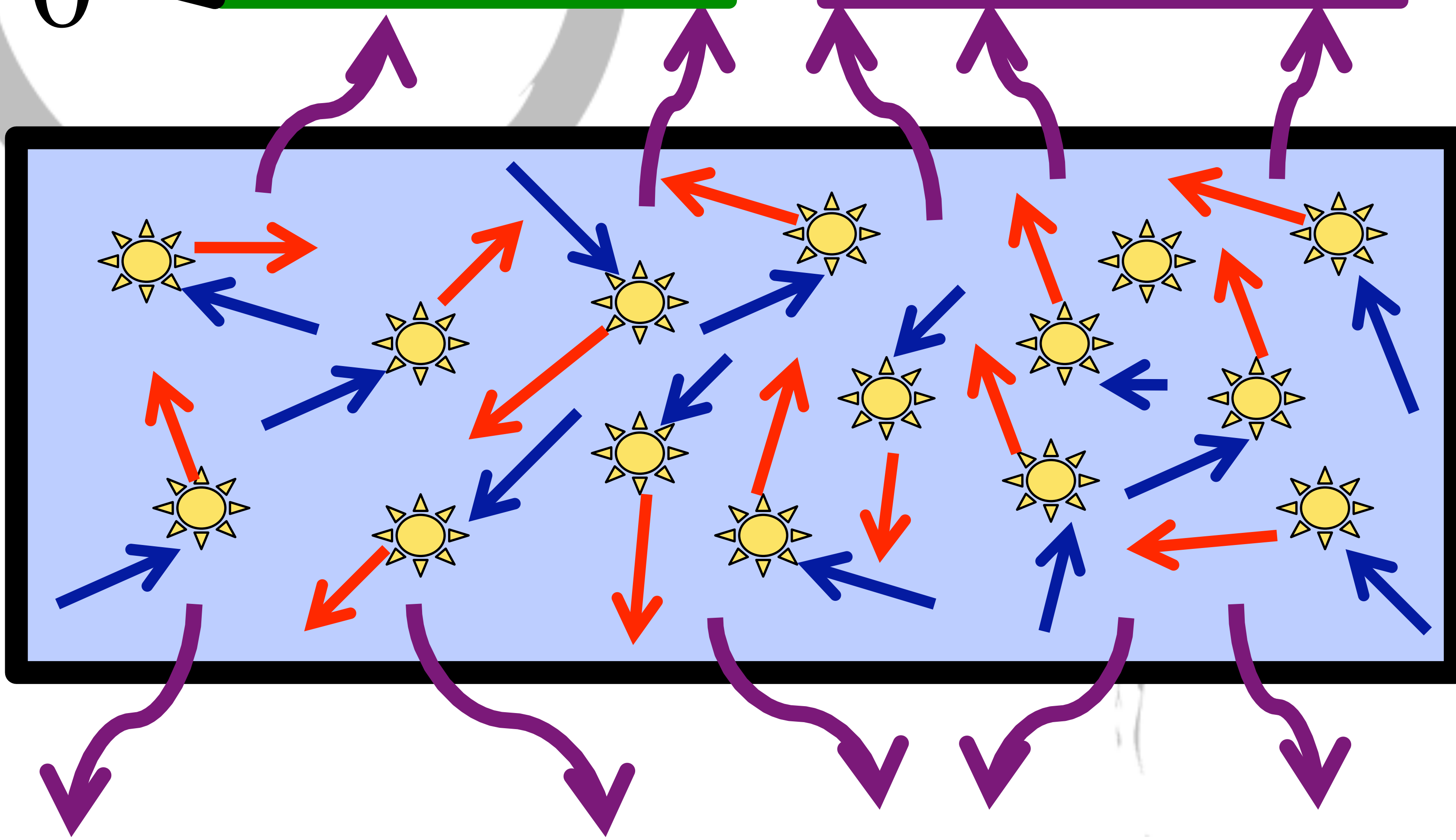
$$\dot{M}_{\mathrm{Z}} = \boxed{Z_{\mathrm{ej}}\dot{M}_{\mathrm{recy}}} - \boxed{Z_{\mathrm{g}}\dot{M}_{\mathrm{SFR}}} + \boxed{\begin{array}{l}\text{inflowing}\\ \text{metals}\end{array}} - \boxed{\begin{array}{l}\text{outflowing}\\ \text{metals}\end{array}}$$



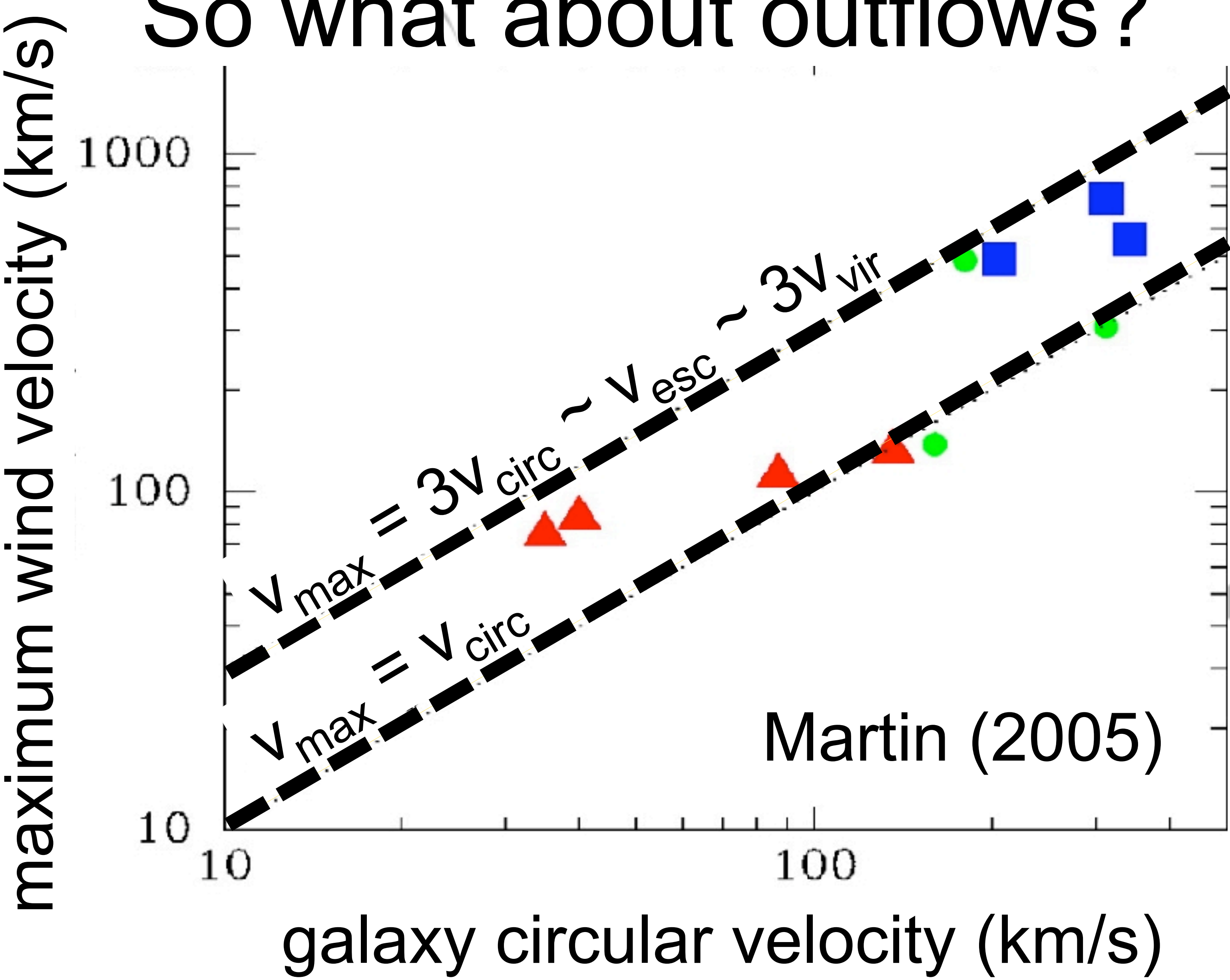
$$\dot{M}_{\mathrm{Z}} = \boxed{Z_{\mathrm{ej}}\dot{M}_{\mathrm{recy}}} - \boxed{Z_{\mathrm{g}}\dot{M}_{\mathrm{SFR}}} + \boxed{Z_{\mathrm{IGM}}\dot{M}_{\mathrm{acc}}} - \boxed{Z_{\mathrm{wind}}\dot{M}_{\mathrm{wind}}}$$



$$\dot{M}_Z = \boxed{Z_{ej}\dot{M}_{recy}} - \boxed{Z_g \dot{M}_{SFR}} + \boxed{\cancelto{0}{Z_{IGM}\dot{M}_{acc}}} - \boxed{Z_{wind}\dot{M}_{wind}}$$



So what about outflows?



So how does velocity relate to the outflow mass rate?

All supernova **energy** ➔ into driving wind?
(e.g., **thermal** pressure) then...

$$\dot{E}_{\mathrm{SN}} = \dot{M}_{\mathrm{SFR}} \Gamma_{\#\mathrm{SN}} \xi_{\mathrm{eff}} E_{\mathrm{SN}} = \frac{1}{2} \dot{M}_{\mathrm{wind}} v_{\mathrm{wind}}^2$$

$$\eta_{\mathrm{wind}} \equiv \frac{\dot{M}_{\mathrm{wind}}}{\dot{M}_{\mathrm{SFR}}} \approx \left(\frac{70\mathrm{km/s}}{v_{\mathrm{vir}}} \right)^2$$

"mass loading factor"

So how does velocity relate to the outflow mass rate?

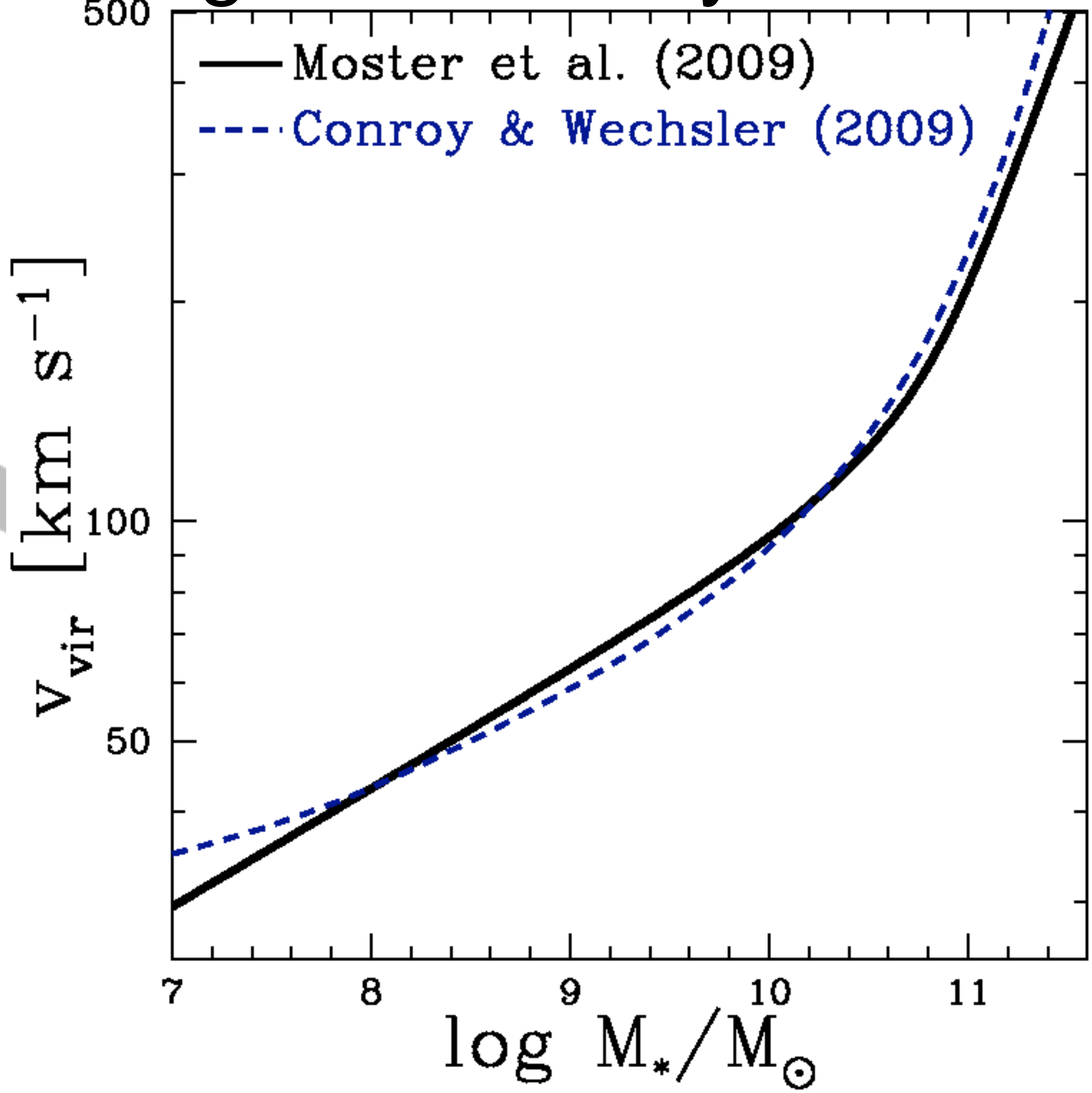
All **momentum** from SN photons ➔ driving wind? (e.g., **radiation** pressure [c.f. cosmic rays]) then...

$$\frac{L}{c} = \dot{M}_{\mathrm{SFR}}\varepsilon_{\mathrm{nuclear}}c = \dot{M}_{\mathrm{wind}}v_{\mathrm{wind}}$$

$$\eta_{\mathrm{wind}} \equiv \frac{\dot{M}_{\mathrm{wind}}}{\dot{M}_{\mathrm{SFR}}} = \frac{\varepsilon_{\mathrm{nuclear}}c}{v_{\mathrm{wind}}} \approx \frac{80\mathrm{km/s}}{v_{\mathrm{vir}}}$$

"mass loading factor"

Connecting virial velocity and stellar mass



Include winds in source/sink equation:

$$\dot{M}_{\mathrm{Z}} = \dot{M}_{\mathrm{SFR}}\left(\boxed{y} - Z_{\mathrm{g}} - \boxed{Z_{\mathrm{w}}\eta_{\mathrm{w}}}\right)$$

And get the metallicity:

$$\dot{Z}_{\mathrm{g}} = \frac{\mathrm{d}}{\mathrm{d}t}\frac{M_{\mathrm{Z}}}{M_{\mathrm{g}}} = \frac{\dot{M}_{\mathrm{Z}}}{M_{\mathrm{g}}} - \frac{Z_{\mathrm{g}}}{M_{\mathrm{g}}}\dot{M}_{\mathrm{g}}$$

$$\frac{\dot{Z}_{\mathrm{g}}}{\dot{M}_{\mathrm{SFR}}} = \frac{1}{1 - f_{\mathrm{recy}}}\frac{\mathrm{d}Z_{\mathrm{g}}}{\mathrm{d}M_{*}}$$

So how do outflows & gas affect the mass-metallicity relation?

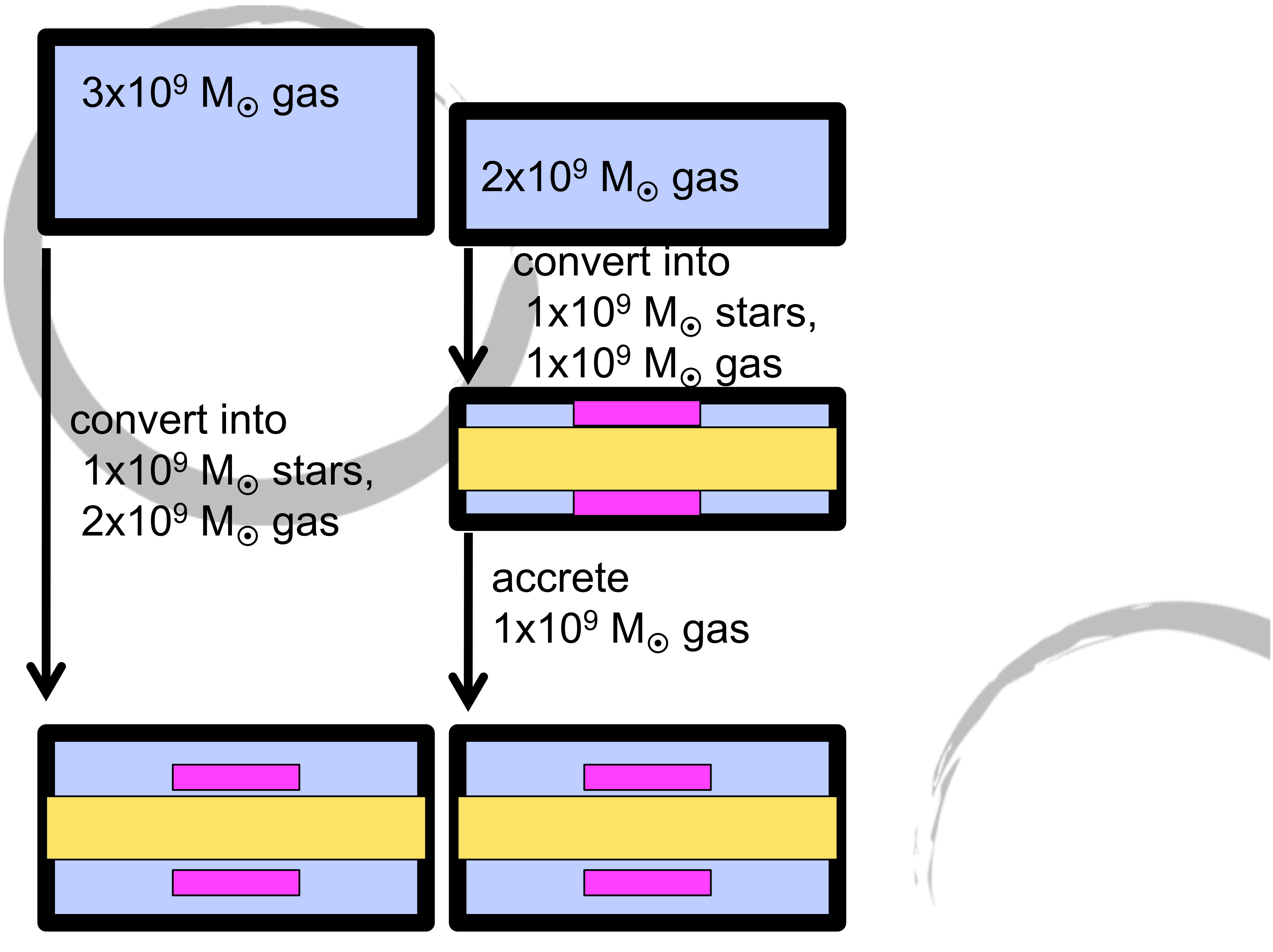
$$\frac{\mathrm{d}Z_g}{\mathrm{d}M_*} = \frac{y - Z_g(\boxed{\zeta_w} + 1 + \boxed{F_g[1-\gamma]})}{\boxed{M_g}(1 - f_{recy})}$$

Winds

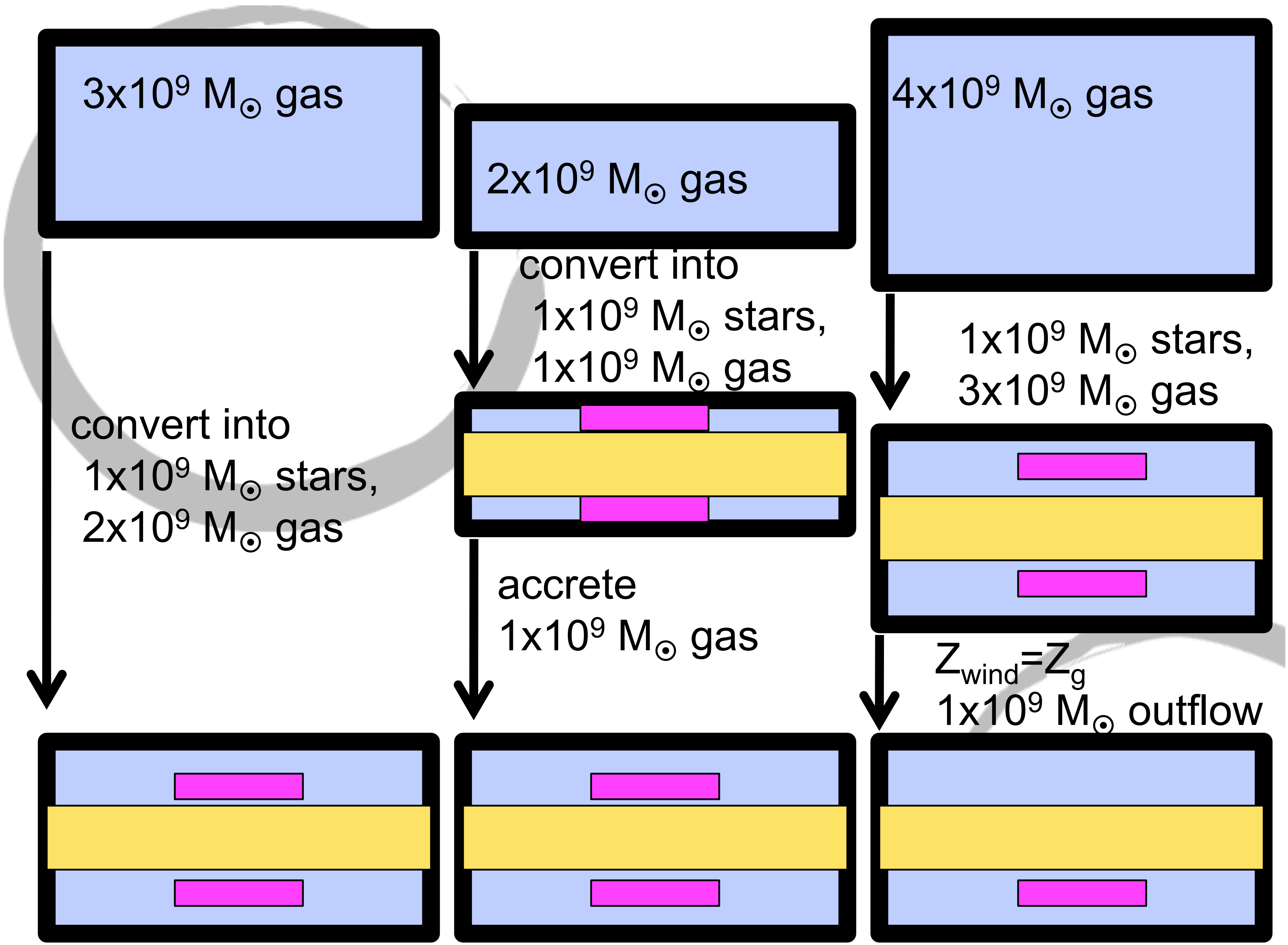
$$\boxed{\zeta_w \equiv \frac{Z_w}{Z_g}\eta_w = \frac{Z_w \dot{M}_w}{Z_g \dot{M}_{SFR}}}$$

Dilution

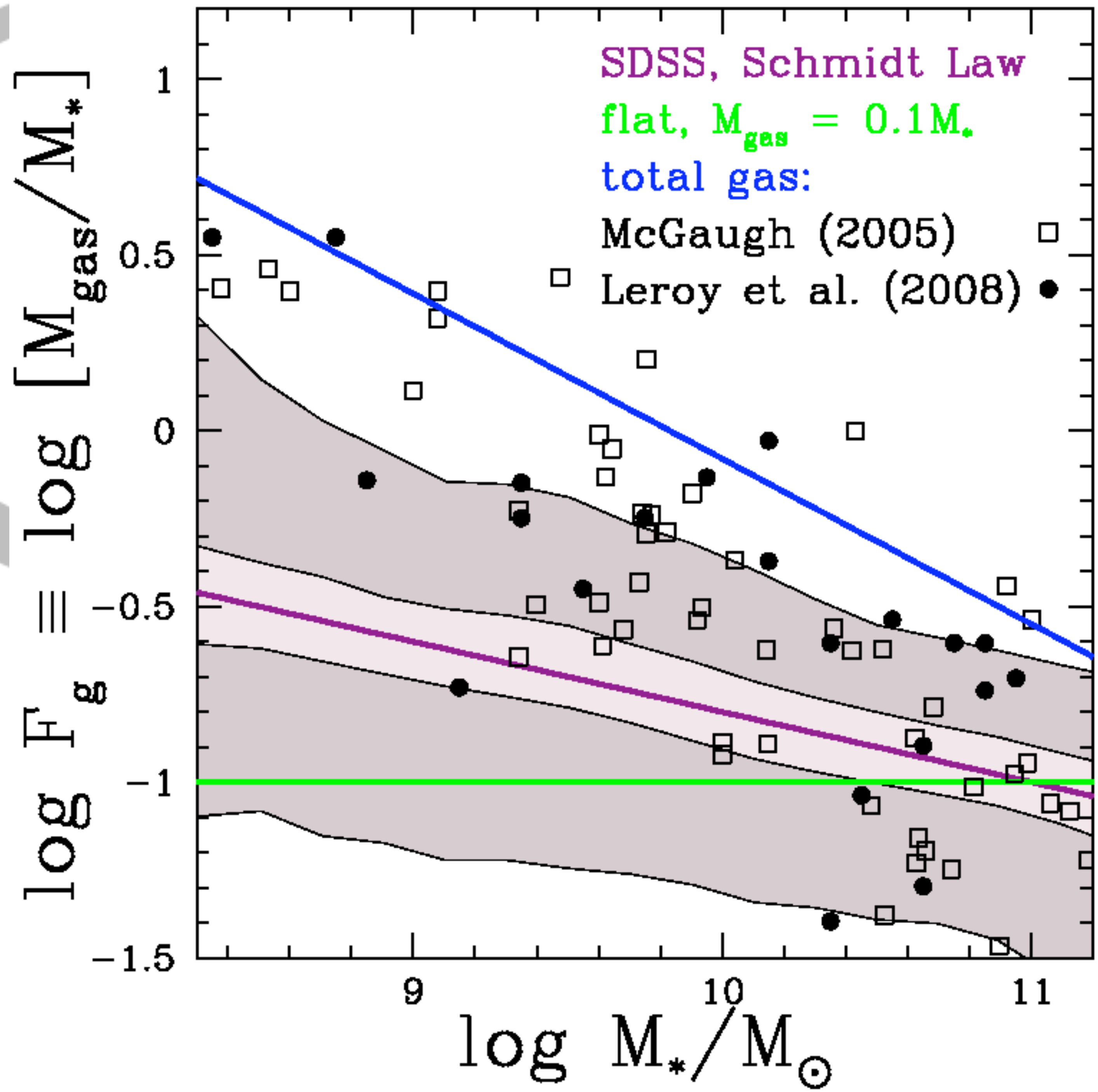
($F_g=M_g/M_*$ $=kM_*^{-\gamma}$)



3x10⁹ M⊙ gas
2x10⁹ M⊙ gas
convert into
1x10⁹ M⊙ stars,
1x10⁹ M⊙ gas
convert into
1x10⁹ M⊙ stars,
2x10⁹ M⊙ gas
accrete
1x10⁹ M⊙ gas

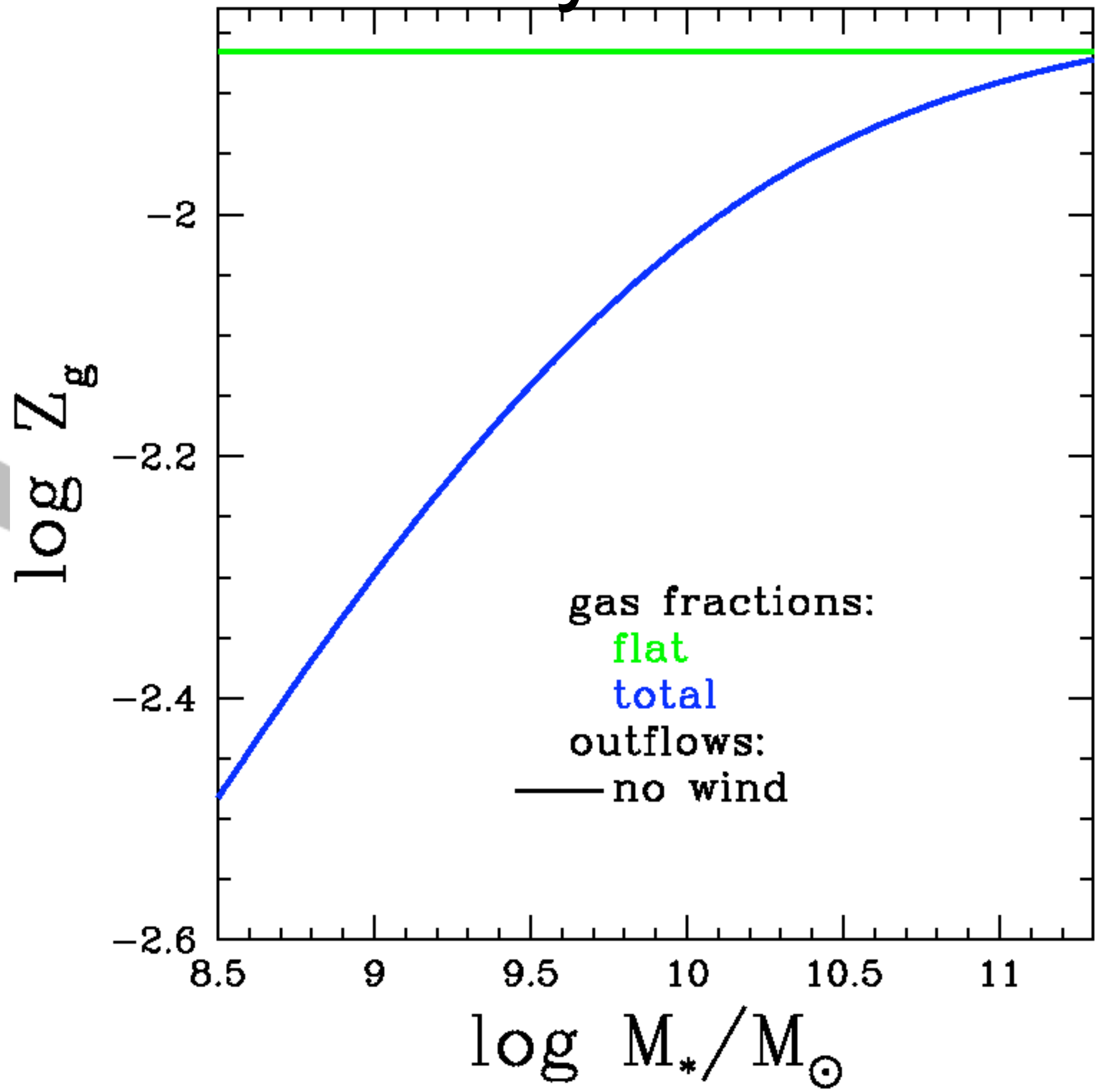


3x10^9 M⊙ gas
2x10^9 M⊙ gas
4x10^9 M⊙ gas
convert into
1x10^9 M⊙ stars,
1x10^9 M⊙ gas
1x10^9 M⊙ stars,
3x10^9 M⊙ gas
convert into
1x10^9 M⊙ stars,
2x10^9 M⊙ gas
accrete
1x10^9 M⊙ gas
Z_wind=Z_g
1x10^9 M⊙ outflow

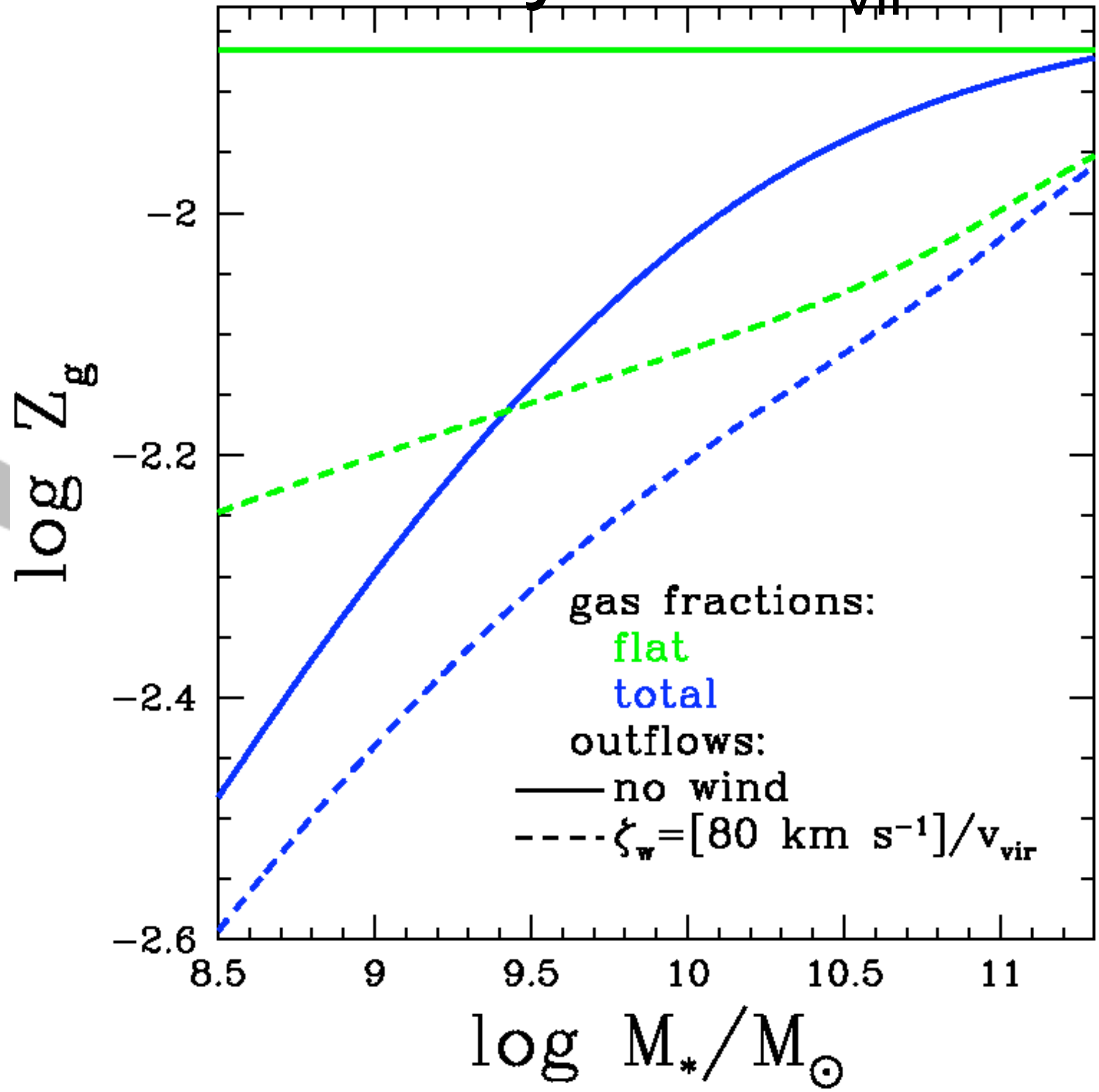


SDSS, Schmidt Law
flat, $M_{gas} = 0.1M_*$
total gas:
McGaugh (2005)
Leroy et al. (2008)
$\log F_g \equiv \log [M_{gas}/M_*]$
$\log M_*/M_\odot$
1
0.5
0
−0.5
−1
−1.5
9
10
11

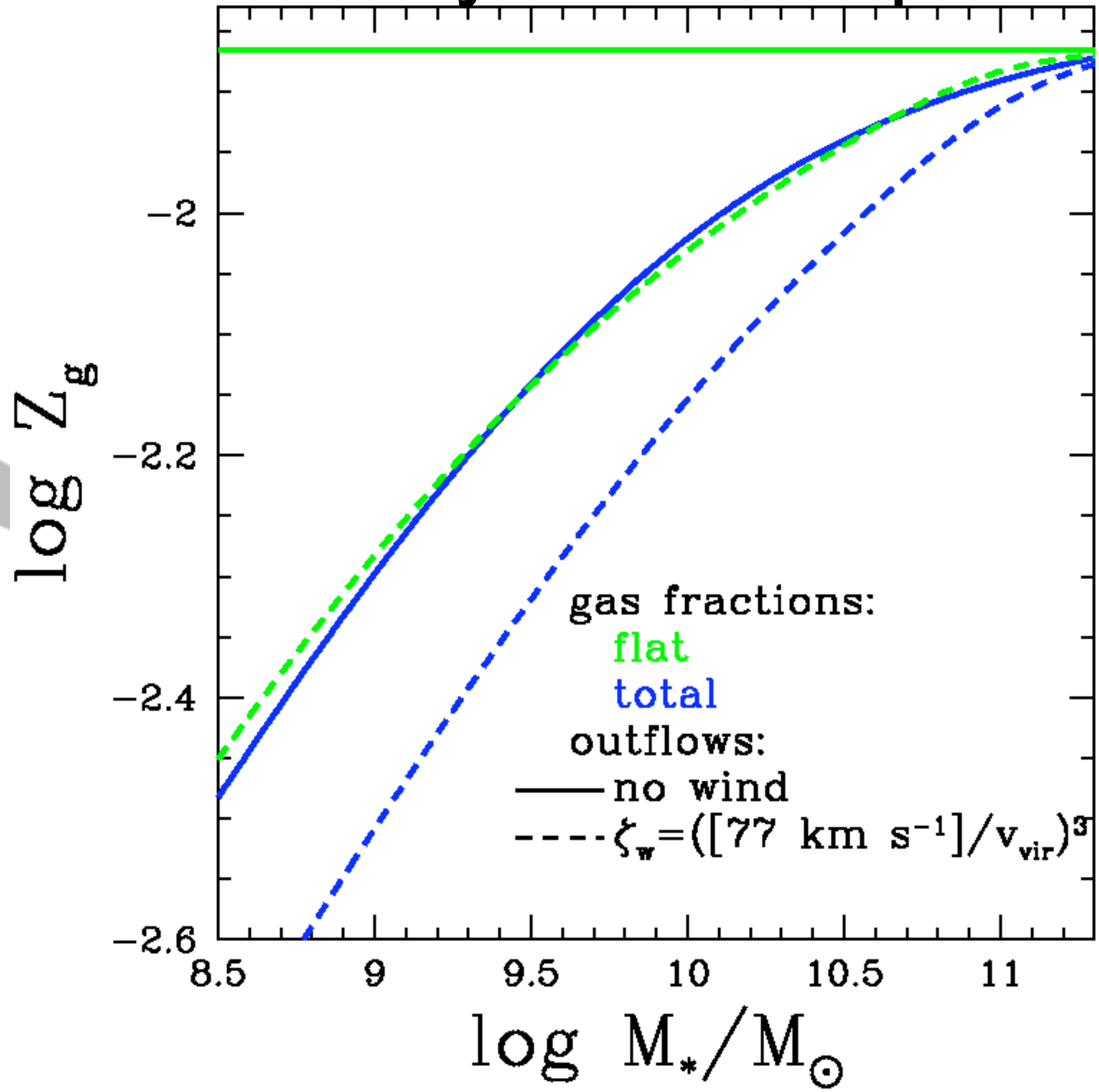
mass-metallicity with no winds...



mass-metallicity with v_{vir}^{-1} winds...



mass-metallicity with steeper winds...



So how do outflows & gas balance?

$$\frac{dZ_g}{dM_*} = \frac{y - Z_g\left(\boxed{\zeta_w} + 1 + \boxed{F_g[1-\gamma]}\right)}{\boxed{M_g}(1 - f_{recy})}$$

Winds

$$\boxed{\zeta_w \equiv \frac{Z_w}{Z_g}\eta_w = \frac{Z_w \dot{M}_w}{Z_g \dot{M}_{SFR}}}$$

Dilution

($F_g = M_g/M_*$
$= kM_*^{-\gamma}$)

So how do outflows & gas balance?

$$\frac{y}{Z_{\mathrm{g}}} - 1 = \boxed{\zeta_{\mathrm{w}}} + (1 - f_{\mathrm{recy}})\left[\frac{d\log M_{\mathrm{g}}}{d\log M_{*}} + \frac{d\log Z_{\mathrm{g}}}{d\log M_{*}}\right]\boxed{F_{\mathrm{g}}}$$

Winds

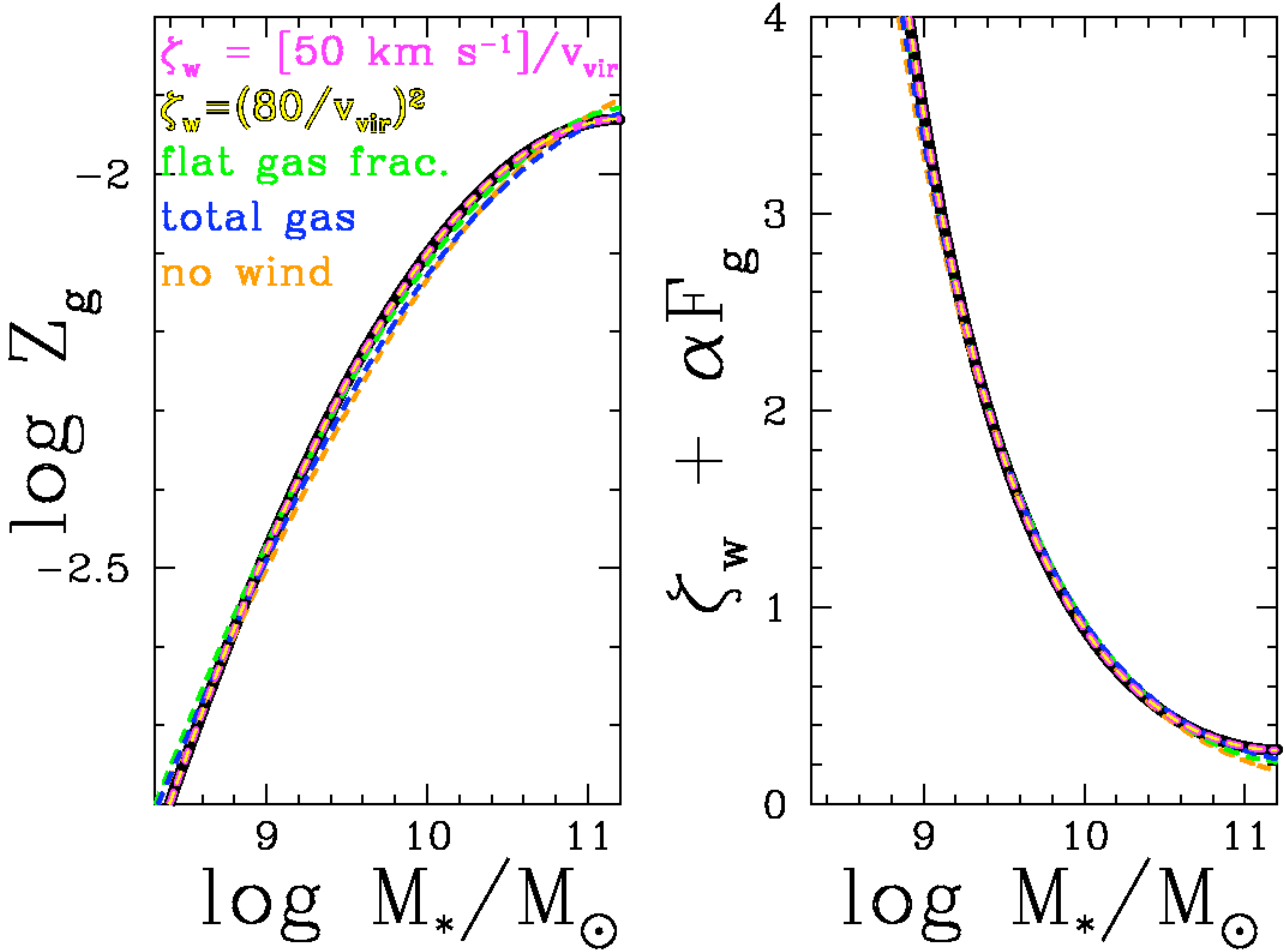
Dilution

So how do outflows & gas balance?

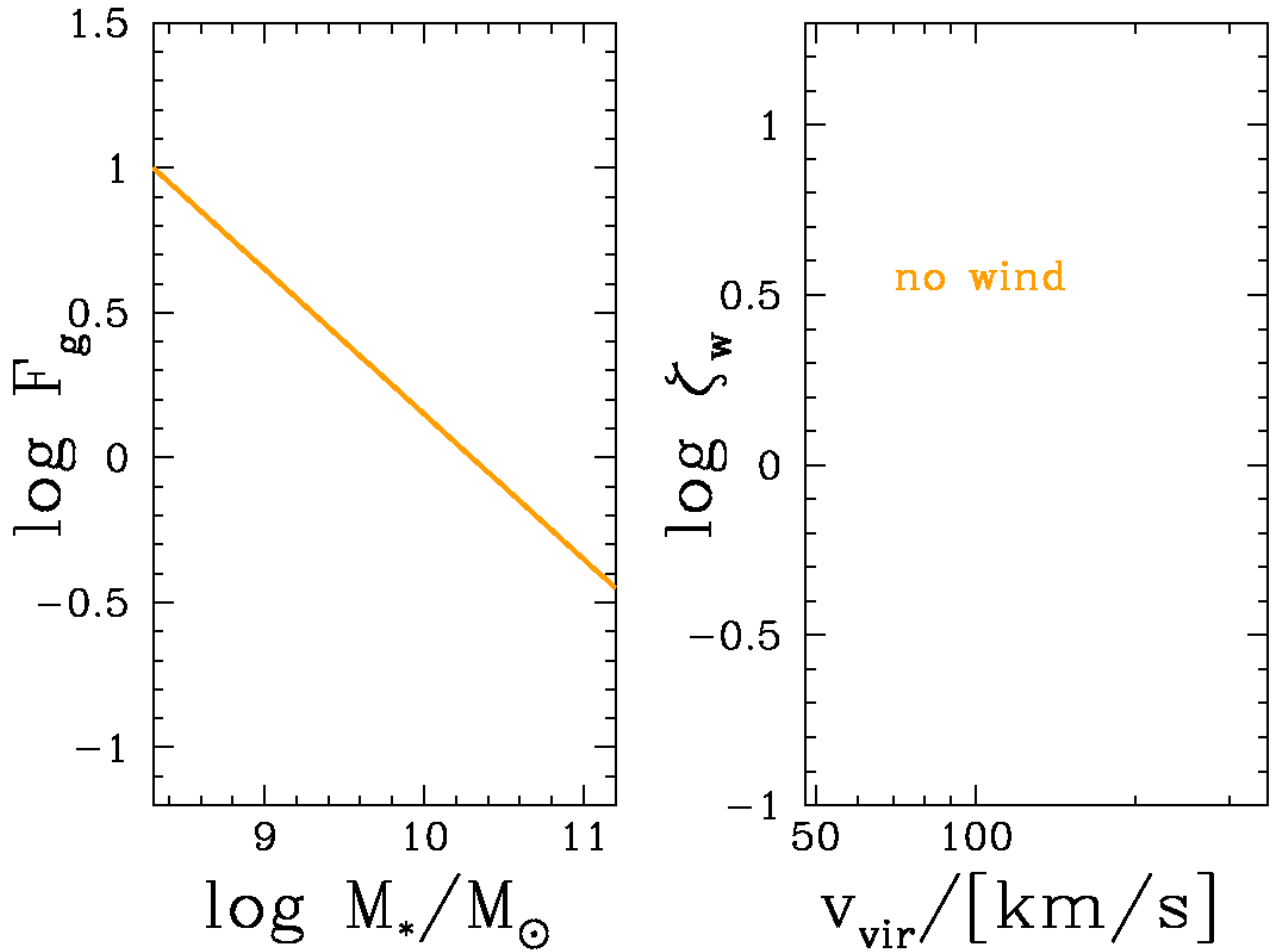
$$\frac{y}{Z_g} - 1 = \boxed{\zeta_w} + \boxed{\alpha F_g}$$

Winds

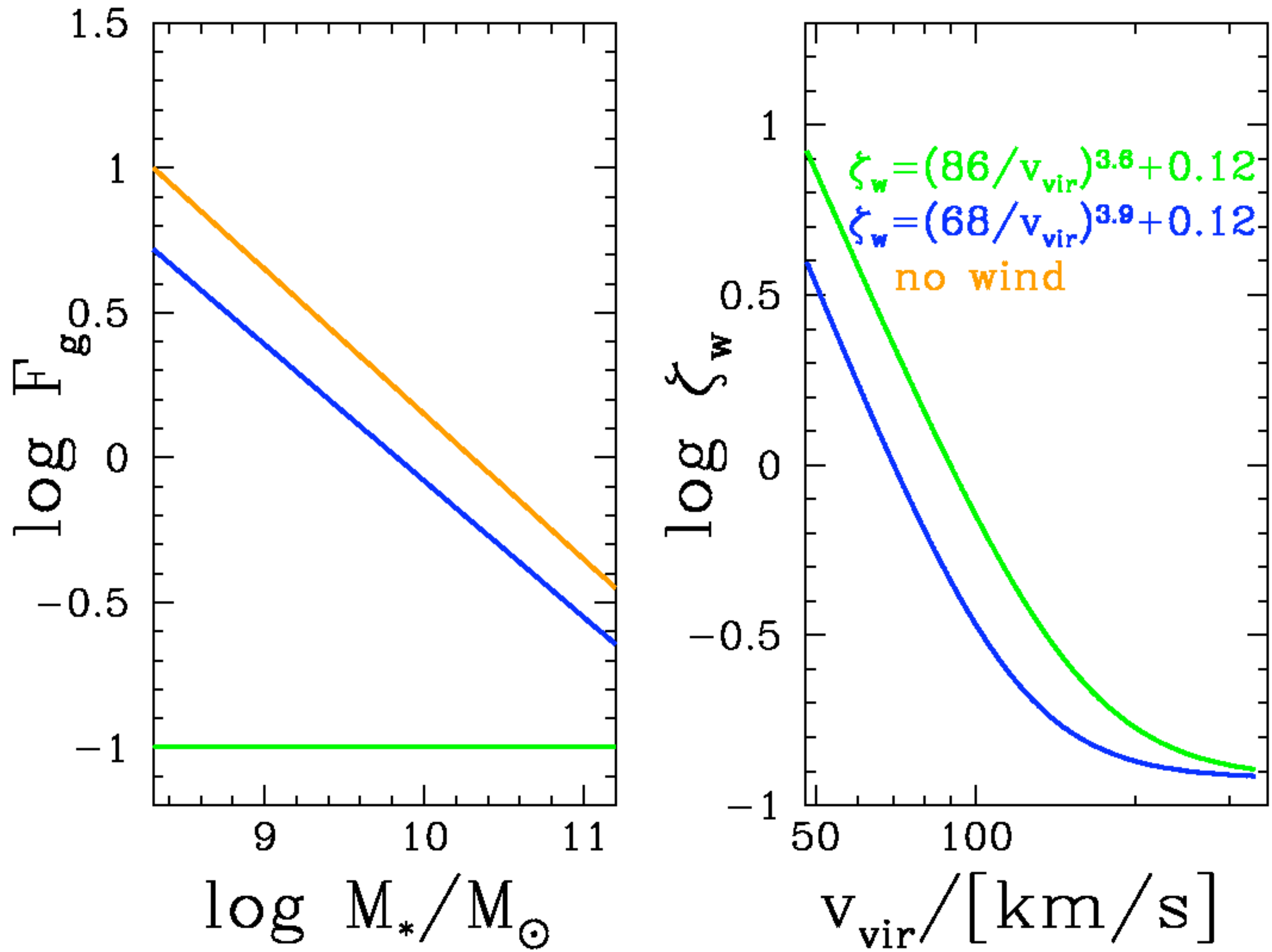
Dilution



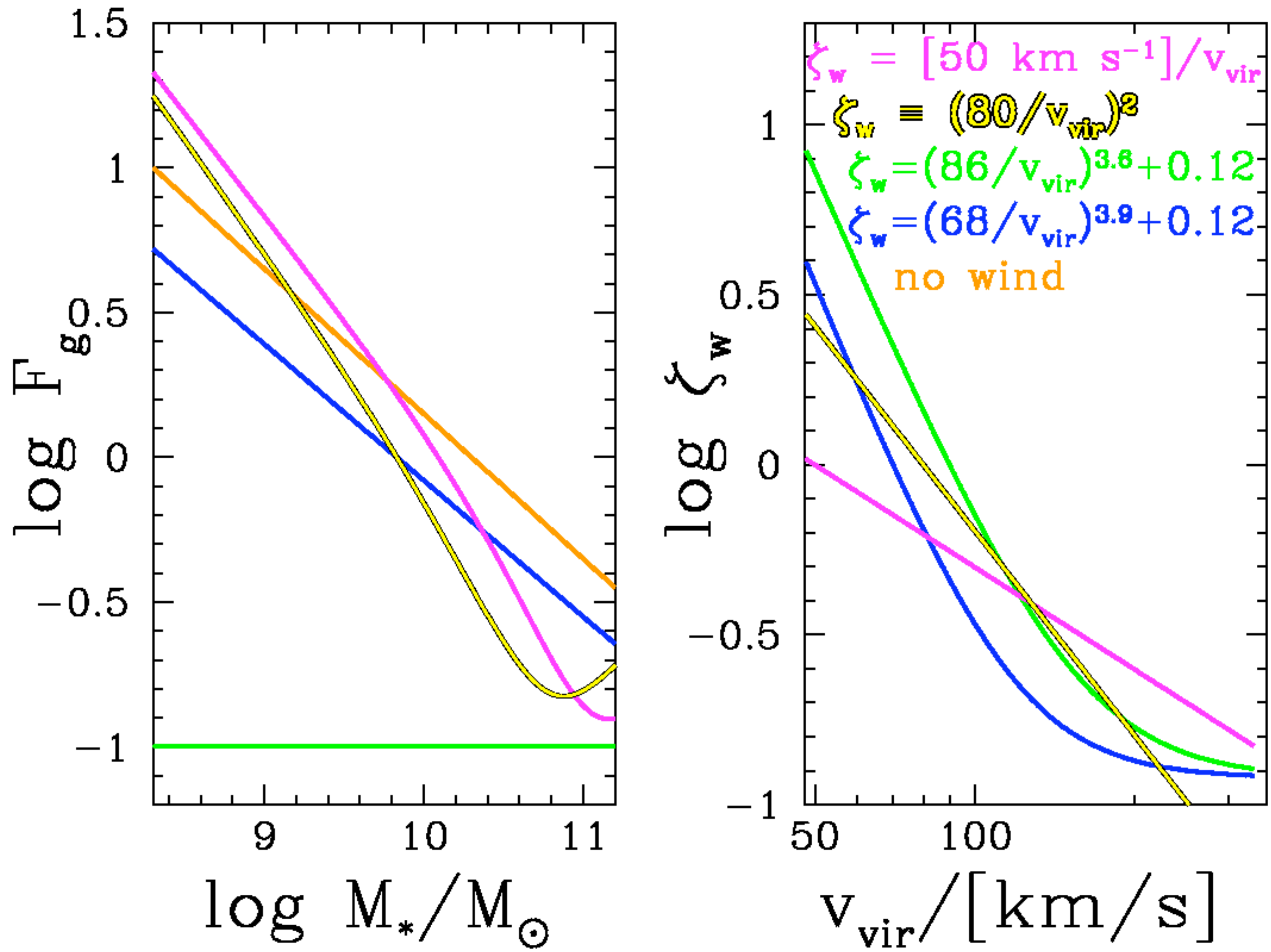
ζ_w = [50 km s^{-1}]/v_{vir}
ζ_w=(80/v_{vir})^2
flat gas frac.
total gas
no wind
$\log Z_g$
−2
−2.5
9
10
11
$\log M_*/M_\odot$
$\zeta_w + \alpha F_g$
0
1
2
3
4
9
10
11
$\log M_*/M_\odot$



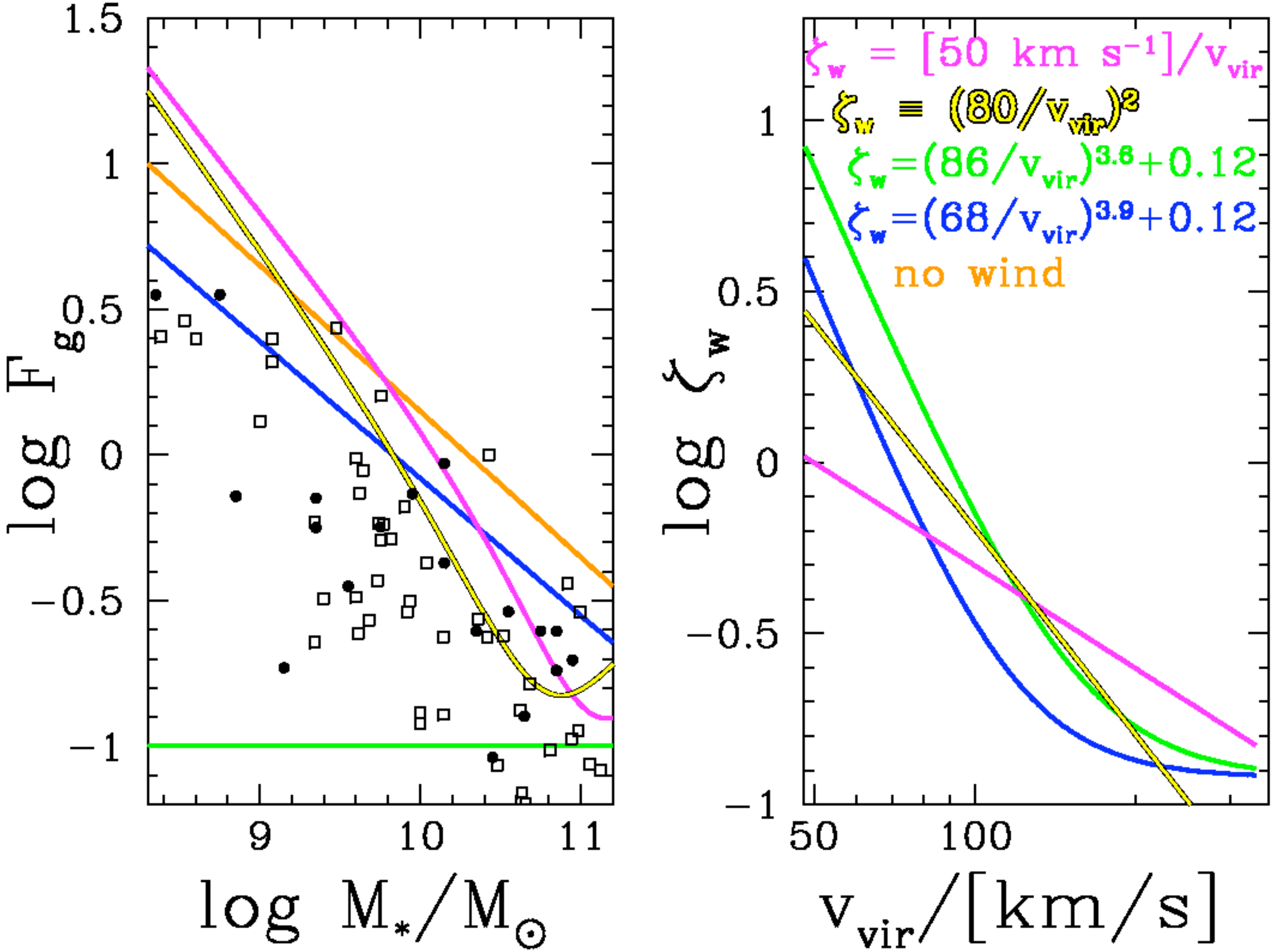
1.5
1
0.5
0
−0.5
−1
log F_g
9
10
11
log $M_*/M_\odot$
no wind
1
0.5
0
−0.5
−1
log ζ_w
50
100
v_{vir}/[km/s]



1.5
1
0.5
0
−0.5
−1
log F_g
9
10
11
log $M_*/M_\odot$
1
0.5
0
−0.5
−1
log ζ_w
$\zeta_w=(86/v_{vir})^{3.6}+0.12$
$\zeta_w=(68/v_{vir})^{3.9}+0.12$
no wind
50
100
$v_{vir}/[km/s]$



1.5
1
0.5
0
−0.5
−1
log F_g
9
10
11
log $M_*/M_\odot$
ζ_w = [50 km s^{-1}]/v_{vir}
$\zeta_w \equiv (80/v_{vir})^2$
$\zeta_w=(86/v_{vir})^{3.6}+0.12$
$\zeta_w=(68/v_{vir})^{3.9}+0.12$
no wind
log ζ_w
50
100
v_{vir}/[km/s]



$\zeta_w = [50 \text{ km s}^{-1}]/v_{vir}$
$\zeta_w \equiv (80/v_{vir})^2$
$\zeta_w = (86/v_{vir})^{3.6} + 0.12$
$\zeta_w = (68/v_{vir})^{3.9} + 0.12$
no wind
log F_g
log $M_*/M_\odot$
log ζ_w
v_{vir}/[km/s]

Where might the model be breaking down?

- Assumptions:
  - $Z_{wind}=Z_{gas}$ implies $\zeta_w=\eta_w$
  - gas is well mixed
  - galaxies forming stars stay on relations (gas fraction and mass-metallicity relations)
  - monotonic halo-galaxy model works
  - constant IMF (yield)

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- Assumptions:
  - $Z_{wind}=Z_{gas}$ implies $\zeta_w=\eta_w$ ➔ enforcing shallower letting η_w scaling gives unphysical $Z_{wind}(M_*)$
  - gas is well mixed ➔ observations average over large fraction of galaxy
  - galaxies forming stars stay on relations (gas fraction and mass-metallicity relations) ➔ but small scatter
  - monotonic halo-galaxy model works ➔ OK for many other applications
  - constant IMF (yield) ➔ no good observational evidence

Mass-metallicity relation modeling: take-home message

- outflows and dilution balance in simple way:

$$Z_{\mathrm{g}} = y(\zeta_{\mathrm{w}} + \alpha F_{\mathrm{g}} + 1)^{-1}$$

- this is a **general** result; pieces can vary with [stellar or halo] mass or redshift arbitrarily
- z=0 implications: if accreted metals negligible, then steep ζ_w (& therefore η_w) scaling with v_{vir} (or M_{halo}) required