Inflow and outflow rate of star-forming galaxies at z~1.4

Kiyoto Yabe (Kavli IPMU)

Based on Yabe et al 2015, ApJ, 798, 45

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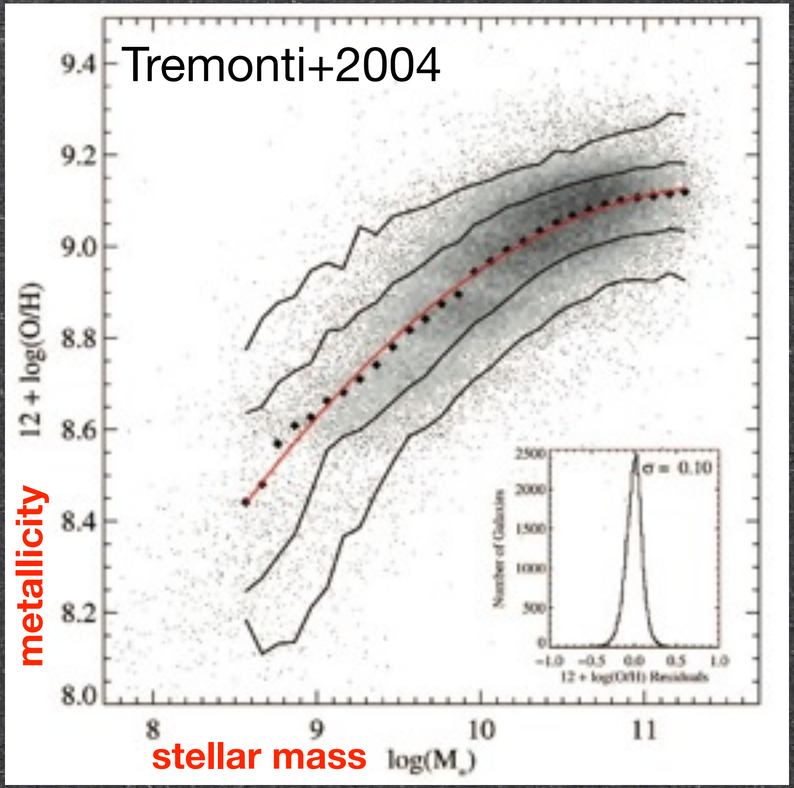
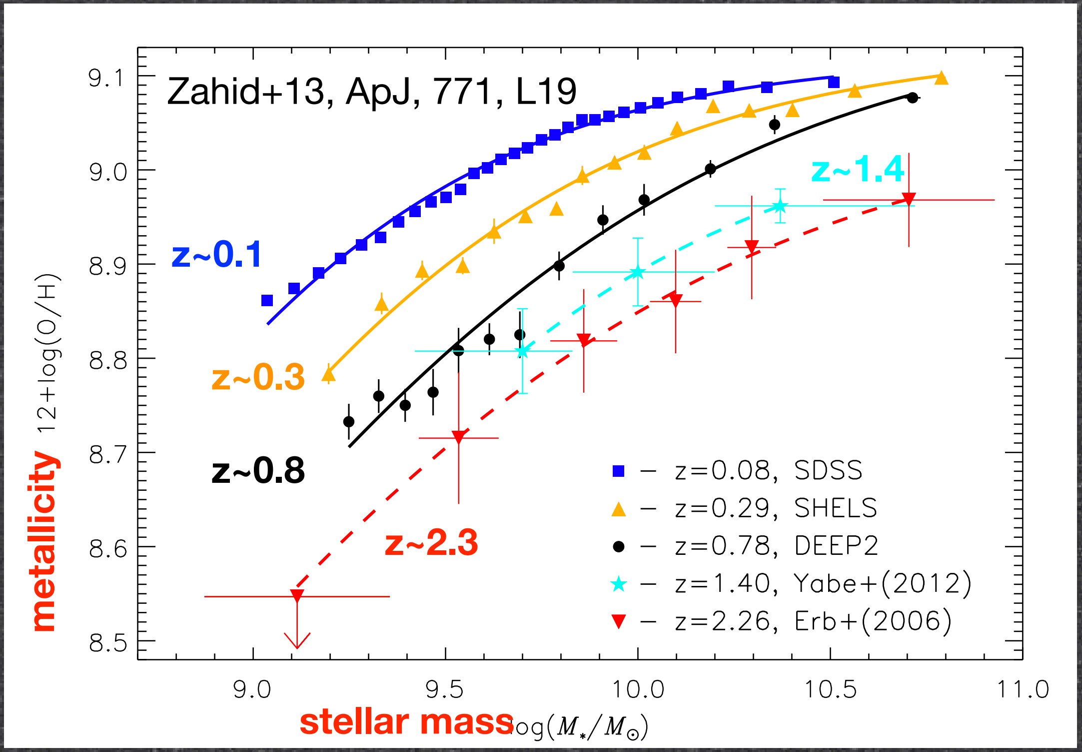
Scientific Background:

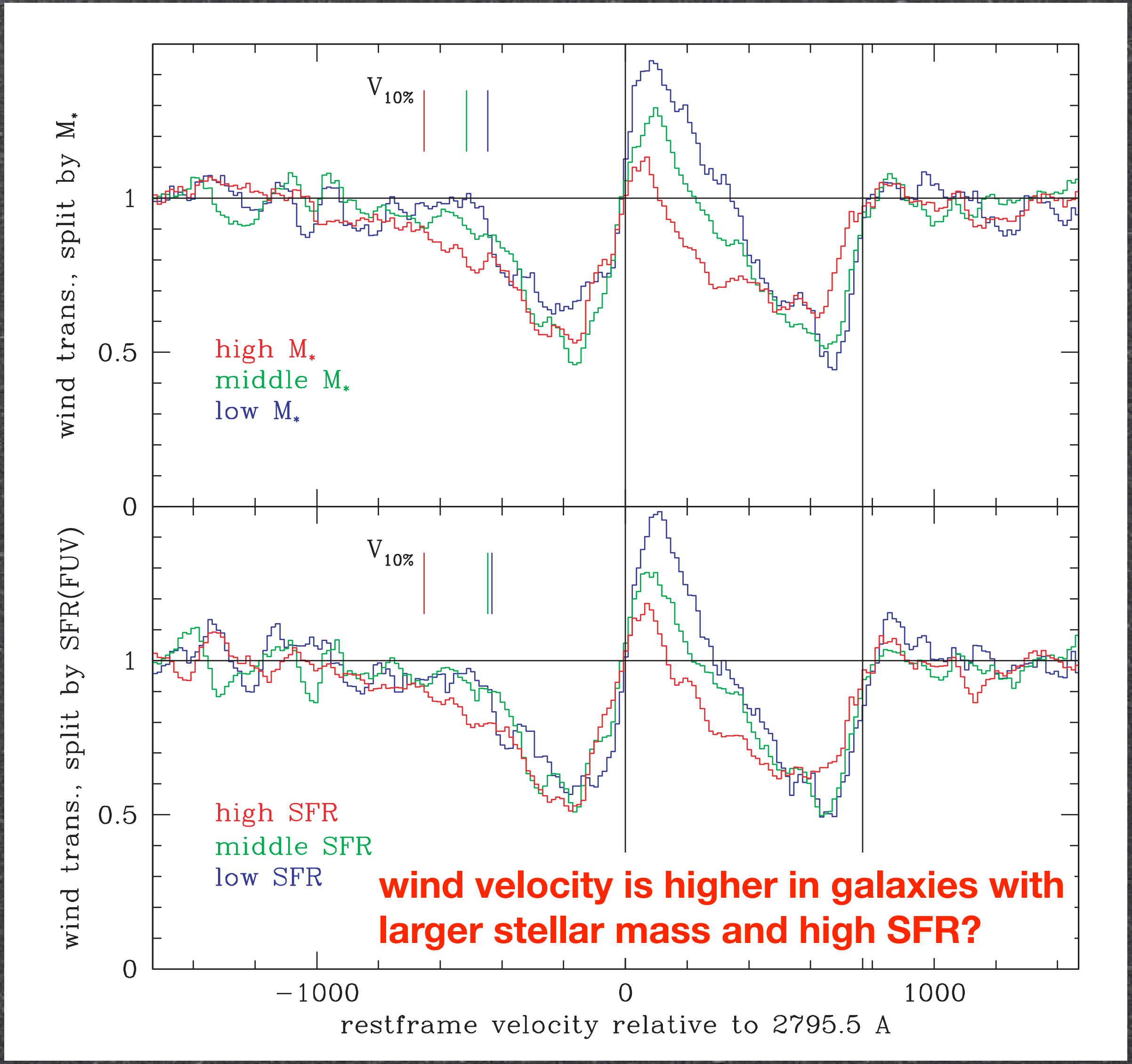
- Star-formation history traced by gas phase metallicity
  - ✓ Metallicity as a tracer of the past star-formation activity
  - ✓ Correlation between stellar mass and metallicity (mass-metallicity relation; MZR)
  - ✓ MZR evolves with redshift (higher metallicity with increasing redshift)
  - ✓ MZR at z>1 still remains unclear due to limited sample size
- Metallicity is affected by gas inflow (dilution effect) and outflow (expel of enriched gas)

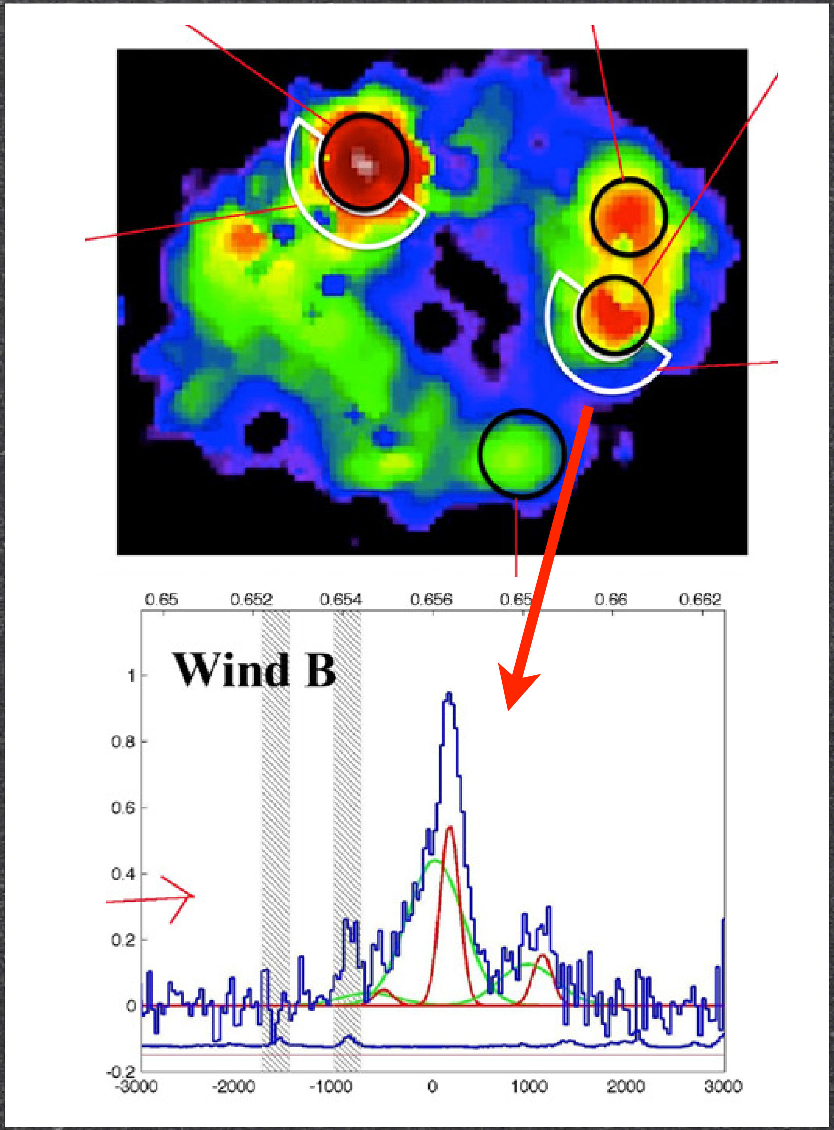




Importance of Inflow and Outflow:

- Various observational evidences of gas outflows in high-z galaxies
- Strong and ubiquitous outflows at high redshift





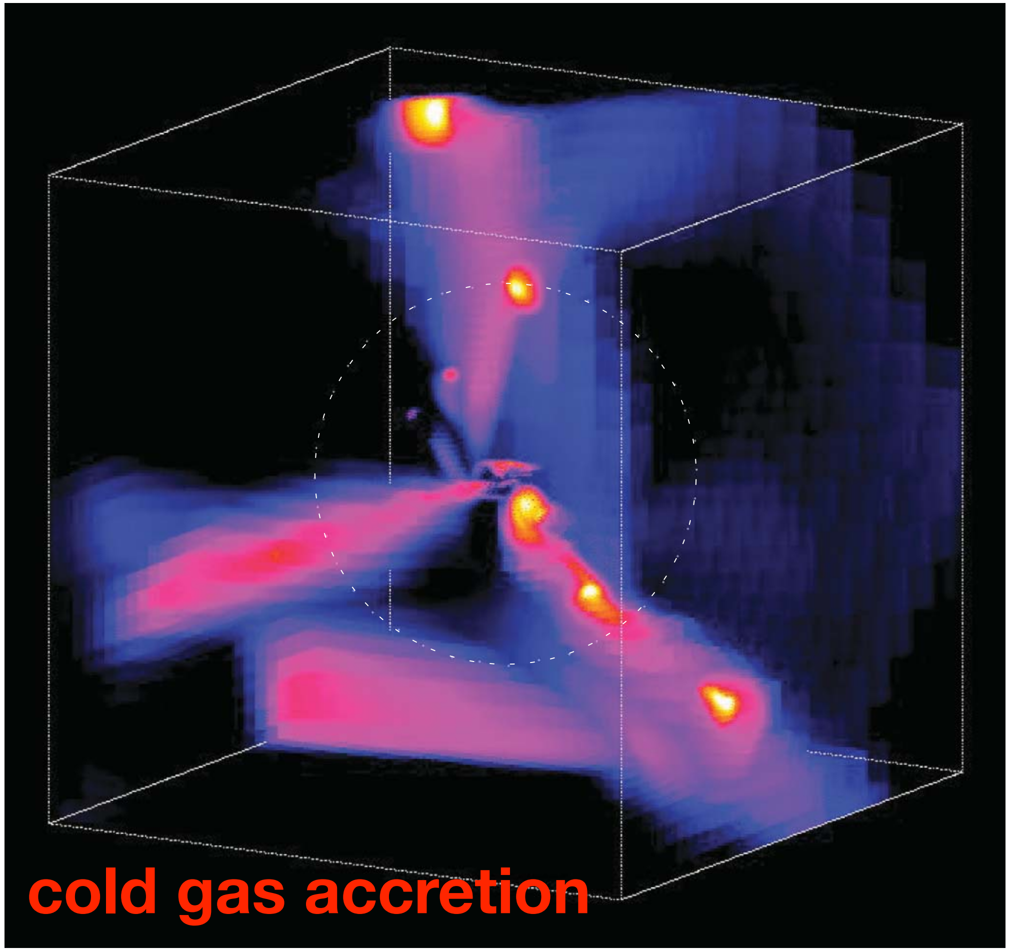
Weiner et al. 2009, ApJ, 692, 187

Newman et al. 2012, ApJ, 752, 111

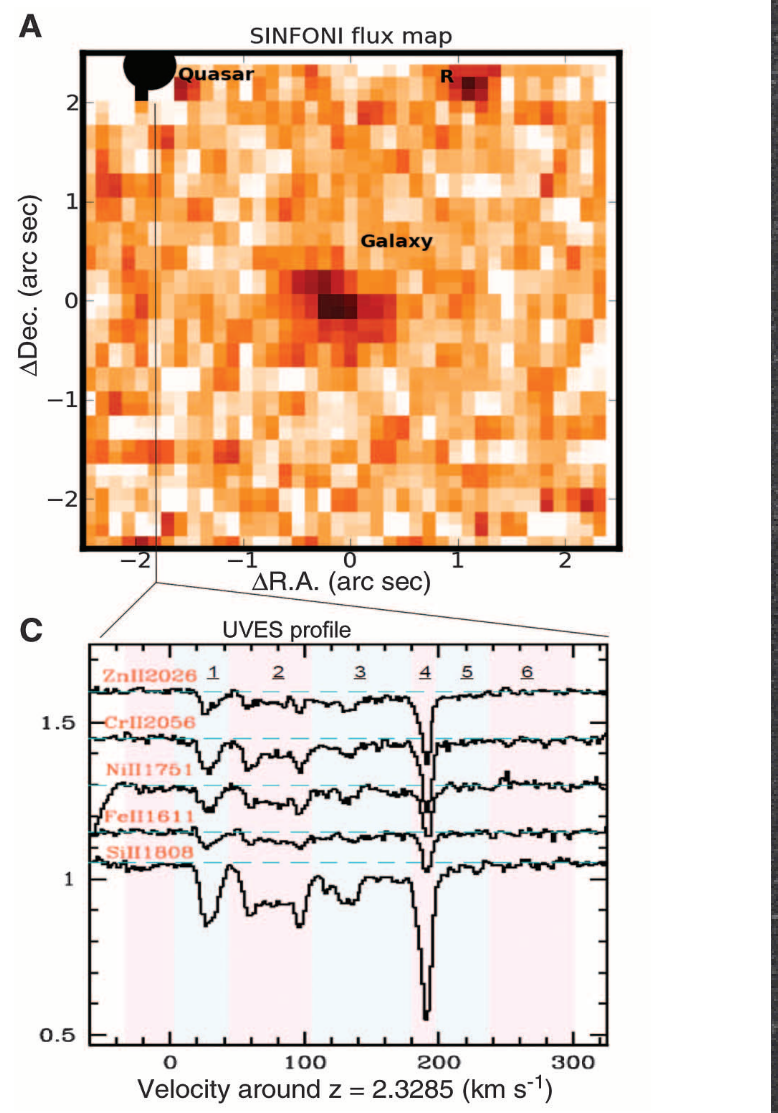
Importance of Inflow and Outflow:

- Importance of cold accretion of gas in the galaxy evolution
- Some observational evidence of gas inflow at high redshift?
- But, the direct detection of pristine gas inflow is still difficult ...

Dekel et al. 2009, Nature, 457, 22

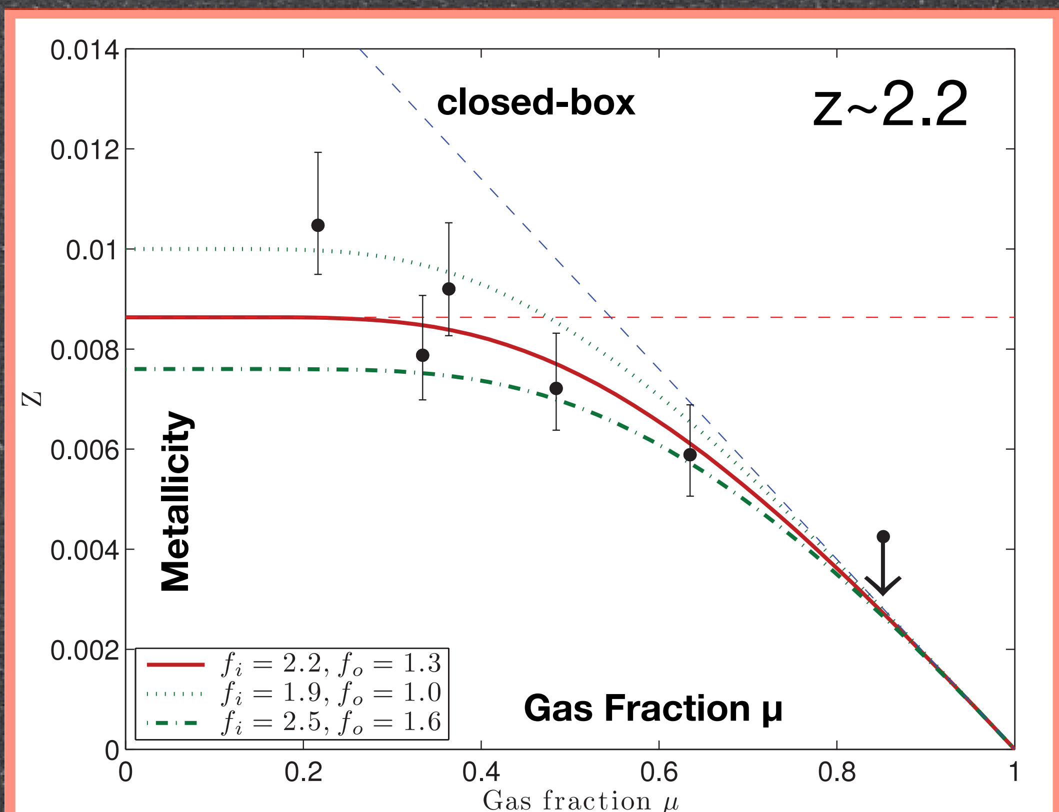


Bouché et al. 2013, Science, 341, 50

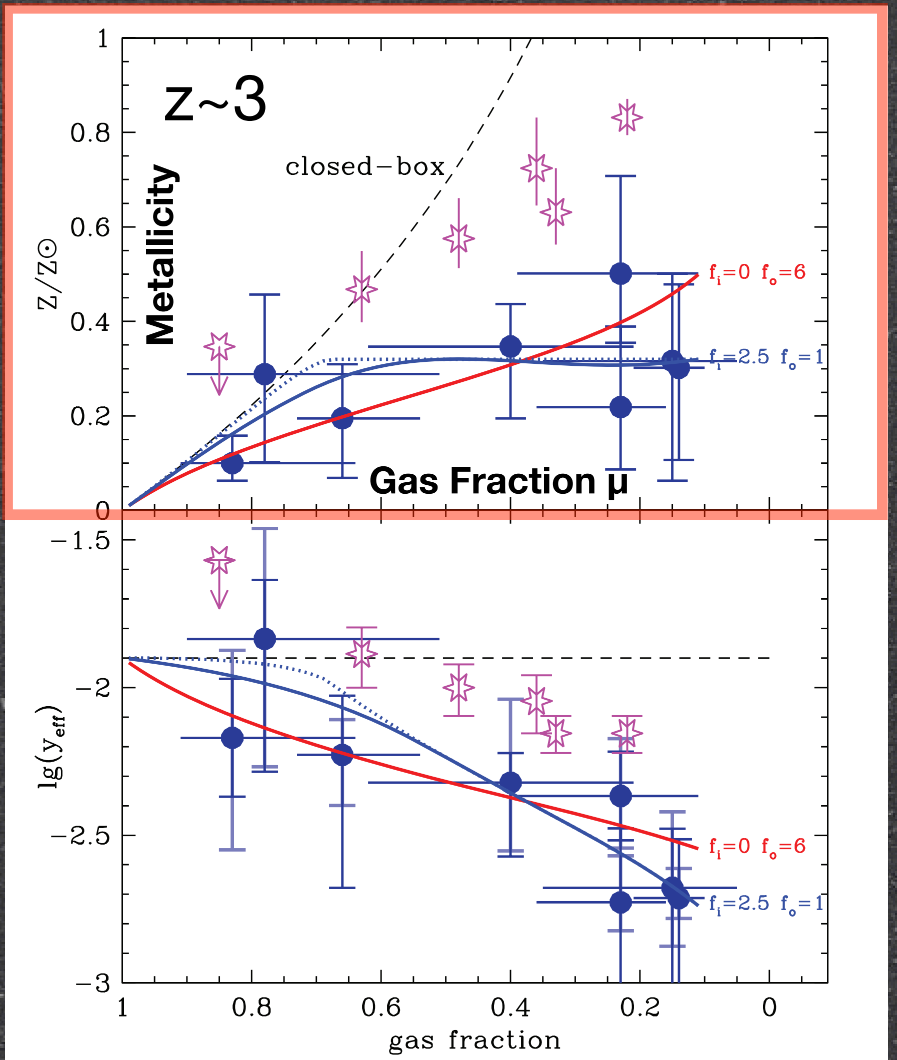


Importance of Inflow and Outflow:

- Metallicity also changes through gas infall/outflow process
- Constraint on the inflow/outflow rate by using metallicity, gas fraction
  - ✓ e.g., Erb et al. 2006, Erb 2008 (z~2), Mannucci et al. 2009 (z~3)
  - ✓ A certain amount of inflow/outflow is required
  - ✓ Sample size, however, is still limited
  - ✓ Gas mass estimation is uncertain



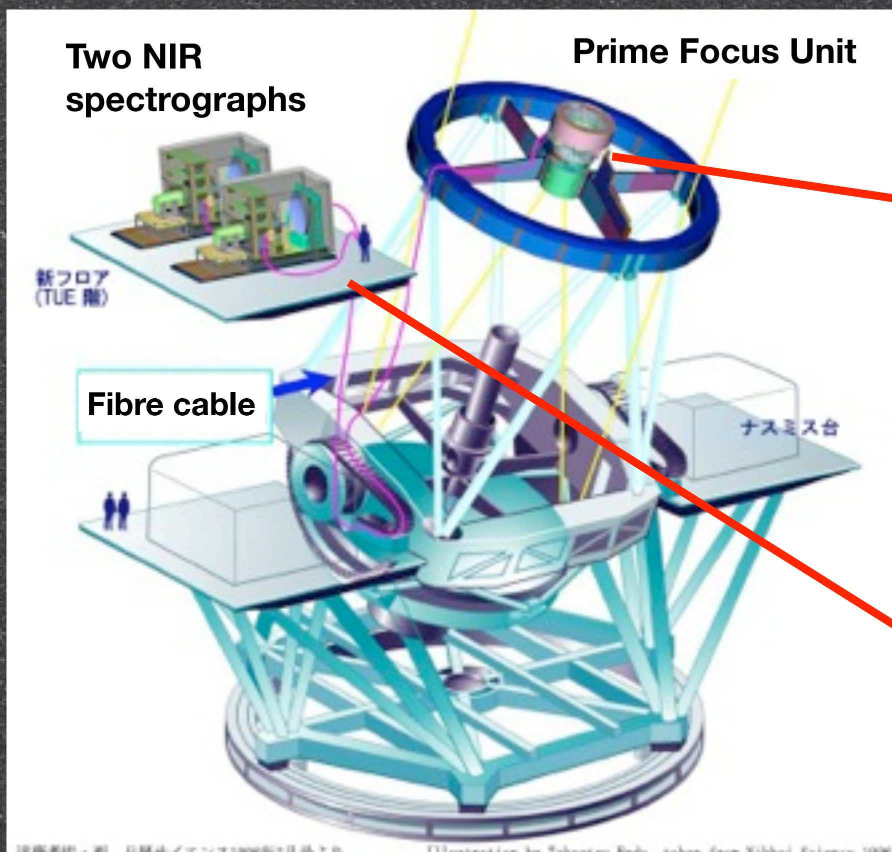
Erb 2008, ApJ, 674, 151



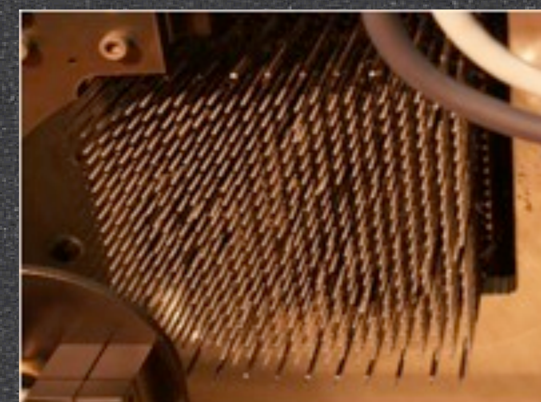
Mannucci et al. 2009, MNRAS, 398, 1915

FMOS (Fibre Multi Object Spectrograph):

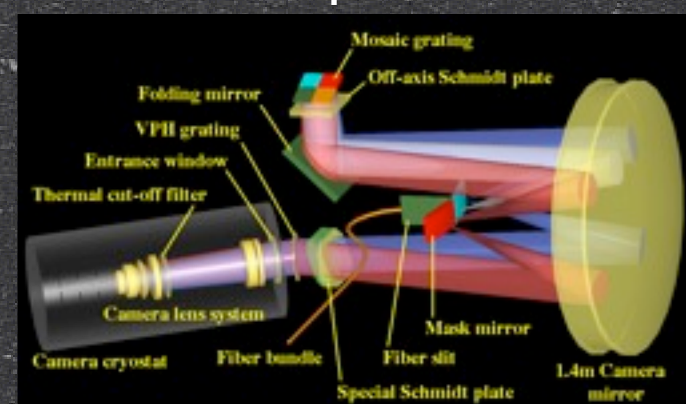
- What is FMOS?
  - ✓ Fibre-fed NIR multi-object spectrograph on the Subaru Telescope (8.2m)
  - ✓ Prime Focus Unit with fibre positioner “Echidna” (400 fibres, 30 arcmin Φ)
  - ✓ Two NIR (0.9 - 1.8μm) spectrographs (IRS1 & 2)
  - ✓ Low Resolution (LR; R~650) and High Resolution (HR; R~3000) mode
  - ✓ Details are presented by Kimura et al. 2010, PASJ, 62, 1135



FMOS on the Subaru Telescope



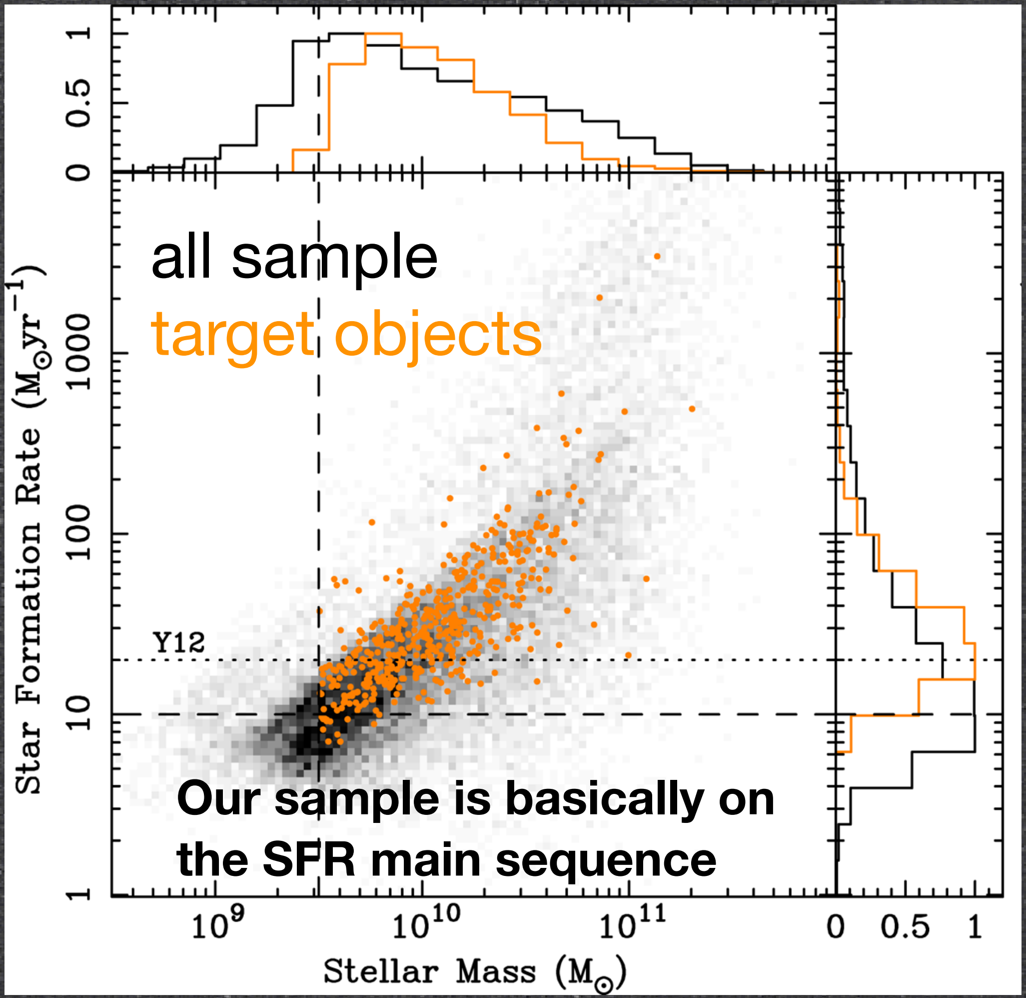
Fiber positioner “Echidna”



Optical design of FMOS including OH-mask mirror

Hα detected sample galaxies at z~1.4:

- Target selection
  - ✓ K-band selected galaxies
  - ✓ $1.2<z_{phot}<1.6$, K<23.9 AB mag, $M_*>10^{9.5}$ M_{sun}
  - ✓ Expected Hα flux cut with $F(H\alpha)^{exp}>5.0\times10^{-17}$ cgs
- Observations
  - ✓ (mainly) GTO time
  - ✓ Low resolution (LR) mode
  - ✓ λ coverage: 0.9 - 1.8 μm
  - ✓ Typical on-source exposure time is 3-4 hours
  - ✓ **Hα detections with S/N>3 from 343 galaxies at z~1.4**



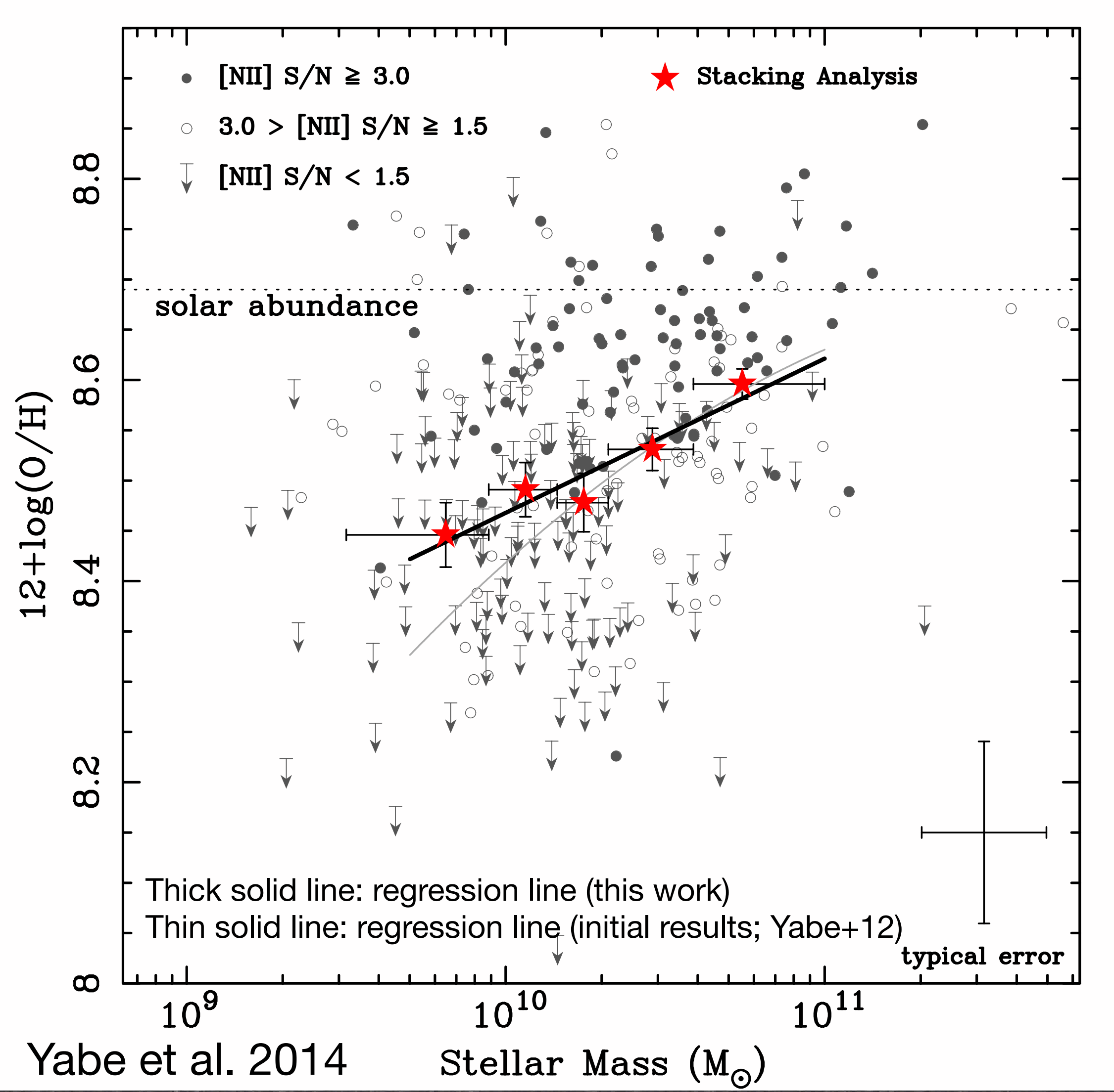
Gas Metallicity:

- Gas metallicity is derived derived from [NII]λ6584/Hα line ratio
- Empirical metallicity calibration with N2 index (Pettini & Pagel 04)
- The mass-metallicity relation at z~1.4 (Yabe et al. 2012, 2014)

✓ Most of our sample show non-detections of [NII] emission lines
➡ stacking analysis

✓ More massive galaxies show high metallicity (MZR)

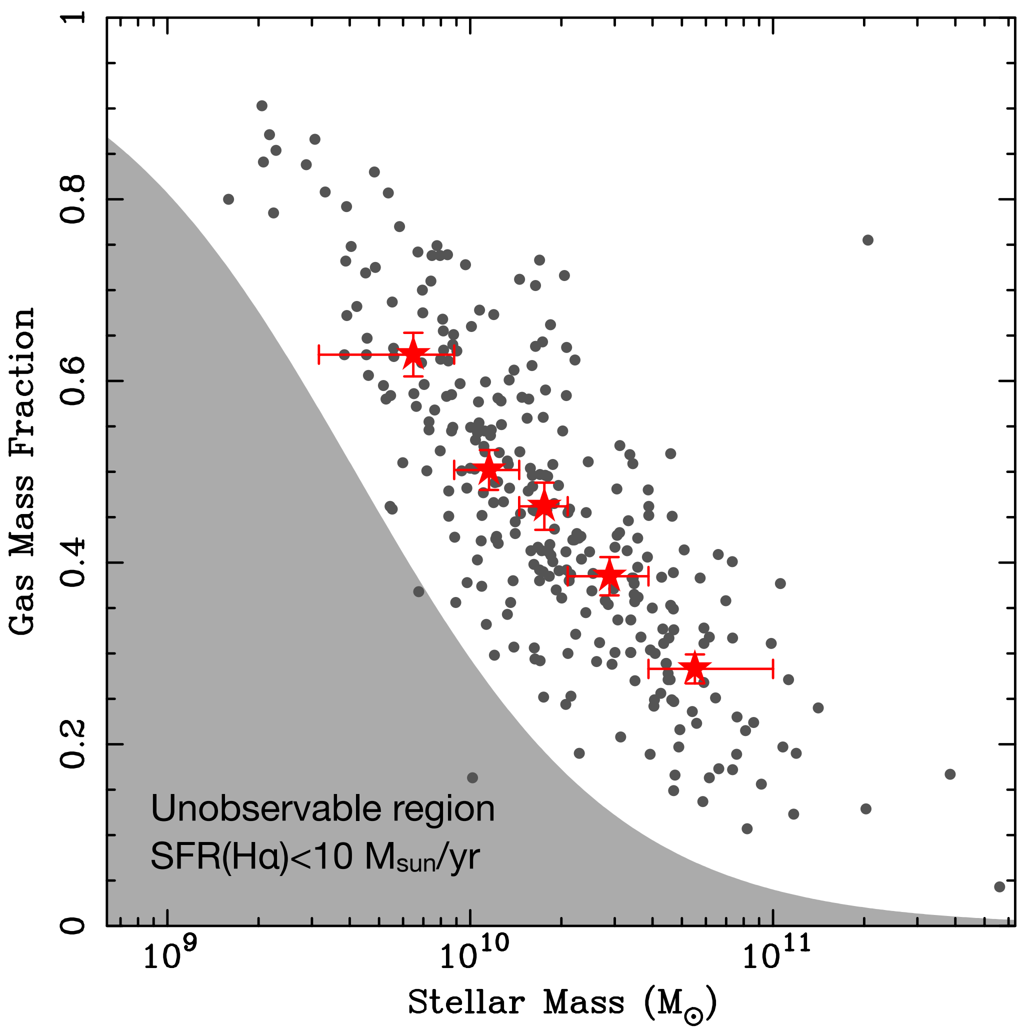
✓ Note that there exists a large scatter in the relation

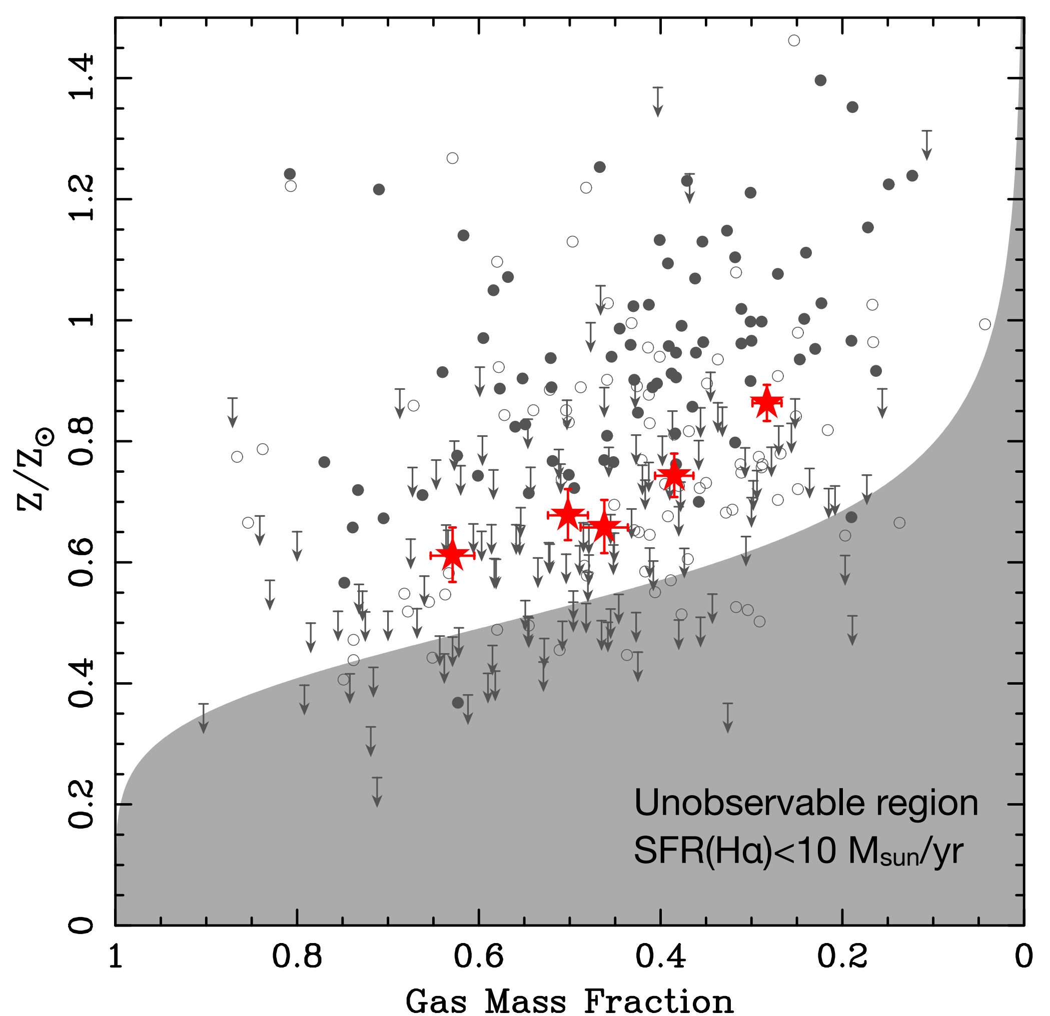


Yabe et al. 2014

Stellar Mass, Gas Mass Fraction, and Metallicity:

- Gas mass is derived from Hα luminosity (Kennicutt-Schmidt law)
- Galaxy size is defined by the half light radius in B-band (rest-UV)
- Gas mass fraction is defined as: $\mu = M_{gas}/(M_{gas}+M_{star})$
- Galaxies with larger stellar mass tend to show lower gas mass fraction
- Galaxies with lower gas mass fraction tend to show higher metallicity





Analytic Model of the Chemical Evolution:

- Inflow/Outflow rate is constrained by using a simple analytic model
- c.f., Matteucci 2001 “The chemical evolution of galaxies” (ASSL)
- (Basically) the same simple model as Erb 08 and Mannucci+09 used
- We assume both inflow and outflow rate is proportional to the SFR, i.e., the inflow rate is $dM_{in}/dt=(1-R)f_i\Phi(t)$ and the outflow rate is $dM_{out}/dt=(1-R)f_o\Phi(t)$, where R is return fraction and Φ(t) is SFR.

$$Z = \frac{y_Z}{f_i}\{1-[(f_i-f_o)-(f_i-f_o-1)\mu^{-1}]^{\frac{f_i}{f_i-f_o-1}}\},$$

$$\mu = \frac{M^0_{gas}+(f_i-f_o-1)M_*}{M^0_{gas}+(f_i-f_o)M_*},$$

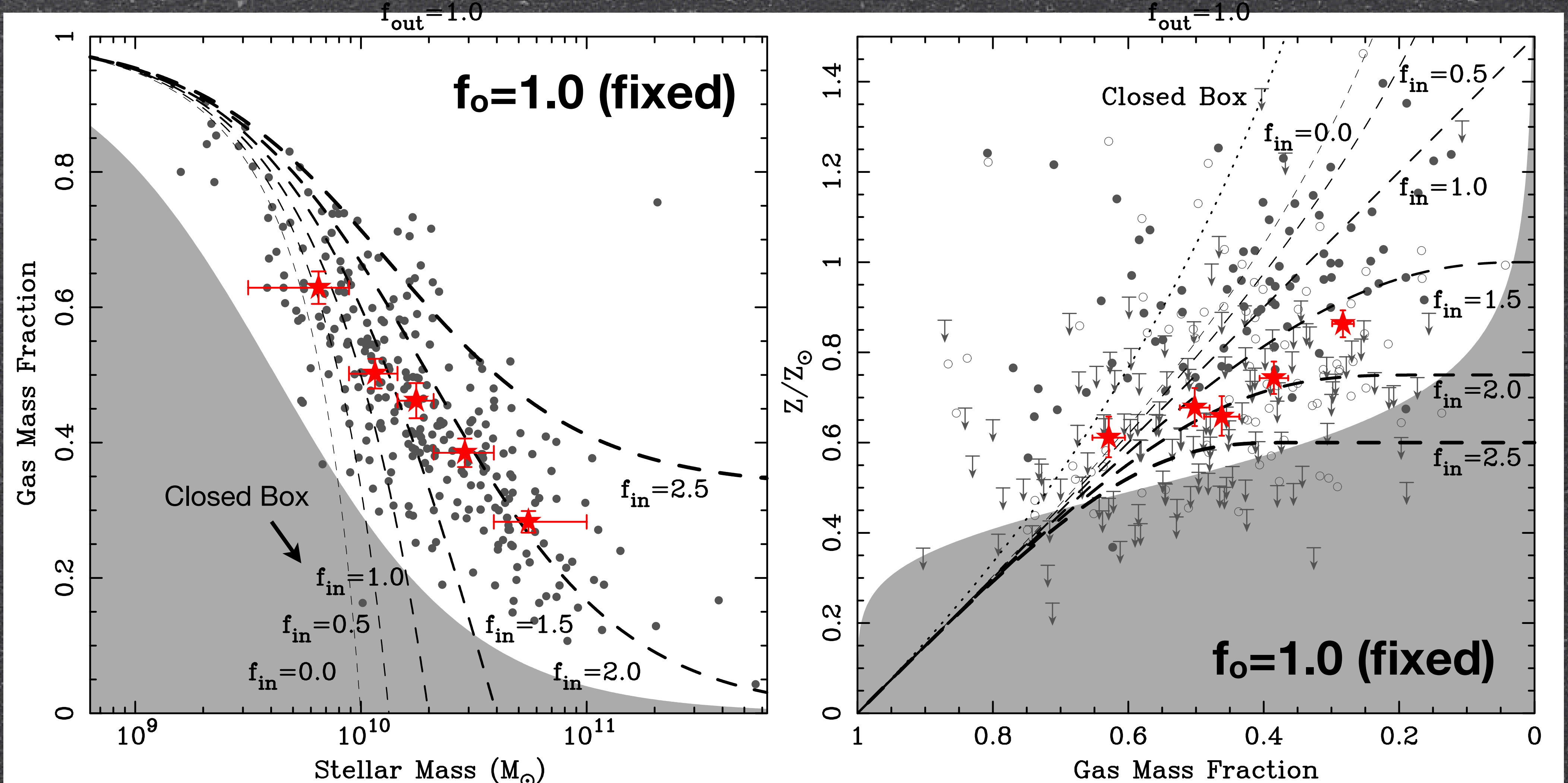
where Z is the metallicity and μ is the gas mass fraction. M^0_{gas} is the initial gas mass and M* is the stellar mass.

Other assumptions:

- Instantaneous Recycling Approximation (IRA)
- The initial gas is primordial (metal free)
- The initial mass function (IMF) is constant in time
- The true yield (y_Z) is assumed to be 1.5 Z_{sun}

Inflow/Outflow Rate in galaxies at z~1.4:

- Inflow/Outflow rate is constrained by using a simple analytic model
- c.f., Matteucci 2001 “The chemical evolution of galaxies” (ASSL)
- Gas mass fraction increases with increasing inflow at a fixed stellar mass
- Metallicity decreases with increasing inflow at a fixed gas mass fraction
- Note that simple closed box models can not explain the observations



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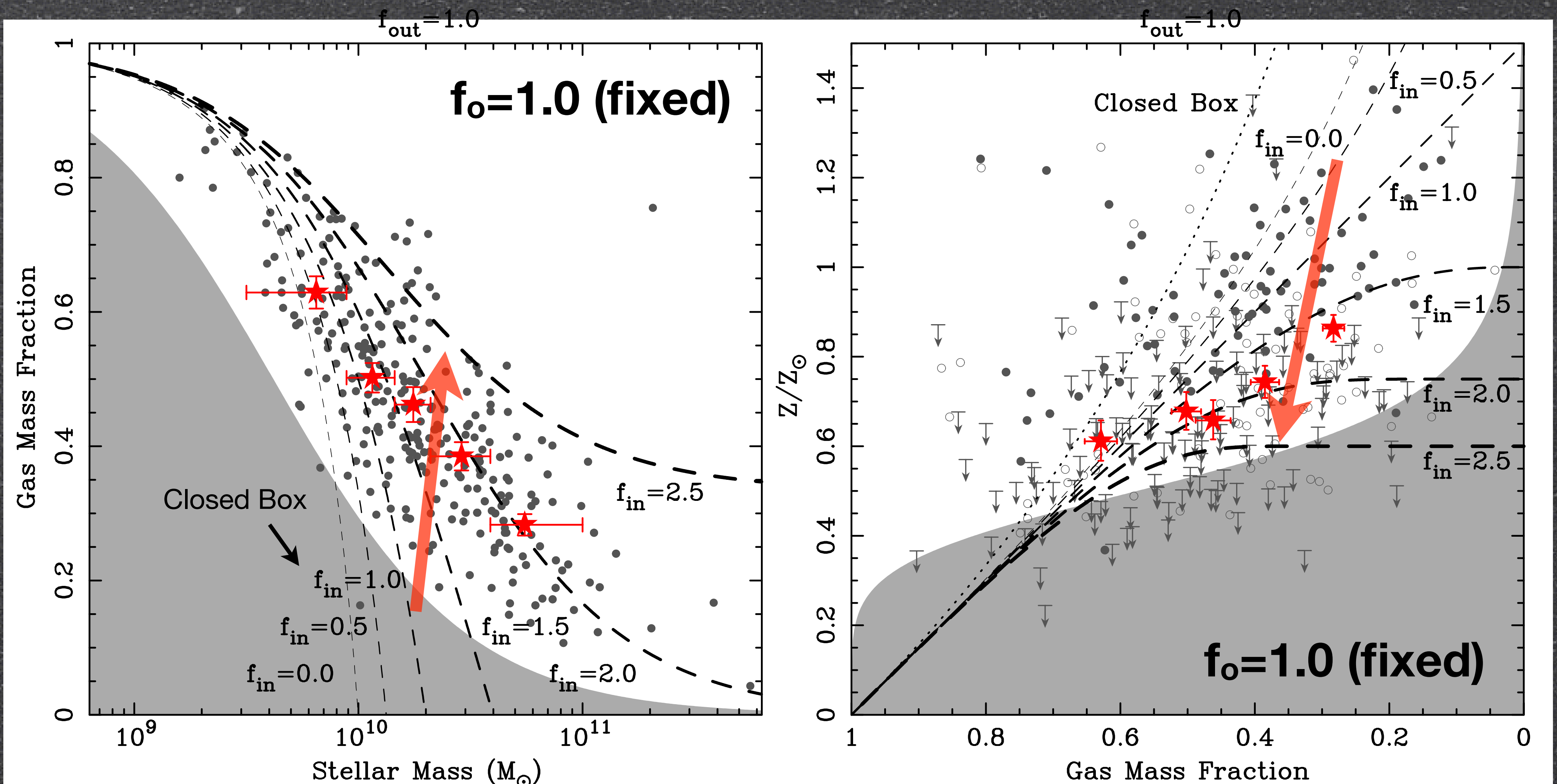
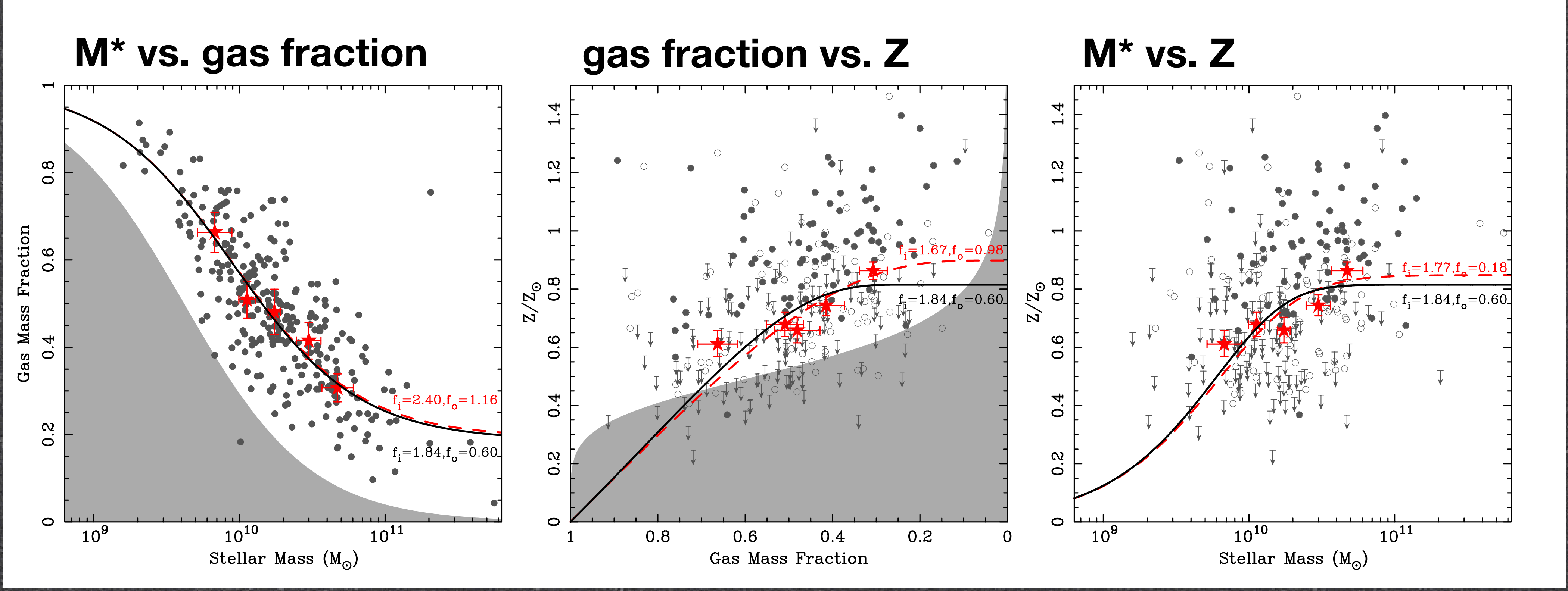
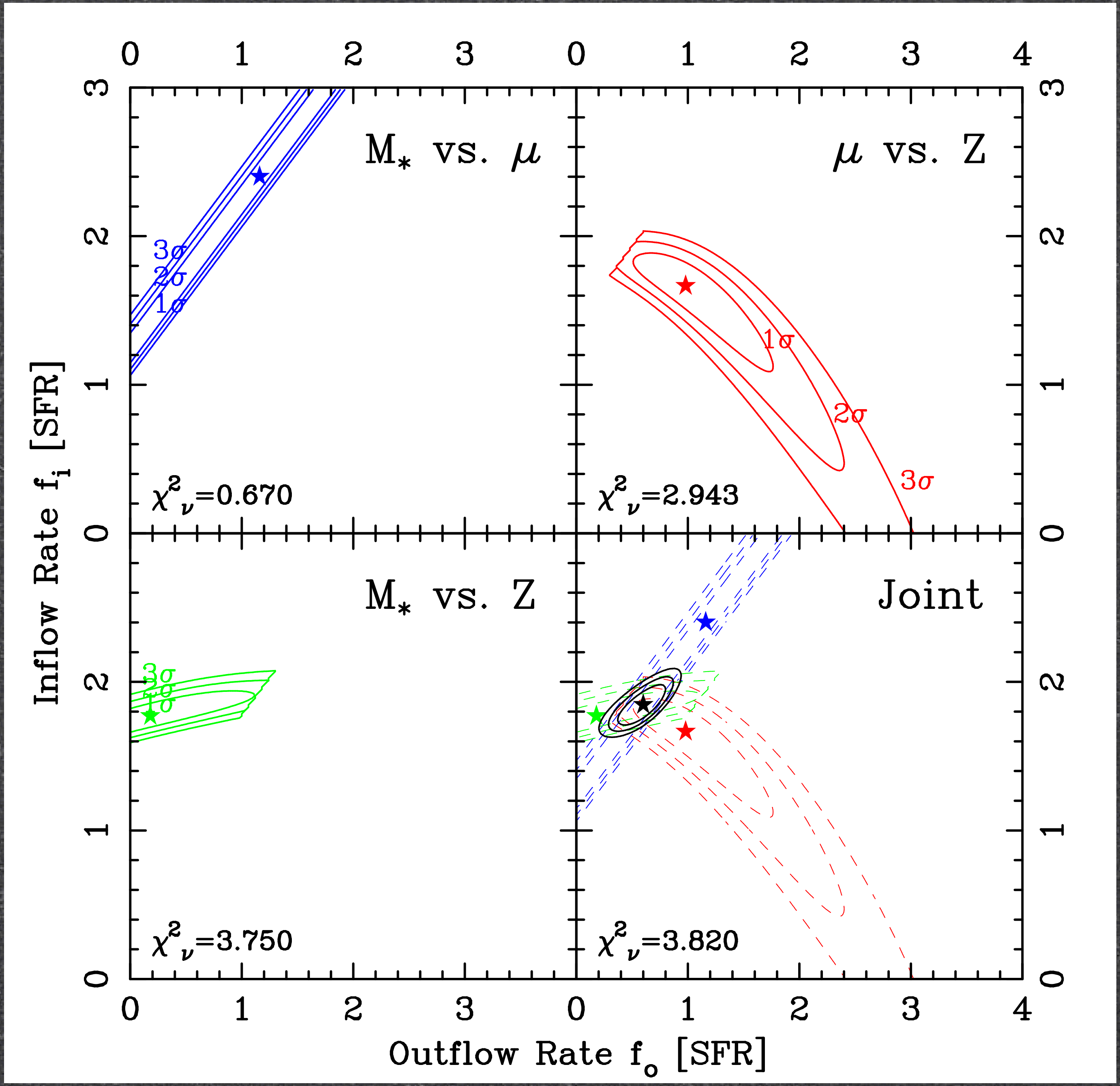


Inflow/Outflow Rate in galaxies at z~1.4:

- We fit observations (M* vs. μ, μ vs. Z, M* vs. Z) by a simple analytic model of chemical evolution
- f_{in}, f_{out}, M^0_{gas} are free parameters

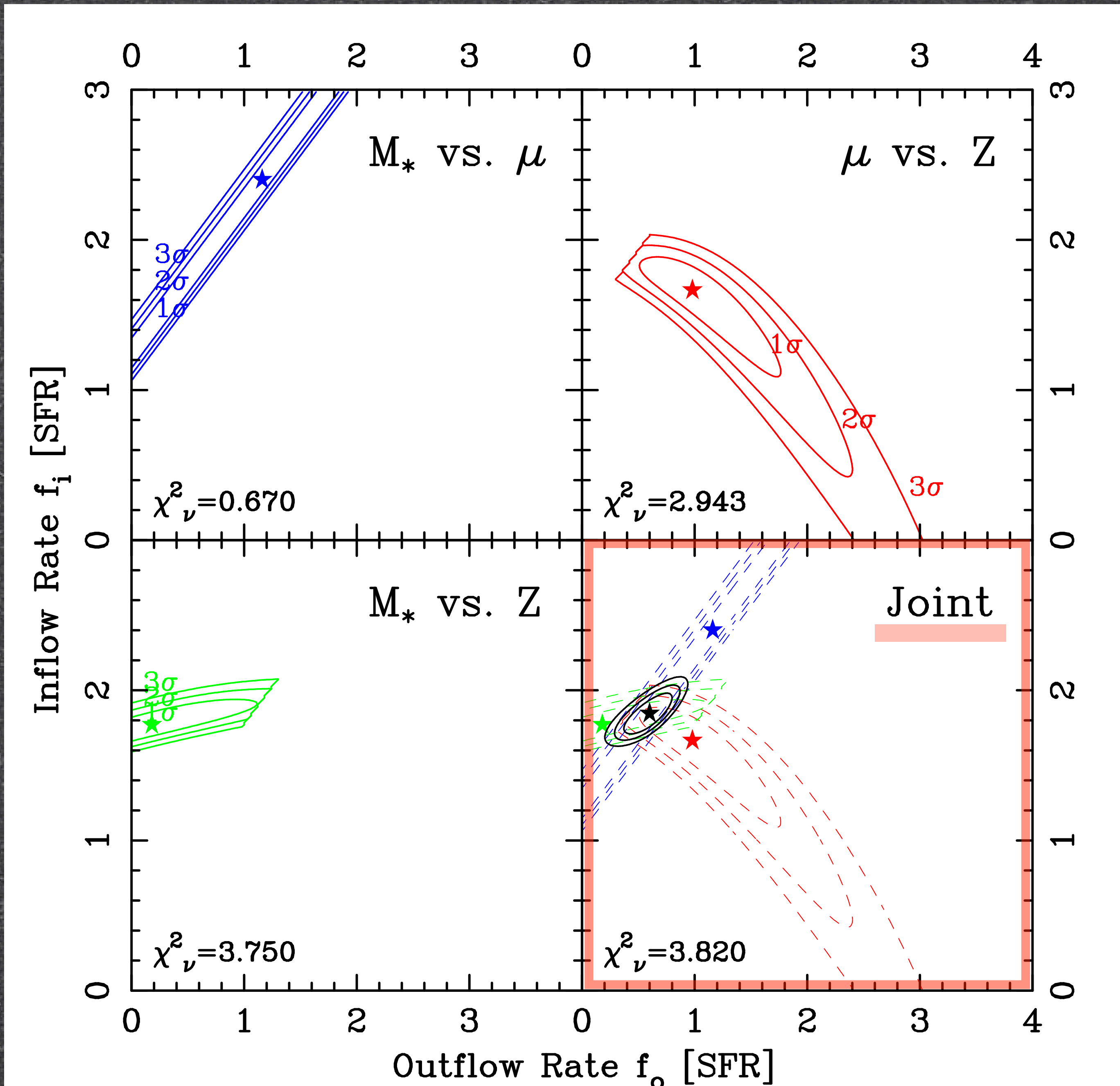


Inflow/Outflow Rate in galaxies at z~1.4:



χ^2 contour map of each fitting

Inflow/Outflow Rate in galaxies at z~1.4:

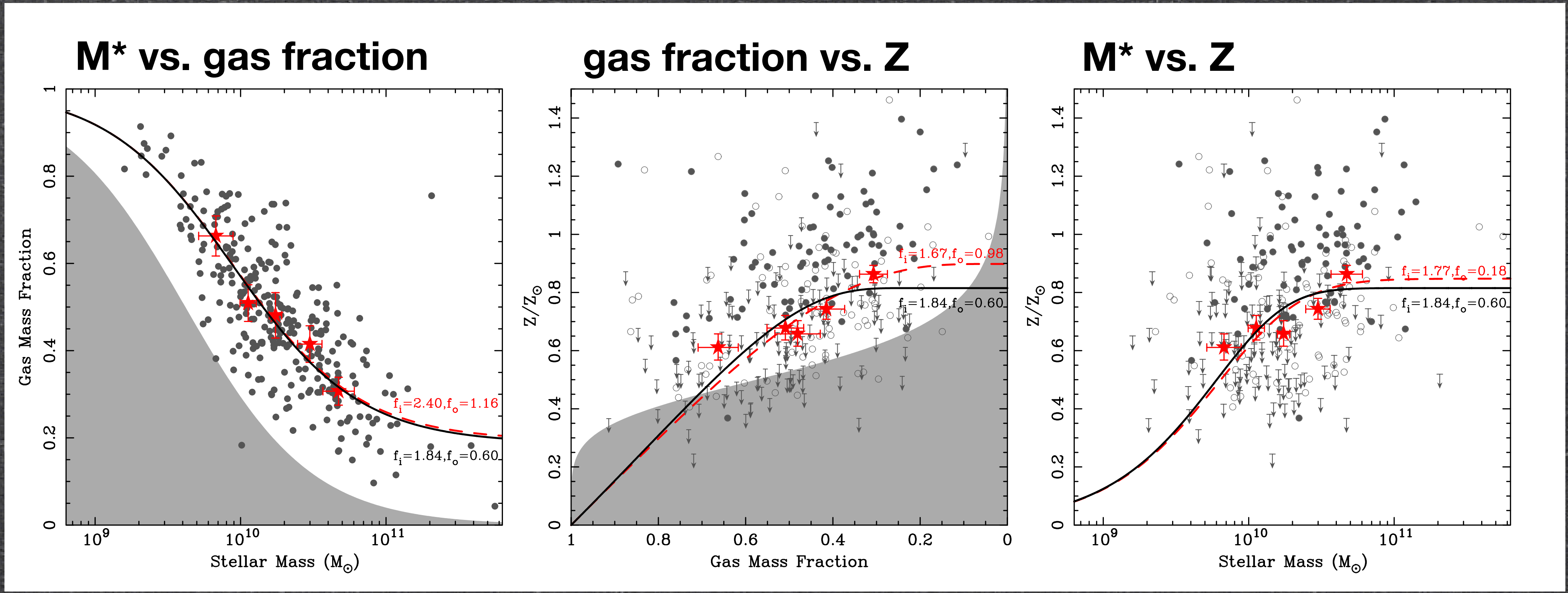


χ^2 contour map of each fitting

The joint constraint by M* vs. μ plot and M* vs. Z plot.

Inflow/Outflow Rate in galaxies at z~1.4:

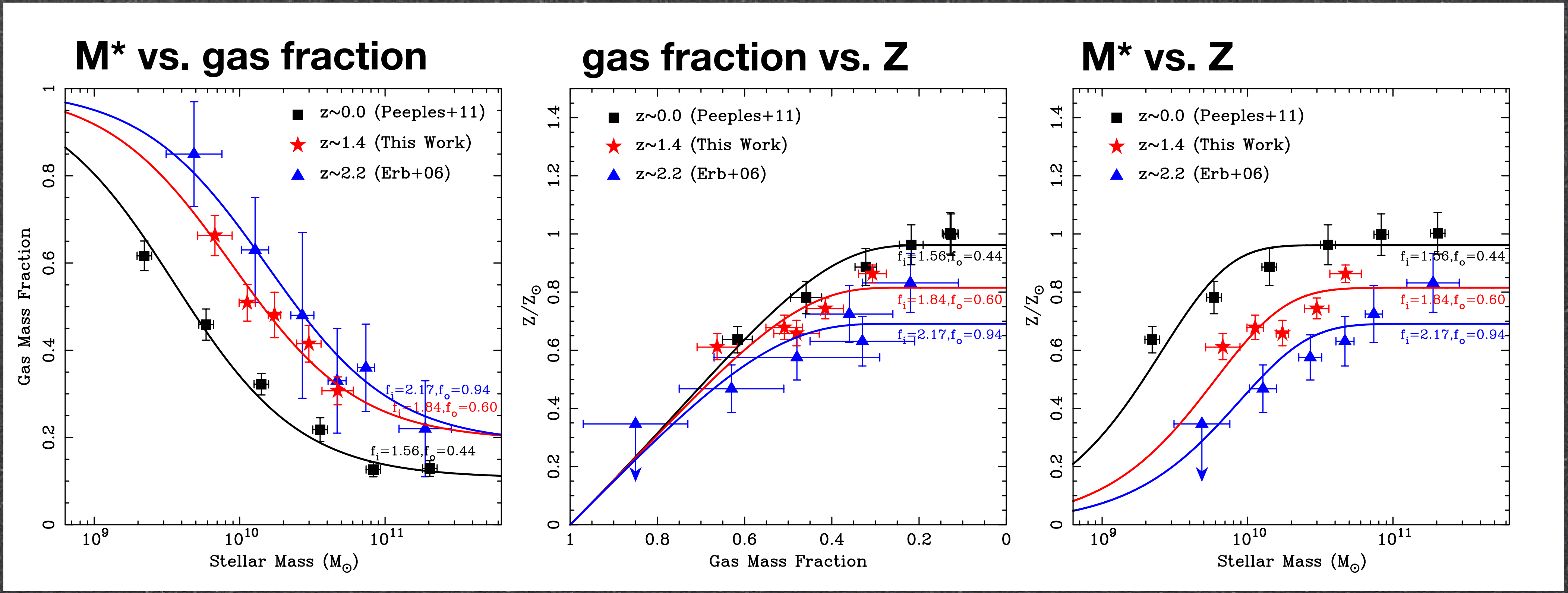
- We fit observations (M* vs. μ, μ vs. Z, M* vs. Z) by a simple analytic model of chemical evolution
- f_{in}, f_{out}, M^0_{gas} are free parameters
- Note that the unit of f_{in}, f_{out} is "SFR [M_{sun}/yr]"



- **The best-fit f_{in} is 1.84**
- **The best-fit f_{out} is 0.60**

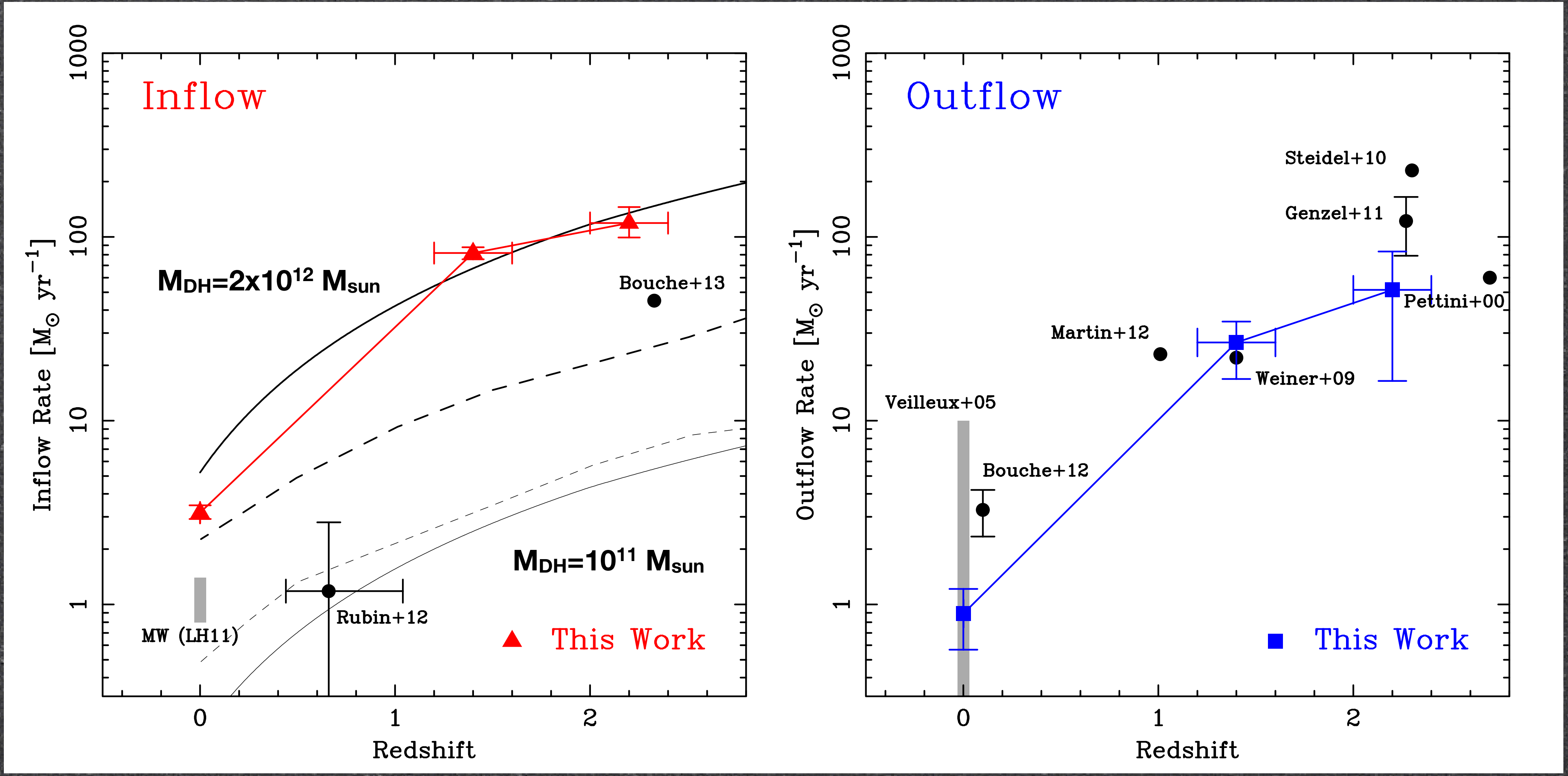
Evolution of Inflow/Outflow Rate:

- Comparison with studies at other redshifts from z~2 to z~0
- Sample at z~0 by Peeples+11 (metallicity is taken from Tremonti+04)
- Sample at z~2.2 by Erb+06
- We see the evolution in each figure
  - ✓ Gas mass fraction decreases with decreasing redshift
  - ✓ Metallicity increases with decreasing redshift
- We fit these observations at other redshifts in the same analytic model



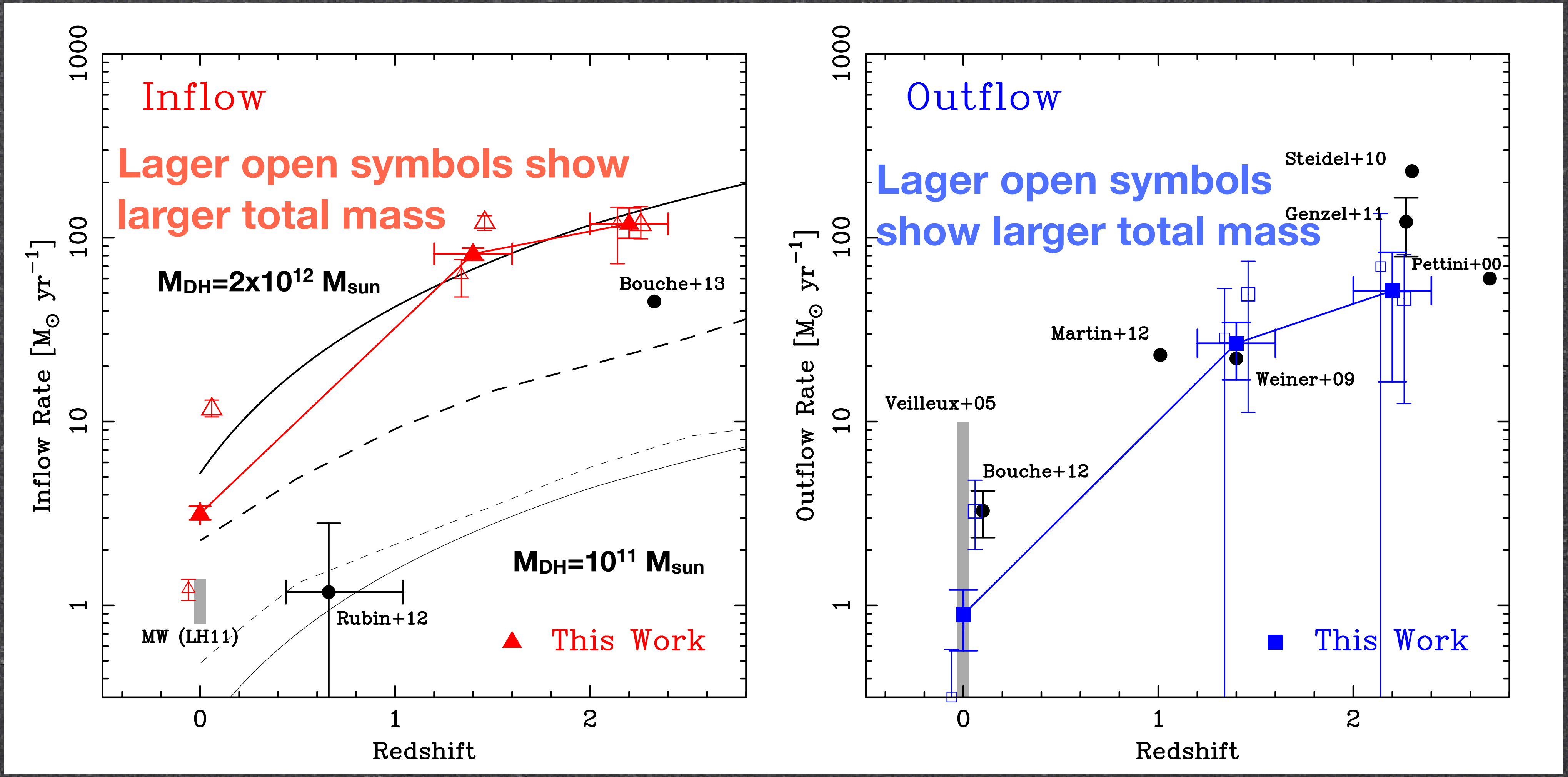
Evolution of Inflow/Outflow Rate:

- Comparison of inflow and outflow rate with previous results
- Inflow/outflow rate are all converted to “mass” rate in the unit of M_{sun}/yr
- Both inflow and outflow rates increase with increasing redshift
- Inflow rate in this work well agrees with the models by Bouché+10
- Outflow rate in this work well agrees with the past observations



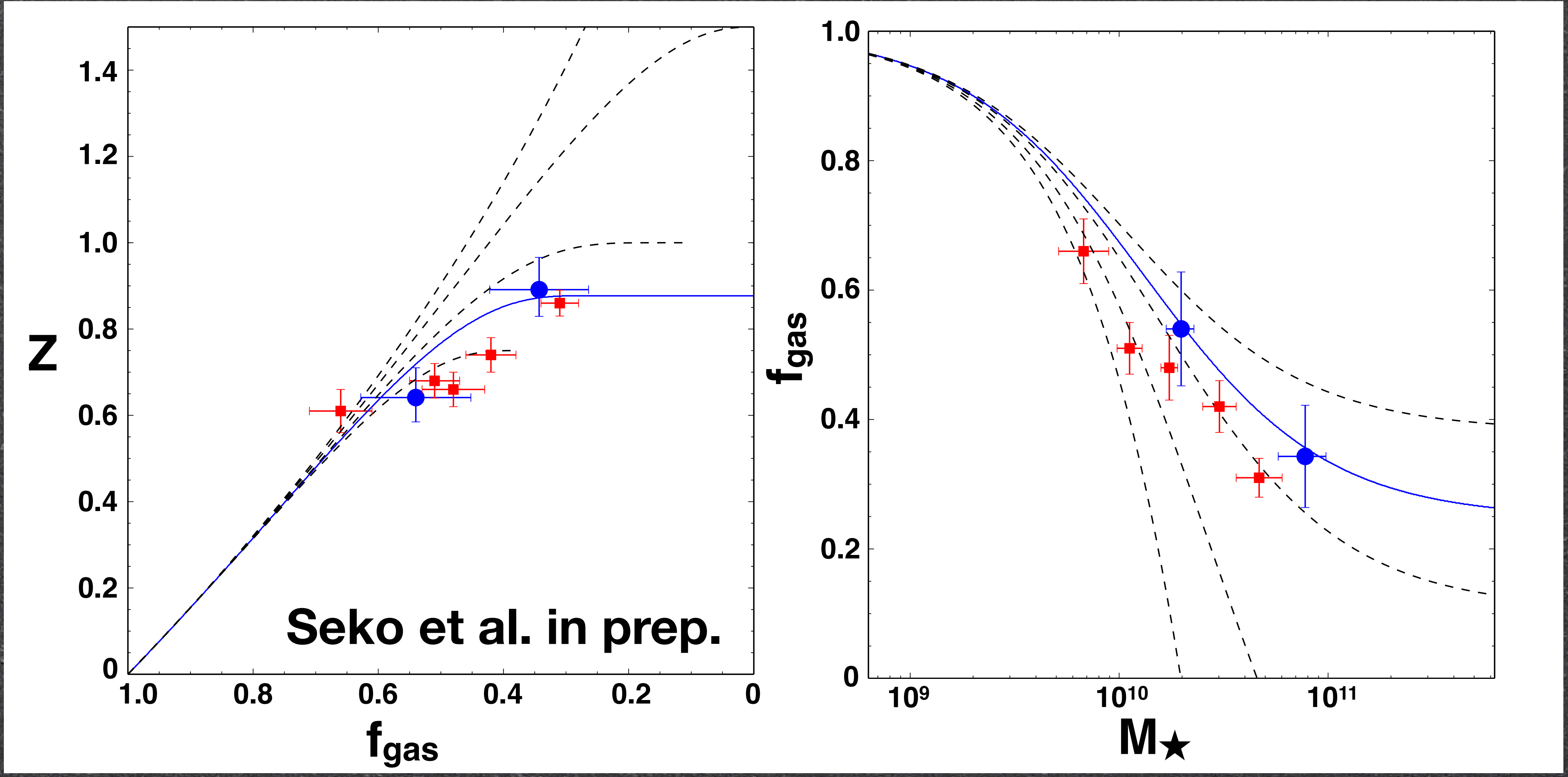
Total Mass Dependence of Inflow/Outflow Rate:

- It is natural that the gas flow (esp. outflow) depends on the galaxy mass
- Two sub-samples according to the total (stellar + gas) mass
- The larger total mass shows the larger inflow/outflow rate?
  - The trend is not so clear
  - Note that the trend reflects the correlation between mass and SFR?



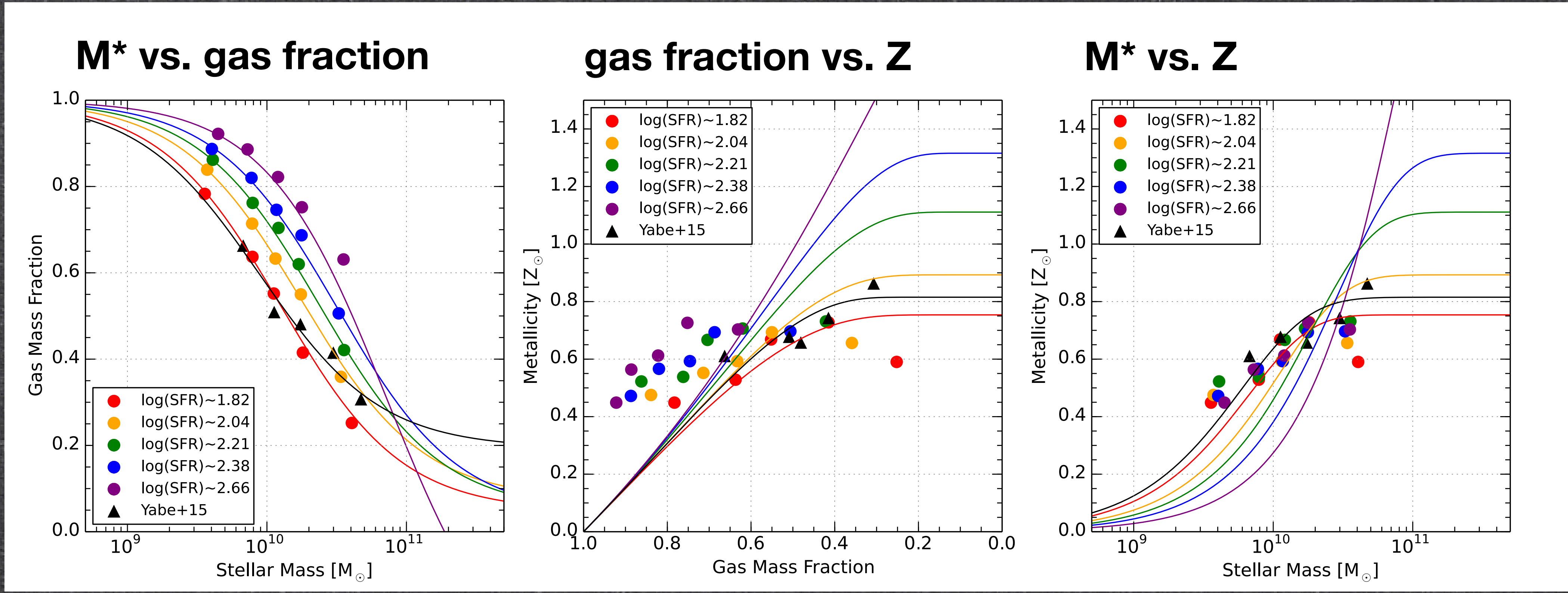
(More) direct gas measurement with ALMA:

- ALMA observations of 20 FMOS targets (Seko et al. in prep.)
- Significant CO(J=5-4) detections from 11 objects
- CO(J=1-0) conversion / metallicity dependent CO-H2 conversion factor
  - f_i=1.7×SFR f_o=0.4×SFR (from CO measurement)
  - f_i=1.8×SFR f_o=0.6×SFR (from Hα assuming KS law)



(Larger) sample from FastSound survey:

- Much larger NIR spectroscopic sample from FMOS FastSound survey
- ~4000 Hα detections at z~1.4 (Yabe et al. 2015, submitted)
- The mass-metallicity relation agrees with previous obs. (such as GTO)
- Similar analysis for inflow and outflow with this sample
- Larger gas mass fraction compared to the GTO sample



Note that the FastSound sample traces relatively higher SFR

- The best-fit f_{in} is 0.7-2.0
- The best-fit f_{out} is 0.0-1.0

Gas Mass Fraction and Inflow/Outflow Rate:

- Much larger NIR spectroscopic sample from FMOS FastSound survey
- ~4000 Hα detections at z~1.4 (Yabe et al. 2015, submitted)
- The mass-metallicity relation agrees with previous obs. (such as GTO)
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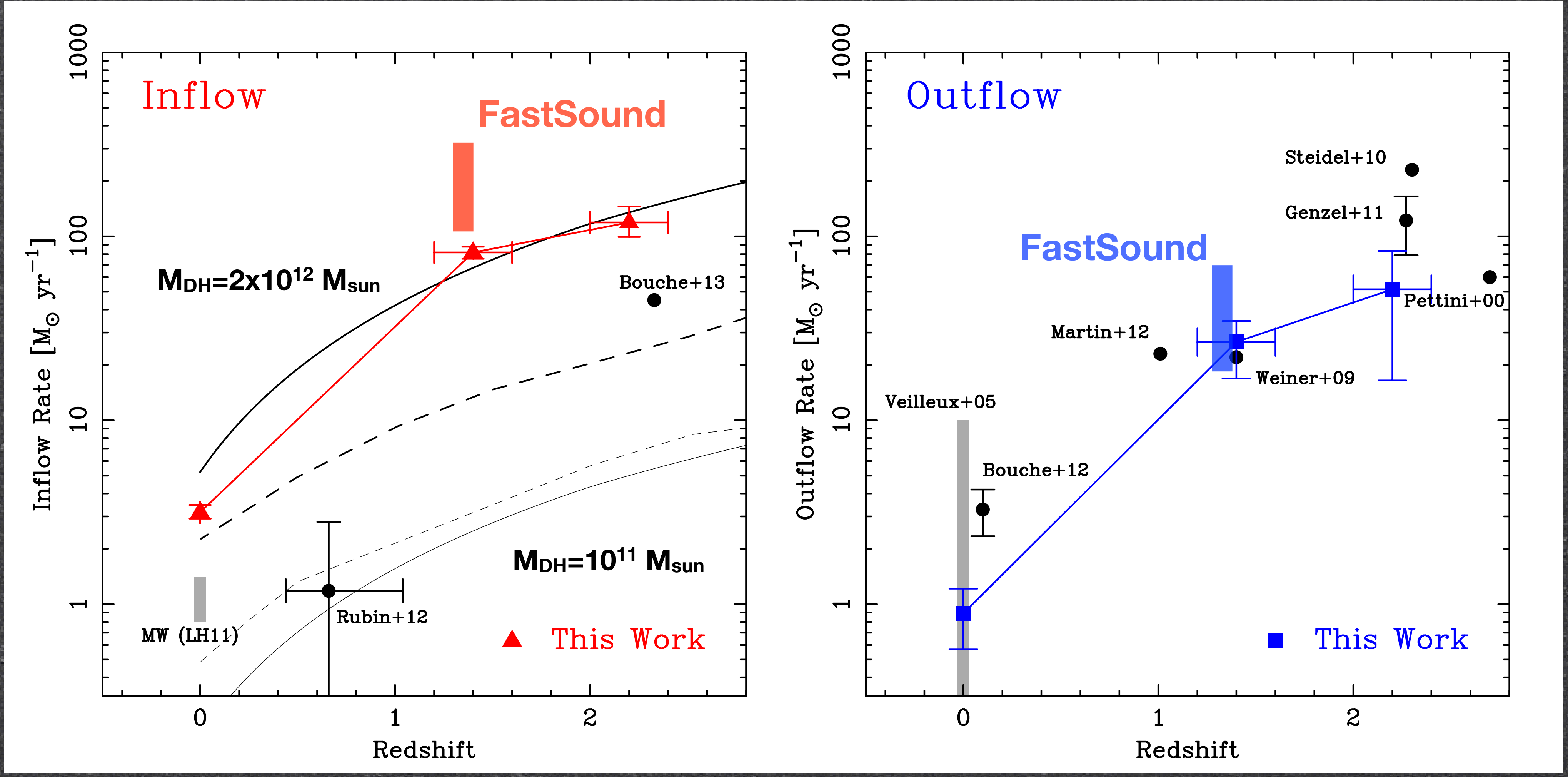

Summary：

- Inflow and outflow of gas play an important role in galaxy formation and evolution
- Constraints of the gas inflow and outflow rate by using stellar mass, gas mass fraction, and metallicity at z~1.4
  - ✓ Fit with a simple analytic model of chemical evolution
  - ✓ The best-fit inflow rate is ~1.8 times SFR
  - ✓ The best-fit outflow rate is ~0.6 times SFR
- The same analysis applied to the previous results at z~0 and z~2.2
  - ✓ The inflow and outflow rates increase with increasing redshift
  - ✓ The trend of redshift evolution of inflow and outflow rates is in good agreement with the previous observations and the theoretical models
- Analysis by using more direct gas mass estimation from ALMA CO detected sample shows similar results
- Larger sample from FMOS FastSound survey also shows similar SFR normalized inflow and outflow rate, but slightly larger mass inflow and outflow rate