Gas inflow and outflow of star-forming galaxies around cosmic noon as revealed by chemical evolution

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Outline

1. **Background**

   Dependence of gas flows on properties of galaxies (e.g. environment)

2. **Assumptions and model**

3. **Comparison between observational data and model to constrain rates of inflow and outflow of individual star forming galaxies at z~1.4**

   →Derived ranges of IFR and OFR are broad

4. **Simulation of the constraint on rates using mock galaxies**

   →IFR and OFR can be constrained if we have precise data, but there might be some caveats

5. **Summary**

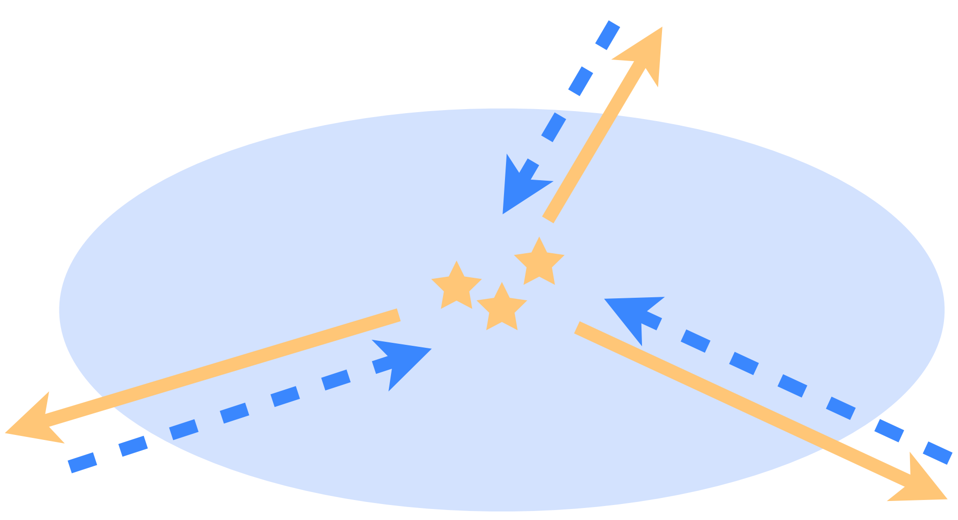
Background

<u>Why measure gas inflow and outflow?</u>

Quantifying gas flows and studying the dependence on properties of galaxies provide insights into the evolution

<u>Environmental dependence is still unknown</u>

General field



Gas accretes onto galaxies stochastically through filaments

Interstellar gas is expelled by supernovae and/or AGN

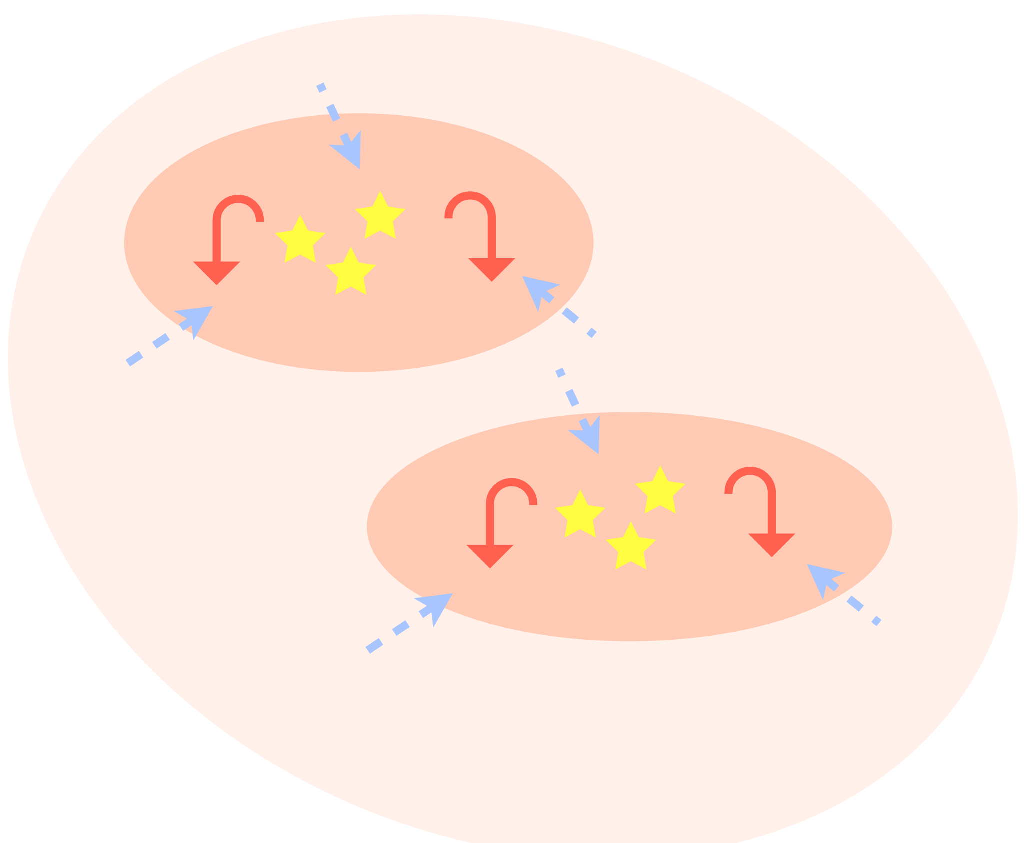
Background

Why measure gas inflow and outflow?

Quantifying gas flows and studying the dependence on properties of galaxies provide insights into the evolution

Environmental dependence is still unknown

Dense regions
(cluster of galaxies)



High number density
→Formation of common halo
→Inefficient inflow

Fall back of expelled gas
due to pressure of IGM

Gas removal through tidal effects
and/or ram pressure stripping

These effects related to outflow
might be more prominent
for lower mass galaxies

Background

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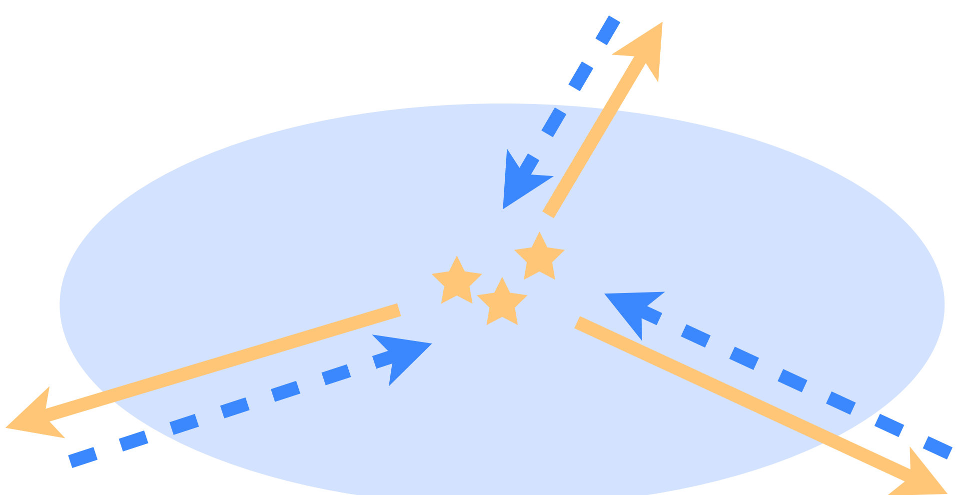
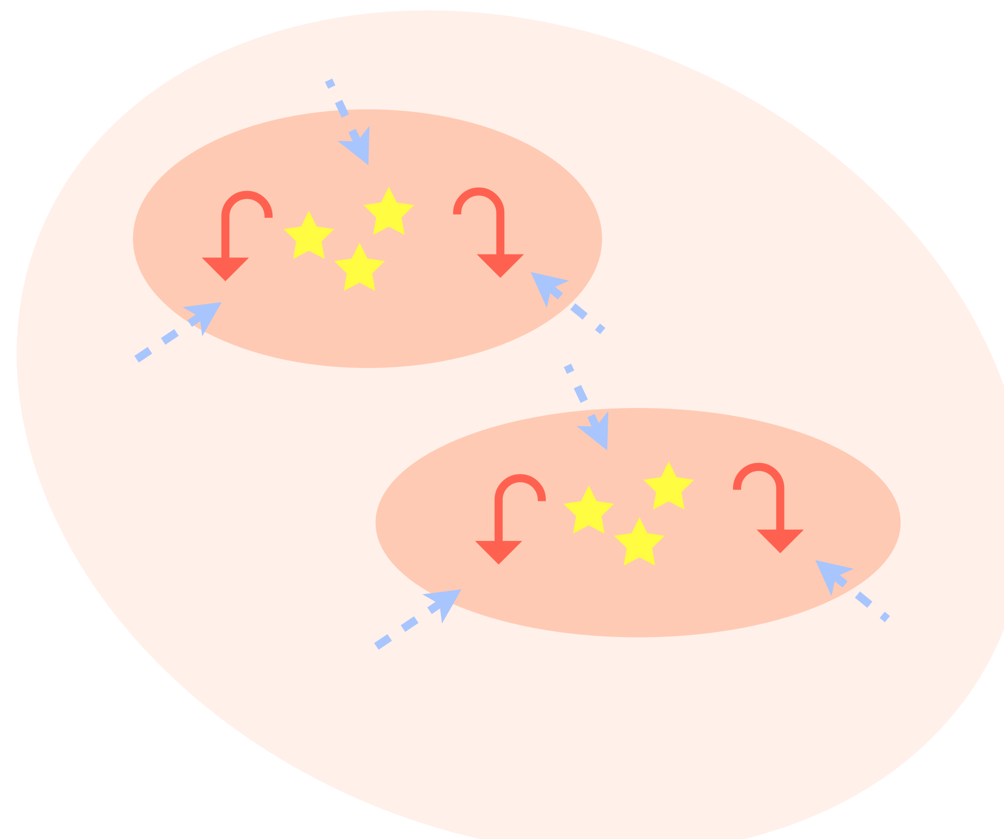
Environmental dependence is still unknown





The difference of gas flows might be reflected to the properties of galaxies

Uncover mass- & environmental dependence of gas flows from the viewpoint of chemical evolution

Assumptions and model

formation epoch : t_{form} (Gyr)

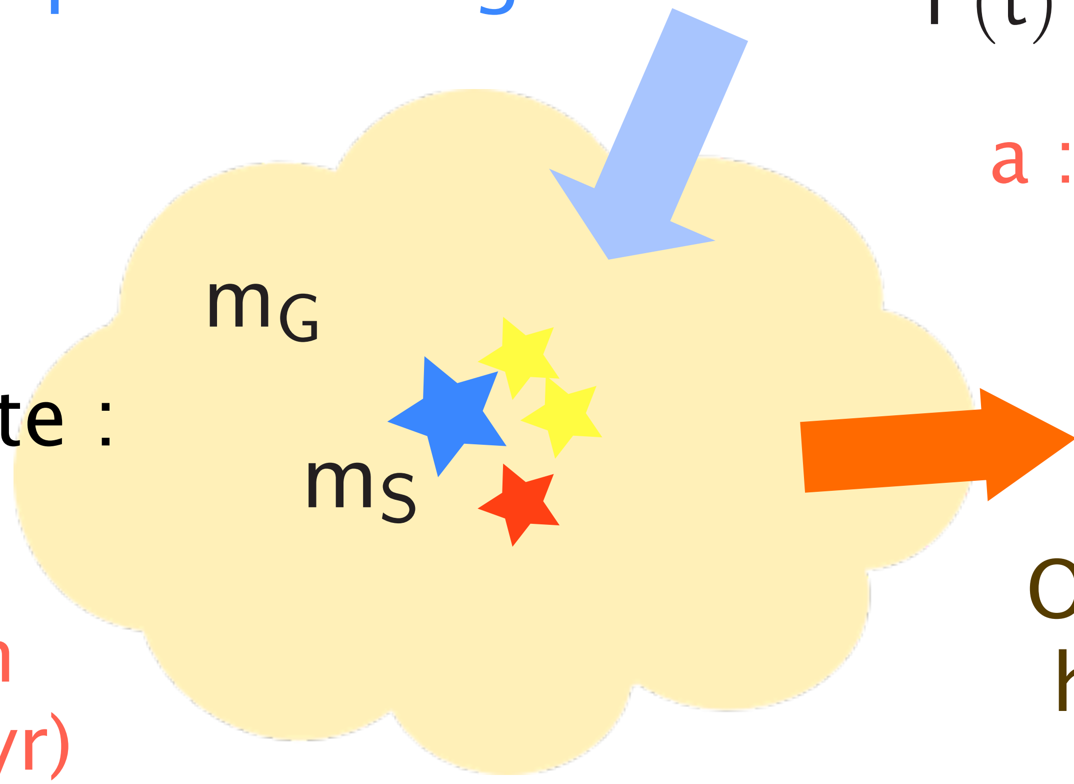
$m_{G,H}$

Accretion of primordial gas

Inflow rate :

$$F(t) = a \cdot m_{G,H}(t)$$

a : accretion efficiency (/Gyr)



Star formation rate :

$$\Psi(t) = \nu \cdot m_G(t)$$

ν : star formation efficiency (/Gyr) (determined by data)

IMF: Chabrier(03)

Outflow of gas & heavy elements

Outflow rate :

$$O(t) = \eta \cdot \Psi(t)$$

η : mass-loading factor

Abundance of element i

SNII : M ≥ 10Msun (Nomoto+2013)

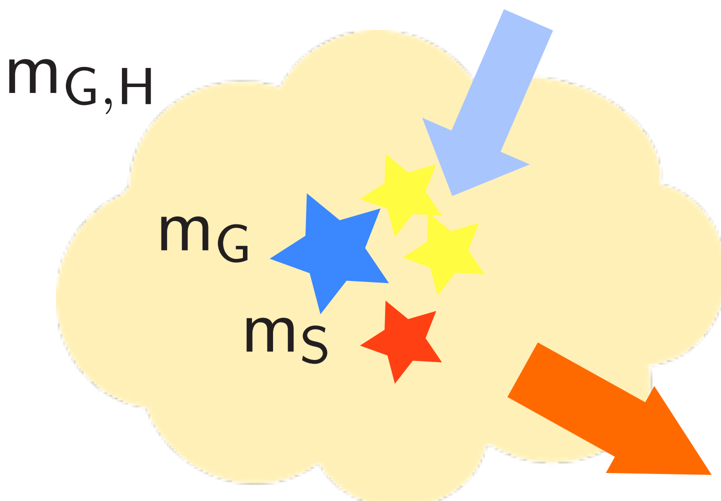
Assumptions and model

Evolution of gas & element i

$$\frac{dm_G}{dt} = -\Psi(t) + E_G(t) + F(t) - O(t)$$

gas→stars　stars→gas　inflow　outflow

$$\frac{d(m_G X_i)}{dt} = -\Psi(t)X_i(t) + E_i(t) - O(t)X_i(t)$$



Inflow rate :

$$F(t) = a \cdot m_{G,H}(t)$$

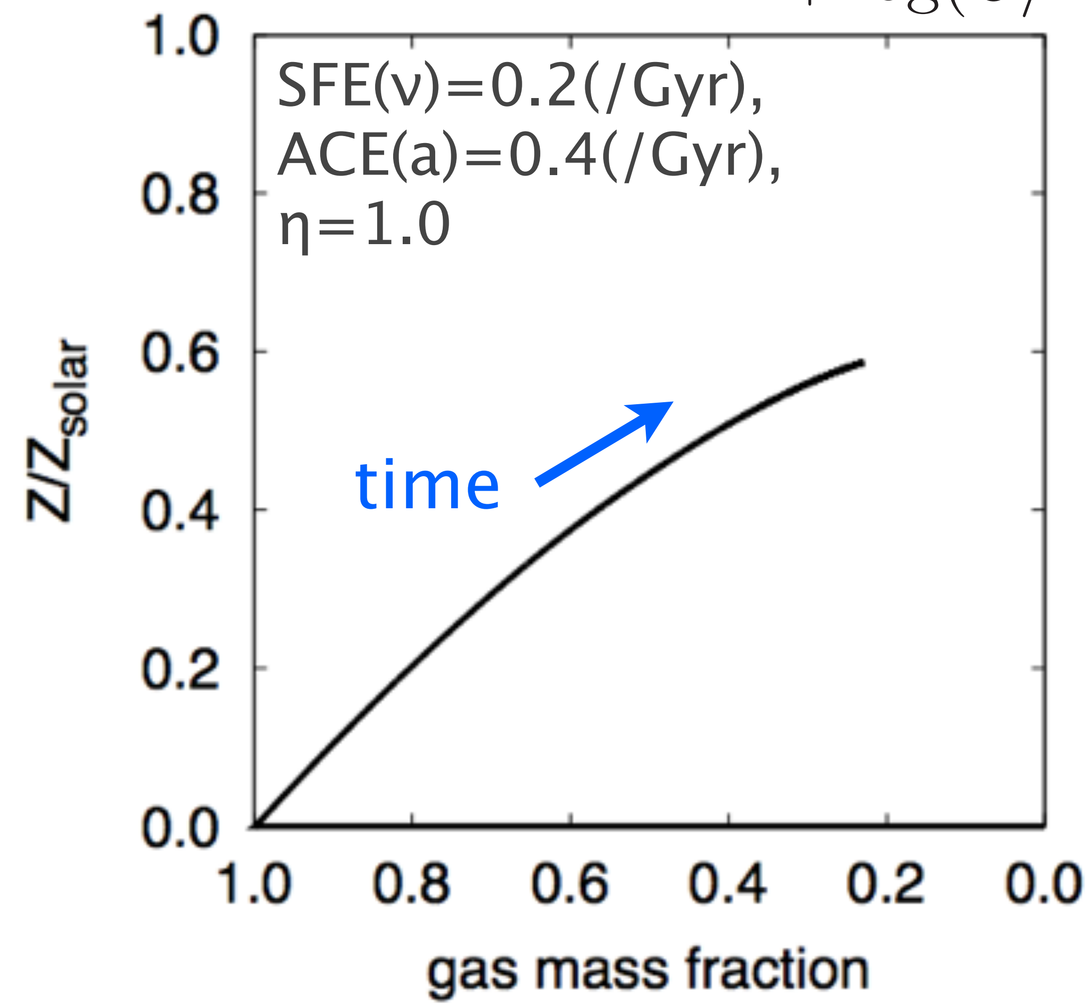
Outflow rate :

$$O(t) = \eta \cdot \Psi(t)$$

Star formation rate : $\Psi(t) = \nu \cdot m_G(t)$

Time variation of gas mass fraction & metallicity

※ $Z = 12 + \log(O/H)$



$$= \frac{M_g}{M_g + M_*}$$

Observables

gas-phase metallicity
gas mass fraction
specific SFR
stellar population age

Model parameters

accretion efficiency
mass loading factor

(star formation efficiency)
(formation epoch)

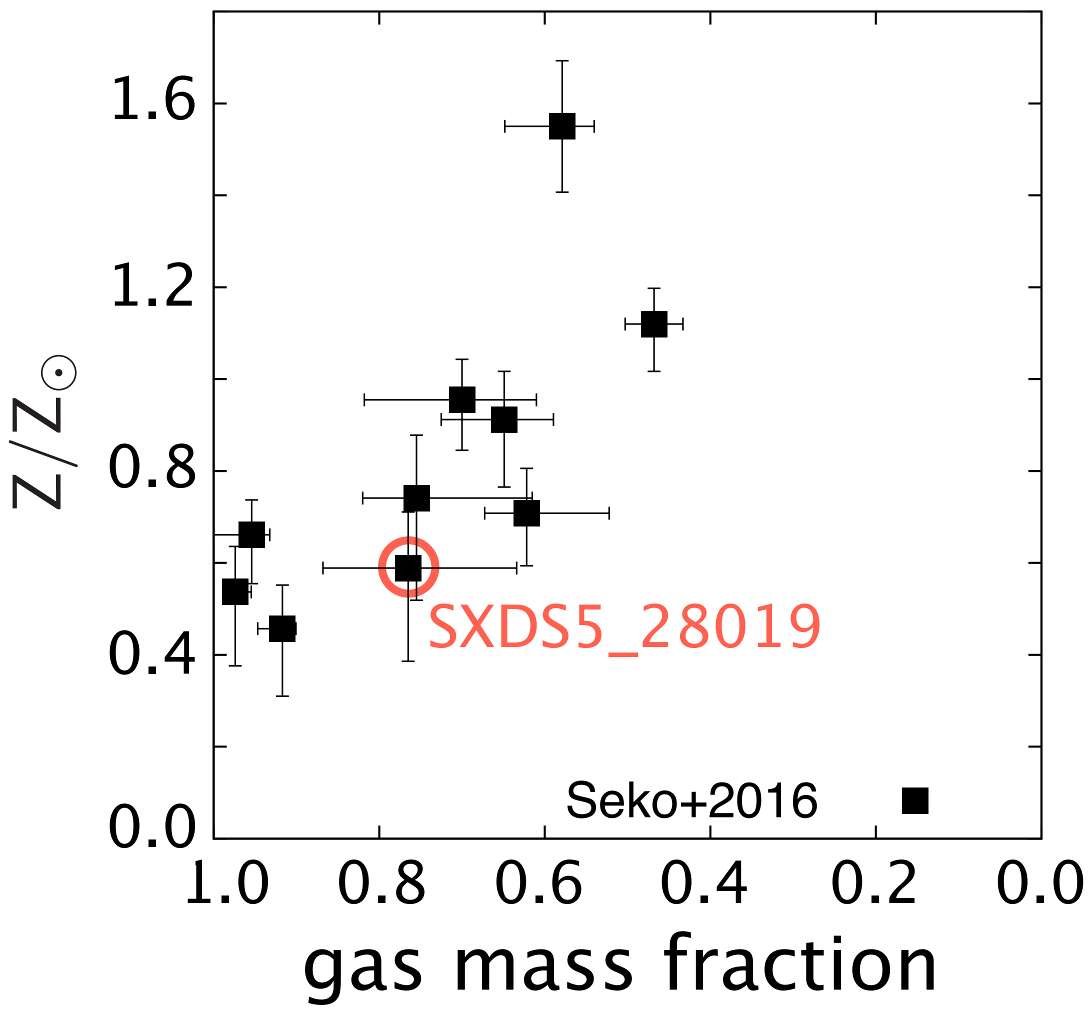
→ inflow rate & outflow rate

Constraints of rates of inflow & outflow

Inflow rate : $F = a \cdot m_{g,h}$
Outflow rate : $O = \eta \cdot \Psi$
mass-loading factor : η

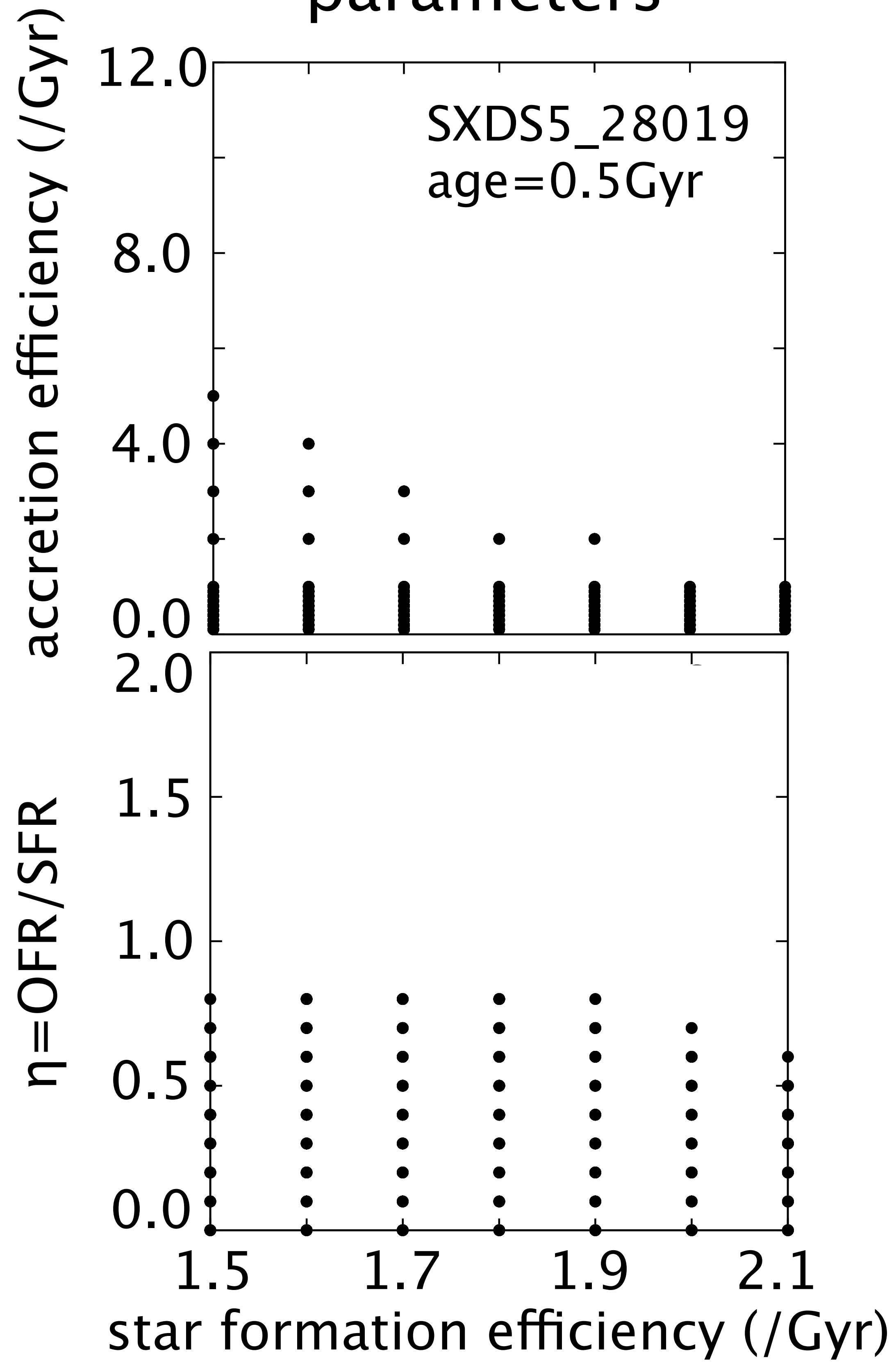
Data : star-forming main sequence galaxies in general field

(z~1.4, Seko et al. 2016)



Models are extracted as the predictions are consistent with data within 1σ error

parameters



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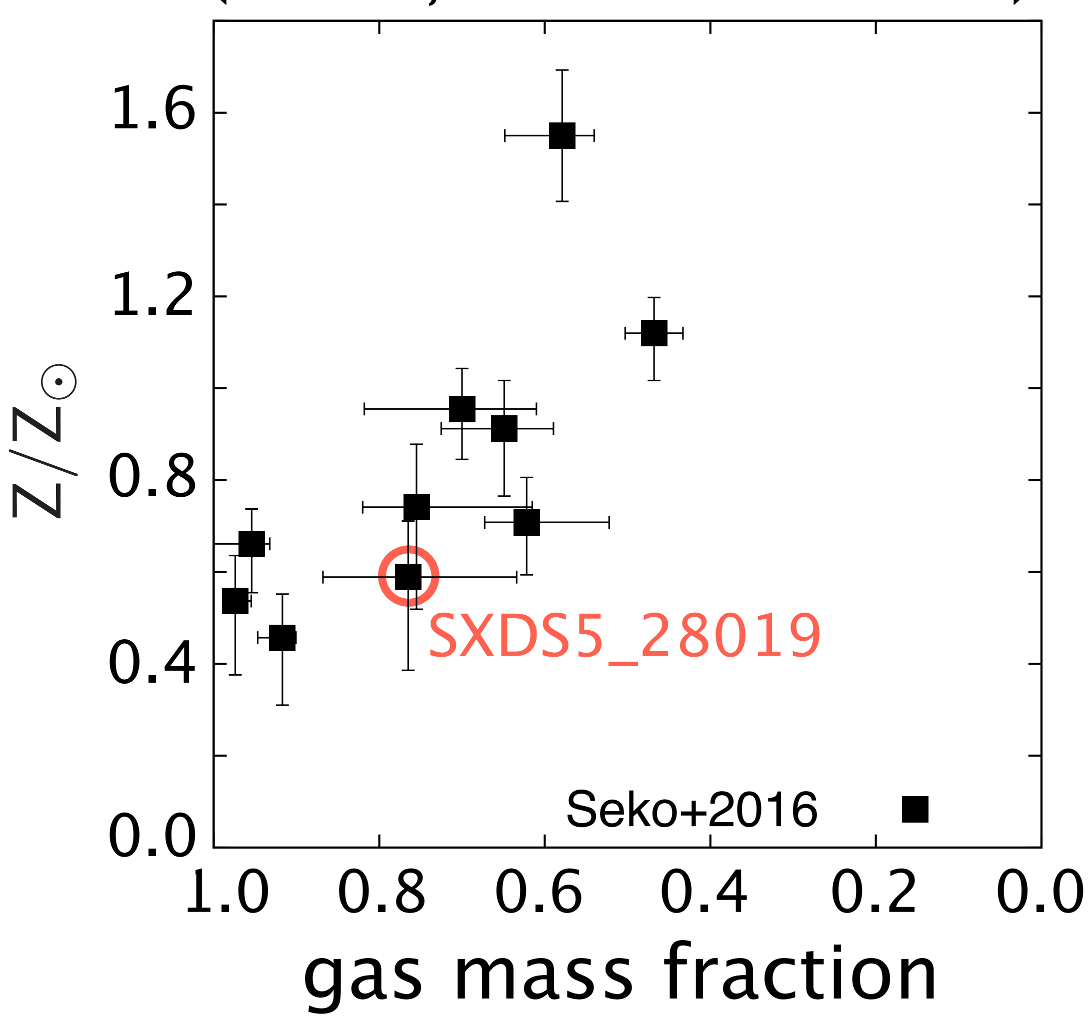
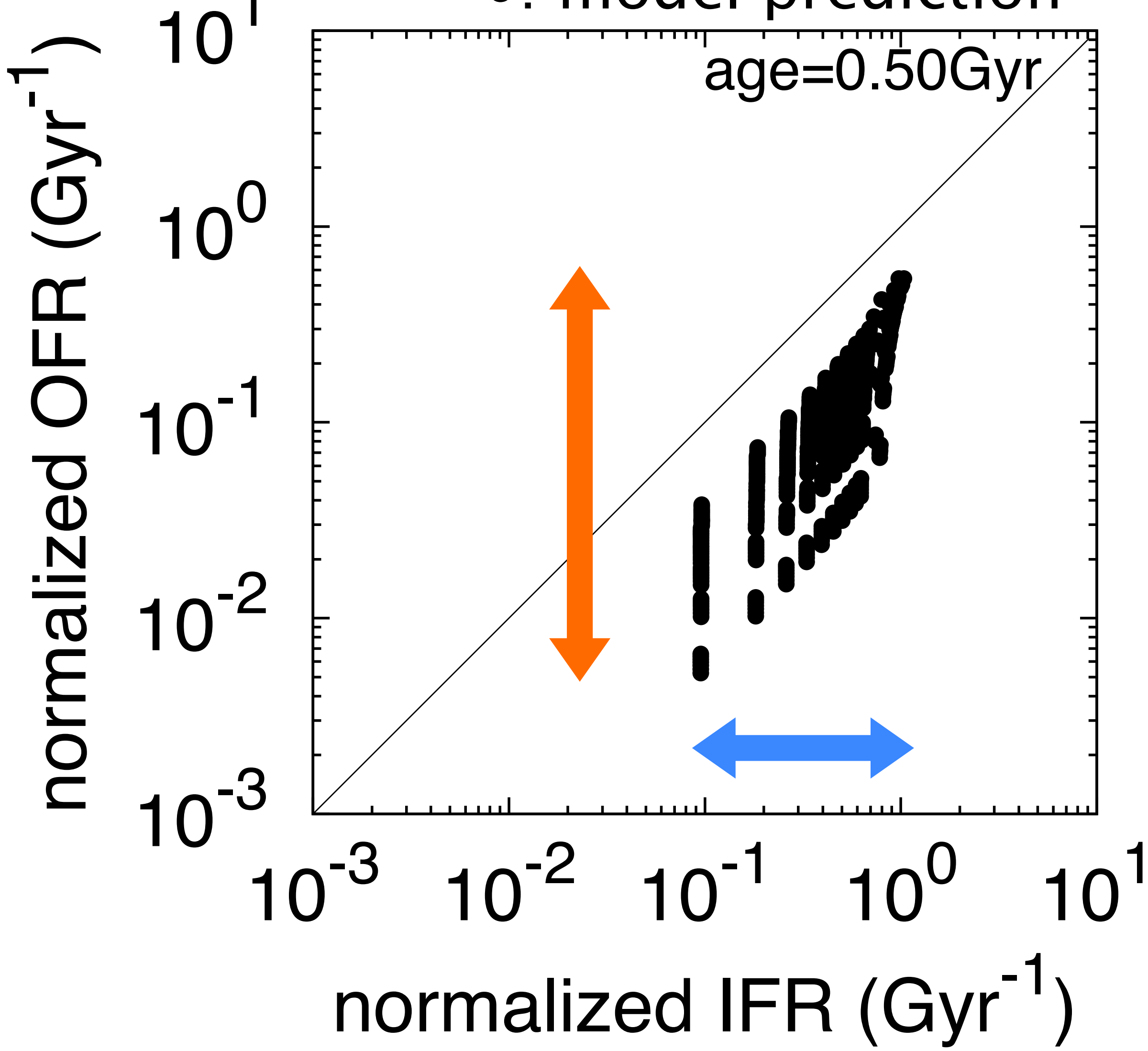


●: model prediction



Ranges of IFR&OFR are broad due to uncertainty about the data & degeneracy of model parameters

To see the mass & environmental dependence, the rates have to be constrained

Constraints of rates of inflow & outflow

Inflow rate : $F = a \cdot m_{g,h}$
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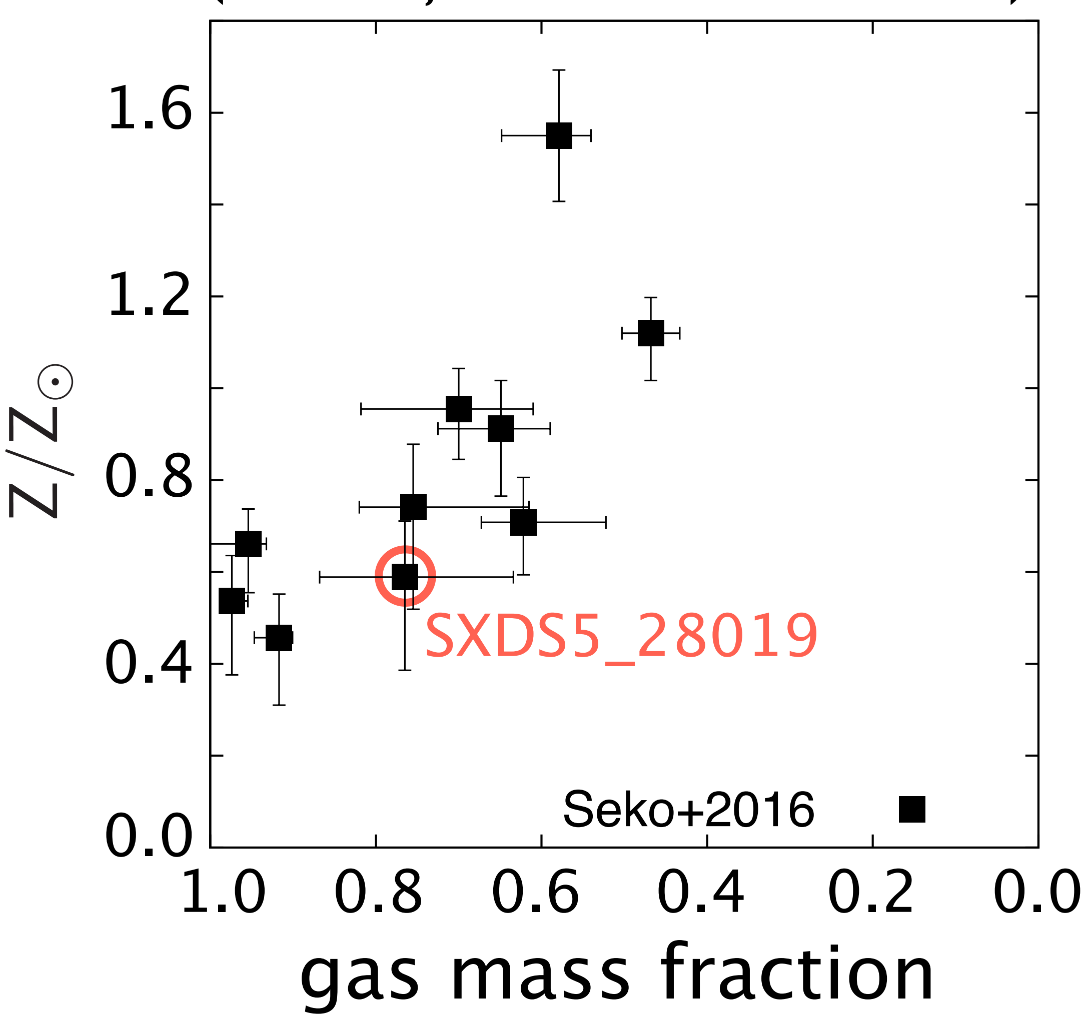
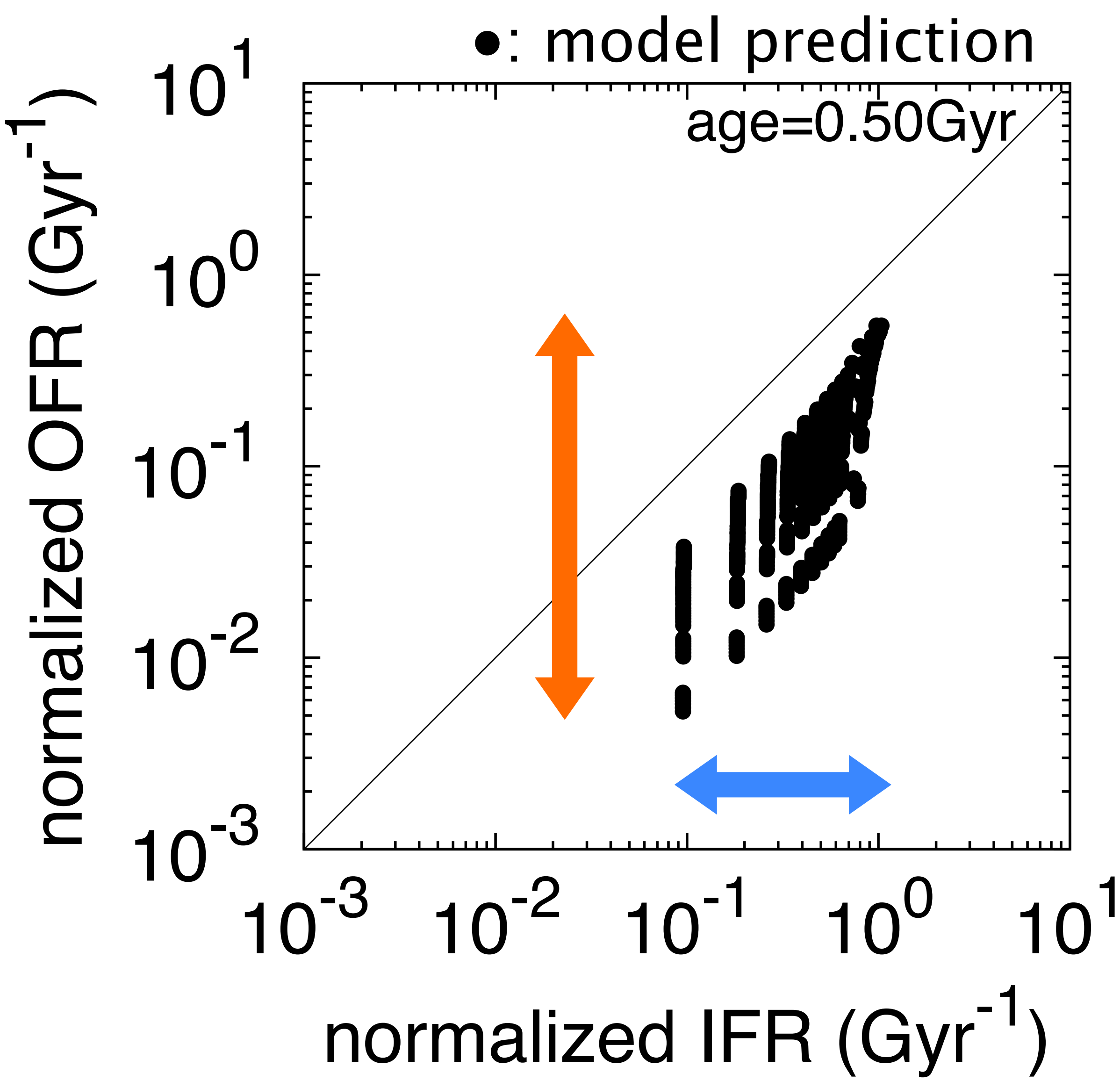
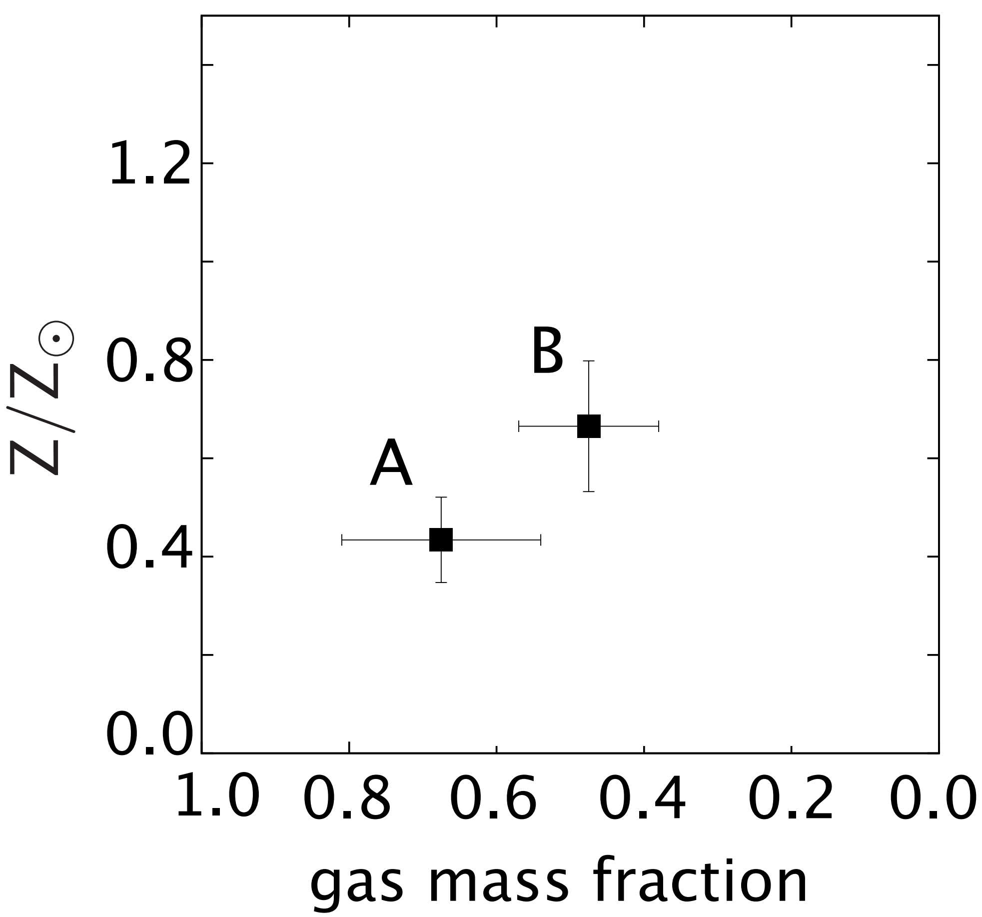




Can we well constrain IFR and OFR with this method?
How is the precision of the data related to model parameters?

Constraint of IFR&OFR with mock data

Generate mock galaxies → Derive probability functions → Investigate ranges of IFR&OFR



Mock galaxies are generated based on model predictions

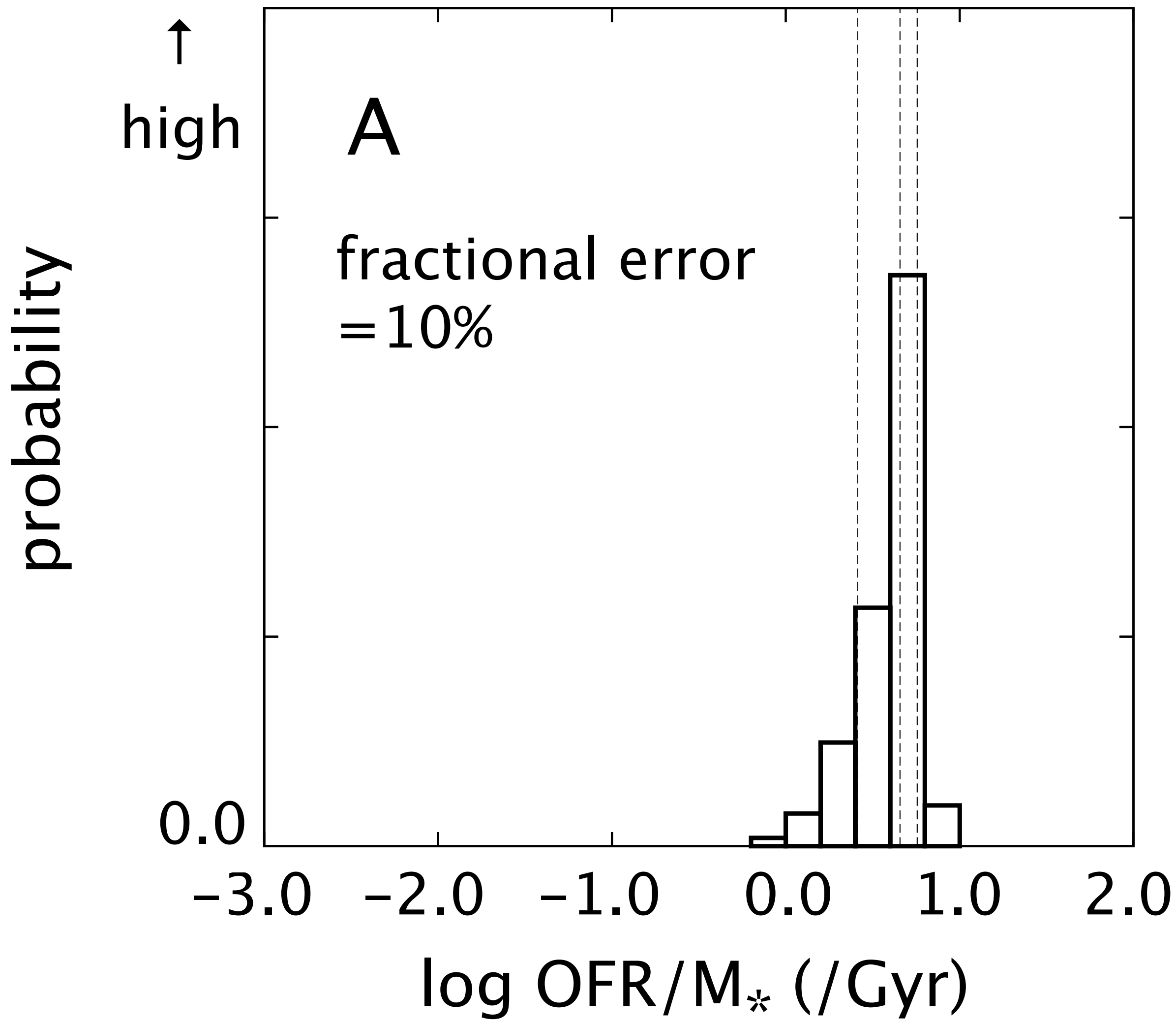
Fractional error is assigned to gas fraction, metallicity and sSFR

Fractional error
$= \Delta\mu/\mu, \Delta Z/Z, \Delta sSFR/sSFR$

	age(Gyr)	μ	Z/Zsun	sSFR(/Gyr)	ACE(/Gyr)	η	SFE(/Gyr)	IFR(/Gyr)	OFR(/Gyr)
mockA	0.500	0.675	0.434	3.533	1.585	1.259	1.700	0.960	0.566
mockB	1.000	0.475	0.665	1.536	1.259	1.000	1.700	0.628	0.404

Constraint of IFR&OFR with mock data

Generate mock galaxies → **Derive probability functions** → Investigate ranges of IFR&OFR



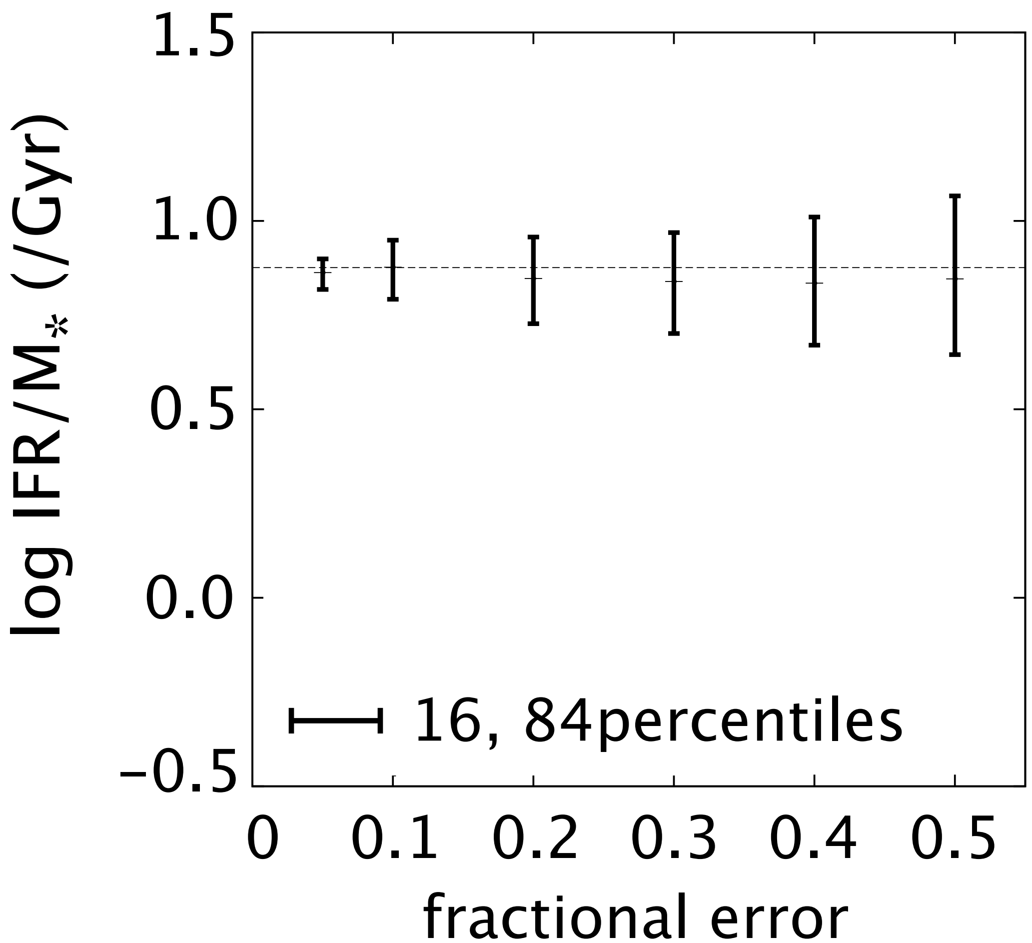
Assume Gaussian error for metallicity, gas fraction, sSFR

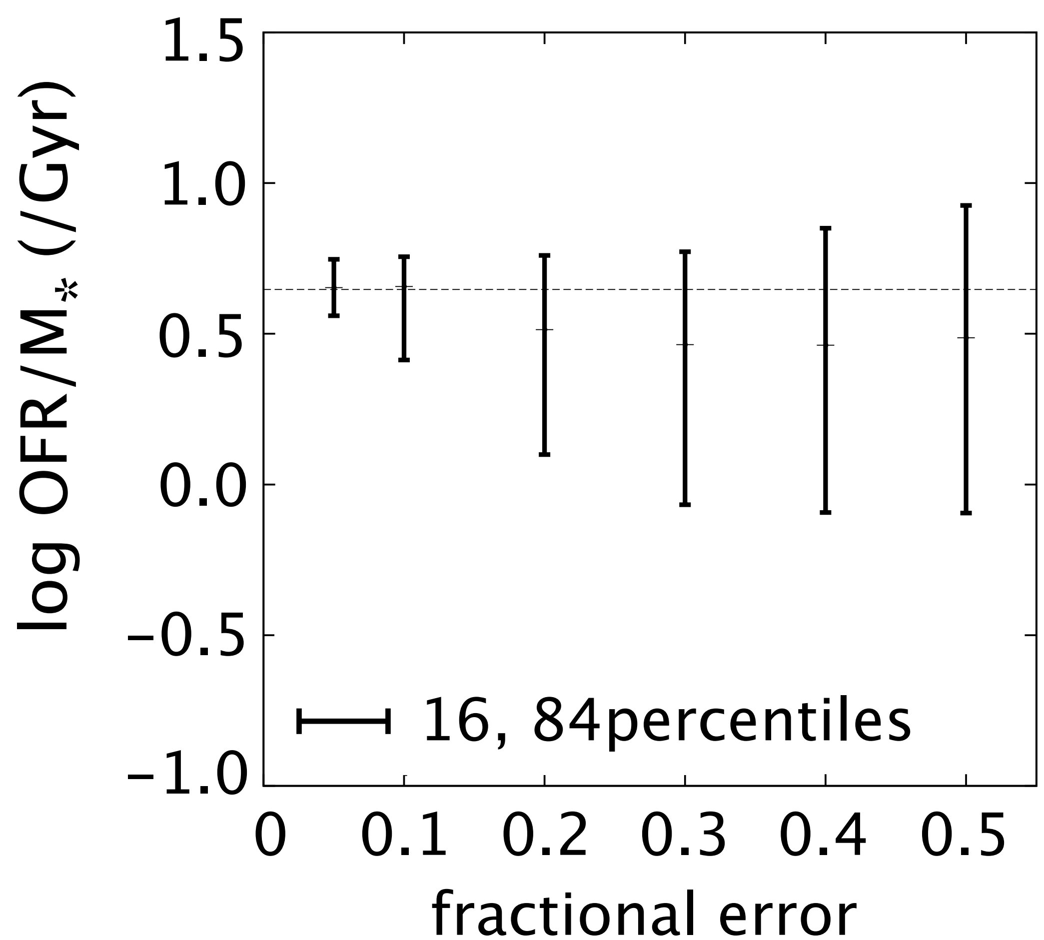
Derive probability functions of IFR&OFR (uncertainty about age=0.2dex)

Examine the cases of different size of fractional error

Constraint of IFR&OFR with mock data

Results of galaxy A #Similar trend for galaxy B

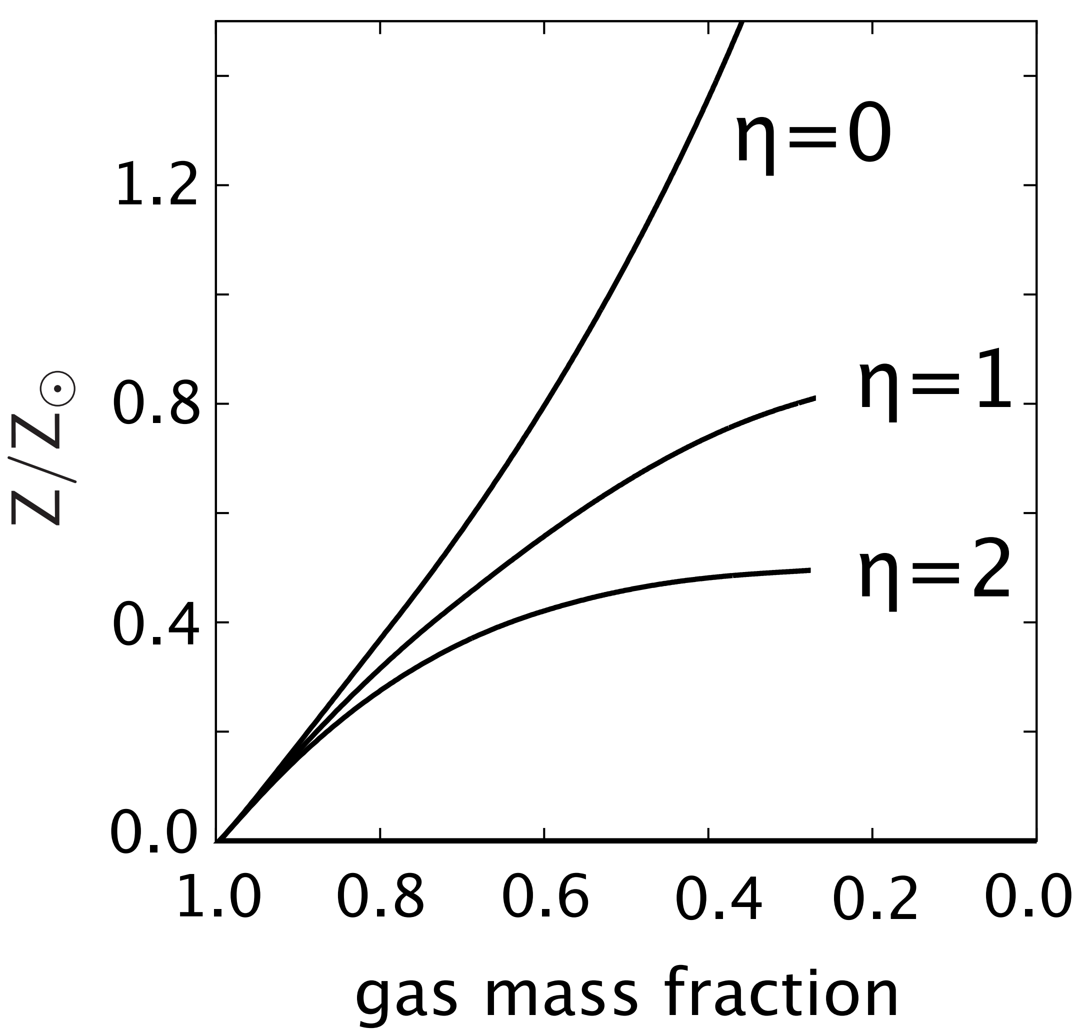




IFR and OFR can be reasonably constrained
even with degeneracy of model

Constraint of IFR&OFR with mock data

This method might work well
if metallicity of a galaxy is not too high
at a given gas fraction



Smaller mass loading factor,
higher metallicity at a given gas fraction

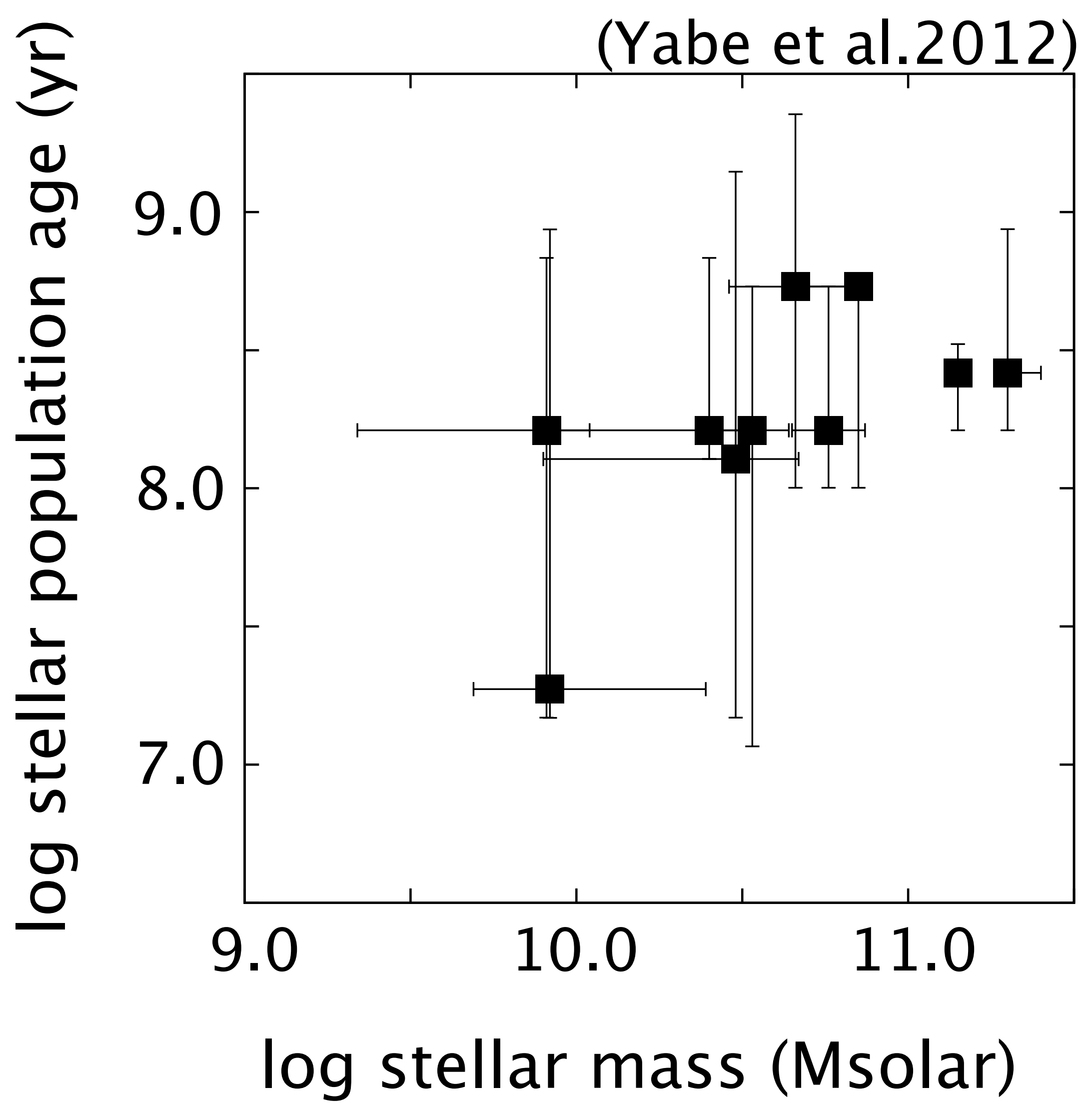
→If an observed galaxy locates above model track of no gas flow, the rates are not derived

Adding assumptions require more observables to constrain parameters

Measurement of properties also involve uncertainty
(e.g. line ratios, conversion factor)

Constraint of IFR&OFR with mock data

This method might work well
if galaxies are assumed to be young



To explain sSFR,
galaxies are assumed to be younger than 1-Gyr-old
→These galaxies started to form stars around z~2

These galaxies are not on the main sequence at z>2.5

The assumption might be extreme and inconsistent with other observational facts

Summary

What we do :

We attempt to quantify inflow and outflow of star-forming galaxies in general field at z~1.4 using chemical evolution model.

What we find :

The ranges of rates of inflow and outflow can be constrained if uncertainty about observational data is small.

This method might work well if metallicity of a galaxy is not so high at a given gas fraction.

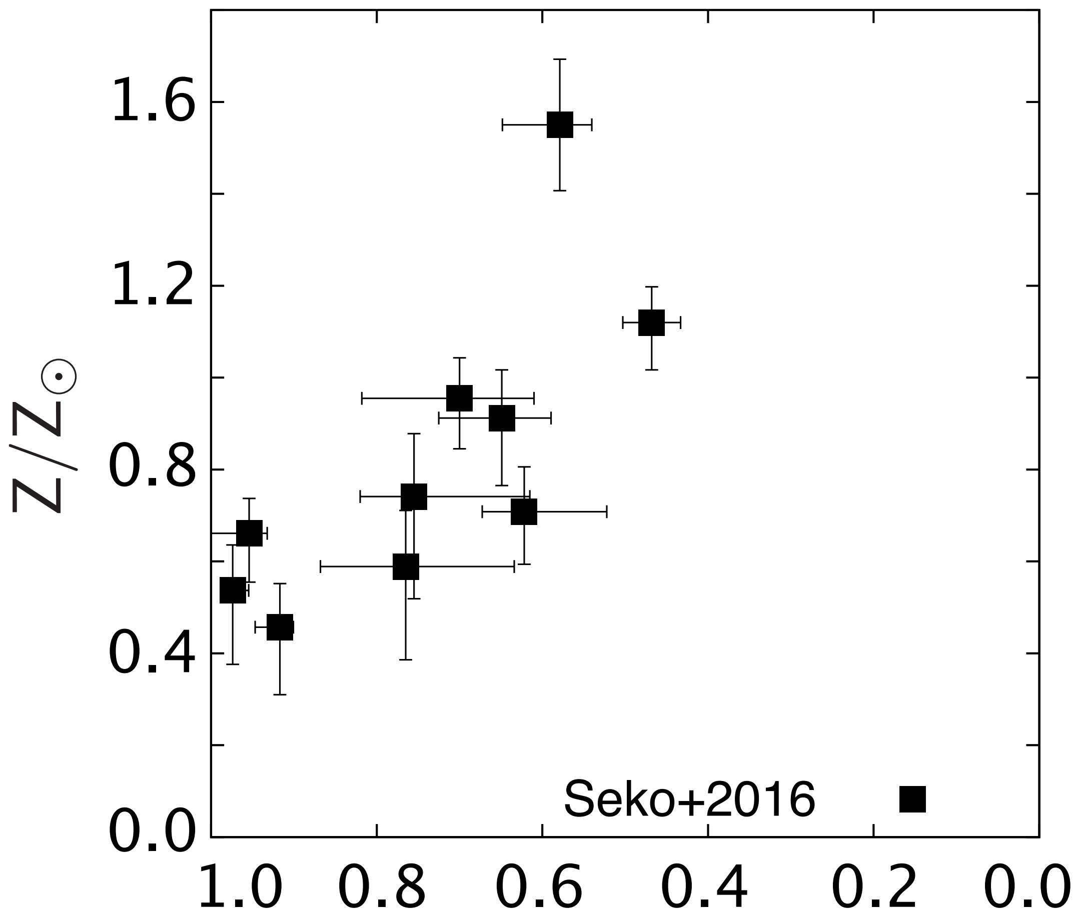
Galaxies have to be assumed to be young.

Constraints of rates of inflow & outflow

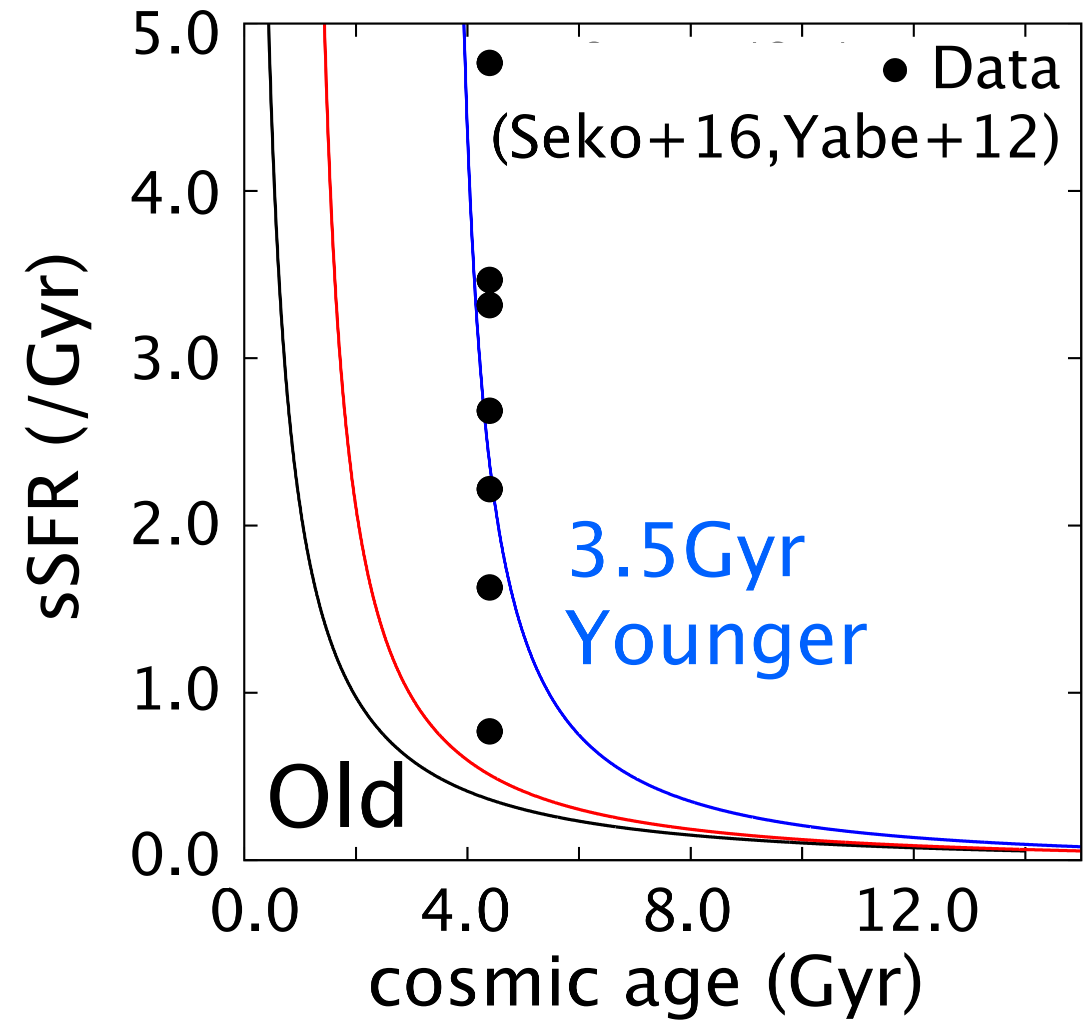
Inflow rate : $F = a \cdot m_{g,h}$
Outflow rate : $O = \eta \cdot \Psi$
mass-loading factor : η

Data : individual star-forming main-sequence galaxies

(z~1.4, Seko et al. 2016)



Data can be explained if ages are different



Predicted sSFRs are much lower than observed value

Time variation is not sensitive to parameters
(e.g., Peng&Maiolino 2014)

We treat galactic age as a parameter

Determined range of age is within those by SED fitting
(Yabe+2012)