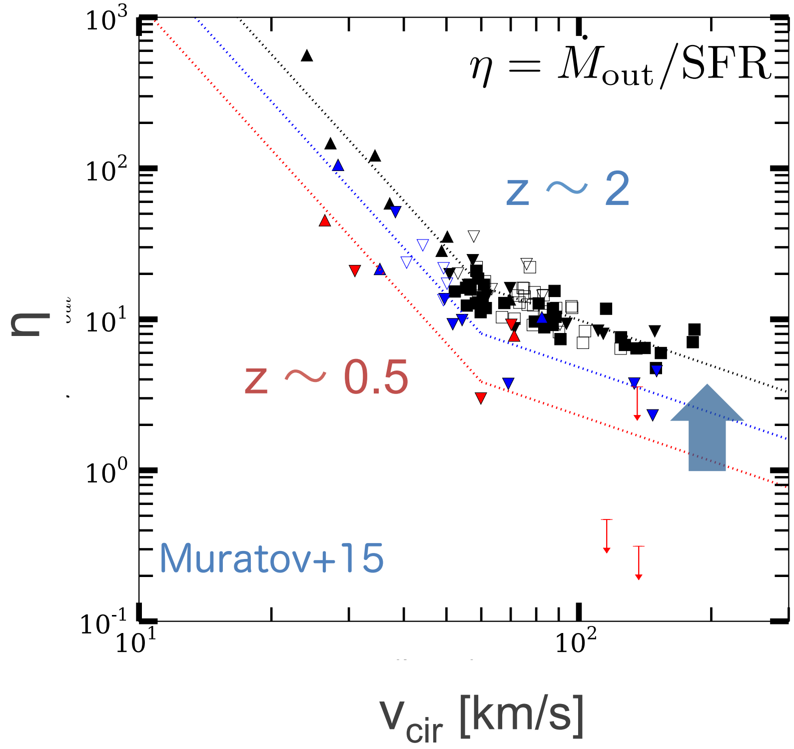
Evolution of Galactic Outflows at z=0–2 Revealed with SDSS, DEEP2, and Keck spectra

Yuma Sugahara
Tokyo, ICRR, D1

Collaborators:
M. Ouchi (Tokyo), **L. Lin** (ASIAA), **C. L. Martin** (California),
Y. Ono, **Y. Harikane**, **T. Shibuya** (Tokyo), **R. Yan** (Kentuchy)

Introduction

Numerical Simulation

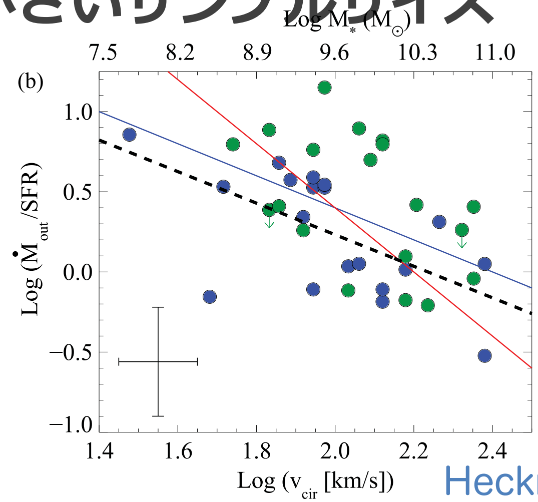


- ► Negative Feedback to SF
- ► Redshift evolution of outflow
- ► No observational results

現状の研究の問題点

アウトフローの赤方偏移進化を探りたい

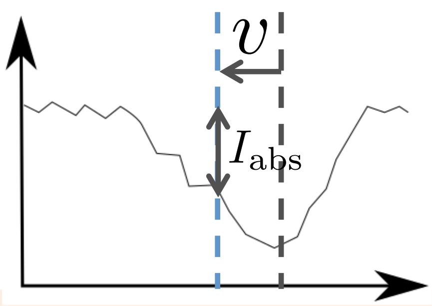
1. 小さいサンプルサイズ



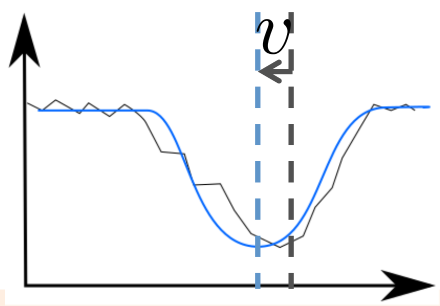
Heckman+15

2. 不均一な測定法

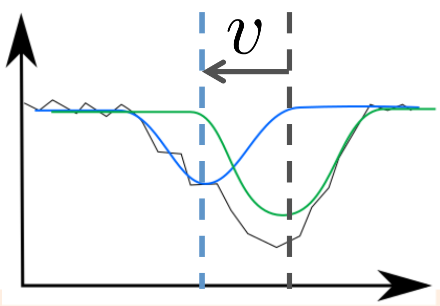
a. 非パラメータ法



b. 1成分法



c. 2成分法



Purpose

Purpose:

Study outflow of star-forming galaxies at z$\sim$0–2

Method:

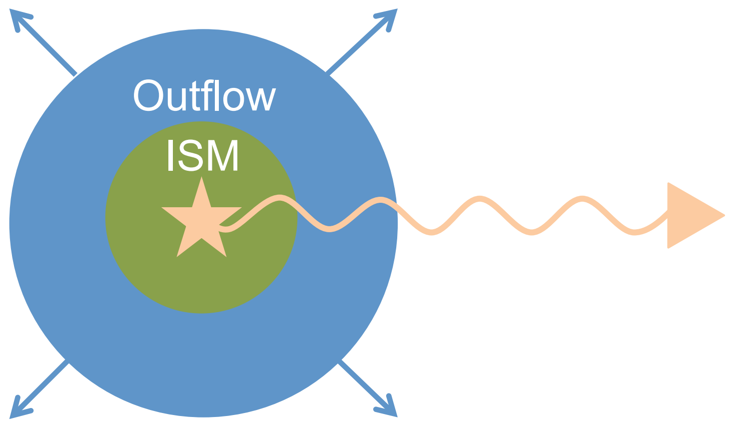
1. Large sample size

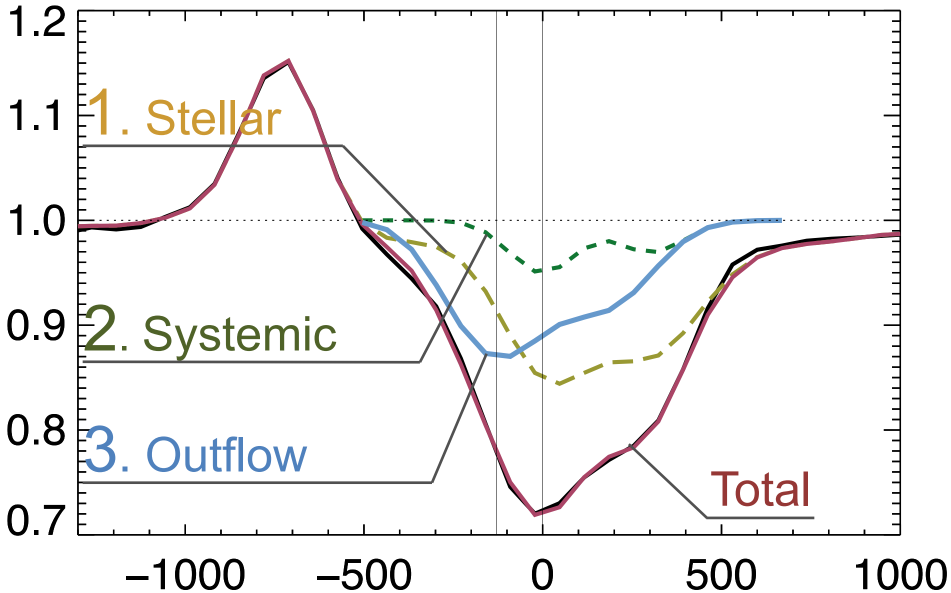
2. Same analysis

3. Same stellar mass range

Analysis

Three kinds of absorption





1. Stellar

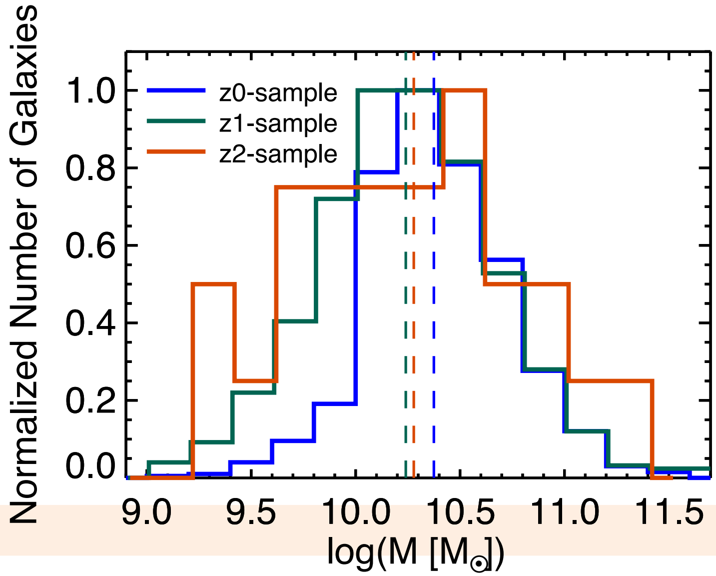
2. Systemic ··· Absorption by ISM

3. Outflow ··· Blueshifted absorption

Samples

Large sets of optical spectra

Sample	z0-sample	z1-sample	z2-sample
Data	SDSS DR7	DEEP2 DR4	Erb+06b,c
z	0.05 < z < 0.18	1.2 < z < 1.5	2.0 < z < 2.5
Line	Na ID	Mg I, Mg II	C II, C IV
Number	785	1337	25

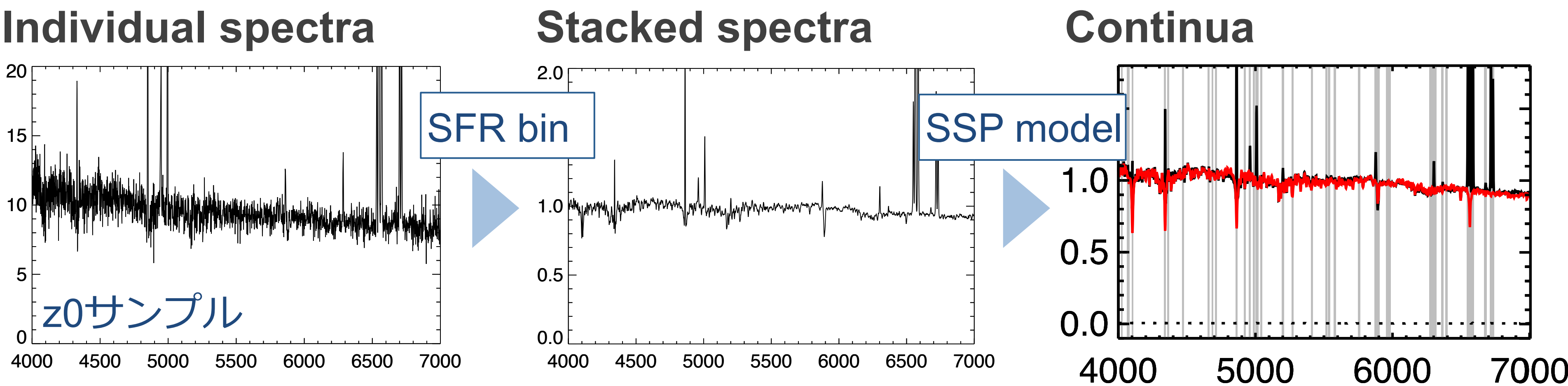


Compare absorption lines that have similar Ionization energy (IE) and depths

z∼0–1 : NaID & MgI (IE ∼ 5 eV)

z∼1–2 : MgII & CII (IE ∼ 20 eV)

Estimate outflow components



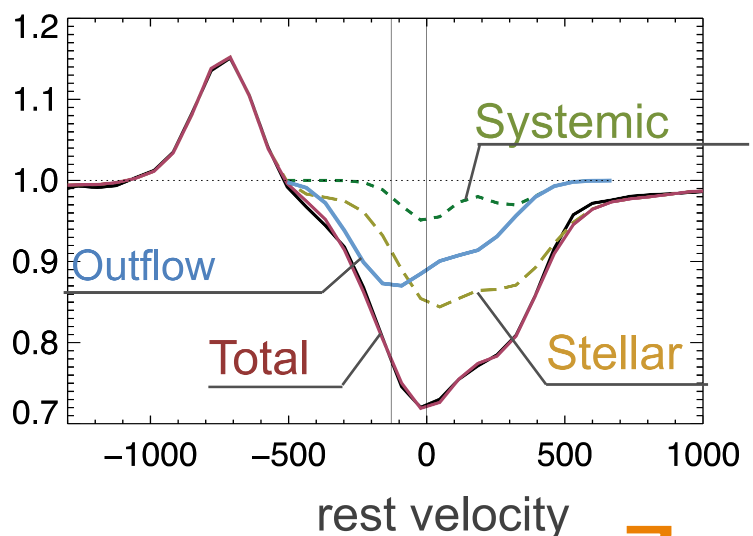
Gas component (**Outflow** & **Systemic**)

○ radiation transfer + covering factor (C_f)

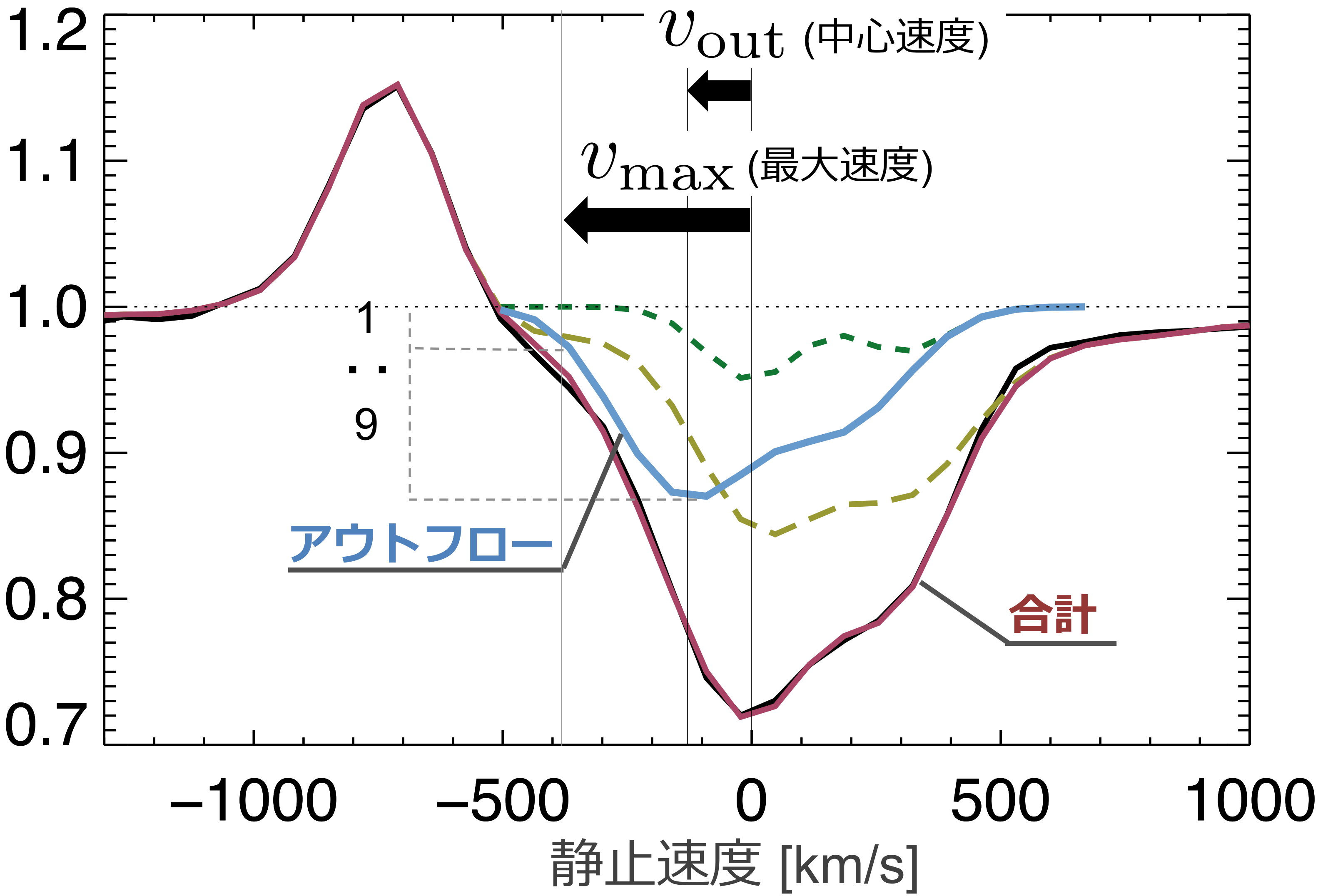
$$I = (1 - C_f)I_0 - C_f I_0 e^{-\tau}$$

○ optical depth → Gaussian

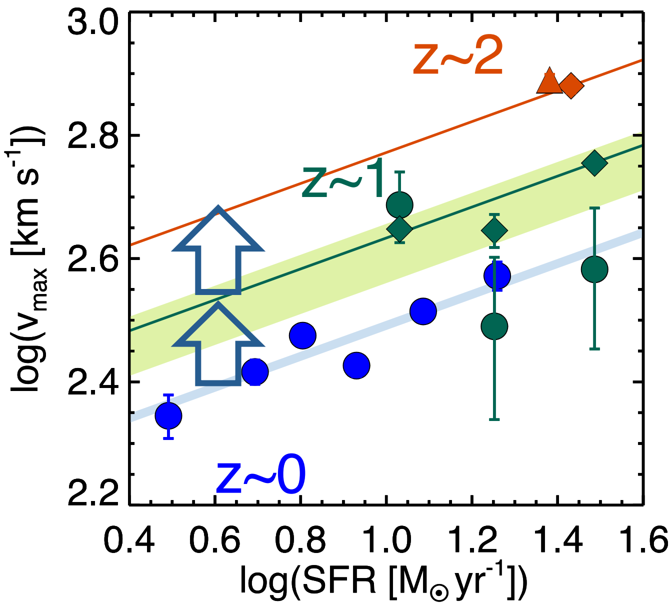
$$\tau(\lambda) = \tau_0 \exp\left(-\frac{(\lambda - \lambda_0)^2}{(\lambda_0 b/c)^2}\right)$$



2種類のアウトフロー速度



Redshift Evolution (v_{out}, v_{max})



$v_{\rm max}$: Increase at z~0-2

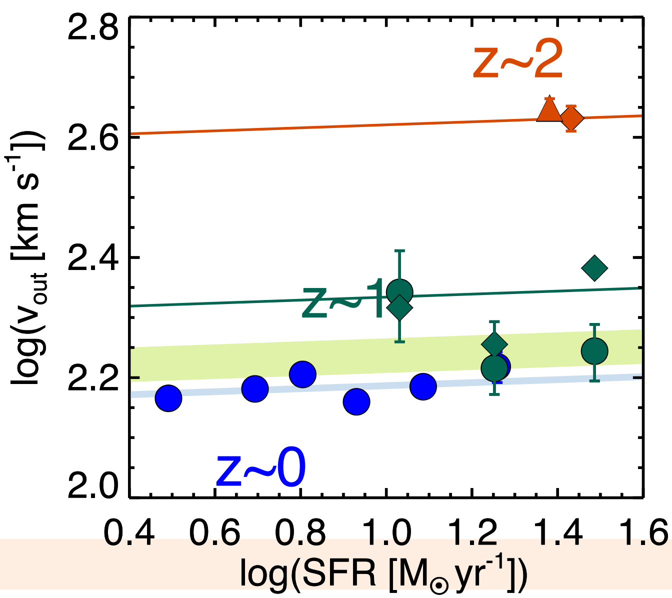
z = 0→1

z = 1→2

$v_{\rm out}$: Increase at z~0-2

z = 0→1

z = 1→2



Outflow velocities increase with increasing redshift.

Mass Loading Factor η

Standard outflow model

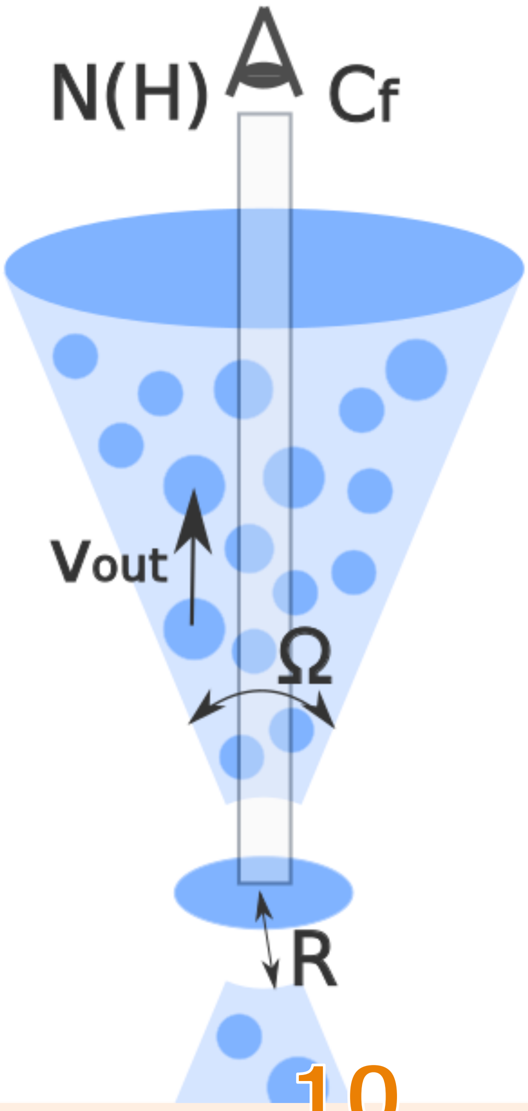
○ Fitting results

$$C_f, v_{\rm out}, N(\rm X^n)$$

○ Assumption

R: inner radius of outflow (effective radius)

Ω: solid angle (4π)



Mass outflow rate

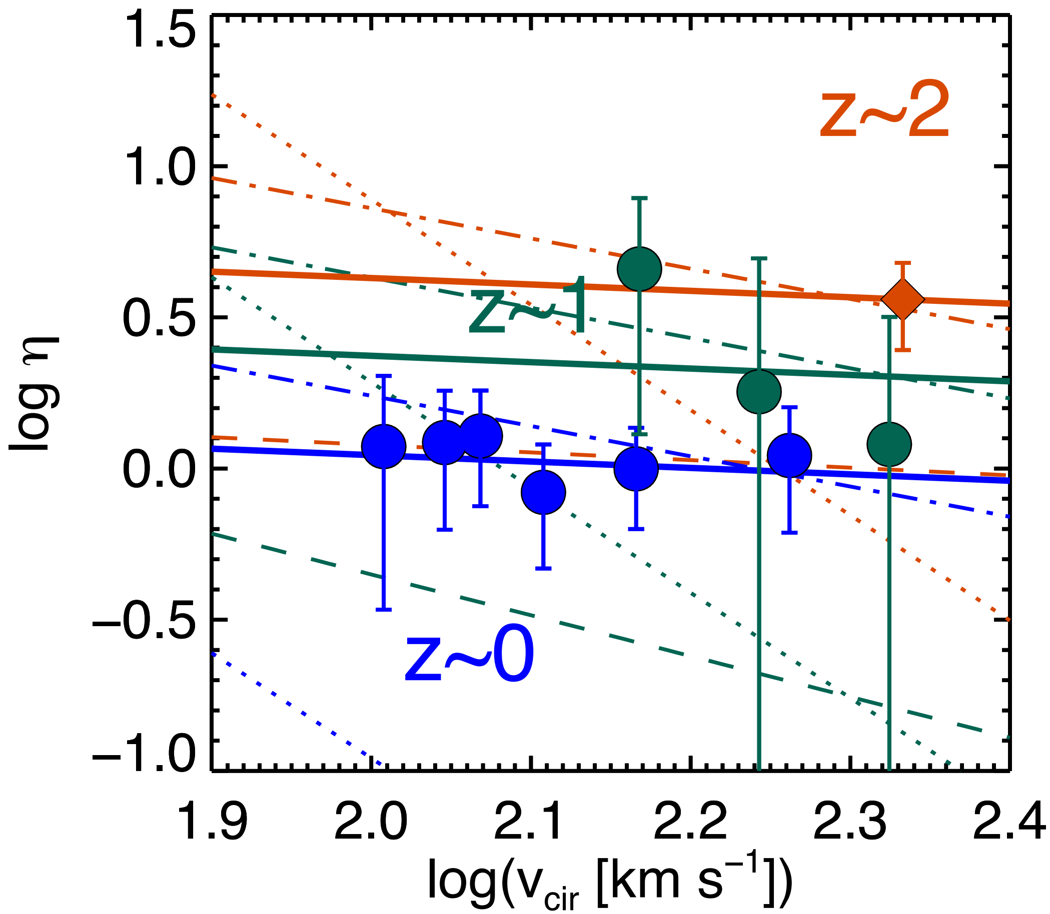
$$\dot{M}_{\rm out} = \bar{m}_p \Omega C_f R N(H) v_{\rm out}$$

mass loading factor

$$\eta = \dot{M}_{\rm out}/{\rm SFR}$$

representing efficiency of outflow

Redshift evolution (η)



η increase with increasing redshift

$$\eta \propto (1 + z)^{1.2 \pm 0.3}$$

赤方偏移進化の考察

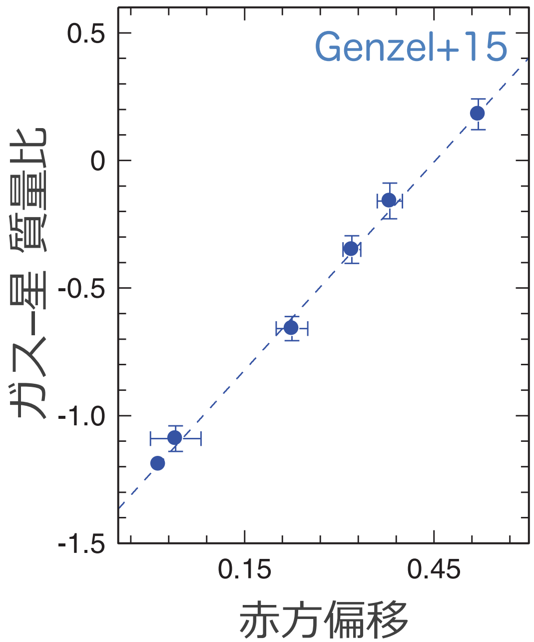
仮定：M_{out}が銀河の M_{gas}^{cold} と比例

$$\eta = \frac{\dot{M}_{out}}{SFR} \propto \frac{M_{gas}^{cold} v_{out}}{SFR}$$

$$M_{gas}^{cold} \propto \frac{\eta SFR}{v_{out}}$$

観測

独立な観測 (電波)



本研究 + 星形成率進化 Speagle+14

$\log(M_*/M_\odot)=10.5$において

$$M_{gas}^{cold} \propto (1+z)^{3.4\pm0.7}$$

$$M_{gas}^{cold} \propto (1+z)^{2.7}$$

高赤方偏移の M_{gas}^{cold} の増加が鍵

Explanation of Outflow Evolution

Best-fit relation

$$\mathbf{v}_{\max} \propto (\mathbf{1}+\mathbf{z})^{\mathbf{0.59\pm0.03}}$$

Analytical relation

Shibuya et al. 2015

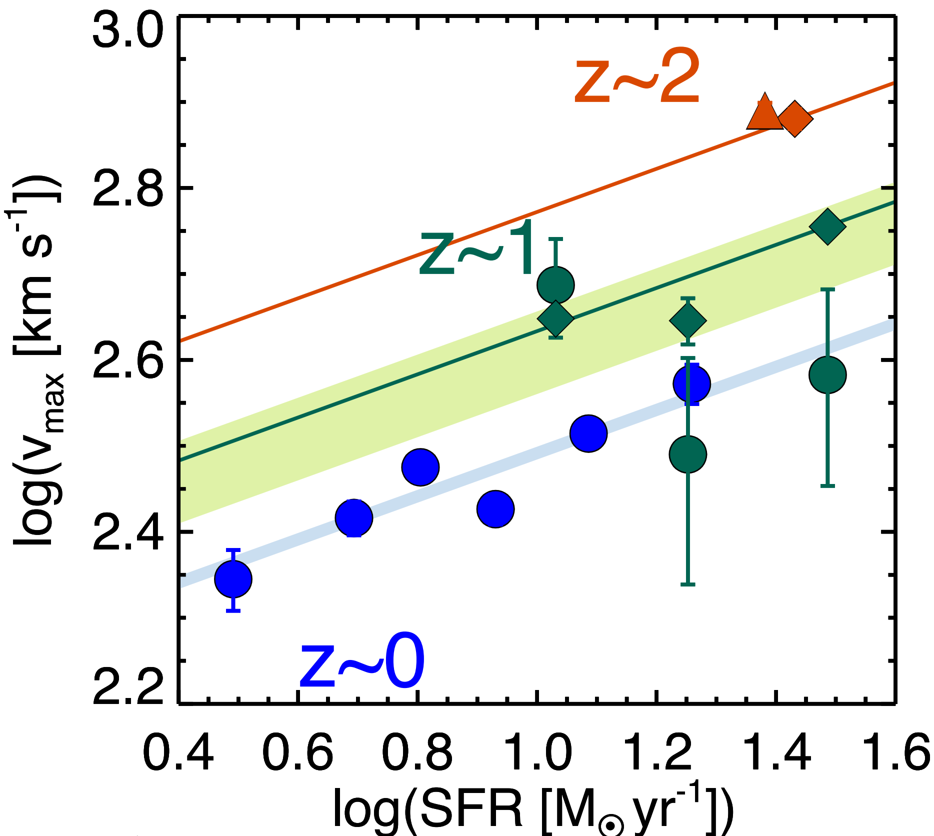
$$r \propto (1+z)^{-1}$$

At fixed SFR,

$$\Sigma_{\rm SFR} \propto (1+z)^2$$

Heckman et al. 2016 (z ~ 0)

$$v_{\max} \propto \Sigma_{\rm SFR}^{1/3} \propto (1+z)^{2/3}$$



Evolution may be explained by low-z relation.

Summary

Sugahara et al. (submitted) **arXiv:1703.01885**

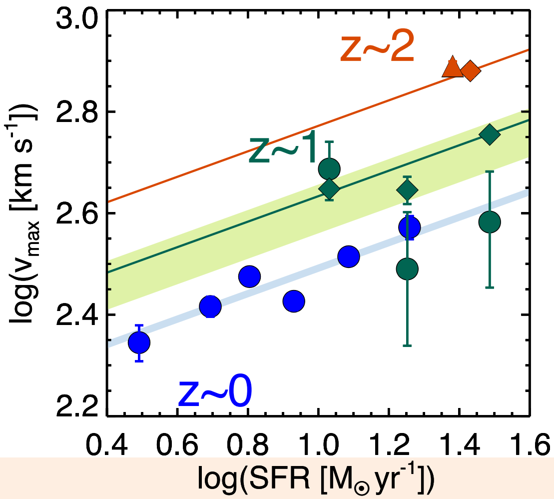
Purpose: Study redshift evolution of outflows

Methods: Use samples of star-forming galaxy at z~0-2

Derive **outflow velocity** v & **mass loading factor** η

Results:

1. v & η increase at z~0→2



2. explained by low-z relation

Shibuya et al. 2015

$$r \propto (1+z)^{-1}$$

At fixed SFR,

$$\Sigma_{\rm SFR} \propto (1+z)^2$$

Heckman et al. 2016

$$v_{\rm max} \propto \Sigma_{\rm SFR}^{1/3} \propto (1+z)^{2/3}$$