Observations for Outflows of Very Low-Mass Galaxies with $M_* \sim 10^{5-8} M_\odot$

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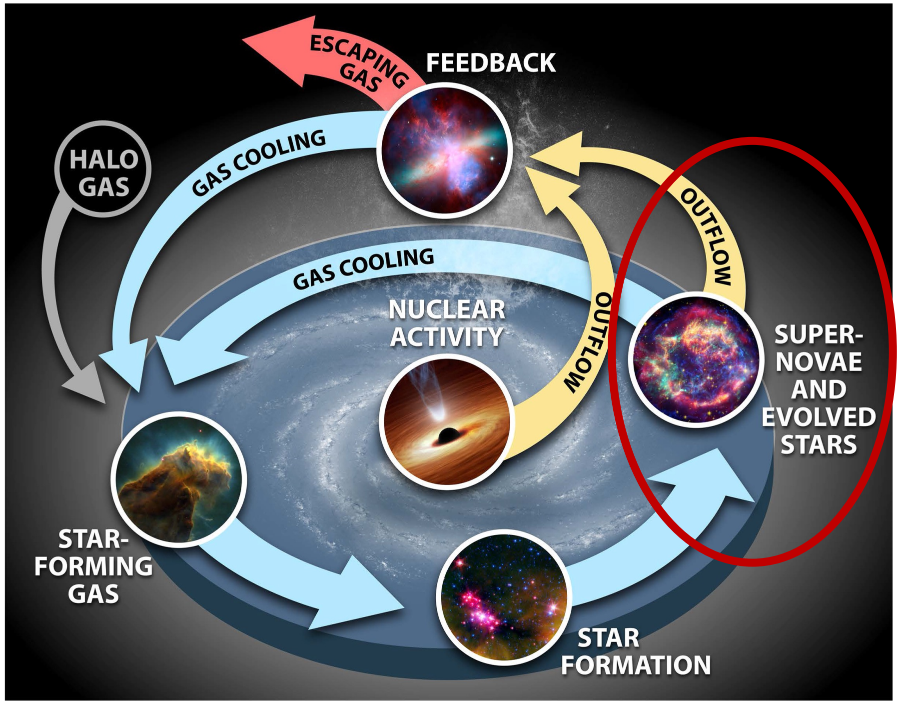
Galaxy-IGM workshop

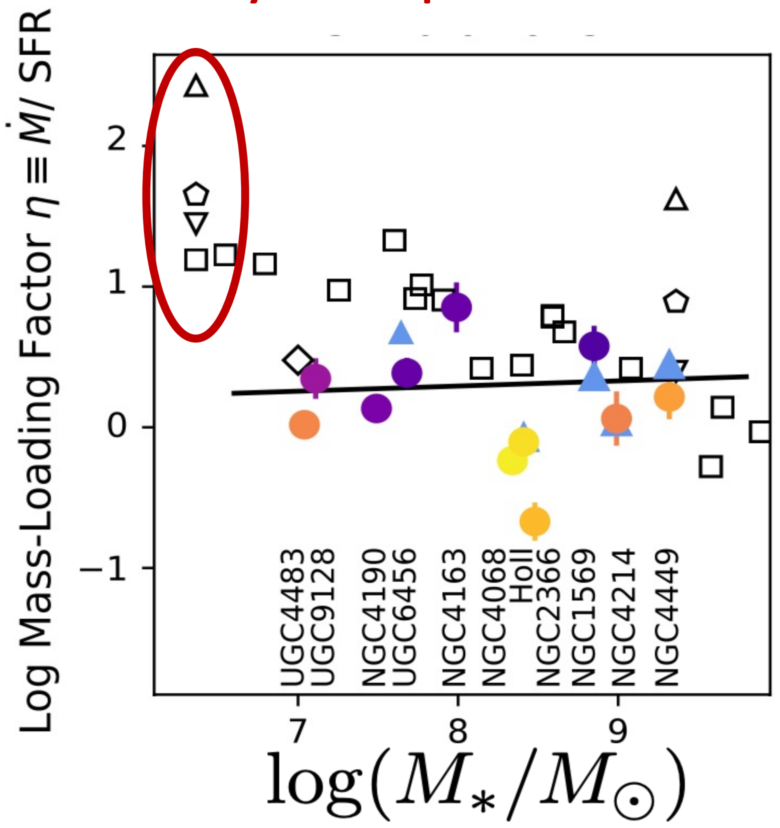
Motivations

➢ Galactic outflow is closely related to
  - Star formation activity
  - CGM and IGM
  - …



➢ Two main questions investigated in this study
1. Are there escaping gas?
2. How strong is the feedback in low mass regime

Low mass regime no observation study ever explored



Filled symbols: Observations results from Martin 1999 and McQuinn+19

Open symbols: Simulations results

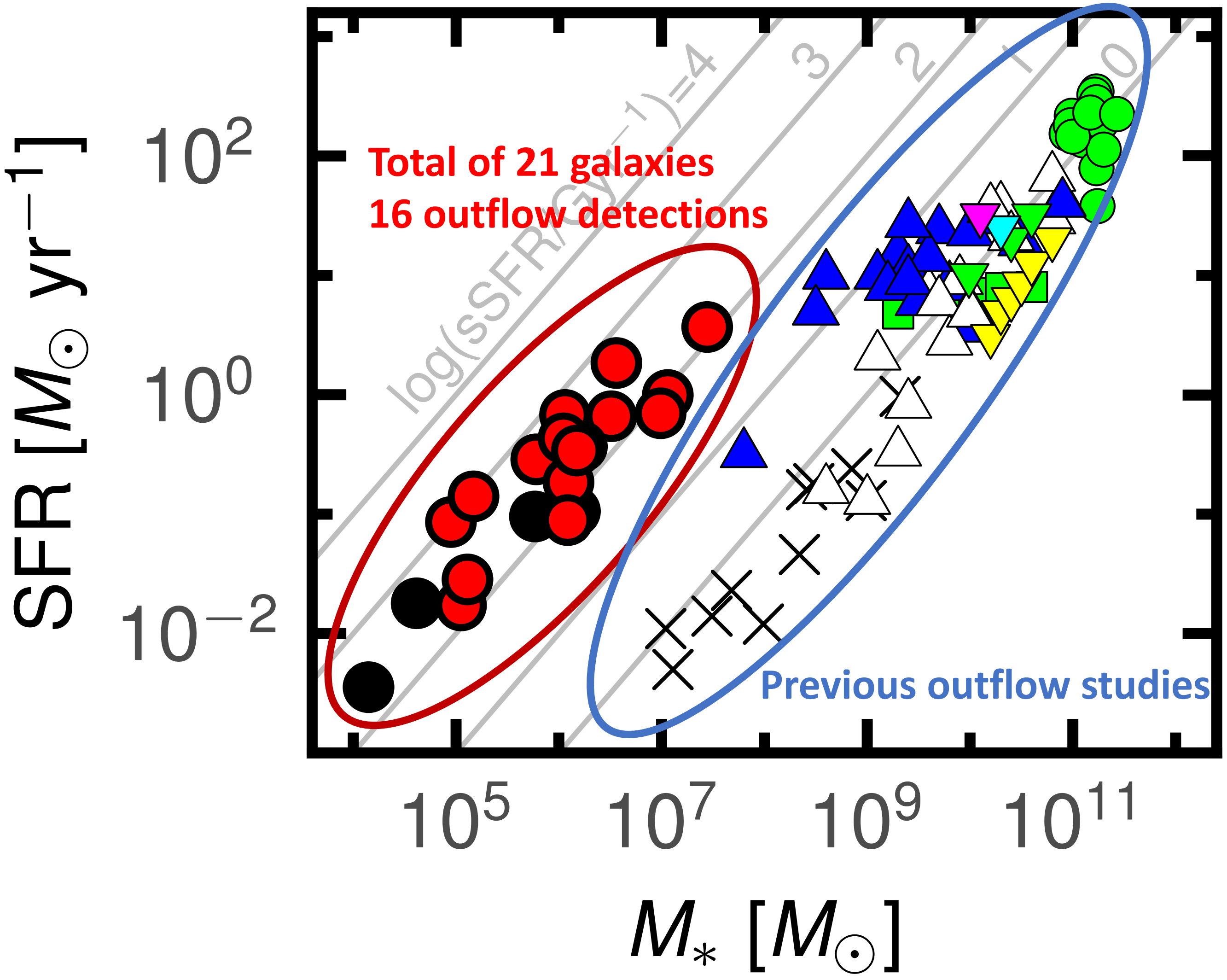
Galaxy Sample and Observations

- Galaxy sample
  - Local low-mass star-forming galaxies

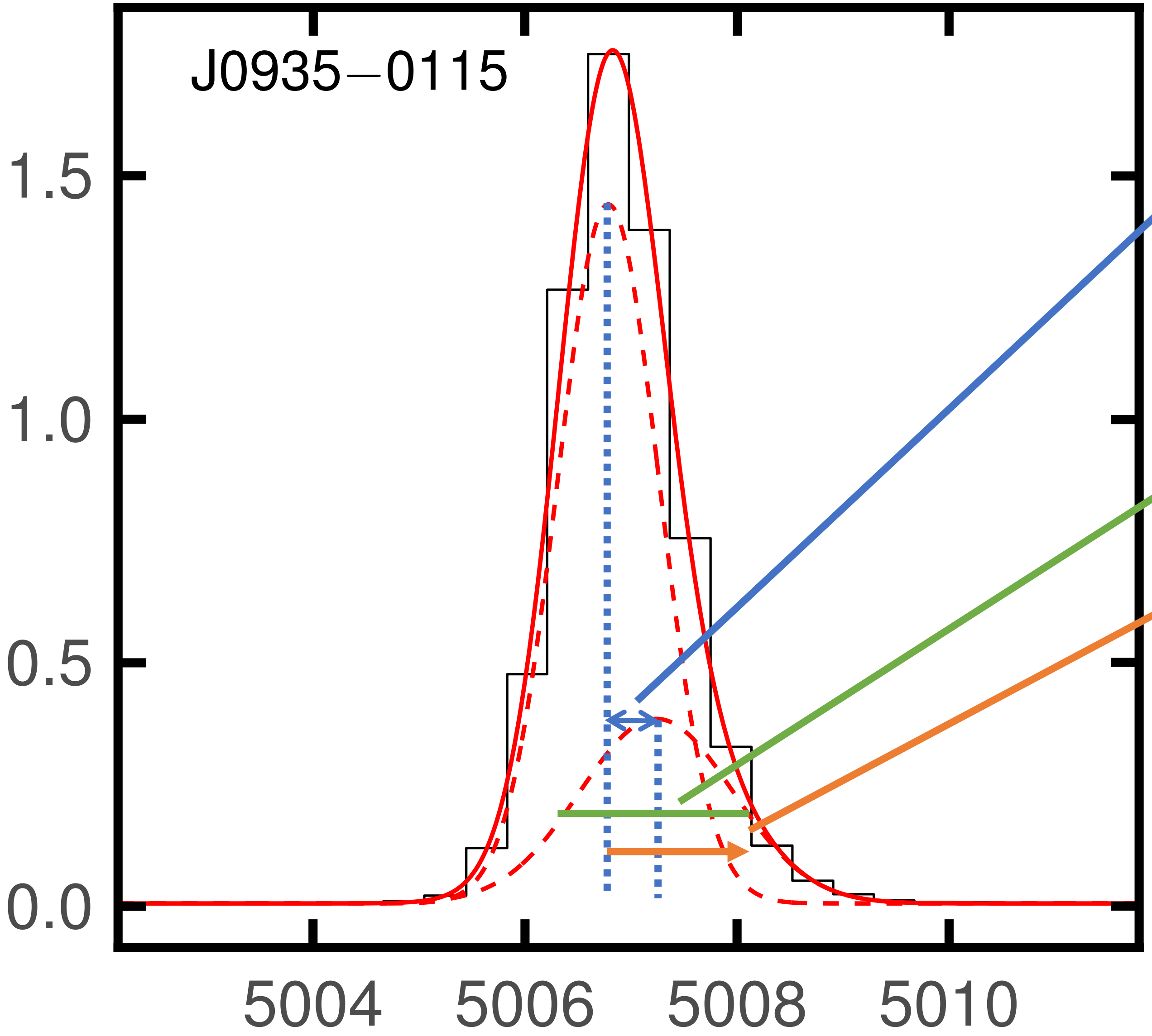
  (Kniazev+03,04, Izotov+12, Sanchez-Almeida+16, Kojima+20, Nakajima+ in prep.)
  - $M_* \sim 10^{5-8} M_\odot$
- Observations
  - Two observation runs with Magellan/MagE

    June 2018 and Feb. 2021
  - Spectral resolution ~4000
- Outflow detection
  - double-Gaussian profile fitting of emission lines (Ha and [OIII]5007)

  → tracing warm-phase ionized outflows



Outflow Properties



① $\Delta v = c(\mathrm{center_b} - \mathrm{center_n})/\mathrm{center_n}$

- In previous studies: caused by dust attenuation (assuming symmetric bi-conical outflows)
- In our sample: 6 galaxies show significant redshifted broad components

→ asymmetric outflow

② $\mathrm{FWHM_b}$

③ $v_{\mathrm{max}} = |\Delta v| + \mathrm{FWHM_b}/2$

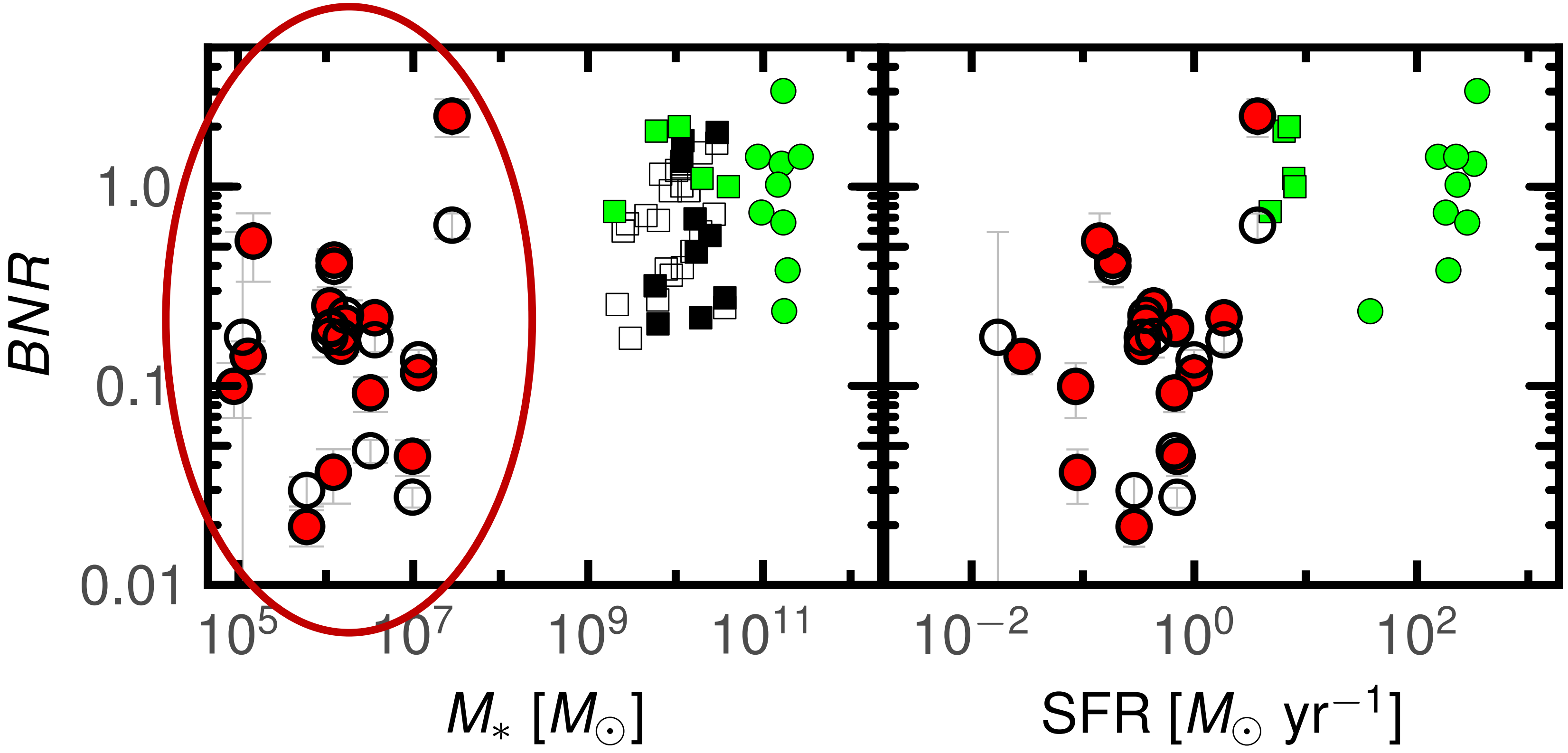
④ $BNR = \mathrm{flux_b}/\mathrm{flux_n}$

Roughly indicate the mass ratio between outflowing gas and star-forming nebulae

Results and Discussions

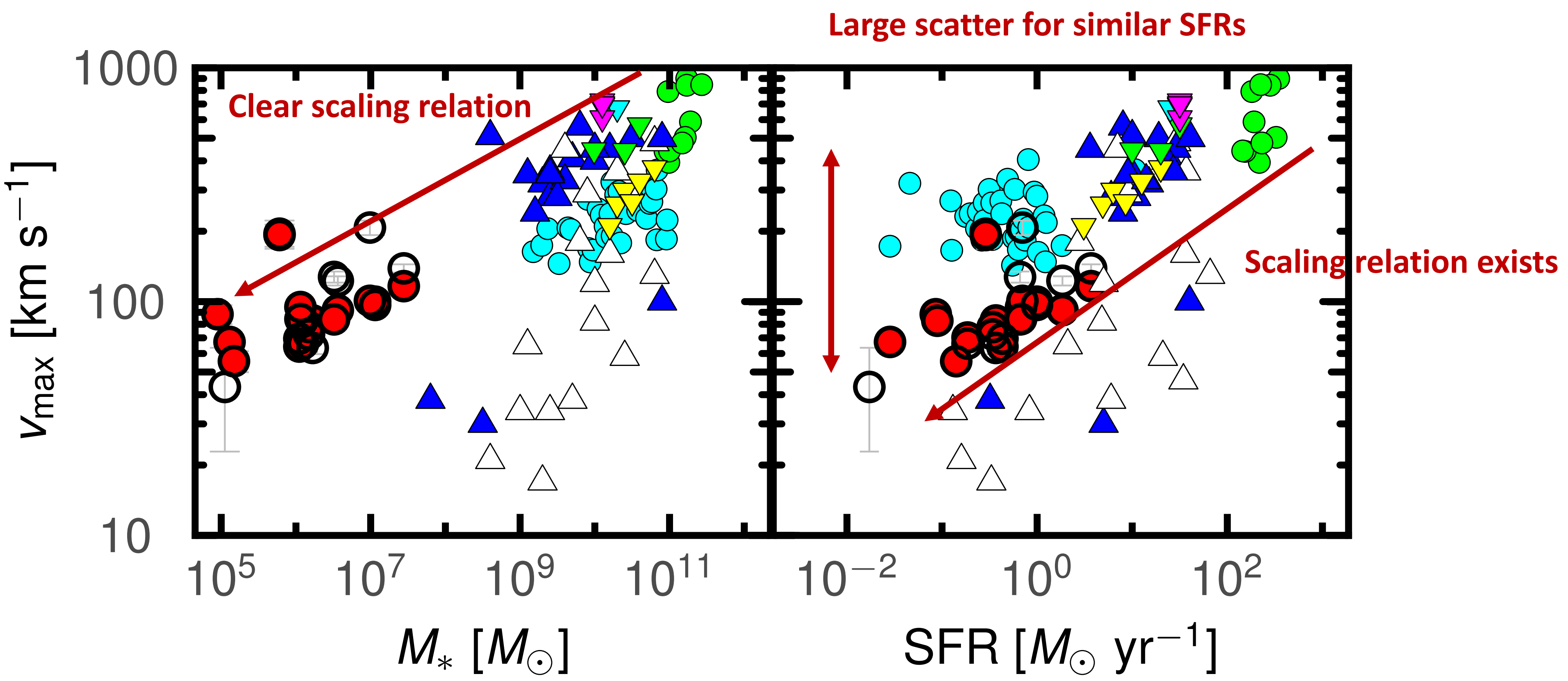
Scaling Relations of Outflow Properties

- *BNR* – no clear correlation with mass or SFR
- Small values are detected for our galaxies

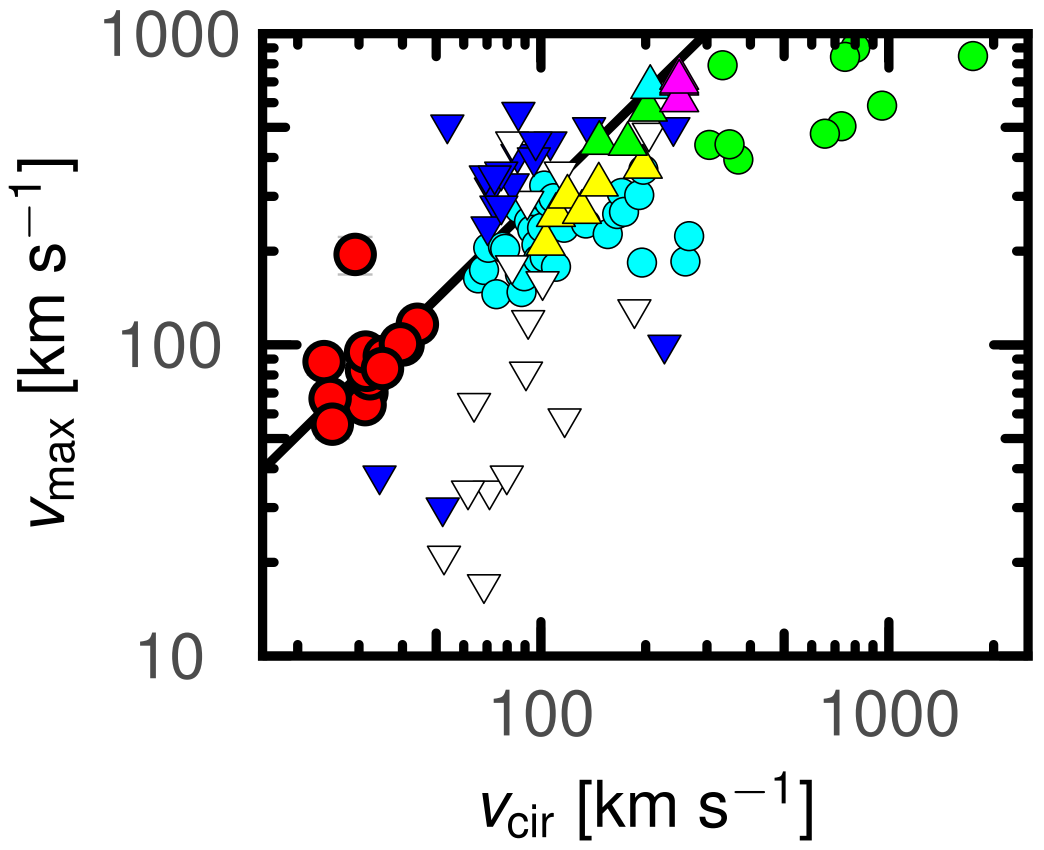


Red-filled circles: calculated from Ha lines
Open circles: calculated from [OIII] lines

Scaling Relations ($v_{\max}$ vs M_* and SFR)



Scaling Relations (v_{max} vs v_{cir})



- Circular velocity of dark matter halo (v_{cir})

$$v_{\mathrm{cir}} = \left(\frac{GM_{\mathrm{h}}}{r_{\mathrm{h}}}\right)^{1/2}$$

→ A proxy of gravitational potential

- Strong correlation: circular velocity is the fundamental parameter that determines outflow velocity (Sugaraha+19)

- Agree well with the solid line predicted by FIRE simulation (Muratov+15)

Can Outflowing Gas Escape?

- Answer by estimating escape velocity
  - Assume a truncated isothermal sphere for DM Halo

$$v_{\rm esc} = [2(1+\ln\boxed{\frac{r_{\rm h}}{r}})]^{1/2} v_{\rm cir}$$

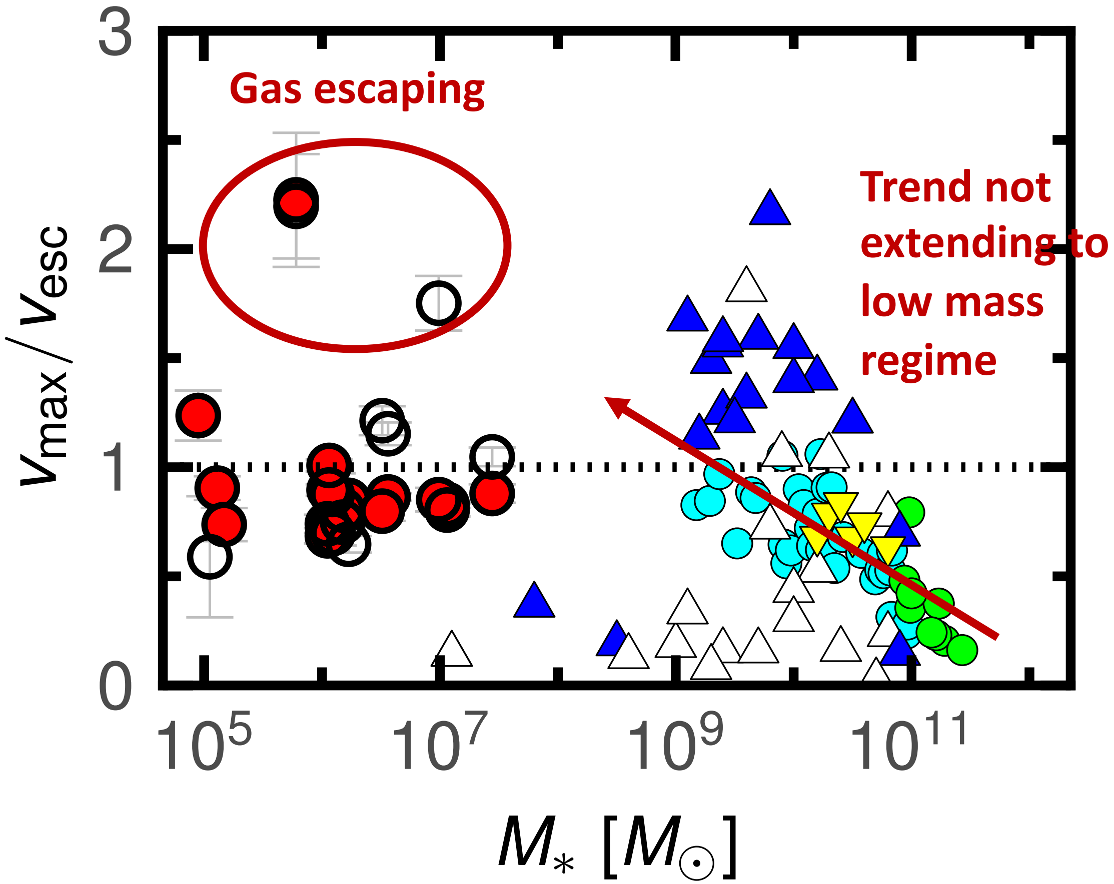
Which radius to evaluate escape velocity?

  - Approximation

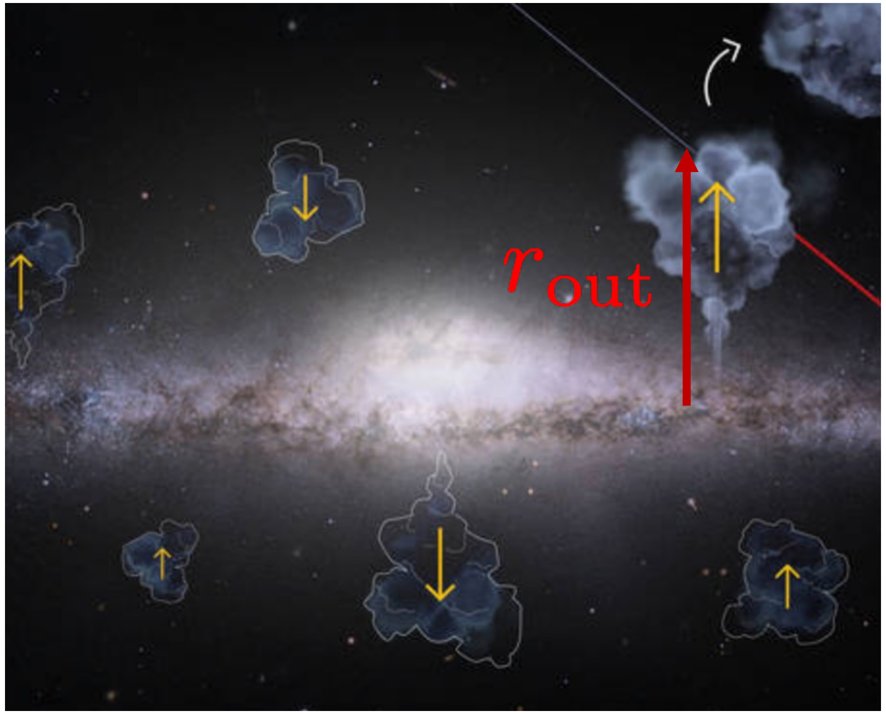
$$v_{\rm esc} = 3v_{\rm cir}\ (r_{\rm h} = 33r)$$

- Results
  - Most cases: $v_{\rm max}/v_{\rm esc} \sim 1$ -> gravitationally bounded
  - Two galaxies: $v_{\rm max}/v_{\rm esc} \sim 2$ -> gas escaping

→ gas escaping is not commonly observed in our low-mass galaxies



Mass Outflow



- Outflowing mass $M_{\mathrm{out}} = \dfrac{1.36 m_{\mathrm{H}}}{\gamma_{\mathrm{H}\alpha} n_{\mathrm{e}}} L_{\mathrm{H}\alpha,\mathrm{b}}$

- Mass outflow rate

Outflow timescale

$$\dot{M}_{\mathrm{out}} = M_{\mathrm{out}} / \boxed{\frac{r_{\mathrm{out}}}{v_{\max}}}$$

$$SFR \sim 7.9 \times 10^{-42} L_{\mathrm{H}\alpha}$$

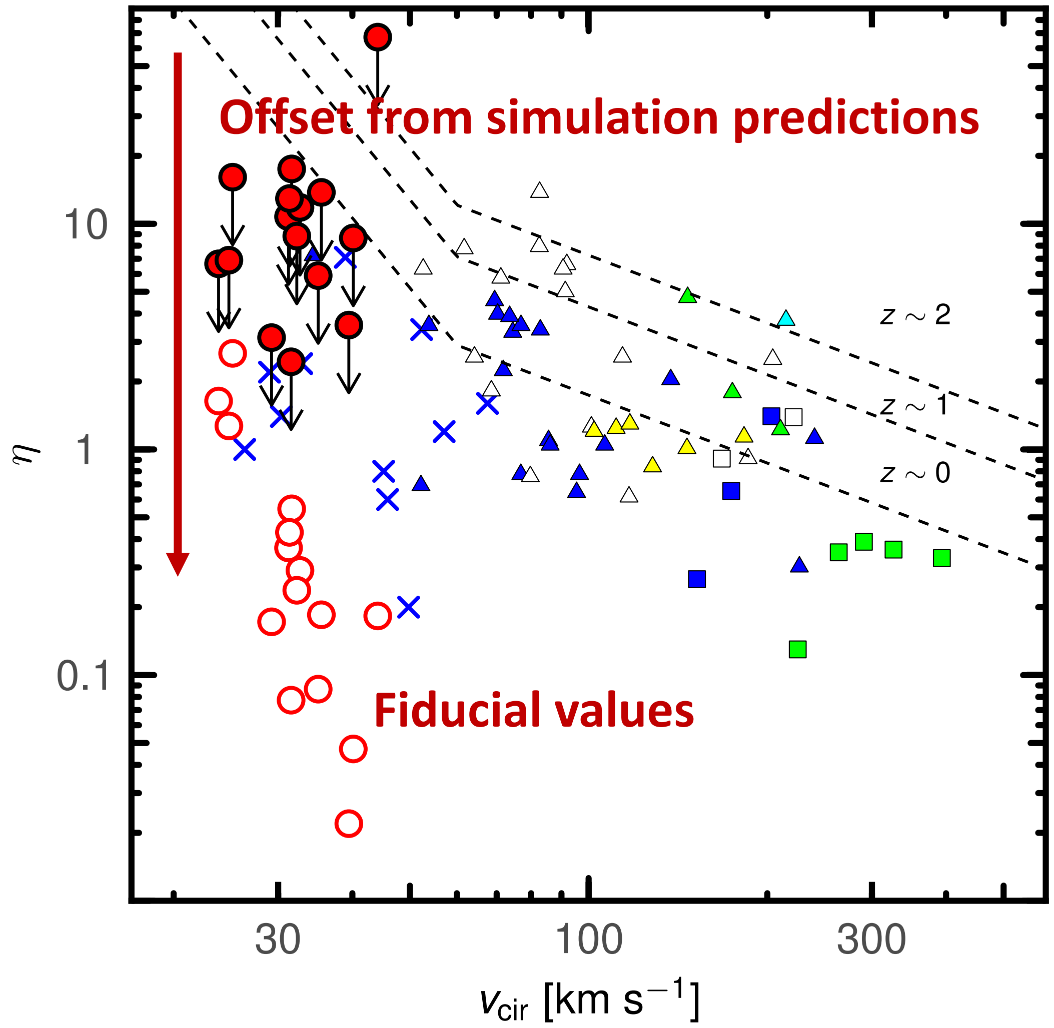
- Mass loading factor:

$$\eta = \dot{M}_{\mathrm{out}} / SFR \sim \left(\frac{300\ \mathrm{cm}^{-3}}{\mathrm{n_e}}\right)\left(\frac{v_{\max}}{100\ \mathrm{km\ s}^{-1}}\right)\left(\frac{100\ \mathrm{pc}}{r_{\mathrm{out}}}\right)\left(\frac{BNR}{1 + BNR}\right)$$

The efficiency of SFR to “push” outflow / removing gas

- Calculation have large uncertainties
  - Estimates of electron density and Rout -> use ne=50 and rout=10 pc for ”upper limits” of eta
  - Only warm ionized gas traced by emission lines

Mass Loading Factor vs Circular Velocity



- Simulations in Muratov+15 (dashed lines)
  - Energy-driven: circular velocity < 60 km/s
  - Momentum-driven: circular velocity > 60 km/s
- This study
  - Mass loading factor smaller than simulation results (both "upper limits" and fiducial values)
  - → Strong feedback is not observed in our galaxies
- Possible reasons
  - Relative low outflow velocities -> constrained by gravitational potential
  - Light outflow mass (low BNR)

Summary

- Ionized outflows are observed in 16 very low-mass galaxies using double-Gaussian profile fitting technique

- There are no clear correlation between BNR and M* (SFR)
- $v_{\rm max}$ show positive correlations with M*, SFR and $v_{\rm cir}$

- $v_{\rm max}$ in most galaxies is bounded by gravitational potential
- Relatively small mass loading factors suggest that feedback in low-mass regime is smaller than the one adopted by simulations