Properties and Scaling Relations of Ionized Gas Outflows at z~1-3

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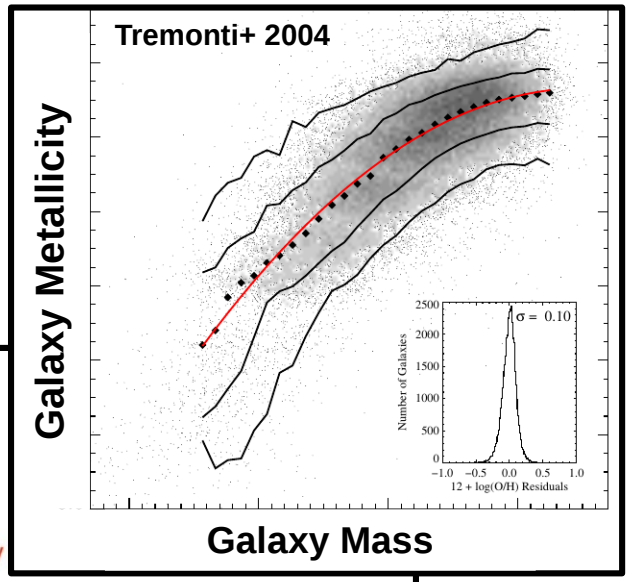
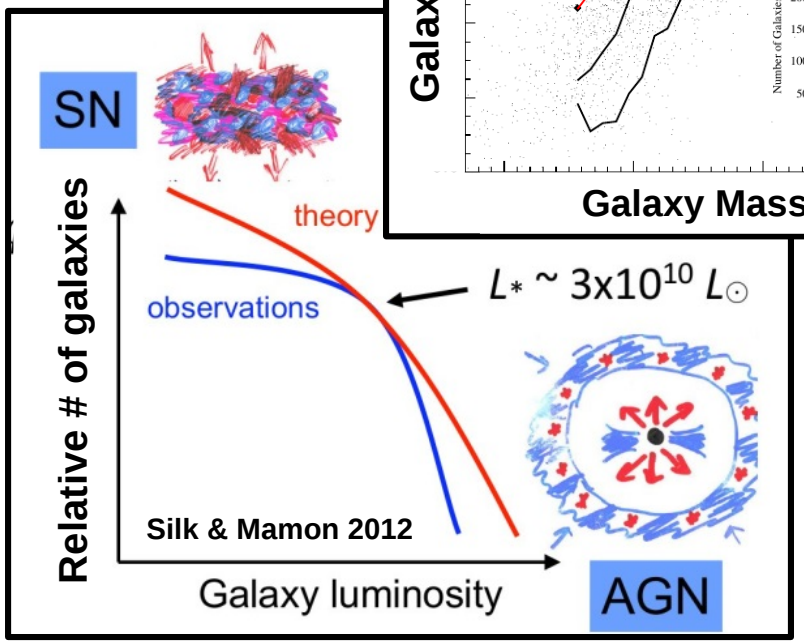
With Natascha Förster Schreiber, Reinhard Genzel, Hannah Übler, and the KMOS^3D/SINS/zC-SINF teams

Potsdam Thinkshop, September 3 2018

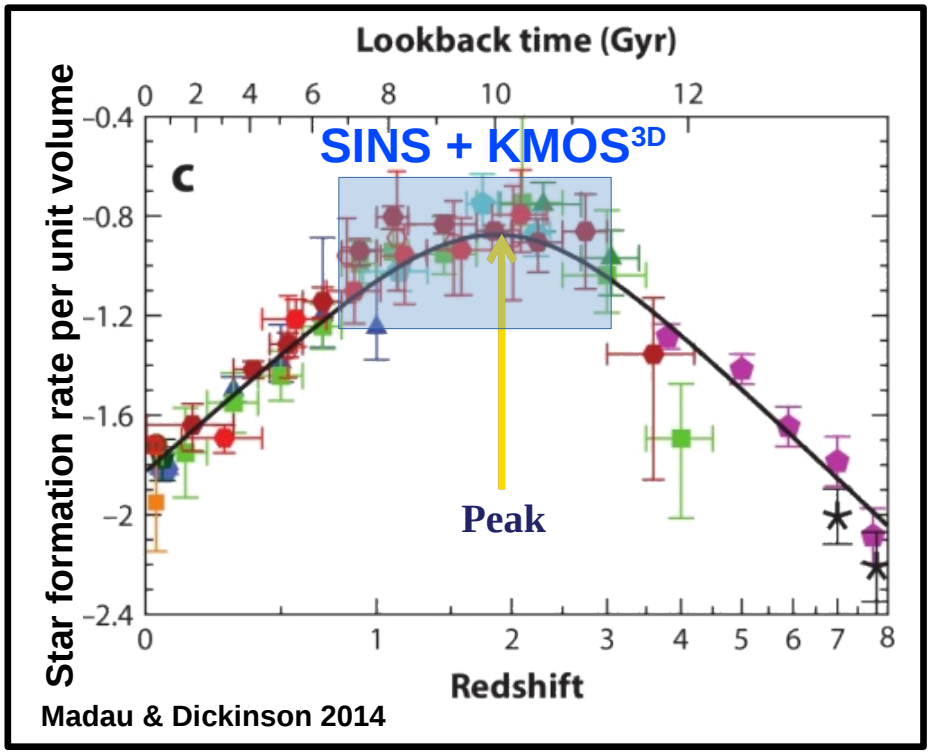
Why Study Outflows at z~1-3? Peak Epoch of Star Formation

Outflows required to explain properties of z~0 galaxy population

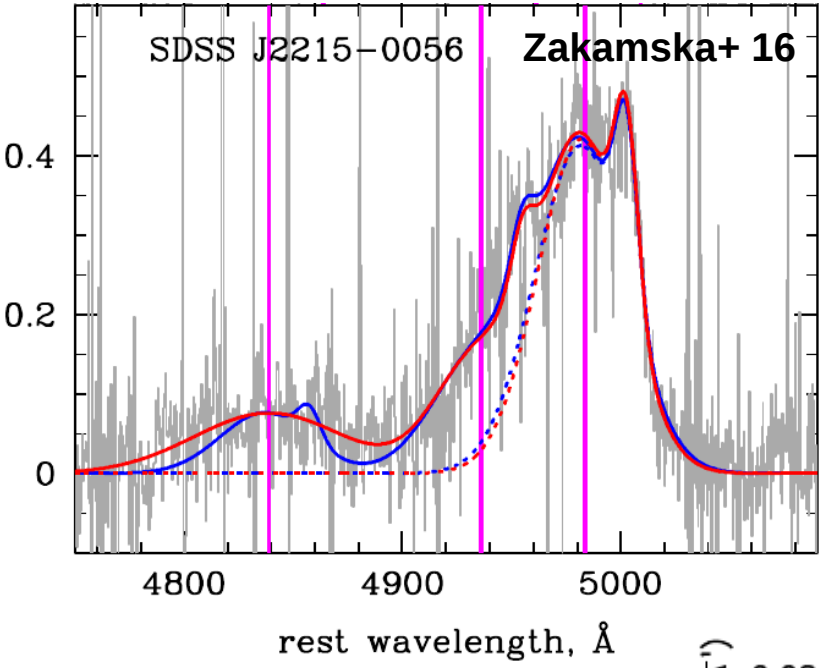


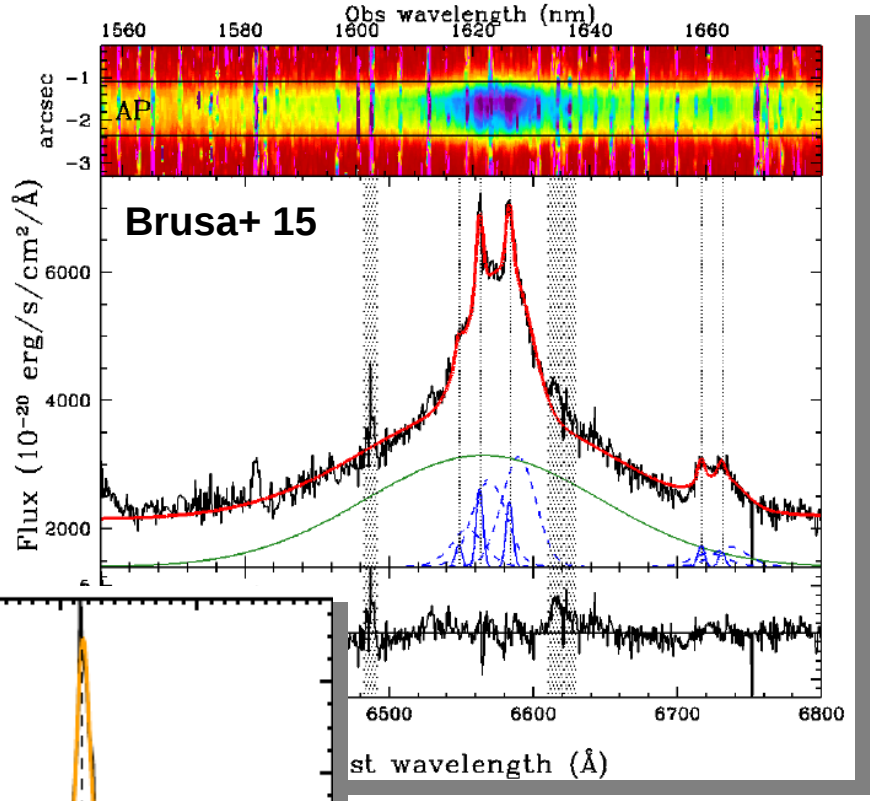


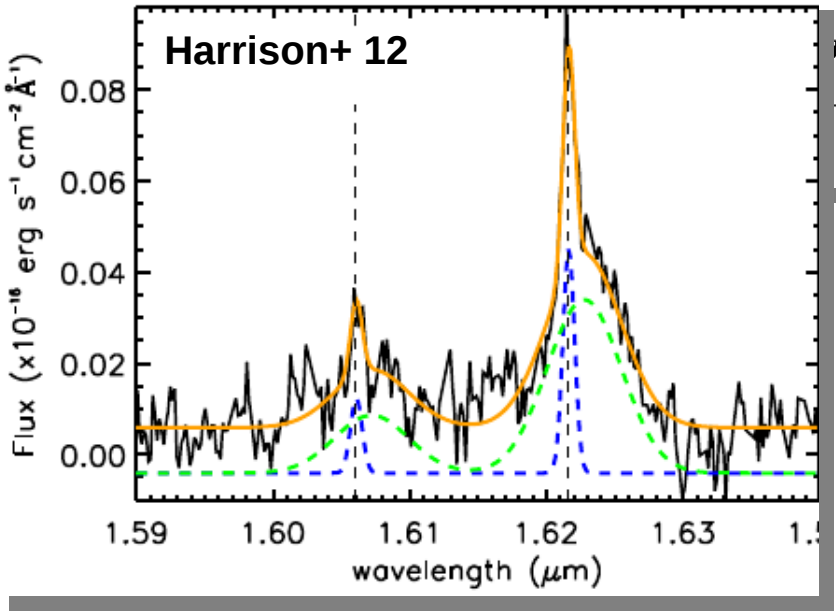
Study outflows at z~1-3 to gain insight into feedback processes impacting galaxies when they are forming most of their stars



Strong Outflows in Luminous AGN at z~1-3



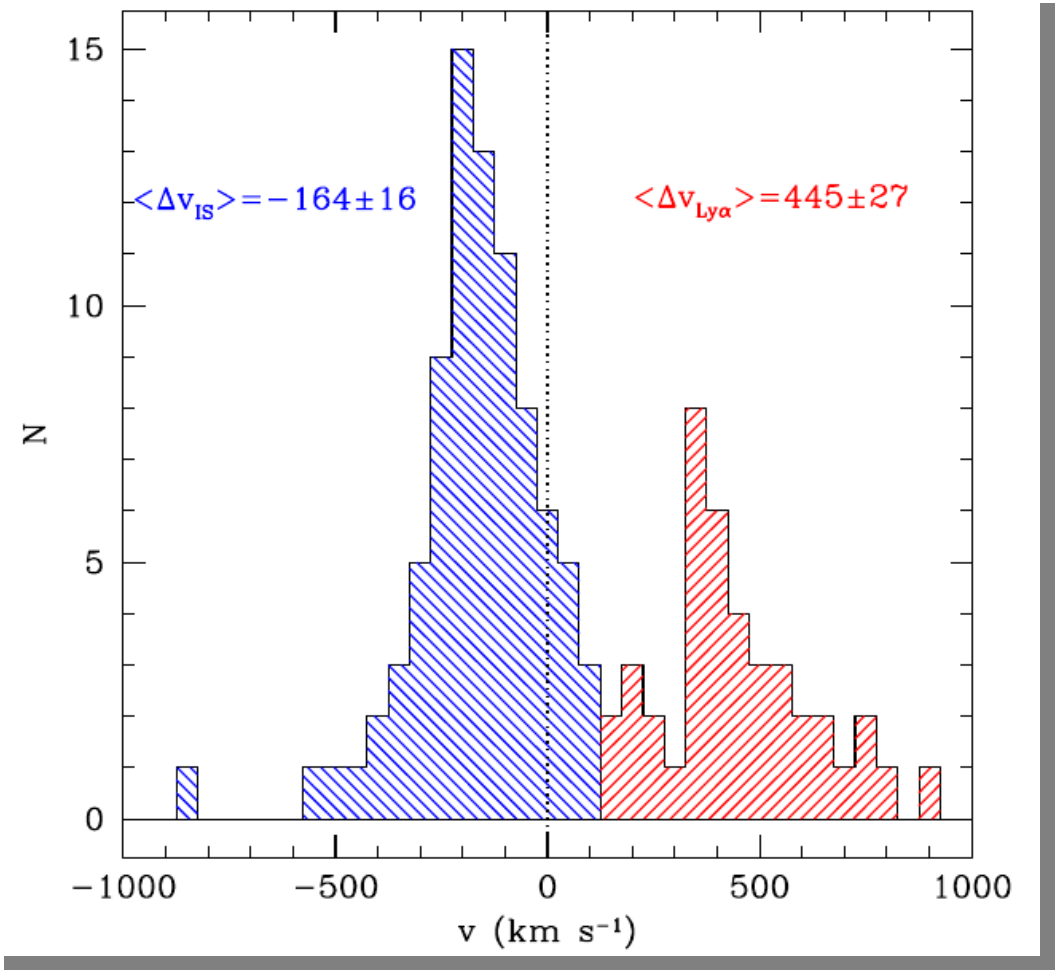




Ubiquitous Outflows in Lyman Break Galaxies at z~2

- 89 LBGs at z = 1.9-2.6 with Hα emission and UV absorption line measurements
- Absorption lines
  - blueshifted by ~165 km/s
  - FWHM ~550 km/s

→ ubiquitous outflows, with velocities of several hundred km/s



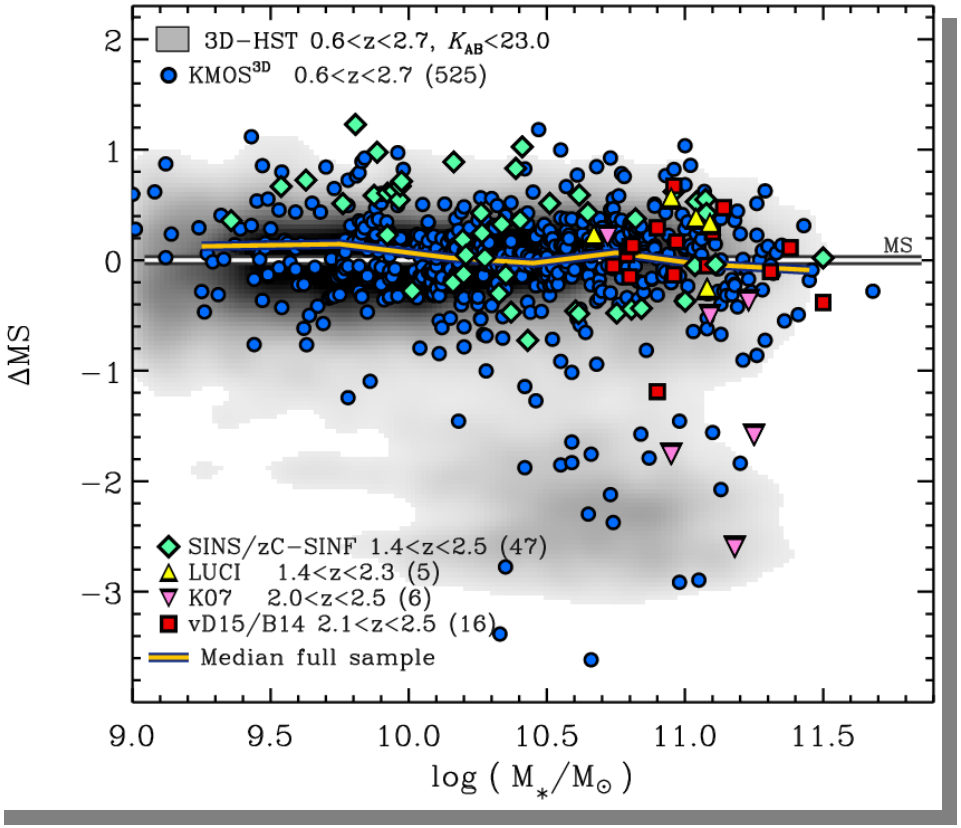
Steidel+10

Also, e.g., Steidel+96,10,14; Franx+97; Pettini+00,01,02; Heckman+03,15; Shapley+03;Martin+05,12; Tremonti+07; Weiner+09; Quider+09,10; Rubin+10,14; Bordoloi+11; Kacprzak+11; Coil+11; Kulas+11; Law+12b; Kornei+12; Chen+12; Bouché+12,14; Cicone+14; and many others

1) Demographics of Ionized Gas Outflows at z~1-3 with KMOS^{3D}

*Förster Schreiber, Übler, **Davies**, Genzel et al. 2018*
(Submitted to ApJ, arXiv:1807.04738)

- Sample of 599 galaxies @z~0.6-2.7
- Primarily from KMOS^{3D}
- Cover the main sequence at $\log(M_*/M_{sun}) \sim 9.5 - 11.5$
- Identify outflows based on broad or asymmetric Hα emission
- Separate into AGN and inactive (star forming) galaxies



Förster Schreiber+18

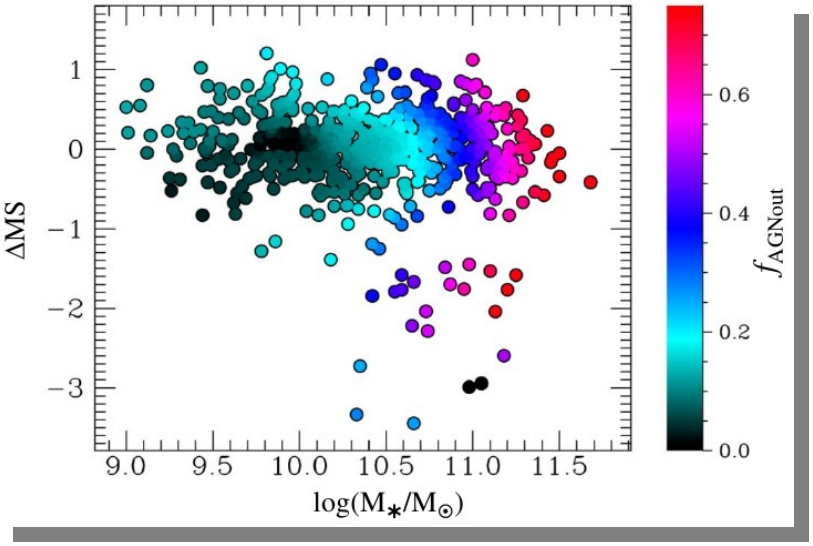
How are Outflow Galaxies Distributed in the M_*-SFR Plane?

AGN Outflows

- Incidence depends *only* on stellar mass
- No dependence on vertical offset from star formation main sequence

→ Consistent with Harrison+16 (*KASHz*) who find that 50% of X-ray AGN at z~1.4 have strong outflows

→ Consistent with Leung+17 (*MOSDEF*) who find that the incidence of AGN outflows does not depend on the level of star formation.



Genzel+14; Förster Schreiber+14,18

Also, e.g., Shapiro+09; Harrison+14,16; Maiolino+12; Cano Diaz+12; Fabian12; Mullaney+13; Brusa+15a; Perna+15a,15b;Carniani+15,16; Kakkad +16

How are Outflow Galaxies Distributed in the M_*-SFR Plane?

AGN Outflows

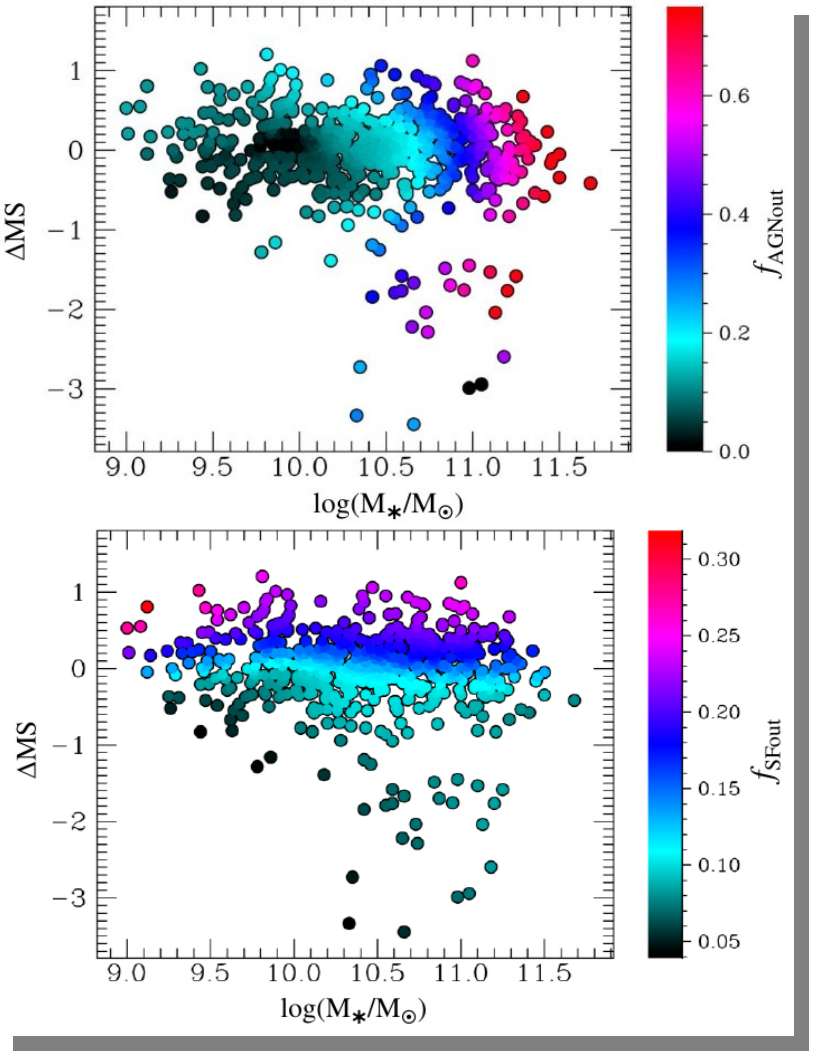
- Incidence depends *only* on stellar mass
- No dependence on vertical offset from star formation main sequence

Stellar Outflows

- Incidence depends *only* on vertical offset from star formation main sequence
- No dependence on stellar mass

→ Consistent with results from *KASHz* (Harrison+16) and *MOSDEF* (Leung+17)

<u>Clearly two different classes of outflows</u>



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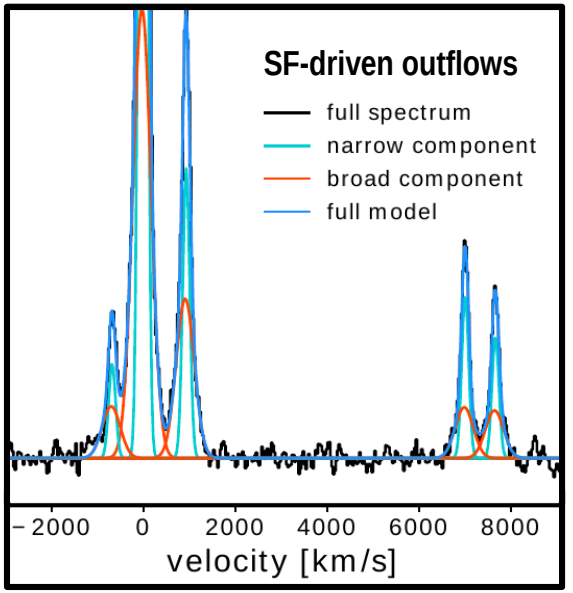
Spectra of Stellar and AGN Outflows

Stellar Outflows

- Outflow velocity ~ 450 km/s
- $n_e = 76^{+24}_{-23}$ cm^{-3} (narrow), 380^{+249}_{-167} cm^{-3} (broad)



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Spectra of Stellar and AGN Outflows

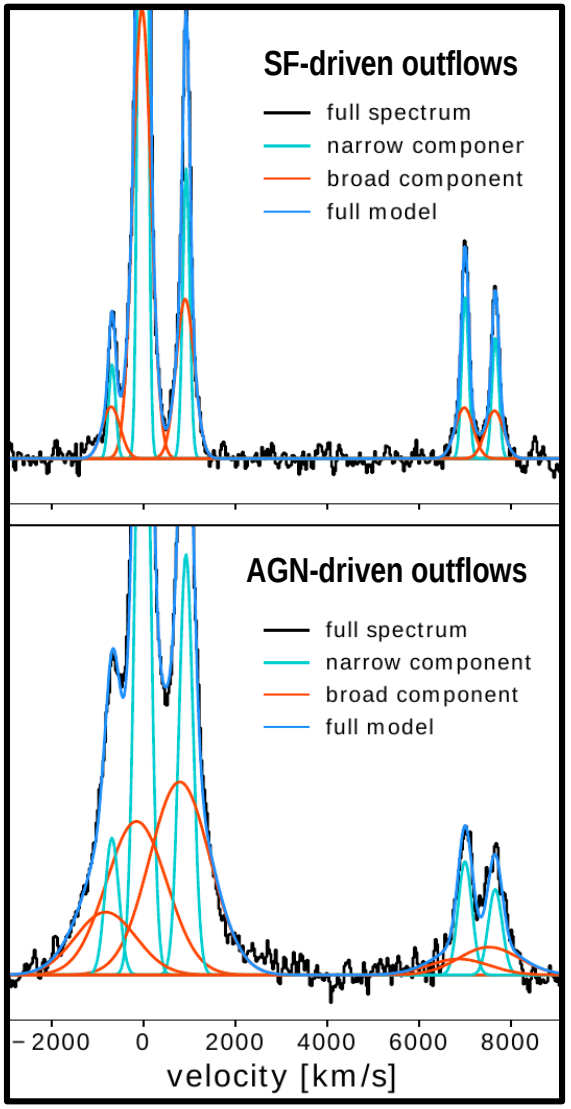
Stellar Outflows

- Outflow velocity ~ 450 km/s
- $n_e = 76^{+24}_{-23}$ cm^{-3} (narrow), 380^{+249}_{-167} cm^{-3} (broad)

AGN Outflows

- Outflow velocity 2300 km/s
- n_e~1000 cm^{-3} (broad)
  - ➔ Consistent with Perna+17 who find n_e~1200 cm^{-3} in the outflowing gas
- LINER spectrum ([N II]/Hα ratio ~ 1.3)

→ High n_e and [N II]/Hα in the broad component suggest that the emission lines trace compressed clumps of ionized gas entrained in the outflows (see also Harrison+ 16, Freeman+17, Perna+17)



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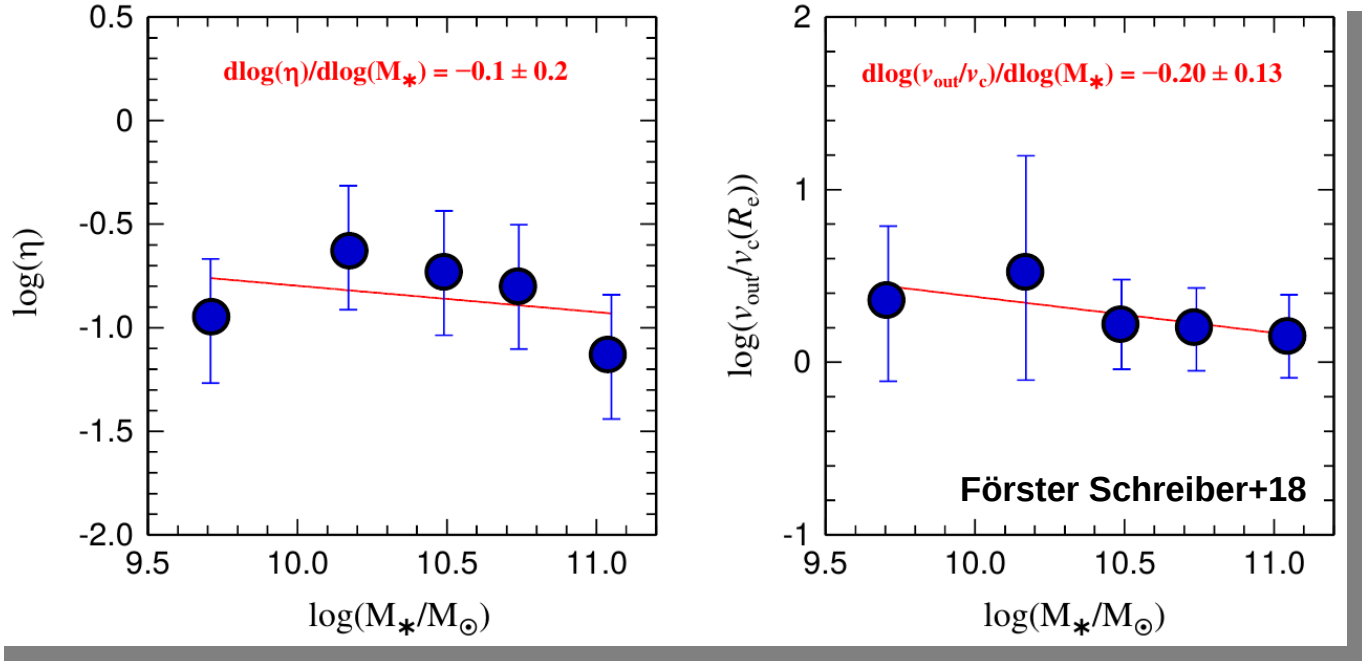
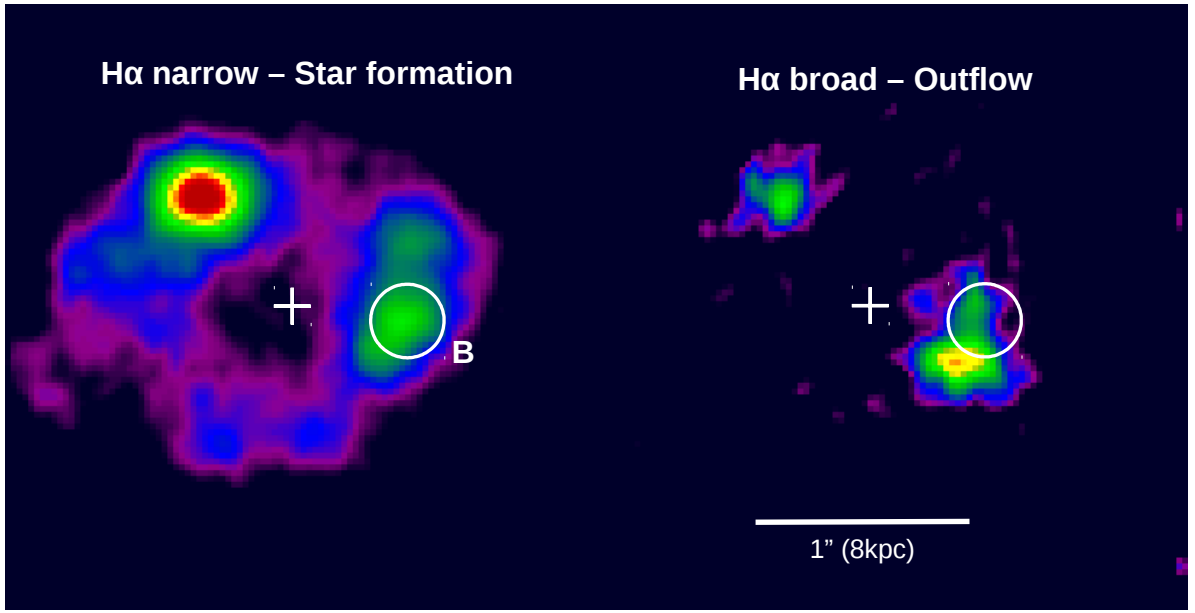
Stellar Mass Dependence of SF-driven outflow properties



- In tension with M_*-Z-SFR and M_*-M_{halo} relations which require a power law index of -0.35 to -0.8 and $\eta \geq 0.3$-1 at $\log(M_*/M_{sun})\sim10$ (e.g. Lilly & Carollo 2013, Davé+17)
- Discrepancy potentially resolved by considering mass in other outflow phases
- Slight tendency for lower v_{out}/v_c at higher M_* - consistent with observations of higher metallicities and baryon fractions in high mass galaxies

Moving to Sub-Galactic Scales...

- Star formation driven outflows launched in the vicinity of HII regions
- Important to investigate relationship outflow properties and resolved physical properties, on 1-2 kpc scales



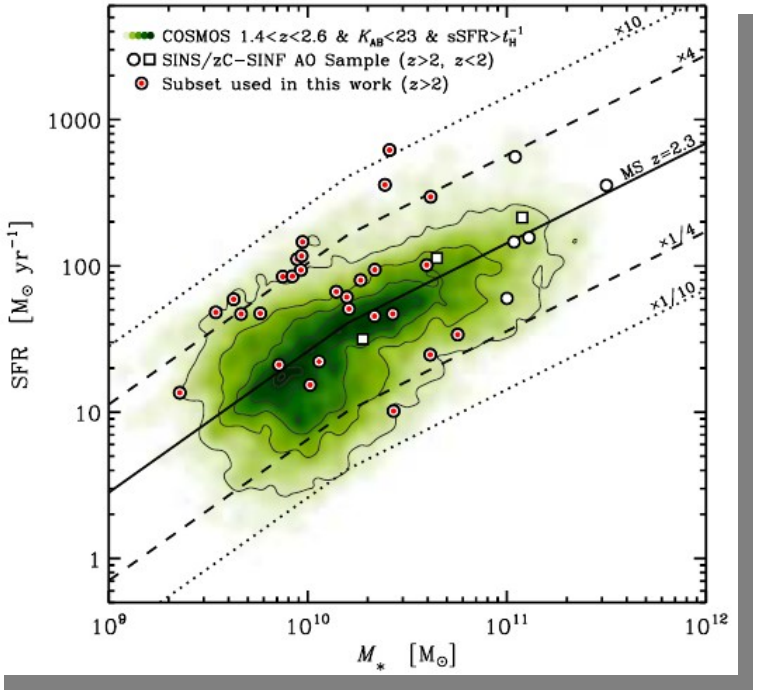
Newman+12a

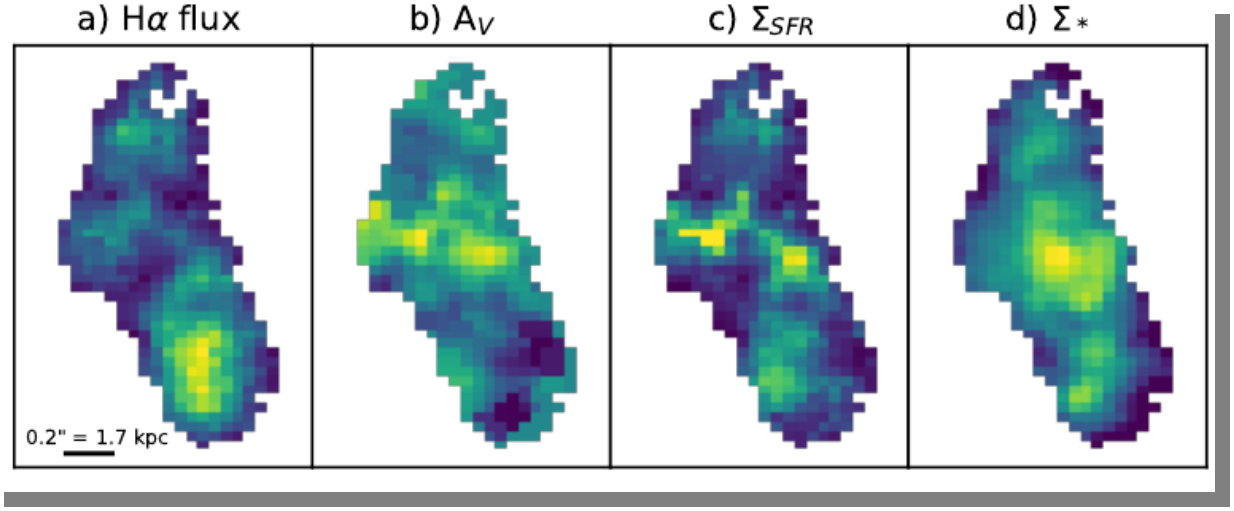
See also Genzel+11, Newman+12b

2) Resolved Properties of Stellar Outflows at z~2.3 in SINS/zC-SINF

***Davies**, Förster Schreiber, Übler, Genzel et al. 2018*
*(Submitted to ApJ, on arXiv **TODAY**)*

28 normal star forming galaxies at z = 2-2.6, observed with SINFONI+AO to obtain flux and kinematic maps at 1-2 kpc resolution

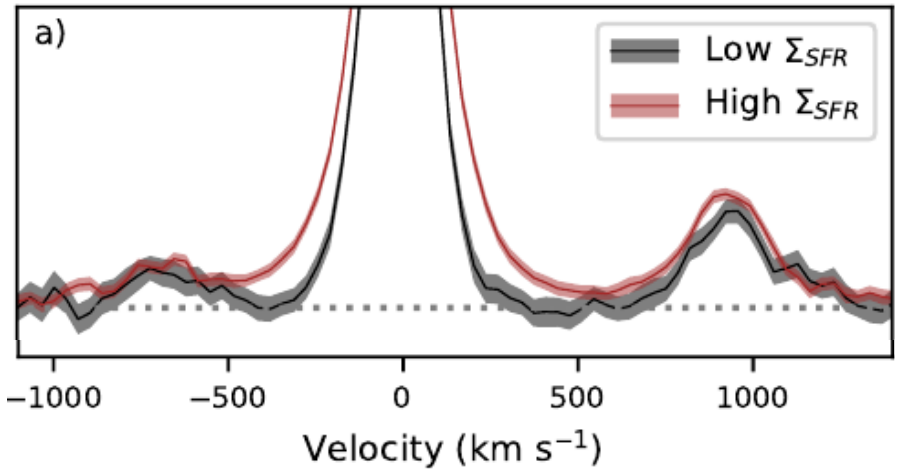




Davies+ 18

See also Genzel+11, Newman+12a,b, Tacchella+15a, Tacchella+18, Förster Schreiber+18a

Line Profile Shape Strongly Dependent on Σ_{SFR}



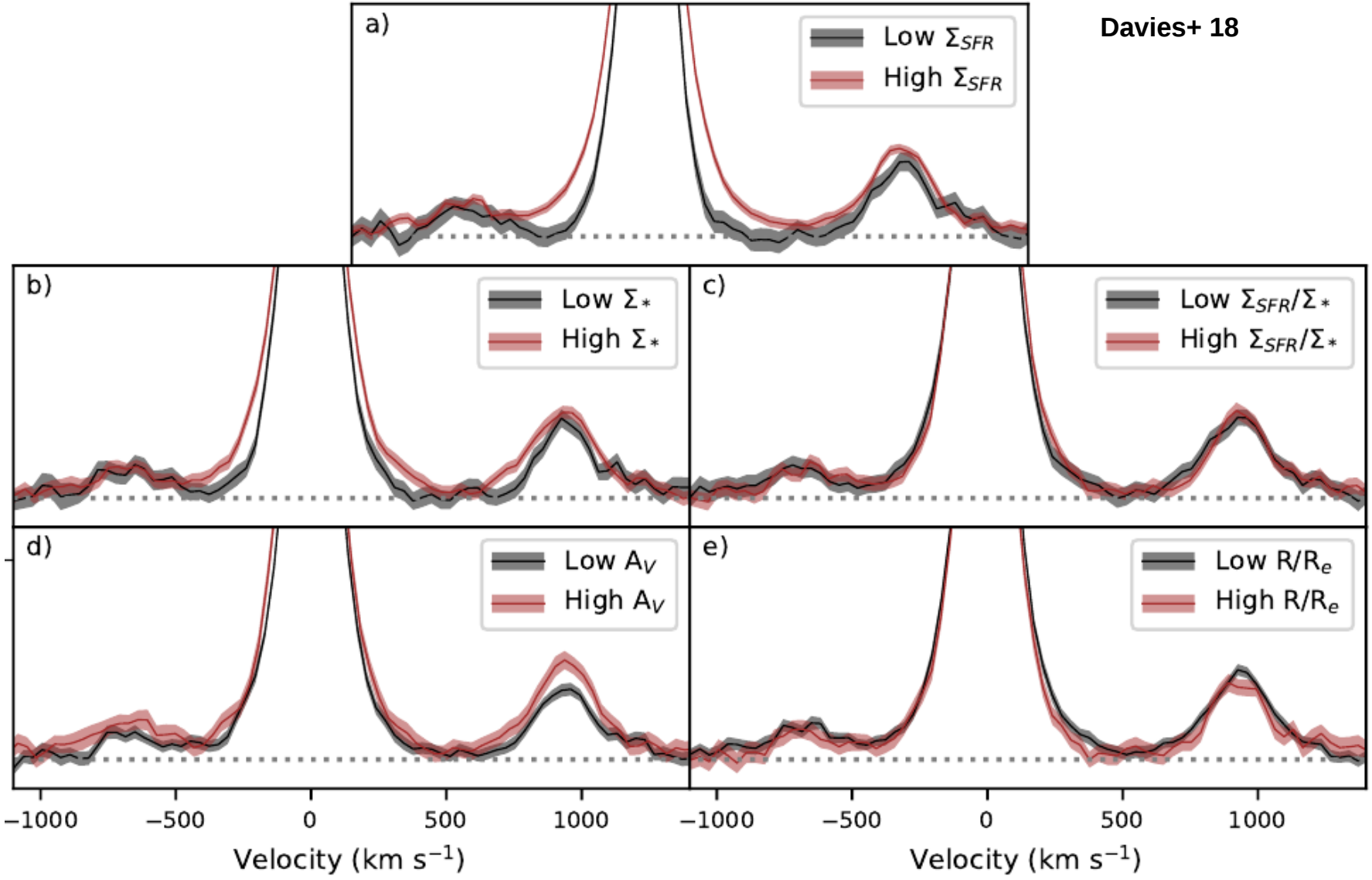
Davies+ 18

Prominent broad base in high Σ_{SFR} spaxels but not in low Σ_{SFR} spaxels

→ Σ_{SFR} closely related to outflow driving

Line Profile Shape Governed by Σ_{SFR} → Star Formation Driven Outflows

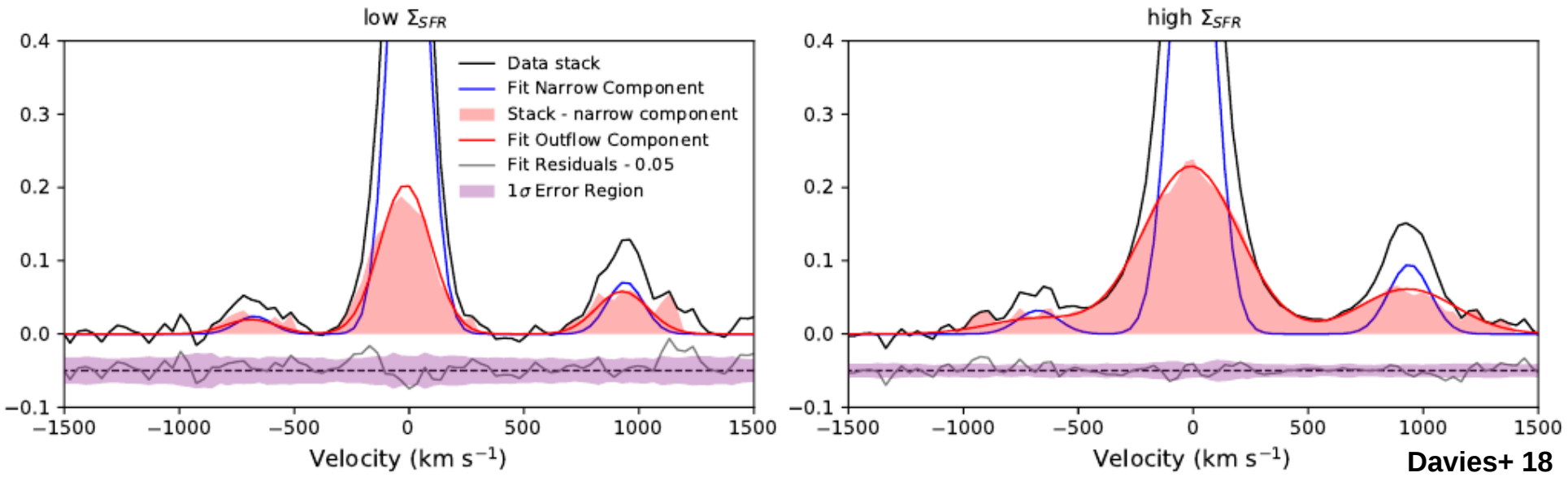
Davies+ 18



See also Genzel+11, Newman+12b, Förster Schreiber+18b

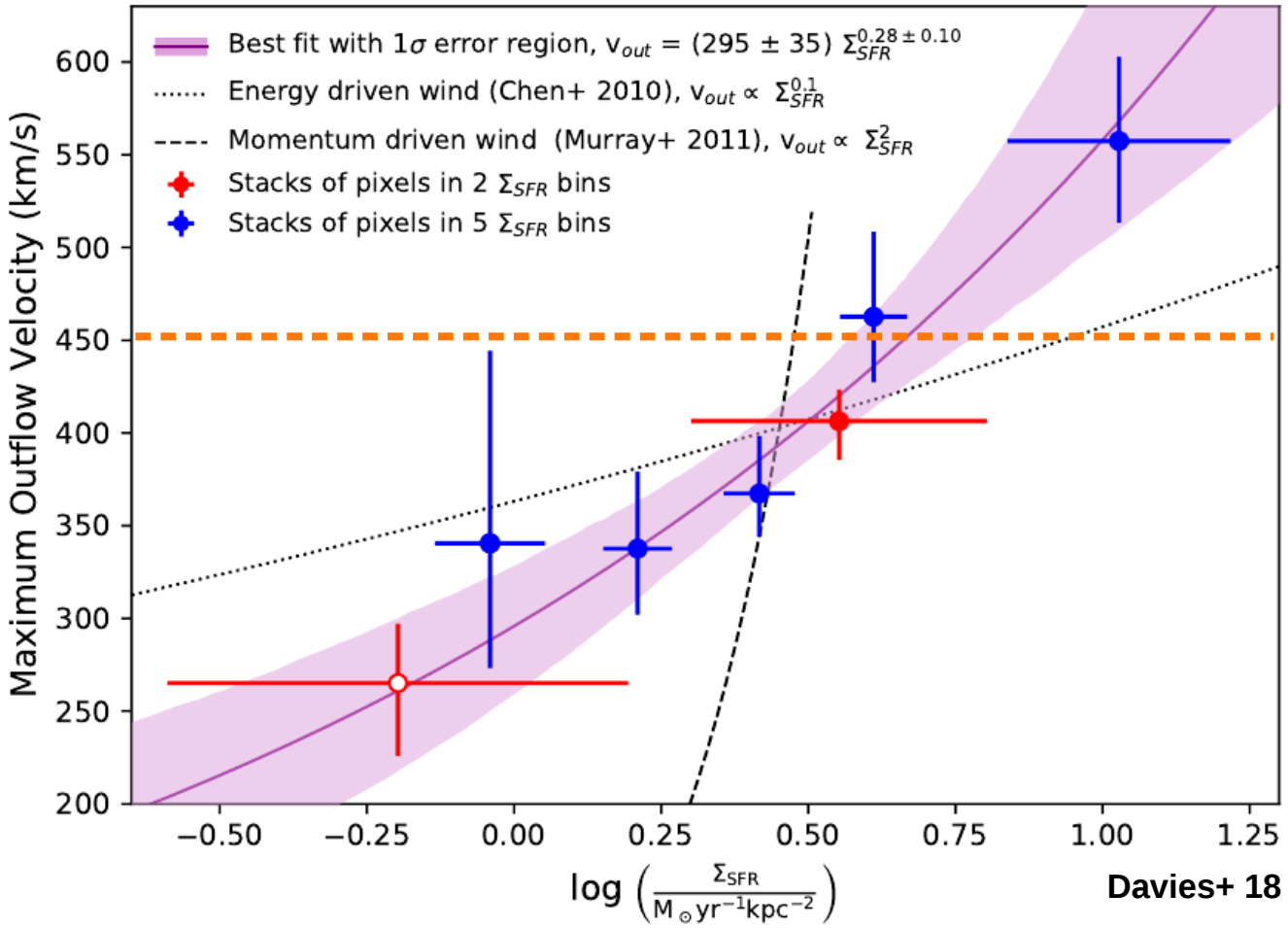
Quantify Outflow Properties

- Split spaxels into 5 bins in Σ_{SFR}
- Fit emission line profiles of all stacks with a two component Gaussian model



Davies+ 18

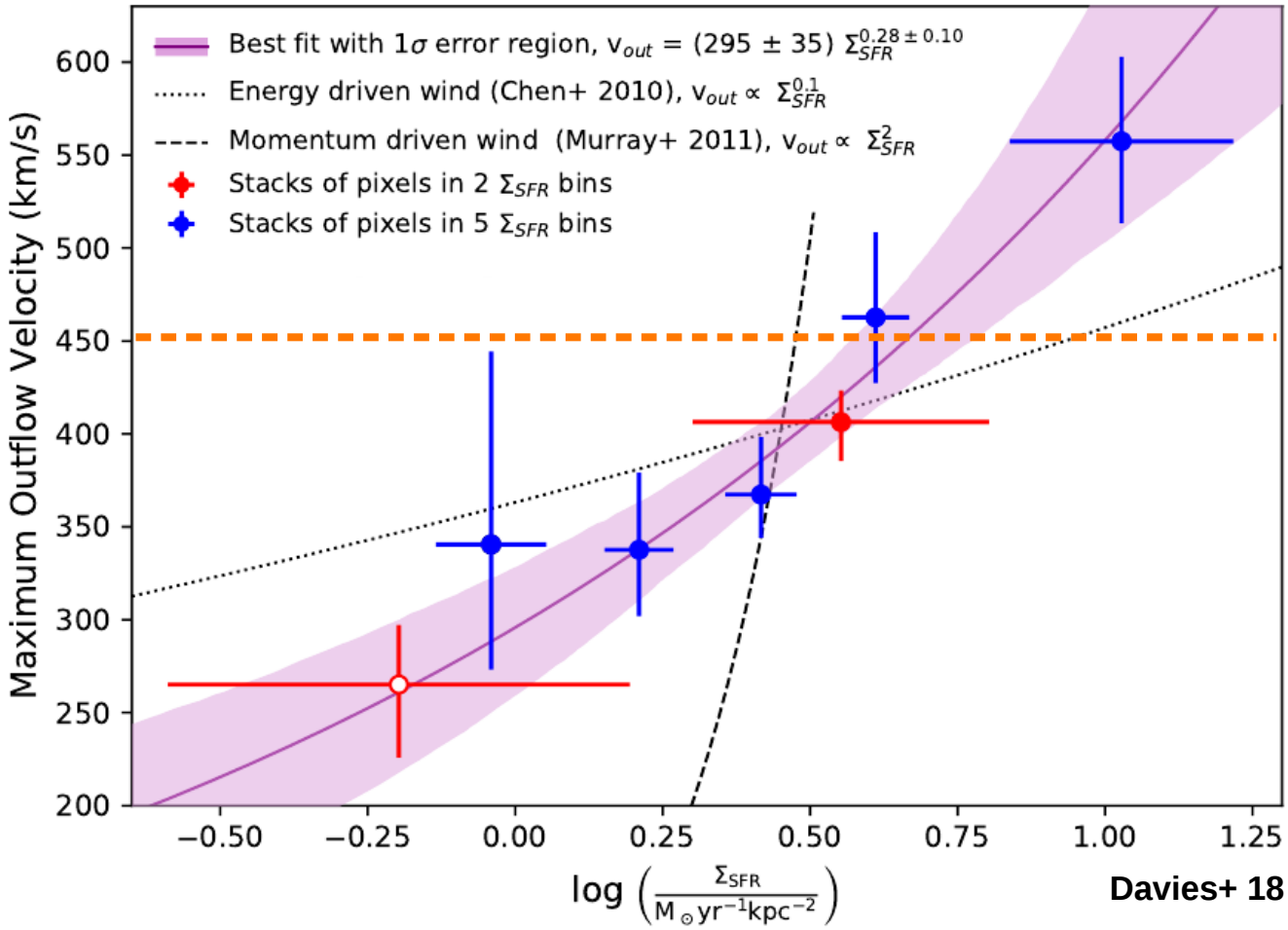
Outflow Velocity



Velocity of star formation driven outflows in KMOS^{3D} (galaxy integrated)

→ Consistent with Σ_{SFR}-v_{out} scalings reported by e.g. Weiner+09, Martin+12, Kornei+12, Heckman+16

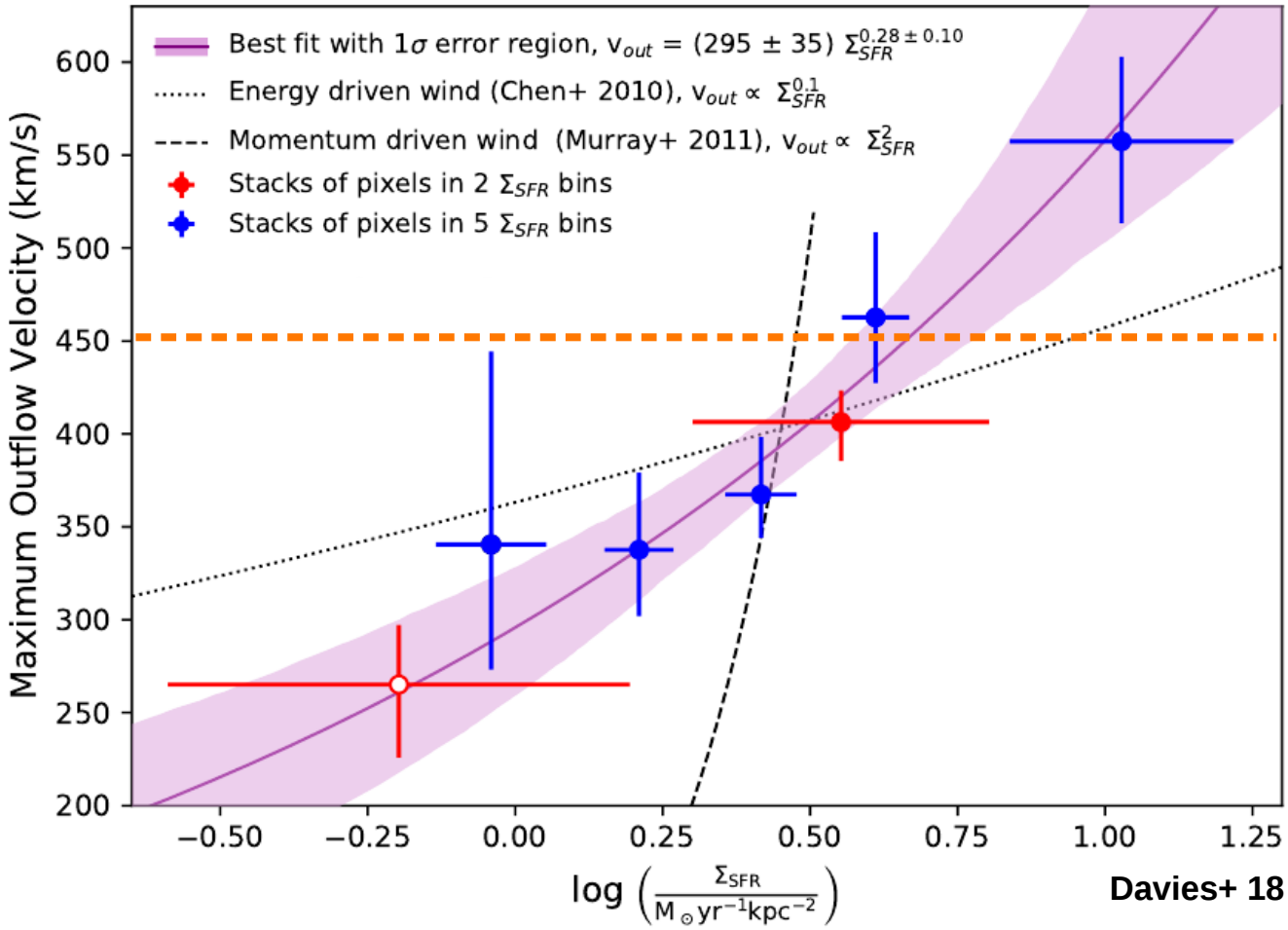
Energy or Momentum Driven Winds?



Velocity of star formation driven outflows in KMOS^{3D} (galaxy integrated)

Measured scaling is between predictions from energy driven and momentum driven models. Both mechanisms important?

Can Outflowing Material Escape the Halos?

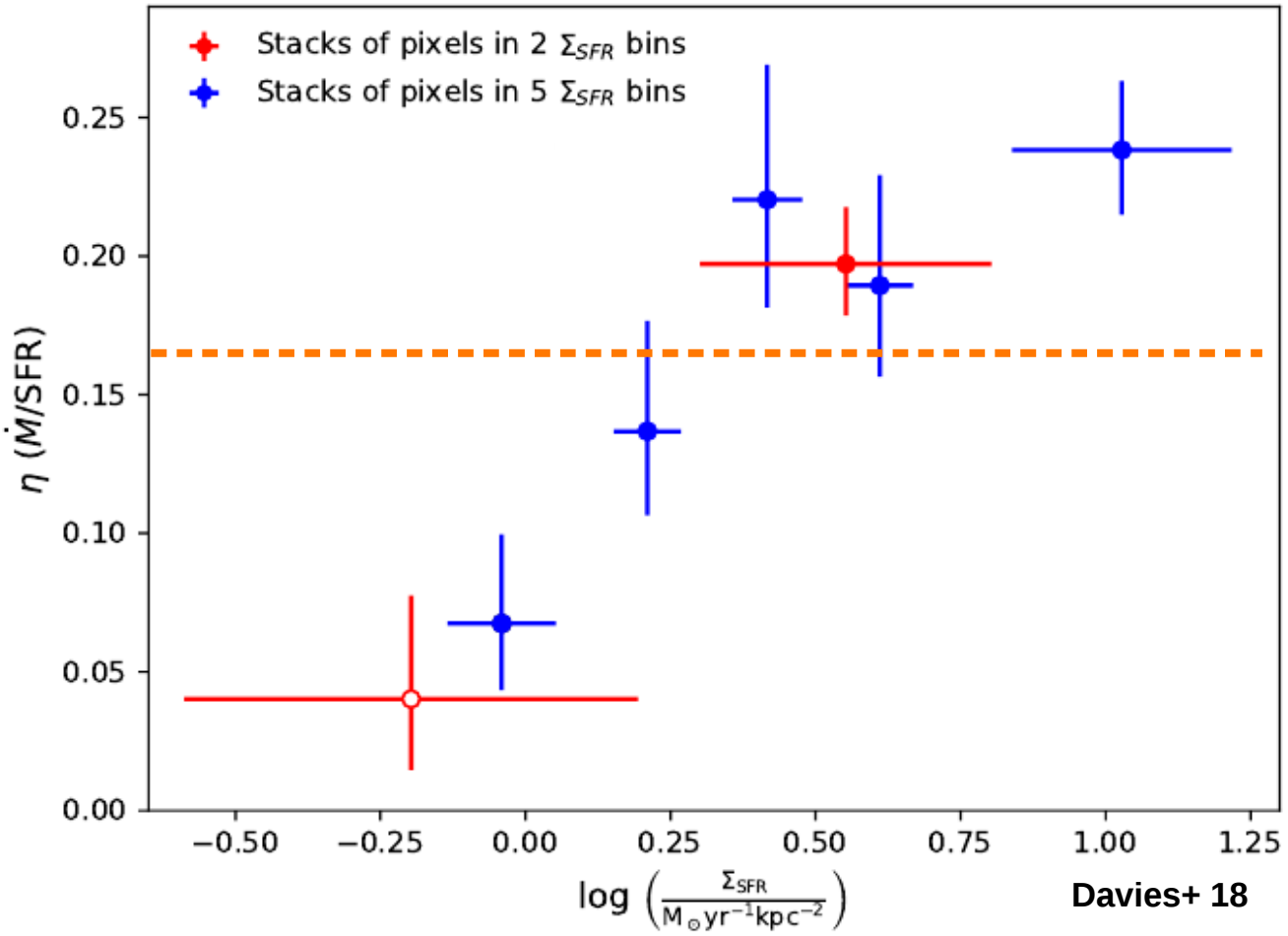


Velocity of star formation driven outflows in KMOS^{3D} (galaxy integrated)

Escape velocity ~ 650 km/s, so most material will probably be re-accreted (but if the outflows are bipolar, need to consider inclination).

Mass loading factor

Assume n_e(broad) = 380^{+249}_{-167} cm^{-3} (based on results from KMOS^{3D})



Mass loading of star formation driven outflows in KMOS^{3D} (galaxy integrated)

Davies+ 18

Concluding Remarks

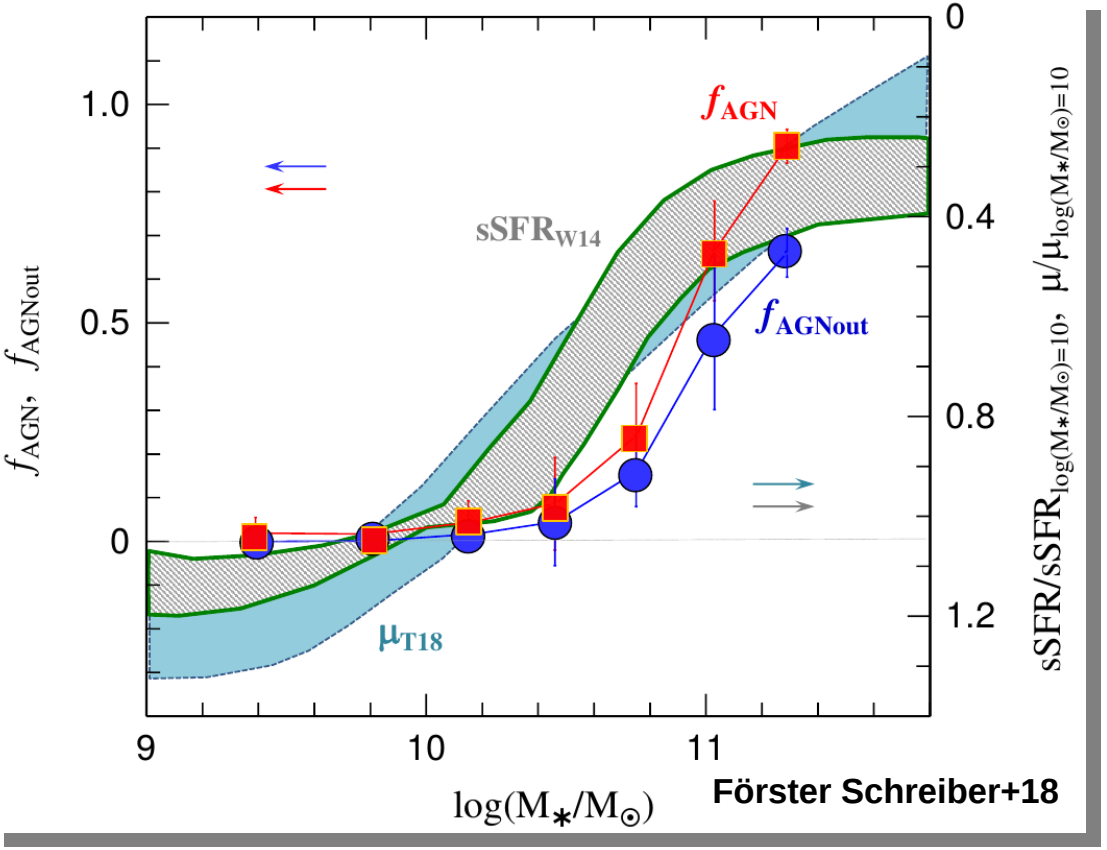
- Large samples of galaxies at z~2 are making it possible to do systematic studies of outflows at these redshifts.
- However, significant challenges remain. Need better observational constraints on:
  - Electron density in the outflowing gas
  - Multi-phase mass budget
  - Velocity structure and geometry of outflows

Summary

- SF outflows most prominent *above the main sequence*, AGN outflows most prominent at *high stellar mass*
- Outflow components of optical emission lines trace dense, shocked clumps of ionized gas entrained in wind fluid
- Low mass loading factors (0.1-0.3) – most outflowing mass in other gas phases?
- Sharp onset of AGN driven outflows at ~Schechter mass – causal connection between AGN feedback and SF quenching?
- Incidence of outflows on 1-2 kpc scales driven by local Σ_{SFR}
- Outflow velocity scales as $v_{out} \propto \Sigma_{SFR}^{0.28 \pm 0.10}$ → outflows driven by a combination of mechanical energy and momentum transport.
- η positively correlated with Σ_{SFR} (may flatten at highest Σ_{SFR})


Extra slides - KMOS^3D

Link between AGN activity, ouftlows, SFR and molecular gas content

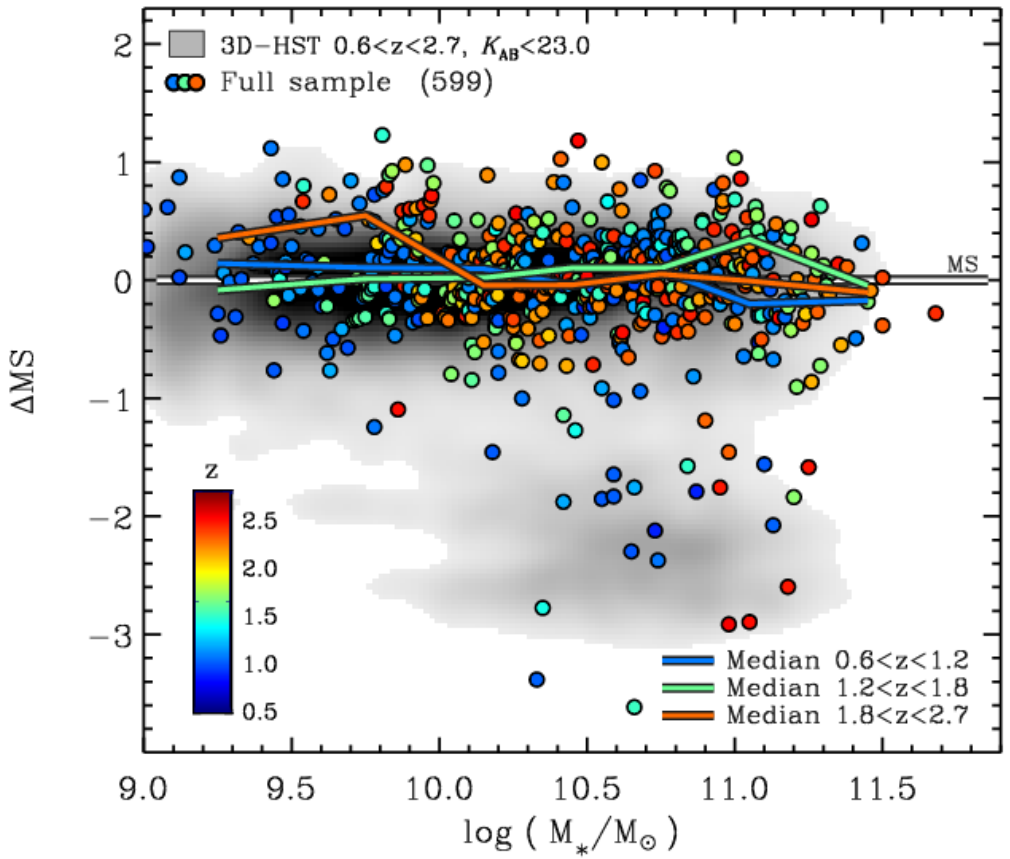


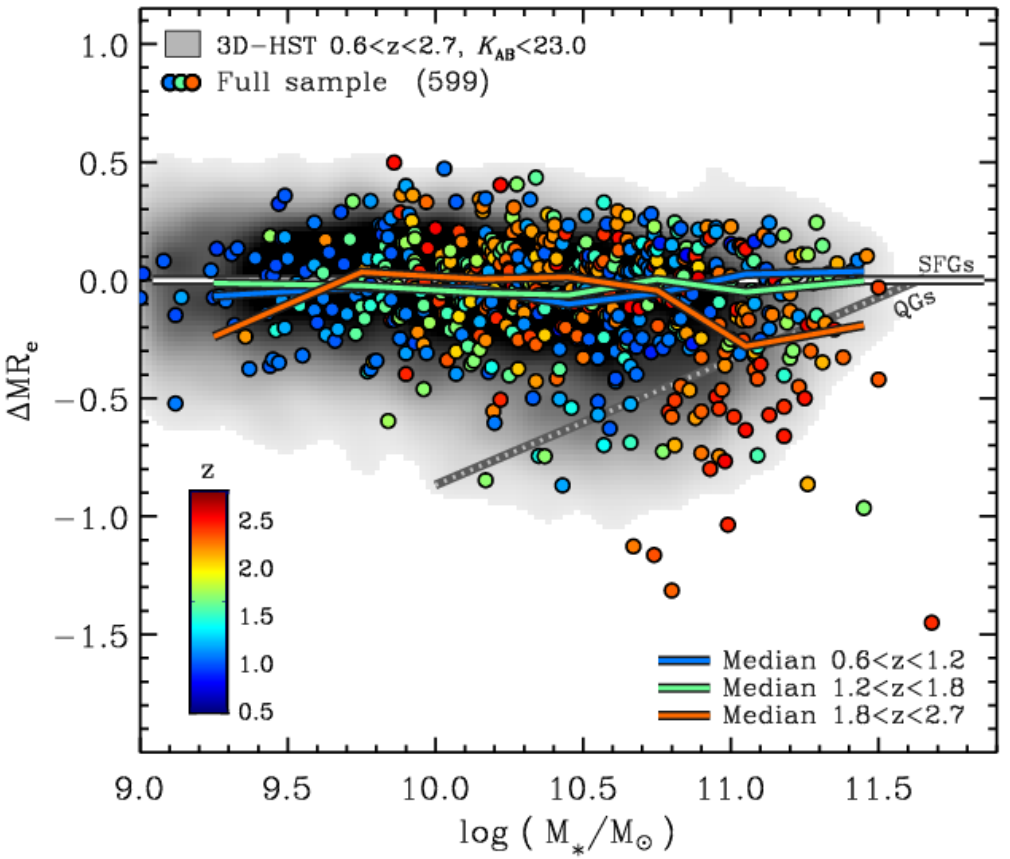
- Sudden onset of AGN and AGN driven outflows coincident in mass with the sudden decrease in sSFR and gas fraction → causal connection between AGN-driven outflows and mass quenching?

Implication of AGN selection method

- [N II]/Hα selected AGN appear to have the same properties as X-ray selected AGN
  - Spectra and multi-component fits very similar
  - Similar luminosity and eddington ratio distributions
  - Fraction of AGN with outflows is the same when considering only X-ray AGN or the whole sample

Distribution in M*-SFR and M*-Re planes as a function of *z*





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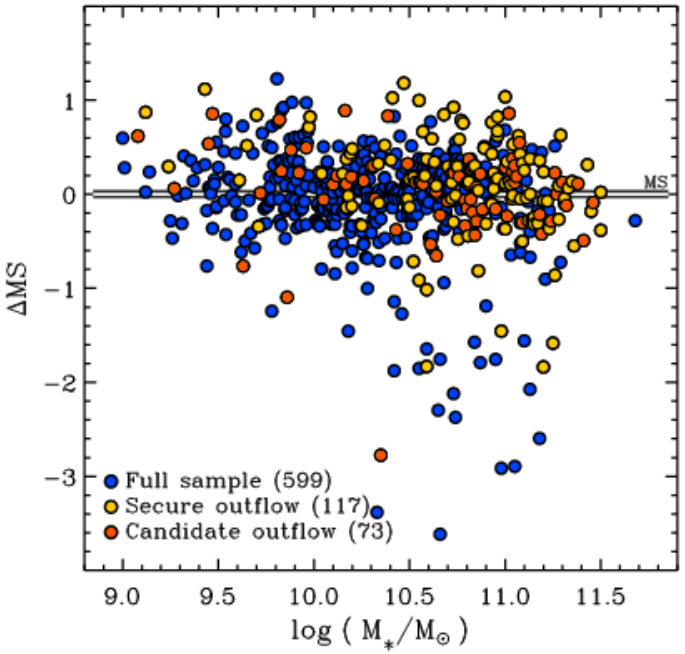
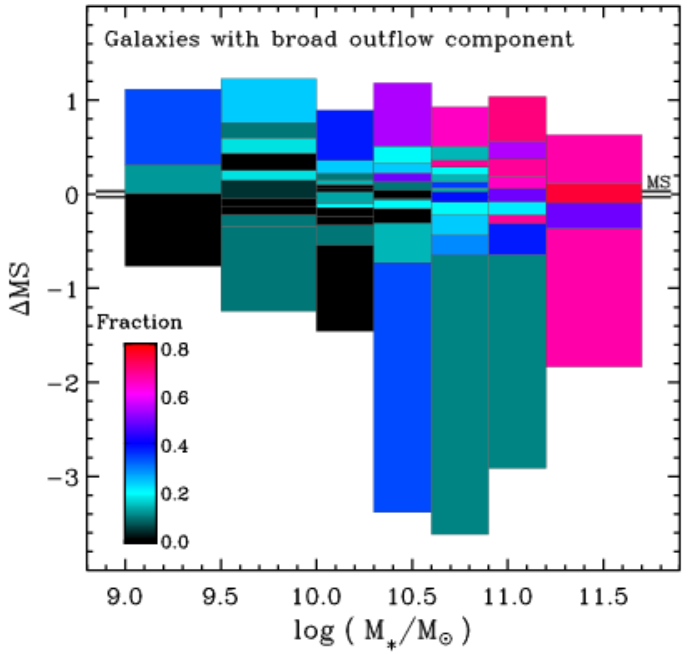
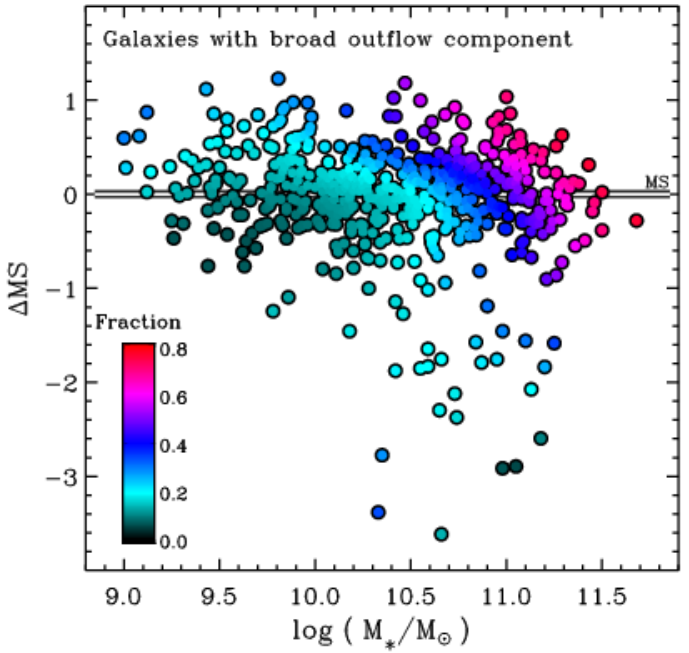
Demonstration of binning and LOESS smoothing







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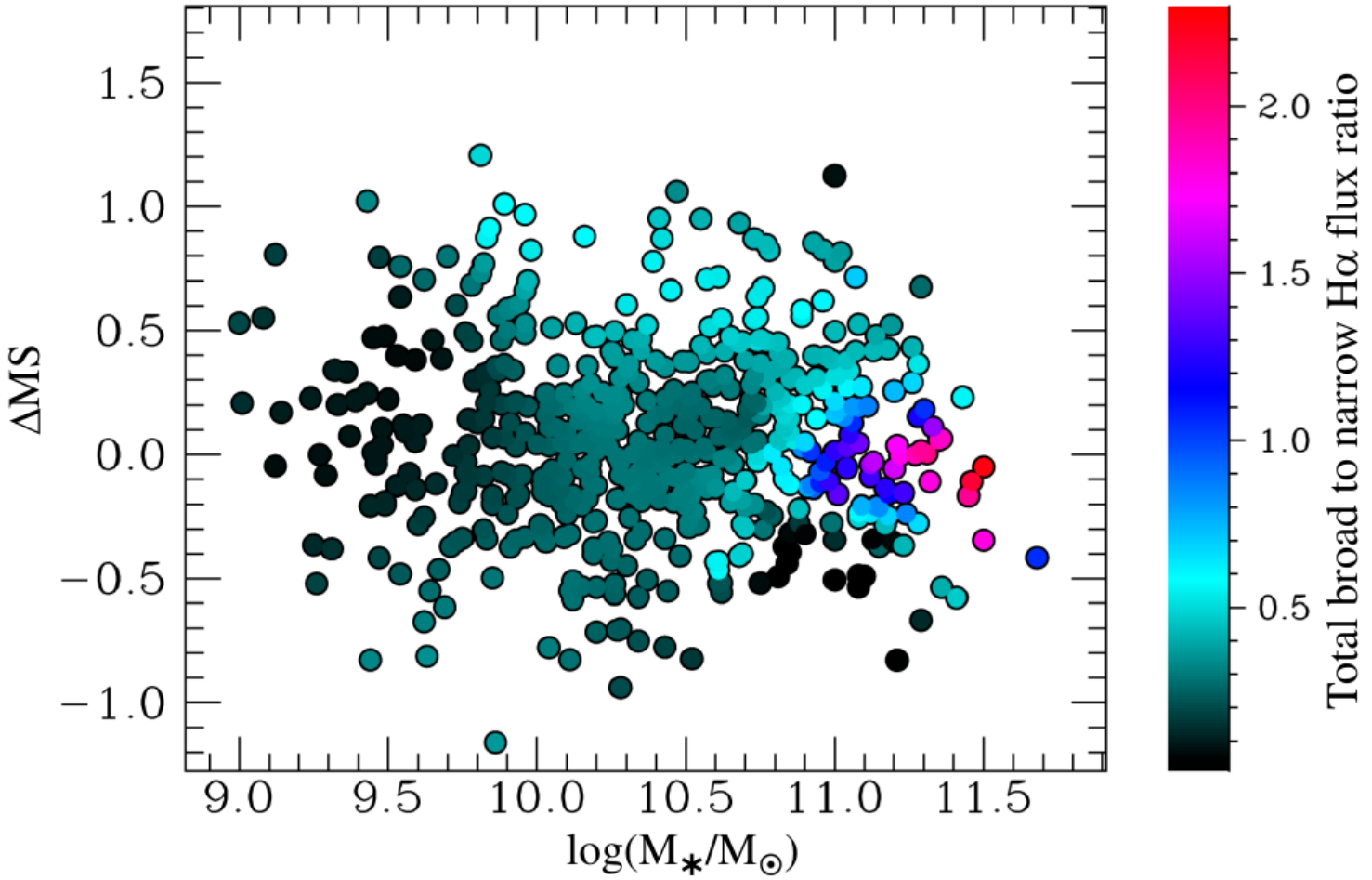
Total broad-to-narrow ratio as a function of M_* and SFR (all galaxies)



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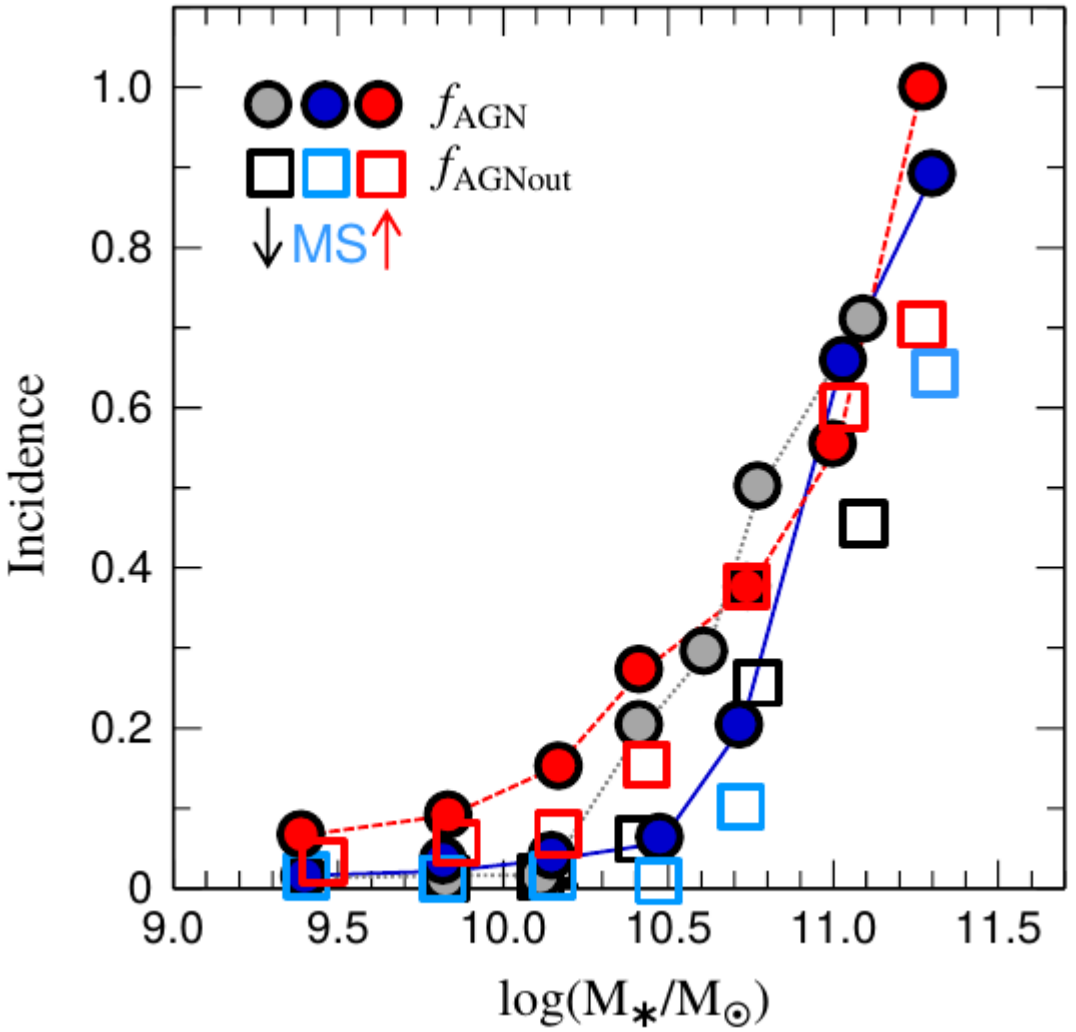
AGN and outflow incidence as a function of M_* and SFR



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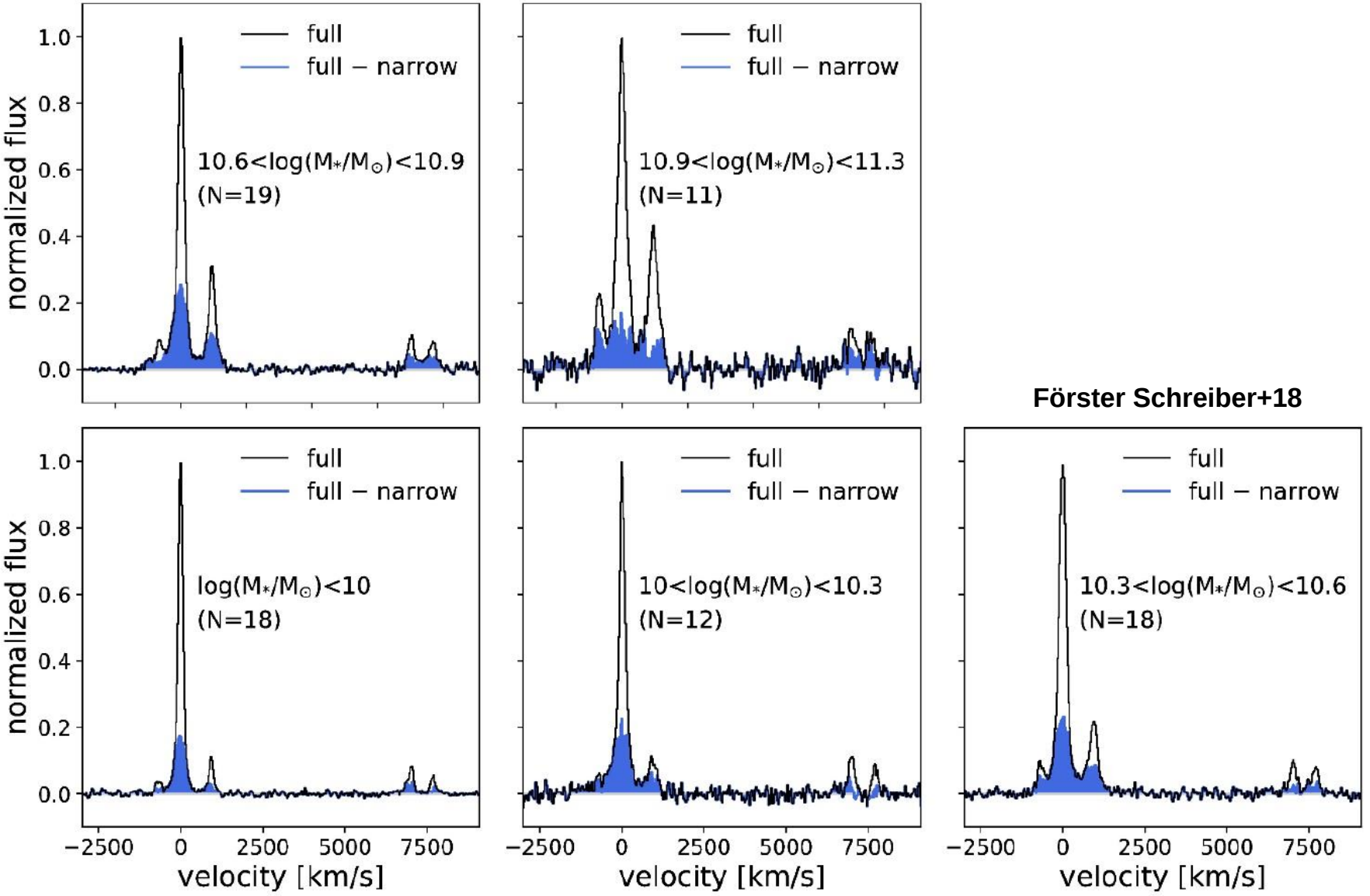
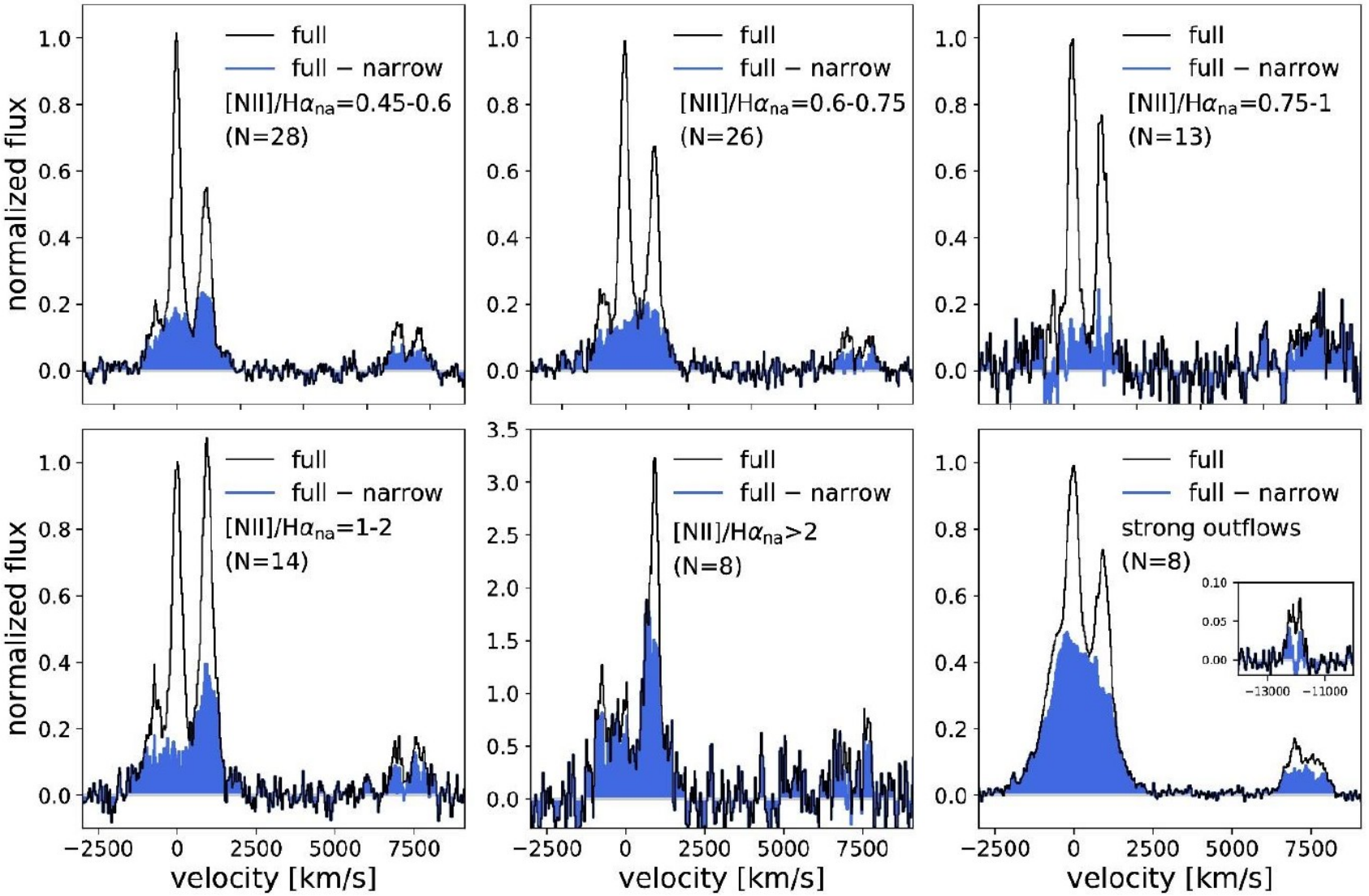
SF-driven outflow spectra as a function of M_*



AGN-driven outflow spectra as a function narrow component line ratios



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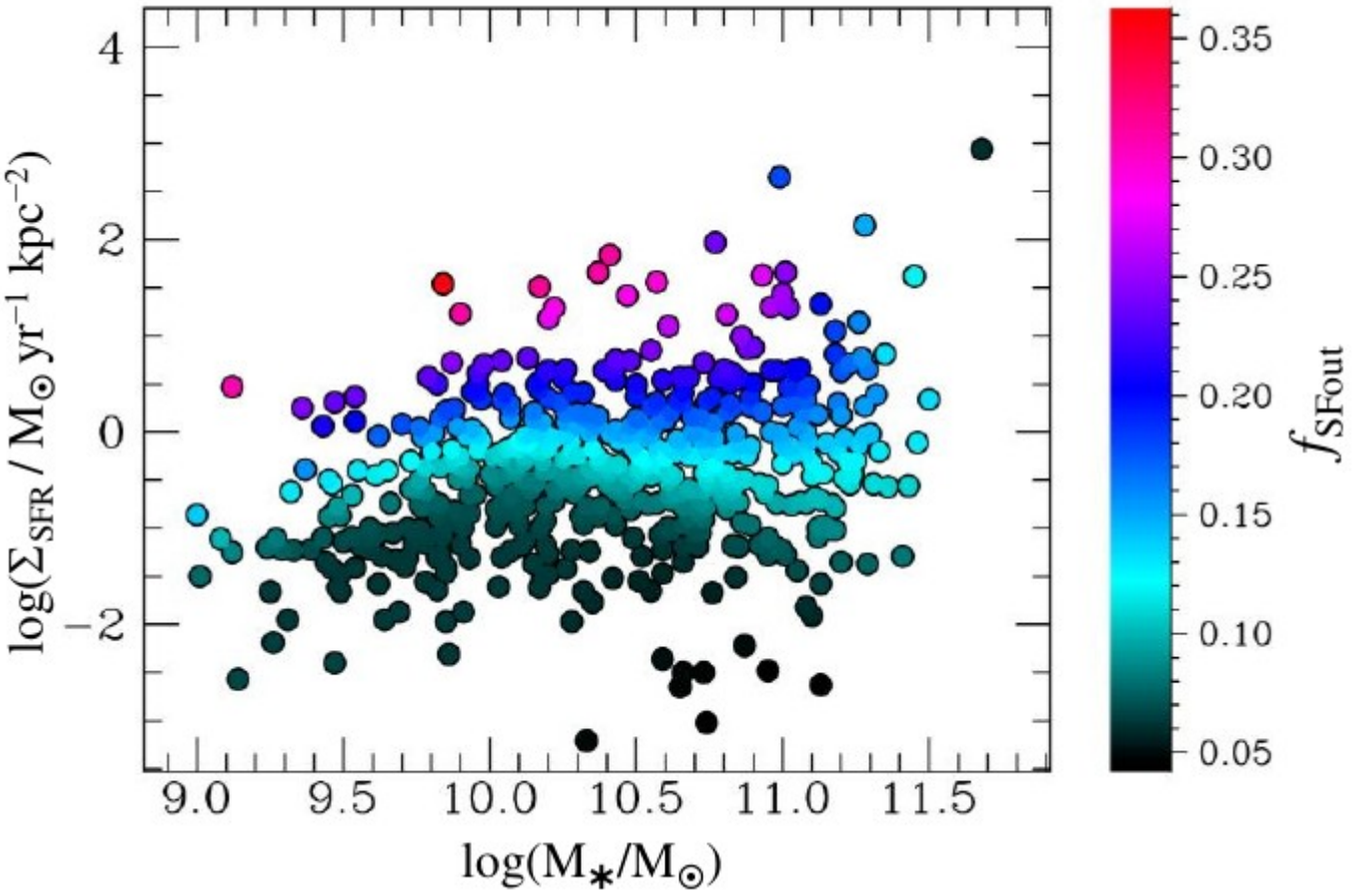
Fraction of galaxies with SF-driven outflows as a function of Σ_{SFR} and M_*



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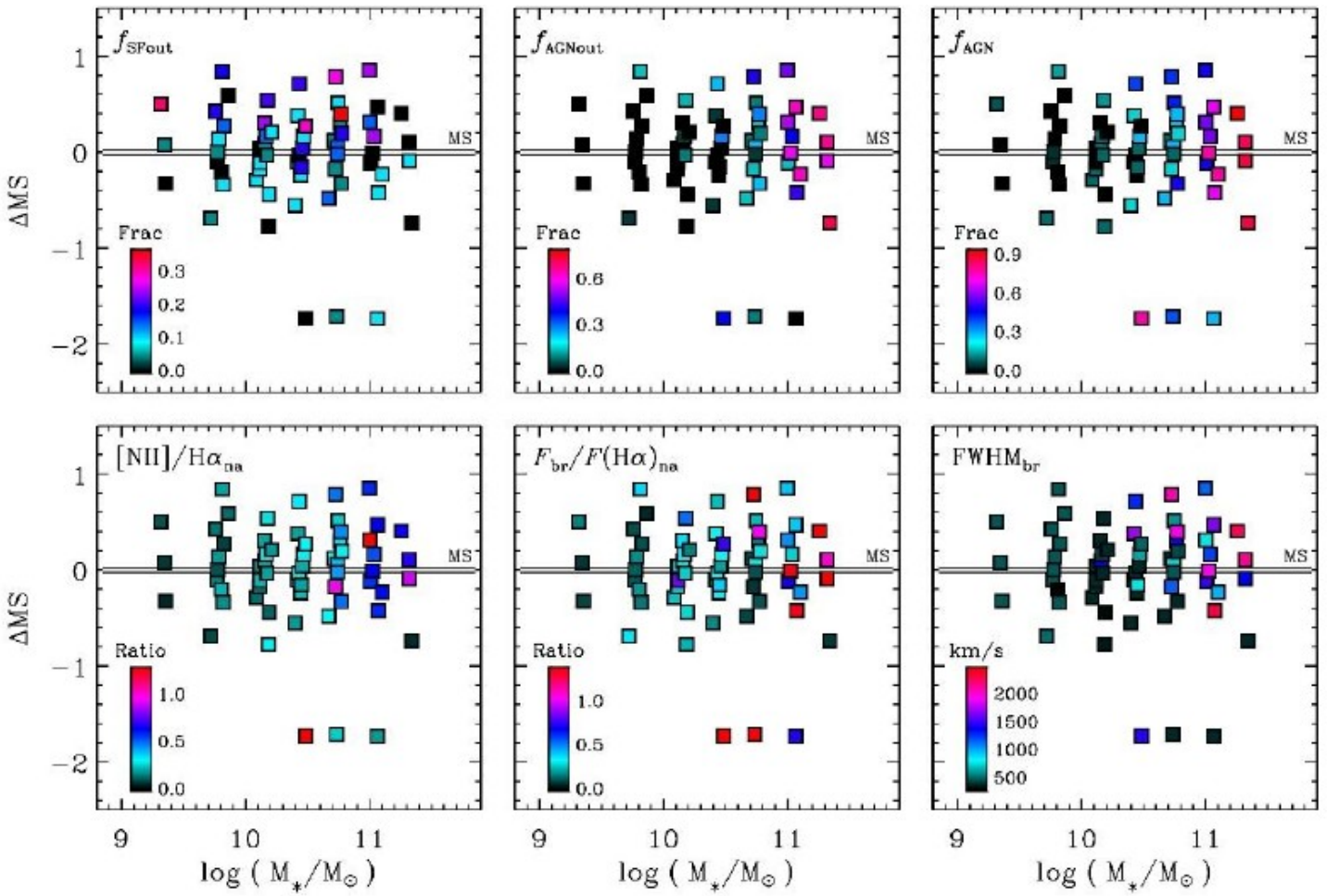
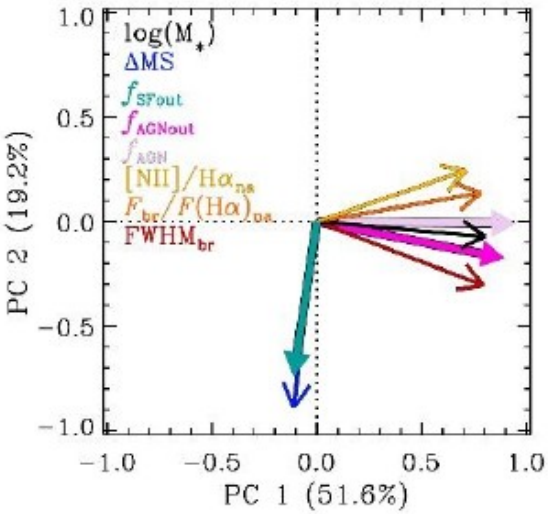
PCA confirms stellar and AGN outflows are different phenomena





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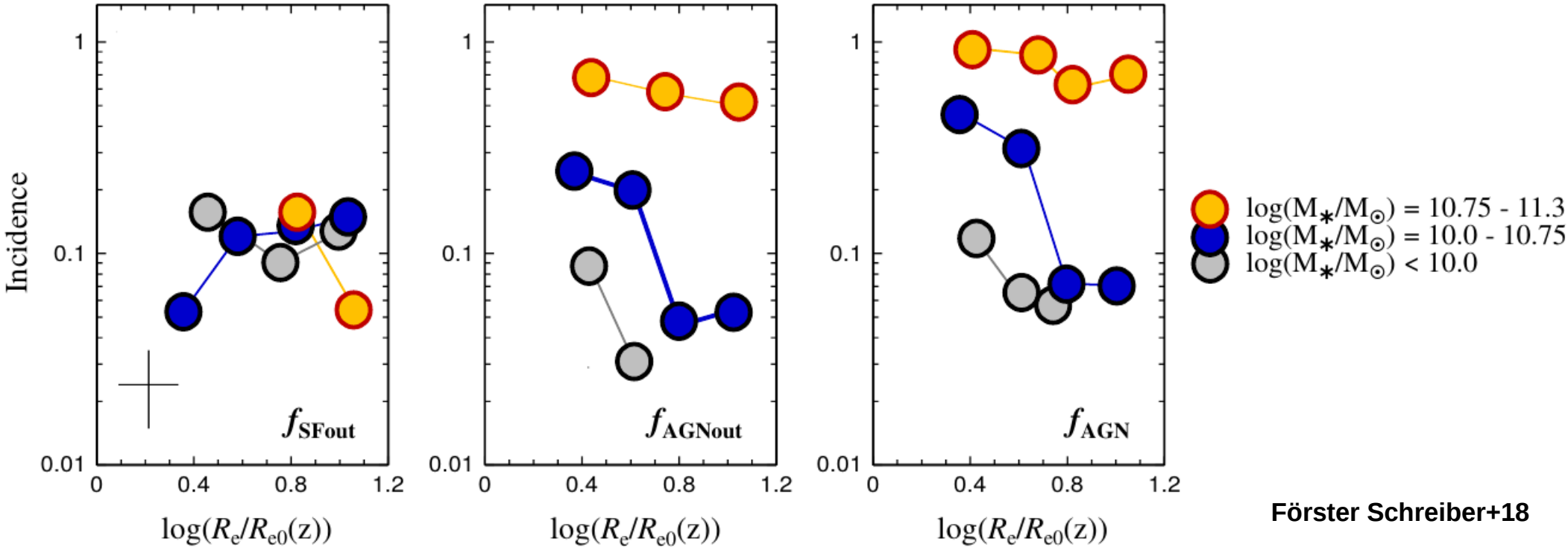
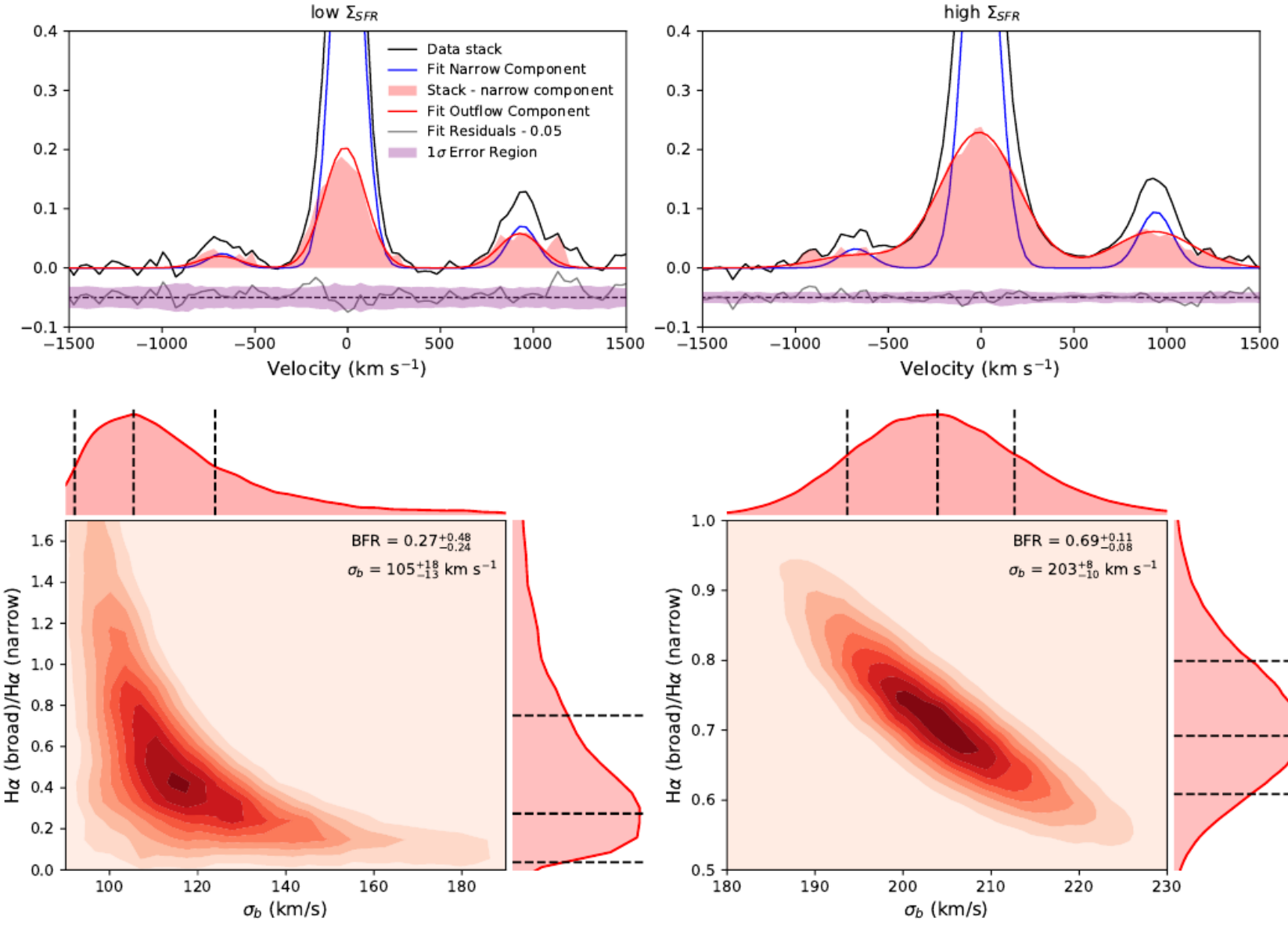
Trends with galaxy size



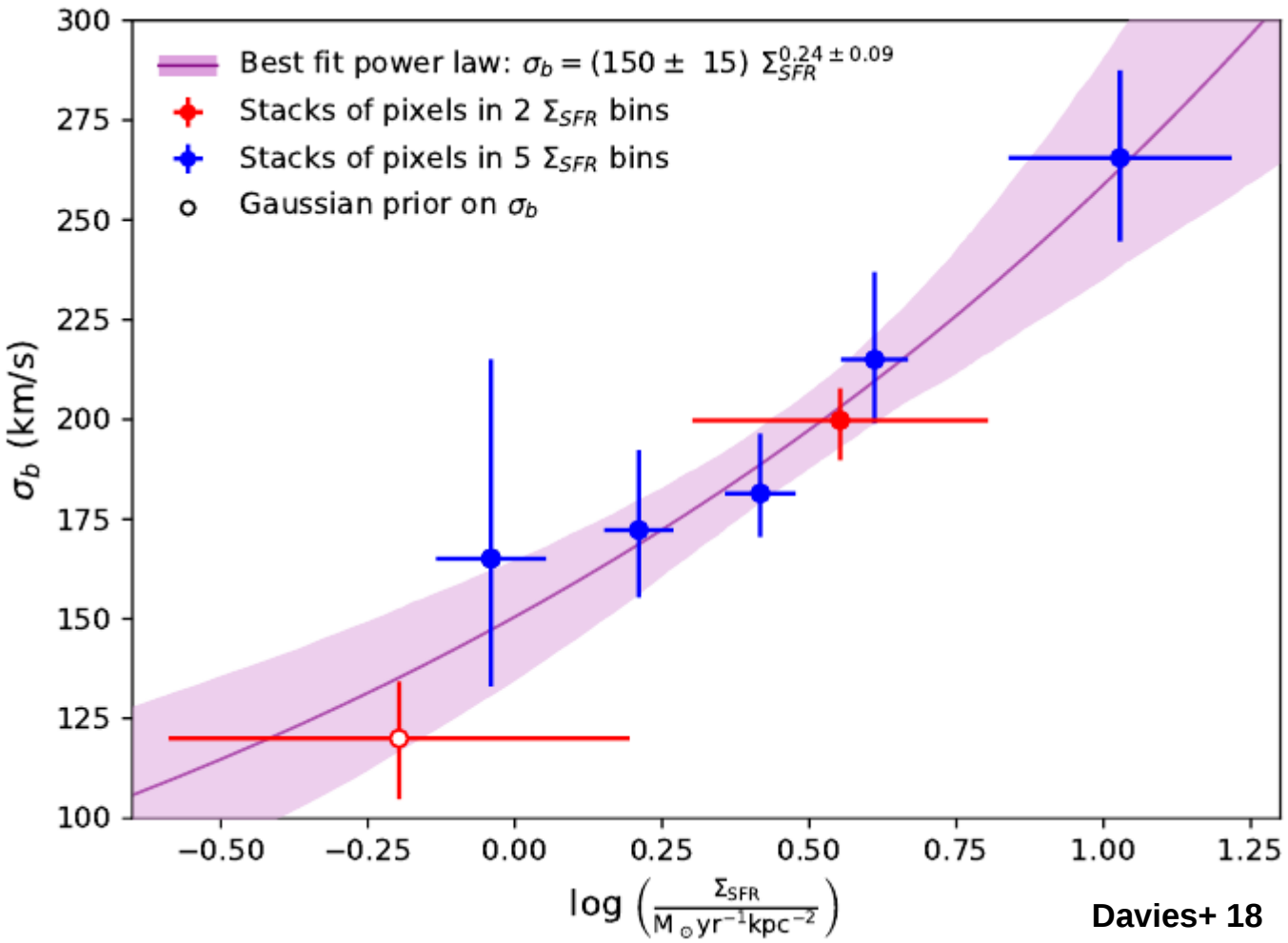
Förster Schreiber+18

Extra slides - SINS/zC-SINF

MCMC Fitting Results

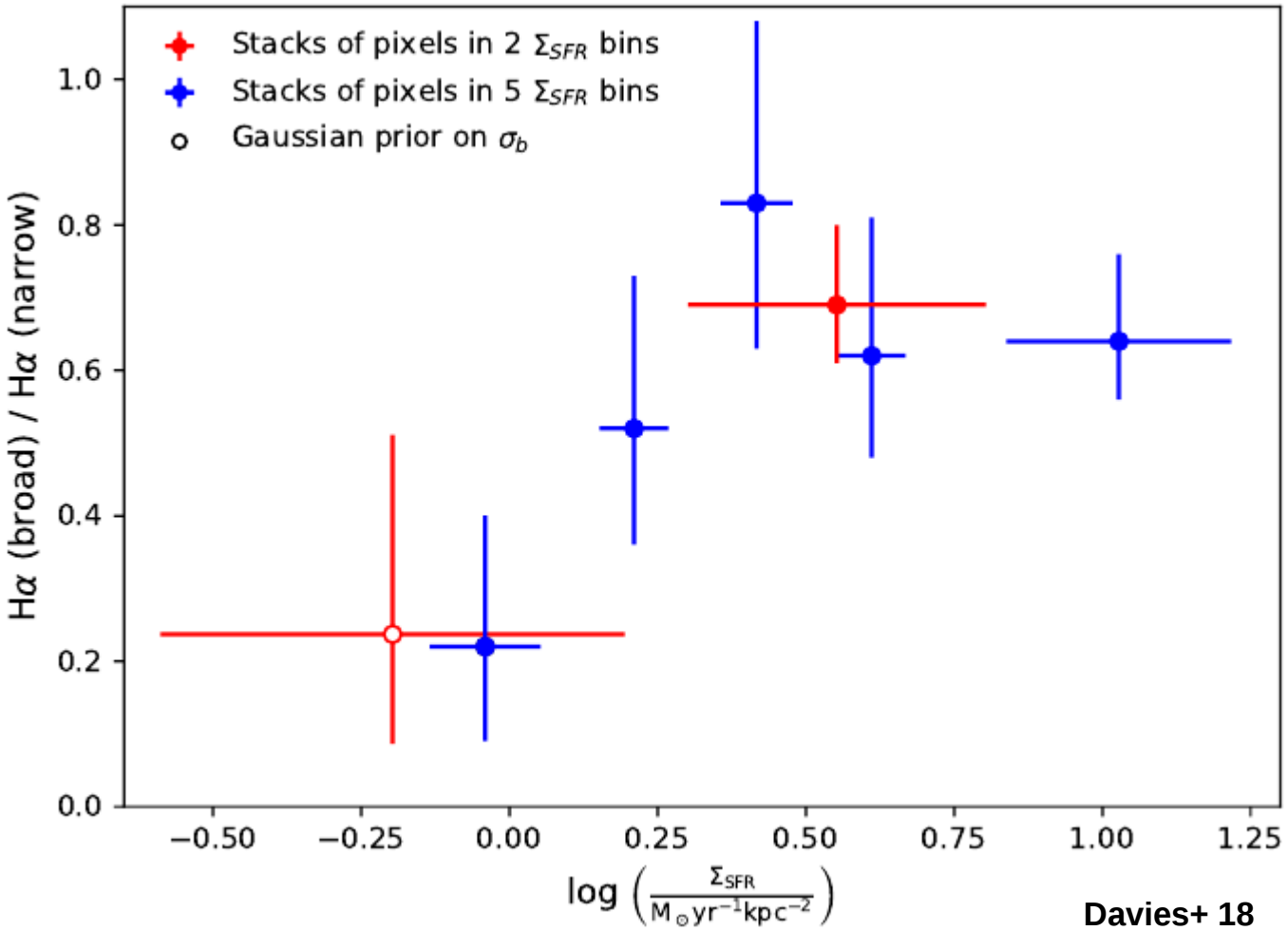


σ of Outflow Component as a Function of Σ_{SFR}



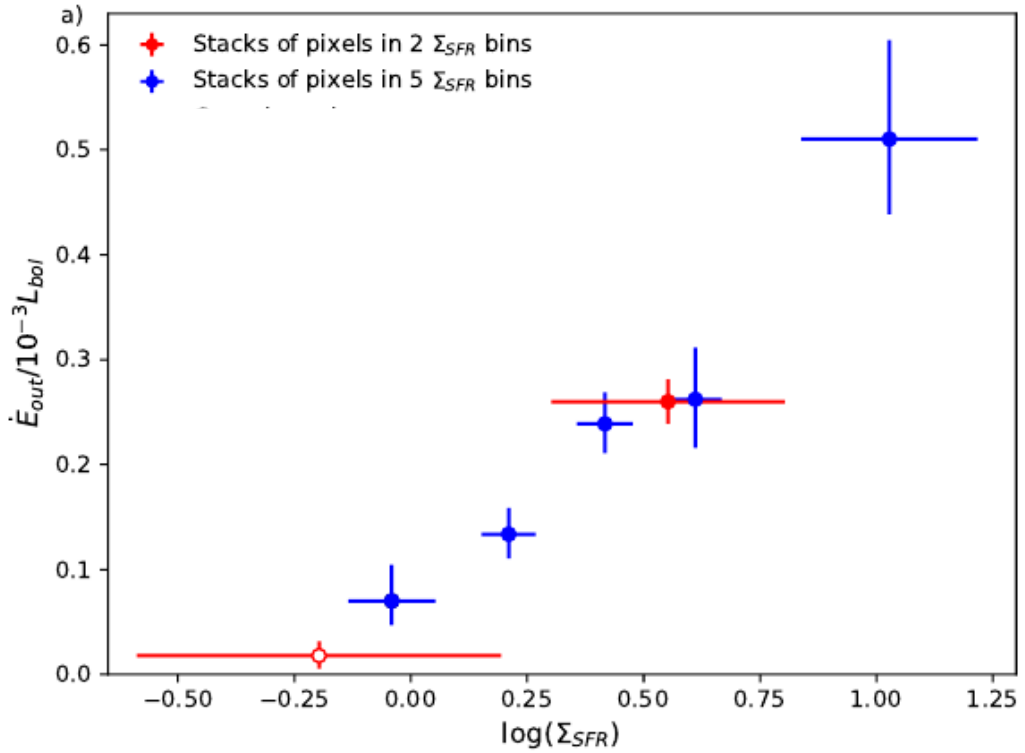
Davies+ 18

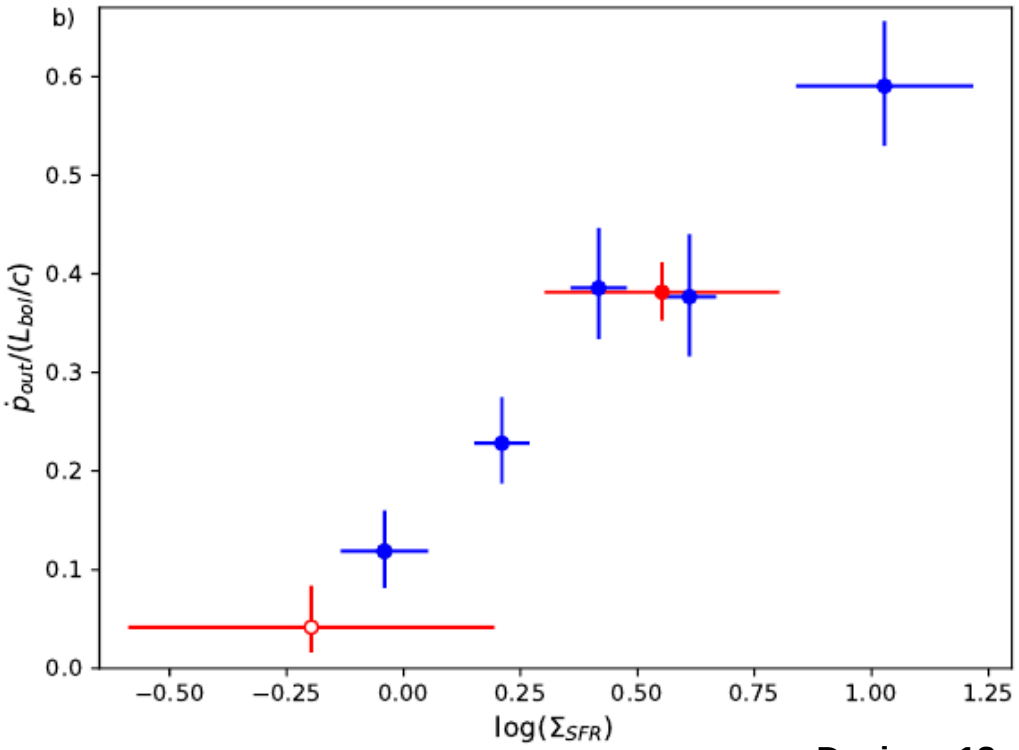
Hα broad-to-narrow flux ratio as a function of Σ_{SFR}



Davies+ 18

Outflow Energetics





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Current star formation activity is sufficient to drive the observed outflows – no additional energy source required.