Resolving Feedback and Gas Accretion with SDSS-IV/MaNGA

Kate Rubin
(San Diego State University)

P.S. On the Small-Scale Structure of the MgII-Absorbing CGM

Resolving Feedback and Gas Accretion with SDSS-IV/MaNGA

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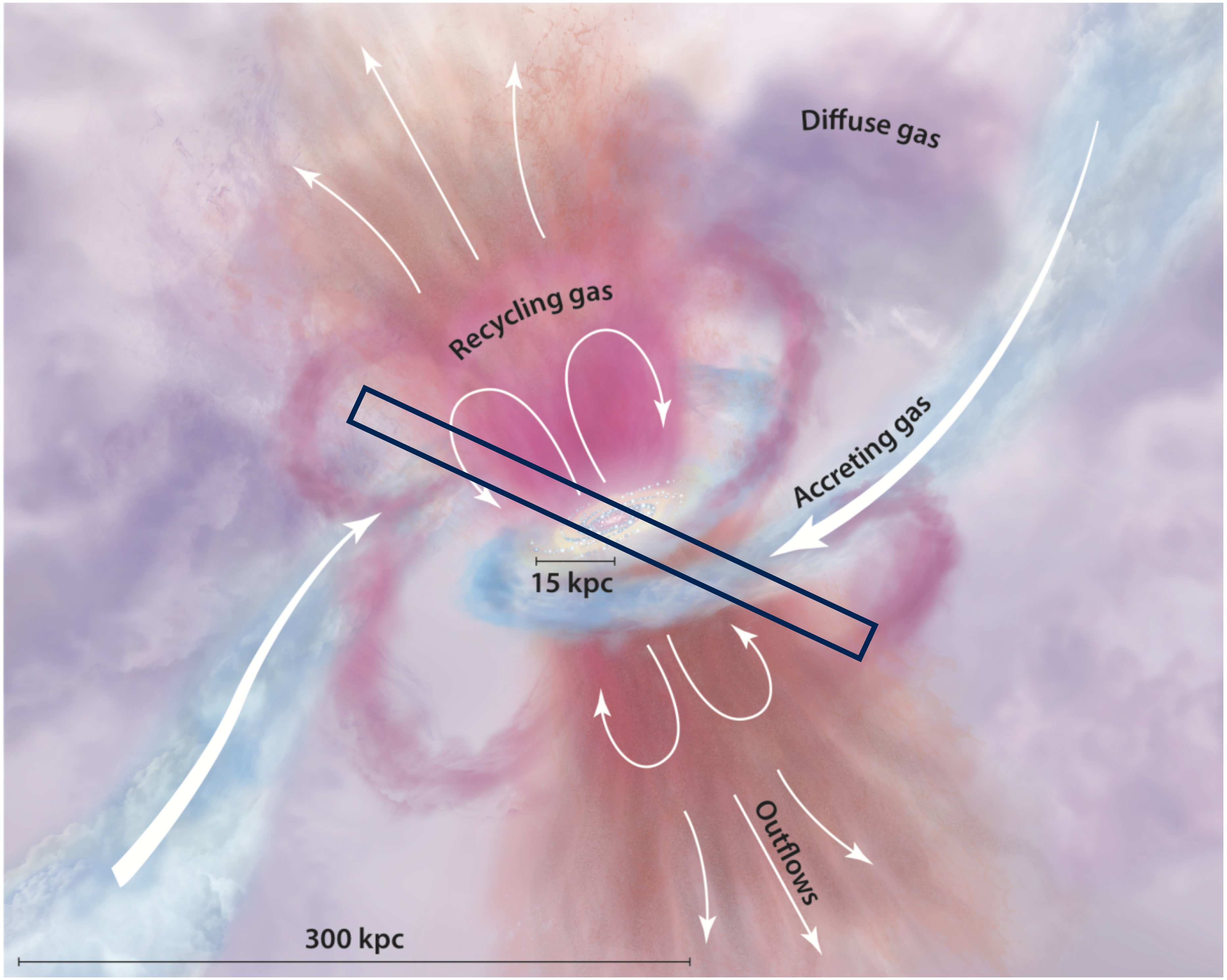
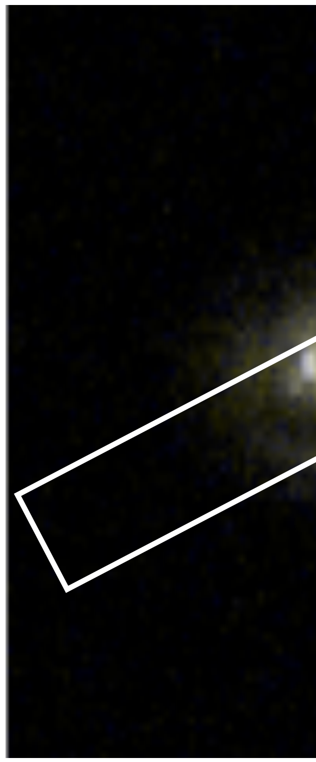
Brace yourselves:

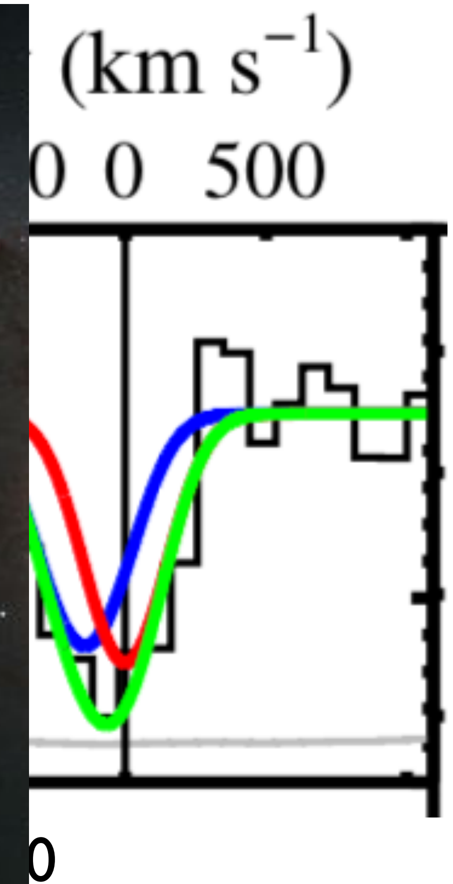


Tumlinson, Peeples & Werk 2017

for some observations. And worse graphics.

Uncontroversial statement: galaxies probably have more than one wind velocity.

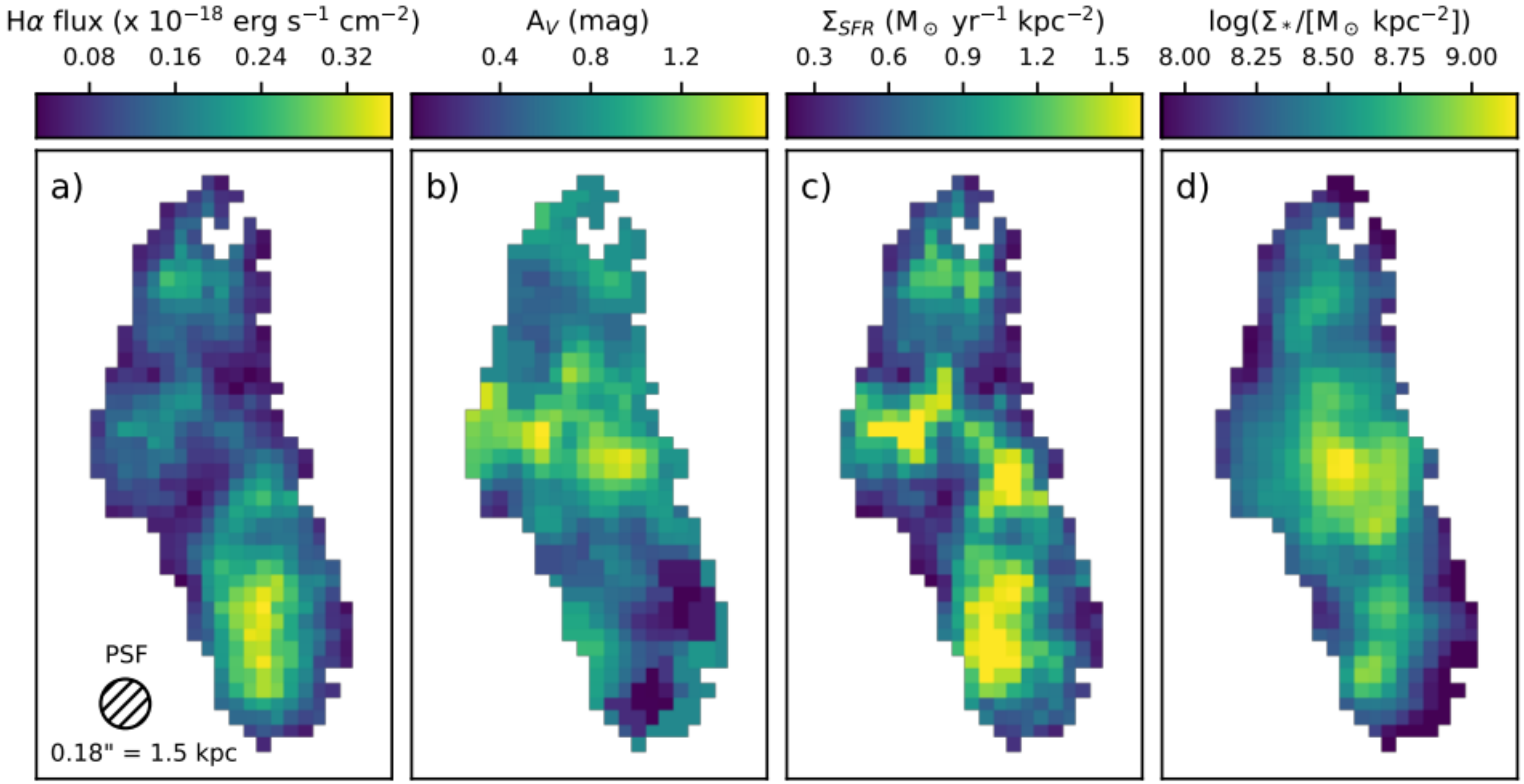




Single slit/fiber Martin 04,
Martin 05, 06, R 2, Rubin+14,
Heckman+15, C

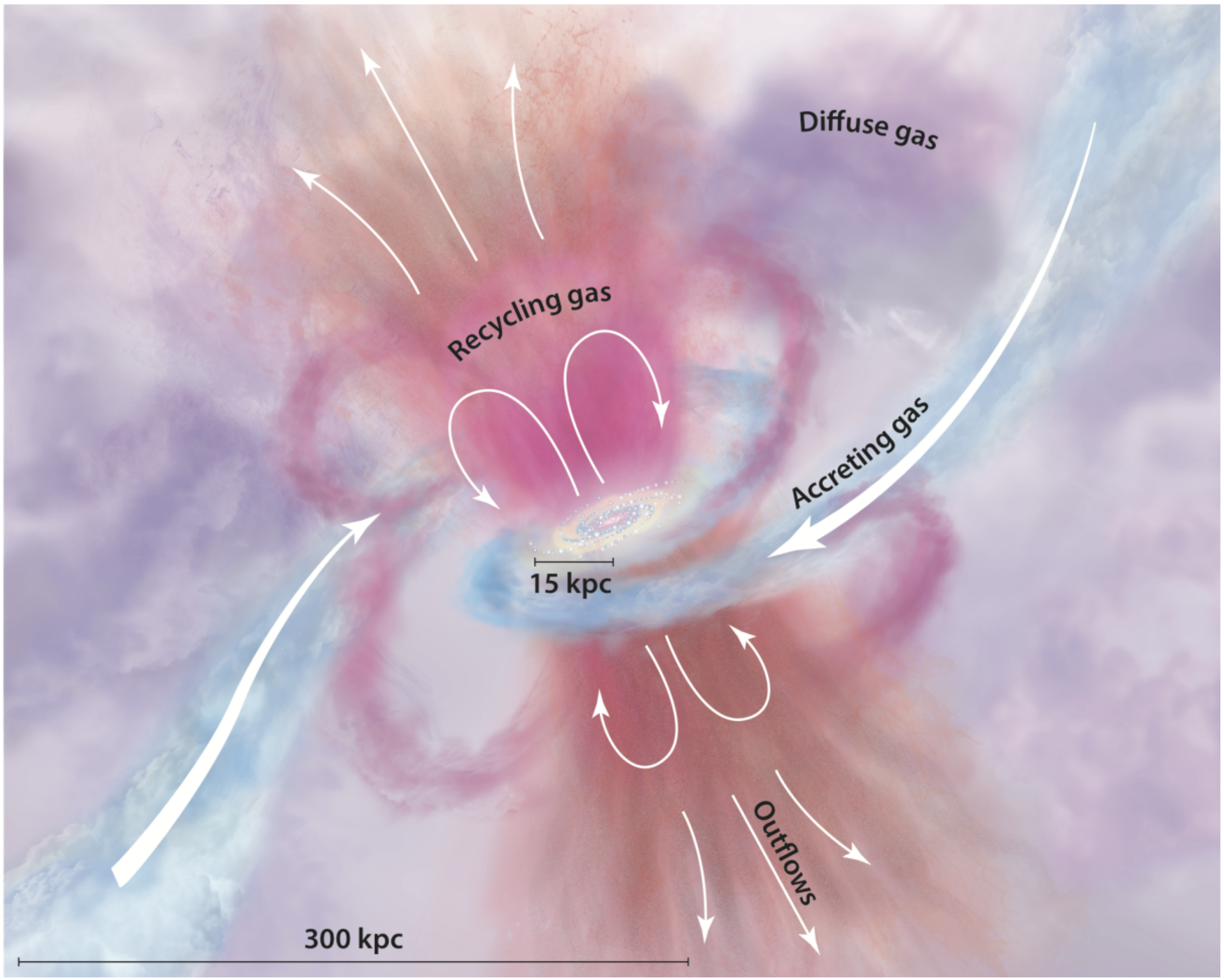
"What is happening down below is affecting what is observed up above the disk." — N. McClure-Griffiths (Ford+08)

Uncontroversial statement: galaxies probably have more than one wind velocity.



Davies et al. 2018: kiloparsec-resolupion mapping of outflow velocities at z~2.3!

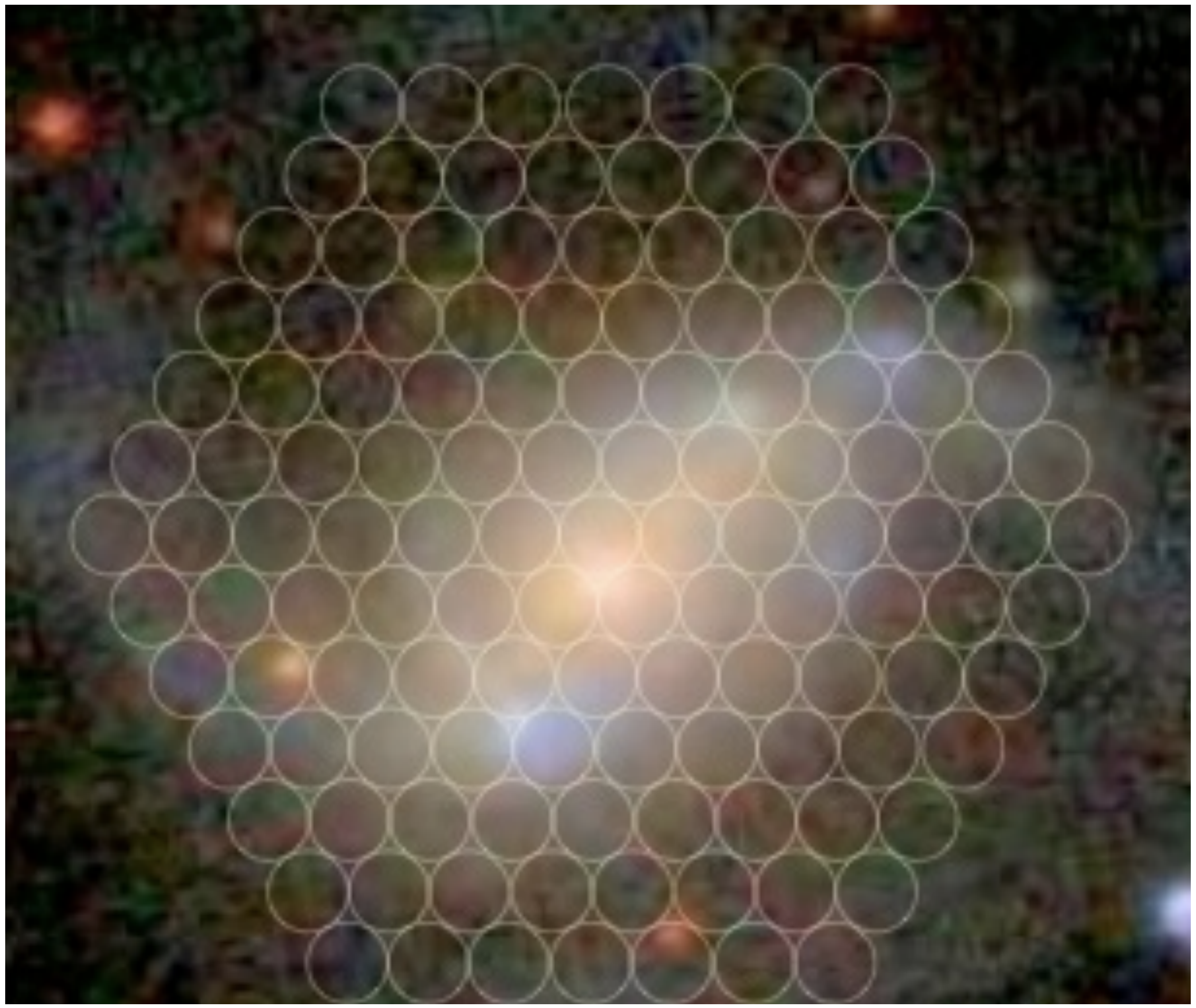
And maybe they have both winds and accretion at once.



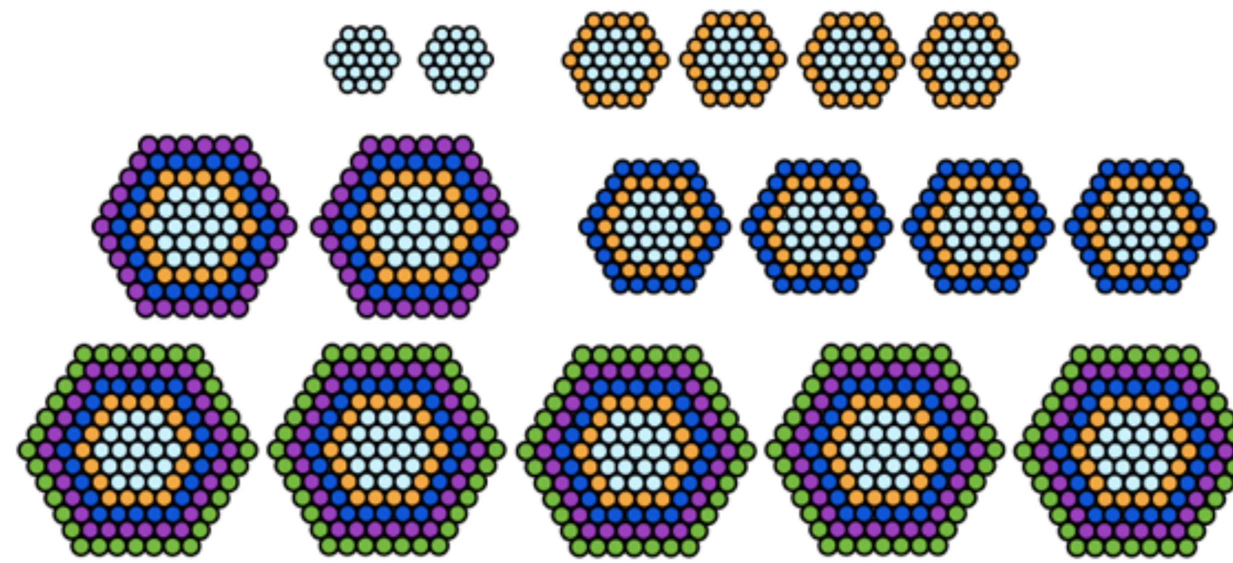
Tumlinson, Peeples & Werk 2017

SDSS-IV / MaNGA

(Mapping Nearby Galaxies at APO)



Optical integral field spectroscopy of 10,000 z~0 galaxies

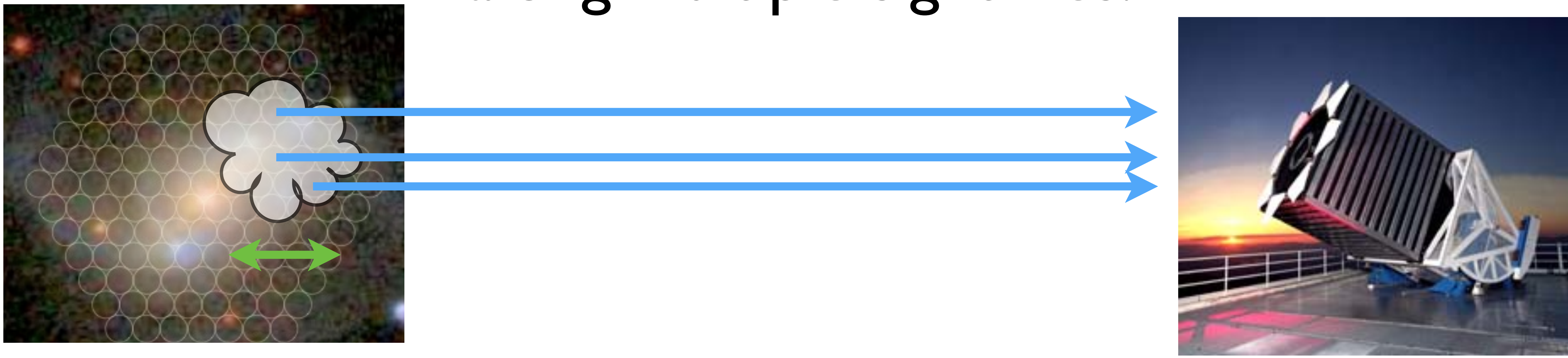


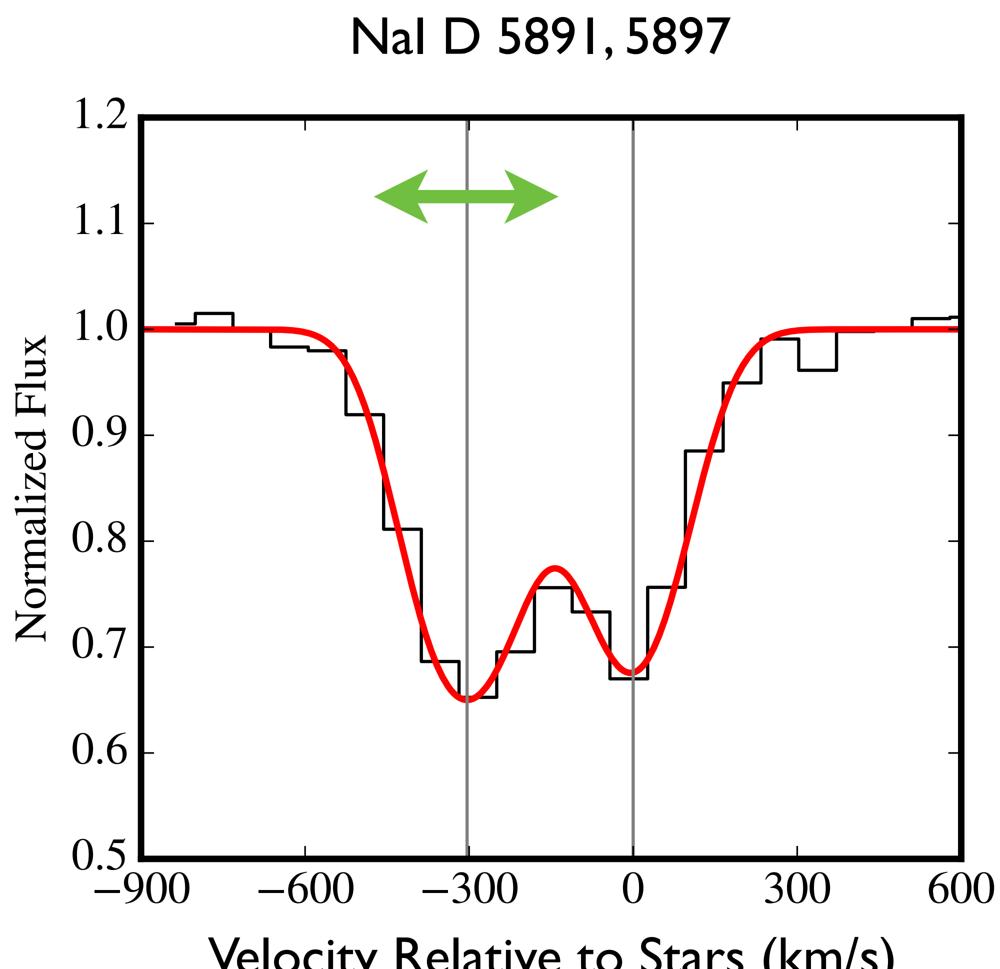
PI: Kevin Bundy (UCO/Lick)

MaNGA VIPs: Kyle Westfall, Renbin Yan, David Law, Matt Bershady, Niv Drory, Cheng Li, Alfonso Aragon-Salamanca, Nick MacDonald, David Wake, Anne-Marie Weijmans

VIPs on this project: Kyle Westfall, David Law, Kevin Bundy, Christy Tremonti, Chris Howk, Aleks Diamond-Stanic

SDSS-IV / MaNGA probes the disk-halo interface along multiple sightlines.



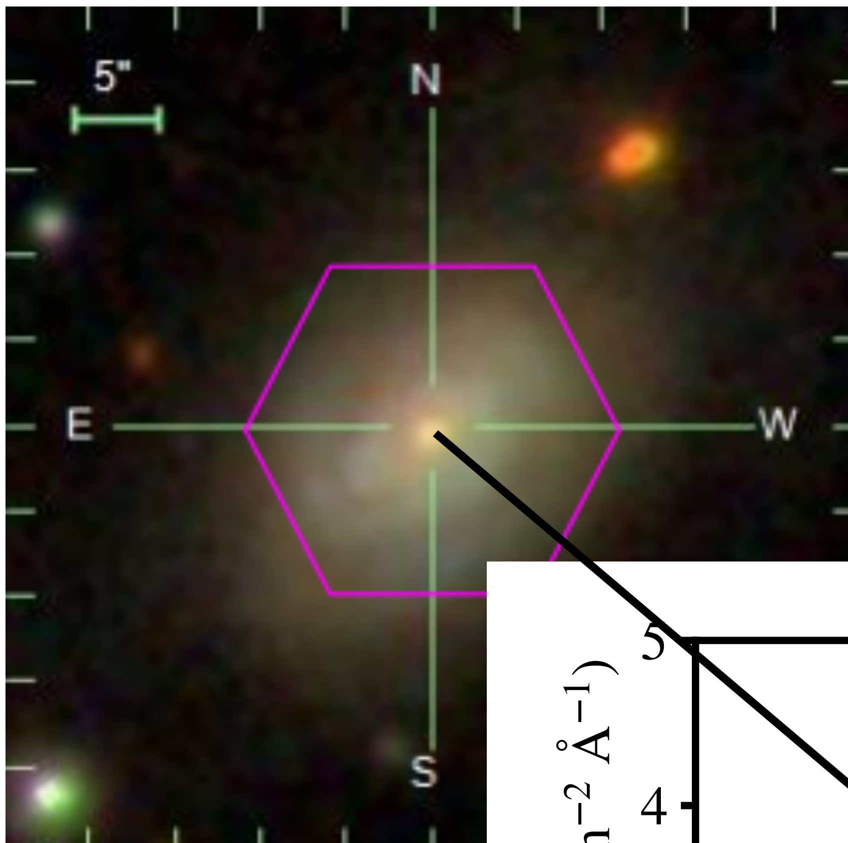


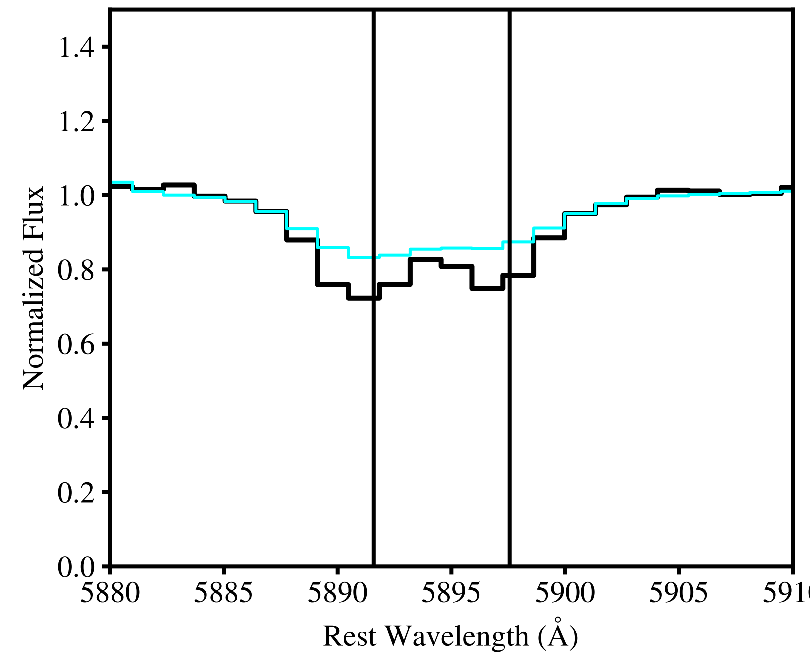
cold (~100 K), dusty gas!

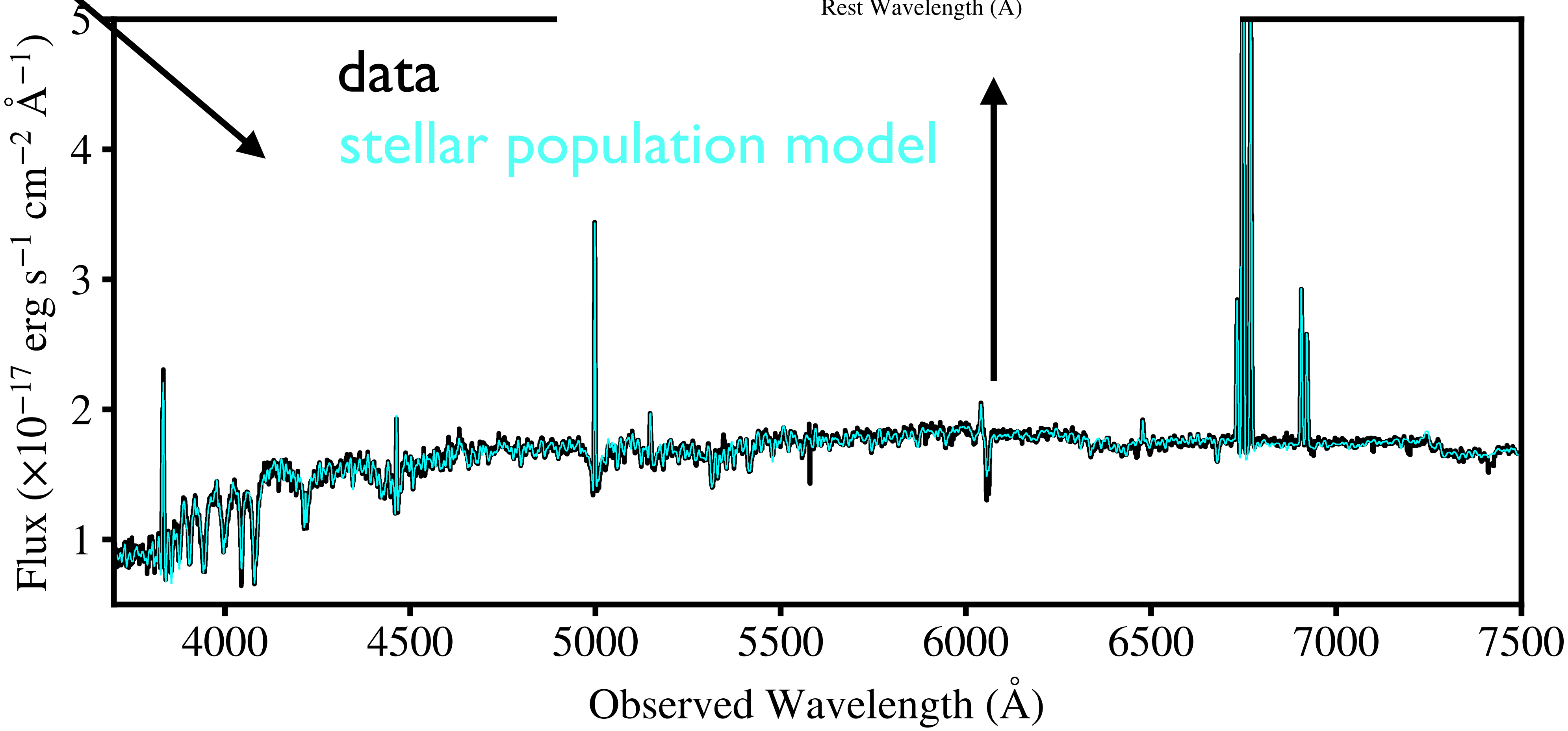
e.g., Heckman+00, Schwartz & Martin 04, Martin 05, Martin 06, Rupke+05abc, Schwartz+06, Chen+10, Rupke & Veilleux 2015, Roberts-Borsani+18

A test case (observed with 61-fiber bundle):

$M^* = 1.6 \times 10^{10}\ M_{sun}$

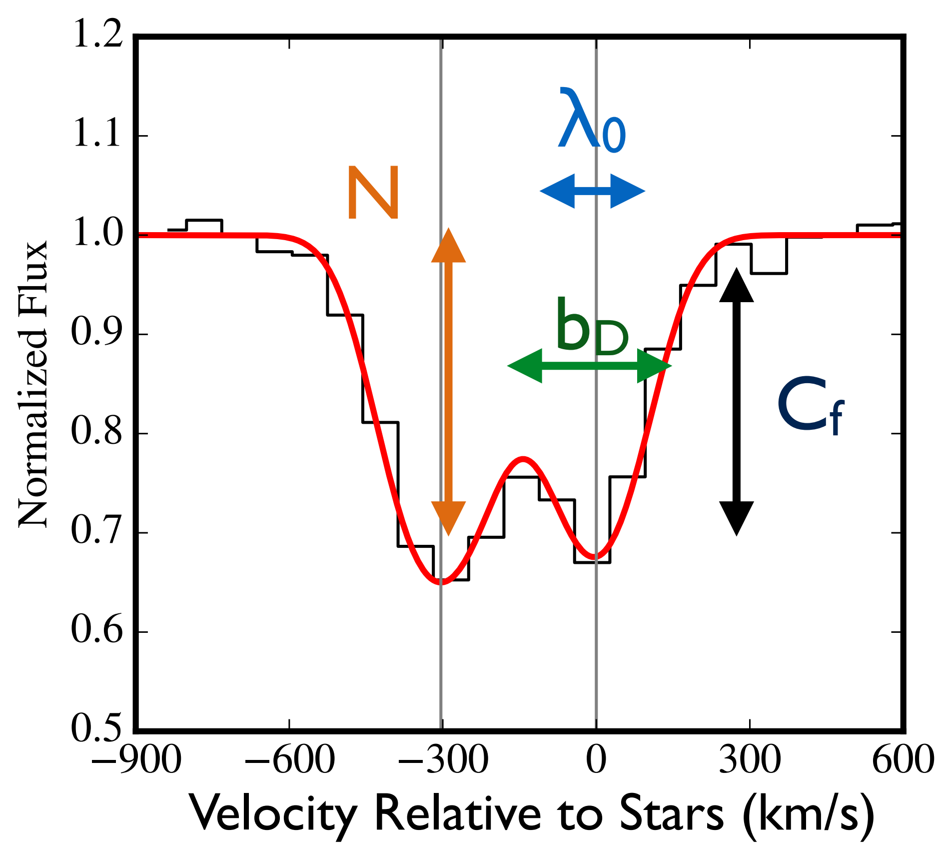


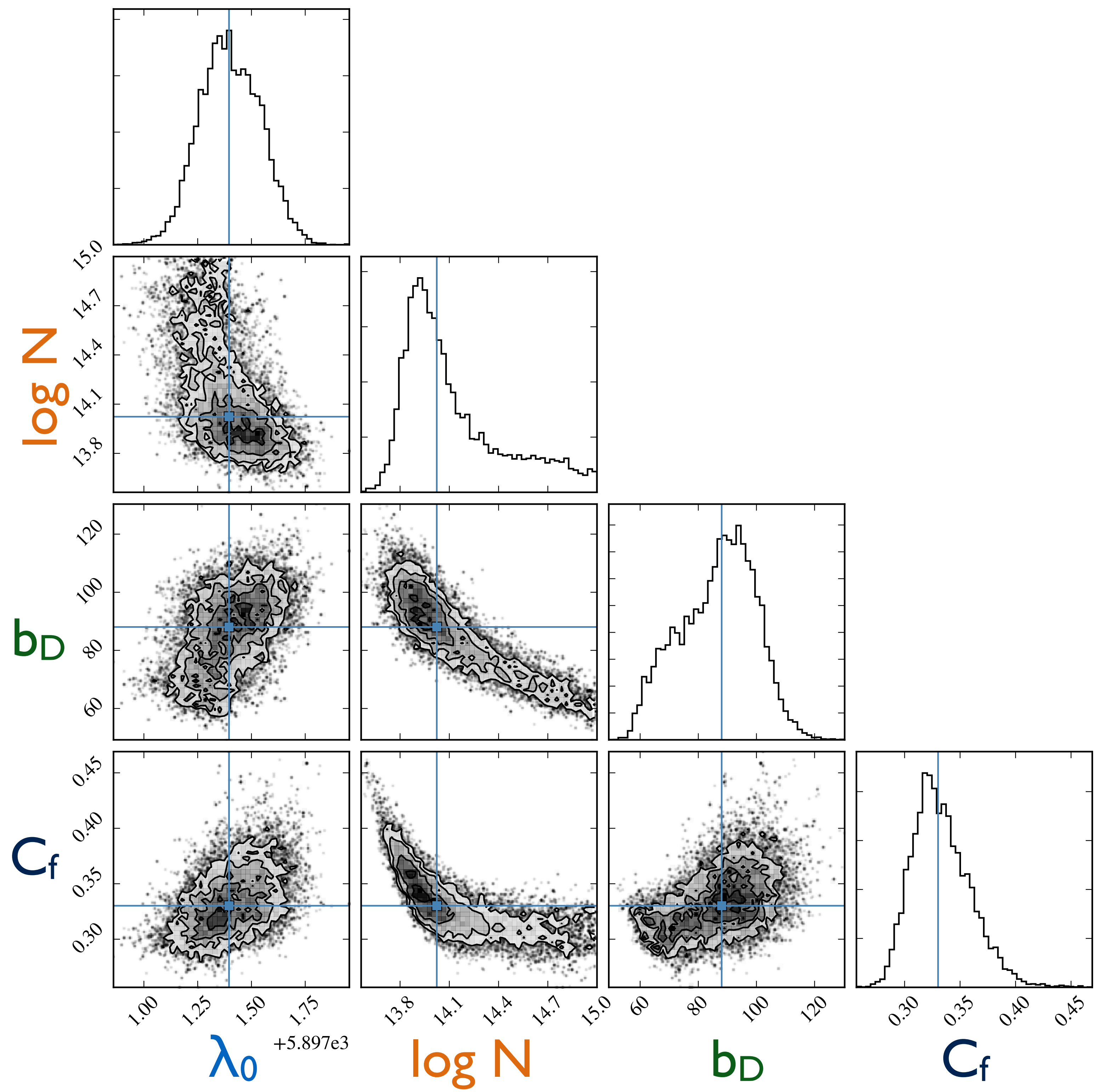




Thanks to the MaNGA Data Analysis Pipeline (Westfall et al. in prep)

Modeling the NaI D doublet:





$I(\lambda) = F(\lambda_0, N, b_D, C_f)$

λ_0 = central wavelength

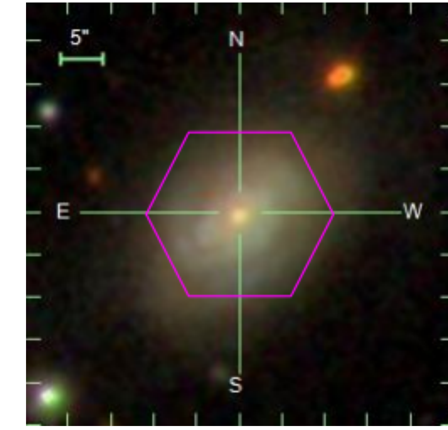
N = column density

b_D = Doppler parameter

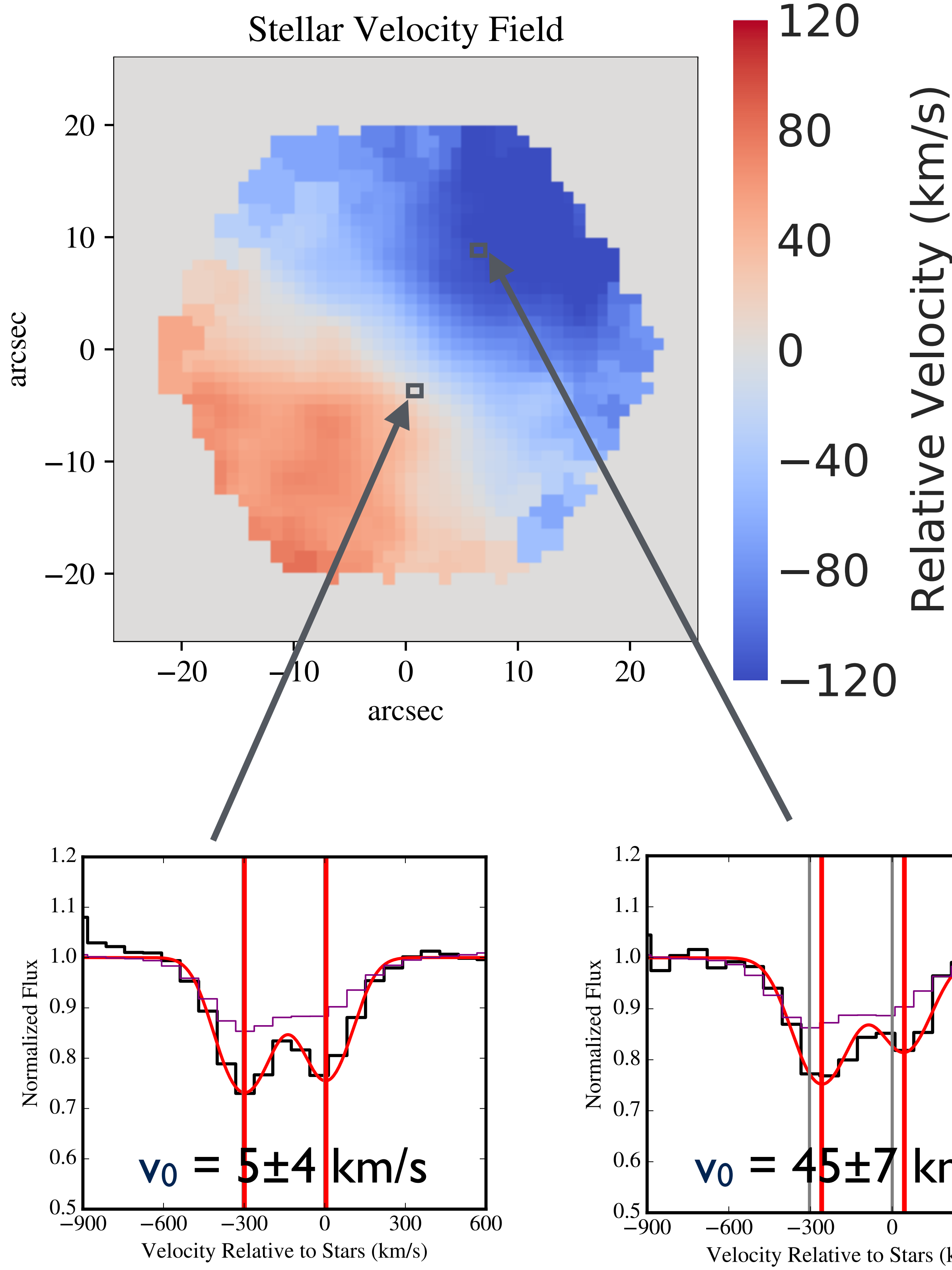
C_f = covering fraction

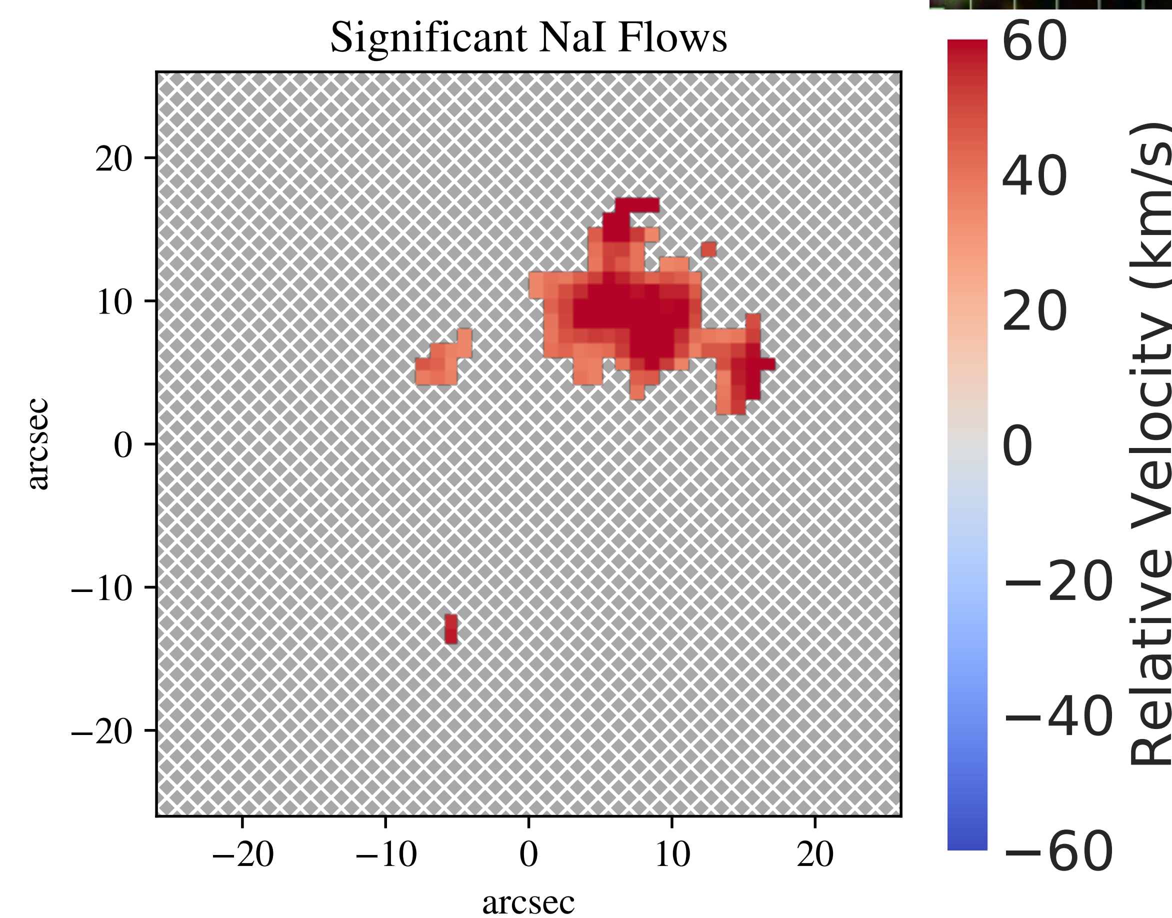
Rubin et al. in prep

A test case (observed with 61-fiber bundle):



$M^* = 1.6 \times 10^{10}\ M_{sun}$



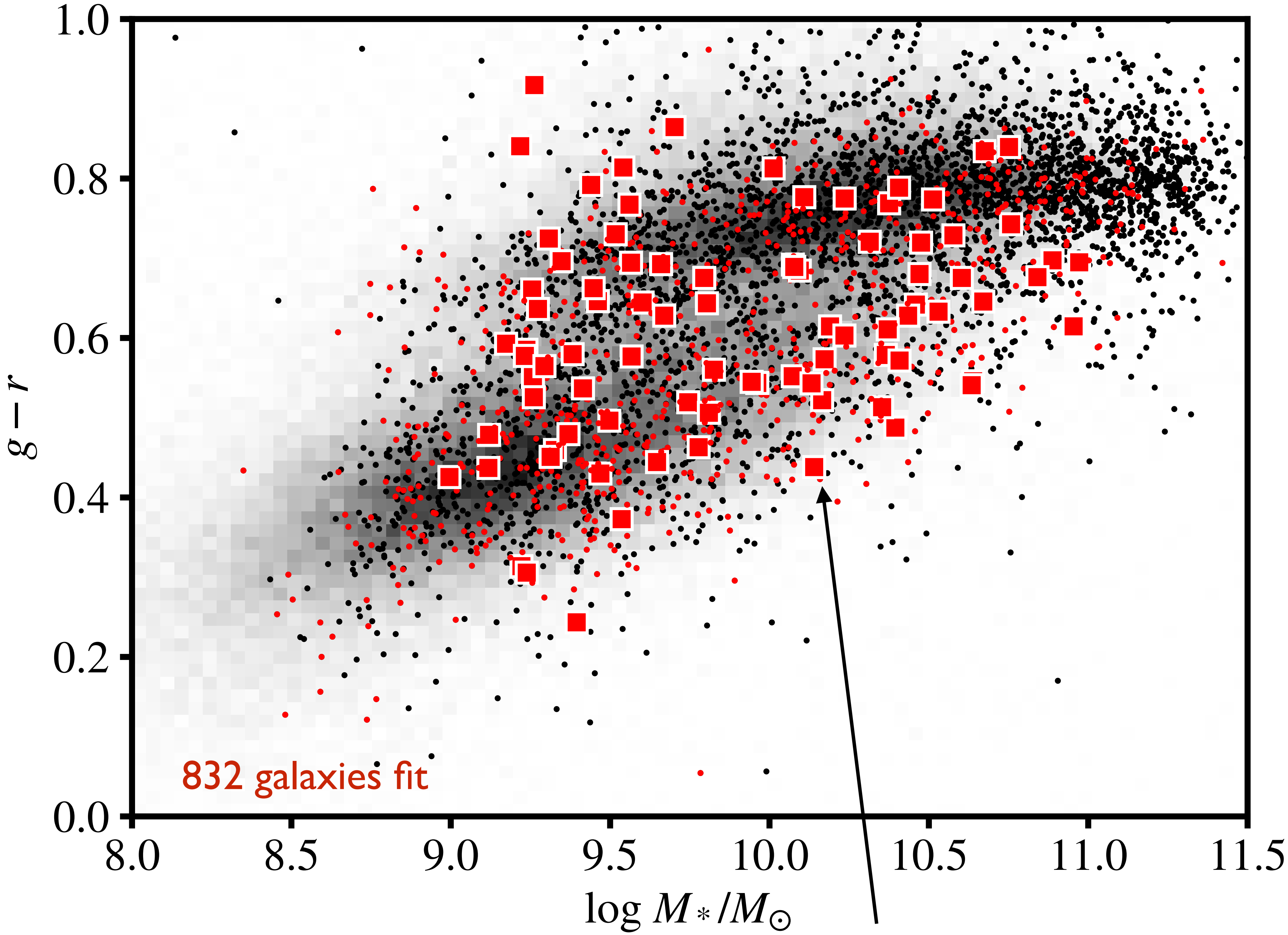


"significant":

1. velocity offset from stars by > 35 km/s
2. >95% of PPDF offset from both stars and emission lines

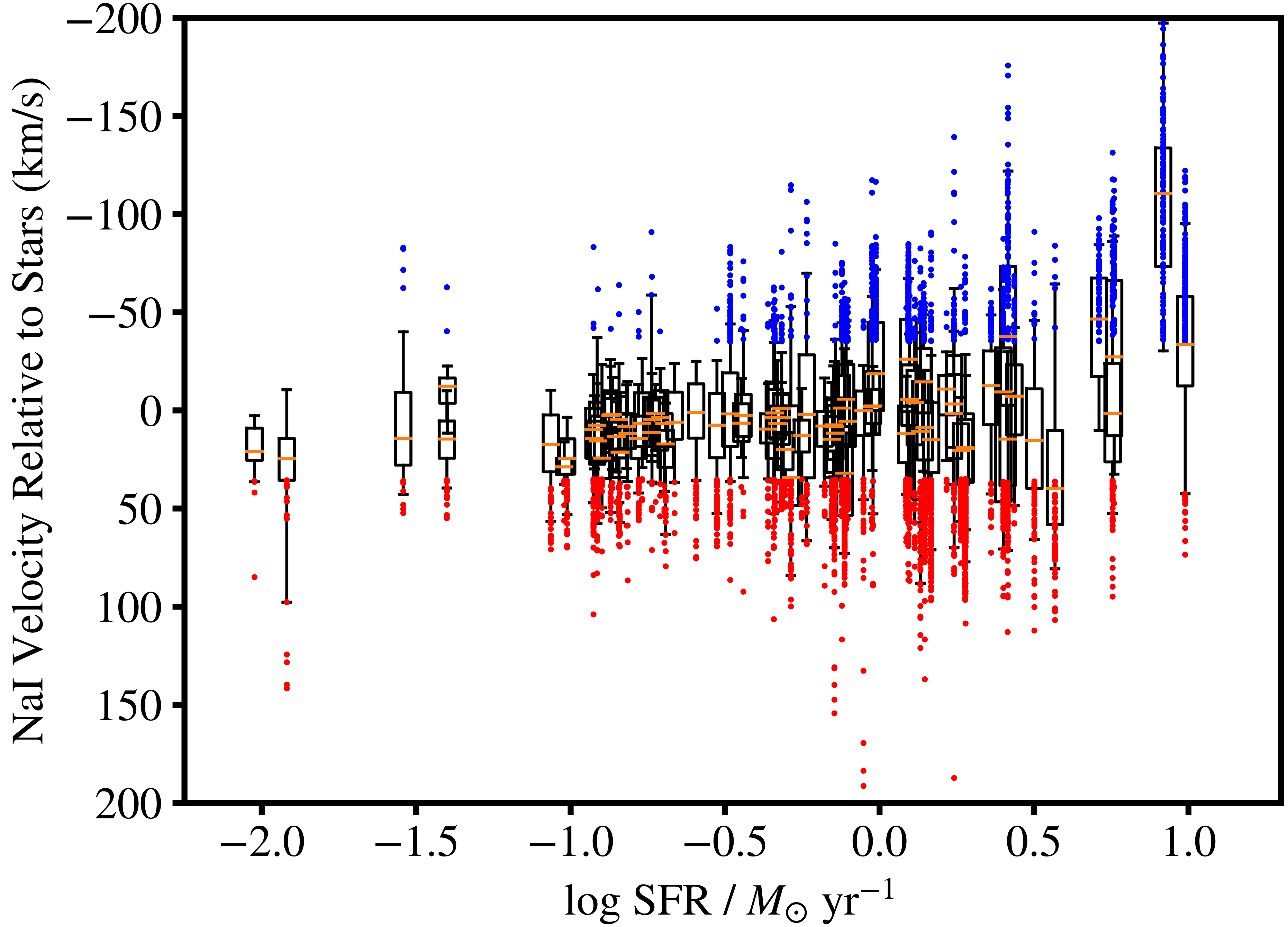
MaNGA Status

4620 galaxies observed



86 high S/N fits: NaI velocity +/-1σ interval < 50 km/s over at least 75% of the galaxy's effective area (A_e = pi (b/a) R_e^2)

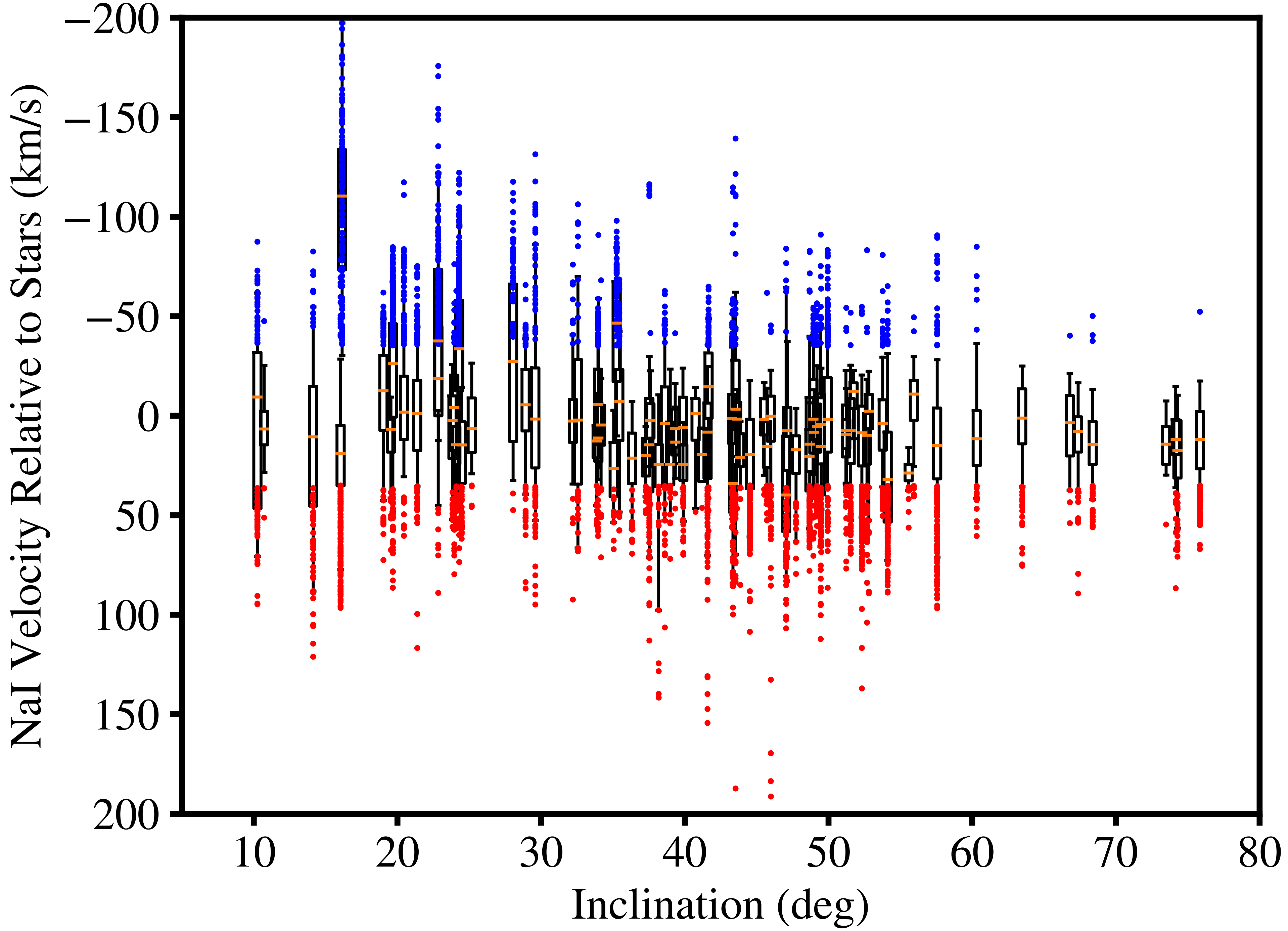
NaI velocity distributions, sorted by SFR.



blue/red: spatial bins with velocity shifts > 35 km/s

Rubin et al. in prep

NaI velocity distributions, sorted by inclination.



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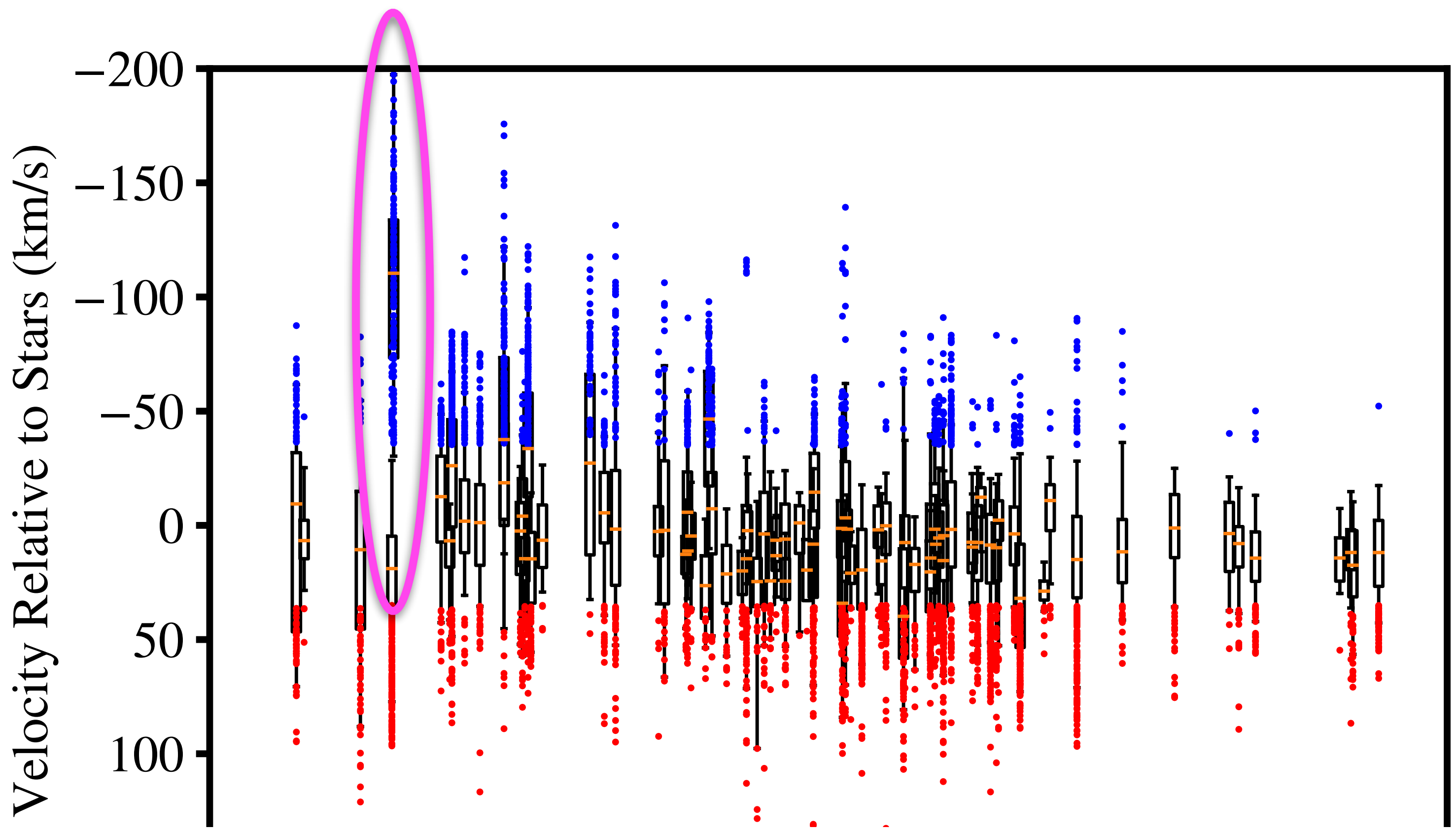
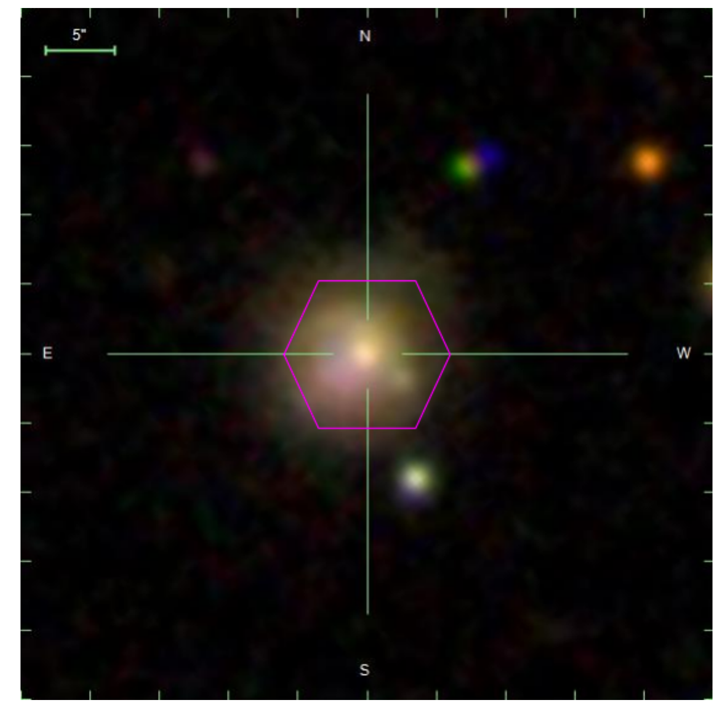
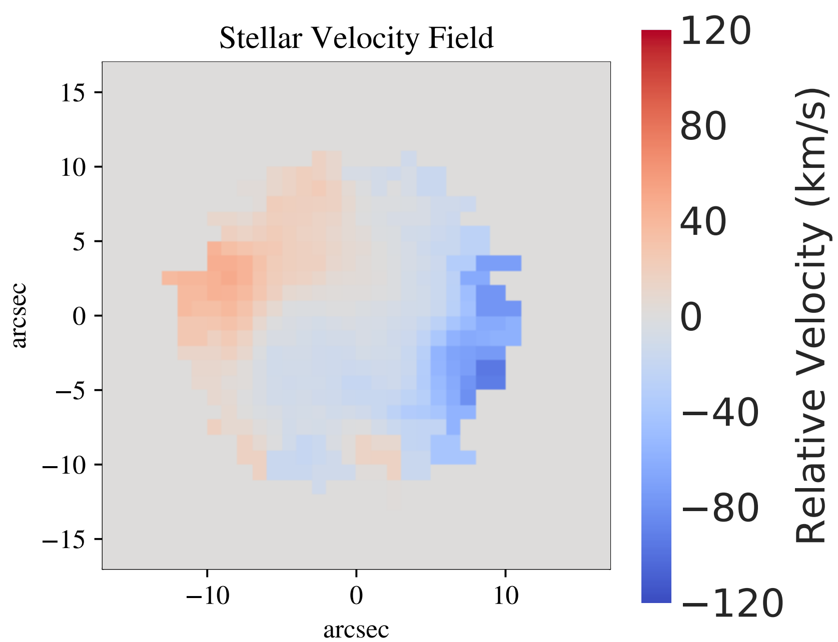
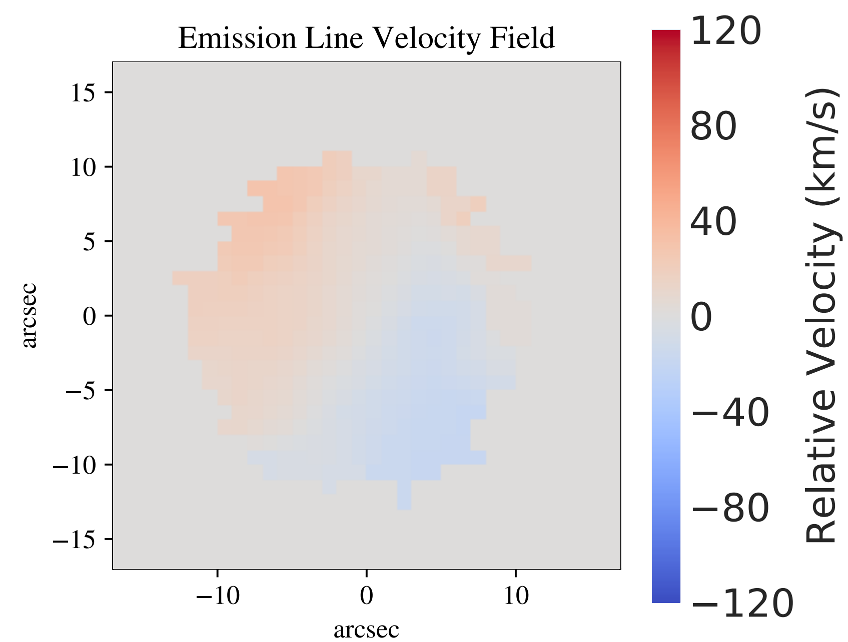
Rubin et al. in prep

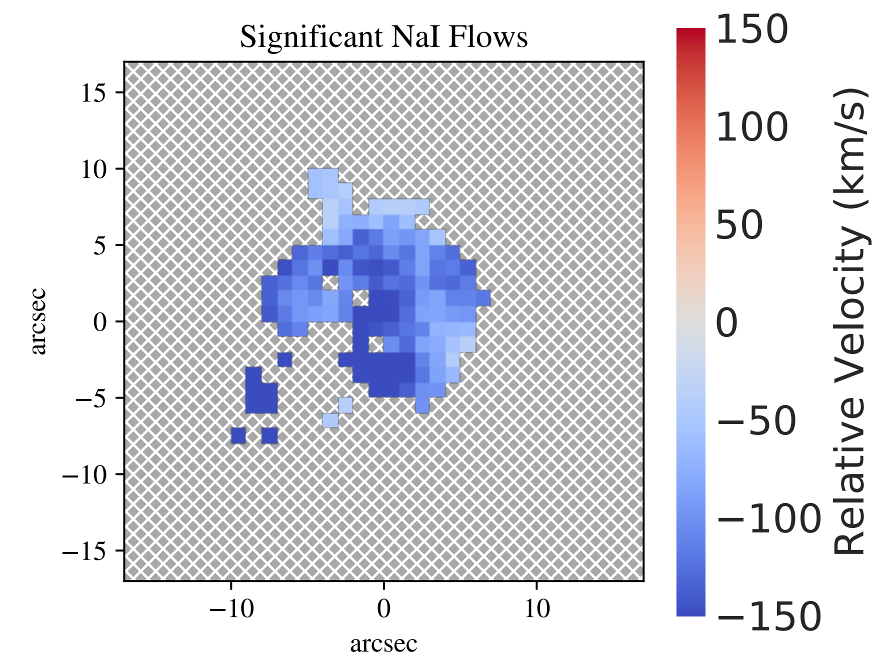
NaI velocity distributions, sorted by inclination.





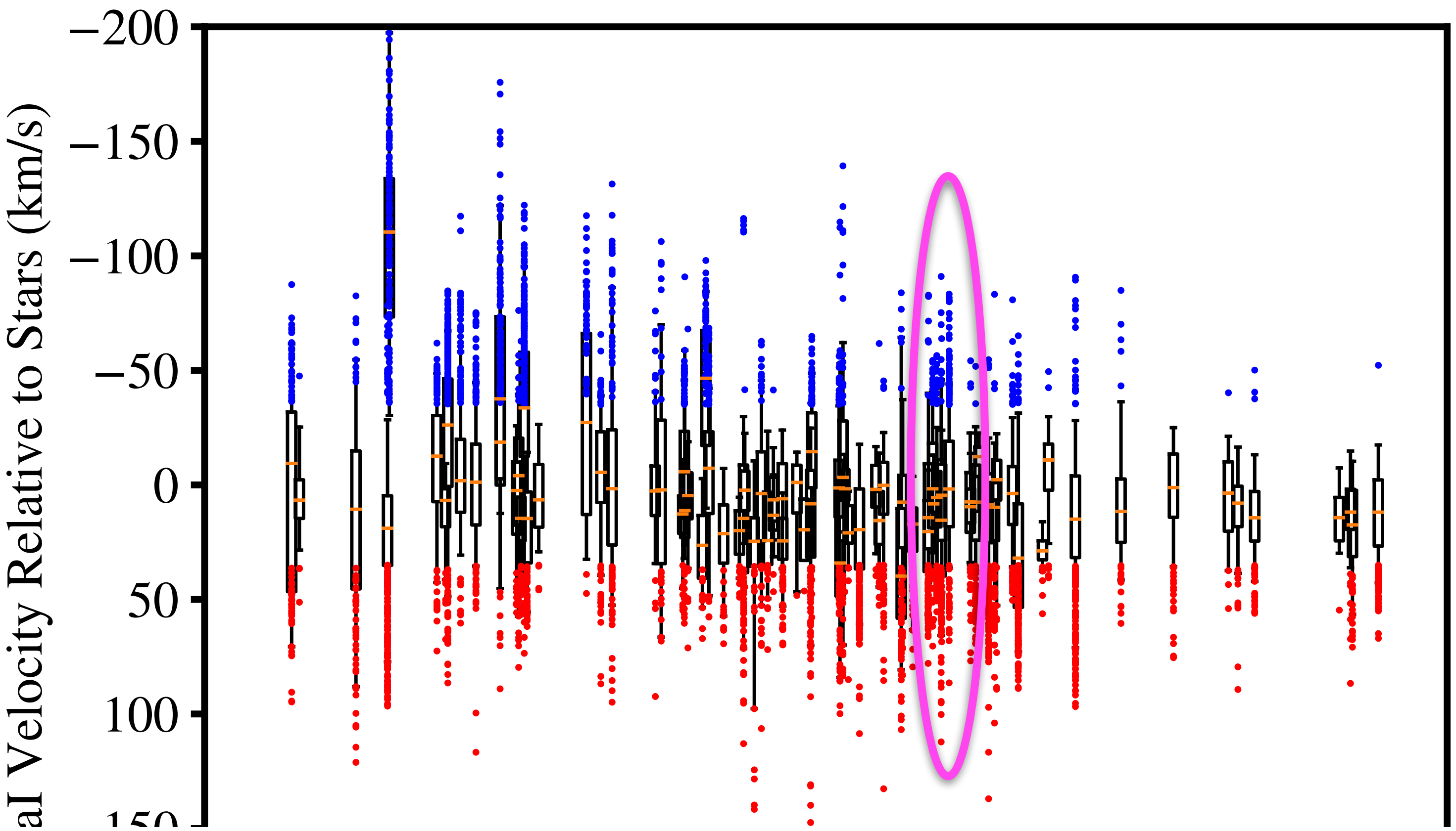


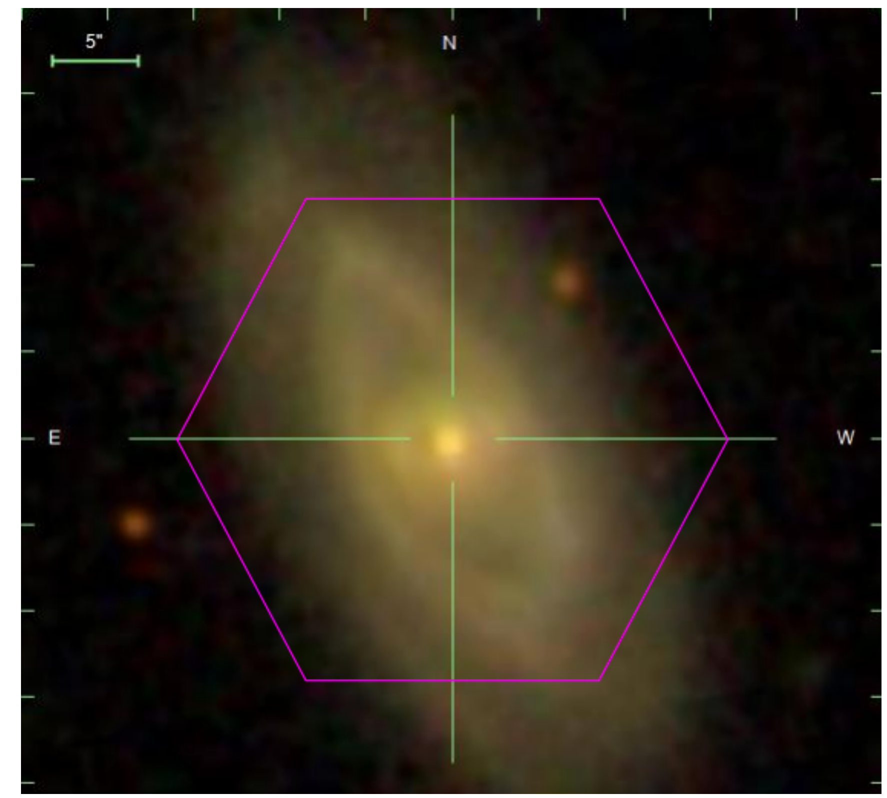


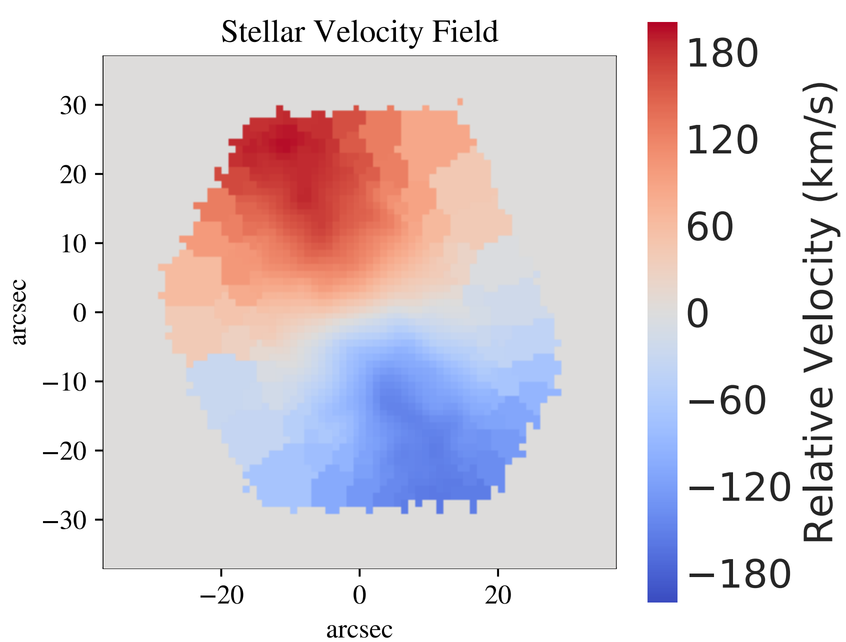


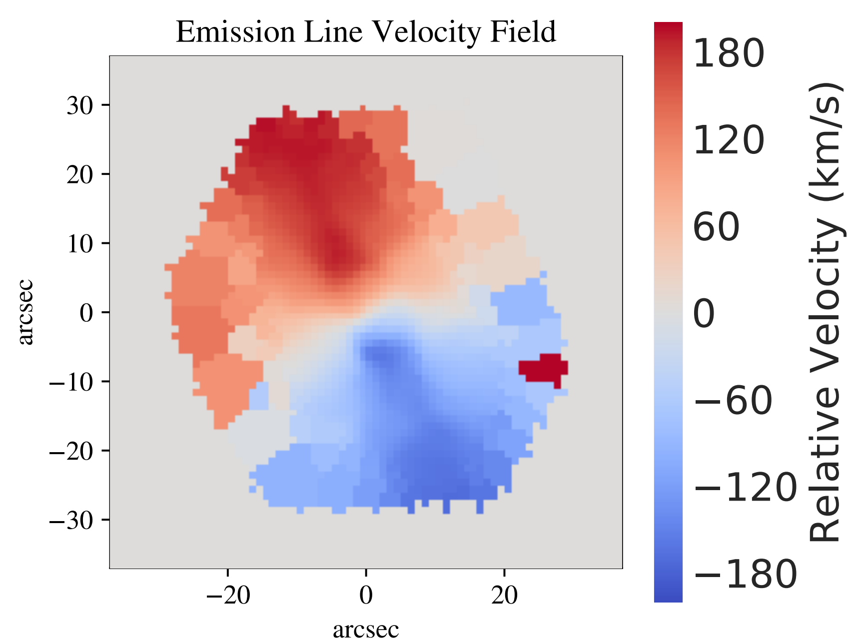
SFR ~ 10 M_{sun}/yr, log M_* = 10.4

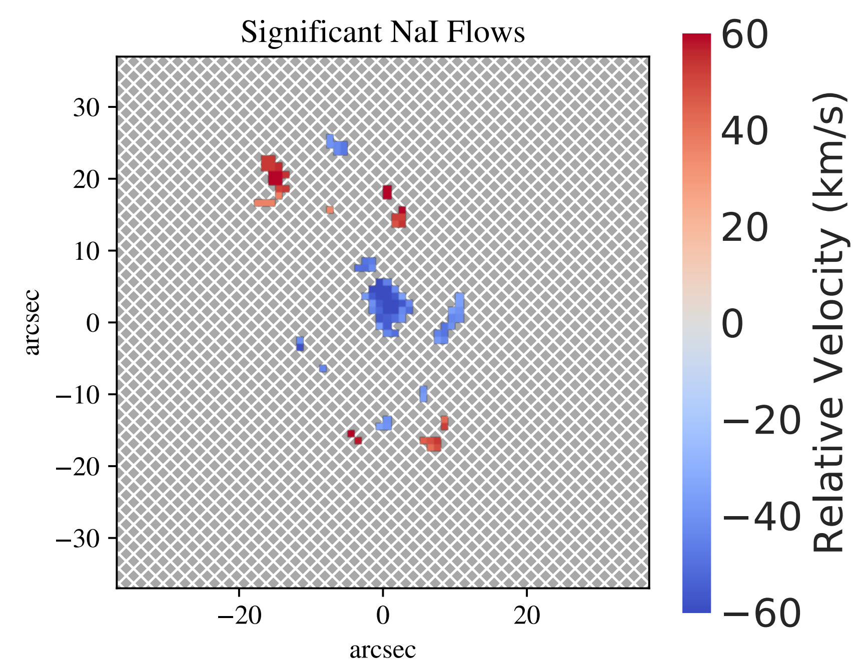
NaI velocity distributions, sorted by inclination.





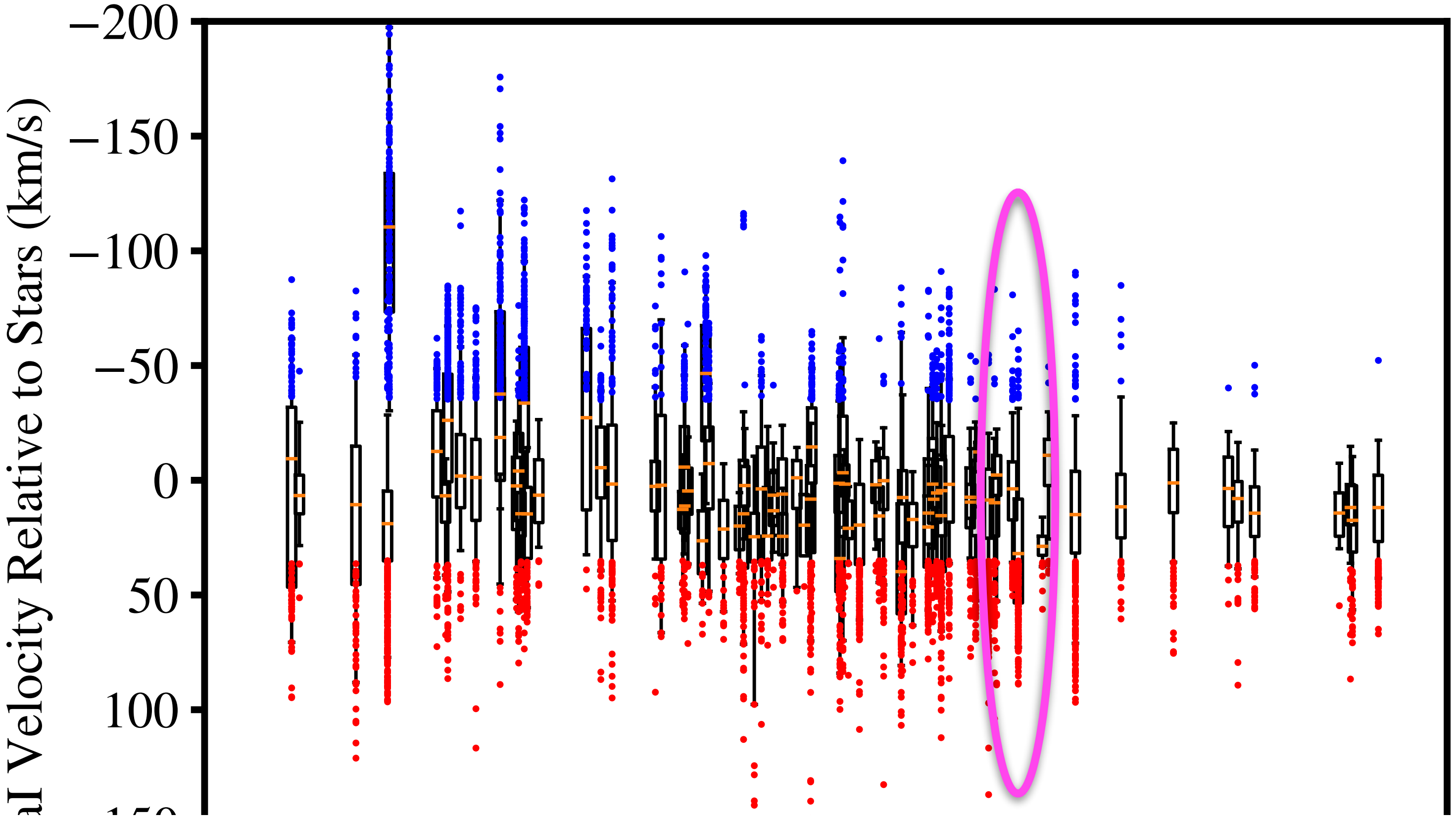


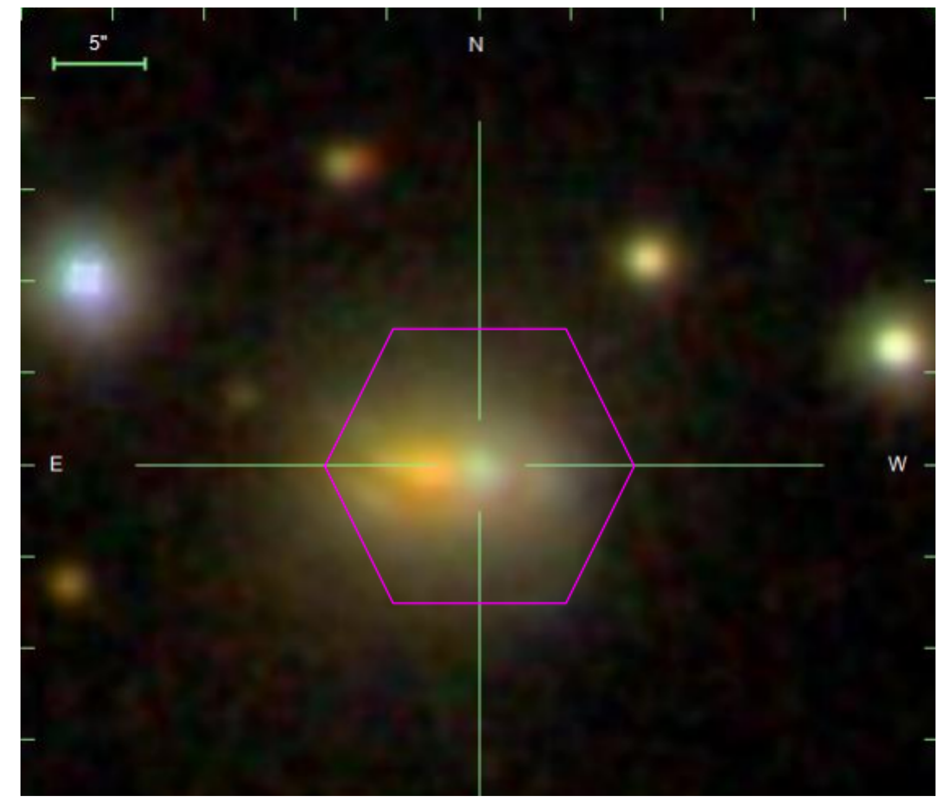


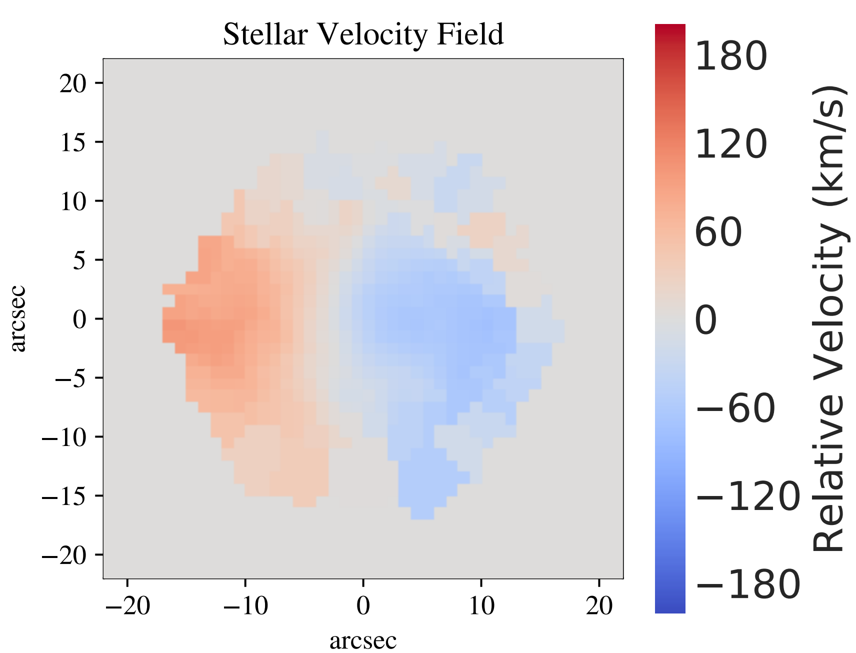


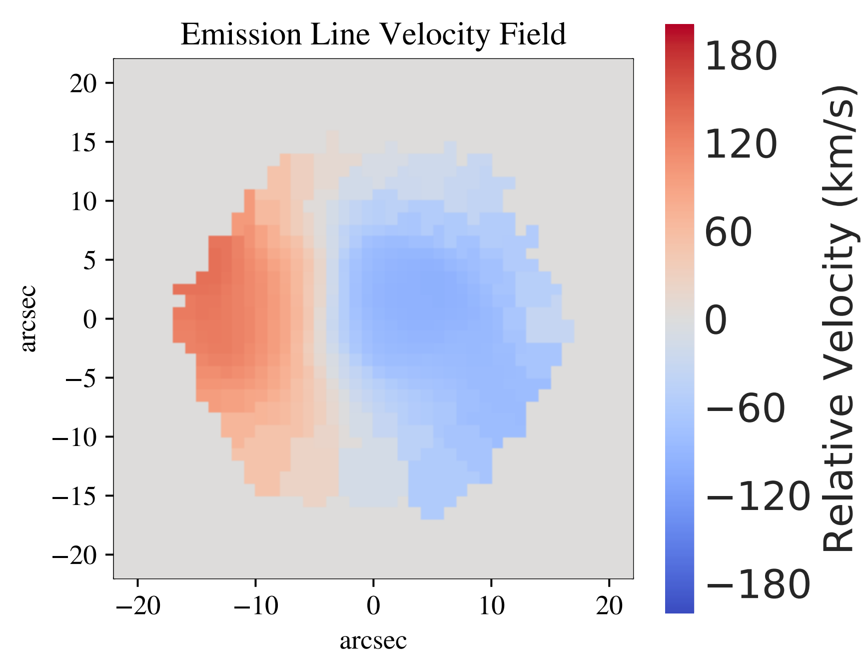
SFR ~ 0.3 M_{sun}/yr, log M_* = 10.3

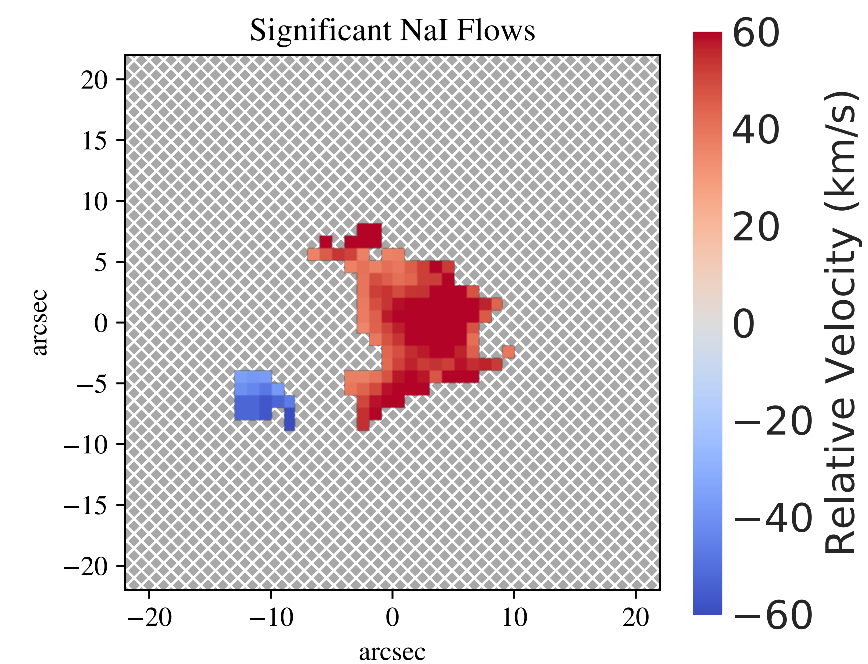
NaI velocity distributions, sorted by inclination.





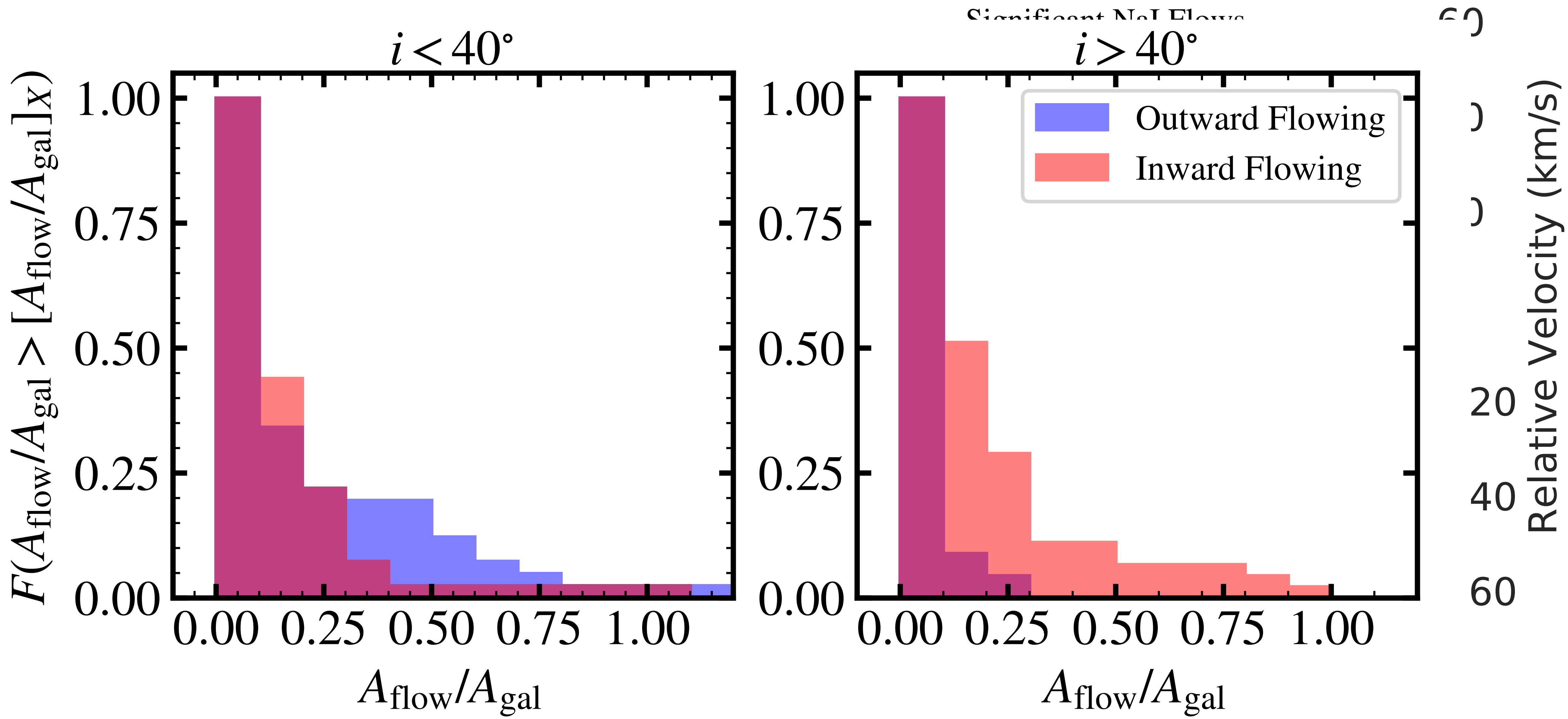






SFR ~ 0.8 M_{sun}/yr, log M_* = 9.6

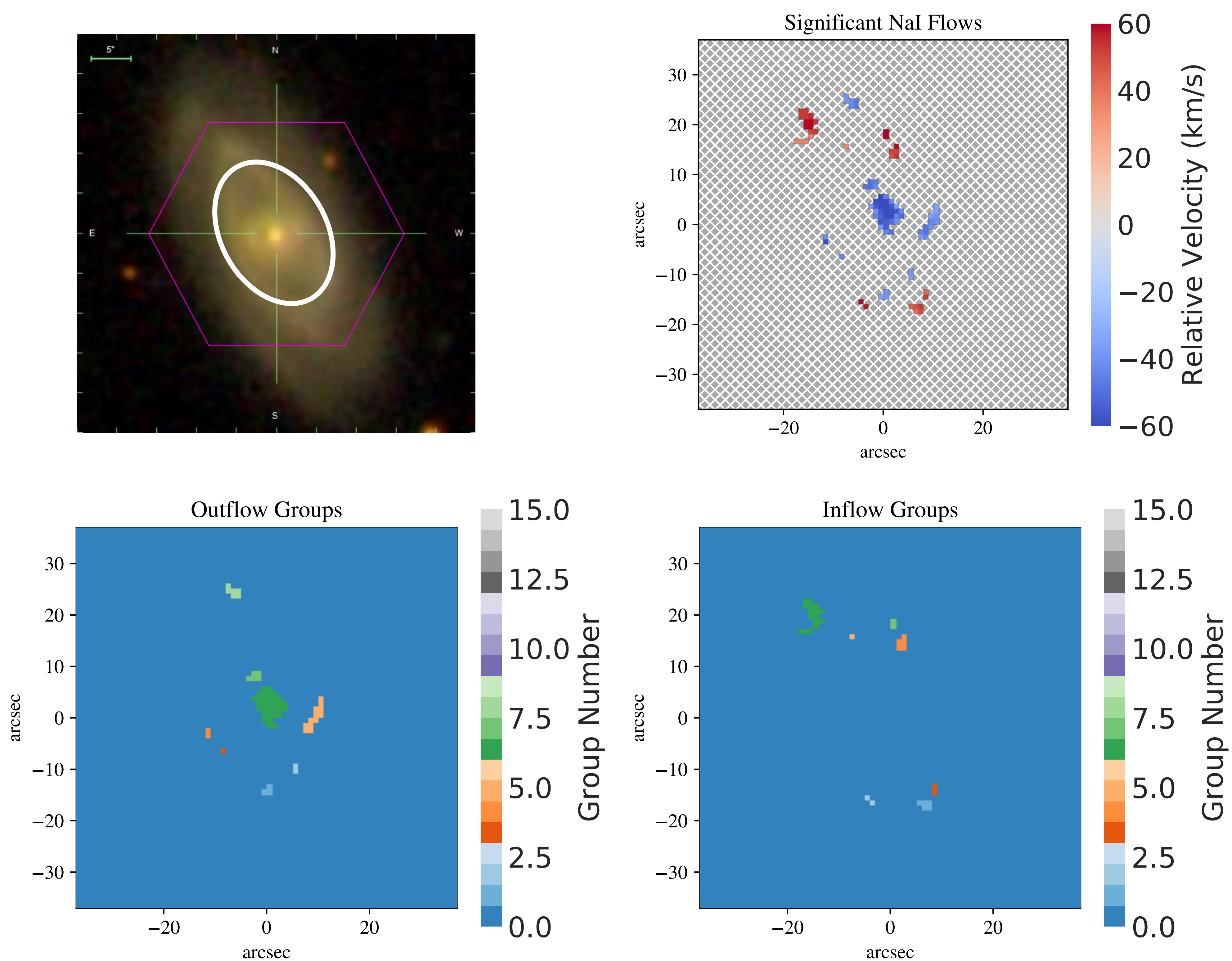
Fractional area covered by NaI flows



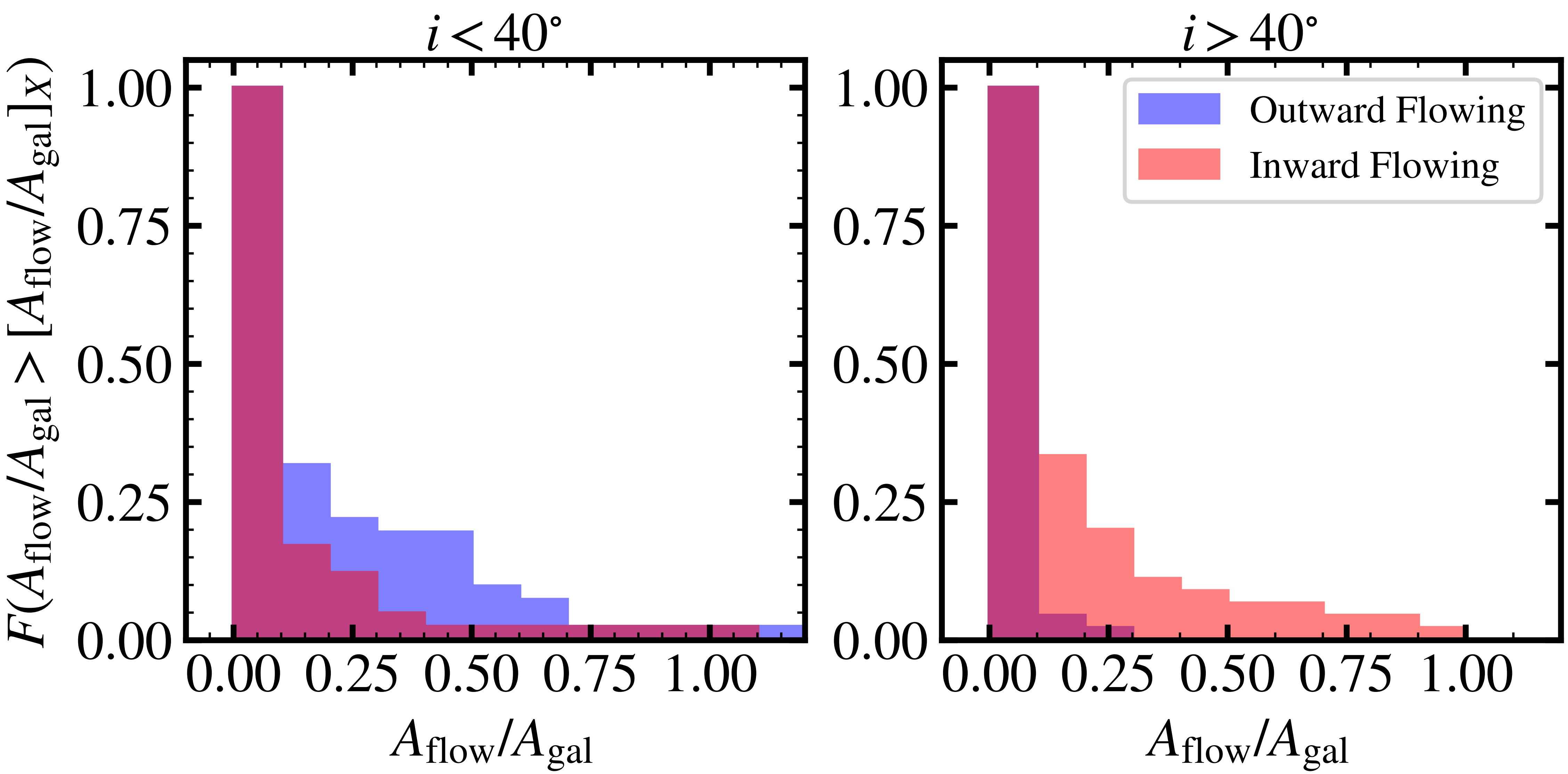
- ~20% of face-on galaxies are 40% covered by outflow
- ~20% of face-on galaxies are 25% covered by inflow
- ~50% of edge-on galaxies are 10% covered by inflow

Rubin et al. in prep

Fractional area covered by NaI flows extending over > 4.5 sq. arcsec (9 spaxels)



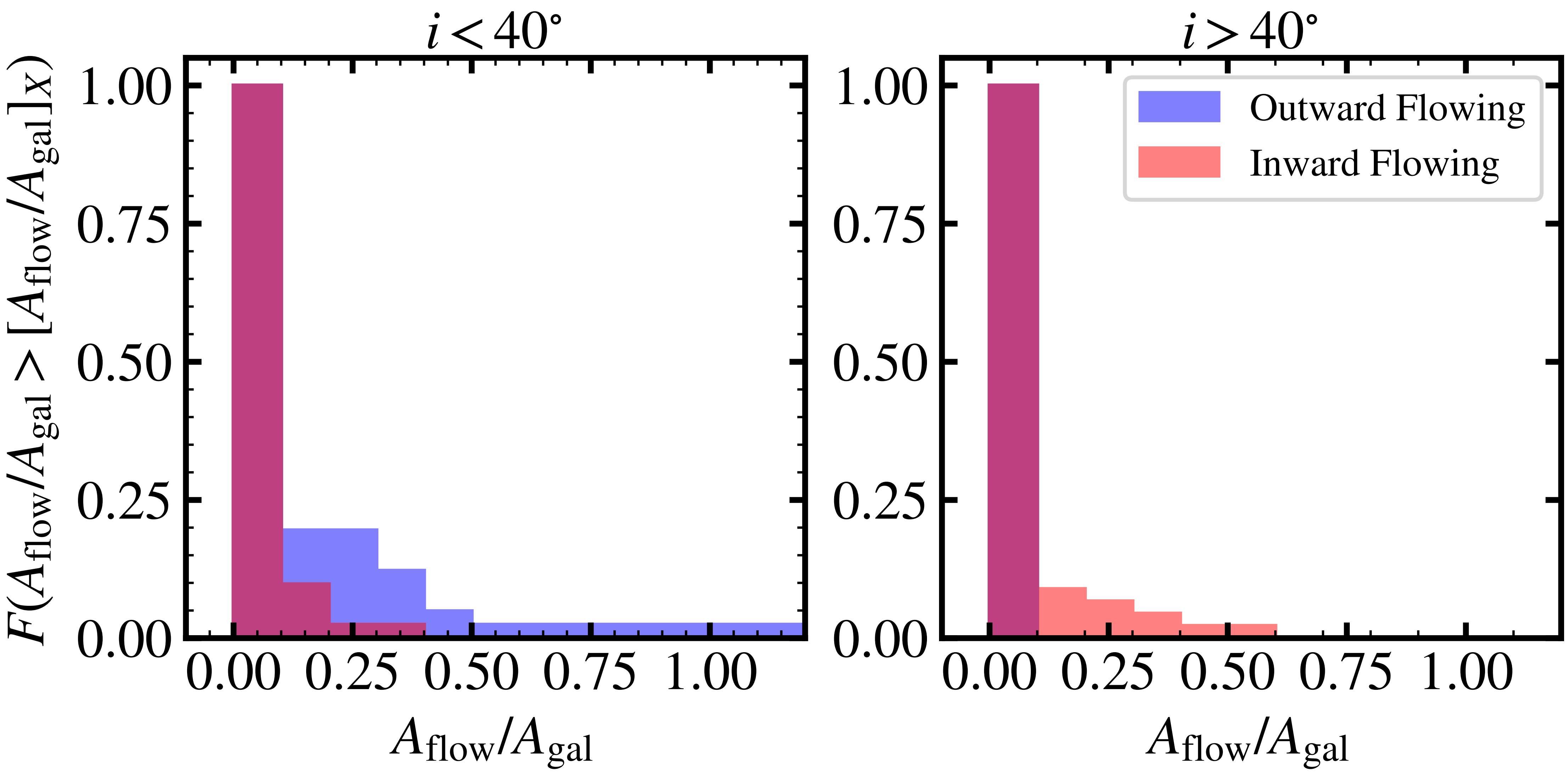
Fractional area covered by NaI flows extending over > 4.5 sq. arcsec (9 spaxels)



- ~20% of face-on galaxies are 40% covered by outflow
- ~15% of face-on galaxies are 25% covered by inflow
- ~30% of edge-on galaxies are 10% covered by inflow

Rubin et al. in prep

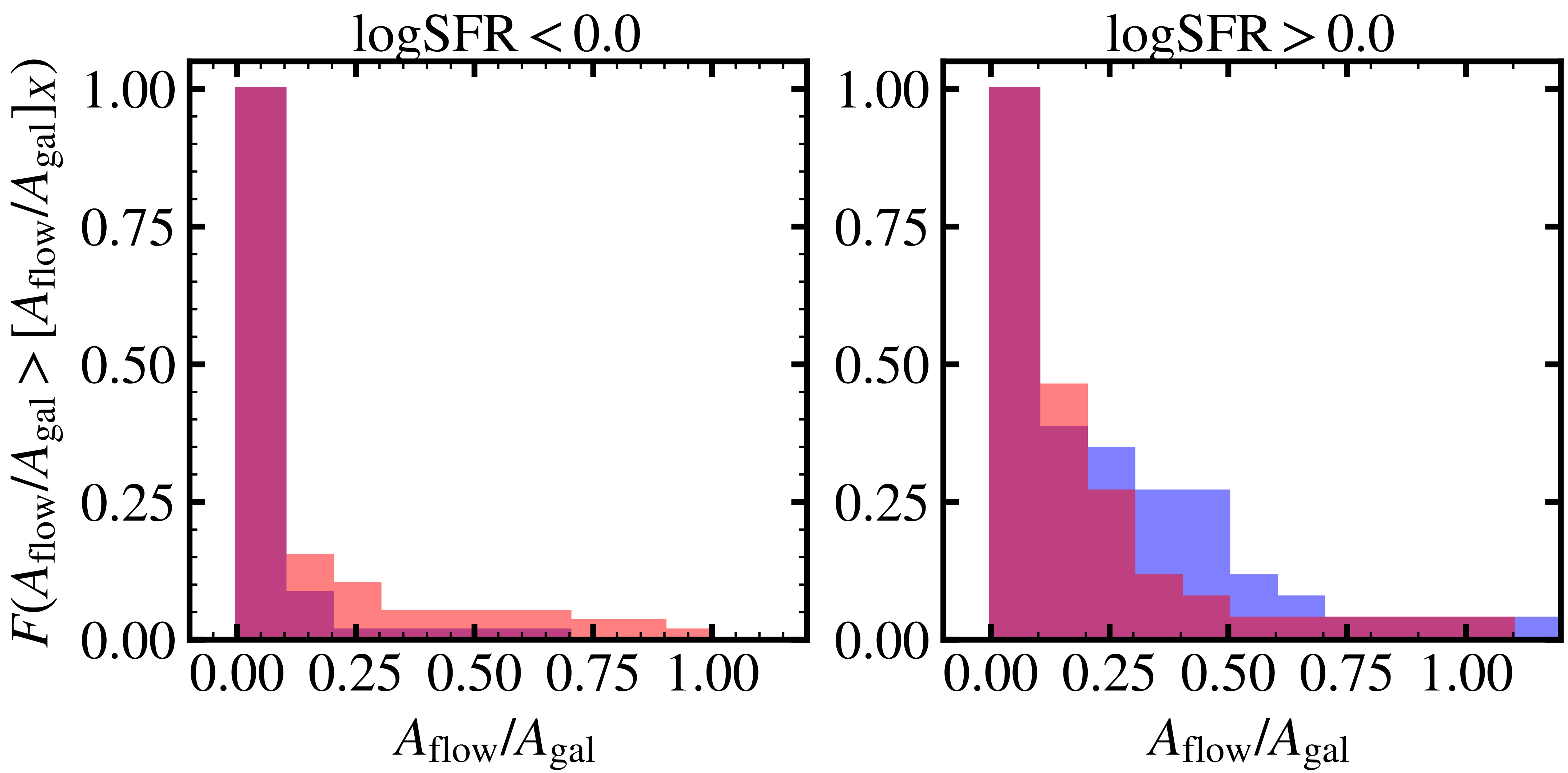
Fractional area covered by NaI flows **> 50 km/s** extending over > 4.5 sq. arcsec (9 spaxels)



- inflows with velocities > 50 km/s are much rarer, covering >10% of only ~10% of edge-on galaxies

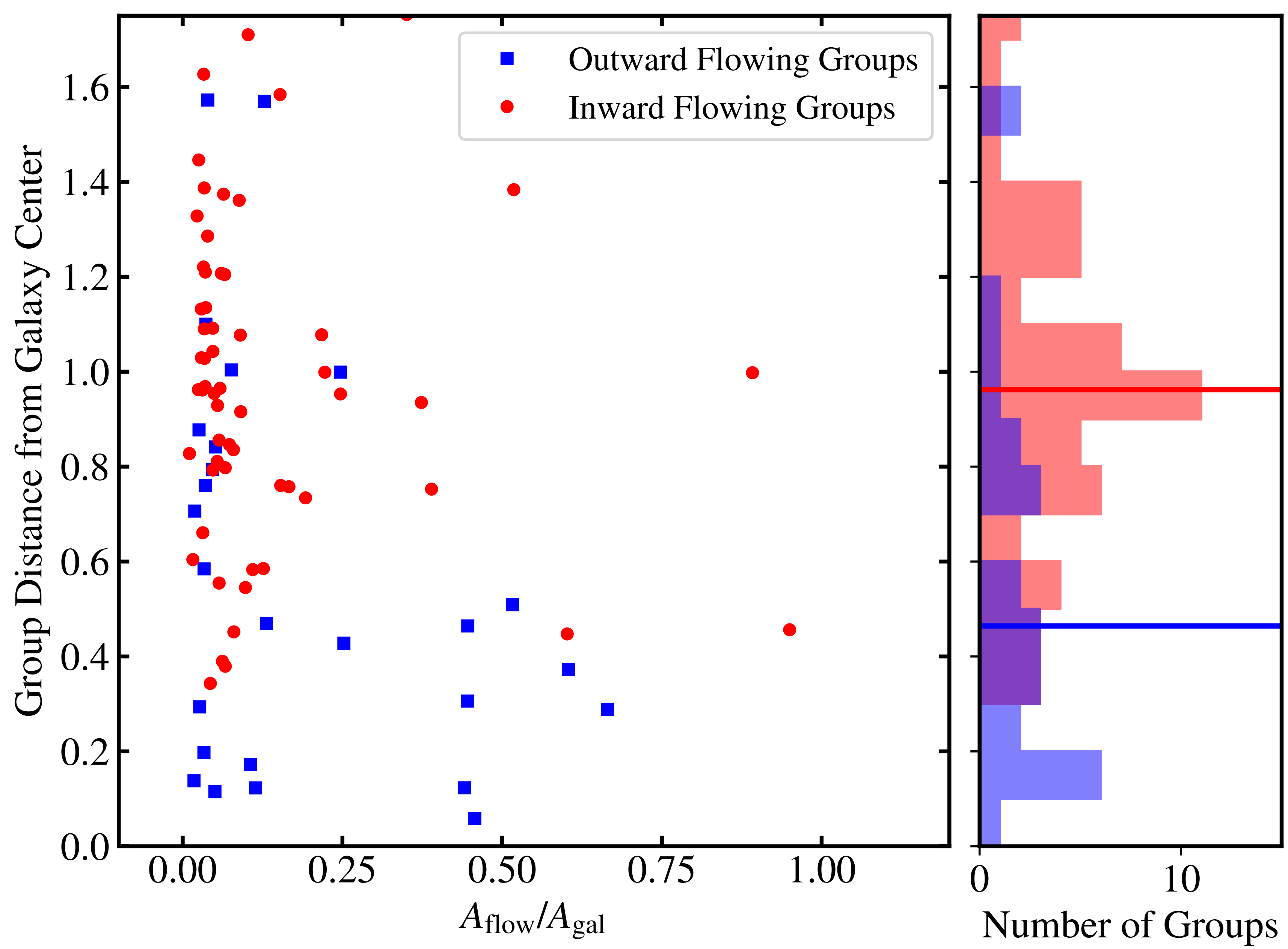
Rubin et al. in prep

Fractional area covered by NaI flows extending over > 4.5 sq. arcsec (9 spaxels)



High-SFR galaxies have higher incidence of both outflow and inflow.

Blueshifted groups have smaller galactocentric distances than redshifted groups.

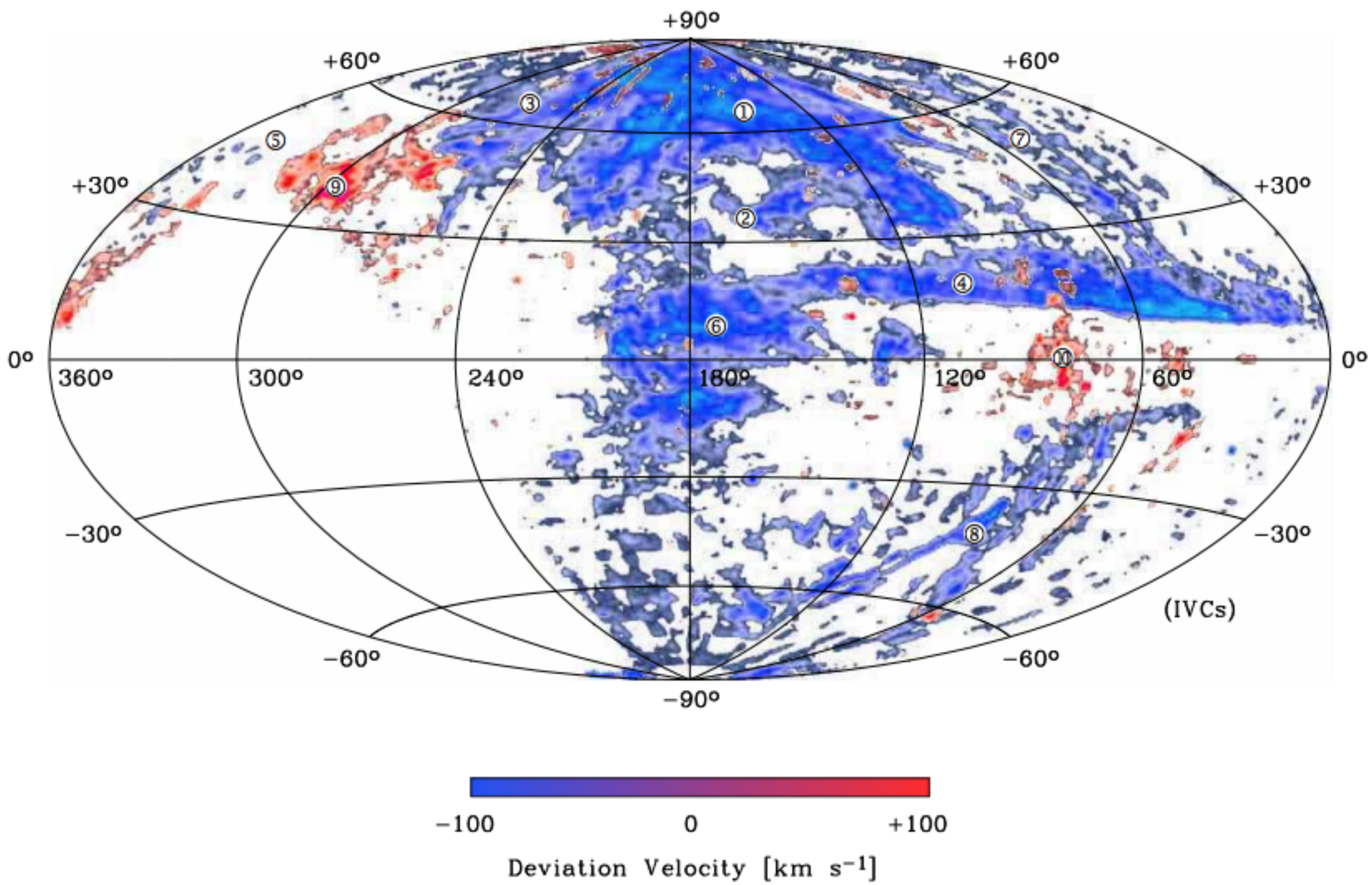


Inward flowing patches tend to be located near ~1R$_e$, whereas outward flowing patches have median distances ~ 0.5R$_e$.

Rubin et al. in prep

Interesting facts about HI:

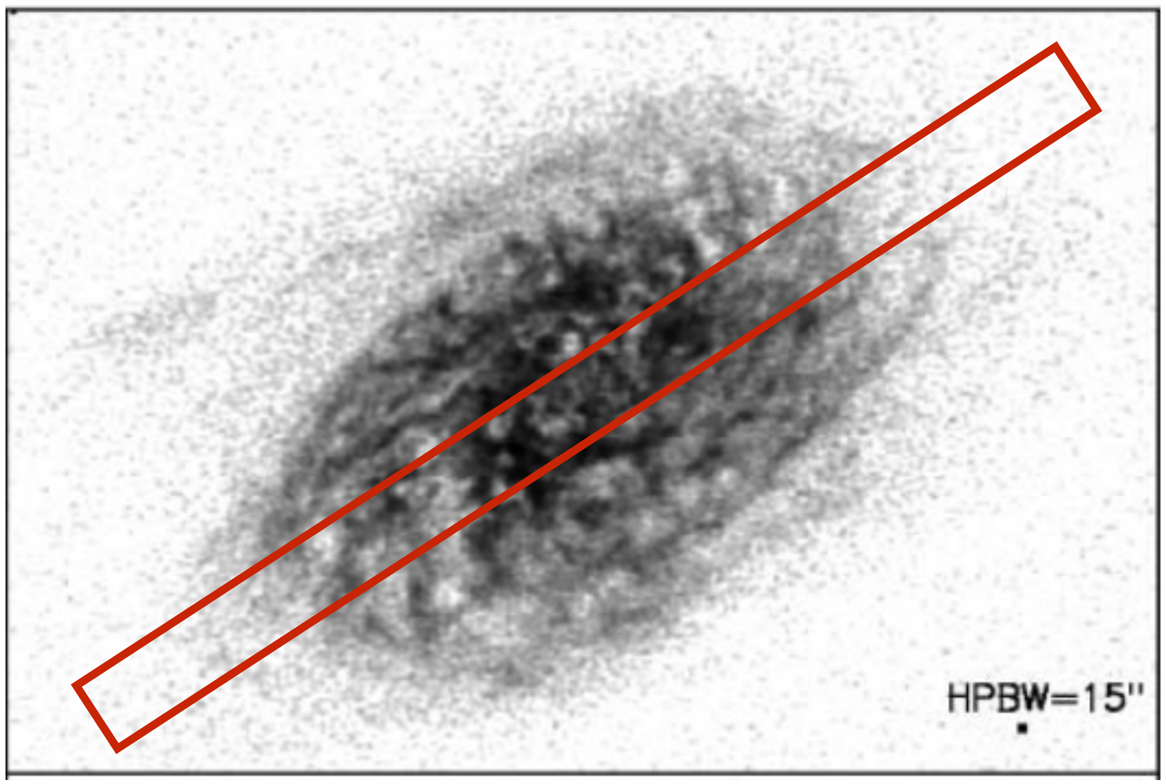
1. Milky Way intermediate velocity clouds (IVCs) are dusty, metal-rich, and have heights < 2.5 kpc above the disk (Richter+2001ab, Wakker 2001, 2004, Richter 2017).



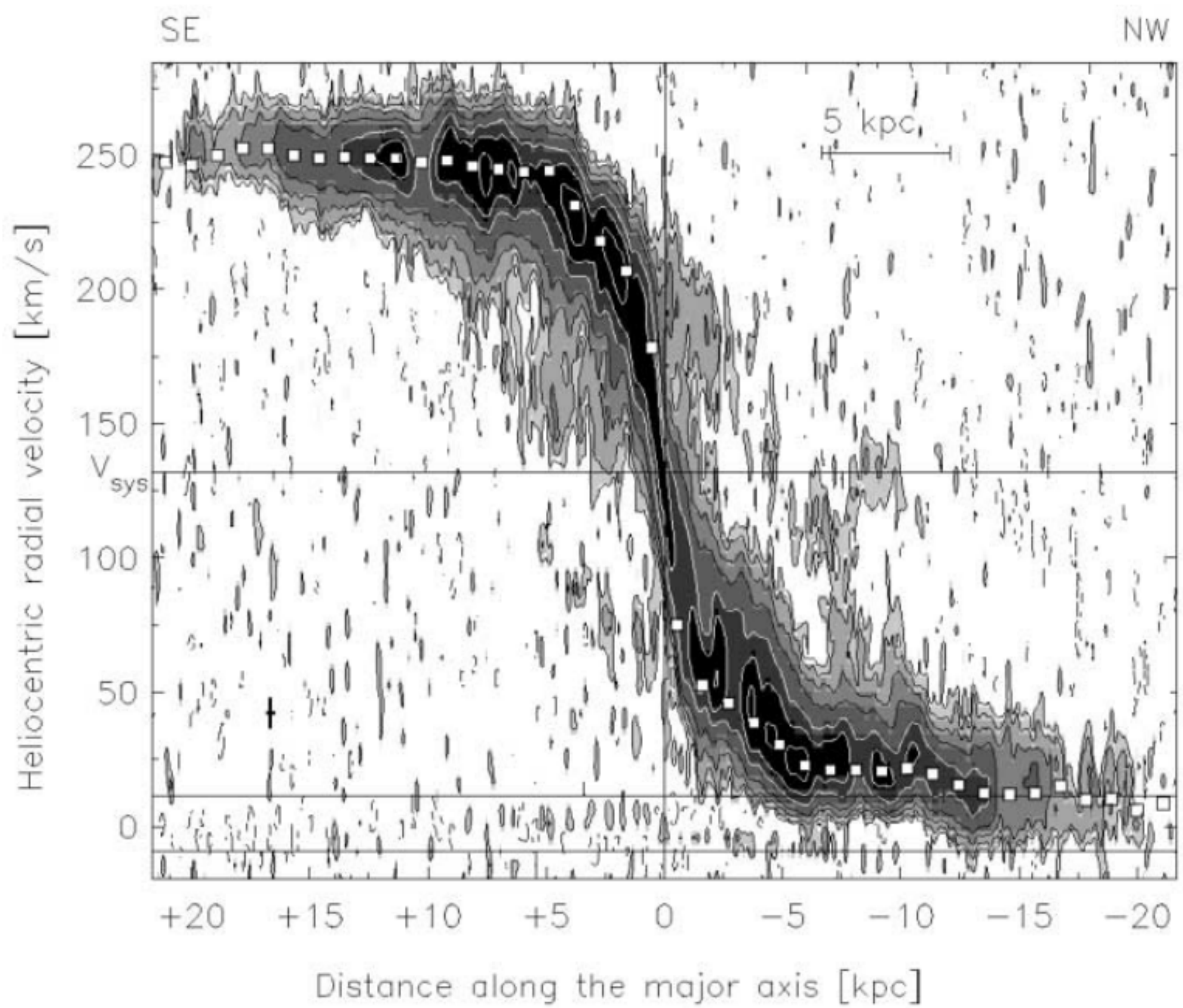
Richter 2017

Interesting facts about HI:

2. Extraplanar HI is extremely common, and its rotation lags that of the disk (Fraternali+01, Oosterloo+07, Vargas+17…)



Fraternali+01



These shifts are not consistent with simple warped extraplanar gas layers.

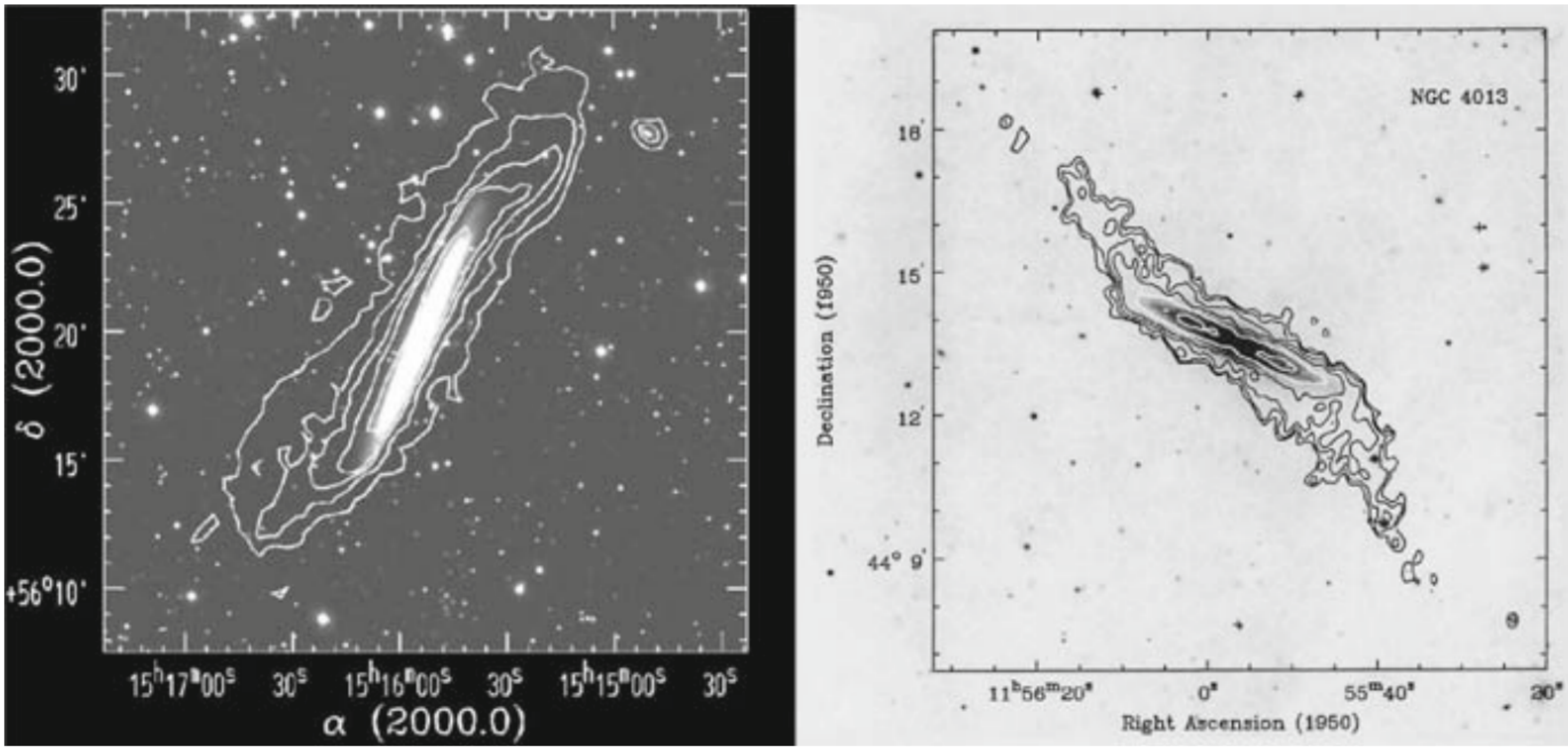
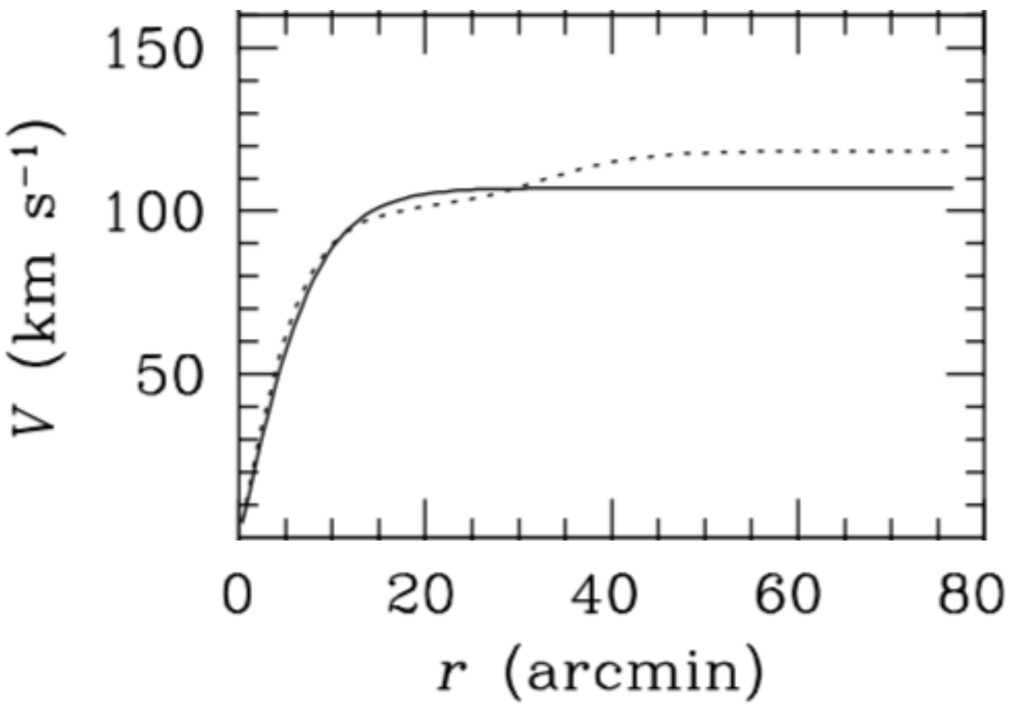


Fig. 12 Total HI maps (*contours*) of two warped edge-on galaxies overlaid on optical images. *Left* NGC 5907 from Shang et al. (1998). *Right* NGC 4013 from Bottema (1996)

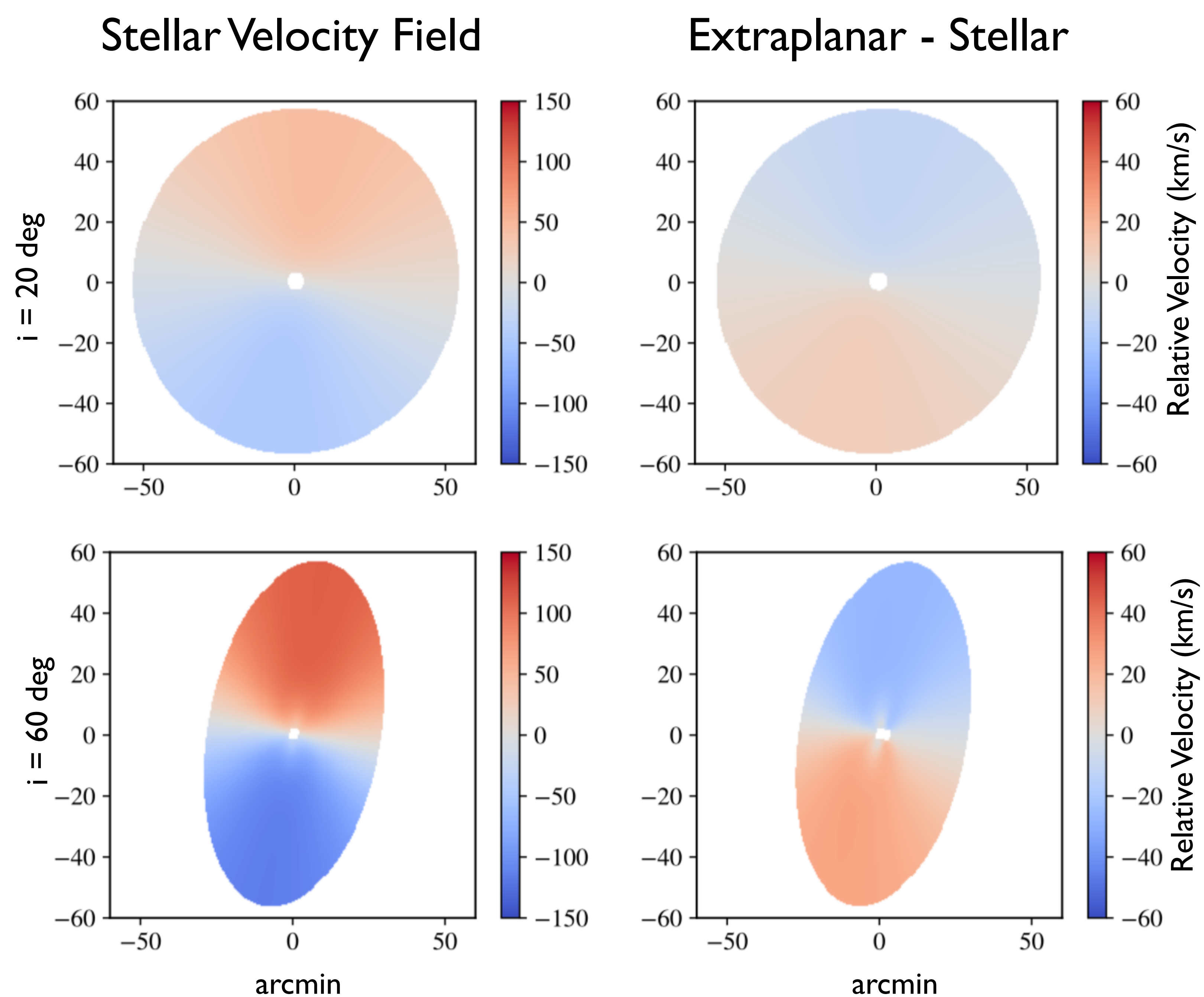
Sancisi et al. 2008: >50% of HI disks are warped

The observed NaI shifts are not consistent with simple lagging extraplanar gas layers.

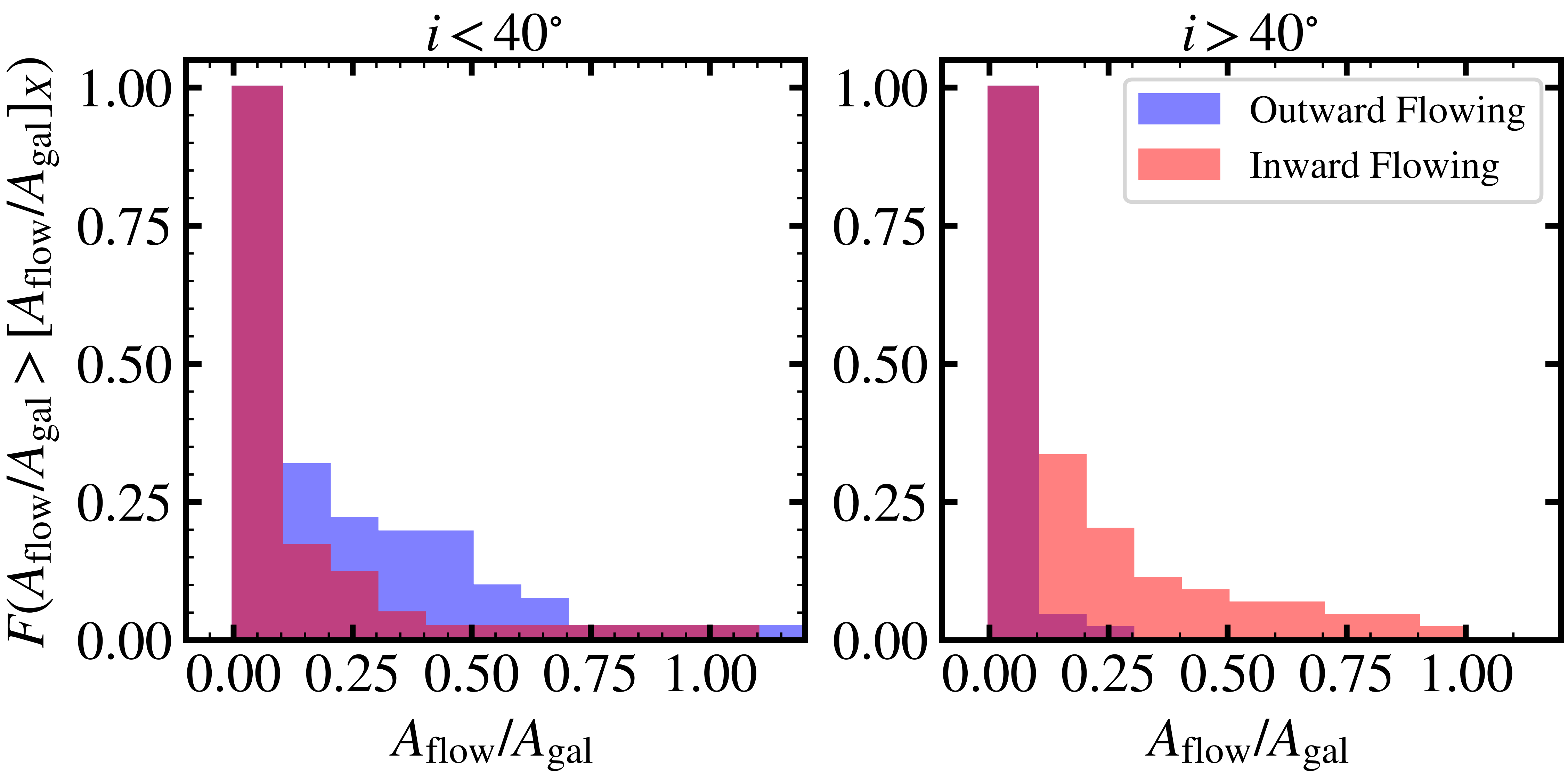


Using the M33 velocity field as inspiration (Corbelli & Schneider 1997, Zheng et al. 2017)…

plus an extraplanar layer with lag of -15 km/s/kpc (at height = 2 kpc)



Fractional area covered by NaI flows extending over > 4.5 sq. arcsec (9 spaxels)



- ~20% of face-on galaxies are 40% covered by outflow
- ~15% of face-on galaxies are 25% covered by inflow
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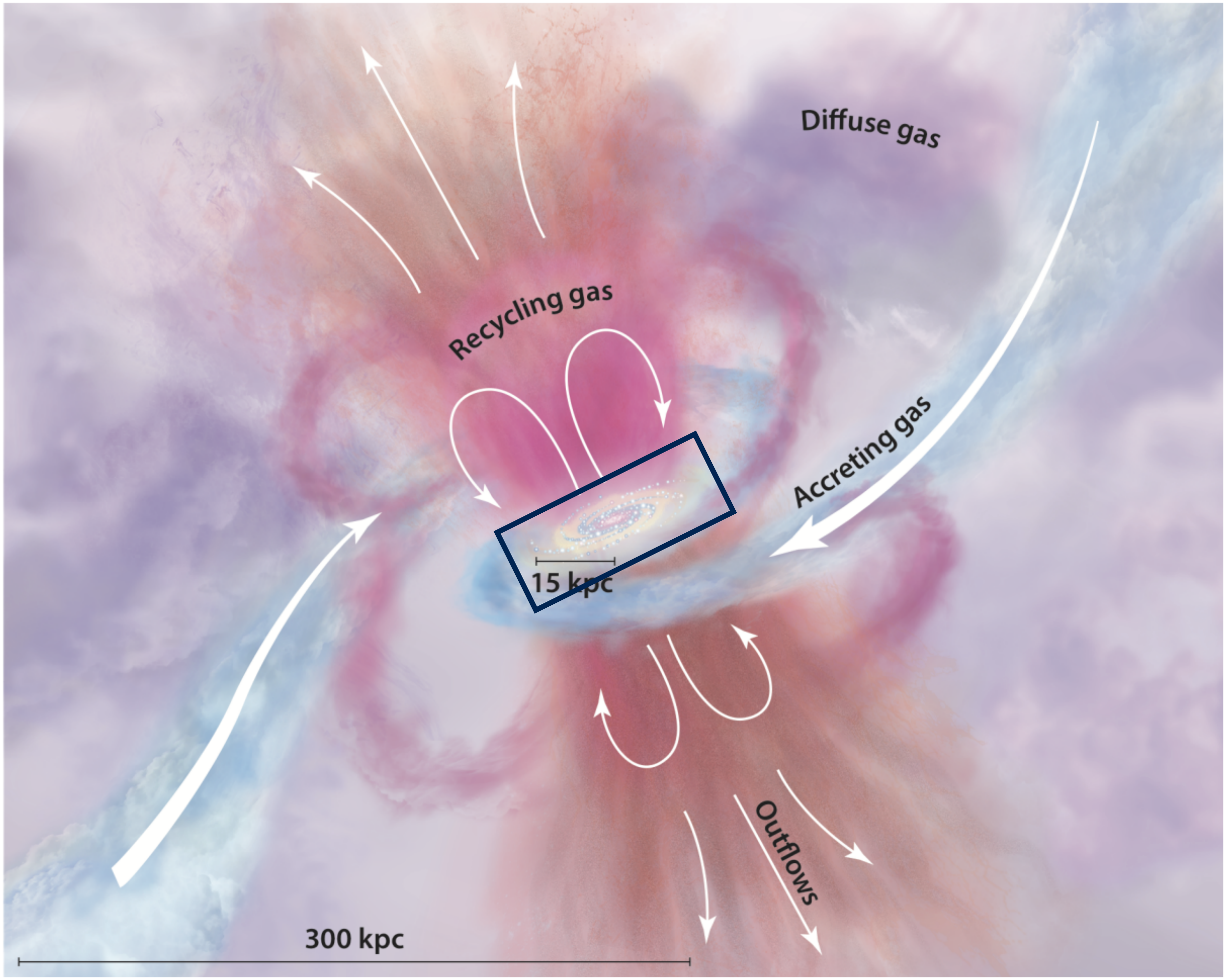
Rubin et al. in prep

Back to the CGM…



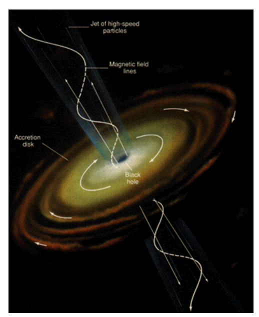
Tumlinson, Peeples & Werk 2017

and its small-scale structure…

Bright background sources: a couple of options

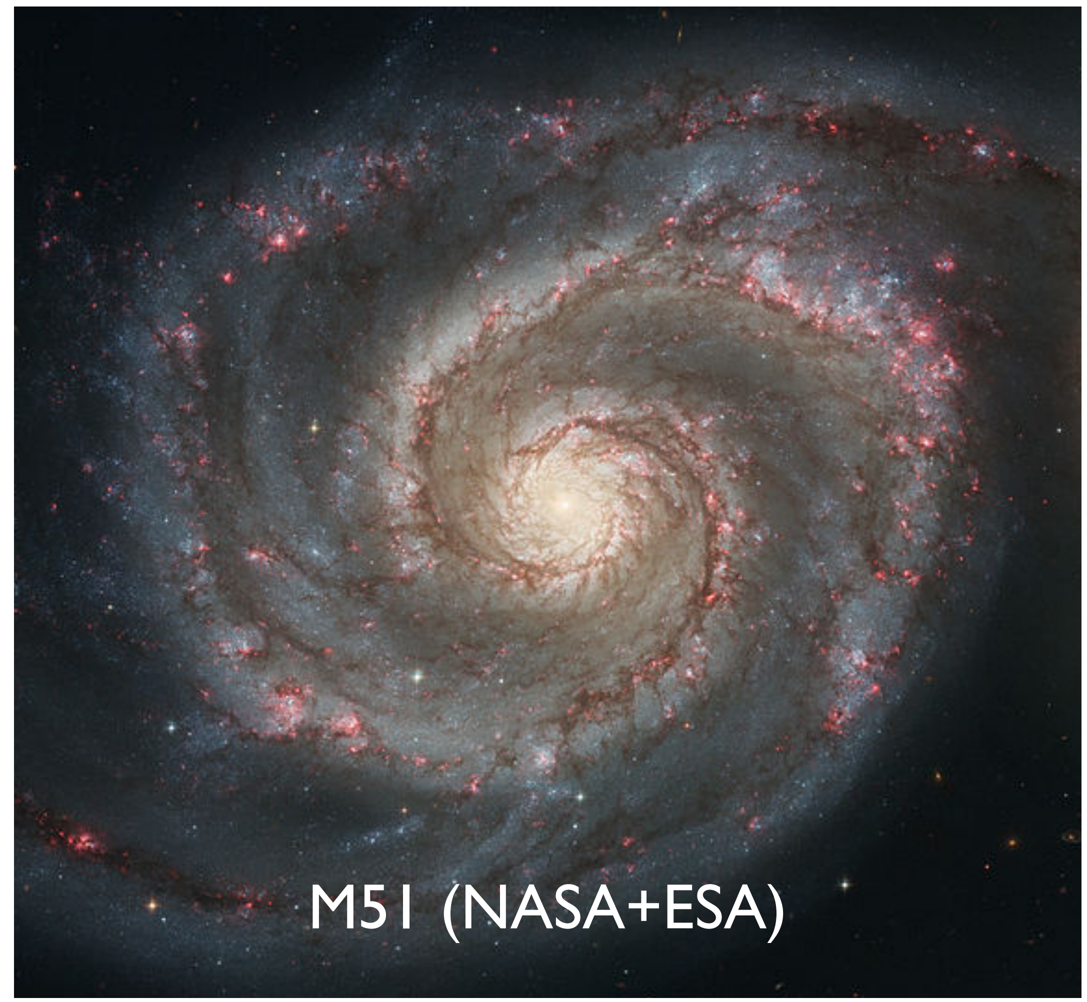
Galaxies

QSOs



R_{QSO}~10^{-3} pc

Shakura & Sunyaev 1973



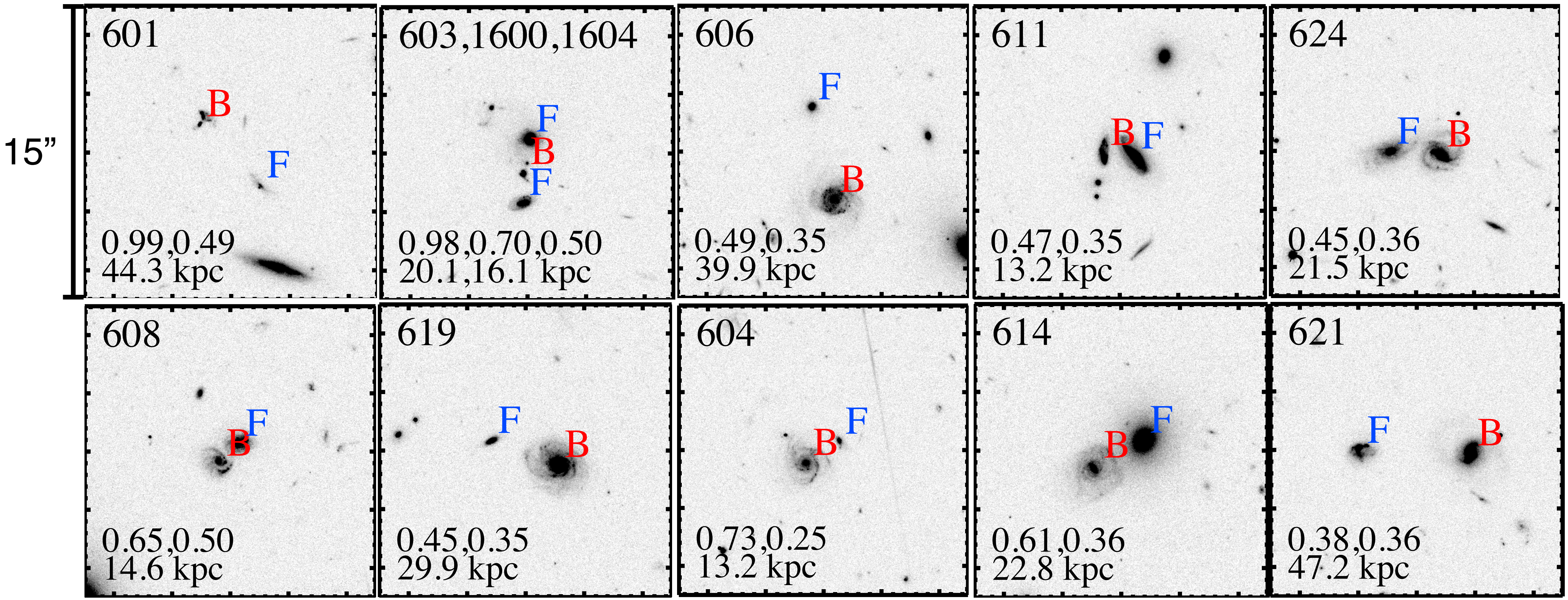
R_{gal}~1 kpc
at z~1

e.g., Steidel+10, Lee+14, Bordoloi+11,
Diamond-Stanic+15, Cooke & O'Meara 2015

A new sample of projected galaxy pairs

All projected pairs in PRIMUS within 50 kpc with

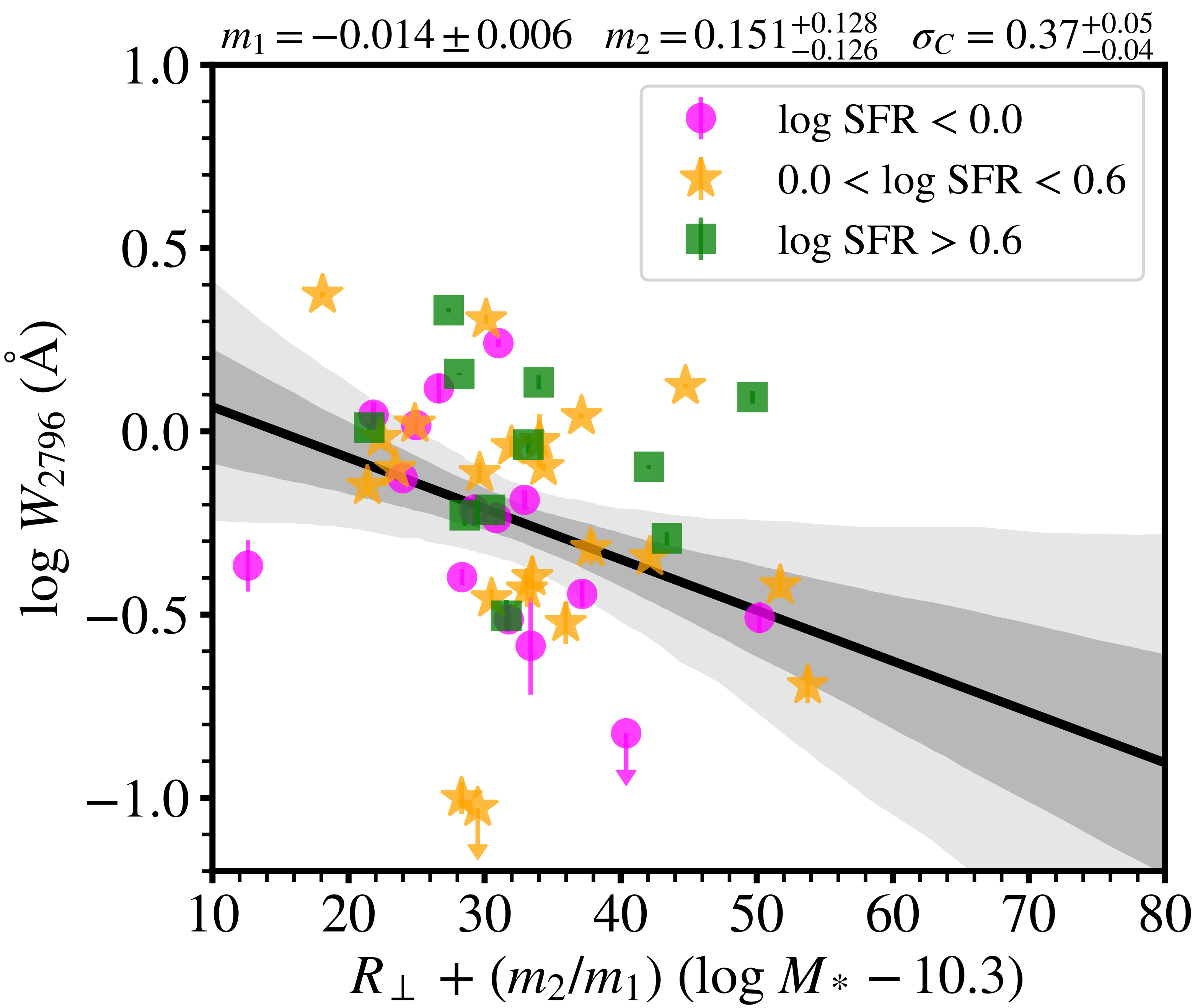
1. background objects having g<22.3
2. foreground objects having r<23, 0.35<z<1.2



Rubin, Diamond-Stanic, Coil, Crighton, Moustakas et al. 2018a

Modeling the z~0.5 circumgalactic medium

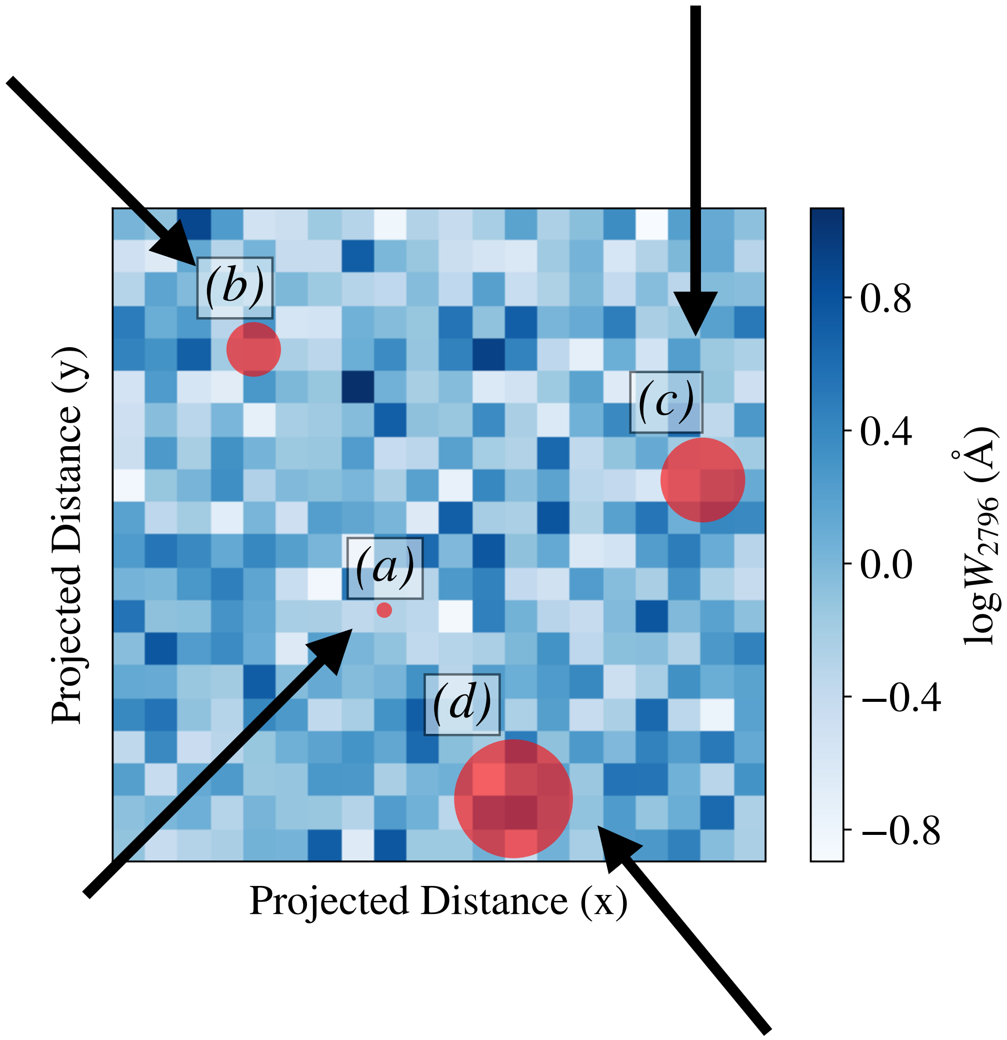
$\log W_{2796} = m_1 R_\perp + m_2 (\log M_* - 10.3) + b$ $\qquad$ $\mathrm{var} = \sigma^2_{\mathrm{measured}} + \sigma^2_{\mathrm{cosmic}}$



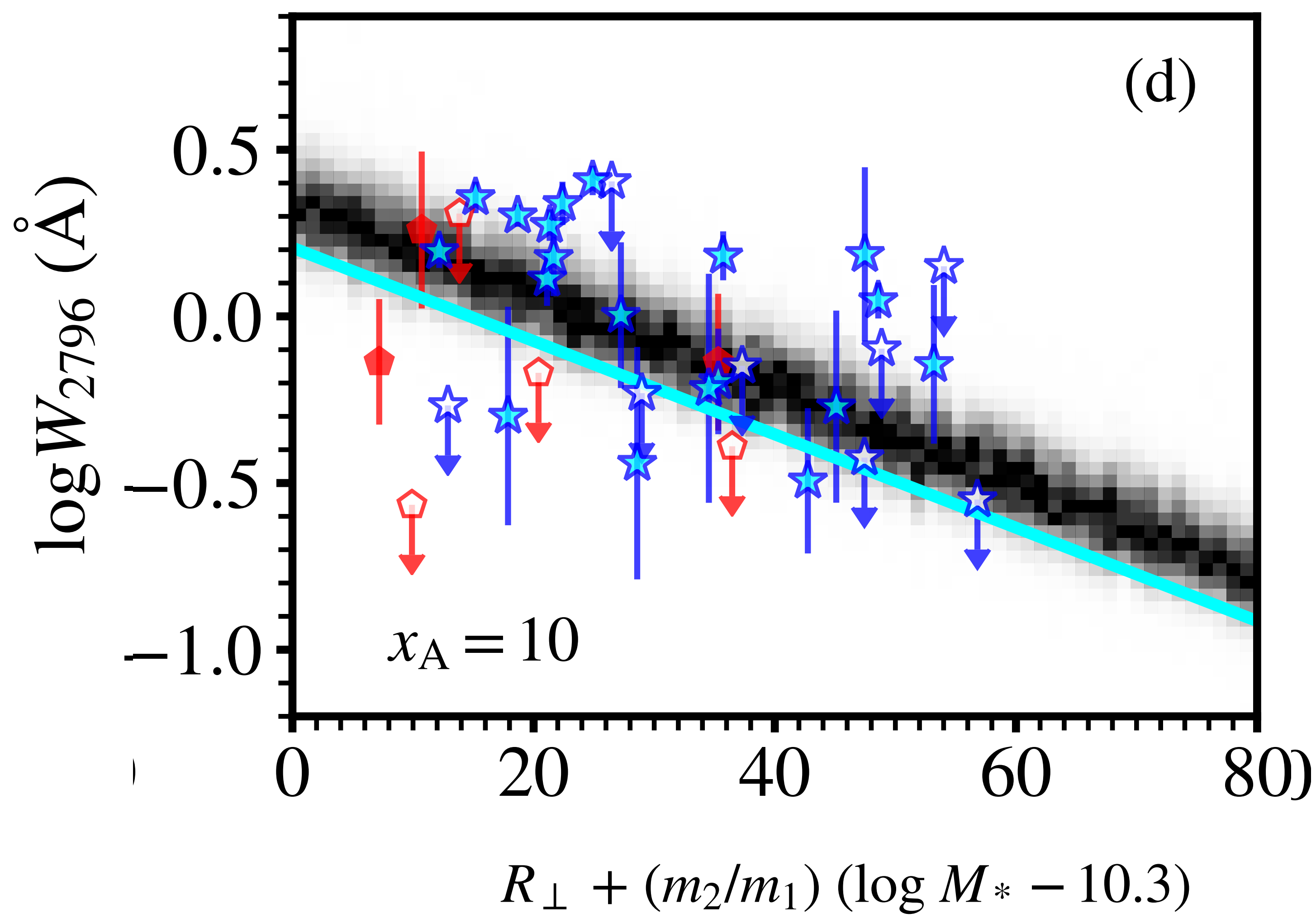
All colored points from Chen et al. (2010) and Werk et al. (2013)

Rubin et al. 2018b

Visualizing the MgII-absorbing circumgalactic medium

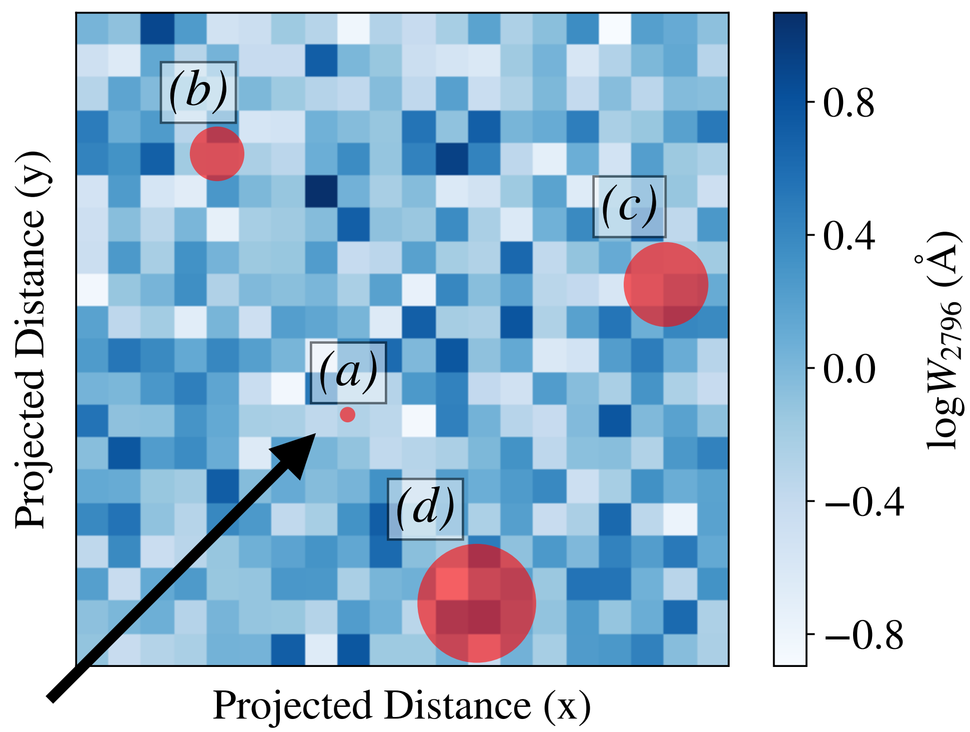


Colored points: MgII toward b/g galaxies

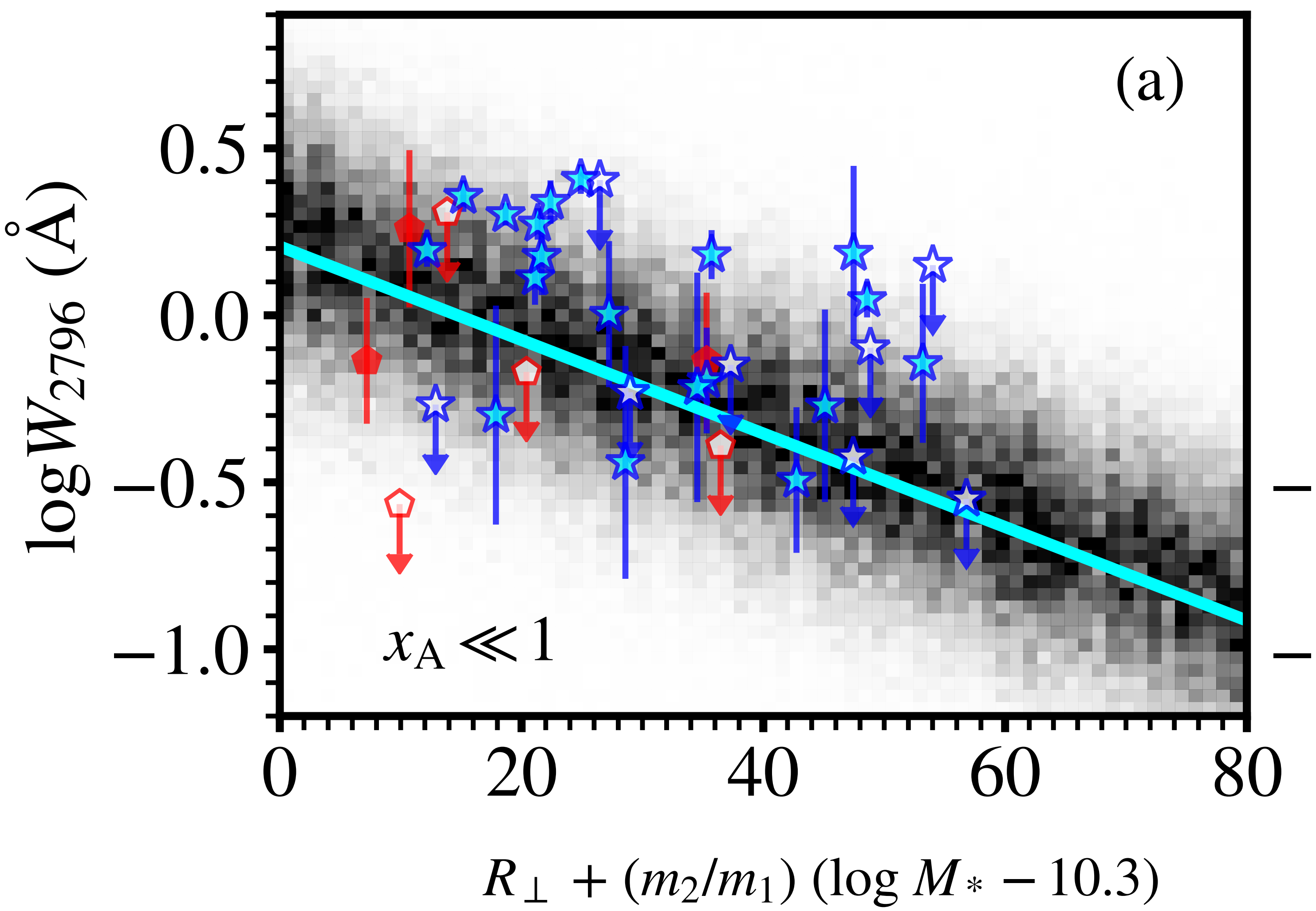


Rubin et al. 2018b

Visualizing the MgII-absorbing circumgalactic medium



Colored points: MgII toward b/g galaxies



Absorbers must be > (galaxy beam area / 15) at 95% confidence, so MgII coherence length > 1.9 kpc

Rubin et al. 2018b

Conclusions

SDSS-IV/MaNGA will constrain the morphology of NaI gas flows around "normal" star-forming galaxies for the first time.

Outflow velocities range up to 200 km/s, but are rarely >70 km/s. ~20% of face-on galaxies are at least 40% covered by outward flows.

~30% of edge-on galaxies are at least 10% covered by inward flows at velocities > 35 km/s.

Background galaxy spectroscopy offers unique constraints on the coherence of CGM absorbers. MgII absorption EW does not vary on scales < 1.9 kpc.

Conclusions

SDSS-IV/MaNGA is constraining the morphology of NaI gas flows around "normal" star-forming galaxies.

Outflow velocities range up to 200 km/s, but are rarely >70 km/s. ~20% of face-on galaxies are at least 40% covered by outward flows.

~30% of edge-on galaxies are at least 10% covered by inward flows at velocities > 35 km/s.

Simple toy models including a lagging extraplanar layer are qualitatively inconsistent with the high incidence of inward flows (and lack of outward flows) in edge-on systems…