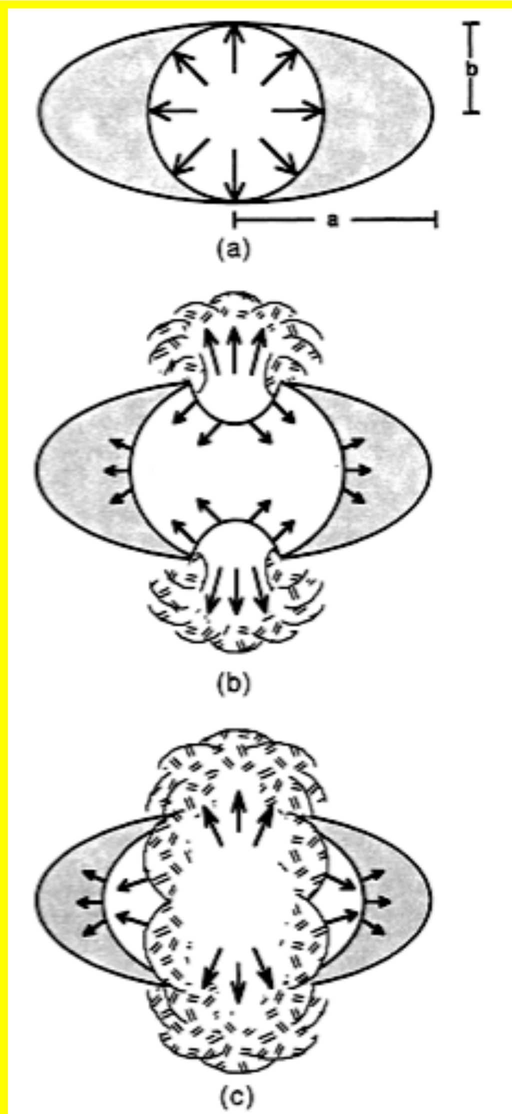
Gas Outflows and Inflows in z < 1.5 Galaxies:

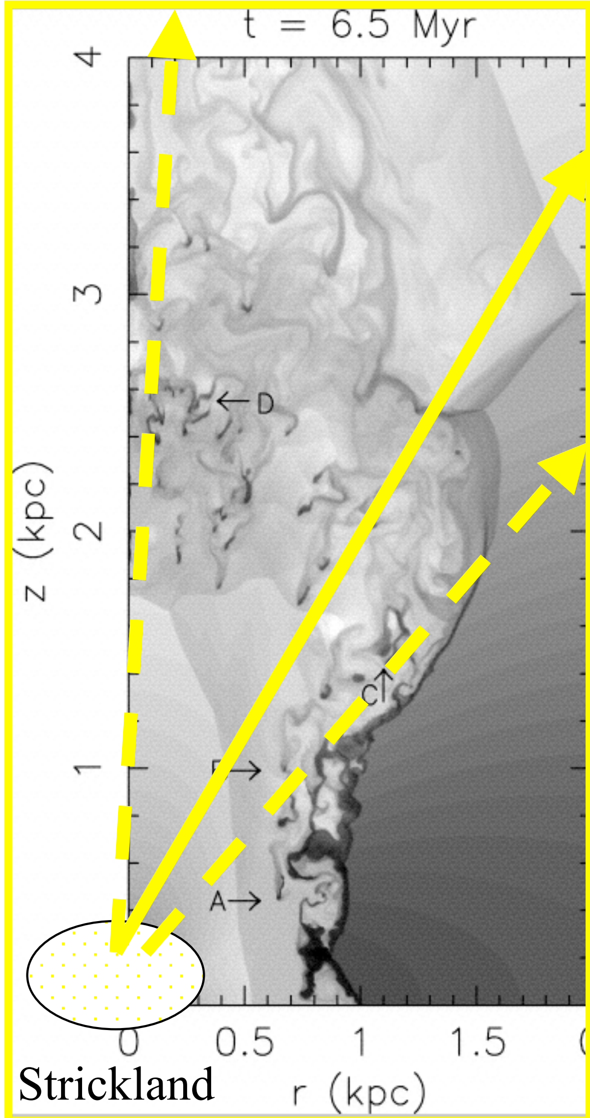
Crystal Martin
(UC Santa Barbara)

Origin of Low-Ionization Gas in Winds?



MacLow et al. 89; Fujita+09

DeYoung & Heckman 2004



Heckman et al. 2000

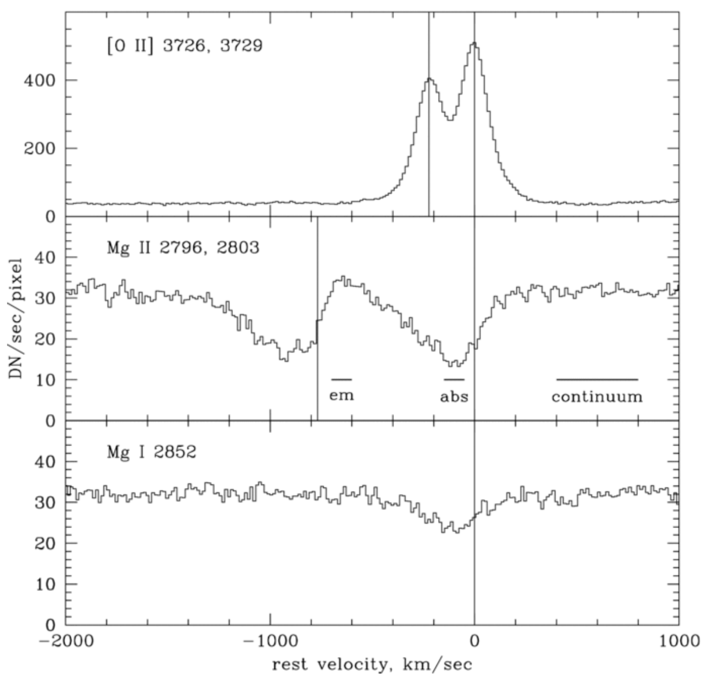
Cooper et al. 2009

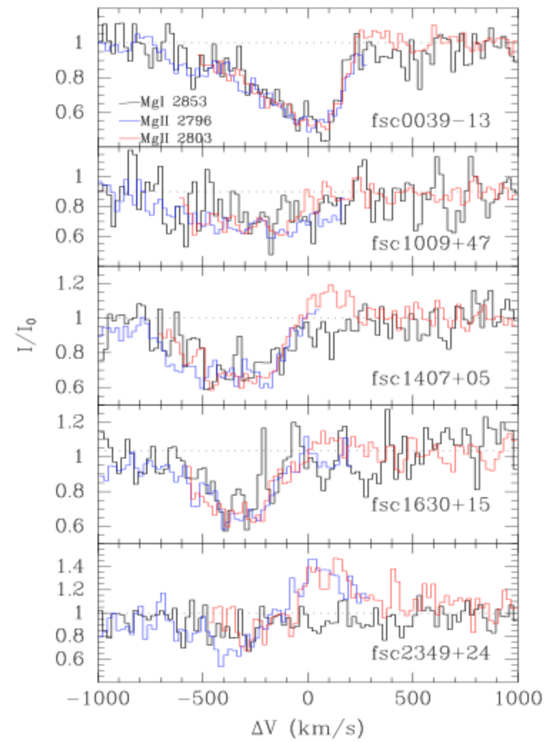
Demographics of Low-Ionization Outflows

- **Na I 5890,96 Absorption**
  - Sato+2009 measured Doppler shifts in 431 galaxies at $0.1 < z < 0.6$
    - Found gas inflows and identified hosts as post-starburst systems
  - Chen+2011 made composite spectra of SDSS/DR7 galaxies
    - Outflows prevalent in massive galaxies with high SFR, A_V, SFRSD, M_*
- **Mg II 2796, 2803 Absorption**
  - Dominate ion of Mg over wide range of physical conditions
  - Accessible in optical over $0.3 < z < 2.5$
  - Intervening systems constrain spatial extent of outflows *(Bouche+2006,2008; Menard 2009; Kacprzak +2008,2010; Chen+2010; Nestor+2010; Bordoloi+2011)*
  - Interpretation of absorption trough complicated by emission filling
- **Near-UV Fe II Absorption (5-7 transitions)**
  - Cosmic abundance of Fe is similar to Mg
  - First and second ionization potentials of Fe are similar those of Mg
  - Some lines fluoresce strongly leaving ‘clean’ absorption troughs
- **Emission**
  - Scattered Mg II Emission
  - Optical emission-line radiation from shocked gas

Mg II 2796, 2803 Absorption in Galaxy Spectra

- Outflows are common
- Highest velocity gas is optically thick
- Mg II emission fills in absorption-line trough near v=0





Weiner+2009 -- Composite of 1496 z~1.4 Star-forming Galaxies

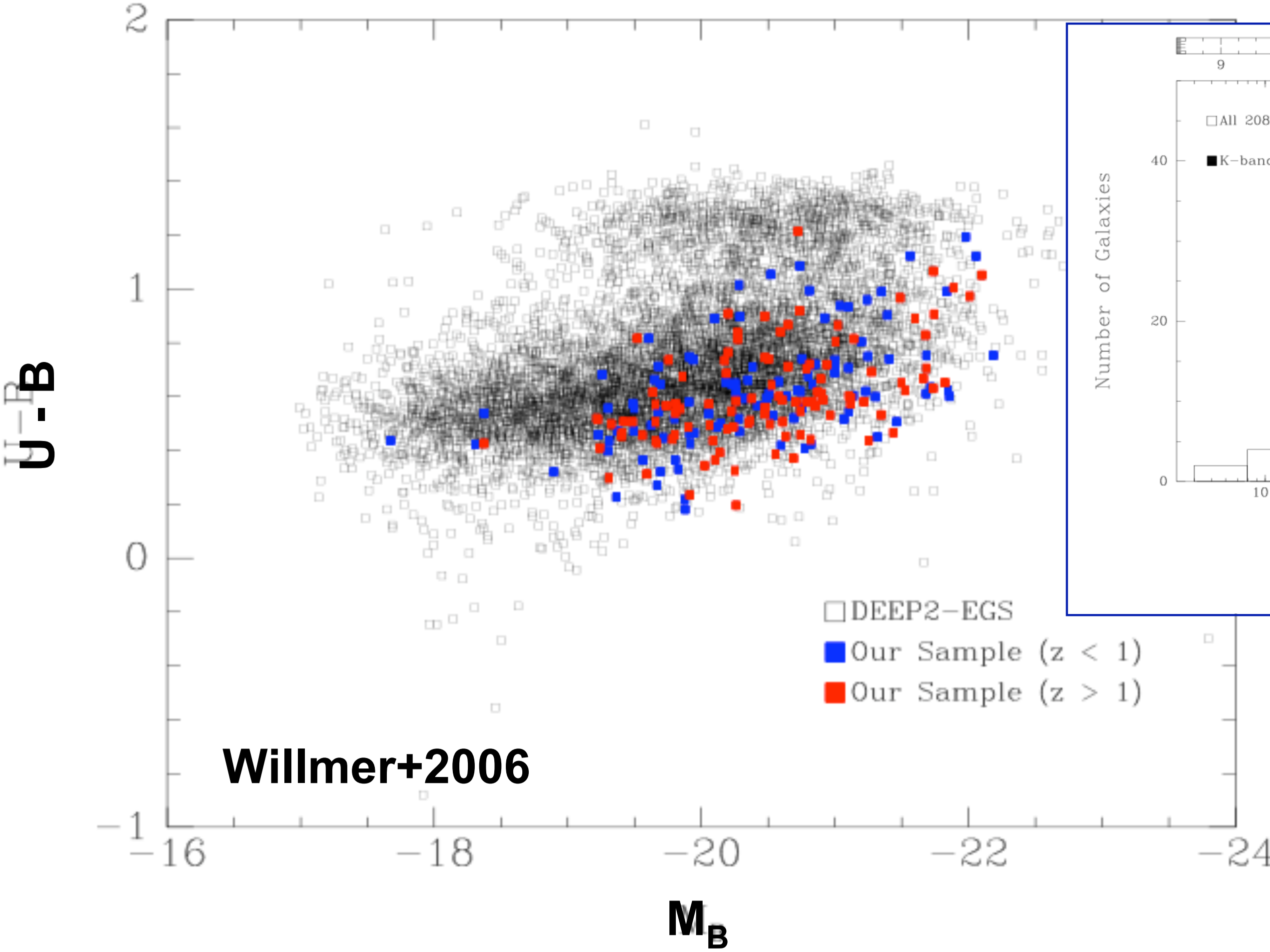
CLM & Bouche 2009 -- Velocity-dependent covering fraction

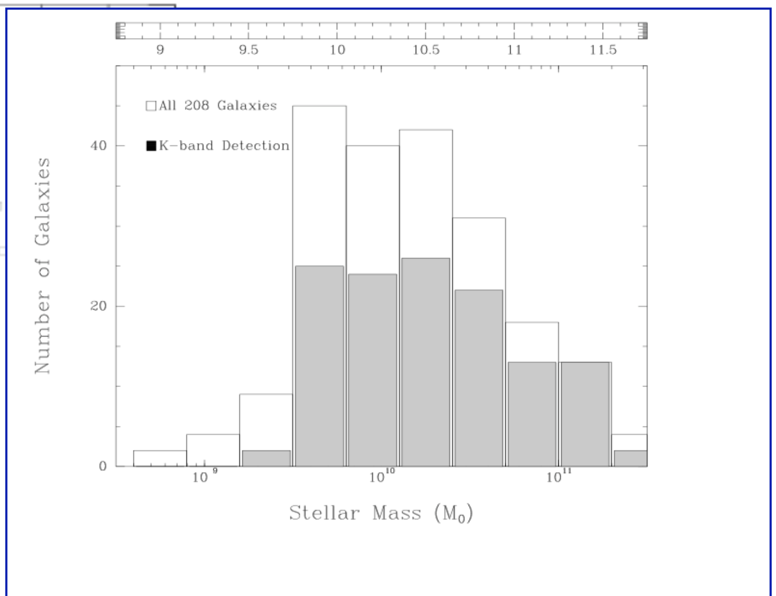
See Also: Tremonti+2007; Rubin+2010a,b; Coil+2011; Prochaska+2011

Outflow/Inflow Survey at 0.6 < z < 1.4

Collaborators: Alice Shapley & Kathy Kornei (UCLA); Alison Coil (UCSD); Anna Pancoast (UCSB)

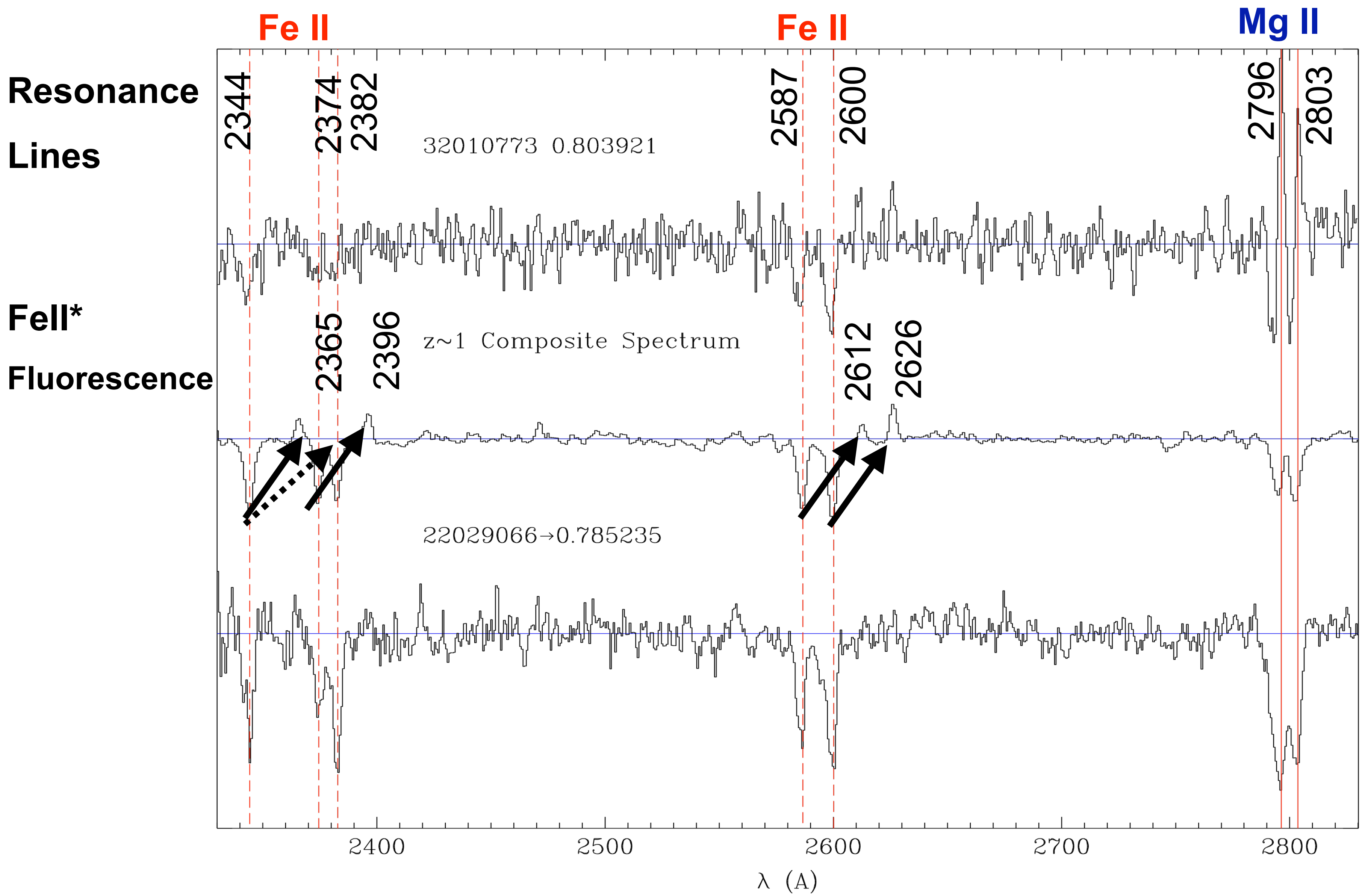
- Keck/LRISb spectra of 208 DEEP2 galaxies cover NUV (+FUV)
- Spectral Resolution ~ 120 to 185 km/s





Stellar Masses from Bundy (2006)

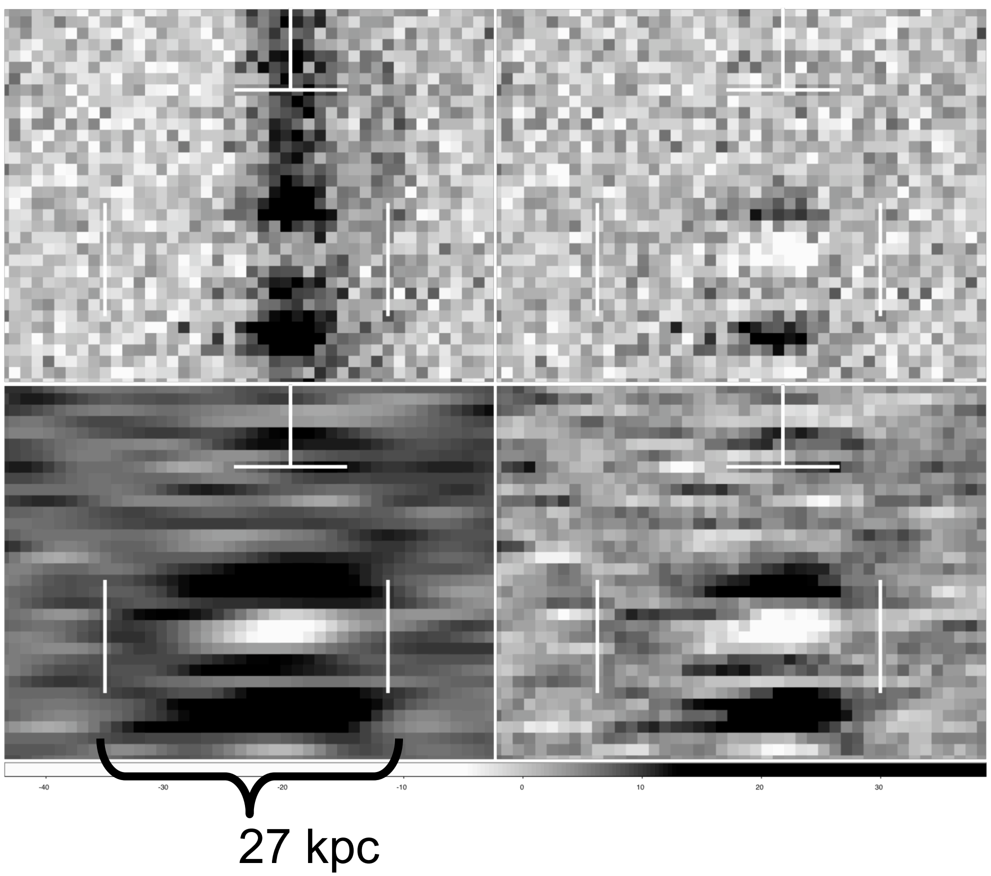
Near-UV Spectra of z~1 Galaxies



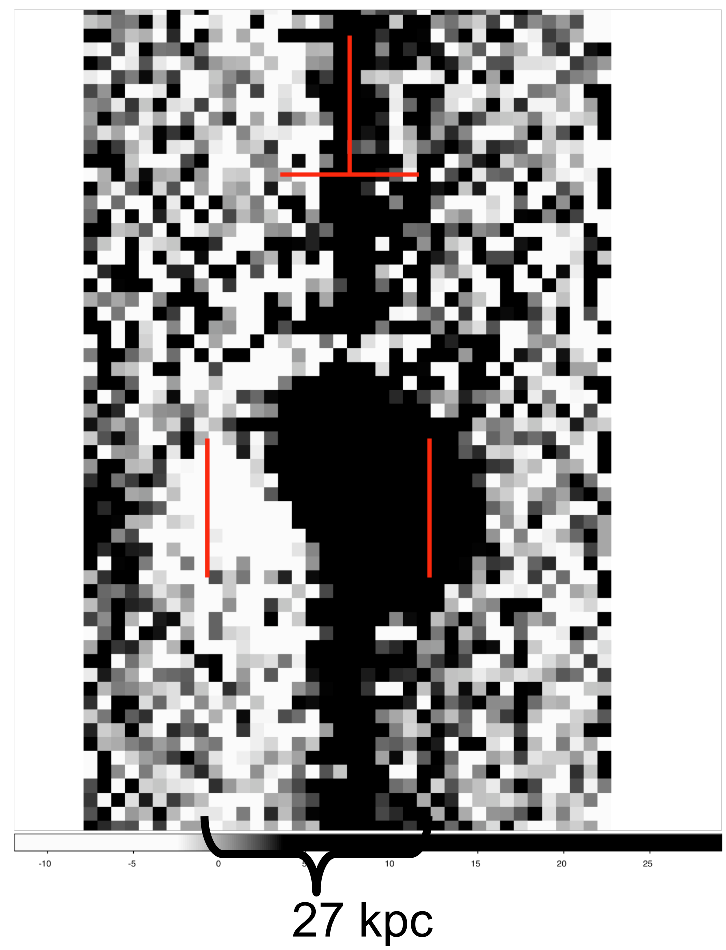
Origin of MgII Emission: Properties Inconsistent with HII Regions

- Spatial extent is at least 3.4” or 27 kpc
- Gas kinematics show the emission is not from the galactic disk.

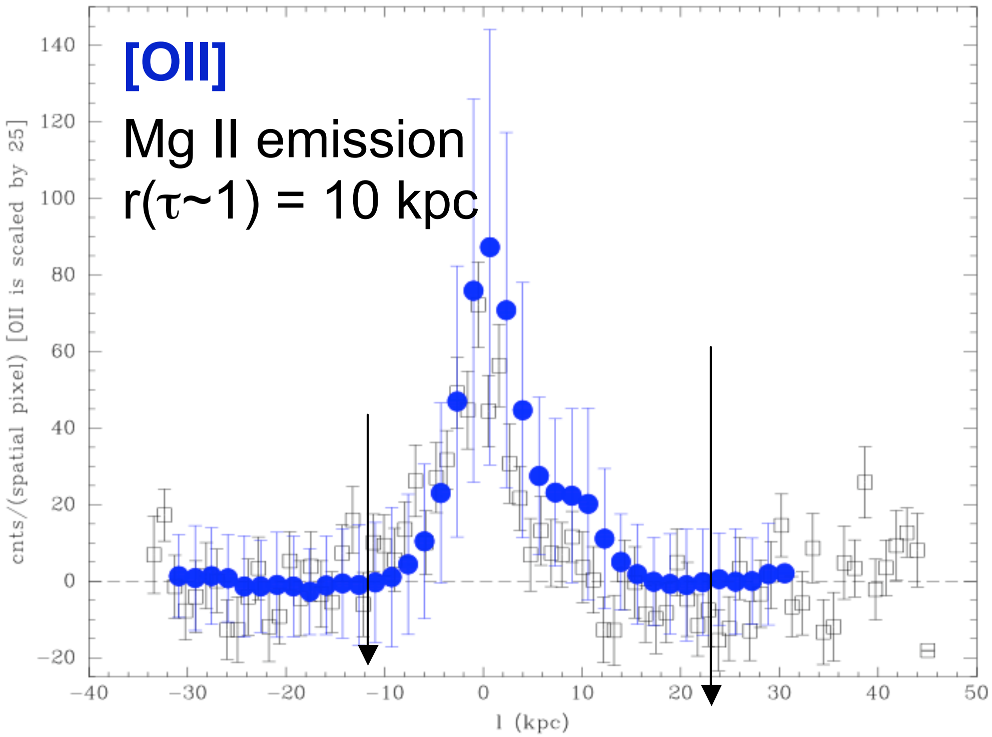
MgII Emission



[OII] Emission

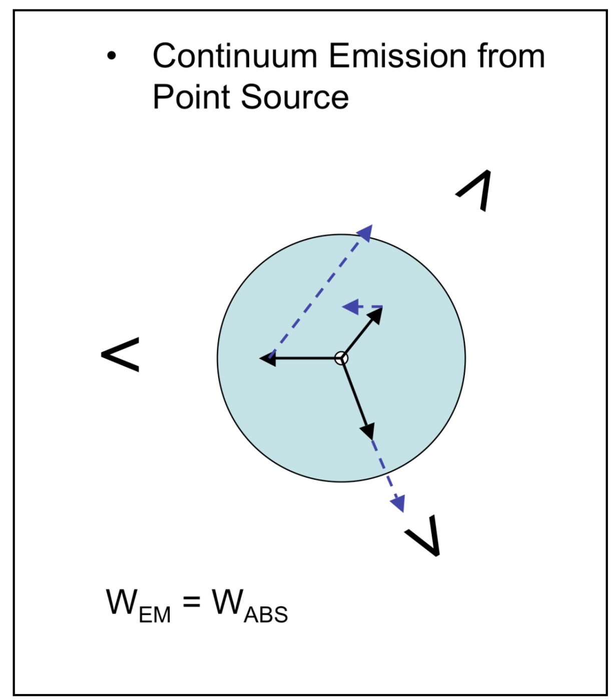


Physical Properties from Scattered Emission



- **Optical Depth of Scattered Line (e.g., Murray+1999)**

$$\tau = \kappa\, \rho\, v_{th}\, |dv/dr|^{-1}$$



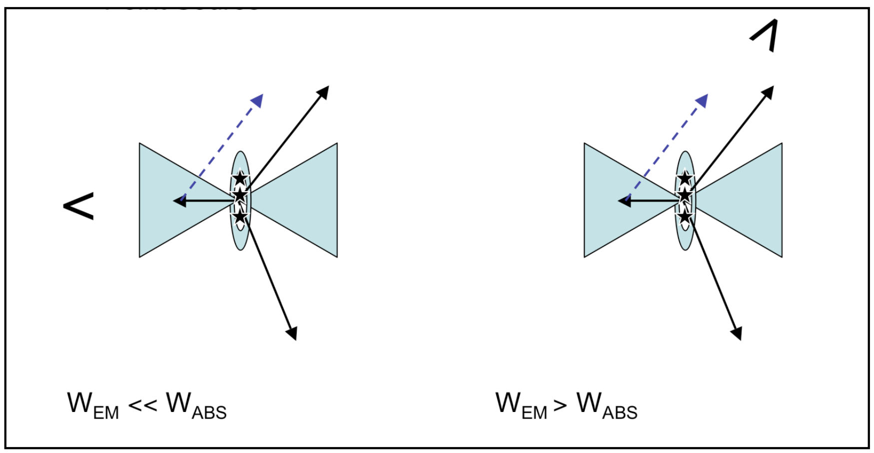
- $n(\text{Mg II}) \sim 5.6 \times 10^{-9}\ \text{cm}^{-3}$ at b = 10 kpc
- $n(\text{H}) \sim 1.5 \times 10^{-4}\, \chi^{-1}\, (Z/Z_0)^{-1}\ \text{cm}^{-3}$ at b=10 kpc
- Small Ionization correction (Murray + 2007)
- Mass loss rate (in low-ionization gas)

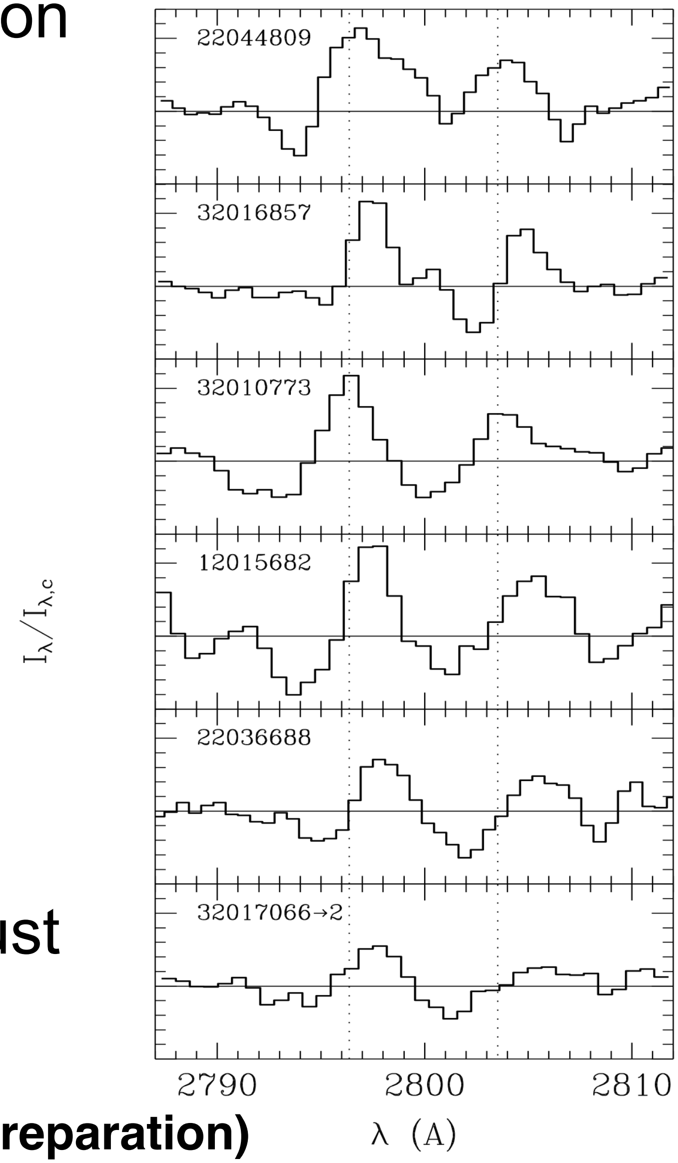
$$dM/dt = \rho(r_s)\, \Omega(r_s)\, r_s^2\, v(r_s)$$
$$\sim 5\ M_o/yr \sim SFR$$

See Also: Rubin+2010; Prochaska+2011

Properties of Mg II Emitters

- Show relatively bluer Fe II absorption
- Favor less reddened galaxies
- Stronger in lower mass galaxies





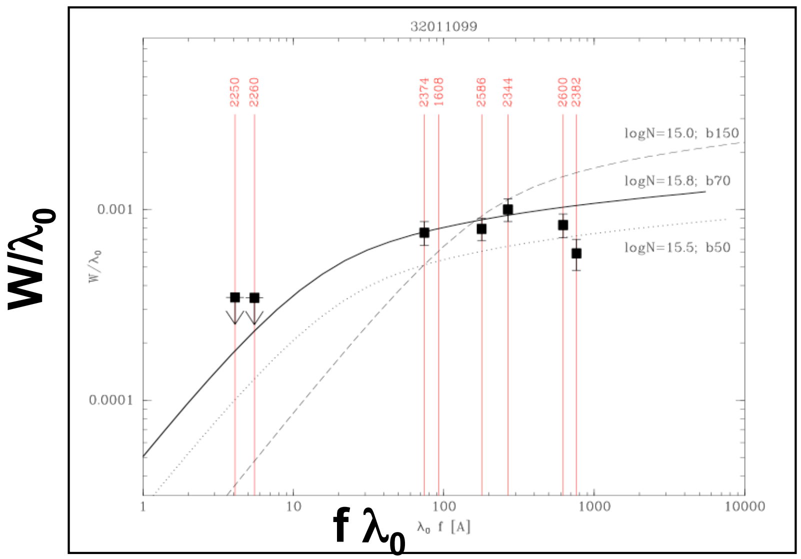
- Associated with outflow
- Scattered photons destroyed by dust
- Scattered halo fits within slit

Quider+2011; Martin+2011; Kornei+2011 (all in preparation)

Emission Filling

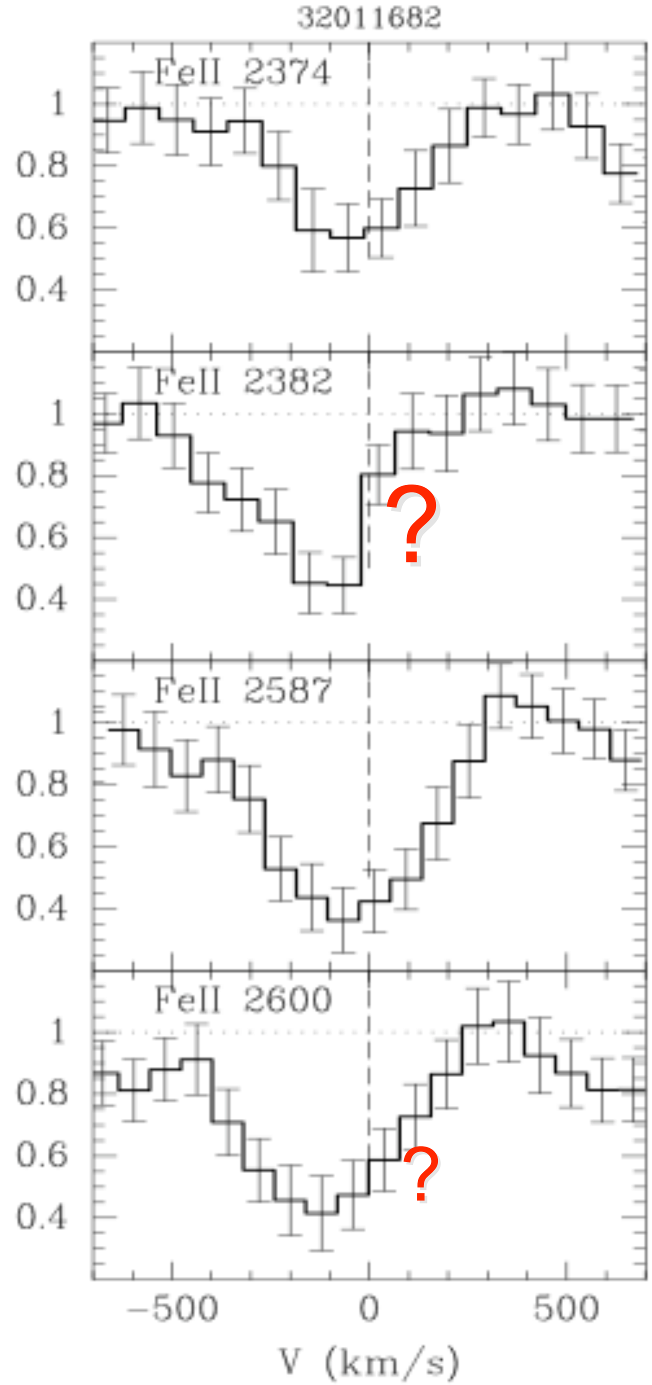
1. Curve-of-Growth
   - MgII W(2308) > W(2796)
   - FeII W(2374) > W(2382)

Log N_{FeII}(cm-2) = 15.8, b = 70 km/s

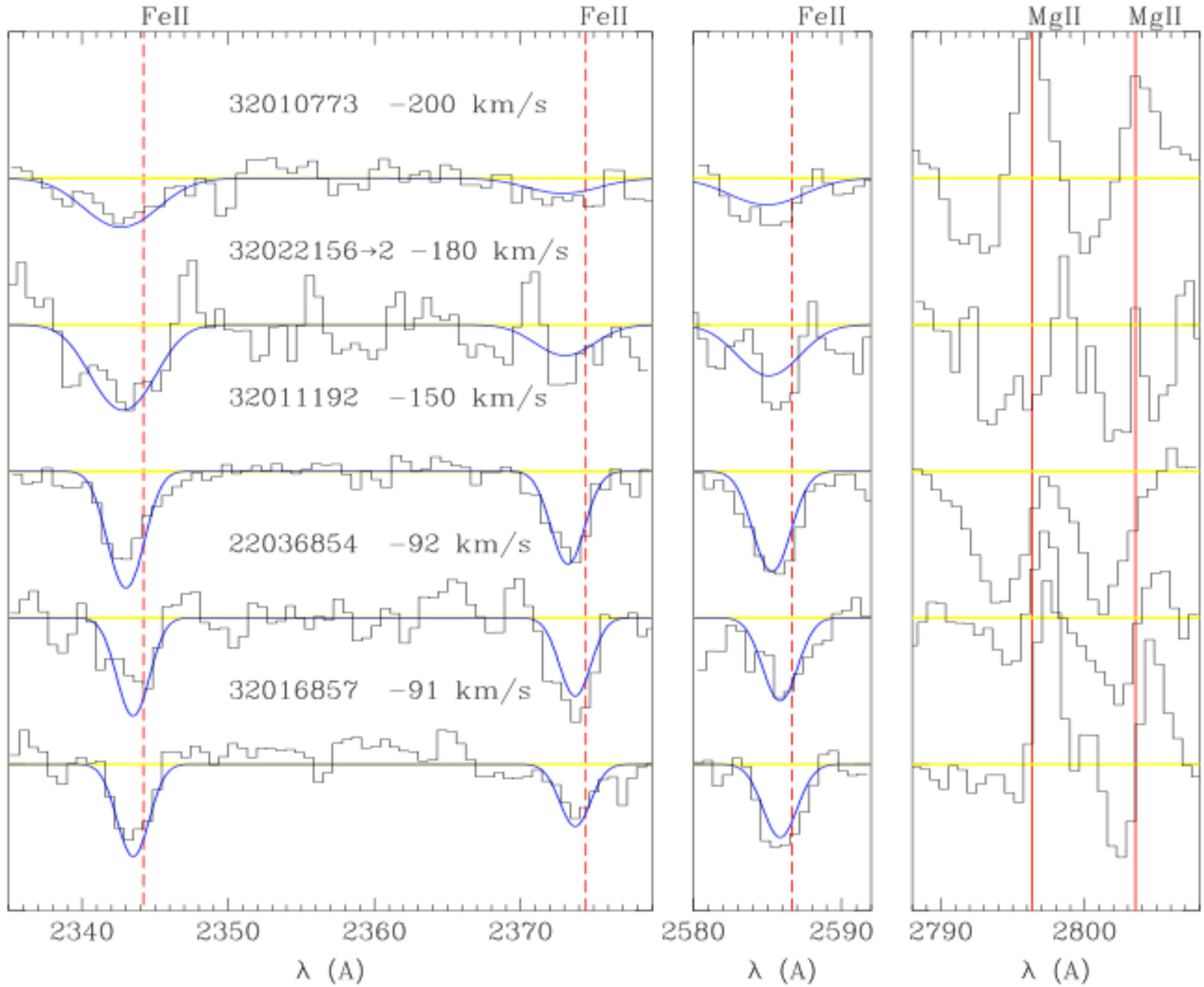


2. Pushes absorption bluer
3. Solution: Measure Doppler shifts from the most fluorescent lines, I.e., FeII 2374, 2587, 2344

CLM, Shapley, Kornei, Coil, Pancoast



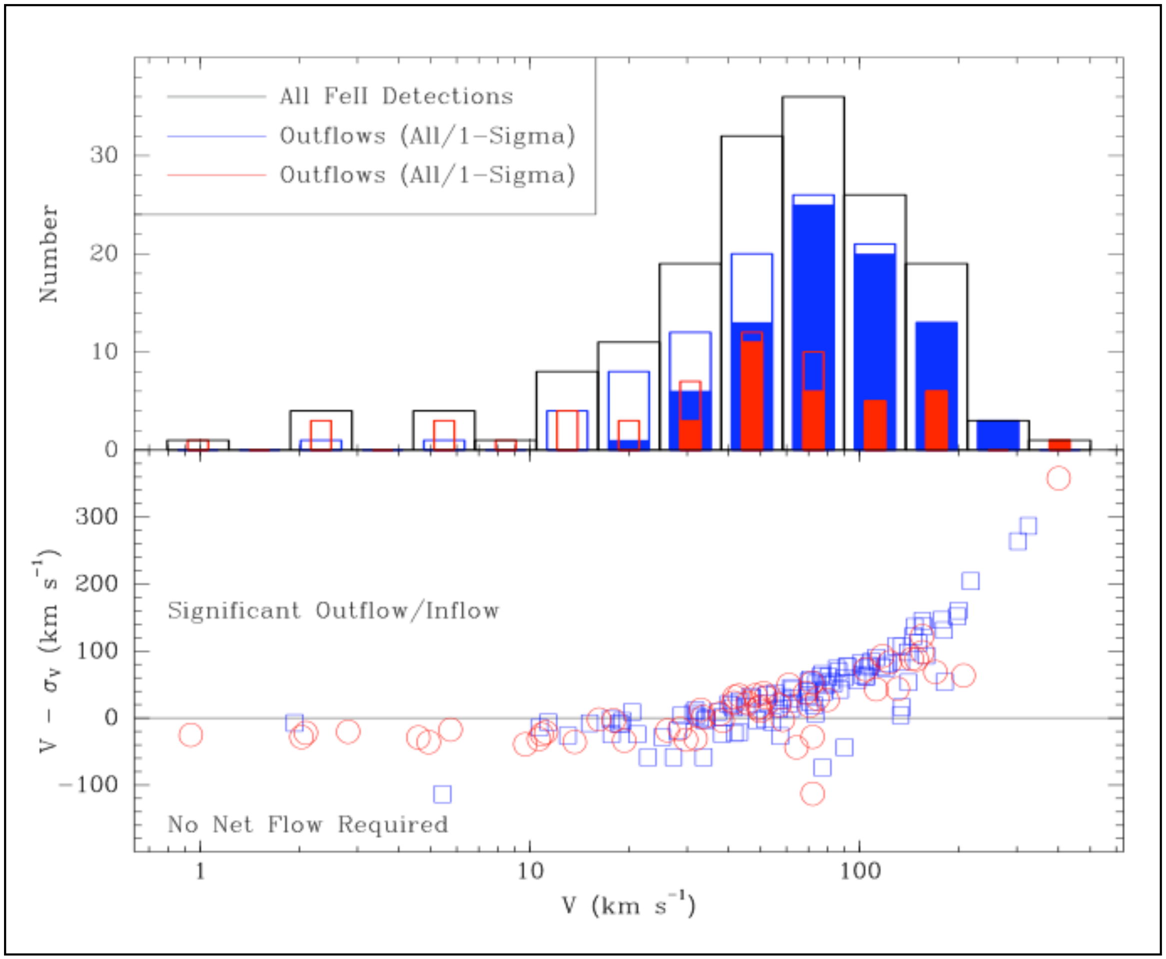
Joint Fits to Five Clean FeII Lines



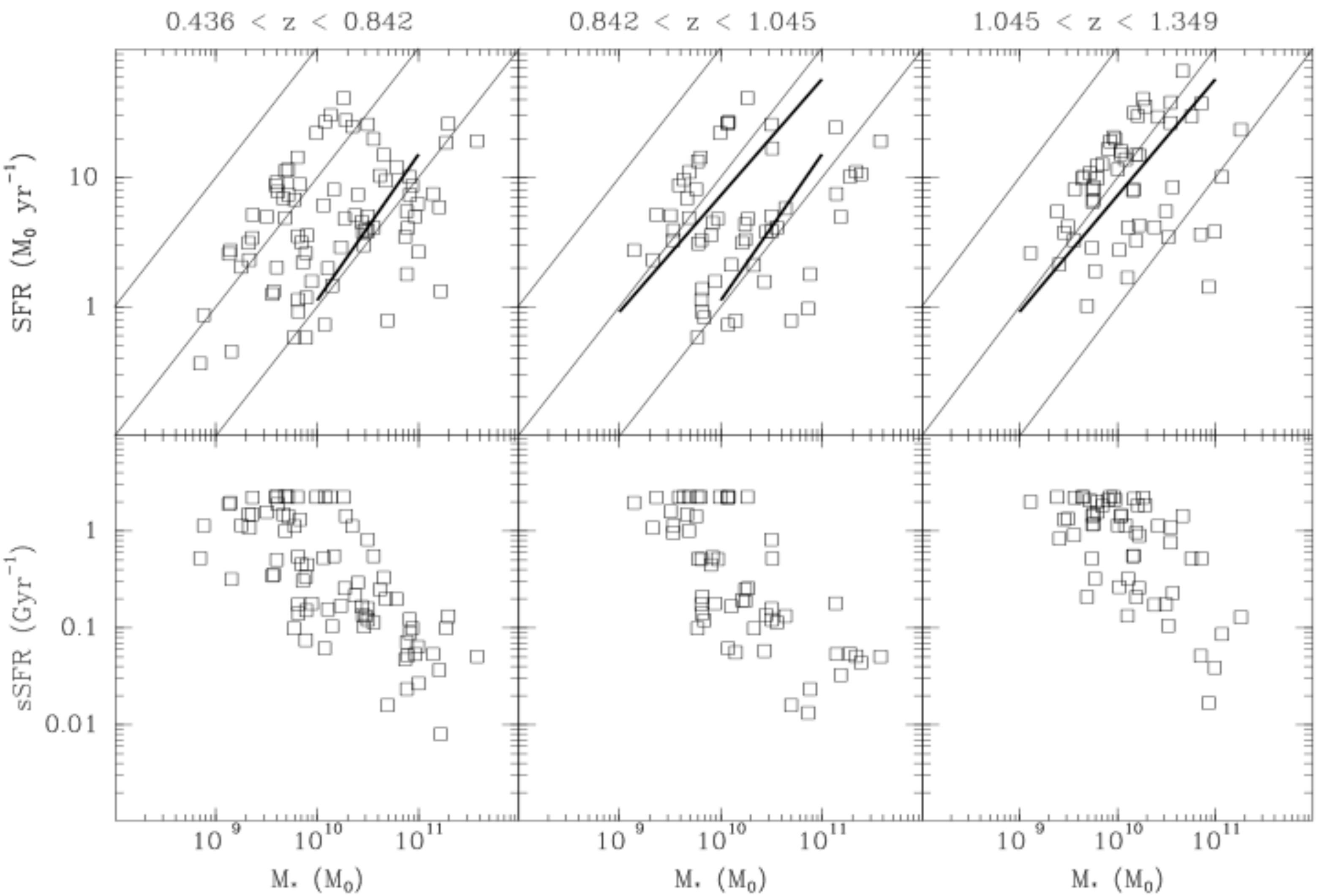
Outflow Examples

Which Galaxies Present Net Flows?

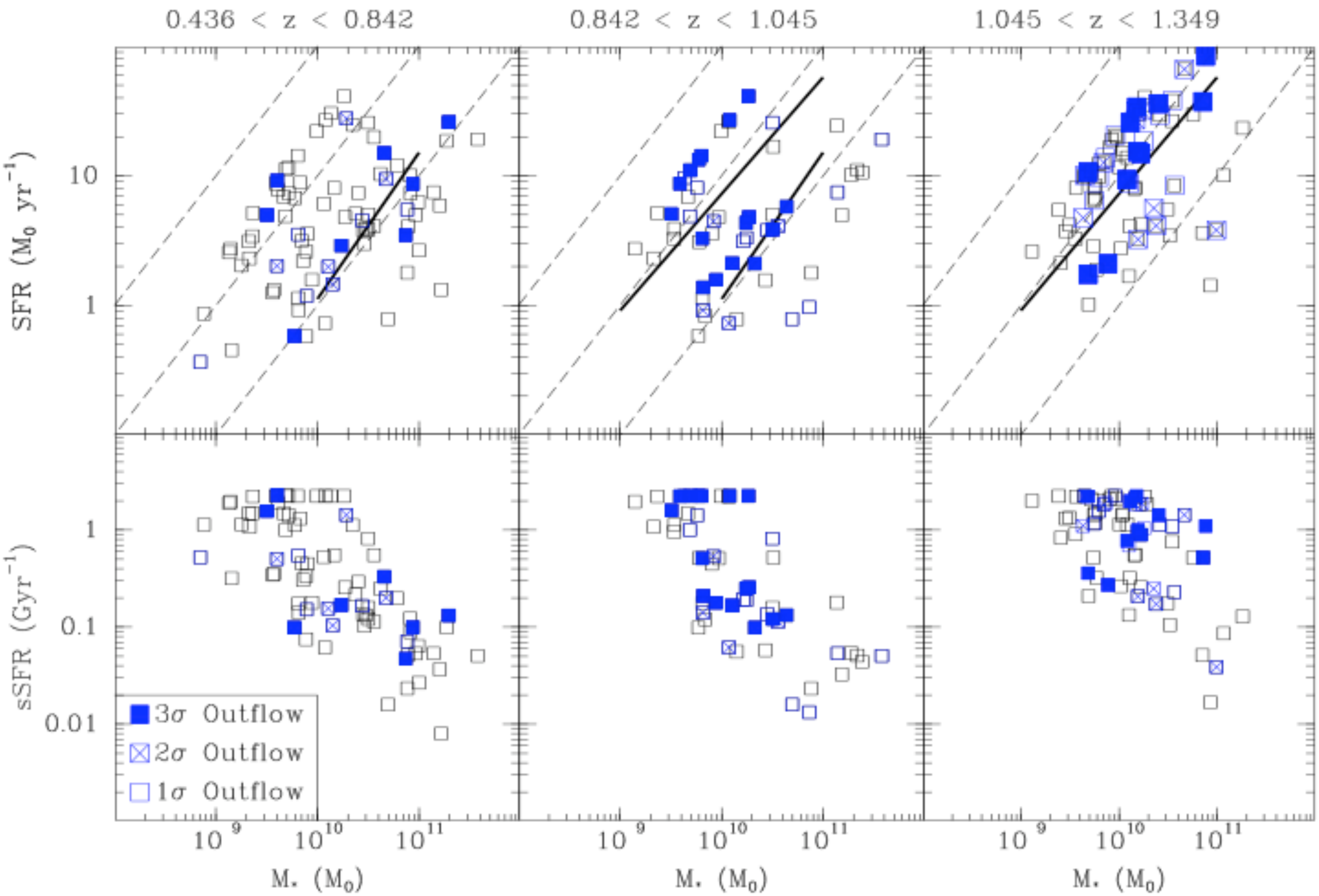
- Detection significance depends on SNR and velocity
- Detect (1-sigma) outflows in 51%
- 11 certain (3-sigma) inflows out of 208 ==> rare



Which Galaxies Have Outflows?



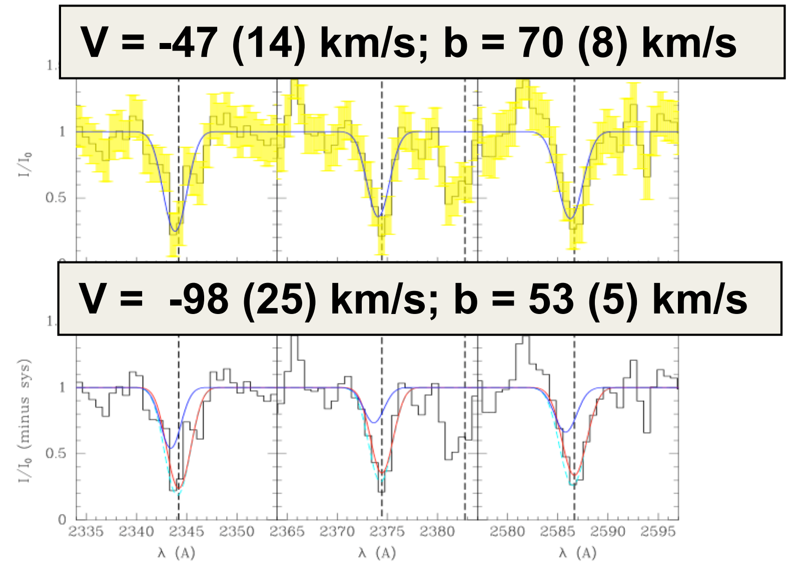
Which Galaxies Have Outflows?



Interstellar Absorption Reduces Doppler Shift

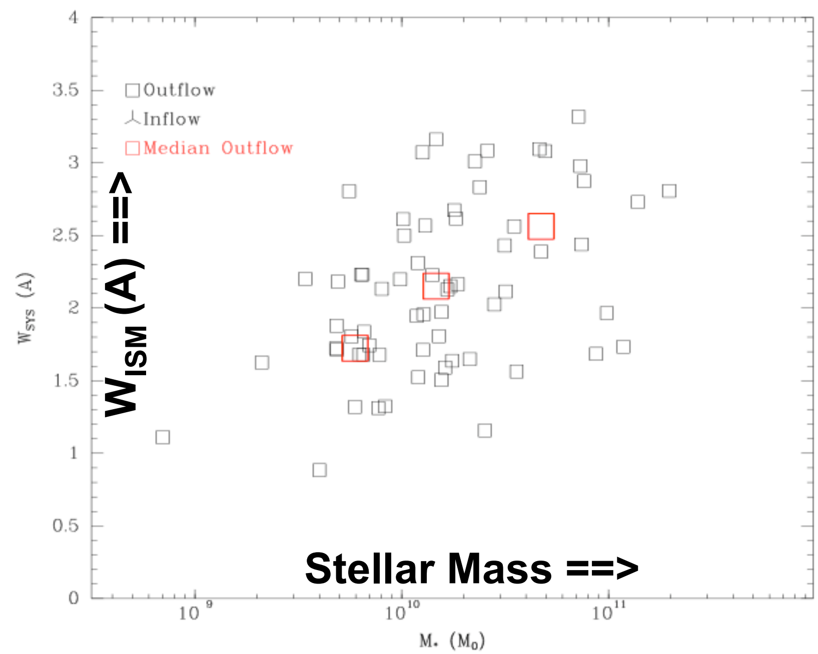
PRIOR

- Two velocity components
- Systemic component at v=0 has a Doppler parameter estimated from [OII] linewidth.
- Fit the maximum ISM absorption (τ), and then fit the residual with a Doppler-shifted component.



RESULT

- Equivalent width of the "interstellar" absorption increases with M_*
- Attributed to larger line widths in more massive galaxies, although there may also be more ISM



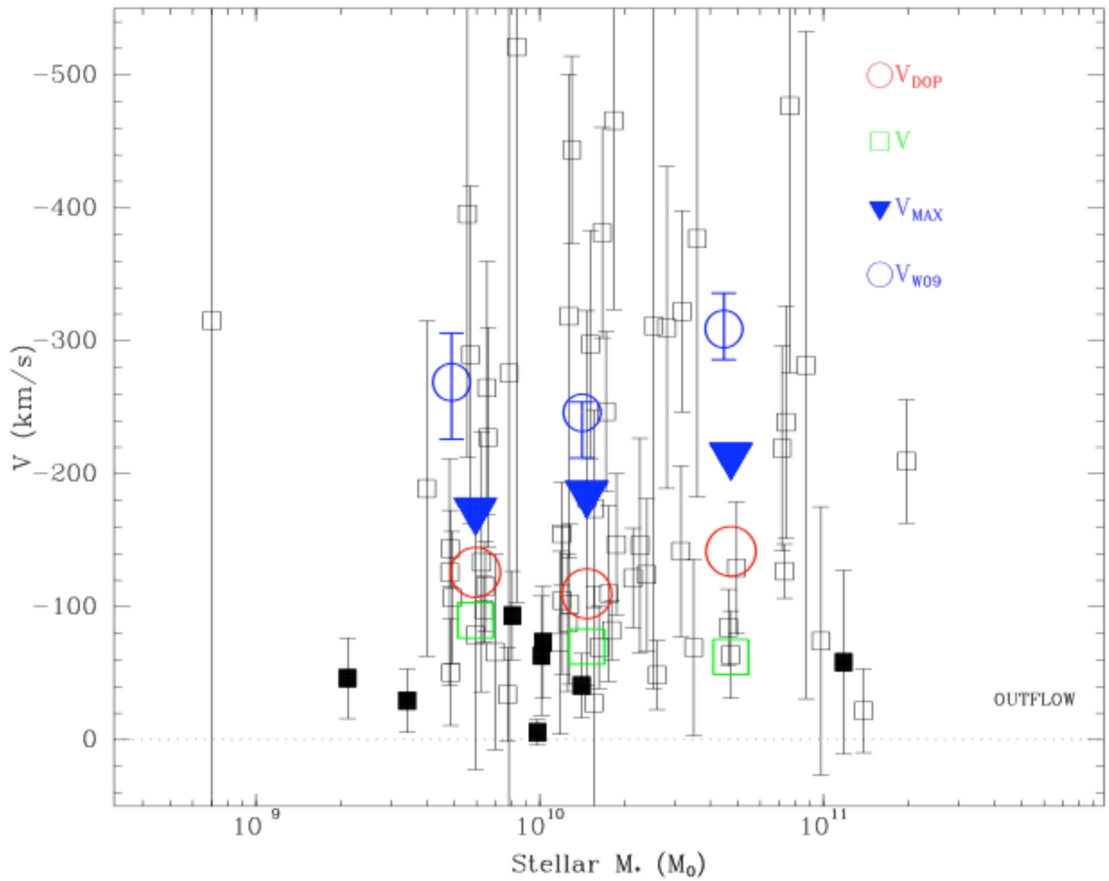
CLM,+2011; Rubin+2011

Outflow Velocity vs. Stellar Mass

- 208 galaxies

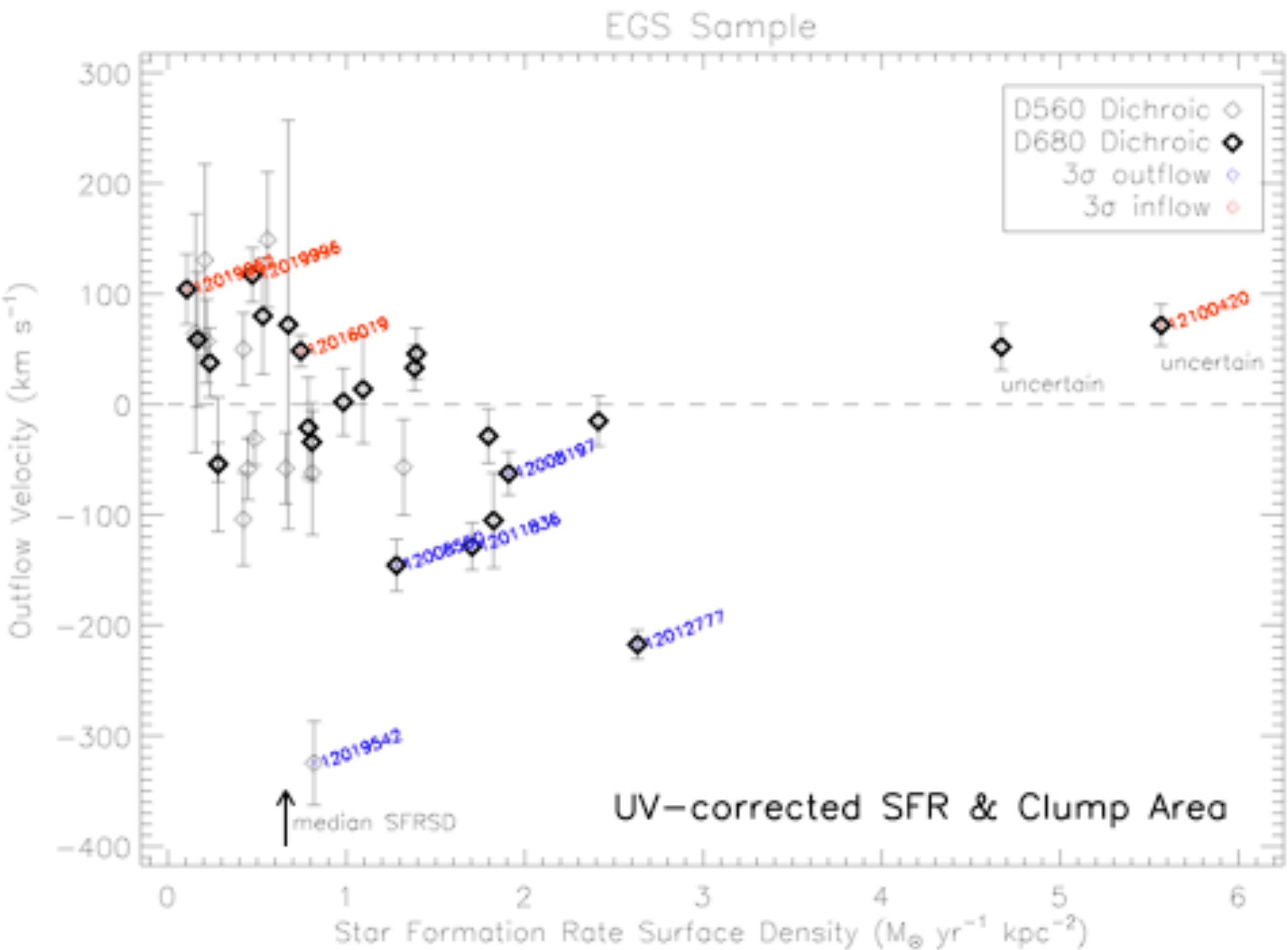
  37 no absorption

  85 require outflow =>
- **Median velocity** is roughly constant with stellar mass
- Most (not all) of the rest consistent with low-ionization gas at v=0.
- Note that **Weiner+09 points** are terminal velocities, and the ISM has been substracted out.



Outflow Velocities Increase with Surface Density of Young Stars

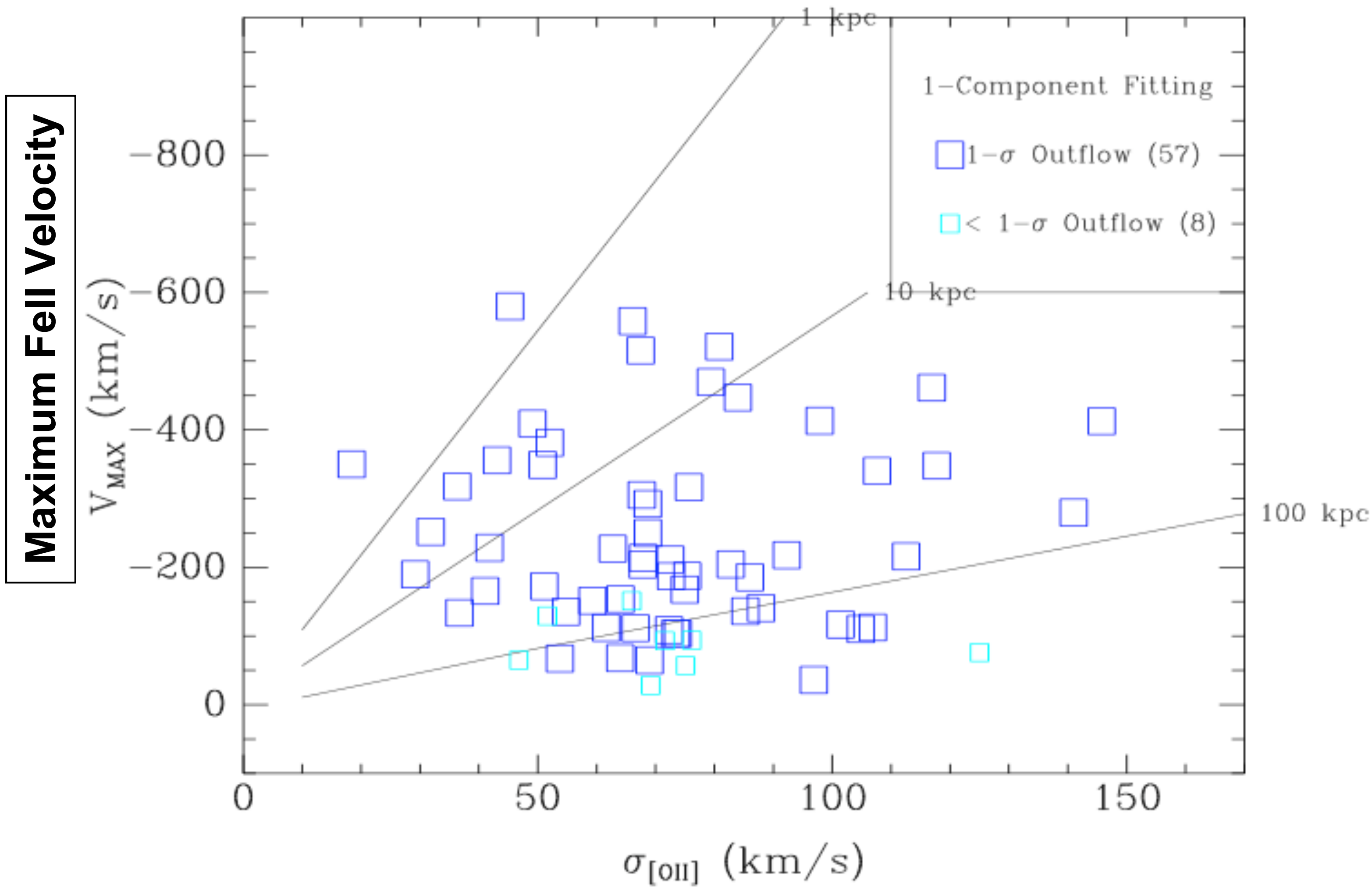
Outflow Velocity (km/s)



SFRSD (M_0/yr/kpc2)

Kathy Kornei
Poster 2.12

Does Low-Ionization Gas Escape?



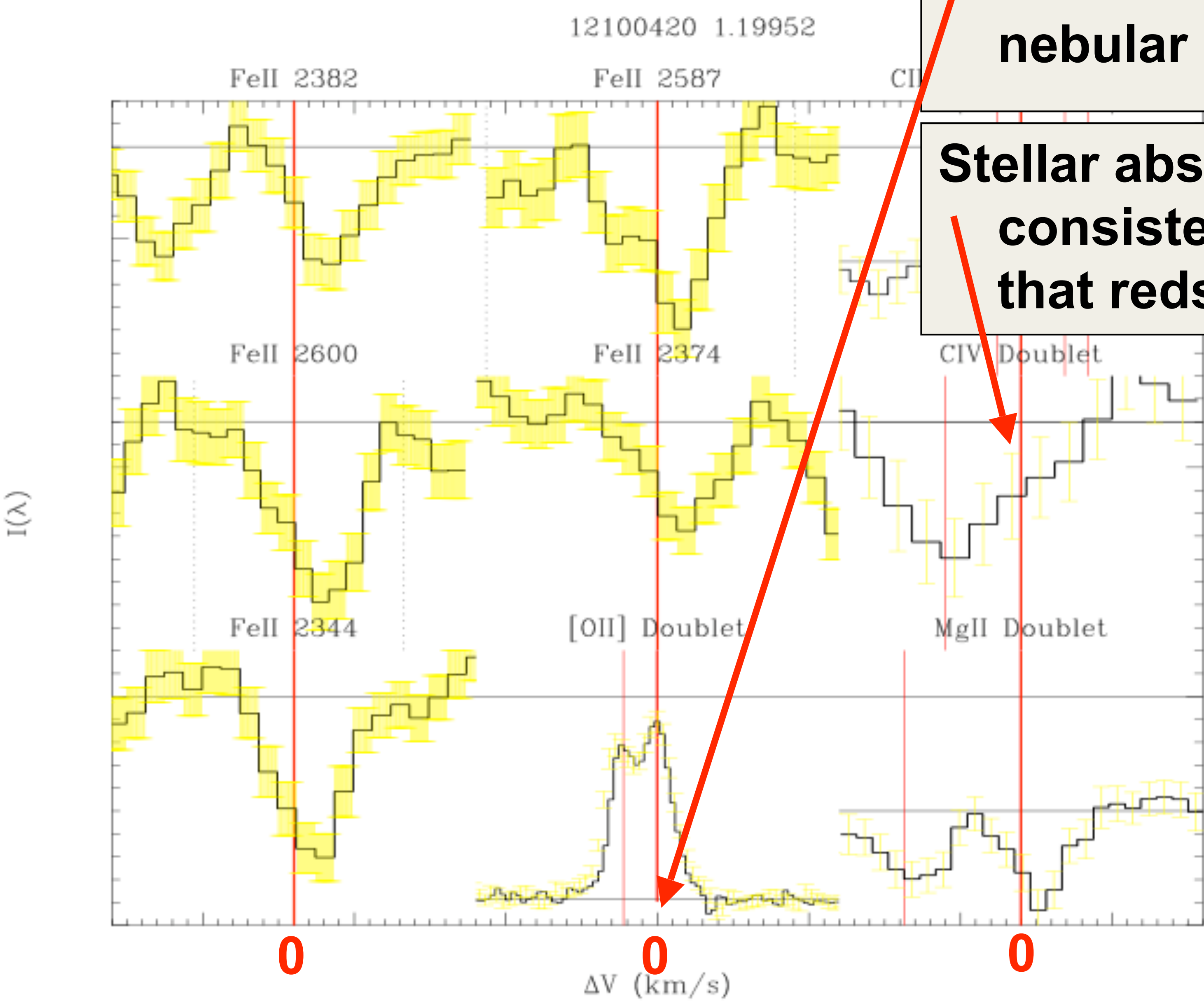
Velocity dispersion from [OII] linewidth

CLM, Shapley, Kornei, Coil, Pancoast

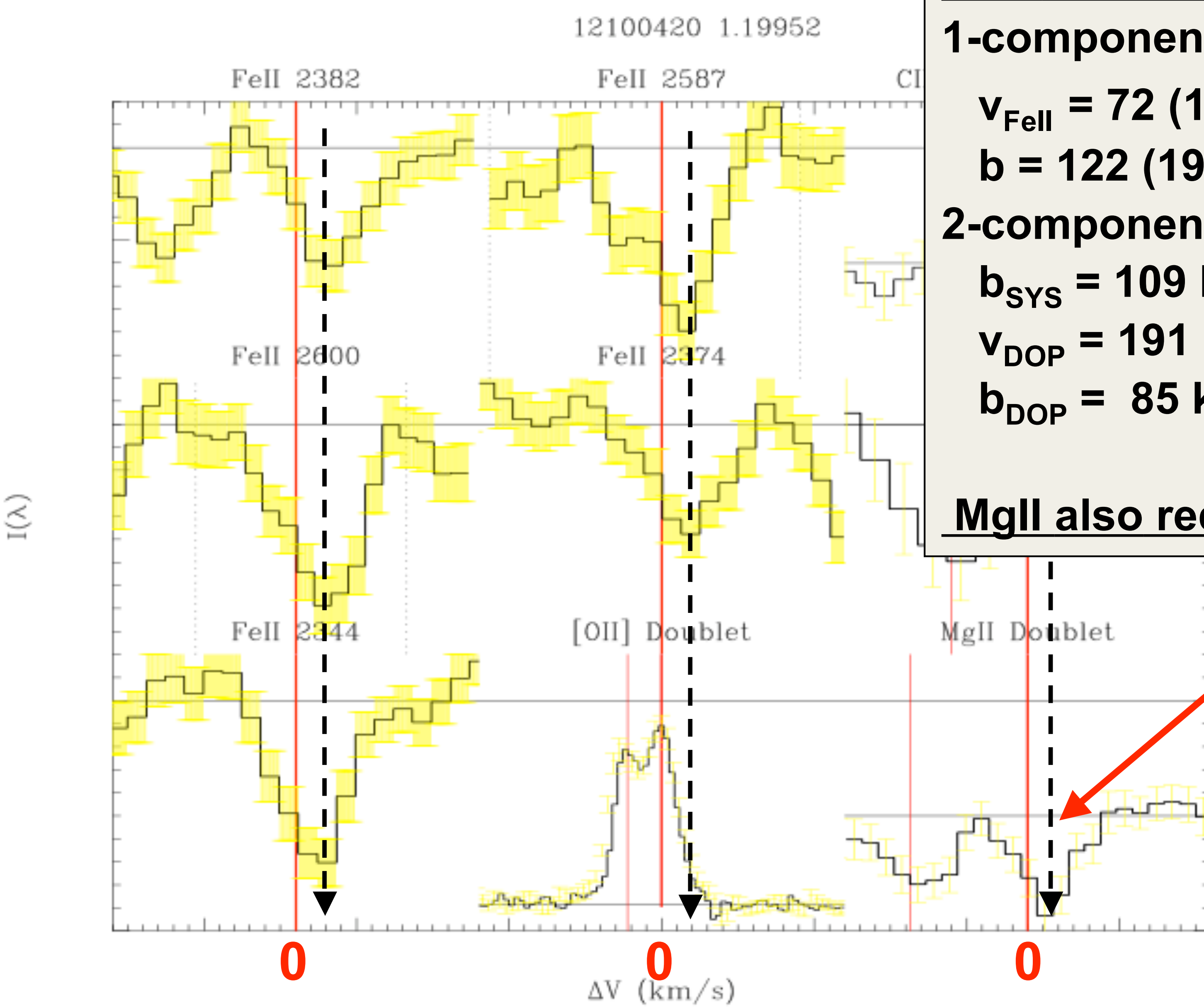
Gas Inflows Detected

Systemic velocity defined by nebular emission.

Stellar absorption consistent with that redshift.



Gas Inflows Detected



Fe II Series Fitting

1-component:

v_{FeII} = 72 (19) km/s

b = 122 (19) km/s

2-components:

b_{SYS} = 109 km/s

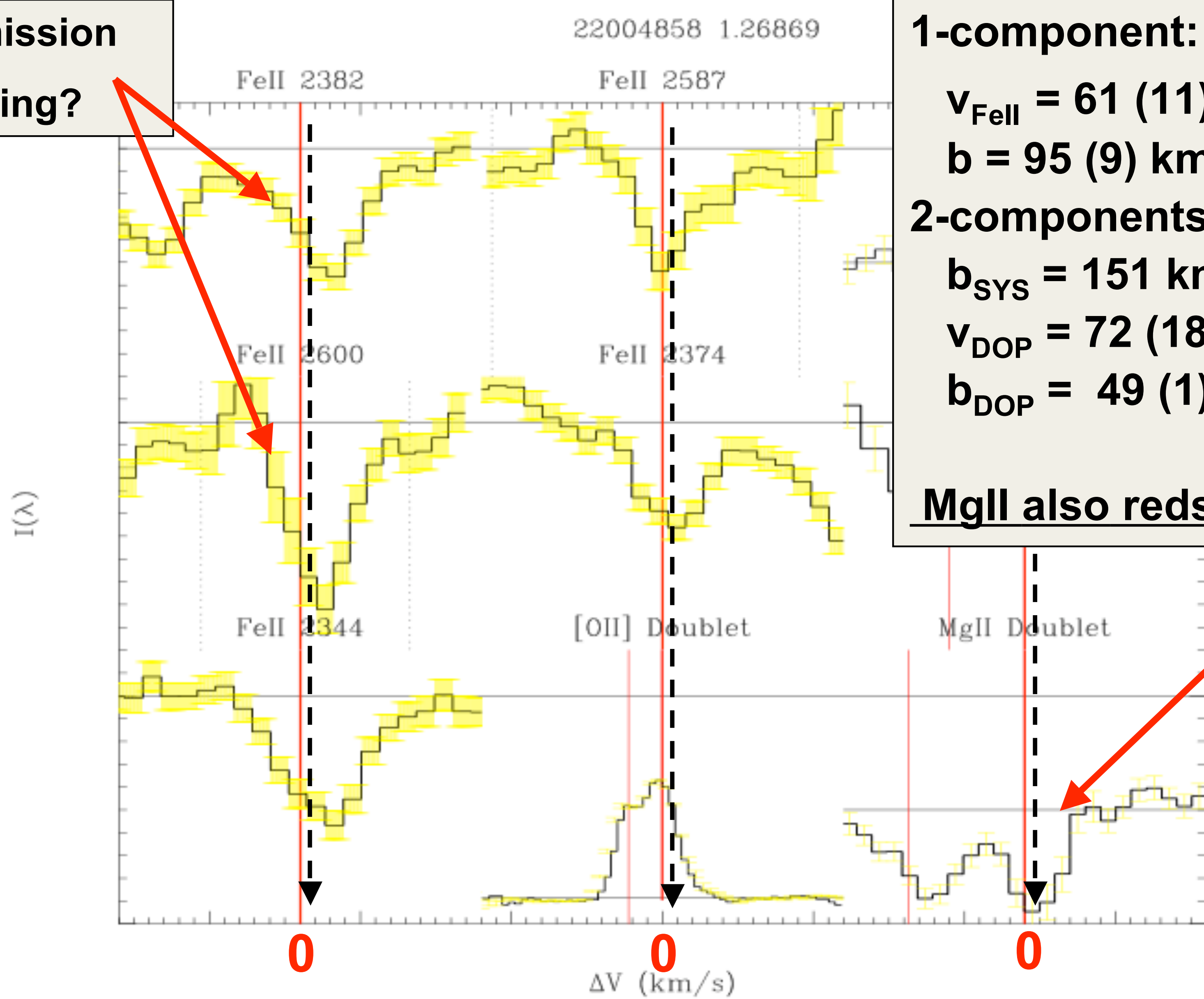
v_{DOP} = 191 (45)

b_{DOP} = 85 km/s

MgII also redshifted

Another Gas Inflow

Emission Filling?



<u>Fe II Series Fitting</u>

1-component:

v_{FeII} = 61 (11) km/s

b = 95 (9) km/s

2-components:

b_{SYS} = 151 km/s

v_{DOP} = 72 (18)

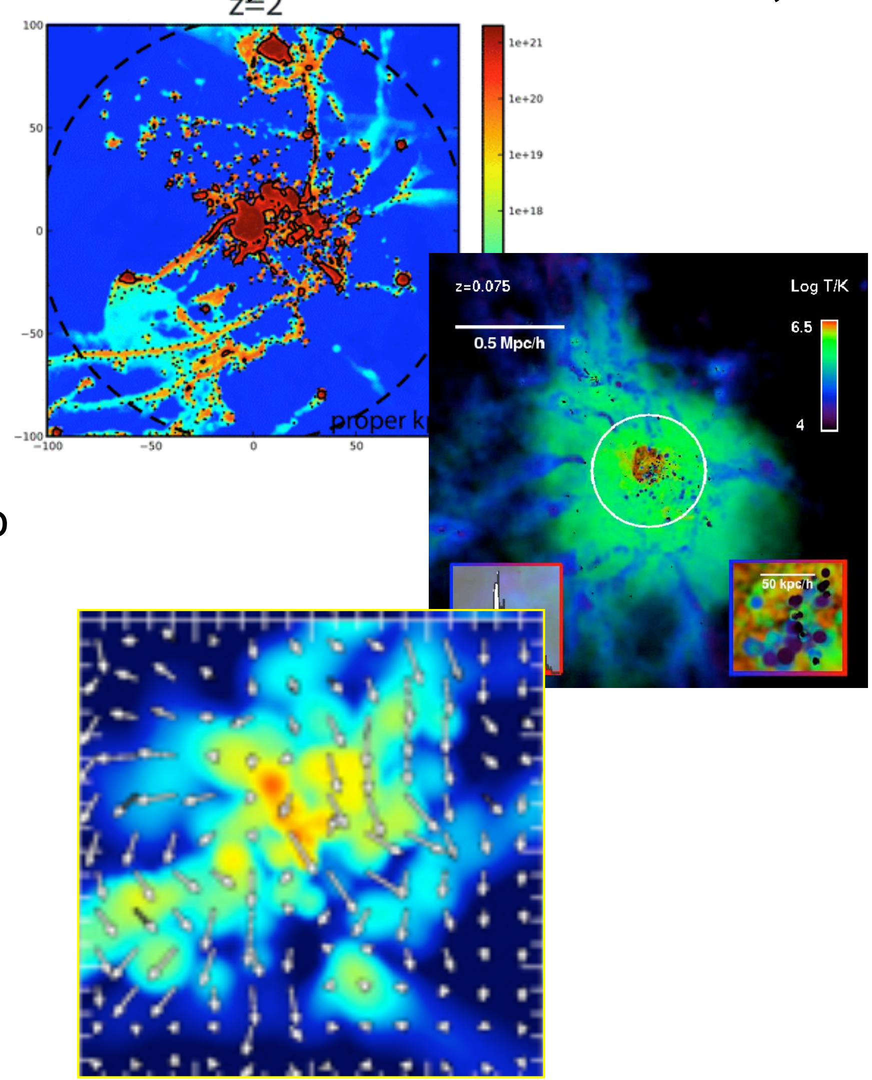
b_{DOP} = 49 (1) km/s

<u>MgII also redshifted</u>

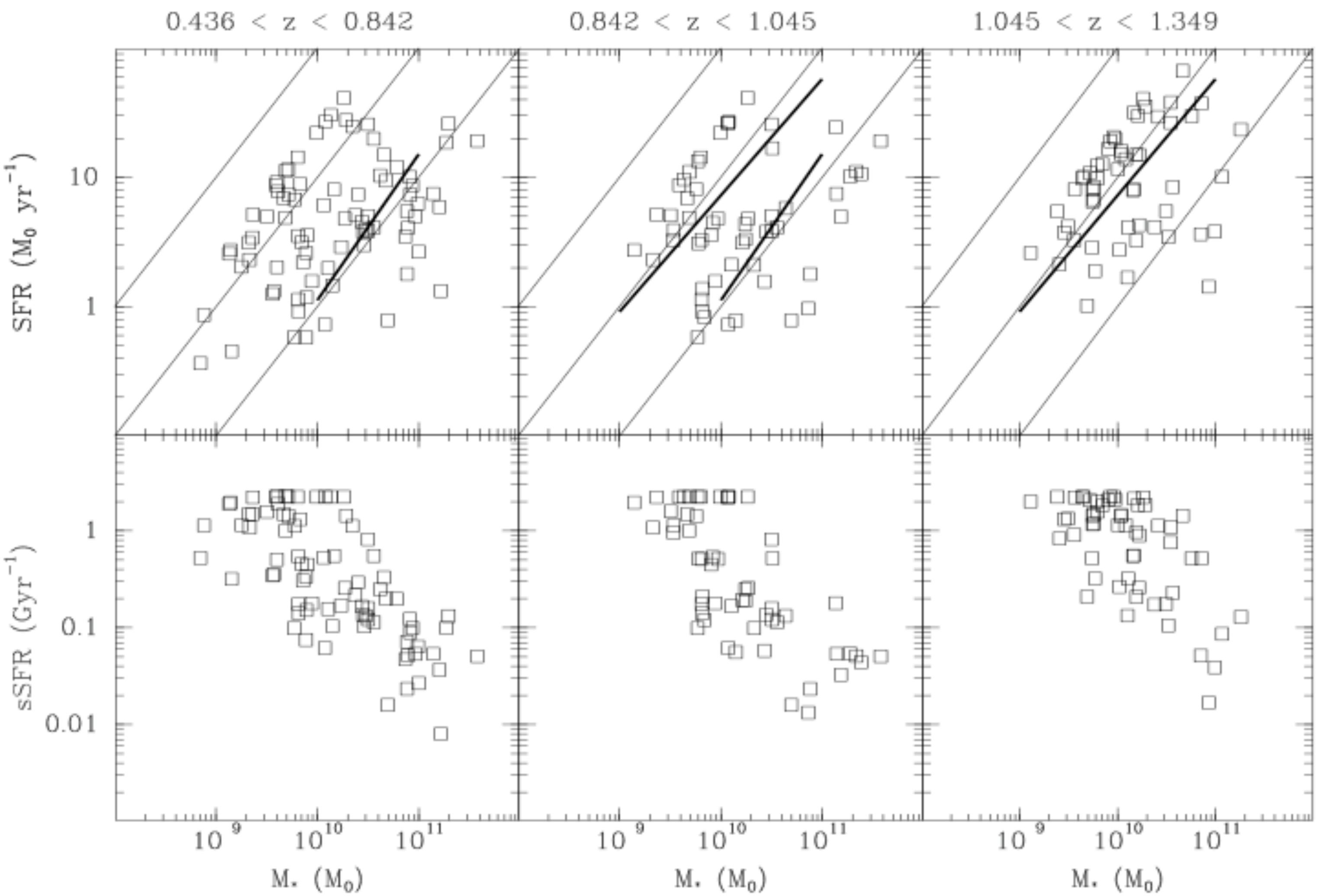
Do We Find Gas Inflow? Yes.

- Properties at z~1.2
  - V ~ 200 km/s up to 400 km/s
  - Log N(Fe II) = 13.6 - 14.8
  - N(H) ~ 1.3-20 X 10^{18} cm^{-2} $(Z/Z_0)^{-1}$
- Is it cosmological inflow?
- Not necessarily, but possibly…
  - Predict low $Z/Z_0 < 10^{-2}$ (Kimm+2011; Fumagalli+2011), but…
  - Recycling could enrich infalling gas to 0.5 Z_0 by z=1 (Dave et al)
  - Predict velocity offset of 50 to 200 km/s (Stewart+2011)
- Not associated with post-starburst activity or mergers

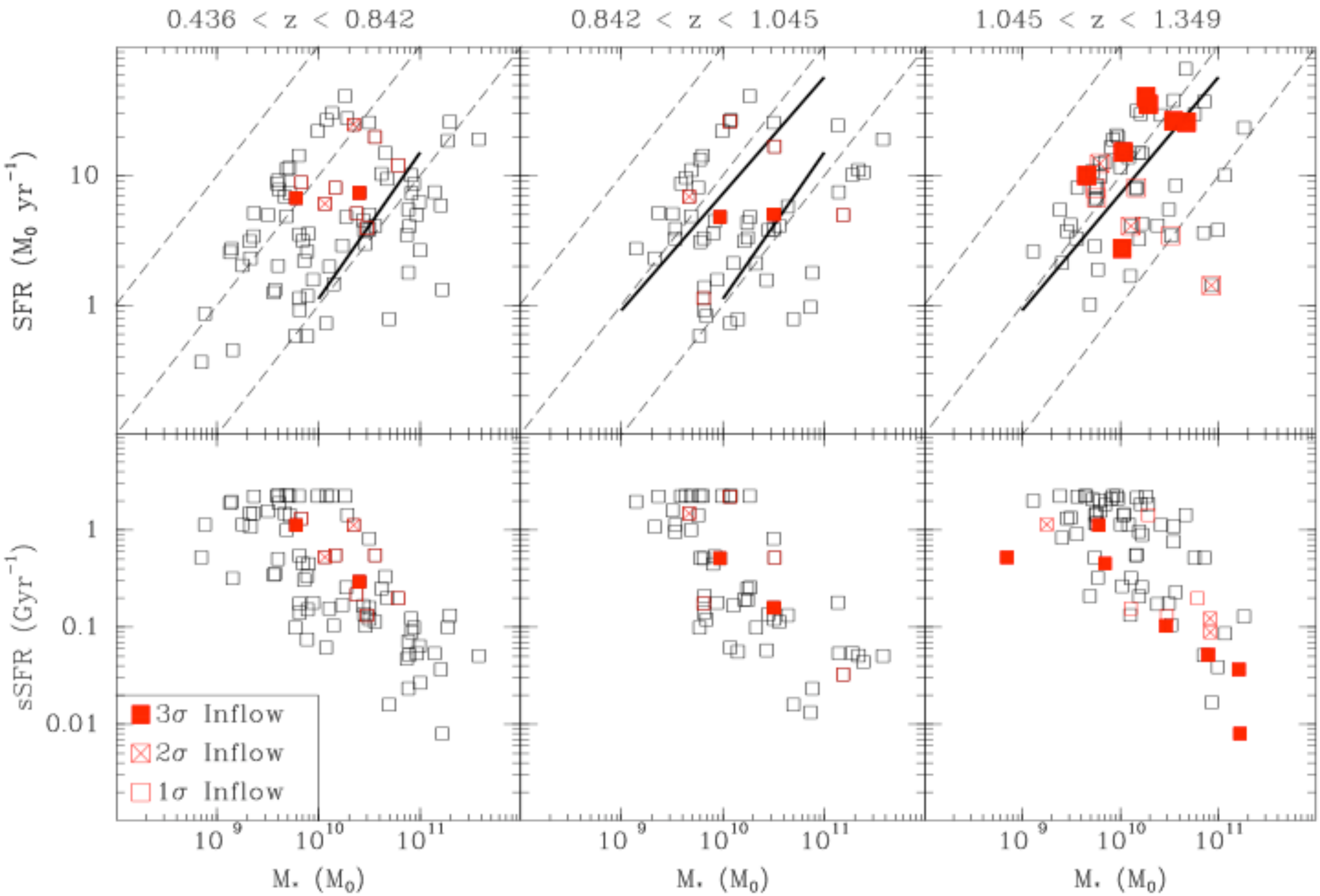
Models: Faucher-Giguere & Keres 2011; Stewart+2011; Fumagalli+2011; Kimm+2010; Kawata & Rauch 2007;



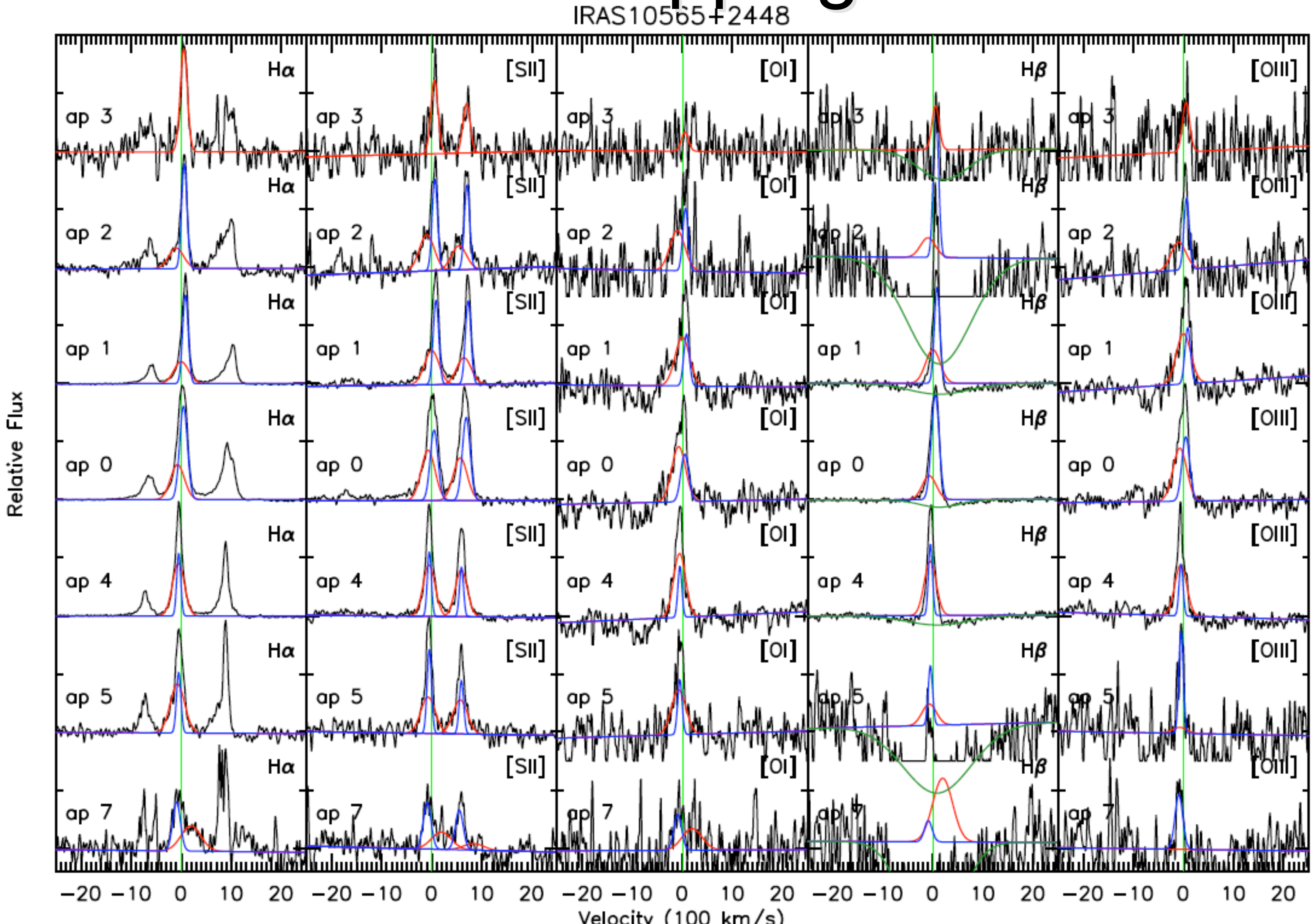
Which Galaxies Have Inflows?



Which Galaxies Have Inflows?



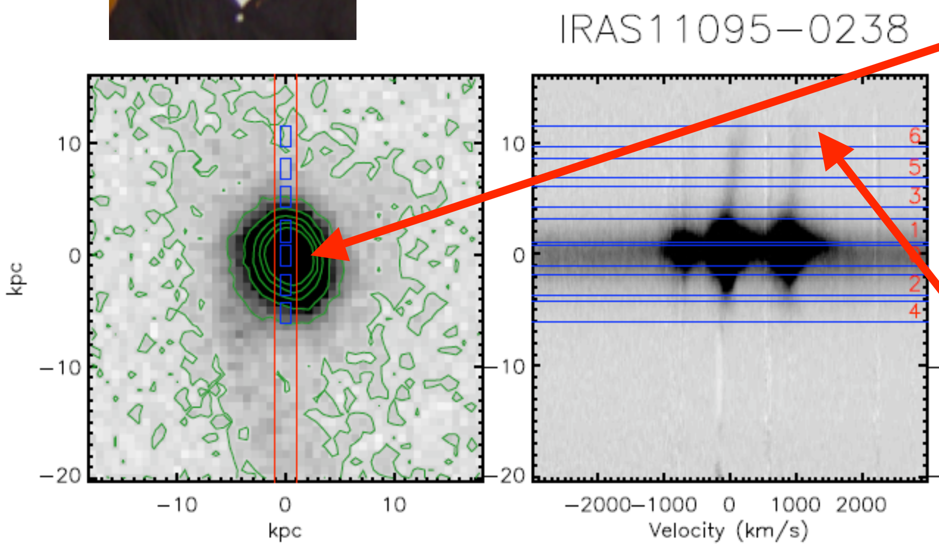
Emission-Line Mapping of Starbursts

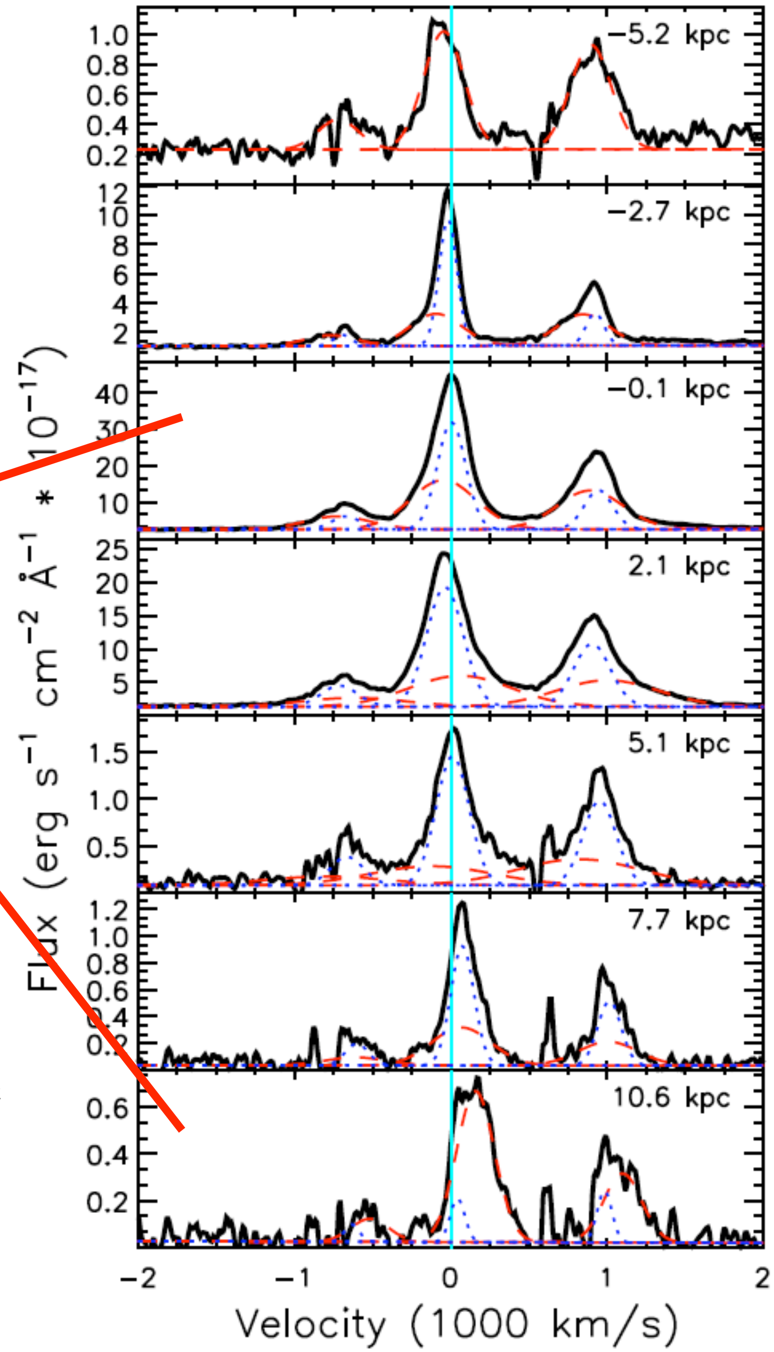


Soto + 2011a,b

Kinematics of Ionized Gas in z~0.1 Starbursts

Kurt Soto +2011a,b

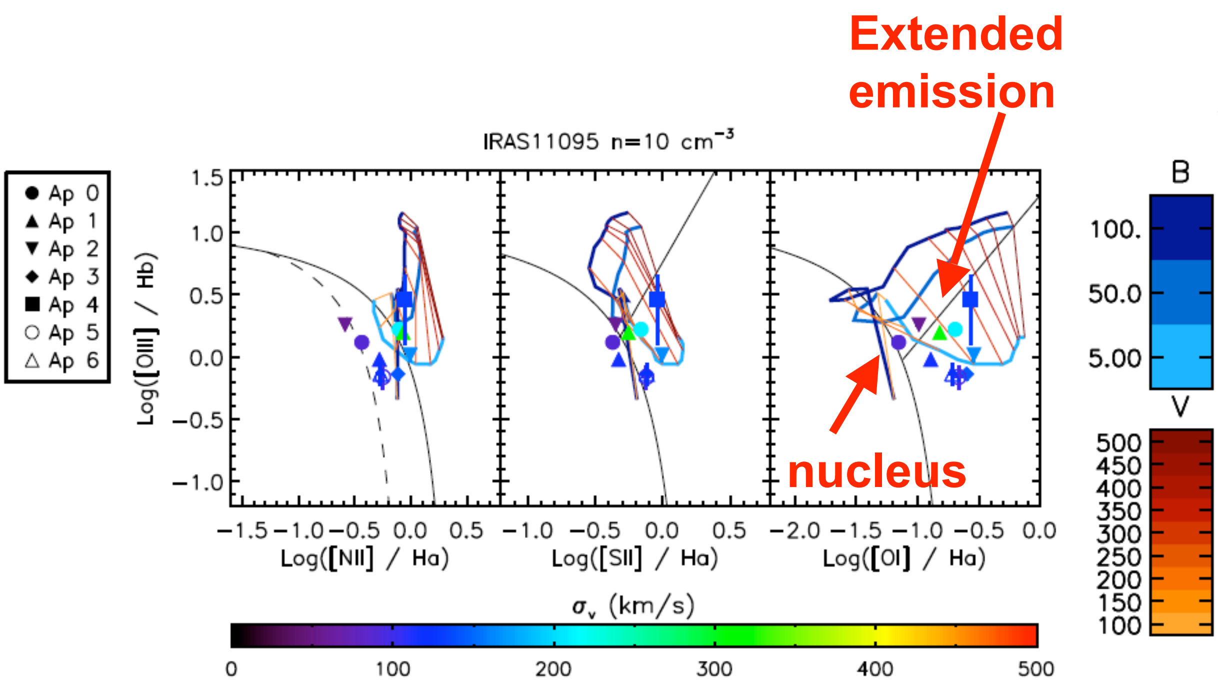


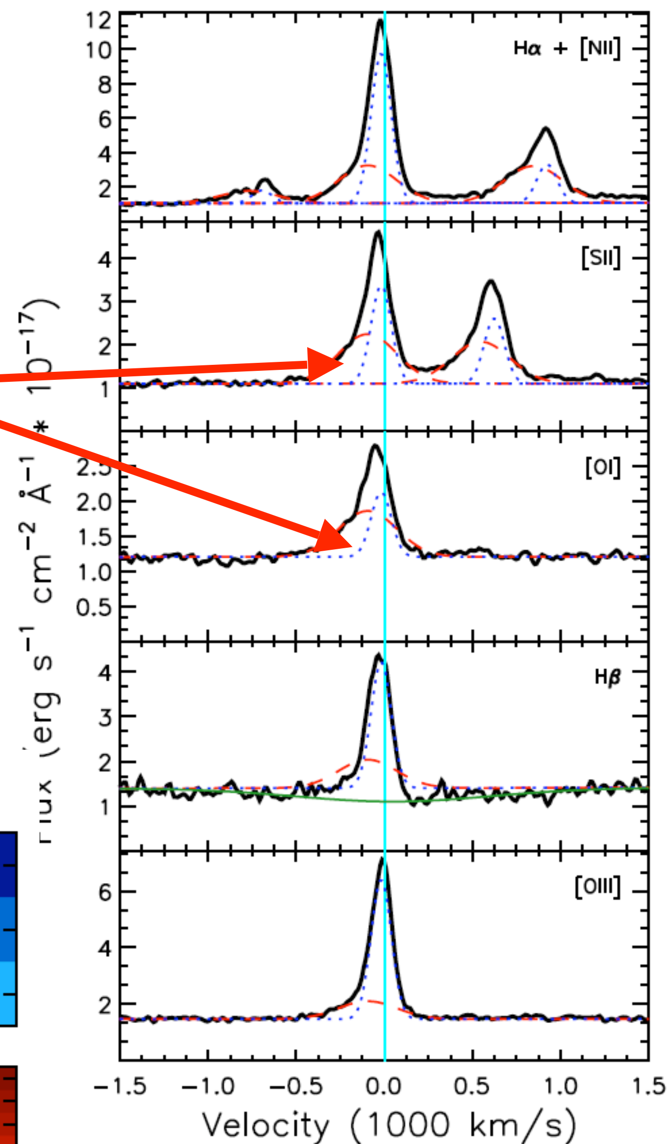


- **Resolution Δv=60 km/s shows asymmetric lines. Fit two velocity components.**
- **Look for relation between kinematics and excitation mechanism**

Broad Emission Excited by Shocks

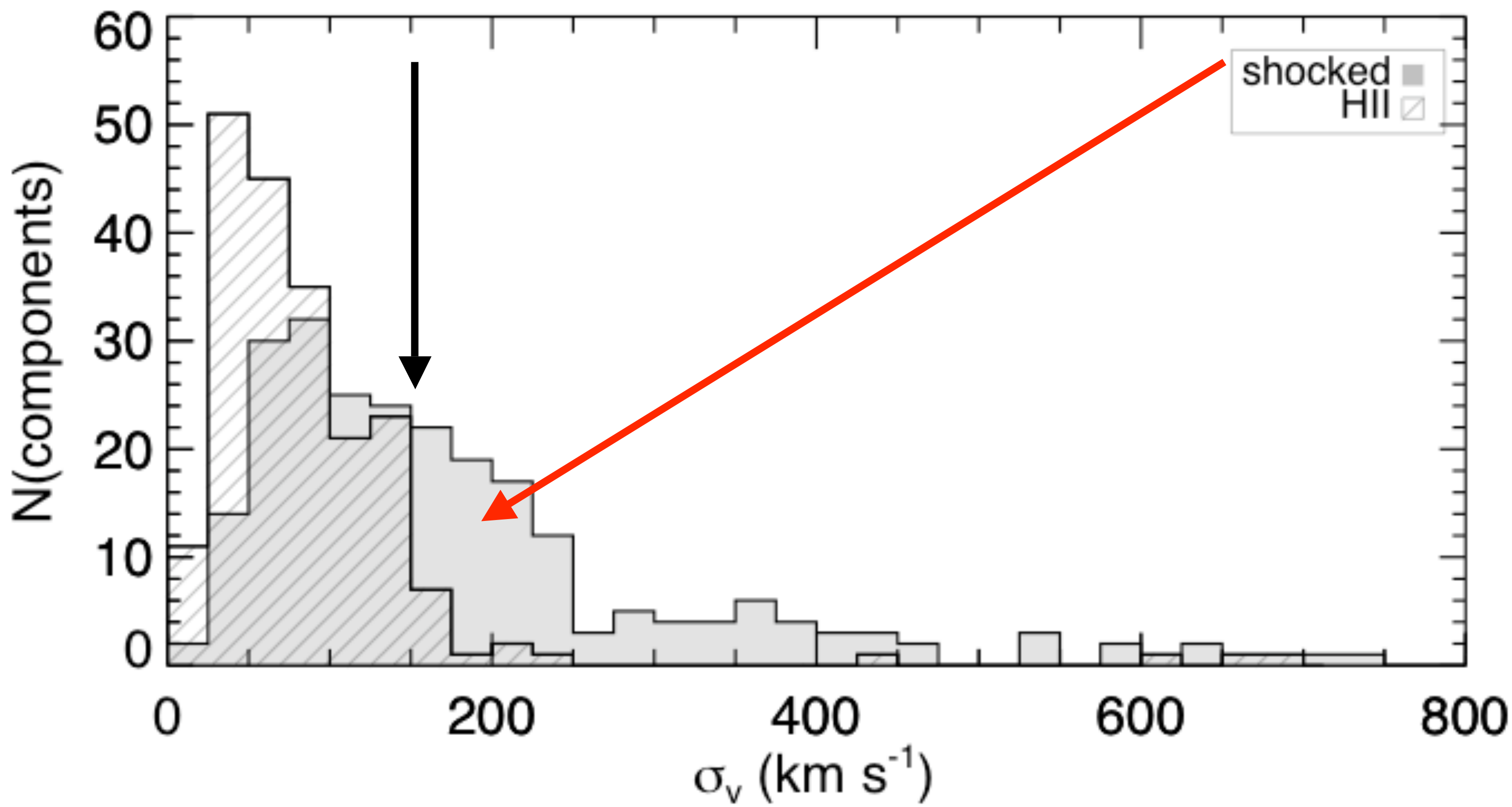
- **Detect broad emission in forbidden lines as well as recombination lines.**
- **Line ratios indicate shocks or AGN.**
- **Spatial extent of 3-5 kpc favors shocks.**





Kurt Soto et al. 2011a,b

Local ULIRGs: High Velocity Dispersion Gas is Excited by Shocks



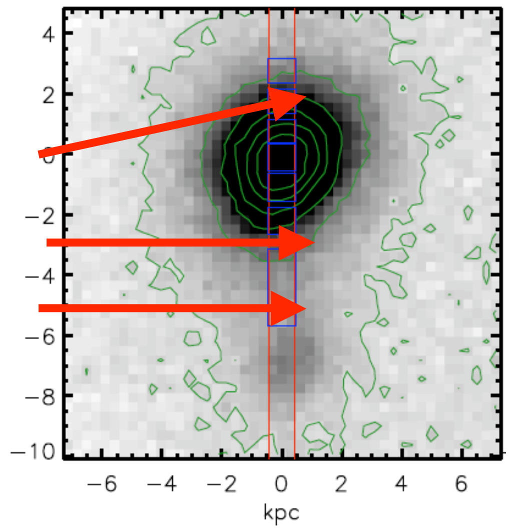
Kurt Soto + 2011a,b

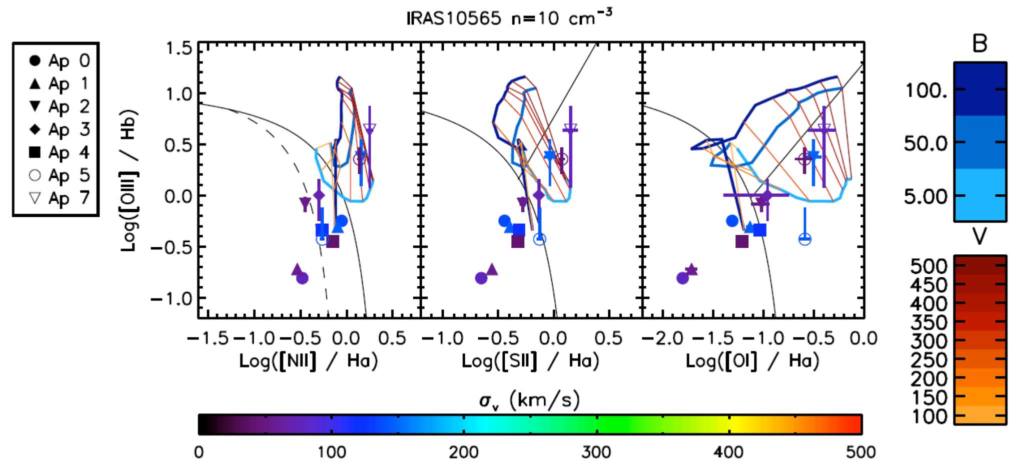
Relation of Outflow Emission and Absorption

300 km/s

300 km/s

400 km/s





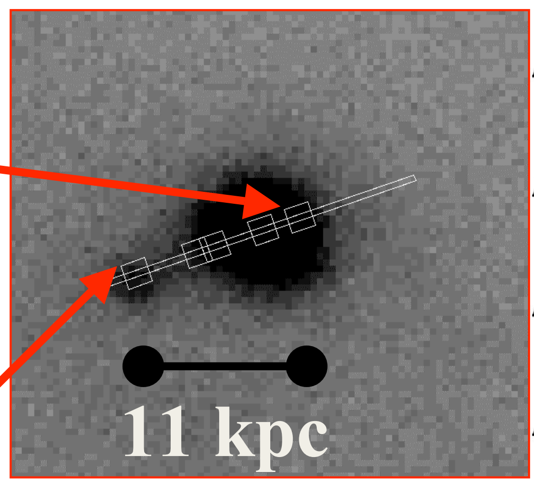
Soto + 2011a,b

-430 km/s

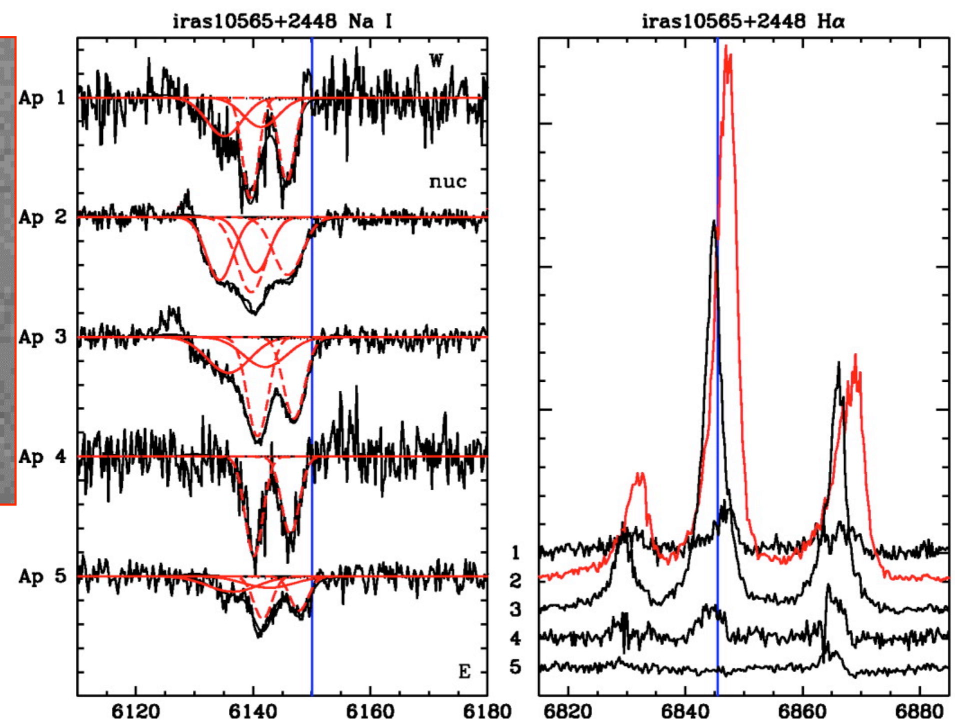
-466 km/s

-392 km/s

-358 km/s

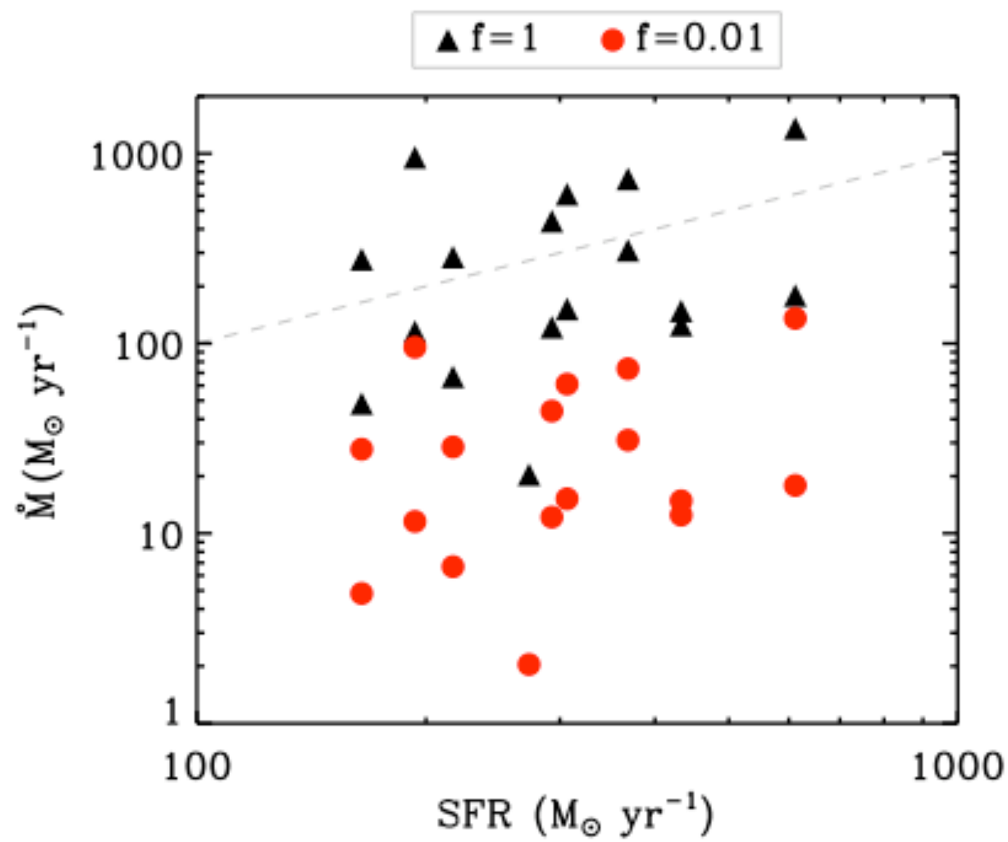


CLM 2006 ApJ



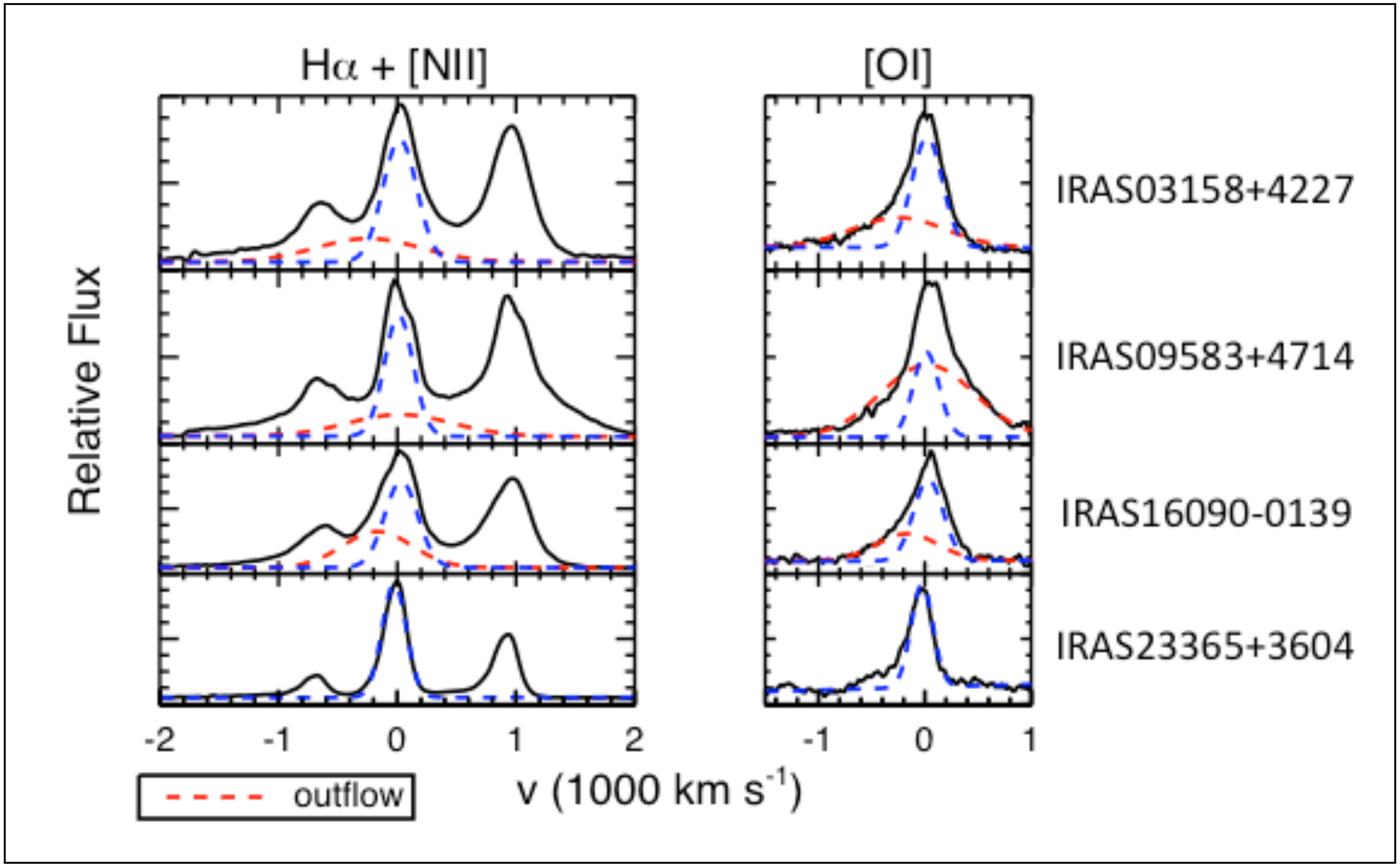
Local Starbursts Mass-Loss Rates

- Implied mass of warm, ionized gas depends on volume filling factor, f ~ 0.01
- Timescale ~ R / v
- η = dM/dt / SFR
- Compare to mass carried by hot phase and by neutral gas



Kurt Soto + 2011a,b

Broad Component Detected in Integrated Spectra!



- **Requires R~6000 and good SNR**
- **Requires coverage of Ha, [NII], [OI], [OIII], Hb**
- **Surveys for outflows across cosmic time with JWST**

SUMMARY: Low-Ionization Out/Inflows

- Outflows are common (not ubiquitous) in galaxies at z~1
- Stronger ISM component in higher mass galaxies
- Outflow speed increases with M_* but more strongly with SFRSD
- Extent of MgII emission and v of absorption indicate dM/dt ~ SFR
- Inflows found in ~5% percent of z~1 galaxies may be a mixture of recycled metals and cold streams.
- Need high-resolution hydro simulations of winds that address (1) relation of low-ionization outflow to hot wind, and (2) model absorption line trough shape
- Emission lines in R~6000 spectra offer another approach

FURTHER READING: CLM & Bouche 2009 ApJ 703, 1394 (Comparison of optical and UV lines); Rubin+2011 ApJ 728, 55 (Emission); Rubin+2010 ApJ 712, 574; Rubin+2010 ApJ 719, 1503; Weiner+ 2009, and Sato+2009 ApJ 696, 214 (Ubiquity of Outflows); Prochaska+2011 (Emission Modeling); Quider+2011 (z < 2); Kornei+2011 (SFRSD); CLM+2011 (Inflows and Scaling Relations)