Gas Outflows and Inflows Towards z~1 Galaxies

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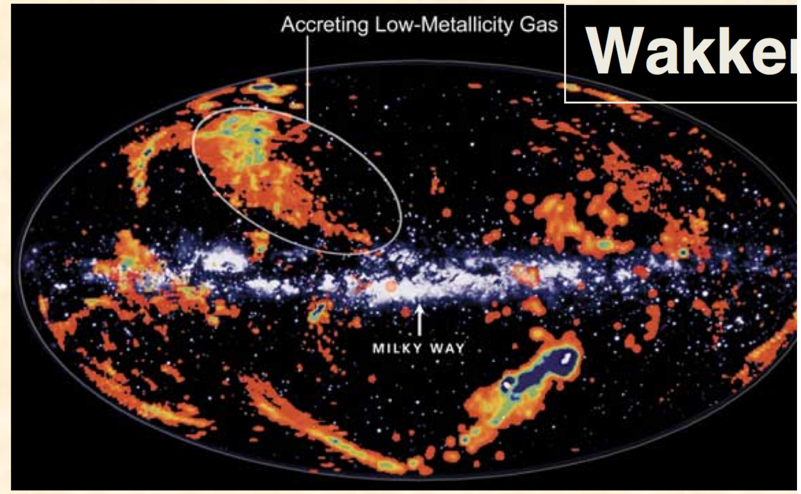
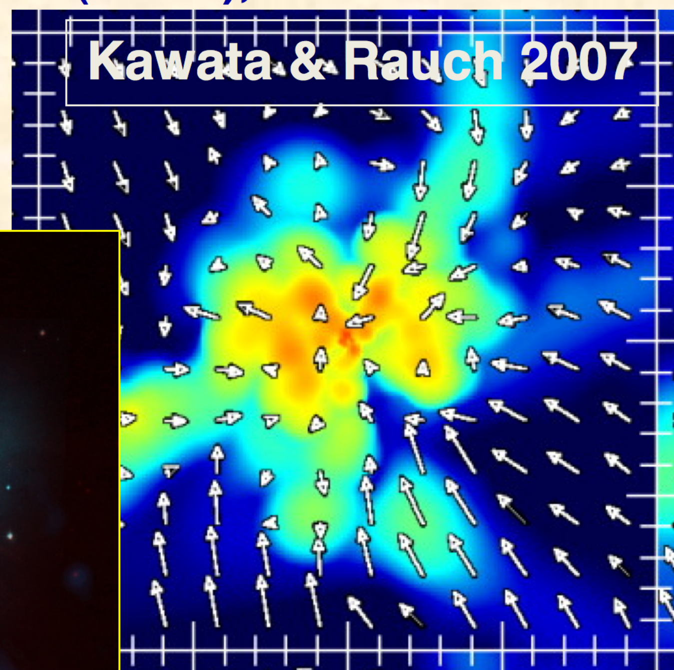
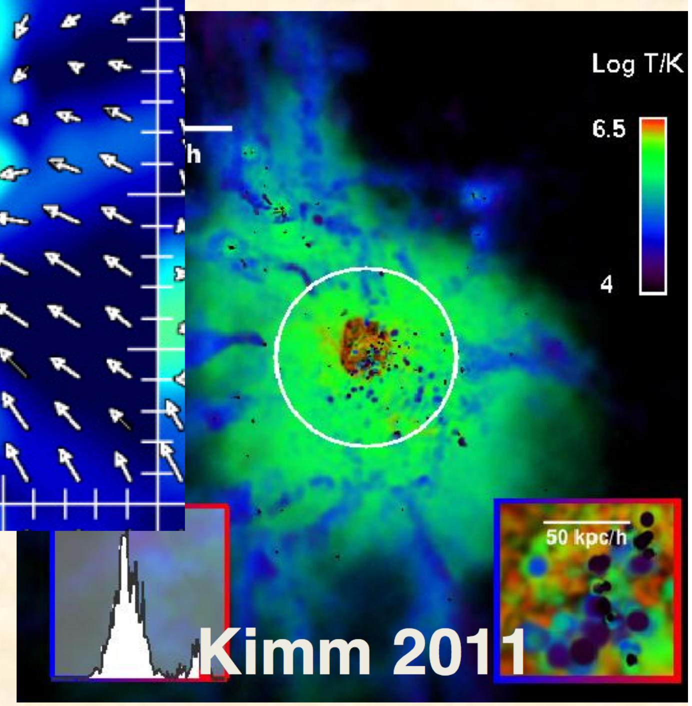
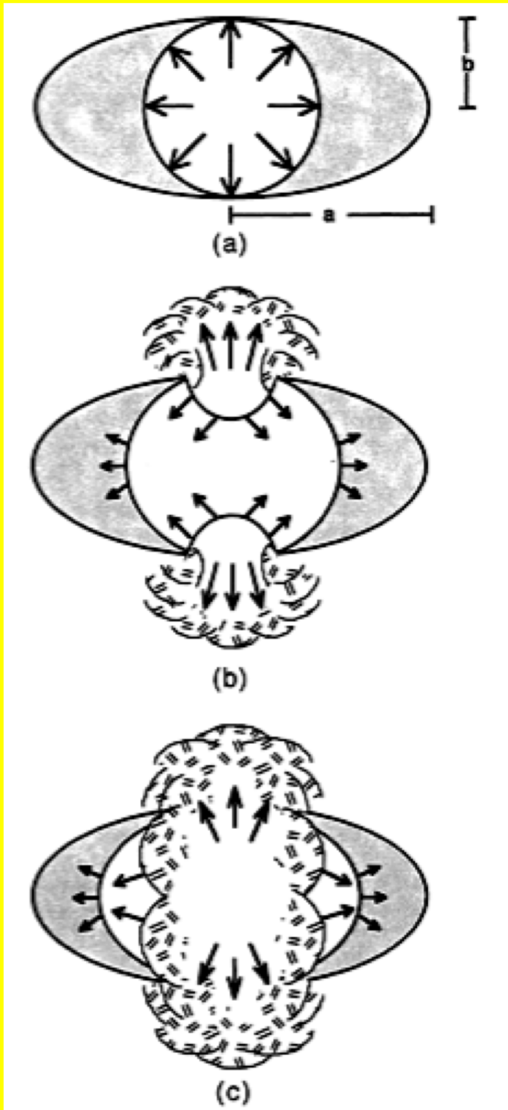
Nicolas Bouche (Toulouse)
Alice Shapley & Kathy Kornei (UCLA),
Alison Coil (UCSD)
Dawn Erb (UW Milwaukee)
Anna Quider (Cambridge)





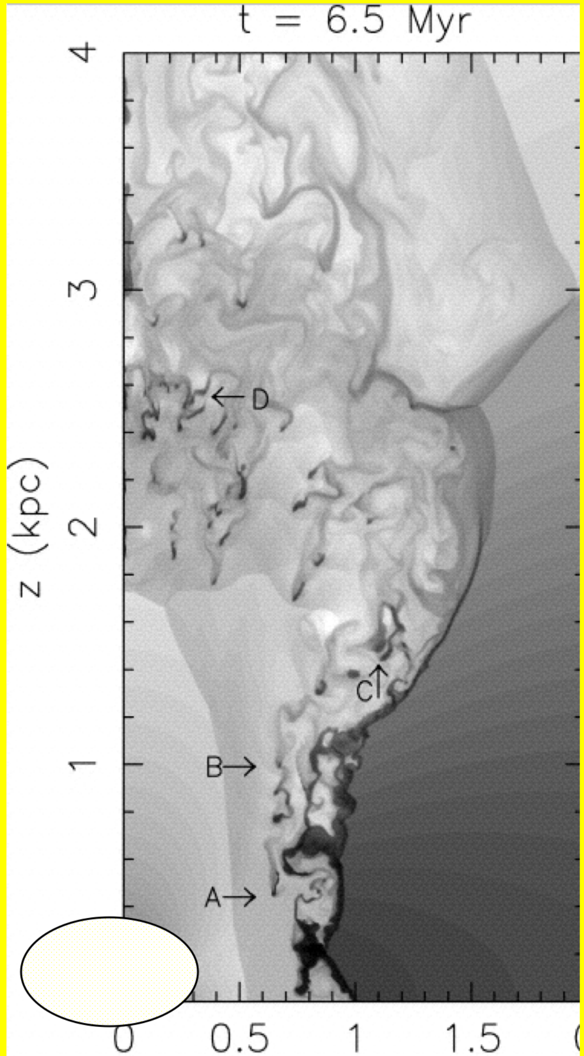


Origin of Low-Ionization Gas in Winds?



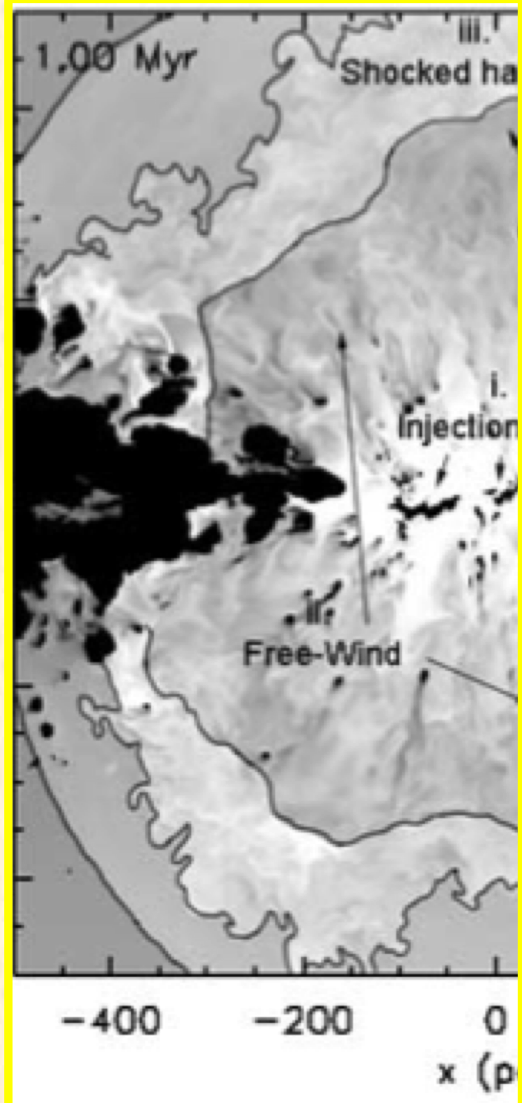
MacLow et al. 89; Fujita+09

DeYoung & Heckman 2004



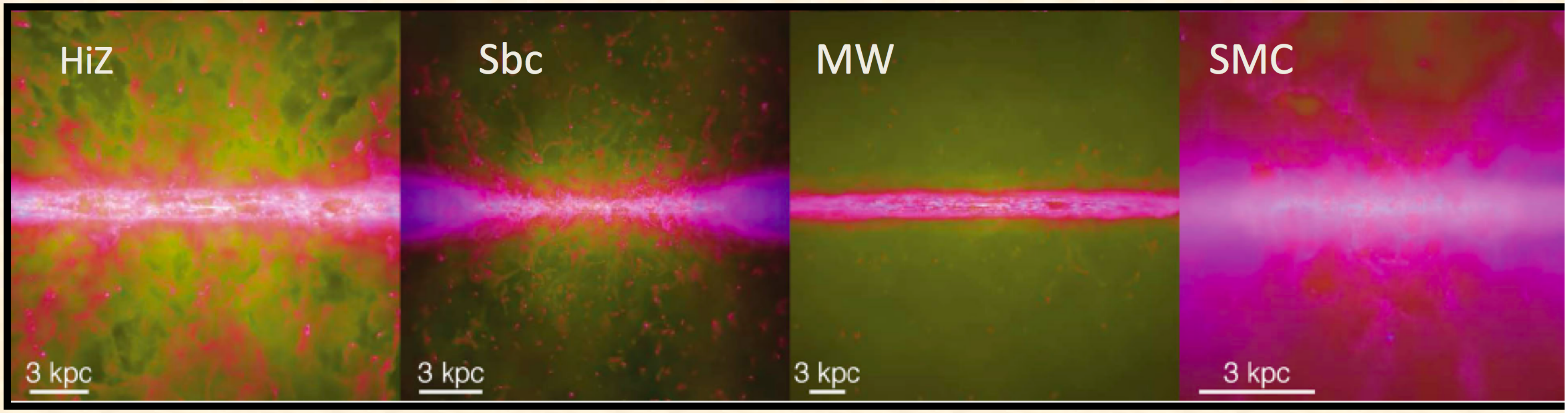
Strickland

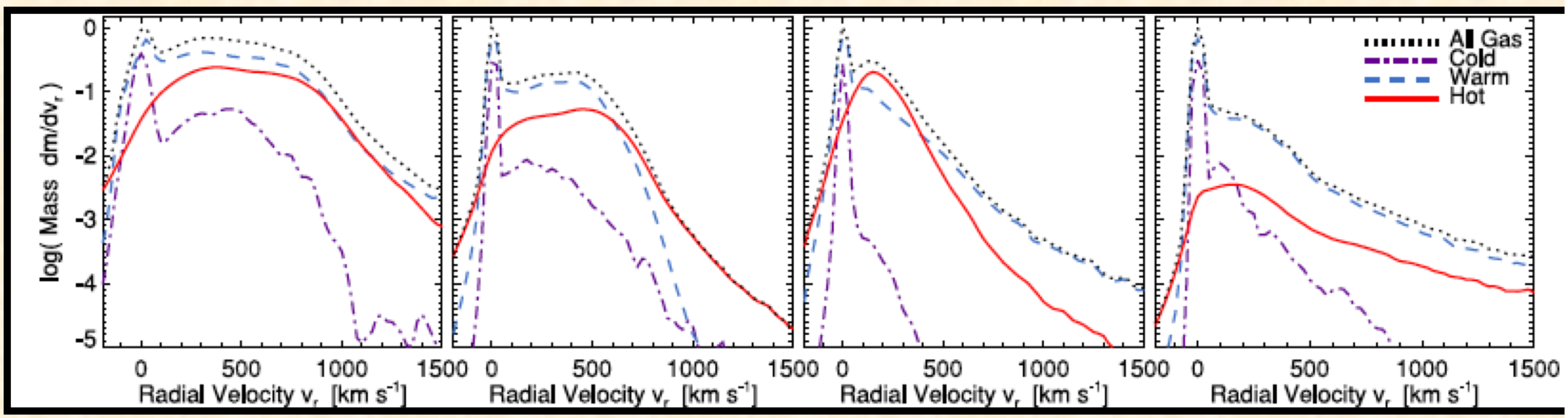
Heckman et al. 2000



Cooper et al. 2009

Warm-Outflow Carries the Mass





Hopkins, Quataert, & Murray 2012

Lines Accessible through the Atmosphere

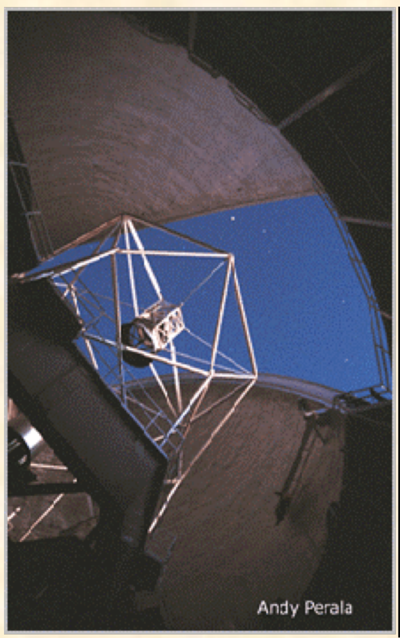
z → 0 0.3 0.5 1.0 1.4 3.0

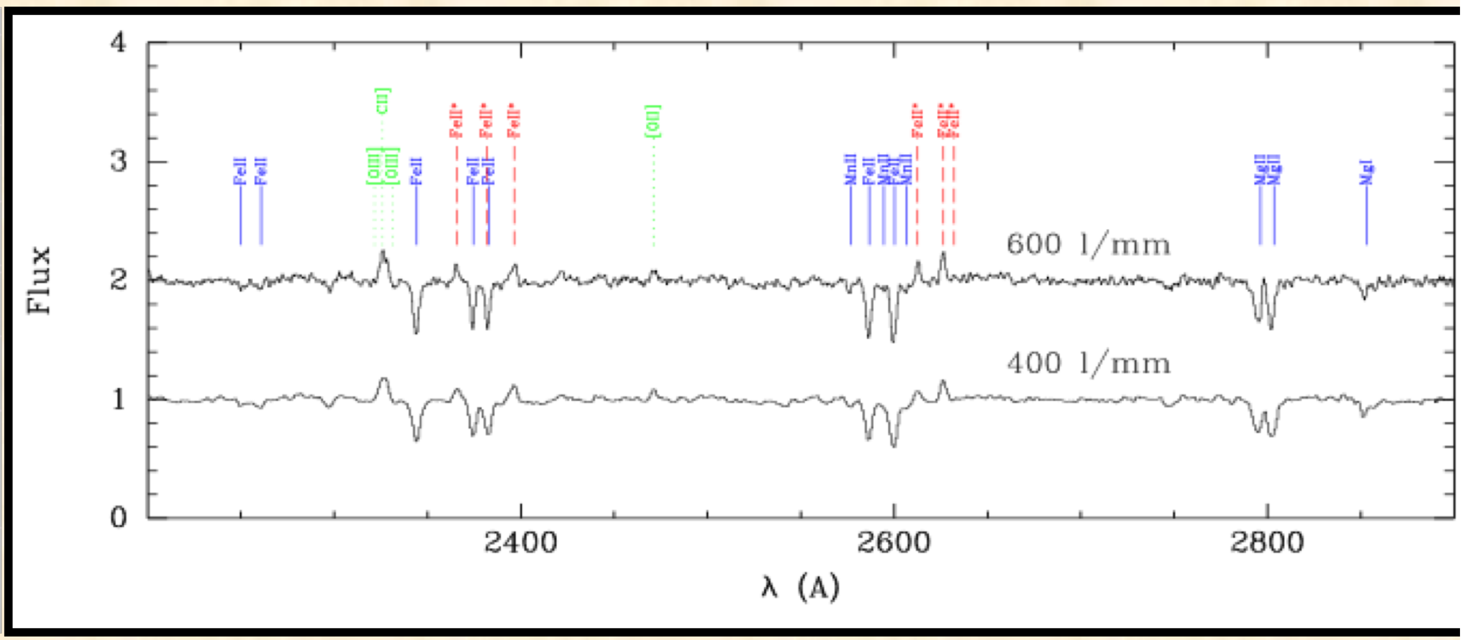
NaI -----------------|

| **MgI, MgII, FeII** --|

| **Si II, Al II, CIV** ---------->

| **OVI** ---------->





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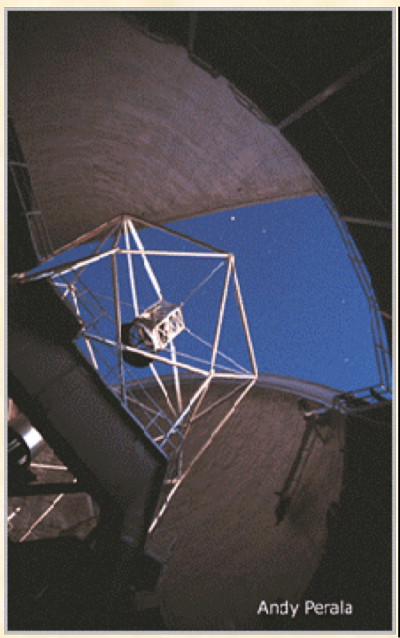
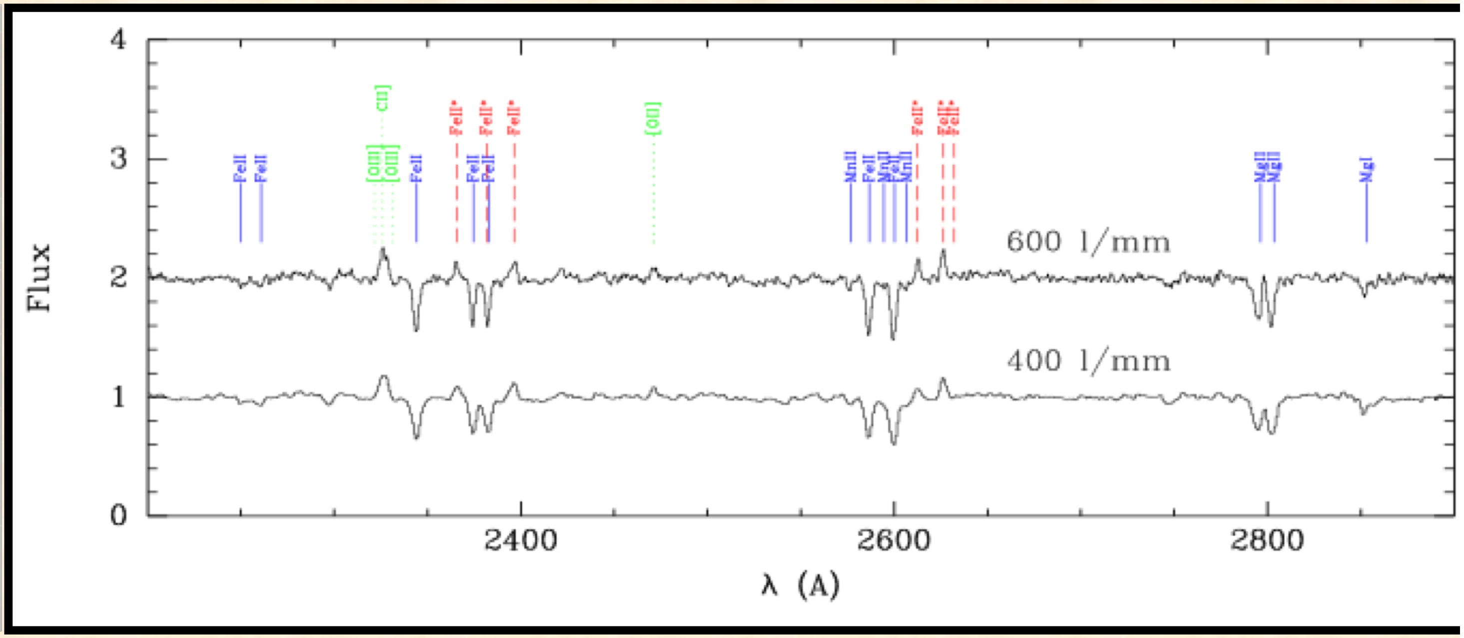
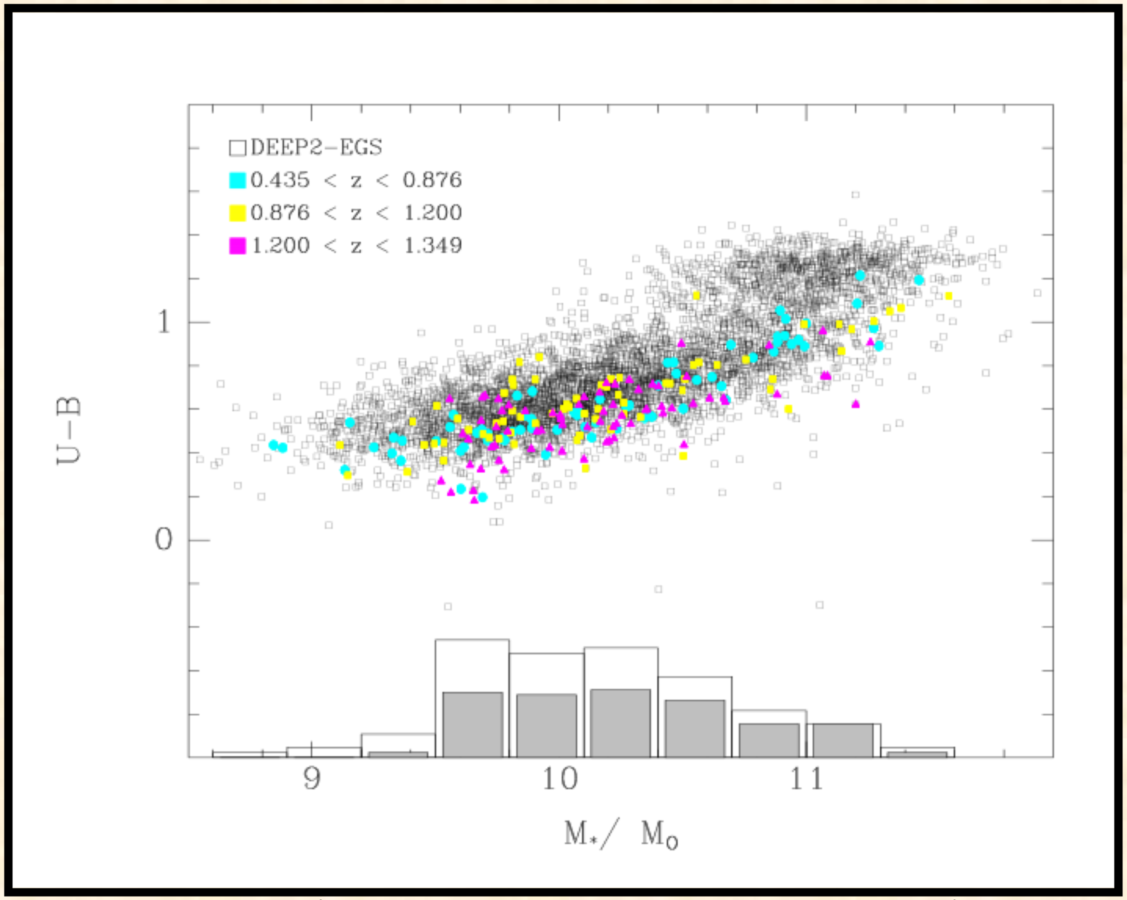




Normal, Star-Forming Galaxies at z~1

Martin, Shapley, Coil, Kornei



- Cosmic SFR falls rapidly
- SFR at fixed M* declines in a manner reminiscent of the halo growth rate. Suggests a model (Bouche+2010; Dave+2012)
  - SFR = Inflow - Outflow
  - $10^{11} < M_h/M_0 < 10^{12}$
- Galaxy Properties (DEEP2/AEGI
  - Willmer+2006 -- Rest-frame Colors and Absolute Magnitude
  - Bundy+2006 -- Stellar Masses from SED Fitting
  - Star Formation Rates from GALEX UV Photometry (EGS only: D. Schiminovich)
- Estimate halo masses of host galaxies from abundance matching results (Behroozi+2010).

- Composite survey spectra show blueshifted MgII absorption (Weiner+2009; Rubin+2010)

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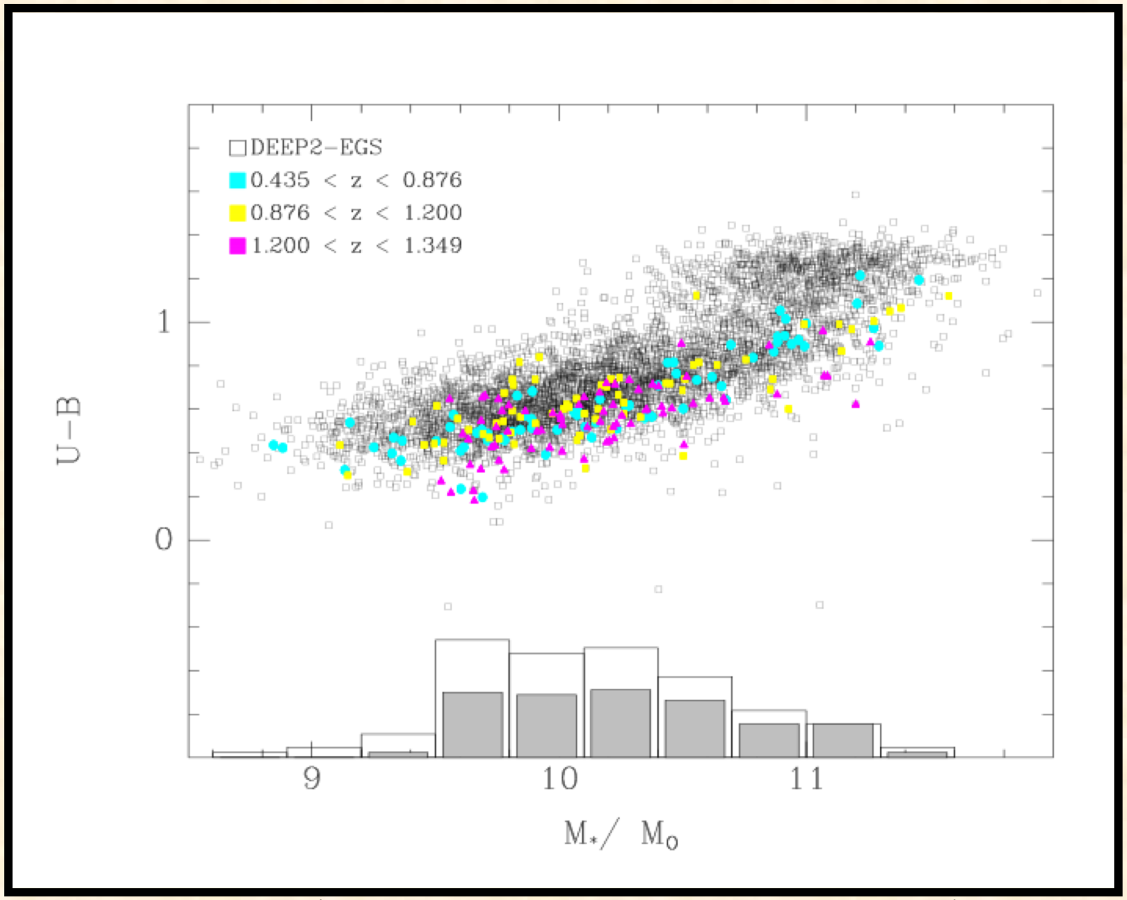

Log (Halo Mass):

11.25 - 14.24 @ z=1

11.20 - 14.70 @ z=0.5

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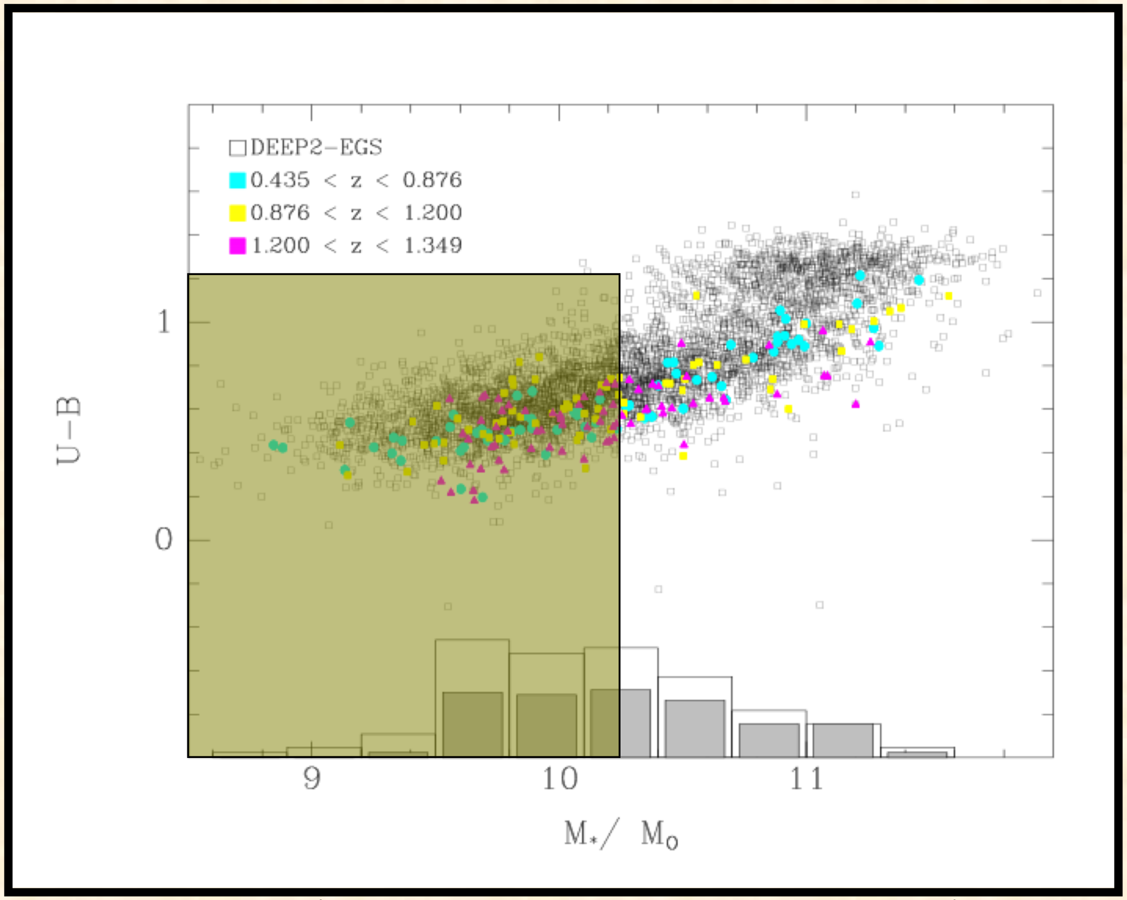

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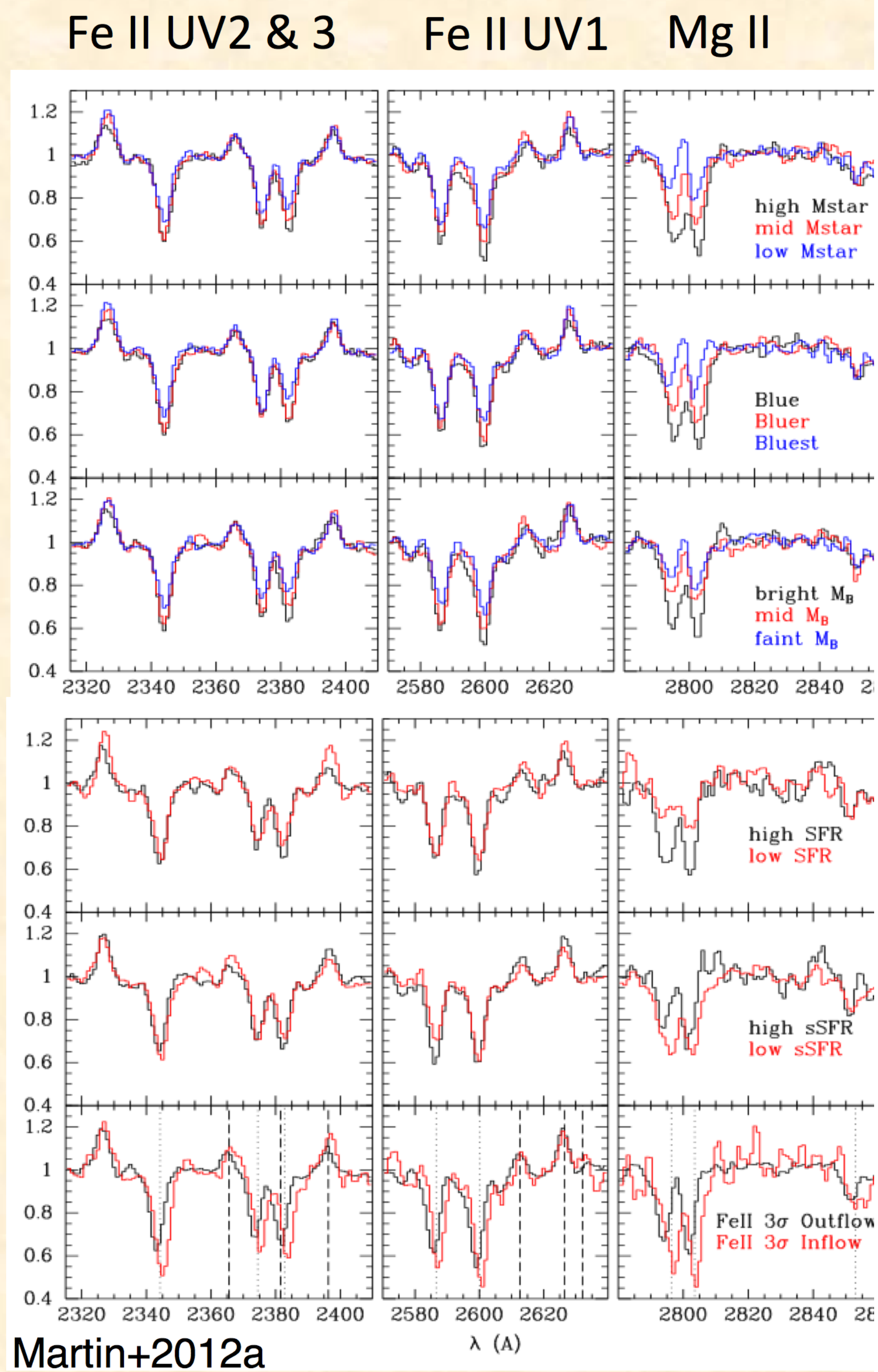
Composite Spectra:

<u>208 galaxies observed with Keck/LRIS</u>

1. More Mg II absorption at higher stellar mass, redder color, higher luminosity, and SFR. Why?
    - Stellar absorption? *Small effect.*
    - Interstellar absorption? *Yes.*
    - Emission filling? *Dominant Effect.*
2. Fe II absorption strength grows more slowly with stellar mass, redder color, higher luminosity, and SFR.
    - The transitions that scatter change more rapidly than those that mainly fluoresce.
    - Clearly more emission filling in lower mass, bluer, lower luminosity, lower SFR galaxies.
3. Fe II outflow galaxies, -119 (6) km/s, have bluer MgII absorption reaching -900 (99) km/s.
4. FeII 2374 and FeII 2587, which usually fluoresce, provide the most accurate picture of the intrinsic absorption trough.



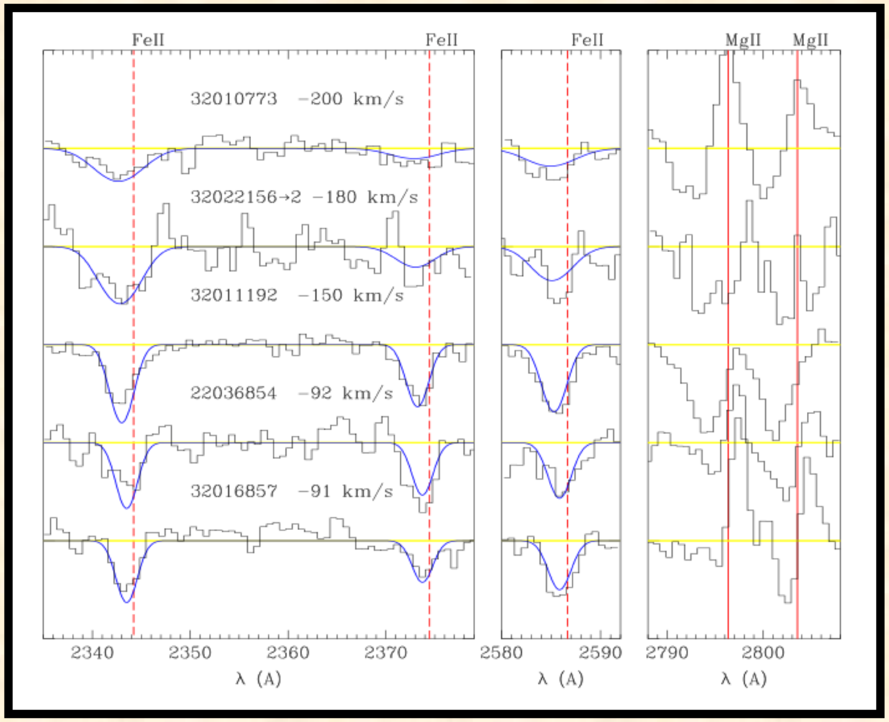
Martin+2012a

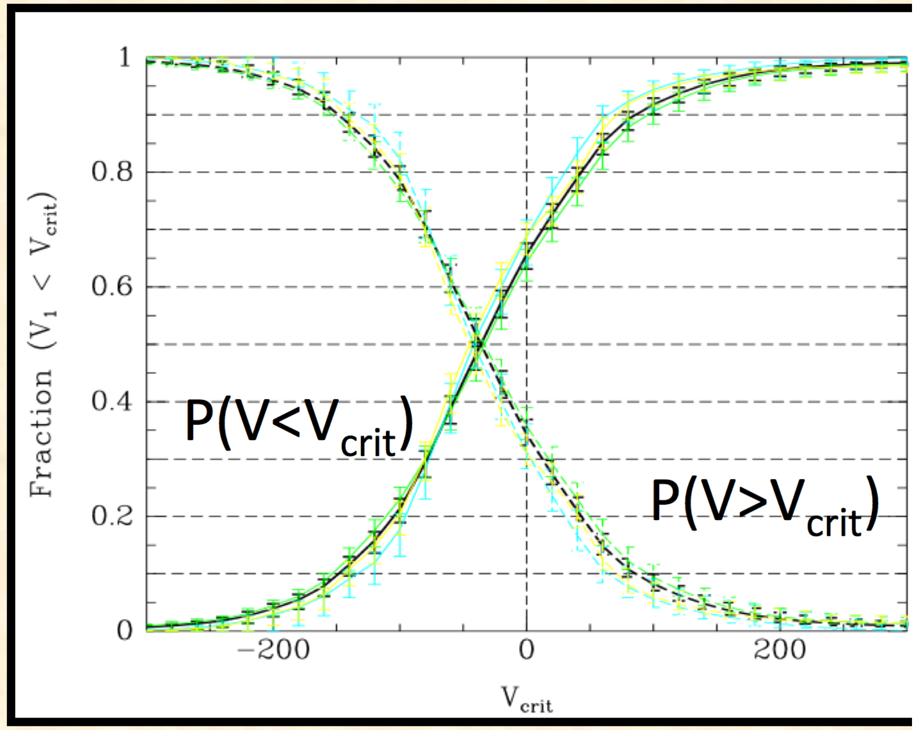
Individual Spectra:

(1) Measure Fe II Doppler Shift (V_1) and bluest Mg II absorption (V_{max})

(2) Compute Outflow Probability

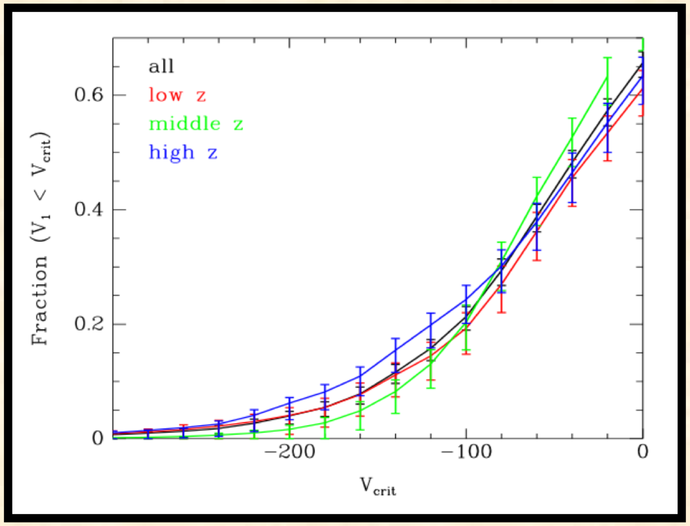
Martin + 2012a



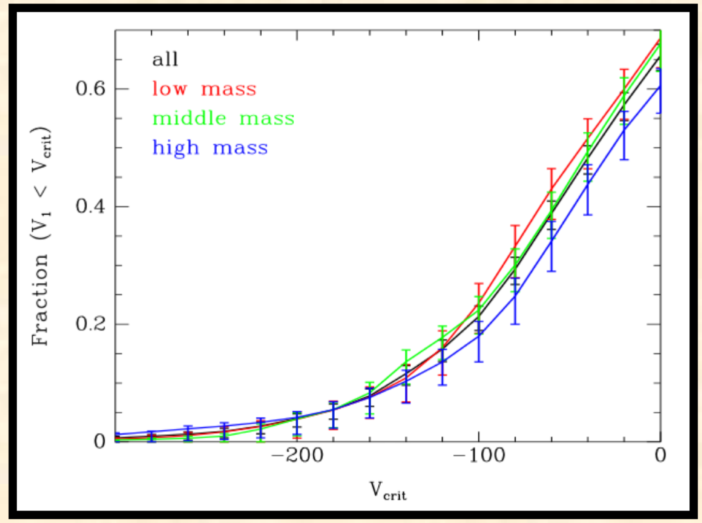


- V_1 is the mean of the Gaussian probability density distribution for the Doppler shift.
- Calculate $P(V < V_{crit} \mid V_1, \sigma)$ for each galaxy
- Find the average probability for the entire sample.
- Calculate the 68.3% confidence interval from the cumulative probability distribution

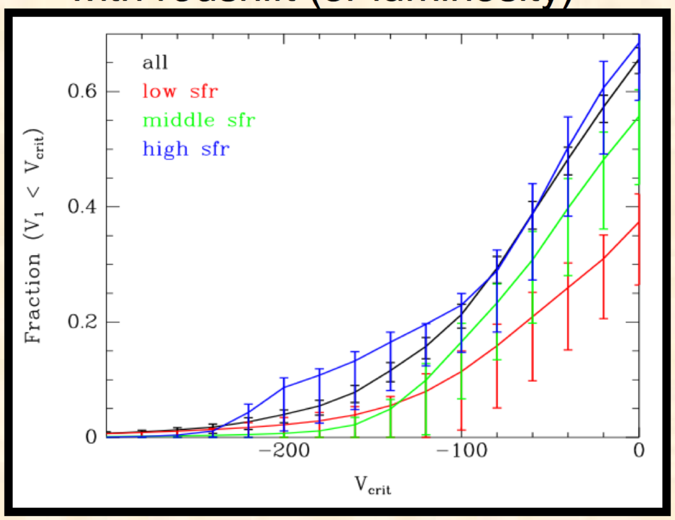
Doppler Shift of Fe II Absorption



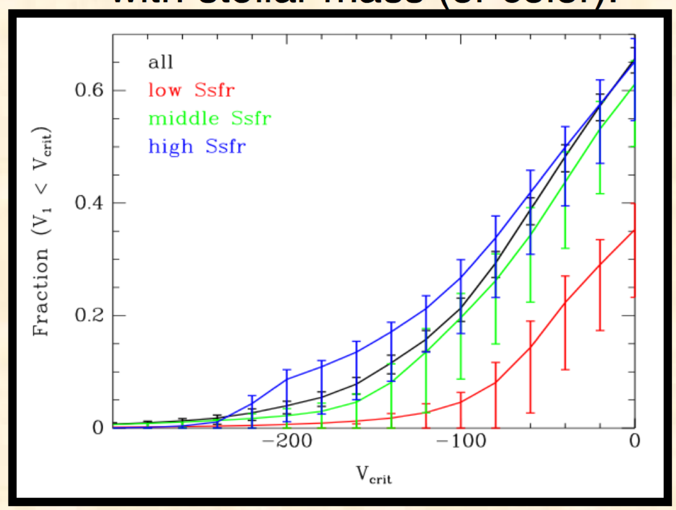
1. Small increase in outflow fraction with redshift (or luminosity)



2. No increase in outflow fraction with stellar mass (or color).

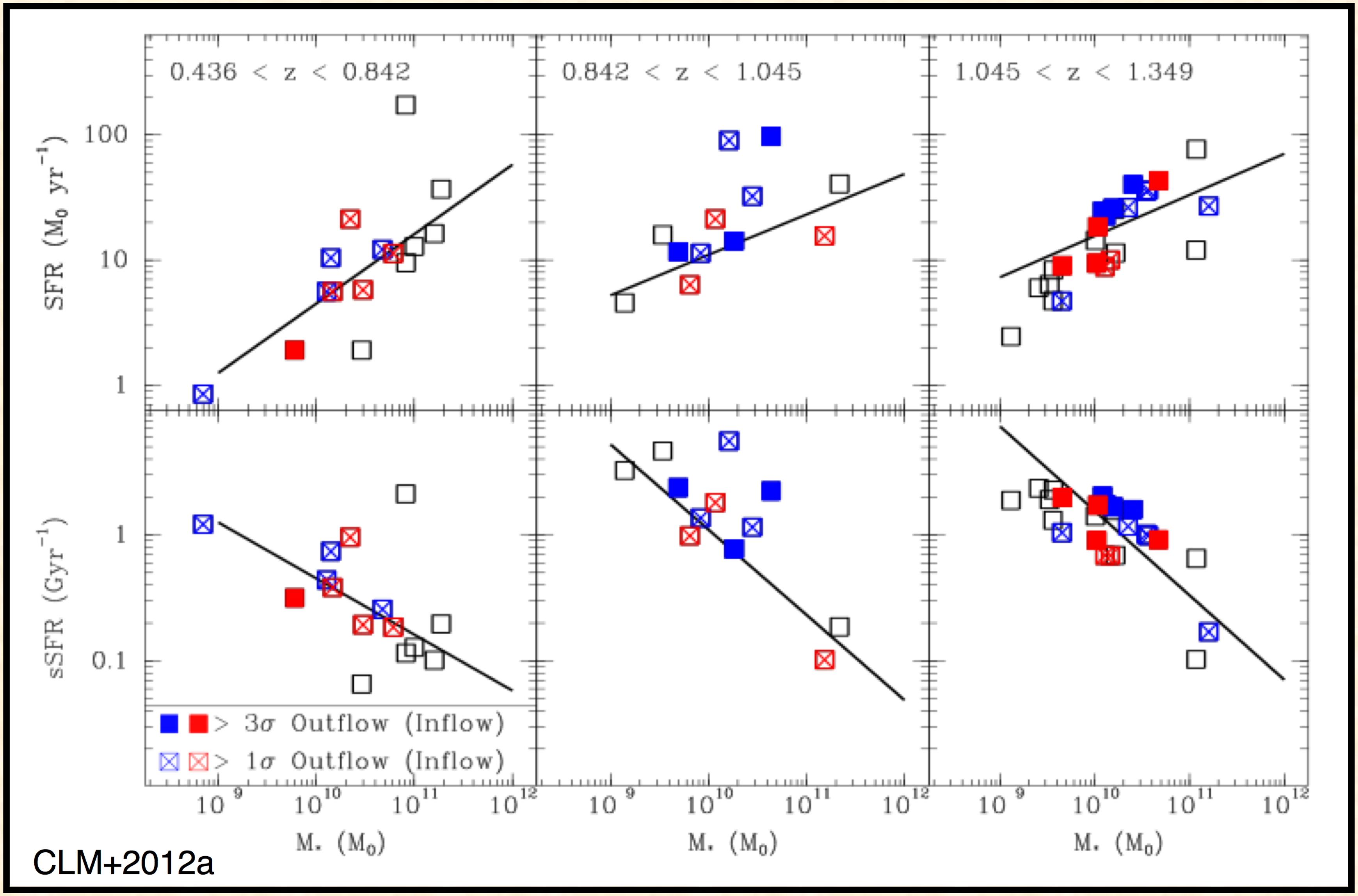


3. Outflow fraction increases by factor of ~2 from SFR of 12 to 60 M_0/yr



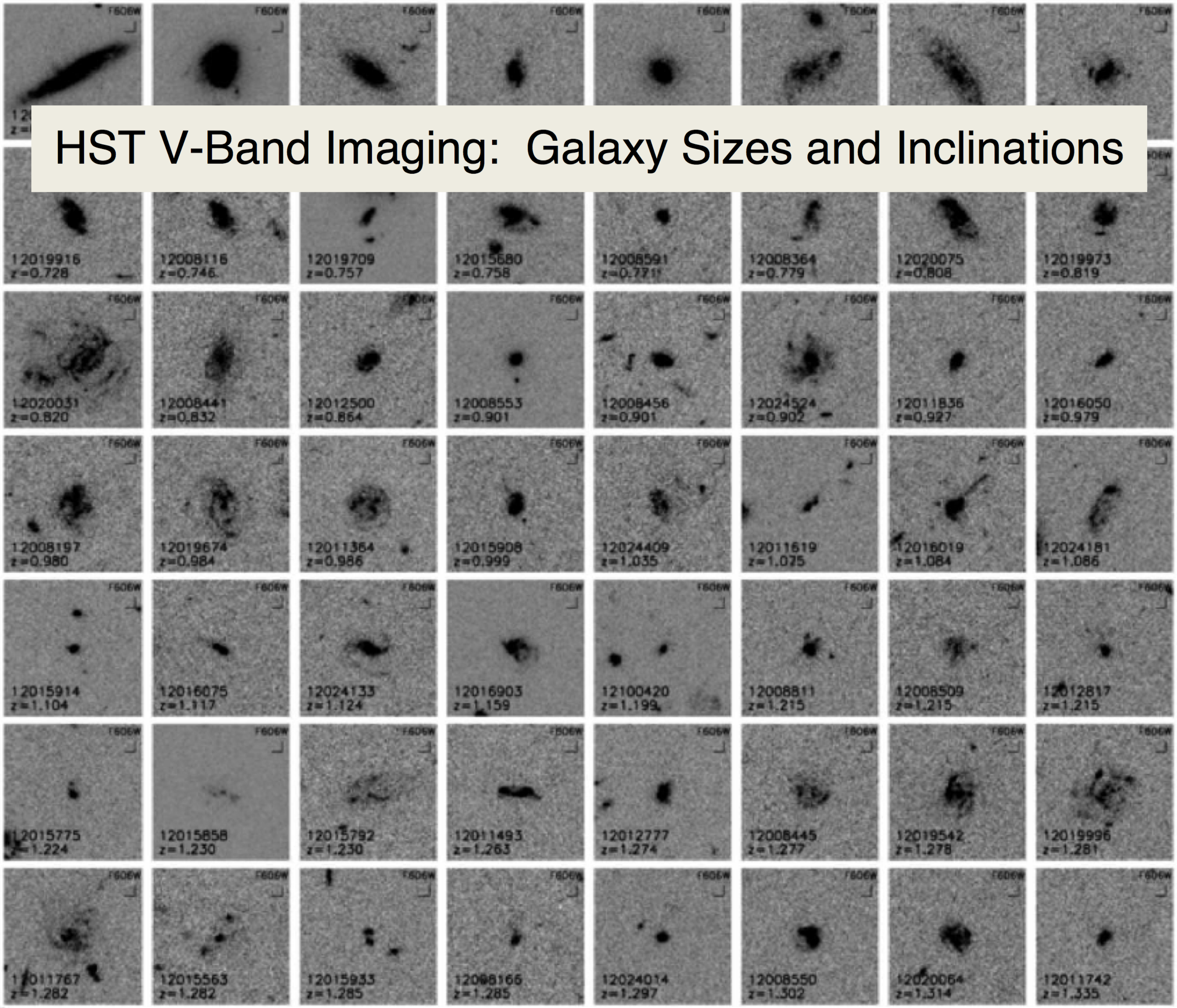
4. Outflow fraction increases by factor of ~5 from $(sSFR)^{-1}$ of 3.8 Gyr to 500 My

Properties of Galaxies with Fe II Doppler Shifts



Galaxies with outflowing gas have higher than average specific SFR; sSFR > 1 Gyr^{-1}.

HST V-Band Imaging: Galaxy Sizes and Inclinations



Kornei + 2012

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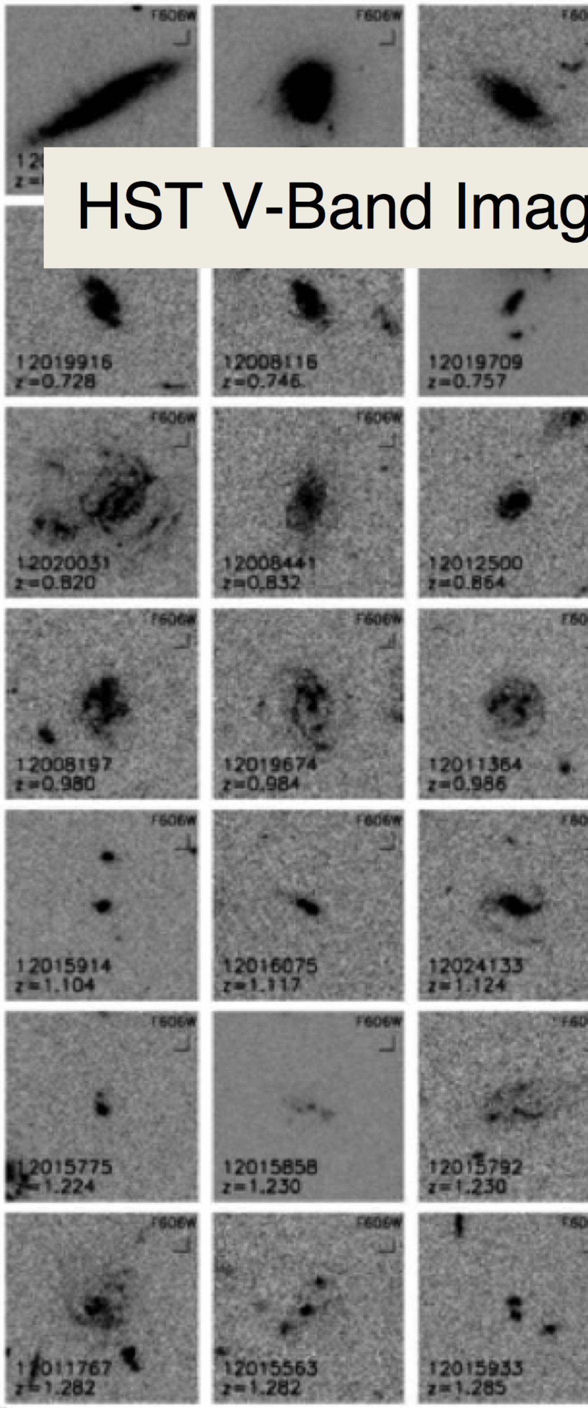
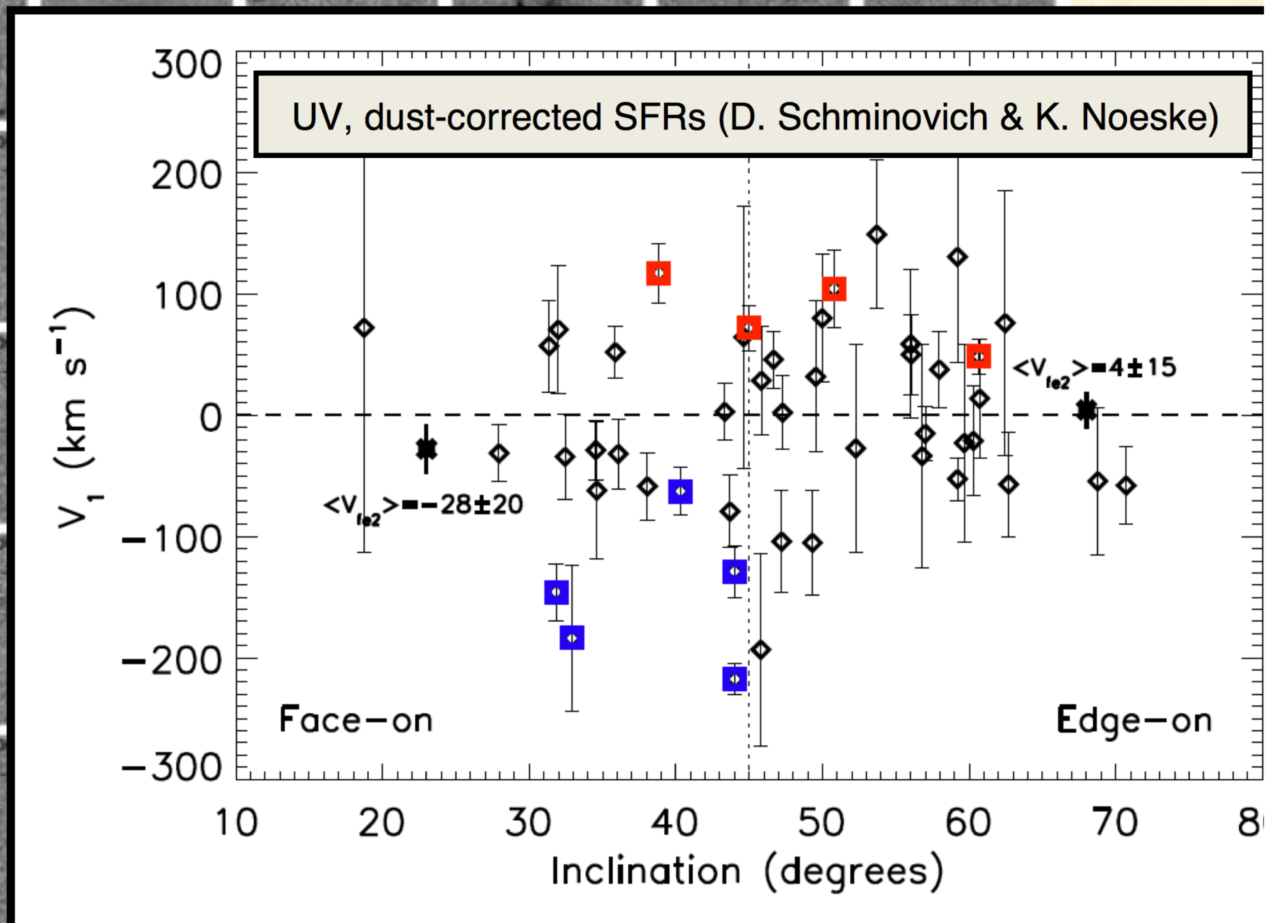
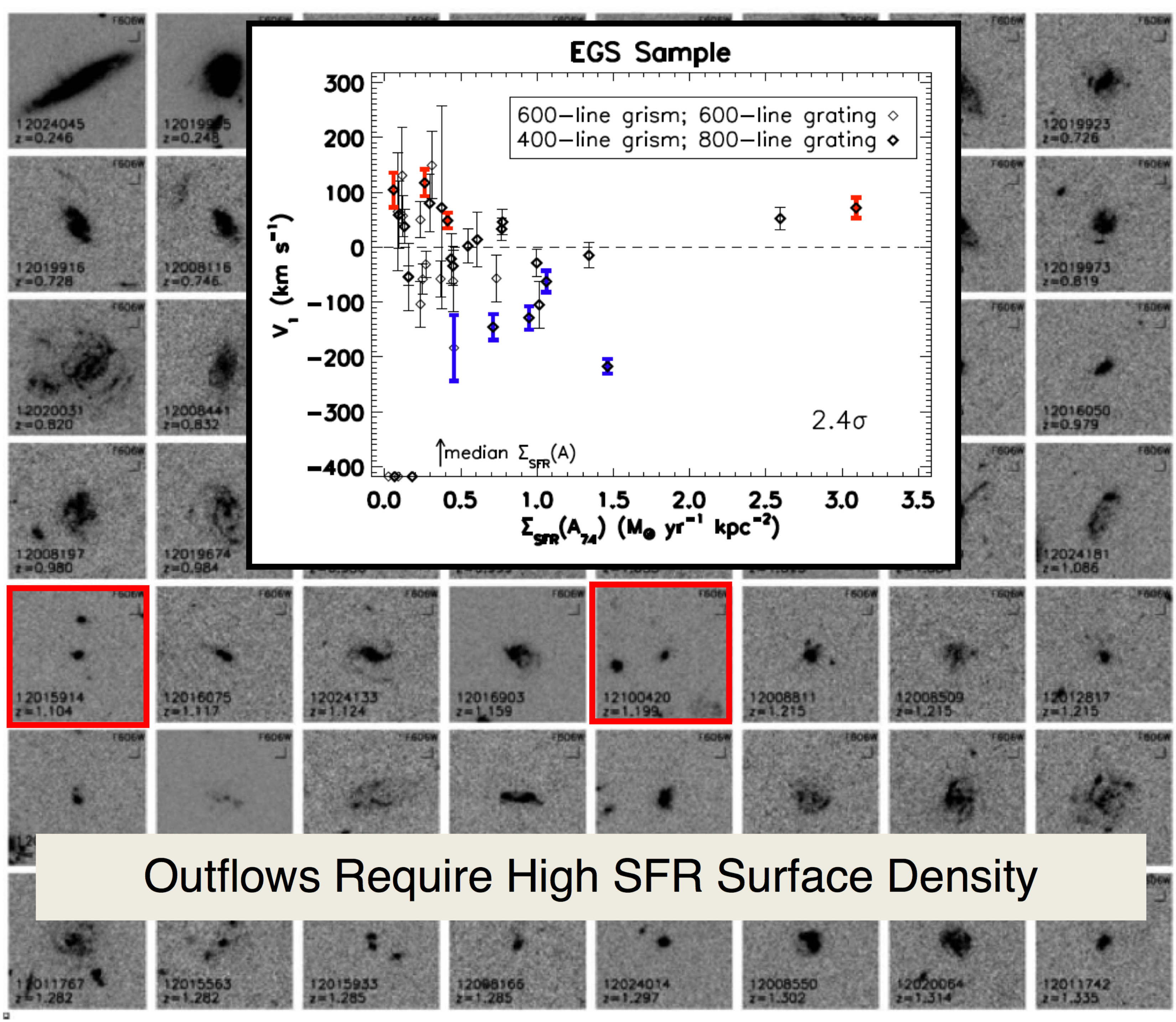


Kornei + 2012

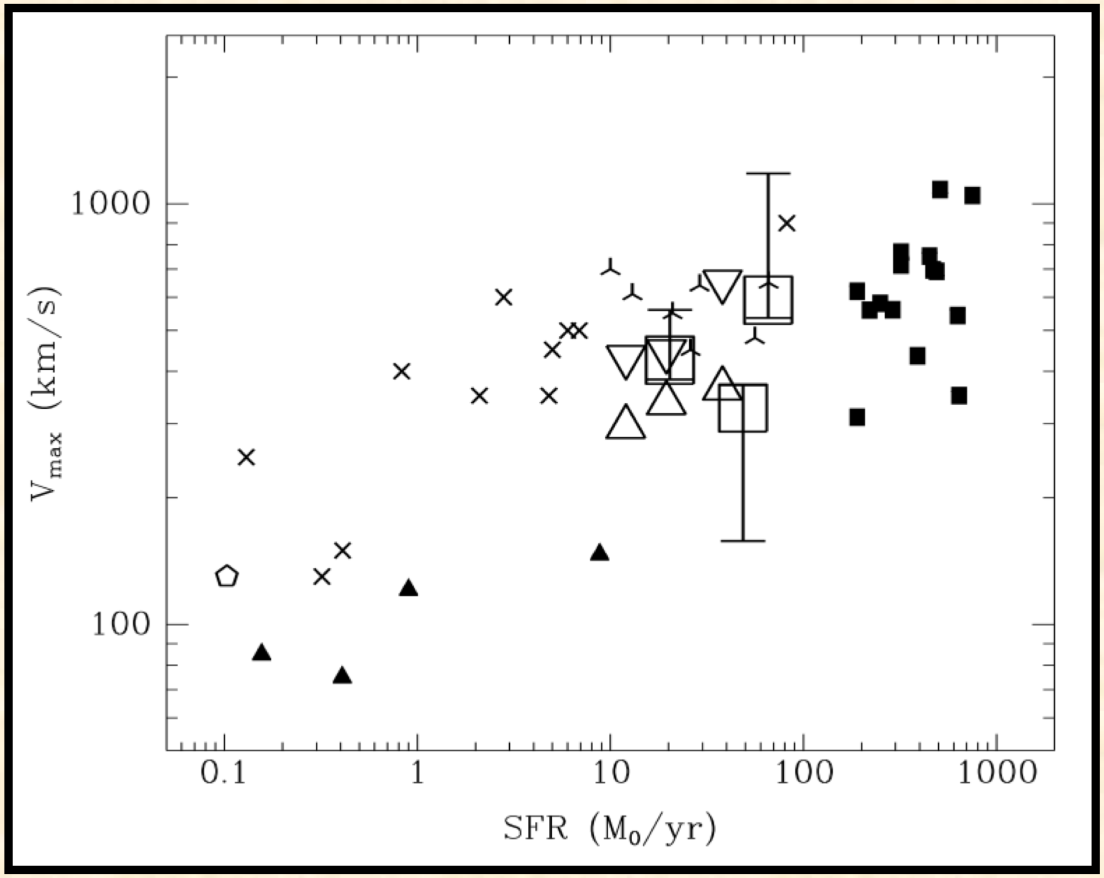




Kornei + 2012

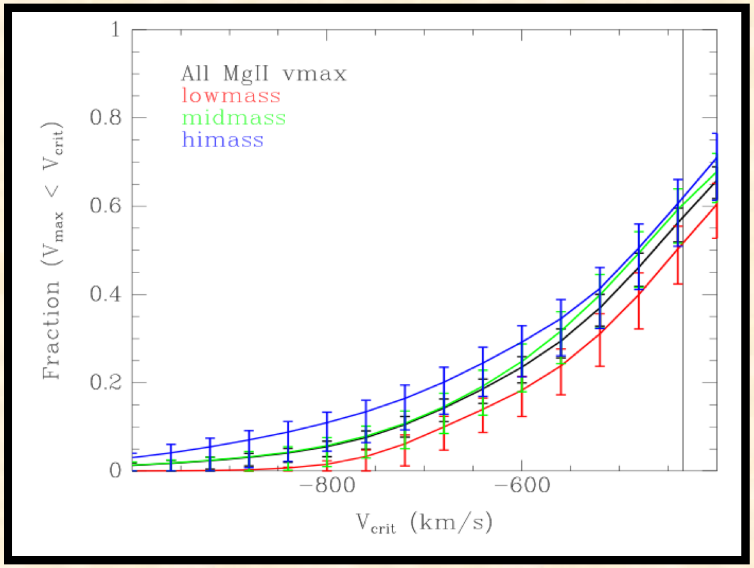
Outflows Require High SFR Surface Density

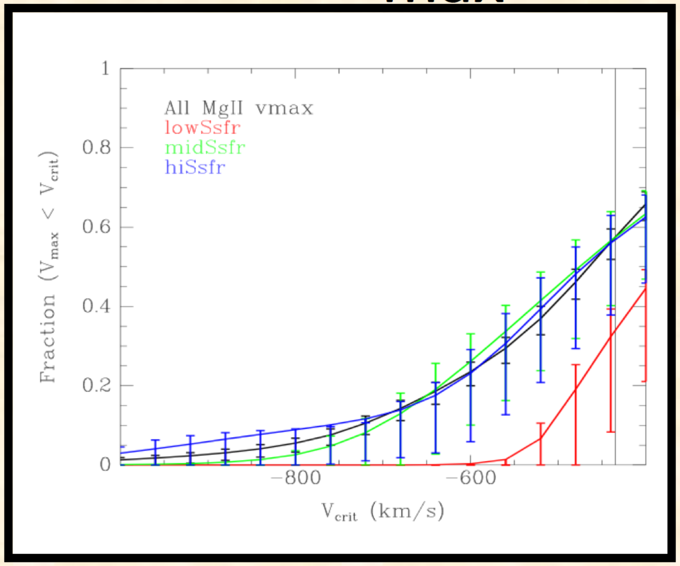
Outflow Speed vs. Galaxy Properties



- Martin 2005 found V(NaI) ~ $SFR^{0.35}$; confirmed by Weiner+2009 for V_{max}(MgII)
- Variations at fixed SFR are too large to see trends with SFR over just one decade.
- Weiner+2009 found V_{max} increase with stellar mass, which we confirm
- V_1(FeII) is not strongly correlated with any galaxy parameter.

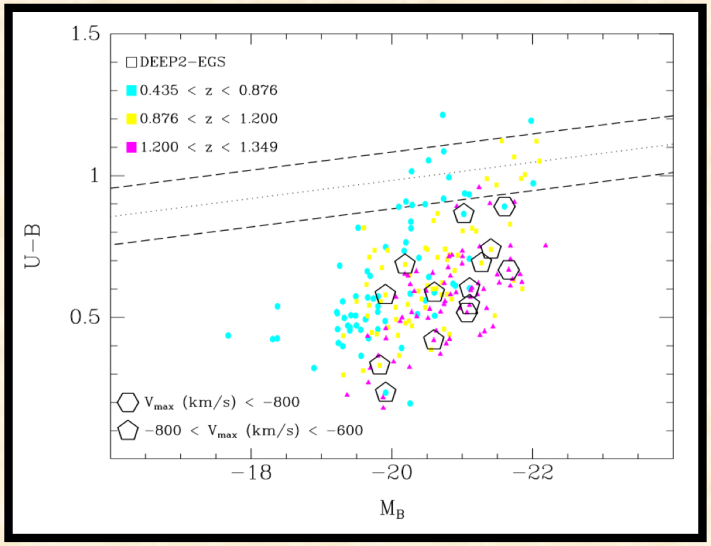
Max. Absorption Blueshift: V_{max}(MgII)



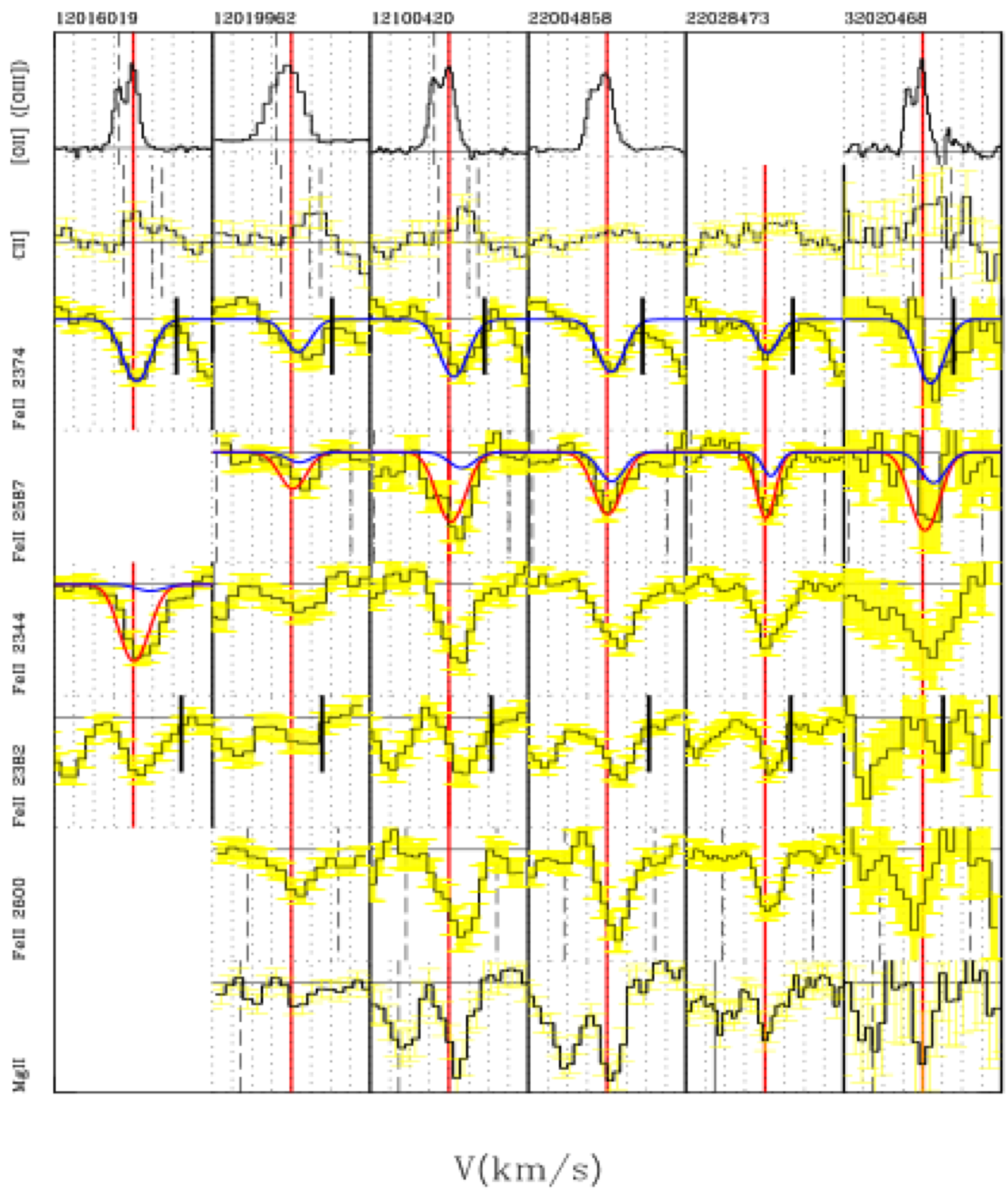


5. Fraction with blue wing increases slightly with mas, luminosity, and color.

6. Compared to V_1, fraction with blue wing is less sensitive to sSFR (and SFR).



- The V_{max} and V_1 measurements are not correlated (r_s= 0.17; 0.93σ).
- A blue wing on the Mg II profile is more common at higher stellar mass, redder color, and higher luminosity.



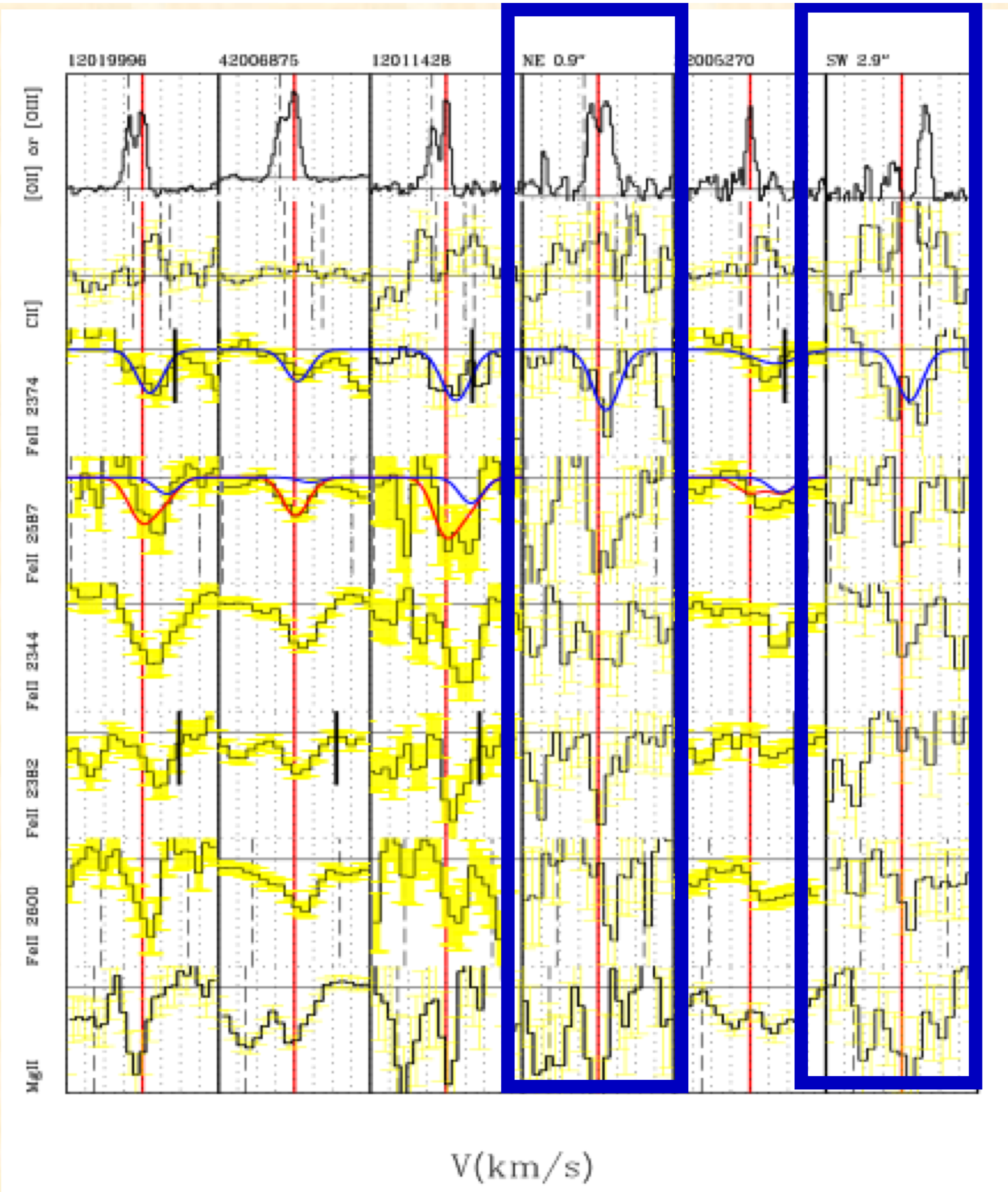
z~1 Inflow Galaxie

- Fe II centroid velocity significantly redshifted in 10 galaxies
- Possible origins: tidal flows, cold accretion, cooling hot halo, recycled wind

INFLOW PROPERTIES:

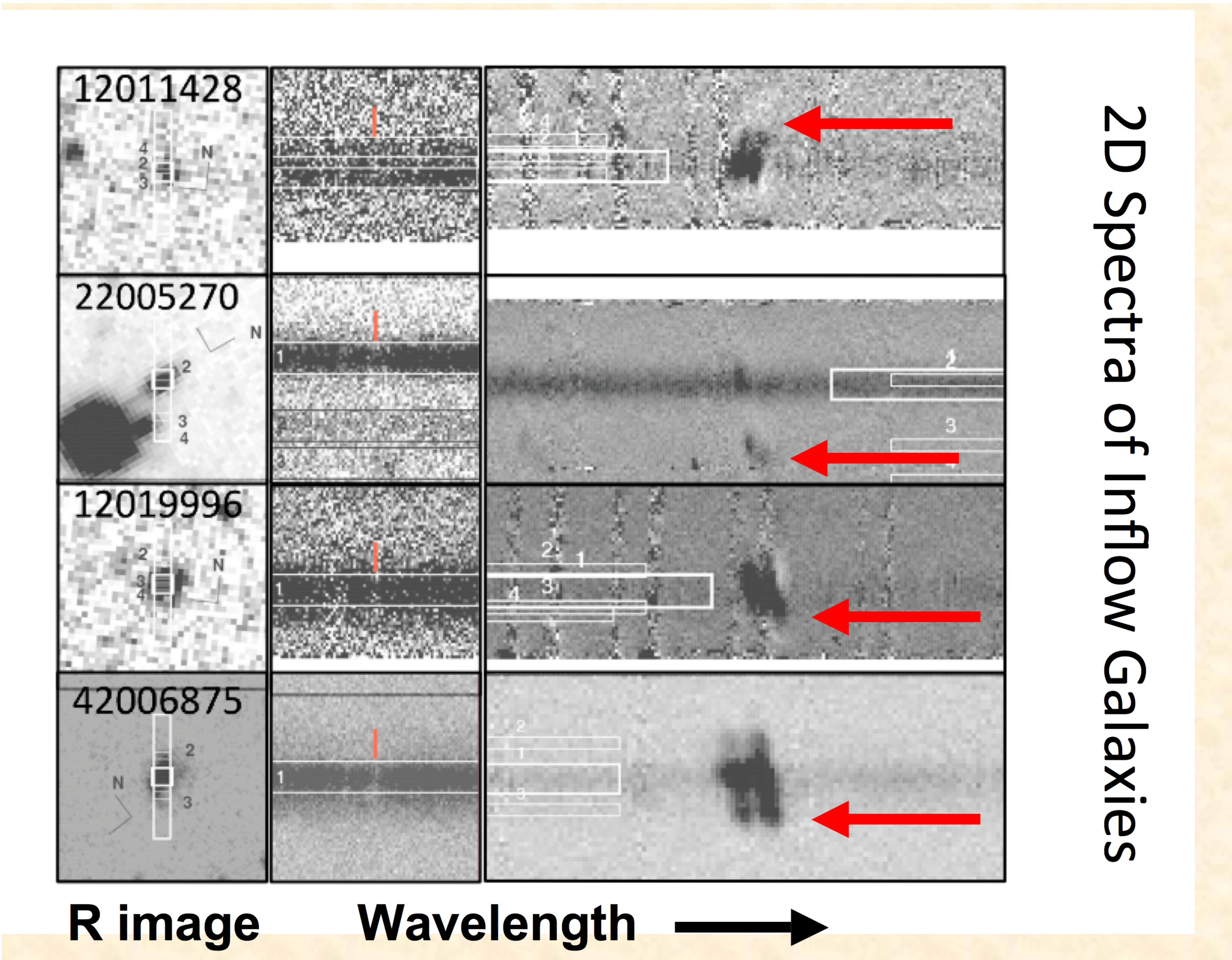
- Rare (10/208 ~ 5%)
- V_1 ~ 100 - 200 km/s
- V_{max} ~ 300-800 km/s
- Total log N(FeII) = [14.8,16.0]; and log N(FeII) > 13.5 (14.8) in Doppler component
- Implies log N(H) > 18 (19.3) - log(Z/Z_0)

See also Rubin+2011 arXiv:1110.0837.



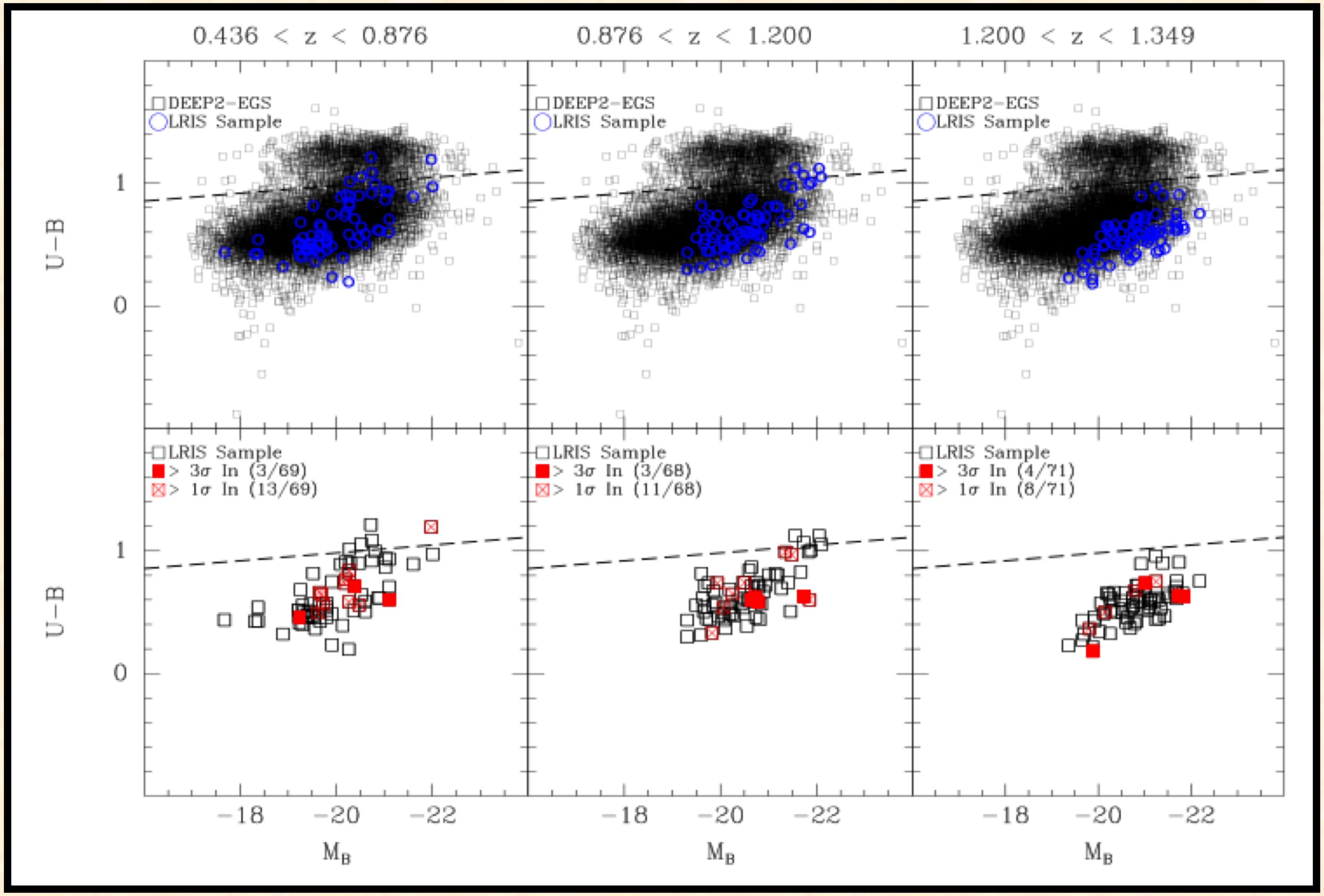
Z~1 Inflow Galaxies

- Doppler shift of resonance absorption off the nucleus is similar to velocity towards the nucleus.
- Hence the absorption appears to originate in a structure covering at least 10's of kpc.


12011428
22005270
12019996
42006875
R image
Wavelength
2D Spectra of Inflow Galaxies

Demographics of Galaxies with Fe II Inflows

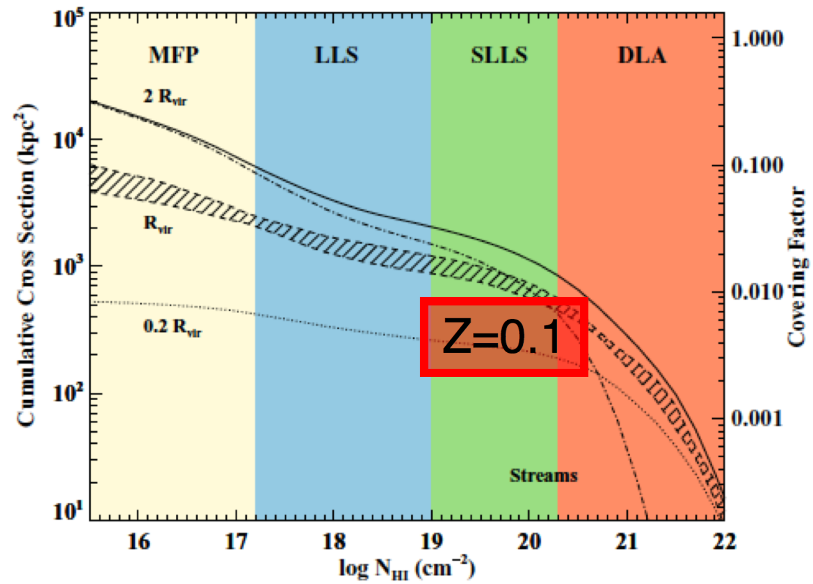
- Fraction does not change with redshift.
- Fraction (among blue galaxies) does not change with M*.
- Fraction (among all galaxies) likely decrease with increasing M*.
- The inflow galaxies are not post-SB as found at lower redshift (Sato + 2009)

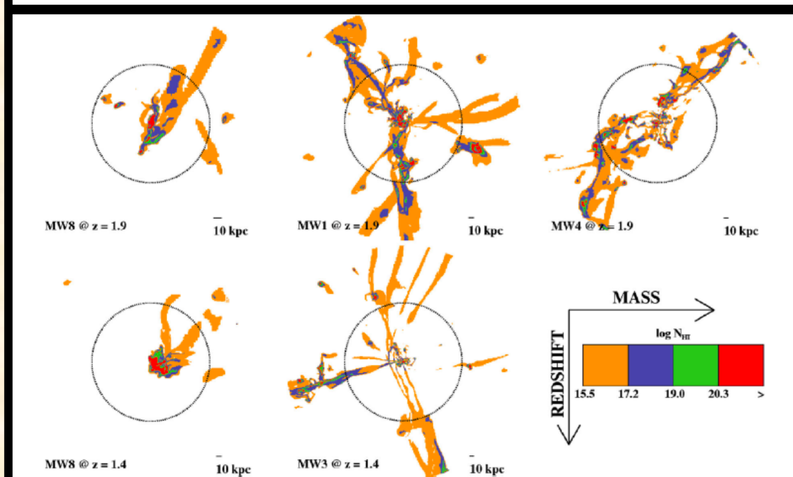


Simulated Gas Inflows in Galaxies

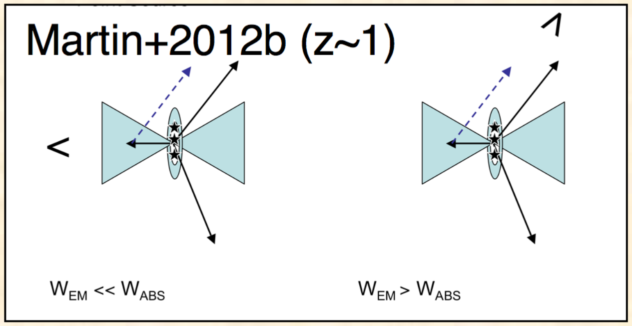
Dekel + 2009; Kimm + 2011; **Fumagalli + 2011**; Faucher-Giguere + 2011; Stewart + 2011a,b; Goerdt + 2011

- Cross section threaded with cool gas is expected to be much larger than a galaxy.
- Accreted gas orbits with high angular momentum.
- Covering fraction declines with increasing column density
  - Few percent for log N(H) > 20.3 at b = 100 kpc
- Metallicity of accreting gas is highly model dependent.
  - Impossible to see in a metal line
  - Mixed with recycled gas near galaxy?



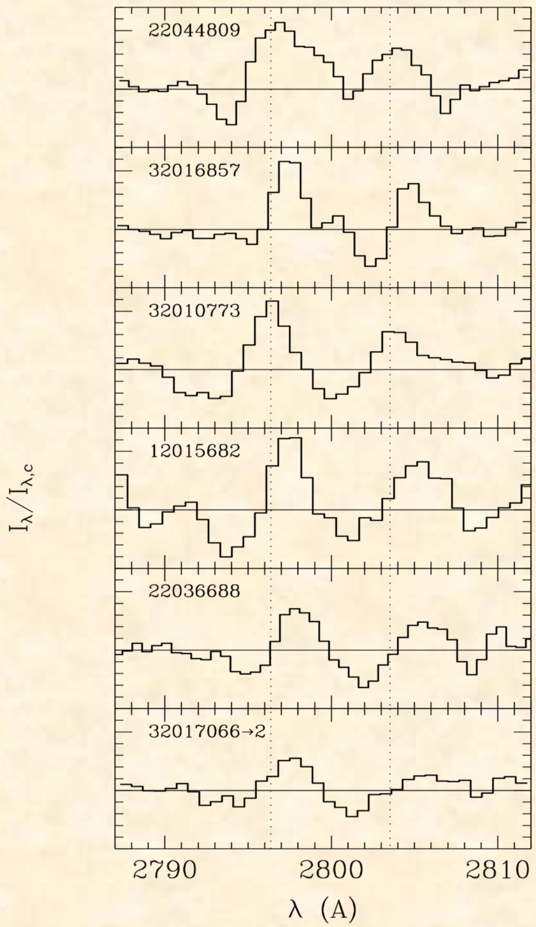


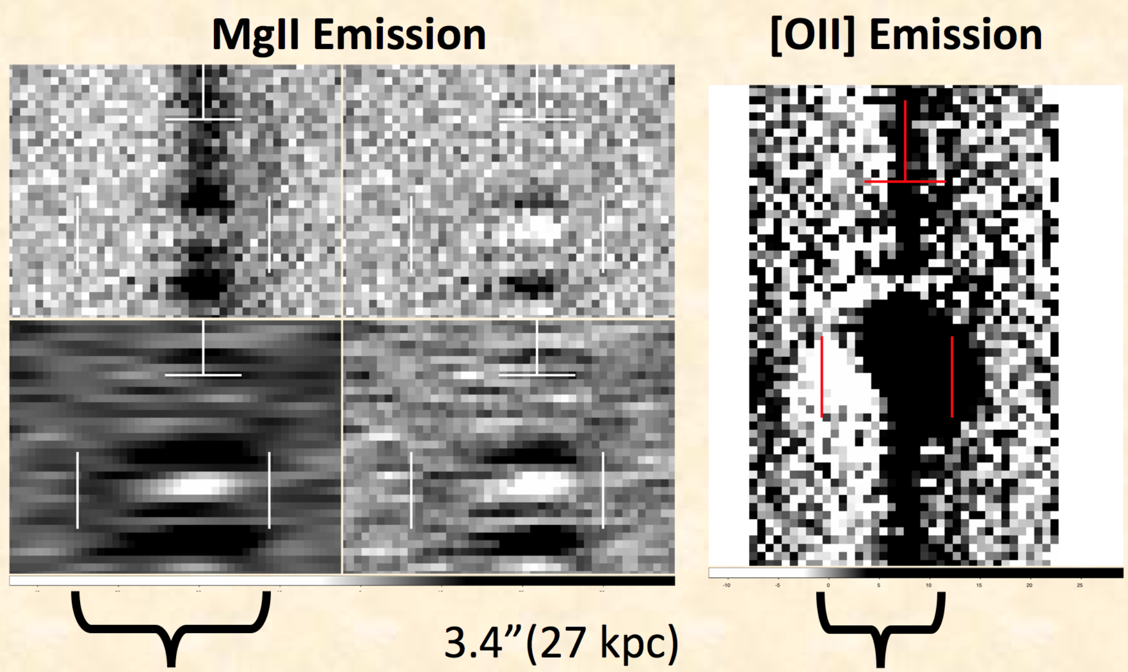
Mg II Emission in Galaxy Spectra



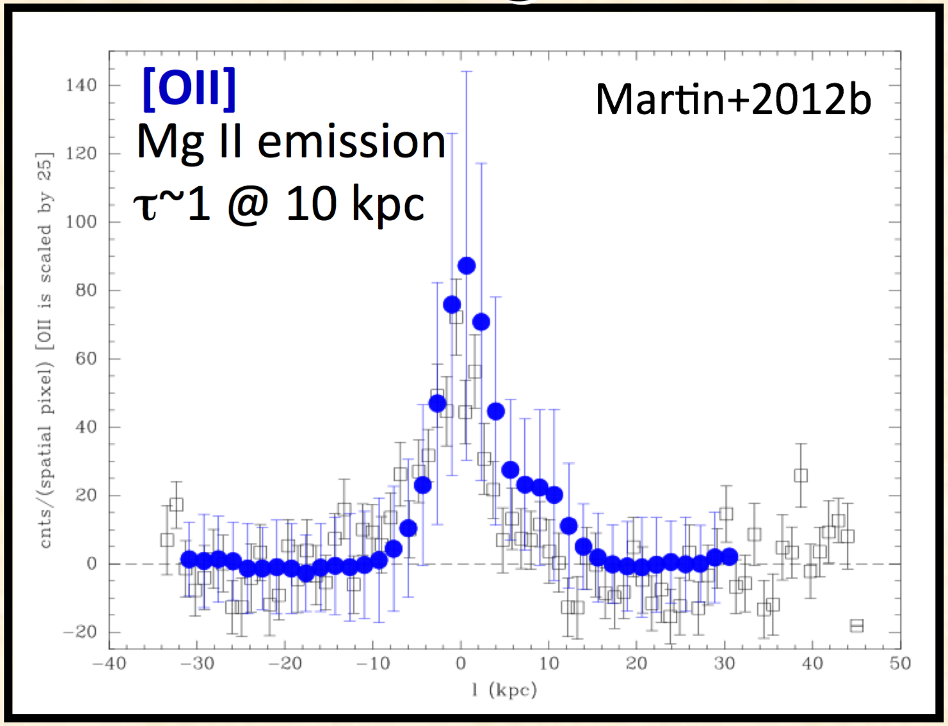
See also Weiner+2009(z~1.4); Martin & Bouche 2009 (z~0.3); Rubin + 2010, 2011 (z~1); Erb+2012 (z~1.6)

- Strongest in lower mass, bluer galaxies
- Scattered photons
  - Prochaska+2011 present simple models
  - Destroyed by dust
  - Depends on geometry
  - More extended than the galaxy
  - Not part of the gas disk kinematically

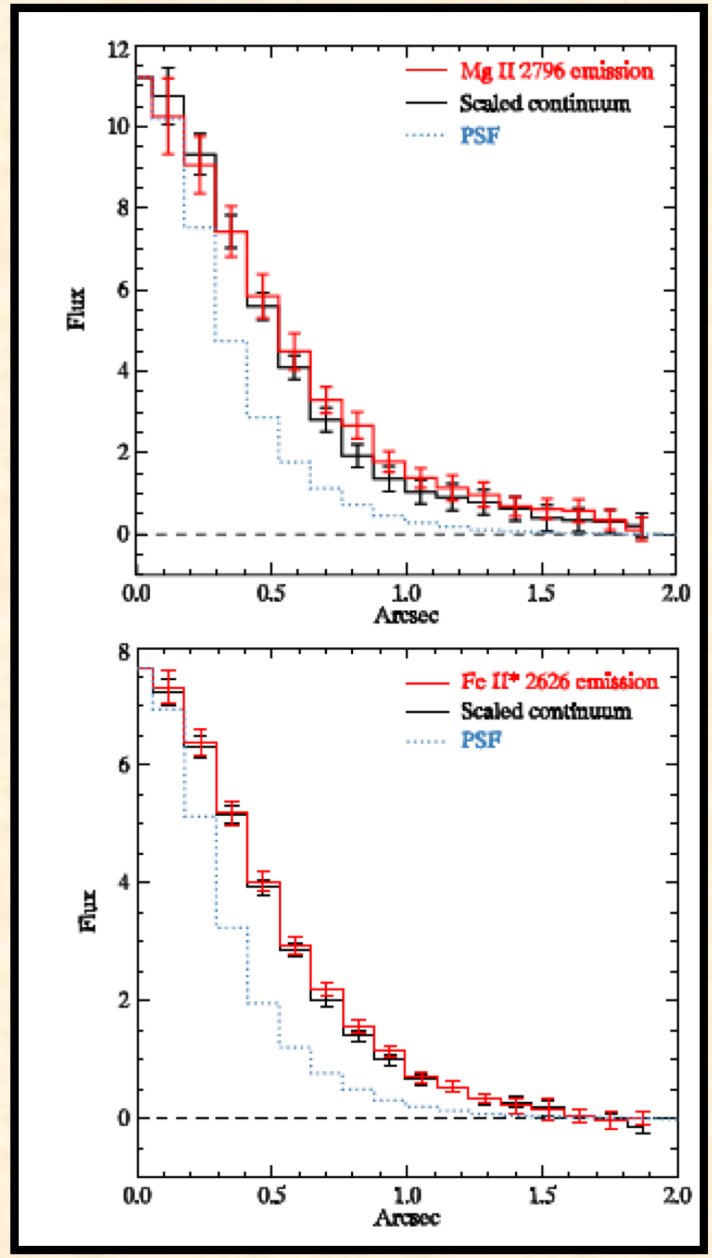




Scattered Mg II Emission Constrains Gas Density



Stacks of z=1.6 Galaxies (Erb+2012)



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

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

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

$dM/dt = \rho(r_s)\, \Omega(r_s)\, r_s^2\, v(r_s)$

$\sim 5\ M_o/yr \sim SFR$

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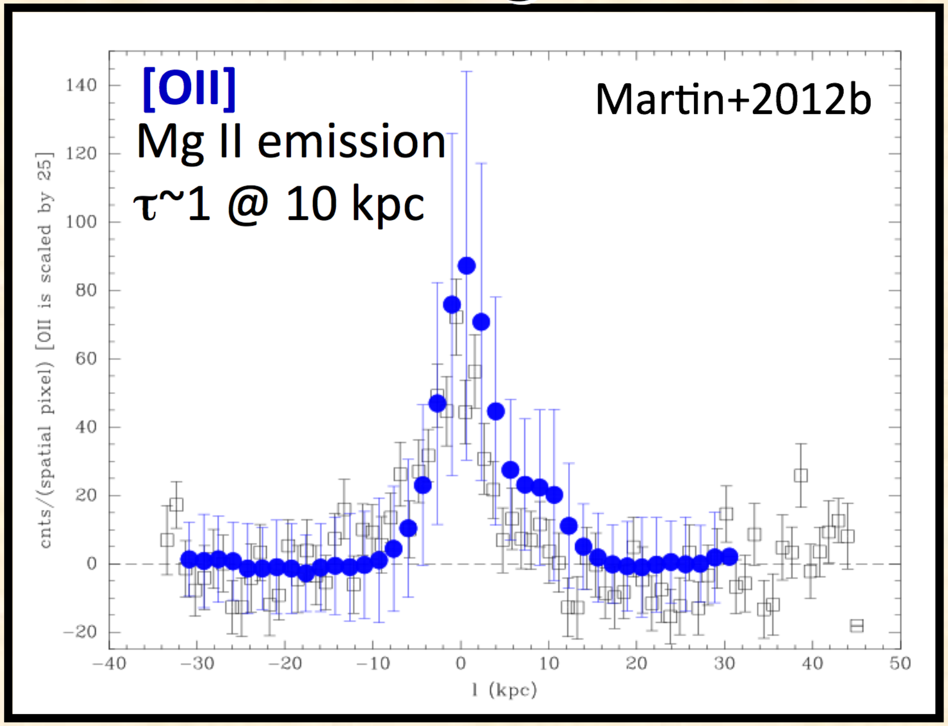

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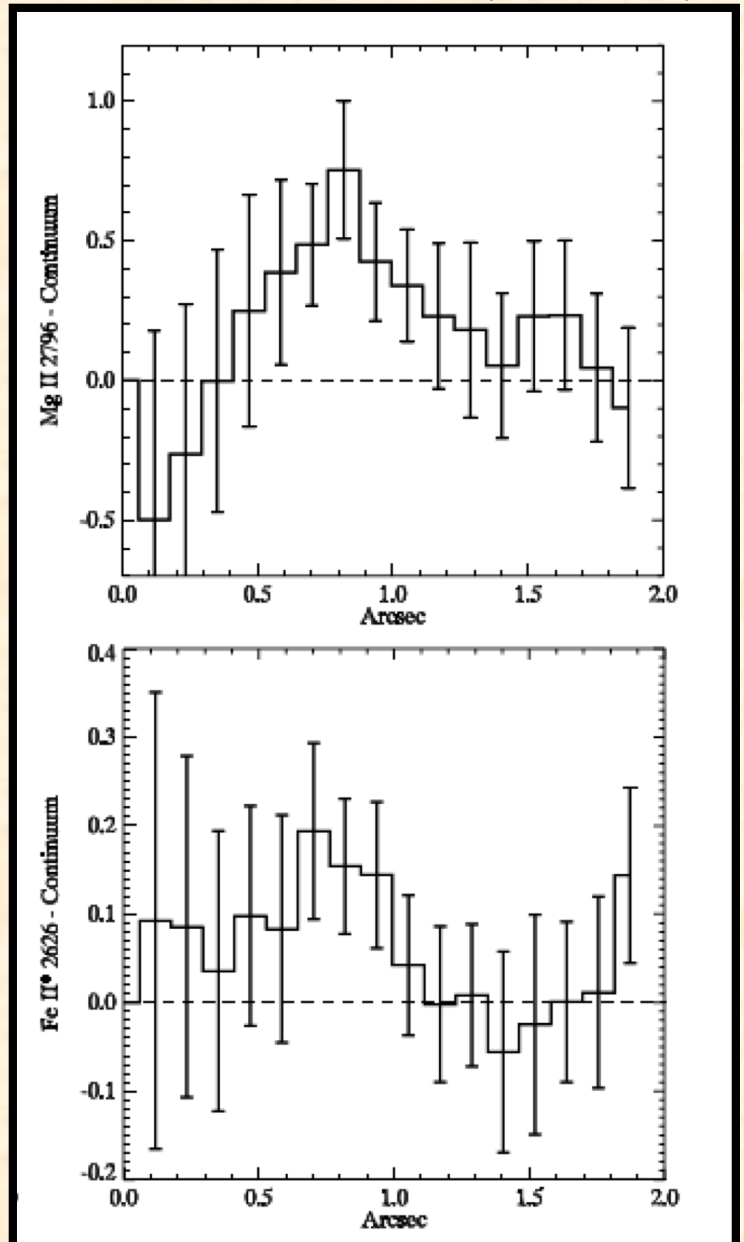

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Outflows/Inflows: Star-Forming Galaxies at 0.4 < z < 2.0

- Highest outflow fraction among 'starburst galaxies'
  - Increases for specific SFR > 1 Gyr^{-1}
  - Increases for high SFR surface density
  - No change with M_*
  - Slight increase with z due to evolution of sSFR
- Fraction of galaxies with blueshifted, resonance absorption lines is less than unity.
  - 50% have $V_1 <$ -50 km/s
  - 20% have $V_1 <$ -100 km/s
  - 5% have $V_1 <$ -200 km/s
- Outflow Properties
  - Opening angle << 4 pi
  - V_{max} increases with M*
  - Doppler shift increases slowly with stellar mass
  - Total Log N(FeII) = 14.6 - 16.3
  - Doppler Log N(FeII) = 13.9 - 15.8
- Inflow Properties
  - V_1 = 100-200 km/s
  - Not more common at higher redshift
  - Not more common at lower M_*
  - About 5% at log N(H) ~ 18 - 19 in Doppler component

FOR FURTHER DETAILS, SEE:

Erb+2012 (astro-ph soon)

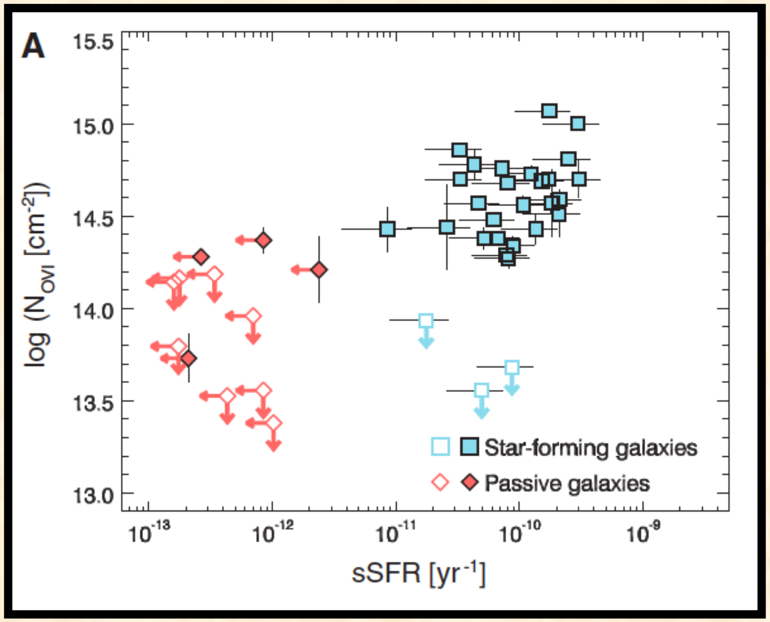
Kornei+2012 arXiv:1205.0812

Martin+2012a (astro-ph soon)

Soto+2012 arXiv:1205.0083

Soto+2012 arXiv:1205.0082

OVI Absorption for sSFR > [Tumlinson + 2011]



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  - Total Log N(FeII) = 14.6 - 16.3
  - Doppler Log N(FeII) = 13.9 - 15.8
  - dM/dt ~ few M_0/yr
- Inflow Properties
  - V_1 = 100-200 km/s
  - Not more common at higher redshift
  - Not more common at lower M_*
  - About 5% at log N(H) ~ 18 - 19 in Doppler component

FOR FURTHER DETAILS, SEE:

Erb+2012 (astro-ph soon)

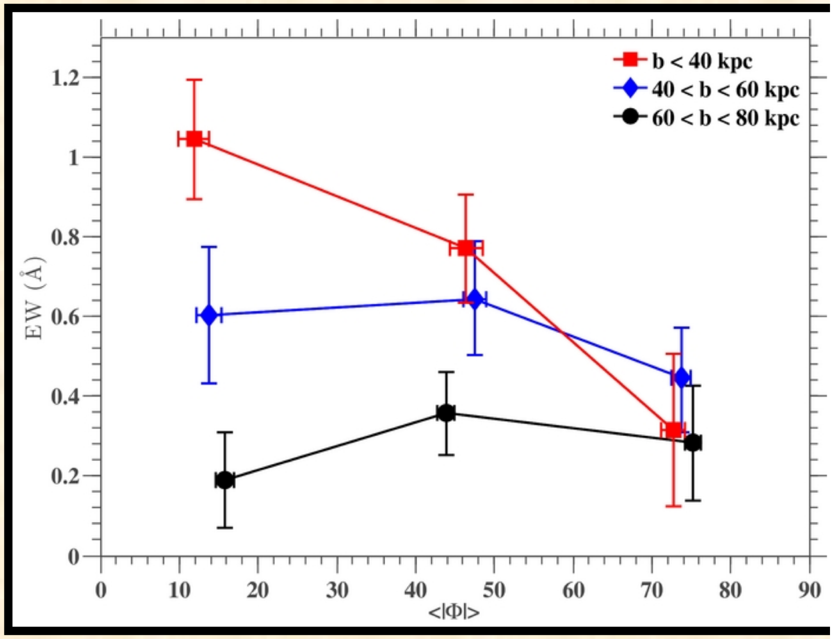
Kornei+2012 arXiv:1205.0812

Martin+2012a (astro-ph soon)

Soto+2012 arXiv:1205.0083

Soto+2012 arXiv:1205.0082

Bordoloi + 2011; Bouche + 2012; Churchill +2012; Kacprzak + 2012



Outflows/Inflows: Star-Forming Galaxies at 0.4 < z < 2.0

- Highest outflow fraction among 'starburst galaxies'
  - Increases (5x) from $sSFR^{-1}$ of 3.8 Gyr to 500 Myr
  - Increases for high SFR surface density
  - No change with M_*
  - Slight increase with z due to evolution of sSFR
- Fraction of galaxies with blueshifted, resonance absorption lines is less than unity.
  - 50% have $V_1 < -50$ km/s
  - 20% have $V_1 < -100$ km/s
  - 5% have $V_1 < -200$ km/s
- Outflow Properties
  - Opening angle << 4 pi
  - V_{max} increases with M*
  - Total Log N(FeII) = 14.6 - 16.3
  - Doppler Log N(FeII) = 13.9 - 15.8
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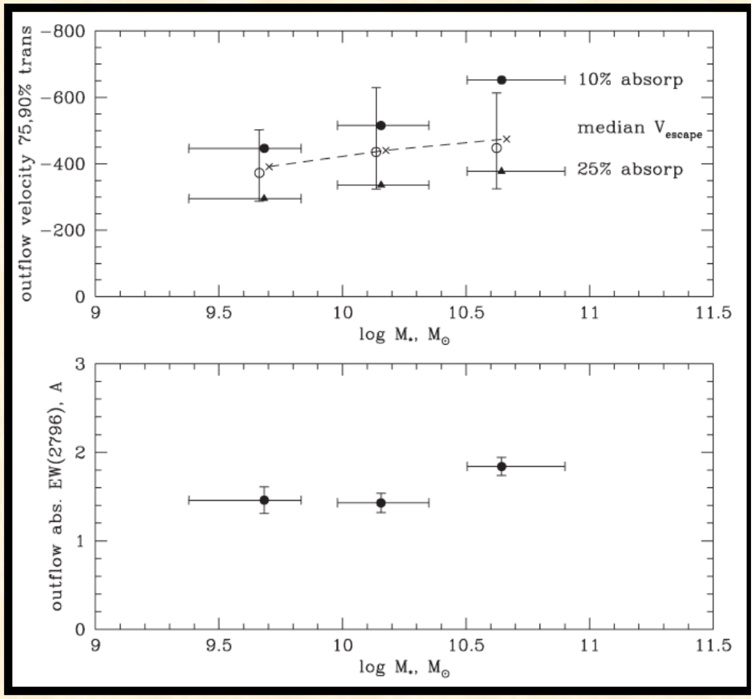
Soto+2012 arXiv:1205.0083

Soto+2012 arXiv:1205.0082

Weiner+2009



Outflows/Inflows: Star-Forming Galaxies at 0.4 < z < 2.0

- Highest outflow fraction among ‘starburst galaxies’
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- Fraction of galaxies with blueshifted, resonance absorption lines is less than unity.
  - 50% have $V_1 < -50$ km/s
  - 20% have $V_1 < -100$ km/s
  - 5% have $V_1 < -200$ km/s
- Outflow Properties
  - Opening angle << 4 pi
  - Doppler shift increases slowly with stellar mass
  - Total Log N(FeII) = 14.6 - 16.3
  - Doppler Log N(FeII) = 13.9 - 15.8
- Inflow Properties
  - V_1 = 100-200 km/s
  - Not more common at higher redshift
  - Not more common at lower M_*
  - About 5% at log N(H) ~ 18 - 19 in Doppler component

FOR FURTHER DETAILS, SEE:

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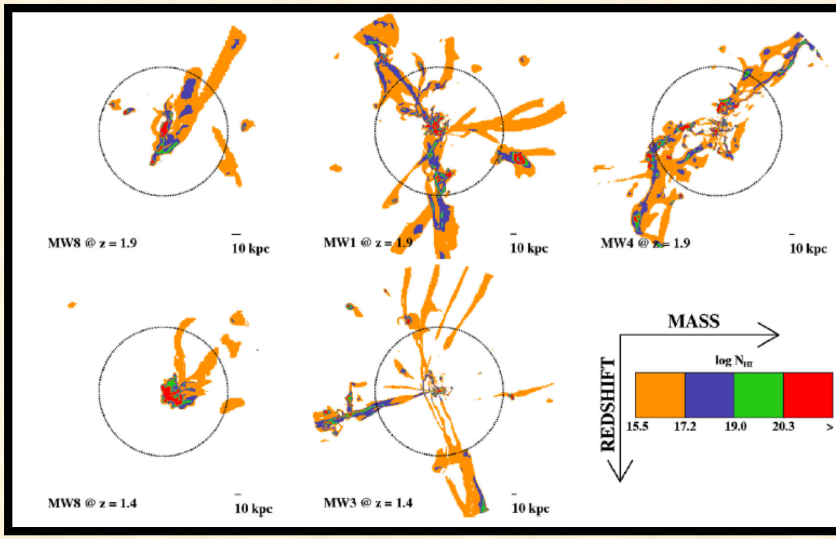
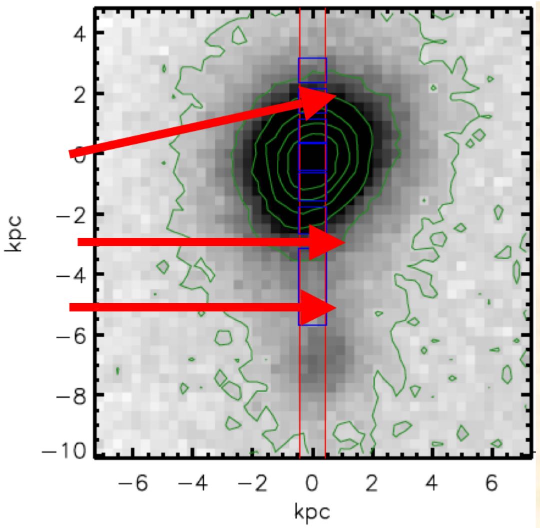


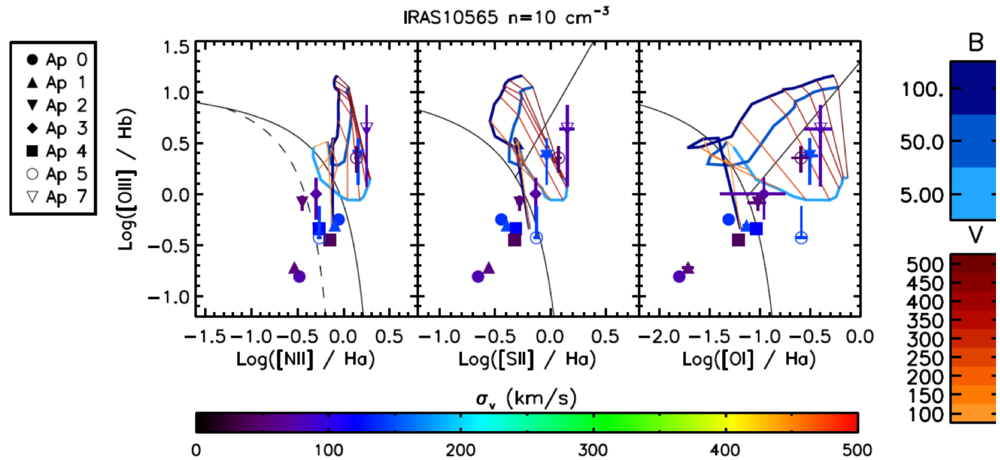
Relation of Outflow Emission and Absorption

300 km/s

300 km/s

400 km/s



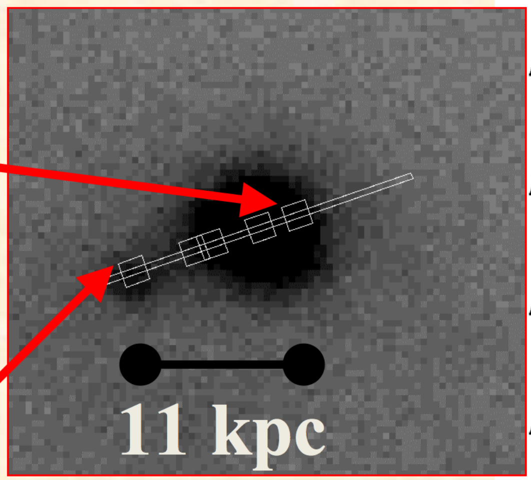


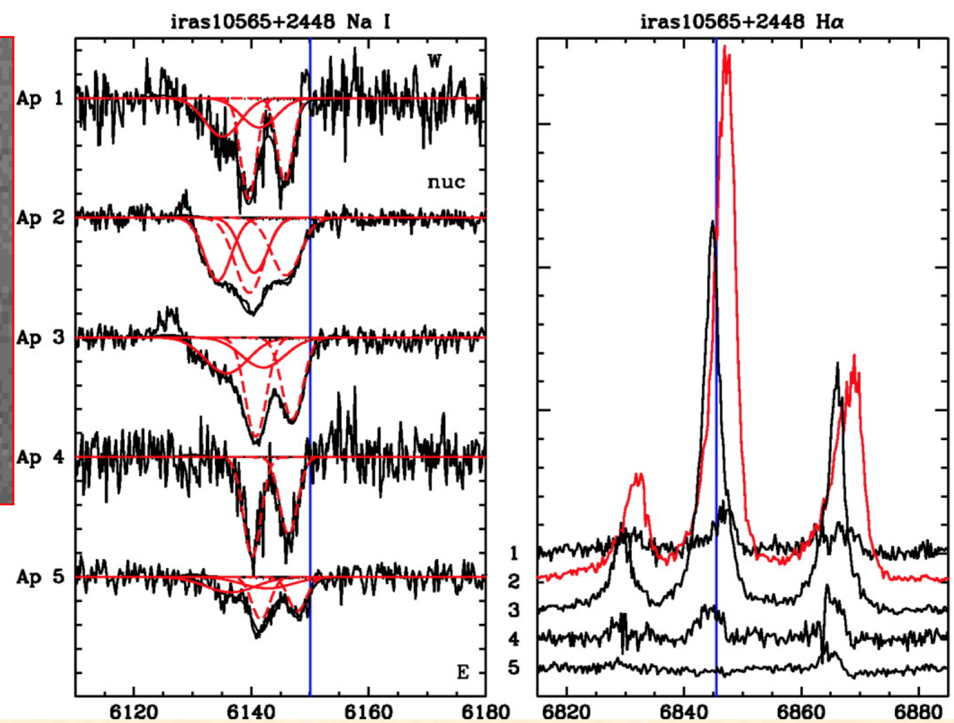
-430 km/s

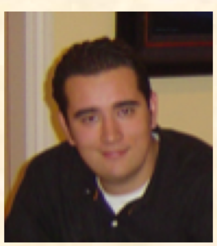
-466 km/s

-392 km/s

-358 km/s



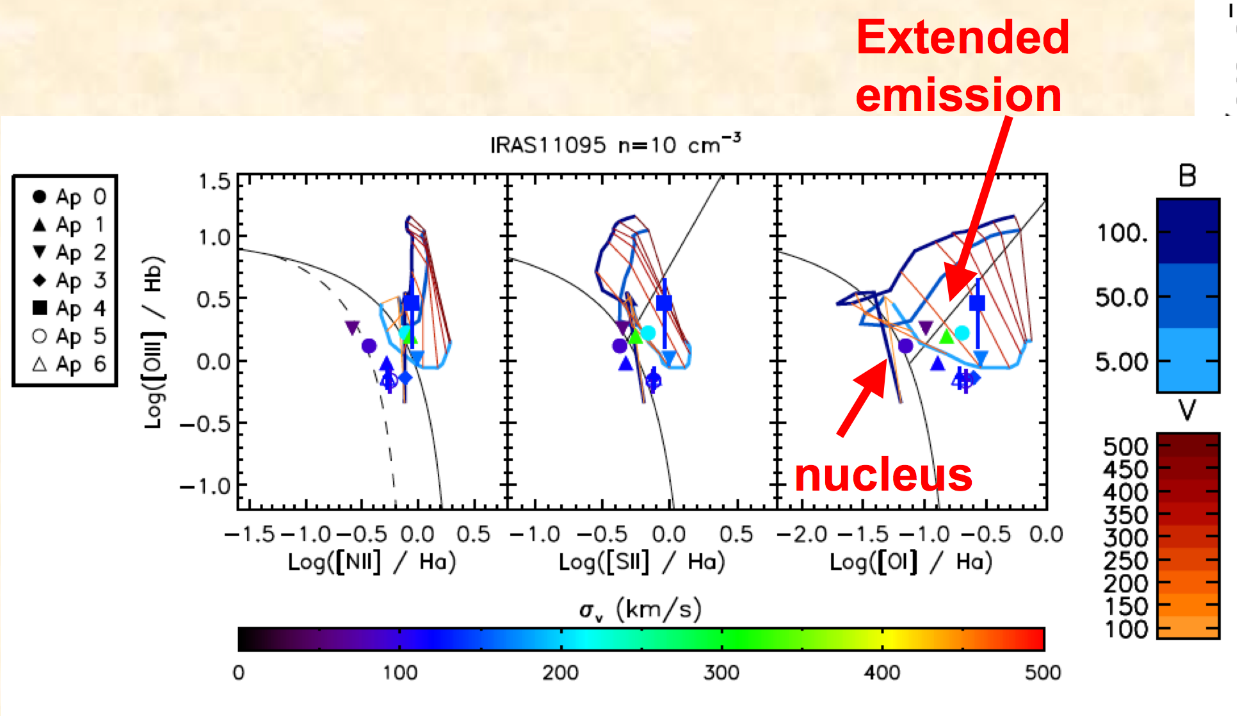


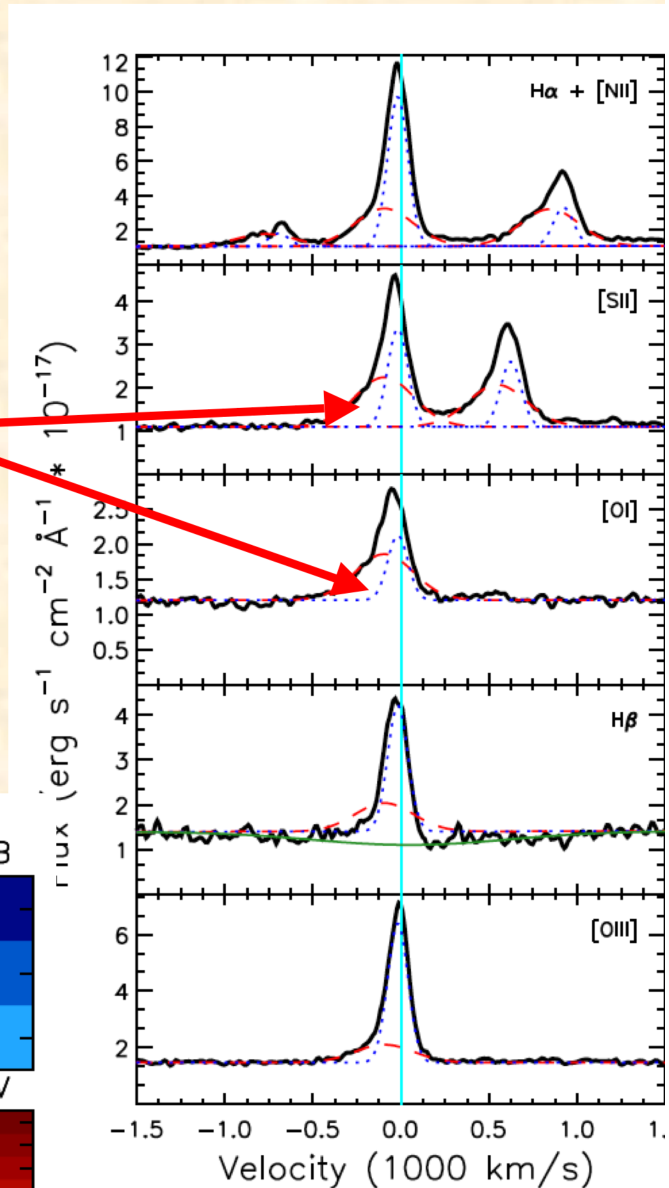


Kurt Soto + 2012a,b

Broad Emission Excited by Shocks

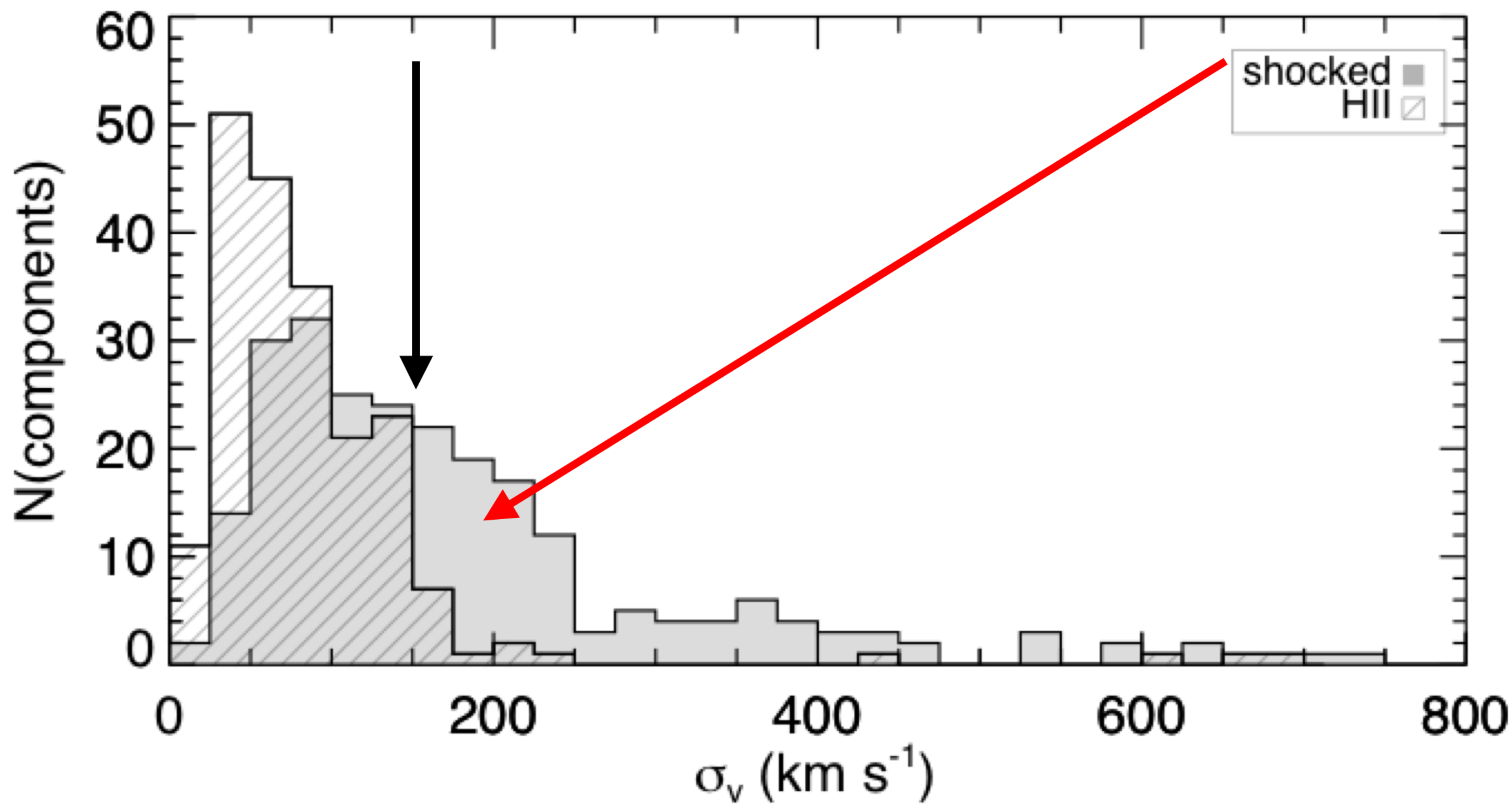
- Detect broad emission in forbidden lines as well as recombination lines.
- Line ratios indicate shocks or AGN.
- Spatial extent of 3-5 kpc favors shocks.





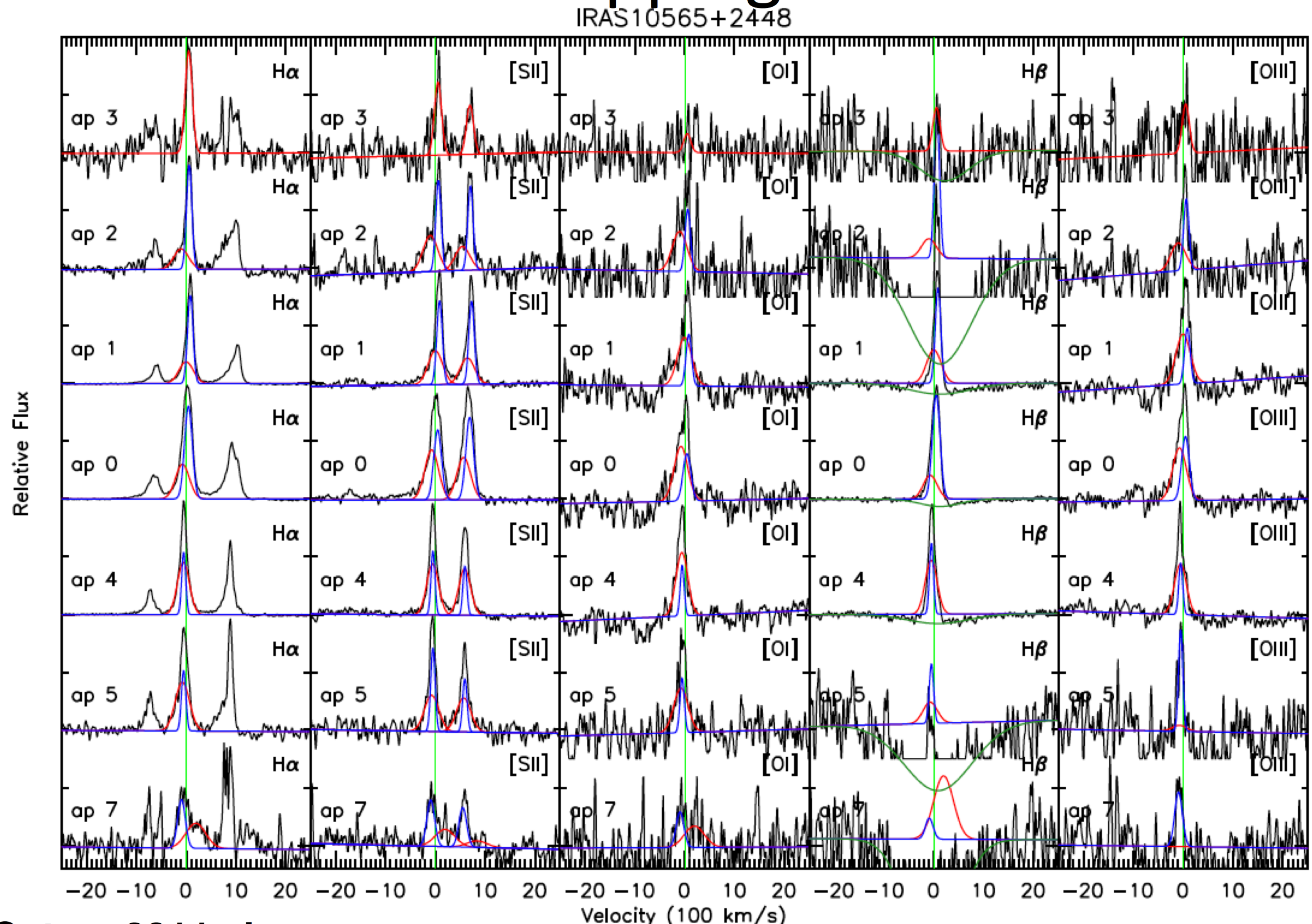
Kurt Soto et al. 2012a,b

Local ULIRGs: High Velocity Dispersion Gas is Excited by Shocks



Kurt Soto + 2012a,b

Emission-Line Mapping of Starbursts



Soto + 2011a,b