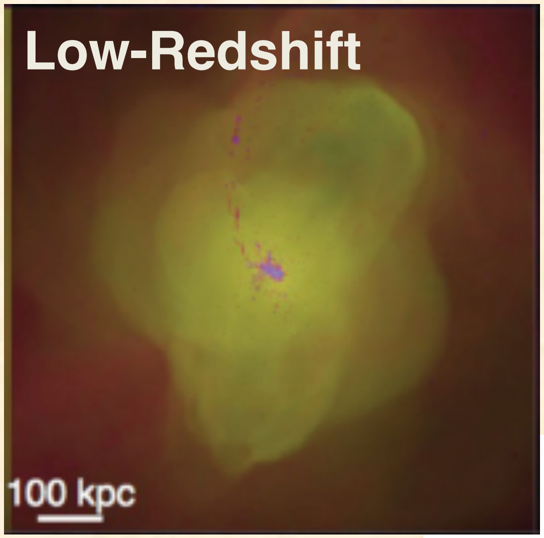
Galactic Outflows and Inflows at z < 1.5

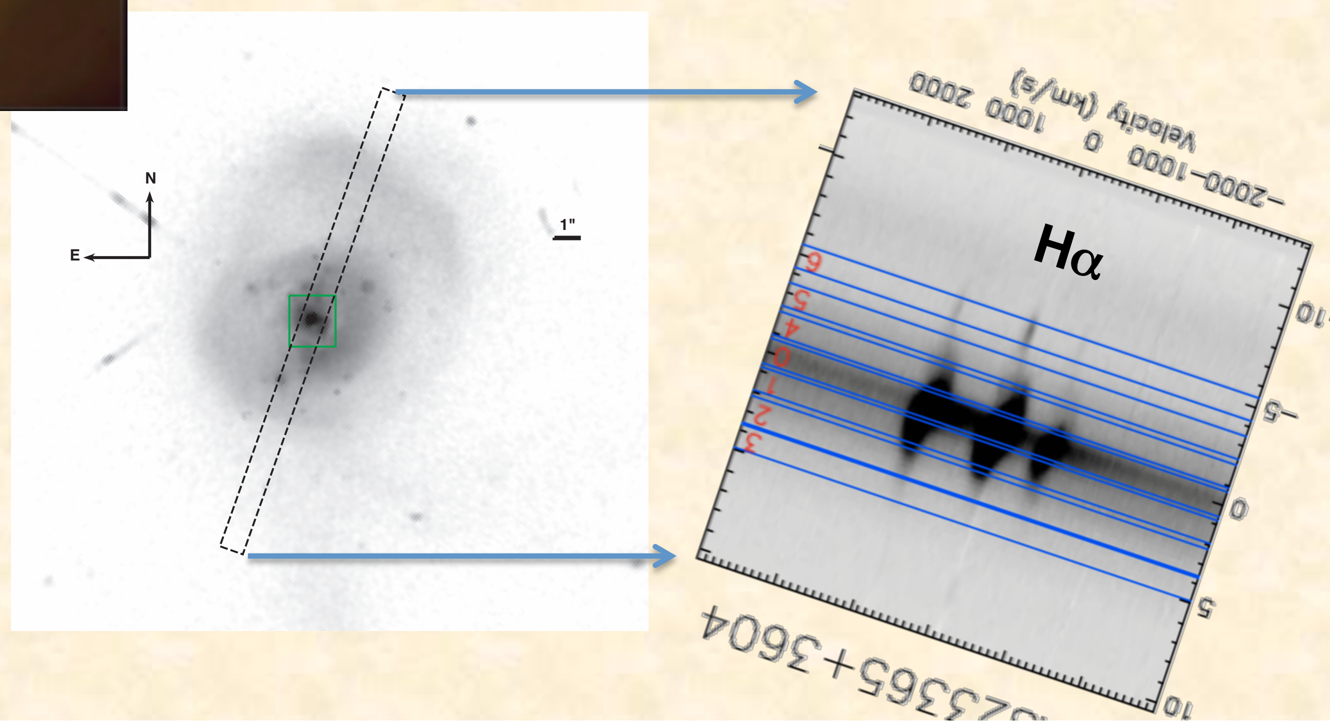
Crystal Martin (UC Santa Barbara)

Galaxy Mergers Fuel the Strongest Local Starbursts



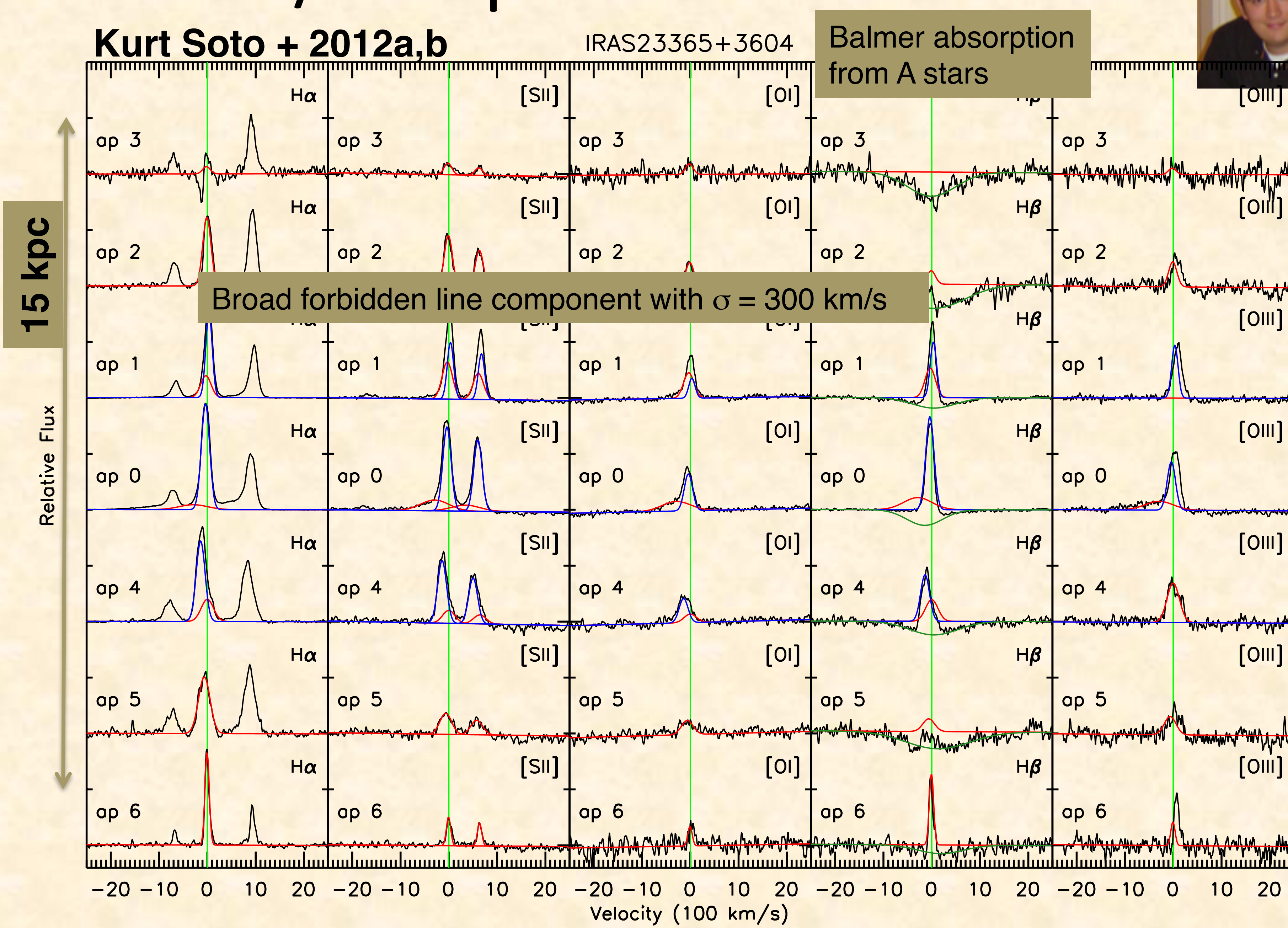
Zoom Simulations (Hopkins et al 2013):
Mergers generate overlapping outflows.
Winds accelerate low density gas.
Low angular momentum gas feeds bulge.

IRAS 23365+3604
F814W
50 kpc X 50 kpc
SFR = 280 M_0/yr

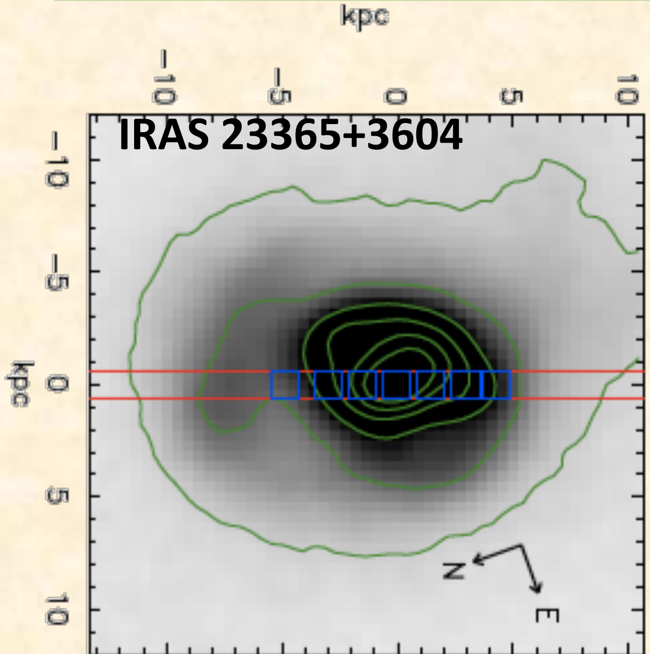


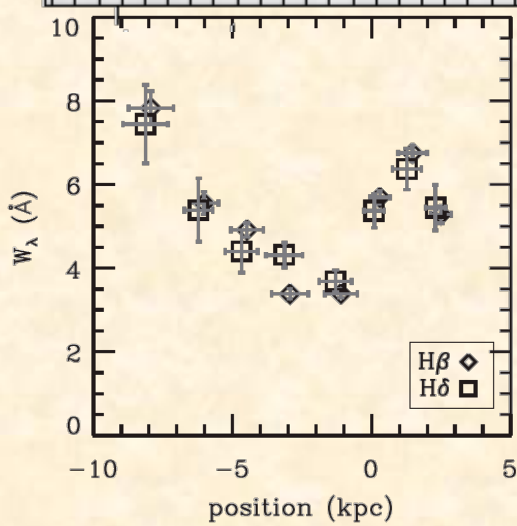
Keck II/ESI Spectrum

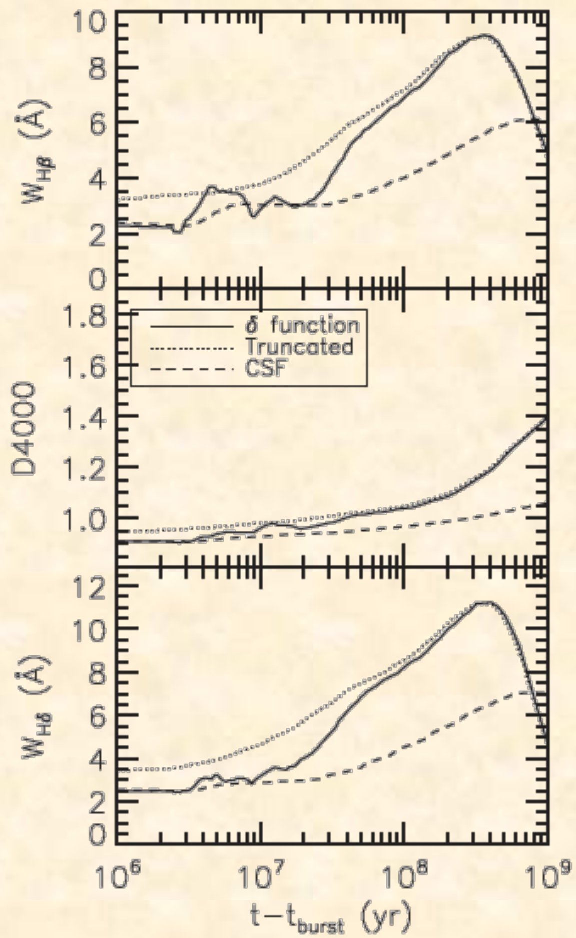
Kurt Soto + 2012a,b



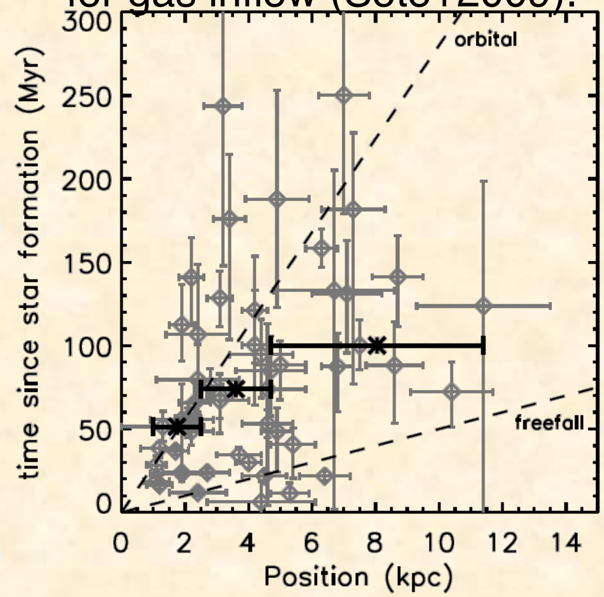
Star Formation in Mergers Truncated from the Outside Inwards







- Stellar age gradients in 25 ULIRGs provide evidence for gas inflow (Soto+2009).

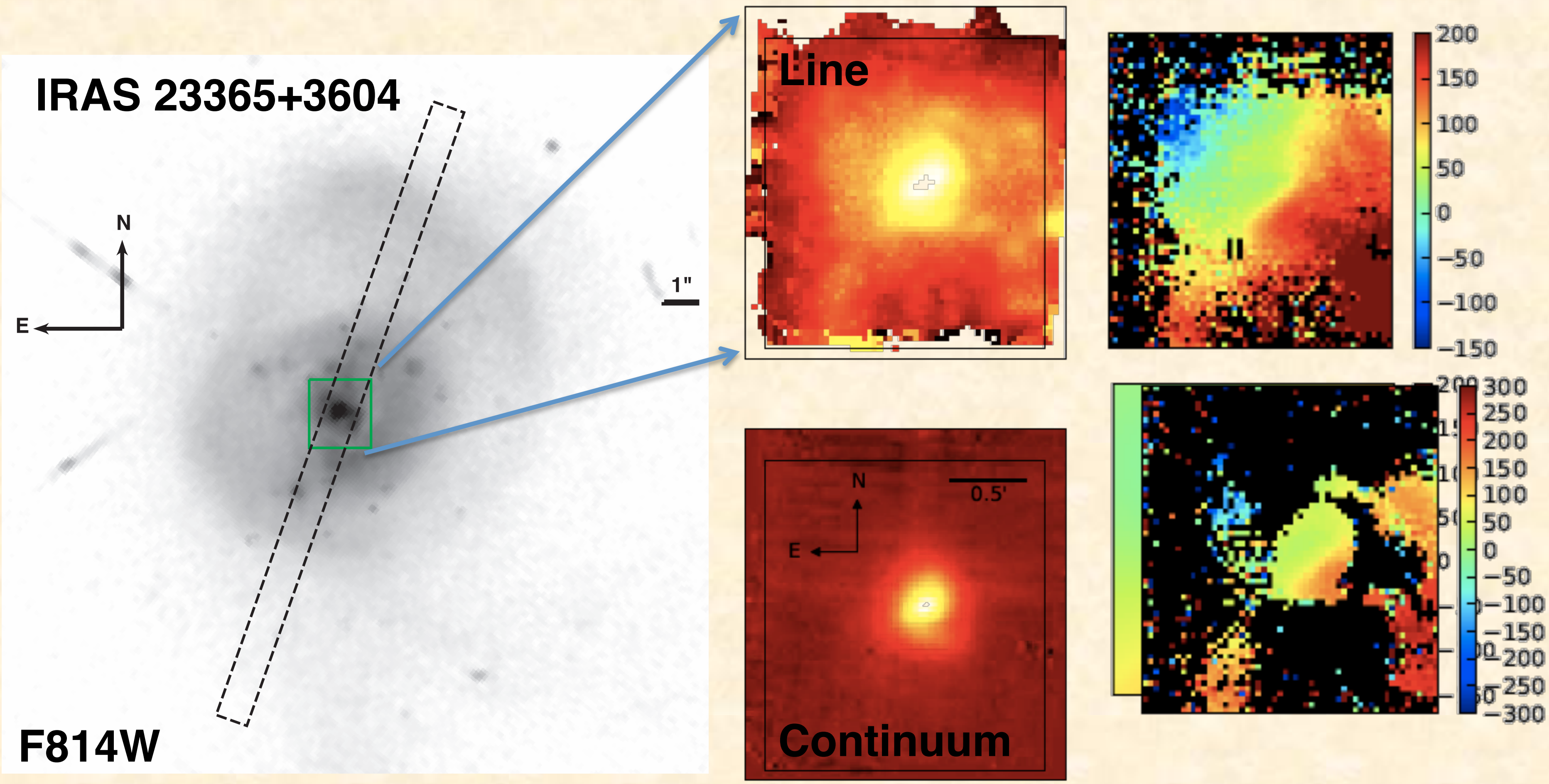


- Also, inverted metallicity gradient, low gas-phase metallicity in central kpc, indicates this inflow is metal poor (Rupke+2010).

Gas Dynamics in the Inner 2.4 kpc:

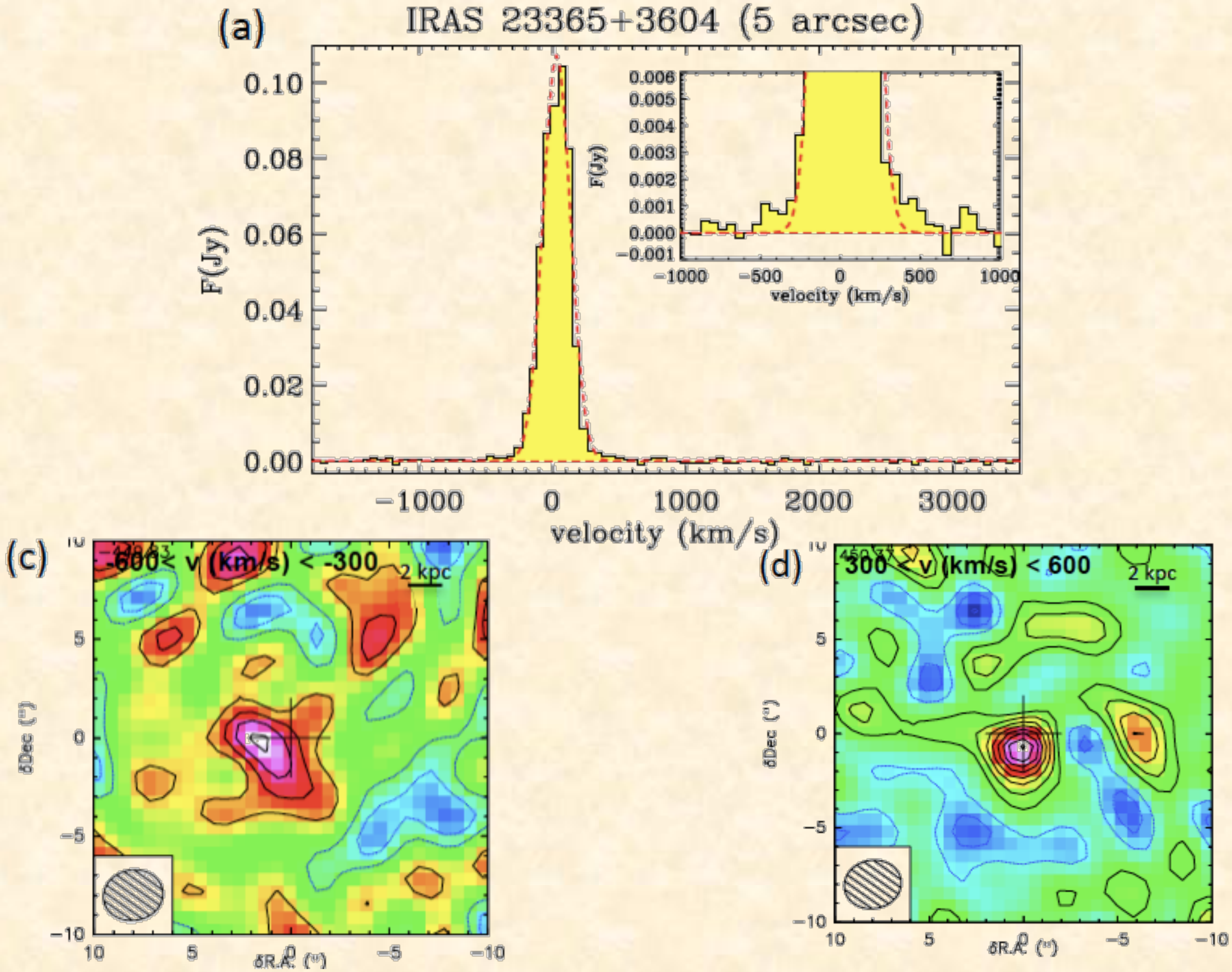
Keck LGS Adaptive Optics w/ OSIRIS

- Paschen-α data cube @ 100 pc resolution
- Rotating disk, non-axisymmetric structure, high velocity dispersion component



Broad Line Wings in CO 1-0 Observation:

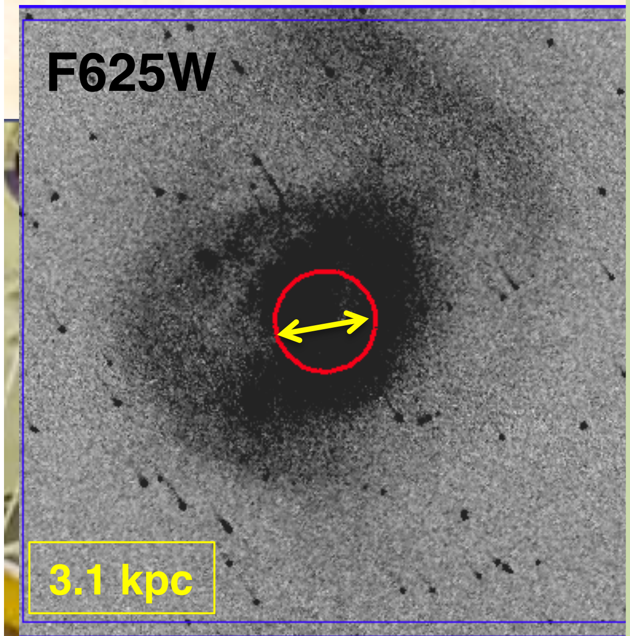
Cicone, Maiolino +2013

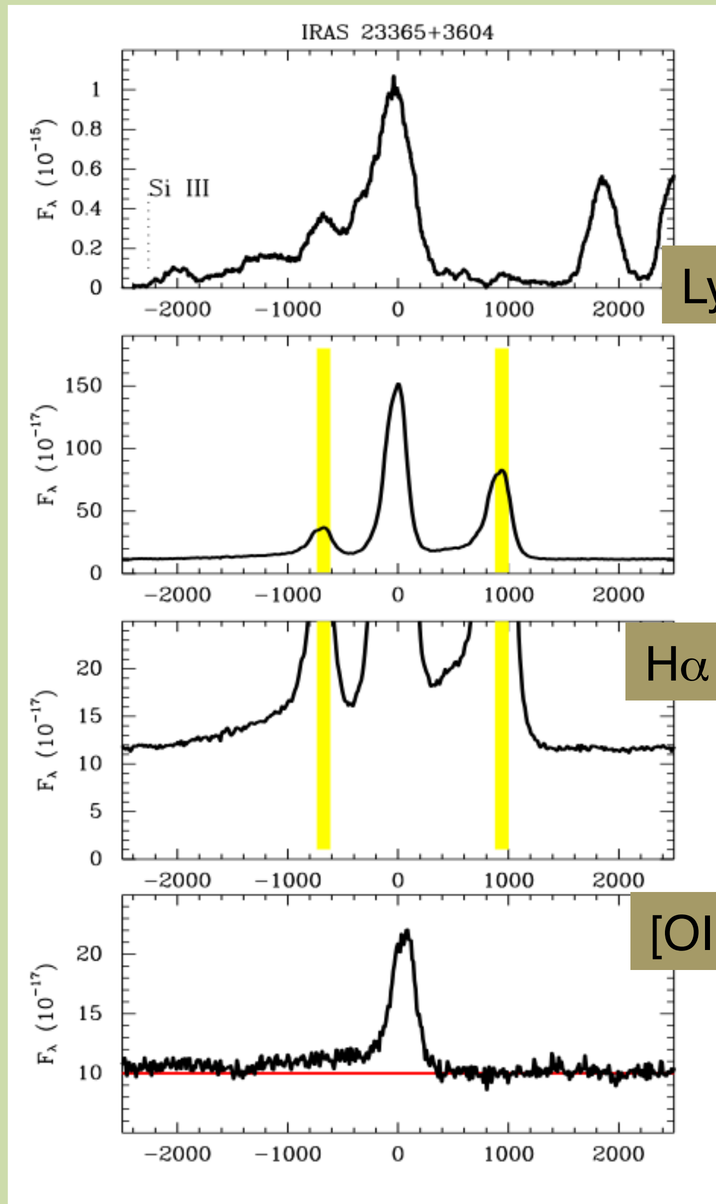


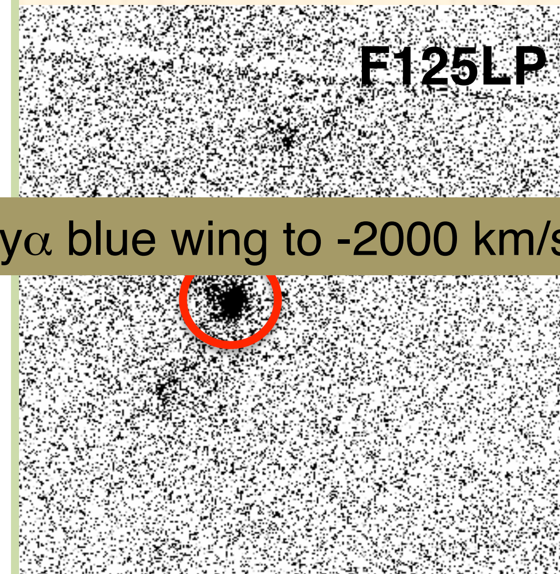
Pα

FWHM

High-Velocity Gas Most Prominent in FUV
HST/COS G130M (CLM+, in prep)



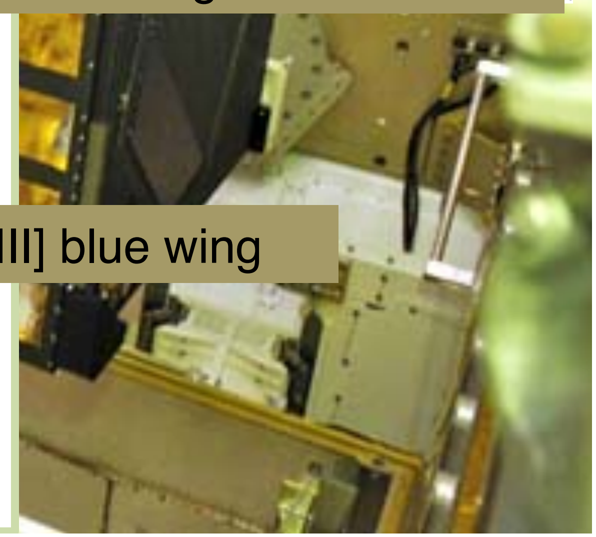




Lyα blue wing to -2000 km/s

Hα blue wing to -2000 km/s

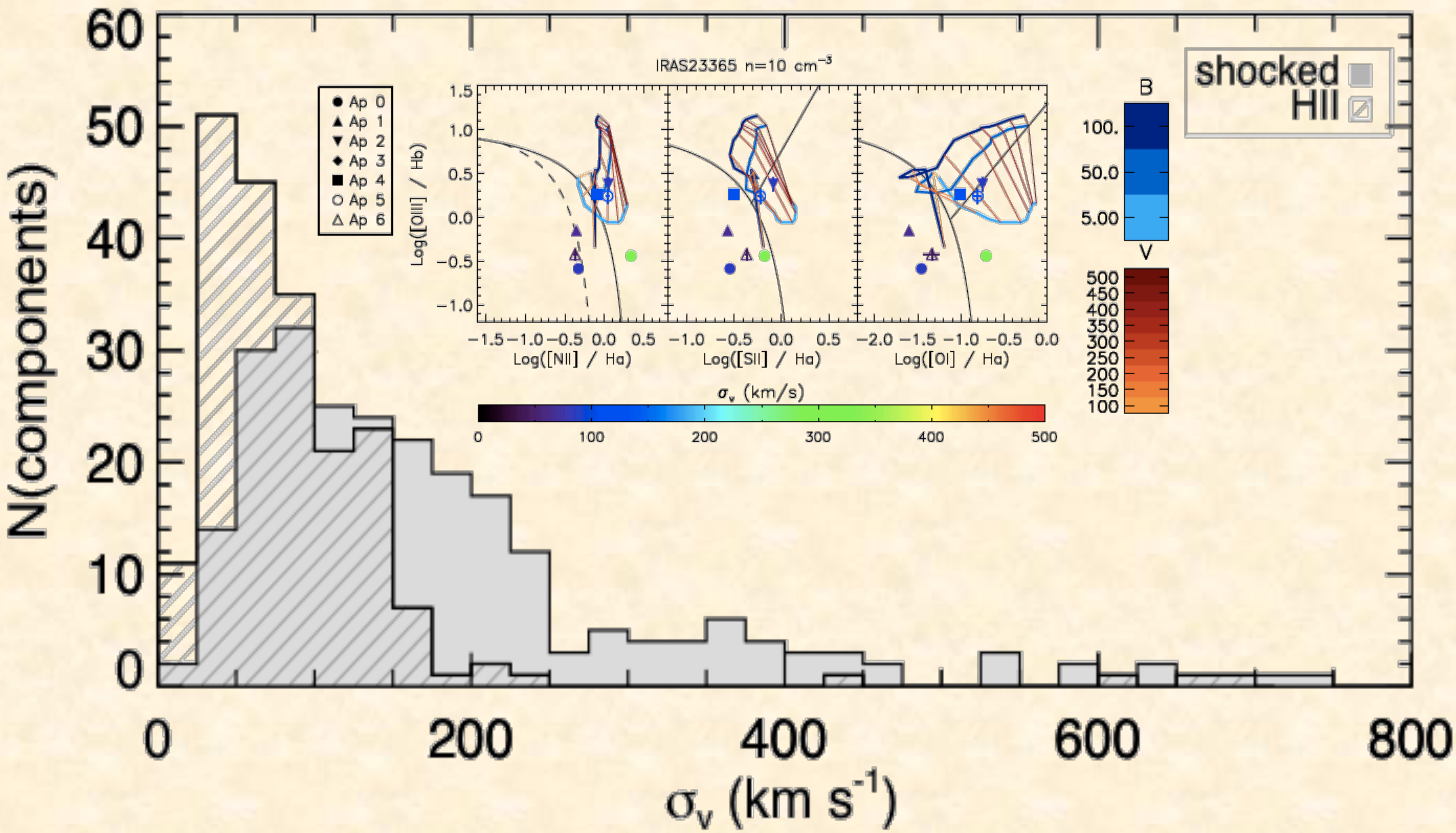
[OIII] blue wing



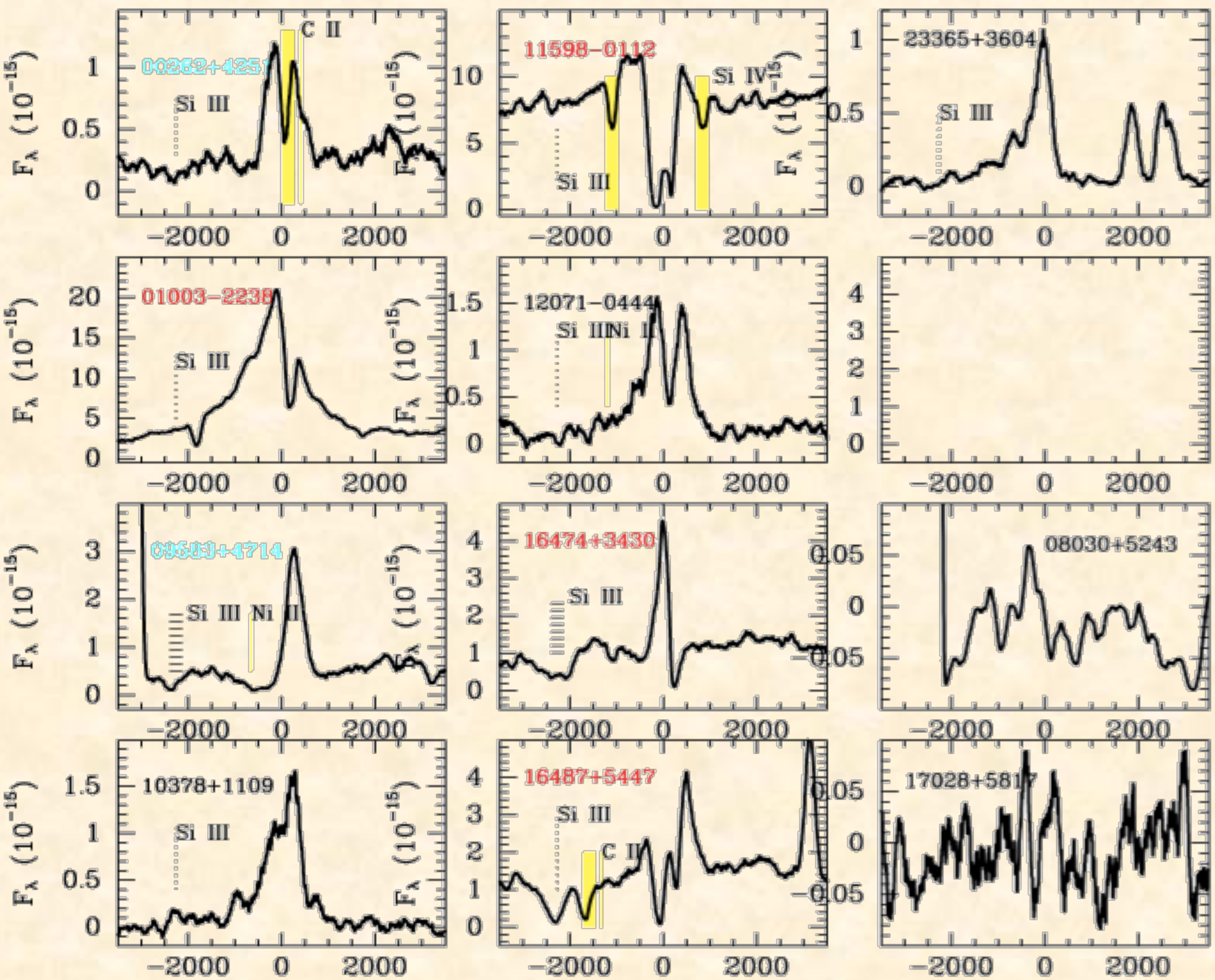
High Velocity Dispersion Gas Excited by Shocks

v ≈ 100 - 400 km/s

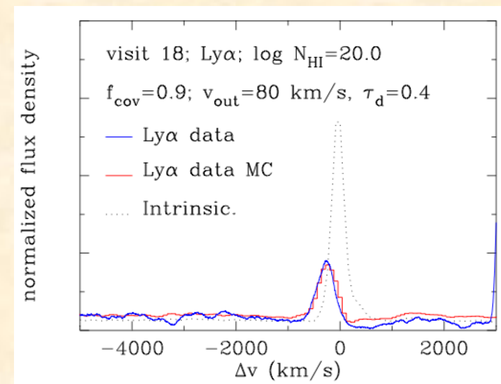
Kurt Soto + 2012a,b – 42 ULIRGs

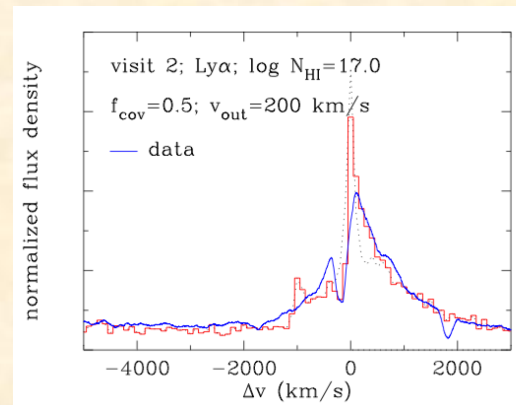


Strong Variations among Lyα Line Profiles



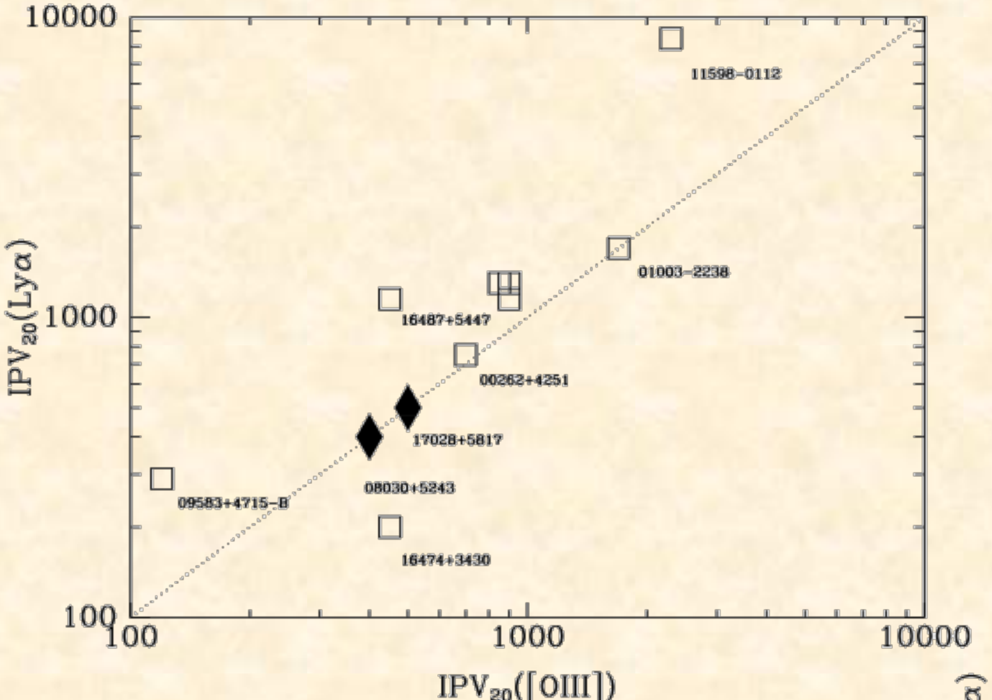
Mark Dijkstra's models:

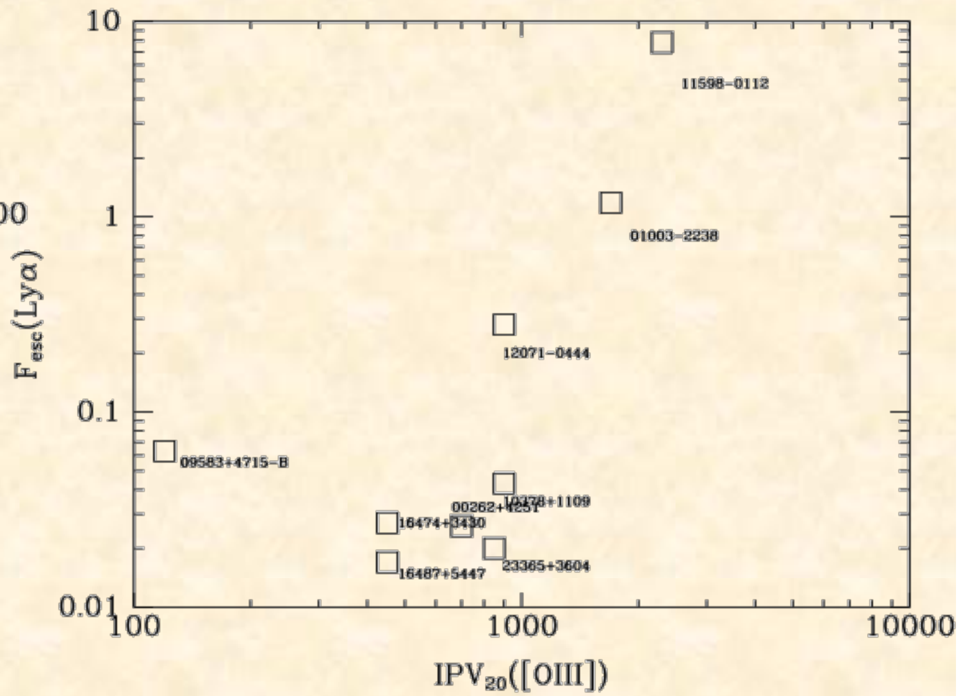




Lya Escape Fraction

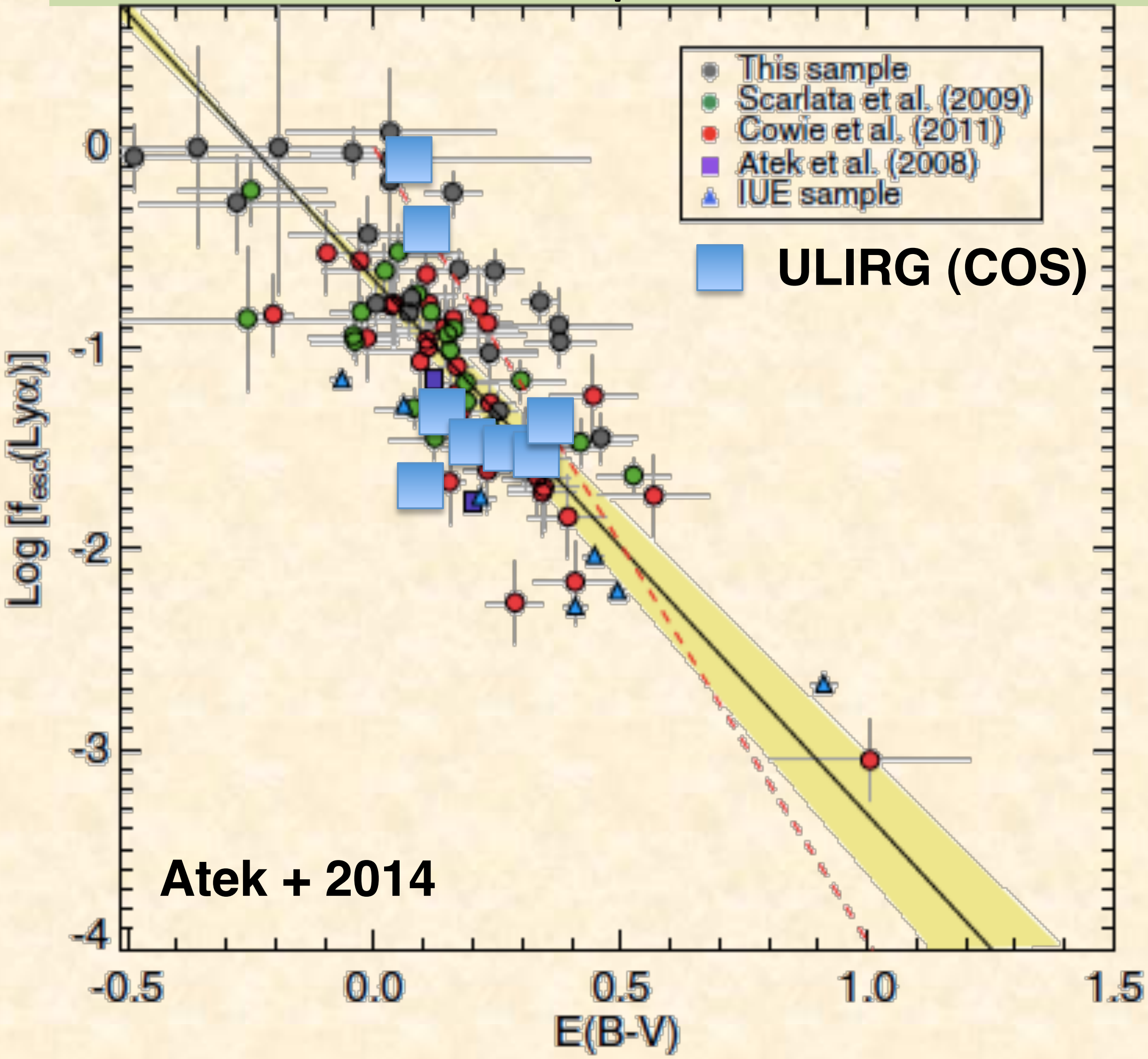
Depends on Gas Kinematics





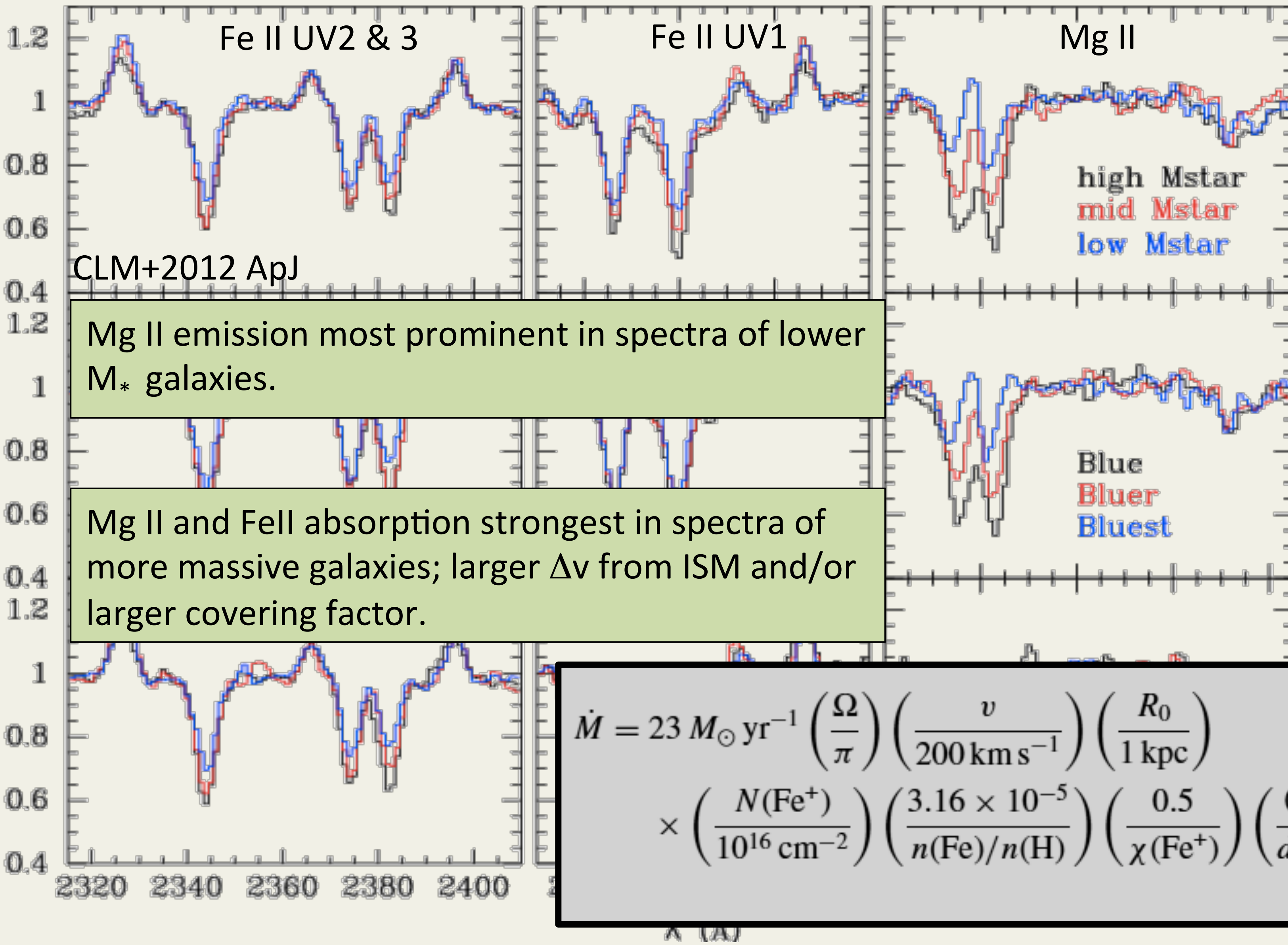
Lyα Escape Fraction

Depends on Reddening



Outflow Properties in “Normal” Galaxies at z = 0.4 – 1.4

Near-UV Absorption Lines in 208 Spectra (CLM+2012)

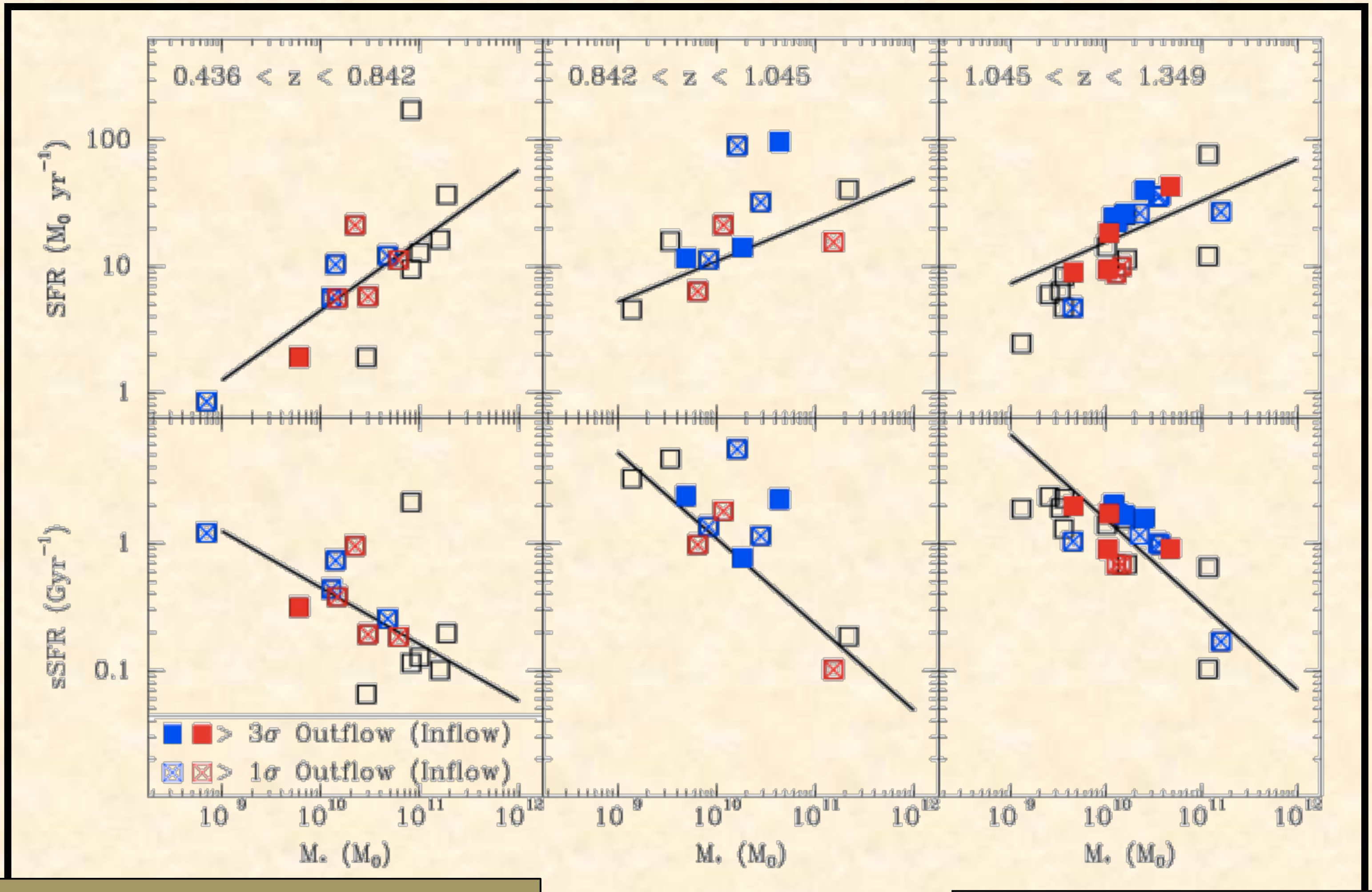


Mg II emission most prominent in spectra of lower M_* galaxies.

Mg II and FeII absorption strongest in spectra of more massive galaxies; larger Δv from ISM and/or larger covering factor.

$$\dot{M} = 23\, M_\odot\, \mathrm{yr}^{-1} \left(\frac{\Omega}{\pi}\right) \left(\frac{v}{200\,\mathrm{km\,s^{-1}}}\right) \left(\frac{R_0}{1\,\mathrm{kpc}}\right) \times \left(\frac{N(\mathrm{Fe^+})}{10^{16}\,\mathrm{cm^{-2}}}\right) \left(\frac{3.16\times10^{-5}}{n(\mathrm{Fe})/n(\mathrm{H})}\right) \left(\frac{0.5}{\chi(\mathrm{Fe^+})}\right) \left(\frac{0.20}{d(\mathrm{Fe})}\right), \qquad (12)$$

Outflows (and Inflows) Collimated by z=1.4

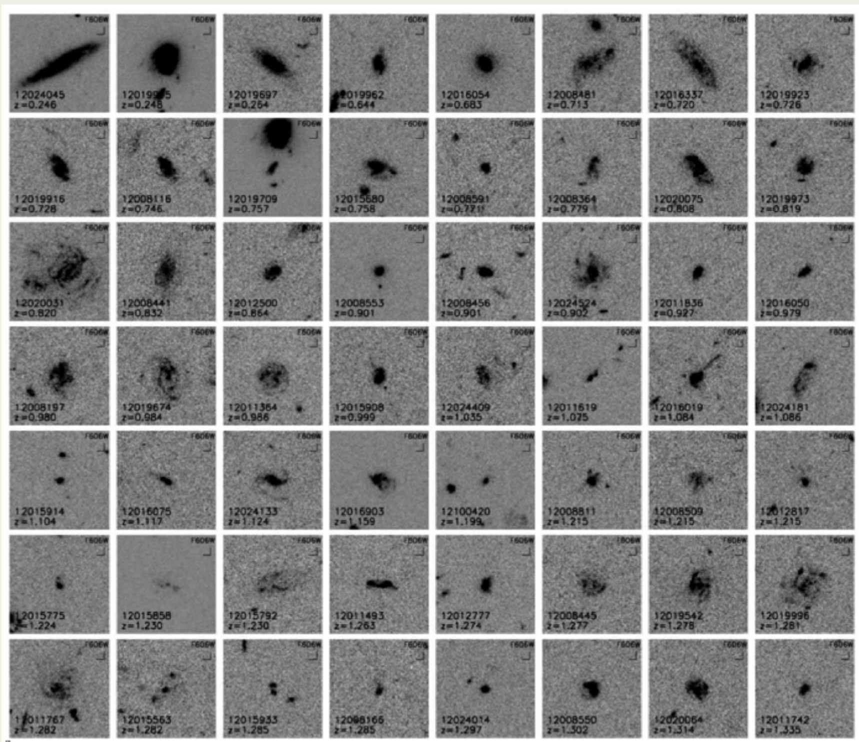


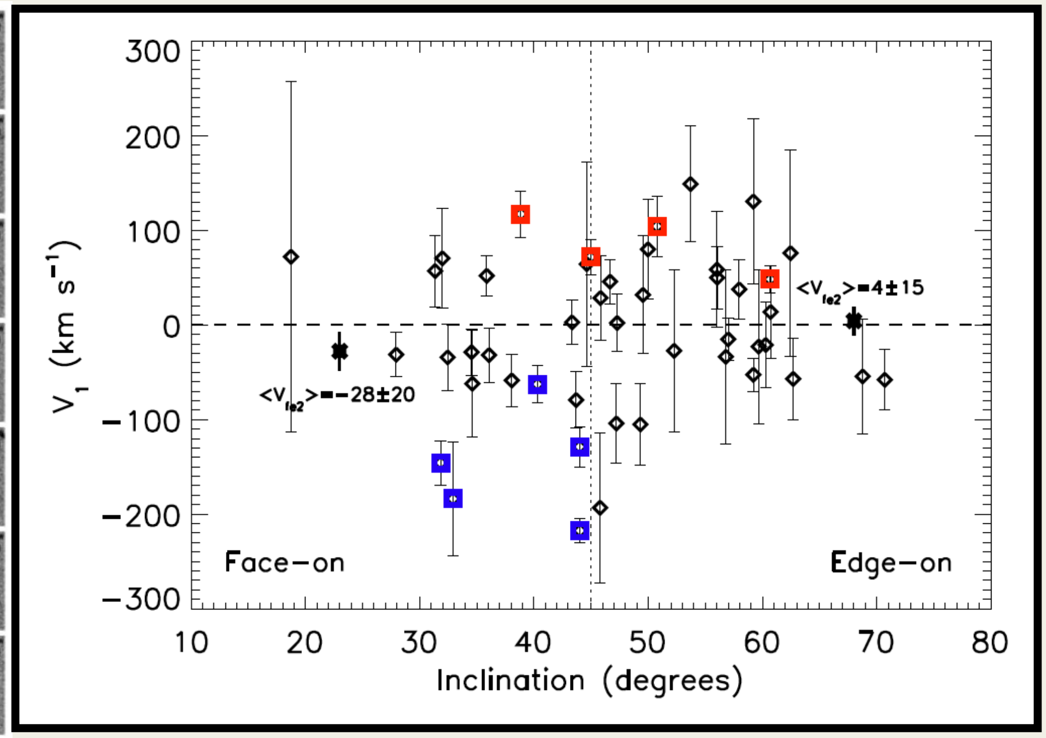
Fraction of 4π filled by outflow is
50% (V_1 < -50 km/s),
20% (V_1 < -100 km/s), and
5% (V_1 < -200 km/s)

Log (Halo Mass):
11.25 - 14.24 @ z=1
11.20 - 14.70 @ z=0.5

Galactic Disks Collimate the Outflows

Kornei, Shapley, Martin + 2012

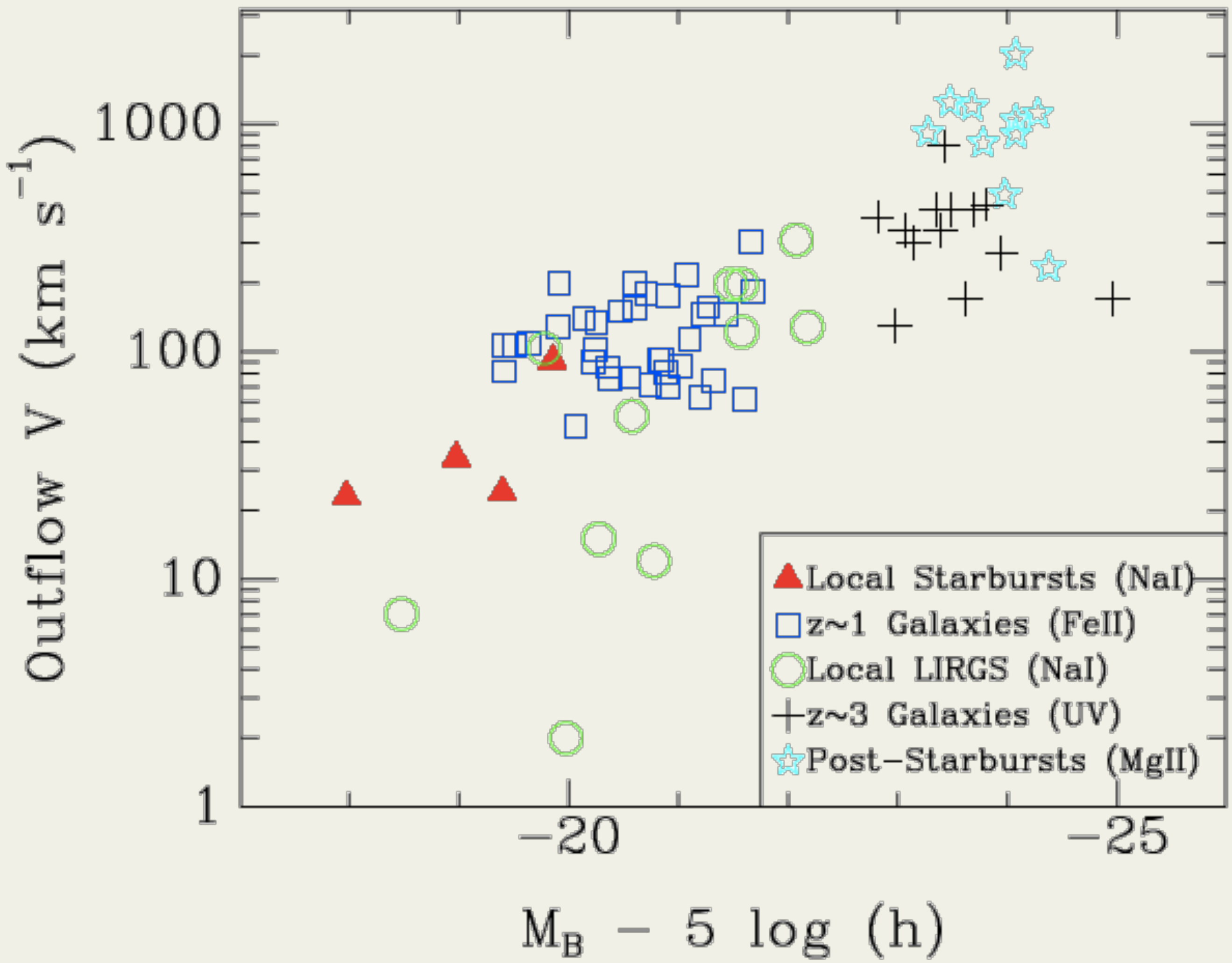




- Galaxies with blueshifted absorption viewed at lower inclination.
- Outflow fraction approaches unity.

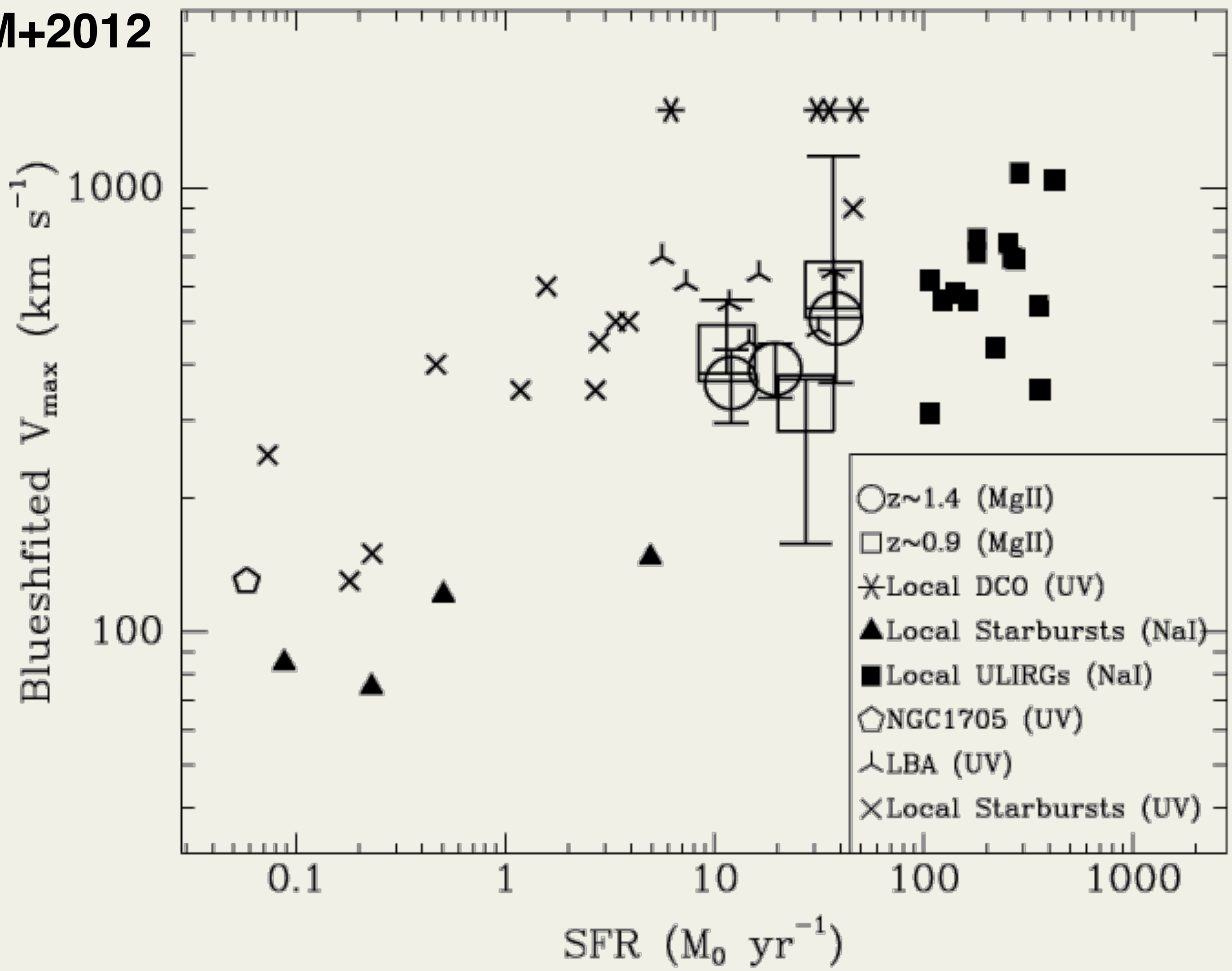
Velocities in Warm Gas: Absorption Lines in Galaxy Spectra

CLM+2012



Velocities in Warm Gas: Absorption Lines in Galaxy Spectra

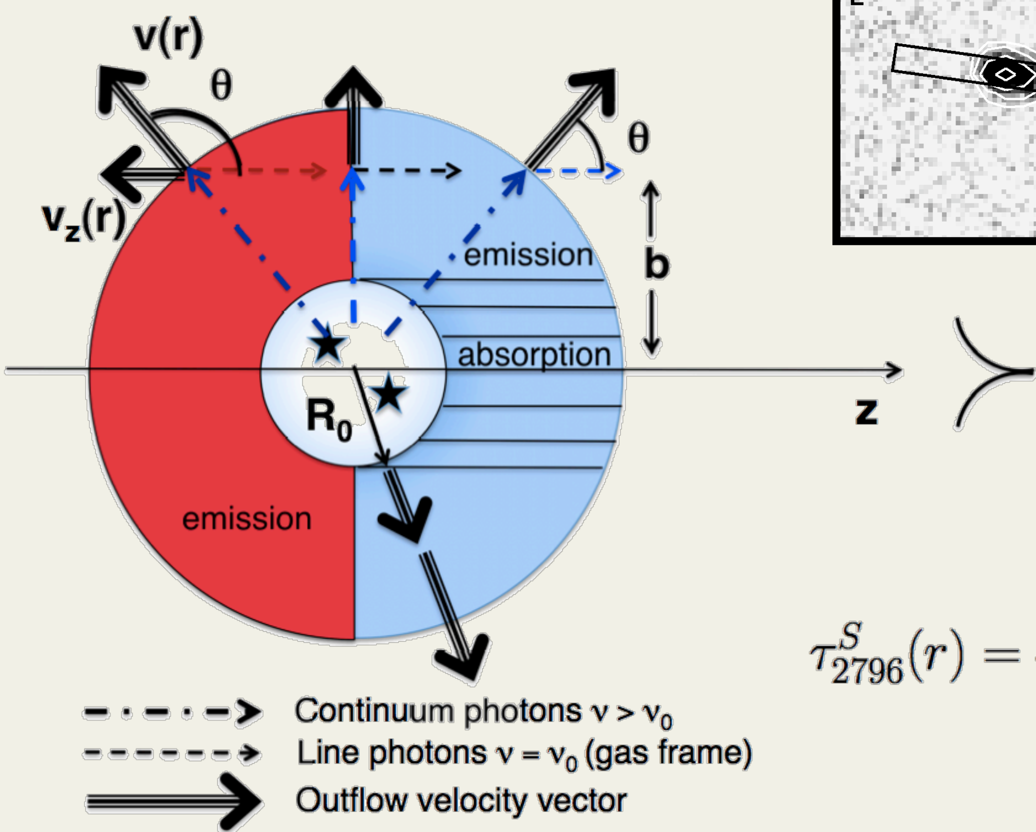
CLM+2012

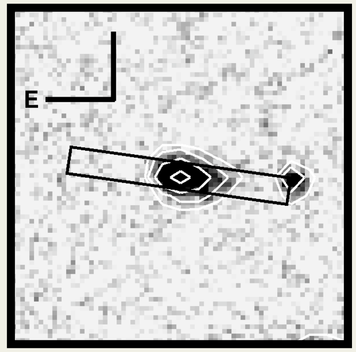


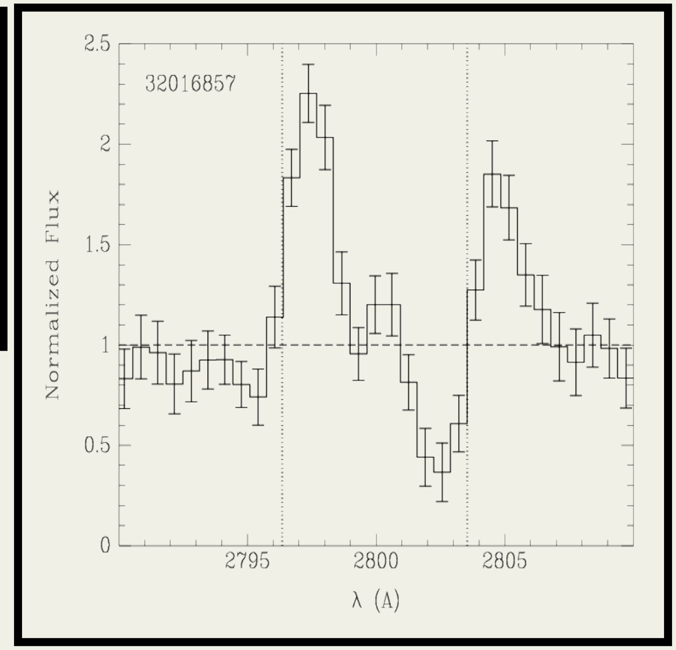
Mass Flux in Warm Gas:

Spatially & Spectrally Resolved Resonance Emission at z~0.1

CLM+2013 ApJ







$$\tau^S_{2796}(r) = 4.6 \times 10^{-7}\ \mathrm{cm^3\ s^{-1}}\ n_{Mg+}(r) \left|\frac{dv}{dr}\right|^{-1}$$

$$n_{Mg+}(r_S) \approx 1.4{\times}10^{-9}\ \mathrm{cm^3} \left|\frac{dv}{230\ \mathrm{km\ s^{-1}}} \frac{11.4\ \mathrm{kpc}}{dr}\right|_{r_S}$$

Ionization Fraction & Gas Density

$$n_H = 0.30\ \mathrm{cm}^{-3} \left(\frac{n_{\mathrm{Mg}^+}}{10^{-9}\ \mathrm{cm}^{-3}}\right)^{1/2} \left(\frac{11.4\ \mathrm{kpc}}{r_S}\right) \times \left(\frac{6.3\times10^{-2}}{d(\mathrm{Mg})}\right)^{1/2} \left(\frac{3.8\times10^{-5}}{\eta(\mathrm{Mg})}\right)^{1/2} \left(\frac{Q}{10^{55}\ \mathrm{s}^{-1}}\right)^{1/2}$$

32016857:
n_H = 0.12 – 0.18 cm^{-3}
at r = 18 - 12 kpc

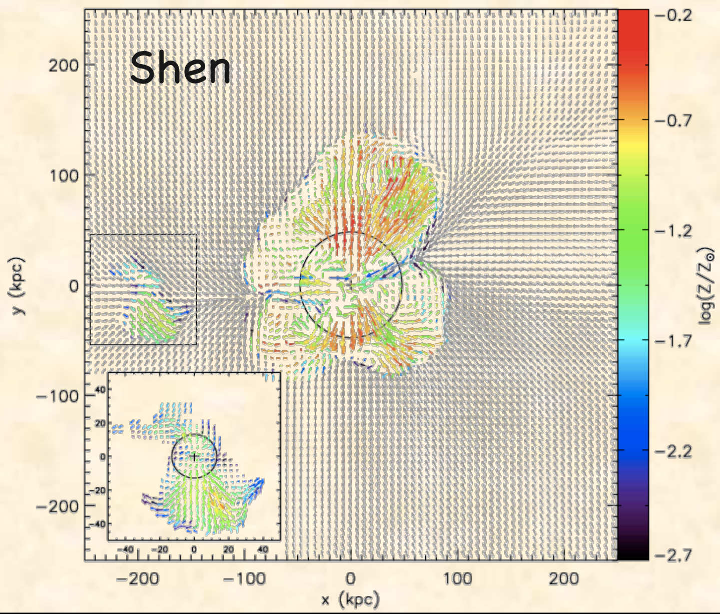
TKRS4389:
n_H = 0.15 – 0.33 cm^{-3}
at r = 20 - 8 kpc

$$\dot{M}(r) = 500\ \mathrm{M}_\odot\ \mathrm{yr}^{-1} \left(\frac{\Omega}{\pi}\right) \left(\frac{f_c}{1}\right) \left(\frac{r}{11.4\ \mathrm{kpc}}\right)^2 \times \left(\frac{v}{230\ \mathrm{km\ s}^{-1}}\right) \left(\frac{n_H}{0.3\ \mathrm{cm}^{-3}}\right)$$

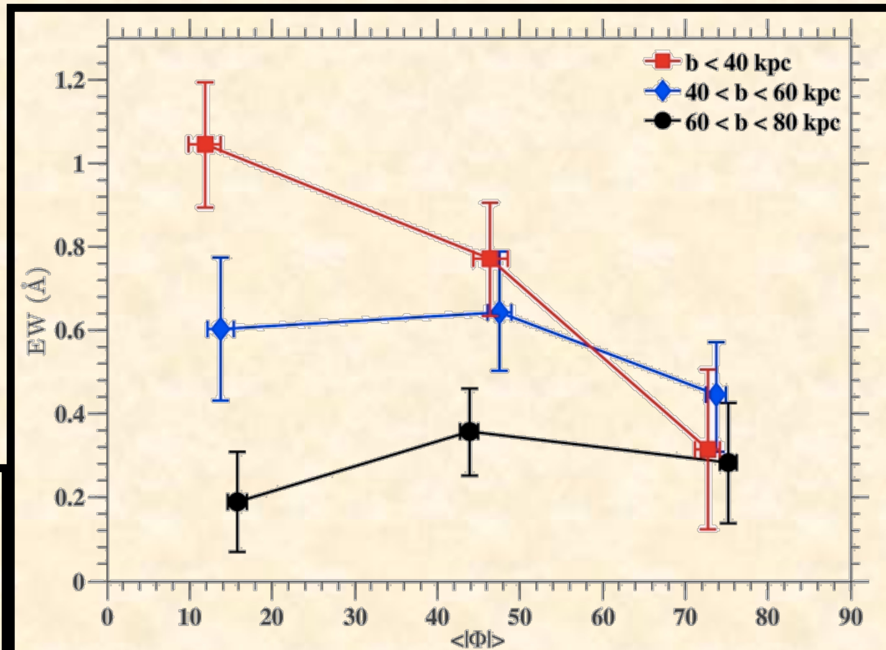
The mass loading factor in

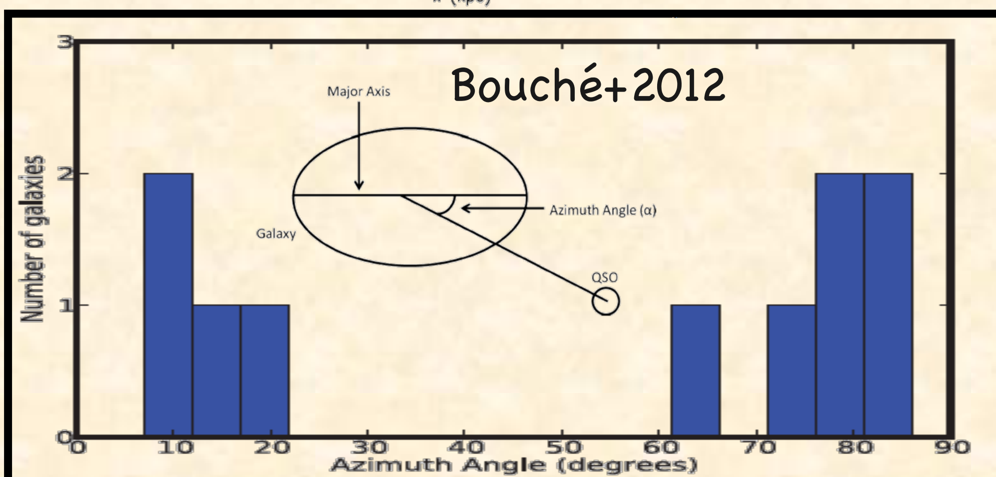
- **32016857 (log M^*/M_0 = 9.82) is η ~ 330 to 500 / 80 = 4 to 6**
- **TKRS 4389 is η ~ 35 to 40 / 80 = 0.5**

Orientation of Quasar Sightlines Determines Physical Origin of Strong Absorption



zCOSMOS Stacks (Bordoloi+2011)





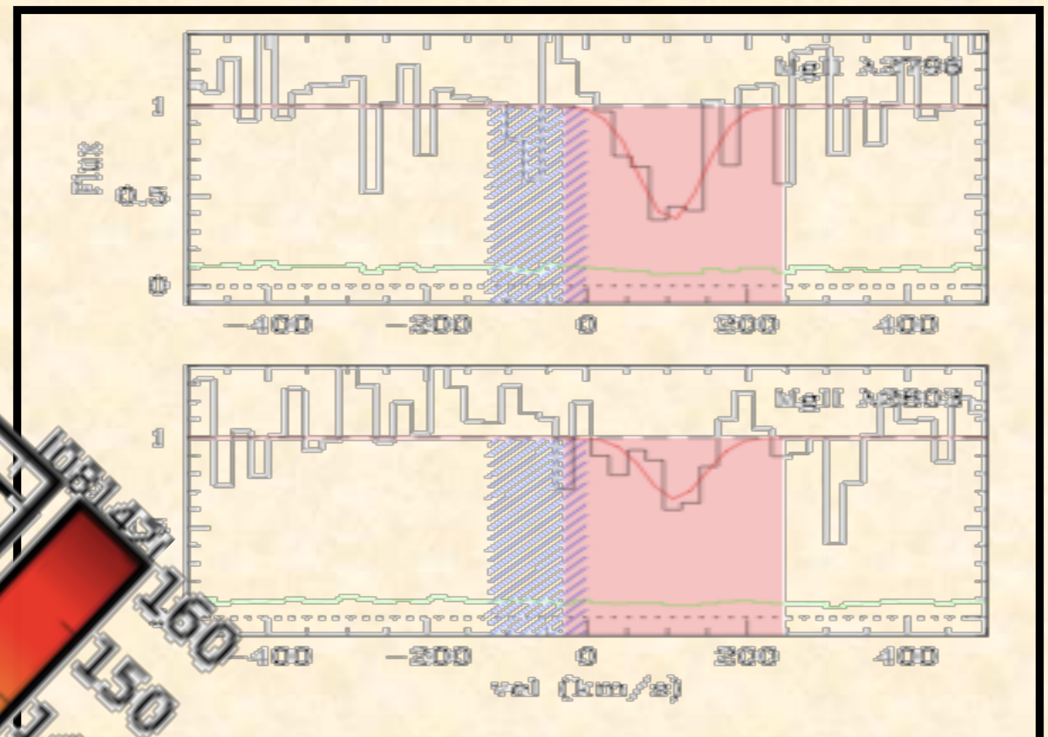
Minor Axis Sightlines

Major Axis Sightlines

Quasars Probing Galactic Outflows

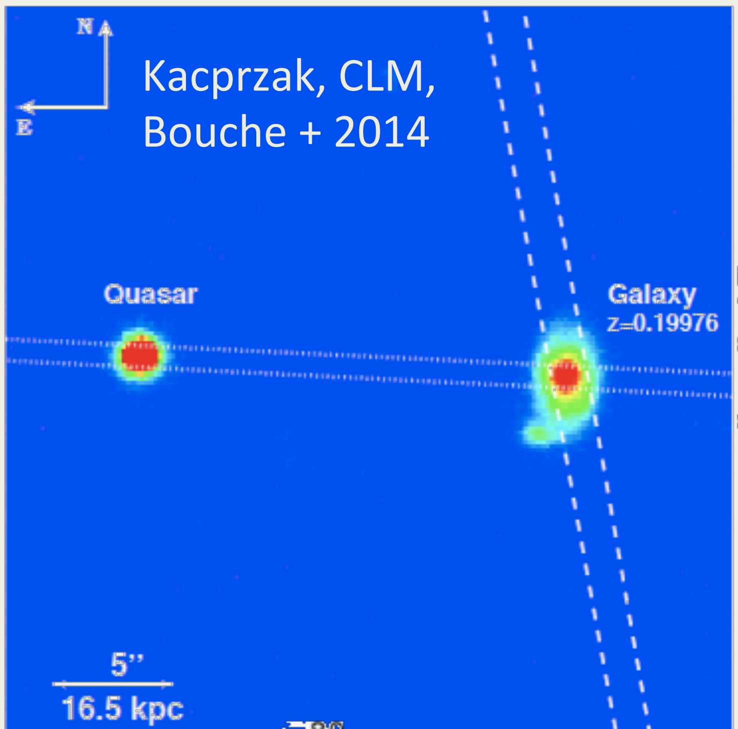
J08[illegible]1420+282408 G1:

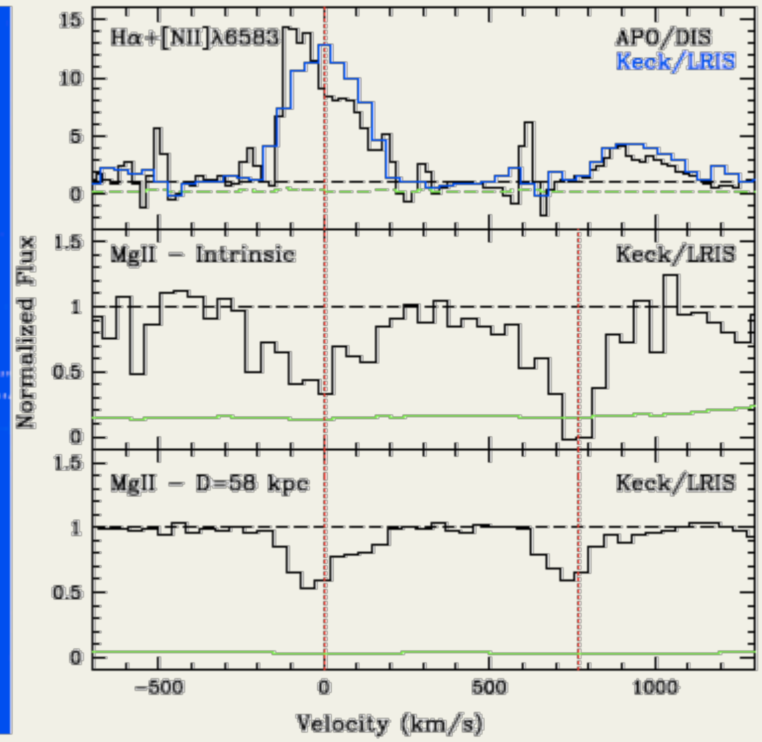
Bou[illegible]+2012 (also Barton & Cooke 2009; Kacprzak+2011)

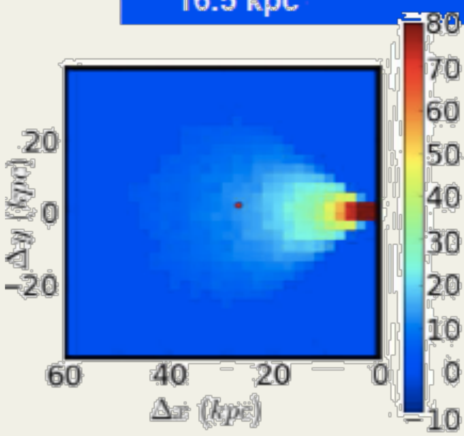


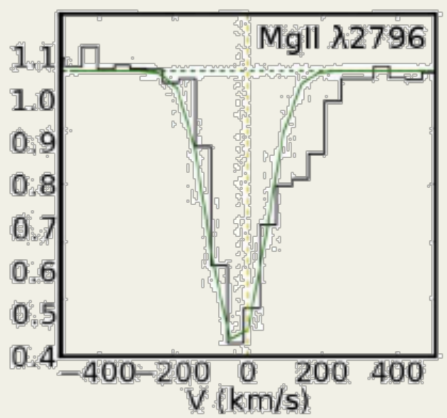
- Mg II kinematics co[illegible]t with outflow (red) but not disk model (blue).
- Impact paramet[illegible]tes the location of the absorbing gas.
- Mass loadin[illegible] 1.3 ~ 0.3 with empirical N(HI) -- N(MgII) relation; ri[illegible]es to ~[illegible]ization model

Combining Halo Sightlines & Galaxy Sightlines Provides Redundancy in Outflow Modeling

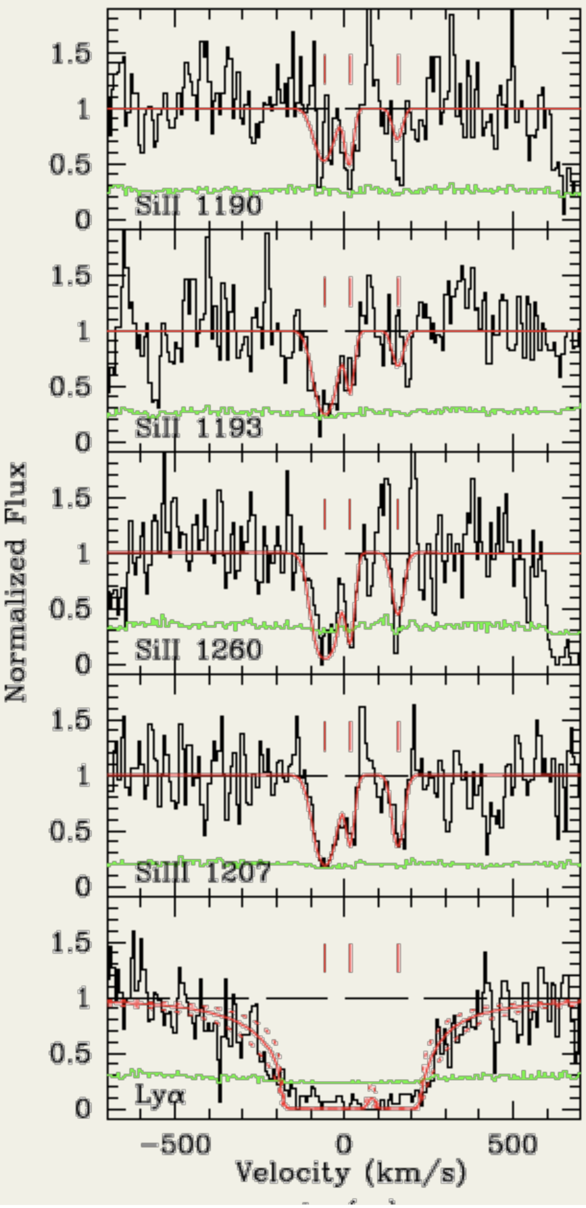


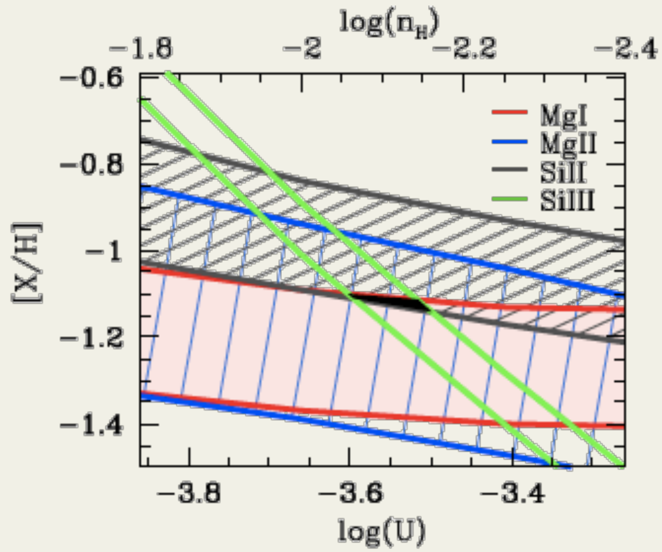






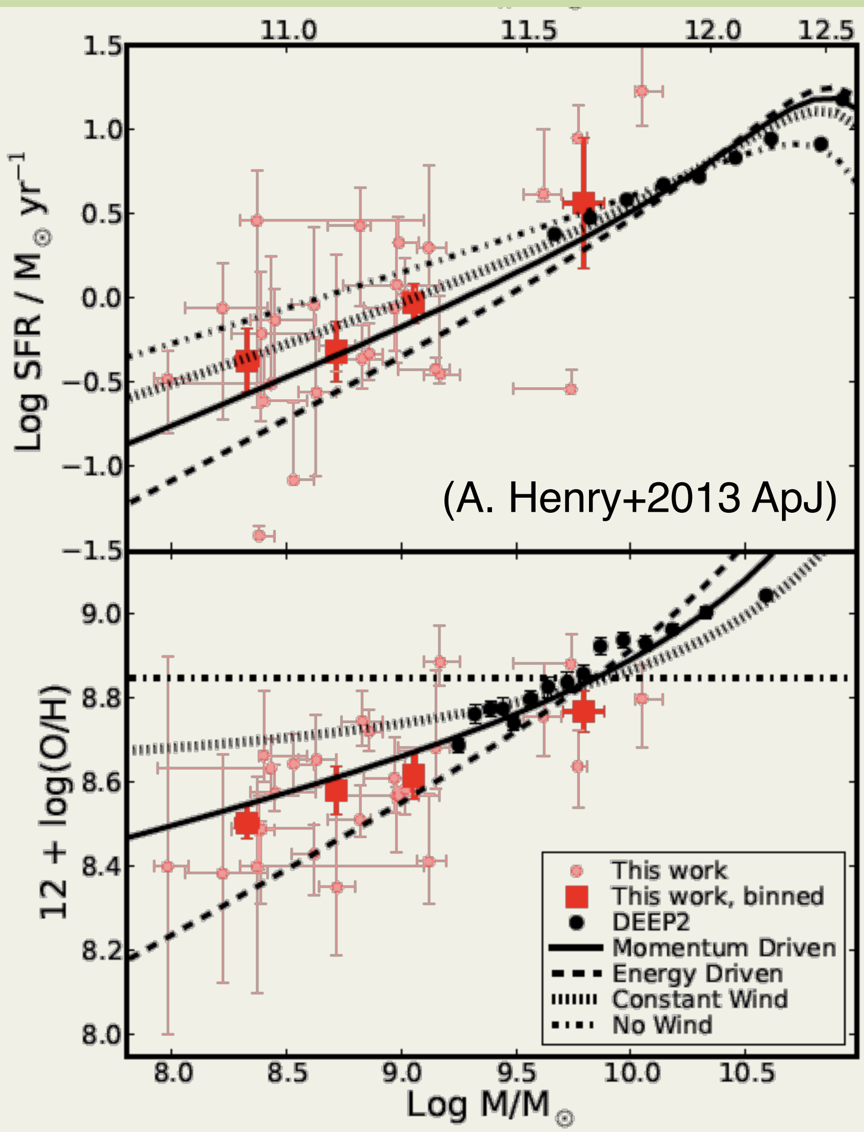
Measured Mass Flux





- Down-the-barrel absorption suggests outflow velocities of 45 to 214 km/s.
- Transverse absorption fitted with constant velocity, conical outflow at 40 to 80 km/s.
- Galaxy metallicity is [O/H] = -0.21 (0.08).
- Halo metallicity is [X/H] = -1.12 (0.02).
- SFR is 4.6 to 15 M_0/yr.
- Mass loading is 0.1 to 0.9.

Empirical Constraints on Variation in Average Mass Loading with Halo Mass



Gas-phase MZ relation

Equilibrium models for momentum-driven winds (Dave et al; Bouche et al.)

$$Z_{g,eq} \approx y \text{ for } \eta < 1$$
$$Z_{g,eq} \approx y\eta^{-1} \sim V_{vir} \sim M_h^{1/3} \text{ for } \eta >> 1$$

Galactic Winds at z < 1.5

- High velocity gas is detected in luminous local starbursts.
  - Accelerate some gas to a few 1000 km/s
  - Gas excited by shocks and prominent in Lyα emission
  - Warm outflow covering fraction evolves
  - No AGN obviously required in most of these galaxies
  - Systems with AGN show the highest velocities and lowest N(HI) column
- Outflow solid angle found to evolve with cosmic time.
  - More collimated at $z \sim 1.5$ than at $z \sim 2.5$, presumably due to thin, gas disk formation
  - Possible to distinguish physical origin of intervening metal-line absorption geometrically
- Estimates of mass outflow rates have improved accuracy.
  - Accurate columns of certain ions from curve of growth
  - Accurate volume density from resolved scattering halos
  - Theoretical and empirical estimates of ionization corrections