Evolution of Galactic Winds

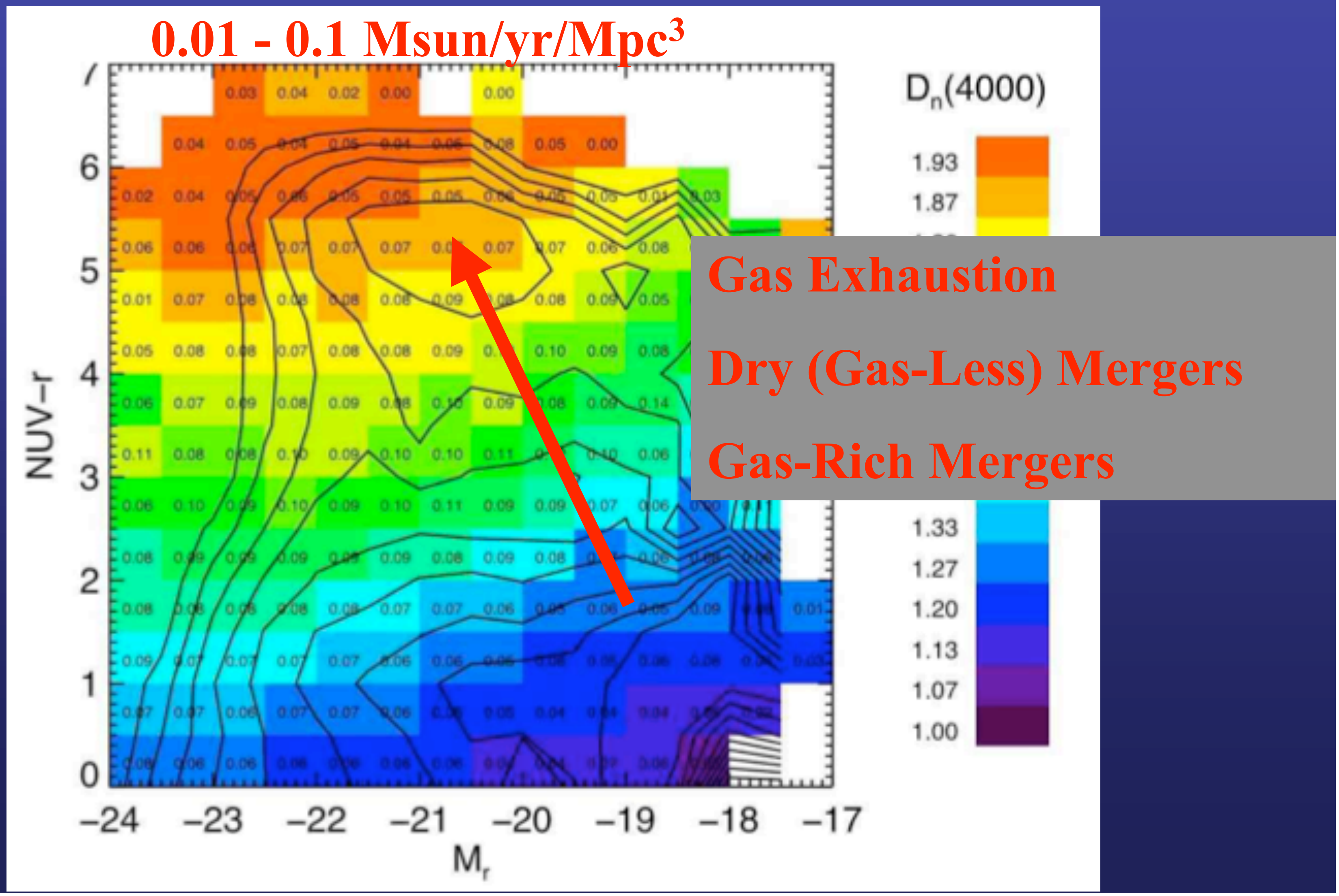
Crystal Martin (UC Santa Barbara)

1. **Dynamical Evolution ==> R(t)**
2. **Cosmological Evolution ==> $f_{Metals}(z)$, SFR(z)**
3. **Merger Sequence Evolution ==> d(SFR)/dt**

Collaborators: Taro Sato, Victor Sciortino, Kurt Soto, Amanda Fournier, Mark Seibert, Norm Murray, Lee Armus, Nicolas Bouche, Sara Ellison, Joe Hennawi, Akimi Fujita, Mordecai Mac-Low

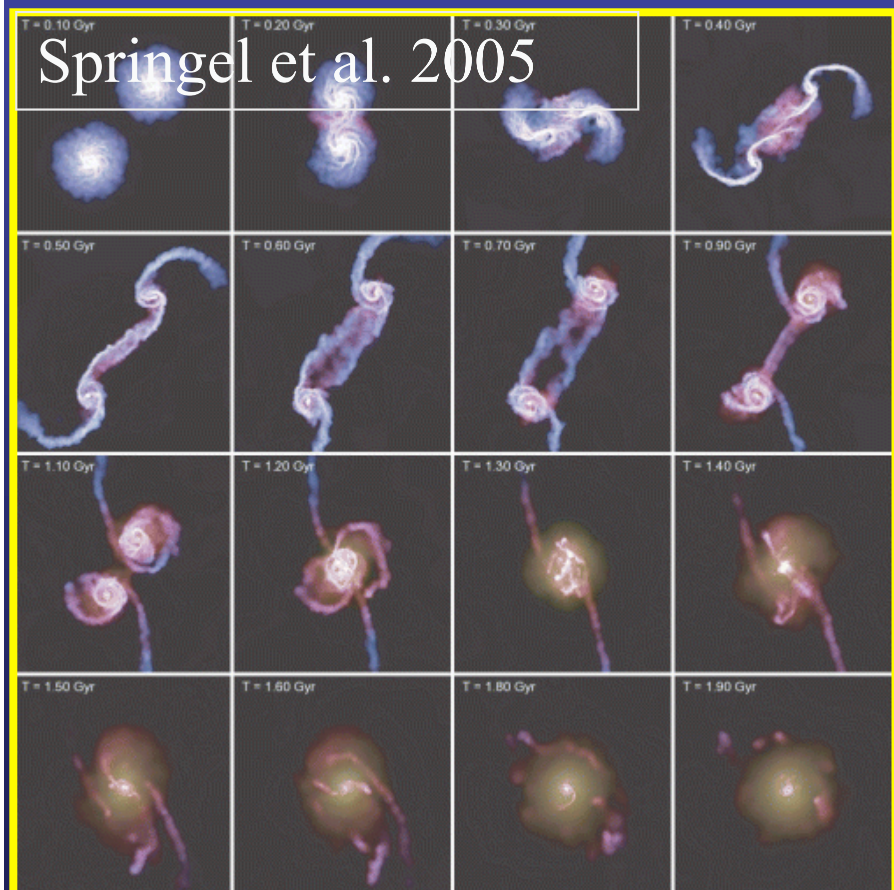
From the Blue Cloud to the Red Sequence: UNDERSTANDING = MECHANISM

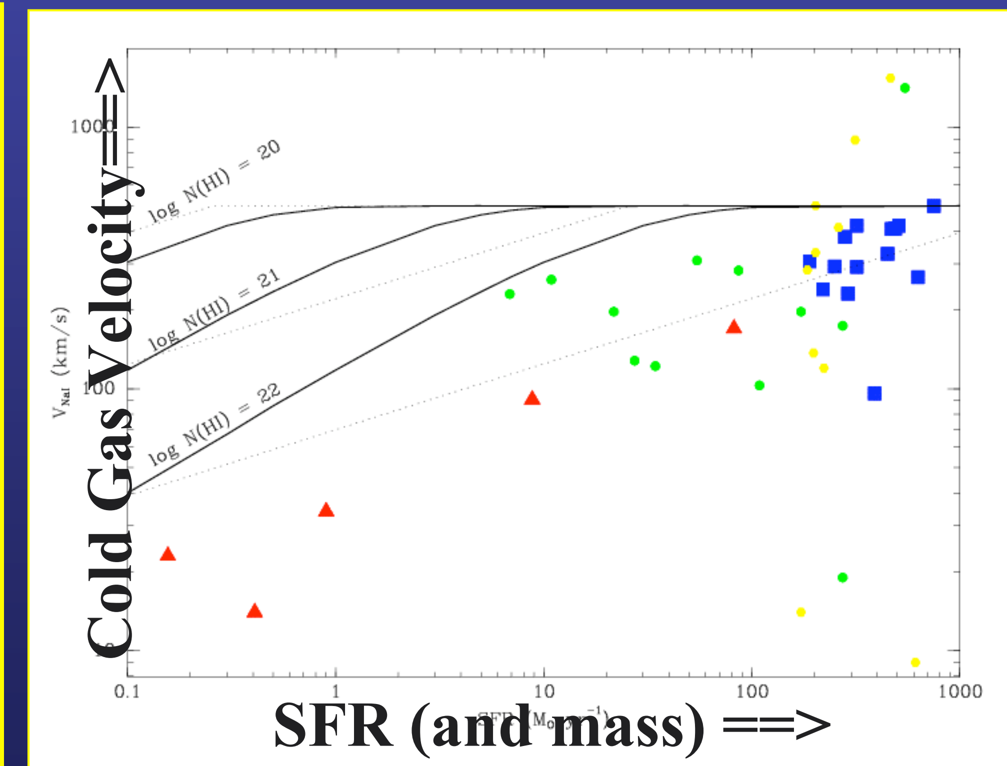
D.C.Martin+2007; Wyder+2006; Faber+2005; Bell+2004



Gas-Rich Disks => Cool ULIRGs => Warm ULIRGs ==> Field E

- ULIRGs ($L_{IR} > 10^{12}$ L_O) discovered with IRAS; Rare today (Soifer; Sanders)
- $R^{1/4}$ profile; high σ/v (Genzel & Tacconi)
- Na I Doppler Shifts 200-600 km/s2 (CLM 2005, 2006; Rupke et al. 2005)

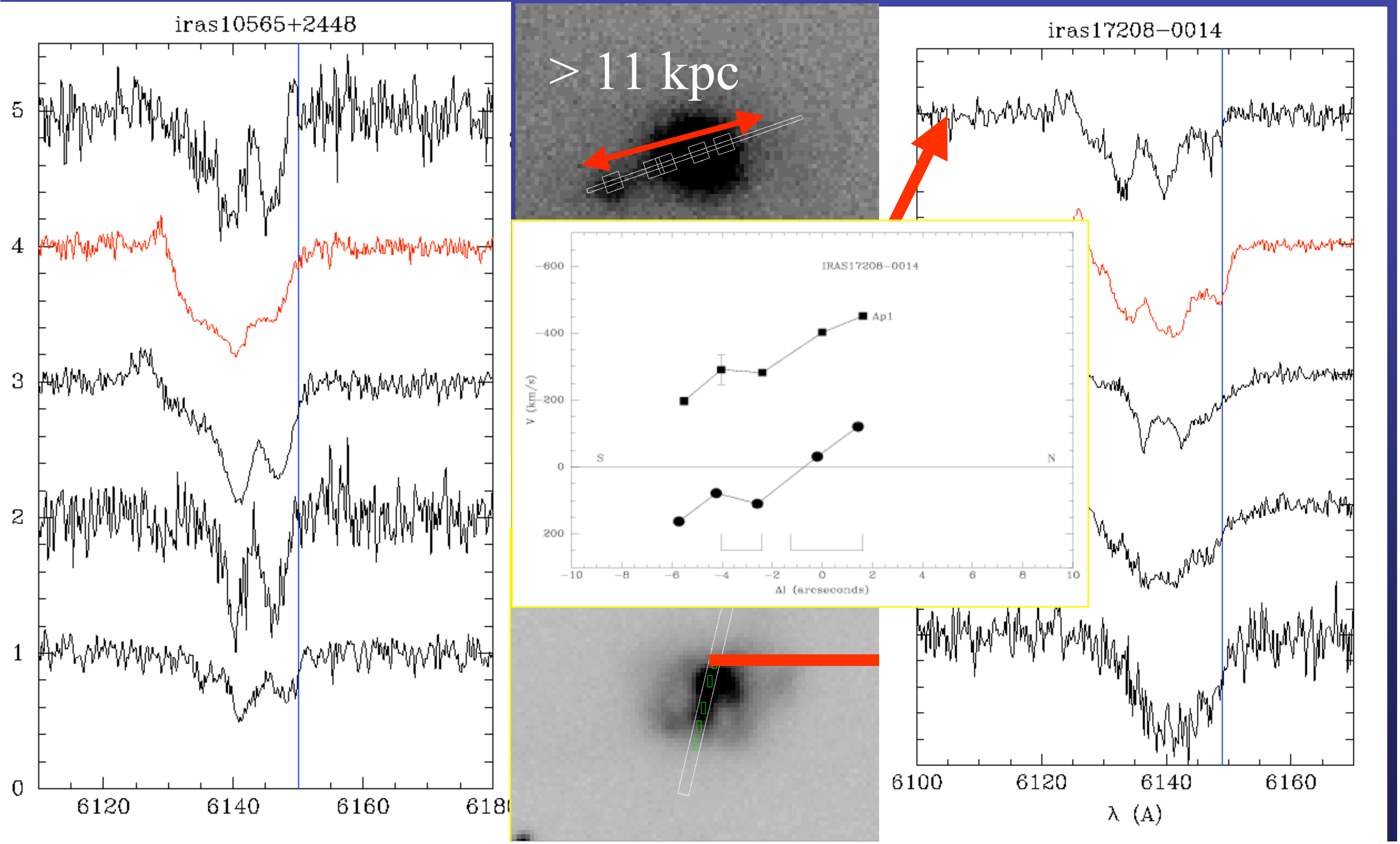




Do SB or AGN power the wind?

Outflows Emerge from Nucleus + Gas Disk!

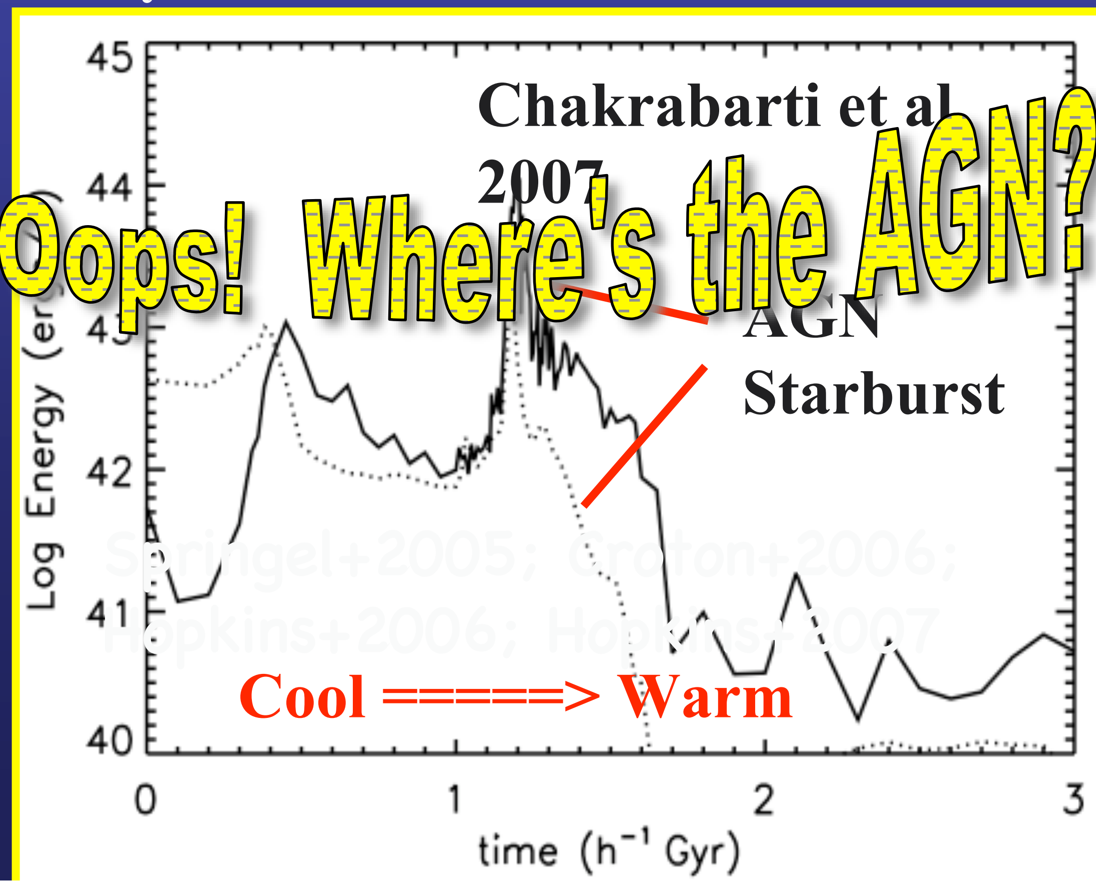
CLM 2006 ApJ



ULIRG Outflows: Starburst or AGN Driven?

1. **Spatially Extended Energy Injection Region**
2. **Mass loss rate: dM/dt ~ 1-30% SFR**
3. **Mechanical Power: dE/dt ~ 1-30% E_{SN}**
4. **Momentum: dp/dt ~ dp_{SN}/dt ~ L/c**
5. **Terminal Velocity ~ Escape Velocity from SB**

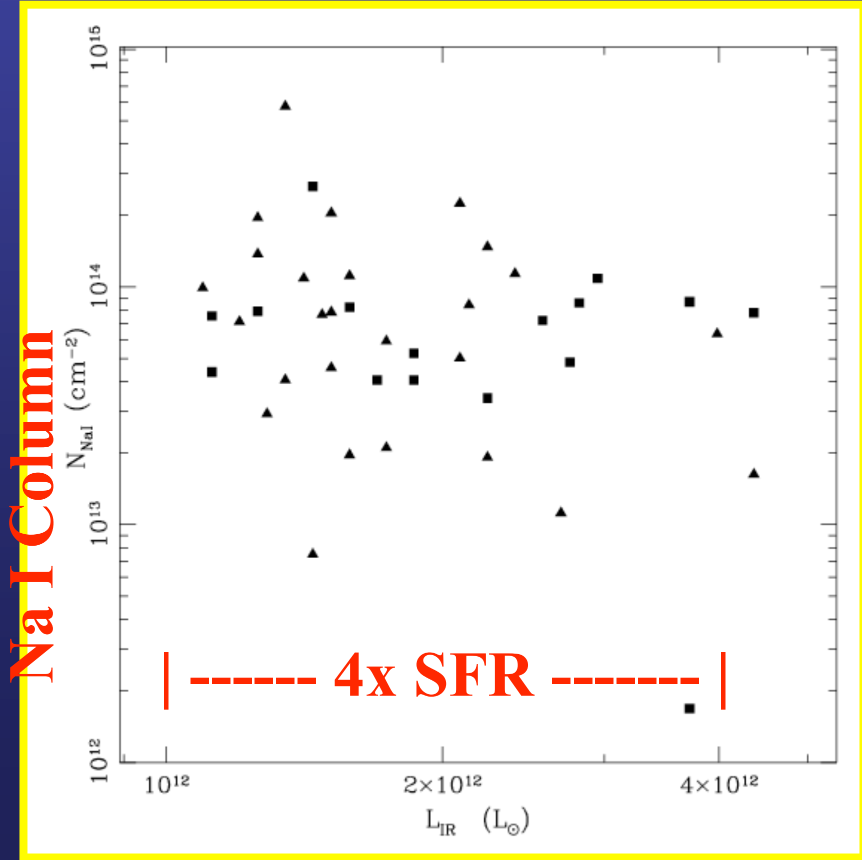
Consistent with being powered entirely by the starburst. Mass loss rate is highly uncertain.



Shortcoming: What is the Mass Loss Rate in the Cold Phase?

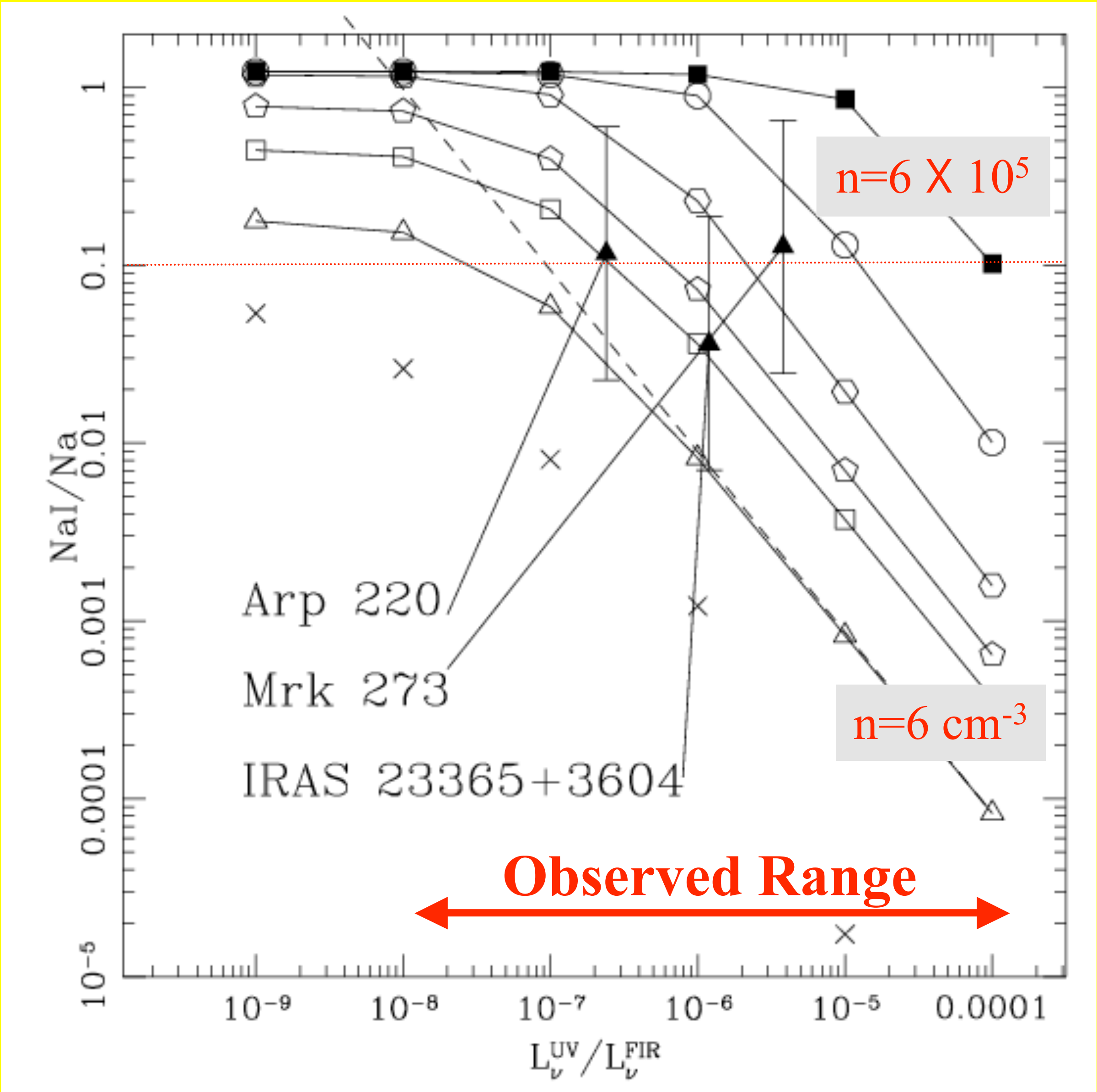
$$\dot{M}_c = 280\ \mathrm{M}_\odot\ \mathrm{yr}^{-1} \left(\frac{N_H}{4.9\times10^{20}\ \mathrm{cm}^{-2}}\right)\left(\frac{R}{10\ \mathrm{kpc}}\right)\left(\frac{v}{400\ \mathrm{km/s}}\right)\left(\frac{\Omega}{4\pi}\right)$$

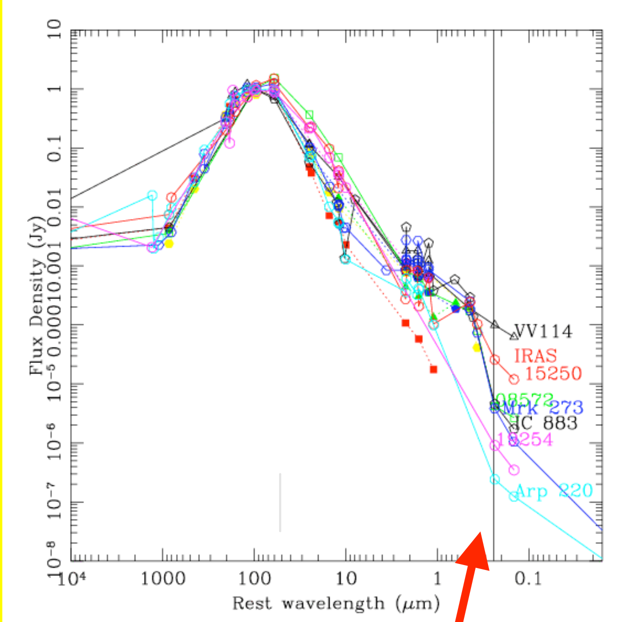
$$N_H = 4.90\times10^{20}\,\mathrm{cm}^{-2} \left(\frac{N_{NaI}}{10^{14}\ \mathrm{cm}^{-2}}\right)\left(\frac{d_{Na}}{10}\right)\left(\frac{N(Na)}{N(NaI)}\right)$$



Mass Outflow Rate Sensitive to Na Ionization

Murray, CLM, Quataert, Thompson 2007

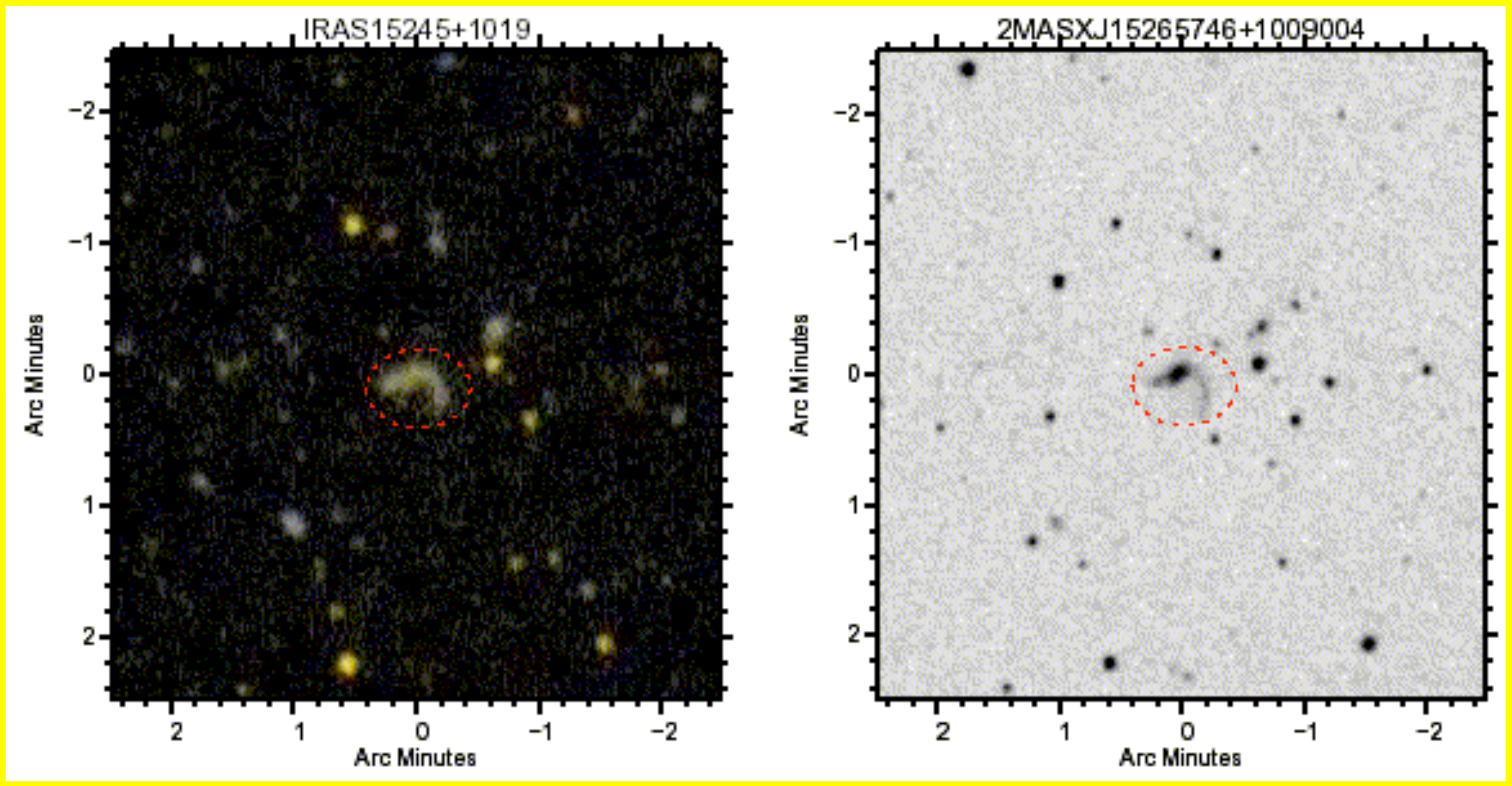




Na I Ionization Edge in NUV

GALEX Imaging of ULIRGS

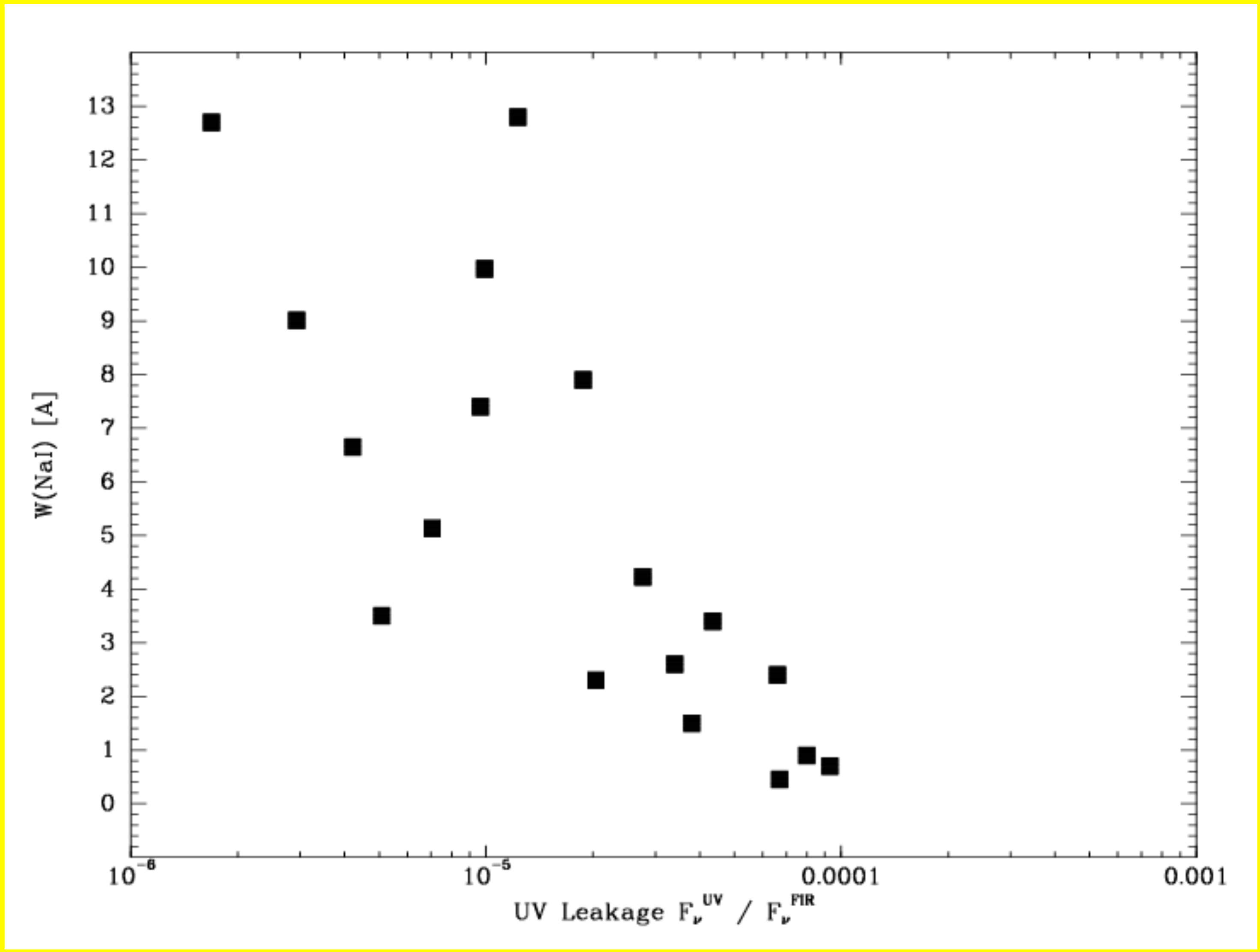
(try getting that by any TAC!)



NaI vs. F_{UV}/F_{FIR} Anti-Correlation?

CLM, Seibert, & Murray 2007

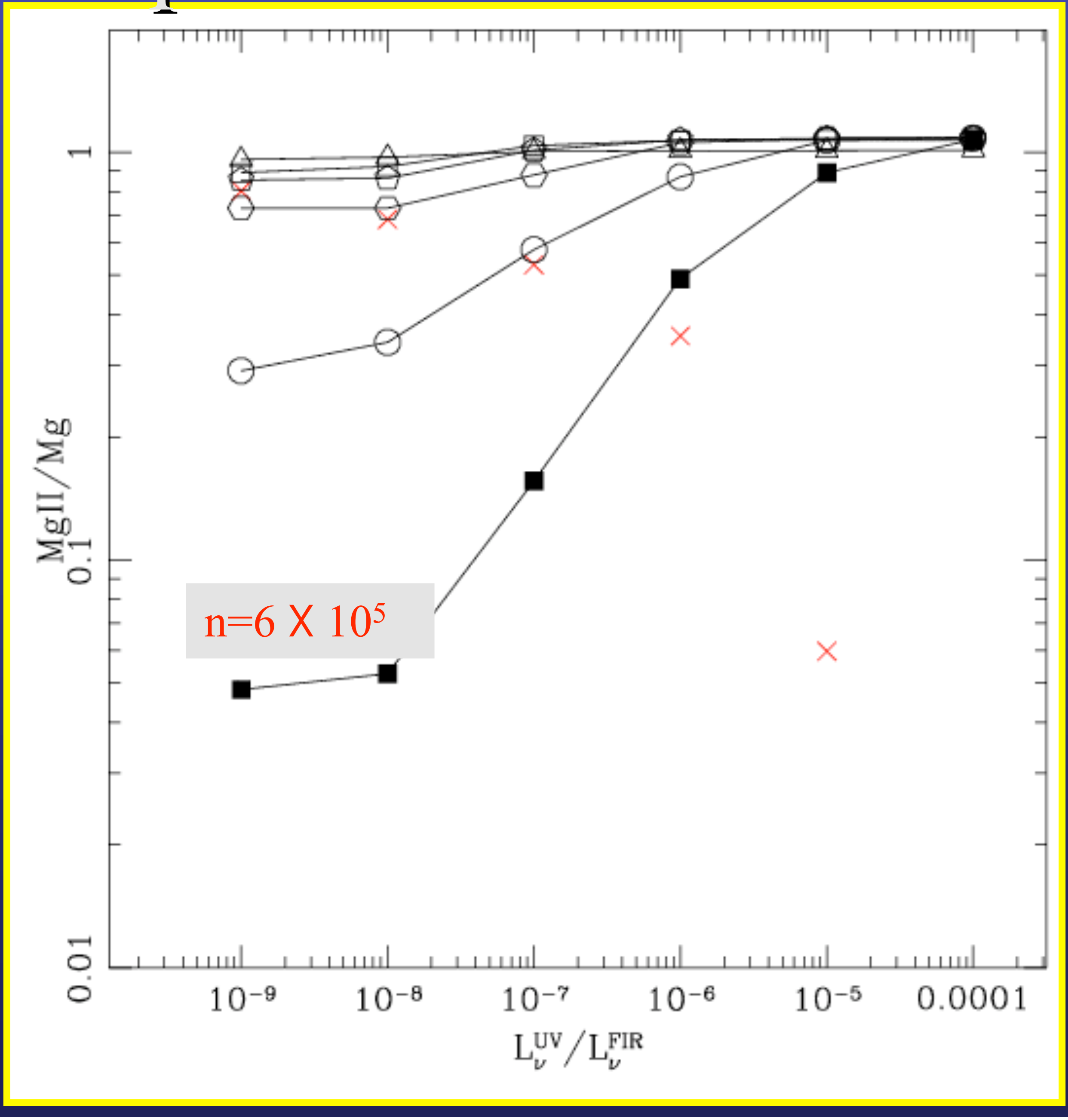
Low Ionization Outflow Column



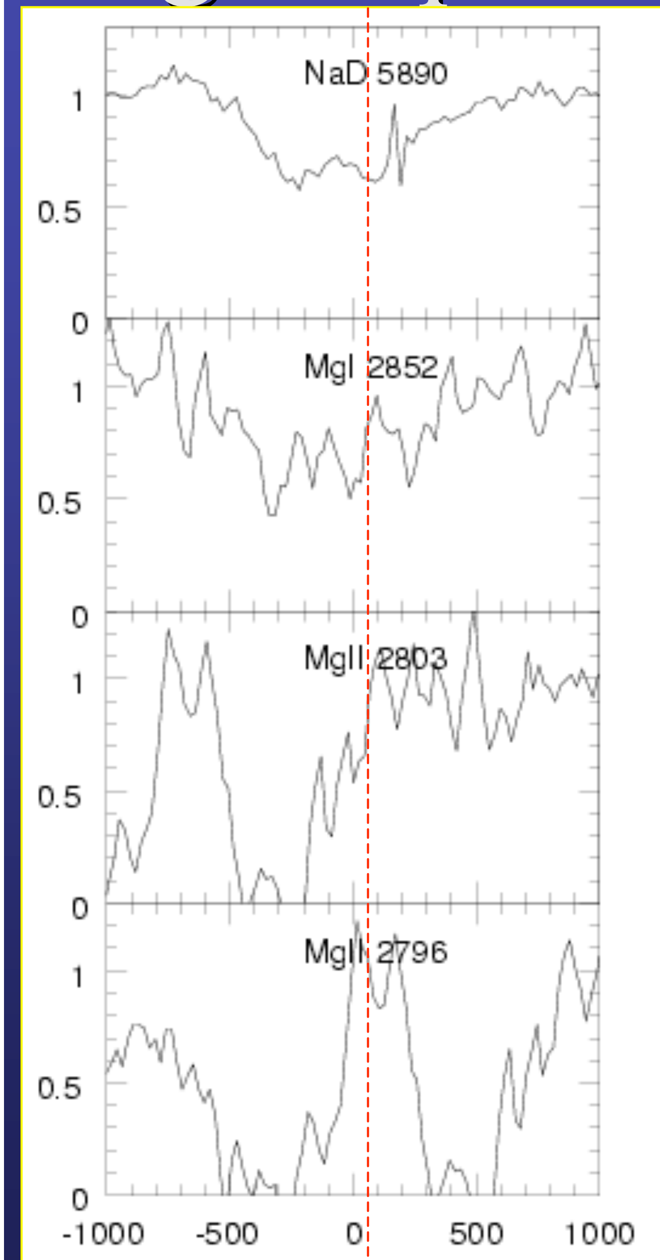
UV Leakage ==>

Mg Absorption from Winds

- N(Mg I) should look much like N(Na I).
- As the spectral hardness increases, Mg becomes more ionized.
- In the low density wind, Mg is mostly ionized for any starburst SED.



Mg II Spectroscopy of z~0.3 Galaxies



<== KeckI/LRIS Spectroscopy of **z~0.3 ULIRG** Winds (CLM & Bouche 2007)

- Na I, MgI, and Mg II all blue-shifted, so absorption from outflowing gas
- Mg II lines are black ==> 100% coverage of continuum ==> Na I and Mg I in clouds
- EW(MgII) ~ strong absorber

SDSS **z~0.3 Post-Starbursts** (Tremonti et al. 2007) \/

- High doppler shifts of 1000 km/s ==> AGN was there?

Rough estimates of ULIRG outflow rates are several tens of M_{O}/yr, a substantial amount of gas over the ~ 0.1 - 1 Gyr duration of the merger-induced starburst.

ULIRGs are too rare today to explain the stellar mass flux from the blue cloud to the red sequence.

Absorption Cross Section of ULIRG Winds

vs. Statistics from Intervening (Strong MgII) Absorbers

•Dynamical model describes V[R]. Solve for dR[t] = V[R]dt

•Examples (CLM 2006 ApJ):

Ram Pressure Wind: Decelerates R~19 kpc; Distant Turnaround

Radiative Acceleration: Decelerates R~ 4 kpc; Turnaround ~32 kpc

$$dN/dz \sim n_0 \, \sigma \, c \, / \, H_0$$

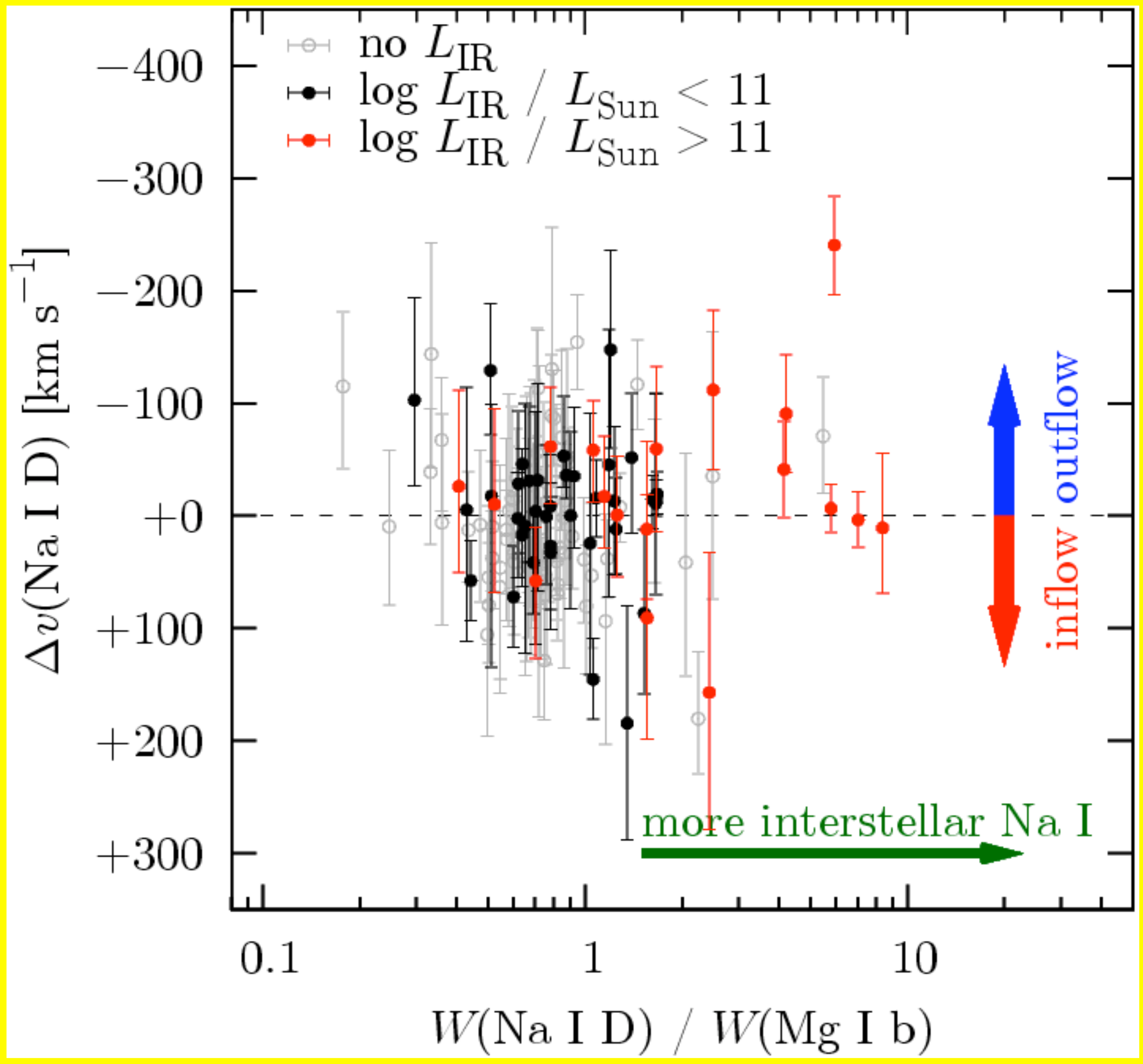
• Density of ULIRGs is very low, $\sim 10^{-5}$ Mpc^{-3}; but all L* galaxies may go through a ULIRG phase. How much dN/dz accounted for?

Prochter et al. (2006) describe local MgII dN/dz. In the limit that all (strong) MgII systems are winds, the required number density of wind bubbles is -- $n_0 = 0.0087$ Mpc^{-3} (30 kpc/ R)^2, or all **L > 0.12 L*.**

Spectroscopic Wind Survey in EGS

Na I Survey @ z~ 0.4 with DEEP2 (Work in Progress)

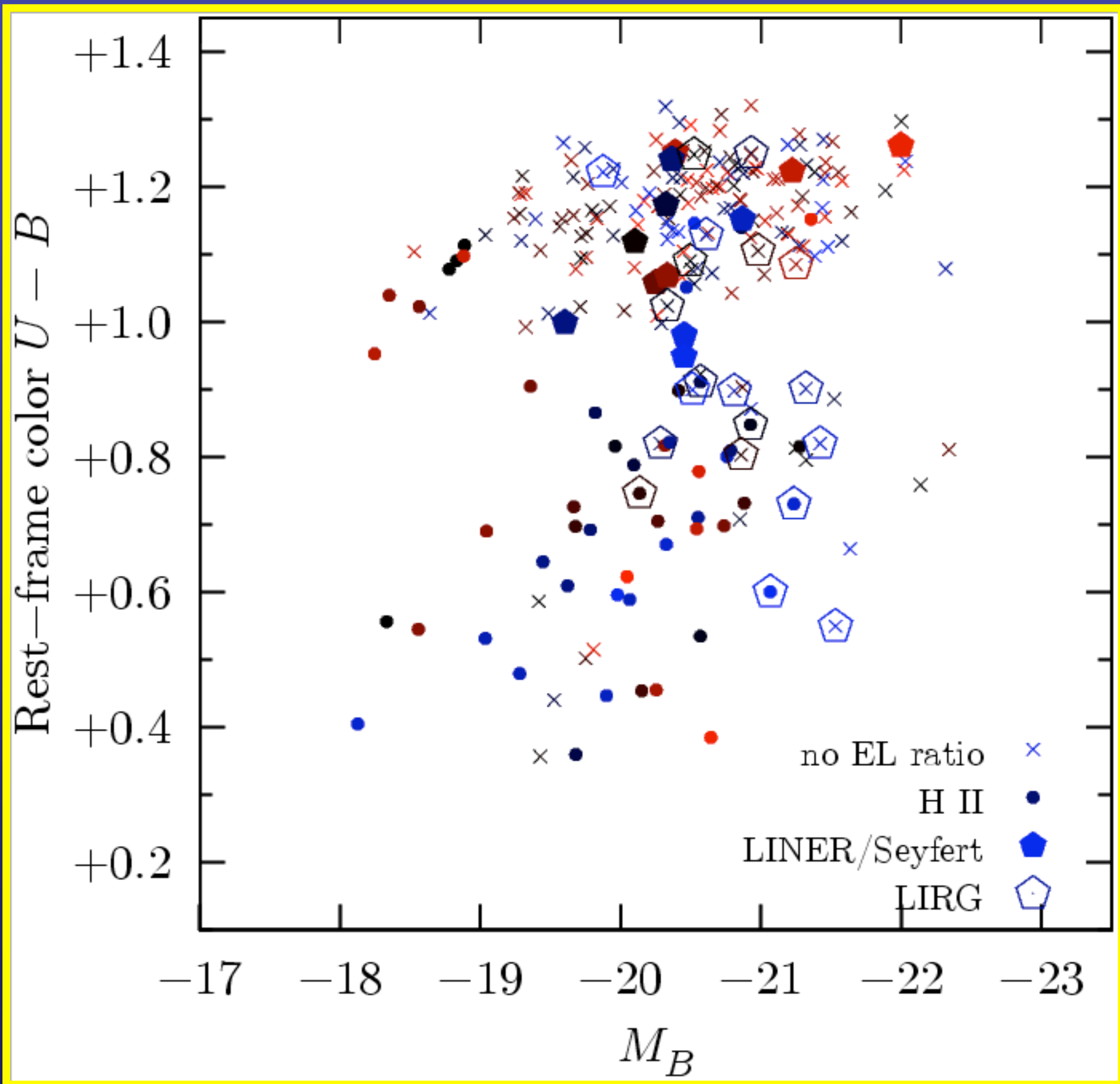
Work of **Taro Sato**

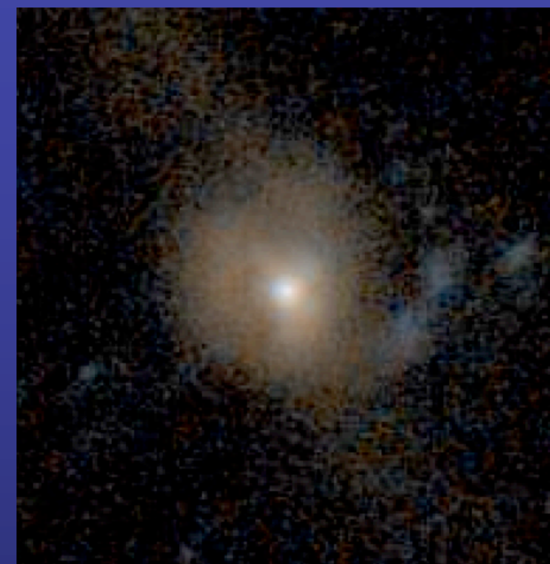


Line Strength ~
Doppler Parameter

Find Outflows in Blue Cloud and on Red Sequence

Find outflows in high fraction of LIRGs ($L_{IR} > 10^{11} L_{O}$)

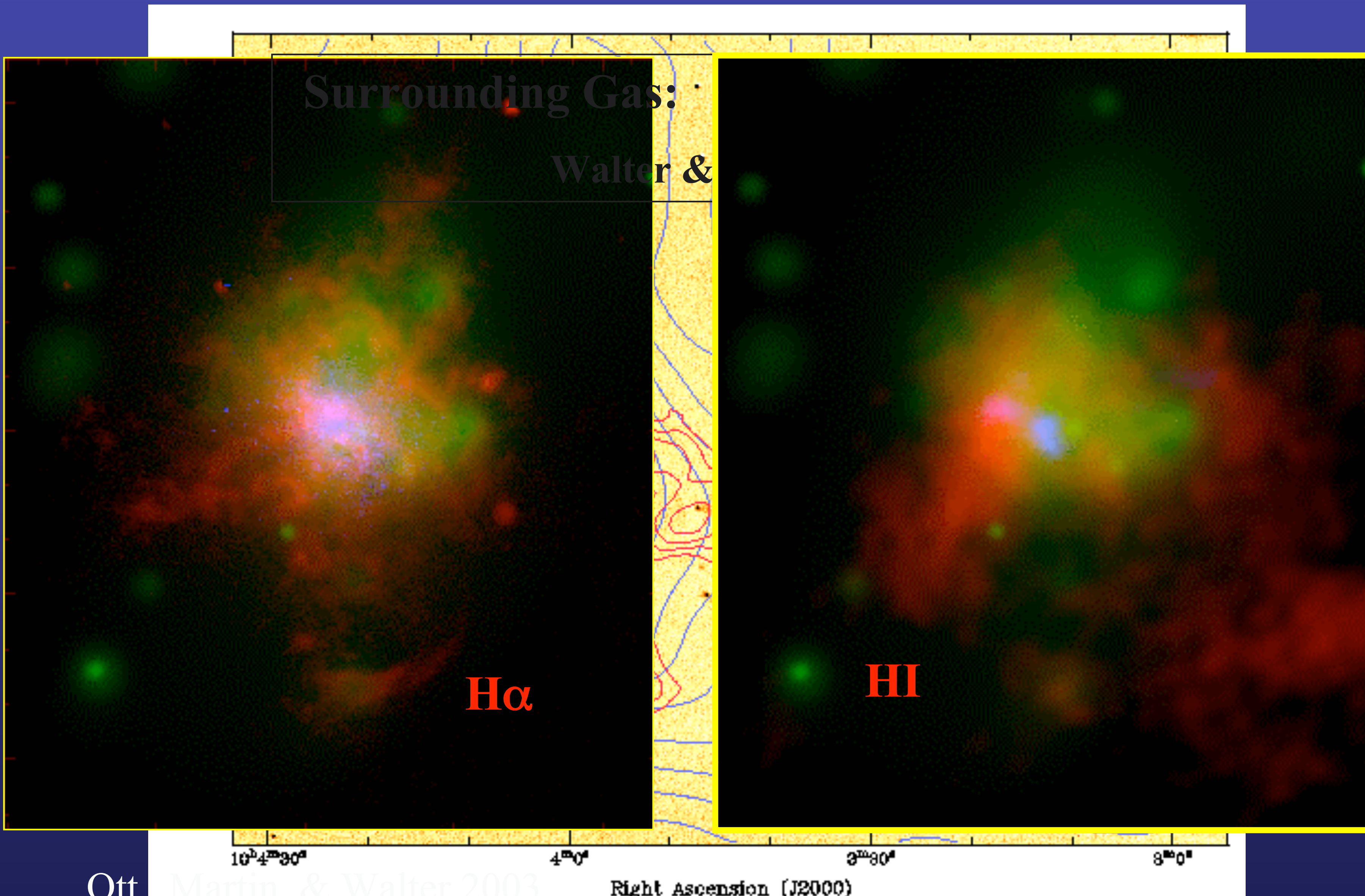




Feedback at z < 1

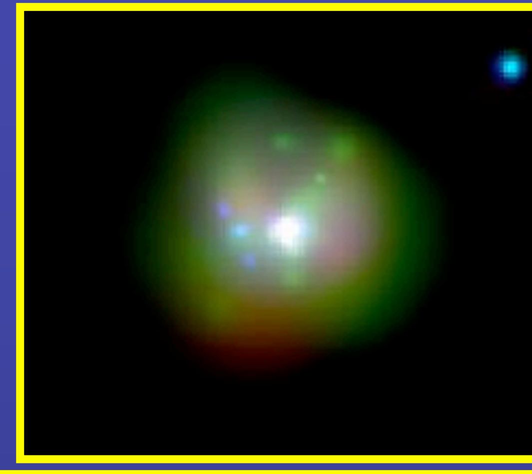
Dwarfs play a key role in enriching
the intergalactic medium.

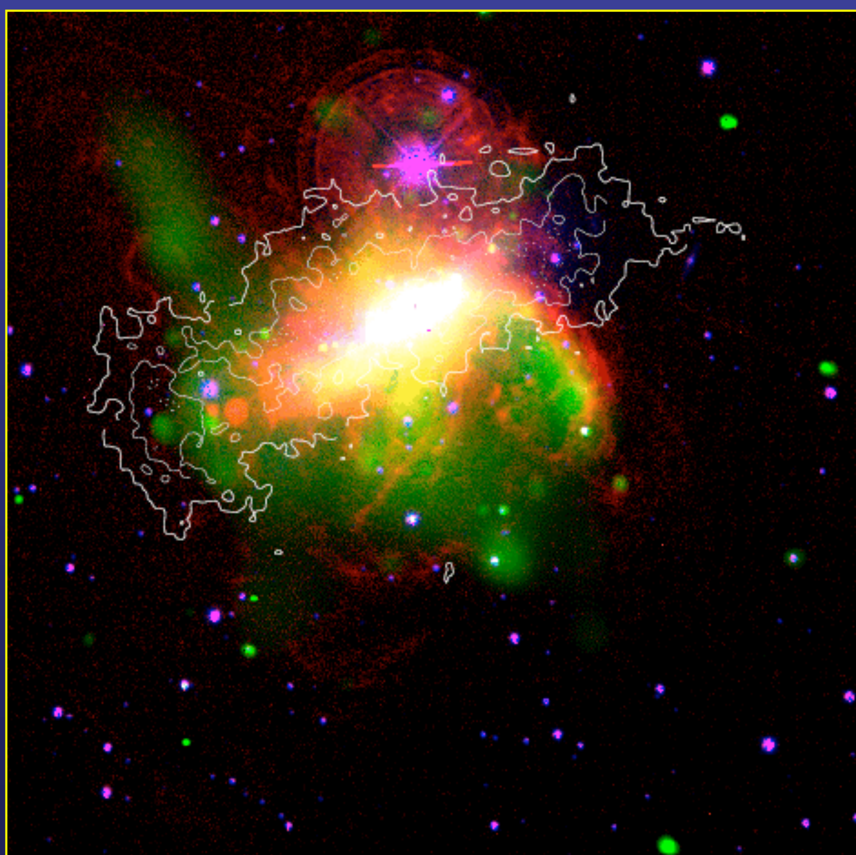
Do the Bubbles Become Winds?

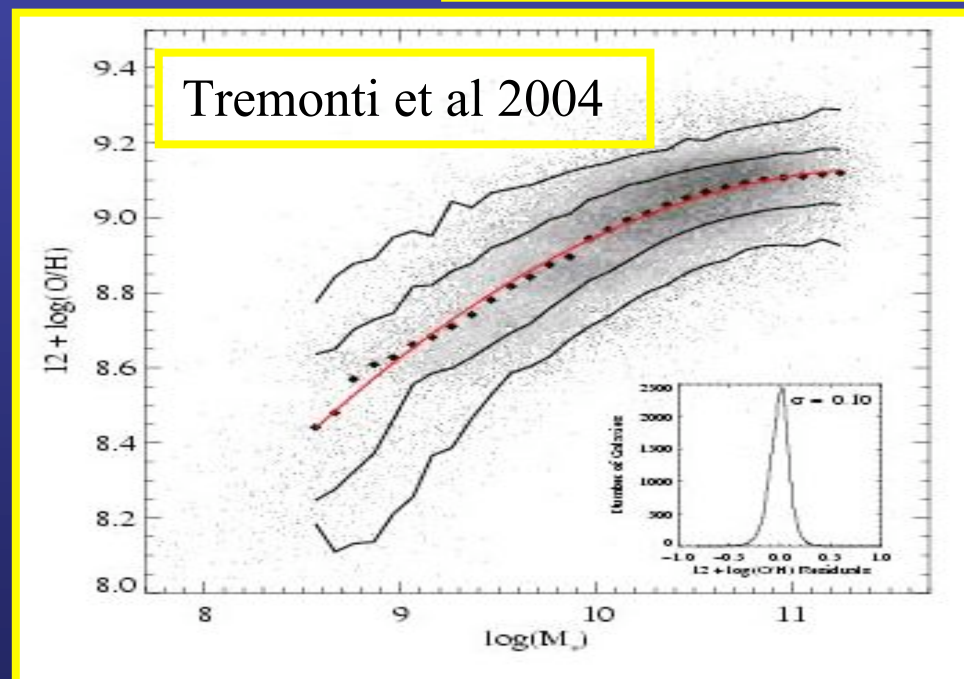


Ott, Martin, & Walter 2003

Opinion: Have studied outflows in detail in such a small volume of space that the discovery of even 1 dwarf galaxy wind is very significant considering their short duty cycle. *Indirect evidence from M-Z...*







Also: Lee + 2006, Dalcanton 2006, Kratsov 2006

DESIRE direct evidence that winds reach ~100 kpc scales.

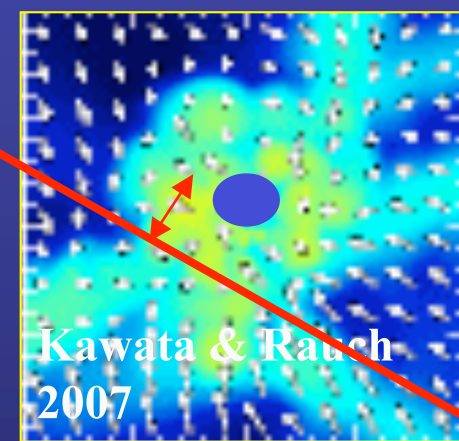
Local Intervening OVI Systems

• **Impact parameters of OVI systems indicate dwarfs**

$z<0.15$ OVI ($N_{OVI} > 10^{13.2}$ cm-2) systems (Stocke et al. 2006)

200-270 kpc from 0.1 L* galaxies

350-500 kpc from L* galaxies



• **Weak absorbers contribute comparable mass to strong absorbers**

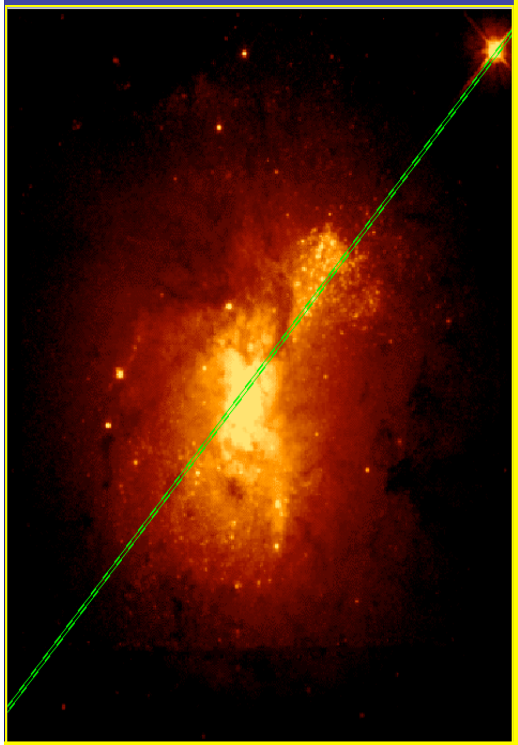
$d\eta_{OVI}/dN_{OVI} \sim N^{-2.2}$ (Danforth & Shull 2005)

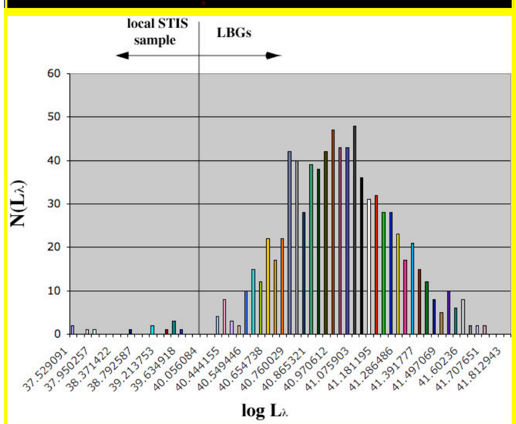
• **Winds disturb a limited volume of the IGM**

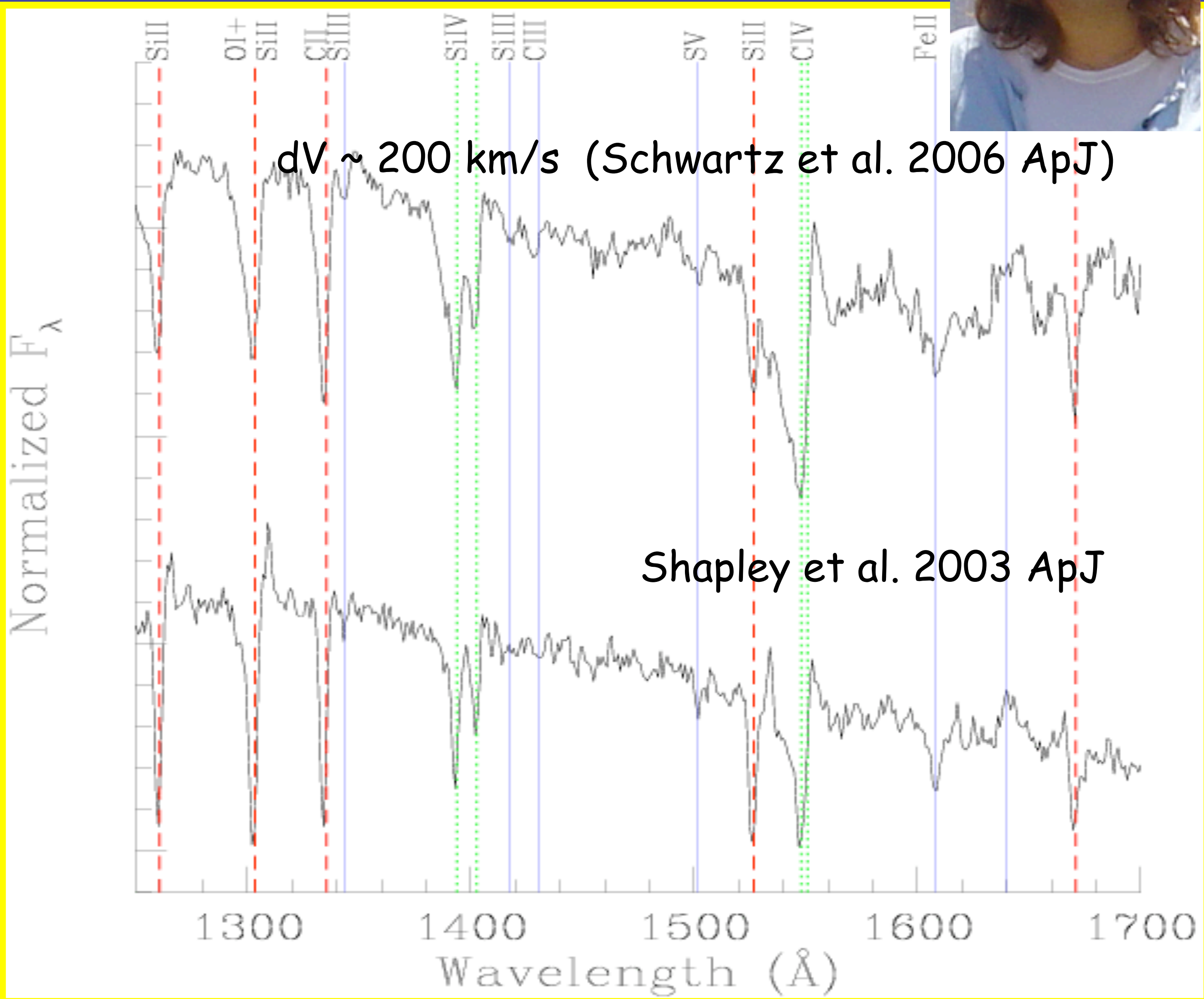
$d\eta_{OVI}/dNdz$ Turnover below $10^{13.5}$ cm^{-2} (Tumlinson & Fang 2005)

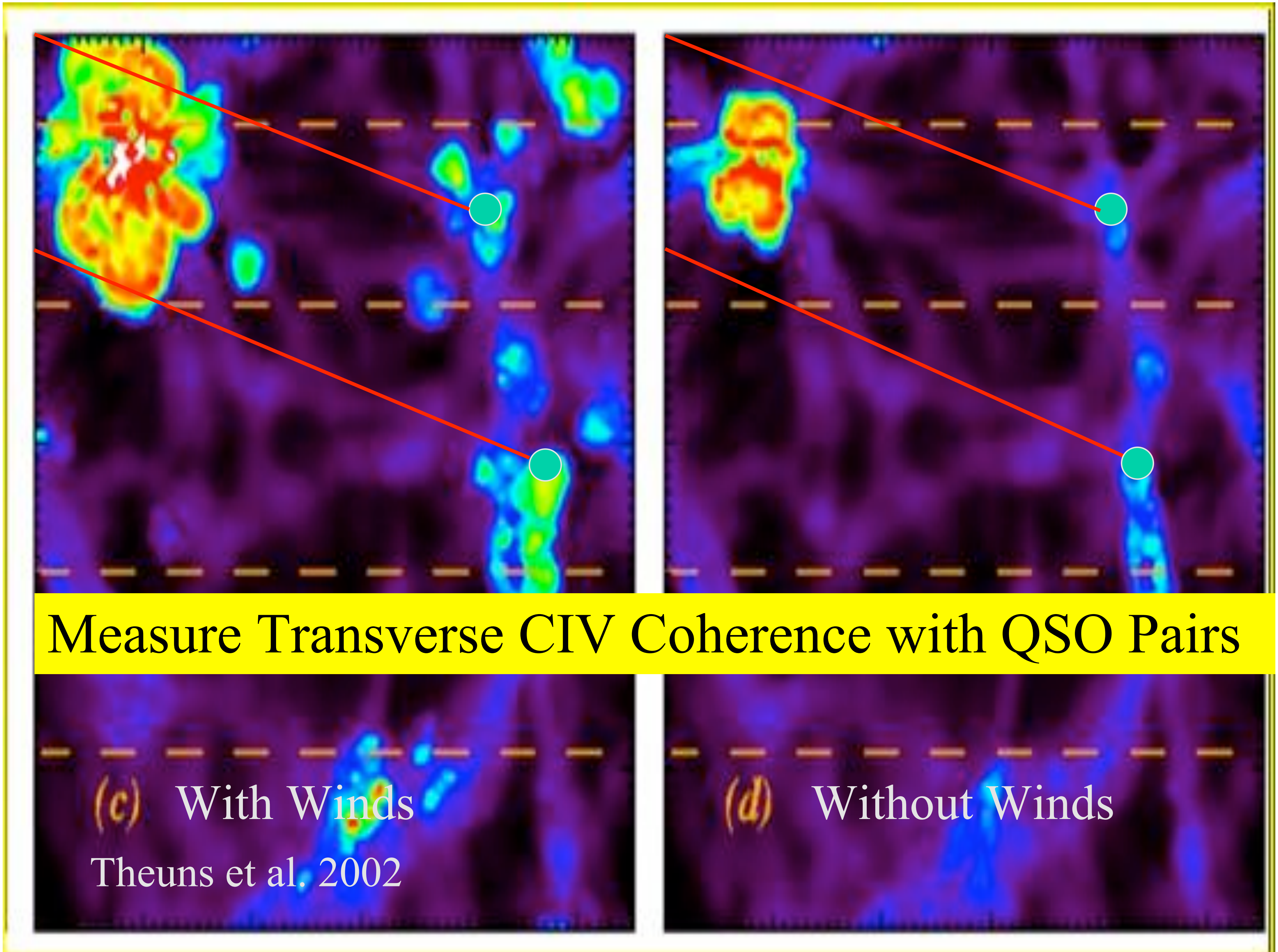
Interstellar Resonance Lines

STIS Spectra of UV-brightest, Nearby Galaxies



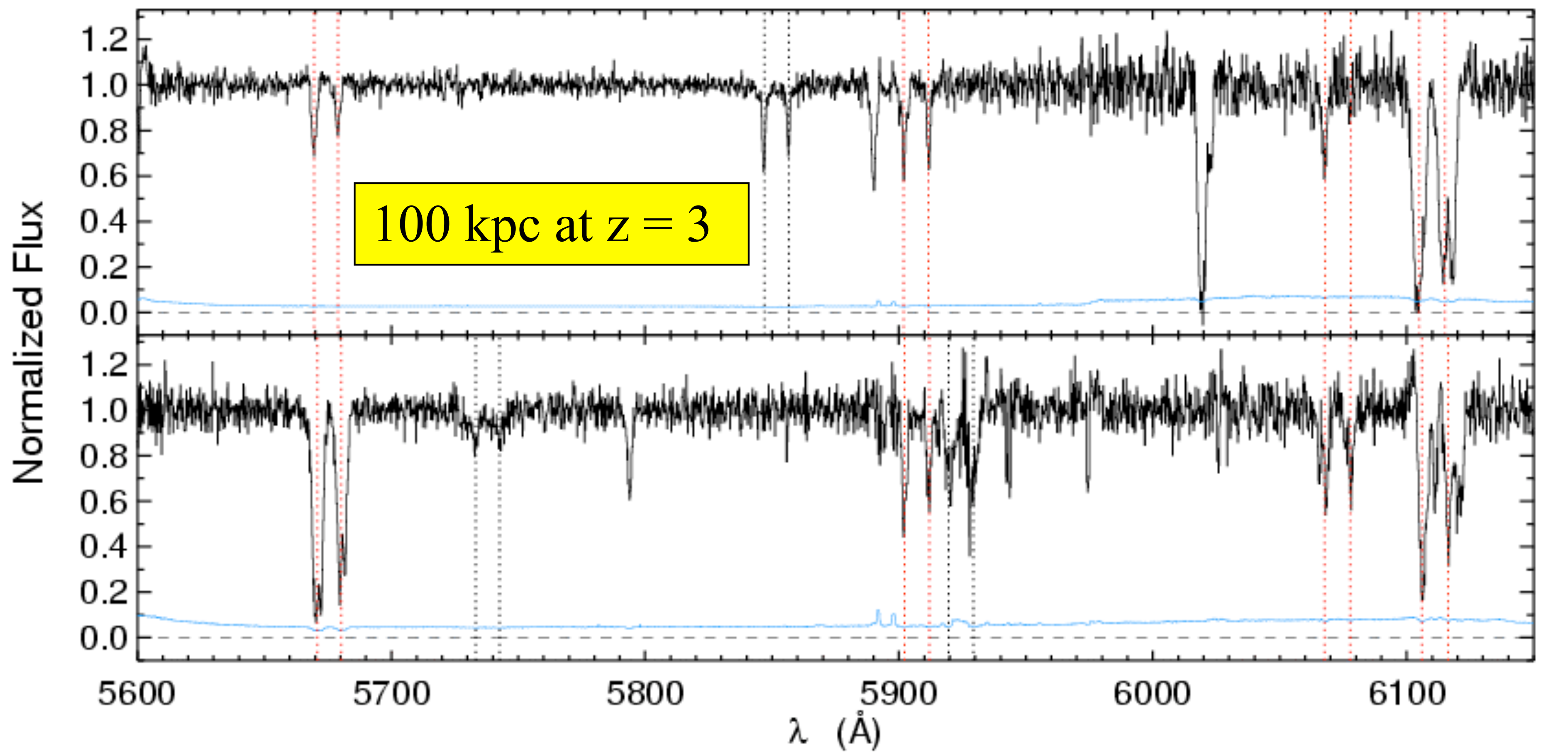


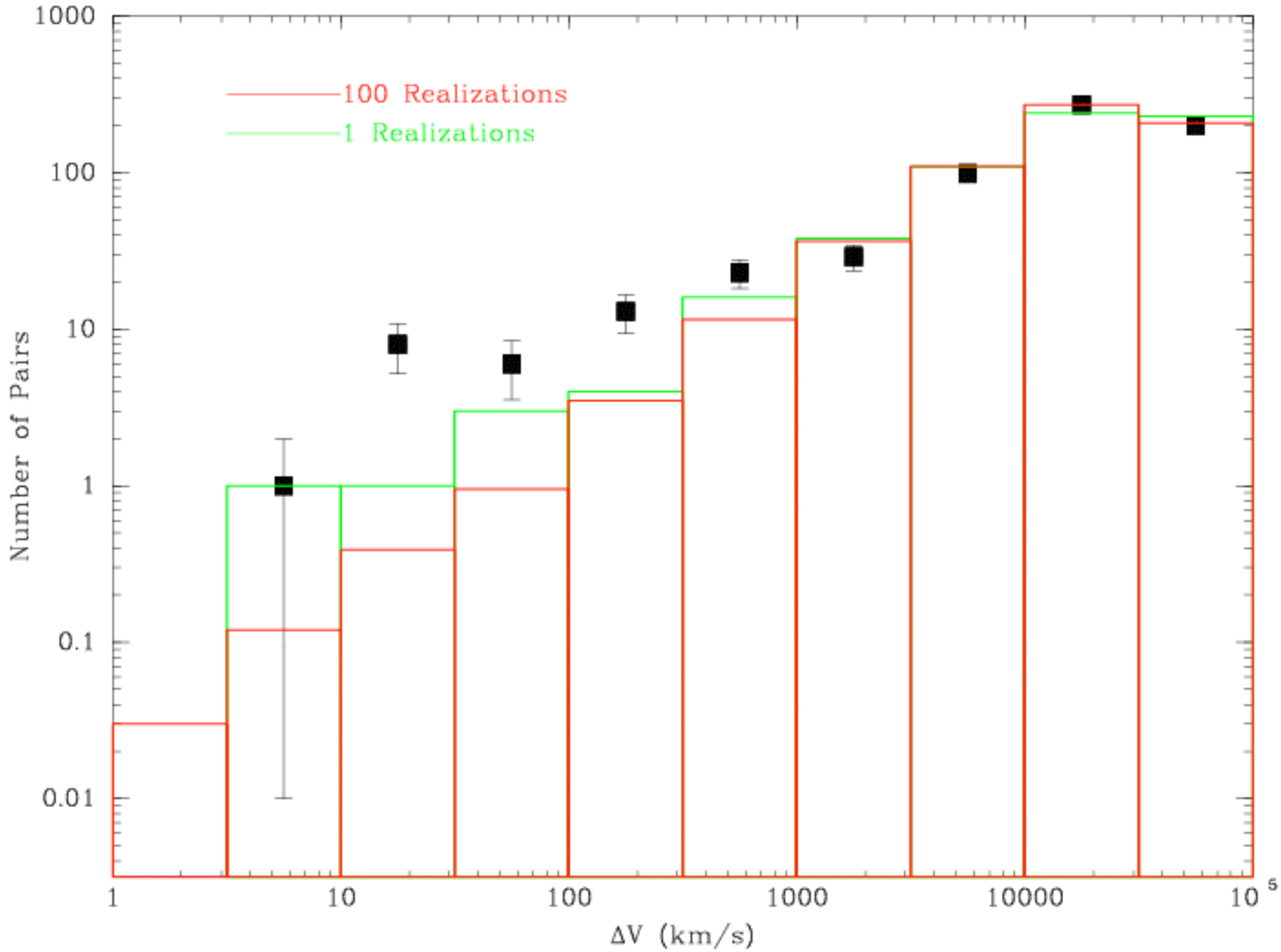



Measure Transverse CIV Coherence with QSO Pairs
(c) With Winds
Theuns et al. 2002
(d) Without Winds

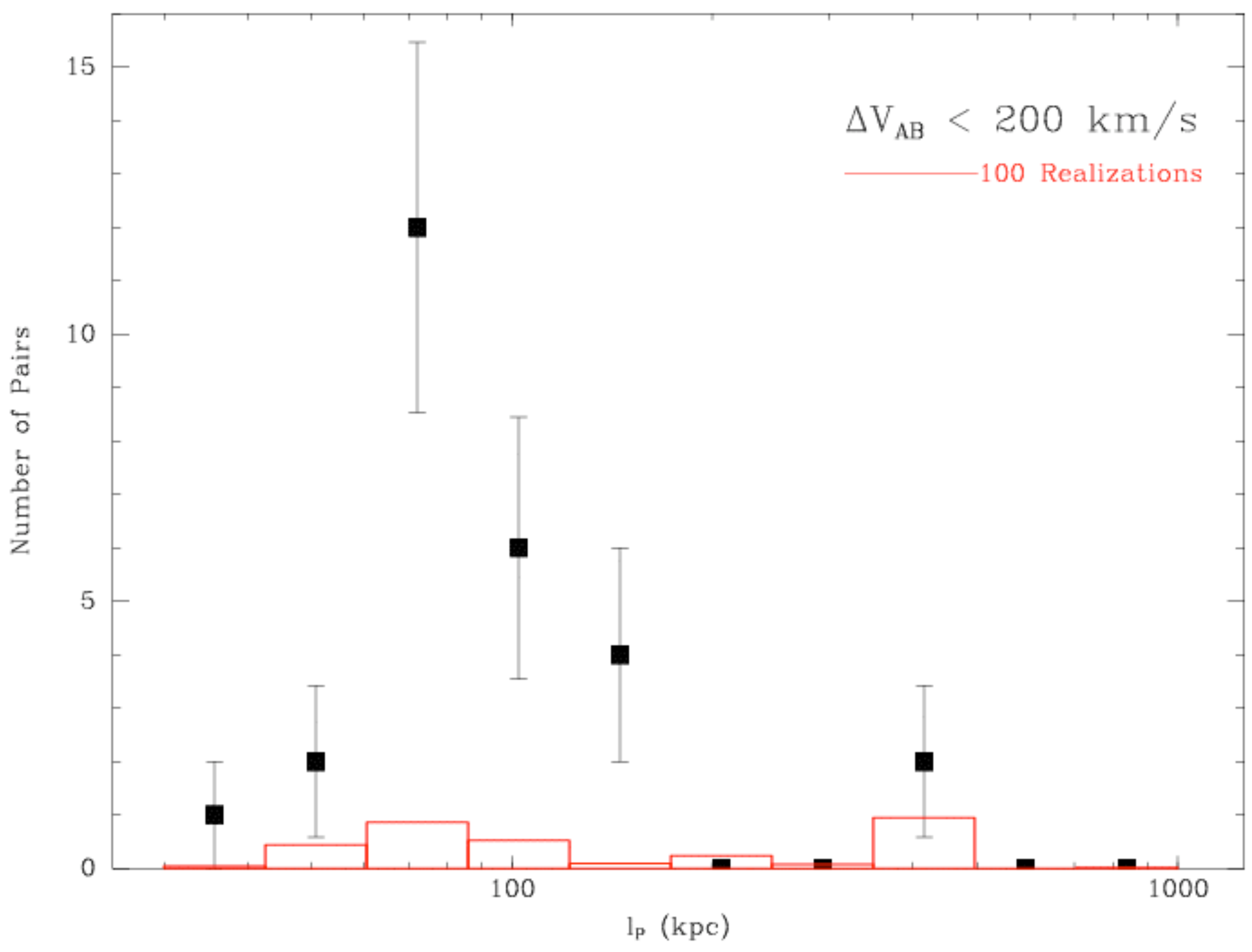
Keck II/ESI and Keck I/HIRES Spectroscopy

- Pairs from SDSS (Hennawi)
- 42 Sightlines (over 3 years) @5-9 CIV systems each
- Proper separation ~ few X 100 kpc;   1.8 < z < 4.5





1000
100
10
1
0.1
0.01
100 Realizations
1 Realizations
Number of Pairs
1
10
100
1000
10000
10 5
ΔV (km/s)



ΔV_{AB} < 200 km/s
100 Realizations
Number of Pairs
15
10
5
0
100
1000
l_P (kpc)

Feedback at $z > 1$

Winds observed in galaxy spectra look a lot like starburst winds in the local universe. The differences are that the cosmic SFR density is much higher and the surrounding halo gas is denser. Look for this evolution in the IGM.