Galactic Winds at Intermediate Redshifts

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Outline

1) Introduction: Key Idea: Use galaxies as background spectral probes of distant gas.
2) Ben Weiner+09: Ubiquitous Cool Gas Outflows from Blue Luminous Galaxies at z ~ 1.4
3) Kate Rubin+10: The Persistence of Cool Galactic Winds in High Stellar Mass Galaxies at z~ 0.7 - 1.5
4) Taro Sato+09: Nature of the Host Galaxies of Cool Gas Inflows/Outflows at z < 0.6
5) Kate Rubin+11: Detection of Cool Gas Inflow at z~0.5
6) Summary & Future Work

Outline

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1) Introduction: Key Idea: Use galaxies as background spectral probes of distant gas.

2) What's DEEP, TKRS, & AEGIS?

3) Taro Sato+09: Nature of the Host Galaxies of Cool Gas Inflows/Outflows at $z < 0.6$

4) Ben Weiner+09: Ubiquitous Cool Gas Outflows from Blue Luminous Galaxies at $z \sim 1.4$

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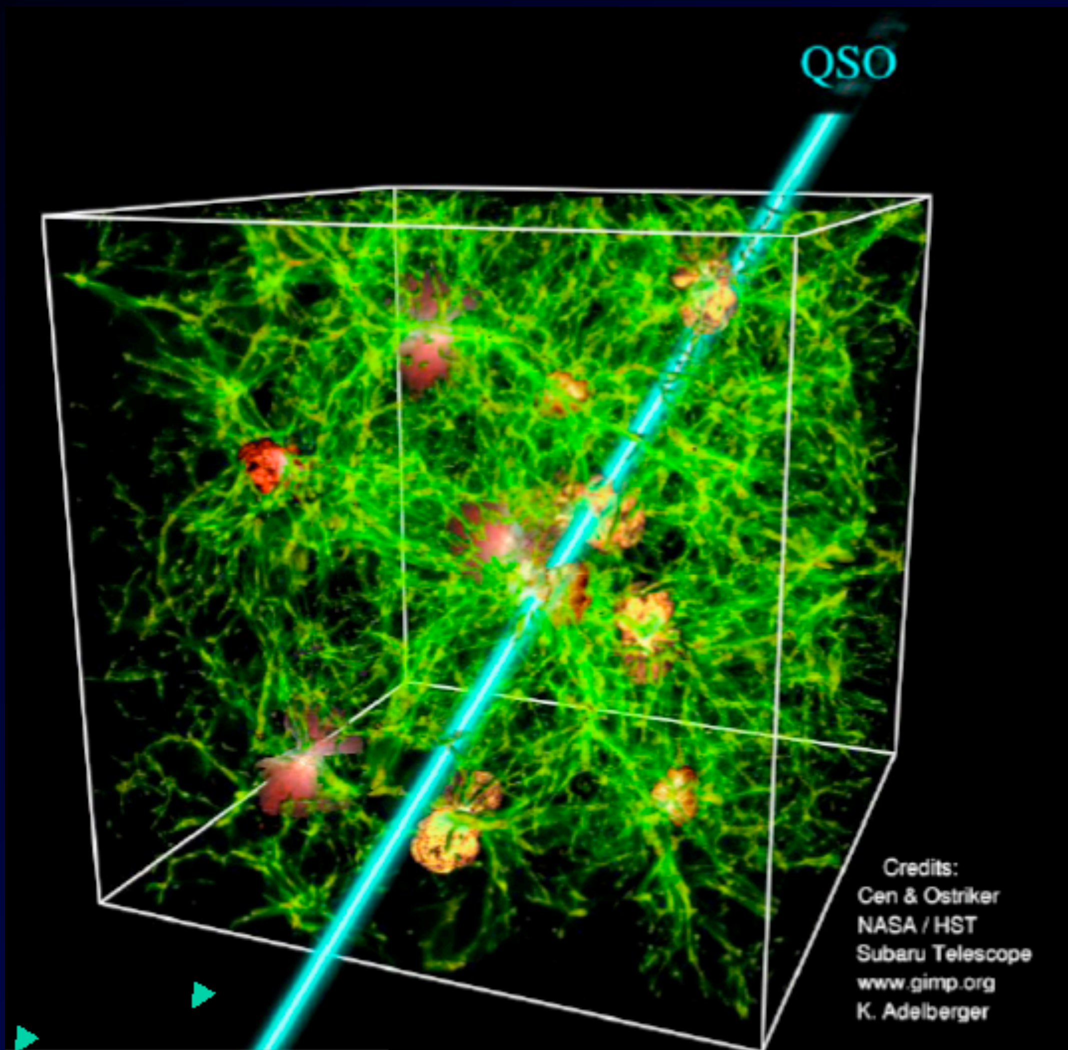
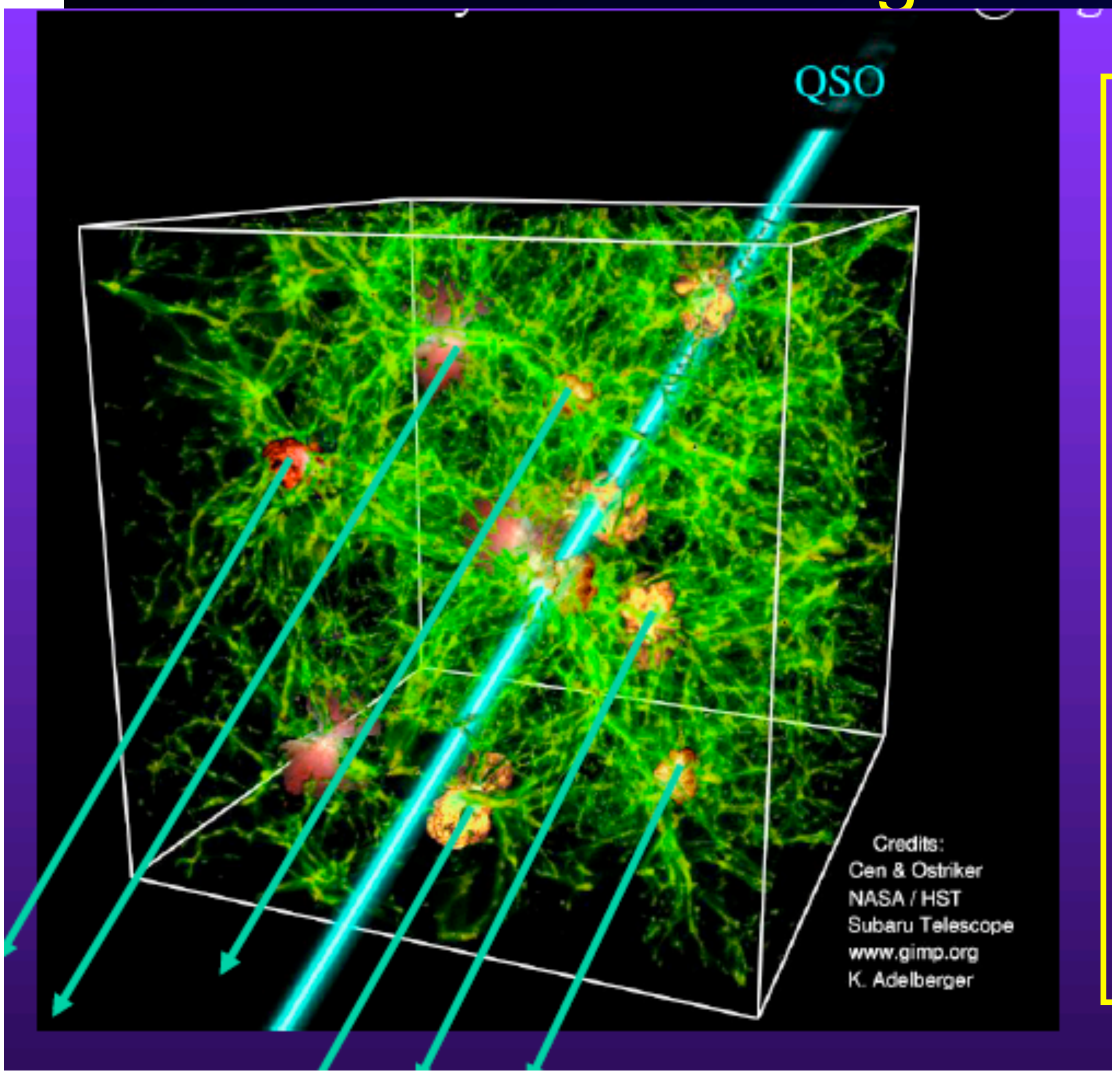
Traditional Method for Studying Galaxy Halos & IGM at High Redshift



Use galaxies as Background Sources for their own gas & those of foreground sources.



PROS: inflow vs outflow; huge numbers; high surface density; not TOO bright for HST; work in data-rich regions; better match of volume for simulations; extended background source.

CONS: much lower S/N -- but can stack; need blue galaxies to see UV; stellar light contamination;

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BASIC DATA for UV MgII Survey at z ~ 1.4

See Weiner+09 for details

SPECTRA from DEEP2: OII emission z for velocity reference & width for dynamical mass and escape velocity estimates; UV Mg II absorption and emission line strengths and profiles for study of gas flows.

SAMPLE SELECTION: from full DEEP2 (32,308), see MgII 2800A & z < 1.5 (1409); with AEGIS MIPS (194); with HST (119);

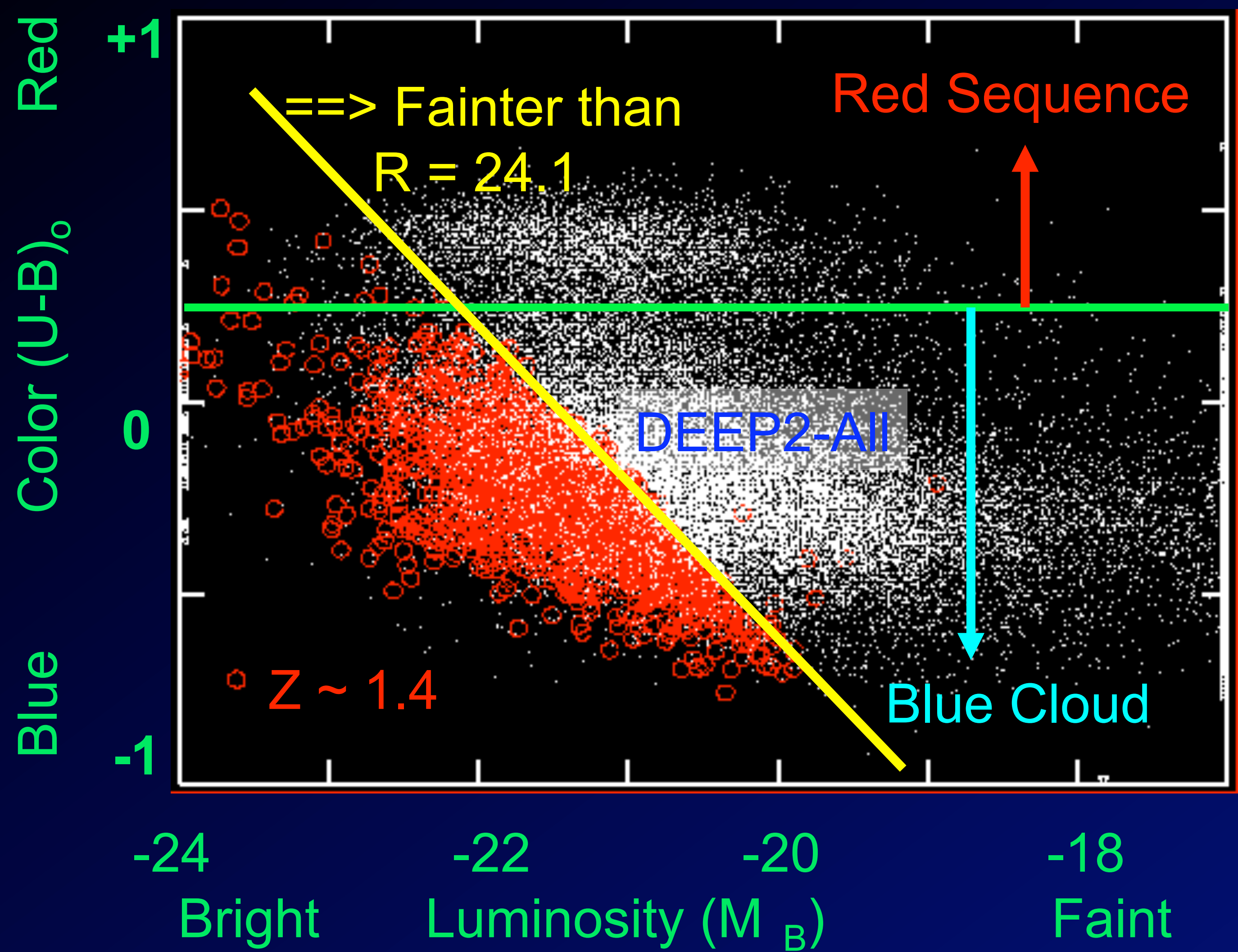
CFHT Images: rest B luminosities and U-B colors

Palomar K band + optical: stellar masses

HST images: morphology, merger, size, inclination

Spitzer MIPS: IR Luminosity and dusty SFR

Color - Luminosity of 1.31 < z < 1.45
Weiner+09 Sample from DEEP2



Coadded Spectra of 1409 Galaxies

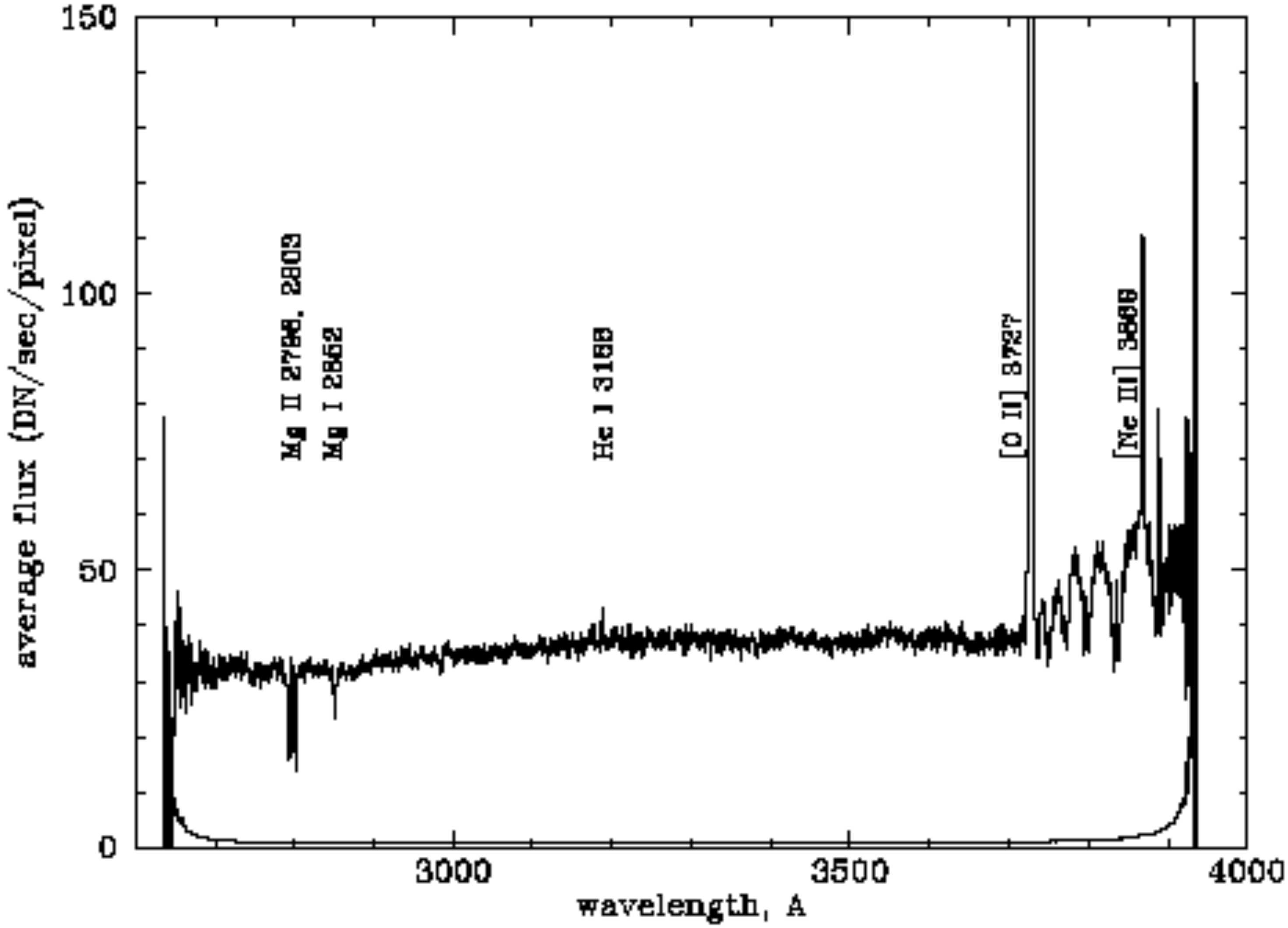
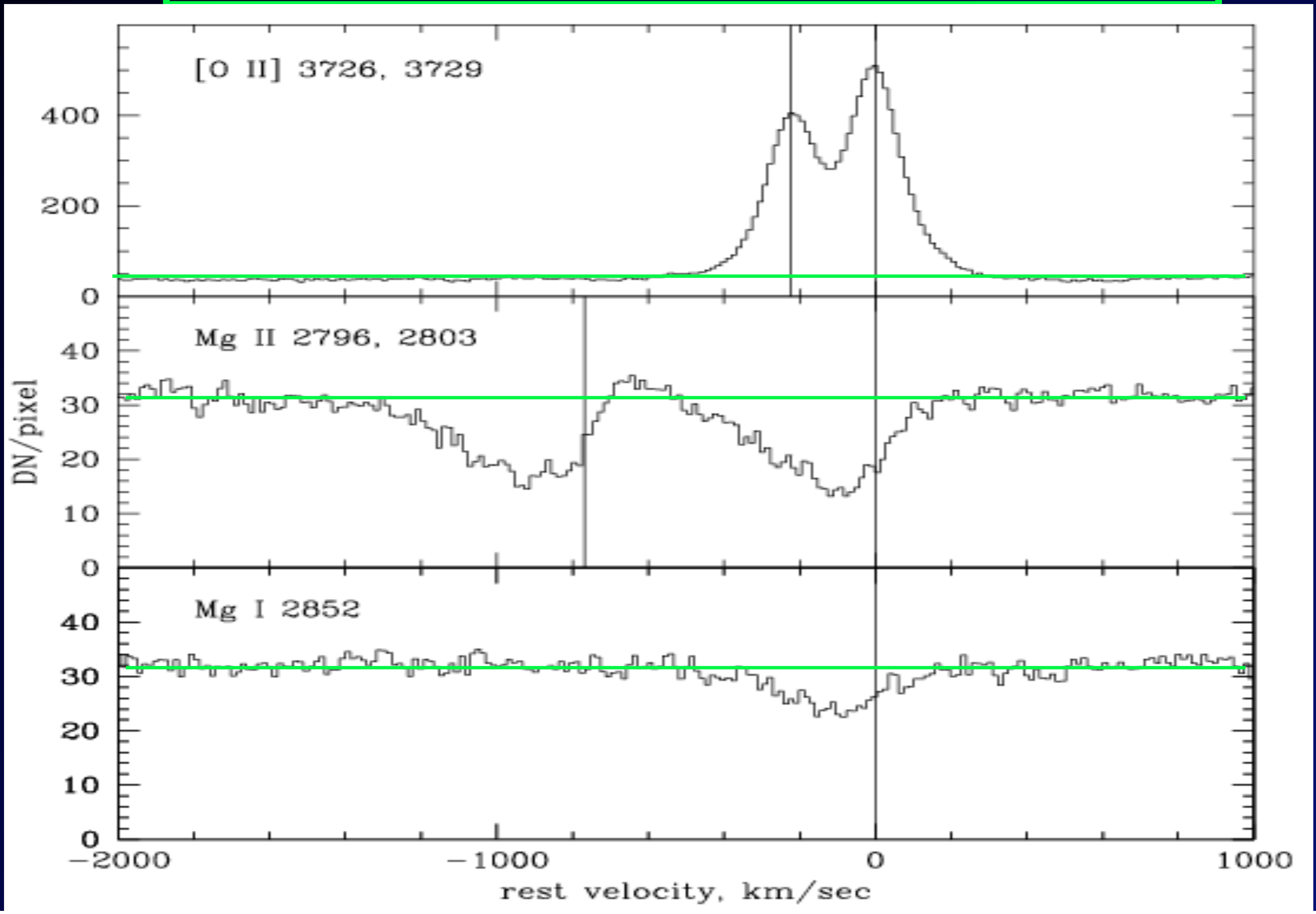


FIG. 2.— The coadded spectrum of all 1406 galaxies in the

Stack of ~1400 DEEP2 galaxies at high z~1.35 - 1.40 shows strong absorption lines of cool gas (Mg II and Mg I) with outflow winds of many 100’s km/s.



Implications of z ~ 1.4 MgII Results for models of Galaxy Formation and Galactic Winds

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Very Strong 55% Absorption: almost all galaxies in sample have outflows -- ; substacks confirm this independent of luminosity, color (within sample), SFR, stellar mass, morphology; imply common Milky Way type galaxies had winds and did not quench

Sawtooth Absorption Profile: median ~ 250 km/s with extension to 500 km/s for 10% depth and as high as 1000 km/s for largest mass galaxies; > escape velocity!

SFR of sample: 10 - 100 Mo/yr (~ LIRG) roughly matches mass outflow of 20 Mo/yr estimated from speed, column density (ratio of doublet gives optical depth of 10 and Log N(H) ~ 20), and size (~ 5kpc galaxy);

Implications of z ~ 1.4 MgII Results for models of Galaxy Formation and Galactic Winds

HST Images: only 3/118 were merger-like so mergers is not required for strong winds as might be inferred from studies of ULIRGS and poststarbursts studied by others; sizes and SFR satisfy Heckman 02 local threshold of 0.1 Mo/yr/kpc ^{2};

Outflow Velocities scaling: higher for larger stellar mass, higher SFR (V(wind) ~ SFR $^{0.3}$ like local ULIRG by Martin 05 and favors momentum vs energy driven winds), and higher escape velocity; implies massive galaxies, not dwarfs, may dominate wind activity and enrichment of IGM and should be included in models of galaxy formation

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BASIC DATA for TKRS Study at z ~ 0.7 - 1
see Rubin+10 for more details

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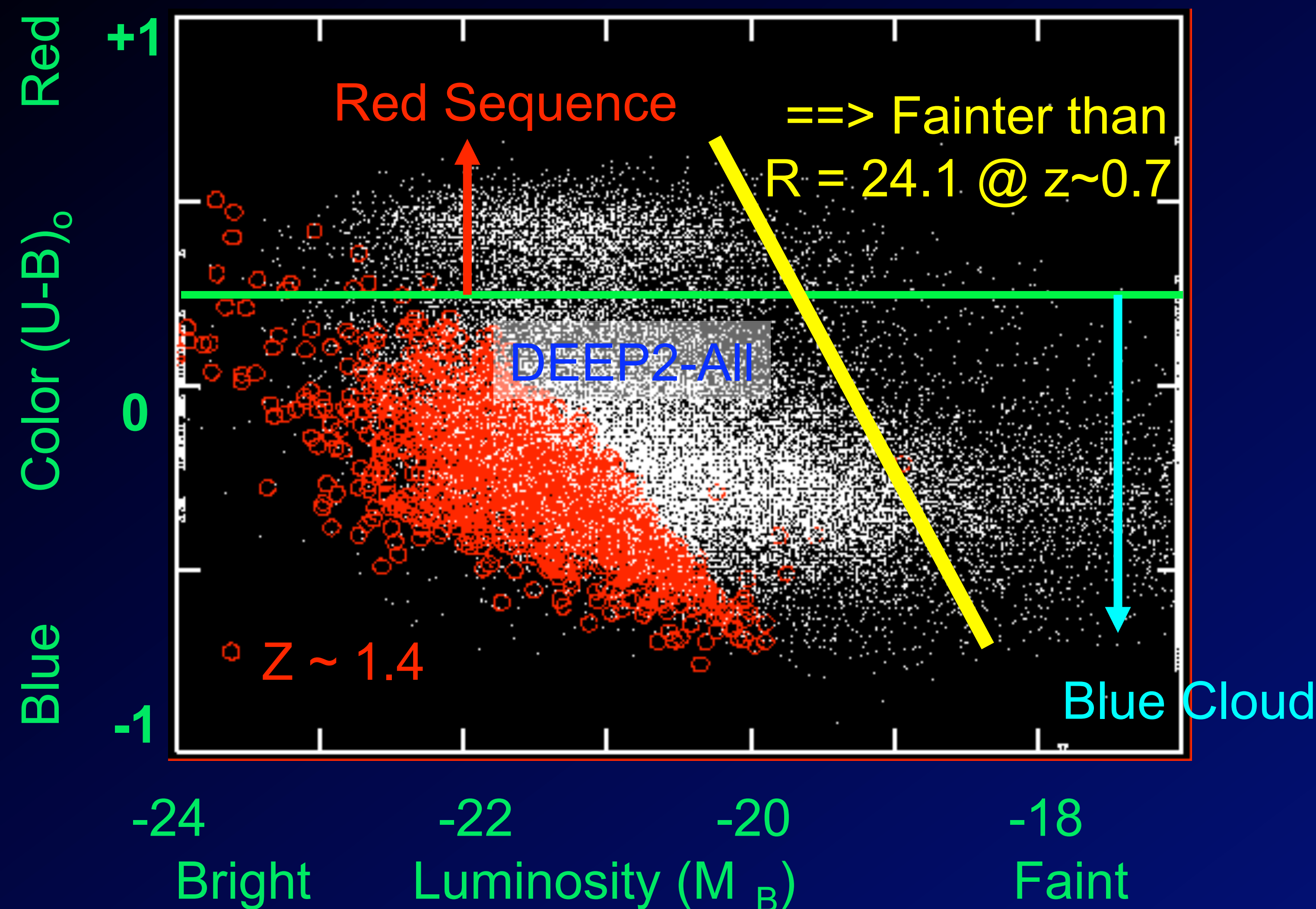
TKRS Spectra of GOODS-North: provide MgII, FeII absorption strength and line profiles for detection of gas flow; OII emission for zero reference for flow velocity;

Sample Selection: MgII/FeII must be visible with sky spectra indicating reliable wavelength and continuum (#468);

CFHT Images: provide luminosities and U-B colors
Palomar K Images: provide stellar masses
HST Images: galaxy sizes to derive SFR surface density; galaxy morphology (Gini,M20)

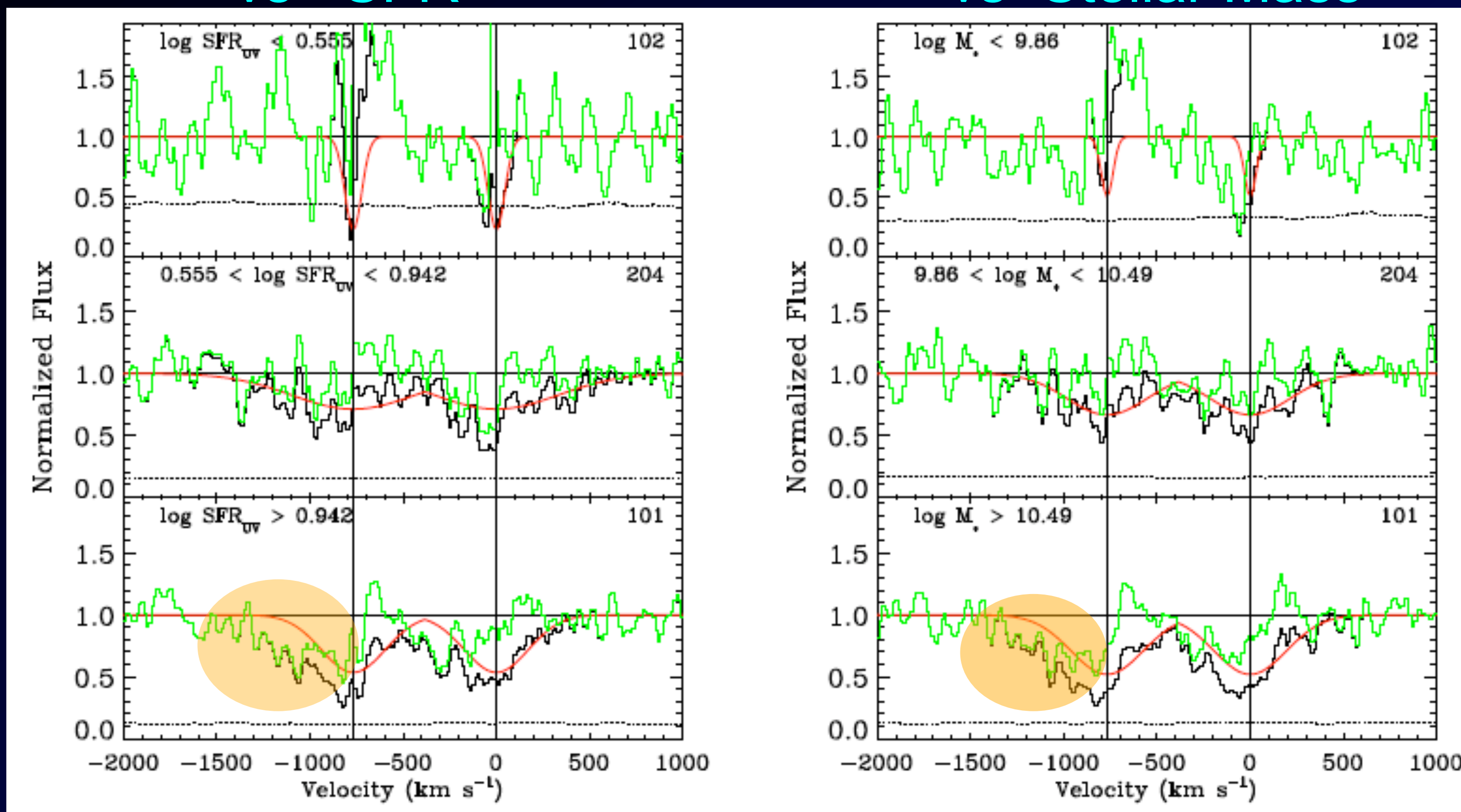
Spitzer MIPS Fluxes: determine IR luminosity (LIRG, ULIRG) and total SFR

Color - Luminosity of z ~ 0.7
Rubin+10 Sample from TKRS



Mg II Absorption vs SFR & stellar Mass

vs SFR | vs Stellar Mass



See winds for only for highest SFR and stellar Masses

Results from TKRS at z ~ 1 &

IMPLICATIONS for Galaxy Formation Models

Most massive and highest SFR galaxies (similar to Weiner +09 sample) show evidence for strong outflow absorption signatures. Lower SFR or less massive galaxies do not.

Massive galaxies with high (but lower) SFR continue to have winds from z ~ 1.4 to z ~ 1. SFR, not SSFR, is key driver.

Outflowing gas density only a bit less than seen by Weiner +09 or local ULIRGs; Fe II suggest Log N(H) ~ 19.3

Mass outflow continues to be roughly the same as the SFR.

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BASIC DATA for Na I Absorption Study
see Sato+09 for more details

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DEEP2 EGS Spectra: provide Na I Absorption strength and line profiles for detection of gas flow; stellar population fit for subtraction of continuum and zero velocity reference for flow velocity; emission lines for optical-based SFR; Balmer lines to detect post-starburst signatures

Sample Selection: NaI is visible (2248); S/N > 5 near NaI (493); successful NaI measurement (203)

CFHT BRI Images: provide luminosities and U-B colors

Palomar K and optical colors: stellar masses

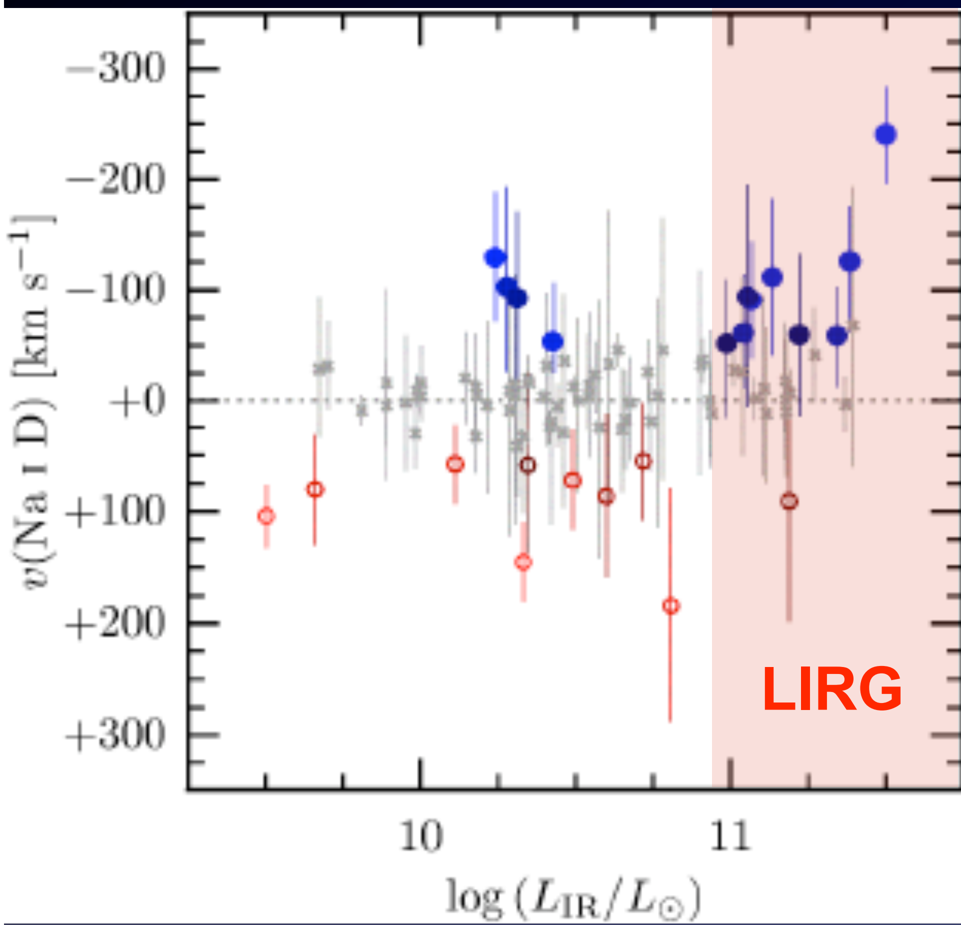
HST Images: host galaxy morphology - merger, spheroid

GALEX-optical Colors: very sensitive to presence of young stars in even optically very red galaxies

Spitzer MIPS Fluxes: determine IR luminosity (LIRG, ULIRG) and dusty SFR

KEY RESULTS OF NaI SURVEY

Blue: OUTFLOW **Red: INFLOW**
Gray: X NEITHER **Dot-Low S/N**



Outflow detection rate correlates with L_{IR}

Outflow speed of ~ 100 km/s also comparable with LIRGs (e.g., Heckman et al. 2000)

TABLE 2
DETECTION RATES FOR NA I D OUTFLOWS SELECTED BY L_{IR}

Criterion	$N_{subsample}$	$N_{outflow}$	Detection Rate
With MIPS observation	169	24	0.14 ± 0.03
$\log(L_{IR}/L_\odot) > 11$	21	8	0.38 ± 0.11
$\log(L_{IR}/L_\odot) \leq 11$	148	16	0.11 ± 0.03

NOTE. — The conventional cut for LIRGs is $\log(L_{IR}/L_\odot) > 11$. Only the objects with high-S/N Na I D velocities are included for the calculation of detection rates; i.e., the objects in the low-S/N sample (§ 2.4.1) are treated as if they are not detected. The uncertainties are estimated from binomial statistics.

38 ± 11% of LIRGs host outflows

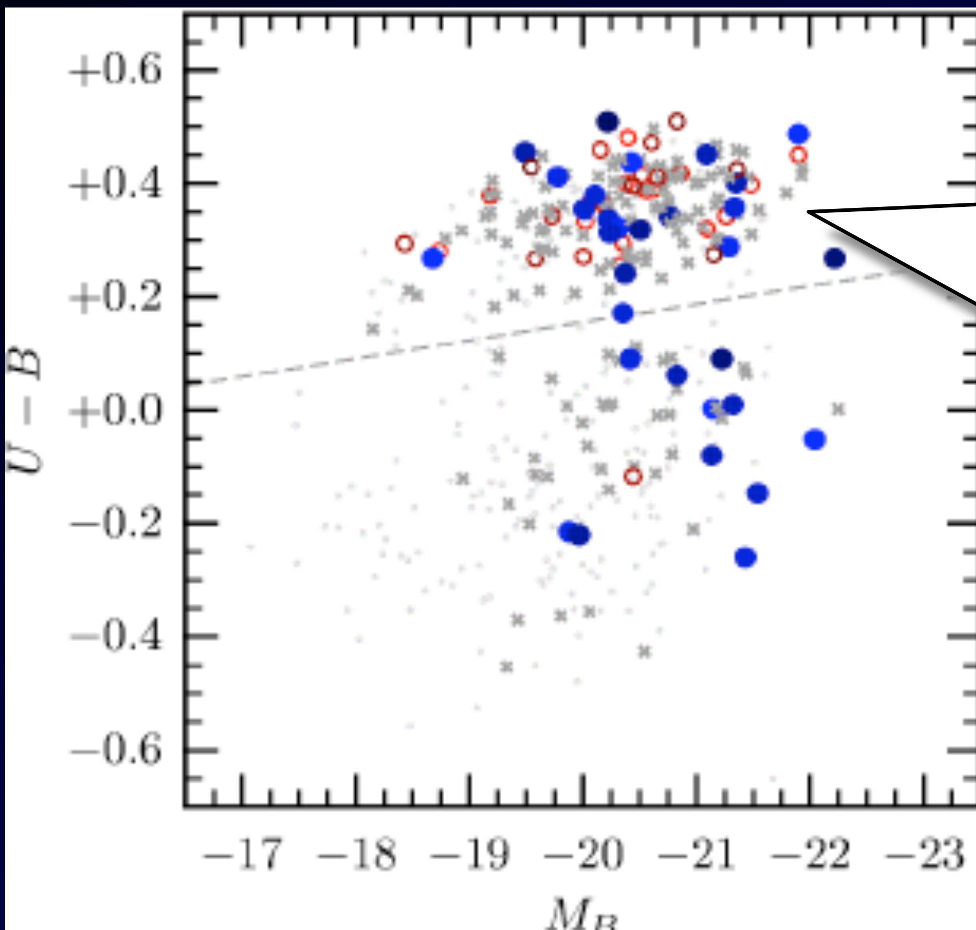
Comparable to: inflow (?)

42 ± 8% by Rupke et al. (2005)

32 ± 12% by Heckman et al. (2000)

COLOR MAGNITUDE DIAGRAM of Na I SAMPLE

Blue: OUTFLOW **Red: INFLOW**
Gray: X NEITHER Dot-Low S/N



Many **red-sequence outflows**!

Red, dead galaxies should not be forming stars...

Conclusions of Sato et al. on z ~ 0.4 LIRG-like outflows

- ☺ **Detection rate of outflows increases strongly with SFR**
- ☺ **Outflow speeds (~ 100 km/s) -- comparable to the literature**
- ☺ **Outflows seen, for first time, in distant *red sequence* galaxies!!**

UV/visible color: Sign of recent star formation

Balmer absorption: Poststarburst

ACS morphology: Spheroids

Strong indications of important roles of outflows in quenching star formation in massive objects, and thereby transforming blue galaxies into red at z < 1

Direct measurement of gaseous feedback!?

Puzzle: Are the inflows seen among the most massive quiet galaxies real? If so, what are they due to?

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BASIC DATA for Detection of Cool Gas Inflow at z ~ 0.5 (Rubin+11 for details)

Keck LRIS Spectra: 2h-3h exposures of 3200A – 8000A; R ~ 200-400 km/s provide UV Absorption strength and line profiles for detection of gas flow; eigenspectral stellar fit for subtraction of continuum and zero velocity reference for flow velocity

Sample Selection: GOODS-N&S & EGS with prior DEIMOS spectra: 0.3 < z < 1.4 & B<23 (150); based on analysis of 1 or 2 component flow model fits to FeII and MgII lines (abs & em), 6 were found with significant (>1.4 sig) inflow signatures.

Prior photometry & Kcorrect code: provide luminosities (L_B) rest frame U-B colors

HST ACS: color images and inclination

High Confidence Examples

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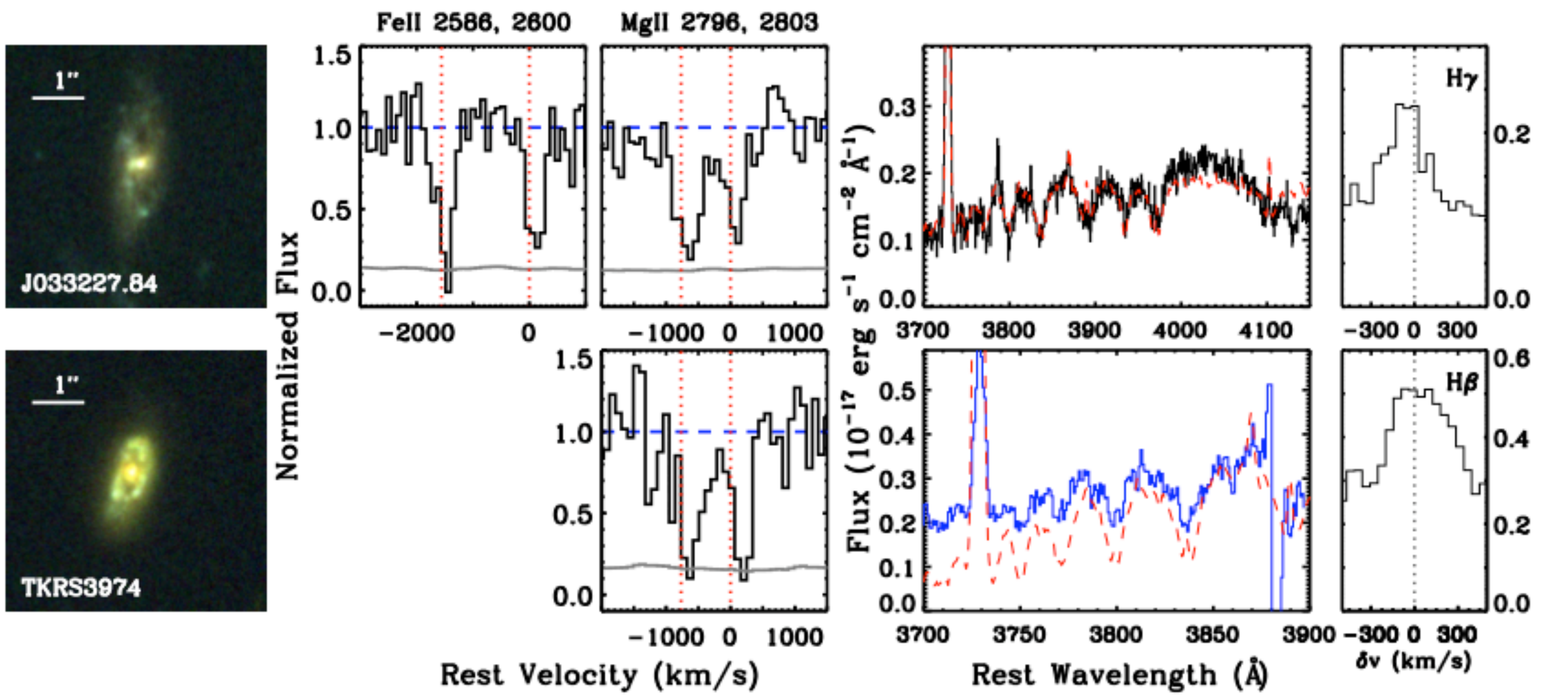

Fig. 1.— Two galaxies with inflows measured with high confidence. *Left column: BVi* color HST/ACS images of 5″ × 5″. *Second and third from left:* Fe II and Mg II transitions in the galaxy spectra where spectral coverage is available. Velocities are measured relative to the 2600 Å line and the 2803 Å line, respectively, and systemic velocities of each transition are marked with vertical dotted lines. Horizontal dashed lines mark the continuum level. *Fourth column:* Sections of the galaxy spectra showing higher-order Balmer transitions and

Remaining 4 still good

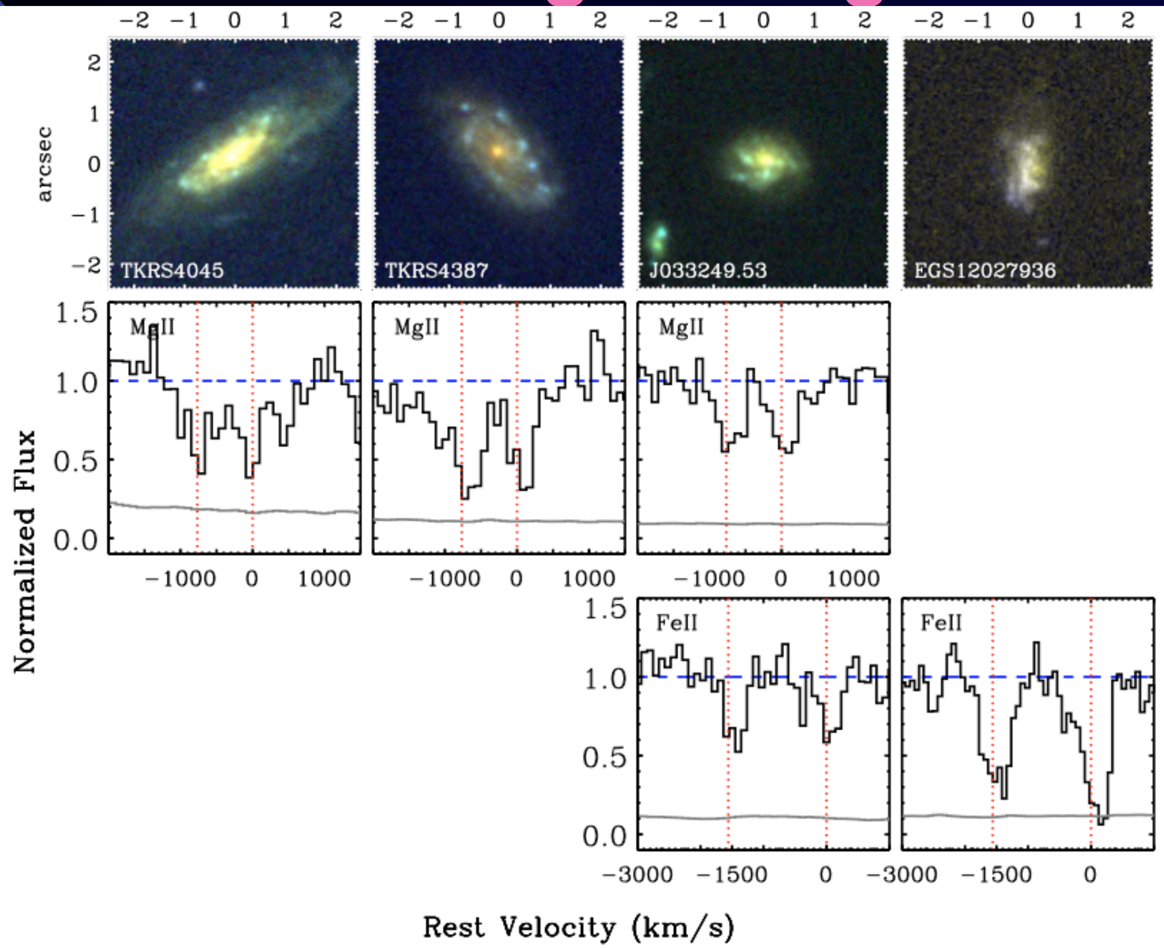

Fig. 2.— The remaining four objects in our inflow sample. The top row shows BVi color HST/ACS images. The middle row shows Mg II transitions, with velocities measured relative to the 2803 Å line. The bottom row shows Fe II transitions, with velocities measured relative to the 2600 Å line. Vertical dotted lines mark systemic velocities, and horizontal dashed lines mark the continuum level.

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Inflow Targets in Color-Luminosity and inclination (Rubin+ 11)

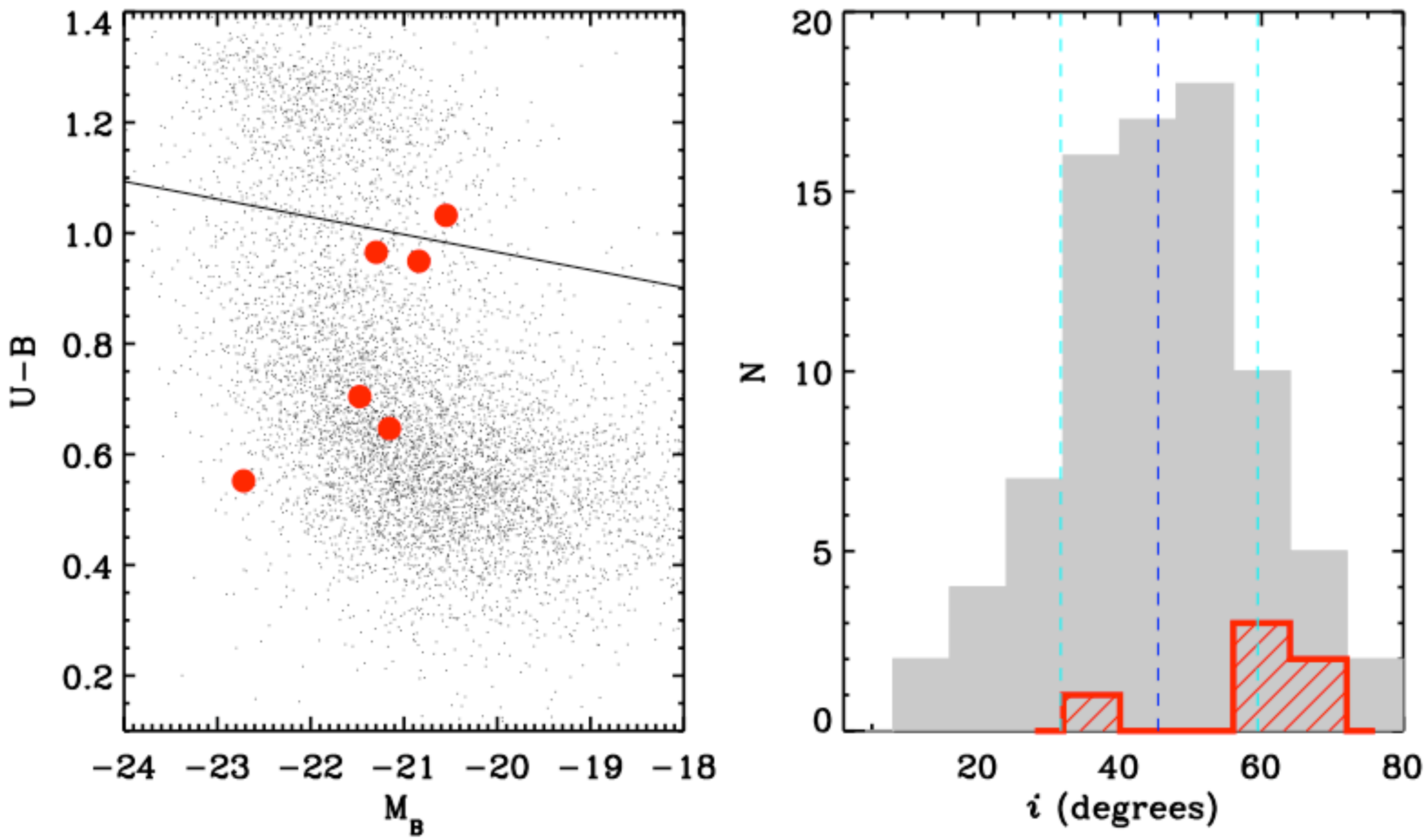
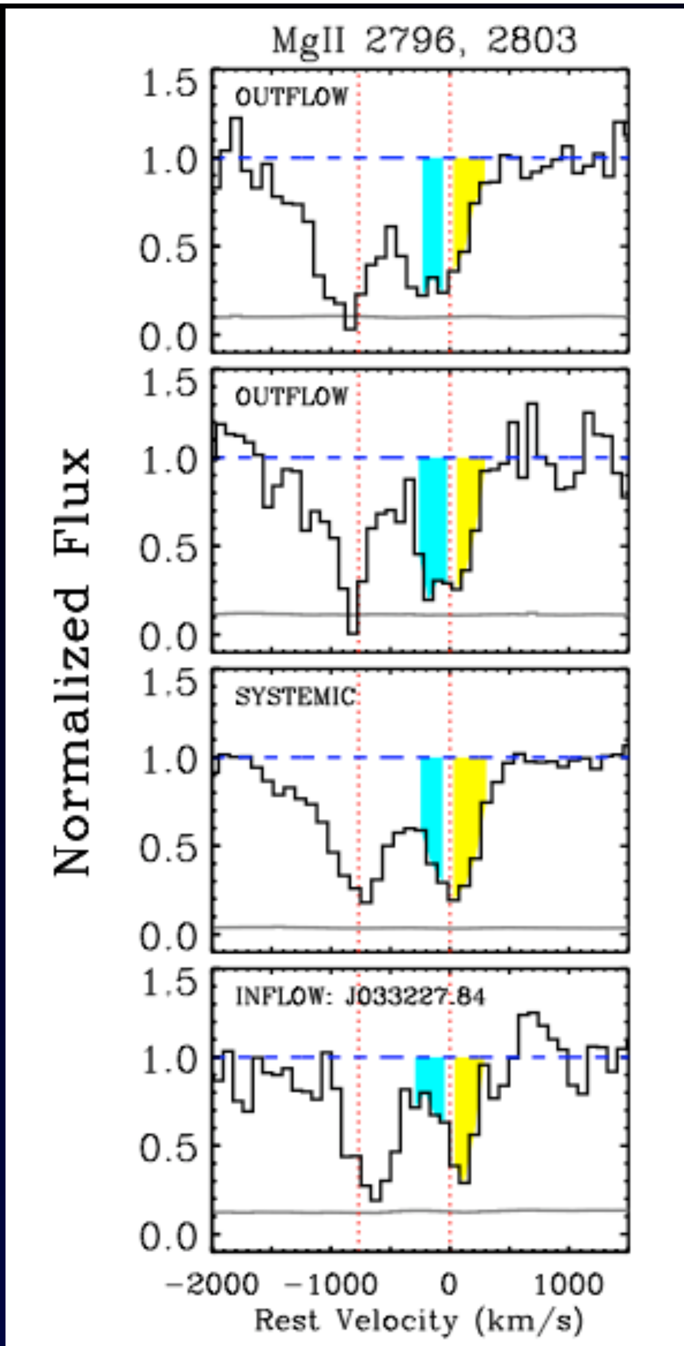


Fig. 3.— *Left:* Rest-frame color-magnitude diagram for AEGIS galaxies with $0.3 < z < 1.05$. Galaxies which exhibit inflows are shown with large red circles. The solid line divides the "red sequence" from the "blue cloud" as given in Willmer et al. (2006). Half of the inflow sample are star-forming galaxies in the blue cloud (see also SFRs in Table 1), while the other



Note key is less Blueshifts vs strong Redshifts!

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- Top 3 show examples of absorption line profiles showing systemic and outflows (blue shaded region of redder of MgII doublet lines)
- while all 4 have same strength (~1.3A) of the inflow component (yellow shaded region)
- Inflow candidates like this one are selected to have inflow EW > outlfow EW + 0.5A (visual confirmed by model fits)

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Summary

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Using galaxies instead of QSOs as background sources, we are entering a new era of powerful spectral & multiwavelength surveys to study distant galaxy gas flows, both in and out.

Our Keck observations are providing interesting & rich data at $z < 1.4$:

B. Weiner+09 finds that almost all luminous blue galaxies at z ~1.4 have outflows of 100's km/s with speeds correlated with mass and SFR as found locally; the high numbers of galaxies with outflows imply winds are *not* sufficient to quench subsequent SF (need AGN?)

K. Rubin+10 finds that massive high SFR z ~ 1 galaxies continue to have outflows (~ SFR). Less massive galaxies with higher SSFR do not.

~All massive galaxies with high SFR have winds at z ~ 1

T. Sato+09 studied galaxies at $z < 0.6$ using NaI and find outflows associated with recent SF among red galaxies, suggestive of outflow's role in quenching; inflow among passive systems is important, if true, and thus needs confirmation.

K. Rubin+11 have found 6 of 150 galaxies at z ~0.5 dominated by inflows; inclined and low inflow vs SFR; IGM, satellite, galactic fountain?

Summary

Near Term Future: completed DEEP3 in AEGIS will add more and richer spectral data for galactic winds work:

- AEGIS is growing to be a premier panchromatic survey field with ever deeper optical-NIR imaging, Spitzer-MIPS, AKARI, Chandra (3.4Ms), & HST ACS +WFC3 data already arriving from CANDELS, and more support from SCUBA2, LMT, & Herschel, and maybe JWST.

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