Galactic Winds at Intermediate Redshifts

David C. Koo, Taro Sato, Ben Weiner, Kate Rubin,
Crystal Martin, Jason Prochaska, DEEP2, TKRS, & AEGIS Teams
UCO/Lick Observatory
University of California, Santa Cruz

20 Aug 2010 Galaxy Formation Workshop, UCSC

Outline

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 ~ 1.4
5) Kate Rubin+10: The Persistence of Cool Galactic Winds in High Stellar Mass Galaxies at z~ 0.7 - 1.5
6) Summary & Future Work

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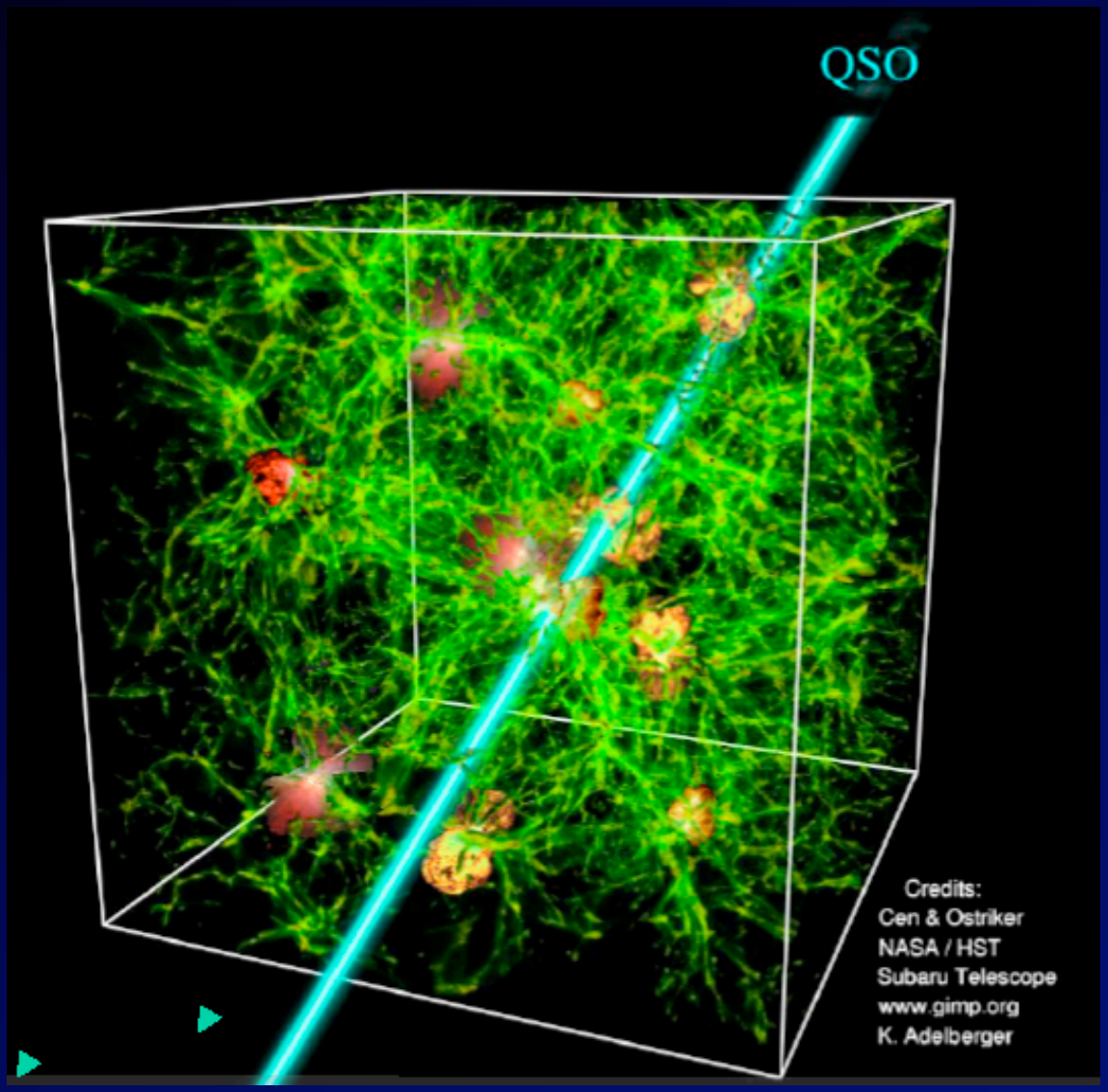
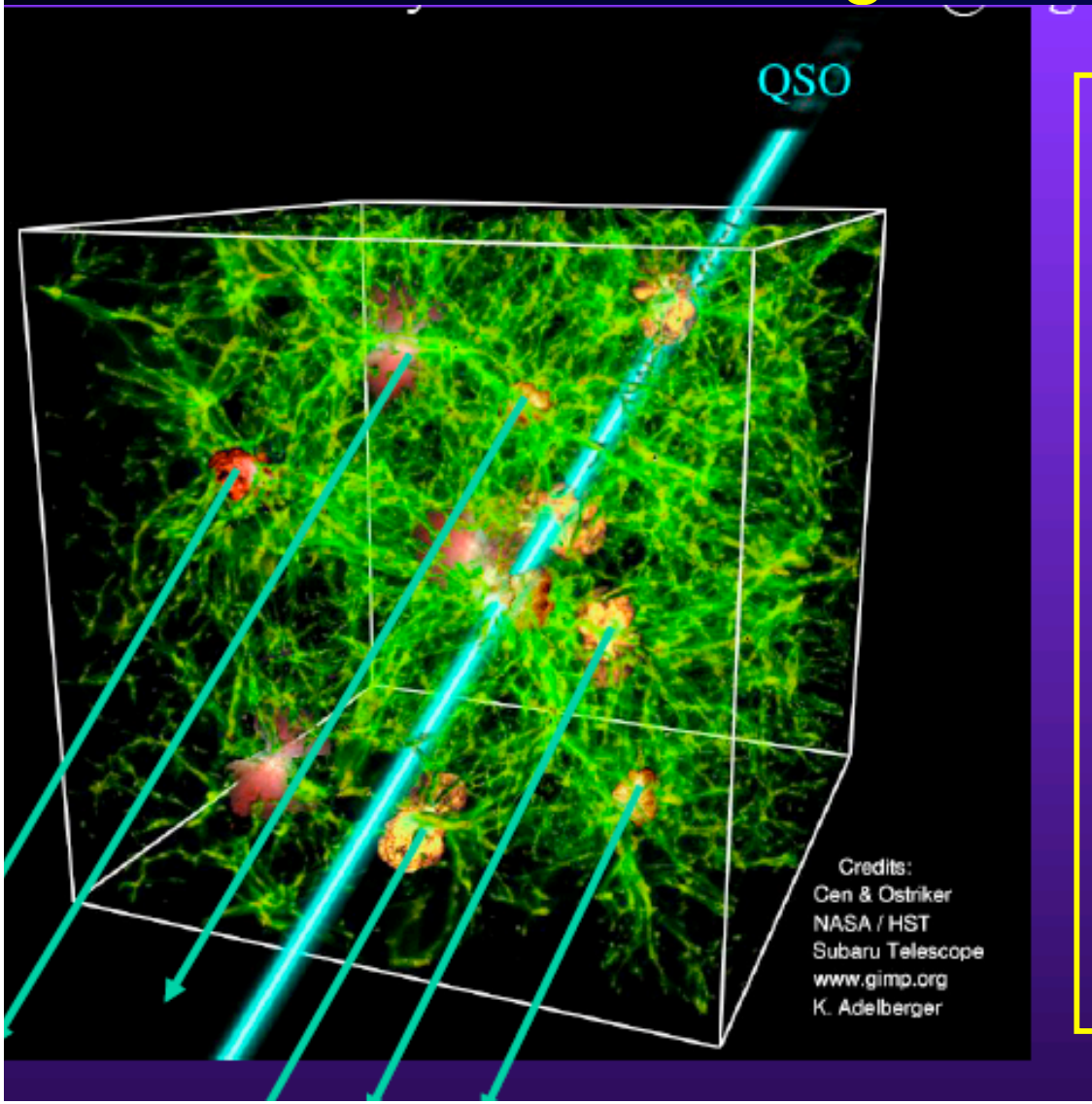
Traditional Method for Studying Galaxy Halos & IGM at High Redshift



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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What's DEEP, TKRS, & AEGIS?

W.M. Keck Observatory

Deep Extragalactic Evolutionary Probe (DEEP2):

Major Completed Redshift Survey with the Keck Telescope

~100 Keck nights, 2002-2005

- Keck spectra : **DEIMOS**, Resolution ($\lambda/\Delta\lambda$) = 5000, 6200A-9300A
- 4 Target Regions: 3 of 0.5x2 deg & Special 0.25x2 deg ***Extended Groth Strip (EGS)*** ==> AEGIS
- Redshifts: 40,000 to R = 24.1; except ***EGS***, uses photo-z for z = 0.7 - 1.4

DEEP3: Followup Redshift Survey of EGS with 25 more Keck DEIMOS nights; still underway (2007-2011) with focus on HST region - 5000 more redshifts: denser sampling, bluer spectra (4600A-9400A), & fainter targets, especially of X-ray and Spitzer sources

Team Keck Redshift Survey (TKRS): GOODS North Keck DEIMOS Redshift Survey (4600A - 9300A) of 1400 galaxies to R ~ 24.4

All-wavelength Extended Groth strip International Survey (AEGIS):

EGS DEEP2 plus full suite of very deep surveys from X-ray to radio

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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

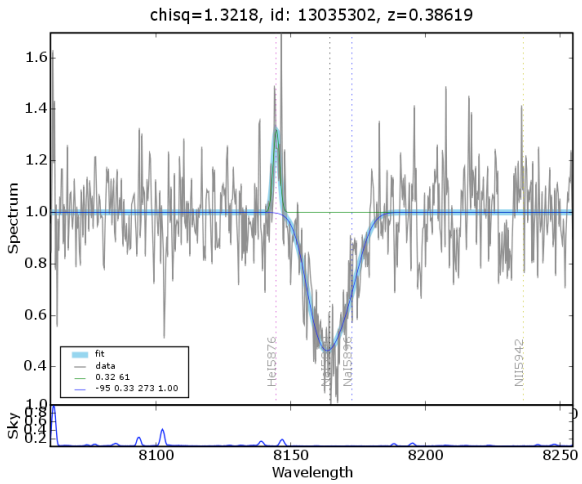
Palomar K and optical colors: stellar masses

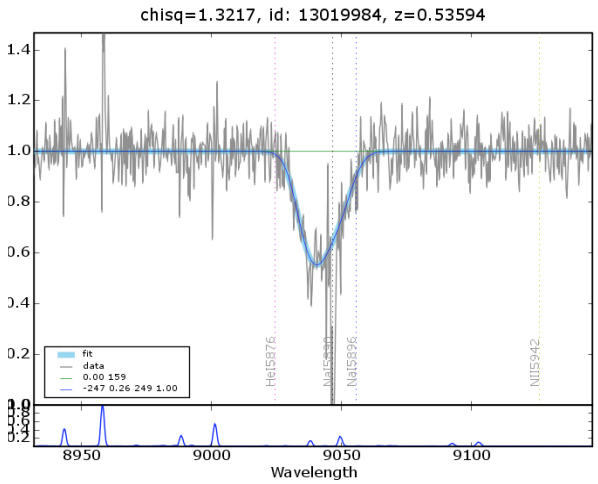
HST Images: host galaxy morphology - merger, spheroid

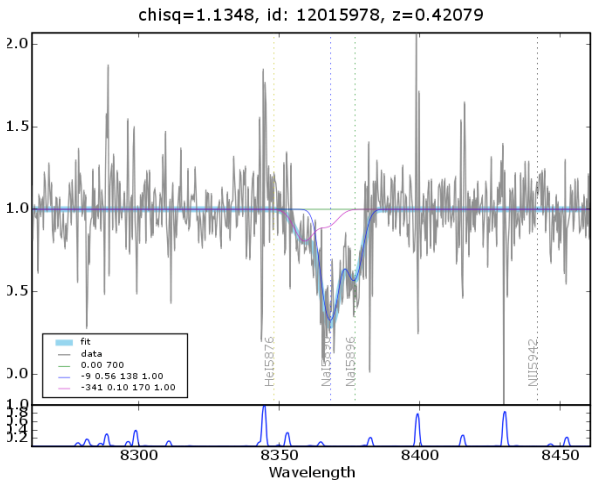
GALEX-optical Colors: very sensitive to presence of young stars in even optically very red galaxies

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

Examples of HST/ACS Morphology & Outflow



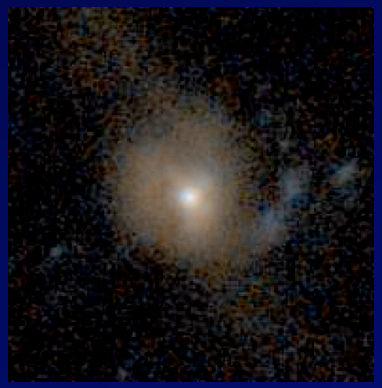




Δv(Na I D) = -95 km/s

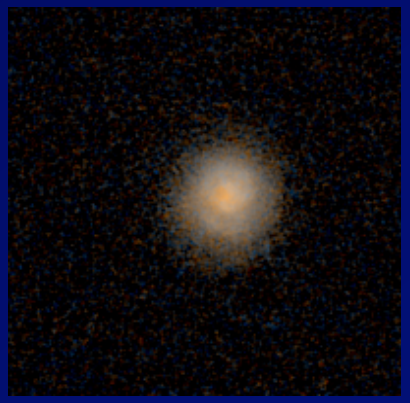
Face-on spiral with a ring?

Δv = -247 km/s



Blue core and tidal feature?

Δv = -341 km/s



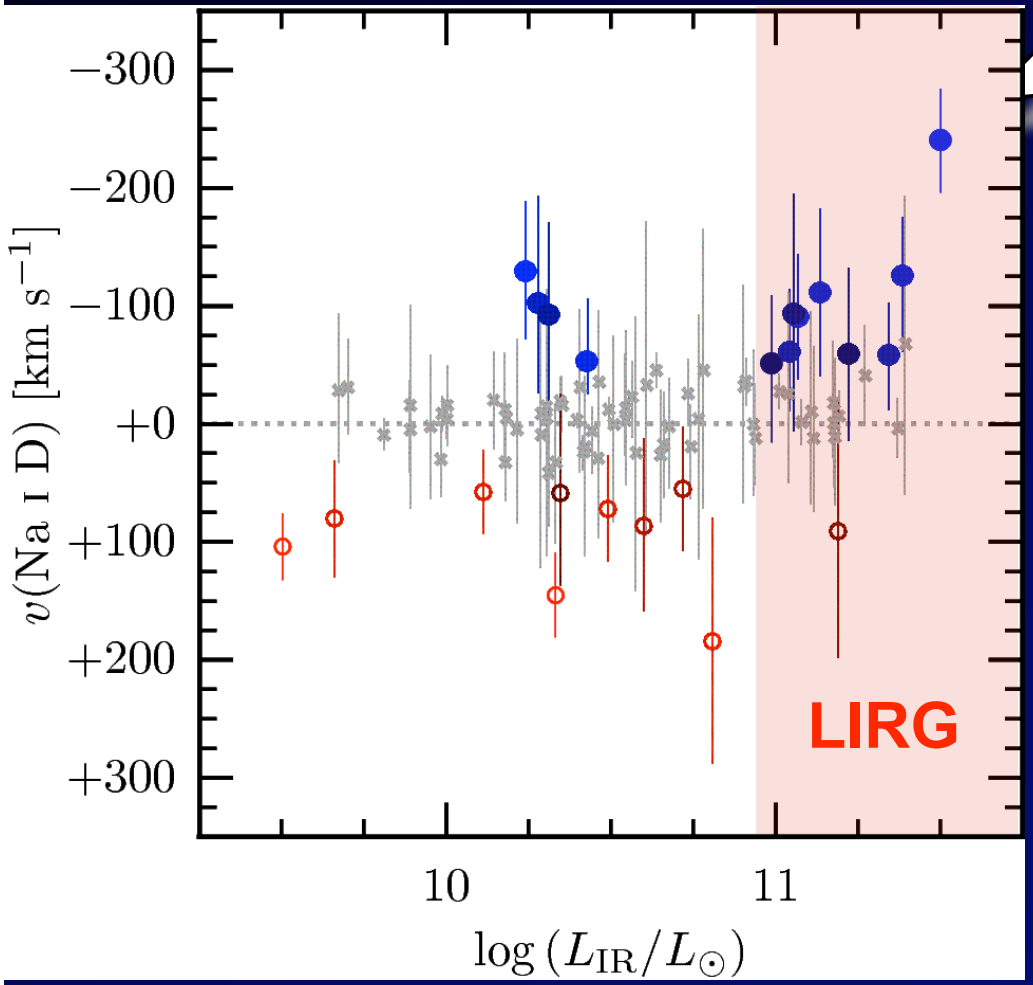
Seems quite red & dead...

Outflow in a **dead spheroid** would be surprising!

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

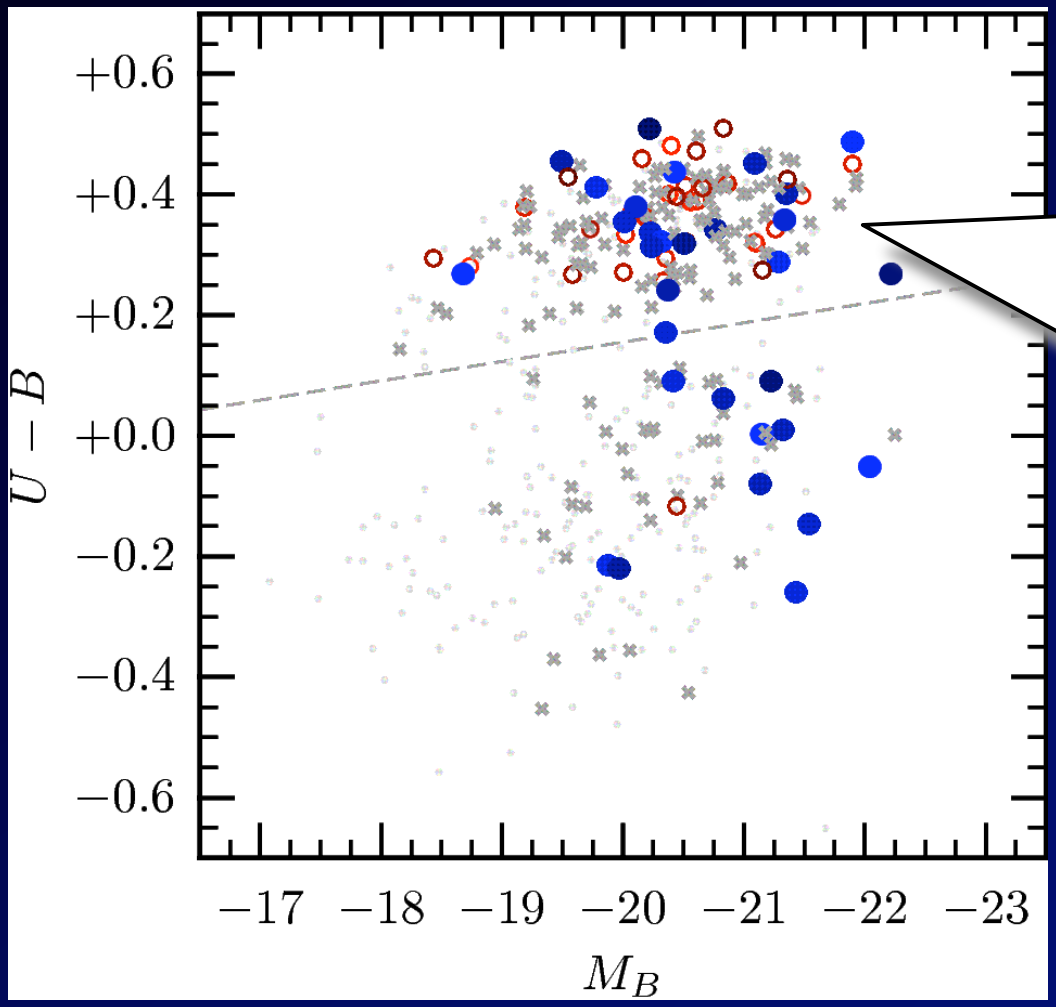
Comparable to: inflow (?)

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...

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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 UV MgII Survey at z ~ 1.4

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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);

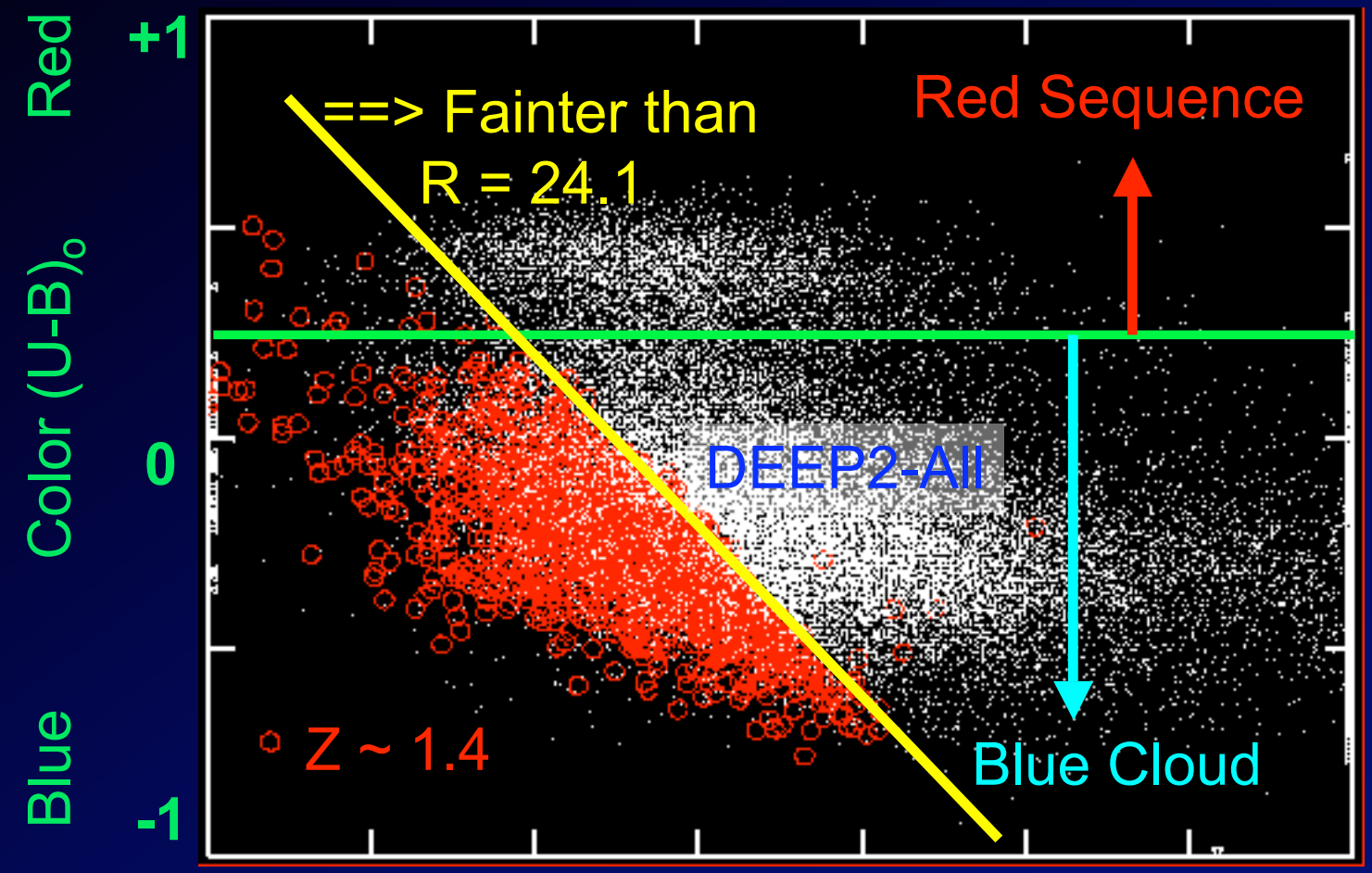
CFHT Images: rest B luminosities and U-B colors

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



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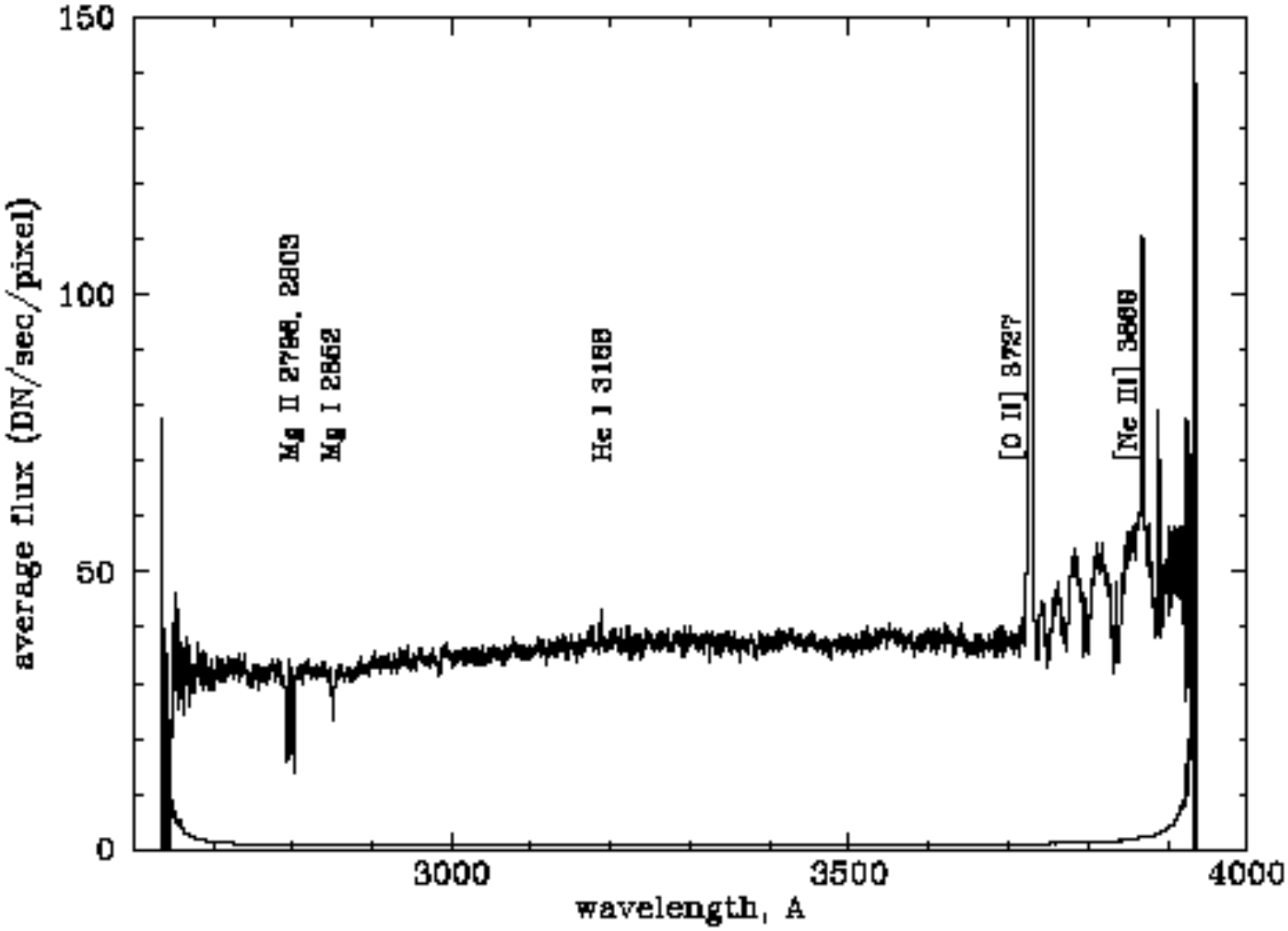
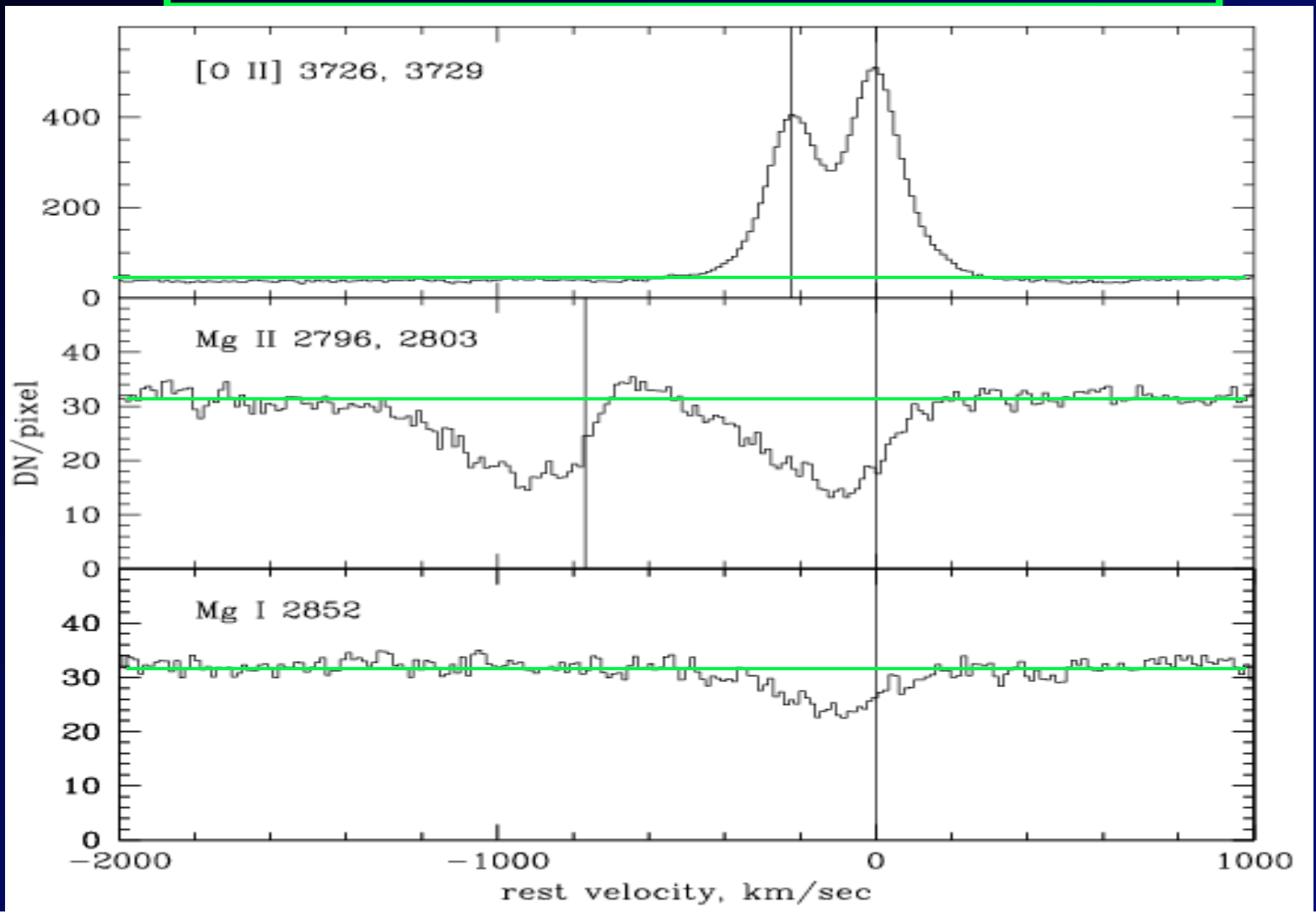
Coadded Spectra of 1409 Galaxies



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

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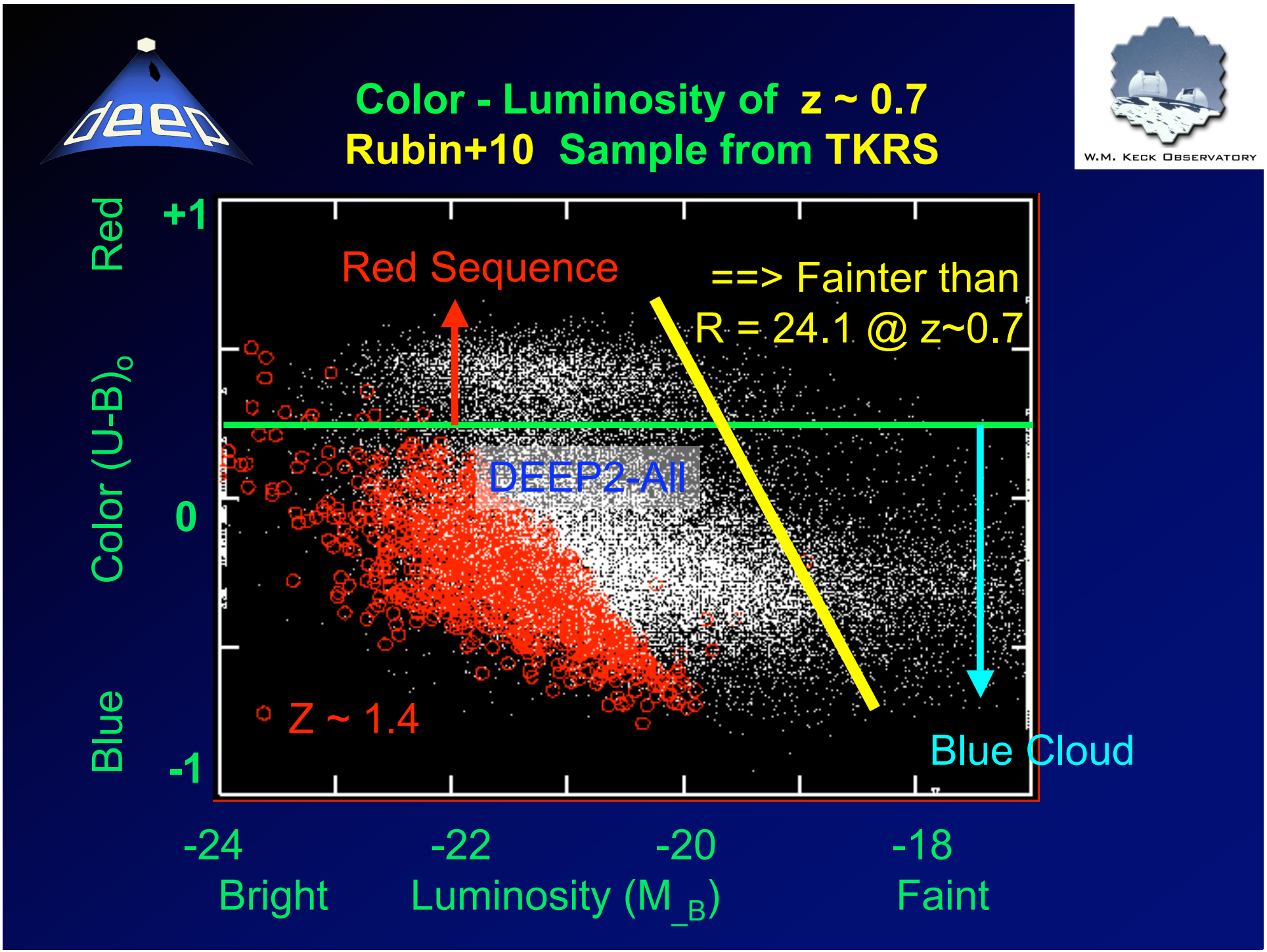
TKRS Spectra of GOODS-North: provide MgII, FeII absorption strength and line profiles for detection of gas flow; OII emission for zero reference for flow velocity;

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)

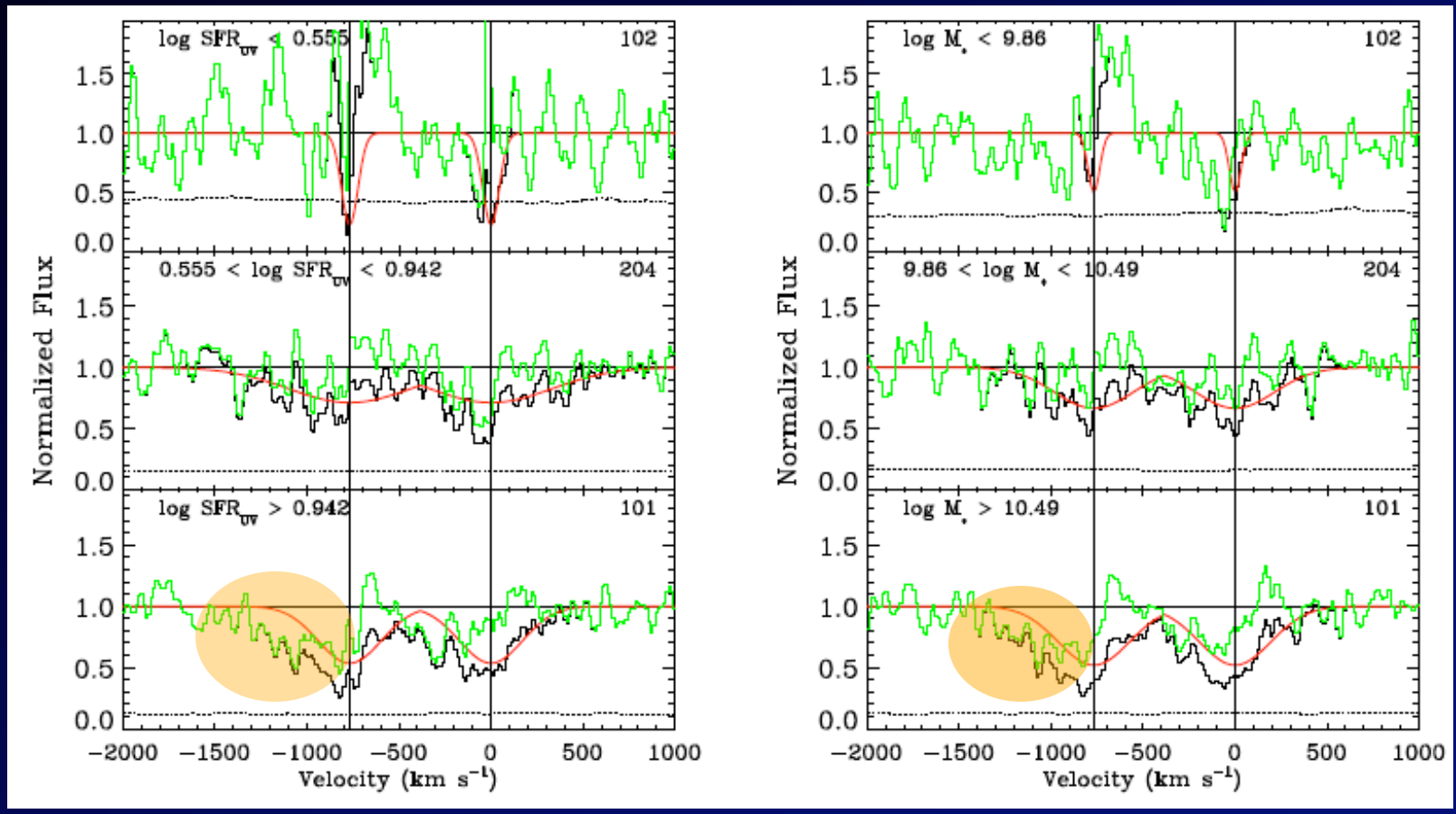
Spitzer MIPS Fluxes: determine IR luminosity (LIRG, ULIRG) and total SFR


Color - Luminosity of z ~ 0.7
Rubin+10 Sample from TKRS
W.M. Keck Observatory
Red
Color (U-B)o
Blue
+1
0
-1
Red Sequence
==> Fainter than
R = 24.1 @ z~0.7
DEEP2-All
Z ~ 1.4
Blue Cloud
-24
Bright
-22
-20
Luminosity (M_B)
-18
Faint

Mg II Absorption vs SFR & stellar Mass

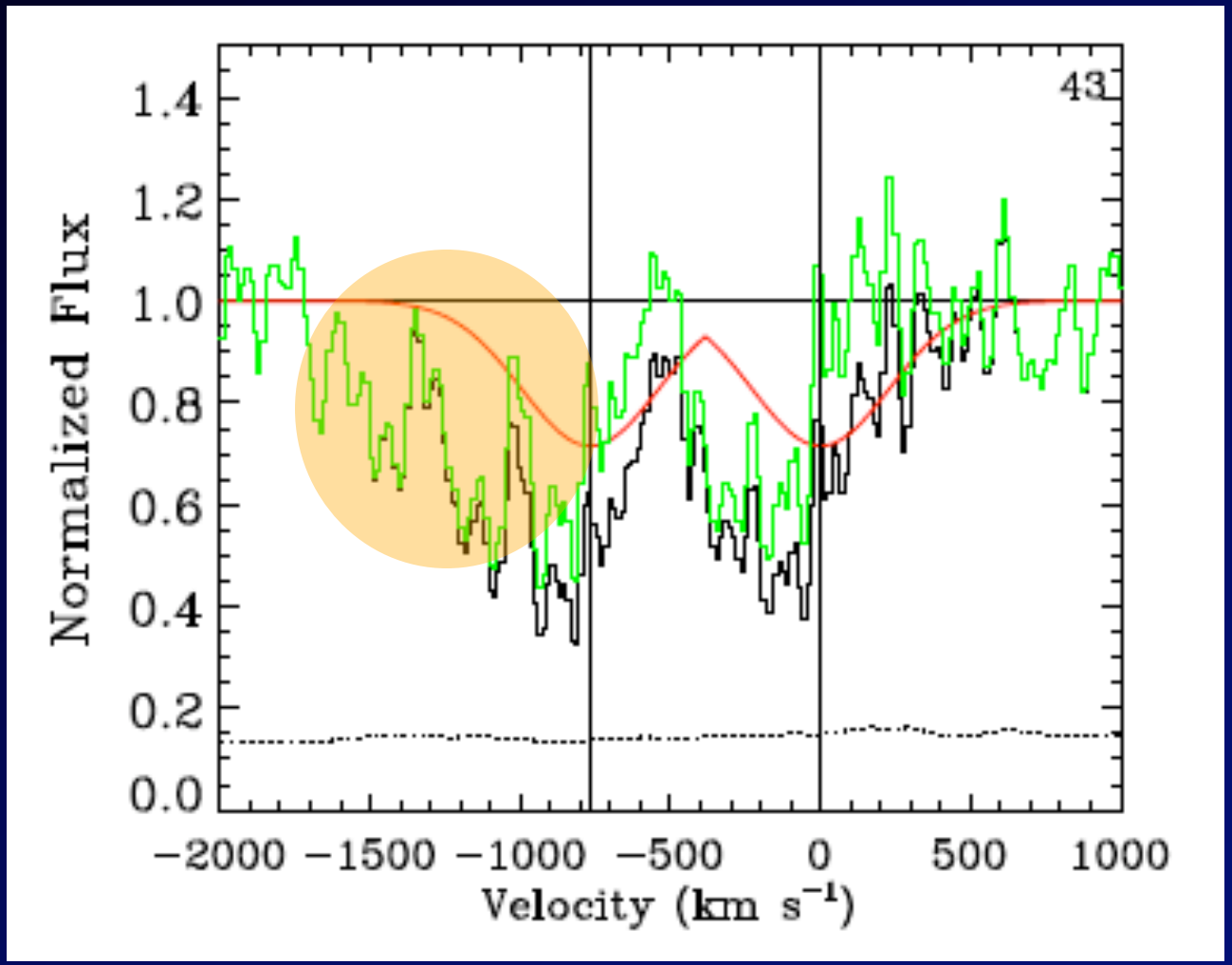
vs SFR

vs Stellar Mass



See winds for only for highest SFR and stellar Masses

TKRS Subsample Similar in SFR & M* to that of DEEP2 Weiner+09



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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6) **Summary & Future Work:**

Summary

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.

DEEP2, TKRS, & AEGIS already provide interesting & rich data at $z < 1.4$:

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.

B. Weiner+09 finds that almost all luminous blue galaxies at $z \sim 1.4$ 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 $z \sim 1$ galaxies continue to have outflows (~ SFR). Less massive galaxies with higher SSFR do not.

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

Summary

Near Term Future: soon to be completed DEEP3 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 forthcoming (Sandy's talk on CANDELS), and expected longer term support from SCUBA2, LMT, Herschel, and JWST.**

Future with 20-30m Telescopes: Full IGM-Halo-Galaxy Tomography