Gas Accretion & Outflows from Redshift z~1 Galaxies

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DEEP2, TKRS, & AEGIS Teams

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GAS FLOWS DESERVE AN OLYMPIAN GOLD MEDAL

W.M. Keck Observatory

for influence on galaxy formation and evolution

Their amount, densities, velocities, T, Z:

1) directly affect the key components of stellar populations: SFR-history, ages, metallicity, IMF?

2) Directly control stellar structure & kinematics

3) Affect dust extinction and scattering → SED

4) Induce feedback from SMBH & starbursts

5) Enrich the IGM and environment (clusters)

YET, our observations of this critical component are almost nil in comparison to its importance

Outline

W.M. Keck Observatory

1) **Introduction:** Key Idea: Use galaxies (not QSOs) as light sources to probe foreground gas and their flows.

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) **Kate Rubin+12a,b:** Cool *Winds* still Ubiquitous to z ~ 0.5 and Detection (Finally!) of Cool Gas *Inflow* at z~0.5

5) **Summary**

TAKE-AWAY MESSAGE

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OUTFLOW GALACTIC WINDS are UBIQUITOUS from z~0.5 to 1.4 among STAR-FORMING GALAXIES

INFLOWS appear RARE (few %) but due to BI-POLAR WINDS, and accounting for INCLINATION, may actually be common (40%)

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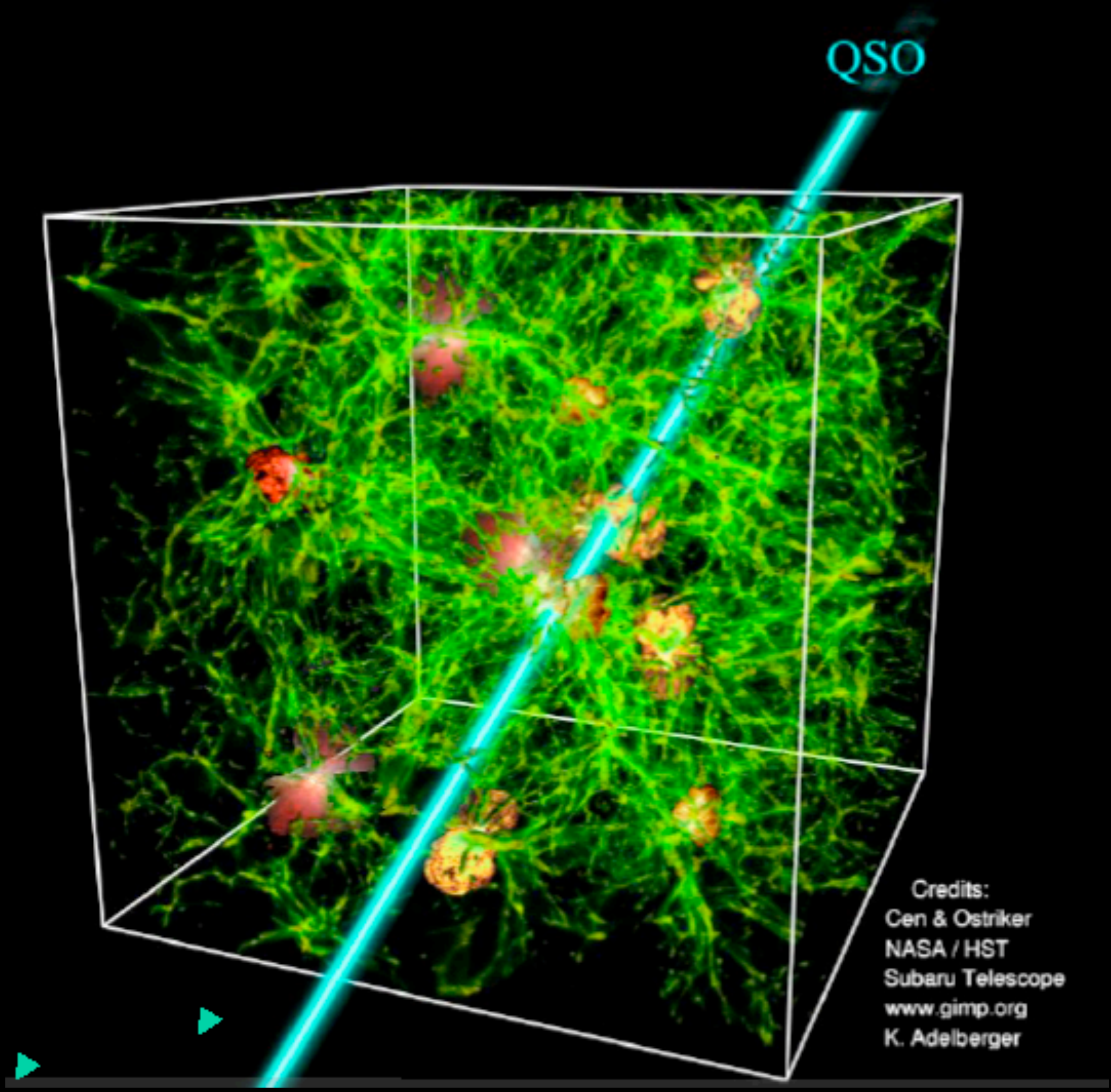
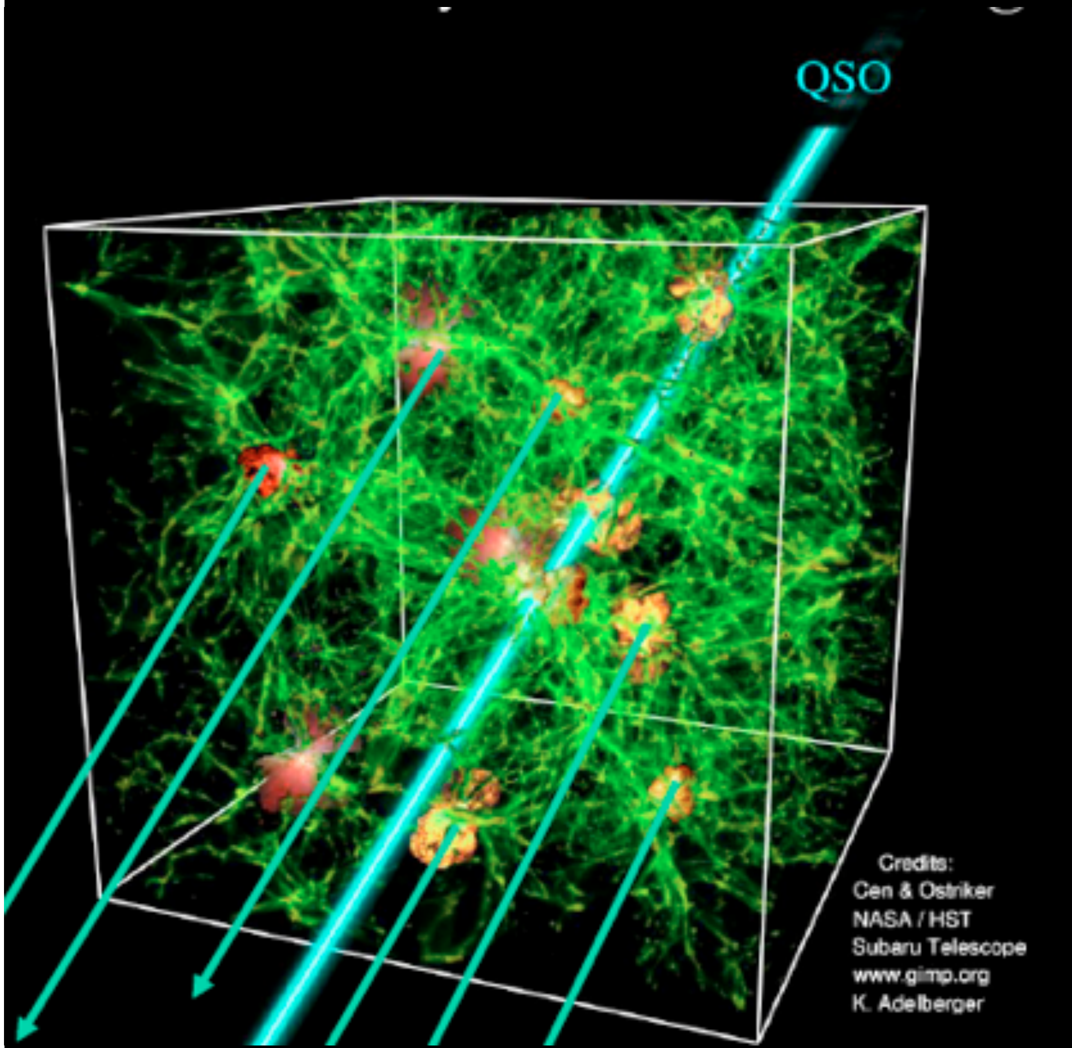
Traditional Method for Studying Galaxy Halos & IGM at High Redshift



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 backgd source.

CONS: much lower S/N -- but can stack;
need blue galx to see UV;
stellar light contamination;
no radial info

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BASIC DATA for UV MgII Survey at Redshift z ~ 1.4

See Weiner+09 for details

SPECTRA from DEEP2 Keck Redshift Survey:

[OII] emission for velocity reference;
UV Mg II absorption and emission line strengths
and line profiles for study of foreground gas flows.
velocity width for dynamical mass & escape velocity

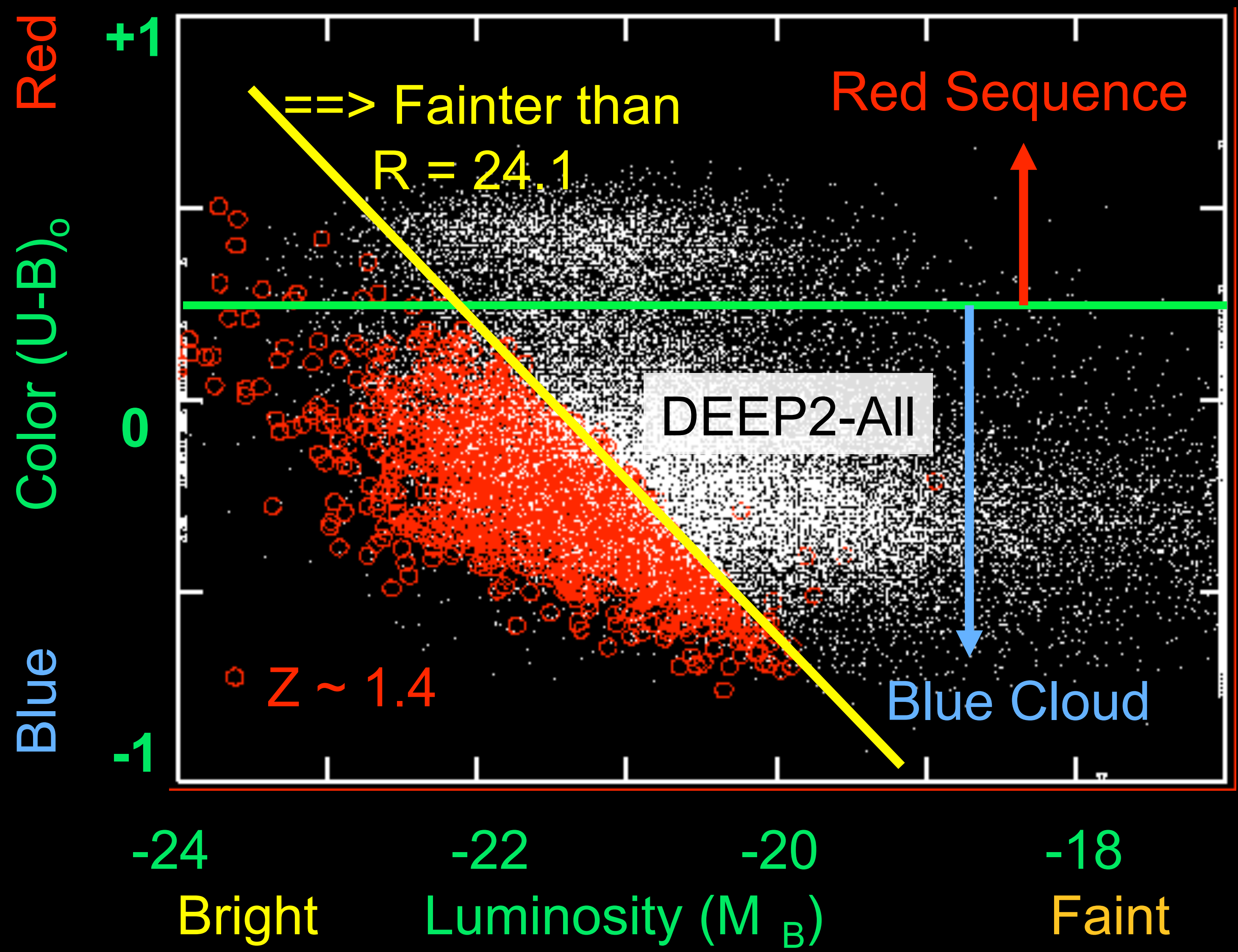
SAMPLE SELECTION: from full DEEP2 (32,308);
see MgII 2800A at redshifts z ~ 1.4 (1406);
with Spitzer MIPS 24um for dusty SFR (194);
with HST for morph, size, incl., merger (119);

CFHT Optical & Palomar K band Images:

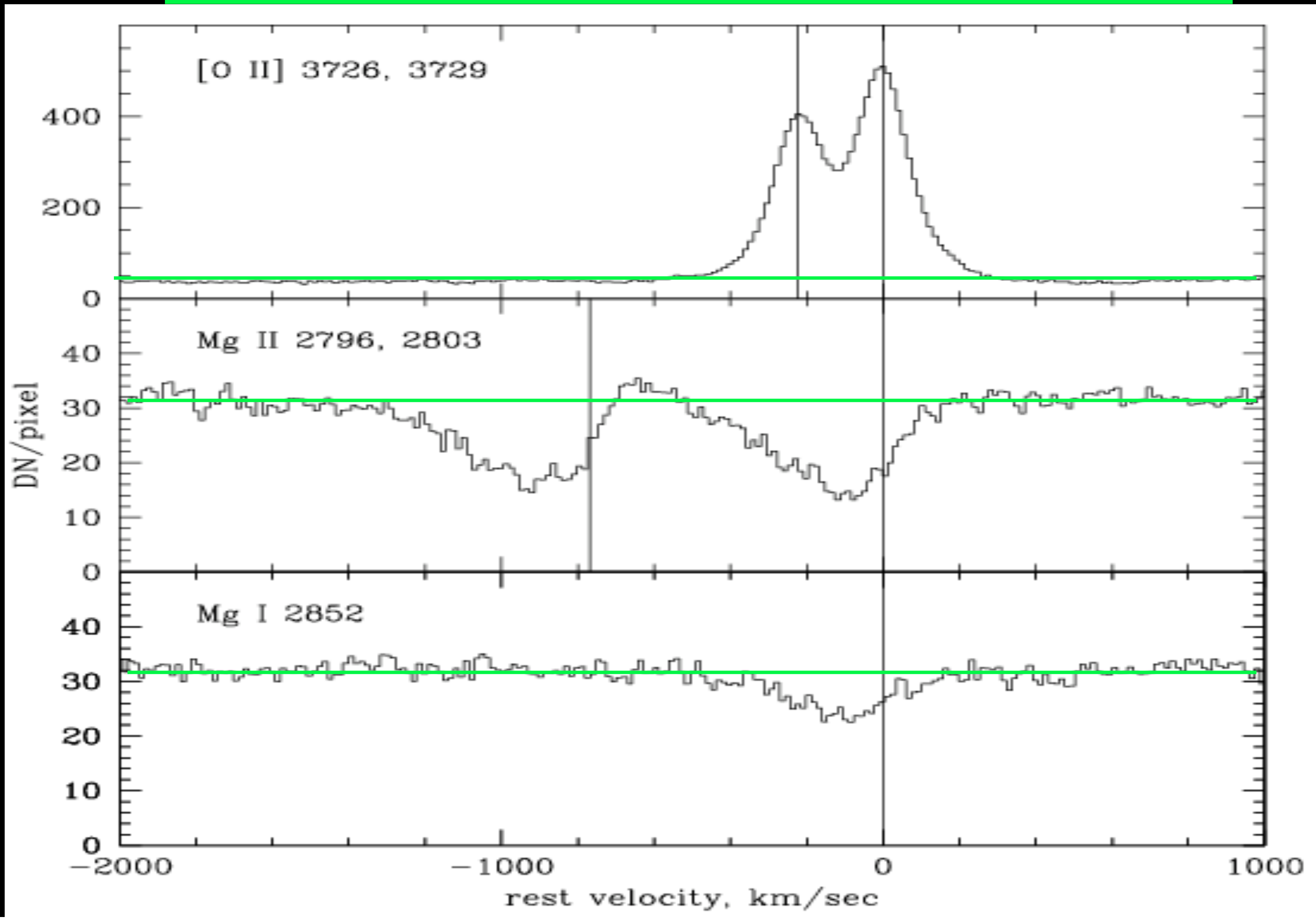
get luminosities (B), colors (U-B), & stellar masses

HST images: morphology, merger, size, inclination

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



Stack of 1406 DEEP2 galaxies at redshifts z ~ 1.35 -1.40 shows strong absorption lines of cool gas (Mg II and Mg I) with outflow winds moving at 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 the sample have outflows -- ;
substacks show ***non***-dependence on luminosity, color (within sample), SFR, stellar mass, morphology;
typical massive SF galaxies (not just dwarfs) had winds;
winds appear not to globally quench SF

Sawtooth Absorption Profile:

median outflow velocity ~ 250 km/s
with extension to 500 km/s for 10% depth and
up to 1000 km/s (> escape velocity) for very massive galaxies)

SFR vs Wind Mass:

SFR of galaxies in the sample: 10 - 100 Mo/yr (~ LIRG)
roughly matches mass outflow of ~ 20 Mo/yr
as estimated from speed, column density, and size of < wind >

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

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HST Images: only 3/118 had merger-like morphologies;
so mergers are not required for strong winds,
as might be inferred from studies of ULIRGS and post-starbursts studied by others ;

Outflow Velocities: scaling relationships:
higher for larger stellar mass,
higher for higher SFR, with V(wind) ~ $SFR^{0.3}$
as found for local ULIRG (Martin 05) ;
higher than escape velocity imply massive galaxies, not dwarfs, *may* dominate wind activity and enrichment of IGM at high redshifts

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TKRS Study at z ~ 0.7 - 1

see Rubin+10 for more details

Kate Rubin
(MPIA)

TKRS (Team Keck Redshift Survey) of GOODS-North: Compared to Weiner et al. 2009, TKRS spectra reached bluer limits and thus accessed lower redshifts (& lower mass galaxies) for the UV lines of MgII, FeII; OII emission was still used for the zero velocity reference for flow velocity;

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

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)

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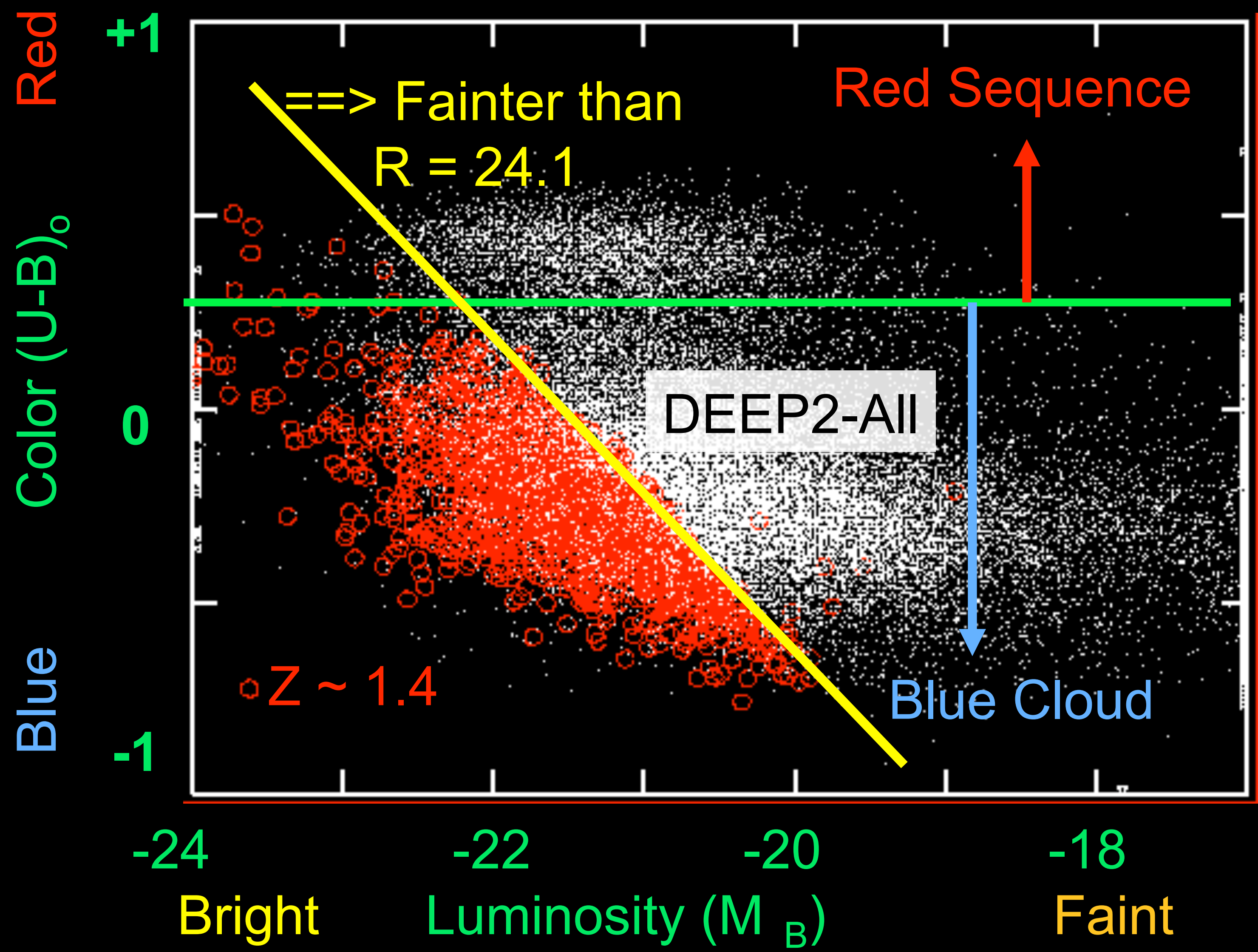
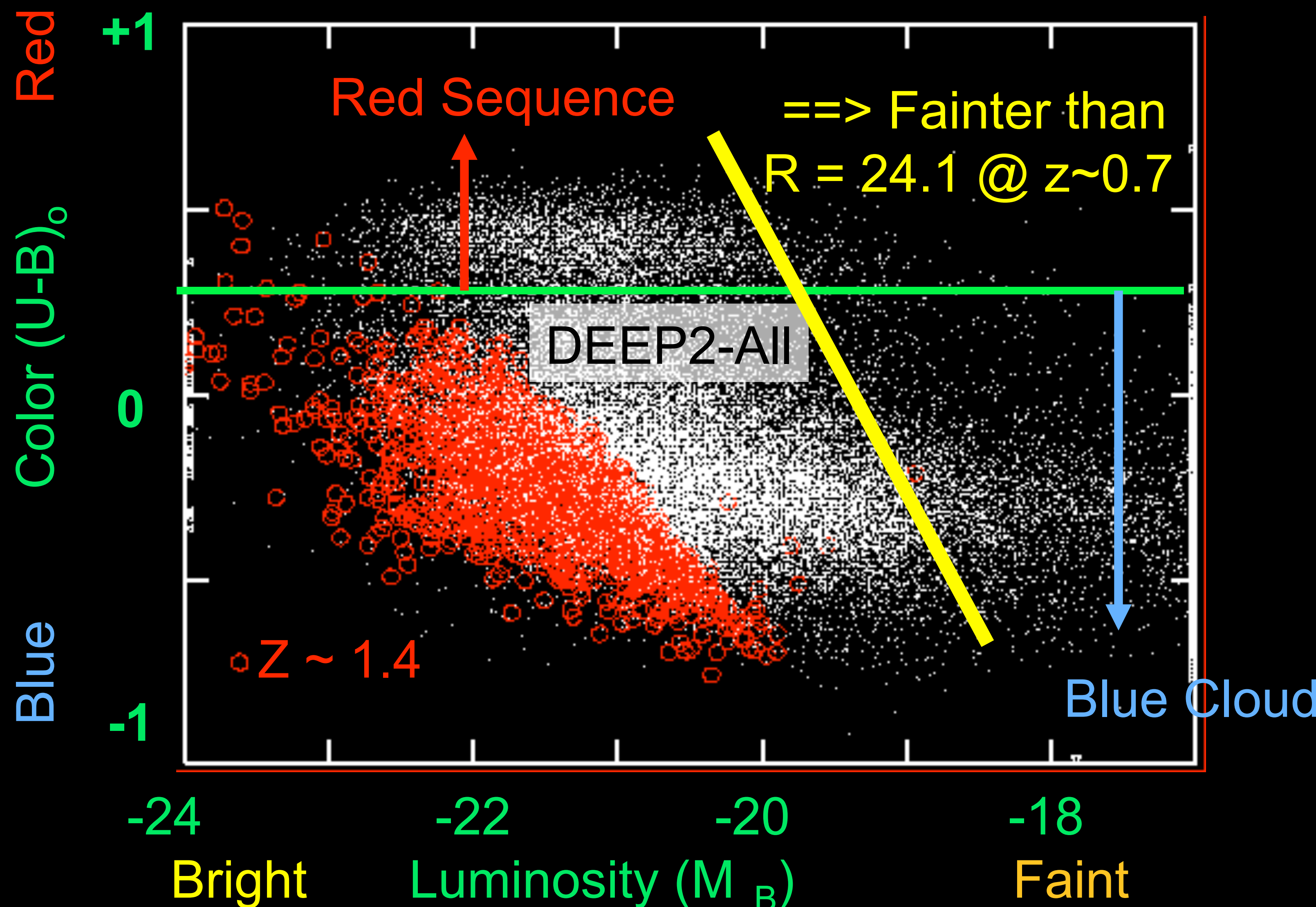
Weiner+09 Sample from DEEP2



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



Results from TKRS at z ~ 1 &
IMPLICATIONS for Galaxy Formation Models

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Most massive and highest SFR galaxies show evidence for strong outflow absorption signatures -- similar to Weiner+09 sample.

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.

Mass outflows continue to be roughly the same as the SFR.

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BASIC DATA for Detection of Cool Gas Flows at z ~ 0.5 (Rubin+12a,b for details)

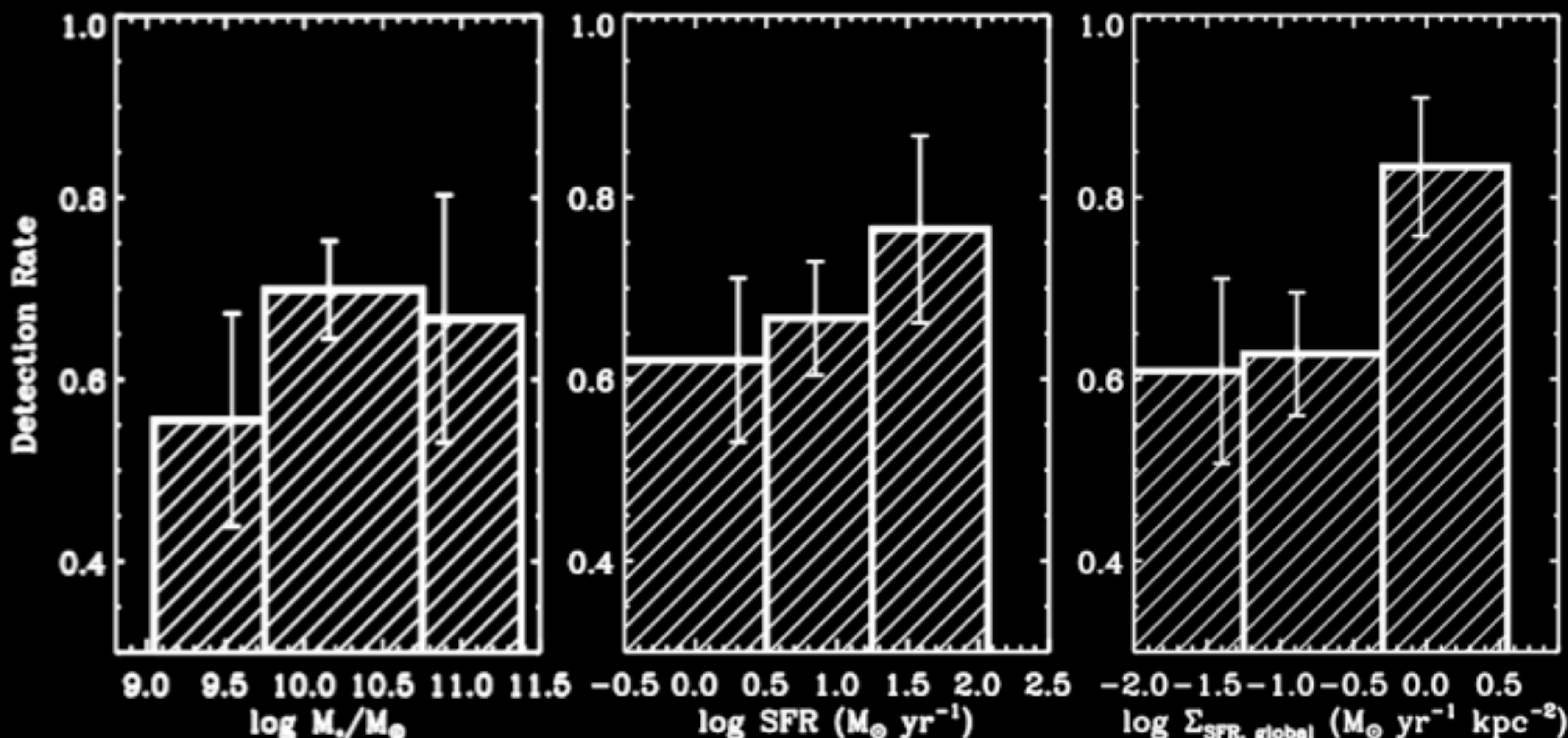
Keck LRIS Spectra: 2h-3h exposures of 3200A – 8000A;
Resolution ~ 200-400 km/s provide UV Absorption strength and line profiles for detection of gas flow;

Sample Selection:
GOODS-N&S & EGS with prior DEIMOS spectra:
Redshifts 0.3 < z < 1.4 & bright (B<23) (**150 galaxies**);
Based on analysis of 1 or 2 component flow model fits to FeII and MgII lines (abs & em) of individual galaxies,
2/3 had outflows, and 6 seen with clear inflow

Prior Optical photometry: luminosities (L_B) and colors (U-B)
HST ACS: color images, morphologies, and inclinations

Detection Rate Dependencies

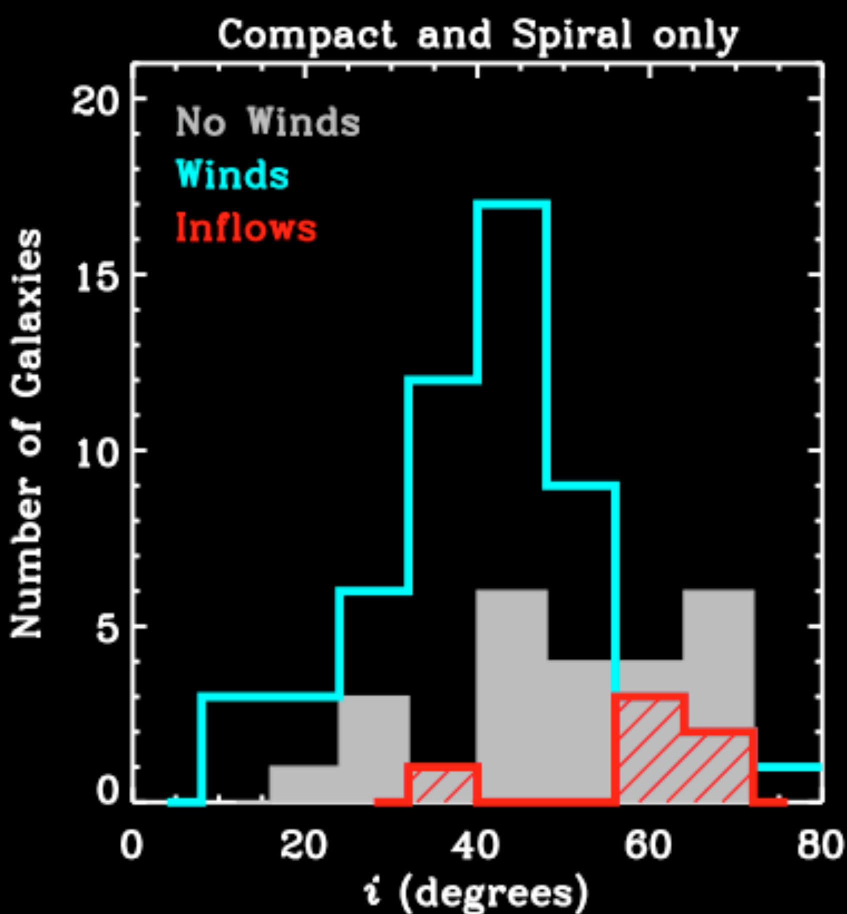
MASS SFR SFR / Area

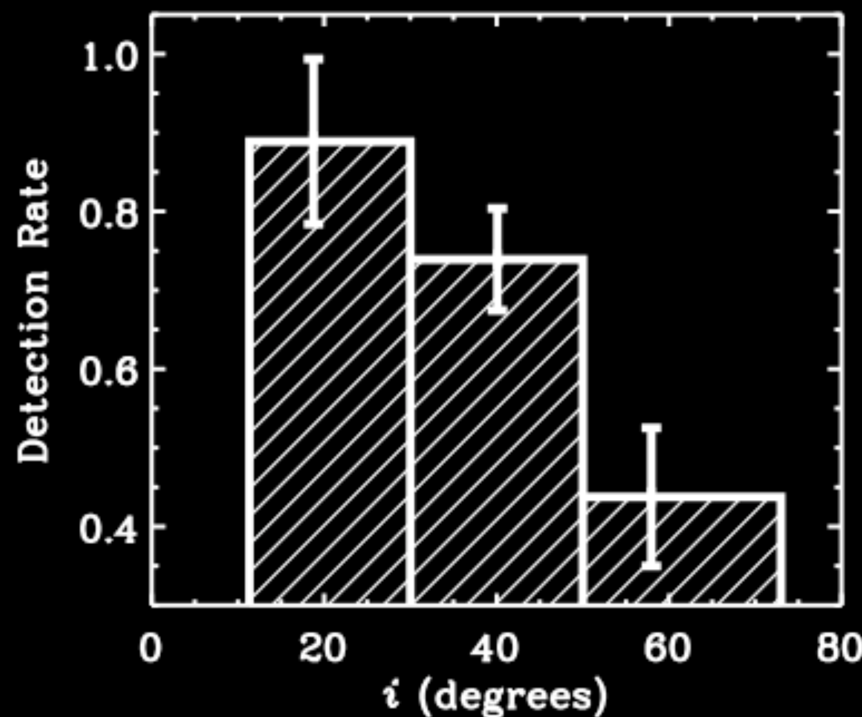


Rubin+12b (in prep)

see also Bordoloi+11,Kacprzak+11,Kornei+12

VOILA ! DETECTION of OUTFLOWS/WINDS depends STRONGLY on INCLINATION





...which suggests that nearly *all* star-forming galaxies at z~0.5 are driving winds (with opening angle ~ 70°).

Rubin+12b (in prep) see also Bordoloi+11,Kacprzak+11,Kornei+12

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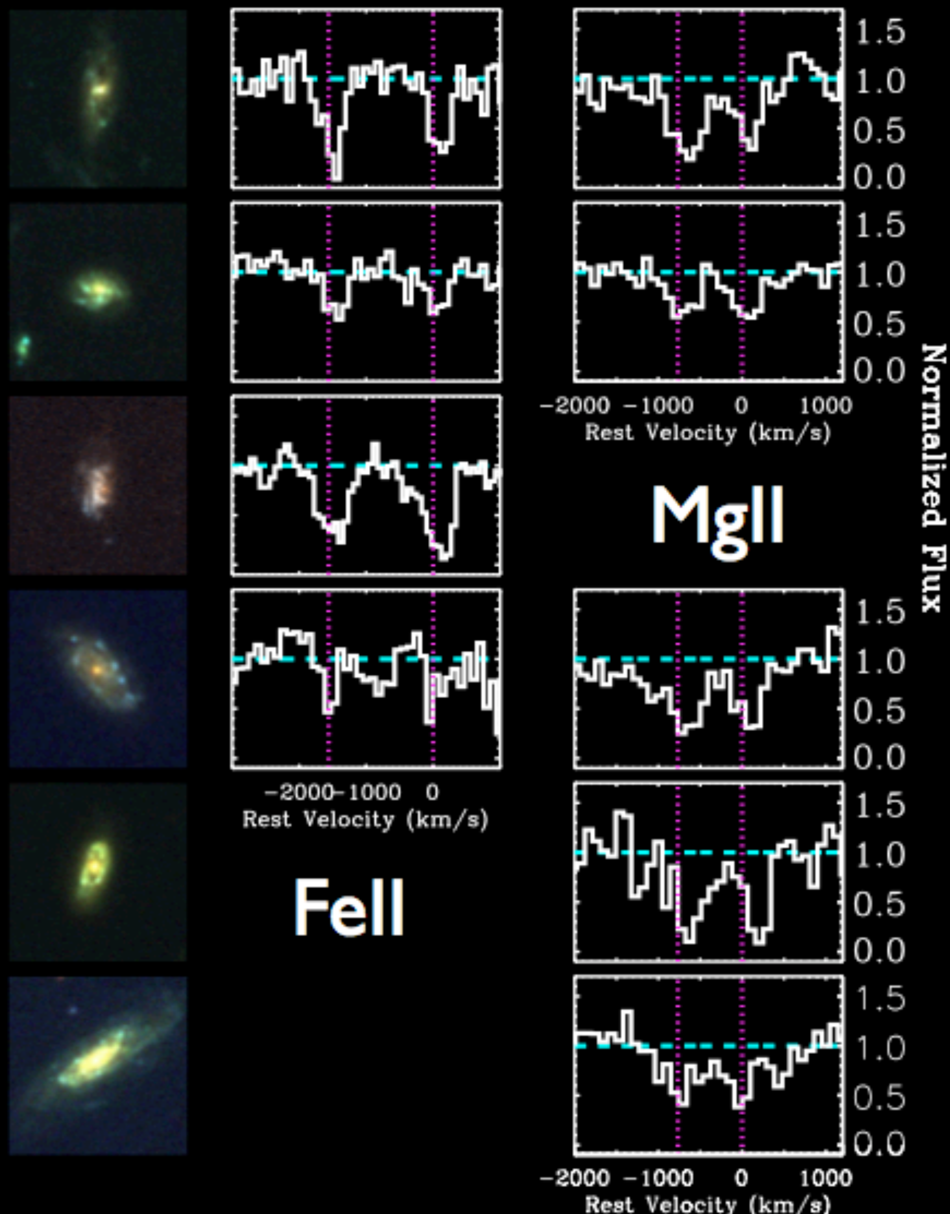
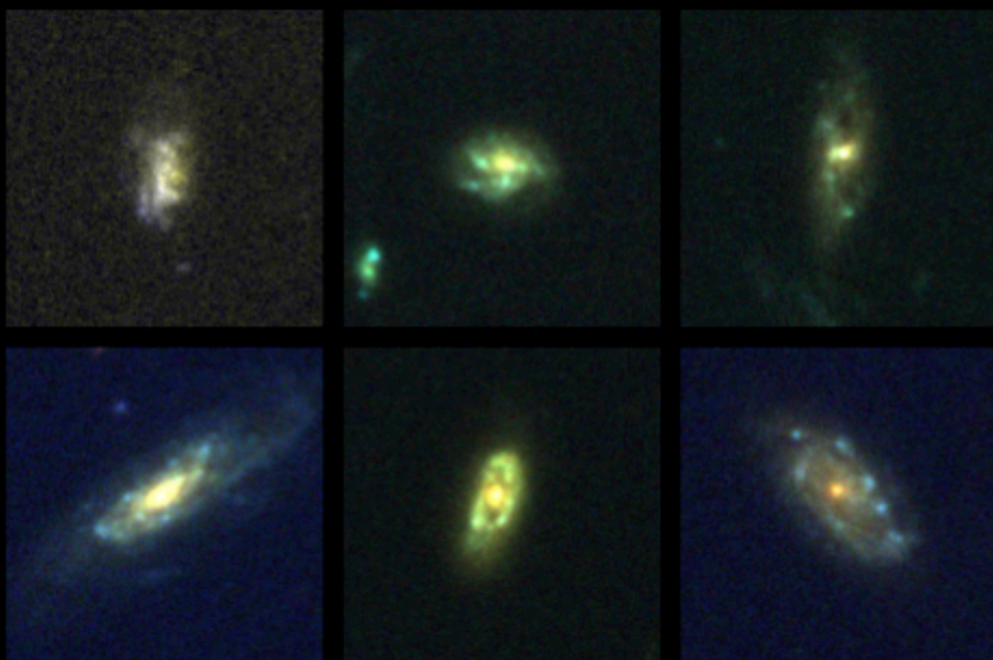
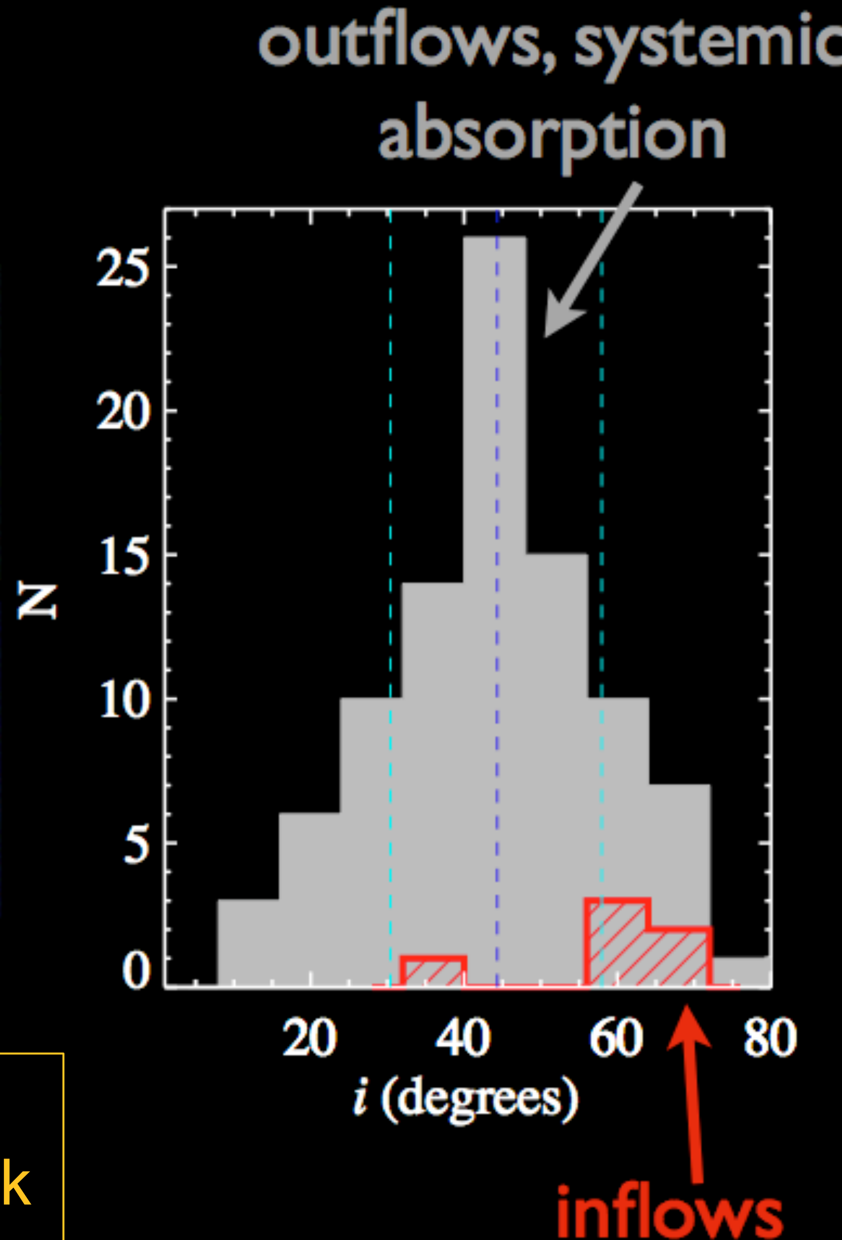
6 of the 150 Galaxies show INFLOWS



Rubin, Prochaska, Koo & Phillips 2012

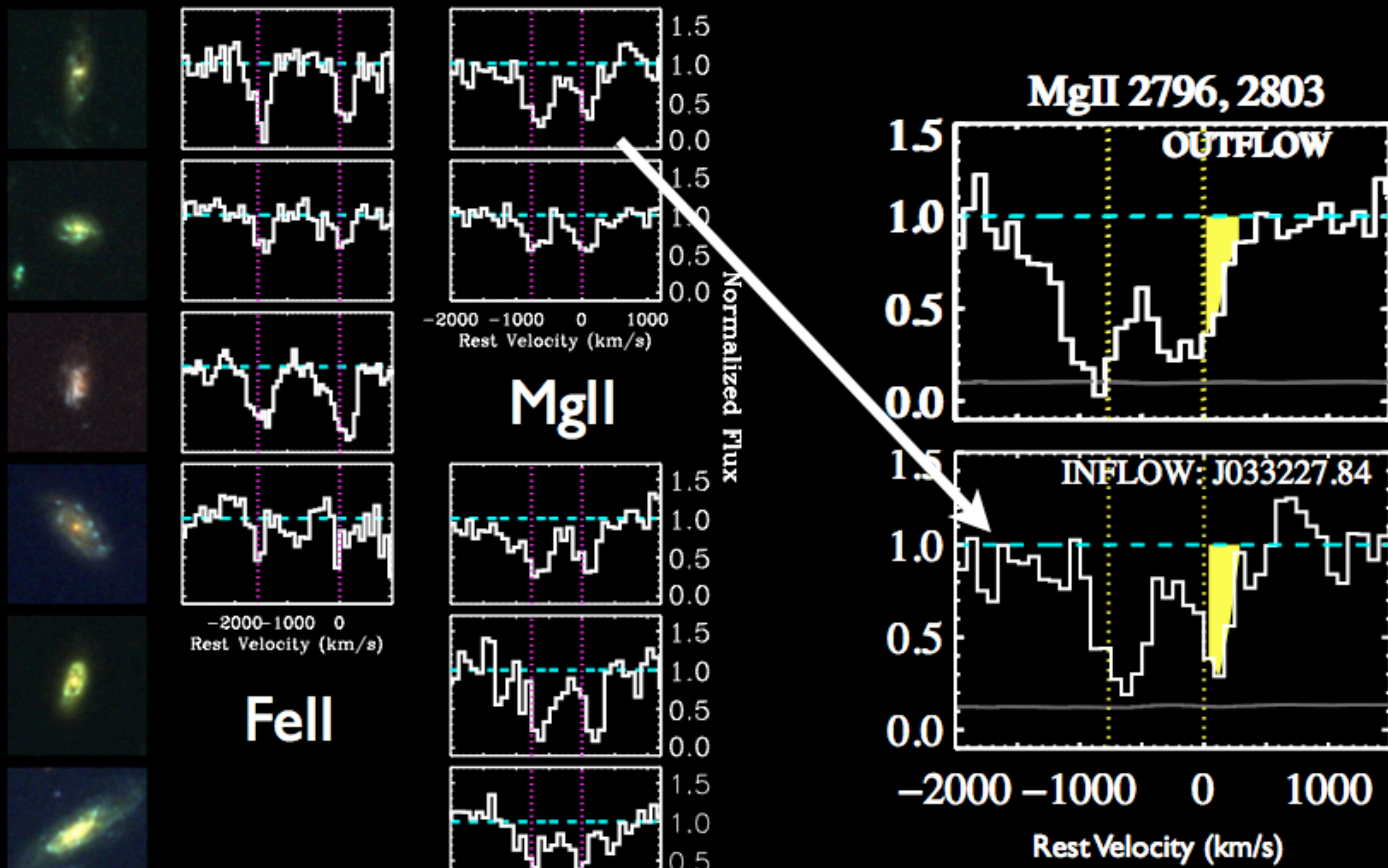
INCLINATION seems to be key





Inclination dependence also observed by Bordoloi+11, Kacprzak+11,Kornei+12,Martin+12

Why so rare? Maybe not!
Winds easily hide inflows



40% of sample has comparably strong red EWs

Implications

"First" solid detections of inflowing, cool *metal-rich* gas among individual galaxies at intermediate redshifts

Amount of inflow is small compared to the SFR: (0.2 – 0.6 Mo/yr vs SFR of galaxies (1-40 Mo/yr):

5/6 (3%-4% of total) have high inclinations (dusty?): If absorption lines of inclined galaxies are less confused with absorption due to strong bipolar/disk outflows; ➔ 40% of 150 show similar level of redshifted absorption

Origin of the inflow is unclear – Possibilities:

inflow from IGM (but too metal rich) – mixed?;
part of accreting satellites (why inclined galx?)
recycled winds circulating in a galactic fountain

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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 into and out of the galaxy.

B. Weiner+09:

finds that almost all luminous blue galaxies at z ~1.4 have winds of 100's km/s with speeds correlated with mass and SFR as found locally;

the high fractions of galaxies with outflows imply winds are *not* sufficient to quench subsequent SF (need AGN?)

K. Rubin+10:

finds that massive, high SFR, lower 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

K. Rubin+12a & b:

finds 2/3 show outflows; inclination dependence with bipolar winds➔

~All massive galaxies with high SFR have winds at z ~ 0.5

6 of 150 galaxies are dominated by inflows; 5/6 are edge-on.

source of inflow TBD: IGM, satellite, galactic fountain are still viable

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