Empirical Evidence for AGN Feedback

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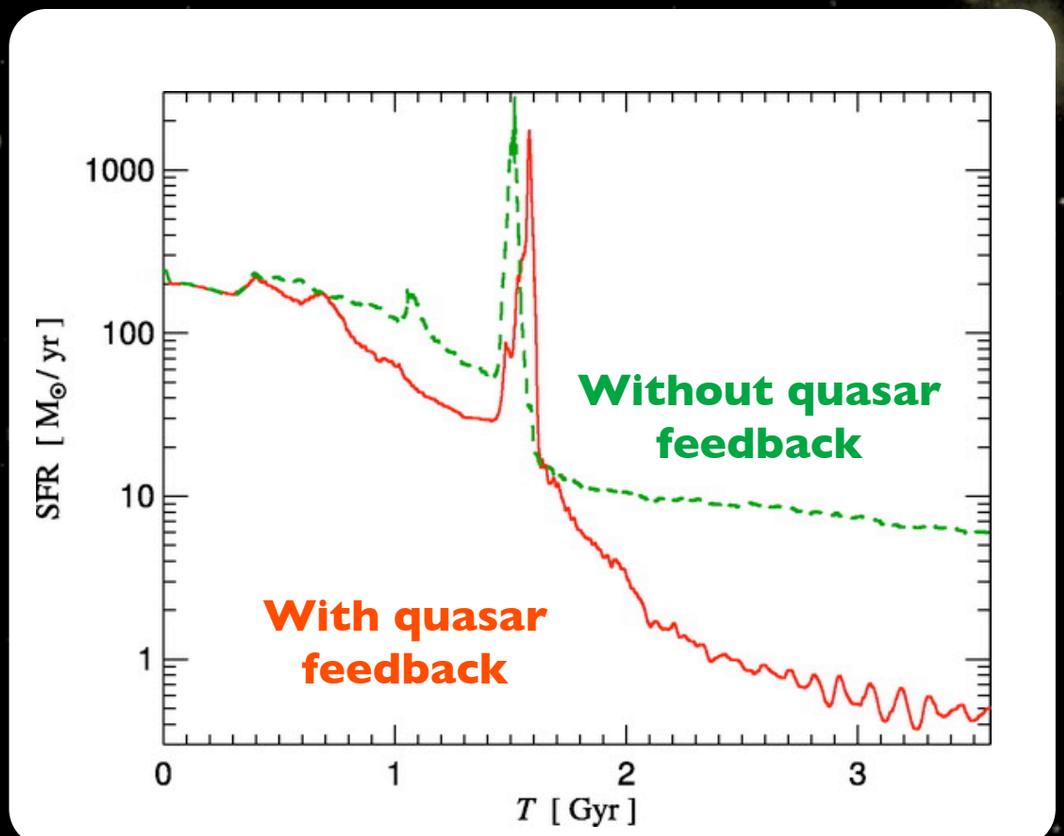
Much observational and theoretical evidence supports a basic evolutionary scenario

Merger of gas-rich disks → Ultra-Luminous Infrared Galaxy → Quasar → Massive Early-type

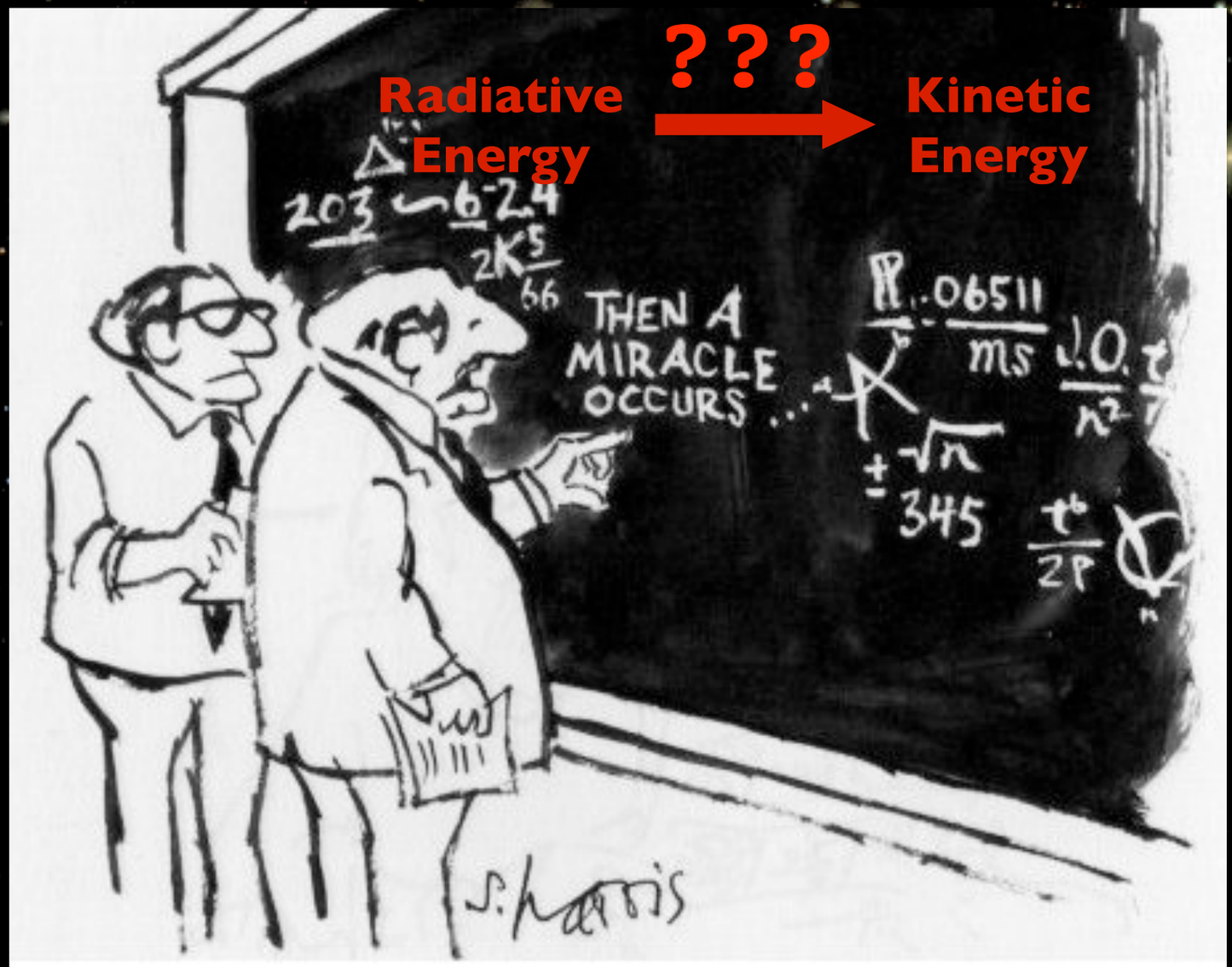
Do quasars play an important role in this transition?

Theoretical models that include quasar-mode feedback shut-off star formation quickly following the merger



Springel et al. 2005

Why should we be skeptical?



"I think you should be more explicit here in step two."

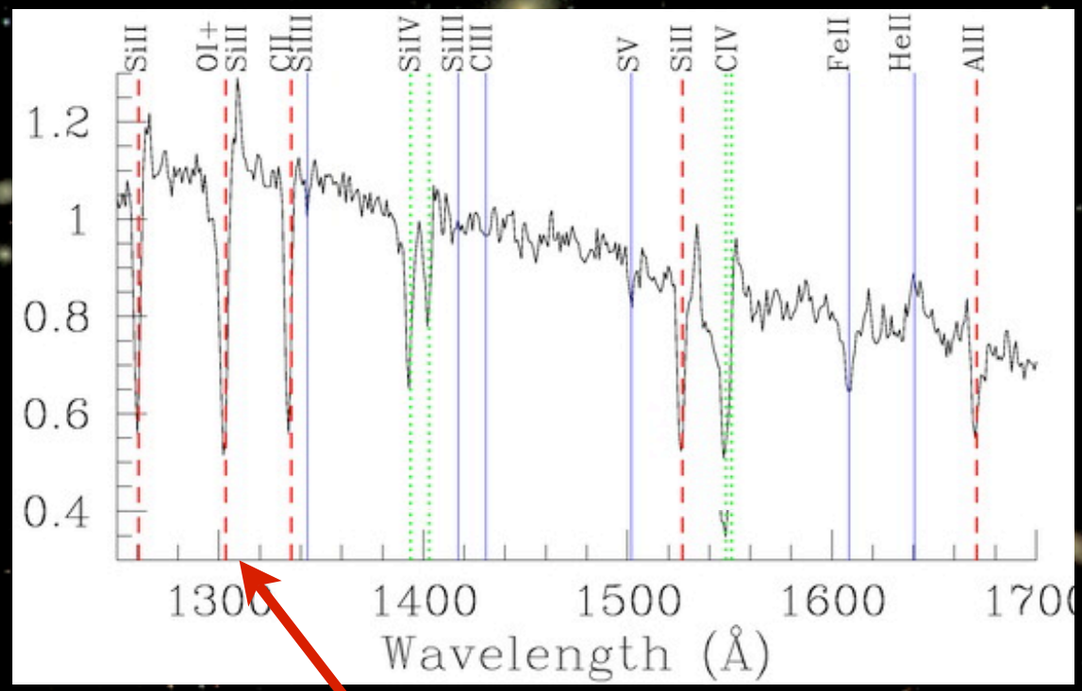
from *What's so Funny about Science?* by Sidney Harris (1977)

We lack a good physical model... and we have limited observational evidence

We have abundant observational evidence for feedback from star formation

Starburst driven outflows are usually detected via blueshifted absorption lines (from clumps of cold gas entrained in the hot wind)

Compostie UV spectrum of local starbursts
Schwartz & Martin 2006



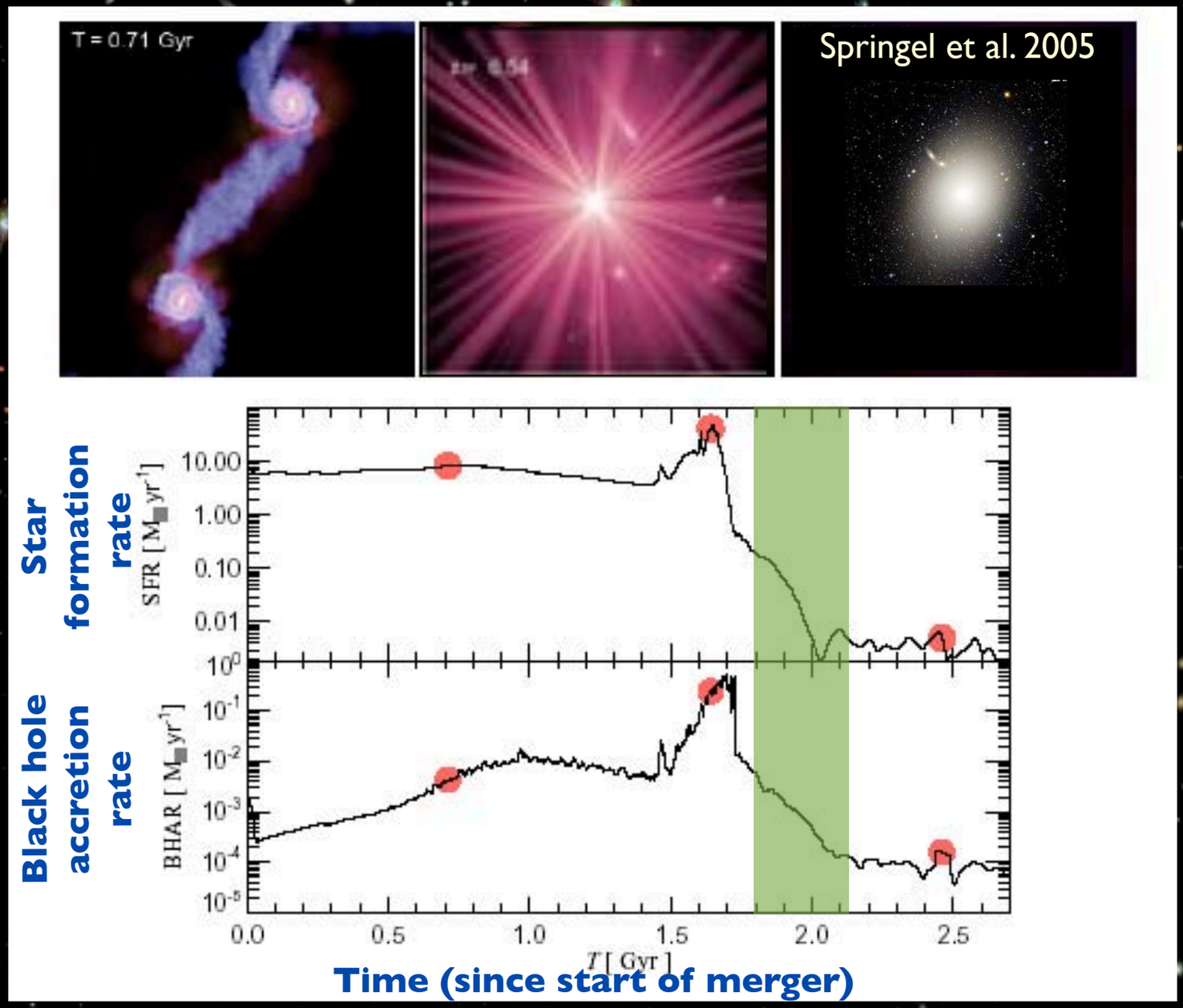
Blueshifted ISM lines

Can we detect quasar powered outflows the same way?

Feedback energy is maximum during the quasar phase, but this is not the best time to look for outflows

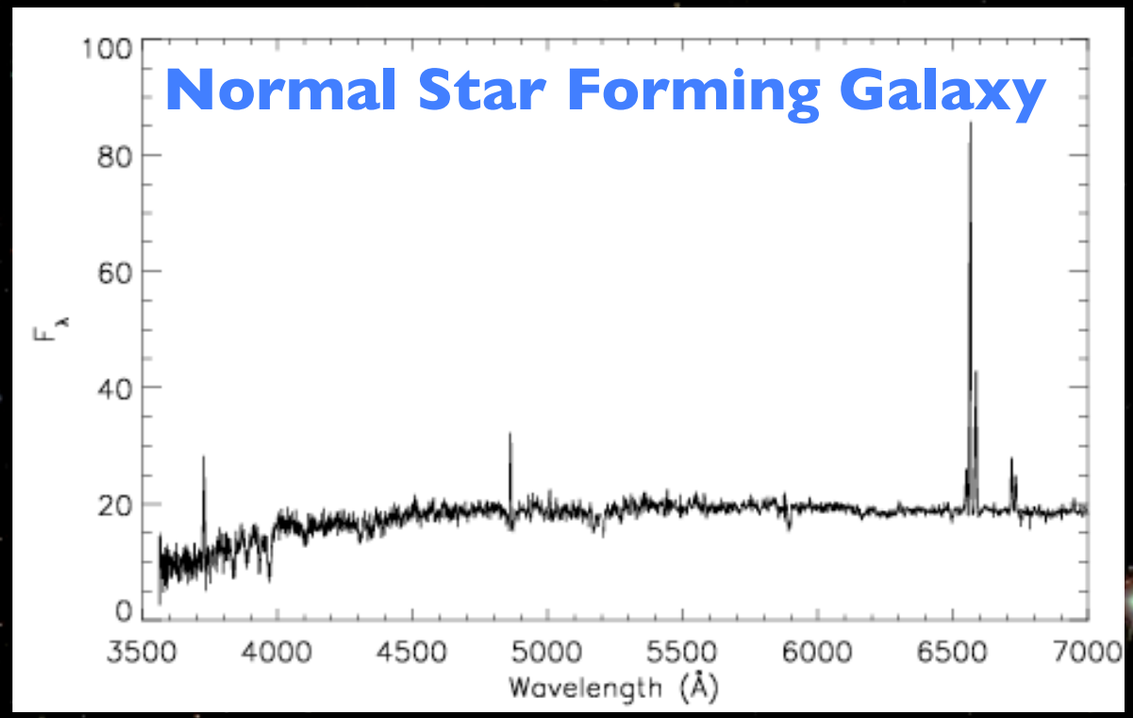
1) quasars ionize the cold gas used to trace outflows

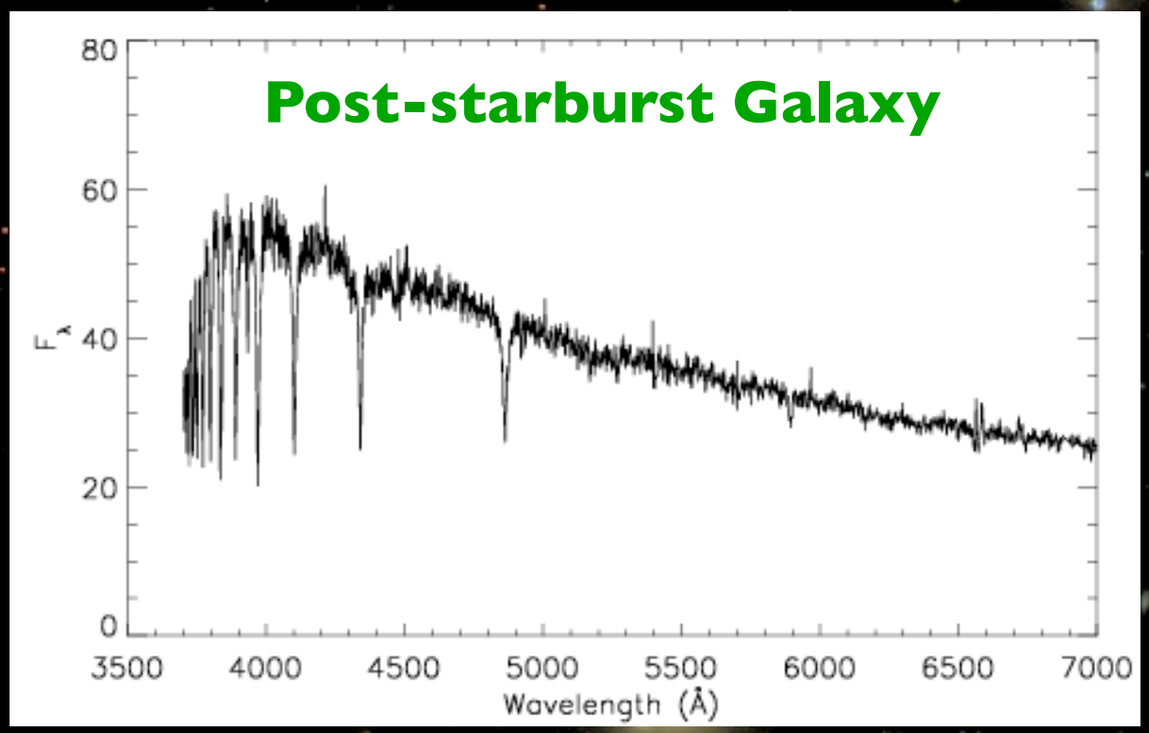
2) absorption lines are harder to interpret: a small cloud near the quasar is indistinguishable from a galaxy-wide outflow

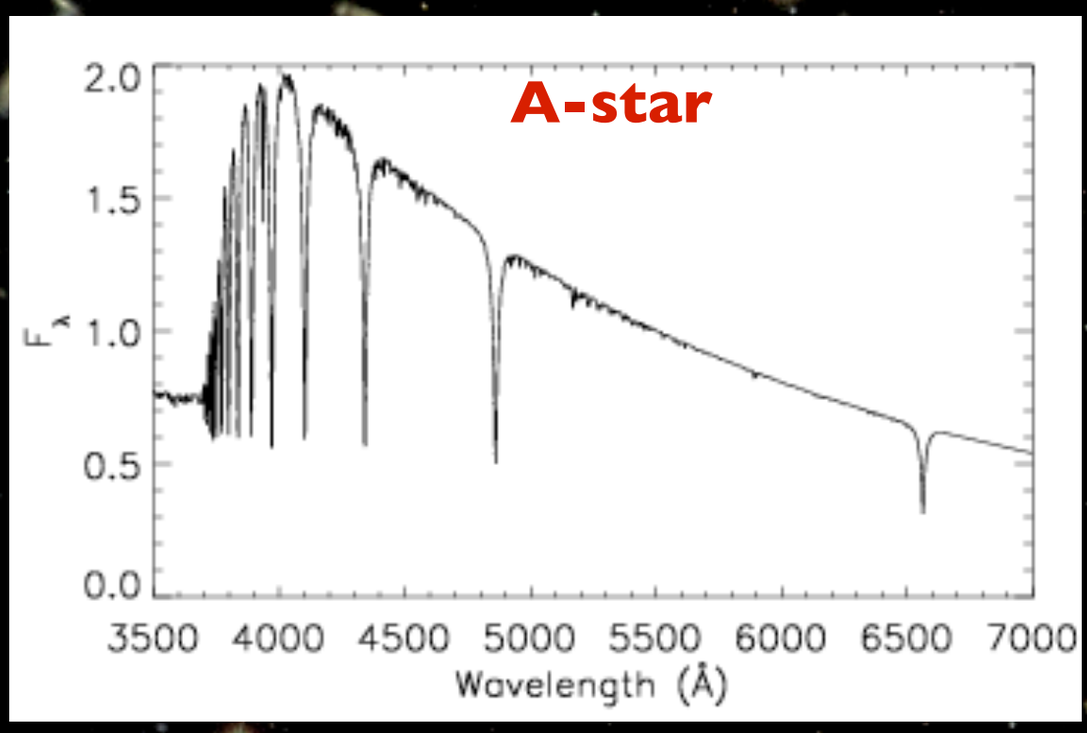


Post-starburst phase

Post-starburst galaxies can be identified by their distinctive spectra which lack strong nebular lines and resemble A-stars







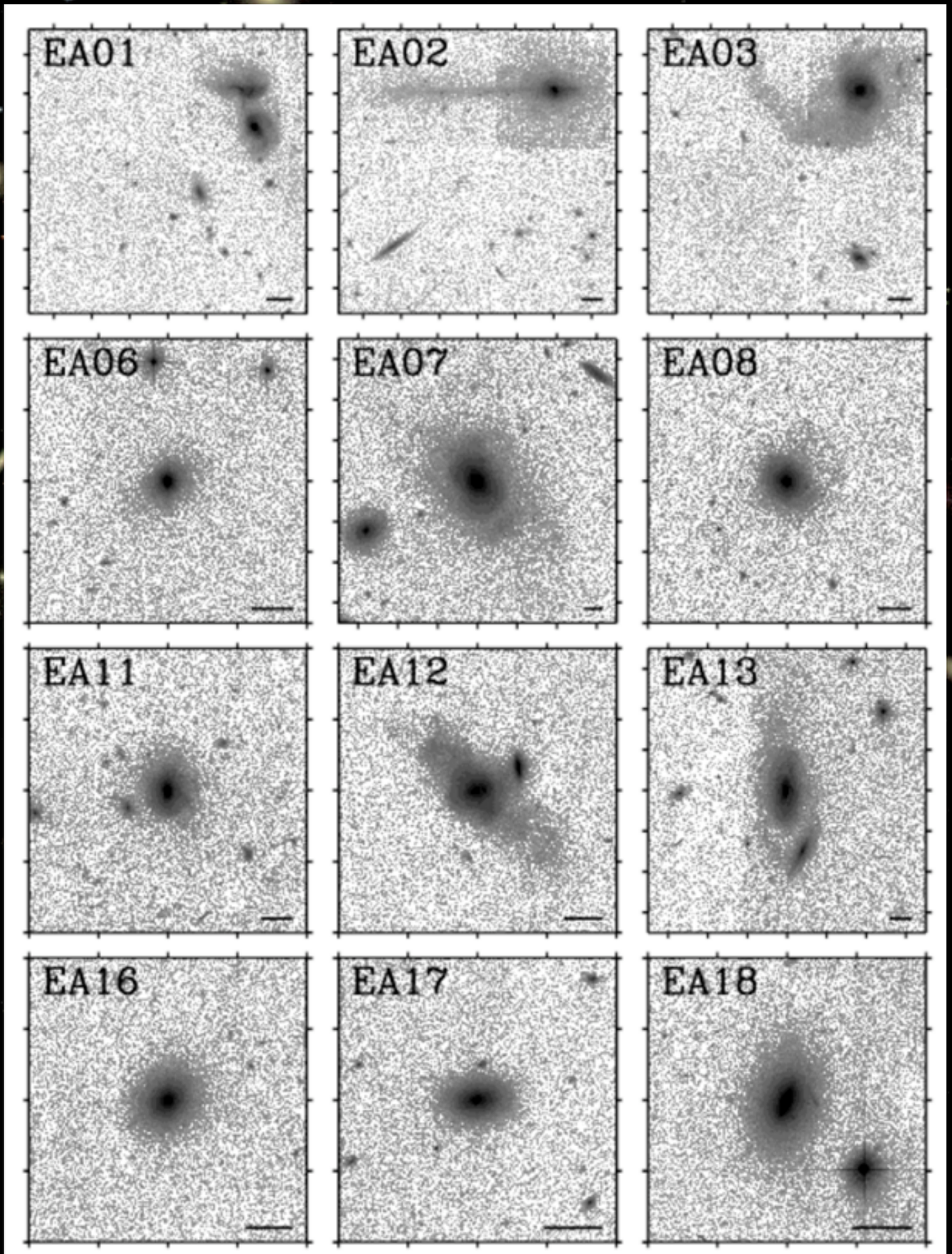
Local post-starbursts (E+A, K+A galaxies) are consistent with being late-stage mergers

- group environments
Zabludoff et al. 1996

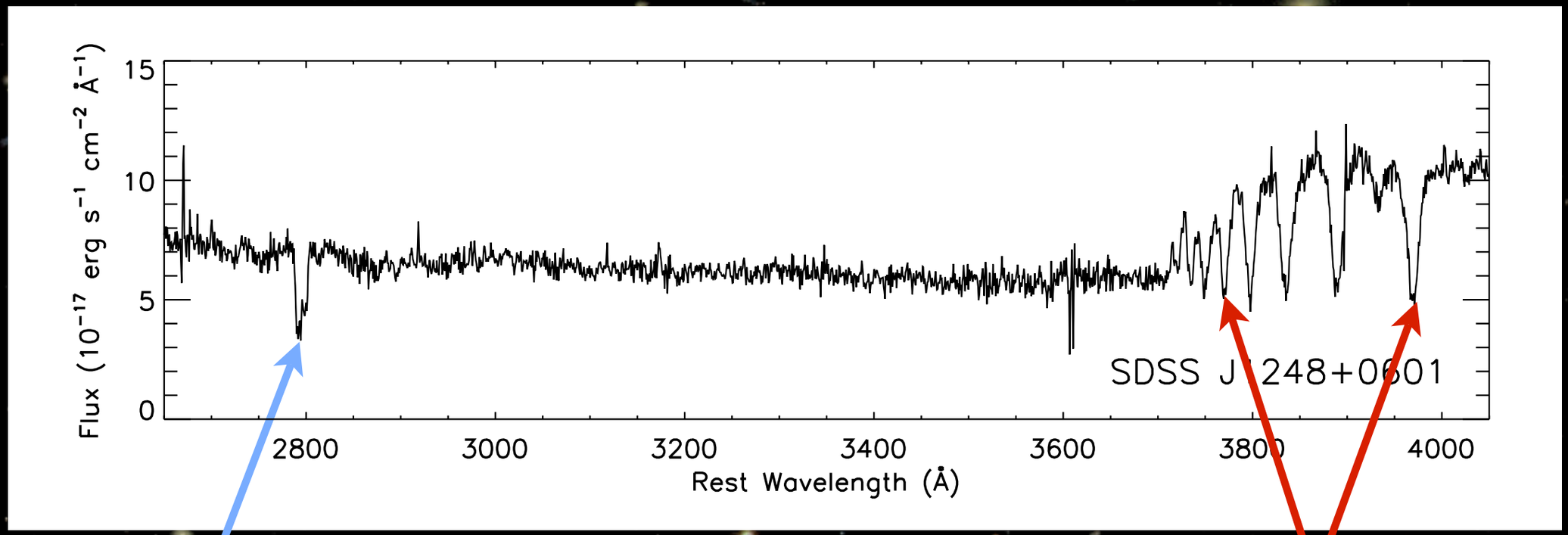
- bulge-dominated morphologies with faint tidal features
Yang 2004, 2007

- Low-luminosity AGN (LINERS)
Yan et al. 2005

- Rare locally (~1% of galaxies) but more common at high-z
Le Borgne et al. 2006



Our Goal: observe a sample of massive post-starbursts at z=0.4 - 0.8 to look for evidence of quasar-powered outflows

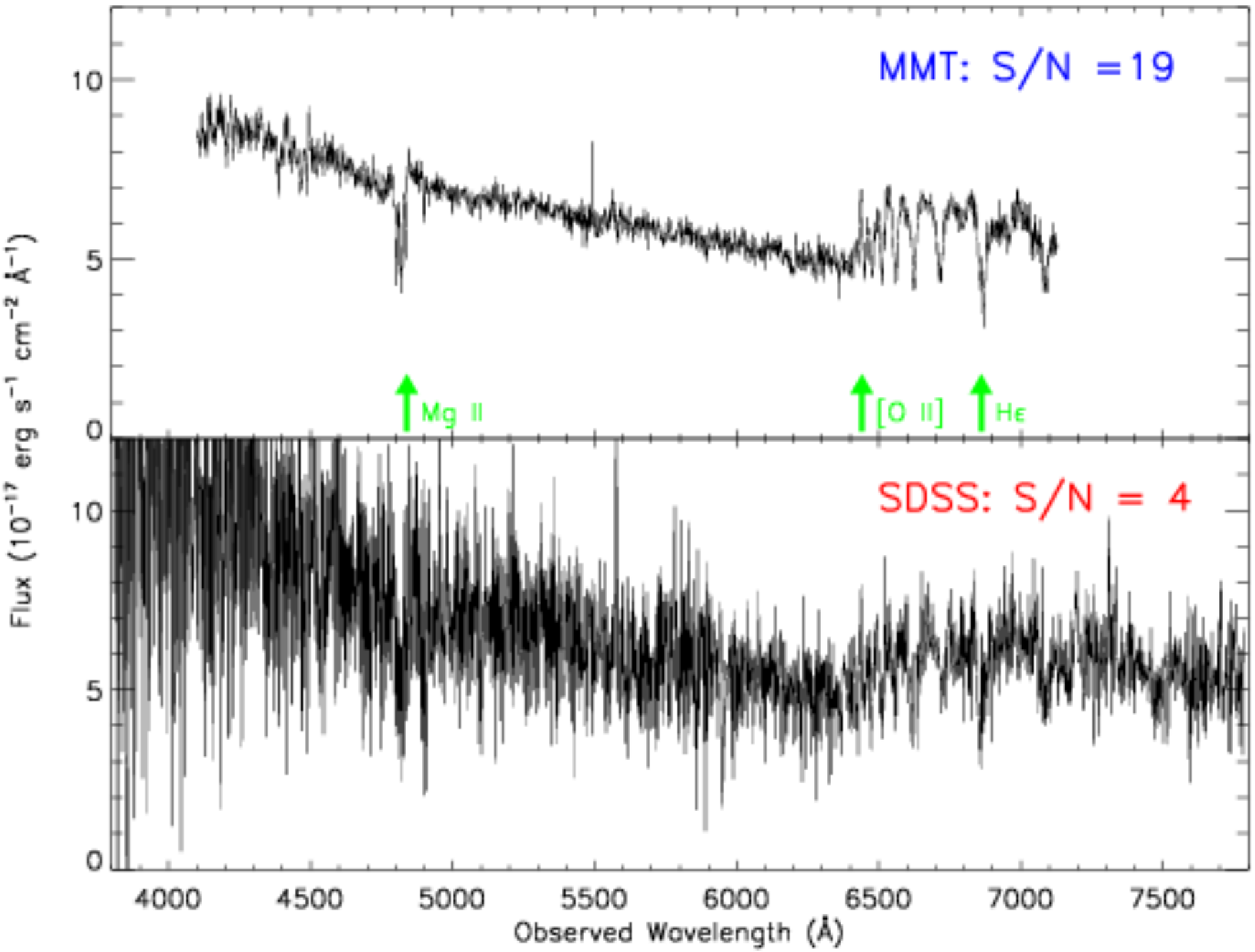


Interstellar Mg II

Stellar Balmer Lines

70 targets selected from SDSS

37 followed up with 6.5-m MMT

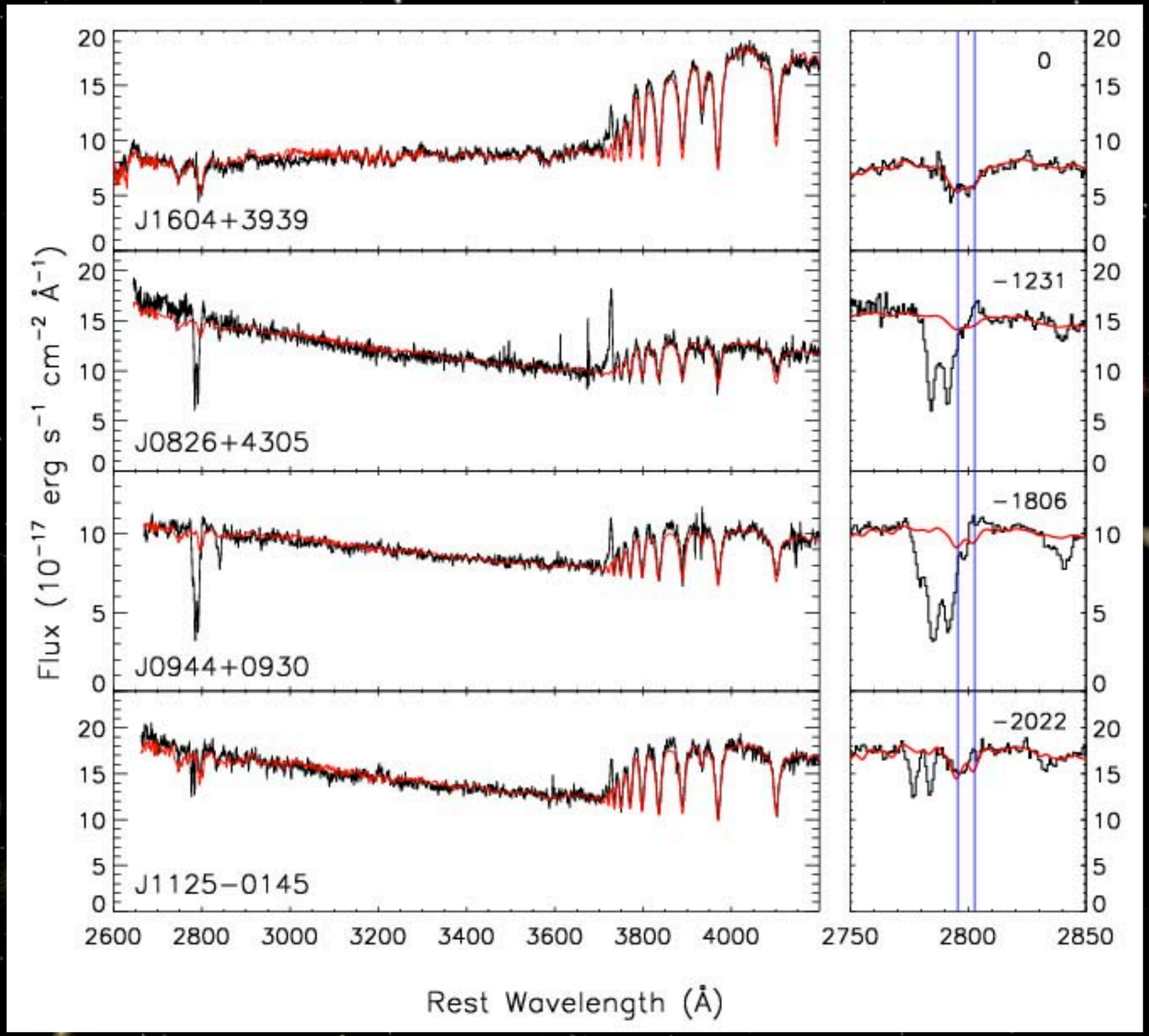

SDSS J2116−0634
MMT: S/N =19
SDSS: S/N = 4
Mg II
[O II]
Hε
Flux (10^{-17} erg s^{-1} cm^{-2} Å^{-1})
Observed Wavelength (Å)
0
5
10
4000
4500
5000
5500
6000
6500
7000
7500

Mg II detected in all 37 sources

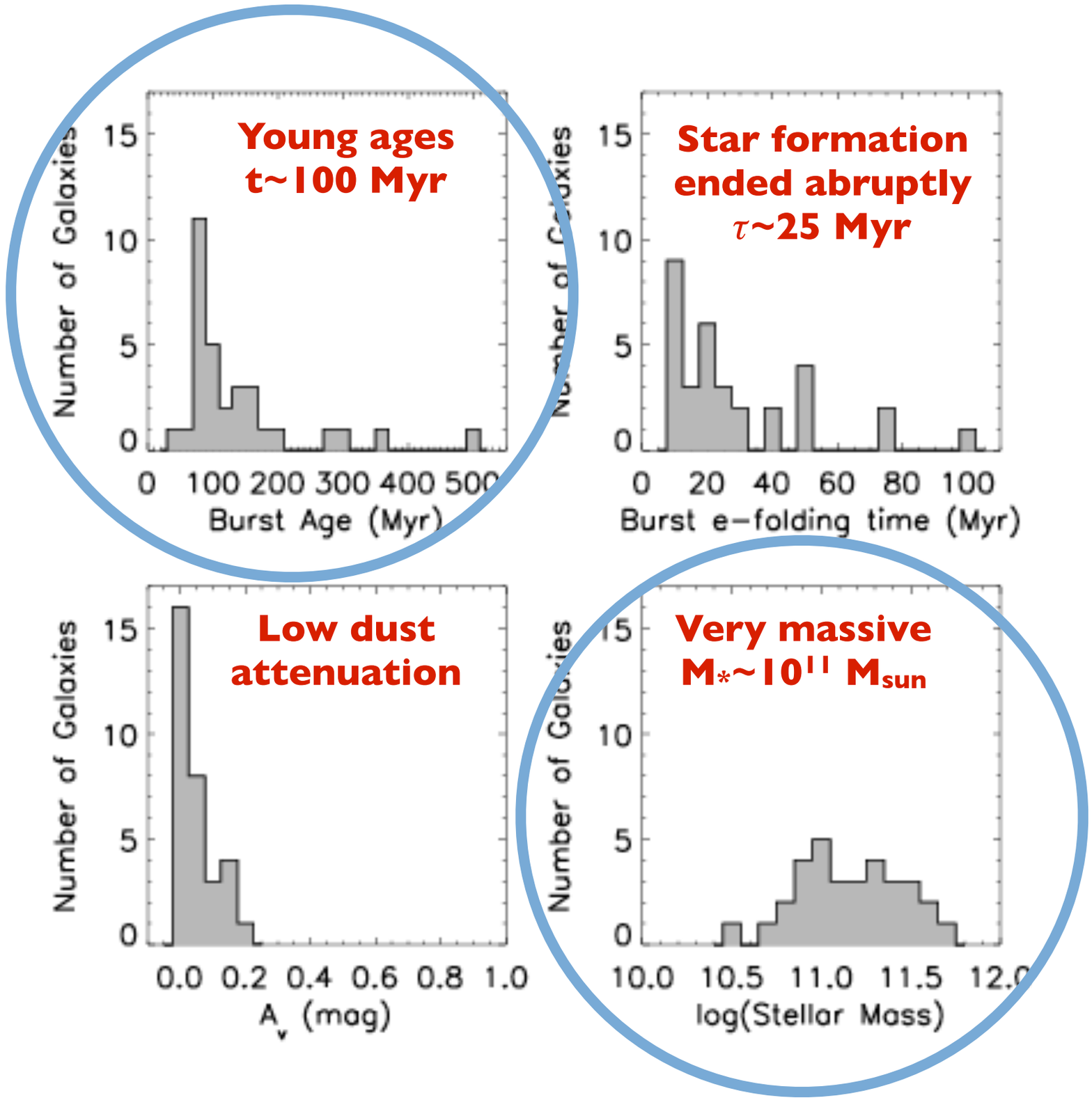
We fit models to determine the stellar contribution

ISM absorption in 2/3

Strongly blueshifted!



We model the galaxies stellar populations



Fossil Galactic Winds

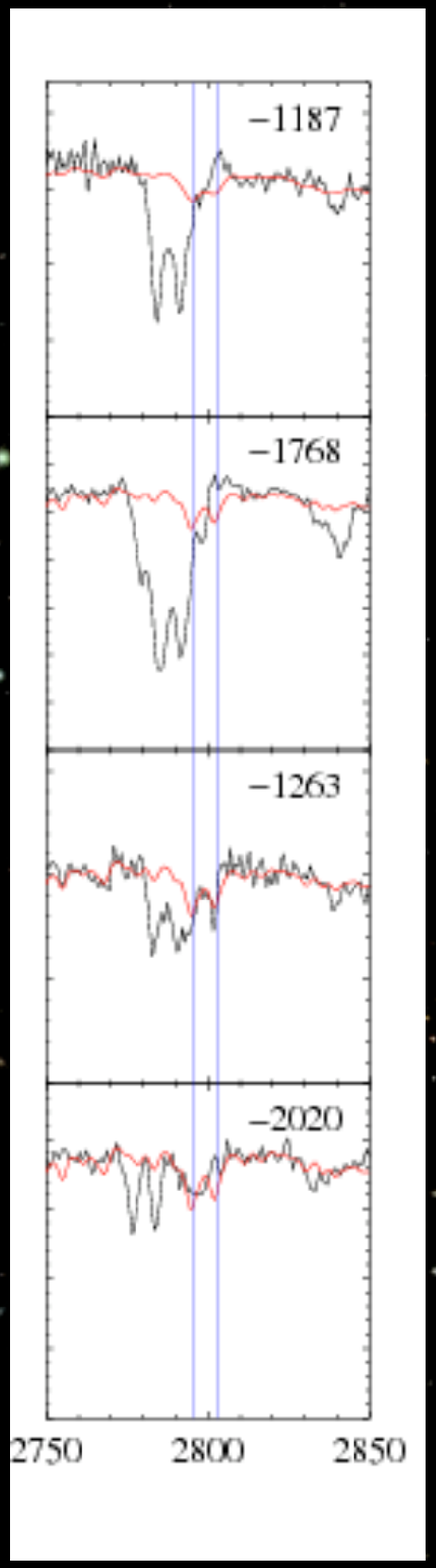
Interstellar Mg II in 24/37 galaxies

In all cases it is blueshifted from the stellar lines by 400 - 2000 km/s

We assume that the outflows were launched at the peak of the galaxies' activity ~100 Myr ago

starburst, t=0 Myr

post-starburst, t=100 Myr



How far does the wind get?

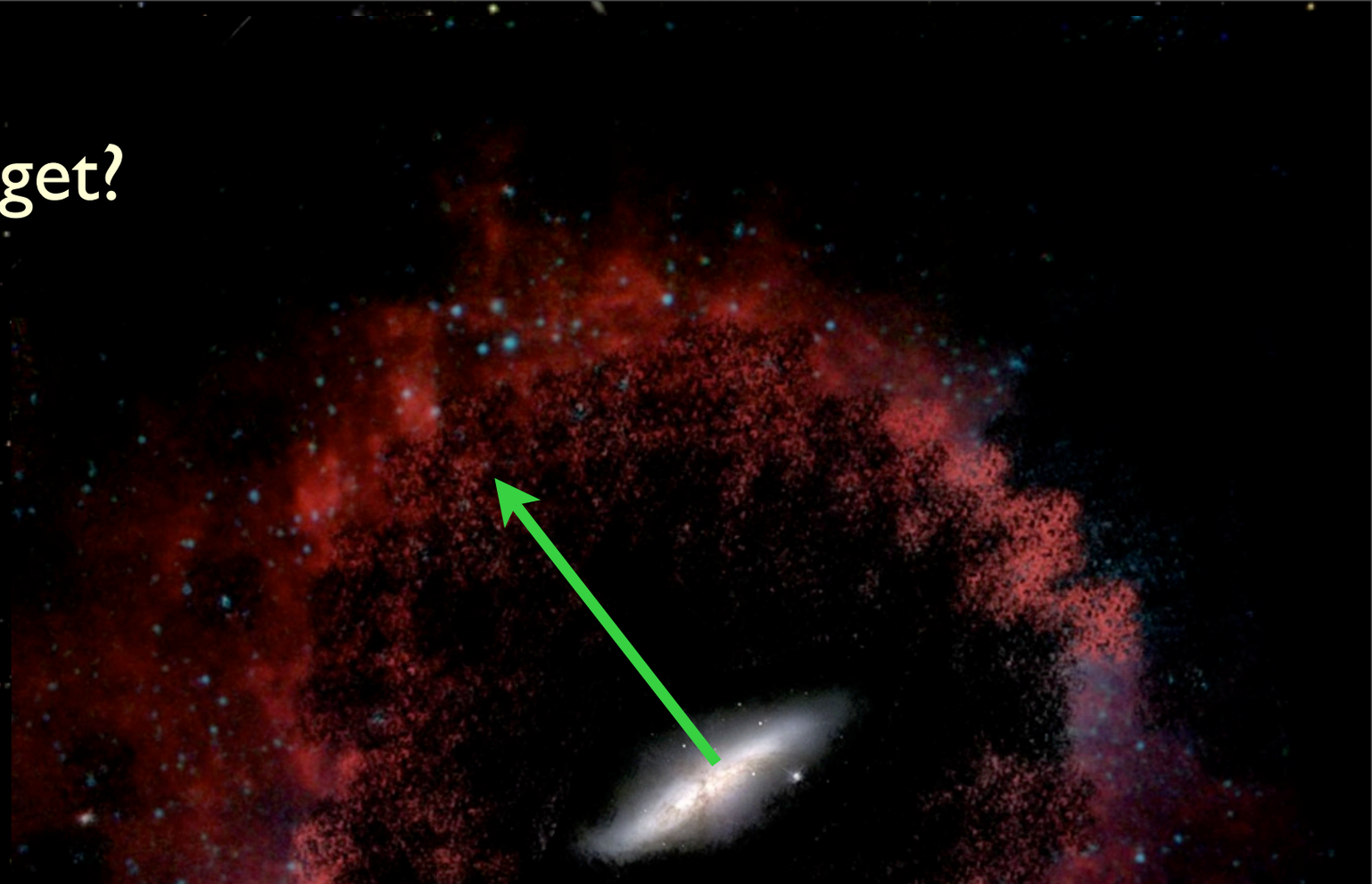
$d = v\ t$

$v = 1000$ km/s

$t = 100$ Myr

$d = 100$ kpc

winds will escape



How much mass is in the outflow?

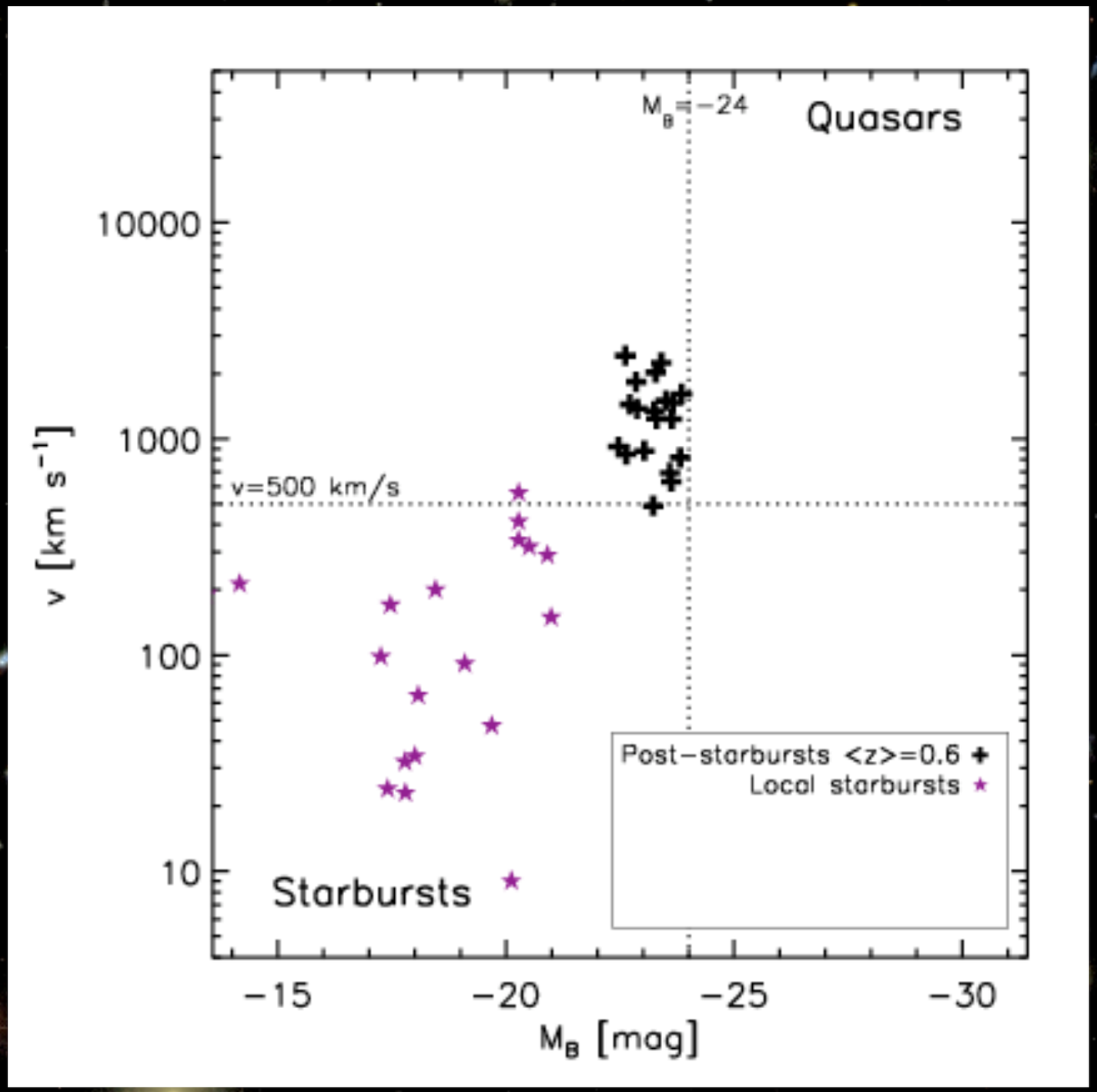
$N(H) \sim 10^{20}$ cm^{-2}

$M_{wind} = 10^{9.3}$ - 10^{11} M_{sun}

depends strongly on assumed geometry!

5 - 50% of the galaxy's baryons

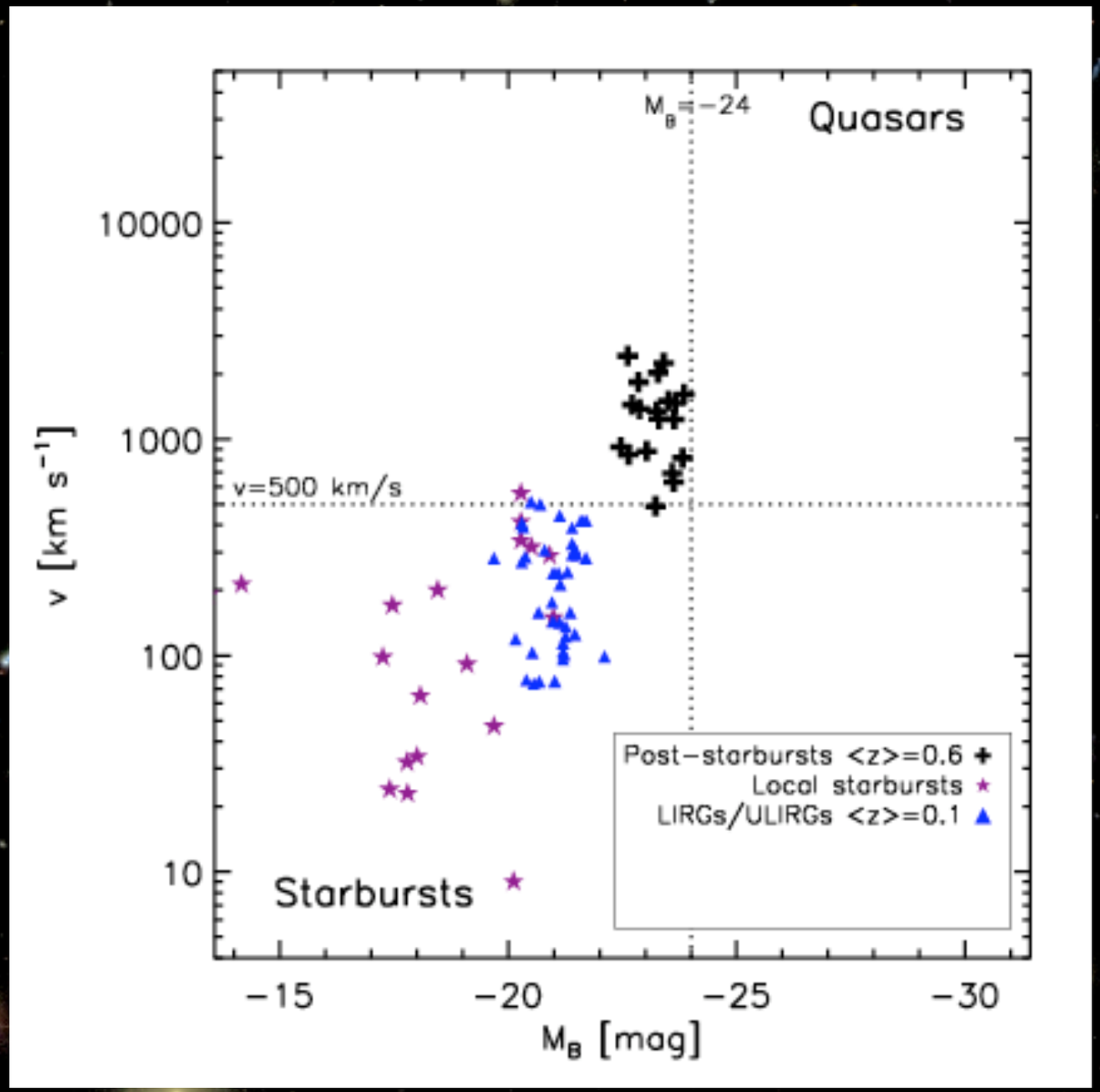
Are these outflows really powered by quasars?



Local Starbursts
Schwartz & Martin 2004, 2006

B-band Magnitude

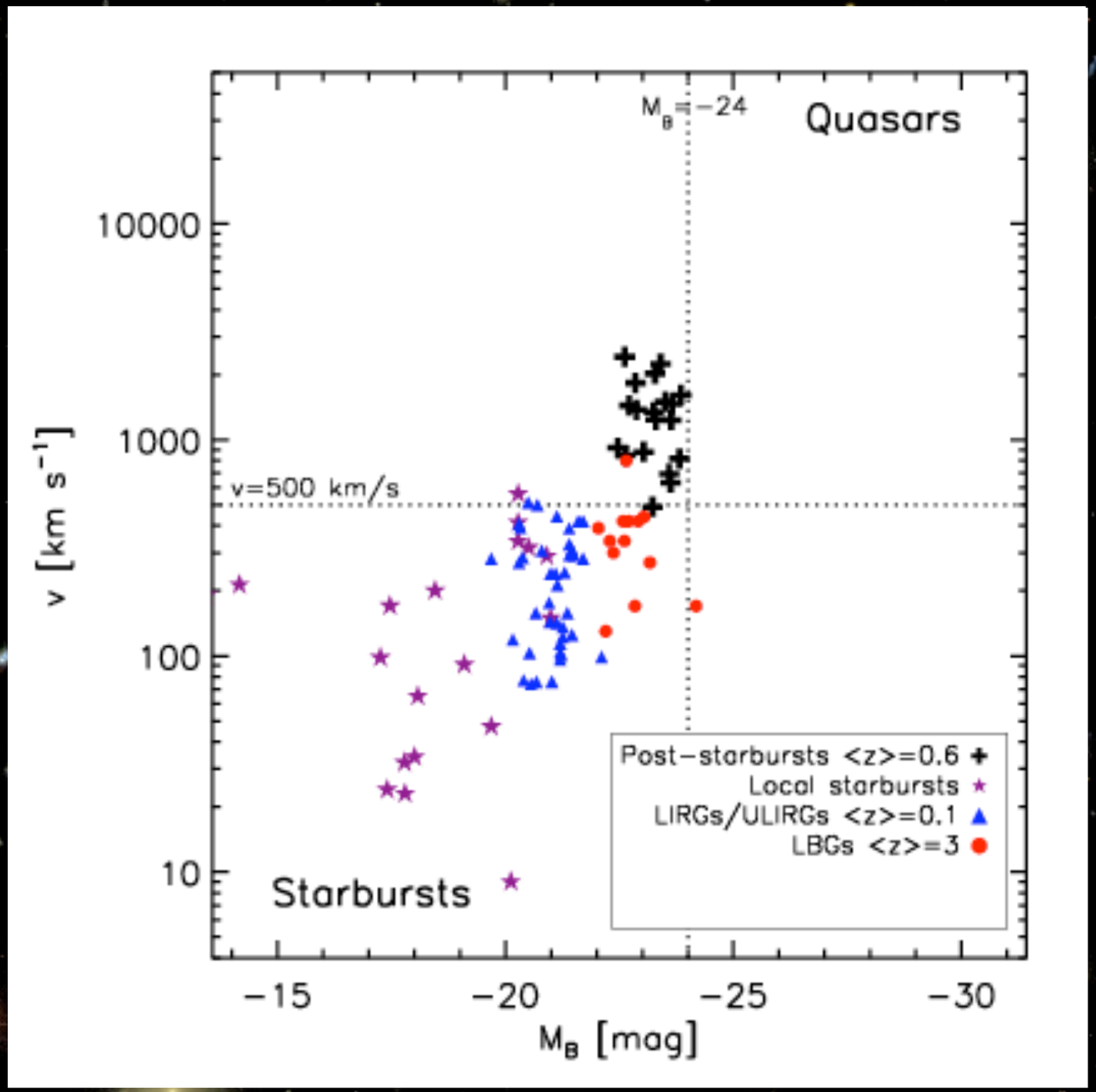
Are these outflows really powered by quasars?



LIRGs/ULIRGs
Rupke et al. 2005
Martin 2005

B-band Magnitude

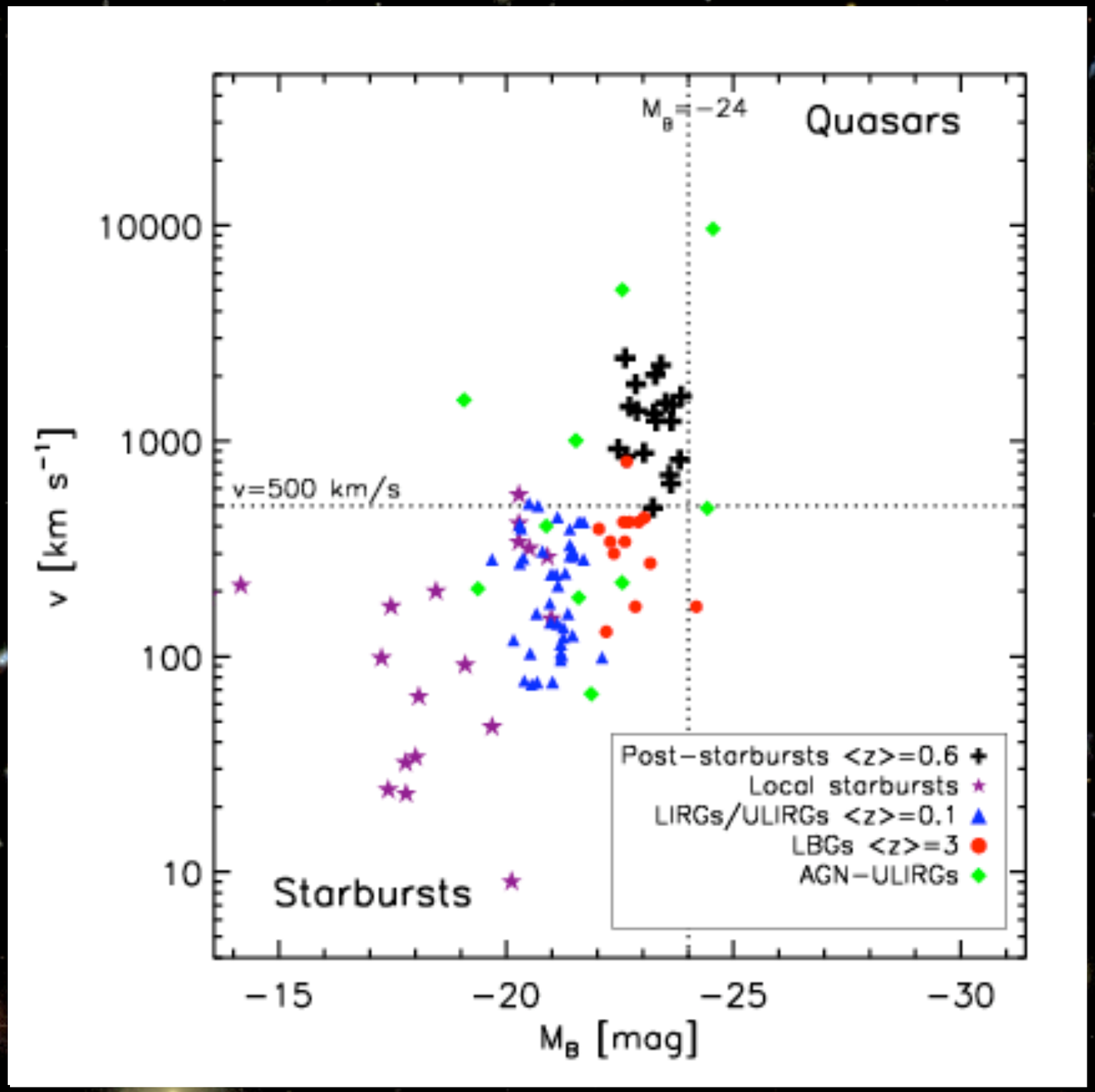
Are these outflows really powered by quasars?



Lyman Break Galaxies (z=3) Pettini et al. 2001

B-band Magnitude

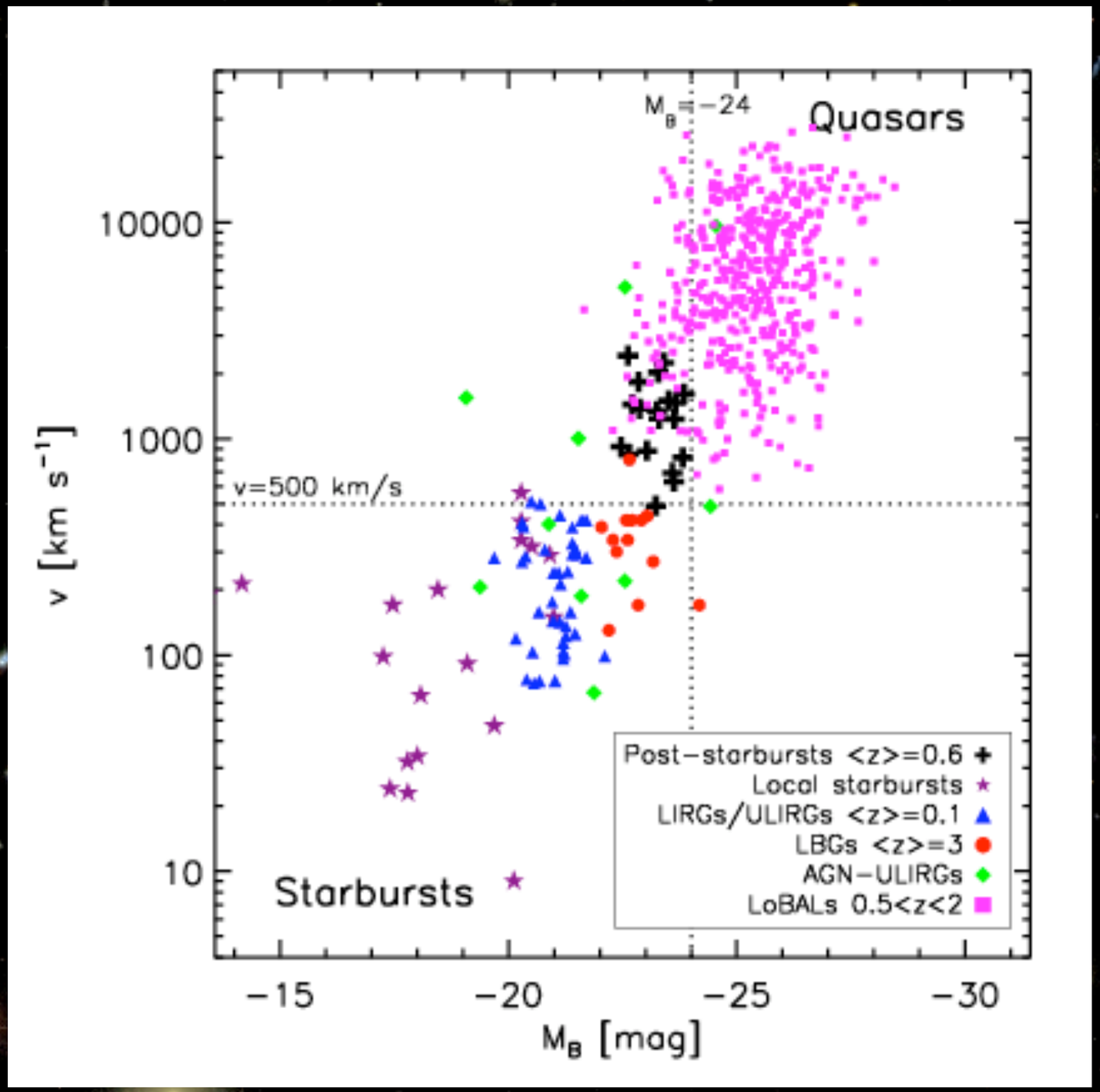
Are these outflows really powered by quasars?



AGN-ULIRGs
Rupke et al. 2005

B-band Magnitude

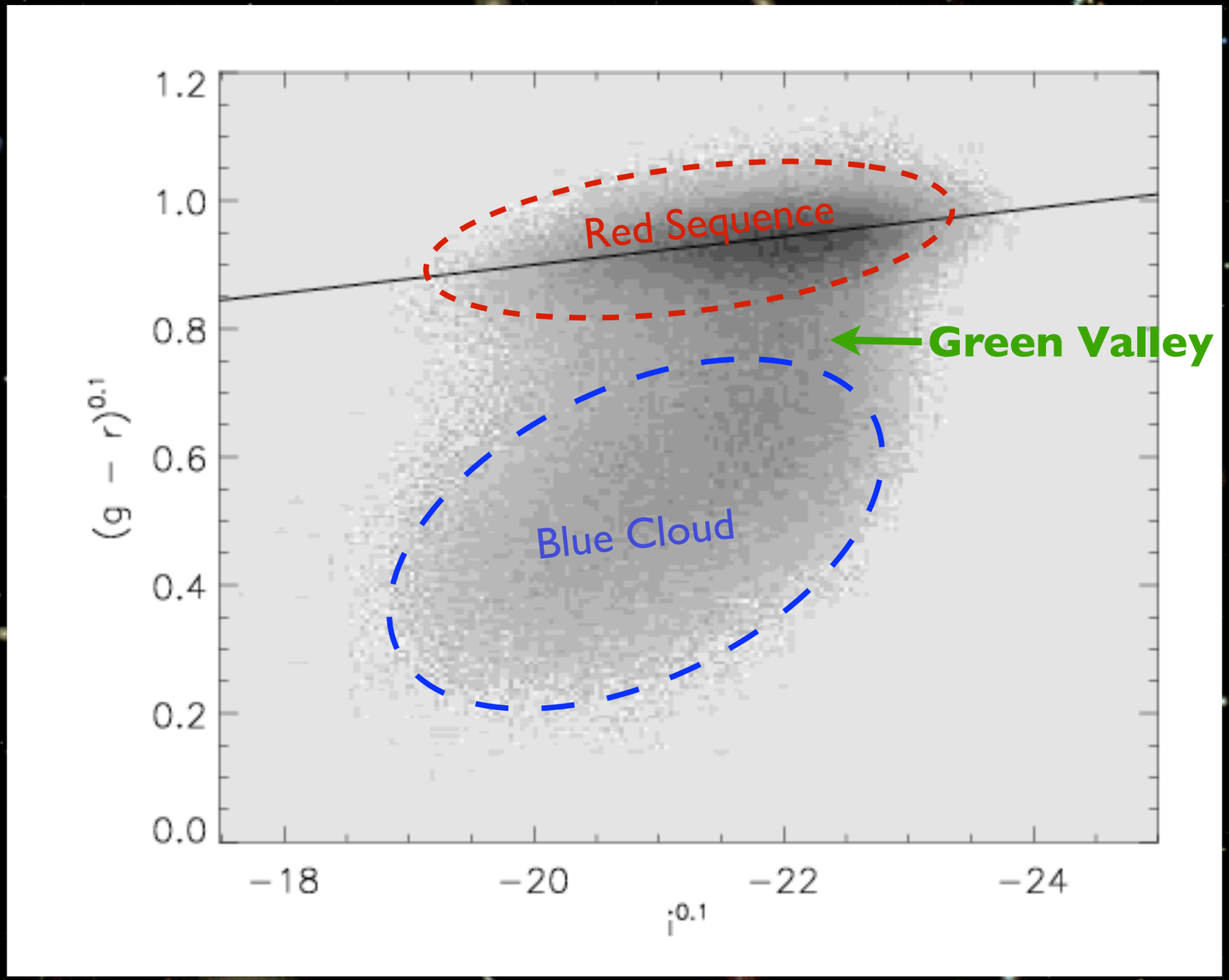
Are these outflows powered by quasars? .... Probably



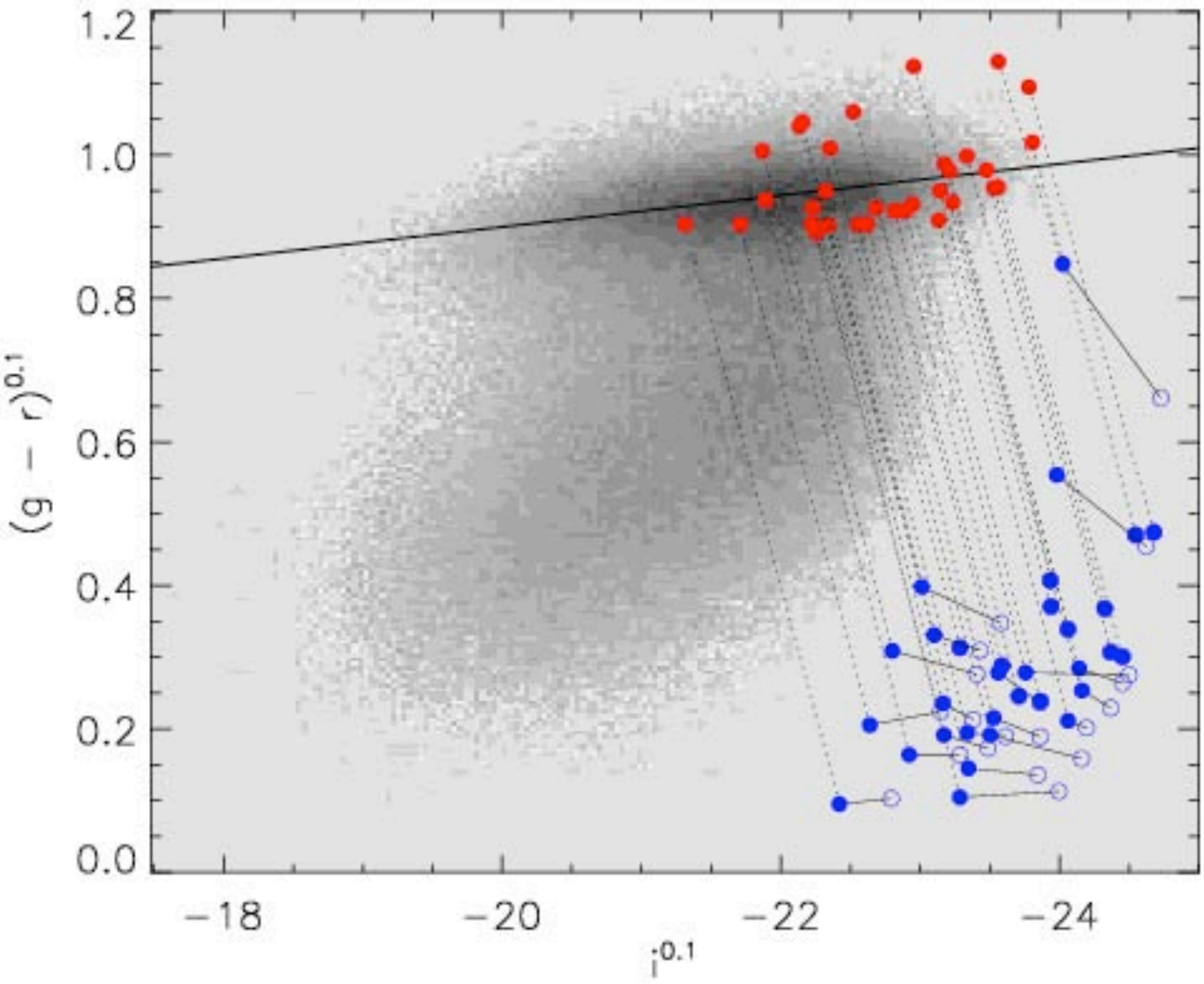
LOBAL QSOs
Trump et al. 2006

B-band Magnitude

What will these galaxies become?



Our post-starbursts will evolve passively into intermediate mass to massive early-types



1 Gyr later

Now (z~0.6)

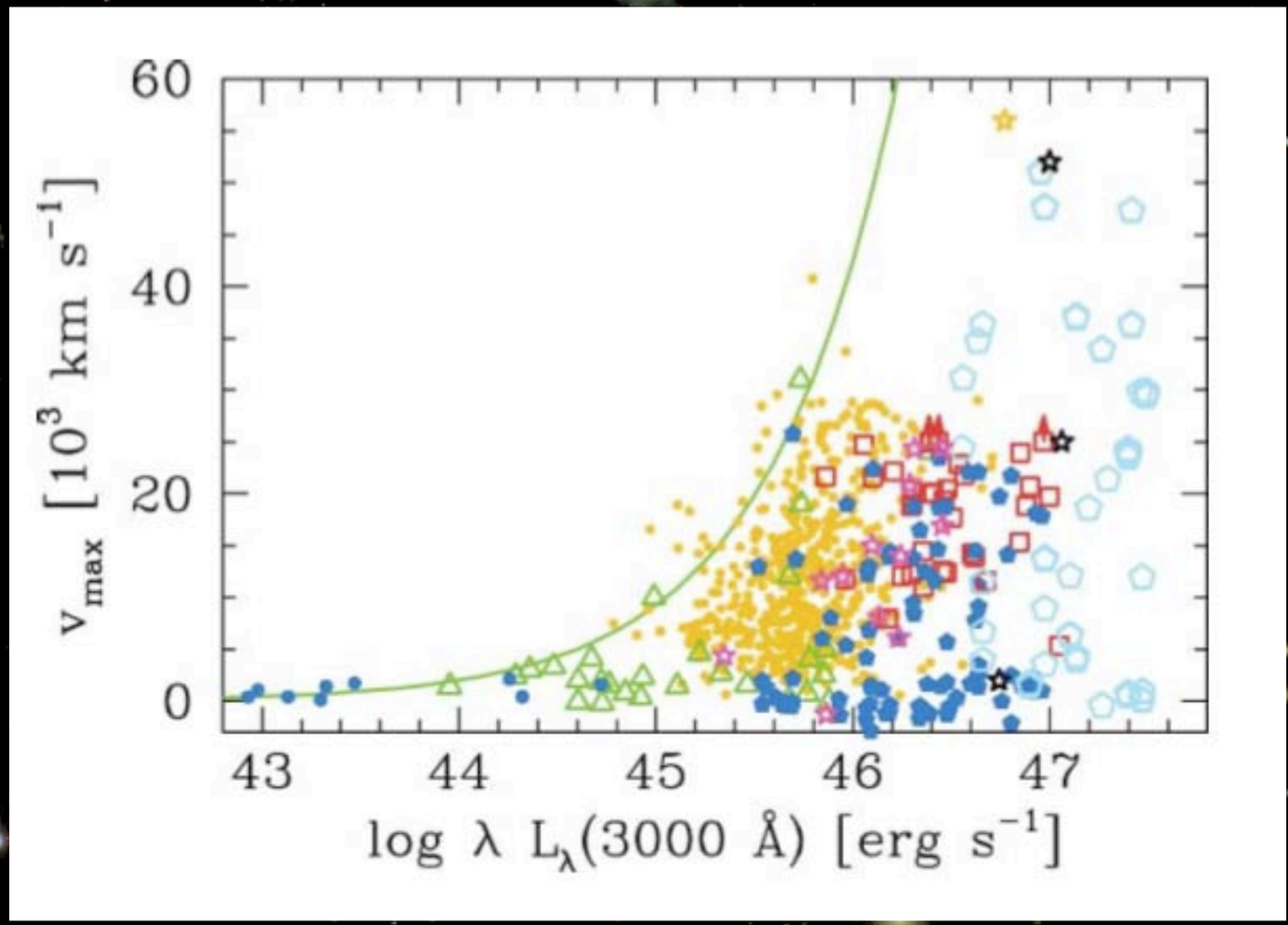
How does quasar feedback work?

1) Momentum-driven winds

Radiation pressure on dust grains?

Line-driving?

Some evidence from BAL Quasars



Ganguly & Brotherton 2008

2) Mechanical Energy Injection by Radio Jets

Emission line nebula in z~2 radio galaxies

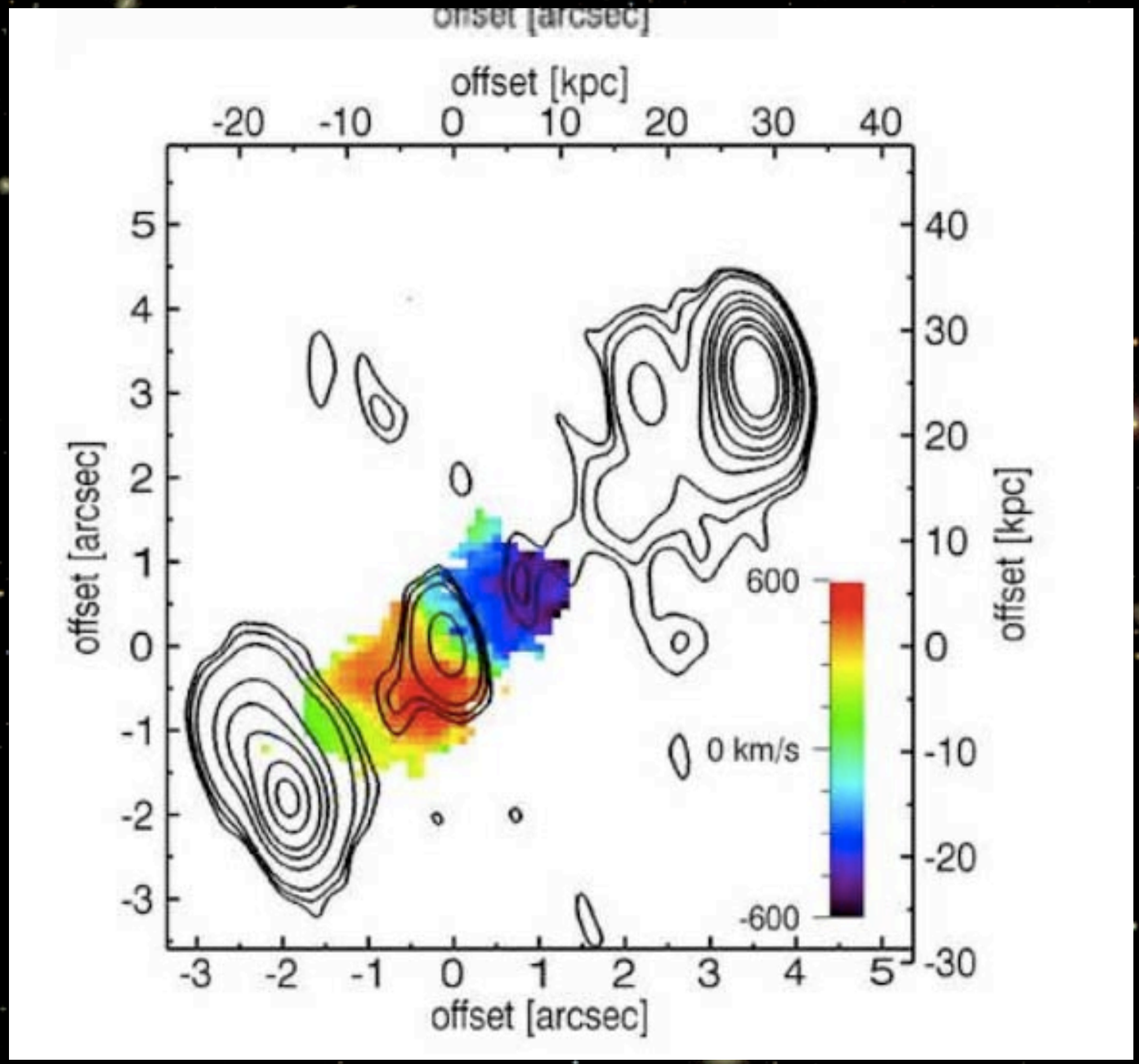
SINFONI maps of [OIII]

sizes 10 - 20 kpc

~500 km/s outflows

~1000 km/s line widhts - powerful shocks

10^{10} M_{sun} of gas

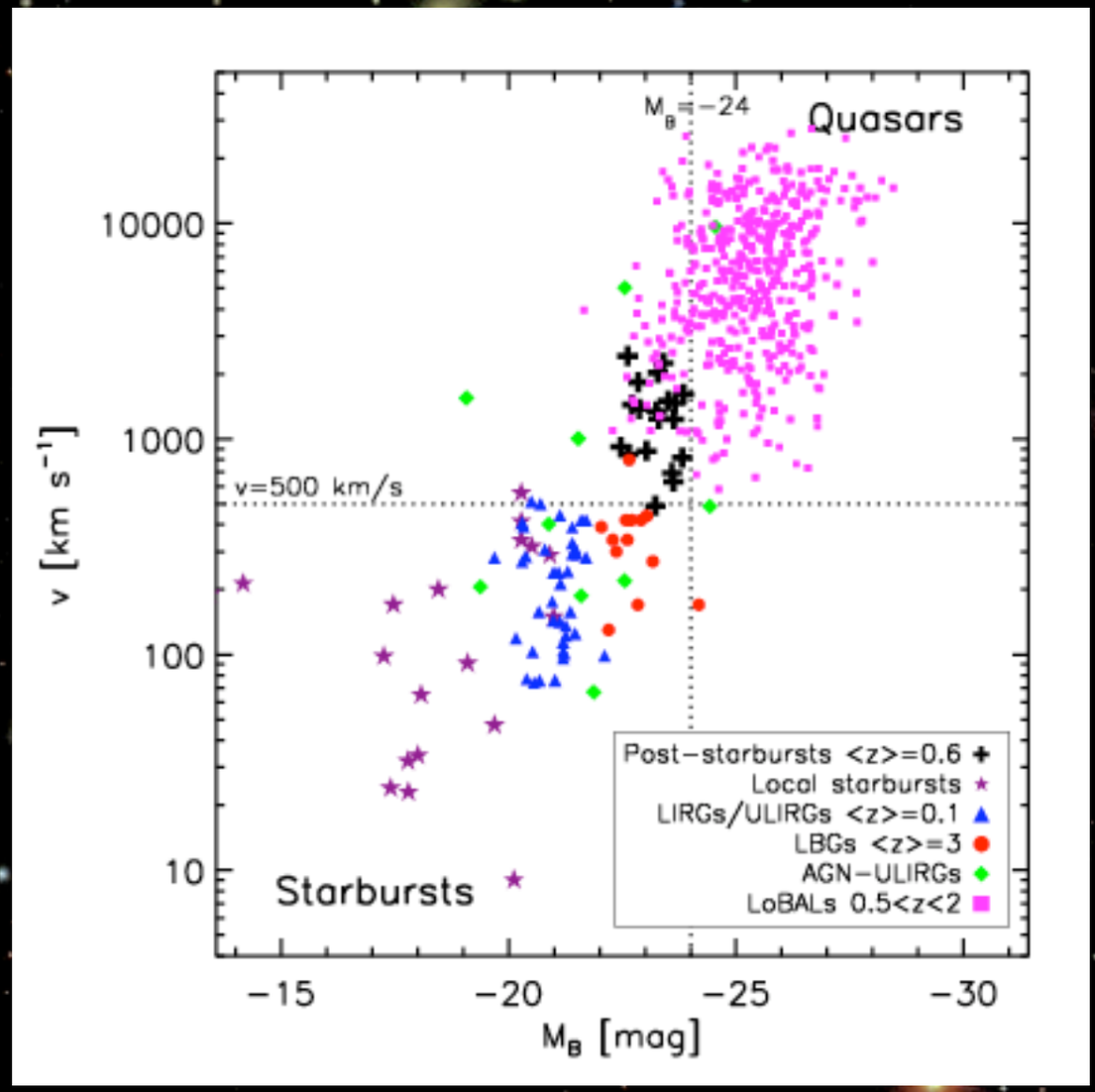


Nesvadba et al. arXiv:0809.5171v2.

Summary

We looked for signs of fossil galactic winds in 37 post-starburst (post-quasar) galaxies

- We detected blueshifted Mg II in 2/3 of the sample
- Outflow velocities are v=400 - 2000 km/s
- The velocities exceed those of starbursts and show some overlap with BAL quasars
- The outflows entrain 5 - 50% of the galaxies' baryons



Quasars are likely to have played a role in expelling the cool gas and quenching star formation