Starbursts and AGN Feedback

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How is star formation regulated?

1) Supernovae and winds from massive stars

2) Accreting black holes (????)

One way to study feedback is to look at its most dramatic manifestations: galactic scale gaseous outflows -- "galactic winds"

"Energy-driven" Winds

Basic superbubble theory -- Chevalier & Clegg 1985, Heckman et al. 1990

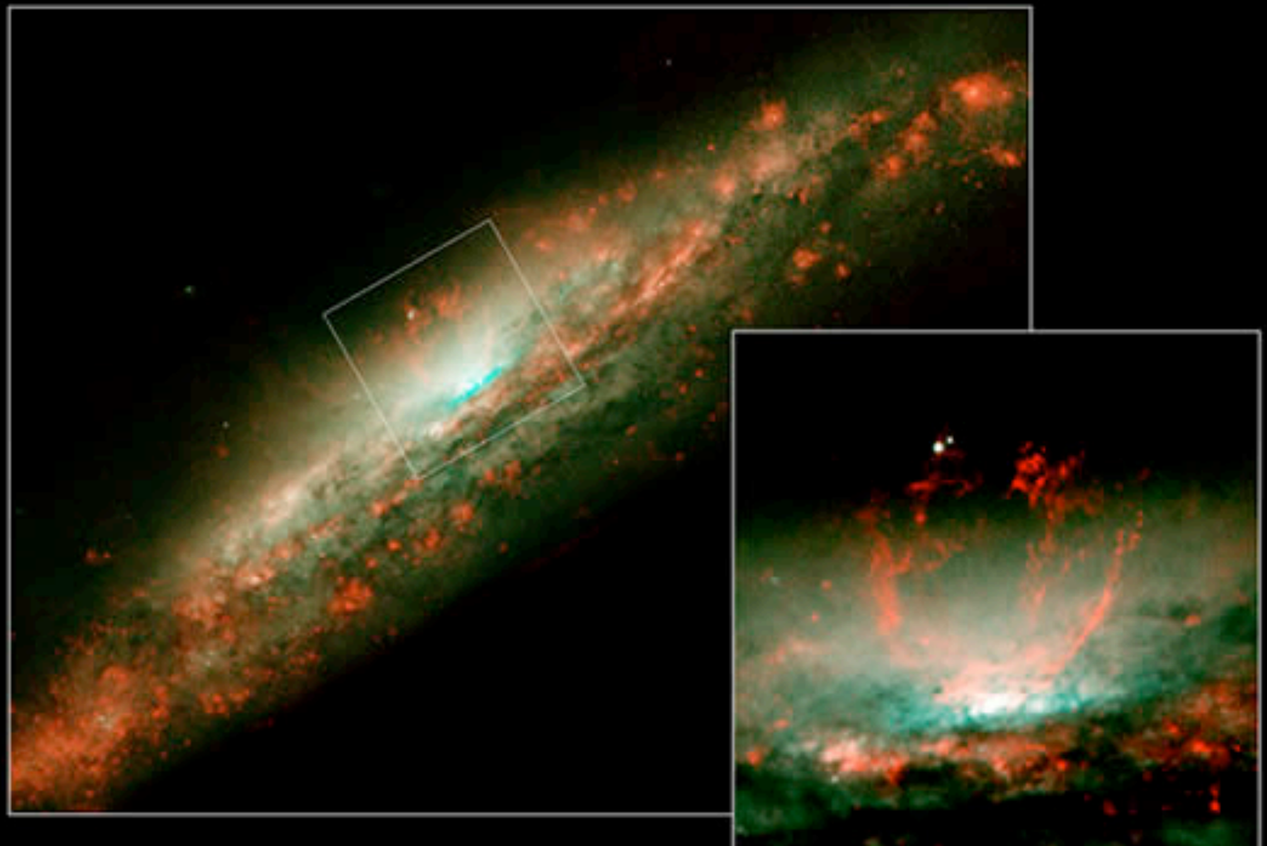
1) Core-collapse SNe and massive star winds create a super-heated ($T \sim 10^7$-10^8 K) bubble of metal-enriched plasma in the star forming region

2) The gas is too hot to cool effectively via line radiation, and it is out of pressure equilibrium with its surroundings. It expands and sweeps up cool ambient ISM.

3) When the bubble reaches several disk scale heights it accelerates and fragments allowing the hot gas to vent into the halo

4) The hot gas expands freely into the halo and entrains fragments of the cool shell. These clouds are accelerated by the wind's ram pressure to velocities of a few 100 km/s.

(See Todd Thompson's talk on momentum driven winds)



Galaxy NGC 3079
Hubble Space Telescope • WFPC2
NASA and G. Cecil (University of North Carolina) • STScI-PRC01-28

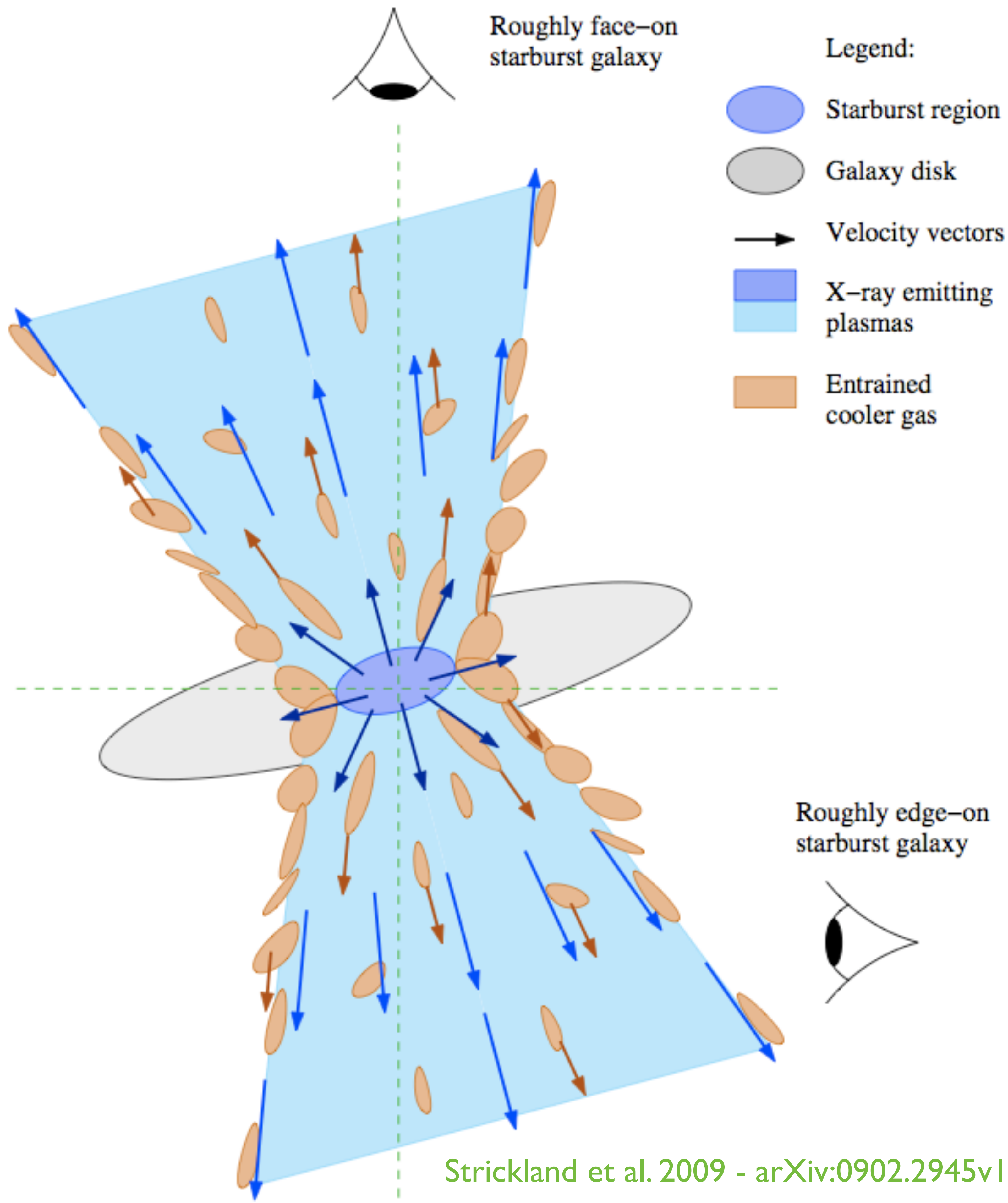
The Anatomy of a Galactic Wind

The Engine: hot (10^7-10^8 K) gas in the star forming region
- diffuse hard X-rays (2-10 keV)

Coronal phase gas (10^5-10^7 K) in the wind
- diffuse soft X-rays (0.1-2 keV)
- OVI absorption

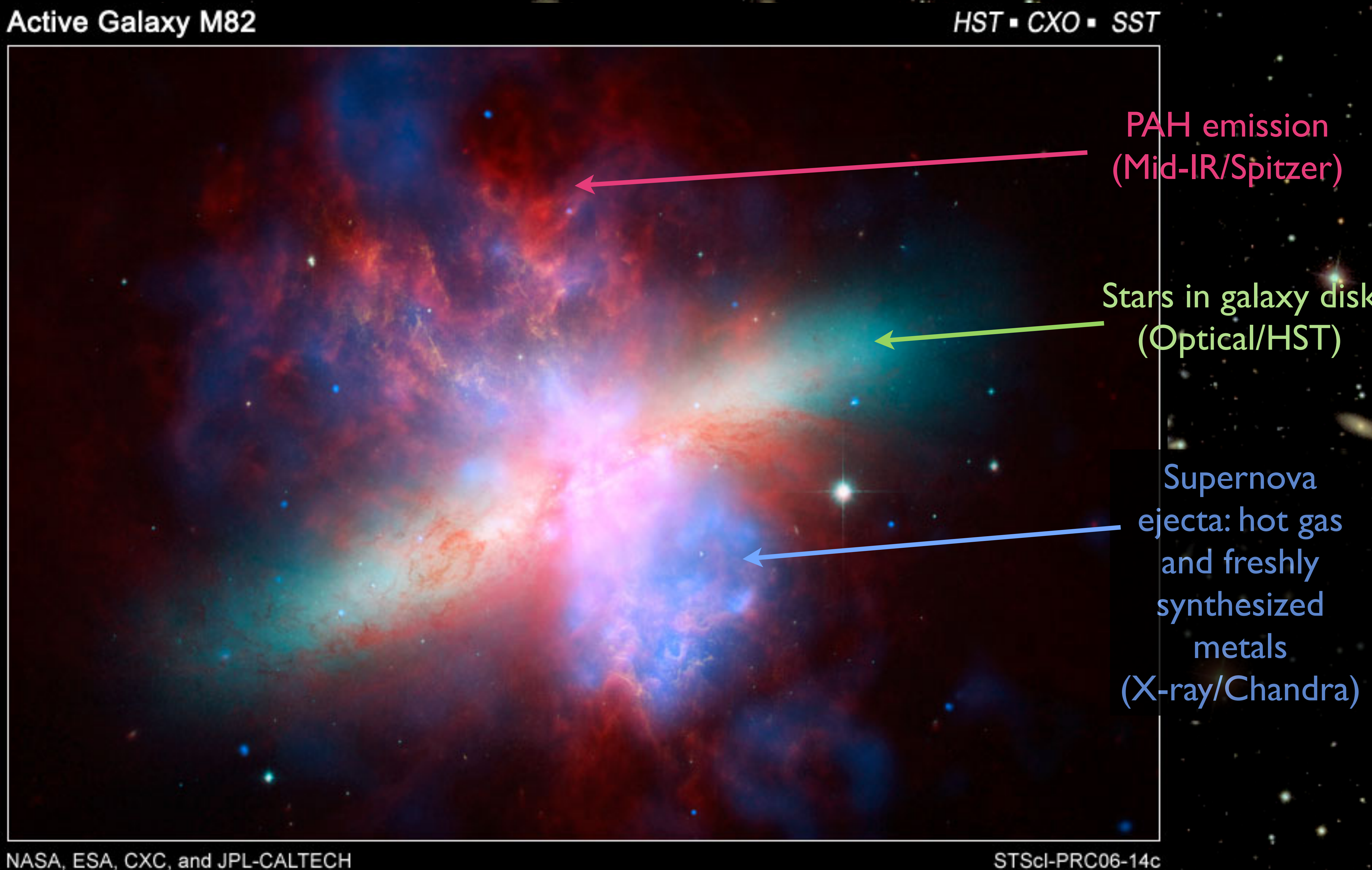
Warm entrained gas (at hot/cold interface regions)
- Hα, [NII] emission
- Mg II, Si II, CII absorption

Cool entrained gas & dust
- HI, CO, H_2 emission
- PAH (dust) emission
- Na I, Ca I, Mg I absorption

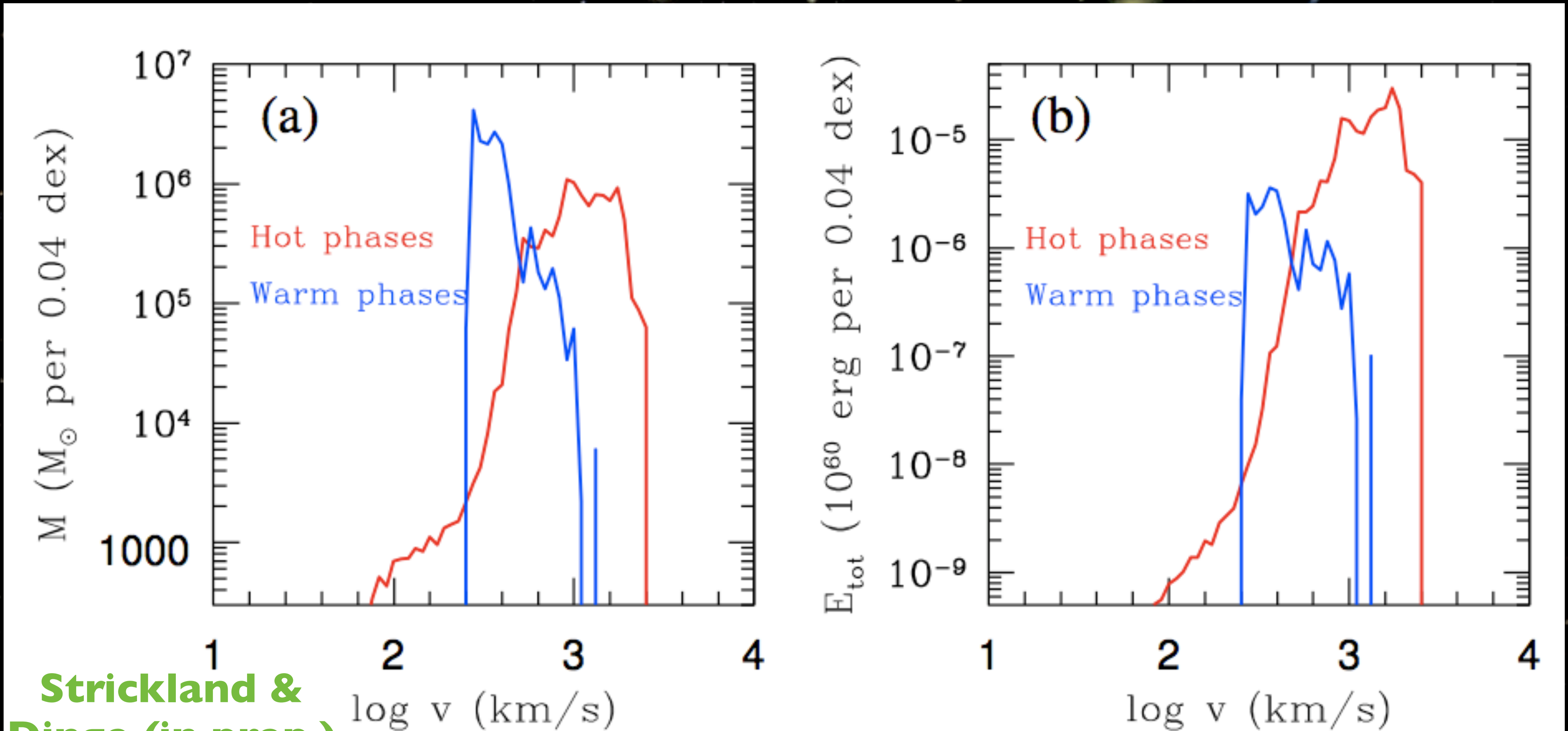


Strickland et al. 2009 - arXiv:0902.2945v1

The Multi-phase wind in M82



Simulations suggest that the different phases have different kinematics



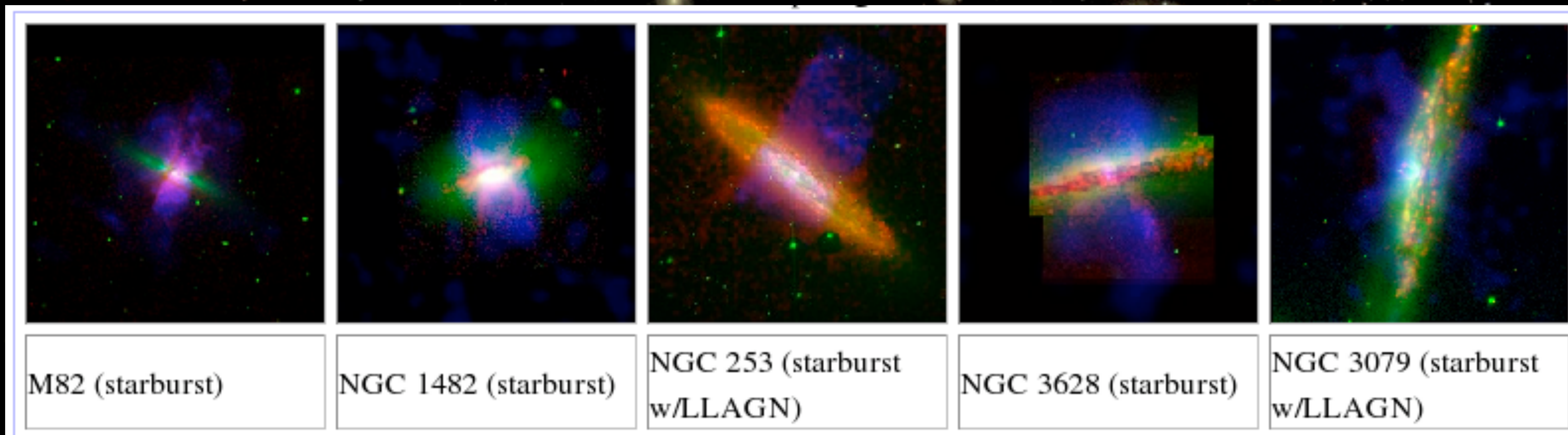
Strickland & Dinge (in prep.)

The hot phase carries 90% of energy and metals and has a velocity of ~1000 km/s

The warm/cool phase carries most of the mass and has a velocity of ~300 km/s

Nearly all observations to date are of the warm phase!

Observations of Galactic Winds: Imaging



Strickland et al. 2004: Hα, R-band, X-ray

Mostly soft X-ray and Hα

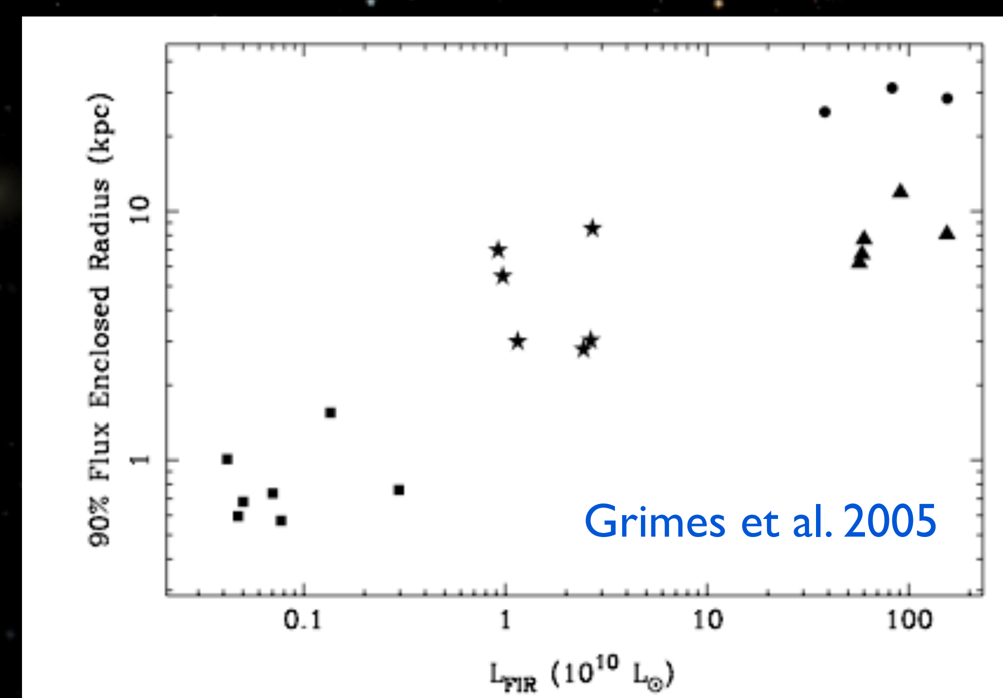
Limited to ~20 nearby starbursts

(emission ∝ density^2 & density in wind is low!)

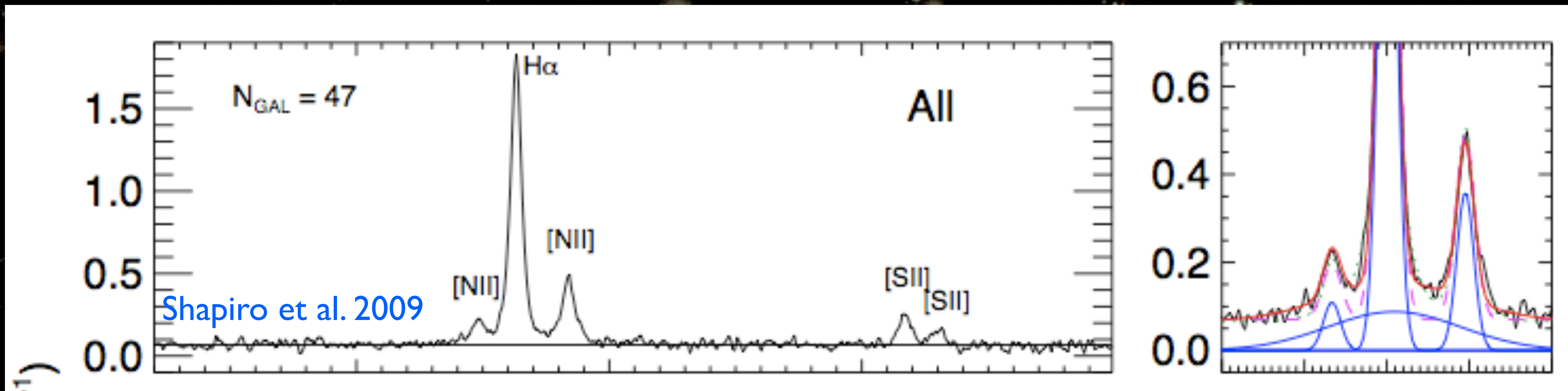
Results:

Wind luminosity ∝ SFR

Wind size ∝ SFR

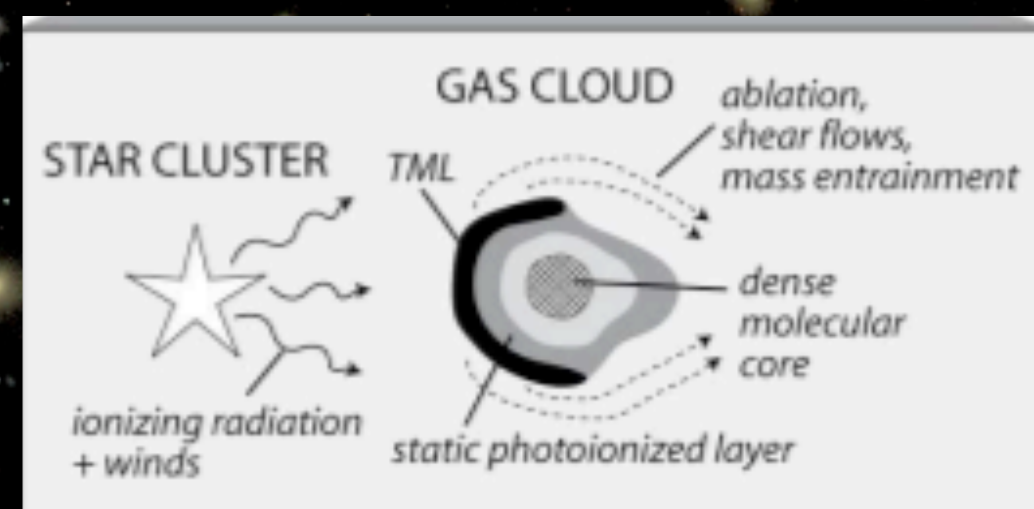


Observations: Hα spectroscopy



Westmoquette et al. 2009 -- broad Hα emission component (FWHM~300 km/s) identified in IFU spectra of local starbursts -- due to turbulent mixing layers?

Shapiro et al. 2009 -- also seen in z~2 disk galaxies (SINS sample)

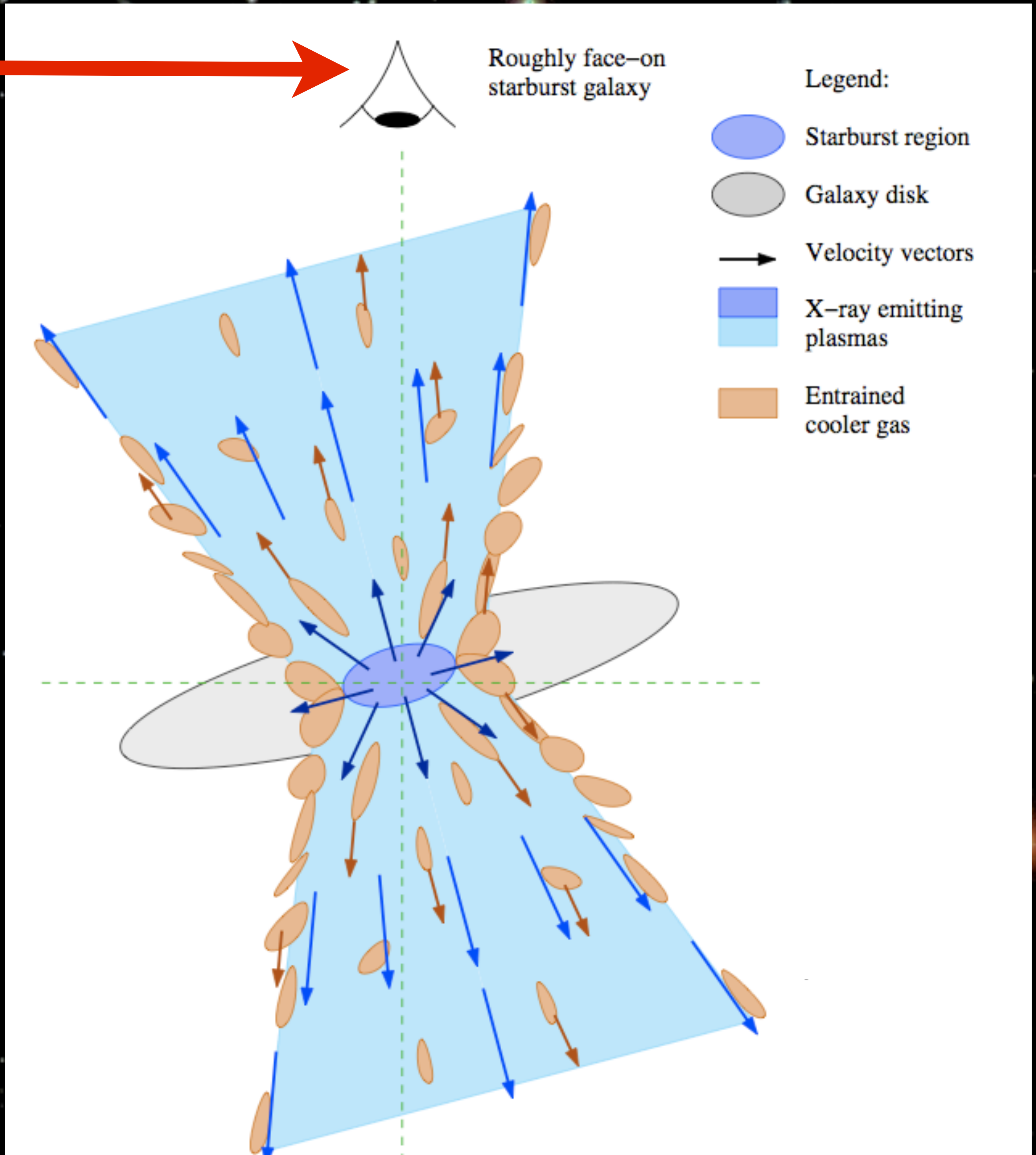


Are we seeing "mass loading" of hot wind?

Observations: absorption line spectroscopy

Look for gas absorption lines that are blueshifted relative to the starlight

Linearly sensitive to column density along line of sight



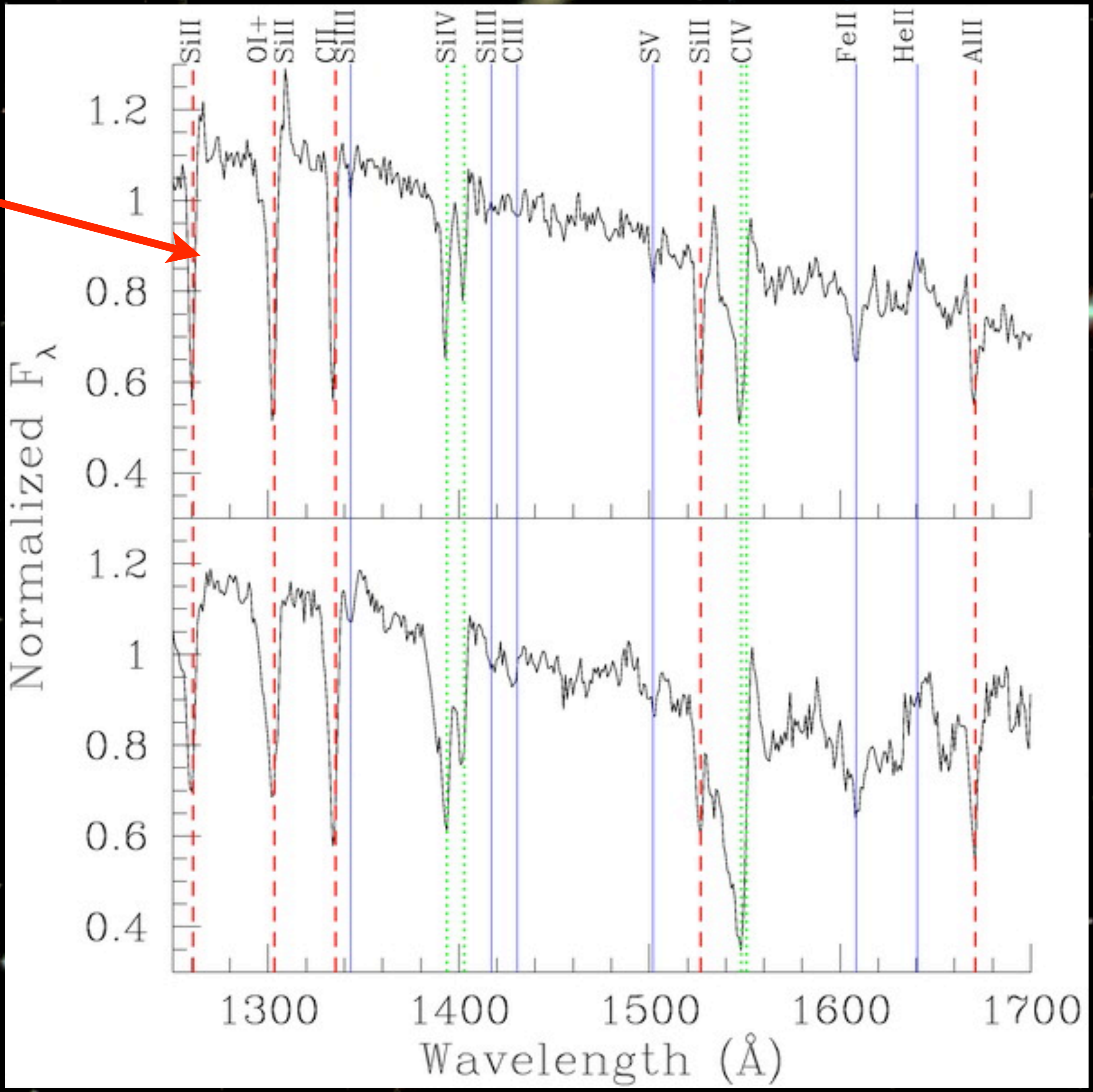
Strickland et al. 2009 - arXiv:0902.2945v1

Observations: UV absorption line spectroscopy

Large numbers of low-ionization ISM absorption lines in the vacuum UV

Composite KECK spectrum of z=3 Lyman Break Galaxies (Shapley et al. 2003)

Composite STIS spectrum of local young massive star clusters (Schwartz & Martin 2006)



Galactic winds with velocities of ~50-500 km/s are ubiquitous in starburst galaxies at low and high redshift!

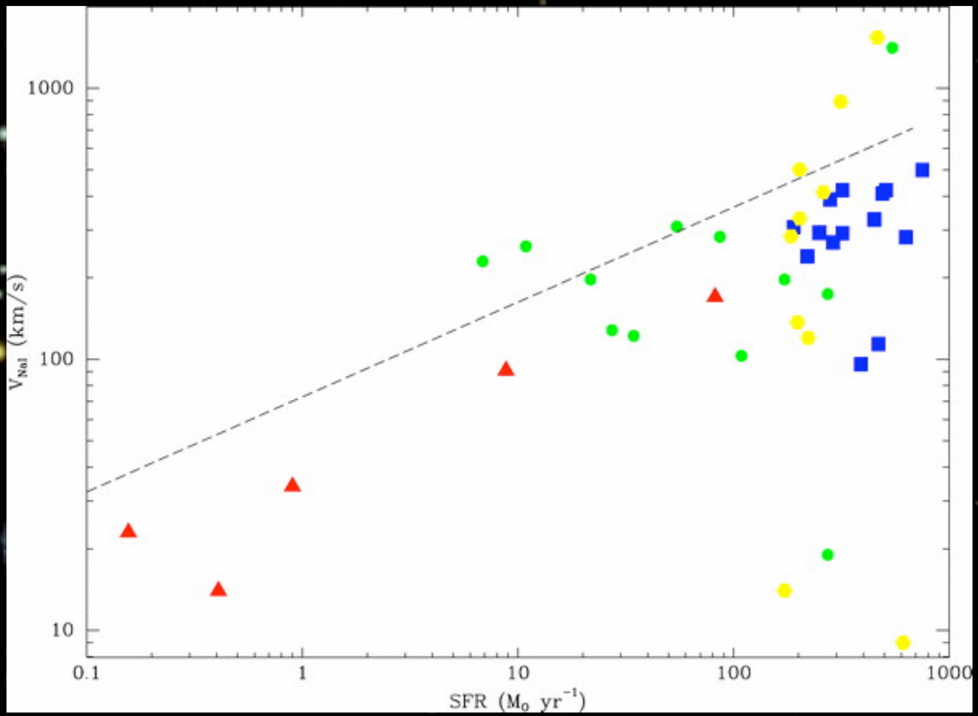
(see also Weiner et al. 2008)

Observations: optical absorption line spectroscopy

Na I "D" λλ5890, 5896
- ionization potential = 5.1 eV (less than H)
- associated the warm neutral phase of the ISM, dust

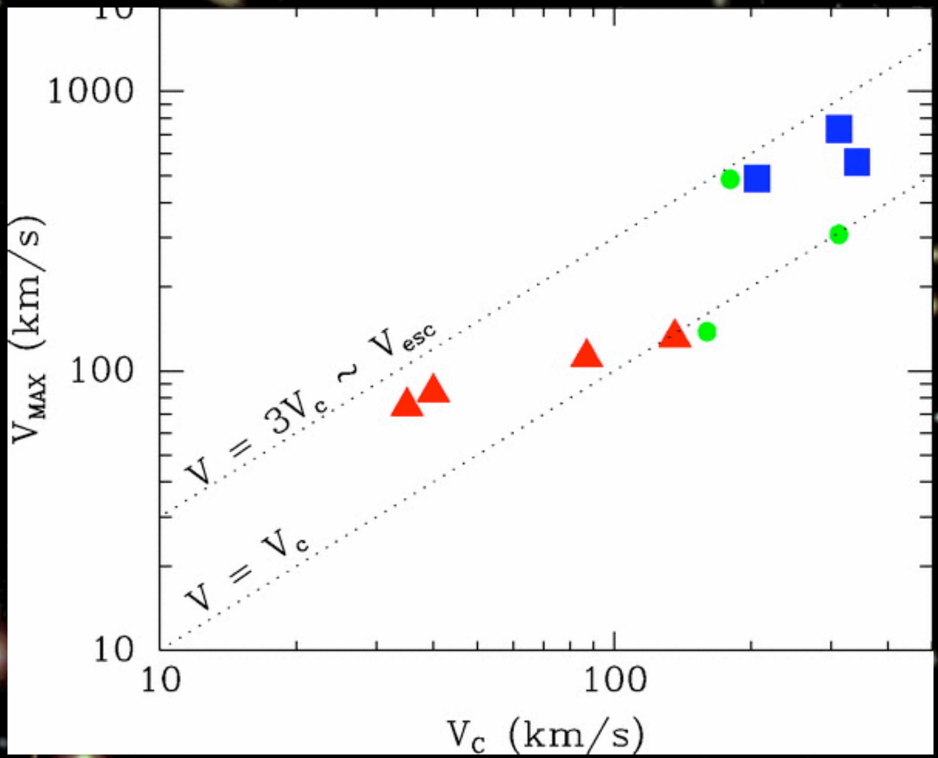
Martin 2005, Rupke et al. 2005
* Outflows present in ~80% of U/LIRGs
* Outflow velocity increases with SFR and galaxy mass
* Cool gas moving near escape velocity in galaxies of *all* masses
* Estimates of mass/energy of warm phase (but subject to uncertain ionization corrections)

Outflow Velocity



Star Formation Rate

Outflow Velocity



Dynamical Mass

Simulations of Galactic Winds: Cosmological

The Problem:

- SPH particles too big (>10^6 $M_\odot$) to capture relevant physics!

- SN occur in dense regions where cooling time is short -- energy is radiated away before the bubble can expand

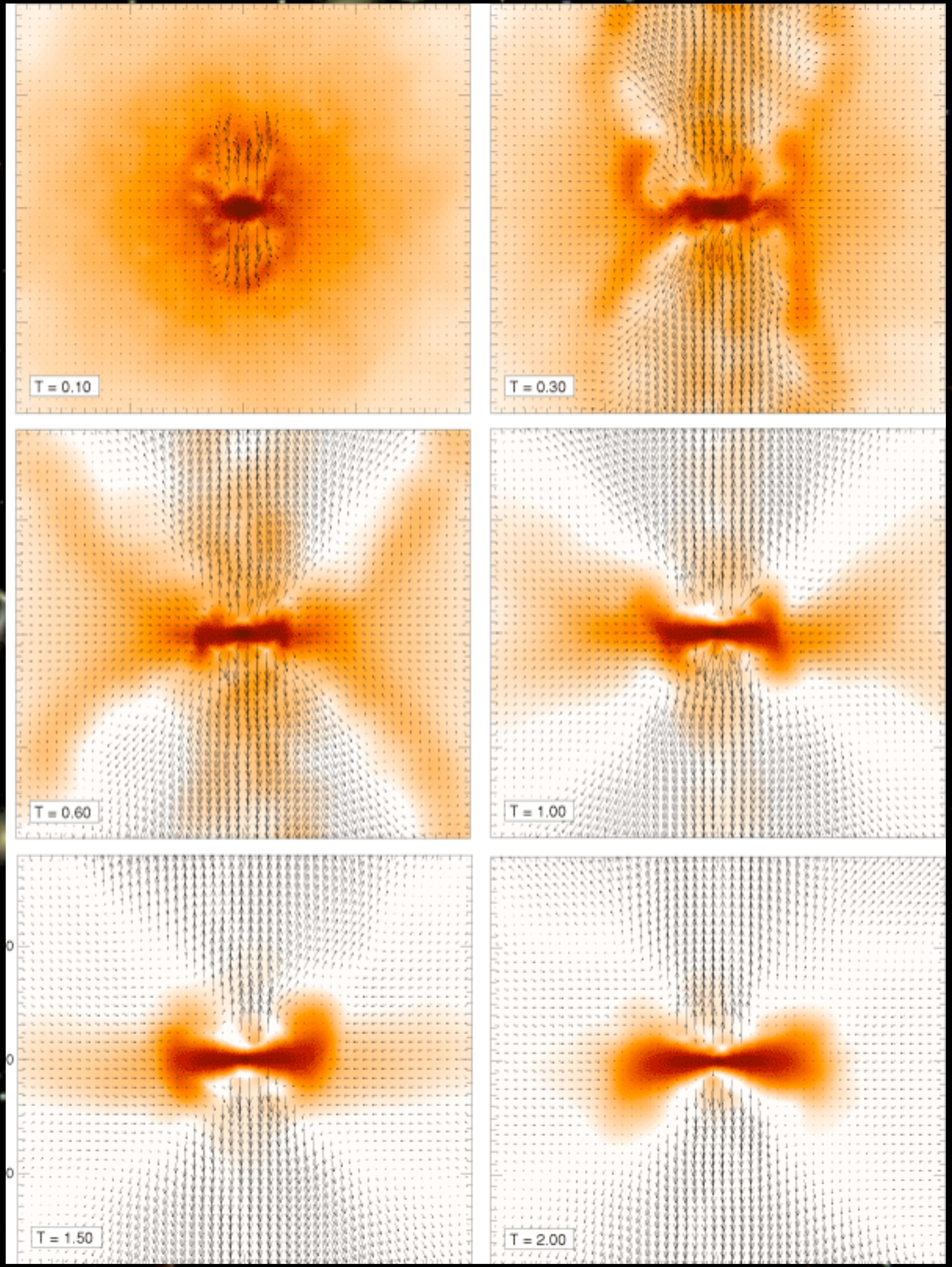
Common fixes:

1) Turn off cooling for a fixed time after a stars form (blast wave solution)

2) Give gas particles kinetic "kicks"

Issues:
- hot and cold phases coupled together
- need to input velocities by hand

Subgrid prescriptions need to be better constrained/motivated by observations

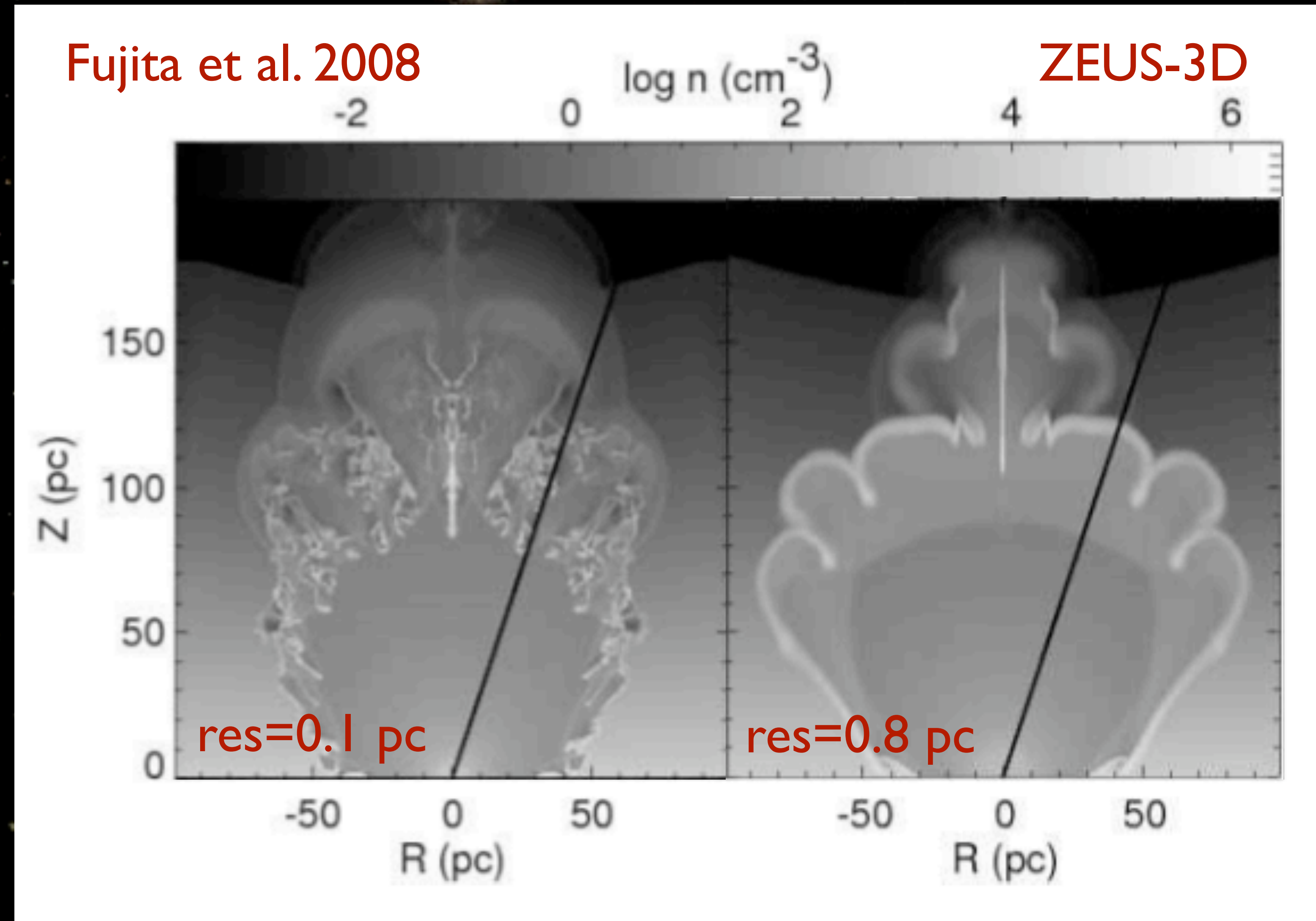


Gadget: Springel & Hernquist 2003

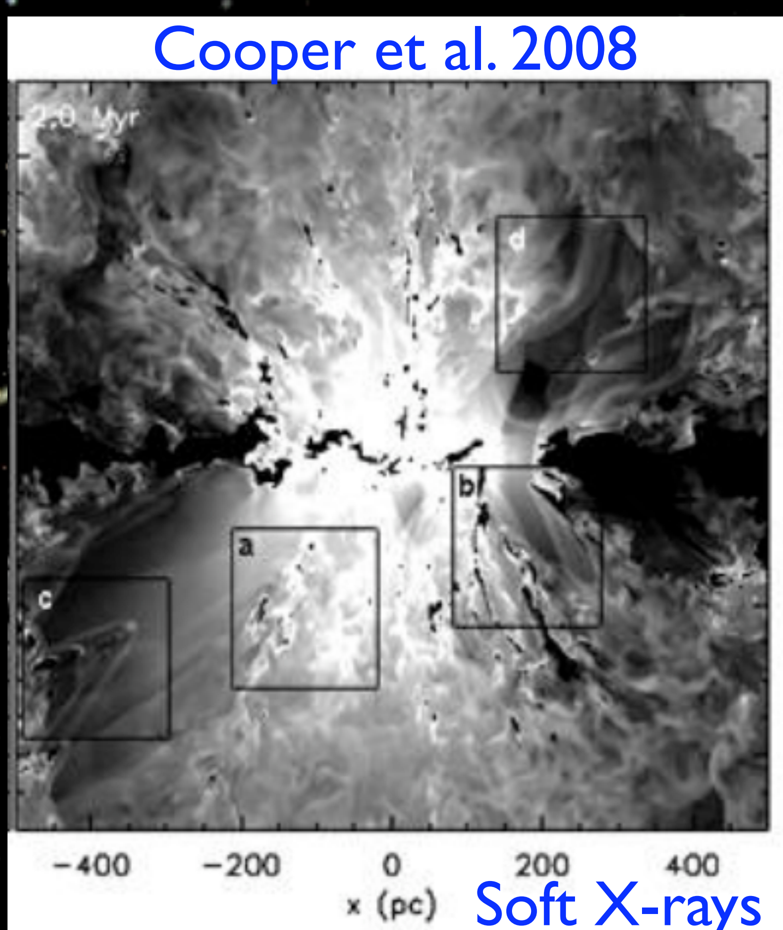
Simulations

Resolution is critical to modeling shell fragmentation during disk blow out

- can explain broad Na I absorption troughs (FWHM~350 km/s)



3d simulations with an inhomogeneous disk ISM result in even more small scale structures



Summary

Galactic winds are ubiquitous in galaxies with $\Sigma_{SFR} > 0.1\ M_{\odot}\ yr^{-1}\ kpc^{2}$

Galactic winds are highly multi-phase

- The hot phase dominates the energy budget and contains most of the metals
- The cool phase dominates the mass budget

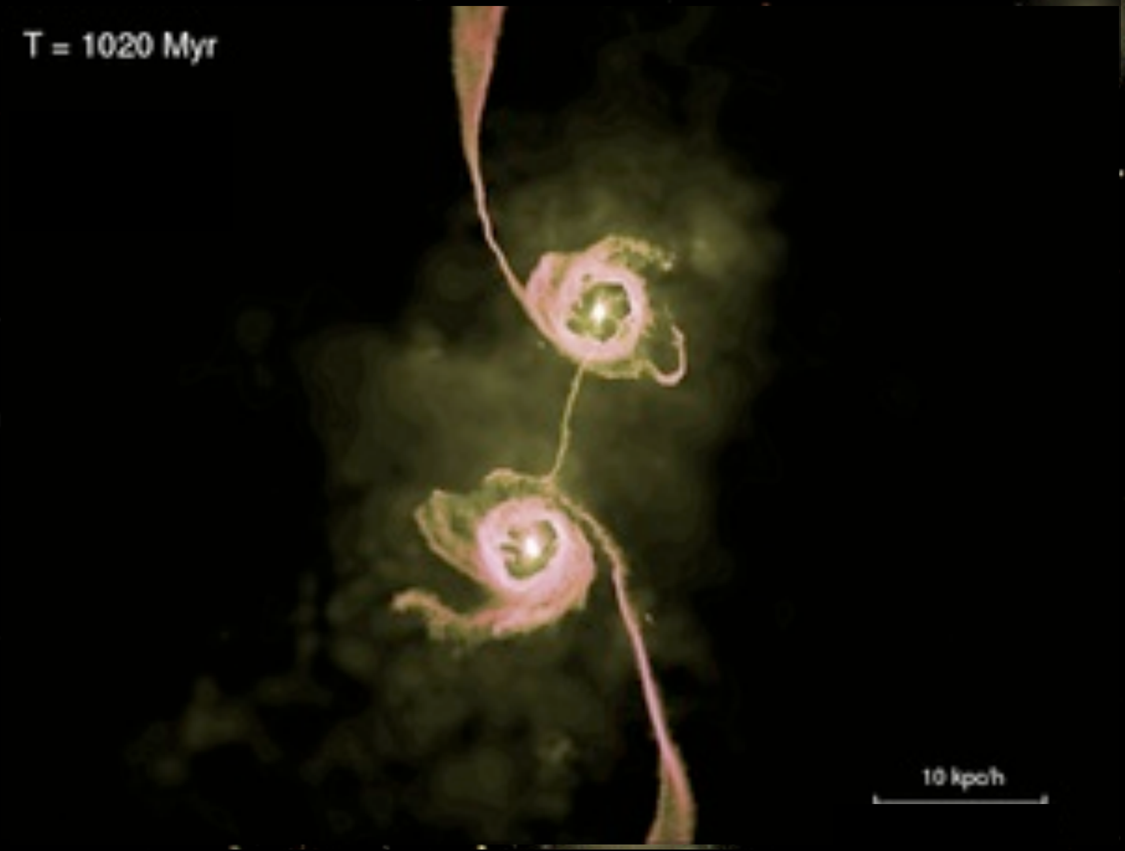
Nearly all studies to date have focused on the warm/cool phase

We need detailed studies of both phases to understand the how massive stars return energy to the ISM and how gas and metals are lost from galaxy halos

Black Hole Feedback

1) "Quasar Mode"

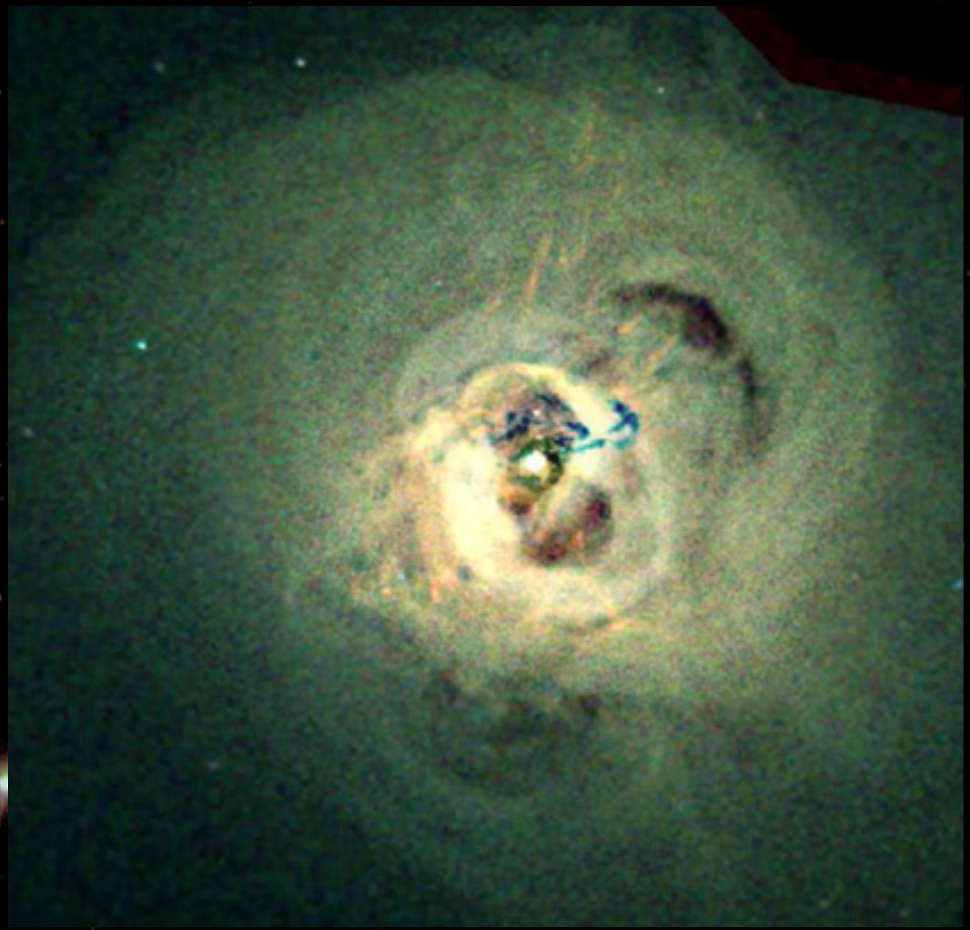
- black holes accreting at a high rate
- shuts star formation off
- physics not well understood
- limited observational evidence to date



Simulation - Springel et al. 2005

2) "Radio Mode"

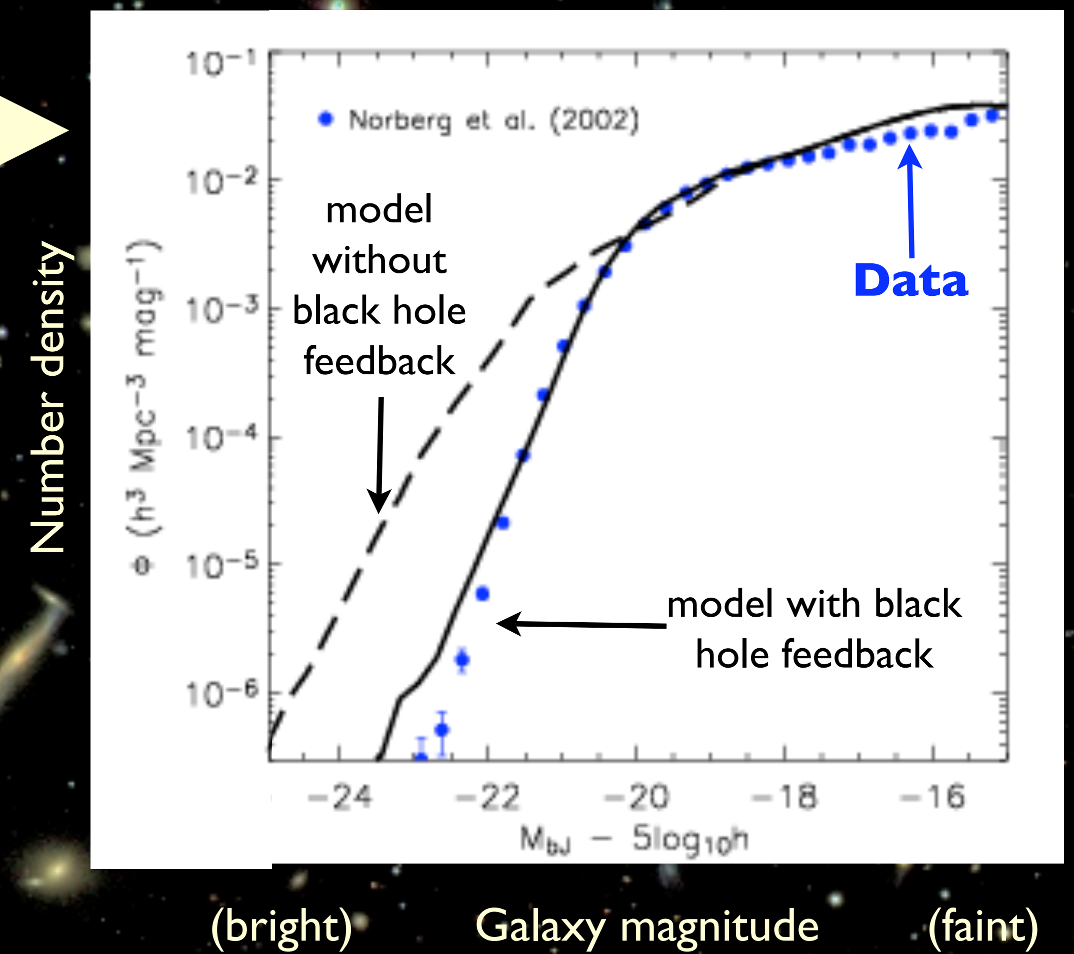
- black holes accreting at a low rate
- keeps star formation off (maintenance mode)
- mechanical energy from radio jets
- copious observational evidence



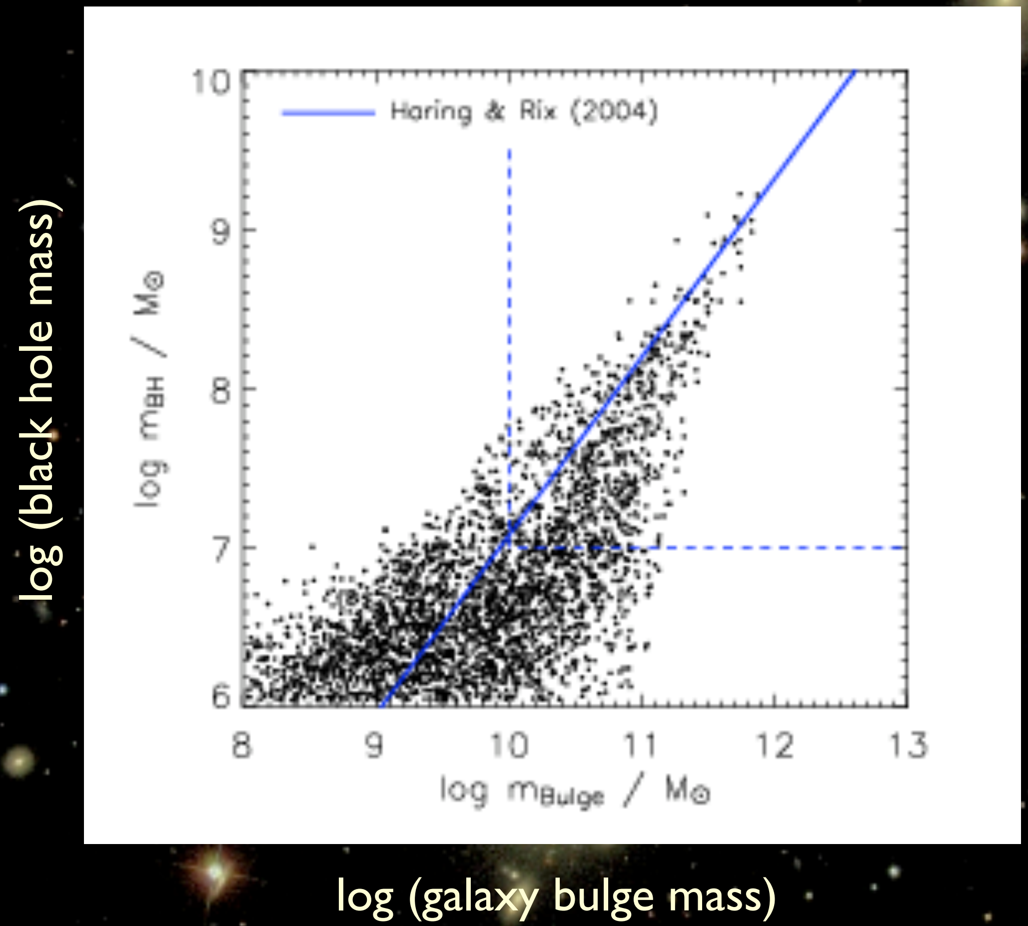
Perseus Cluster -- Fabian et al. 2005

Feedback from black holes has been invoked to solve several persistent problems in numerical simulations

It suppresses the formation of massive galaxies and improves the fit to the galaxy luminosity function

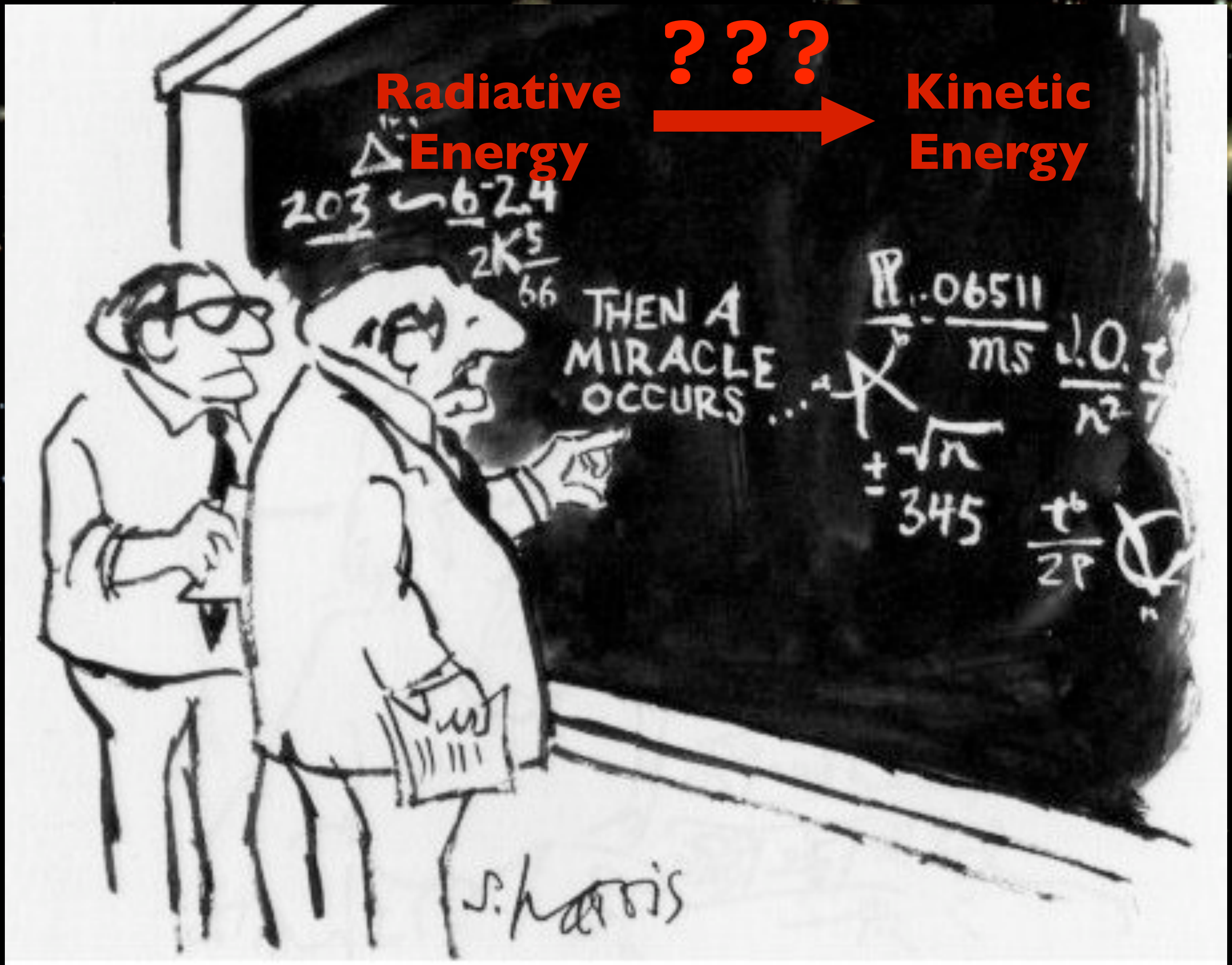


Croton et al. 2006



It provides a means of connecting the black hole and the galaxy bulge

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)

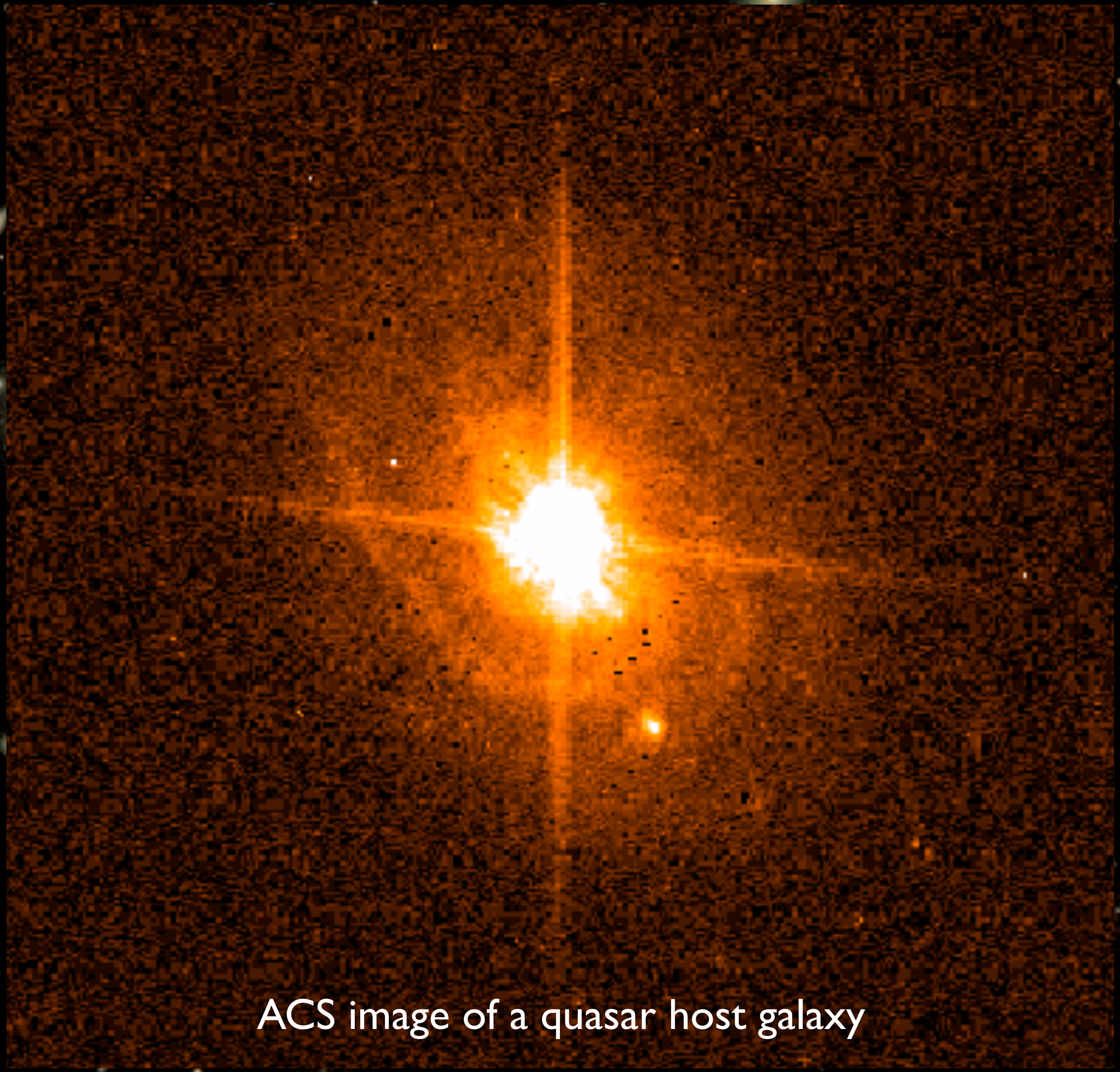
We lack a good physical model... and we have limited observational evidence

AGN-driven outflows may be difficult to detect during the optically luminous quasar phase

1) quasars outshine their host and any low surface brightness wind features

2) quasars ionize the cold gas used to trace outflows in absorption

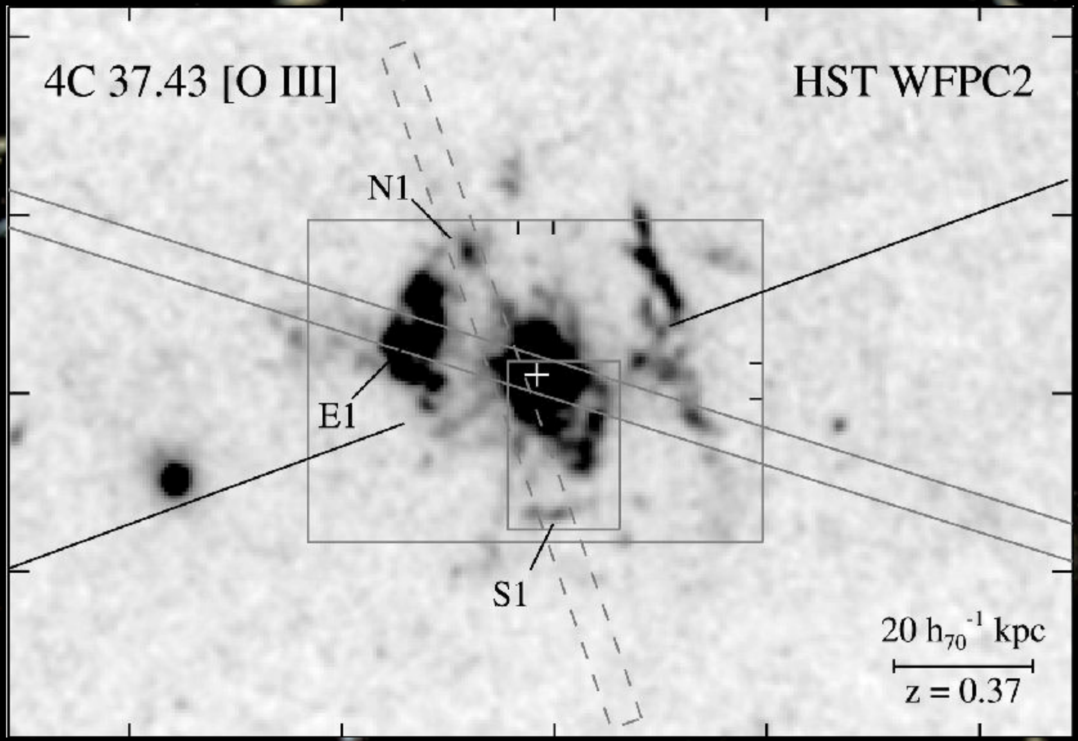
3) absorption lines are harder to interpret: a small cloud near the quasar is indistinguishable from a galaxy-wide outflow



ACS image of a quasar host galaxy

Extended [OIII] 5007 emission line nebula

Fu & Stockton 2006 ... 2009



Steep-spectrum radio-loud quasars z < 0.5

Quiescent black holes re-triggered by minor mergers (BLR and EELR has low metallicity)

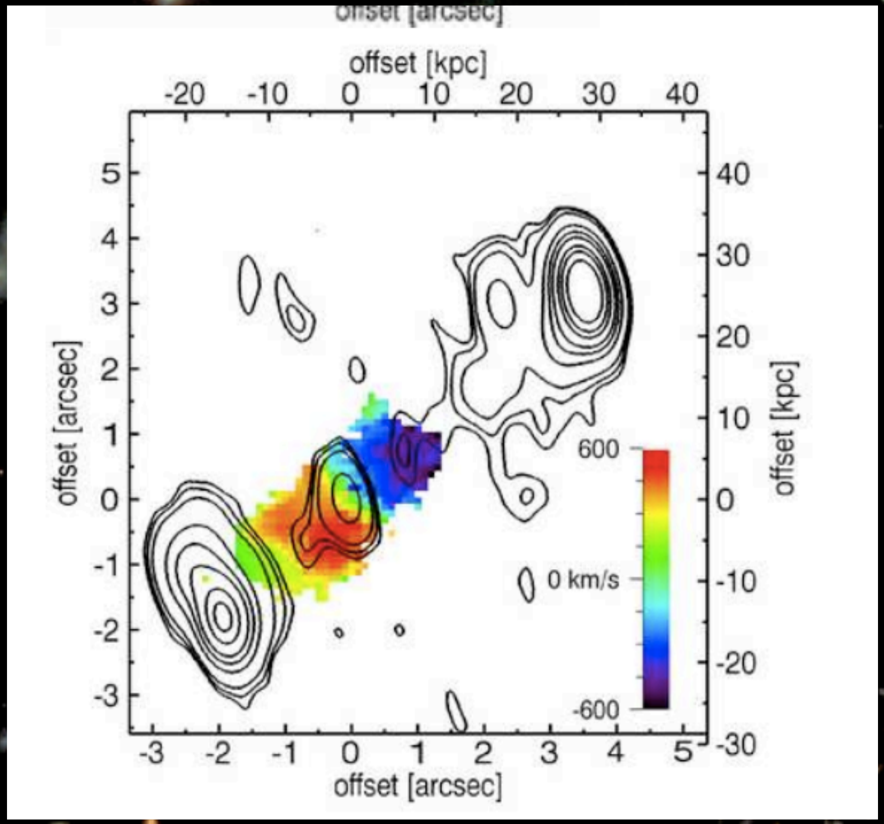
v~500 km/s

Sizes10-20 kpc -- not aligned with radio jets

Ionized gas masses ~ 10^9 - 10^{10} $M_\odot$

EELR due to a wide-angle blast wave accompanying production of radio jets?

Nesvadba et al. 2006 ... 2009



Massive z=2 radio galaxies

v~800 km/s

Sizes ~10 x 30 kpc

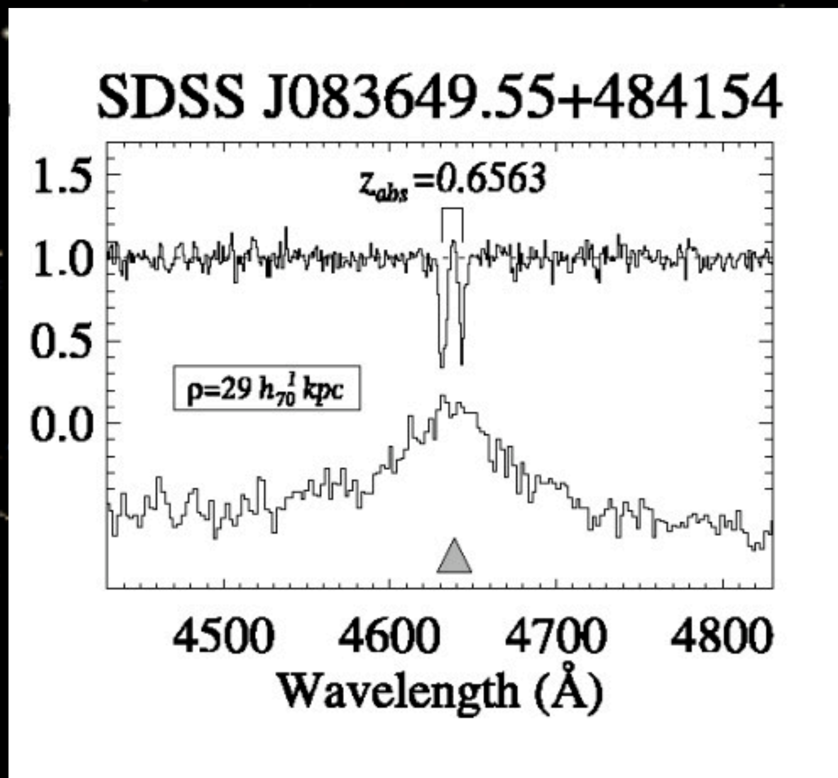
aligned with radio jet

Ionized gas masses ~ 10^{10} $M_\odot$

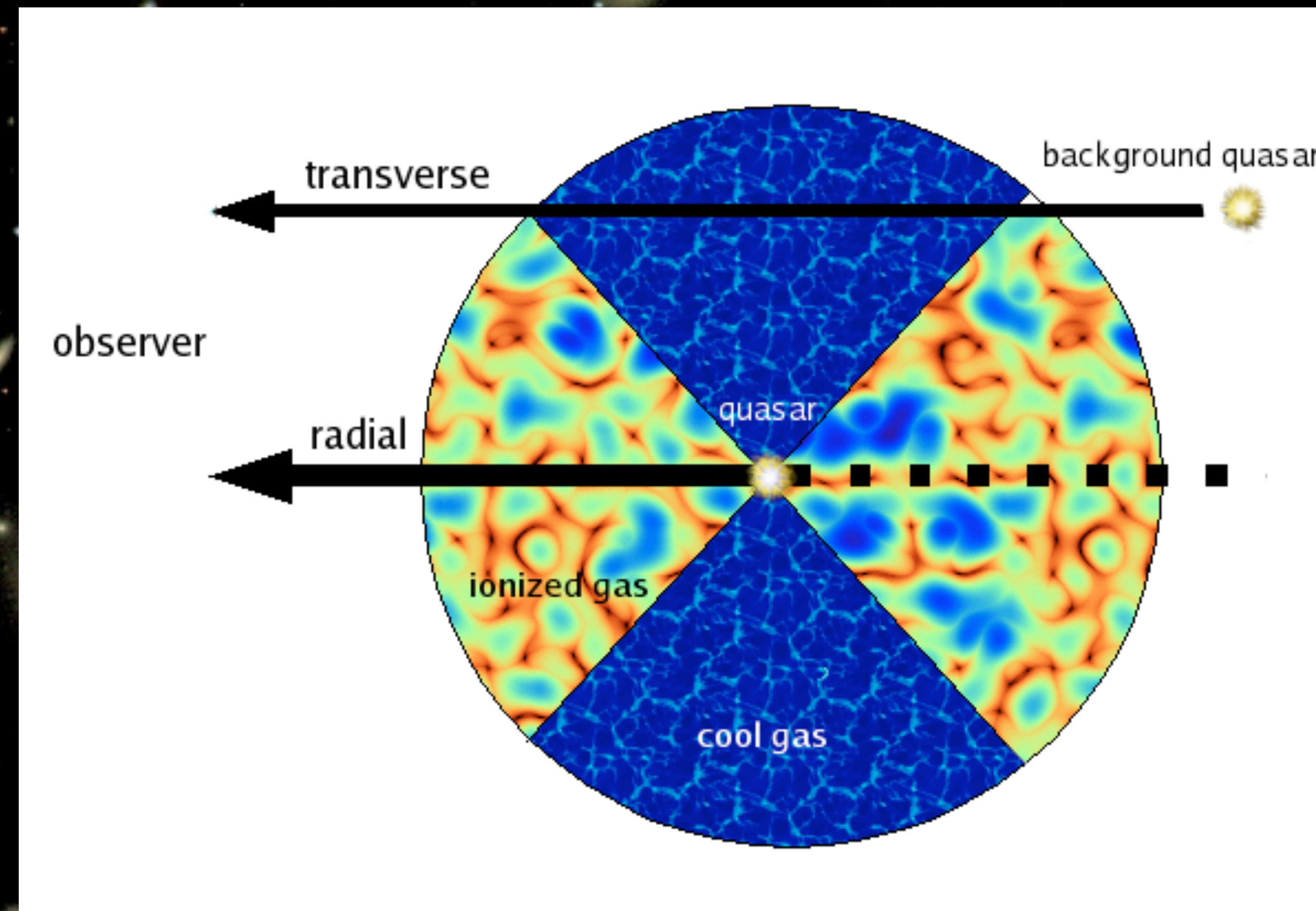
KE ~10^{60} ergs!

Powered by mechanical energy from jets

Observations of close quasars pairs:



Mg II - Bowen 2006



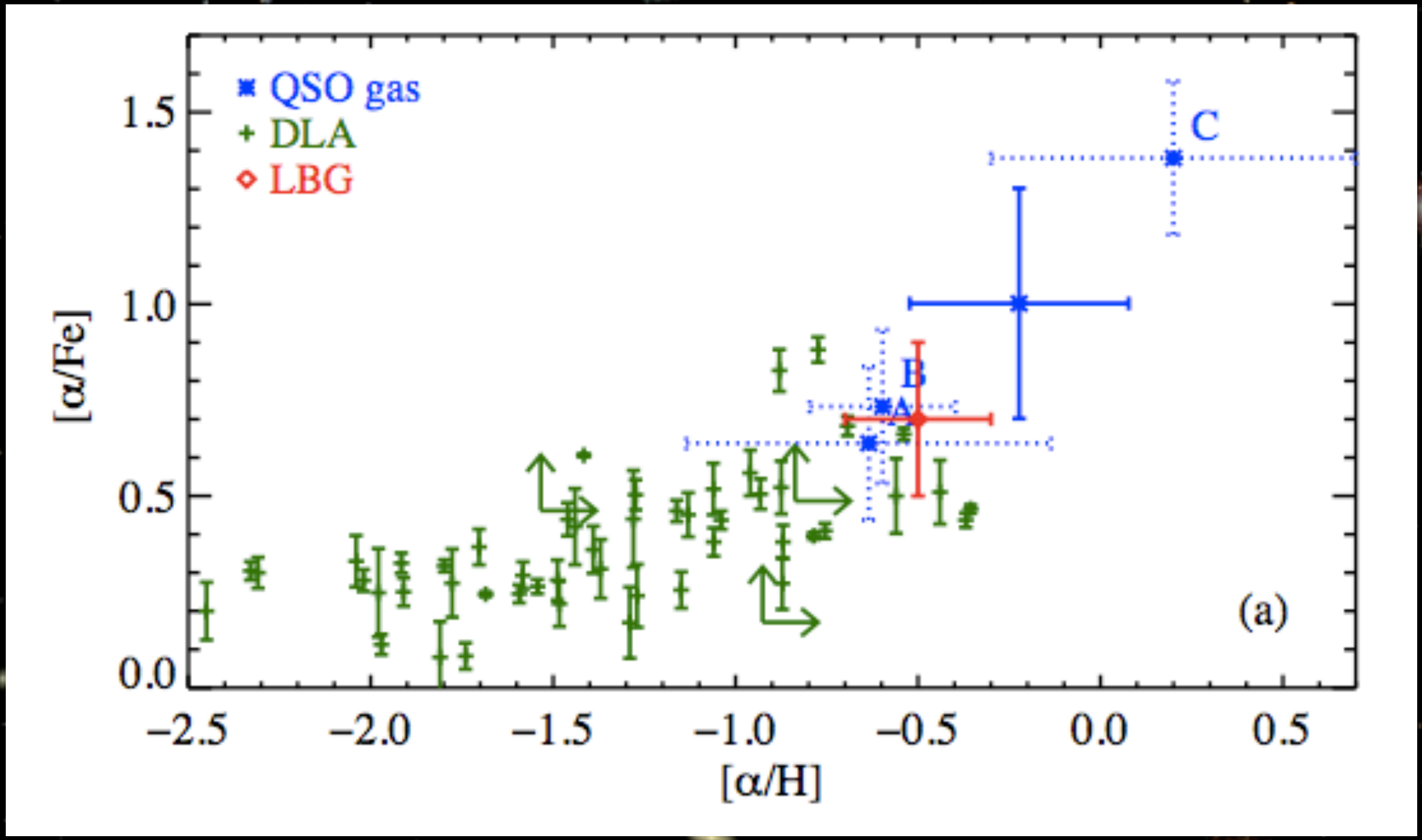
Advantages
- gas shielded from quasar's ionizing radiation
- distance of gas from quasar well constrained

Disadvantages
- Not many close pairs!!
- Need statistics to infer global covering

Observations of close quasars pairs:

Hennawai et al. 2008: 6/8 absorbers at R < 150 kpc show optically thick HI absorption
-lots of gas at large radii!!

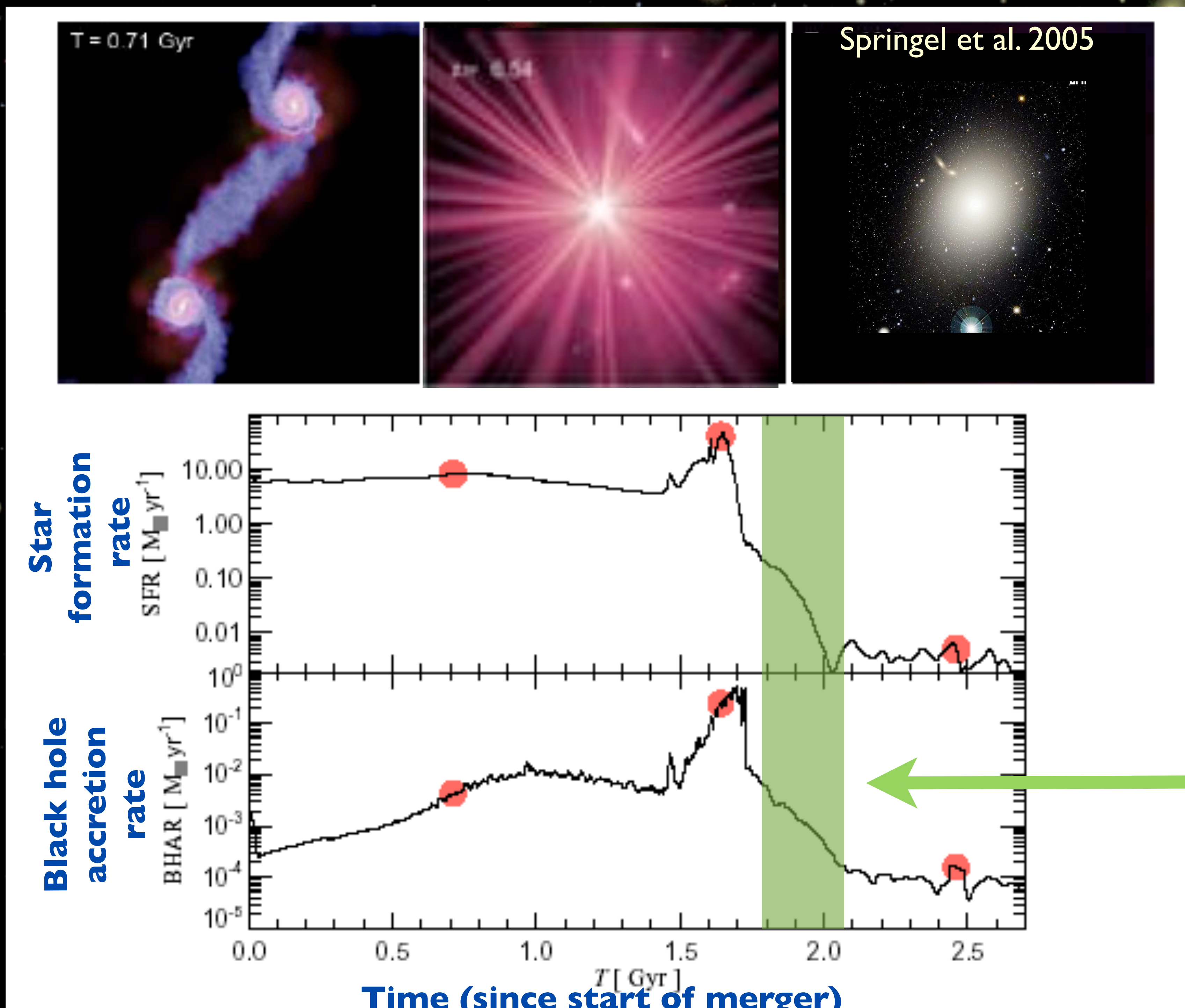
Prochaska & Hennawi 2009
- near solar metallicity and N/O, enhanced α/Fe
- outflow origin for the gas



R	= 108 kpc
N_H	= 4×10^{20} cm^{-2}
M_{wind}	= 3×10^{11} $M_\odot$
v	= +750 km/s
E_{wind}	= 3×10^{60} ergs

Energy of outflow is 10x higher than energy available from a starburst

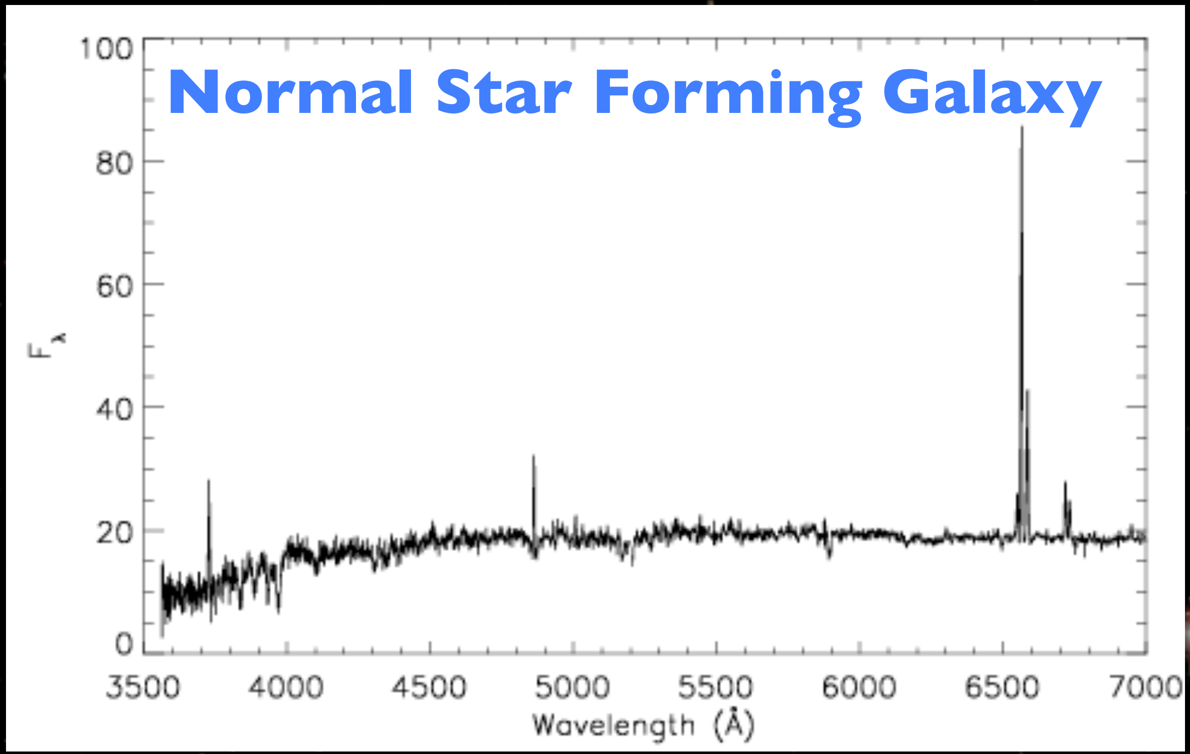
The Search for Fossil Galactic Winds

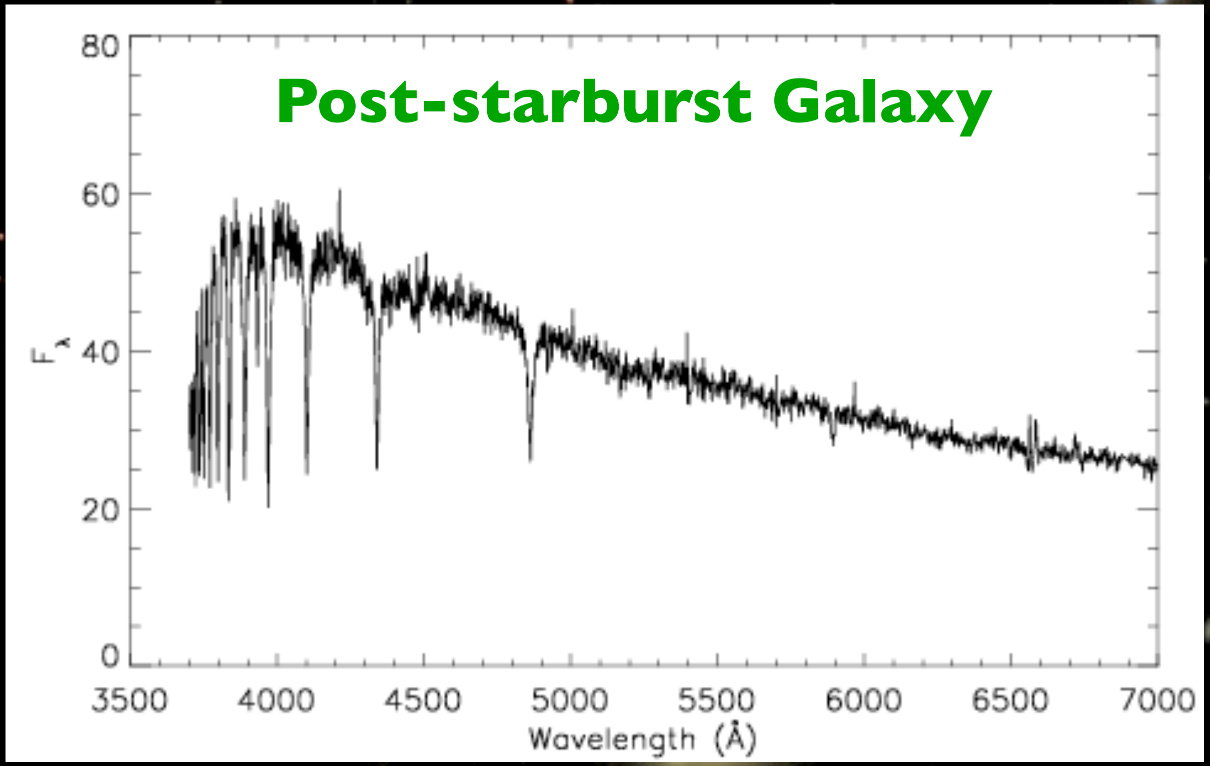


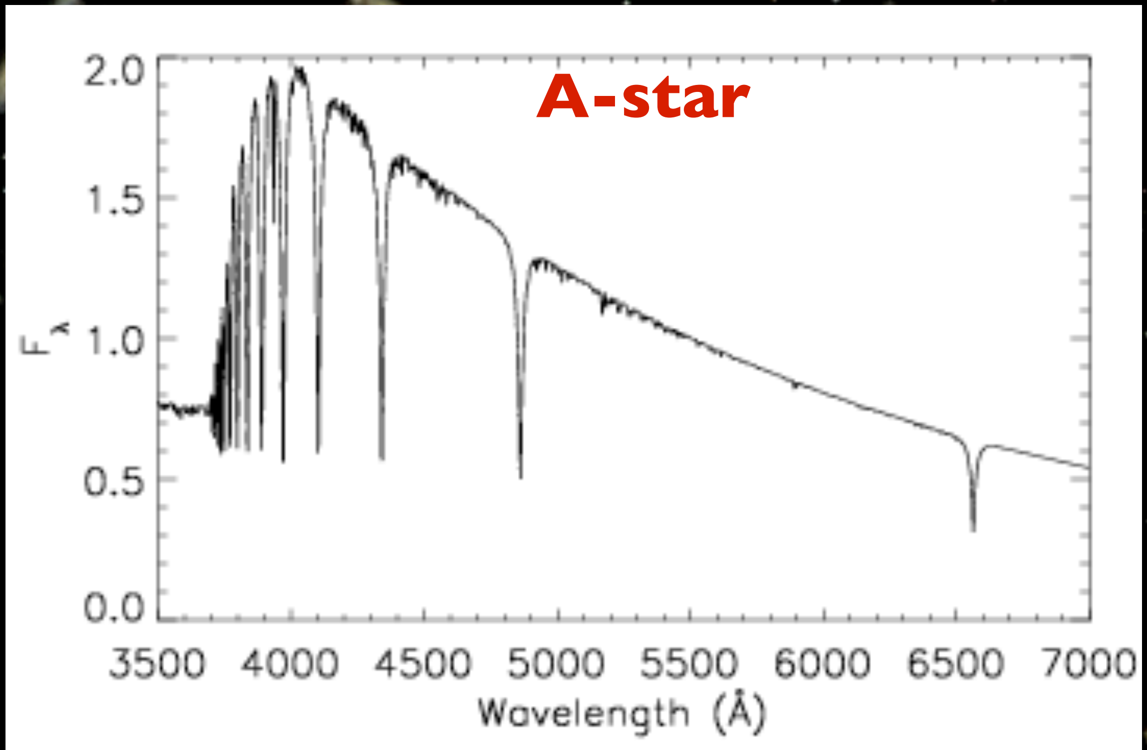
Post-starburst

A better time to look for AGN-driven outflows may be shortly after the quasar has faded from view, when the galaxy is in a post-starburst phase

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



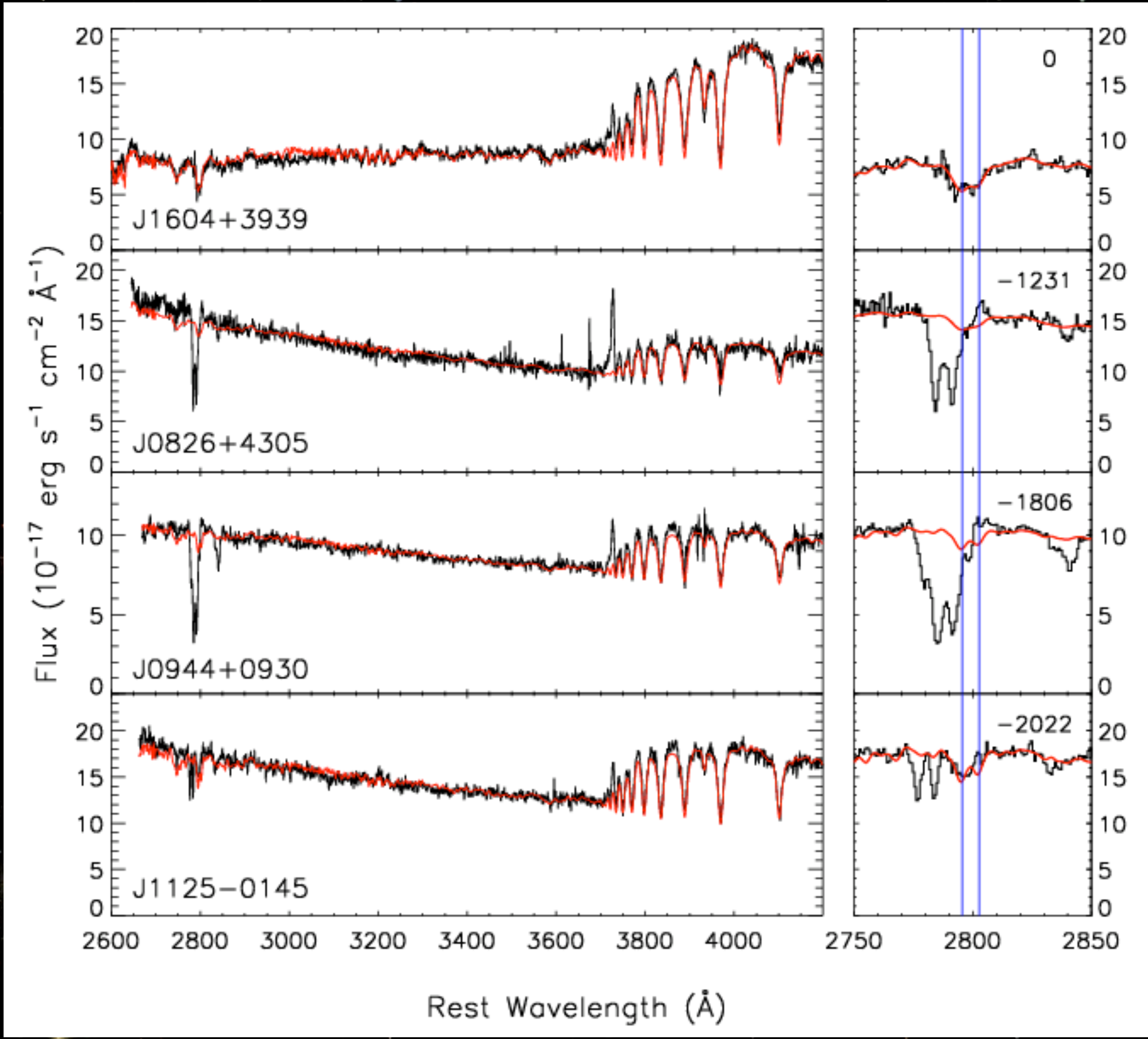




Our goal: look for quasar-powered outflows in massive z~0.5 post-starbursts using the Mg II (2796, 2803) ISM absorption lines

We detect strong ISM absorption in 24/37 galaxies

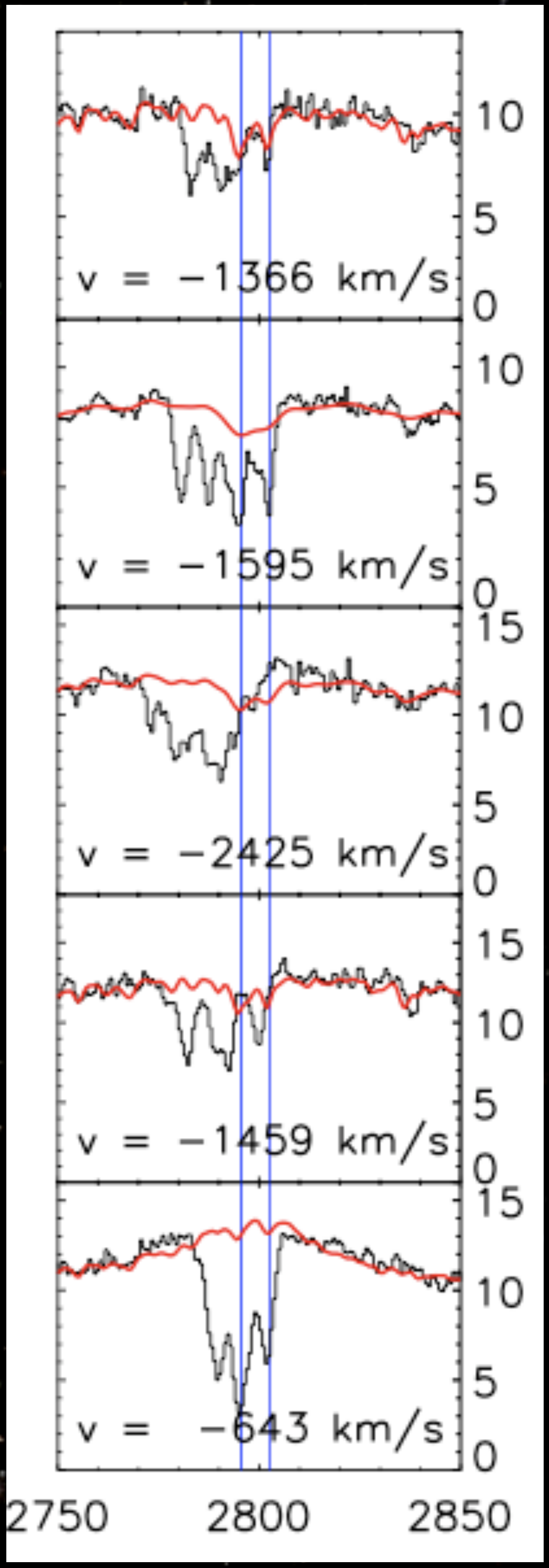
Strongly blueshifted!



Fossil Galactic Winds

starburst, t=0 Myr

post-starburst, t=100 Myr



How far does the wind get?

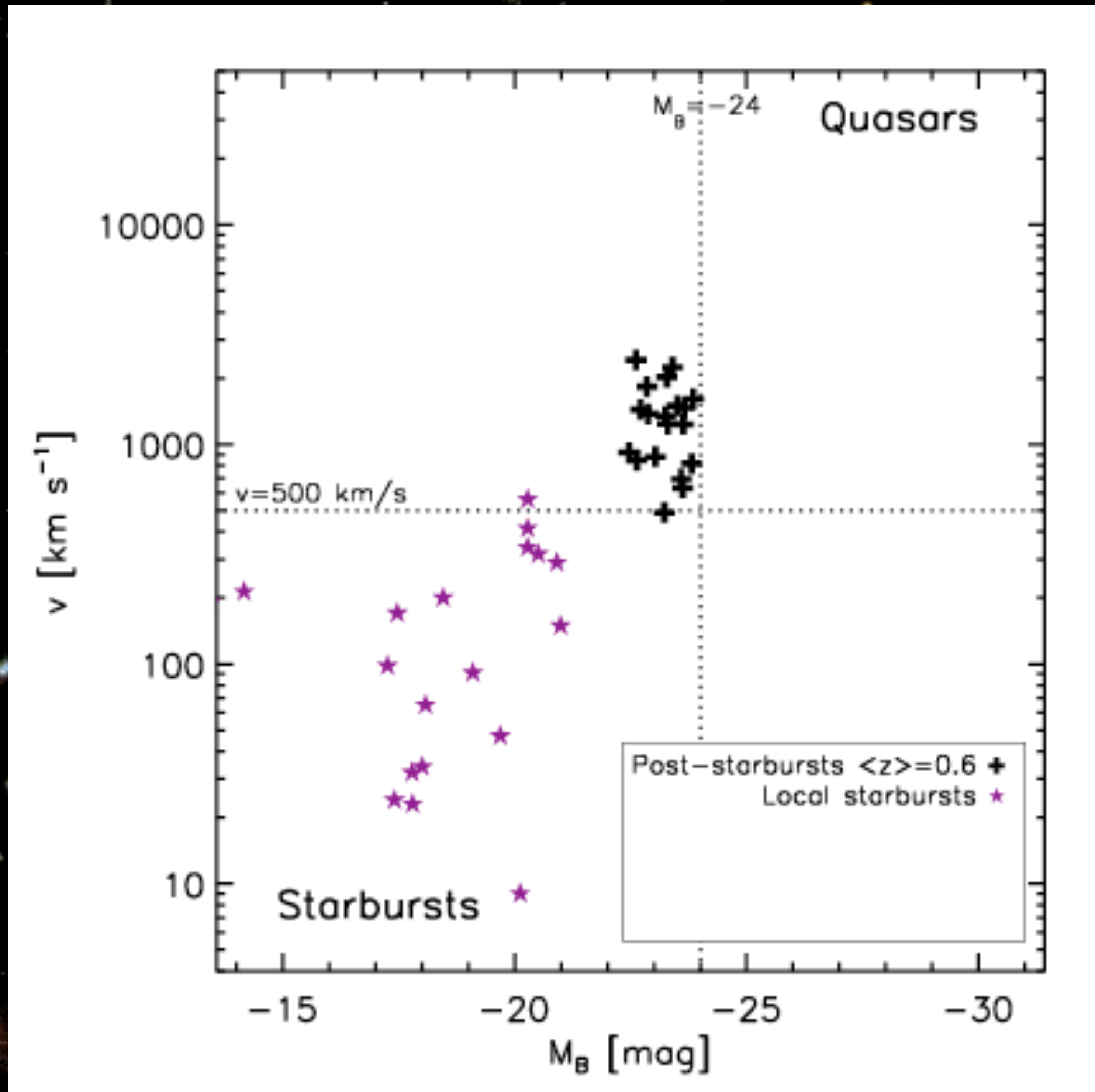
d = v t

= 1000 km/s x 100 Myr

= 100 kpc

Are these outflows really powered by quasars?

Outflow velocity

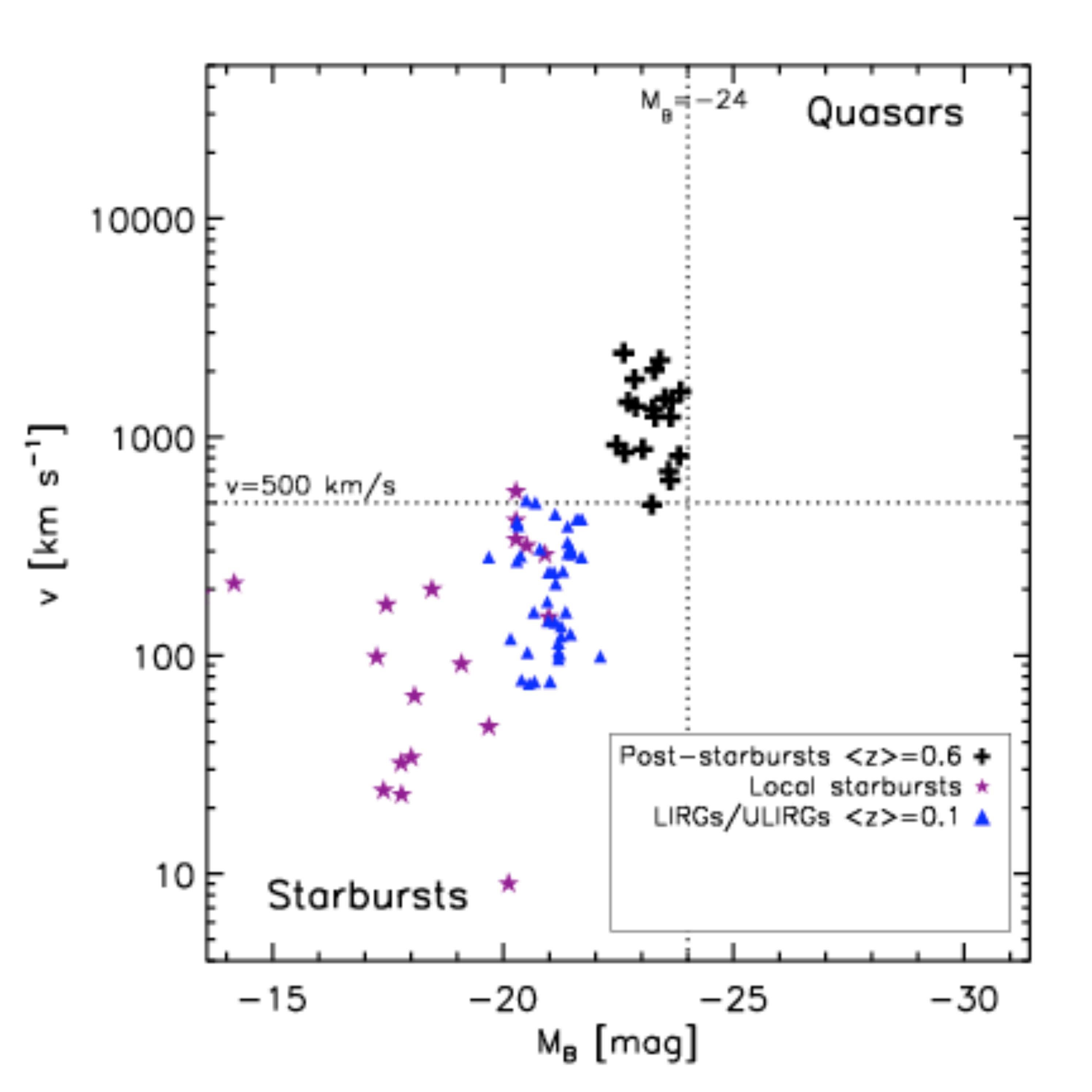


B-band Magnitude

Local Starbursts Schwartz & Martin 2004, 2006

Are these outflows really powered by quasars?

Outflow velocity

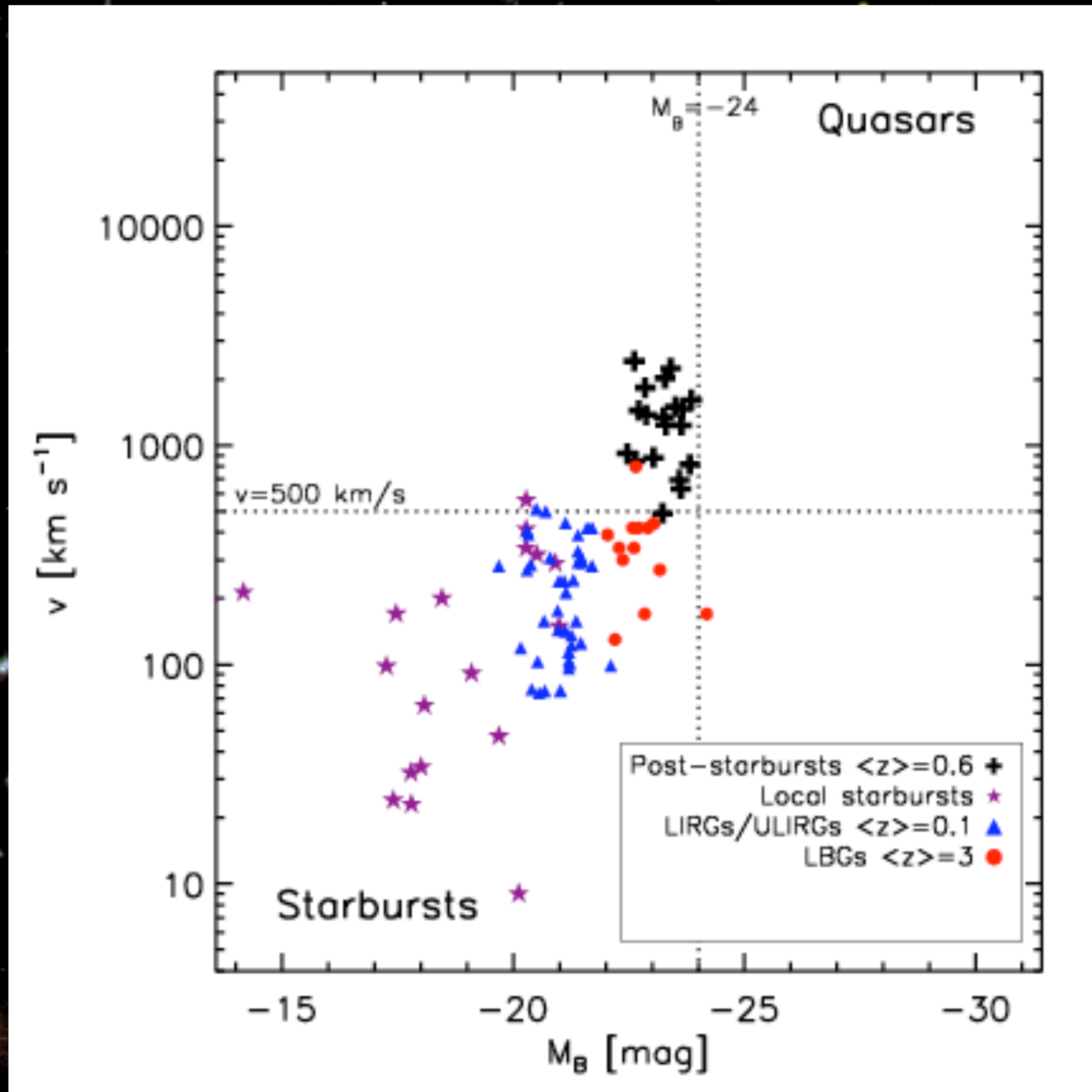


B-band Magnitude

LIRGs/ULIRGs
Rupke et al. 2005
Martin 2005

Are these outflows really powered by quasars?

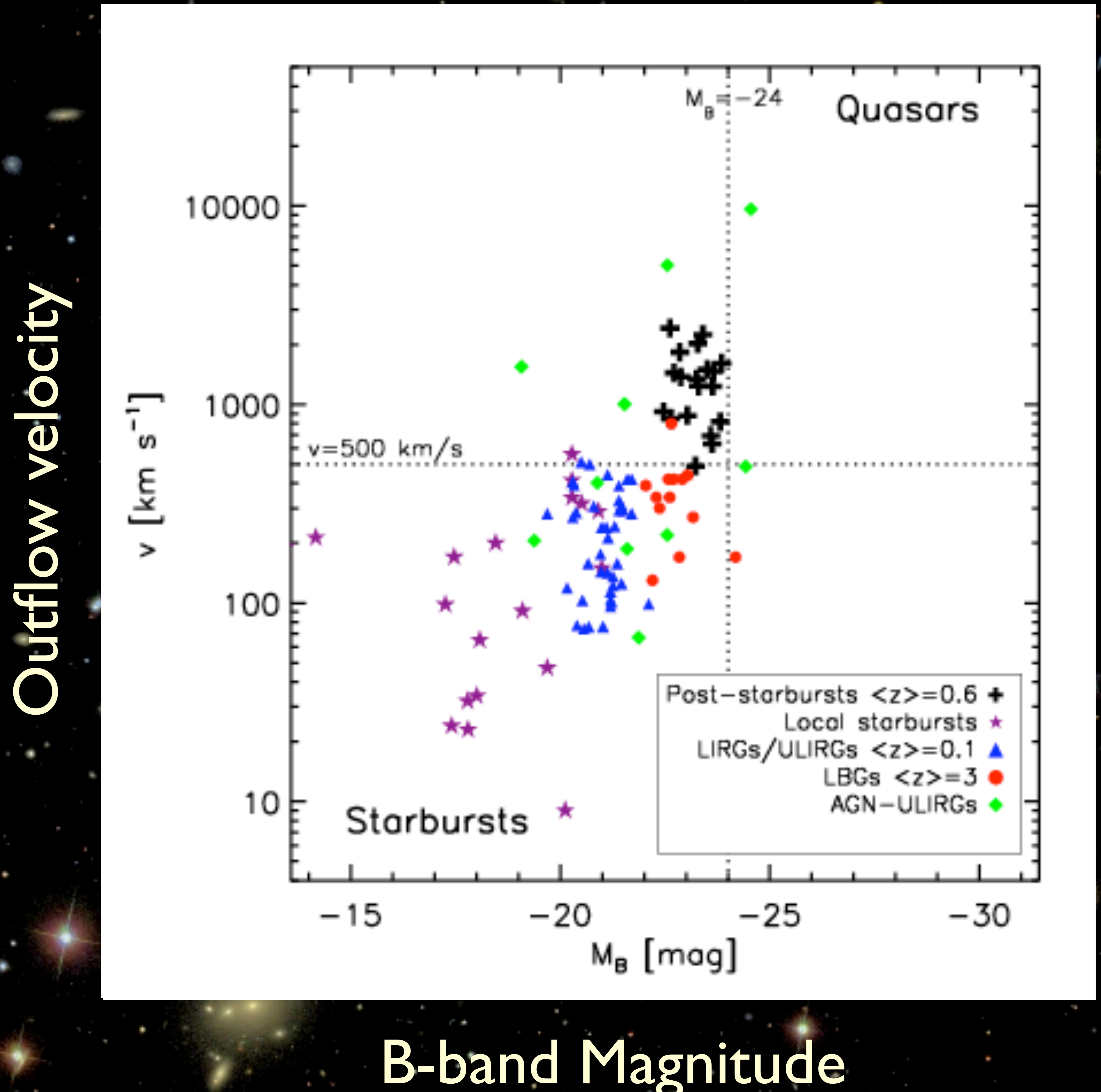
Outflow velocity



B-band Magnitude

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

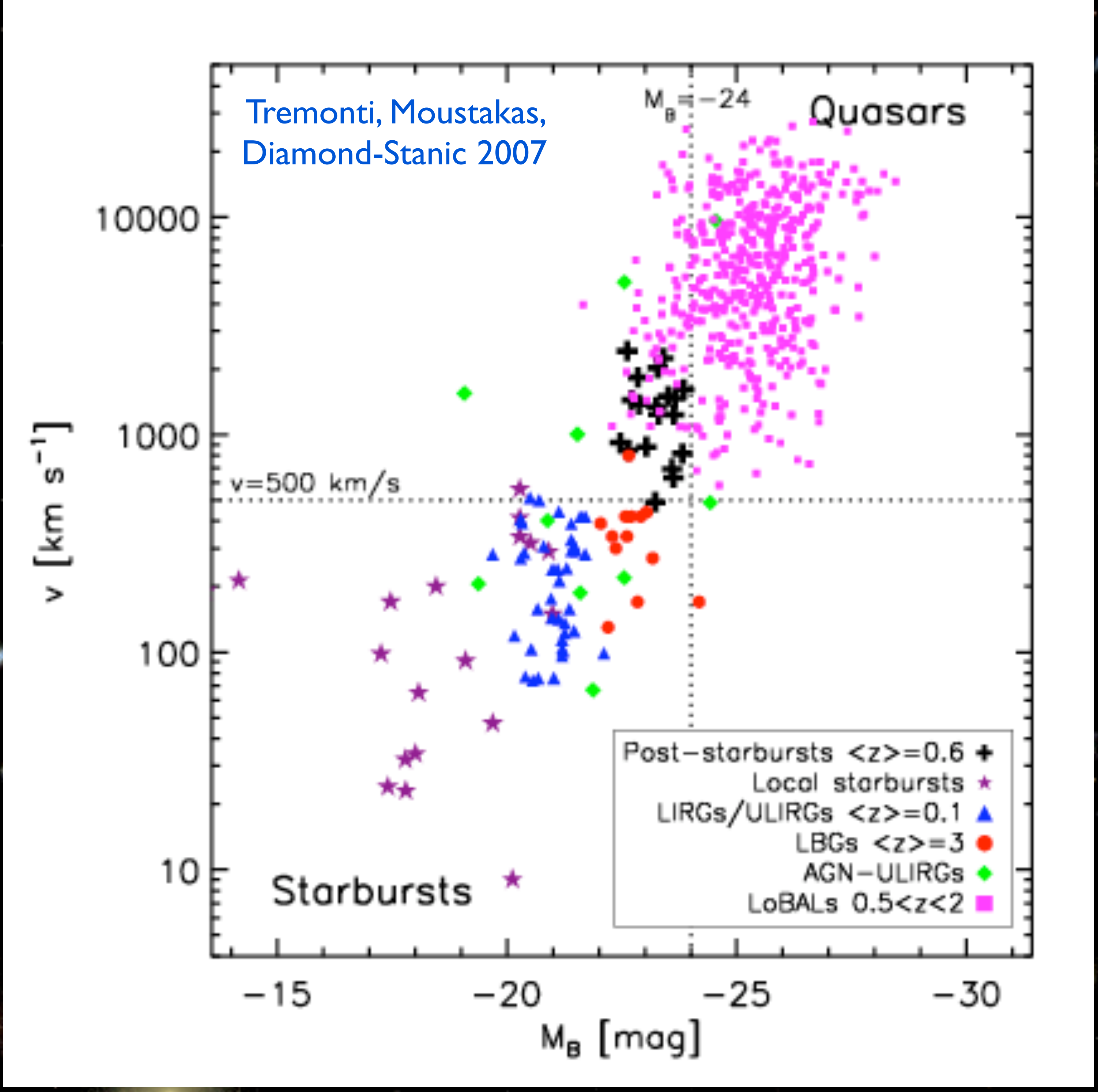
Are these outflows really powered by quasars?



AGN-ULIRGs
Rupke et al. 2005

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

Outflow velocity



LOBAL QSOs
Trump et al. 2006

B-band Magnitude

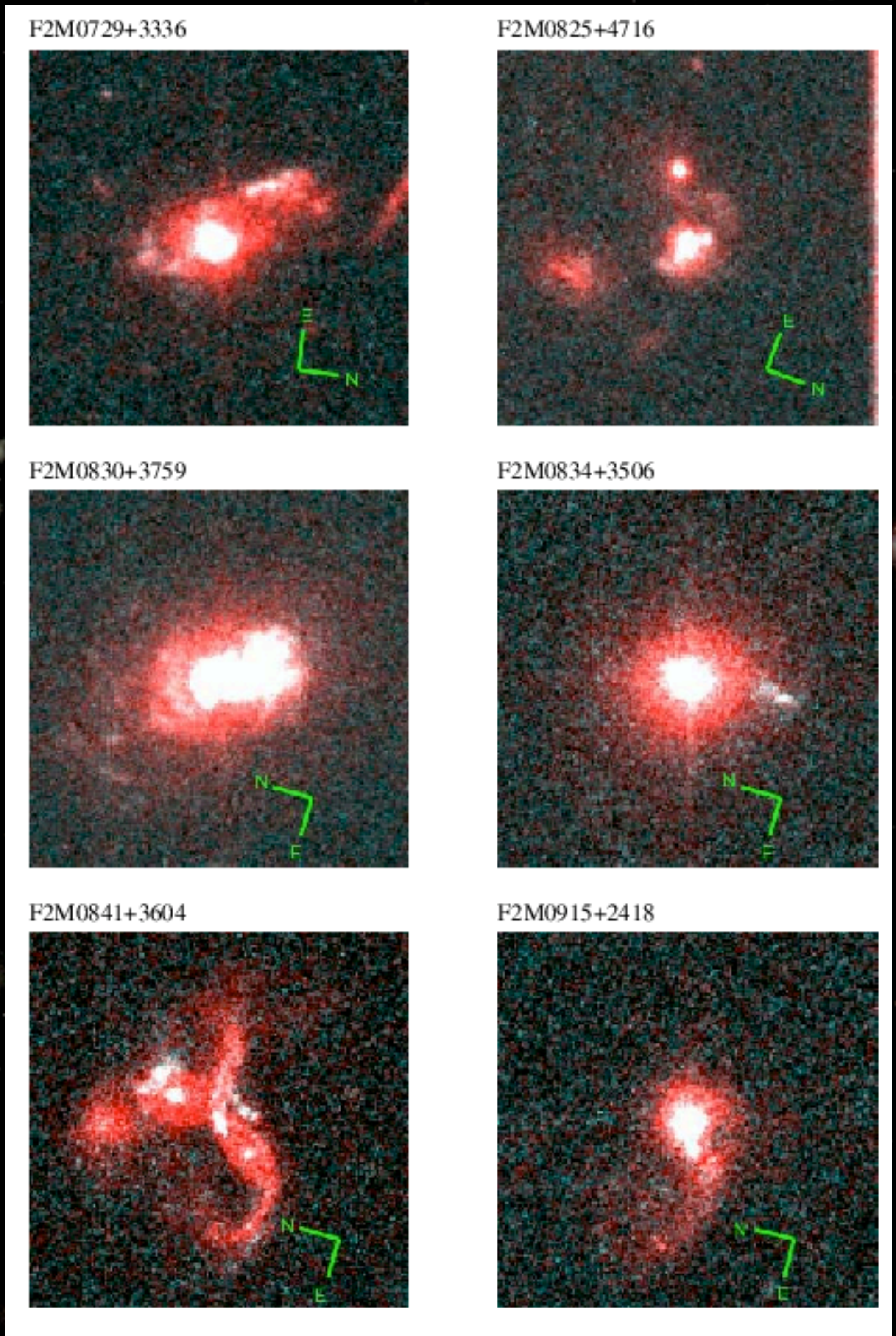
Highly dust-reddened quasars

Black holes in the process of removing their natal cocoon of gas and dust? (See talk by Mark Lacy)

- late stage merger morphologies (Urrutia et al. 2007)

- low-ionization broad absorption lines (Urrutia et al 2009)

- measurements of absorber distances via detailed photoionization modeling imply that the outflows are at kpc scales (Arav, Korista et al., in prep.) -- i.e. these are not simply low mass, low energy nuclear outflows



HST/ACS -- Urrutia et al. 2007

Summary

Highly energetic outflows are a key *prediction* of quasar feedback models

Outflows around quasars are more challenging to observe for a variety of reasons

Observations of extended emission line nebula, close quasar pairs, post-starburst galaxies, and LoBAL quasars provide some support for the basic picture.

We need larger samples with better constraints on the mass and energy in the outflows to rule out star formation feedback.

More theoretical work on the physics

The Future

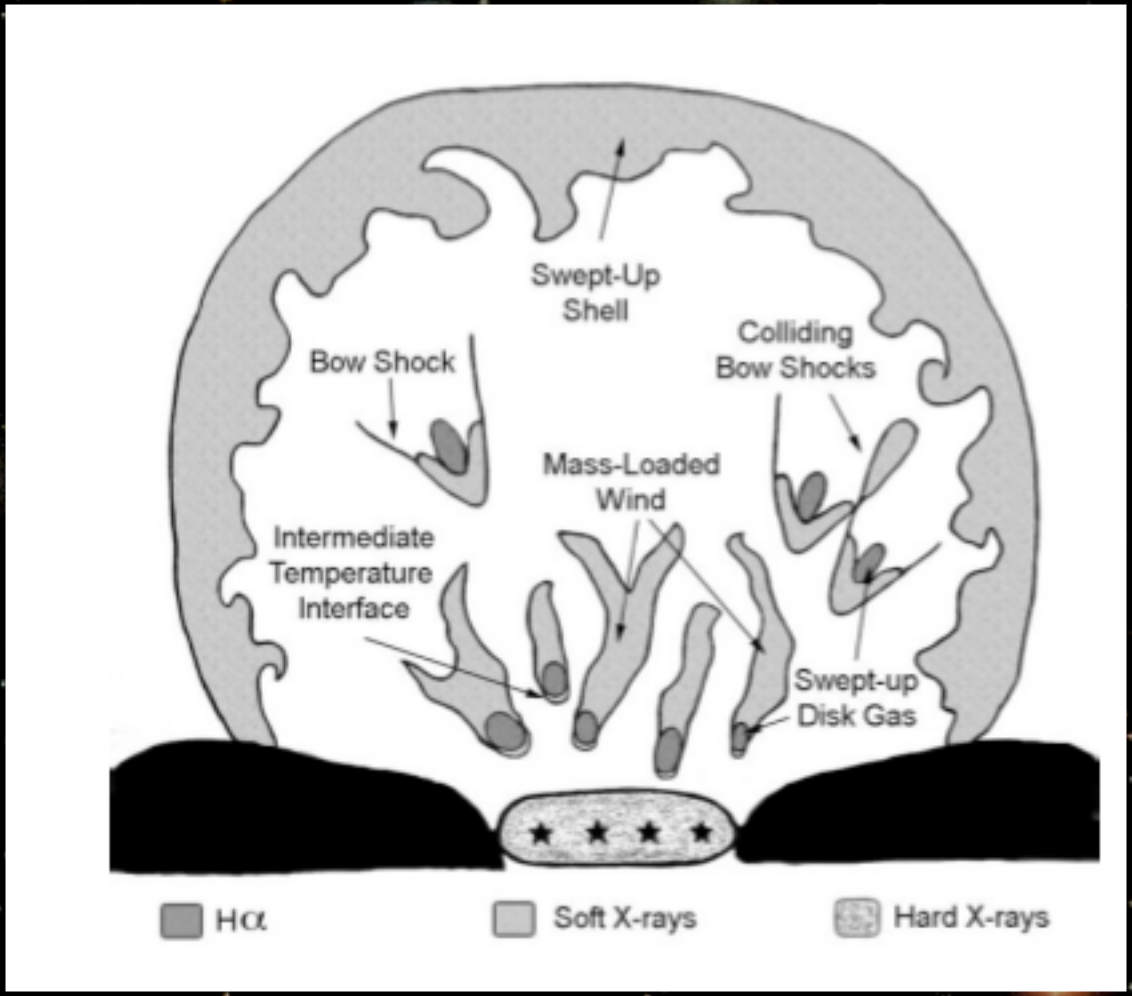
We need information on both the hot and cold phases

XMS microcalorimetr on the International X-ray Observatory

High spatial and spectra resolution X-ray spectrometer to measure the temperature, kinematics, and metal enrichment of the diffuse hard-X ray emitting gas in the central starburst (see Strickland et al. 2009 White Paper - arXiv:0902.2945v1)

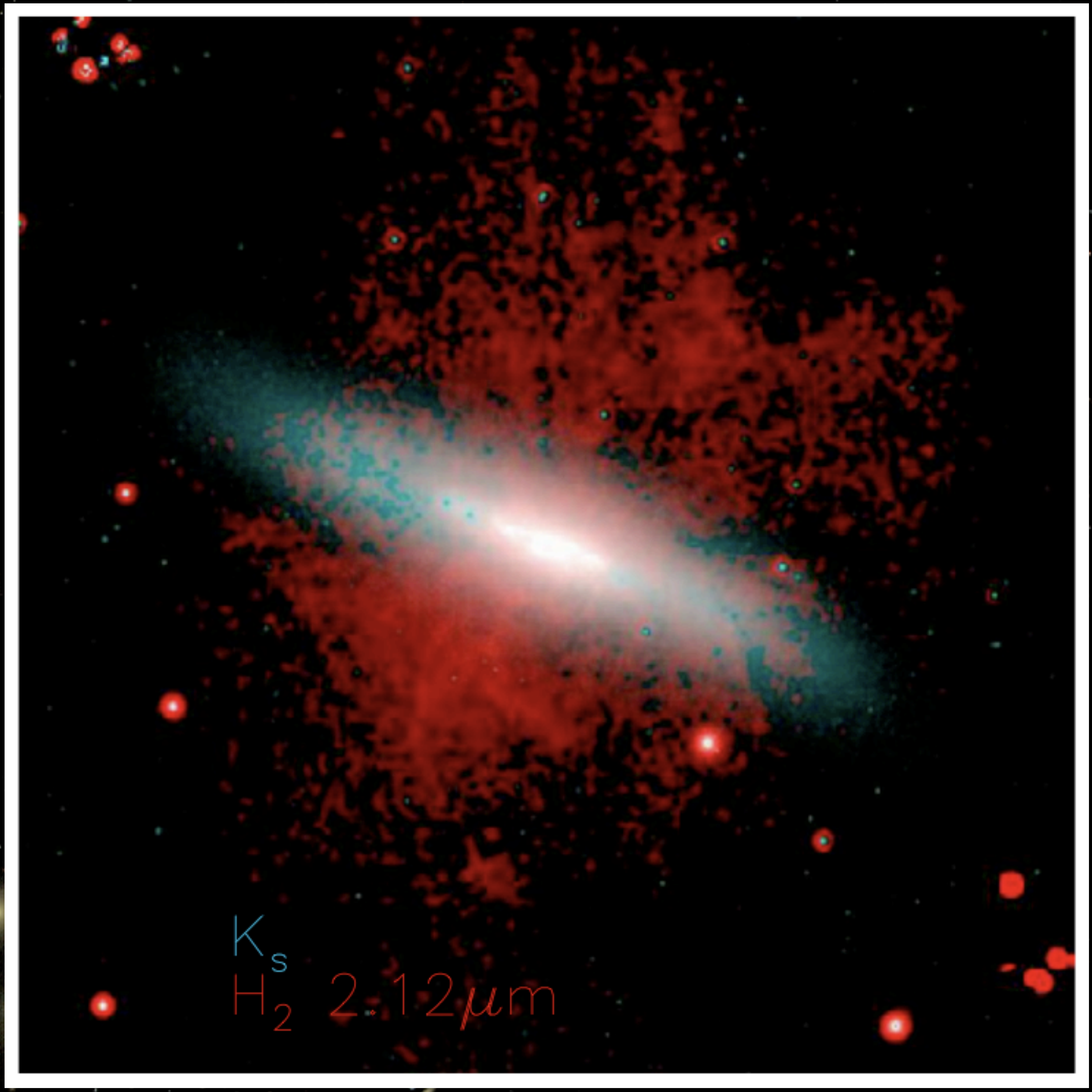
ALMA

Maps of the cold gas distribution and kinematics in more distant starbursts galaxies & quasars



Cooper et al. 2008

Yes, there are molecules!



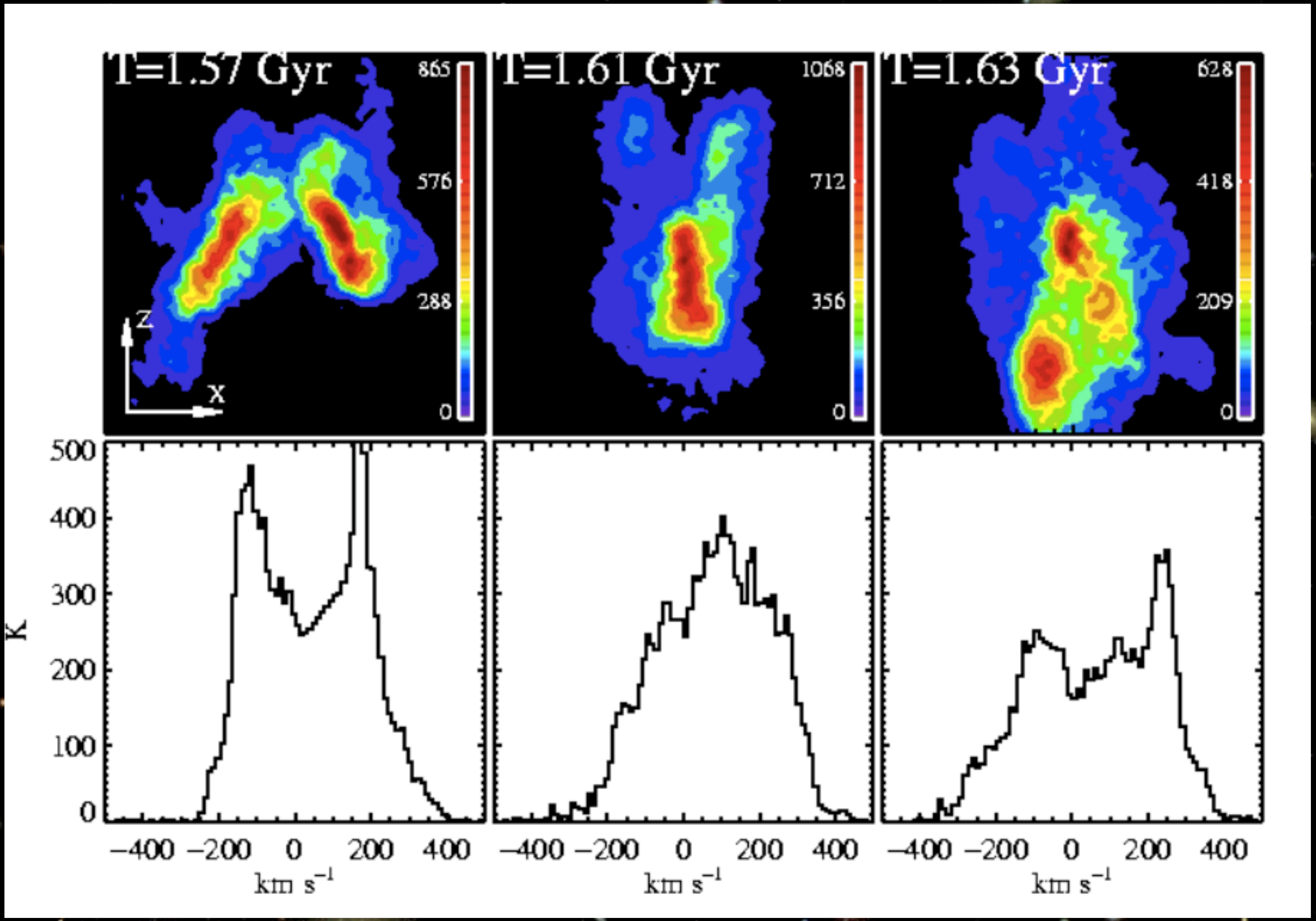
M82

H_2 ν=(1- 0) S(1)

KPNO 4m + NEWFIRM

Veilleux, Rupke, Swaters 2009

Predicted CO signatures of outflows in galaxy mergers: Narayanan et al. 2008



ALMA:

Map molecular cloud sizes in the starburst region of nearby galaxies like M82