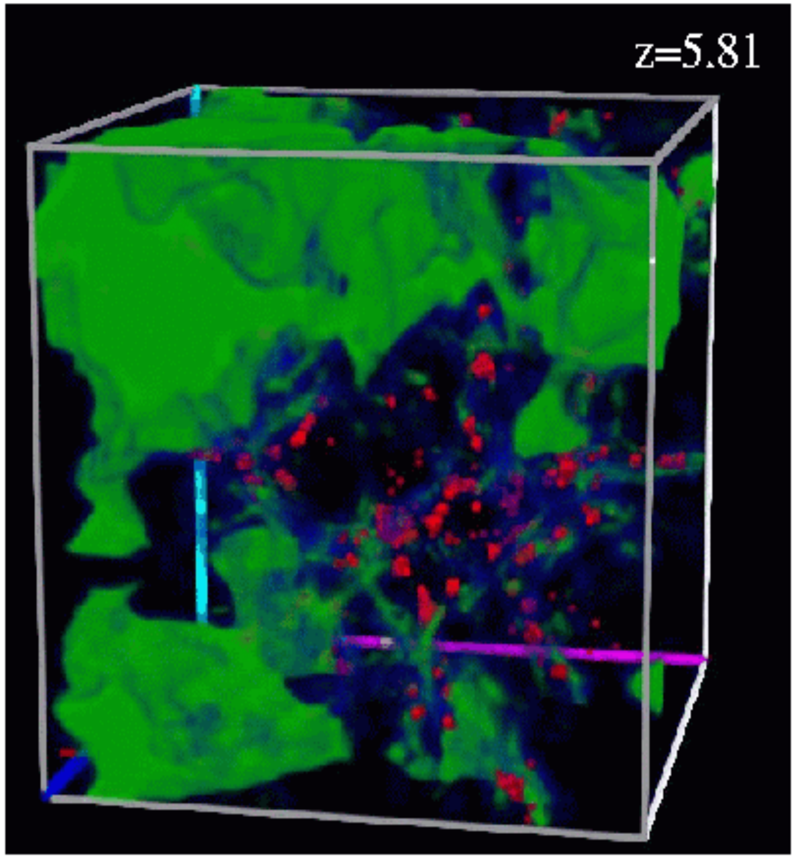
T. Heckman

Local Starbursts in a Cosmological Context

I will introduce some of the major issues that motivate the conference, with an emphasis on how starbursts fit into the bigger picture. I will argue that local starbursts are unique laboratories in which to study the processes at work in the early Universe. I will define starbursts in several different ways, and discuss the merits and limitations of these definitions. I will argue that the most physically useful definition of a starburst is its intensity (star-formation rate per unit area). This is the most natural parameter to use for comparing local starbursts with physically similar galaxies at high redshift. I will describe how the systematic properties of local starbursts can be understtod on the basis of the Schmidt-Kennicutt Law and mass-metallicity relation. I will briefly summarize the properties of starburst-driven galactic superwinds and their possible implications for the evolution of galaxies and the intergalactic medium. These complex multiphase flows are best studied in nearby starbursts, where we can study the hot X-ray gas that contains the bulk of the energy as well as newly produced metals. I will discuss what we can learn from local starbursts about the processes responsible for the reioniztion of the universe at $z > 6$. Finally, I will summarize the link between post-starbursts and the growth of supermassive black holes, and will suggest that the lag in black hole growth is caused by feedback from supernovae during the starburst phase.

Local Starbursts in a Cosmological Context



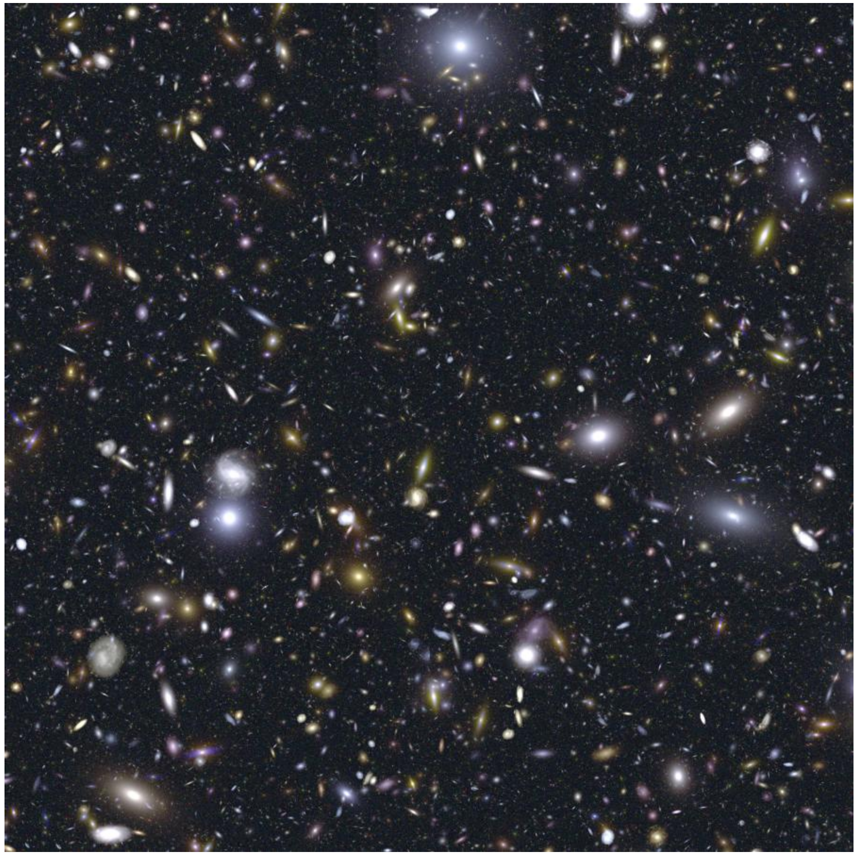
OUTLINE

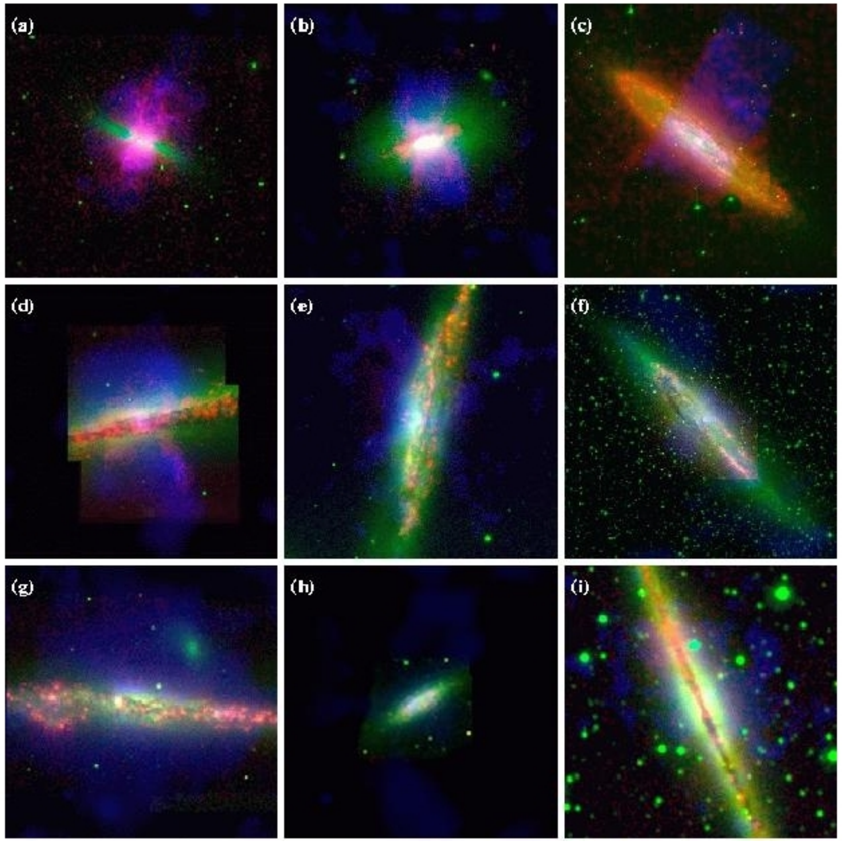
- MOTIVATION
- DEFINING STARBURSTS
- STARBURST AS LOCAL ANALOGS
- STARBURSTS SYSTEMATICS
- FEEDBACK IN STARBURSTS
- STARBURSTS & REIONIZATION
- THE STARBURST-AGN CONNECTION
- SUMMARY

Why are local starbursts important?

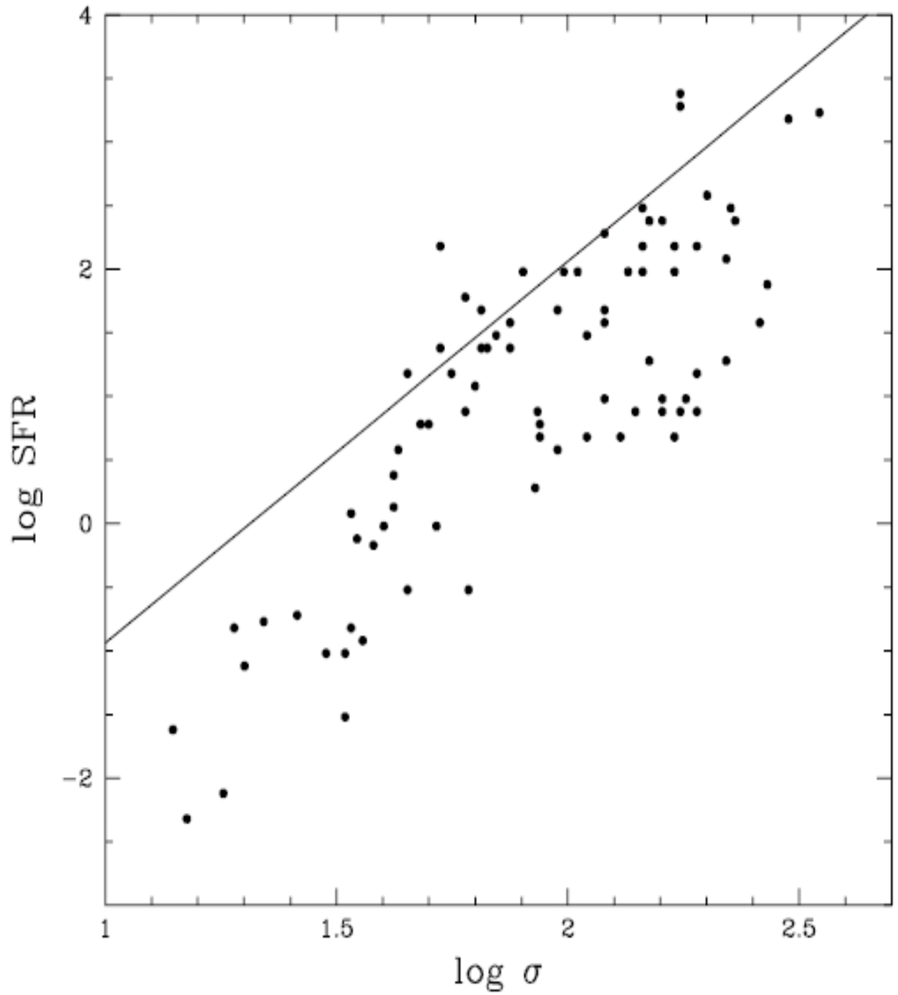
- They are the sites of the formation of about 20% of all the star formation today
- They are laboratories to study the gas-star-black-hole "ecosystem" under extreme conditions
- They are the best/only local analogs to typical forming galaxies at high-redshift

Think globally, observe locally



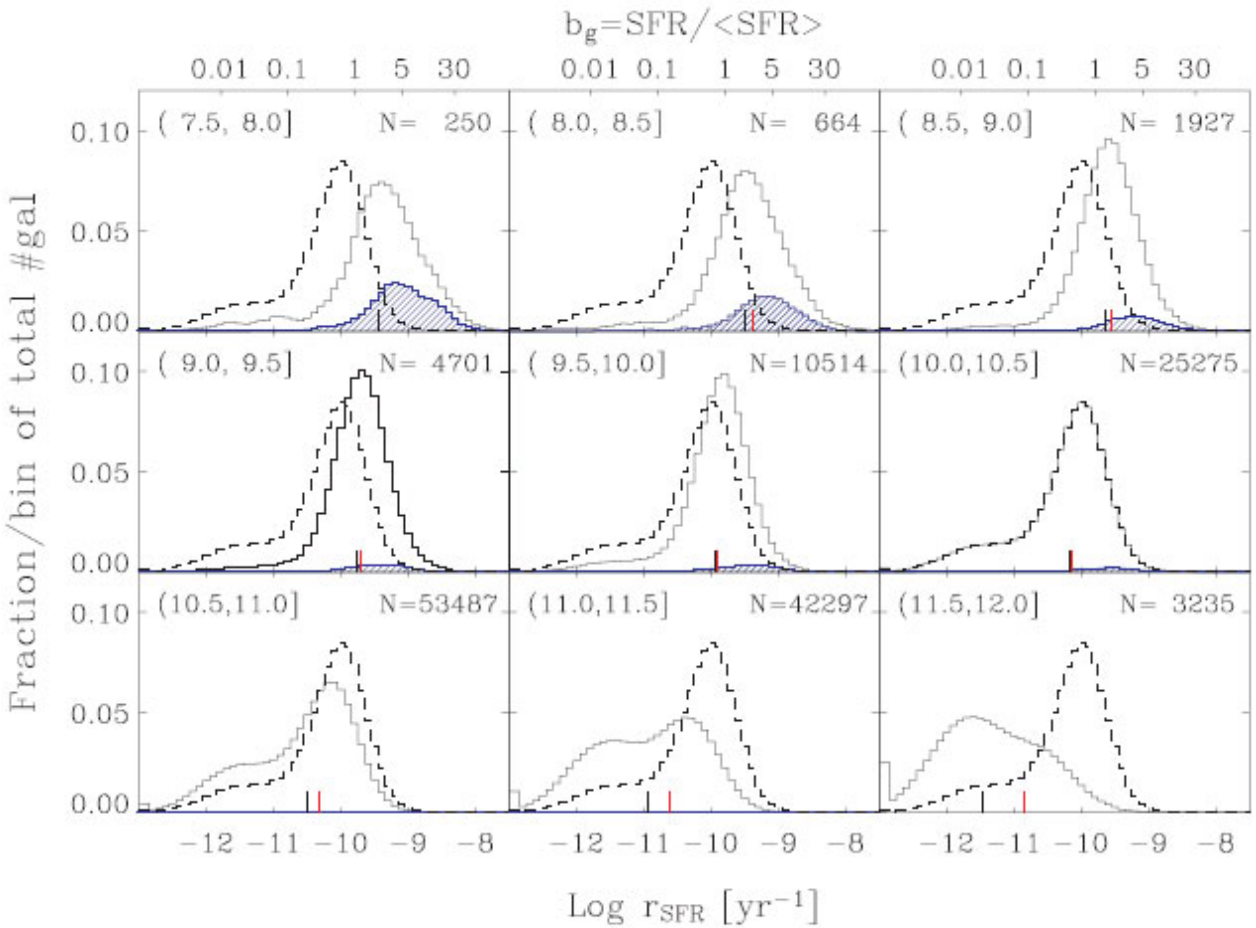


What is a starburst: Definition 1



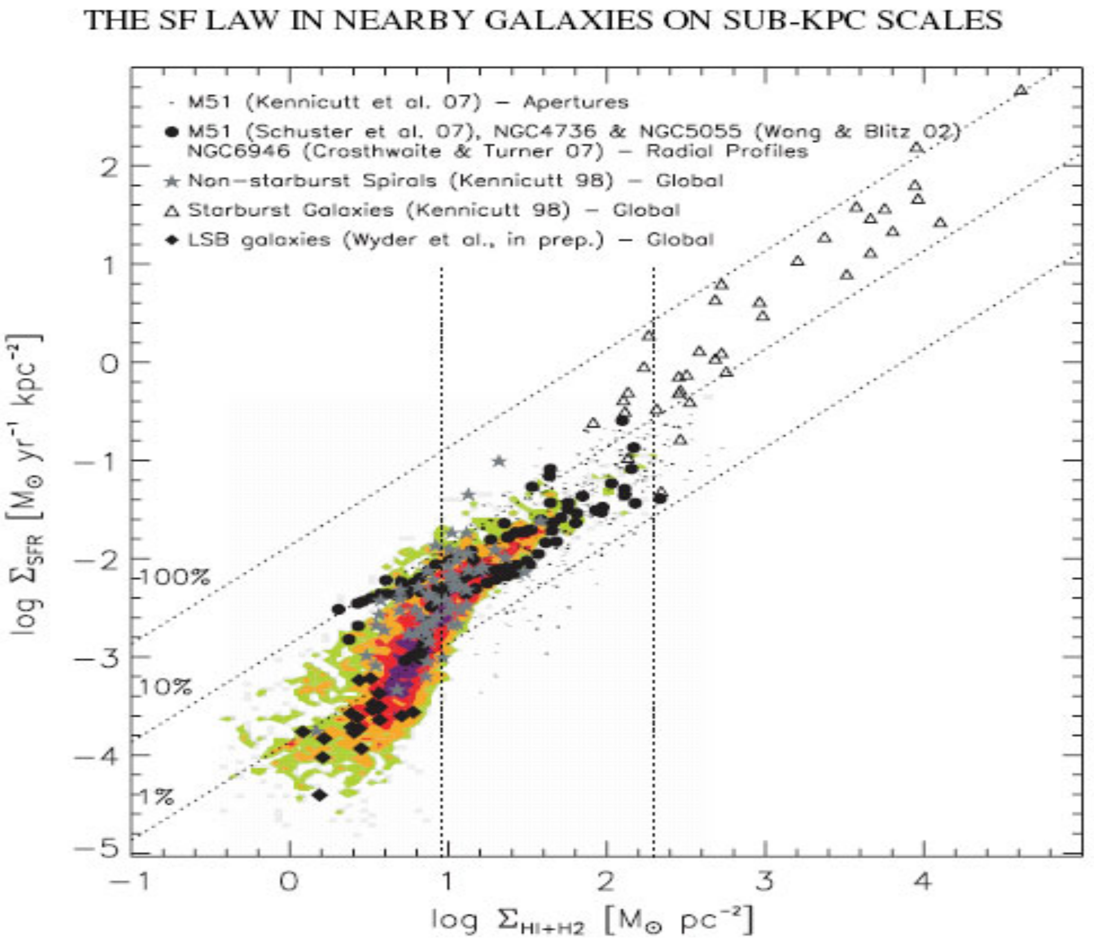
- Maximum allowed SFR ~ M_gas/t_dyn
- Implies SFR_max ~ f_gas sigma^3/G
- Starbursts approach this limit!
- This clearly requires rapid inflow
- Link to interactions, bars, and mergers

What is a starburst: Definition 2a



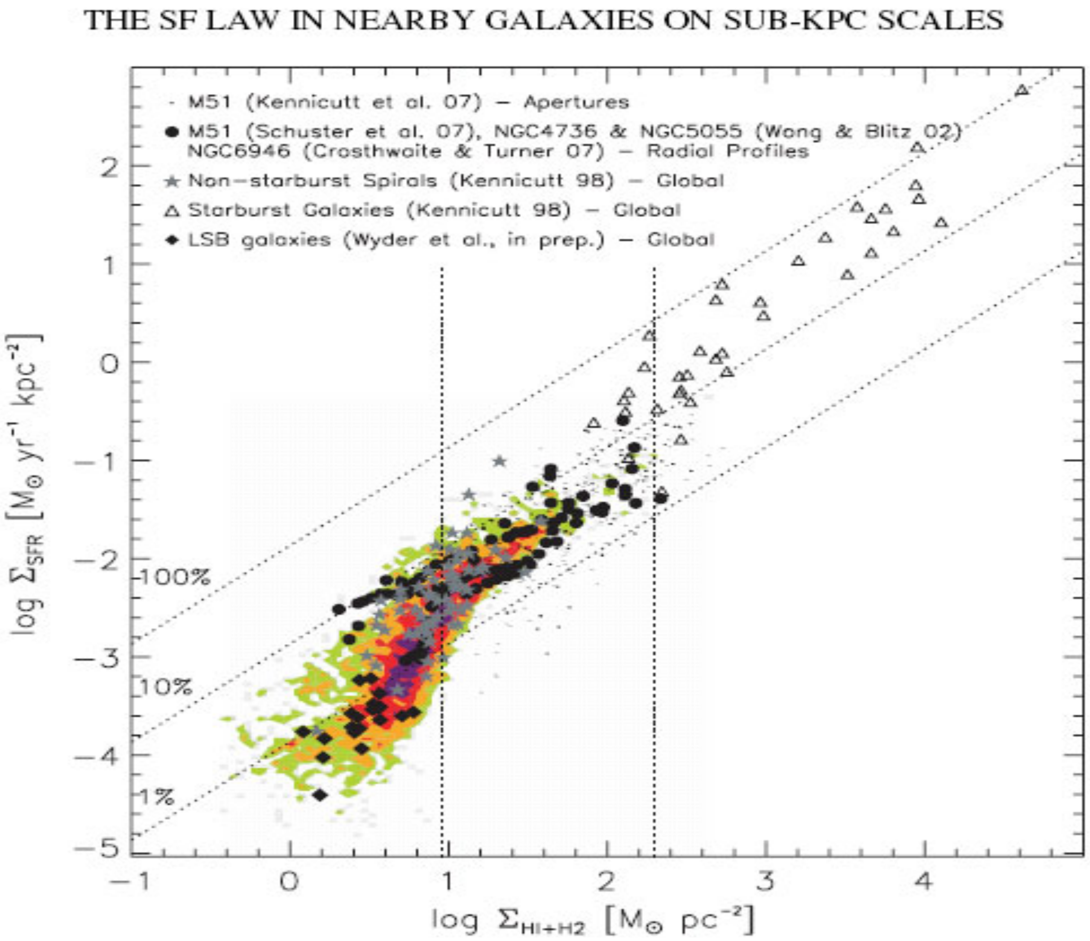
- Classic definition: duration is << t_Hubble
- M_*/SFR << t_Hubble   Brinchmann et al.

What is a starburst: Definition 2b



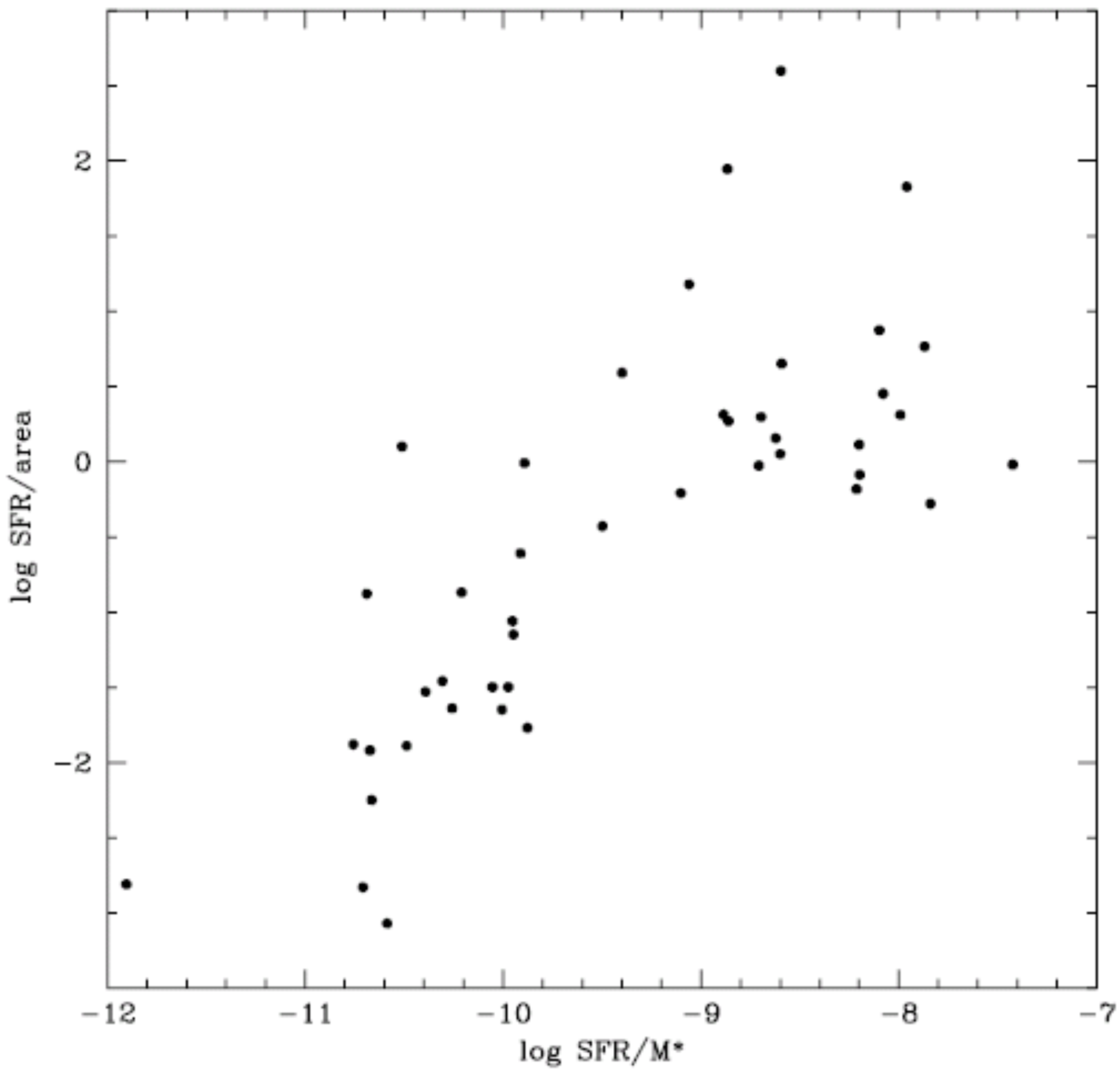
- Duration << t_Hubble
- M_gas/SFR << t_Hubble - Bigiel et al.

What is a starburst: Definition 3



- High "Intensity" – SFR/area
- Requires high gas column densities

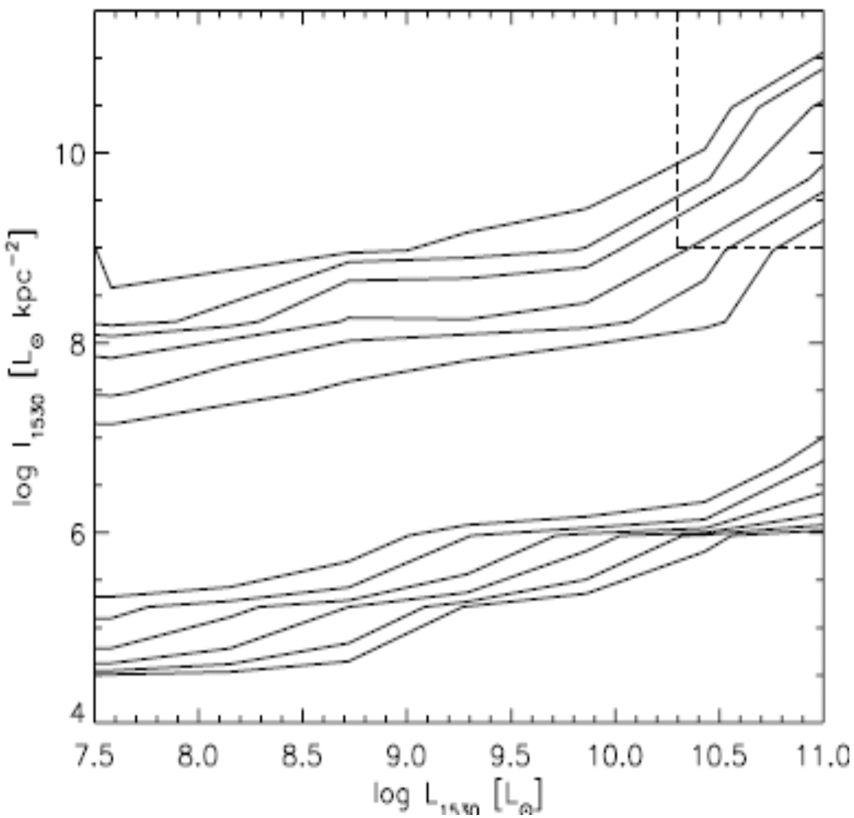
The definitions agree!

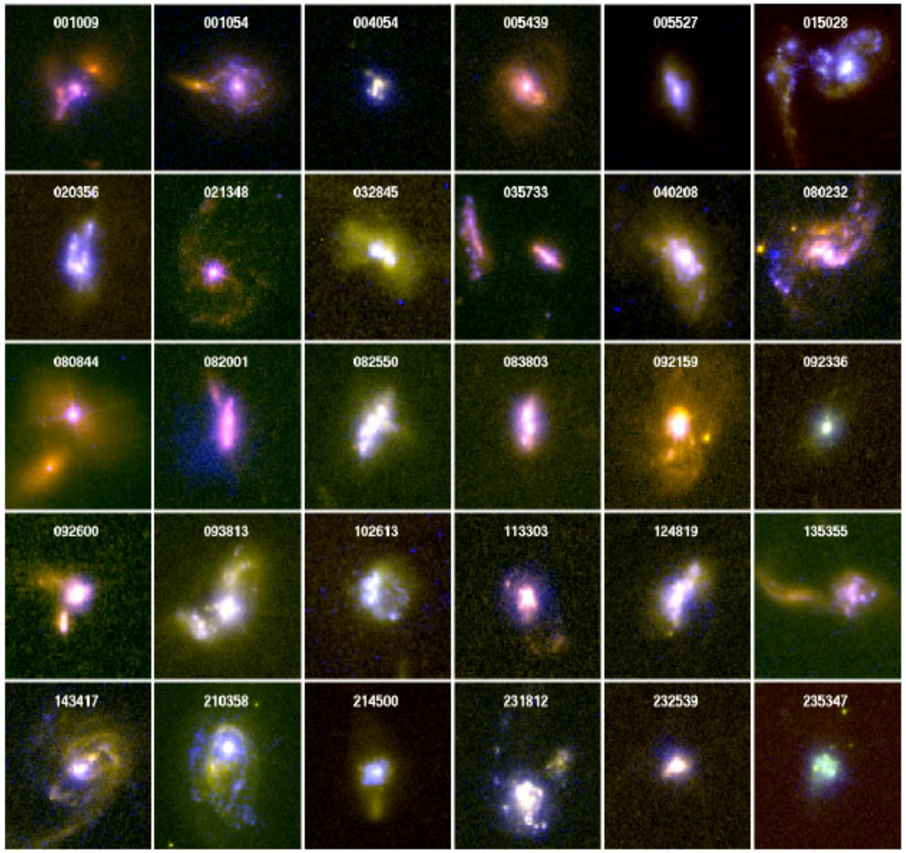


Consequences of High Intensity

- High gas columns imply large extinction
- Large SFR/area implies large radiant intensity and energy density in starburst
- Hydrostatic equilibrium requires high pressures: P ~ N_gas^2/f_gas
- High densities imply short dynamical times: t_dyn ~ (G N_tot/r)^{-1/2}
- High supernovae rate per unit volume: High efficiency in driving galactic winds

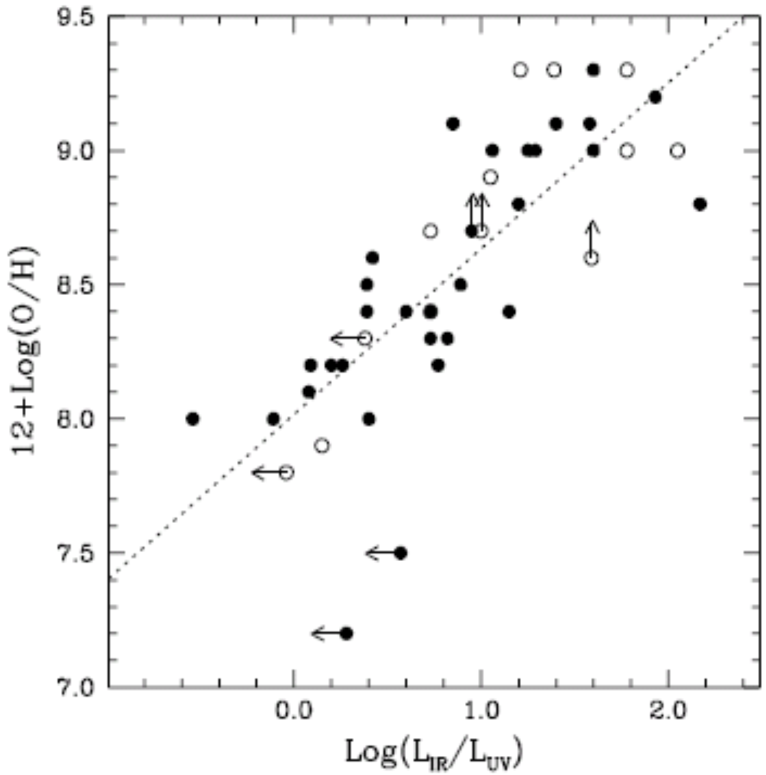
Starbursts as Local Analogs

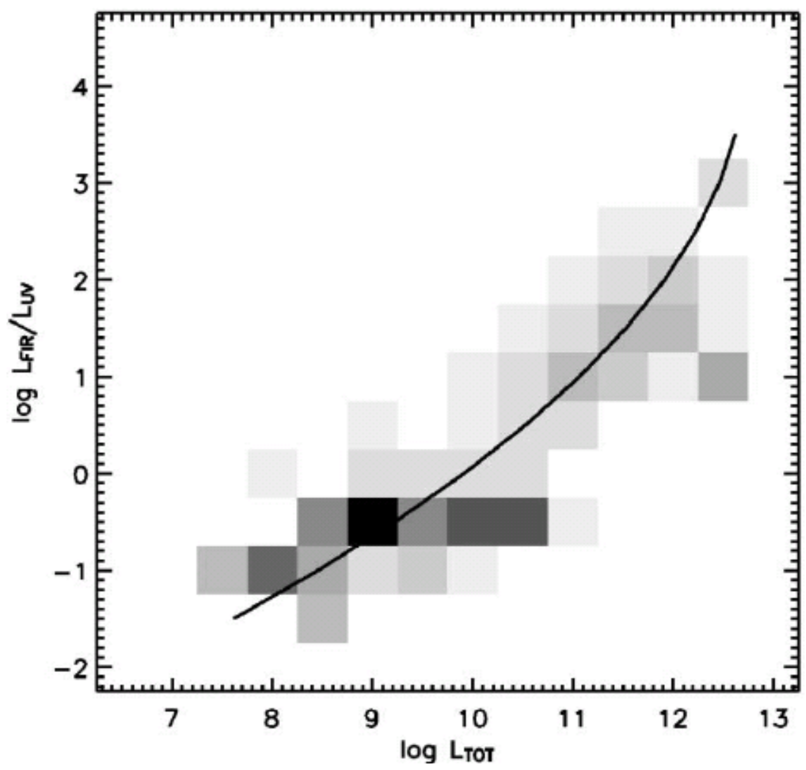




- Only local starbursts have intensities (SFR/area) comparable to high-z forming galaxies
- These are our local laboratories (Hoopes;Overzier)

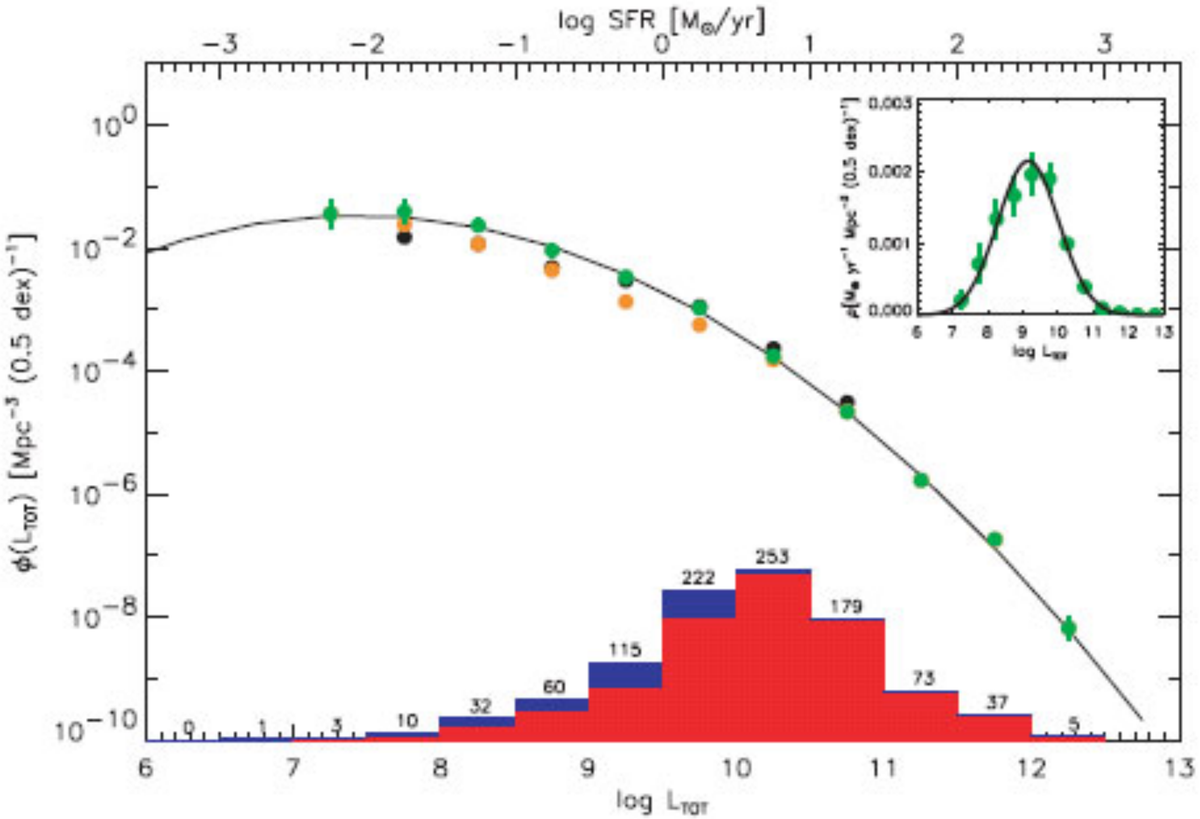
Starburst Systematics





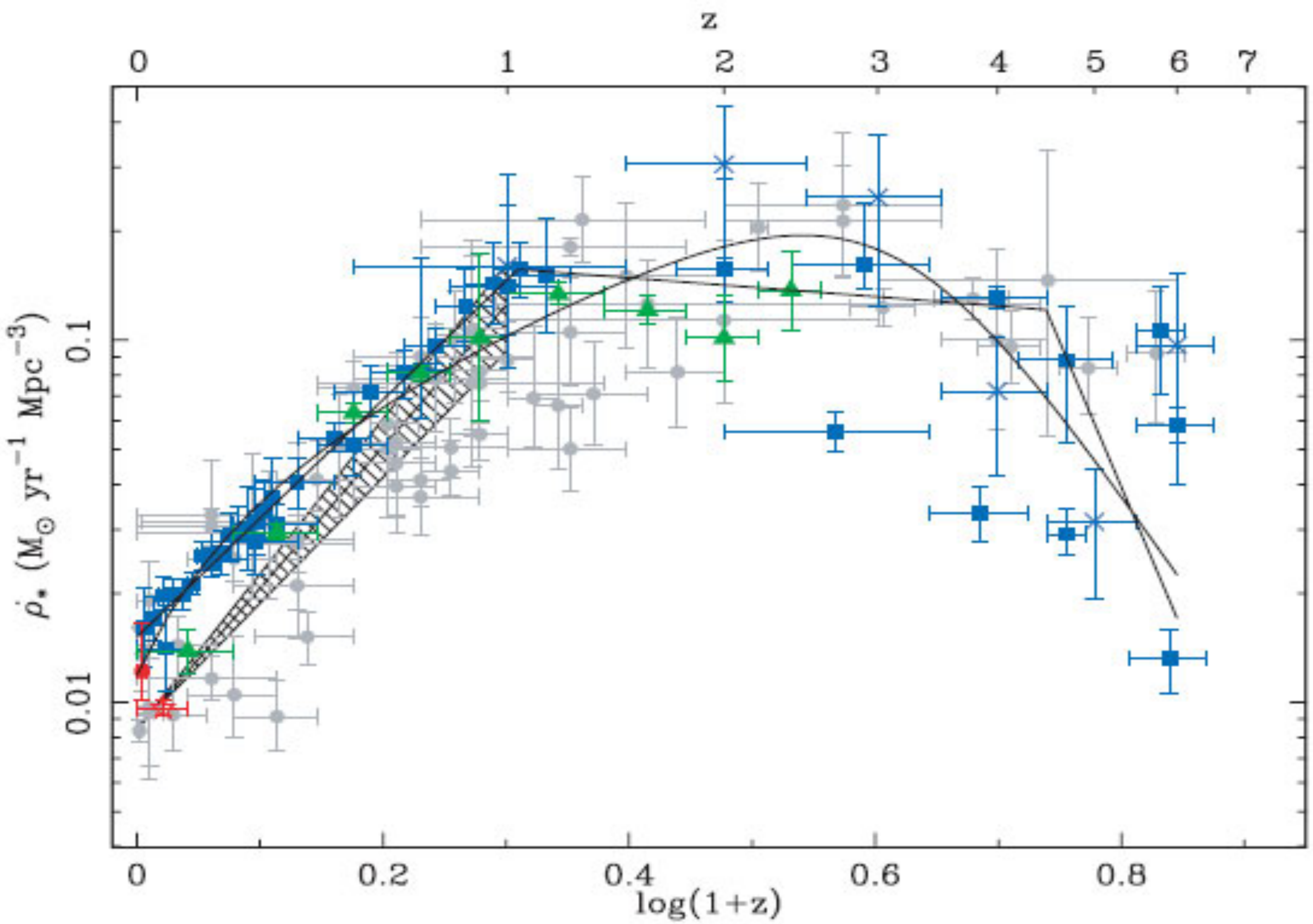
- The more metal rich starbursts are the more obscured (more dust per unit gas)
- The more powerful starbursts are the more obscured (Martin et al.)

A Panchromatic Approach



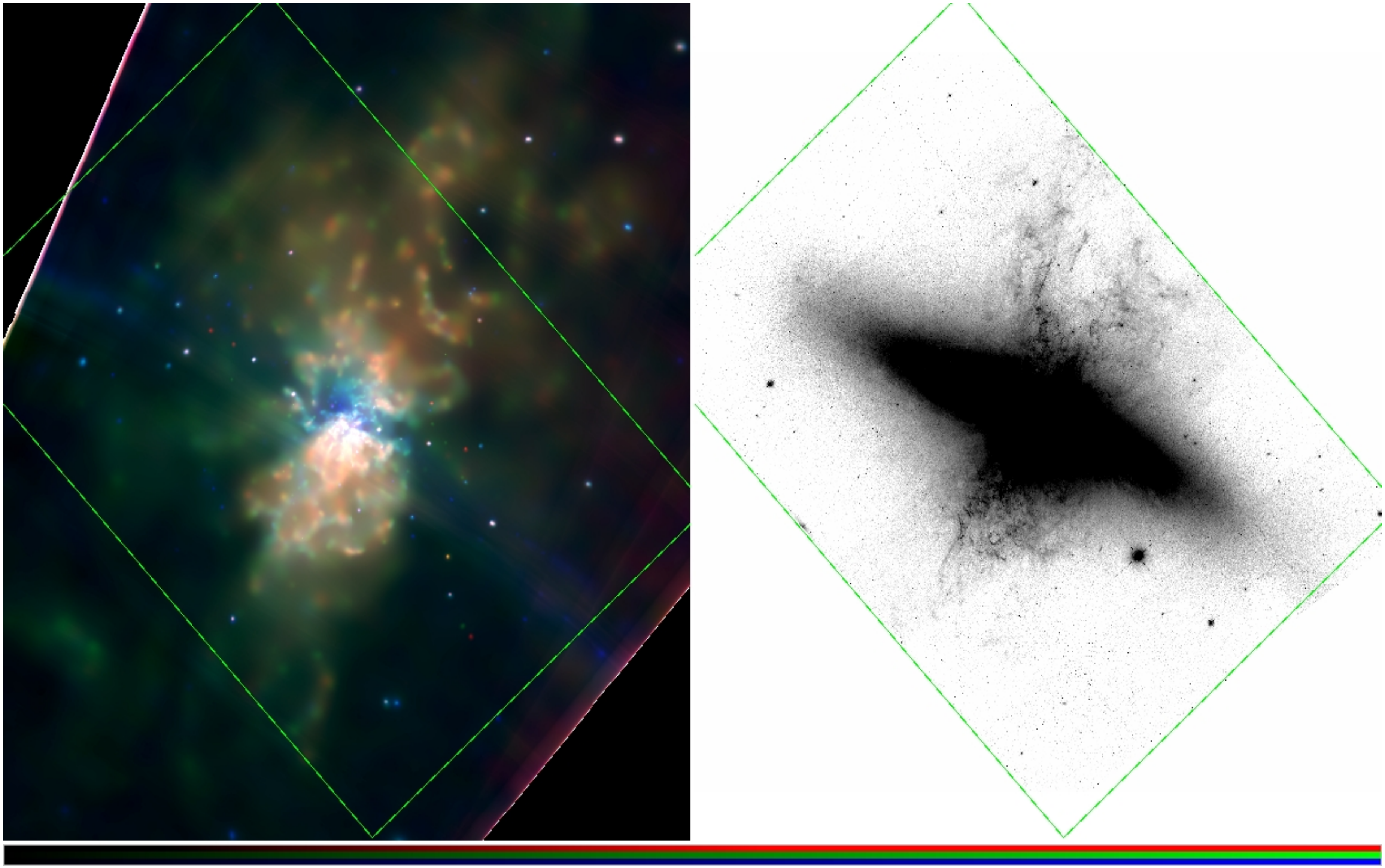
- Because of the systematics in the obscuration, a joint UV and FIR approach is essential to track the full starburst population (Martin et al.)

Also true at high-z

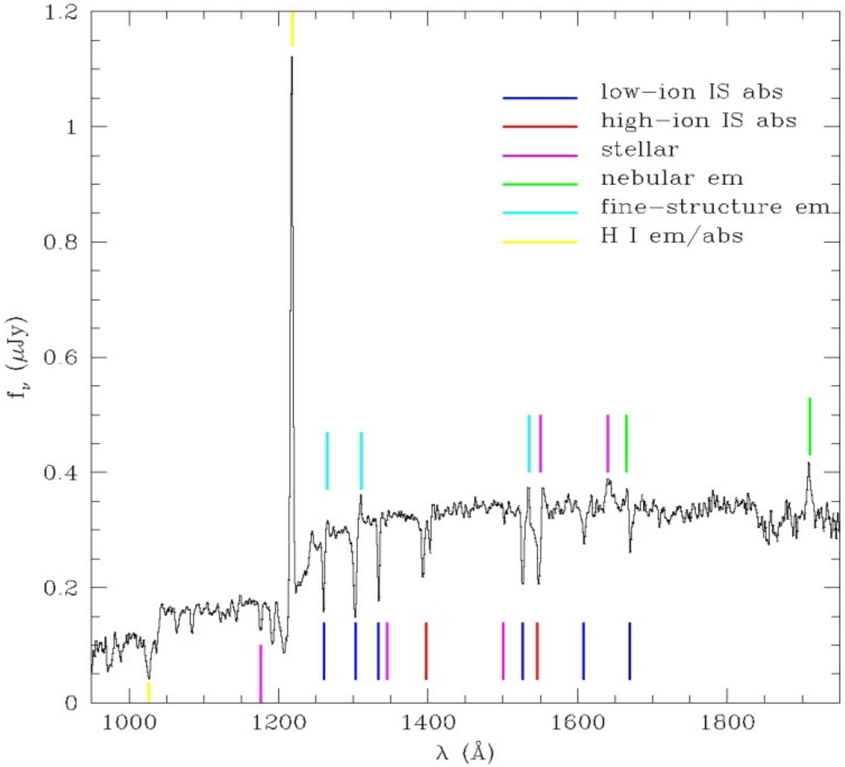


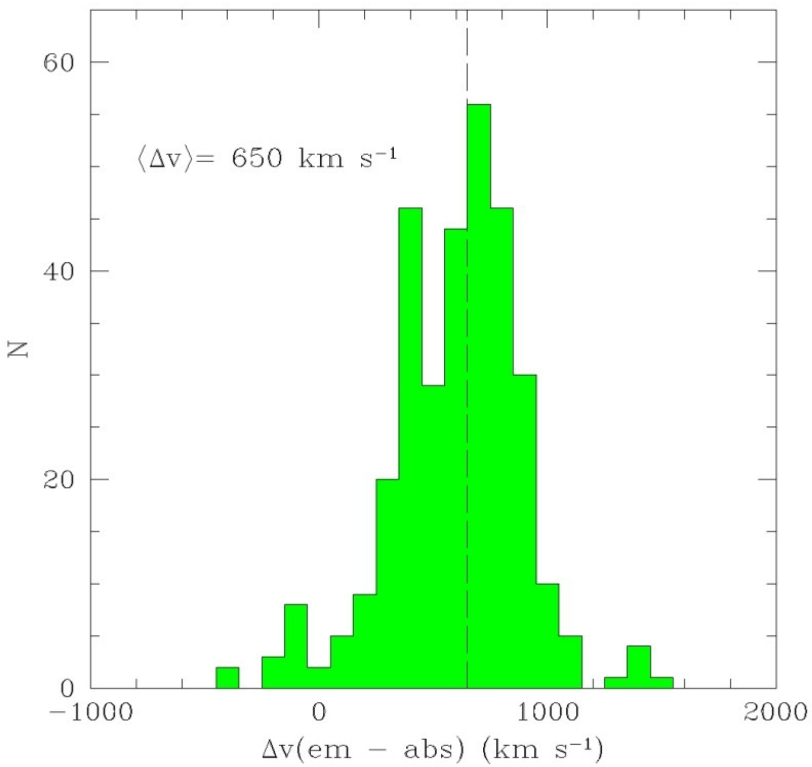
- Hopkins & Beacom panchromatic compilation

Feedback in Starbursts



Feedback at High-Redshift



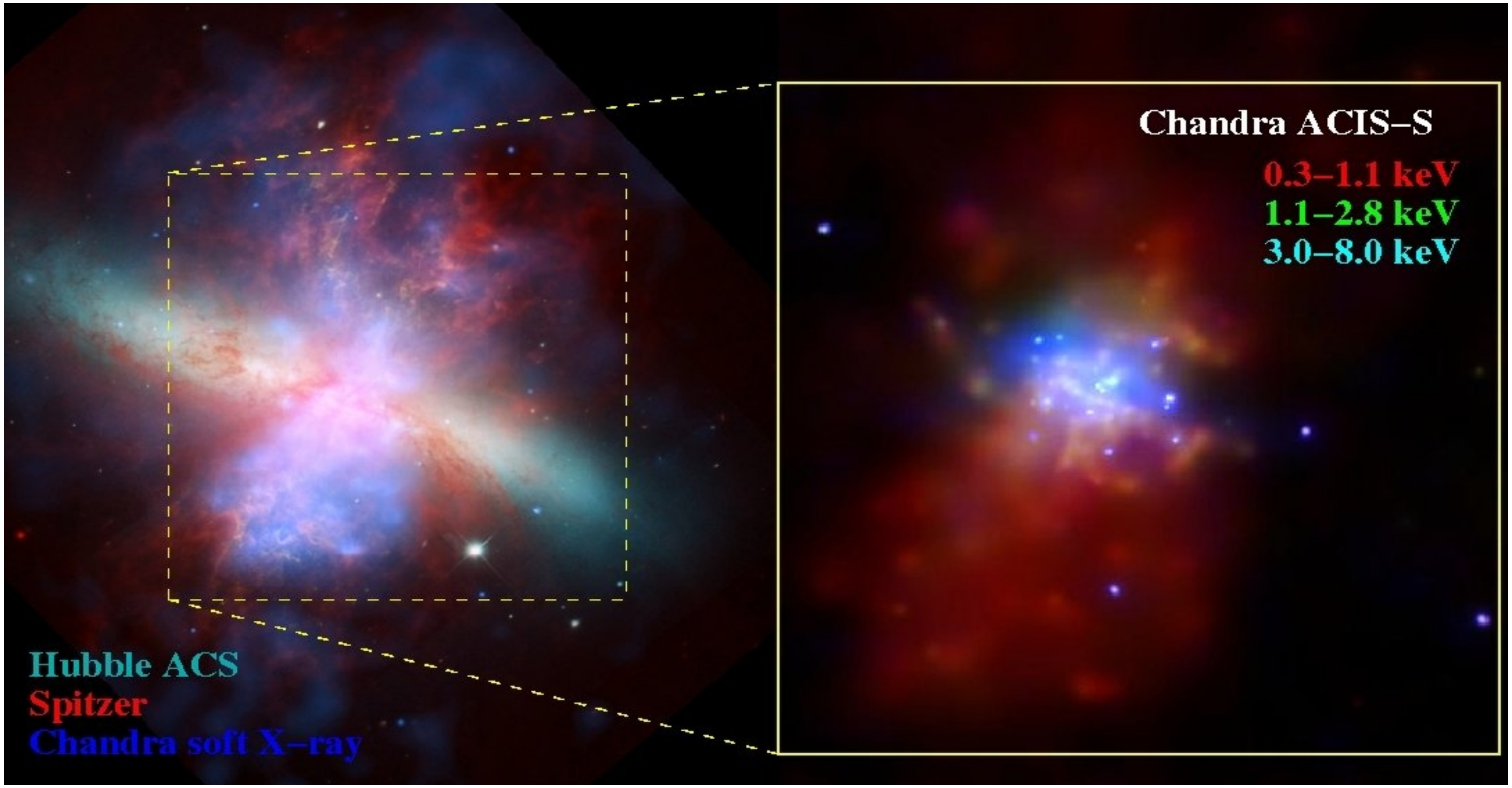


- Outflows ubiquitous at high-redshift (Shapley et al.)
- They are much less common today, but….
- They are a complex multiphase phenomenon
- Only in the nearby analogs can we develop a complete physical picture

A Multi-phase Flow!

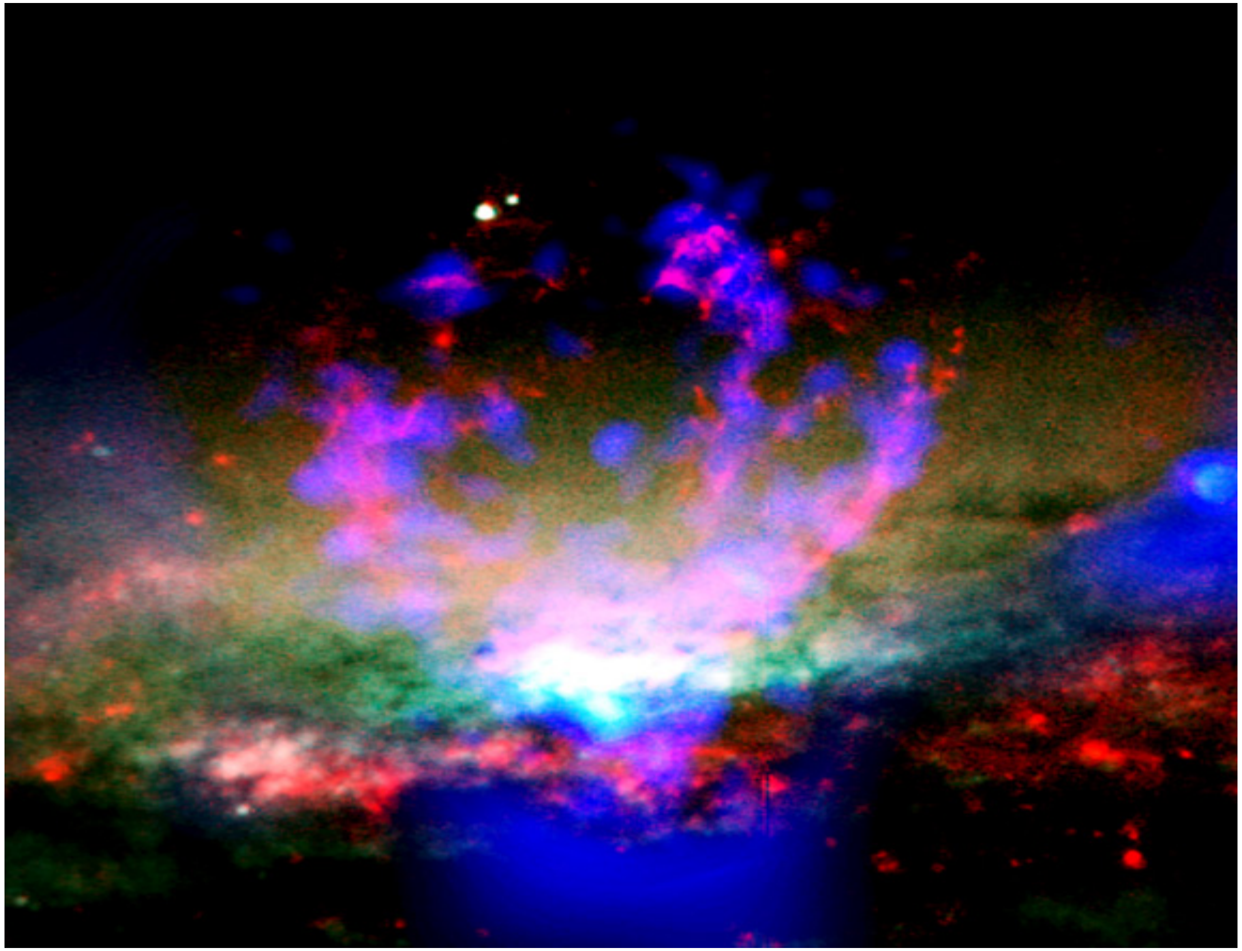
- M82 w/ Spitzer mid-IR & Chandra & HST

The Very Hot Phase



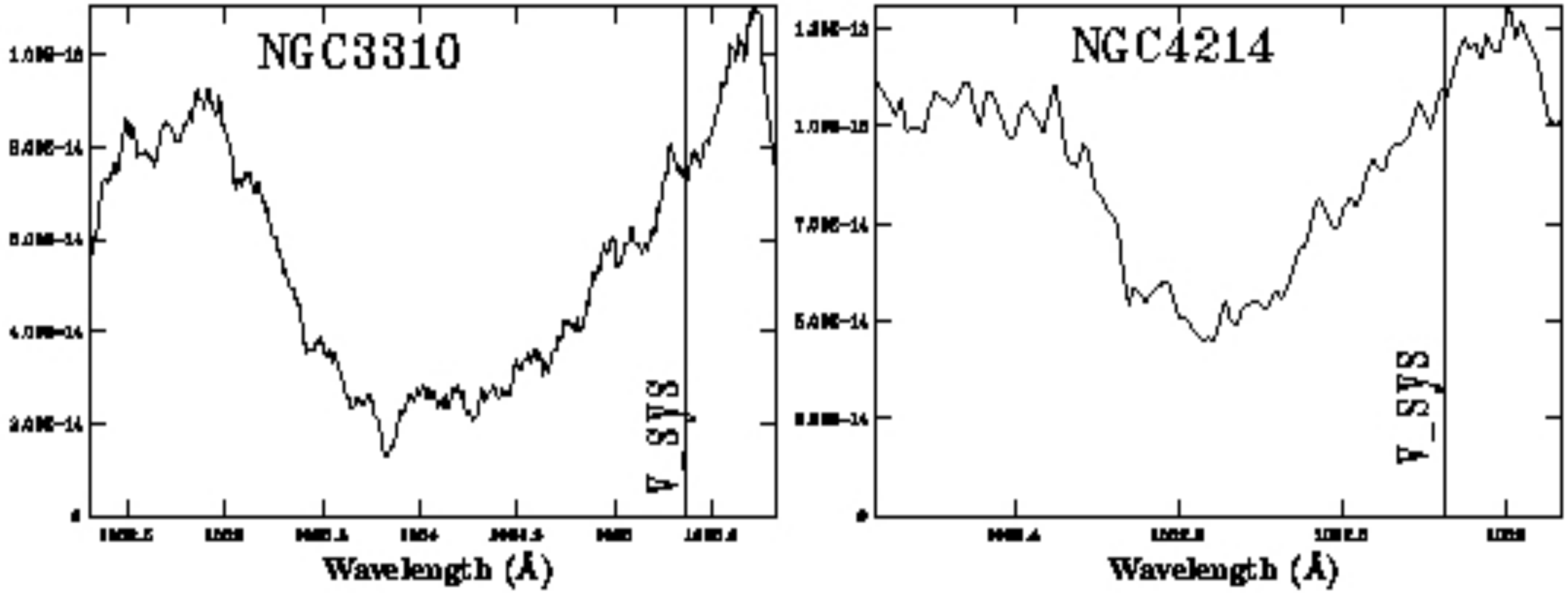
- Dave Strickland & TH
- Diffuse hard X-ray emission (T ~ 60 million K)
- Confined to central starburst (r ~ few hundred pc)
- Adiabatic expansion and cooling is severe

The Hot & Warm Phases



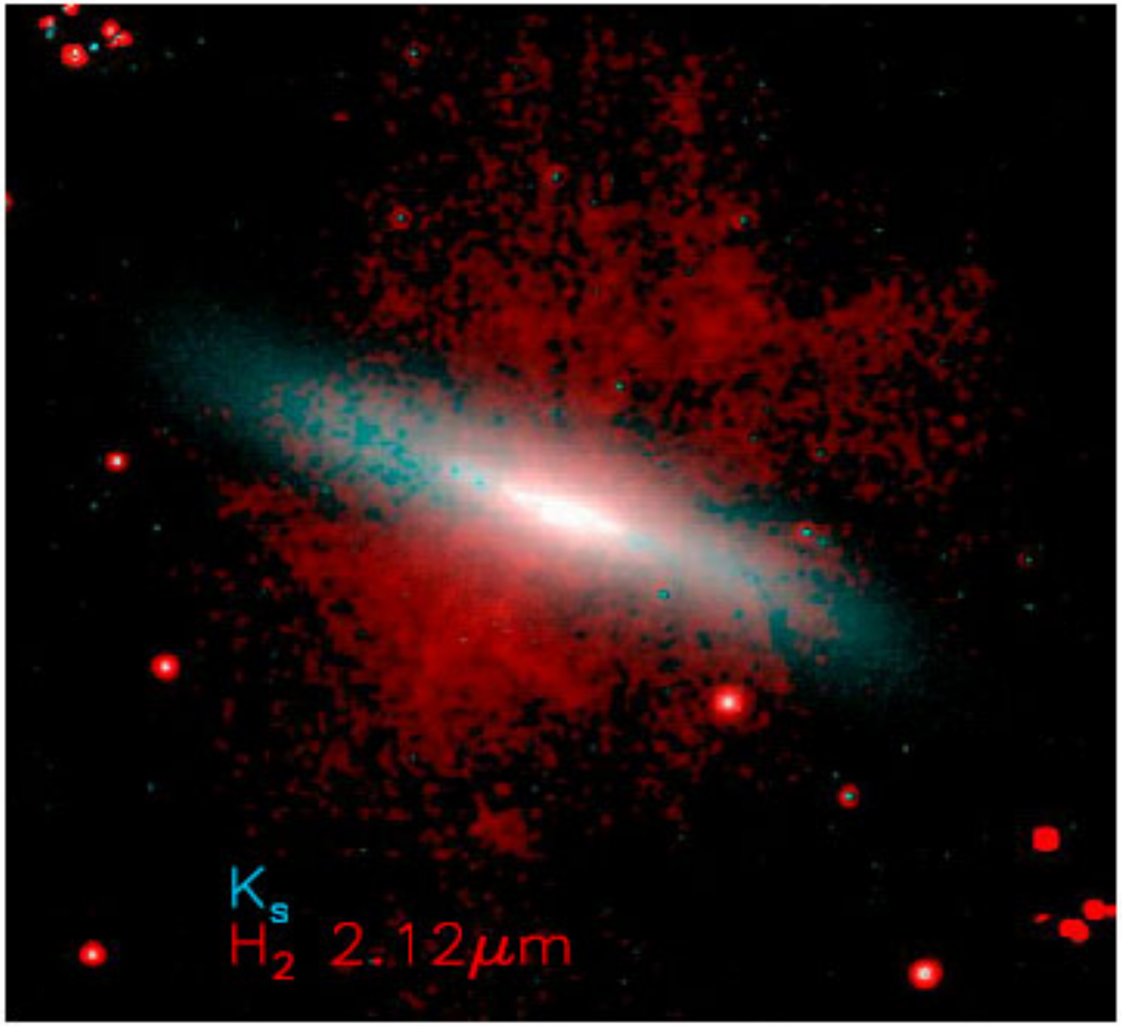
- Soft X-rays & optical emission-lines trace wind-cloud collisions
- Implied wind velocity ~500 to 800 km/s
- Cecil et al.

The Warm Phase(s)



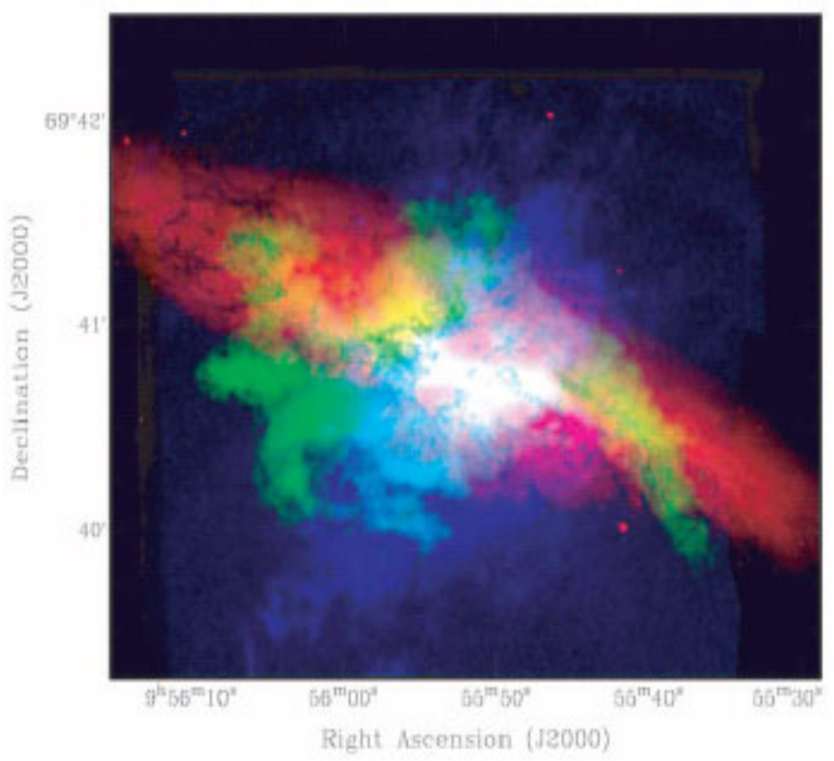
- Blue-shifted absorption-lines: entrained clouds
- Traces a range from neutral to coronal phases

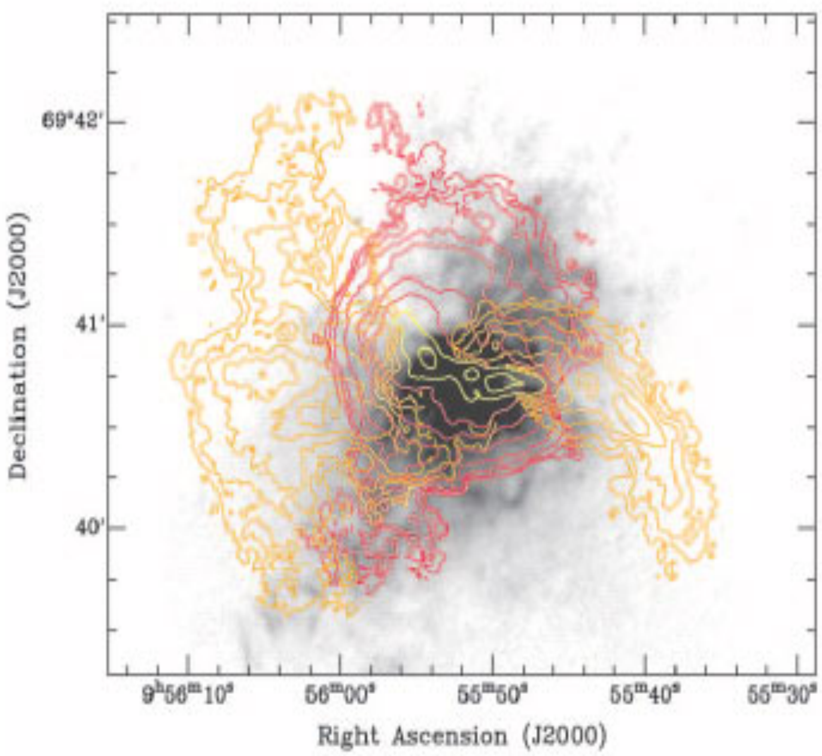
The Warm Molecular Phase



- Hot (NIR) molecular hydrogen (Veilleux et al)

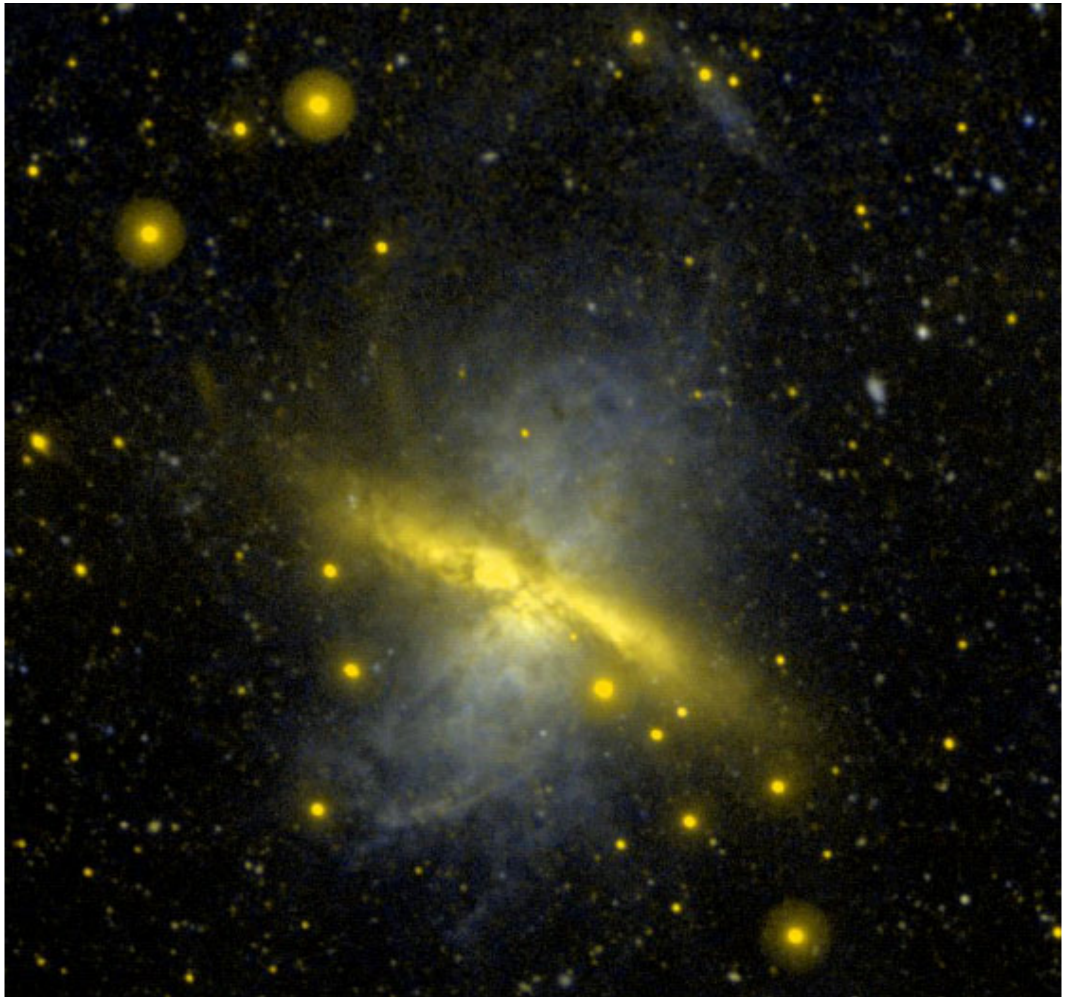
The Cool Molecular Phase





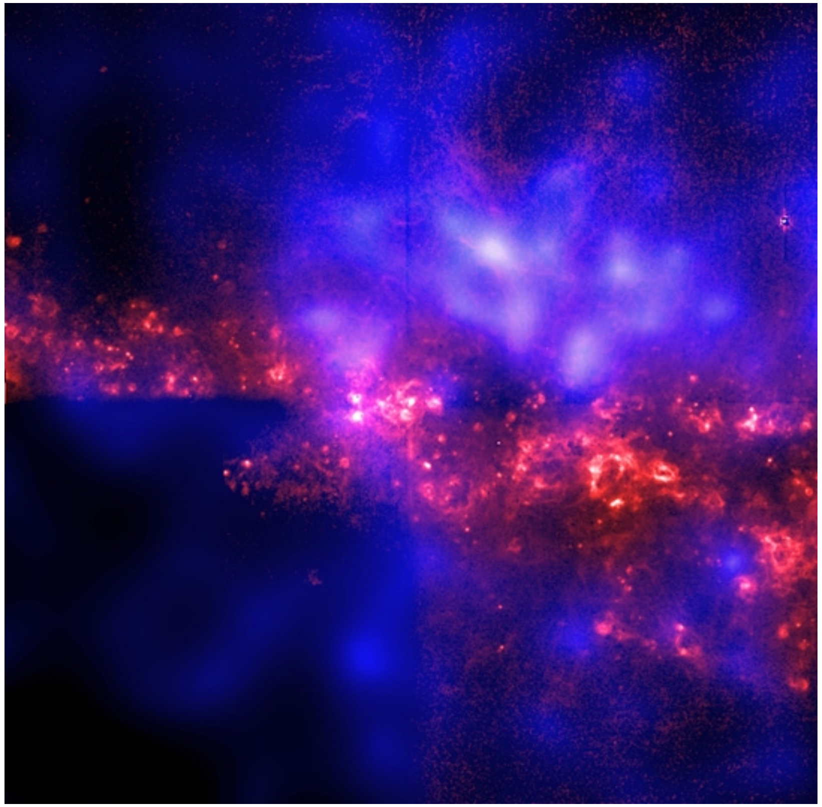
- Few hundred million solar masses at ~ 100 km/s
- KE ~ 3 x10^55 ergs
- Walter et al.

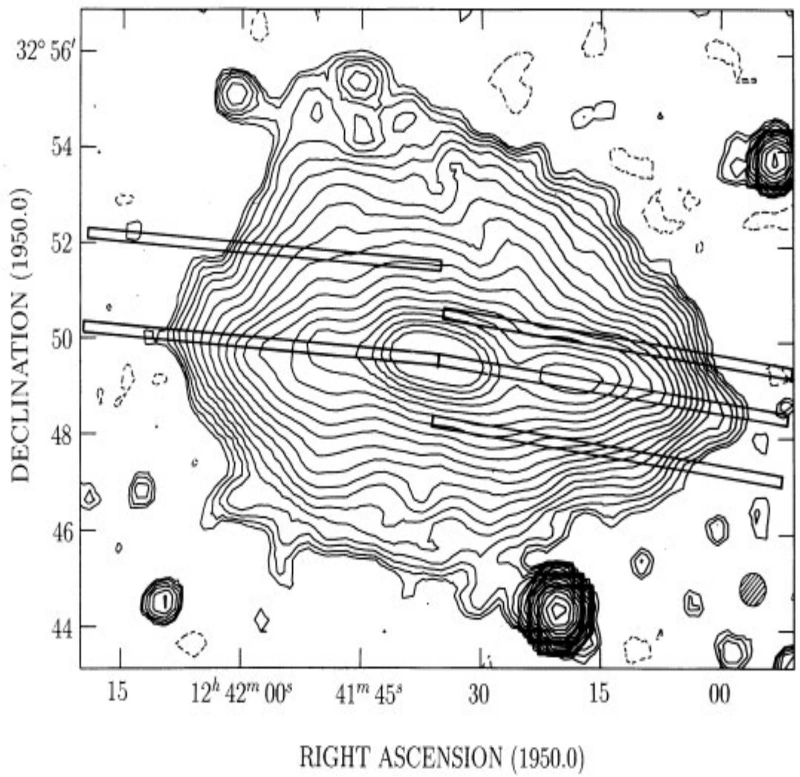
The Dusty Phase



- The entrained gas is dusty: radiation pressure?
- M82 with GALEX (Hoopes et al.)

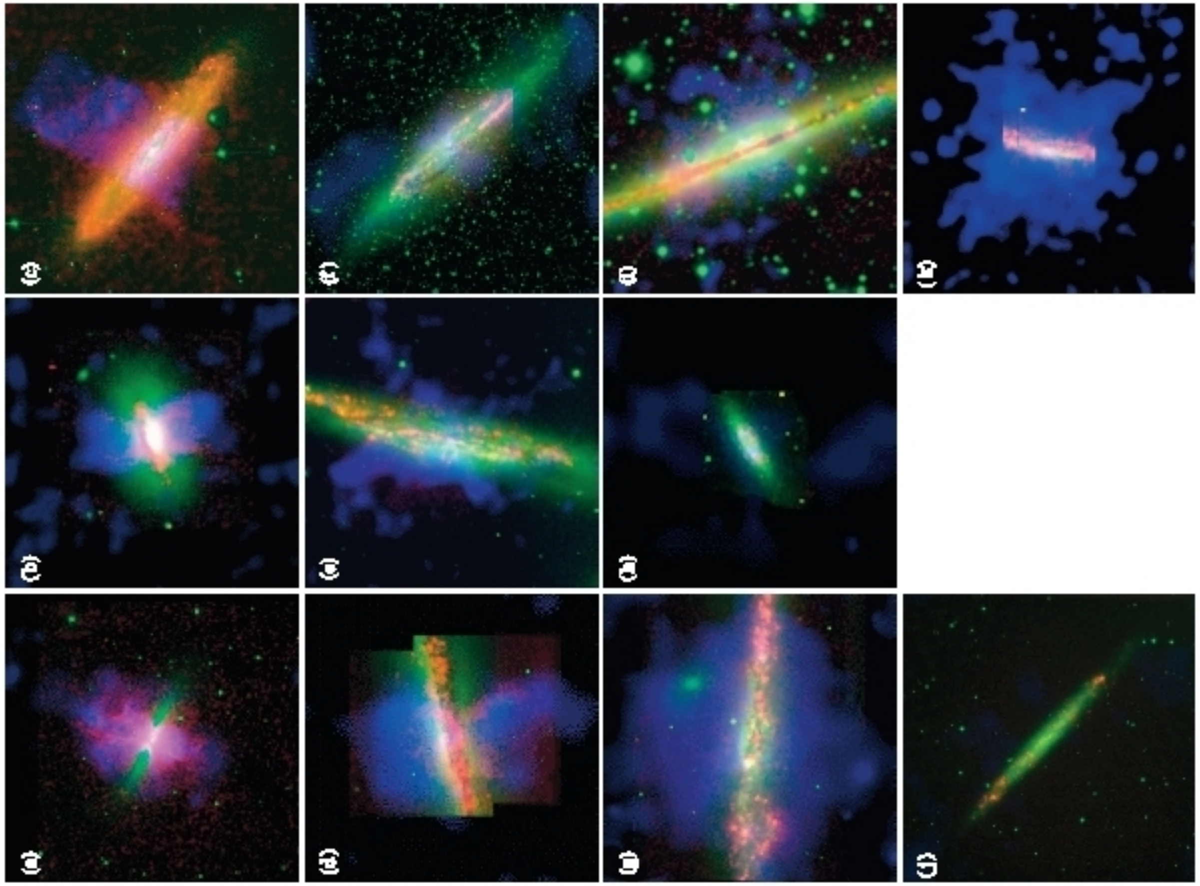
The Relativistic Phase





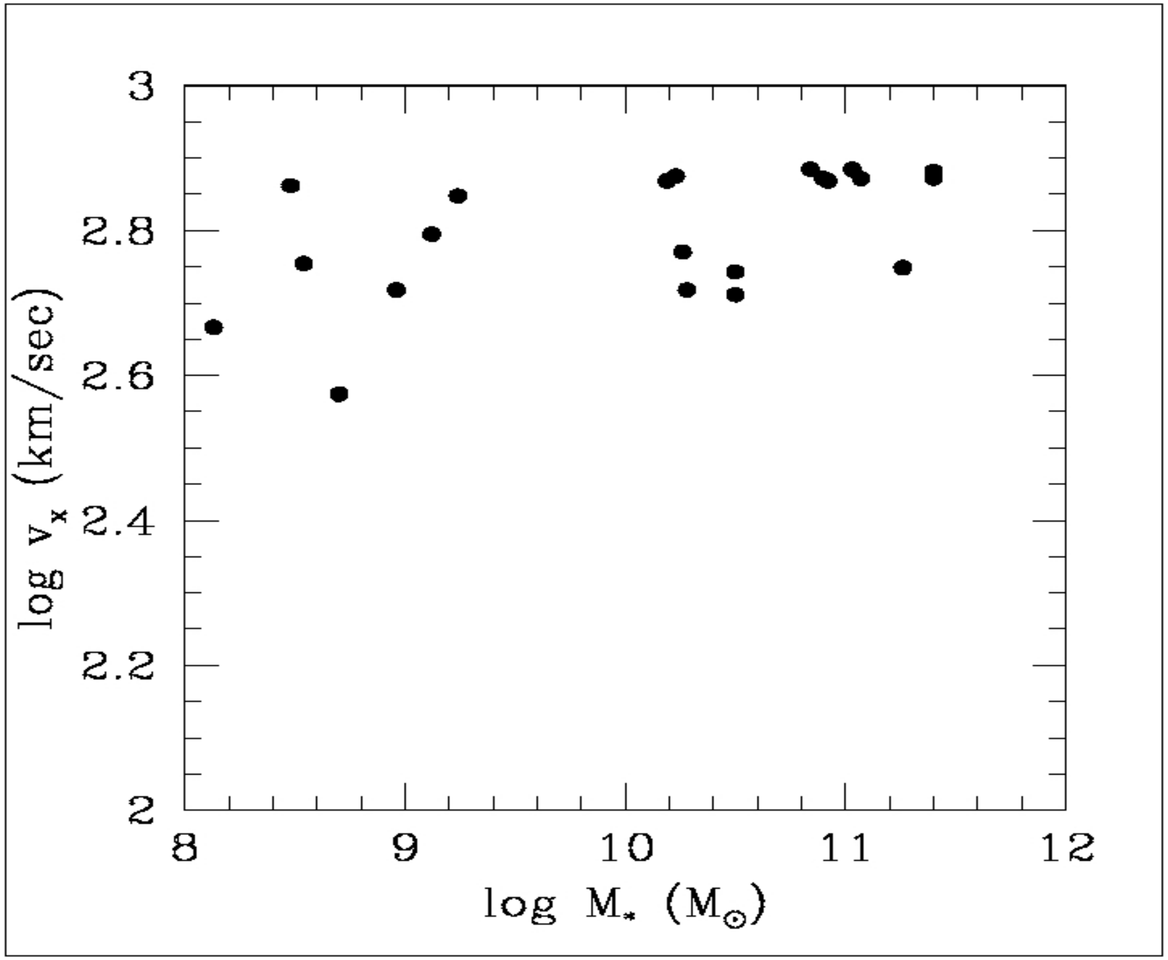
- Radio synchrotron emission from advected cosmic ray electrons and magnetic field
- NGC 4631 (Wang; Dahlem)

Demographics



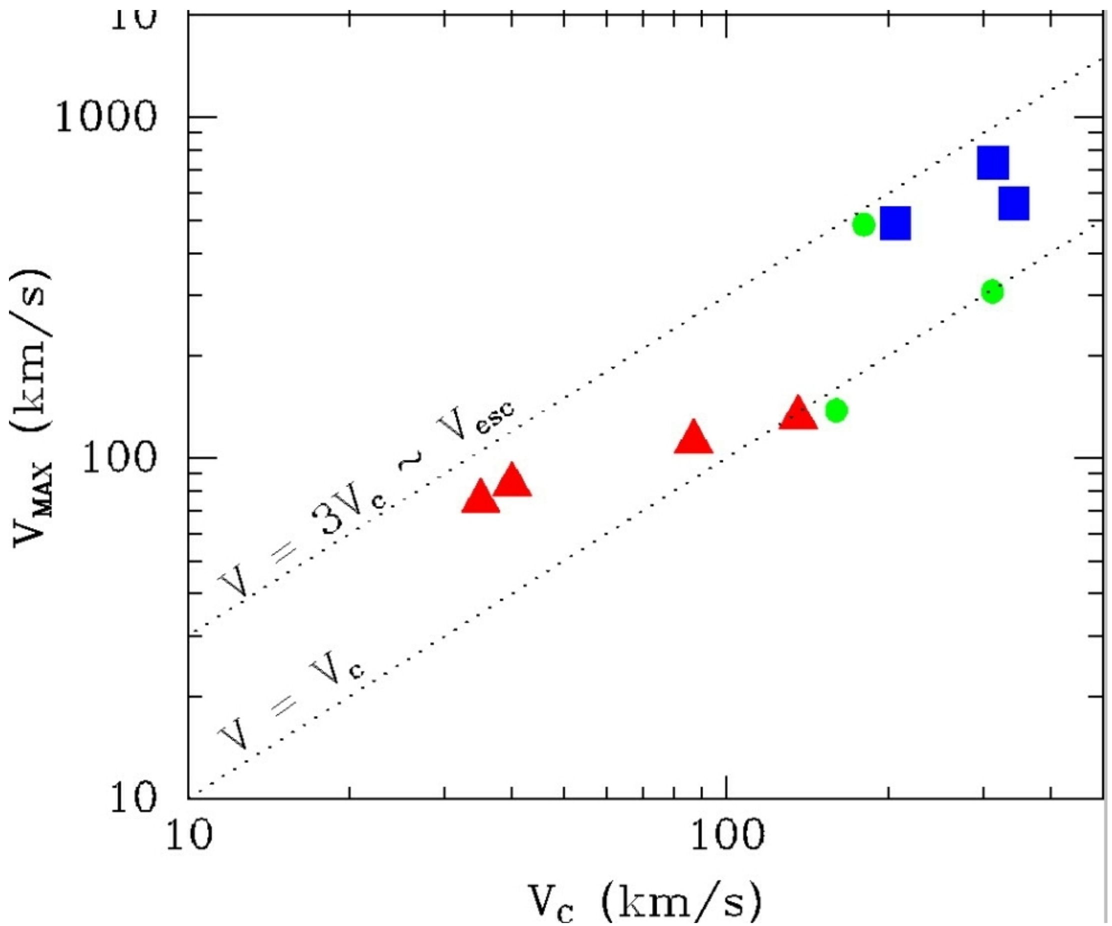
- Winds evident when SFR intensity > 0.1 solar mass/(year square-kpc) D. Strickland & TH

Do Winds Escape?



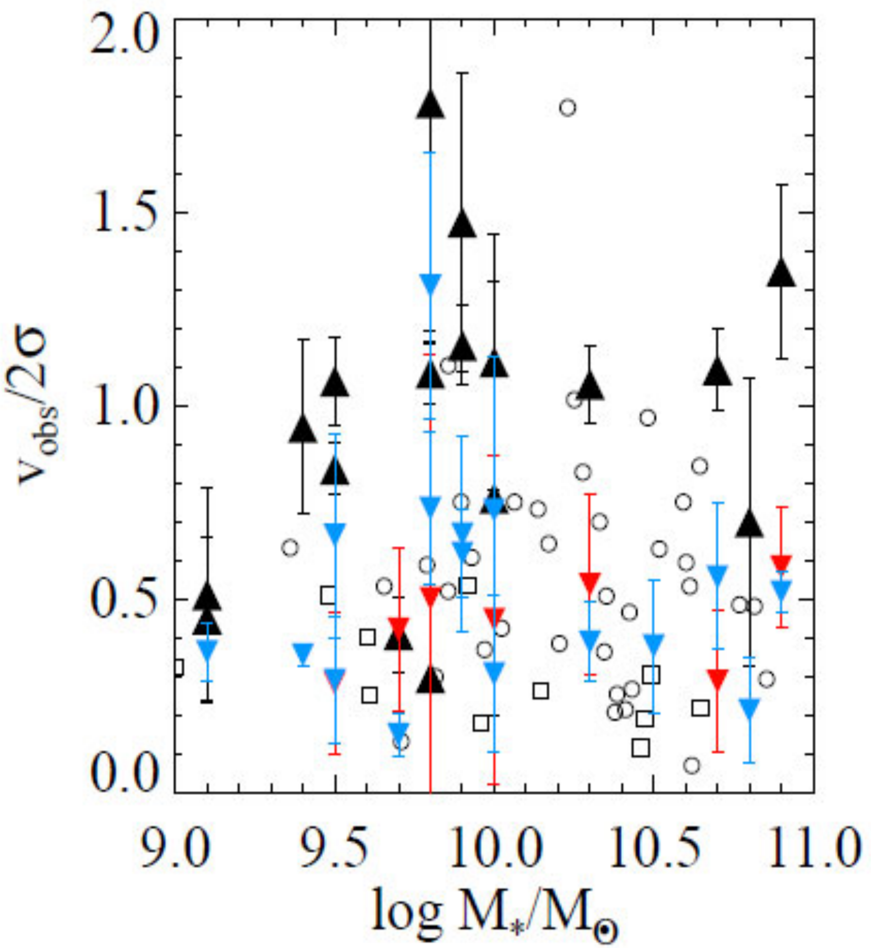
- X-ray temperature (velocity) invariant w/ mass
- Selective metal loss from low mass galaxies

Do Winds Escape?



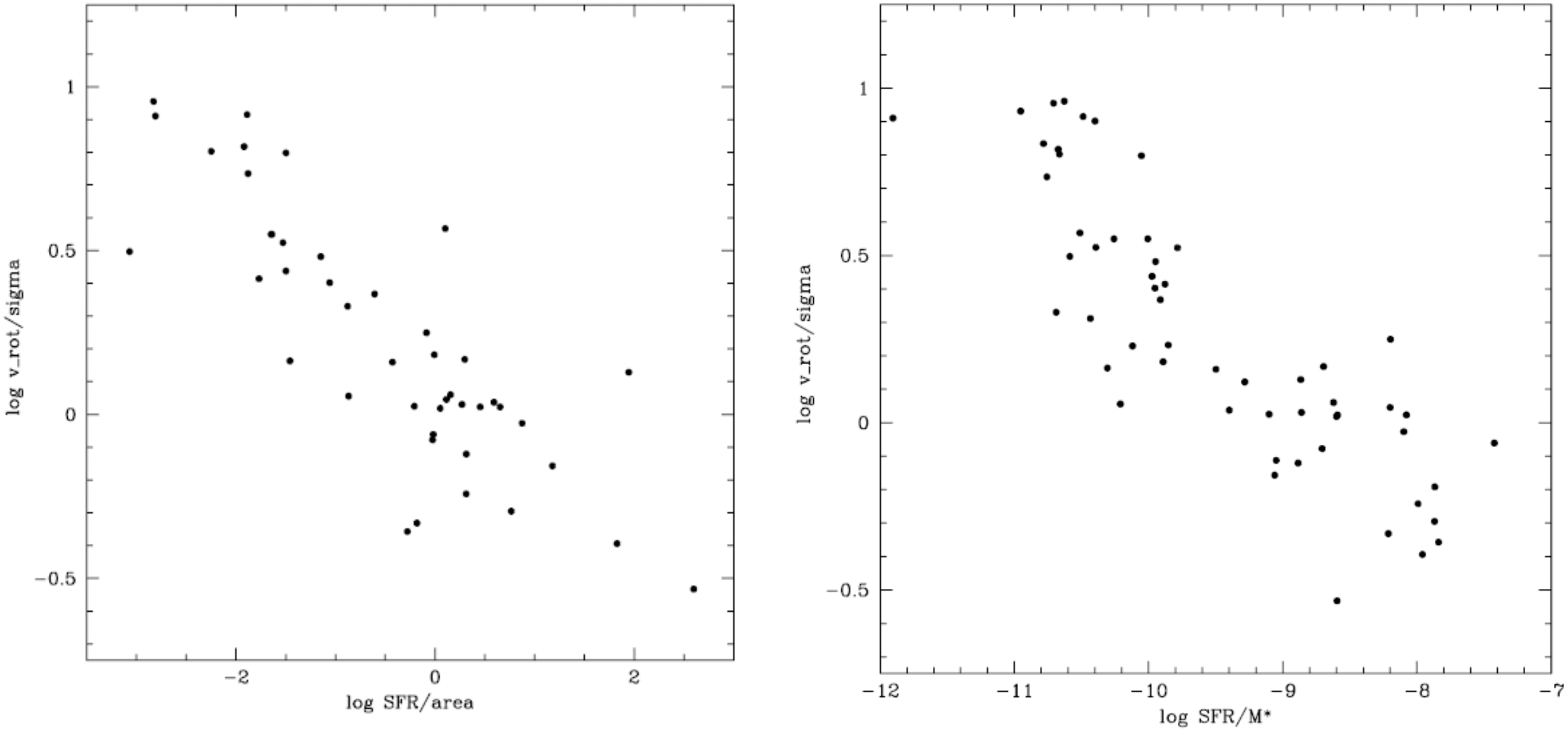
- C. Martin (see also Rupke et al.)
- Outflow speeds in cool gas < escape velocity
- Escapability is phase-dependent

Feedback at High Redshift?



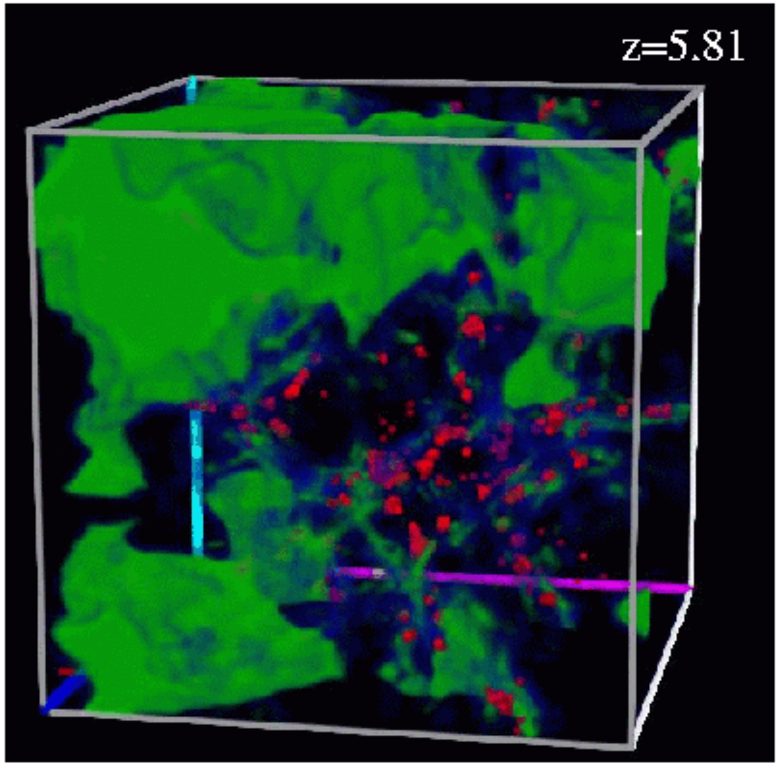
- What is the origin of the high velocity dispersions seen in the ionized gas in high-z galaxies?
- Feedback from massive stars or turbulence due to accretion of gas? Law et al.; Forster-Scheiber et al.
- Similar results in local analogs (Goncalves et al)

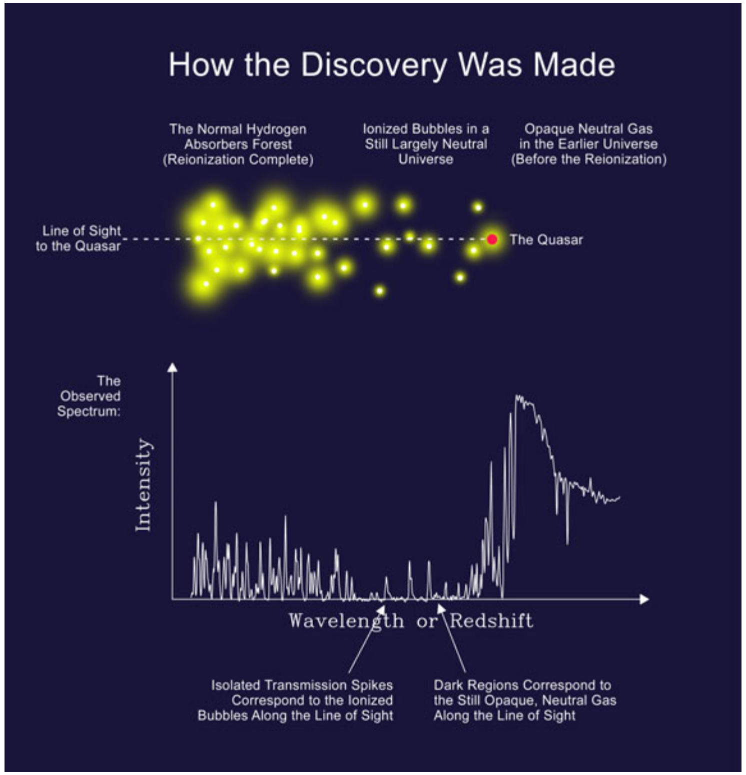
Clues in Low-z Starbursts



- A strong trend for increasing velocity dispersion in objects with higher SFR/M and SFR/area
- Supports the idea of feedback-driven turbulence

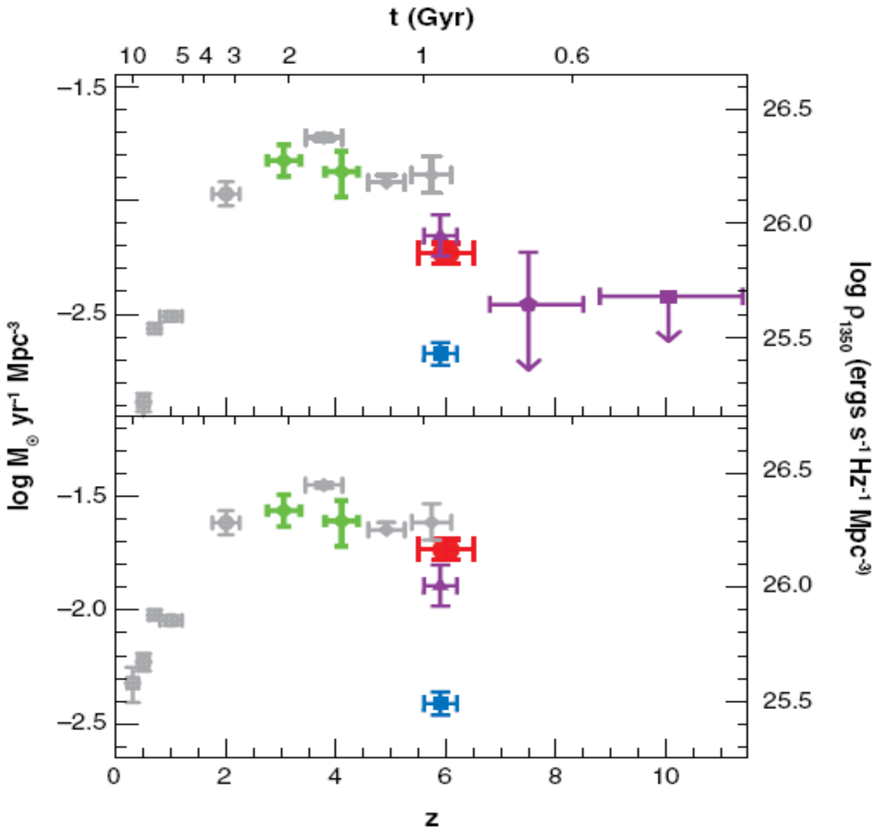
Reionization





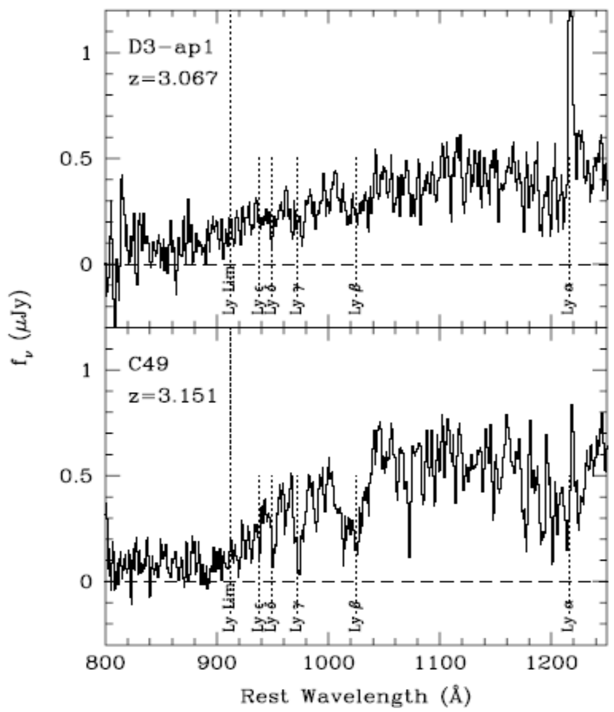
- WMAP – Reionization started early
- SDSS – It ended late
- The source (black holes vs. stars) is unclear

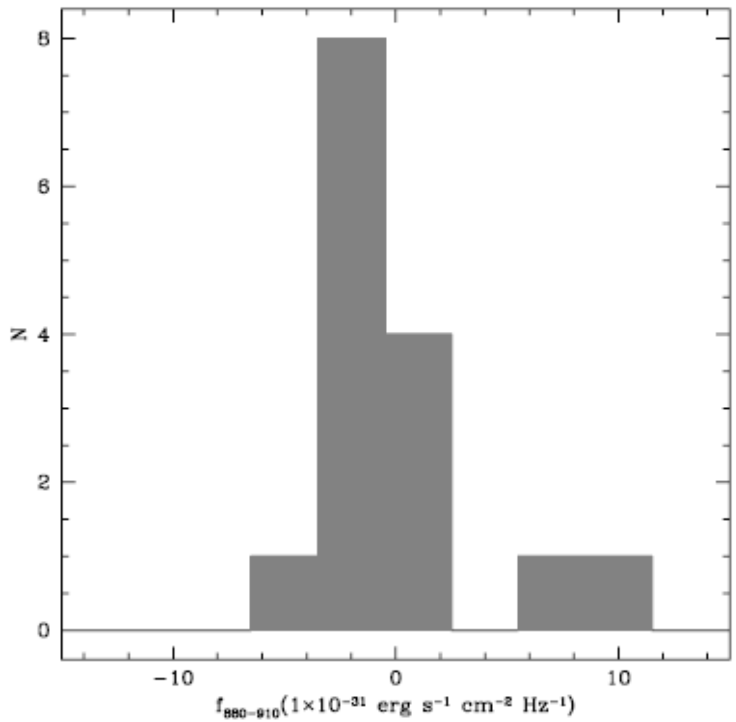
Reionization by Stars?



- The population of star-forming galaxies at z > 6 could be enough to reionize the universe (e.g. Bouwens et al.)
- But…what fraction of the ionizing radiation actually escapes from these galaxies?

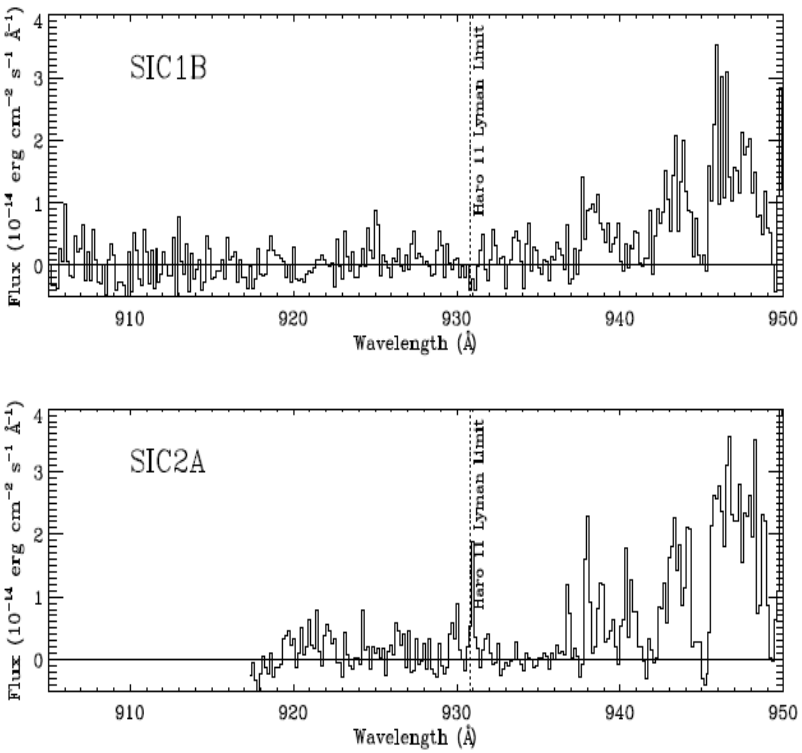
Direct measures at high-z

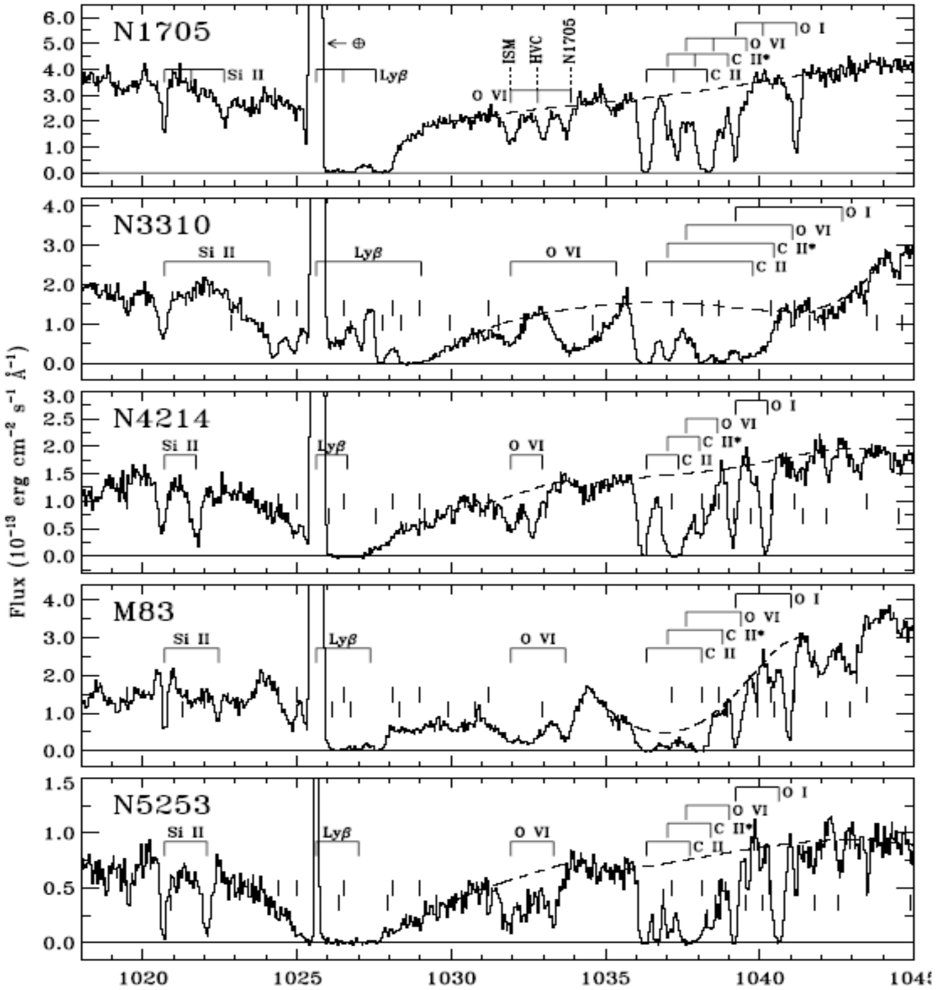




- Only a minority (~15%) of Lyman Break galaxies show a significant escape of ionizing radiation
- What determines this?
- Shapley et al.

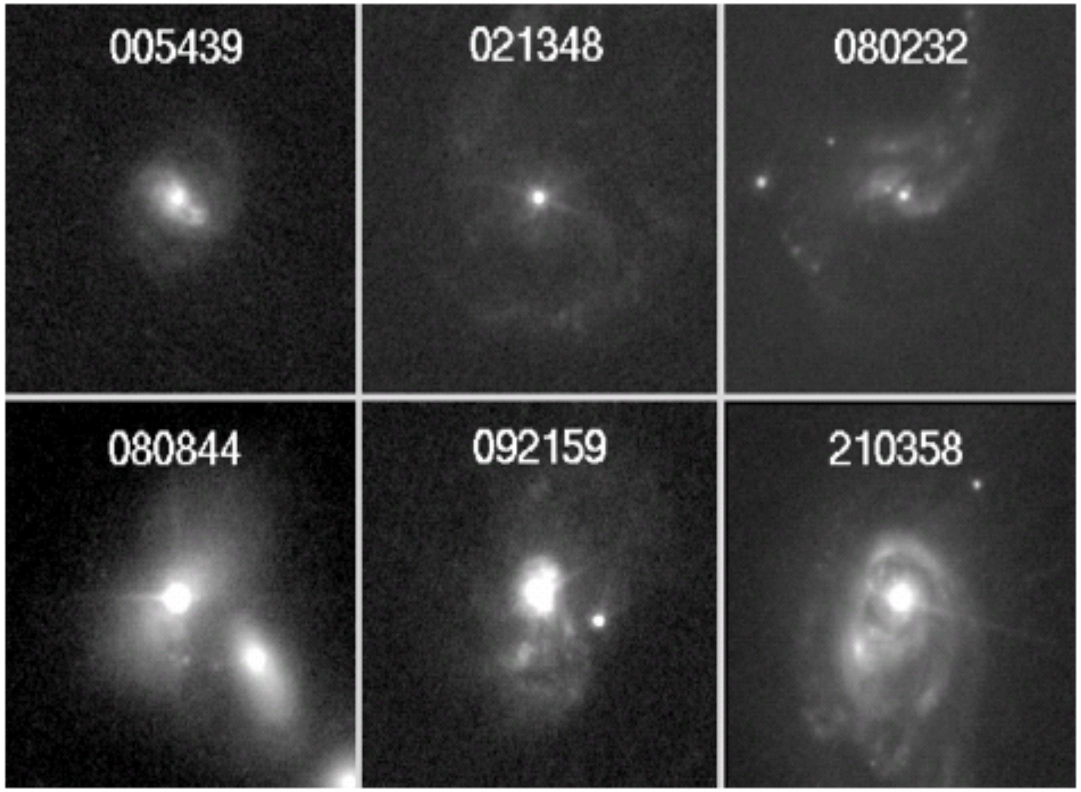
Clues at low-redshift





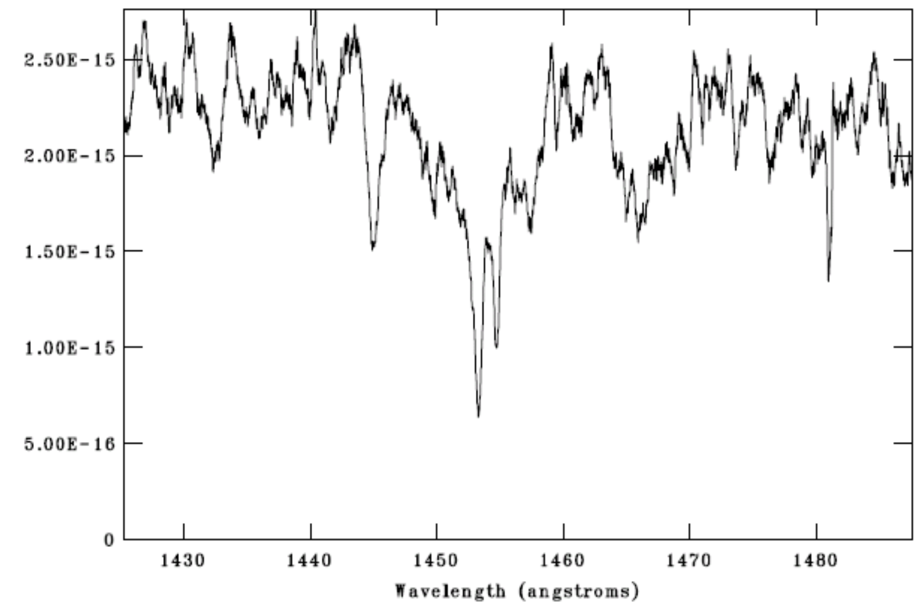
- FUSE data for starbursts: no detection of escaping Lyman continuum radiation (Grimes et al.)

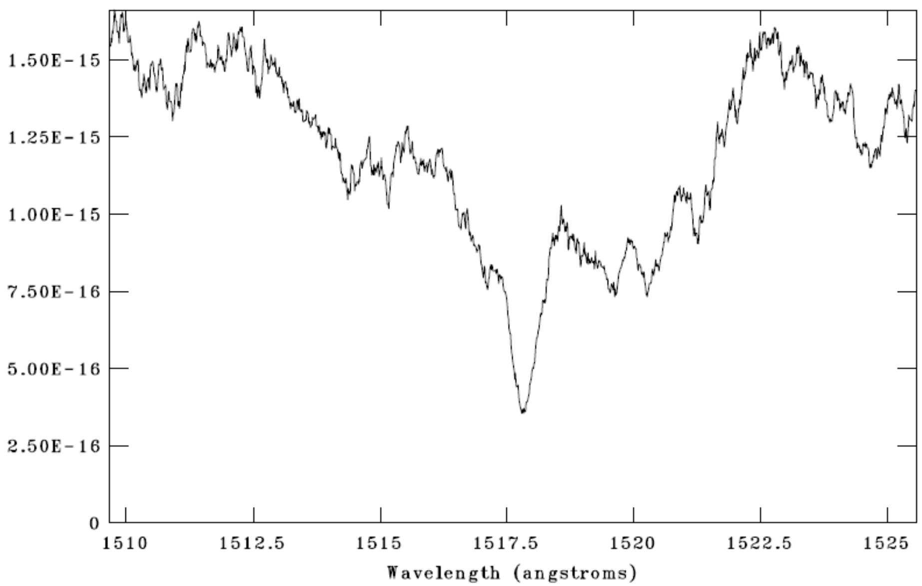
A possible breakthrough?



- A subset of local extreme starbursts (“Lyman Break Analogs”) have massive (few billion solar mass), compact (~100 pc) dominant central objects

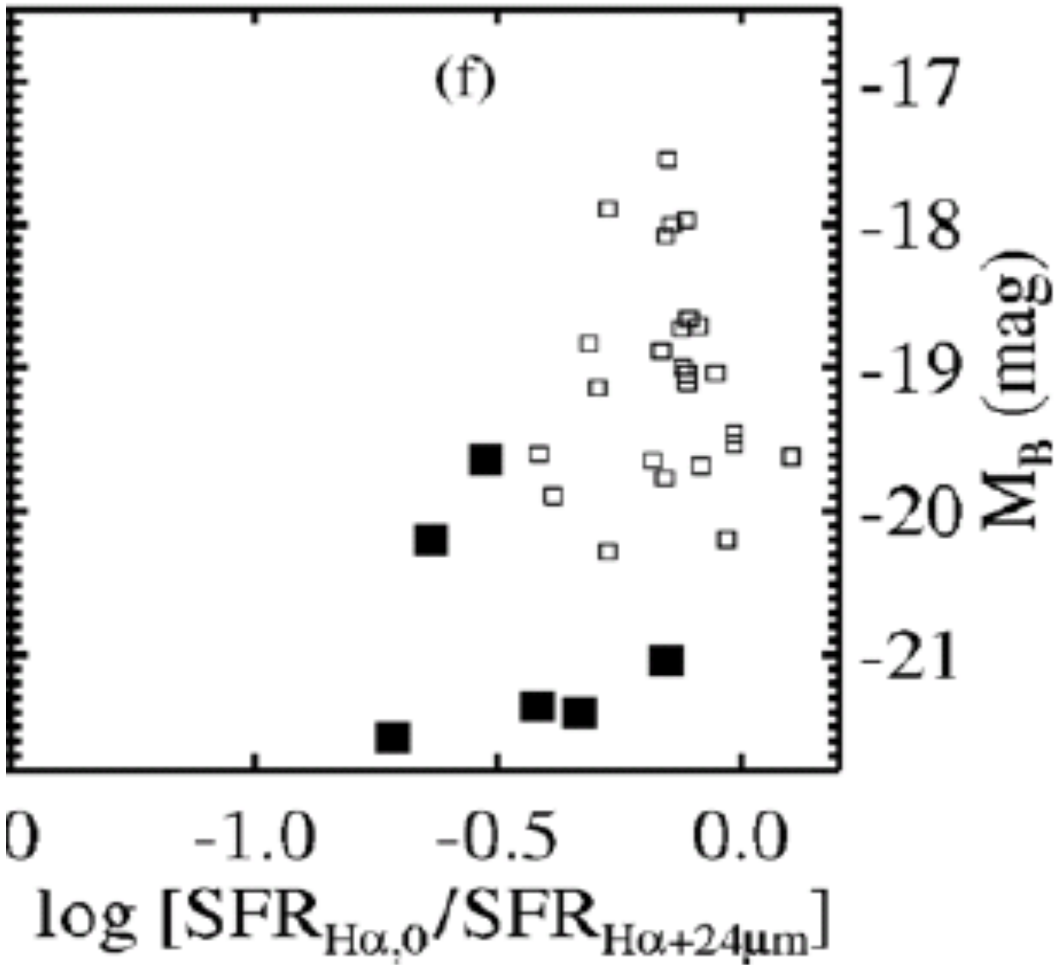
The Escape of Lyman Continuum?





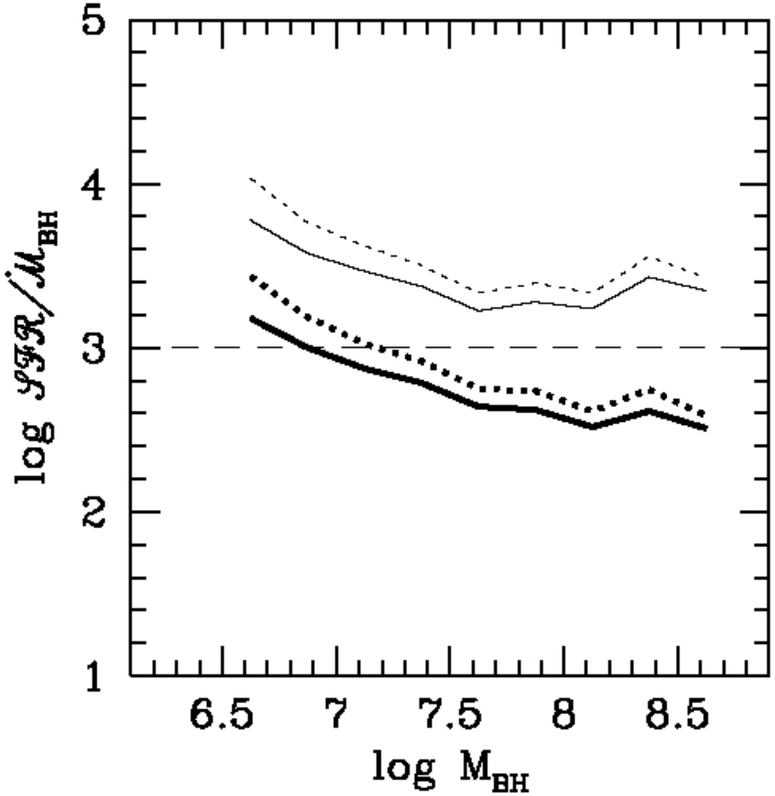
- HST COS FUV
- These galaxies are optically-thin in the strongest lines from the HI phase
- Outflowing gas is detected at velocities of up to 1500 km/s

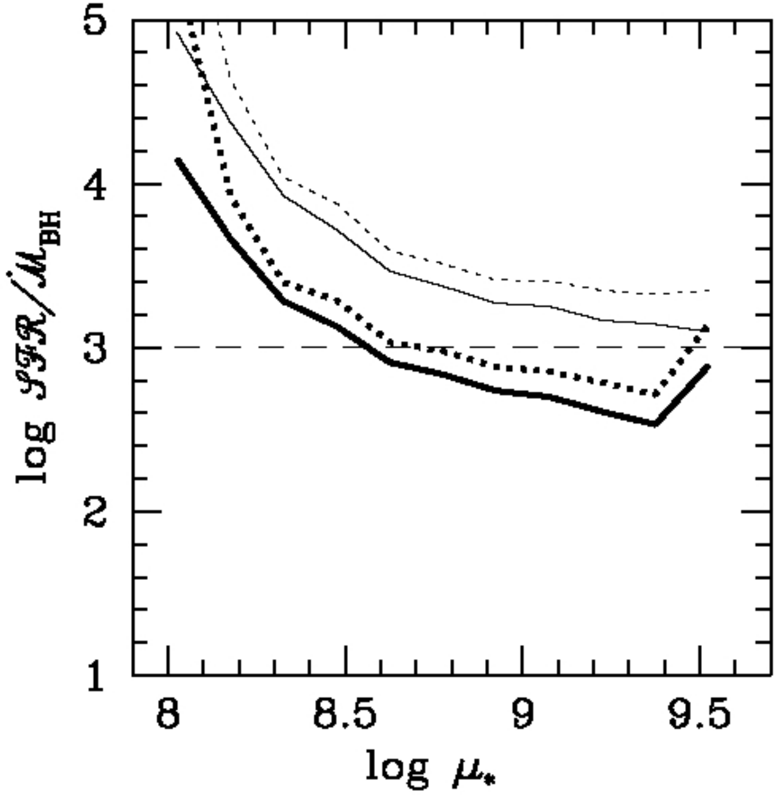
Consistent with ‘Weak’ H-alpha



- Overzier et al.
- Will need confirmation by direct observations below the Lyman edge

The Starburst-AGN Connection

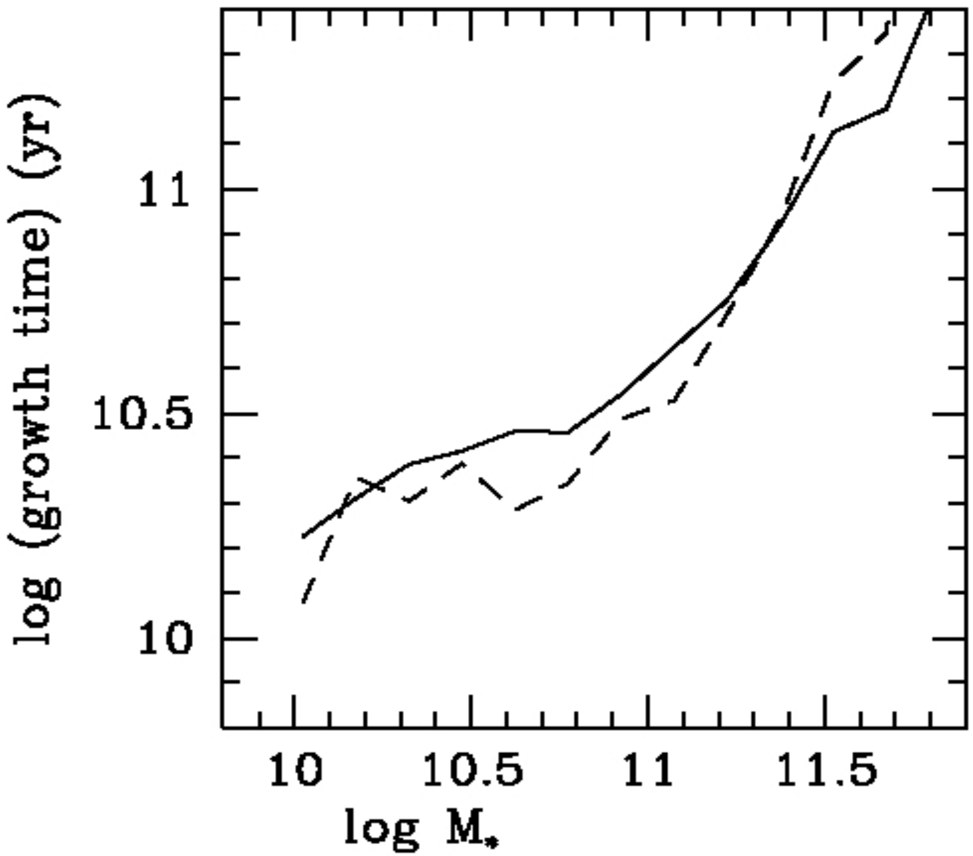




> Ratio of SF/black-hole-growth: volume average over early-type galaxy population is ~1000

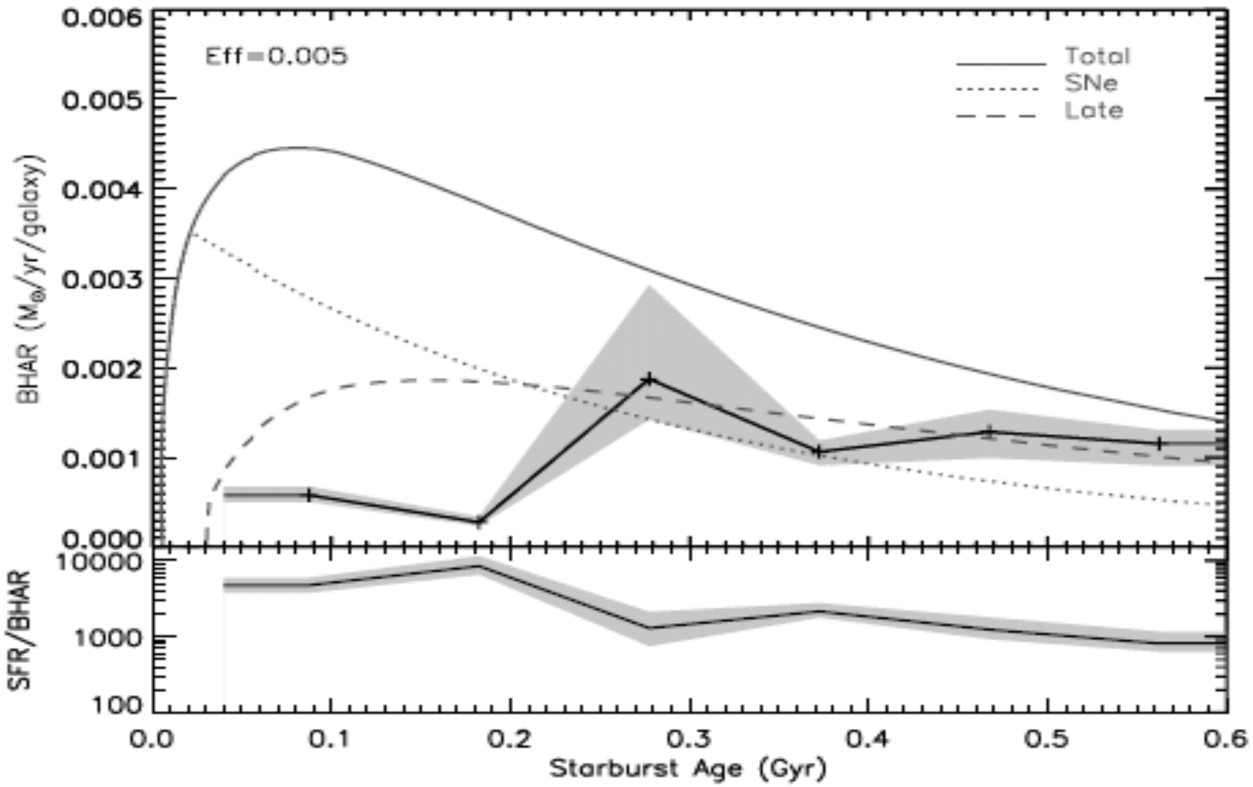
> Much larger ratio for disk-dominated galaxies

COUPLED DOWNSIZING



- The mass-doubling timescales of the populations of black holes and bulges both increase in parallel with increasing mass

The Post-Starburst/AGN Connection



> The growth of BH tracks stellar mass loss, but only after the supernova-dominated phase ends

> BH growth limited by stellar feedback – Wild et al

> Implications for the M_BH vs. M_bulge relation

Summary

- Starbursts are important!
- They provide an excellent local laboratory
- The key property is the intensity (SFR/area)
- Explains their systematic properties
- Only in local starbursts can galactic winds be studied in detail: multiphase phenomena
- Reionization may take extreme conditions
- The processes that produced the bulge-black hole connection in the fossil record are still at work today