Feedback from Massive stars:
Global Manifestations & Cosmological Implications

Goal: Discuss the potential impact of starburst-driven winds on the evolution of galaxies & the IGM

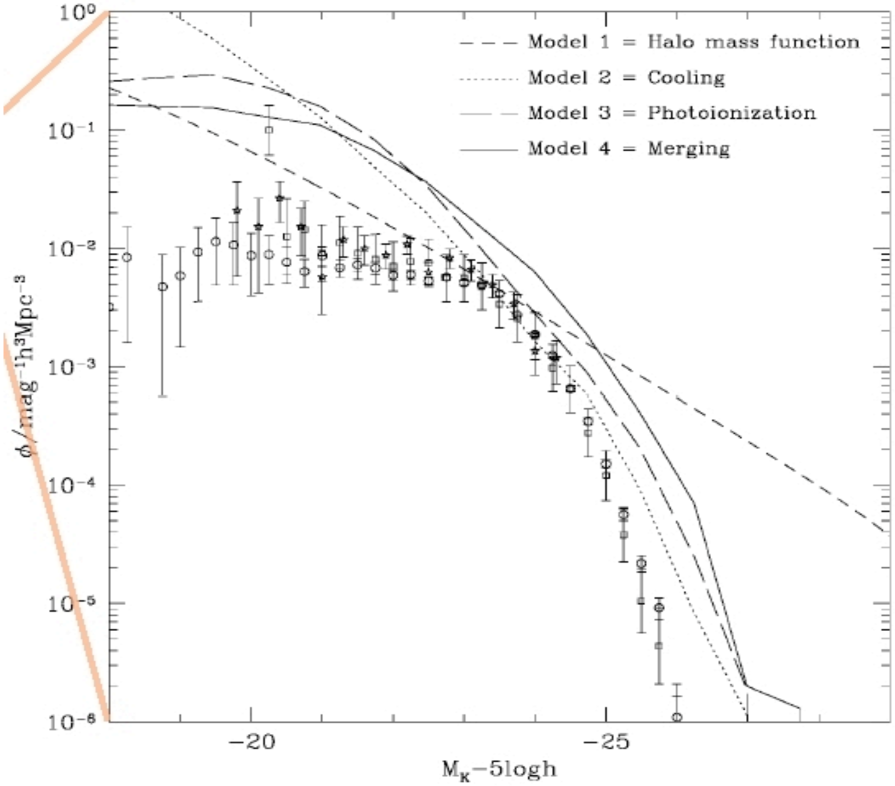
OUTLINE

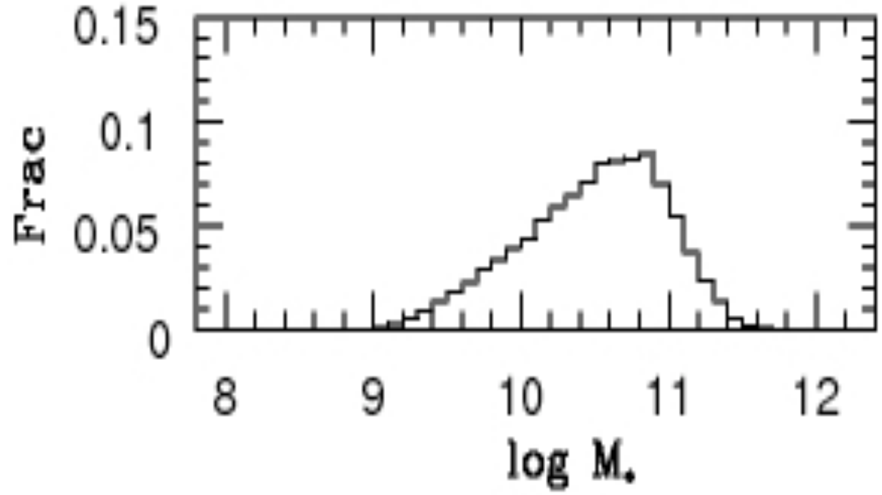
1) MOTIVATION
2) BASIC WIND PHYSICS
3) WIND PHASES
4) OUTFLOW RATES
5) DO WINDS ESCAPE?
6) CLUES FROM ALMA

I) MOTIVATION

Feedback and galaxy evolution

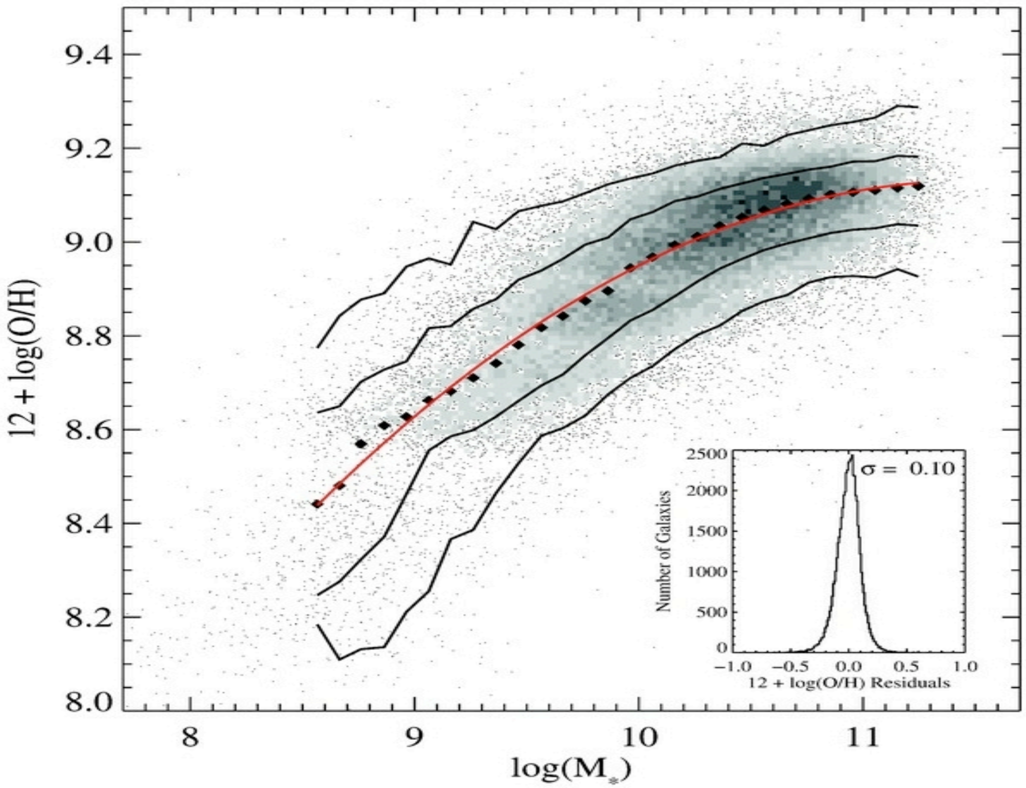
Benson et al. (2003)





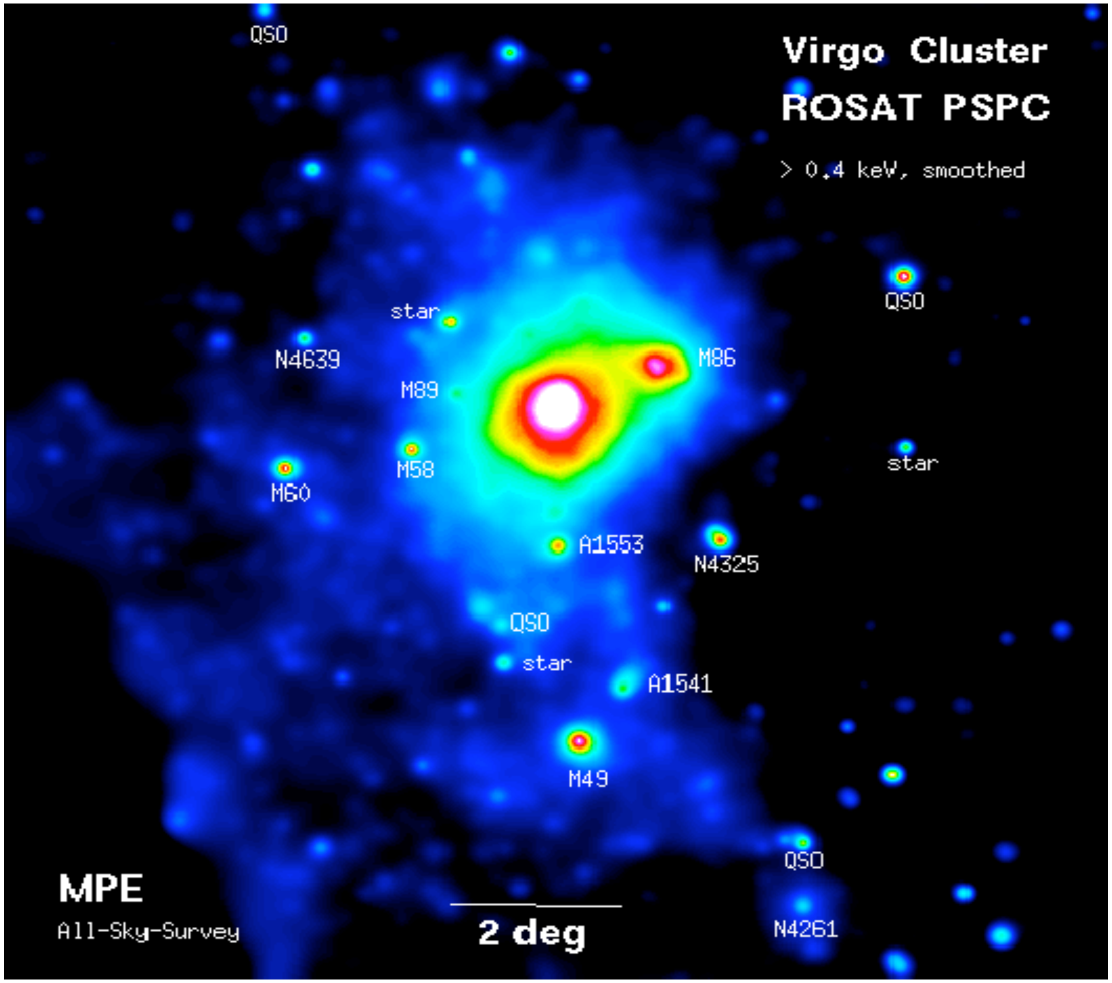
- Unlike dark matter, galaxies have a characteristic baryonic mass scale: Why?
- Feedback needed to cure “overcooling” in both low- and high-mass dark matter halos

Feedback & Galaxy Evolution



- The mass-metallicity relation for galaxies implies the selective loss of metals from the shallower potential wells (Tremonti et al.)

Feedback & the IGM



- The mass of metals in the intracluster medium is several times that in galaxies

Some global considerations: are massive stars enough?

- Supernovae (plus stellar winds) supply 10^49 ergs in kinetic energy per solar mass of stars formed
- This is ~10^60 ergs in KE per L* galaxy (ignoring radiative cooling)
- The corresponding specific kinetic energy v ~ 1000 km/s
- This exceeds the escape velocity for all but the most massive galaxies

The key questions

Massive stars can do the job in principle

We see starburst-driven galactic winds

BUT

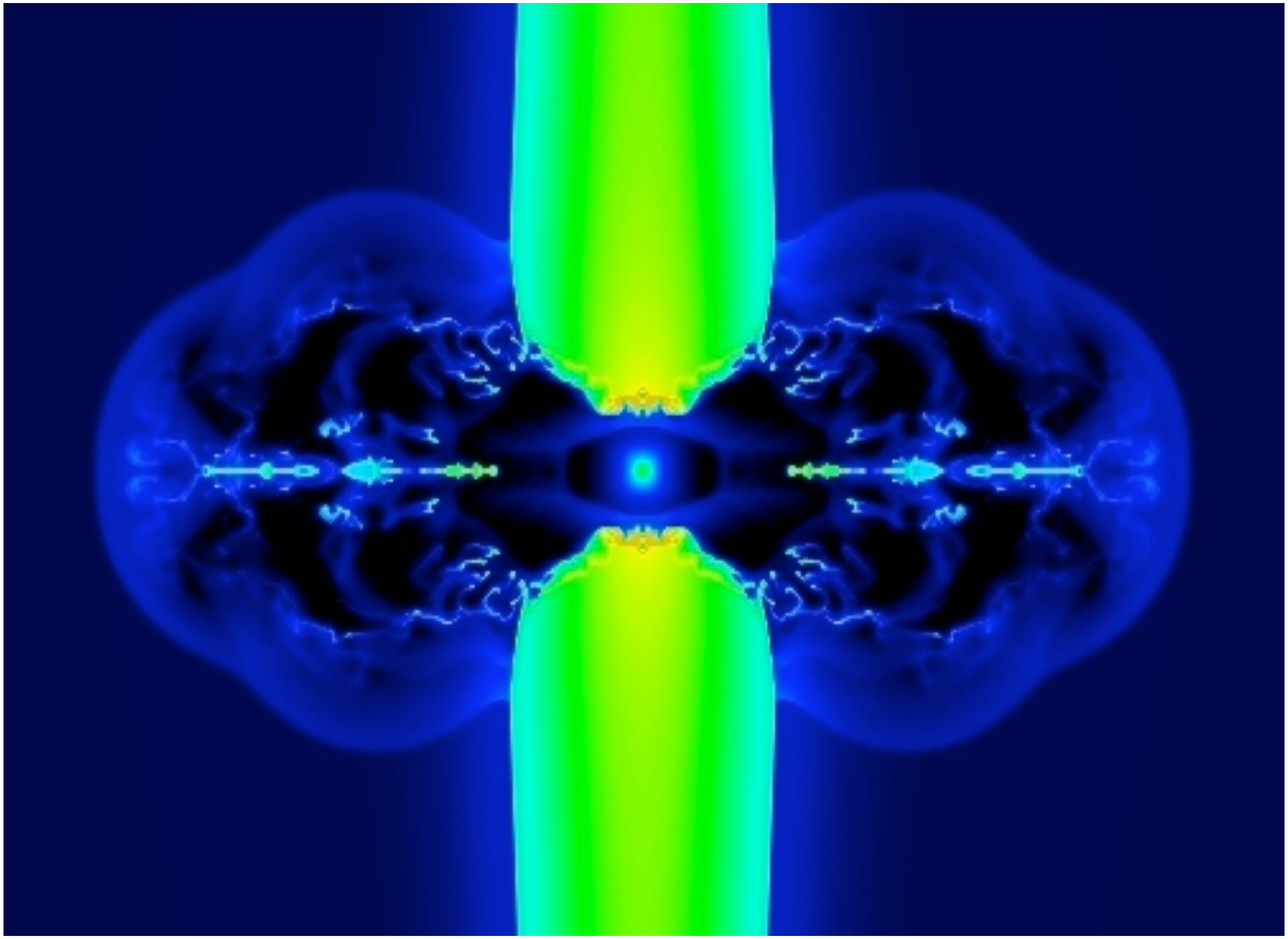
- What are the transport rates in these winds?

  Mass outflow rate/SFR

  Energy outflow rate/energy injection rate

  Metals-out/metals-retained
- Do these outflows escape the galaxy and make it to the IGM (fountain vs. wind)?
- Upon what physical parameters do the answers to these questions depend?

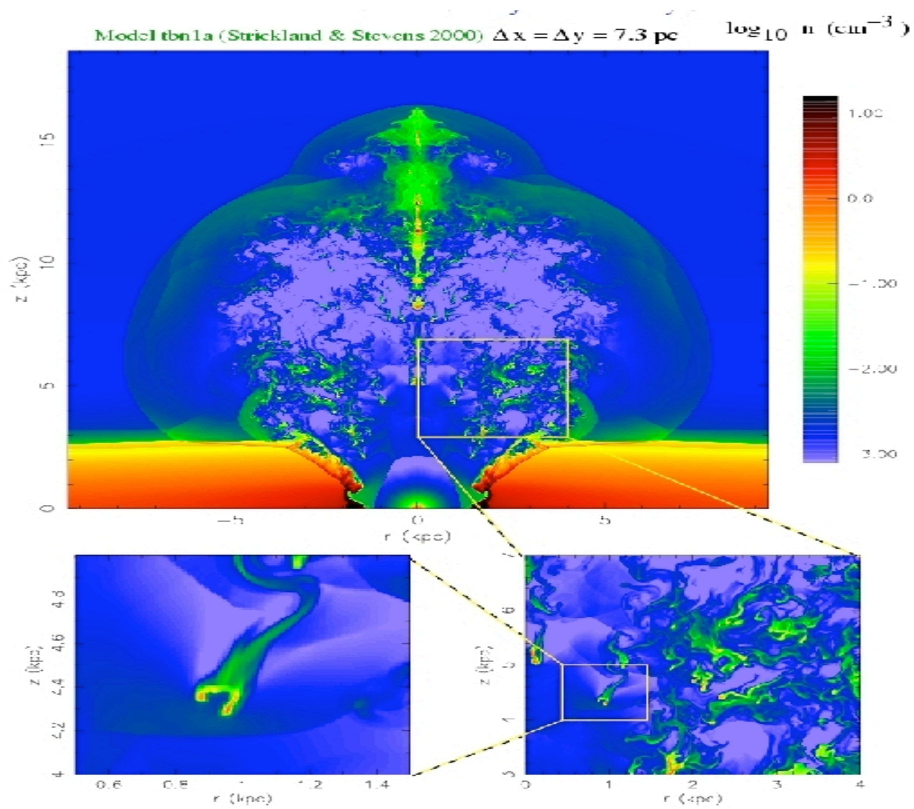
II) BASIC WIND PHYSICS



ENERGETICS/DYNAMICS

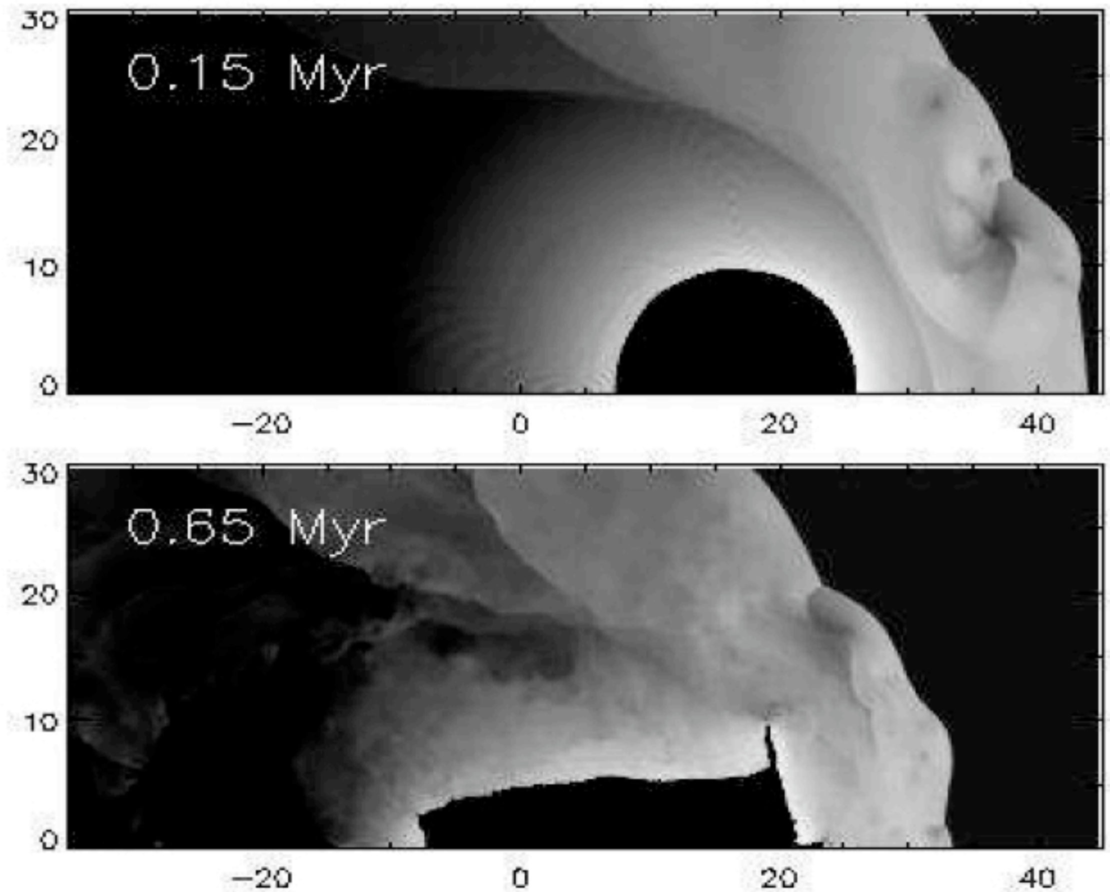
- Kinetic energy from massive stars
- IF radiative losses are not too large: the collective effect is a bubble of very hot over-pressured gas
- Expansion preferentially along minor axis
- “Blow Out” into galactic halo
- Weakly collimated bipolar wind

BLOW OUT INTO THE HALO



- Most of the volume is occupied by the very hot and tenuous wind fluid
- Most of the emission comes from dense material interacting with the wind fluid

WIND-CLOUD COLLISION

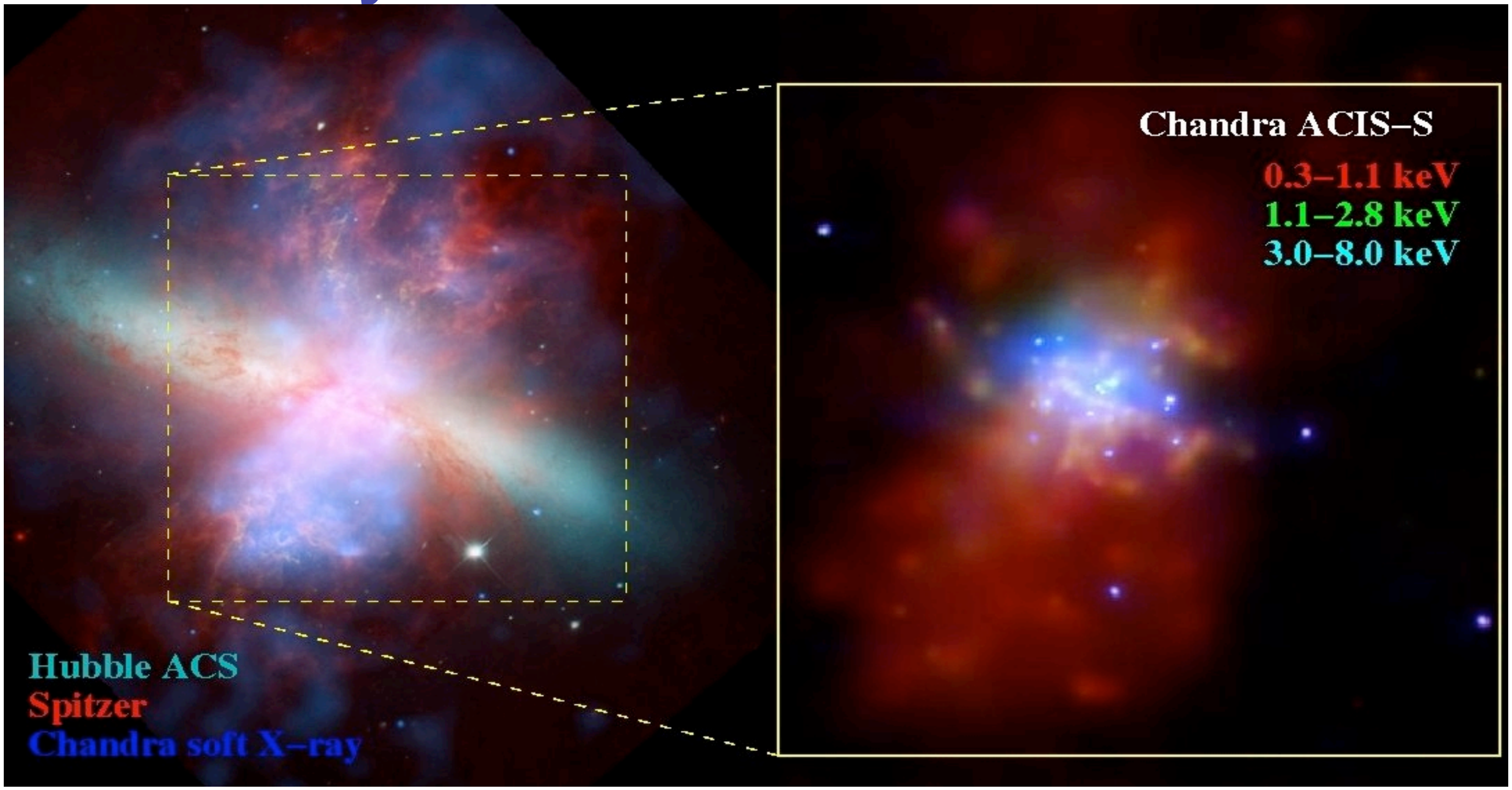


- Soft X-rays from wind/cloud interface
- Cloud is accelerated by wind
- A. Marcolini et al.

III) WIND PHASES

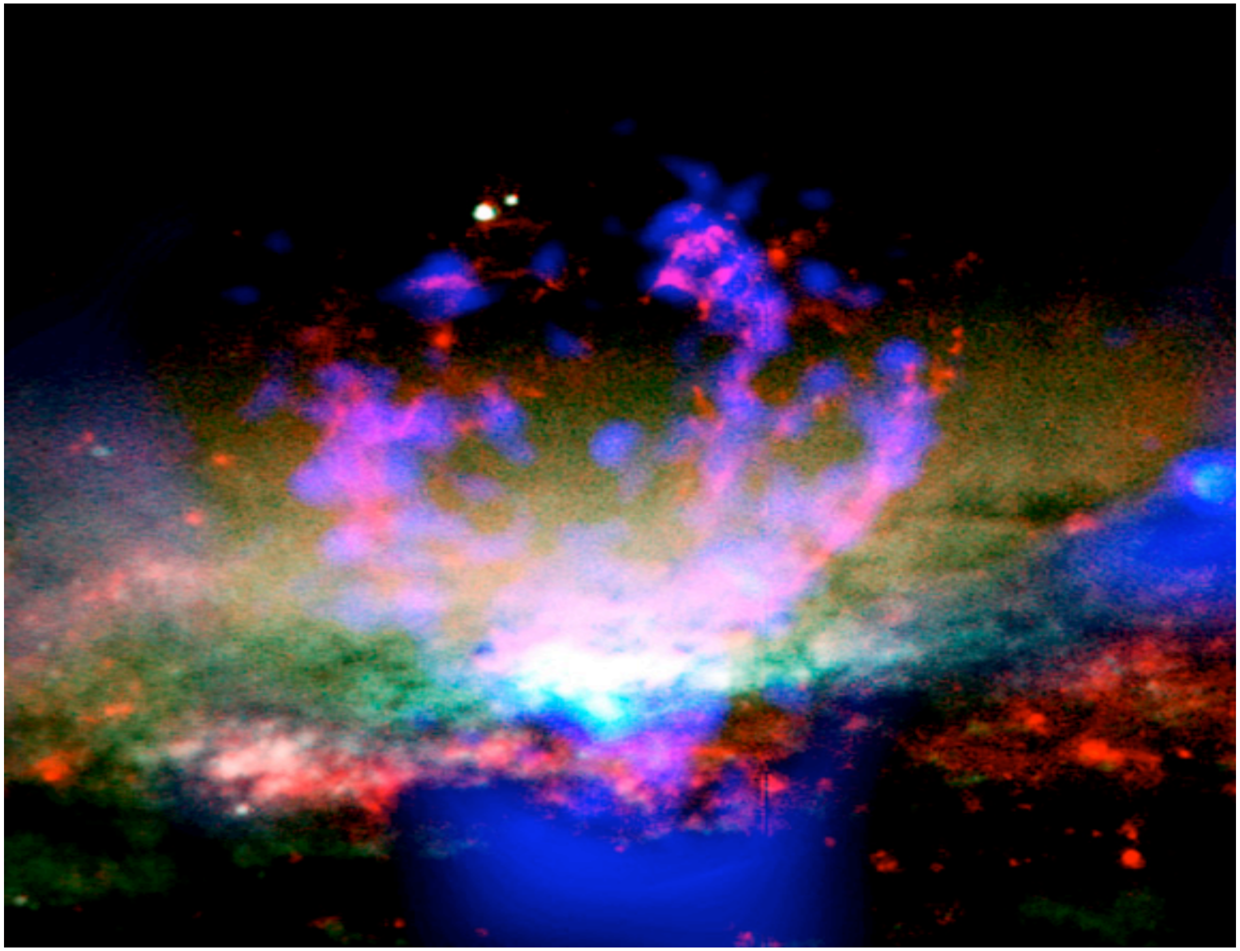
- M82 w/ Spitzer mid-IR & Chandra & HST

The Very Hot Phase: the wind fluid



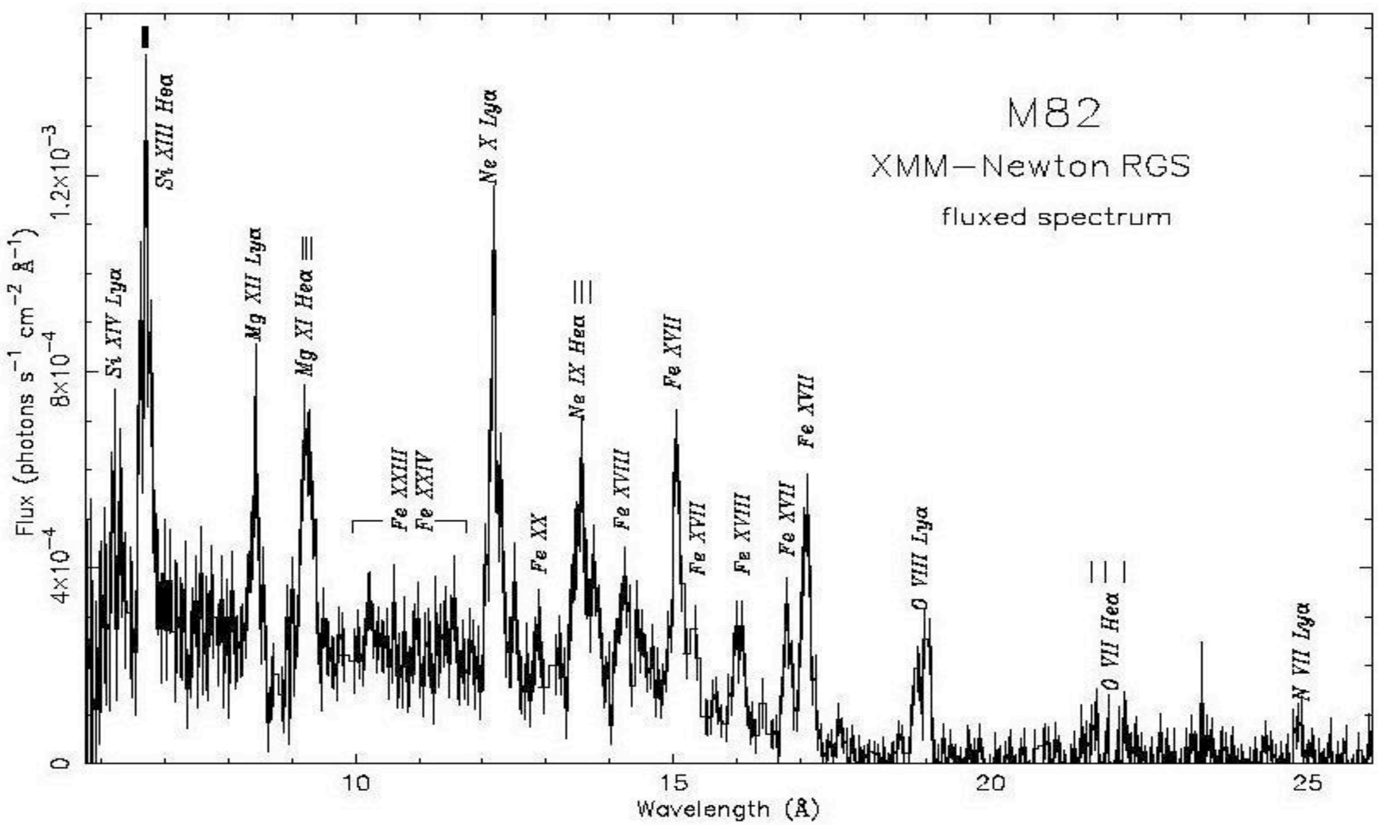
- Very hot (T ~ 60 million K): implies v_term ~ 2000 km/s
- Tenuous (~0.1 cm^-3)
- Detected only in M82 central region (adiabatic expansion & cooling causes it to disappear outside this region)

THE SOFT X-RAY PHASE



Soft X-rays trace gas at T ~ 3 to 10 Million K
Corresponding velocity ~500 to 800 km/s
At the interface between the wind and clouds

ABUNDANCES IN THIS HOT GAS

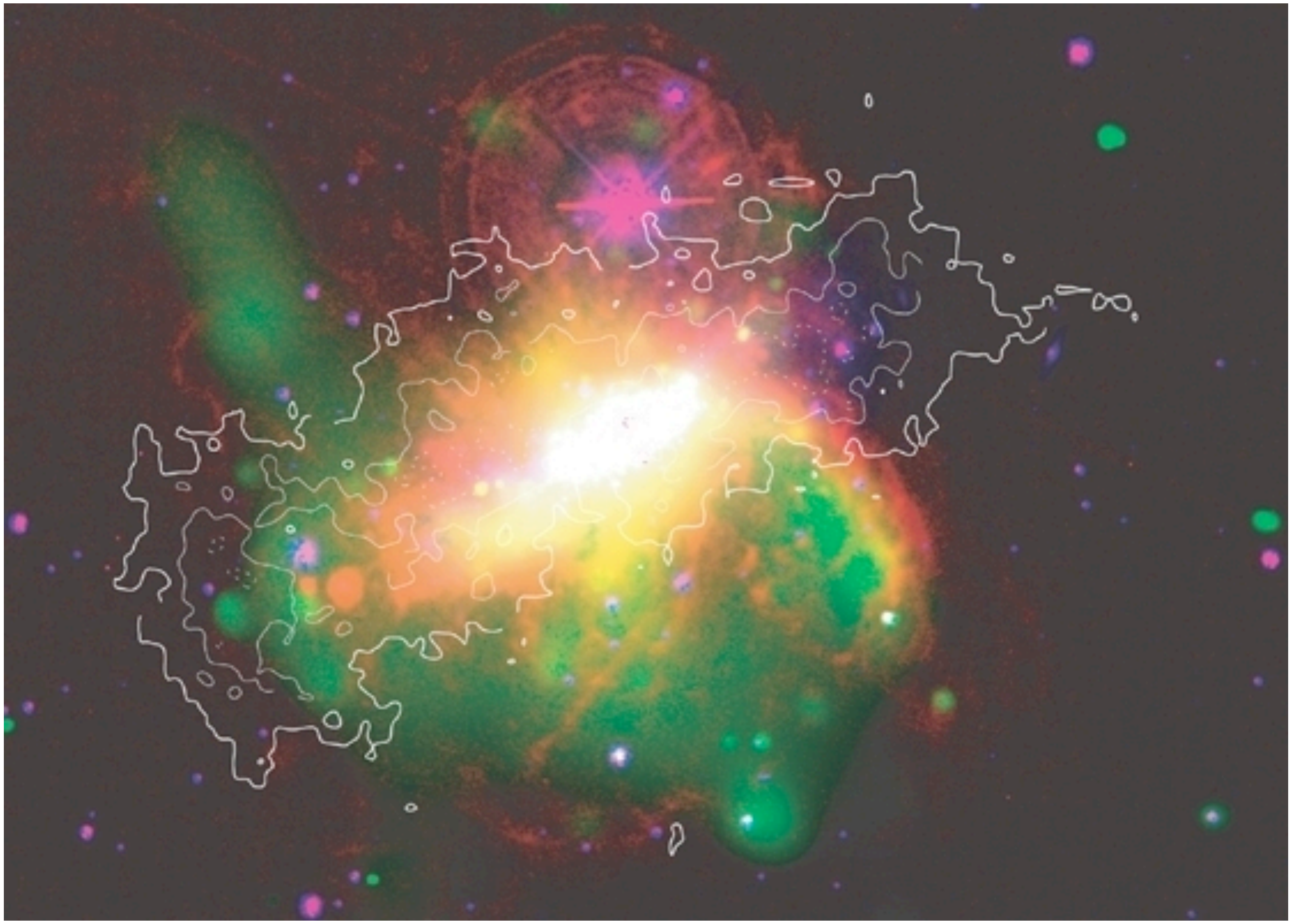


X-ray spectrum of the superwind starburst galaxy M82

European Space Agency

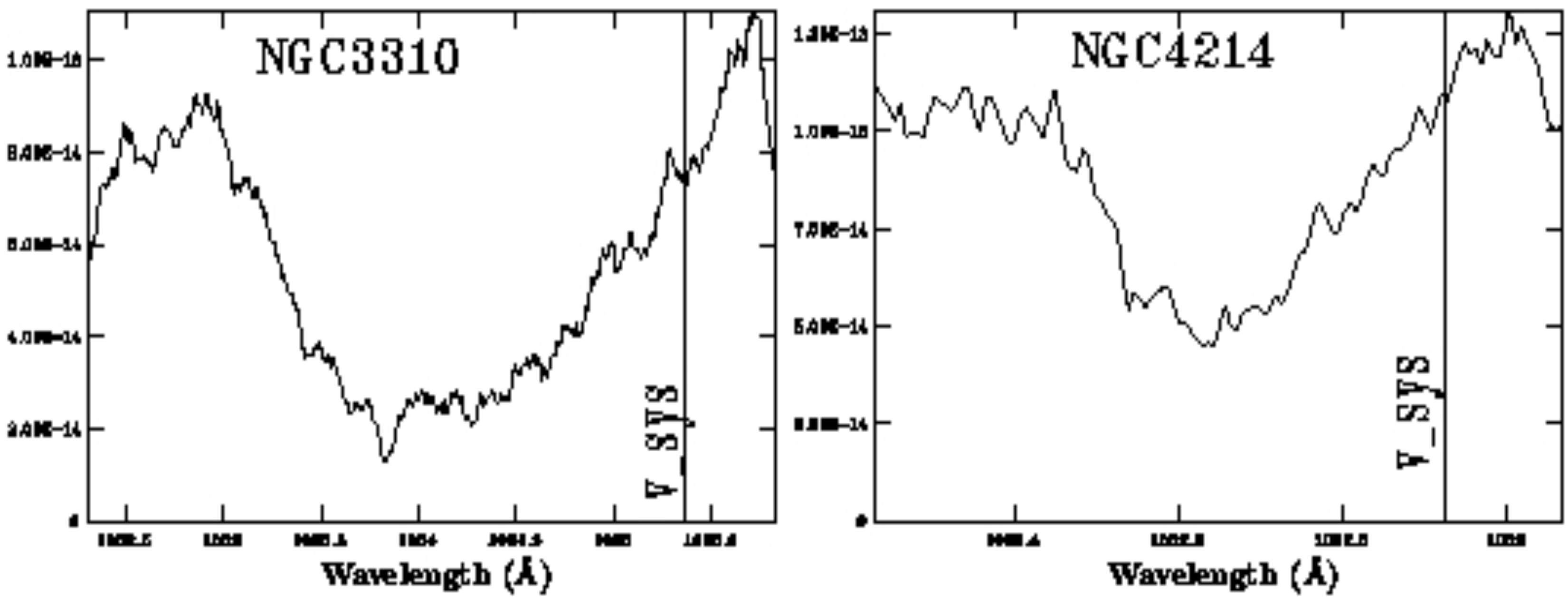
- Alpha/Fe several times solar
- Consistent with wind driven by core-collapse supernovae

THE WARM PHASE



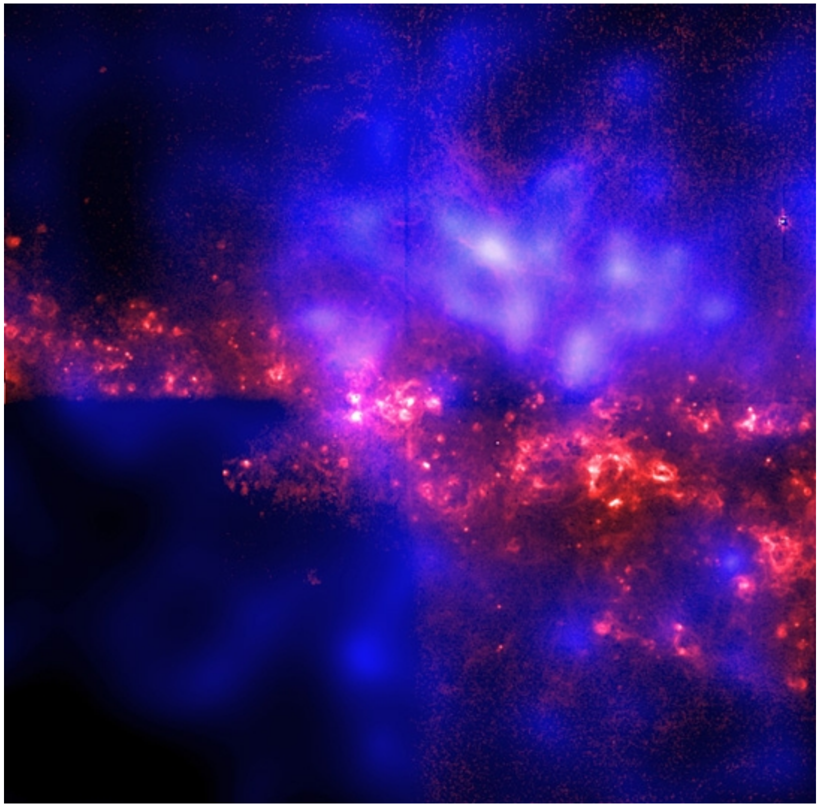
- Optical emission from clouds accelerated by wind
- Velocity ~one to few hundred km/s
- NGC 1569 (Martin et al.)

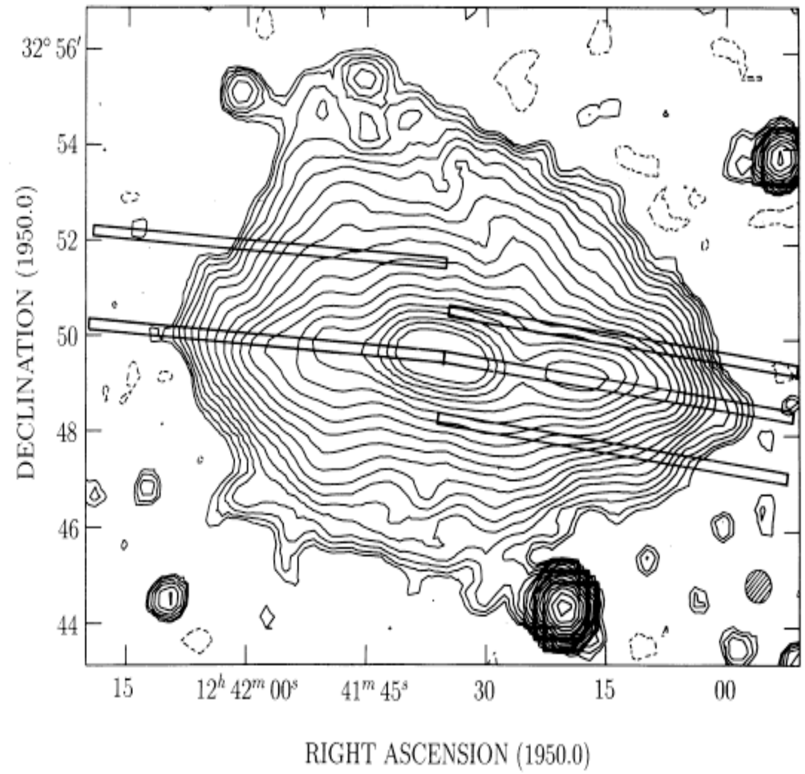
THE WARM PHASE(S)



- Blue-shifted absorption-lines: entrained clouds
- Traces a range from neutral to coronal phases
- Typical velocities one-to-few hundred km/s

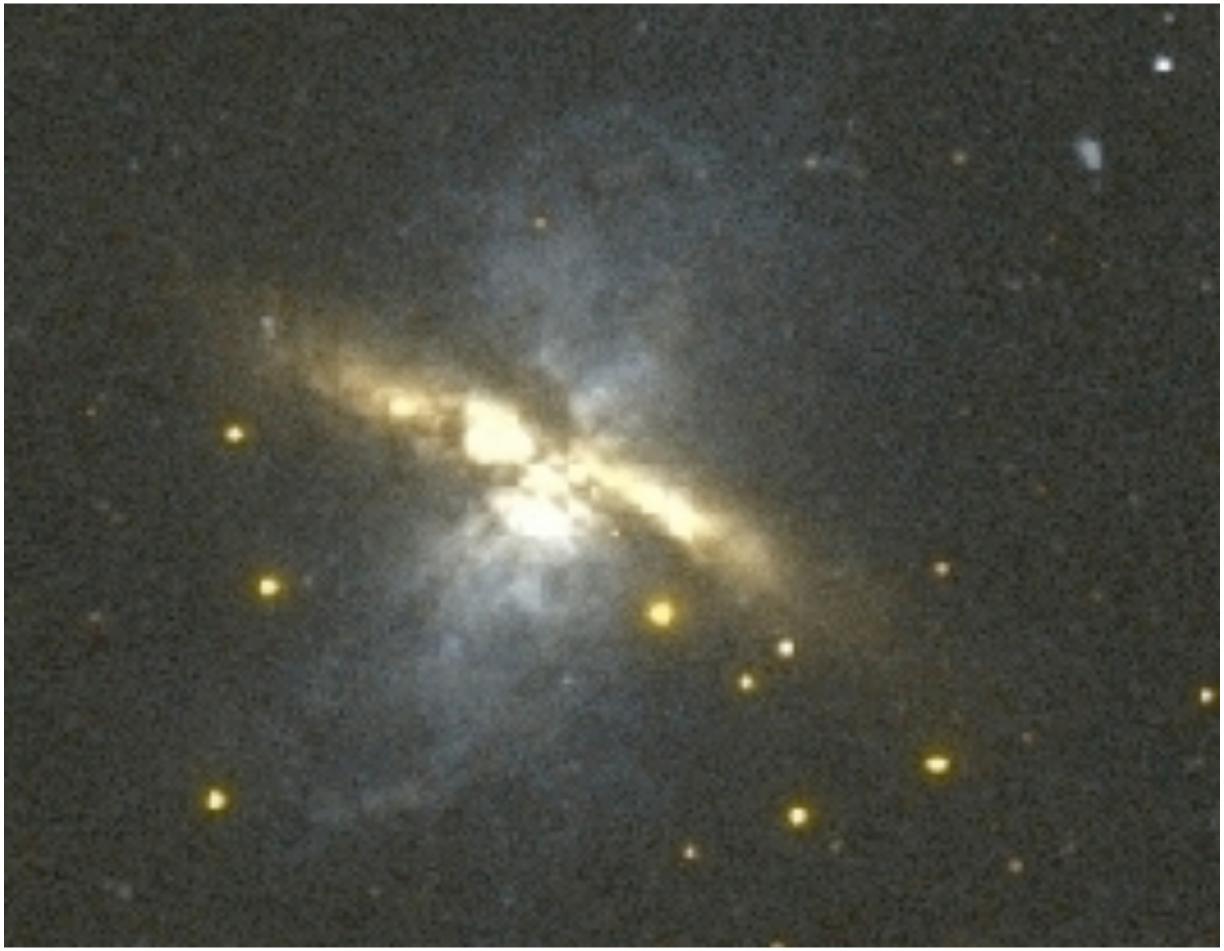
THE RELATIVISTIC PHASE





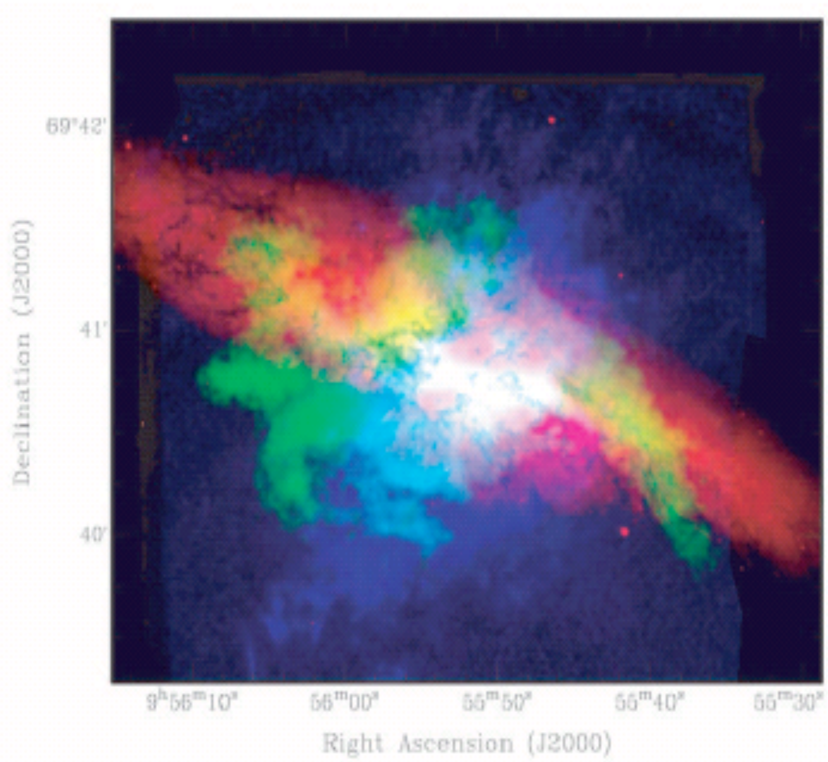
- Radio synchrotron emission from advected cosmic ray electrons and magnetic field
- NGC 4631 (Wang; Dahlem)

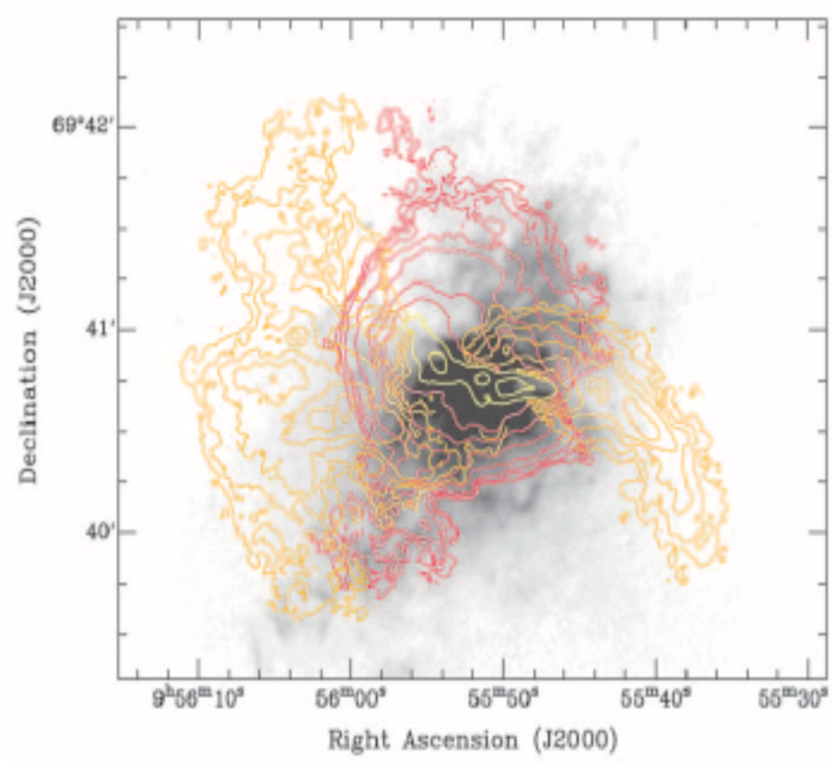
THE DUSTY PHASE



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

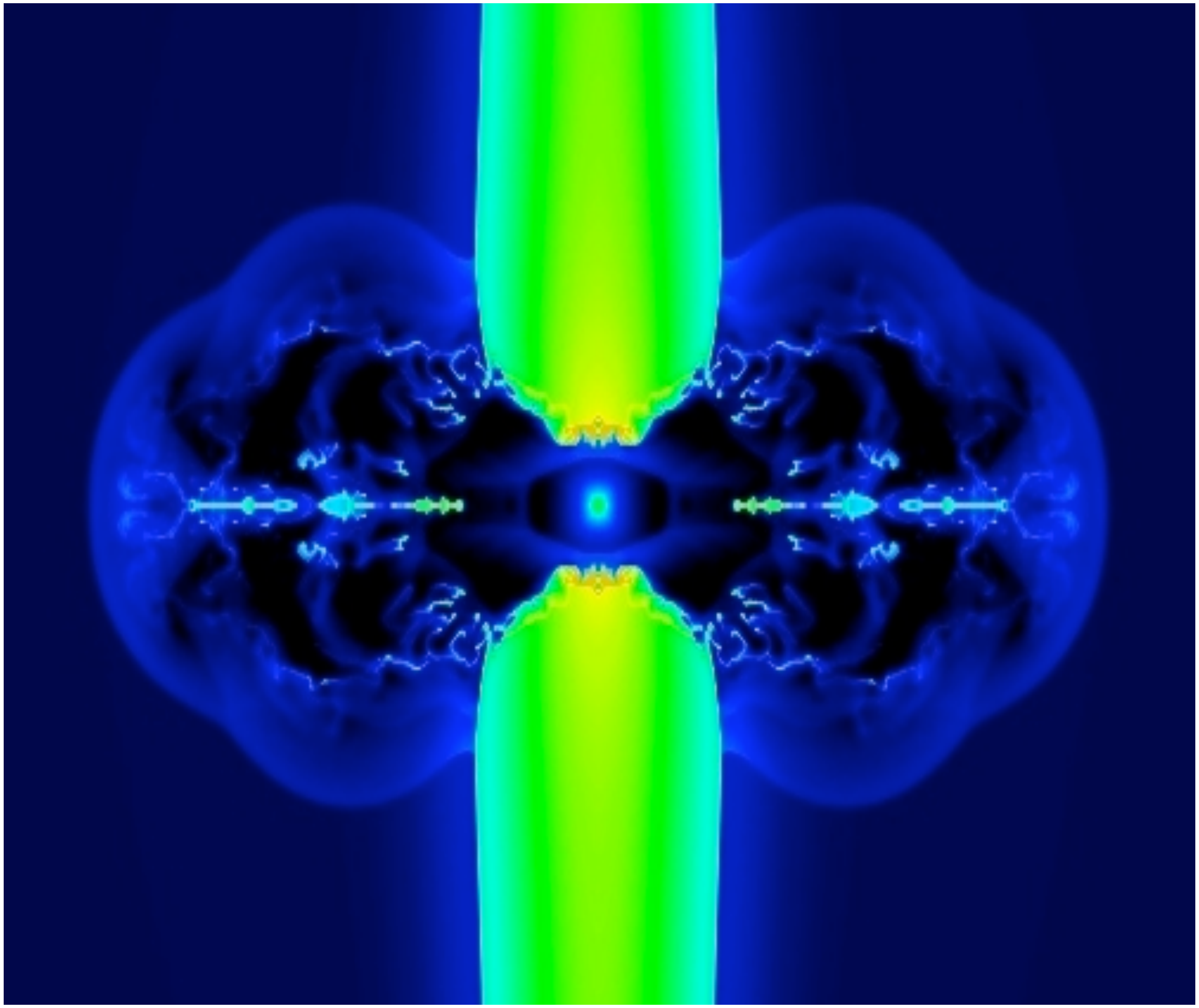
THE MOLECULAR PHASE



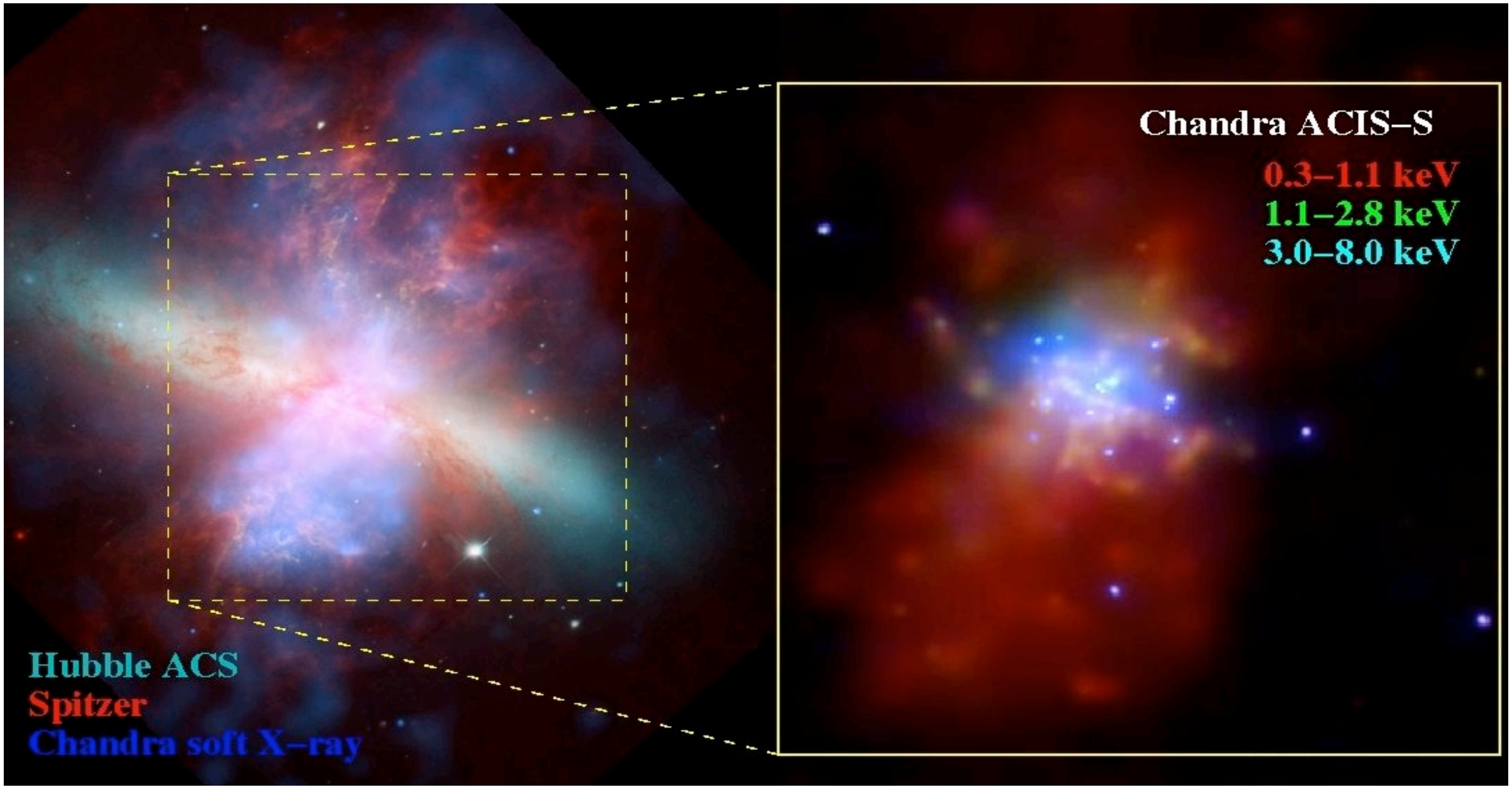


- Few hundred million solar masses at ~ 100 km/s
- KE ~ 3 x10^55 ergs
- Fabian et al.

IV) OUTFLOW RATES



OUTFLOW RATES
The Very Hot Wind Fluid



Luminosity and temperature require of-order unit efficiency (~all the kinetic energy from massive stars goes into heating this gas)

OUTFLOW RATES

X-Rays

- The X-ray luminosity, temperature, and size yield M $F^{-1/2}$, P $F^{1/2}$, and TE $F^{-1/2}$, where "F" is the volume filling factor
- The X-ray size and temperature lead to a "crossing-time" and hence $\dot{M}$ and $\dot{E}$
- For $F \sim 1$, $\dot{E} \sim \dot{E}_{sne}$ and $\dot{M}$ = several times the SFR (Λ of-order 10)
- Note: PΔV $\propto$ $F^{-1/2}$

OUTFLOW RATES

Optical Emission Lines

- Measure mass directly (measure n_e) and can also directly measure outflow velocities

- Measure the wind ram pressure:
  $P(r) \; = \; \dot{M} \; v/r^2\Omega_W$
  $\dot{M} \; v = P(r) \; r^2 \; \Omega_W$

- Implied outflow rates in the hot wind fluid:
  $\dot{M} \; = \; 20 \; (v/10^3)^{-1} \; (\Omega/4\pi) \; (L_{bol}/10^{11}) \; M_\odot/\mathrm{yr}$
  $\dot{E} \; = \; 10^{43} \; (v/10^3) \; (\Omega/4\pi) \; (L_{bol}/10^{11}) \; \mathrm{erg/s}$

- $\dot{M}$ is several times the SFR and $\dot{E} \sim \dot{E}_{sne}$

OUTFLOW RATES

Interstellar Absorption Lines

- **Gas columns are a few $\times 10^{21}$ cm^{-2} and outflow speeds are a few hundred km/s**
- **Outflow rate:**
  $10\ (r_*/kpc)\ (N_H/10^{21})\ (\Delta v/100)(\Omega_W/4\pi)\ M_\odot/\mathrm{yr}$
- **Typical values:**
  $\dot{M}$= a few times the SFR
  $\dot{E} \sim 10\%\ \dot{E}_{sne}$

OUTFLOW RATES:
Molecular Gas

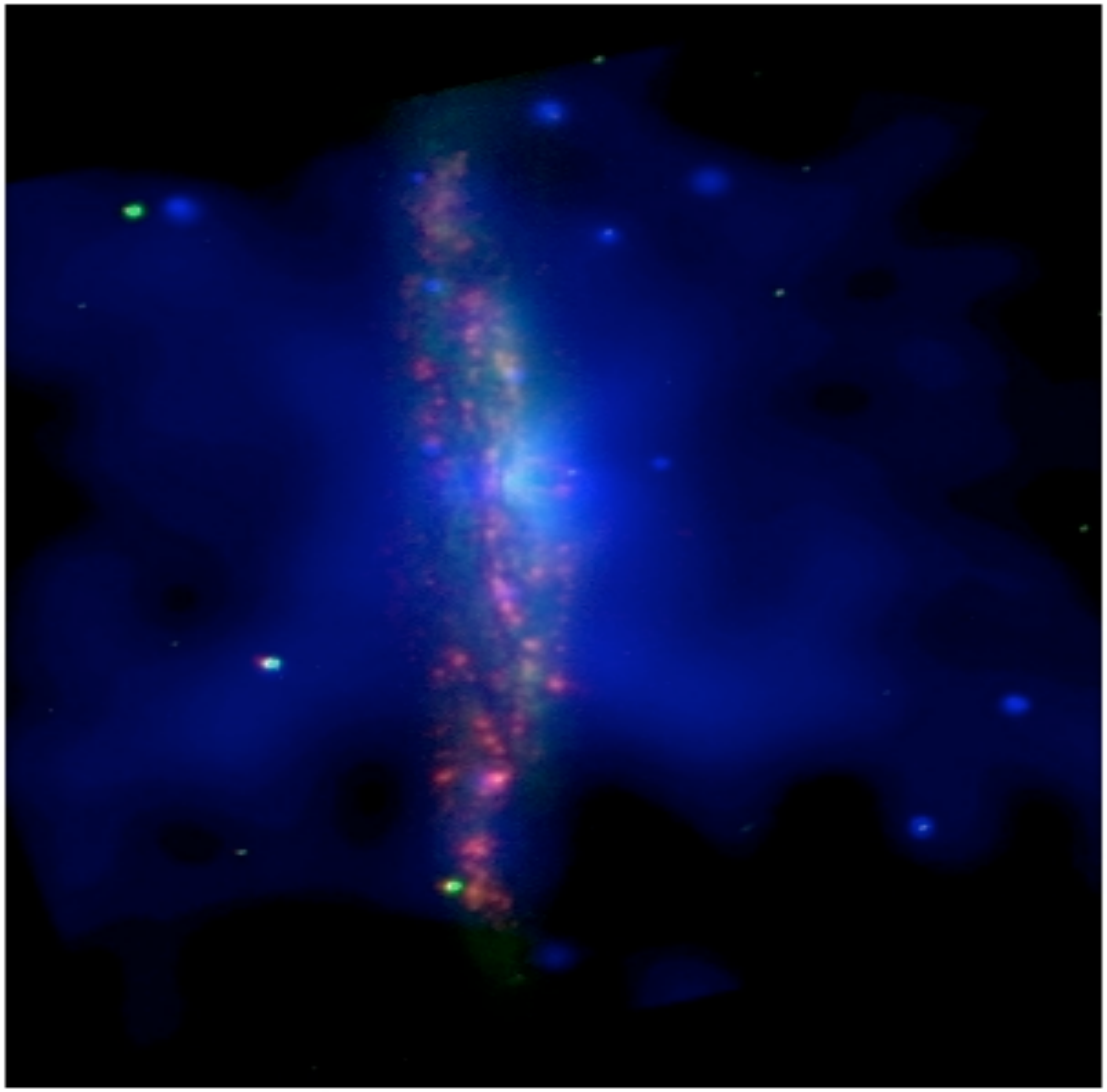
- M82: M_mol ~ 3 x 10^8 solar masses
- Radius 1.2 kpc
- V ~ 100 km/s
- t_out ~ 12 Myr
- Outflow rate ~ 25 M_sun/year
- This is ~ 3 to 5 times the SFR

OUTFLOW RATES

Summary

- Although the methods above all require uncertain assumptions, they are independent of one another
- Conclusion: the outflows require of-order unit-efficiency for the conversion of supernova KE and carry out mass at a rate of-order the SFR

V) DO WINDS ESCAPE?

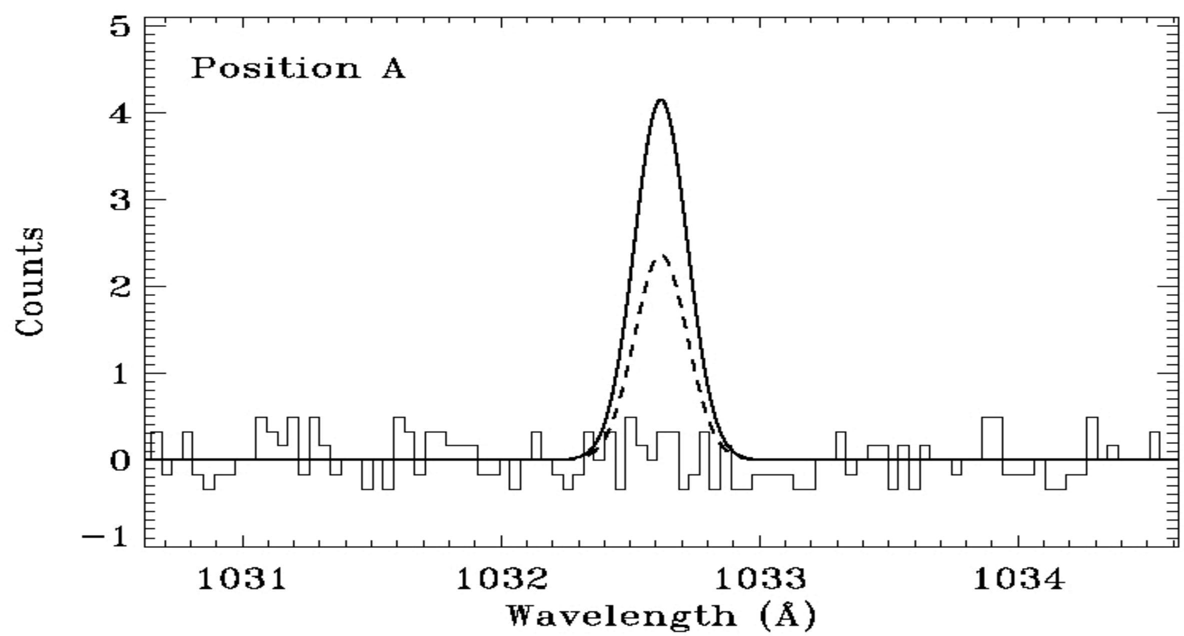


THE FATE OF WINDS

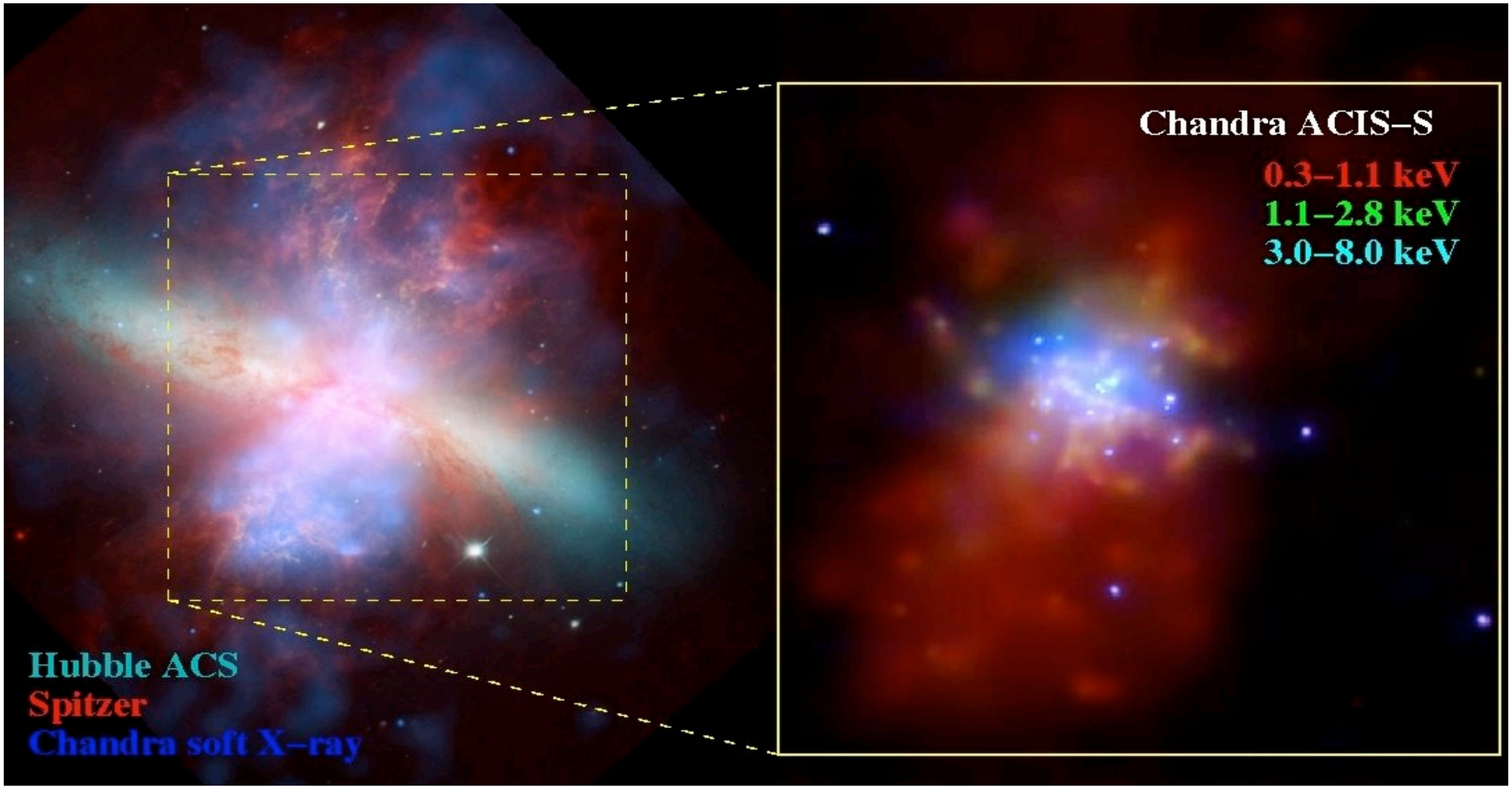
Are they "quenched" by radiative cooling?

- $L_X \sim 10^{-2} \dot{E}_{sne}$
  Radiative cooling by hot gas insignificant
- **FUSE observations of OVI:**
  Radiative losses from coronal phase insignificant

- Hoopes et al.
- M82 et al.

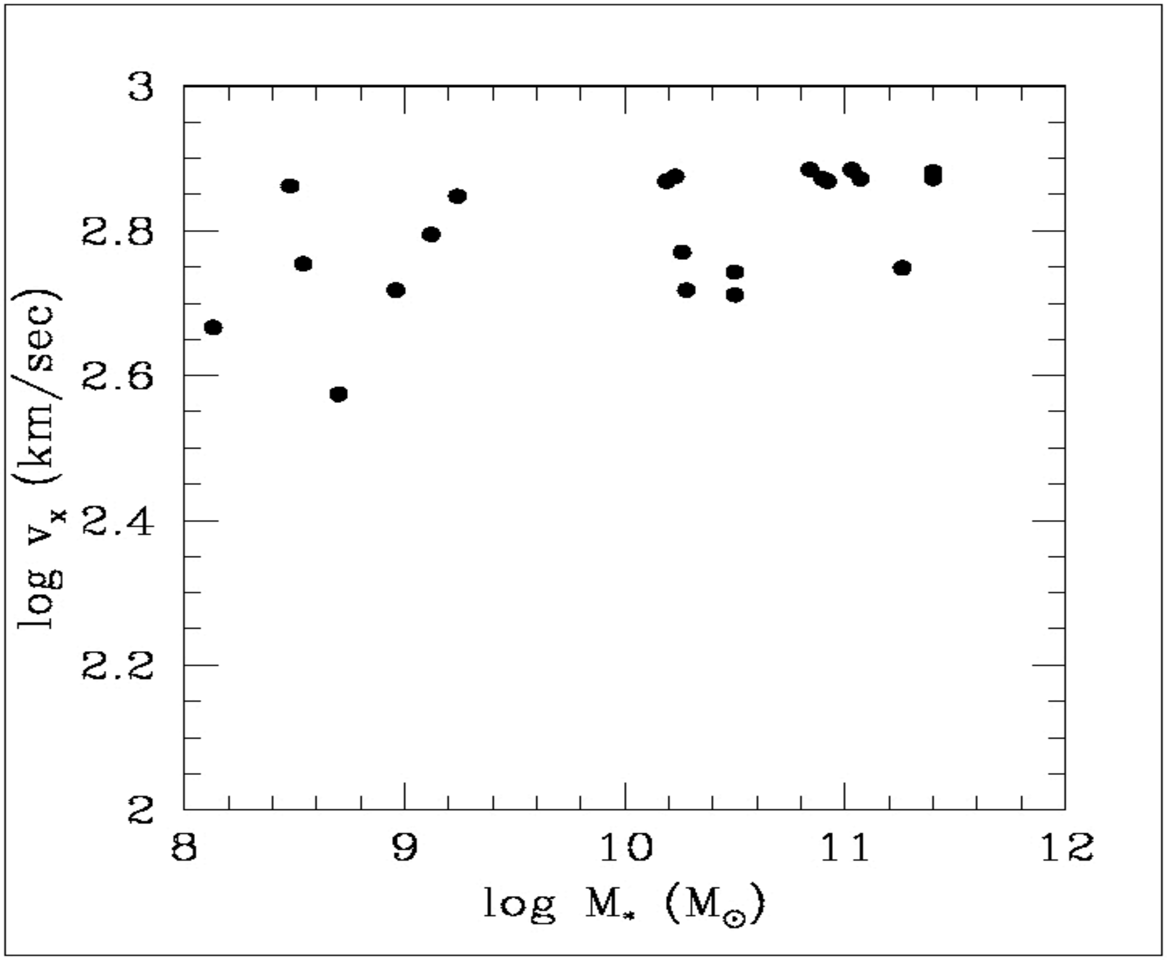


THE VERY HOT WIND FLUID



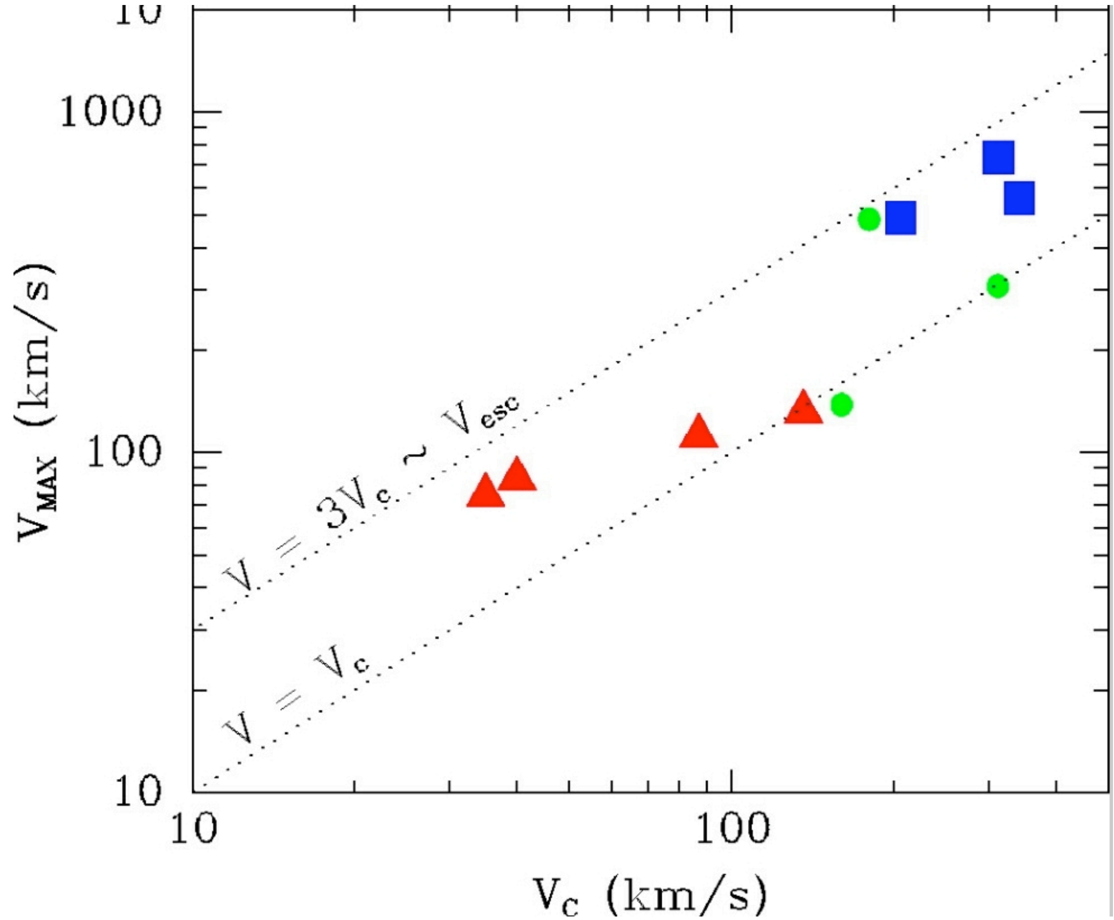
- The wind fluid itself is very hot (~60 Million K)
- The corresponding velocity is ~ 2000 km/s
- Way above escape velocity from any galaxy
- But what about the stuff carried out by this wind?

THE SOFT X-RAY GAS



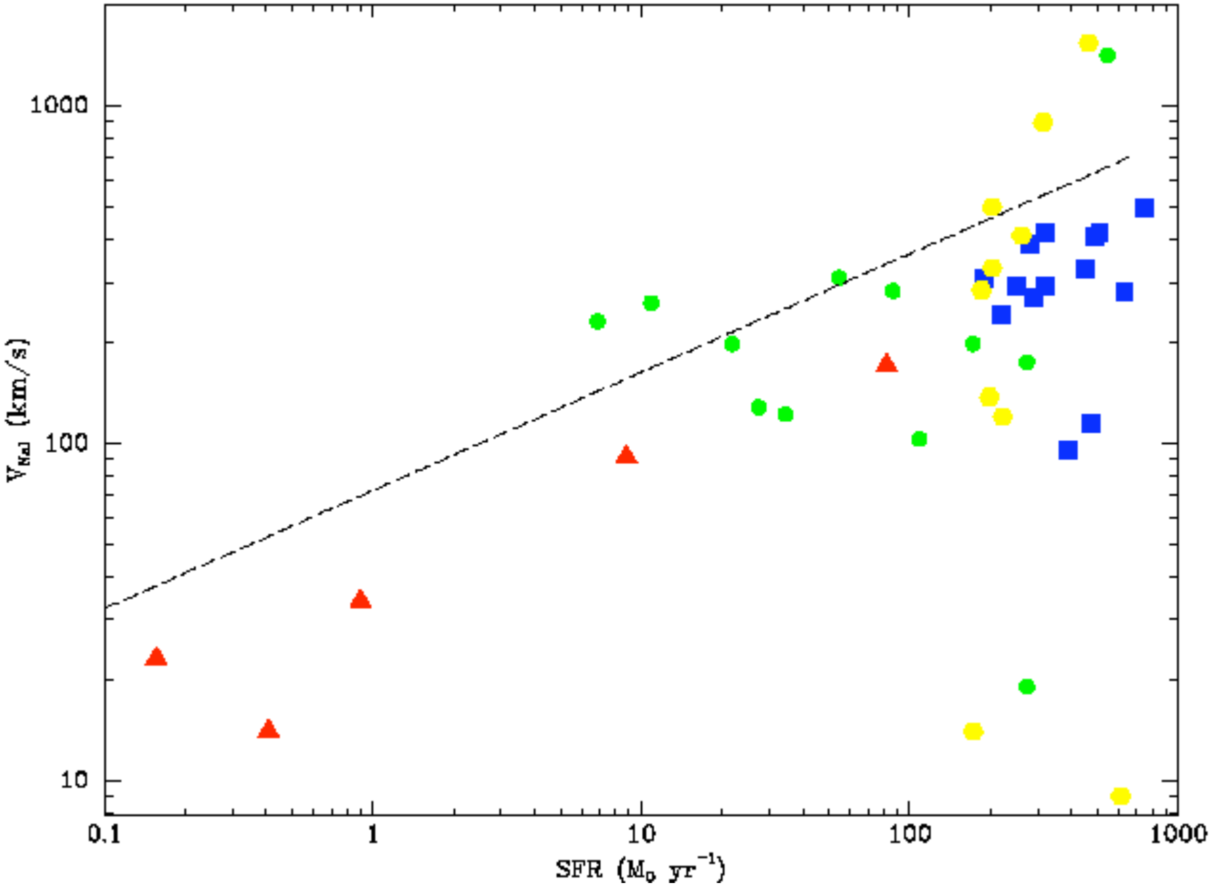
- Soft X-ray temperature invariant w/ galaxy mass
- Preferential escape from low mass galaxies?

THE COLD & WARM GAS



- C. Martin (see also Rupke et al.)
- Outflow speeds of-order the escape velocity

Dependence on SFR

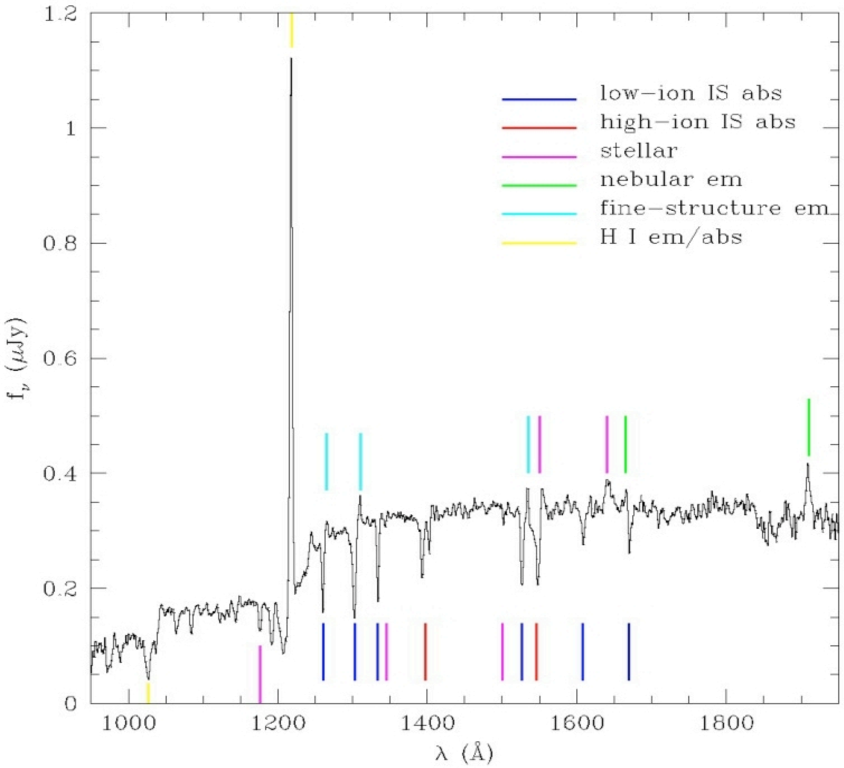


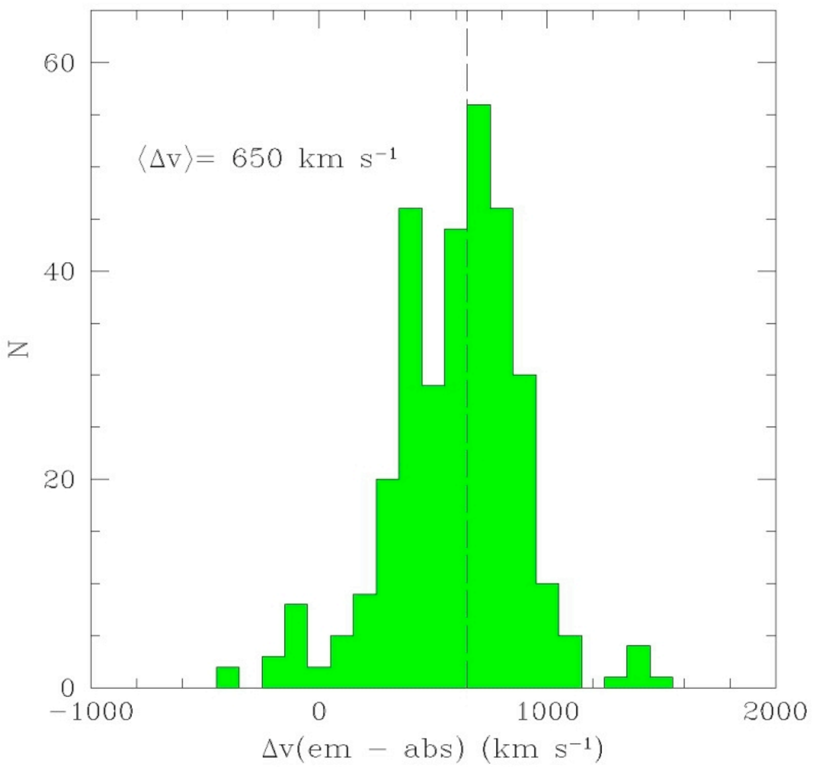
- Winds in dwarf galaxies have insufficient thrust
- C. Martin (see also Rupke et al.)

The Bottom Line

- “Escapability” is different for different phases !
- The hot phase carries most of the energy & new metals
- Beware of inferences based on a single “view”

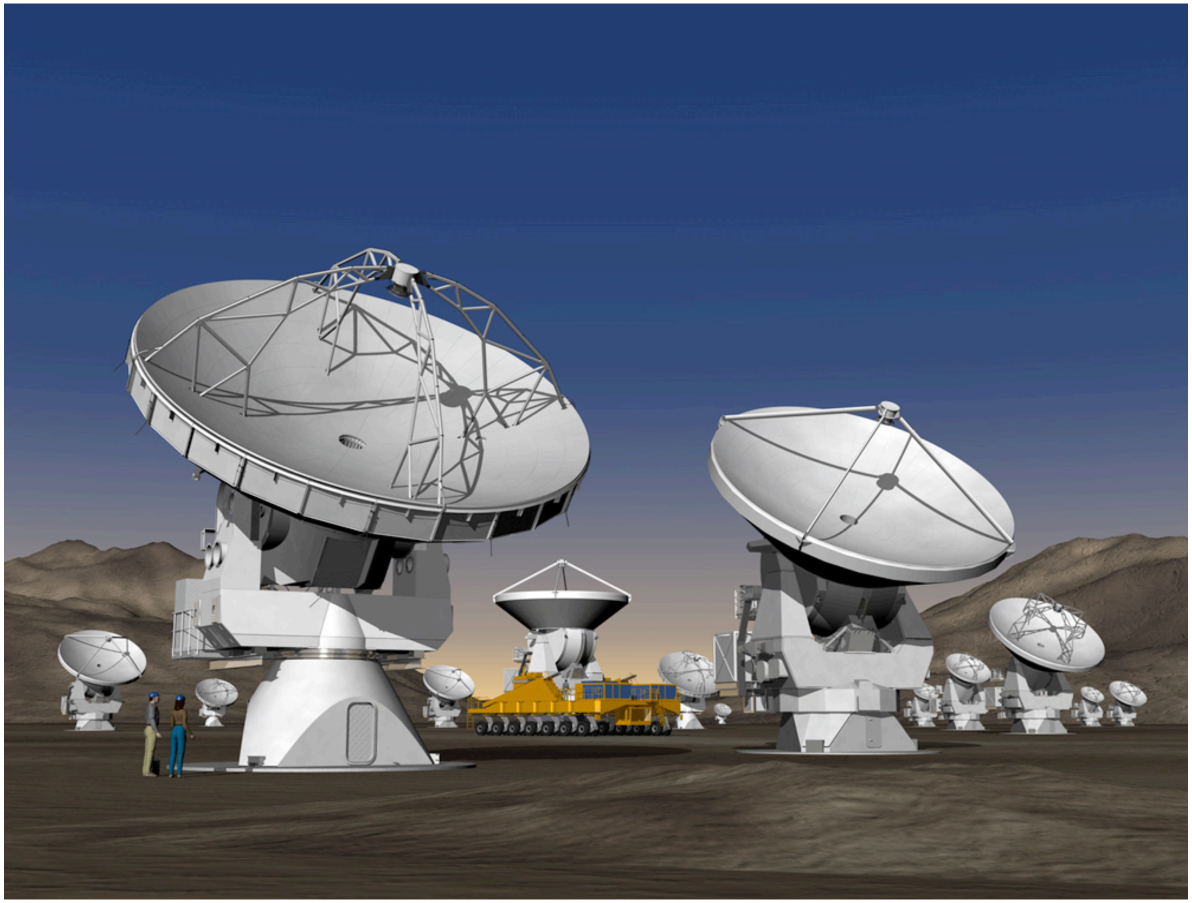
Lessons for High-Redshift





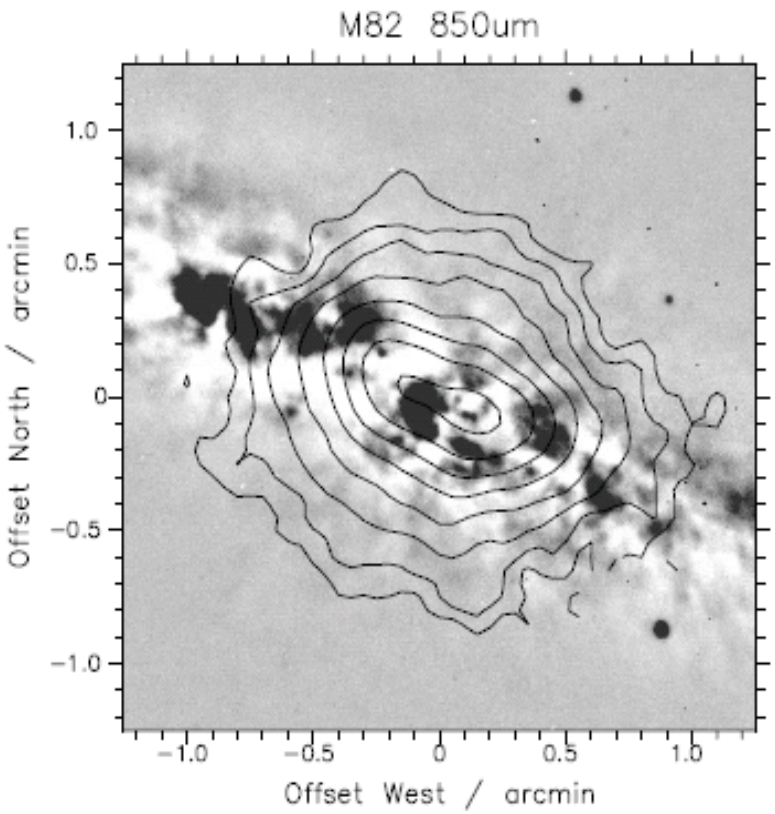
- Winds are unbiquitous in Lyman Break Galaxies (e.g. Shapley et al.)
- All we know about them is via the cool/warm phase
- Lesson from local starbursts: there’s more going on!

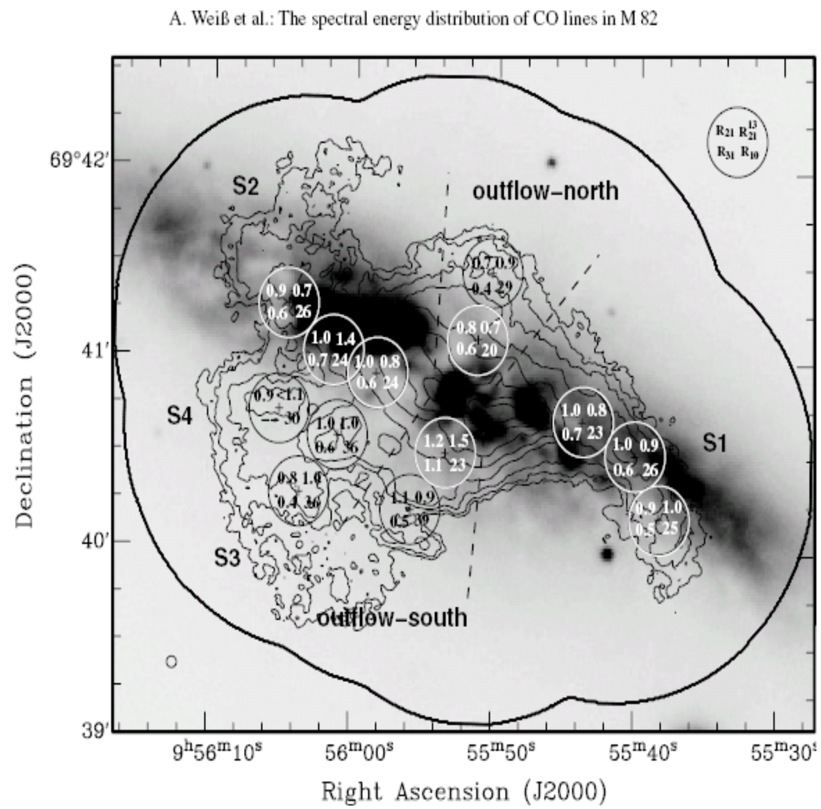
VI) THE ROLE OF ALMA



- Exploring the cold wind phase
- What sets the efficiency (KE_wind/KE_SNe)?

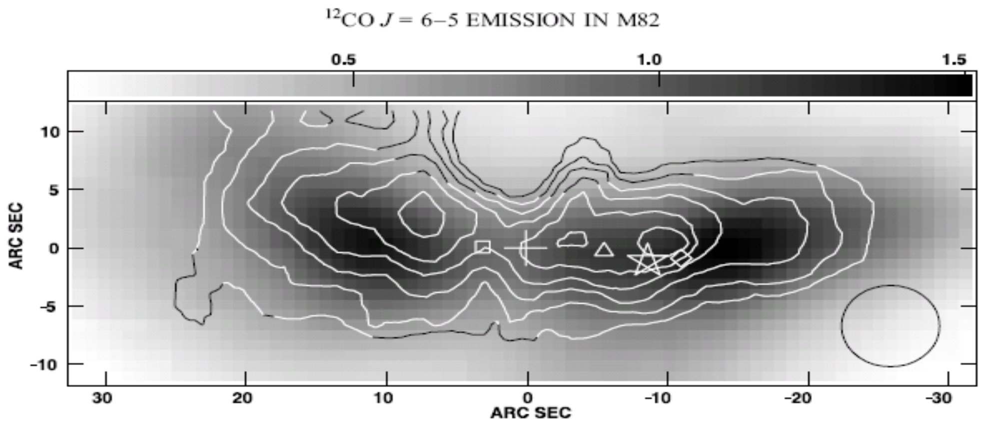
Molecular gas & dust in the wind





- The detection & characterization of molecular gas and dust has only been done in a few cases
- The molecular phase may dominate the mass
- ALMA: statistically robust, complete sample

Launch! The base of the wind



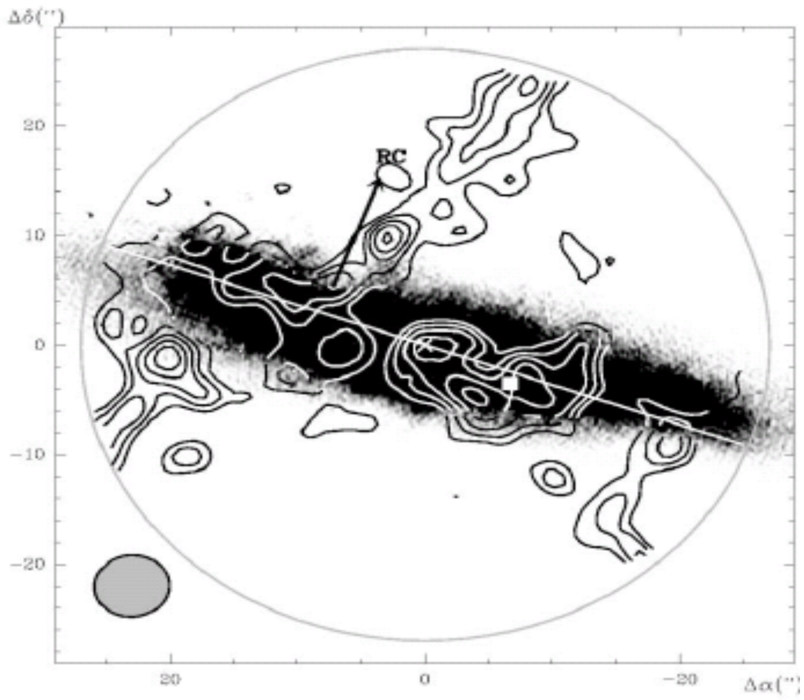
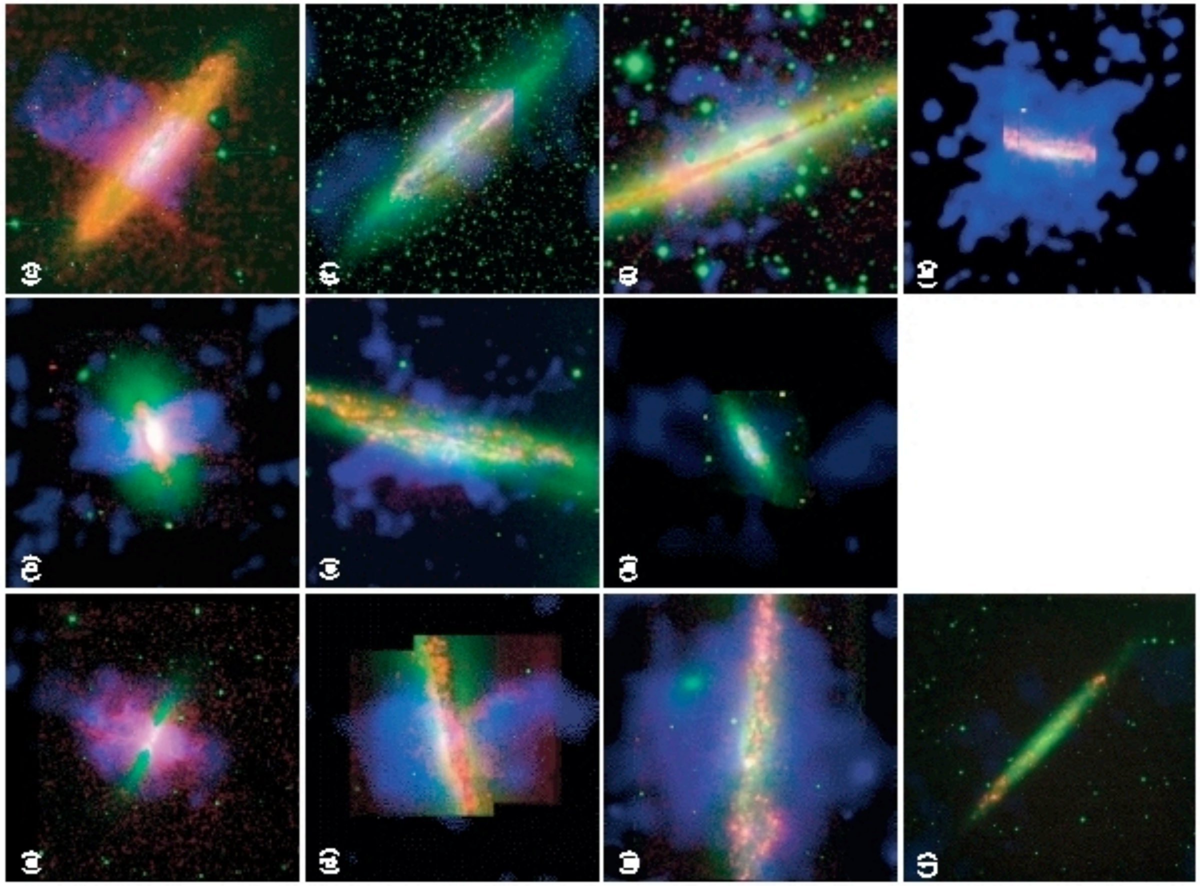


FIG. 1.—Velocity-integrated intensity map of SiO (v = 0, J = 2–1), i

- Tracers like J =6-5 CO and SiO probe the region where the wind is launched
- Seaquist et al. & Garcia-Burillo et al.

Wind Efficiency: Empirical Clue



- Winds evident when SFR intensity > 0.1 solar mass/(year square-kpc)   Strickland & TH
- ISM “topology” is different above this threshold?

What sets this threshold?

- ALMA: Probe the “meso-scale” sites of energy injection
- ALMA: Measure the porosity of the molecular ISM
- Most stars form in super star-clusters: impact on ISM?
- What determines the wind efficiency (the fraction of injected energy in the wind)?

SUMMARY

- Winds are driven whenever global SFR/area is high (the norm at high-z, only in starbursts now)
- They are complex multi-phase phenomena
- They carry a large fraction of SNe energy and newly created metals out of the starburst
- Mass outflow rate > SFR
- The hot gas escapes and cooler gas may not
- Similar winds enriched and may have significantly heated the IGM at high-z
- ALMA: understanding why/when winds are produced and probing the cold wind phase