Multi-Phase Starburst-Driven Winds

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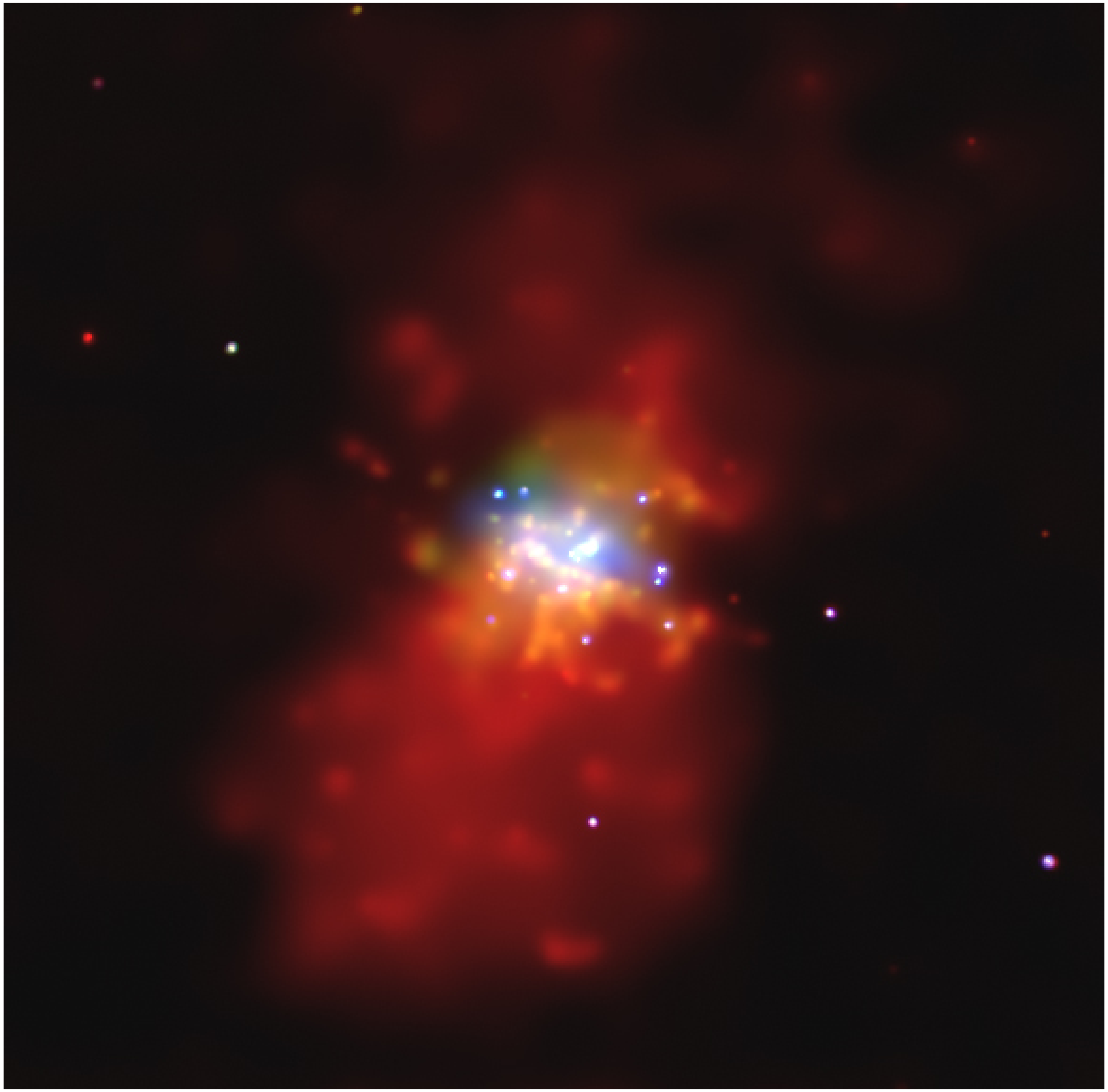
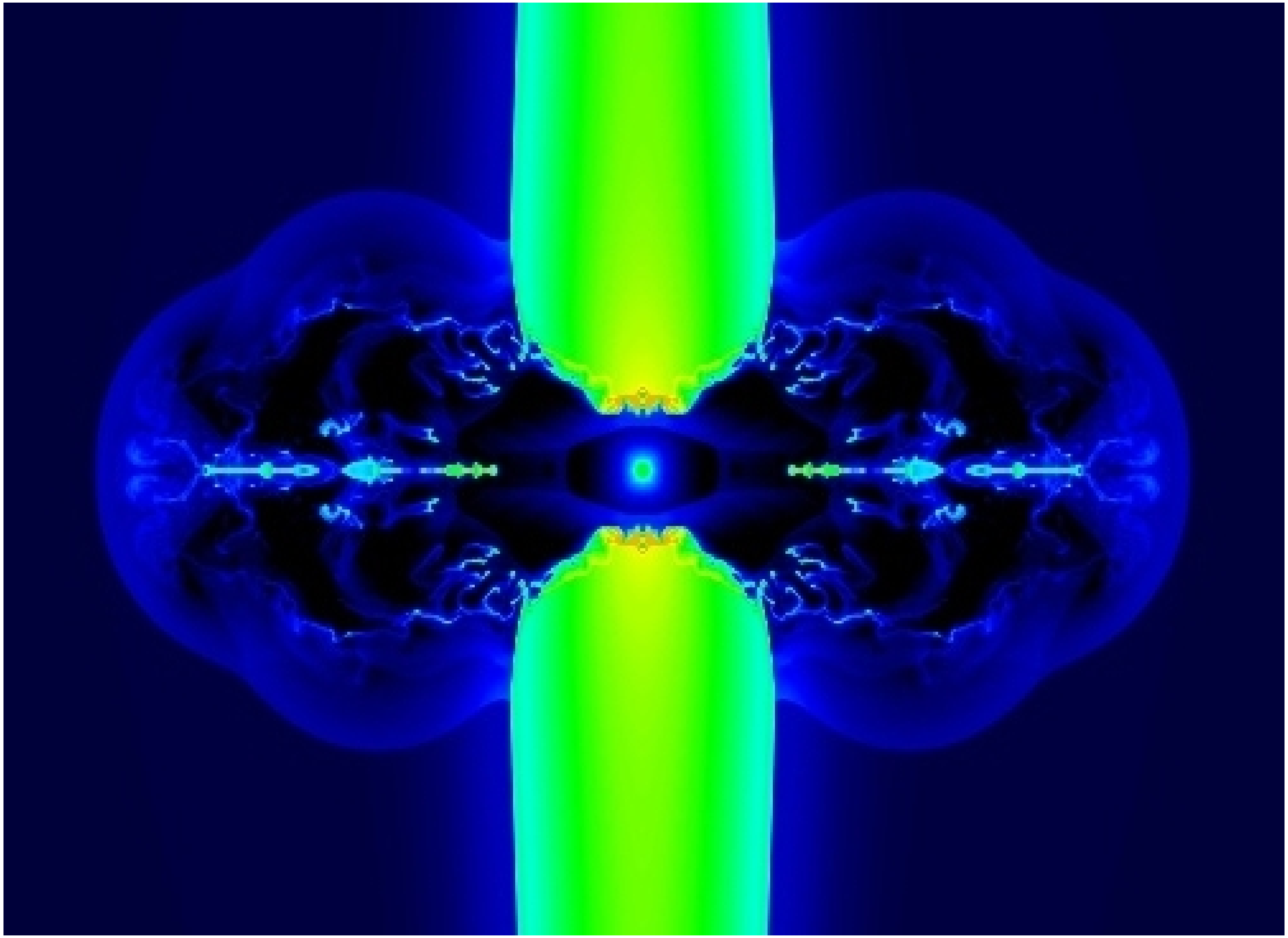


Outline

- BASIC WIND PHYSICS
- OVERVIEW OF WIND PHASES
- THE PRIMARY WIND FLUID
- THE WARM/HOT INTERFACE
- OUTFLOW RATES
- WIND FATE (Cooling rates, Speeds, Distances)
- SUMMARY

1) Basic Wind Physics



Chevalier & Clegg Model

Spherically symmetric & ignores gravity

Characterized by starburst radius (r*), mass injection rates (~20% β^(0.5) SFR, where β is "poisoning" factor and KE injection rate (~1% L_bol ~ 10% L_ion)

Central static region (r < r*)

T ~ 10^8/β K

dp/dt = $\sqrt{2}$ (Ė dM/dt)^(0.5) ~ 3 β^1/2 L_bol/c

P ~ dp/dt/(starburst surface area)

Sonic radius at r ~ r*

Supersonic adiabatically cooled wind. At r >> r*:

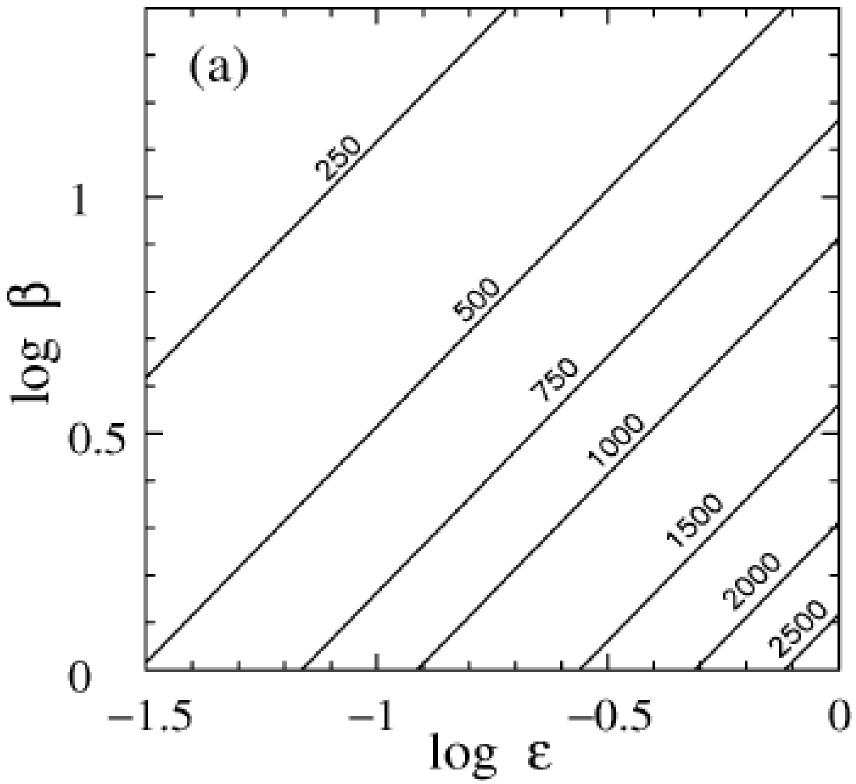
P_ram ~ dp/dt/(Ω̣ r^2)

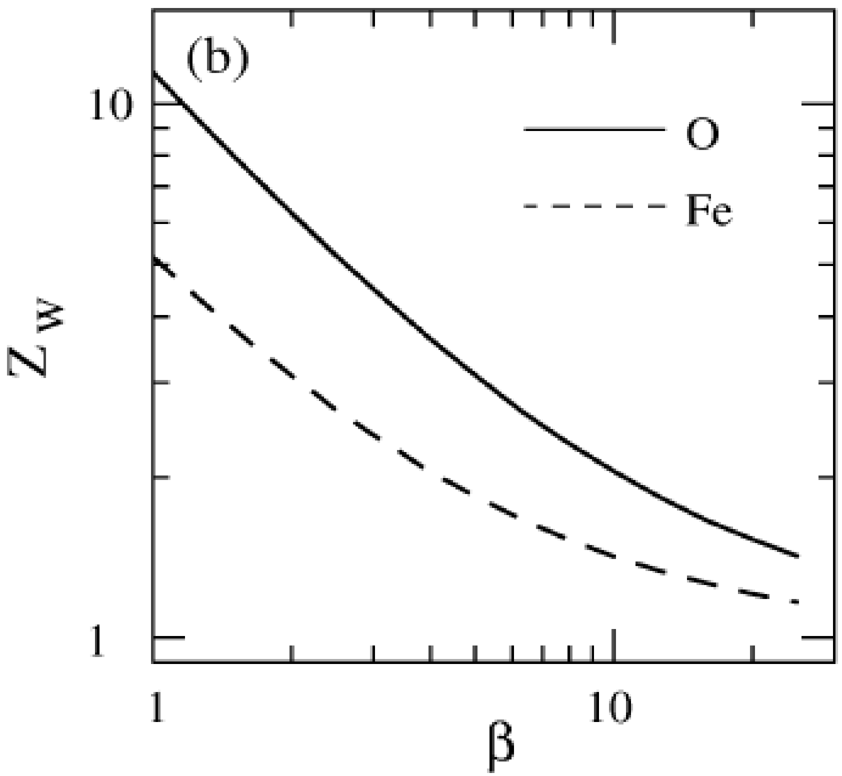
v ~ 3000 β^(-0.5) km/sec

Pure wind (β = 1) highly metal enriched

T α r^(-4/3)

Properties of the Wind Fluid



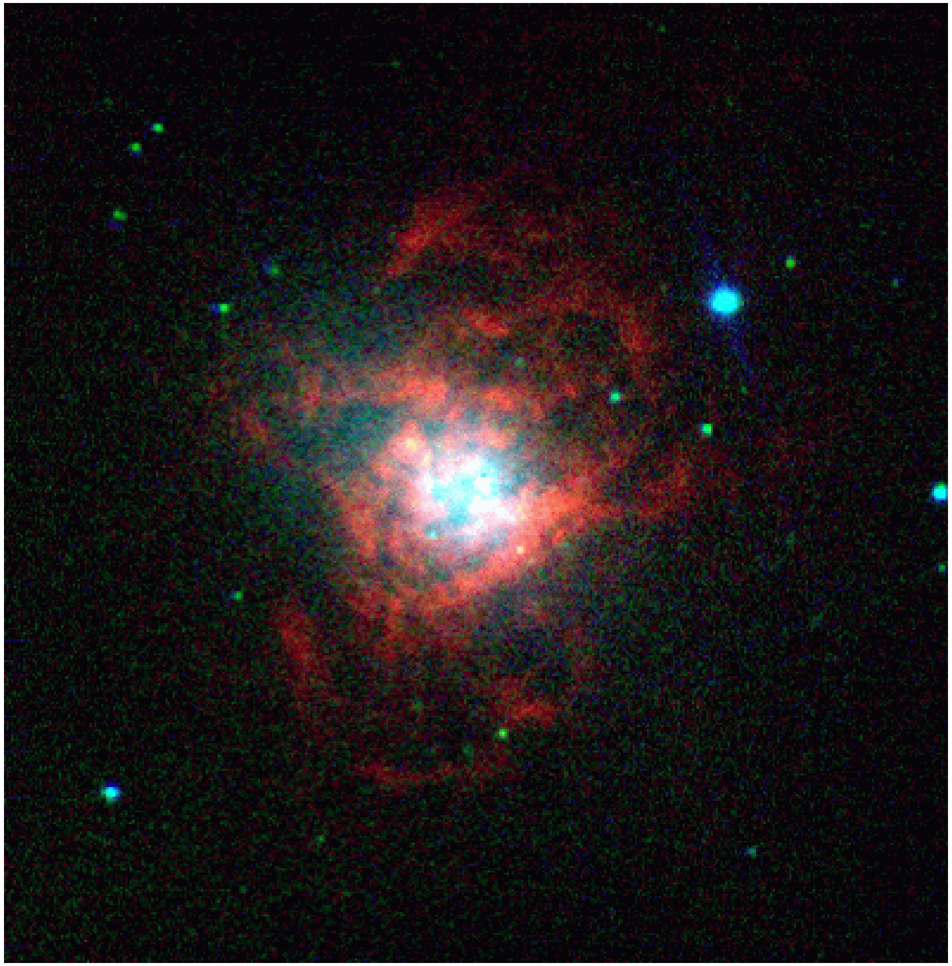


- Outflow speed of wind fluid up to ~3000 km/s
- Outflow speed set by amount of "poisoning" (β) and radiative cooling (ε), where L_rad/Ė = (1-ε)
- Very high metallicities in pure wind fluid

Add an ambient medium

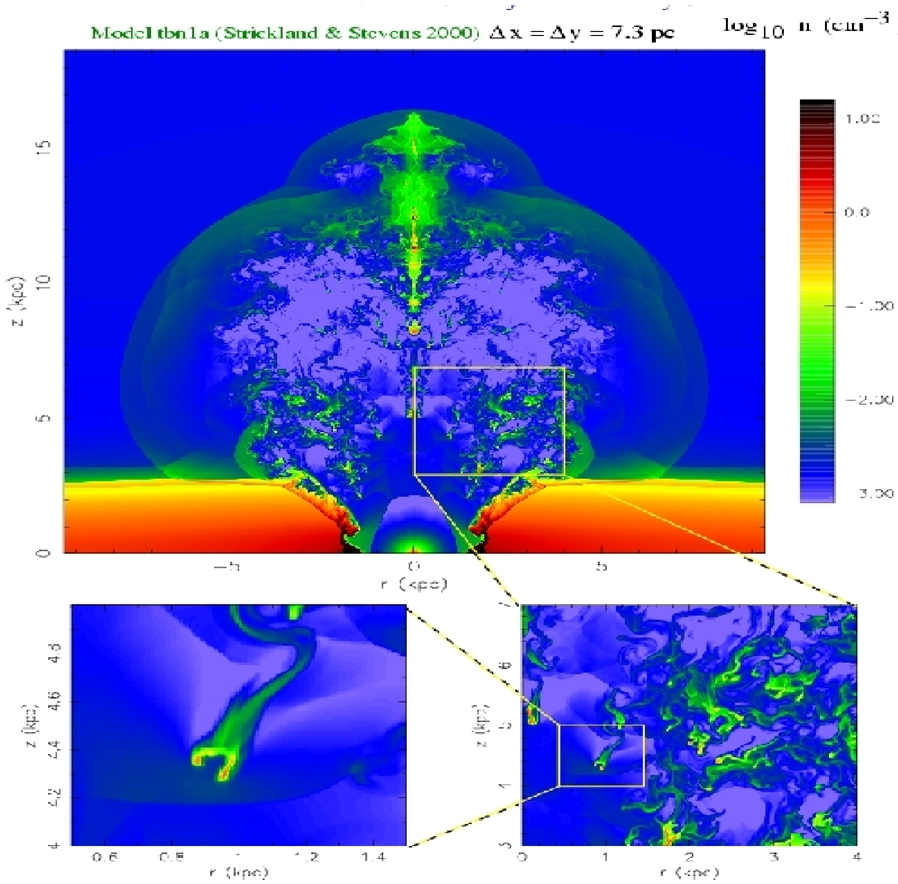
- A plane-parallel medium with some scale-height (“disk”)
- “Halo” (spherical or thick-disk?)
- Must consider multi-phase in both disk and halo gas (need “clouds”)

Stage 1: The Super Bubble



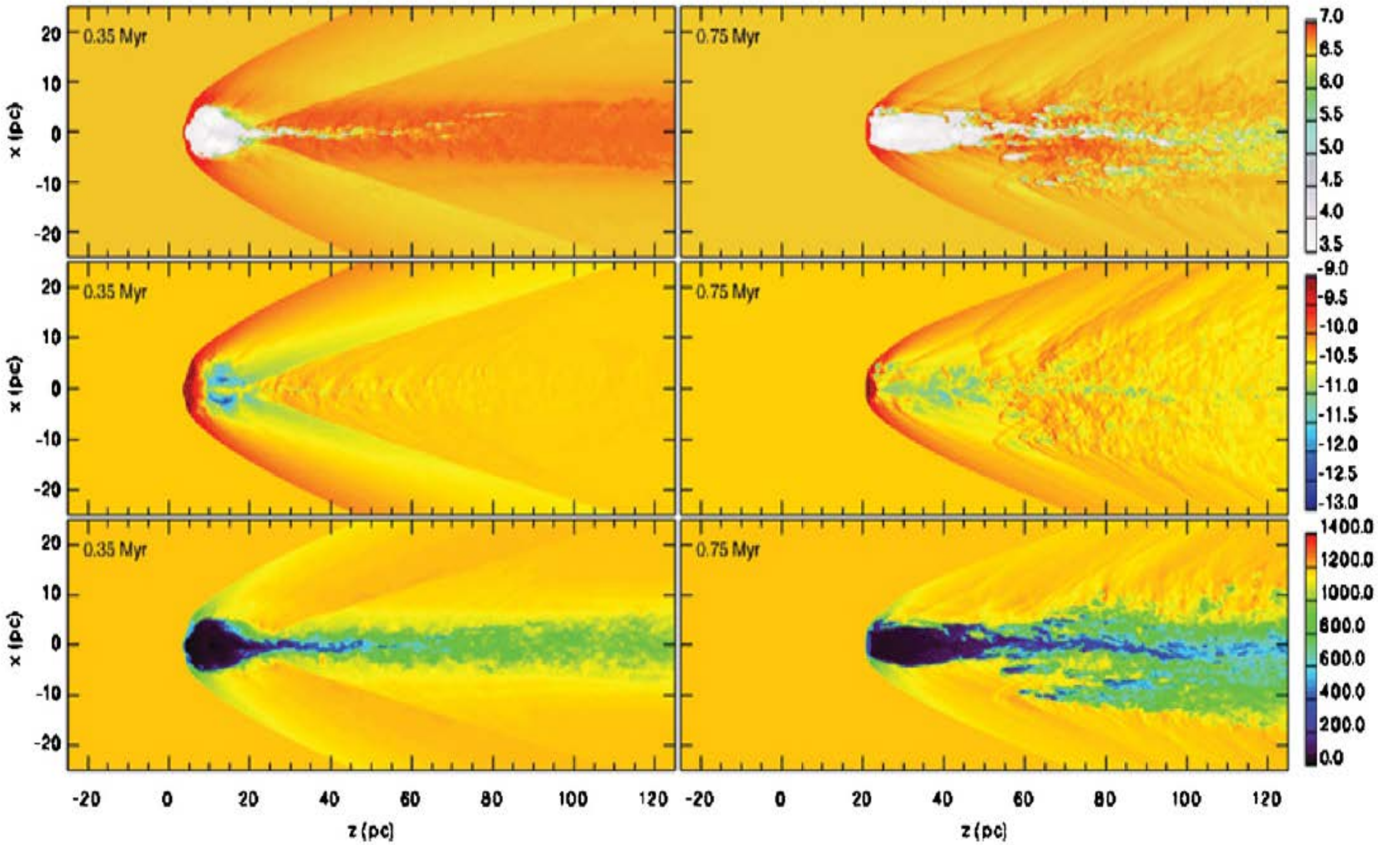
- Hot gas inflates an expanding bubble, driving a shock into ambient gas
- Super bubble will stall for low energy injection rate and large ISM scale-height

Stage 2: Blow-Out Into the Halo



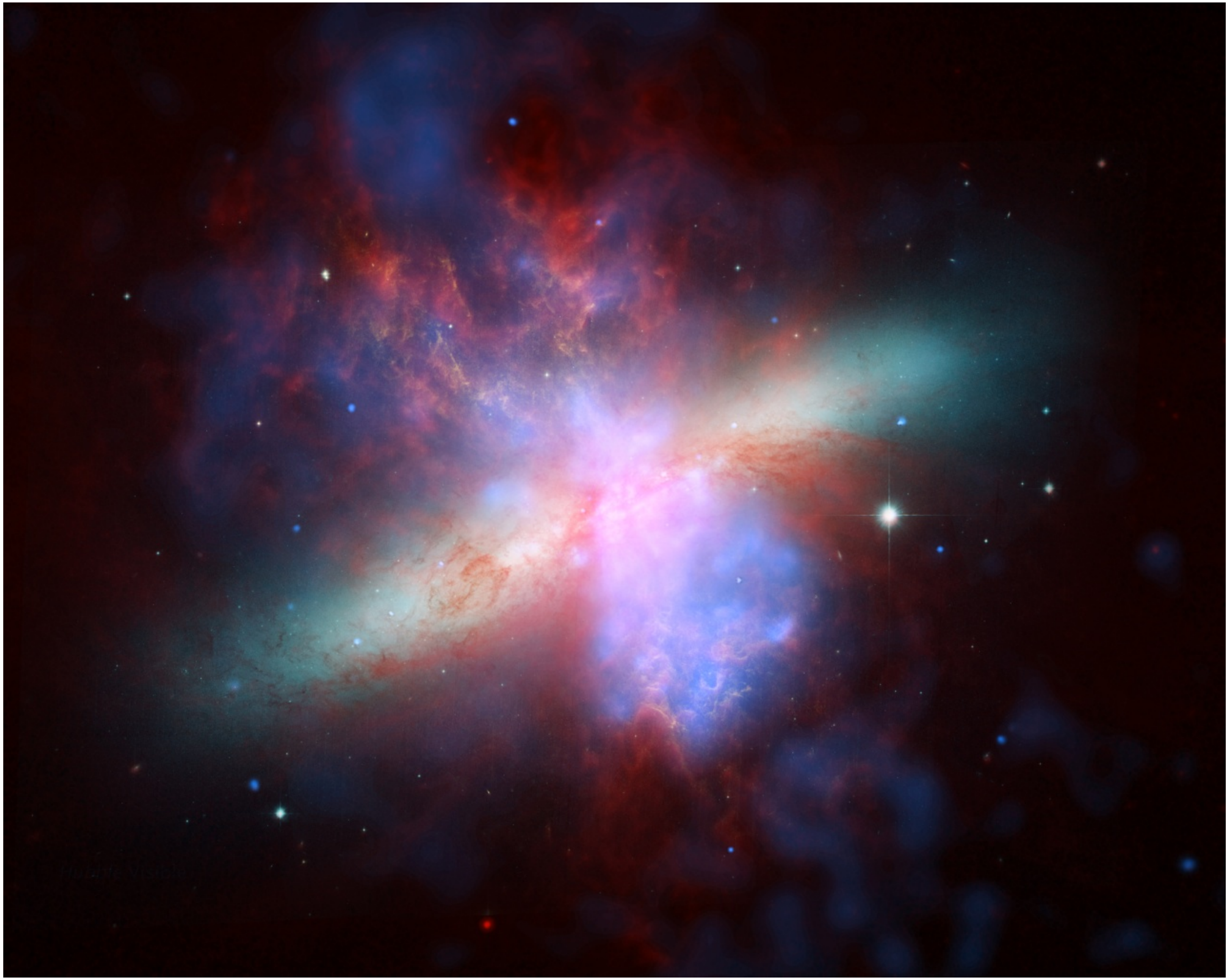
- Most of the halo volume is occupied by the very energetic and tenuous “WIND FLUID”
- Most of the emission and absorption comes from denser material interacting with the wind fluid

Wind-Cloud Interaction

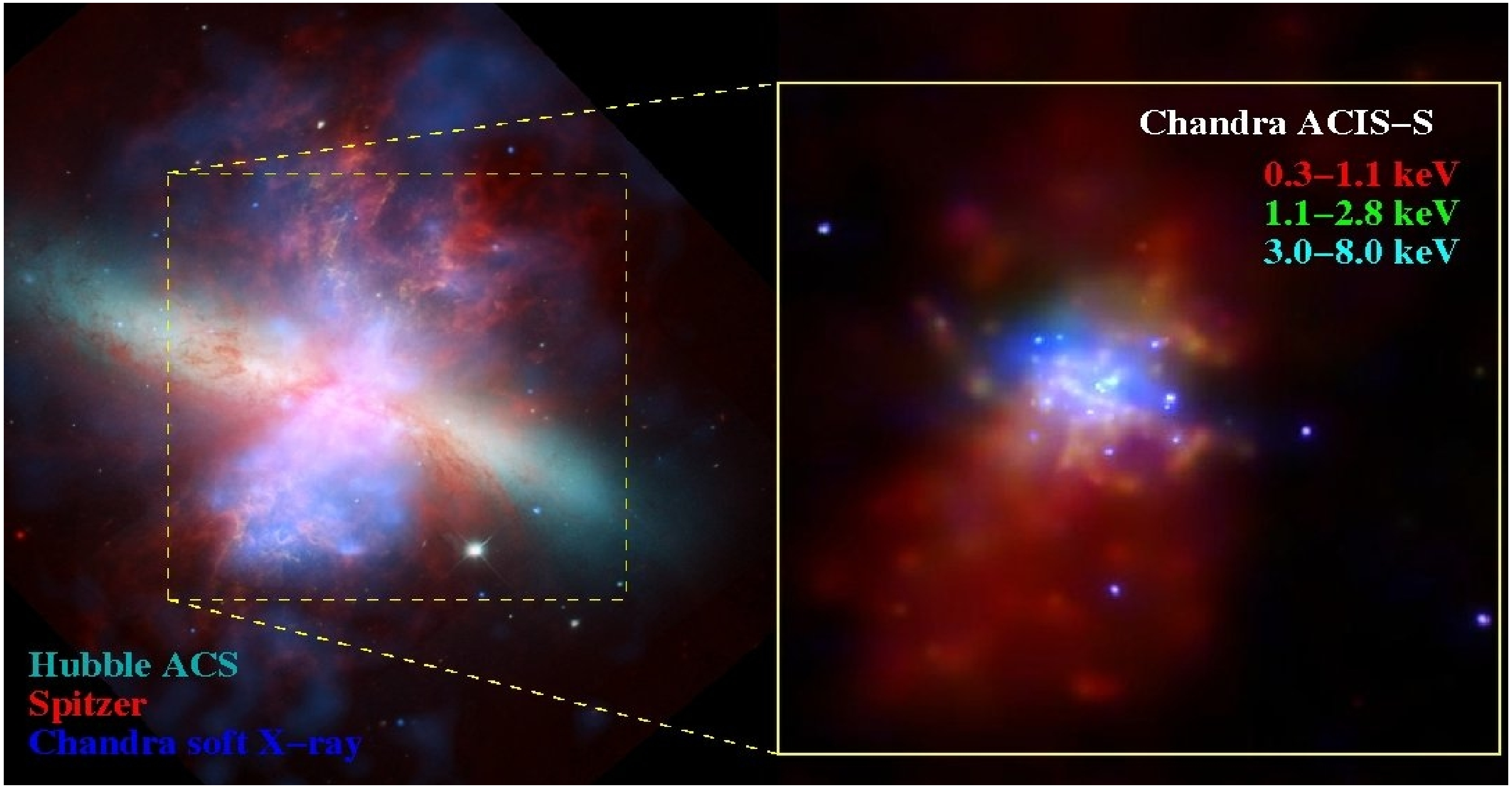


- Soft X-rays from wind/cloud interface
- Optical line emission from shocked/photoionized cloud
- Cloud is accelerated by wind ram + radiation pressures
- Cooper et al. (2009): Plots of T, P, v at two epochs

2) Overview of Wind Phases



The Primary Wind Fluid

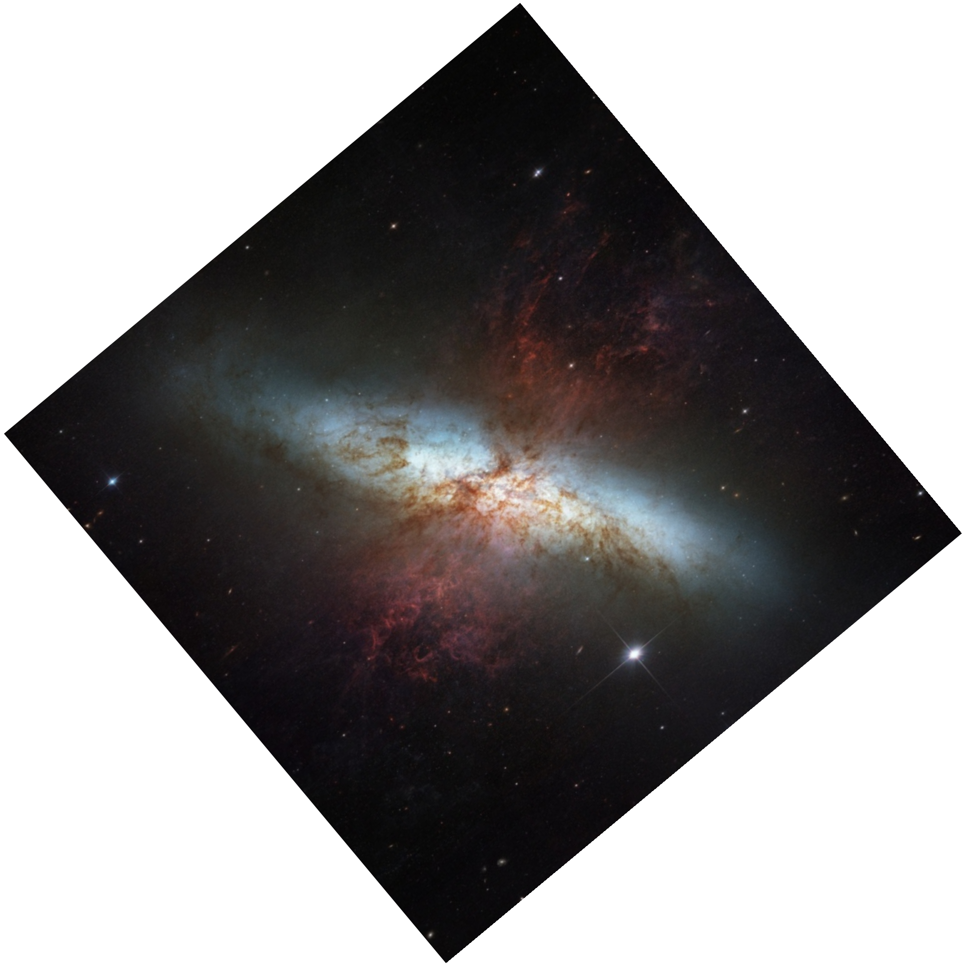


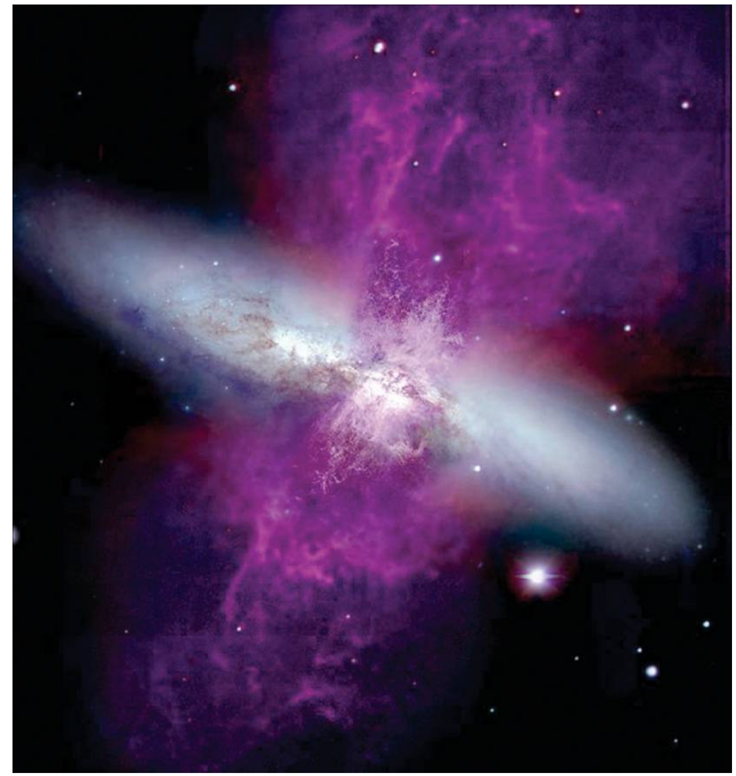
- Thermalized stellar ejecta
- Diffuse hard X-ray emission (T ~ 60 million K)
- Confined to central starburst (Dave Strickland & TH)

The *Soft* X-Ray (“Hot”) Phase

T ~ 3 to 10 million K and thus can not be the “pure” wind fluid. Clumpy (not volume-filling)

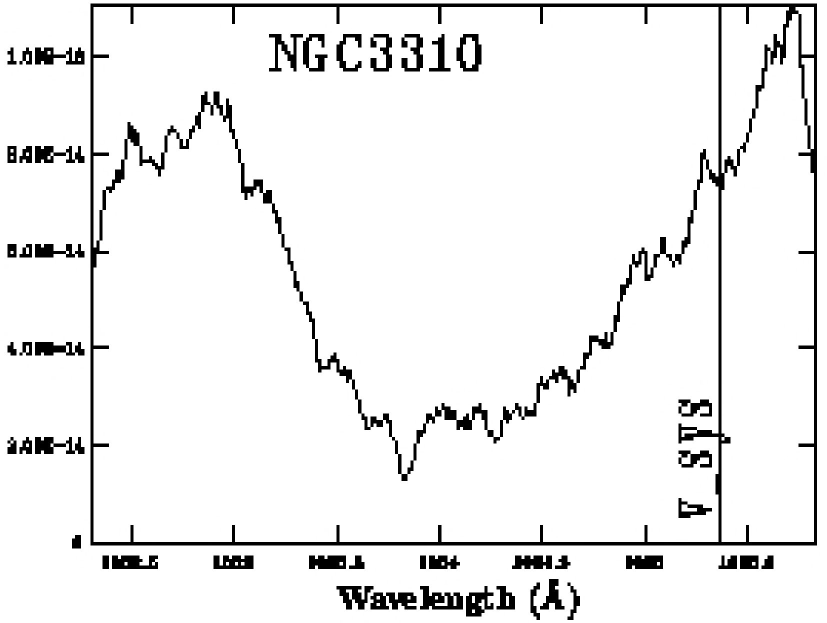
The Warm Ionized Phase

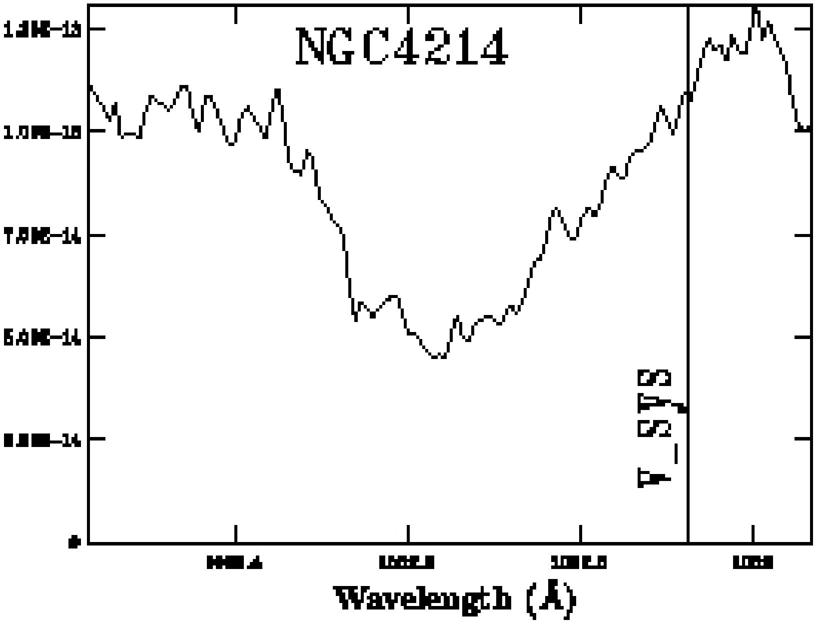




Ambient material that is shock-heated and accelerated by the wind fluid + radiation

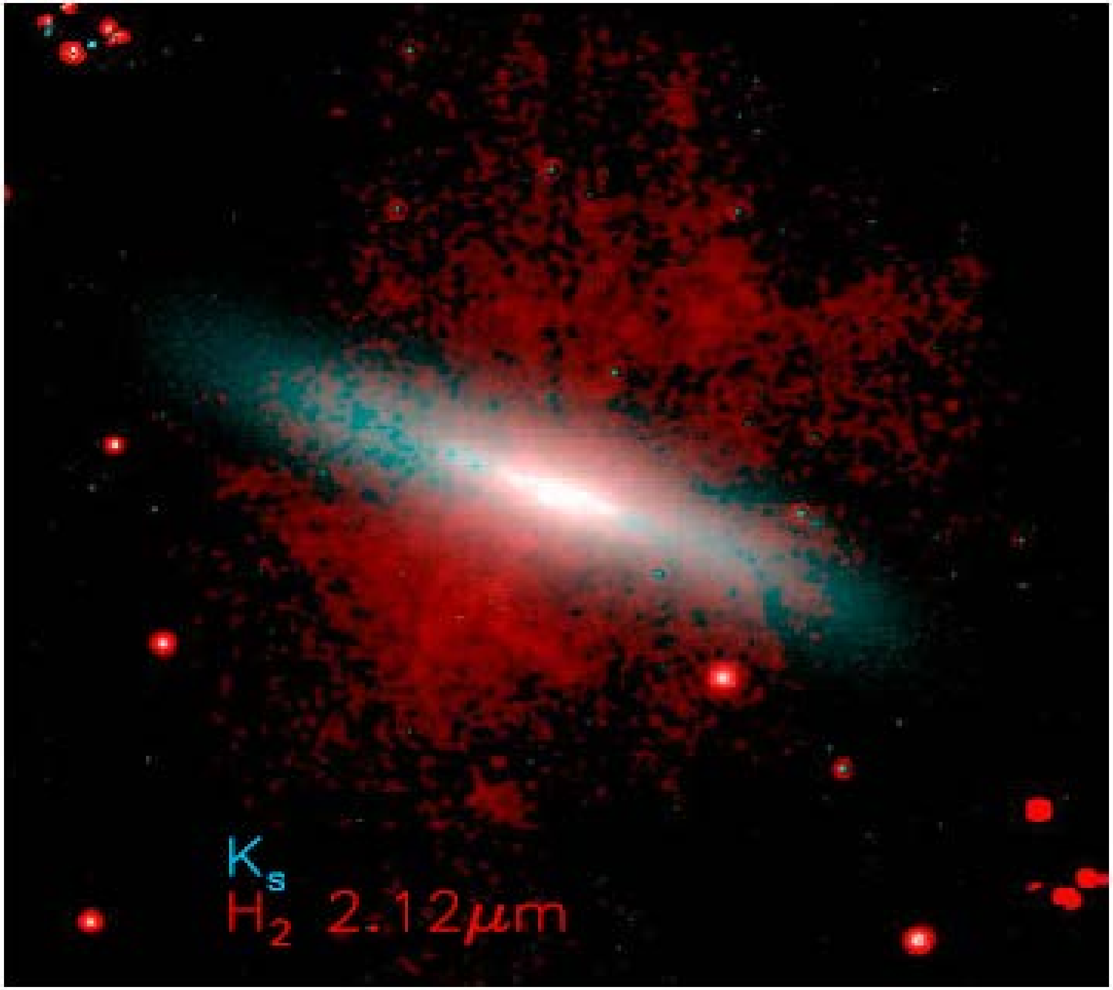
The Warm Phase(s)





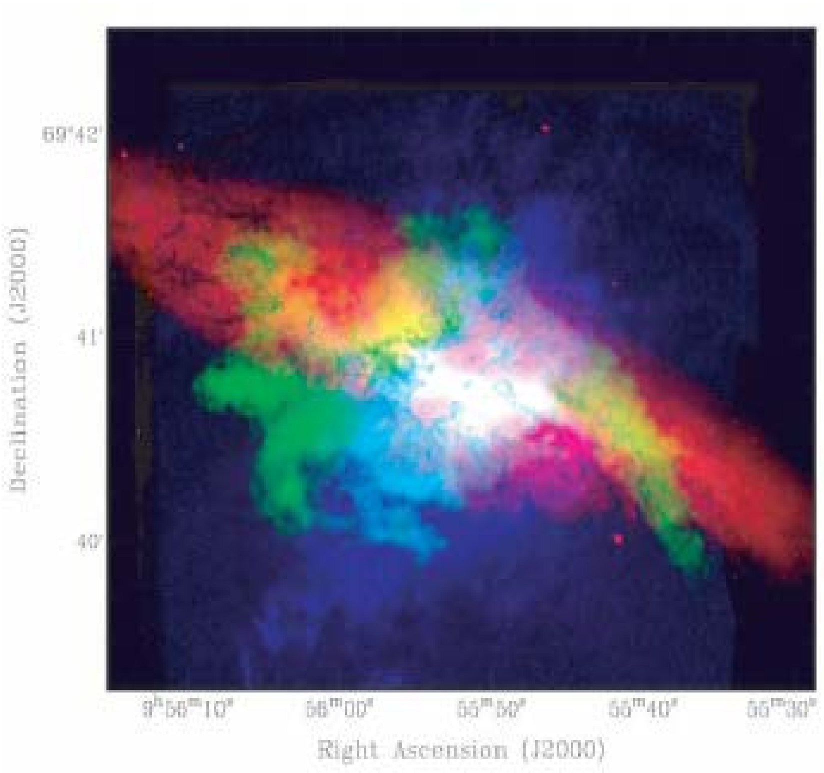
- Blue-shifted absorption-lines: entrained clouds
- Traces a range from ***neutral*** to ***coronal*** phases

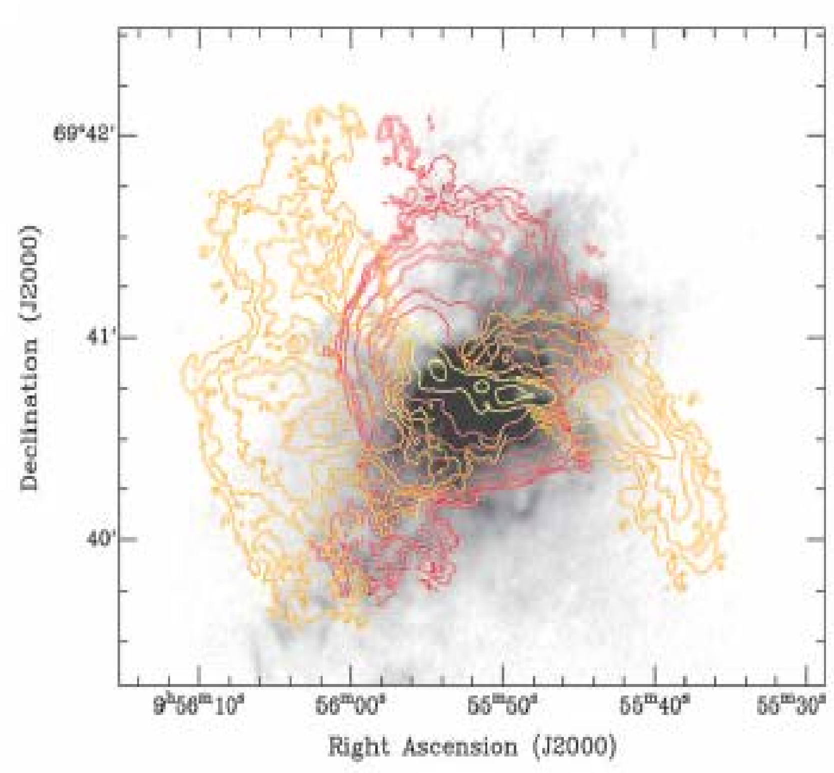
The Warm Molecular Phase



- Hot (~10^3 K) molecular hydrogen (Veilleux et al)
- Warm (~few 10^2 K) as well (Beir˜ao et al.)

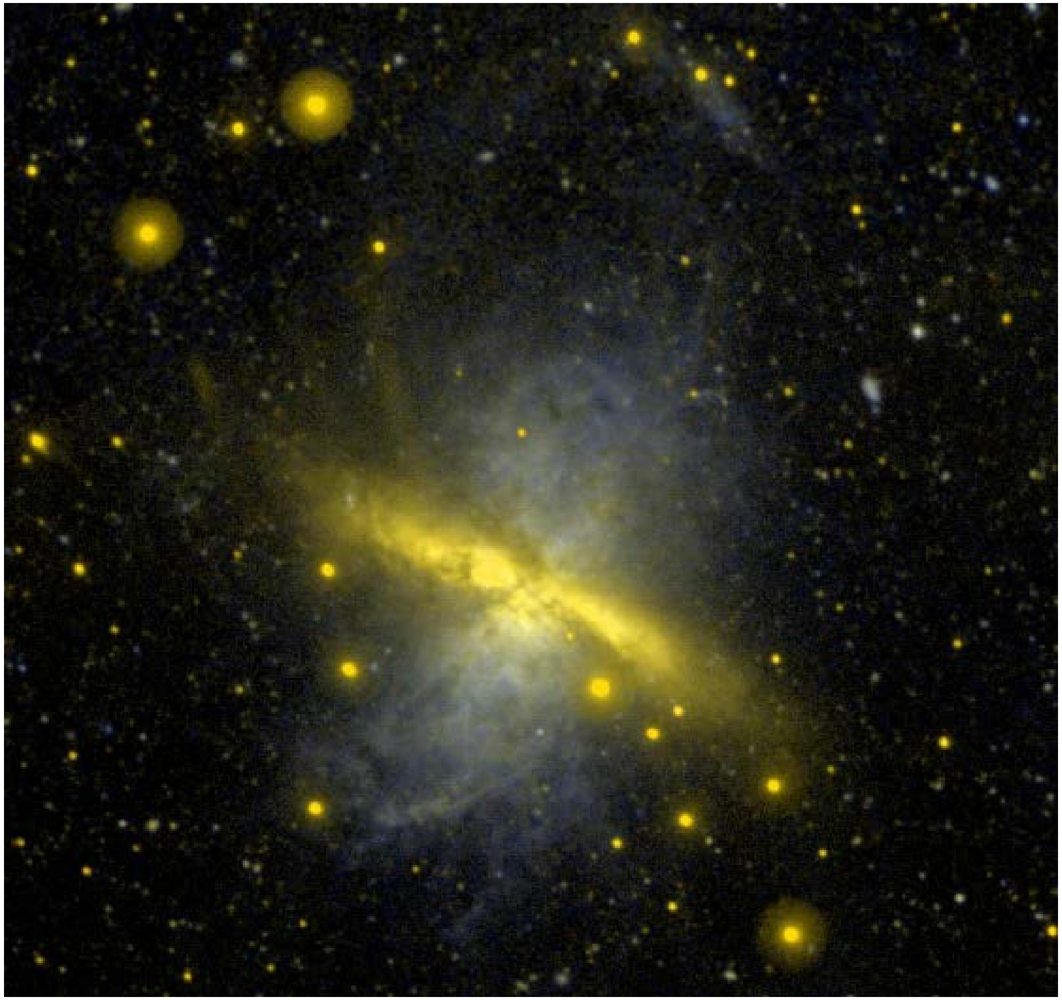
The Cold Molecular Phase





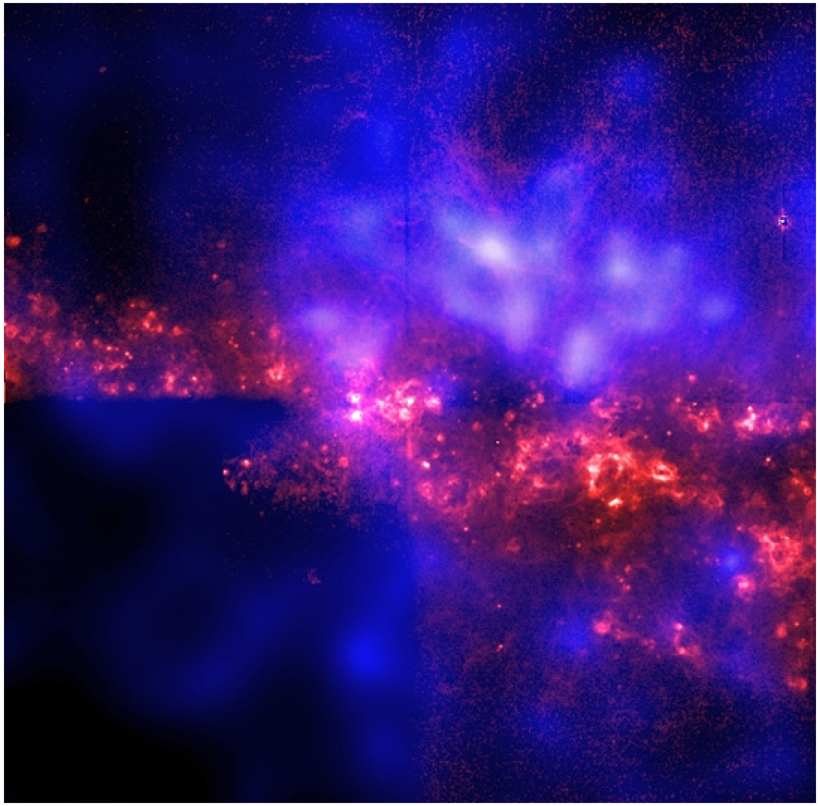
- Few hundred million solar masses at ~ 100 km/s
- KE ~ 3 x10^55 ergs
- Walter et al.

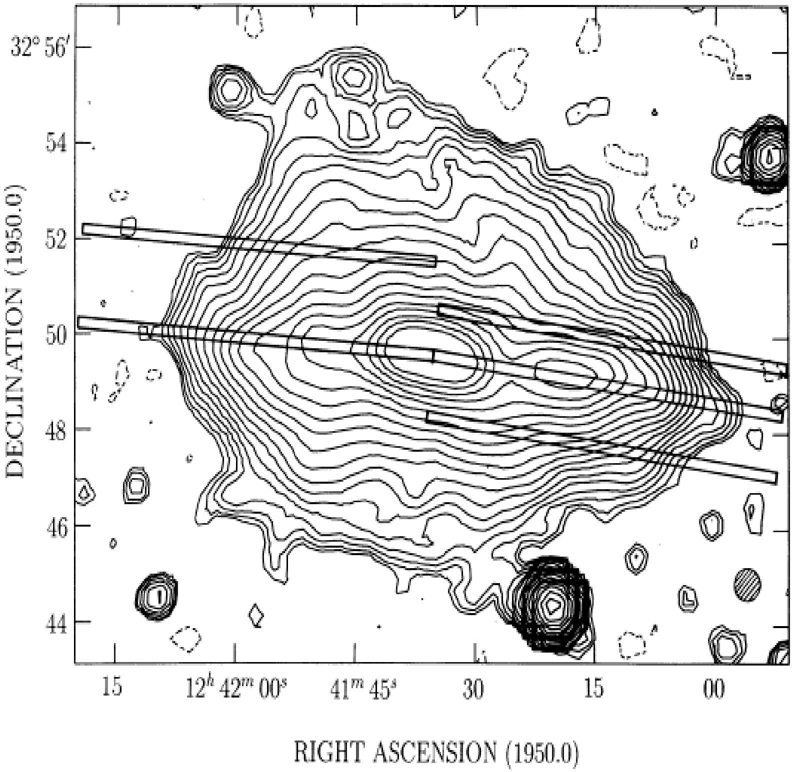
The Dusty Phase



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

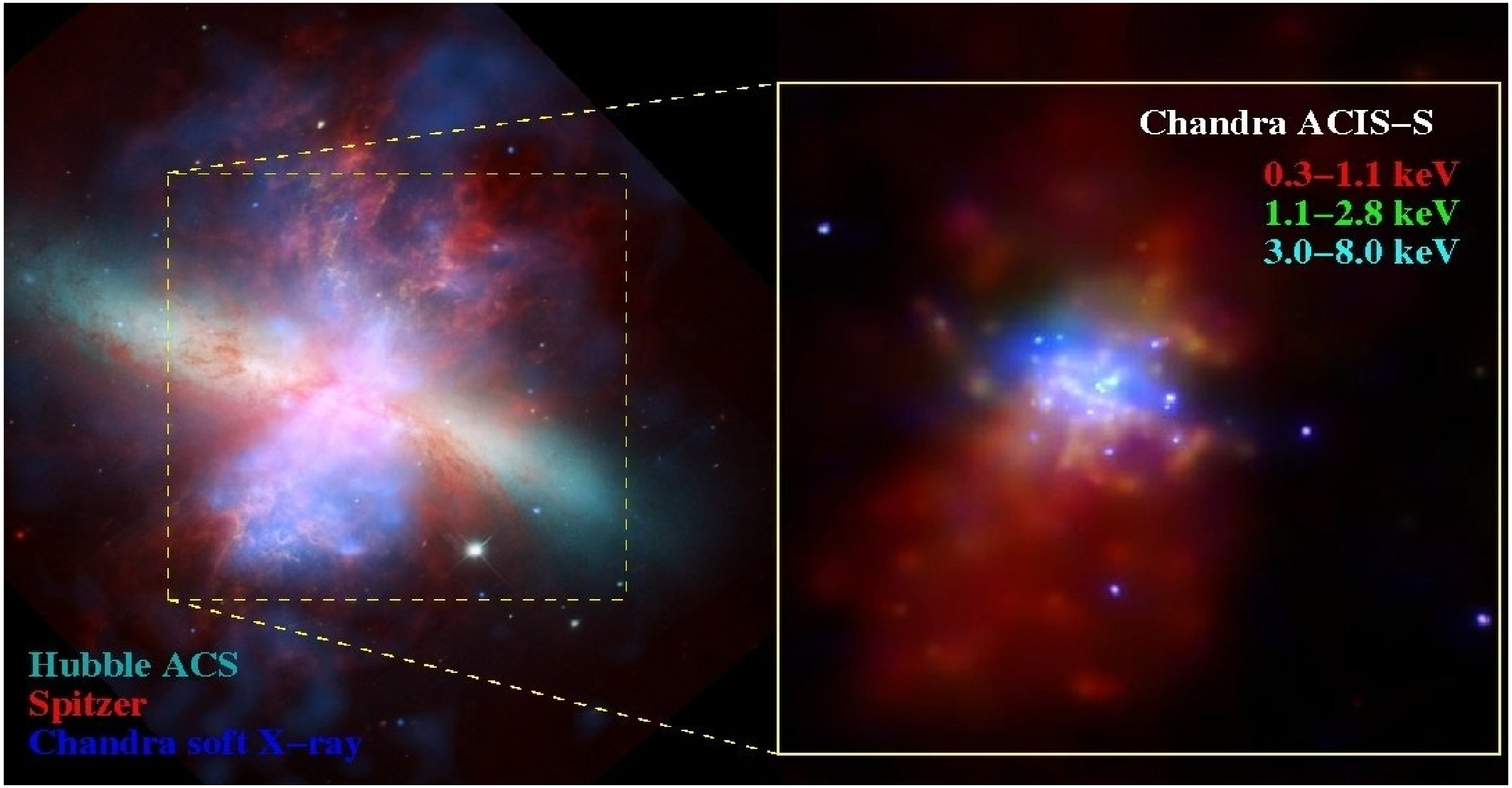
The Relativistic Phase





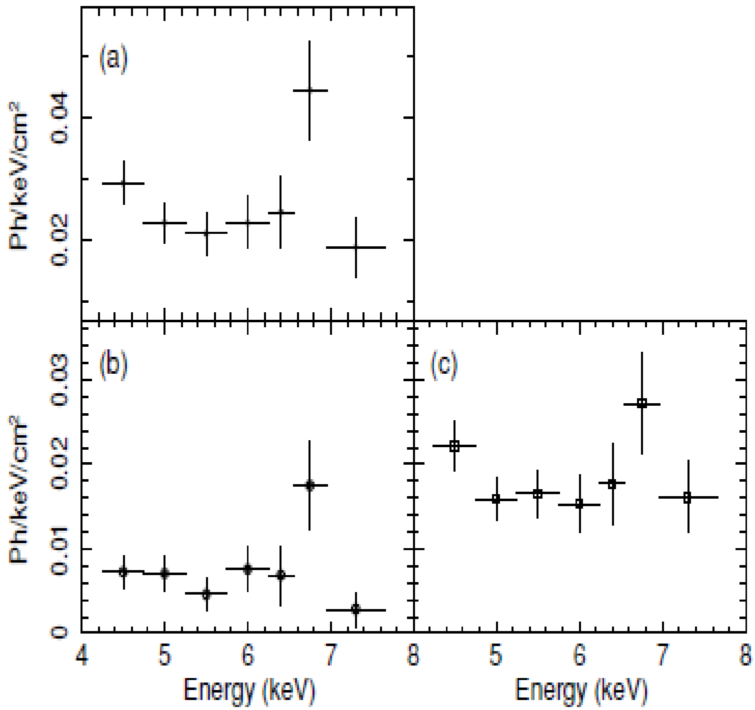
- Radio synchrotron emission from advected cosmic ray electrons and magnetic field
- NGC 4631 (Wang; Dahlem)

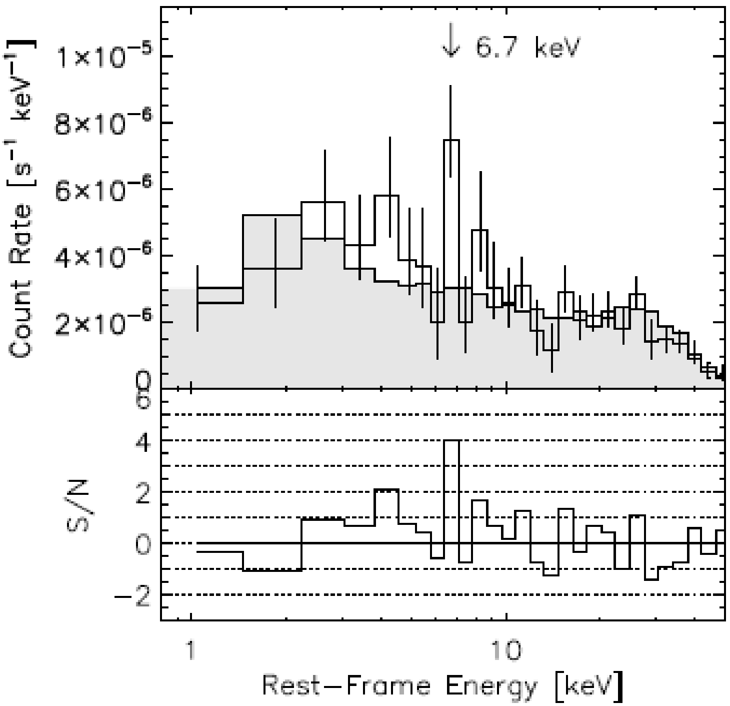
3) The Primary Wind Fluid



- Very hot (T ~ 60 million K) inside the starburst: implies maximum wind speed ~ 2000 km/s at larger radii
- Tenuous (~0.1 per cc) w/ P/k ~ 10E7 K/cc inside starburst
- Detected in M82 central region (adiabatic expansion & cooling causes it to disappear outside this region)

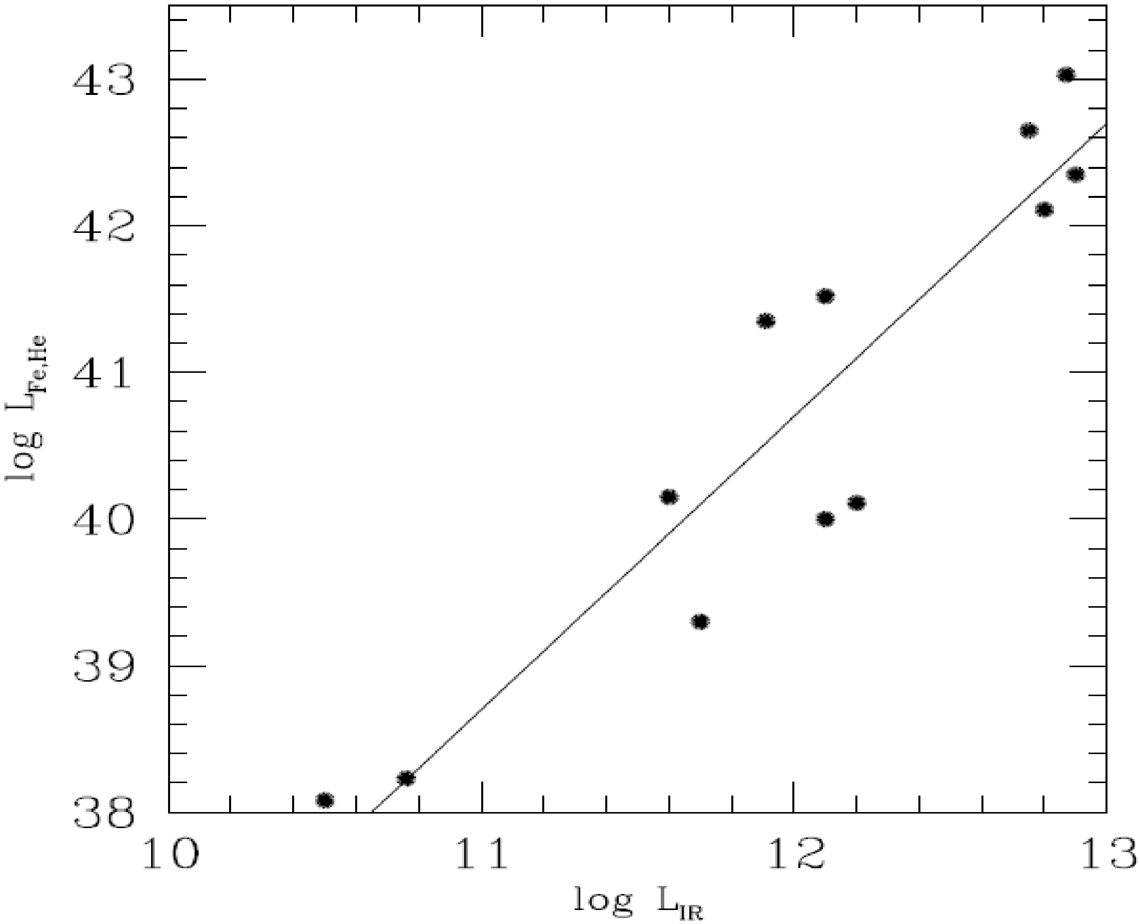
The wind fluid in other systems





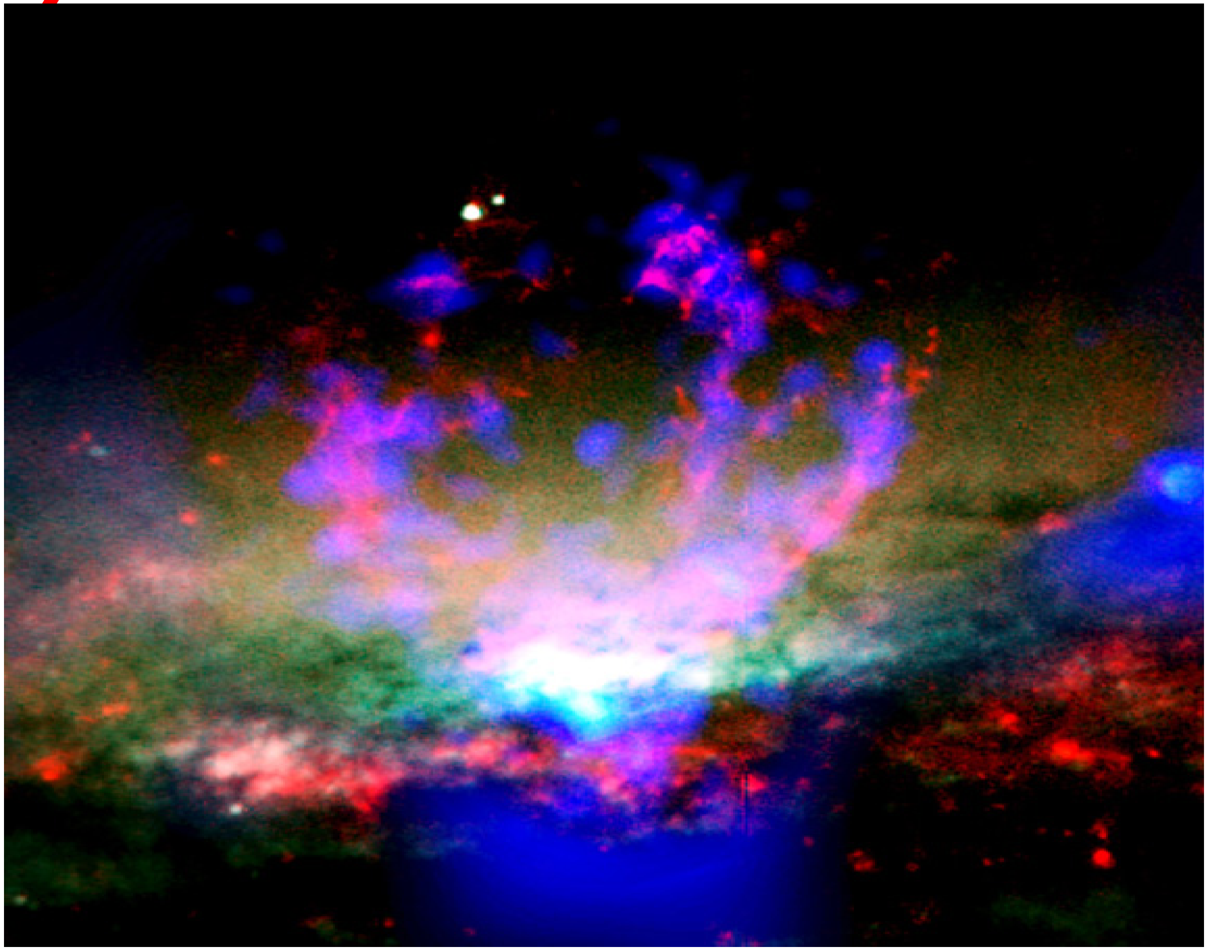
- Emission from He-like iron also seen in **non-AGN** LIRGs/ULIRGs (e.g. Iwasawa et al)
- And in stack of high-z sub-mm galaxies (Lindner et al.)

Luminosity of He-like Fe line



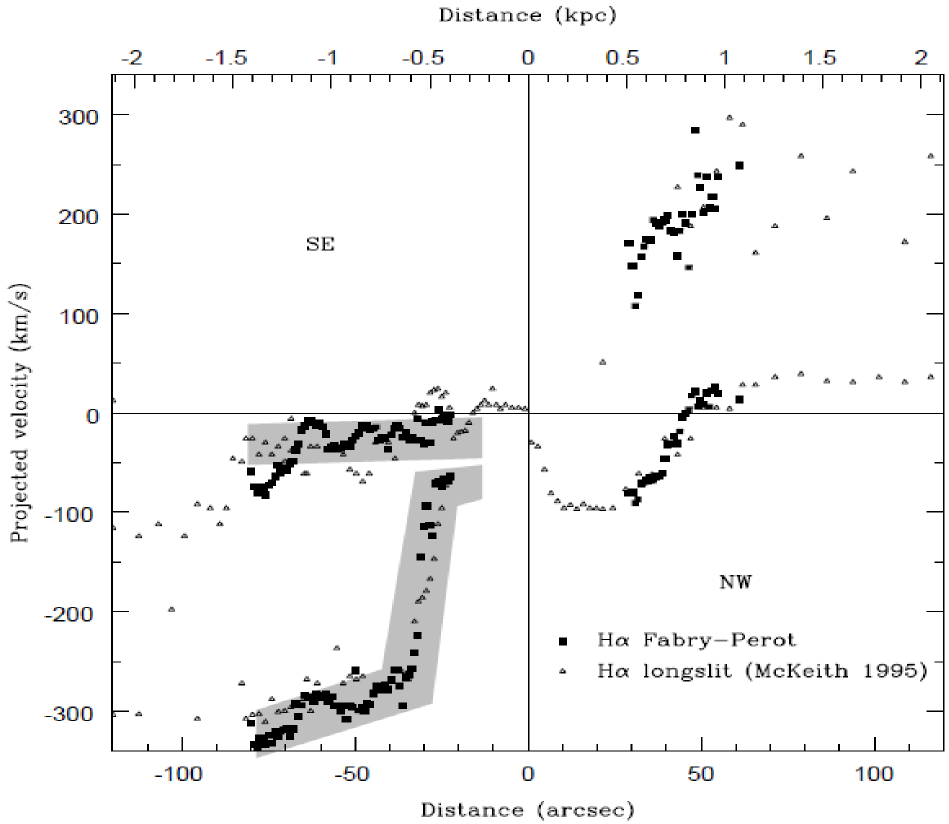
- Expect L α SFR^2/r_* for β ~ ε ~ 1
- Data agree with simple scaling

4) The Warm-Hot Interface



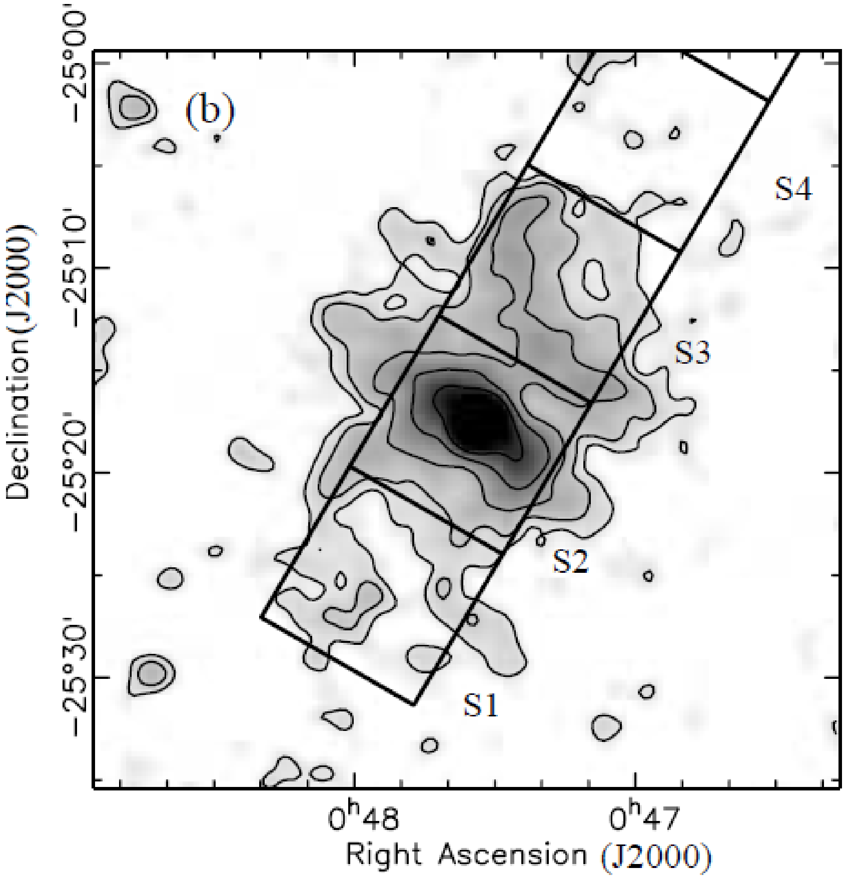
Close relationship between ***soft*** X-rays and optical emission-lines.Trace wind-cloud interaction in boundary layer (Cecil et al.)

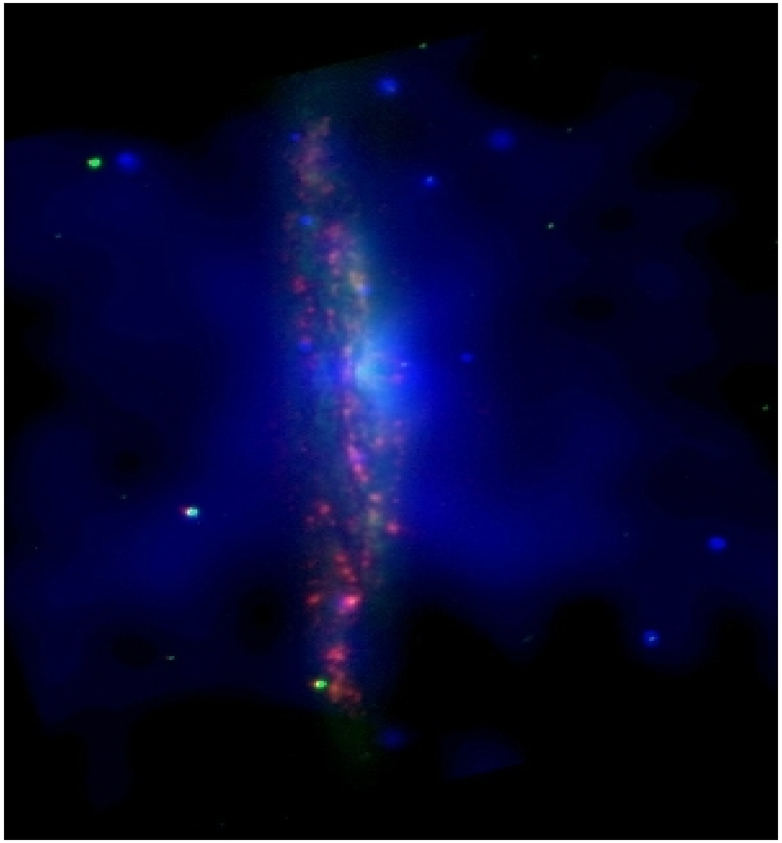
Kinematics of emission-line gas: flow along the surfaces of bi-cone (boundary layer)



- Rapid acceleration of entrained material to de-projected outflow speed of 600 km/s
- M82 - Shopbell & Bland-Hawthorn

Limb-Brightened Morphology

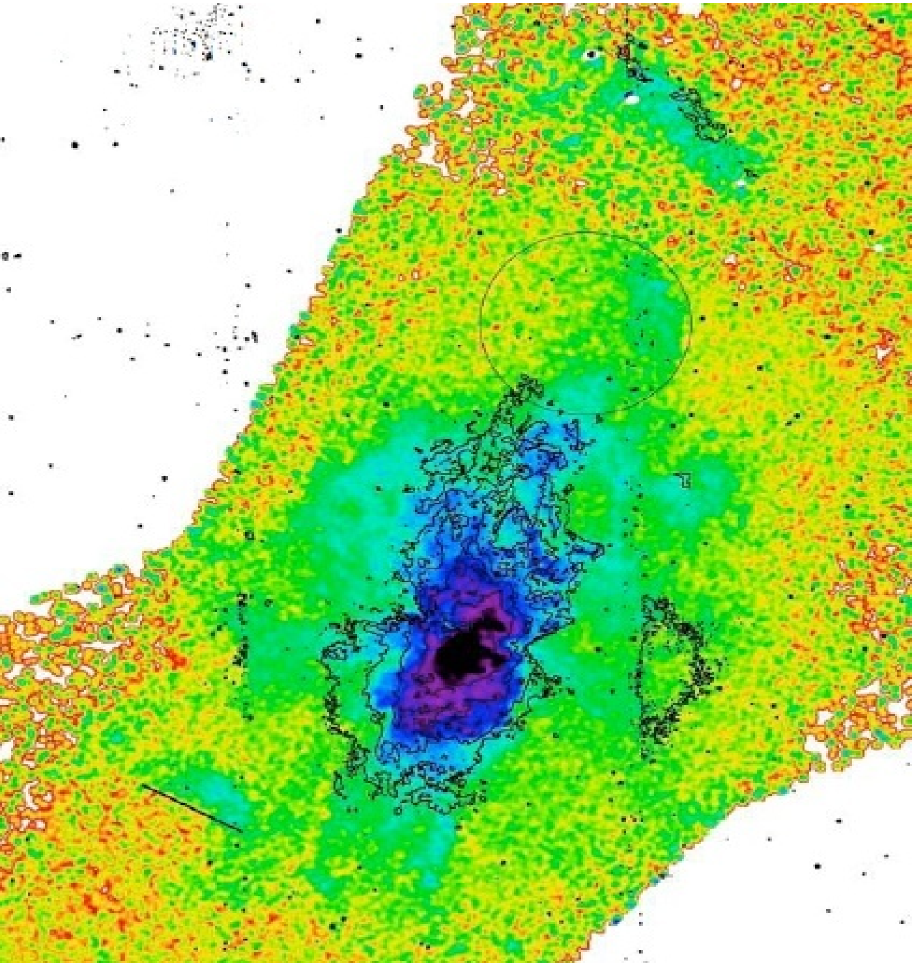


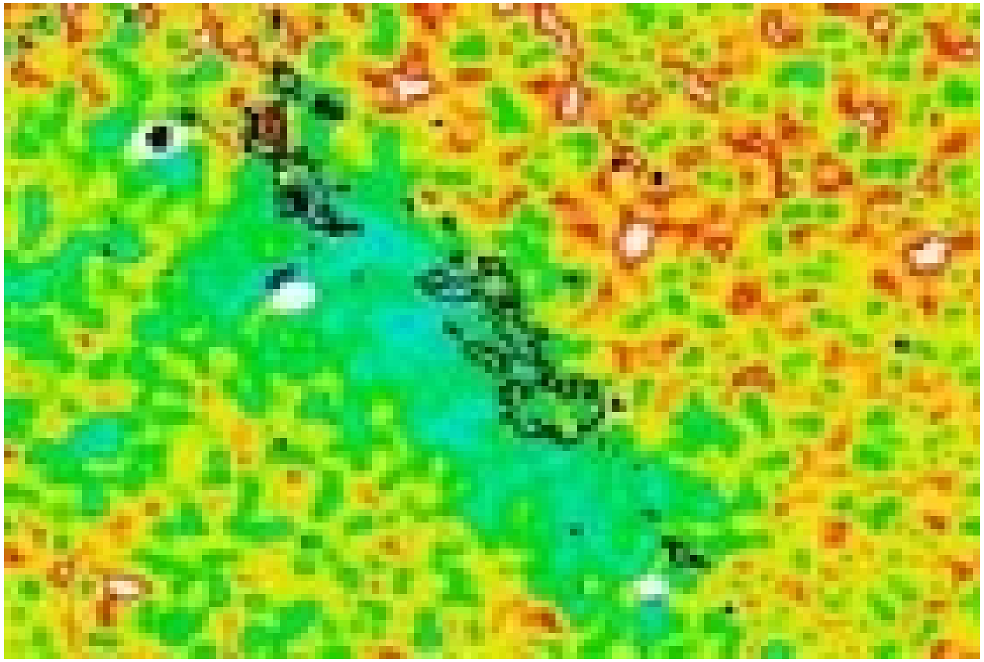


Soft X-rays on halo-scales in a layer bounding the tenuous volume-filling wind fluid

The Warm-Hot Interface in M82

"The Cap": X-ray gas located upstream of optical line emission: bow shock in wind and wind-shocked cloud ?

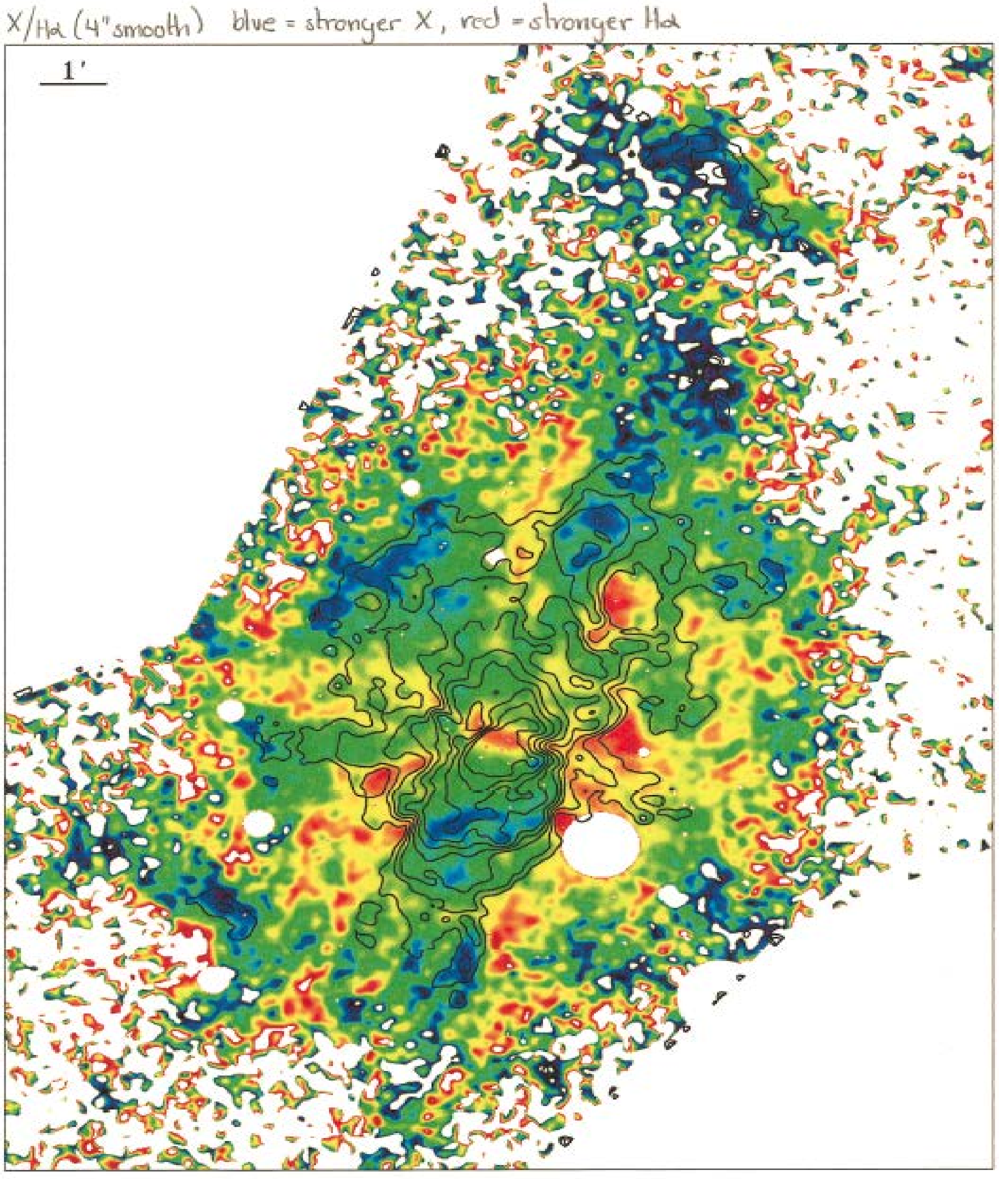




Implied wind speed:

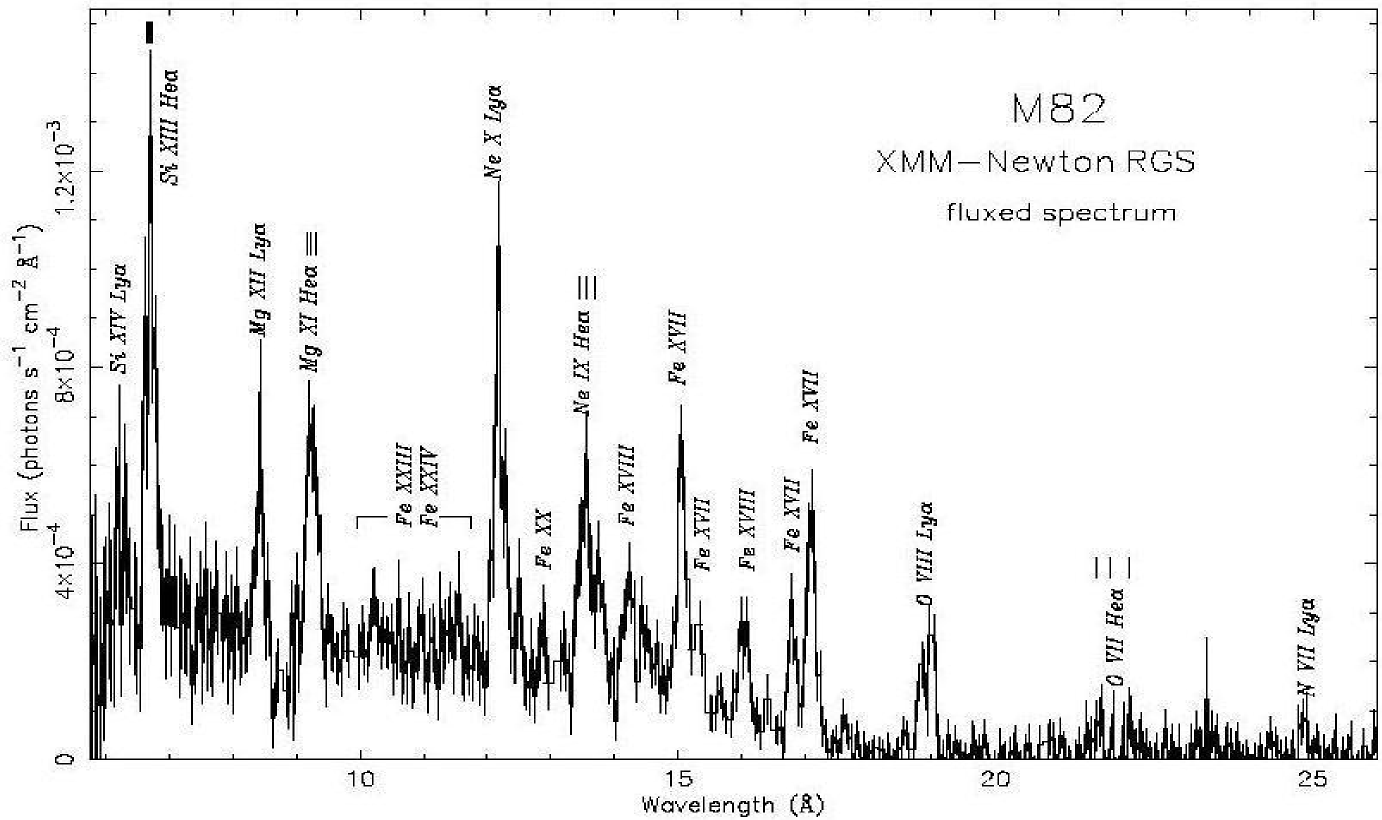
V_wind – V_cloud ~ 800 km/s

The Warm-Hot Interface in M82



- Ratio of X-ray and Hα surface brightness
- Warm gas encloses the hot X-ray gas
- Kuntz et al.

Abundances in the hot phase

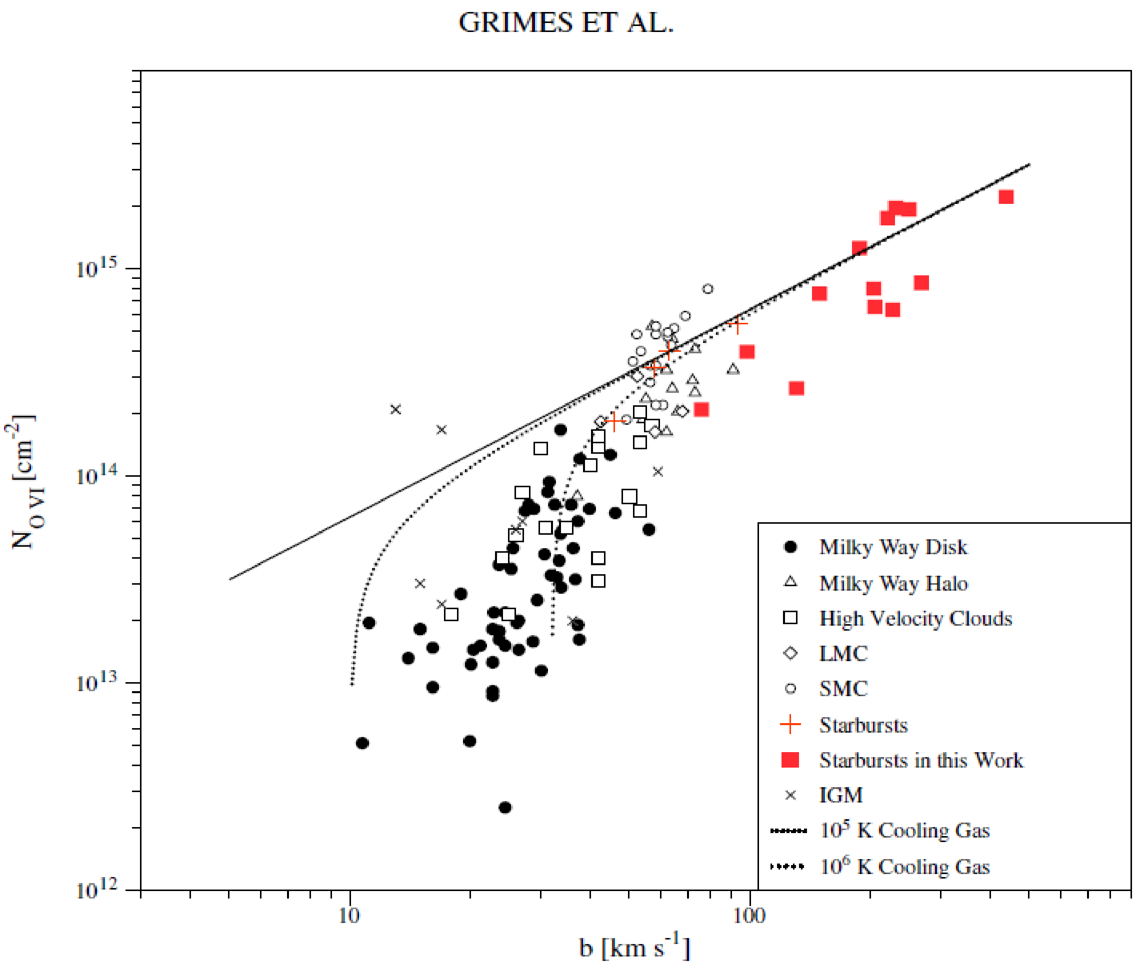


X-ray spectrum of the superwind starburst galaxy M82

European Space Agency

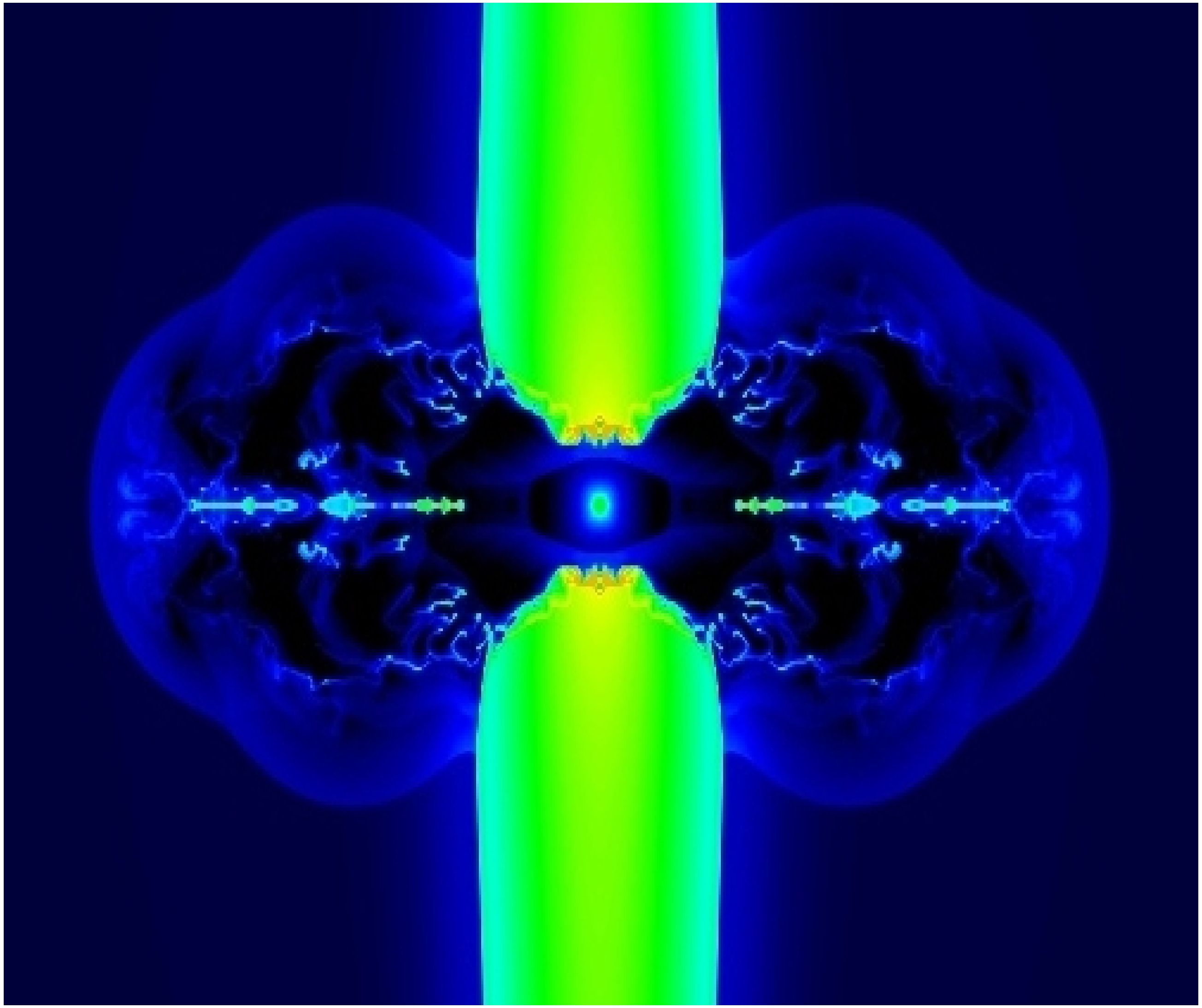
- Alpha/Fe several times solar
- Consistent with enrichment by core-collapse supernovae

Hot/Warm Interaction Traced by OVI?



- Relationship between N_OVI and v_flow consistent with radiative cooling flow

5) Outflow *rates*: Phase dependent!



Outflow rates in the wind fluid

> *This is the "engine" that drives the flow*

> It contains (a large fraction of) the kinetic energy supplied by the starburst

> *It contains the **newly synthesized** metals*

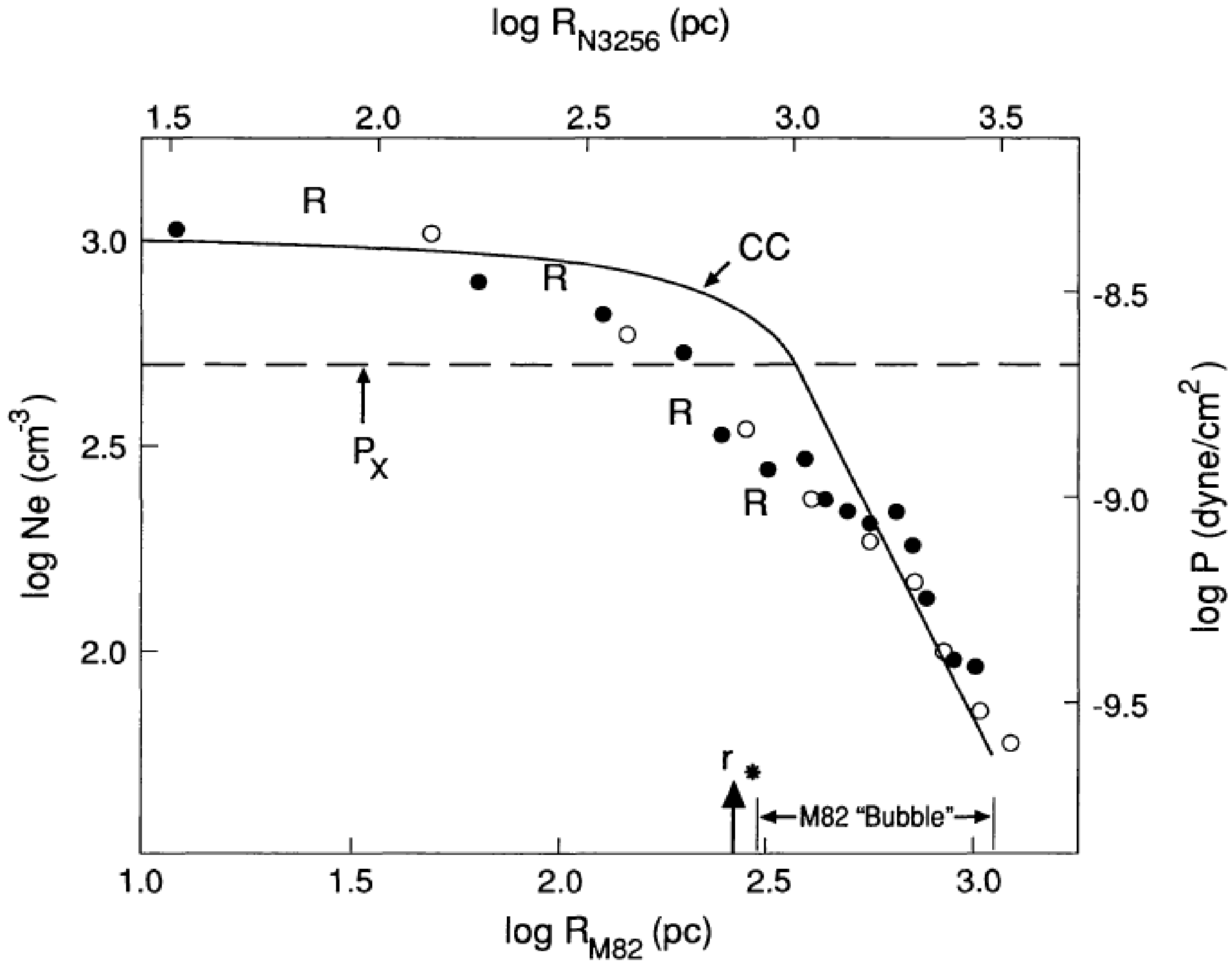
> It contains much of the total metal content

Pure wind fluid has $Z_w \sim 10$ times solar

Entrained metals significant for large "poisoning" $(\beta > [Z_w/Z_g] + 1)$

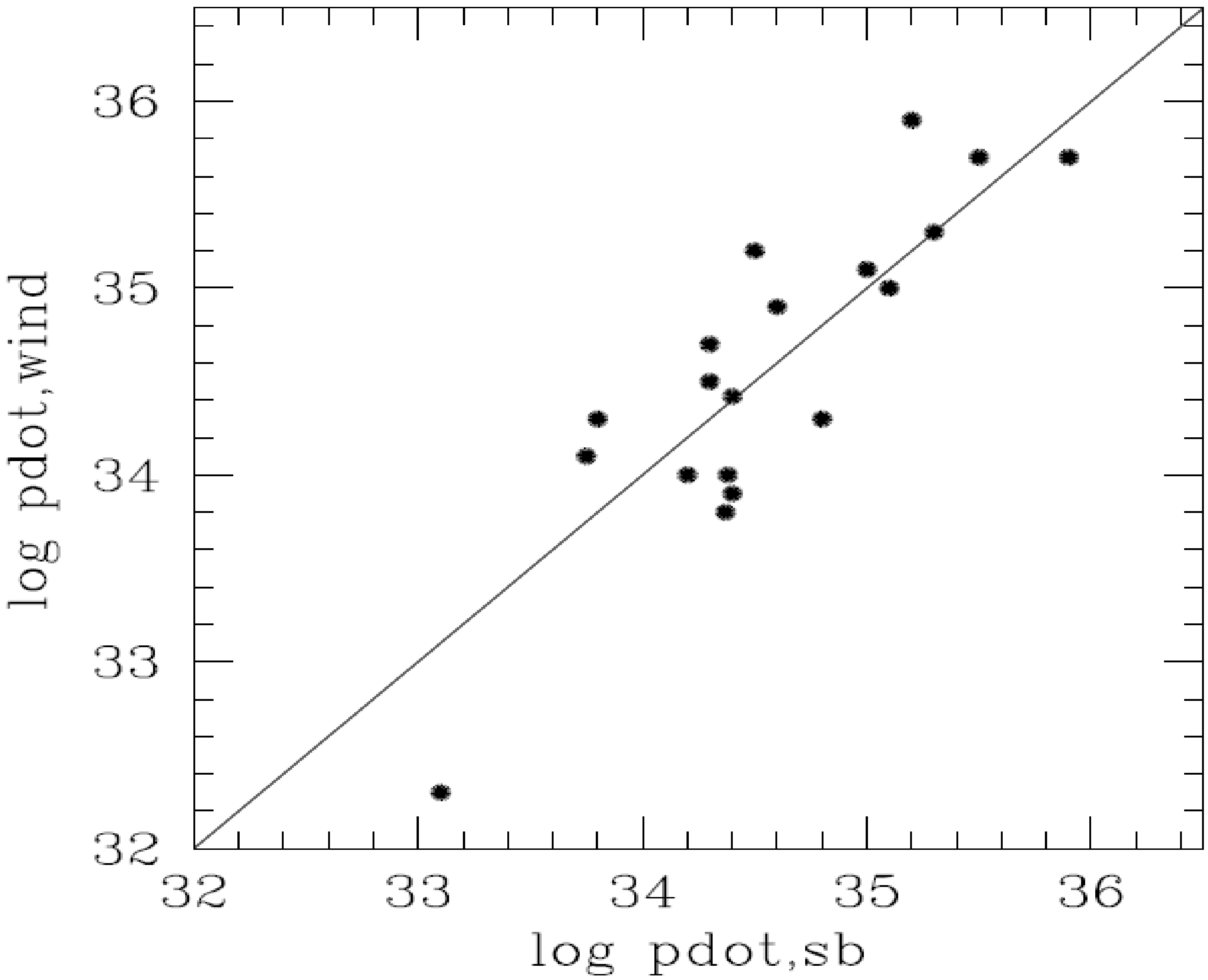
> *High specific energy – most likely to escape*

Probes using the warm phase



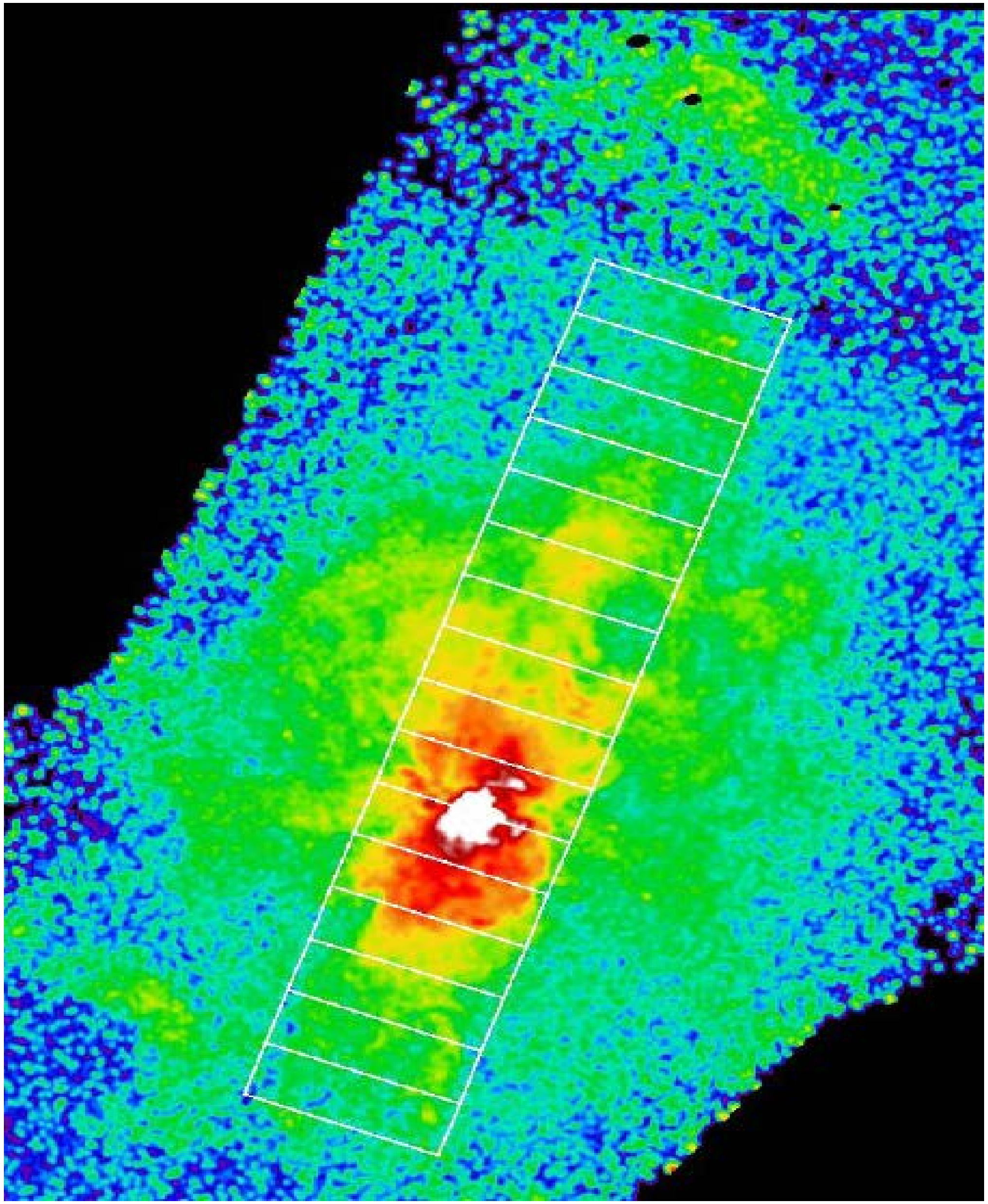
Measure the radial pressure profile directly to measure ram pressure of wind fluid

The momentum flux of the wind fluid



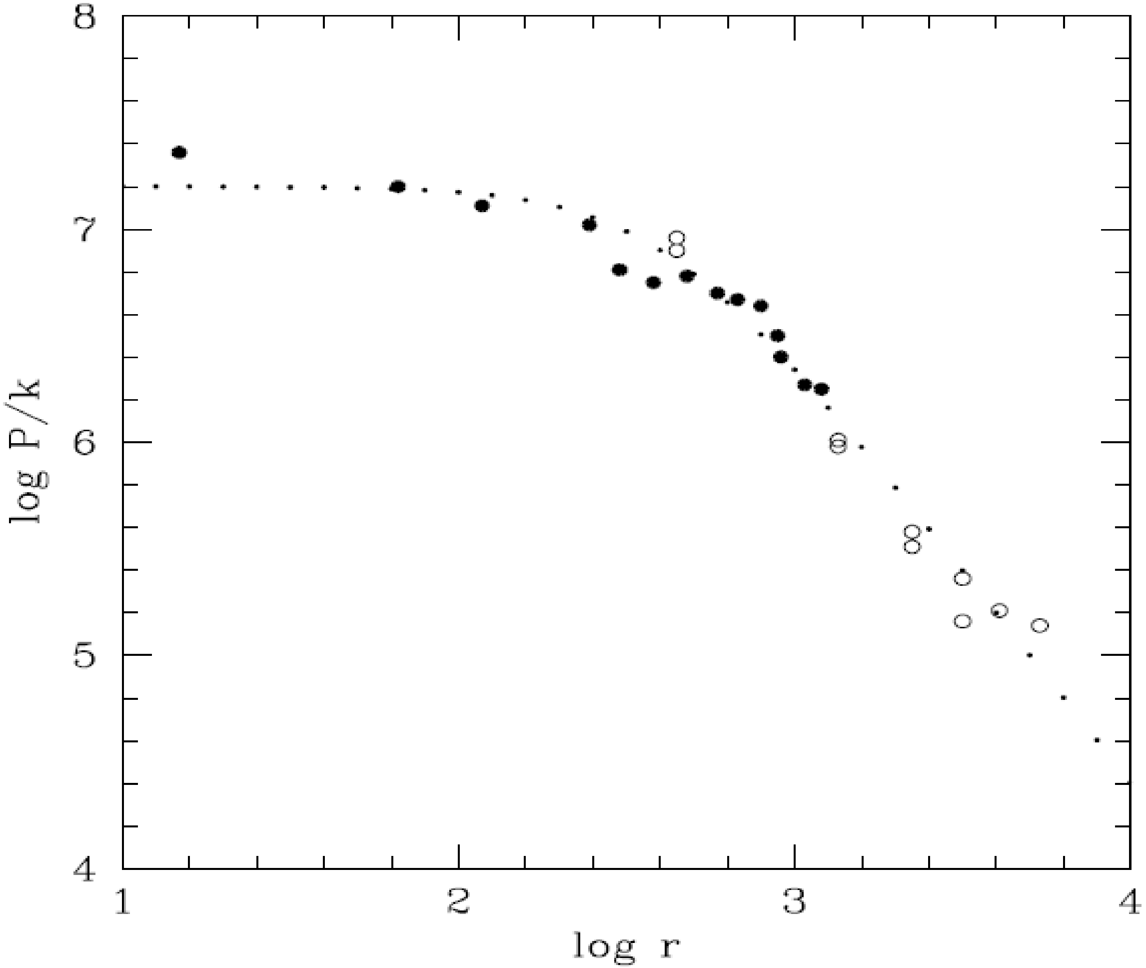
Good match to output by the starburst

Probes using the hot phase



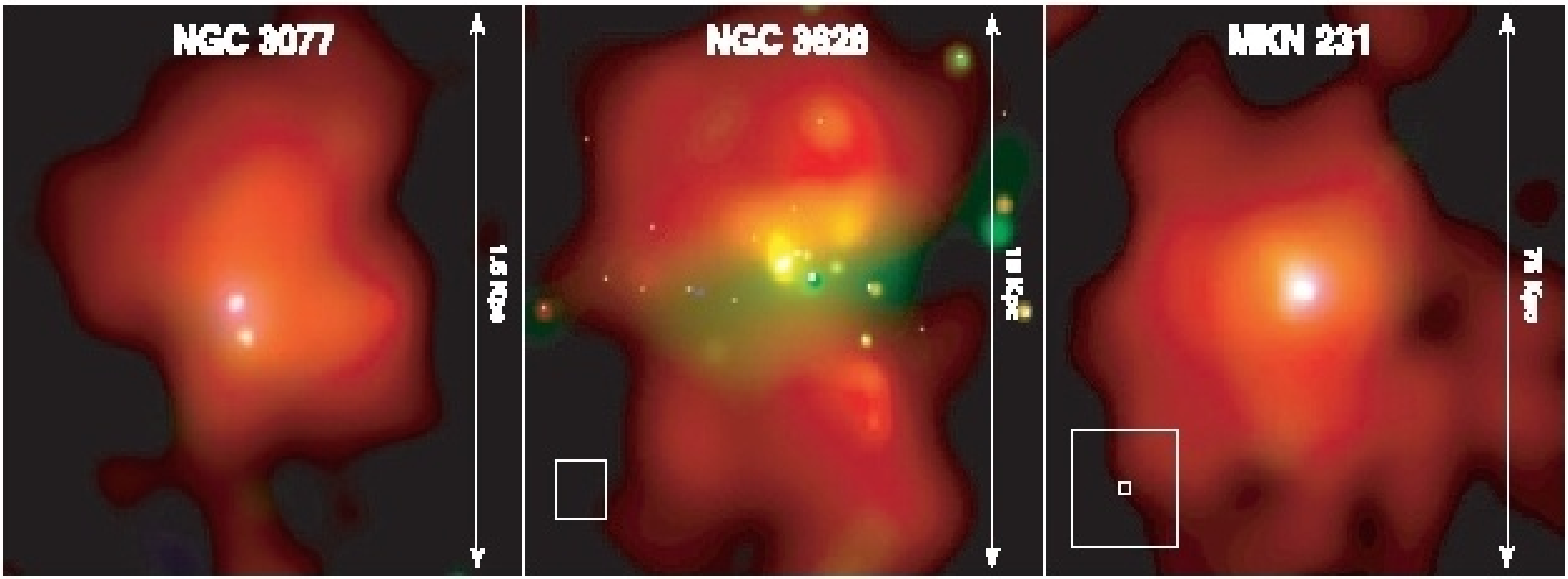
- Measure the pressure profile in the X-ray data
- Yields minimum pressure (for unit volume filling factor "ff")
- Kuntz et al.

The combined pressure profile



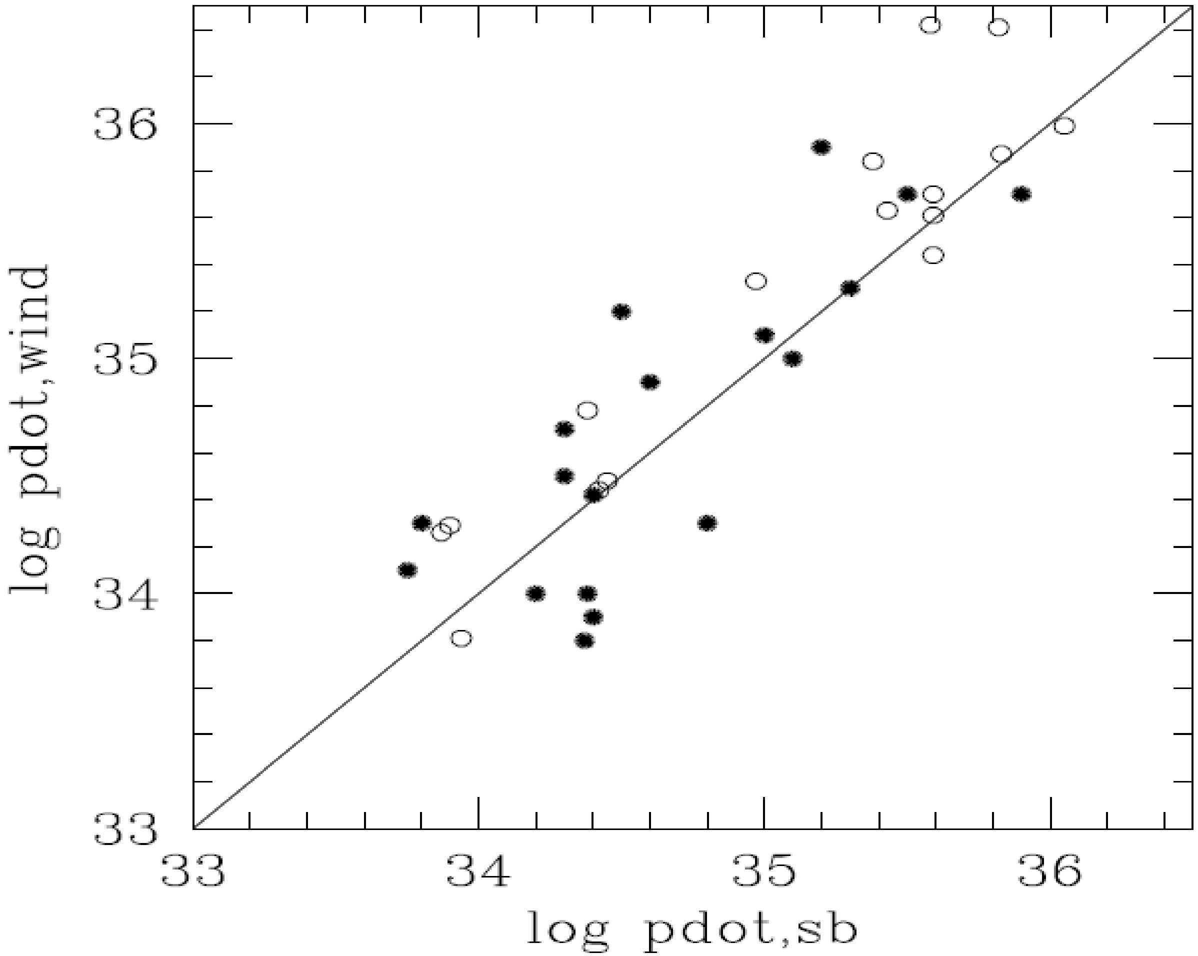
- Requires ff ~15%
- Excellent fit to model predictions for M82

Soft X-rays as a probe from dwarf starbursts to ULIRGs



- X-ray data map the minimum pressure (ff = 1) over the volume occupied by the wind fluid
- Adopt a ff = 0.15 to estimate pressure (M82)

Momentum Flux of Wind Fluid



- X-ray data (hollow dots) assumes ff ~ 15%
- Momentum flux ~ starburst injection rate

Outflow rates in soft X-ray phase

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: $P\Delta V \propto F^{-1/2}$

Outflow Rates in Warm Phases

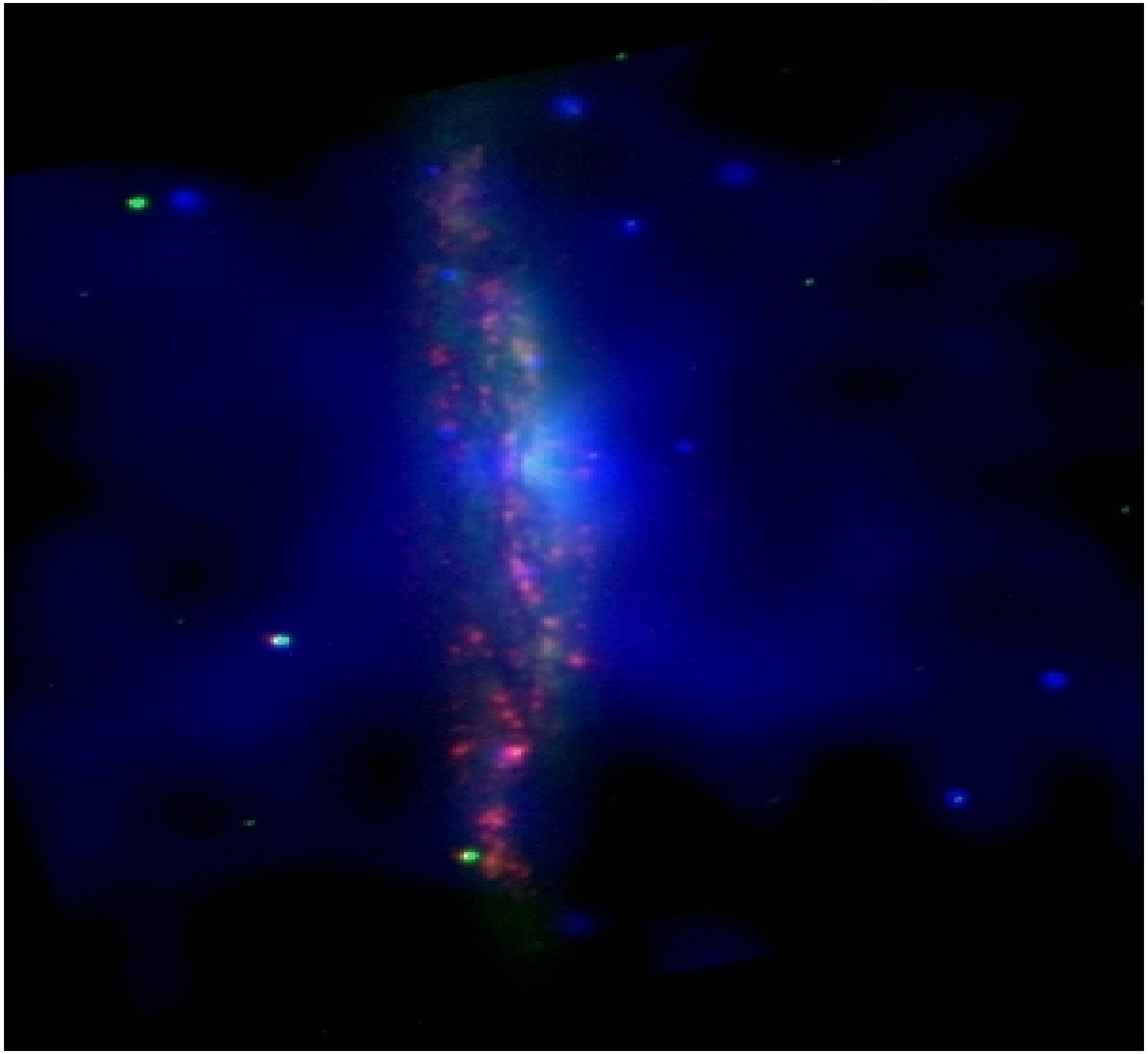
Interstellar Absorption Lines

- **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
  $\dot{E}\ \sim 10\%\ \dot{E}_{sne}$

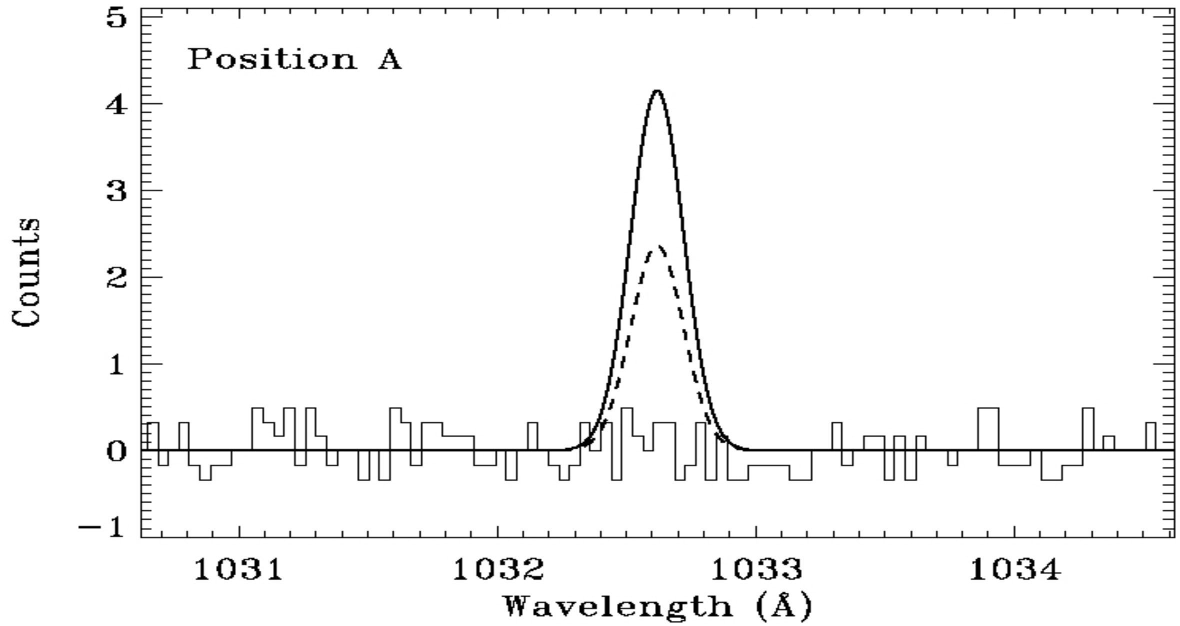
6) The Fate of the Wind



Radiative Losses

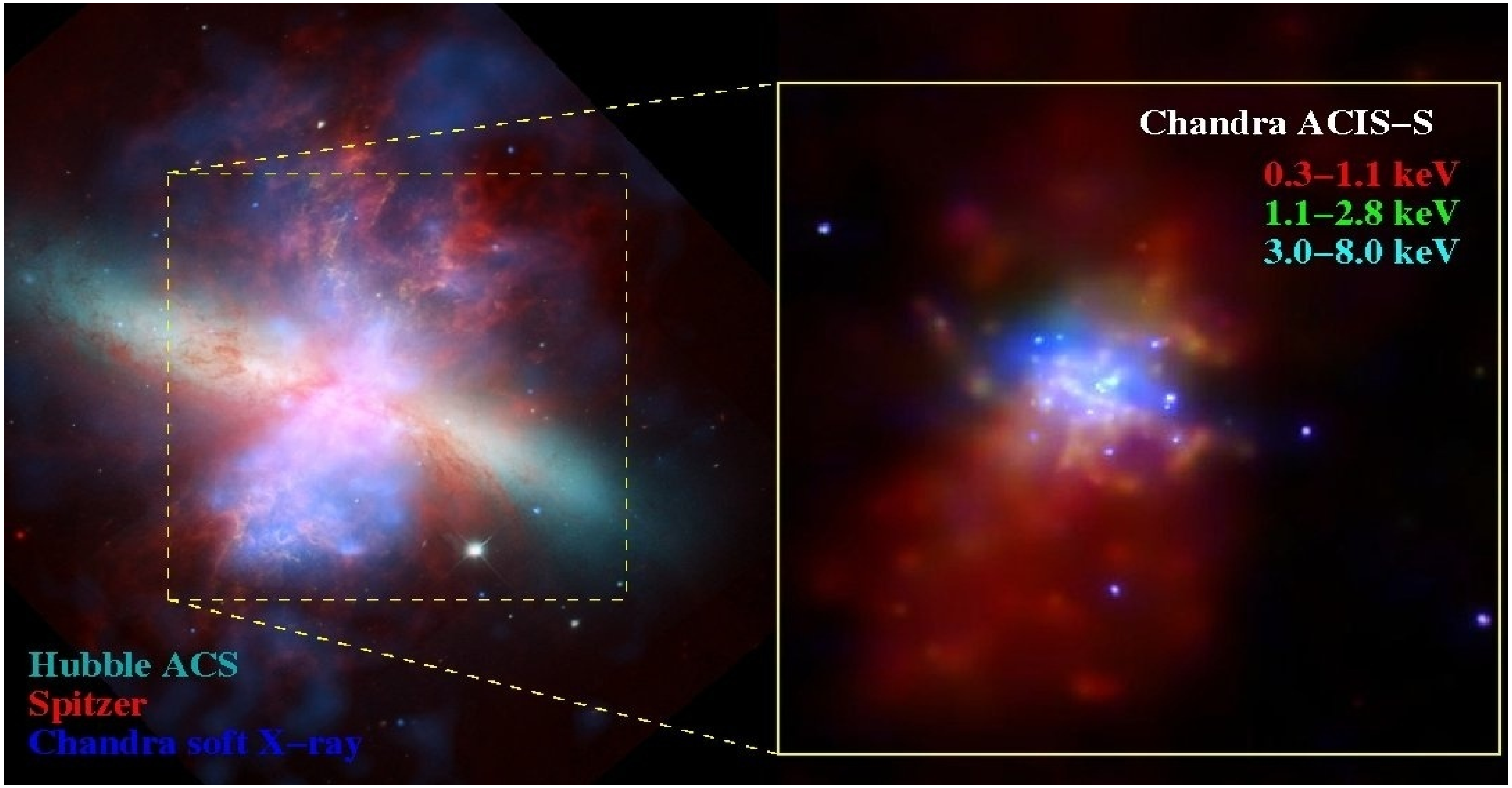
Are they "quenched" by radiative cooling?

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



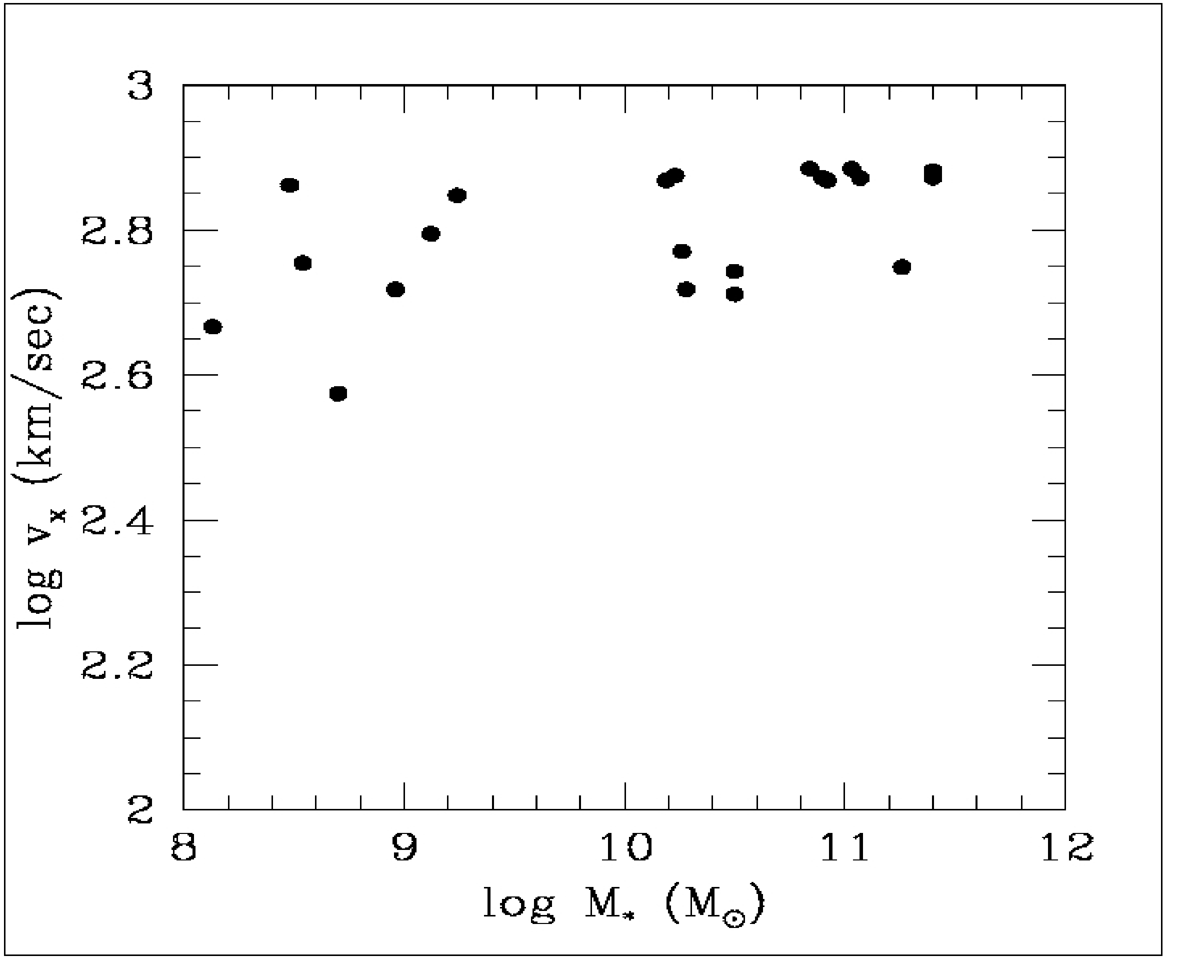
- Hoopes et al.
- M82 et al.

How fast? The wind fluid



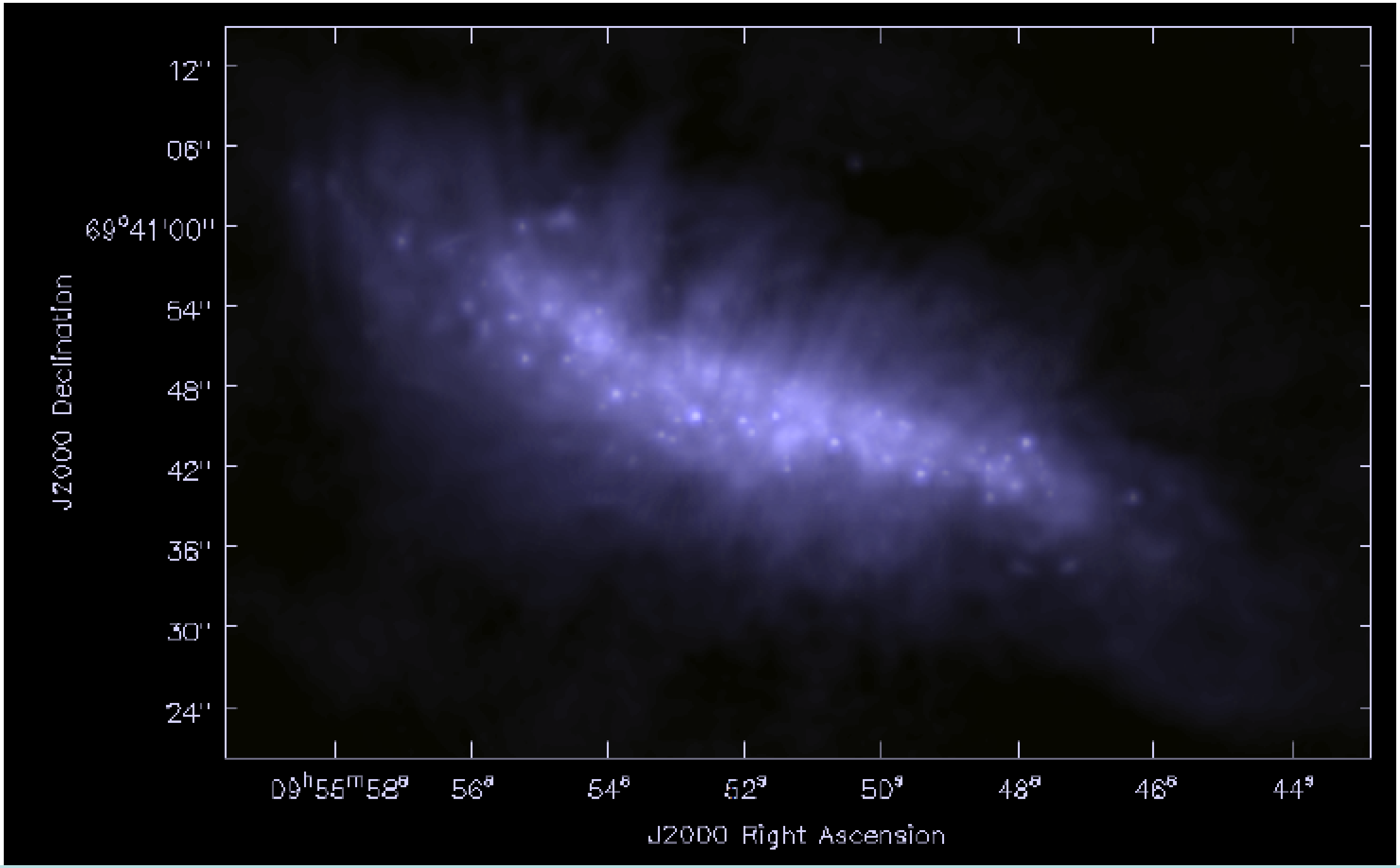
- The wind fluid itself starts out very hot (~60 Million K)
- The corresponding outflow velocity is ~ 2000 km/s
- Far above escape velocity from any galaxy
- But what about the stuff carried out by this wind?

How fast? The hot phase



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

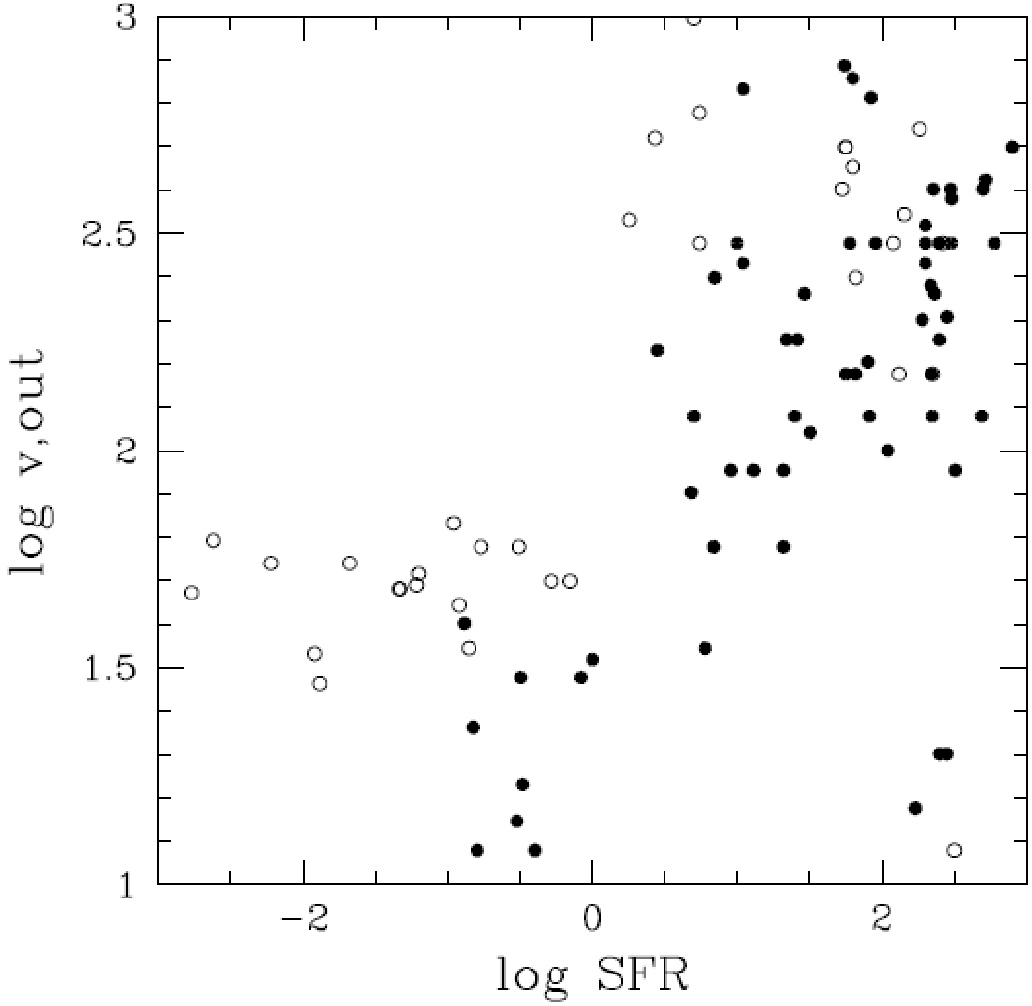
How fast? The relativistic phase



> Spectral steepening of synchrotron emission with height yields estimate of 1000 – 2000 km/s for wind fluid outflow speed (Seaquist & Odegard)

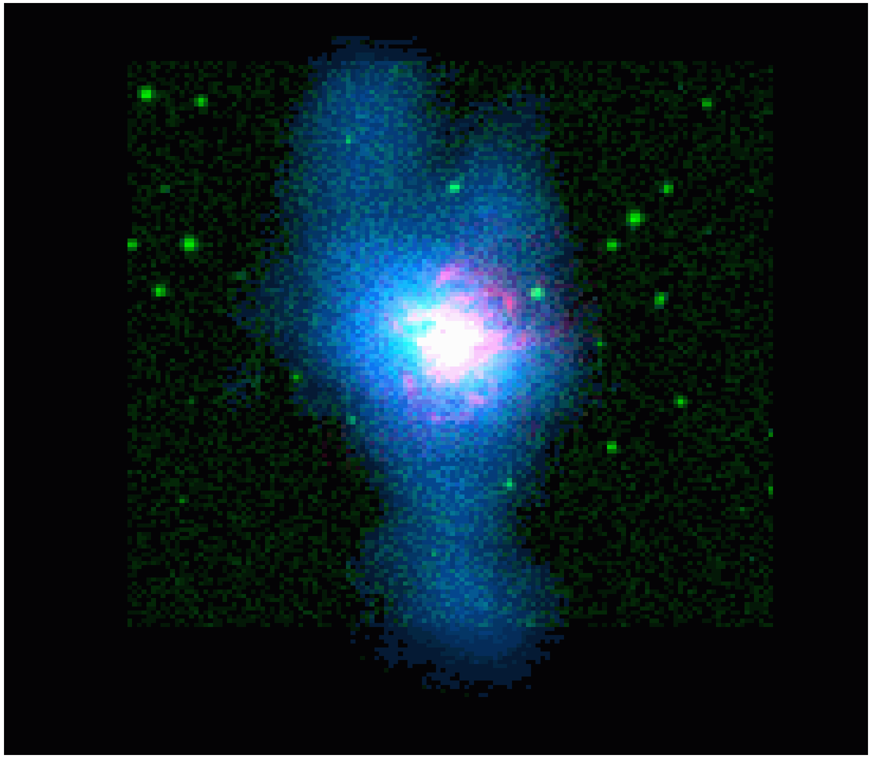
> Modeling gamma-rays plus radio in core of M82 and NGC 253 yield lower speeds of ~300-1000 km/s (Yoas-Hull et al.)

How fast? The cool/warm phase



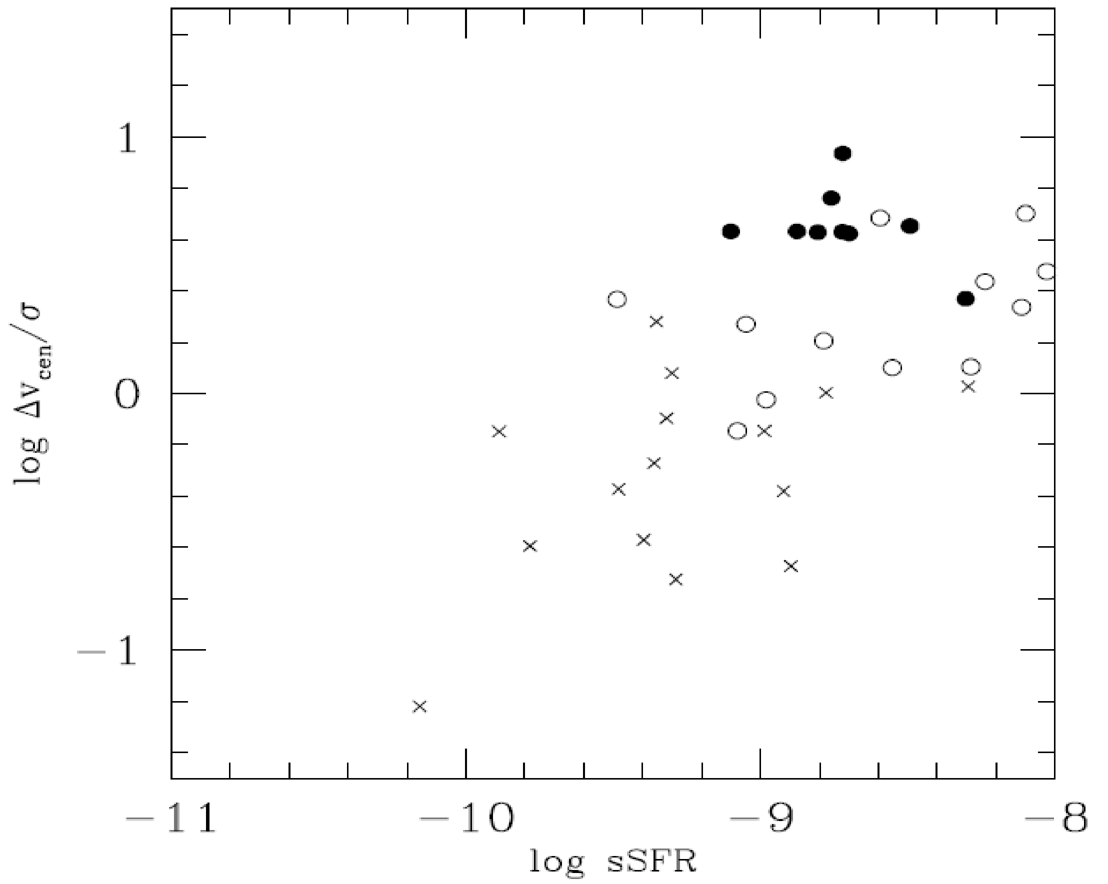
Transition from super-bubbles (in dwarf starbursts) to blow-out?

Dwarf Starbursts: Super Bubbles



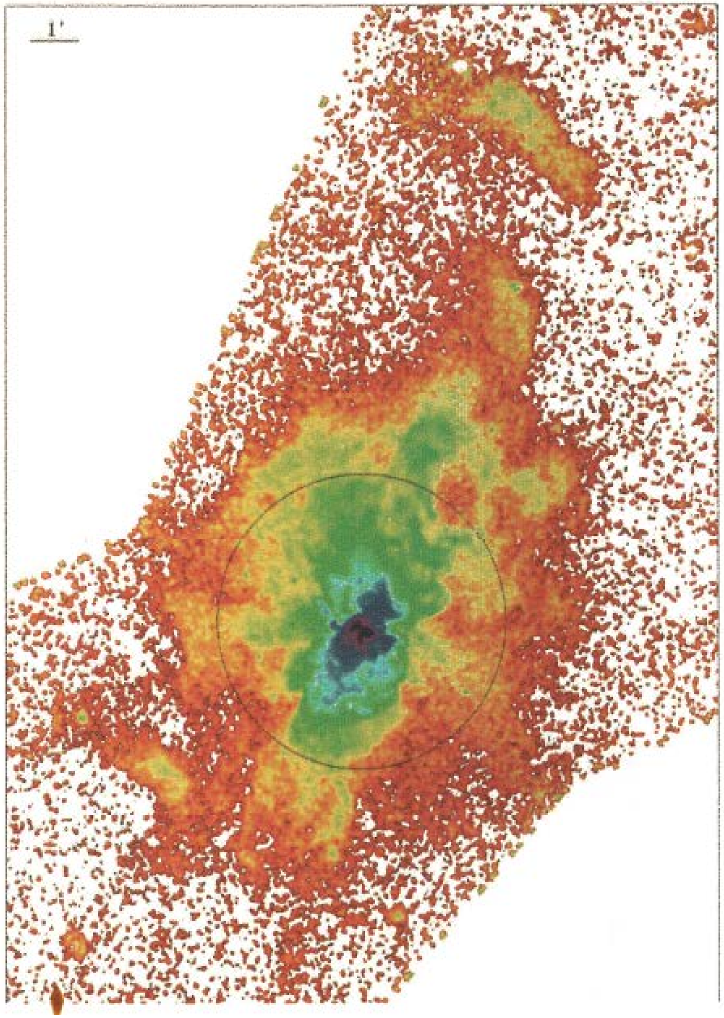
- Low energy injection rate and large ISM scale-height keep the gas confined (Meurer et al.)

Scaling w/ galaxy velocity dispersion



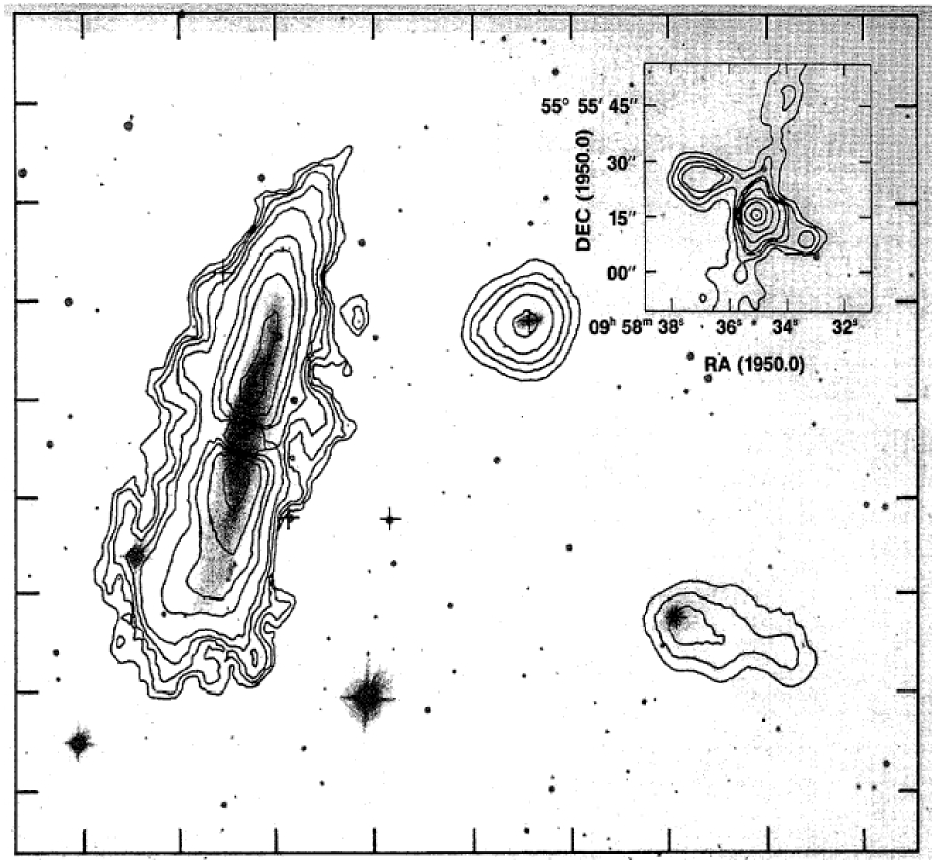
- V_out for cool/warm gas does not simply scale with sigma
- V_out/sigma rises with SFR/M*
- Show a range of ~2 orders-of-magnitude

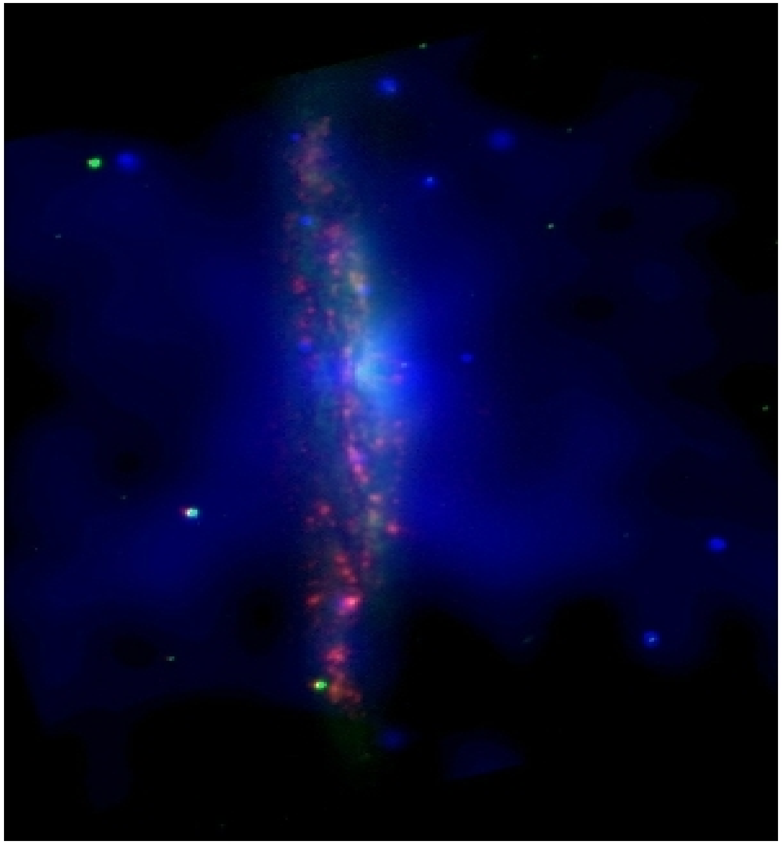
How far do they travel?



- Adiabatic expansion and cooling: steep radial decline in surface brightness
- Wind "lights up" when it collides with halo cloud
- M82 – Kuntz et al.

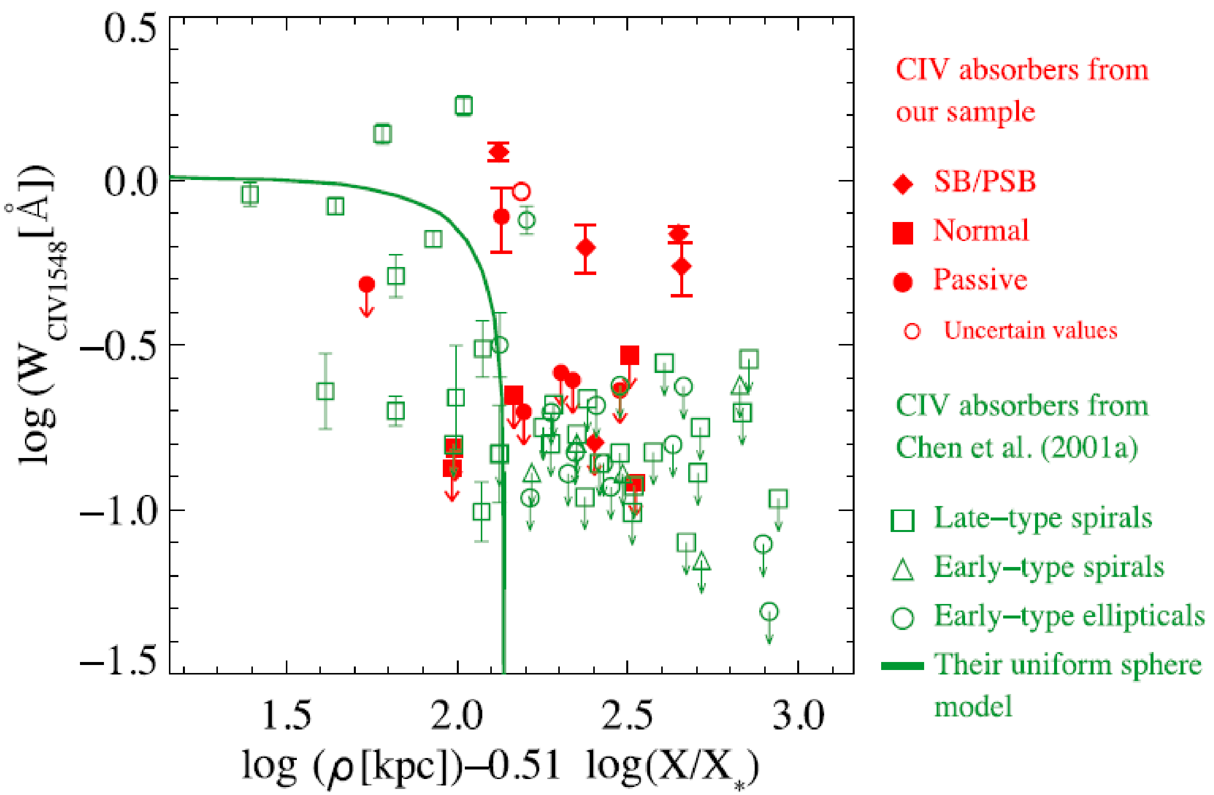
Ram pressure stripping of HI in a companion galaxy





- NGC 3079 (Irwin et al.)

CIV absorption probes to virial radii



- Strong (EQW >500 mA) CIV absorption seen at large impact parameters (50 to 200 kpc) in starburst halos (4/5 cases)
- Only seen in 2/15 of the other galaxies
- Borthakur et al. (2013)

Summary

- Outflows from starburst galaxies are driven by the thermalized ejecta and radiation from massive stars
- *This “wind fluid“ itself is an energetic, tenuous fluid seen in hard X-ray emission in the starburst core*
- (Nearly) everything we see is a result of the interaction of the wind fluid (and radiation) with ISM and CGM
- *These outflows are multiphase, best studied locally*
- Parameters like “outflow rate” and “wind speed” are phase-dependent and can currently be estimated at the ~ ½ order-of-magnitude level at best
- *Better numerical simulations of winds to inform the sub-grid physics in the cosmological simulations*