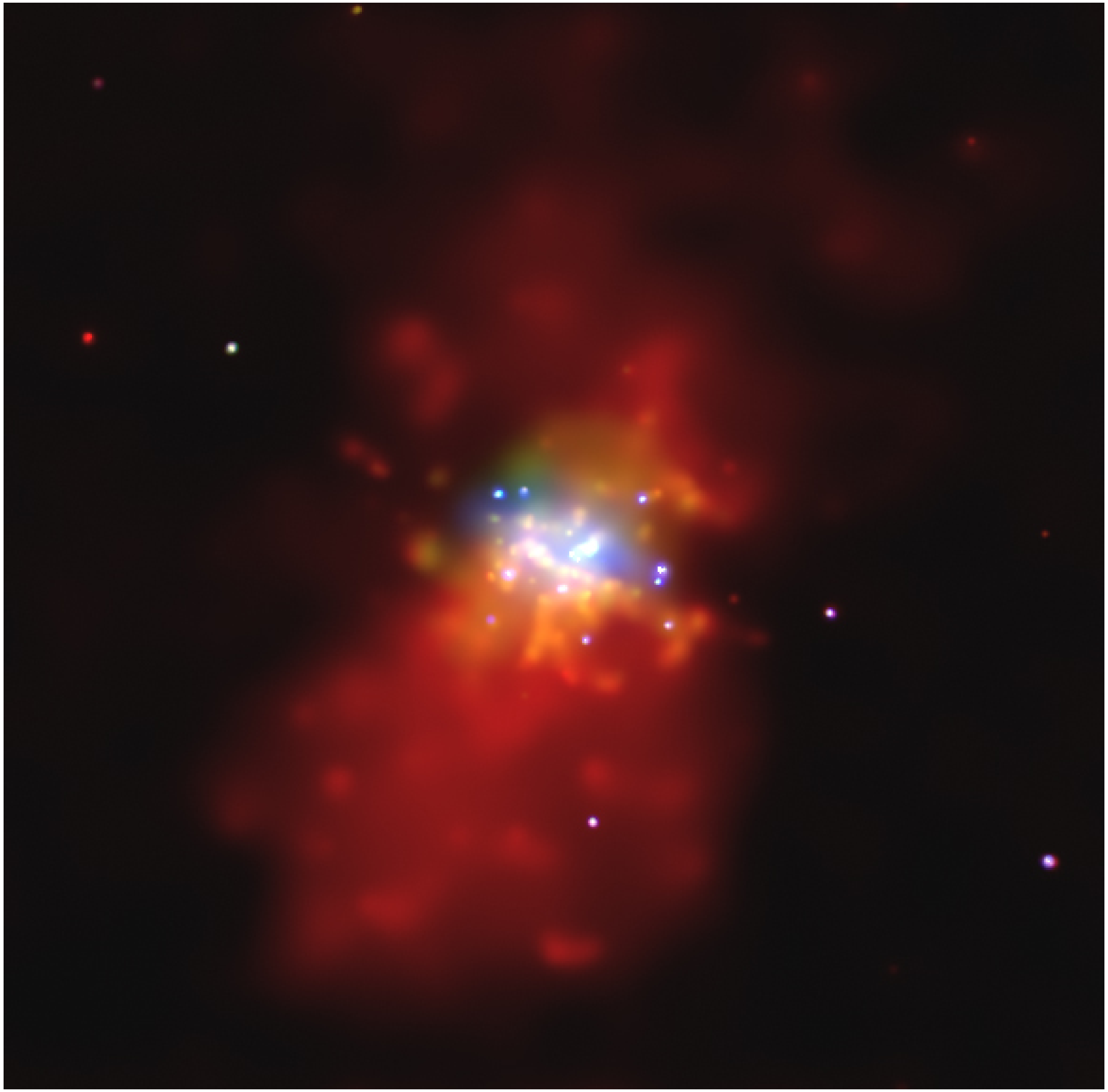
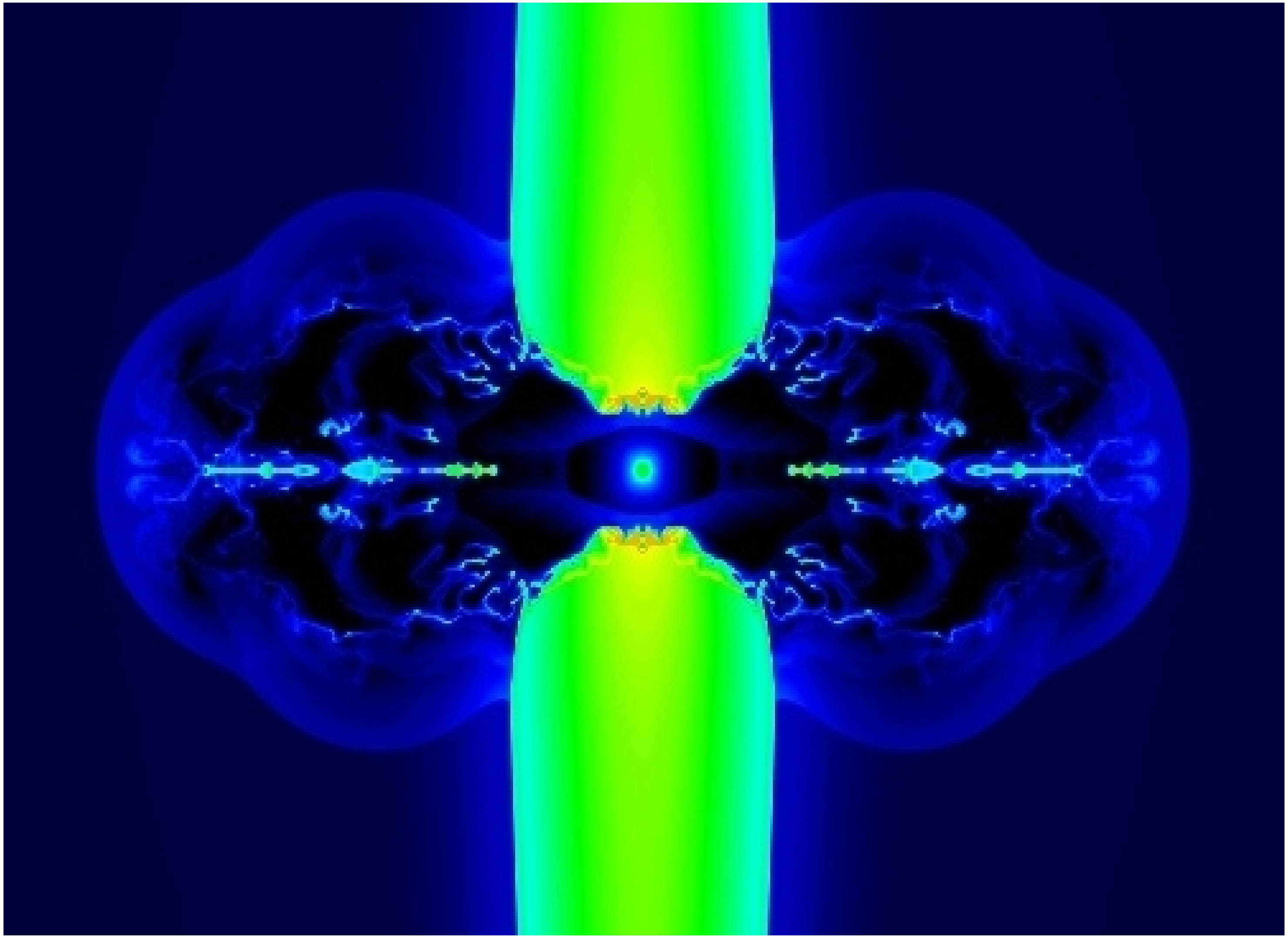
Starburst-Driven Winds



1) BASIC WIND PHYSICS



Chevalier & Clegg Model

Spherically symmetric & ignores gravity

Characterized by starburst radius (r*), mass and energy injection rates (~30% SFR and 1% L_bol)

Central static region (r < r*)

P ~ momentum injection/starburst surface area

T ~ 10^8/beta K where beta is “poisoning” factor

Sonic radius at r ~ r*

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

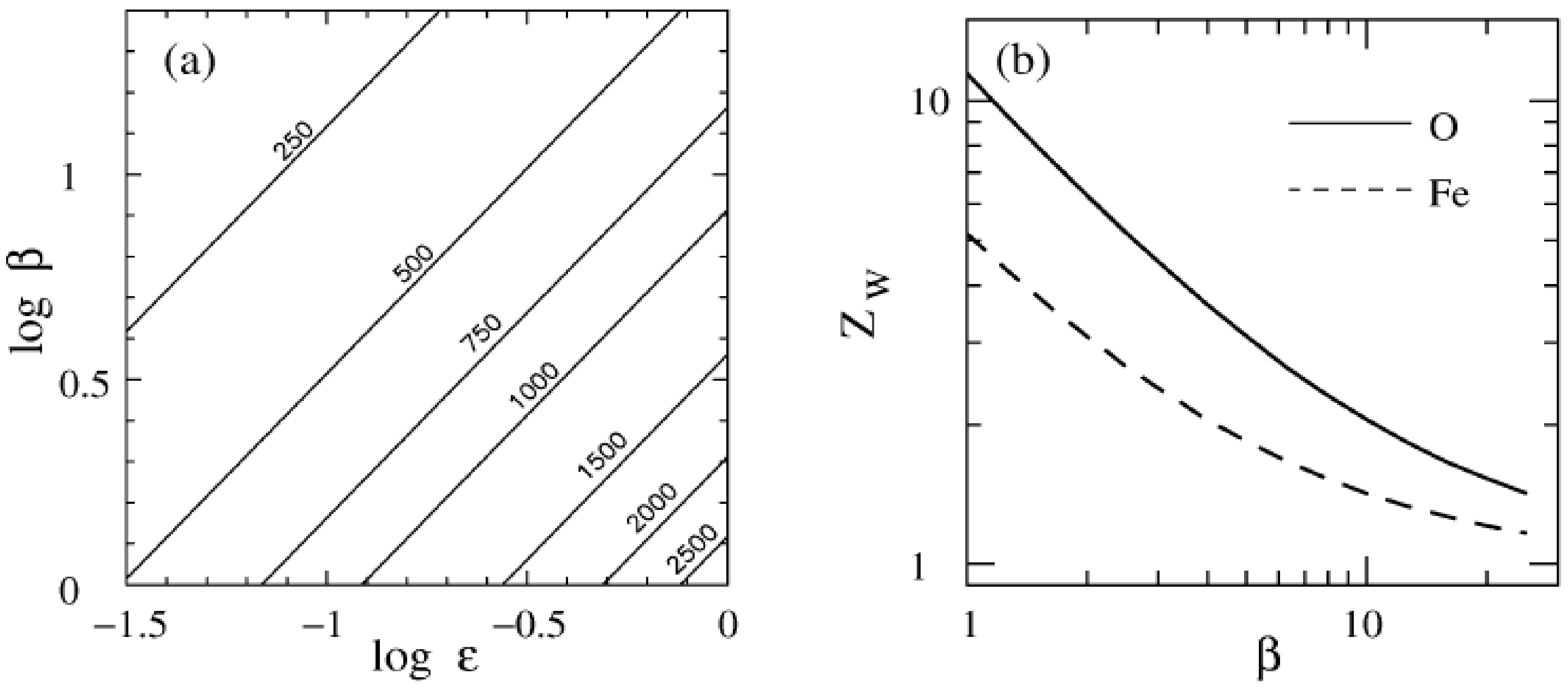
P ~ momentum injection rate/distance squared

v ~ 3000/(beta)^0.5 km/sec

Pure wind (beta = 1) highly metal enriched

T drops like 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” (beta) and radiative cooling (epsilon)
- Very high metallicities in pure wind fluid

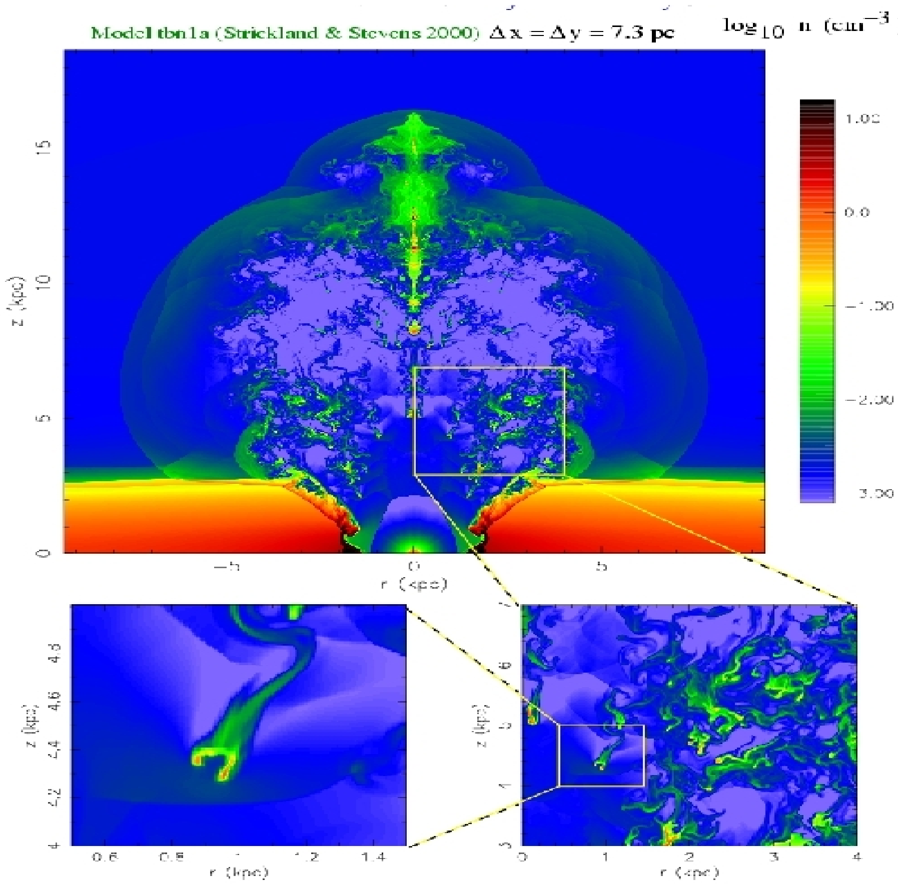
Add an ambient medium

- 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

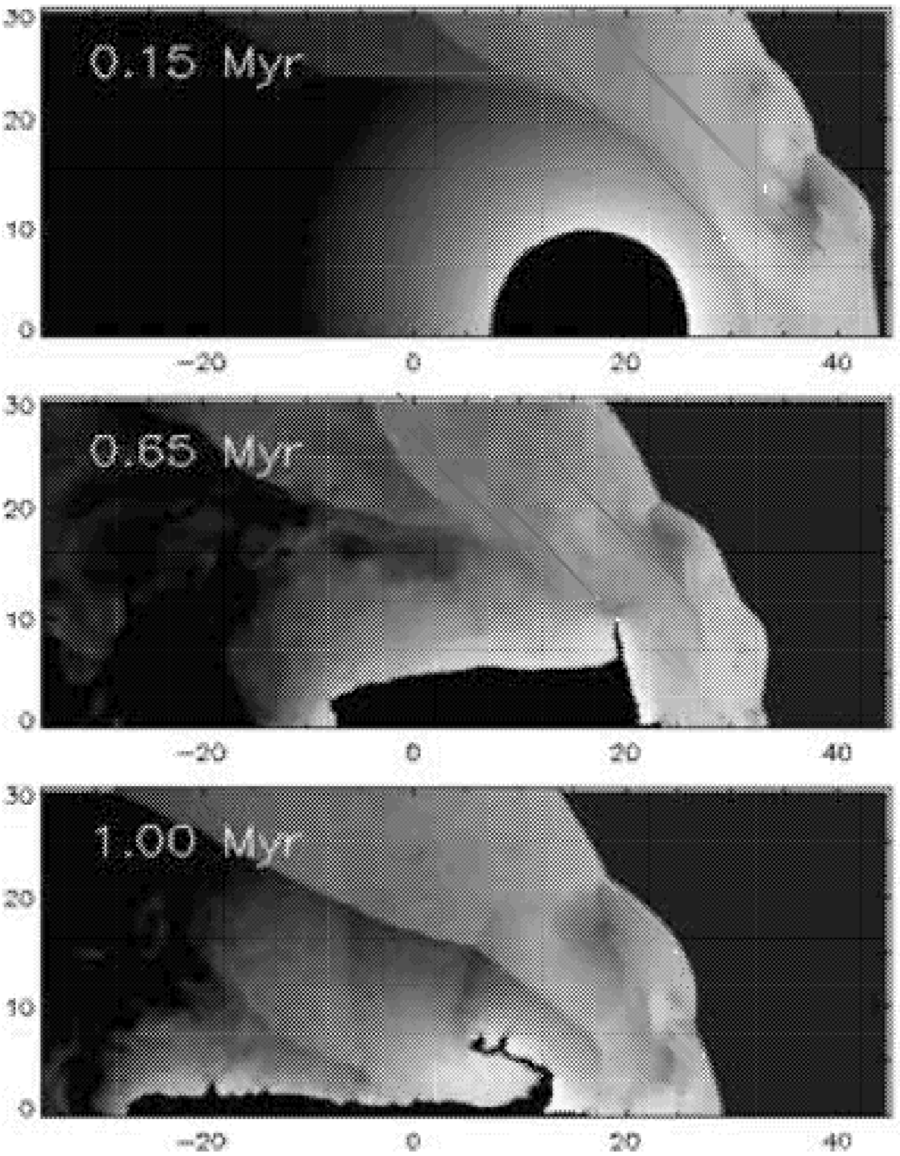
- Hot gas inflates an expanding bubble, driving a shock into ambient gas
- Super bubble will stall for low energy injection rate and large ISM scale-height

Stage 2: Blow-Out Into the Halo



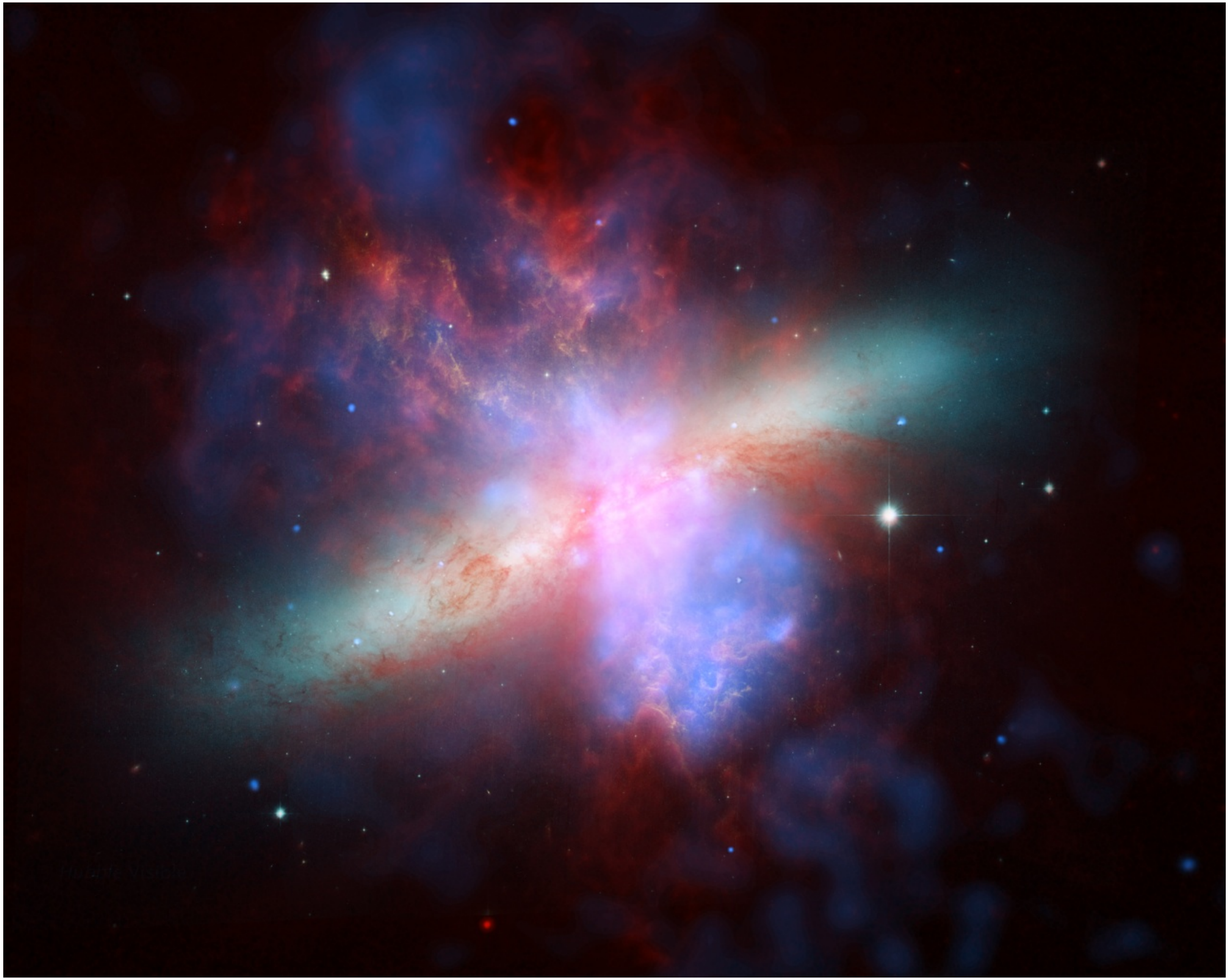
- Most of the halo volume is occupied by the very energetic and tenuous “WIND FLUID”
- Most of the emission and absorption comes from denser material interacting with the wind fluid

WIND-CLOUD INTERACTION

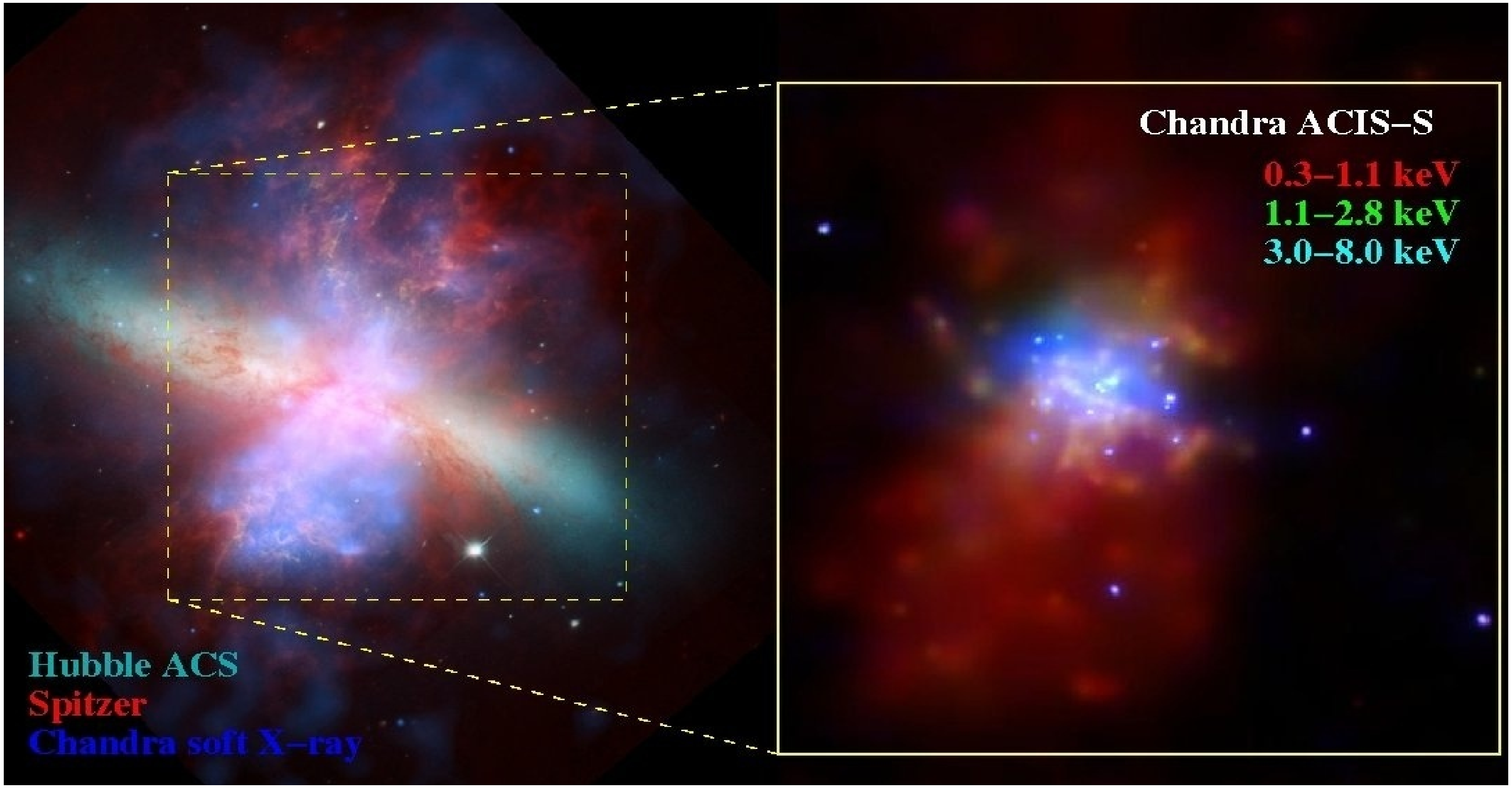


- Soft X-rays from wind/cloud interface
- Cloud is accelerated by wind ram pressure (*momentum-driven flow*)
- Radiation pressure can help (P_ram several times P_rad)
- Marcolini et al.

2) Observed Properties

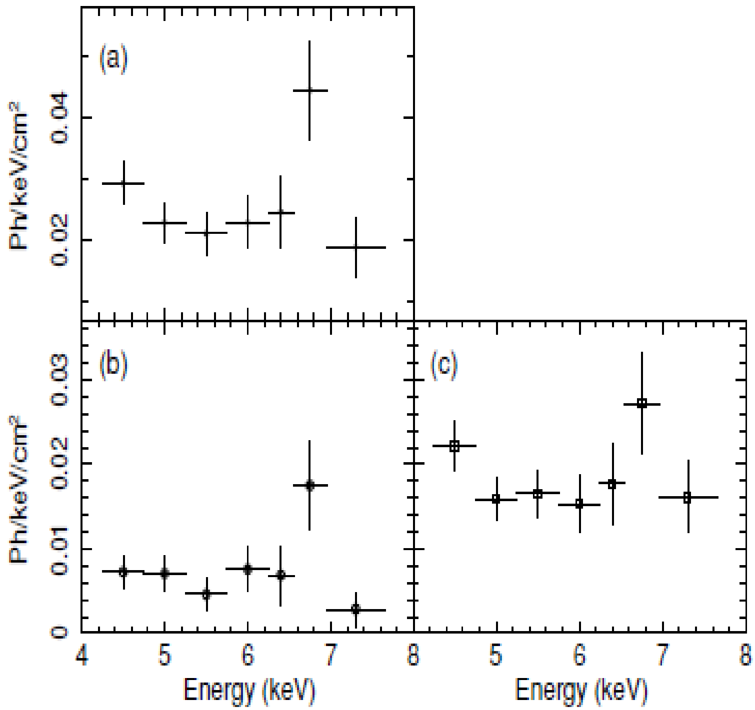


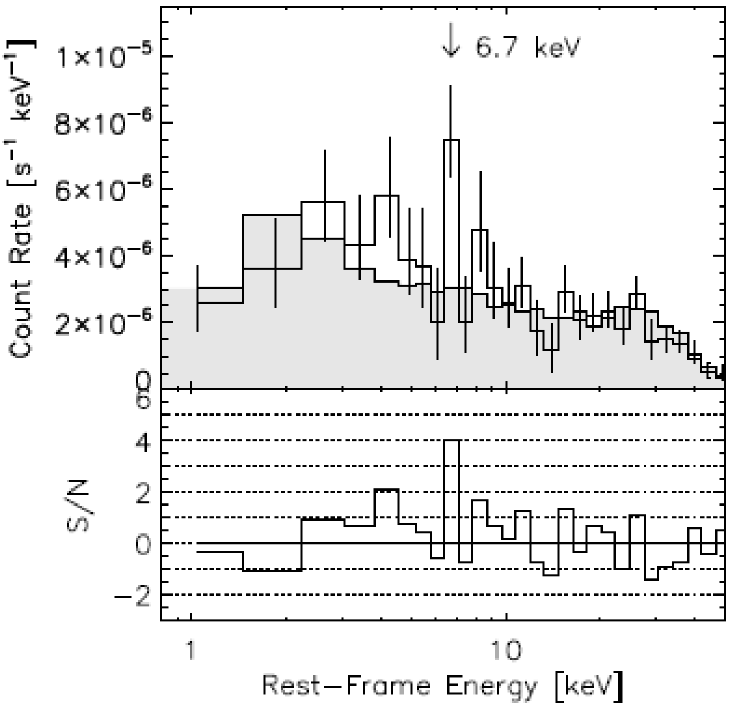
The Wind Fluid in M82



- 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 only in M82 central region (adiabatic expansion & cooling causes it to disappear outside this region)

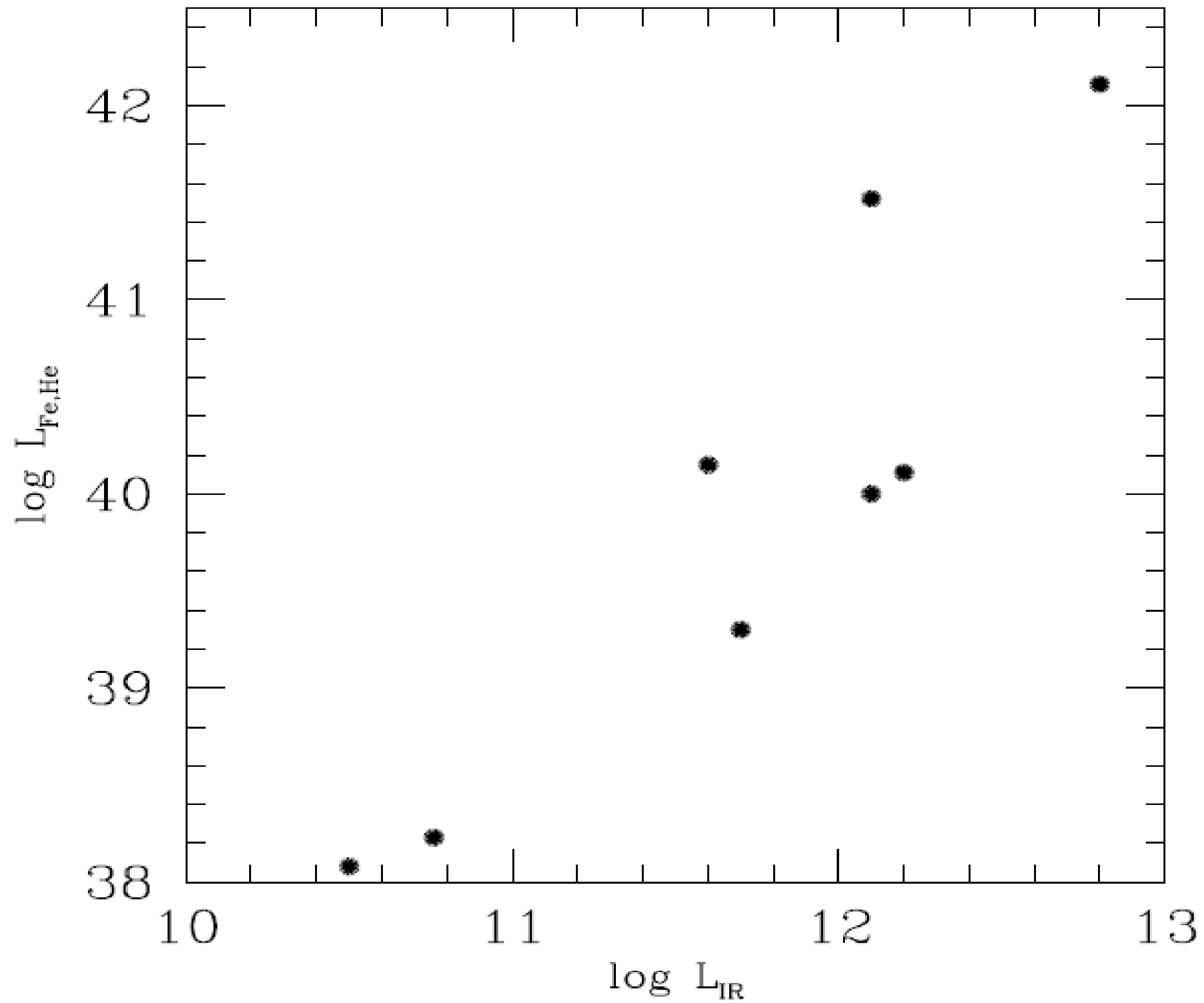
The wind fluid in other systems





- 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.)

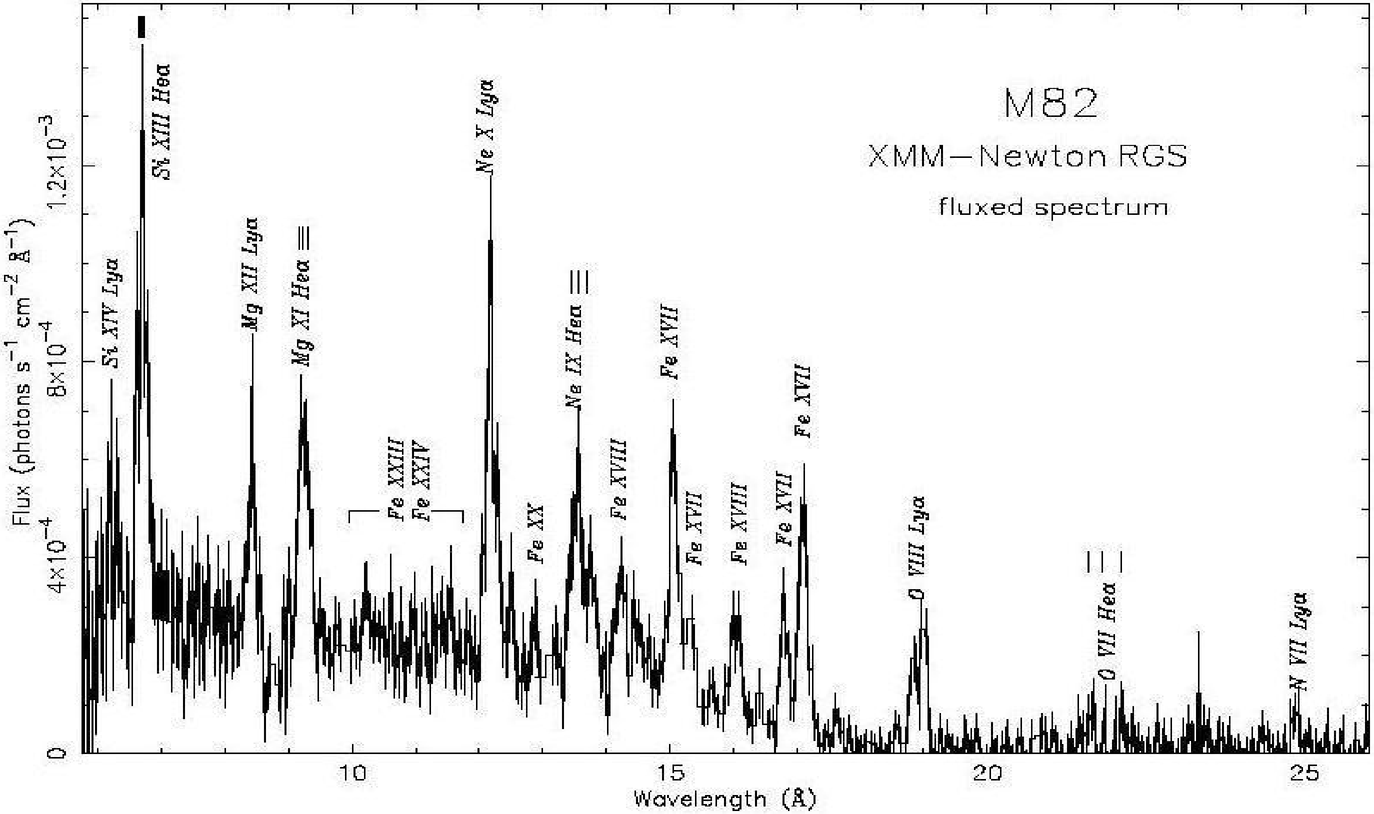
Luminosity of He-like Fe line scales with SFR



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)

Abundances in the hot phase

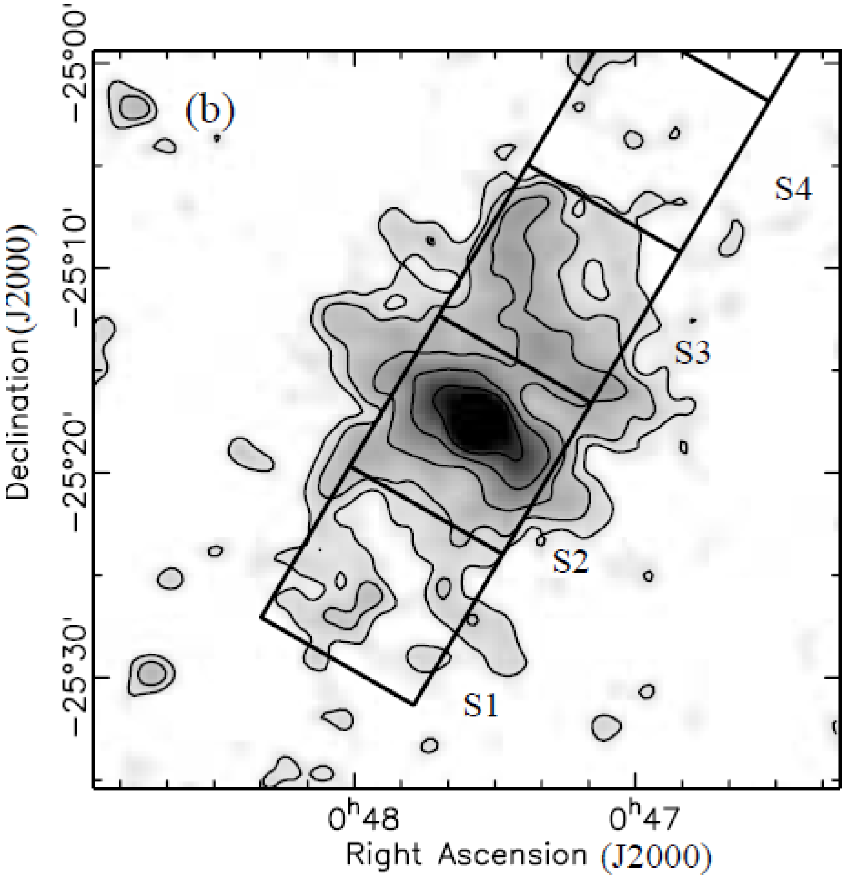


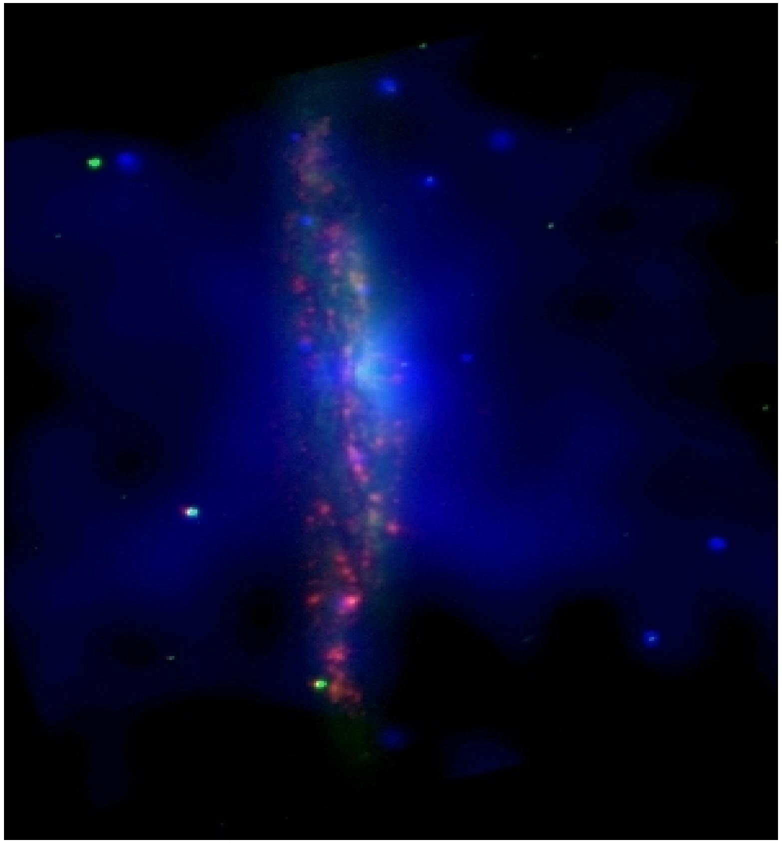
X-ray spectrum of the superwind starburst galaxy M82

European Space Agency

- Alpha/Fe several times solar
- Consistent with enrichment by core-collapse supernovae
- “Poisoned” and shocked wind fluid?

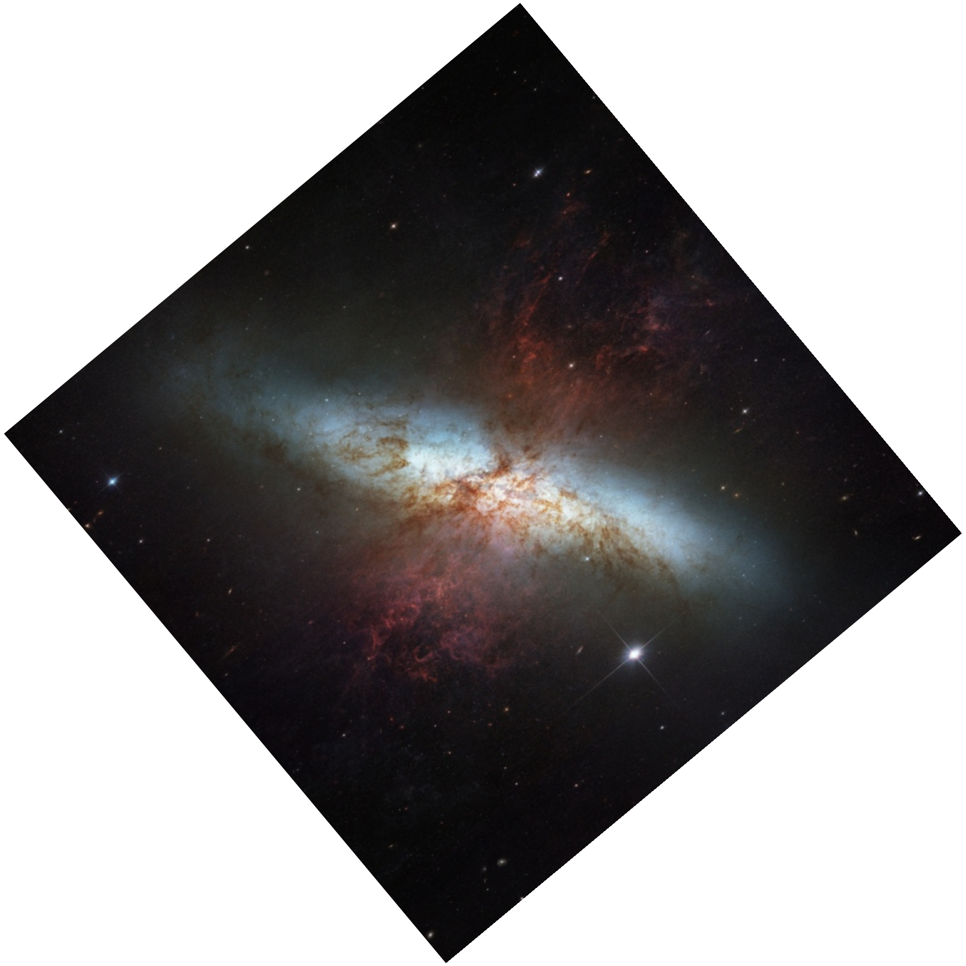
Limb-Brightened Morphology





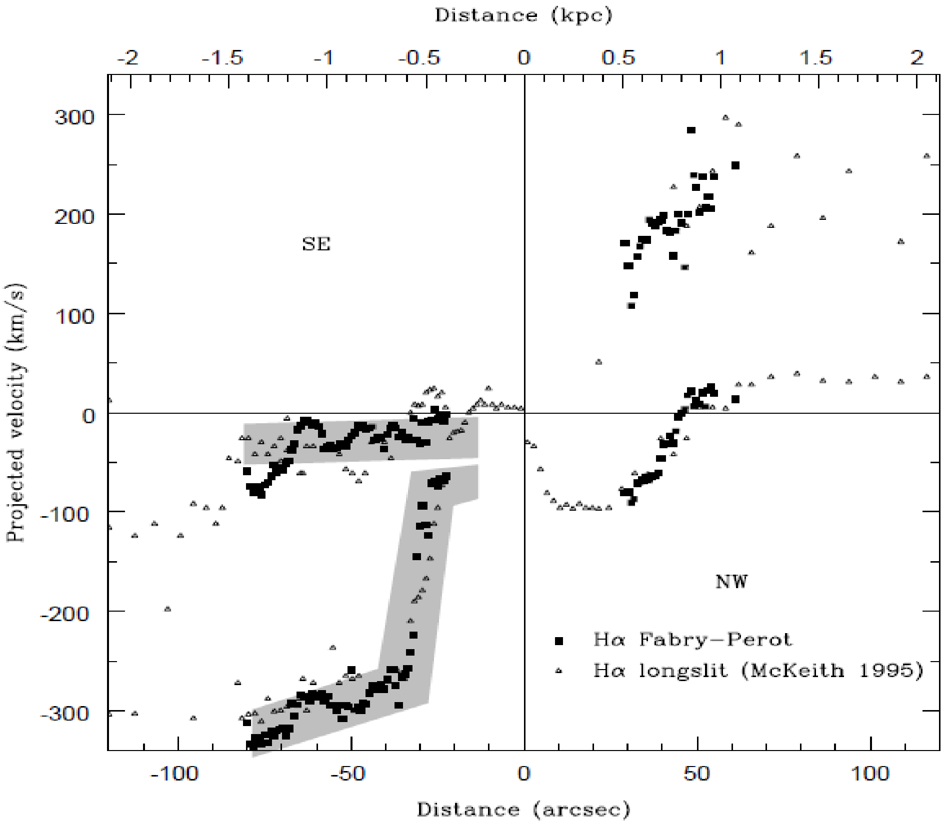
Soft X-rays on halo-scales in a layer bounding the tenuous volume-filling wind fluid

The Warm Ionized Phase



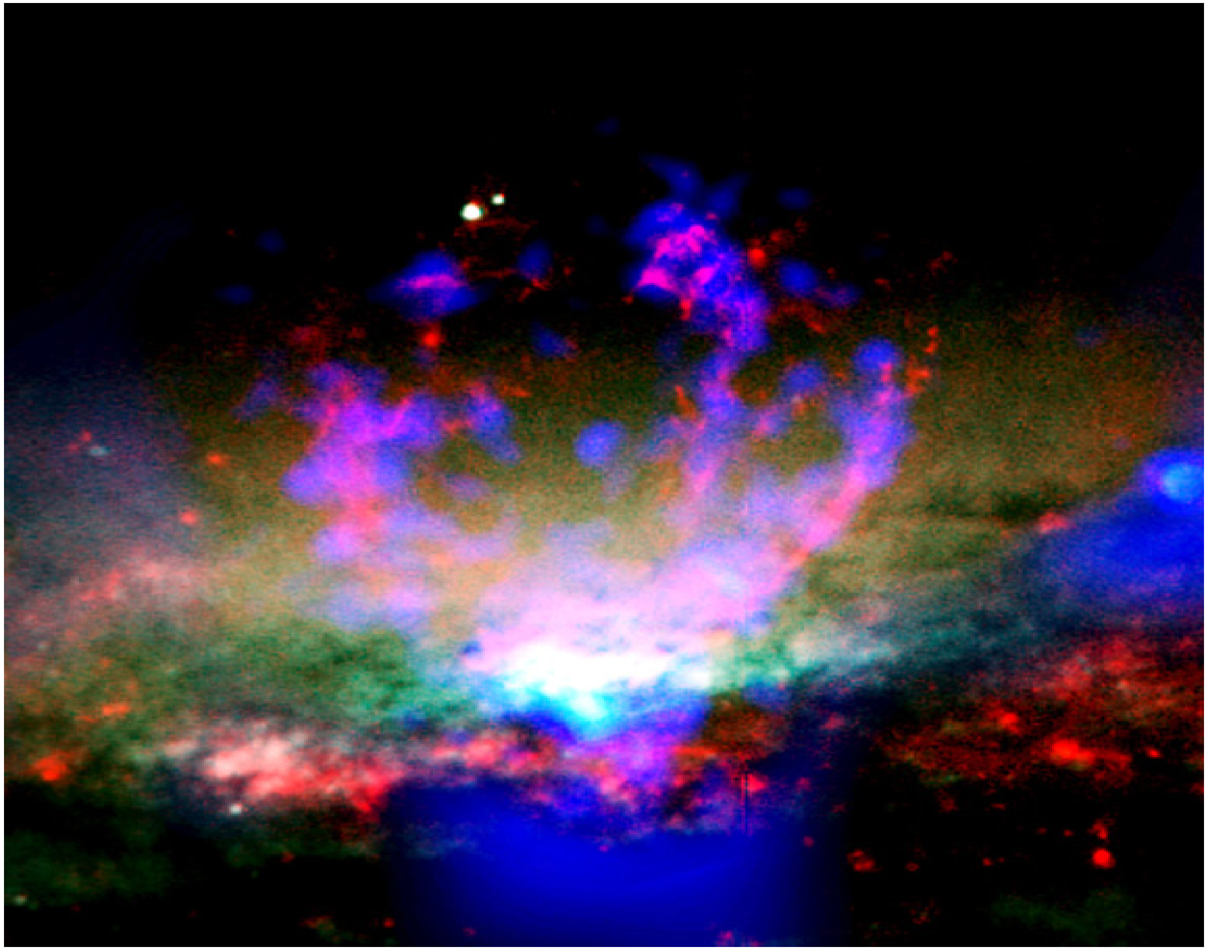
Dense,clumpy material that is shock-heated and accelerated by the wind fluid

Kinematics imply a flow along the surfaces of bi-conic structure (boundary layer)



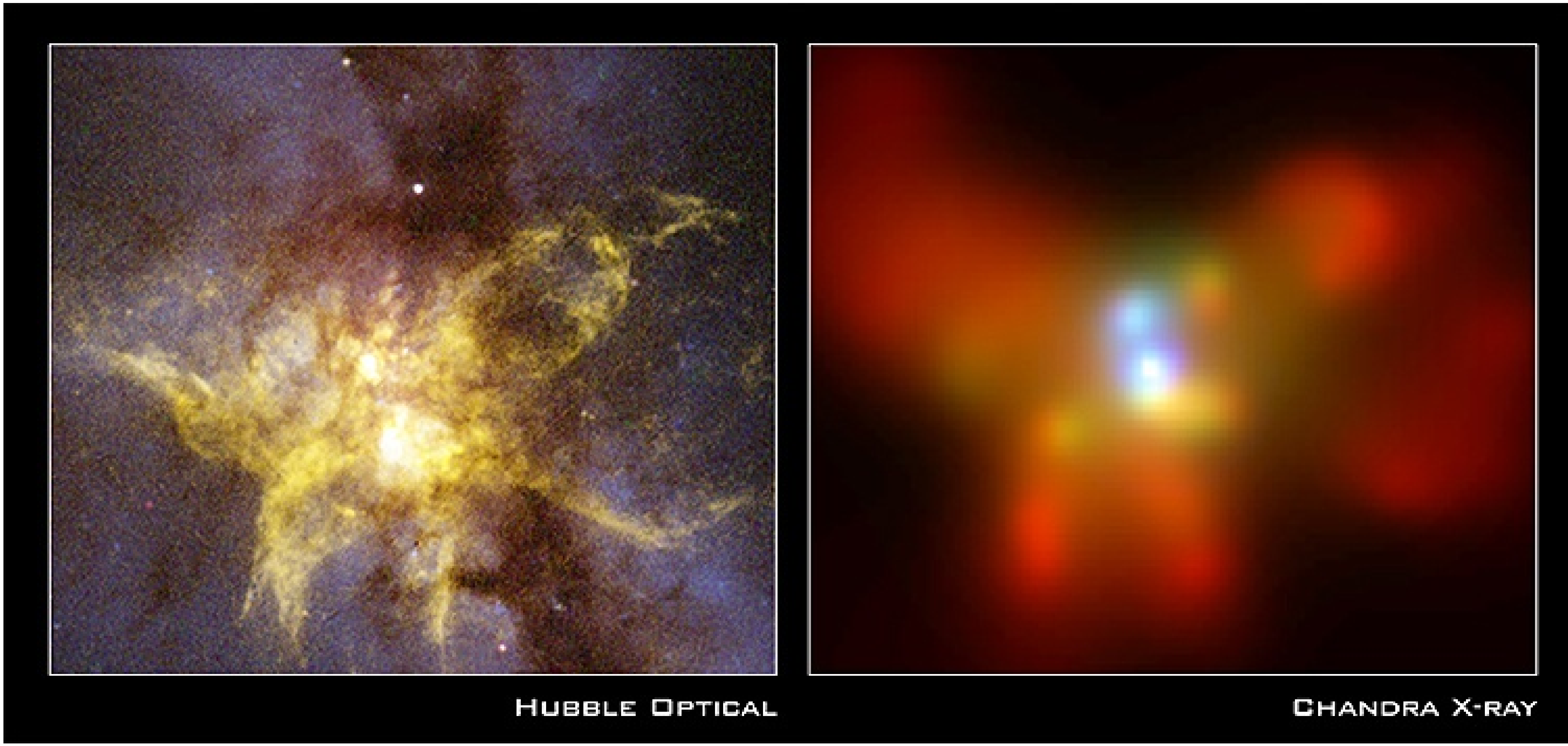
- Rapid acceleration of entrained material to de-projected outflow speed of 600 km/s
- M82 - Shopbell & Bland-Hawthorn

The Warm-Hot Interface



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

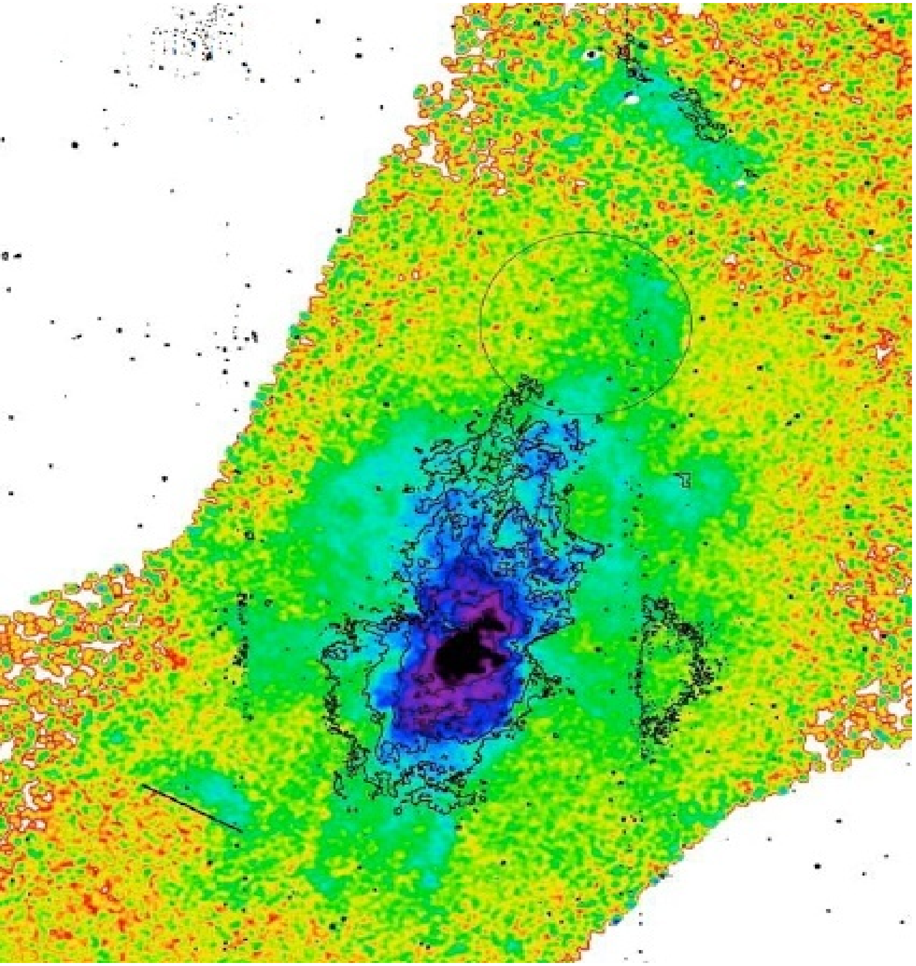
Warm-Hot Interface

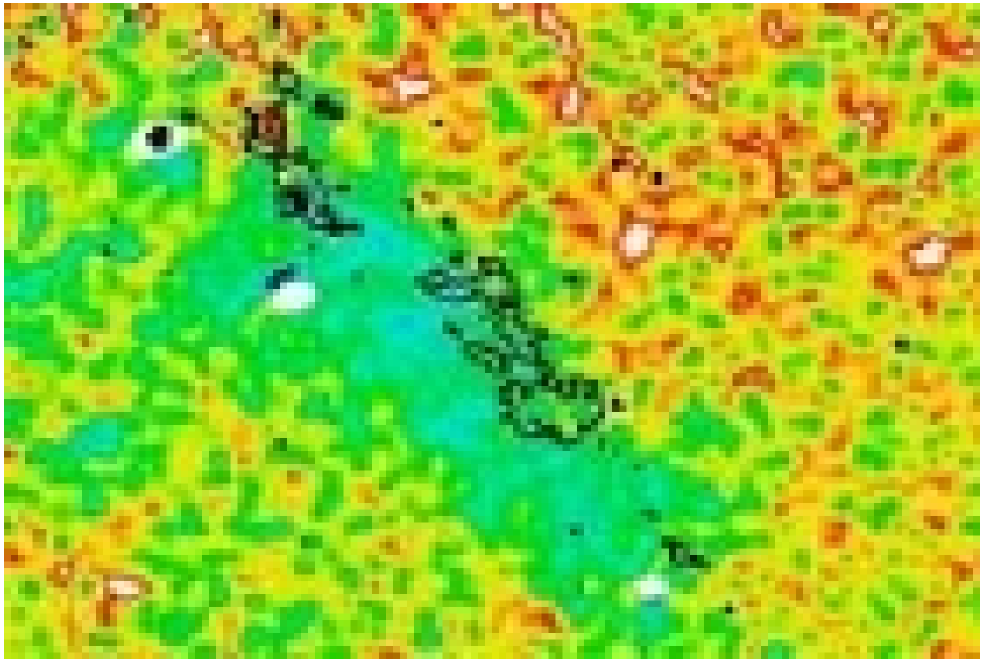


Boundary layers at the surface of the wind fluid

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 ?

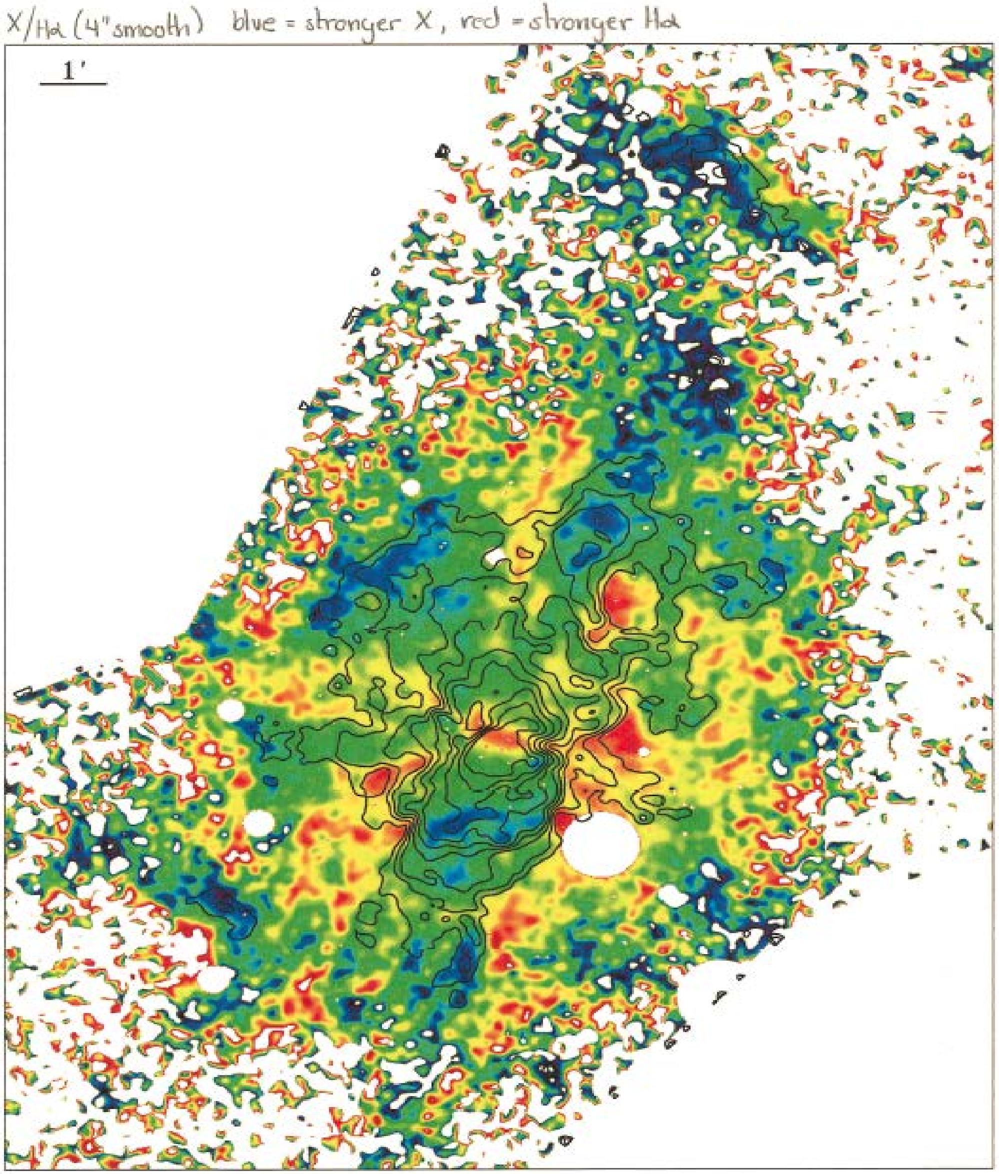




Implied wind speed:

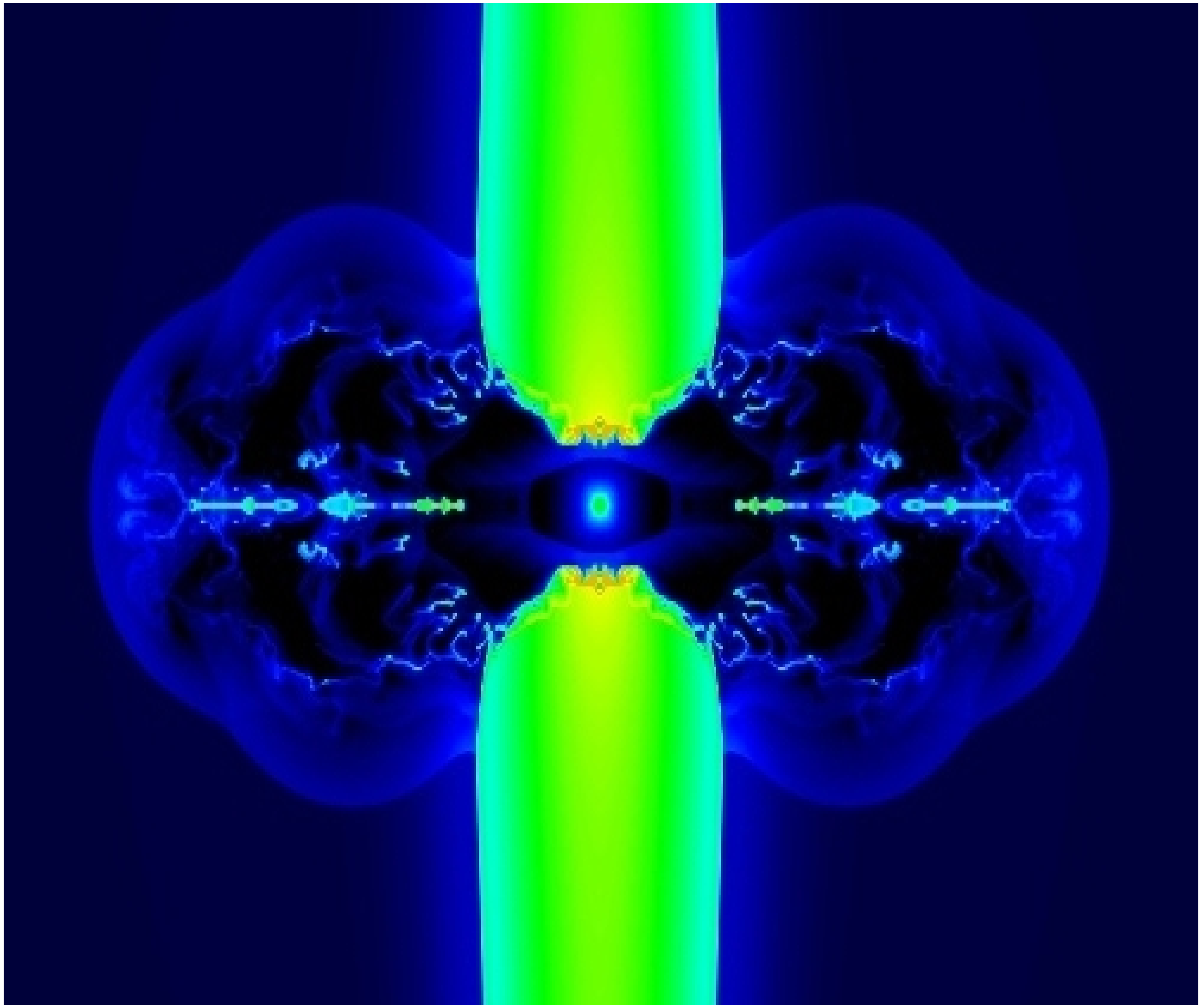
V_wind – V_cloud ~ 800 km/s

The Warm-Hot Interface in M82



- Ratio of X-ray and H-alpha images
- Warm gas encloses the hot X-ray gas
- Kuntz et al.

3) Outflow rates in the wind fluid



Why focus on 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 all the ***newly synthesized*** *metals*

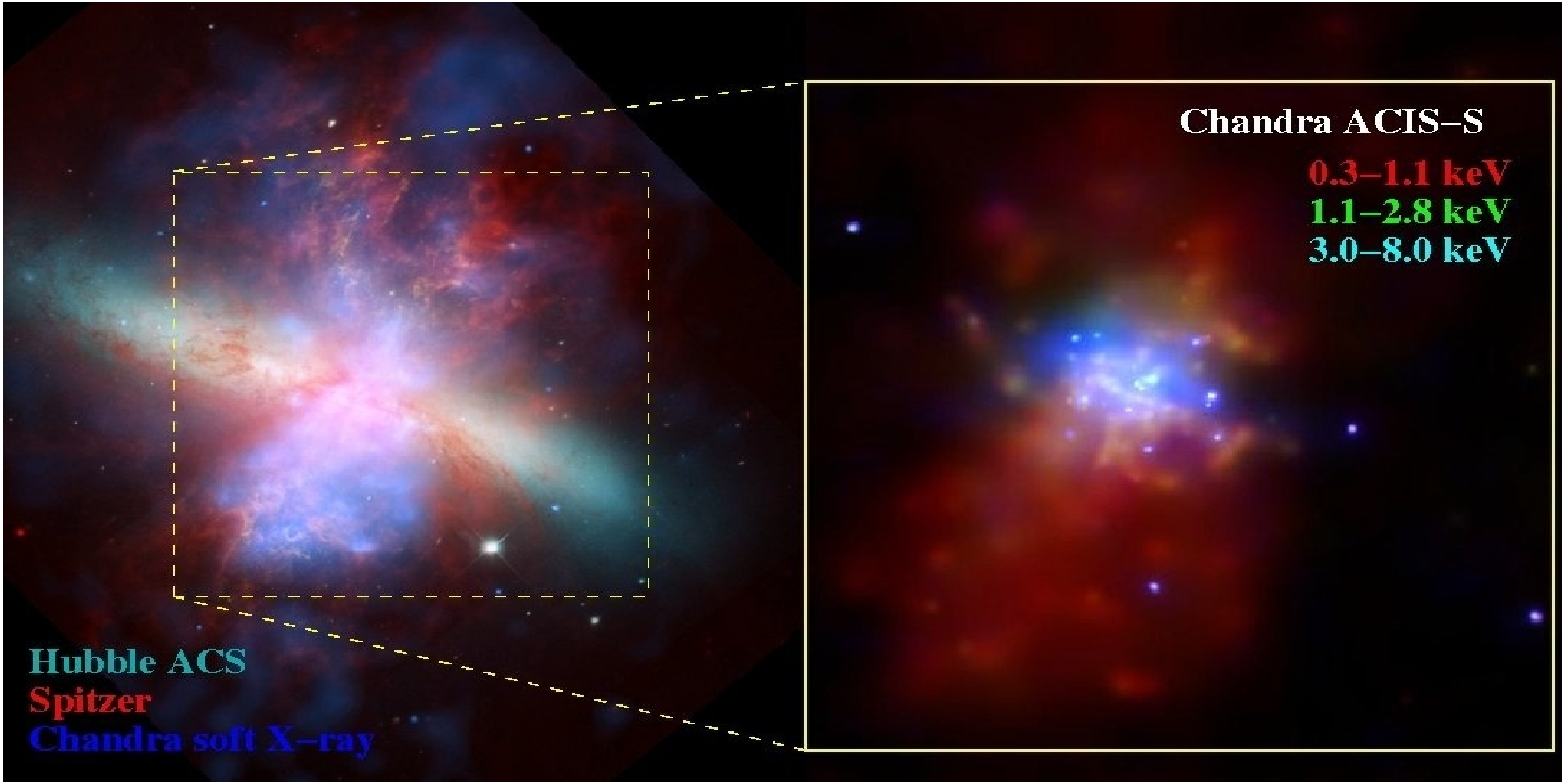
> It contains much of the total metal content

Pure wind fluid has Z ~ 6 - 10 times solar

Entrained metals significant only for very large amount of "mass-loading"

> High specific energy – most likely to escape

Direct probes of the wind fluid

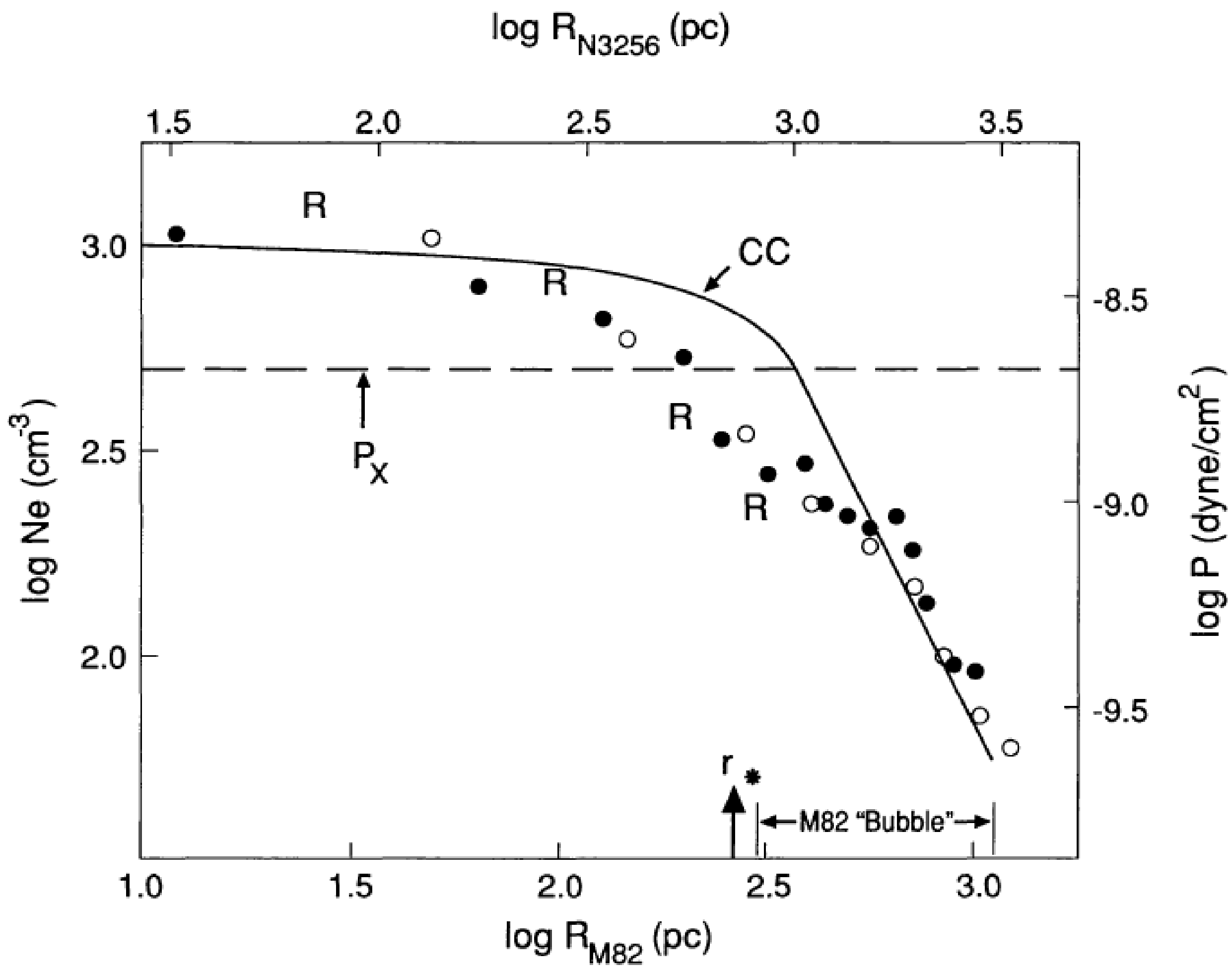


Luminosity & temperature imply ~30-100% efficiency

Directly visible only in the core (r < 500 pc)

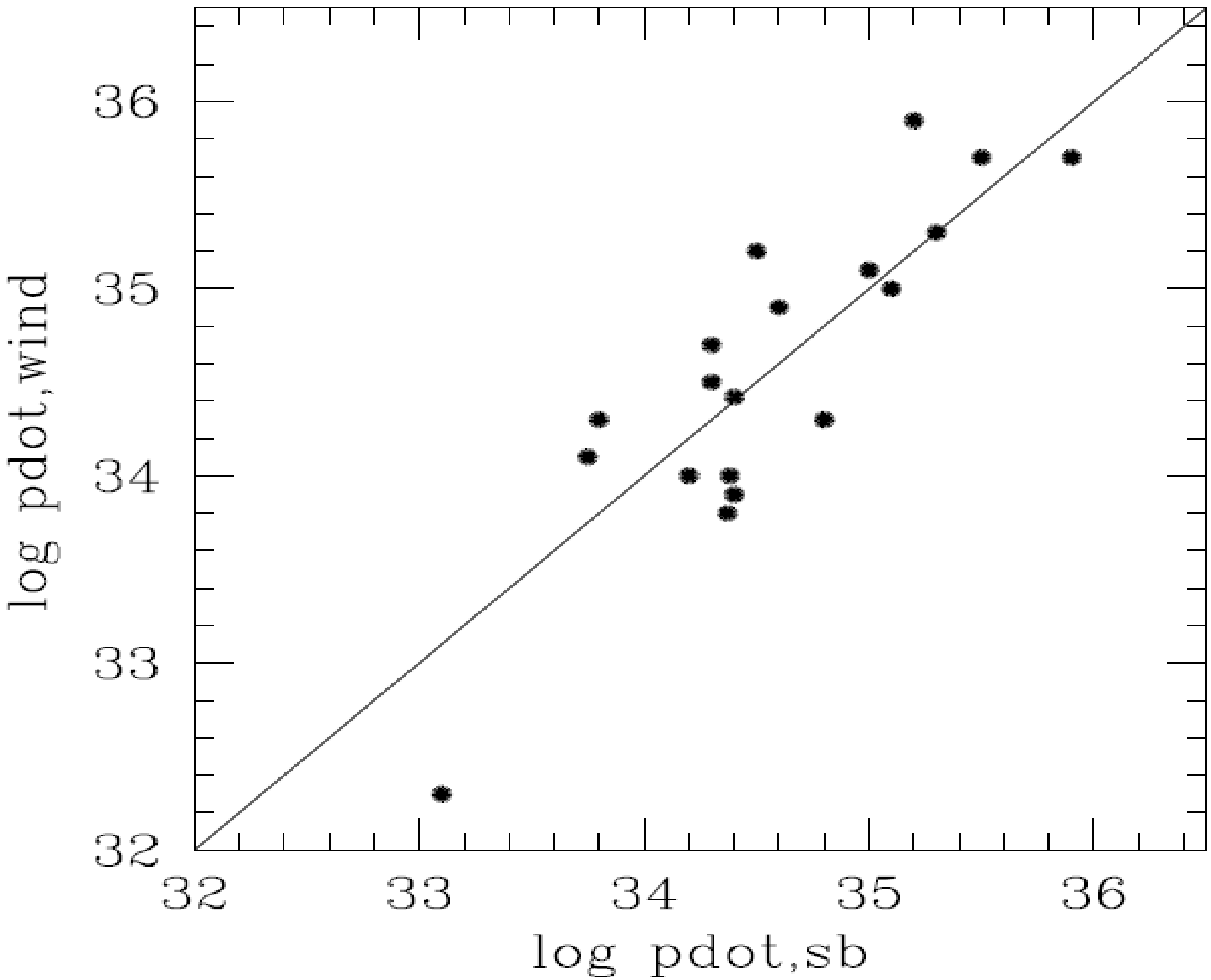
Require indirect probes to trace this fluid at large radii

Probes using the warm phase



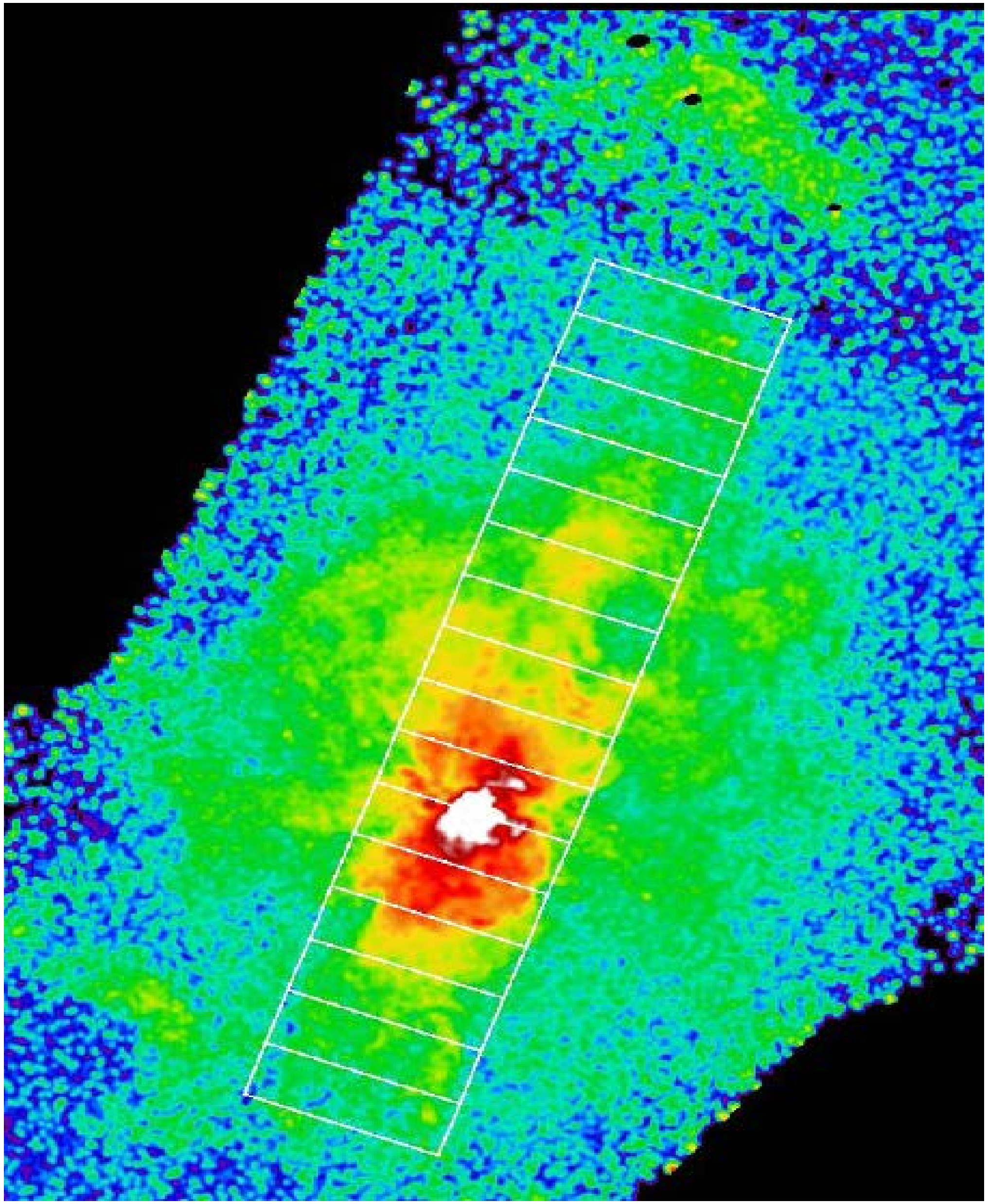
Measure the radial pressure profile directly to measure ram pressure of wind fluid

The momentum flux of the wind fluid



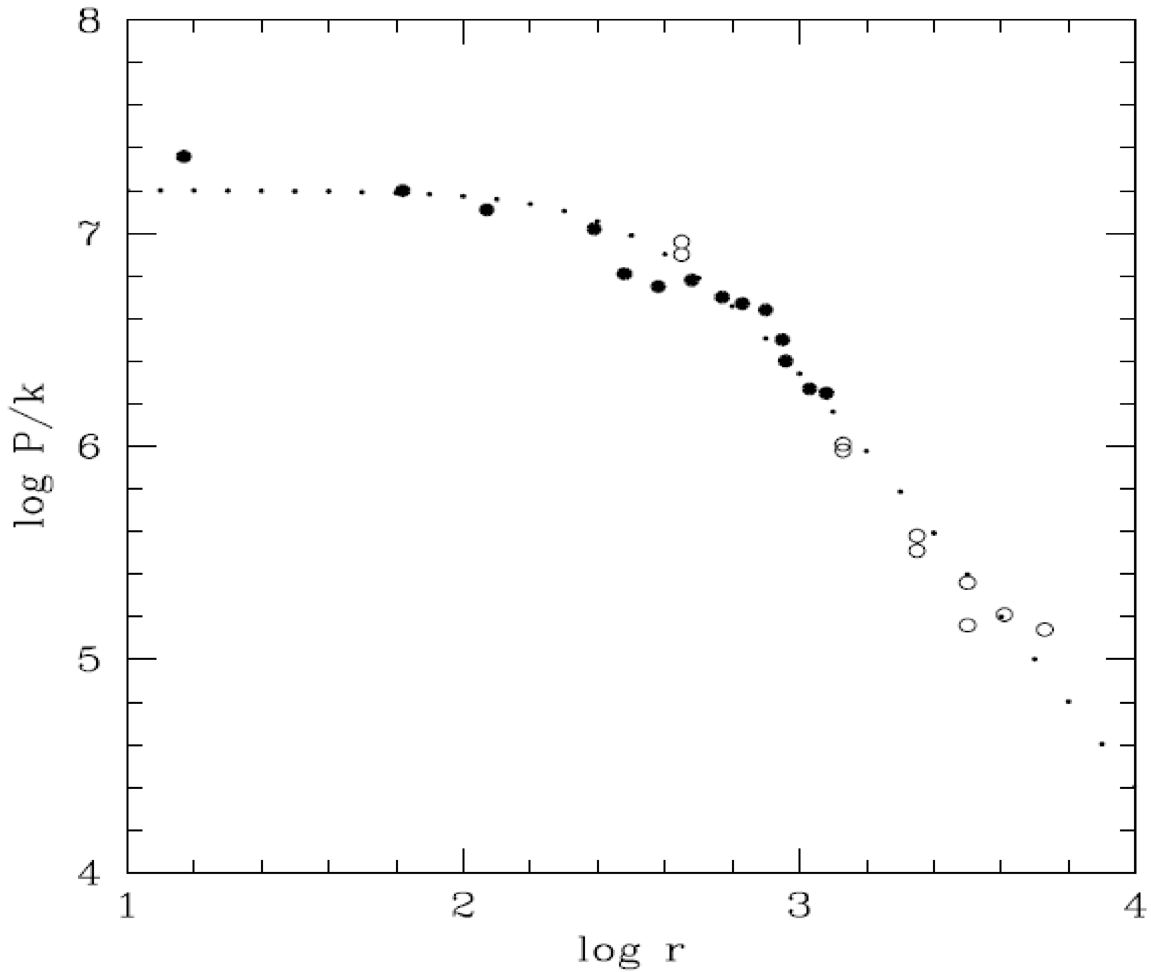
Excellent match to output by the starburst

Probes using the hot phase



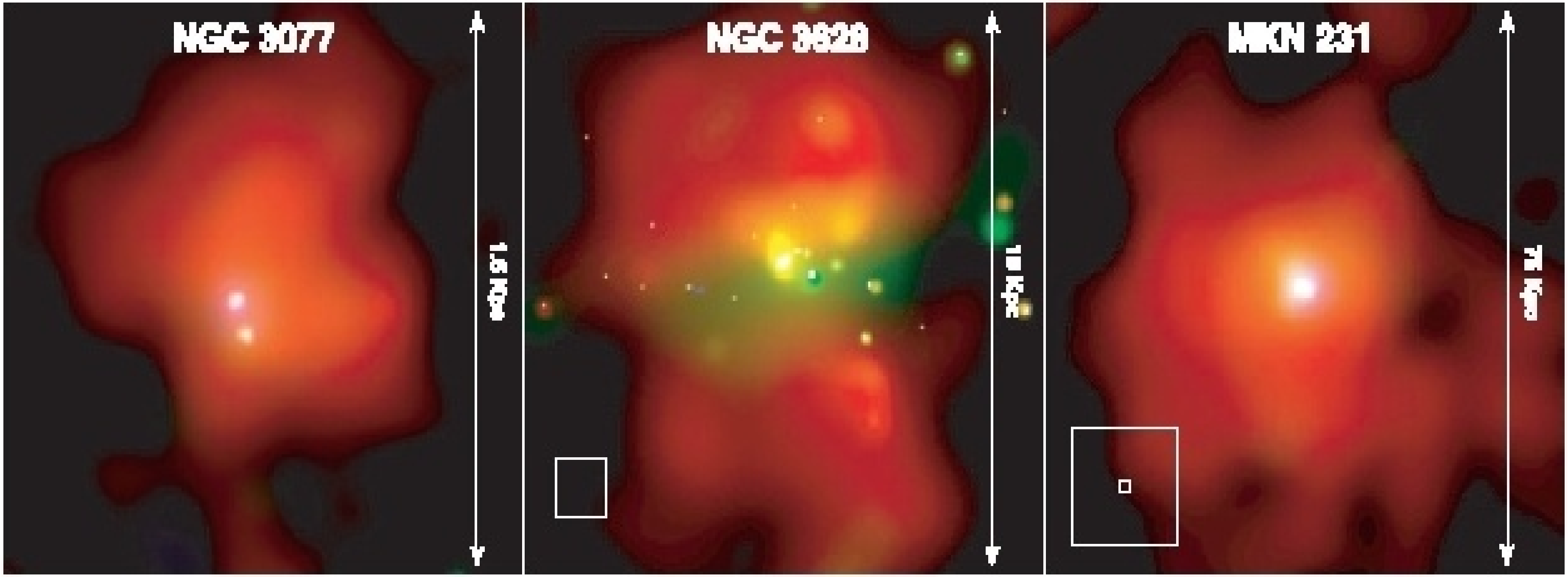
- Measure the pressure profile in the X-ray data
- Yields minimum pressure (for unit filling factor)
- Kuntz et al.

The combined pressure profile



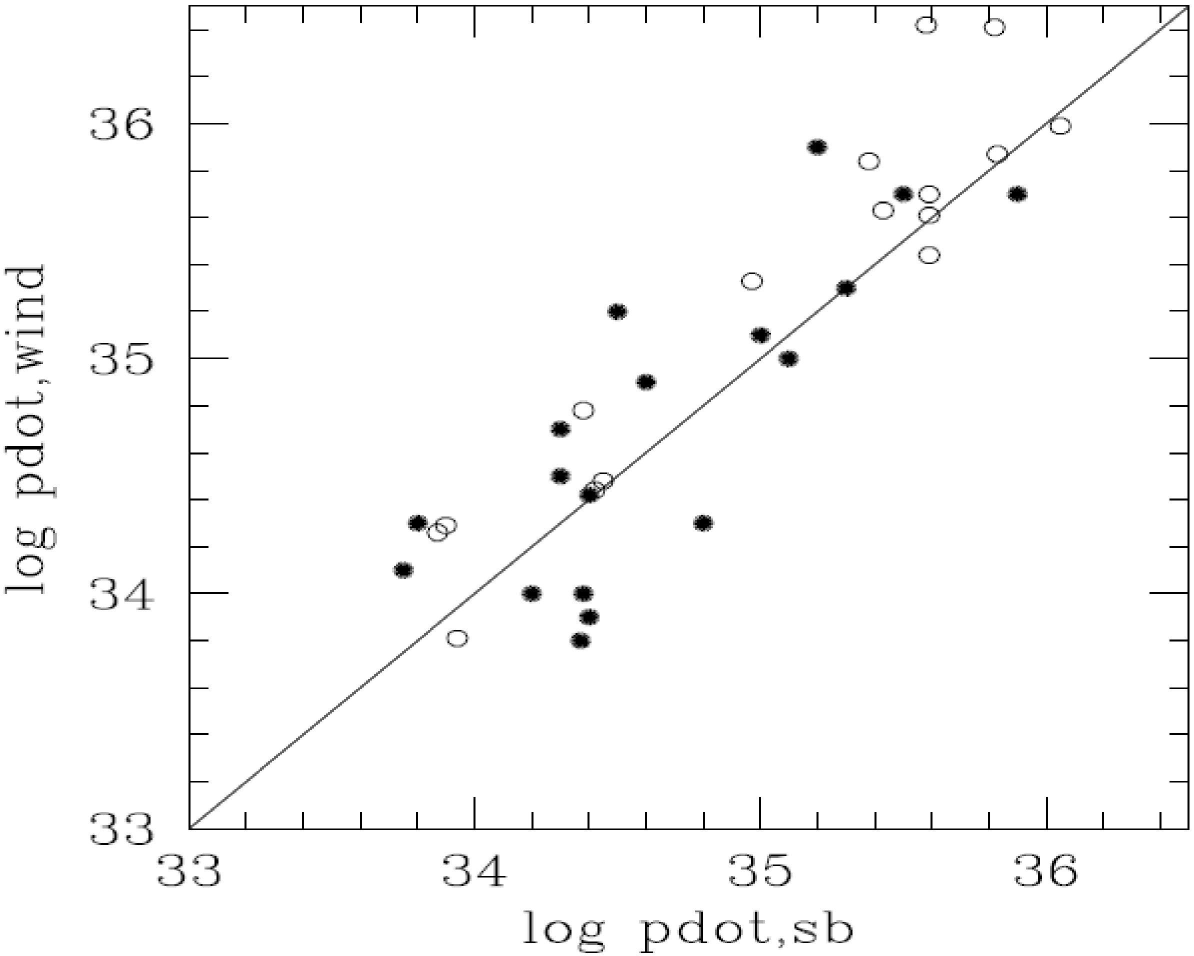
- Match requires filling factor of ~15%
- Excellent fit to model predictions for M82

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



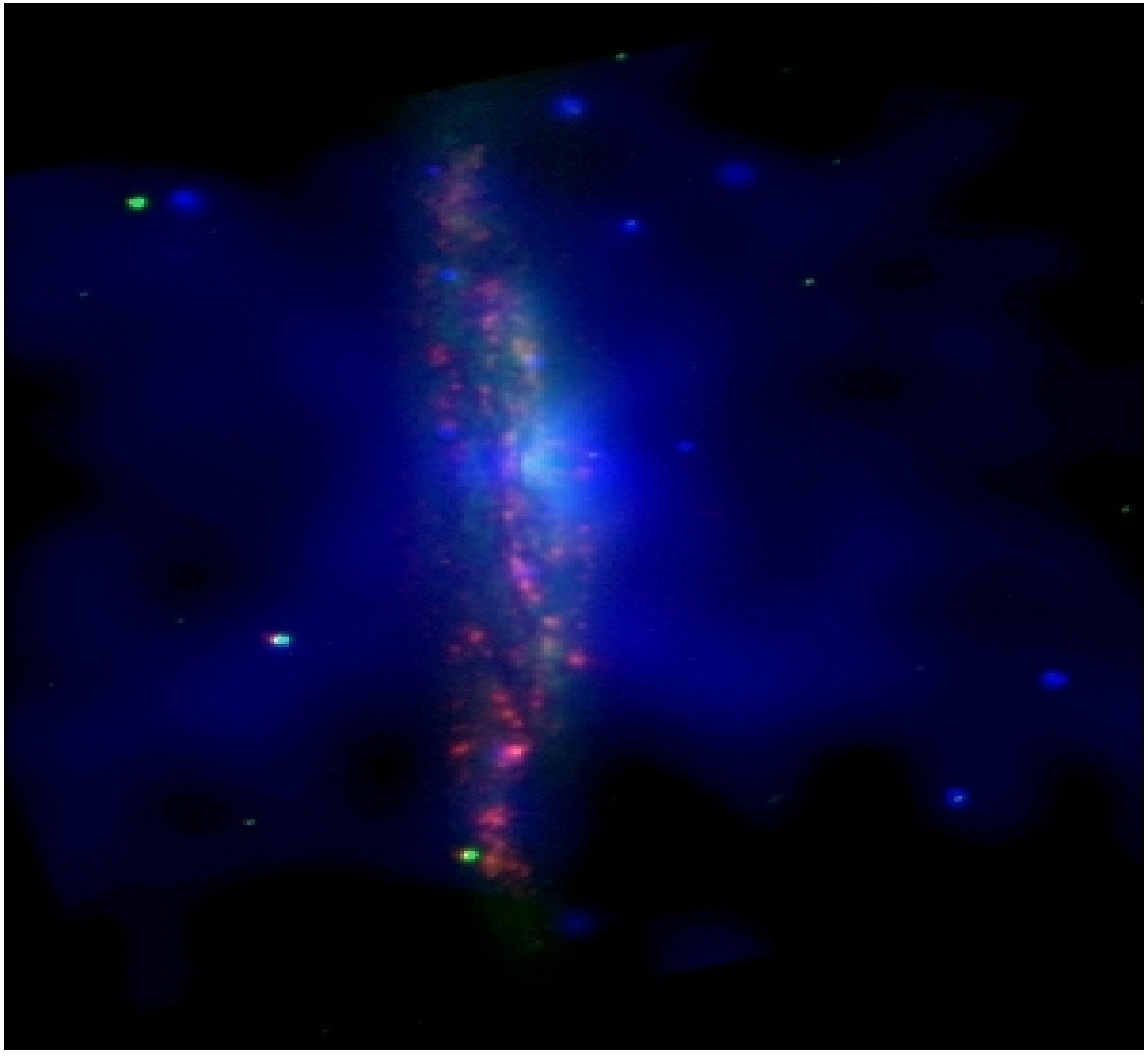
- X-ray data map the minimum pressure (ff = 1) over the volume occupied by the wind fluid
- Adopt a ff = 0.15 to estimate pressure (M82)

Momentum Flux of Wind Fluid

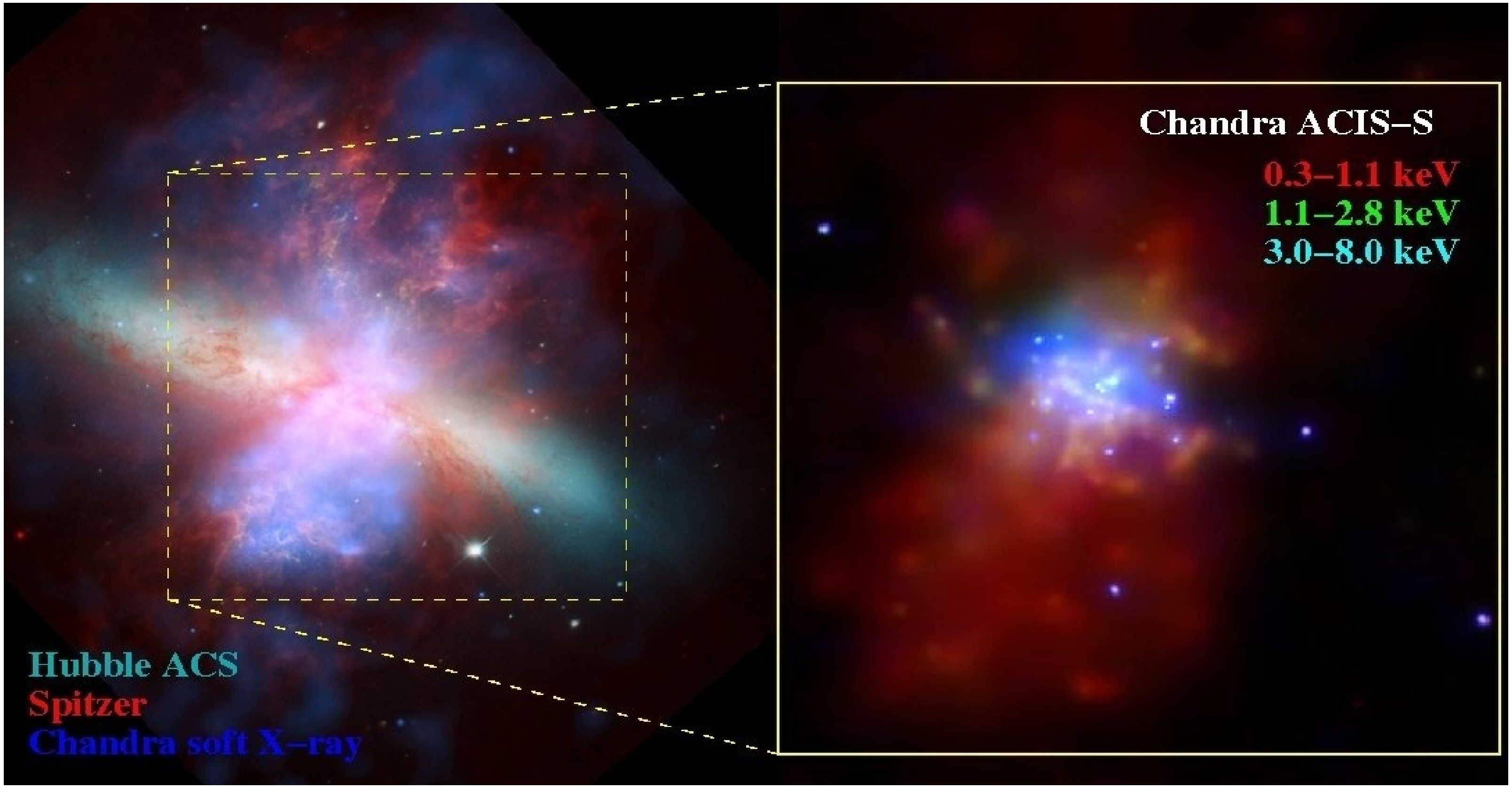


- X-ray data assumes ff ~ 15%
- Momentum flux ~ starburst injection rate

The Fate of the Wind: How Fast, How Far?

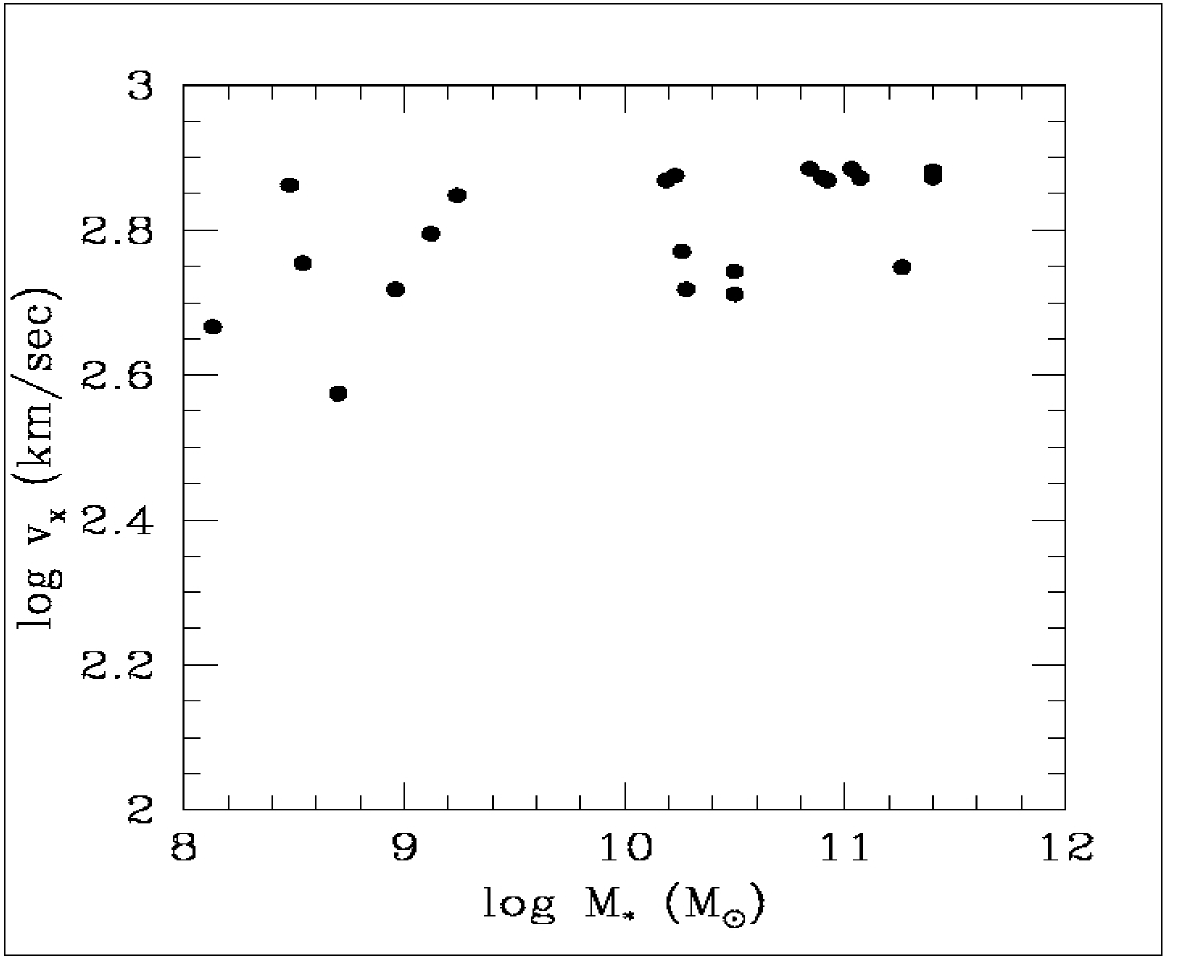


How fast? 1)The wind fluid



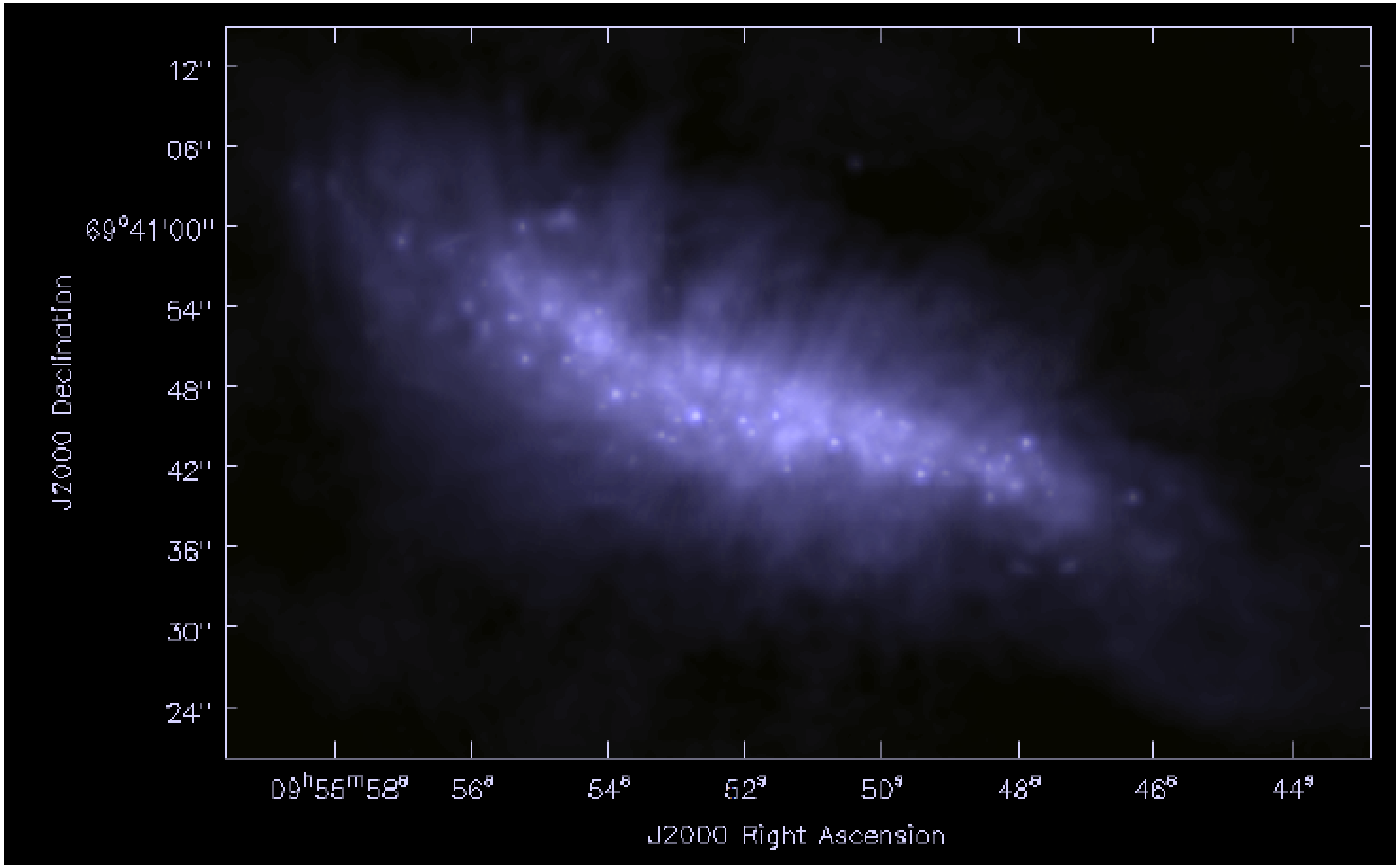
- The wind fluid itself starts out very hot (~60 Million K)
- The corresponding outflow velocity is ~ 2000 km/s
- Far above escape velocity from any galaxy
- But what about the stuff carried out by this wind?

How fast? 2) The hot phase



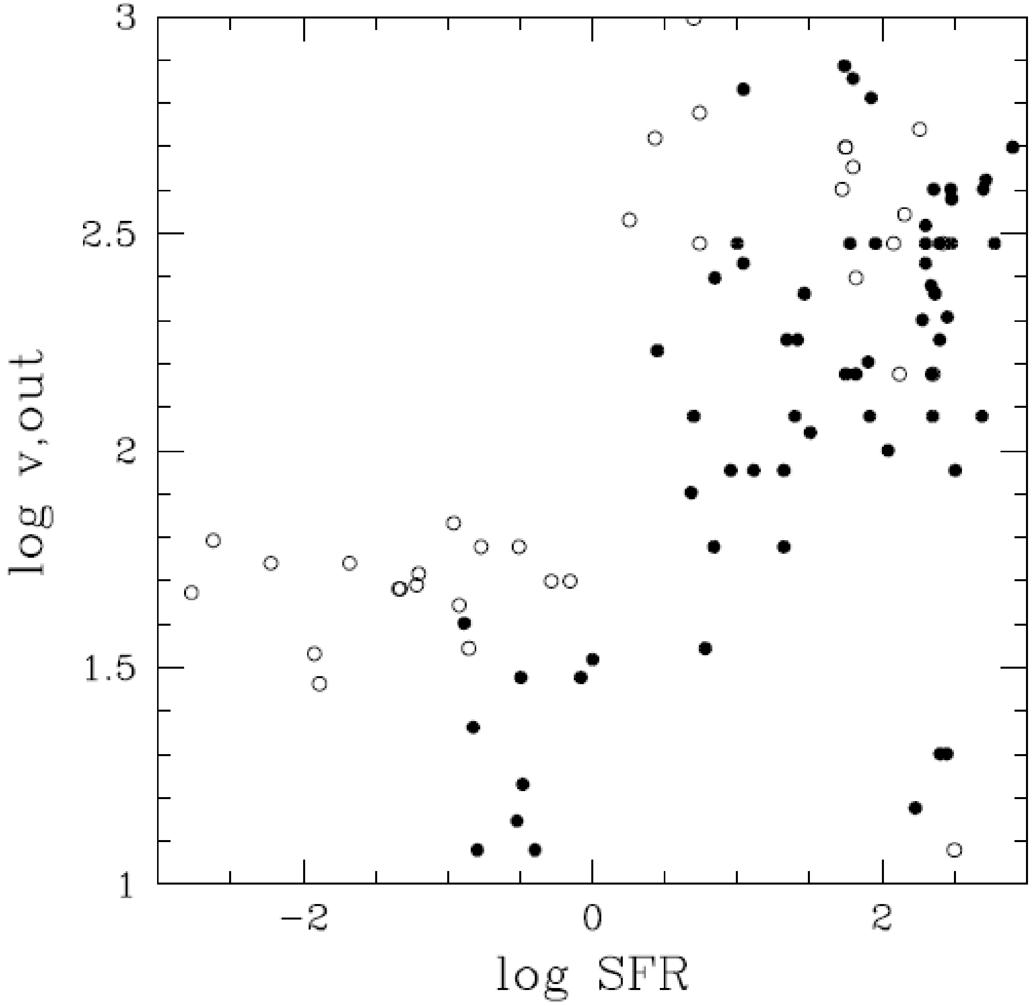
- Soft X-ray temperature invariant w/ galaxy mass
- Preferential escape from low mass galaxies?

How fast? 3) The relativistic phase



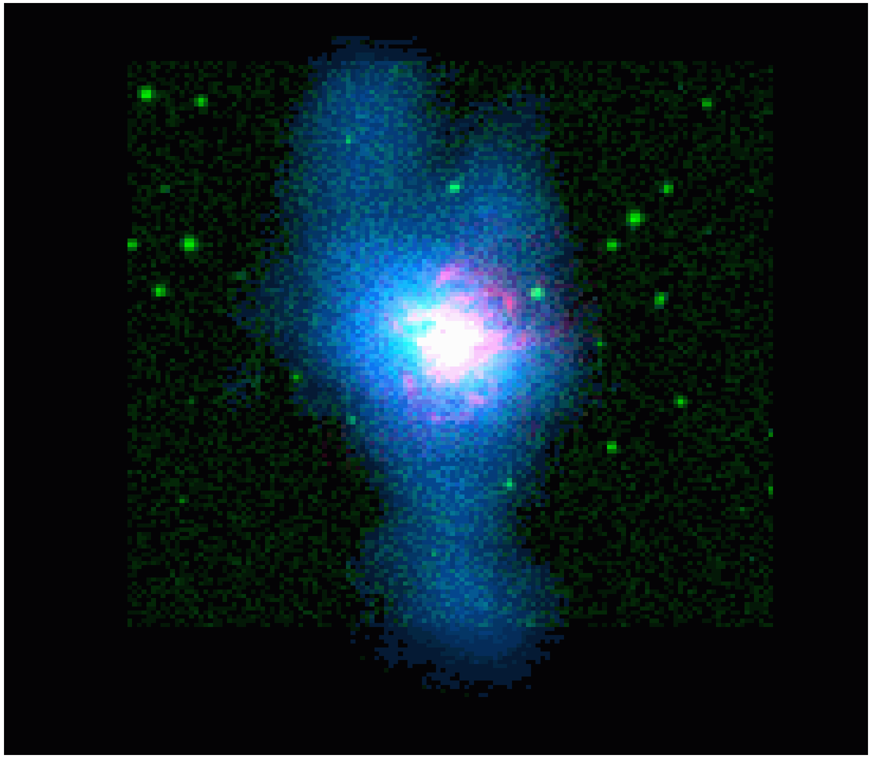
Spectral steepening of synchrotron emission with height yields estimate of 1000 – 2000 km/s for wind fluid outflow speed (Seaquist & Odegard; Marvil)

How fast? 4)The cool/warm phase



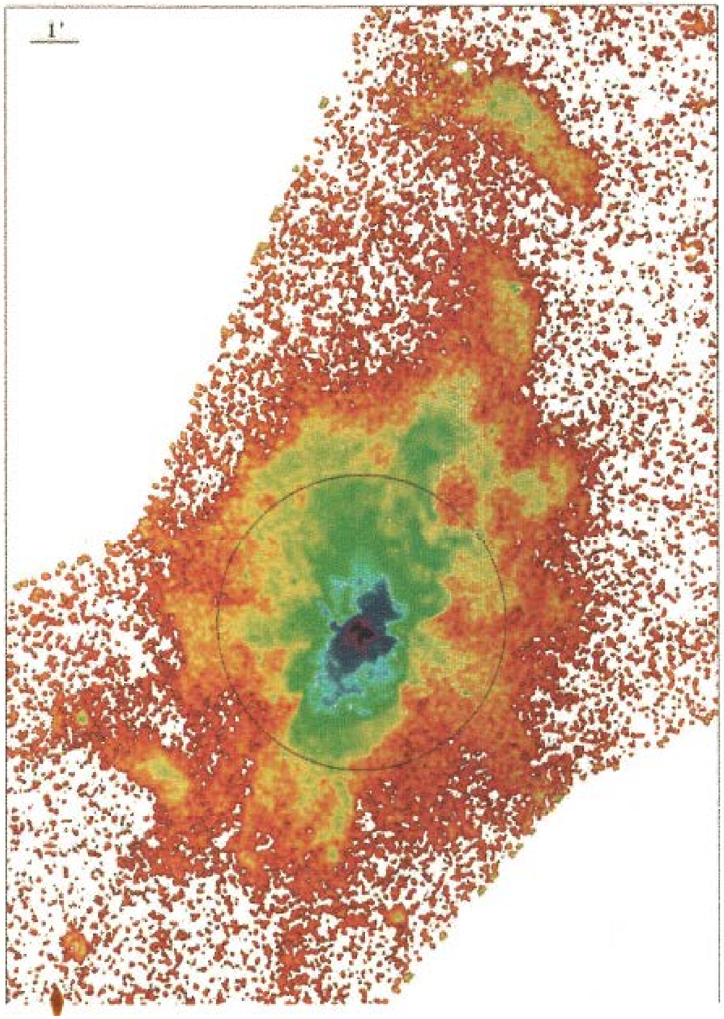
Transition from super-bubbles (in dwarf starbursts) to blow-out for SFR > few M_sun/yr

Dwarf Starbursts: Super Bubbles



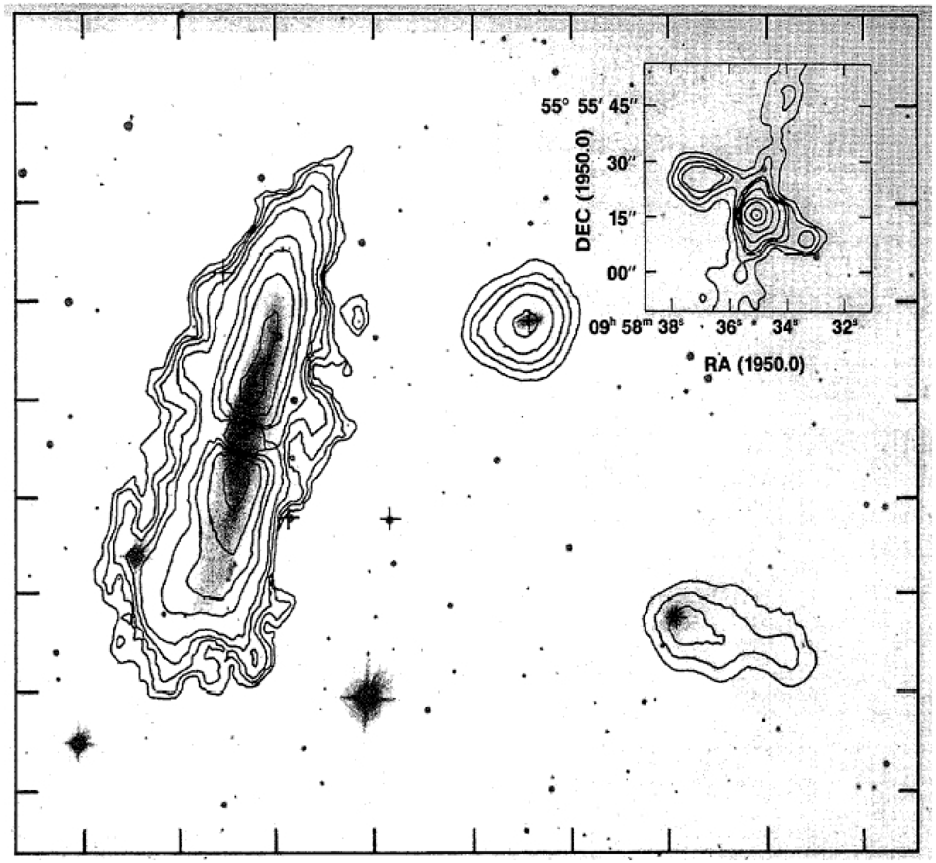
- Low energy injection rate and large ISM scale-height keep the gas confined (Meurer et al.)

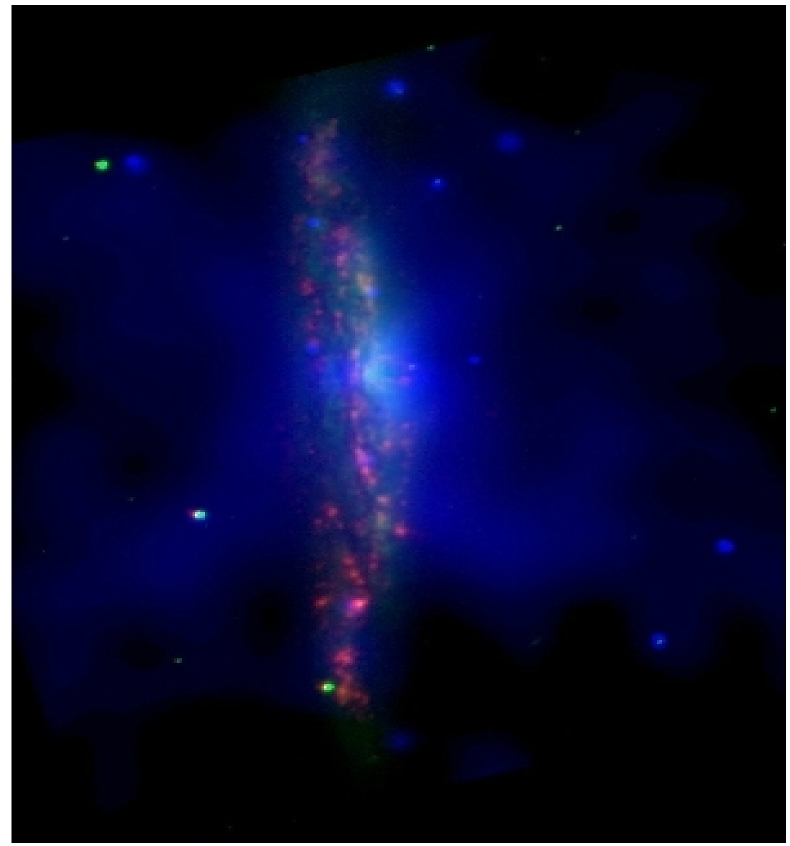
How far do they travel?



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

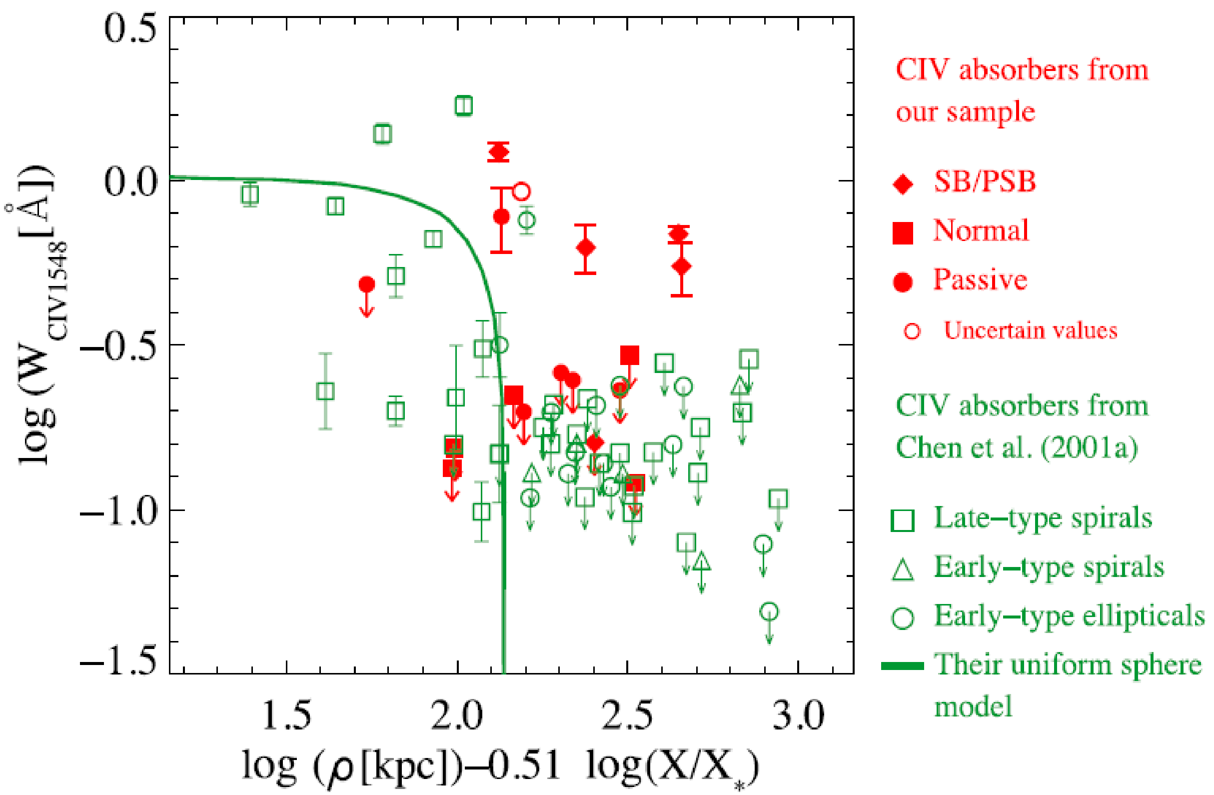
Ram pressure stripping of HI in a companion galaxy





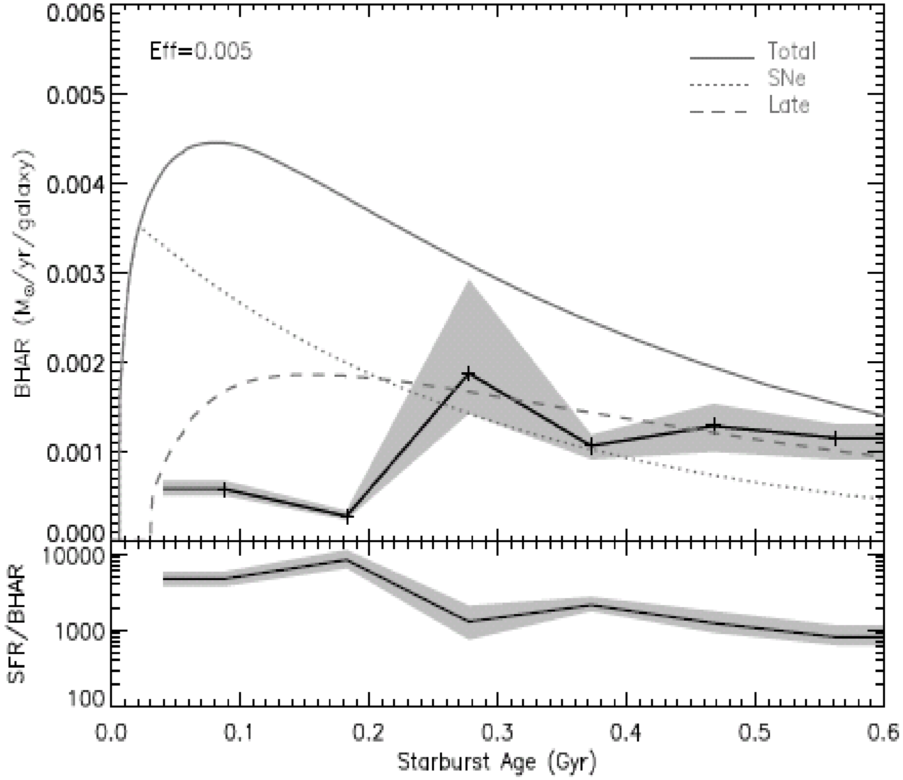
- NGC 3079 (Irwin et al.)

CIV absorption probes large 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)

Stellar feedback suppresses BH fueling?



- Black hole growth is suppressed until the supernova rate drops
- Accretion rate then tracks mass loss from intermediate mass stars
- Roughly 0.5% accreted by black hole
- 1000:1 ratio of new stars to black hole mass growth over the event

Wild et al

Summary

- Outflows from local starburst galaxies are driven *primarily* by the thermalized ejecta from massive stars
- *This "wind fluid" itself is an energetic, tenuous fluid seen in hard X-ray emission only in the starburst core*
- (Nearly) everything we see is a result of the interaction of the wind fluid with ISM and CGM
- *The wind fluid contains the bulk of the energy and newly synthesized metals that may be delivered to the CGM/IGM*
- Starburst-driven outflows are multiphase, so…
- *Beware of inferences at high-z based on probes of only the cooler wind phases*